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TERA high gradient test program of RF cavities for medical linear accelerators

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ABSTRACT

The scientific community and the medical industries are putting a considerable effort into the design of compact, reliable and cheap accelerators for hadrontherapy. Up to now only circular accelerators are used to deliver beams with energies suitable for the treatment of deep seated tumors. The TERA Foundation has proposed and designed a hadrontherapy facility based on the cyclinac concept: a high gradient linear accelerator placed downstream of a cyclotron used as an injector. The overall length of the linac, and therefore its final cost, is almost inversely proportional to the average accelerating gradient achieved in the linac.

TERA, in collaboration with the CLIC RF group, has started a high gradient test program. The main goal is to study the high gradient behavior of prototype cavities and to determine the appropriate linac operating frequency considering important issues such as machine reliability and availability of distributed power sources. A preliminary test of a 3 GHz cavity has been carried out at the beginning of 2010, giving encouraging results. Further investigations are planned before the end of 2011. A set of 5.7 GHz cavities is under production and will be tested in a near future. The construction and test of a multi-cell structure is also foreseen.

1. Introduction

Hadrontherapy has been developing very fast in the last decades. Compared to conventional radiation therapy with X-rays, protons and carbon ions allow a higher tumor control due to the advantageous depth-dose profile of hadrons.

In case of carbon ions the higher radiobiological effectiveness opens a way to the treatment of radio-resistant tumors too. The typical energies needed for such applications are of about 200 MeV for protons and 400 MeV/u for carbon ions, with beam currents of the order of nanoamperes. Up to now only cyclotrons and synchrotrons have been used to deliver suitable beams, but new technical solutions are being investigated to find more compact and cost effective hadrontherapy machines.

In this framework, the TERA Foundation has proposed the “cyclinac”, which combines a cyclotron (used as injector) with a high frequency linac. A cyclinac complex for carbon ions called CABOTO (CArbon BOoster for Therapy in Oncology) is shown in Fig. 1.

The linac (in this case a side coupled linac) is divided into several modules. Each module is powered by independently controlled klystrons with high repetition rate (200–400 Hz). The beam output energy can be varied electronically from pulse to pulse by changing the amplitude (and/or phase) of the klystrons, while a computer controlled source allows to change the beam intensity every pulse. These characteristics make the cyclinac suitable for implementing the 4D spot scanning technique with multipainting, which is one of the best methods to properly follow moving organs [1].

A prototype of an accelerating module of the proton cyclinac LIBO (LInear BOoster) was built and successfully tested in 2003 [2]. More recently, the research activity of TERA cyclinac Group is focused on reducing the cost and dimension of the cyclinac.

A comparative design study of linac structures for hadrontherapy at different frequencies (S, C and X band) is planned, in order to determine the most appropriate one, allowing high gradient operation (up to 40 MV/m) while considering machine reliability and availability of distributed power sources.

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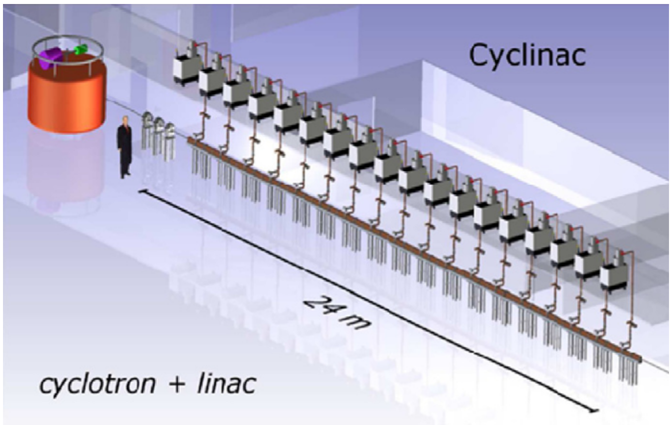

Fig. 1. Artistic view of a carbon ion cyclinac (CABOTO).

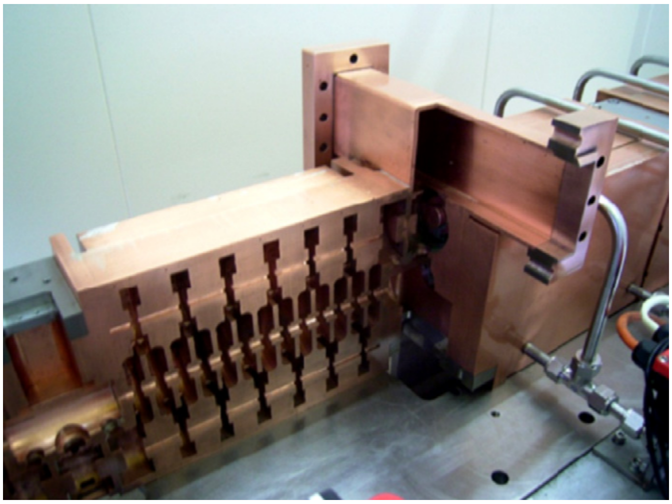

Fig. 2. Particular of the LIBO prototype module.

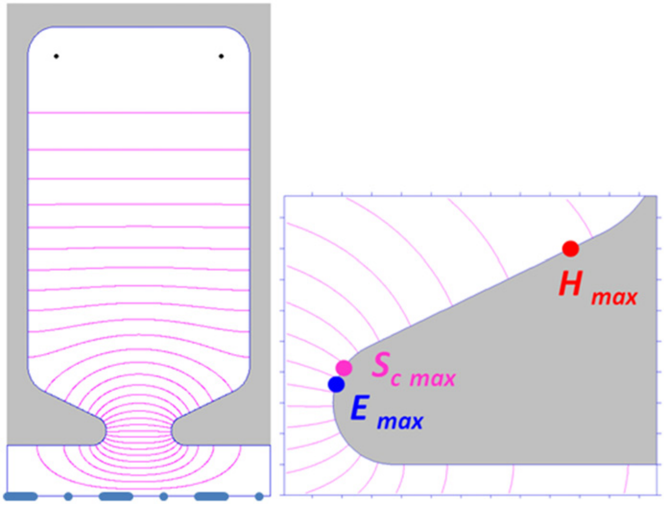

Fig. 3. S-band TC profile with field pattern and position of maximum field quantities.

2. High gradient test program

In order to determine the limitation to high accelerating gradient in RF cavities, TERA has started a high gradient test program in collaboration with the CLIC RF Structure Development Group at CERN. The main goal is to study the behavior at high power of a set of prototype cavities, to measure limiting quantities such as surface electric field E_{max} and modified Poynting vector S_c [3], and to validate scaling laws between breakdown Rate (BDR) and accelerating gradient E_0.

Even though the aim and the geometry of TERA and CLIC structures are very different, both groups share the same operational limits in terms of maximum surface electric field E_{max} (260 MV/m) and of maximum BDR (3×10^{-7} bpp/m) [3]. The first one is strictly related to the cell geometry, which defines the ratio between peak surface electric field (E_{max}) and average accelerating gradient (E_0). The second limit, for what concerns TERA's cyclinac, corresponds to about one breakdown per treatment course (10 fractions of 3 min at 200 Hz), which is considered to be acceptable for medical applications.

The two new projects of TERA–CABOTO of Fig. 1 [4] and TULIP (TUrning LInac for Protontherapy) [5]–are based on the fact that such low BDR can be achieved for the accelerating gradient of interest. The first one is an optimized design of a carbon ion cyclinac, while the second has the goal to study the feasibility of a turning linac for a proton therapy single-room facility.

The research program consists of three steps:

- test of an S-band single-cell cavity (RF frequency of 2.998 GHz);
- test of a C-band single-cell cavity (RF frequency of 5.712 GHz);
- test of a multi-cell structure at S- or C-band.

The S-band test cavity (TC) has been built and a preliminary test has been performed in February 2010. The C-band TC has been machined, and low power measurements are currently being performed. After the high power test of this cavity, it will be decided whether the multi-cell structure will be designed at 3 or 5.7 GHz.

3. TERA test cavities

A typical accelerating tank for a cyclinac is a side coupled linac structure working in $\pi/2$ mode [6]. It is composed of symmetric half-cells brazed together. The accelerating cells are on-axis, while the coupling cells are moved to the sides, as shown in Fig. 2. The cell geometry is optimized in order to have the highest shunt impedance for a given bore radius and a given ratio E_{max}/E_0. The bore radius is determined by beam dynamics reasons. The ratio E_{max}/E_0 is chosen as a compromise between the limiting value of the surface electric field and the losses in shunt impedance. As particles are not relativistic, to increase the acceleration efficiency, nose cones are required to enhance the electric field along the beam axis.

In the next paragraphs a description of the design and production process of the TCs is reported.

3.1. RF design

A first design of the cavities is performed with Superfish. Then the structures are simulated with HFSS. The most important difference between the TERA TCs and a nominal accelerating cavity in a side coupled linac is the absence of the coupling cavities and therefore the need of a slot to couple the TC directly to the waveguide. The presence of the slot will influence the position of the brazing lines. These constraints have been taken into account leaving enough space for the coupling slot. As an example, the profile of the 3 GHz TC is shown in Fig. 3. The expected location of the maximum field quantities have been evaluated and are also shown in Fig. 3.

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At this stage the tuning range due to mechanical error tolerances and the cooling system requirements have been evaluated. The values obtained for the two TCs are reported in Table 1. The diameters of the cells have been adjusted to compensate for the frequency shifts due to thermally induced deformation of the structures.

3.2. *Thermo-mechanical calculations*

The geometry and the material determine the temperature distribution for a given power (Fig. 4). Water cooling systems have been designed in order to dissipate the average RF power with turbulent flow.

The temperature gradients between the nose and the cooled surface are 15 and 30 K for the S- and C-band TC (at the condition of average power indicated in Table 1), respectively. The resulting micrometric deformations are taken into account during the RF design.

Table 1
Main design characteristics of the TCs.

Frequency [MHz]	2998.5	5712
Cell length [mm]	18.9	18.8
Cell diameter [mm]	64.50	34.54
Cavity volume [cm^3]	50.68	13.87
Shunt impedance [MΩ/m]	84	150
Expected Q value	8990	8990
E_{max}/E_0	6.48	4.63
H_{max}/E_0 [A/kV] (nose region)	2.66	2.80
β_H^{slot} $(=H_{max}^{slot}/H_{max})$	1.5	1.5
$\sqrt{S_c}/E_0$ [$\sqrt{W}$/V]	29×10^{-3}	25×10^{-3}
Peak power [kW][a]	360	200
E_{max} [MV/m][a]	260	185
$S_{c,max}$ [MW/mm^2][a]	1.38	1.03
# Parallel cooling channels	2	3
Total water flow [l/min]	5	7.5
Average power [W]	350[b]	500[c]
Thermal resistance [K/W]	0.035	0.050
ΔT pulsed surface heating [K]	6[b]	30[c]
Required tuning range [MHz]	±7	±12
Tuning strategy	Nose cones deformation	Tuning ring
Tolerance bandwidth [μm]	20	10
Surface roughness [μm]	0.4	0.4

[a] Values calculated for $E_0=40$ MV/m.
[b] Values calculated for $E_{max}=260$ MV/m.
[c] Values calculated for $E_{max}=400$ MV/m.

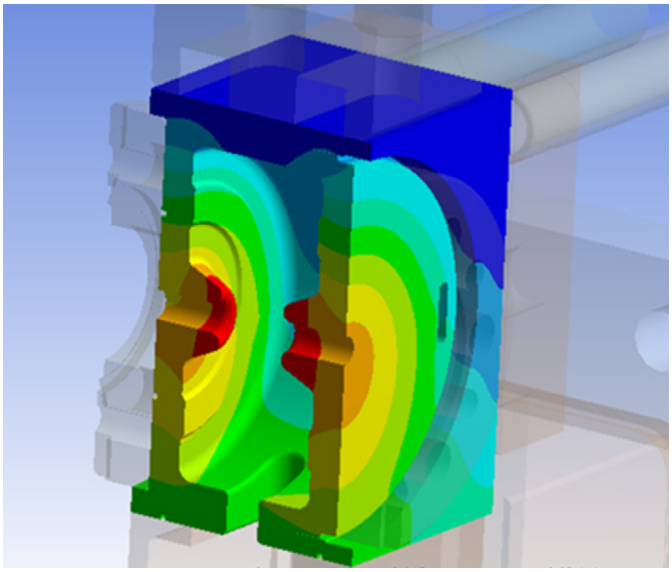

Fig. 4. Simulated temperature distribution for the C-band TC with 500 W average power.

The currents induced by the magnetic field heat up the cavity by Joule effect and produce pulsed surface heating. The evaluation of the consequent temperature rise within each pulse was performed for both TCs (Table 1).

3.3. *Matching of the test cavities*

The coupling slot provides magnetic coupling between the waveguide and the TCs. The opening of the slot enhances the magnetic field in this region of about 50% with respect to the maximum value obtained in the nose region, as indicated in Table 1.

The slot dimensions have been chosen such that the cavities are over-coupled (coupling factor $\beta=1.4$). After the first low power measurement the coupling factor is modified by choosing the position of the short termination in the waveguide. The chosen coupling factor will be slightly bigger than 1, in order to take into account the coupling degradation when the temperature of the cavity increases during operation.

3.4. *Machining, tuning and brazing*

The machining tolerances required are a compromise between the tuning range needed and the total cost for manufacturing. Different tuning strategies have been considered for the two TCs (Table 1). While tuning rods are preferable for the final tuning of the linac, they are avoided in case of high gradient TC because of the induced field enhancement.

In C-band, a second cavity with tighter tolerance band (5 μm) will be built, thus avoiding the use of tuning rings and enabling the study of the machining procedure's influence on the overall performance of the structures.

3.5. *Test cavities comparison*

In Table 1 the main characteristics of TERA TCs are summarized.

The higher shunt impedance of the C-band TC is due to a smaller bore hole, while the lower E_{max}/E_0 ratio is related to the fact that the nose region geometry could not be scaled with respect to the frequency because of machining limitations. The length of the TC could neither be scaled due to the presence of the coupling slot.

The power requirements specified for the design of the cooling systems are higher in the C-band TC in order to reach higher surface electric fields. The expected increase in BDR would allow collecting more statistics during the short testing time.

4. Preliminary results

A preliminary high power test of the 3 GHz TC was performed in February 2010 at the CLIC test facility (CTF3, CERN). Three points are here recalled. More details can be found in [7].

(a) Cavity was connected to a 35 MW klystron delivering 5 μs pulses at 50 Hz. The power level inside the cavity was evaluated from the power forwarded to and reflected by the TC, which were monitored by a peak power meter. The maximum peak power inside the TC was of 1 MW, and the maximum surface electric field was above 350 MV/m, with an error of about 10%. The corresponding accelerating gradients were over 50 MV/m.

(b) A Faraday cup, connected to the cavity through LIL flanges, was used to monitor the dark current and to identify breakdown events. The measured breakdown rate with a flat top pulse length of 2 μs was between 10^{-2} and 10^{-1} bpp/m. These values rescaled to a BDR of 10^{-6} bpp/m and a pulse length of 200 ns give modified Poynting vector values comparable with the ones achieved by structures at 12 and 30 GHz.

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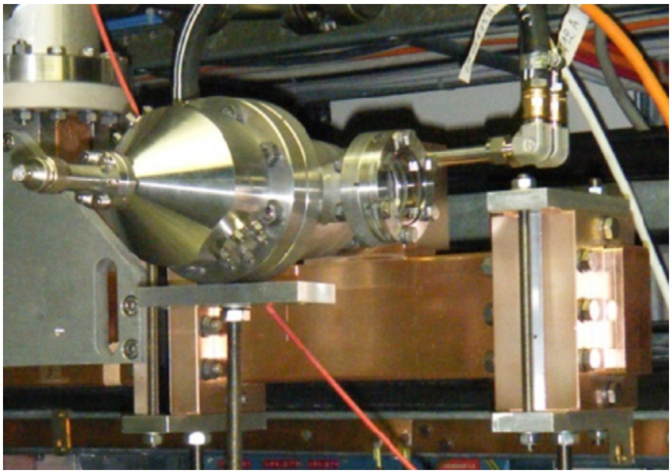

Fig. 5. S-band TC during the preliminary high gradient test at CTF3-CERN.

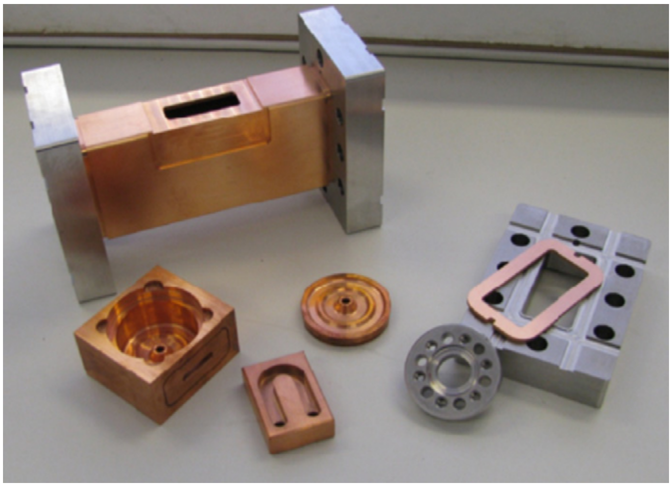

Fig. 6. Pieces of the C-band TC. Tuning rings are visible around the nose.

(c) Contact temperature sensors were placed on the cooling pipes and on the top of the cavity to monitor the temperature behavior during operation.

In Fig. 5 the test set-up is shown.

The cavity was operated for about 40 h. The collected data show an encouraging agreement with the literature data in terms of the modified Poynting vector. However, the scaling of the breakdown rate as a function of maximum field does not follow the empirical law founded at higher frequency. It has to be stated that the test was intended to debug the system more than to collect data. A longer test, with more time for conditioning, is foreseen to improve the statistics and evaluate the scaling laws.

The pieces of the 5.7 GHz TC have been recently machined (Fig. 6). After tuning, matching and brazing, the 5.7 GHz TC will be ready for testing at the end of 2011. Surface inspections by scanning electron microscopy (SEM) will be performed at each production step, in order to evaluate the spatial distribution of future breakdowns.

5. Conclusion

The tests will provide useful data for the performance studies of high gradient structures. Assuming the same scaling law that was found to be valid for 11.4 and 30 GHz, the data from these tests can be rescaled and used to better understand the role of the modified Poynting vector as the limiting quantity on high gradient operations [3]. In addition, to prove reliable operation in terms of BDR is crucial for the development of innovative high gradient medical hadron linacs such as CABOTO [4] and TULIP [5].

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