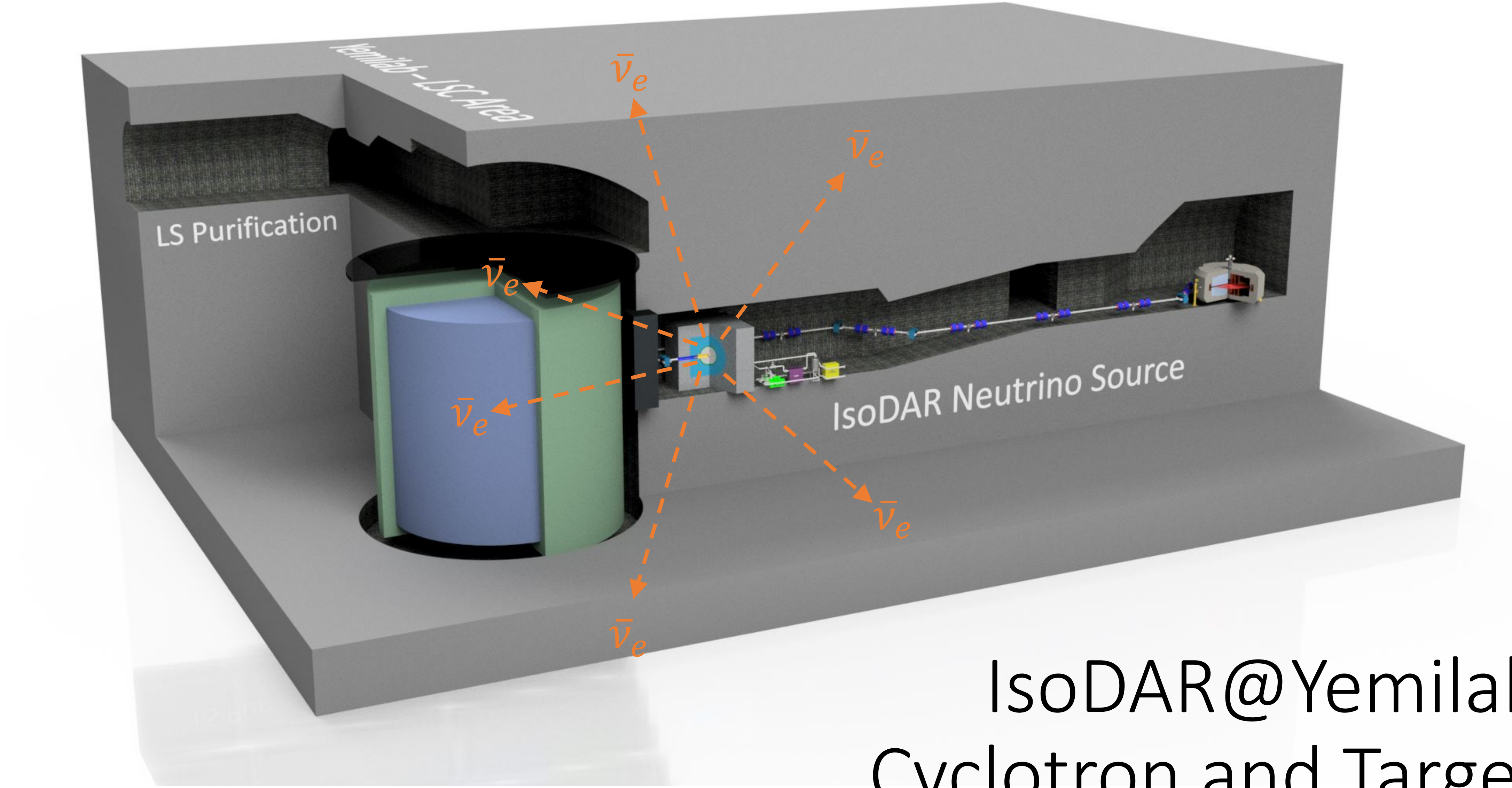


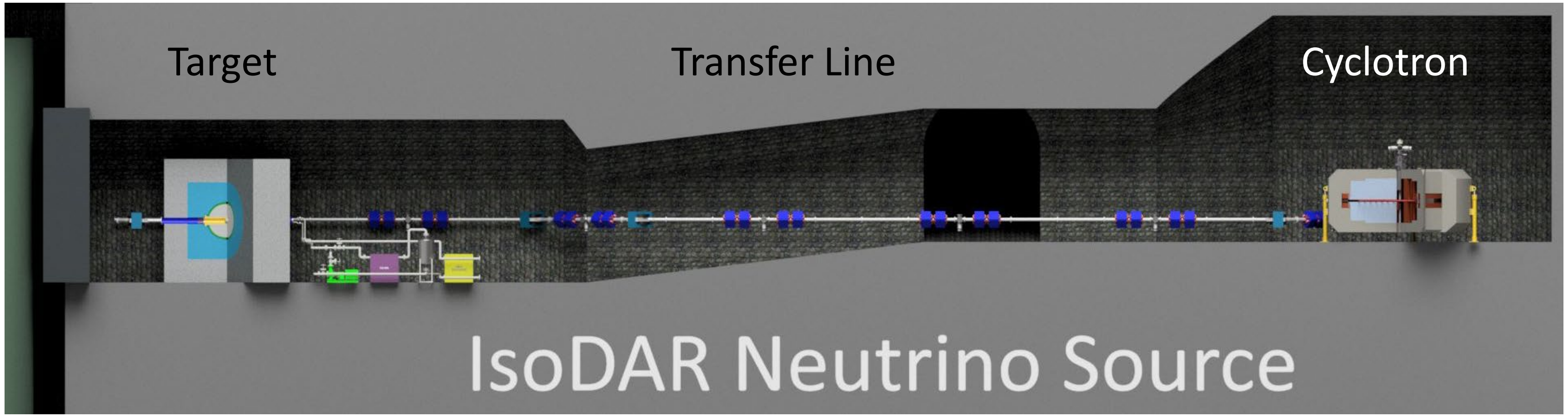
IsoDAR@Yemilab
Cyclotron and Target

Daniel Winklehner (MIT) on behalf of the IsoDAR collaboration

Sterile Neutrino Search Mini-Workshop – 07/01/2021

With a cyclotron and a high power target we can produce 10^{23} neutrinos in 5 years!

- 10 mA of 60 MeV protons are needed on target at 80% duty factor
- Translates to 600 kW power on target
- We have shown that this is possible through calculation, experiment and simulation



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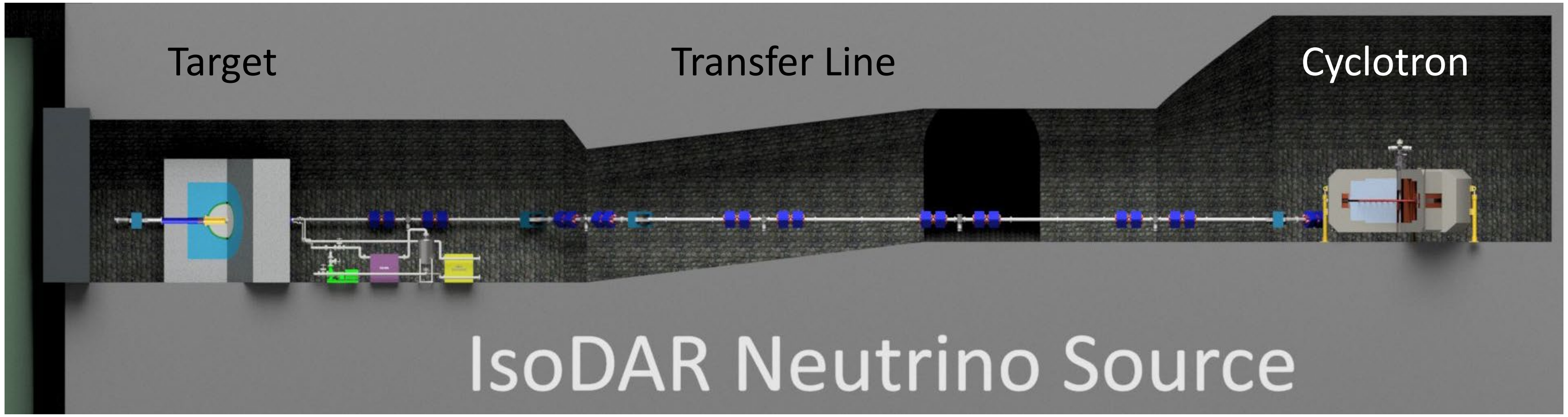
DAEδALUS IsoDAR

- 10 mA of 60 MeV protons are needed on target at 80% duty factor
- Translates to 600 kW power on target
- We have shown that this is possible through calculation, experiment and simulation
- Cyclotrons are best-suited (cost-effective, compact, well-established)

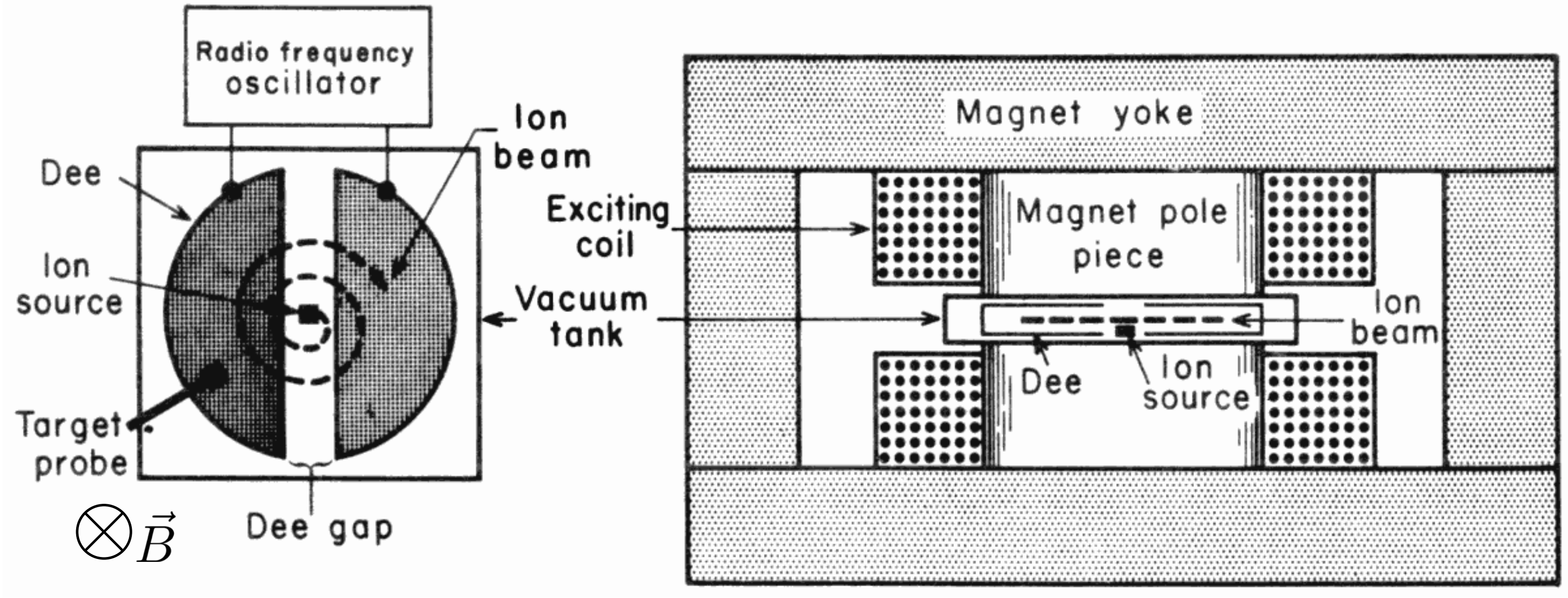


The Cyclotron – A brief introduction

Cyclotrons – Basic operating principle

- Particles are forced on circular orbits by a dipole magnetic field
- Acceleration is added by oscillating copper shells (Dees) → spiral orbit

$$V(t) = V_{max} \cdot \cos(\omega_{RF} \cdot t - \Phi_S) \qquad \omega = 2\pi f = \frac{qB}{\gamma m_0} \qquad r = \frac{\gamma \beta m_0 c}{qB}$$



Cyclotrons – Three types

<u>cw</u>
continuous wave =
every RF period
contains one bunch

$$\omega = 2\pi f = \frac{qB}{\gamma m_0} \qquad r = \frac{\gamma \beta m_0 c}{qB}$$

- Classical: No accounting for relativity → low energy, cw
- Synchrocyclotron: Change frequency with time → high energy, pulsed
- Isochronous cyclotron: Increase B-field with radius → high energy, cw

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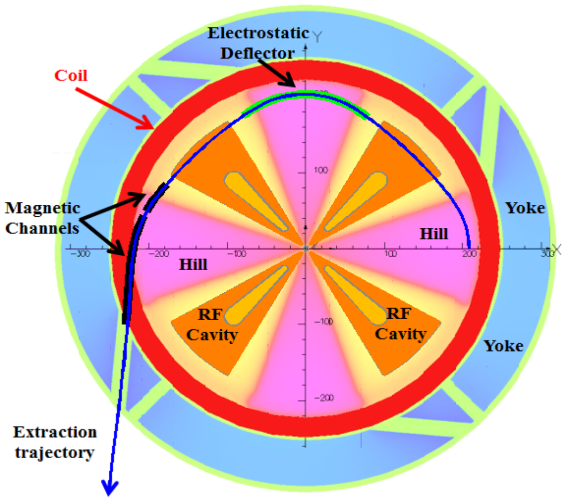
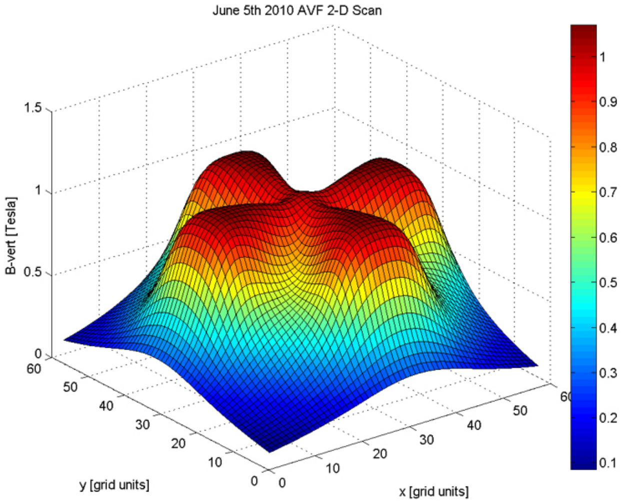


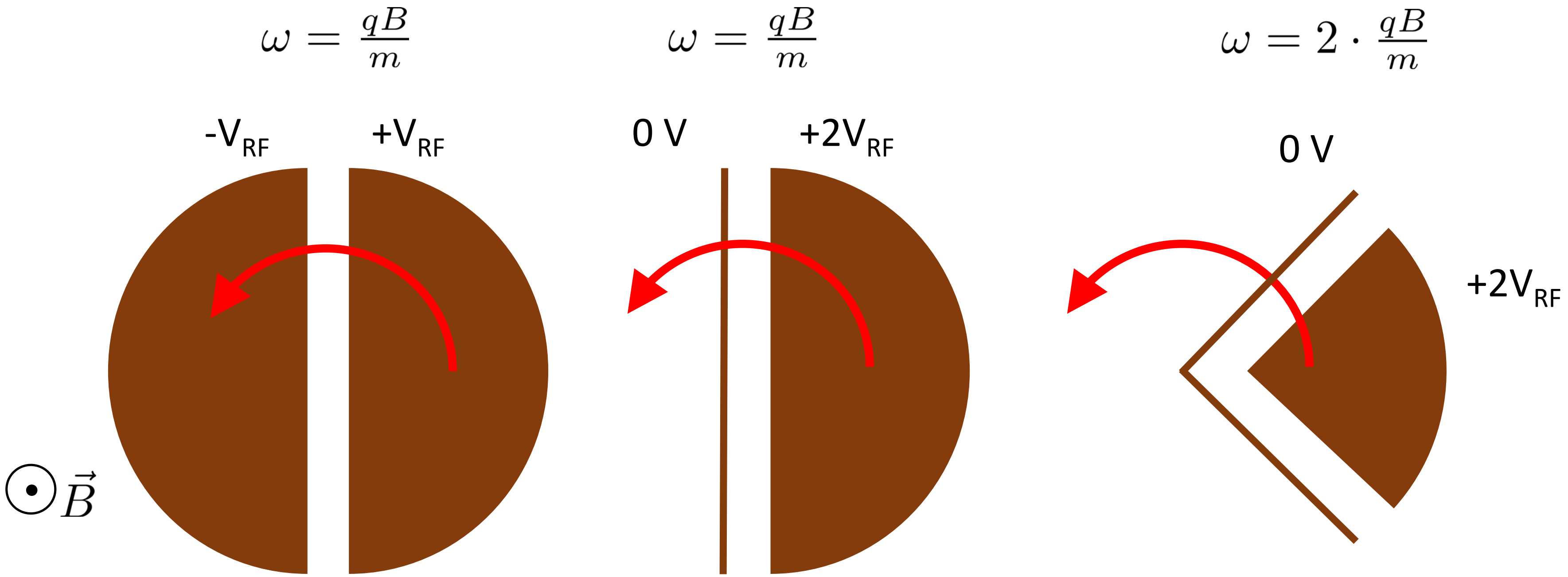


AVF
Azimuthally Varying Field (for vertical focusing)

Cyclotrons – RF Cavities/Dees

Harmonic
Integer multiple of base frequency

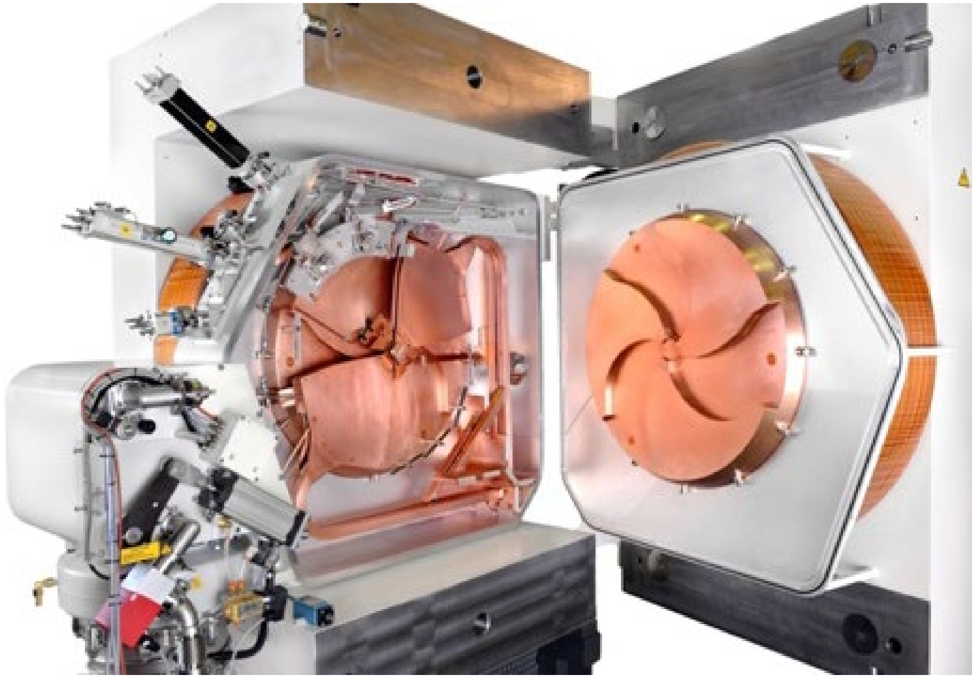
- Dee doesn't have to be "D"-shaped:



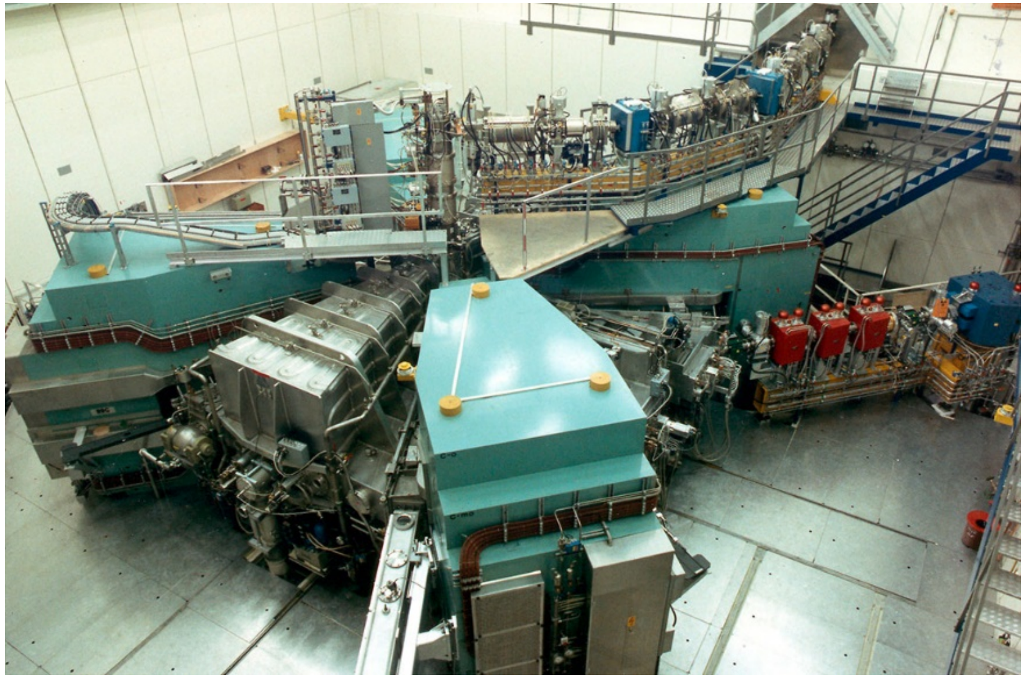
- In general: $\omega = h \cdot \frac{qB}{m}$, RF can be any integer multiple of particle frequency.
- Dees can be made into double gap cavities with angle = 180/h

The state-of-the-art in cyclotrons

Commercial: 1 mA (compact)
Medical Isotope Production



PSI Injector II: 2.7 mA (sectors)
Research



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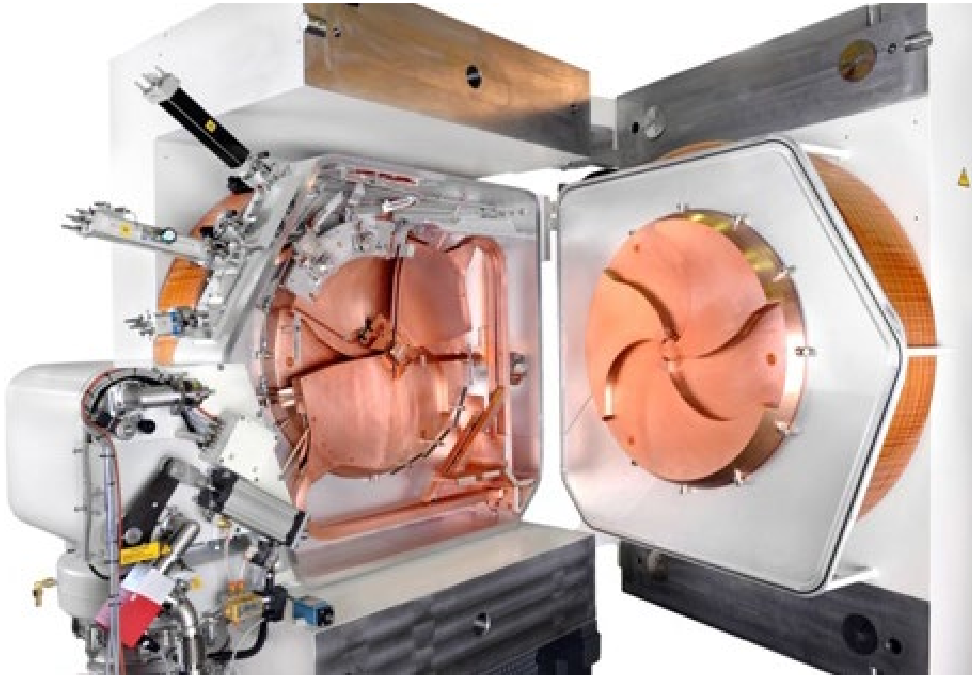

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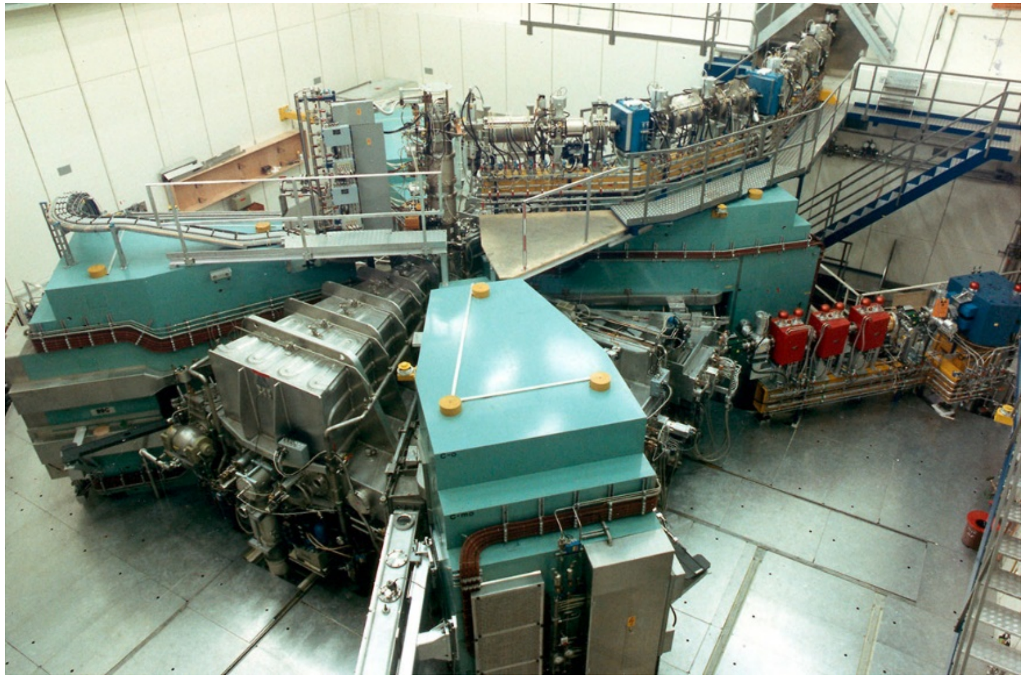
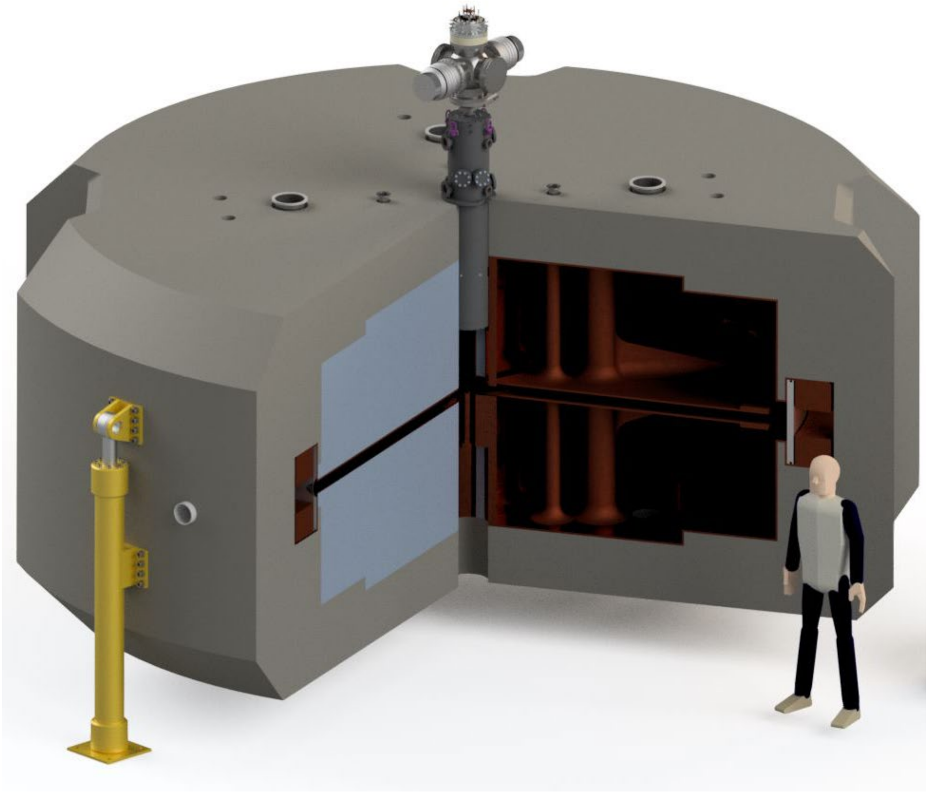


We took lessons from both and added innovations to design a record beam of 10 mA

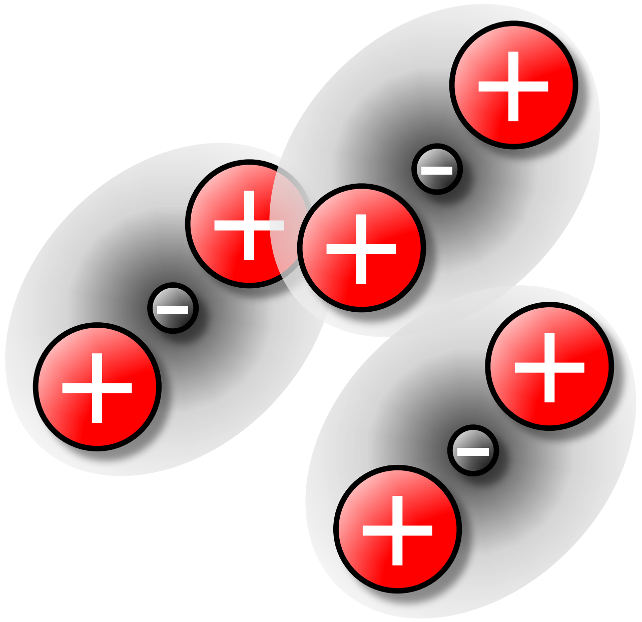
The IsoDAR cyclotron – main parameters

- Room-temperature coils (no cryogenics needed)
- Isochronous, cw, 80% duty factor
- Operates at 32.8 MHz (4th harmonic)
- 4 double-gap cavities
  → high energy gain/turn
- Accelerates H_2^+ ions instead of protons
- Direct axial injection through a Radiofrequency Quadrupole (RFQ)
  - Efficient bunching
  - Moderate pre-acceleration
- Utilizes vortex motion
  (a beam dynamics effect during acceleration)



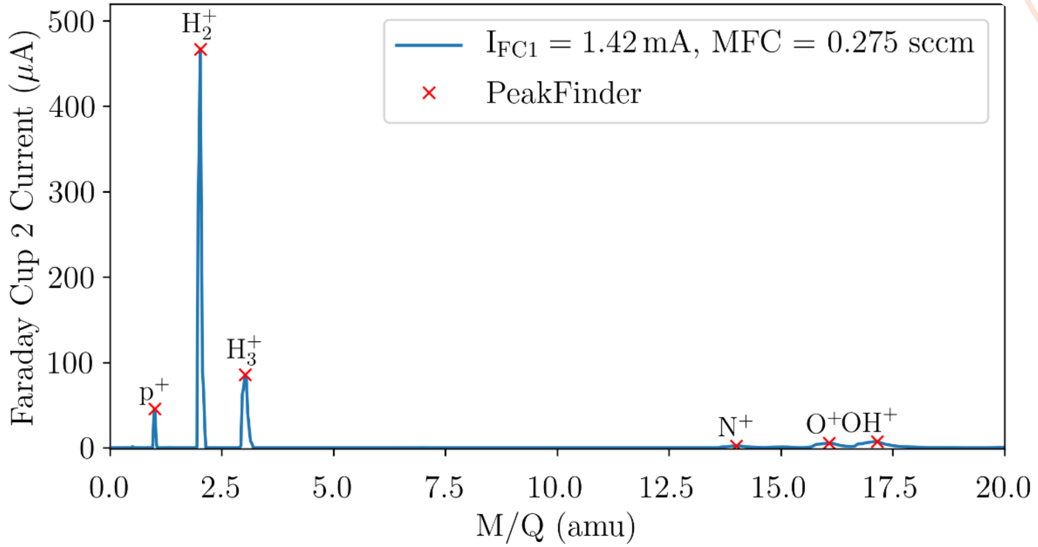
Accelerating H_2^+ alleviates space charge

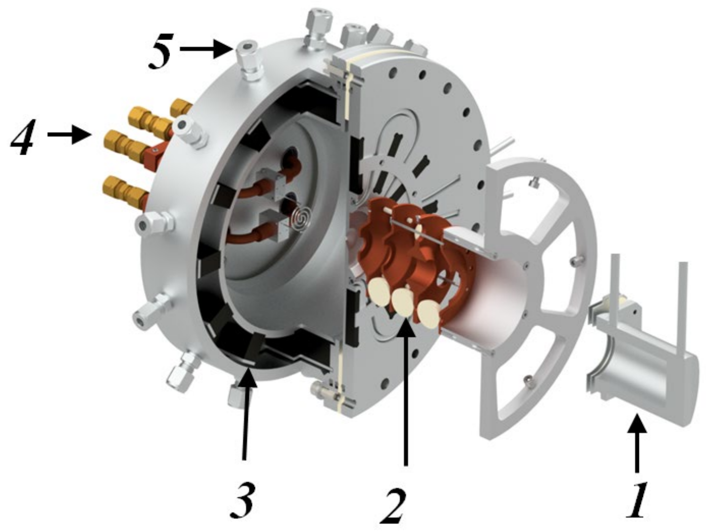
- Two units of charge for one!
- After extraction from cyclotron:
  - Remove electron by foil-stripping
  - → get two protons
- Easier to:
  - bring beam from ion source to RFQ
  - bring beam from RFQ onto cyclotron median plane
  - accelerate high currents
- Slight drawback:
  - higher rigidity → larger machine
  - accommodated this in the design



H_2^+ ion source (MIST-1) commissioned at 25% power at MIT

- Filament-driven multicusp ion source
- > 1 mA of H_2^+
- 80% purity
- High quality beam emittance: 0.05 π-mm-mrad (RMS, norm.)
- Now ramping up to 100% power





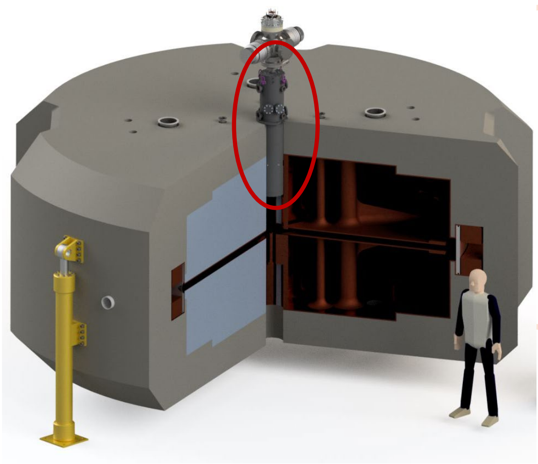
https://arxiv.org/abs/2008.12292

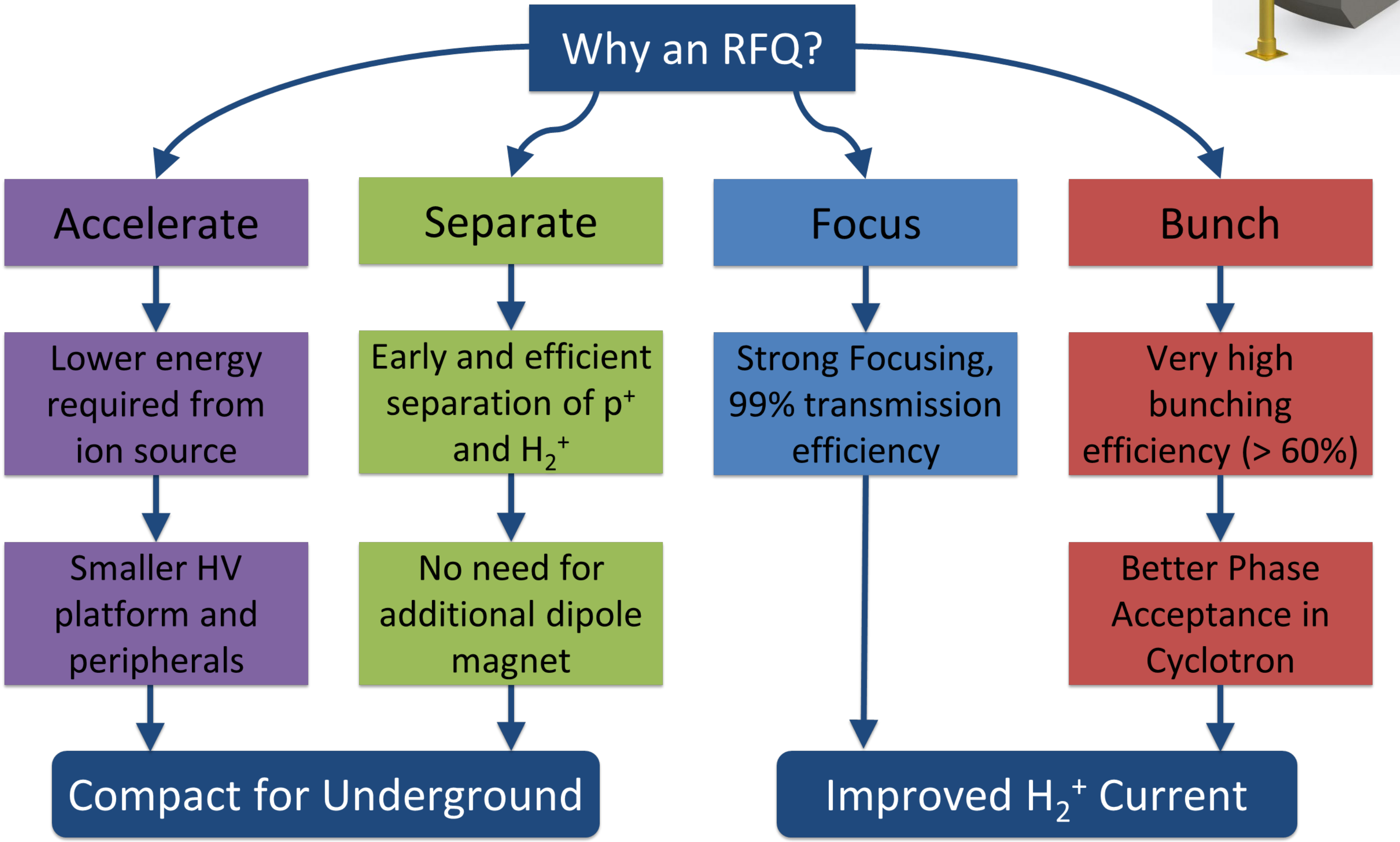
Emittance
Figure of merit for how quickly beam will spread out

Multicusp Ion Source Technology at MIT

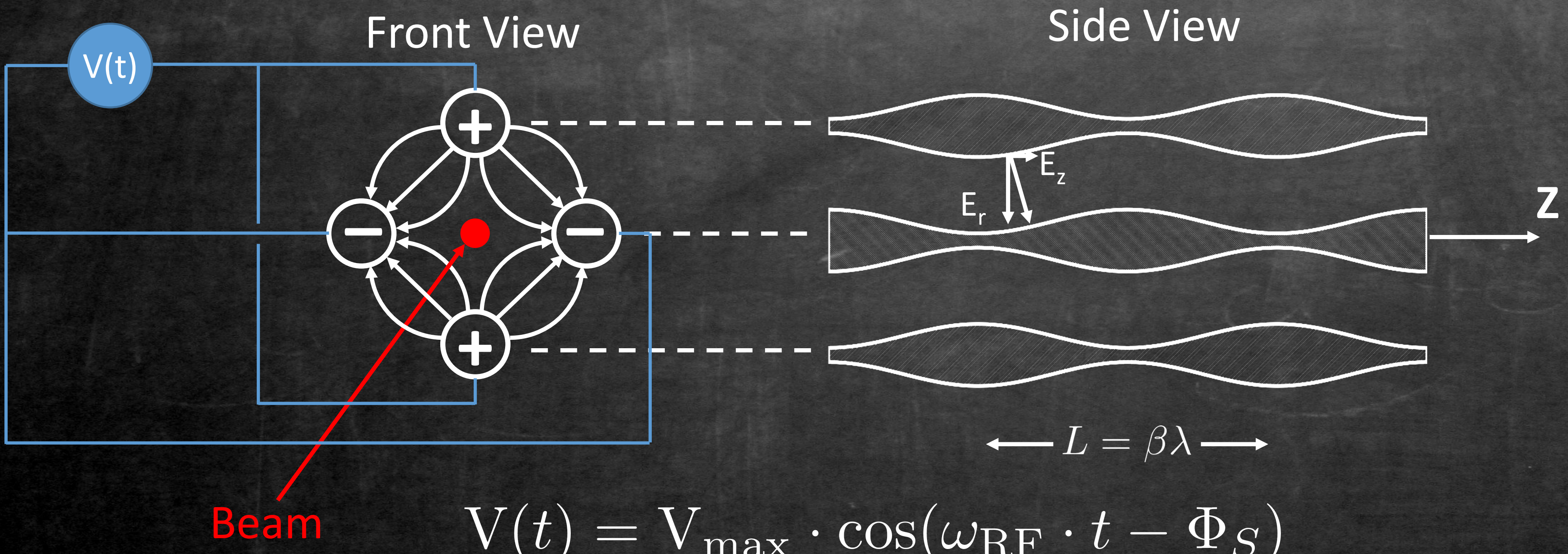
Accelerator Design

Radiofrequency Quadrupole (RFQ)





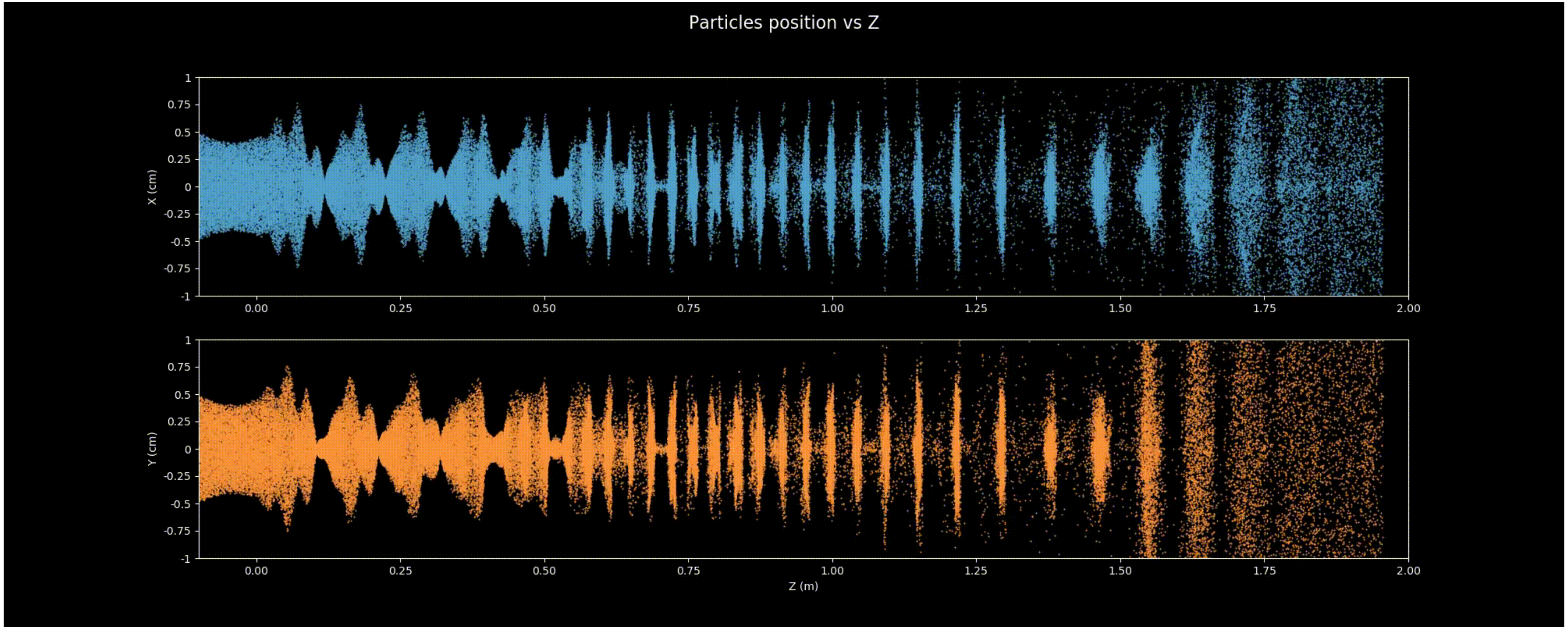
RFQ General Principle



$$V(t) = V_{\max} \cdot \cos(\omega_{RF} \cdot t - \Phi_S)$$

- Continuous focusing like in a series of alternating F/D Electrostatic quadrupoles
- Modulations lead to acceleration and bunching (RF bunching similar to cyclotron)
- Same frequency as cyclotron

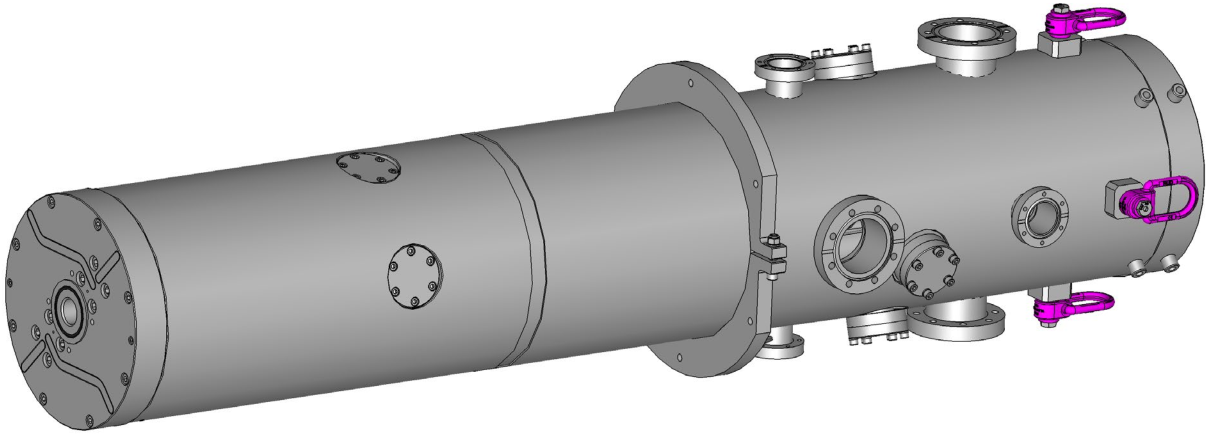
Particles are continuously focused transversally, while being bunched longitudinally

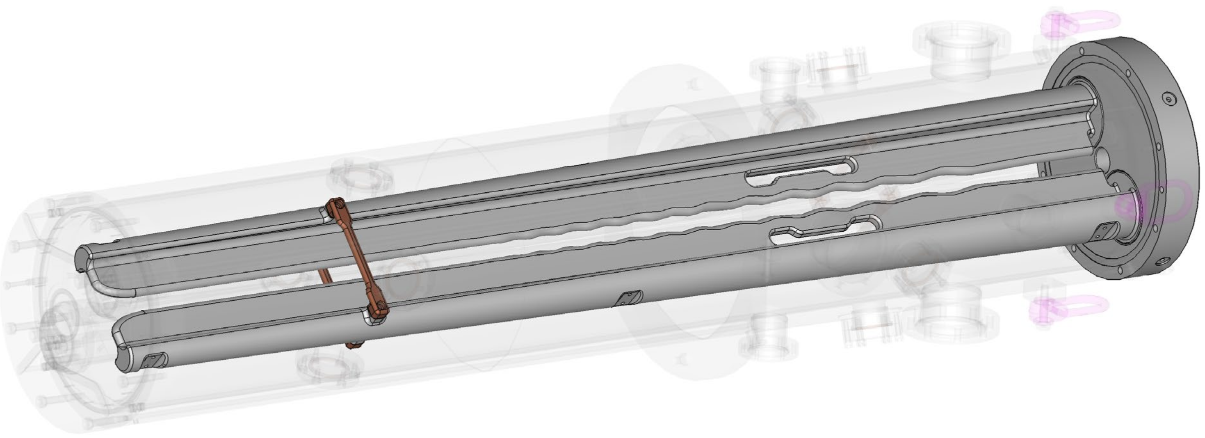


Highly accurate particle in cell (PIC) simulations using well-established WARP code

RFQ technical design is currently being finalized – manufacturing commences soon

<u>Split-Coaxial RFQ</u>
Eigenmode of tank allows low frequency with small diameter





Elements	Unit	Design parameters
Frequency	MHz	32.8
Particle	A/q	H_2^+ (2)
Length	**mm**	**1378.69**
No. of cells		58
Transmission rate	%	97.27
Beam energy	keV	15 → 70
Input Trans. emit (rms, norm)	mm-mrad	~~0.3000~~ ~0.25
Trans. emittance (rms, norm)	mm-mrad	~~0.3427~~ ~0.25
Long. emittance (rms)	**keV-deg**	~~**40.24**~~ ~30
Vane voltage	kV	20.14
min. vane-tip aperture	mm	6.83
vane-tip curvature	mm	9.30
r_0, mid-cell aperture	mm	9.30
Octupole term		0.070

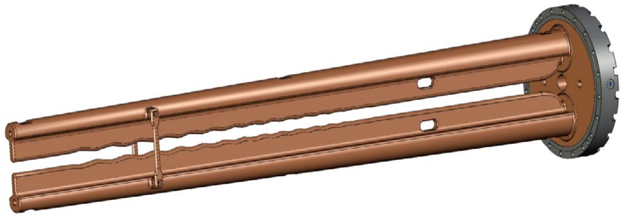
Power: kW < 6

Technical Design by Bevatech, GmbH, Germany

Details about the RFQ design

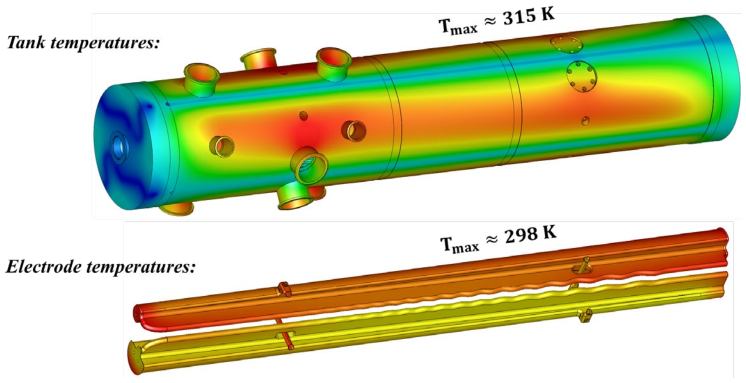
RFQ technical design

- Split-Coaxial
- Good frequency tuning capabilities
- Mechanical Stability through stabilizer bars



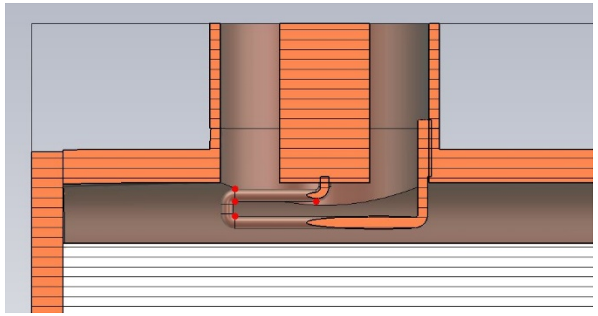
Thermal properties and cooling

- CFD & FEA
- Good agreement between CST & COMSOL
- Frequency detuning (24 kHz) can be compensated by tuner



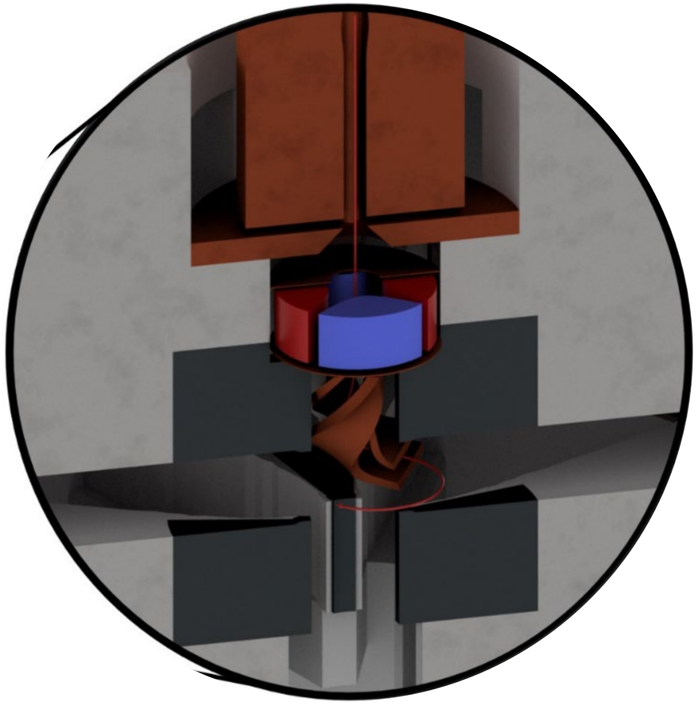
Loop coupler optimization

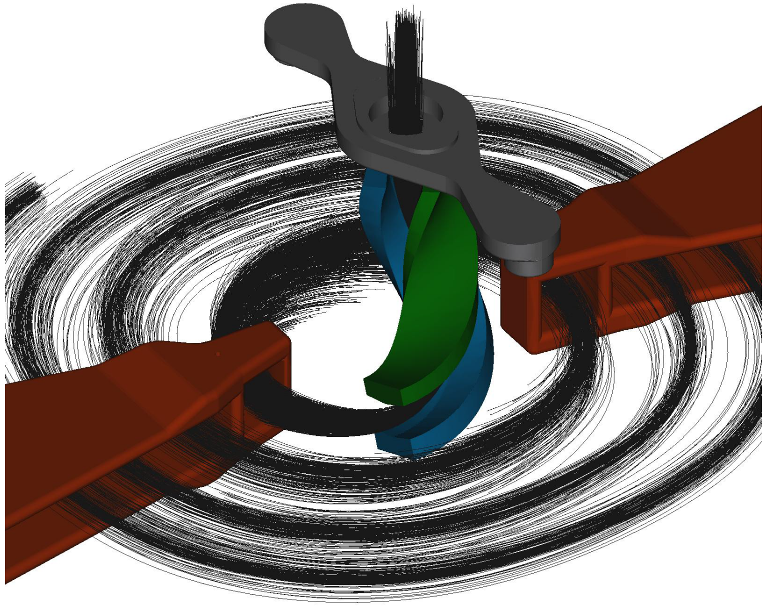
- Position-, shape-, rotation studies
- Good agreement between CST & COMSOL
- Estimated power (with beam & contingency): 5.33 kW



After being bunched and pre-accelerated, beam is brought into the cyclotron and accelerated

- We have upgraded the PIC code OPAL to simulate this process accurately
- Benchmarked against theory and experiment with very good agreement

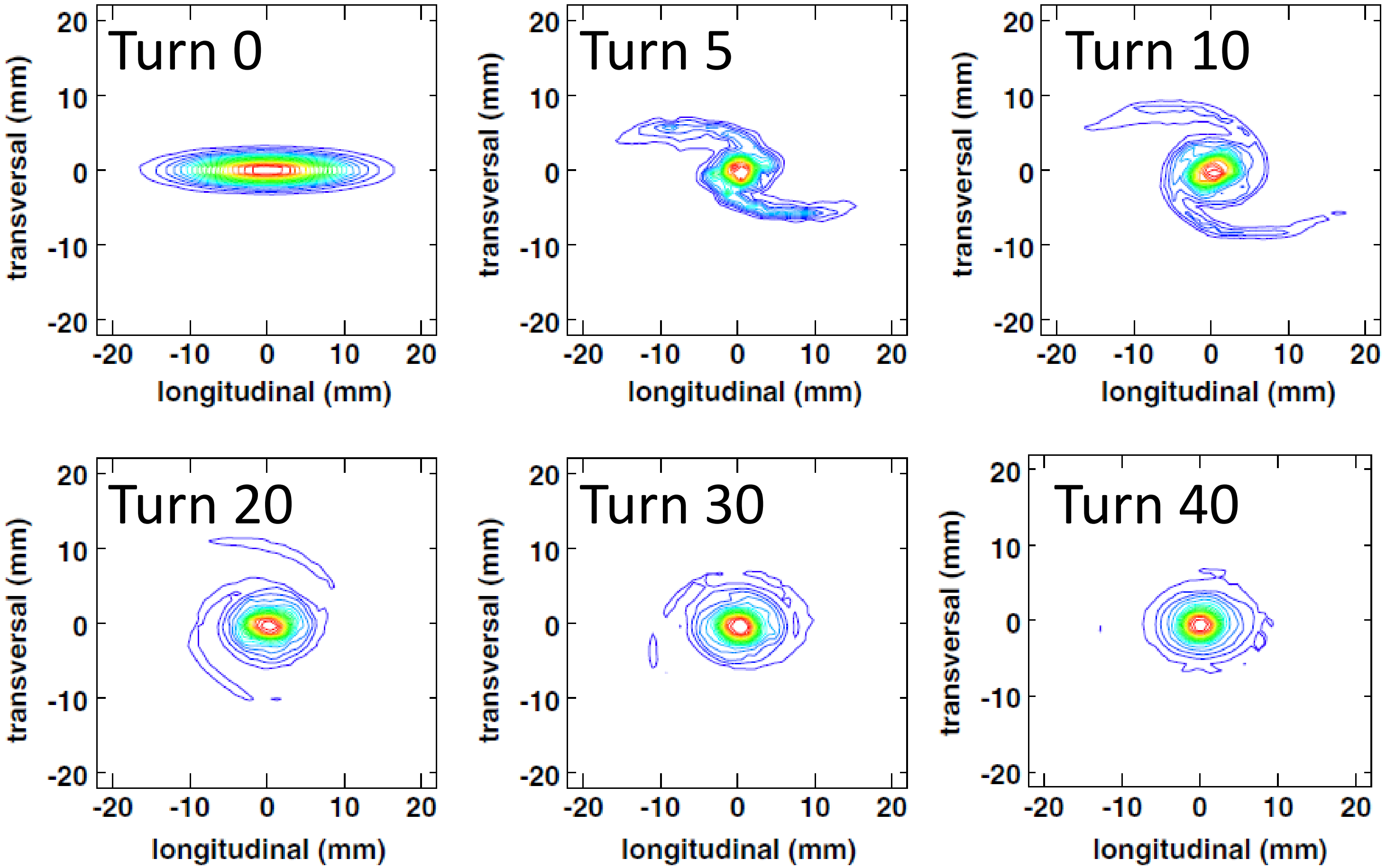


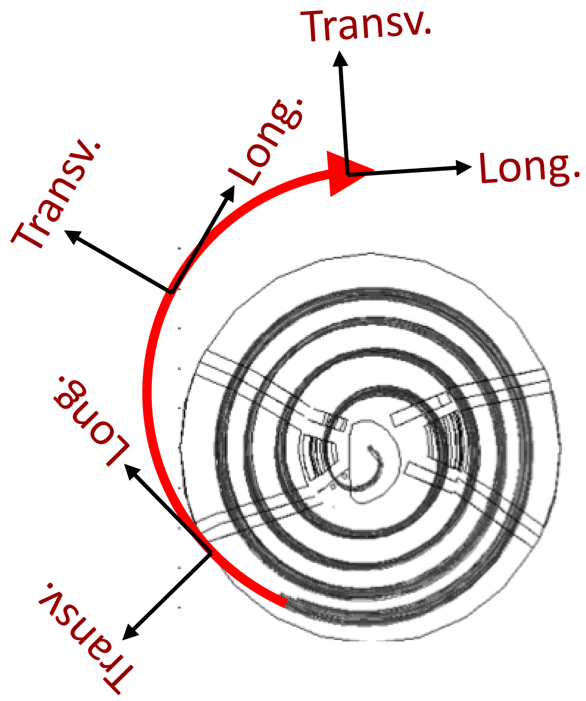


https://arxiv.org/abs/1612.09018

<u>PIC</u>
Particle-In-Cell
A method to solve the collisionless Vlasov equation

Vortex motion – OPAL Simulations for PSI Injector II

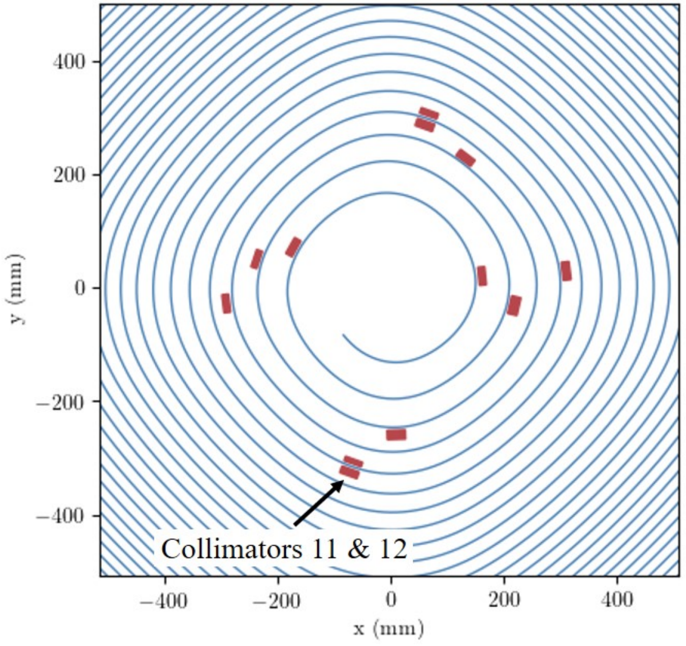


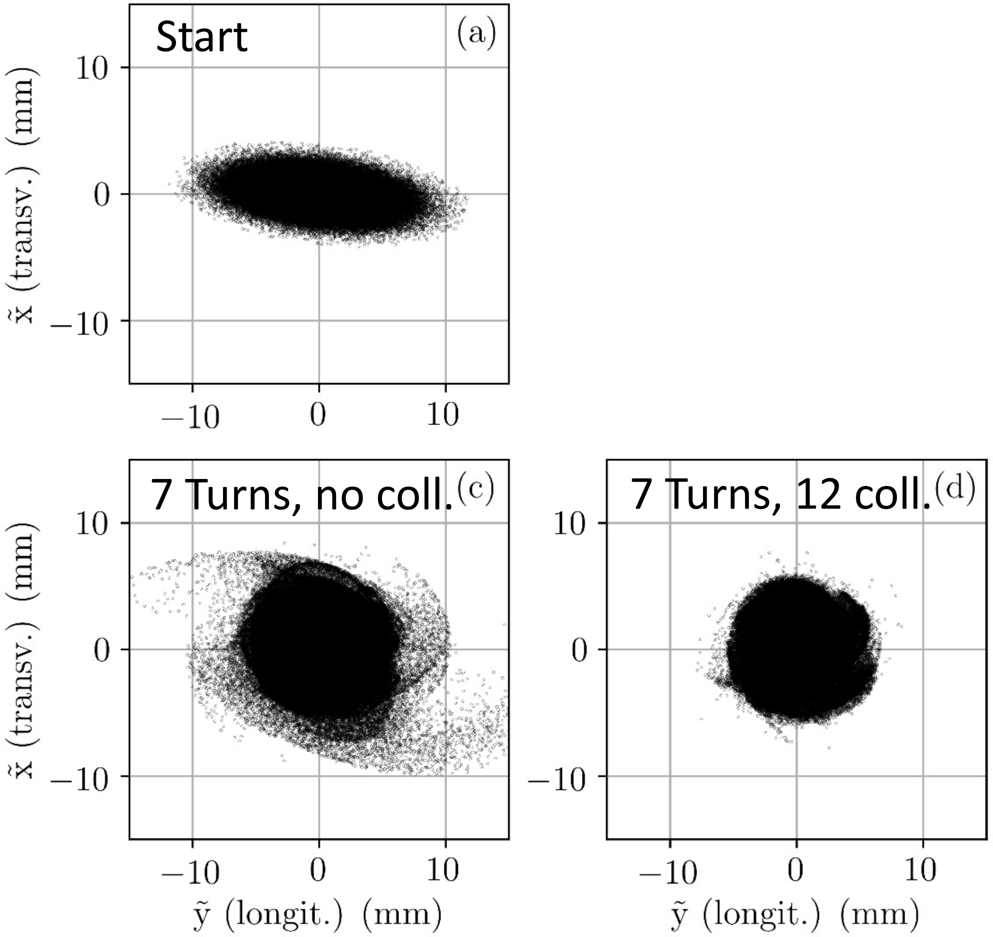


"Local Frame"

We performed highly accurate PIC simulations of our cyclotron design

- In IsoDAR the halo is removed with collimators
- Beam forms stable, round distribution (vortex) after 6 turns

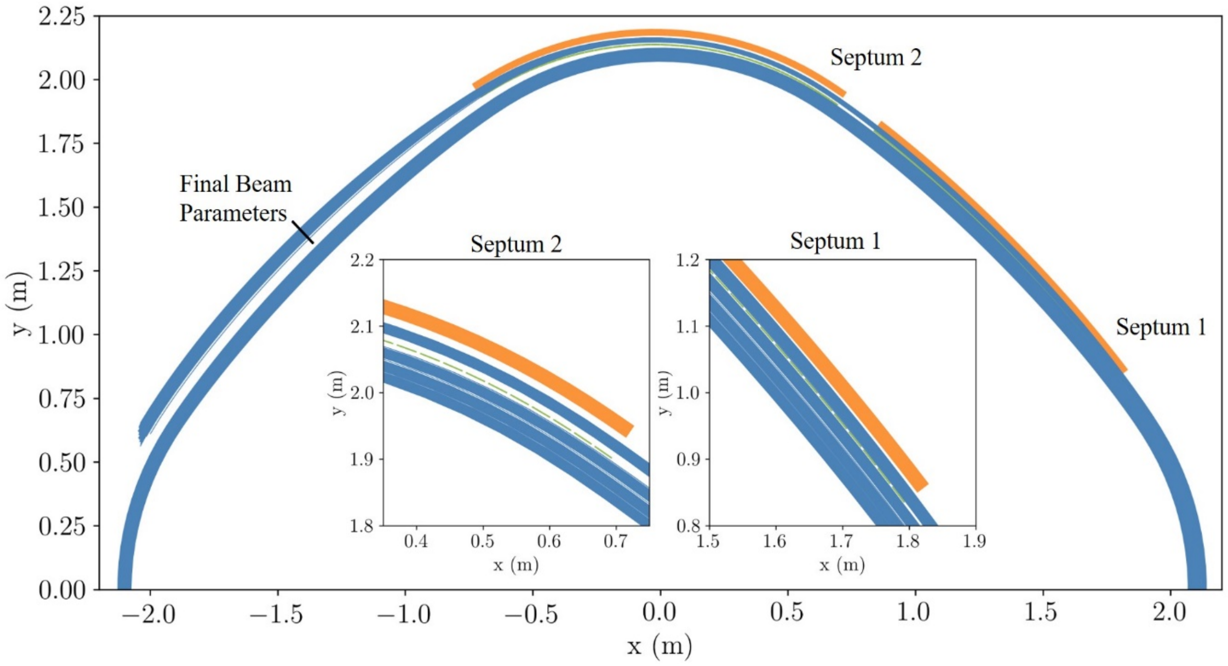




https://arxiv.org/abs/2103.09352

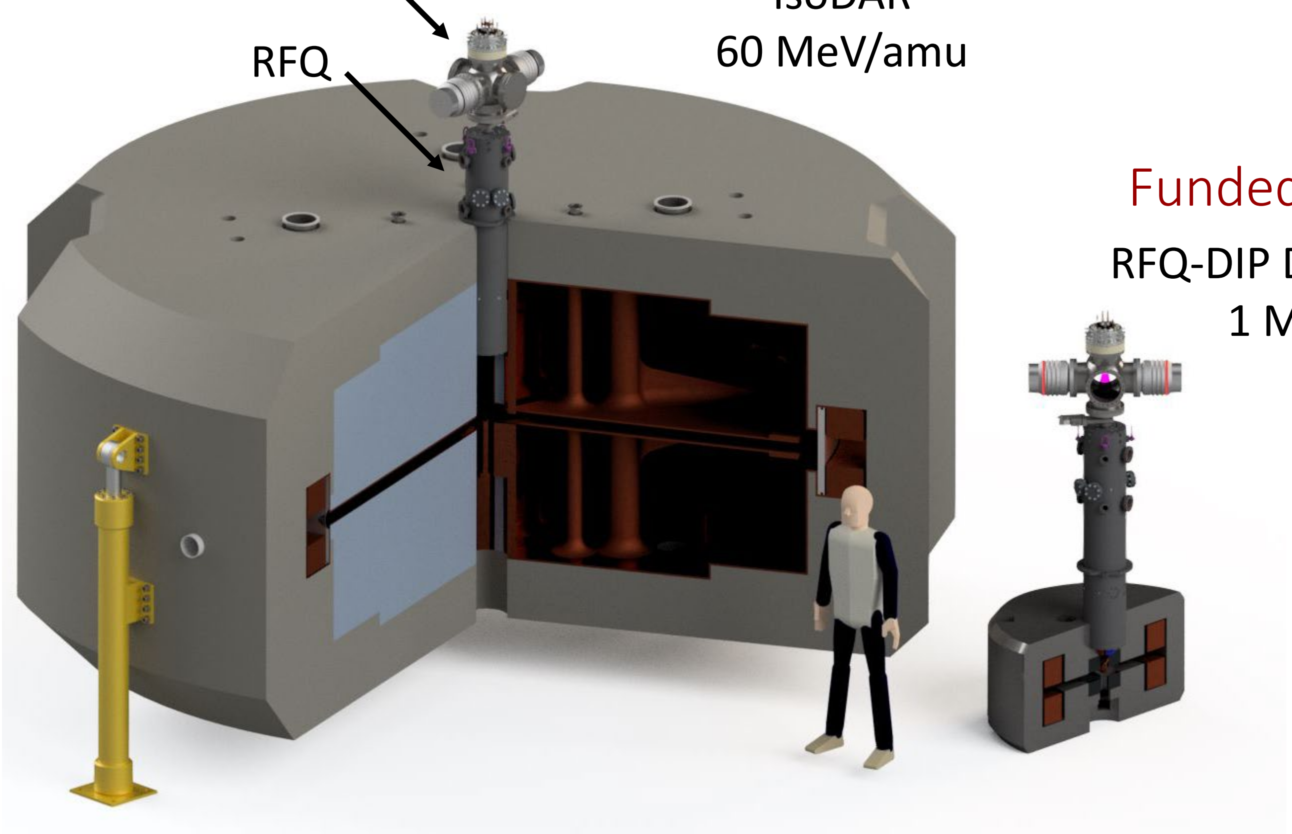
Beam can be extracted with good quality

- Minimal losses at 60 MeV/amu: < 48 Watt!
- RMS Size:
  - Vertical: 7.5 mm
  - Longitudinal: 11 mm
  - Vertical: 1.9 mm
- RMS, normalized emittance:
  - vertical: 0.44 mm-mrad
  - Radial: 3.8 mm-mrad
- Longitudinal emittance:
  - 0.1 MeV-deg



https://arxiv.org/abs/2103.09352

Prototype under construction: RFQ-Direct Injection (RFQ-DIP)



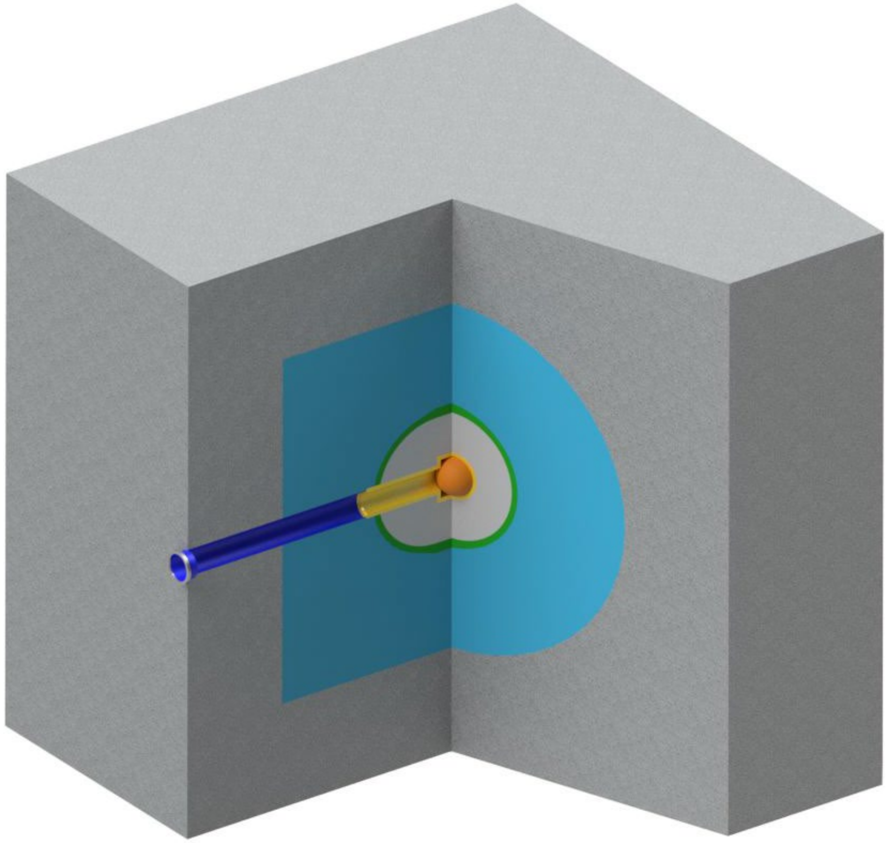
Funded by US NSF

RFQ-DIP Demonstration
1 MeV/amu

https://aip.scitation.org/doi/abs/10.1063/1.4935753
https://arxiv.org/abs/1807.03759

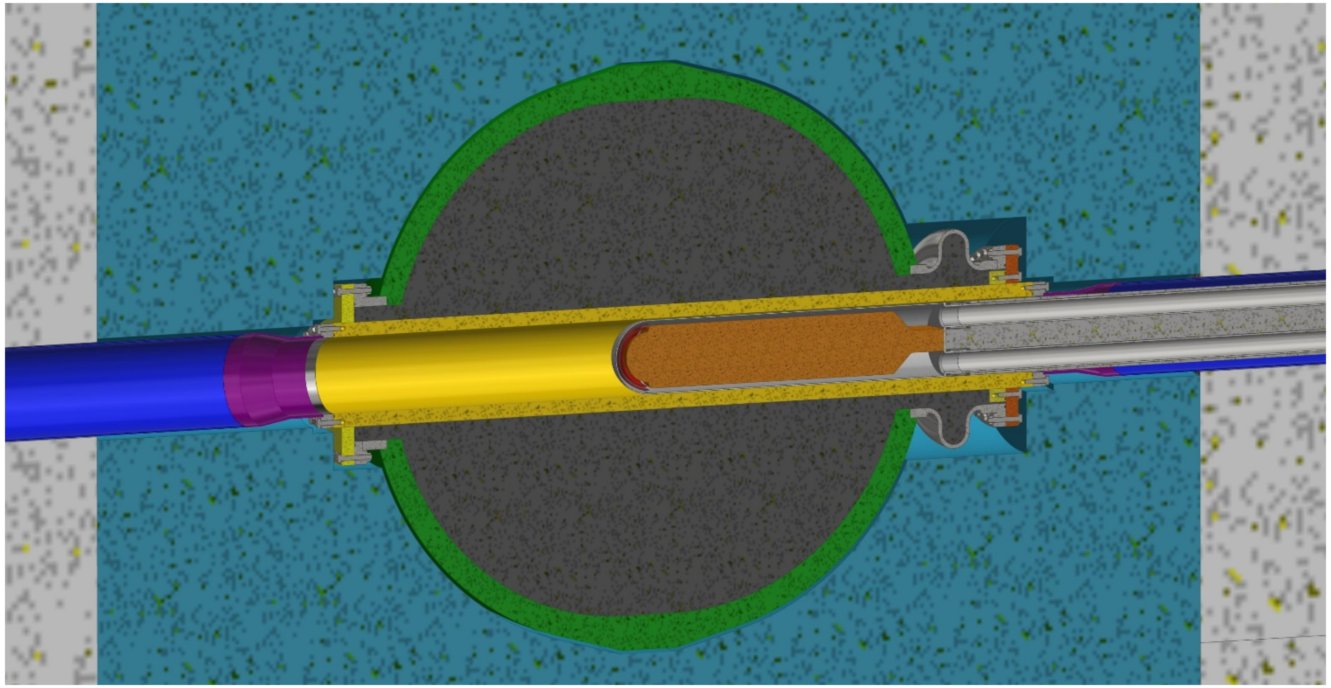
The IsoDAR high power neutrino target

- The 10 mA proton beam is spread out transversally and “painted” across the ~20 cm target.
- Neutrons are produced in the ^{8}Be…
- …and captured on ^{7}Li in a surrounding sleeve
- Intermixed ^{8}Be increases the overall yield
- The resulting ^{8}Li decays at rest and produces electron-antineutrinos.



Lithium-beryllium mix must be filled at high pressure

- The lithium-beryllium mixture must be filled under pressure
  - special vessel (green)
- Prototype underway
  - funded by US-NSF
  - built at the University of Michigan



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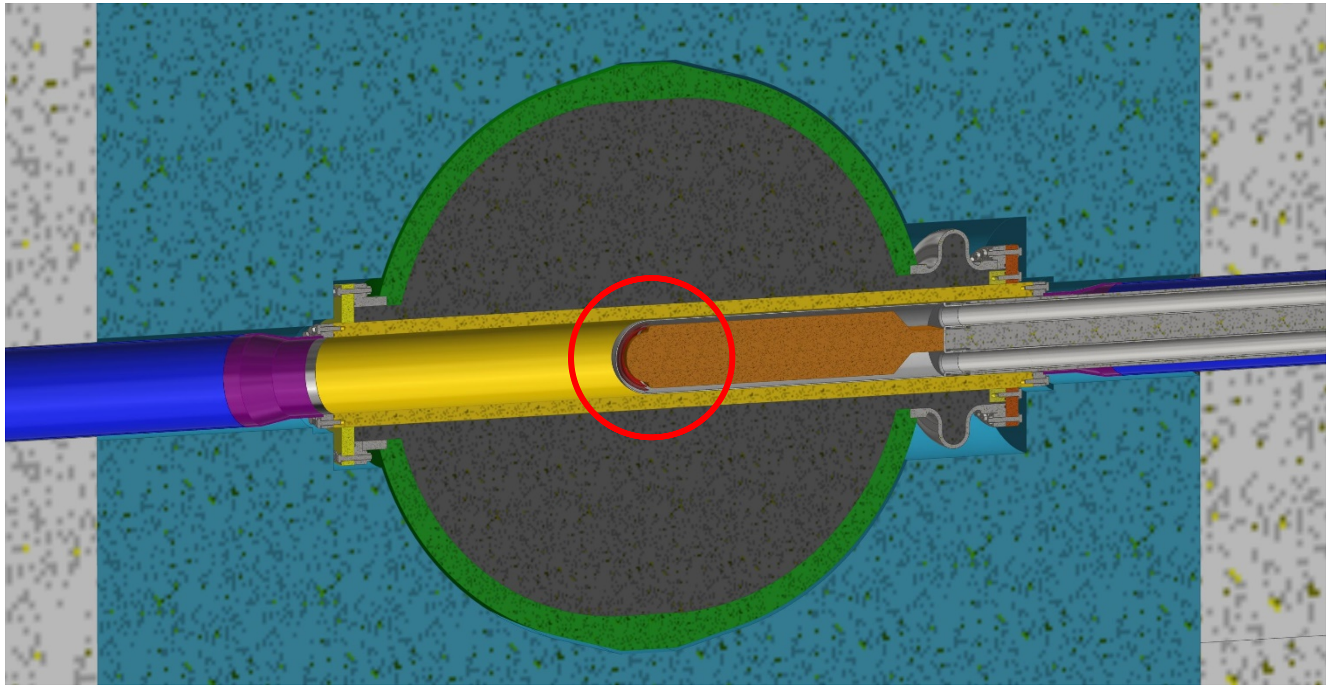
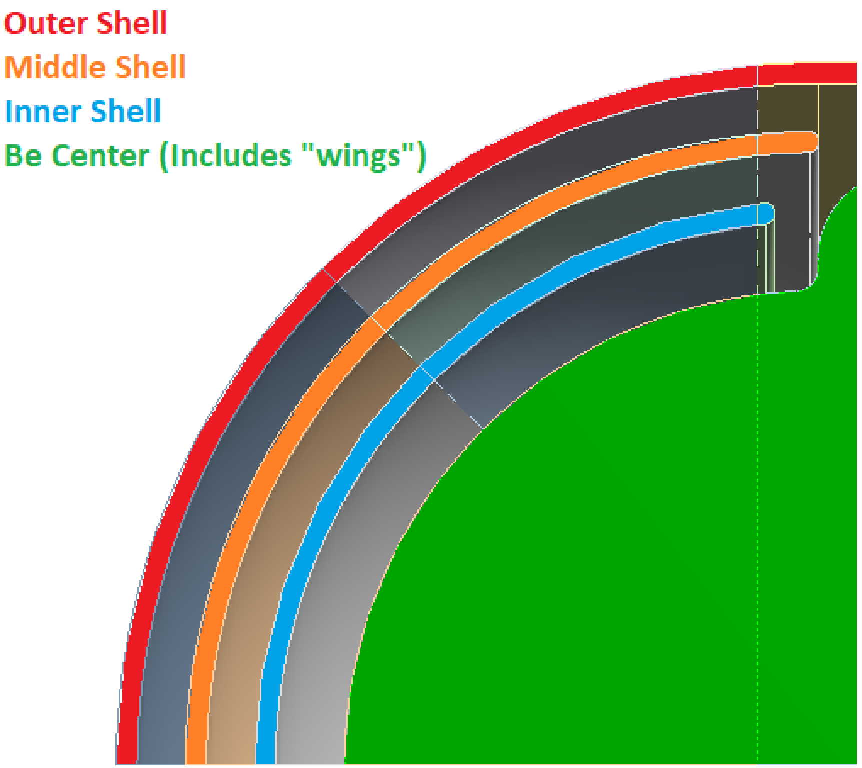
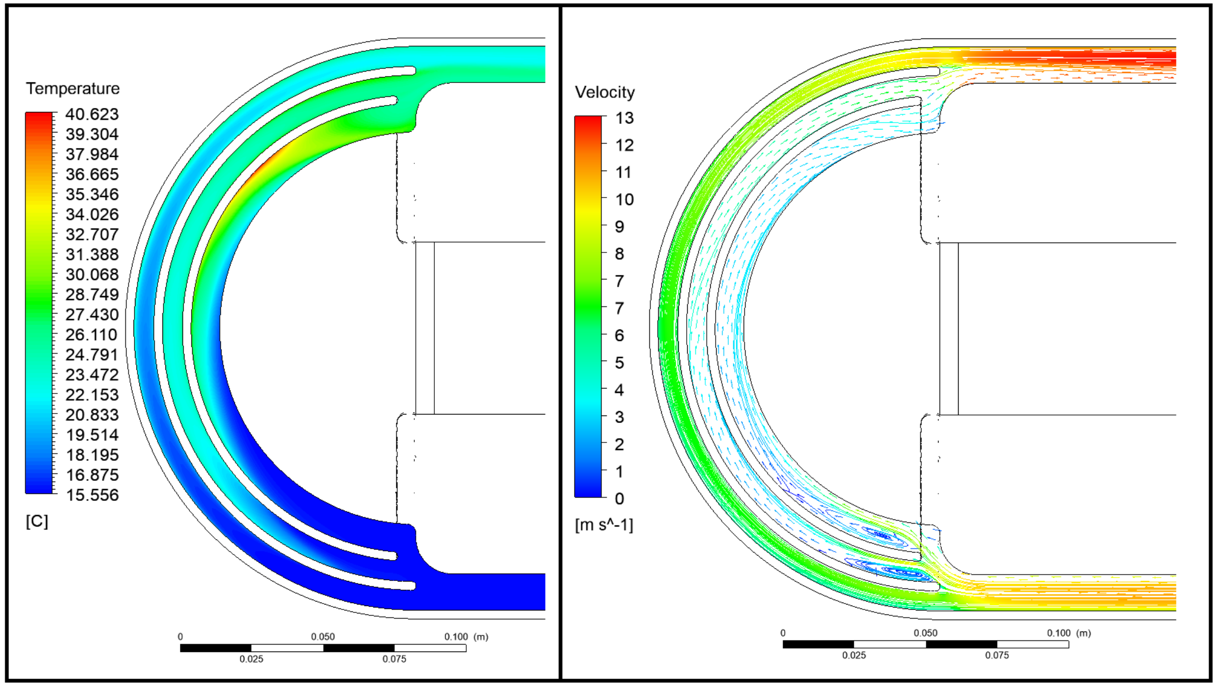


Target cooling with heavy water

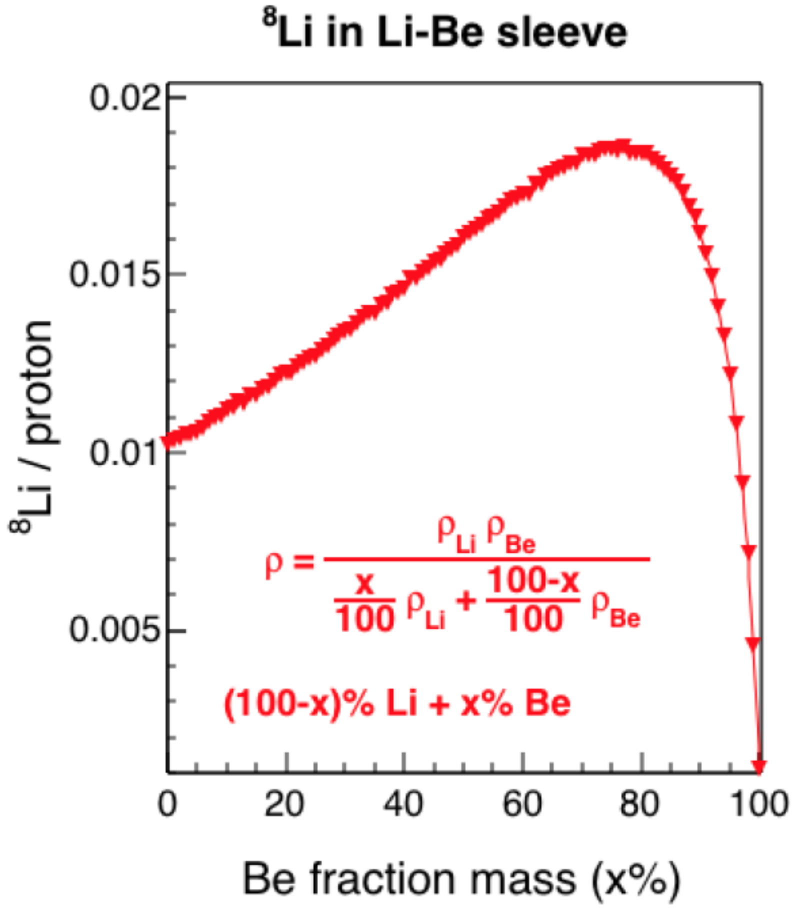
- Heavy water is pumped through a nested-shell beryllium structure
- CFD/FEA calculations show adequate cooling, stresses, and deformation





We have a full Geant4 model for ^{8}Li yield and neutron backgrounds

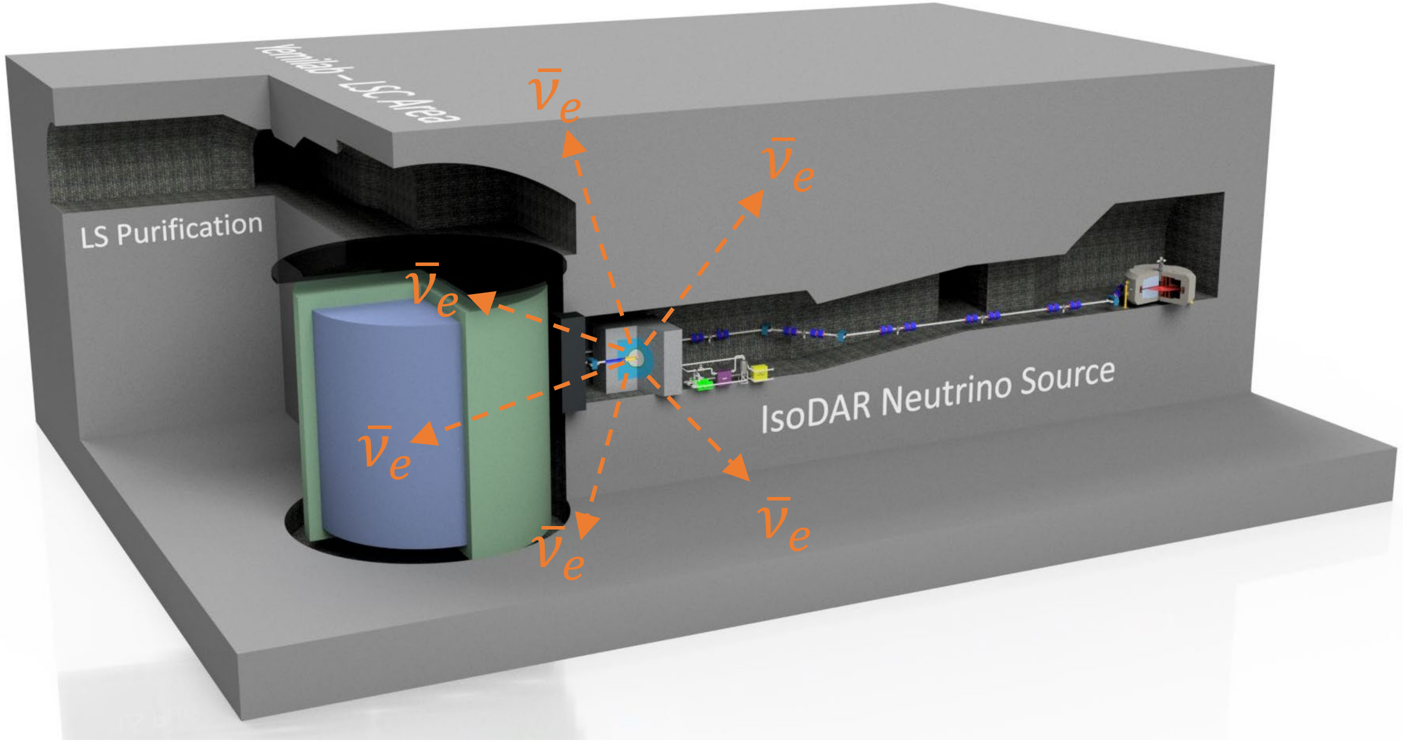
- ^{8}Li yield was carefully optimized to meet the IsoDAR requirement of 0.016 ^{8}Li/p
  - Li-Be ratio
  - Geometry of target and sleeve
- Contamination with other isotopes is very low



https://arxiv.org/abs/1805.00410
https://arxiv.org/abs/1909.08009

Conclusion: IsoDAR promises a rich physics program and has a mature design

- Our compact cyclotron can produce 10 mA of 60 MeV protons
- Target can handle 600 kW
- Demonstrated this through:
  - Experiments
  - PIC Simulations
  - CFD/FEA calculations
- Prototypes (funded):
  - Ion source (built)
  - Test cyclotron with RFQ injection
  - Pressure vessel for Li/Be mixture



References

- IsoDAR CDR: https://arxiv.org/abs/1511.05130
- Ion source: https://arxiv.org/abs/2008.12292
- RFQ-DIP: https://aip.scitation.org/doi/abs/10.1063/1.4935753
- RFQ-DIP: https://arxiv.org/abs/1807.03759
- Spiral Inflector: https://arxiv.org/abs/1612.09018
- Cyclotron simulations: https://arxiv.org/abs/2103.09352
- Target, ^{8}Li yield: https://arxiv.org/abs/1805.00410
- Target, shielding: https://arxiv.org/abs/1909.08009

DAEδALUS IsoDAR

On behalf of the IsoDAR collaboration

Columbia University in the City of New York

University of Huddersfield

INFN

University of Michigan

MIT

Paul Scherrer Institut PSI

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

AIMA Developpement

Best Cyclotron Systems

BEVATECH

iba

BARTOSZEK ENGINEERING

Thank you for your attention!

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