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Compact Carbon Ion Linac

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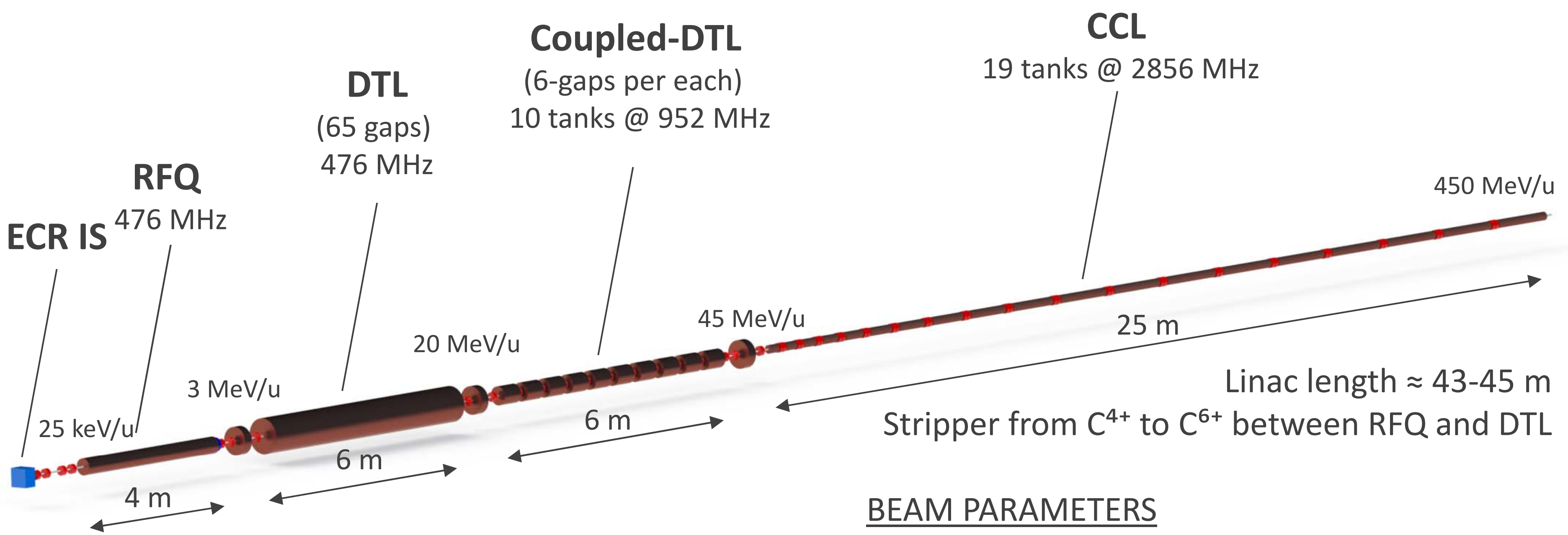
Outline

- Compact Carbon linac
  - General layout
  - Main application
  - Low-β and High-β accelerating structures
  - Power consumption
  - End-to-end beam dynamics simulation
  - Comparison with synchrotron
- Testing of beta=1 high gradient S-band accelerating structure
- Summary

Advanced Compact Carbon Ion Linac (ACCIL)

1 GV voltage over 45 meters



Linac length ≈ 43-45 m

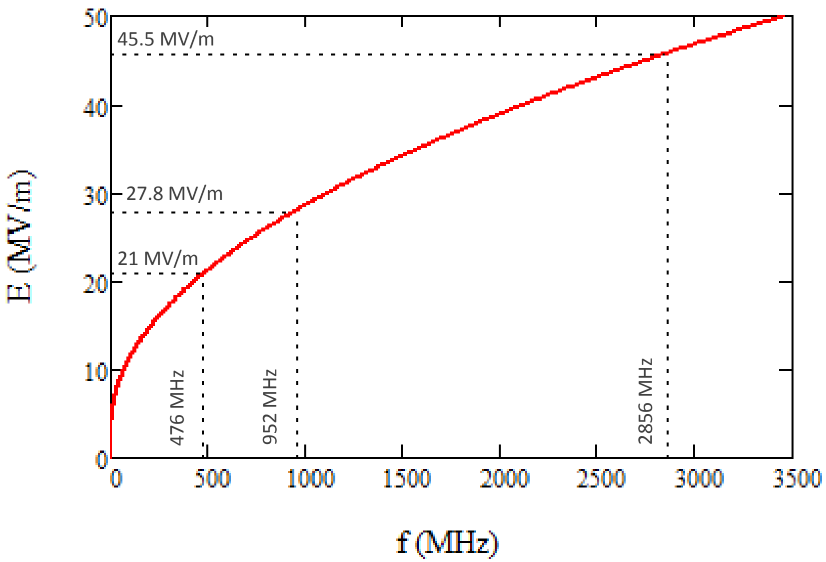
Stripper from C^{4+} to C^{6+} between RFQ and DTL

	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 pμA (10^{10} protons/second), 2.7 pμA (10^{9} ions/second), 11 eμA of $^{12}C^{4+}$
Beam average current:	1.62 enA of proton beam, 0.642 enA of $^{12}C^{4+}$

S-band accelerating structure

Two main reasons to use S-band accelerating structure in therapy linac:

- Higher breakdown limit



$$f(MHz) = 1.64E^2 e^{-8.5/E}, E\left[\frac{\mathrm{MV}}{\mathrm{m}}\right]$$

$$\frac{\Delta W_L}{L} = E_{eff} = E_0 T cos\varphi$$

$$E_{eff} = (k \cdot E_{s\,max}) T cos\varphi$$

$$E_{eff} = (k \cdot b \cdot E_{lim}) T cos\varphi$$

$$k = \frac{E_{s\,max}}{E_0}$$ - depends on geometry (a,Lcell,…)

b – bravery factor

T – transit-time factor

$$\boxed{k, b, T \sim f^?}$$

- Higher effective shunt impedance per unit length

$$ZT^2 = \frac{(E_0 T)^2}{P/L}$$

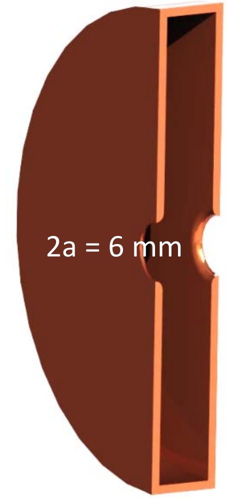
$$ZT^2 \sim \sqrt{f}$$

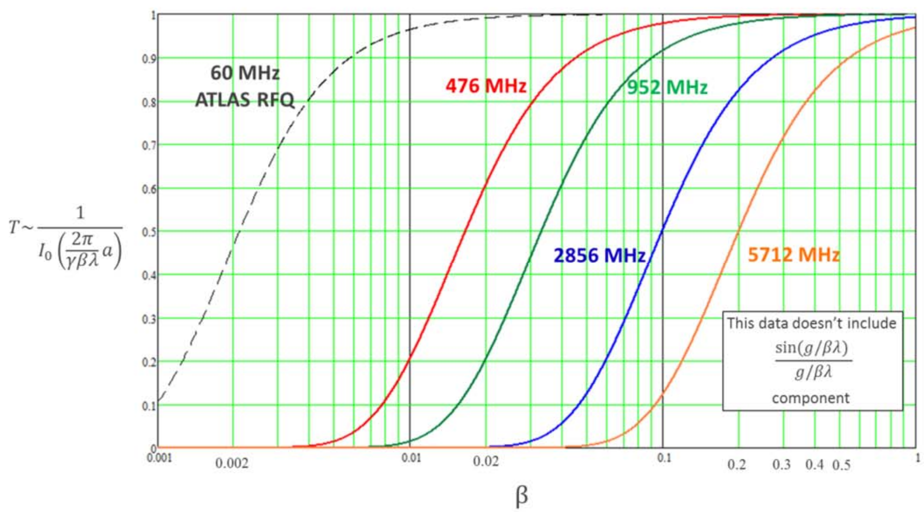
Accelerating efficiency / Effective shunt impedance

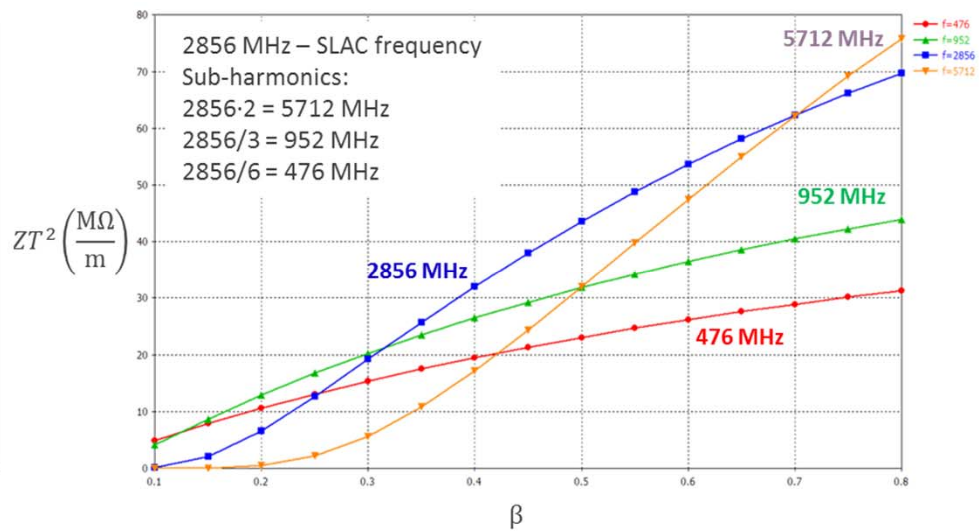
$$\boxed{T \sim \frac{\sin(g/\beta\lambda)}{g/\beta\lambda}}$$

$$\boxed{T \sim \frac{1}{I_0\left(\frac{2\pi}{\gamma\beta\lambda}a\right)}} \Rightarrow ZT^2 \sim \sqrt{f}$$

only @ β → 1 & a → 0

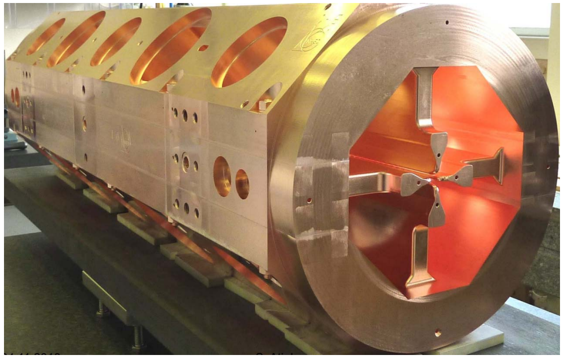




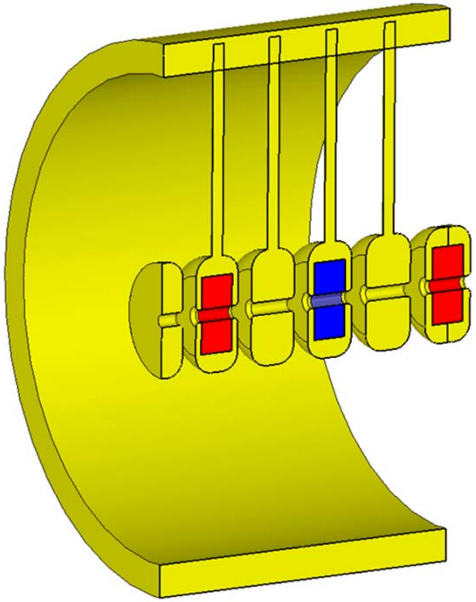


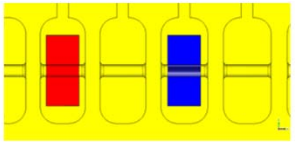
RFQ and DTL (476 MHz)

	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

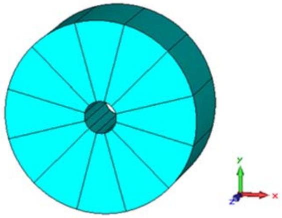


Brazed segment of 352 MHz Linac4 RFQ (Courtesy of CERN)





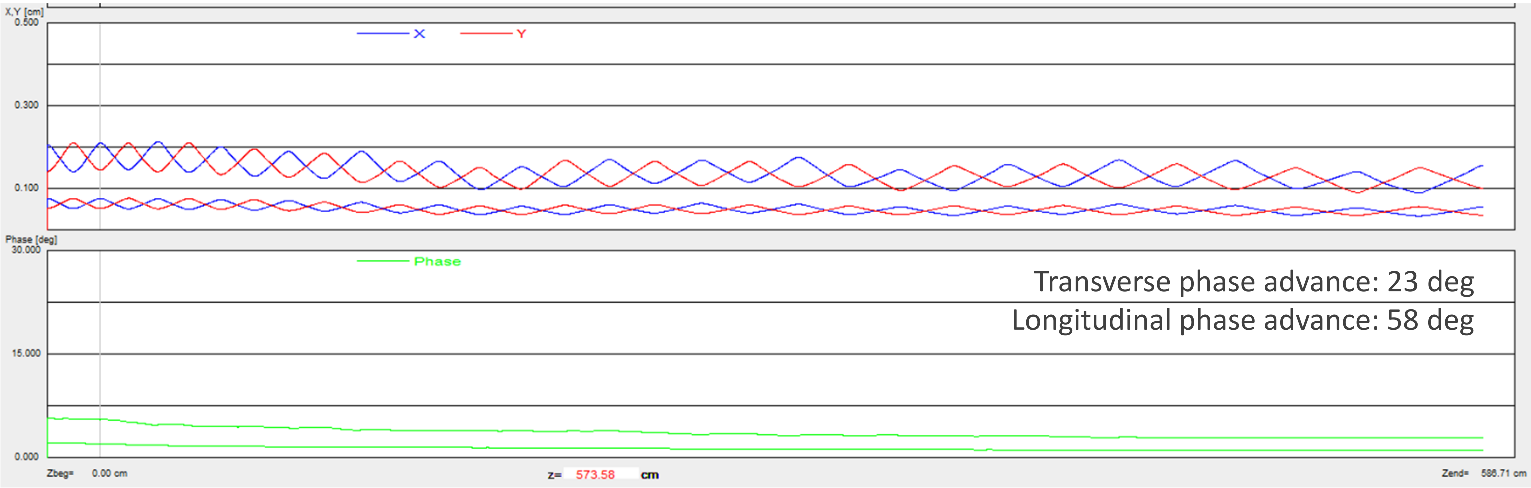
FODO lattice $L_f = 4\beta\lambda$



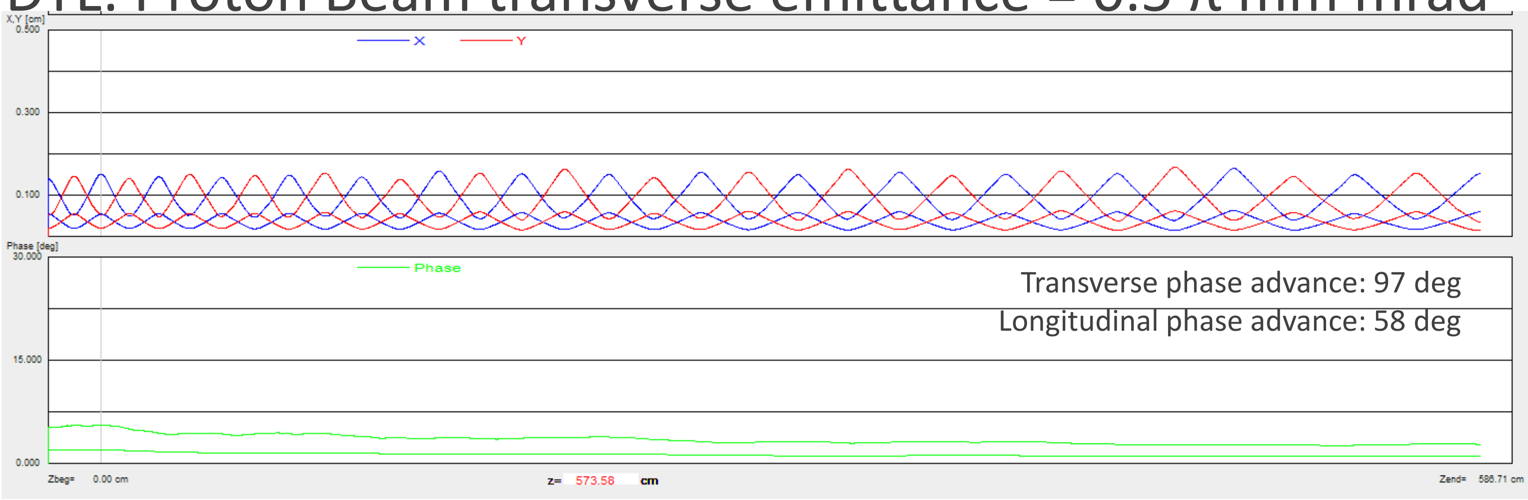
PMQ (140 T/m)

Beam dynamics

DTL: Carbon Beam transverse emittance = 0.5 π mm mrad



DTL: Proton Beam transverse emittance = 0.5 π mm mrad



Coupled-cavity DTL (952 MHz)

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

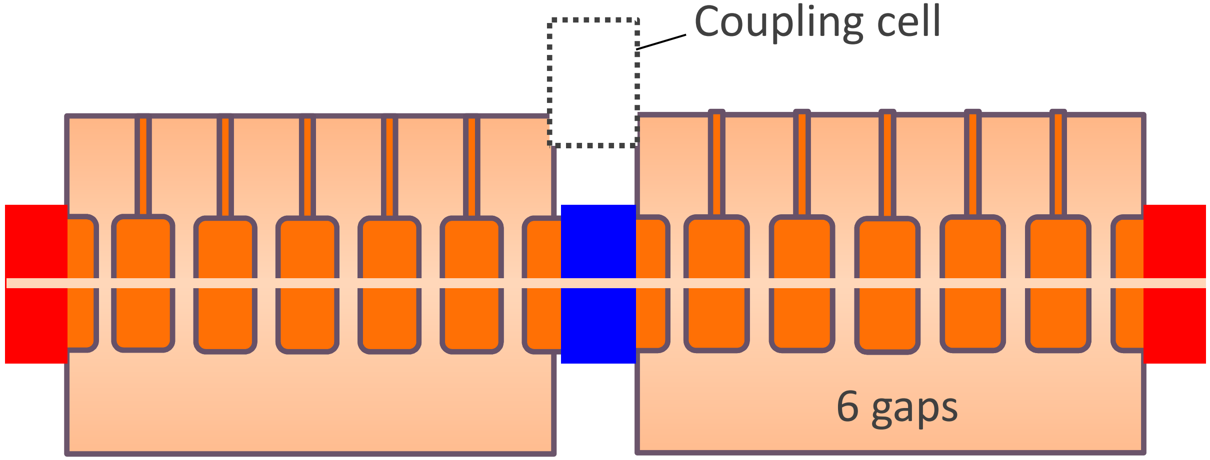
ϕ_s = -24..-17 deg

3τ = 52 μsec

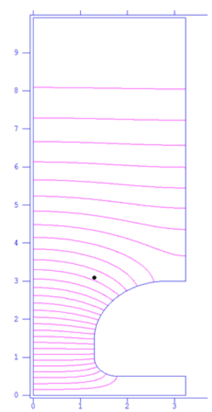
Δ = 0.2% @ 120 Hz

G = 90 T/m

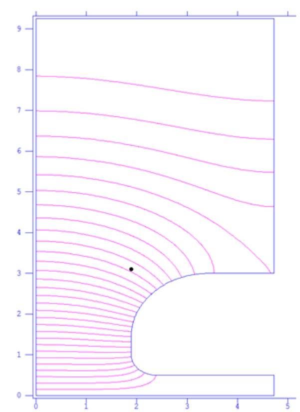
L_q = 6.2 cm



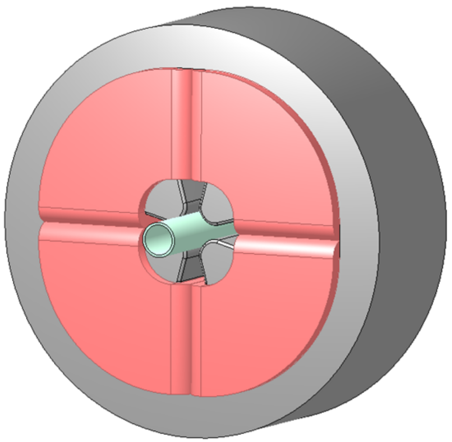
10 tanks $L_f \approx (13-15)\beta\lambda$



First tank cell
β = 0.2



Last tank cell
β = 0.3

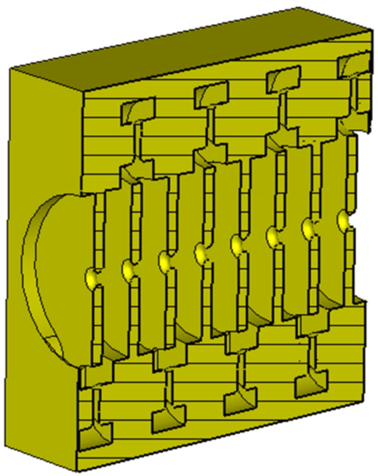


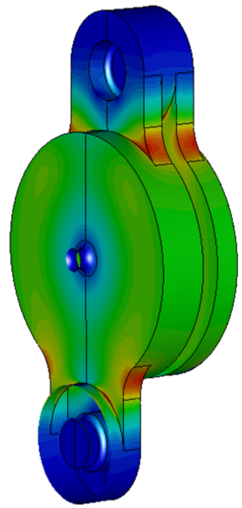
Compact EMQ (90 T/m)

High-Gradient S-band standing wave structures

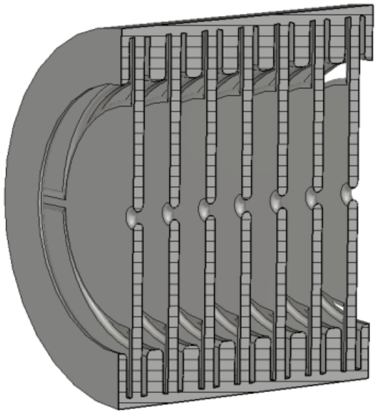
SW stabilized 50 MV/m structures

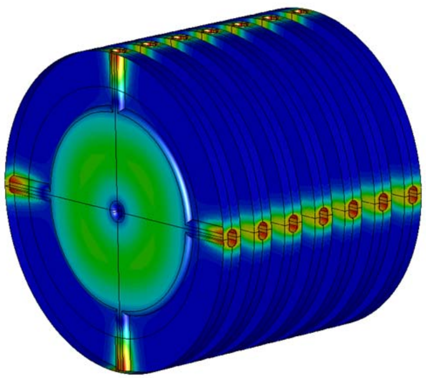
Side-Coupled Structure



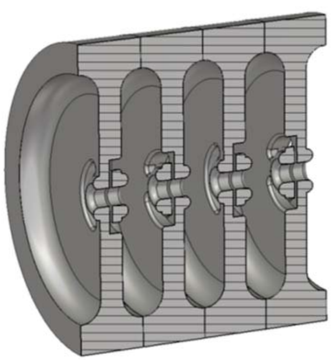


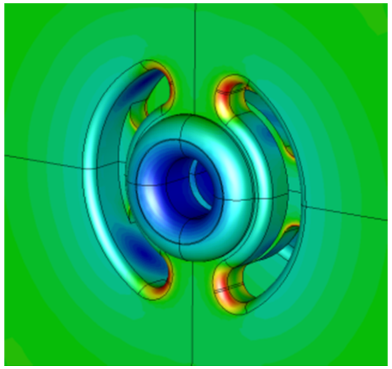
Disk-And-Washer structure



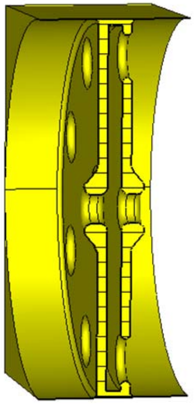


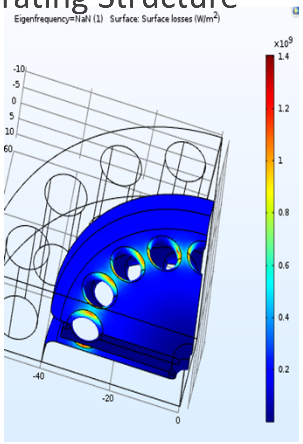
Cut-Disk Structure





Biperiodic Accelerating Structure





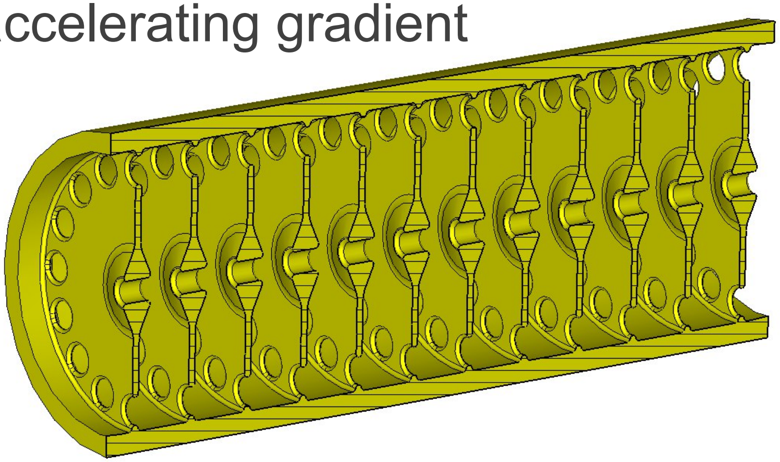
By Evgeny Savin (RadiaBeam)

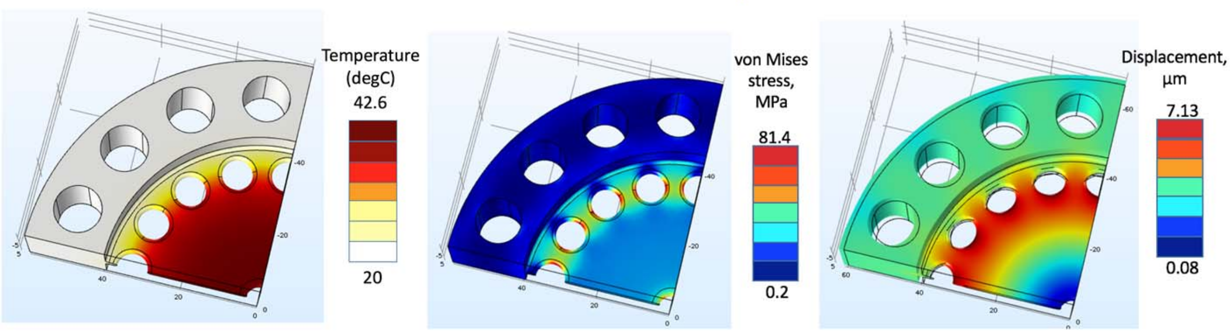
The choice of structure for high-β part will be based on thermal and mechanical design

Backward traveling wave (BTW)

- Magnetic coupling through off-axis holes
- Can provide high accelerating gradients due to reduced density of Poynting vector
- Designed to operate at constant accelerating gradient

Beta = 0.43 BTW structure

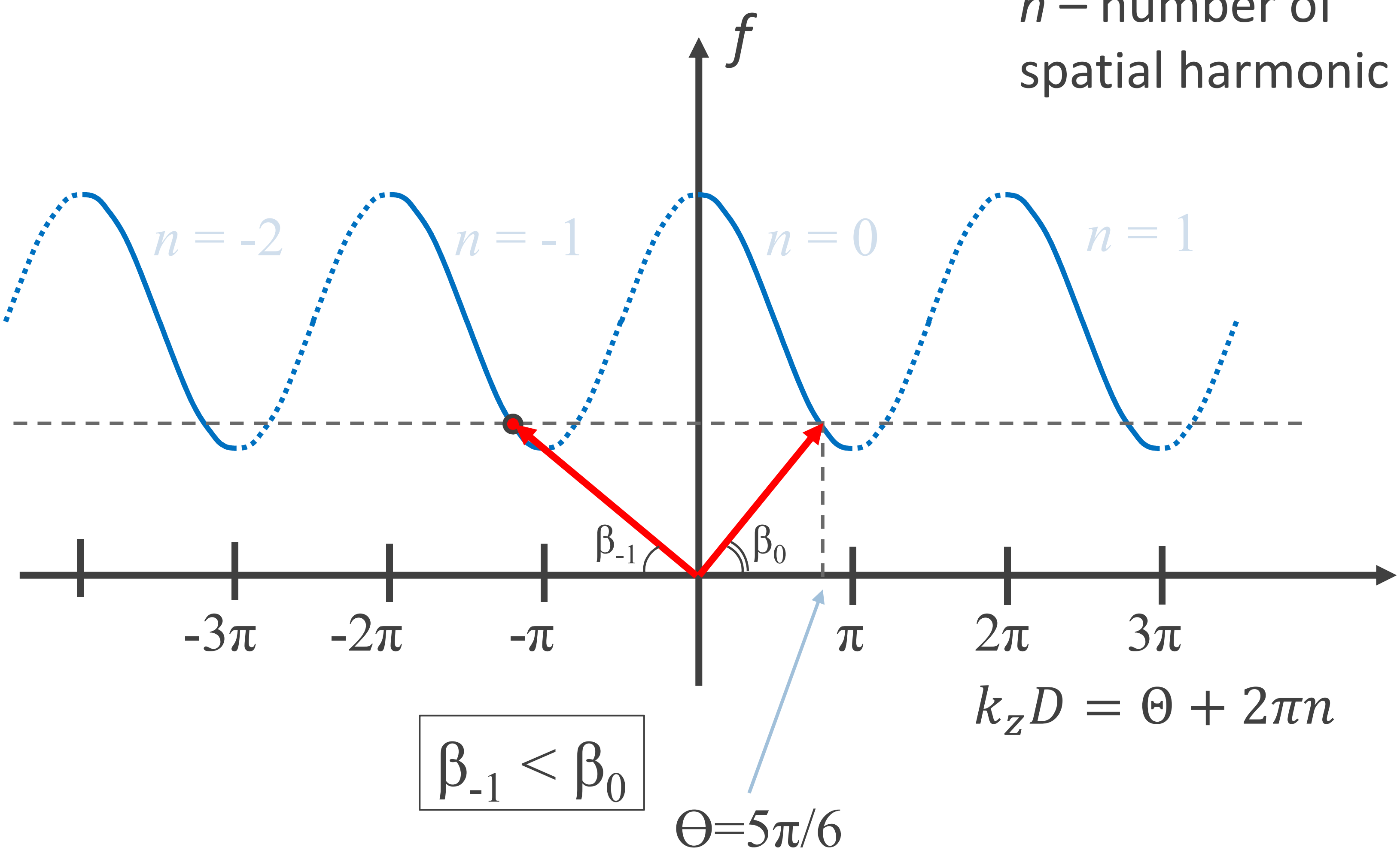




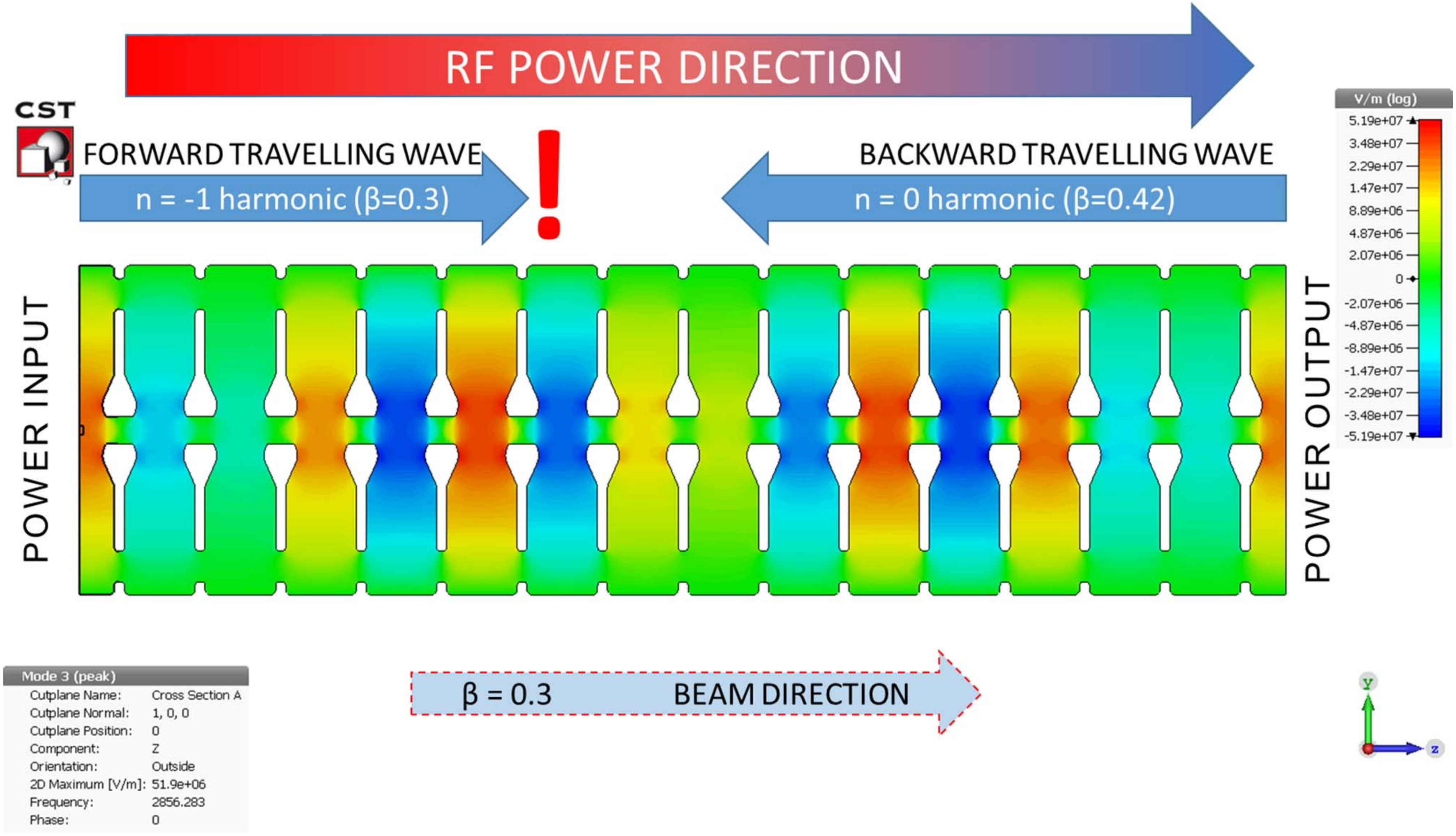
- Temperature (left), mechanical stress (central) and displacement (right) maps of BTW structure

Dispersion diagram for travelling wave structure with magnetic coupling holes

n – number of spatial harmonic

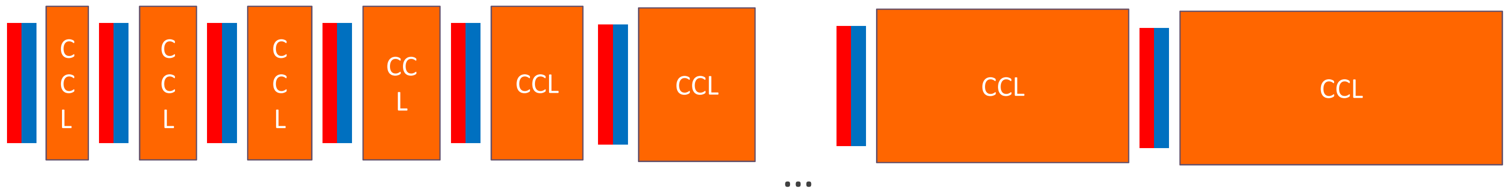


15-cell 3D model for negative harmonic TW structure



CCL

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



Doublet focusing lattice

Ions: Carbon (6+)

Energy Range: 45 – 450 MeV/u

Length: 0.32-1.4 m

Q: 8500..17000

RF Power : 1041 MW

ZT^2 = 26..64 MΩ/m

E_{smax}: 2.17 Kilpatricks

2a = 0.6 cm

E_0 = 67-72 MV/m

E_0T = 50 MV/m

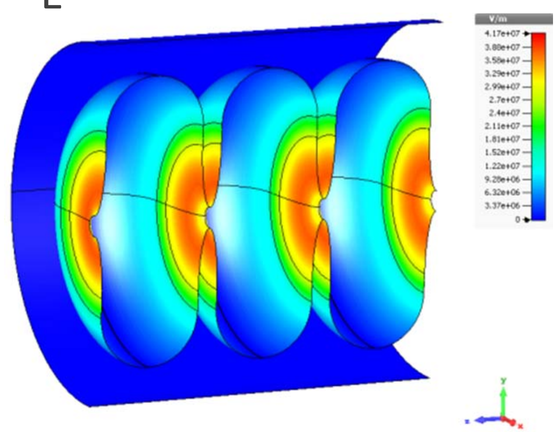
ϕ_s = -20 deg

G = 120 T/m

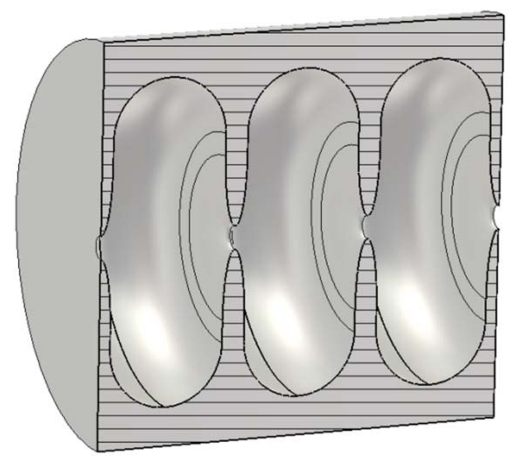
L_q = 14.0 cm

Coupling cells aren't shown

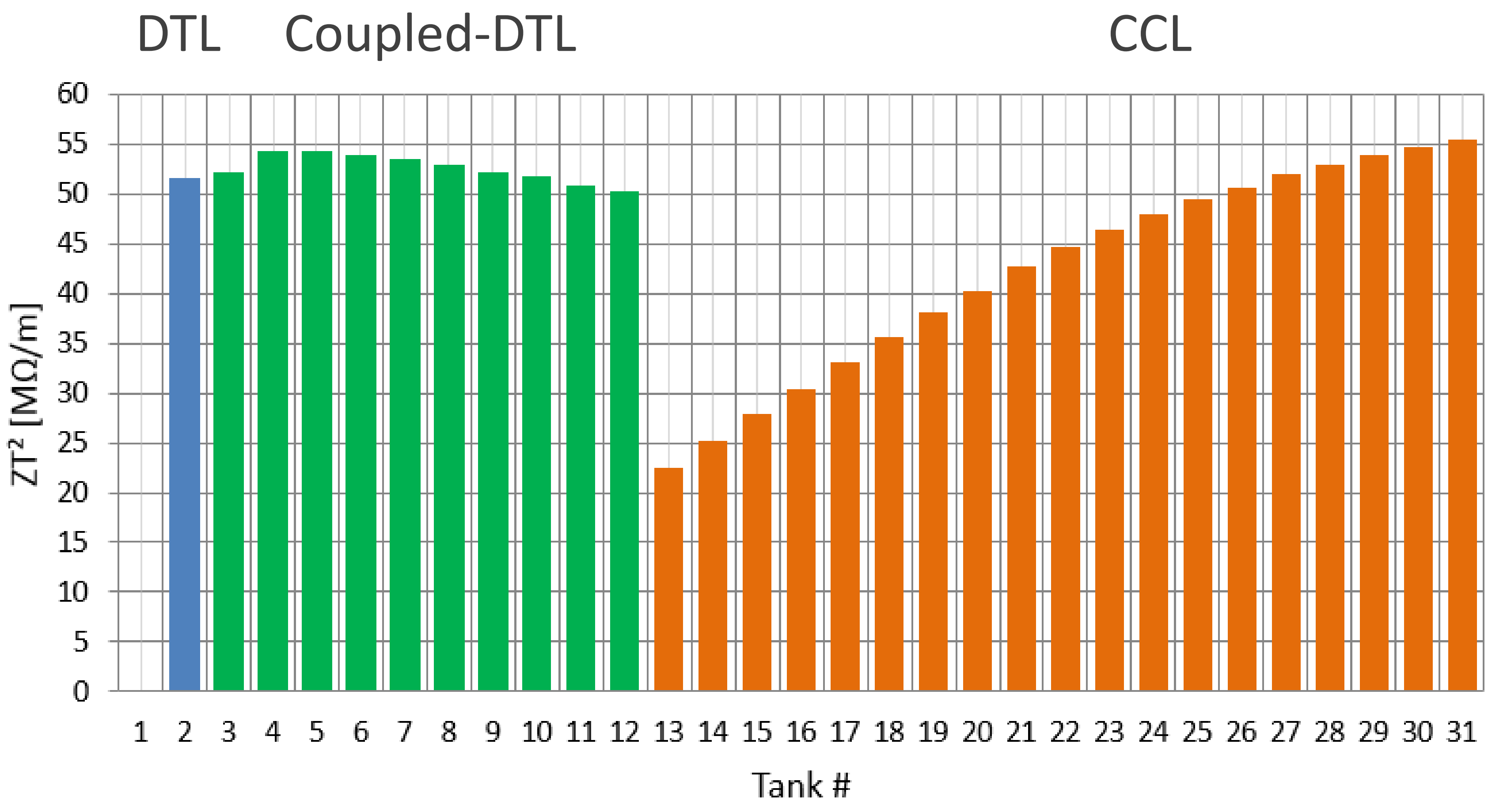
E



Elliptical disk tips

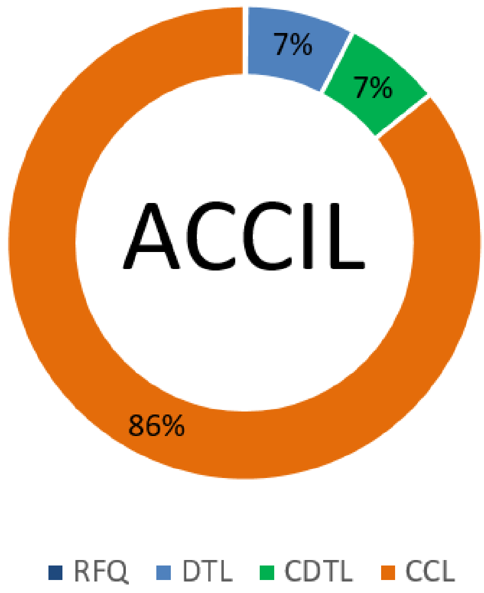


Effective shunt Impedance

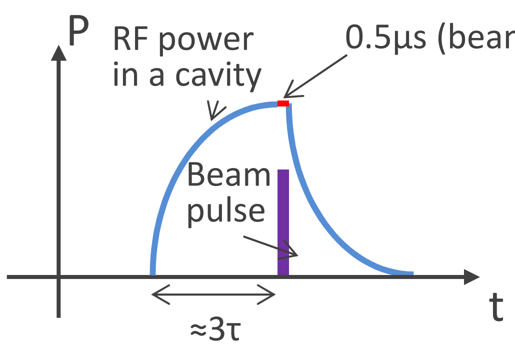


Power consumption @ 120 Hz

	RFQ 476 MHz	DTL 476 MHz	C-DTL 952 MHz	CCL 2856 MHz
Pulsed RF power	0.44 MW	4.88 MW	12.7 MW	1041 MW
Average RF power	0.54 kW	30 kW	26 kW	356 kW
RF source efficiency	40 %	40 %	40 %	40 %
"Plug" power	1.34 kW	75 kW	65 kW	890 kW



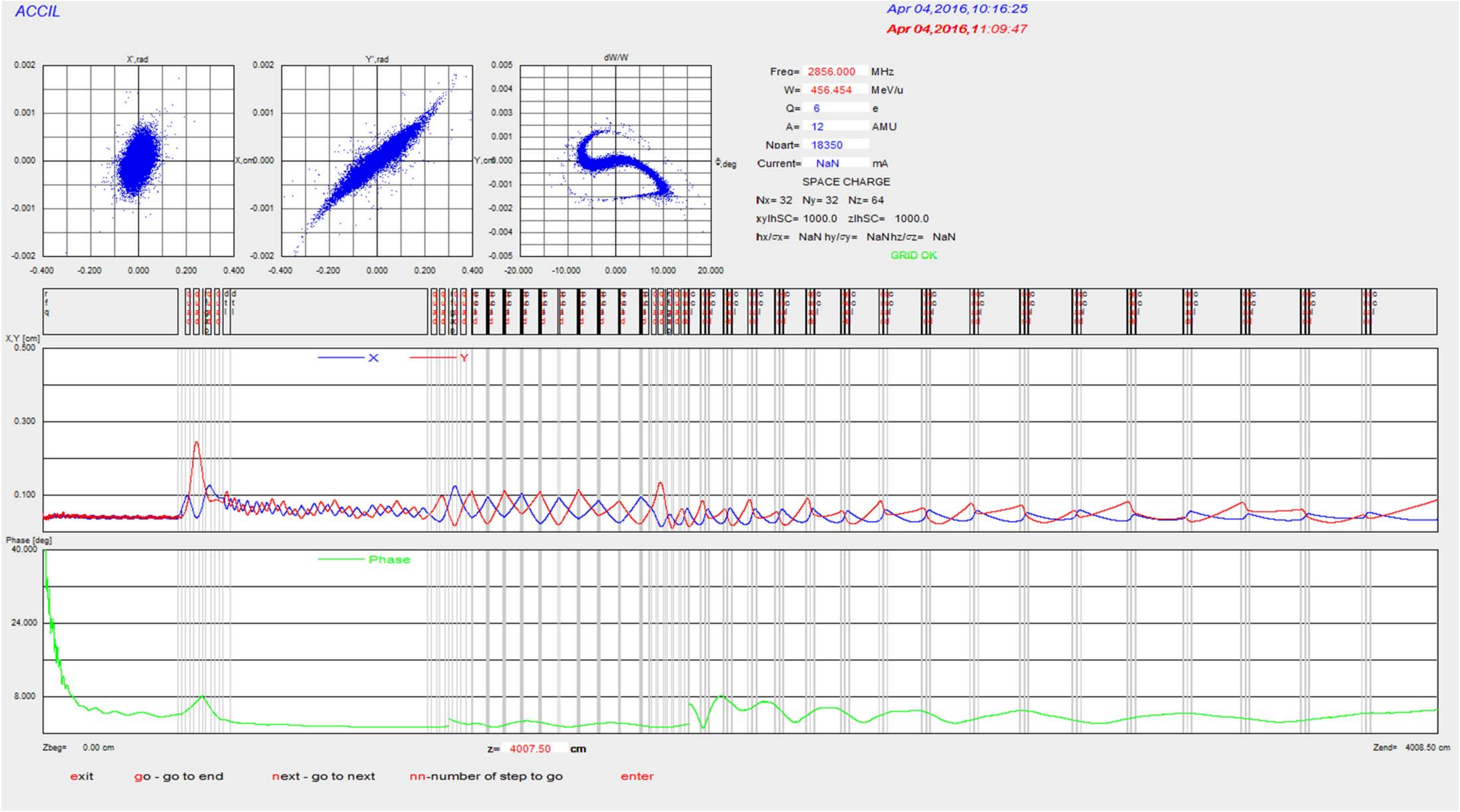
Total wall plug power: 1,031 kW



$\Delta(\text{DTL}) \approx 0.6\%$

$\Delta(\text{CCL}) \approx (0.02\text{-}0.04)\%$

Dynamics of carbon beam



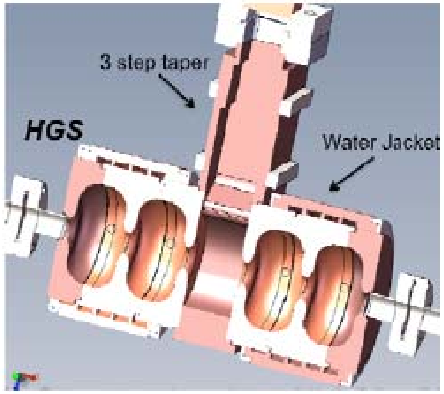
Comparison

MedAustron Synchrotron Vienna, Austria (Started operation in 2015)		ACCIL
	Accelerator cost	
$95M		< $50M
	Power consumption*	
5 MW		1 MW
	Perimeter/Length	
77 m		45 m

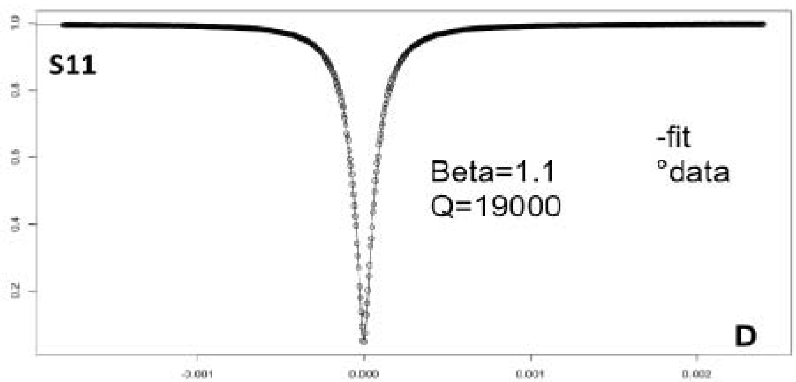
* Power values don't include power for gantry magnets

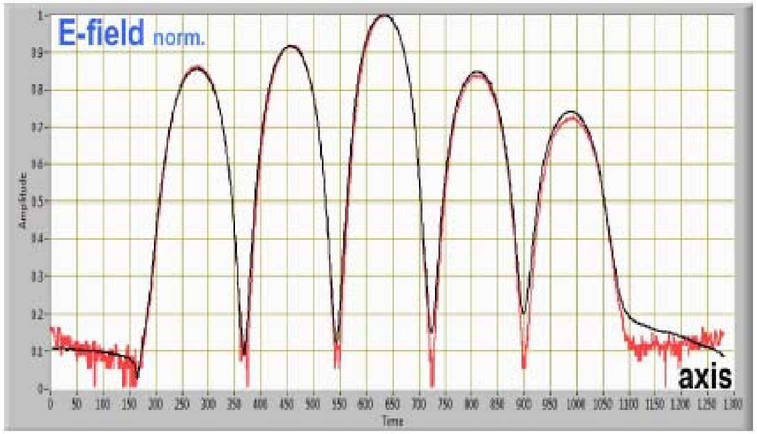
5-cell beta=1 test cavity

- Cavity was built by RadiaBeam for high gradient electron linac
- Initial high power test at LLNL @ 10 Hz rep rate and max field 45 MV/m



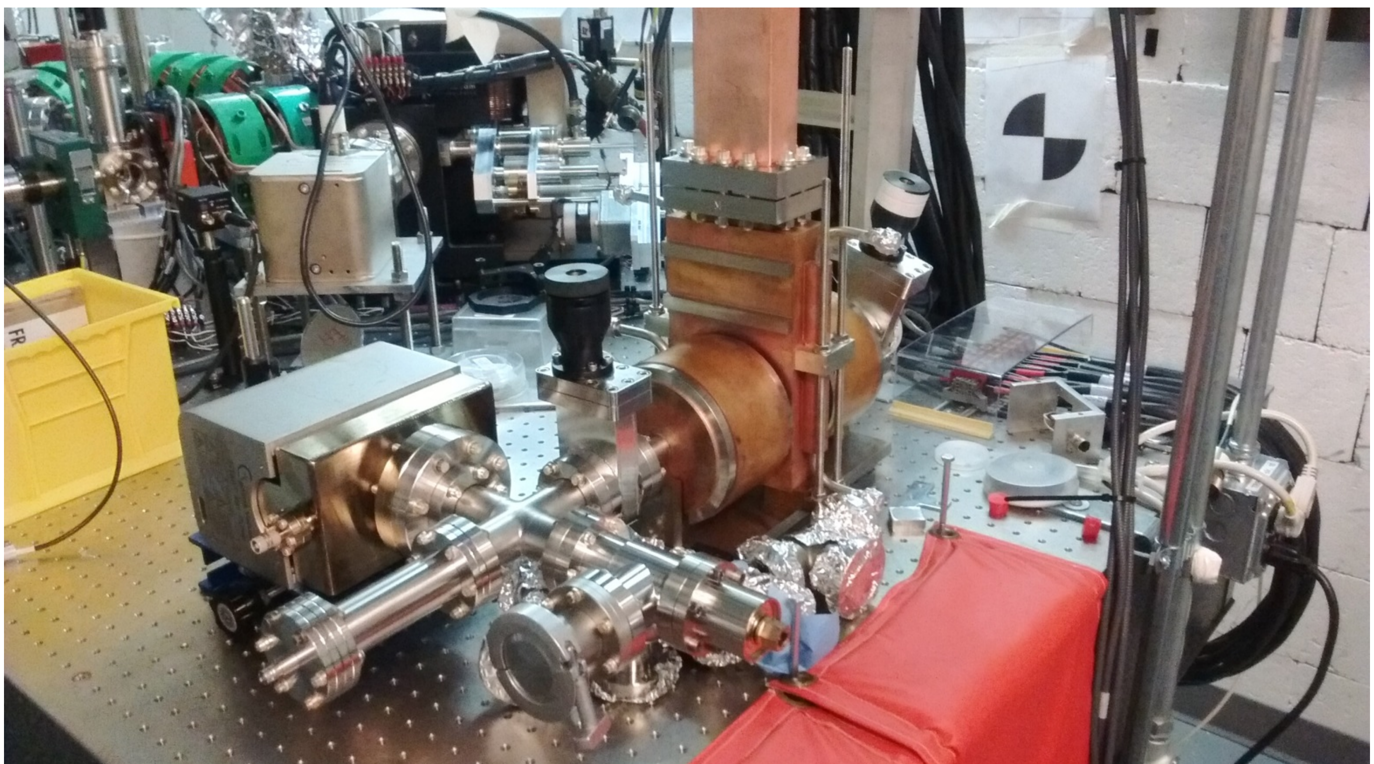
Parameter	Simulated value
f_π	2.856 GHz
R_S (Effective R_S)	93 MΩ/m (51 MΩ/m)
Δf	2.5 MHz
Q_0	19,500
R/Q	143.2 Ω
E_{acc}	50 mV/m
E_{max}/E_{acc}	1.8
P_{diss}/cell	2.4 MW





RadiaBeam HGS structure at Argonne Test Facility (Advanced Photon Source, ANL).

- This 5-cell 2856 MHz cavity for electrons (beta=1.0) was developed and built by Radiabeam for high gradient application
- After backing, initial conditioning the testing was performed at 30 Hz
- 16.7 MW @ 2 μs was finally achieved. Cavity was operated for 24 hrs at this level. Corresponds to 52 MV/m Eacc.

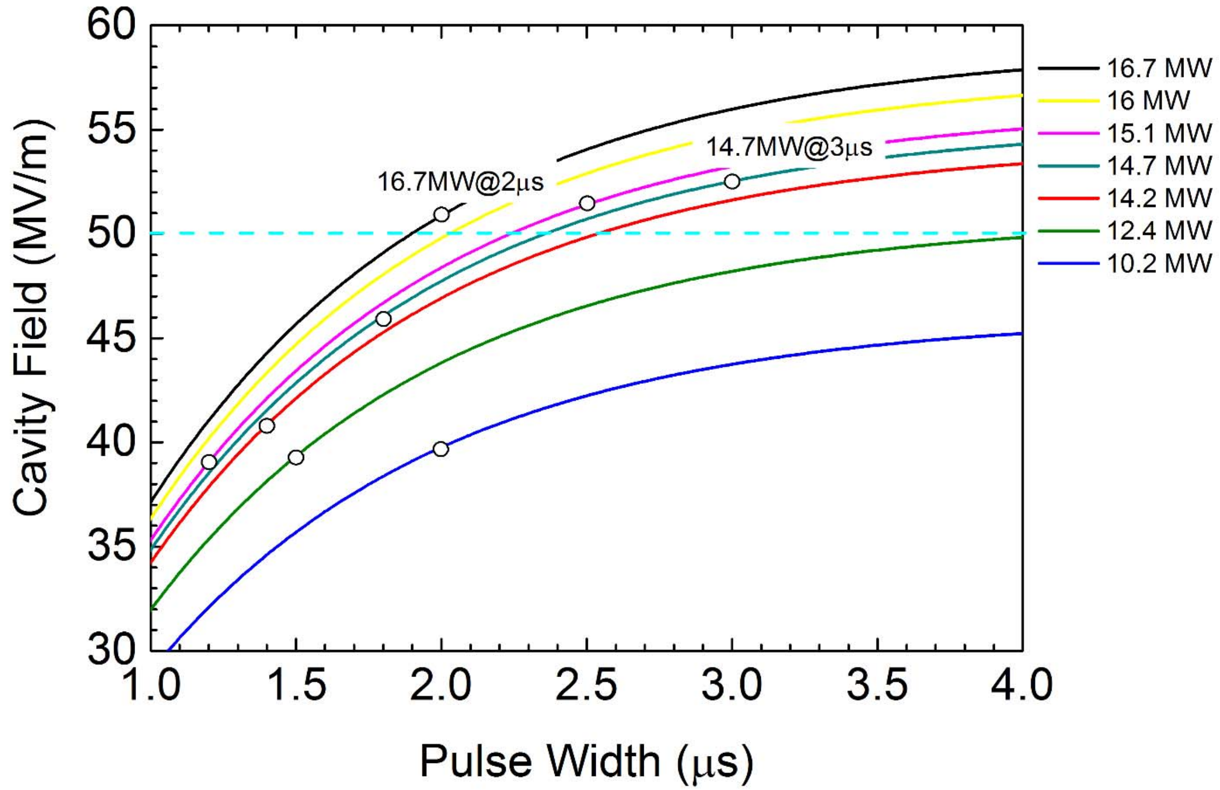


RF conditioning

- Cavity conditioning started on 25th Feb, 2016 with 30Hz Rep rate
- Stable operation of ~10MW was achievable. But severe outgassing prevented further progress
- The cavity was baked to 110°C for 3 days (Mar 18th-20th). Static vacuum levels improved from $5{\cdot}10^{-8}$ Torr to $5{\cdot}10^{-9}$ Torr level.
- Stable operation at 12MW@1.8µs was achieved on 30th March but operation beyond this levels was unstable.
- Another bake was scheduled at 130° C for 3 days (Apr 1st-3rd). Static vacuum levels improved to $8{\cdot}10^{-9}$ Torr.
- After initial conditioning power levels of 16.7MW@2µs was finally achieved. Cavity was operated for 24 Hrs. at this level.
- Pulse length was increased to 3µs and conditioning was started at 14MW after 6 Hrs at this level the cavity behavior changed and the test was stopped.
- All data were collected over EPICS – so limited to 1 data sample per 4 seconds

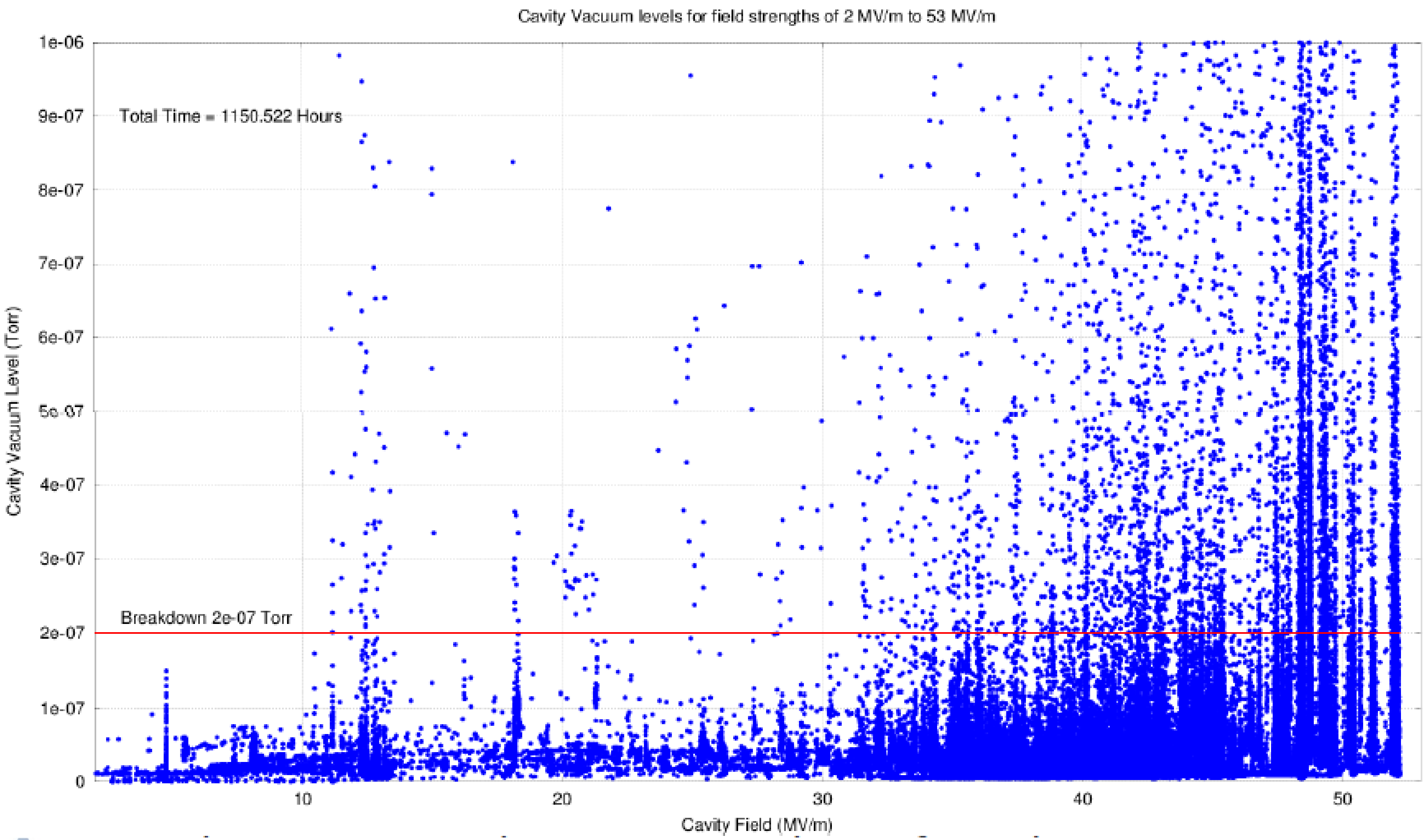
Data analysis

- Cavity field, Breakdown event counts and time spent at each level was calculated.
- Vacuum spikes above $2{\cdot}10^{-7}$ on cold cathode gauge was defined as a breakdown event.
- Breakdown Rate (BDR) defined as No. of breakdown events per hour (varying definitions in literature)
- Cavity needs 3µs to reach steady state value.
- Open circles represent highest power level at each pulse width.



Data analysis

- Breakdown rate becomes more frequent at higher field levels



Summary

- Compact carbon ion linac is feasible
  - Pulse-to-pulse adjustable beam energy
  - The same linac can deliver protons
- ACCIL features
  - Compact, ~45 meters
  - 22 klystrons, 19 klystrons are SLAC-type
  - ~1.02 MW wall plug power for RF, the goal is to reduce this value down to ~0.7 MW with optimized design
- Application: carbon beam cancer therapy
  - Fast 3D scanning of the tumor, not available with synchrotrons or cyclotrons
  - Lower construction and operational costs than for synchrotrons
- Challenges
  - Handling of high heat load in CCL, 25 kW/m average dissipated power at 120 Hz repetition rate
  - High alignment accuracy of accelerator components