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Study of the Transient Voltage Behaviour of the Present ITER TF Coil Design for Determination of the Test Voltages and Procedures

S. Fink, W. H. Fietz, A. M. Miri, X. Quan, A. Ulbricht

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S. Fink, W. H. Fietz, A. M. Miri*, X. Quan*, A. Ulbricht

Institut für Technische Physik

* University of Karlsruhe, Institut für Elektroenergiesysteme und Hochspannungstechnik

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Abstract

ITER is designed as an experimental tokamak fusion reactor in which the conditions for controlled fusion reactions will be created and maintained. The confinement and control of the reacting plasma is performed by superconducting magnets. Insulation faults are regarded from the ITER International Team as the most probable cause of fusion magnet failure. Considering the difficulties involved in the replacement of a toroidal field coil in the ITER magnet system and the different problems occurring during high voltage tests of the ITER model coils further improvements in several aspects of high voltage technology for the realisation of the ITER magnets are indispensable.

One of these aspects is the consideration of the transient electrical behaviour because it is well known that fast changes of voltages (e. g. lightning and switching impulses) may cause a non linear voltage distribution on the coil turns and possibly excite resonances within a large coil. Such high voltage stress can cause local overloading and irreversible destruction of the insulation system.

This report will present the calculation of the terminal voltages within the ITER TF coil system and the voltage stress of the three insulation types (ground, radial plate and conductor insulation) within an individual ITER TF coil for the fast discharge and two fault cases.

An electrical network model for the ITER TF coil is developed and simulated with the code PSpice. The internal inductances and capacitances as well as the capacitances to ground for the establishment of this network model are determined. Skin and proximity effect as well as the damping caused by eddy currents in the stainless steel radial plates, in which the conductor is embedded, are calculated by the FEM code Maxwell. For the complete TF circuit, composed of 18 TF coils and 9 fast discharge units, an additional network model is set up and implemented with the code PSpice.

Due to the large size of the individual ITER TF magnets the resonance frequency is lower than for the TF model coil. It was also determined that the three types of insulation within a single TF coil are stressed with a nonlinear voltage distribution under a fast discharge condition. The non linear voltage distribution is enhanced in case of fast excitations applied in consequence of ground faults. Therefore the test voltages have to be defined in consideration of the stresses caused by fast discharges and realistic fault cases to ensure a reliable operation during the foreseen ITER lifetime. Proposals for the high voltage test procedures will be discussed based on the calculated voltage stress and the experiences gained during the ITER TF Model Coil test. Several acceptance criteria are suggested and recommendations are added to avoid unacceptable stress during the high voltage tests.

Studie über das transiente elektrische Verhalten der aktuellen ITER Spulenkonstruktion zur Bestimmung von Testspannung und Testverfahren

Zusammenfassung

ITER ist ein experimenteller Tokamak Fusionsreaktor, in dem die kontrollierte Kernfusion gezündet und aufrechterhalten wird. Einschluß und Regelung des Plasmas erfolgen hierbei mit supraleitenden Magneten. Vom "ITER International Team" wird als wahrscheinlichste Ursache für einen Ausfall eines Großmagneten ein Isolationsfehler angesehen. Aufgrund der schwierigen Austauschbedingungen für Toroidalfeldspulen (TF) im ITER Magnetsystem und der verschiedenen Probleme, die sich während der Tests der ITER Modellspulen gezeigt hatten, sind für die ITER Magnete Verbesserungen in unterschiedlichen Bereichen der Hochspannungstechnik erforderlich.

Besonders wichtig ist die Berücksichtigung des transienten elektrischen Verhaltens, da schnelle Spannungsänderungen (z. B. Blitz- und Schaltstoßspannungen) nichtlineare Spannungsverteilungen und Resonanzen in Spulen erzeugen können. Derartige Hochspannungsbeanspruchungen können örtliche Überlastungen und Zerstörungen am Isolationssystem verursachen.

Dieser Bericht zeigt für die Schnellentladung und zwei Fehlerfälle die Berechnungen der Spannungen an den Spulenenden im ITER TF System sowie die Spannungsbelastungen der 3 Arten elektrischer Isolierung (Erd-, Radialplatten- und Leiterisolation) innerhalb einer ITER TF Einzelspule.

Für eine ITER TF Einzelspule wird das elektrische Ersatzschaltbild erstellt. Hierzu werden die internen Induktivitäten und Kapazitäten sowie die Erdkapazitäten bestimmt. Mit FEM-Berechnungen werden Skin- und Proximity-Effekt sowie die von Wirbelströmen in den Radialplatten verursachten Dämpfungen ermittelt. Ein weiteres Netzwerkmodell wird für das aus 18 TF Einzelspulen und 9 Schnellentladeeinheiten bestehende ITER TF System erstellt.

Das Ergebnis einer niedrigeren Resonanzfrequenz für die TF Spule als für die TF Modellspule kann auf die größeren Abmessungen der TF Spule zurückgeführt werden. Für die Schnellentladung ergibt sich für alle 3 Isolierungsarten eine nichtlineare Spannungsbelastung, die im Falle eines Erdschlusses verstärkt wird. Zur Sicherstellung eines zuverlässigen Betriebes für die vorgesehene Einsatzdauer von ITER muß die Festlegung der Testspannungen somit unter Berücksichtigung von Spannungsbelastungen erfolgen, die bei Schnellentladungen und realistischen Fehlerfällen auftreten können. Ausgehend von den berechneten Spannungsbelastungen und den Erfahrungen, die während dem ITER Modellspulentest gemacht wurden, werden Vorschläge für Testverfahren diskutiert und verschiedene Abnahmekriterien vorgeschlagen. Als Ergänzung werden Sicherheitsempfehlungen vorgestellt, die der Verhinderung unzulässiger Belastungen während der Tests dienen.

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1 Introduction

Large magnet systems have relative low resonance frequencies [Sih96b]. If the ITER coil system is excited by transient voltages during fast discharge or a fault with relevant portions in the range of the resonance frequency, it will cause a high dielectric stress of the electrical insulation system. The most stressed areas may have no possible access for voltage measurement. It is therefore necessary to verify by calculation if the rated and fault condition stress of a proposed coil system design is compatible with the dielectric strength of every kind of proposed insulation (e. g. conductor insulation, radial plate insulation).

High voltage acceptance tests at the factory or tests during assembly and commissioning of the magnets are indispensable for the qualification of the coils for a reliable operation and handling of specified fault cases.

This report presents the calculation of the maximum voltages for each kind of TF coil insulation during fast discharge and two fault cases. In addition, proposals for the high voltage tests are shown and safety aspects are described to prevent damaging caused by over stressing during the tests.

2 ITER Toroidal Field coil system description

2.1 ITER TF single coil

The insulated conductor of an ITER TF coil is embedded in 7 stainless steel plates (so called radial plates) to handle the occurring Lorentz forces. The radial plates are insulated by vacuum impregnation and stacked to a winding pack. This winding pack is enclosed in a D-shaped stainless steel case (Fig. 2-1).

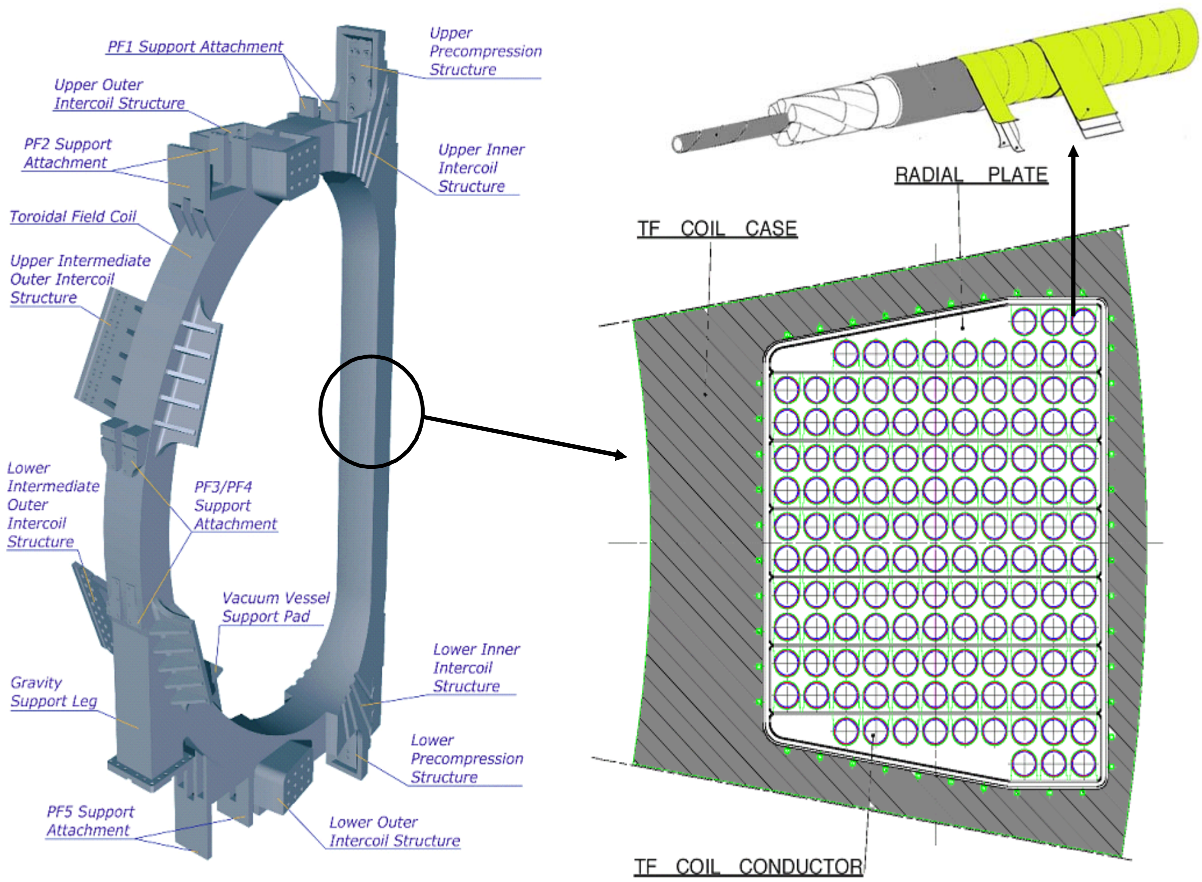

Fig. 2-1 D-shaped steel case, cross section of this steel case in the mid plane of the straight section (inboard leg) and the construction of the conductor insulation of the ITER TF coils.

The winding terminals looking out at the case on the lower curved part, the other double pancake joints are contained within a local extension case (terminal and joint area). Some of the coil parameters are summarised in Tab. 2-1. Parameters of the TF Conductor are shown in Tab. 2-2. [DDD01a].

Length of the coil centre line	34.1 m
Cross section of the steel at inboard mid plane (jacket, radial plate, case)	0.568 m^2
Cross section of the steel at outboard mid plane (jacket + radial plates, case)	0.643 m^2
Materials: TF inboard leg (forgings) TF outboard leg including OIS (castings) Radial plates and covers OIS bolts, IIS poloidal keys, PCRs bolts	 EK1 steel EC1 steel SS 316LN Inconel 718

Tab. 2-1: Coil parameters [DDD01a] (OIS: Outer Intercoil Structures, IIS: Inner Intercoil Structures, PCR: Precompression ring)

Total number of conductor turns per coil (circular steel jacket type)	134
Number of turns per pancake (from side pancake to middle pancake)	3-9-11-11-11-11-11
Coolant inlet temperature	≤ 4.6 K
Type of strand	Nb_3Sn
Operating current (kA)	68.00
Nominal peak field (T)	11.8
Operating temperature (K)	5.0
Operating strain (%)	- 0.5
Equivalent discharge time constant (s) hot spot	15
Tcs (Current sharing temperature) (K)	6.03
Iop/Ic (Operating current/critical current)	0.765
Cable diameter (mm)	40.2
Central spiral outer x inner diameter (mm)	8x6
Conductor outer diameter (mm)	43.4
Jacket material	Steel 316LN
SC strand diameter (mm)	0.71
SC strand cu : non-cu ratio	1.30
Cabling pattern	(((3x41)x4+1)x4+1)x6
SC strand number	1080
Cu core 2/3/4 stage (mm)	1.0/2.6/3.7
Local void fraction (%) in strand bundle	34.2
SC strand weight/m of conductor (kg/m)	4.273

Tab. 2-2: TF conductor [DDD01a]

The insulation between the conductor and the radial plate is a polyimide glass sandwich with a nominal thickness of 1.25 mm; the remaining 0.75 mm is filled with epoxy resin and additional layers of glass insulation as shown in [DRA01a].

The insulation between the adjacent radial plates has a thickness of 5 mm [DRA01b]. This insulation consists of an interleaved polyimide and dry glass wrap.

The insulation between the radial plate and the case has a thickness of 11.2 mm at the side towards other coils and 14 mm at the inner leg and outer leg sides [DRA01c].

2.2 The Fast Discharge Unit (FDU)

A fast discharge is initiated in case a quench has been detected in one of the coils or other specified disturbances in the operation of the magnet system (compare with Fig. 3-2, the short circuit path for continuous current parallel to the vacuum circuit breaker FDU_S2 is not drawn; the discharge resistor is drawn as switch U2 (with an increasing resistance value after starting of heating)). The coil current is then commutated from the bypath in the vacuum circuit breakers path and the power supply is short circuited and switched off. Then the make switches in each FDU activate the counter pulse capacitors, which have been charged to 8 kV before. During the discharge of the counter pulse capacitors a counter current flows through the vacuum circuit breaker that compensates the coil current. In the zero-crossing of the current, the arc in the vacuum circuit breaker extinguishes and the coil current is commutated to a dump resistor.

2.3 The ITER TF coil system

The TF coil system consists in 18 TF coils and 9 FDUs (Fig. 2-2). Every coil is connected at one terminal with a grounding resistor. During fast discharge the current I leads to a voltage drop of $U = R \cdot I$ over the discharge resistor R of each FDU. Due to the symmetrical grounding of the FDU the voltages at the FDU terminals are $\pm U / 2$. The connected coil has therefore on the terminal of the FDU side a voltage of $\pm U / 2$, too. In a perfect symmetrical system the other coil terminal (which is connected to the adjacent coil) has 0 V.

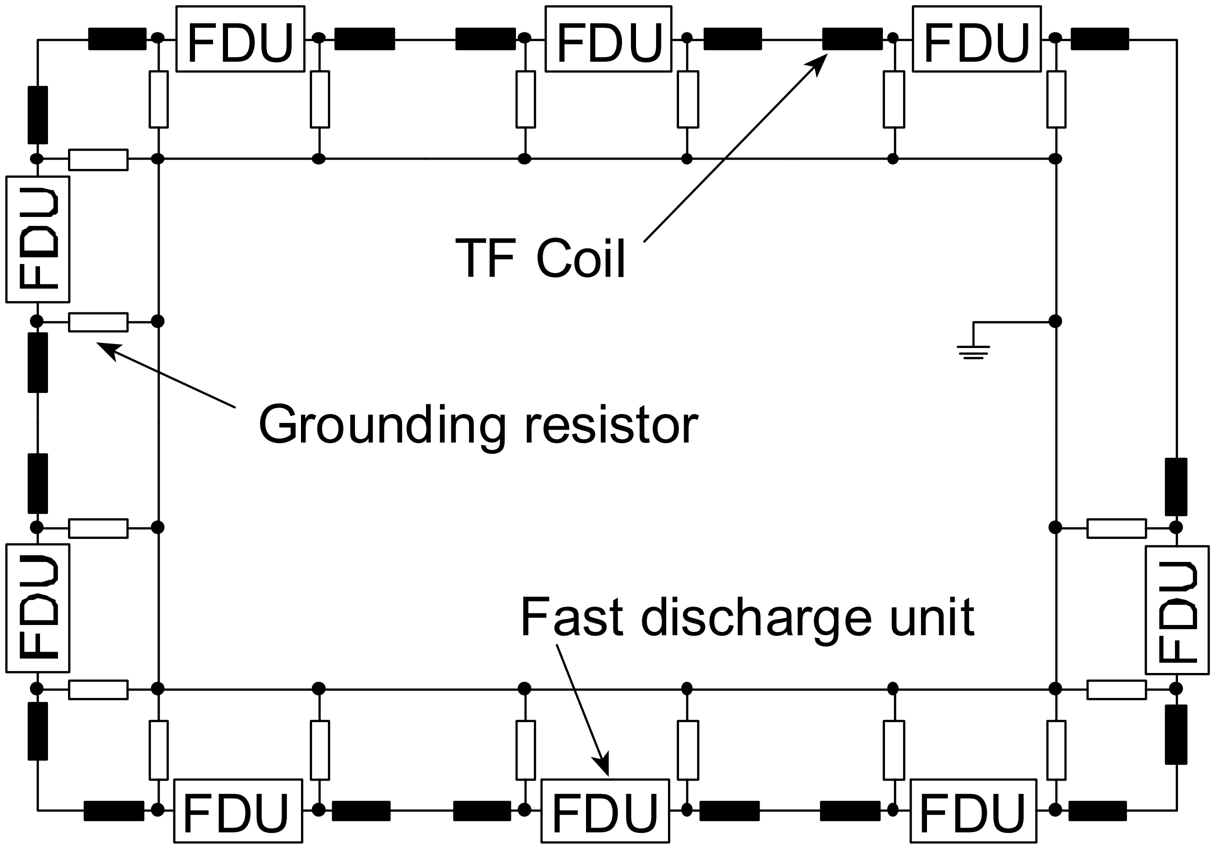

Fig. 2-2 Simplified analogue circuit of the TF coil system during fast discharge (power supply already disconnected).

3 Network models for ITER TF

A key task of this report is the calculation of the maximum voltage for each kind of insulation within the ITER TF coil system. Based on the experience gained from the calculations for the ITER TF Model Coil a network model with lumped elements is established and solved with the code PSpice [ORC98].

From [Sih96] it is known that the impedances of the coil are strongly frequency depending but the frequency dependence of the lumped network elements cannot be integrated in a PSpice network model directly [Mir99]. The strategy for the solution of this problem consists in several steps.

In the first step network models of a single coil were established for the value of the natural frequency (for ITER TF: 50 kHz), for a rise time in the range of few ms (chosen: 1 kHz) and for the DC case.

The single coil models are excited at their terminals with a voltage to investigate the internal voltage distribution and find out the amount and location of the maximum internal stress for every kind of insulation. The maximum voltages across a coil in the TF system during fast discharge and two fault cases have been calculated and are taken as excitation. Then the calculation is repeated with the terminal voltages that appear on the coil with the maximum voltage to ground within the TF system.

For the calculation of the terminal voltages superconducting (R = 0) single coil models are taken because the transport current in the conductor changes only very slowly and the normal conducting zone is neglected. For the determination of the internal voltages, within a single coil the 1 kHz and 50 kHz models (and not the DC model) are used because the transient current occurs in a higher frequency range.

3.1 Network model for an ITER TF single coil

Each TF Coil consists of 134 turns embedded in 7 radial plates (Fig. 2-1). Each turn has been modelled by a resistance, a capacitance and an inductance. The 7 double pancakes are connected in series. The capacitance represents the insulation between the turn and the radial plate. The radial plates have capacitive coupling between each other and to the grounded case.

Fig. 3-1 shows the built network model for one TF coil. For the calculation of the voltages the programme PSpice [ORC98] has been used. The frequency dependent damping of the radial plates was treated by a FEM model (Maxwell [MAX99]).

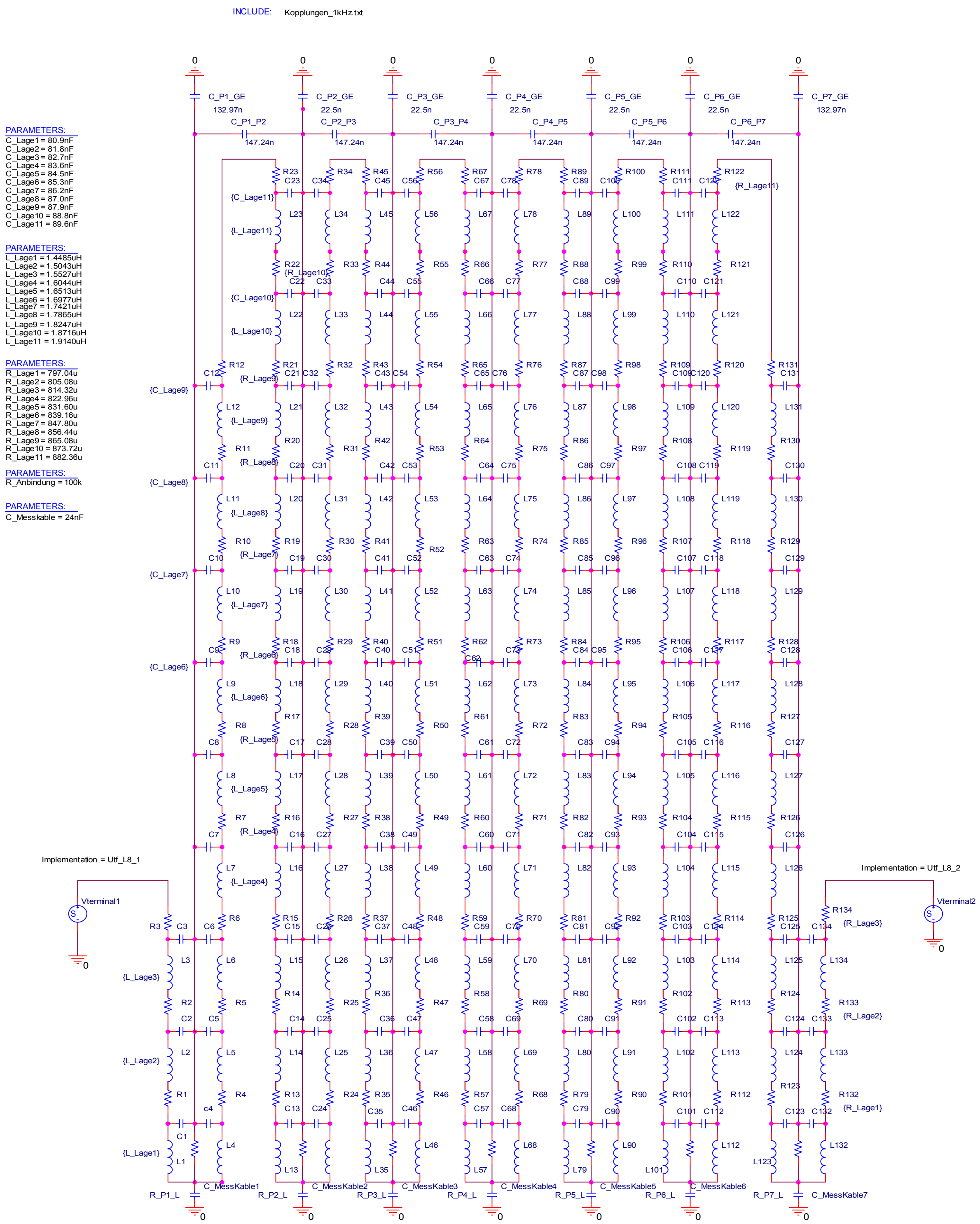

Fig. 3-1 Network model of the ITER TF single coil for a frequency of 1 kHz

3.1.1 Resistances

Measurements have shown that the superconducting filaments of cable-in-conduit conductors of the type similar to the ones used for ITER TF do not participate in high-frequency oscillations [Sih96b]. A possible reason is that at 4 K the skin depth in the copper matrix surrounding the filaments is very small already for frequencies of some kHz. Furthermore, the flux penetration of the superconductor is also related to a time constant. In other words, the transient current occurs in the surrounding copper matrix. Hence, for the network model, the superconducting strands were regarded as normal conducting. For the total DC resistance of the coil, a value of 1.0 mΩ was found, assuming an RRR (Residual Resistance Ratio) of the stabilising copper of 120 [Mei03].

It can be proved that there is no effective skin- and proximity effect for the conductor as a whole. A frequency dependent resistance is only effective due to local current displacement inside the strands by a local skin-effect, and the local proximity effect among the strands. To calculate the frequency-dependent resistance R_{skin} (f) an analytic formula or a finite element method (FEM) can be used. The FEM (it refers to the programme Maxwell [MAX99]) has been chosen to do the calculation of the ratio of resistance by certain frequencies to DC values. Some results are shown in Tab. 3-1.

Resistance Ratio	Frequency / Hz
25	100
37	170
108	470
108	1k
533	20k
860	50k

Tab. 3-1: Resistance ratio compared to the DC copper resistance.

3.1.2 Conductor to radial plate capacitance

The capacitance between turns and radial plates can be regarded as cylindrical capacitors. The capacitance between one turn of layer k and the radial plate is given by

$$C_{k,TtoR} = 2\pi\varepsilon_0\varepsilon_r \frac{l_k}{\ln(R_a / R_i)} \qquad (3.1)$$

where R_a and R_i are the outer and inner radius of the winding. l_k is the length of the winding of "layer" k (k =1…11). (Although ITER TF is no layer coil the turn numbers are called "layers" to distinguish from the pancakes.)

3.1.3 Radial plate to radial plate capacitance

The capacitance between adjacent radial plates can be regarded as plate capacitors (Fig. 2-1). The capacitance between two radial plates is given by

$$C_{RtoR} = \varepsilon_0 \varepsilon_r \frac{L \cdot W}{d} \tag{3.2}$$

where L = 34.1 m (Tab. 2-1) is the length of the coil centre line. W is the width of the radial plate in the direction from the layer 1 to layer 11 and d is the insulation thickness between radial plates. This formula has a good approximation compared with the formula with the application of different radiuses.

3.1.4 Ground Capacitance

There are capacitances between the grounded case and the radial plates. For the calculation of additional capacitances of the outermost radial plates, equation 3.2 applies.

3.1.5 Instrumentation cables and current limiting resistors

An optimization study considering the transient behaviour gave the best results that means the lowest transient voltage if the potential of the "centre" of the double pancake is connected with the radial plate potential [Sih96b]. For reducing the fault current and the caused insulation damage in case of a short between conductor and radial plate, a current limiting resistor has been introduced. This concept has been successfully checked during the ITER TF model coil tests with current limiting resistors outside the vacuum vessel. The present ITER design with the current limiting resistors directly integrated in the helium pipe insulation has several disadvantages, e. g. an influence to the measurement accuracy during transient voltage measurement. Hence it is assumed that at least for the helium inlet cables this concept is improved by taking the current limiting resistors to a magnet panel box outside the cryostat. The instrumentation cables for the helium inlet cables of 60 m length cause considerable ground capacitances. It is assumed that the capacitance per unit length is 0.4 nF / m which is in agreement with the data of the cryogenic instrumentation cables used during the ITER TFMC test. The resistance and the inductance of the instrumentation cables are neglected. The input resistance of the measurement equipment was taken as infinity. Hence for the instrumentation cables only the capacitance was included in the model.

The radial plate potential is connected with the potential of the embedded double pancake at the helium inlet. The resistance value is 2 * 50 kΩ = 100 kΩ according to [DDD01b]. The cable lengths for the connection of these resistors are neglected because it is assumed that the wiring for this connection is made relatively short.

The capacitance of the double pancake joint cables are neglected because for these cables the current limiting resistors are assumed to be integrated in the pipe insulation at the input of the cables which reduces the transient influence.

3.1.6 Self and mutual inductances

The DC self and mutual inductance values are calculated using analytical formulae for circular cylindrical conductors [Gro73]. The self inductance of one turn of layer k is given by

$$L_k = \frac{\mu_0}{2\pi} l_k \cdot (\ln(\frac{4 l_k}{d}) - 0.75) \tag{3.3}$$

where l_k is the length of layer k and d is the diameter of the winding.

The mutual inductance between k^{th} winding and j^{th} winding is calculated by using the Neumann equation

$$M = \frac{\mu_0}{4\pi} \oint_{l1} \oint_{l2} dl_1 dl_2 / r_{12} \tag{3.4}$$

where:

l_1 is the k^{th} winding and l_2 is the j^{th} winding,

dl_1 is the length element of the k^{th} winding,

dl_2 is the length element of the j^{th} winding,

r_{12} is the distance between dl_1 and dl_2.

The total inductance of one TF coil was calculated in the Programme MATLAB [MAT02] with the value of 0.3498 H, which agrees well with the value of 0.349 H found in literature [DDD01a].

The calculation for the DC values of self and mutual inductance have been discussed above. But during the transient process, there are many different frequency portions, which are included in a voltage signal or a current signal. To get the right frequency response it is necessary to set the inductance value in the model for the corresponding frequencies. That means the frequency-dependent inductances need to be calculated. This has been done with the use of the Finite Element Method (FEM), because the eddy current effect can't be described through analytical formulae.

3.1.7 The first dominant resonance frequency of an ITER single coil

To make a better statement about the frequency response to the stimulating signals, which contain different frequencies, it is necessary to know the first dominant resonant frequency or so called eigenfrequency of the single coil network model.

To get that an iterative method was used, i.e. all inductances and resistances were set as DC values in the coil network model, then the coil was excited with a step function to see which frequency is the first dominant. After that the value of the inductances and resistances was set up for this frequency in the model and again stimulate with a step function and so on until to the eigenfrequency, which doesn't change any more. This means that the frequency which was taken for the calculation of the network elements and the calculated resonance frequency with these network elements are the same.

For the ITER TF single coil 50 kHz is the calculated resonance frequency obtained by this method.

3.1.8 Admissibility of the single coil model

The admissibility of the network model can be evaluated by calculating the valid frequency range. The propagation velocity is given by

$$c = \frac{c_0}{\sqrt{\mu_r \varepsilon_r}} = 1.5 \cdot 10^8 \, \frac{m}{s} \tag{3.5}$$

where $\mu_r = 1$ and $\varepsilon_r = 4$.

The maximum allowed frequency for the lumped parameter of a wave through the winding with the length of 34.1 m is $f_{max} = c / (8*l) = 1.1$ MHz. As calculated before the first dominant eigenfrequency of our model is 50 kHz, far below 1.1 MHz.

Here the critical value of λ / 8 was used to be regarded as standard if a model should be modelled as a lumped circuit or distributed circuit while usually the value of λ / 60 was used in the power electric system and λ / 4 was used in communication technique [Mir00].

3.2 Model for the ITER TF Fast Discharge Unit

Besides the ITER coils the fast discharge units (FDU) are the components of the ITER TF system. The network model, shown in Fig. 3-2, included a counter pulse capacitor and snubber circuits. The bus bars which connect the FDU components are represented by inductances. The parameters, which are shown in the FDU, are taken from the second version from [DDD01c] where the saturable inductors are eliminated and the capacitor banks were increased by a factor of 2 compared with the first version.

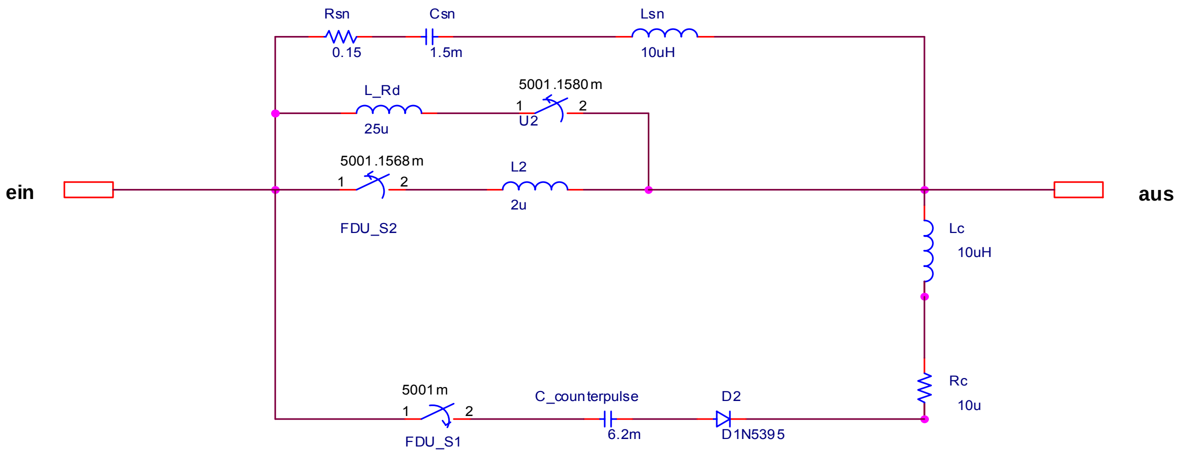

Fig. 3-2 Analogue circuit of the Fast Discharge Unit (Program: OrCAD Capture).

3.3 Network model for the ITER TF coil system

For the calculation of the maximum terminal voltages on the ITER TF single coil the complete system with 18 TF coils and 9 FDUs must be established and examined. In a first step a network according to Fig. 2-2 was established which contains the coils as superconducting inductances. The terminal to neutral and the neutral to ground resistors are assumed with 500 Ω. The values of the coupling factors are taken from [DDD01a].

The quality of this first step model is good enough when the event of discharge is only analysed without fault conditions that cause fast excitations. But in case of a short circuit on the coil terminals the capacitances between the coil terminals and the ground should be considered which exist between the insulations of the radial plates and ground. A replacement of the 18 pure inductances by 18 coupled single coil models would cause huge calculation time. Therefore the capacitances were summarised and distributed within the circuit.

In the network model of the system the earth capacitances of each coil are divided into two parts. One part represents the resulted insulation between the 7 radial plates and the ground, additionally the resistance with the value of 1 Ω formed by the case has been taken into account as well. Another part represents the capacitances formed by the helium inlet instrumentation cables, therefore additionally the inductance of 5 µH from the instrumentation cable has also been considered. The network model of the complete system with the simplified coils is shown in Fig. 3-3.

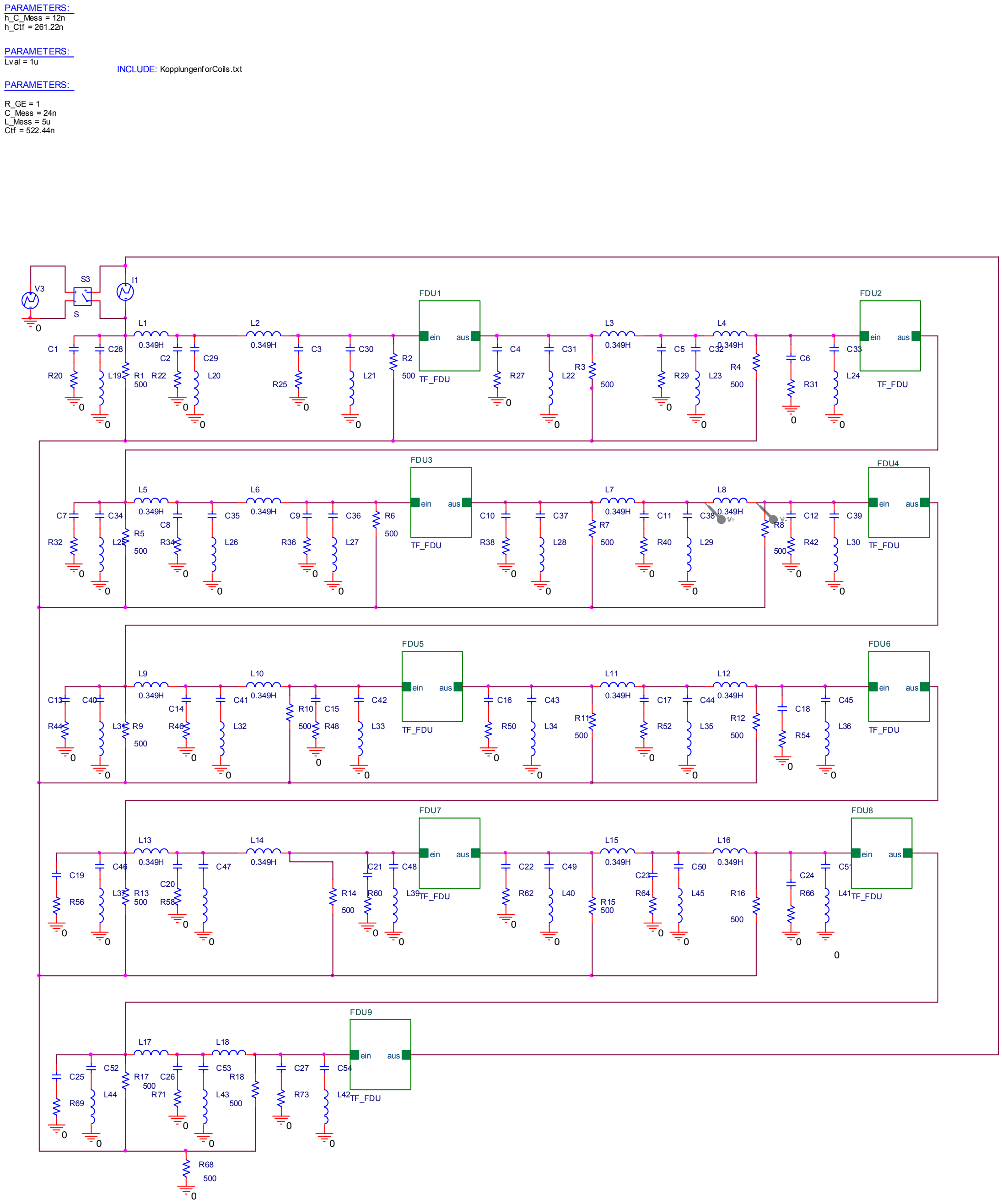

Fig. 3-3 Network model of the ITER TF coil system. The 9 FDUs are shown as blocks.

4 Calculated voltages in the frequency domain

A measurement in the frequency domain with a low voltage frequency generator will be useful for the comparison of the single coil network model with the real world ITER TF coil behaviour. The frequency generator will be connected with the terminals and the voltage can be measured at the instrumentation cables, which are connected with the helium inlet potentials. The measured values should be compared with prepared simulated results.

Hence a calculation of the transfer functions between the helium inlet voltages and the not grounded terminal voltage side was performed. An rms voltage value of only 1 V was simulated to ensure a non critical stress even in the resonance case.

The voltages are shown in Fig. 4-1 for the excitation with 1 V of the 1 kHz and 50 kHz model. In a mathematical view the functions can only be correct for 2 frequency values. The first one is at 1 kHz for the 1 kHz model and the second one at 50 kHz for the 50 kHz model.

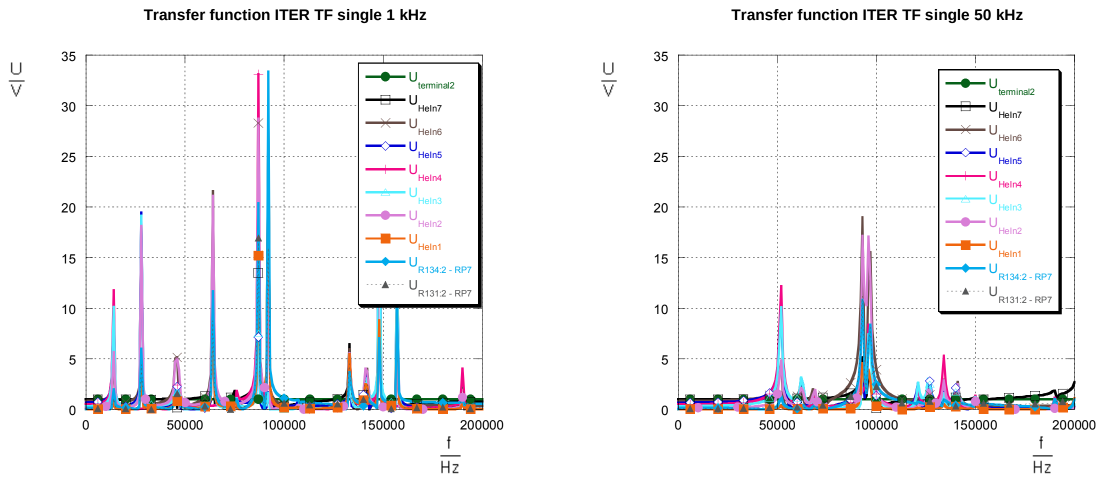

Fig. 4-1 Voltages for the 1 kHz (left) and 50 kHz (right) model. The models are excited with 1 V at one terminal. The other terminal is grounded.

For the transfer functions of the 1 kHz model the first resonance frequency appears above 10 kHz which means that no resonance is to be expected for voltage excitations with rise times in the range of few ms.

For the transfer functions of the 50 kHz model the first resonance appears around 50 kHz. For a good prediction of the behaviour of a real world ITER TF coil the natural frequency is about 50 kHz. A second dominant resonance was calculated for about 100 kHz. Since the 50 kHz model delivers for frequencies above 50 kHz too low frequency values it can be assumed that the resonance appears at a higher value than 100 kHz.

5 Calculated voltages for the fast discharge and two fault cases

For the calculation of the maximum voltage stress for every type of insulation the TF system model is operated in fast discharge mode. In the fault case the additional events are included in the switching sequence. All 18 coils are examined to identify the coil with

- the highest terminal to terminal voltage,

- the highest terminal to ground voltage.

The voltage data for both terminals of these coils are collected for each case and used for the excitation of the TF single coil. The maximum stress within the coil was calculated for every type of insulation and for every excitation to find an overview for the expected load under rated and fault conditions and give the basis for the determination of the test voltages. The voltage waveforms are presented in detail in the appendix.

5.1 Fast discharge

The stored energy in the coils should be discharged within a time constant of about 11 s [DDD01d] (in other references 15 s [DDD01a]) if a quench is detected. For the simulation of this event the TF coil system (Fig. 3-3) is charged with a current source of 68 kA and stabilised. The transport current flows through all coils and the short circuit path of the FDUs because all coils and FDUs are in series. The event of a quench detection is assumed for t = 5 s. Then the current source is switched off and the FDUs begin to operate.

During current operation in a real discharge circuit the current will flow through a bypass switch which can carry continuously 68 kA. After detection of a quench the current is commutated in the vacuum breaker path. But this switching sequence is not necessary for the calculation of the voltages and neglected. Therefore the short circuit path of the FDU (Fig. 3-2) is only represented by the vacuum breaker (FDU_S2 in Fig. 3-2) and an inductance.

After 1 ms (t = 5.001 s) the make switch (FDU_S1 in Fig. 3-2) closes and the counter pulse current starts to flow through the circuit caused by the discharge of the capacitor bank C_counterpulse (initial condition U_C = - 8 kV). This current cancels increasingly the current in the short circuit path because it runs in the opposite direction as the transport current. After the current through the vacuum circuit breaker in the short circuit path reaches a zero-crossing and the arc in the circuit breaker extinguishes the circuit breaker opens (t = 5.001 156 8 s). The coil current commutates from the short current path to the dump resistor path and begins to decrease, resulting in a discharge voltage U across the discharge resistor.

Due to the symmetrical "soft grounding" of every FDU with the neutral to ground resistors the voltage at the FDU terminal is ±U / 2 (i.e. at one terminal the potential to ground is –U / 2 and the other terminal has a potential to ground of +U / 2). All terminals of the coils which are connected to a FDU are therefore at ±U / 2, too. Every pair of coils has a combination of terminals with ±U / 2 and because both coils have the same impedance the terminals which are connected with another coil terminal are at ground potential. Hence the voltage drop over each coil is U / 2.

For the simulation of a such a perfect symmetrical system, it is sufficient to calculate one voltage waveform of any coil terminal adjacent to a FDU. (The difference may only be polarity.). The maximum voltage value was calculated as 3.47 kV, which is in good agreement with [Bar01]. The 10% to 90% rise time of the terminal voltage from zero point to maximum voltage is 1.6 ms. The calculation of the voltage of the other terminal is not necessary because it is on ground potential. Hence the maximum voltage to ground is identical with the maximum voltage between both terminals.

The calculated terminal voltage of the ITER system is then used as the stimulating voltage for the TF single coil models (1 kHz and 50 kHz) to calculate the maximum insulation stresses and their locations. For both models the maximum ground insulation appears at terminal 2 to ground with 3.47 kV. For the radial plate and conductor insulation the values of the two models are slightly different. Taking the values for the 1 kHz model (which is obviously more relevant for the calculated rise times in the ms range) the maximum voltage between two radial plates is 0.65 kV and the maximum voltage between radial plate and conductor is 0.58 kV.

5.2 Fast discharge with failure of 2 FDUs

For the simulation of a fast discharge with the failure of 2 FDUs the initial conditions and switching sequence are the same as during fast discharge without a fault with the exception of the vacuum breakers of the FDU2 and FDU3 which do not open. The pyro breakers (not included in the model) of the two FDUs with the malfunction are not activated. Hence the 18 coils are only discharged by the 7 remaining discharge resistors.

The simulation with the TF system shows a maximum voltage U = 3.6 kV over coil 14 and coil 15. The misbalancing of the grounding system leads to a high potential lifting of coil 8 and coil 3. The maximum voltage to ground is for these coils U = ±8.1 kV. The rise time remains in the range of several ms.

The excitation of the two single coil models (1 kHz and 50 kHz) with the two sets of terminal voltages delivers a maximum stress for ground insulation of 8.1 kV. The 1 kHz model delivers a load of the radial plate insulation of 0.69 kV and for the conductor insulation of 0.81 kV.

5.3 Fast discharge with failure of 2 FDUs and earth fault

For the simulation of the fast discharge with failure of 2 FDUs and earth fault it is assumed that the sequence is identical with the case without the earth fault until the maximum terminal to ground voltage occurs at terminal 1 of coil 3. (This voltage value is the highest one in the complete system.)

For the simulation of the breakdown the network model of the coil system was extended by an open switch between the terminal 1 of coil 3 and earth. The time of the maximum terminal voltage for the case with failure of 2 FDUs is t = 5.080 4 s. With a short delay the starting of the breakdown to earth is simulated at t = 5.081 920 s. During 1.2 µs the switch closes, i.e. it changes its resistance to 1 Ω, which was assumed as residual resistance to earth.

This "hard" earthing leads to an additional misbalancing of the system with a potential lifting of terminal 2 of coil 8 from 8.1 kV to 16.4 kV during a rise time of 3.5 ms. This is the maximum potential to earth in the TF system but the maximum terminal to terminal voltage occurs on coil 2 with a value of 13.5 kV.

For the determination of the maximum possible stress of all types of insulation, the excitation of the two single coil models (1 kHz and 50 kHz) are performed with the terminal voltages of coil 2 and coil 8. The maximum stress for the ground insulation appears for both models at a terminal and is identical with the waveform of terminal 2 of coil 8. The maximum of the radial plate and conductor insulation are calculated with the 1 kHz model as 4.8 kV and 4.3 kV with rise times of few µs. Therefore it is important to investigate the 50 kHz model, too, where values of 4.3 kV and 3.7 kV occur.

5.4 Overview of all calculated maximum voltages

The results for the maximum voltage stress of all types of insulation for the fast discharge and the two fault cases are given in Tab. 5-1. It makes no sense for some rise times to be calculated related to a starting voltage of zero. In this case the starting voltage value is given in brackets after the rise time value.

For every case, the maximum value for each type of insulation is coloured in yellow. The maximum value for all cases is marked in red.

All calculated voltages are described more in detail in the appendix.

		No fault Coil voltage and voltage to ground for all coils 3.467 kV				Failure of FDU 2 and FDU 3								Failure of FDU 2, 3 and earth fault at L3:1							
						Coil with maximum coil voltage 3.644 kV: L14 (L15)				Coil with maximum voltage to ground 8.061 kV: L8:2 (L3:1)				Coil with maximum coil voltage 13.49 kV: L2				Coil with maximum voltage to ground 16.35 kV: L8:2			
	fmodel / kHz	location	U / kV	t / s	TA / s	location	U / kV	t / s	TA / s	location	U / kV	t / s	TA / s	location	U / kV	t / s	TA / s (from x V))	location	U / kV	t / s	TA / s (from x kV)
Terminal	1	terminal 2	3.47	8.5 m	1.6 m	L14:2	3.46	8.1 m	1.6 m	L8:2	8.06	80.4 m	17 m	L2:2	9.66	81.9 m	2.4 µ (-1145)	L8:2	16.35	87.7 m	3.5 m (8.06)
	50	terminal 2	3.47	8.5 m	1.6 m	L14:2	3.46	8.1 m	1.6 m	L8:2	8.06	80.4 m	17 m	L2:2	9.66	81.9 m	2.4 µ (-1145)	L8:2	16.35	87.7 m	3.5 m (8.06)
Ground insulation	1	terminal 2	3.47	8.5 m	1.6 m	L14:2	3.46	8.1 m	1.6 m	L8:2	8.06	80.4 m	17 m	DPJ45	10.56	82.7 m	some µs	L8:2	16.35	87.7 m	3.5 m (8.06)
	50	terminal 2	3.47	8.5 m	1.6 m	L14:2	3.46	8.1 m	1.6 m	L8:2	8.06	80.4 m	17 m	DPJ67	10.67	81.9 m	3.7 µ (-1382)	L8:2	16.35	87.7 m	3.5 m (8.06)
Radial plate insulation	1	RP 3 – RP 2	0.650	4.3 m	1.6 m	RP 4 – RP 3	0.614	6.0 m	1.6 m	RP 2 – RP 1	0.686	29.8 m	11 m	RP 6 – RP 5	4.81	81.9 m	6.1 µ (442)	RP 2 – RP 1	1.30	87.8 m	3 m (0.61)
	50	RP 4 – RP 3	0.564	76.8 m	1.6 m	RP 4 – RP 3	0.544	5.9 m	2 m	RP 2 – RP 1	0.700	29.1 m	10.3 m	RP 6 – RP 5	4.33	81.9 m	3 µ (-1.4 k)	RP 2 – RP 1	1.31	86.8 m	3 m (0.62)
Conductor insulation	1	terminal 2 – RP 7	0.584	4.5 m	1.5 m	terminal 2 – RP 7	0.539	6.0 m	1.6 m	terminal 2 – RP 7	0.811	23.2 m	8 m	terminal 2 – RP 7	4.25	81.9 m	2 µs (15)	terminal 2 – RP 7	1.41	86.7 m	3 m (0.57)
	50	terminal 2 – RP 7	0.535	5.2 m	1.5 m	terminal 2 – RP 7	0.544	5.9 m	1.7 m	terminal 2 – RP 7	0.815	23.2 m	9 m	Near DPC joint of PC13 – RP 7	3.66	81.9 m	1.4 µ (0)	terminal 2 – RP 7	1.42	86.7 m	3.5 m (0.6)

Tab. 5-1: Overview about all calculated maximum voltages for all types of insulation

5.5 Remarks to the accuracy of the simulations

The results of the simulation of the electrical transient behaviour of the large scale ITER TF coil system cannot be taken as absolute accurate values. For the simulation a lot of estimations, simplifications, assumptions or neglects were made to use a defined system, which can be handled in a reasonable time. Some of these are listed below. Hence it is recommendable to make an update to the models after the design is totally fixed and eventually after some measurements (e. g. capacitances between conductor and radial plate).

Only the magnetic field of the TF system is considered. Other fields (e. g. from the plasma) are neglected.

The conductor is assumed to be embedded in the middle of the closed groove of the radial plate so that the inner and outer diameter of the conductor insulation are concentrical.

The length of the instrumentation cables is assumed with 60 m and the capacitance of the instrumentation cables is set to 0.4 nF / m.

In contradiction to the actual design it is assumed that the current limiting resistor between helium inlet and radial plate is placed outside the cryostat to improve the measurement of voltages with fast rise times and avoid problems during AC tests. The cable to the helium inlet voltage tap measurement is assumed to be not conducted directly over this resistance. (The wires may be protected with high voltage fuses against shorts of the "data acquisition side".)

For the terminal voltage tap the resistance is assumed to be installed directly at the coil side of the cable. These cable capacitances are neglected and not included in the models.

The normal conductive zone was neglected.

No change of ε_r due to lower temperature or radiation was assumed.

No significant change in the transient behaviour under ambient conditions was assumed due to the low skin depth of copper at 4 K. (This is important to consider an impulse test under ambient conditions as relevant.)

The second version of the FDU was chosen (version without saturable inductance). All FDUs with no malfunction work perfectly synchronised.

The starting resistance of the discharge resistor is assumed as 102 mΩ at 30° C (at 20° C it is only 96 mΩ). The discharge resistor was modelled as a switch which increases its value from 102 mΩ to 240 mΩ in 22 s.

Time steps of the calculation programme (PSpice) are taken in a manner that seems to be reasonable. Sometimes it is not clear if oscillations are caused by numerical instability.

Especially for the earth fault a lot of assumptions are made concerning impedances and times (see 5.3).

6 Tests

Tests for the assessment of the high voltage quality are necessary to ensure a safe operation during the lifetime of the coil. Several tests should be performed during certain steps of fabrication to minimise the effort in case of a necessary repair or improvement. Acceptance tests are necessary after the completion of each coil. In addition tests are required after delivery to the reactor site and after completion of installation as well as after every maintenance period of the machine.

ITER gives also the opportunity to a simultaneous technology development due to the fact that the fabrication of superconducting magnets in that size is a new step on the way to a Tokamak fusion reactor. This is true especially for the partial discharge measurement but also for low voltage high frequency measurement and Schering Bridge measurement.

6.1 Definition of ideal test voltage amplitudes

The dielectric strength of the coil design is related to the expected values which appear during fast discharge and fault cases which are considered as events that must be handled without (additional) damaging of the insulation.

For the following considerations the two fault cases which are examined in 5 are taken as basis.

From the technical point of view the orientation for the choice of the safety factors according to the ones taken for the tests of the ITER model coil with their shorter life time may not be sufficient. In addition a fault in the ITER TF insulation was detected after installation of the complete coil in the vacuum vessel. A higher test voltage may have lead to an earlier fault detection. Comparison with [Sch98] for superconducting power apparatus shows a recommendation for a safety factor of 4.

An other aspect is that in several standards the safety factor decreases if the rated voltage of the electrical device increases. It may therefore be useful to set different safety factor levels or lowest test voltage levels. An additional possible comparison for the conductor insulation is the standard for power transmission cables because during e. g. DC and AC tests the voltage stress acts similar. In [IEC98] the test voltage for electrical type tests is 4 times U_0 (the rated power frequency voltage between conductor and earth) for 4 h. The impulse test peak voltage for a cable with U_0 = 3.6 kV is 60 kV. Taking in mind that events like stressing with lightning-strokes can be excluded and that the rated voltage is not a continuous sinus waveform the test conditions "time" and "impulse test peak voltage" can be reduced for ITER. For routine tests according to [IEC98] the power frequency test voltage is reduced to 3.5 U_0. Standards for reactors and power transformers ([IEC88], [IEC00]) give factors for U_m (highest voltage in equipment) and test voltages which are between 2 and 3 in the relevant voltage ranges.

Tab. 6-1 gives an overview of the first step for the suggested test voltage levels compared with the related calculated voltage stress.

Type of insulation	Fast discharge without fault	Failure of 2 adjacent FDUs		Failure of 2 adjacent FDUs plus earth fault at terminal with maximum voltage to ground		
	Calculated maximum voltage	Calculated maximum voltage	Proposed ideal test voltage	Calculated maximum voltage	Proposed ideal test voltage for DC and AC tests (peak value)	Proposed ideal test voltage for µs impulse tests
Ground insulation	3.5 kV	8.1 kV	18 kV	16.4 kV	34 kV	21 kV at high voltage terminal
Radial plate to radial plate	0.7 kV	0.7 kV	5 kV	4.8 kV	11 kV	(control: U ≤ 11 kV)
Conductor to radial plate	0.6 kV	0.8 kV	5 kV	4.3 kV	11 kV	(control: U ≤ 11 kV)

Tab. 6-1: Calculated maximum voltages and proposed ideal test voltages.

The proposed ideal test voltages derived from the following considerations:

- The standard rule for voltage tests related to single fault events is proposed to be only 2 * U_{fault} + 1 kV. The value is rounded up to integer values (e. g. 2*8.1 kV + 1 kV = 17.2 kV => 18 kV).
- The test voltage for values < 5 kV is taken as 5 kV.
- For radial plate and conductor insulation the higher value is taken for both.

The (terminal) test voltage for impulse voltages with rise times in the range of some µs is reduced to avoid too high stress of radial plate and conductor insulation.

According to the standard for power transformers ([IEC00], chapter 9) repetition of tests on new power transformers are to be performed with 100% and the level is reduced to 80% for most voltage tests of refurbished or serviced transformers, unless otherwise agreed upon. (The 80% level may be ITER relevant for e. g. PD testing after several years of operation.)

The test voltages for the first test should be increased with a certain factor if the manufacturer or the ITER community prefers a higher safety margin for the first test. If the manufacturer wants to have added a certain safety margin for the manufacturing tests the margin must be added to the specified test levels. No limitation in test time or number of tests for the proposed test voltages should be accepted. It is also in the hand of the manufacturer to specify sufficient high test voltage levels when the insulation is incomplete, e.g., no vacuum impregnation to eliminate fabrication faults as early as possible and allow repair.

The increasing of the test voltage must be performed in defined steps related to the maximum test voltage. The proposal is: 10%, 30%, 50%, 70%, 90%, 100%.

6.2 Realistic test voltages

For the DC and AC tests no restrictions compared with the ideal test voltages are necessary, i.e. the (realistic) test voltages are the same as the ideal test voltages proposed in 6.1. For AC tests the peak value is derived from the ideal voltage value.

For an impulse test in the ms range the capacitor bank would have a non realistic size. A generation of such an impulse caused by the charged coil would have several disadvantages (lot of stored energy, expensive, would take a long time). An other possibility is to skip this test taking in mind that a complete set of AC tests on ground, radial plate and conductor insulation gives enough information for rise times in the range of few ms. Especially in combination with an impulse test in the µs range the test program seems to be sufficient.

Taking in mind the discussions of the test voltage waveforms for ITER TFMC it should be stressed that an AC waveform (50 Hz or 60 Hz) seems to be suitable for representative testing of the voltage rise during the fast discharge without earth fault. The large number of voltage cycles (e. g. during 1 min for 50 Hz: 50 * 2 * 60 = 6000 tests per minute) should be no problem for a component that is designed according to the criteria of AC technology, which must be considered as the state-of-the-art in electrical energy systems. A design of a large electrical device according to the short time AC withstand voltage is not reported so far and absolutely not recommendable. A design according to DC testing only is not sufficient because ITER TF is no DC coil.

For the cases without an earth fault, the only excitation with rise times in the 1 µs range is caused by the discharge of the capacitor bank. Because the voltage of such an excitation is expected to remain in the 1 kV range an impulse test with a rise time in the µs range with a terminal voltage of 5 kV is sufficient although this value is lower than the DC and AC test voltages.

A potential distribution for a specific circuit was calculated for the impulse test. It is assumed that a capacitor bank of 150 µF excites the coil. The damping resistor is 0.77 Ω. For this arrangement Tab. 6-2 gives the relationship between the different voltages for the fault case with the earth fault. The calculated maximum voltage stress of 10.7 kV is lower than the value in the ms range. As basis for an excitation an impulse with 21 kV at the high voltage terminal was simulated but the calculated set of voltage stress does not meet the ideal voltage stress exactly, esp. the radial plate and conductor insulation would be stressed not high enough. The voltage at a double pancake would exceed 34 kV (maximum DC test level) if the excitation was increased to a value, which allows to meet 11 kV for radial plate or conductor insulation. Hence the circuit is calculated in a way that limits the maximum double pancake joint voltage to 34 kV. The terminal excitation of 29.6 kV was calculated to achieve this voltage.

Type of insulation	Failure of 2 adjacent FDUs plus earth fault at terminal with maximum voltage to ground			
	Calculated maximum voltage in µs range in the ITER coil system (according to Tab. 5-1)	Ideal test voltage for impulse tests according to the definitions in 6.1	Calculated test voltage for impulse tests with ideal test voltage (= 21 kV) on HV terminal	Proposed test voltage for impulse tests
Ground insulation on HV terminal	9.7 kV	21 kV	21.0 kV	29.6 kV
Ground insulation on double pancake joint	10.7 kV	23 kV	24.1 kV	34.0 kV
Radial plate to radial plate	4.8 kV	11 kV	6.7 kV	9.5 kV
Conductor to radial plate	4.3 kV	11 kV	7.1 kV	10.0 kV

Tab. 6-2: Calculated voltage and test voltages related to the case with failure of 2 adjacent FDUs and earth fault at terminal with maximum voltage to ground.

6.3 Test arrangements

The connection of the helium inlet tap and the radial plate tap must be changed during the high voltage tests. It is therefore recommended to install at least for these cables the current limiting resistors in a magnet panel box and not at the input of the instrumentation cables. The cables from the double pancake joints are always connected with high voltage and can therefore be closed at the end with blind plugs.

6.3.1 Tests on ground insulation

For the ground insulation tests the helium inlet potential is connected directly with the radial plate (Fig. 6-1).

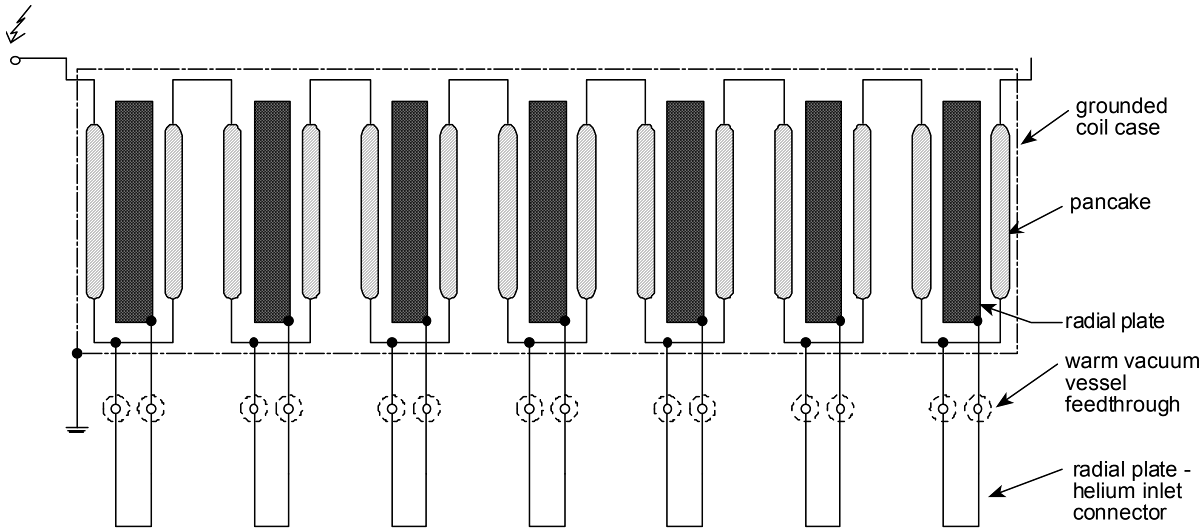

Fig. 6-1 Arrangement G for ground insulation tests.

6.3.2 Tests on radial plate insulation

The radial plates are connected alternately to ground and to inner helium inlet potential for the test on radial plate insulation (Fig. 6-2). The outer radial plates are connected to the helium joint because they are adjacent to the grounded case.

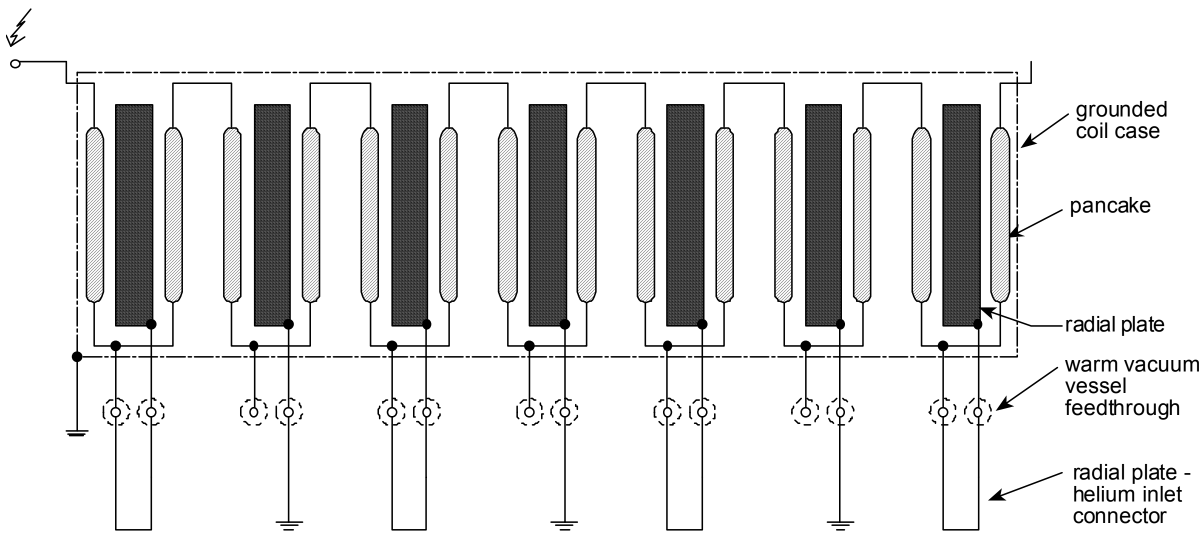

Fig. 6-2 Arrangement R for tests on radial plate insulation.

6.3.3 Tests on conductor insulation

All radial plates are connected to ground for the test of the conductor insulation (Fig. 6-3).

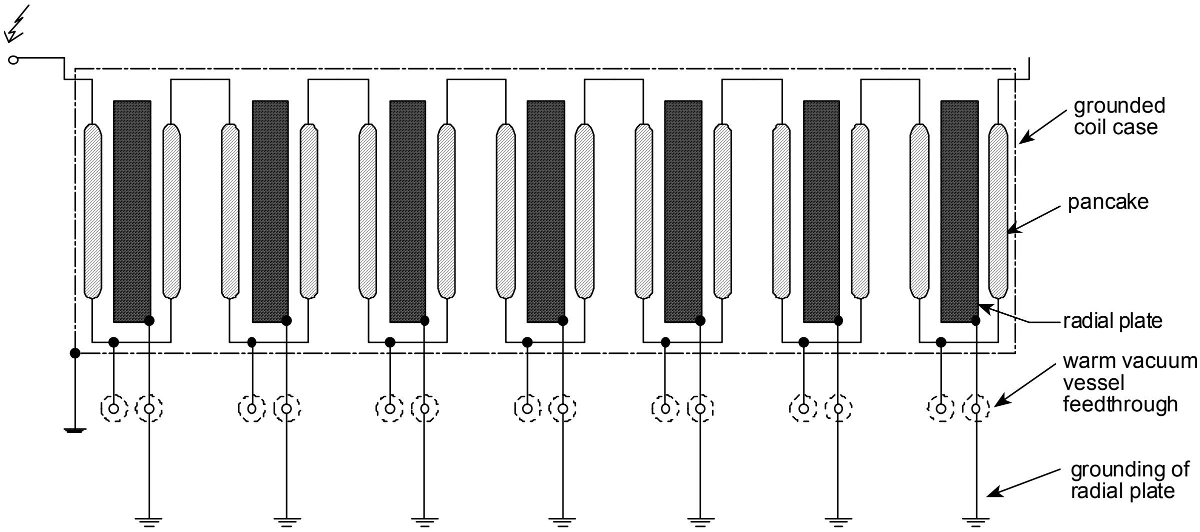

Fig. 6-3 Arrangement C for tests of conductor insulation.

6.3.4 Tests with operation mode arrangement

The complete set of cable lengths are connected to the coil for the test in operation mode arrangement, e. g. for the impulse tests (Fig. 6-4).

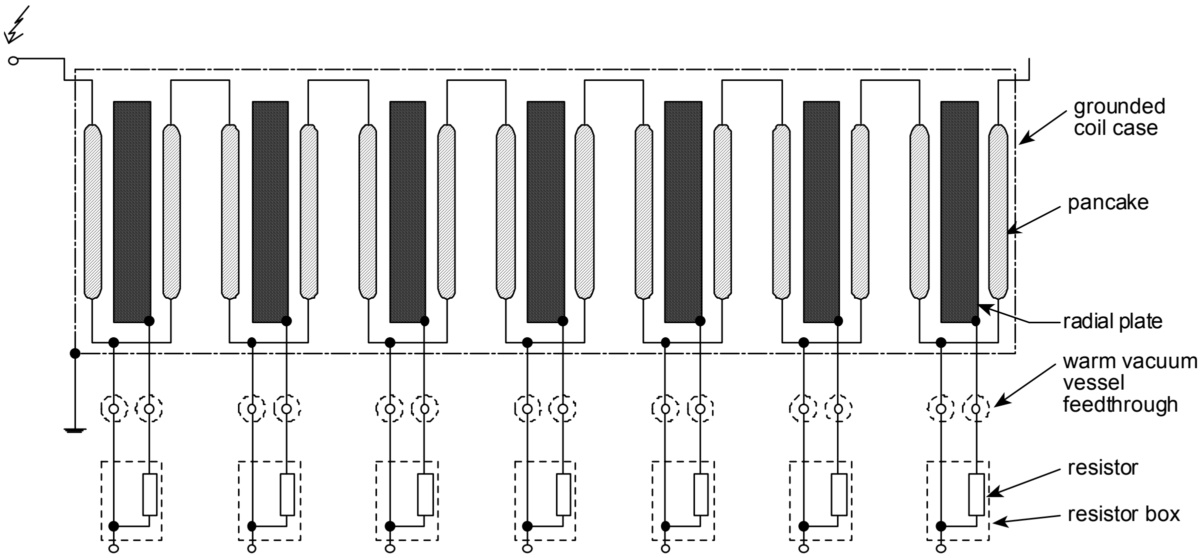

Fig. 6-4 Arrangement O for tests in operation mode arrangement.

6.4 Power supply and high voltage extensions

Different power supplies are connected with the test arrangements (see 6.3). The high voltage output of the power supply is connected with one terminal of the coil. The second coil terminal is left open or the coil is short circuited for AC and DC excitation. The second coil terminal is grounded for impulse tests.

For DC tests the high voltage DC power supplies are usually equipped with internal voltage and current measurement (Fig. 6-5).

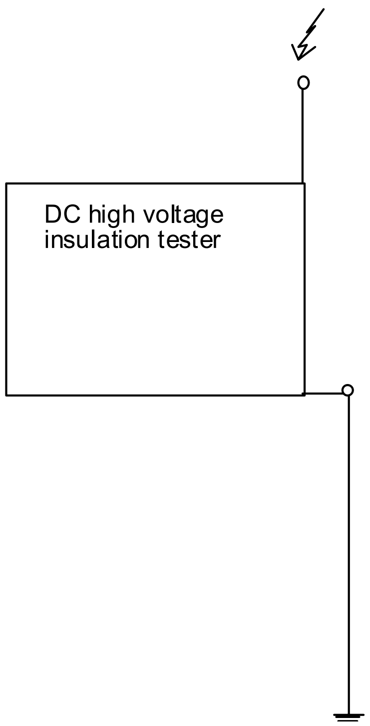

Fig. 6-5 Power supply for DC tests (internal current and voltage indication not shown)

For AC tests external high voltage dividers are used. A possible example of the power supply is shown in Fig. 6-6. A partial discharge measurement is added. The detection impedance is in series to the coupling capacitance C_K. This detection impedance may be put in the grounding path to increase the sensitivity, e. g. for partial discharge measurement of the conductor insulation in one radial plate.

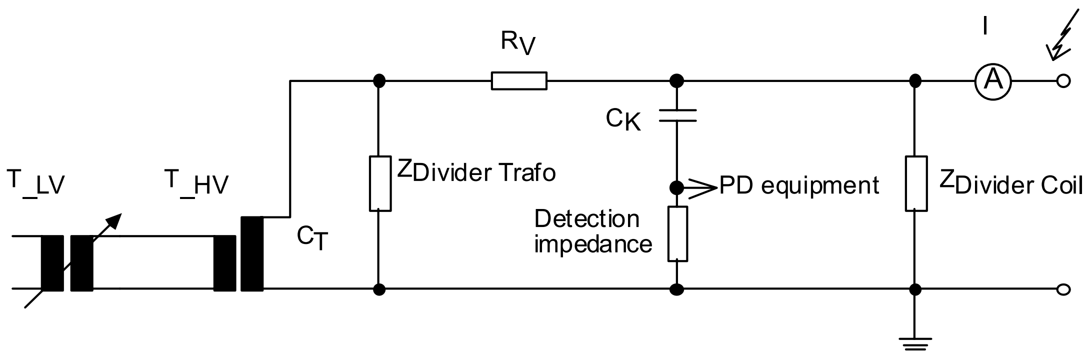

Fig. 6-6 AC power supply (T_LV, T_HV) with external high voltage dividers for voltage measurements. The detection impedance, coupling capacitance C_K and resistor R_V are added for partial discharge measurement.

A Schering-Bridge is used for the determination of the dissipation factor under AC excitation. One possible example is given in Fig. 6-7. The detailed arrangement of the Schering bridge will be defined if the boundary conditions are known (type of Schering-Bridge, capacitance of standard capacitor, grounding of the coil case, eventually auxiliary branches). The measurement with the Schering Bridge will be probably easier if it is possible to lift the coil case with the bridge to a potential of about 2 V.

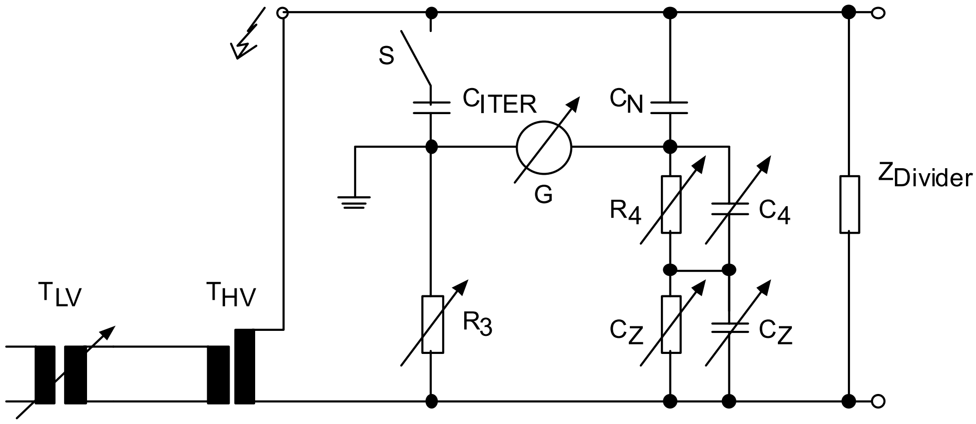

Fig. 6-7 Power supply and Schering-Bridge ACS. C_{ITER} represents a TF coil.

An impulse voltage generator is used for the excitation of the coil with impulse voltage rise times (or virtual front times) in the µs range (Fig. 6-8). The detailed settings of the impulse generator will be defined if the specifications of the impulse generator are known (capacitance of the capacitor bank, maximum voltages, internal damping resistors).

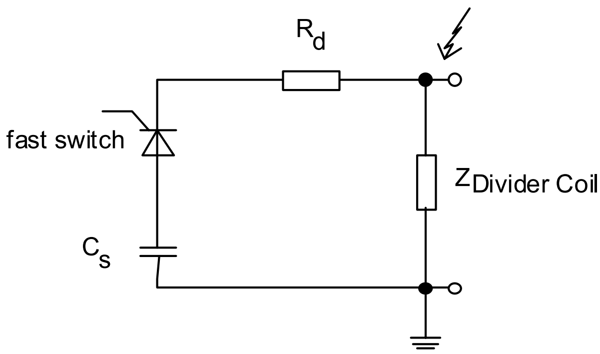

Fig. 6-8 Impulse generator I containing a capacitor bank C_S, a damping resistor R_d and a fast switch (e. g. ignitron, spark gap, thyristor).

6.5 Test criteria and additional informations

For each test a criterion must be defined. Some criteria are indispensable. Others may be developed during the tests or taken as additional information, e. g. the partial discharge activity.

6.5.1 Criterion NB: no breakdown

The most important criterion is that no breakdown appears. Hence this criterion is relevant for every test.

6.5.2 Criterion R: insulation resistance

The insulation resistance of all types of insulation must be > 1 GΩ.

For such high insulation resistances and the high capacitance of the coil the charging current is expected to be in the same range (or even higher) as the current caused by the insulation resistance after a test time of 1 min. It may therefore be useful to apply the maximum voltage value for e. g. 15 min for some measurements. In addition it is recommendable to use always the same DC test equipment because the internal resistance of this equipment may be in the range of the coil.

The measured insulation resistance is strongly effected if the coil is connected with additional conductivities (water cooling hoses, measurement equipment, wet room temperature axial breaks, ...). In this case the value is no more related to the coil and the criterion of the insulation resistance value can be skipped.

6.5.3 Criterion IC: constant charging current

The residual leakage current can be neglected compared with the capacitive charging current during AC tests on well insulated and high capacitive samples. A constant charging current is therefore a criterion during a test with constant AC voltage.

6.5.4 Additional information PD: partial discharge activity

The inception voltage, extinction voltage and apparent charge (shape of a partial discharge fingerprint) of the partial discharge measurements may deliver useful information, esp. for the judgement of the insulation quality of a single element within a series production.

6.5.5 Additional information DF: dissipation factor

The measurement of the dissipation factor may deliver useful information, esp. for the insulation diagnostic of a single element within a series production.

6.5.6 Additional information SW: shape of the waveform

The voltage waveform shape during the impulse test may deliver useful information, esp. for the judgement of the insulation quality of one coil within the series production.

6.6 Test sequence and procedure

The test sequence should be performed in a way that:

delivers a maximum amount of information,

minimises additional damage in case of an insulation fault,

minimises assembly work.

The full set of tests (Tab. 6-3) is relevant for the completed coil including instrumentation cables.

Number	Test arrangement – power supply	Test voltage according to fault case 1 / kV	Test voltage according to fault case 2 / kV	Criterion	Additional information		
1	O-DC	18.00	34.00	NB, R			
2	O-I	5.00	29.60	NB	SW		
3	O-DC	18.00	34.00	NB, R			
4	G-DC	18.00	34.00	NB, R			
5	G-AC	12.73	24.04	NB, IC	PD		
6	G-ACS	12.73	24.04	NB	DF		
7	R-DC	5.00	11.00	NB, R			
8	R-AC	3.54	7.78	NB, IC	PD		
9	C-DC	5.00	11.00	NB, R			
10	C-AC	3.54	7.78	NB, IC	PD		
11	O-DC	18.00	34.00	NB, R			

Tab. 6-3: Test procedure for a complete acceptance test. AC voltages are given as rms values.
Row 2: O: operation mode, G: ground insulation, R: radial plate insulation, C: conductor insulation, I: impulse, ACS: AC excitation with Schering-Bridge measurement. (Test arrangements O, G, R, C are explained in chapter 6.3. Power supplies I, DC, AC, ACS are explained in 6.4.) Row 5: NB: no breakdown, R: insulation resistance, IC: constant charging current. (Criterions NB, R, IC are explained in chapter 6.5.) Row 6: PD: partial discharge, DF: dissipation factor, SW: shape of waveform. (Additional information PD, DF, SW are explained in chapter 6.5.)

A full acceptance test is recommended for ITER TF single coils:

after completion of fabrication under ambient conditions,

for a cold test,

after the cold test.

Depending on the boundary conditions of the available equipment (vacuum vessel, impulse generator) it will be defined if these tests are performed on site or by the manufacturer. At least the DC and AC tests should be performed at the manufacturer to reduce the probability of a re-transportation in case of a necessary repair by the manufacturer. At least the test G-DC at full voltage level should be performed on site if all tests are possible at the manufacturer and the transport causes only acceptable mechanical stress. The ITER site must have a high voltage mode which allows a high voltage test with the maximum test voltage level after installation of all coils. Depending on the boundary conditions of the switching circuit it may be discussed if a full acceptance test should be performed after installation in the ITER TF system – in this case it must be possible to switch in a second high voltage mode that makes it possible to separate each coil (at the terminals) from its FDU and adjacent coil. A routine DC check is necessary for the complete coil system before a new current operation period starts.

A reduced test sequence should be performed during manufacturing. Before impregnation with the radial plate insulation the tests C-DC and C-AC should be performed to verify the dielectric strength of the conductor insulation. After insulation of a radial plate the tests R-DC and R-AC should be performed with half of the voltage level. For the simulation of a neighboured radial plate during this test the radial plate is covered with grounded objects e. g. metallic foils.

The tests R-DC and R-AC should be performed with the full maximum voltage after stacking of the radial plate pack (i.e. the 7 radial plates are stacked together) to ensure that the radial plate insulation fulfils the specification.

A room temperature test under Paschen Minimum conditions is necessary with at least G-DC. One method to be sure that the Paschen Minimum is passed is achieved by applying permanently the full DC voltage while increasing the pressure continuously and slowly from vacuum till about 100 mbar.

6.7 Safety aspects

All high voltage tests must be performed in a way that no risk appears for humans. Damaging of equipment must be excluded. Additional damaging of a test sample that does not fulfil the specification should be as low as possible. Therefore the following safety rules must be respected:

At least one high voltage expert is present during high voltage testing.

The test equipment and the location are in agreement with the state-of-the-art for high voltage testing.

All single components (e. g. breaks, feedthroughs, cables) are DC and AC tested according to the specified test voltages before installation for ITER TF coils. It must be proved that the instrumentation cables are able to carry the capacitive blind current during the AC tests. In case of long time DC tests (e. g. some hours during Paschen Minimum test) it must be verified that no damaging of the bushings occurs (capacitive bushings are not designed to handle long time DC voltages at the rated AC level).

The breakdown strength of warm gases are relatively low compared with solid dielectrics. Especially pure inert gases like helium have low breakdown voltages. The cold axial breaks must therefore be qualified for the test voltage levels concerning pressure and kind of gas under room temperature conditions.

A visible mechanical (!) pressure indication is strongly recommended. An acoustic alarm should start if the pressure decreases over a certain boundary.

Parts on high potential are completely covered (e. g. blind plug for socket) or must have sufficient distance to parts with ground potential.

If there are open terminals (for testing under ambient conditions) the insulation between grounded paint and the open terminals is covered with semi conductive paint. The length of this zone must be approved with a model.

The DC power supply should have a power in a range that limits the danger of additional destruction in case of an insulation fault. I.e. a low power insulation tester should be used if the leakage current of the complete arrangement is low.

All arrangements are DC tested before AC or impulse tests to minimise the destructive energy.

All high voltage equipments (transformers, impulse generators, dividers, ...) are pretested before using for ITER TF tests. The reliable operation esp. for the impulse generator must be proved.

A terminal overvoltage protection may be discussed but this may cause more problems by a chopped voltage. (During the tests of the ITER TF model coil no terminal overvoltage protection was installed and no terminal overvoltage occurs.)

Grounding and earthing is a very important topic for transient excitations of large systems. A proper grounding for the arrangement during impulse test is necessary for a proper voltage distribution and for correct measurements. Hence metal bands are necessary, simple wires or cables are not sufficient.

As described in 6.1 the voltage is increased step by step. An observation of the most important voltage values which are accessible for measurement is necessary before increasing the voltage to a step with a higher voltage value. A measurement system with sufficient channels, bandwidth, sampling rate, vertical resolution and available memory and a (fibre optical) potential separation between the channels is strongly recommended for the observation of the impulse tests with rise times in the range of µs.

A production sample of every high voltage component (e. g. axial break, feedthrough) should be placed in the reactor on a accessible location with representative radiation. This samples should be partial discharge tested in reasonable time steps (e. g. after 1 year, than every 3 years).

7 Conclusion

A network model for the superconducting ITER TF system was established for the simulations of a fast discharge and two fault cases. The simulations delivered the maximum voltages between both terminals of a coil and the maximum terminal voltage to ground. The calculated voltages were applied to ITER TF single coil network models for the determination of the values, rise times and locations of the maximum internal voltages for each type of insulation.

A set of ideal test voltages was defined based on the calculated values and a suitable safety margin. Two complete sets of test voltages were defined under consideration of technical boundary conditions. One set is related to the maximum calculated voltages, the second set may be considered if it will be defined that it is not necessary to handle safely the second fault case. But in this case it is strongly recommended to examine a third fault case where an earth fault occurs at a coil terminal during a fast discharge with no malfunction of the fast discharge units.

Test procedures and test sequences were proposed for several production, assembly and delivery stages. High voltage safety aspects were described.

It should be noticed that changes of design, assumptions or simplifications may make it necessary to modify the models.

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Appendix

Appendix 1: Calculations of transient voltages in the coils of the ITER TF system

1 Calculation of the coil voltages in the ITER TF coil system

The maximum voltages over a coil or to ground will be calculated for a fast discharge. One case without a fault and 2 fault cases are examined. For all cases the first 5 seconds are used for charging and running a DC current of 68 kA through all coils.

1.1 FD without fault

Starting of switch for capacitor bank: t = 5.001 s, dt = 10 µs
Starting of vacuum breaker: t = 5.001 156 8 s, dt = 1.2 µs
Dump resistor acting as a switch t = 5.001 158 s, R0 = 0.102 Ω, R1 = 0.240 Ω, dt = 22 s

Maximum time steps of simulation (RELTOL = 0.0001):

tstart / s	dt / s
0	1 m (no data collection)
5.000	0.1 µ
5.002	1 µ
5.007	10 µ
5.018	100 µ
5.137	1 m
6 = TSTOP	

The data after t = 5 s are collected in a result file. This result file has 24206 steps.

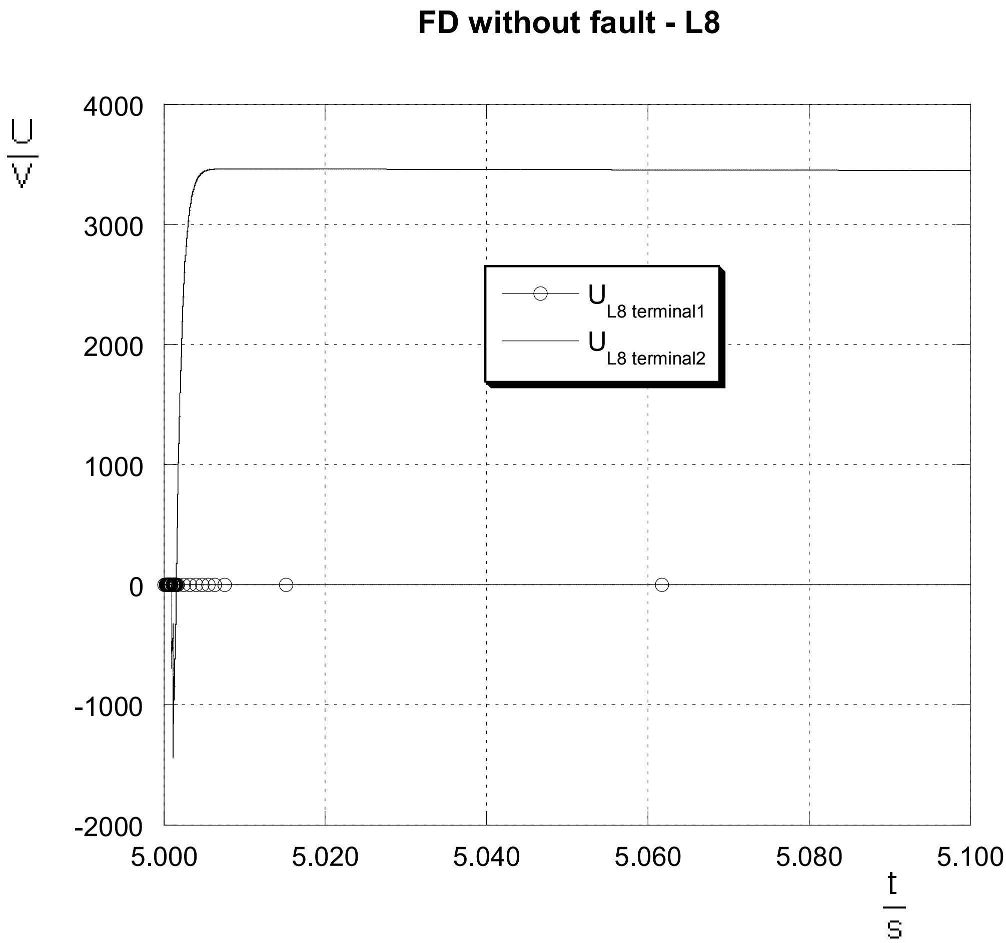


Fig. 1.1-1: Fast discharge without fault.

Terminal voltage to ground (e. g. L8:2): 3467 V (t = 5.008 5 s),
rise time from zero point to maximum: 1.6 ms.
Capacitor discharge: -696 V, rise time: 1.1 µs (t = 5.001 006 s)

Terminal to terminal voltage (e. g. L8): 3467 V, rise time: 1.6 ms (t = 5.008 5 s)

1.2 FD with failure of FDU 2 and 3

Vacuum breaker of FDU2 and FDU 3 remain closed. The vacuum breakers of all other FDUs work correctly (i.e. with the same settings as in 1.1).

Starting of switches for capacitor bank: t = 5.001 s, dt = 10 µs
Starting of all working vacuum breakers: t = 5.001 156 8 s, dt = 1.2 µs
Dump resistors acting as a switch t = 5.001 158 s, R0 = 0.102 Ω, R1 = 0.240 Ω, dt = 22 s

Maximum time steps of simulation (RELTOL = 0.0001):

tstart / s	dt / s
0	no data collection
5.000	0.2 µ
5.001 766 0	25 µ
6 = TSTOP	

The data after t = 5 s are collected in a result file. This result file has 57 618 time steps.

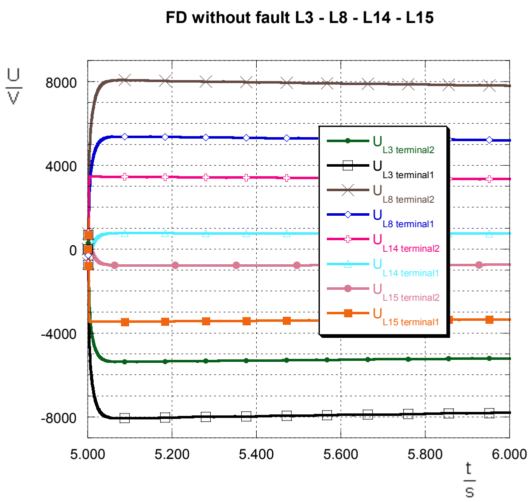


Fig. 1.2-1: Voltages to ground on coil 3, 8, 14 and 15 during fast discharge with failure of FDU 2 and FDU 3.

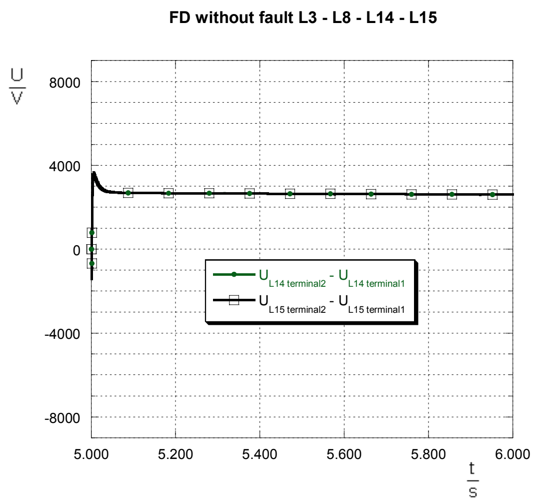


Fig. 1.2-2: Voltages over coil 14 and 15 during fast discharge with failure of FDU 2 and FDU 3.

Maximum amplitudes of voltages at outer terminals (FDU side): L3:1 (U = -8.0645 kV), L8:2 (U = 8.0609 kV) with low oscillations at t = 5.080 4 s;
rise time for zero point (t = 5.001 521 75 ms) to maximum: 17 ms.

Maximum terminal to terminal voltage for L14 and L15:
U = 3.6438 kV t = 5.005 98 s; rise time for zero point (t = 5.001 52 s) to maximum: 2 ms.

1.3 FD with failure of FDU 2 and 3 and failure at Terminal 3:1

The breakdown to ground is assumed at one of the two terminals with the highest voltage to ground in the time range of the maximum voltage (with a delay of about 1.5 ms).
Breakdown at terminal L3:1 at t = 5.081 920 s.

Starting of switches for capacitor bank: t = 5.001 s, dt = 10 µs
Starting of all working vacuum breakers: t = 5.001 156 8 s, dt = 1.2 µs
Dump resistors acting as a switch t = 5.001 158 s, R0 = 0.102 Ω, R1 = 0.240 Ω, dt = 22 s
Vacuum breakers of FDU2 and FDU3 remain closed (switch time 1000 s).
=> Breakdown set to 5.081 920 s. Time for breakdown 1.2 µs. Resistance at fault location 1 Ohm.

Time steps of simulation (RELTOL = 0.0001):

tstart / s	dt / s
0	1 m (no data collection)
4.987	10 µ (no data collection till 5.000 s)
5.054	5 µ
5.062	1 µ
5.078	0.5 µ
5.081	0.1 µ
5.084	1 µ
5.09	10 µ
5.106	1 m
6 = TSTOP	

The data after t = 5 s are collected in a result file. This result file has 65939 steps.

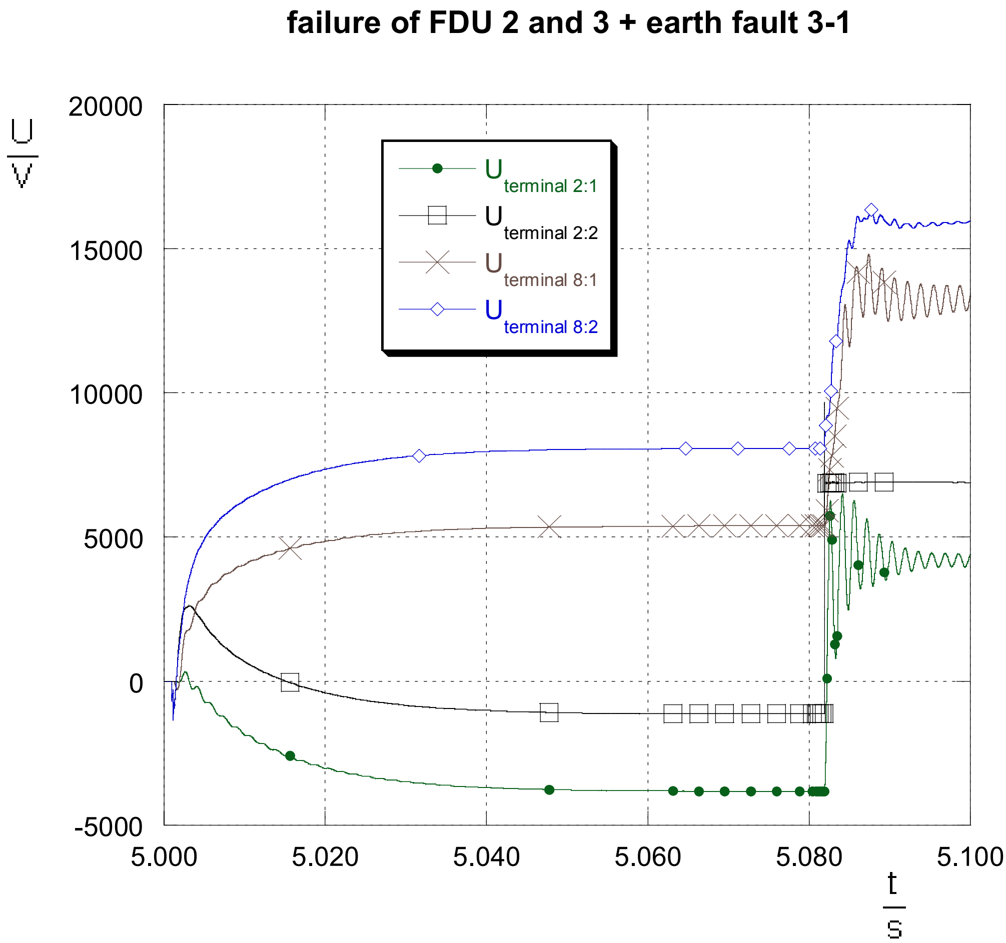


Fig. 1.3-1: Fast discharge with failure of 2 FDUs and earth fault.

Maximum voltage at terminal: L8:2
U = 16.35 kV with oscillations t = 5.087 s
rise time from 8.06 kV to maximum voltage: 3,5 ms

Maximum terminal to terminal voltage: L2
U = 13.49 kV at t = 5.081 9 s,
rise time from 2.69 kV to maximum kV: 2.4 µs

1.4 Overview

The following table gives an overview about voltages and rise times for the different cases.

	FD without fault	FD with failure of 2 FDUs	FD with failure of 2 FDUs + earth fault at L3:1
Maximum terminal to ground voltage	all terminals at FDUs, 3467 V, 1.6 ms	L3:1, L8:2, 8061 V, -8064 V, 17 ms	L8:2 16.35 kV, 3.5 ms
Fast breakdown terminal to ground voltage			L3:1, breakdown time is chosen as 1.2 µs
Maximum terminal to ground voltage caused by capacitor discharge	all terminals, -696 V, 1.1 µs	 -693 V, 1.1 µs	
Maximum terminal to terminal voltage	all coils, 3467 V, 1.6 ms	L14, L15, 3644 V, 2 ms	L2, 13.49 kV, 2.4 µs

2 Calculation of the maximum voltages within the coils

For the determination of the maximum voltage stress for ground, radial plate and conductor insulation the coils with the maximum voltage to ground and with the maximum coil voltage were examined in detail for each case.

2.1 FD without failure

2.1.1 Excitation of the 50 kHz model with the terminal voltages of L8

The 50 kHz model single coil was excited with V(L8:2) on the right side and grounded on the left side. No maximum step size was set, RELTOL = 0.001. Calculation time was 17.4 h. The result file has 106 367 time steps.

2.1.1.1 Examination of the ideal voltage distribution for the two radial plate types

From the examination of the ITER TF model coil it is known that the ideal voltage distribution is an important basis for the understanding of the transient behaviour. Before analysing the stress of the different insulation types the voltage drop over the two different types of double pancakes (DPs) should be examined (fig. 2.1.1.1-1, fig. 2.1.1.1-2).

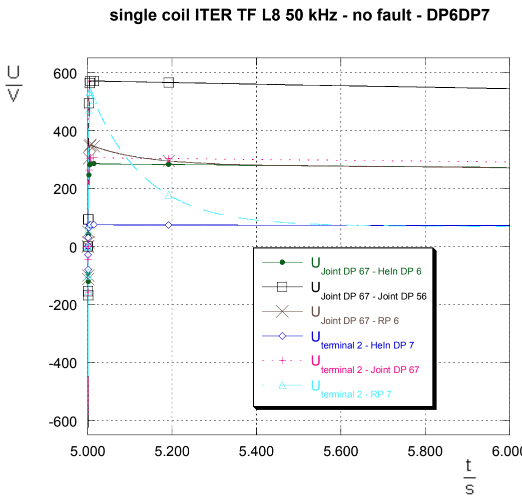


Fig. 2.1.1.1-1: Voltages along double pancake 7 and 6 in the time range between 5.00 s and 6.00 s. (Joint DP 67 = joint between double pancake 6 and double pancake 7).

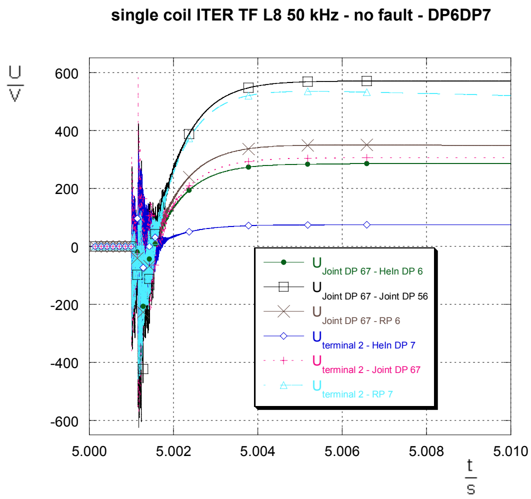


Fig. 2.1.1.1-2: Voltages along double pancake 7 and 6 in the time range between 5.00 s and 5.01 s. (Joint DP 67 = joint between double pancake 6 and double pancake 7).

The ideal potentials of the radial plates are the same as for the helium inlet point (comparison to ITER TFMC: inner pancake joint). The radial plate number 7 reaches its “ideal value” with a considerable delay and transient voltage difference compared to radial plate number 6 because the capacitive distribution differs very much from the “DC” distribution. The voltage stress of the outer radial plates is therefore expected to be very different from the voltage stress of the inner radial plates.

The first peak at t = 5.001 0 s in fig. 2.1.1.1-2 is caused by the discharging process of the capacitor bank. The voltage disturbances with the second peak at t = 5.001 2 s and a voltage minimum of about -600 V by opening the vacuum breaker is only caused by calculation and not a real world effect.

2.1.1.2 Results for ground insulation

Highest voltage on terminal 8:2 is 3.466 kV at t = 5.008 5 s (t_A = 1.6 ms from 0 V to maximum)
Highest voltage of radial plate to ground appears on radial plate number 7 with 3.3073 kV at t = 5.399 s (t_A = 17 ms). The rise time of this voltage is higher than the rise time of the other radial plate voltages to ground (fig. 2.1.1.2-1).

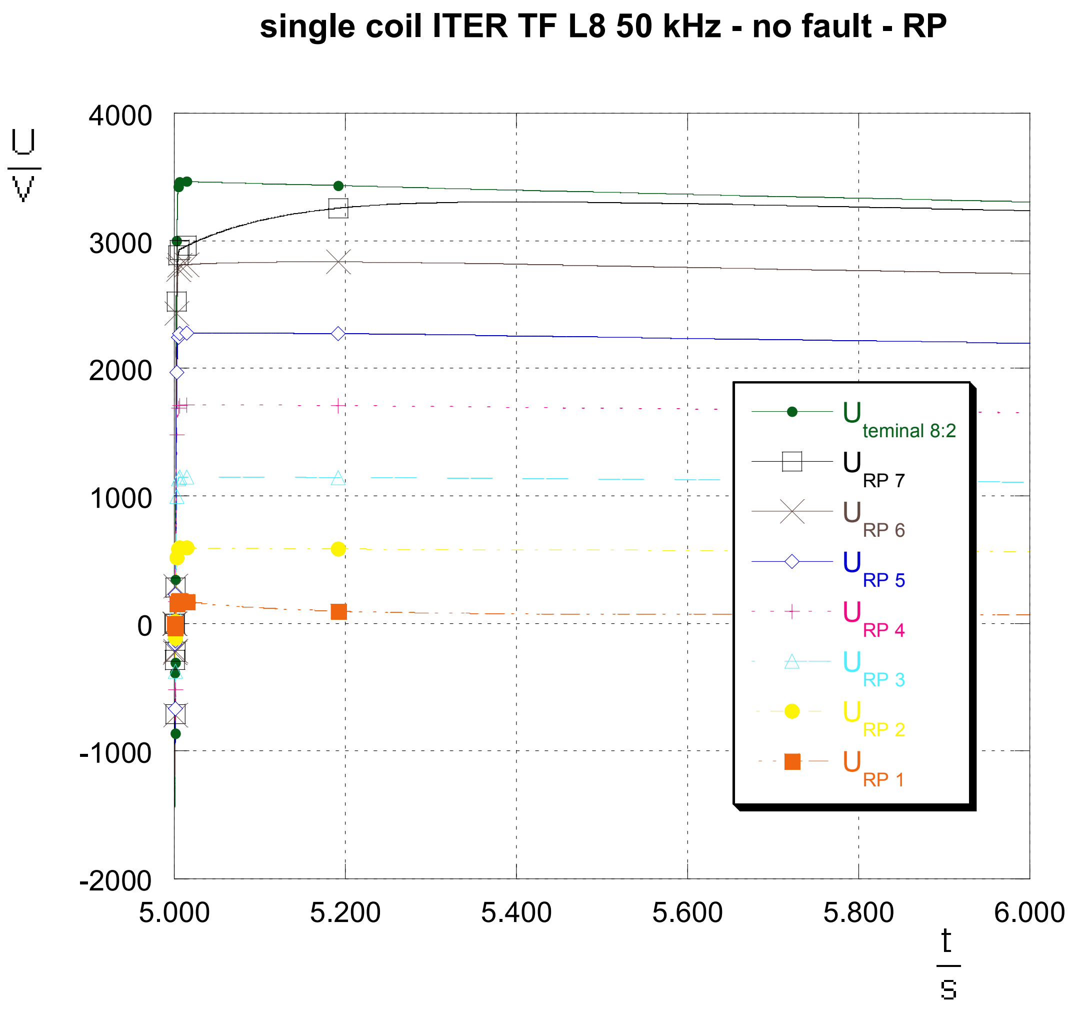
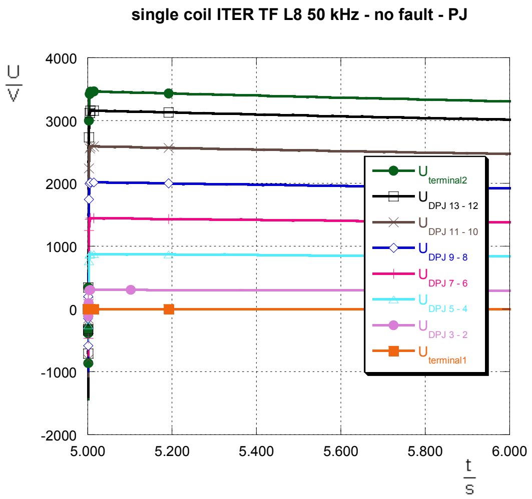


Fig. 2.1.1.2-1: Terminal 2 and radial plate to ground (= case) voltages for coil 8 during a fast discharge with no fault.

Highest voltage of double pancake joint to ground appears on double pancake joint of joint 13 to joint 12 with 3.161 kV at t = 5.008 5 s (t_A = 1.6 ms) (fig. 2.1.1.2-2).
Highest voltage of helium inlet to ground appears on helium inlet 7 with 3.392 kV at t = 5.008 5 s (t_A = 1.6 ms) (fig. 2.1.1.2-3).



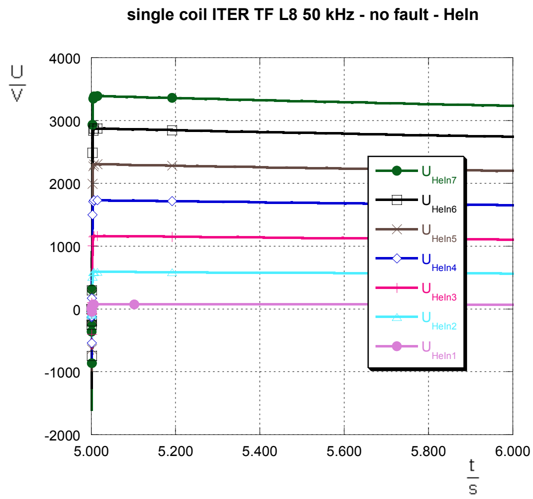
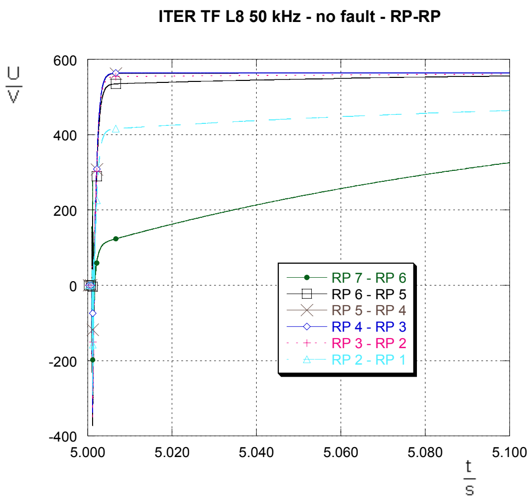


Fig. 2.1.1.2-2: Terminal 2 and radial plate to ground (= case) voltages for coil 8 during a fast discharge with no fault.

Fig. 2.1.1.2-3: Helium inlet to ground voltages for coil 8 during a fast discharge with no fault.

2.1.1.3 Results of radial plate insulation

Highest radial plate to radial plate voltage is between radial plate 4 and radial plate 3 U = 564.15 V at 5.076 8 s (t_A about 1.6 ms from 0 V to maximum) (fig. 2.1.1.3-1, fig. 2.1.1.3-2).



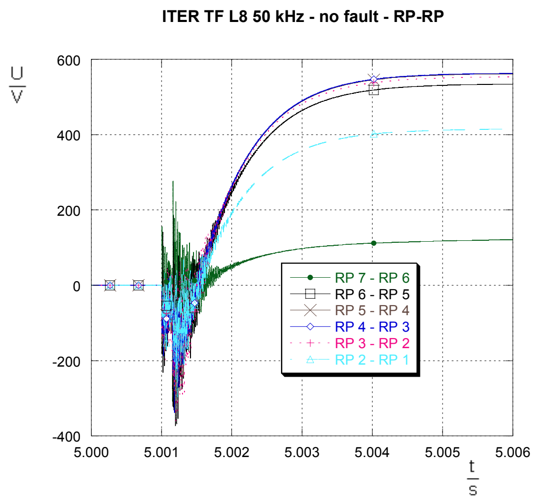


Fig. 2.1.1.3-1: Radial plate to radial plate voltage for coil 8 during a fast discharge with no fault for the time range 5.000 s to 5.100 s.

Fig. 2.1.1.2-3: Radial plate to radial plate voltage for coil 8 during a fast discharge with no fault for the time range 5.000 s to 5.006 s.

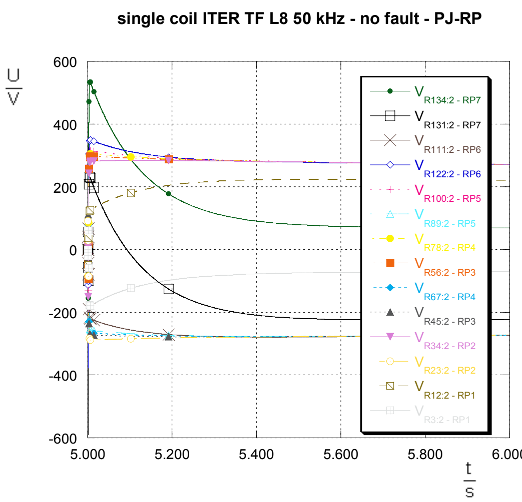
The radial plate insulations of the outermost radial plate are stressed with lower voltage values and slower rise times than the inner radial plate insulations. This result was expected by the considerations of 2.1.1.1.

2.1.1.4 Results of conductor insulation

The examination of the conductor to radial plate voltage is divided into certain sub steps.

The first step is the examination of the double pancake joints ("outer joints") to radial plate voltage (fig. 2.1.1.4-1): maximum of 535.08 V at PC 14 to RP 7 (t = 5.005 3 s). The rise time of this voltage from 0 V to maximum is about 1.5 ms. Second most is 349.87 V at PC 12 to RP 6. Most negative voltage is -289.04 V at PC 3 to RP2. The voltage between pancake joint of PC 13 and radial plate number 7 starts with a positive voltage and crosses the zero point at t = 5.093 s. All other voltages do not make a zero transition after the switching disturbances (t > 5.001 8 s).

The helium inlet ("inner joints") to radial plate voltage (fig. 2.1.1.4-2) has the maximum voltage of 460.72 V at t = 5.005 2 s with a rise time of 1.5 ms and a non realistic minimum of -517.3 V (due to vacuum breaker "effect") at radial plate 7. The voltages of the other radial plates do not exceed ±200 V.



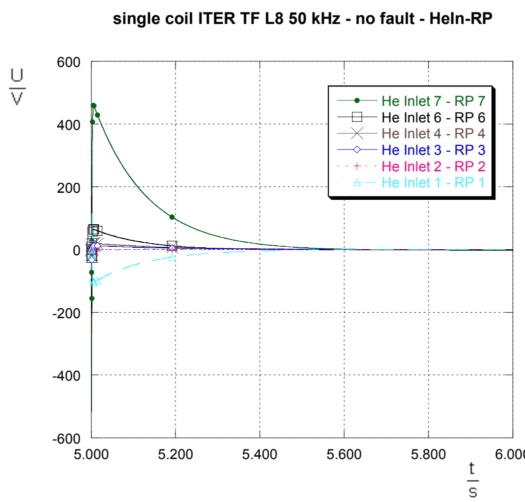


Fig. 2.1.1.4-1: Voltages between double pancake joint and radial plate.

Fig. 2.1.1.4-2: The helium inlet ("inner joint") to radial plate voltages.

The next step was the examination of the voltages of pancake 13 to RP 7. All these voltages are between the joint to RP voltage and the He inlet to RP voltage in the order how they are arranged within the radial plate, i.e. for smaller distances to the helium inlet the voltage is higher. The voltages make a zero transition but the minima do not reach -300 V.

For PC 14 to RP 7 the maximum voltage appears at the outer terminal. The smaller the distance to the He inlet is, the lower is the voltage.

2.1.1.5 Summary of the maximum voltages for the 50 kHz model during fast discharge without a fault

	location	voltage, time	rise time
Maximum terminal to ground voltage	Terminal 2	3.47 kV, 5.008 5 s	1.6 ms
Ground insulation	Terminal 2	3.47 kV, 5.008 5 s	1.6 ms
	Radial plate: RP 7	3.31 kV, 5.399 s	17 ms
	Double Pancake joint DPC67	3.16 kV, 5.008 5 s	1.6 ms
	Helium inlet HeIn7	3.39 kV, 5.008 5 s	1.6 ms
Radial plate insulation	Radial plate to radial plate: RP 4 – RP 3	564.15 V, 5.076 8 s	1.6 ms
Conductor insulation	Double pancake joints to radial plate: terminal 2 – RP 7	535.08 V, 5.005 3 s	1.5 ms
	Helium inlet to radial plate: HeIn 7 - RP 7	460.72 V, 5.005 2 s	1.5 ms
	Pancake 13 to radial plate 7: HeIn 7 - RP 7	460.72 V, 5.005 2 s	1.5 ms
	Pancake 14 to radial plate 7: terminal 2 – RP 7	535.08 V, 5.005 3 s	1.5 ms

2.1.2 Excitation of the 1 kHz model with the terminal voltages of L8

The 1 kHz model of a single coil was excited with the voltage V(L8:2) on the right side and grounded on the left side. No maximum step size was set, RELTOL = 0.001.
Calculation time was 11.03 h. The result file has 106 367 time steps.

2.1.2.1 Results for ground insulation

Highest voltage on terminal L8:2 is U = 3.467 kV at t = 5.008 5 s. Rise time for zero point to maximum: 1.6 ms.
Highest voltage of radial plate to ground appears on radial plate number 7 with 3.308 kV at t = 5.394 2 s (t_A = 17 ms). The rise time of this voltage is higher than the rise time of the other radial plate voltages to ground (fig. 2.1.2.1-1).

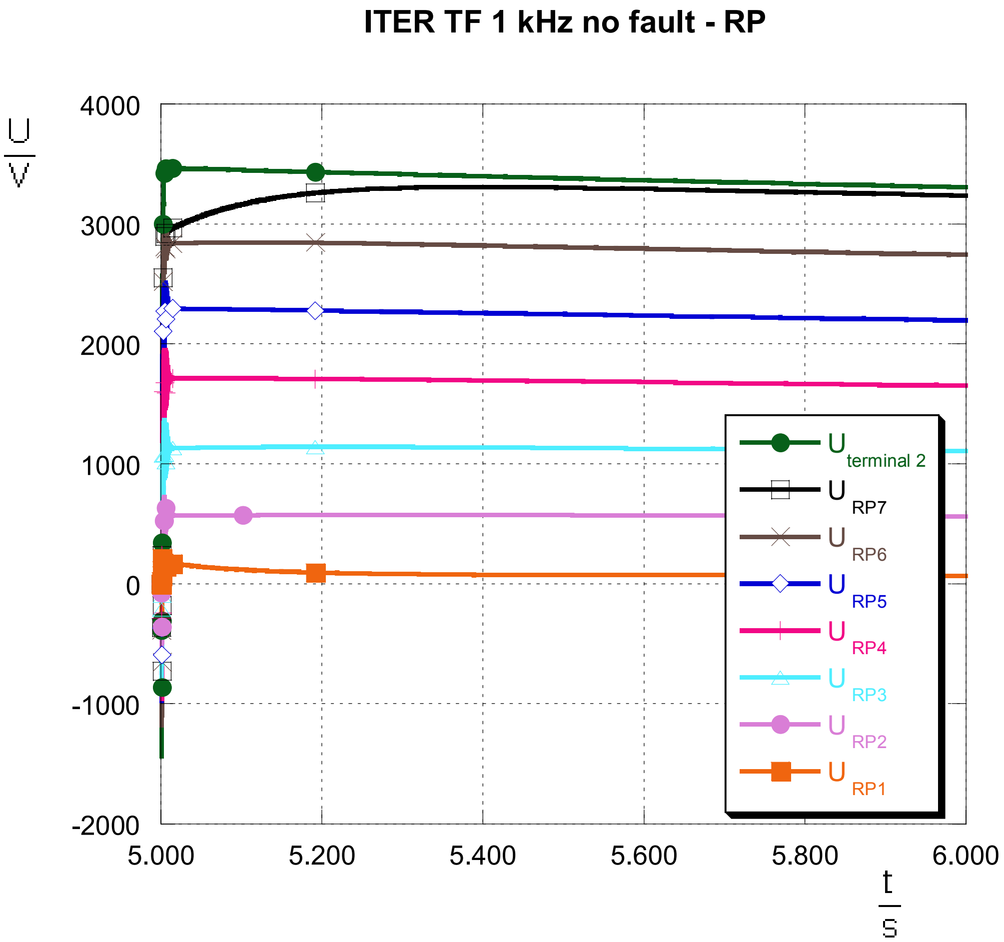


Fig. 2.1.2.1-1: Terminal and radial plate to ground (= case) voltages for coil 8 during a fast discharge without fault.

Highest voltage of double pancake joint to ground appears on double pancake joint of joint 13 to joint 12 with 3.249 kV at t = 5.005 6 s (t_A = 1.6 ms) (fig. 2.1.2.1-2).
Highest voltage of helium inlet to ground appears on helium inlet 7 with 3.412 kV at t = 5.005 9 s (t_A = 1.6 ms) (fig. 2.1.2.1-3).

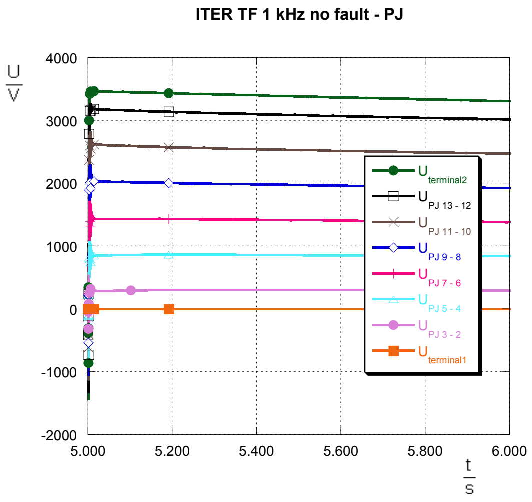


Fig. 2.1.2.1-2: Terminal and double pancake joint to ground (= case) voltages for coil 8 during a fast discharge without fault.

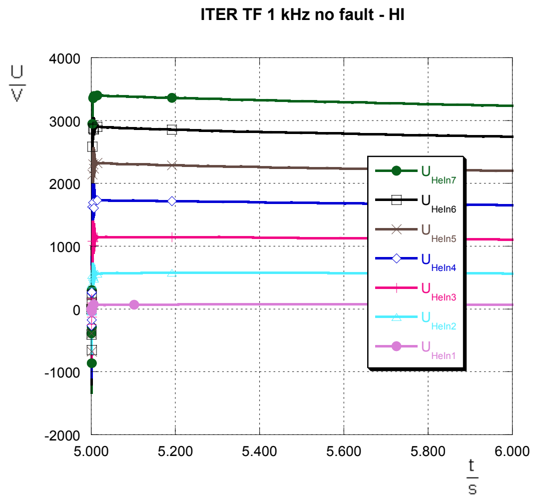


Fig. 2.1.2.1-3: Helium inlet to ground (= case) voltages for coil 8 during a fast discharge without fault.

2.1.2.2 Results of radial plate insulation

Highest radial plate to radial plate voltage is between radial plate 3 and radial plate 2 U = 650.02 V at 5.004 3 s (t_A is 1.6 ms from 0 to maximum) (fig. 2.1.2.2-1, fig. 2.1.2.2-2).

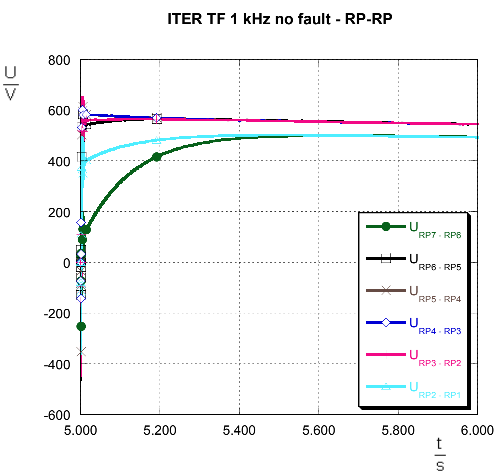


Fig. 2.1.2.2-1: Radial plate to radial plate voltage for coil 8 during a fast discharge without fault for the time range 5.0 s to 6.0 s.

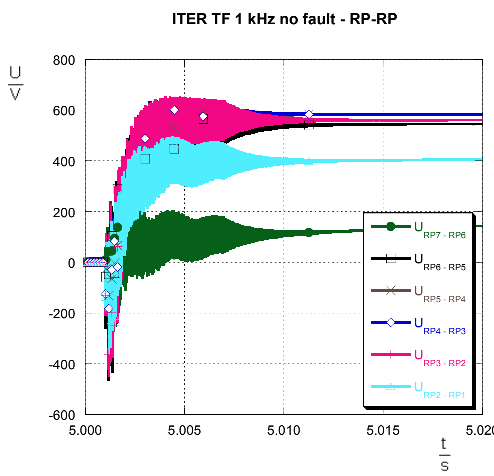


Fig. 2.1.2.2-2: Radial plate to radial plate voltage for coil 8 during a fast discharge without fault for the time range 5.0 s to 5.02 s.

Between 5.001 s and 5.014 s remarkable oscillations are superposed to all radial plate to radial plate voltages. The voltages with the outer radial plates are lower than the voltages with the inner radial plates only.

2.1.2.3 Results of conductor insulation

The examination of the conductor to radial plate voltage is divided into certain steps.

The double pancake joints to radial plate voltage (fig. 2.1.2.3-1) has the maximum of 583.59 V at PC 14 to RP 7 (t = 5.004 5 s). The rise time of this voltage from 0 V to maximum is 1.5 ms. Second most is PC 12 to RP 6. The voltage between pancake joint of PC 13 and radial plate number 7 starts with a positive voltage and crosses the zero point between at 5.1 s. All other voltages do not make a zero transition after the switching disturbances (t > 5.002 s).

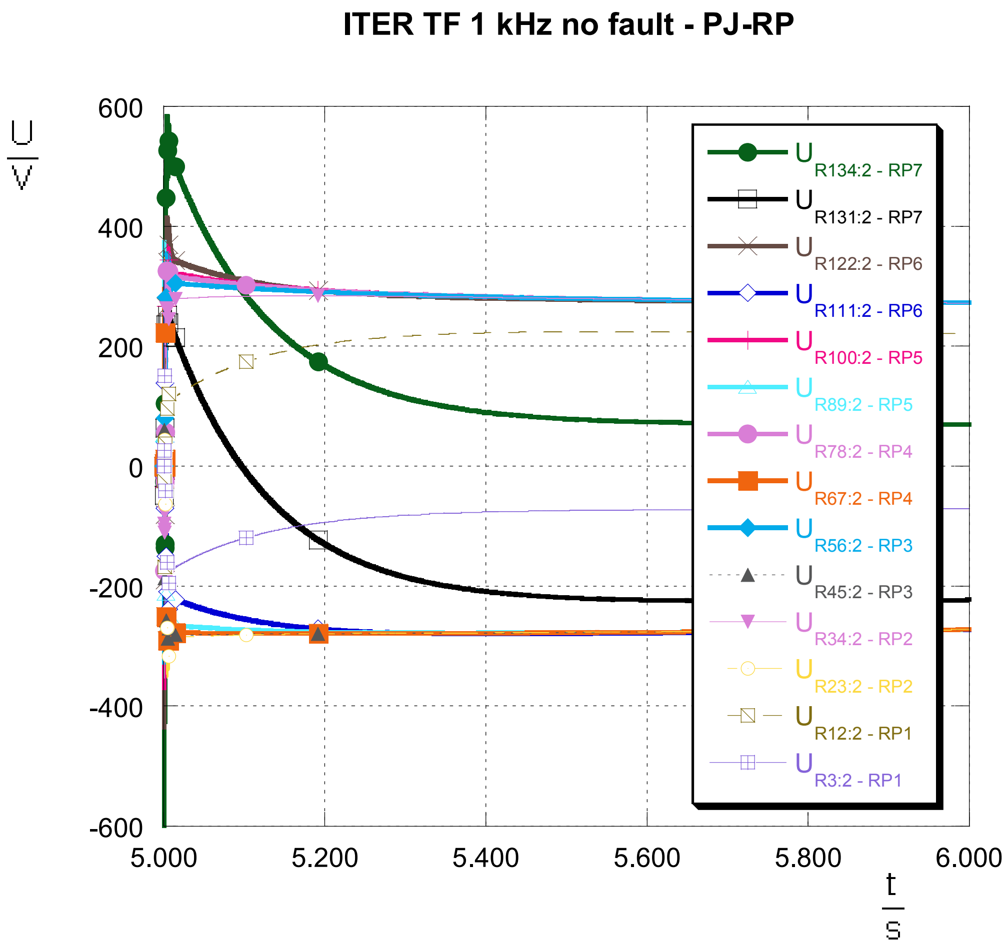


Fig. 2.1.2.3-1: Voltages between double pancake joints and radial plates.

The helium inlet ("inner joints") to radial plate voltage has the maximum voltage of 498.33 V at t = 5.004 5 s with a rise time of 1.6 ms (fig. 2.1.2.3-3) on RP 7. Between helium inlet and RP 1 the minimum of the negative voltage is -144.90 V. The voltages of the other radial plates do not exceed ±100 V after the non real switching disturbances.

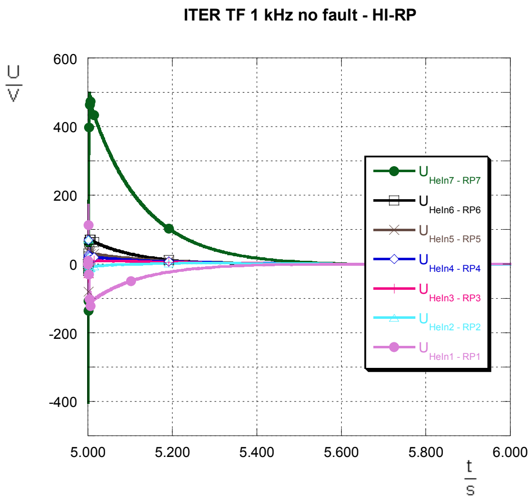


Fig. 2.1.2.3-3: The helium inlet to radial plate voltages.

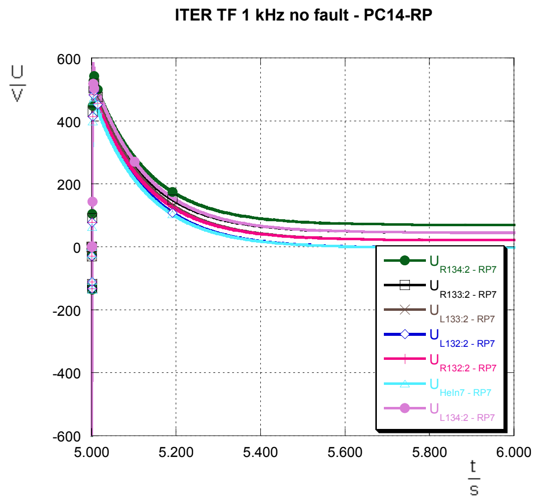


Fig. 2.1.2.3-4: The voltages along pancake 14 to radial plate 7.

For PC 14 to RP 7 the maximum voltage appears at the outer terminal (583.59 V) (fig. 2.1.2.3-4). The smaller the distance to the He inlet is, the lower is the voltage. The voltages do not make a zero transition after the maximum.

The voltages of pancake 12 to RP 6: All voltages are between the joint to RP voltage and the He inlet to RP voltage in the order how they are arranged within the radial plate, i.e. for smaller distances to the helium inlet the voltage is higher. The maximum voltage between the joint and radial plate 6 is 413.81 V.

2.1.2.4 Summary of the maximum voltages on coil 8 for the 1 kHz model during fast discharge without fault

	location	voltage, time	rise time
Maximum terminal to ground voltage	Terminal 2	3.47 kV, 5.008 5 s	1.6 ms
Ground insulation	Terminal 2	3.47 kV, 5.008 5 s	1.6 ms
	Radial plate: RP 7	3.31 kV, 5.394 2 s	17 ms
	Double Pancake joint DPC67	3.25 kV, 5.005 6 s	1.6 ms
	Helium inlet HeIn7	3.41 kV, 5.005 9 s	1.6 ms
Radial plate insulation	Radial plate to radial plate: RP 3 – RP 2	650.02 V, 5.004 3 s	1.6 ms
Conductor insulation	Double pancake joints to radial plate: terminal 2 – RP 7	583.59 V, 5.004 5 s	1.5 ms
	Helium inlet to radial plate: HeIn 7 - RP 7	498.33 V, 5.004 5 s	1.6 ms
	Pancake 14 to radial plate 7: terminal 2 – RP 7	583.59 V, 5.004 5 s	1.5 ms
	Pancake 12 to radial plate 7: DPC joint - RP 6	413.81 V, 5.004 4 s	

2.2 FD with failure of FDU 2 and FDU 3

2.2.1 Excitation of the 50 kHz model with the terminal voltages of L14

The 50 kHz single coil model was excited with the positive voltage V(L14:2) on the right side and positive voltage V(L14:1) on the left side. No maximum step size was set, RELTOL = 0.001. Calculation time was 40.66 h. The result file has 254 034 time steps.

2.2.1.1 Results for ground insulation

Highest voltage on terminal 14:2 is U = 3.4649 kV at t = 5.008 1 s. Rise time for zero point (t = 5.001 5 ms) to maximum is 1.6 ms.
Highest voltage of radial plate to ground appears on radial plate number 7 with 3.3370 kV at t = 5.425 3 s (t_A = 18.2 ms). The rise time of this voltage is higher than the rise time of the inner radial plate voltages to ground (fig. 2.2.1.1-1).

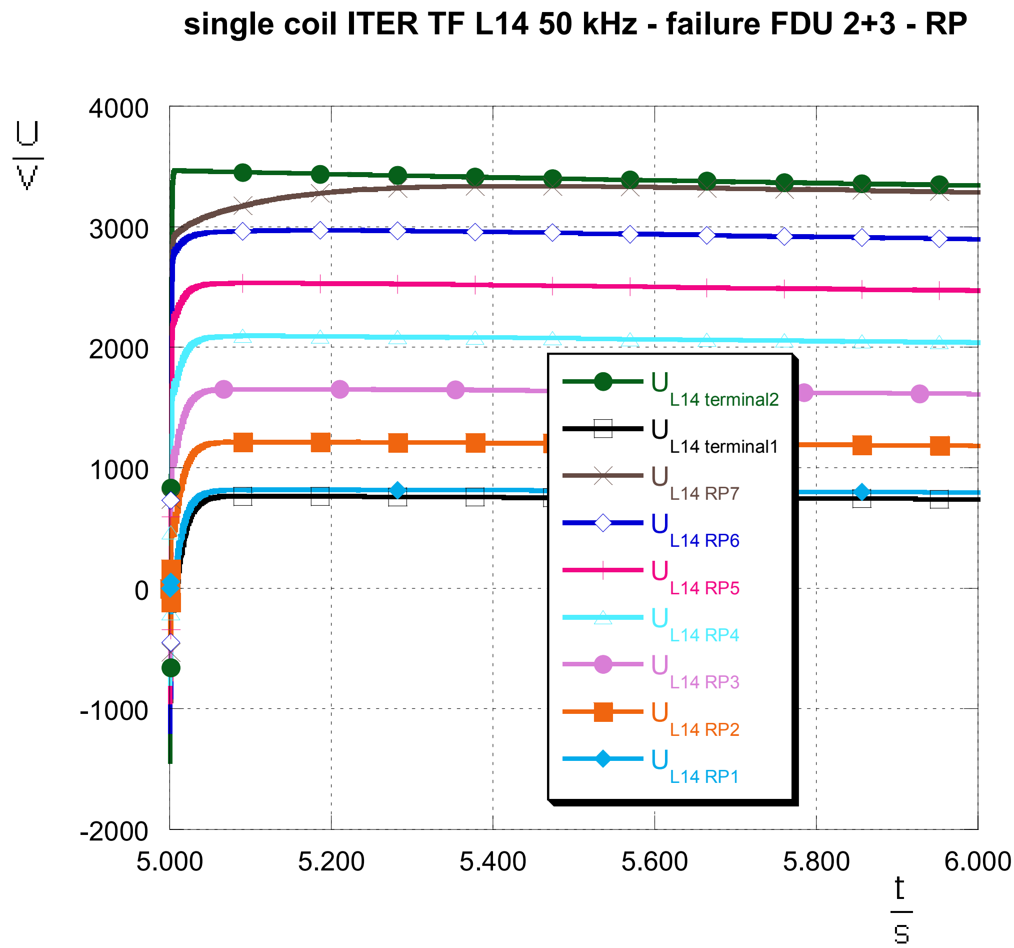


Fig. 2.2.1.1-1: Terminal and radial plate to ground voltages for coil 14 during a fast discharge with failure of FDU 2 and FDU 3.

Highest voltage of double pancake joint to ground appears on DPJ67 with 3.214 kV at t = 5.029 5 s. (fig. 2.2.1.1-2). The rise time of this voltage is t_A = 1.7 ms.

Highest voltage of helium inlet to ground appears on HeIn7 with 3.401 kV at t = 5.034 4 s. (fig. 2.2.1.1-3). The rise time of this voltage is t_A = 1.6 ms.

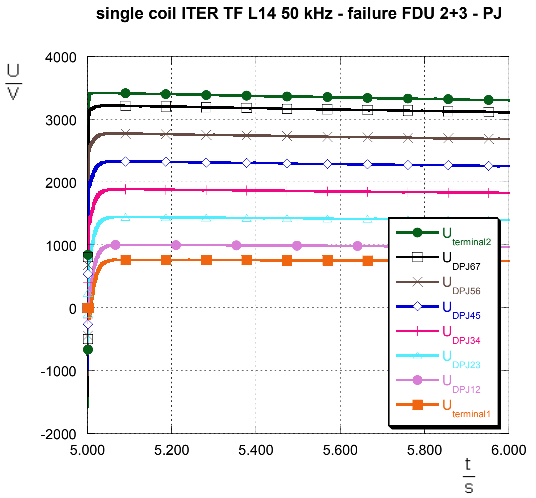


Fig. 2.2.1.1-2: Terminal and double pancake joint to ground voltages for coil 14 during a fast discharge with failure of FDU 2 and FDU 3.

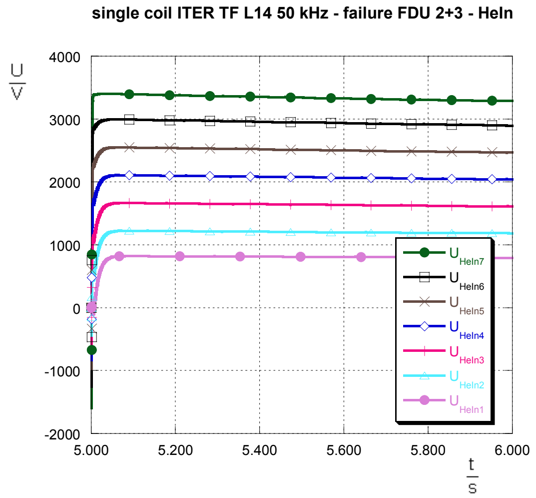


Fig. 2.2.1.1-3: Helium inlet to ground voltages for coil 14 during a fast discharge with failure of FDU 2 and FDU 3.

2.2.1.2 Results of radial plate insulation

Highest radial plate to radial plate voltage is between radial plate 4 and radial plate 3 U = 592.31 V at 5.006 0 s (t_A is 2 ms from 0 to maximum) (fig. 2.2.1.2-1, fig. 2.2.1.2-2).

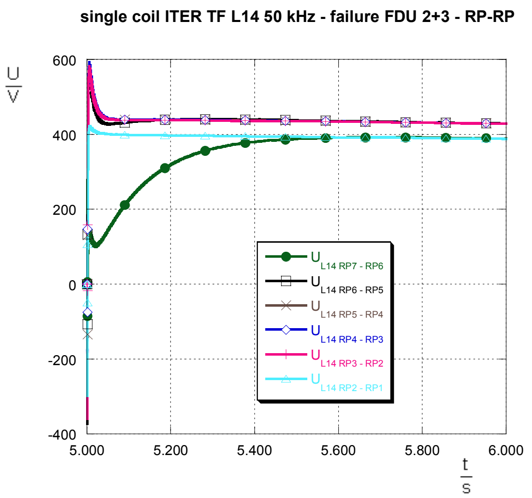


Fig. 2.2.1.2-1: Radial plate to radial plate voltages for coil 14 during a fast discharge with failure of FDU 2 and 3 for the time range 5.0 s to 6.0 s.

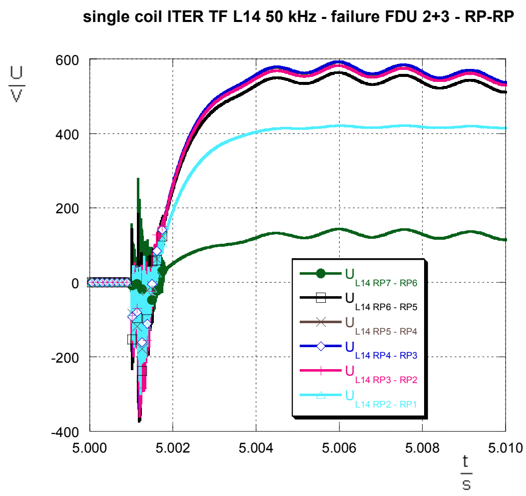


Fig. 2.2.1.2-2: Radial plate to radial plate voltages for coil 14 during a fast discharge with failure of FDU 2 and 3 for the time range 5.0 s to 5.01 s.

2.2.1.3 Results of conductor insulation

The double pancake joint (“outer joints”) to radial plat voltages (fig. 2.2.1.3-1) have the maximum of 543.668 V at PC 14 to RP 7 (t = 5.005 9 s). The rise time of this voltage from 0 V to maximum is 1.7 ms. Second most is PC 12 to RP 6. The voltage between pancake joint of PC 13 and radial plate number 7 starts with positive voltage and crosses the zero point between 5.1 s and 5.2 s. All other voltages do not make a zero transition after the switching disturbances (t > 5.0018 s). The minimum voltage caused by the capacitor switch on is -358.5 V at t = 5.001 0 s on R131:2 (DPC joint of PC 13) to RP 7.

The helium inlet (“inner joints”) to radial plate voltages have the maximum voltage of 465.215 V at t = 5.005 9 s with a rise time of 1.5 ms (fig. 2.2.1.3-2) on RP 7. The other helium inlet to radial plate voltages do not exceed ±200 V.

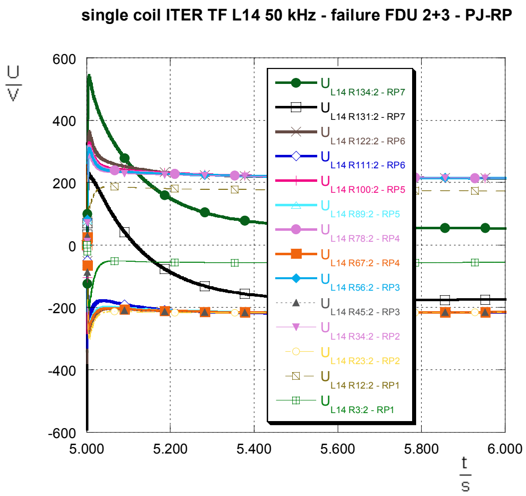


Fig. 2.2.1.3-1: Voltages between double pancake joint and radial plate.

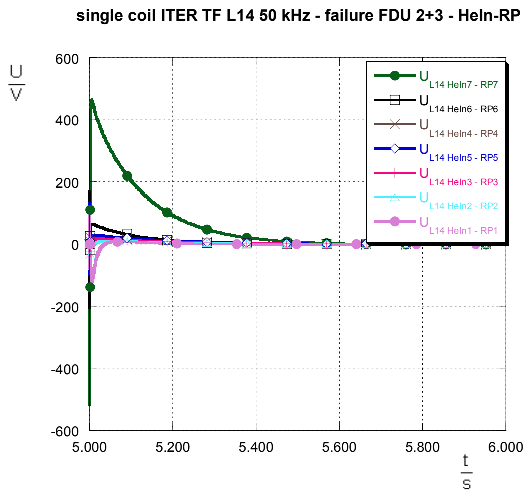


Fig. 2.2.1.3-2: The helium inlet (“inner joints”) to radial plate voltages.

For PC 14 to RP 7 the maximum voltage appears at the outer terminal (543.7 V). The smaller the distance to the He inlet is, the lower is the voltage. The voltages do not make a zero transition after the maximum.

2.2.1.4 Summary of the maximum voltages on coil 14 for the 50 kHz model during fast discharge with failure of FDU 2 and 3

	location	voltage, time	rise time
Maximum terminal to ground voltage	Terminal 2	3.4649 kV, 5.008 1 s	1.6 ms
Ground insulation	Terminal 2	3.4649 kV, 5.008 1 s	1.6 ms
	Radial plate: RP 7	3.3370 kV, 5.425 3 s	18.2 ms
	Double Pancake joint DPC67	3.2139 kV, 5.029 5 s	1.7 ms
	Helium inlet HeIn7	3.4008 kV, 5.034 4 s	1.6 ms
Radial plate insulation	Radial plate to radial plate: RP 4 – RP 3	592.31 V, 5.006 0 s	2 ms
Conductor insulation	Double pancake joints to radial plate: terminal 2 – RP 7	543.69 V, 5.005 9 s	1.7 ms
	Double pancake joints to radial plate: DPC joint of PC 13 – RP 7	-358.5 V 5.001 009 557 s	0.85 μs
	Helium inlet to radial plate: HeIn 7 - RP 7	465.22 V, 5.005 9 s	1.5 ms
	Pancake 14 to radial plate 7: terminal 2 – RP 7	543.69 V, 5.005 9 s	1.7 ms

2.2.2 Excitation of the 50 kHz model with the terminal voltages of L8

The 50 kHz single coil model was excited with the positive voltage V(L8:2) on the right side and positive voltage V(L8:1) on the left side. No maximum step size was set, RELTOL = 0.001. Calculation time was 40.81 h. The result file has 254 034 time steps.

2.2.2.1 Results for ground insulation

Highest voltage on terminal 8:2 is U = 8.0609 kV at t = 5.080 4 s. Rise time for zero point (t = 5.001 521 75 ms) to maximum: 17 ms.
Highest voltage of radial plate to ground appears on radial plate number 7 with 7.8706 kV at t = 5.416 s (t_A = 33 ms). The rise time of this voltage is higher than the rise time of the inner radial plate voltages to ground (fig. 2.2.2.1-1).

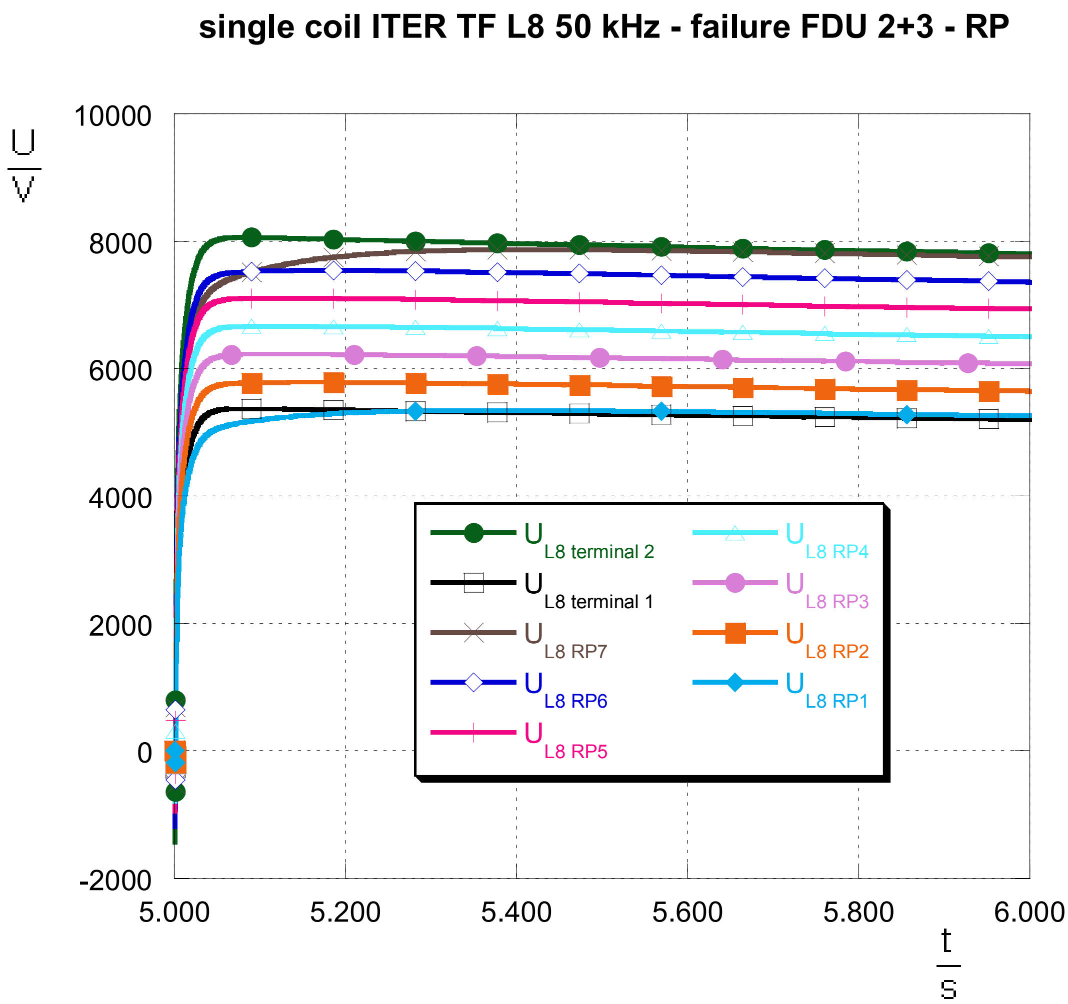


Fig. 2.2.2.1-1: Terminal and radial plate to ground (= case) voltages for coil 8 during a fast discharge with failure of FDU 2 and FDU 3.

Highest voltage of double pancake joint to ground appears on DPJ67 with 7.824 kV at t = 5.080 5 s. The rise time of this voltage is t_A = 17 ms (fig. 2.2.2.1-2).

Highest voltage of double helium inlet to ground appears on HeIn7 with 8.00 kV at t = 5.080 4 s. The rise time of this voltage is t_A = 17 ms (fig. 2.2.2.1-3).

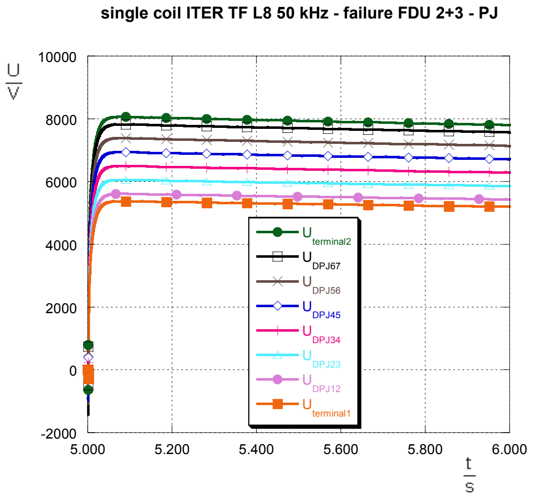


Fig. 2.2.2.1-2: Terminal and double pancake joint to ground voltages for coil 8 during a fast discharge with failure of FDU 2 and FDU 3.

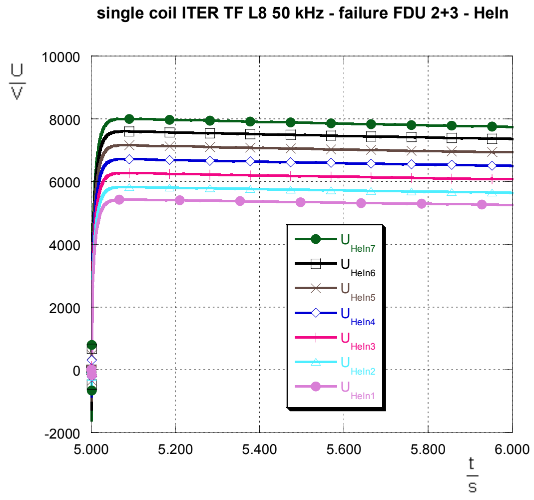


Fig. 2.2.2.1-2: Helium inlet to ground voltages for coil 8 during a fast discharge with failure of FDU 2 and FDU 3.

2.2.2.2 Results of radial plate insulation

Highest radial plate to radial plate voltage is between radial plate 2 and radial plate 1 U = 700.01 V at 5.029 1 s (t_A is 10.3 ms from 0 V to maximum) (fig. 2.2.2.2-1, fig. 2.2.2.2-2).

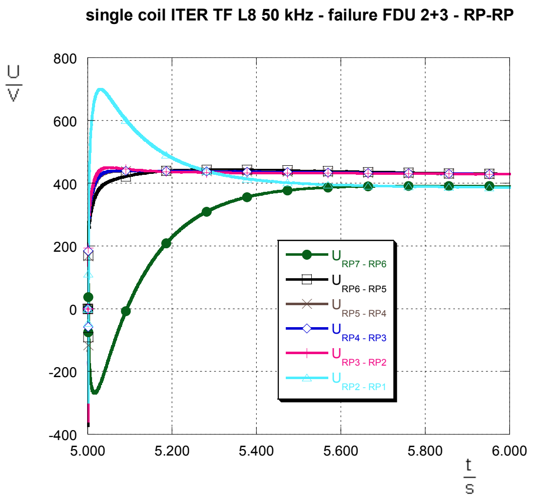


Fig. 2.2.2.2-1: Radial plate to radial plate voltages for coil 8 during a fast discharge with failure of FDU 2 and 3 for the time range 5.0 s to 6.0 s.

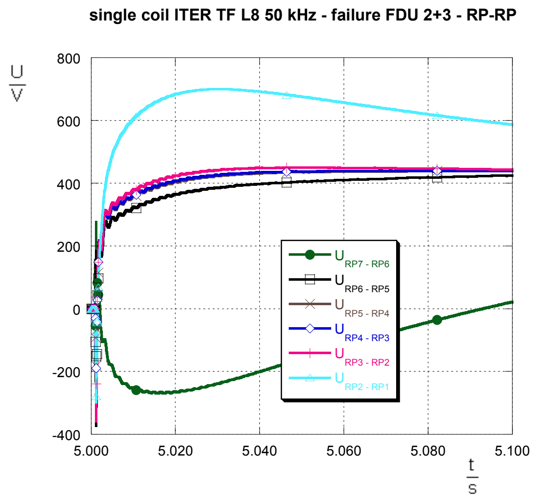


Fig. 2.2.2.2-2: Radial plate to radial plate voltages for coil 8 during a fast discharge with failure of FDU 2 and 3 for the time range 5.0 s to 5.1 s.

The voltage between radial plate 7 and radial plate 6 starts negative, all other radial plate voltages are positive.

2.2.2.3 Results of conductor insulation

The double pancake joint to radial plate voltages (fig. 2.2.2.3-1) have the maximum of 814.69 V at PC 14 to RP 7 (t = 5.023 2 s). The rise time of this voltage from 0 to maximum is 9 ms. Second most is PC 13 to RP 7. The voltage between pancake joint of PC 13 and radial plate number 7 and the voltage between PC 1 and radial plate 1 start with positive voltage and cross the zero point between 5.2 s and 5.3 s. All other voltages do not make a zero transition after the switching disturbances (t > 5.0018 s). The minimum voltage caused by the capacitor switch on is -358.5 V at t = 5.001 009 557 s with a rise time of 0.85 µs on R131:2 (DPC joint of PC 13) to RP 7 (fig. 2.2.2.3-2).

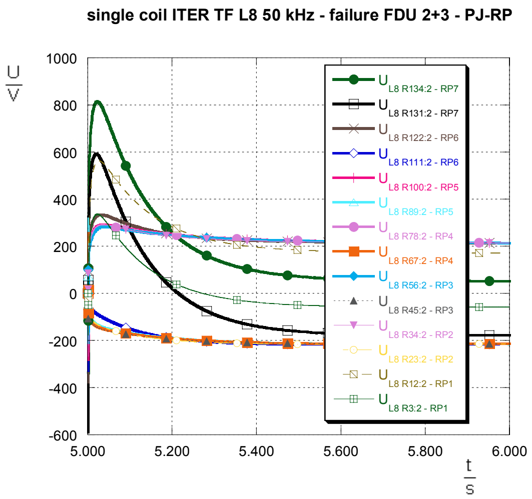


Fig. 2.2.2.3-1: Voltages between double pancake joint and radial plate.

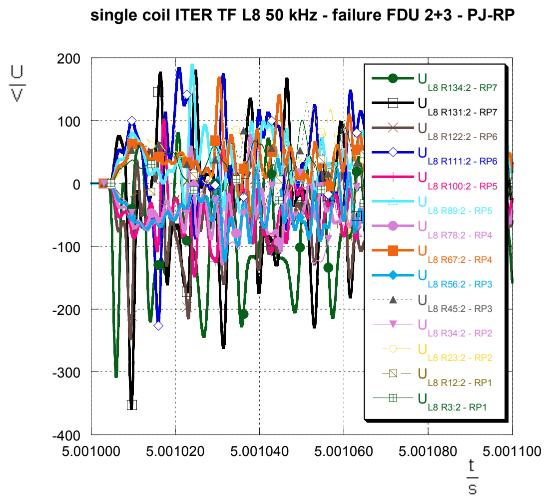


Fig. 2.2.2.3-2: Oscillating voltages between double pancake joint (“outer joints”) and radial plate after activation of the capacitor bank.

The helium inlet (“inner joints”) to radial plate voltage has the maximum voltage of 759.77 V at t = 5.001 7 s with a rise time of 7.8 ms (fig. 2.2.2.3-3) on RP 7. Between helium inlet and RP 1 the maximum voltage is 392.11 V. The voltages of the other radial plates do not exceed ±200 V.

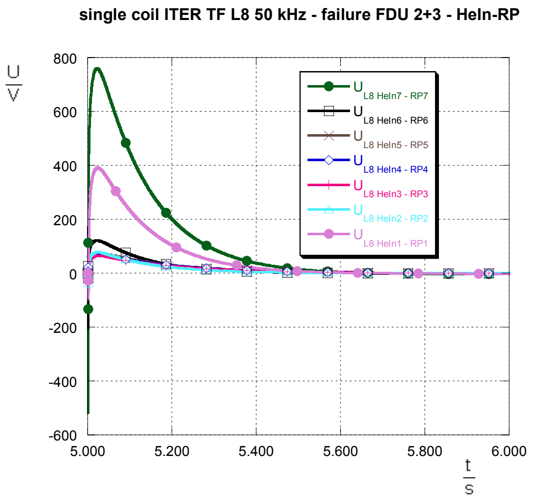


Fig. 2.2.2.3-3: The helium inlet (“inner joints”) to radial plate voltages.

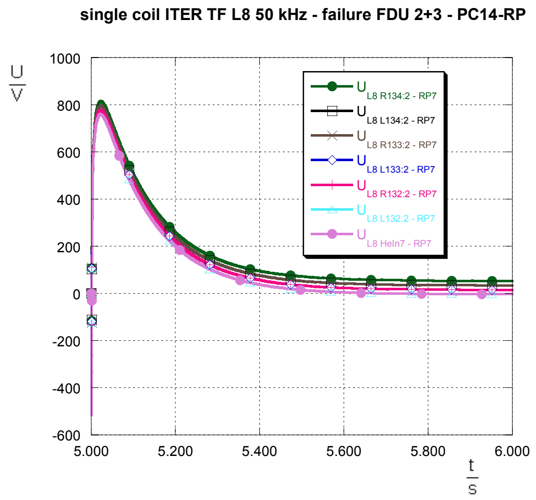


Fig. 2.2.2.3-4: The voltages along pancake 14 to radial plate 7.

For PC 14 to RP 7 the maximum voltage appears at the outer terminal (814.69 V) (fig. 2.2.2.3-4). The smaller the distance to the He inlet is, the lower is the voltage. The voltages do not make a zero transition after the maximum.

The voltages of pancake 13 to RP 7: All voltages are between the joint to RP voltage and the He inlet to RP voltage in the order how they are arranged within the radial plate, i.e. for smaller distances to the helium inlet the voltage is higher. The voltages not reach -200 V after the zero transition.

2.2.2.4 Summary of the maximum voltages on coil 8 for the 50 kHz model during fast discharge with failure of FDU 2 and 3

	location	voltage, time	rise time
Maximum terminal to ground voltage	Terminal 2	8.06 kV, 5.080 4 s	17 ms
Ground insulation	Terminal 2	8.06 kV, 5.080 4 s	17 ms
	Radial plate: RP 7	7.87 kV, 5.416 s	33 ms
	Double Pancake joint DPC67	7.82 kV, 5.080 5 s	17 ms
	Helium inlet HeIn7	8.00 kV, 5.080 4 s	17 ms
Radial plate insulation	Radial plate to radial plate: RP 2 – RP 1	700.01 V, 5.029 1 s	10.3 ms
Conductor insulation	Double pancake joints to radial plate: terminal 2 – RP 7	814.69 V, 5.023 2 s	9 ms
	Double pancake joints to radial plate: DPC joint of PC 13 – RP 7	-358.5 V 5.001 009 557 s	0.85 µs
	Helium inlet to radial plate: HeIn 7 - RP 7	759.77 V, 5.021 7 s	7.8 ms
	Pancake 14 to radial plate 7: terminal 2 – RP 7	814.69 V, 5.023 2 s	9 ms
	Pancake 13 to radial plate 7: HeIn 7 - RP 7	759.77 V, 5.021 7 s	7.8 ms

2.2.3 Excitation of the 1 kHz model with the terminal voltages of L14

The 1 kHz model of a single coil was excited with the voltage V(L14:2) on the right side and the voltage V(L14:1) on the left side. No maximum step size was set, RELTOL = 0.001. Calculation time was 28.08 h. The result file has 254 034 time steps.

2.2.3.1 Results for ground insulation

Highest voltage is at terminal L14:2 U = 3.4649 kV at t = 5.008 1 s. Rise time for zero point to maximum: 1.6 ms.
Highest voltage of radial plate to ground appears on radial plate number 7 with 3.338 kV at t = 5.420 3 s (t_A = 18 ms). The rise time of this voltage is higher than the rise time of the other radial plate voltages to ground, e. g. for radial plate 6 the rise time is 1.6 ms (fig. 2.2.3.1-1).

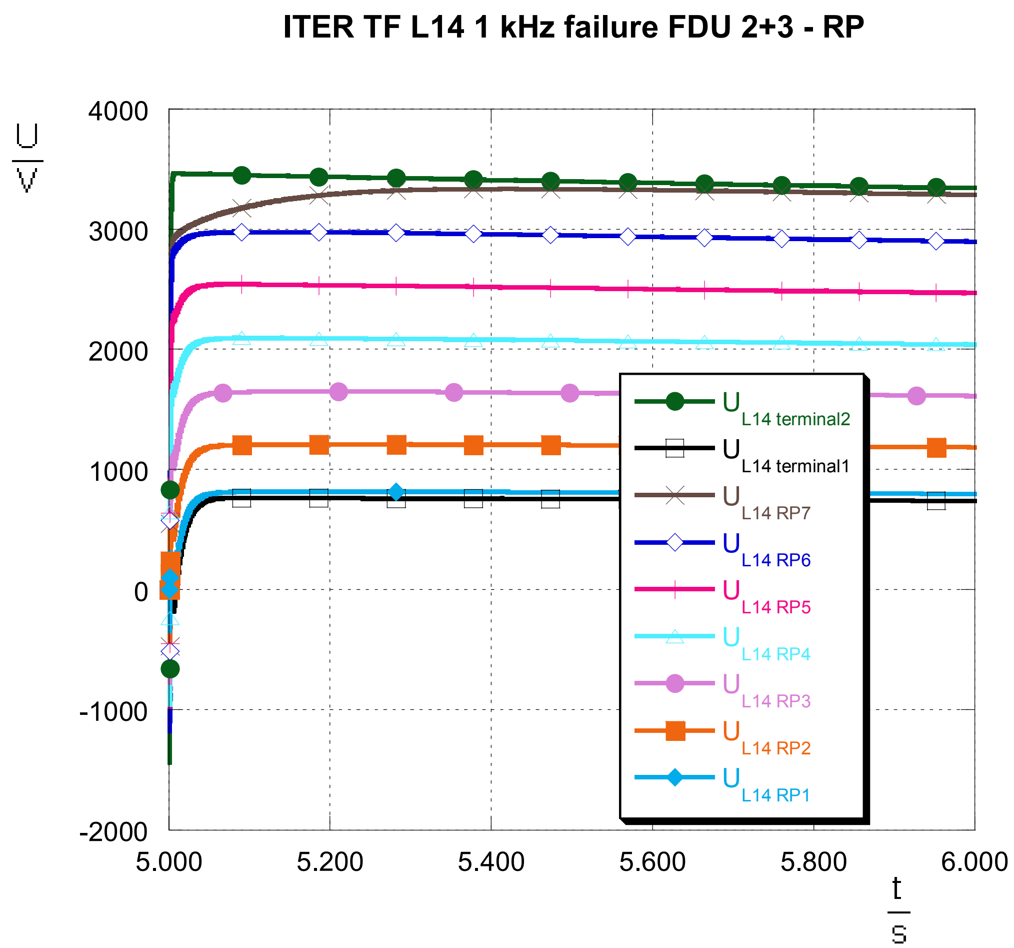


Fig. 2.2.3.1-1: Terminal and radial plate voltages to ground for coil 14 during a fast discharge with failure of FDU 2 and 3.

Highest voltage of double pancake joint to ground appears on DPJ67 with 3.232 kV at t = 5.042 6 s. The rise time of this voltage is 1.7 ms (fig. 2.2.3.1-2).
Highest voltage of helium inlet to ground appears on HeIn7 with 3.407 kV at t = 5.027 9 s. The rise time of this voltage is 1.6 ms (fig. 2.2.3.1-3).

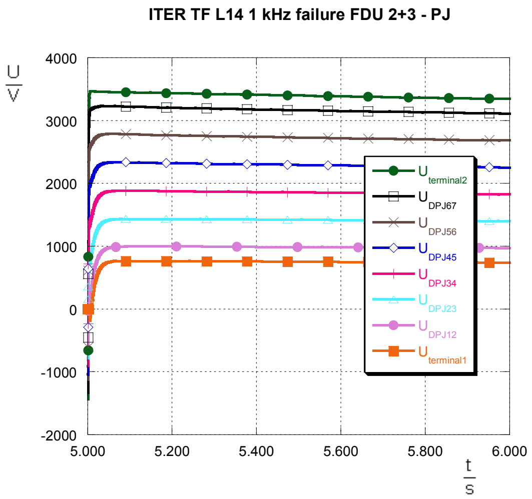


Fig. 2.2.3.1-2: Terminal and double pancake joint to ground voltages for coil 14 during a fast discharge with failure of FDU 2 and 3.

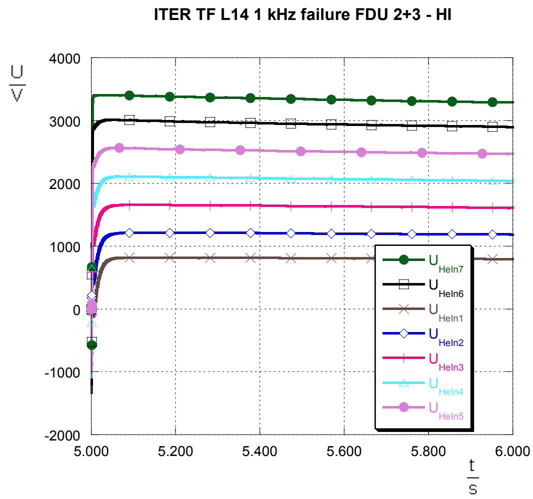


Fig. 2.2.3.1-3: Helium inlet voltages to ground for coil 14 during a fast discharge with failure of FDU 2 and 3.

2.2.3.2 Results of radial plate insulation

Highest radial plate to radial plate voltage is between radial plate 4 and radial plate 3 U = 613.63 V at 5.006 0 s (t_A is 1.6 ms from 0 V to maximum) (fig. 2.2.3.2-1, fig. 2.2.3.2-2).

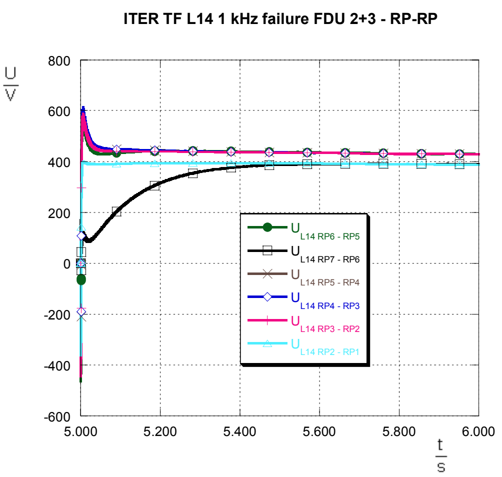


Fig. 2.2.3.2-1: Radial plate to radial plate voltages for coil 14 during a fast discharge with failure of FDU 2 and 3 for the time range 5.0 s to 6.0 s.

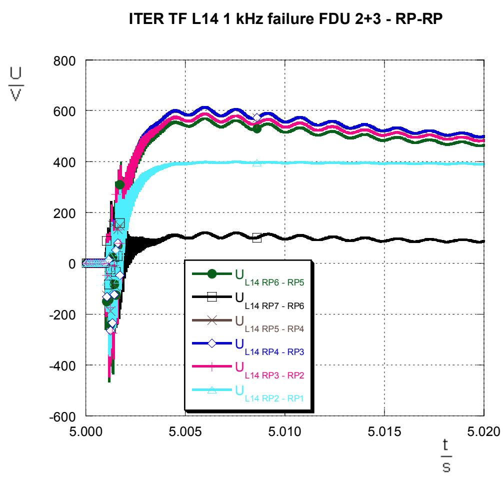


Fig. 2.2.3.2-2: Radial plate to radial plate voltages for coil 14 during a fast discharge with failure of FDU 2 and 3 for the time range 5.0 s to 5.02 s.

2.2.3.3 Results of conductor insulation

The examination of the conductor to radial plate voltage is divided into certain steps.

The double pancake joints to radial plate voltage (fig. 2.2.3.3-1): maximum of 539.206 V at PC 14 to RP 7 (t = 5.006 0 s). The rise time of this voltage from 0 to maximum is 1.6 ms. Second most is PC 12 to RP 6. The voltage between pancake joint of PC 13 and radial plate number 7 starts with a positive voltage and crosses the zero point at 5.1 s. All other voltages do not make a zero transition after the switching disturbances (t > 5.002 s).

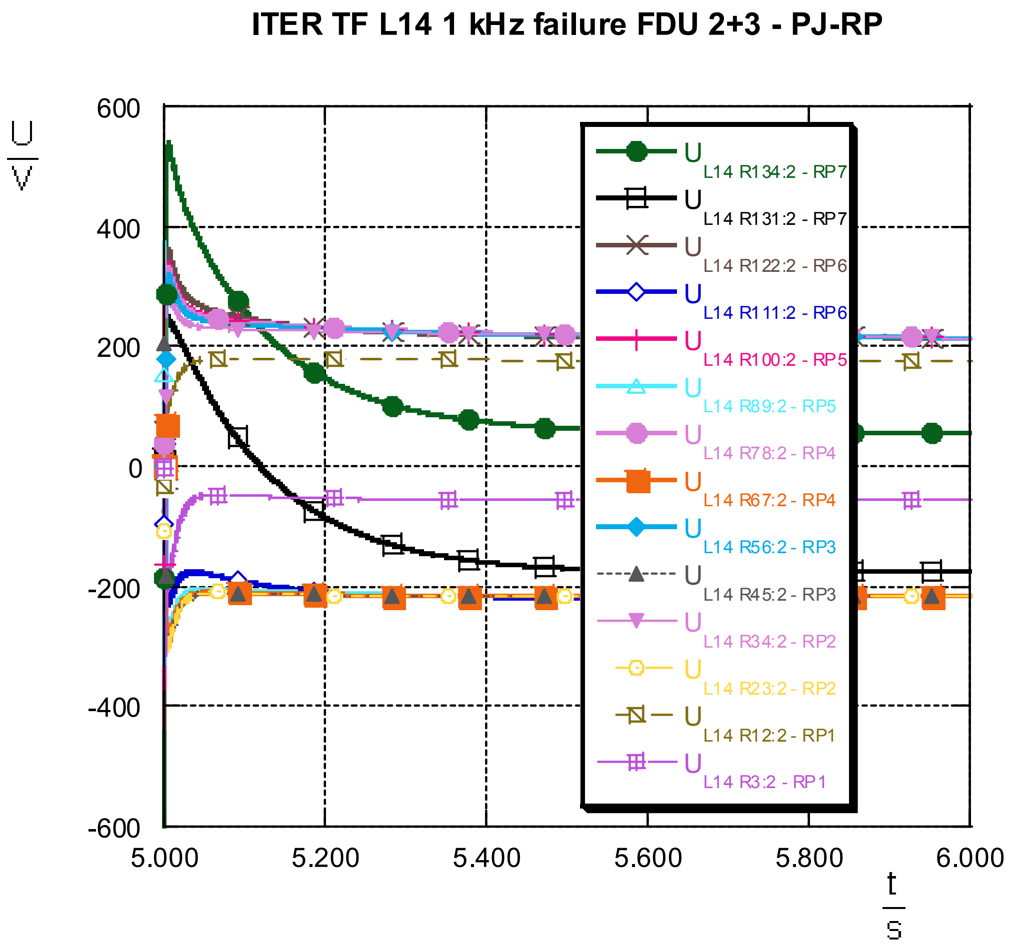


Fig. 2.2.3.3-1: Voltages between double pancake joint and radial plate.

The helium inlet ("inner joints") to radial plate voltages have the maximum voltage of 470.867 V at t = 5.005 9 s with a rise time of 1.6 ms (fig. 2.2.3.3-3) on RP 7. Between helium inlet and RP 1 the minimum of the negative voltage is -135.21 V. The voltages of the other radial plates do not exceed ±100 V after the non real switching disturbances.

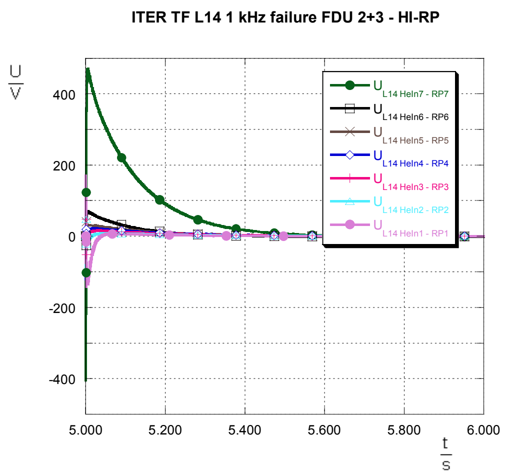


Fig. 2.2.3.3-3: The helium inlet to radial plate voltages.

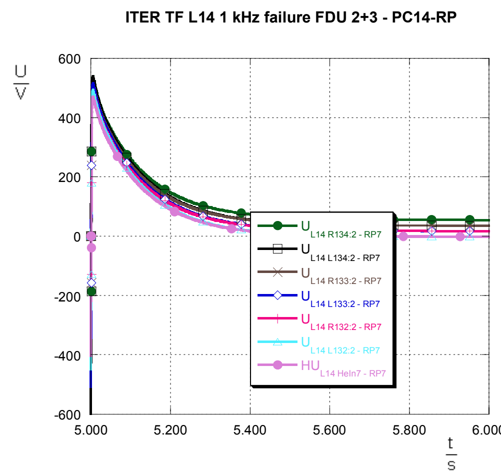


Fig. 2.2.3.3-4: The voltages along pancake 14 to radial plate 7.

For PC 14 to RP 7 the maximum voltage appears at the outer terminal (539.21 V) (fig. 2.2.3.3-4). The smaller the distance to the He inlet is, the lower is the voltage. The voltages do not make a zero transition after the maximum.

2.2.3.4 Summary of the maximum voltages on coil 14 for the 1 kHz model during a fast discharge with failure of FDU 2 and 3

	location	voltage, time	rise time
Maximum terminal to ground voltage	Terminal 2	3.46 kV, 5.008 1 s	1.6 ms
Ground insulation	Terminal 2	3.46 kV, 5.008 1 s	1.6 ms
	Radial plate: RP 7	3.338 kV, 5.420 3 s	18 ms
	Double Pancake joint DPC67	3.23 kV, 5.042 6 s	1.7 ms
	Helium inlet HeIn7	3.41 kV, 5.027 9 s	1.6 ms
Radial plate insulation	radial plate to radial plate: RP 4 – RP 3	613.63 V, 5.006 0 s	1.6 ms
Conductor insulation	Double pancake joints to radial plate: terminal 2 – RP 7	539.21 V, 5.006 0 s	1.6 ms
	Helium inlet to radial plate: HeIn 7 - RP 7	470.87 V, 5.005 9 s	1.6 ms
	Pancake 14 to radial plate 7: terminal 2 – RP 7	539.21 V, 5.006 0 s	1.6 ms

2.2.4 Excitation of the 1 kHz model with the terminal voltages of L8

The 1 kHz model of a single coil was excited with the voltage V(L8:2) on the right side and the voltage V(L8:1) on the left side. No maximum step size was set, RELTOL = 0.001. Calculation time was 27.18 h. The result file has 254 034 time steps.

2.2.4.1 Results for ground insulation

Highest voltage is at terminal 8:2 U = 8.0609 kV at t = 5.080 4 s. Rise time for zero point to maximum is 17 ms.
Highest voltage of radial plate to ground appears on radial plate number 7 with 7.871 kV at t = 5.413 8 s (t_A = 32.6 ms). The rise time of this voltage is higher than the rise time of the other radial plate voltages to ground, e. g. for radial plate 6 the rise time is 18 ms (fig. 2.2.4.1-1).

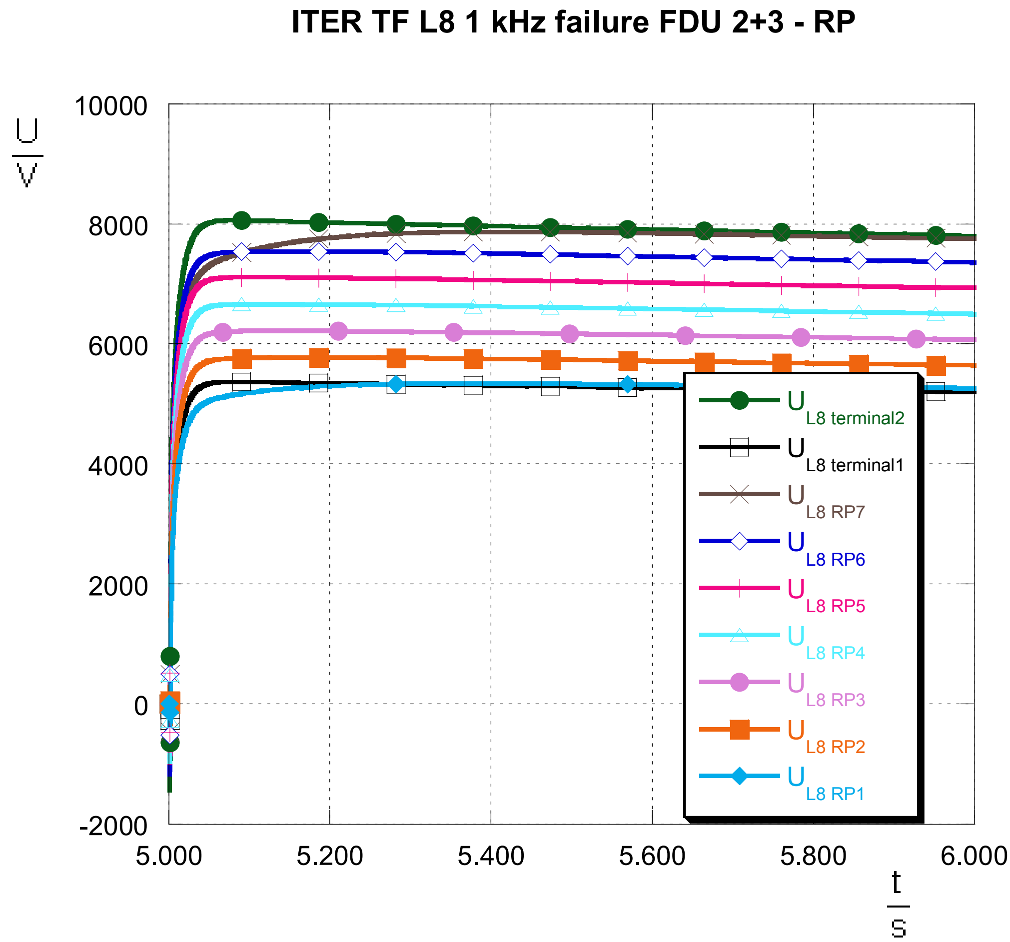


Fig. 2.2.4.1-1: Terminal and radial plate voltages to ground for coil 8 during a fast discharge with failure of FDU 2 and 3.

Highest voltage of double pancake joint to ground occurs on DPC67 with 7.834 kV at t = 5.077 2 s (t_A = 17 ms) (fig. 2.2.4.1-2).
Highest voltage of helium inlet to ground occurs on helium inlet 7 with 8.008 kV at t = 5.078 8 s (t_A = 17 ms) (fig. 2.2.4.1-3).

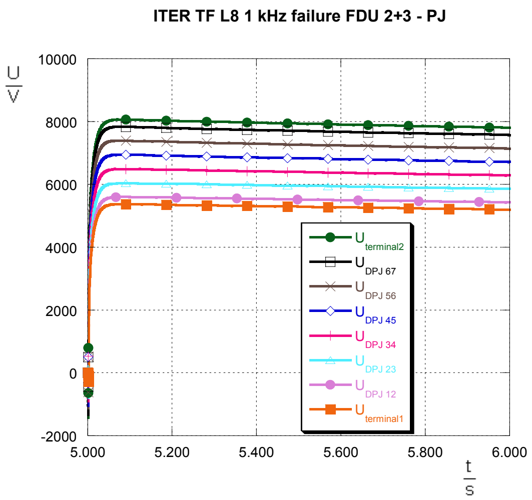


Fig. 2.2.4.1-2: Terminal and radial plate voltages to ground for coil 8 during a fast discharge with failure of FDU 2 and 3.

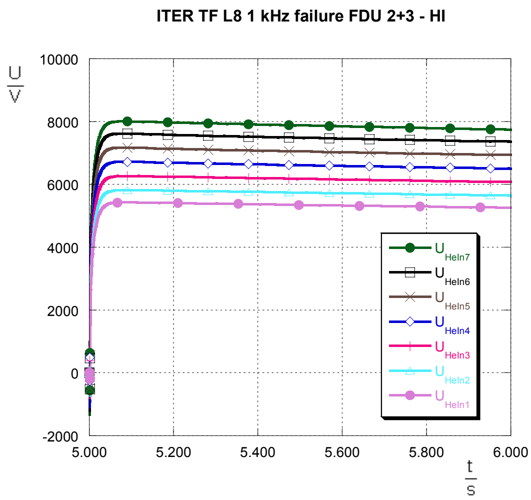


Fig. 2.2.4.1-3: Helium inlet to ground voltages for coil 8 during a fast discharge with failure of FDU 2 and 3.

2.2.4.2 Results of radial plate insulation

Highest radial plate to radial plate voltage is between radial plate 2 and radial plate 1 U = 686.48 V at 5.029 8 s (t_A is 10.5 ms from 0 V to maximum) (fig. 2.2.4.2-1). The voltage between radial plate 7 and radial plate 6 has a minimum of -283.27 V and a zero transition at 5.015 7 s. All other radial plate to radial plate voltages do not have a zero transition.

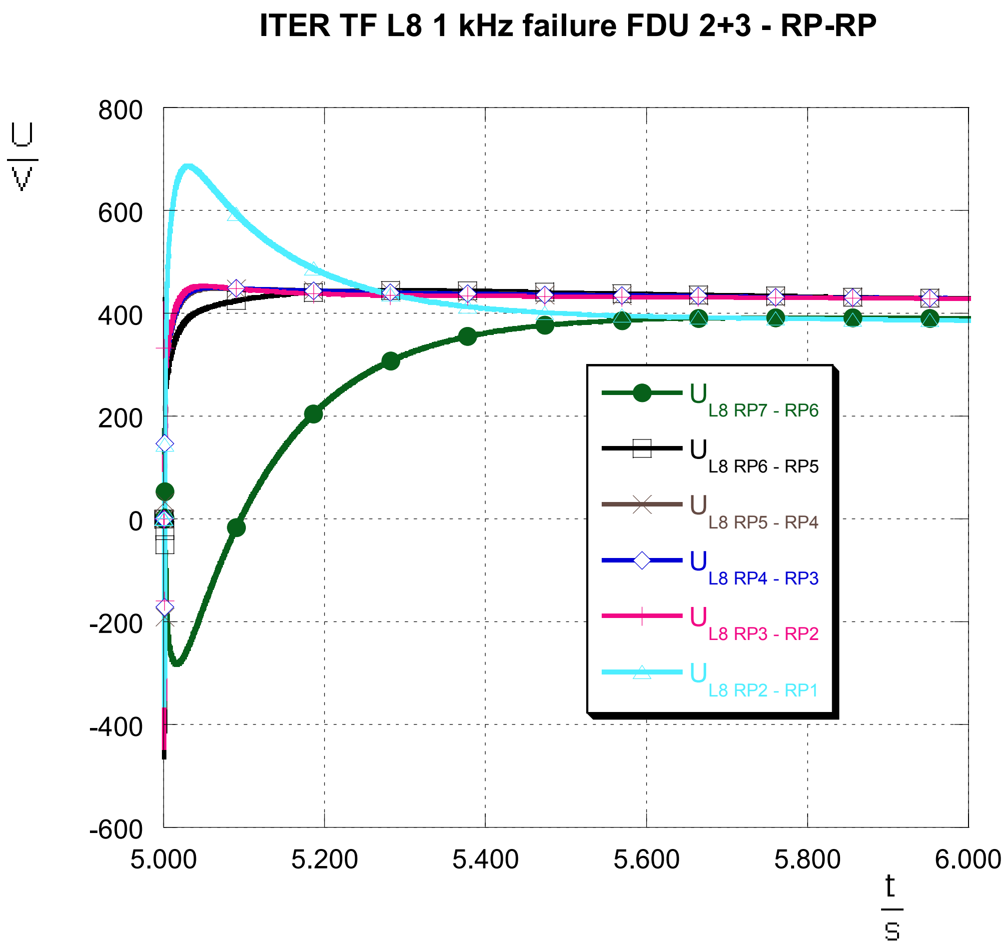


Fig. 2.2.4.2-1: Radial plate to radial plate voltages for coil 8 during a fast discharge with failure of FDU 2 and 3.

2.2.4.3 Results of conductor insulation

The maximum of the double pancake joints to radial plate voltages (fig. 2.2.4.3-1) is 811.44 V at PC 14 to RP 7 (t = 5.023 2 s). The rise time of this voltage from 0 V to maximum is 8 ms. Second most is PC 13 to RP 7 with 603.49 V. The voltages between pancake joint of PC 13 and radial plate number 7 and between the joint of PC 1 and RP 1 start with a positive voltage and cross the zero point between at 5.2 s and 5.3 s. All other voltages do not make a zero transition after the switching disturbances (t > 5.002 s).

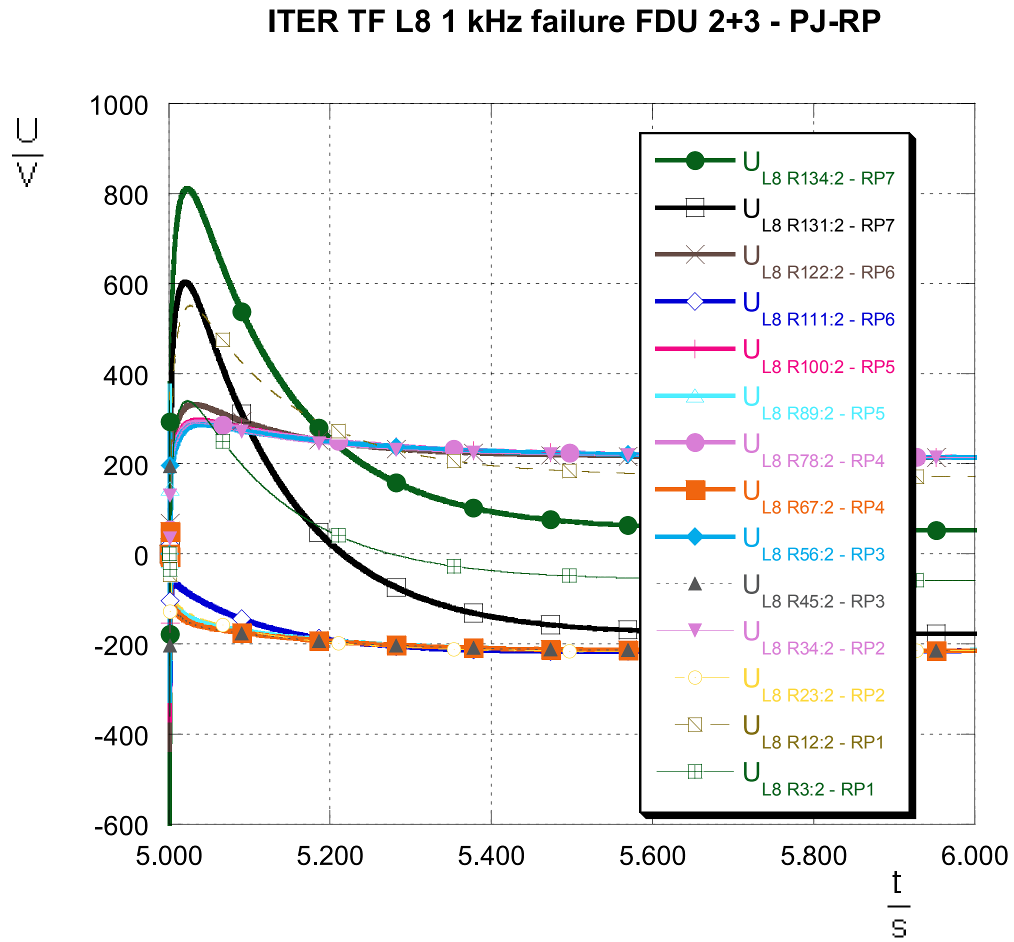


Fig. 2.2.4.3-1: Voltages between double pancake joint and radial plate.

The helium inlet to radial plate voltages have the maximum voltage of 762.95 V at t = 5.021 7 s with a rise time of 7.7 ms (fig. 2.2.4.3-3) on RP 7. Between helium inlet and RP 1 the maximum voltage is 389.02 V. The voltages of the other radial plates do not exceed 150 V after the non real switching disturbances.

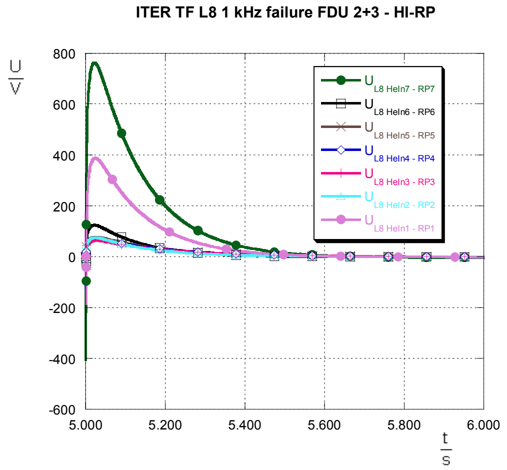


Fig. 2.2.4.3-3: The helium inlet to radial plate voltages.

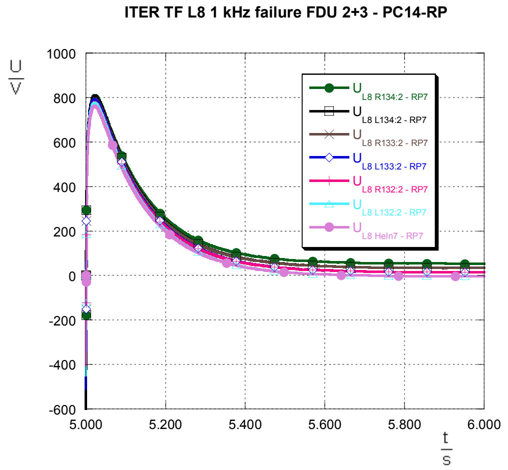


Fig. 2.2.4.3-4: The voltages along pancake 14 to radial plate 7.

For PC 14 to RP 7 the maximum voltage appears at the outer terminal (811.44 V) (fig. 2.2.4.3-4). The smaller the distance to the He inlet is, the lower is the voltage. The voltages do not make a zero transition after the maximum. For PC 13 the highest voltage appears on the helium inlet (762.95 V).

2.2.4.4 Summary of the maximum voltages on coil 8 for the 1 kHz model during a fast discharge with failure of FDU 2 and 3

	location	voltage, time	rise time
Maximum terminal to ground voltage	Terminal 2	8.06 kV, 5.080 4 s	17 ms
Ground insulation	Terminal 2	8.06 kV, 5.080 4 s	17 ms
	Radial plate: RP 7	7.87 kV, 5.413 8 s	33 ms
	Double Pancake joint DPC67	7.83 kV, 5.077 2 s	17 ms
	Helium inlet HeIn7	8.01 kV, 5.078 8 s	17 ms
Radial plate insulation	Radial plate to radial plate: RP 2 – RP 1	686.48 V, 5.029 8 s	11 ms
Conductor insulation	Double pancake joints to radial plate: terminal 2 – RP 7	811.44 V, 5.023 2 s	8 ms
	Helium inlet to radial plate: HeIn 7 - RP 7	762.95 V, 5.021 7 s	7.7 ms
	Pancake 14 to radial plate 7: terminal 2 – RP 7	811.44 V, 5.023 2 s	8 ms
	Pancake 13 to radial plate 7: HeIn 7 – RP 7	762.95 V, 5.021 7 s	

2.3 FD with failure of FDU 2 and 3 and failure at Terminal 3:1

2.3.1 Excitation of the 50 kHz model with the terminal voltages of L2

The 50 kHz model single coil was excited with V(L2:1) on the left and V(L2:2) on the right side. No maximum step size was set, RELTOL = 0.001. Calculation time was 32.2 h (47.6 h with the old system and software). Result file has 290 355 time steps.

2.3.1.1 Results of ground insulation

Highest voltage on terminal L2:2 is 9656 V at t = 5.081 9 s (fig. 2.3.1.1-1). The rise time for the terminal voltage is t_A = 2.4 µs from voltage value before breakdown (–1145 V) to maximum. Highest voltage of radial plate to ground appears on radial plate number 6 with 8697.4 V at t = 5.081 9 s (t_A = 4.2 µs).

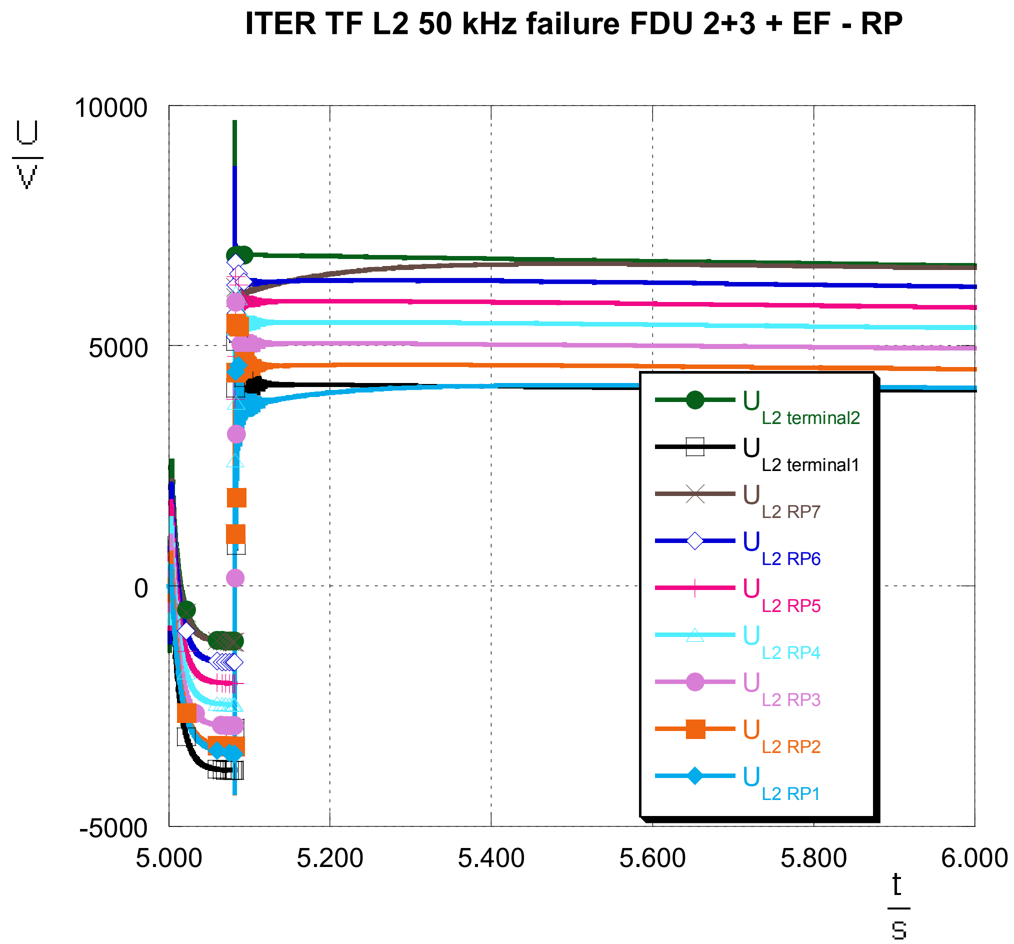


Fig. 2.3.1.1-1: Terminal and radial plate to ground voltages for coil 2 during a fast discharge with failure of 2 FDUs and earth fault.

Highest voltage on double pancake joint to ground appears at DPJ67 and is 10.669 kV at t = 5.081 9 s (fig. 2.3.1.1-2). After the fault the double pancake voltages are swinging with several frequencies. The rise times for the double pancake joint DPJ67 voltage from -1.38 kV to maximum is 3.7 µs.

Highest voltage of helium inlet to ground appears on HeIn7 with 10.200 kV at t = 5.081 9 s (fig. 2.3.1.1-3). After the fault the helium inlet voltages are swinging with several frequencies. The rise times for the HeIn7 voltage from -1.20 kV to maximum is 2.3 µs.

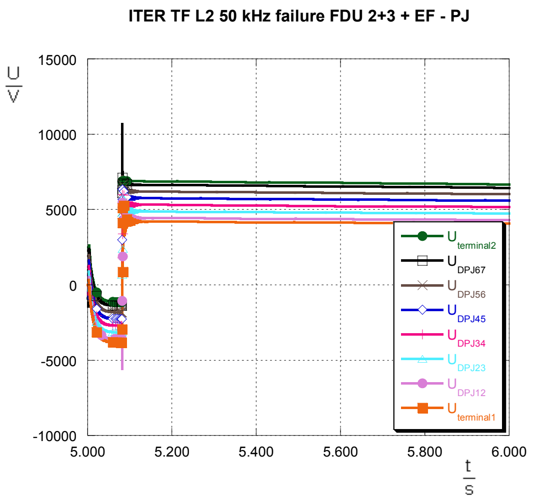


Fig. 2.3.1.1-2: Terminal and double pancake joint to ground voltages for coil 2 during a fast discharge with failure of 2 FDUs and earth fault.

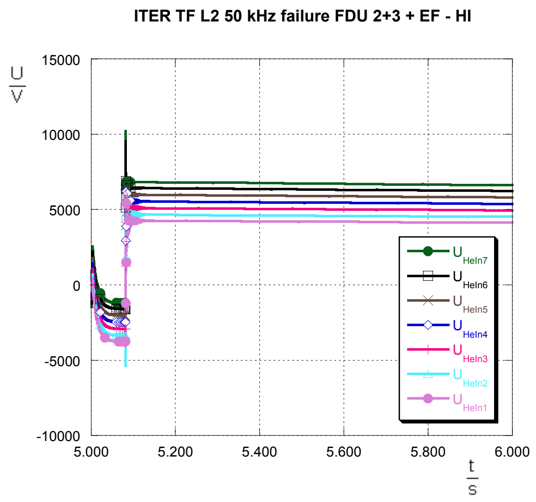


Fig. 2.3.1.1-3: Helium inlet to ground voltages for coil 2 during a fast discharge with failure of 2 FDUs and earth fault.

2.3.1.2 Results of radial plate insulation

Highest radial plate to radial plate voltage is between radial plate 6 and radial plate 5 U = 4.3301 kV at t = 5.081 9 s. The rise time t_A is about 3 µs from -1.4 kV to maximum (maximum is at the second oscillation, first oscillation swings in negative polarity). Second most voltage is between radial plate 3 and 2 U = 3.5792 kV.

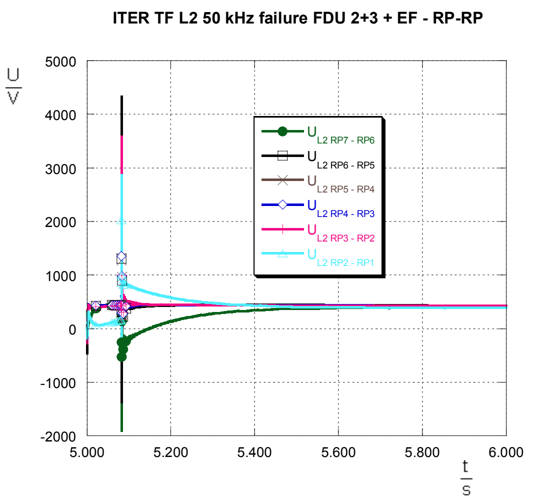


Fig. 2.3.1.2-1: Radial plate to radial plate voltages for coil 2 during a fast discharge with failure of 2 FDUs and earth fault.

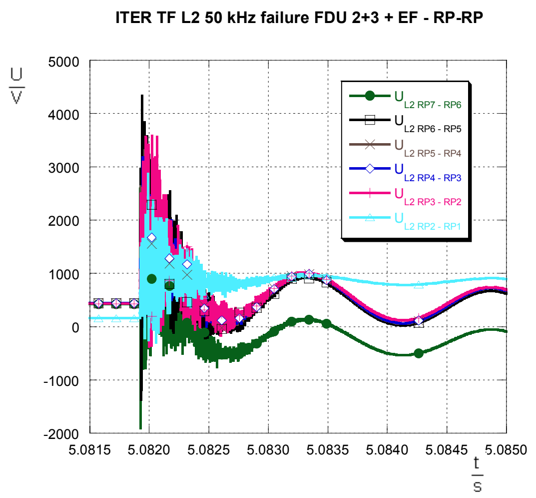


Fig. 2.3.1.2-2: Radial plate to radial plate voltages for coil 2 in the time range after the earth fault during a fast discharge with failure of 2 FDUs and earth fault.

2.3.1.3 Results of conductor insulation

The double pancake joints to radial plate voltages have a maximum of 3657.5 V (t = 5.081 9 s) at PC 13 to RP 7. The rise time from zero transition to maximum is 1.4 µs. Second most is 3577.0 V at PC 14 to RP 7.

The maximum of the helium inlet to radial plate voltage is -2859.5 V of RP 7 at t = 5.081 9 s. The rise time of this voltage is 1.7 µs. The second most voltage difference between helium inlet and radial plate is U = -1416.0 V for RP 1.

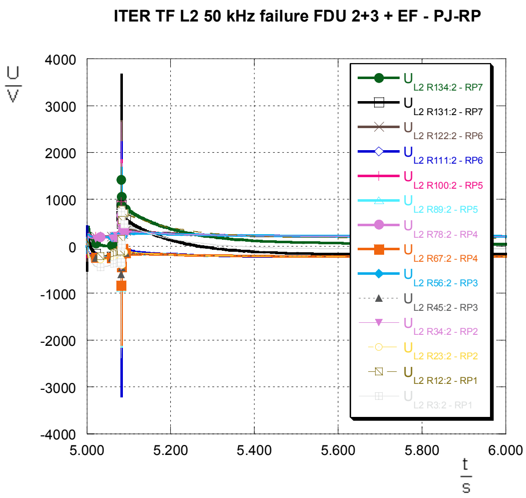


Fig. 2.3.1.3-1: Double pancake joint to radial plate voltages for coil 2 during a fast discharge with failure of 2 FDUs and earth fault.

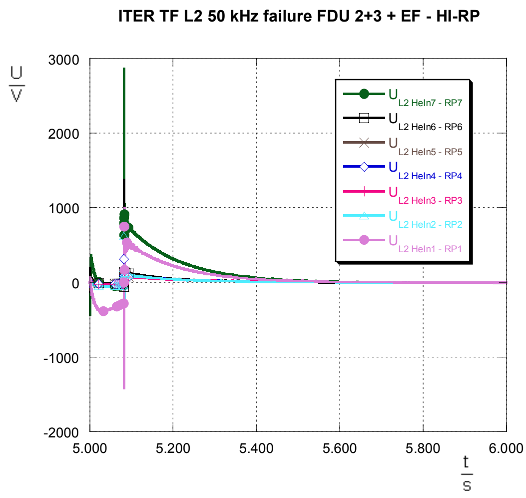


Fig. 2.3.1.3-2: Helium inlet to radial plate voltages for coil 2 during a fast discharge with failure of 2 FDUs and earth fault.

The voltages of pancake 13 to RP 7 (fig. Fig. 2.3.1.3-3) have the maximum voltage of 3682.0 V at the outer most inductance (L131:1). The second most voltage is found at the double pancake joint. Both waveforms have the same rise time of 1.4 µs.

For PC 14 to RP 7 the maximum voltage appears at the outer terminal.

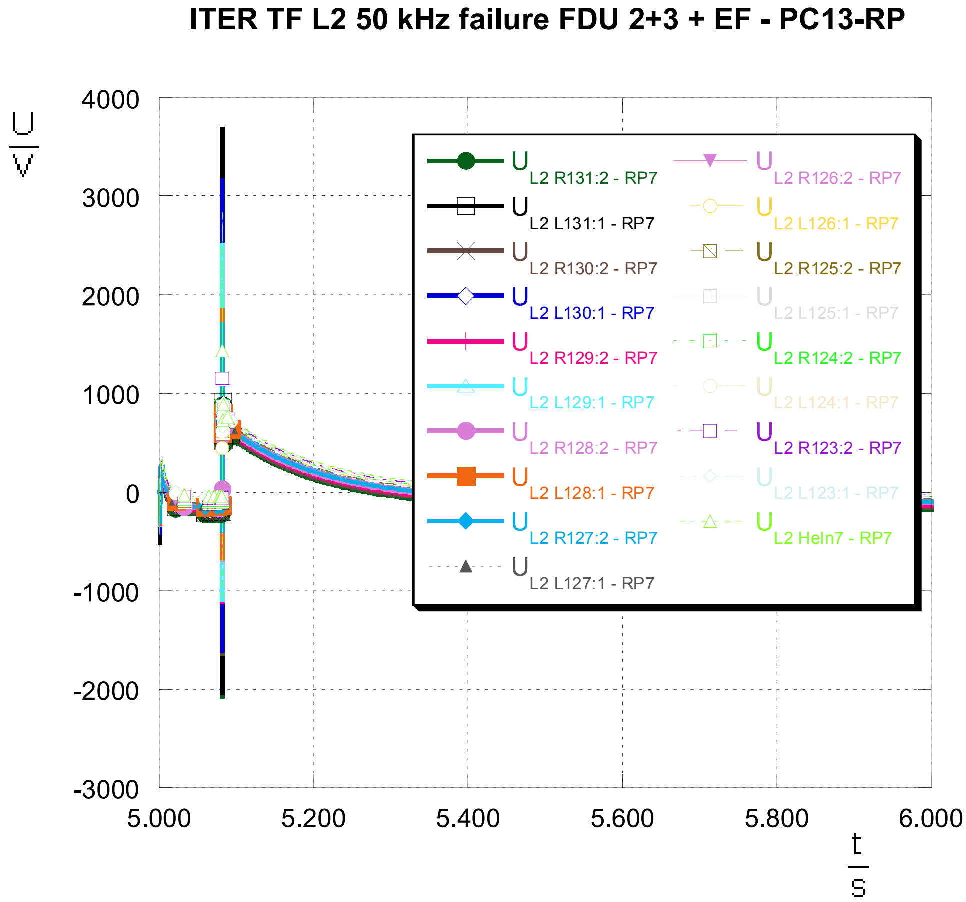


Fig. 2.3.1.3-3: Voltages along pancake 13 to radial plate 7 for coil 2 during a fast discharge with failure of 2 FDUs and earth fault.

2.3.1.4 Summary of the maximum voltages on coil 2 for the 50 kHz model during fast discharge with failure of FDU 2 and 3 and earth fault

	location	voltage, time	rise time
Maximum terminal to ground voltage	Terminal 2	9.656 kV, 5.081 9 s	2.4 µs
Ground insulation	Terminal 2	9.656 kV, 5.081 9 s	2.4 µs
	Radial plate: RP 6	8.697 kV, 5.081 9 s	4.2 µs
	Double Pancake joint DPJ67	10.669 kV, 5.081 9 s	3.7 µs
	Helium inlet HeIn7	10.200 kV, 5.081 9 s	2.3 µs
Radial plate insulation	Radial plate to radial plate: RP 6 – RP 5	4.330 kV, 5.081 9 s	About 3 µs
Conductor insulation	Double pancake joints to radial plate: Near DPC joint of PC 13 – RP 7	3.658 kV, 5.081 9 s	1.4 µs
	Helium inlet to radial plate: HeIn 7 - RP 7	2.860 kV, 5.081 9 s	1.7 µs
	Pancake 13 to radial plate 7: Near DPC joint of PC 13 – RP 7	3.682 kV, 5.081 9 s	1.4 µs
	Pancake 14 to radial plate 7: terminal 2 – RP 7	3.577 kV	About 2 µs

2.3.2 Excitation of the 50 kHz model with the terminal voltages of L8

The 50 kHz model single coil was excited with the voltage V(L8:2) on the right side and the voltage V(L8:1) on the left side. No maximum step size was set, RELTOL = 0.001.
Calculation time was 52.2 h. The result file has 290 362 time steps.

2.3.2.1 Results for ground insulation

Highest voltage on terminal 8:2 is U = 16.354 kV at t = 5.087 7 s (fig. 2.3.2.1-1). Rise time for the step after earth fault (t = 5.081 920 ms, U = 8.06 kV) to maximum voltage is about 3.5 ms.
Highest voltage of radial plate to ground appears on radial plate number 6 with 15.777 kV at t = 5.087 6 s (t_A similar to voltage on terminal 8:2).

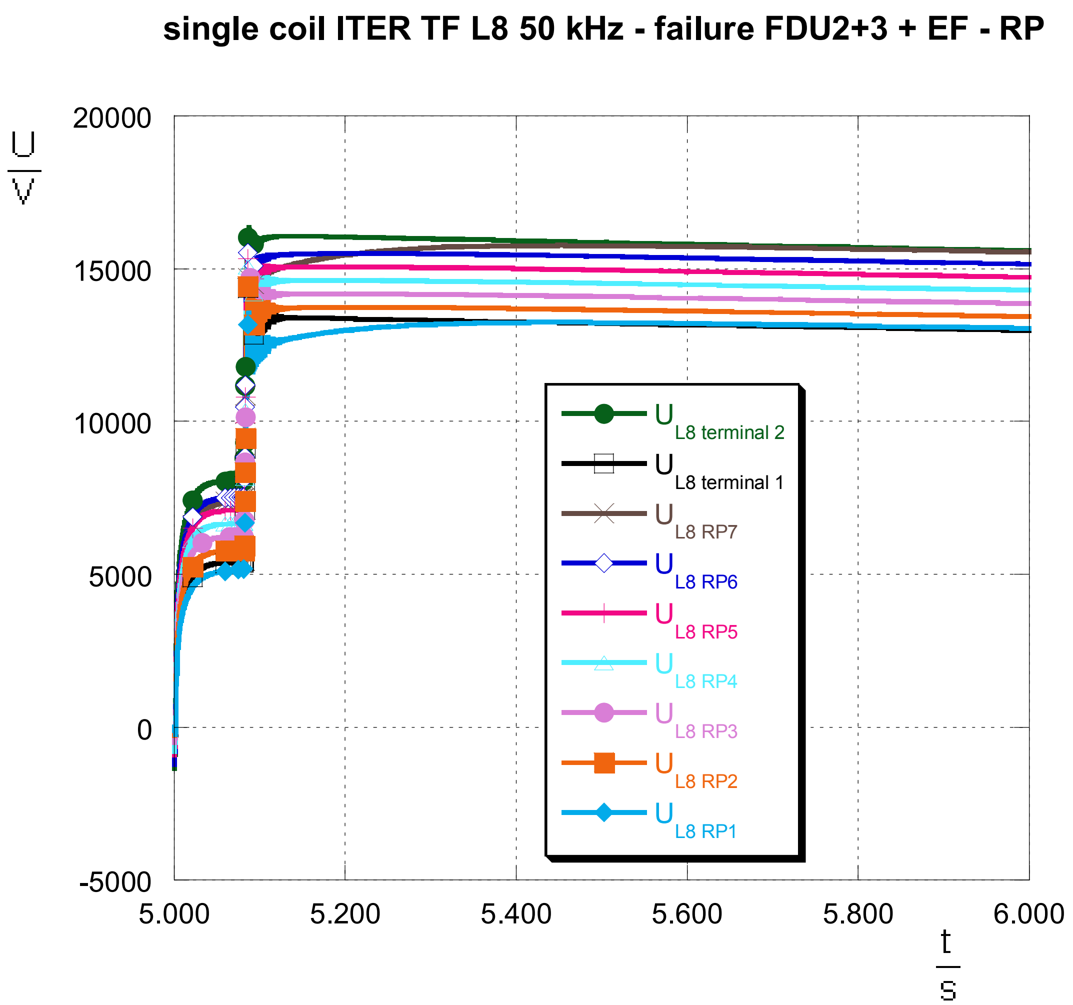


Fig. 2.3.2.1-1: Terminal and radial plate to ground (= case) voltages for coil 8 during a fast discharge with failure of FDU 2 and FDU 3 and breakdown to ground (earth fault).

The double pancake joint to ground voltages are examined (fig. 2.3.2.1-2) due to the fact that this case produces the highest terminal to ground voltages. No double pancake joint voltage exceed the voltage at terminal 2. Highest voltage value of 16.161 kV at 5.087 7 s with a rise time of 3.3 ms occurs on the joint between PC 12 and PC 13 (= DPJ67).

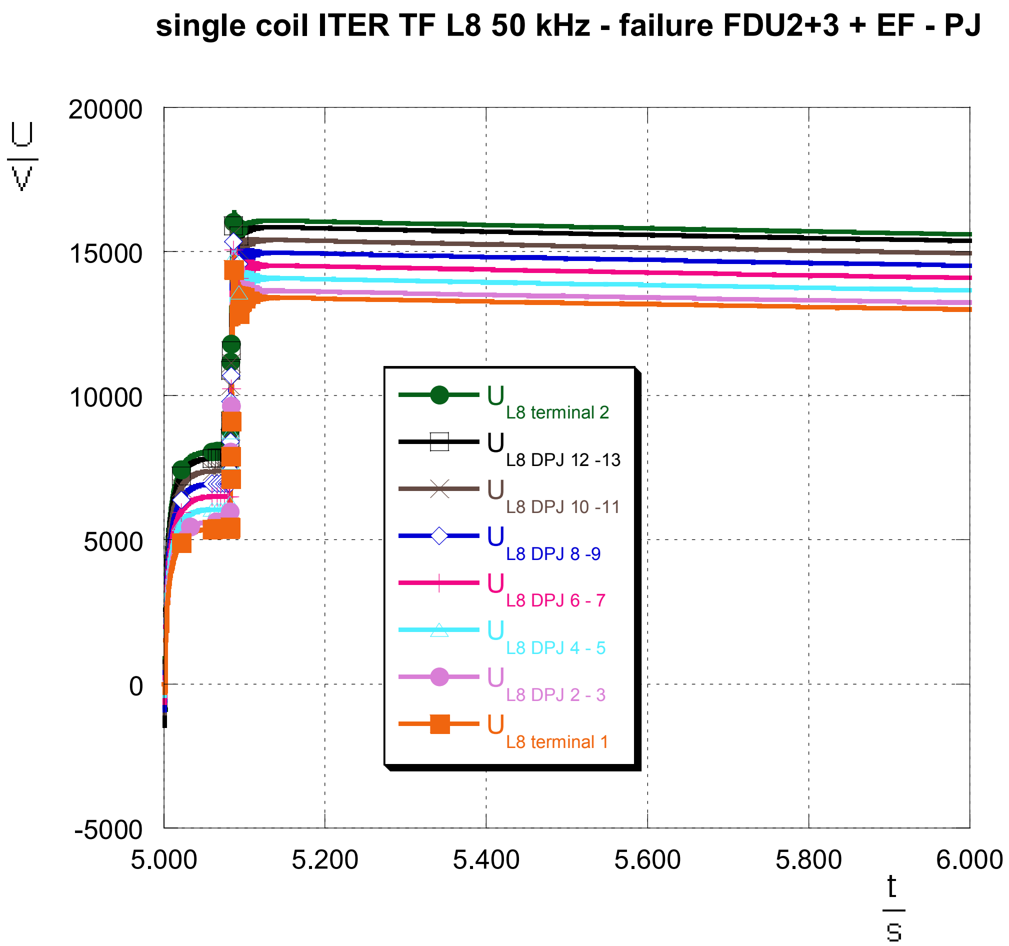


Fig. 2.3.2.1-2: Terminal and double pancake joint to ground voltages for coil 8 during a fast discharge with failure of FDU 2 and FDU 3 and breakdown to ground (earth fault).

Highest voltage value to ground on helium inlets of 16.305 kV at 5.087 7 s with a rise time of 3.6 ms occurs on HeIn7 (fig. 2.3.2.1-3).

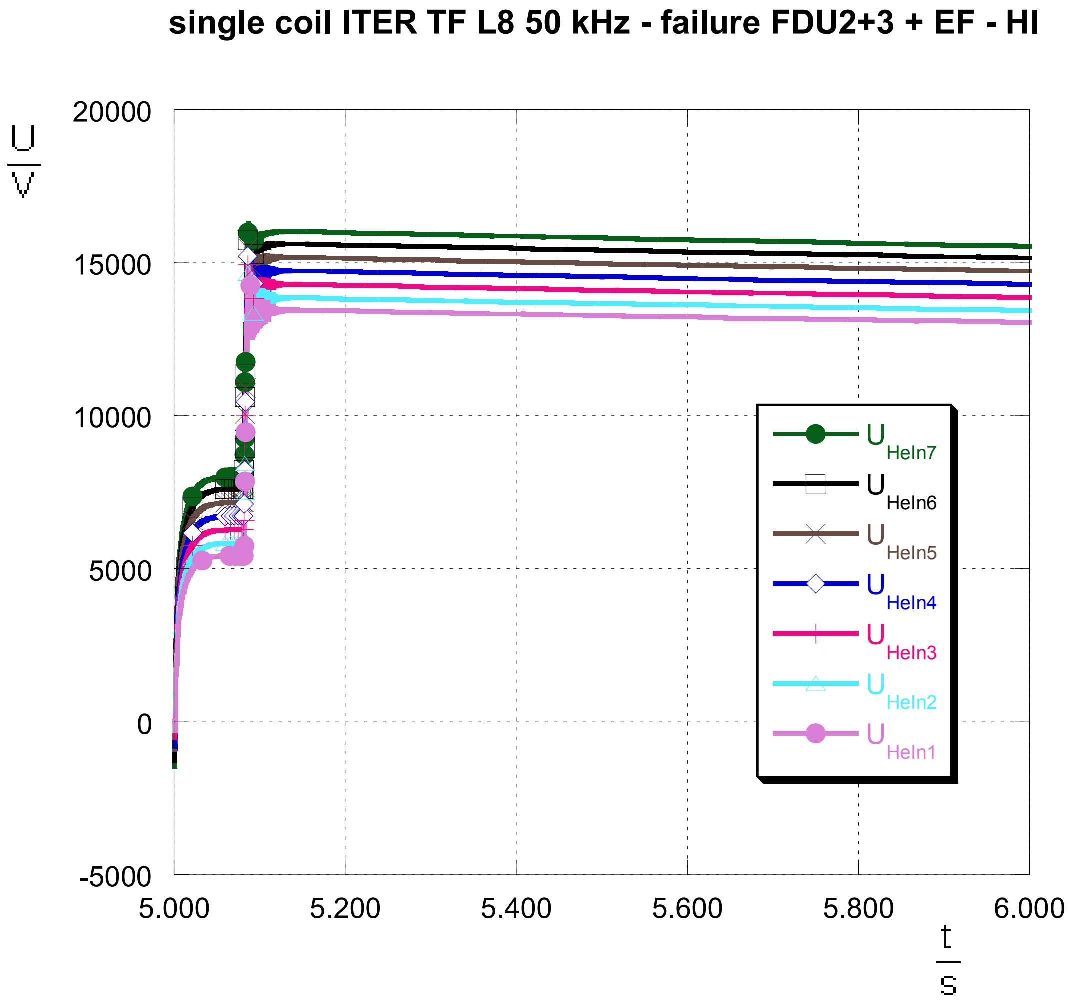


Fig. 2.3.2.1-3: Helium inlet to ground voltages for coil 8 during a fast discharge with failure of FDU 2 and FDU 3 and breakdown to ground (earth fault).

2.3.2.2 Results of radial plate insulation

Highest radial plate to radial plate voltage is between radial plate 2 and radial plate 1 U = 1.308 kV at 5.086 8 s (t_A is about 3 ms from occurrence of earth fault to maximum) (fig. 2.3.2.2-1).

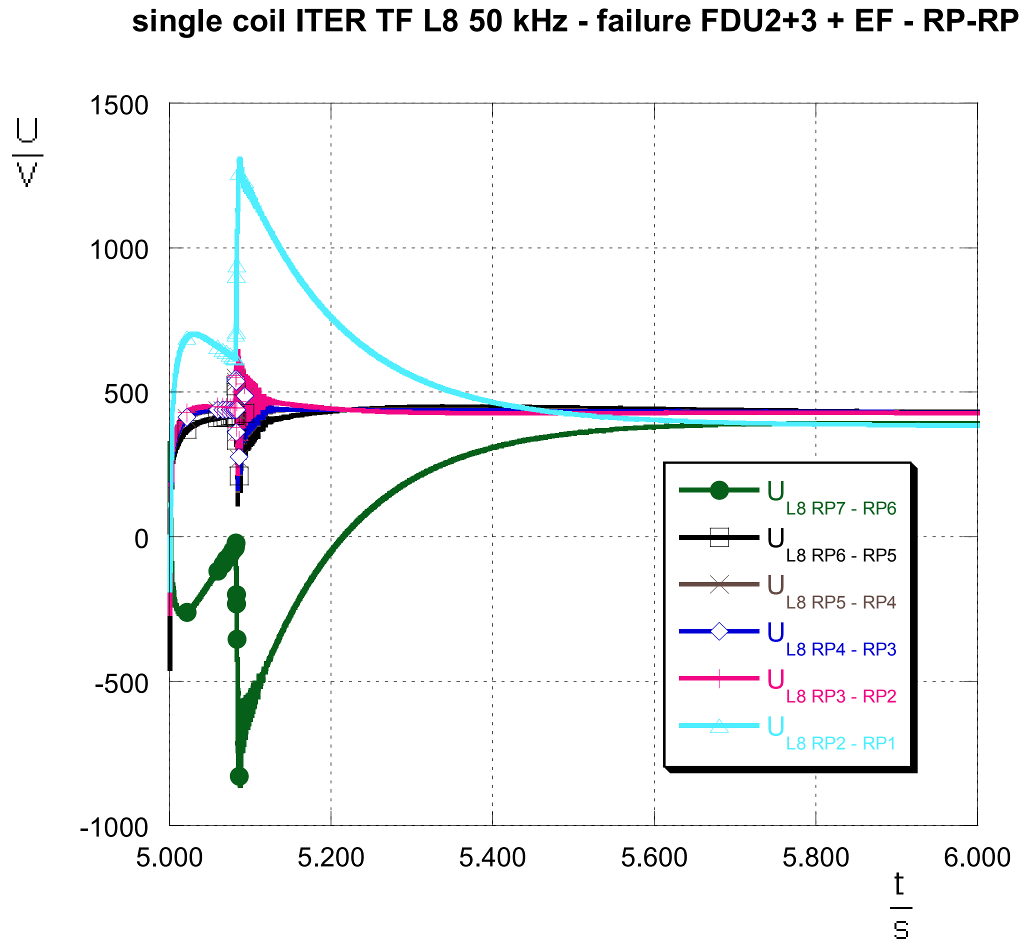


Fig. 2.3.2.2-1: Radial plate to radial plate voltages for coil 8 during a fast discharge with failure of FDU 2 and 3 and earth fault for the time range 5.0 s to 6.0 s.

2.3.2.3 Results of conductor insulation

The double pancake joint to radial plate voltages (fig. 2.3.2.3-1) have a maximum of 1.4146 kV at PC 14 to RP 7 (t = 5.086 7 s). The rise time of this voltage from earth fault (U = 0.6 kV) to maximum is about 3.5 ms. Second most is PC 2 to RP 1. Zero crossings occur for several double pancake joint to radial plate voltages.

The helium inlet ("inner joints") to radial plate voltages have the maximum voltage of 1.3418 kV at t = 5.086 8 s on RP 7 with a rise time of about 3 ms (fig. 2.3.2.3-2) from earth fault (0.5 kV) to maximum. Helium Inlet to radial plate 1 has a similar maximum (1.27 kV). The other helium inlet to radial plate voltages do not exceed ±300 V.

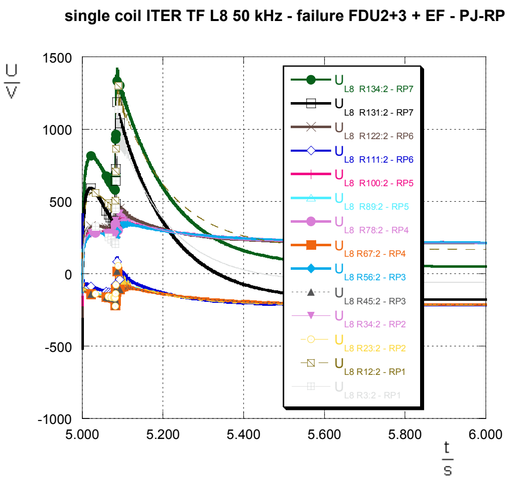


Fig. 2.3.2.3-1: Voltages between double pancake joints ("outer joints") and radial plates.

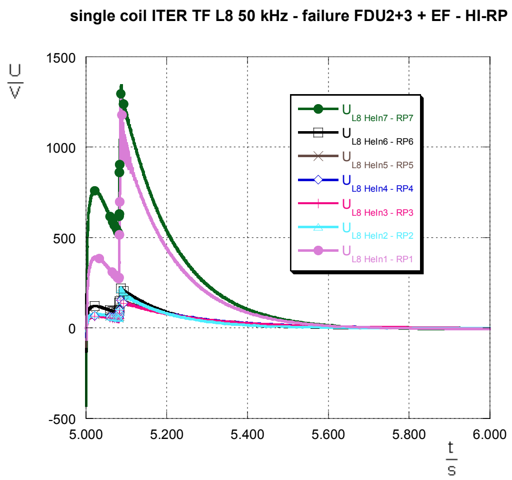


Fig. 2.3.2.3-2: The helium inlet ("inner joints") to radial plate voltages.

For PC 14 to RP 7 the maximum voltage appears at the outer terminal (1.4146 V). The smaller the distance to the He inlet is, the lower is the voltage. The voltages do not make a zero transition after the maximum.

For PC 2 to RP 1 the maximum voltage appears at the double pancake joint (1.3592 V). The smaller the distance to the He inlet is, the lower is the voltage.

2.3.2.4 Summary of the maximum voltages on coil 8 for the 50 kHz model during fast discharge with failure of FDU 2 and 3 and earth fault

	location	voltage, time	rise time
Maximum terminal to ground voltage	Terminal 2	16.354 kV, 5.087 7 s	3.5 ms
Ground insulation	Terminal 2	16.354 kV, 5.087 7 s	3.5 ms
	Radial plate: RP 6	15.777 kV, 5.087 6 s	3.5 ms
	Double pancake joints: DPJ67	16.161 kV 5.087 7 s	3.3 ms
	Helium inlet HeIn7	16.305 kV 5.087 7 s	3.6 ms
Radial plate insulation	Radial plate to radial plate: RP 2 – RP 1	1.308 kV, 5.086 8 s	3 ms
Conductor insulation	Double pancake joints to radial plate: terminal 2 – RP 7	1.415 kV, 5.086 7 s	3.5 ms
	Double pancake joints to radial plate: DPC joint of PC 2 – RP 1	1.359 V 5.087 4 s	3.5 ms
	Helium inlet to radial plate: HeIn 7 - RP 7	1.342 V, 5.086 8 s	3 ms
	Pancake 14 to radial plate 7: terminal 2 – RP 7	1.415 kV, 5.086 7 s	3.5 ms
	Pancake 2 to radial plate 1: DPC joint of PC 2 – RP 1	1.359 V 5.087 4 s	3.5 ms

2.3.3 Excitation of the 1 kHz model with the terminal voltages of L2

The 1 kHz model of a single coil was excited with the voltage V(L2:2) on the right side and the voltage V(L2:1) on the left side. No maximum step size was set, RELTOL = 0.001. Calculation time was 30.69 h. The result file has 290 354 time steps.

2.3.3.1 Results for ground insulation

Highest voltage is at terminal L2:2 U = 9.656 kV at t = 5.081 9 s (fig. 2.3.3.1-1). Rise time from voltage before breakdown to earth at terminal L3:1 (-1.1447 kV) to maximum: 2.4 µs.
Highest voltage of radial plate to ground appears on radial plate number 6 with 9.642 kV at t = 5.082 9 s. Large oscillations are calculated for these voltages, e. g. voltage on radial plate number 6 has oscillations in the range of 67 kHz (starting with t_A = 6 µs from -1.576 kV for the first oscillation).

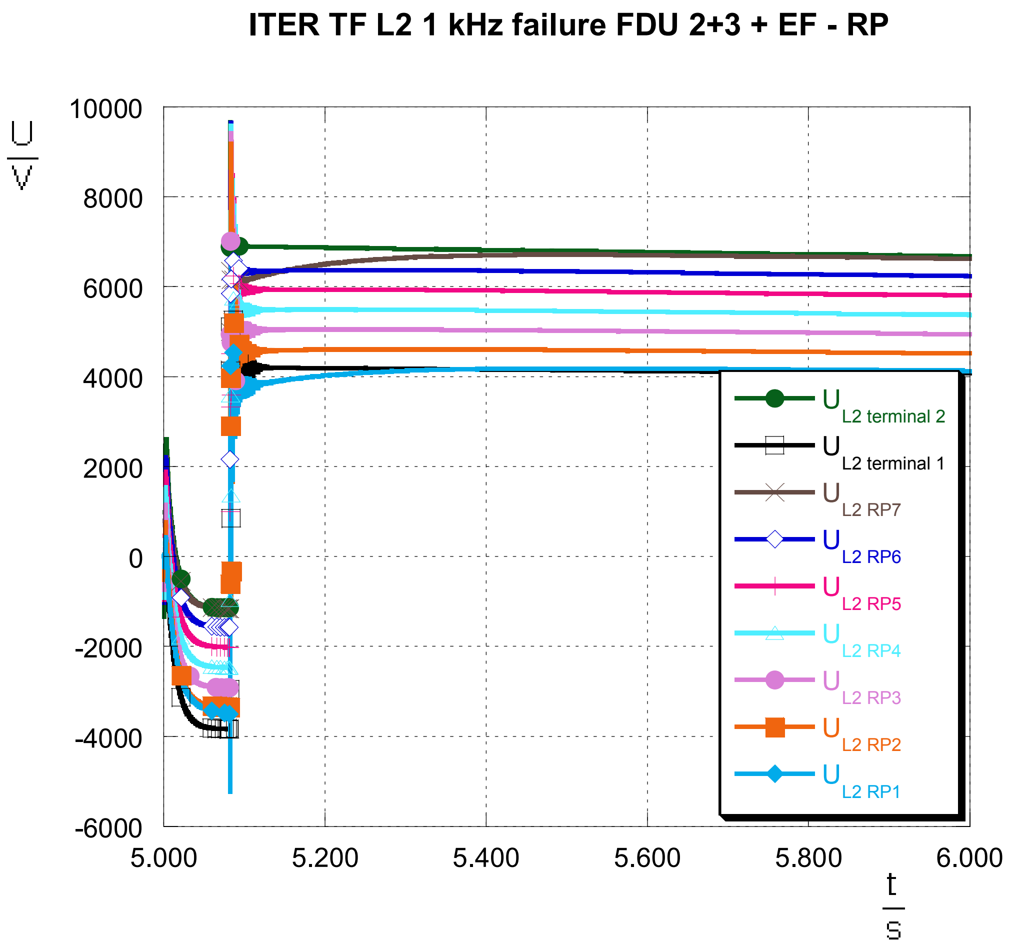


Fig. 2.3.3.1-1: Terminal and radial plate potentials to ground for coil 2 during a fast discharge with failure of FDU 2 and 3 and voltage breakdown to earth potential at terminal L3:1.

Highest voltage on double pancake joint to ground appears at DPJ45 and is 10.555 kV at t = 5.082 7 s (fig. 2.3.3.1-2). After the fault the double pancake voltages are swinging with a frequency of about 90 kHz. The rise times for the double pancake joint voltages are in the range of some µs.

Highest voltage of helium inlet to ground appears on HeIn6 with 10.433 kV at t = 5.082 9 s (fig. 2.3.3.1-3). After the fault the helium inlet voltages are swinging with a frequency of about 100 kHz. The rise times for the helium inlet voltages are in the range of some µs.

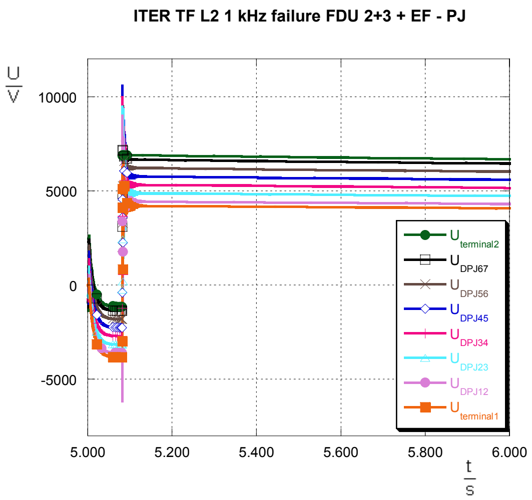


Fig. 2.3.3.1-2: Terminal and double pancake joint to ground voltages for coil 2 during a fast discharge with failure of 2 FDUs and earth fault.

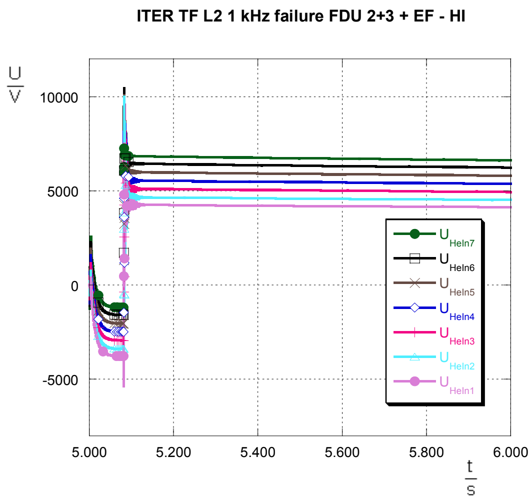


Fig. 2.3.3.1-3: Helium inlet to ground voltages for coil 2 during a fast discharge with failure of 2 FDUs and earth fault.

2.3.3.2 Results of radial plate insulation

Highest radial plate to radial plate voltage is between radial plate 6 and radial plate 5 U = 4809.9 V at 5.081 9 s (t_A is 6.1 µs from 442 V to maximum) (fig. 2.3.3.2-1). The voltage between radial plate 7 and radial plate 6 has a minimum of -2262.3 V and a zero transition at 5.15 s. All other radial plate to radial plate voltages do not have a zero transition.

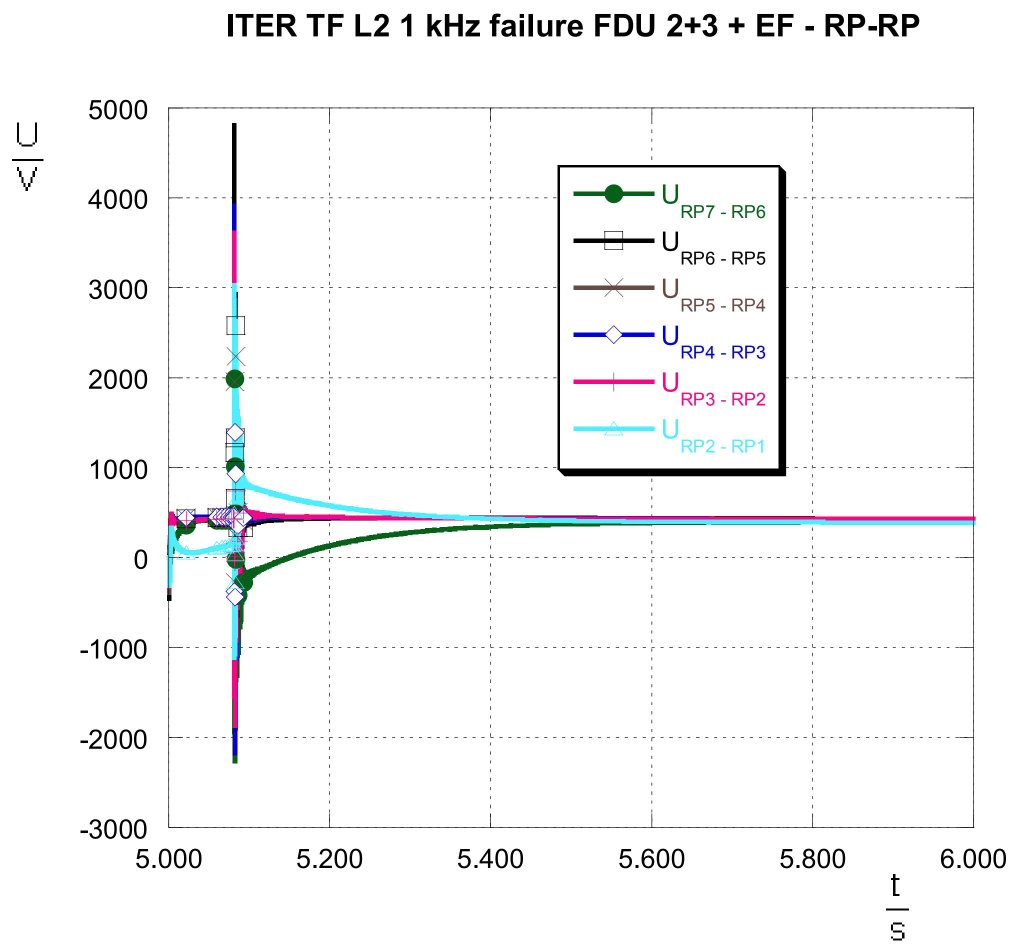


Fig. 2.3.3.2-1: Radial plate to radial plate voltages for coil 2 during a fast discharge with failure of FDU 2 and 3 and voltage breakdown to earth potential at terminal L3:1.

2.3.3.3 Results of conductor insulation

The maximum of the double pancake joints to radial plate voltages (fig. 2.3.3.3-1) is 4248.6 V at PC 14 to RP 7 (t = 5.081 9 s). The rise time of this voltage from 15 V to maximum is 2.0 µs. Second most is PC 12 to RP 6 with 3487.6 V. The voltages between pancake joint of PC 13 and radial plate number 7 and between the joint of PC 1 and RP 1 start with a positive voltage and cross the zero point between 5.2 s and 5.4 s. All other voltages do not make a zero transition after the switching disturbances (t > 5.002 s).

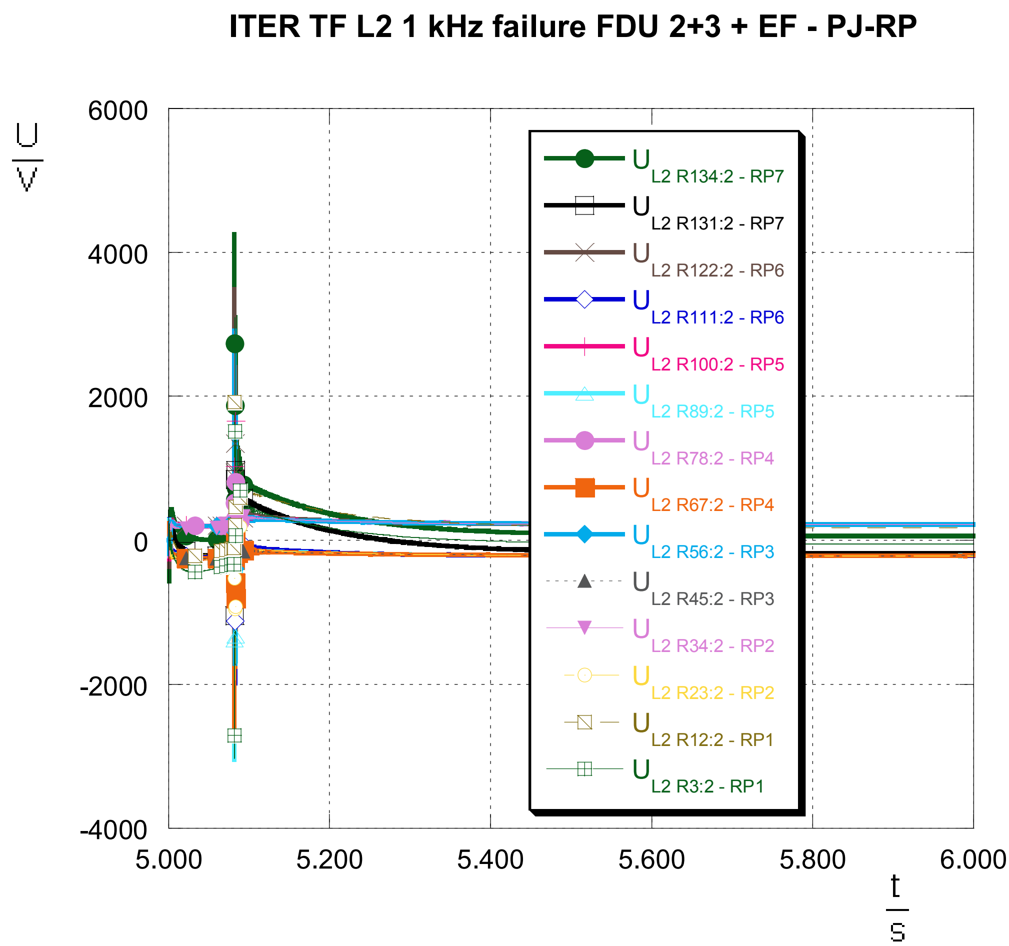


Fig. 2.3.3.3-1: Voltages between double pancake joint and radial plate.

The helium inlet to radial plate voltages (fig. 2.3.3.3-2) have the maximum voltage of 2786.3 V at t = 5.081 9 s with a rise time of 2.2 µs from -38.6 V to maximum on RP 7. Between helium inlet and RP 1 the minimum voltage is -1504.4 V. The voltages of the other radial plates do not exceed ±1.1 kV.

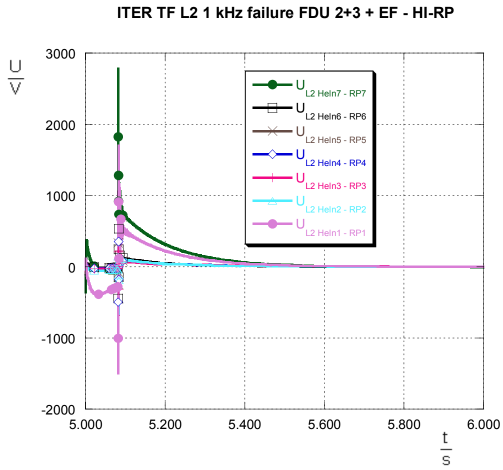


Fig. 2.3.3.3-2: The helium inlet to radial plate voltages.

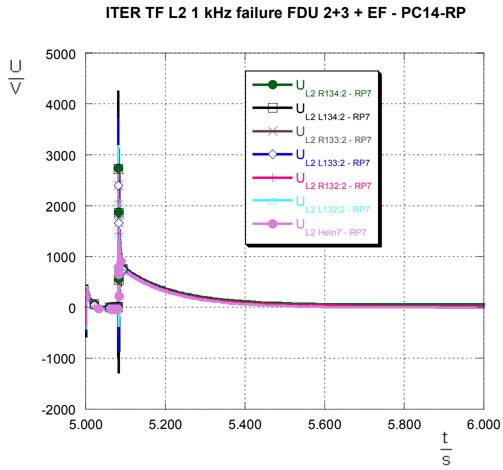


Fig. 2.3.3.3-3: The voltages along pancake 14 to radial plate 7.

For PC 14 to RP 7 the maximum voltage appears at the outer terminal (4249 V) (fig. 2.3.3.3-3). The smaller the distance to the He inlet is, the lower is the voltage.

2.3.3.4 Summary of the maximum voltages on coil 2 for the 1 kHz model during a fast discharge with failure of FDU 2 and 3 and voltage breakdown on terminal 3:1 to earth potential.

	location	voltage, time	rise time
Maximum terminal to ground voltage	Terminal 2	9.66 kV, 5.081 9 s	2.4 µs
Ground insulation	Terminal 2	9.66 kV, 5.081 9 s	2.4 µs
	Radial plate: RP 6	9.64 kV, 5.082 9 s	Starting from -1.6 kV to 6 kV with 6 µs
	Double Pancake joint DPJ45	10.56 kV, 5.082 7 s	Some µs
	Helium inlet HeIn6	10.43 kV, 5.082 9 s	Some µs
Radial plate insulation	Radial plate to radial plate: RP 6 – RP 5	4.81 kV, 5.081 9 s	6.1 µs
Conductor insulation	Double pancake joints to radial plate: terminal 2 – RP 7	4.25 kV, 5.081 9 s	2.0 µs
	Helium inlet to radial plate: HeIn 7 - RP 7	2.79 kV, 5.081 9 s	2.2 µs
	Pancake 14 to radial plate 7: terminal 2 – RP 7	4.25 kV, 5.081 9 s	2.0 µs
	Pancake 12 to radial plate 6: DP joint PC12/PC13 – RP 6	3.49 kV, 5.081 9 s	

2.3.4 Excitation of the 1 kHz model with the terminal voltages of L8

The 1 kHz model of a single coil was excited with the voltage V(L8:2) on the right side and the voltage V(L8:1) on the left side. No maximum step size was set, RELTOL = 0.001. Calculation time was 33.85 h. The result file has 290 354 time steps.

2.3.4.1 Results for ground insulation

Highest voltage is at terminal L8:2 U = 16.354 kV at t = 5.087 7 s. Rise time from voltage before breakdown to earth at terminal L3:1 (8.067 kV) to maximum: 3.5 ms.
Highest voltage of radial plate to ground appears on radial plate number 6 with 15.789 kV at t = 5.087 6 s (t_A = 3.5 ms from 7.539 kV to maximum) caused by a certain overshooting with an oscillation. On radial plate number 7 a voltage of 15.766 kV was reached at t = 5.451 5 s. The rise time of the voltage of the outer plates is higher than the rise time of the other radial plate voltages to ground, e. g. for radial plate 7 the rise time is 5.5 ms (from 7.492 kV to maximum) (fig. 2.3.4.1-1).

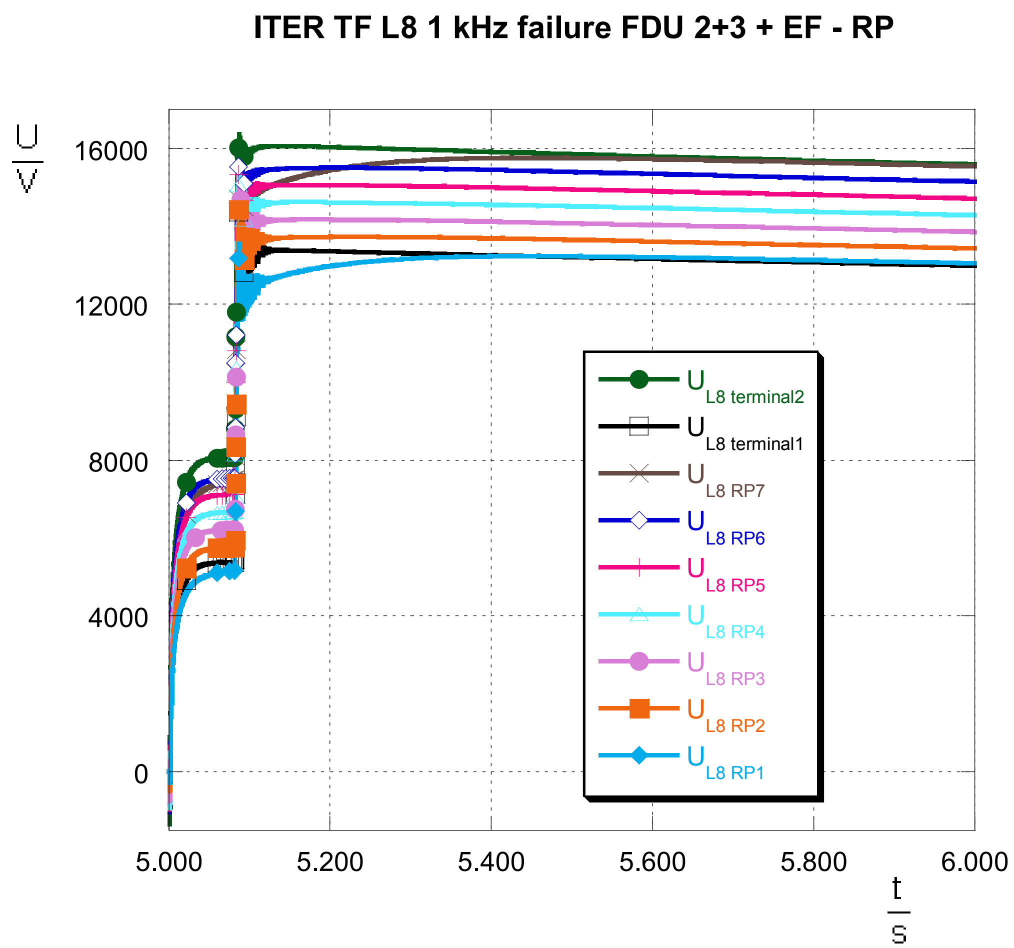


Fig. 2.3.4.1-1: Terminal and radial plate to ground voltages for coil 8 during a fast discharge with failure of FDU 2 and 3 and voltage breakdown to earth at terminal L3:1.

Highest double pancake joint to ground voltage appears on DPJ67 with 16.167 kV at t = 5.087 7 s (fig. 2.3.4.1-2). The rise time for this voltage is 3.6 ms.
Highest helium inlet to ground voltage appears on HeIn7 with 16.308 kV at t = 5.087 7 s (fig. 2.3.4.1-3). The rise time for this voltage is 3.5 ms.

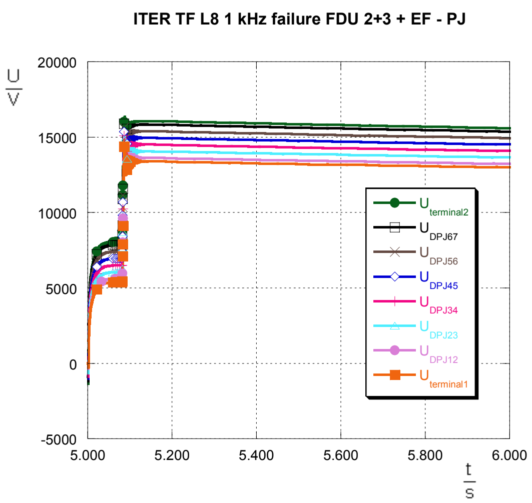


Fig. 2.3.4.1-2: Terminal and double pancake joint to ground voltages for coil 8 during a fast discharge with failure of FDU 2 and 3 and voltage breakdown to earth at terminal L3:1.

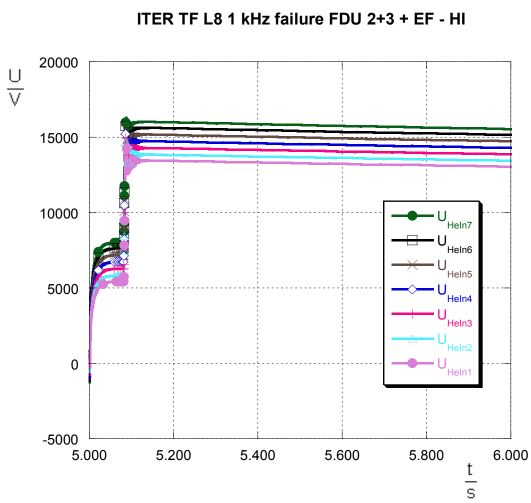


Fig. 2.3.4.1-3: Helium inlet to ground voltages for coil 8 during a fast discharge with failure of FDU 2 and 3 and voltage breakdown to earth at terminal L3:1.

2.3.4.2 Results of radial plate insulation

Highest radial plate to radial plate voltage is between radial plate 2 and radial plate 1 U = 1300.6 V at 5.087 8 s (t_A is about 3 ms from 607 V to maximum) (fig. 2.3.4.2-1). The voltage between radial plate 7 and radial plate 6 has a minimum of -867.949 V and a zero transition at 5.216 s. All other radial plate to radial plate voltages do not have a zero transition.

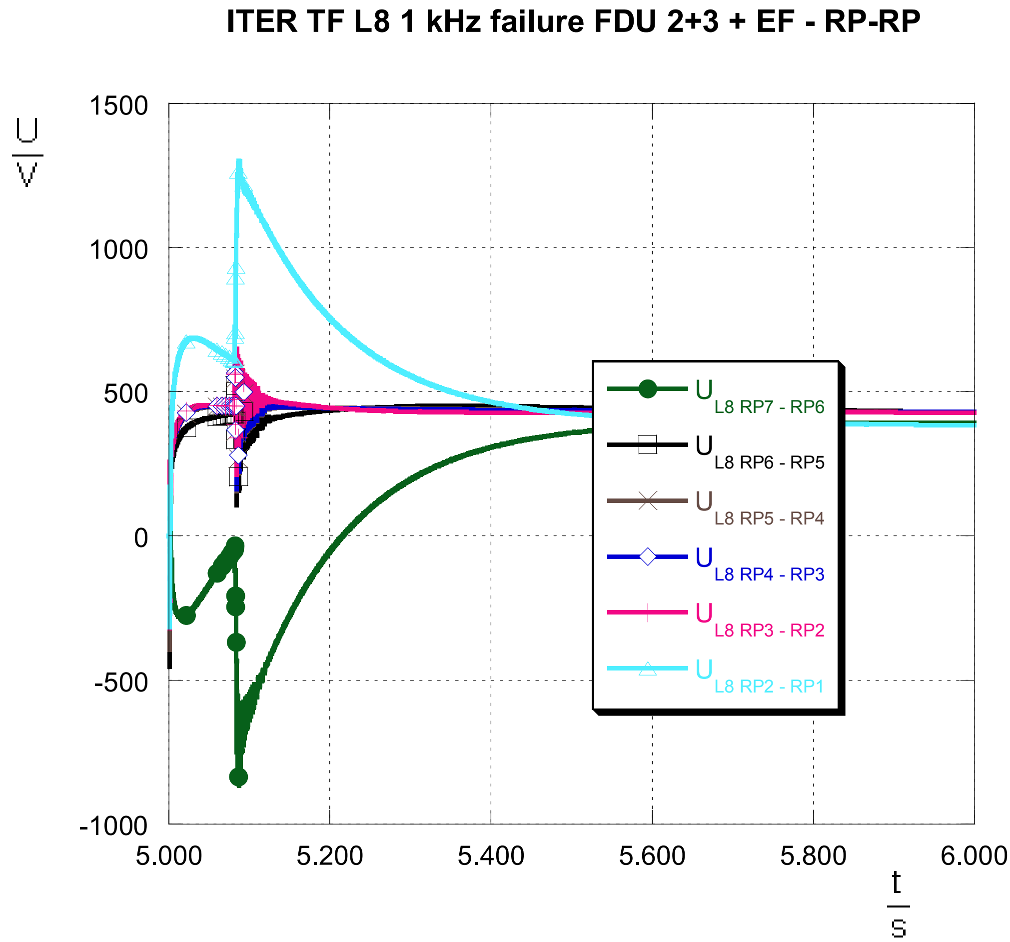


Fig. 2.3.4.2-1: Radial plate to radial plate voltages for coil 8 during a fast discharge with failure of FDU 2 and 3 and voltage breakdown to earth potential at terminal L3:1.

2.3.4.3 Results of conductor insulation

The maximum of the double pancake joints to radial plate voltages (fig. 2.3.4.3-1) is 1411.9 V at PC 14 to RP 7 (t = 5.086 7 s). The rise time of this voltage from 574 V to maximum is about 3 ms. Second most is PC 2 to RP 1 with 1349.8 V. The voltages between pancake joint of PC 13 and radial plate number 7 and between the joint of PC 1 and RP 1 start with a positive voltage and cross the zero point between 5.3 s and 5.5 s. All other voltages do not make a zero transition after the switching disturbances (t > 5.002 s).

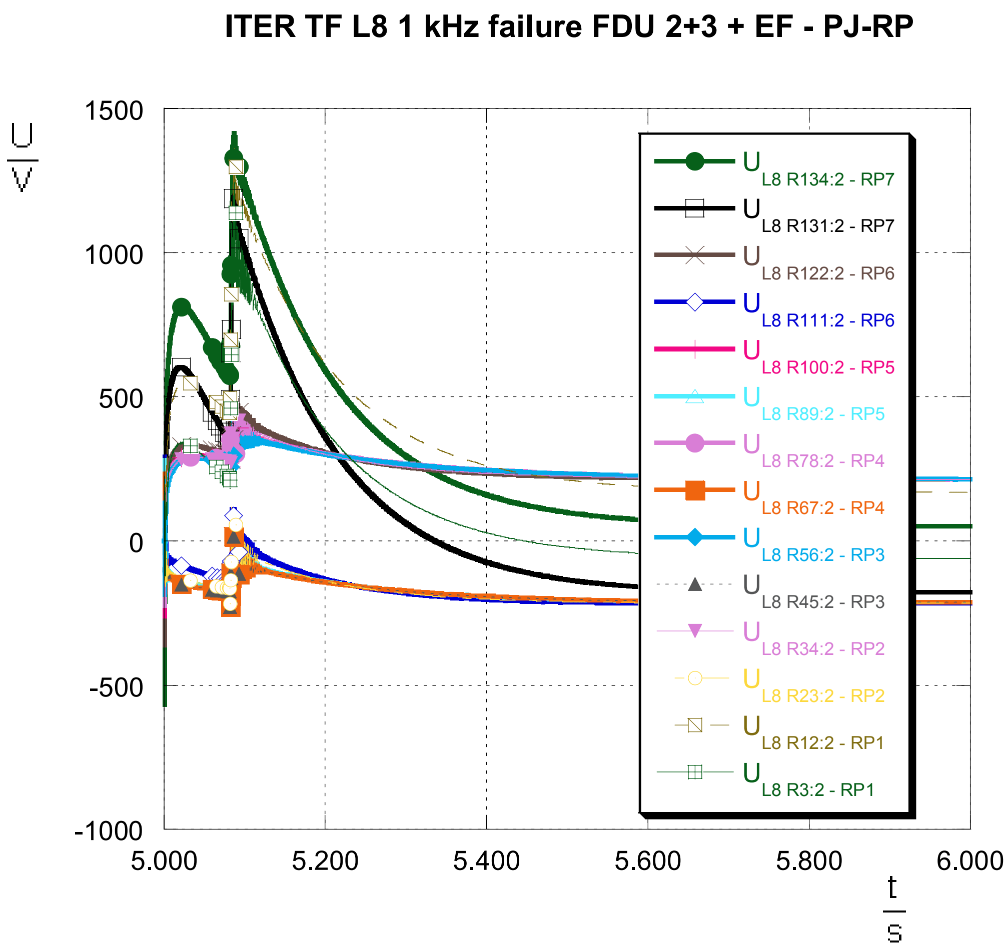
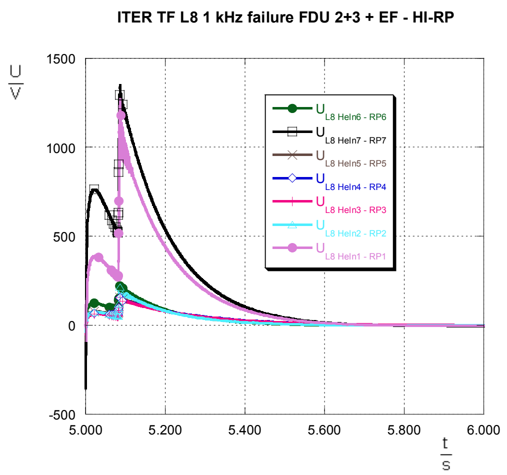


Fig. 2.3.4.3-1: Voltages between double pancake joint and radial plate.

The helium inlet to radial plate voltages have the maximum voltage of 1344.3 V at t = 5.086 8 s with a rise time from 520 V to maximum of about 3 ms (fig. 2.3.4.3-3) on RP 7. Between helium inlet and RP 1 the maximum voltage is 1269.3 V. The voltages of the other radial plates do not exceed 250 V after the non real switching disturbances.



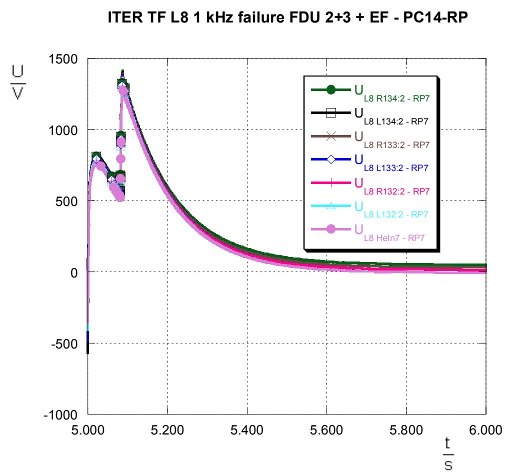


Fig. 2.3.4.3-3: The helium inlet to radial plate voltages.

Fig. 2.3.4.3-4: The voltages along pancake 14 to radial plate 7.

For PC 14 to RP 7 the maximum voltage appears at the outer terminal (1412 V) (fig. 2.3.4.3-4). The smaller the distance to the He inlet is, the lower is the voltage. The voltages do not make a zero transition after the maximum.

2.3.4.4 Summary of the maximum voltages on coil 8 for the 1 kHz model during a fast discharge with failure of FDU 2 and 3 and voltage breakdown to earth at terminal L3:1

	location	voltage, time	rise time
Maximum terminal to ground voltage	Terminal 2	16.35 kV, 5.087 7 s	3.5 ms
Ground insulation	Terminal 2	16.35 kV, 5.087 7 s	3.5 ms
	Radial plate: RP 6	15.79 kV, 5.087 6 s	3.5 ms
	Double Pancake joint DPJ67	16.12 kV, 5.087 7 s	3.6 ms
	Helium inlet HeIn7	16.31 kV, 5.087 7 s	3.5 ms
Radial plate insulation	Radial plate to radial plate: RP 2 – RP 1	1300.6 V, 5.087 8 s	3 ms
Conductor insulation	Double pancake joints to radial plate: terminal 2 – RP 7	1411.9 V, 5.087 7 s	about 3 ms
	Helium inlet to radial plate: HeIn 7 - RP 7	1344.3 V, 5.087 8 s	about 3 ms
	Pancake 14 to radial plate 7: terminal 2 – RP 7	1411.9 V, 5.087 7 s	about 3 ms

Appendix 2: Impulse test voltages

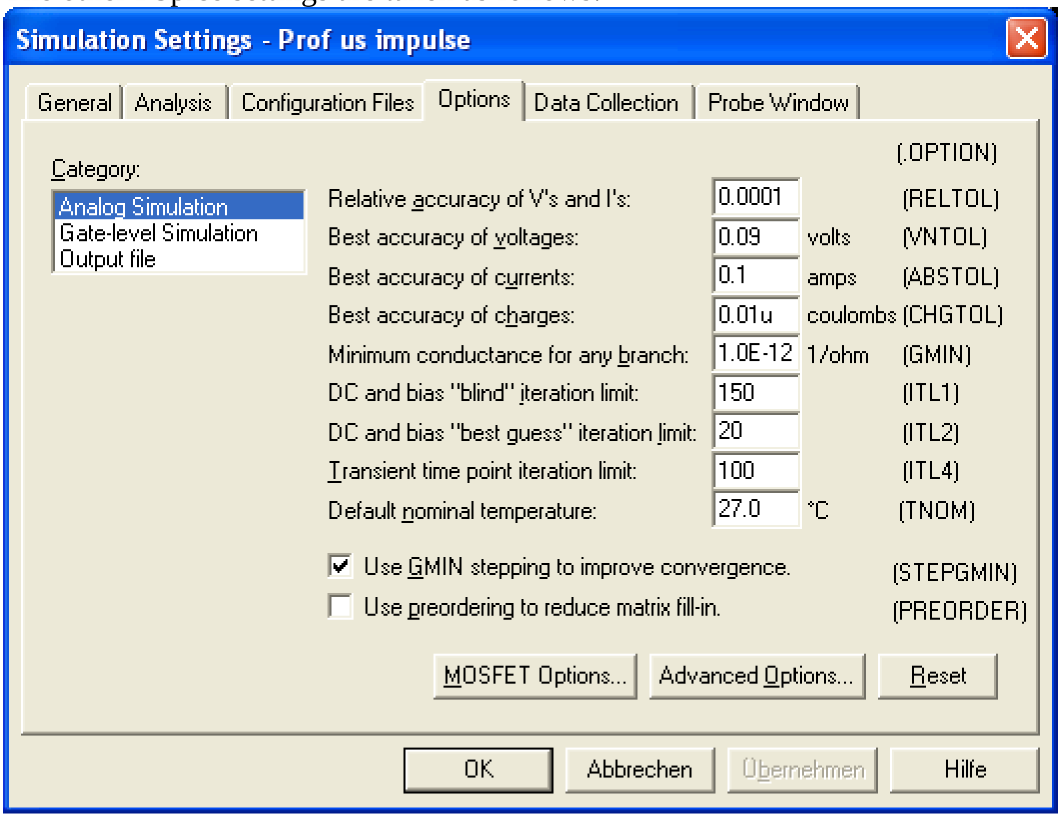
The impulse tests should be calculated for two different time ranges. If the system is not changed and the voltages are calculated for one excitation, the relationship for an other voltage amplitude with the same voltage shape can easily be calculated because the excited system is linear.

1 Impulse tests with rise times in the µs range

For the simulation of an impulse test in the µs time range the following target values are assumed:
rise time: 2.4 µs,
maximum voltage to ground: 21 kV.

The following values are taken to obtain the target values:
ITER TF single coil: 50 kHz model
capacitor bank: C = 150 µF, UC = -17.0 kV,
switch: Tclose = 1 µs, Ttran = 10 µs, Ropen = 1 GΩ, Rclosed = 1 µΩ,
damping resistor: R = 0.58 Ω,
series inductance: 10 µH.

Maximum time steps: 100 ns,
The other PSpice settings are taken as follows:



The simulation was performed till t = 500 µs. The result file has 5013 data points.

1.1 Results of the ground insulation

The voltages are swinging with frequencies between about 12 kHz and 45 kHz. Highest voltage of 21.03 kV occurs on terminal2 at t = 9.750 µs. The maximum voltage of 20.87 kV occurs on radial plate 6 at t = 12.95 µs.

The rise time for the terminal voltage is 2.4 µs. The rise time for radial plate 6 is 3.7 µs.

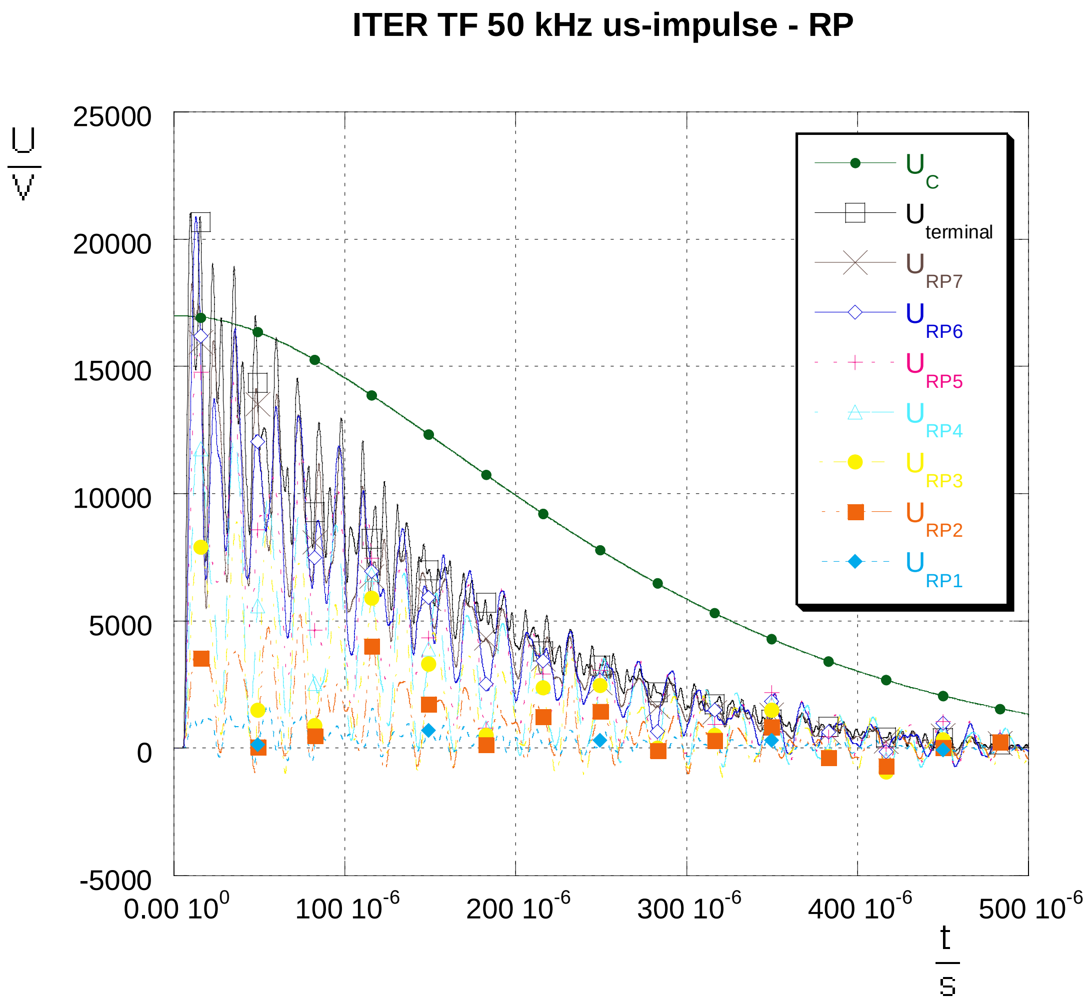


Fig. 1.1: Terminal and radial plate voltages to ground during the impulse test with a rise time of 2.4 µs.

1.2 Results of radial plate insulation

The maximum radial plate to radial plate voltage of 6.73 kV occurs between RP6 and RP5 at t = 23.8 µs. Second most voltage is 5.00 kV between RP3 and RP2 at t = 36.7 µs. The rise times are in the range of some µs. All voltages are oscillating in the range of some 10 kHz.

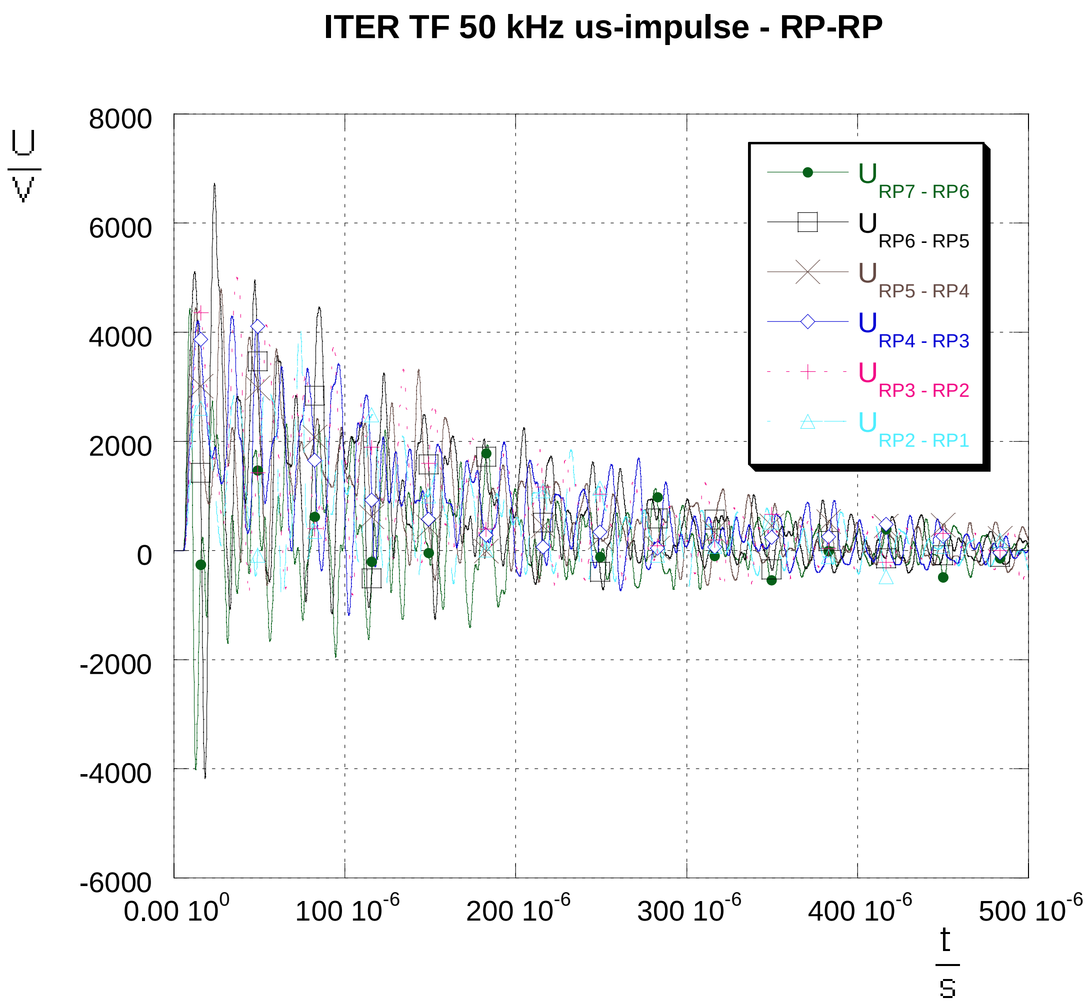


Fig. 1.2: Radial plate to radial plate voltages during the impulse test with a rise time of the terminal voltage of 2.4 µs.

1.3 Results of the conductor insulation

1.3.1 Pancake joint to radial plate voltage

Highest conductor joint to radial plate voltage of 7.07 kV occurs on joint PC12PC13 to radial plate 7 at t = 12.150 µs. The rise time for this voltage is 1.4 µs counted from 0 to maximum.

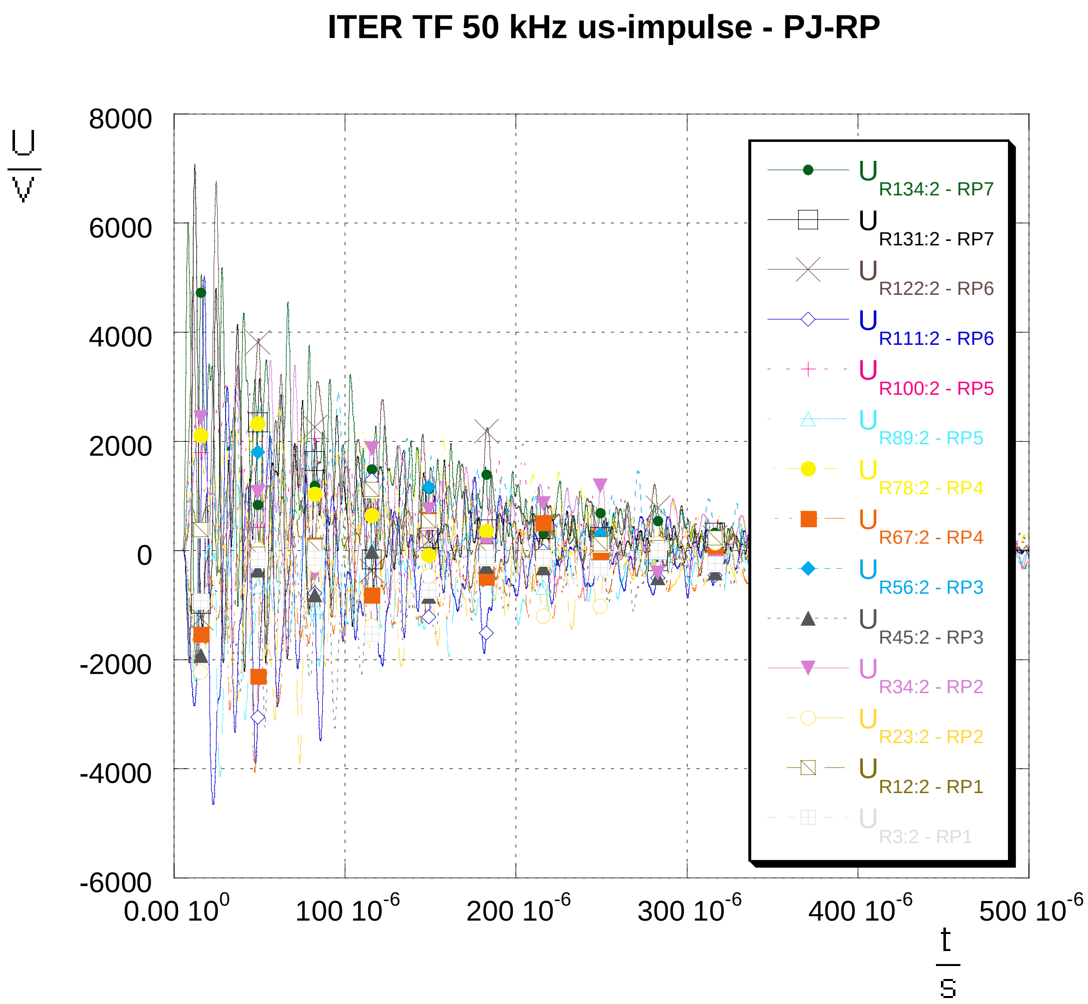


Fig. 1.3.1: Pancake joint to radial plate voltages during the impulse test with a rise time of the terminal voltage of 2.4 µs.

1.3.2 Helium inlet to radial plate voltage

Highest helium inlet to radial plate voltage of 5.49 kV occurs on helium inlet 7 to radial plate 7 at t = 8.9504 µs. The rise time for this voltage is 1.5 µs. The other helium inlet to radial plate voltages are lower than ±3 kV.

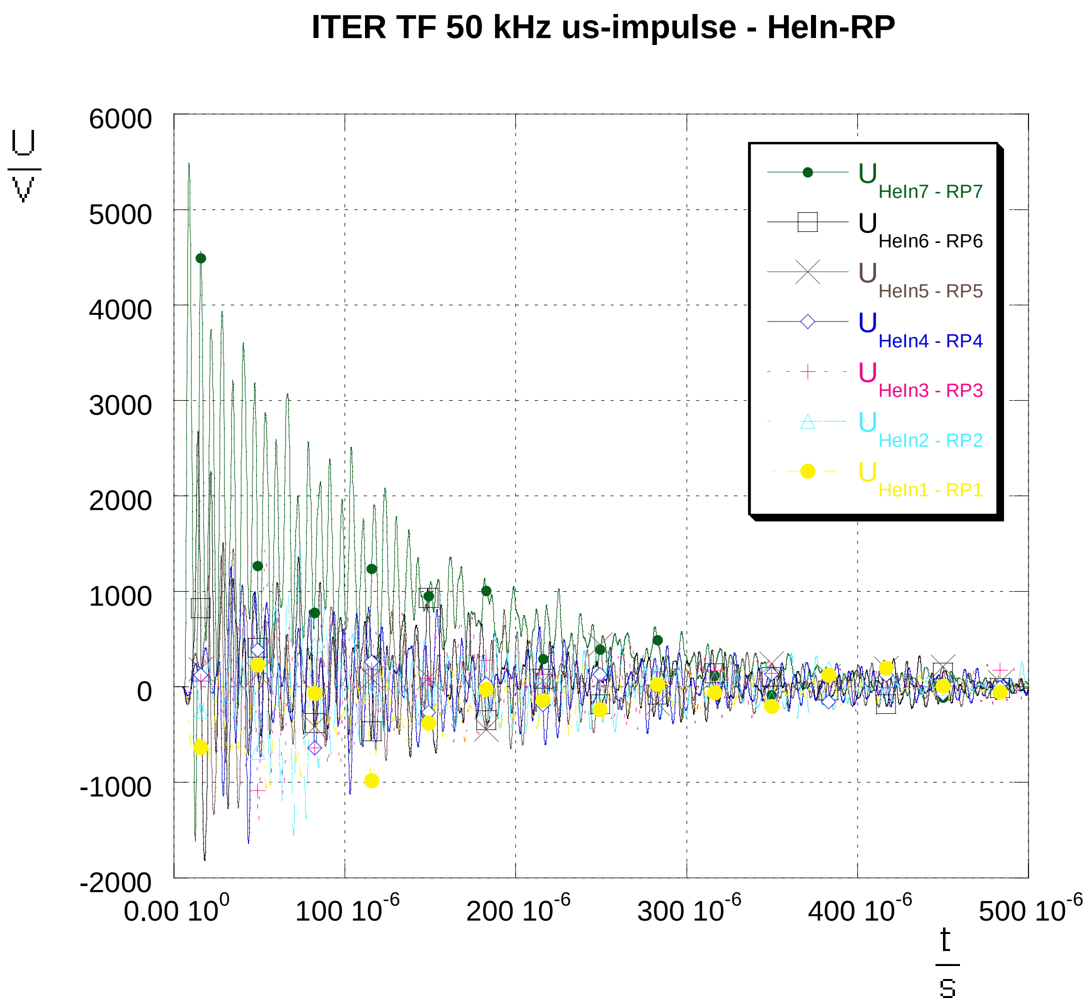


Fig. 1.3.2: Helium inlet to radial plate voltages during the impulse test with a rise time of the terminal voltage of 2.4 µs.

1.3.3 Pancake 13 to radial plate voltage

The voltage between PC13 and radial plate 7 is examined because the highest voltages were found on joint PC12PC13 and helium inlet 7. Highest PC13 to radial plate 7 voltage of 7.08 kV occurs at L131:1 (in the first turn near the pancake joint) at t = 12.150 µs. The shape of this waveform is very similar as for the pancake joint and has therefore the same rise time of 1.4 µs.

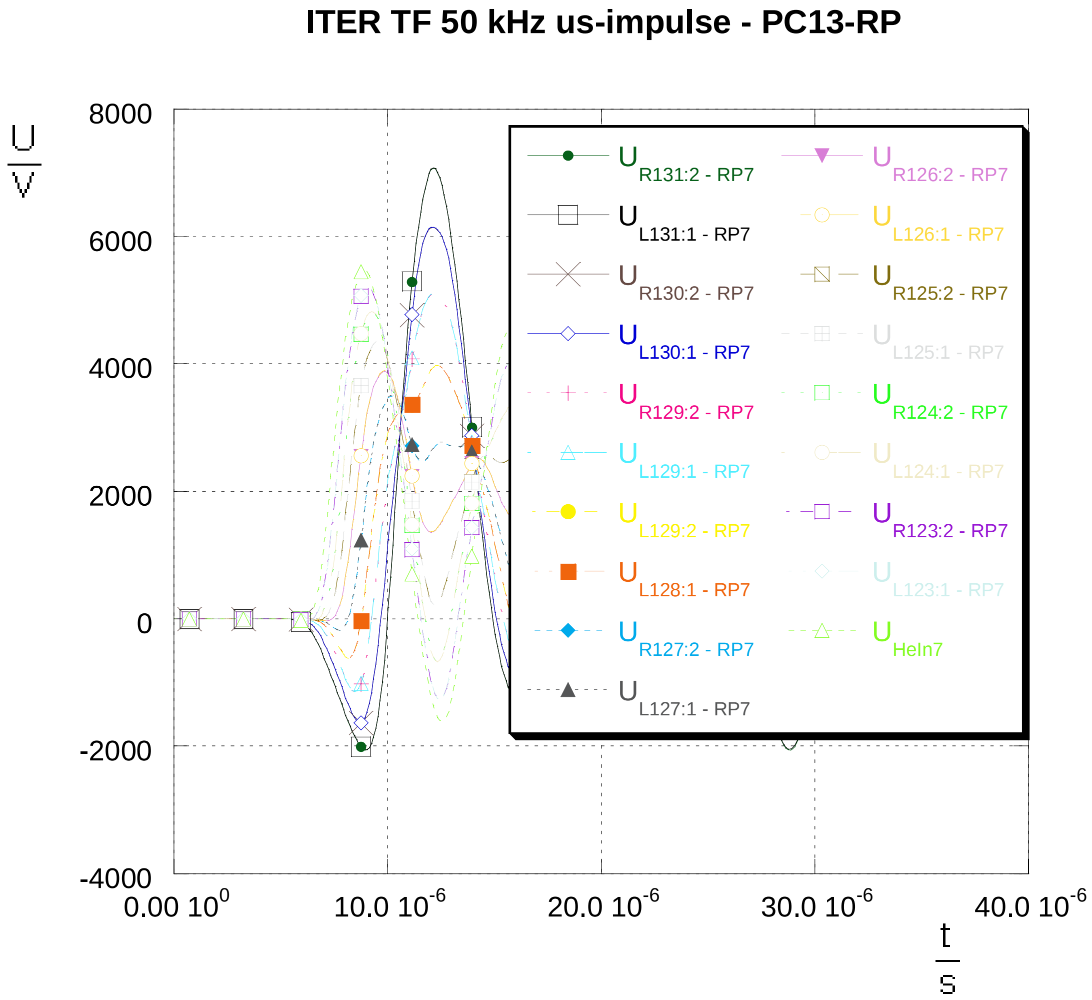


Fig. 1.3.3: Pancake 13 to radial plate voltages during the impulse test with a rise time of the terminal voltage of 2.4 µs.

1.4 Helium inlet voltages

The helium inlet voltages are accessible for the measurement. Voltage data are calculated for comparison of a possible future impulse test.
Highest helium inlet voltage of 22.89 kV occurs on helium inlet 6 at t = 13.650 µs. The rise time for this voltage is 6.6 µs.

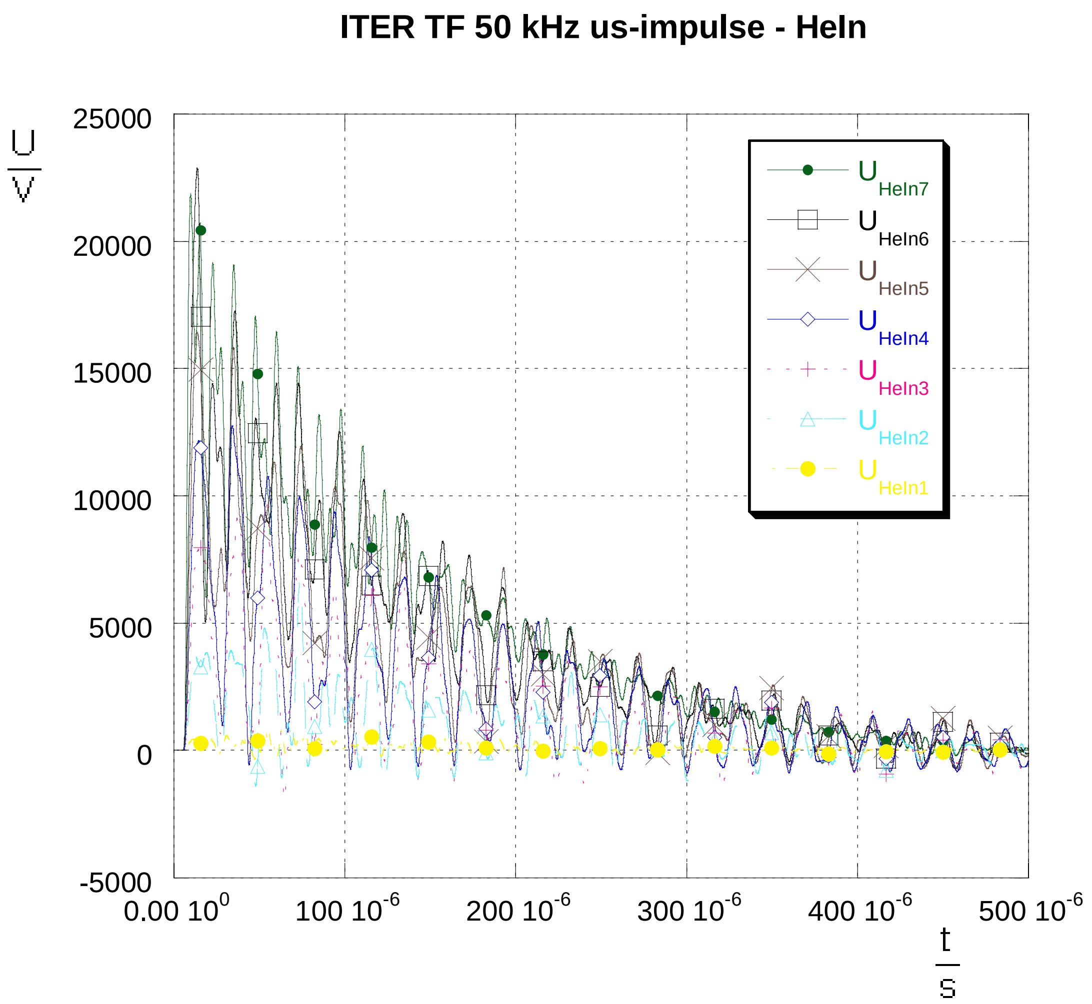


Fig. 1.4: Helium inlet to ground voltages during the impulse test with a rise time of the terminal voltage of 2.4 µs.

1.4 Summary of the results for the impulse test in the µs range

	location	voltage, time	rise time
Maximum terminal to ground voltage	Terminal 2	21.03 kV, 9.75 µs	2.4 µs
Ground insulation	Terminal 2	21.03 kV, 9.75 µs	2.4 µs
	Radial plate: RP 6	20.87 kV, 12.95 µs	3.7 µs
	Double Pancake joint DPJ67	24.10 kV, 12.95 µs	3.9 µs
	Helium inlet HeIn6	22.89 kV, 13.65 µs	6.6 µs
Radial plate insulation	Radial plate to	6.73 kV,	About 3 µs

	radial plate: RP6 – RP6	23.75 µs	
Conductor insulation	Double pancake joints to radial plate: DPJ67 – RP7	7.07 kV, 12.15 µs	About 2 µs
	Helium inlet to radial plate: HeIn 7 - RP 7	5.49 kV, 8.95 µs	1.5 µs
	Pancake 13 to radial plate 7: L131:1 – RP 7	7.08 kV, 12.15 µs	About 2 µs

2 Impulse tests with rise times in the ms range

The calculation of rise times in the ms range is not successful. Such an impulse would make necessary high voltage devices which are probably not available under economic aspects.