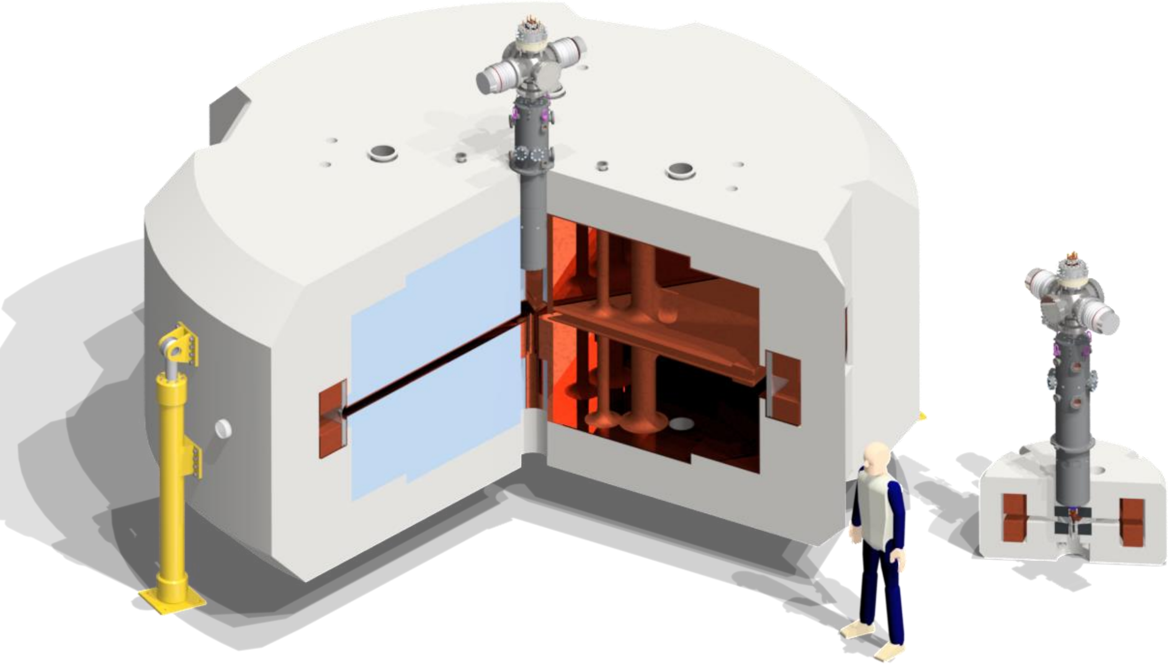
Development of an innovative compact cyclotron

Daniel Winklehner

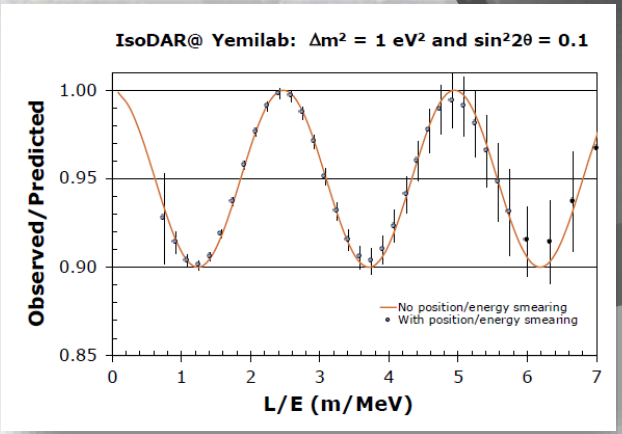
Awards Plenary
CPAD'22 - 12/01/2022

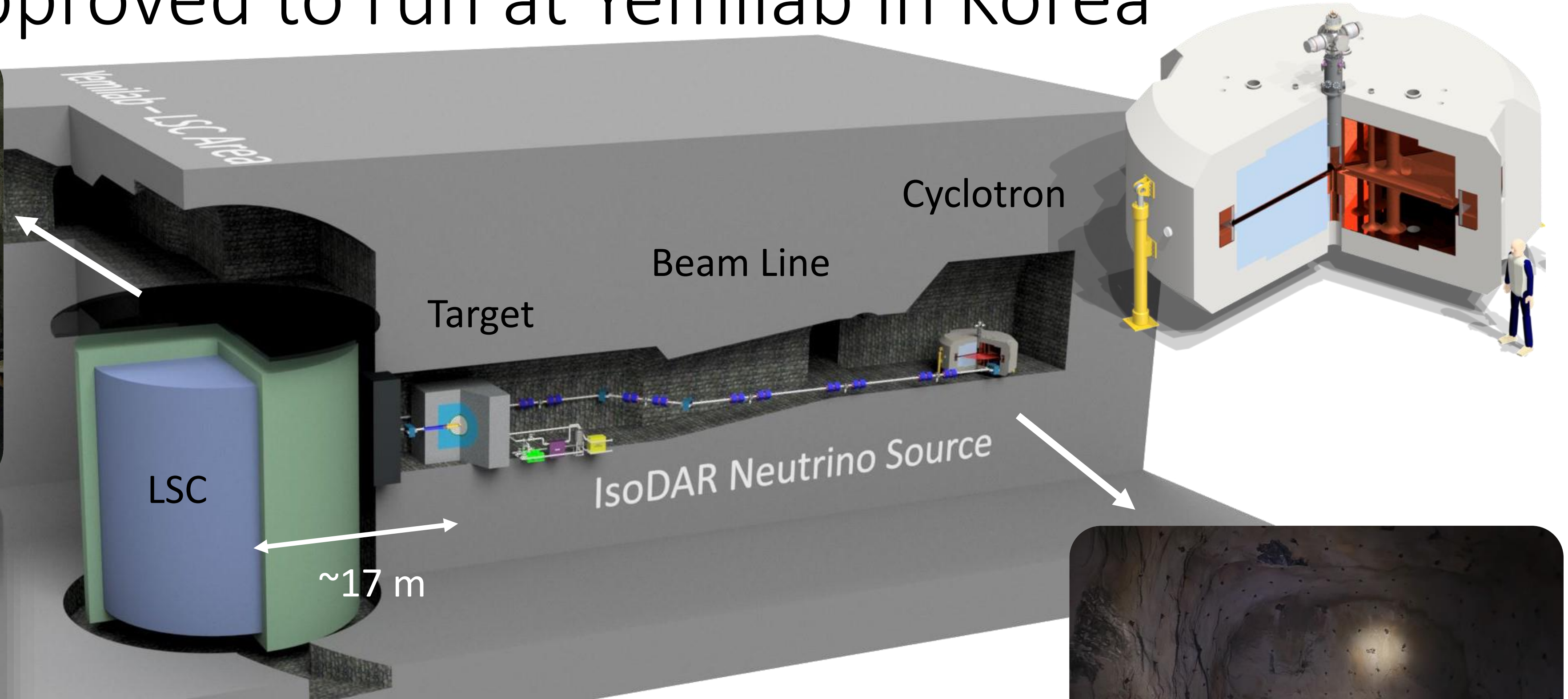


Thank You!

- To the APS-DPF and 2022 Instrumentation Award Committee
- To the CPAD'22 Organizers
- To my PI and Colleagues:
  - Janet Conrad
  - Andreas Adelmann
  - Luciano Calabretta
  - Daniela Campo
  - Alessandra Calanna
  - Roger Barlow
  - Michel Abs
  - Jose Alonso
  - Bill Barletta
  - …many more!
- To Postdocs/Students:
  - Jungbae Bahng
  - Medani Sangroula
  - Daniel Koser
  - Spencer Axani
  - Joseph Smolsky
  - Loyd Waites
  - Philip Weigel
  - Josh Villarreal

IsoDAR is a definitive search for sterile neutrinos (pre-approved to run at Yemilab in Korea

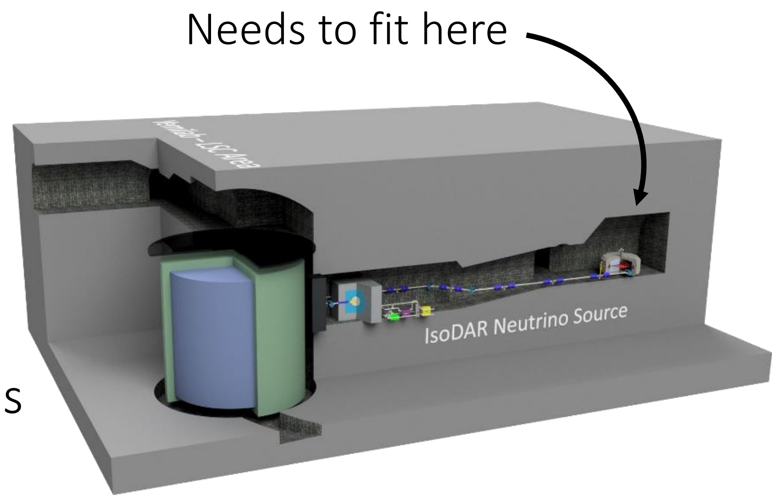




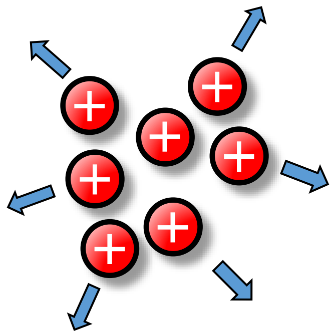
Caverns are already constructed

Physics Paper: http://arxiv.org/abs/2111.09480, PRD 2022
IsoDAR@Yemilab – CDR: http://arxiv.org/abs/2110.10635 arXiv 2021

Accelerator Requirements/Challenges

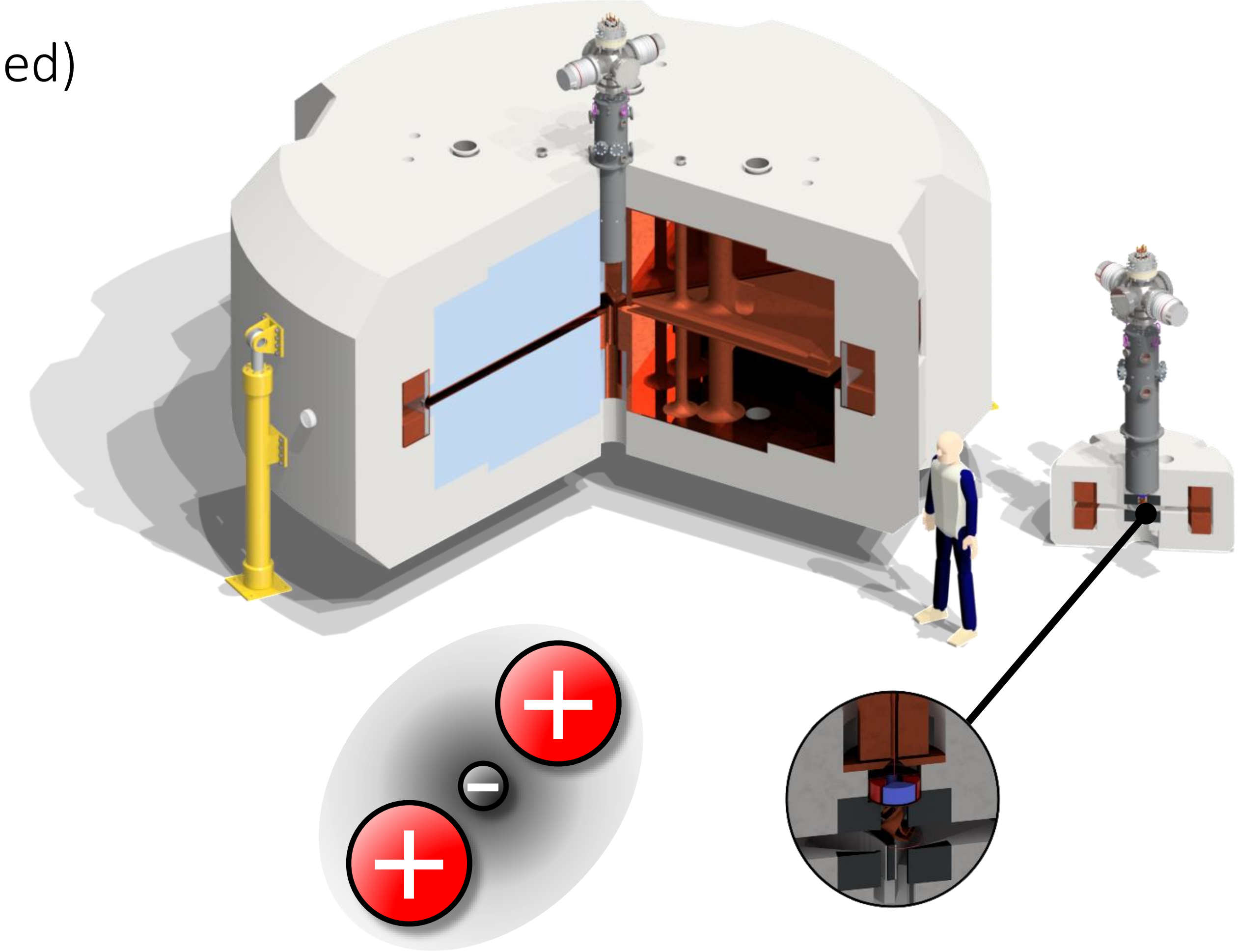


- Requirements (for IsoDAR):
  - Compact, robust, cost-effective (underground installation)
  - Continuous Wave (CW) operation, 80% duty factor (for maintenance)
  - 10 mA, 60 MeV protons on target – 10x more than commercial devices
- Challenges:
  - Related to space-charge (Coulomb-repulsion of particles in bunch)
  - Leads to beam spread and non-linear behavior
  - Beam losses which lead to activation of the machine
    (limit is 200 W in extraction region – PSI experience)



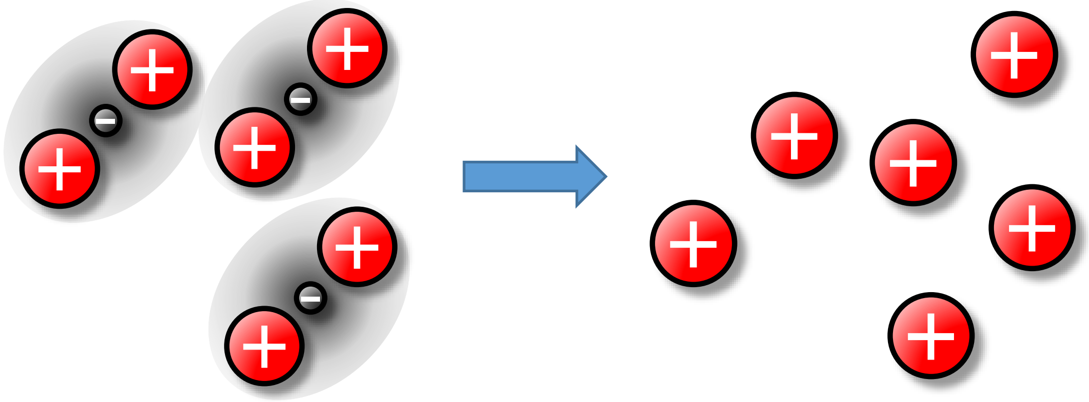
The HCHC-XX design addresses these challenges

- 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)



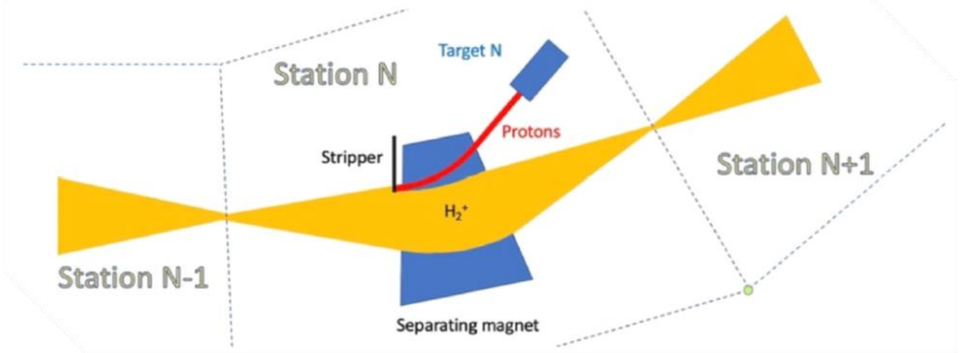
5 mA of H_2^+ = 10 mA of protons

- Two units of charge for one
- Remove electron by stripping
  → get two protons per H_2^+



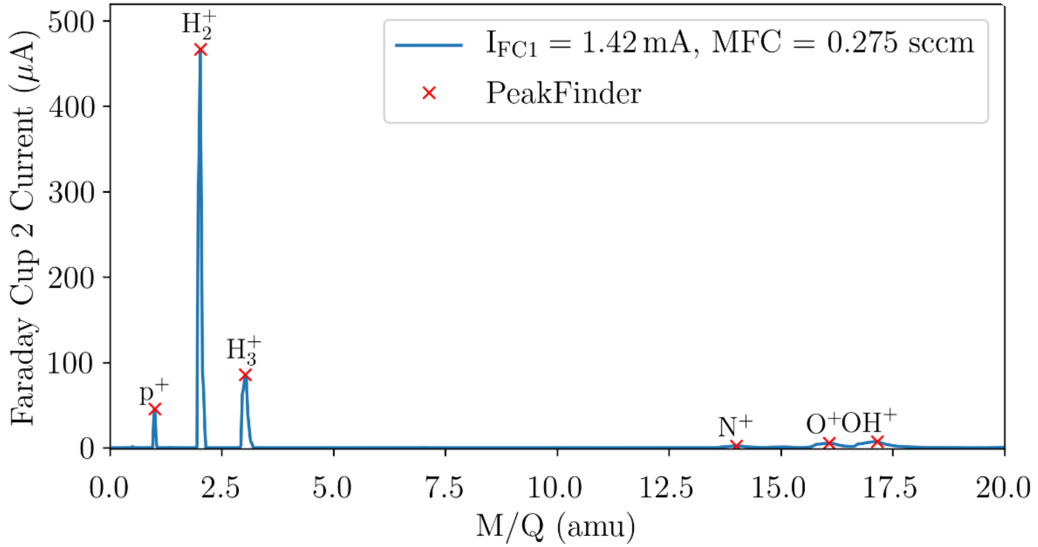
- Helps with Injection
- Helps with Low Energy Beam Transport

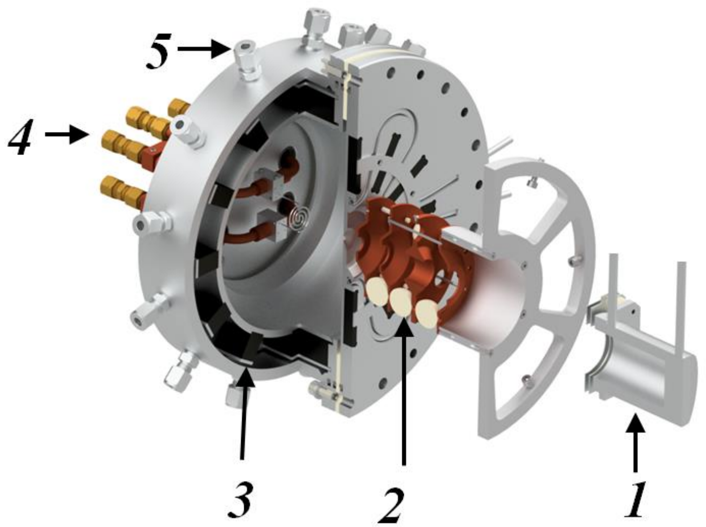
- This is also how we can split the beam to go to different target stations!



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

- 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

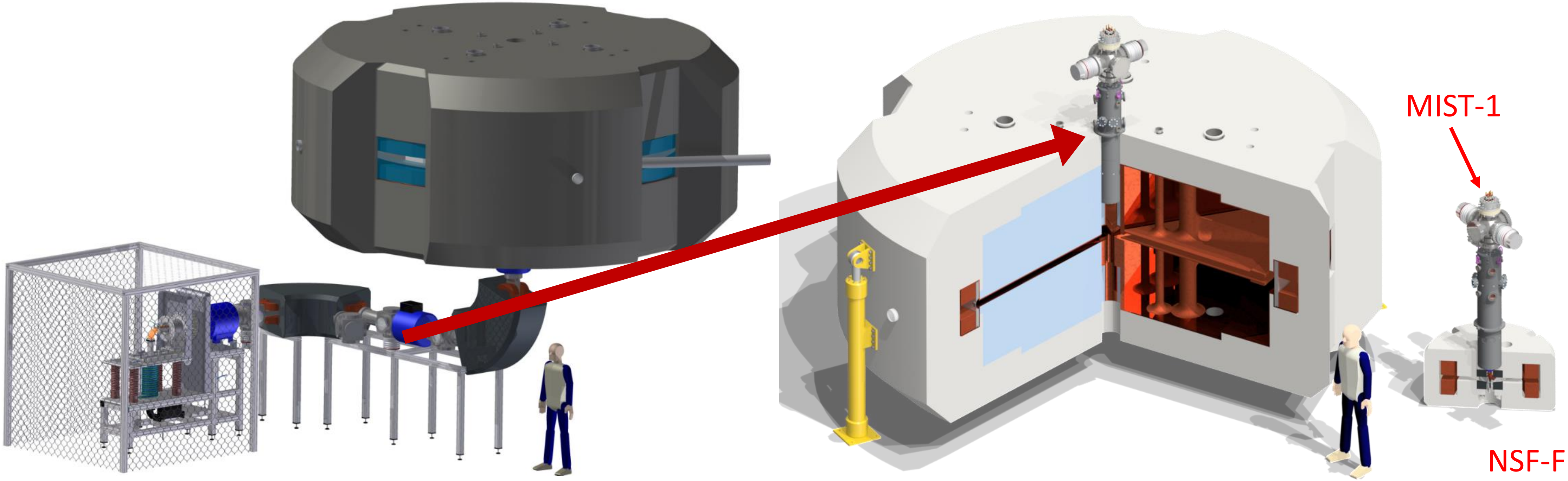




Axani, DW et al. **RSI** (2016) https://aip.scitation.org/doi/10.1063/1.4932395
DW et al., **AIP Conf. Proc.** (2017) https://arxiv.org/abs/1811.01868
DW et al. **RSI** (2021) https://arxiv.org/abs/2008.12292

RFQ-DIP

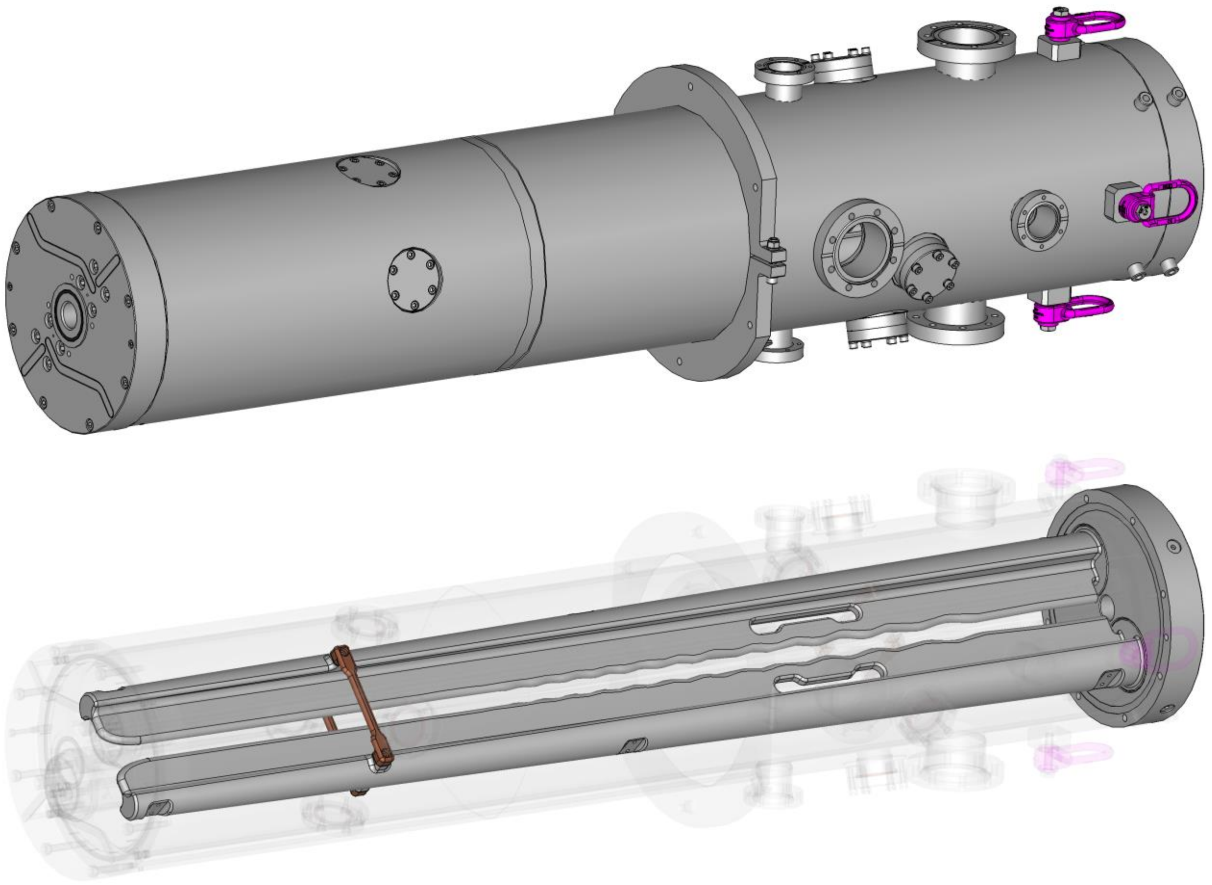
- Radio Frequency Quadrupole – Direct Injection Project
  - Bunch and focus→ Increased injection efficiency
  - Pre-accelerate and select H_2^+ → More compact



NSF-Funded
RFQ Prototype
under construction

DW et al. **RSI** (2016) https://aip.scitation.org/doi/abs/10.1063/1.4935753
DW et al. **NIMA** (2018) https://arxiv.org/abs/1807.03759
DW et al. **JACoW** IPAC2021-TUXB07 (2021) https://inspirehep.net/literature/1962316

Split-coaxial RFQ bunches the beam at 32.8 MHz



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	0.25
Trans. emittance (rms, norm)	mm-mrad	0.25
Long. emittance (rms)	**keV-deg**	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

Split-Coaxial RFQ
Eigenmode of tank allows low frequency with small diameter

Technical Design by Bevatech, GmbH, Germany

7 Papers at the IPAC'21 Conference

Excellent opportunity to use Machine Learning ("Virtual Accelerators")

- Particle accelerator simulations can be complex with large sets of input parameters
- Optimization requires repeated evaluation of points in parameter-hyperspace.
- Surrogate model: train neural net on sparse set of points in this hyperspace
- Evaluation of surrogate model is orders of magnitude faster than original simulation
  - Optimization
  - Real-Time Feedback

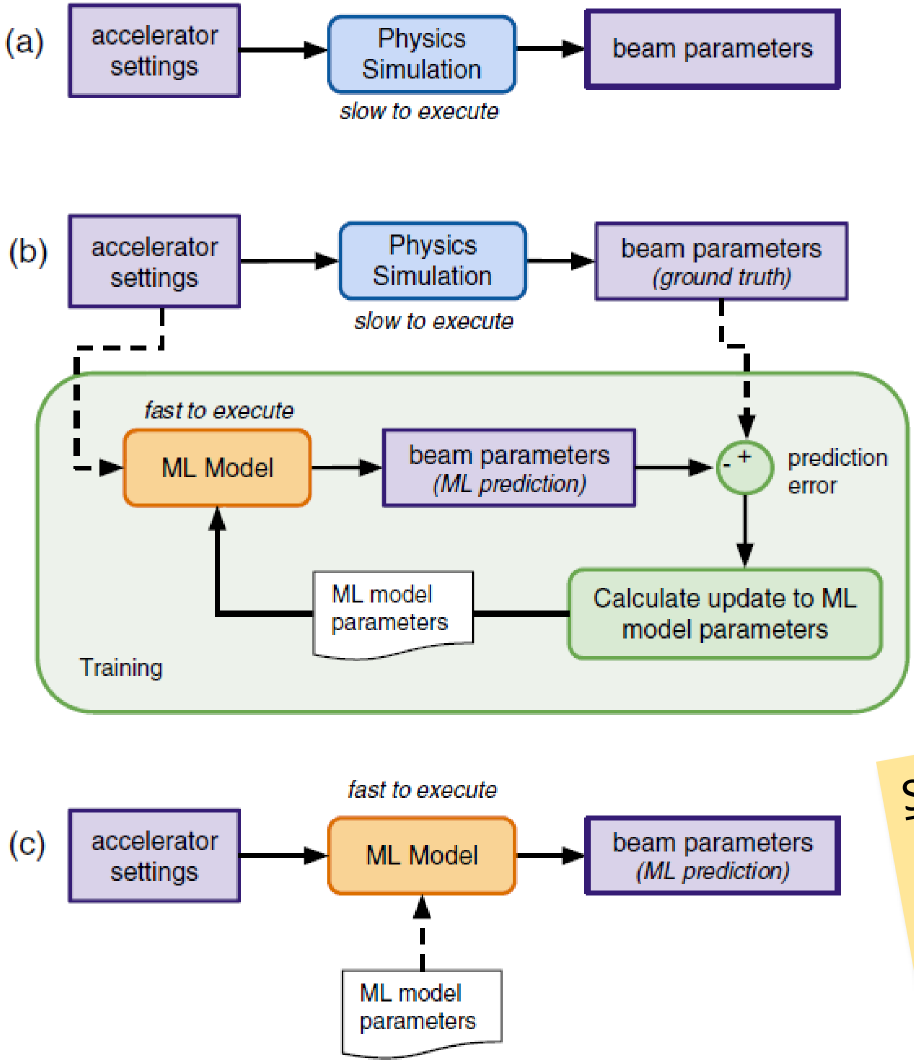


Image: A. Edelen et al. *PRAB* 23, 044601 (2020)

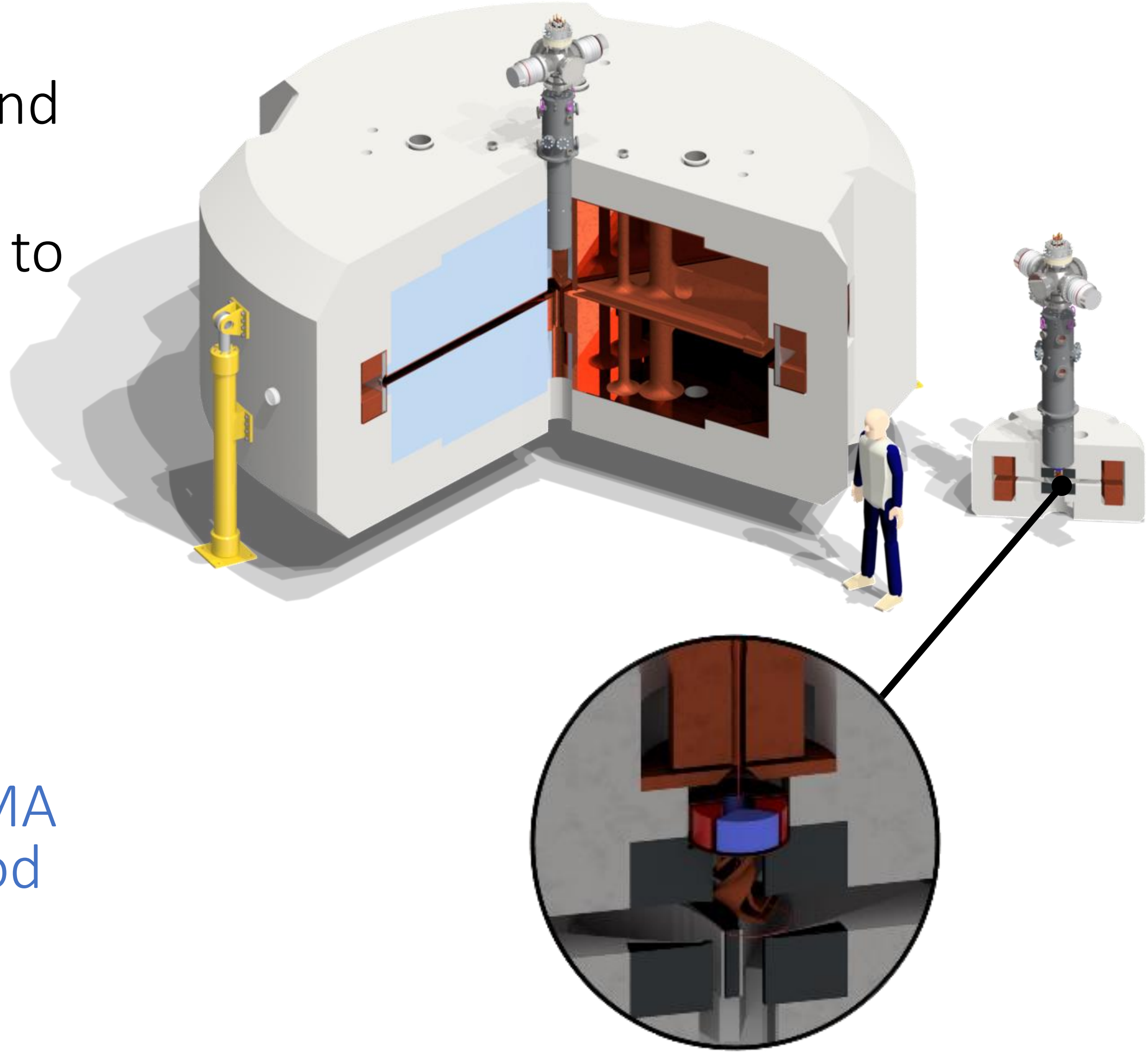
Surrogate Model
A ML-trained NN to replace costly PIC simulations.

D. Koser et al. **Front. Phys.** (2022) https://arxiv.org/abs/2112.02579
J. Villarreal, DW and J.M. Conrad (2022) http://arxiv.org/abs/2210.11451

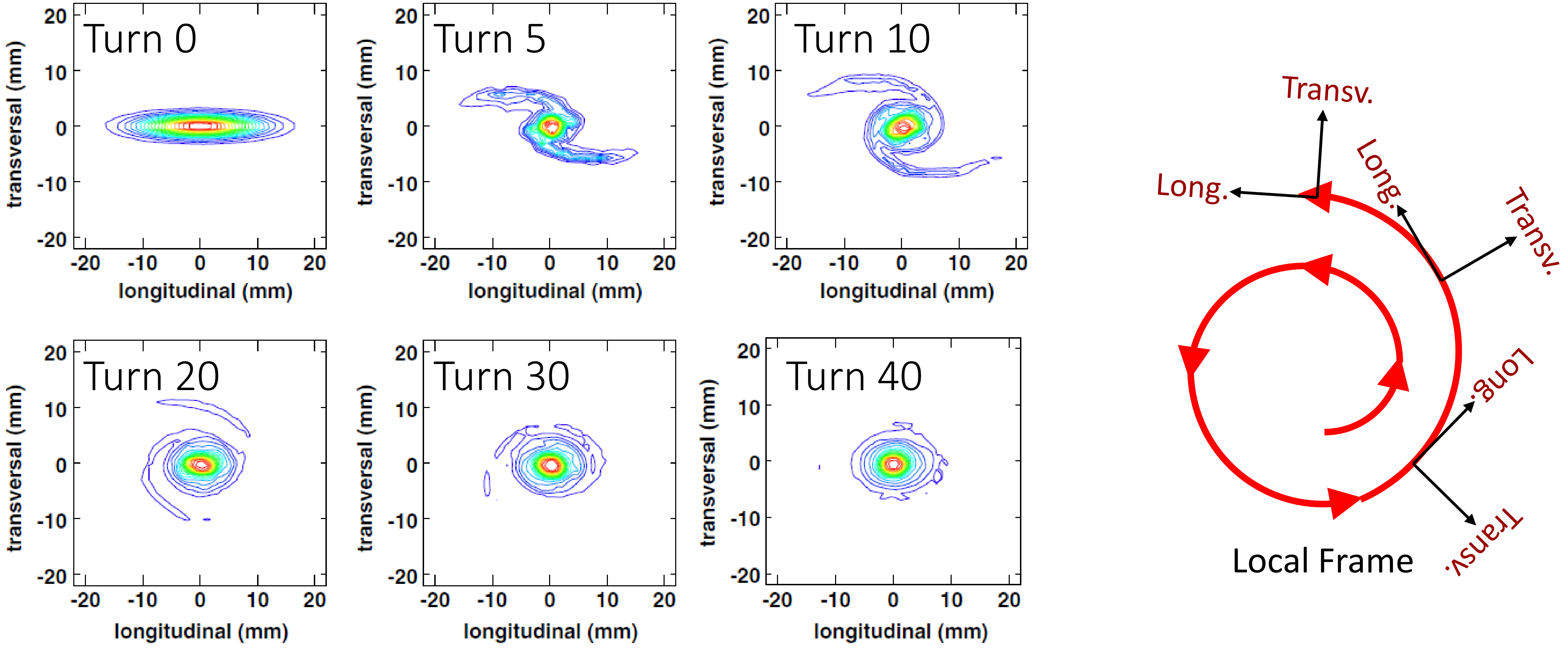
The Central Region

- Beam from the RFQ de-bunches and diverges quickly
- Bring RFQ exit as close as possible to median plane
- Add transverse focusing element
- Guide through spiral inflector
- Place collimators in first turns

- Note: Full Start-To-End Simulation Ongoing. Preliminary Study by AIMA showed acceptable losses and good vertical acceptance.

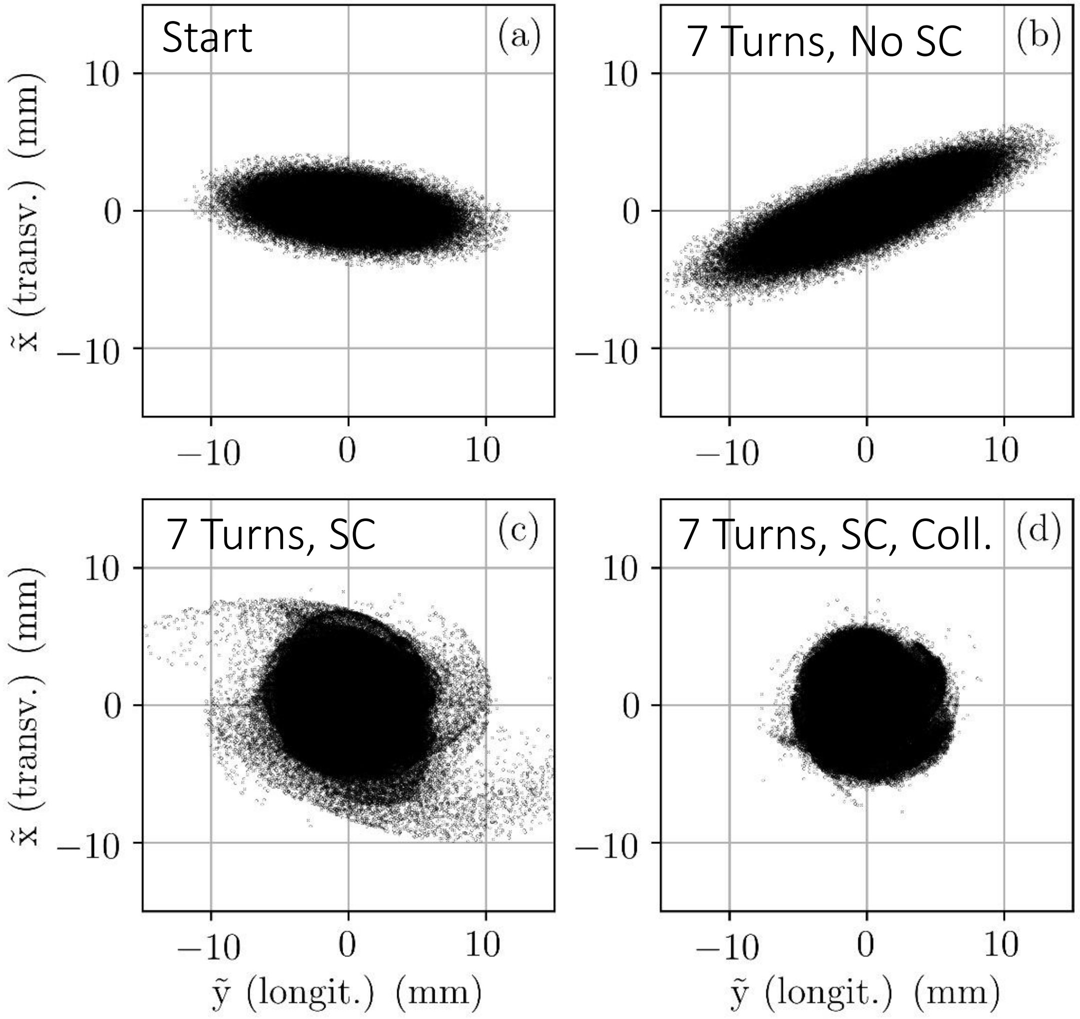


Vortex motion – Discovered in PSI Injector II Simulated with OPAL → Good Agreement



Yang et al. **PRSTAB** (2010) https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.13.064201

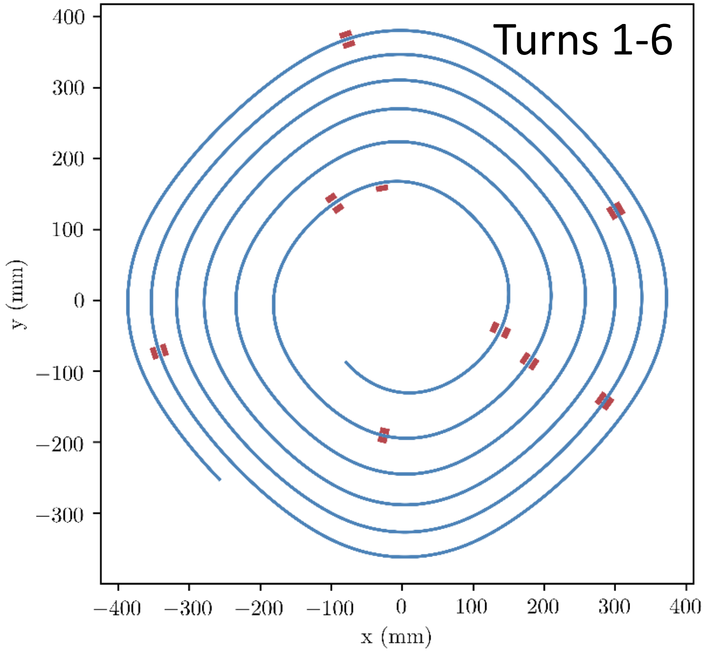
Vortex Motion in the IsoDAR 60 MeV/amu cyclotron

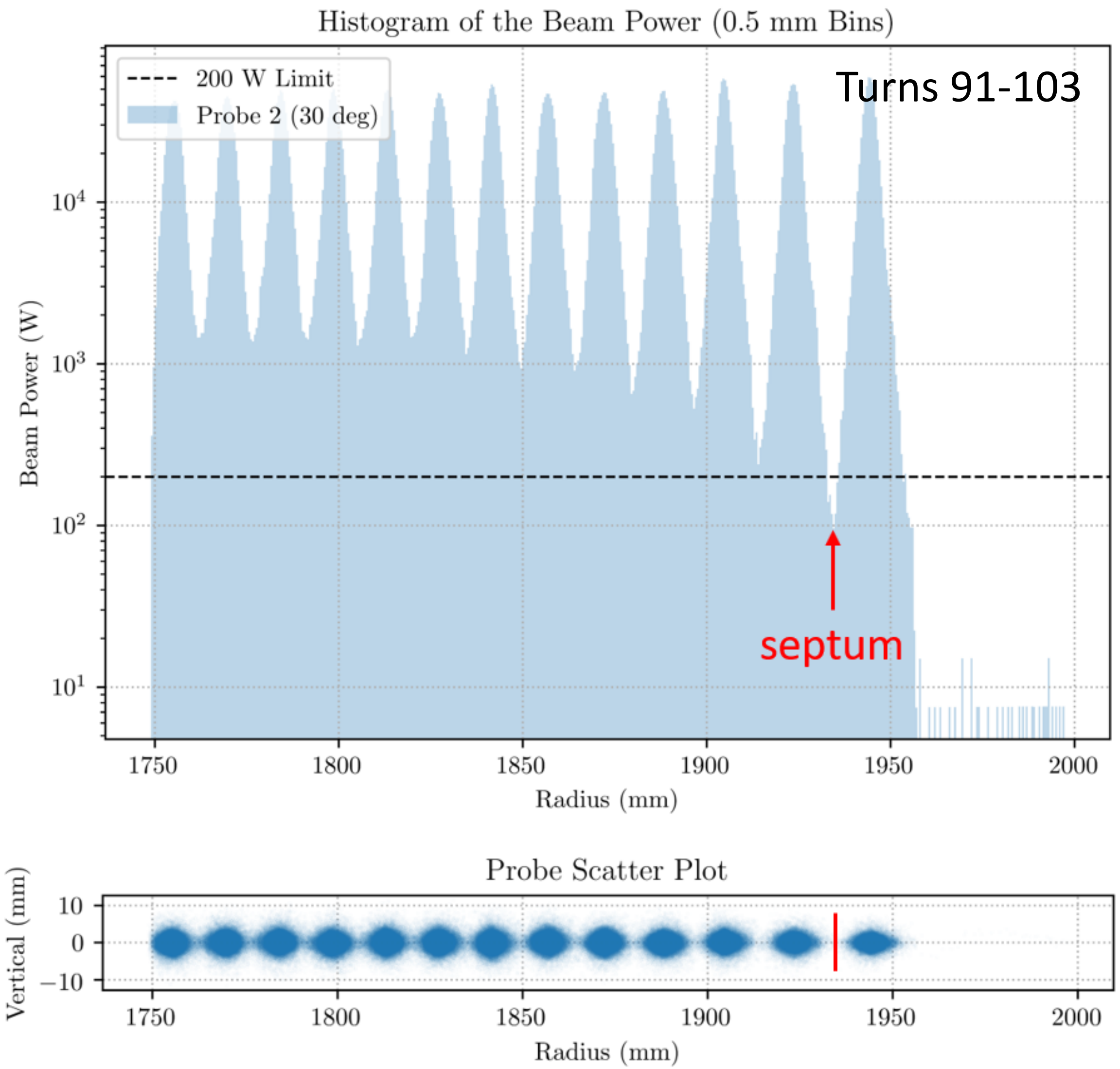


DW et al., **New J. Phys.** (2022) https://doi.org/10.1088/1367-2630/ac5001

Optimize phase, RF voltage, cavity shape, collimator placement

- Phase: -5°, V = 70-240kV
- Collimate Halo → ~30% loss
- 98 W on septum (~1e-4 rel.)

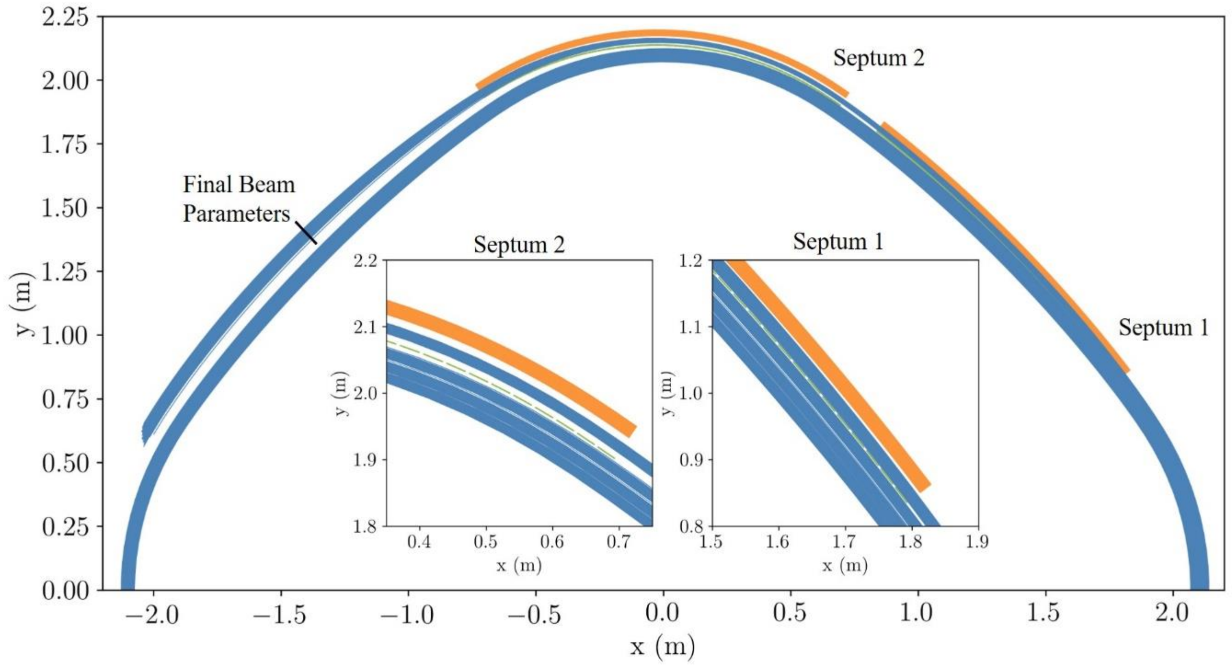




DW et al., **New J. Phys.** (2022) https://doi.org/10.1088/1367-2630/ac5001

Beam can be extracted with good quality

- Minimal losses at 60 MeV/amu: < 100 Watt!
- RMS Size:
  - Radial: 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

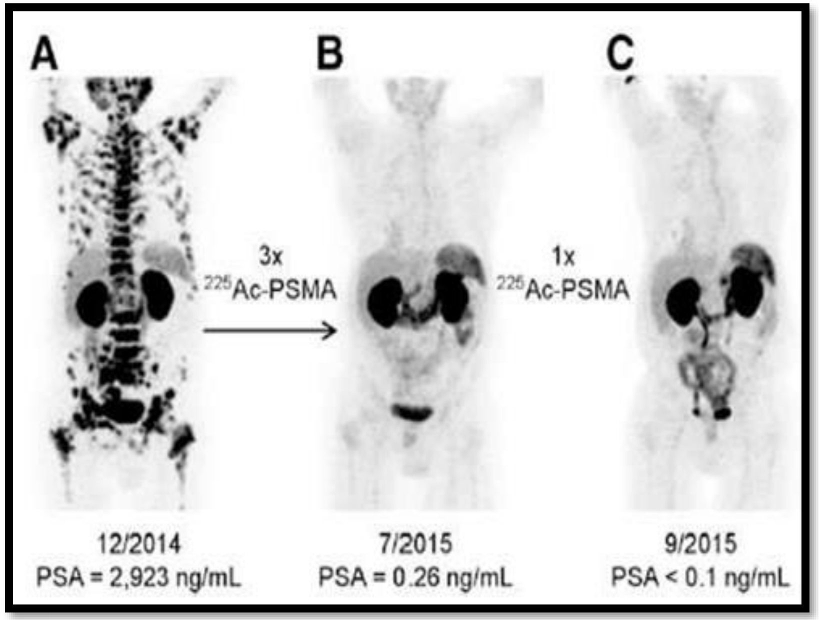


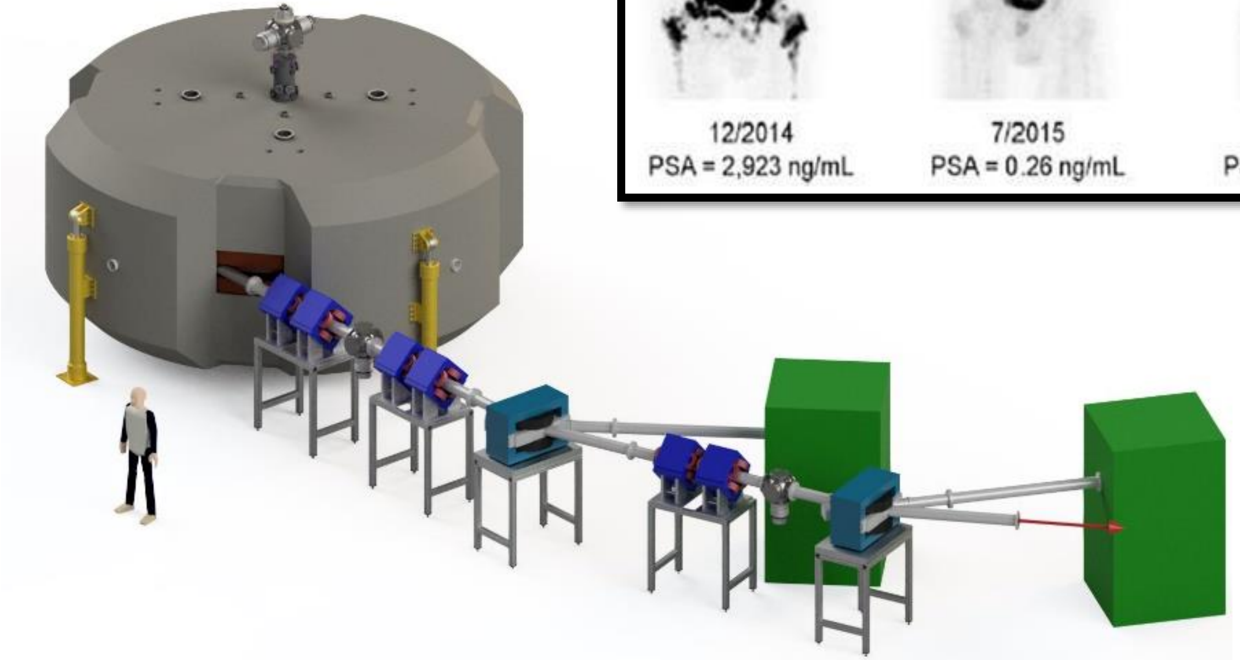
- Note: Also used Surrogate Modeling for uncertainty quantification here

DW et al., **New J. Phys.** (2022) https://doi.org/10.1088/1367-2630/ac5001

Other Applications - Isotopes

- Few 60 MeV/amu accelerators,
  - On market machines < 1 mA
  - Lab-based accelerators are not at dedicated facilities
  - HCHC-XX could be built by consortia of hospitals
- There is real need for...
  - $^{68}Ge/^{68}Ga$: PET isotope
  - ^{225}Ac: Alpha emitter
  - Many others
- Currently single targets can't handle 600 kW - but
  - Split beam inside-
  - Or outside Cyclotron





J. Alonso et al. **Nature** (2019) https://www.nature.com/articles/s42254-019-0095-6
L. Waites et al. **EJNMMI** (2020) https://doi.org/10.1186/s41181-020-0090-3

Thank You!

IsoDAR: International collaboration of ~30 scientists

Co-spokesperson: Josh Spitz (spitzj@umich.edu)
Co-Spokesperson: Daniel Winklehner (winklehn@mit.edu)

Industry Partners

References

- IsoDAR@Yemilab – CDR: IsoDAR Collaboration **arXiv** (2021) arxiv:2110.10635
- IsoDAR@Yemilab – Physics: J. Spitz, … DW, … **PRD** (2022) arxiv:2111.09480
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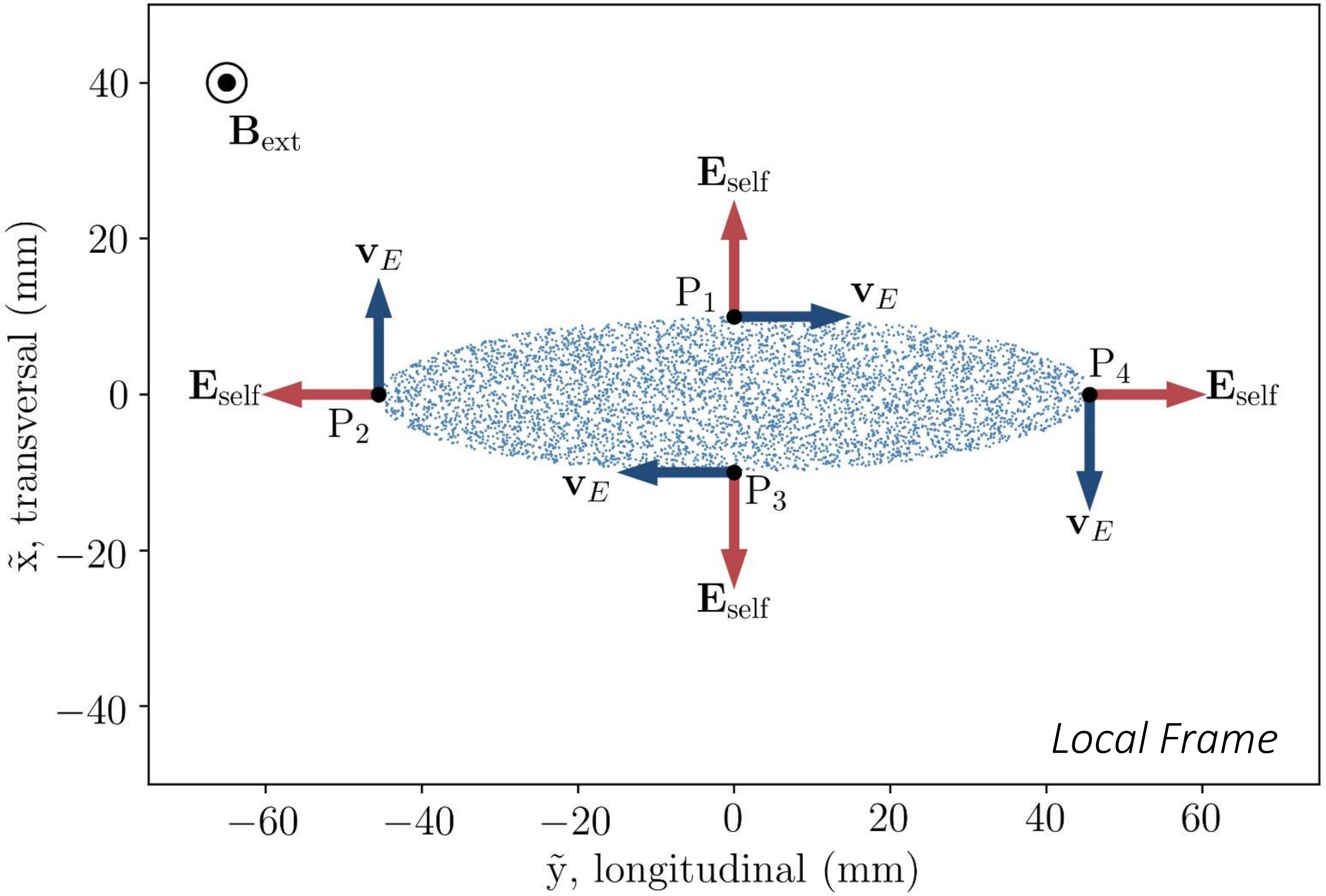
- Isotopes: L. Waites et al. **EJNMMI** (2020) https://doi.org/10.1186/s41181-020-0090-3
- Target, ^{8}Li yield: A. Bungau et al. **arXiv** (2018) https://arxiv.org/abs/1805.00410
- Target, shielding: A. Bungau et al. **arXiv** (2019) https://arxiv.org/abs/1909.08009
- First experimental tests: D. Winklehner et al. **JINST** (2015) arXiv:1508.03850
- Yang et al. **PRSTAB** (2010) PhysRevSTAB.13.064201
- The OPAL Code: Adelmann, …, DW, … **arXiv** (2019) https://arxiv.org/abs/1905.06654
- High-Power Cyclotron Report: D. Winklehner et al. **arXiv** (2022) https://arxiv.org/abs/2203.07919
- *Modeling of advanced accelerator concepts*, J.-L. Vay, …, DW 2021 JINST **16** T10003
- *Simulations of future particle accelerators: issues and mitigations*, D. Sagan, …, DW, … 2021 JINST **16** T10002
- *Snowmass21 Accelerator Modeling Community White Paper,* S. Biedron, …, DW, … 2022 arXiv:2203.08335

Backup Slides

Vortex Motion – Highly Simplified Picture

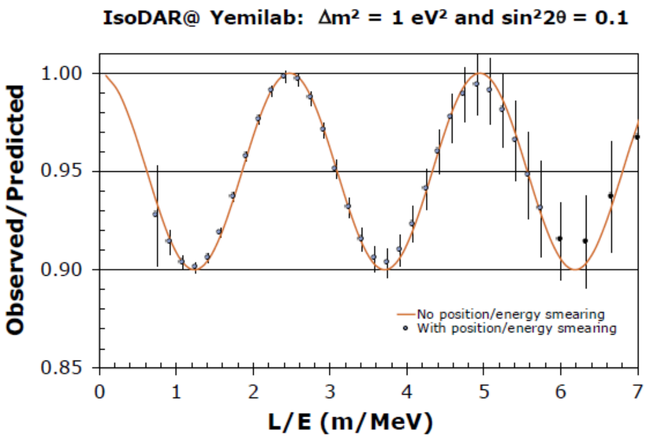


Lorentz force: $\mathbf{F} = q \cdot (\mathbf{v} \times \mathbf{B}_{\text{ext}}) + q \cdot \mathbf{E}_{\text{self}}$ E x B drift: $\mathbf{v}_E = \dfrac{\mathbf{E}_{\text{self}} \times \mathbf{B}_{\text{ext}}}{\mathrm{B}_{\text{ext}}{}^2}$

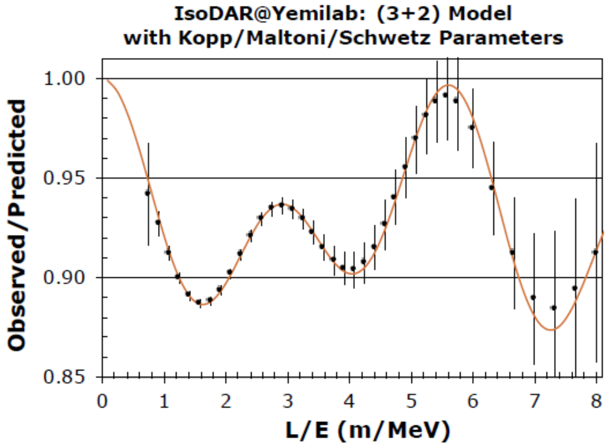
http://arxiv.org/abs/2111.09480

Physics 1: World-leading search for exotic (sterile) neutrinos through precision L/E measurements

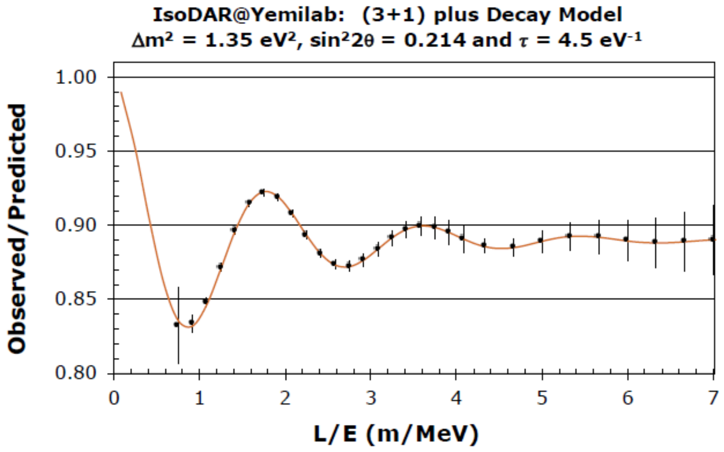
one exotic neutrino



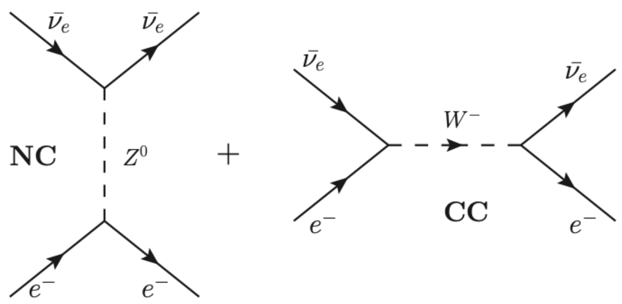
two exotic neutrinos

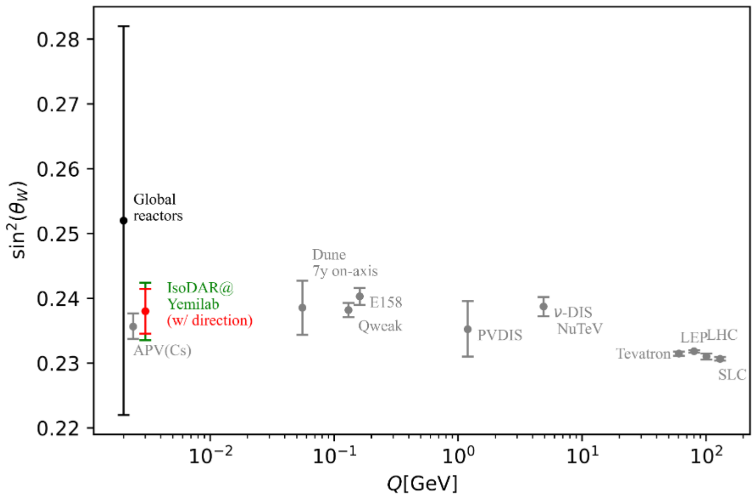


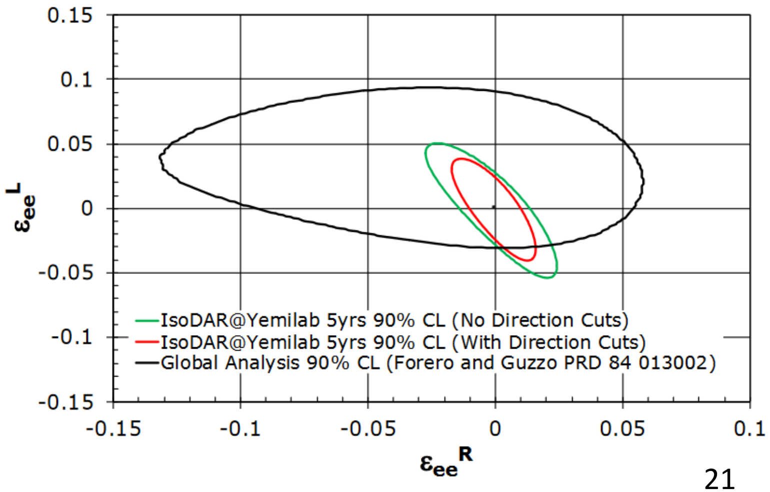
one that decays...



Physics 2: Unprecedented $\bar{\nu}_e - e^-$ elastic scatter sample (>7000 events) at low Q

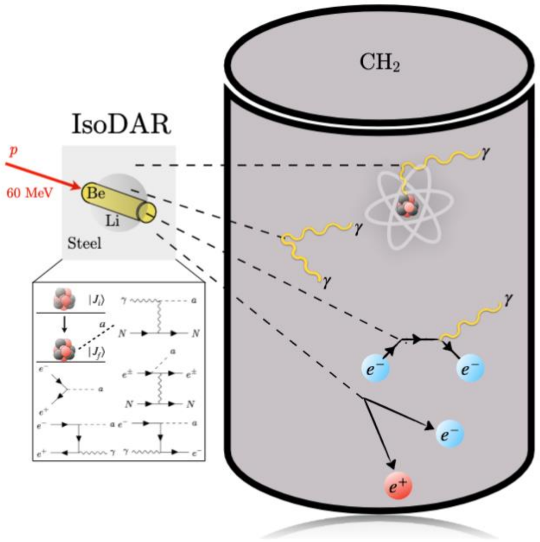


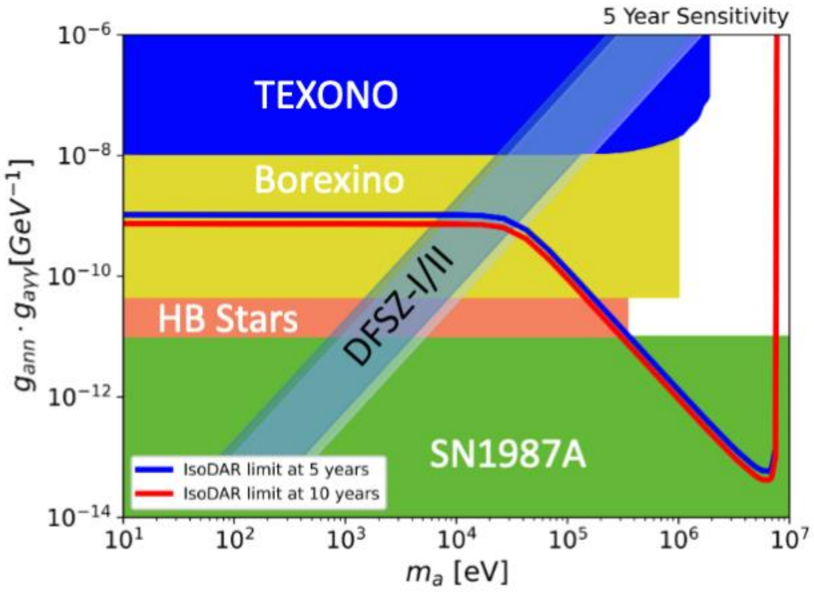




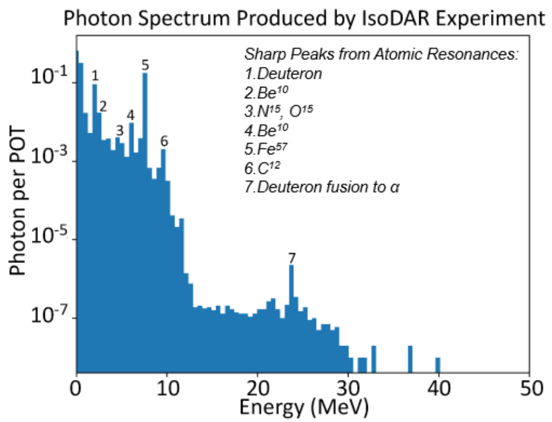
http://arxiv.org/abs/2111.09480

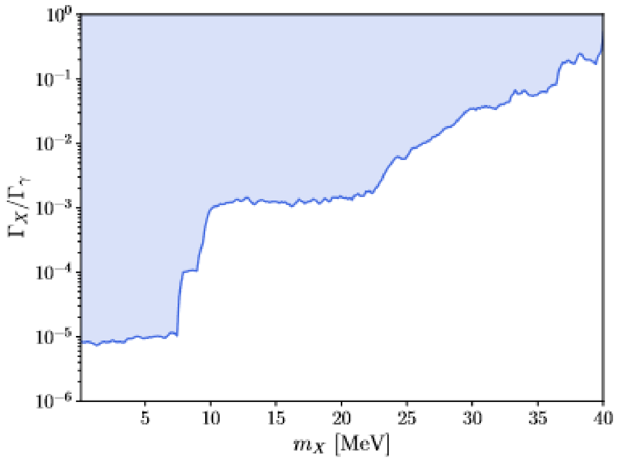
Physics 3: Search for Axion-Like Particles (ALPs)

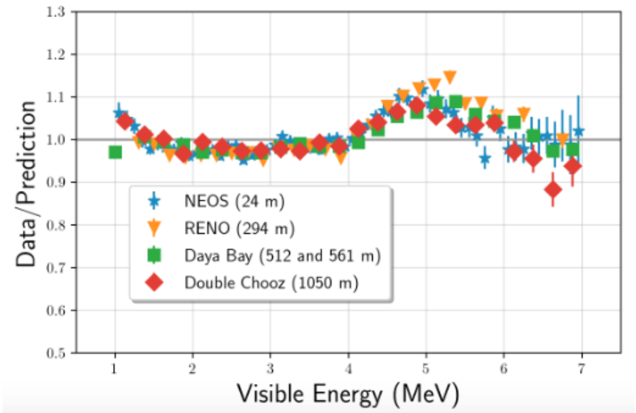




Physics 4: Bump hunt in the neutrino spectrum, *light X particles* produced in the target → $\nu_e\bar{\nu}_e$







Produced by mixing w/ photons in target

Sensitivity

Help explain 5 MeV bump in reactors?