A NEW COMPACT LARGE FREQUENCY-SWING RF SYSTEM FOR HADRON ACCELERATION: TEST RESULTS

M. Crescenti[1], G. Primadei[2] and A. Susini[2].

ABSTRACT

A prototype RF cavity for hadron acceleration in synchrotrons has been developed in CEA-LNS Saclay and is now at CERN under test for the TERA collaboration.

The system is designed to give a very large frequency swing (0.15-10 MHz) and gap voltages of more than 5 kV. The longitudinal space occupied in the ring is under 1.5 m, less than a conventional RF system of the same performance. The novelty in this design is the use of a new amorphous iron core that replaces the conventional ferrites. The permeability μ of this ferromagnetic medium is very high and very sensitive to the bias current, making large frequency swings possible with just a few tens of amperes, instead of the hundreds of amperes needed for ferrites.

This report gives an overview of the characteristics of the RF system, and shows how the system has been configured at CERN with the modifications made for TERA. The first tests were carried out with a total installed power of 2x10 kW (Saclay configuration) and later tests with 2x50 kW. The measurements and the performance obtained are described. The results show that the system fulfils the expectations and meets the requirements for the acceleration of protons and carbon ions in the TERA synchrotron.

---

[1] M. Crescenti is a member of the TERA Foundation and Unpaid Associate of the CERN PPE Division, currently working on the Proton Ion Medical Machine Study (PIMMS) hosted by the CERN PS Division.

[2] G. Primadei and A. Susini are consultants to the TERA Foundation.

INTRODUCTION

Over the last few years, the LNS-CEA Saclay has been engaged in the development of a new RF cavity for MIMAS, the SATURNE injector. The reason for building this new cavity was to replace the two existing ferrite-loaded cavities with a single unit, giving the same performance, while saving space in the ring for other instrumentation [1]. The basic structure of the cavity was built at Saclay and several tests were performed, in the framework of a French - German collaboration between the teams of Dr. C. Fougeron (CEA) and Professor H. Meuth (KFA). Unfortunately, the work on this project then slowed down due to the lack of funds and staff.

Meanwhile, contacts had been established with the TERA collaboration that was interested in the possibility of using this type of cavity in the TERA synchrotron. Under an agreement signed with the LNS laboratory, TERA has sponsored the transfer of the system to CERN to continue the experiments.

The objectives of TERA were to:

- re-assemble the cavity at CERN,
- re-produce the experimental results obtained at LNS,
- improve the performance to meet the specifications of the TERA synchrotron.

The staff of COSY at the KFA Jülich and a group at Darmstadt University are also interested in the development of this type of accelerating structure and are collaborating with advice and material. The performance will be compared to the one achievable with conventional ferrite-tuned systems and in case of better results, TERA will buy the cavity.

GENERALITIES

The accelerating structure is composed of two face to face $\lambda/4$ transmission lines with the accelerating gap in the middle (see Figure 1). A capacitance is added at the high voltage side to shorten the resonator. This results in a compact structure of 1.340 m total length. The two resonators are powered in anti-phase, in the push-pull configuration. In this way, the RF voltage given to the beam is twice that given by a single resonator. The resonator is loaded by a new ferromagnetic medium: VITROVAC6025F®[*], (called hereafter VVC). Tuning is obtained by varying the inductance of the VVC with a bias field. This material has high magnetic permeability, and high sensitivity to the bias, that allows large frequency swings to be obtained with a relatively small effort (in comparison with ferrite materials).

THE VVC

The ferromagnetic medium is an amorphous iron (cobalt-based) alloy and is produced by an extremely rapid cooling of a laminated ingot. It is delivered in the form of a ribbon wound on a bobbin. This structure necessitates careful handling during transport. Preliminary tests made at Saclay [2] and confirmed by experiments at CERN show that:

---

[*] The producer is VACUUMSCHMELZE GmbH, Grünen Weg 37, P.O. Box 2253, D-6450 Hanau 1, Germany.

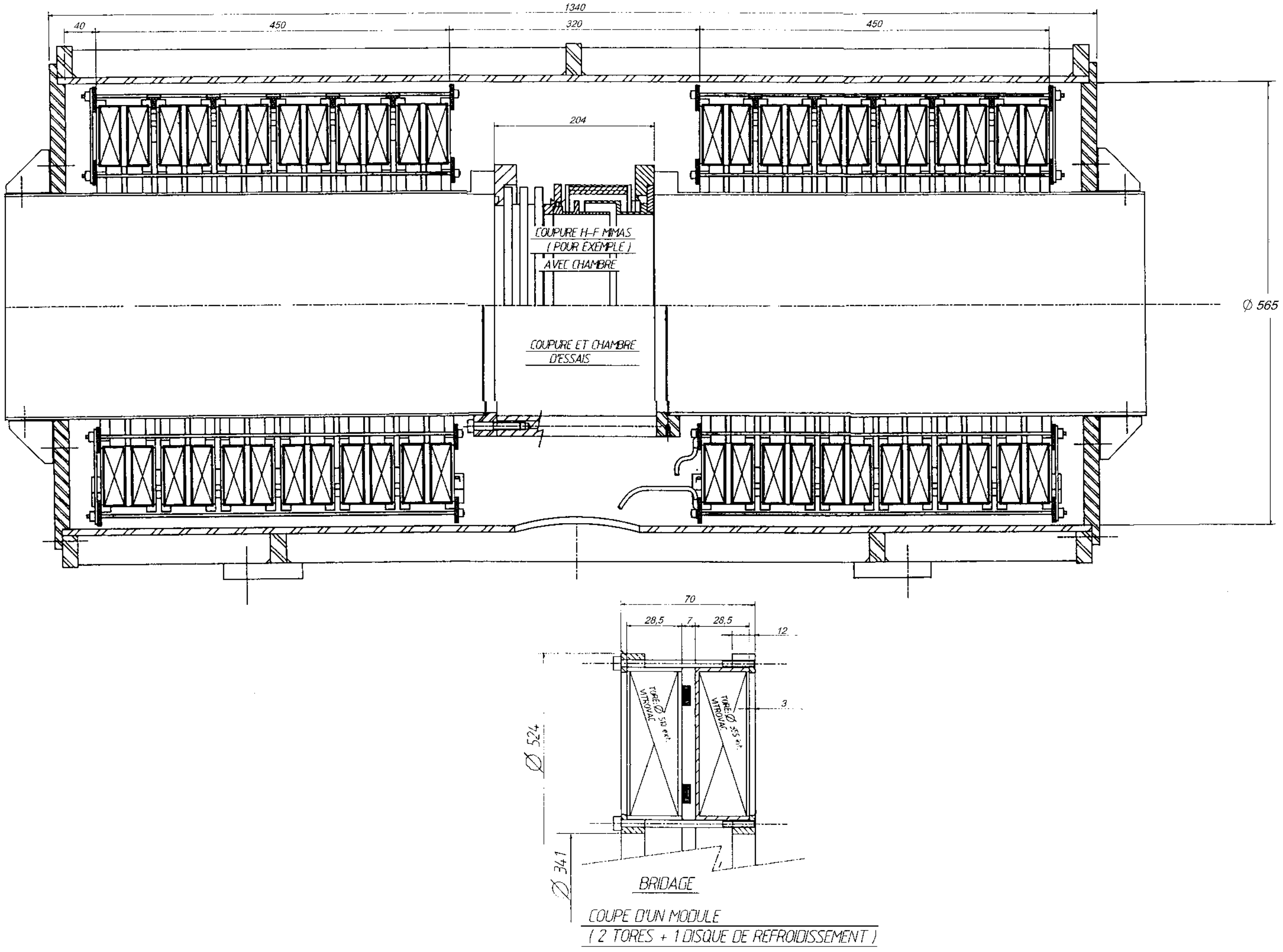

Figure 1: Mechanical drawing of the resonator, and, in the lower part, detail of VVC support (courtesy of LNS-CEA).

- At low frequency (150 kHz), the permeability μ is 10 times higher than conventional ferrite ($\mu_{VVC} \sim 10^4$ against $\mu_{ferrite} \sim 10^3$). It decreases with frequency. Unlike ferrite, μ is independent of the amplitude of the RF signal (an experimental confirmation of this was made, see below in the impedance measurements).
- The magnetic sensitivity is high, so the bias current requirements are limited to a maximum of a few tens of amperes.
- The quality factor Q is lower than that of ferrite (also confirmed below in the Q measurements), but the product $\mu Q f$ (f is the frequency) is still high due to the high permeability.
- No Q decrease was observed in the range 150 kHz-10 MHz.
- The sensitivity to temperature changes is very low. The Curie point is at 90°C and destructive. It is a metal, with a thermal conductivity of about 2 orders of magnitude higher than that of ferrite, so that it is more easily cooled.
- The cost of this material is about twice that of the ferrite, but about half the volume gives the same result. The auxiliary equipment is less expensive (power supplies, mechanical construction, needed space).
- On a reduced scale model, a corresponding (scaled) gap voltage of more than 5 kV has been obtained in the range 0.15-10 MHz.
- The gap voltage waveform can be obtained by simultaneous addition of many harmonics.

PARAMETERS AND PHYSICAL CHARACTERISTICS OF THE CAVITY

The parameters of the VVC disk, as well as the physical characteristics of the cavity, have been calculated and/or measured. The values of the relative permeability come from the experiments made at Saclay [1]. A summary is presented in Tables 1 and 2.

Radius of the vacuum chamber [m]	~0.140 (not yet defined)
Inner radius of the disk [m]	0.185
Outer radius of the disk [m]	0.260
Thickness of the disk [m]	0.025
Thickness of copper plates for cooling[m]	0.005
Total number of disks	24
Total magnetic length [m]	1.2
Total volume of the disks [cm^3]	24 x 5243

Table 1: Geometrical characteristics of the VVC disk.

Shunt impedance R_s [Ω] at 0.5 MHz	~450
Shunt impedance R_s [Ω] at 4.0 MHz	~300
Capacitance C [pF]	130
Added gap capacitance C_{gap} [pF]	300
Relative permeability at 0.5 MHz	10000
Relative permeability at 4.0 MHz	2000
Maximum RF magnetic field in the core [Tesla]	0.01

Table 2: Physical characteristics for a half resonator.

The VVC is enclosed in aluminium “C” shaped cross-section supports, and insulated by a kapton film (see lower part of Figure 1). Two of these supports are sandwiched back-to-back with a copper ring in which the cooling water flows. 12 of these modules (6 per half resonator) are aligned around the beam pipe. This system allows the evacuation of more than 2 kW per ring, with the cooling circuit delivering about 30 l/min.

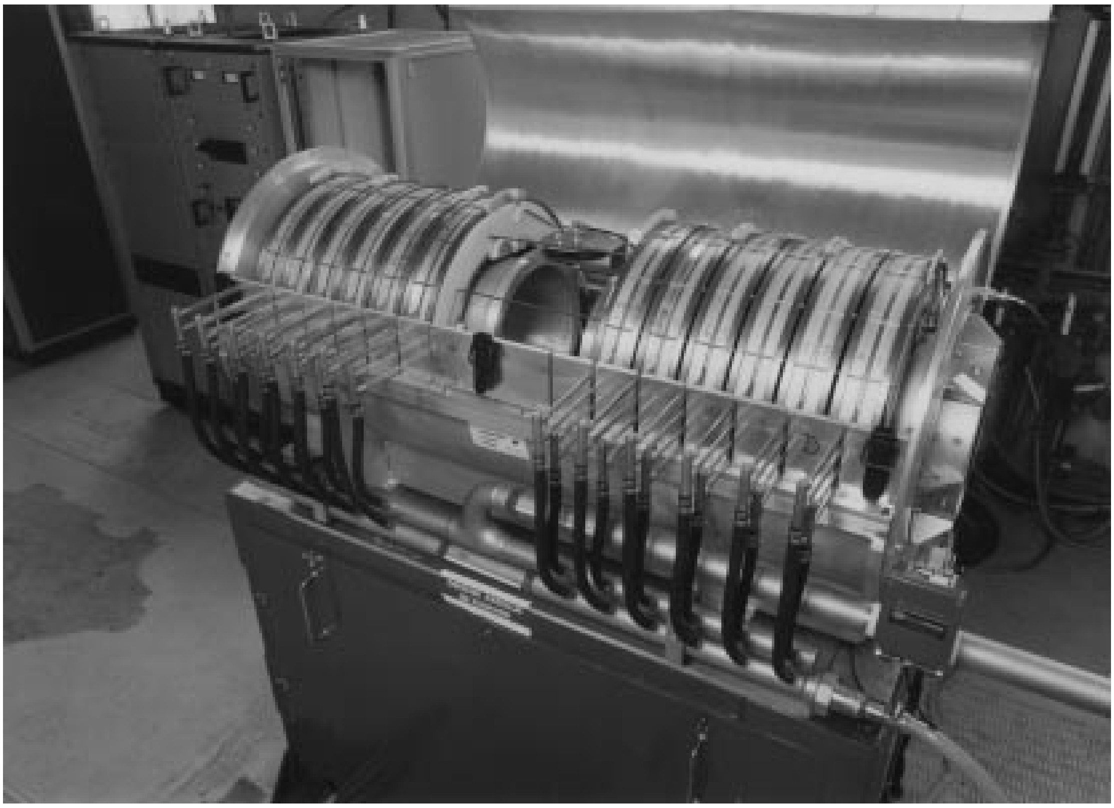

Figure 2: Internal structure of the resonator.

POWER SET-UP

Two Thomson TH541 tetrodes are installed with a total DC power of 20 kW. The configuration is a grounded cathode class A amplifier. The RF input is given to the control grid via a matched network. This imposes a limitation on the maximum voltage that can be obtained at the accelerating gap in this configuration. The class A amplifier gives a low distortion output, but has the drawback of a higher anode power consumption. The configuration has been kept unchanged for the tests, except for some small modifications (see Figure 3) made in order to improve the performance. Coupling the RF voltage to the cavity is done by two 13 nF blocking capacitors. The high voltage filter, not present in Figure 3, has been rebuilt.

The screen and control grid were originally connected to the 220 V transformer by means of two 50 Ω resistors. This gave a (~20%) 50 Hz modulation of the gap voltage. When all the grids were grounded (see Figure 3), the modulation decreased to less than a few per cent. An

artificial centre-tap, to completely avoid this modulation, is at this stage unnecessary. A HF filter has been added at the screen grid input, to avoid oscillations induced at particular frequencies.
The tests on this configuration showed that the return flow of the anode current to the ground is not well controlled. This can give problems of ground mismatching, but is not a serious problem with the 10 kW power per tube presently installed. The situation may be worse at 50 kW power per tube, and in this case a better ground connection has been built.

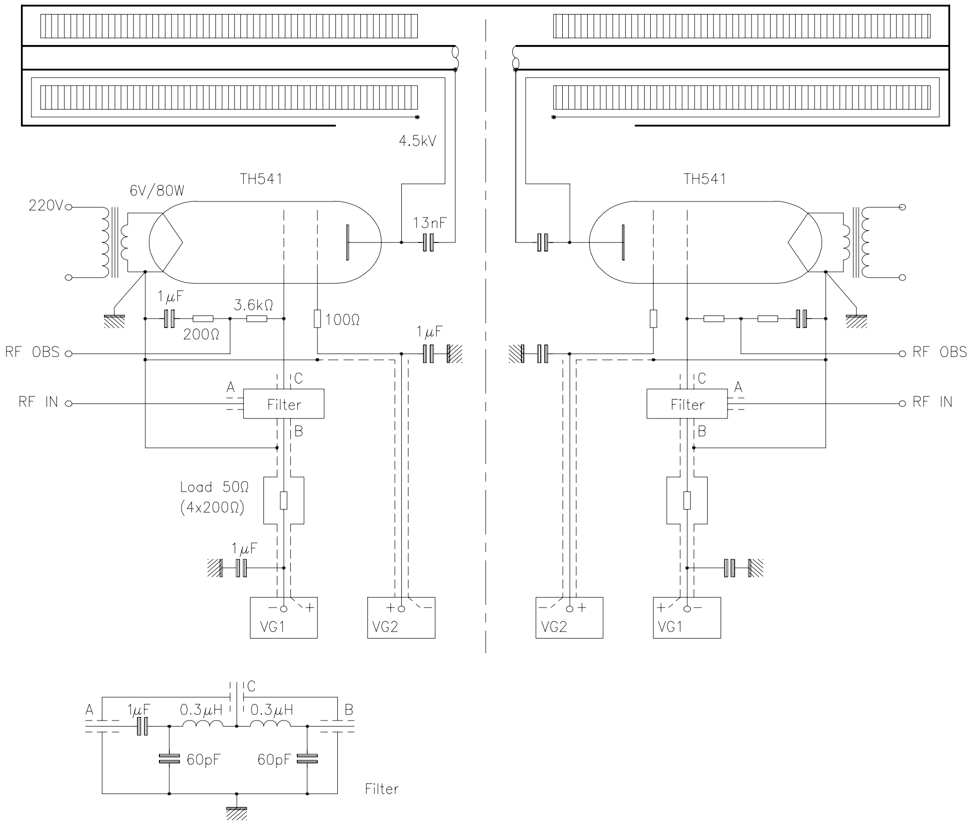

Figure 3: Electrical set-up (2x10 kW installed power). The high voltage filter and the bias circuit for the VVC are not represented in the drawing.

BIAS CIRCUIT

The high sensitivity of the VVC to the field variation allows a very large frequency swing to be obtained with only a few tens of amperes of bias current. The bias circuit is arranged in 4 windings of a section of 7 mm^2. The figure-of-eight configuration is needed, in order to suppress the currents induced by the RF varying field. A ferrite choke and some capacitance have been added to ensure power supply HF damping.
For the needs of TERA, a capacitance C_{gap} ~ 300 pF was added to obtain a 0.5-4 MHz swing with a current variation from 1 to 32 A.

INTERLOCKS

For the preliminary tests, a simple circuit was built, with electromechanical switches allowing a semi-automatic control of the services and of the supplied voltages. The interlocks are organised in two levels (see Table 3).

LEVEL 1	Air flow (filament) water flow (tubes and VVC cooling) tubes water temperature below 50°C filament heating control grid voltage
LEVEL 2	screen grid voltage high voltage

Table 3: Interlocks.

At ‘power on’, a programmable timer starts, giving the delay during which all the conditions of *LEVEL1* have to be fulfilled. Once *LEVEL1* is OK, *LEVEL2* can be started manually by a push-button. Whenever one of the conditions of *LEVEL1* fails, the corresponding interlock interrupts, and the operation restarts from the beginning. An emergency stop push-button is also implemented.

MEASUREMENTS

During most of the tests, the frequency swing was limited to that requested by the TERA specifications, i.e. 0.5-4 MHz [4]. However the limits for frequency swing are far beyond this specification and have been experimentally demonstrated down to 0.15 and up to 8 MHz.

Impedance

Impedance measurements have been performed at zero power and with the tubes disconnected by means of the HP4815A vector Z-meter, tuning a half-resonator for $\varphi = 0$. The values obtained for the half-resonator in the frequency range specified are shown in Figure 4. The beam will see twice the impedance shown in Figure 4.

The correspondence of the actual tubes’ performance with theoretical TH541 characteristics [3] has been checked by loading each half-resonator with a 50 Ω resistor. This allows an approximate estimate of the anode current emitted by the tubes to be made, and, as a result, the cavity impedance under high-voltage conditions can be found. Within measurement errors, the impedance did not vary with the RF voltage level. This is an implicit confirmation to the statement that μ does not vary with the RF voltage level.

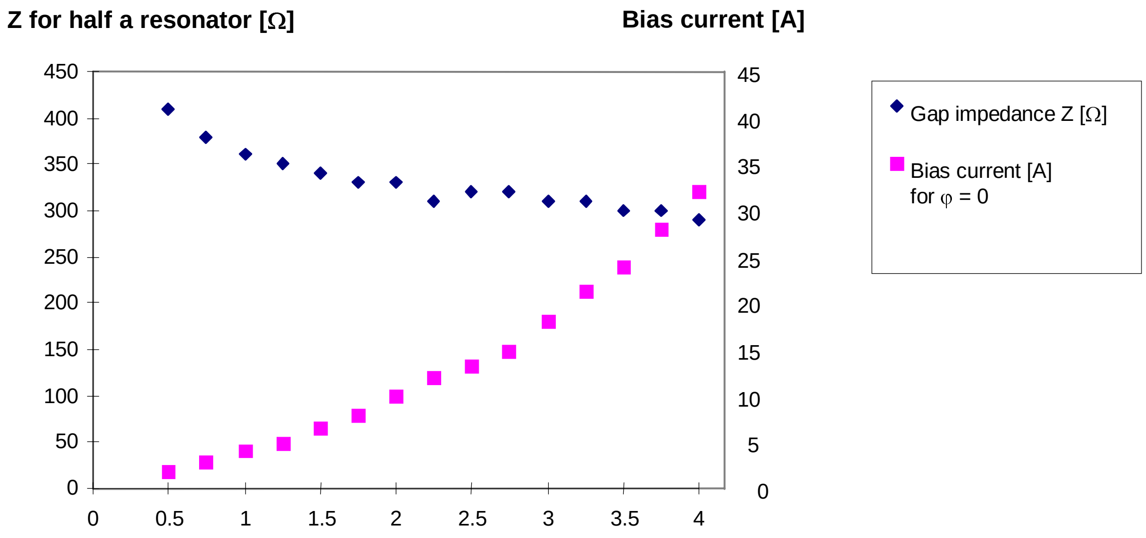

Figure 4: Impedance and bias current versus frequency.

Quality factor *Q*

For losses of the order of the reactive power (i.e. $Q \leq 1$), the formula:

$$Q = \frac{\omega_0}{\Delta\omega} \qquad ,$$

ω_0 being the resonant frequency and $\Delta\omega$ being the bandwidth at -3db amplitude, loses its physical meaning. In this case, σ, the distance of the poles of the driving impedance function from the imaginary axis is more meaningful. The property of this function is that:

$$\sigma = \frac{d\omega}{d\varphi} ,$$

$d\varphi$ being the small phase angle corresponding to a $d\omega$ frequency variation from resonance ω_0.
In the case that $\sigma << \omega_0$ (i.e. $Q >> 1$), $\sigma \rightarrow \Delta\omega/2$ and the phase angle $\varphi = \pm 45°$ at frequencies $\omega = \omega_0 \pm \sigma$.

Instead of measuring $\Delta\omega$ at –3db, which is difficult in this case, the σ of each half resonator at zero power was estimated by means of the vector Z-meter: once at resonance frequency (i.e. zero phase) the resonator is detuned by a small $\Delta\omega$, which gives a small phase angle $\Delta\varphi$. Then Q is estimated by the formula [5]:

$$Q = \frac{\omega_0}{2 \cdot \sigma} \cdot \tan \Delta\varphi$$

In this way, *Q* values between 0.5 and 5 have been obtained.

Gap voltage

The first tests have been completed with the tubes TH541, which deliver a total power per tube of 10 kW. The configuration used is shown in Figure 3. The tubes used for the tests have completed about 20,000 hours of working time. This probably explains why one of them presents a behaviour that is slightly different from the theoretical characteristics, calculated with a test program developed for this purpose. The push-pull had, therefore, to be balanced by lowering the DC voltage of the control grid of this tube by 10 V in order to get ~1 A DC anode current at the quiescent point (that is RF = 0) as in the other tube.

Measurements of the gap voltage have been performed by means of a capacitive divider, installed in the accelerating gap, that gives 1/1000 of the gap voltage on a matched load. High-power measurements were made at constant frequency. A maximum voltage of 2 kV peak has been obtained for each half resonator, which gives a total of 4 kV peak voltage delivered to the beam. Measurements have been made step-by-step every 500 kHz, from 500 kHz to 4 MHz. Due to the present power set-up this limit cannot be increased. In Table 4 the working values of the tubes are summarised. Comparison with calculations is done at 1 MHz and 1.5 kV peak RF anode voltage; values at which the measurements could easily be performed.

TH 541 (1.5 kV RF)	Calculated	Measured
V screen [V]	700	700
V_{DC} grid [V]	-120	-120
V_{DC} anode [V]	4500	4500
V_{RF} grid [V]	27	30
V_{RF} anode [V]	1500	1500
I_{DC} anode [A]	1.0	1.0
Z anode [Ω]	333	320

Table 4: Working values of TH 541 (example at 1 MHz and 1.5 kV peak).

After these low power tests, another amplifier built at COSY-KFA, copy of SATURNE amplifiers, has been installed, with the tubes TH120 giving a total power per tube of 50 kW. Some modifications were needed in the mechanical set-up of the amplifier to obtain a good ground connection.

A maximum of 10 kV peak to peak has been obtained in the range 0.5-4 MHz. Automatic frequency sweeps have been performed at 4 kV constant gap voltage, with the help of an amplitude control loop. The minimum sweep time tested is 0.5 s. An example of the measured gap voltage is shown in Figure 5.

The tubes used for the tests have completed 25,000 hours of working time at SATURNE, and this probably explains why a decrease of the performance was noticed after a few tens of hours of continuous functioning. A regeneration of the tubes has been tried, by a 10% increase of filament voltage for a 24 h period. This improved the results only temporarily. With new tubes the performance should be better.

No problems were encountered at the resonator level (breakdowns, instabilities). No significant water cooling temperature increase has been detected during the tests.

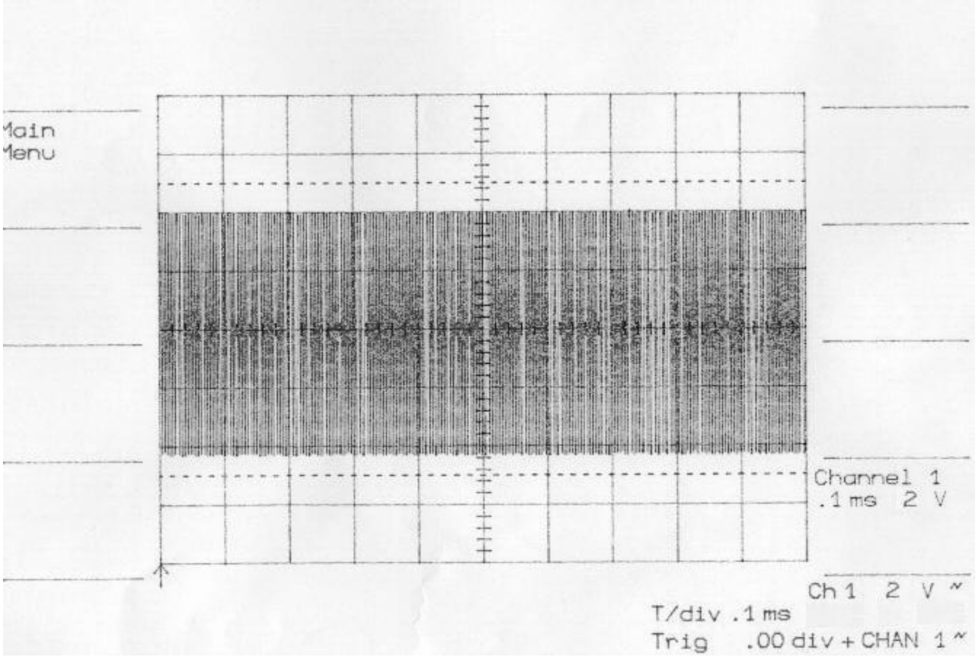

Figure 5: Example of frequency swing in the range 0.5-4 MHz, with phase and amplitude control loops. Constant gap voltage of 4 kV peak (attenuation is 1/1000 on a matched load).

CONCLUSION

The RF cavity has been successfully installed at CERN. Pushed to its limits, the system gives 4 kV peak gap voltage (obtained at fixed frequency). This is about twice the maximum value reached at Saclay.

Already in the low-power (2x10 kW) configuration, the system fulfils the specifications for the TERA synchrotron, as presently foreseen [4], in terms of frequency swing (0.5-4 MHz) and maximum voltage needed (≤ 4 kV).

After improving the ground connections, the new 2x50 kW RF amplifier developed at KFA has been installed, which allowed the design value of 5 kV peak to be easily obtained. This means that the maximum RF voltage limit is beyond this value. Frequency sweeps of 0.5 s at 4 kV constant gap voltage have also been obtained.

ACKNOWLEDGEMENTS

We would like to thank the teams of LNS-CEA, COSY-KFA and Prof. H. Meuth of Darmstadt University for allowing us to continue the project started at SATURNE and for their constant help with material and advice throughout the work.

We would also like to thank CERN PPE Division for providing the space for the laboratory, and CERN PS Division for hosting the study and for the loan of the measuring instrumentation.

Last but not least thanks go to P. Bryant, head of the PIMMS group at CERN, who followed this work with great interest and also carefully revised the manuscript.

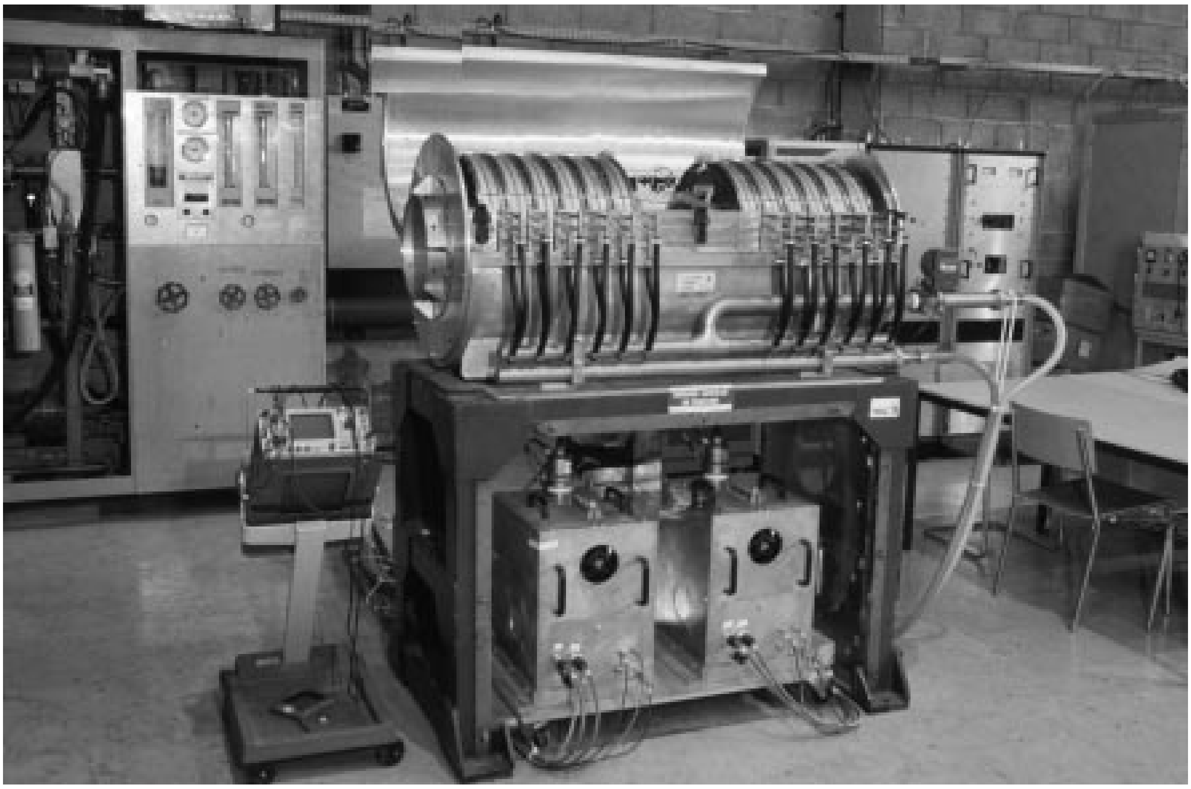

Figure 6: Laboratory set-up at CERN with the tubes TH541 (2x10 kW power installed). At present the configuration has changed, and the new set-up is with the COSY-KFA amplifier and the tubes TH120 (2x50 kW power installed).

REFERENCES

[1] C. Fougeron, P. Ausset, D. de Menezes, J. Peyromaure, G. Charruau, *Very Wide Range and Short Accelerating Cavity for MIMAS*, 1993 IEEE Publications (1993), p.858-861.

[2] C. Fougeron, private communication.

[3] Thomson TH541 and TH120 Data sheets.

[4] Private Communication, M. Crescenti and S. Rossi, *PIMMS RF Programme 1 and 2,* notes of the PIMMS informal meeting held at CERN in February 1997.

[5] H. Klein, *Basic Concepts I*, in *RF Engineering for Particle Accelerators* (S.Turner ed.), CERN 92-03 (CAS) vol. I, p. 111.