HIGH GRADIENT ACCELERATING STRUCTURES FOR CARBON THERAPY LINAC*

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Abstract

Carbon therapy is the most promising among techniques for cancer treatment, as it has demonstrated significant improvements in clinical efficiency and reduced toxicity profiles in multiple types of cancer through much better localization of dose to the tumor volume. RadiaBeam Systems, in collaboration with Argonne National Laboratory, are developing a high-gradient linear accelerator, Advanced Compact Carbon Ion Linac (ACCIL), for the delivery of ion beams with end-energies up to 450 MeV/u for $^{12}C^{6+}$ ions and 250 MeV for protons. In this paper, we present a thorough comparison of standing and traveling wave designs for high gradient S-Band accelerating structures operating with ions at various velocities, relative to the speed of light, in the range 0.3-0.7. In this paper, we will compare these types of accelerating structures regarding RF, beam dynamics, and thermo-mechanical performance.

INTRODUCTION

ACCIL is designed for the full energy range from the ion source to 450 MeV/u for $^{12}C^{6+}$ and includes the following main sections: a radio-frequency quadrupole (RFQ) accelerator, a drift-tube linac (DTL), and a coupled-DTL sections operating at a sub-harmonic of the S-band frequency to accelerate carbon ions up to 45 MeV/m. For effective acceleration to higher energies, a high gradient S-band structure will be used. An overview of the linac is given in [1].

The compact footprint of ACCIL (8x45m) can be achieved if the accelerating structure capable of providing 50 MV/m for the particles with beta from 0.3 to 0.7 is developed. Such high accelerating gradients of the ACCIL linac will be feasible due to the operation at high frequency, 2856 MHz, at very low duty cycle <0.06% and very short <0.5 μs beam pulses. The known RF breakdown limit is much higher for high-frequency structures than for traditional low-β structures operating at lower frequencies.

There are several known criteria for RF breakdown limit that we have used for the EM design:

- Peak surface fields of 250 MV/m at 11-12 GHz, and ~160 MV/m for S-band have been demonstrated in RF guns and side-coupled linacs [2,3,4];
- Peak surface magnetic field that causes pulse heating, which can damage the structure if the peak temperature rise is higher than 50 ºC [5];
- There are also new theories of a unified criterion, such as a modified Poynting vector (<S>) [6] that may impact the gradients. However, there is not many experimental data for S-band structures;

In our design, we considered keeping all three parameters below known limits.

HIGH BETA STRUCTURE

Recently, A compact ultra-high gradient S-Band β=1 accelerating structure, operating in the π-mode at 2856 MHz, has been developed at RadiaBeam [7] (see Fig.1). The electromagnetic design and optimization of the cell shape to maximize RF efficiency and minimize surface fields at very high accelerating gradients included elliptical iris geometry to decrease surface electric field and "fat-lip" coupler to reduce surface RF pulsed heating. A 5-cell prototype HGS structure was fabricated with 4-6 μm surface finish, followed by SLAC prescription for cleaning and surface processing, and initially tested in 2013 at LLNL at 10Hz rep rate and max accelerating gradient of 50MV/m at 1.3 μs pulse duration [8].

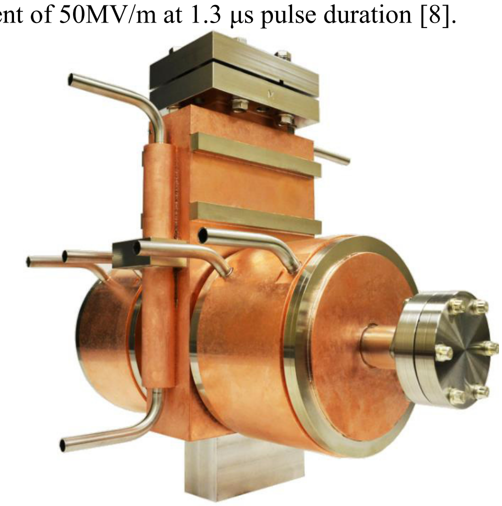

Figure 1: S-band 50 MV/m high-gradient structure (HGS) developed at RadiaBeam.

In February 2015, the structure was delivered to Argonne to perform high power tests and to check if the structure parameters deteriorated during the extended storage. Cavity conditioning was conducted with a 30 Hz pulse rep rate and varying pulse widths. With no bake, a

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max field level of ~40 MV/m was achieved at 10 MW power and 2 µs pulse length. However, severe outgassing prevented further progress. After three days bake, the static vacuum levels improved by one order of magnitude. Following this, a stable field of ~44 MV/m was achieved but again outgassing issues prevented progress. After another bake and about two weeks of RF conditioning peak field levels of 52 MV/m were obtained at 16.7 MW power and 2 µs pulse length and sustained for 24 hours. Further attempts to increase the peak fields in the cavity by increasing pulse width resulted in an internal failure of the cavity.

To determine the cause of the failure, the cavity surface was observed by a borescope. Multiple imperfections were observed ranging from pitting marks in the iris areas to arcing in the central waveguide feed area, possibly, due to pulse heating effect. No baseline observations with a borescope were made before the start of the test, so it is hard to determine how much of the observed damage was pre-existing and how much was induced by the testing at APS. However, from the amount of time and difficulty of reaching high gradients during the tests at APS, it appears that the cavity had some residual damage from previous testing efforts. From start to finish the test ran for about seven weeks.

MAGNETIC COUPLED STRUCTURE

The same approach of cavity design, however, can't be applied to the low-energy section. Although coupled cavity linac (CCL) types of accelerating structures demonstrate excellent performance when designed for particles with high β, its RF parameters degrade dramatically for structures with β<0.7.

To solve this problem, the coupling can be provided by magnetic field via coupling holes in the outer disc. This fact allows increasing inter-cell coupling, leaving the aperture radius reasonably small and thus not reducing the shunt impedance of the cell. As a reference design, we used a CERN 50 MV/m β=0.43 2856 MHz 5π/6 magnetically coupled structure (MCS) section that was designed for TULIP proton therapy accelerator [9].

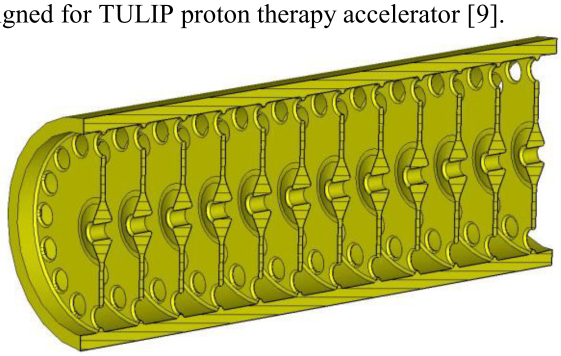

Figure 2: S-band MCS structure for particles with β=0.43.

Although this MCS design with noses, shown in Figure 2, can be adapted well for cells with β≥0.5, we found that for lower betas the peak fields exceed the known limits. To avoid this risk, we removed the noses for the low-beta design. Table 1 presents the comparison between high shunt impedance and low peak field options of the structure.

Table 1: RF Parameters of β=0.43 MCS Structure

Noses	Yes	No
Accelerating gradient, MV/m	50	50
Peak surface E-field, MV/m	200	86
Pulse heating (@1.5µs), K	18.7	19.1
Modified Poynting Vector, MW/mm^2	0.7	1.3
Shunt impedance, MΩ/m	51	36

The parameters of the accelerating sections with constant 50 MV/m gradient for different betas are presented in Table 2.

Table 2: Parameters of MCS Constant Gradient Accelerating Section with Different β

Phase velocity (β), %c	0.43	0.5	0.6	0.7
Section length, m	0.6	0.79	1.1	1.16
Shunt impedance, MΩ/m	35	56	57	58
Input/output group velocities, %c	0.5-0.05	0.6-0.08	0.7-0.04	0.7-0.04
Filling time, µs	1.0	1.0	1.6	1.72
Required power, MW	49	40	54	54

Thermal and structural analysis were done by using finite elements methods. We calculated the temperature rise, mechanical stress and deformations for the optimized structure assuming input pulse repetition rate of 120 Hz, and input pulsed power per period required to obtain 50 MV/m gradient. The simulation results are presented in Figure 3 and the values are within the reliable operating limits.

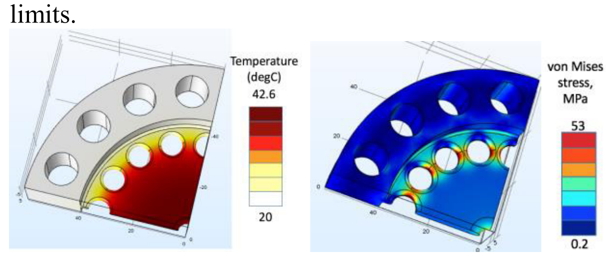

Figure 3: Temperature (left) and mechanical stress (right) maps of MCS β=0.43structure.

HIGHER SPATIAL HARMONIC STRUCTURE

Since for MCS structures with β=0.43, either the surface fields are too high (>200 MV/m), or the shunt impedance is too low (~35 MΩ/m), for smaller betas, the RF losses problem becomes much more important.

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To work around this issue, we propose to design the cavity where the beam will be synchronous with the higher spatial harmonic. Periodic structures have an infinite number of spatial harmonics (see Fig. 4). These harmonics have the same frequency but different spatial field distribution. An accelerating structure can be designed not for the fundamental harmonic m=0 but for the m=-1 harmonic which will make the accelerating period longer [10]. In structures with longer periods, it is possible to implement noses that will increase the shunt impedance without significant increase of the peak fields.

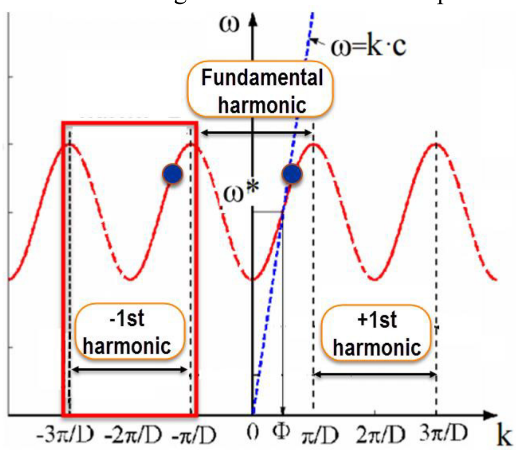

Figure 4: Typical dispersion curve of periodic waveguide structures.

We optimized the phase advance, nose geometry, and harmonic number for the β=0.3 to allow a reliable operation at 50 MV/m gradient. Table 3 compares the RF parameters of the structures operating at fundamental harmonic, and -1st harmonic with and without noses. Operation at higher harmonic allowed the increase of shunt the impedance by 45% compared to the fundamental harmonic without exceeding the limit of 160 MV/m peak field.

Table 3: Comparison of β=0.3 MCS Structures at Fundamental and -1st Harmonic at 50 MV/m Gradient

Harmonic number	**0**	**-1**	**-1**
Optimal mode	2π/3	5π/6	5π/6
Noses	No	No	Yes
Shunt impedance, MΩ/m	22.0	18.6	31.7
Peak surface E-field, MV/m	92.5	130	156.5
Pulse heating (@1.5μs), K	24	33	28

Beam dynamics PIC simulations done in CST Particles Studio confirmed the feasibility of operation at the higher harmonics. We noticed that the beam dynamics simulation did not show any focusing effect from the fundamental harmonic of the electromagnetic field. Although the focusing effect is not required, we believe it would be beneficial for the beam dynamics.

STANDING WAVE STRUCTURES

Standing wave (SW) structures could be alternative candidates for high-gradient accelerating structure. We have considered several types of SW accelerating structures: on-axis coupled biperiodic structure (BPS), side-coupled structure and disk-and-washer structure, but found that the BTW structure has better parameters for β=0.43 . The comparison of BPS and BTW structures is presented in Table 4.

Table 4: RF Parameters of 50 MV/m β=0.43 BPS and MCS Structures

Structure	MCS	**BPS**
Optimal mode	2π/3	π/2
Peak surface E-field, MV/m	86	112
Pulse heating (@0.5μs flat), K	19.1	31.4
Modified Poynting Vector, MW/mm^2	1.3	1.35
Shunt impedance, MΩ/m	36	32
Filling time, μs	1.0	1.5

CONCLUSIONS

We have investigated several candidates for medium beta (0.3-0.7) accelerating structures for the ACCIL carbon therapy linac including TW and SW structures. The structures were optimized to comply with the 50 MV/m accelerating gradient. There are two known critical parameters for the breakdown development: peak surface electric field (should be <160 MV/m for reliable operation), and pulse heating due to peak surface magnetic field (should be < 50 ºC). Also, there is one novel criterion, the modified Poynting vector that can potentially be used instead of these two. For structures with β≥0.5, the MCS structure with the design adopted from [7] can be employed. For lower-β, the structure with flat irises is required. Such modification increases heat losses significantly. To improve shunt impedance for the low-β structure, we designed the structure that operates at negative first harmonic and were able to increase the shunt impedance by 44% for a β=0.3 structure. 3D beam dynamics simulations confirmed the feasibility of operation at higher harmonics. We plan to perform an engineering design and build a structure prototype soon.

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REFERENCES

[1] A. Plastun *et al.*, “Beam Dynamics Studies for Compact Carbon Ion Linac for Therapy”, LINAC16,

East Lansing, MI, September 2016, paper THPLR042, this conference.
[2] V.A. Dolgashev *et al.*, “Geometric dependence of radio-frequency breakdown in normal conducting accelerating structures”, *Appl. Phys. Lett.* 97, 171501 (2010).
[3] C.J. Karzmark *et. al*, “Medical Electron Accelerators”, McGraw-Hill Inc., 1993.
[4] J.B. Rosenzweig *et al.*, “Next Generation High Brightness Electron Beams from Ultra-High Field Cryogenic Radiofrequency Photocathode Sources”, Proceedings of ICHEP 2016, Chicago.
[5] V.A. Dolgashev, “High Magnetic Fields in Couplers of X-band Accelerating Structures”. Paper presented at the Particle Accelerator Conference PAC 03, 2003
[6] A. Grudiev *et al.*, “New local field quantity describing the high gradient limit of accelerating structures”, *Phys. Rev. ST-AB* 12, 102001 (2009).
[7] L. Faillace *et al.*, “Fabrication and Initial Tests of an Ultra-High Gradient Compact S-Band (HGS) Accelerating Structure”, Proceedings of IPAC2012, New Orleans, Louisiana, USA, p. 3392.
[8] L. Faillace *et al.*, “High-Power Tests of an Ultra-High Gradient Compact S- Band (HGS) Accelerating Structure”, Proceedings of IPAC13, Dresden, Germany.
[9] S. Benedetti *et al.*, “RF Design of a Novel S-band Backward Travelling Wave Linac for Proton Therapy”, Proceedings of LINAC2014, Geneva, Switzerland p. 992.
[10] D. Tronc, “Traveling wave acceleration of protons”, *Nuclear Instruments and Methods in Physics Research A,* 327 (1993) 253-255.