DAEδALUS
IsoDAR

IsoDAR
Isotope Decay-At-Rest for Sterile Neutrino Searches

Daniel Winklehner for the IsoDAR/DAEδALUS Collaboration
Snowmass21 – NF09 Workshop – Dec. 4th, 2020

MIT

LNS
Laboratory for Nuclear Science

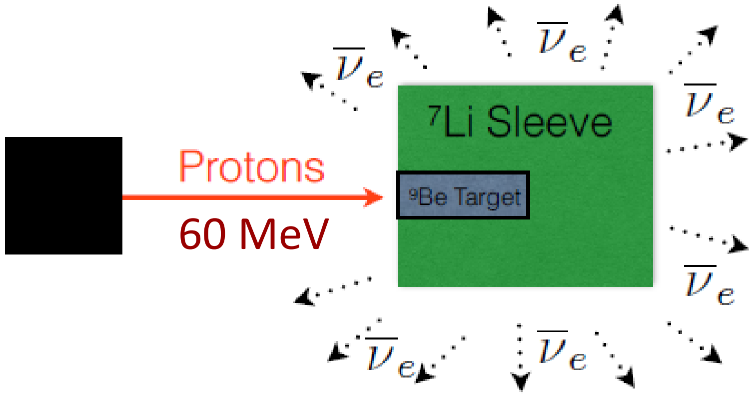
SNOWMASS21-AF2_AF0-NF9_NF0-121.pdf
SNOWMASS21-NF9_NF0-AF7_AF0-UF1_UF0-047.pdf
SNOWMASS21-NF2_NF9-080.pdf
SNOWMASS21-AF1_AF6_Winklehner-241.pdf

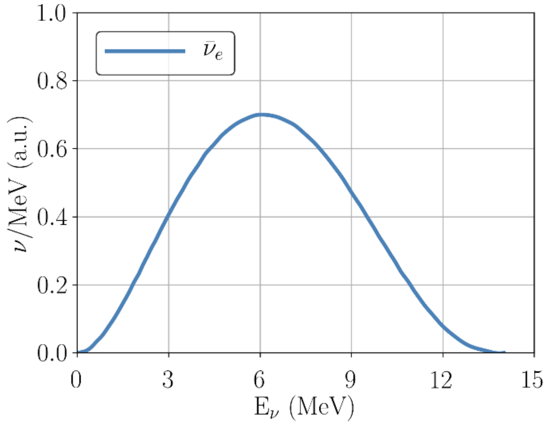
DAEδALUS IsoDAR

IsoDAR – Isotope Decay At Rest @ KamLAND

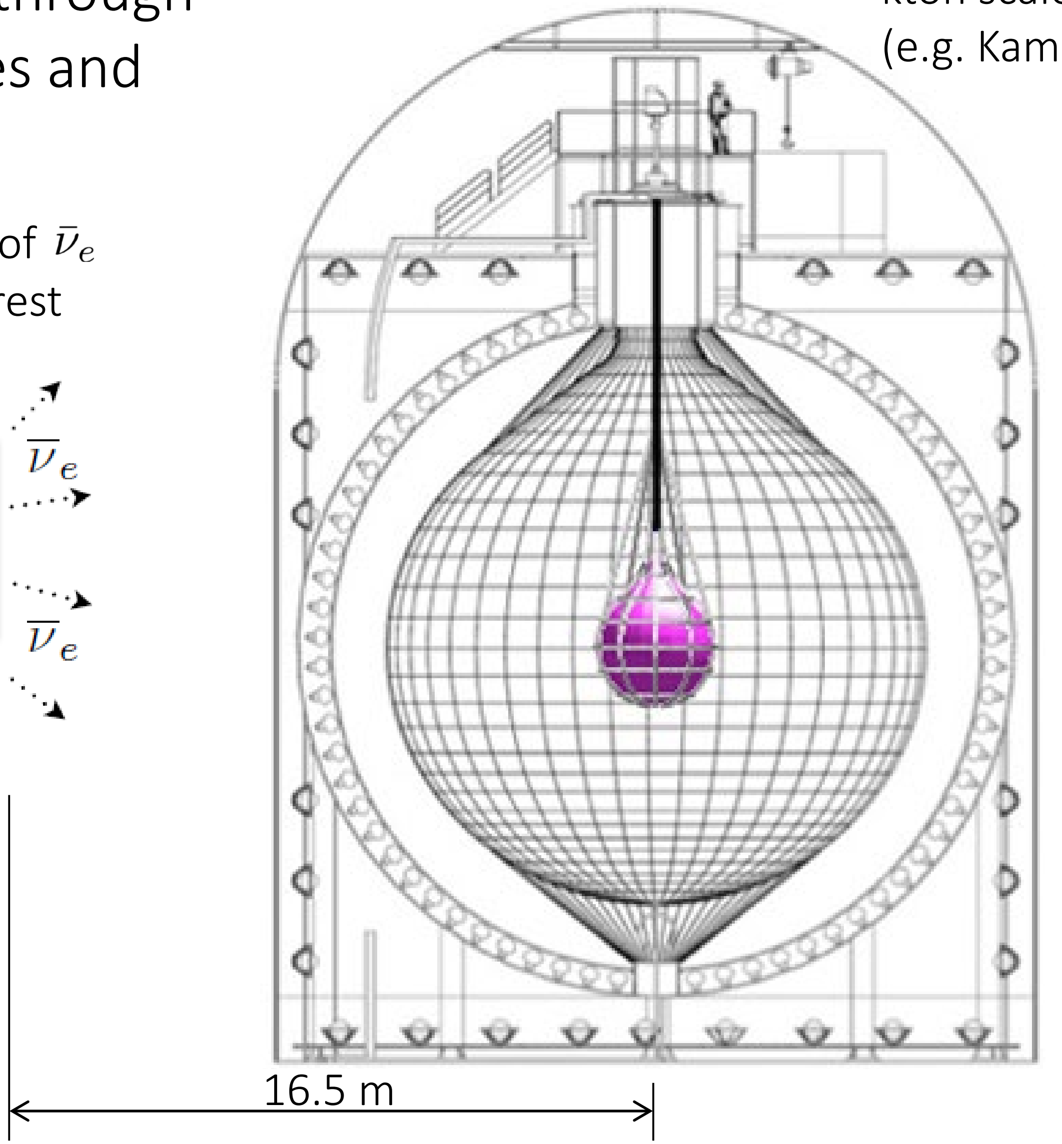
Search for sterile neutrinos through oscillations at short distances and low energy

Isotropic source of $\bar{\nu}_e$ through decay at rest





kton scale detector (e.g. KamLAND)



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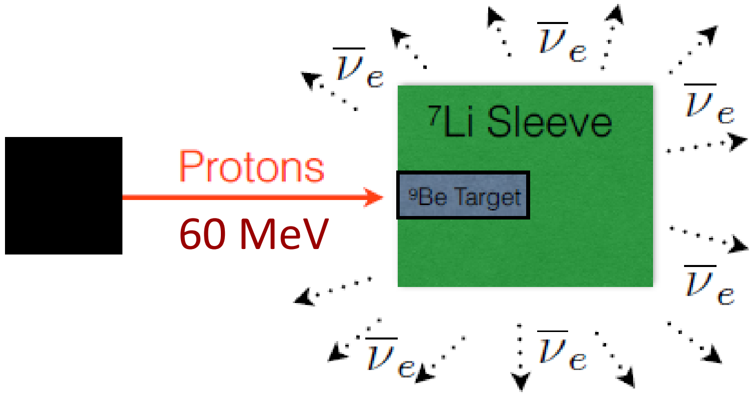

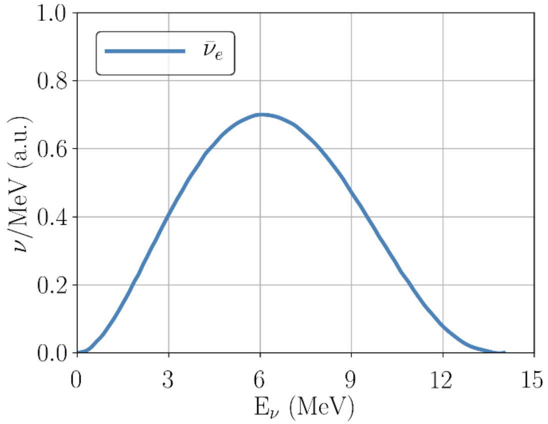

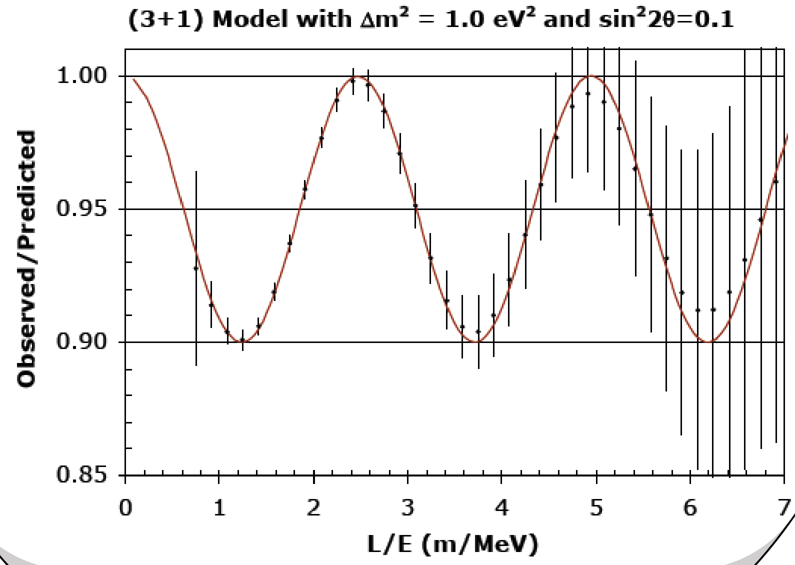

$$P_{osc.} = |\langle \nu_s | \nu_\mu(t) \rangle|^2 = \sin^2 2\theta \cdot \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

16.5 m

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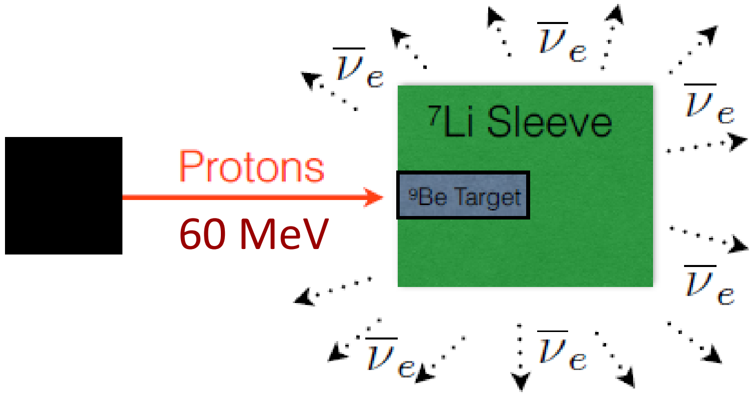

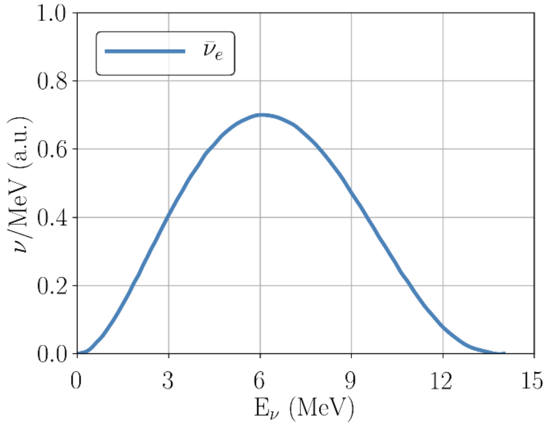

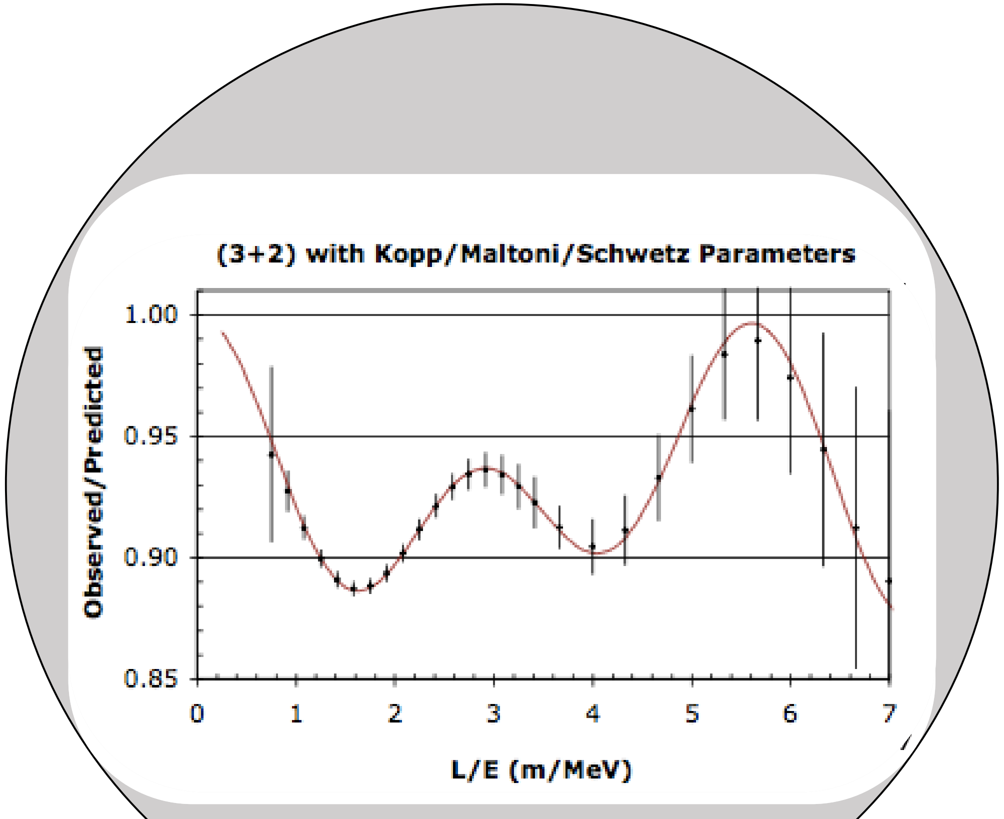

$$P_{\text{osc.}} = |\langle \nu_s | \nu_\mu(t) \rangle|^2 = \sin^2 2\theta \cdot \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

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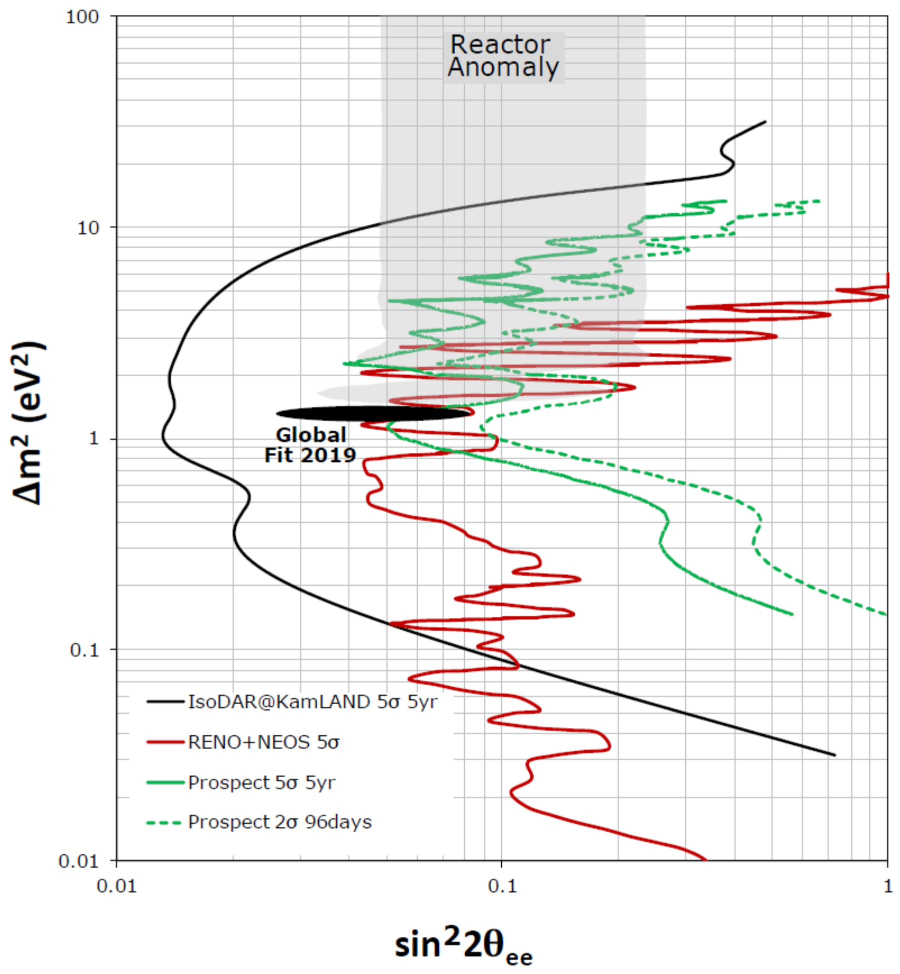
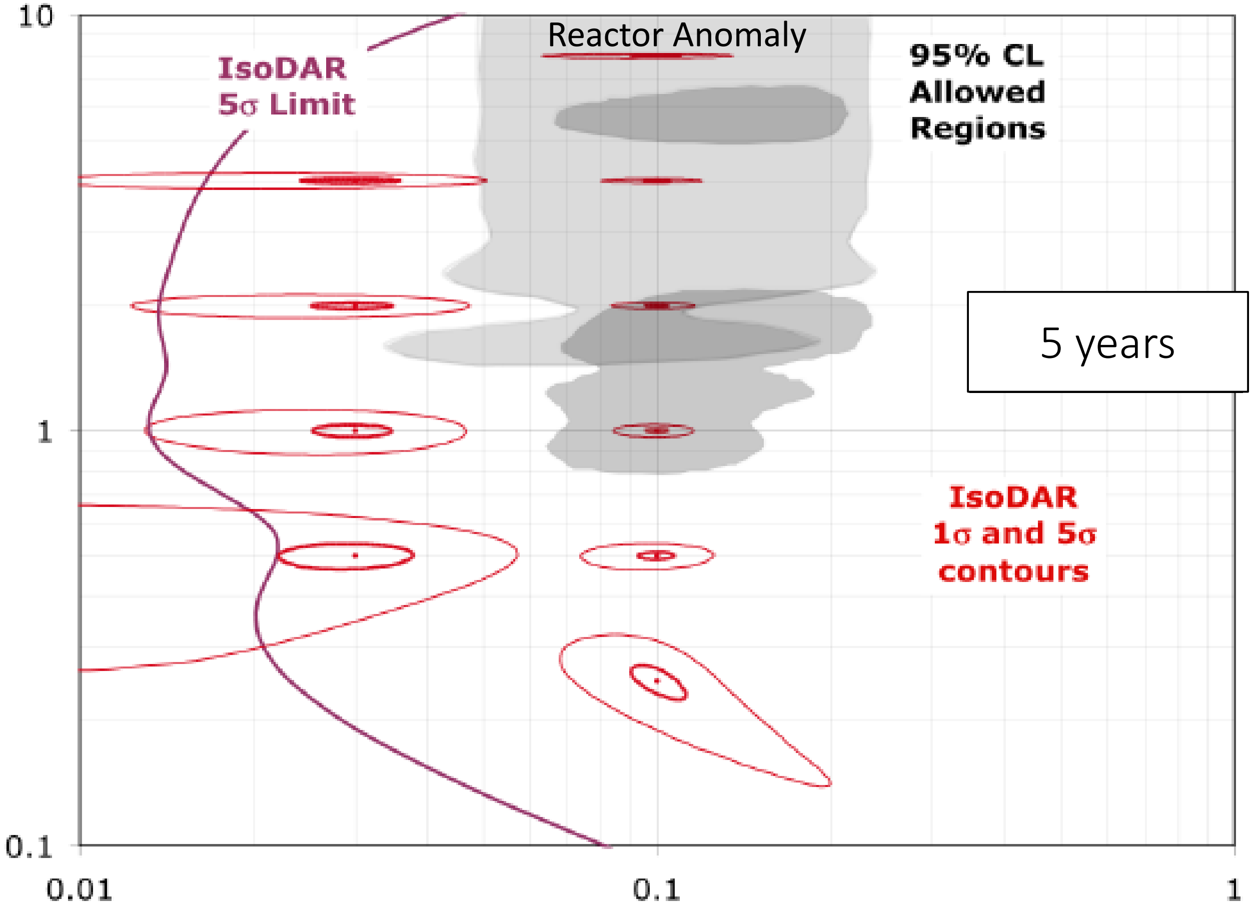
IsoDAR – Exclusion and simulated signals - 5 years



(older plot, global fits outdated)



5 years

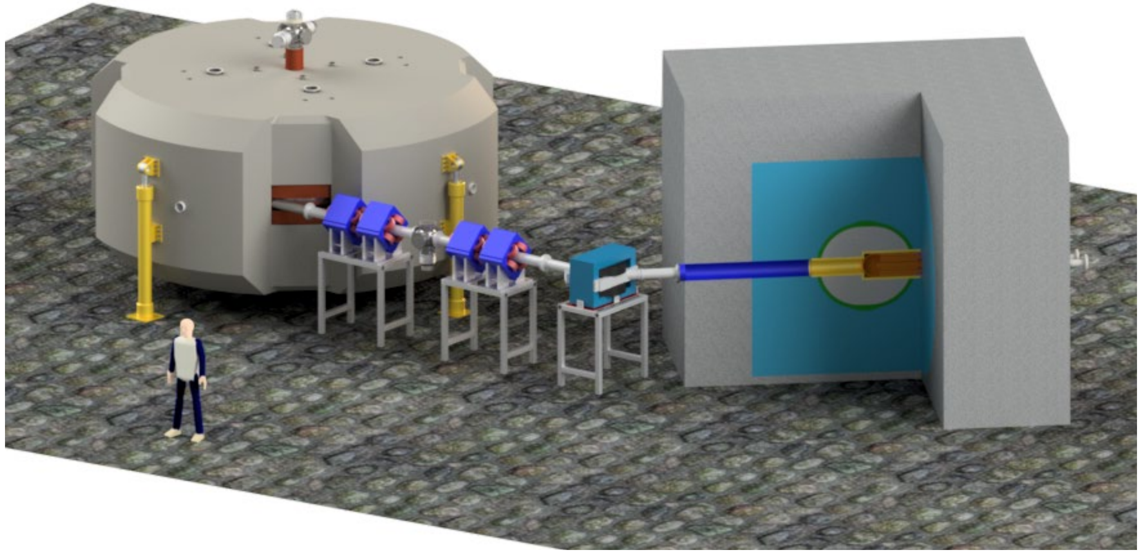
Other Physics (not necessarily @KamLAND)

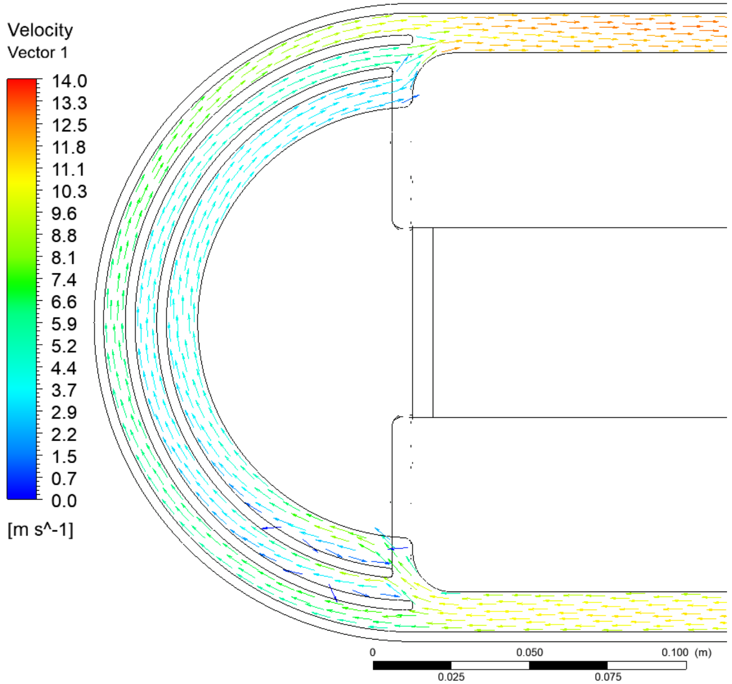
- High statistics neutrino-electron scattering
  - IsoDAR@KamLAND will collect 2400 events in 5 years, a sample
  - Allow for a 3.2% measurement of $\sin^2\theta_W$

  SNOWMASS21-NF2_NF9-080.pdf
- Measurement of low energy cross sections for supernova
  - Using other detectors with different target material
- Production of exotic particles in the target
  - E.g. dark photons

Target

- Challenge: 600 kW cw beam
- Shell structure of Be target cooled with D_2O provides cooling and adequately low thermal stresses

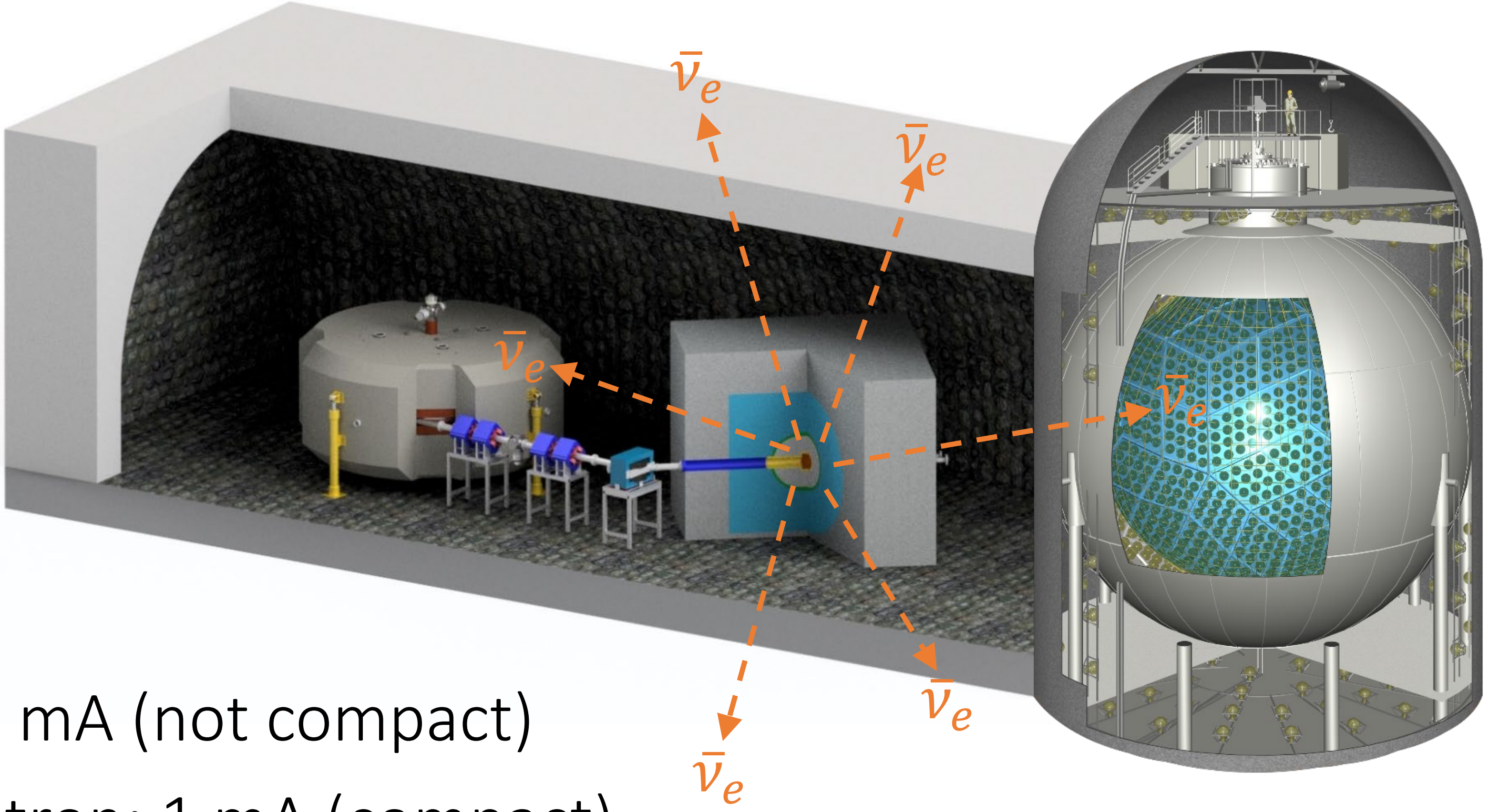




Columbia University in the City of New York
BARTOSZEK ENGINEERING
University of Michigan

Cyclotrons are the best suited accelerators

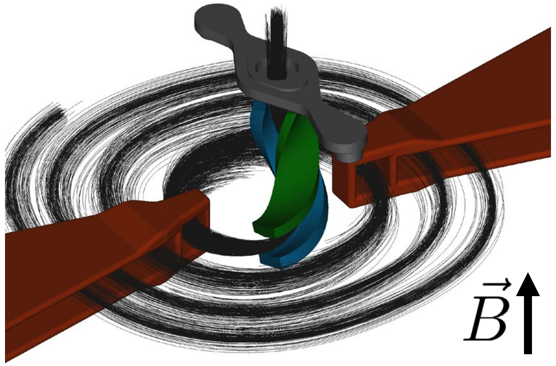
- High intensity demonstrated (1 - 2.5 mA)
- Well-understood
- Cost-effective
- Compact

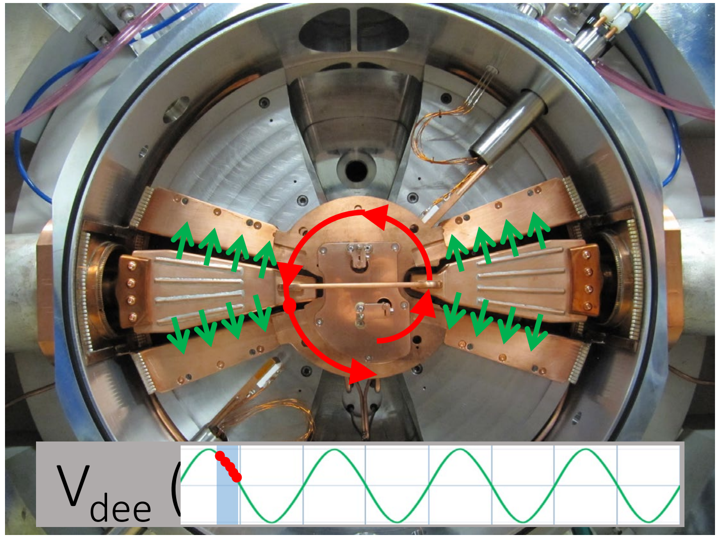


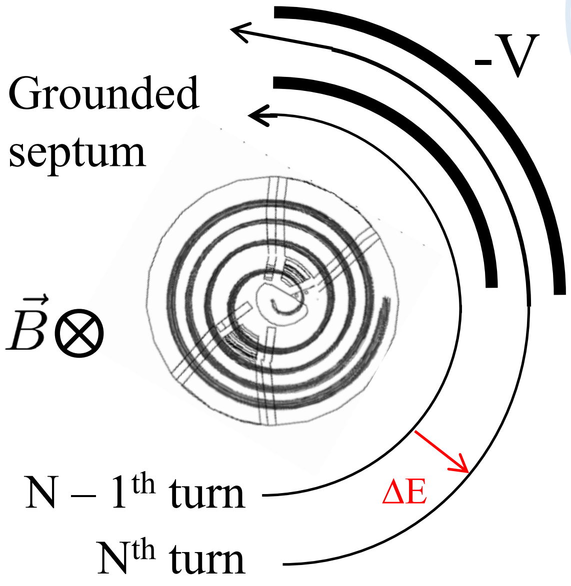
State-of-the art:

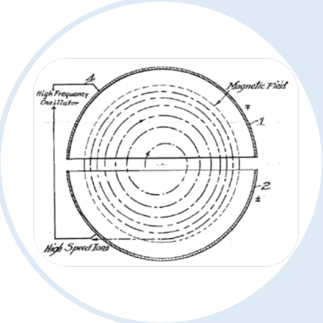
- PSI Injector II: 2.7 mA (not compact)
- Commercial cyclotron: 1 mA (compact)

The main building blocks





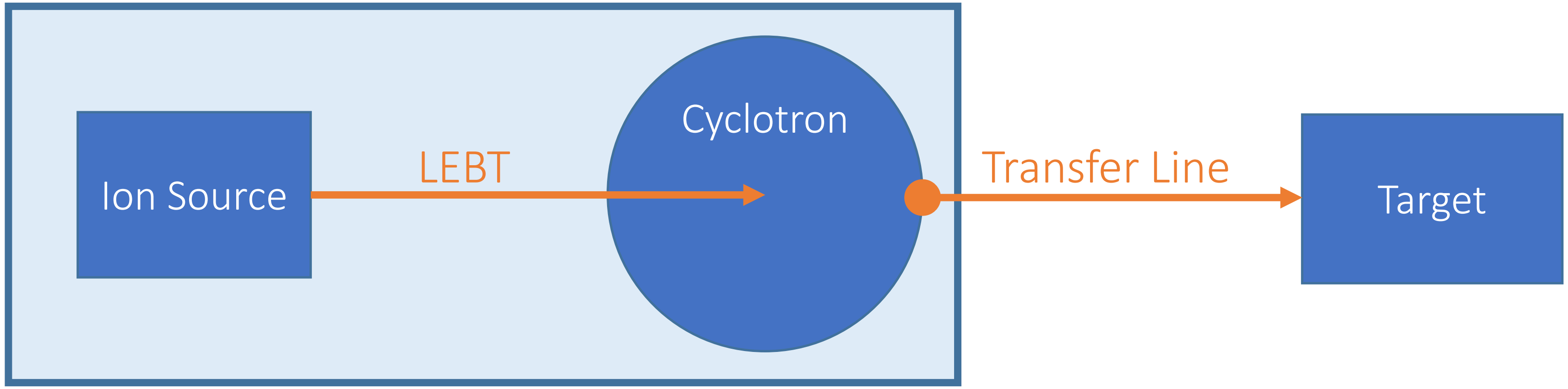


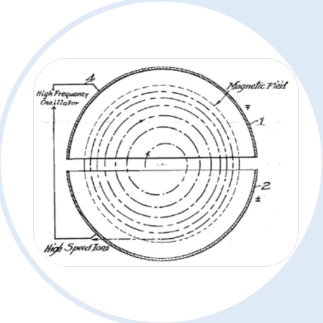


Injection

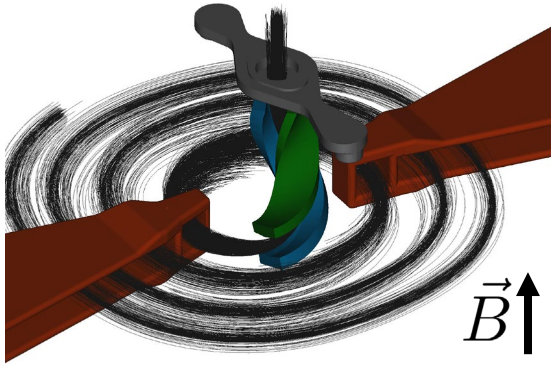
Acceleration

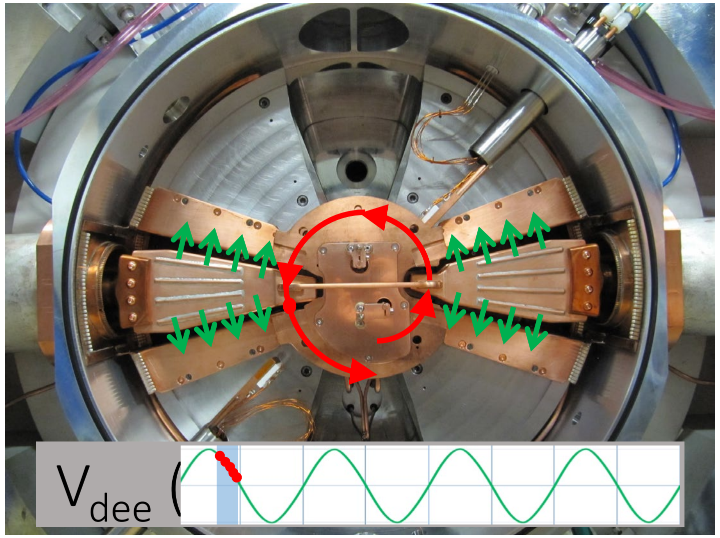
Extraction

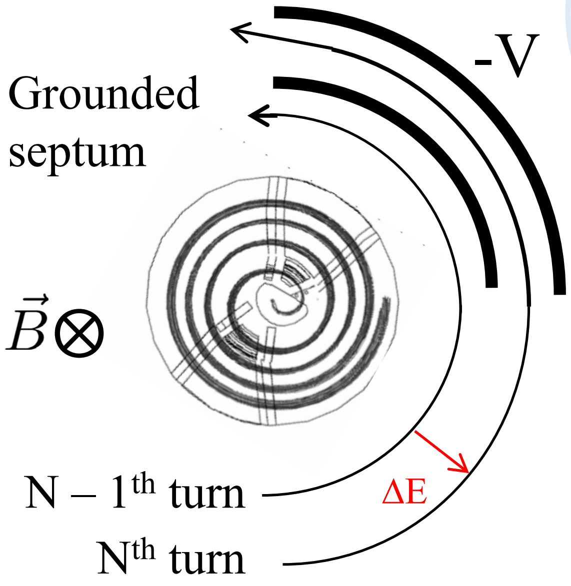




What are the challenges?





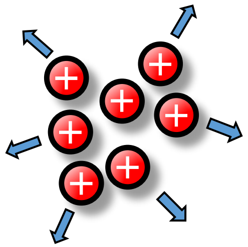


Injection	Acceleration	Extraction

Challenge: Space charge

- Beam growth

→ Beam loss



Challenge: Phase acceptance

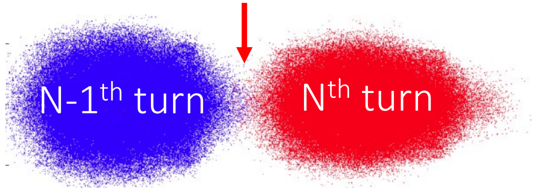
- Only 15-20° of RF period can be populated

→ Beam loss
→ Need more current from ion source
→ Energy spread

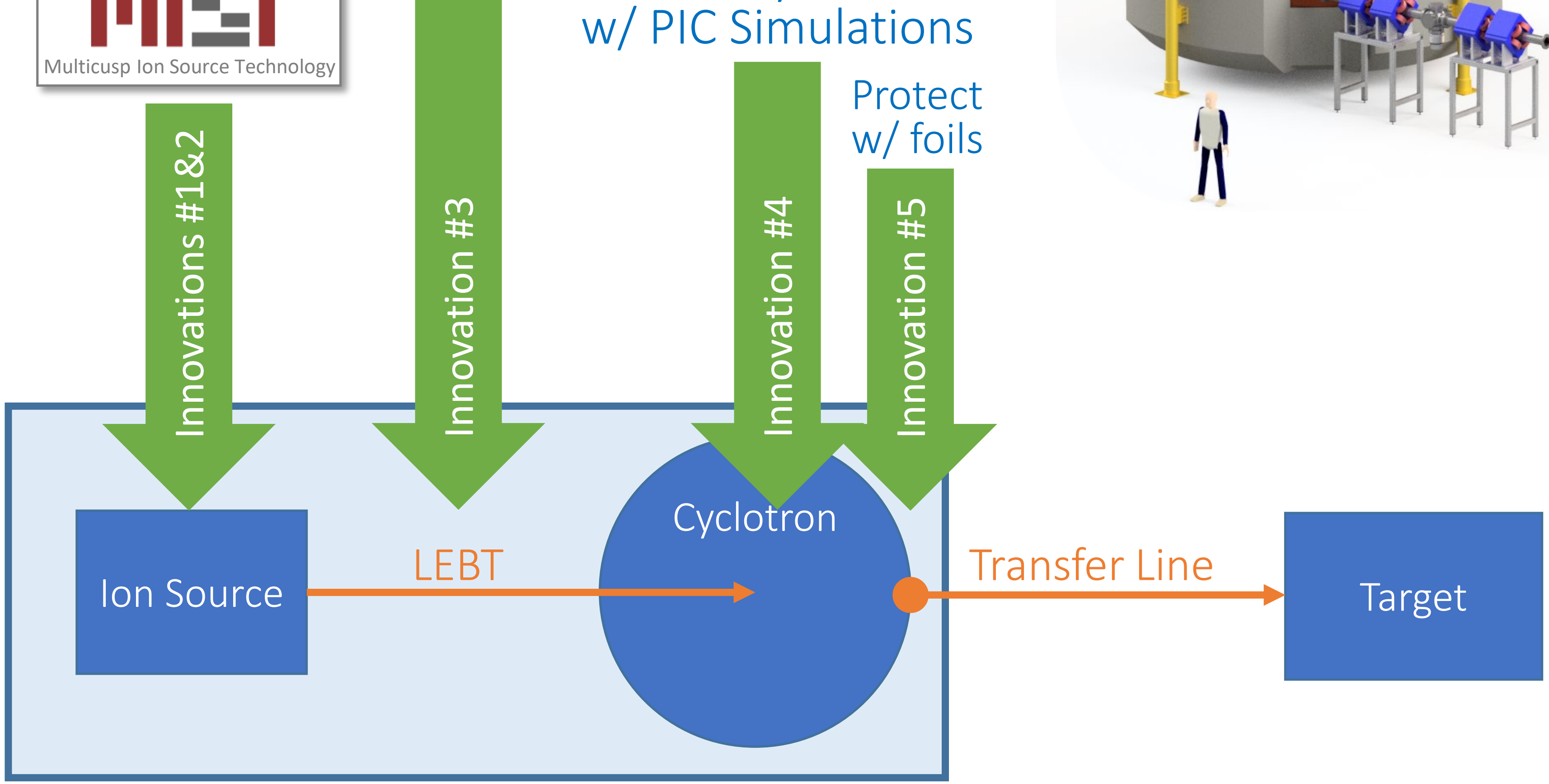
Challenge: Turn separation

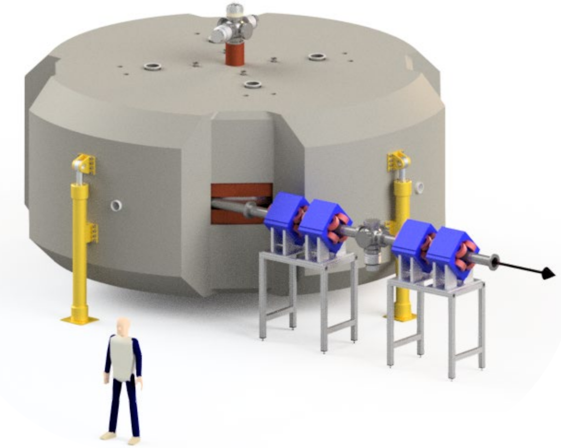
- Overlap of halo
- Beam loss

→ Activation! (Limit <200 W)

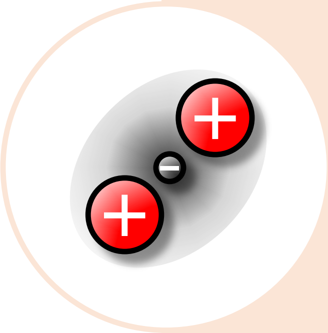


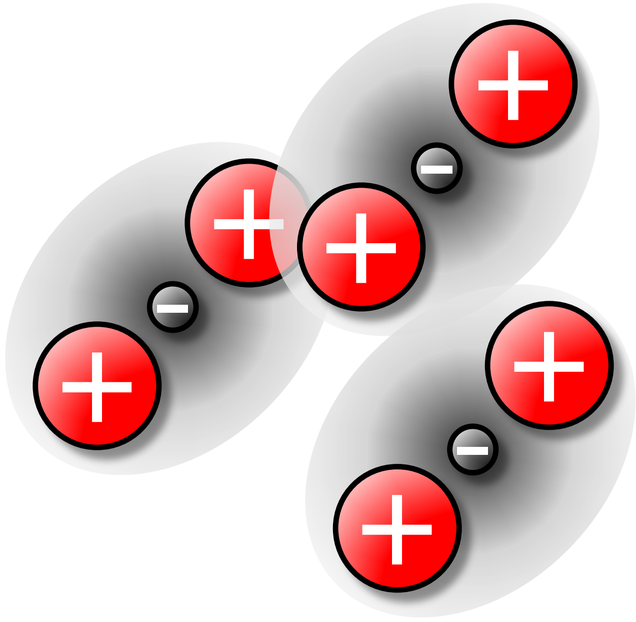
What building blocks can we improve?





Innovation #1: H_2^+ instead of protons

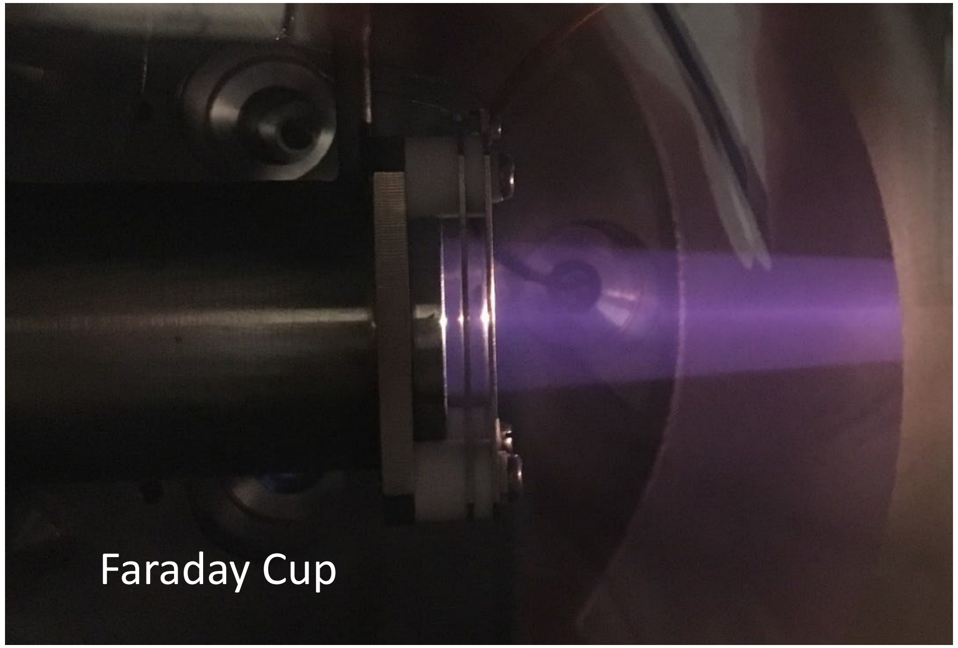


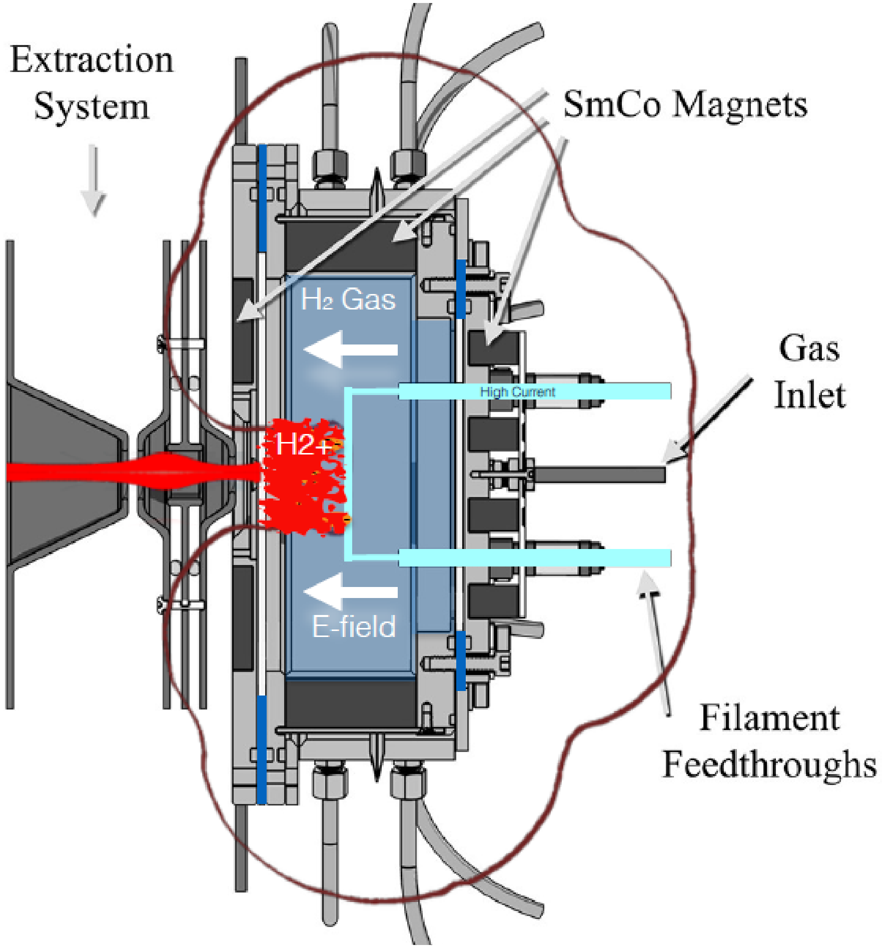


- Two units of charge for one!
- Remove electron by stripping
  → get two protons
- Helps with Injection
- Helps with Low Energy Beam Transport
- And there are additional exciting ways to exploit this!

Innovation #2: Dedicated H_2^+ ion source

Beam direction



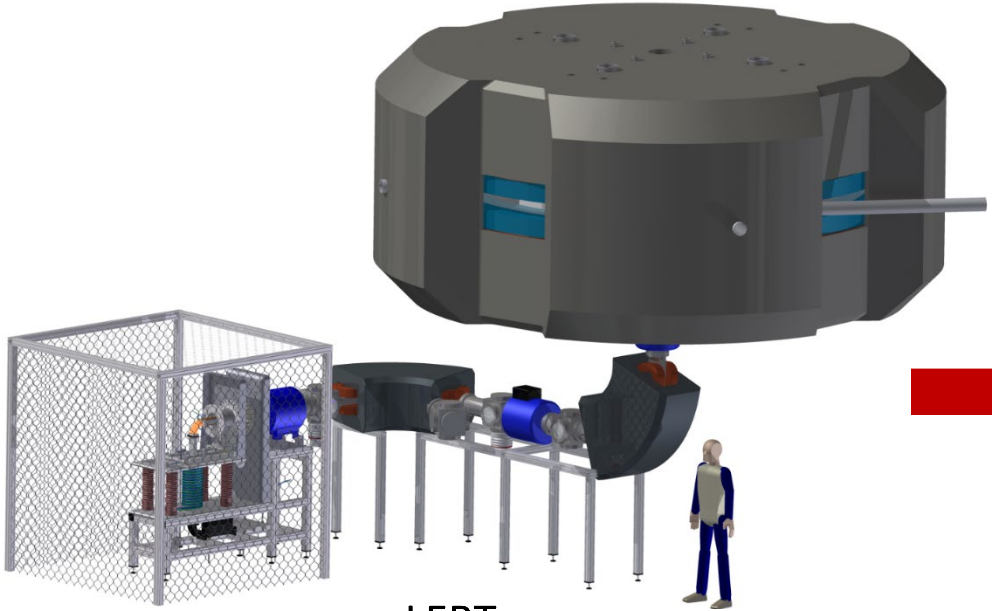


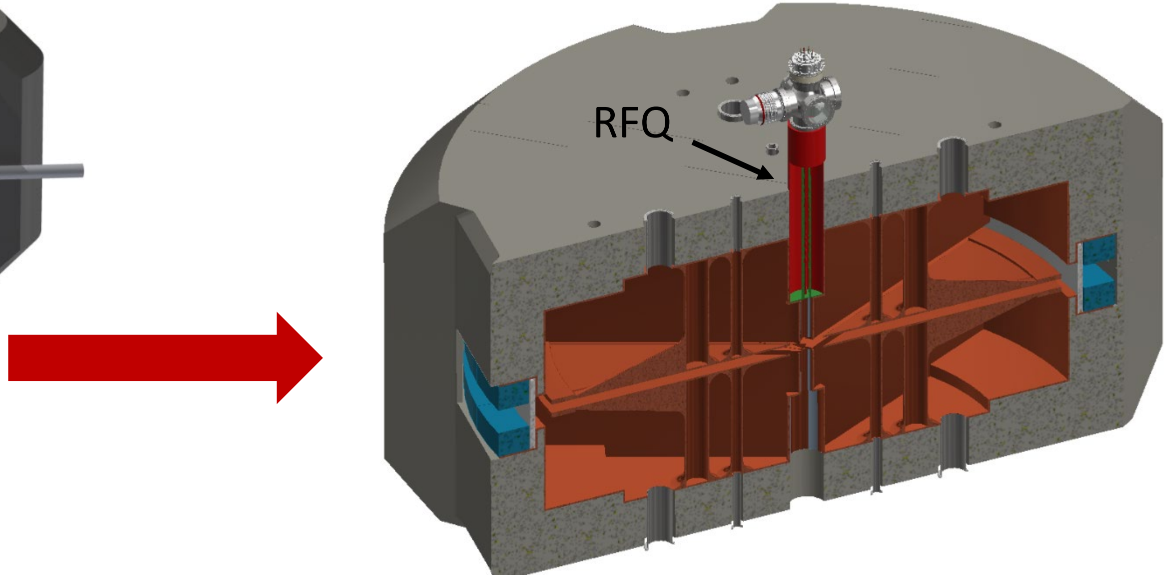
- Filament-Driven Multicusp Ion Source
- Based on: Ehlers and Leung (LBNL)
- Currently commissioning at MIT (highest current density: 40 mA/cm^2)

Axani, DW et al. **RSI** (2016) https://aip.scitation.org/doi/10.1063/1.4932395
DW et al., **AIP Conf. Proc.** (2017) https://arxiv.org/abs/1811.01868

Innovation #3: RFQ-DIP

- Radio Frequency Quadrupole – Direct Injection Project





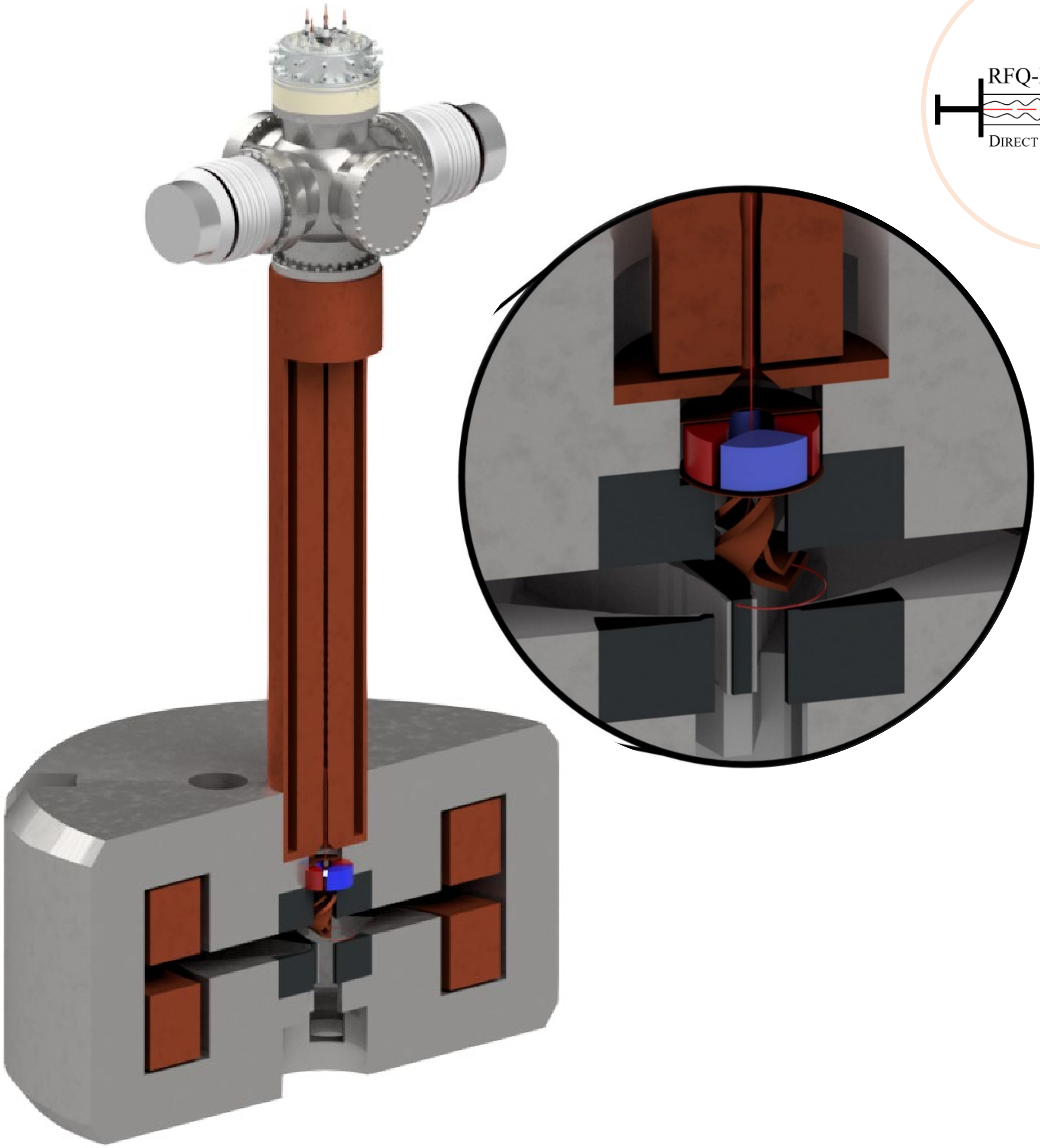
DW et al. RSI 87.2 (2016): 02B929. https://aip.scitation.org/doi/abs/10.1063/1.4935753
DW et al. NIMA (2018) https://arxiv.org/abs/1807.03759

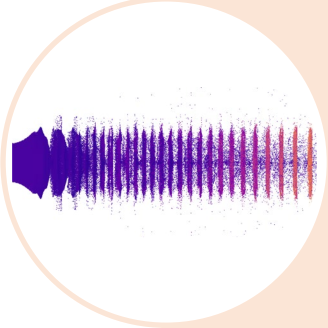
RFQ-DIP Prototype

Radiofrequency Quadrupole – Direct Injection Project

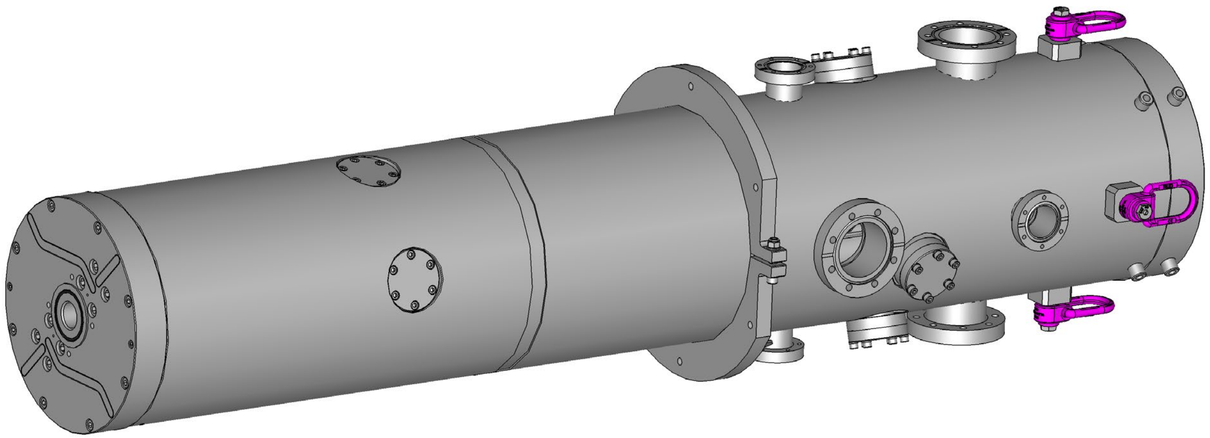
- Ion Source (MIST-1)
- RFQ
- 1 MeV/amu test cyclotron
- Diagnostics

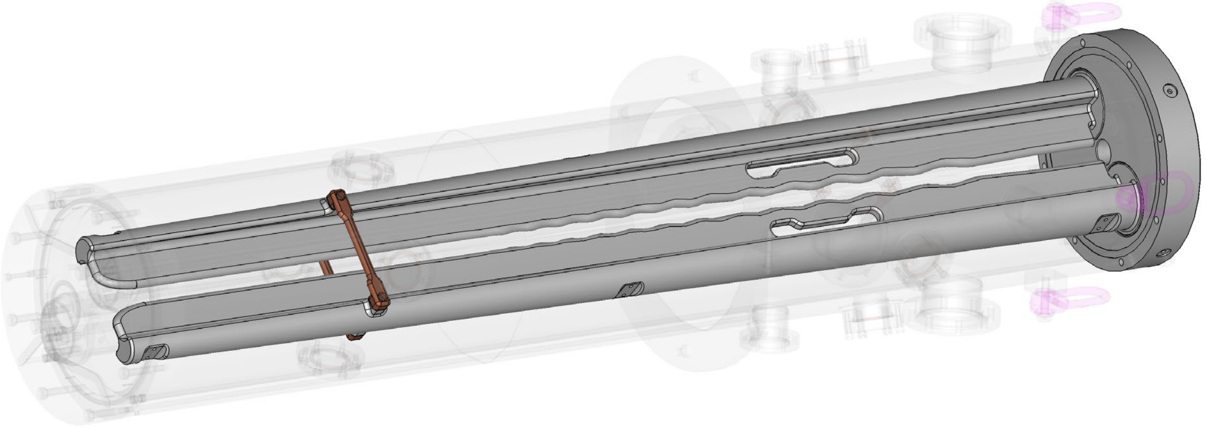
Funded by NSF MRI





Split-Coaxial RFQ Design





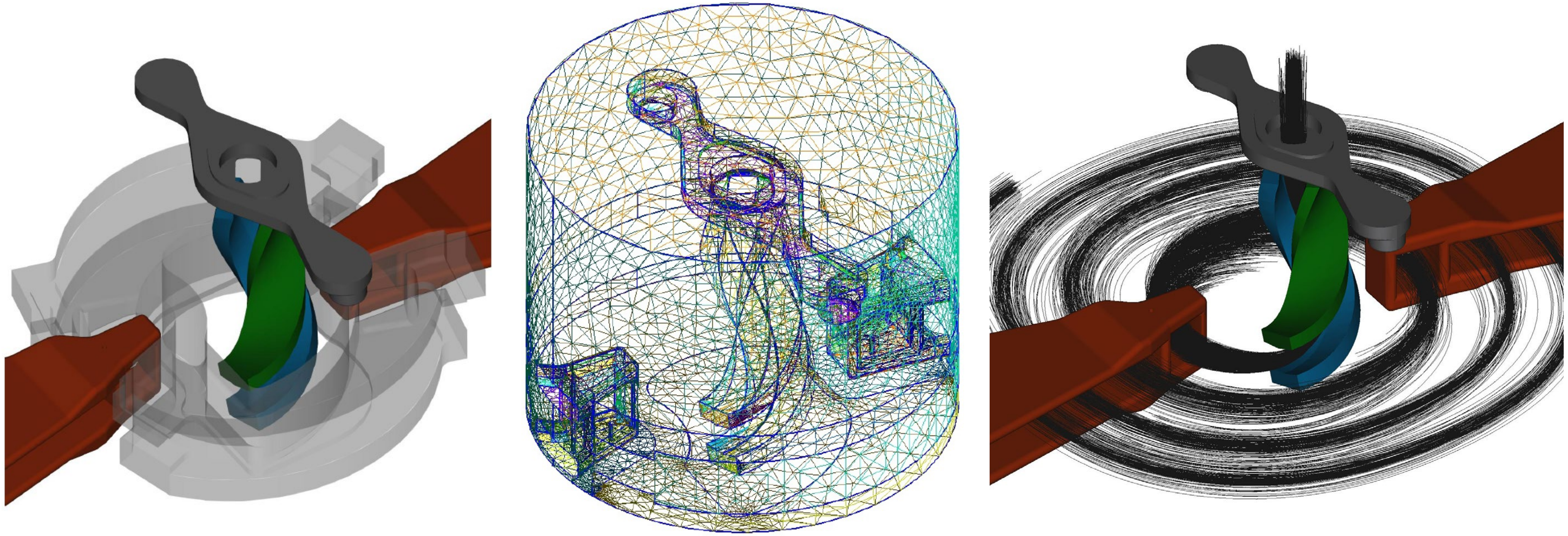
Elements	Unit	Design parameters
Frequency	MHz	32.8
Particle	A/q	H_2^+ (2)
Length	**mm**	**1378.69**
No. of cells		58
Transmission rate	%	97.27
Beam energy	keV	15 → 70
Input Trans. emit (rms, norm)	mm-mrad	0.3000
Trans. emittance (rms, norm)	mm-mrad	0.3427
Long. emittance (rms)	**keV-deg**	**40.24**
Vane 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

Good emittances: ε_x = 0.34 mm-mrad, ε_y = 0.34 mm-mrad, ε_z = 40.24 keV-deg

Currently being optimized using Machine Learning – Prelim.: $\varepsilon_x = \varepsilon_y$ = 0.3 mm-mrad, ε_z = 30 keV-deg

Innovation #4: Highly accurate PIC simulations – New code development, exploiting physics (vortex effect)

DW et al. **Phys. Rev. AB** (2017) https://arxiv.org/abs/1612.09018

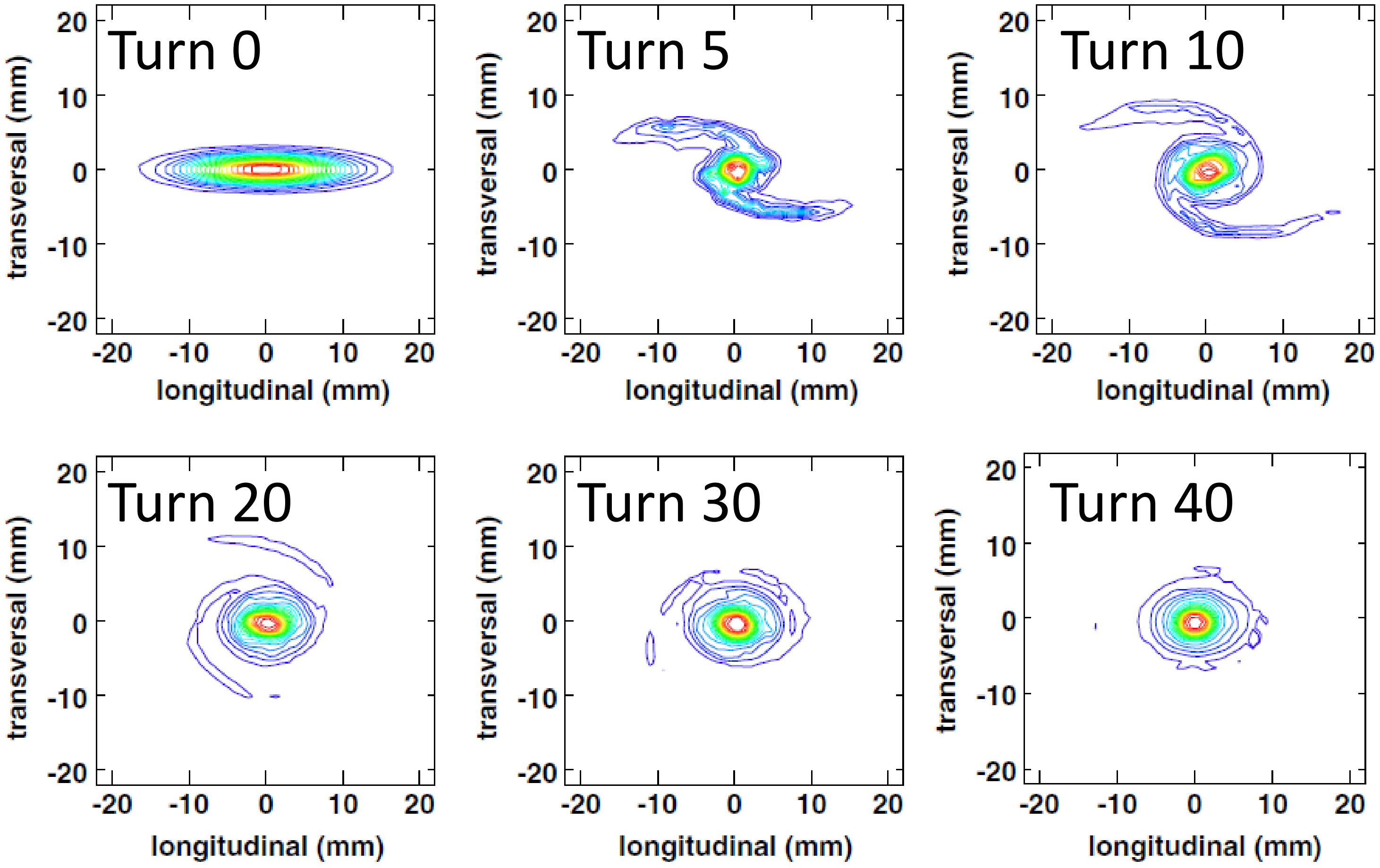


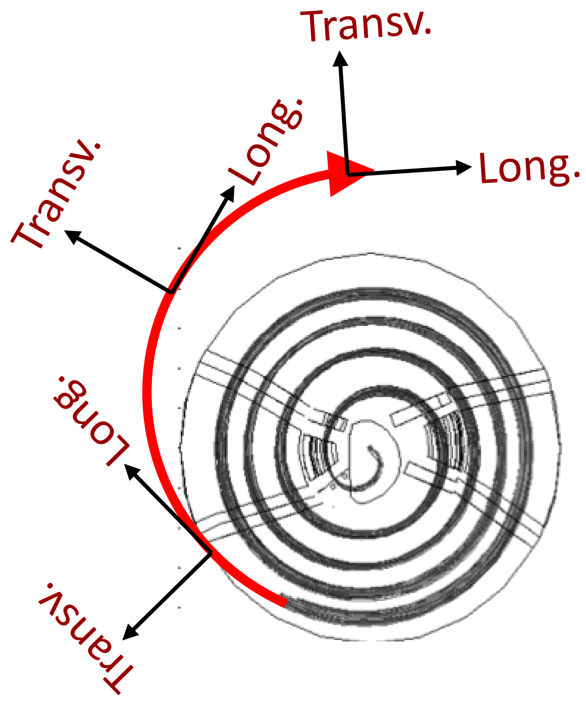
- Load 3D electromagnetic fields into OPAL
- Include boundaries for particle termination and field solver
- Benchmarked against theory and experiment with very good agreement

An aside: Experimental Result was 8 mA before, 7.5 mA inside

→ 94% transmission - Large Inflector Works!

Vortex motion – OPAL Simulations for PSI Injector II



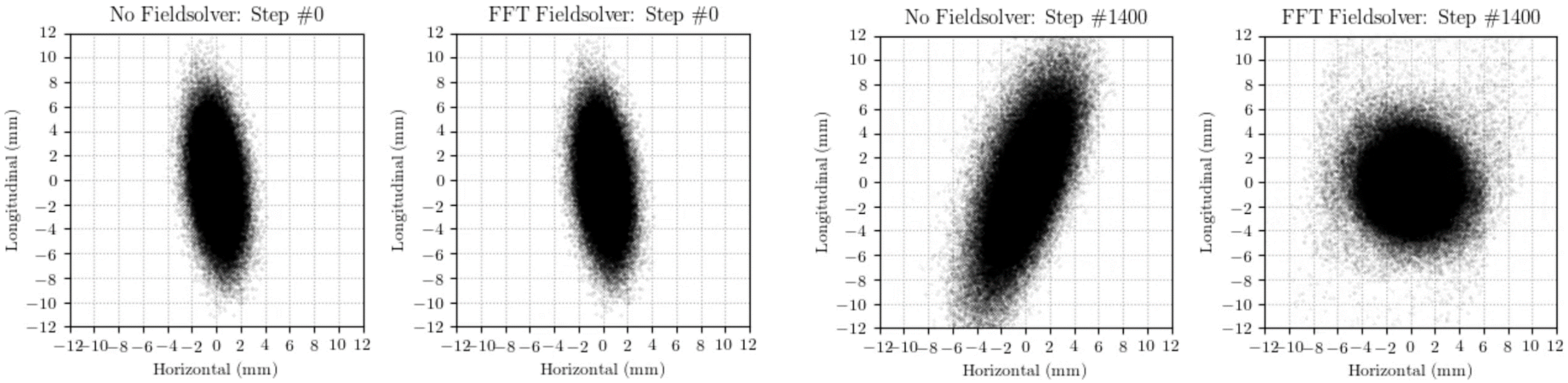


"Local Frame"

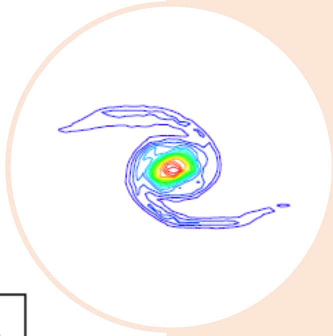
Comparison of 0 mA and 6.65 mA for IsoDAR

Start

After 7 Turns

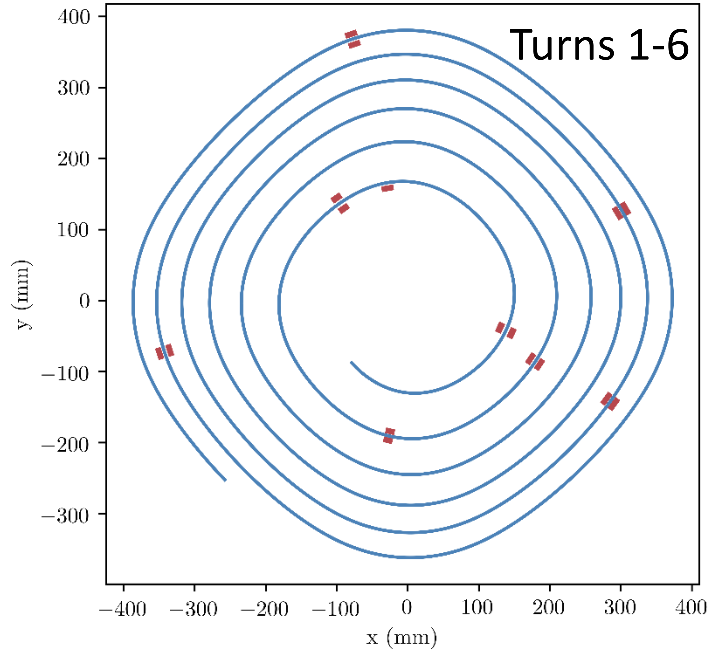


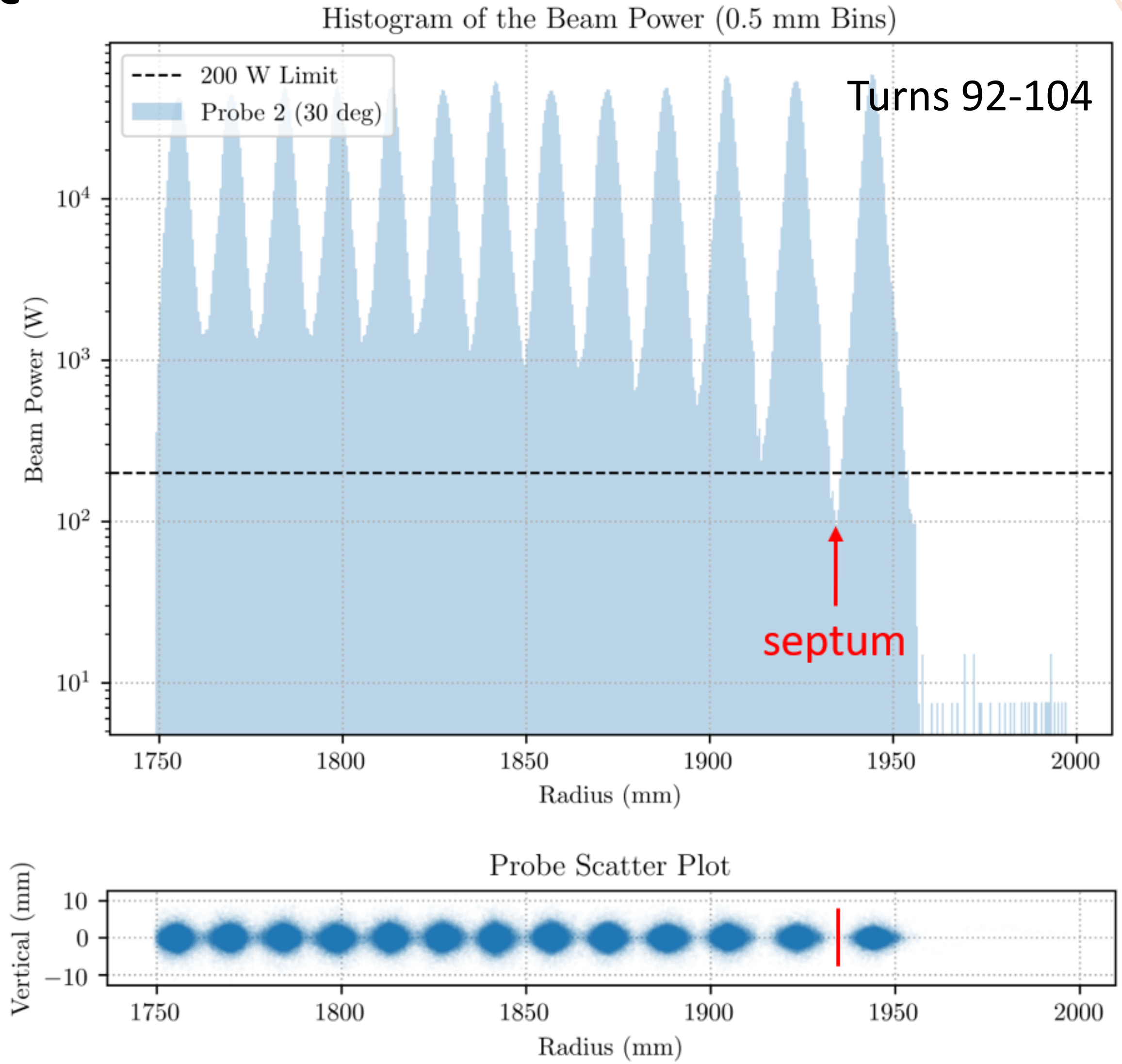
DW, *IsoDAR 60 MeV/amu simulations,* http://arxiv.org/abs/2002.11264 (2020)



Optimize phase, RF voltage, cavity shape, collimator placement

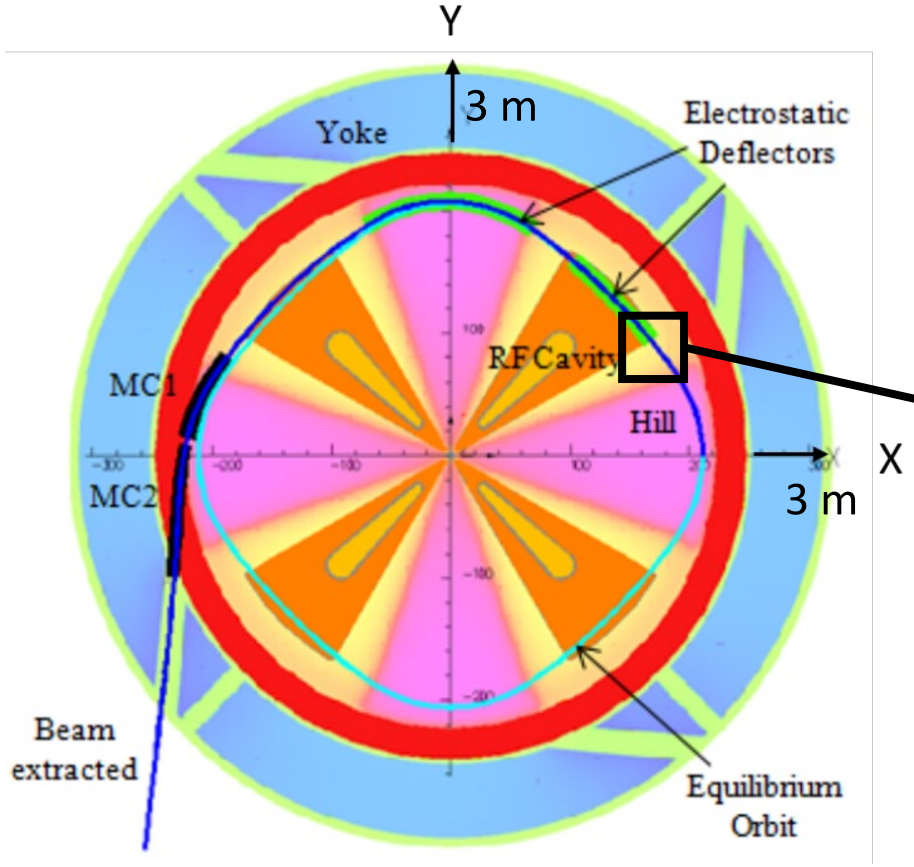
- Phase: -5°, V = 70-240kV
- Collimate Halo → 25% loss
- 48 W on septum

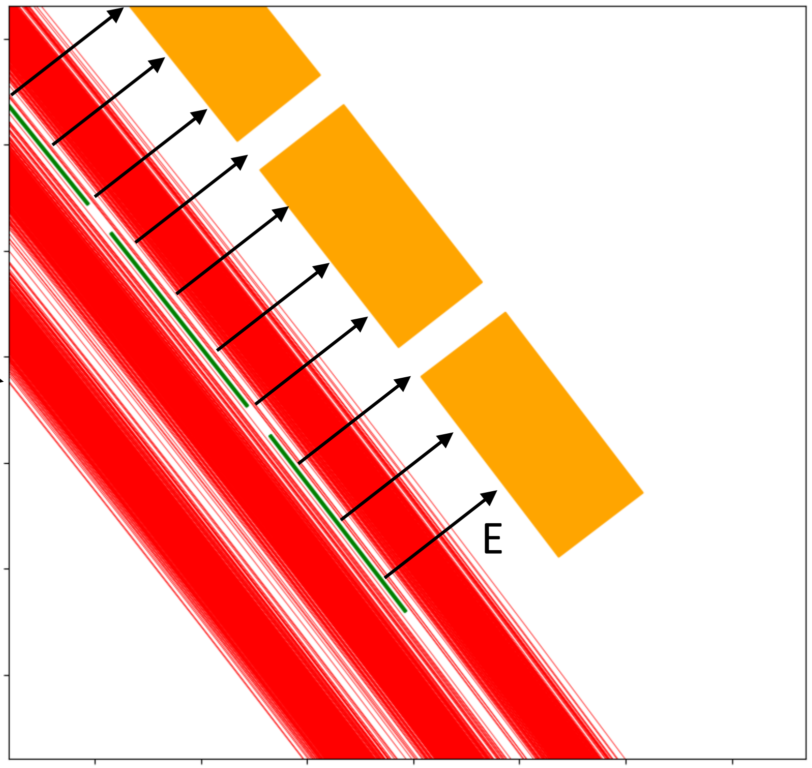




DW, *IsoDAR 60 MeV/amu simulations*, http://arxiv.org/abs/2002.11264 (2020)

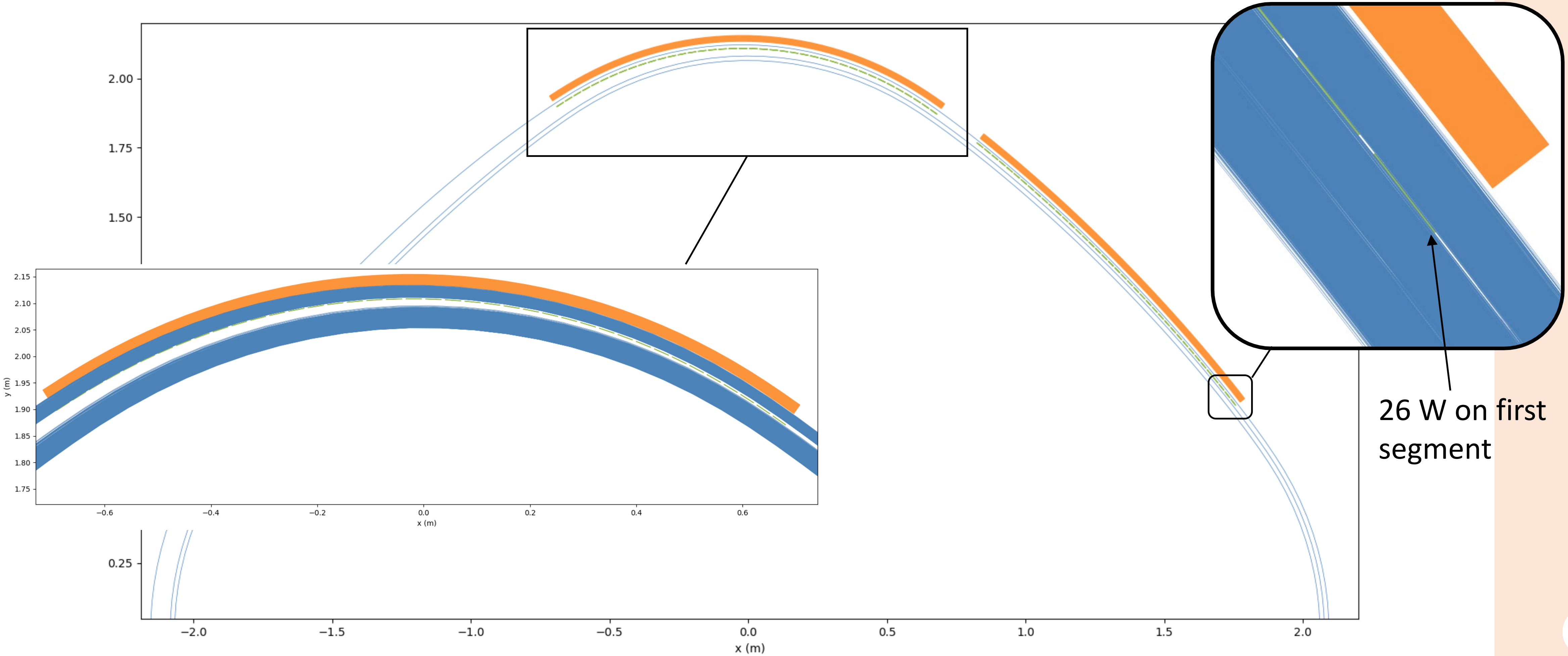
Zoom in on the Beginning of Septum



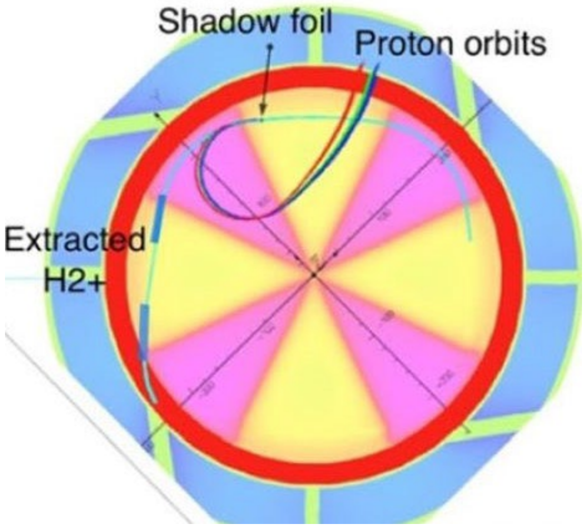


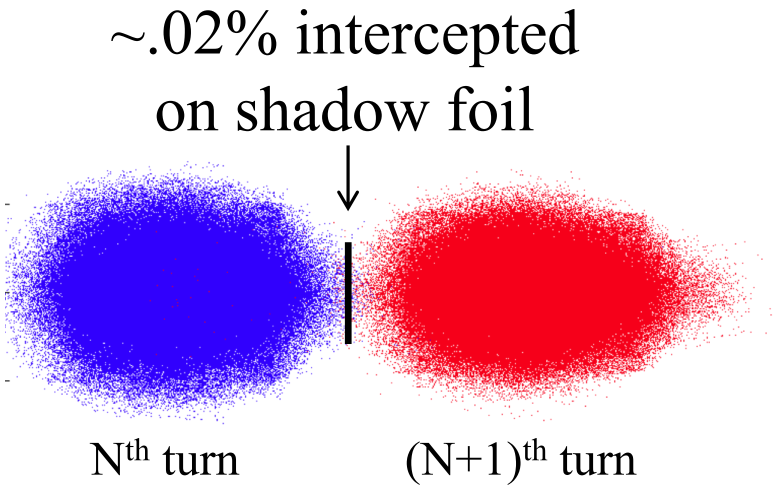
PIC simulation of electrostatic channels

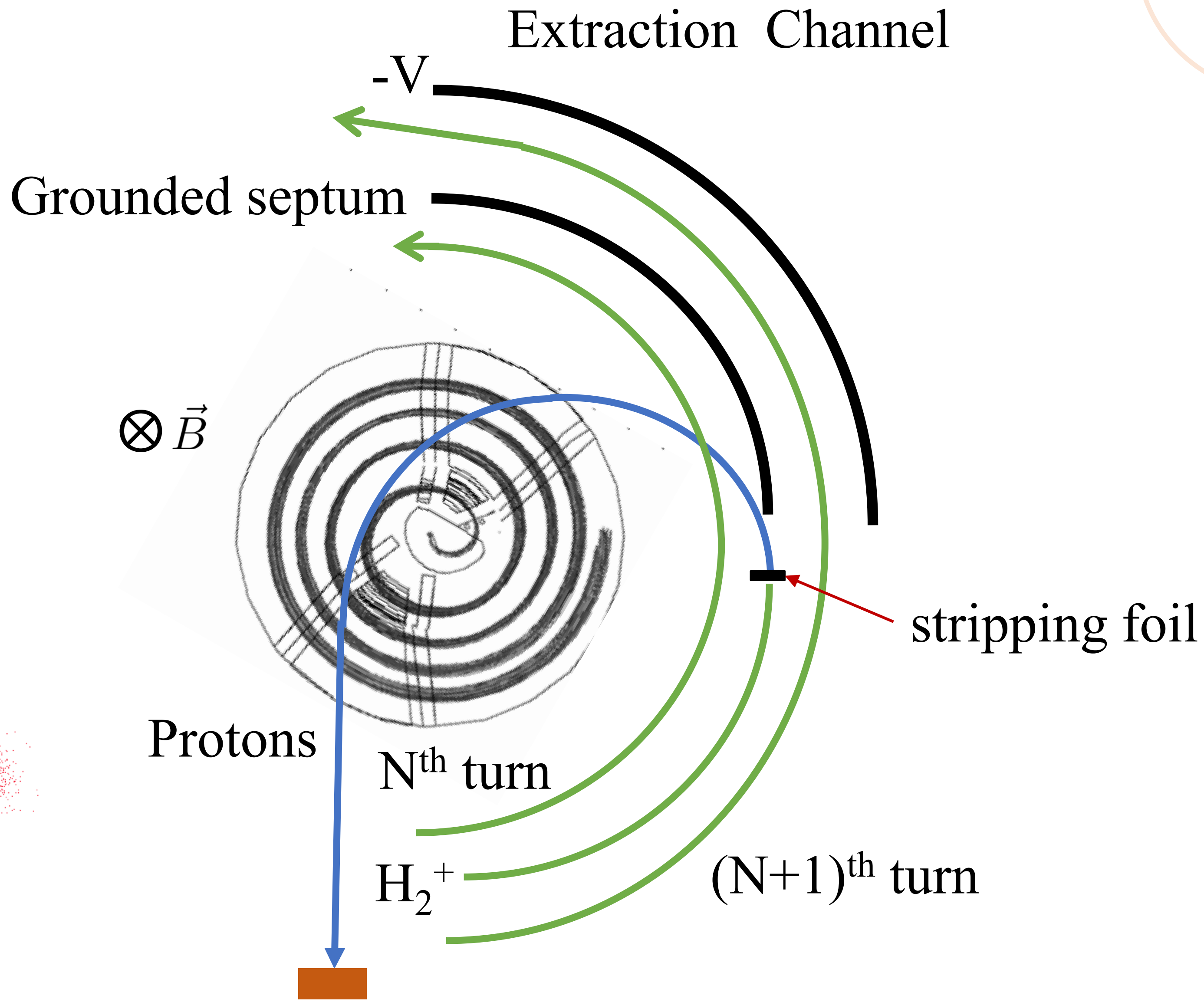
OPAL counts particles ending in septum electrodes: 48 W loss on ESD1. (0 W on ESD2)



Innovation #5: A carbon stripping foil can protect the septum



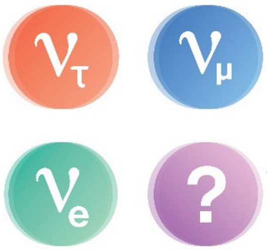




There are many applications that require high intensity beams!

- (Pulsed beams: Spallation Neutron Sources, Future Colliders, …)
- CW Beams:

60 MeV: IsoDAR
Discovery level
particle physics



https://arxiv.org/abs/1205.4419

800 MeV: DAEδALUS
CP-violation in
neutrino sector

$$\delta_{CP} \stackrel{?}{=} 0$$

https://arxiv.org/abs/1307.2949

Protons
10 mA cw

100 MeV	500 MeV	1.0 GeV
1.0 MW	5.0 MW	10.0 MW

Power

10-100 MeV:

$^{68}Ge/^{68}Ga$ $\quad$ ^{225}Ac

→ Production of much needed medical isotopes
https://doi.org/10.1186/s41181-020-0090-3

→Material research for Fusion
https://doi.org/10.1016/j.scriptamat.2017.06.041

500 MeV to 1.0 GeV: Demonstrations
for Accelerator Driven Systems
and Accelerator Driven Subcritical Reactors

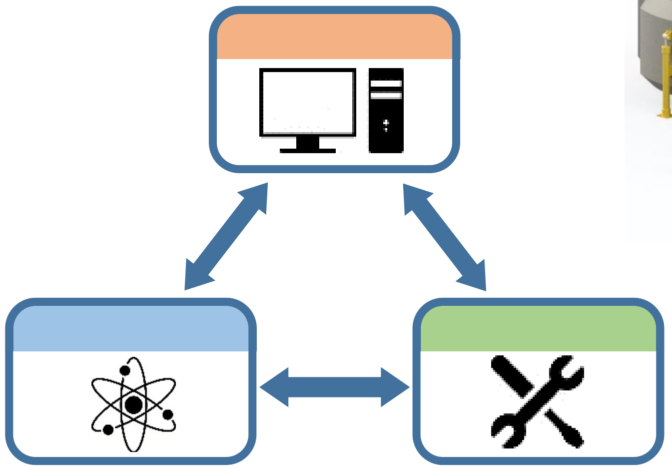
IsoDAR: Pushing the intensity frontier through cost-effective, compact accelerators, leading to MW beams

60 MeV

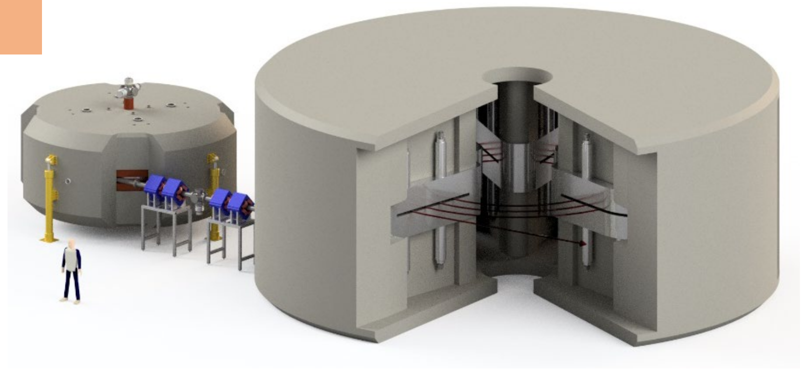
Computation

Understand High Intensity

Explore New Methods (AI/ML)



https://arxiv.org/abs/2002.11264
https://arxiv.org/abs/1807.03759
https://arxiv.org/abs/1205.4419



800 MeV

Impact on other fields

Medical Isotopes

Neutron Sources

ADS(R)

Particle Physics

Hardware Development

RFQ-DIP Prototype

Hands-On Teaching

Thank You!

To the IsoDAR/DAEδALUS collaboration,
especially members contributing to accelerator design:

To NSF,

And to all of you for your attention!