ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MOPO077

# DESIGN OF THE HIGH GRADIENT NEGATIVE HARMONIC STRUCTURE FOR COMPACT ION THERAPY LINAC*

S.V. Kutsaev[1], R. Agustsson[1], A. Barcikowski[2], R. Fischer[2],
B. Mustapha[2], A.Yu. Smirnov[1], A. Verma[1],
[1]RadiaBeam Systems, LLC, Santa Monica, CA, 90404, USA
[2]Argonne National Laboratory, Lemont, IL, 60439, USA

*Abstract*

A novel concept for an Advanced Compact Carbon Ion Linac (ACCIL) that will deliver up to 1 pnA of carbon ions with variable energy from 45 MeV/u to 450 MeV/u in a 45m footprint, has been developed by Argonne National Laboratory (ANL) in collaboration with RadiaBeam. The ACCIL will have a 35 MV/m real-estate accelerating gradients that became possible to achieve with the development of novel S-band high-gradient structures, capable of providing 50 MV/m accelerating gradients for particles with β>0.3. In particular, a β=0.3 structure based on the novel approach of operation at the first negative spatial harmonic with the increased distance between the accelerating gaps will be presented. This is the first attempt to reach such high gradients at such small velocities. RadiaBeam and ANL have demonstrated the feasibility of building this structure for accelerating carbon ions by means of advanced computer simulations and are currently working towards the fabrication of this structure for high power tests.

## INTRODUCTION

A usable device for cancer therapy needs to produce up to 200-250 MeV protons or/and up to 400-450 MeV/u carbon ions [1]. Both cyclotrons and synchrotrons that are currently used for these purposes are expensive and bulky constructions with large magnets and have significant limitations with rapid and efficient energy adjustment [2].

Within hadron therapy, proton therapy is the most common [3], although studies indicate that carbon ion therapy offers additional advantages [4], and combined proton and carbon therapy could achieve the most precise dose confinement to the tumor volume [5], while sparing healthy tissues.

Argonne National Laboratory and RadiaBeam are seriously considering the development of an ultra-high gradient linear accelerator, named ACCIL, for the full energy range from ion source to 450 MeV/u for $^{12}C^{6+}$ and 250 MeV for protons [6], which includes the following main sections: a radiofrequency quadrupole (RFQ) accelerator operating at a sub-harmonic of the S-band frequency, a conventional DTL section followed by a CCDTL section up to 45 MeV/u, and a high-energy section made of high-gradient structures for the energy range from ~45 MeV/u to ~450 MeV/u.

The compact footprint of ACCIL (8x45m) can be achieved by the development of accelerating structures capable of providing 50 MV/m for the particles with beta from 0.3 to 0.7. Such a high accelerating gradient for the ACCIL linac is possible due to the operation at high frequency, 2856 MHz, at very low duty cycle <0.06% and very short <0.5 μs beam pulses.

There are several ongoing projects worldwide [7,8] pursuing the development of S-band high gradient structures. Among the proposed structures only TULIP's backward-traveling wave structure (BTW) provides parameters close to ACCIL requirement. However, the direct scaling of BTW cells design from β=0.38 to β=0.3 beam velocities lead to unacceptably high peak fields (>220 MV/m) or dramatically lower power efficiencies.

* This work was supported by the U.S. Department of Energy, Office of High Energy Physics, under Accelerator Stewardship Grant, Proposal No. 0000219678 and STTR grant DE-SC0015717

## ACCELERATING STRUCURE

To work around this issue, we have designed a cavity where the beam is synchronous with the higher spatial harmonic (NHS) [9]. The structure was designed to operate at the -1st harmonic, capable of producing 50 MV/m gradient at peak field levels of <160 MV/m with 50% higher shunt impedance than the β=0.3 structure scaled from TULIP's fundamental harmonic BTW. However, the NHS design had mechanical stresses of ~60 MPa as shown in Fig.1, left, which is slightly above the yield stress of the annealed copper.

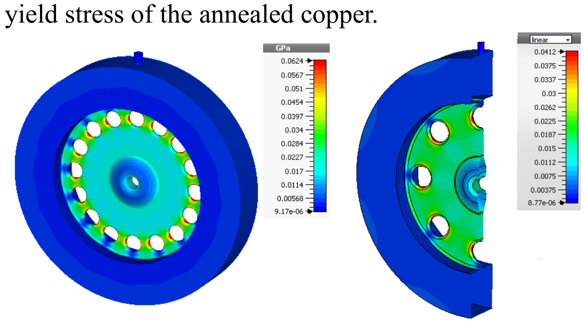

Figure 1: Mechanical stress maps in NHS with 16 (left) and 8 (right) coupling holes.

To reduce peak stresses, we investigated several approaches. Since the location of these stresses is the coupling hole, the strategy to reduce them is by reinforcing the iris part between the holes. The first obvious approach was to reduce the number of coupling holes, and thus increase the distance between them. The simulation results, shown in Fig.1, right, demonstrate that lesser number of holes makes the structure more rigid and improves thermal conductance at the cost of the group velocity, which can be compensated by increasing the hole diameter. The optimal number of holes is eight since

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MOPO077

the four-holes option has a much higher (~40%) Poynting vector value while the stresses are only 10% lower.

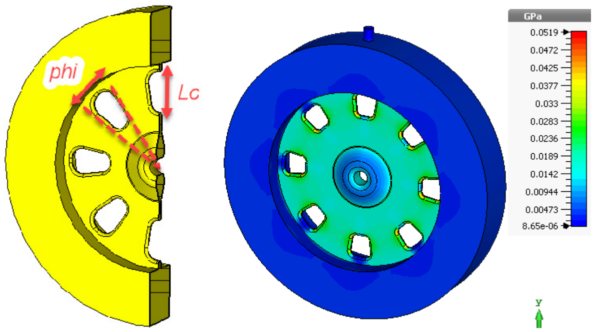


Figure 2: The cell with sector-shaped geometry (left) and the stress distribution map (right).

Since the stresses are still located in the coupling holes, we have attempted to apply a sector-shaped geometry to make holes' edges parallel and reduce peak stresses, as shown in Fig.2. In this case, the cell's group velocity doesn't depend on the hole length but only on the opening angle. However, this approach hasn't solved the problem, since stresses are still on the hole roundings and their peak values remain the same. We have also tried to reduce blending radius of the holes, but this has increased the stresses.

The other way to reinforce the iris is to increase its thickness. Thicker irises have higher thermal conductivity, and thus lower thermal gradient can develop, which results in lower stresses. However, since the EM field are concentrated in a smaller volume (around the beam axis), the modified Poynting vector becomes larger, which increases the risks of voltage breakdown. The simulation results suggest that increasing the iris thickness by 0.5mm is an acceptable solution leading to the reduction of the stresses by ~20%.

Another option is to increase the cell blend radius to improve the thermal conductivity further. However, in this case, the thermal conductivity is only increased outside the coupling holes, while the thermal gradient across the cell is even higher. Also, the Poynting vector becomes dramatically higher, which makes the idea of increasing the blending radius risky and unreasonable.

Table 1: Optimized NHS Parameters for Different Group Velocities

| **Group velocity, %c** | **0.45** | **0.30** | **0.15** |
|---|---|---|---|
| Peak E-field, MV/m | 155.2 | 155.5 | 155.6 |
| Pulsed heating, K | 24.7 | 21.5 | 17.54 |
| Shunt impedance, MΩ/m | 32.3 | 33.1 | 34.2 |
| Mod. Poynt. vect., MW/mm$^2$ | 1.68 | 1.39 | 1.02 |
| Temperature gradient, K | 11.9 | 10.7 | 9.5 |
| Mechanical stresses, MPa | 37.0 | 32.8 | 29.0 |

Finally, by implementing 8 round holes, 3 mm thick iris, and 1 mm blending radius we were able to reduce the peak stresses by almost a factor of two: from 62.4 MPa to 33.8 MPa (as simulated in CST Studio for the individual cells) for the cell with 0.33%c group velocity, which is a great result in conjunction with 5MW peak power reduction, achieved by the increase of filling time from 350 ns to 500 ns due to the smaller group veloicty. We have also checked that the parameters stay within the required limits within the broad range of group velocities as shown in Table 1.

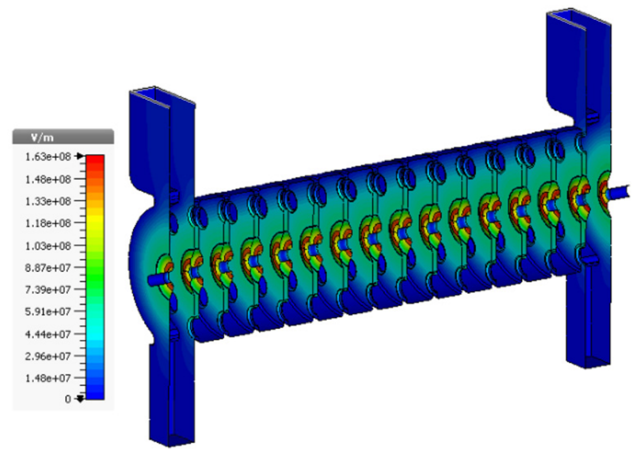


Figure 3: Surface electric field distribution in full 15-cells NHS section.

The input and output couplers were tuned by adjusting coupler cell diameter and coupling window width individually for both couplers so that there are no reflections from the couplers, which yields to two criteria: high field flatness inside the structure, which should be <2%, and low reflection from input port 1 at operation frequency <-30 dB. The actual achieved field flatness is 1.36% and $S_{11}$=-31.5 dB. From figure 3 it is possible to calculate VSWR=1.069, which refers to the internal reflection coefficient of -29.5 dB. The phase advance spread is less than 0.6° while the cumulative phase advance error is 0.25°. The tuned 15-cells model is shown in Fig. 3.

## ENGINEERING DESIGN

We have performed static thermal, fluid dynamic and structural analysis in ANSYS Multiphysics. The designed cooling blocks geometry is shown in Fig.4. These blocks have a flat bottom and are easier to machine. CFD Conjugate Heat Transfer simulations with flow velocity ~ 1.5 m/s demonstrate the average heat transfer coefficient of 8300 W/m$^2$-C and maximum temperature of the whole structure 18.2 C above the ambient level as shown in Fig.5, with cooling water temperature increase of only ~0.5 C. Ansys Mechanical Transient Heat Transfer analysis for one cycle at 1.0 ms heating time was also performed and demonstrated peak heating of 19.8 C, similar to analytical calculations.

Loading for the structural analysis consisted of vacuum, physical constraints, and temperatures from the thermal analyses. All material data used in the structural analysis was taken in the annealed state. This included Young's modulus, yield strength, the stress-strain curve used for

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MOPO077



the BISO material model, and the low and high cycle fatigue data taken from [10, 11]. The physical constraints were chosen to approximate a stress-free state. The heat load consisted of the temperature distribution from the steady-state analysis, with temperatures from the transient analysis superimposed on the whole structure. Two load cases consisting of the temperature at the end of the last pulse, and the temperature at the end of the last cycle were run to determine the mean and alternating stresses.

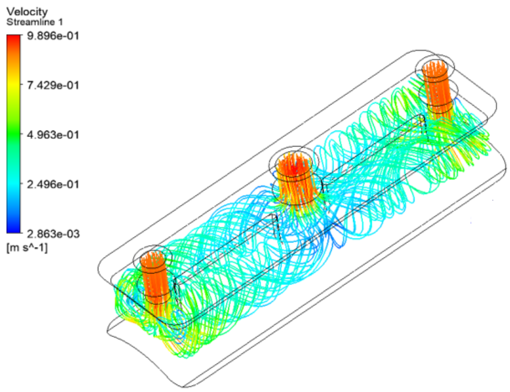


Figure 4: Water flow in the structure cooling blocks.

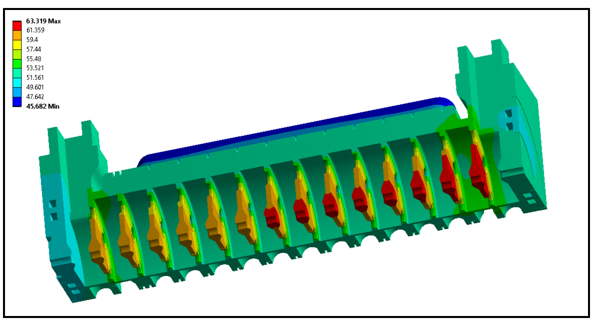

Figure 5: Stationary temperature distribution in the 15-cell NHS section.

At 70°C, copper yield occurs at about 52 MPa. The calculated von Mises stress at end of RF pulse during the stationary regime is 46.4 MPa. Therefore, no yielding or plastic strain is expected.

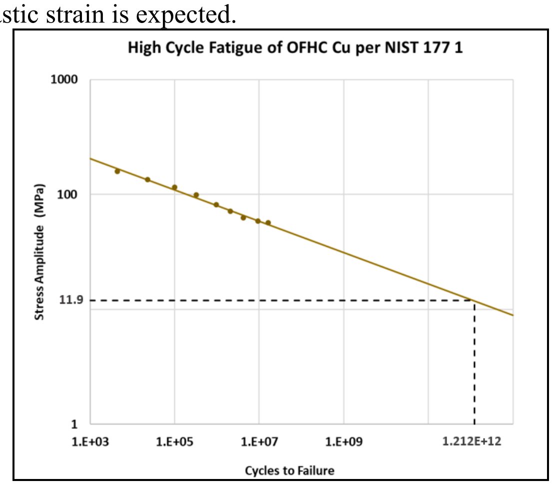


Figure 6: High Cycle Fatigue of copper calculated with different models. The actual amplitude is 11.9 MPa.

Fatigue does not appear to be an issue. The calculated maximum fatigue stress is 11.9 MPa. Fig. 6 shows the total strain range and stress amplitude are well below the allowable values. The low cycle fatigue data is taken at 56.7°C, so using that data is conservative. The high cycle fatigue was generated at room temperature. Estimated maximum cycle count of the structure is about $10^7$ cycles, and the projected life is ~$10^{12}$ cycles, which corresponds to 320 years of operation.

## SUMMARY

The proposed acceleration with higher spatial harmonics has enabled the development of a novel high-gradient accelerating structure design for protons and carbon ions with low β. The prototype structure being developed will become the enabling technology for compact hadron therapy linacs. We have performed electromagnetic optimization of 50 MV/m β=0.3 NHS cell to achieve mechanical stresses below the annealed yield stresses of 52 MPa. The design of a robust cooling system and the careful structural analysis helped to ensure the stable operation at high gradients in long-term applications. The NHS section is currently being built and is planned to be tested in 2019.

## REFERENCES

[1] K. Yamanouchi *et al.*, “Progress in Ultrafast Intense Laser Science XII”, Springer International Publishing (Switzerland), 2015.

[2] K. Peach *et al.*, “Accelerator science in medical physics”, Br J Radiol. 2011 Dec; 84(Spec Iss 1): S004–S010.

[3] Hadron Therapy Patient Statistics: Particle Therapy Co-Operative Group, 2013.

[4] U. Amaldi and G. Kraft, "Radiotherapy with beams of carbon ions" in Rep. Progr. Physics 68, 2005.

[5] A.J. Lomax, “Charged particle therapy: the physics of interaction”, Cancer J. 2009, 15(4):285-91.

[6] P. Ostroumov *et al.*, “Compact Carbon Ion Linac”, NAPAC’16, Chicago, IL, 2016, MOA4CO04.

[7] S. Benedetti *et al.*, “High gradient linac for proton therapy”, Phys. Rev. Accel. Beams 20, 040101 (2017).

[8] U. Amaldi et al., “LIBO a linac-booster for proton therapy: construction and test of a prototype”, NIM A, 521:512–529, 2004.

[9] S.V. 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).

[10] J. Esposito, R. Zabora, “Thrust Chamber Life Prediction”, Volume I, Mechanical and Physical Properties of High Performance Rocket Nozzle Materials, NASA CR 124806, Boeing Aerospace Co, Seattle WA, March 1975.

[11] J.E. Jensen *et al.*, “Selected Cryogenic Data Notebook”, Volume I, BNL 10200-R, Brookhaven National Laboratory, Upton NY, August, 1980.