An iron-free cyclotron for proton beam radiotherapy treatment

Conceptual Design

Daniel Winklehner, MIT, September 24th, 2019

MIT PSFC LNS Laboratory for Nuclear Science

Outline

- Introduction
  - Proton beam radiotherapy (PBRT)
- Engineering aspects of an iron-free cyclotron
  - Coils & Cryostat
  - RF system
- Beam dynamics in an iron-free cyclotron
  - Central region
  - Acceleration
  - Extraction

Team

There used to be a cyclotron here

- Concept & Engineering
  - Leslie Bromberg[a]
  - Philip Michael[a]
  - Joseph Minervini[a]
  - Alexey Radovinsky[a]
- Beam Dynamics:
  - Daniel Winklehner[b]

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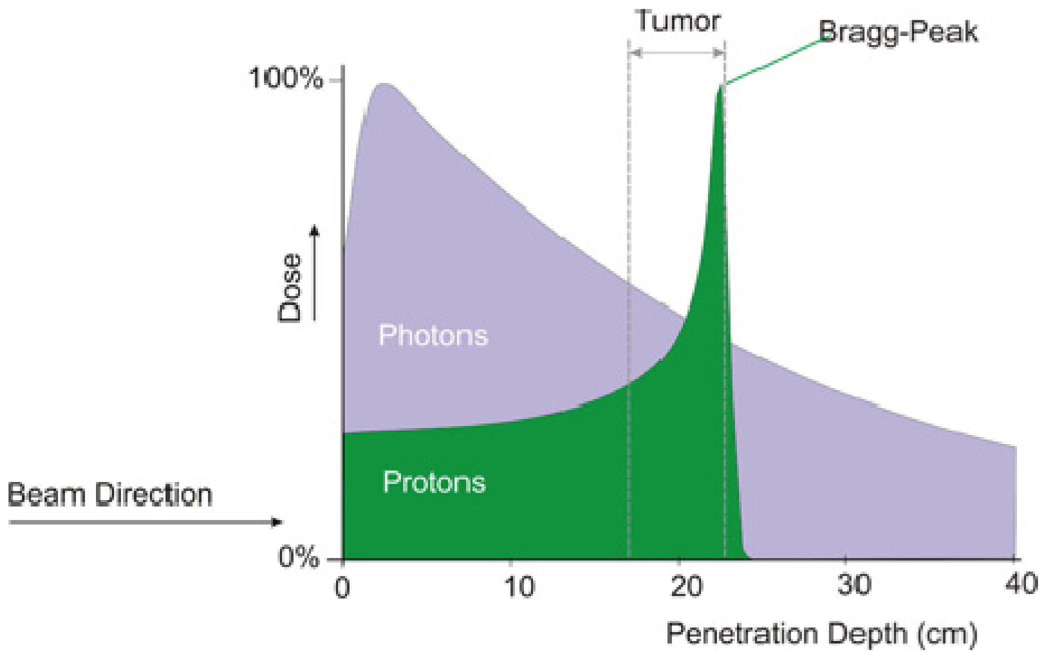
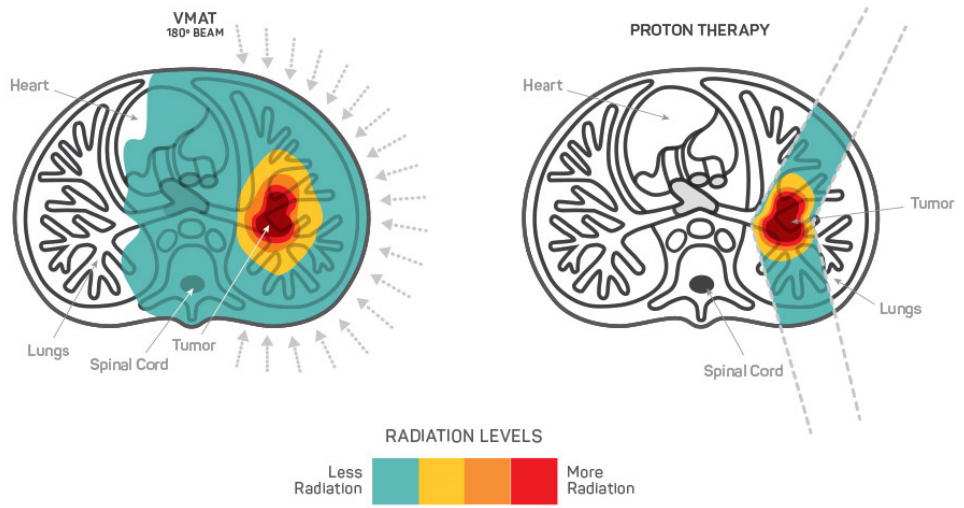
Proton beam radiotherapy – in a nutshell

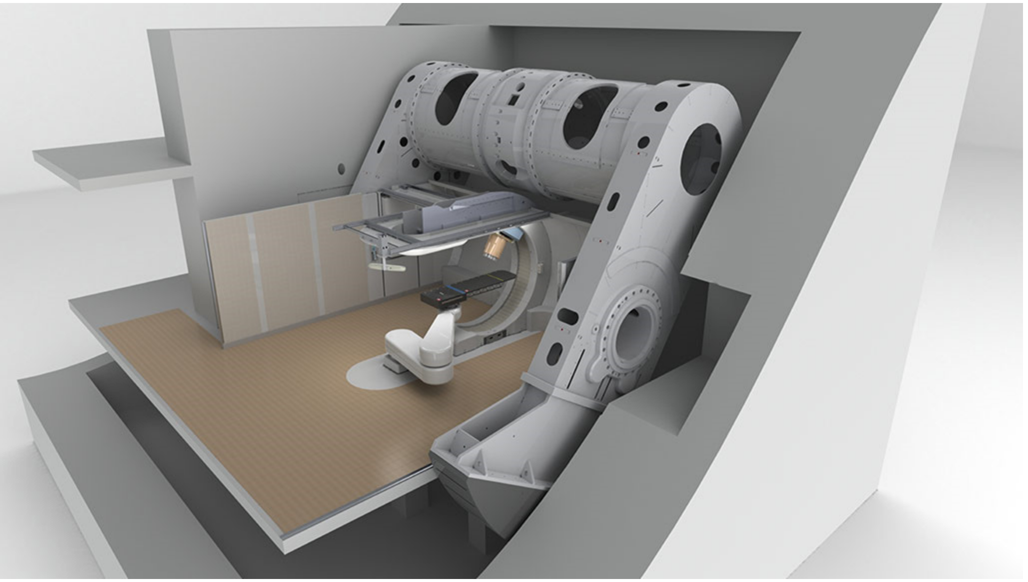
- Dose-depth distribution – Bragg-peak minimizes proximal and distal tissue damage
- Bragg-peak is energy dependent → proton therapy machines need to provide up to 250 MeV protons (linacs, synchrotrons, cyclotrons)

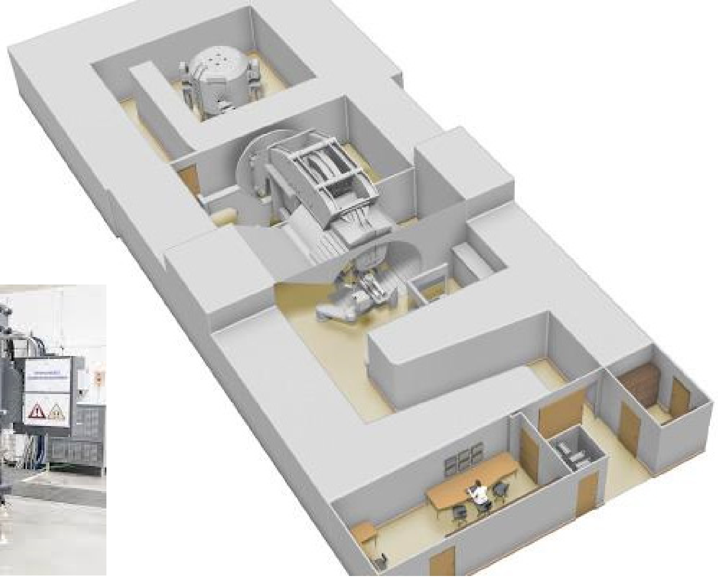




https://www.sccaprotontherapy.com

Superconducting cyclotrons have paved the way for smaller facilities





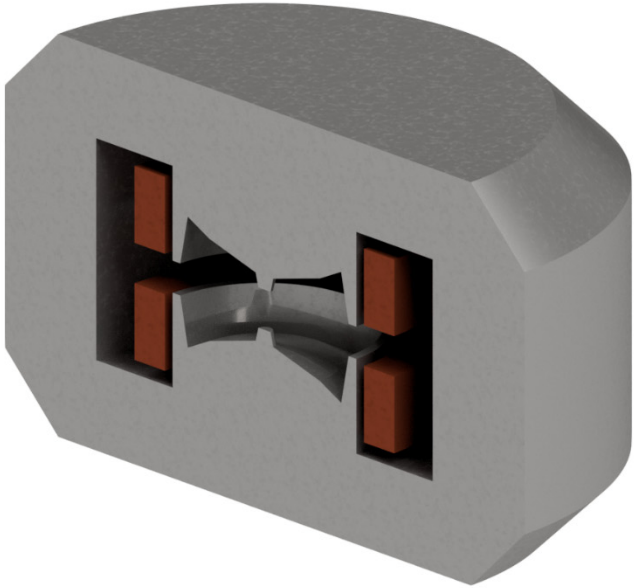
- Mevion S250™
- Synchrocyclotron (S250)
- Mounted on gantry
- Cyclotron weight: ~25 t

mevion.com

- IBA ProteusOne™
- Synchrocyclotron (S2C2)
- Sitting before gantry
- Cyclotron weight: <50 t

iba-worldwide.com

Can we do away with the iron yoke?



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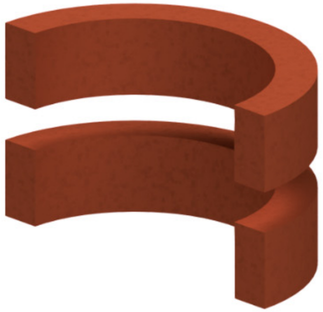
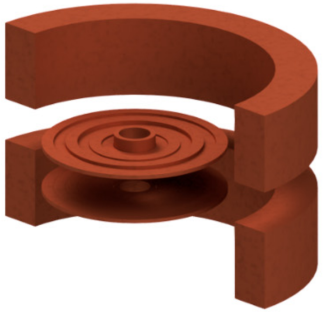
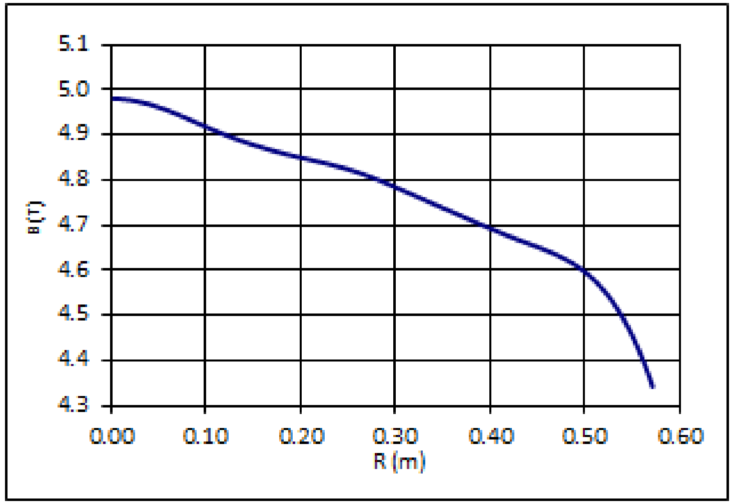
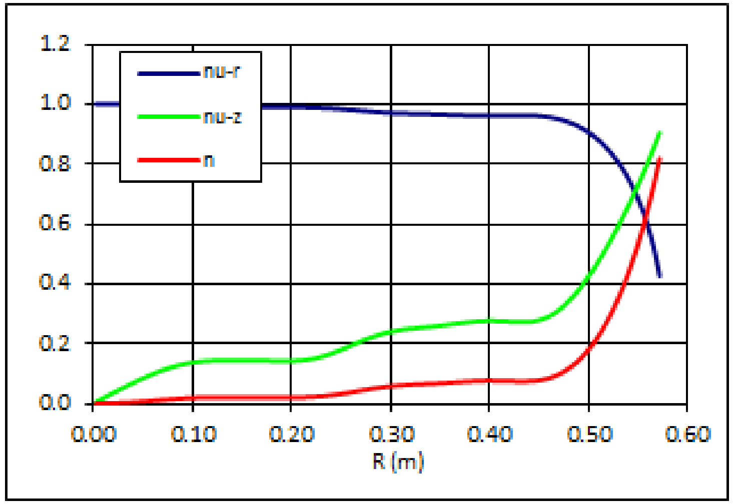


We need more coils to generate the radially decreasing field for vertical focusing.







- Field index:

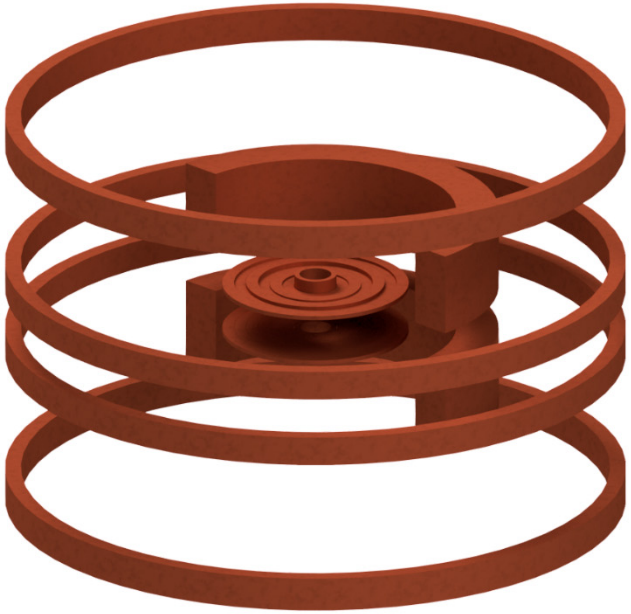
$$n = -\frac{r}{B}\frac{dB}{dr}$$

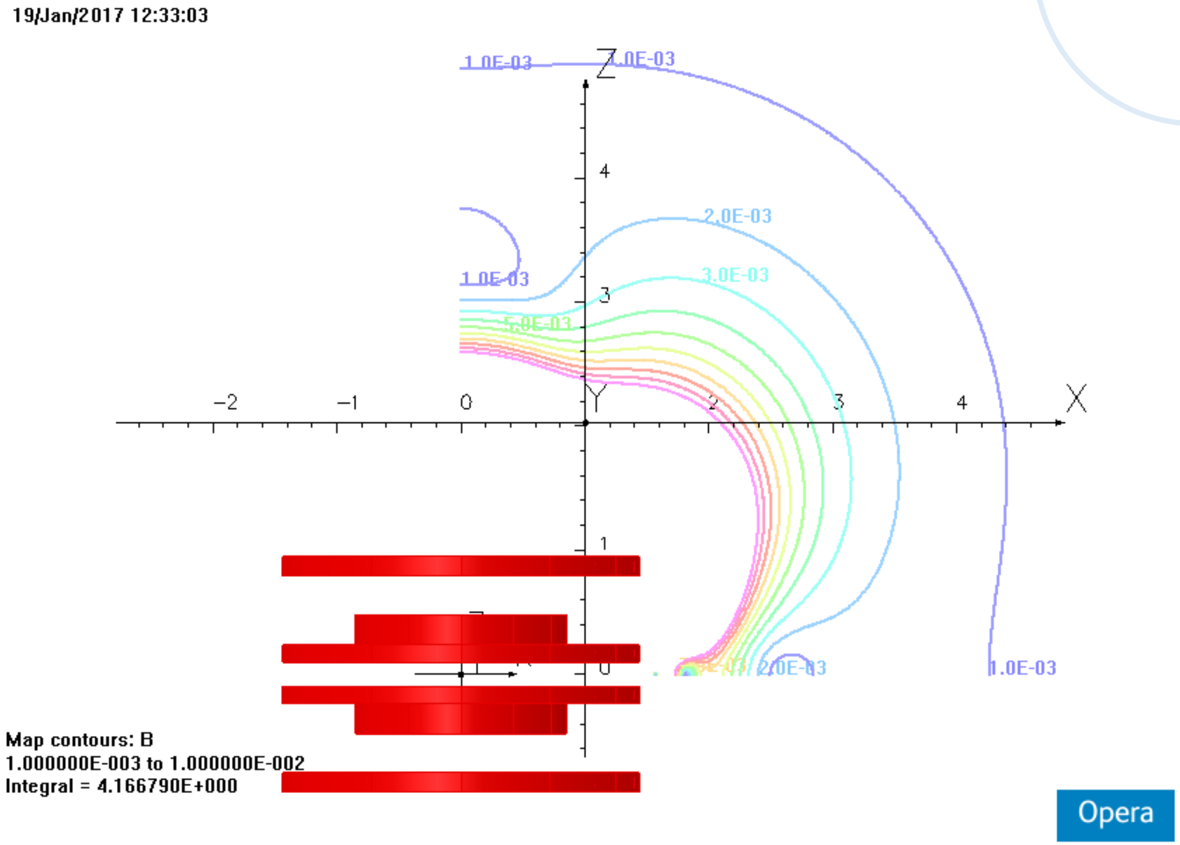
- Tunes:

$$\nu_z = \sqrt{n}$$

$$\nu_r = \sqrt{1-n}$$

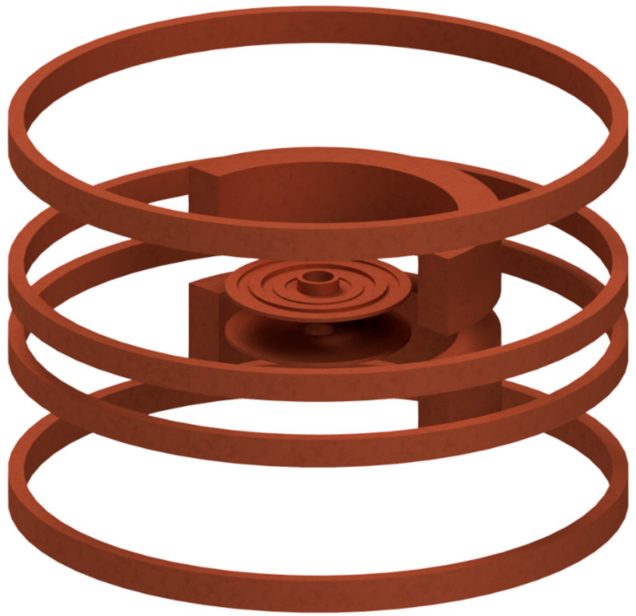
…and active shielding coils to compensate the fringe fields.



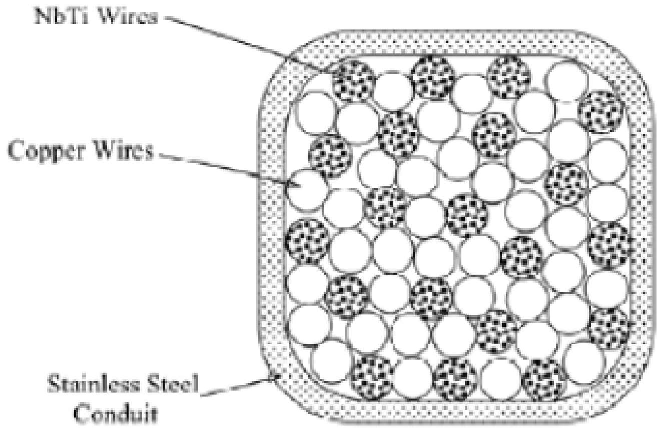


- 10 Gauss line at ~R = 2 m
- For resistive counterpart 180 Gauss

Basic Coil Parameters



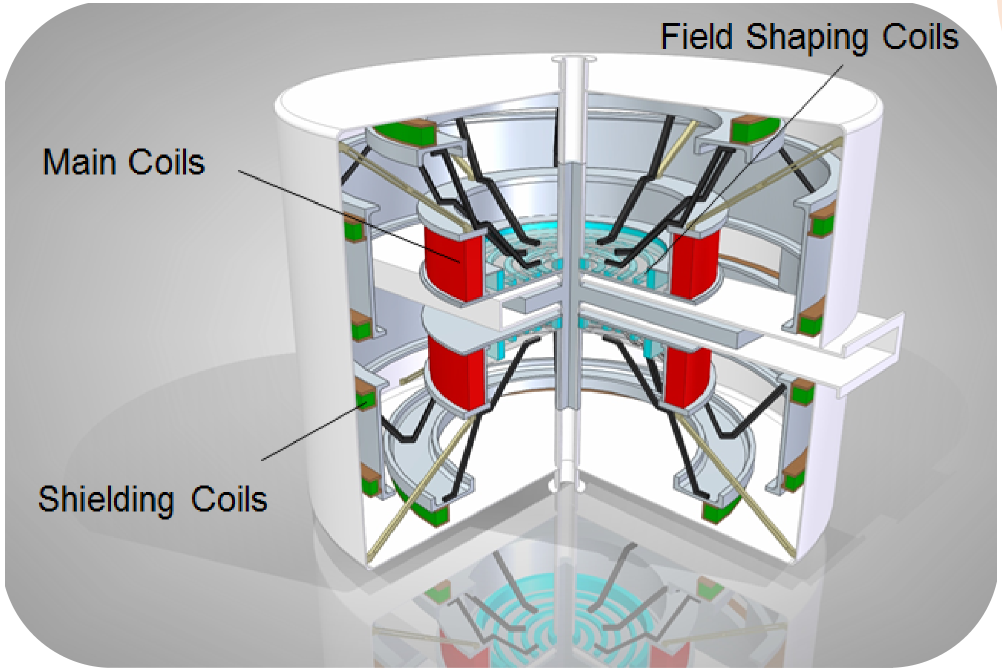
Cable in Conduit Conductor



Beam	
Maximum central magnetic field (at R=0, Z=0)	4.980 T
Maximum magnetic field at extraction (at $R=R_{ex}$, Z=0)	4.596 T
Extraction radius, R_{ex}	0.501 m
Maximum beam energy, $T(R_{ex})$	226.3 MeV/u
Coil	
Stored magnetic energy, E	31.1 MJ
Outer diameter of cryostat, OD	3.00 m
Overall height of cryostat, OH	2.02 m
Magnitude of fringe magnetic field	
In radial direction, B(at R=3.5m, Z=0)	11 Gauss
In axial direction, B(at R=0, Z=4.5m)	12 Gauss

Cryostat

- Operating T = 4 K
- Cold mass: Al-6061-T6
- LiHe-filled
- SS 316 structural base plate
  - 17.5 MN force towards midplane
- Thorough stress analysis showed acceptable max. limits:



Cold Mass Structure	Computed S_{vm}	Limit Value S_m
316 Stainless Steel (MPa)	120	575
Al-6061-T6 (MPa)	62	165
CICC Conduit Hoop Stress (MPa)	200	575
Winding Hoop Strain (%)	0.098	0.2

Magnet system component	Weight [kg]
Main coil and field shielding coils (NbTi-a)	6776
Field shaping coils (NbTi-b)	88
Cold mass structures (SS 316LN & Al-6061-T6)	2631
Cryostat vacuum vessel	3773
Cryostat radiation shield	485
Total magnet system weight	13,753

Changing Magnetic field for layer-to-layer transition in tumor painting

- Stored Energy:

$$E_m(t) = K_b(t)^2 * E_m(0)$$

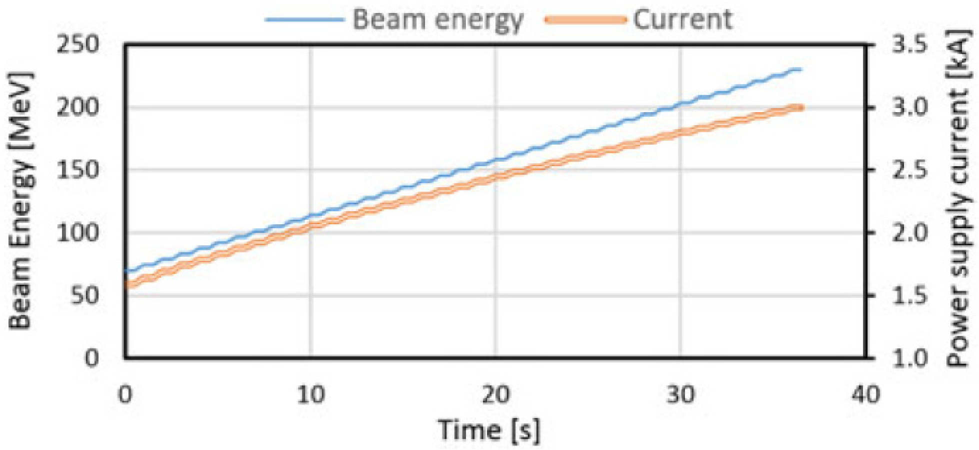
$$K_b(t) = B(R_{ex}, t) / B(R_{ex}, 0) = I_{op}(t) / I_{op}(0)$$

$$= \sqrt{\frac{T(\text{Rex}, t)(2E0 + T(\text{Rex}, t))}{T(\text{Rex}, 0)(2E0 + T(\text{Rex}, 0))}}$$

$E_m(0) = 31$ MJ, $I_{op}(0) = 3$ kA and $B(R_{ex}, 0) = 4.637$ T.

$T_{\min} = 70$ MeV and $T_{\max} = 230$ MeV

$\Delta t = 0.5$ seconds (layer-to-layer). $dt_{\text{layer}} = 0.5$ s.



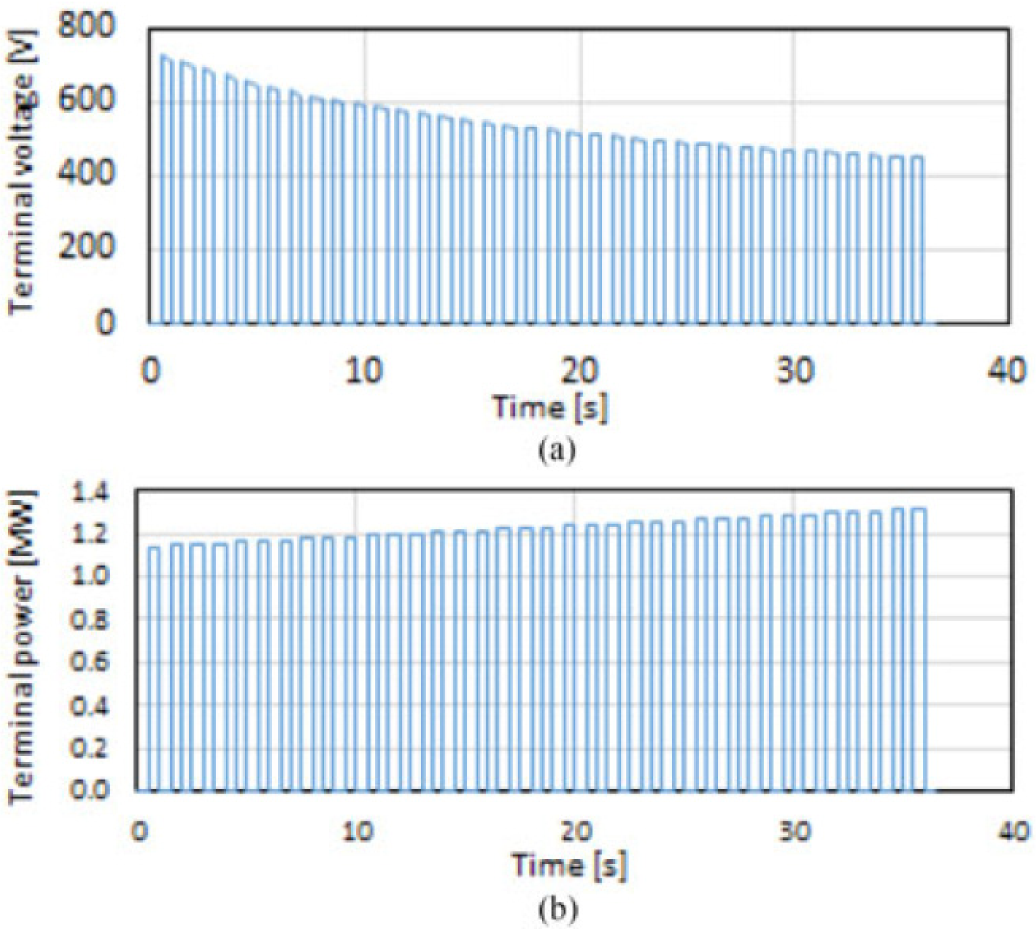
Hysteresis losses

Conductor		NbTi-a	NbTi-b
B_0	T	0.38	0.38
J_0	A/m^2	4.00E + 10	4.00E + 10
d_f	m	6.50E − 06	6.50E − 06
alpha		0.53	0.53
B_f	T	6.56	5.36
E	J/m^3	5349	5261
	mJ/cm^3	5	5

T rise in conductor ~mK after 4 up-down cycles

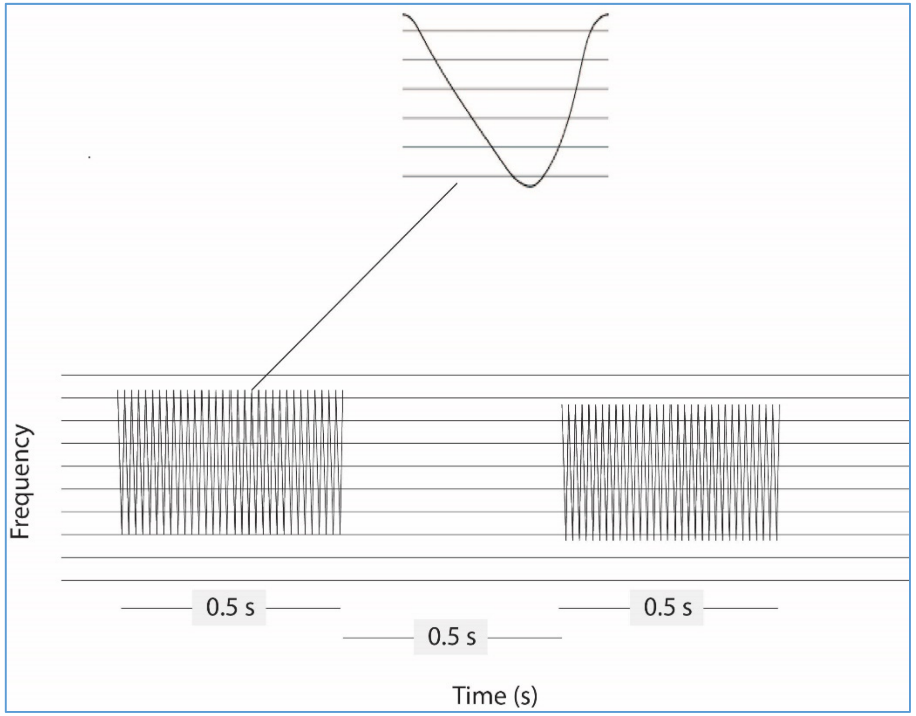
Terminal Voltage and Power during ramp

- "Picket-fencing" for the conservative 0.5 s ramp and transverse layer painting times
- The terminal voltage is far below maximum terminal voltage allowed during fast quench discharge



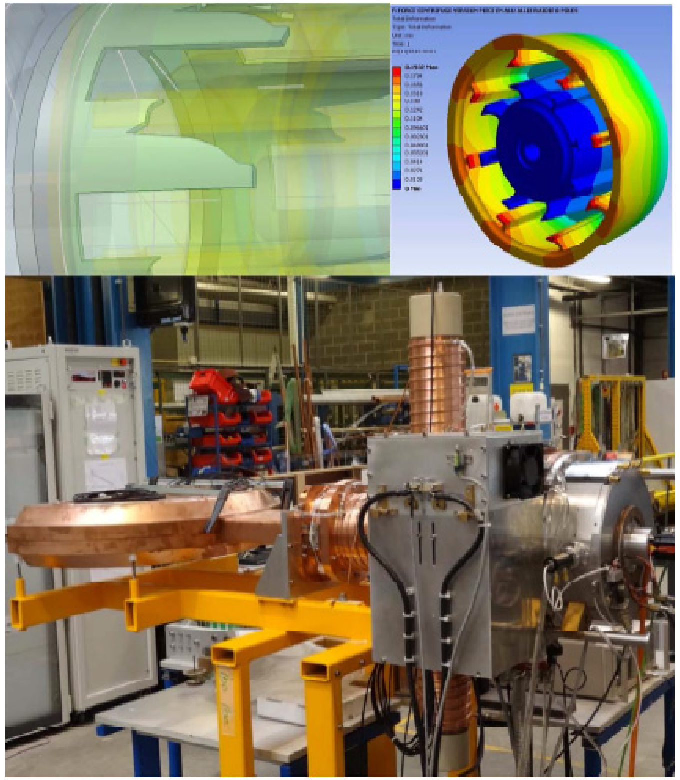
RF System considerations

- During one acceleration cycle, the RF frequency has to match the beam velocity to compensate relativistic effects.
- For each layer, up to 500 repetitions of this cycle.
- 0.5 s pause to adjust magnetic field
- Typical tumor volumes require up to 15 energy levels
- 4-times repainting strategy → 2 min treatment time



RF System considerations II

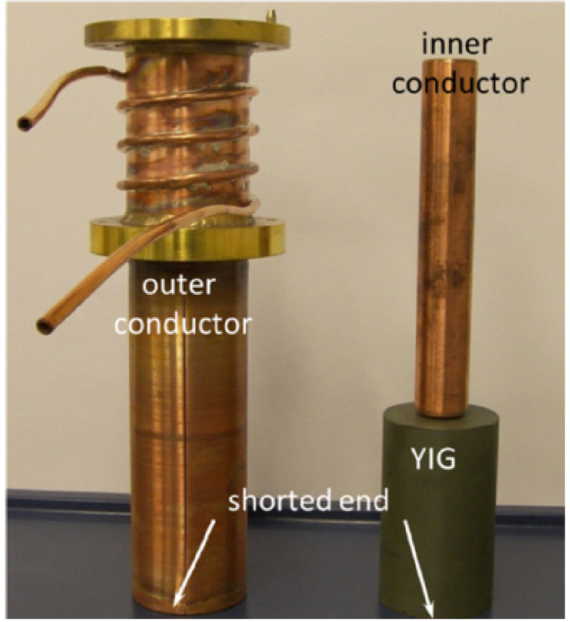
State-of-the-art: RotCo



Michel Abs design

From: Kleeven et al., CYC2013

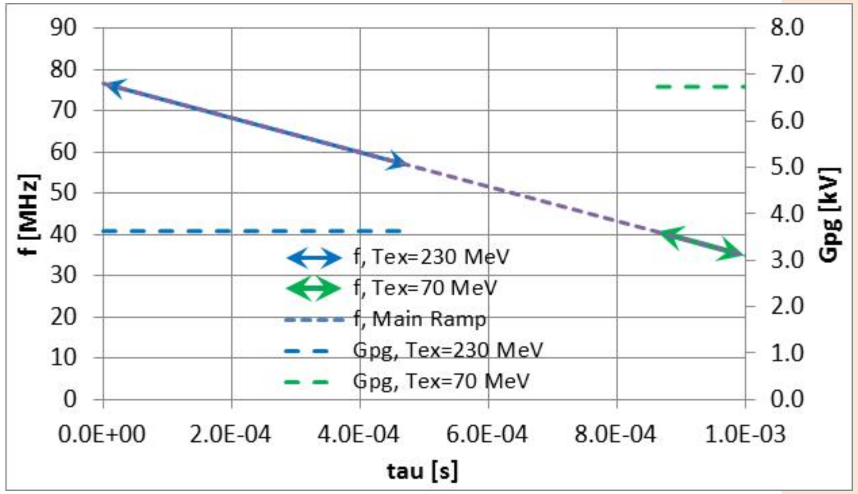
Alternative 1: Ferrite tuner



- 1/2 wave microwave-ferrite-loaded and liquid-filled resonator,
- Perpendicular biasing of the ferrite, and an external solenoidal bias field
- RF supplied by wide-band RF amplifier with computer controlled LLRF

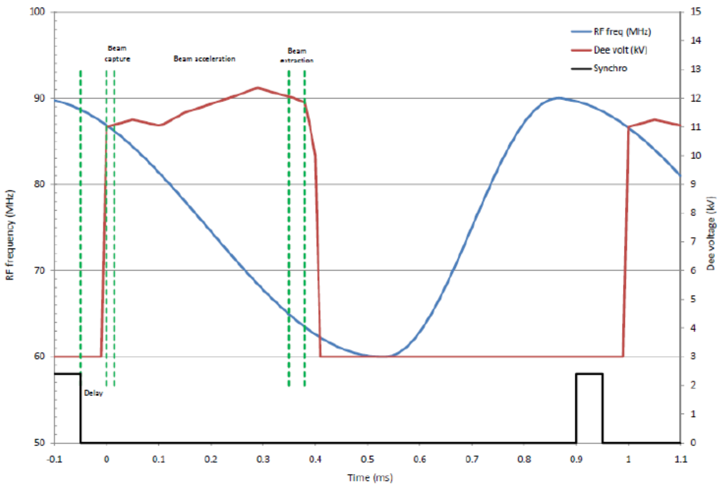
Nielltronix, Inc.

Alternative 2: Linear Ramp

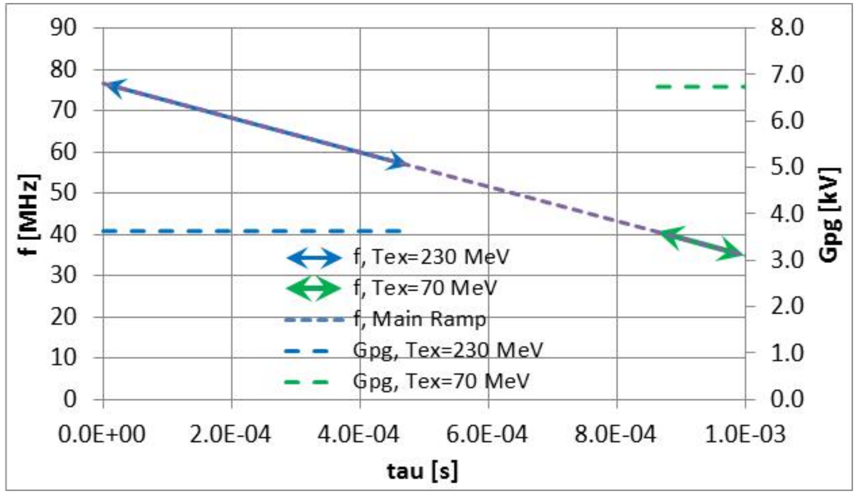


Six test cases for beam dynamics studies

- Arbitrary frequency ramp (ferrite tuner)
  - Dee voltage and frequency directly scale with B-Field
  - 70 MeV, 150 MeV, 230 MeV



- Linear frequency ramp (RotCo)
  - df/dt = const → Lower final energy = higher dee voltage
  - 70 MeV, 150 MeV, 230 MeV



Beam Dynamics

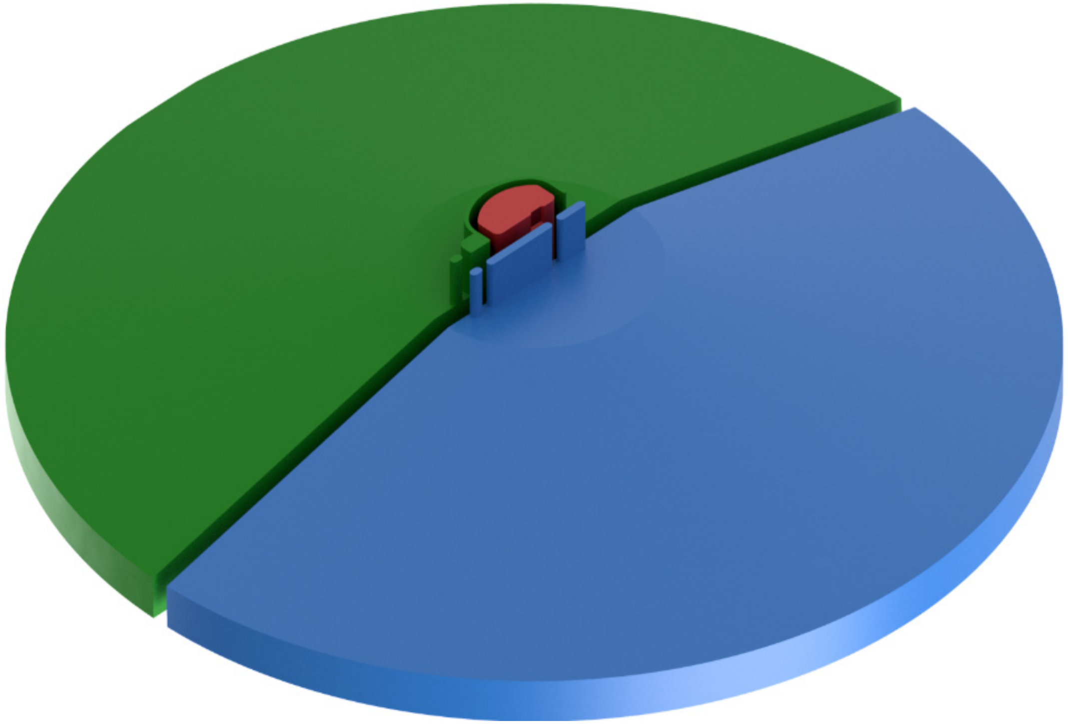
Test Cases cont'd

Parameter	Case 1a	Case 2a	Case 3a	Case 1b	Case 2b	Case 3b
Final Energy [MeV]	70	150	230	70	150	230
B (center) [T]	2.64	3.94	4.98	2.64	3.94	4.98
B (extraction) [T]	2.44	3.64	4.60	2.44	3.64	4.60
f_{RF} (start) [MHz]	40.26	60.13	75.91	40.26	60.13	75.91
f_{RF} (end) [MHz]	34.58	47.86	56.28	34.58	47.86	56.28
f_{RF} slope [MHz/μs]	non-linear	non-linear	non-linear	-5.64e-2	-5.64e-2	-5.64e-2
Turns	~25000	~25000	~25000	3764	11745	23000
V_{dee} peak [kV]	2.8	6.3	10.00	18.6	12.77	10.00

Caveat: Conceptual design: Many beam dynamics results are very preliminary!

Central Region – Conceptual Design

- Field calculation and and particle tracking with COMSOL
- Ion Source biased up to -15 kV to compensate for different dee voltages
- Caveats:
  - B-Field and frequency assumed constant for the first 4-5 turns
  - Ion source plasma not considered
  - Bias voltage influence on beam quality not investigated

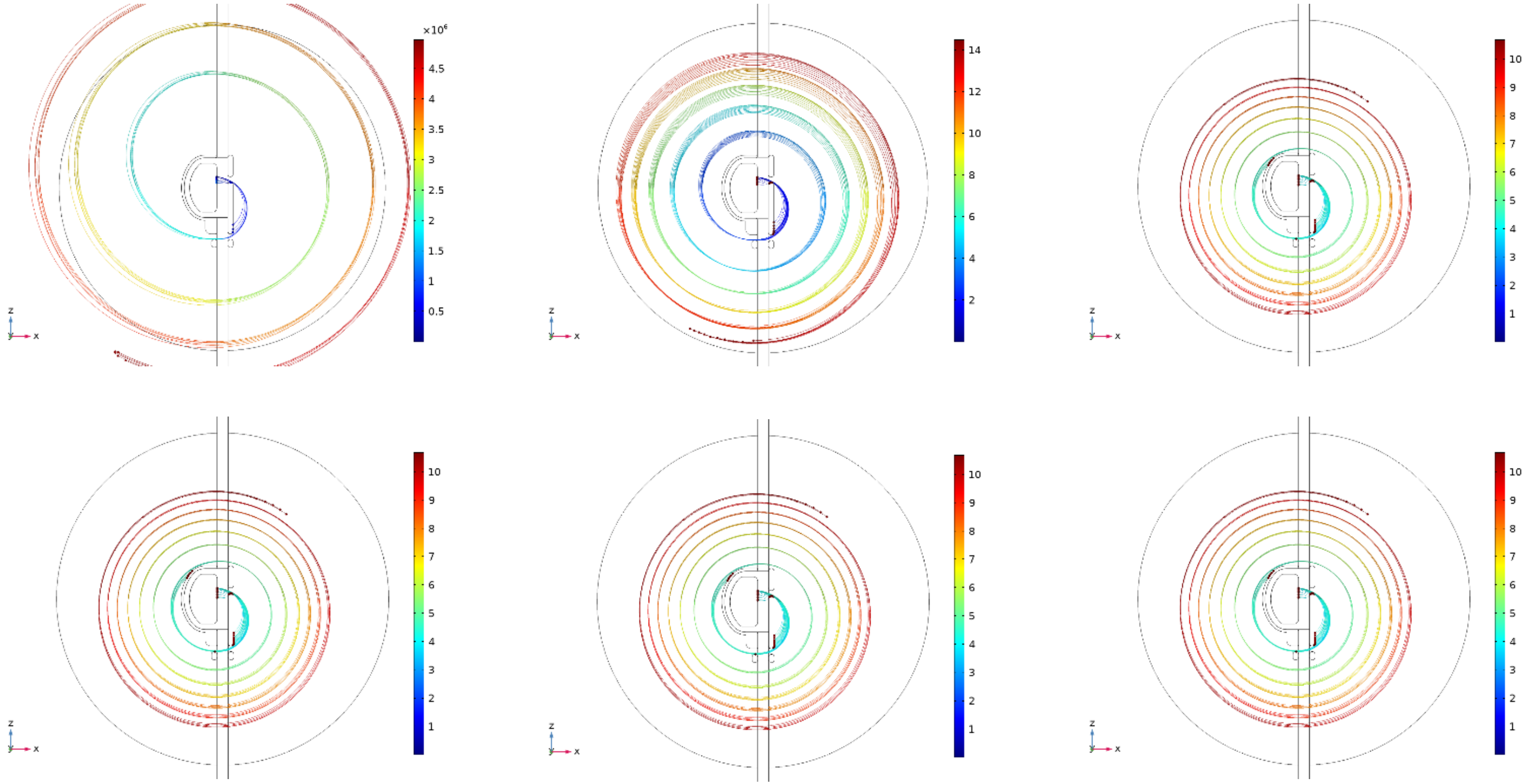


Central Region – Preliminary Simulations

70 MeV | 150 MeV | 230 MeV

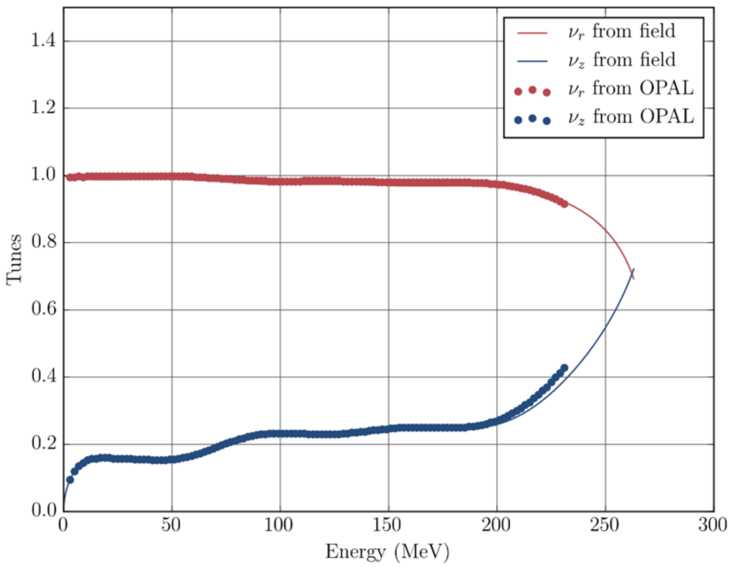
Linear f-ramp

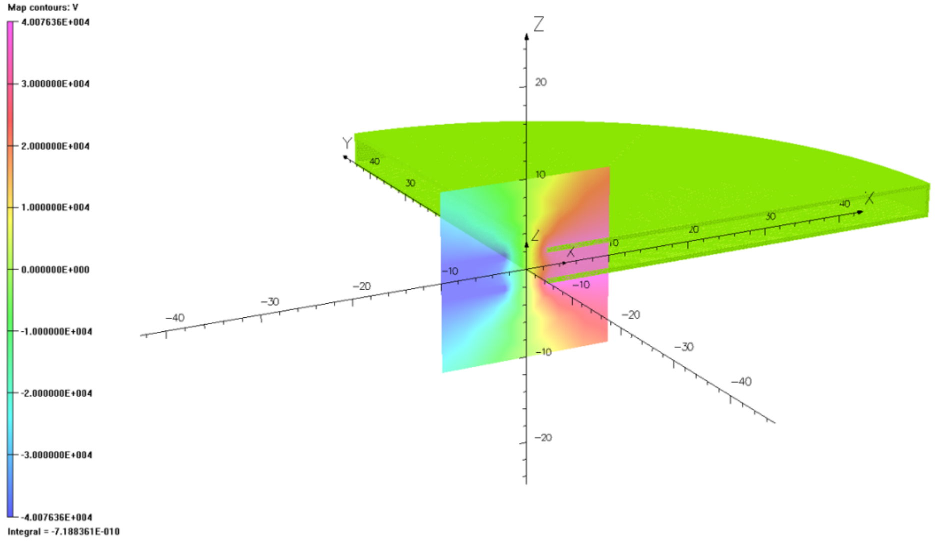
Non-linear f-ramp



Acceleration to final energy

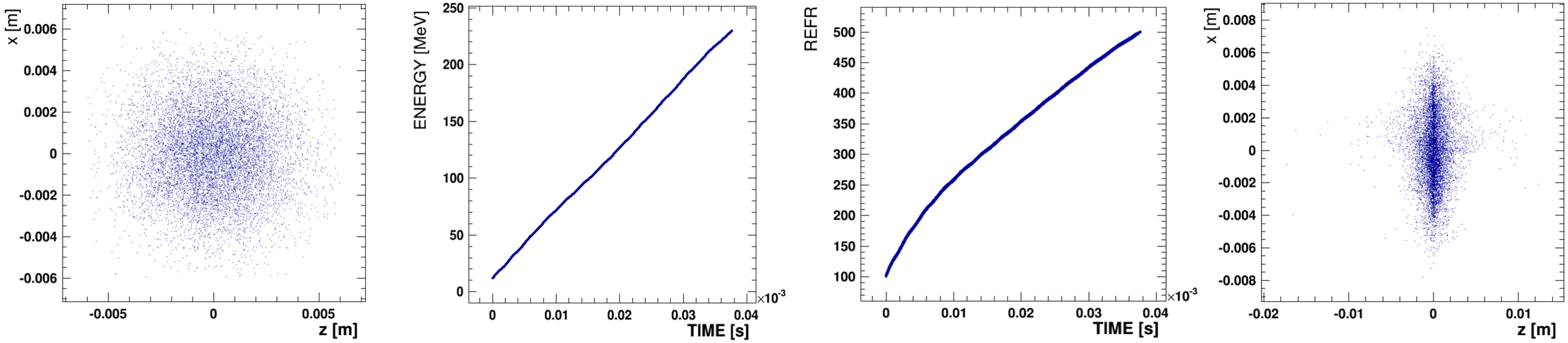
- Using OPAL-cycl for single and multiparticle tracking
- Used B-field calculated in OPERA
- Use simplified dee-dummy dee model in OPERA to generate E-fields
- Caveats:
  - Starting with gaussian beam at R = 5 cm, not considering central region





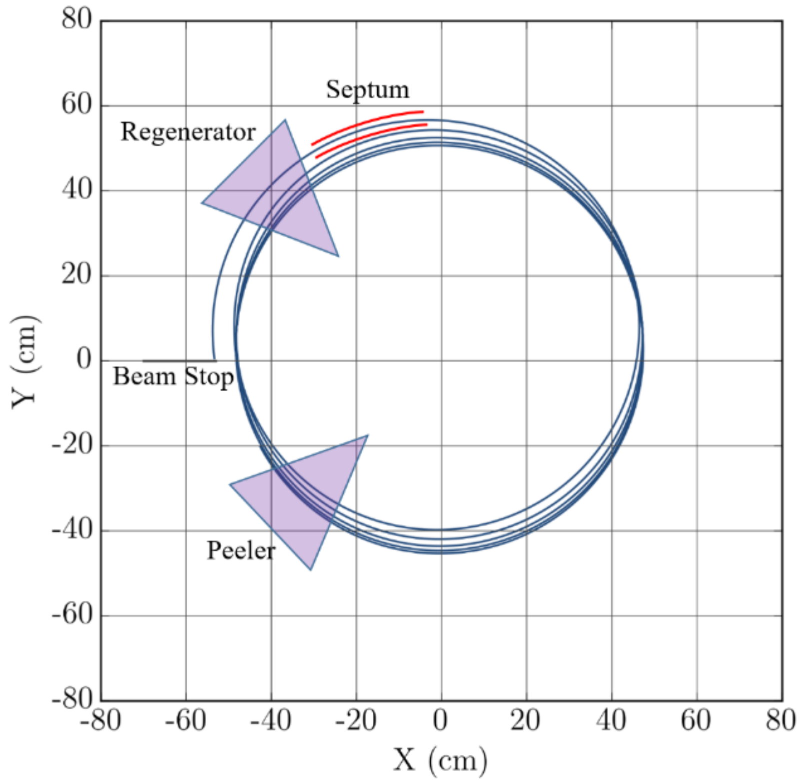
Single and Multiparticle Acceleration yielded very similar results to other machines

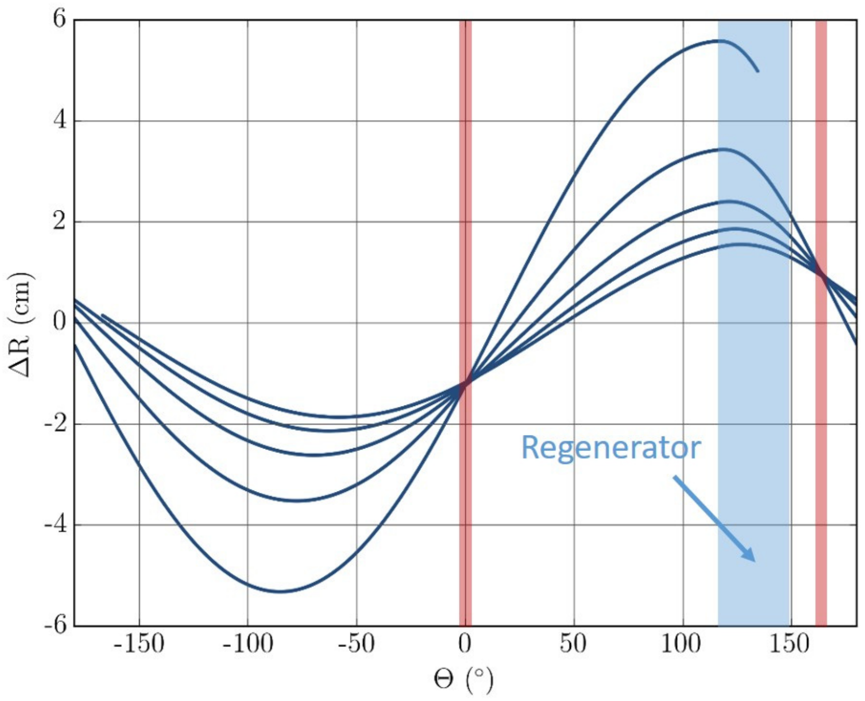
- Left to right: Starting bunch, energy gain, centroid radius, final bunch
- X = radial direction, Z = vertical direction
- Final beam size R = 3 mm 1-RMS



Regenerative Extraction

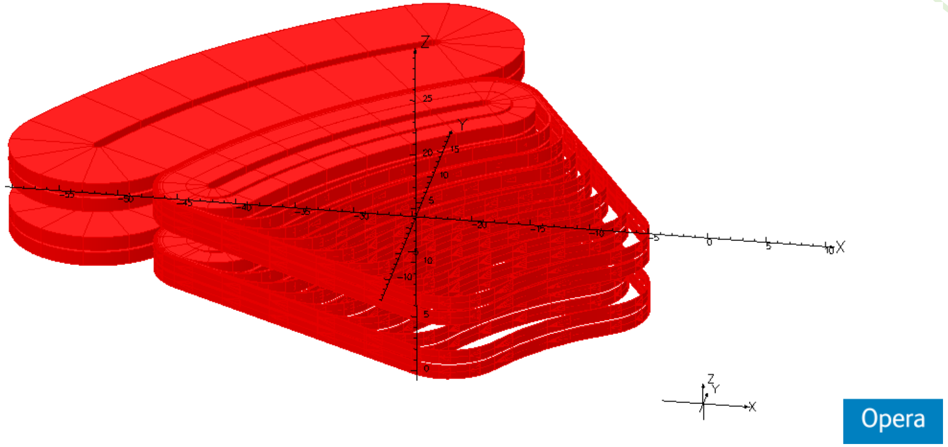
- Excite a $\nu_r = 2/2$ resonance

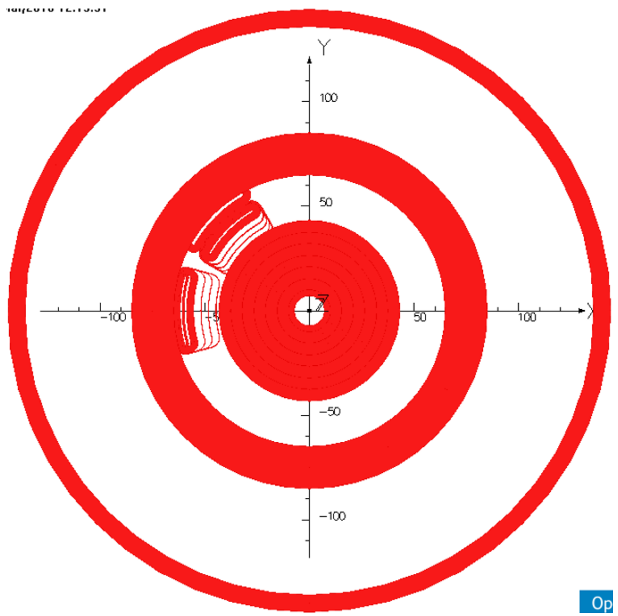




Regenerative extraction – Regenerator coil

- Because of the iron-free design, coils have to be self-compensated
- Optimization program (python) calculates compensated coils, exports to OPERA





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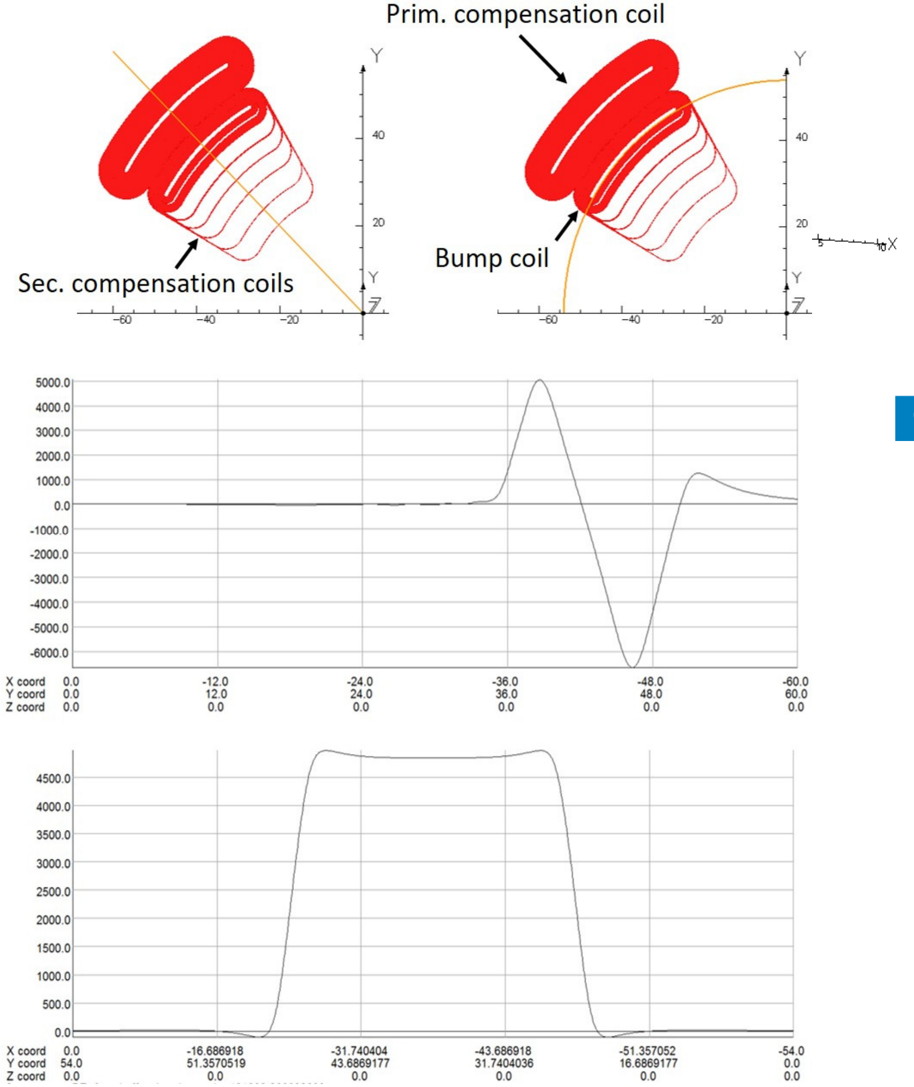
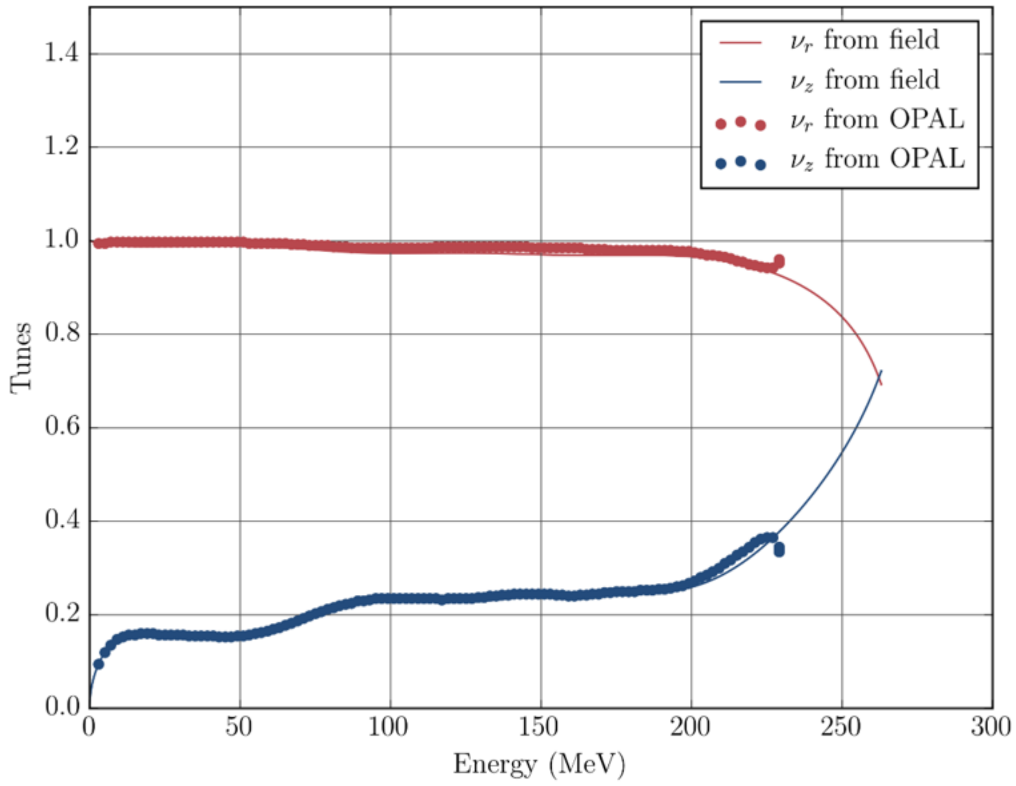
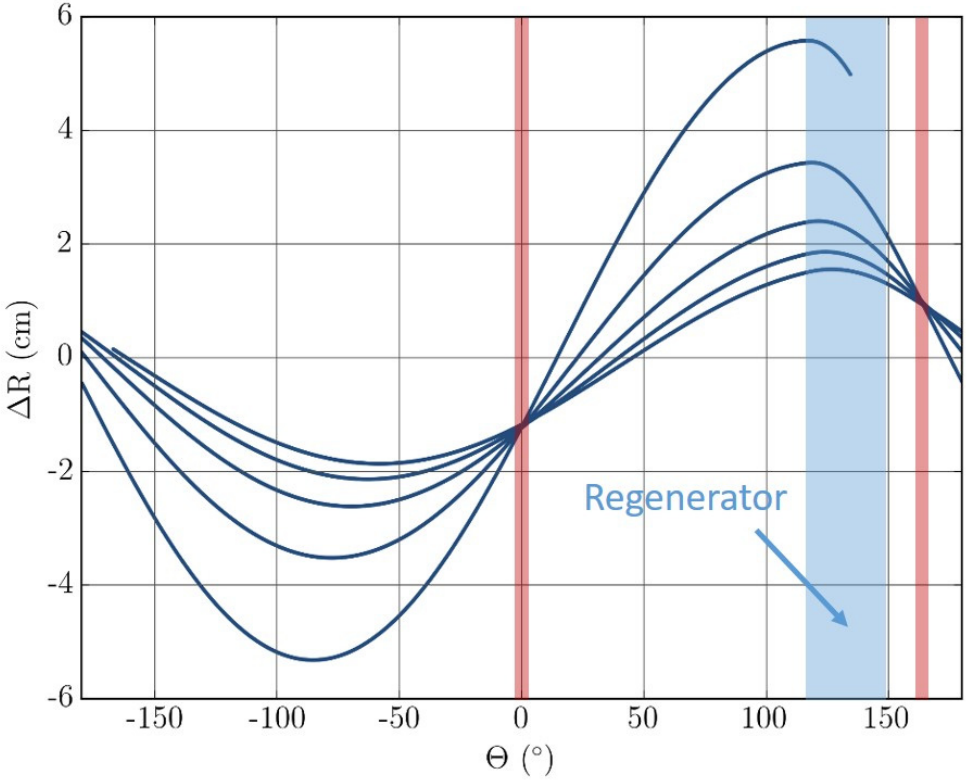


Opera

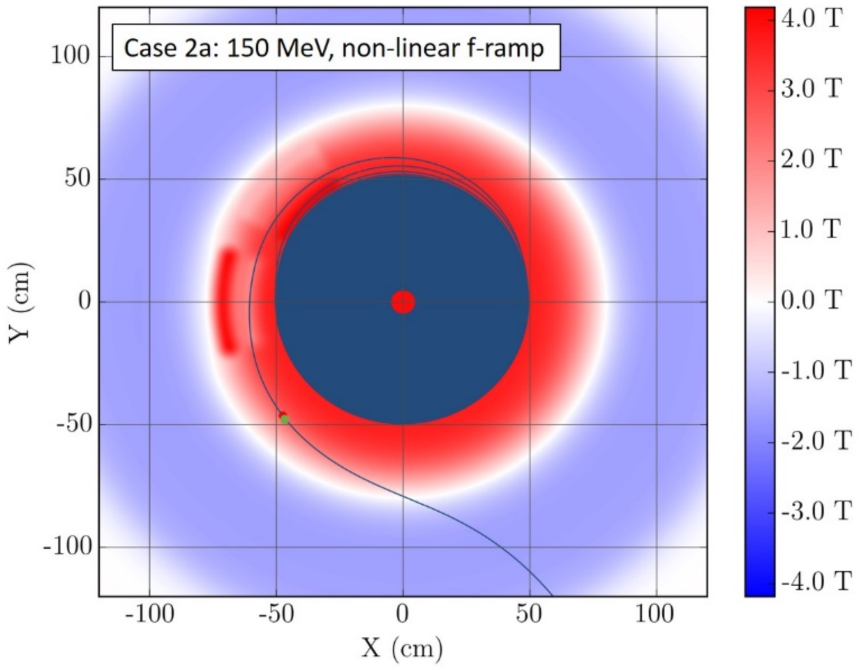
Effect of resonance on tunes (from OPAL) – "locked-in"

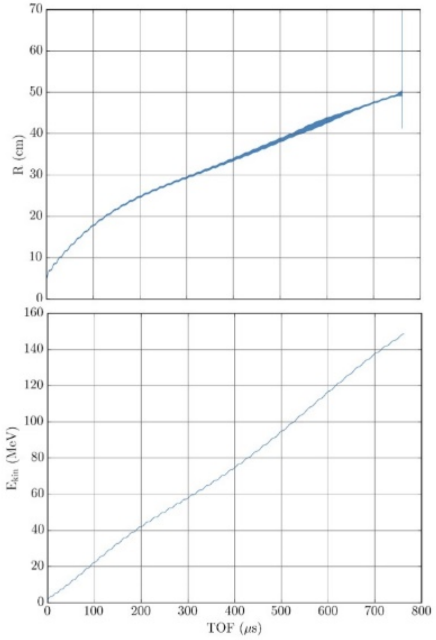


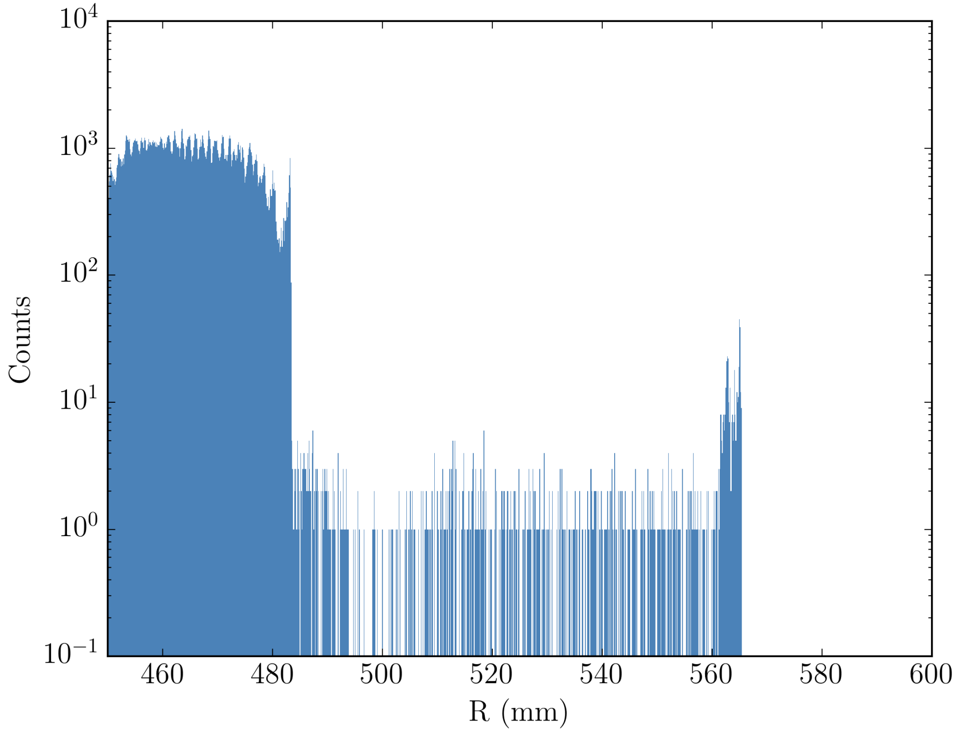


Multiparticle simulation – Preliminary result

- Only one case shown, others are similar







Summary & Conclusion

- The conceptual design for a iron-free cyclotron has been finished at PSFC/LNS at MIT.
- Coil, cryostat, and power supplies have been investigated and acceptable solutions have been listed.
- Preliminary beam dynamics studies showed no immediate show-stoppers
- For variable beam energy, several key components need to be investigated further:
  - Use of ferrite tuners for frequency ramp control
  - Effects of source bias on beam quality
  - Sensitivity of regenerative extraction on other cyclotron parameters
  - Extraction channel design → Full Start-To-End Simulations