NON-LINEAR PHENOMENA STUDIES IN HIGH-GRADIENT RF TECHNOLOGY FOR HADRONTHERAPY AT IFIC*

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Abstract

High-Gradient accelerating cavities are one of the main research lines in the development of compact linear colliders. However, the operation of such cavities is currently limited by non-linear effects that are intensified at high electric fields, such as dark currents and radiation emission or RF breakdowns. A new normal-conducting High Gradient S-band Backward Travelling Wave accelerating cavity for medical application (v=0.38c) designed and constructed at CERN is being tested at IFIC. In this paper, we present experimental measurements and simulation of such non-linear effects. The main goal of these studies is to establish the viability of using these techniques in linear accelerators, in order to improve our understanding in such effects. The main goal of these studies is to determine the viability of techniques in linear accelerators for hadrontherapy treatments in hospitals.

THE IFIC HIGH-POWER S-BAND FACILITY

The design of High-Gradient (HG) accelerating cavities is a key issue in the development of compact linear accelerators. The Compact Linear collaboration [1] developed accelerating cavities capable of reaching accelerating gradients of the order of 100 MV/m compared with the 20-30 MV/m achieved by traditional technology.

Continuous efforts are made to apply this technology for medical and industry applications. In particular, the use of the HG technology is being investigated to develop compact linear accelerators for hadrontherapy. Currently, circular accelerators are used for hadrontherapy due to their compactness. However, linear accelerators have the advantage of a fast energy modulation which could be of great interest for 3D dose painting and to treat moving organs.

Nevertheless, the intense electromagnetic fields in HG technology lead to undesirable non-linear effects, i.e., electrons emission from the cavity walls due to field emission, also called dark currents, and vacuum discharges, known as RF breakdowns. These effects, in addition lead to beam instabilities and high radioactive dose emission, preventing the cavities from reaching straightaway the designed gradient. Thus, an RF conditioning treatment is needed for this kind of structures in order to work at high gradients under an acceptable confidence level of performance. The breakdown rate (BDR), defined as the number of breakdowns per pulse and unit length increases as:

$$BDR \propto E_{acc}^{30} \cdot \tau^{5}, \tag{1}$$

where E_{acc} is the accelerating gradient and τ the pulse length.

At the Instituto de Fisica Corpuscular (IFIC) a High-Power S-Band (3 GHz) Radio-Frequency laboratory was built to condition and characterize HG cavities as well as to investigate the mechanism of vacuum arcs and RF breakdowns. This laboratory works at a central frequency of 2.9985 GHz. The laboratory at IFIC was designed to reach a peak power of 15 MW with pulses of 5 μs length and it is capable of performing the conditioning of two structures at 200 Hz simultaneously or one structure at 400 Hz.

THE BTW S-BAND CAVITY

A new design for a HG Backward Travelling Wave (BTW) cavity for low energy protons was developed and manufactured at CERN for the TUrning LInac for Protontherapy (TULIP) [2]. The main parameters of the cavity summarized in Table 1 and a picture of the cavity is shown in Fig. 1.

Table 1: BTW RF Accelerating Cavity Main Parameters

Parameter (unit)	**Value**
Frequency (GHz)	2.9985
Phase advance per cell (rad)	$5\pi/6$
Phase velocity	0.38c
Pulse width (μs)	2.5
Average accelerating gradient (MV/m)	50
Number of cells	12
Structure length (mm)	189.9
Quality factor (first/last cell)	6954/7415
Normalised shut impedance (MΩ/m)	51.5/54.6
Filling time (ns)	224
Group velocity (first/last cell) (%c)	0.39/0.21
Peak input power (MW)	20.6
Max S_c/E_a^2 (A/V)	3.1×10^{-4}
Max E_s (MV/m)	219

In Fig. 2 the Modified Poynting Vector of one coupling cell is shown [3]. It is maximum in the iris, due to the high surface electric field, and also in the upper coupling hole, because of the high magnetic field.

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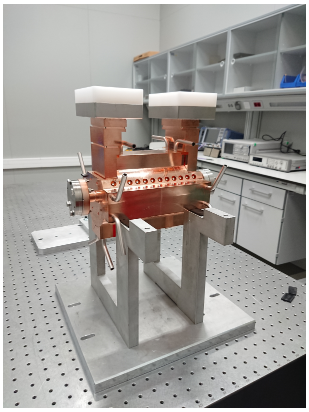

Figure 1: High-Gradient S-Band Backward Travelling Wave cavity.

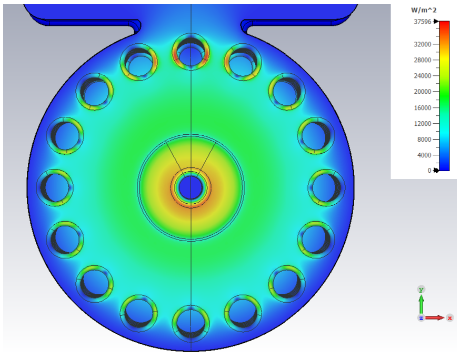

Figure 2: Modified Poynting vector profile in the outer RF coupling cell.

RF Conditioning

The HG BTW S-Band accelerating cavity was subjected to an RF conditioning process, which consists of slowly increasing the input power in the cavity, as shown in Fig. 3.

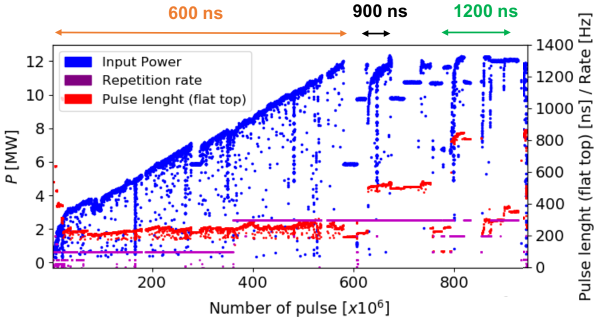

Figure 3: Conditioning process of the S-Band BTW accelerating cavity.

The maximum power reachable in the laboratory was 12 MW, which corresponds to an accelerating gradient of around 39 MV/m, which is already higher than normal accelerating structures.

The process was started with an RF pulse of 100 ns rise time, 200 ns flat top and 300 ns fall time with a repetition rate of 100 Hz. Later, the repetition rate was increased up to 300 Hz, making the the conditioning process 3 times faster, since the evolution increases linearly with the number of pulses. Once the maximum power was reached, the same process was followed for a longer pulse of 500 ns flat top. As can be seen in Fig. 3, region between 610-680×10^6 pulses was conditioned much faster. Finally, the structure was conditioned for a flat top of 800 ns, which was also faster than the previous case.

Besides, the dark currents and the radiation emitted from the cavity were measured using a Faraday cup and an ionization chamber, respectively. These measurements are shown in Fig. 4

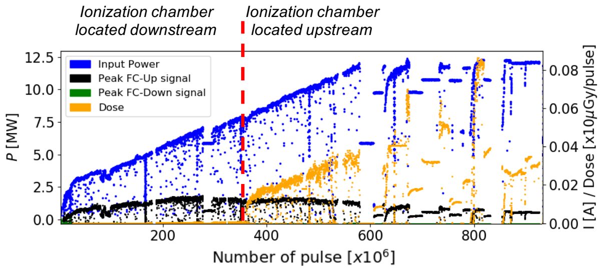

Figure 4: Dark currents and radiation dose evolution during conditioning.

Field emitted electrons are not able to reach Downstream Faraday Cup whereas they do arrive at the Upstream Faraday Cup. This observation is in agreement with CST [4] tracking simulations, which showed that due to the low phase velocity of the accelerating cavity, electrons travelling Downstream get higher energies but they are quickly deviated and collide with the inner walls of the cavity. However, electrons travelling Upstream get lower energy but they are able to reach larger distances before they collide, which explains this experimental difference between both measurements. In addition, The pulse of dark current collected by Upstream Faraday Cup saturates at a certain level in the conditioning. Nevertheless, the radiation dose level kept increasing during the whole process[1].

During the conditioning process, several scans of dark current as a function of power were made. This allowed us to perform Fowler-Nordheim plots [5] of these scans, where we could obtain the evolution of the beta enhancement factor, following the expression:

$$\frac{d\log_{10}(I/E_0^{2.5})}{d(1/E_0)} = -\frac{G\phi^{3/2}}{\beta}, \tag{2}$$

where $G = 2.84 \times 10^9$ V/m eV$^{3/2}$ is a constant, I is the dark current, E_0 is the electric field, ϕ is the work function of the material and β is the enhancement factor that relates the electric field with the value of electric field in the field emission spot.

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[1] In the beginning, the dosimeter was placed next to the Downstream Faraday Cup, but the location was changed due to the experimental measurements obtained.

Using the measured data and Eq. (2) the beta has been estimated at different points in the conditioning process corresponding to a given maximum electric field recheable by the cavity at this point. As can be seen in Fig. 5 a linear dependence is observed.

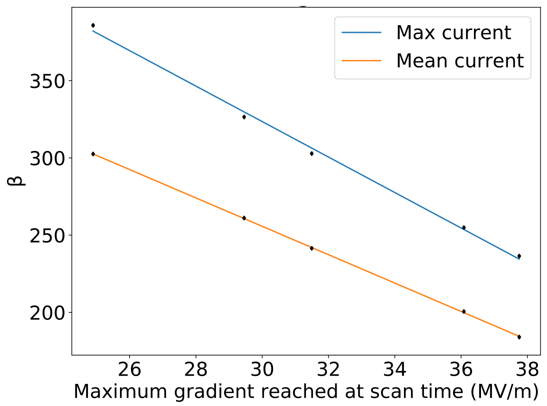

Figure 5: Beta enhancement factor evolution with the maximum electric field reached at that time in the conditioning process.

BDR and Radiation Studies

Once the maximum power was reached for the longest pulse, the breakdown rate was measured for different accelerating gradients. The results can be seen in Fig. 6.

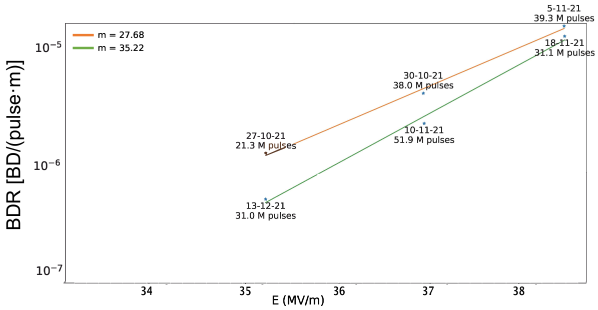

Figure 6: Breakdown rates studies.

A first measurement campaign was done just after finishing the conditioning process and a second one after some days of conditioning at the maximum power. BDR improved for the second, even though the values of BDR are still over the operation efficiency needed for medical applications (7.7×10^{-7} BD/(pulse·m)). In both cases, the slope of the fit to the data is in the order of magnitude of Eq. (1).

In order to characterize the radiation emitted from the cavity, several measurements were taken using a scintillating crystal of $CeBr_3$. As there is such a large amount of bremsstrahlung photons emitted during the RF pulse, measurements were taken with a fast data acquisition oscilloscope, since it allows us to filter the pile-up. The first measurements are shown in Fig. 7.

The first peak corresponds to Lead X-rays, used for the collimation system of the detector, and the second peak corresponds to a typical bremsstrahlung spectrum, with a cut-off energy of 600 keV for the 7 MW pulses and 750 keV for the 8 MW pulses, in agreement with the energies of the electrons colliding with the structure in CST simulation.

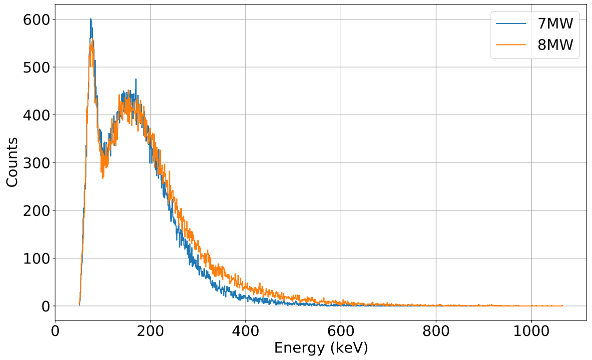

Figure 7: Photon spectrum emitted from the cavity at 7 MW and 8 MW.

CONCLUSION

An S-band BTW HG accelerating cavity designed for hadrontherapy has been tested at the IFIC High-Power laboratory up to 12 MW reaching an accelerating gradient of 39 MV/m.

First measurements and simulations of the non-linear electromagnetic phenomena in this cavity have been performed. The beta enhancement factor is found to have a linear behaviour with the maximum electric field at the conditioning point.

Furthermore, a good agreement is observed between measured and simulated dark current dynamics. First radiation measurements are also in agreement with expected kinetic energy of the dark current electrons inside the cavity.

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