HIGH-GRADIENT TEST OF A 3 GHz SINGLE-CELL CAVITY*

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Abstract

Accelerators can be used for hadrontherapy, a cancer treatment in which the patient is irradiated with hadron beams. For this purpose, the Italian foundation TERA proposes the "cyclinac", composed of a high-frequency linac which boosts the hadrons accelerated by a cyclotron. The main research goal is to reduce the length of the linac by achieving higher accelerating gradients, without compromising the reliability of the accelerator. In order to measure the high gradient limitation, a 3 GHz single-cell gauge cavity has been designed, built and high-power tested by TERA. Results from the first high power test are presented and discussed in this paper.

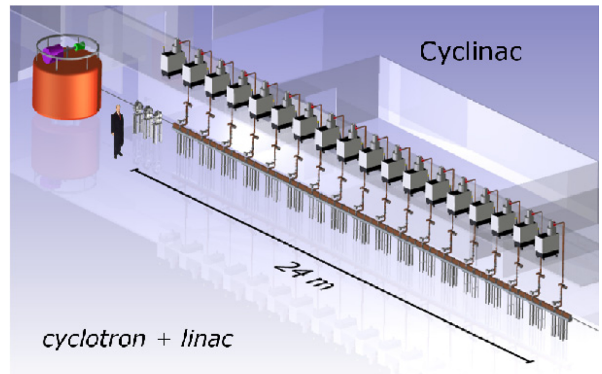

Figure 1: Cyclinac complex for hadrontherapy [2].

INTRODUCTION

Hadrontherapy is a local method for cancer treatment based on the exploitation of the advantageous depth-dose profile of hadrons with respect to X-rays. In the case of carbon ions, they allow a better control of "radioresistant" tumours due to their radiobiological effectiveness. For treating deep-seated tumours proton and carbon ion beams of some nanoamperes and energies of about 200 MeV and 400 MeV/u respectively are needed. An accelerator for hadrontherapy should be reliable, provide the best possible treatment modalities, require little power, have small dimensions and require a reasonable investment.

For this application TERA has proposed the "cyclinac", composed of a high-frequency linac (typically a Cell Coupled Linac) which boosts the hadrons accelerated by a cyclotron. The structure is powered by many independently controlled klystrons. By regulating amplitude (and/or phase) of the klystrons that feed the different modules in which the linac is subdivided, the beam energy can be varied from pulse to pulse. This characteristic, together with the high repetition rate (200–400 Hz) at which the machine can be operated, makes the cyclinac suitable to apply the 3D spot scanning technique with multipainting, which would be most adapted for treating moving organs [1]. A sketch of a cyclinac complex for carbon ions is shown in Fig. 1.

The dimensions of the complex can be reduced if higher accelerating gradients are achieved in the linac. However, the probability of having breakdowns in the accelerating cavities increases with the value of the maximum surface electric field. Breakdowns induce a loss of beam pulse and affect the machine reliability. At 3 GHz, the field limit for reliable operation is larger than 150 MV/m [3].

In this context, TERA is collaborating with the CLIC RF structure development group at CERN, which works on normal-conducting high-gradient linacs for a future electron-positron collider. Although TERA and CLIC are working on very different RF structures, both share the same operational limits: a 250 MV/m maximum surface electric field and a maximum 10^{-7} BDR (breakdown rate, the number of breakdowns per pulse per meter of an accelerating structure) [4]. This corresponds to about one breakdown per treatment course, the acceptable breakdown rate for a medical accelerator.

3 GHz SINGLE-CELL CAVITY DESIGN

In order to experimentally measure the high gradient limitation of RF cavities suitable for hadron accelerators and to determine the scaling laws that relate breakdown rate, pulse length and electric field or modified Poynting vector, a 3 GHz single-cell cavity was designed, built and tested.

The 18.9 mm-long cell was designed to be excited at 200 Hz by 3 μs duration RF pulses and to reach an accelerating gradient of at least 40 MV/m, which corresponds to a 260 MV/m peak surface electric field. The RF design of the cavity is based on 2D and 3D simulations, respectively done with Poisson Superfish [5] and Ansoft HFSS11 [6]. The cell geometry has been optimized to maximize the shunt impedance for a bore radius of 3.5 mm in order to

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reach high electric fields. The cell presents nose cones to enhance the electric field along the beam axis, as it can be seen in Fig. 2. Locations of the maximum electric and magnetic field values and the maximum modified Poynting vector (a recently introduced local quantity which may present a determinant role on high gradient performance [4]) are shown in Fig. 2.

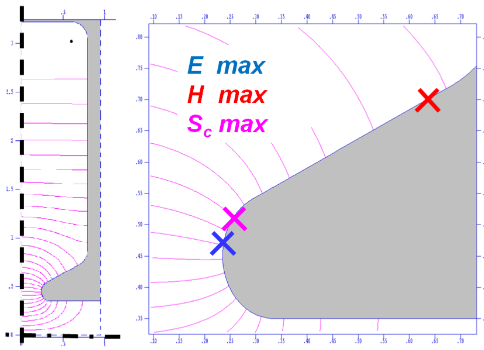

Figure 2: Cell profile with electric field distribution (left) and zoom in the nose region, where the maximum electric and magnetic field and the maximum modified Poynting vector are located (right).

The power is provided to the cell by magnetic coupling. The cavity geometry was designed such that the structure was overcoupled. In order to match the waveguide feeder to the cell, a movable short was placed at one end of the waveguide. Subsequently, the short was brazed at the position which led to critical coupling, so that the structure was matched at the resonant frequency.

A 10 degrees temperature increase would lead to a frequency shift of -0.5 MHz due to thermally induced structure expansion. The thermal resistance of the cavity is 0.035 degrees/W (i.e. an average power of 100 W would result in a temperature difference of 3.5 degrees between hottest and coolest points in the cavity). Thus a total detuning of around -2 MHz is expected when the coolant inlet temperature is 15 degrees above ambient temperature and the cavity is fed with 350 W average power. The cavity incorporates two parallel circuits of 5.5 mm diameter sized to cool down 350 W (power corresponding to 260 MV/m peak surface electric field) with a 2.5 l/min water flow per circuit in turbulent regime.

The pulsed surface heating has been calculated for a maximum surface electric field of 260 MV/m and a 5 μs pulse. Currents of about 100 kA/m are expected in the nose region, which bring to a 5 degrees transient increase of temperature.

The prototype is made of UNS C10100 OFE copper, chosen because of its enhanced electromagnetic and thermal conductivity characteristics. It was machined at VECA s.r.l.(Italy) with a cell profile bandwidth tolerance of 20 μm and a surface roughness of 0.4 μm. The vacuum furnace brazing procedure was performed at Bodycote (France) while the necessary cleaning procedure (degreasing, pickling and passivation) was done at CERN workshops (Switzerland). The cavity is shown in Fig. 3.

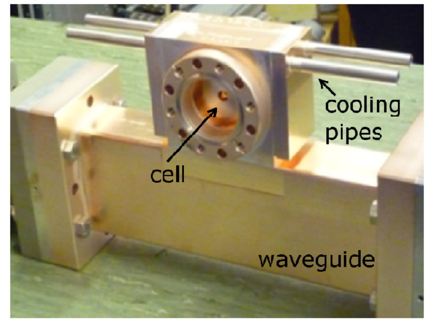

Figure 3: 3 GHz single-cell cavity.

After construction, the cavity was tuned by deforming its nose region. Mechanical stresses have been calculated using ANSYS [7] to evaluate the viability of this tuning technique. Once the cavity was tuned, a Q-value within 5% of simulation results and a reflection coefficient of -27 dB were measured. The main electromagnetic quantities of the test cavity are summarized in Table 1.

RESULTS OF FIRST HIGH-POWER TEST

In a first high-power test performed in the CLIC Test Facility (CTF3) at CERN, the cavity was operated at 50 Hz with a maximum peak input power of 1 MW. Power was provided by a 35 MW klystron delivering 5 μs pulses. A Faraday cup was connected to the cavity to monitor the dark current. From this signal, breakdown events were identified and the breakdown rate was estimated. The maximum electric field achieved during operation was evaluated from the power forwarded to and reflected by the cavity, which were monitored by a peak power meter. Contact temperature sensors were placed on the inlet and outlet cooling pipes and at the top of the cavity, to monitor the temperature increase of the cavity.

The maximum surface electric field achieved in the cell was above 350 MV/m, corresponding to accelerating gradients over 50 MV/m. The measured BDR at these field values was around 10^{-1}. The preliminary maximum value

Table 1: Characteristics of the 3 GHz Single-cell Cavity

$E_{particles}[MeV/u]$	70
$f[GHz]$	3.000
$Q_{measured}$	8650
$ZTT[M\Omega/m]$	67
β	0.92
$\Gamma[dB]$	-27
E_{max}/E_0	6.5

of the modified Poynting vector is very close to the best values achieved by high gradient accelerating structures at 12 and 30 GHz, as shown in Fig. 4.

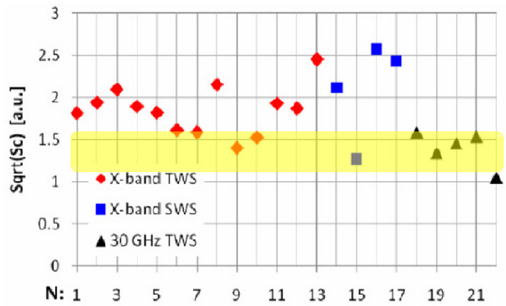

Figure 4: Modified Poynting vector for different high gradient experiments as presented in [4]. In yellow, region where data from the TERA 3 GHz single-cell cavity test are found.

Assuming an exponential scaling law for the BDR dependence on the electric field like the following

$$\frac{E^x_{surf}}{BDR} = const, \tag{1}$$

it is possible to estimate the BDR for different choices of the exponent (see Fig. 5). A value of x=30 can be found in literature [4], which would allow reliable operation at around 220 MV/m of peak surface field. However, a value of x=6 is found by fitting the measured data.

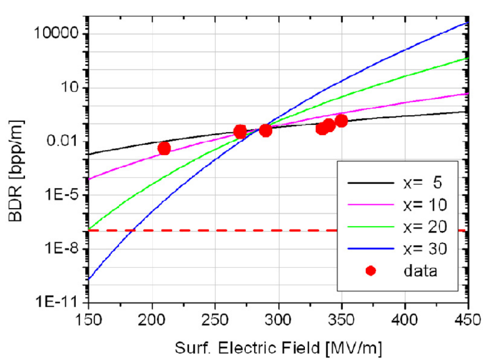

Figure 5: BDR dependence on surface electric field with exponential scaling law. The red dots are the measured data point at a fixed pulse length of 2 μs, with an uncertainty on the electric field of around 10%.

The cavity suffered about 14000 breakdowns during 40 hours of operation. The nose region surface of the cavity, where maximum electric and magnetic field values and maximum Poynting vector are achieved, has been inspected with an optical microscope through the bore hole. A picture of one of the noses is shown in Fig. 6. The surface is considerably damaged. As the cavity is intended to be tested again, firm conclusions will come later on, when the cavity will be cut and all its surface will be carefully inspected.

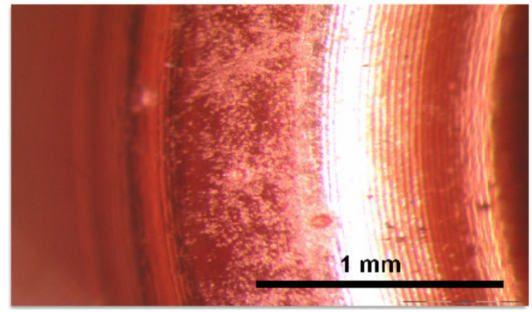

Figure 6: Surface damage in the nose region.

FUTURE STEPS

The agreement of the measurements with literature data in terms of the modified Poynting vector is very encouraging. However, the scaling of the breakdown rate as a function of the maximum field does not follow the empirical law found at higher frequency, probably because the cavity was not conditioned. This will be done before the next high power tests. Once the tests have concluded, the cavity will be cut to inspect its surface.

In order to explore the possible utility of higher frequencies for creating shorter linacs, the machining of a single-cell cavity at 5.7 GHz has already started, and a high power test in C-band is foreseen to be performed by the beginning of 2011.

ACKNOWLEDGEMENTS

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