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HIGH-GRADIENT ACCELERATING STRUCTURE FOR HADRON THERAPY LINAC, OPERATING AT kHz REPETITION RATES*

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Abstract

Argonne National Laboratory and RadiaBeam have designed the Advanced Compact Carbon Ion Linac (ACCIL) for the acceleration of carbon an proton beams up to the energies of 450 MeV/u, required for image-guided hadron therapy. Recently, this project has been enhanced with the capability of fast tumour tracking and treatment through the 4D spot scanning technique. Such solution offers a promising approach to simultaneously reduce the cost and improve the quality of the treatment. In this paper, we report the design of an accelerating structure, capable of operating up to 1000 pulses per second. The linac utilizes an RF pulse compressor for use with commercially available klystrons, which will dramatically reduce the price of the system..

INTRODUCTION

Radiation therapy with X-ray, electron and hadron beams, is used to treat over 60% of cancer patients. Compared to X-ray therapy, which is currently the standard treatment method, hadron therapy offers significant advantages, such as a sharp Bragg peak and the capability to treat "radioresistant" tumours [1]. Unless the position of the tumour and treated organs are accurately known both before and during the treatment, and the therapy system can track the motion of the patient's organs, the small beam spot benefit of ion therapy may not be realized. However, by combining ion beam therapy with real-time image guidance and fast transverse and longitudinal (i.e. beam energy variation) scanning is potential game changer in the future of cancer radiation therapy [2].

Argonne National Laboratory, in collaboration with RadiaBeam Technologies has been working on the development of the Advanced Compact Carbon Ion Linac (ACCIL), an ultra-high gradient linear accelerator for cancer therapy capable of delivering the full energy range from ion source to 450 MeV/u for $^{12}C^{6+}$ and protons [3]. The latter can also be used for imaging. However, it's design must be adjusted for the pulse repetition and the beam energy variation rates up to a thousand per second (~1000 Hz). Such flexibility in beam tuning will enable the fast and efficient beam scanning and 3D dose painting, as well as real-time image-guided range calculation and targeting of moving targets, while reducing the treatment time to several minutes [4].

One of the key technical challenges of the ACCIL system is the need for a high gradient accelerating structure to limit the footprint to ~45 m and improve the overall efficiency of the linac [5]. In ACCIL the high-gradient section starts from the energy of 45 MeV/u (β=0.3), allowing to replace ~3 meters of low-frequency DTLs with a 30 cm long S-band structure, operating at 50 MV/m gradient. In order to achieve such high gradients at so low velocity, the beam is accelerated by the negative -1st harmonic. Such negative harmonic accelerating structure (NHS), consisting of 15 magnetically coupled cells [6], was build and tested at ANL. The structure was conditioned up to 33-MW peak power, corresponding to 50 MV/m gradient with RF breakdown rate of 1 per 1000 pulses [7].

In this paper we will discuss the improvements made to thus structure design to enable its operation at 1 kHz repetition rates. The second challenge to be addressed is the requirement for the RF power system. With the current prototype, up to 33 MW of RF power is required for each accelerating section. At 1 kHz repetition rate, this would require the development of a custom klystron and modulator system. Instead, we have designed the accelerating structure for operation with standard medical klystrons (~ 5-MW, up to 1% duty cycle) that are available at reasonable costs. Such breakthrough improvement was enabled by relaxing the peak gradient from 50 MV/m to 40 MV/m reducing a peak power requirement to 20 MW. Thanks to short 300 ns beam pulses such peak power can be achieved by utilizing an RF pulse compressor (SLED) [8].

RF DESIGN

The goals of the upgraded negative harmonic structure (NHS) design are to reduce peak power requirements from 34 MW to 20 MW and reduced the filling time to 300 ns to be used with SLED. This was achieved by reducing the accelerating gradient to 40 MV/m, improving the shunt impedance (R_{sh}), and adjusting the group velocity of the structure.

In order to improve its shunt impedance, we modified the cell design of the previous NHS [9]. We reduced the gap between the noses, adjusted the nose shape, and increased the blending radius of the outer wall (Fig. 1). These modifications allowed to increase the shunt impedance from 32 MΩ/m up to 47 MΩ/m while maintaining the peak fields below 180 MV/m at 40 MV/m. The number of coupling holes was reduced from eight to five, and the

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thickness of the iris (t_i) was increased from 3.0 to 3.9 mm, which has improved the thermal conductance, and allowed to keep the temperature raise within 26°C and mechanical von Mises stress of 69 MPa, below the copper yield, as shown in Fig. 1.

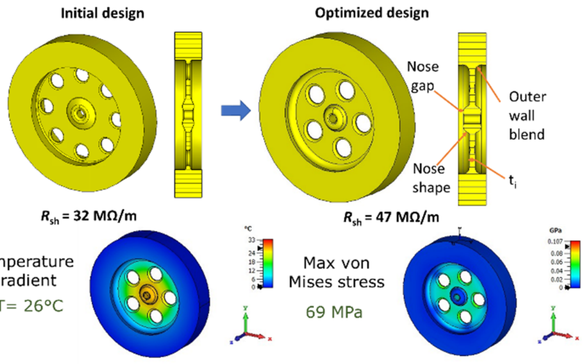

Figure 1: Initial and optimized cell design of the NHS (top). Thermal and stress maps for the optimized cell (bottom).

The modulation of the group velocity in 15-cell section in the range of 0.43%c-0.232%c resulted in 287 ns filling time. The input and output couplers were matched by adjusting coupler cell diameter and coupling slot width individually for both couplers. This corresponds two criteria: high field flatness inside the structure, which we aimed to be < 2%, and low reflection from input port 1 at operation frequency <-30 dB.

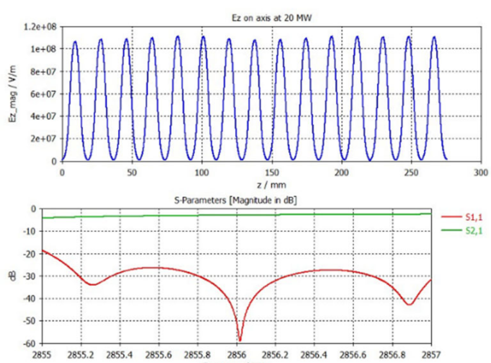

Figure 2. E-field profile along the axis (top) and S-parameters (bottom) for the new 15-cell NHS.

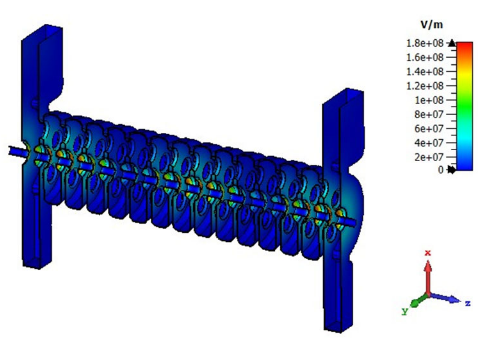

Figure 3. Surface electric field of the improved 15-cell NHS at 2856 MHz and 20 MW input power.

Figure 2 shows the electric field magnitude along the axis and the S-parameters of the tuned structure for 20 MW of input power. The simulated field flatness is 1.37% and S11=-50.45 dB. The cumulative phase advance error is 1.69°. The tuned 15-cells model is shown in Fig. 3. According to electromagnetic simulations of the full-length model, the required peak RF power to achieve 40 MV/m gradient, is 20-MW. Table 1 compares of the RF parameters for the original NHS, designed for 120 Hz repetition rate and the upgraded structure for 1000 Hz rate. The pulse heating and modified pointing vector were also improved in the new design.

Table 1: RF parameters for the Initial and New NHS

Structure	Initial	New
Repetition rate, Hz	120	1000
Group velocity, %c	0.12-0.33	0.23-0.43
Filling time, ns	450	287
Shunt impedance, MΩ/m	32	47
Gradient, MV/m	50	40
Input RF power, MW	33.8	20
Average RF losses, kW	3.9	5.6
Peak E-field, MV/m	160	180
Pulse heating, K	28	12.2
<Sc>, MW/mm^2	1.3	1.1

ENGINEERING DESIGN

The engineering design of the new NHS structure is shown in Fig. 4. It includes the accelerating section, input and output couplers, RF flange ports, transition to standard WR-284 RF flanges, cooling channels, and tunning pockets in each cell.

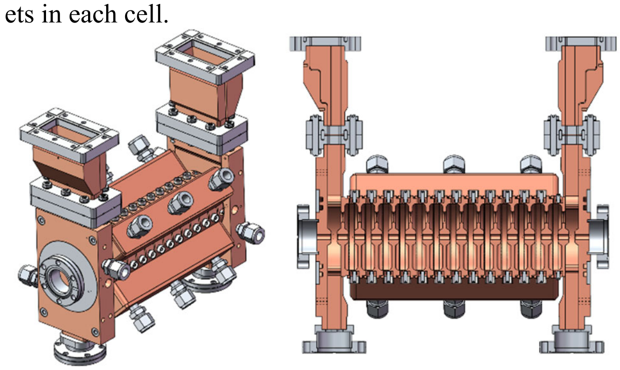

Figure 4. Engineering design of the new NHS.

We performed thermal analysis of the structure, which included fluid dynamics, considering forced water cooling with a flow rate at each inlet of 0.12 l/s at 30°C and natural convection of the outside surface of 2 W/(m^2.K). The steady-state temperature field is shown in Fig. 5, which was further applied as an initial condition for transient thermal analysis. We simulated 10 thermal pulse load cycles were input as thermal load (Fig. 6), showing the maximum temperature at end of a power cycle (location 1) and the maximum temperature at the end of a heat pulse (location

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2), which are in agreement with preliminary estimations, and are within the range of operational values.

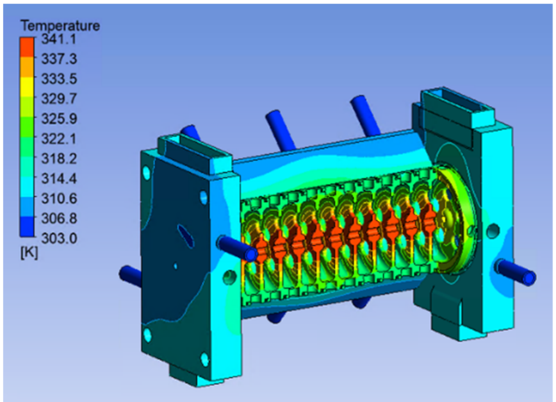

Figure 5. Steady state temperature field of the NHS with 0.117 kg/s water flow rate at 30°C.

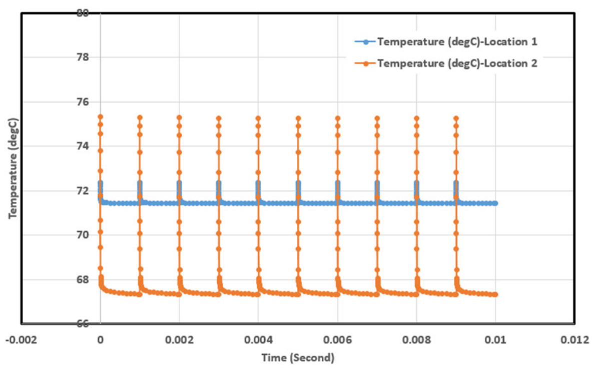

Figure 6. Results of the transient thermal analysis.

RF PULSE COMPRESSOR

We have designed a compact 2856 MHz RF pulse compressor of a SLED type based on a E-plane polarizer and a TE_{112} spherical cavity [10,11]. To facilitate vacuum pumping of the SLED we added a cut-off circular port opposite to the circular waveguide. The whole device without vacuum pump will fit in a box with size 60x40x40cm. The E-field and S-parameters of the device are shown in Fig. 6. We have used the parameters of the SLED in a circuit model to simulate its performance. The SLED will produce a flat 18 MW 600 ns RF pulse from a 7 µs 5 MW klystron pulse, with 62% efficiency for pulse.

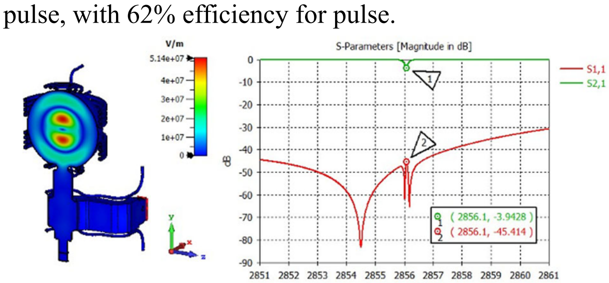

Figure 6. The electric field inside the SLED at 2856 MHz normalized to 5 MW input power (left) and its S-parameters (right).

The engineering design of the SLED incorporates cooling channels distributed on the cavity and the polarizer. We performed a thermo-mechanical steady state analysis considering an average water flow rate of ~0.53 l/s at 30°C in ANSYS. The results shown in Fig. 7 indicate a 20°C temperature raise, and 0.1 mm maximum deformation which will cause a <1 MHz frequency shift which is manageable. The SLED is currently being fabricated.

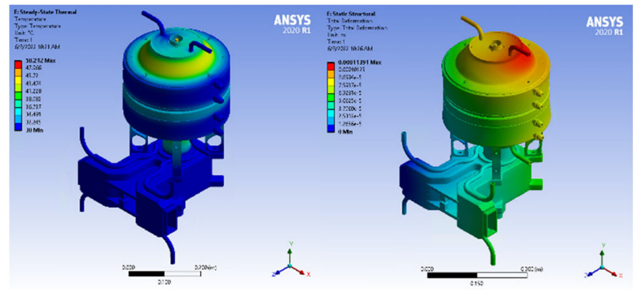

Figure 7. Thermo-mechanical analysis on the SLED.

SUMMARY

We improved the design of the S-band, β=0.3, negative harmonic accelerating structure for operation at repetition rates as high as 1 kHz at 20 MW RF power The design reduces treatment time and is compatible with guided therapy methods. Engineering design of an accelerating module which includes the accelerating structure and SLED RF pulse compressor has been completed. The module will be fed by 5 MW klystron, enabling its practical application.

REFERENCES

[1] A.M. Allen *et al.*, "An evidence based review of proton beam therapy: The report of ASTRO's emerging technology committee", Radiotherapy and Oncology, 103, pp. 8-11 (2012). doi:10.1016/j.radonc.2012.02.001

[2] B.M. Oborn *et al.*, "Future of medical physics: Real-time MRI-guided proton therapy", *Med. Phys.* 44 (8), 77 (2017). doi:10.1002/mp.12371

[3] P. Ostroumov *et al.*, "Compact Carbon Ion Linac", in *Proc-NAPAC'16*, Chicago, IL, 2016. doi:10.18429/JACoW-NAPAC2016-MOA4CO04

[4] B. Mustapha *et al.*, "Prospects for an advanced heavy ion therapy center in the Chicago area", in *Proc. 25th International Conference on the Application of Accelerators in Research and Industry,* 2160, 050009 (2019)*,* Grapevine, Texas, USA, Aug 2018. doi:0.1063/1.5127701

[5] A. Plastun *et al.*, "Beam Dynamics Studies for a Compact Carbon Ion Linac for Therapy" in *Proc. 28th Linear Accelerator Conference (LINAC'16),* East Lansing (USA), 2016. doi:10.18429/JACoW-LINAC2016-THPLR042

[6] S. Kutsaev *et al.*, "High-gradient low-β accelerating structure using the first negative spatial harmonic of the fundamental mode", *Phys. Rev. Accel. Beams* 20, 120401, 2017. doi:10.1103/PhysRevAccelBeams.20.120401

[7] S. V. Kutsaev *et al.*, "Test Results of a High-Gradient 2.856-GHz Negative Harmonic Accelerating Waveguide," in *IEEE Microwave and Wireless Components Letters*, vol. 31, no. 9, pp. 1098-1101, 2021. doi: 10.1109/LMWC.2021.3081358

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-MOPOPA22

[8] M. Franzi *et al*., “Compact rf polarizer and its application to pulse compression systems”, *Phys Rev Accel Beams*19(6): 062002, 2016. doi: 10.1103/PhysRevAccelBeams.19.062002

[9] S.V Kutsaev *et al*., “Design of the High Gradient Negative Harmonic Structure for Compact Ion Therapy Linac” in *Proc. 29th Linear Accelerator Conference (LINAC'18)*, Beijing, China, 2018. doi: 10.18429/JACoW-LINAC2018-MOPO077

[10] J.W. Wang et al., “Development for a super compact X -band pulse compression system and its application at SLAC,” *Phys. Rev. Accel. Beams* 20, 1104016 2017. doi: 10.1103/PhysRevAccelBeams.20.110401

[11] P. Craievich et al., “Novel X-band transverse deflection structure with variable polarization”, *Phys. Rev. Accel. Beams* 23, 112001, 2020. doi: 10.1103/PhysRevAccelBeams.23.112001