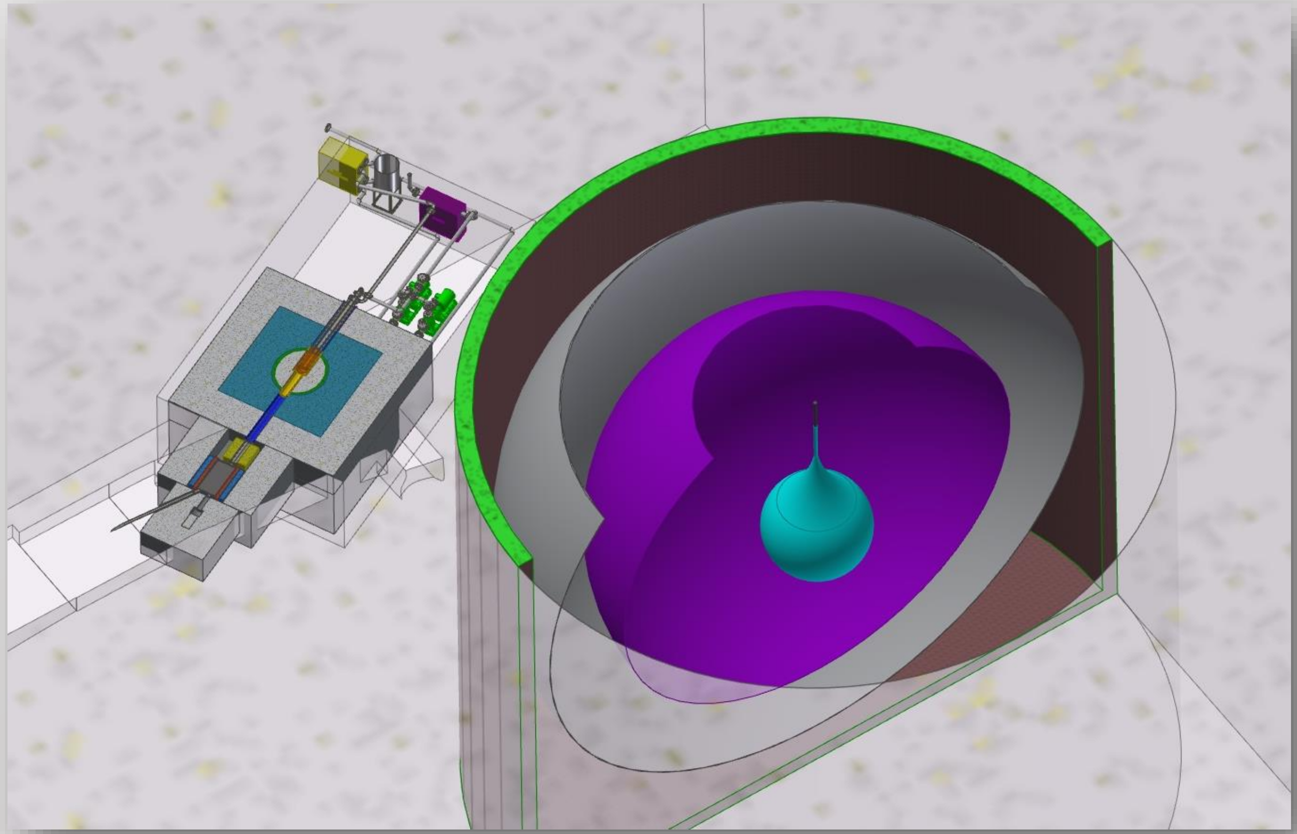
IsoDAR:
Neutrino Physics Using a High Current Cyclotron

Joe Smolsky for the IsoDAR collaboration

Overview

<u>Motivation</u>
- Standard model
- Neutrino oscillations
- Anomalies
- Sterile neutrinos

<u>IsoDAR</u>
- Setup
- Physics
- Current Status
- Beyond IsoDAR



IsoDAR

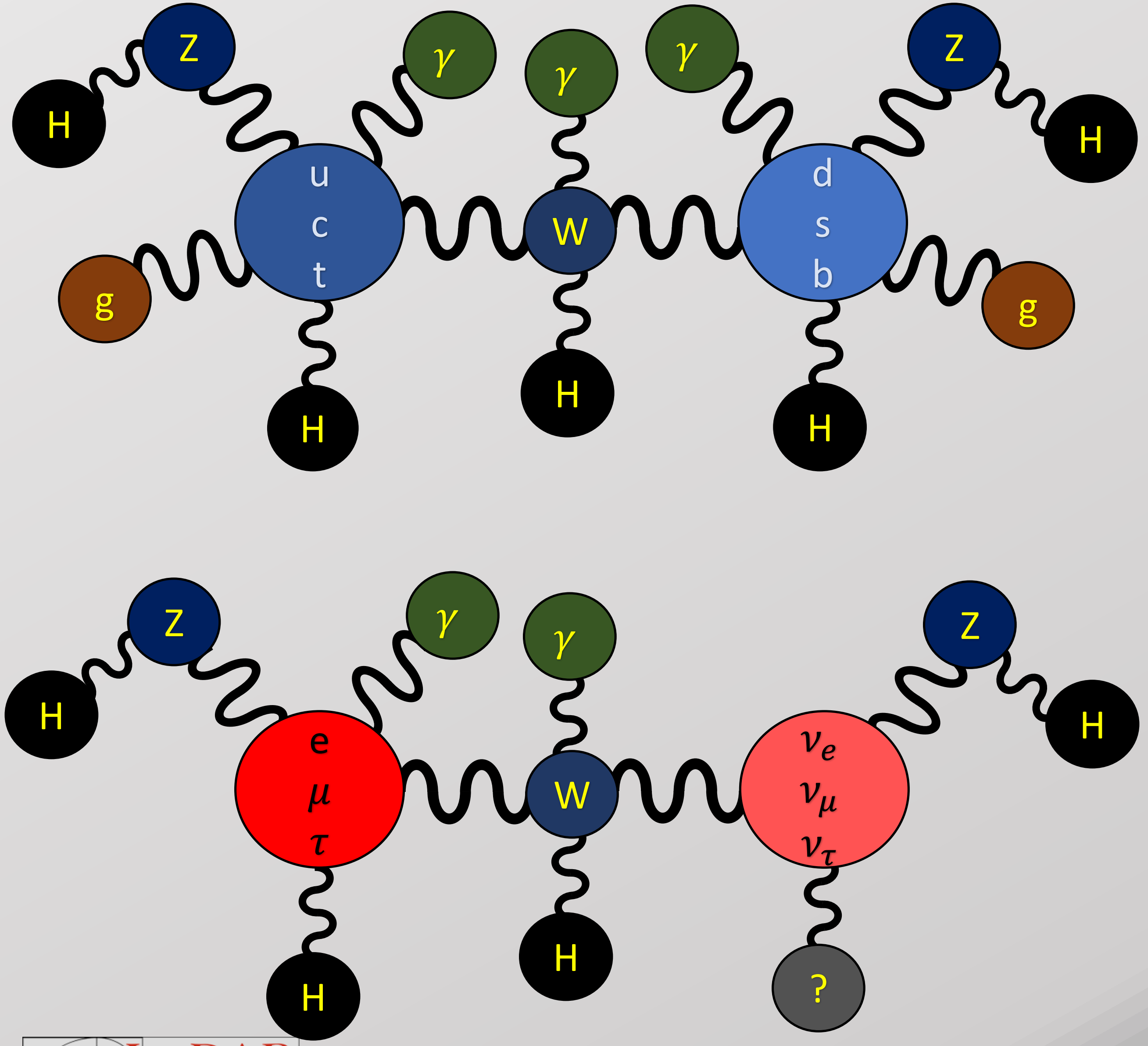
Standard Model

Quarks
up, charm, top
down, strange, charm

Leptons
electron, muon, tau
ν_e, ν_u, ν_τ

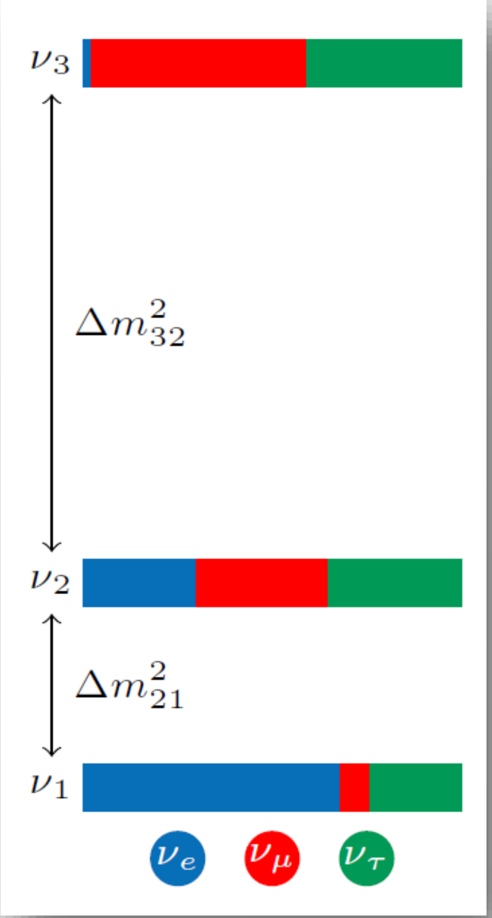
Force carriers
photon
gluon
W, Z

Mass
Higgs



IsoDAR

Neutrino oscillations



- Interact in flavor eigenstates
- Propagate in mass eigenstates

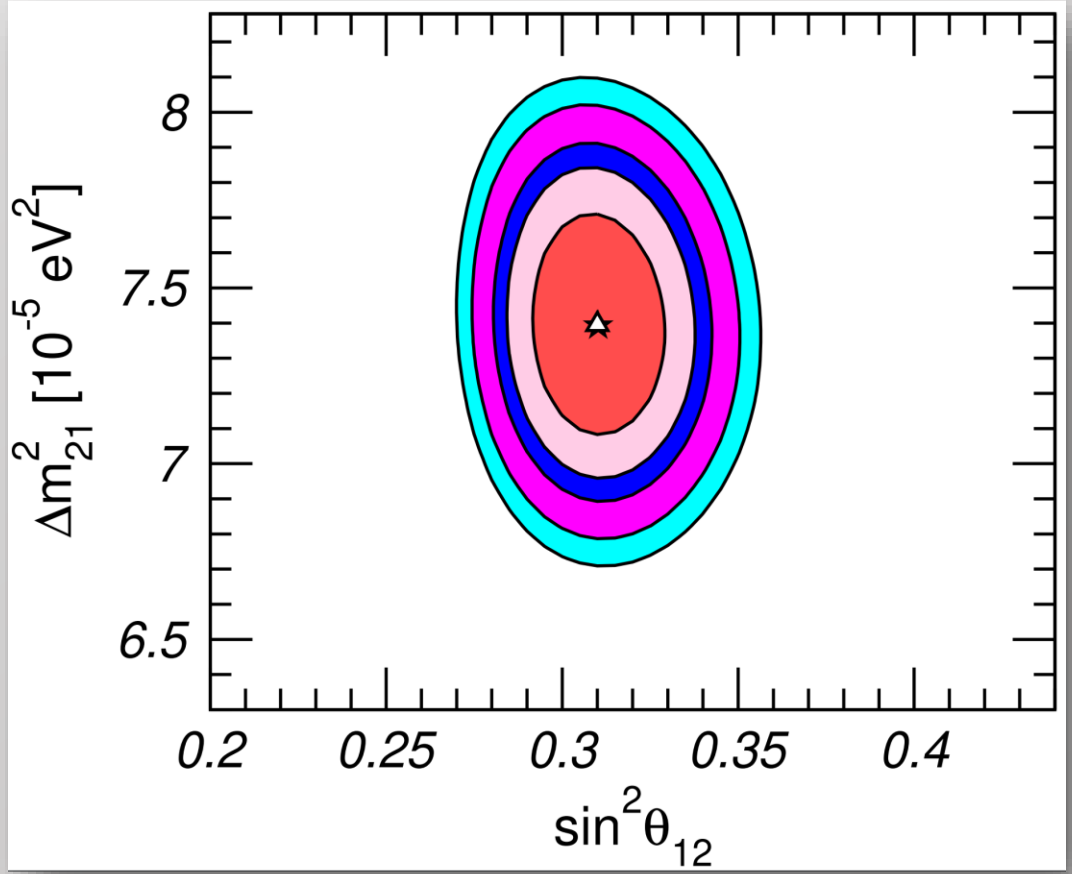
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4 \sum_{j>i} \mathrm{U}_{\alpha i} \mathrm{U}_{\beta i} \mathrm{U}^*_{\alpha j} U^*_{\beta j} \sin^2\left(1.27 \Delta m^2_{ij} \frac{L}{E}\right)$$

arXiv:1609.07803v2 [hep-ex] 2 Aug 2017

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

- $\sin^2 2\theta$ → statistics
- $\frac{L}{E}$ → experiment setup
- $\sin^2 2\theta$ vs. Δm^2
- Allow/exclude regions

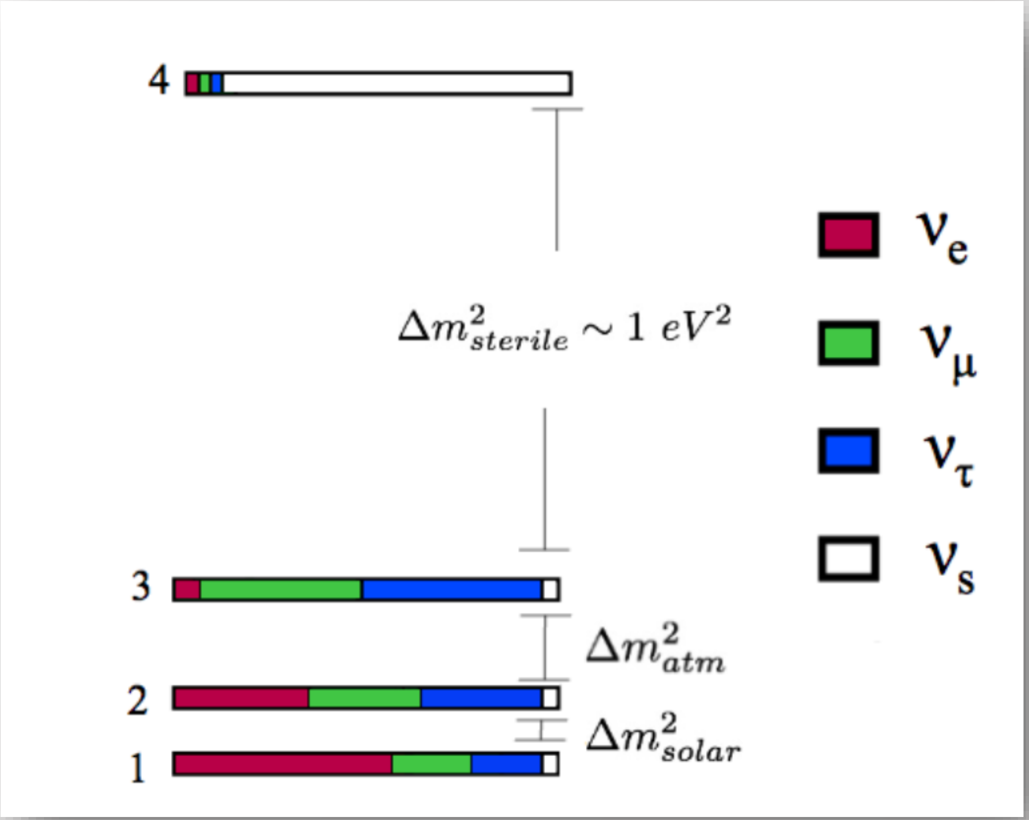


Example plot from ν_{fit}:

http://arxiv.org/abs/1811.05487

http://www.nu-fit.org/

Sterile neutrinos

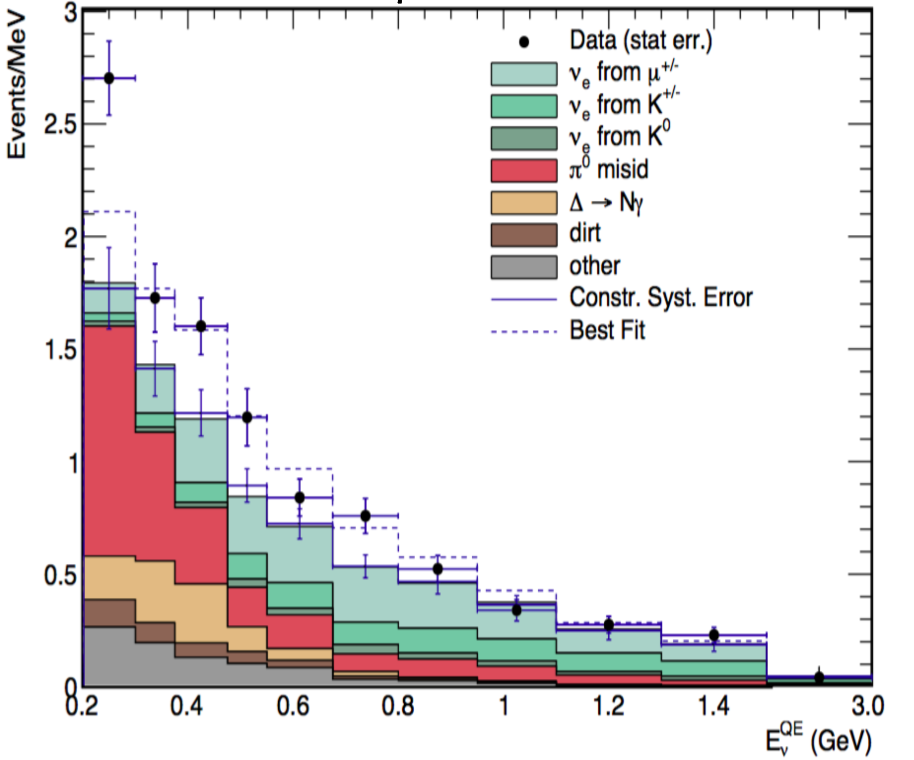


- Additional neutrino flavors
- Sterile flavors don't interact through weak force
- Active neutrinos can oscillate into sterile neutrinos

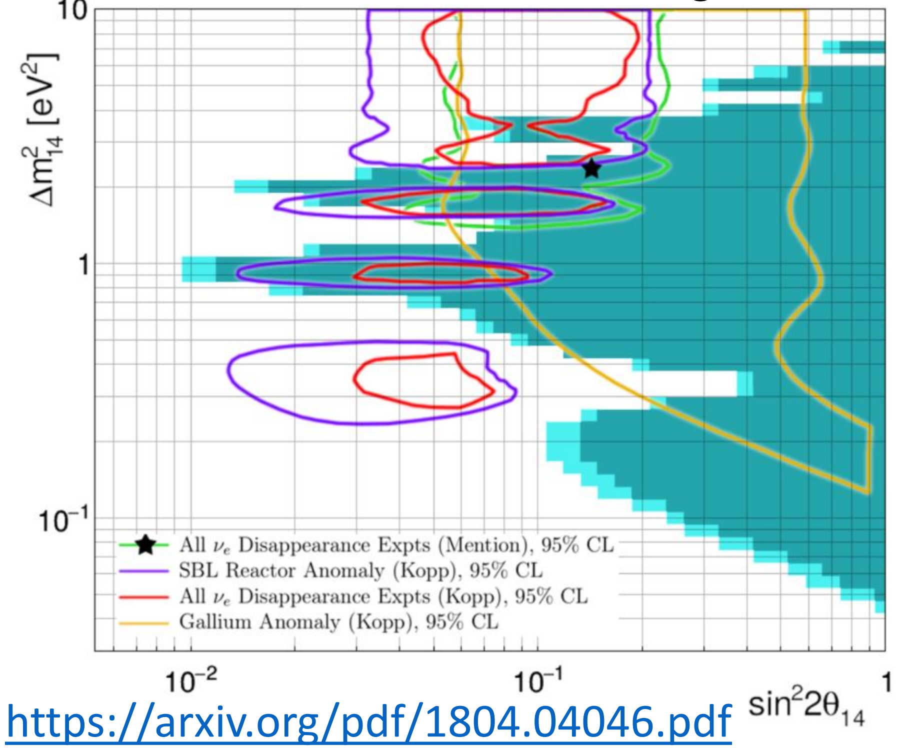
arXiv:1906.00045v1 [hep-ex] 31 May 2019

Oscillation Experiments

MiniBooNE: $\boldsymbol{\nu_\mu \rightarrow \nu_e}$ excess $\mathbf{4.8\sigma}$



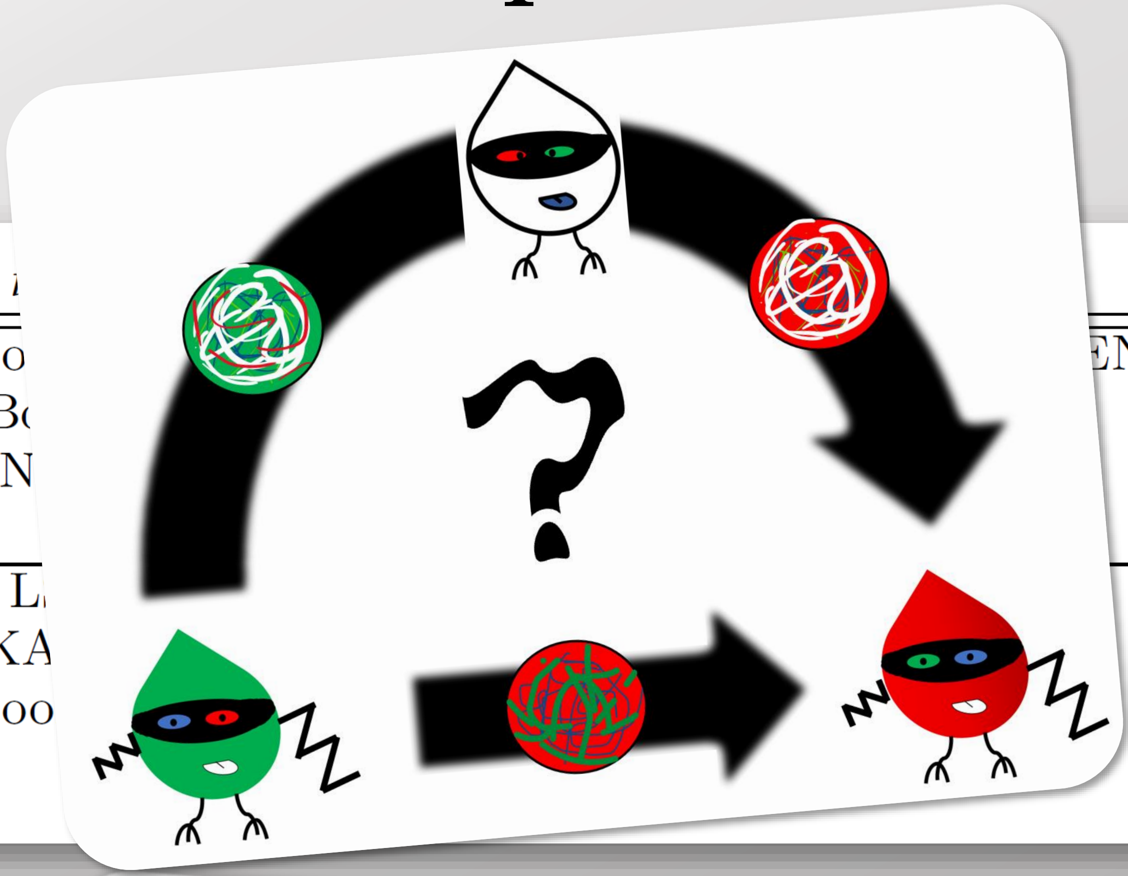
DANSS Results and allowed regions



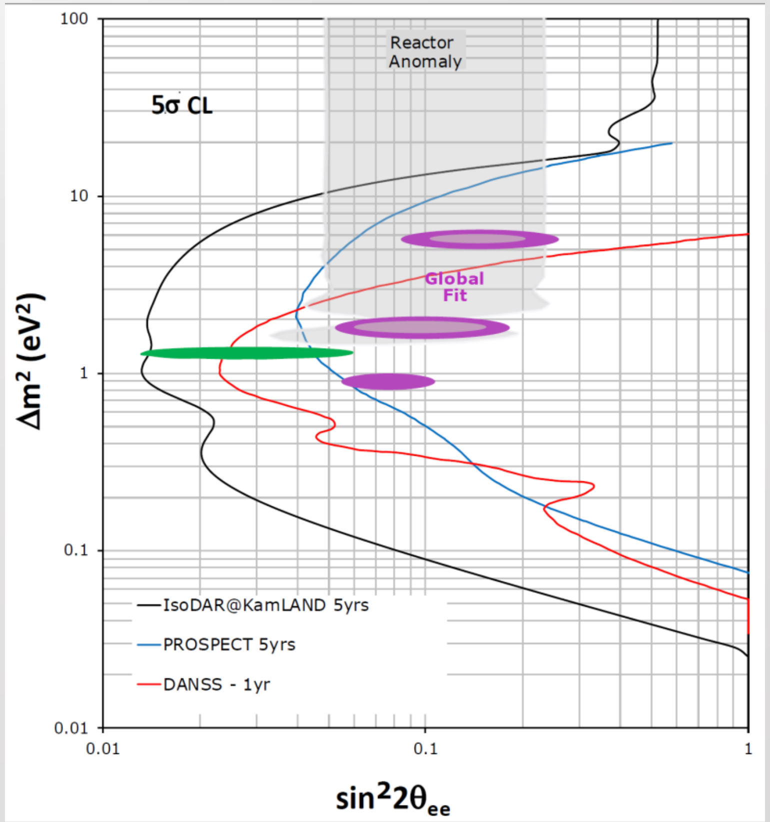
https://arxiv.org/pdf/1804.04046.pdf

More oscillation experiments

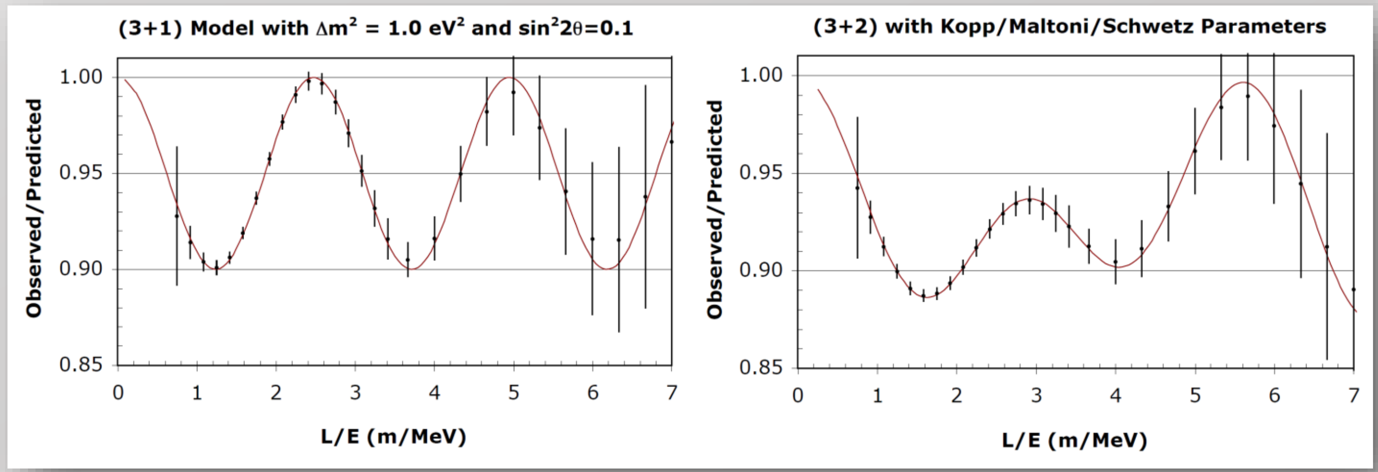
		$\nu_e \to \nu_e$
Neutrino	MiniBo MiniB N	EN/LSND Cross Section Gallium *
Antineutrino	L KA MiniBoo	Bugey NEOS DANSS * PROSPECT



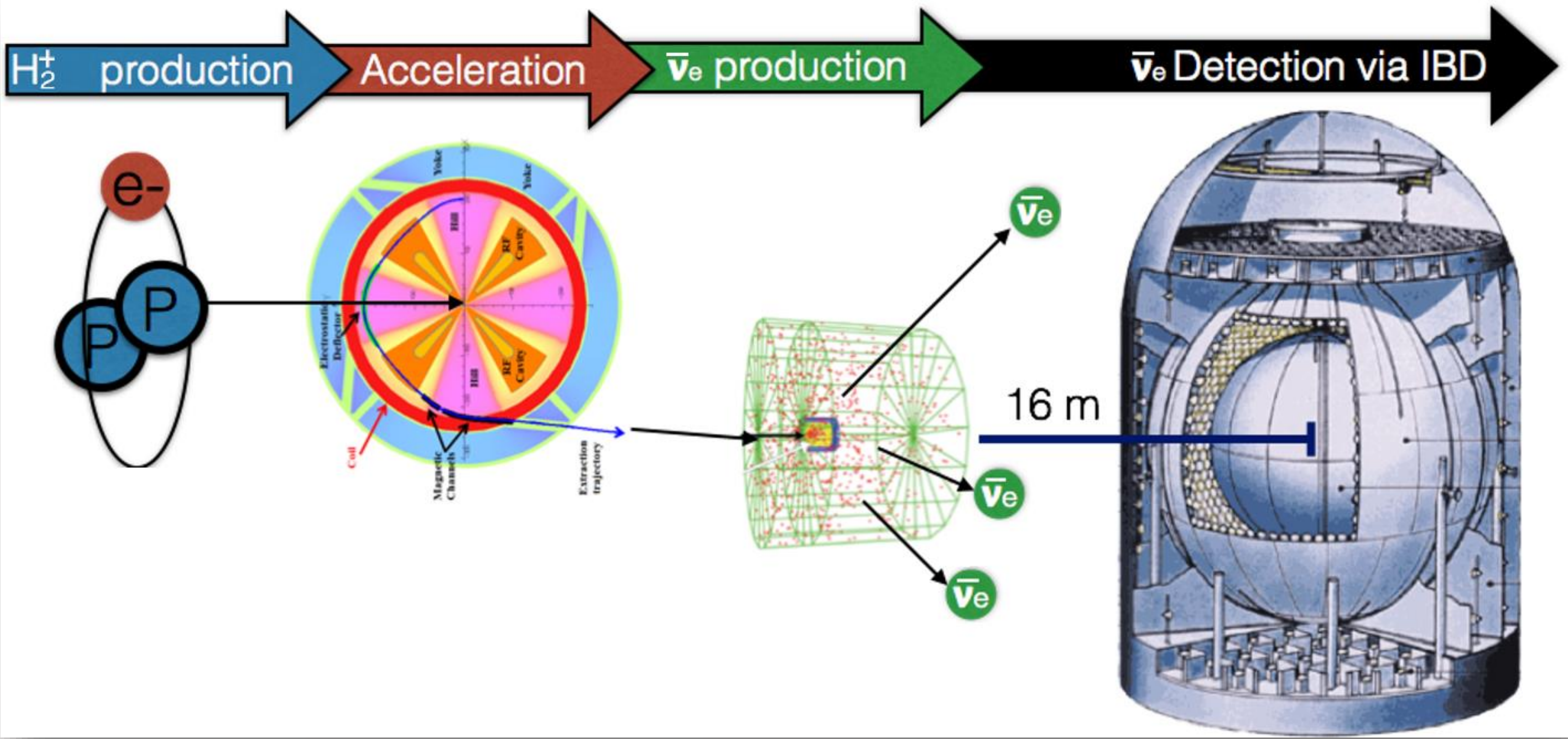
IsoDAR @ KamLAND: as a definitive ν_s search



- 5σ experiment for allowed regions
- Distinguish between models



IsoDAR: Isotope Decay-At-Rest



IsoDAR

5 years @ KamLAND

Detector	KamLAND
Distance between face of target and center of detector	16.1 m
Fiducial mass	897 metric tons
Fiducial radius	6.5 m
Total detector radius	13 m
Detection efficiency	92%
Vertex resolution	12 cm/$\sqrt{E\ (\mathrm{MeV})}$
Energy resolution	6.4%/$\sqrt{E\ (\mathrm{MeV})}$
Visible energy threshold (IBD and $\overline{\nu}_e$-electron)	3 MeV
IBD event total	8.2×10^5
$\overline{\nu}_e$-electron event total	2600
Expected $\bar{\nu}_e$ disappearance sensitivity	$\sin^2 2\theta_{new} > 0.005$ @ $\Delta m^2 = 1\mathrm{eV}^2$
Expected $\sin^2\theta_W$ 1σ precision	3.2%

IsoDAR

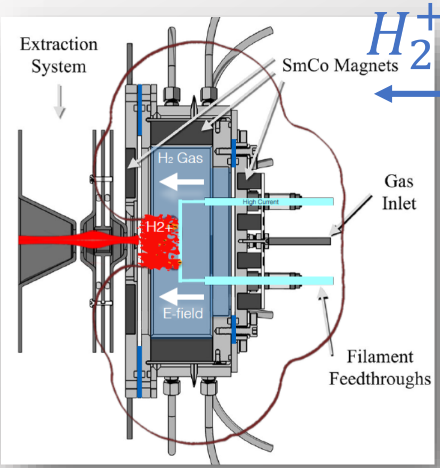
5 years @ KamLAND

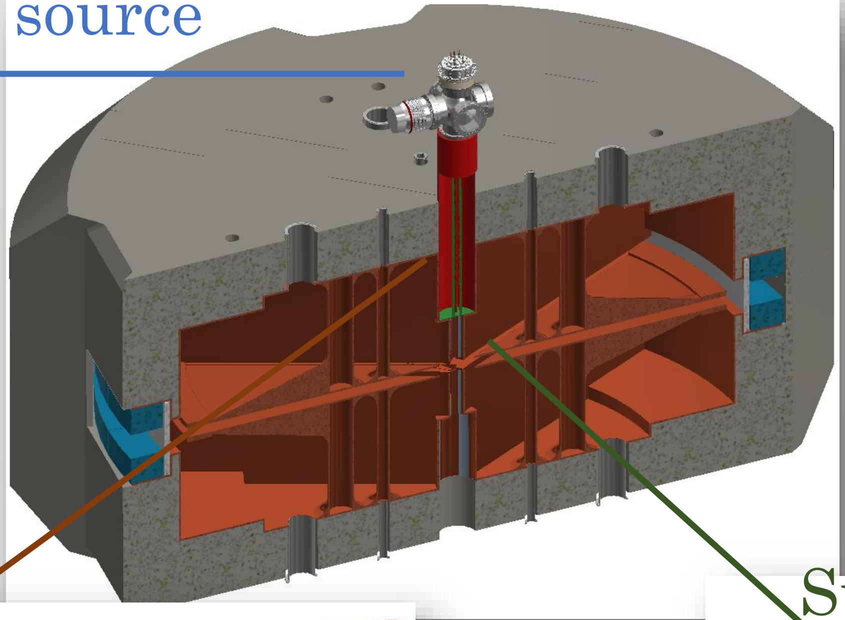
Accelerator	60 MeV/amu of H_2^+
Beam Current	10 mA of protons on target
Beam Power (CW)	600 kW
Duty cycle	90%
Protons/(year of live time)	1.97×10^{24}
Run period	5 years
Live time	5 years×0.90=4.5 years
Target	^{9}Be with FLiBe sleeve (99.995% pure ^{7}Li)
Sleeve diameter and length	100 cm and 190 cm
$\overline{\nu}$ source	^{8}Li β decay (6.4 MeV mean energy flux)
Fraction of ^{8}Li produced in target	10%
$\overline{\nu}$ flux during 4.5 years of live time	$1.3\times10^{23}\ \overline{\nu}_e$
$\overline{\nu}$ flux uncertainty	5% (shape-only is also considered)

IsoDAR

RFQ – Direct Injection Project (RFQ-DIP)

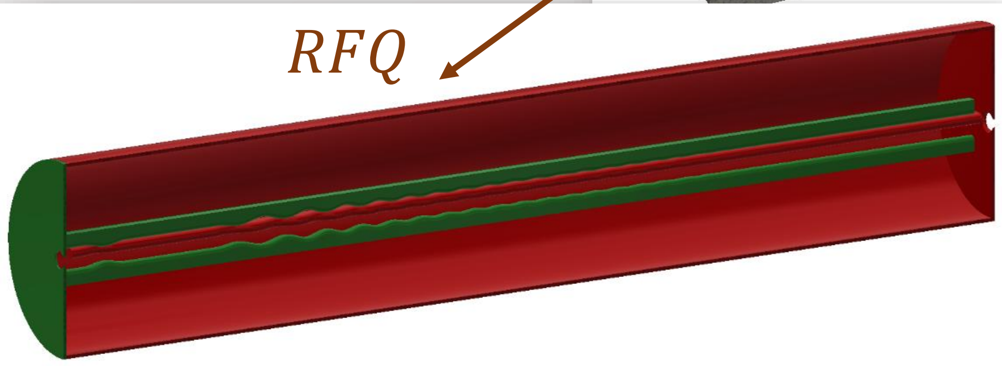
H_2^+ ion source



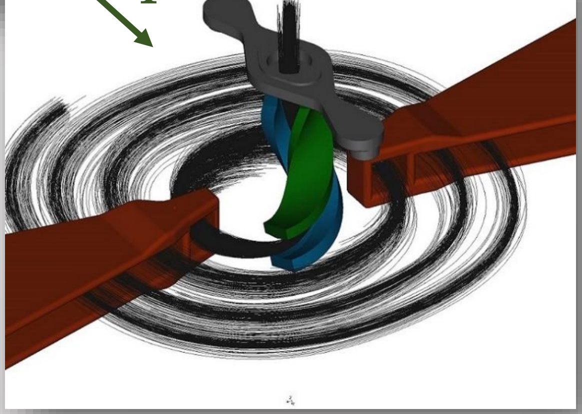


- H_2^+ to reduce space-charge effects
- RFQ for bunching, sorting, accelerating
- Inflector for axial injection

RFQ



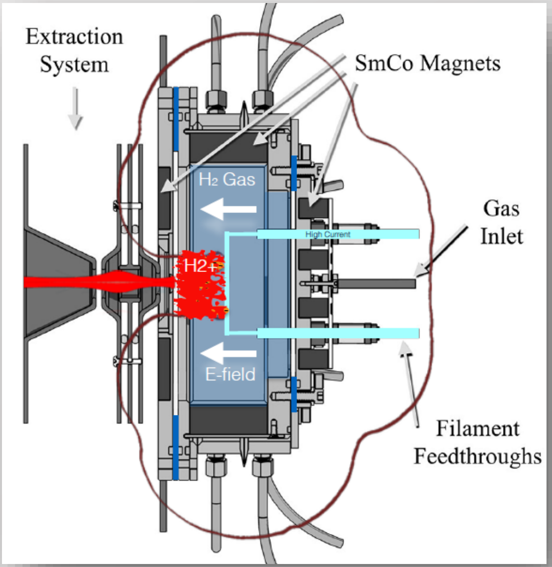
Spiral inflector and central region

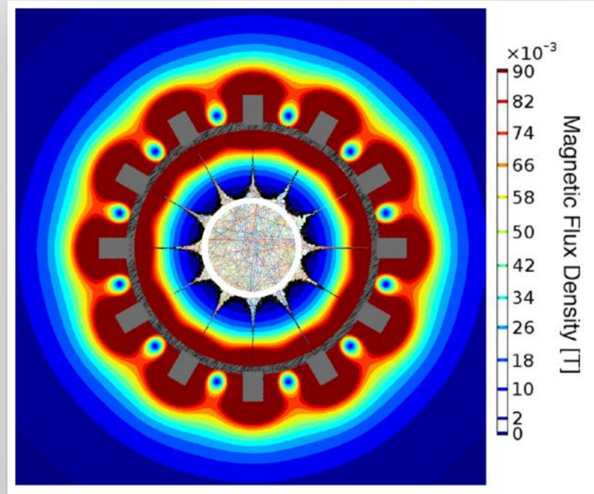


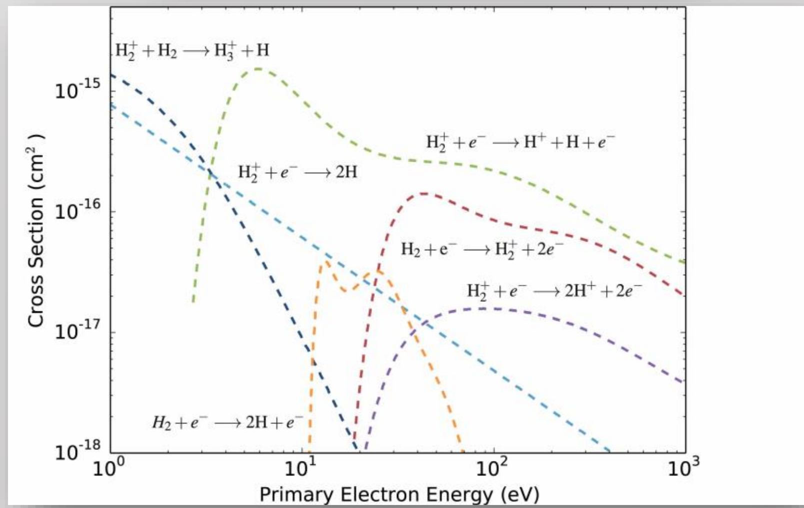
IsoDAR

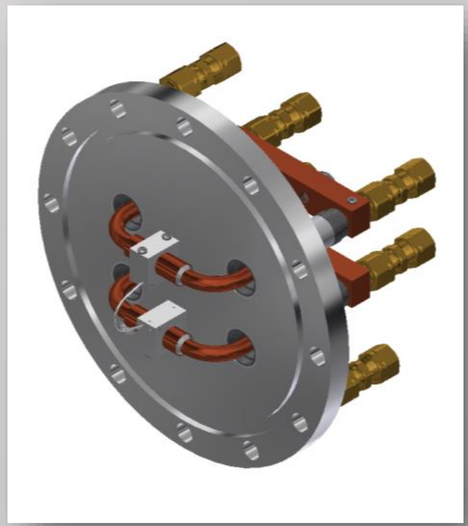
H_2^+ production

- Hot tungsten filament ionizes hydrogen molecules
- Plasma is confined by SmCo magnets
- Small aperture allows ions to drift into extraction system
- Current output 35 mA/cm² (Sufficient for IsoDAR)



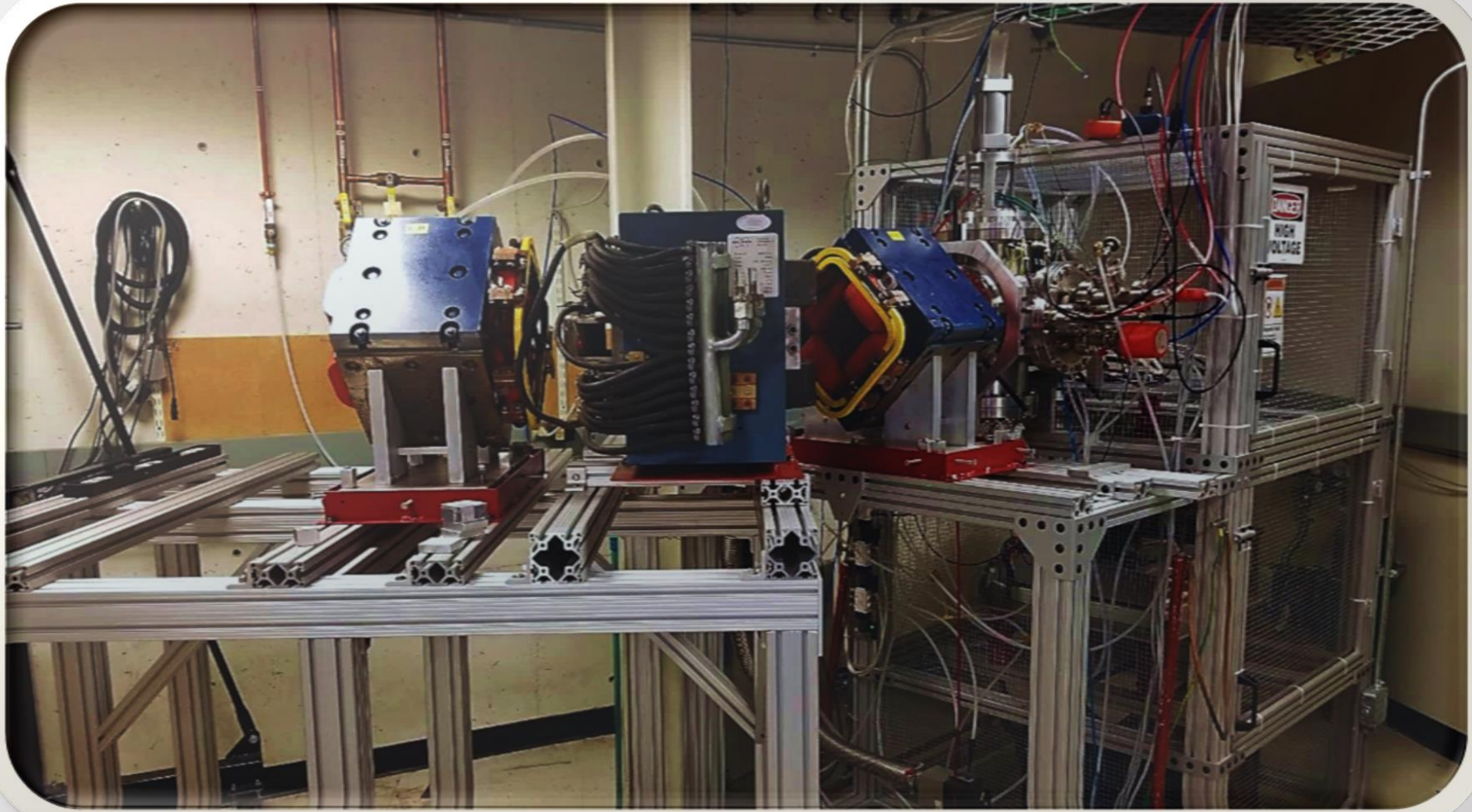






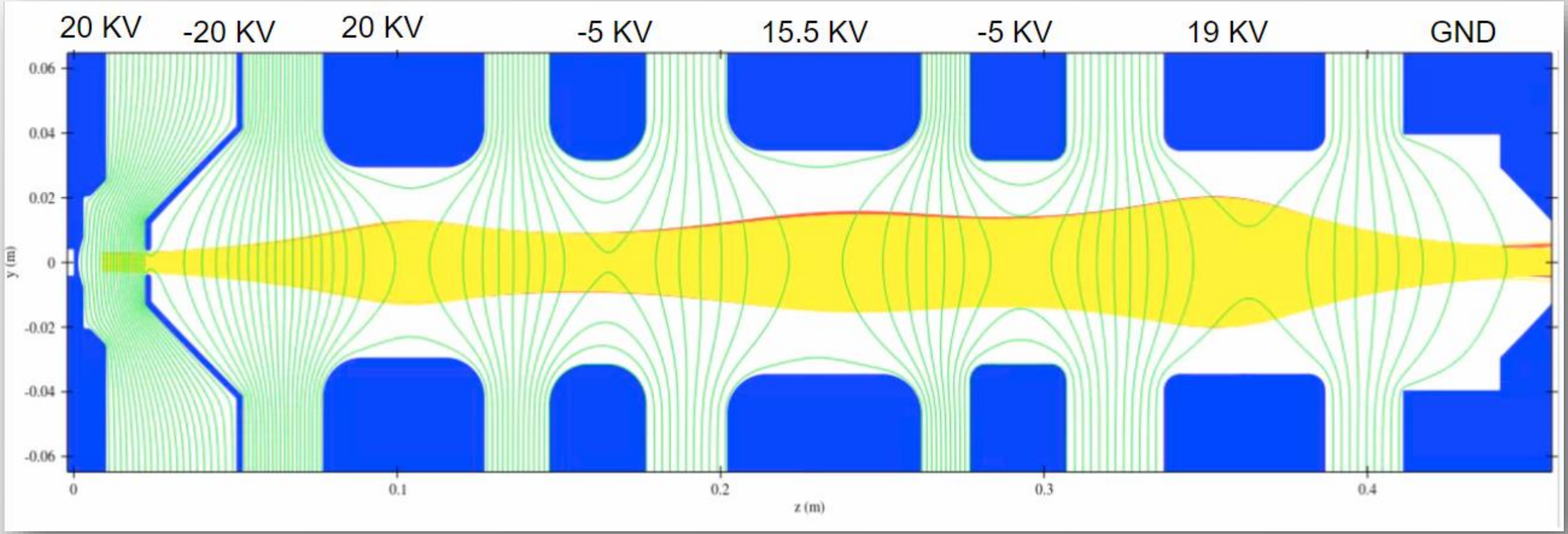
IsoDAR

MIST-1

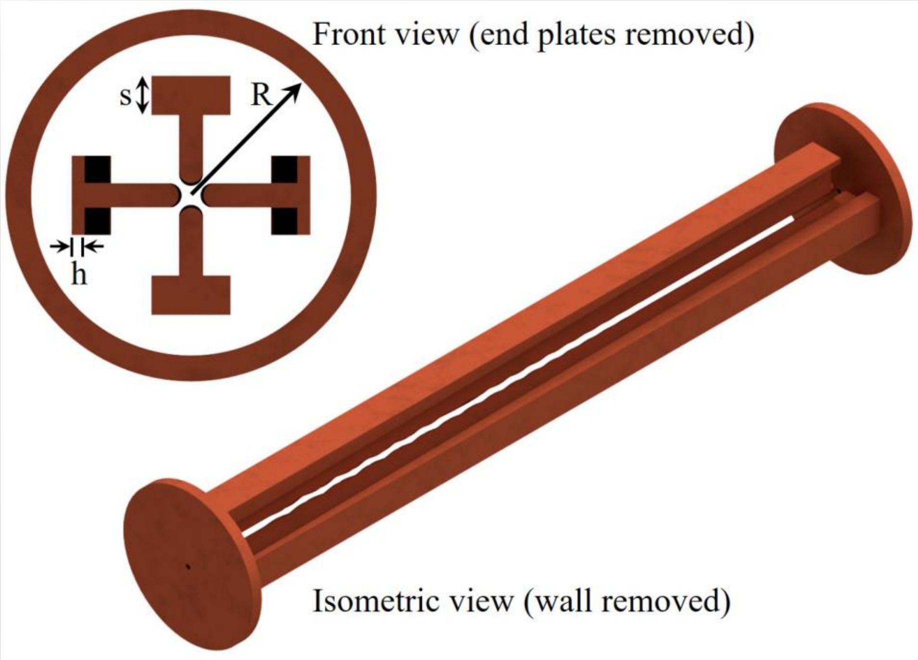


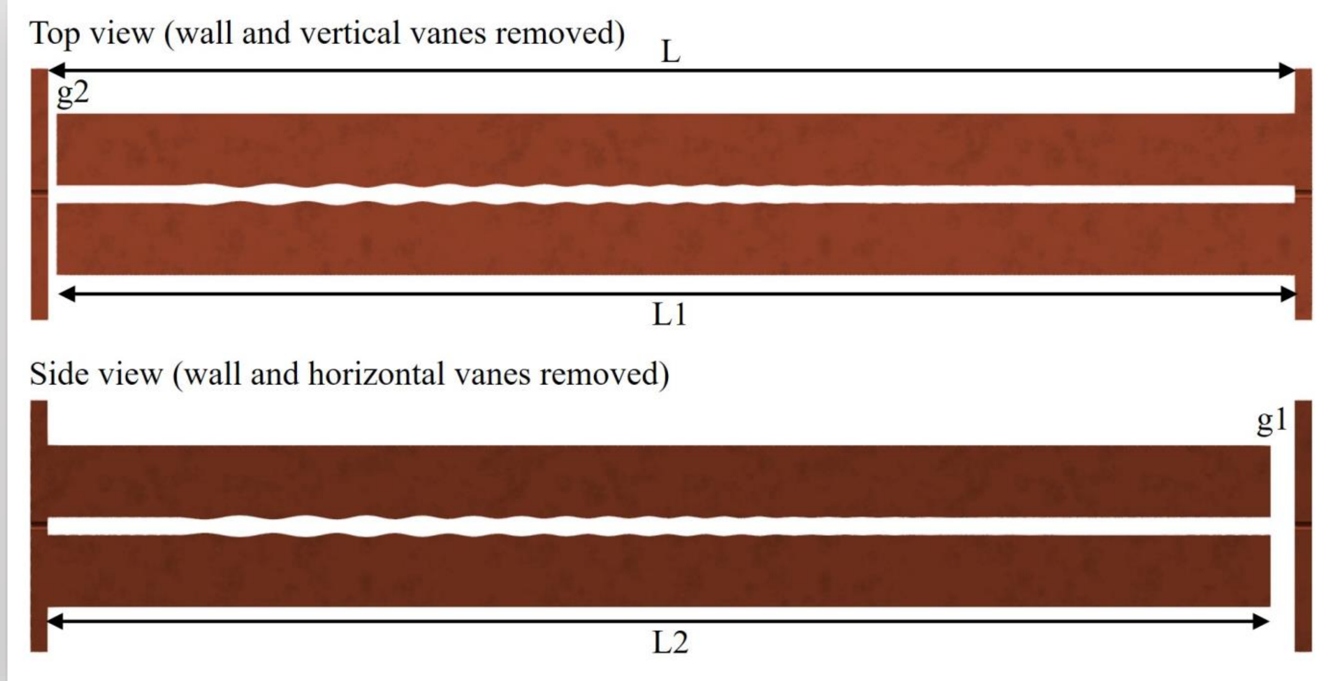
IsoDAR

Extraction system

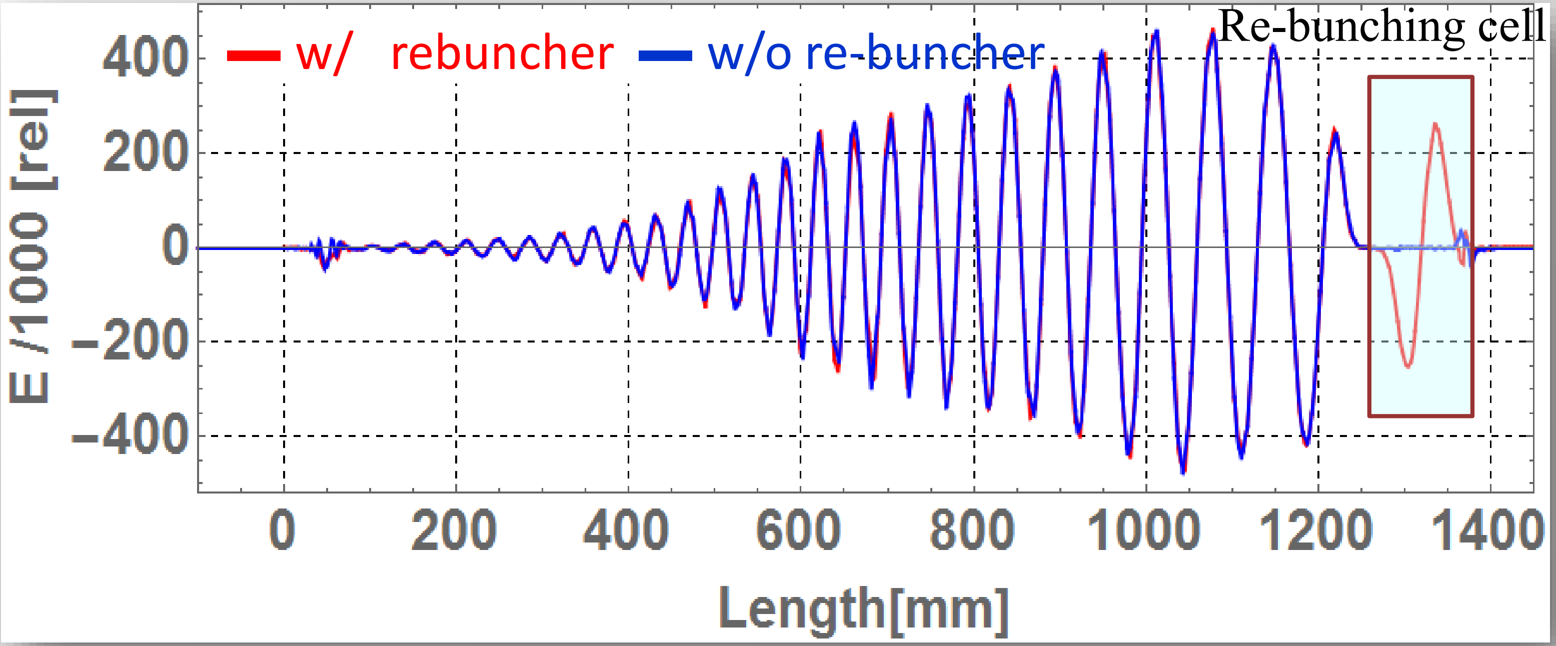


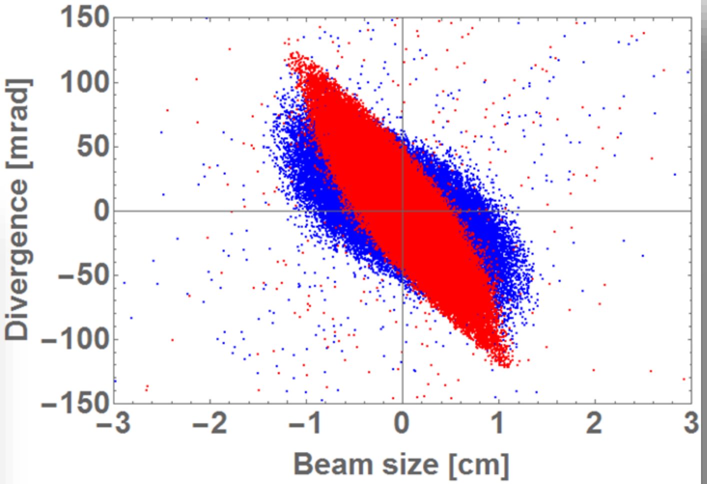
RFQ: 4-vane, split-coaxial design

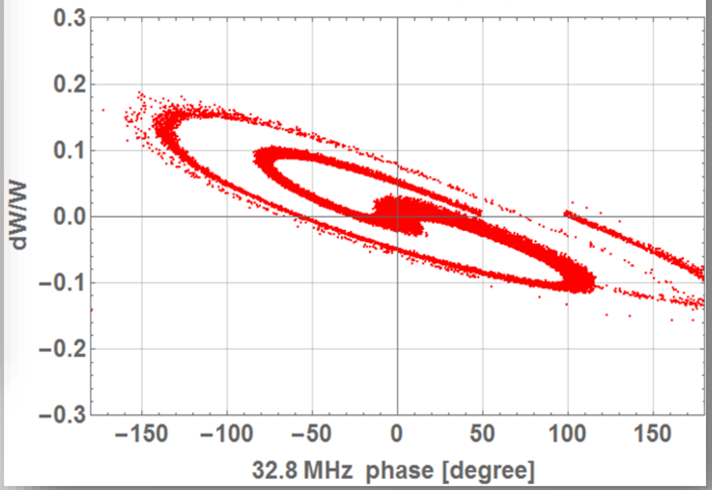




RFQ Simulations

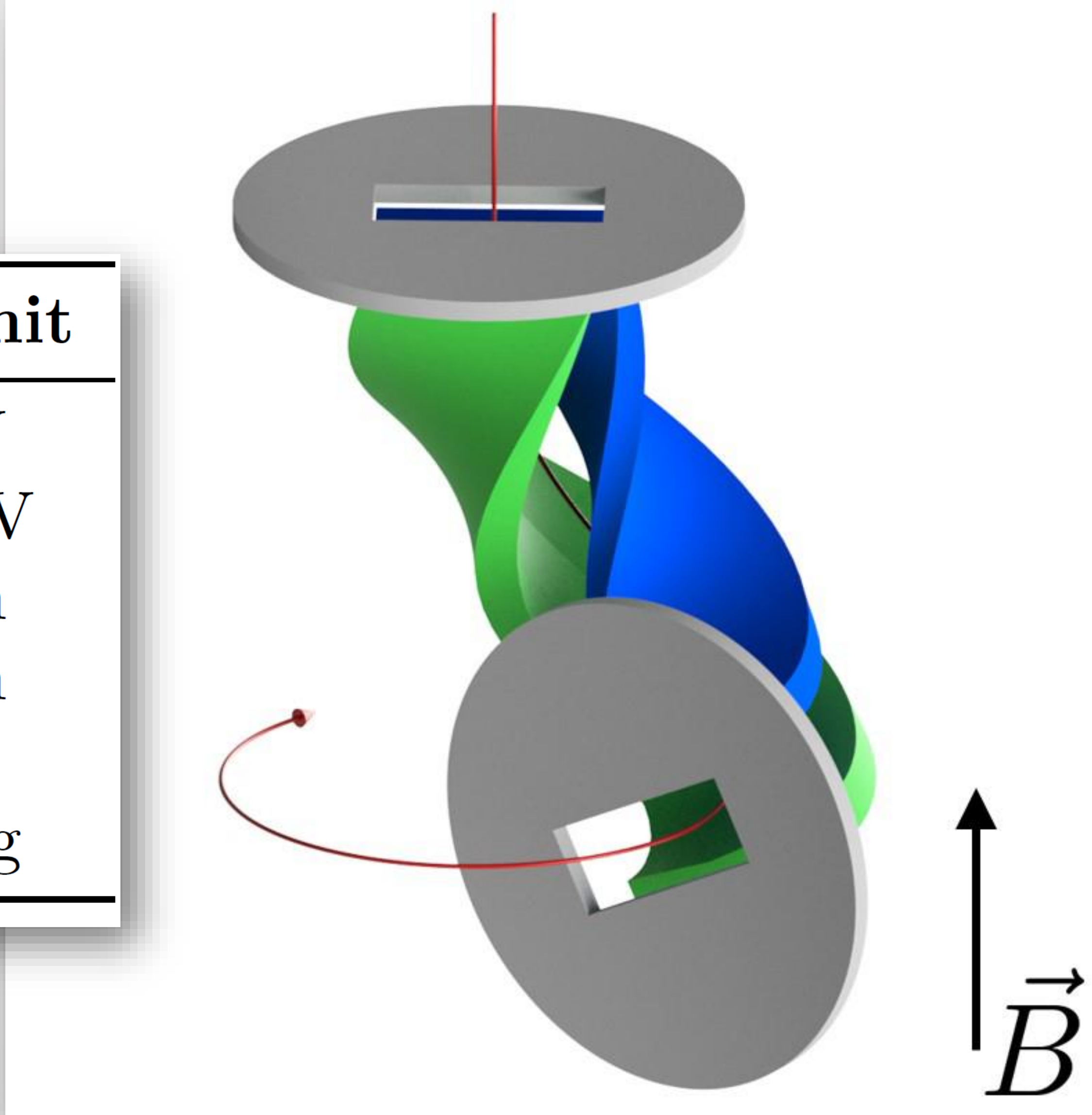


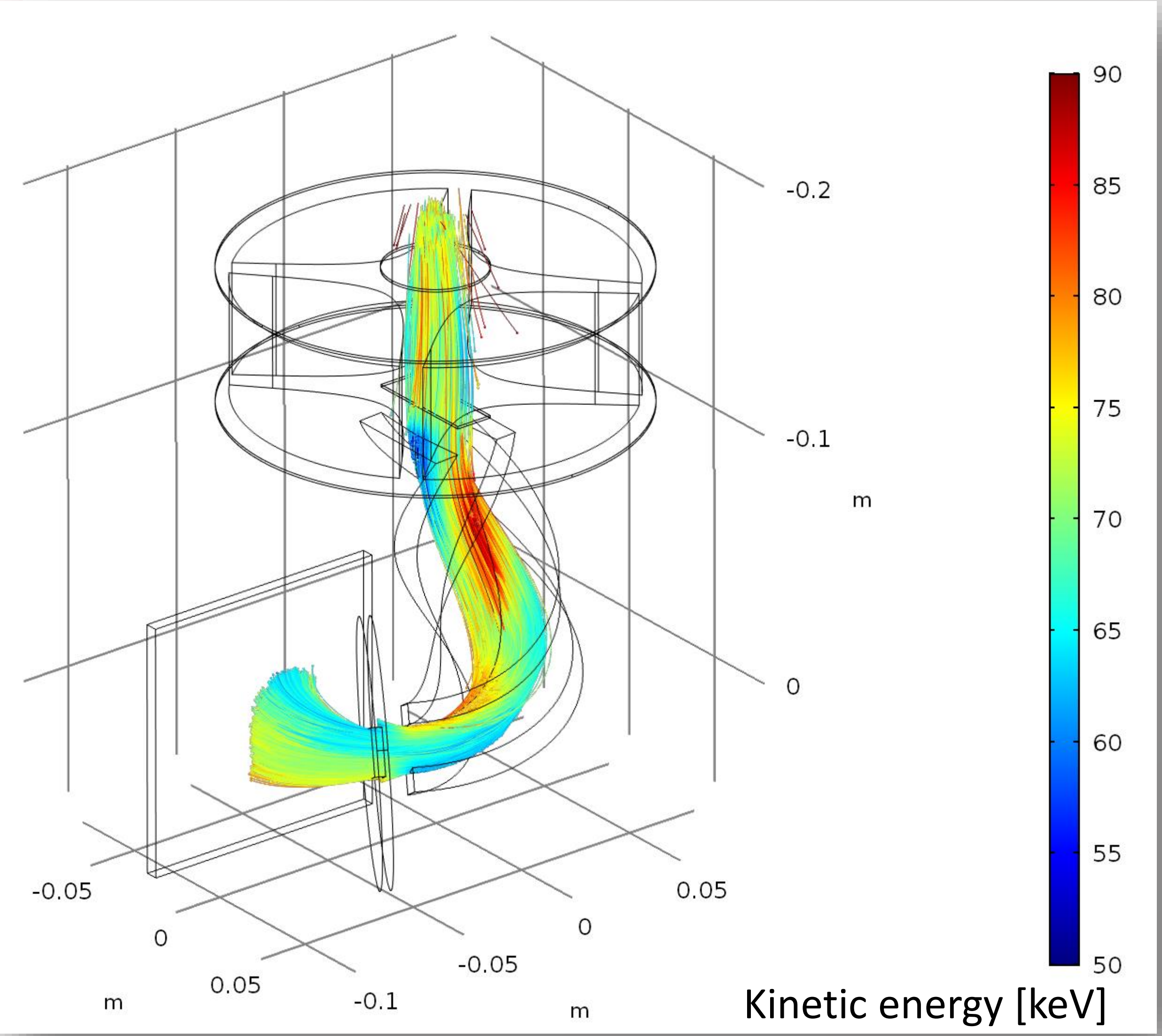




Spiral Inflector

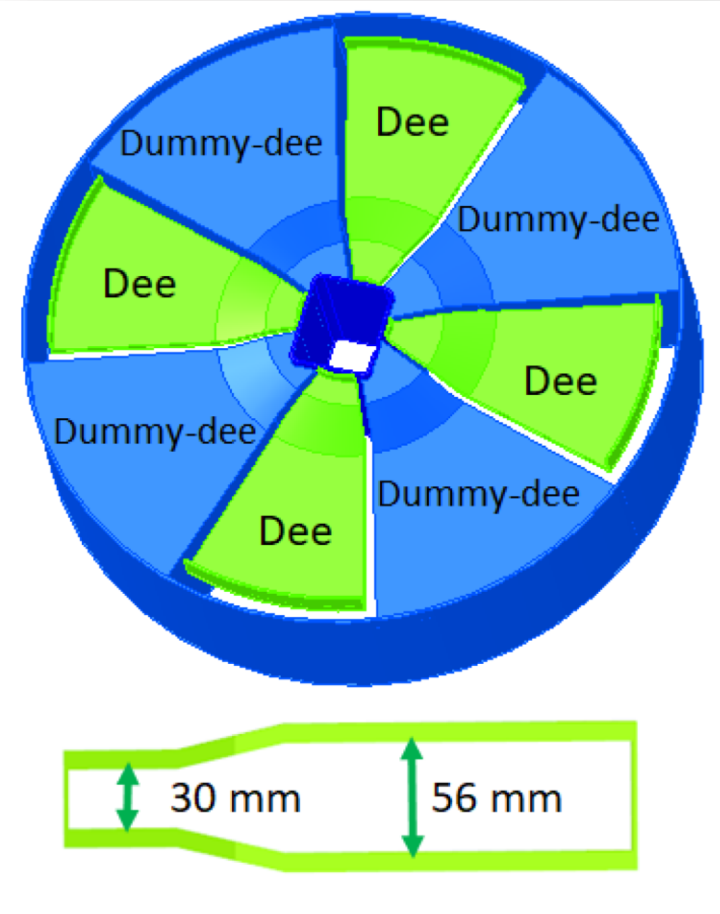
Parameter	Value	Unit
Electrode voltages	±12	kV
Input energy	70	keV
Electrode width	1.0	cm
Gap distance	1.8	cm
Aspect ratio	2.5	
Tilt angle	27	deg



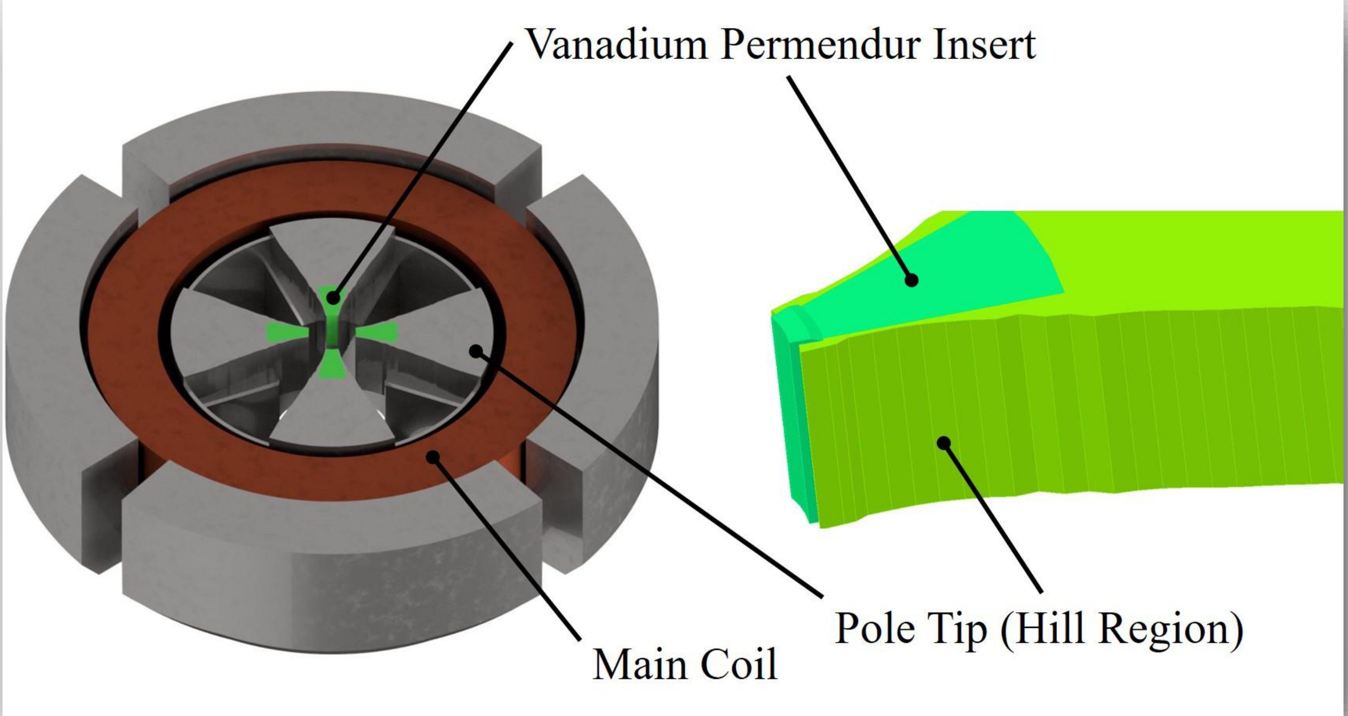


Spiral inflector simulation

Central region

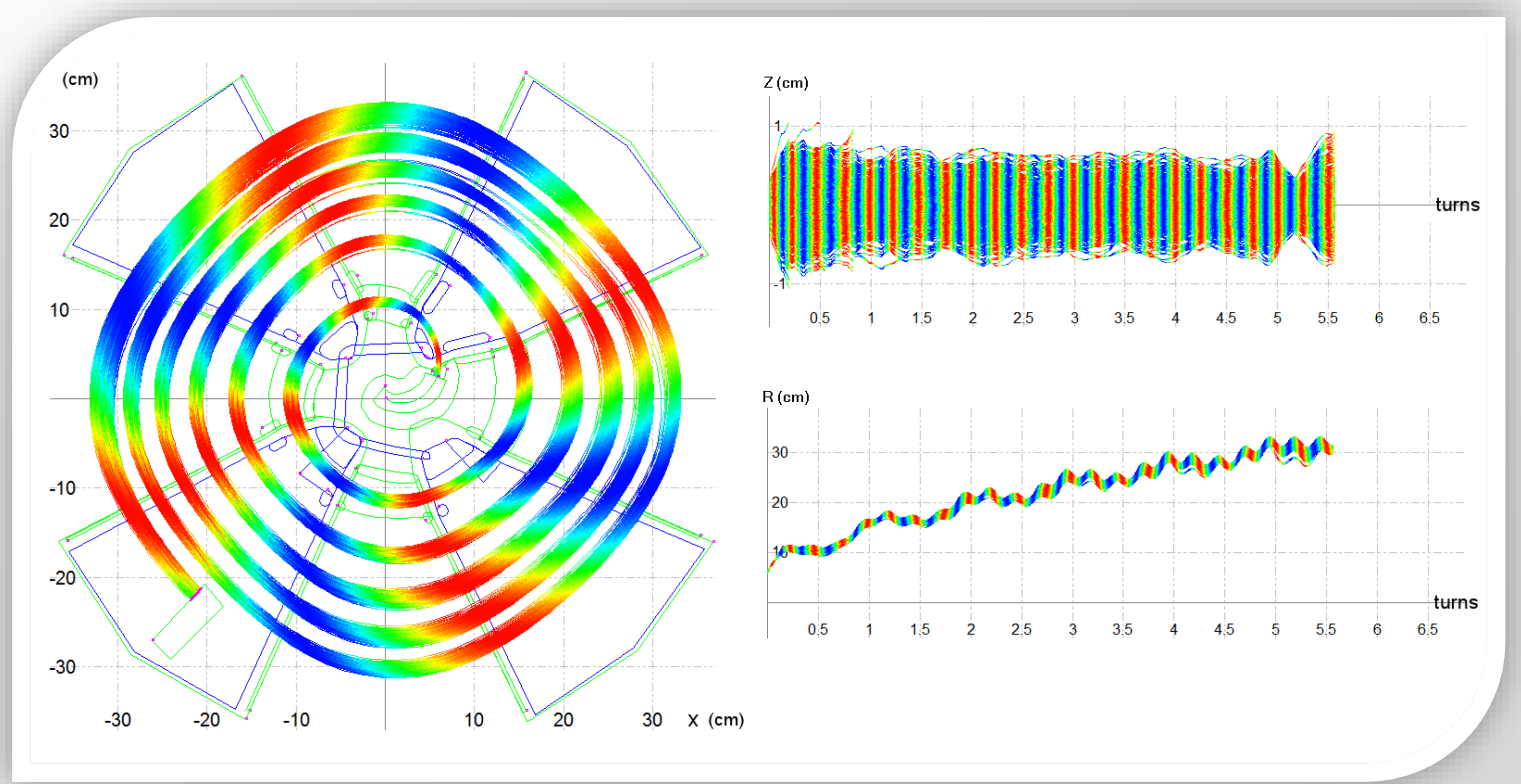


INFN-Catania



- Collimators to scape halo particles
- VP inserts for vertical focusing

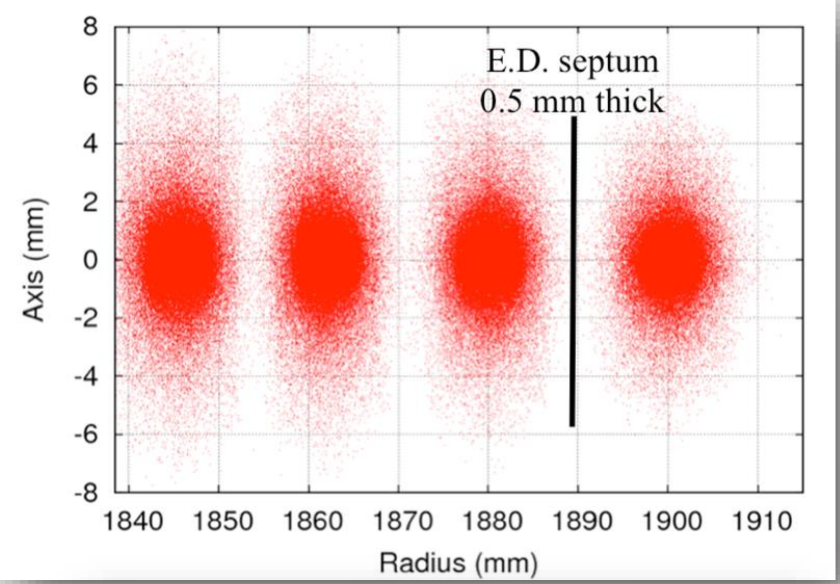
Central region

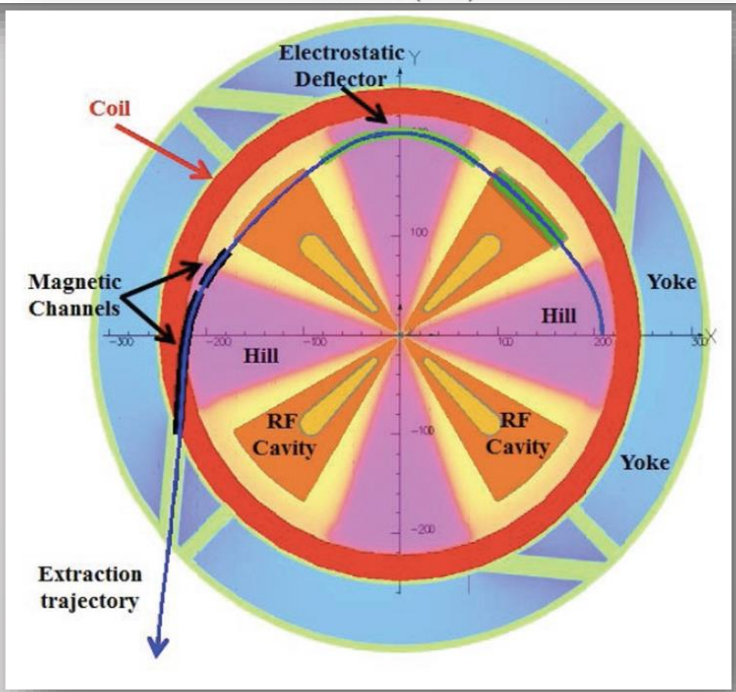


- Preliminary study by AIMA Developpement
- RFQ-DIP: 1 MeV cyclotron

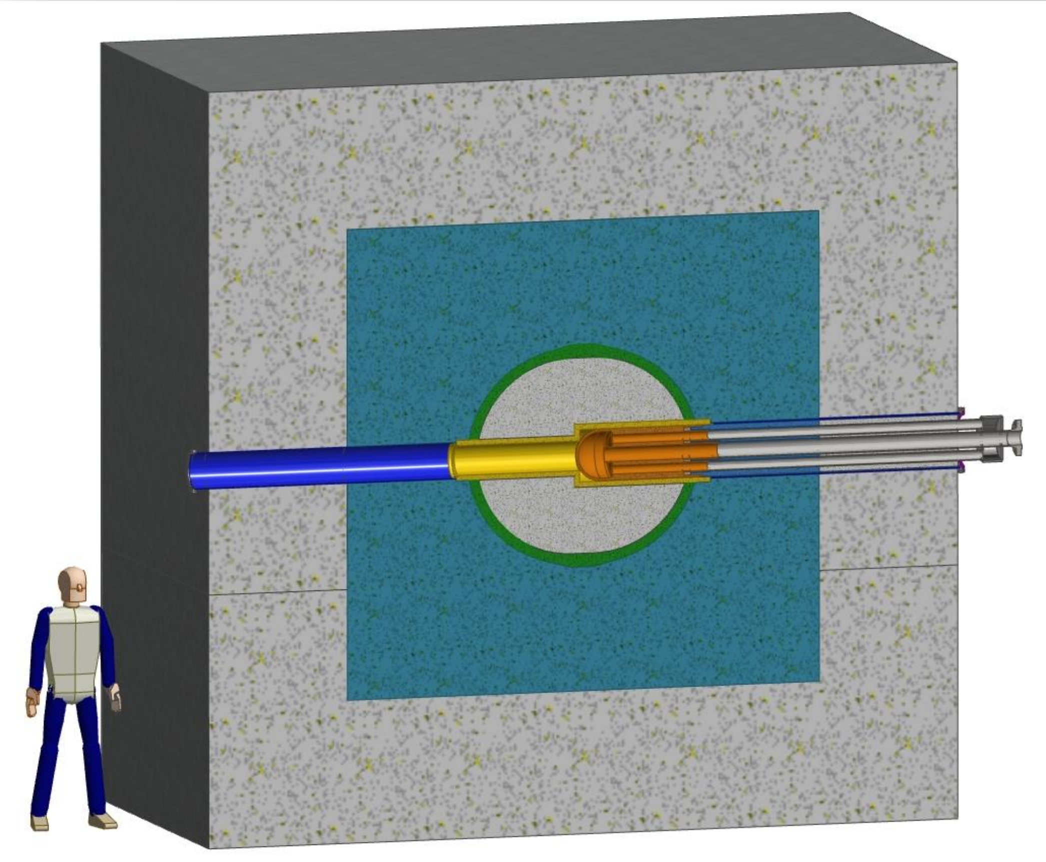
Cyclotron extraction

- Septum at last turn for H_2^+ extraction
- Use stripper foil to minimizes septum activation
- Second foil to transport protons in MEBT





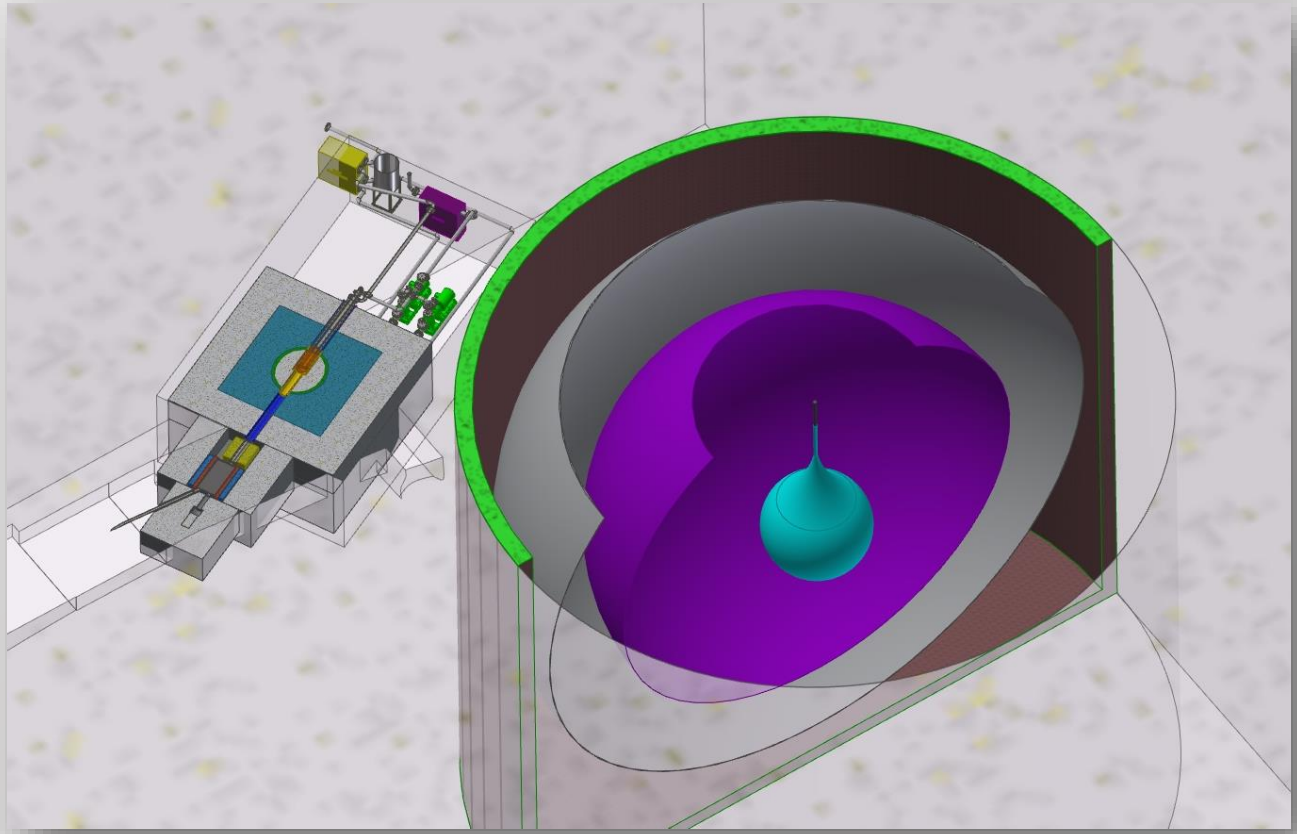
IsoDAR $\bar{\nu}_e$ production



- Protons impinge on ^{9}Be target producing neutrons
- Surrounding ^{7}Li sleeve captures neutrons producing ^{8}Li
- ^{8}Li β^{-}decays yielding a localized, isotropic $\bar{\nu}_e$ source with known energy distribution

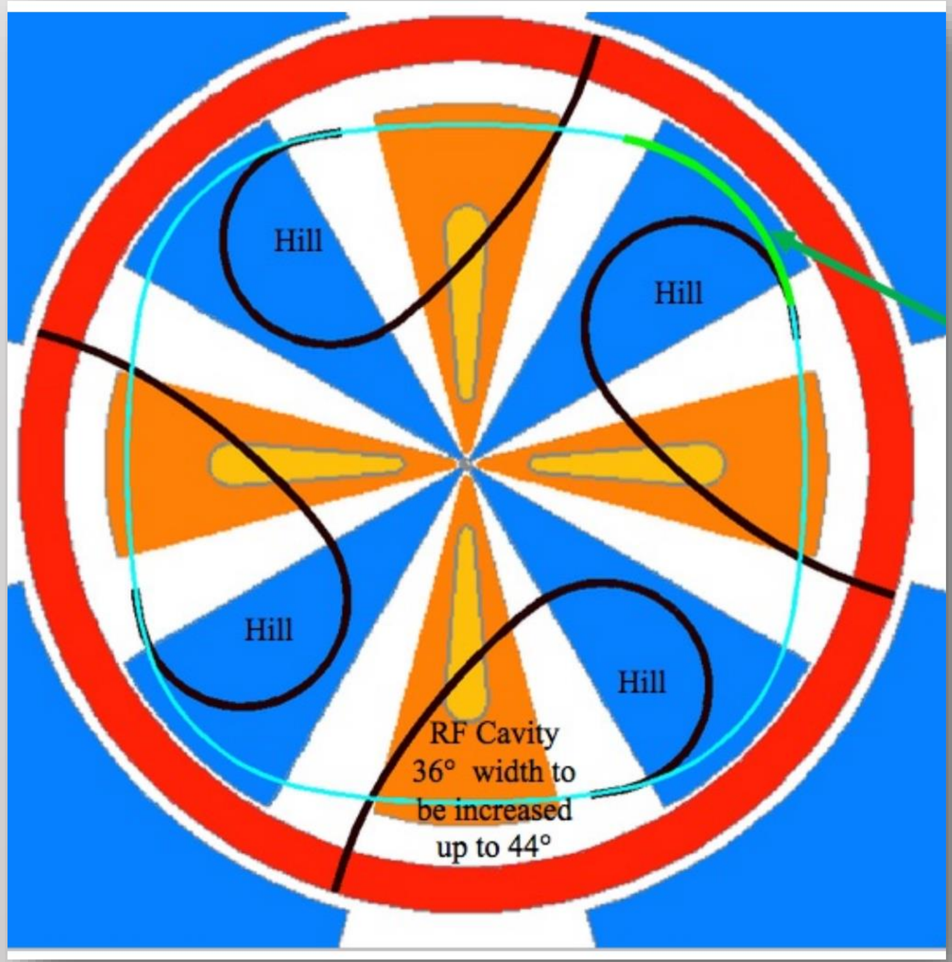
Concurrent research for IsoDAR

- Target designed for high power beam
- Injection of Li-Be mixture into sleeve pressure vessel
- Graphite, steel, concrete for neutron shielding



Isotope production

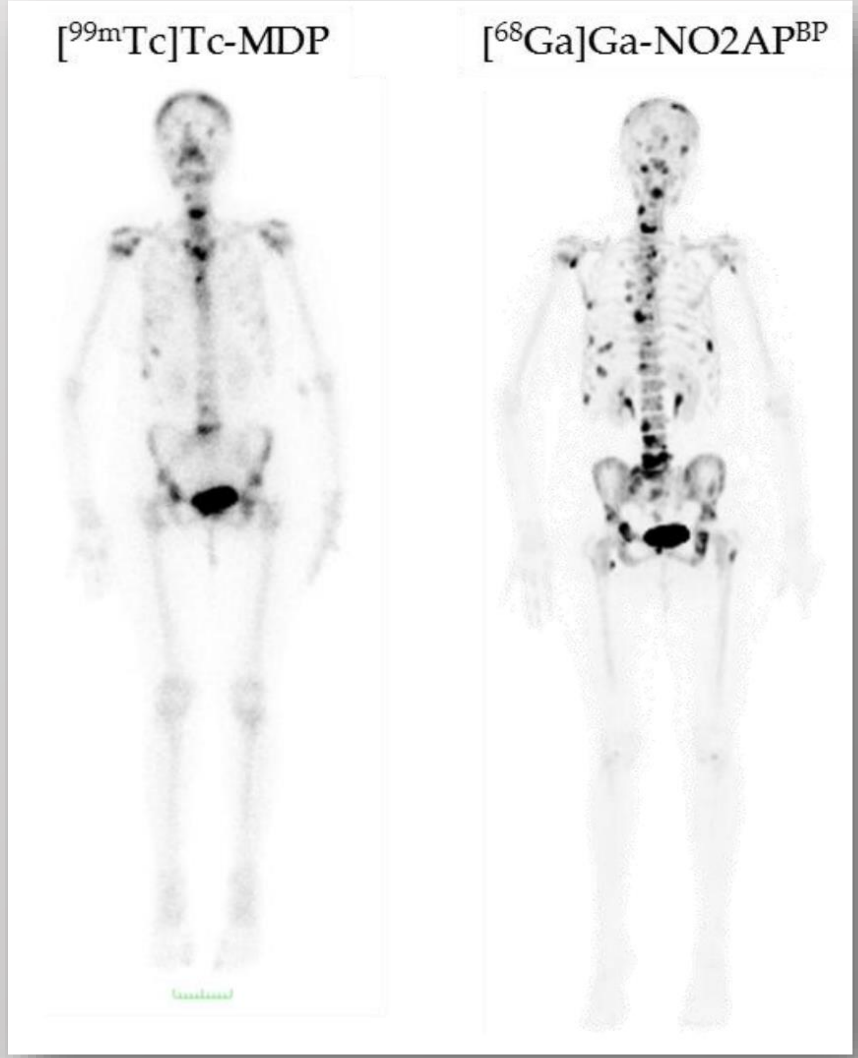
- ~50 μA of protons extracted to protect septum
- Up to 4 stripping locations possible
- Protons can be used to produce medical isotopes
- Or also build machine dedicated to isotope production



Imaging: ^{68}Ge/ ^{68}Ga

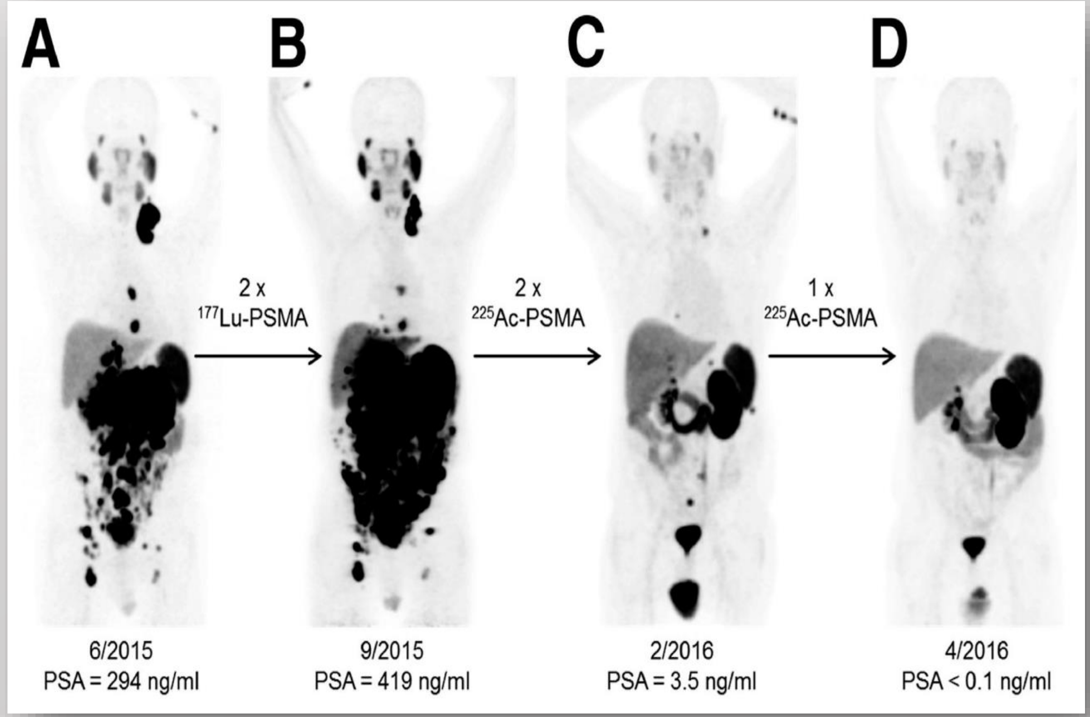
- $^{69}Ga/^{71}Ga + p \rightarrow {}^{68}Ge \rightarrow {}^{68}Ga$
- Similar uses as $^{99}Mo \rightarrow {}^{99m}Tc$
- Longer parent half-life:
  270 days vs. 66 hours
- Shorter emitter half-life:
  68 minutes vs. 6 hours
- $1000 / mCi of ^{68}Ga
- IsoDAR → 50 Ci / week

Image from: Semantic Scholar



Therapy: ^{225}Ac

- $p + {}^{229}Th \rightarrow {}^{225}Ac \rightarrow 4\alpha + {}^{209}Bi$
- Current targets ^{226}Ra from purified reactor waste
- BLIP, LANCE at 100 μA → 60x world supply
- \$1300 / mCi
- IsoDAR at 10 mA → 200 mCi / hr



Medical isotopes with IsoDAR: https://arxiv.org/abs/1807.06627

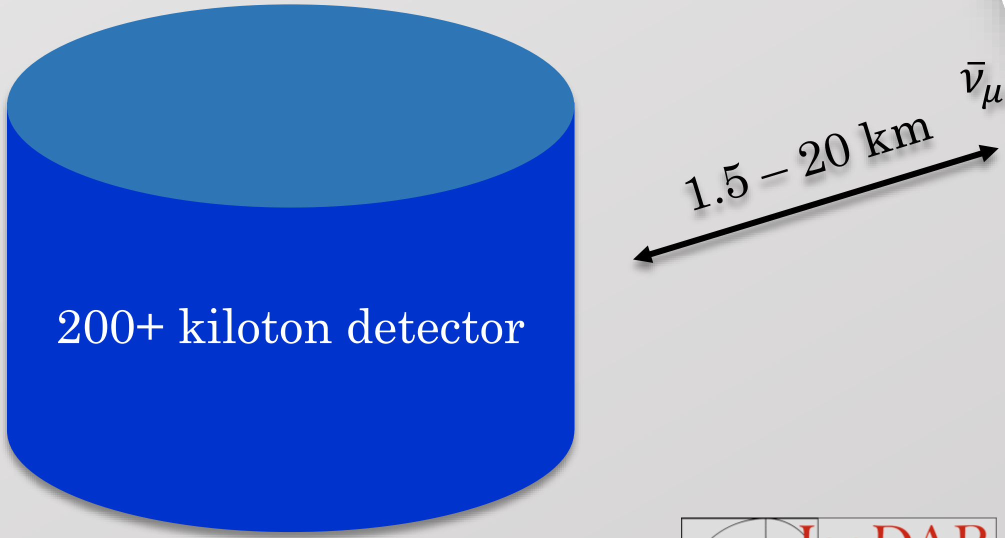
Image from: Semantic Scholar

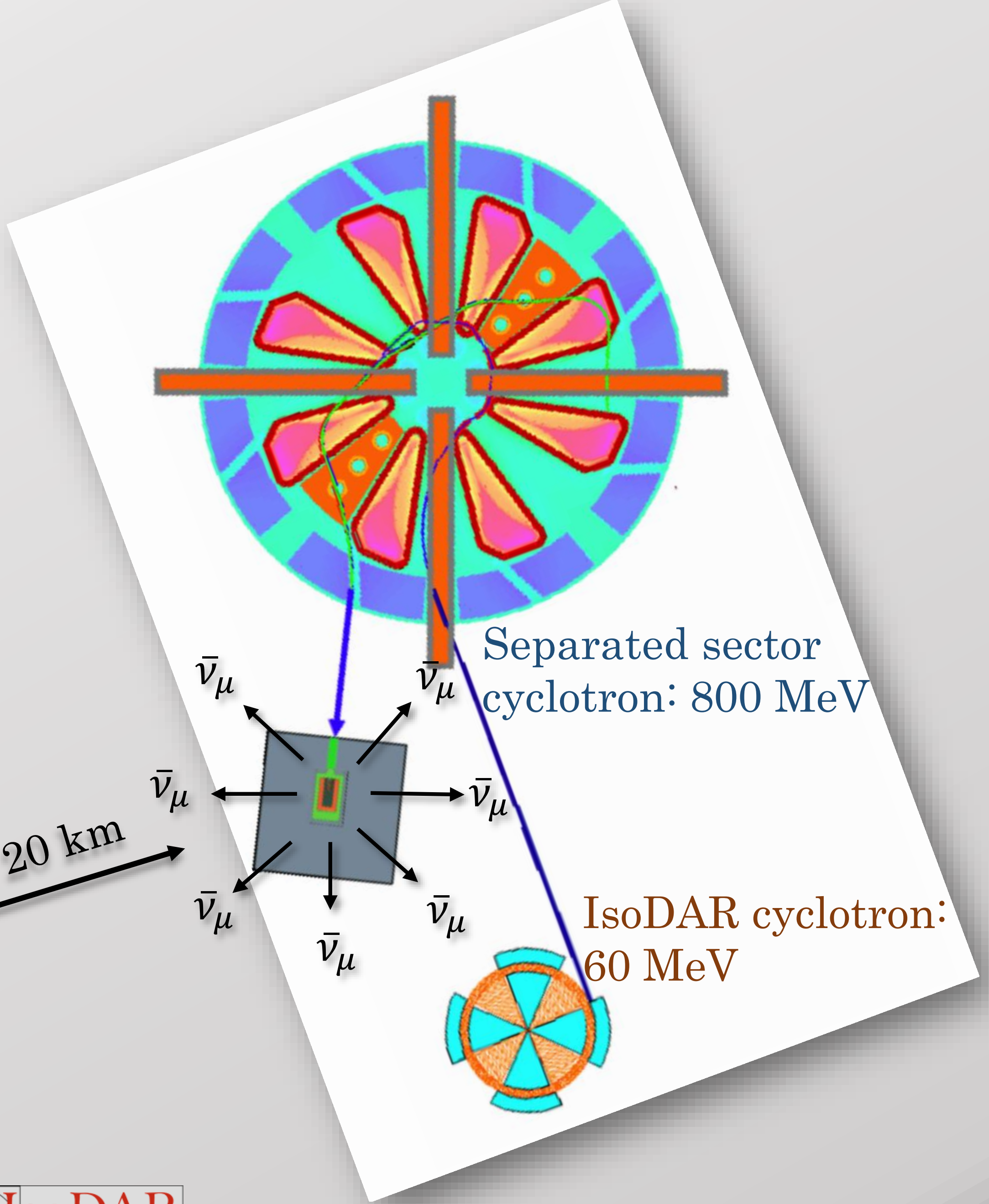
Nature Reviews Physics: DOI : 10.1038/s42254-019-0095-6NATREVPHYS-19-343V1

IsoDAR

DAEδALUS

- IsoDAR as injector for 800 MeV cyclotron
- Decay-at-rest pions as neutrino source
- Make three of these setups

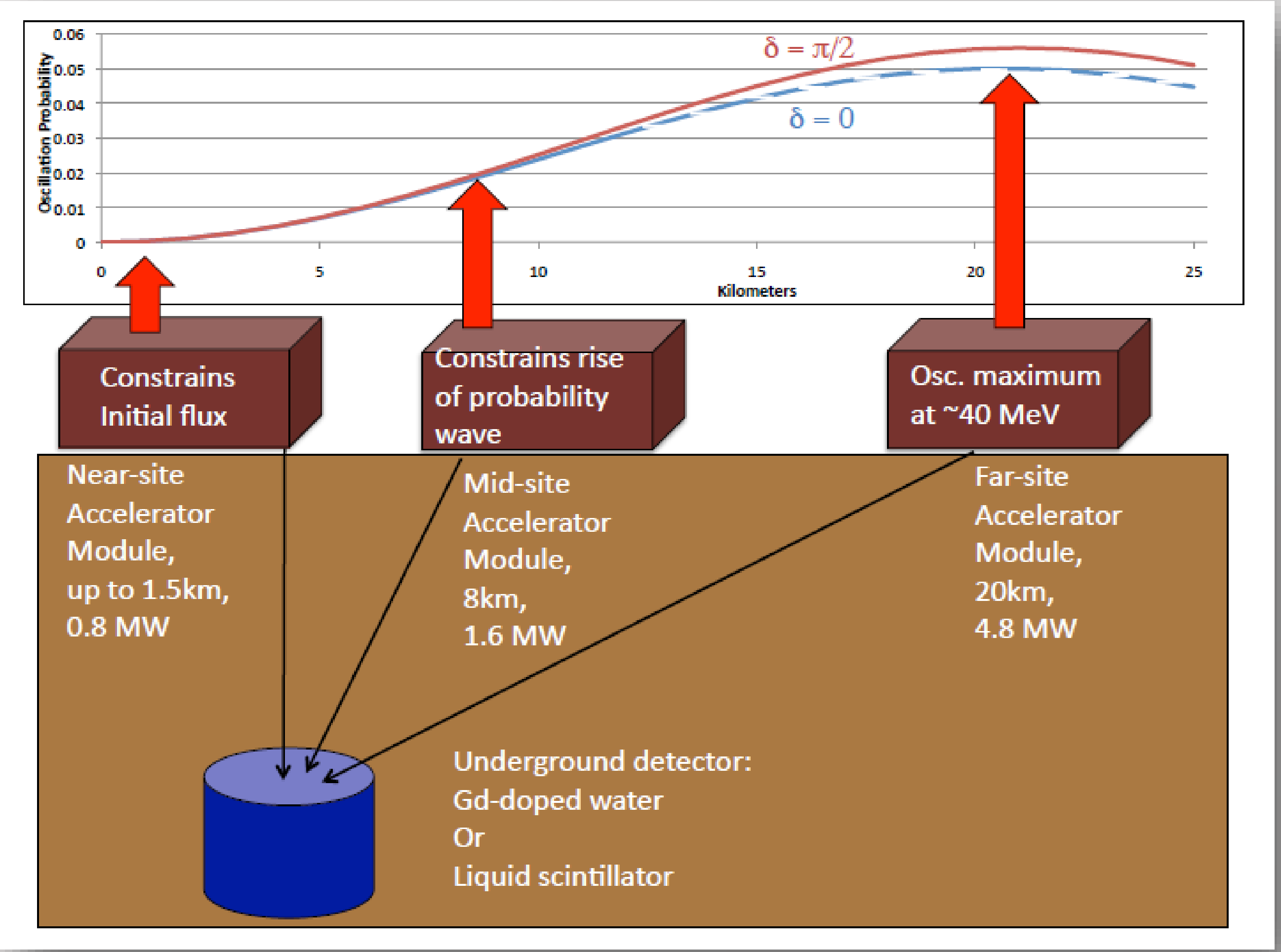




IsoDAR

δ_{CP} measurement

- π^+ decay-at-rest produces: $\bar{\nu}_\mu, \nu_\mu$
- Sensitive to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation wave
- 3 accelerators at different distances



Summary

- IsoDAR can definitively answer the ν_s question with 5 years of runtime at KamLAND
- RFQ-DIP is developing technology for 10 mA, 60 MeV cyclotrons
- Target, sleeve, and shielding research is well underway
- IsoDAR cyclotrons have other potential uses such as *DAEδALUS* and medical isotope production

Resources

- IsoDAR: https://www.nevis.columbia.edu/daedalus/docs/publications.html
- Oscillation Experiments: arXiv:1609.07803v2 [hep-ex] 2 Aug 2017
- Sterile Review: arXiv:1906.00045v1 [hep-ex] 31 May 2019

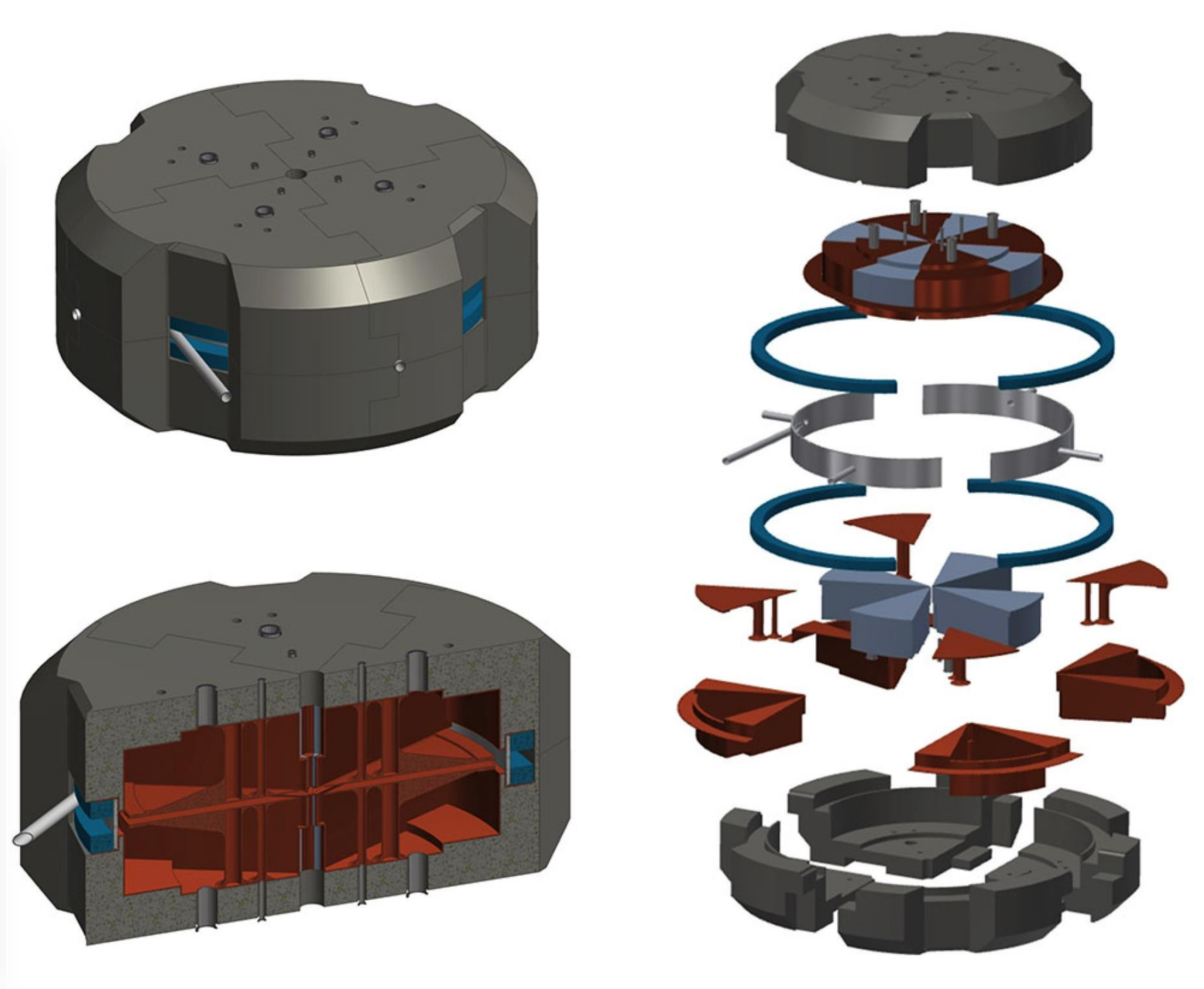
Acknowledgements

NSF GRFP NSF GRADUATE RESEARCH FELLOWSHIP PROGRAM

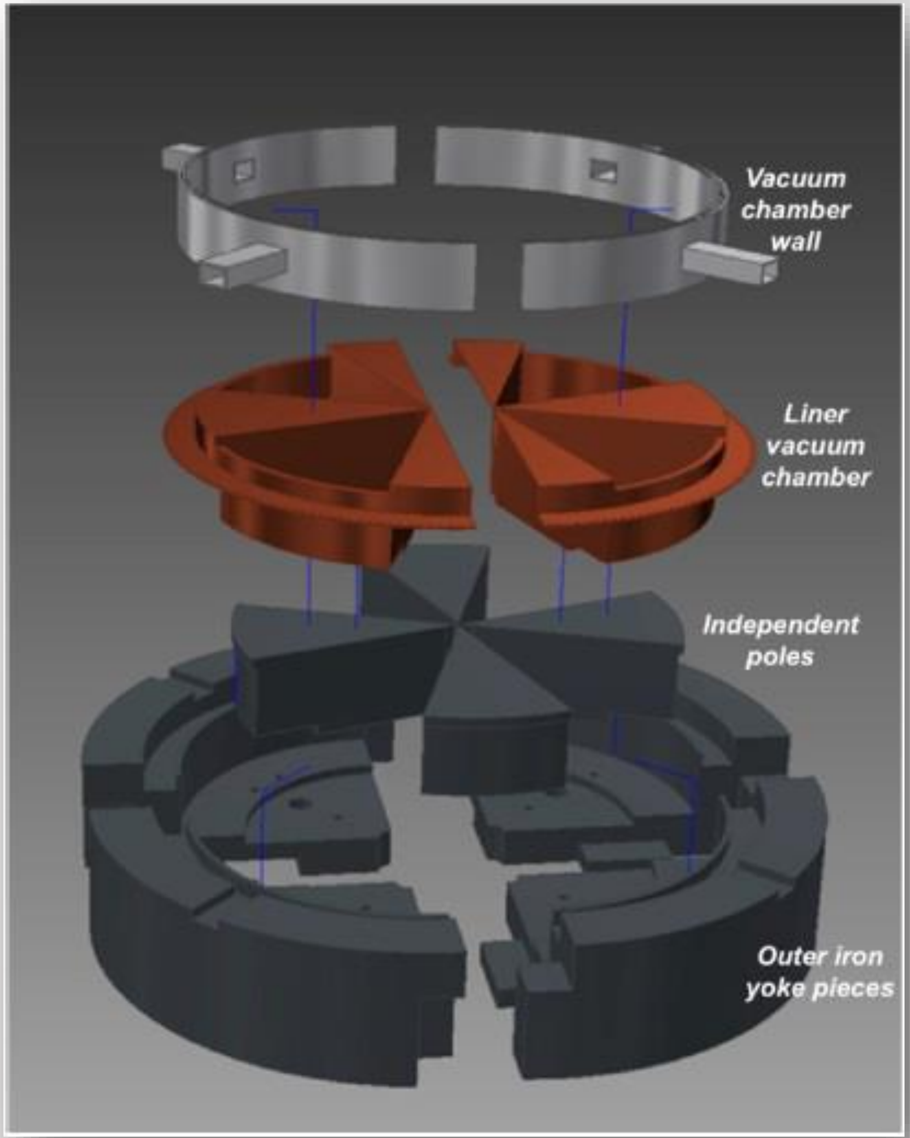
HEISING-SIMONS FOUNDATION

Cyclotron design

Parameter	Value
Ion accelerated	H_2^+
Max Energy	60 MeV/amu
Extraction radius	1.99 meters
Average magnetic field	1.16 tesla
Number of sectors	4
RF frequency	32.8 MHz
Accel. Voltage	70 – 240 kV
ΔE/turn	(ave) 1.7 MeV
Turns	95
Outer diameter	6.2 meters
Iron weight	450 tons



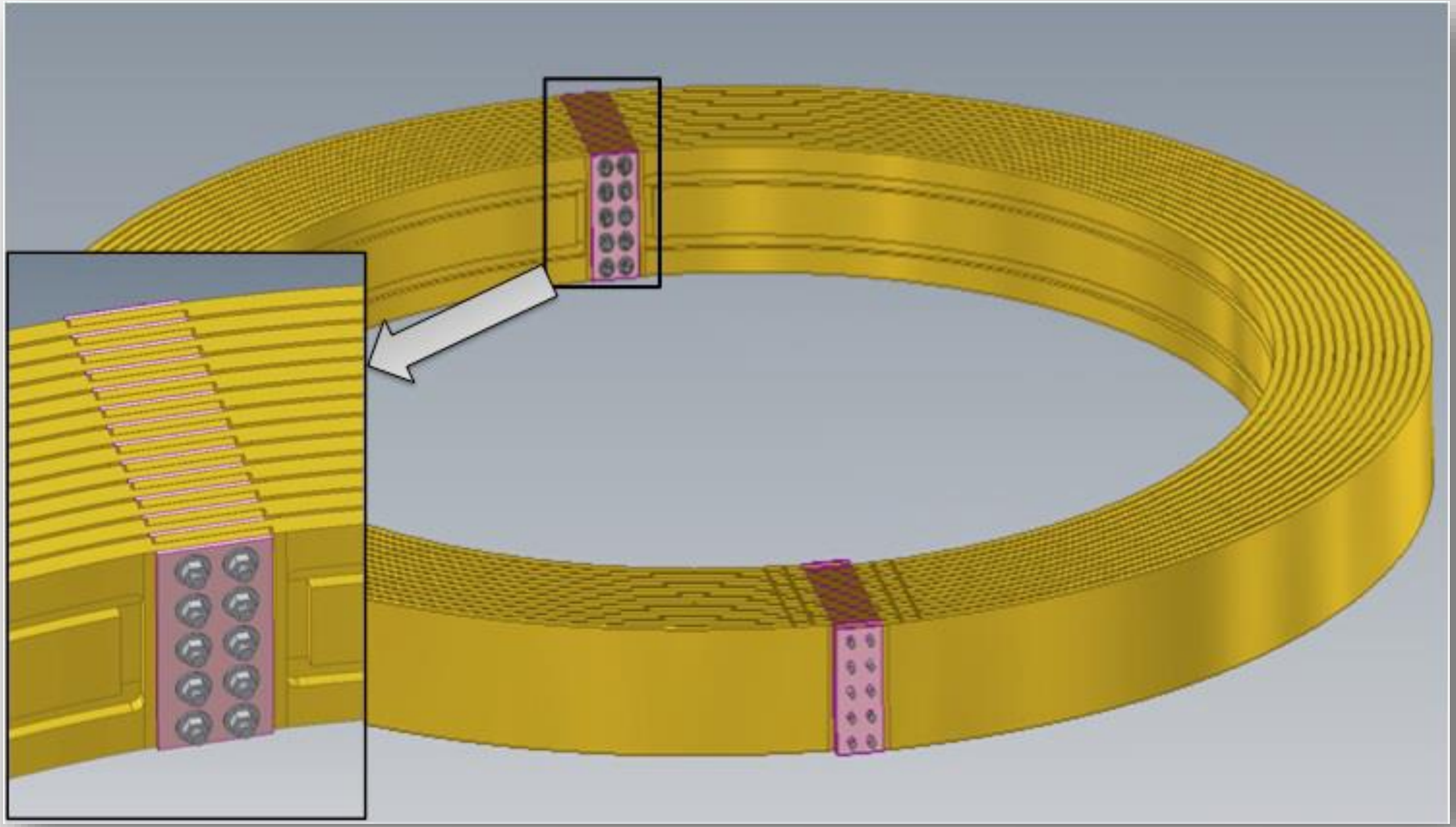
Technical CDR: https://arxiv.org/abs/1511.05130 Conventional CDR: https://arxiv.org/abs/1710.09325



Segmentation

- Designed for assembly within Kamioka mine
- Size limited by mining tunnels
- Weight restrictions due to transportation

Split-coil design



- Coils come in two pieces
- No winding in mine

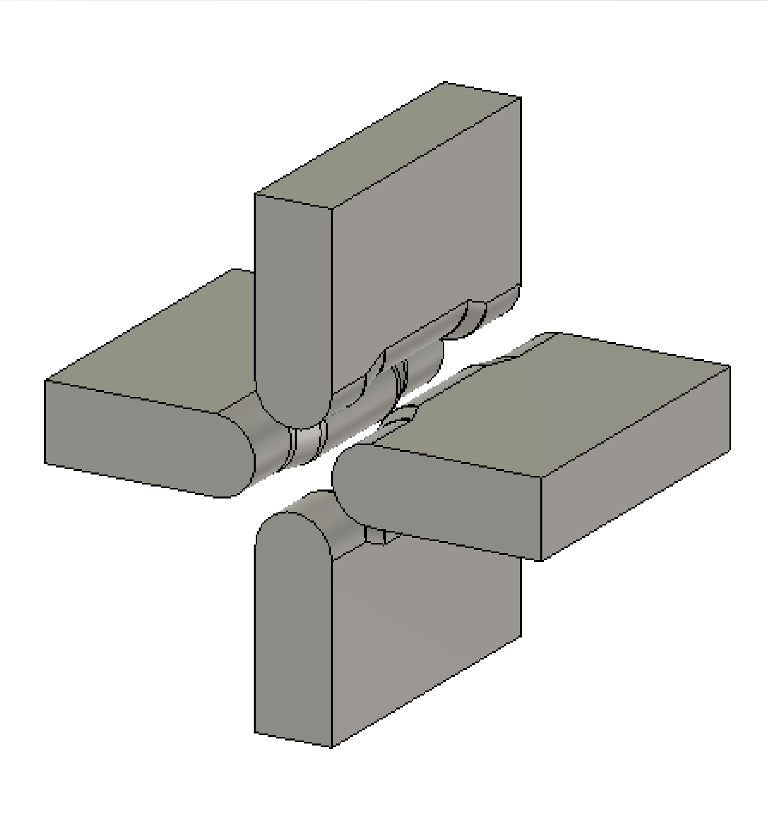
Table 2: MIST-1 ion source parameters.

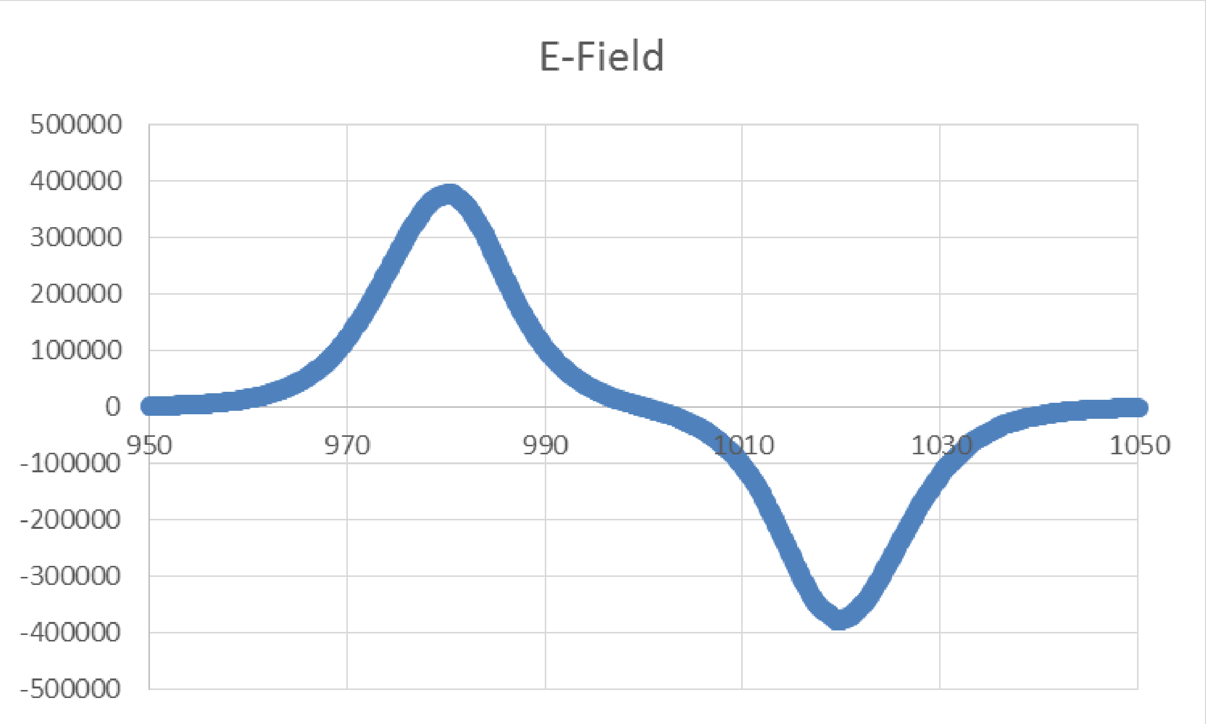
Parameter	Value (nominal)
Plasma chamber length	6.5 cm
Plasma chamber diameter	15 cm
Permanent magnet material	Sm_2Co_{17}
Permanent magnet strength	1.05 T on surface
Front plate magnets	12 bars (star shape)
Radial magnets	12 bars
Back plate magnets	4 bars, 3 parallel rows
Front plate cooling	embedded steel tube
Back plate cooling	embedded copper tube
Chamber cooling	water jacket
Water flow (both)	(1.5 l/min)
Filament feedthrough cooling	air cooled heat sink
Filament material	98% W, 2% Th
Filament diameter	$\approx$ 1.5 mm
Discharge voltage	max. 150 V
Discharge current	max. 24 A
Filament heating voltage	max. 8 V
Filament heating current	max. 100 A

Table 5: RFQ cavity geometrical parameters. Select parameters are also shown in Figure 8.

Parameter (description)	Value	Unit
R (cavity radius)	120.00	mm
r (electrode radius)	9.30	mm
d (electrode distance)	18.60	mm
g1 (gap vert. vane ↔ end plate)	25.62	mm
g2 (gap horz. vane ↔ end plate)	8.35	mm
p (vane skirt position)	60.0	mm
l1 (horizontal vane length)	1353.07	mm
l2 (vertical vane length)	1370.34	mm
L (cavity length)	1378.69	mm
t (cavity thickness)	20.0	mm
s (vane skirt max. thickness)	30.0	mm
h (vane skirt min. thickness)	10.0	mm

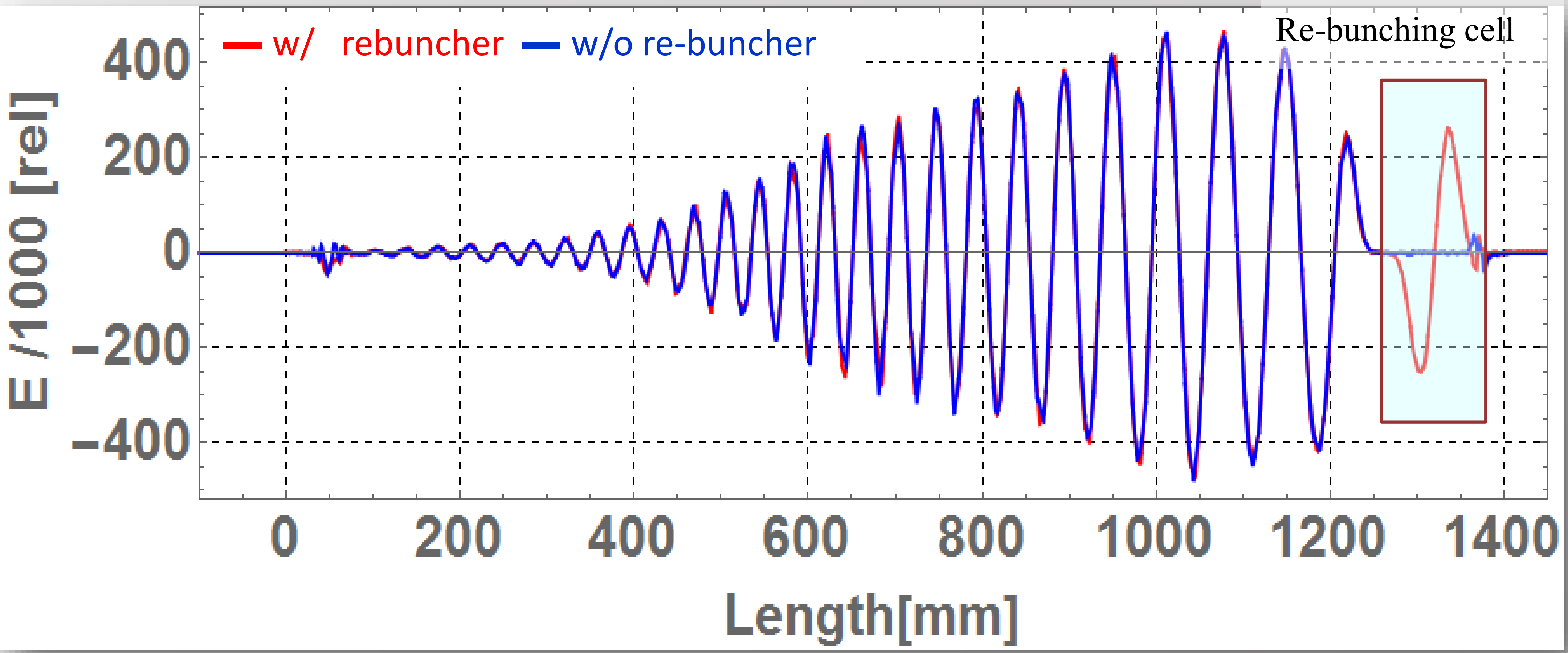
Rebunching cell



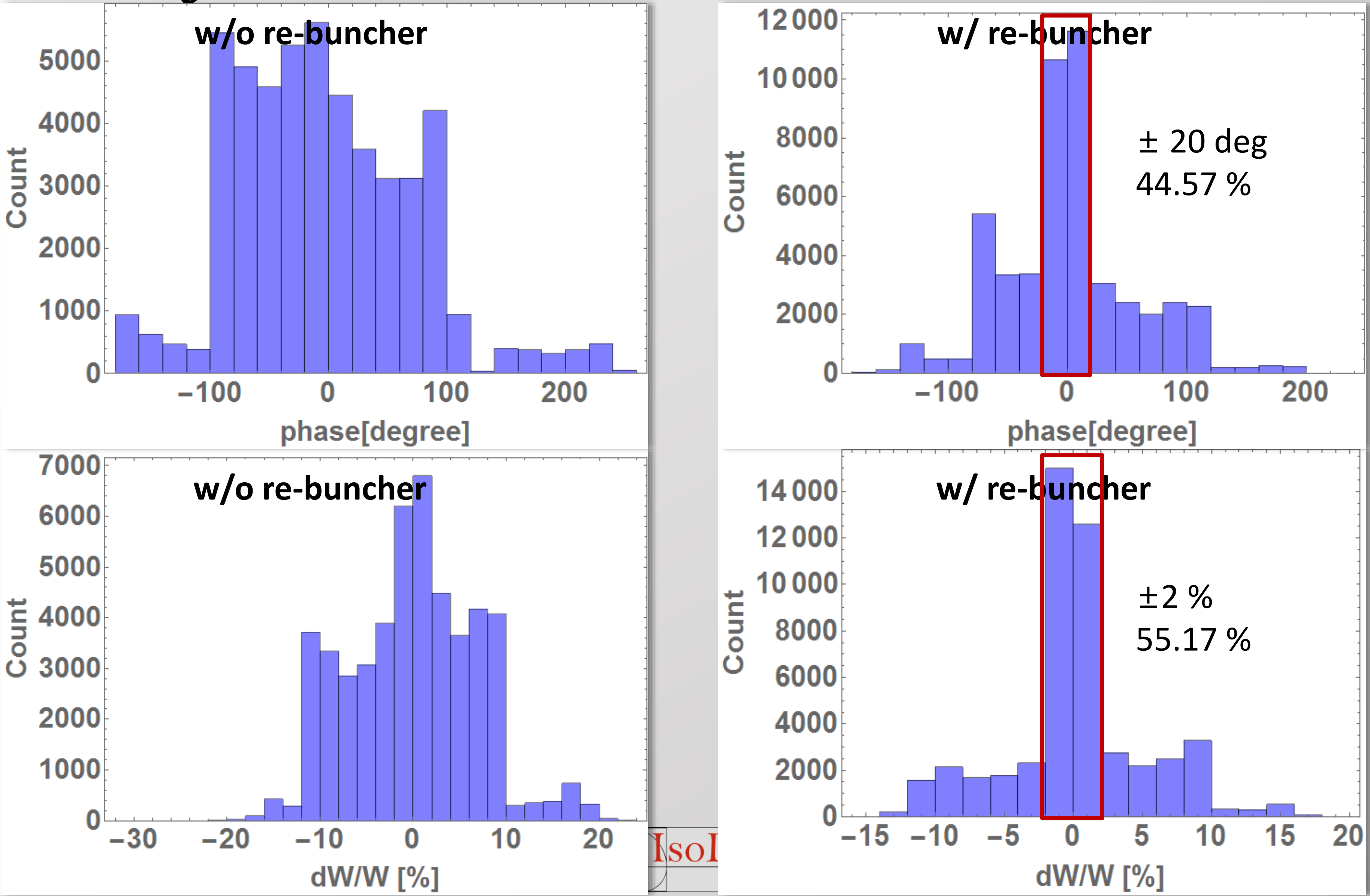


- Longitudinal focusing at end of RFQ
- Adjustable parameter in design

RFQ longitudinal E-field

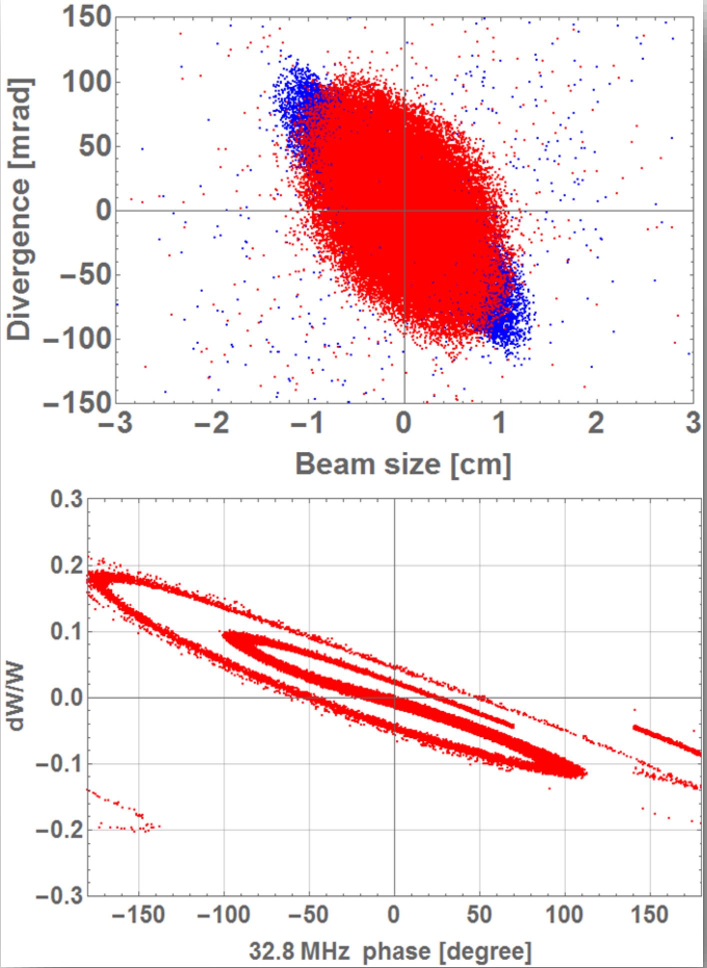


Beam dynamics with re-buncher

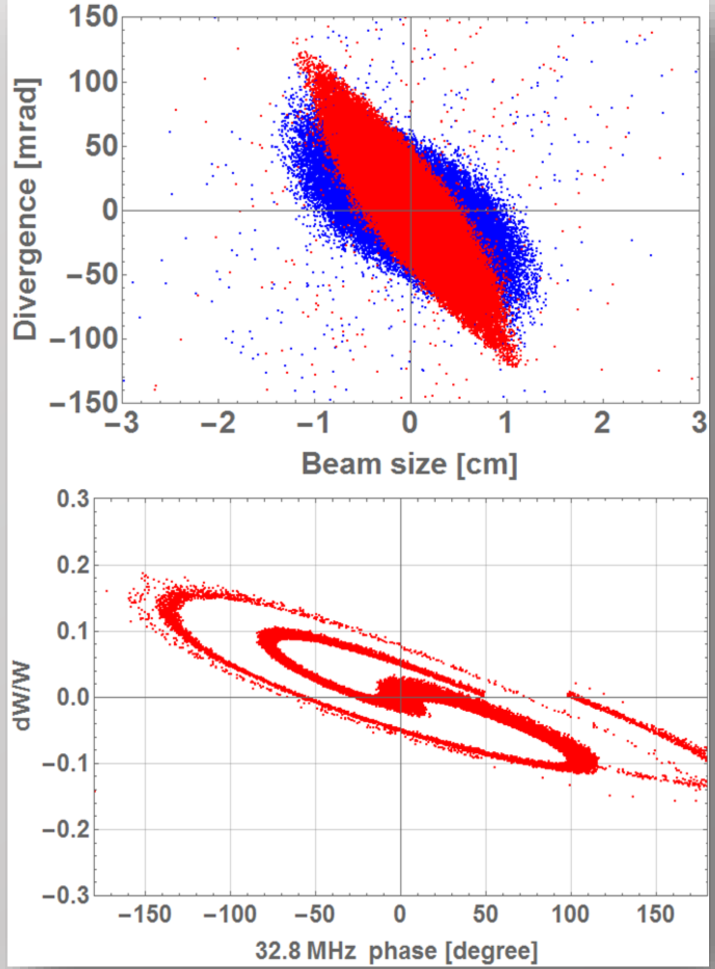


Rebunching cell effects

Without rebunching



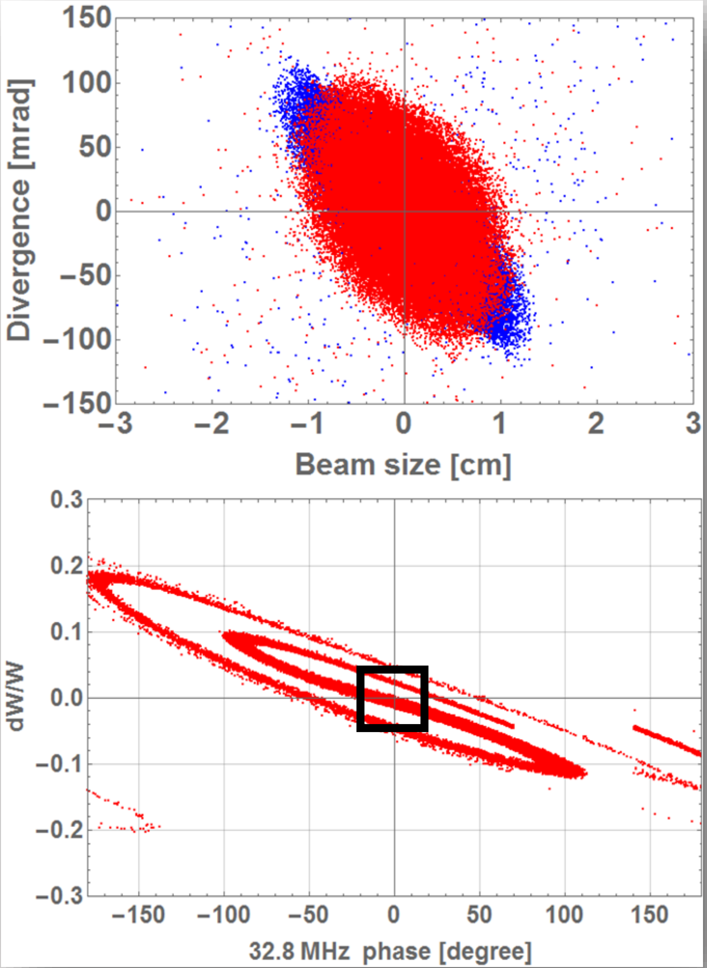
With rebunching



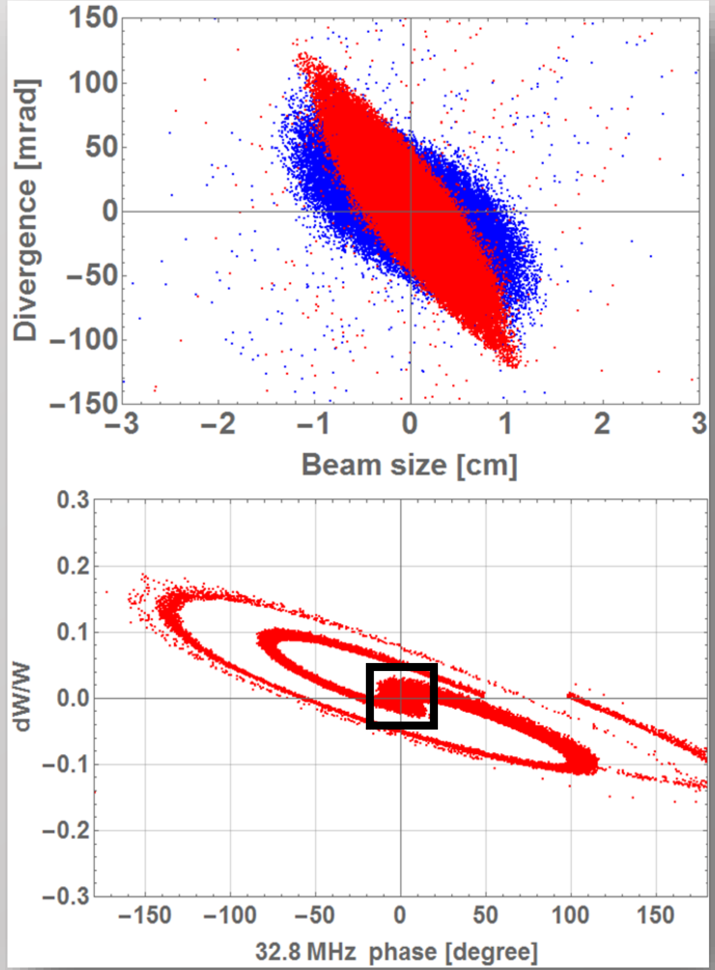
IsoDAR

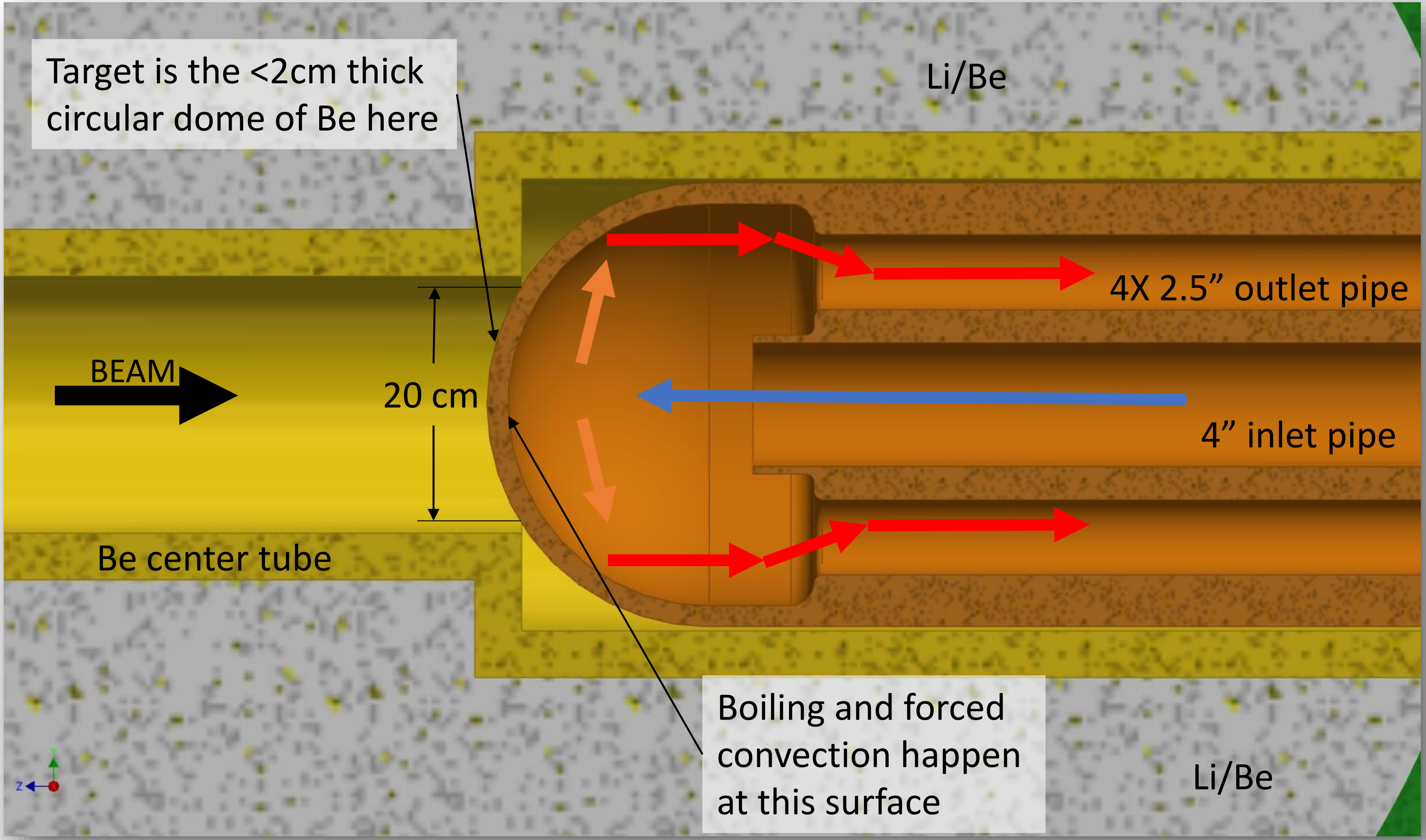
Rebunching cell effects

Without rebunching

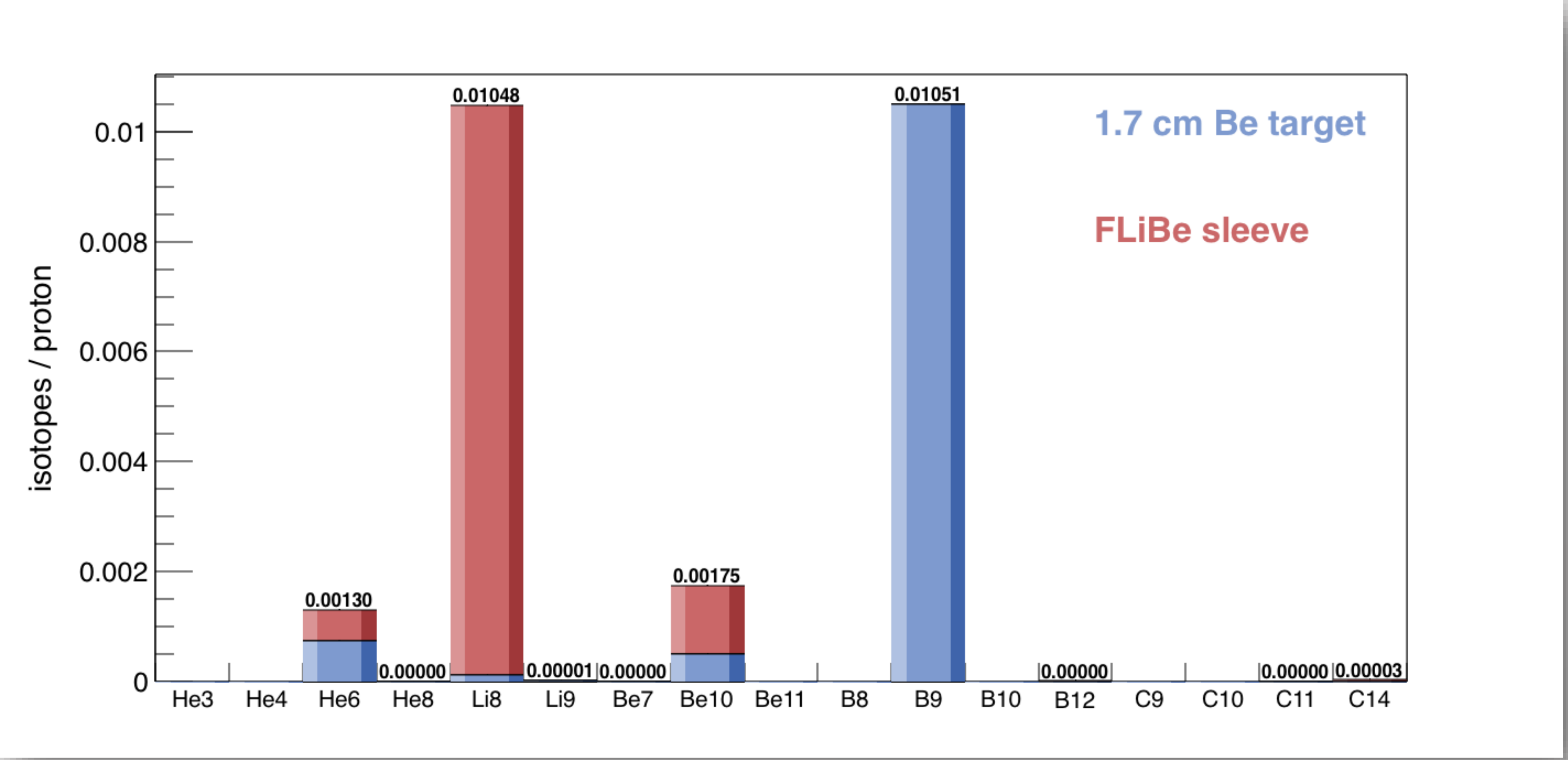


With rebunching




Target is the <2cm thick
circular dome of Be here
Li/Be
4X 2.5” outlet pipe
BEAM
20 cm
4” inlet pipe
Be center tube
Boiling and forced
convection happen
at this surface
Li/Be

Production in target and sleeve



$\bar{\nu}$ production

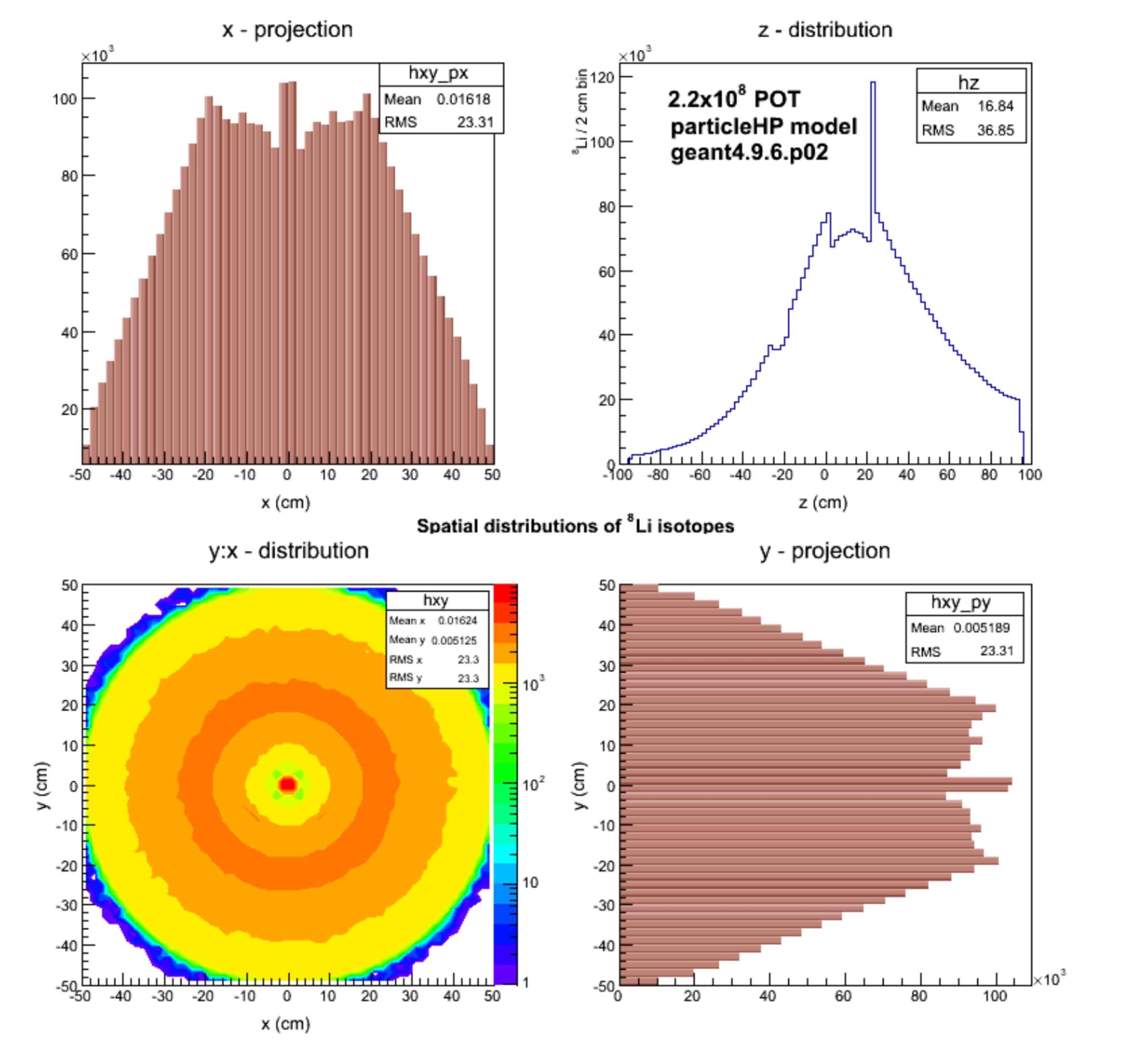


Figure 4.28: Distributions for the antineutrino $\bar{\nu}_e$ production points in the IsoDAR target.