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High gradient RF test results of S-band and C-band cavities for medical linear accelerators

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ABSTRACT

TERA Foundation has proposed and designed hadrontherapy facilities based on novel linacs, i.e. high gradient linacs which accelerate either protons or light ions. The overall length of the linac, and therefore its cost, is almost inversely proportional to the average accelerating gradient. With the scope of studying the limiting factors for high gradient operation and to optimize the linac design, TERA, in collaboration with the CLIC Structure Development Group, has conducted a series of high gradient experiments. The main goals were to study the high gradient behavior and to evaluate the maximum gradient reached in 3 and 5.7 GHz structures to direct the design of medical accelerators based on high gradient linacs. This paper summarizes the results of the high power tests of 3.0 and 5.7 GHz single-cell cavities.

1. Introduction

The use of protons and light ions for the treatment of deep-seated solid tumors is spreading worldwide [1]. The field of hadrontherapy would benefit greatly from compact, efficient accelerators that make the setup and operation of a hadrontherapy facility more affordable. In this regard, high-gradient RF technology has the potential of providing more compact and efficient machines.

TERA Foundation has proposed and designed hadrontherapy facilities based on high-frequency linacs [2,3] and has developed acceleration scheme that combines a cyclotron used as injector with a high-gradient linac used as booster [4,5]. The largest contribution to the size of such systems comes from the last linac section. For example, 15–20 m-long linacs are typically needed for accelerating protons between 30 and 230 MeV, while a linac for carbon ions would be more than double in length. High accelerating gradients can be used in order to make the linac more compact and less expensive. However, such high gradients will result in large peak surface fields, thus increasing the probability of vacuum arcs or "breakdowns".

Breakdowns lead to random beam kicks that can result in emittance growth or even loss of the beam if the kick is strong enough. When applying the spot scanning technique to the dose delivery, beam losses lead to unacceptable "cold spots" in the dose distribution [6]. A high *Break-Down Rate* (BDR) (that is the fraction of the RF pulses in which there is a break-down) deteriorates also the linac vacuum and can compromise the reliability of the machine.

A series of high RF power, single-cell experiments have been performed in order to quantify the high gradient operation limitations of 3.0 and 5.7 GHz structures. Both frequencies lead to compact RF structures which still have practical dimensions for fabrication.

The experiments aimed at:

1. measuring the BDR at field levels in the operation range of hadron therapy linacs: above 170 MV/m of surface electric field for 3 GHz and 200 MV/m for 5.7 GHz.
2. determining the scaling laws that relate breakdown rate, pulse length, electric field and modified Poynting vector (which is used to quantify this effect as discussed in [7]) and compare the results with data available for 11.4–12.0 GHz and 30.0 GHz structures [7].

This paper presents the design choices for the cavity test prototypes [8], describes the test setups and discusses the BDR measurements with respect to the major electromagnetic quantities. In the last Sections the results are compared with high-gradient results of structures operating in different frequency bands.

2. Design and prototyping of test cavities

Hadrontherapy typically uses proton beams with energies between 70 and 230 MeV and carbon ion beams with energies between 120 and

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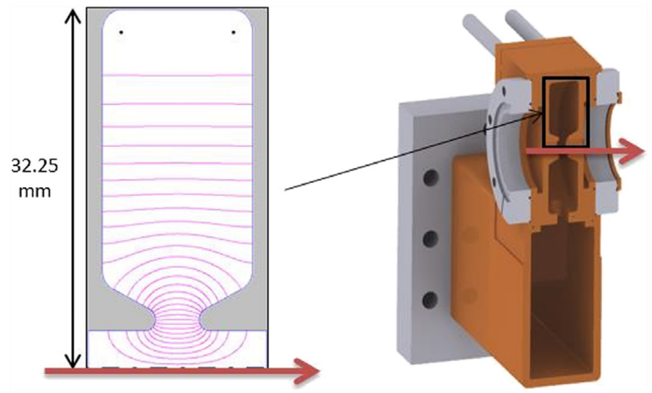

Fig. 1. Inner shape of the S-band (3 GHz) cell structure. The electric field lines are visible in the left figure obtained from simulations with the code Superfish.

430 MeV/u. This corresponds to a relativistic beta in the range 0.4–0.7. The most efficient and stable linac option for such range of energies is the so-called Cell Coupled Linac (CCL) structure in the form of a side coupled linac [9].

A CCL structure consists of a bi-periodic array of RF cells coupled together. Accelerating cells are placed on-axis and provide the longitudinal electric field needed for acceleration of the beam. Coupling cells are off-axis and are used to couple the electro-magnetic field between accelerating cells. A CCL structure works in the $\pi/2$ mode, which is the most stable mode with respect to frequency errors; on the other hand, the beam just sees a phase advance of 180° between the centers of two successive accelerating gaps. This feature allows optimizing the accelerating cells to maximize their shunt impedance and achieve higher acceleration efficiency than a Drift Tube Linac (DTL).

Two test prototypes, having similar layouts, have been designed and built to test their high gradient limitations: one operating at 3 GHz (S-band) and the other at 5.7 GHz (C-band).

A prototype consists of a single-cell cavity operating in the TM_{010} mode. The cavity is fed by a waveguide through a coupling slot opened on the rim of the cell. The main scope of the tests is to achieve the highest possible field inside the structure with the available RF power supplies. The simple layout of the test prototypes was chosen to satisfy this purpose.

The inner geometry of the single cell is the same as the one for the accelerating cells of one of the linacs designed by the TERA Foundation. The cell geometry was designed to maximize the shunt impedance. As the shunt impedance decreases with the bore hole aperture, the bore hole aperture was chosen taking as a reference proposed linac designs [2,3]. The cell geometry is shown schematically in Fig. 1. The length of the S-band test prototypes was chosen to be equivalent to a cell with a synchronous beta of 0.378 (or equivalently for proton at 75 MeV). The C-band test prototype had a similar length, but given the frequency ratio, the synchronous beta was 0.716 (or equivalently for fully stripped carbon ions at 405 MeV/u). The two protrusions close to the axis, called “nose cones” or just “noses”, have the purpose of enhancing the field along the axis and thus increasing the transit time factor. The presence of such noses is a specific feature of low and medium beta accelerating copper structures.

Both test prototypes are made of UNS (Unified Numbering System) C10100 Oxygen-Free Electronic (OFE) copper alloy. The cavities were produced by VECA (Italy). The surface arithmetical-mean roughness (Ra) requested for manufacturing was 0.4 μm. The machining tolerance band was 20 μm for the 3.0 GHz cavity and 10 μm for the 5.7 GHz cavity. The two cavities were cleaned (degreasing, pickling and passivation) at CERN (Switzerland) and vacuum brazed at Bodycote (France). The test cavities were equipped with cooling channels in order to dissipate the RF power and to stabilize the cavity temperature during operation.

Table 1
Main electromagnetic quantities for the S-band and C-band test structures.

Structure	S-band	C-band
RF frequency [GHz]	2.998	5.712
Cell length [mm]	18.9	18.8
Cell diameter [mm]	64.50	34.54
Bore hole radius [mm]	3.5	1.5
Quality factor	9140	8500
Shunt impedance [MΩ/m]	83.3	98.7
Transit time factor	0.893	0.905
Synchronous beta	0.378	0.716
E_{max}/E_0	6.5	4.6
H_{max}/E_0 [kA/MV]	2.96	3.10
sqrt($S_{\mathrm{c},max}$)/E_0 [sqrt (MW/mm^2)/(MV/m)]	0.032	0.025

The 3.0 GHz cavity was tuned by deforming the nose region from the outside on both sides of the bore hole with a bar clamp. By reducing the gap length, or distance between the noses, the resonant frequency of the cavity decreased. The tuning of the 5.7 GHz test cavity was performed in successive steps by reducing the height of the tuning rings of the cell. The design, fabrication and low power RF measurements of the test cavities are fully described in [10,11].

Fig. 2 shows the distribution of the electric, magnetic and modified Poynting vector fields in the cell volumes of the 3.0 and 5.7 GHz test cavities. The modified Poynting vector S_c, introduced in Ref. [7], is defined by the equation:

$$S_c = \mathrm{Re}\{S\} + g_c \cdot \mathrm{Im}\{S\} \qquad (1)$$

where $g_c = 1/6$ and S is the “classic” Poynting vector.

The peak value of electric, magnetic fields and modified Poynting vector – respectively, E_{max}, H_{max} and $S_{\mathrm{c},max}$, – are all located on the cell noses.

The quantities E_{max}/E_0, H_{max}/E_0 and $sqrt(S_{c,max})/E_0$ describing the ratio between the peak surface fields and the average axial electric field E_0, were computed with HFSS simulations. Their values are listed in Table 1, together with other relevant geometric and electro-magnetic quantities.

3. High power test setup

The 3 GHz prototype tests were conducted at the CERN CLIC Test Facility (CTF3). The test setup is shown in Fig. 3.

The S-band structure was connected, through a WR284 waveguide network, to a 35 MW peak-power klystron. A bi-directional coupler installed before the structure allowed measuring forward and reflected power signals. The beam line on one side of the cavity was connected to few diagnostics elements: a Faraday cup (to measure the field emitted current), and a photomultiplier (to detect light sparks during breakdown events). Breakdown detection was automatic, based on the detection of a peak in the reflected signals and of current bursts measured with the Faraday cup (see Section 4).

The 5.7 GHz cavity test was conducted at the test facility of A.D.A.M. SA at CERN. The cavity was fed by a 2.5 MW magnetron (Fig. 4). A 2.5 m-long WR187 waveguide network connected magnetron and cavity. The RF line included a circulator to revert the possible reflected power away from the magnetron. The cavity vacuum was isolated by a commercial RF window. Forward and reflected power signals were extracted from a directional coupler installed 0.5 m upstream of the cavity. A Faraday cup and a photomultiplier were used to identify breakdowns.

4. Measurements and results of the high-power tests

The two structures were conditioned for few days according to a specified procedure: the pulse length was increased step by step at low power level and then the power was ramped up to the maximum value.