10th International workshop on high-gradient acceleration, Valencia, Spain

High-gradient low-β structure based on acceleration with the first negative spatial harmonic

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Collaboration

- RadiaBeam Systems, LLC
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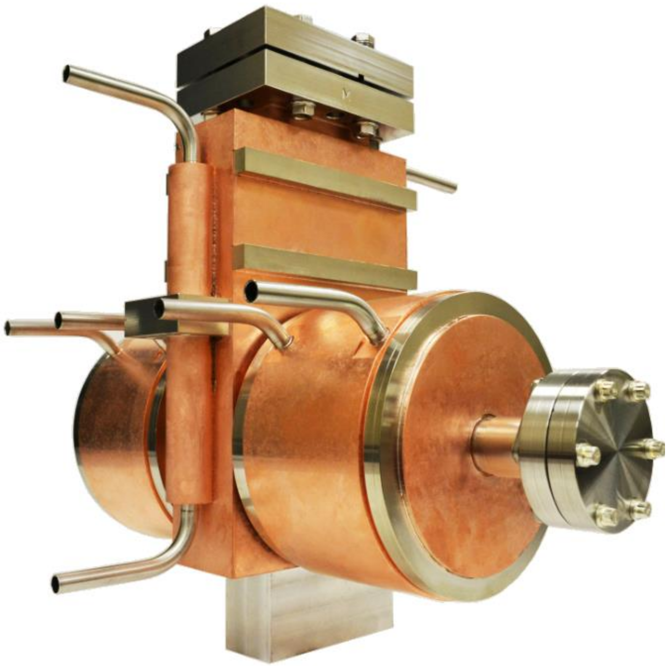
  - Alireza Nassiri
  - Richard Fischer
  - Eddy Goel
- Michigan State University, FRIB
  - Peter N Ostroumov
  - Alexander Plastun

High Gradient Structure for β=1

- RadiaBeam designed, fabricated and high-power tested an ultra-high gradient S-Band accelerating structure (HGS) operating in the pi-mode at 2.856 GHz*.

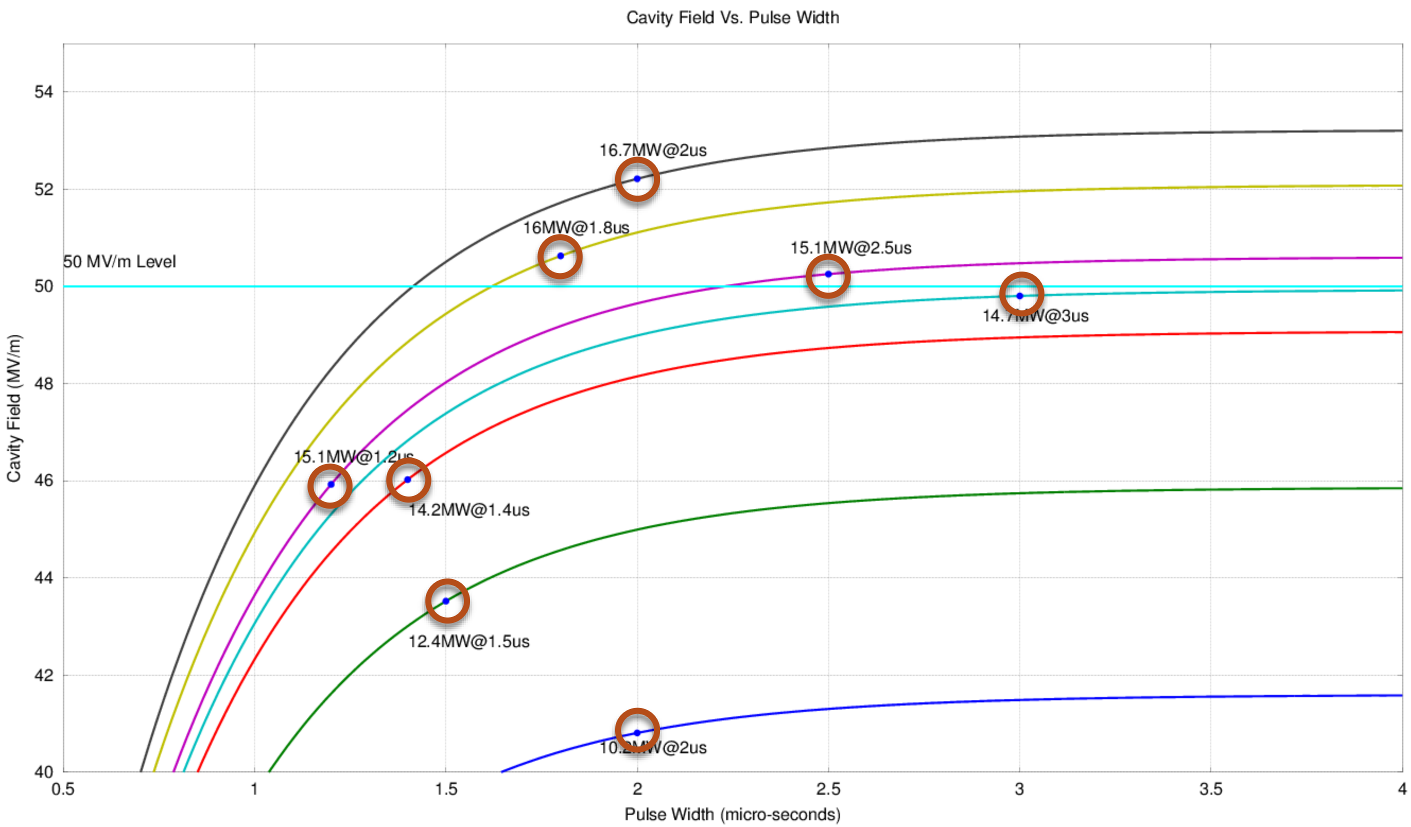


Parameter	Simulated value
f_π	2.856 GHz
R_S (Effective R_S)	93 MΩ/m (51 MΩ/m)
Δf	2.5 MHz
Q_0	19,500
R/Q	143.2 Ω
E_{acc}	50 MV/m
E_{peak}	90 MV/m
P_{diss}/cell	2.4 MW

* L. Faillace at HG'2013 workshop

Achieved Gradients

- Peak field levels of **52.25 MV/m** were achieved for 2μs pulse and 30 Hz repetition rate



Blue dots represent highest power level at each pulse width.

Hadron Therapy

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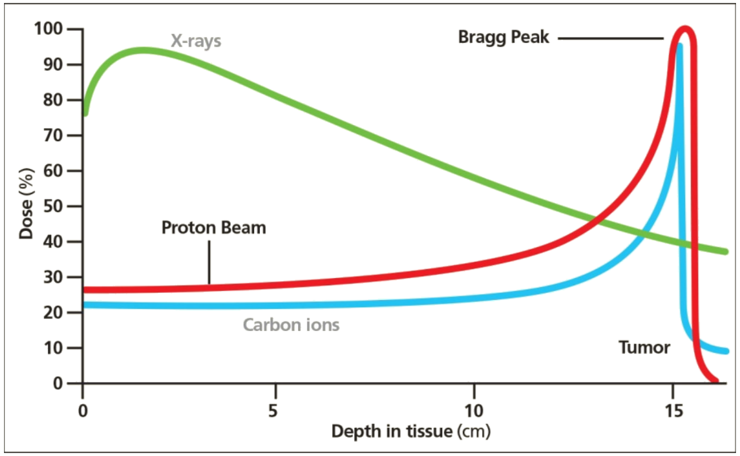
- Radiotherapy is used to treat over 60% of cancer patients and in nearly half of the curative cases
- Existing radiation therapy machines can use beams of X-rays or hadrons for cancer treatment
- Currently, the most common type of the hadron therapy is a proton therapy
- Carbon therapy is the most promising
  - sharper Bragg peak
  - better localization of dose
  - lower scattering before the tumor
  - able to treat “radioresistant” tumors
  - biological efficiency of the dose is higher by factor of 1.5 – 3



Requirements for HT Accelerator

- Cancer therapy accelerator needs to provide particle beams with energies to cover the full penetration depth of the human body that is up to 30 cm
  - 200-250 MeV protons
  - 400-450 MeV/u carbon ions
- Ability to change the energy deposition spot in all three dimensions as fast as possible for treatment of moving organs
  - 0.5 μs pulses at 120-180 Hz
  - continuously variable energy from pulse to pulse
- Deliver sufficient radiation dose to tumor:
  - Beam intensity: up to 10^{10} particles/sec

Accelerators for hadron therapy

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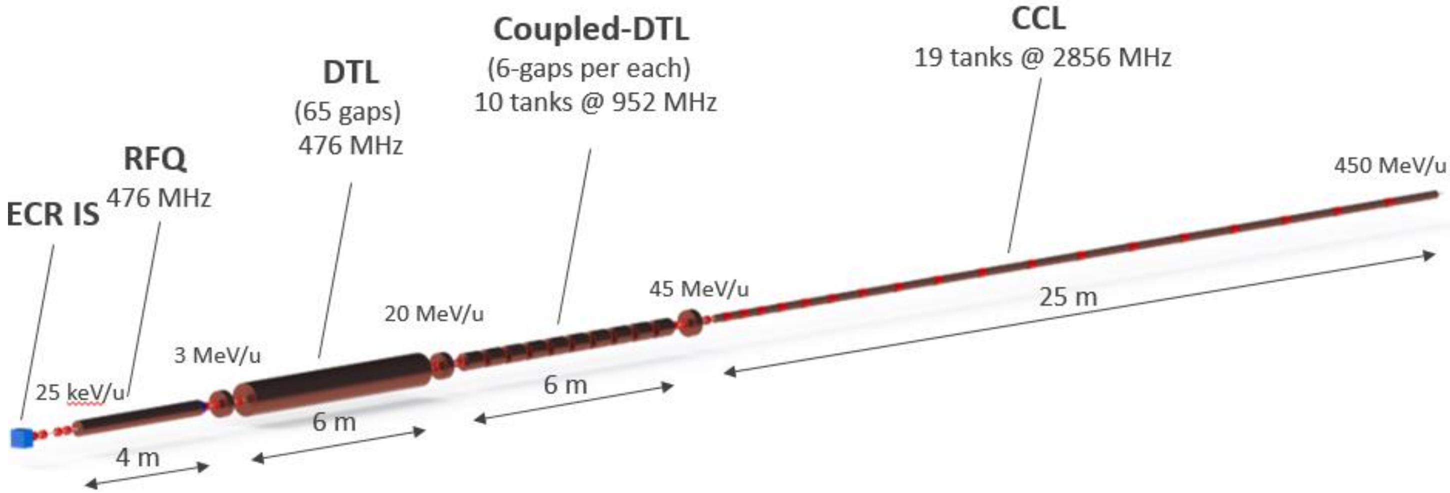
- Currently, cyclotrons and synchrotrons are currently used the treatments
- Linear accelerators can be a promising alternative

	Cyclotron	Synchrotron	Linac
Particles	Only 1 species	Both	Both
Variable energy	With degrader	Possible w/o losses	Possible w/o losses
Beam quality	Bad	OK	Good
Repetition rate	CW	< 1 Hz	> 100 Hz
Size	Most compact	Largest	Depends on gradient

- The high cost of treatments using both proton and carbon beams is the limiting factor preventing hadron therapy from becoming the standard of care for a wider range of cancers

Carbon Therapy Linac

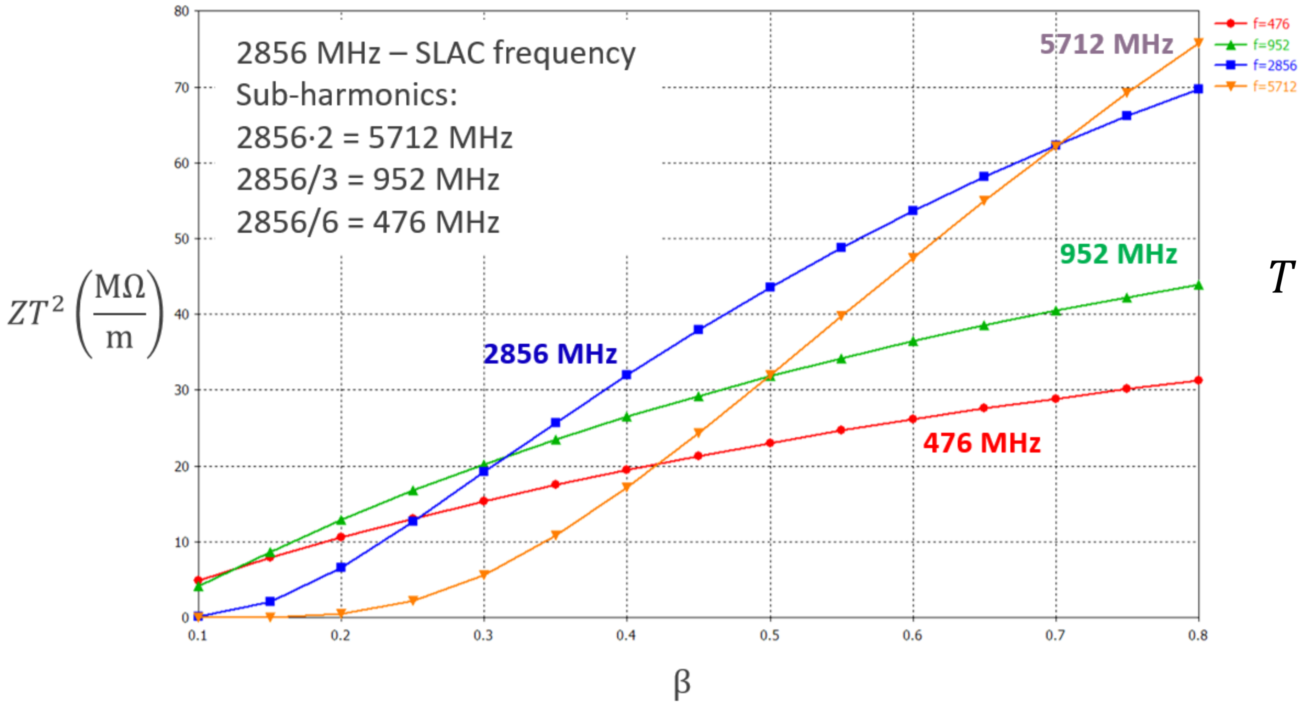
- An Advanced Compact Carbon high gradient Ion Linac (ACCIL) is being developed by collaboration of Argonne National Laboratory and RadiaBeam Systems



- ACCIL must provide 1 GV accelerating voltage in a 40m length
- To achieve this footprint, ~35 MV/m real-estate gradients and <u>50 MV/m</u> accelerating gradients are required.
- The project goal is to develop a 50 MV/m β=0.3 structure

Frequency Choice

- Effective shunt impedance for π-mode of the conventional disk-loaded resonant structure is maximal for S-band
  - Within the required β-range



$$T \sim \frac{\sin(g/\beta\lambda)}{g/\beta\lambda} \frac{1}{I_0\left(\frac{2\pi}{\gamma\beta\lambda}a\right)}$$

Low beta structure for ACCIL

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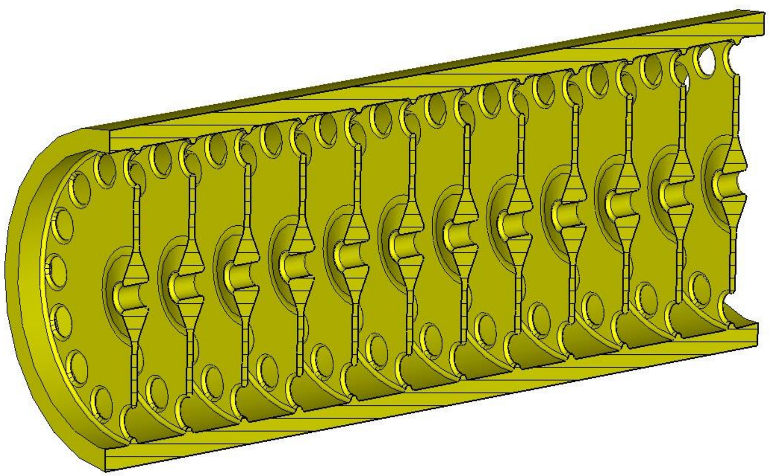
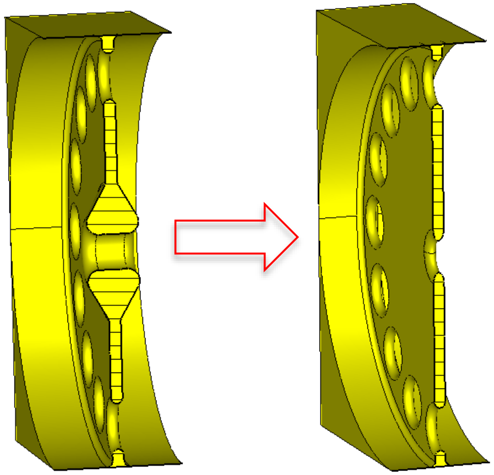
- We used CERN TULIP backward travelling wave (BTW) as a reference*



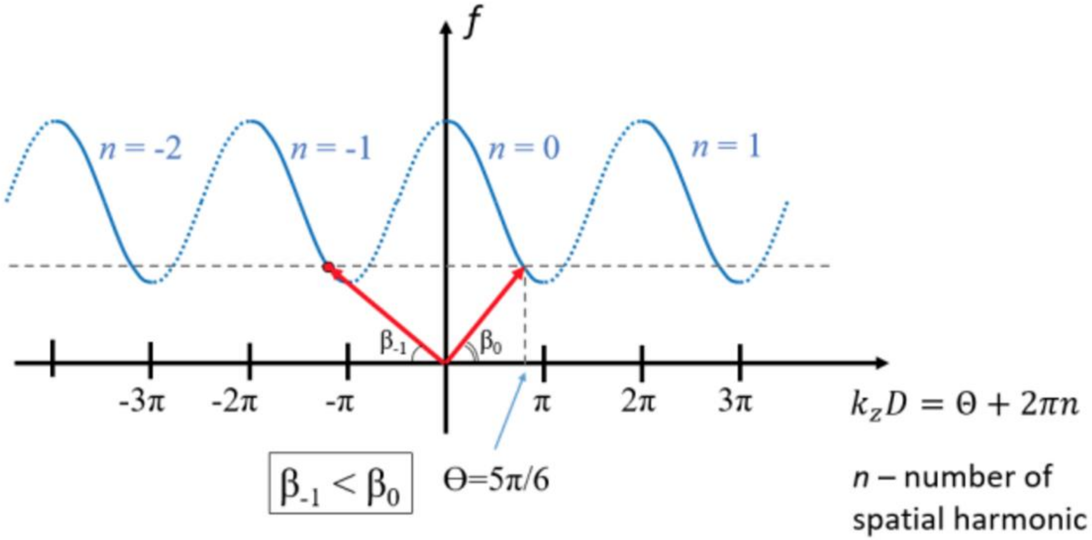


- We found that at β~0.4, the required peak surface field is ~200 MV/m to sustain 50 MV/m accelerating gradient
  - Reducing these fields lead to 160 MV/m lead to a significant shunt impedance drop
- Different approach is required for β=0.3 section

* S. Benedetti, A. Degiovanni, A. Grudiev et al., Proceedings of LINAC2014, Geneva, Switzerland.

Negative Harmonic Structure

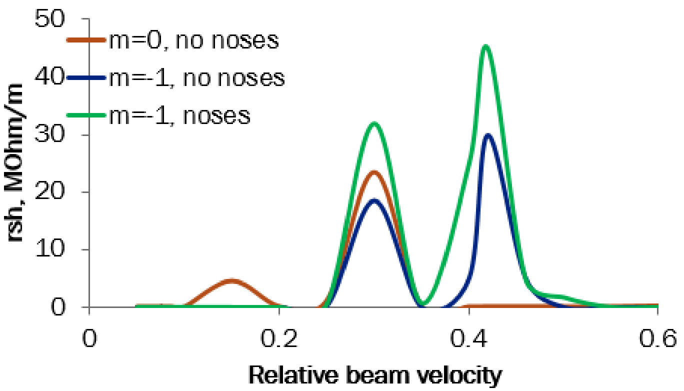
- For the same beta, the cell period is larger for higher harmonics
  - $D = \beta\lambda(1 + n\theta/2\pi)$
- Operation at -1st harmonic will allow to design cells longer by $(2\pi/\theta - 1)$
- Higher harmonic amplitudes are lower

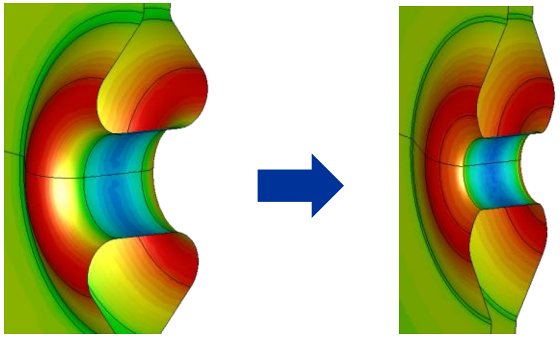


Structure Optimization

- We found the following optimal parameters:
  - 5π/6 mode provides the highest shunt impedance
  - Elliptical noses allow reducing the peak fields
  - 16 round cells provide lower peak magnetic fields

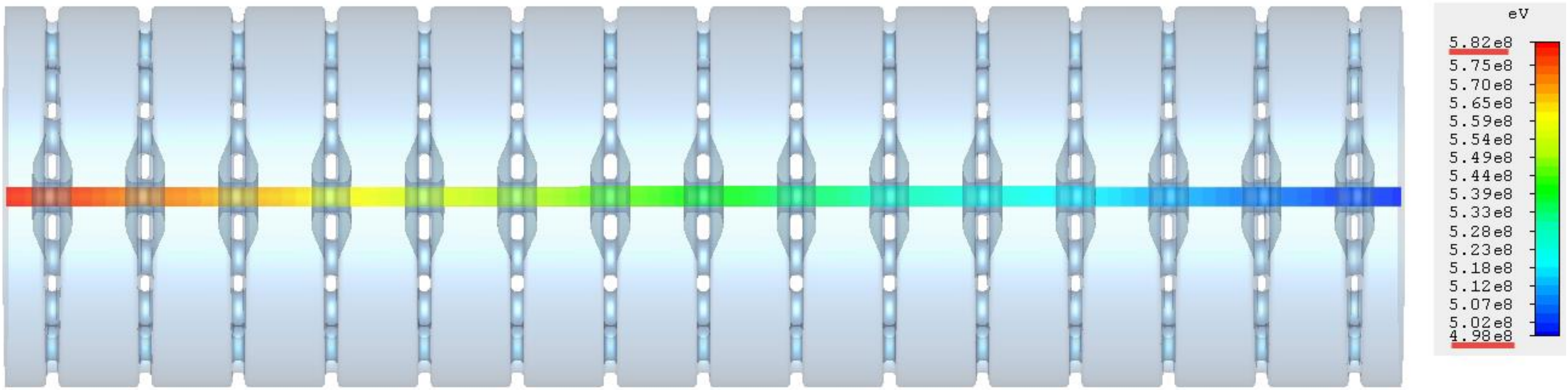
Noses	No	No	Yes
m	0	-1	-1
Mode	2π/3	5π/6	5π/6
t, mm	2	3	2.5
<Sc>, MW/mm^2	1.4	2.03	1.3
Tpulse, K	24	33.46	28.2
Emax, MV/m	92.5	130	156.5
ZTT, MOhm/m	22	18.58	31.7
ΔT, K	39.2	21.2	15.6
σv, MPa	57	75	59.6





Beam Dynamics

- We have done simulations in CST Particle Studio and demonstrated 50 MV/m accelerating gradient that has been later verified by simulations at Argonne
  - Energy gain 83.6 MeV (voltage gain = 13.93 MV) at 27.26 cm
  - Particles injected at -20^{o} phase
  - No interaction with fundamental harmonics



High Gradient Low-β Structures

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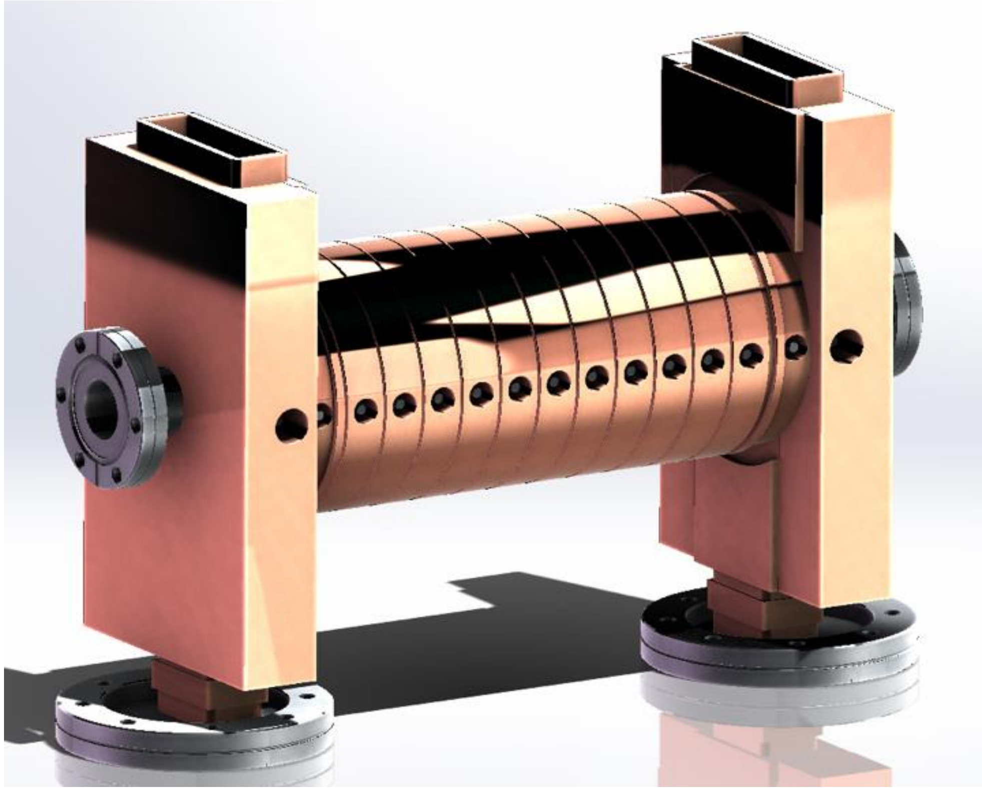
- Comparison with other hadron therapy linac projects

Structure	ACCIL	TULIP[1]	LIBO[2]	CABOTO[2]
Ion types	p^+ and $^{12}C^{6+}$	p^+	p^+	$^{12}C^{6+}$
Minimum beta	0.30	0.38	0.25	0.65
Frequency, MHz	2856	2998.5	2998.5	2998.5
Structure type	BTW	BTW	SCL	SCL
Spatial harmonic	-1st	Fund.	Fund.	Fund.
Accelerating gradient, MV/m	50	50	10	~15
Shunt impedance, MΩ/m	32	52	29	100
Peak electric field, MV/m	160	220	-	-
Modified Poynting vector, MW/mm^2	1.3	1.55	-	-
Beam pulse width, μs	1.0	2.5	3.0	3.0
Filling time, μs	0.5	0.9	1.5	1.5
Repetition rate, pps	120	-	200	400

1. S. Benedetti et al."RF Design of a Novel S-band Backward Travelling Wave Linac for Proton Therapy", Proceedings of Linac'14, Geneva, Switzerland p. 992.
2. U. Amaldi et al. "High Frequency Linacs for Hadronotherapy"., Rev. Accl. Sci. Tech. 02, 111 (2009)

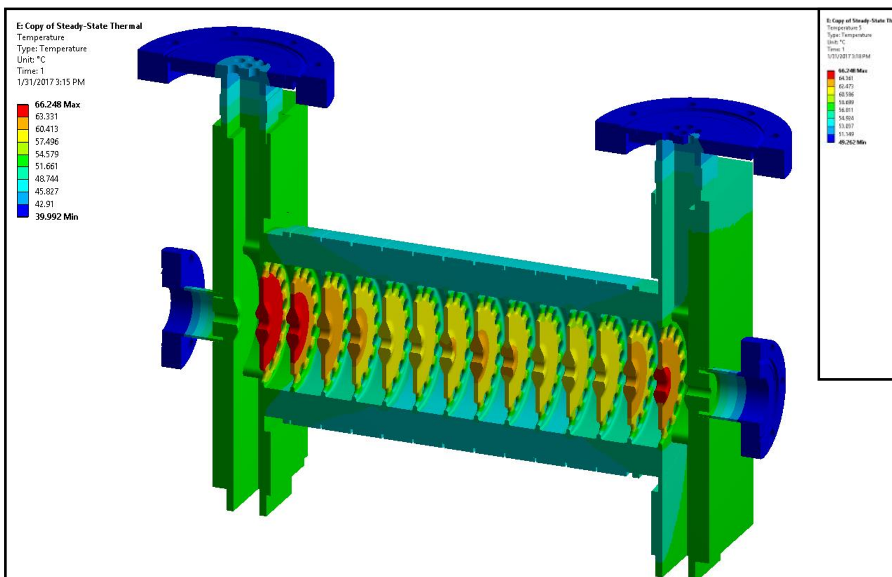
Engineering Design

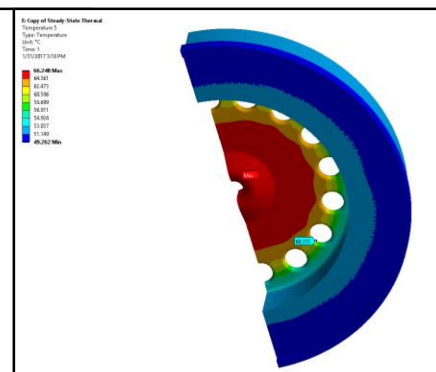
- We have done the conceptual engineering design including the vacuum port pumps and tuning mechanisms

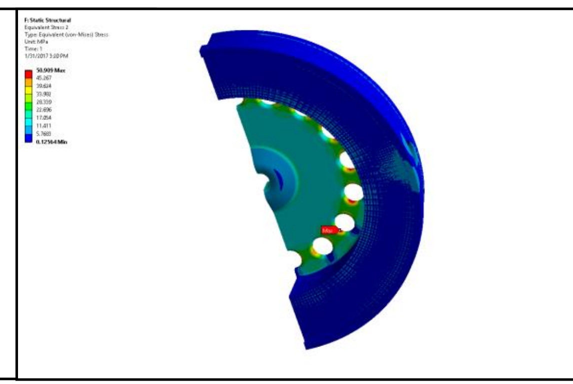


Thermal Analysis

- Thermal analysis was done at ANL for realistic heat load (2.5 kW average, 120 Hz, 1μs pulse length)
  - Temperature dependent material properties, elastic plastic analysis
- For an 18 mm square helical duct to dissipate 2.5 kW
  - Flow velocity = 1.22 ft/s @ 1.9 gpm



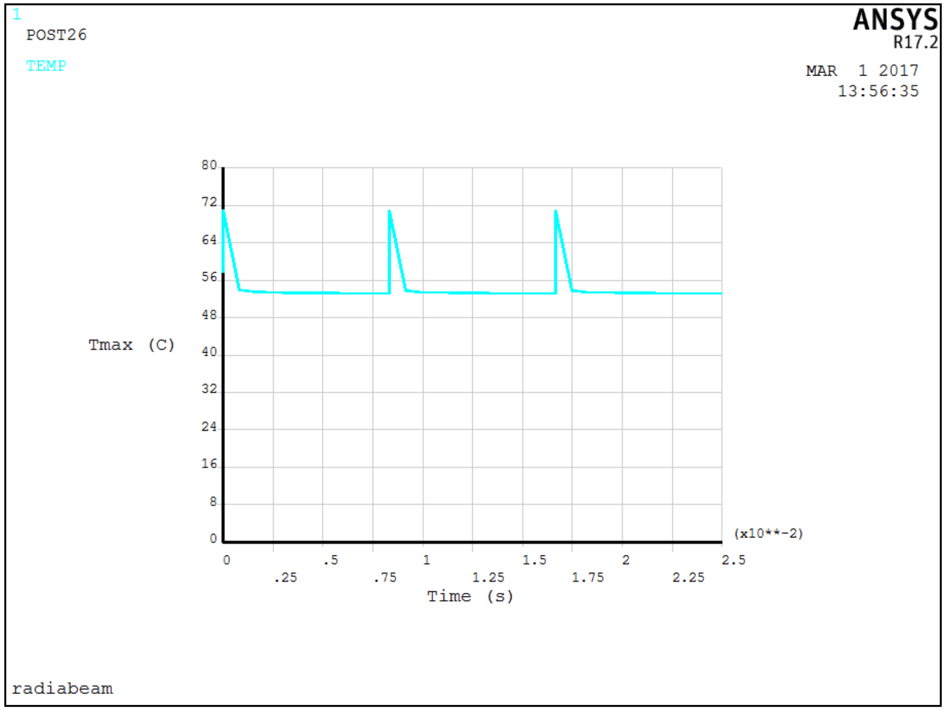


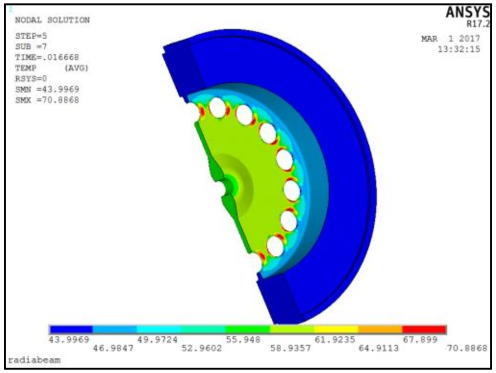


Maximum stress in cells is 50.9 MPa.
Temp @ max stress is 60.2 C.

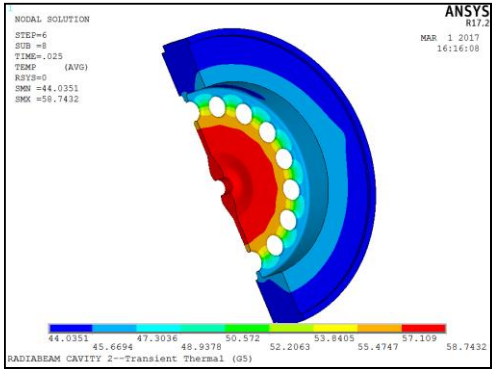
Pulsed Heating

- Transient simulations were done in ANSYS and demonstrated the pulse heating of about 17.2 C
  - Good agreement with analytical estimation (~21.5C)
  - Far below the experimental limit (50C)





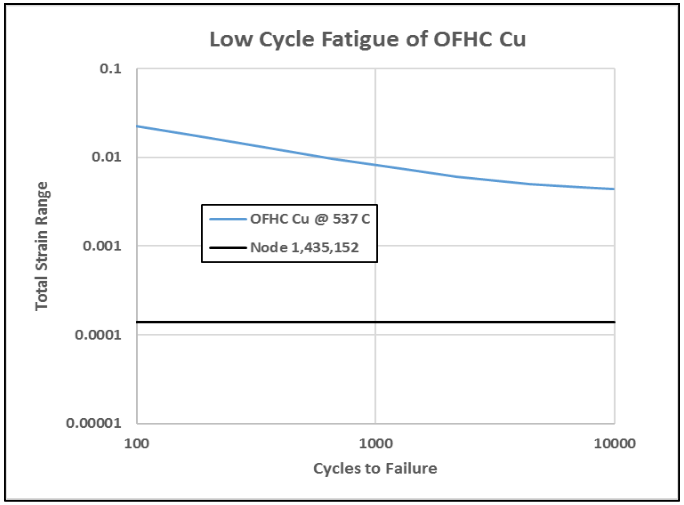
t=0

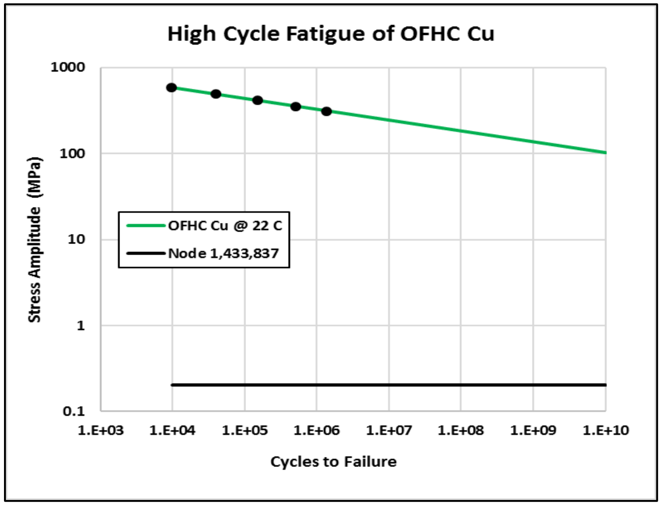


t=3T0

Structural Analysis

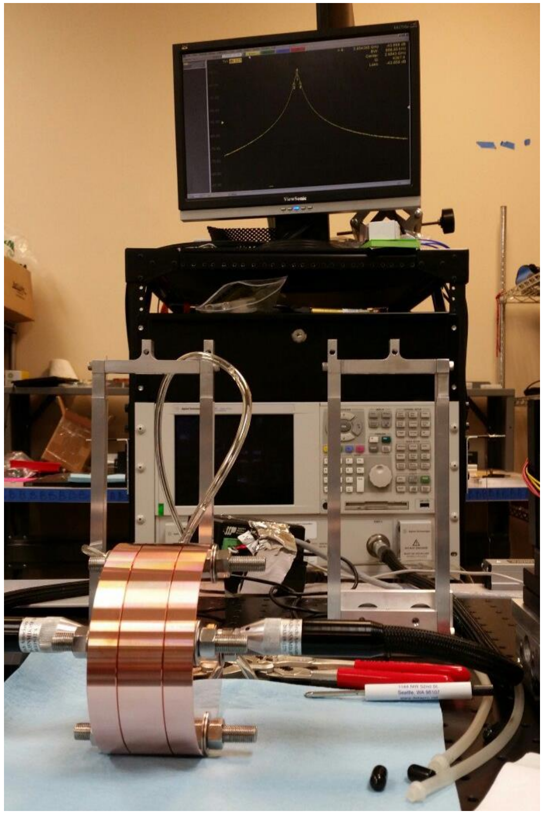
- ANSYS Simulations demonstrated:
  - The cavity is resistant to plastic deformation.
  - The cavity is resistant to ductile rupture.
  - The cavity is resistant to low cycle fatigue.
  - The cavity is resistant to high cycle fatigue.

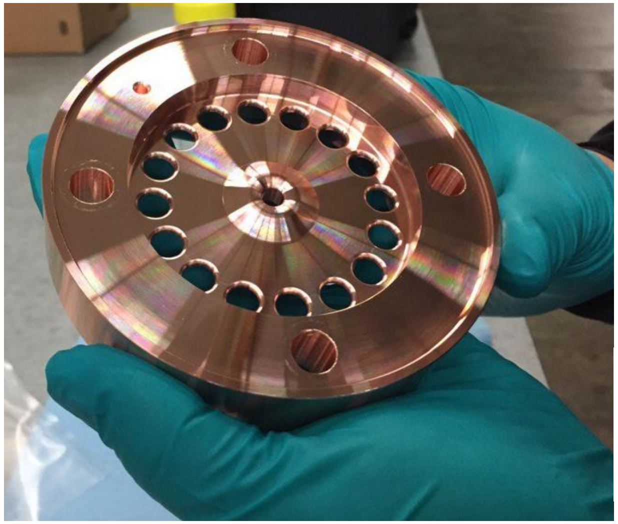


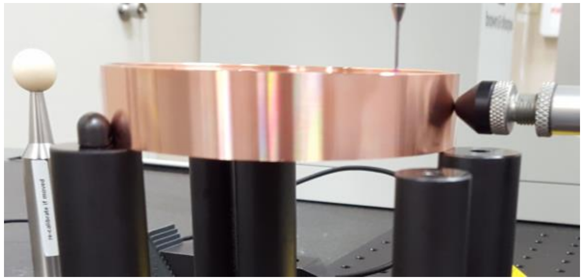


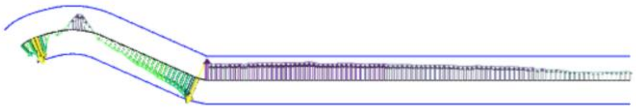
Test Cell Fabrication

- The single test cell was fabricated to develop the machining capabilities and verify that the achieved tolerances are plausible









Parameter	CST (Vacuum)	Measurements w/ corr to vacuum
π-mode freq, MHz	2856.11	2855.06
Q-factor of π-mode	4700	4300 (w/ end caps)

Summary

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- Phase I is successfully finished
- Novel β=0.3 negative harmonic accelerating structure was designed
  - 37.5% lower fields than in β=0.38 CERN structure
  - 50% higher shunt impedance than in fundamental harmonic
- Feasibility of 50 MV/m gradient for β=0.3 was demonstrated
  - Through peak field values that are within the experience range
  - Through thorough thermo-structural analysis
- Test cell was fabricated
- The plans is to build an test 15-cells section within the next two years.