IsoDAR and DAEδALUS

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DPF, 8/4/2015

The DAEδALUS program

- The cyclotron as a new, intense source of decay-at-rest neutrinos.
  - High-Q isotope

$$^{8}\mathrm{Li} \rightarrow {}^{8}\mathrm{Be} + e^{-} + \overline{\nu}_{e}$$

  - Pion/muon

$$\pi^{+} \rightarrow \mu^{+}\nu_{\mu}$$
$$\mu^{+} \rightarrow e^{+}\nu_{e}\overline{\nu}_{\mu}$$

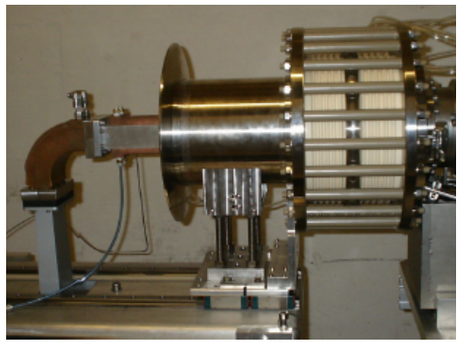
- Sterile neutrinos, weak mixing angle, NSI, δ_{CP}, ν-A coherent scattering, supernova xsec, accelerator, …

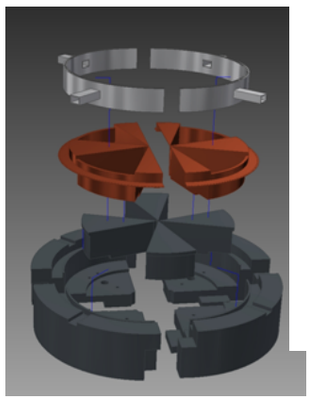
A phased program

Phase	What?	Where?	Science?
I	Produce 50 mA H_2^+ source, inflect, capture 5 mA and accelerate	Best Inc. test-stand INFN Catania	Accelerator science
II	Build the injector cyclotron, extract, produce antinu flux via ^{8}Li	Watchman KamLAND Borexino JUNO	SBL
III	Build the first SRC, run this as a “near accel.” at existing large detector	NOvA LENA Super-K	SBL
IV	Build the high power SRC, construct DAEδALUS	JUNO Hyper-K LENA MEMPHYS	δ_{CP}

The DAEδALUS program

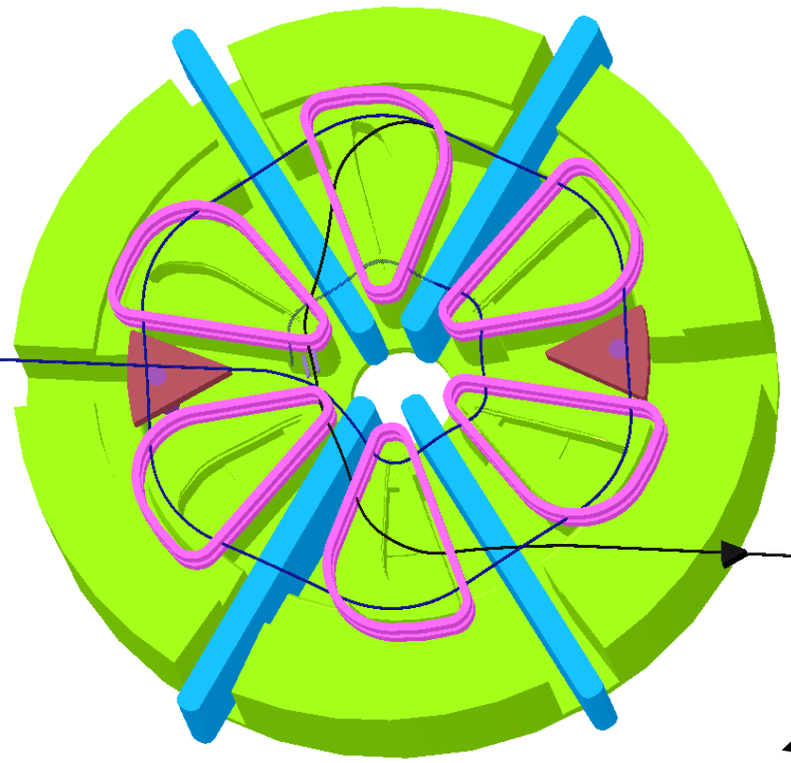
Ion source



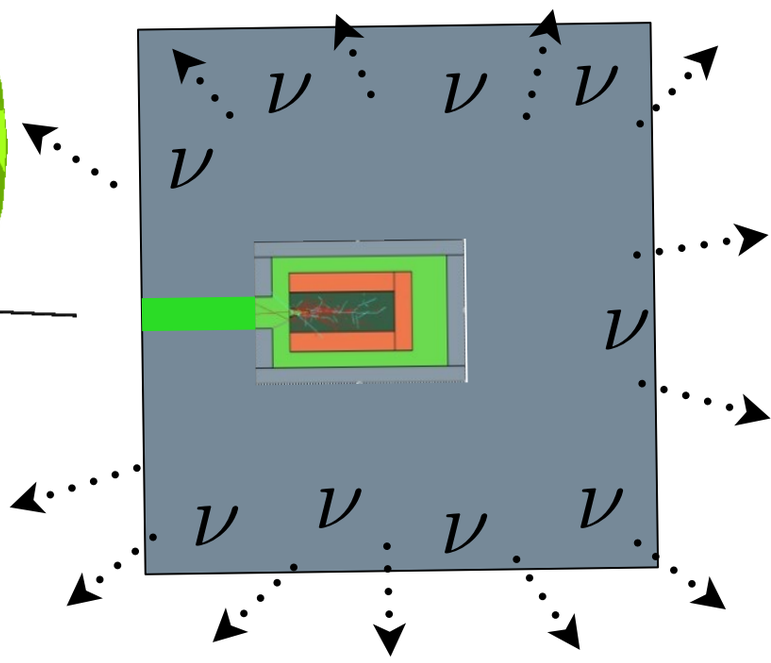


Injector cyclotron
(IsoDAR)

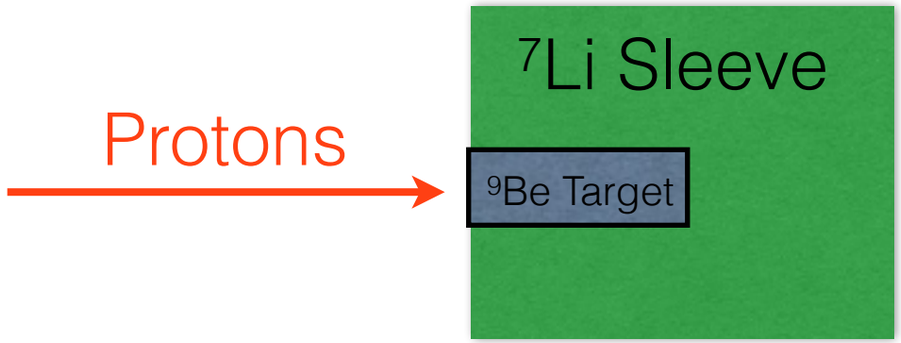
Superconducting
ring cyclotron



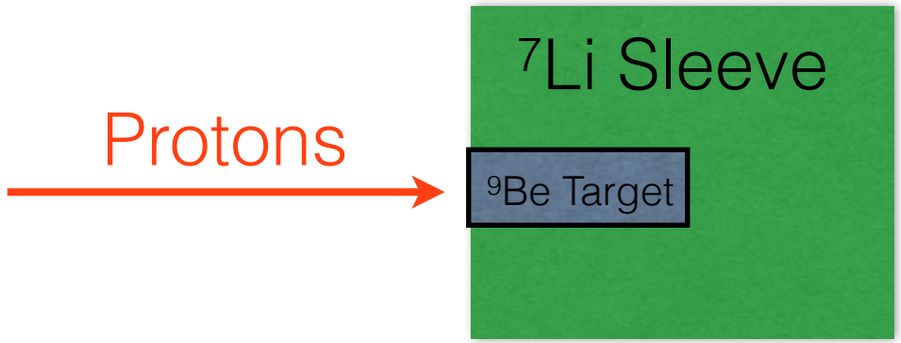
Target/dump



IsoDAR



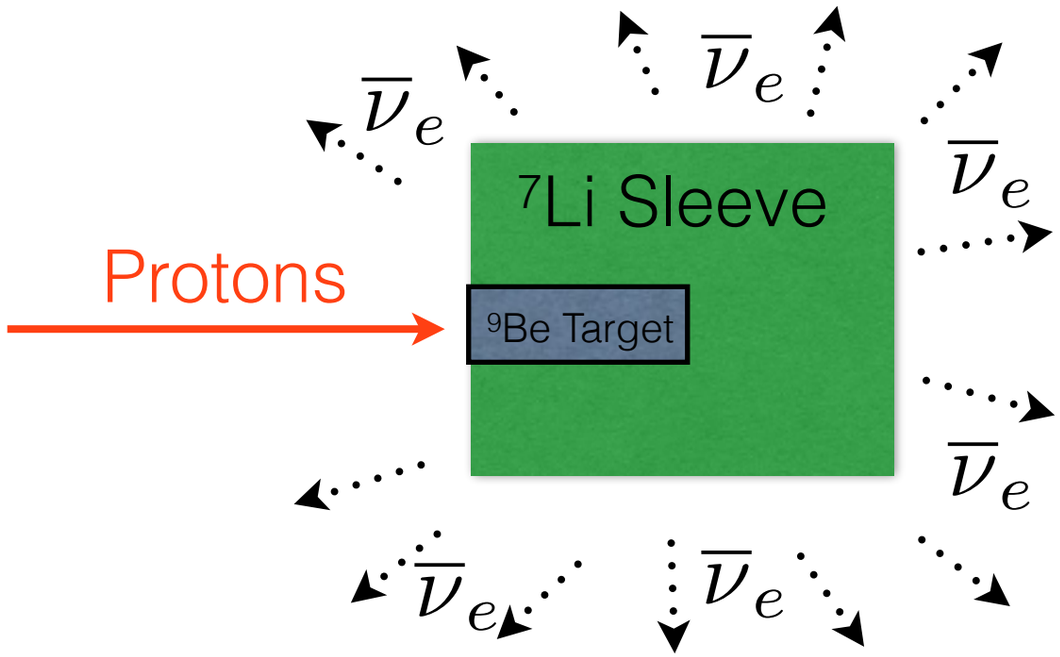
IsoDAR



$$p + {}^{9}\mathrm{Be} \rightarrow {}^{8}\mathrm{Li} + 2p$$

$$p + {}^{9}\mathrm{Be} \rightarrow {}^{9}\mathrm{B} + n$$
$$n + {}^{7}\mathrm{Li} \rightarrow {}^{8}\mathrm{Li} + \gamma$$

IsoDAR



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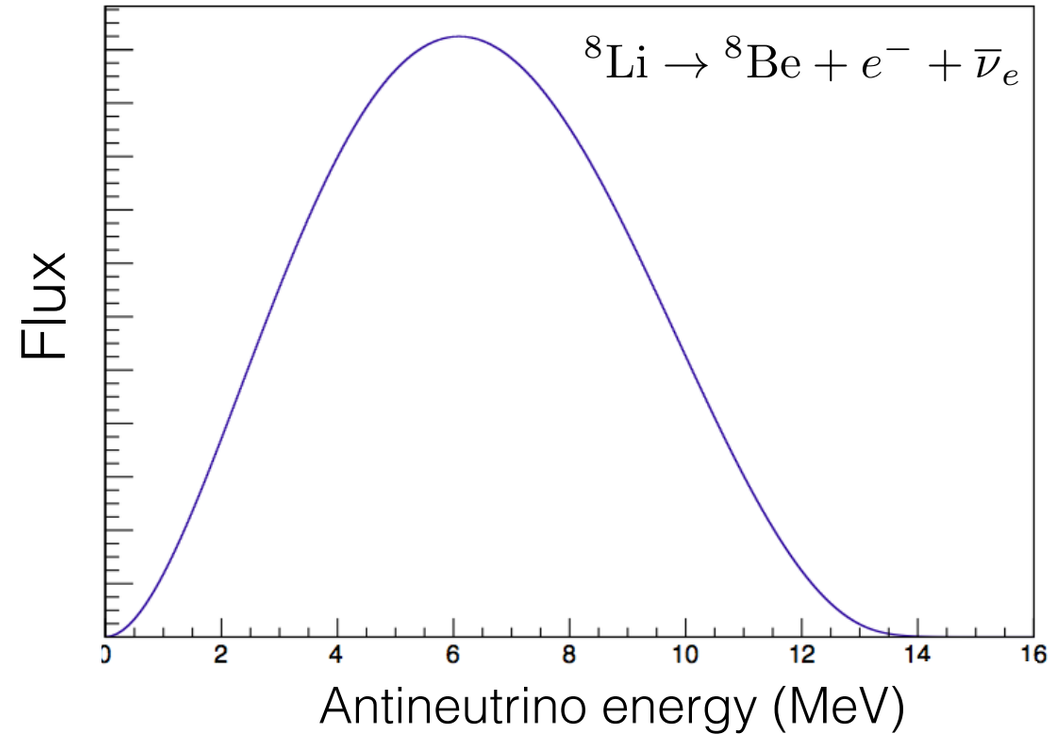
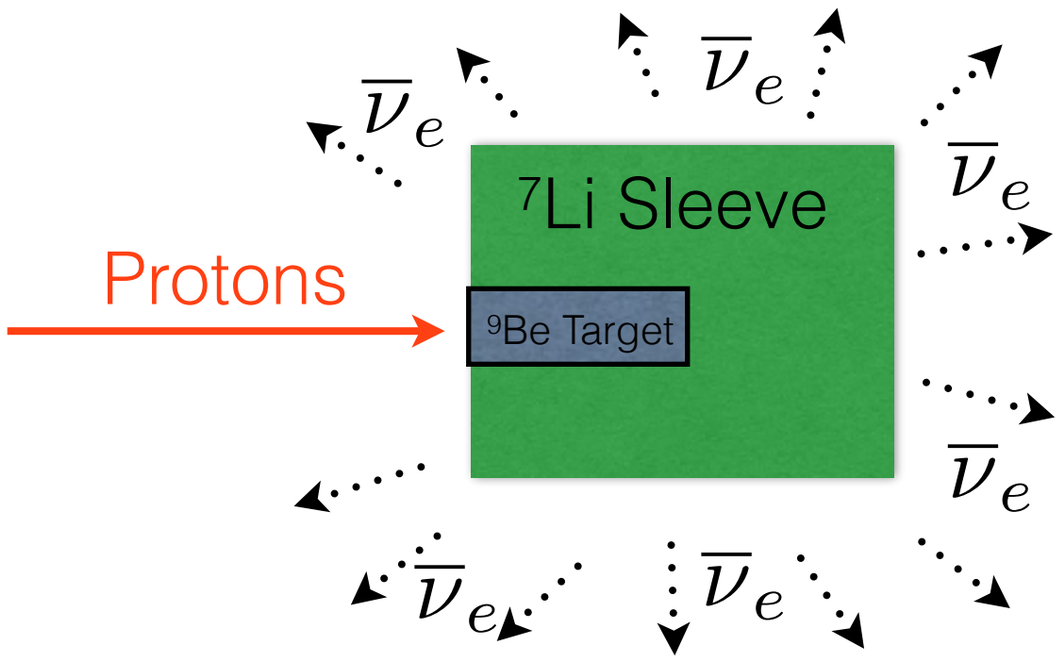
$${}^8\mathrm{Li} \rightarrow {}^8\mathrm{Be} + e^- + \overline{\nu}_e$$

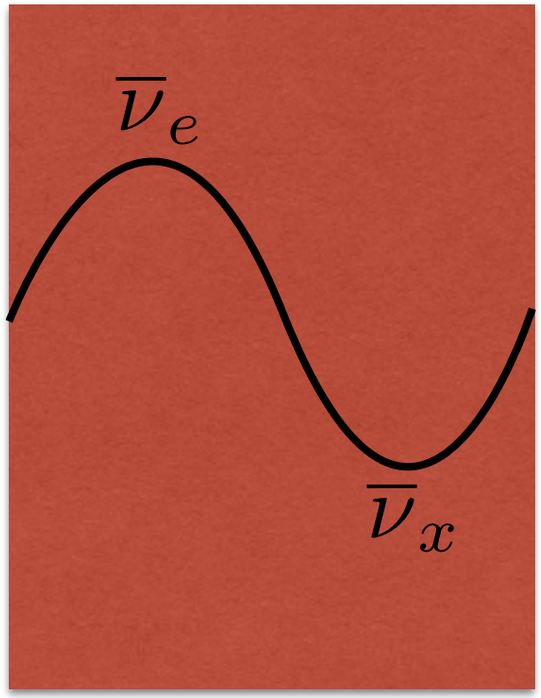


IsoDAR



$$\overline{\nu}_e \rightarrow \overline{\nu}_x \quad ?$$

Detector



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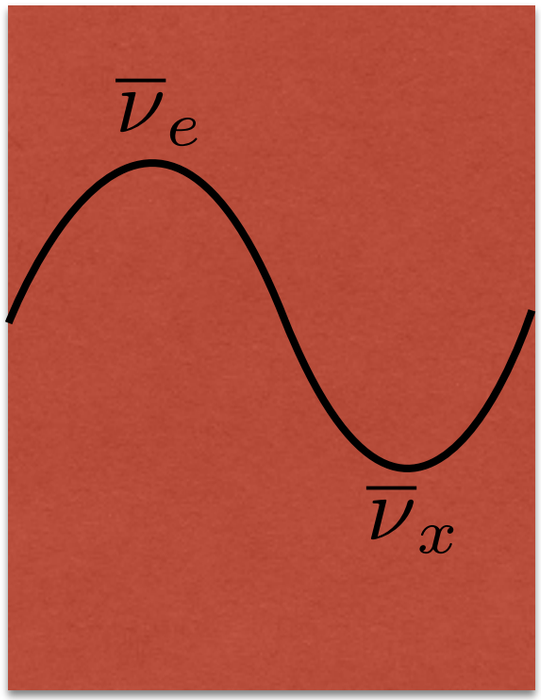
$${}^8\mathrm{Li} \rightarrow {}^8\mathrm{Be} + e^- + \overline{\nu}_e$$

$$\overline{\nu}_e p \rightarrow e^+ n$$

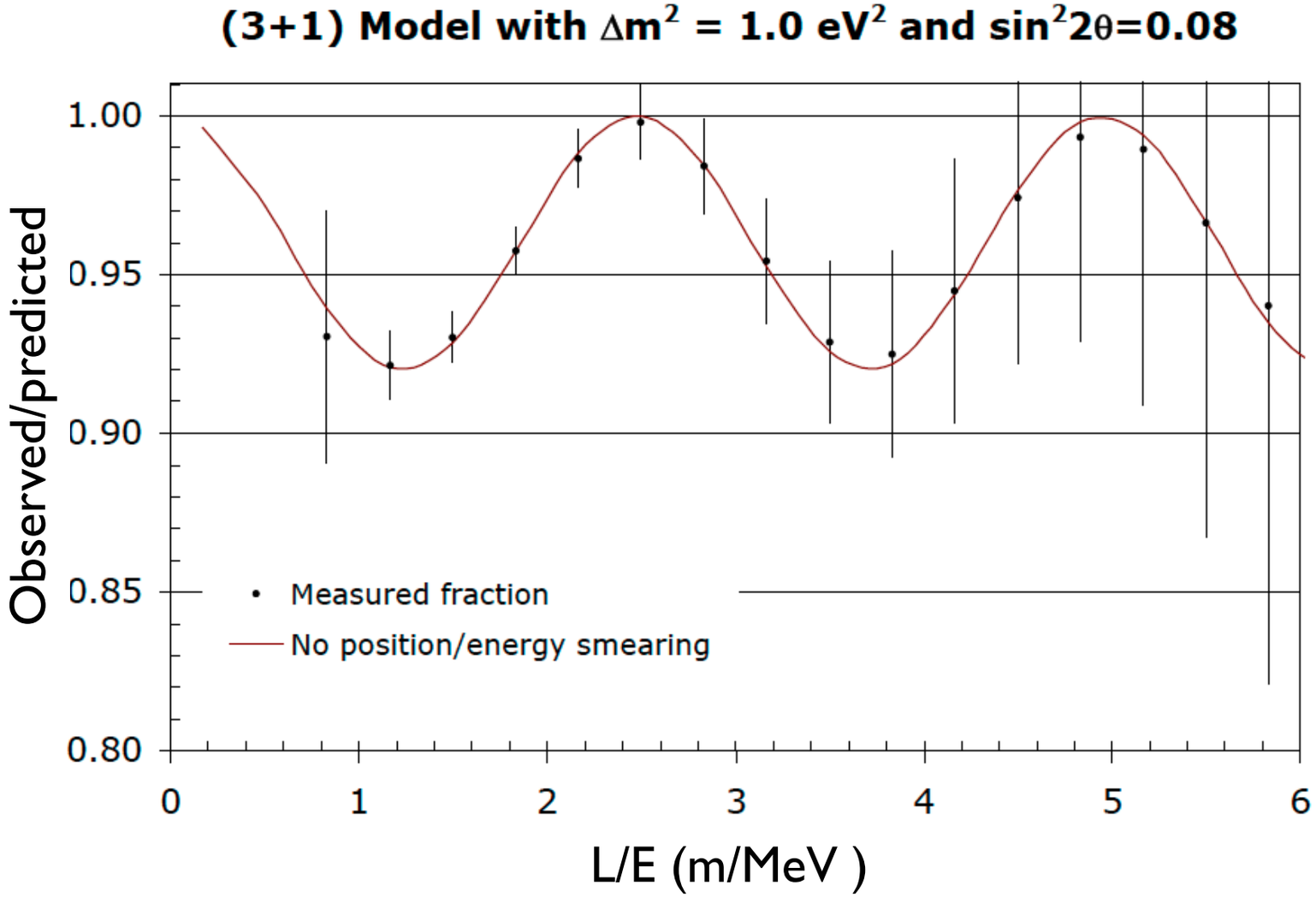
IsoDAR

$$\overline{\nu}_e \rightarrow \overline{\nu}_x \quad ?$$

Detector

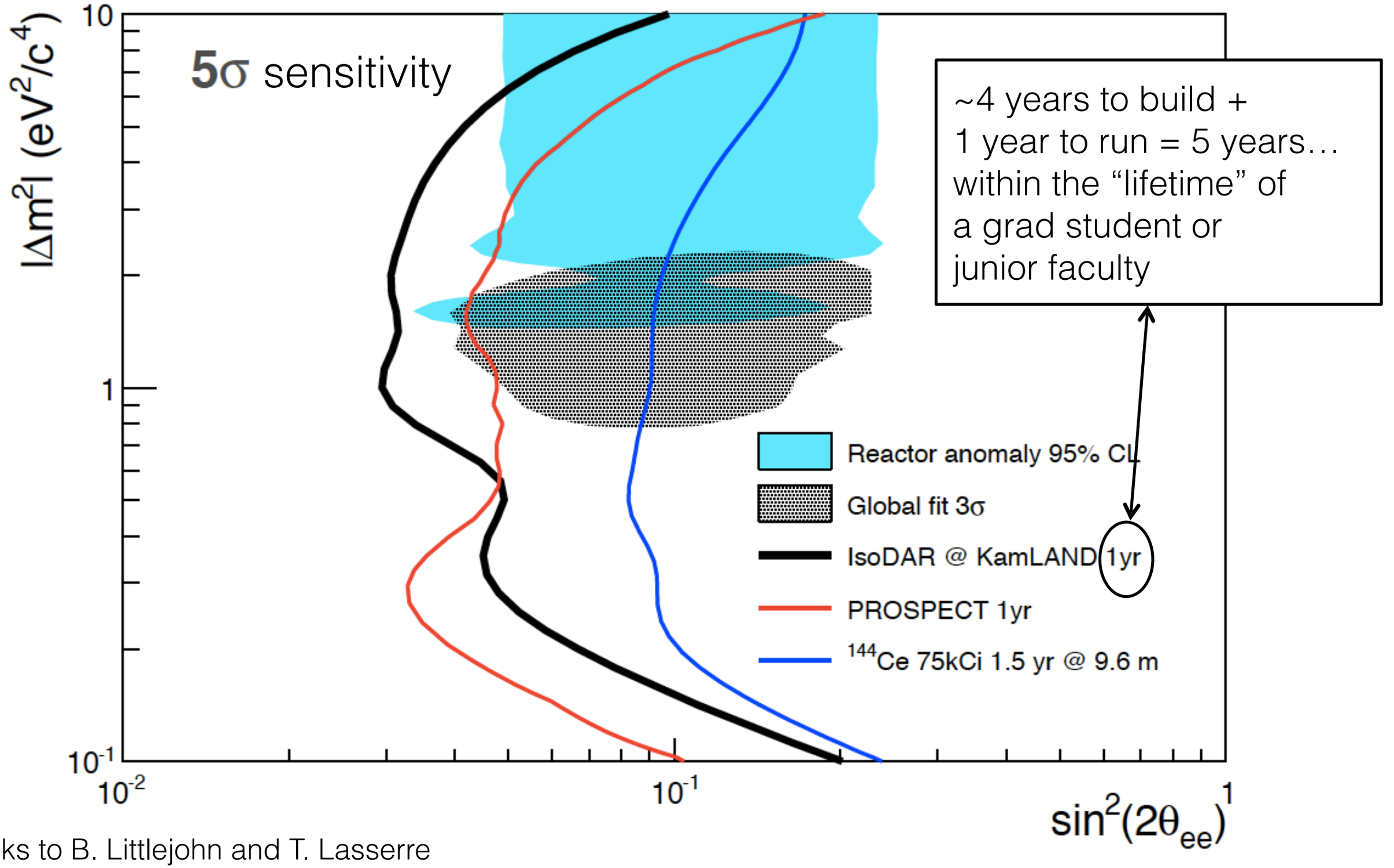


$$\overline{\nu}_e p \rightarrow e^+ n$$



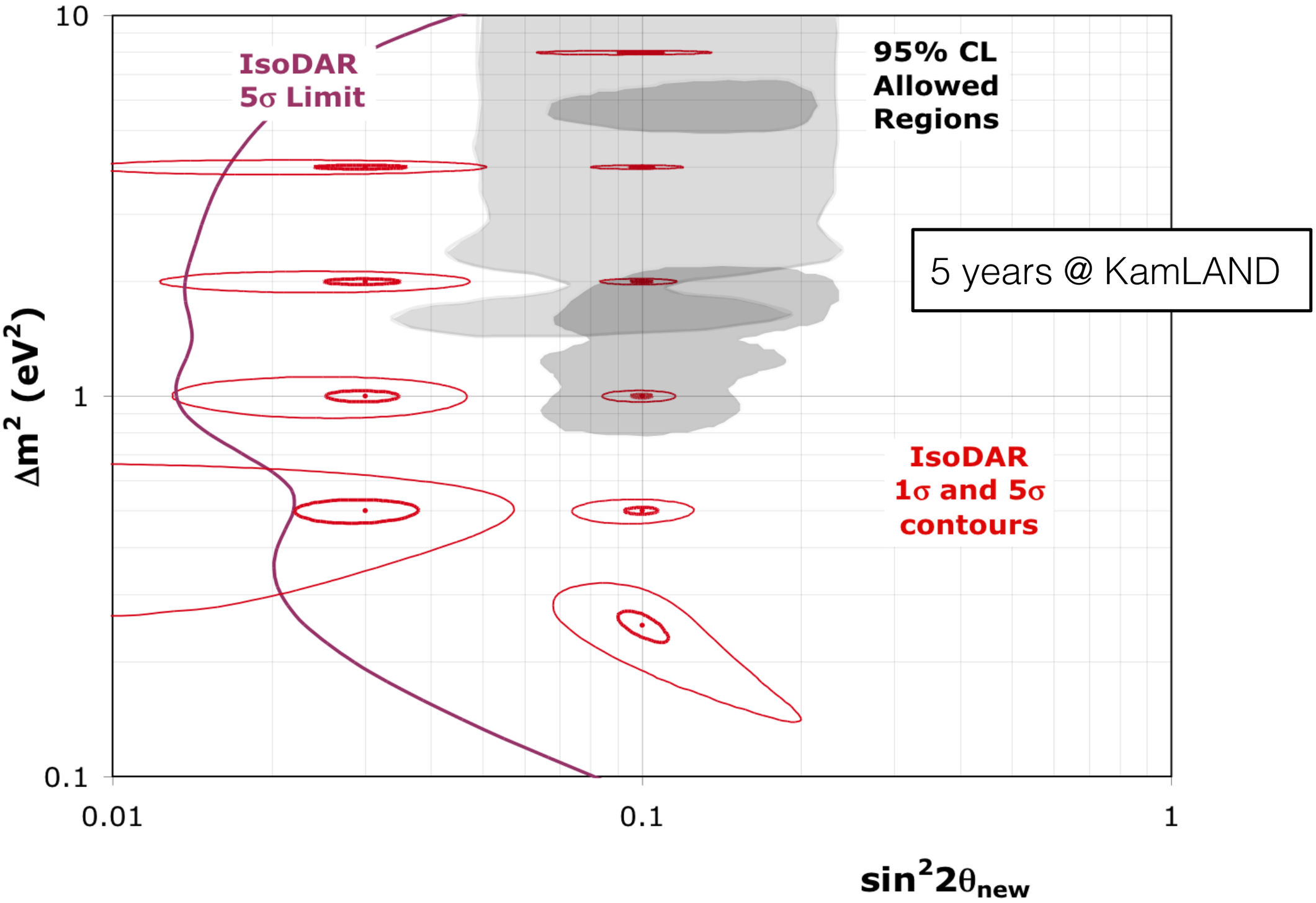
820,000 IBD events in 5 years at KamLAND
(600 kW; 16 m baseline to center of detector)

IsoDAR sensitivity

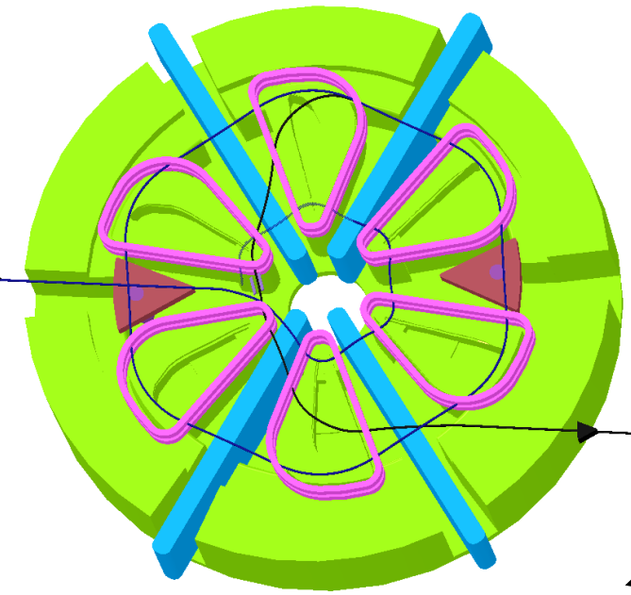


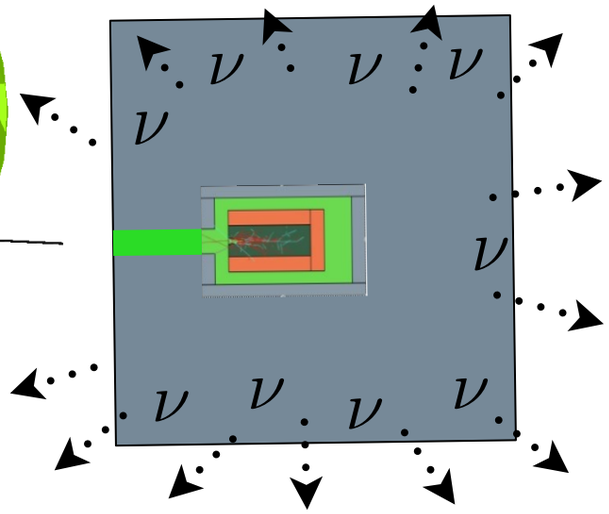
Thanks to B. Littlejohn and T. Lasserre

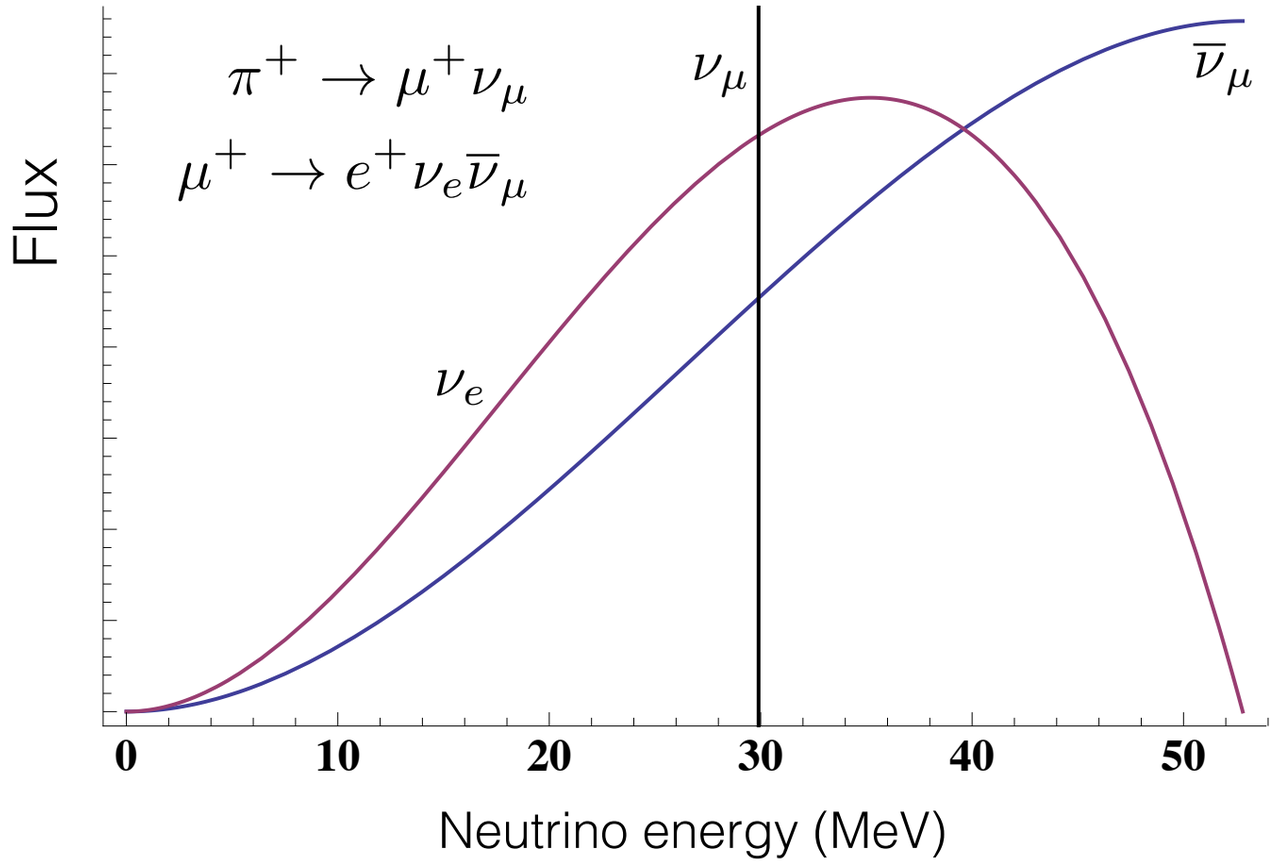
IsoDAR precision



DAEδALUS and δ_{CP}







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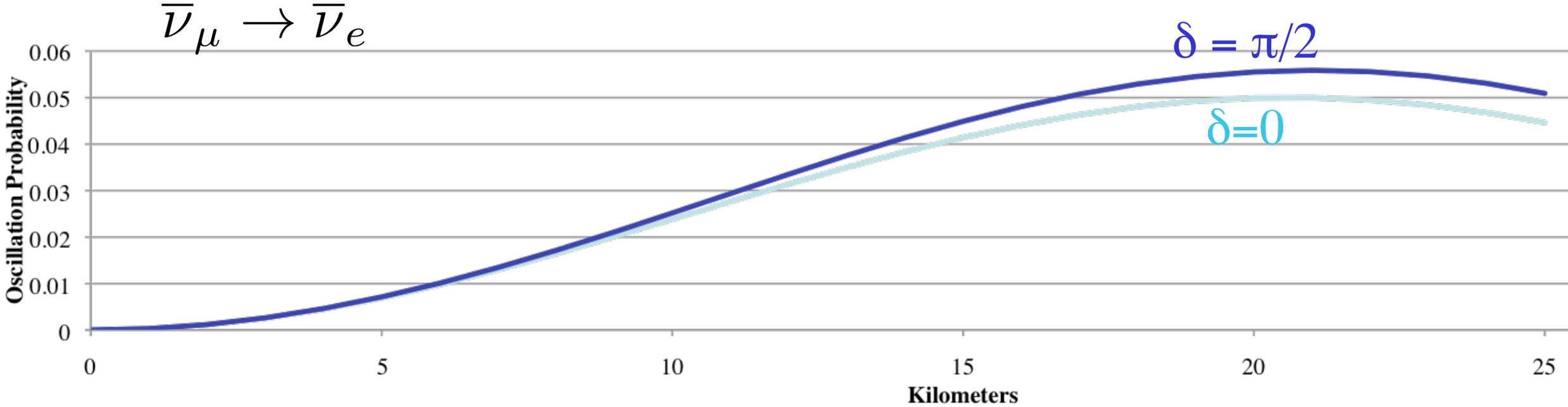
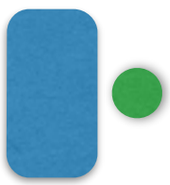




Near site

↓

Constrains initial flux

Mid site

↓

Constrains rise probability

Far site

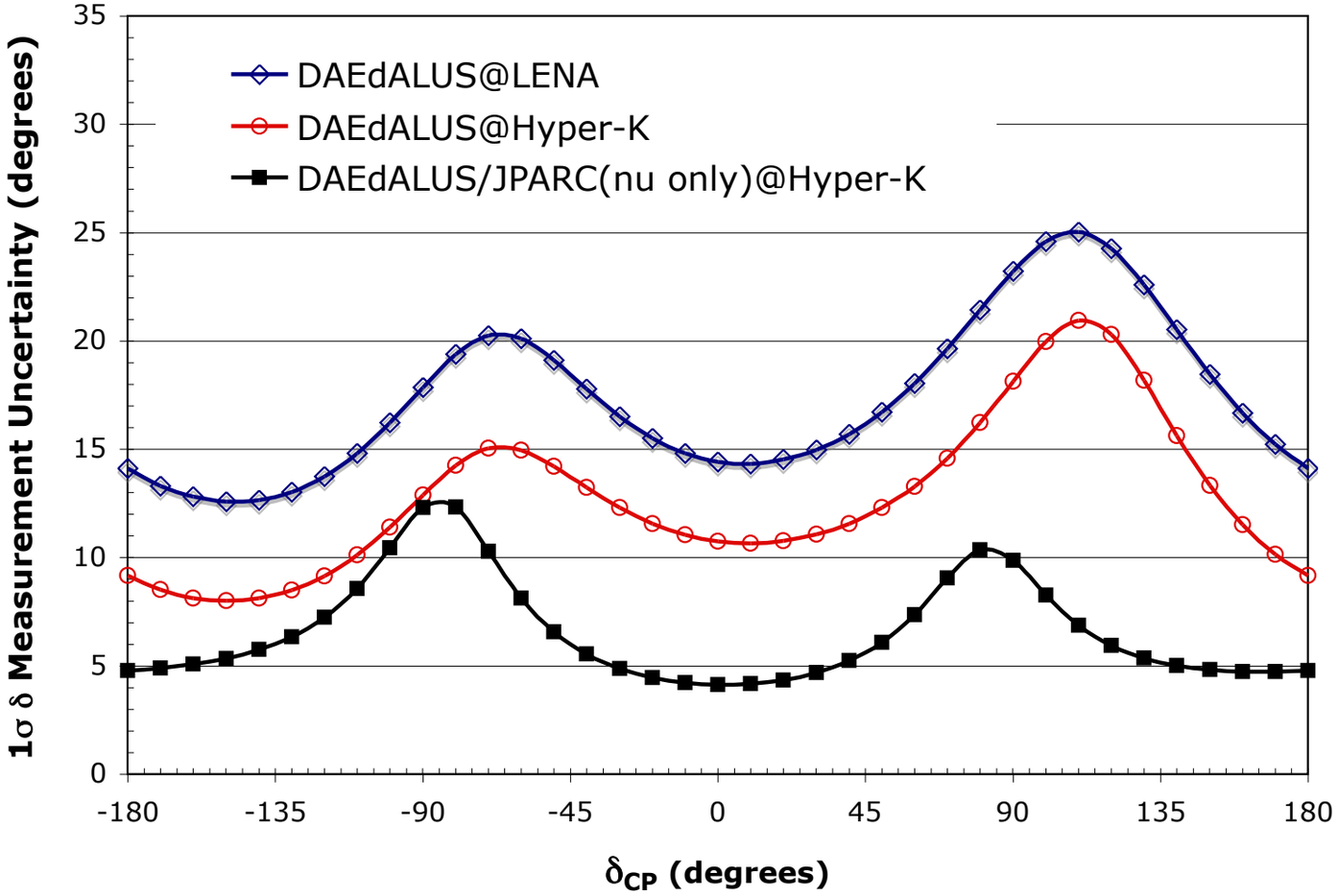
↓

Fit for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ appearance

Near site gives absolute normalization to 1% via ν_e-e
Relative flux between sites can be constrained with ν_eO (ν_eC)

δ_{CP} sensitivity

- DAEδALUS has strong δ_{CP} sensitivity by itself.
- Can be combined with long-baseline data (e.g. Hyper-K) for enhanced sensitivity.
  - Good statistics with anti-neutrinos, no matter effects, orthogonal systematics.
  - Big discoveries want (need?) multiple, independent experiments.



IsoDAR updates

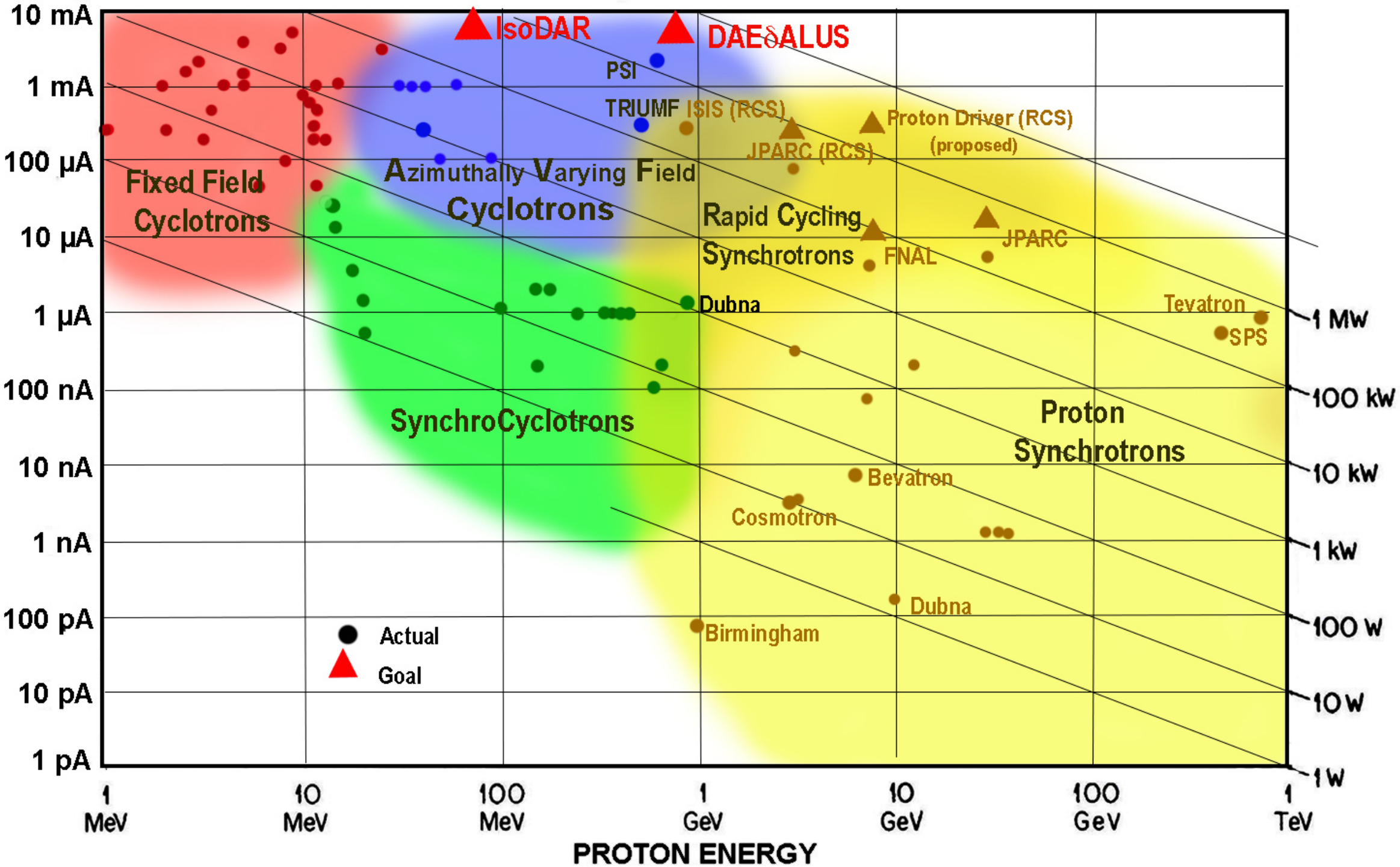
IsoDAR compared to existing cyclotrons

We claim we will be able to produce ~10 mA of protons at 60 MeV. Commercial cyclotrons (IBA, BEST) produce ~1 mA of protons at 60 MeV.

How?

Four issues to solve:

1. Accelerate more particles for same level of space charge.
2. Push the envelope of H_2^+ ion source intensity.
3. Develop an unusually large spiral inflector.
4. Avoid beam losses at extraction.


10 mA
1 mA
100 µA
10 µA
1 µA
100 nA
10 nA
1 nA
100 pA
10 pA
1 pA
IsoDAR
DAEδALUS
PSI
TRIUMF
ISIS (RCS)
Proton Driver (RCS)
(proposed)
JPARC (RCS)
Fixed Field
Cyclotrons
Azimuthally Varying Field
Cyclotrons
Rapid Cycling
Synchrotrons
FNAL
JPARC
Tevatron
SPS
Dubna
1 MW
100 kW
10 kW
1 kW
100 W
10 W
1 W
SynchroCyclotrons
Proton
Synchrotrons
Bevatron
Cosmotron
Dubna
Birmingham
Actual
Goal
1
MeV
10
MeV
100
MeV
1
GeV
10
GeV
100
GeV
1
TeV
PROTON ENERGY

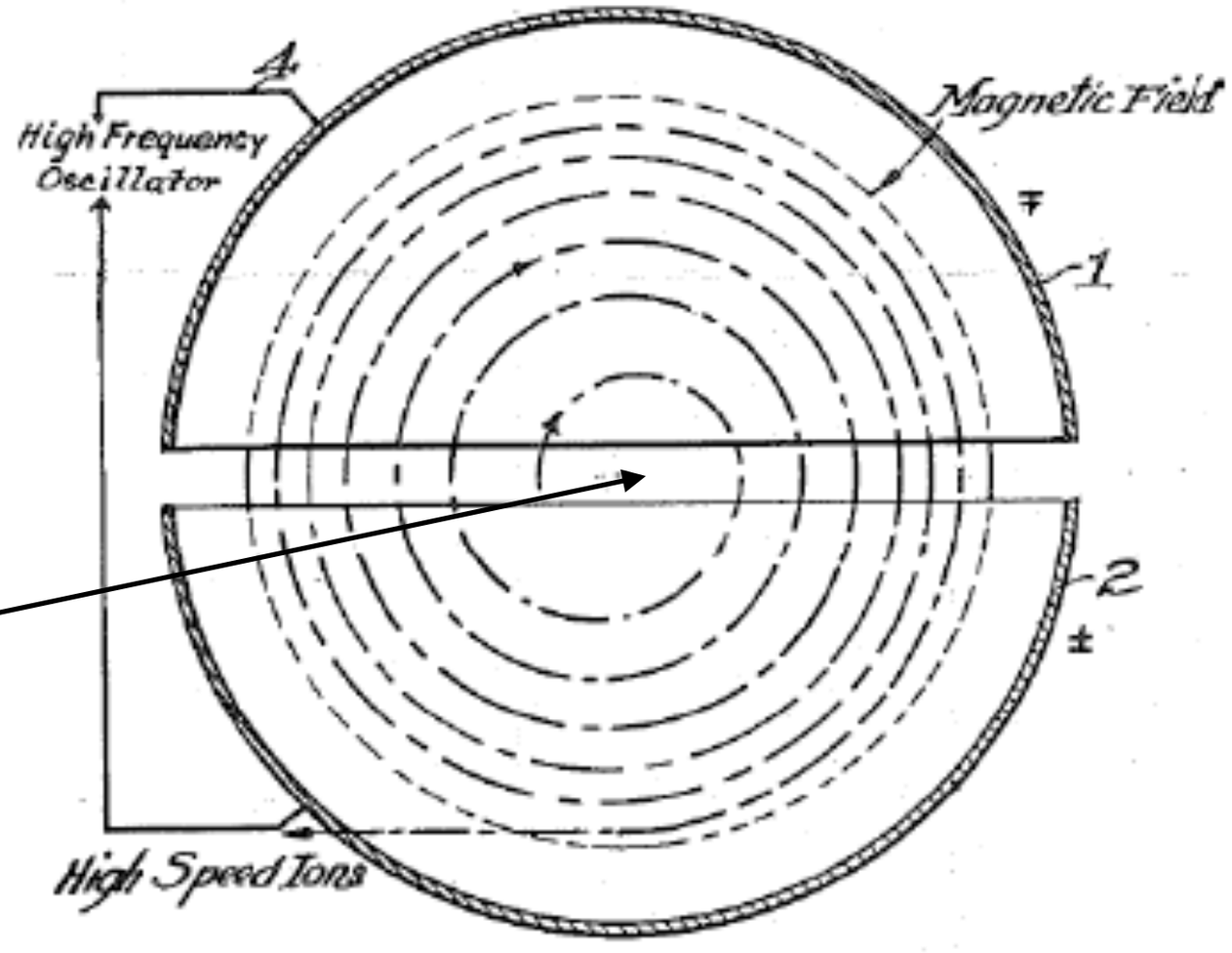
Challenges

- Space charge

The beam width increases because the H_2^+ ions repel each other.
This is a big problem at injection and near the outside of the cyclotron where the turn spacing is low.

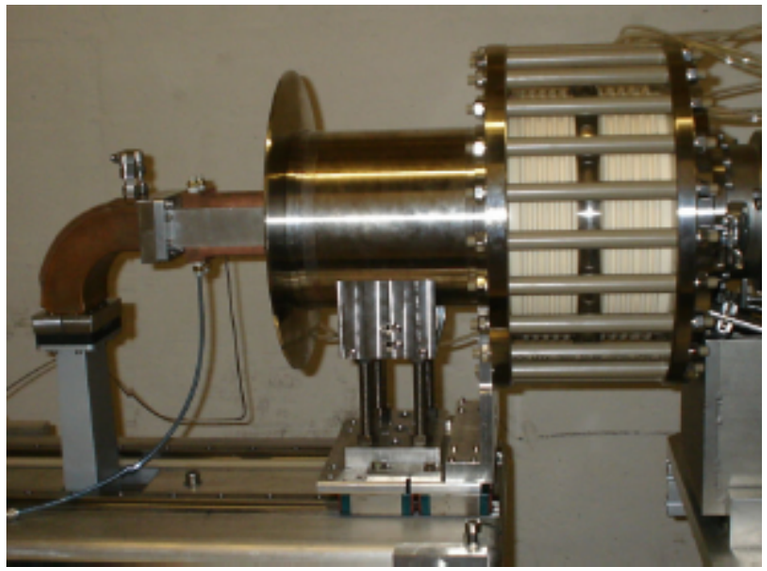
Present machines inject p or H^-

We inject H_2^+

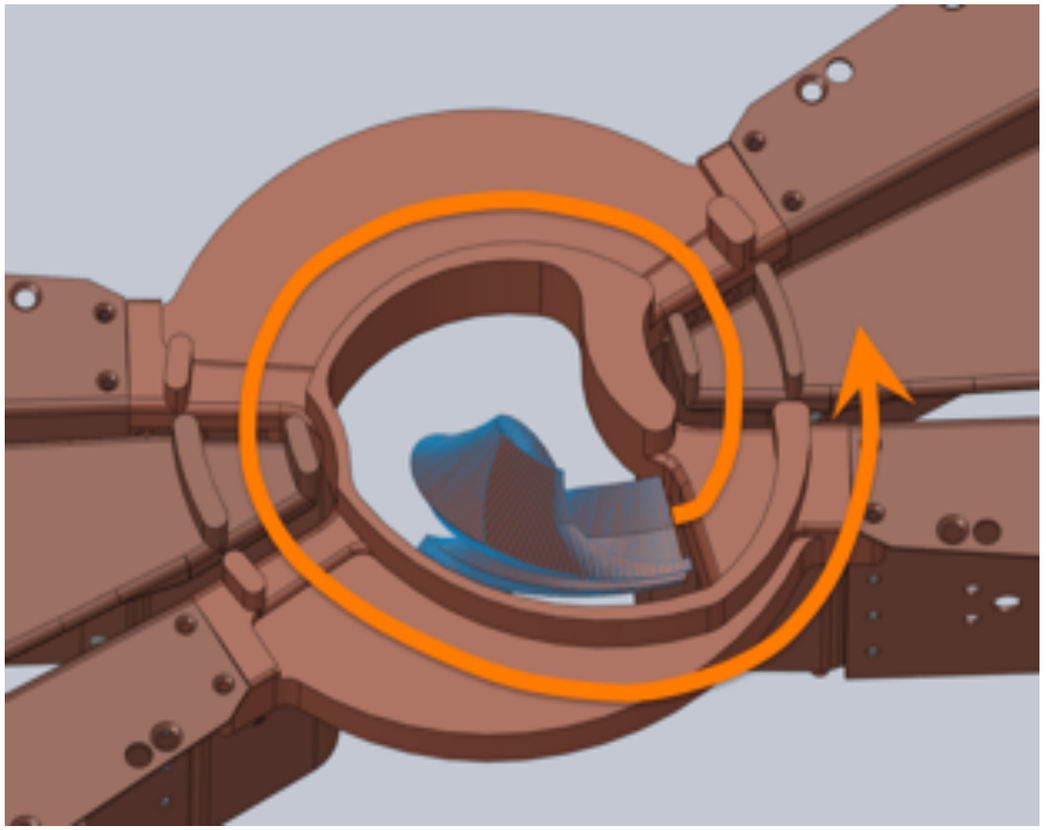


Challenges

- Ion source intensity



The “versatile ion source”



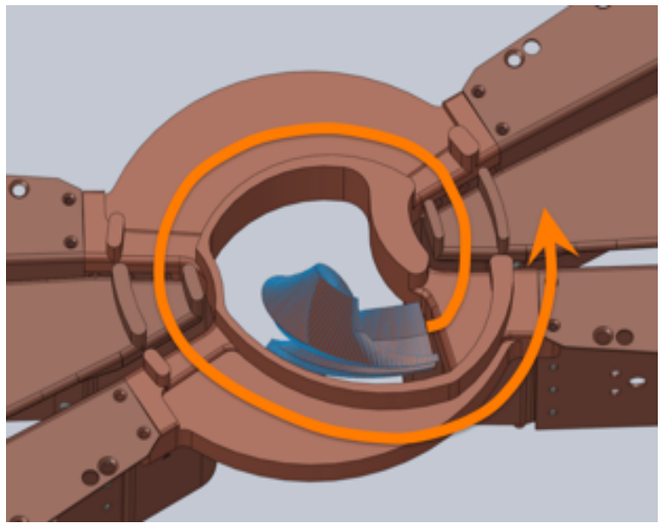
The first turn after axial inflection

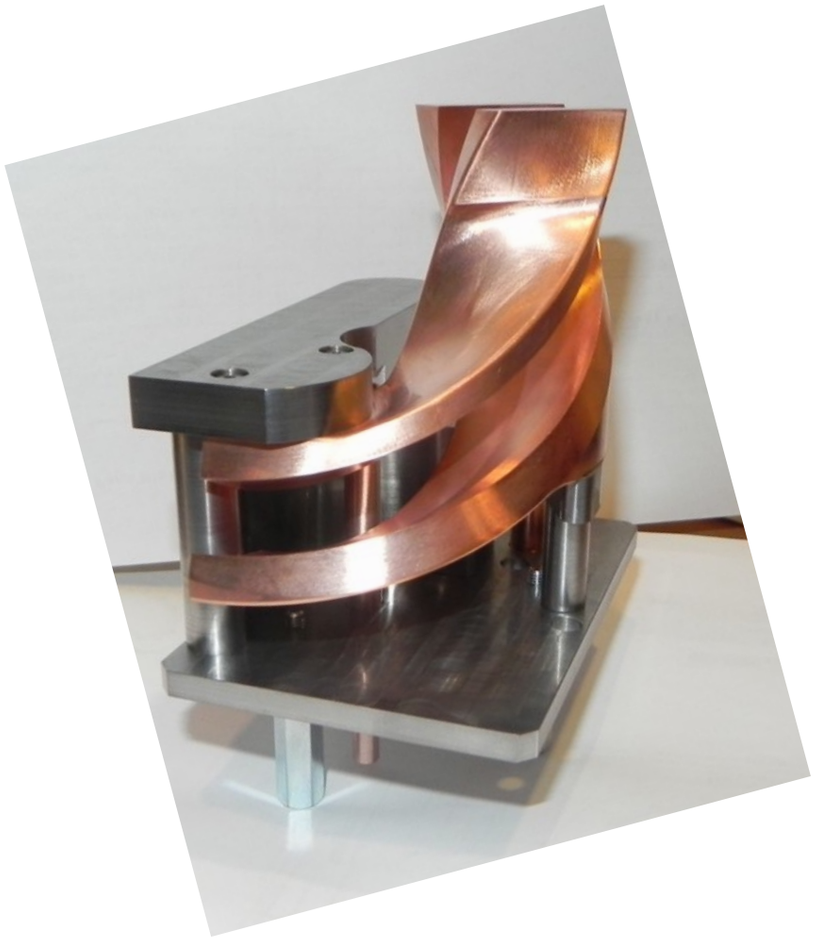
Most ions are lost in the first “turn” because they hit material.

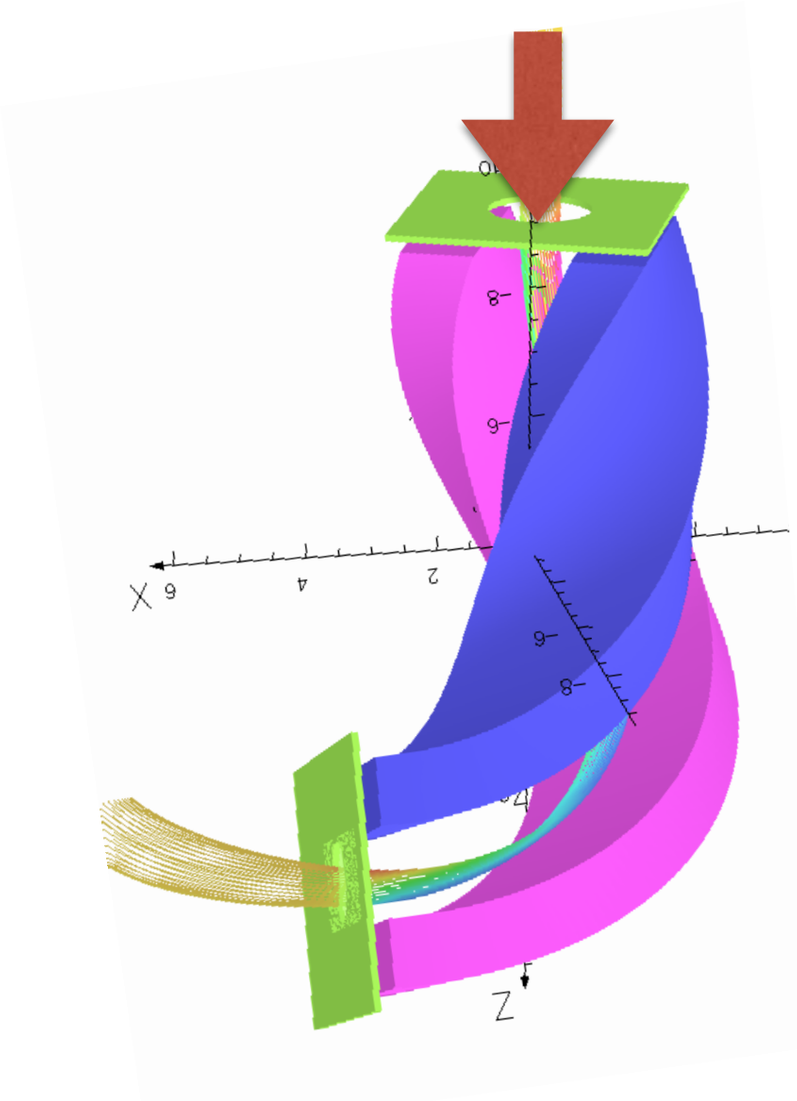
Capture efficiency is extremely low, currently estimated at 5-10%.

Challenges

- Inflection



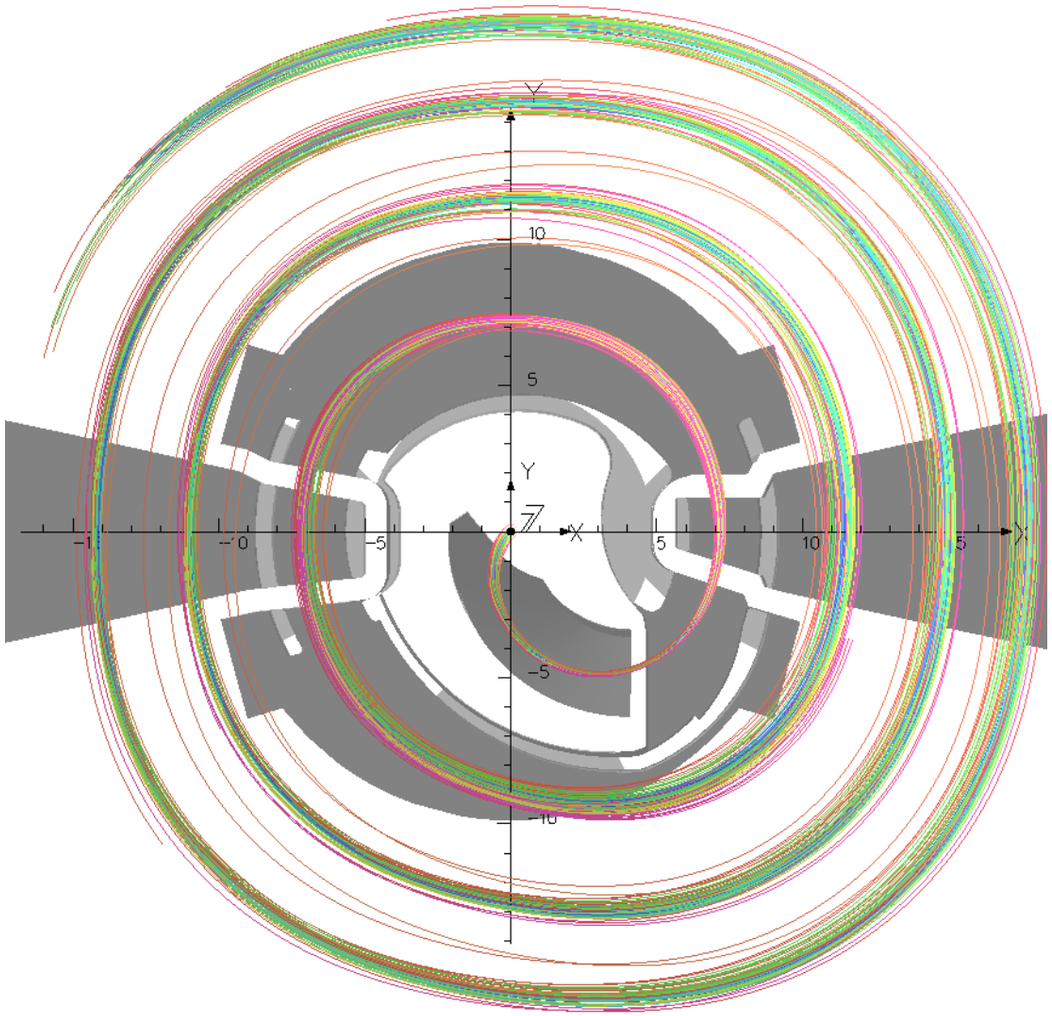




Getting the beam into the cyclotron requires taking it from the vertical to the horizontal plane. This is hard.

->an iterative R&D process.

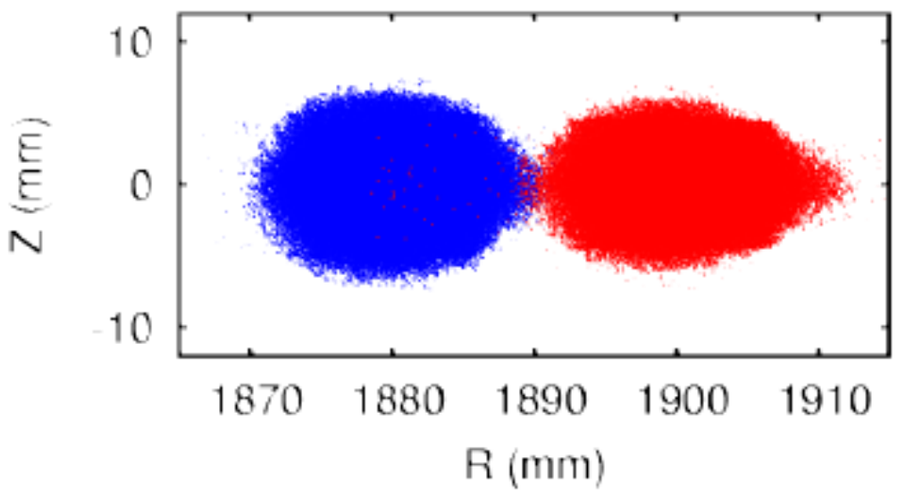
Challenges



Beam dynamics sim

How much beam can we accelerate?
A question for simulation and experiment!

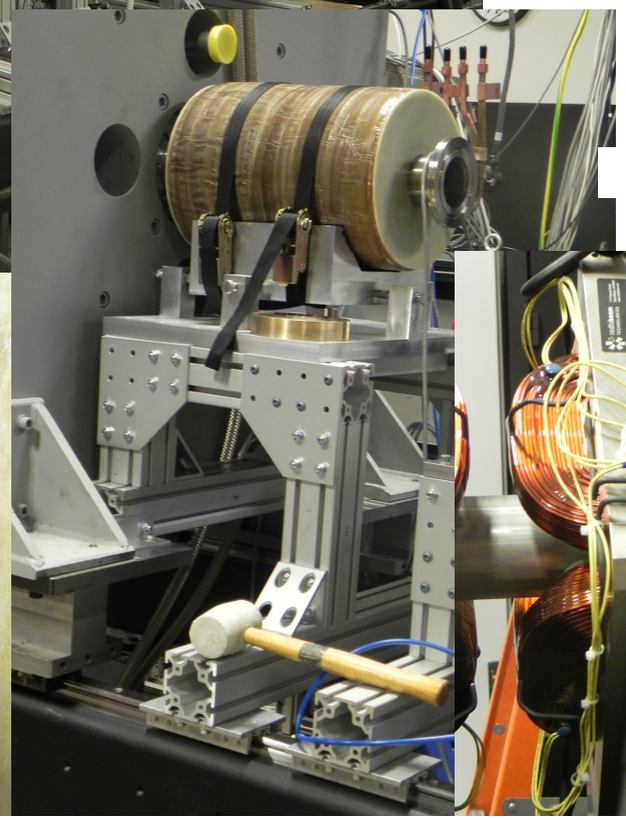
-Intense ion source
-Limit space charge
-Control emittance
-Remove high-vibrational states
-Limit losses at extraction

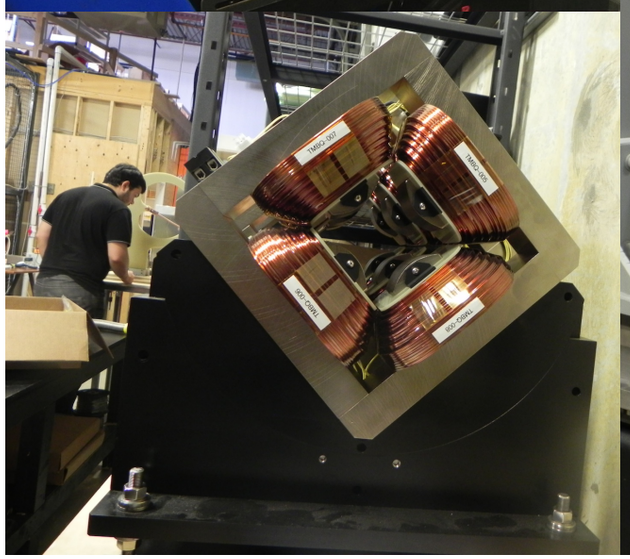


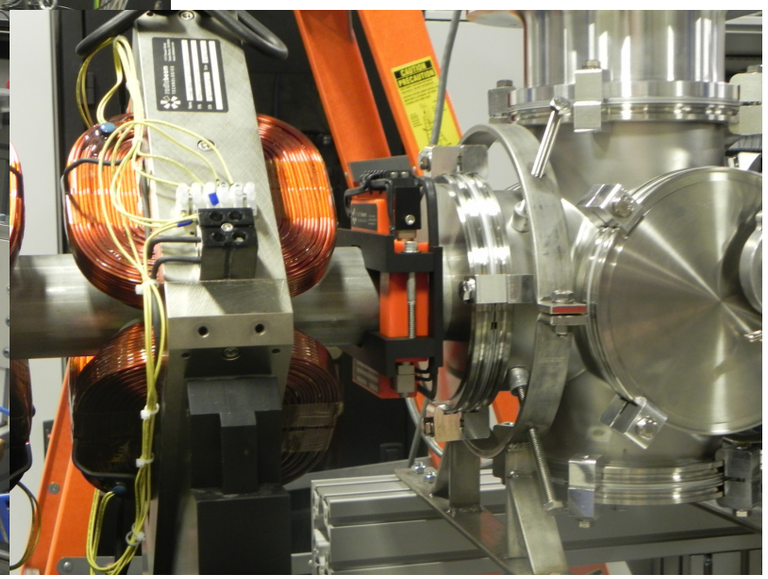
The final turns in the injector

Addressing the IsoDAR challenges

Beam has been characterized at Best Cyclotrons, Inc, Vancouver (Best Cyclotron Systems, INFN-Catania, and MIT -- NSF funded)







GOALS

- How much beam can be captured?
- What are the properties of the captured beam?
- Develop experience for designing the central region of the IsoDAR injector cyclotron.

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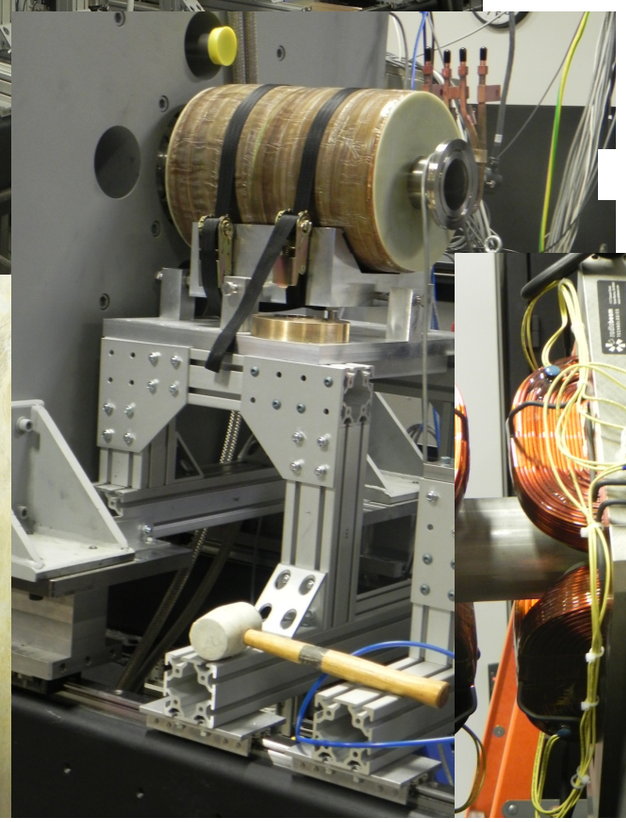
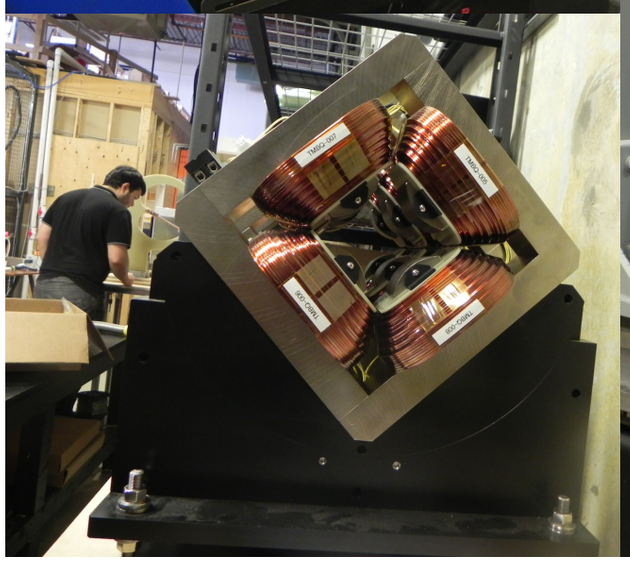
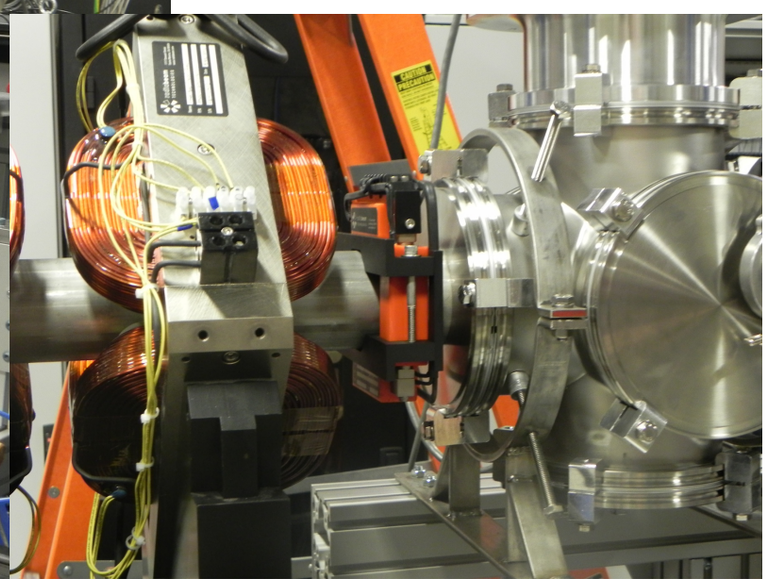
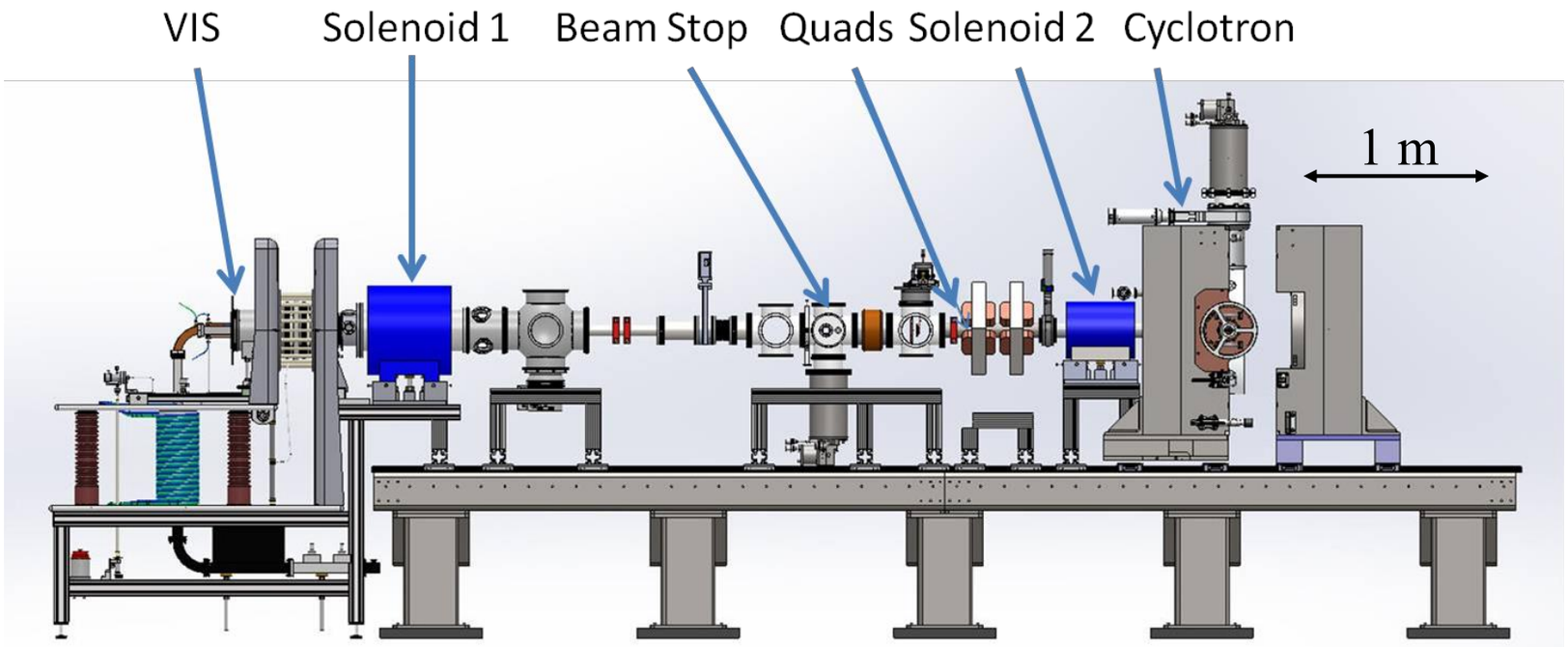


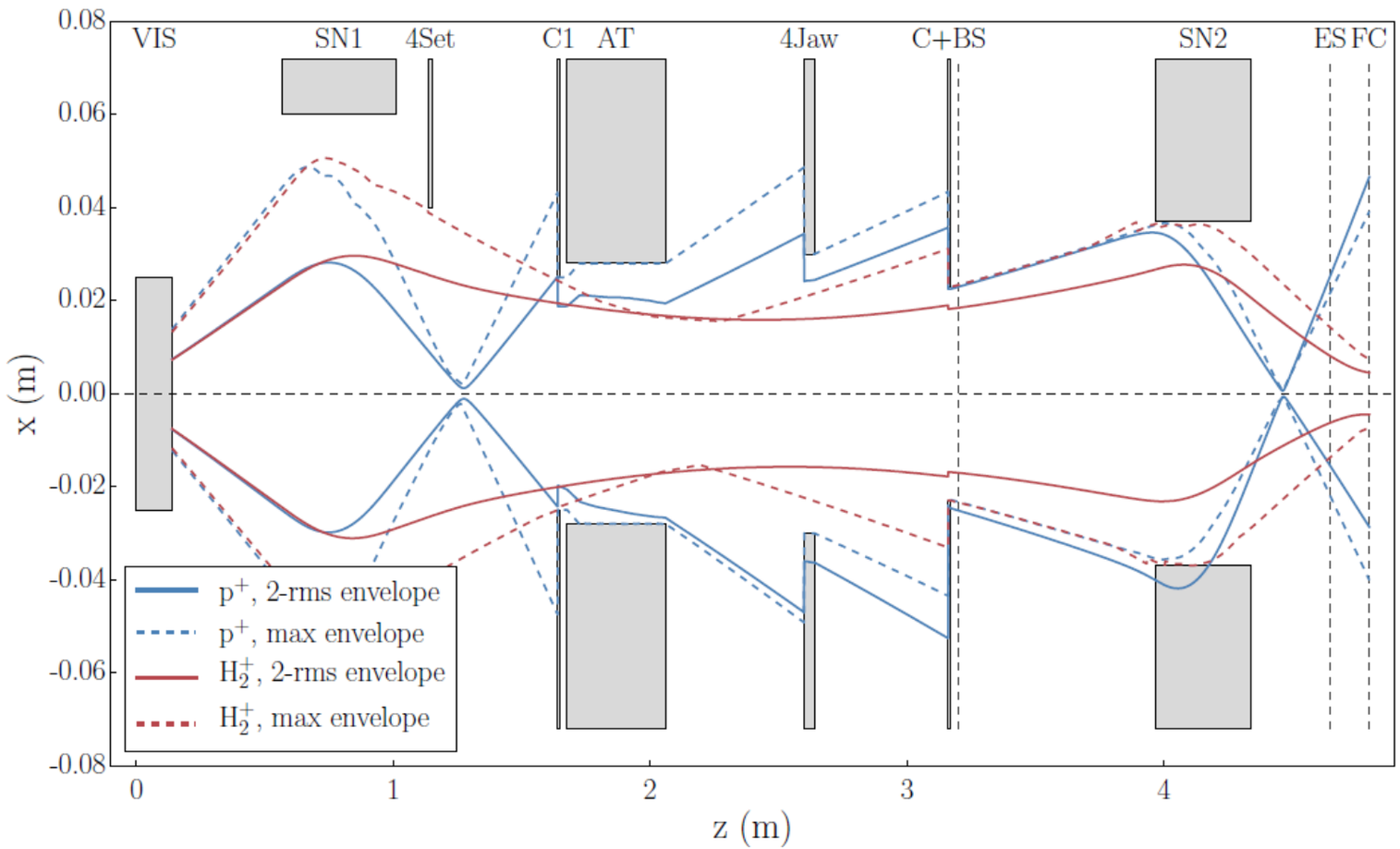




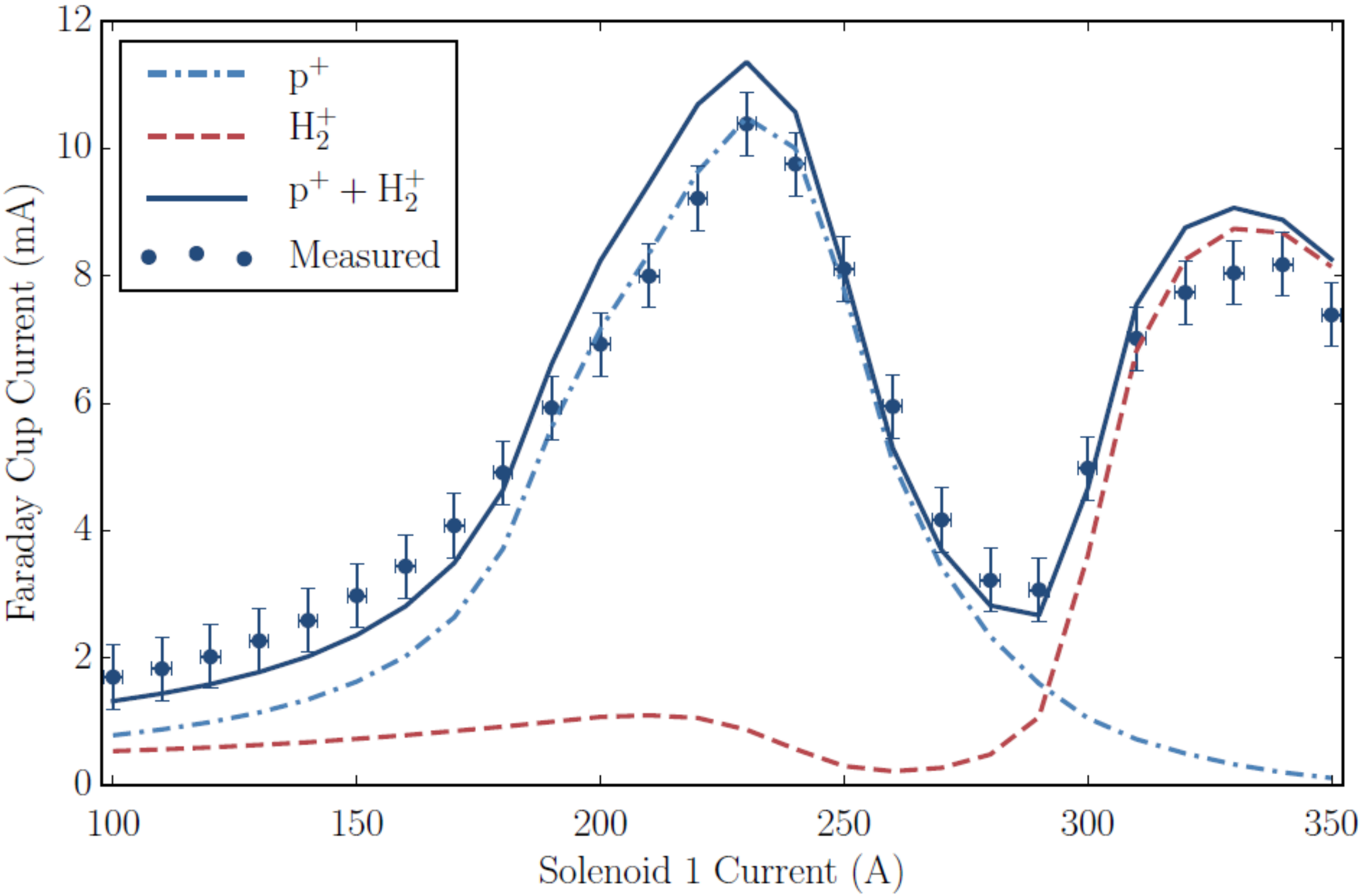
- Ion source from INFN-Catania installed at BEST Cyclotrons Inc. lab in Vancouver.
- 40 mA protons demonstrated (summer, 2013) and now focusing on H_2^+.
- Initial output was 12 mA.

BCS test setup

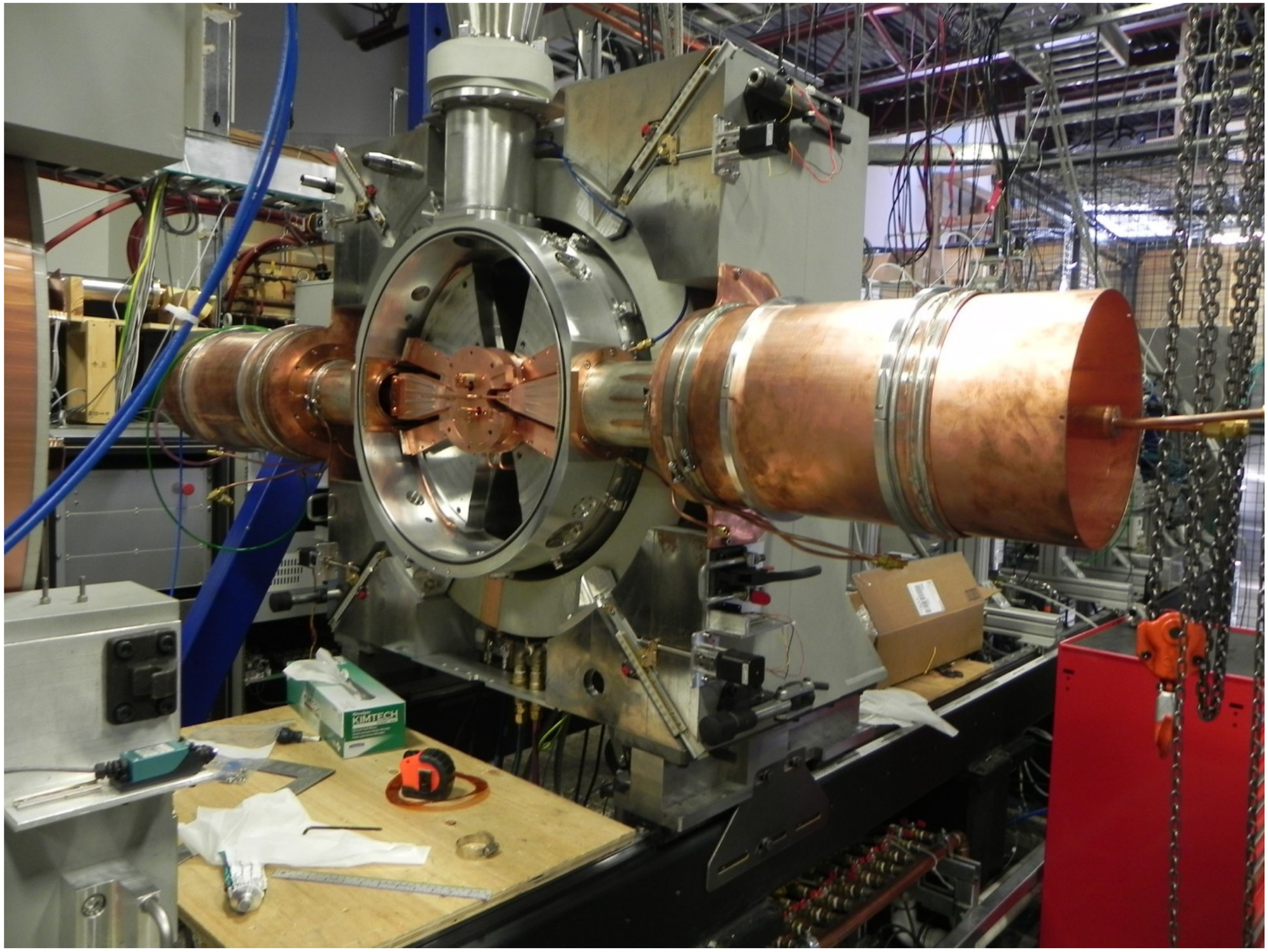




Beam in Faraday cup

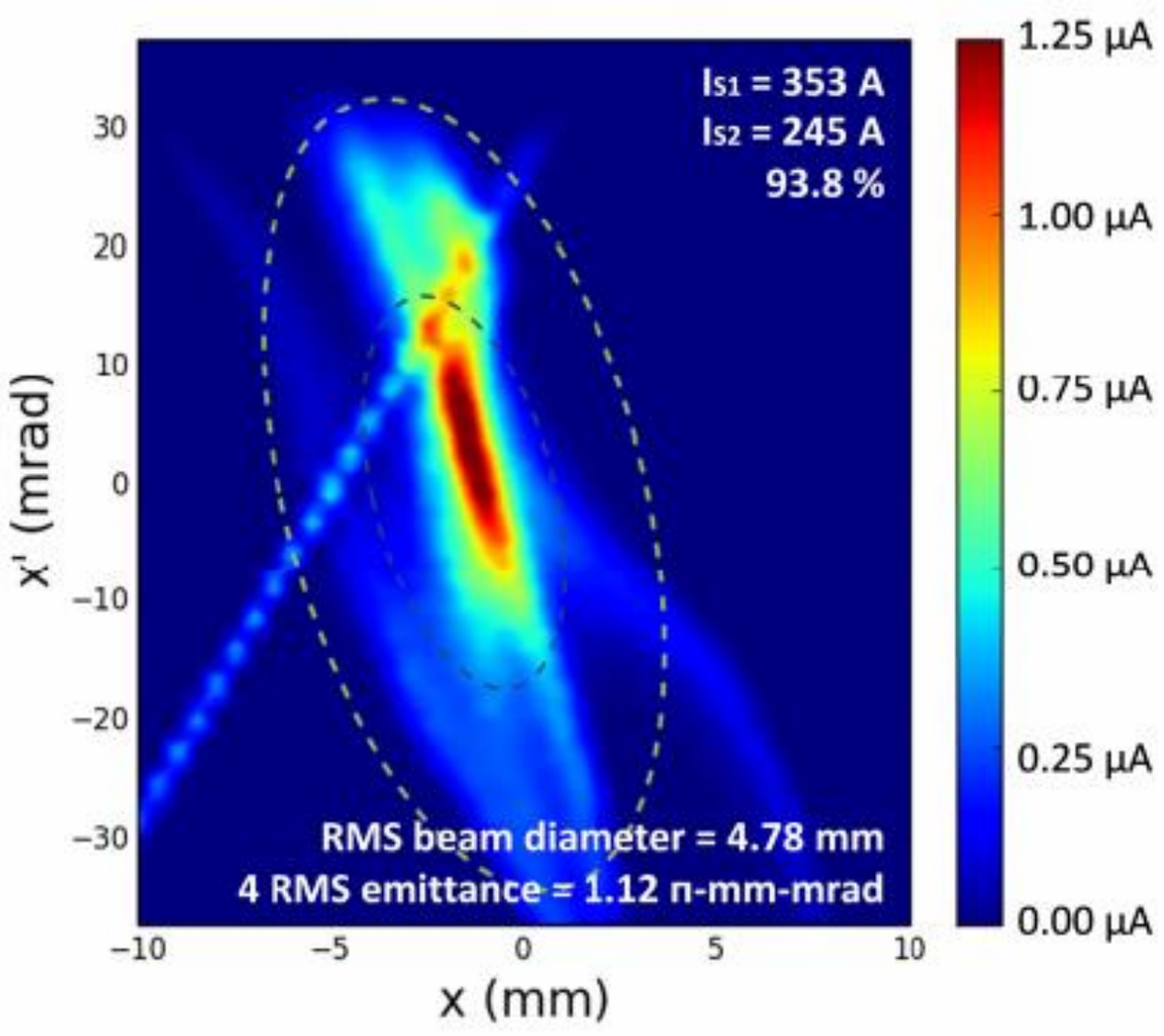


A cyclotron sits at the end of the line

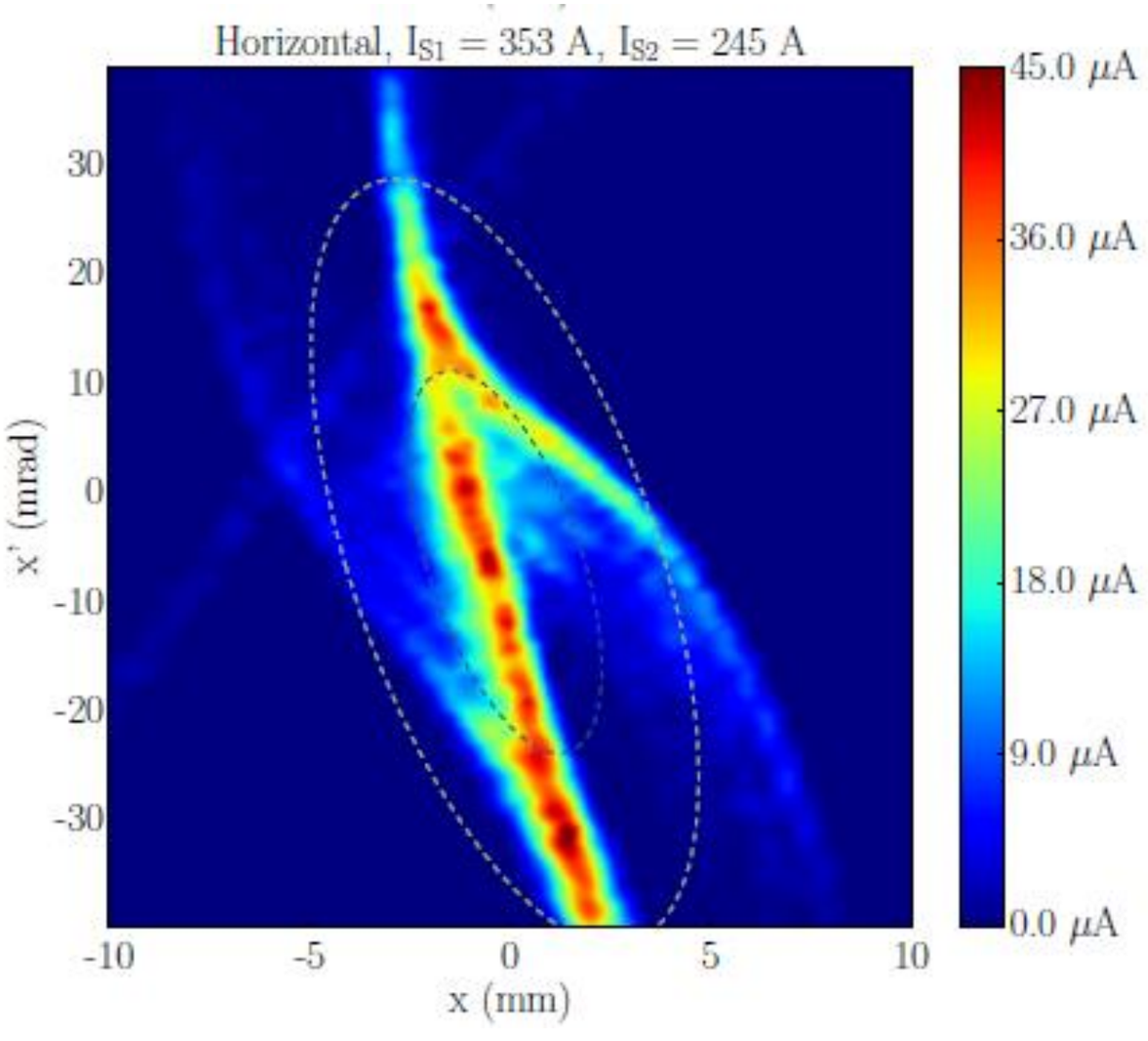


Phase space at cyclotron entrance

Measured



Simulated



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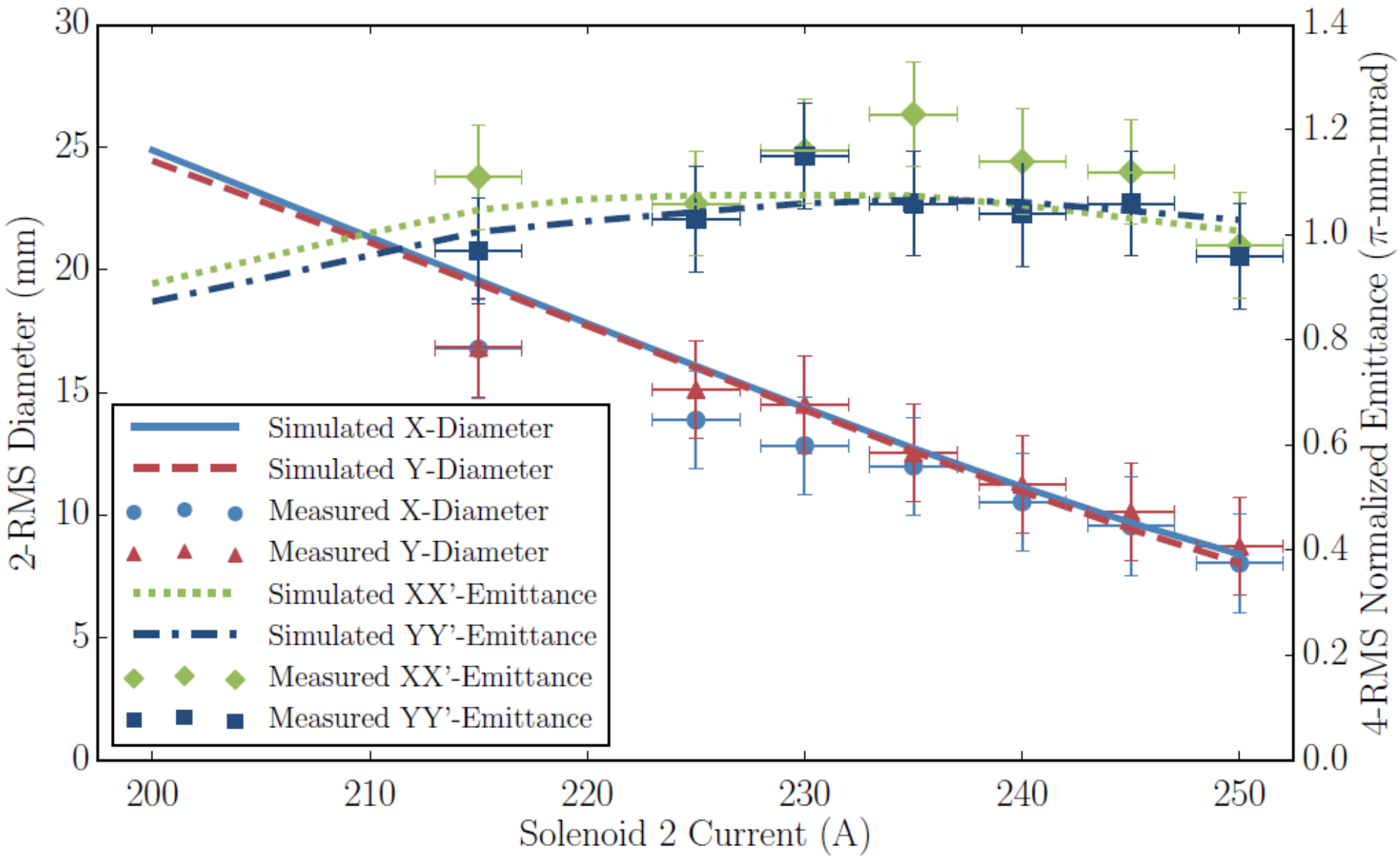
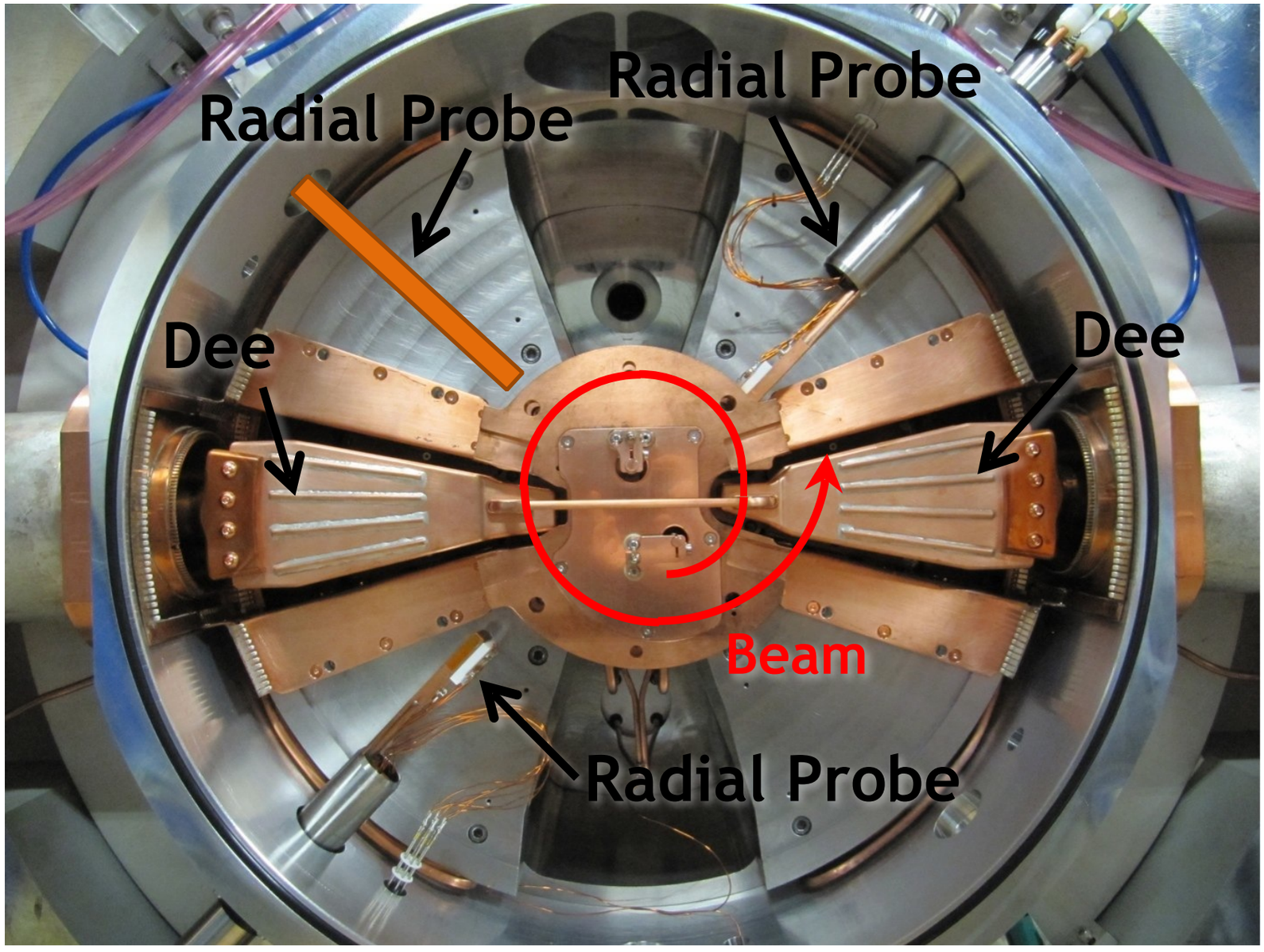
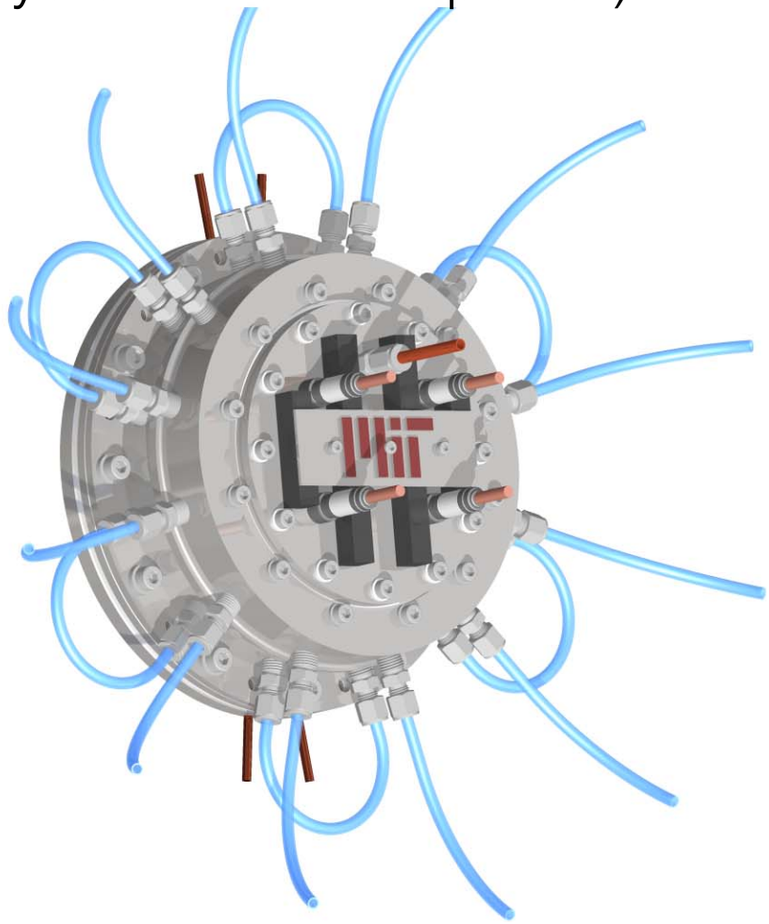




Beam has been brought from the ion source, through the low energy beam transport, through the axial inflector (7.5 mA, 94% transmission), and into the cyclotron where it is accelerated and makes 3.5 turns (600 keV)!

Summary of BCS tests and path forward

- Transported maximum of 10 mA of H_2^+ to cyclotron, with focussed beam at the entrance of the spiral inflector.
- Transported 94% of beam through spiral inflector
- Accelerated 100 uA for four turns in test cyclotron (note: RF system not at full power).
- Need more current!
  - Better source or higher bunching efficiency
- Pursuing both:
  - New ion source
  - Develop RFQ direct cyclotron injection design



Take away

- The DAEδALUS collaboration is pursuing a phased approach towards a precise measurement of δ_{CP}.

- There is physics at each phase.

- IsoDAR, in combination with (e.g.) KamLAND, will provide a definitive statement on the sterile neutrino.

- Accelerator R&D is ongoing. There has been lots of progress!

- These cyclotrons have applications outside of particle physics and industry is pursuing these machines by our side.

Other (published) physics

Precision Anti-nue-electron Scattering Measurements with IsoDAR to Search for New Physics
arXiv:1307.5081 — PRD

Electron Antineutrino Disappearance at KamLAND and JUNO as Decisive Tests of the Short Baseline Anti-numu to Anti-nue Appearance Anomaly
arXiv:1310.3857 — PRD

IsoDAR

Coherent Neutrino Scattering in Dark Matter Detectors
arXiv: 1103.4894 — PRD

Measuring Active-to-Sterile Neutrino Oscillations with Neutral Current Coherent Neutrino-Nucleus Scattering
arXiv:1201.3805 — PRD

Short-Baseline Neutrino Oscillation Waves in Ultra-Large Liquid Scintillator Detectors
arXiv:1105.4984 — JHEP

DAEδALUS

Backup

DAEδALUS/IsoDAR Collaboration
The participating academic institutions are:

- Amherst College
- Cockcroft Institute for Accelerator Science & the University of Manchester*
- Columbia University
- Duke University
- Imperial College London
- Lawrence Livermore National Laboratory
- LNS-INFN (Catania)*
- Los Alamos National Laboratory*
- Massachusetts Institute of Technology*
- Michigan State University*
- New Mexico State University
- Paul Scherrer Institut*
- RIKEN*
- Tohoku University
- University of California, Berkeley (Nuclear Engineering)*
- University of California, Irvine
- University of California, Los Angeles
- University of Maryland*
- University of Tennessee
- University of Huddersfield*

The participating commercial firms are:

- Bartoszek Engineering
- Best Cyclotron Systems, Inc.*
- IBA (Ion Beam Applications S.A.)*

* Group includes experienced accelerator scientists

Broader impacts

Isotope	Half-life	Use
^{52}Fe	8.3 h	The parent of the PET isotope ^{52}Mn and iron tracer for red-blood-cell formation and brain uptake studies.
^{122}Xe	20.1 h	The parent of PET isotope ^{122}I used to study brain blood-flow.
^{28}Mg	21 h	A tracer that can be used for bone studies, analogous to calcium.
^{128}Ba	2.43 d	The parent of positron emitter ^{128}Cs. As a potassium analog, this is used for heart and blood-flow imaging.
^{97}Ru	2.79 d	A γ-emitter used for spinal fluid and liver studies.
^{117m}Sn	13.6 d	A γ-emitter potentially useful for bone studies.
^{82}Sr	25.4 d	The parent of positron emitter ^{82}Rb, a potassium analogue. This isotope is also directly used as a PET isotope for heart imaging.

IsoDAR design is uniquely applicable for medical isotope production

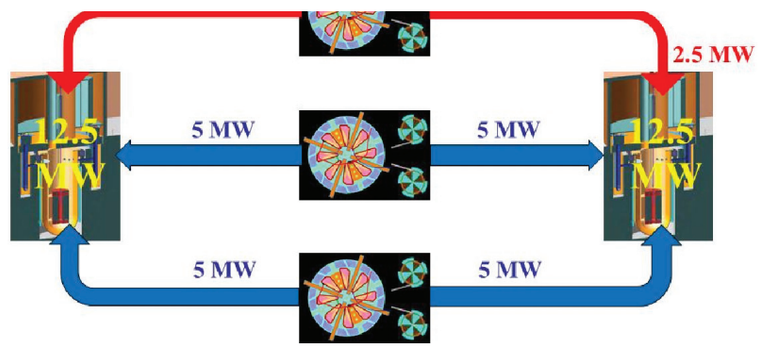
Thorium reactor community is interested in DAEδALUS

MW-CLASS 800 MeV/n H_2^+ SC-CYCLOTRON FOR ADS APPLICATION, DESIGN STUDY AND GOALS*

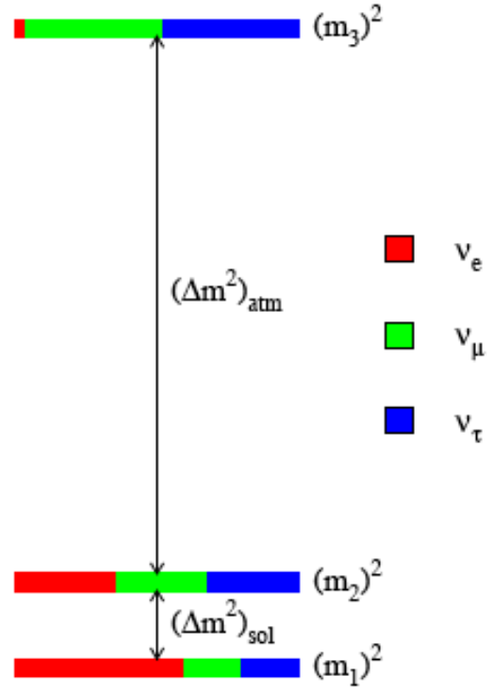
F. Méot, T. Roser, W. Weng, BNL, Upton, Long Island, New York, USA
L. Calabretta, INFN/LNS, Catania, Italy; A. Calanna, CSFNSM, Catania, Italy

Abstract

This paper addresses an attempt to start investigating the use of the Superconducting Ring Cyclotron (SRC) developed for DAEδALUS experiment for ADS application [1, 2], focusing on the magnet design and its implication for lattice parameters and dynamic aperture performance.



The oscillation of muon-flavor to electron-flavor
at the atmospheric Δm^2
may show CP-violation dependence!



in a vacuum…

$$P = (\sin^2\theta_{23}\sin^2 2\theta_{13})\ (\sin^2\Delta_{31})$$
$$\mp \sin\delta\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin^2\Delta_{31}\sin\Delta_{21})$$
$$+ \cos\delta\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21})$$
$$+ (\cos^2\theta_{23}\sin^2 2\theta_{12})\ (\sin^2\Delta_{21}).$$

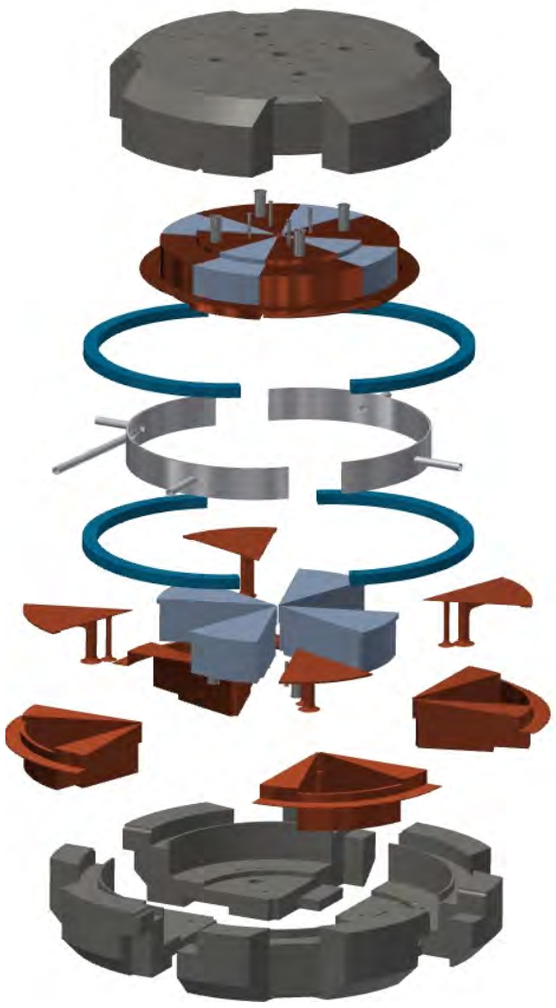
We want to see
if δ is nonzero

terms depending on
mixing angles

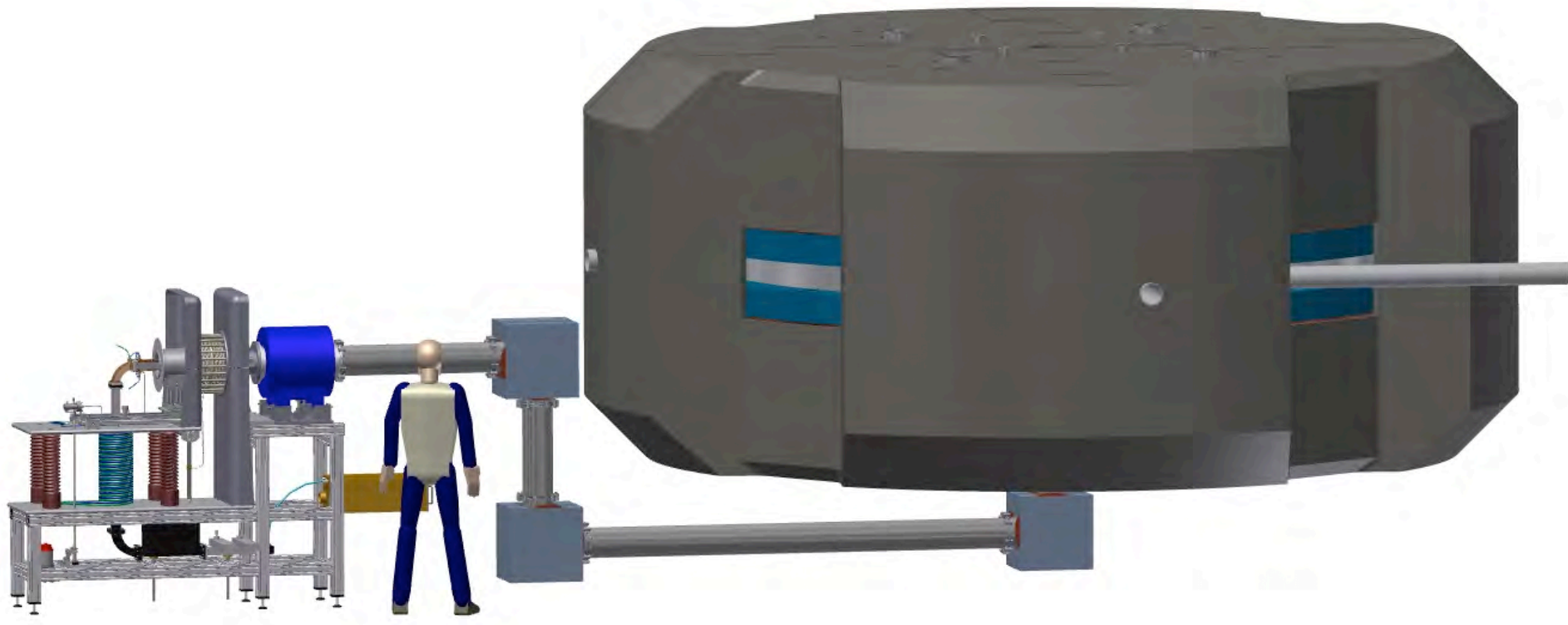
terms depending on
mass splittings

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

What is the IsoDAR timeline?



- Technically-driven schedule
- Currently proposed with KamLAND…but we have no schedule with KamLAND yet.
- First data in 2019, if we had funding now.

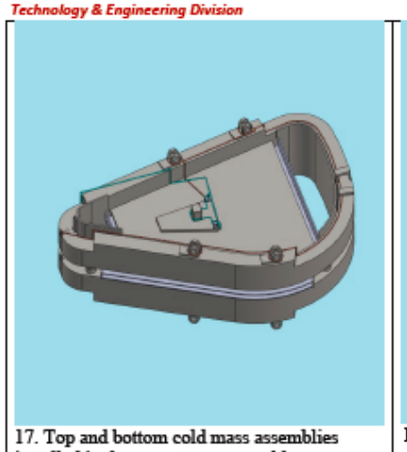


DAEδALUS progress

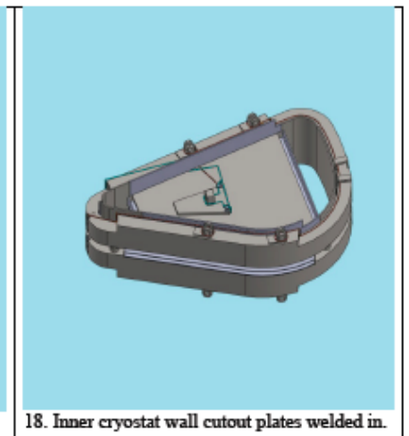
Engineering study of SRC, arXiv:1209.4886

Engineering design
Assembly plan
Structural analysis
Cryo system design

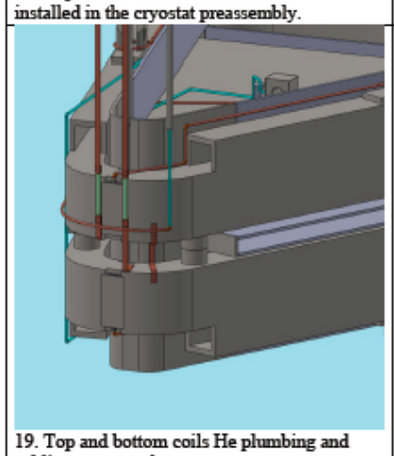
PSFC Technology & Engineering Division — MIT



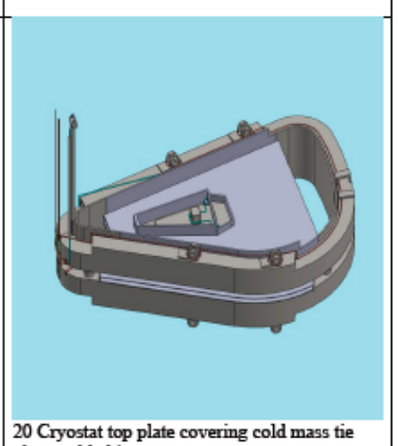
17. Top and bottom cold mass assemblies installed in the cryostat preassembly.



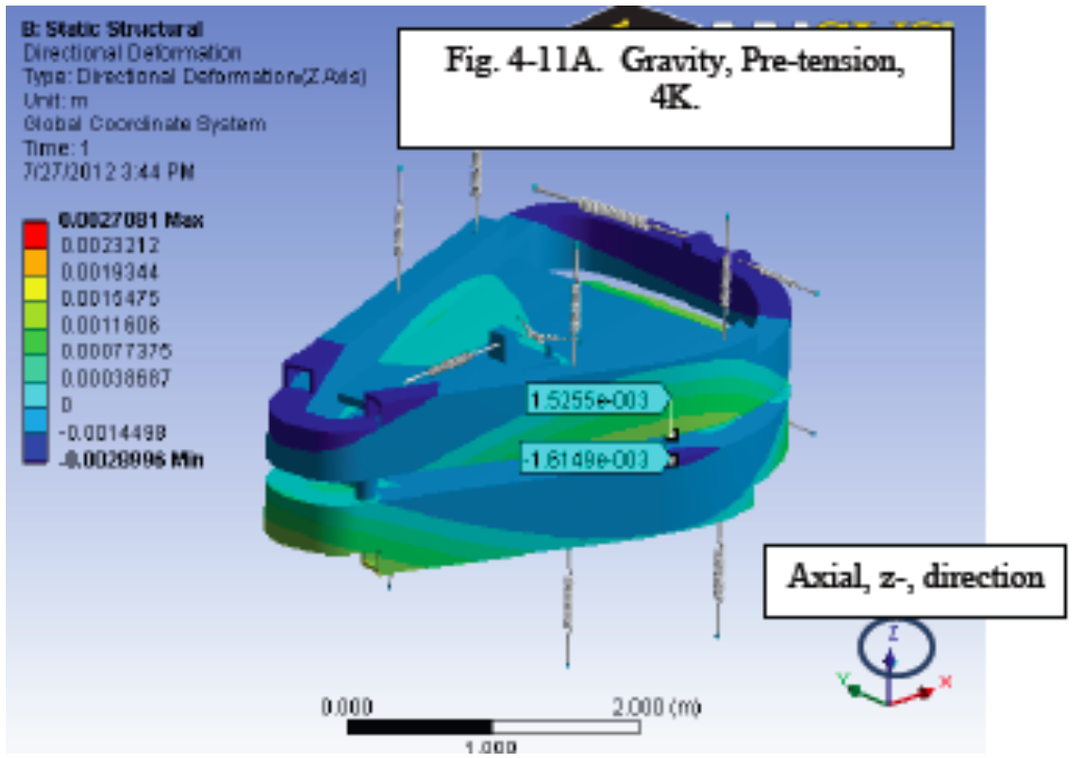
18. Inner cryostat wall cutout plates welded in.



19. Top and bottom coils He plumbing and cabling connected.



20 Cryostat top plate covering cold mass tie plate welded in.



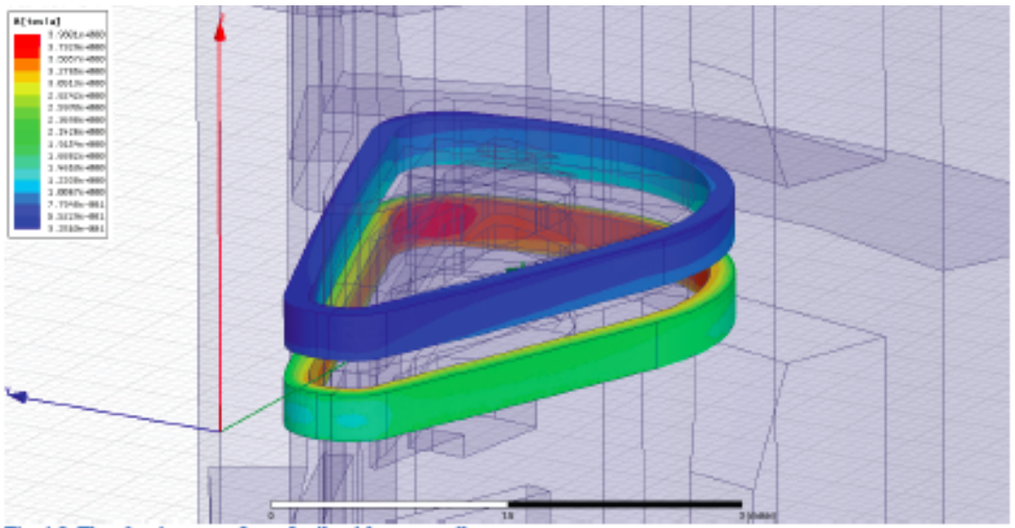


Fig. 4-9. Flux density on surface of coils with upper coil current zero.

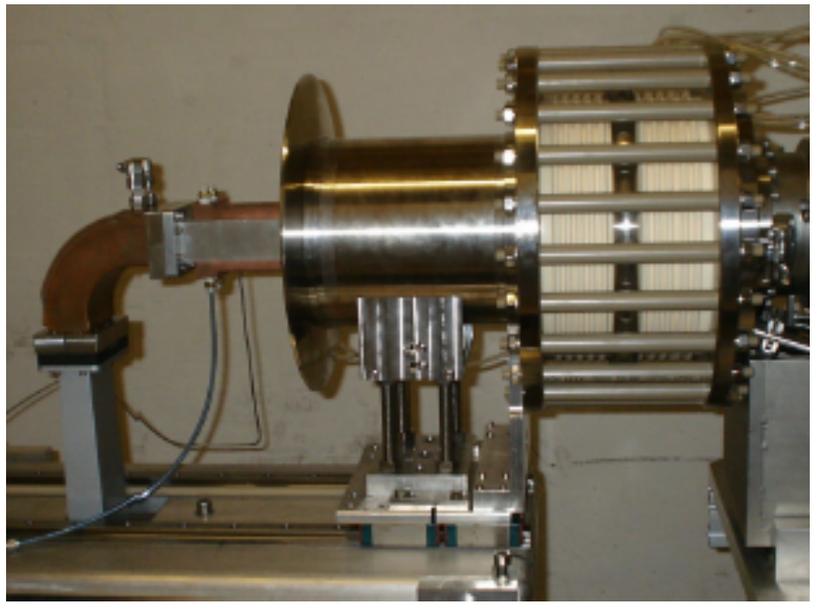
δ_{CP} sensitivity assumptions

Configuration Name	Source(s)	Average Long Baseline Beam Power	Detector	Fiducial Volume	Run Length
DAEδALUS@LENA	DAEδALUS only	N/A	LENA	50 kt	10 years
DAEδALUS@Hyper-K	DAEδALUS only	N/A	Hyper-K	560 kt	10 years
DAEδALUS/JPARC (nu only)@Hyper-K	DAEδALUS & JPARC	750 kW	Hyper-K	560 kt	10 years
JPARC@Hyper-K	JPARC	750 kW	Hyper-K	560 kt	3 years ν + 7 years $\bar{\nu}$ [3]
LBNE	FNAL	850 kW	LBNE	35 kt	5 years ν 5 years $\bar{\nu}$ [6]

Versatile Ion Source

- Plasma generated by 2.45 GHz off-resonance discharge in a 0.1 T magnetic field.

- A four-electrode system allows extraction to a low energy beam transport line.



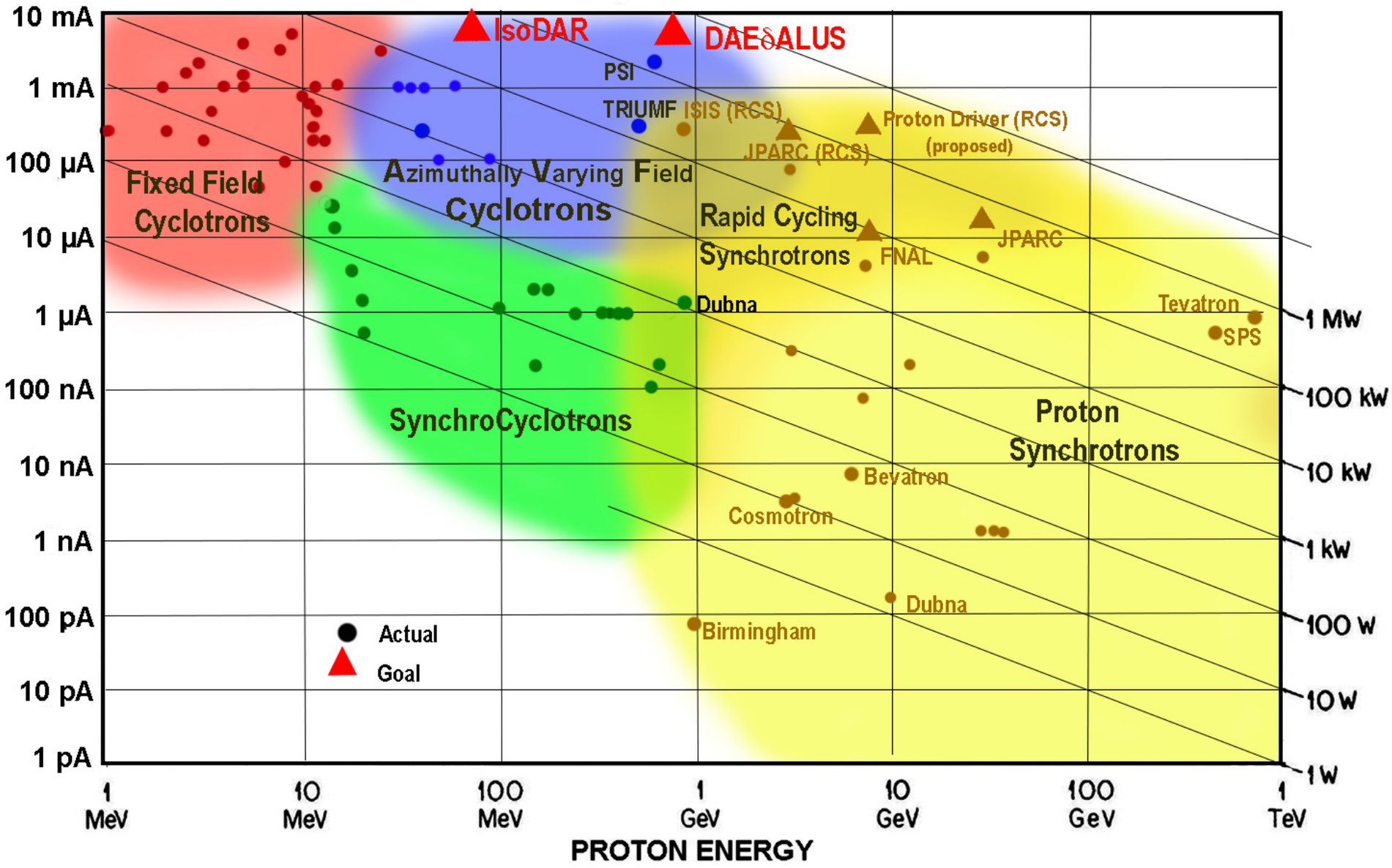
$$H_2 + e^- \rightarrow H + H + e^-$$

$$H_2 + e^- \rightarrow H_2^+ + 2e^-$$

$$H_2^+ + e^- \rightarrow H^+ + H + e^-$$

$$H + e^- \rightarrow H^+ + 2e^-$$

Keys to higher current:
H_2^+, intense ion source, inflect and extract with low losses, limit space charge



TRIUMF accelerates H- but with a much lower peak field because of Lorentz stripping.

PSI is an 8-sector normal conducting machine.

RIKEN is a heavy ion SRC and is most similar to our current design.

IsoDAR cost estimates at present

Cost-effective design options for IsoDAR
A. Adelmann et al. arXiv:1210.4454

1st source constructed -> $30M base cost (2013 $)

If more sources are constructed: $15M each

recommended contingency as of now: 50%
after first engineering design: 20%

DOE-sponsored study on a 2 mA proton machine

COST / BENEFIT COMPARISON

FOR

45 MEV AND 70 MEV CYCLOTRONS

MAY 26, 2005

Conducted for:

U.S. Department of Energy
Office of Nuclear Energy, Science, and Technology
Office of Nuclear Facilities Management
19901 Germantown Road
Germantown, MD 20874

Conducted by:

JUPITER
Technical, Security, and Management Solutions

Suite 900, Westfield North
2730 University Boulevard West
Wheaton, MD 20902

EXECUTIVE SUMMARY

A cost/benefit study was conducted by *JUPITER* Corporation to compare acquisition and operating costs for a 45 MeV and 70 MeV negative ion cyclotron to be used by the Department of Energy in the production of medical radioisotopes. The study utilized available information from Brookhaven National Laboratory (BNL) in New York and from the University of Nantes in France, since both organizations have proposed the acquisition of a 70 MeV cyclotron. Cost information obtained from a vendor, Advanced Cyclotron Systems, pertained only to their 30 MeV cyclotron. However, scaling factors were developed to enable a conversion of this information for generation of costs for the higher energy accelerators.

Two credible cyclotron vendors (IBA Technology Group in Belgium and Advanced Cyclotron Systems, Inc. In Canada) were identified that have both the interest and capability to produce a 45 MeV or 70 MeV cyclotron operating at a beam current of 2 mA (milliamperes).

The results of our analysis of design costs, cyclotron fabrication costs, and beamline costs (excluding building construction costs) resulted in total acquisition costs of:

- $14.8M for the 45 MeV cyclotron, and
- $17.0M for the 70 MeV cyclotron.

Annual operating cost estimates for a 70 MeV cyclotron ranged between $1.9M and $1.1M; the large uncertainty is due to the lack of specificity in available data in comparing costs from BNL and the University of Nantes.

Overall power requirements (exclusive of facility heating and air conditioning) were estimated to be:

- 560 kW for the 45 MeV cyclotron, and
- 831 kW for the 70 MeV cyclotron.

Operational lifetime is expected to be in excess of 30 years for the main components of the accelerator.

Considerable scientific and economic benefits are gained in using the 70 MeV cyclotron compared to use of the 45 MeV cyclotron in terms of the variety and quantity of isotopes that can be produced. Selected examples of benefits in isotope production are discussed.

This is a simpler machine.

IsoDAR will cost more because the machine is larger…but this sets the scale.

Other options?

Assessment

- Good
- Moderate
- Bad

	IsoDAR Base Design	RFQ/Separated Sector Cyclotron	LINAC, 30 MeV, 40 mA	Modified Beta Beam Design	New Detector at Existing Beam
1. Cost	Good	Moderate	Bad	Moderate	Bad
2. $\bar{\nu}_e$ rate	Good	Good	Good	Bad	Good
3. Backgrounds low	Good	Good	Good	Good	Moderate
4. Technical risk	Moderate	Moderate	Moderate	Moderate	Good
5. Compactness	Good	Moderate	Bad	Good	Moderate
6. Simplicity u'ground	Good	Moderate	Moderate	Bad	Moderate
7. Reliability	Good	Good	Good	Bad	Good
8. Value to other exps	Good	Good	Good	Bad	Bad
9. Value to Industry	Good	Moderate	Moderate	Bad	Bad

DAEδALUS cost estimates at present

$130M near accelerator, $450M for the 3 sites.
This includes various contingencies, 20% to 50%

Assumes component cost drops by 50% after first production.
Does not include site-specific cost (buildings)

SRC is the cost driver. See: “Engineering study for the DAEdALUS sector magnet”;
Minervini et al. arXiv:1209.4886

The RF is based on the PSI design, for which we have a cost.

The similarity to RIKEN allows a cost sanity check. We have a cost for this.

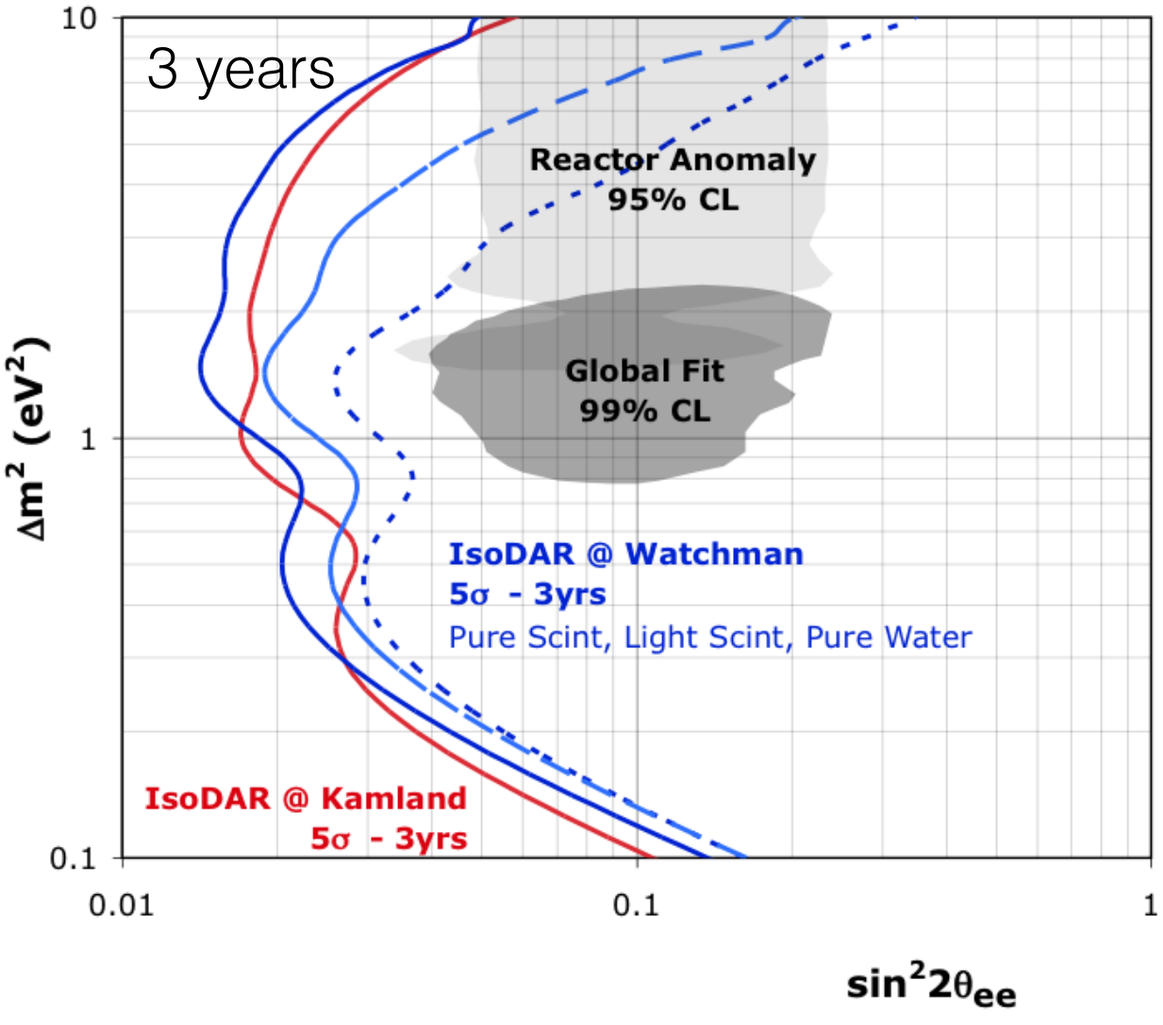
All targets are ~1 MW (similar to existing), noting that each cyclotron can have multiple targets.

For a comparison between DAEδALUS and existing cyclotrons (e.g. RIKEN, TRIUMF, PSI) see:
“Multimegawatt DAEδALUS Cyclotrons for Neutrino Physics” arXiv:1207.4895

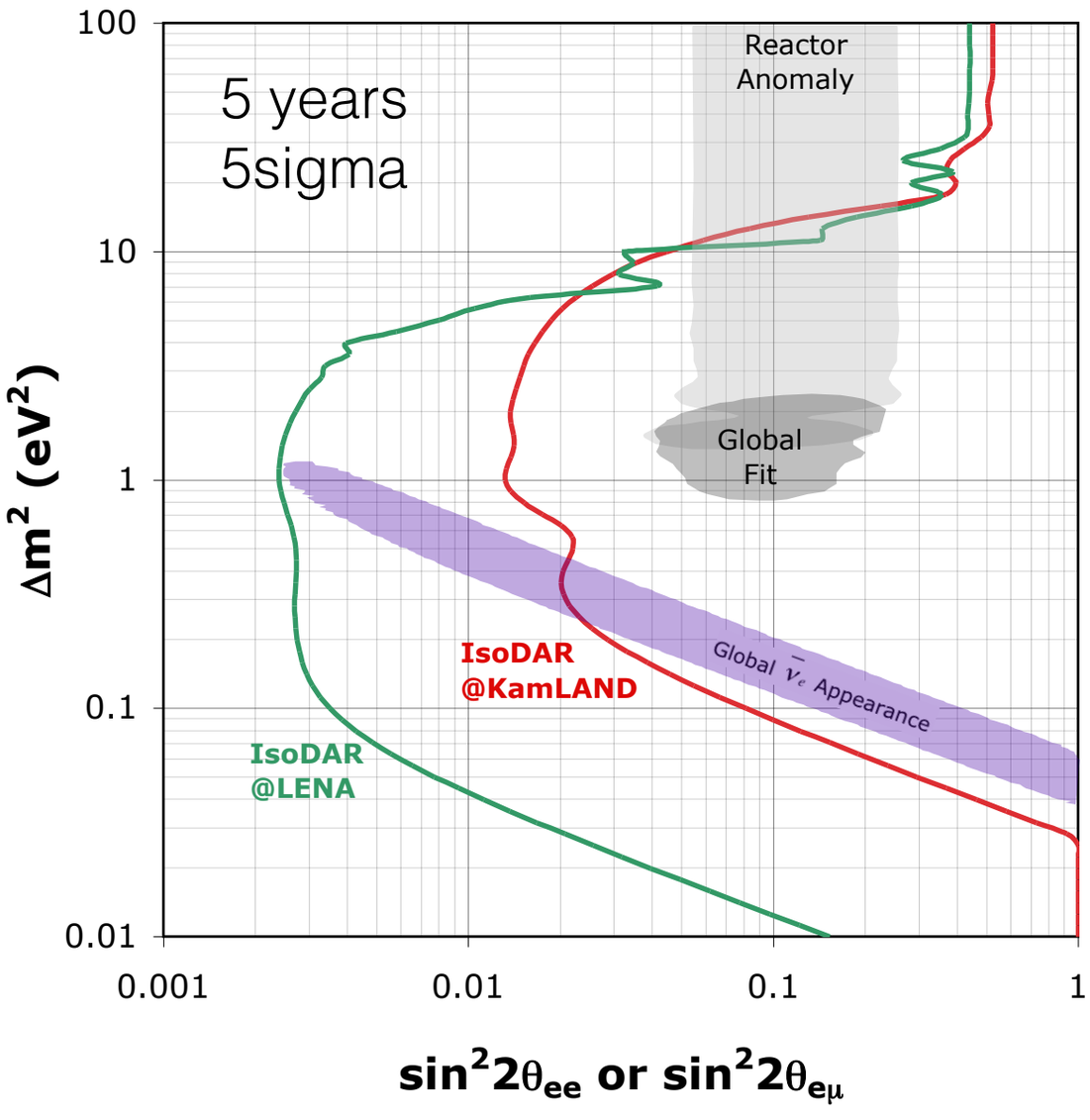
Possible IsoDAR locations

(We are currently pursuing a BDR for IsoDAR@KamLAND)

Disappearance sensitivity with **Watchman**
(1 kton Gd-doped water or scintillator)

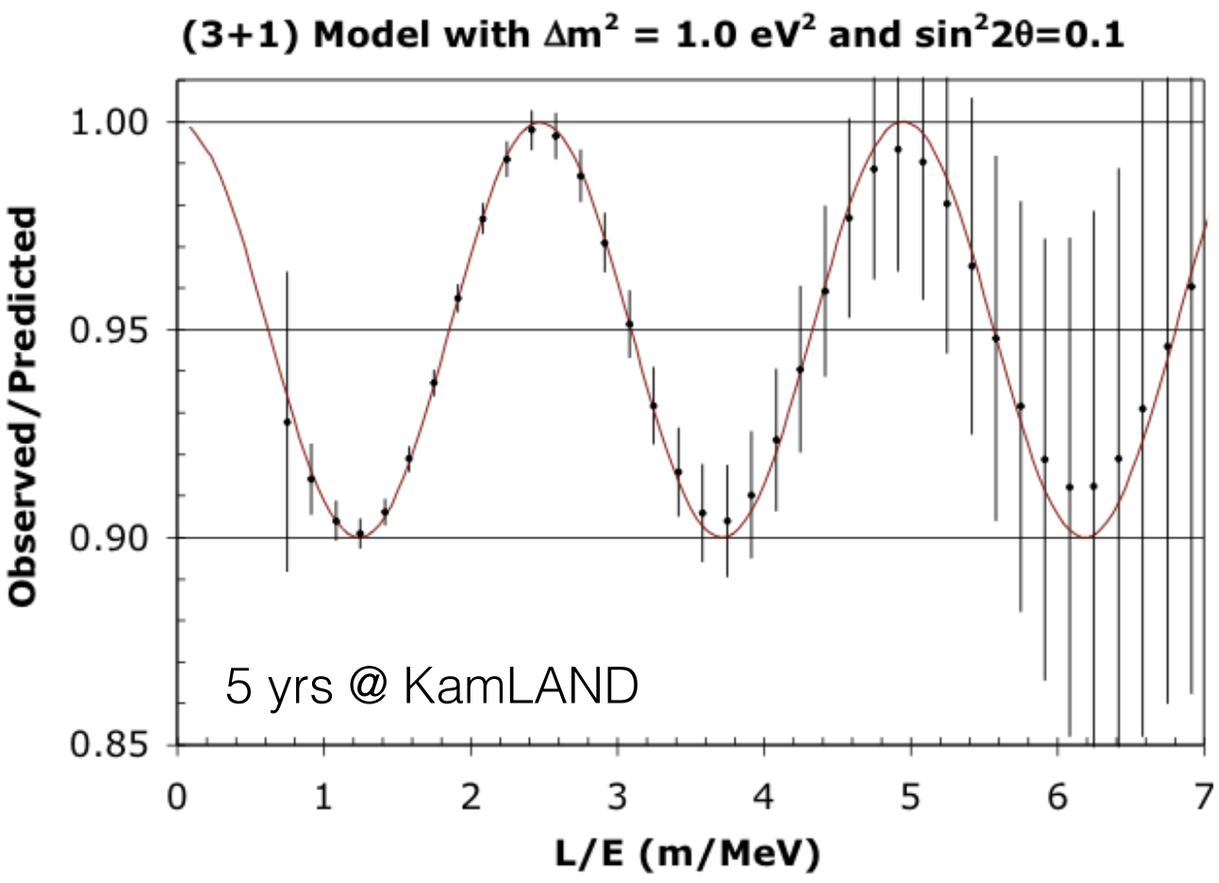


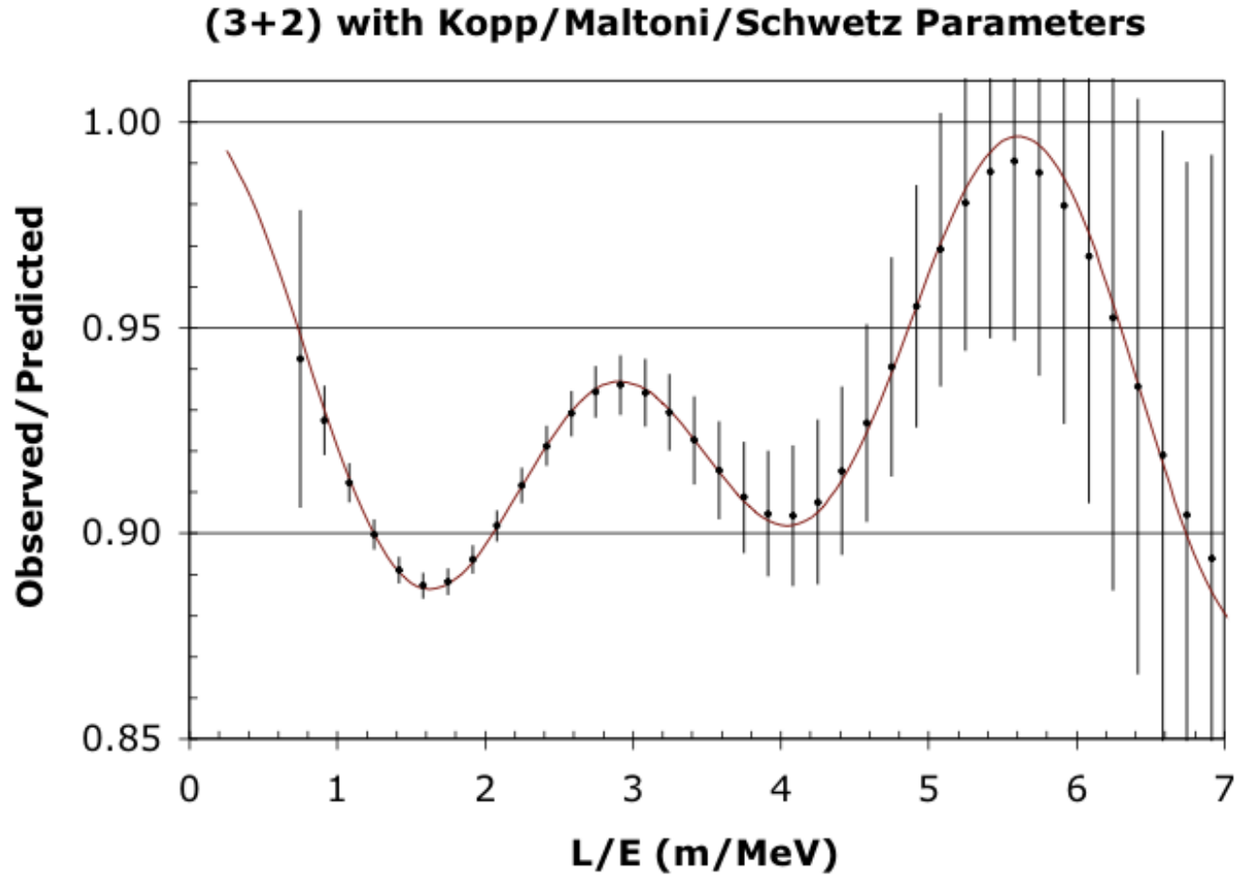
Dis/appearance sensitivity with **LENA**
(50 kton liquid scintillator)



How many steriles?

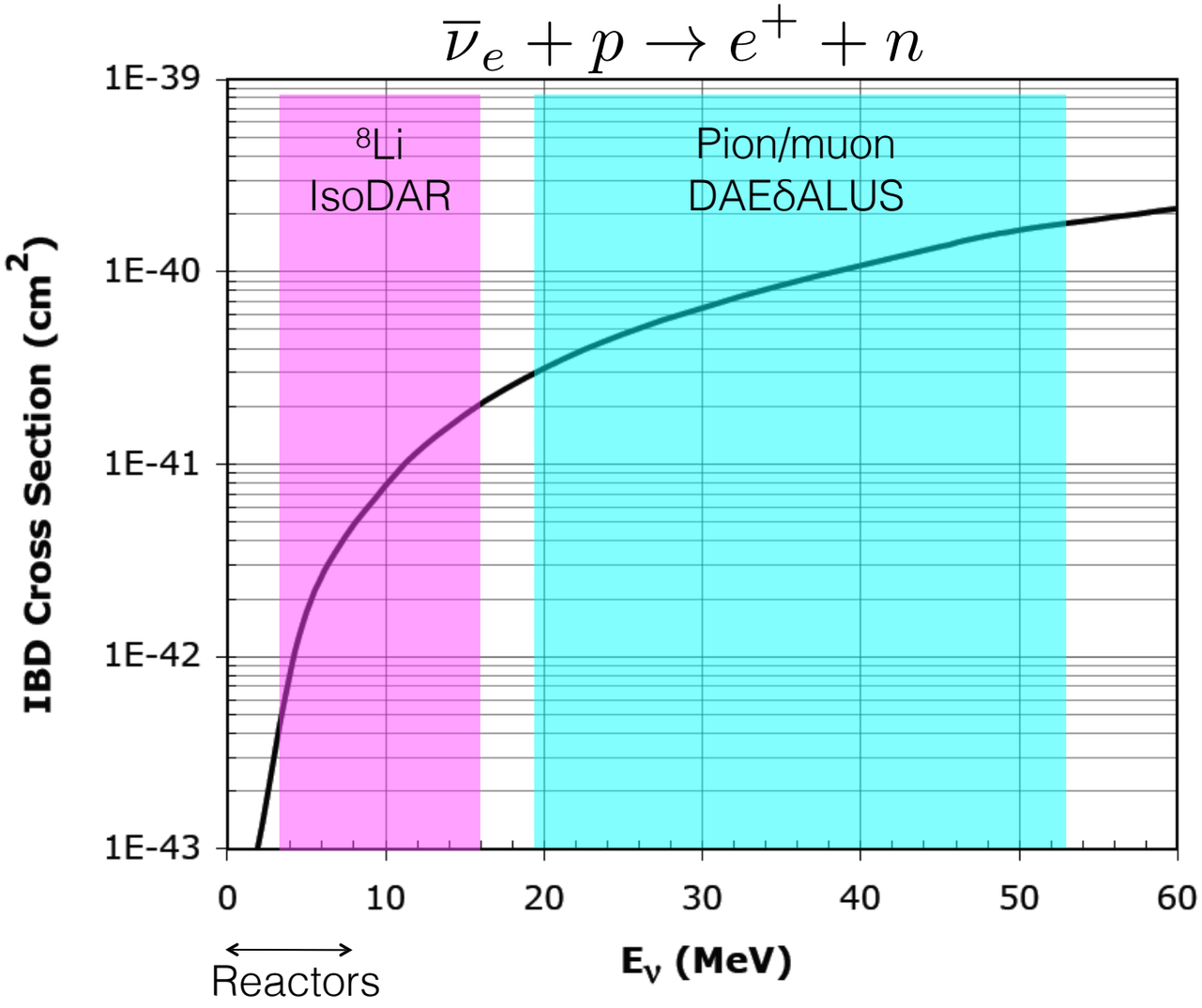
Observed/Predicted event ratio vs L/E, including energy and position smearing

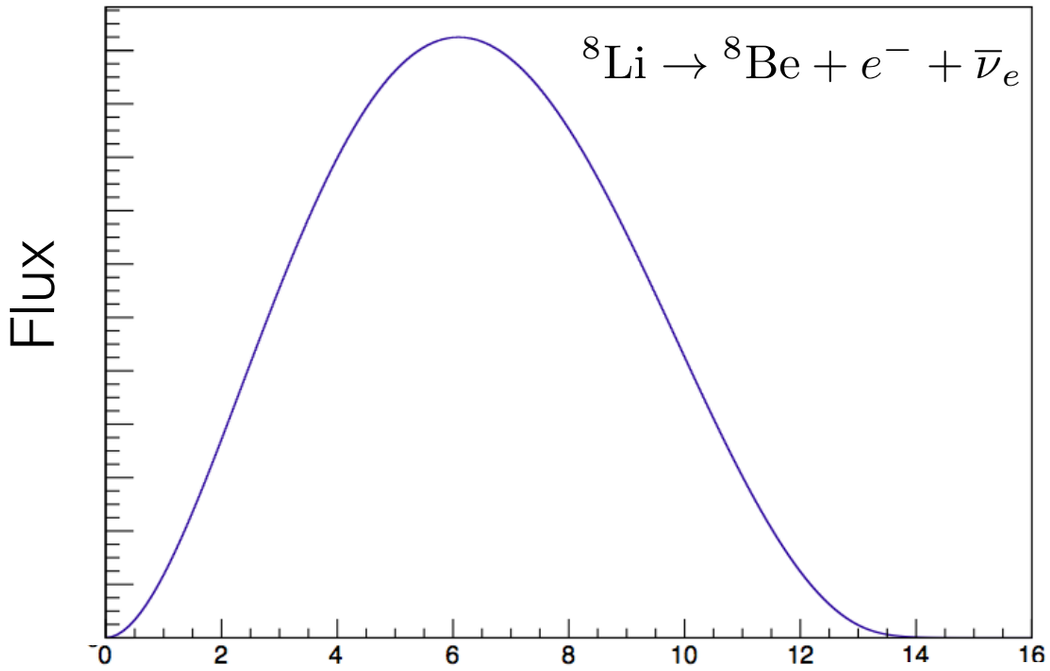


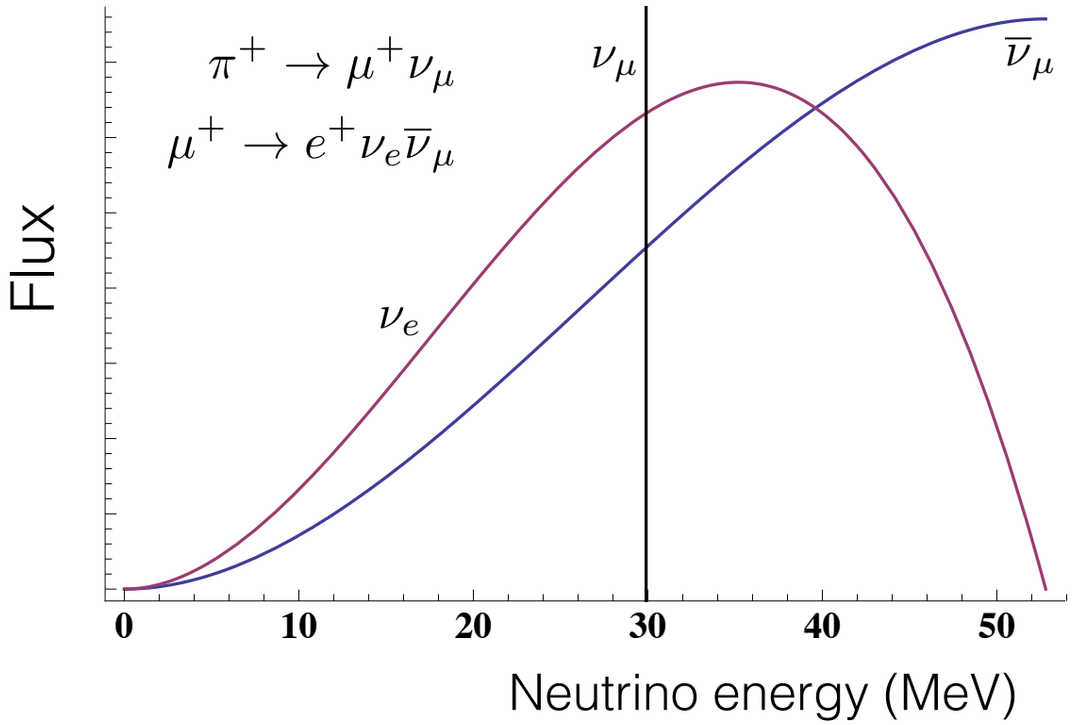


IsoDAR's high statistics and good L/E resolution provide the potential for distinguishing (3+1) and (3+2) oscillation models

Flux and cross section



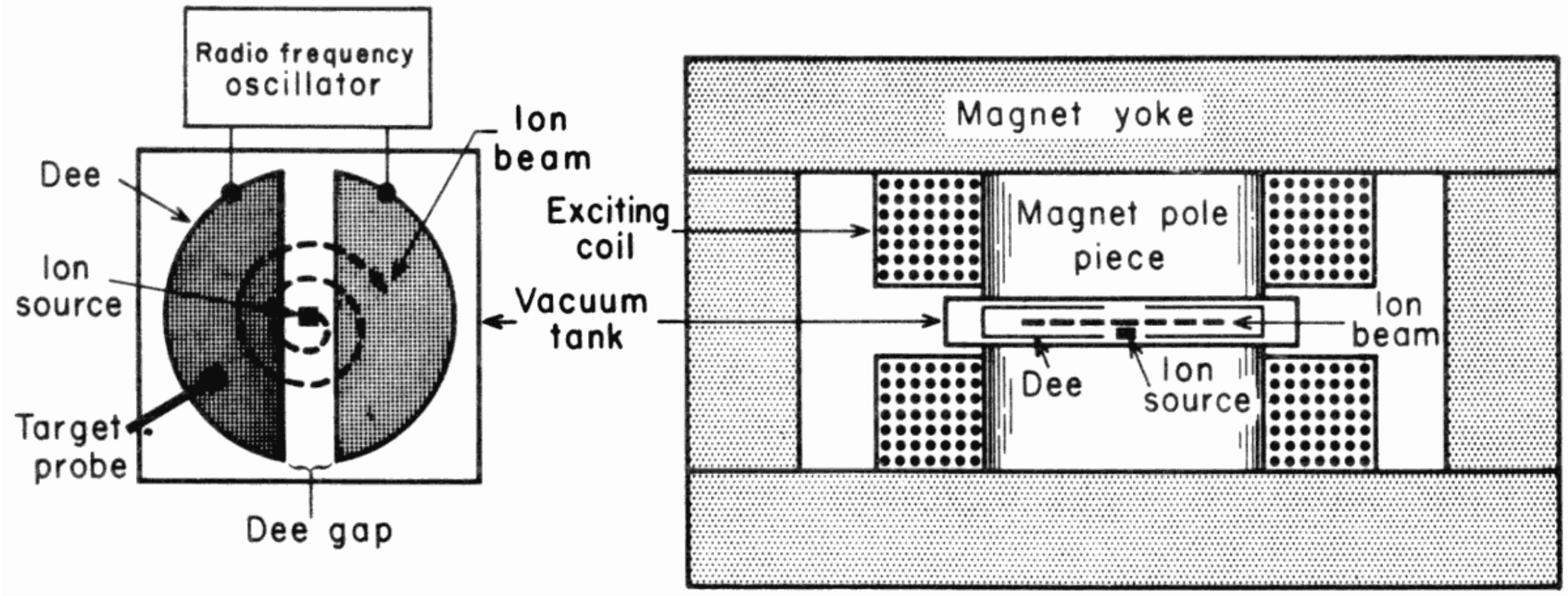




- Scintillator or Gd-doped water detector
- Prompt positron signal followed by neutron capture

$$E_{\overline{\nu}_e} \cong E_{\mathrm{prompt}} + 0.78\ \mathrm{MeV}$$

Cyclotrons



An “isochronous cyclotron” design: magnetic field changes with radius, allowing multibunch acceleration

- Inexpensive (relatively)
- Practical below ~1 GeV
- Good for ~10% or higher duty factor
- Typically single energy
- Taps into existing industry