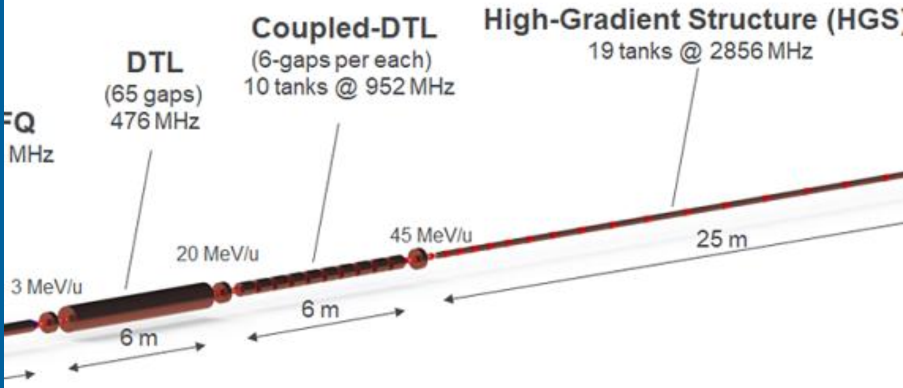
HIAT-2022 CONFERENCE

DARMSTADT, GERMANY, JUNE 27 – JULY 1ST, 2022

Argonne NATIONAL LABORATORY 75 1946–2021

DEVELOPMENTS TOWARDS A COMPACT CARBON ION LINAC FOR CANCER THERAPY



PRESENTER

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U.S. DEPARTMENT OF ENERGY

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June 27th, 2022

HIAT Conference (via Zoom)

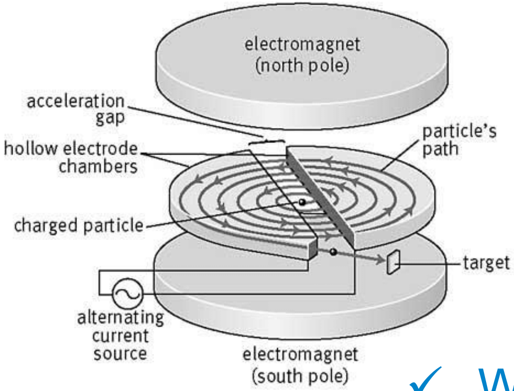
Content

- ❑ Accelerators in Ion Beam Therapy – Why not a Linac?
- ❑ Overview of the Advanced Compact Carbon Ion Linac (ACCIL) Design
- ❑ Main Design Choices / Features of the ACCIL Linac
- ❑ Development of High-Gradient Structures for Ion Beams
- ❑ ACCIL Capabilities for Ion Beam Therapy and Other Applications
- ❑ Future Plans

Accelerators in Ion Beam Therapy

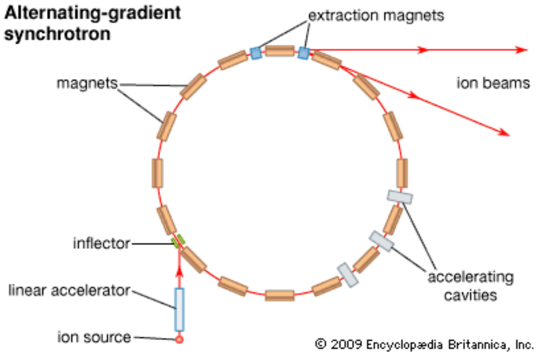
✓ Cyclotrons for protons

Fixed-energy
cw machine



✓ Synchrotrons for carbon ions

Variable energy
Pulsed machine



✓ Why Not a Linac?

	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 energy degrader	Good	Better
Repetition rate	-	~ 1 Hz	~ 100 Hz

Why Not a Linac?

- ✓ Using the same technology used for high-intensity research machines, a 400 MeV/u carbon ion linac would be 100s meters long!

- ✓ BUT, we don't need a high-intensity machine, only 10^{10} particles/second

- ➢ Low intensity → Small aperture → High frequency → High voltage
- ➢ Low intensity → Short pulses → Low duty cycle → Even higher voltage

- ➢ For protons, carbon and other ions, it's possible to deliver the required beam intensity in ~ μs long pulses at ~ 100 Hz repetition rate

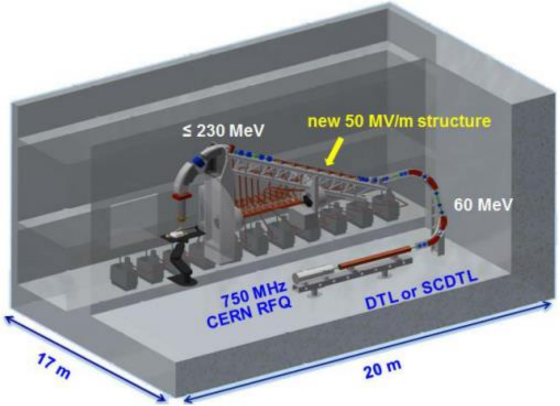
- ➢ We can take advantage and build on recent progress in high-frequency high-gradient structure R&D for electrons

Linacs for Proton / Ion Therapy

- ✓ First proposal for a proton therapy linac: R. W. Hamm et al, "Preliminary Design of a Dedicated Proton Therapy Linac", Proceedings of PAC-91

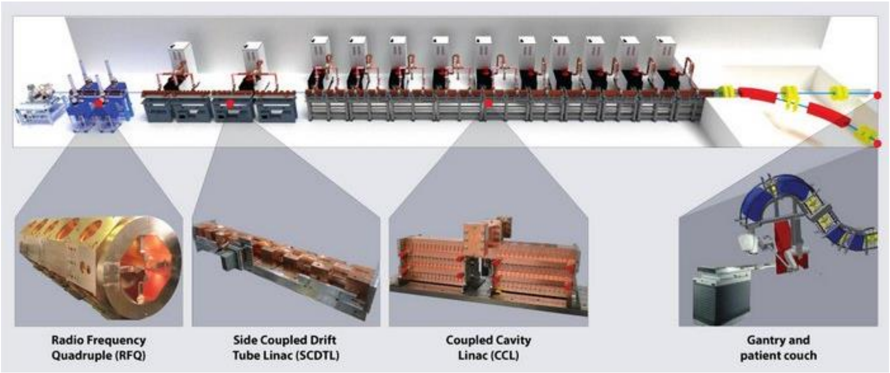
- ✓ Recent developments in Europe → The LIGHT system is now operational in the UK

TULIP (p)



LIGHT (p)

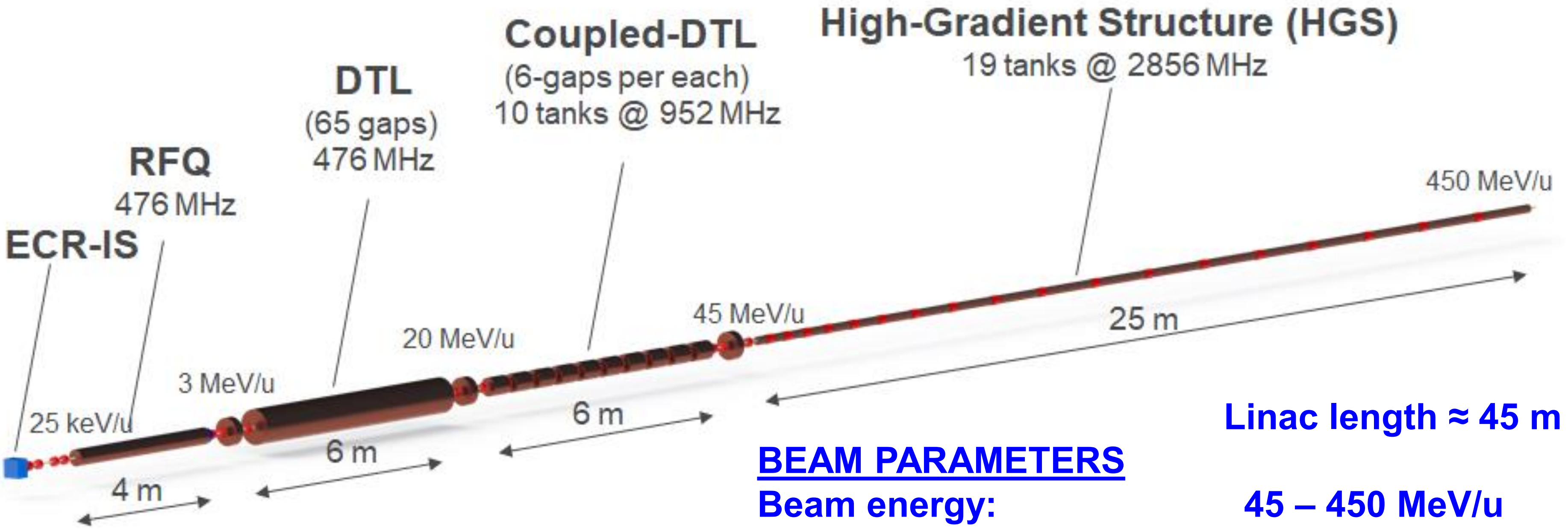
by Advanced Oncotherapy



Others: CABOTO (C), LIBO, IMPLART, PERLA,…

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

ACCIL: Advanced Compact Carbon Ion Linac



Linac length ≈ 45 m

BEAM PARAMETERS	
Beam energy:	**45 – 450 MeV/u**
Beam intensity p/ion	**10^{10} p/s - 10^{9} ion/s**
Beam pulse length:	**500 ns**
Repetition rate:	**120 Hz**

P. Ostroumov et al, NAPAC 2016

✓ **Key Component: High-Gradient Structures for Low-Velocity Ions**

ACCIL DESIGN FEATURES

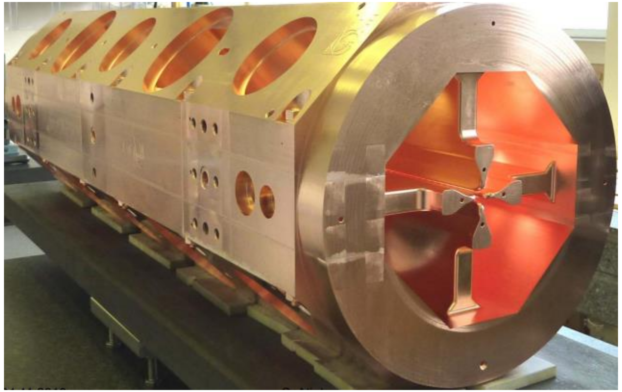
Main Design Features / Choices for ACCIL

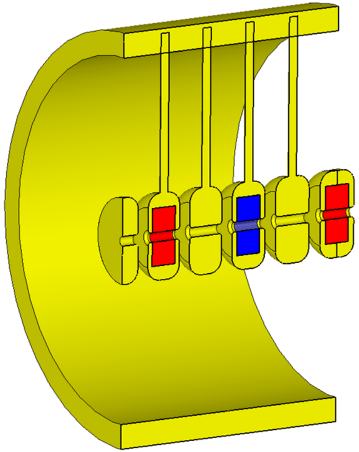
- ✓ Required carbon beam intensities can be provided by commercial ECRs, a 5+ charge state for carbon beam is selected to avoid contaminants
- ✓ The acceleration starts with a 476 MHz RFQ designed for $^{12}C^{5+}$
- ✓ Stripping to 6+ after RFQ, further acceleration by a DTL with PMQs designed to focus both proton and carbon beams without tuning
- ✓ Frequency transition and further acceleration and by a CCDTL at 972 MHz
- ✓ Transition to high-energy linac at 45 MeV/u, based on S-band accelerating structures (2856 MHz) using commercially available klystrons
- ✓ High accelerating gradients up to 50 MV/m in S-band structure are possible due to very short RF pulse, less than 1 μs - Manageable voltage breakdown rate
- ✓ Short beam pulses are acceptable because the average current is very low
- ✓ High repetition rate of beam pulses, ~ 100 Hz or higher, is required for fast scanning of a tumor

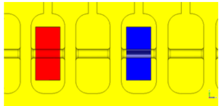
476 MHz RFQ and DTL – Design Parameters

	RFQ	DTL
Ions	C^{5+}	C^{6+}
Energy in, MeV/u	0.025	-
Energy out, MeV/u	3	20
Length, m	4	5.82
Epeak, Kilpatrick units	2.6	2.0
Aperture radius, mm	2.0	5.0
Q_0	10^4	$5*10^4$
Intervane voltage, kV	80	-
Real estate acc. Gradient, MV/m	~1.0	3.5
P_{pulse}, MW	0.44	4.88

Brazed 352 MHz Linac4 RFQ segment (Courtesy of CERN)

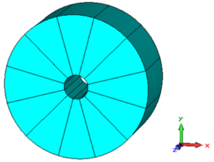






FODO lattice

$L_f = 4\beta\lambda$



PMQ (140 T/m)

DTL with permanent magnet quadrupole focusing – non tunable

PMQ Focusing in DTL for Carbon & Proton

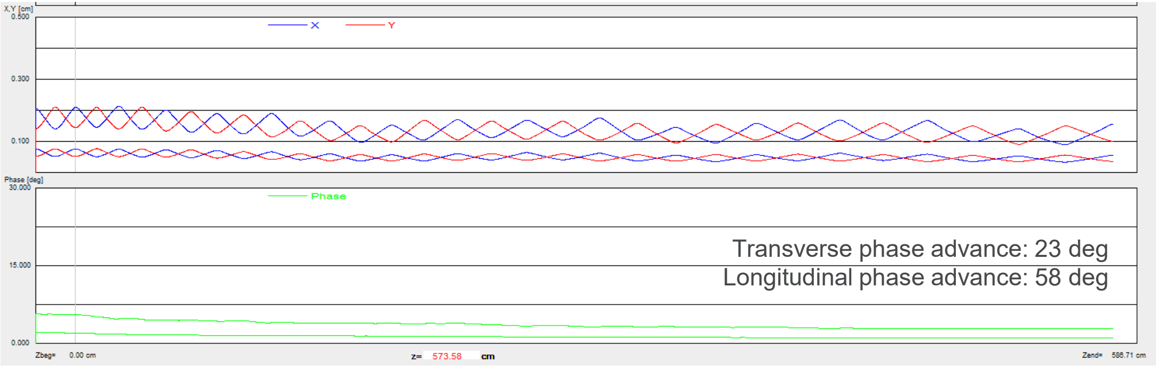
Non-tunable PMQs

↓

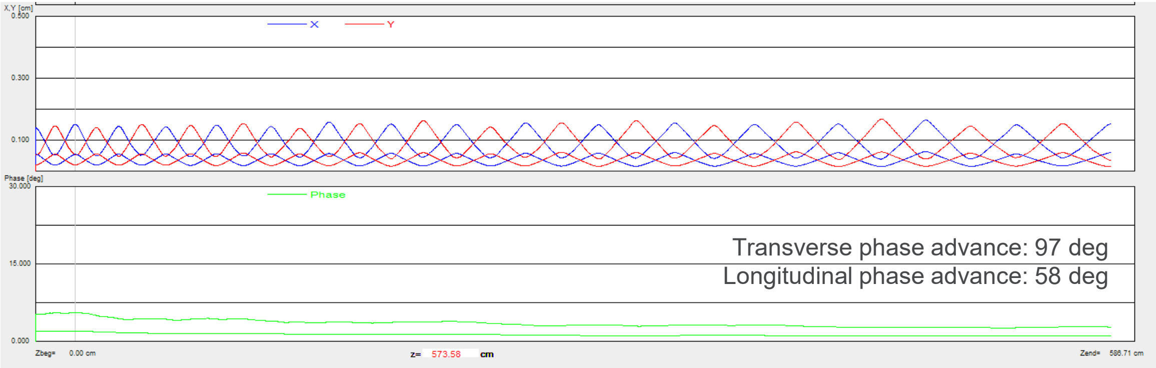
Different transverse phase advances for proton and carbon

Accelerating rate is the same

Carbon Beam in DTL

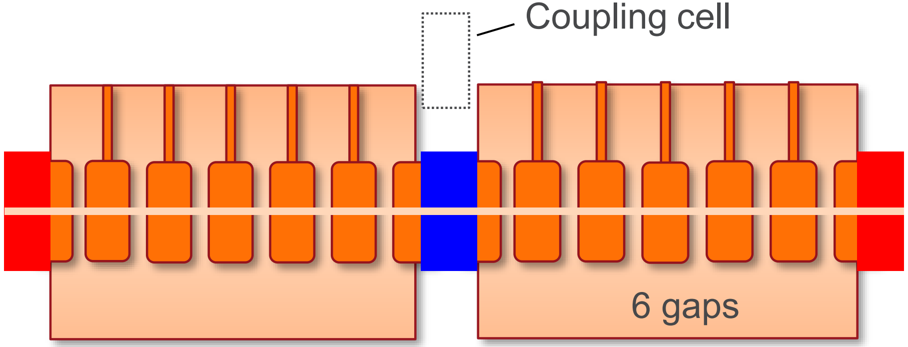


Proton Beam in DTL

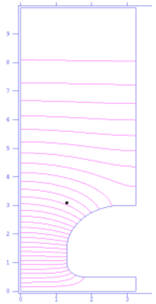


972 MHz Coupled Cavity DTL

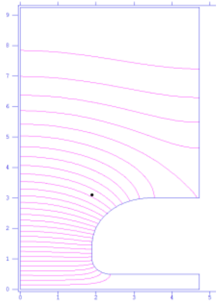
- Ions: Carbon (6+)
- Energy Range: 20 – 45 MeV/u
- Length: 0.37-0.54 m
- Q: 35 000
- RF Power : 12.7 MW
- ZT^2 = 54 MΩ/m
- E_{smax}: 2.05 Kilpatricks
- 2a = 1.0 cm
- E_0 = 18-17 MV/m
- E_0T = 12 MV/m
- φ_s = -24..-17 deg
- 3τ = 52 μsec
- Δ = 0.2% @ 120 Hz
- G = 90 T/m
- L_q = 6.2 cm



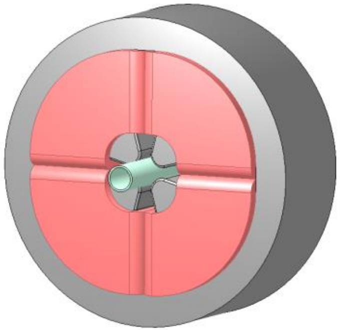
10 tanks $L_f \approx (13 - 15)\beta\lambda$



First tank cell
β = 0.2



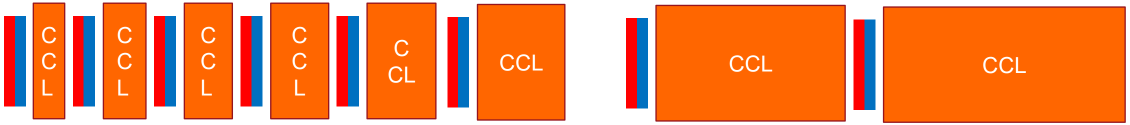
Last tank cell
β = 0.3



Compact EMQ (90 T/m)

2856 MHz Coupled Cavity Linac (CCL)

Constant E0T = 50 MV/m along the whole high-β section (19 tanks)



Doublet focusing lattice

Ions: Carbon (6+)

Energy Range: 45 – 450 MeV/u

Length: 0.32-1.4 m

Q: 7500..17000

RF Power : 1065 MW

ZT^2 = 19..57 MΩ/m

E_{smax}: 2.2-1.6 Kilpatricks

2a = 0.6 cm

E_0 = 67-70 MV/m

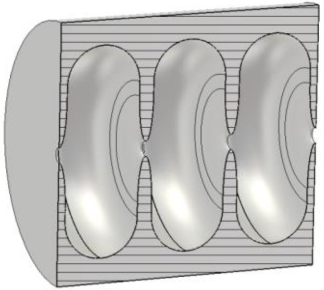
E_0T = 50 MV/m

φ_s = -20 deg

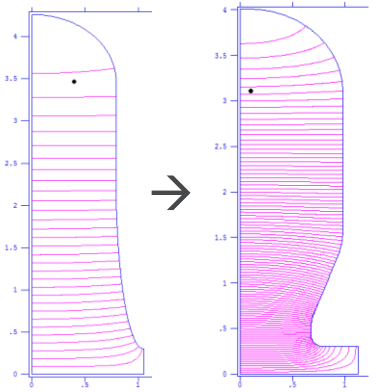
G = 200 T/m

L_q = 10.0 cm

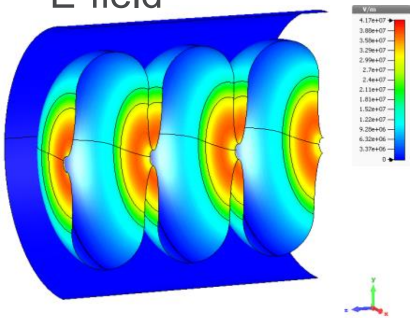
Elliptical disk tips



Geometry may be optimized to maximize power efficiency with reasonable peak fields



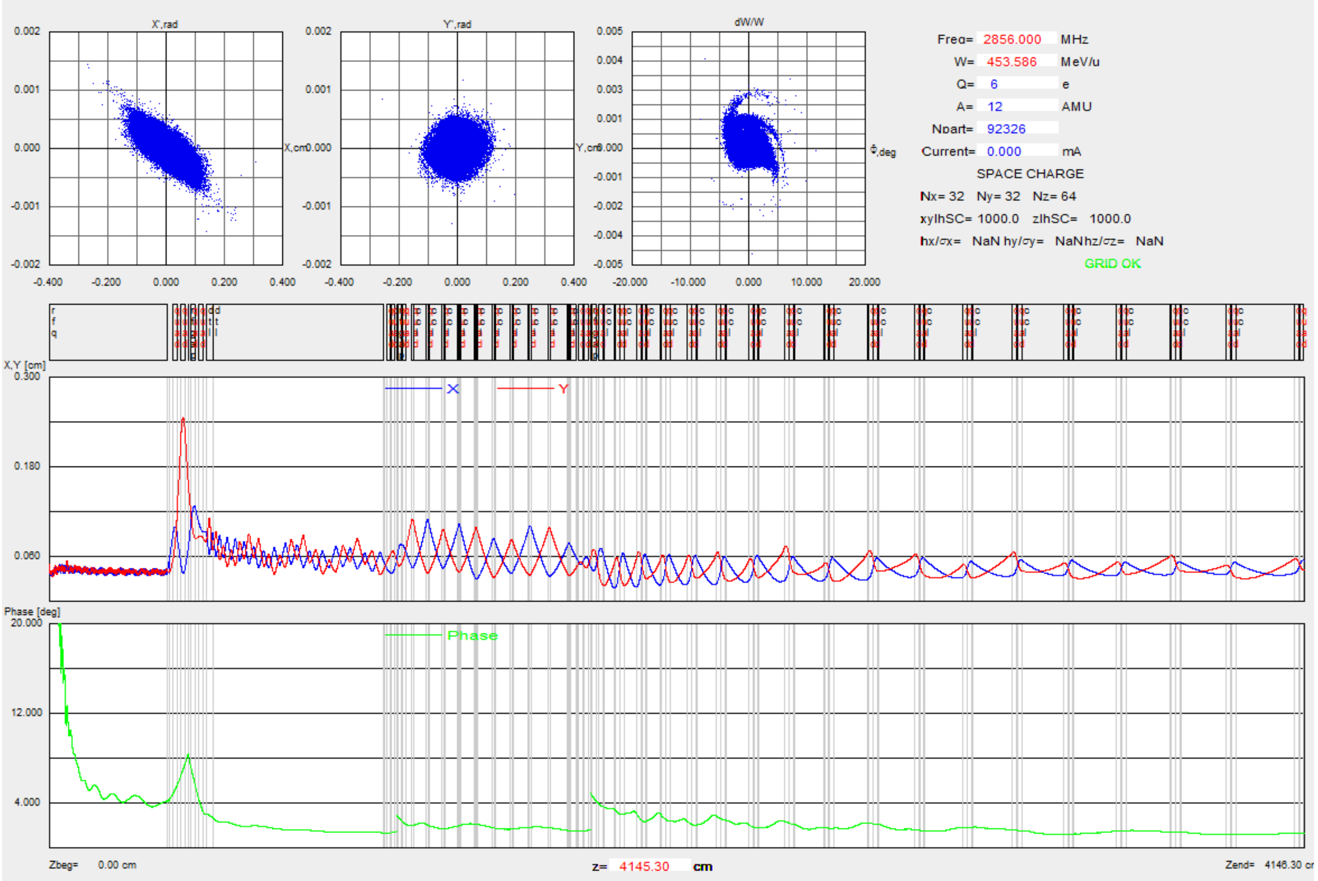
E-field



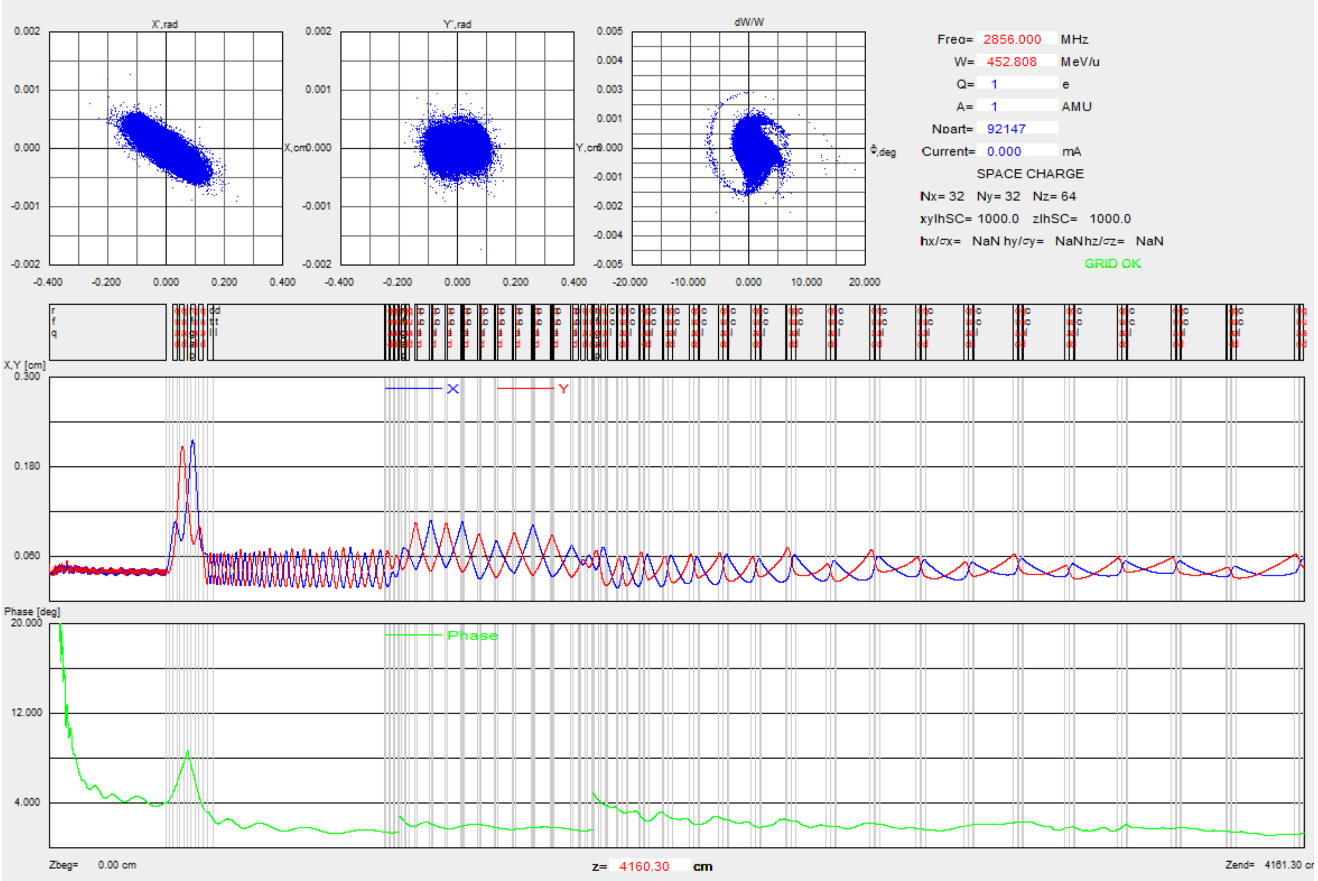
Cells for β=0.43

Geometry	Elliptical tips	Drift tubes
Esmax [Kp]	1.9	3.2
ZT^2 [MΩ/m]	32	59

End-to-end Beam Dynamics - Carbon

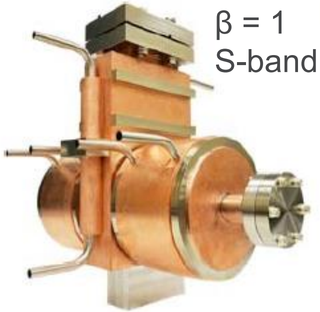


End-to-end Beam Dynamics - Protons

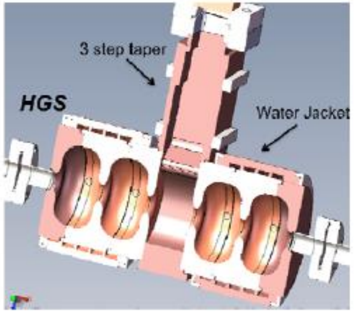


DEVELOPMENT OF HIGH-GRADIENT STRUCTURES FOR ION BEAMS

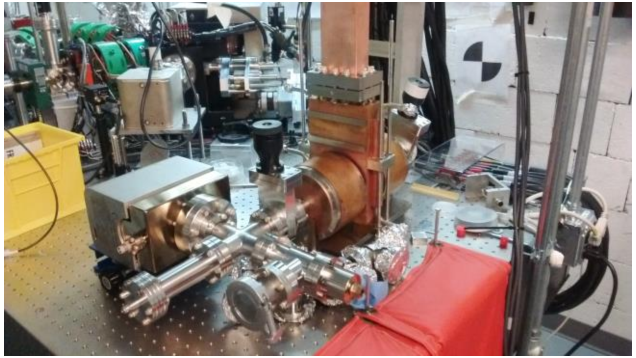
HGS for electrons – built by Radiabeam, tested at Argonne



β = 1
S-band



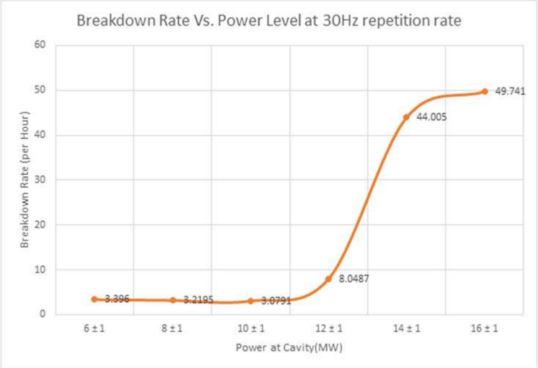
Parameter	Simulated value
f_π	2.856 GHz
R_S (Effective R_S)	93 MΩ/m (51 MΩ/m)
Δf	2.5 MHz
Q_0	19,500
R/Q	143.2 Ω
E_{acc}	50 mV/m
E_{max}/E_{acc}	1.8
P_{diss}/cell	2.4 MW



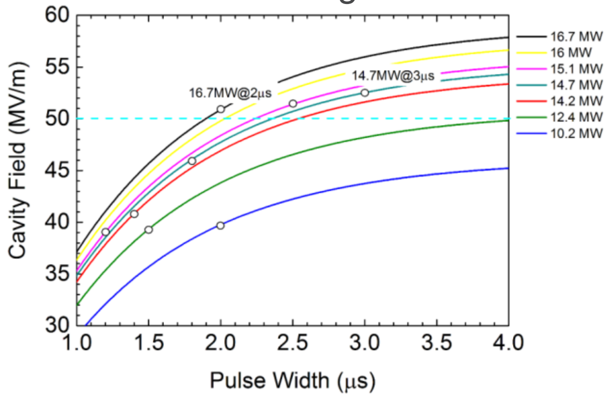
- ✓ Tested at Argonne's High-Power RF Test Facility (APS) up to 52 MV/m @ 30 Hz

Voltage Breakdown Events

Breakdown vs. Power



Accelerating Field

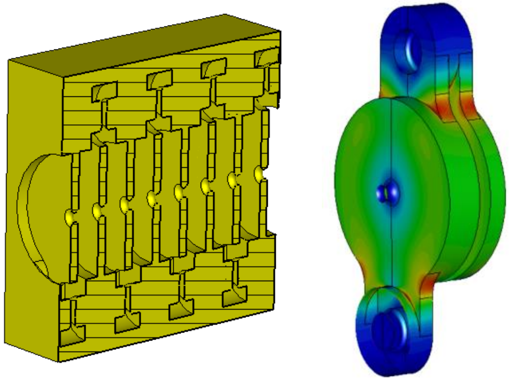


- ✓ A Structure with similar performance is needed for low-velocity ions …

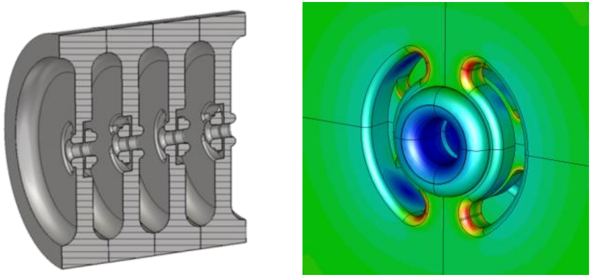
S-Band High-Gradient Structures - Candidates

Standing Wave Structures

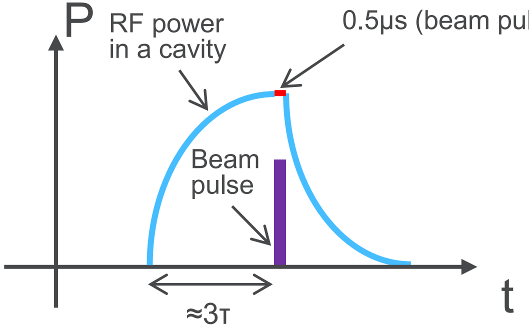
Side-Coupled Structure



Cut-Disk Structure



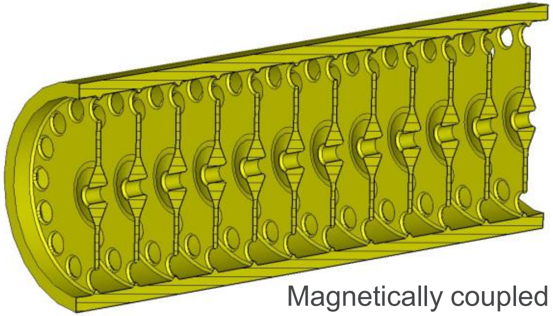
SW vs. TW



- ✓ SW slow filling, longer pulse than TW, affects rep. rate and duty cycle
- ✓ TW requires higher input power to maintain field level and a load to dump output power (~ 50% input)
- ✓ Both have similar power efficiency, peak surface fields and voltage break-down can be minimized
- ✓ SW operate in π-mode, TW offer different phases & harmonics

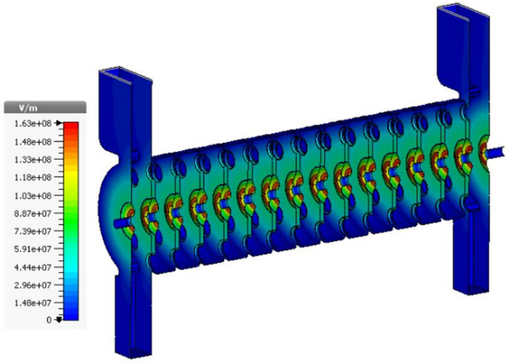
Traveling Wave Structures

Backward Traveling Wave (5π/6)



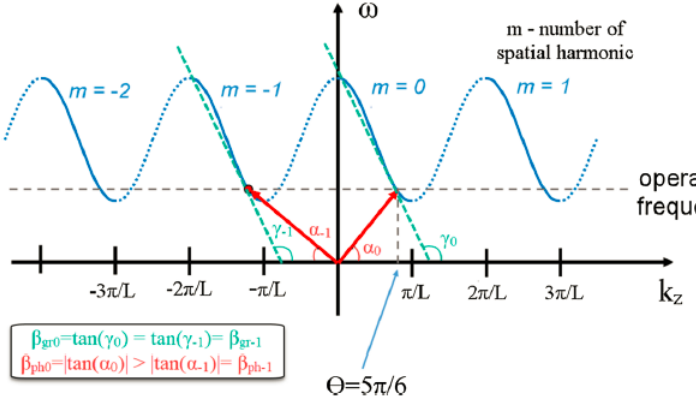
Magnetically coupled

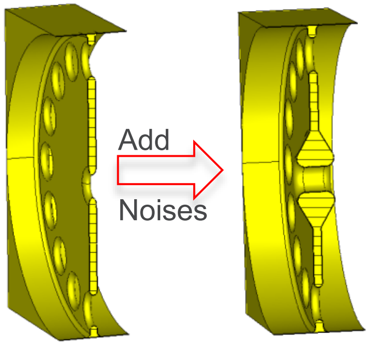
Negative Harmonic Structure (7π/6)

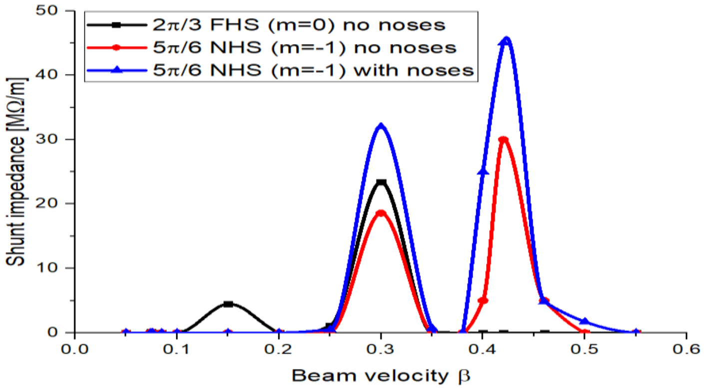


TW – Space Harmonics – Negative Harmonic

- ✓ In TW, the waveform is not a pure sine but consists of an infinite number of spatial harmonics with the same frequency and group velocity, but with different amplitudes and phase velocities.
- ✓ The phase velocity of higher harmonics is lower, and the period length scales as $L = \beta\lambda\left|\frac{\theta}{2\pi} + m\right|$
- ✓ Using the 1st Negative Harmonic, the cell length for β = 0.3 would be equal to that of β = 0.42 of the main harmonic → enhances power efficiency and allows lower transition energy to HGS for ACCIL





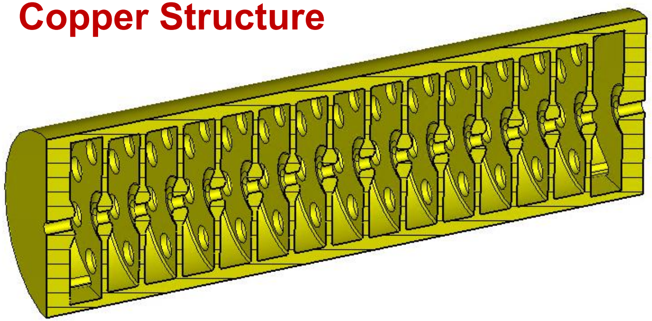


S.V. Kutsaev et al., Phys. Rev. Accel. Beams 20, 120401, 2017.

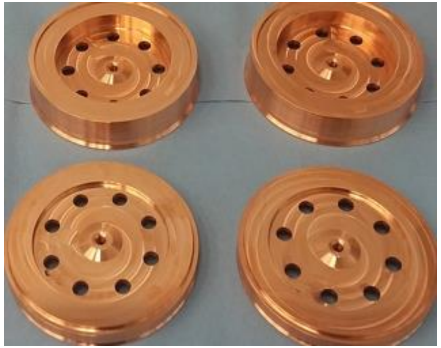
A Novel High-Gradient Traveling Wave Structure

by Radiabeam (DOE/SBIR), S. Kutsaev et al, Phys. Rev. AB 20 (2017)

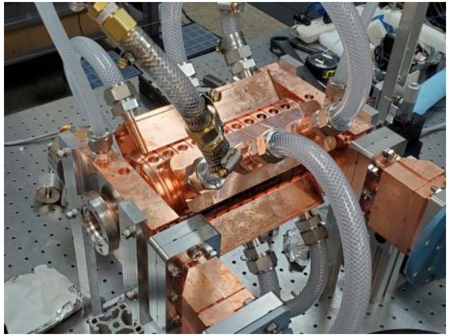
Magnetically Coupled Copper Structure



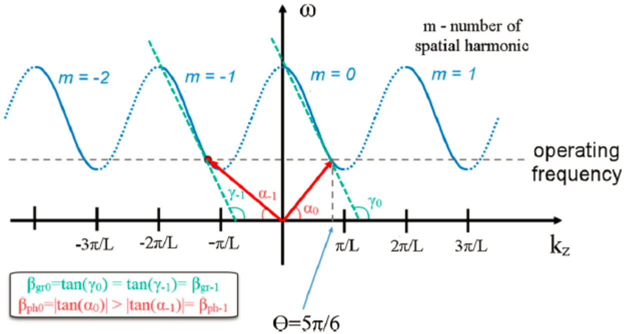
Single Cell Models



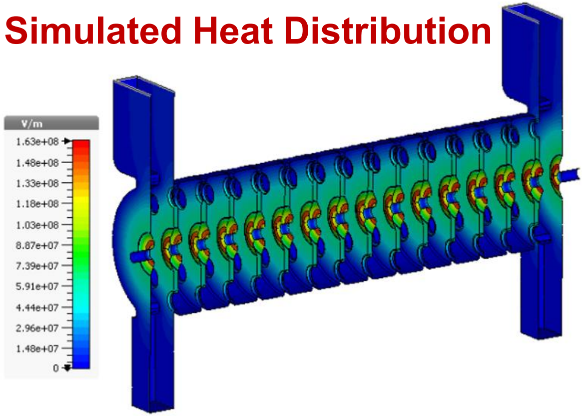
Full Cavity being Tested



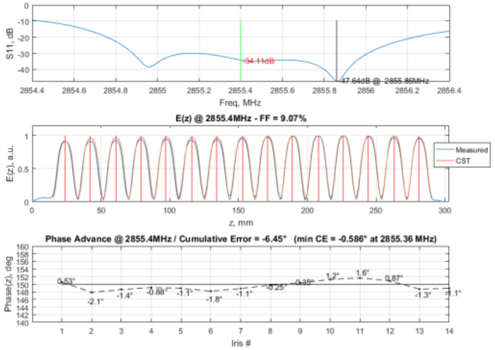
Spatial Negative Harmonic (NHS)



Simulated Heat Distribution

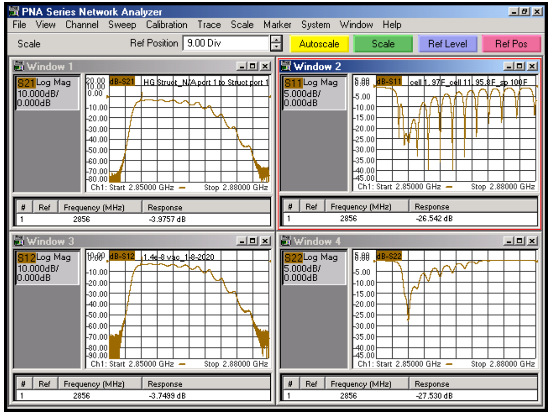


Cavity Tuning Results

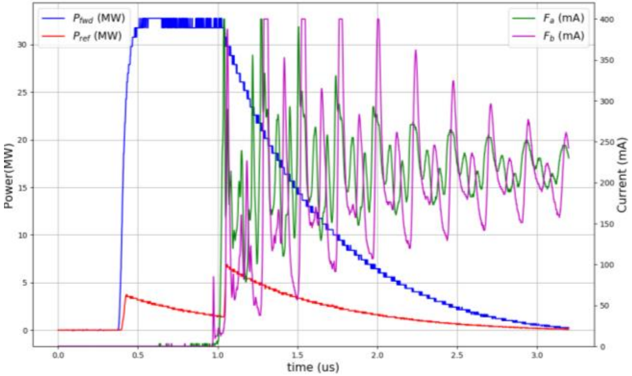


High-Power Testing of the NHS Structure @ ANL

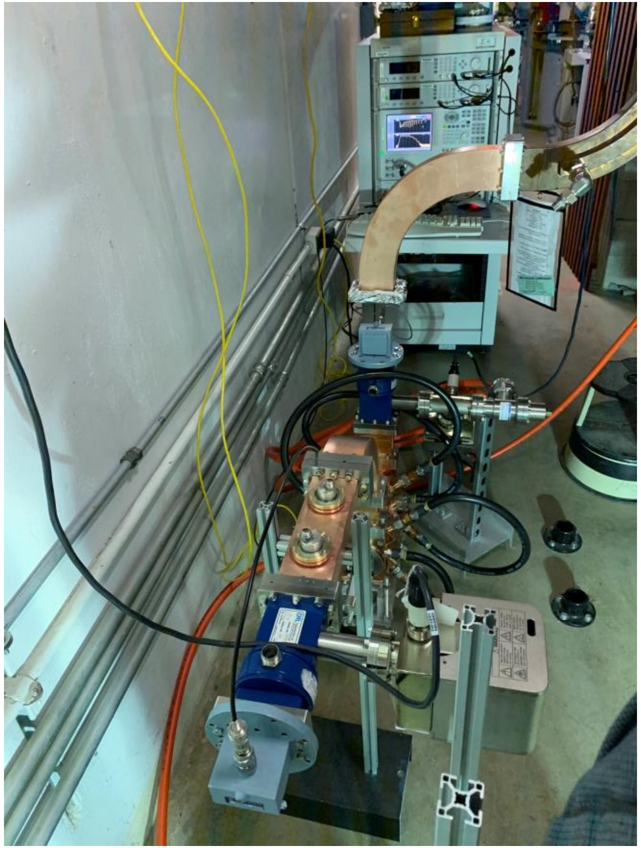
Off-line Testing (low-power)



High-Power Testing



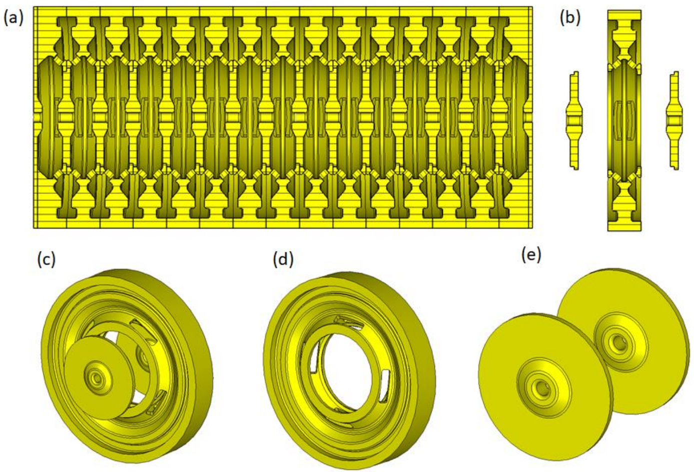
S.V. Kutsaev et al., IEEE Trans. Microw. Wirel. Comp. Lett., 2021



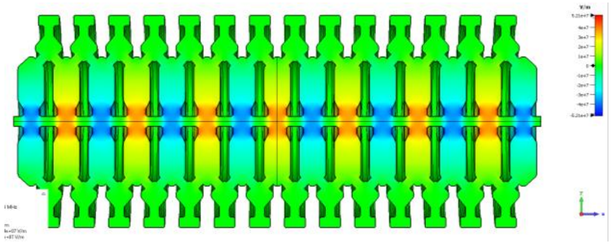
Annular-Coupled HG Standing-Wave Structure

by Argonne (ANL/LDRD), B. Mustapha et al, NAPAC 2019

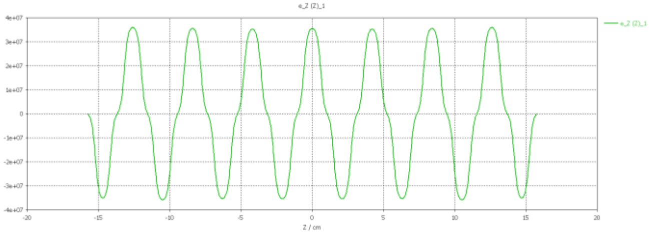
3D Copper Model & Fabrication Method



3D Electric Field Distribution

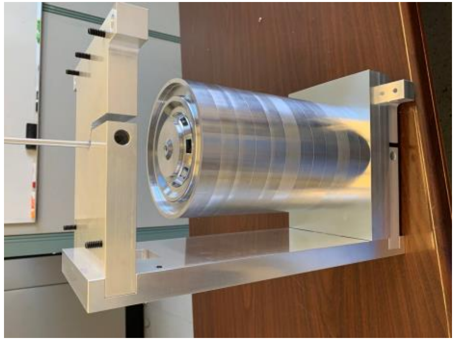


Accelerating Field Profile



Aluminum Model Parts

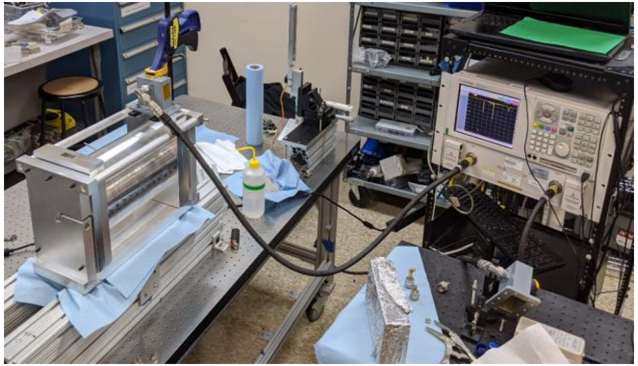
Aluminum Assembly



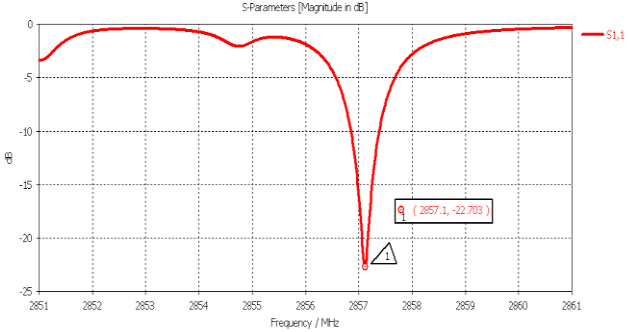
✓ **The Aluminum model is being tested to finalize the design and build the actual copper cavity …**

Cold Model Testing of the ACS Structure @ Radiabeam

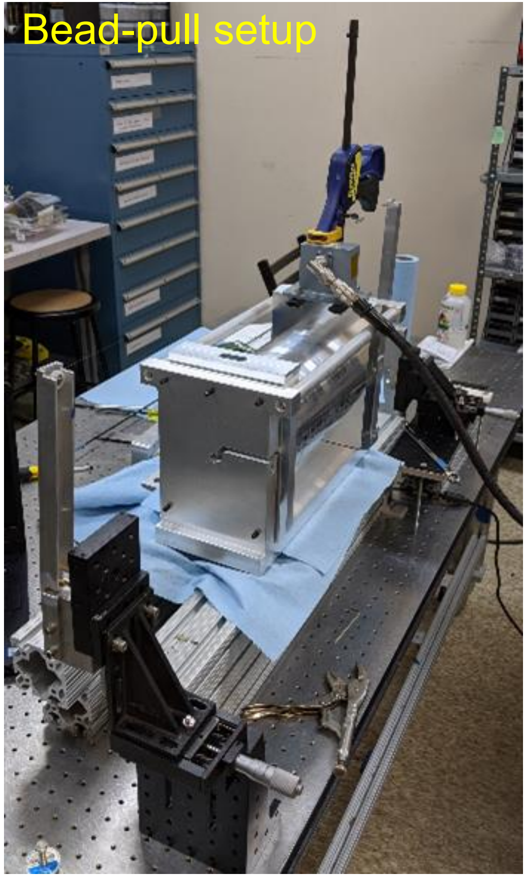
Spectral measurement setup



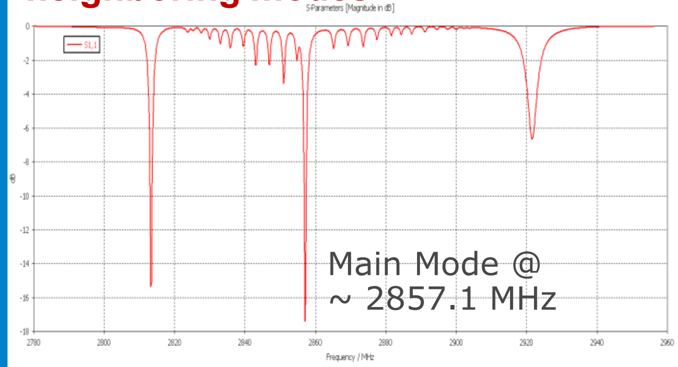
Main mode excitation ~ 2856 MHz



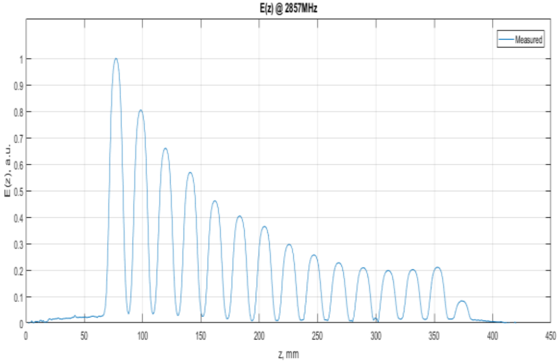
Bead-pull setup



Frequency spectrum, neighboring modes

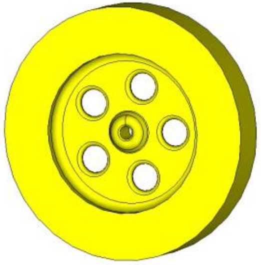


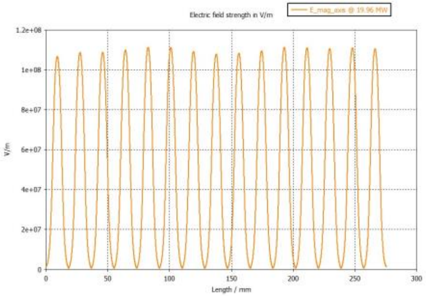
Main mode field profile, no tuners

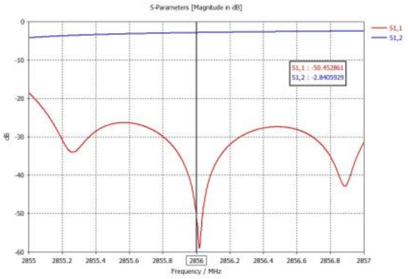


New NHS for β=0.3 and 1000 Hz rep. rate by Radiabeam

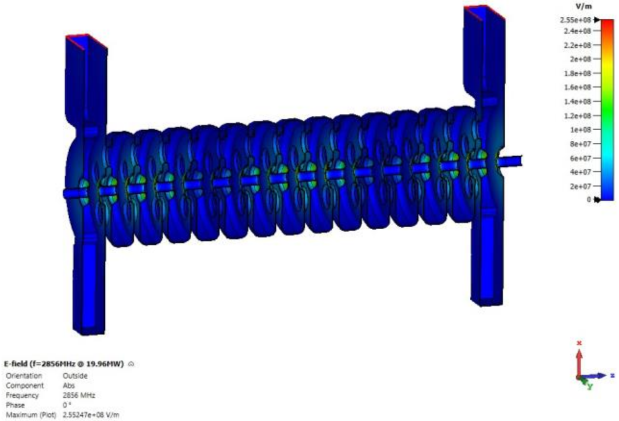
- 15 cell structure design, tuned including input and output couplers

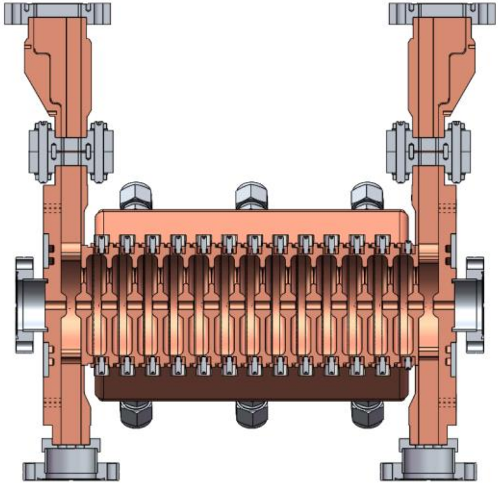






Repetition rate, Hz	120	1000
Phase velocity, c	0.3	0.3
f, MHz	2856	2856
Repetition rate, Hz	120	1000
Pulse Length, ns	700	587
Input RF Power, MW	33.8	19.9
β_{gr} 1st cell, %c	0.12-0.335	0.232-0.43
Fill time, ns	450	287
Shunt Impedance, MΩ/m	32	47
Gradient, MV/m	50	40
Peak E-field @ 40MV/m, MV/m	160	180
Pulse Heating at 1us at 40MV/m, K	28	12.2
<Sc>, MW/mm^2	1.3	1.1





ACCIL CAPABILITIES

ACCIL General Capabilities

✓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

FLASH Capabilities of the ACCIL Linac

✓FLASH Therapy is a “new” fast dose delivery technique that seems to better spare healthy tissues than the traditional slow and fractionated delivery methods …

✓FLASH dose requirements: 40 Gy/s to 100 Gy/s

✓For protons at max energy of 230 MeV

- Beam spot size of ~ 5x5 mm^2, the beam stopping volume (last 10 cm) is 2.5 cm^3
- Assuming beam looses ½ of its energy, the dose in the stopping volume is 64 Gy/s
- Need to increase beam size for 40 Gy/s, and 50% more beam for 100 Gy/s

✓For carbon ions at max energy of 450 MeV/u

- The dose in the stopping volume is 152 Gy/s
- Need to increase beam size for both 40 Gy/s and 100 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

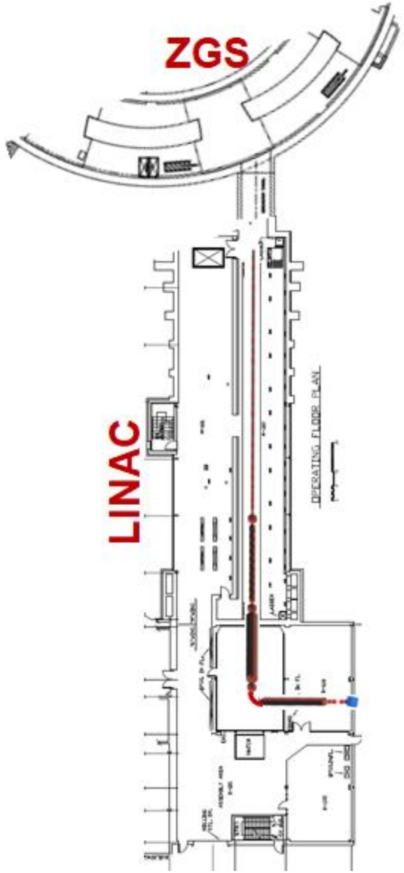
FUTURE PLANS

AITRC: An Advanced Ion Therapy Research Center

- ✓Cancer therapy and radiobiology research with all ion beams up to neon
- ✓Imaging / Tomography (ions lighter than carbon: proton, helium, …)
- ✓ACCIL Combined with a compact SC gantry, will allow the development of 3D scanning and multi-painting techniques for ions
- ✓Combined real-time MRI imaging with beam delivery (gantry or straight lines) will significantly enhance the outcome of ion therapy
- ✓PET imaging using positron emitters (C-11, N-13, O-15, …) produced in the tumor also possible for dose verification
- ✓FLASH Therapy and Other Applications …

Possible Installation at the former IPNS Site

- The former IPNS site is a prime development location for the ACCIL linac and the AITRC center
- The old Linac building exists and could fit the 50 m ACCIL linac. The AGS building can host several beam lines.
- The building has the required infrastructure: Water, Power, Cranes …
- Using the Linac building and part of ZGS for research & treatment would be a significant cost saving
- After accelerator development, initial research program: cellular radiobiology & animal prior to human therapy



Thanks to …

- From Argonne
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- From Radiabeam
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- From MSU FRIB (contribution while at Argonne)
  - P. Ostroumov and A. Plastun
- Others
  - …


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THANK YOU ALL