High gradient hadron linac R&D for medical applications

April 20, 2021

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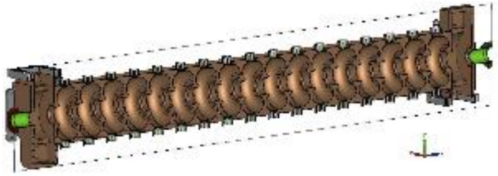
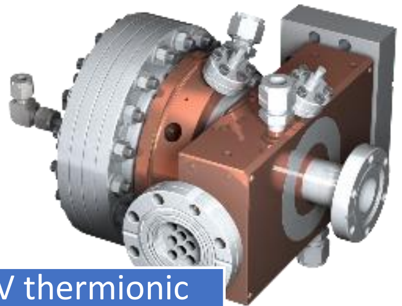
About RadiaBeam

- RadiaBeam founded in 2004
- ~50 employees and growing
- 30,000 ft^2 headquarters in Santa Monica, CA
- Accelerator R&D, design, engineering, manufacturing and testing all under one roof in a dynamic, small-business setting
- Products: accelerator components (RF structures, magnets, diagnostics), medical/industrial accelerator systems


50 MV/m NHS for low-beta ions, 2021


Eight 2m L-band sections, 2020

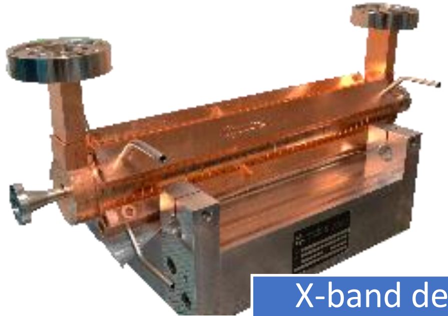

3 MeV thermionic injector, 2019

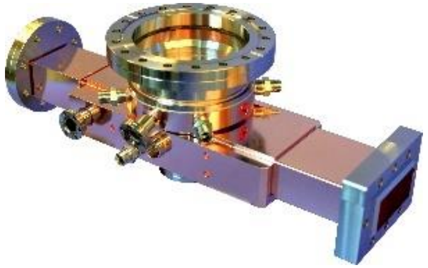

15-25 MeV FEL injector, 2017


RF Photoinjector, 2015


S-band RF deflector, 2013


50 MV/m S-band linac, 2012

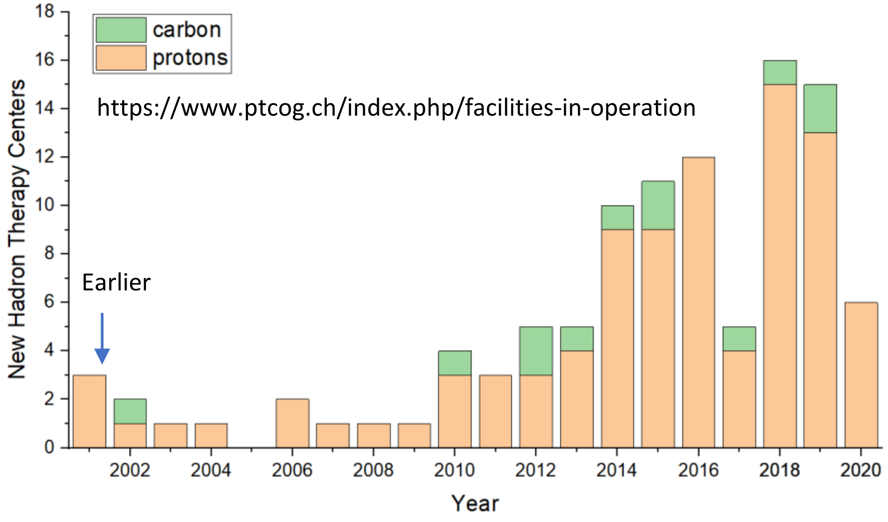

X-band deflector, 2012

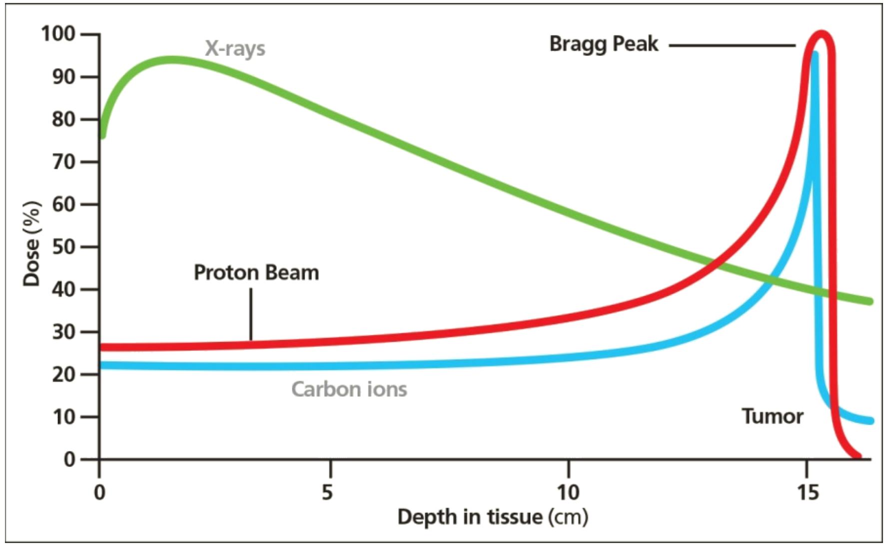

RF photoinjector, 2012

Proton & Hadron Therapy

RadiaBeam

- 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 proton therapy
- Carbon therapy has promising advances
  - 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





Accelerators for Hadron Therapy

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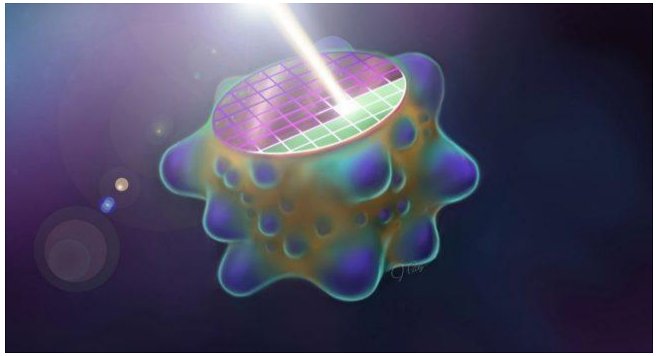


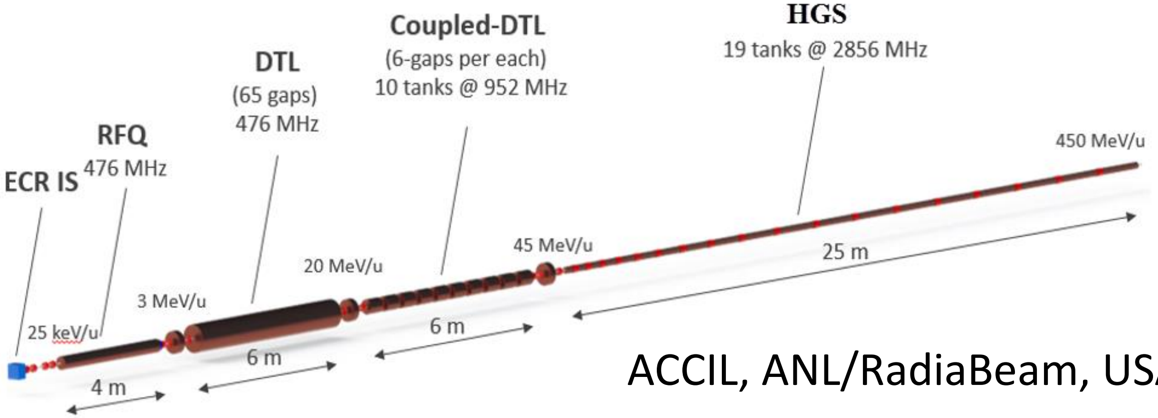
- Cancer therapy accelerator needs to provide particle beams with energies to cover the full penetration depth of the human body (up to 30 cm)
  - 200-250 MeV protons
  - 400-450 MeV/u carbon ions
- Ability to change the energy deposition spot in all three dimensions as fast as possible for treatment of moving organs
  - 0.3 μs pulses at 1000 Hz
  - continuously variable energy from pulse to pulse
- Deliver sufficient radiation dose to tumor:
  - Beam intensity: up to 10^{10} particles/sec
  - FLASH dose requirements: 40 -100 Gy in 1 sec

	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

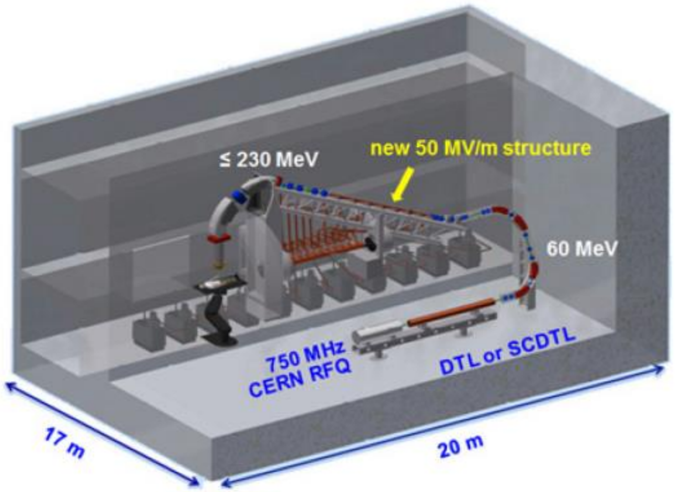
- The high cost of treatments using both proton and carbon beams is the limiting factor preventing hadron therapy from becoming the standard of care for a wider range of cancers
- Currently, cyclotrons and synchrotrons are used for hadron therapy
- Linear accelerators can be a promising alternative

High-Gradient Hadron Therapy Linac

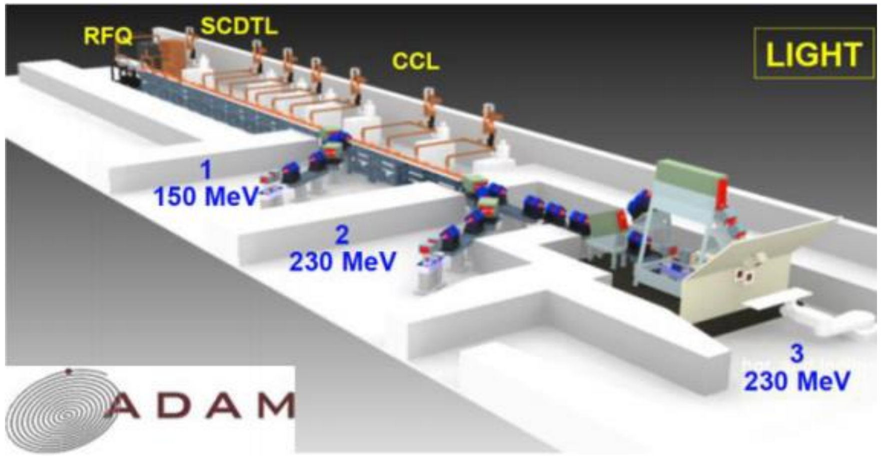
- Several projects for high-gradient therapy linacs are ongoing worldwide
  - Similar approach to use high gradient high frequency structures



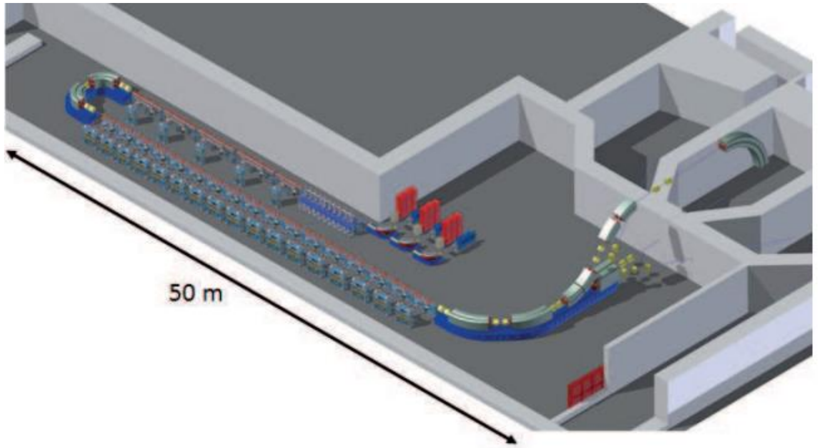
ACCIL, ANL/RadiaBeam, USA



TULIP, CERN, Switzerland



LIGHT, A.D.A.M., Switzerland



CABOTO, TERA Foundation, Novara, Italy

High-Gradient Hadron Therapy Linacs

RadiaBeam

- The main differences are starting energy and accelerating gradients

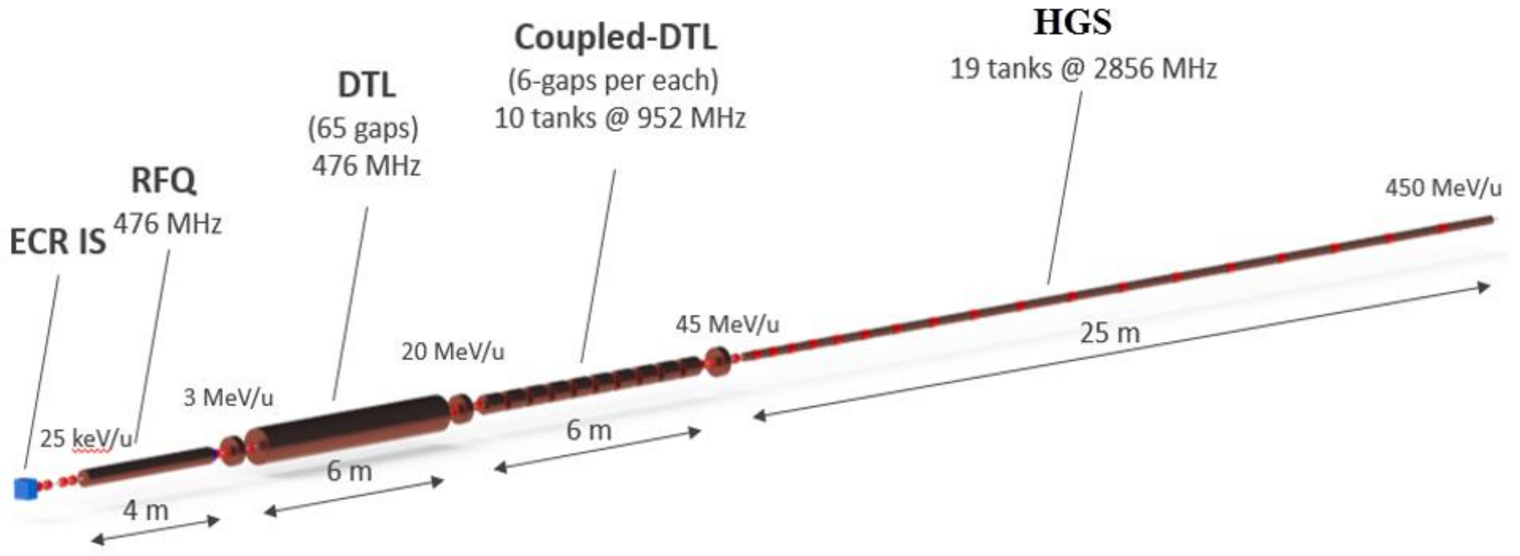
Project	ACCIL	TULIP	LIBO/LIGHT	CABOTO
Ion types	p^+ / $^{12}C^{6+}$	p^+	p^+	$^{12}C^{6+}$
Minimum beta	0.30	0.38	0.35 (0.6)	0.5
Frequency, MHz	2856	2998.5	2998.5	5700
Structure type	BTW	BTW	CCL	SCL
Spatial harmonic	-1st	Fundamental	Fundamental	Fundamental
Accelerating gradient, MV/m	50 (40)	50	16 (25)	32
Shunt impedance*, MΩ/m	32 (50)	52	50 (94)	100
Peak electric field*, MV/m	160	220	75	153
Modified Poynting vector,* MW/mm^2	1.3	1.55	-	0.61
Beam pulse width, μs	0.5 (0.3)	2.5	4.5	2.2
Filling time*, μs	0.5 (0.25)	0.22 (0.9)	0.5	0.7
Peak RF power, MW	34 (5.0 + SLED)	20.6 (9.6)	33 (10)	12
Repetition rate, pps	120 (1000)	100-200	400 (200)	300

S. Benedetti *et al.*, Phys. Rev. Accel. Beams 20, 040101, 2017.
A. Degiovanni et al., Phys. Rev. Accel. Beams 21, 064701, 2018.
S. Verdú-Andrés et al, J Radiat Res. 54(1), 2013.

* Parameters for lowest beta

ACCIL: Advanced Compact Carbon Ion Linac

- The Advanced Compact Carbon high gradient Ion Linac (ACCIL) is being developed by a collaboration of Argonne National Laboratory and RadiaBeam Systems
- ACCIL must provide 1 GV accelerating voltage in a 45m footprint
- To achieve this footprint, ~35 MV/m real-estate gradients and 50 MV/m accelerating gradients are required.
- The project goal is to develop 50 MV/m structures for β=0.3-0.7

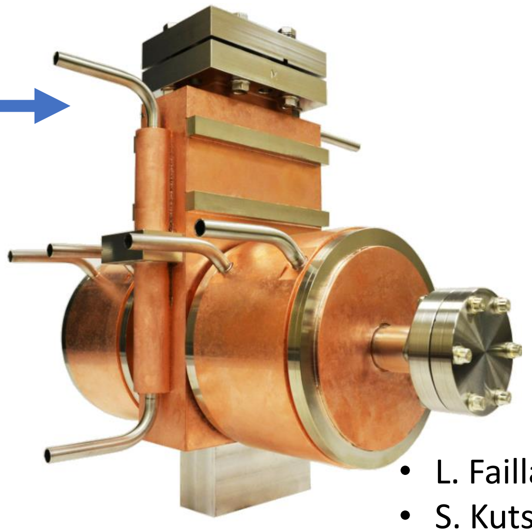


P. Ostroumov *et al.*, Compact Carbon Ion Linac, Proc. NAPAC-2016

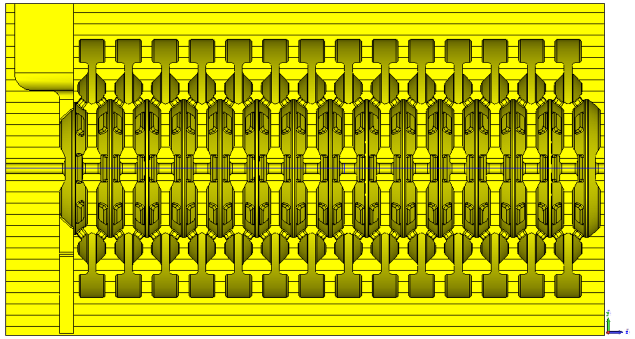
- Capable of accelerating a variety of ion species, proton to neon, up to an energy of 450 MeV per nucleon
- Pulse-to-pulse energy modulation
- Intensity modulation at the source or by changing the pulse rep. rate
- Fast ion beam switching possible from different ion sources in the front-end
- Fast and effective variable energy intensity-modulated multi-ion beam therapy is possible with ACCIL
- In addition to particle therapy, radiobiology research, imaging R&D and other applications are possible

ACCIL R&D Activities

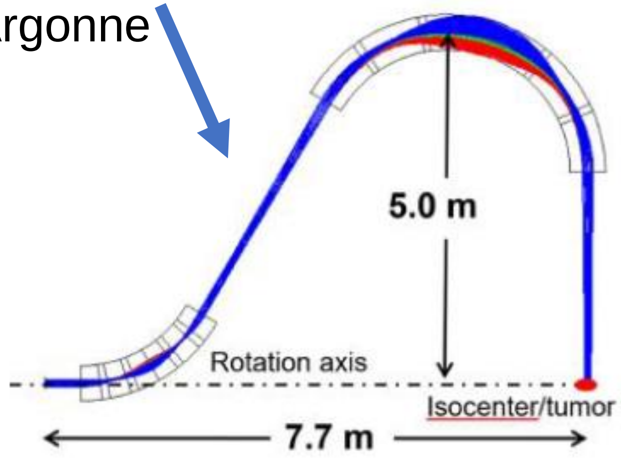
- Development of high-β 50 MV/m CCL structure
  - Developed and built by RadiaBeam, tested at Argonne in 2016
- Negative Harmonic Structure for β=0.3
  - Developed and built by RadiaBeam, tested at Argonne in 2021
- Negative Harmonic Structure for β=0.3 and 1000 Hz rep. rate
  - Under development at RadiaBeam (due 2022)
- Annular Coupled Structure for β=0.4
  - Under development at Argonne (due 2022)
- Compact Ion Beam Scanner & SC Gantry
  - Under development at Argonne



- L. Faillace at HG'2013 workshop
- S. Kutsaev at HG'2016 workshop



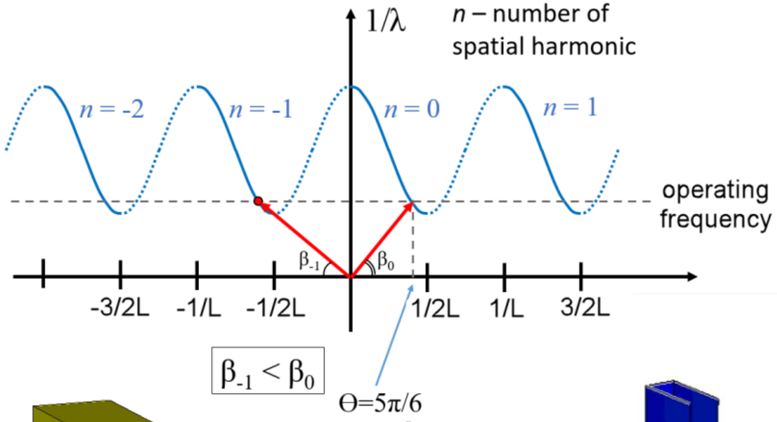
B. Mustapha et al, NAPAC-19.

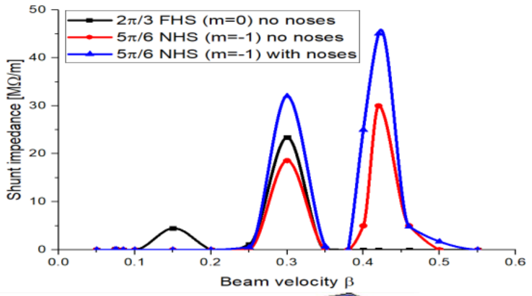


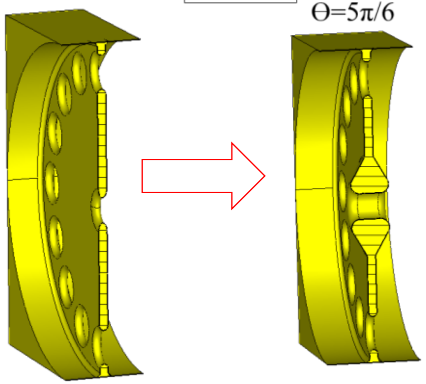
S. Ishmael et al, ASC-2016 Conference, Denver, Co

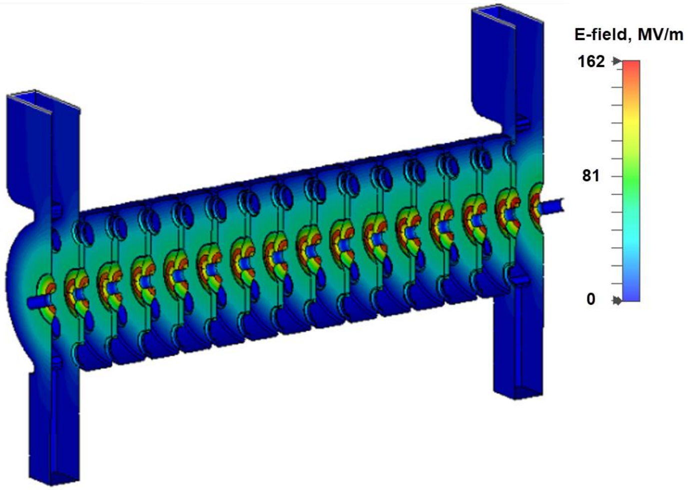
Negative Harmonic Accelerating Structure

- 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 but allow space for nose to improve it









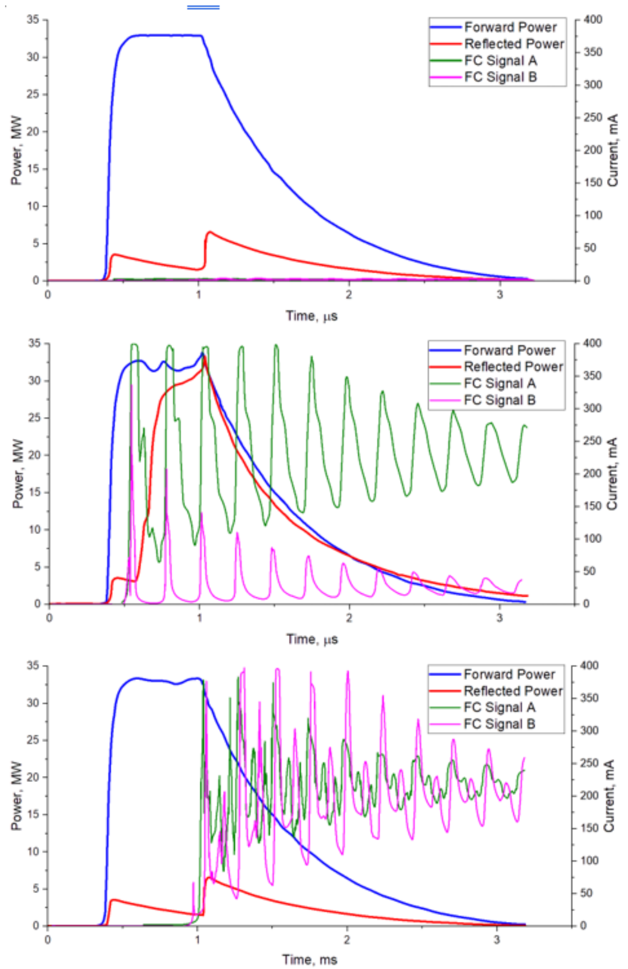
S.V. Kutsaev et al, Phys. Rev. Accel. Beams 20, 120401, 2017.

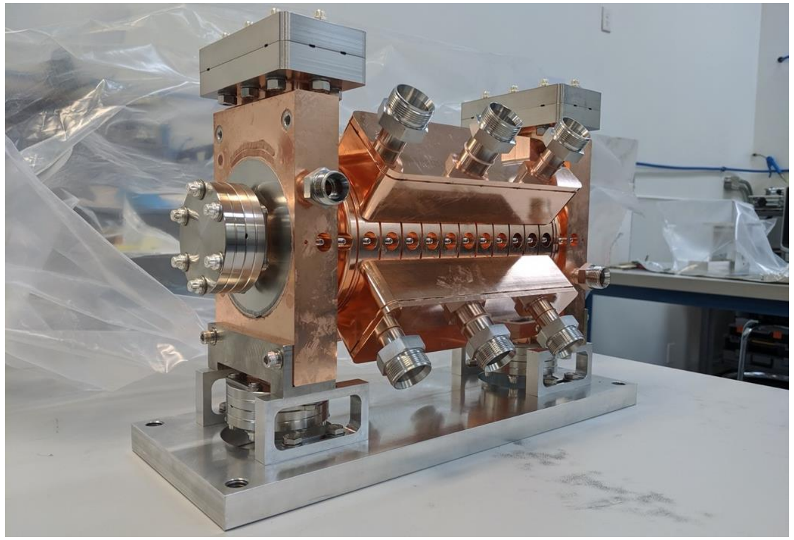
Harmonic	-1
Mode of operation	5π/6
Frequency	2.856 GHz
Length	28.5 cm (15 cells)
Phase velocity	0.3c
Group velocity	0.12-0.335 %c
Filling time	450 ns
Peak RF power	33.8 MW
Average RF losses	3.86 kW
Accelerating gradient	50 MV/m
Peak electric fields	160 MV/m
Pulsed heating	28 K

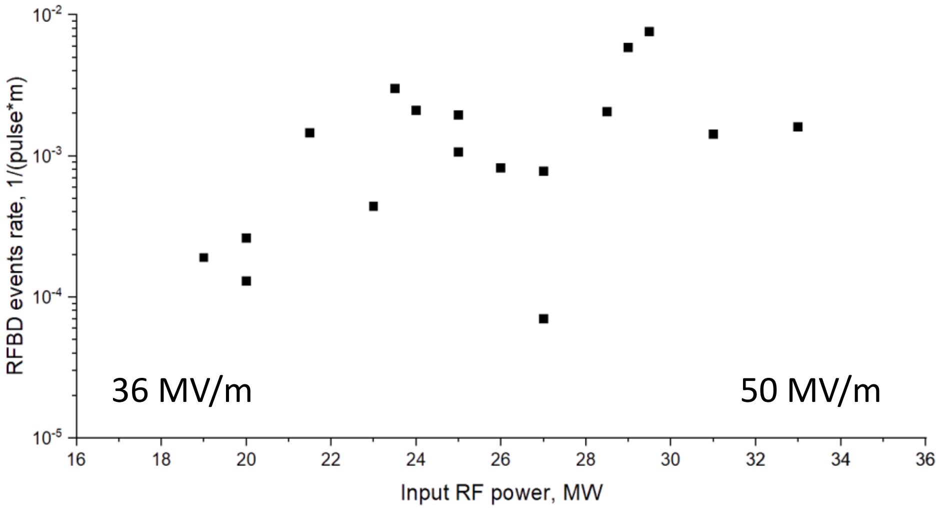
NHS Test Results

RadiaBeam

- The structure was recently tested at ANL
- 50 MV/m gradient was reached
  - Limited by klystron RF power
  - Highest gradient in 15-cells structure
- RF power and Faraday cup signals were measured



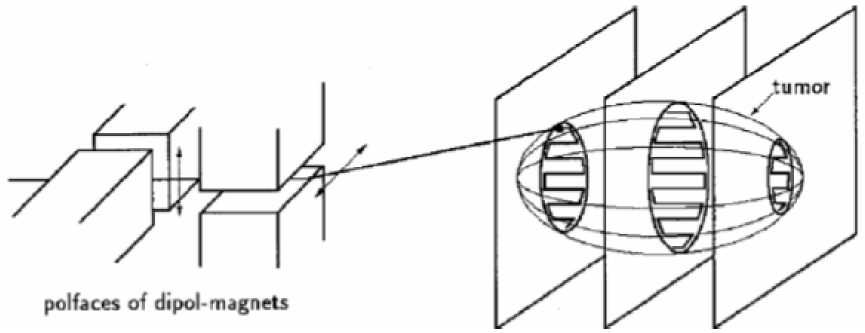




S.V. Kutsaev et al, IEEE Trans. Microw. Wirel. Comp. Lett., 2021, submitted

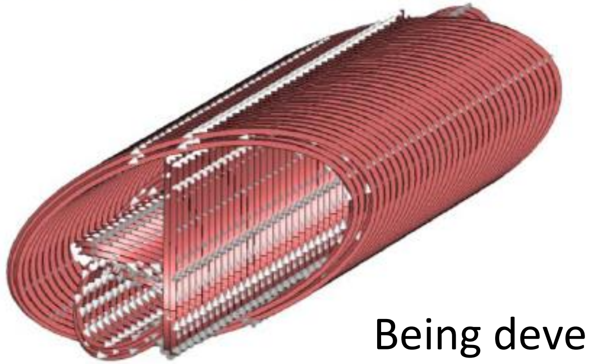
Real-time Image-guided Ion Beam Therapy

- Unless the positions of the target and OARs are accurately known both before and during the treatment, these potential benefits may not be realized.
- Imaging, such as x-ray radiography and cone-beam CT, are routinely used to verify that the patient's internal anatomy is positioned correctly relative to the treatment beam
  - MRI imaging is a compelling alternative image guidance with better soft tissue visualization
- In order to accomplish treatments in between imaging steps, the entire tumor plane must be covered in a short time (~1 sec)
- The beam enters the patient in pulses, irradiating the tumor layer-by-layer, much like a 3-D printer operates. This requires the ability to change the beam position and energy pulse-by-pulse, and leads to the requirement for high repetition rate (~1,000 Hz)



B. Mustapha et al, AIP Conf. Proc. 2160, 050009, 2019.

Novel double-helix design

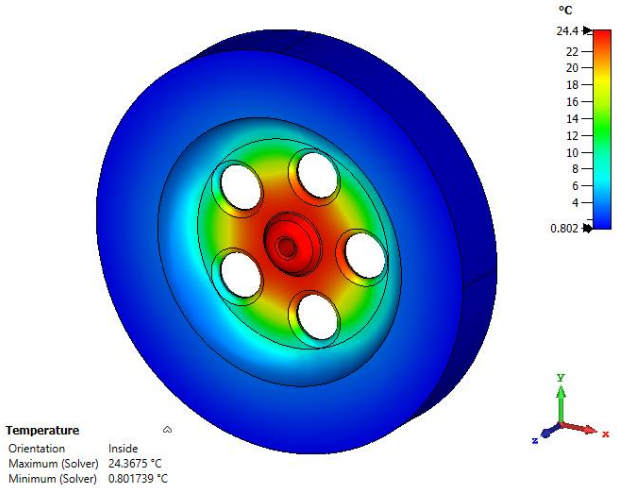


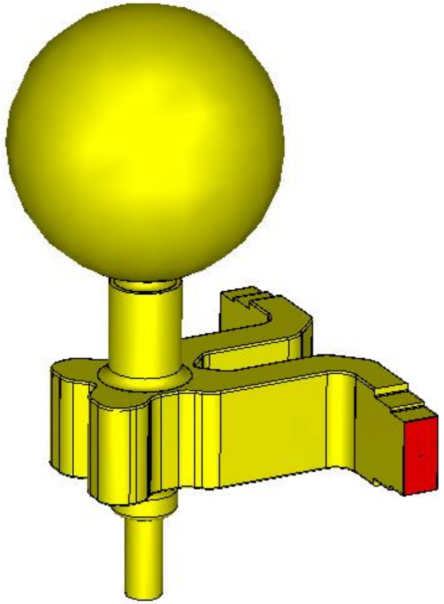
10 x 100 Hz

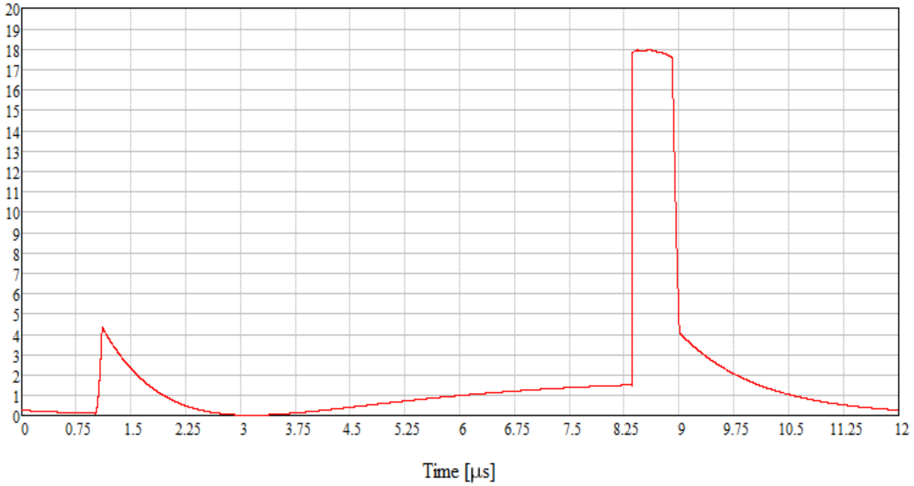
Being developed at ANL

High Repetition Rate NHS

- RadiaBeam is developing an upgraded version of NHS structure
  - Operation at 1000 Hz
  - Shorter beam pulse length – 300 ns
  - Shorter filling time – 250 ns
  - Increased shunt impedance – 50 MOhm/m
- SLED is also planned in order to allow operation from medical klystron
  - 5.0 MW peak power







Phase Velocity, c	0.3
Repetition rate, Hz	1000
Pulse Length, ns	550
Input RF Power, MW	19.7
β_{gr} 1st cell, %c	0.27-0.47
Fill time, ns	255
Shunt Impedance, MΩ/m	50.4
Gradient, MV/m	40
Average power loss, kW	4.4
Peak E-field @ 40MV/m, MV/m	166
Pulse Heating at 1us at 40MV/m, K	10.86
<Sc> at 40MV/m, MW/mm^2	1.07

FLASH Radiotherapy Capabilities

- Recent preclinical trials have shown that ultrafast delivery of large doses (>50 Gy/s) to a tumor significantly reduces damage to surrounding tissues and increases the treatment efficacy
  - FLASH dose requirements: 40 Gy/s to 100 Gy/s
- For protons at max energy of 230 MeV
  - Losing ~ half of its energy in the last 10 cm, ~ 100 MeV per proton
  - Energy deposited: 100 MeV/p at 10^{10}p/s = 10^{12}MeV/s = 0.16 Joules/s
  - Beam spot size of ~ 5x5 mm^2, the beam stopping volume (last 10 cm) is 2.5 cm3
  - The dose in the stopping volume is 0.16 Joules/s /2.5 g = 64 Gy/s
- For carbon ions at max energy of 450 MeV/u
  - Losing ~ half of its energy in the last 10 cm, ~ 200*12 = 2400 MeV per carbon ion
  - Energy deposited: 2400 MeV/ion at 10^9p/s = 2.4 10^{12}MeV/s = 0.38 Joules/s
  - The dose in the stopping volume is 0.38 Joules/s /2.5 g = 152 Gy/s
- For all energies and tumor sizes, we would need 10 times more particles per second (10^{11} protons/s and 10^{10}carbon/s), which is still feasible with the ACCIL linac design.

More details in B. Mustapha, "ACCIL: An ion linac with FLASH capabilities", FLASH Therapy Workshop, January 27, 2021

ACCIL Team

- RadiaBeam:
  - Sergey Kutsaev
  - Alexander Smirnov
  - Ronald Agustsson
  - Robert Berry
  - Salime Boucher *et al.*

- ANL:
  - Brahim Mustapha
  - Ali Nassiri
  - Yawei Yang *et al.*

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  - Reinhard Schulte (LLU)