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

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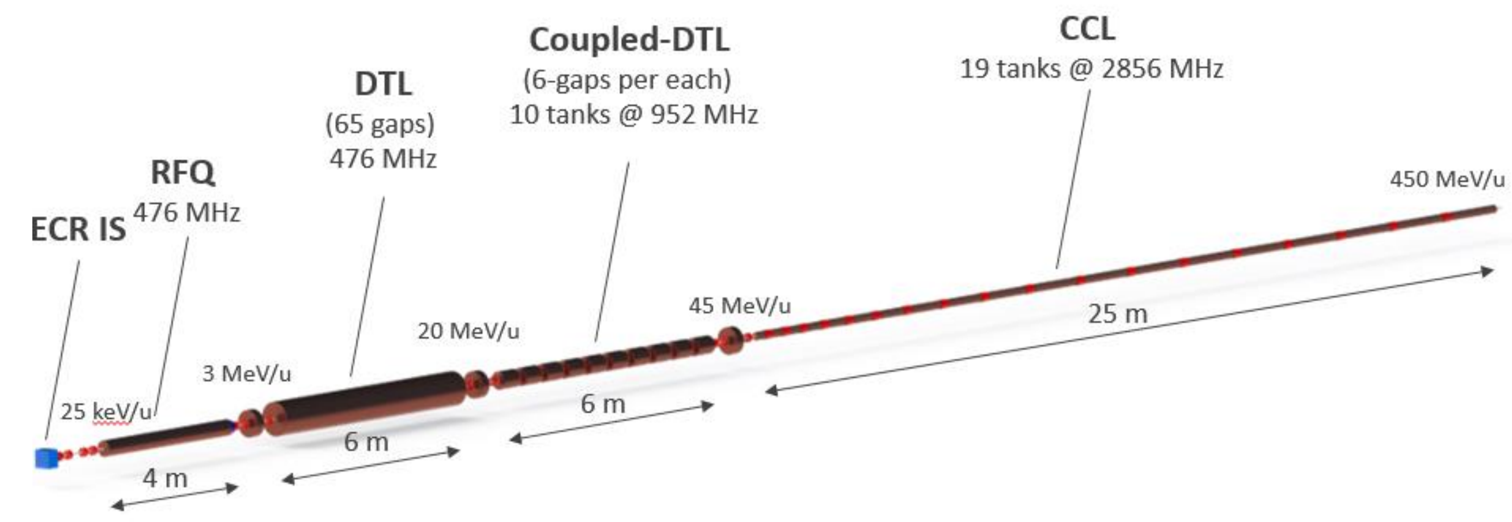
ABSTRACT:
A novel concept for an Advanced Compact Carbon Ion Linac (ACCIL) that will deliver up to 1 pnA of carbon ions with variable energy from 45 MeV/u to 450 MeV/u in a 45m footprint, has been developed by Argonne National Laboratory (ANL) in collaboration with RadiaBeam. The ACCIL will have a 35 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..

ACCIL: Advanced Compact Carbon Ion Linac



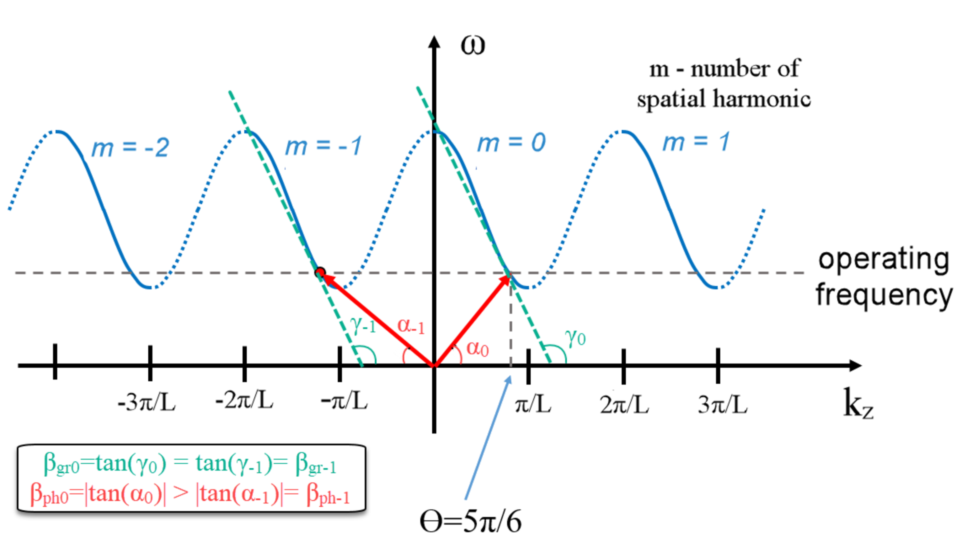
90% of energy is gained in S-band High Gradient Section:

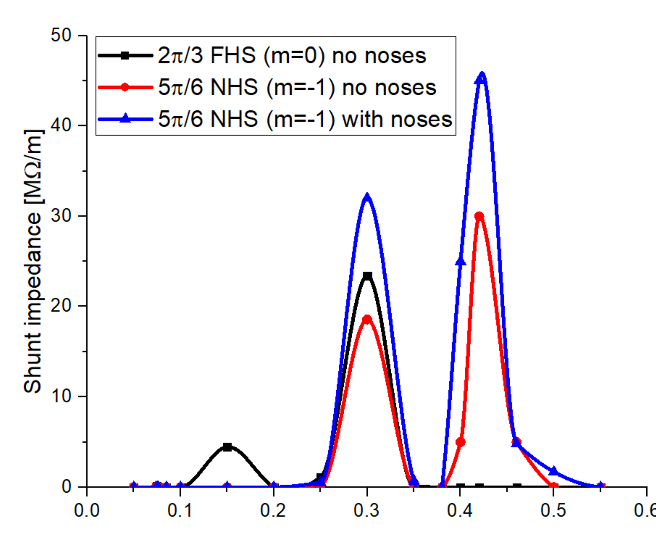
- Operating frequency f = 2856 MHz
- Phase velocity β = 0.3 – 0.7
- Accelerating gradient 50 MV/m, constant along the section
- Aperture diameter 2a = 6 mm
- Beam pulse width τ = 0.5 µs
- Repetition rate F = 120 Hz

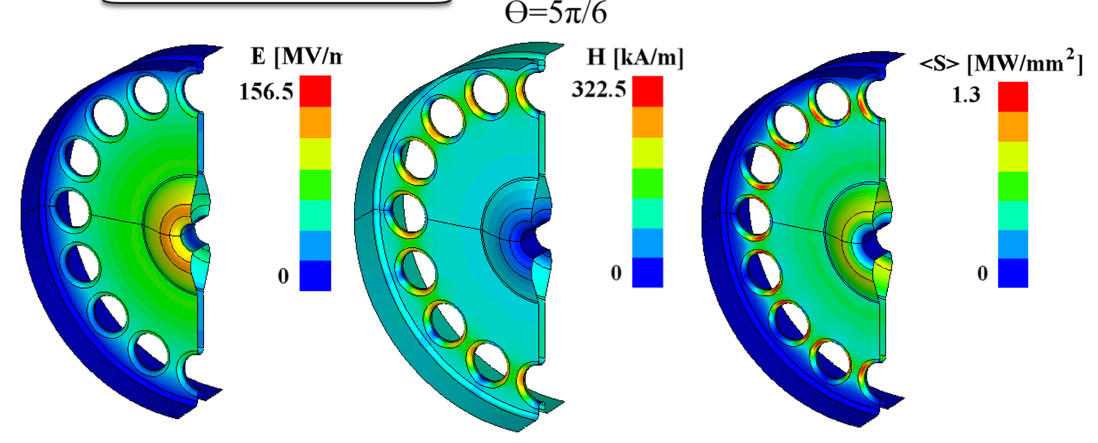
P. Ostroumov et al., "Compact Carbon Ion Linac", NAPAC'16, Chicago, IL, 2016, MOA4CO04

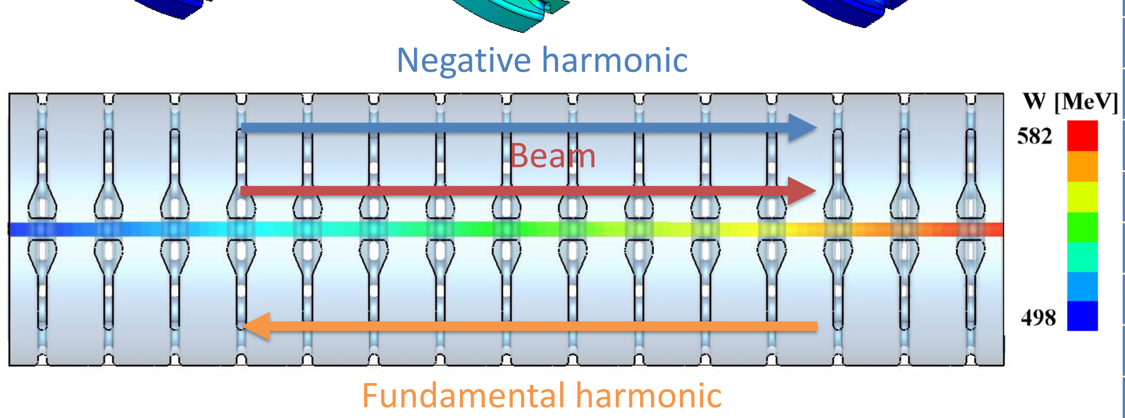
Higher Spatial Harmonics Structure

- Periodic structures have an infinite number of spatial harmonics.
- These harmonics have the same frequency but different spatial field distribution.
- An accelerating structure can be designed for the first negative harmonic m=-1 instead of the fundamental harmonic m=0
- Larger period allows implementing noses for higher shunt impedance









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).

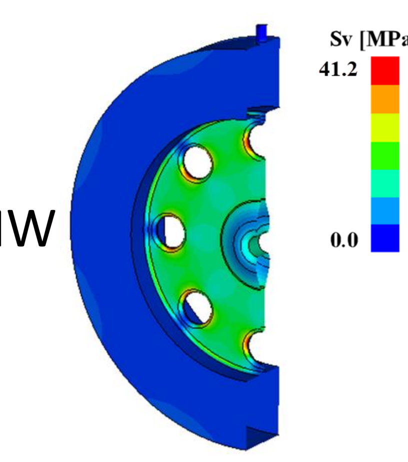
Harmonic	-1
Cell length, mm	18.375
Mode of operation	5π/6
Iris thickness, mm	2.5
Gap length, mm	10.725
Number of cells	15
Shunt impedance, MΩ/m	31.7
Q-factor	8065
Group velocity (out), % of c	0.26
Fundamental harmonic velocity β	0.42
Particle velocity β	0.3
Accelerating gradient, MV/m	50
Peak E-field, MV/m	156.5
Modified Poynting vector, MW/mm²	1.3
Pulsed heating @ 1µs, K	28.2
Temperature gradient, °C	15.6
Peak mechanical stresses, MPa	59.6

Design Optimization

Number of holes	16	12	8	4
Peak E-field, MV/m	155.5	156.0	155.4	155.7
Pulsed heating, K	19.78	20.51	22.48	27.8
Shunt impedance, MΩ/m	33.08	33.64	34.35	35.34
Modified Poytning, MW/mm²	1.08	1.17	1.38	1.90
Temperature gradient, K	14.8	13.34	12.37	11.06
Mechanical stresses, MPa	62.4	49.27	41.21	34.58

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
Modified Poytning, MW/mm²	1.68	1.39	1.02
Temperature gradient, K	11.9	10.7	9.5
Mechanical stresses, MPa	37.0	32.8	29.0

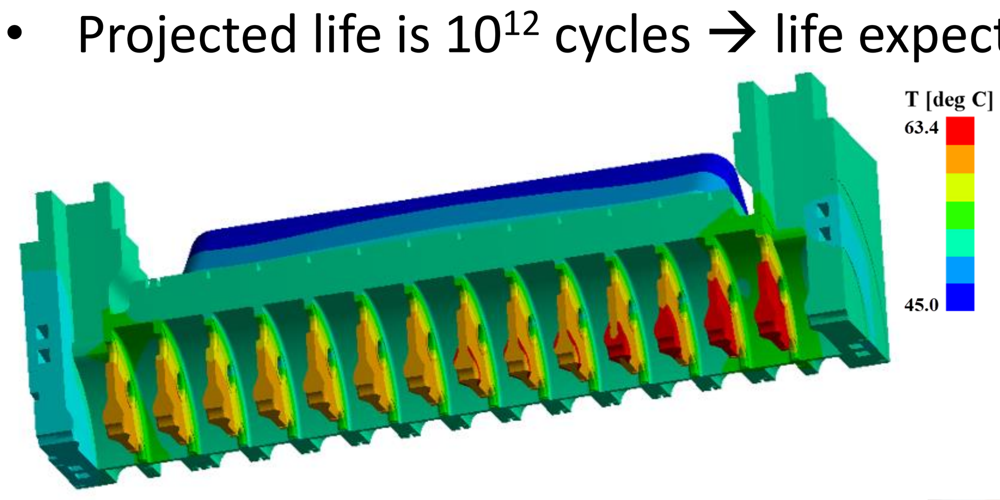
- Reduced number of holes from 16 to 8
- Increased iris thickness from 2.5 mm to 3.0 mm
- Reduced peak power requirement from 42 to 37 MW
- Increased filling time from 350 ns to 500 ns
- Improved thermal conductivity
- Reduced peak stresses by 40%

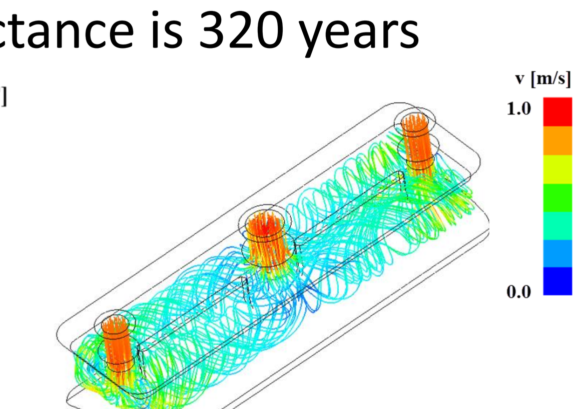


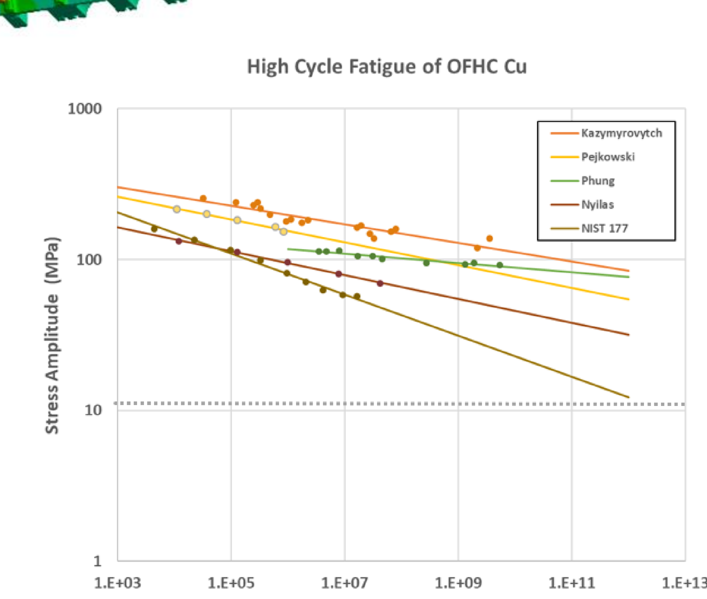
S. Kutsaev, "Compact High Gradient Ion Accelerating Structure", International Patent Application PCT/US2018/030980, 2018

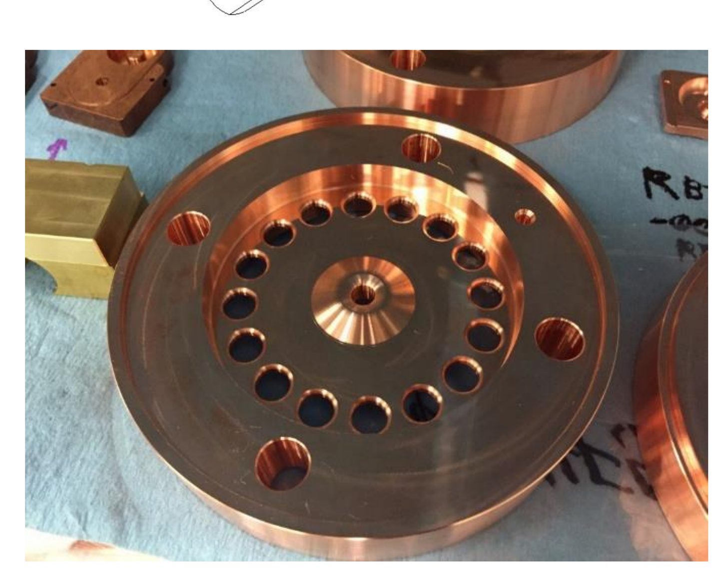
Engineering Design

- Average RF power losses are 2.5 kW
- The structure is cooled with four cooling blocks
- Maximum average temperature rise is 18.2°C
- Maximum pulsed temperature rise is 19.8°C
- Pulsed von Mises stresses (45.8 MPa) are less than yield stresses of OFHC copper (54 MPa)
- Fatigue stress is 11.9 MPa
- Projected life is 10^{12} cycles → life expectance is 320 years









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.

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