An Isotope Decay-At-Rest experiment
IsoDAR Status and Physics

NuFact 2018 08/16/2018

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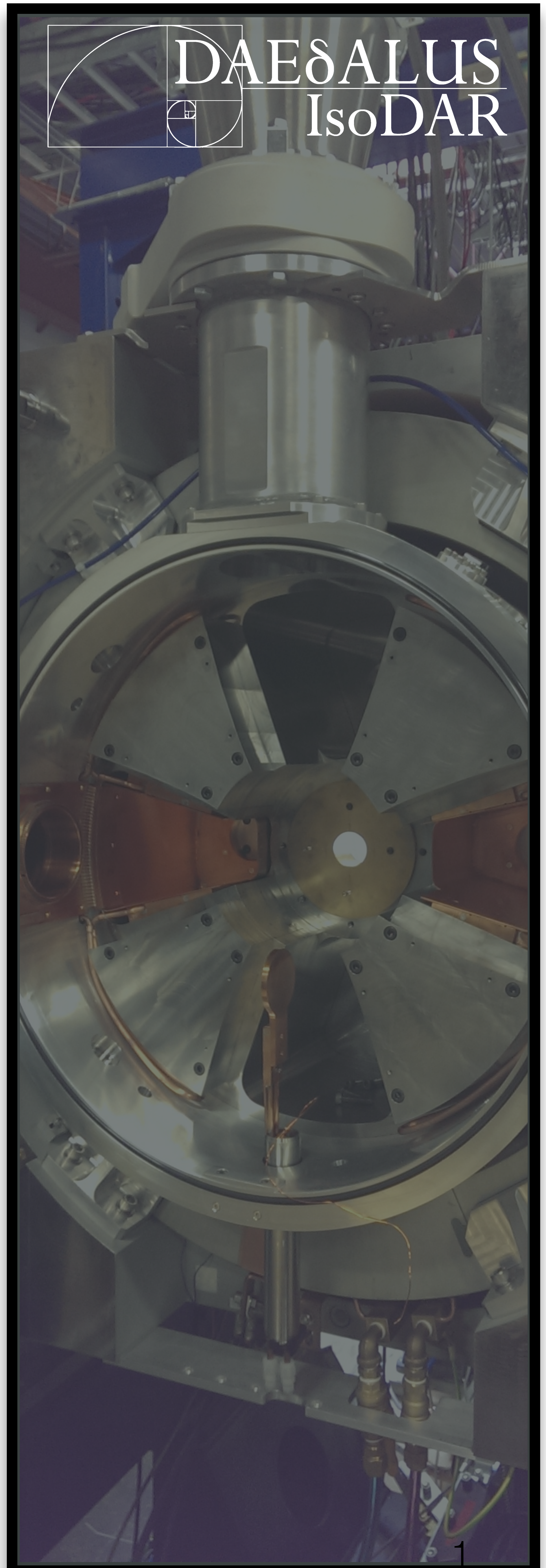
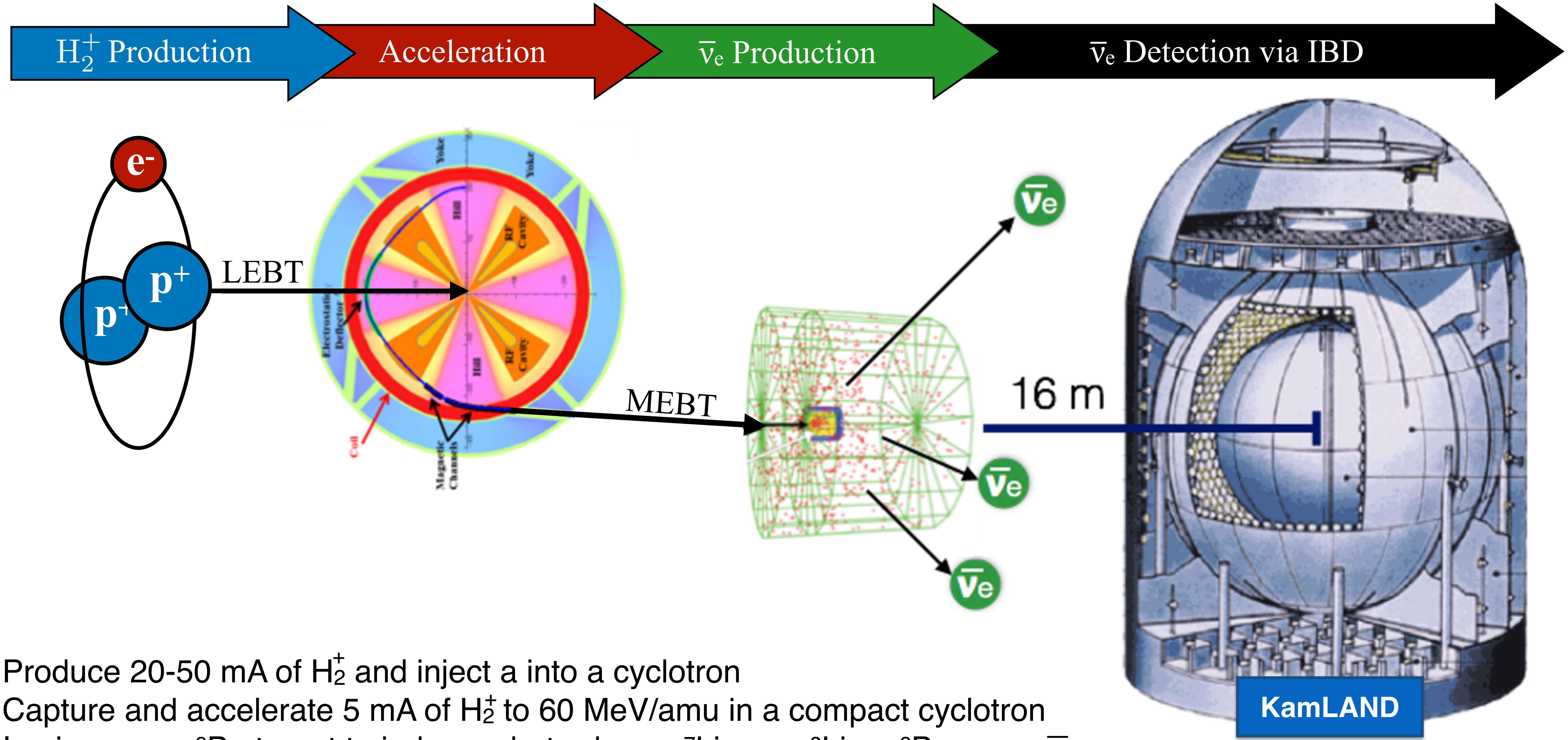
On behalf of the IsoDAR collaboration

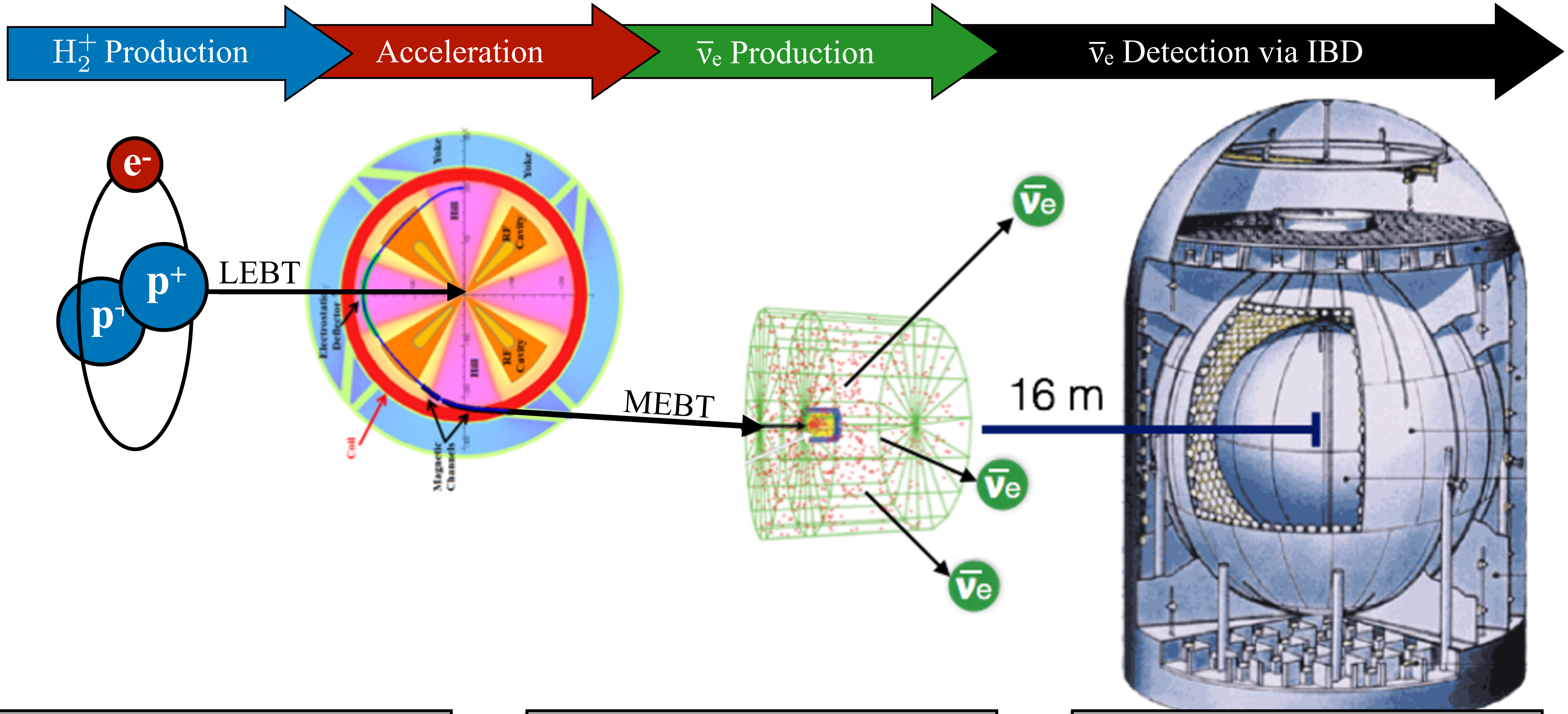


IsoDAR overview



1. Produce 20-50 mA of H_2^+ and inject a into a cyclotron
2. Capture and accelerate 5 mA of H_2^+ to 60 MeV/amu in a compact cyclotron
3. Impinge on a ^{9}Be target to induce a beta-decay. ^{7}Li+n $\longrightarrow$ ^{8}Li $\longrightarrow$ ^{8}Be + e^- + $\bar{\nu}_e$
4. Map out oscillation in anti-electron neutrino disappearance within a kiloton scale detector like KamLAND

This talk will focus on the status and expected physics output

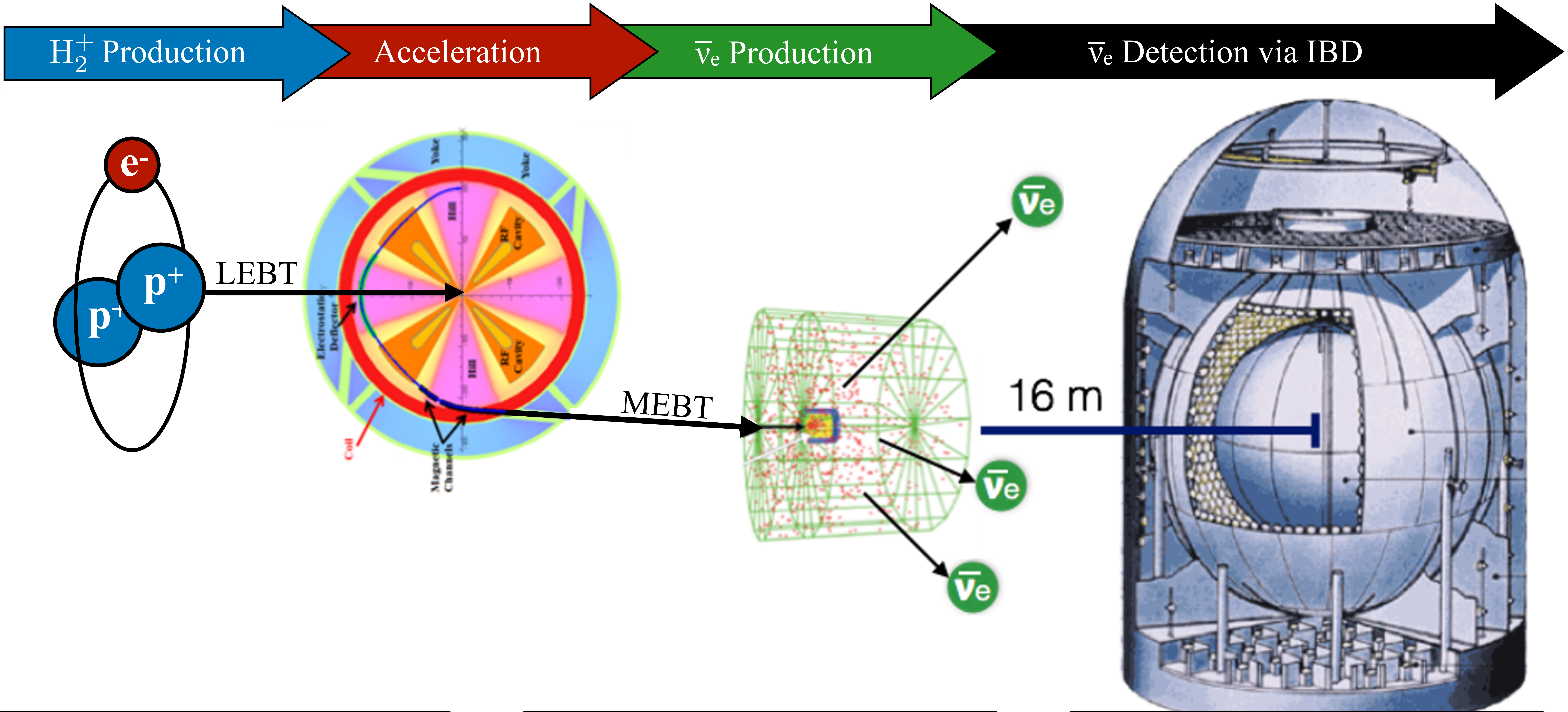


Accelerator Physics

Medical Physics

Particle Physics

Accelerator Physics



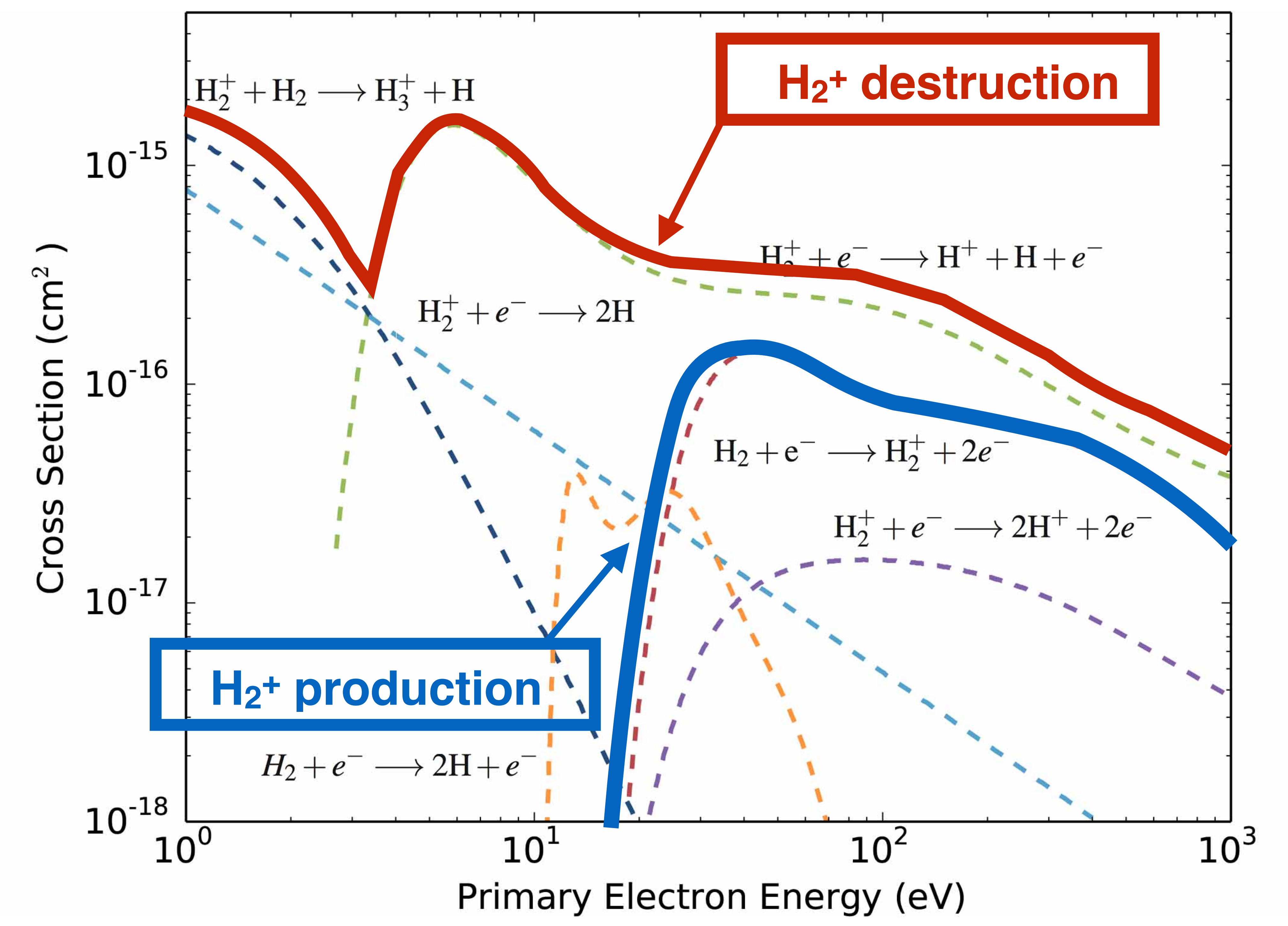
Accelerator Physics | **Medical Physics** | **Particle Physics**

H_2^+ ion source development

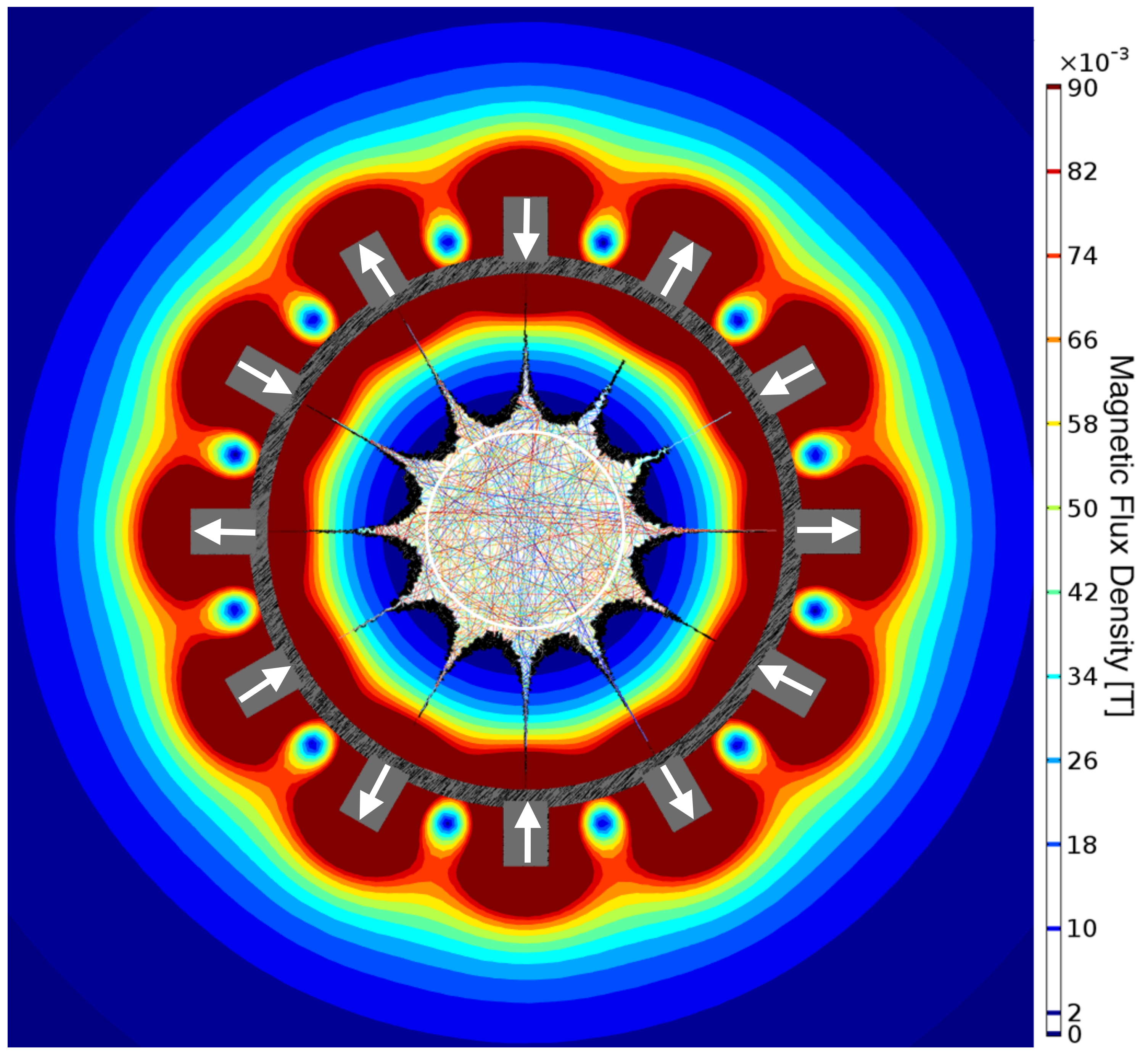
A group at LBL were able to construct a multicusp ion source capable of >50mA/cm² [1].
This would be sufficient for IsoDAR, so the design of our ion source was based off of their source.

Key innovations in designing H_2^+ ion sources:

1. Extract H_2^+ near to where it was produced.



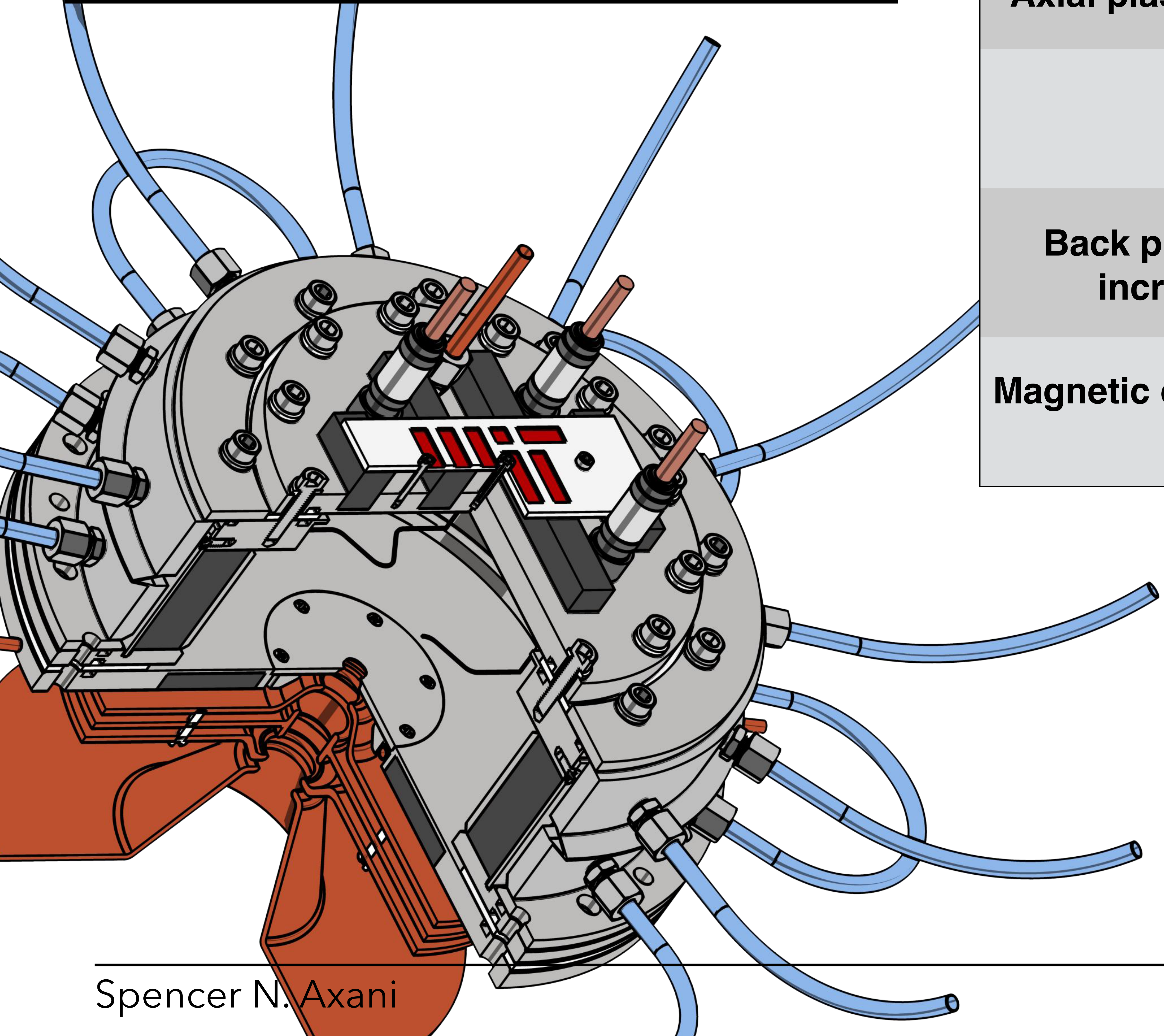
2. Confine the plasma with a multicusp field.



[1] https://aip.scitation.org/doi/10.1063/1.1137452

H_2^+ ion source development

MIST-1
The Multi-cusp Ion Source at MIT



Ehlers and Leung's LBL Source	MIST-1
Axial plasma volume length: 2.0, 4.5 cm	Axial plasma volume length: 1.5 - 5.0 cm
Not water cooled.	Front plate and plasma chamber is water cooled
Back plate biasing (observed a 30% increase in extracted current)	Back plate biasing and plasma chamber biasing
Magnetic configuration: plasma chamber/ back plate	Magnetic configuration: plasma chamber/ back plate/front plate

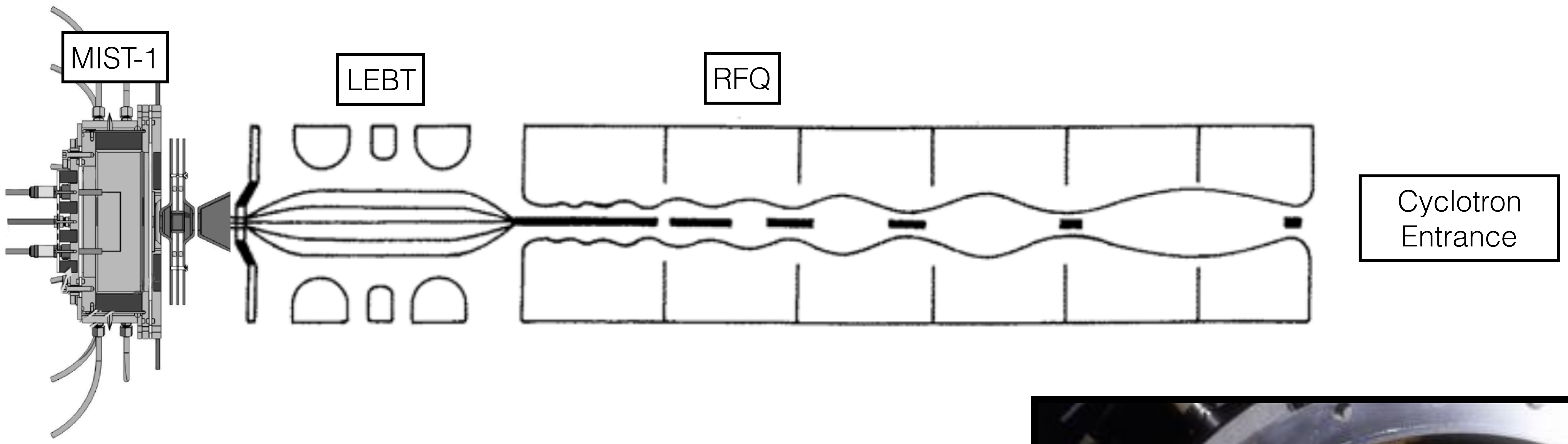
MIST-1 is being optimized at the Plasma Science and Fusion Center at MIT.

First beam was about a year ago.
Currently we've extracted 27mA/cm^2!

See J. Smolsky's talk for further details:
https://indico.phys.vt.edu/event/34/contributions/732/

Radio-Frequency Quadrupole (RFQ) buncher/pre-accelerator

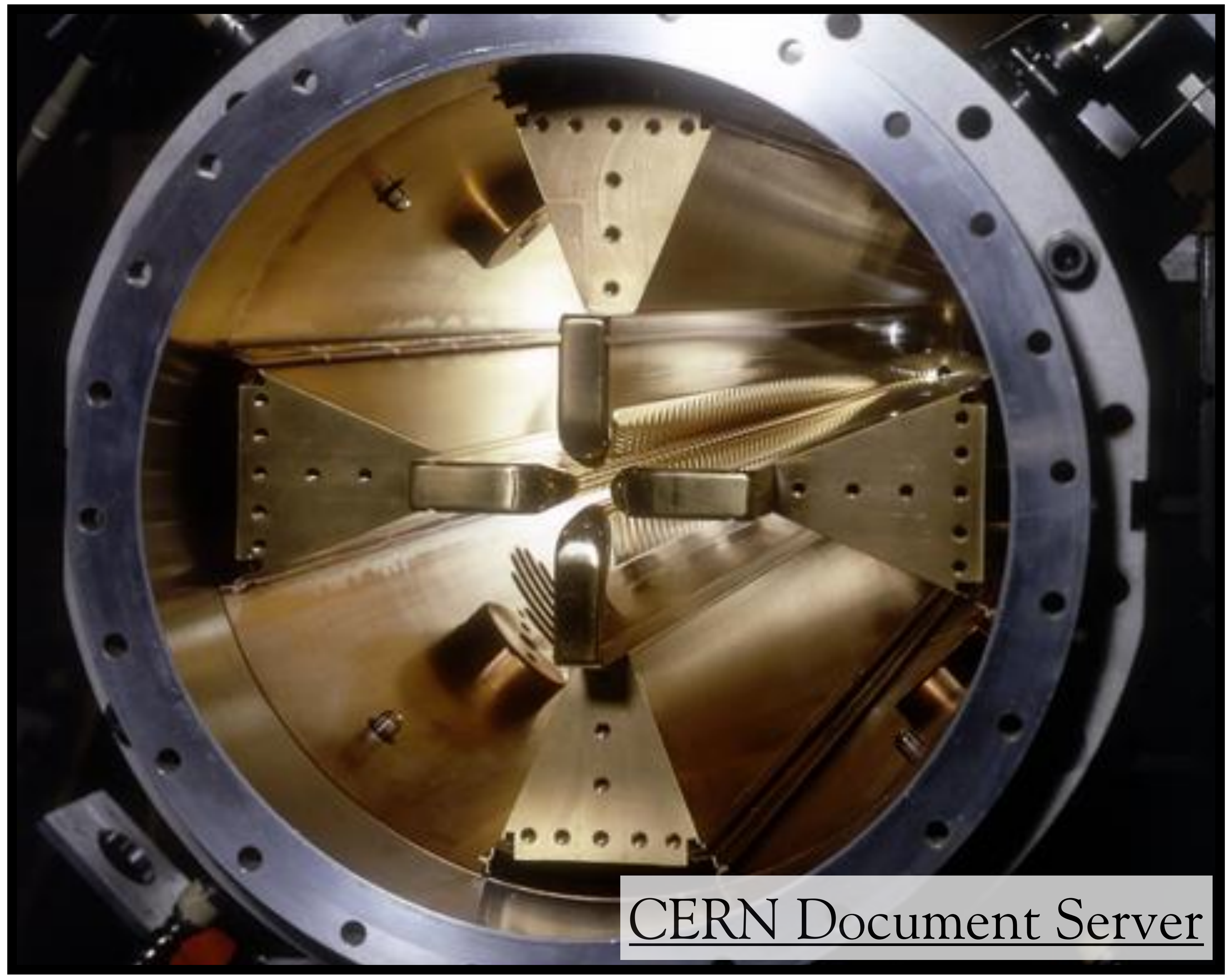
An RFQ is a common component of linear accelerators.



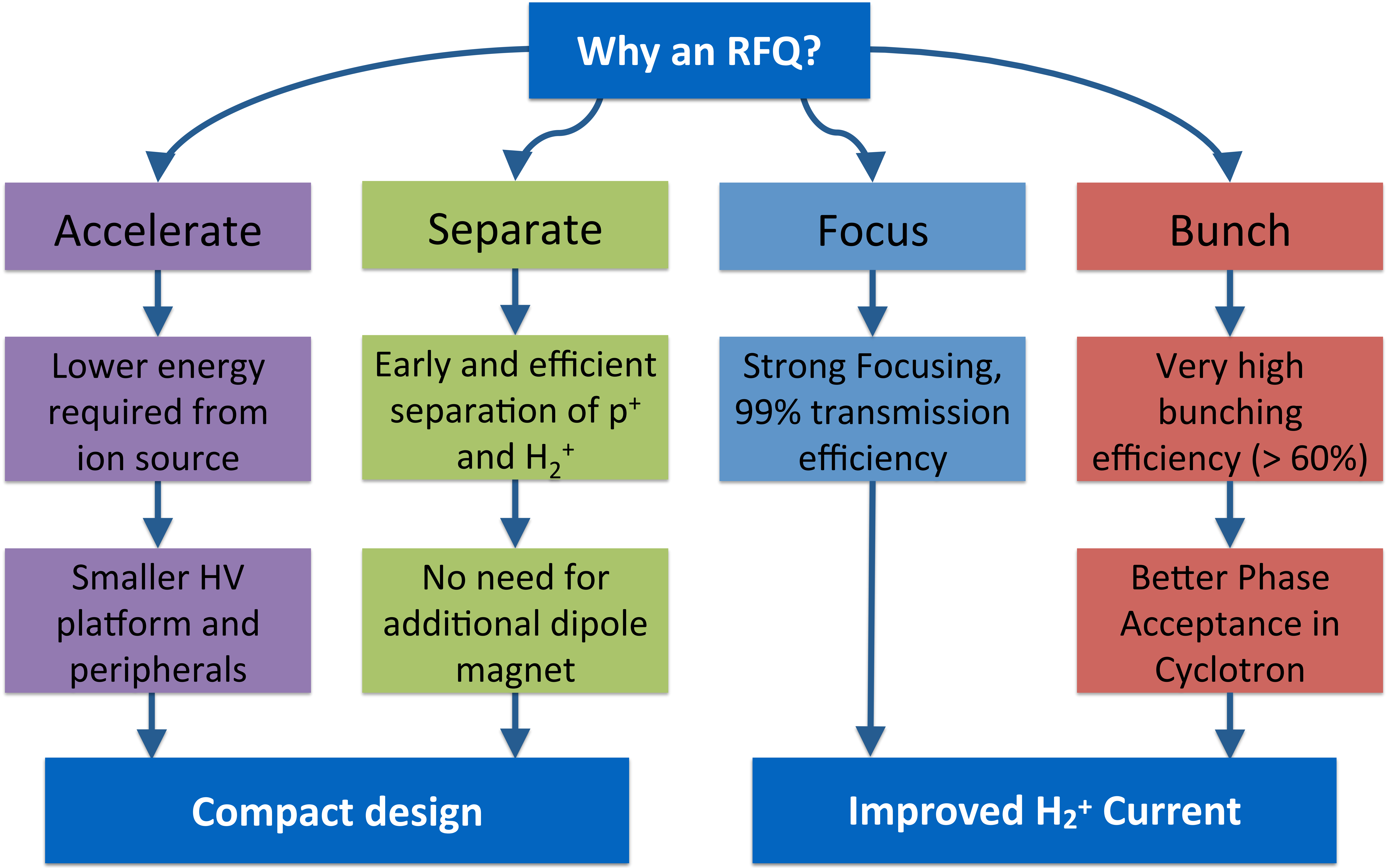
Invented in the 1970s, they are primarily used to accelerate low-energy beams.

IsoDAR is investigating using an RFQ as a buncher and pre-accelerator to inject our beam into the cyclotron.

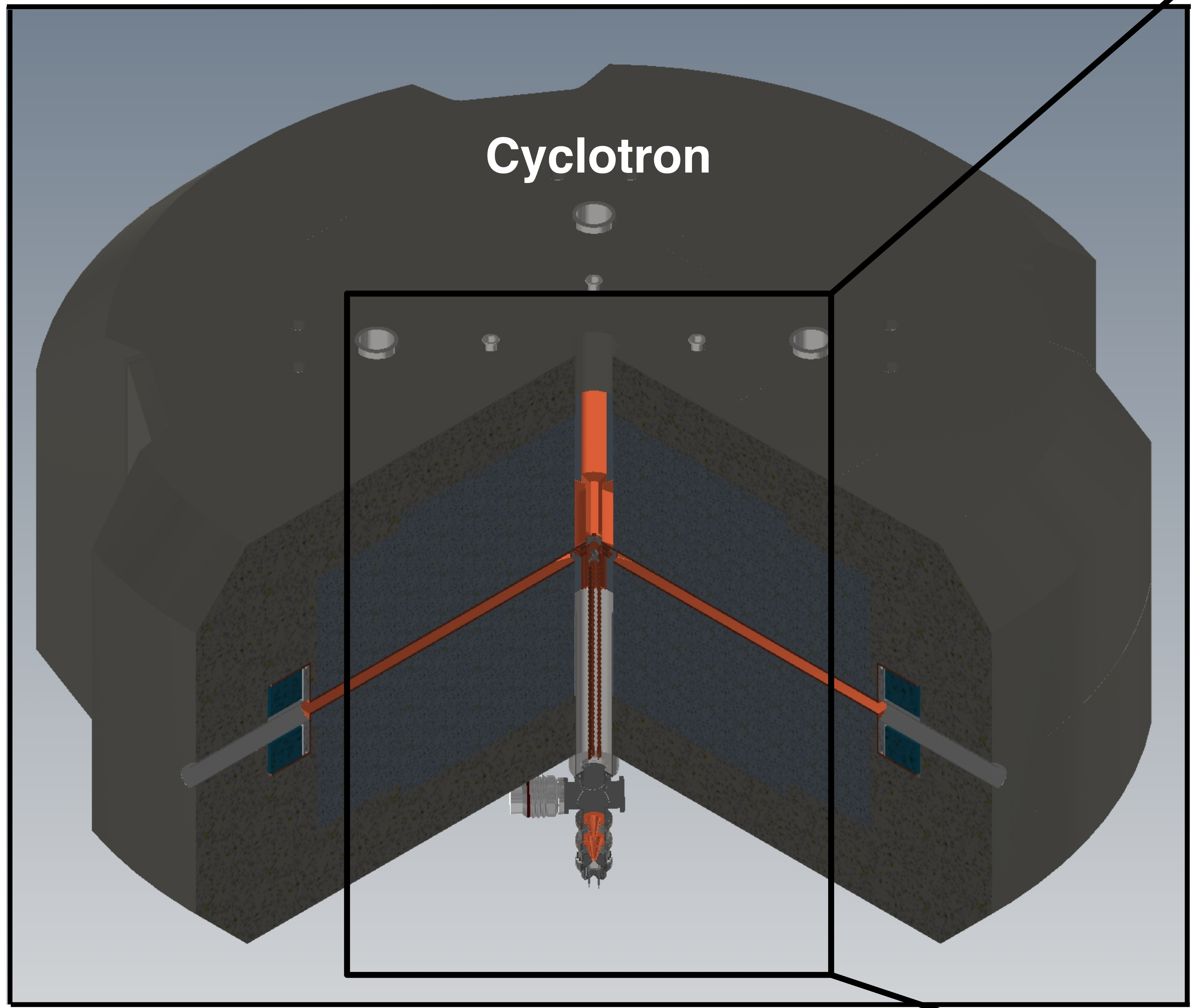
As of yet, using an RFQ as a buncher for axial injection into cyclotron has never been realized.

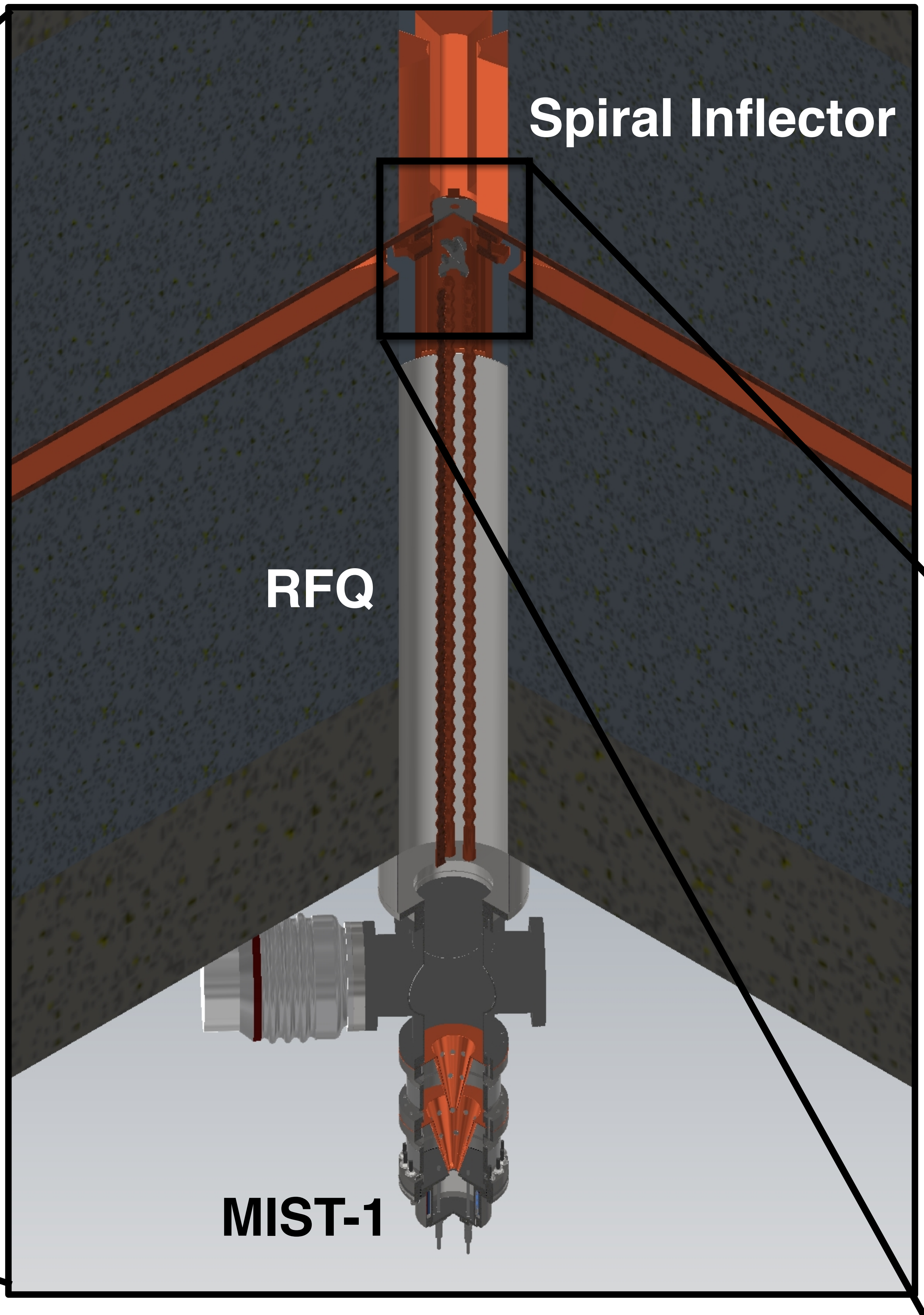


Radio-Frequency Quadrupole (RFQ)



The IsoDAR proton driver

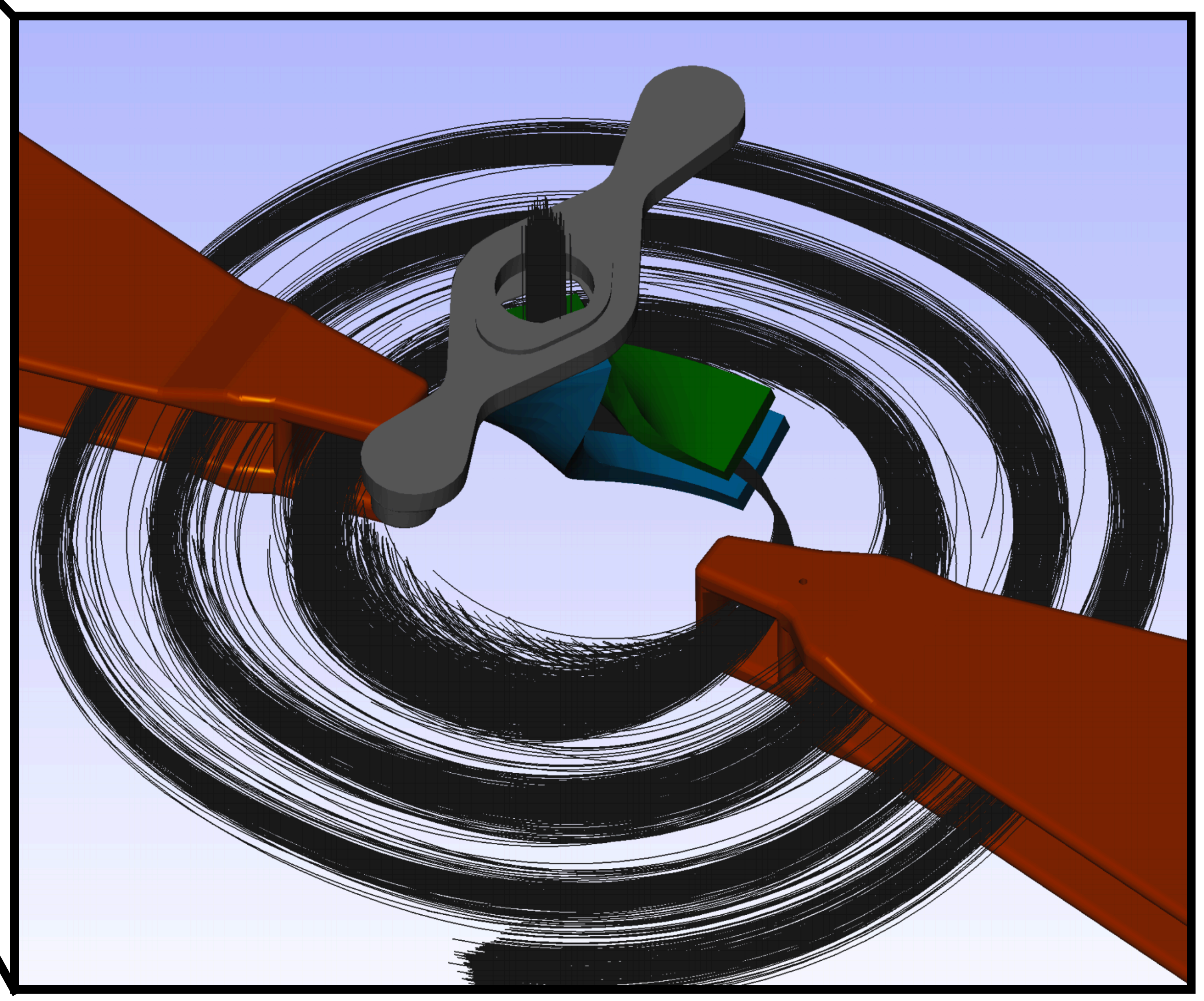




- NSF funding for RFQ and 1 MeV test cyclotron.
- Collaborative development with:

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Legnaro

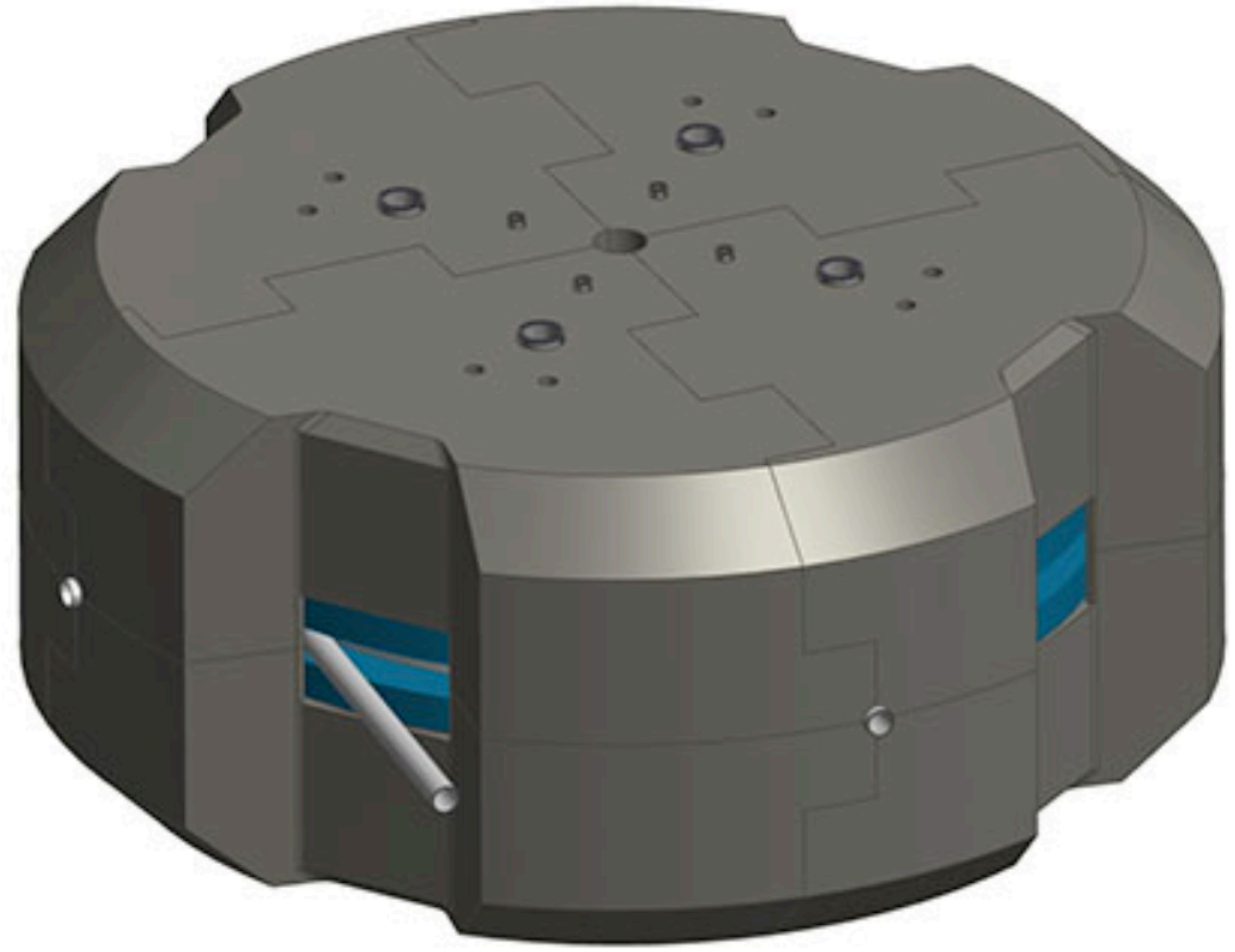
VECC Kolkata

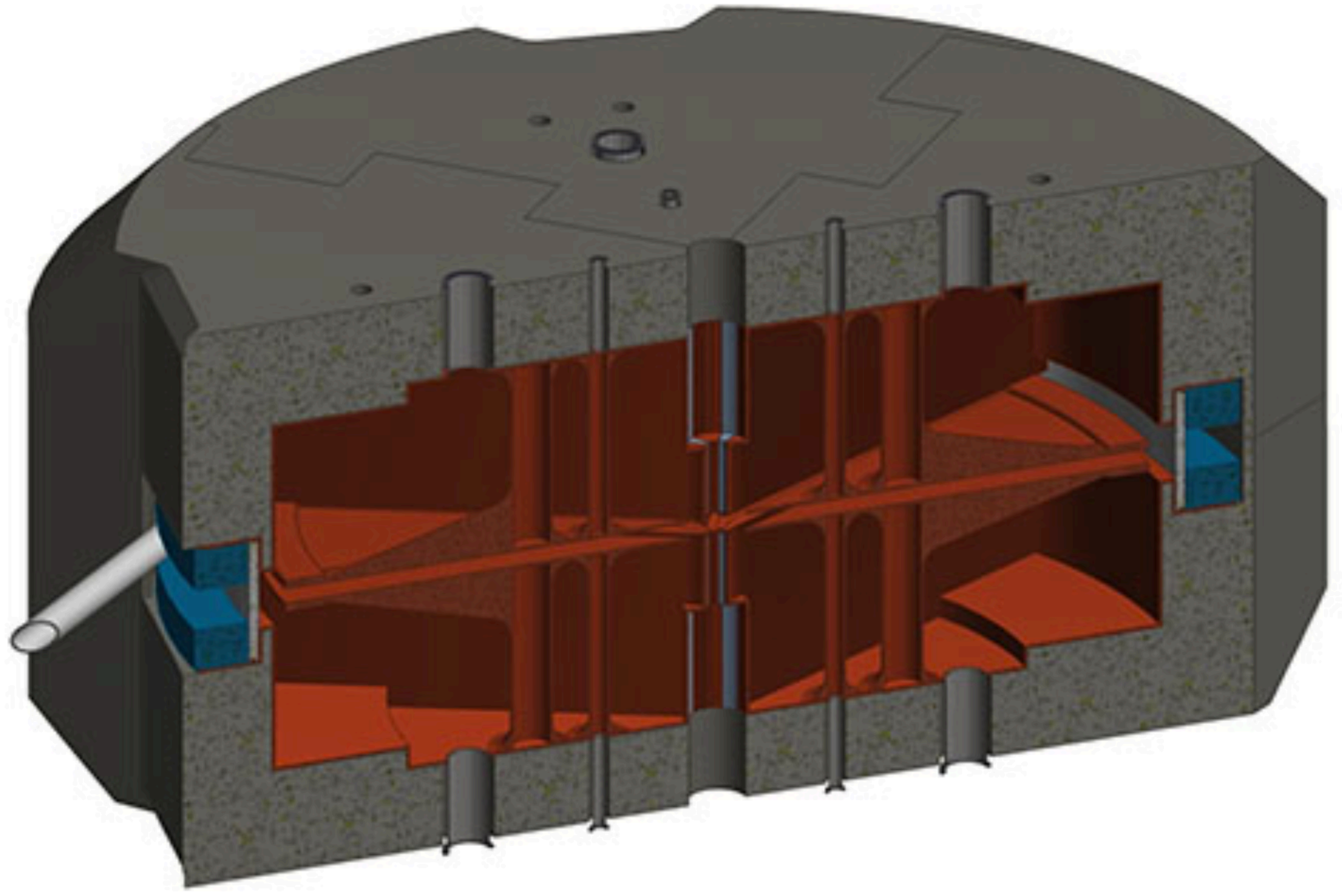


- Rev. Sci. Inst. 87.2 (2016): 02B929.
- arXiv:1612.09018
- Kim, J. H., et al. *Journal of the Korean Physical Society* 46.5 (2005): 1102-1108.

Expected cyclotron performance

State of the art | Commercial



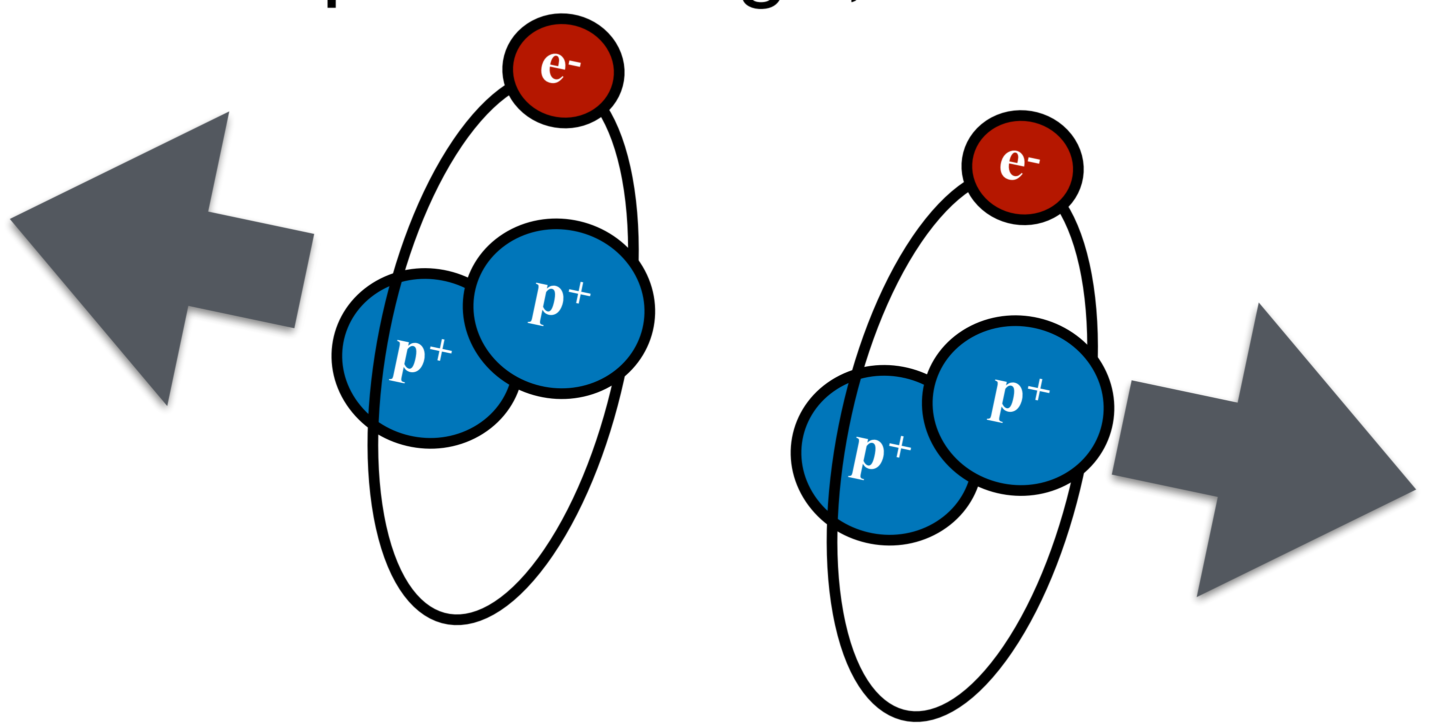


Parameter	IsoDAR	PSI Injector II	IBA C-70
Isotope	H_2^+	H+	H-
Maximum energy [MeV/amu]	60	72	70
Pole radius [m]	1.99	2.5	1.24
Outer diameter [m]	6.2	10	4
Iron weight [tons]	450	250	140
Output current [mA]	10	2.4	0.75

- Generalized perveance (K) is a measure of the space-charge; a limiting factor of modern cyclotrons.

$$K = \frac{qI}{2\pi\varepsilon_0 m_0 c^3 \gamma^3 \beta^3}$$

- RFQ injection will improve the capture efficiency.

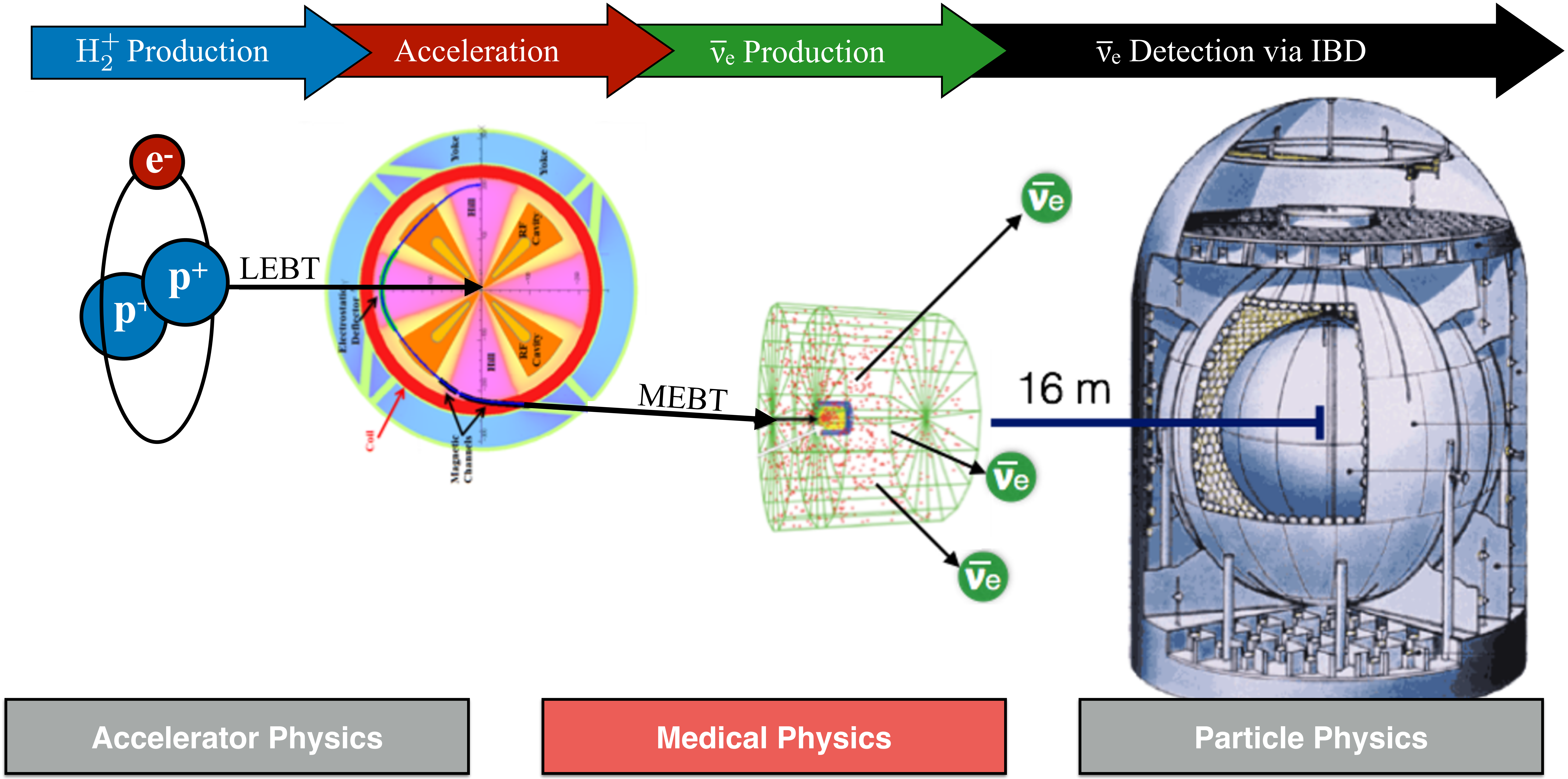


New paper on high power cyclotrons for neutrino physics:
Daniel Winklehner et. al:
https://arxiv.org/pdf/1807.03759.pdf

E_p = 30keV, E_{H2+} = 70keV, $\beta_p = 0.9236\beta_{H2+}$

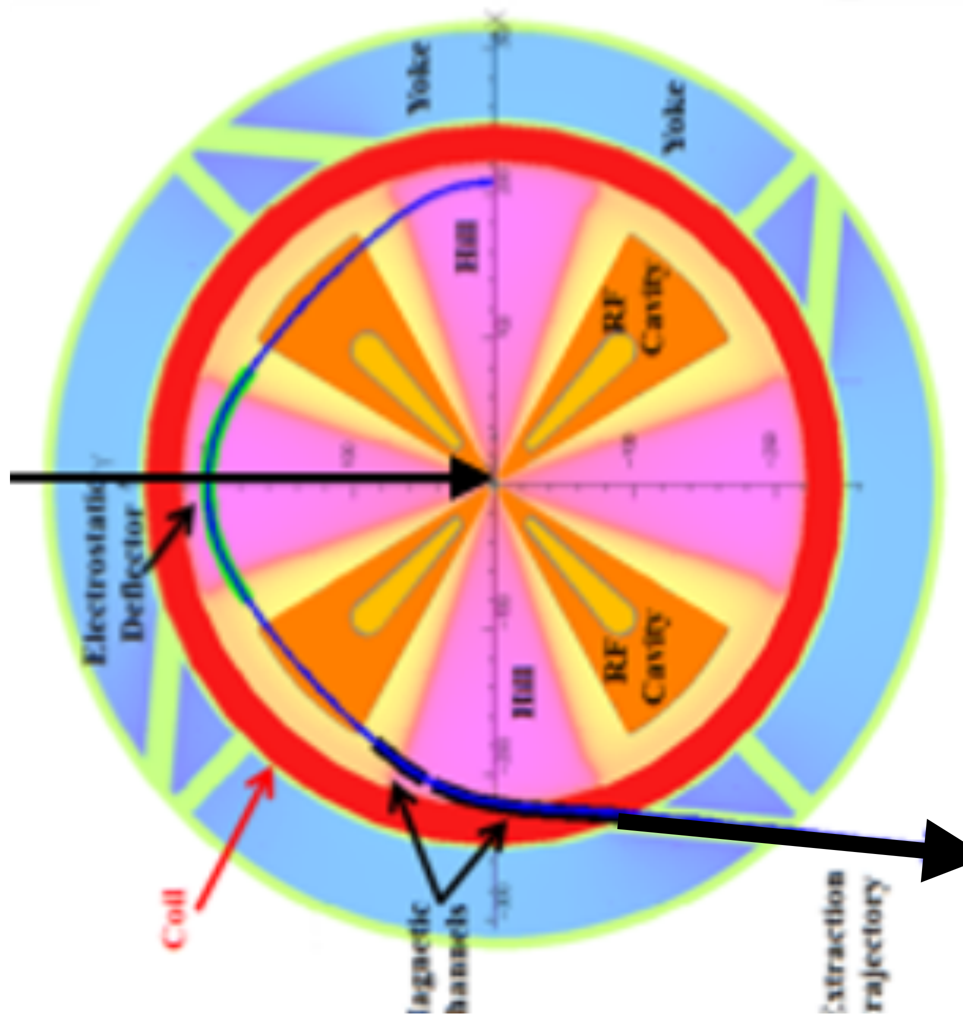
Proton: 2mA	K_p = 0.000239
H_2^+: 5mA	K_{H2+}=0.000247

Medical Physics



Medical isotope production: ^{68}Ge production

A high current beam can be used as a driver to produce isotopes with lower production cross-sections. As an example, ^{68}Ge/^{68}Ga generator.



Germanium Generator:

Natural Gallium

- ^{69}Ga -> ^{68}Ge via a (p,2n)
- 150mb peak cross-section at 25 +/- 5 MeV.
- Long generator lifetime

The IsoDAR cyclotron could generate **50 Curies** of the ^{68}Ge parent in a week of running.

^{68}Ge

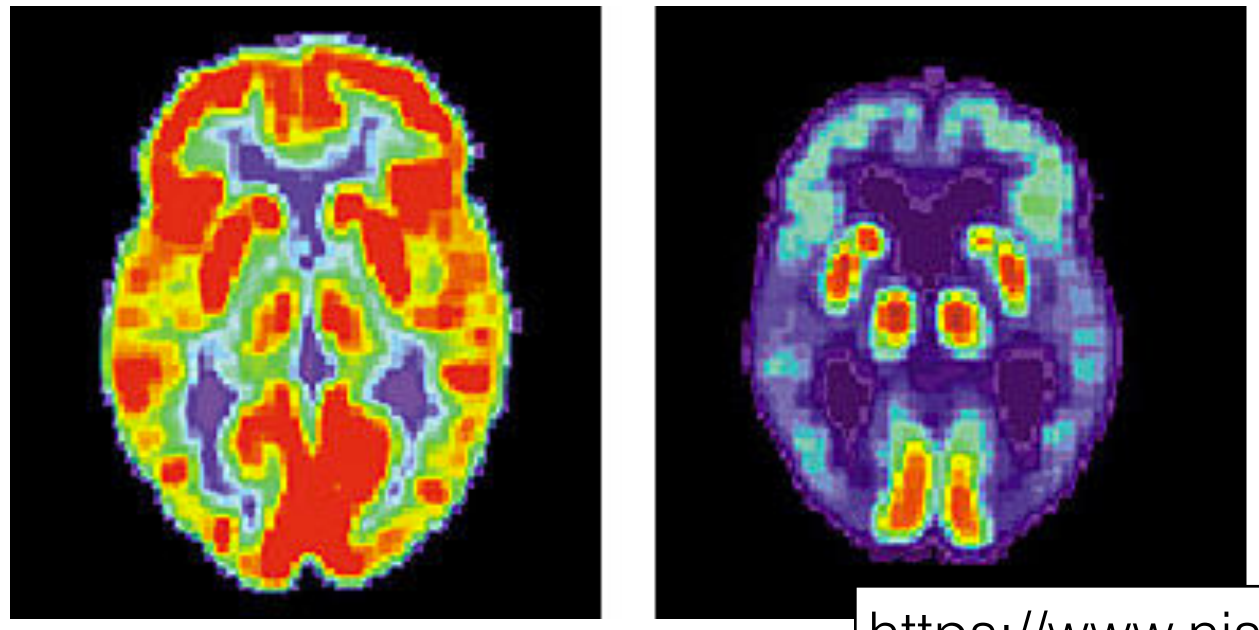
EC transition
$\tau_{1/2}$ = 270d

^{68}Ga

- Short lived state
- Positron emitter (PET)

(88%) β^+ decay
$\tau_{1/2}$ = 1.1h

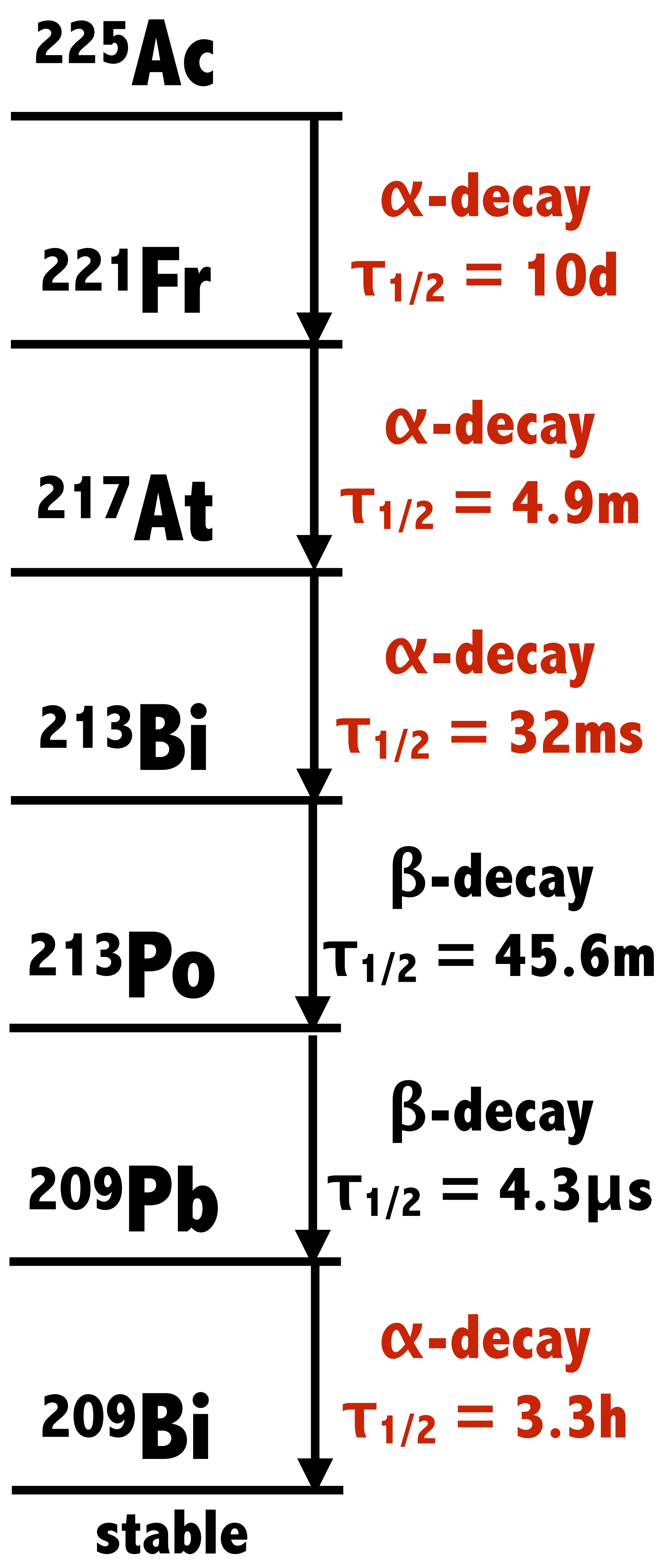
^{68}Zn



https://www.nist.gov/

Medical isotope production: Actinium-225 production

98% of the time ^{225}AC decays through this chain



Alpha-emitting isotopes are in high demand for therapeutic applications.

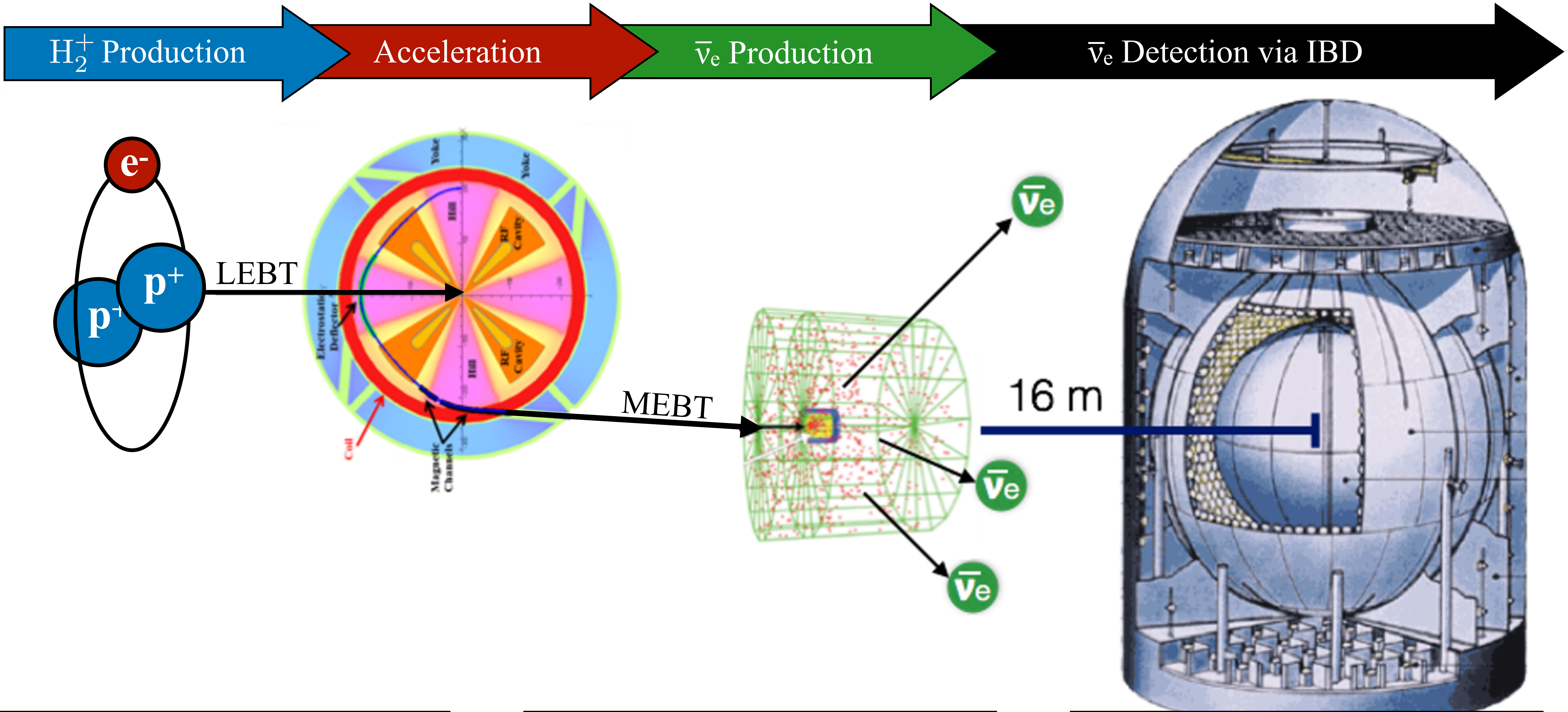
Actinium-225 is a particularly effective isotope.

- limited range in tissue (μm)
- high linear energy transfer which leads to dense radiation damage along the alpha track (5.8 - 8.4MeV).
- 10-day half-life
- four net alpha particles emitted per decay.

The IsoDAR cyclotron could produce 0.2Ci per hour of ^{225}Ac from a natural thorium target.

New paper on the medical isotope production from
Jose R. Alonso, Janet M. Conrad, and Loyd H. Waites:
https://arxiv.org/pdf/1807.06627.pdf

Particle Physics

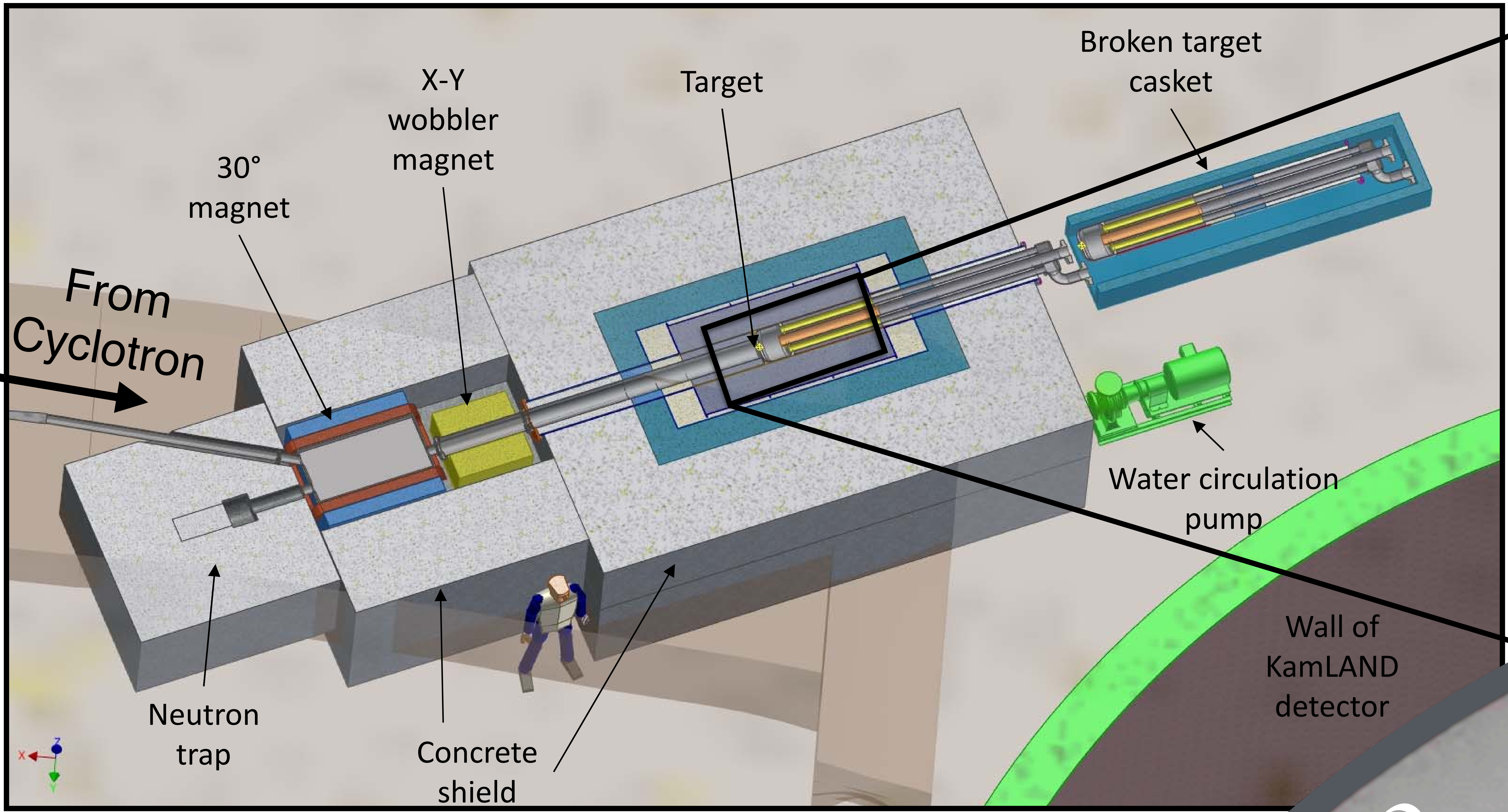


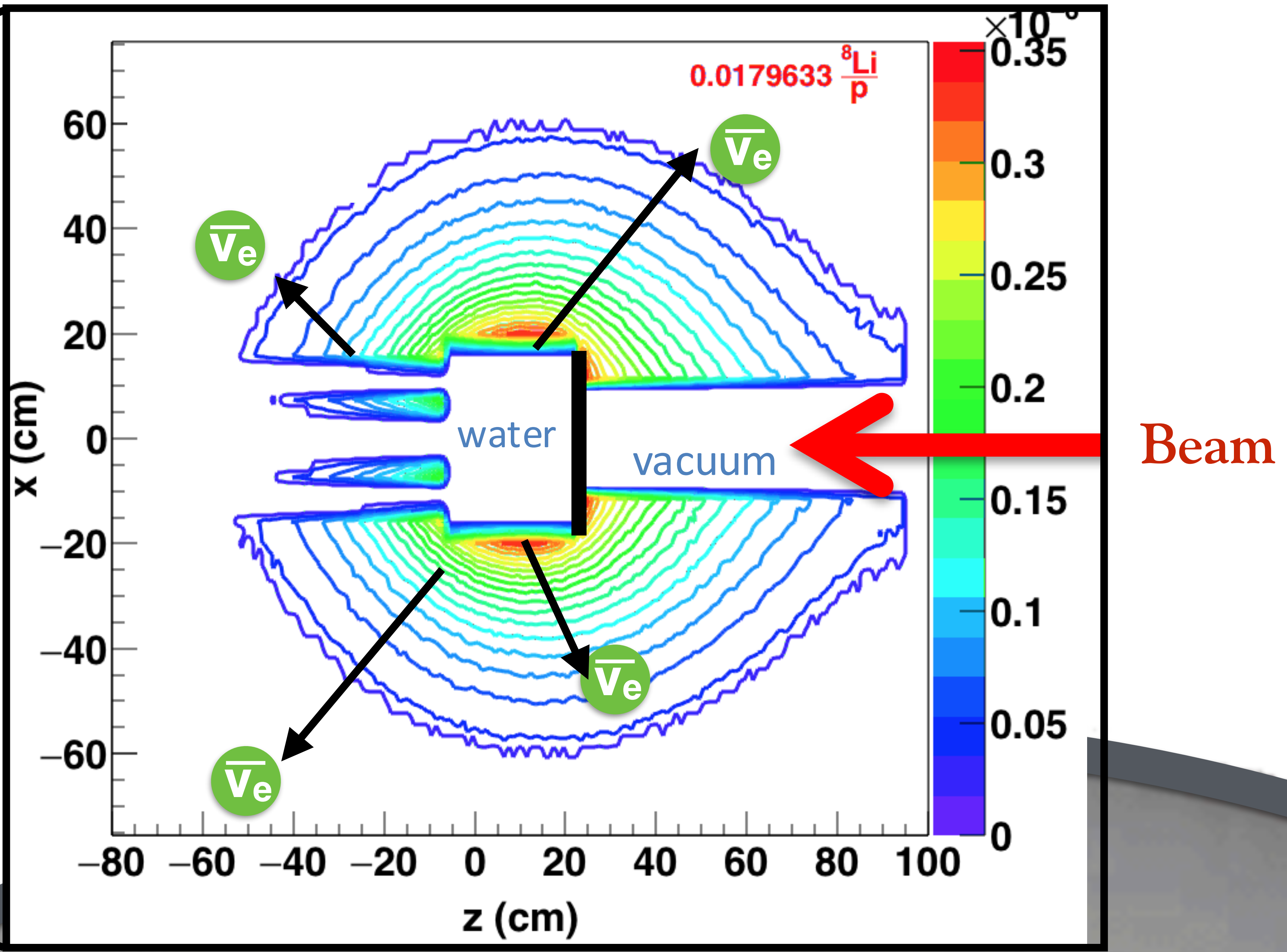
Accelerator Physics

Medical Physics

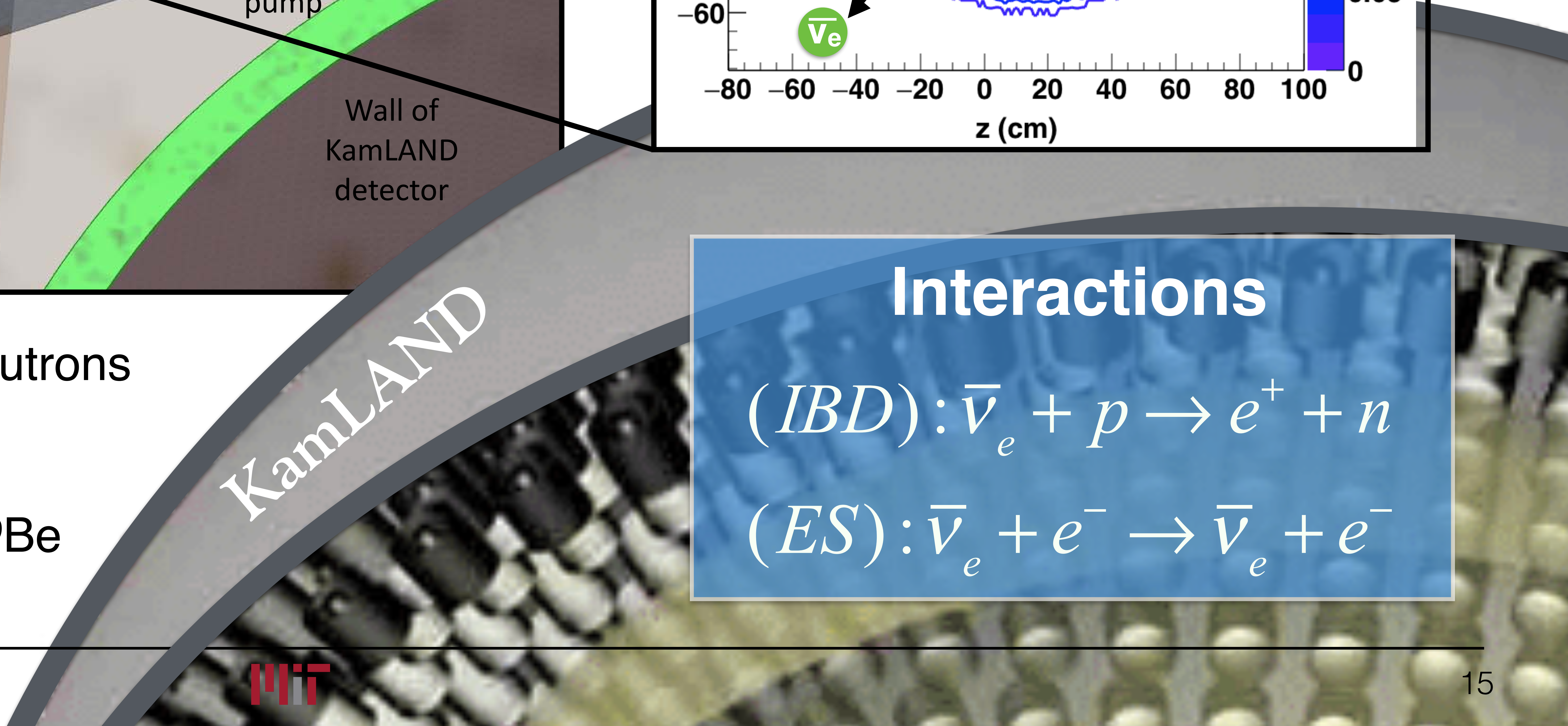
Particle Physics

IsoDAR target and neutrino production





- **Dipole magnet**: reduce back streaming neutrons
- **Wobbler**: distribute beam over target face
- **Target**: replaceable ^9Be torpedo.
- **Sleeve around target**: 99.99% pure ^7Li + ^9Be
- **Shielding**: minimize activation of the mine



Interactions

$$(IBD): \bar{\nu}_e + p \rightarrow e^+ + n$$

$$(ES): \bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$$

Precision electroweak measurements (ES sample)

IsoDAR could collect the largest sample of low-energy $\bar{\nu}_e$-electron scatters (ES) that has been observed to date. Approximately 2600 ES events would be collected above a 3 MeV visible energy threshold over a 5 year run, and both the total rate and the visible energy can be measured.

<u>Standard Model ES differential cross-section:</u>

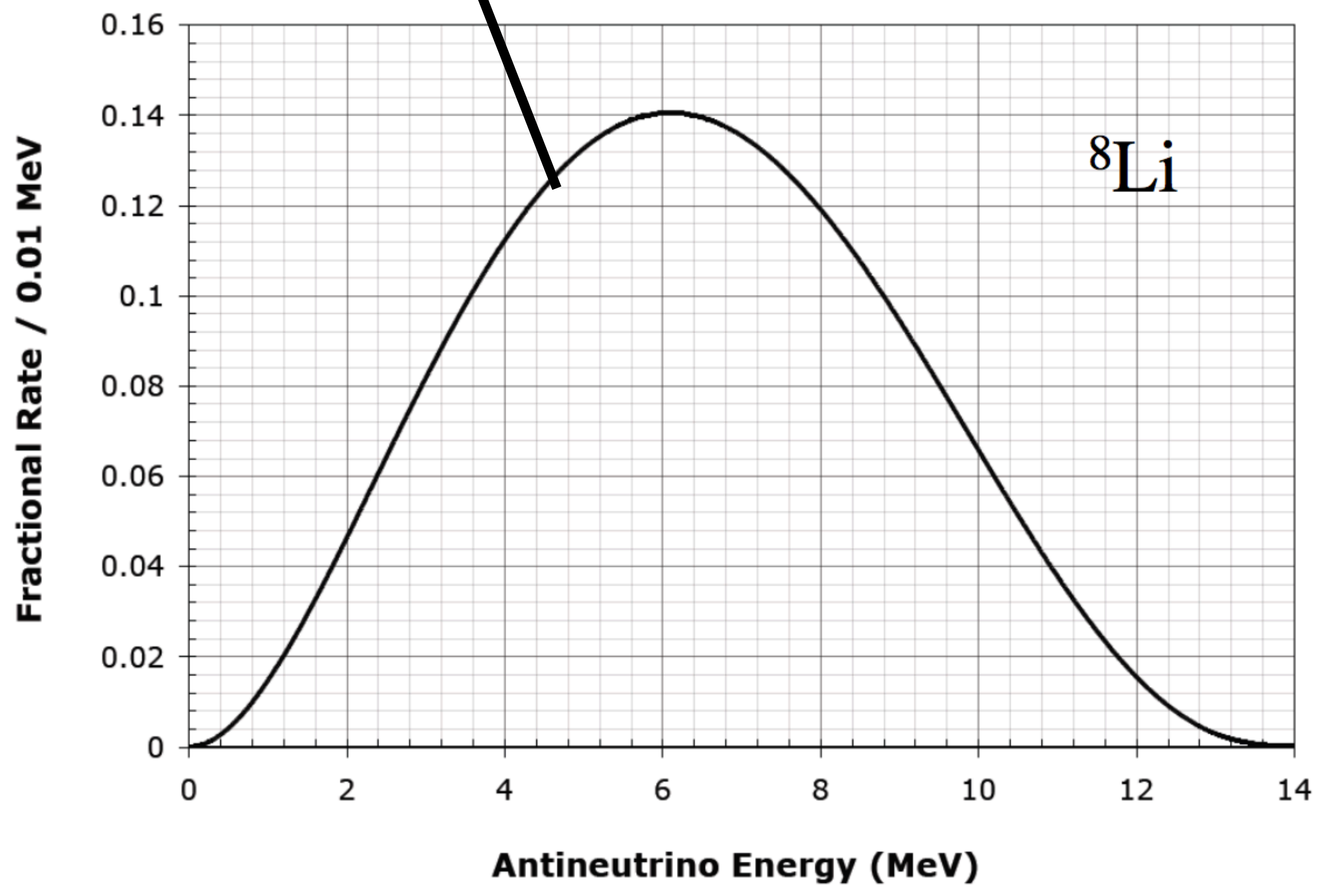
$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}\left(g_R + g_L\left(1 - \frac{T}{E_\nu}\right)^2 - g_R g_L \frac{m_e T}{E_\nu^2}\right)$$

Electron recoil energy

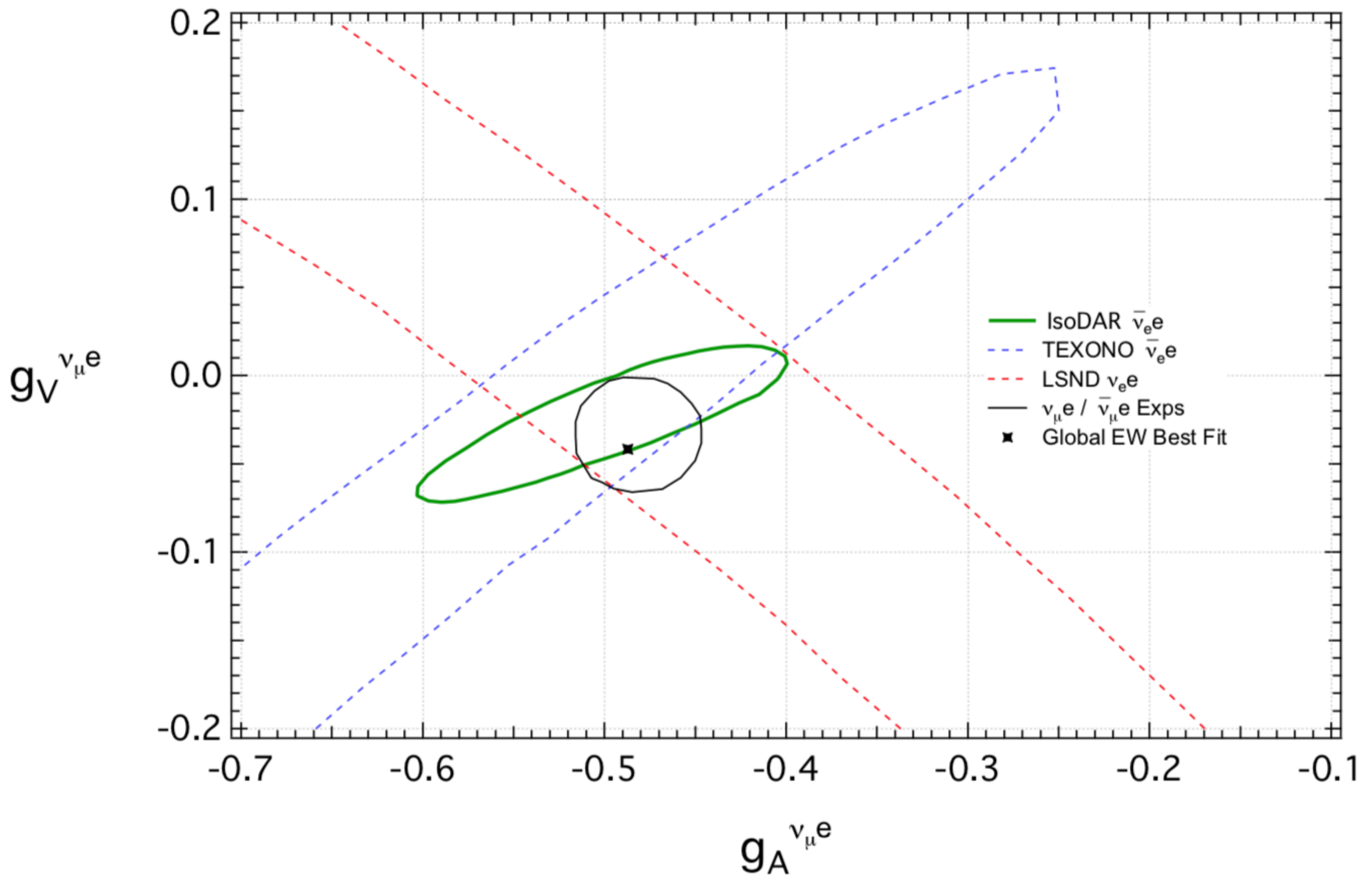
$$g_R = \frac{1}{2}(g_V - g_A) = \sin^2\theta_w$$

$$g_L = \frac{1}{2}(g_V + g_A) = \frac{1}{2} + \sin^2\theta_w$$

$$T \in \left[0, \frac{2E_\nu^2}{m_e + 2E_\nu}\right]$$

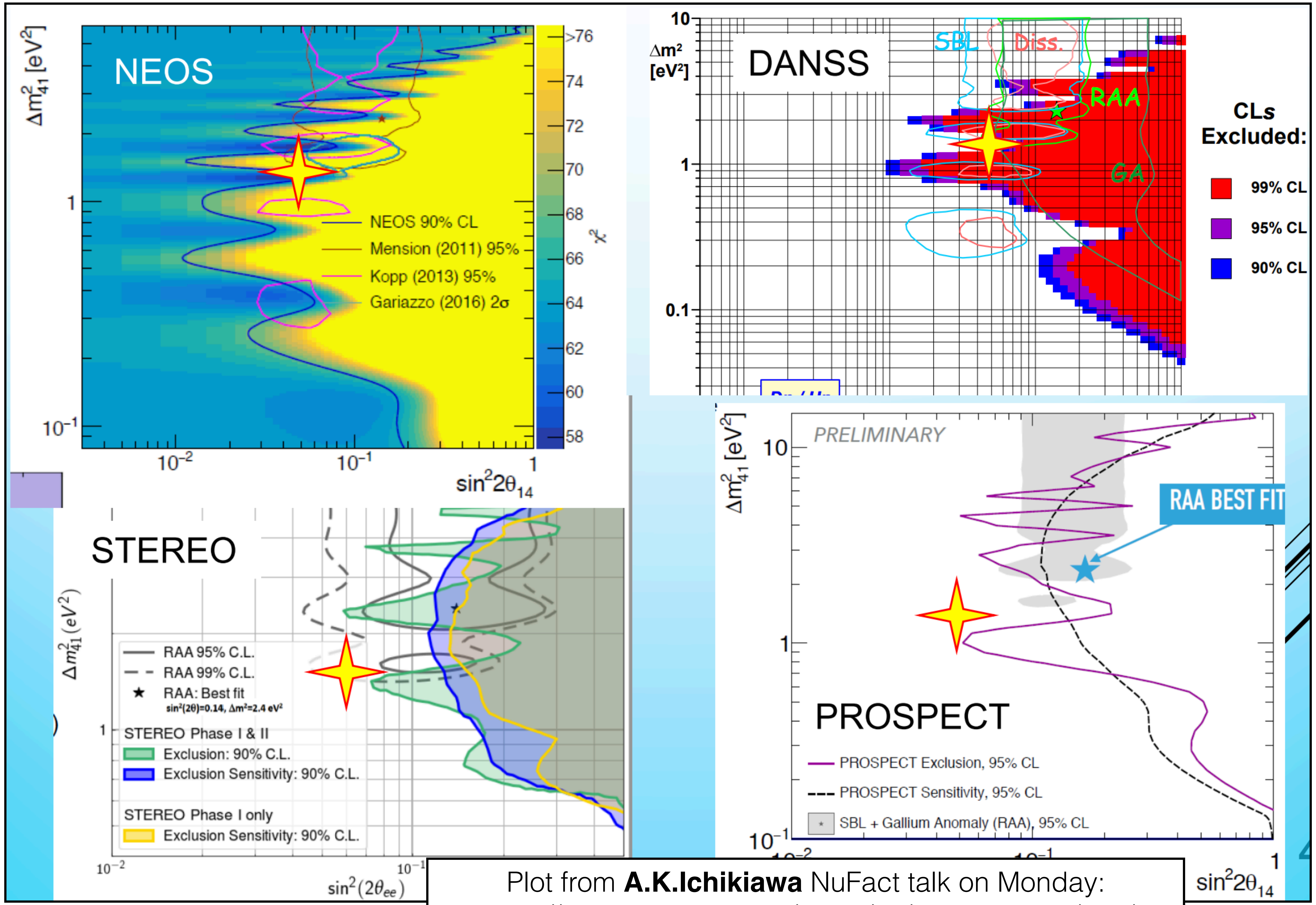


Purely leptonic measurement of $\sin^2\theta_W$



Expected $\sin^2\theta_W$ 1σ sensitivity = 3.2%

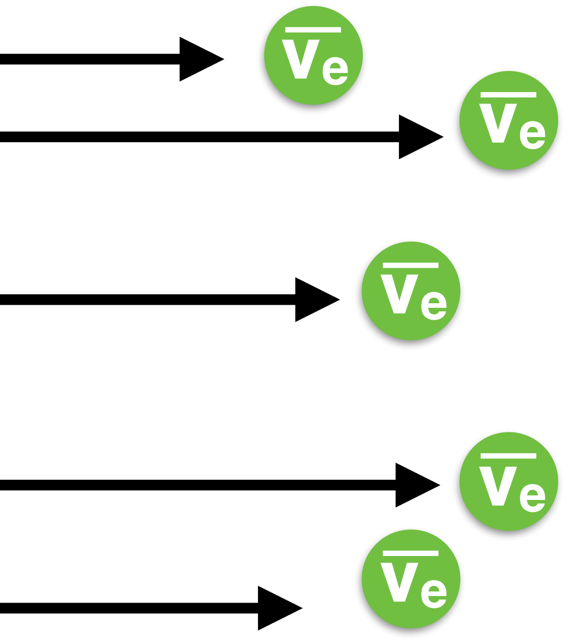
Sterile neutrinos $\bar{\nu}_e$ searches

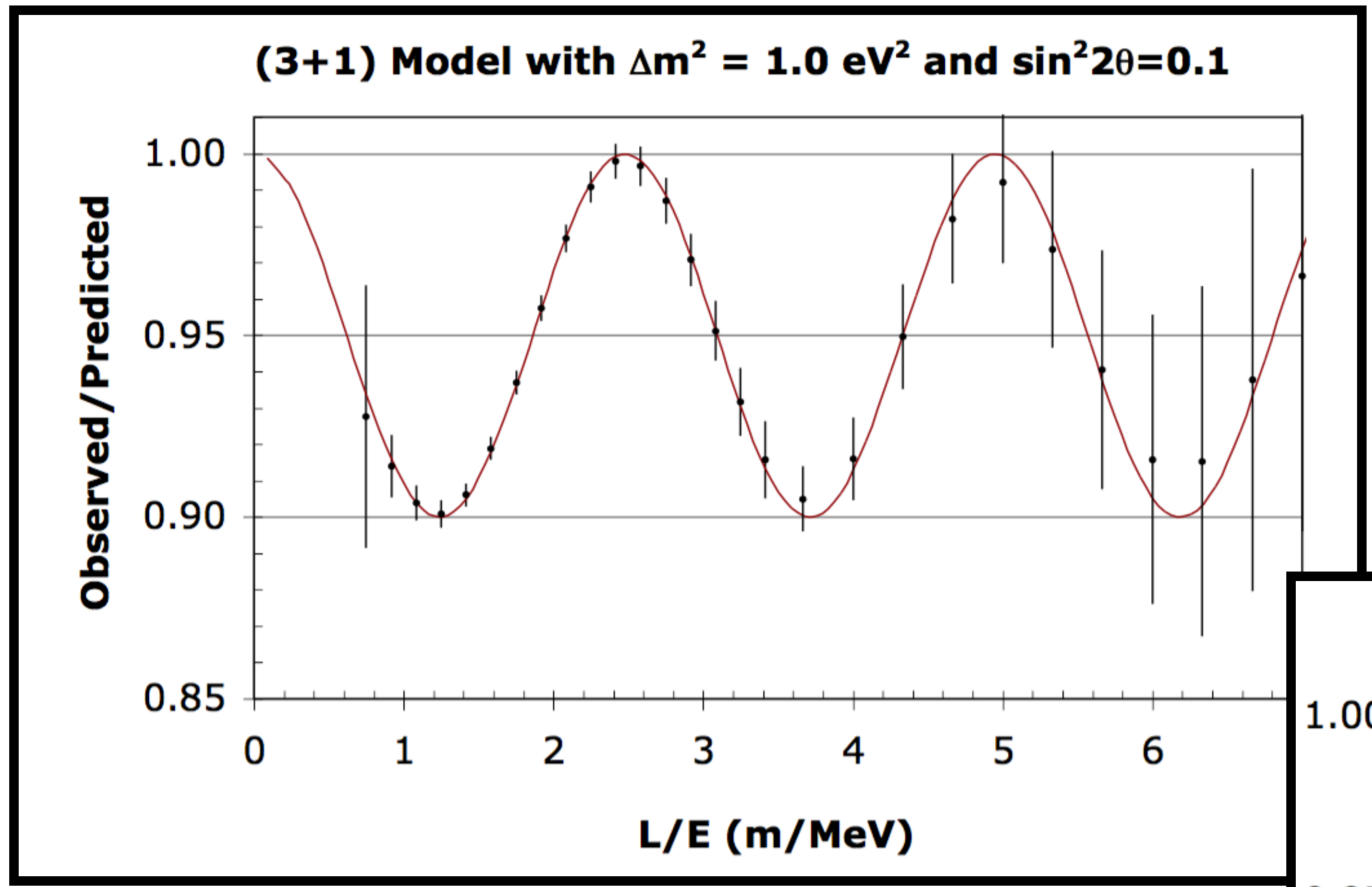


Plot from **A.K.Ichikiawa** NuFact talk on Monday: https://indico.phys.vt.edu/event/34/contributions/599/attachments/511/589/nufact18.ichikawa.pdf

Similar to reactor experiments, IsoDAR will perform a "$\bar{\nu}_e$-disappearance" measurement, however, **unlike reactors**, the neutrinos are generated from a well understood, positionable source.

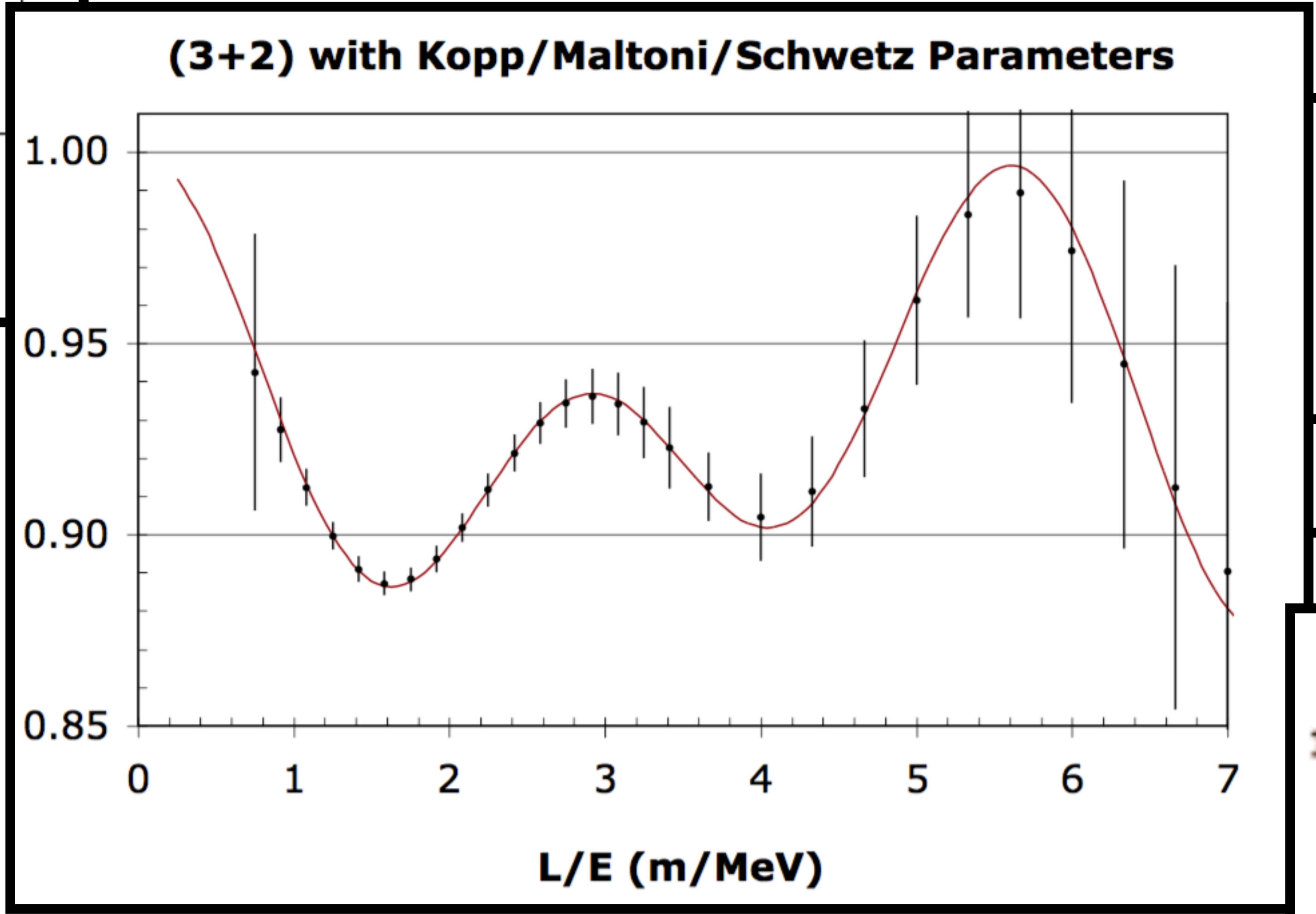
Sterile neutrino search (IBD sample)

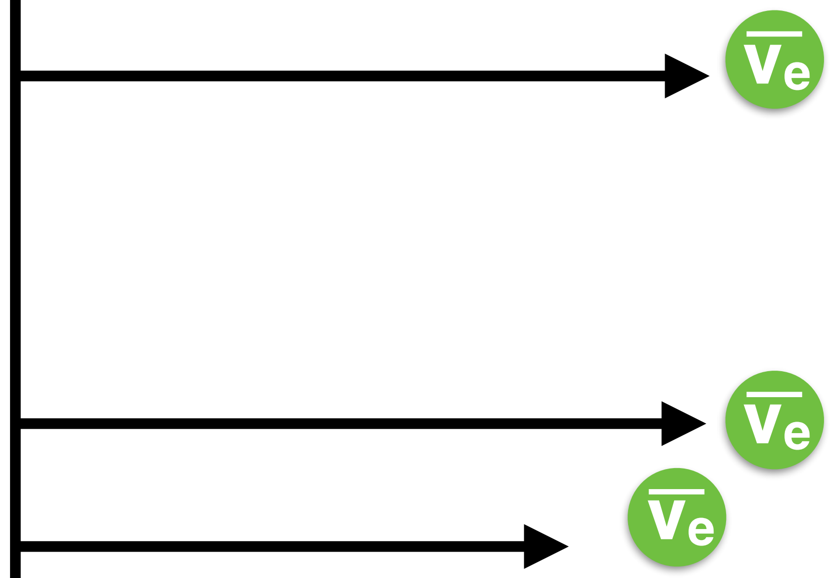




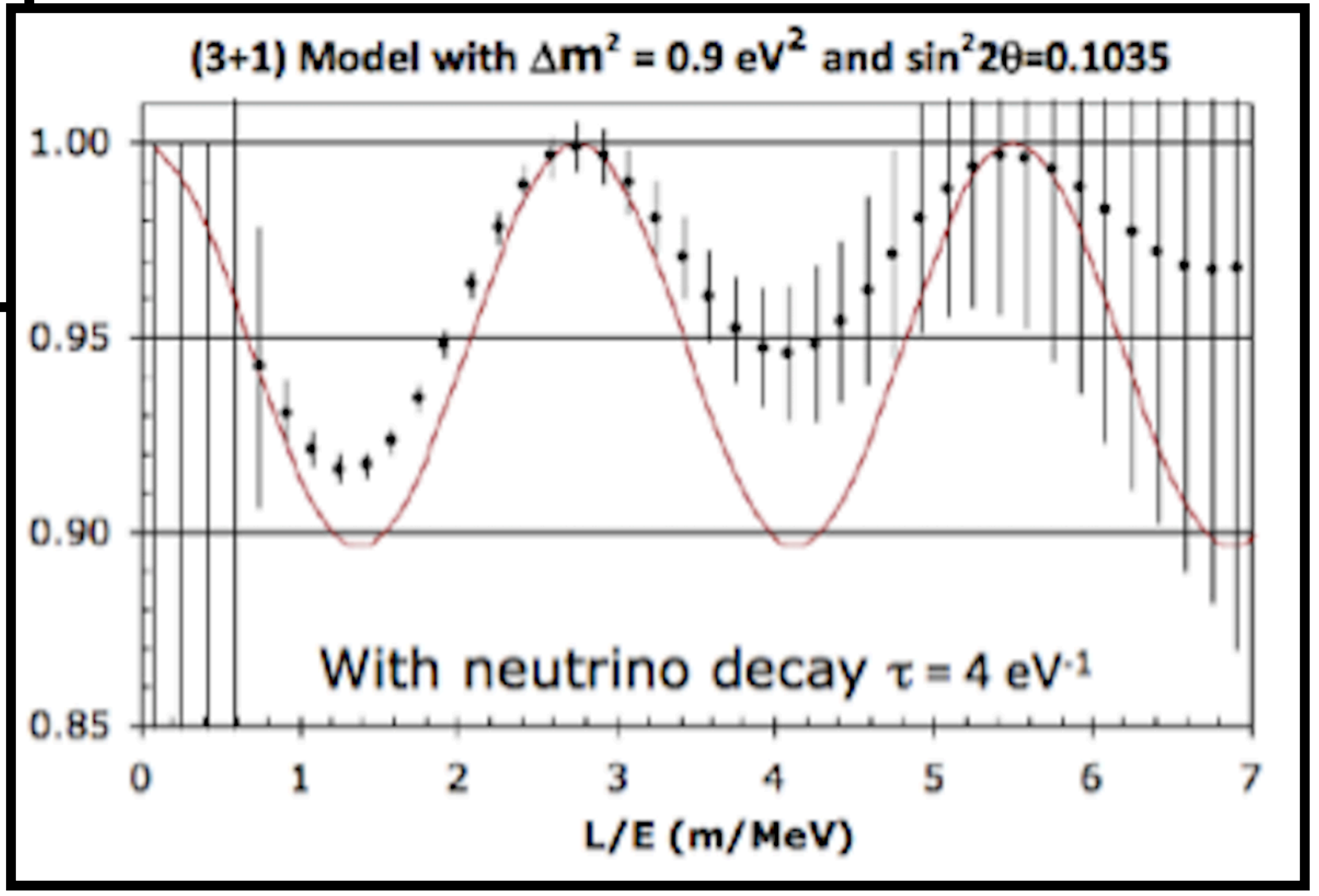
By accurately mapping out the short baseline oscillations through a single detector, over an L/E of 0.6 to 7.0 m/MeV, IsoDAR can test 3+1 sterile model.

...or 3+N sterile models.

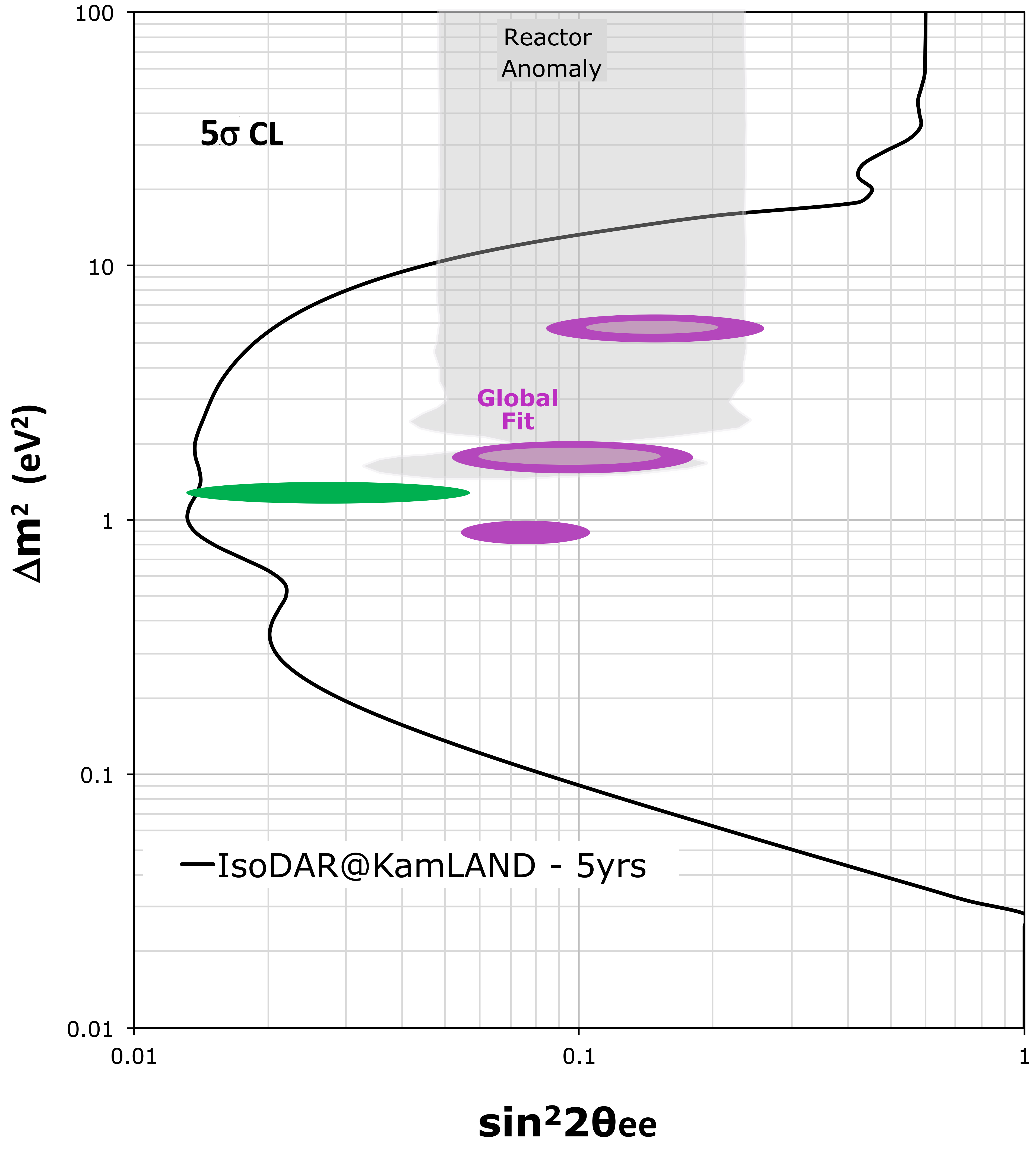




...or sterile decay models.



3+1 sterile neutrinos sensitivity



Anomalous oscillation measurements drive the global allowed regions.

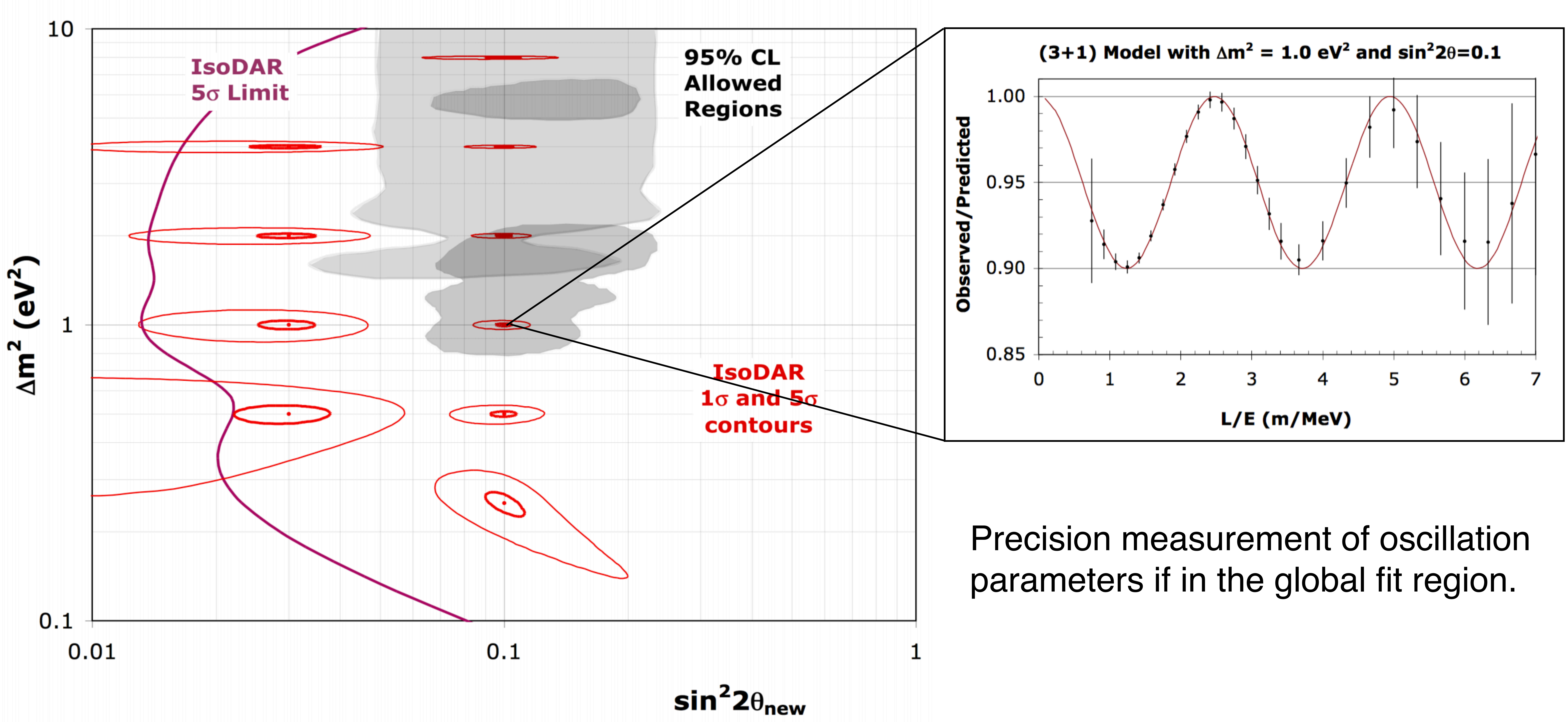
- LSND
- MiniBooNE
- Global reactor deficit
- GALLEX/SAGE anomaly

Including NEOS and DANSS, an updated global allowed favors $\Delta m^2 \sim 1.3 eV^2$

IsoDAR@KamLAND, will be able to make a definitive statement about the existence of light sterile neutrinos.

- Rule out 3+1 global fit region:
  - 20σ in 5 years
  - 5σ in 4 months

Sterile neutrino precision measurement



Precision measurement of oscillation parameters if in the global fit region.

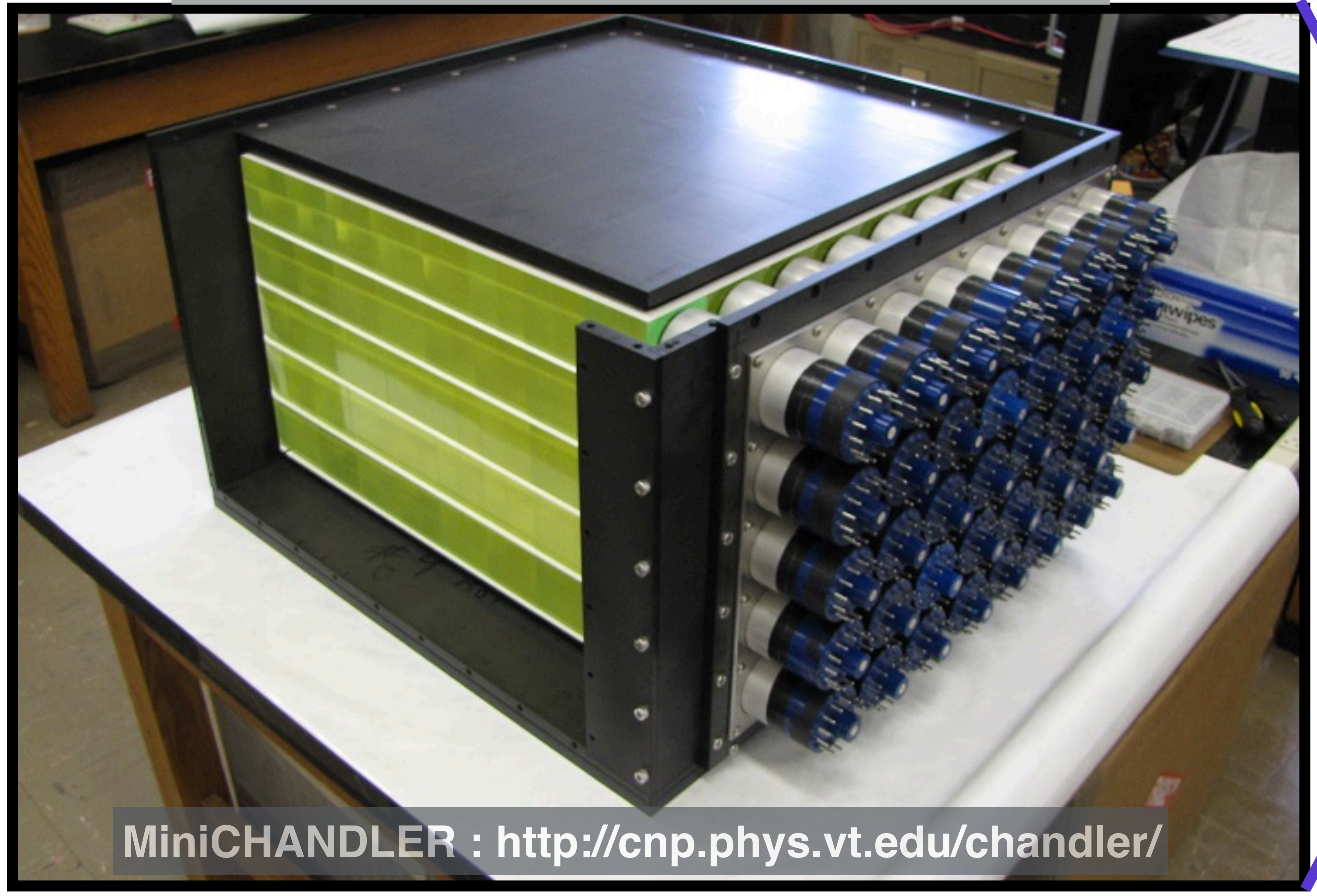
IsoDAR @ CHANDLER

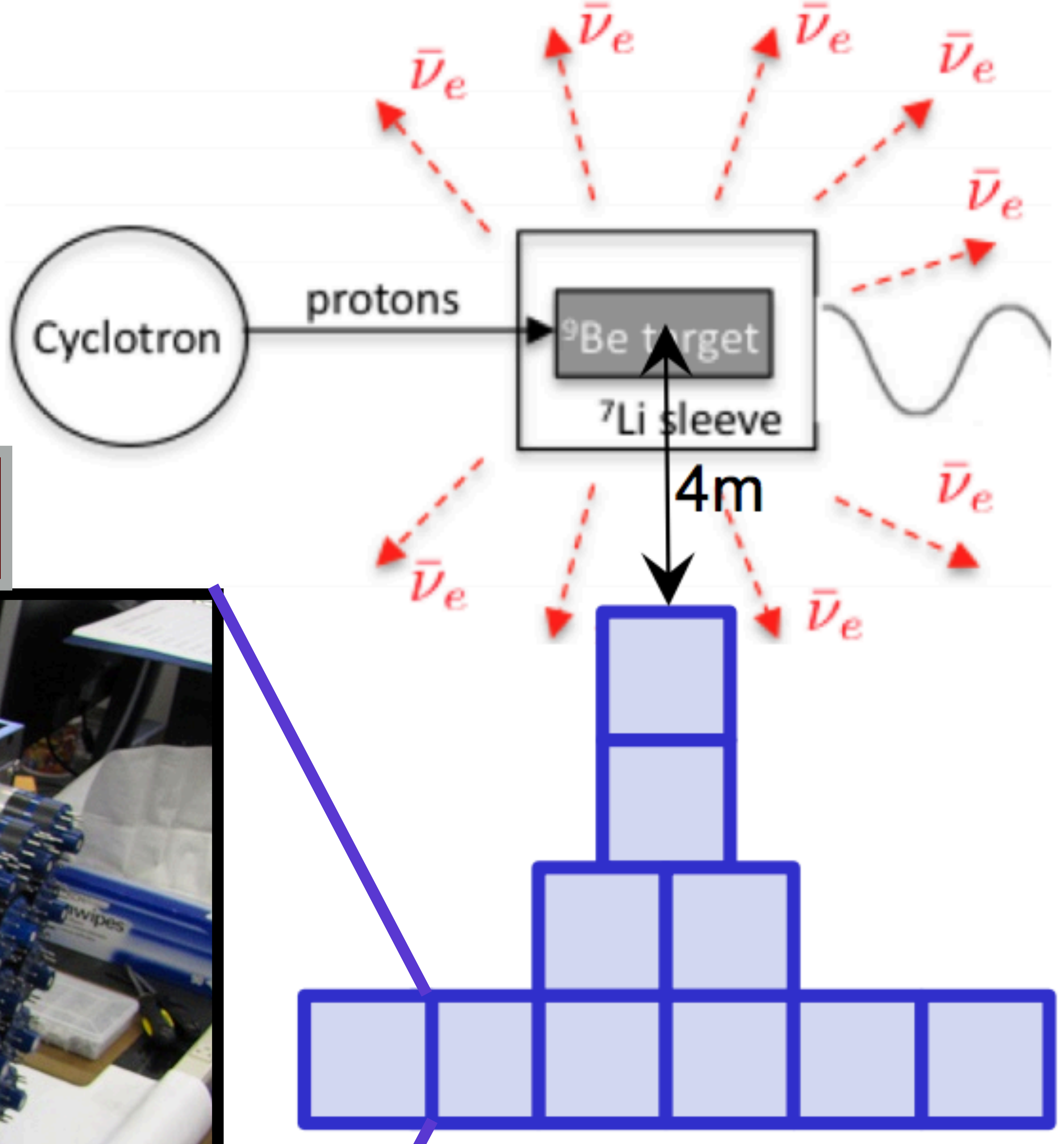
Virginia Tech is home to a scalable, "mobile" $\bar{\nu}_e$ detector called CHANDLER.

Could IsoDAR be combined with a CHANDLER-style detector?

- Similar energy resolution to KamLAND (6.5% at 1MeV).
- Better spatial resolution due to segmented cells.
- Lower fiducial volume, but can be strategically positioned.
- Pulse shape neutron rejection.

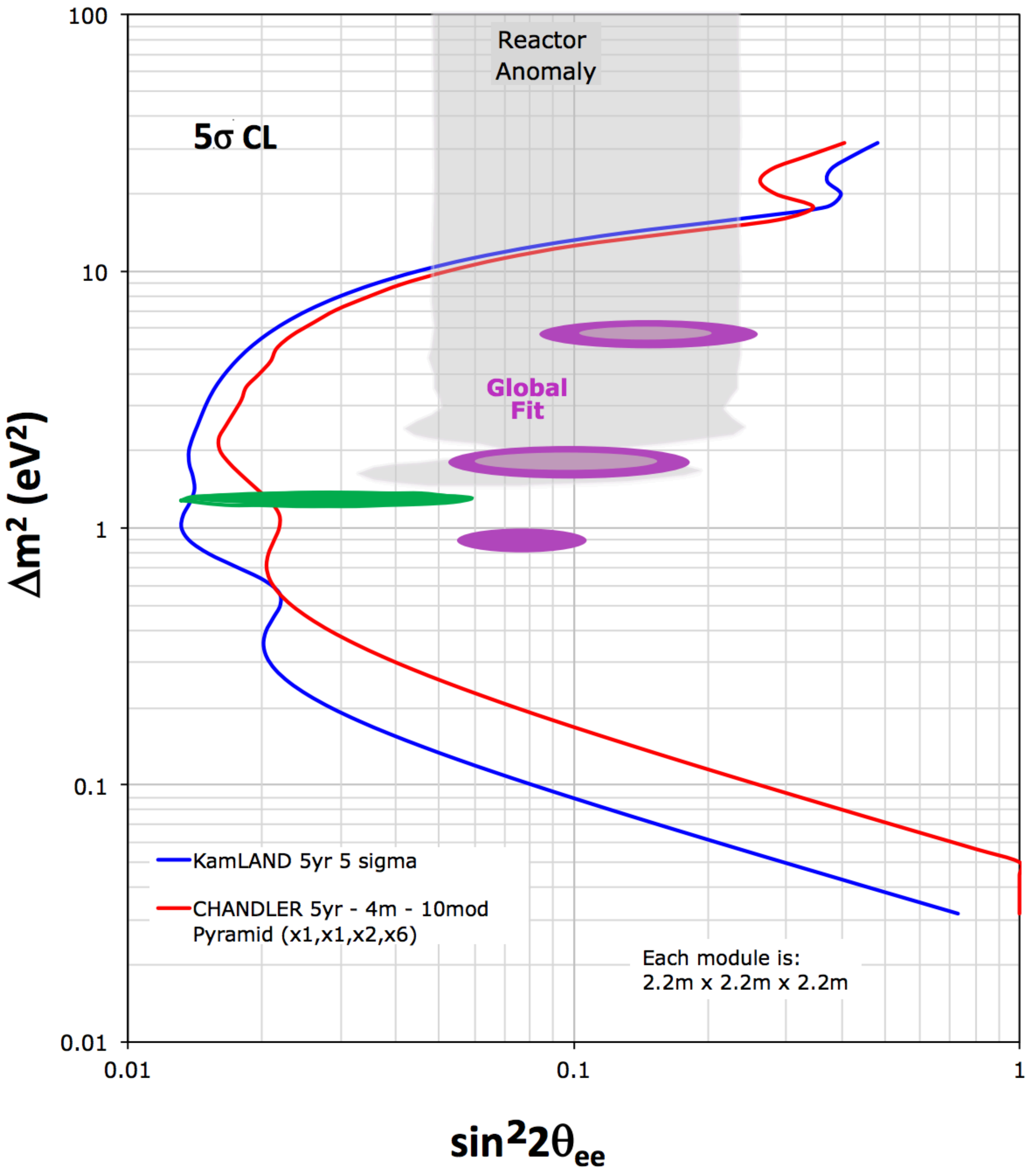
VirginiaTech Invent the Future | Center for Neutrino Physics

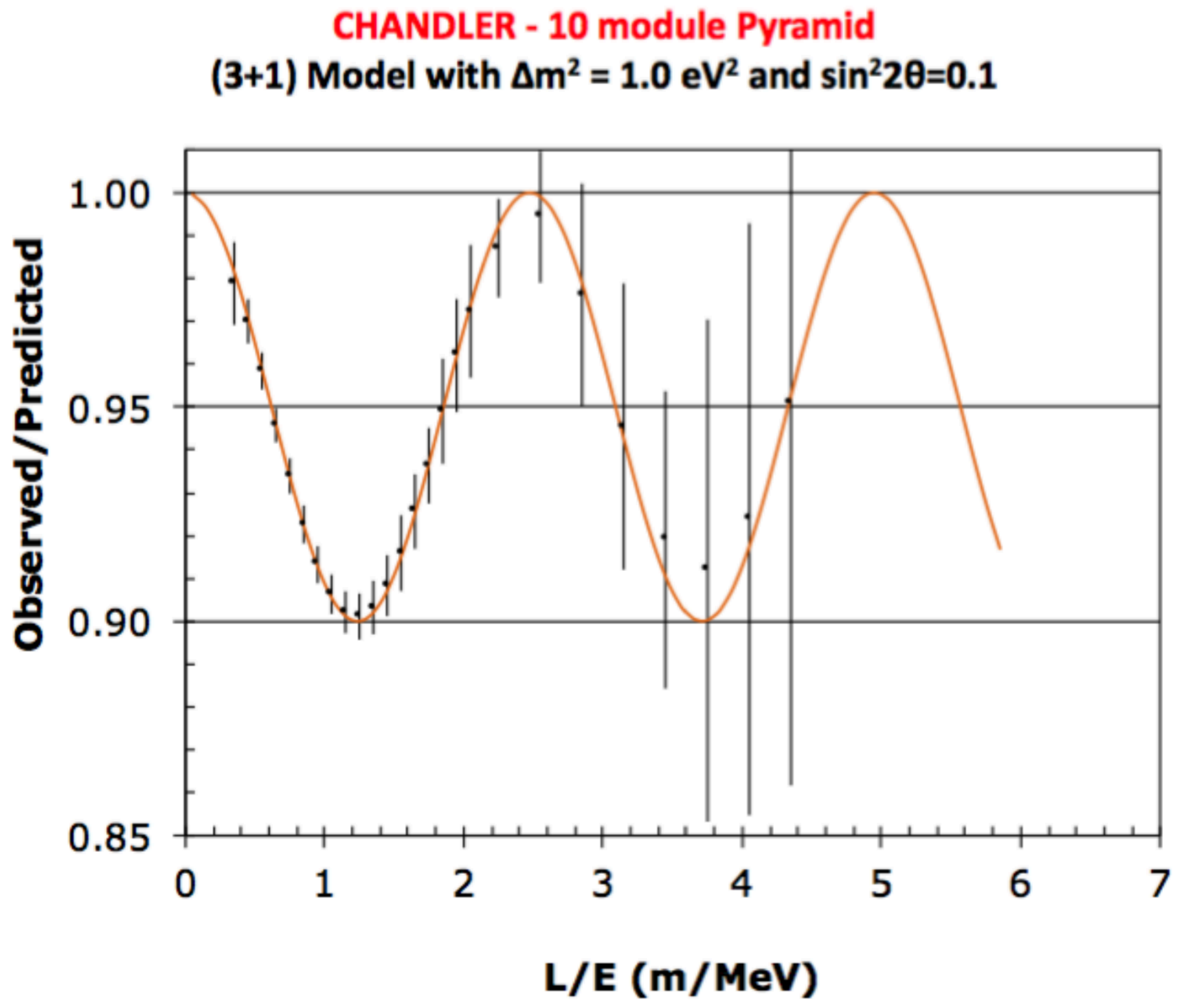




- Ten large CHANDLER-based detectors, each: 2.2m x 2.2m x 2.2m

Plots courtesy of Mike Shaevitz.

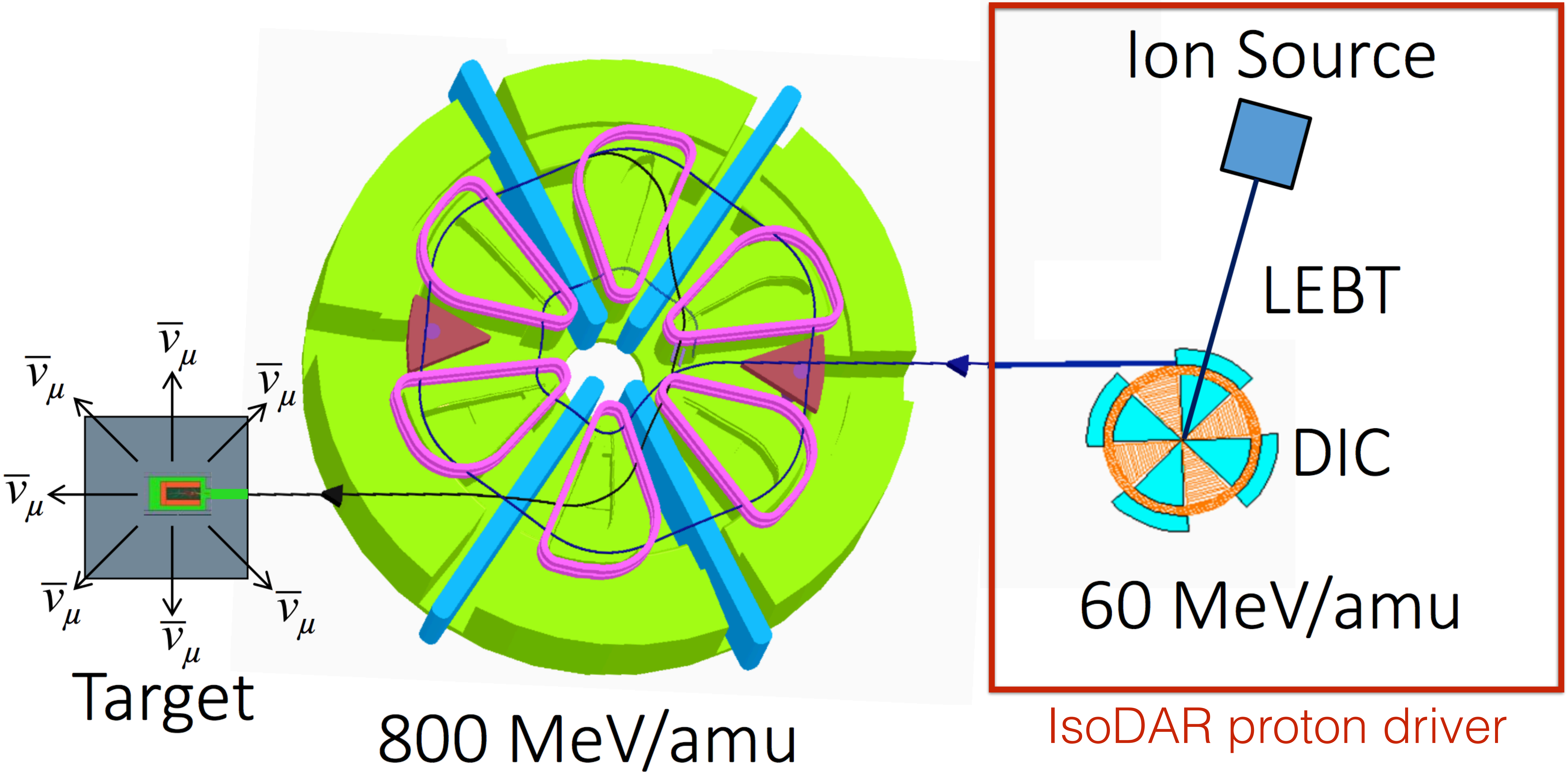




Improved statistics at low L/E in the first disappearance.

The Daeδalus experiment

(Decay At rest Experiment for δ_{cp} At Laboratory for Underground Science)

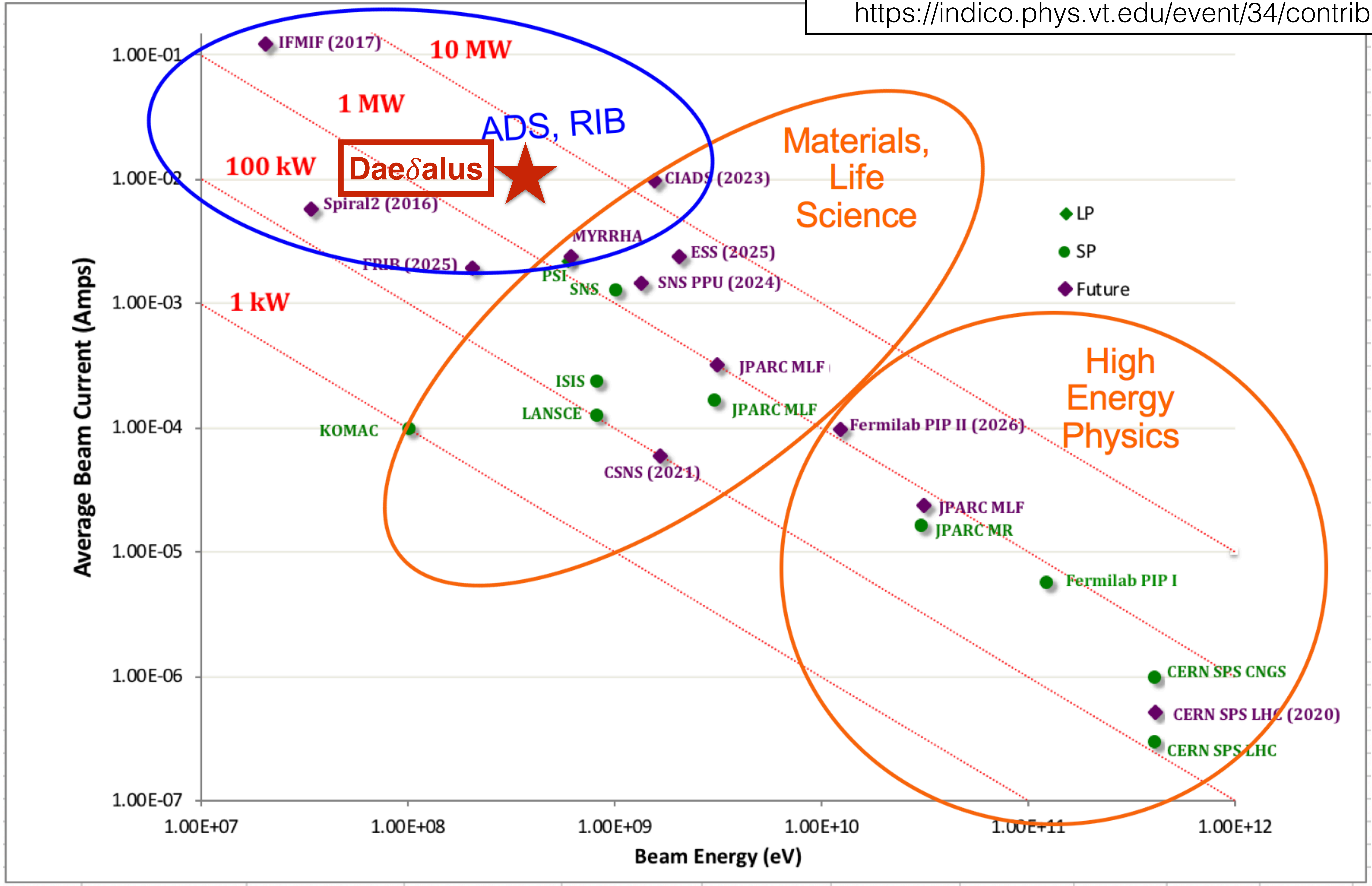


The Daeδalus δ_{cp} measurement

The Daeδalus δ_{cp} measurement

The Daeδalus accelerator for accelerator driven systems (ADS)

Modified from **Sarah Cousineau's** NuFact talk on Tuesday: https://indico.phys.vt.edu/event/34/contributions/609/



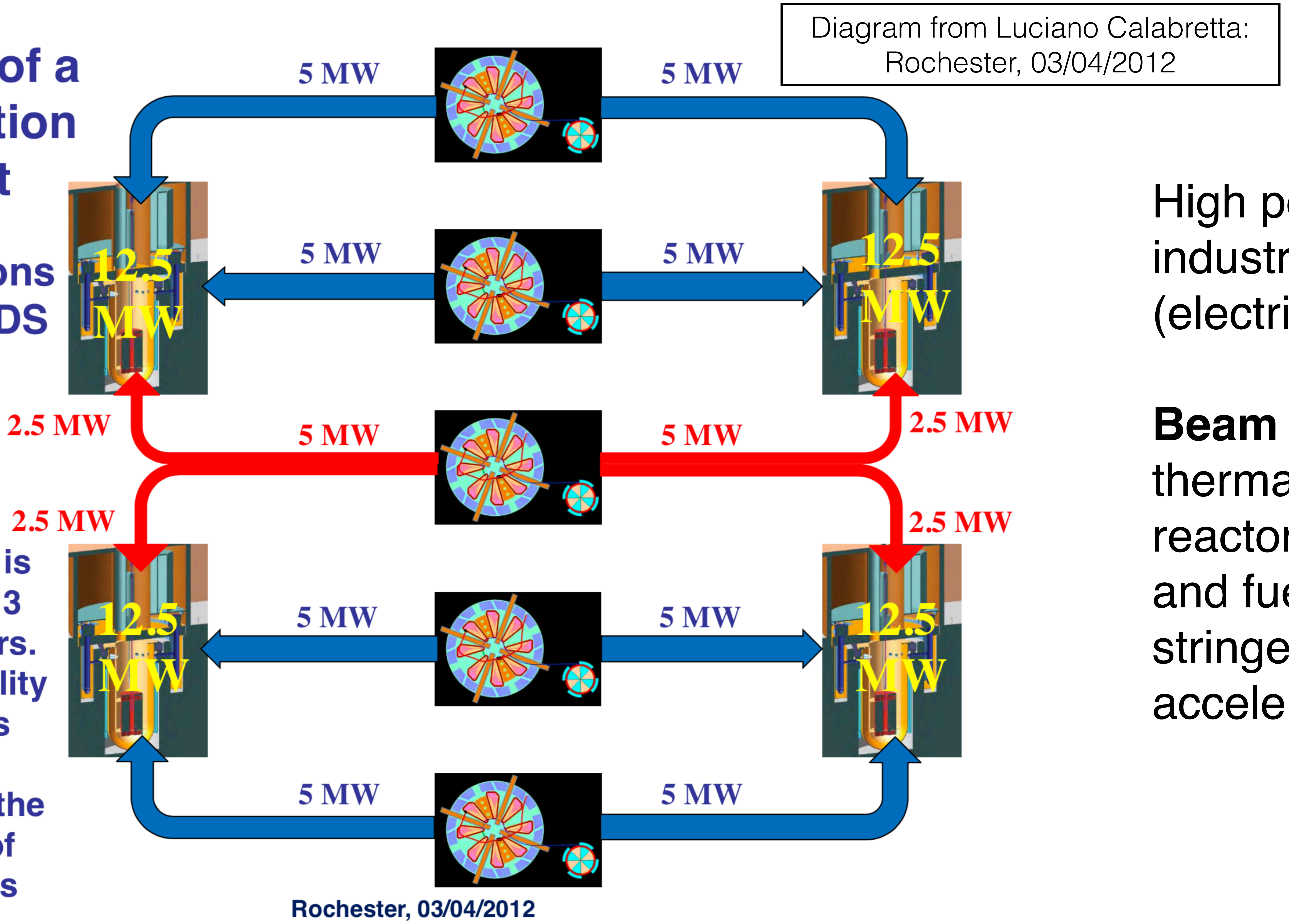
Accelerated Driven Nuclear Technology:

- Nuclear power generation
- Can be used with Thorium based fuel cycle
- operate far from “prompt criticality” (safety)
- Transmutation of long lived nuclear wastes (actinide burning)

The Daeδalus accelerator for ADS

Layout of a production plant

5 cyclotrons drive 4 ADS

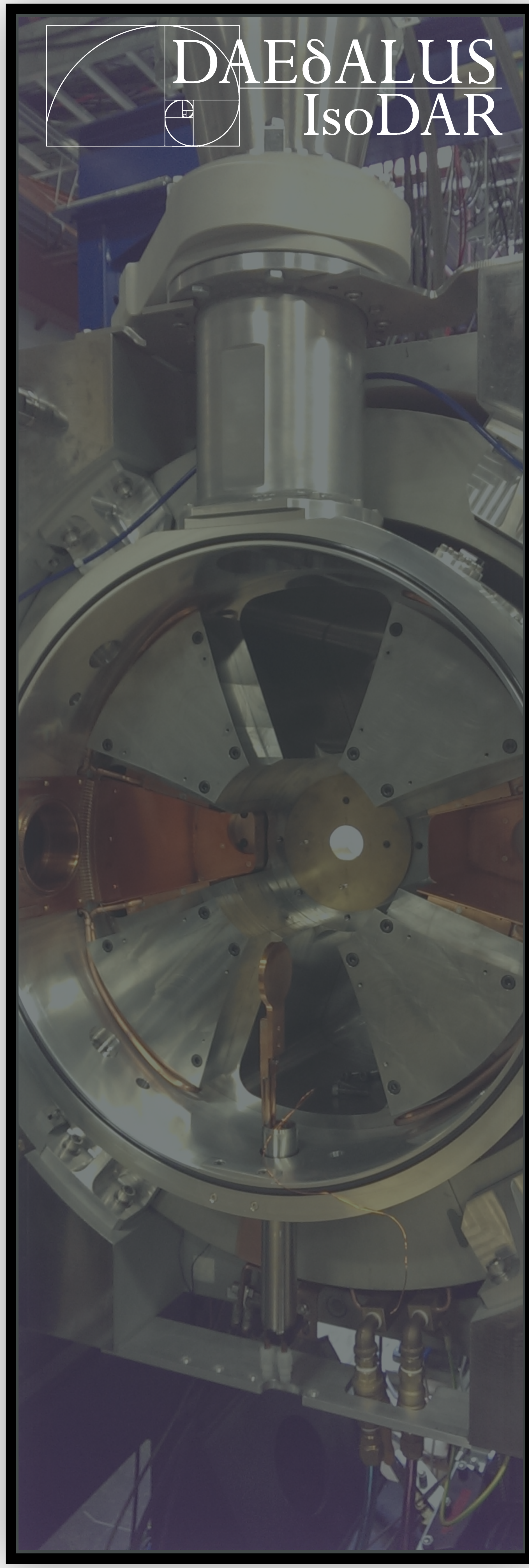


Each ADS is driven by 3 accelerators. Beam stability increases and decreases the number of beam trips

High power requirements for industrial scale applications (electricity generation)

Beam Trip Frequency: thermal stress and fatigue in reactor structural elements and fuel assembly sets stringent requirements on accelerator reliability.

Design basis from S. Henderson, Thorium Energy Conference 2011



Summary

IsoDAR has a broad physics reach.

Accelerator Physics | **Medical Physics** | **Particle Physics**

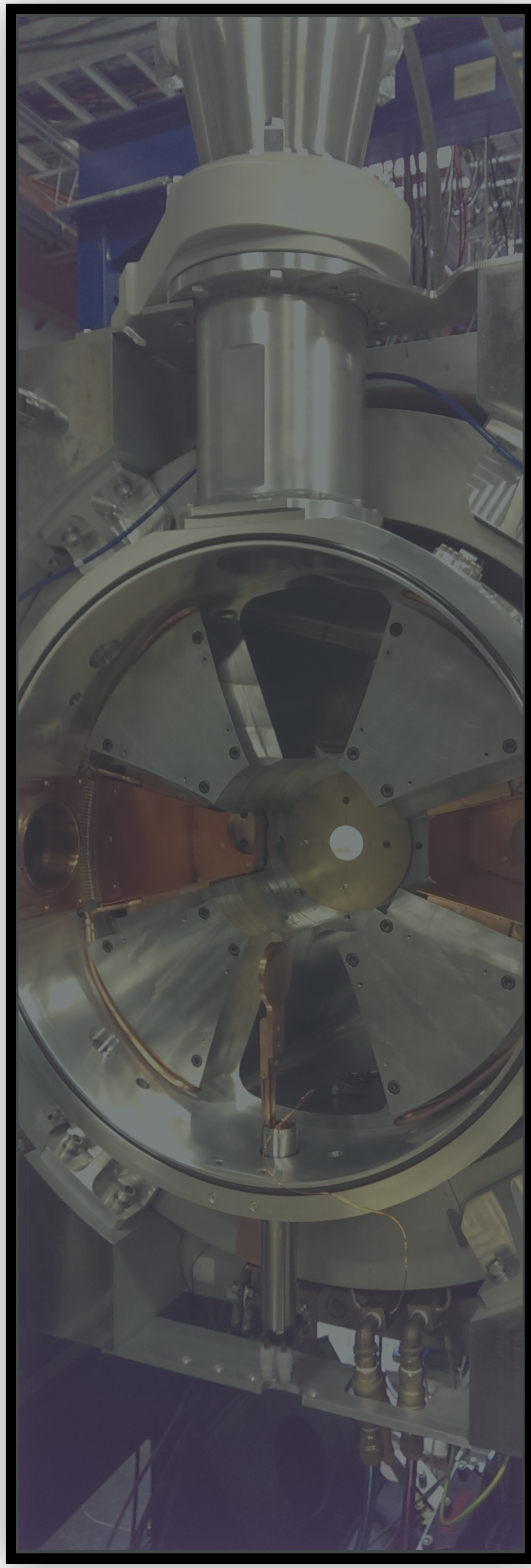
Innovations in H_2^+ multicusp ion source development and RFQ axial injection into a cyclotron will push the cyclotrons into the high-intensity frontier.

The IsoDAR cyclotron can be used for medical isotope production, and for a decisive short baseline neutrino oscillation measurements:

- Probe the global best fit allowed regions to 5σ in just 4-months of livetime.
- Test 3+1 versus 3+N hypothesis.
- Precision sterile measurement

The high-intensity cyclotrons could lead to larger δ_{cp} measurements, and are suitable for accelerator driven nuclear reactors.

Thanks for your attention!



Thanks for your attention!

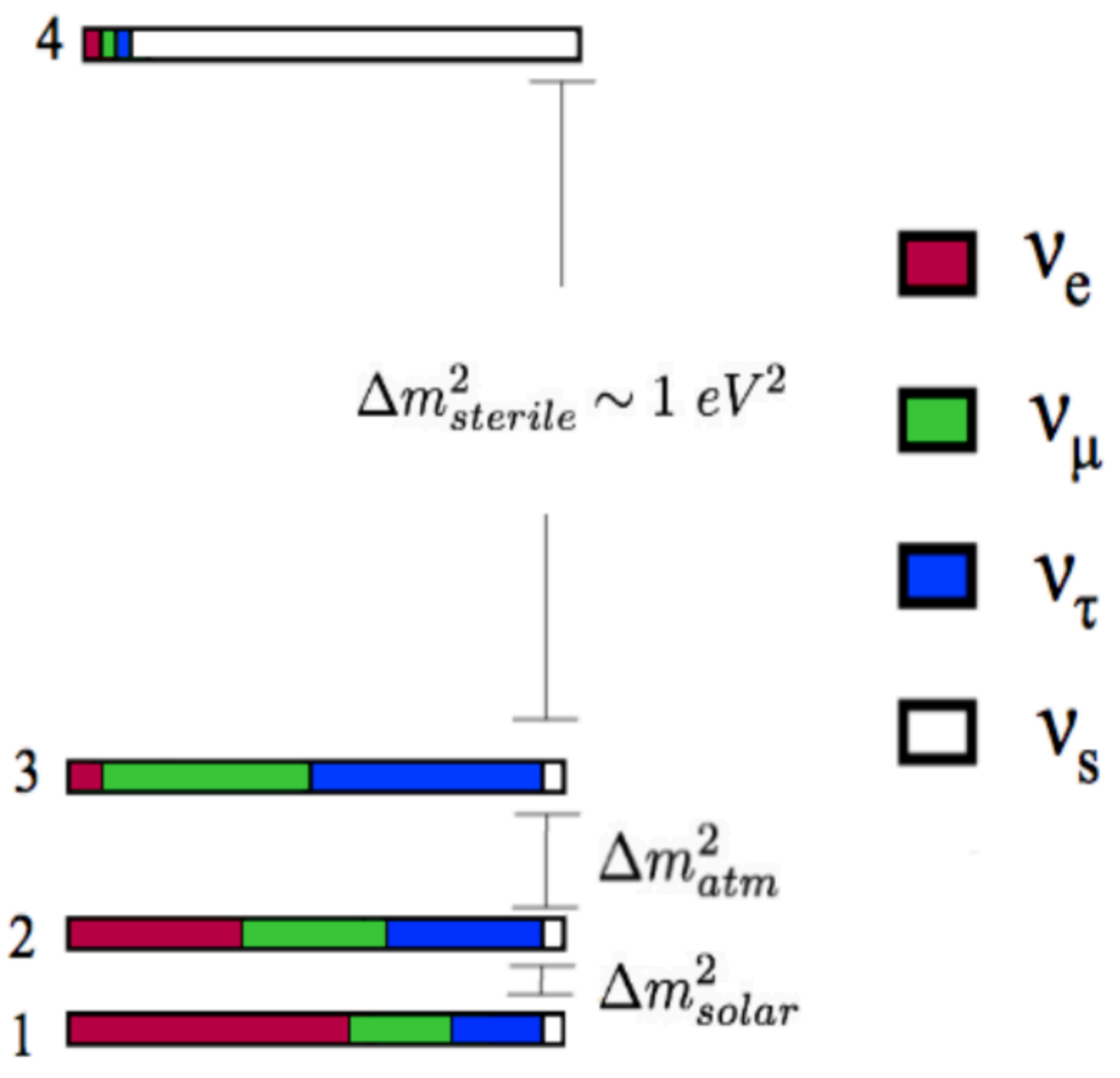
Sterile Neutrino Overview

Backup

Modern searches for ~1 eV scale light sterile neutrinos are motivated by a set of observed anomalies.

Oscillation Channel	Class	Anomalous signals (>2σ)
ν_e disappearance $P(\nu_e \to \nu_e)$	Reactor/Source Experiments	GALLEX ($\bar{\nu}$) SAGE ($\bar{\nu}$) {Global Reactors}
ν_μ disappearance $P(\nu_\mu \to \nu_\mu)$	Long/Short Baseline Experiments	none
ν_e appearance $P(\nu_\mu \to \nu_e)$	Short Baseline Experiments	LSND ($\bar{\nu}$) MiniBooNE ($\bar{\nu}$, ν)

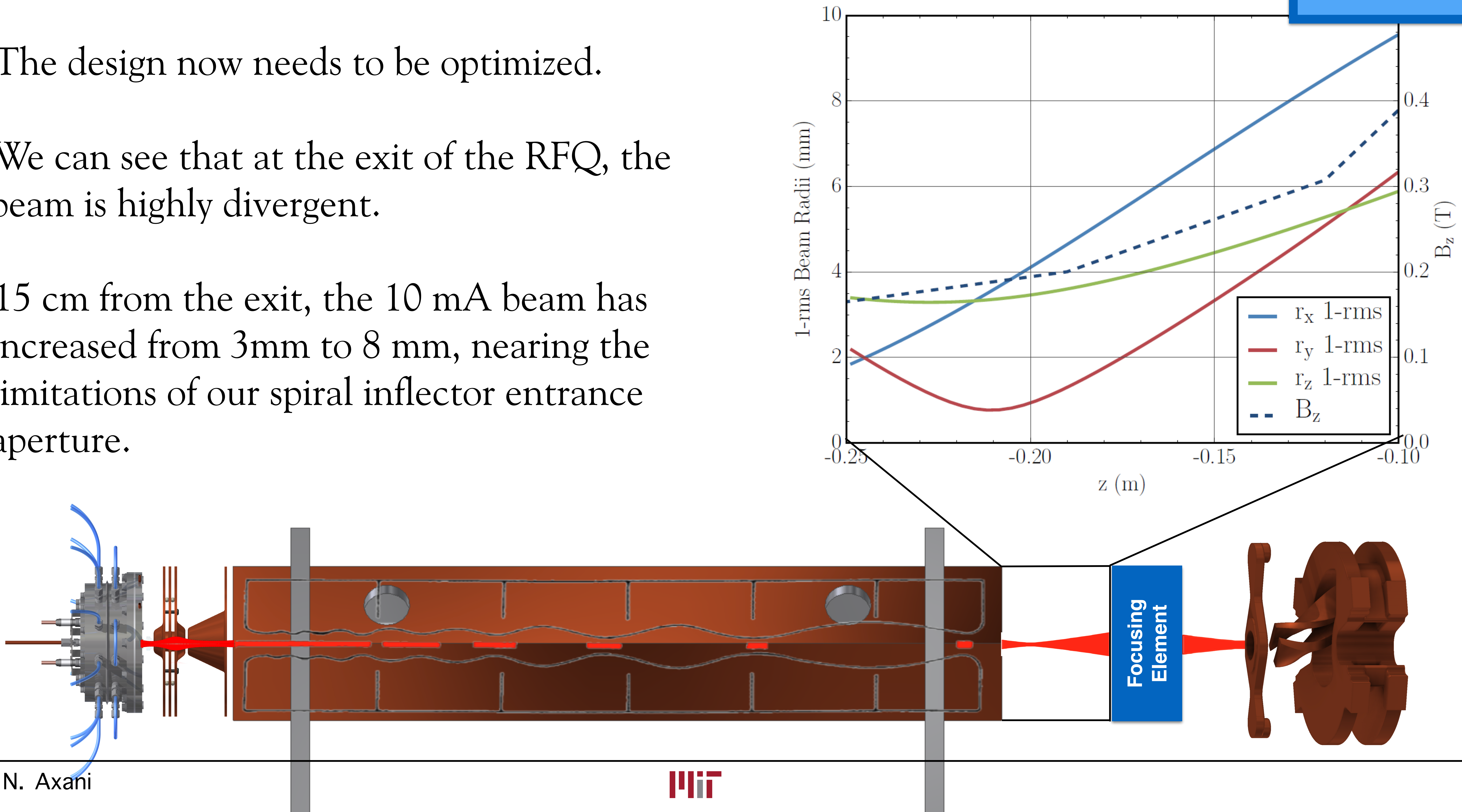
Sub-set of null results
KARMEN Daya Bay Bugey-3
MiNOS CCFR84 IceCube
NOMAD KARMEN



Many of the proposed experiments to test the light sterile neutrino hypothesis do not have sufficient sensitivity to make a definitive >5σ statement.

H2+ production cross-section

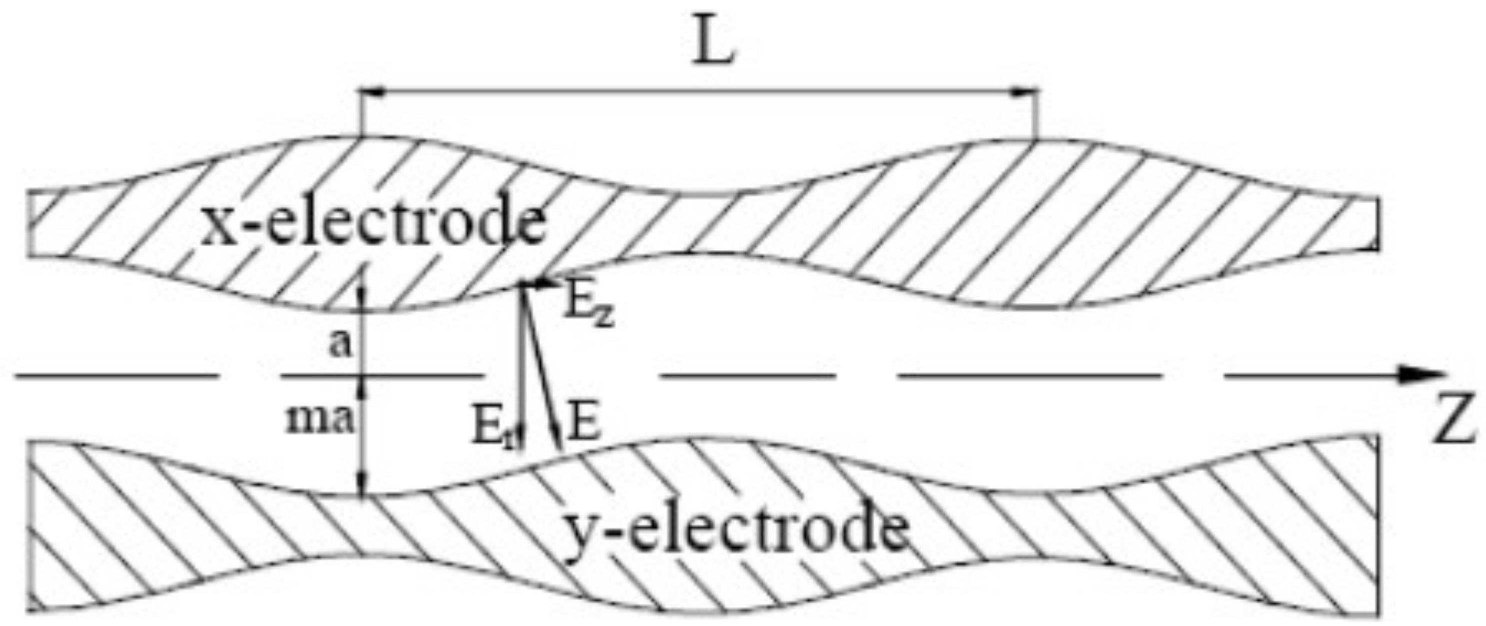
- The design now needs to be optimized.
- We can see that at the exit of the RFQ, the beam is highly divergent.
- 15 cm from the exit, the 10 mA beam has increased from 3mm to 8 mm, nearing the limitations of our spiral inflector entrance aperture.

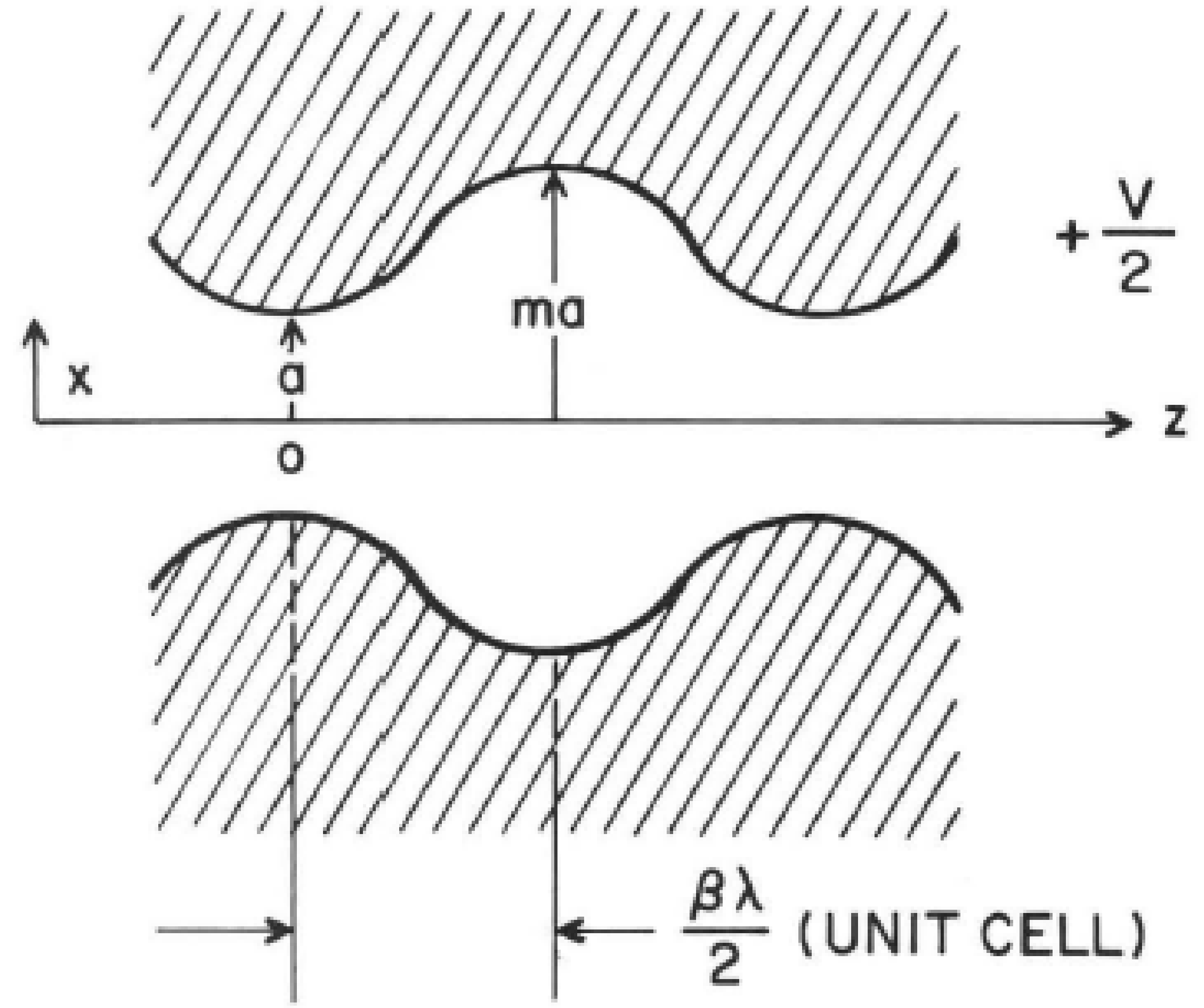


RFQ parameters

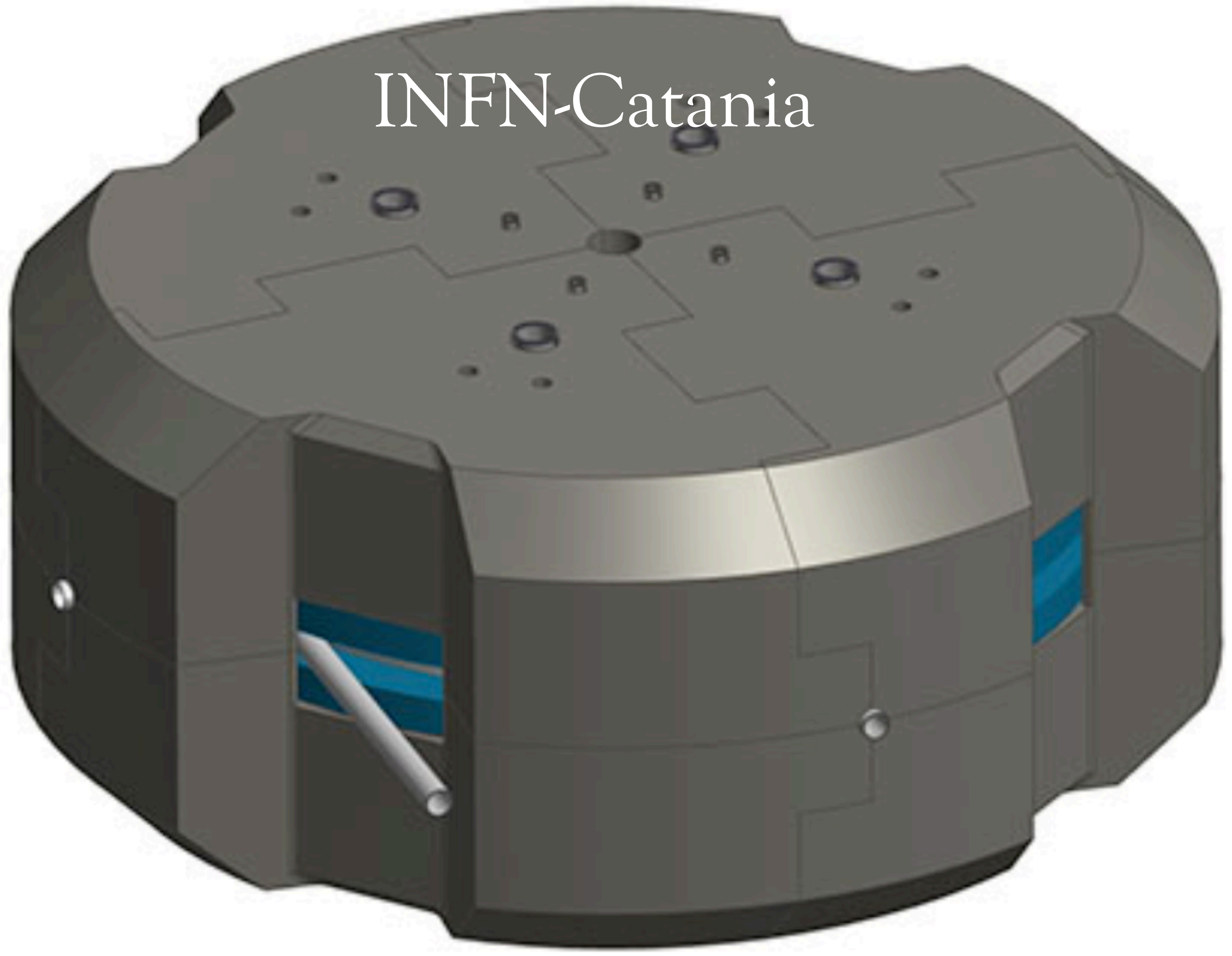
Backup

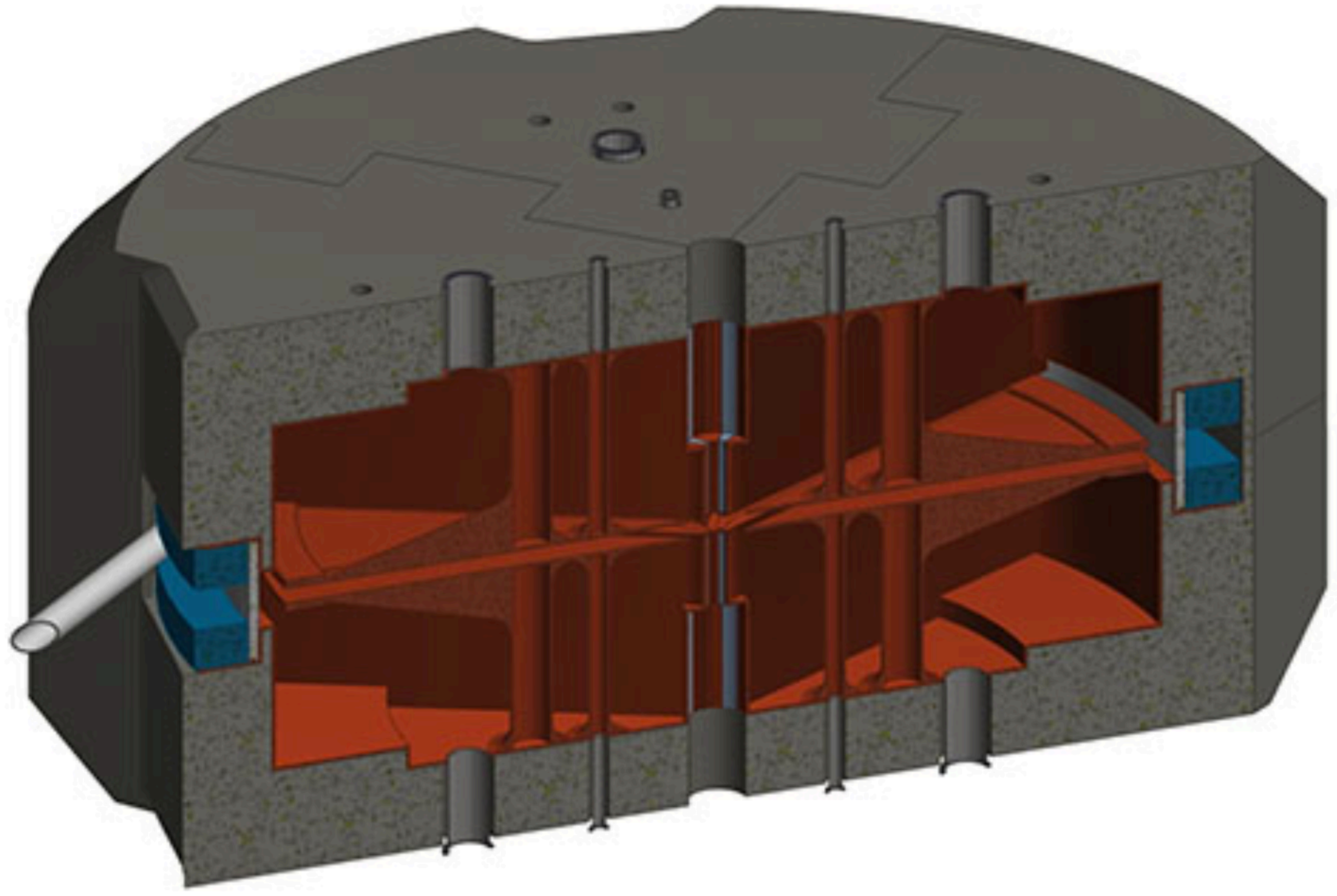
Parameter	Value
Operating frequency	33.2 MHz
Injection energy	15 keV
Final beam energy	80 keV
Design input current	10 mA
Current limit	22 mA
Transmission at 10 mA	99%
Input transverse emittance (6-rms, norm)	0.5 pi-mm-mrad
Nominal vane voltage	43 kV
Bore radius (a)	1.27 cm
Maximum vane modulation (m)	1.94
Structure length	1.09 m
Peak RF field surface gradient	4.66 MV/m
Structure RF power	<9.5 kW
Beam power	0.64 kW
Total input RF power	<10.1 kW

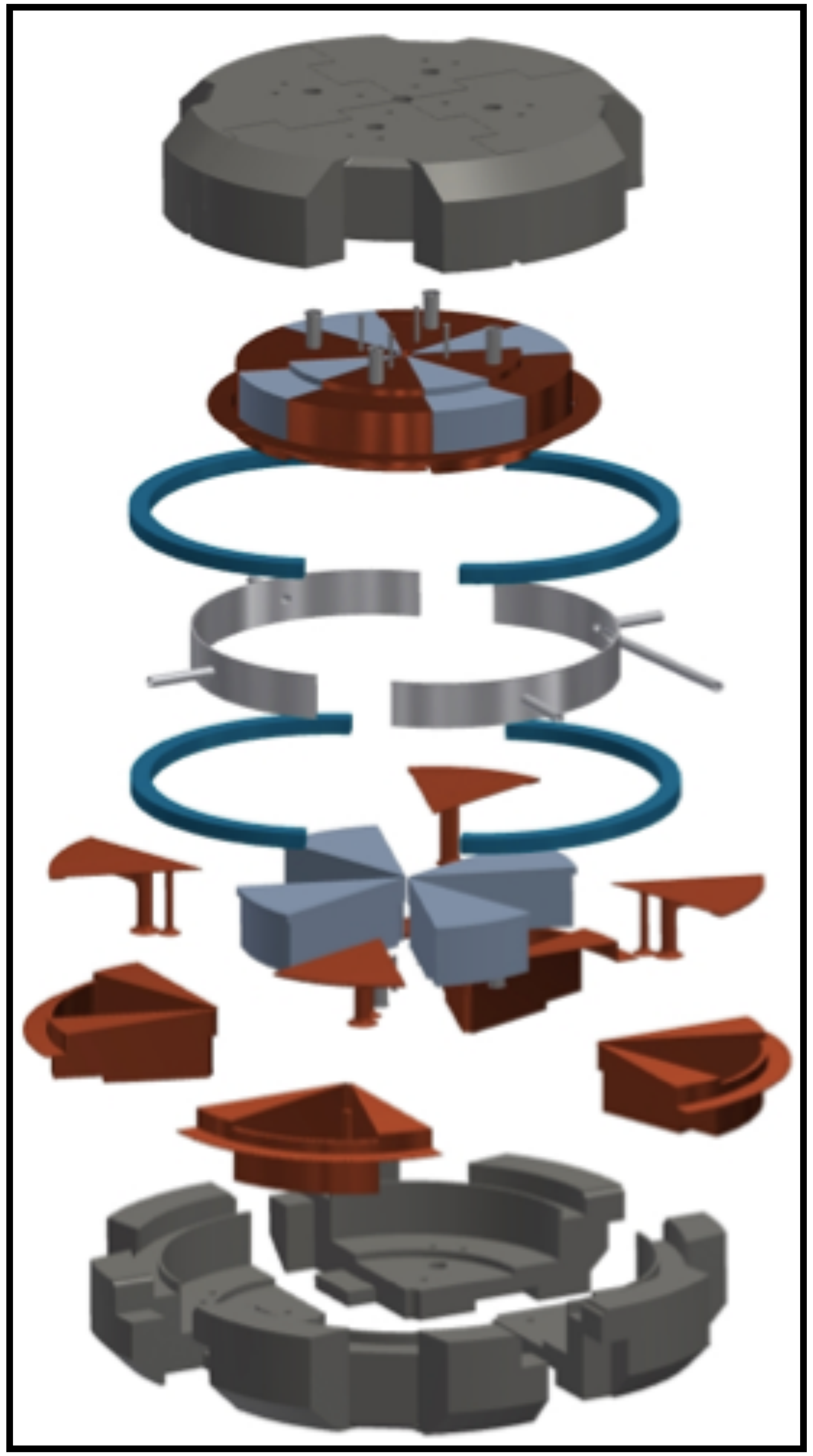




Cyclotron parameters







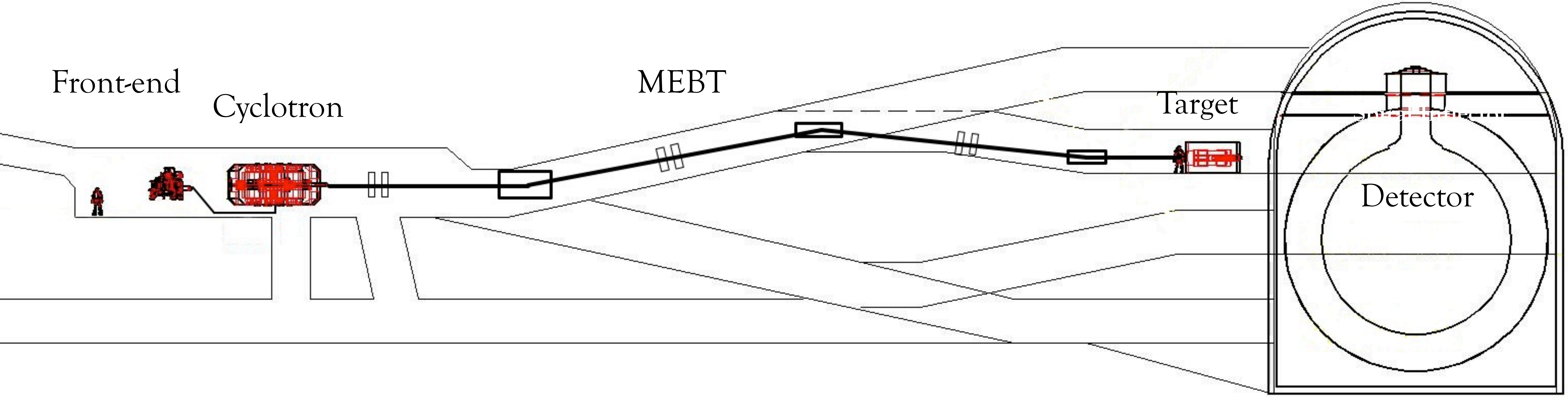
Energy at extraction	60 MeV/amu
Injected energy	35 keV/amu
Radius at extraction	1.99 m
Iron weight	450 tons
Harmonic	4th

Requirements:
- A compact accelerator that can fit into the Kamioka observatory. Mine entrance size restriction and weight limits.
- Extract 10 mA @ 60 MeV protons

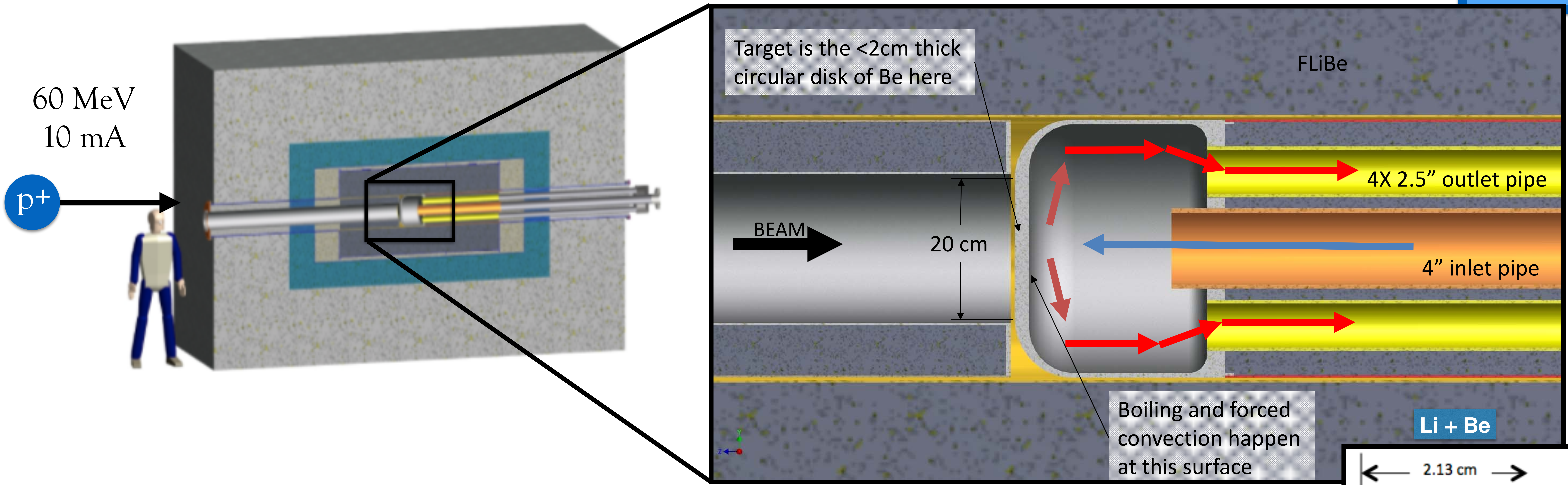
Innovations:
- Usage of H_2^+:
  - decrease the space charge effects
  - 2 protons per ion
  - eliminates the problem of Lorentz stripping
- Inject highly bunched beam from an intense ion source.

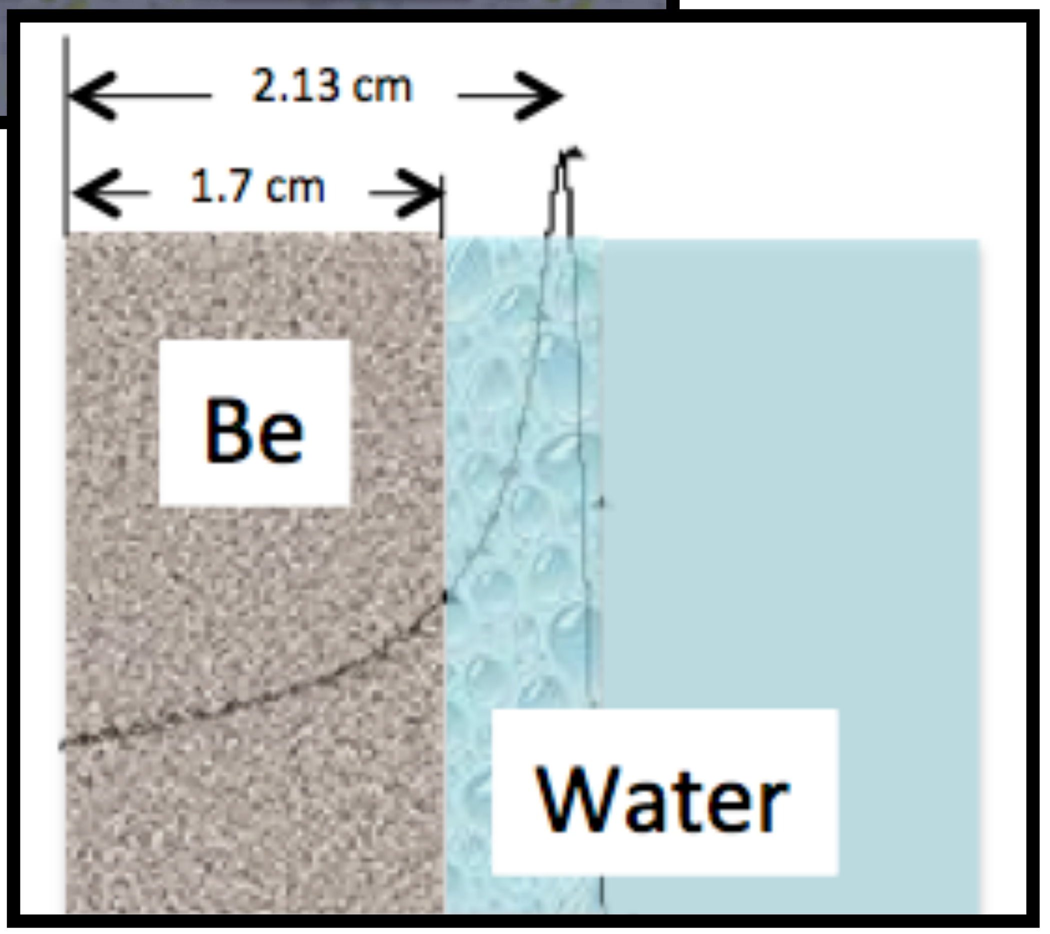
Location in the mine

Backup



Target design and cooling

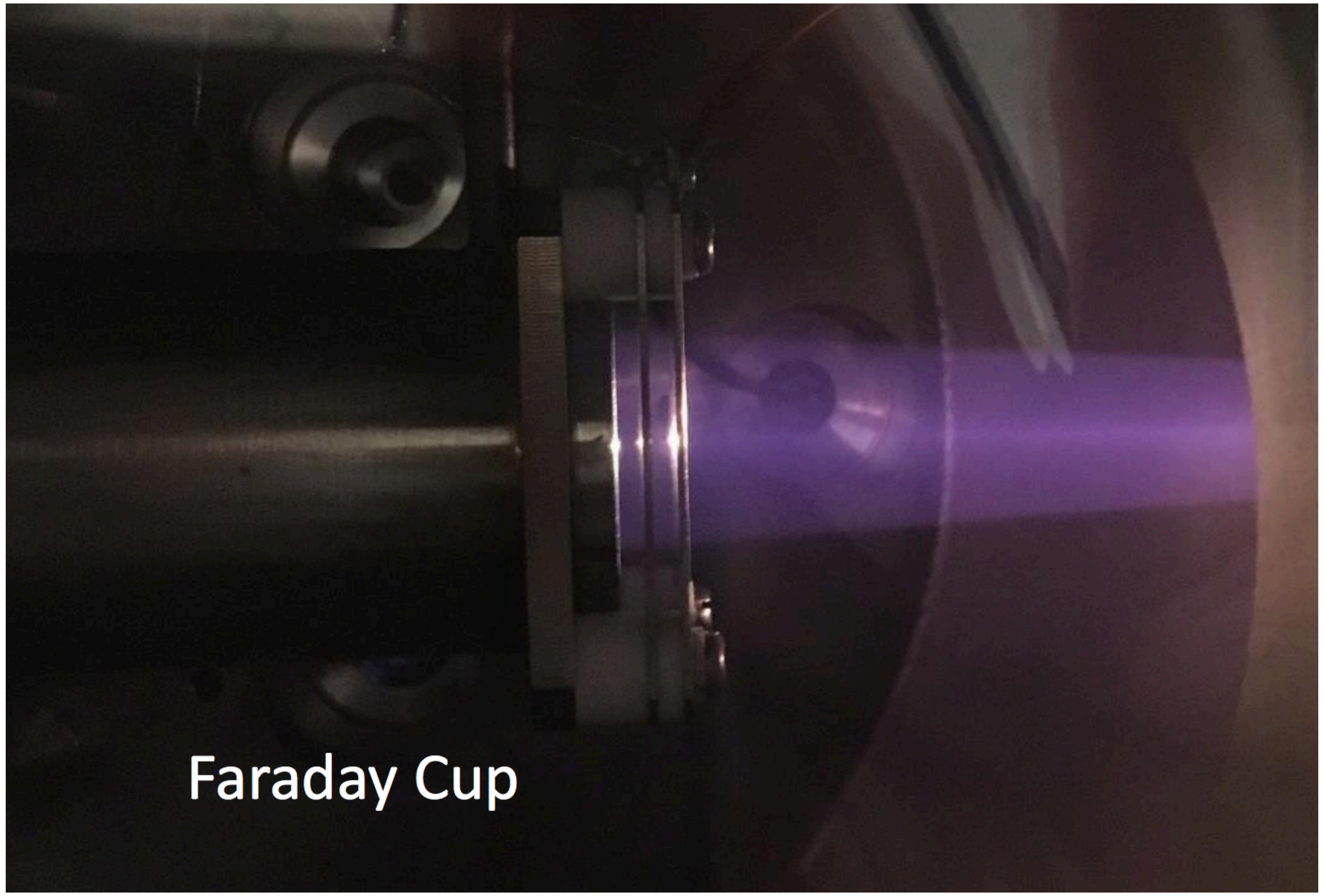


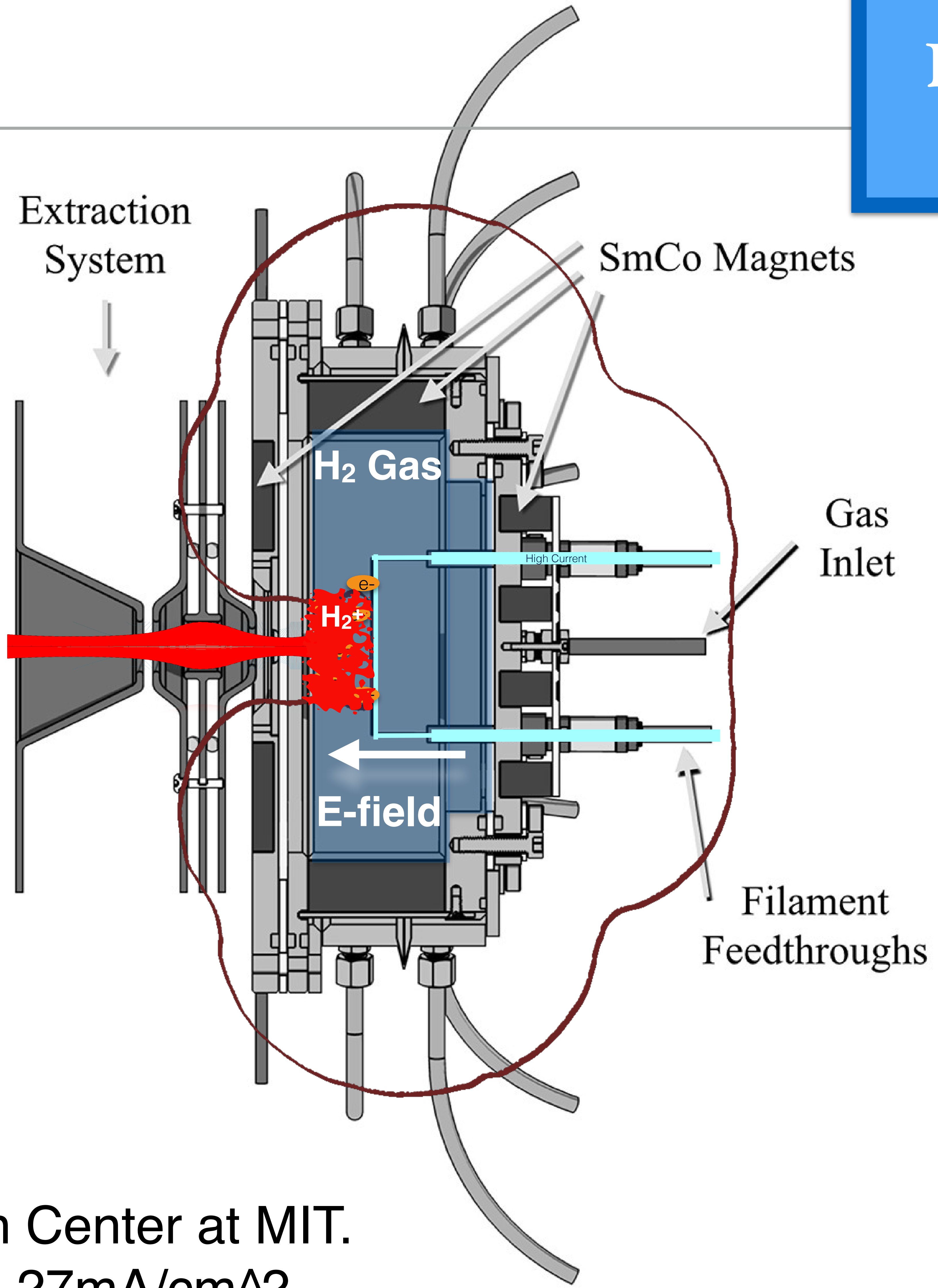


Beam: 600kW
NSF proposal to make a beryllium prototype target
+ simulation + CFD
Test cooling design.

H_2^+ Ion source development

Backup





MIST-v1 is being optimized at the Plasma Science and Fusion Center at MIT. First beam was about a year ago. Currently we've extracted 27mA/cm^2. See Joe Smolsky's talk for further details [link].

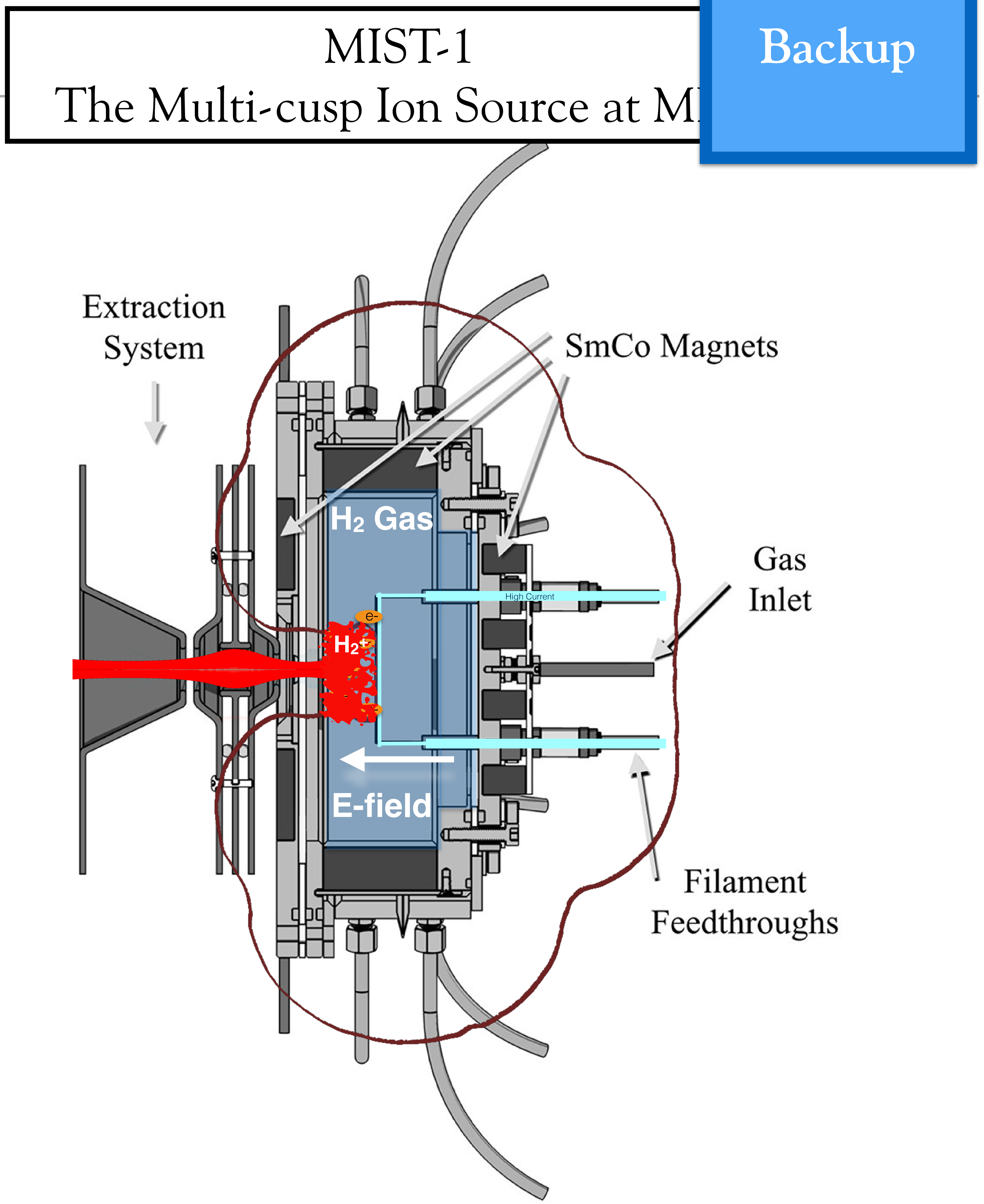
H_2^+ Ion source development

1. We form a multicusp magnetic field around a vacuum chamber

2. Introduced molecular hydrogen into the vacuum chamber and apply an O(100V) electric field in the direction of the extraction.

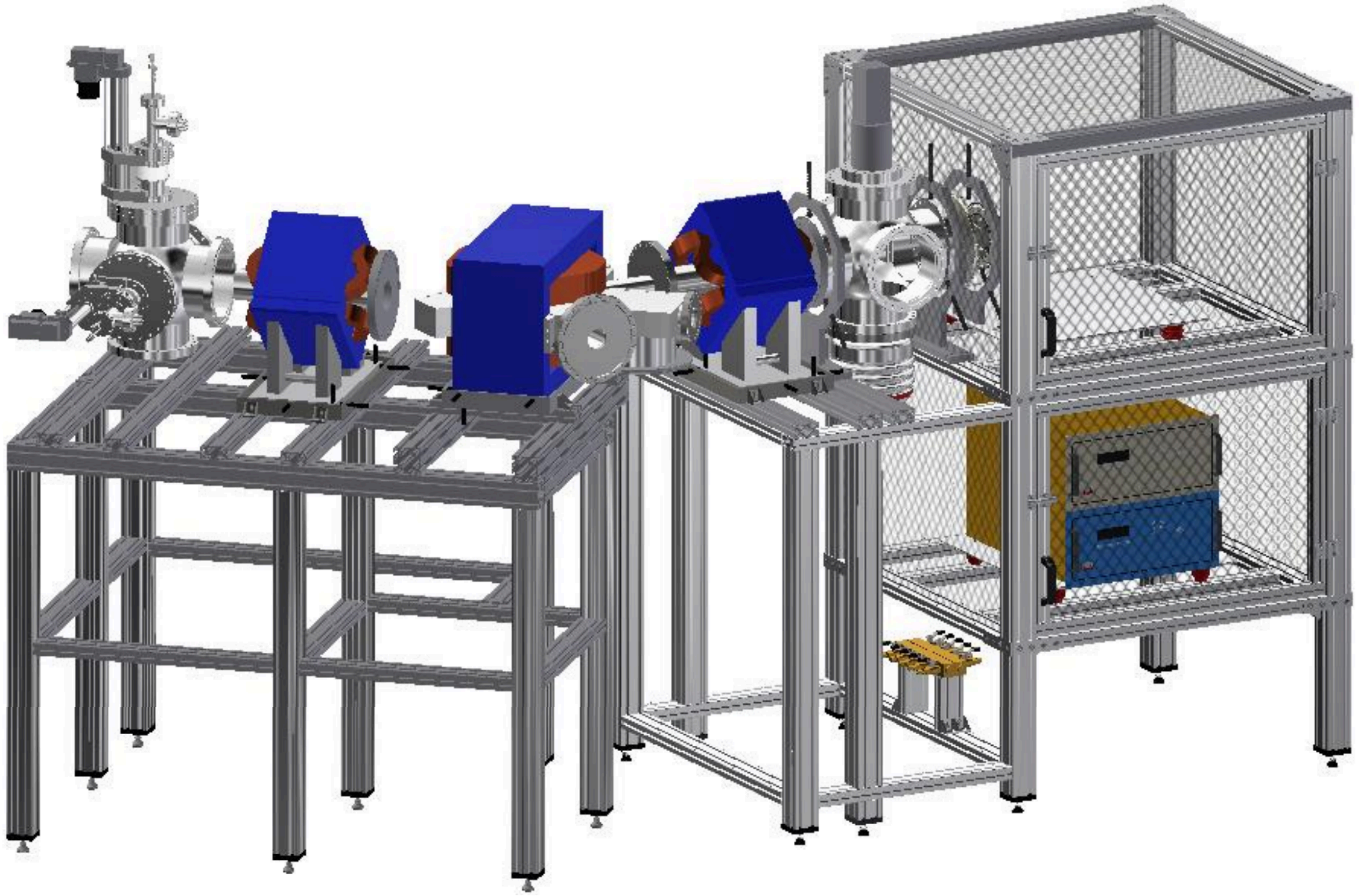
3. Pass a high current through a filament to boil off electrons that are then accelerated towards the extraction plate.

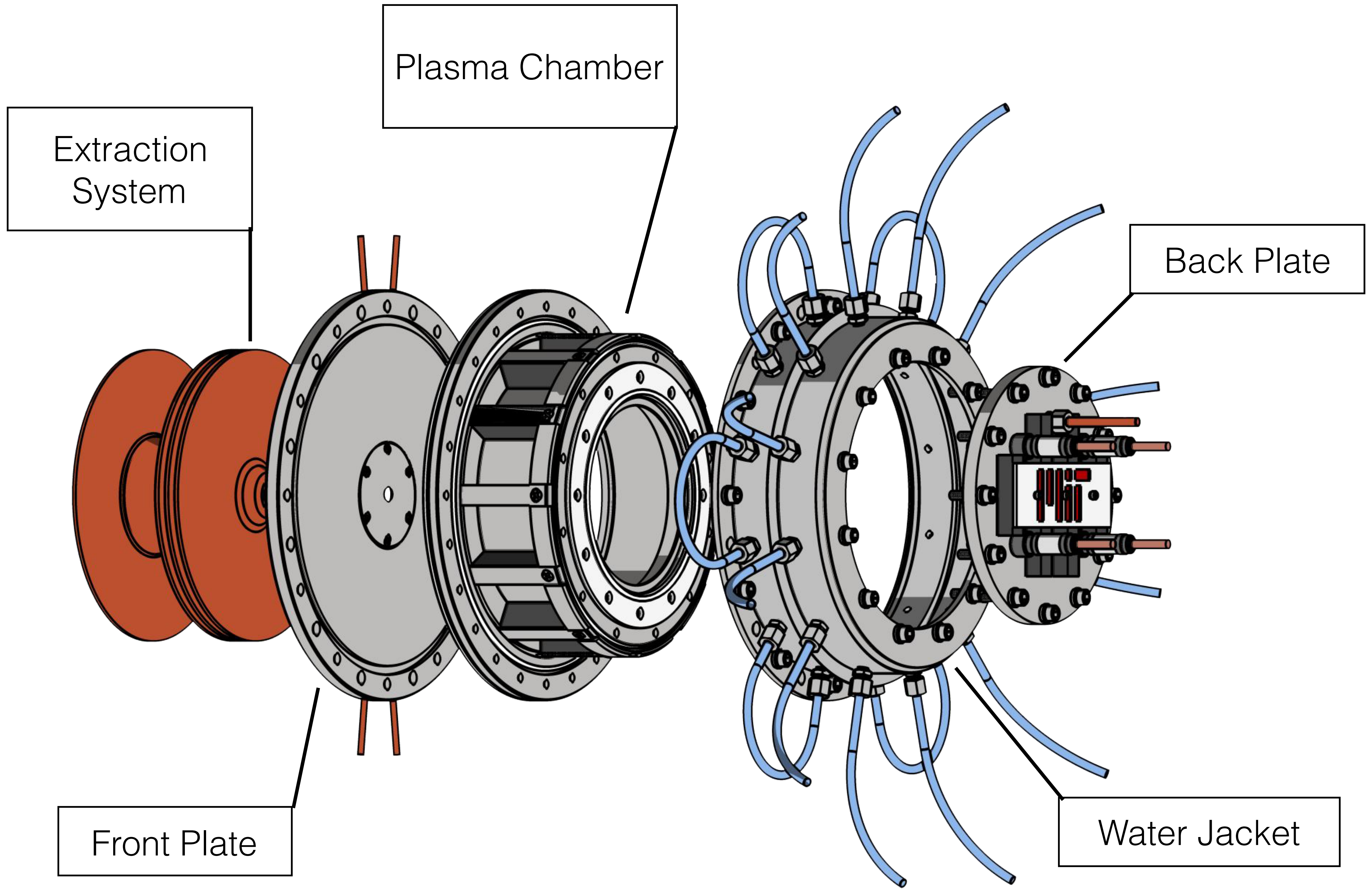
4. The interaction of the electrons with the hydrogen gas cause ionization. Extract and accelerate.



H_2^+ Ion source development

Backup





Daedalus

Backup