Prospects for a Linac-Based Carbon Ion Therapy Facility in the Chicago Area

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ANS AccApp'17 Topical Meeting

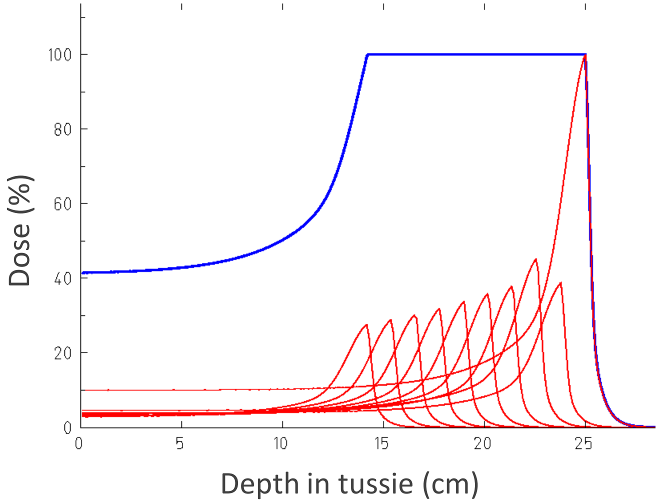
Jul 31st-Aug 4th, 2017, Quebec City, Canada

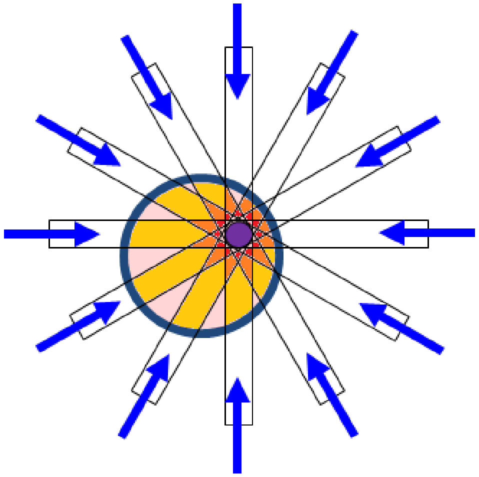
Outline

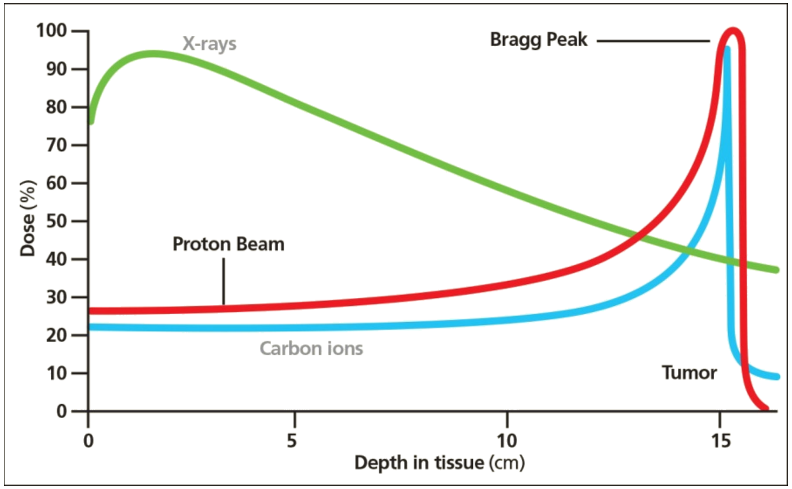
- Why Hadron/Carbon Therapy?
- Why Linac-Based Hadron Therapy?
- ACCIL: The Advanced Compact Carbon Ion Linac
- A Compact SC Gantry Concept: Option for Beam Delivery
- Possibilities with ACCIL …
- Potential for ACCIL-Based CIT in the Chicago Area
- Summary

Why Hadron / Carbon Therapy?

✓ Ions allow depth (energy) scanning and multi-directional irradiation





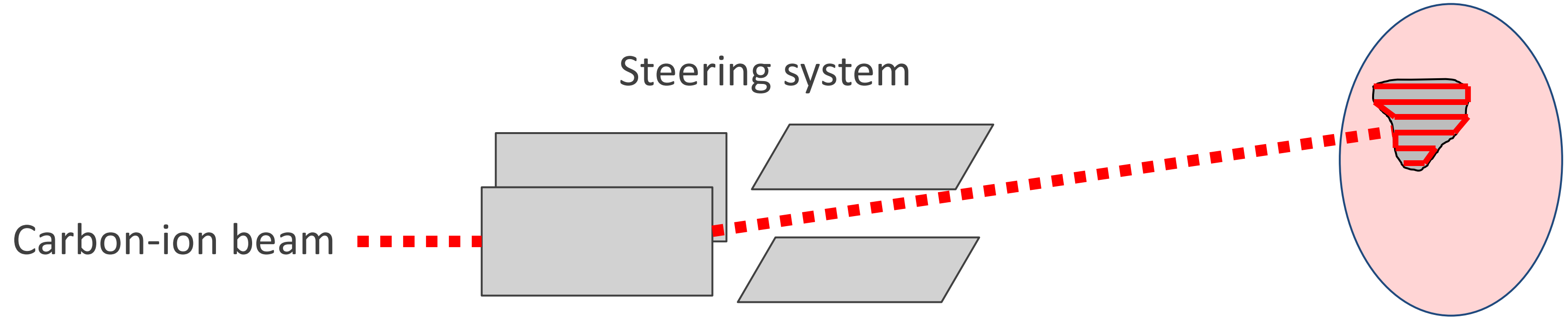


- ❑ Carbon-ions have a sharper Bragg peak → More precise treatment
- ❑ Carbon-ions have larger RBE → Capable of treating more "radio-resistant" tumors
- ❑ For ~ 30 cm range in human body, 230 MeV for protons or 430 MeV/u for carbon-ions

Why Linac-Based Hadron Therapy?

	Cyclotron	Synchrotron	Linac
Variable energy	With degrader	From pulse to pulse without losses	From pulse to pulse without losses
Beam quality	Bad quality due to beam energy degrader	Good	Good
Repetition rate	CW	~ 1 Hz	~ 300 Hz

✓ 3D Spot scanning and multi-painting techniques → Linac is Best Solution

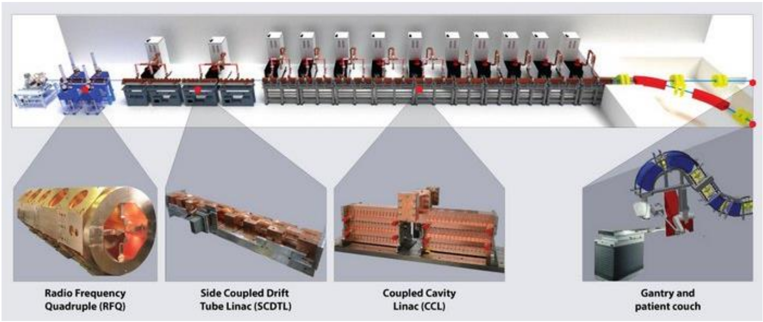


Repetition rate: sub-µsec pulses @ 100-400 Hz
Beam intensity: up to 10^{10} particles/sec
Beam energy: continuously variable from pulse to pulse, up to 450 MeV/u for carbon

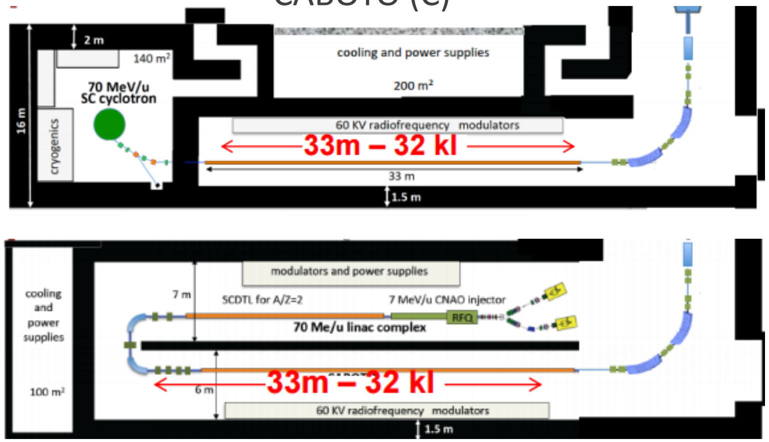
Linacs for Hadron Therapy (Proposed, None exist …)

First proposal for a hadron therapy linac: R. W. Hamm, K. R. Crandall, and J. M. Potter, "Preliminary Design of a Dedicated Proton Therapy Linac", Proceedings of PAC-91 conference, p.2583-2585

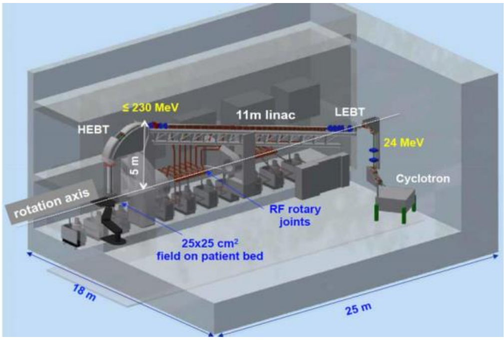
LIGHT (p)



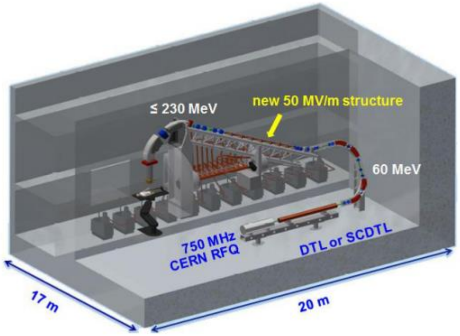
CABOTO (C)



TULIP (p)



TULIP2 (p)

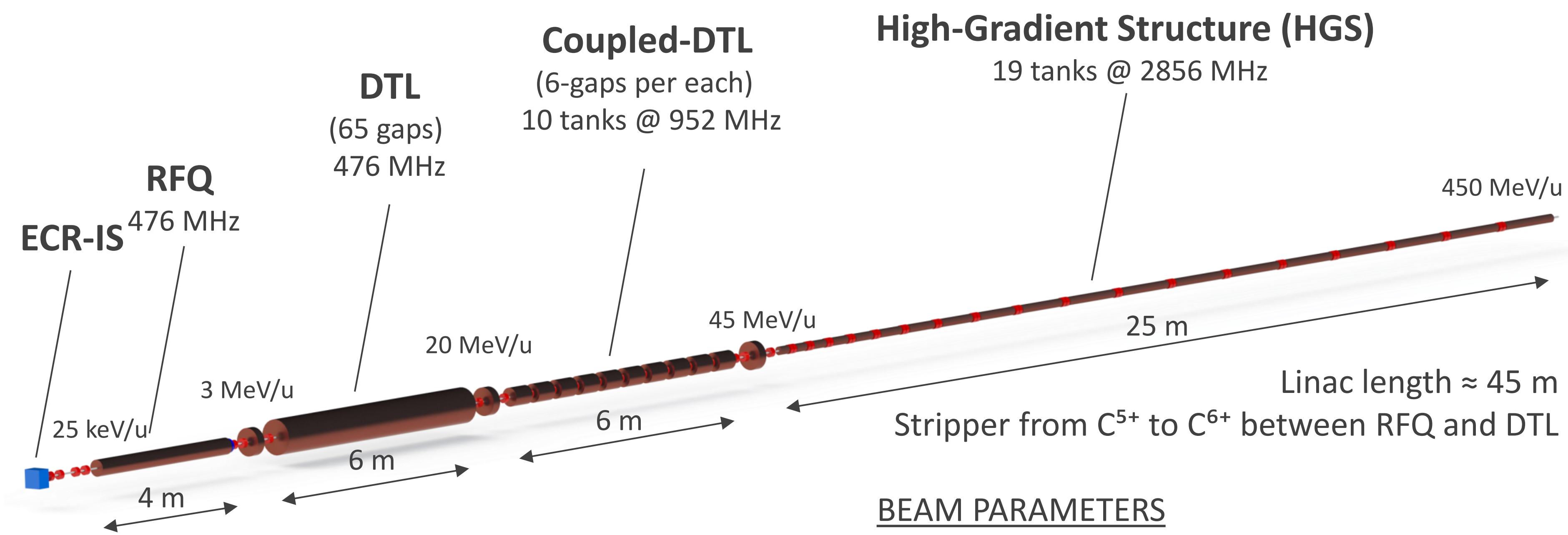


Other: LIBO, IMPLART, PERLA,…

Main parts of these accelerators operate at 3 GHz (S-band)

✓ Why None Exist? → Needs to be Compact & Cost-Effective

ACCIL: The Advanced Compact Carbon Ion Linac



Linac length ≈ 45 m

Stripper from C^{5+} to C^{6+} between RFQ and DTL

Ref: P. Ostroumov et al, Proceedings of NAPAC, Chicago, IL October, 2016

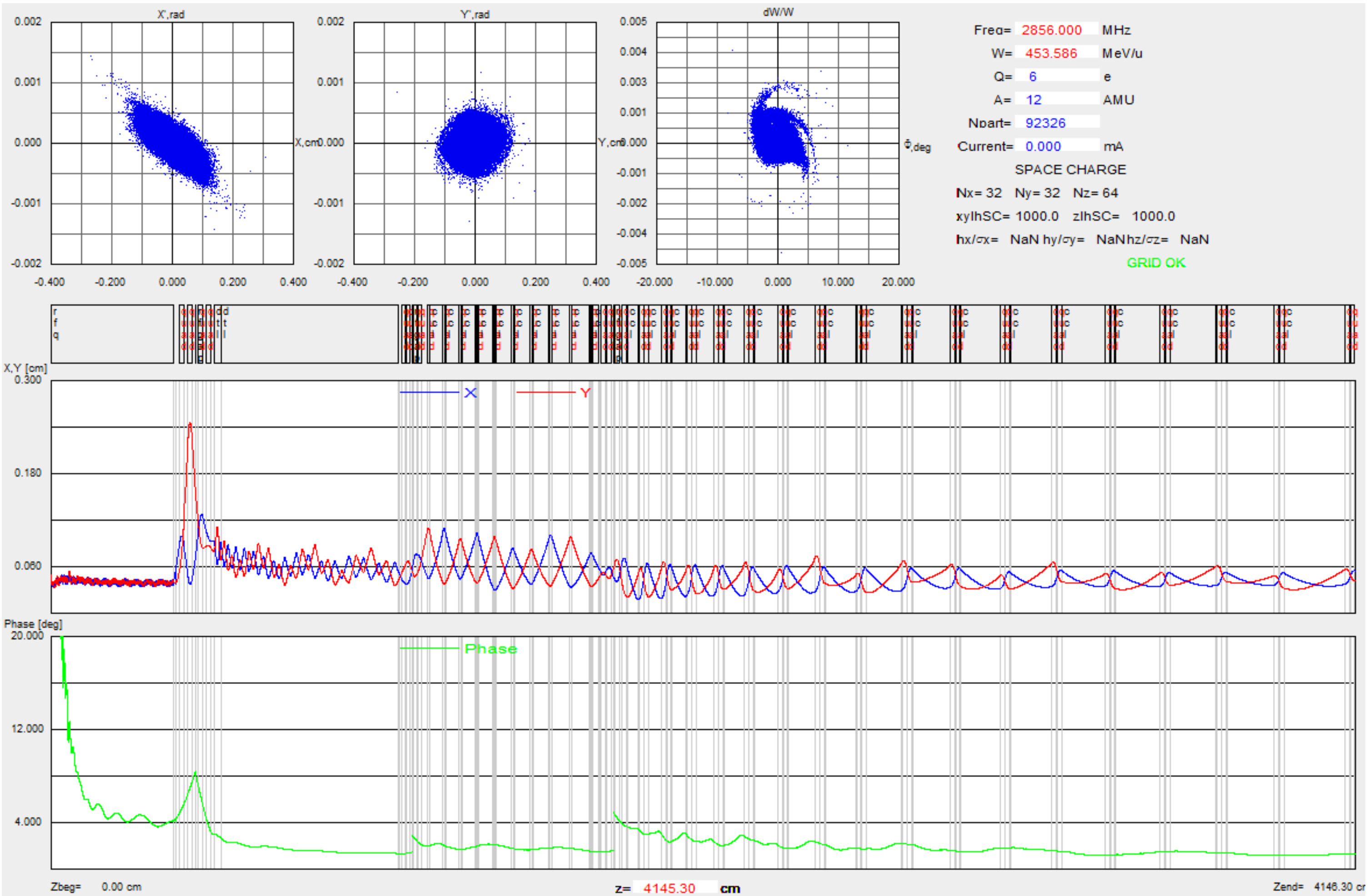
BEAM PARAMETERS

Beam energy:	45 – 450 MeV/u
Beam pulse length:	500 ns
Repetition rate:	120 Hz
Beam duty factor:	$6 \cdot 10^{-5}$
Max. beam pulse current:	27 µA (10^{10} protons/second), 13.4 µA of $^{12}C^{5+}$ (10^9 ions/second),
Beam average current:	1.62 nA of proton beam, 0.8 nA of $^{12}C^{5+}$

✓ Key Component: High-Gradient Accelerating Structures → Compactness

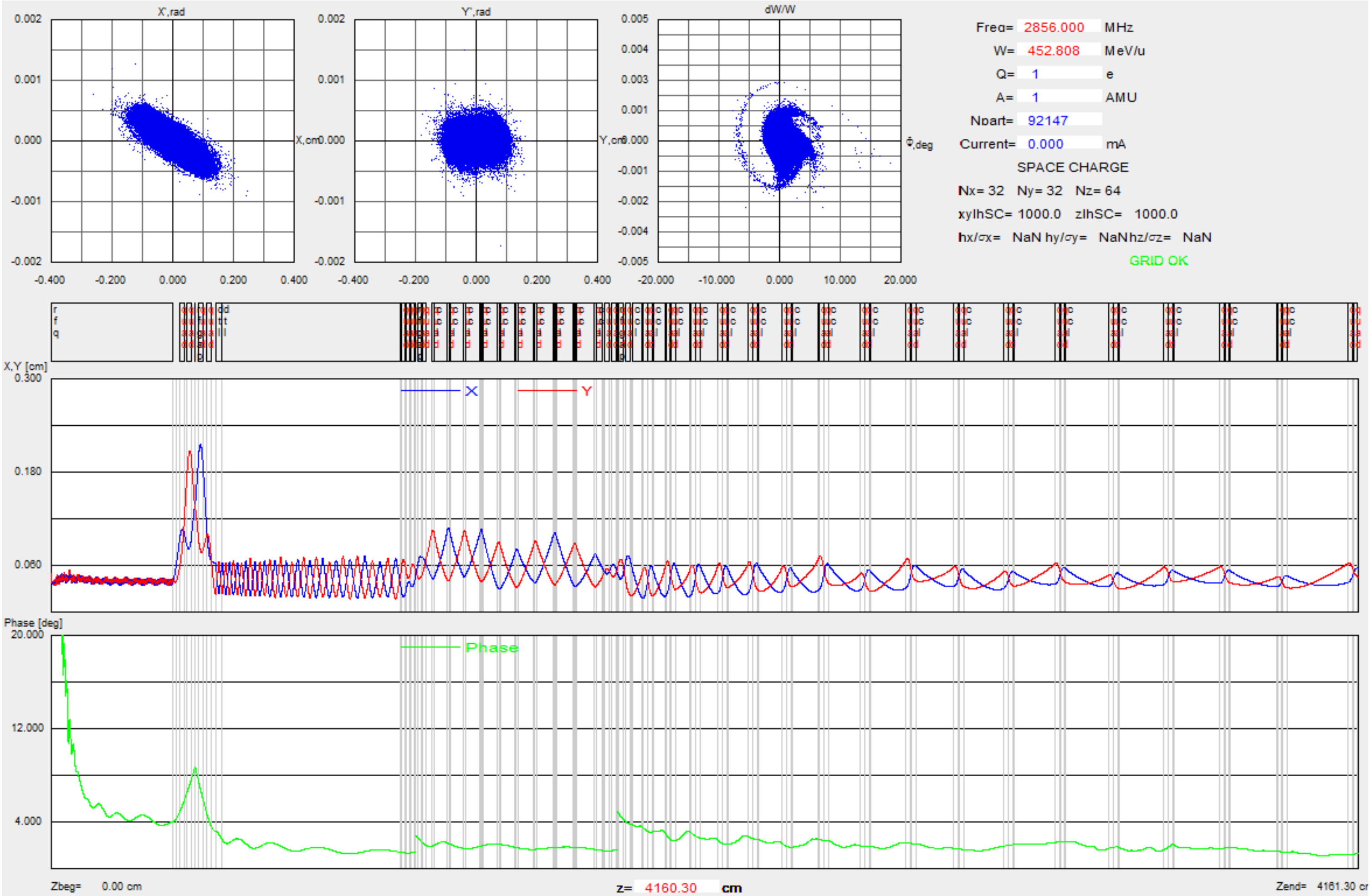
ACCIL End-to-End Beam Dynamics for Carbon Ions

- ✓ RFQ to Linac exit ~ 40 m long
- ✓ 450 MeV/u output energy
- ✓ Over 90% transmission from the source including stripping



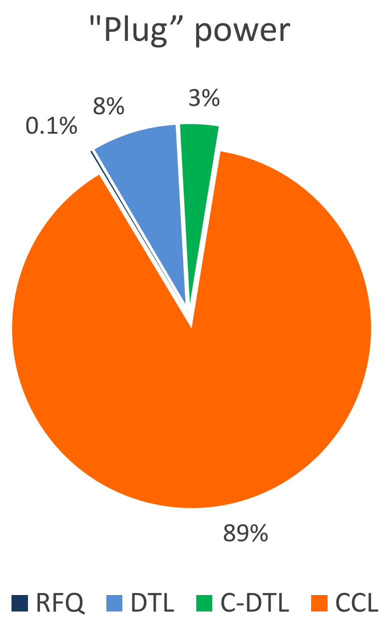
ACCIL End-to-End Beam Dynamics for Protons

- ✓ DTL with permanent magnets designed to allow both proton and carbon beams
- ✓ 250 MeV protons for therapy – 450 MeV available for proton tomography
- ✓ Good beam dynamics, beam quality and transmission similar to carbon

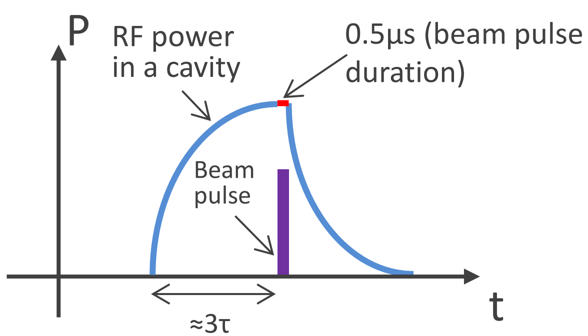


ACCIL Power Consumption @ 120 Hz

	RFQ 476 MHz	DTL 476 MHz	C-DTL 952 MHz	HGS 2856 MHz
Pulsed RF power	0.44 MW	4.88 MW	6.10 MW	1065 MW
Average RF power	0.54 kW	31 kW	14 kW	360 kW
RF source efficiency	40 %	40 %	40 %	40 %
“Plug” power	1.34 kW	77 kW	35 kW	900 kW



Total “plug power”: 1,013 kW ~ 1 MW



Δ(DTL) ≈ 0.6%
Δ(CCL) ≈ (0.02-0.04)%

Courtesy A. Plastun

Comparison to A Recently Built Synchrotron

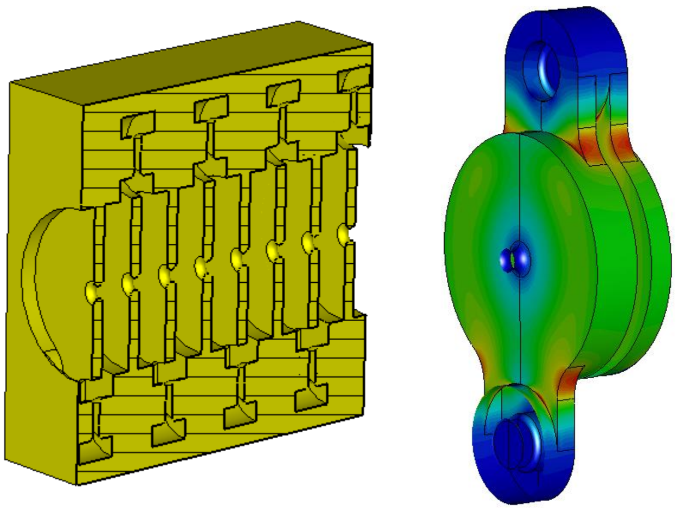
MedAustron Synchrotron Vienna, Austria (Started operation in 2015)		ACCIL (Courtesy, A. Plastun)
	Accelerator cost (only)	
≈ $70-80M		< $50M
	Power consumption*	
5 MW		1 MW
	Footprint	
25x25 m^2		8x45 m^2

✓ ACCIL offers Compactness, Lower Construction & Operation Costs

Requirements & High-Gradient Structure Candidates

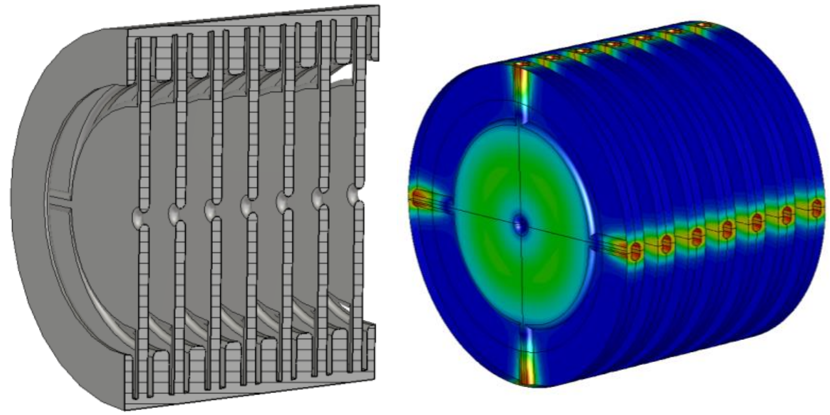
Need 50 MV/m Voltage Gradient

Side-Coupled Structure

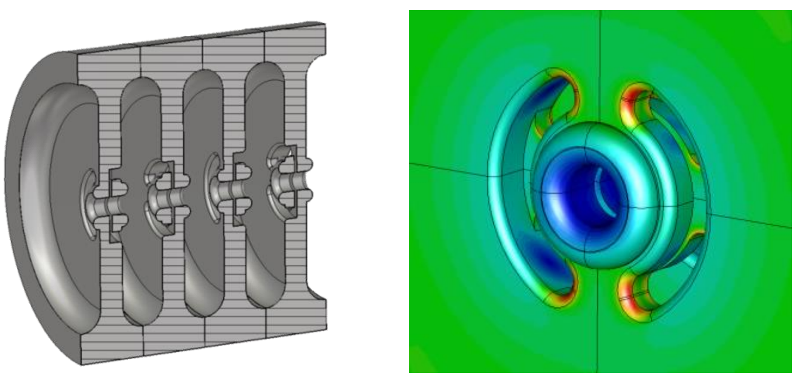


Courtesy
S. Kutsaev

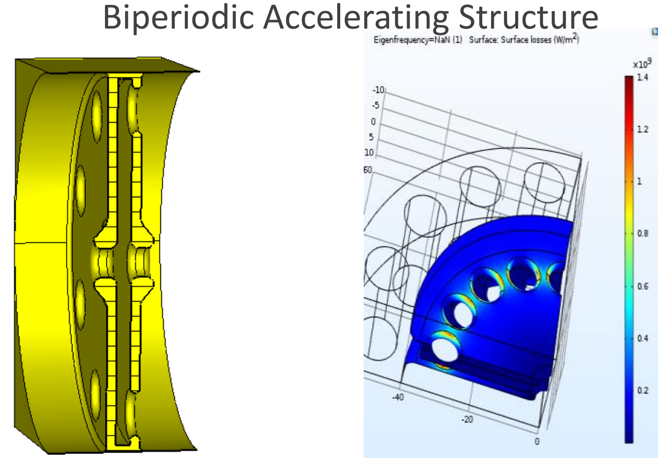
Disk-And-Washer structure



Cut-Disk Structure



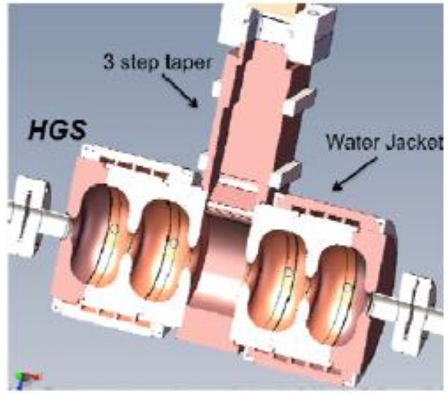
Biperiodic Accelerating Structure



The choice of structure will be based on thermal and mechanical design

A HGS for Electrons: Built by RadiaBeam, Tested at ANL

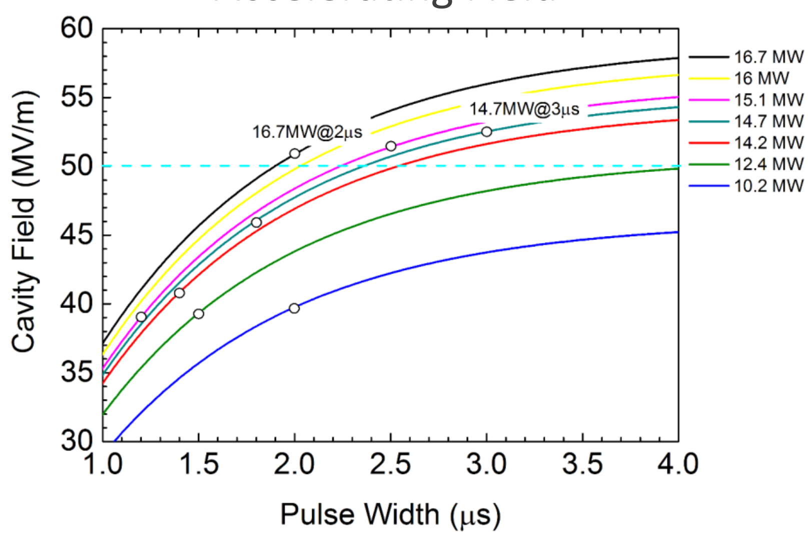
Courtesy Radiabeam



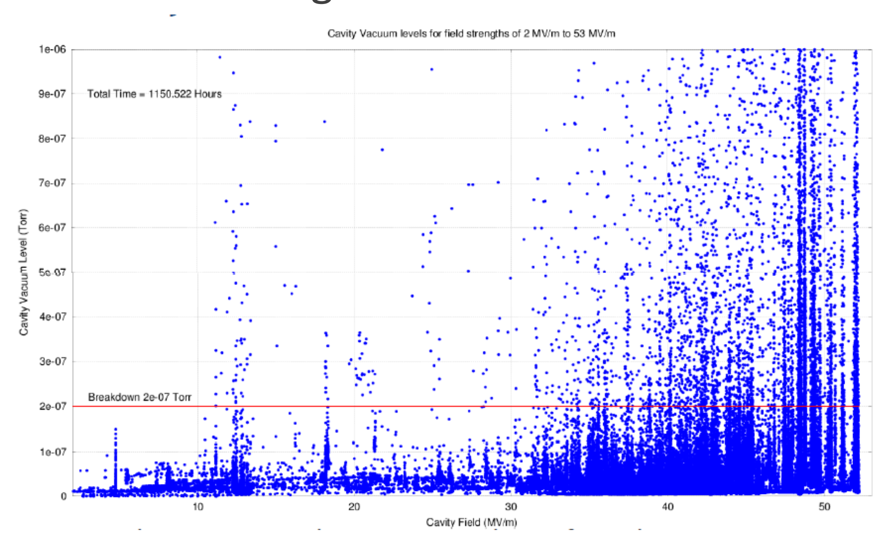
Parameter	Simulated value
f_π	2.856 GHz
R_s (Effective R_s)	93 MΩ/m (51 MΩ/m)
Δf	2.5 MHz
Q_0	19,500
R/Q	143.2 Ω
E_{acc}	50 mV/m
E_{max}/E_{acc}	1.8
P_{diss}/cell	2.4 MW

✓ High-Power Test Results at Argonne RF Test Facility (APS)

Accelerating Field

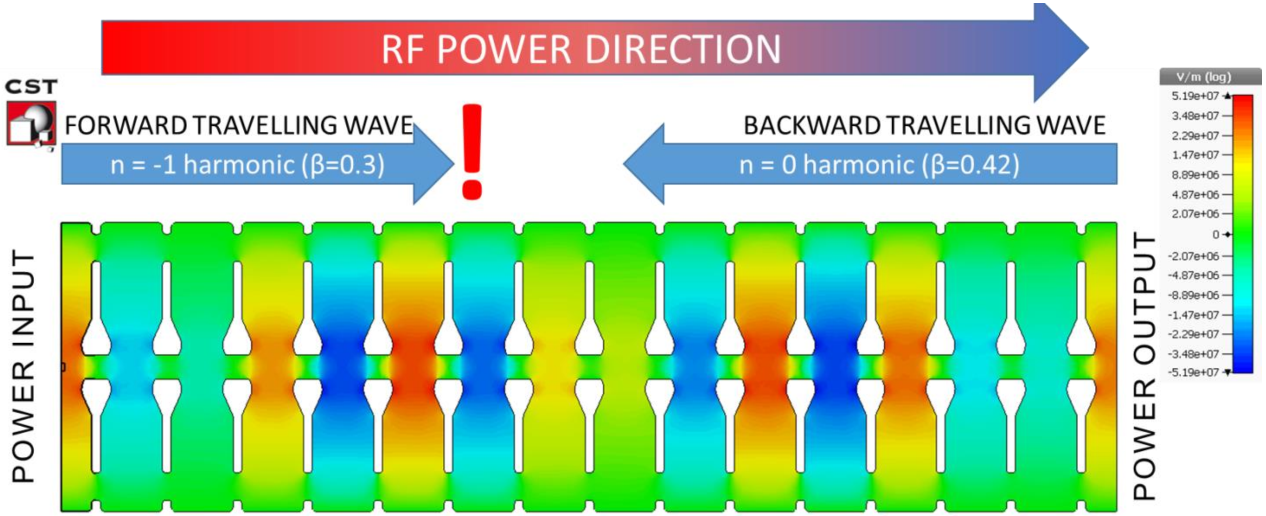


Voltage Breakdown Rate



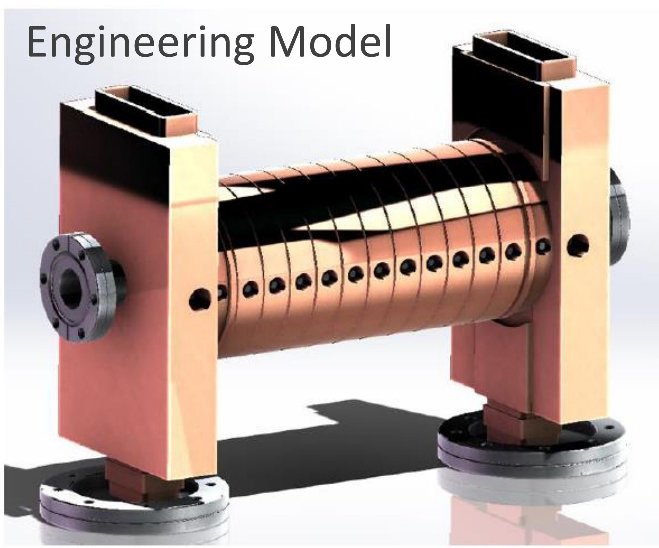
✓ A Structure with similar performance is needed for low-velocity ions …

Negative Harmonic (β~0.3) Traveling Wave Structure, being developed by RadiaBeam & Argonne (SBIR)



Courtesy Radiabeam

Engineering Model



A Prototype Cell

A Compact SC Gantry Concept: Option for Beam Delivery

Layout & Beam Optics Design

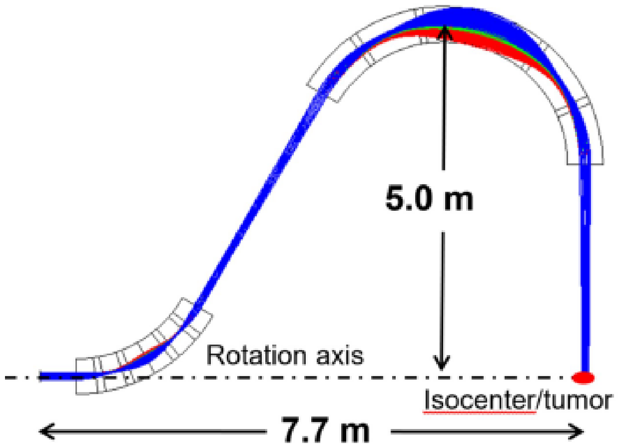


Fig. 1: Layout of carbon isocentric gantry system

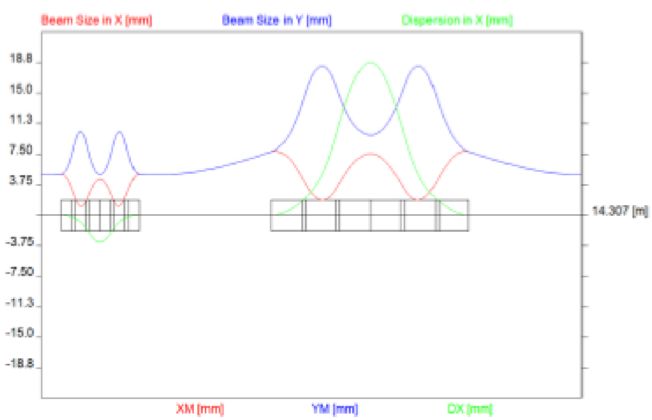
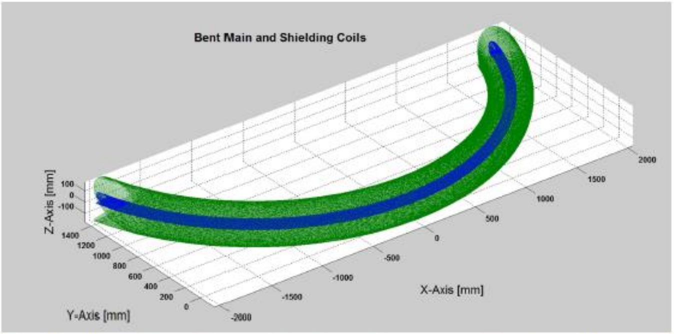


Fig. 2: Beam size and dispersion function with initial ± 5 mm beam size, 10π mm.mrad emittance and ± 2% kinetic energy spread

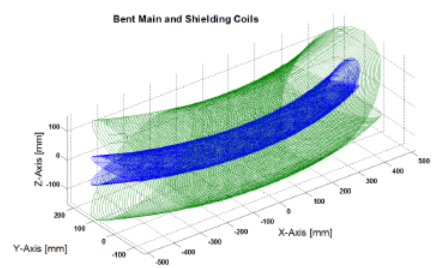
Magnet Technology: Wire & Coil

Multi-Filament Round YBCO Wire		
Parameter	**Unit**	**Quantity**
Wire Diameter	mm	1.3 - 1.6
Ic @ 77 K	A	300
Ic @ 3.5 Tesla, 16-20 K	A	900
Isotropic in Respect to Field Direction	N/A	N/A
Fully Reacted Conductor	N/A	N/A
Minimum Bending Radius	mm	15

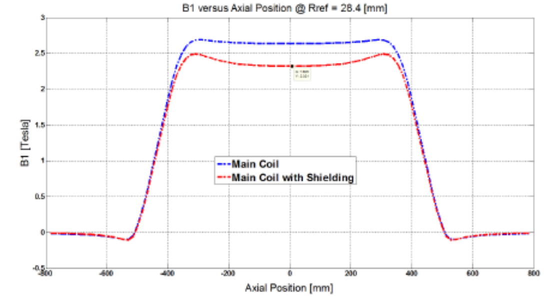


Courtesy AML

Actively shielded 150° dipole coils with 2-m bending radius for carbon gantry. For clarity only 2 winding layers are shown for the Main coil (blue) and for Shielding coil (green).



Actively shielded 60° dipole coils with 1-m bending radius for proton therapy gantry.



Dipole field as a function of axial position. The presence of the outer Shielding coil reduces the field in the beam aperture by about 15 %.

Possibilities with ACCIL: Flexibility in Beam Tuning

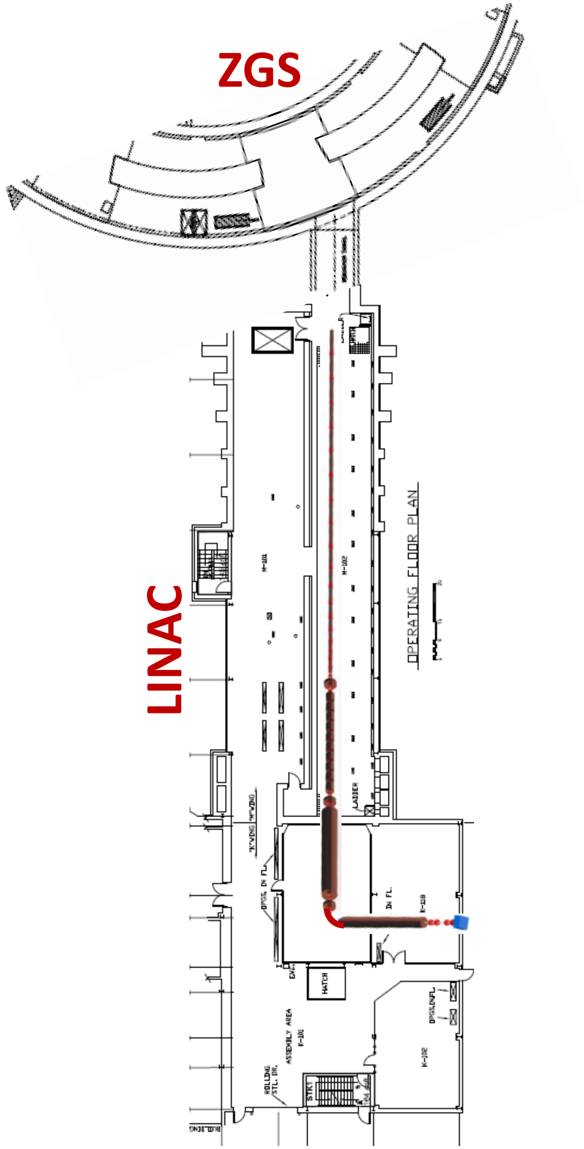
- Capable of accelerating a variety of ion species up to Neon, up to an energy of 450 MeV per nucleon
- Pulse-to-pulse energy modulation with a repetition rate up to 300 Hz
- Intensity modulation is possible by changing the pulse repetition rate
- Fast ion beam switching possible from different ion sources in the front-end
- In principle, fast and effective multi-ion multi-energy multi-intensity ion beam therapy is possible with ACCIL
- …

Possibilities with ACCIL: Applications

- ACCIL was designed for carbon ions, but capable of accelerating ions with similar or lower mass-to-charge ratios to the same energy
- Ions lighter than Carbon (Hydrogen, Helium, …) have ranges exceeding the human body and could be used for treatment or imaging
- Ions heavier than Carbon (Oxygen, Neon,…) could be used for treatment even though their range will be shorter
- Carbon can be used to produce C-11, which is a positron emitter and could be used for treatment and imaging simultaneously
- An ACCIL-based facility will allow comparative studies with different ion species up to Neon.
- Adding a compact SC gantry should allow the development of 3D scanning and multi-painting techniques for these ions

Possible Location of ACCIL-Based Facility at Argonne

- The old IPNS site is a prime development location for ACCIL
- The old Linac building exist and could fit the 50 m ACCIL linac
- The building has the required infrastructure: Water, Power & Cranes …
- Using the Linac building and part of ZGS for treating rooms is a significant saving
- After development, the facility could be moved elsewhere …



Summary

- Hadron and Ion Cancer Therapy is promising
- A Linac-based facility offers more flexibility than existing cyclotrons and synchrotrons with lower construction and operating costs
- The ACCIL design for a Carbon Ion Linac was developed at Argonne
- The required high-gradient accelerating structures are being developed by RadiaBeam and Argonne
- A concept for a compact SC gantry exist
- An estimated cost for an ACCIL-based facility at the old IPNS site is ~ 100 M$, much less than the 200-300 M$ for other CIT centers