π^+ μ^+ K^+ ${}^{A}X$

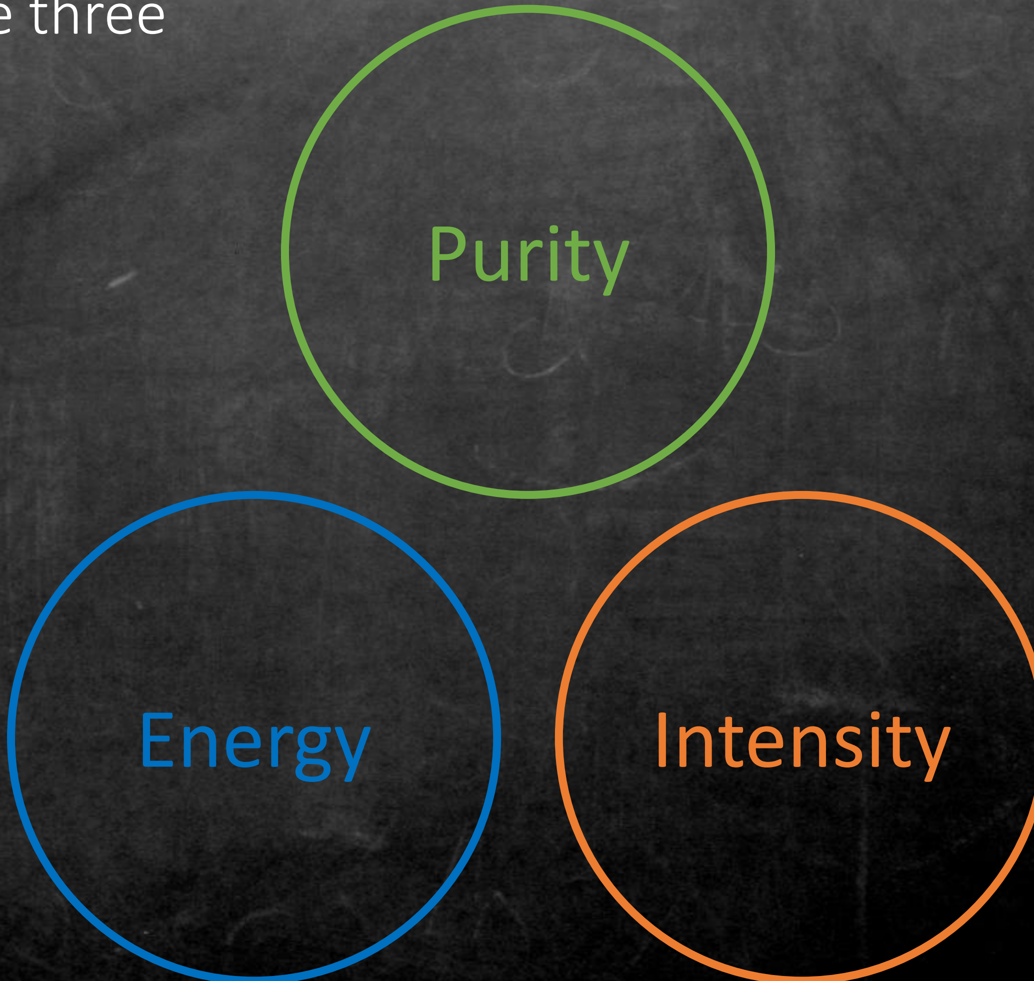
Neutrinos from Decay-At-Rest

Daniel Winklehner, MIT

NUFACT2017, Uppsala, Sweden, 09/29/2017

Some Important Frontiers of Particle Physics

- In devising a new experiment, one might be interested in these three frontiers:
  - Purity
    - Pure ν_x
    - Devoid of ν_x
    - Well understood spectrum
  - Intensity
    - Statistics
    - S/N
  - Energy
    - Specific energy → L/E
    - Low energy spread
    - Etc.
- Decay-At-Rest can provide high Intensity, high purity and a well-understood (low-) energy spectrum…



Outline

- Decay-At-Rest - Overview
- (A few) Experiments
  - COHERENT
  - JSNS^2
  - KPipe
  - DAEδALUS
  - IsoDAR
- IsoDAR: The Anatomy of a Cyclotron Proton Driver

Decay-At-Rest Processes

π^+ μ^+ K^+ ${}^{A}X$

Decay-At-Rest – Four Types

Purity

π^+ μ^+

$$\begin{array}{l} \qquad\qquad\qquad\quad \searrow\!\!\!\!\nearrow \nu_e \\ \pi^+ \to \mu^+ \to e^+ \\ \quad \hookrightarrow \nu_\mu \quad \hookrightarrow \bar{\nu}_\mu \end{array}$$

PiDAR

MuDAR

K^+

$$\mathrm{K}^+ \to \mu^+ + \nu_\mu$$

KDAR

^{A}X

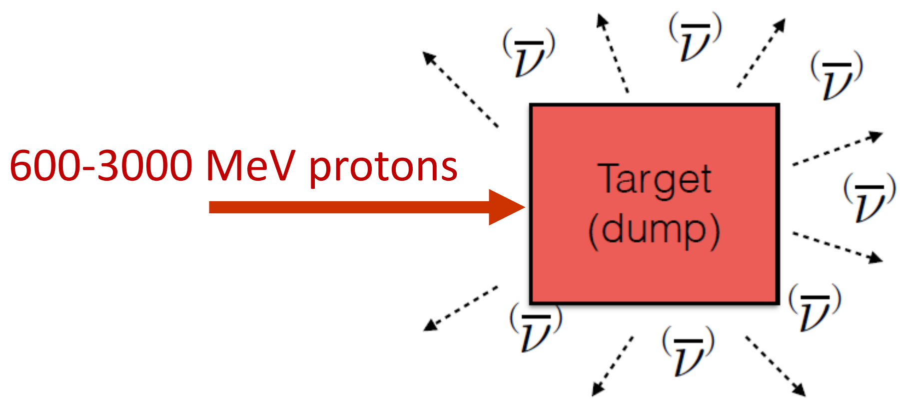
$${}^{\mathrm{A}}_{\mathrm{Z+1}}\mathrm{X}' \to {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} + e^- + \bar{\nu}_e$$

IsoDAR

Decay-At-Rest – Production

Intensity

- Either by protons impinging on a target (Pi/Mu/KDAR)



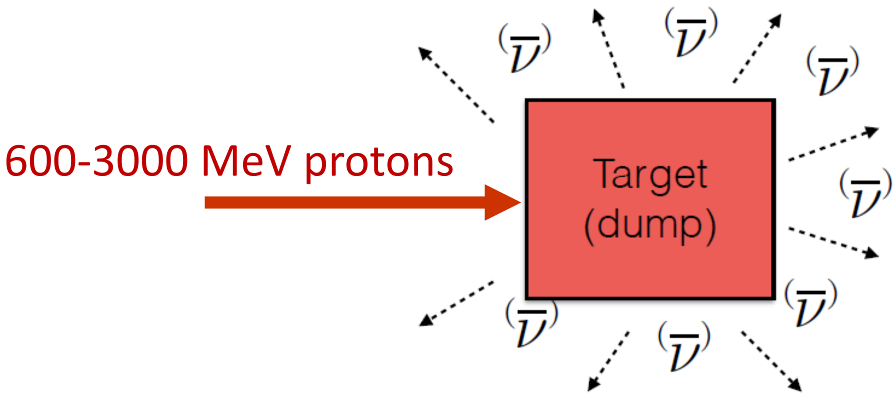
- Or by neutron capture and subsequent beta-decay (IsoDAR) e.g.:

$$\text{proton} \rightarrow {}^{9}\text{Be} \rightarrow n \rightarrow \text{captures on } {}^{7}\text{Li} \rightarrow {}^{8}\text{Li} \rightarrow \bar{\nu}_e$$

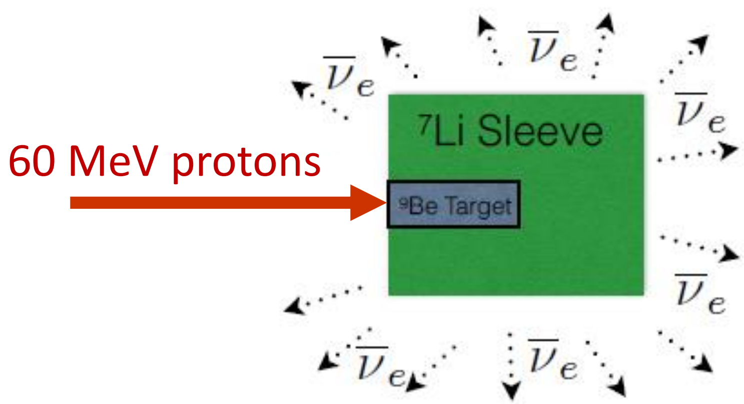
Decay-At-Rest – Production

Intensity

- Either by protons impinging on a target (Pi/Mu/KDAR)



- Or by neutron capture and subsequent beta-decay (IsoDAR) e.g.:



Decay-At-Rest – Energy Spectra

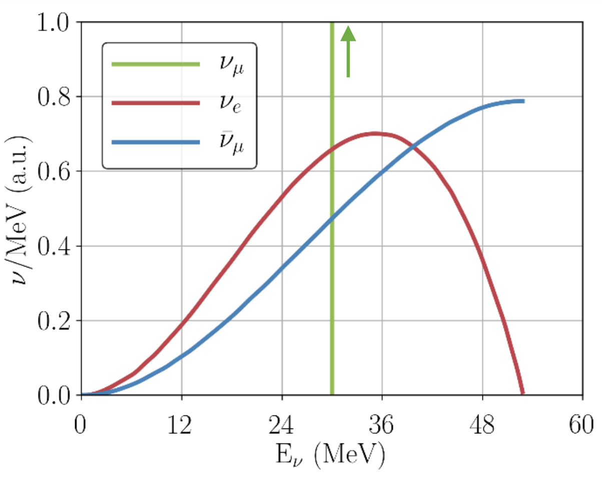
π+

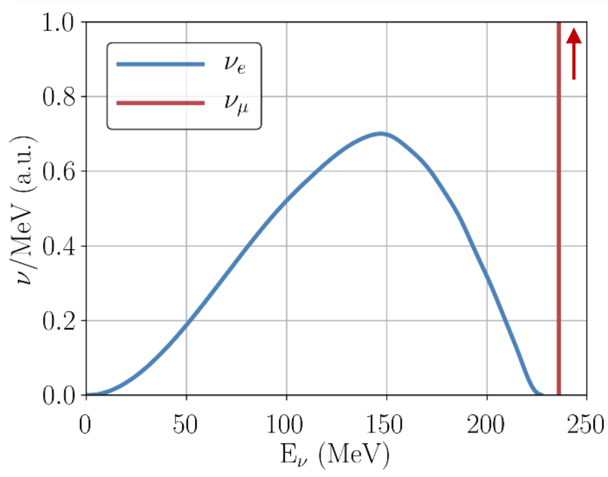
μ+

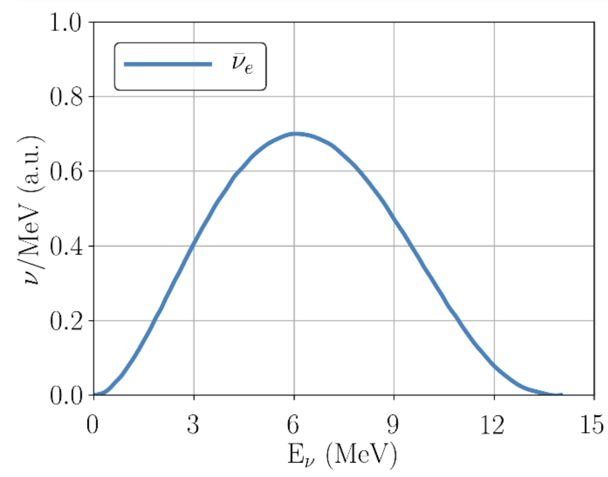
K+

^{A}X

Energy







$$\begin{array}{l} \qquad\qquad\quad \nearrow \nu_e \\ \pi^+ \to \mu^+ \to e^+ \\ \;\hookrightarrow \nu_\mu \;\; \hookrightarrow \bar{\nu}_\mu \end{array}$$

$$\begin{array}{l} K^+ \nearrow \mu^+ + \nu_\mu \\ \quad\;\; \hookrightarrow \pi^0 + e^+ + \nu_e \\ K^0_L \to \pi^- + e^+ + \nu_e \end{array}$$

$${}^{\;\;A}_{Z+1}X' \to {}^{A}_{Z}X + e^- + \bar{\nu}_e$$

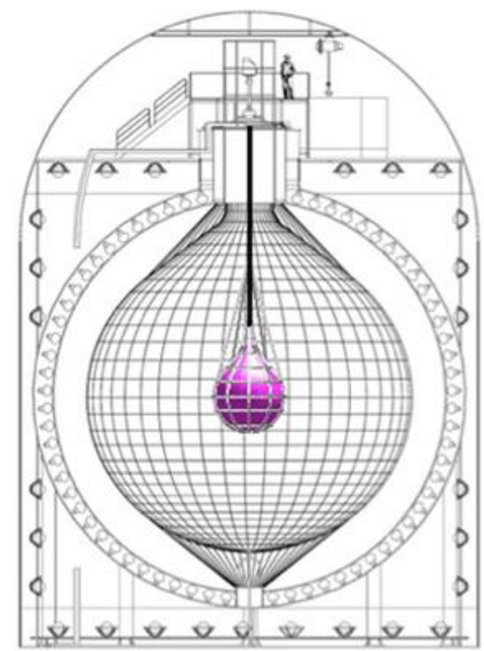
Low Energy (= short baseline)
Narrow, sometimes even mono-energetic

Decay-At-Rest – Detection

- In order to detect neutrinos we must decide:
  - The flavor(s) we are looking for
  - The type of interaction → Charged Current (CC) and Neutral Current (NC)
- Some examples of low energy interaction open to DAR neutrinos
  - NC: Coherent Elastic Neutrino-Nucleus Scattering ($\mathrm{CE}\nu\mathrm{NS}$)
  - CC: At typical DAR-energies, $\bar{\nu}_e$ interact through Inverse Beta Decay (IBD):

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

    Want large number of protons available →
    - Scintillator
    - Gd-doped water-Cherenkov detector
  - CC: $\nu_\mu + {}^{12}\mathrm{C} \rightarrow \mu^- + \mathrm{X}$ in Liquid Scintillator (signal from prompt μ^- and final state proton + delayed Michel electron)



KamLAND

Decay-At-Rest – Detection

- In order to detect neutrinos we must decide:
  - The flavor(s) we are looking for
  - The type of interaction → Charged Current (CC) and Neutral Current (NC)
- Some examples of low energy interaction open to DAR neutrinos
  - NC: Coherent Elastic Neutrino-Nucleus Scattering ($\cancel{\text{CE}\nu\text{NS}}$) (CEvNS) …spreading the meme…
  - CC: At typical DAR-energies, $\bar{\nu}_e$ interact through Inverse Beta Decay (IBD):

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

    Want large number of protons available →
    - Scintillator
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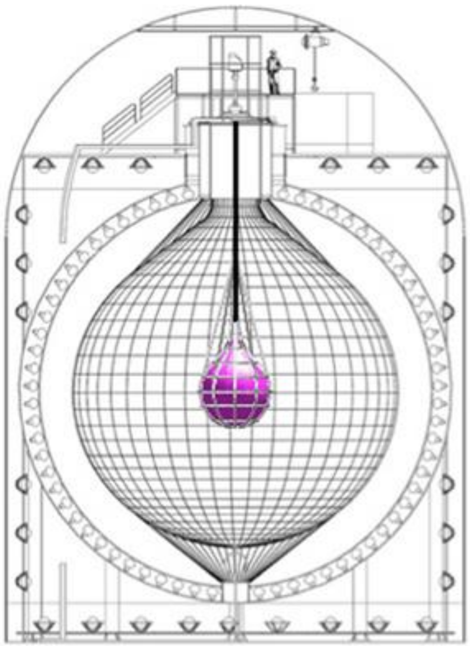
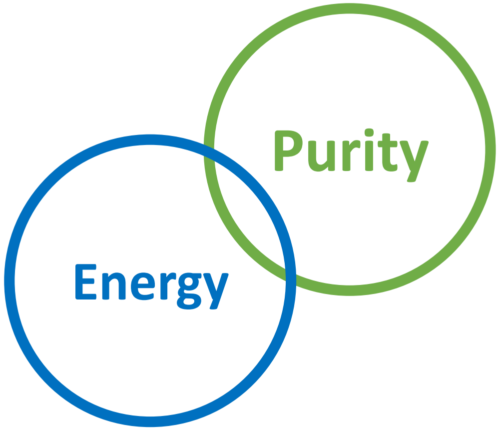


KamLAND

Decay-At-Rest – Advantages



PiDAR/MuDAR/IsoDAR

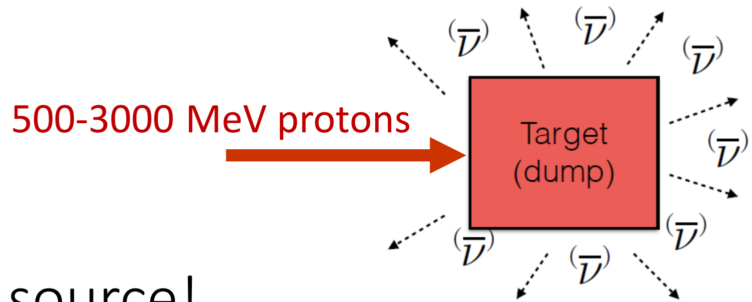
- Known energy shape
- Low Energy is nice:
  - Coherent scattering cross-section is high (compared to other interactions)
  - (L/E-dependent) oscillation studies
- IBD cross-section (for $\bar{\nu}_e$ applications) is well known
- IBD events (for $\bar{\nu}_e$ applications) are easy to record/ID
- Backgrounds can be controlled/understood
- Sometimes come for free in existing facility (e.g. SNS, MLF)

KDAR

- 236 MeV ν_μ, low ν_e background
- Sometimes come for free in existing facility (e.g. MLF)

Decay-At-Rest – Challenges

Intensity



- Isotropic → Lose much in unfavorable direction…
- Need very intense proton source!
- We heard a number of very interesting talks about planned upgrades and studies for future proton drivers, e.g.:
  - *Status of Future High Power Proton Drivers for Neutrino Beams,* Mon – Plenary
  - *Upgrade of J-PARC Accelerator and Neutrino Beamline toward 1.3 MW,* Mon – WG3
  - *Accelerator R&D Toward Proton Drivers for Future Particle Accelerators,* Tue – WG3
  - …
- In the second half of this talk, I will present you with another possibility: Cyclotrons
- Target design (cooling, activation → maintenance) is issue too.

(Proposed) Experiments

π^+ μ^+ K^+ ${}^{A}X$

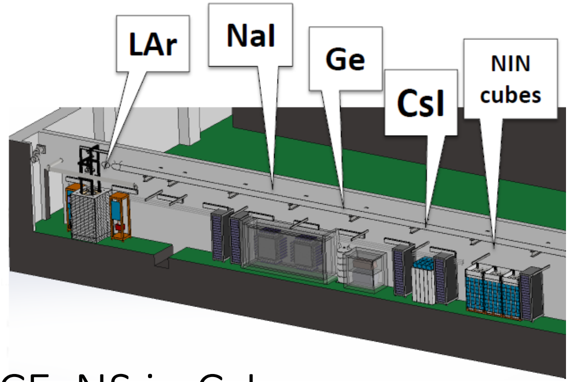
COHERENT

Running

- Talks during this meeting:
  - *The COHERENT Experiment,* Thu: Plenary
  - *COHERENT constraints on non-standard neutrino interactions,* Fri: WG5
  - *COHERENT and the LMA-dark solution,* Fri: WG5
- In a nutshell:
  - Uses neutrinos from PiDAR/MuDAR at Oakridge SNS to measure Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

$$\nu_\mu + {}^{A}_{Z}X \rightarrow \nu_\mu + {}^{A}_{Z}X$$

  - Several detector in a hallway below target dubbed "neutrino alley"
    - Has been measured to have low neutron background
    - 8 mwe overburden



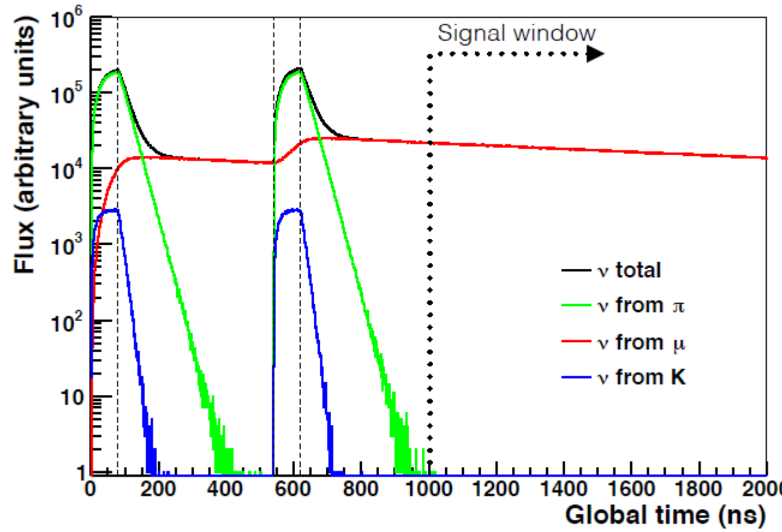
  - Just recently made the very first measurement of CEvNS in CsI:
    http://science.sciencemag.org/content/early/2017/08/02/science.aao0990

JSNS^2

Under Construction

- LSND is THE experiment that drives the high-Δm^2 anomalies. J-PARC's MLF and ORNL's SNS are the best (only) places to directly study the LSND anomaly.
- Uses PiDAR/MuDAR to test LSND anomaly in a cost-effective and timely way at J-PARC
- Aside: KDAR: Collect a large sample (~50k) of mono-energetic 236 MeV muon neutrinos from KDAR for nuclear probe and cross-section measurements.
- Production:

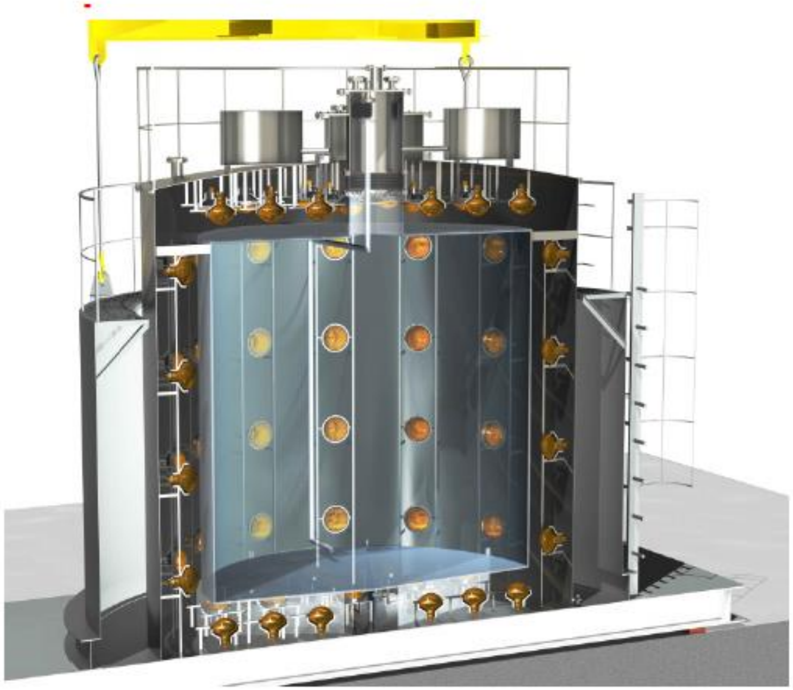
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$$
$$K^+ \rightarrow \mu^+ \nu_\mu$$



JSNS²

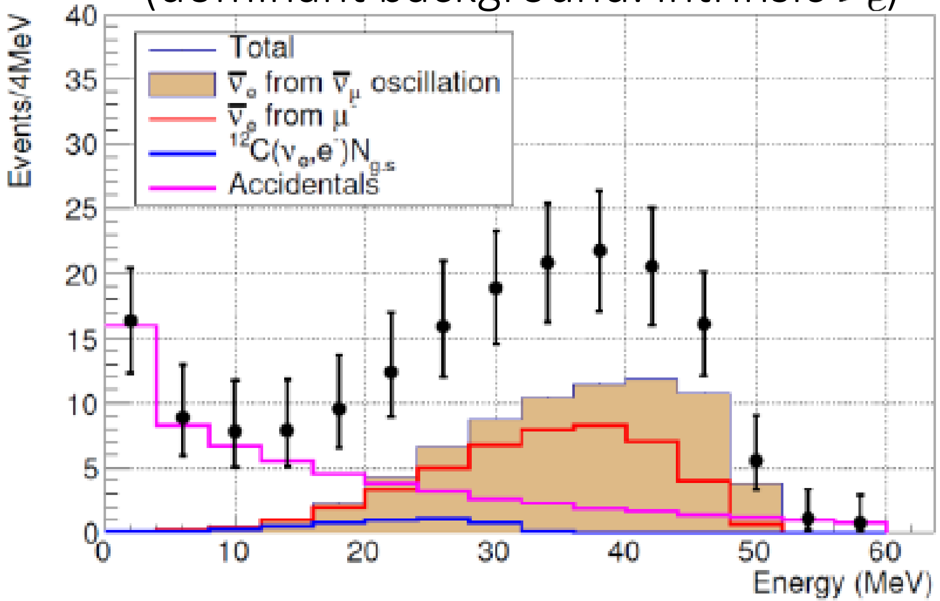
Detection:

- Target volume is Gd-loaded liquid scintillator
- Phase 0: 17 tons w/ 193 x 8'' PMTs
- Future phase: multi-detector (34 t)
- Energy resolution $\approx 15\%/\sqrt{\mathrm{E(MeV)}}$
- Measures $\bar{\nu}_e$ appearance through IBD: $\bar{\nu}_e + p^+ \rightarrow e^+ + n$

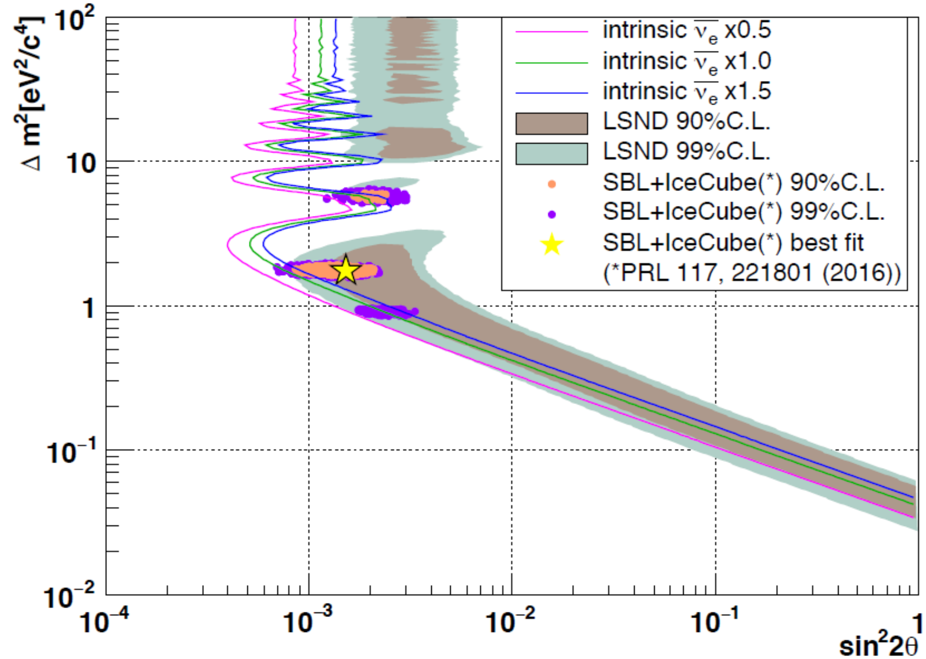


JSNS^2 - Spectrum & Sensitivity

(dominant background: intrinsic $\bar{\nu}_e$)



Case $\Delta m^2 = 1.2\text{eV}^2, \sin^2 2\theta = 0.003$

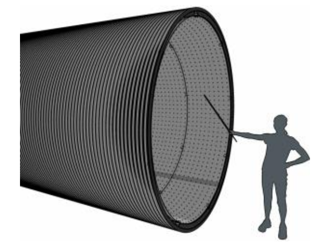


Status:

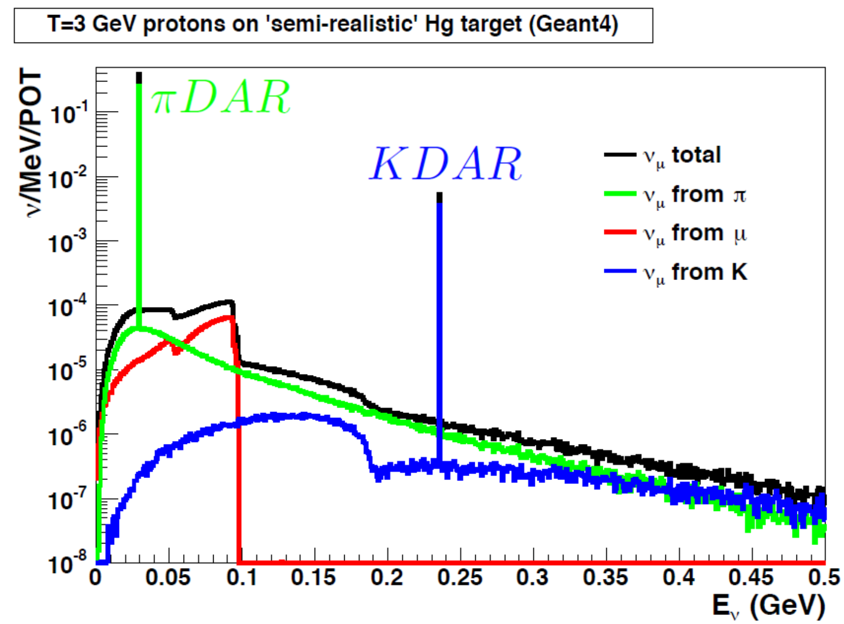
- Obtained Stage 1 (of 2) approval from PAC in 2015
- Secured funding for first 17 ton detector module in 2016
- Submitted TDR to J-PARC PAC (seeking Stage 2 approval) in 2017
- Construction has begun! They expect first data in late-2018

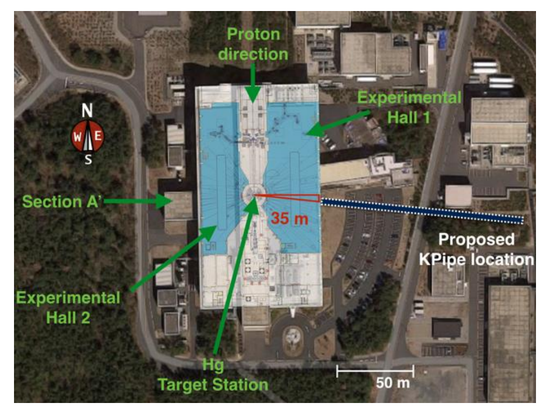
KPipe

Conceptual Design Phase

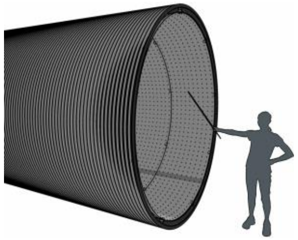


- Use 236 MeV ν_μ from KDAR
- L/E: With long detector (100-120 meters), filled with liquid scintillator, one can contain oscillation period for ν_S with mass splitting >1 eV^2
- To keep cost down, use industrial plastic chemical storage containers for vessel and instrument with 0.6% photocoverage (120k SiPM's)
- Can do this since high-energy resolution not required



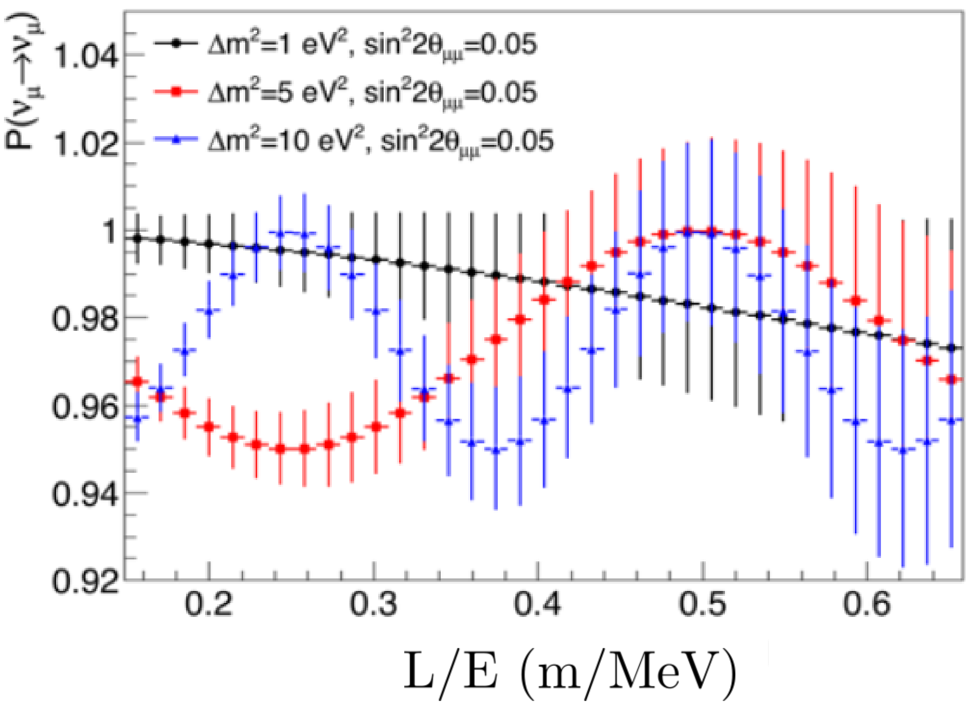


KPipe

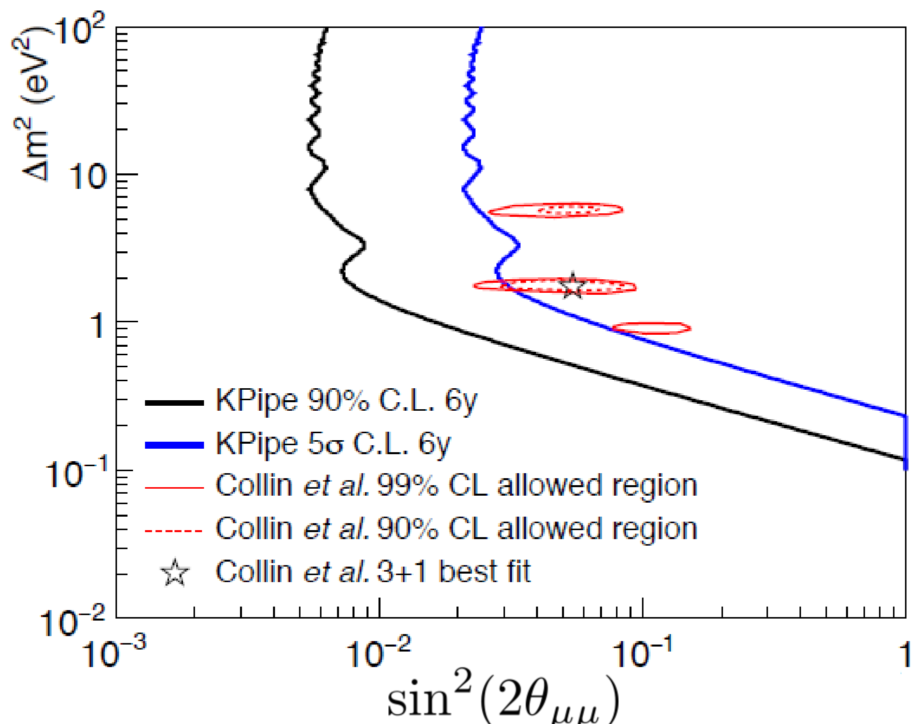


- Trace out oscillation curve in long detector
- High precision ν_μ disappearance search with minimal systematic uncertainties from cross-section and flux
- Cost: 5 M$, Decisive in 6 years of running.

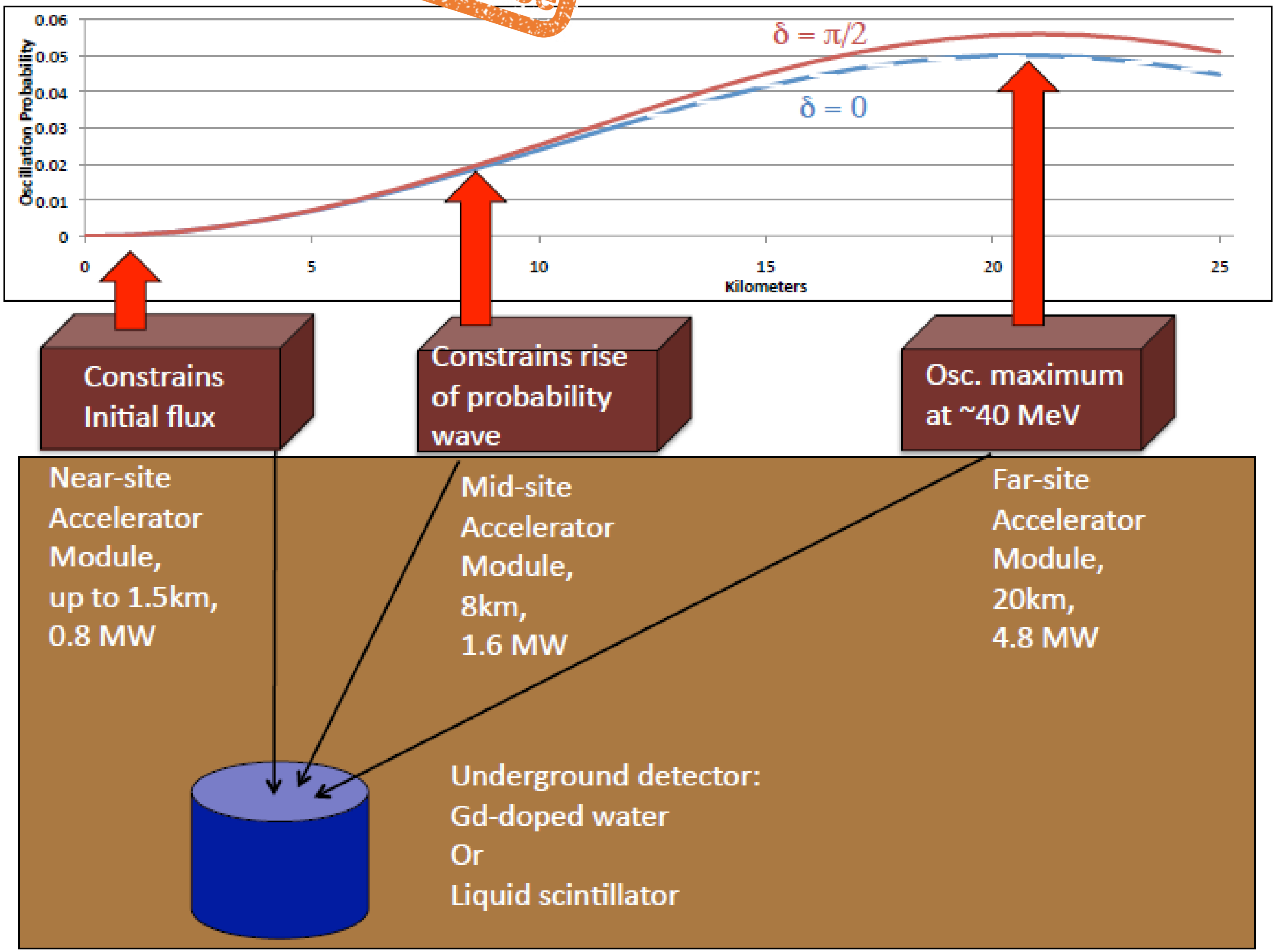
Signal:

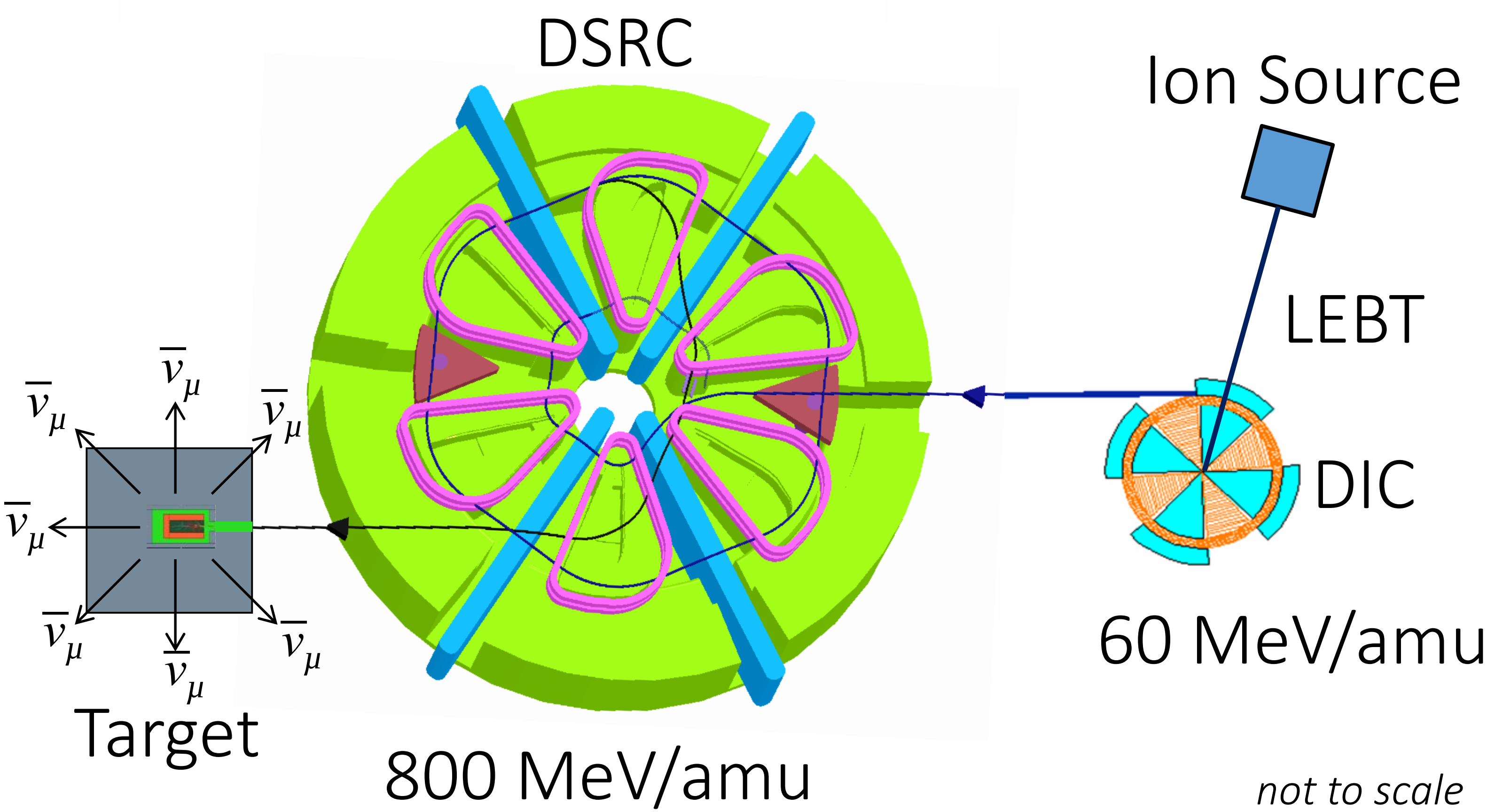


Sensitivities:

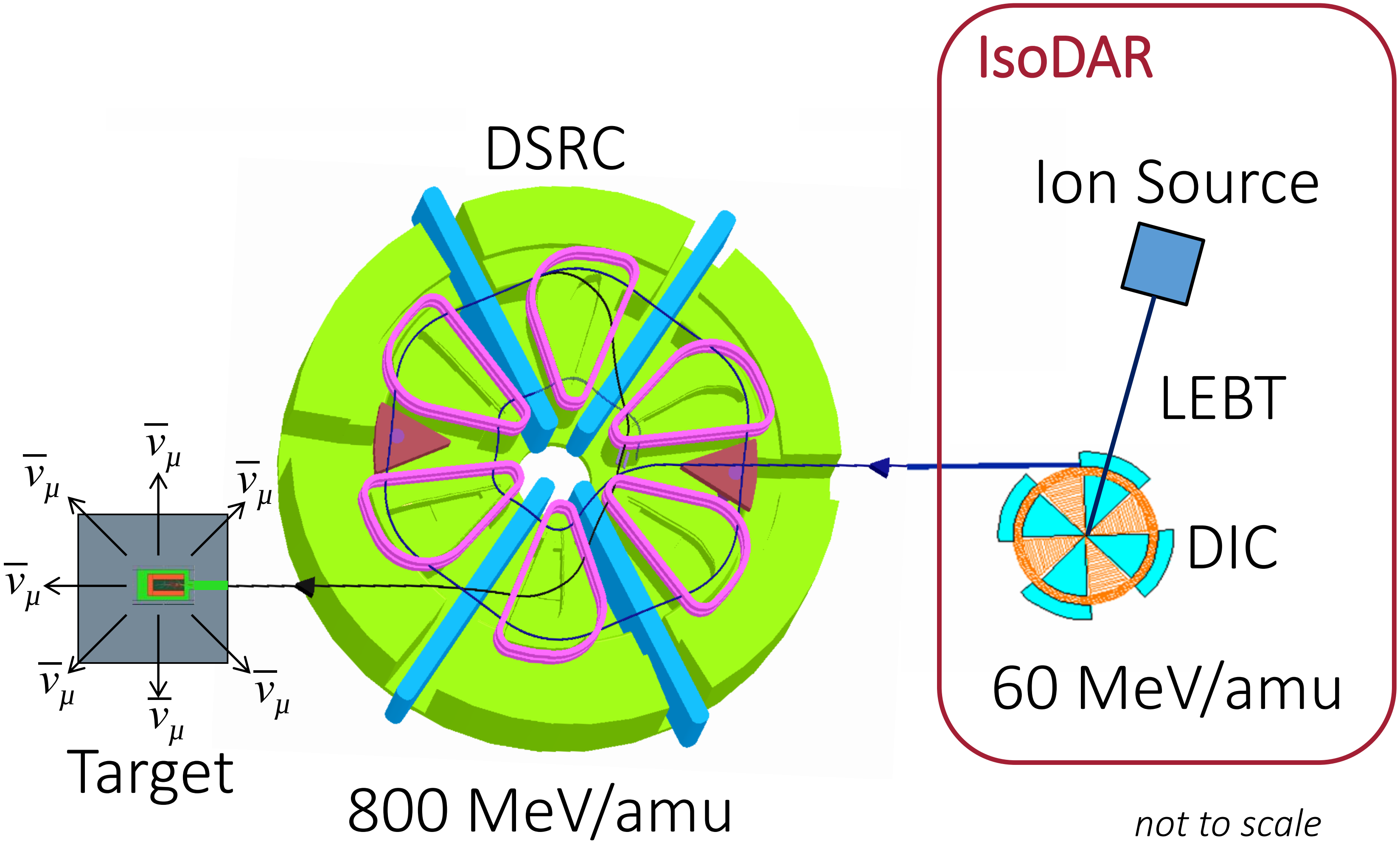


Conceptual Design Phase




DSRC
Ion Source
LEBT
DIC
60 MeV/amu
$\bar{\nu}_\mu$
$\bar{\nu}_\mu$
$\bar{\nu}_\mu$
$\bar{\nu}_\mu$
$\bar{\nu}_\mu$
$\bar{\nu}_\mu$
$\bar{\nu}_\mu$
Target
800 MeV/amu
not to scale

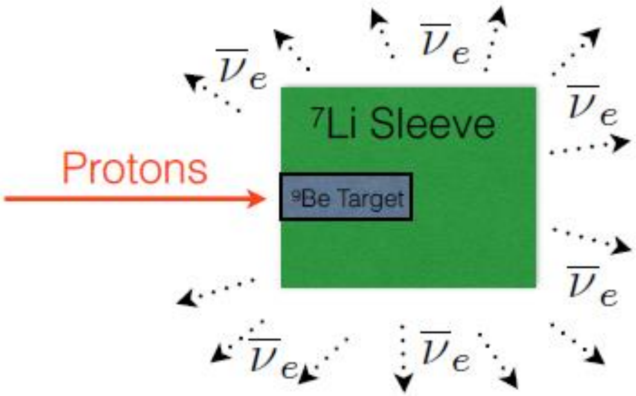
DAEδALUS/IsoDAR

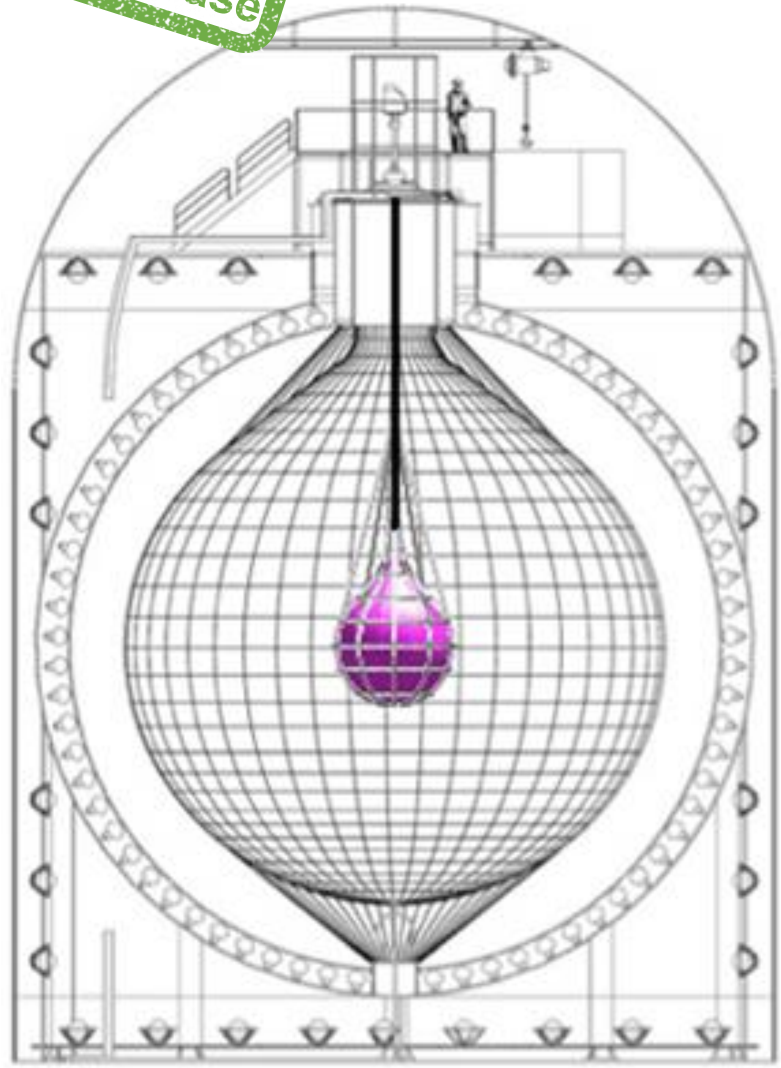


IsoDAR

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

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





16.5 m

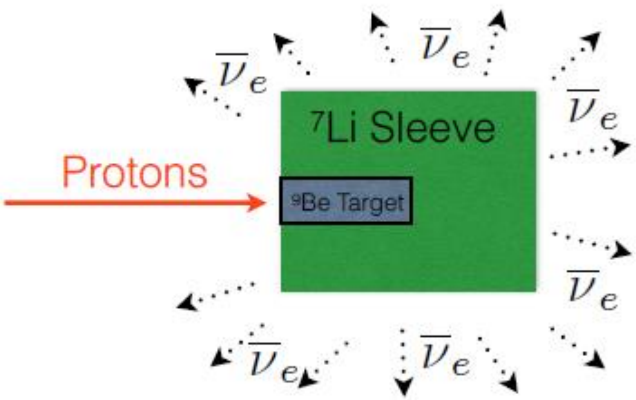
kton scale detector (e.g. KamLAND)

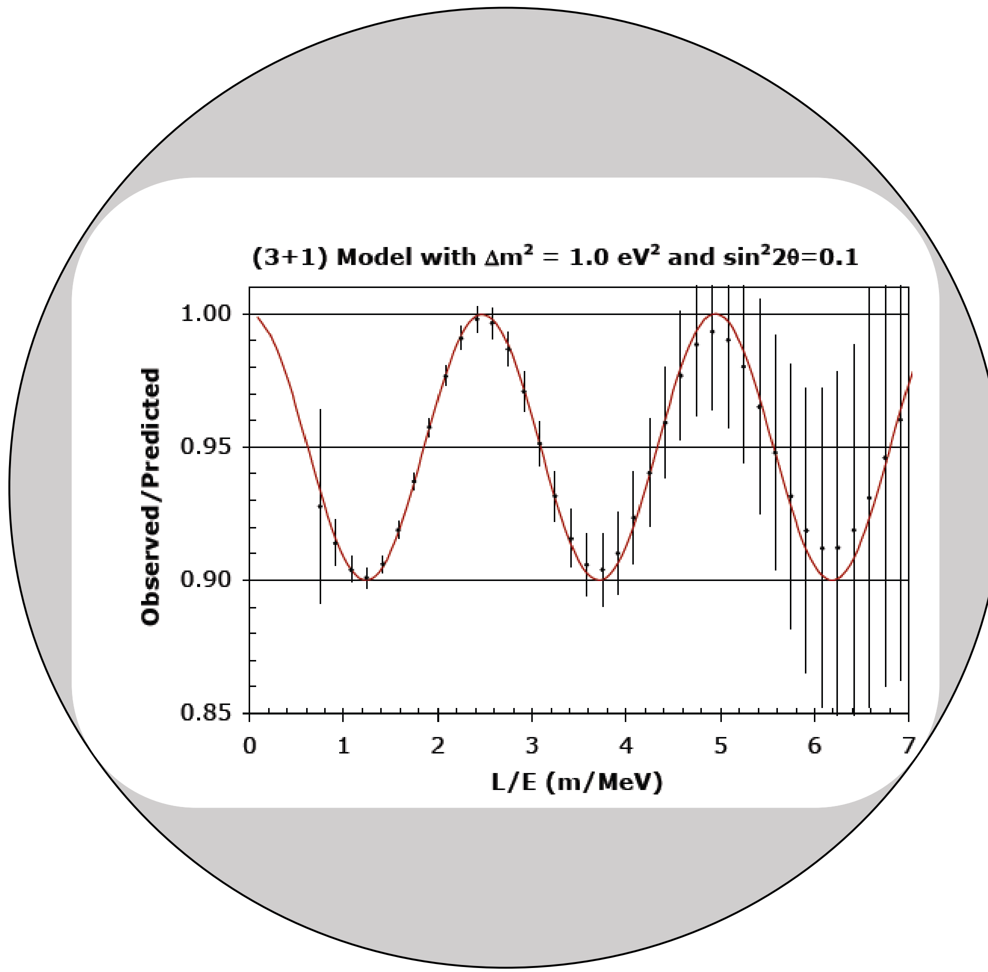
IsoDAR

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

DAEδALUS IsoDAR

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



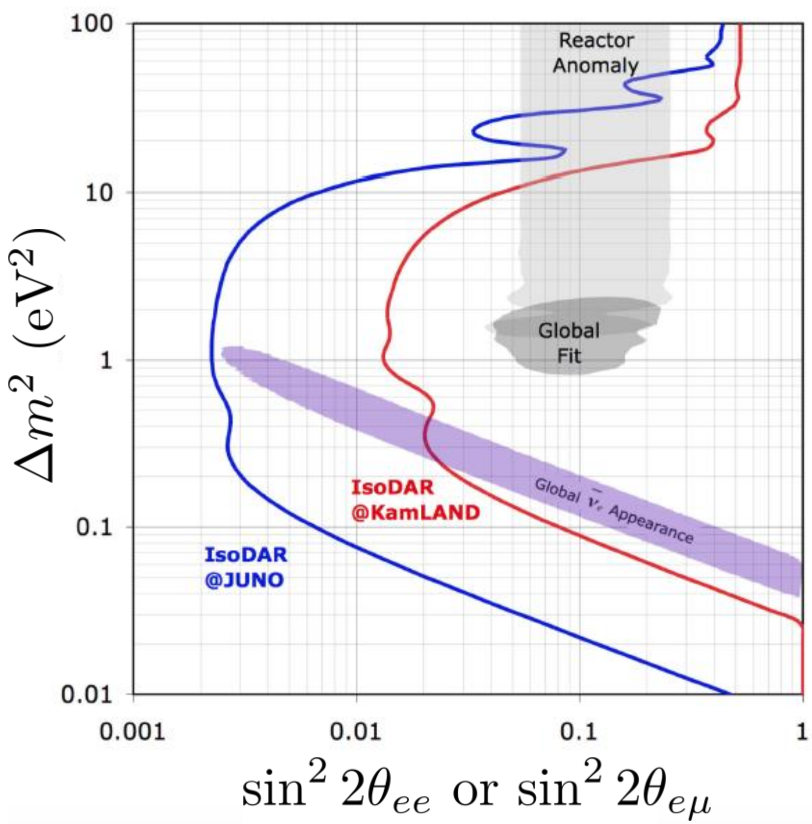


16.5 m

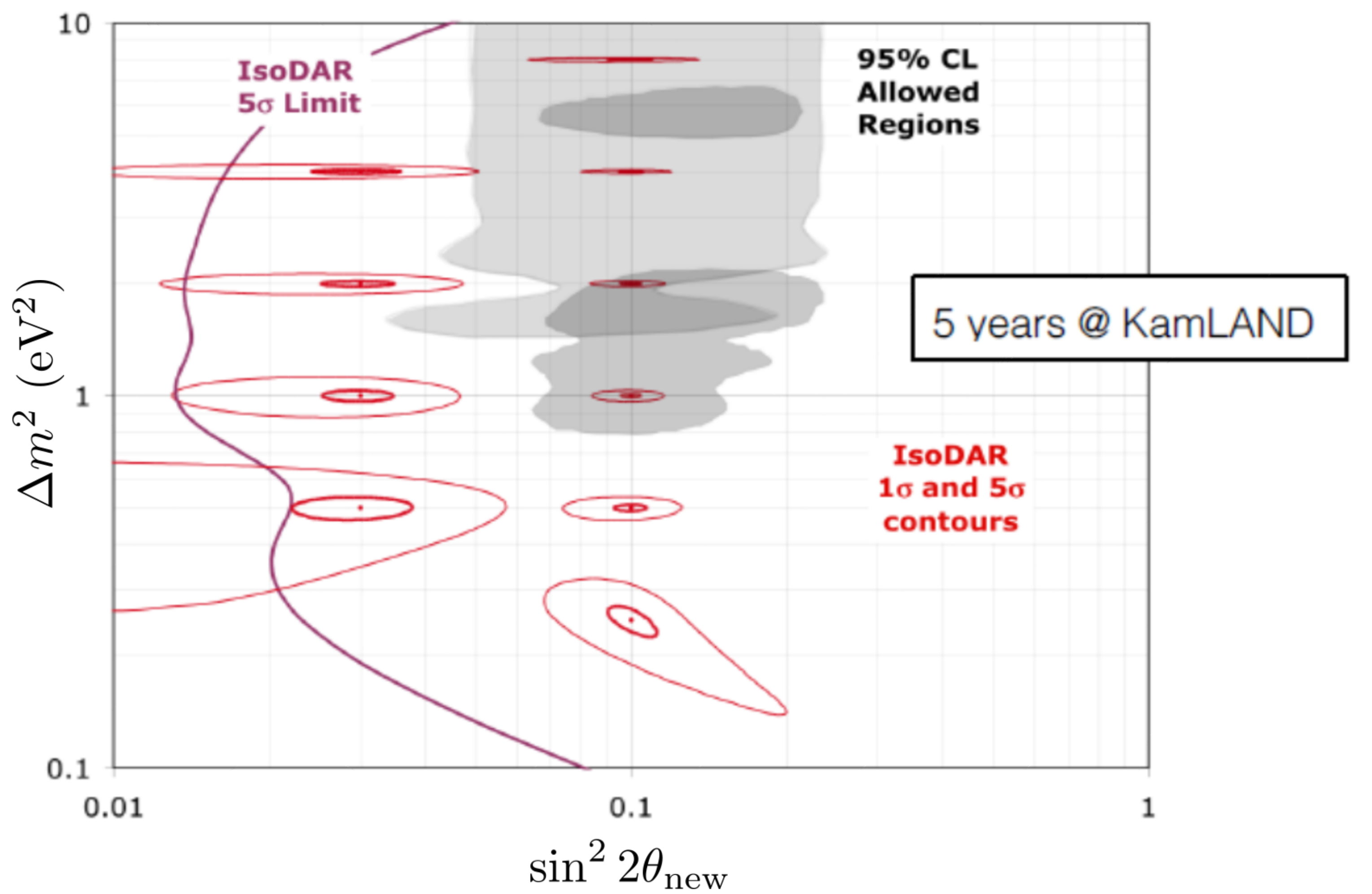
kton scale detector (e.g. KamLAND)

ISODAR

- High Statistics
- Well-understood beam
  - $^{8}\mathrm{Li}$ is virtually the only contributor to neutrino production
  - 0.016 neutrinos per incoming proton
- Fairly Compact neutrino source
  - Sleeve yields production volume ~ $\sigma_x = \sigma_y = 23$ cm, $\sigma_z = 37$ cm
- KamLAND detector resolution:
  - Vertex: $12\ \mathrm{cm}/\sqrt{\mathrm{E(MeV)}}$
  - Energy: $6.4\ \%/\sqrt{\mathrm{E(MeV)}}$
- Conceptual Design Report: https://arxiv.org/abs/1511.05130
- Working on PDR and Facilities CDR with KamLAND and RIKEN



IsoDAR – If we see a signal…



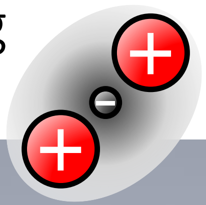
Courtesy of Joshua Spitz

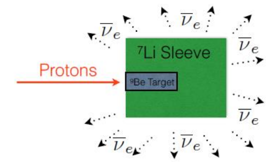
Cyclotron Proton Driver

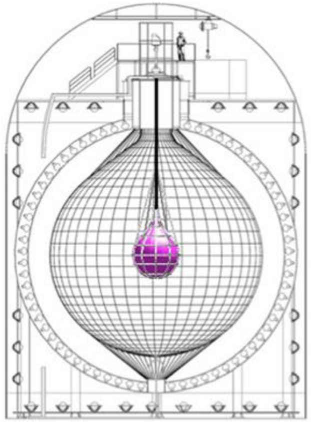
π^+ μ^+ K^+ ^AX

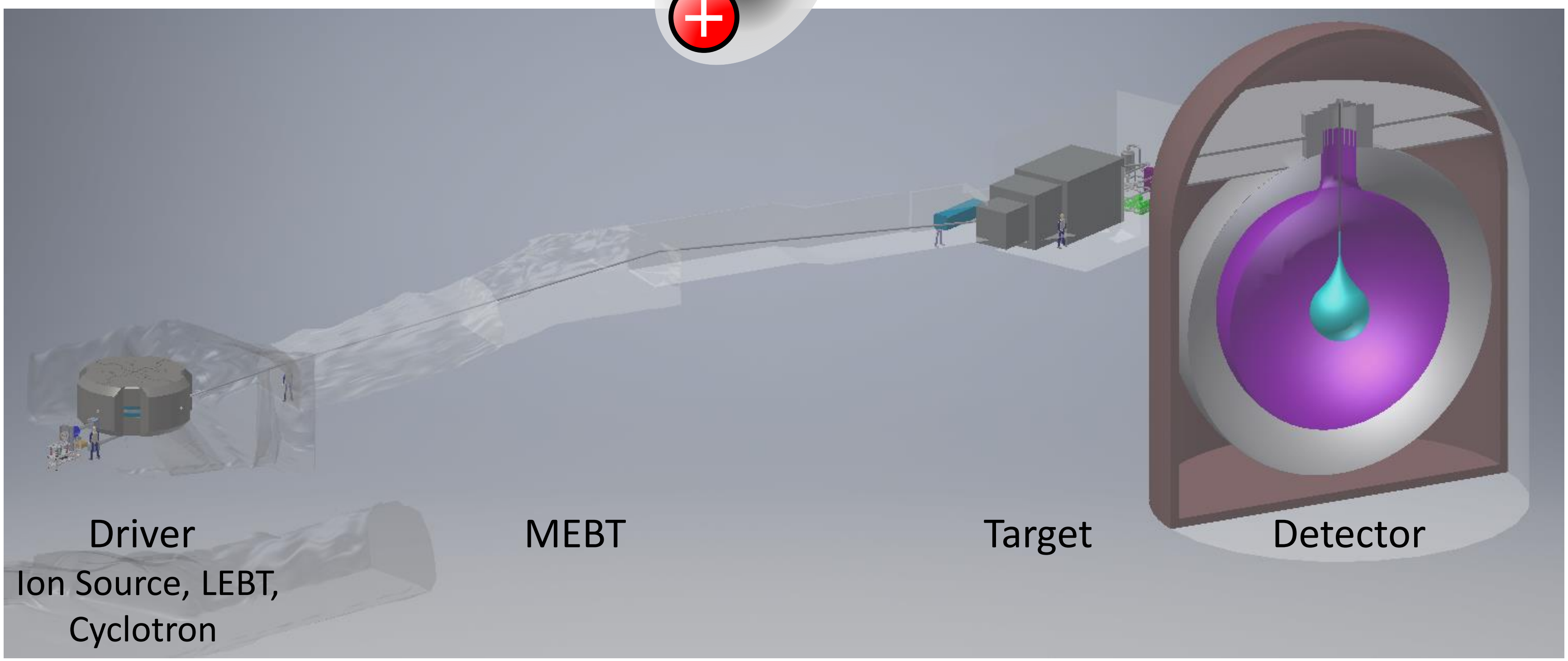
IsoDAR Driver: Overview

- Desired: 10 mA of p^+ on target
- Greatest Challenge: Space Charge
- H_2^+ as mitigation. 5 mA H_2^+ become 10 mA of p^+ after stripping



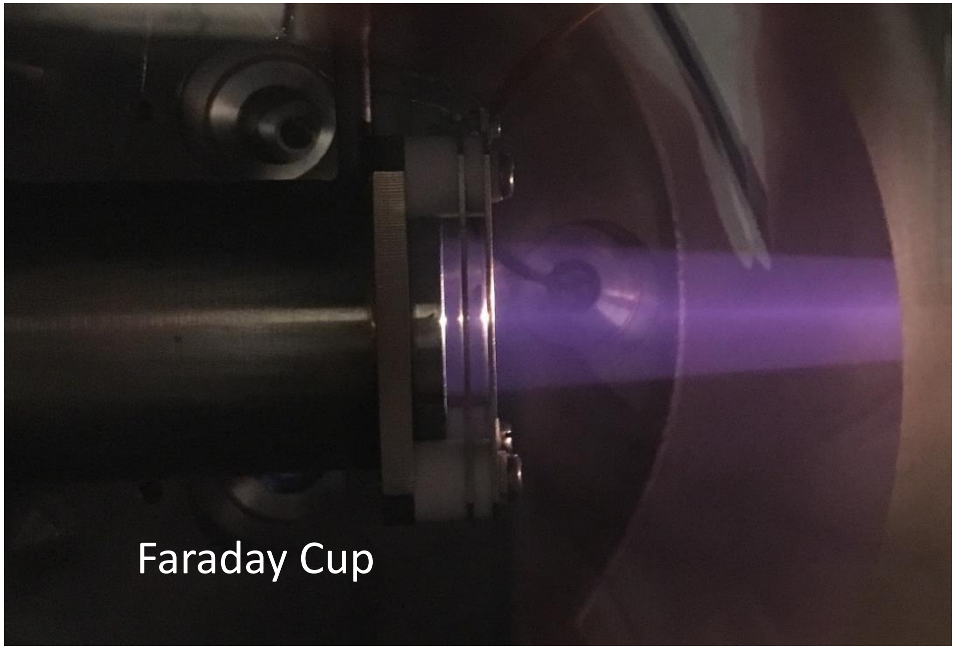


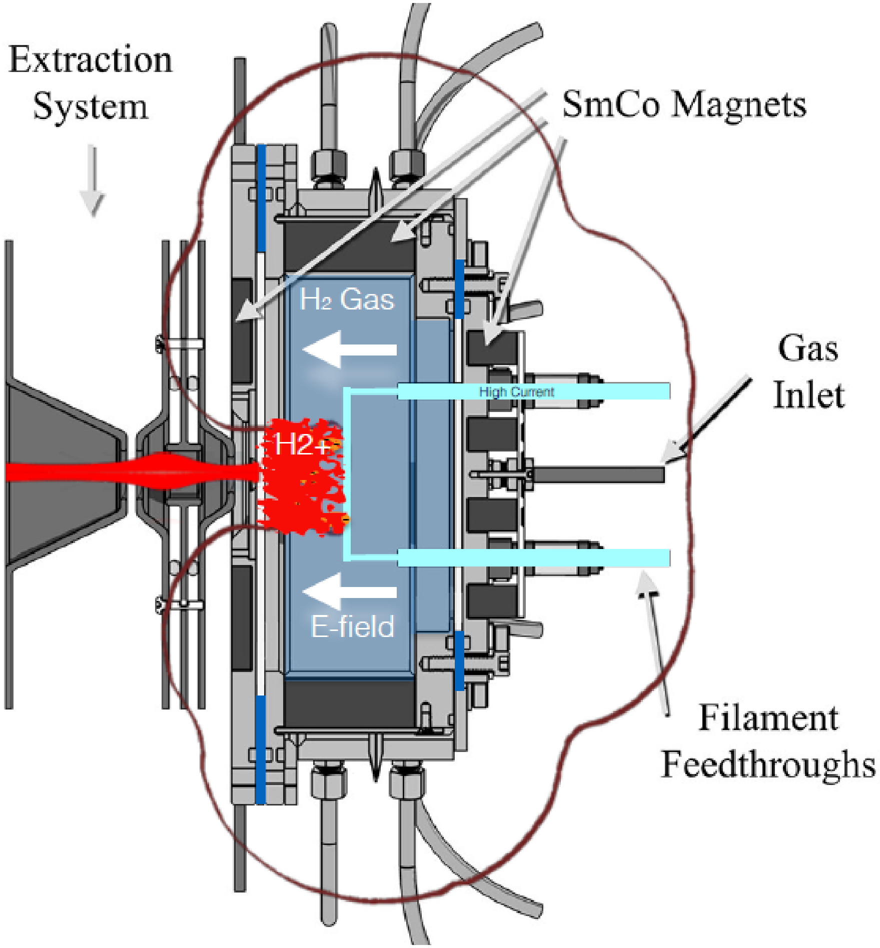




IsoDAR Driver: Ion Source

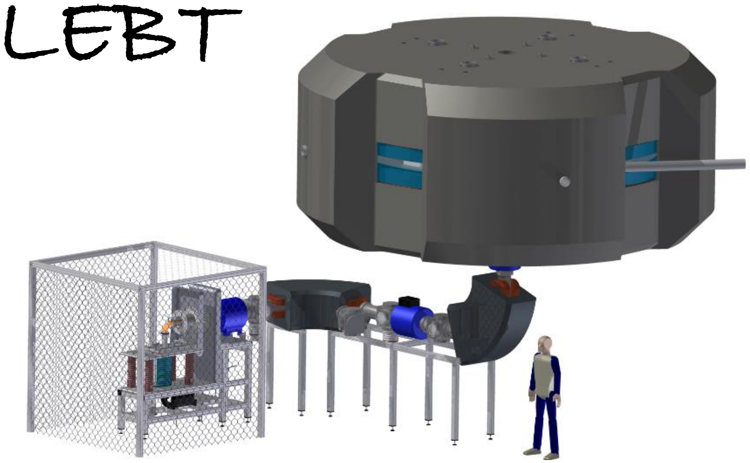
- Producing the H_2^+…





- Filament-Driven Multicusp Ion Source
- Based on: Ehlers and Leung: http://aip.scitation.org/doi/10.1063/1.1137452
- Currently commissioning at MIT (last week: 12 mA/cm^2)

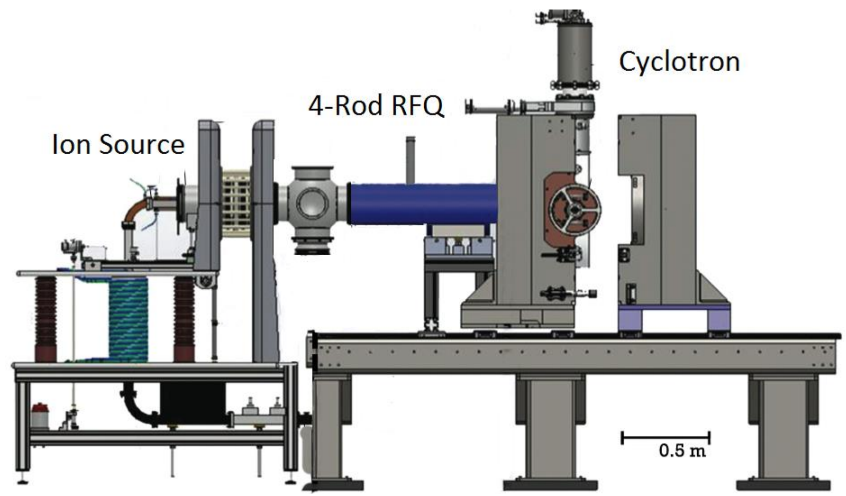
IsoDAR Driver: LEBT



DAEδALUS IsoDAR

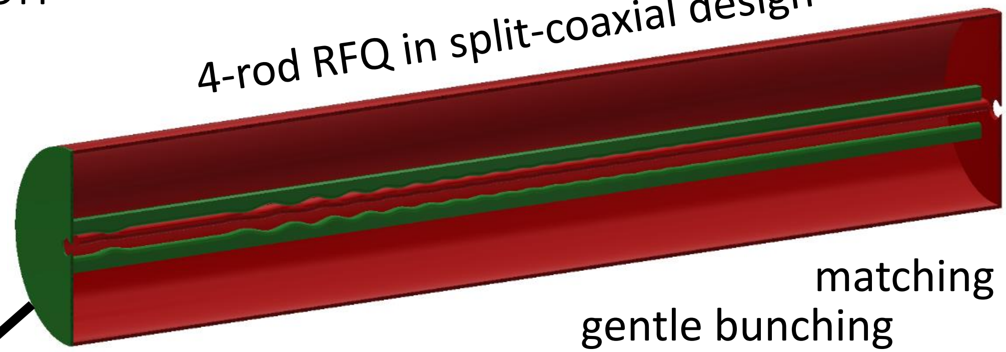
RFQ-DIP

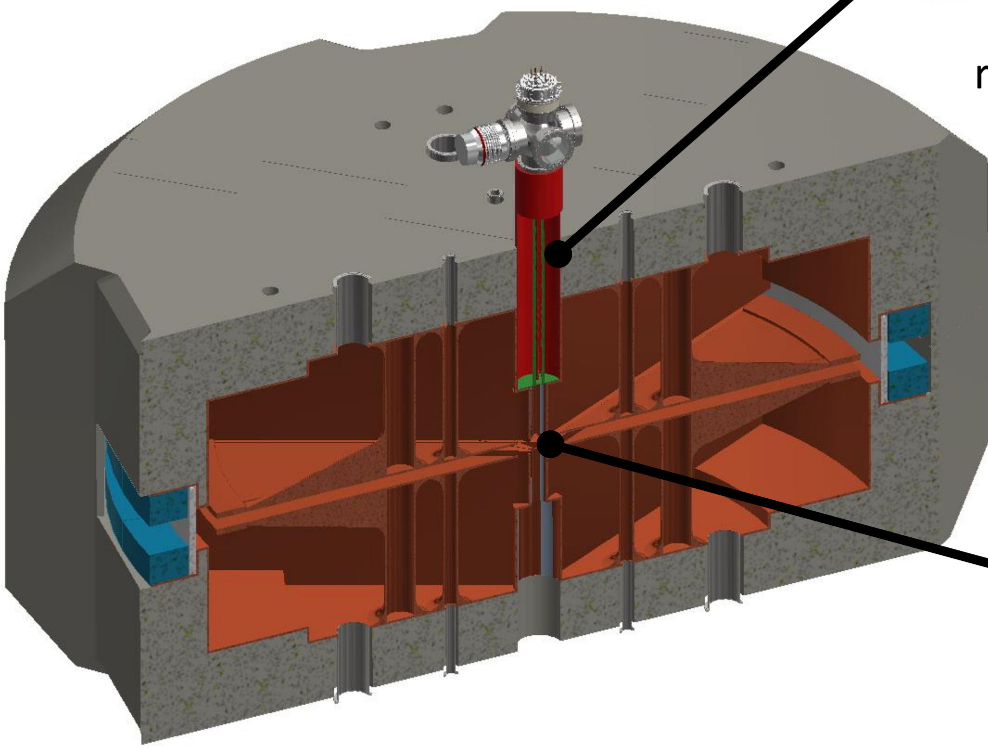
- Two options:
  - Conventional Low Energy Beam Transport (demonstrated experimentally) http://iopscience.iop.org/article/10.1088/1748-0221/10/10/T10003/pdf
  - Better: RFQ-Direct Injection Project (RFQ-DIP); NSF funded at ~1 M$
  - Why? http://dx.doi.org/10.1063/1.4935753
    - Highly efficient bunching
    - sorts out protons
    - accelerates to injection energy of 70 keV
    - Compact (good for underground)
  - Parameters:
    - 32.8 MHz
    - 1.3 m length, 30 cm diameter
    - 15 keV to 70 keV accel
    - <55 kV vane voltage

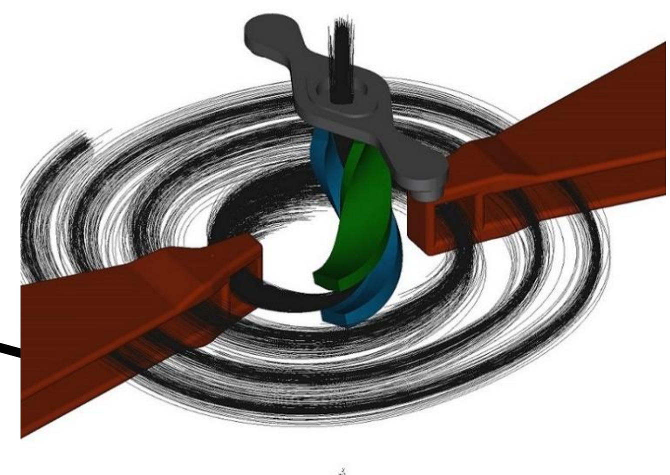


IsoDAR Driver: Cyclotron I

- Compact Isochronous Cyclotron
- Harmonic 4 (→ 32.8 MHz)
- 70-240 kV acceleration
- 4 double-gap cavities



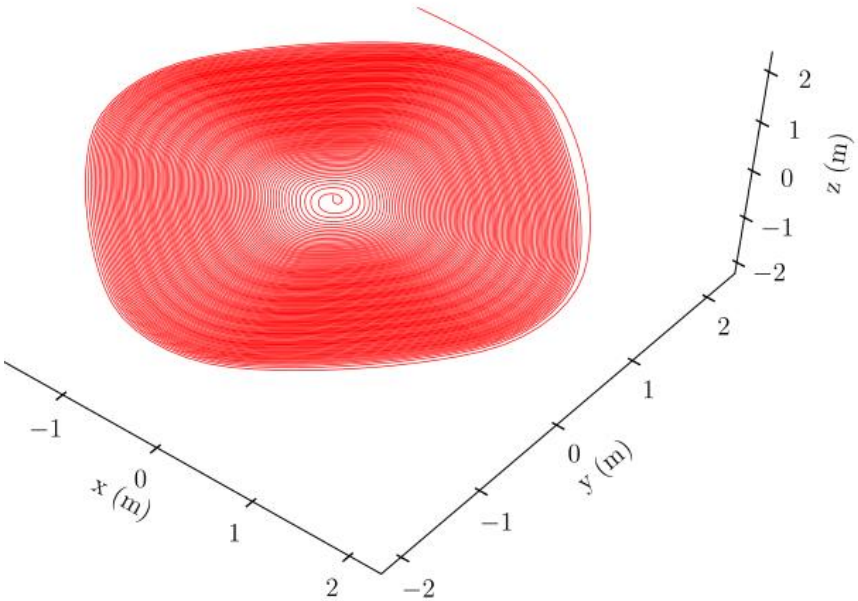


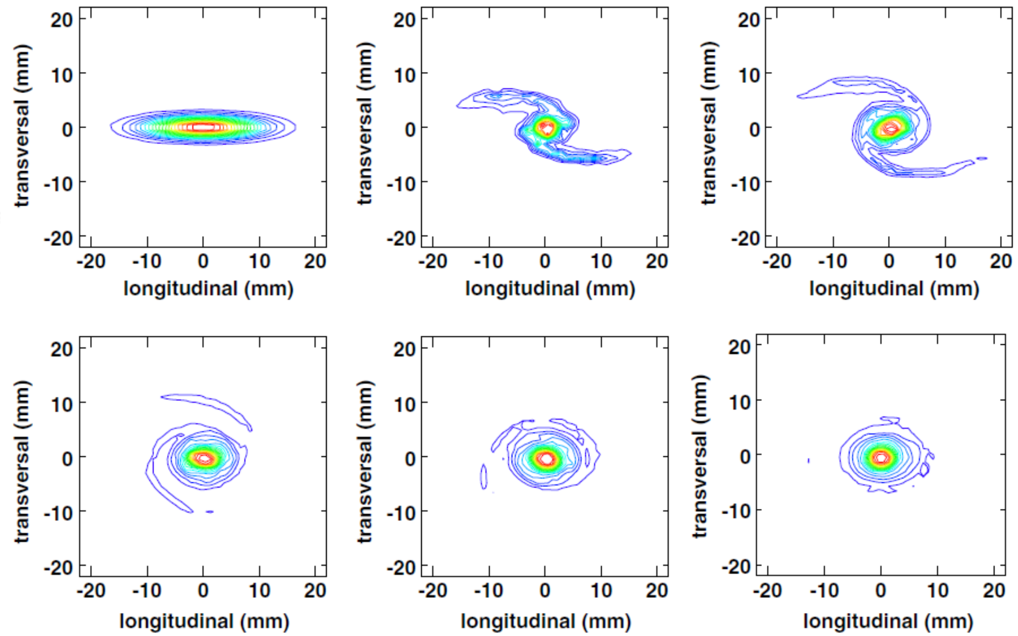


IsoDAR Driver: Cyclotron II

DAEδALUS IsoDAR

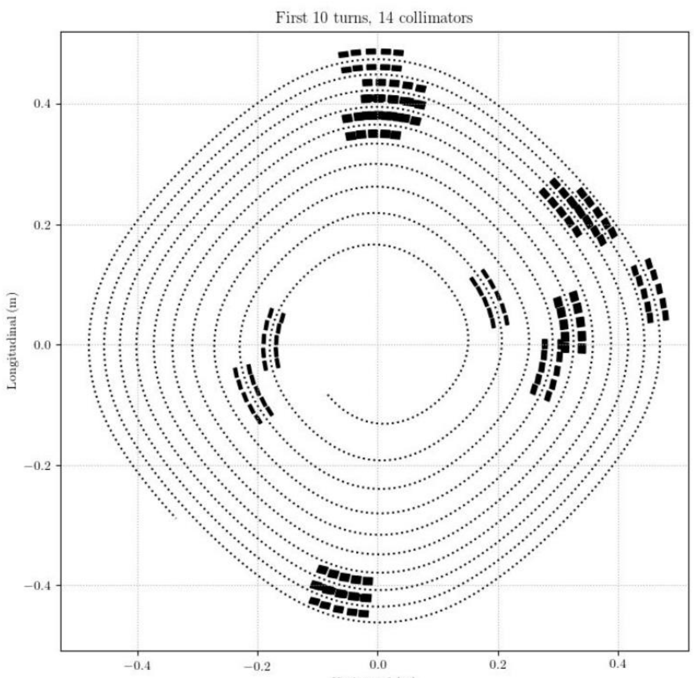
- Acceleration & Extraction. Space-charge again…
- Septum can tolerate about 200 W of controlled beam loss.
- If turn separation is small halo formation is large → big problem.
- Space-charge + Isochronous, AVF cyclotron = Vortex motion. Good!
- Needs to be carefully matched, though!

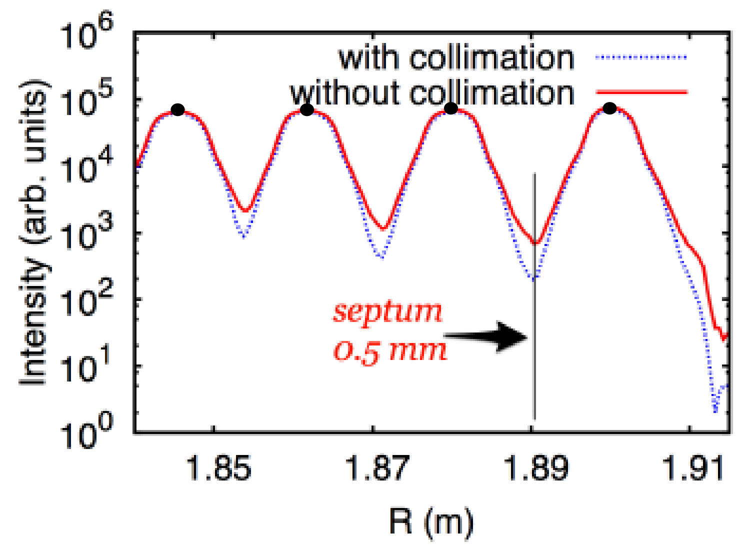




IsoDAR Driver: Cyclotron III

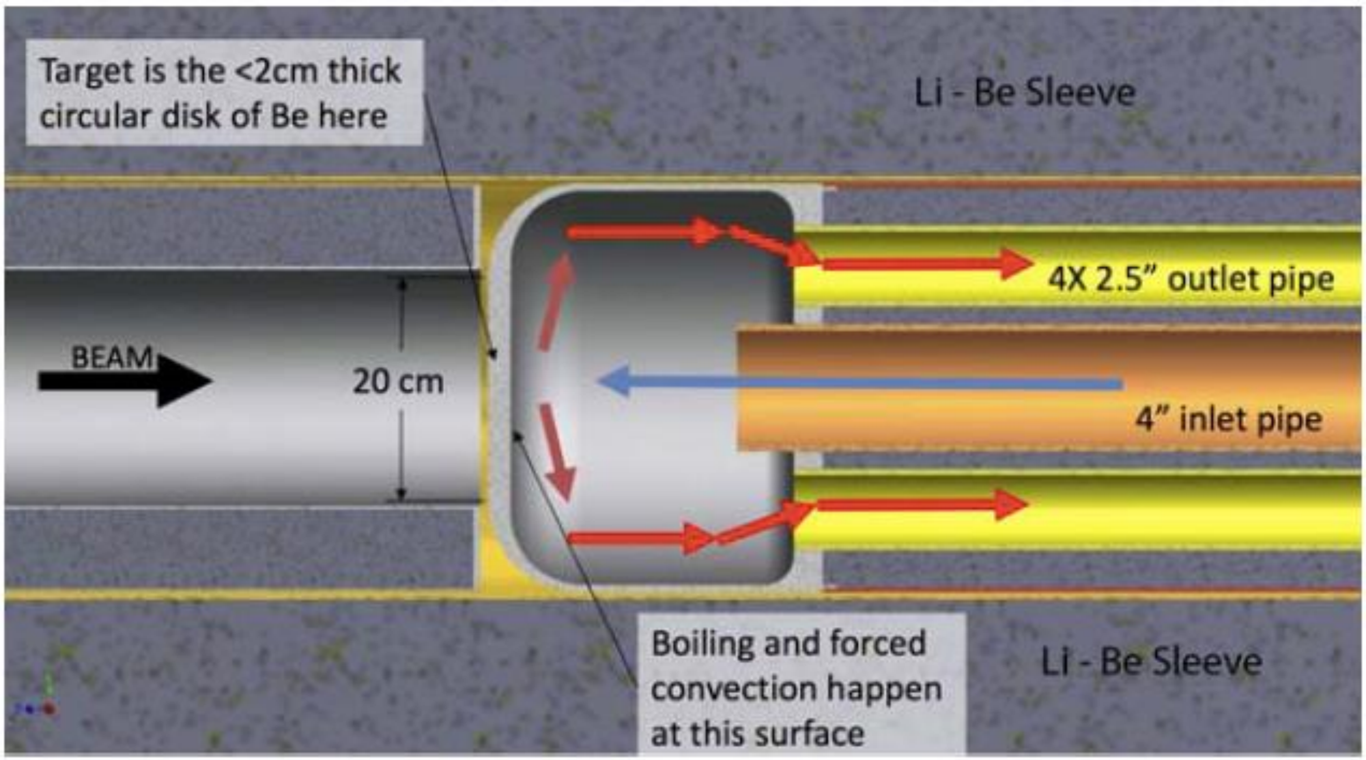
- Acceleration & Extraction. Space-charge again…
- Septum can tolerate about 200 W of controlled beam loss.
- If turn separation is small halo formation is large → big problem.
- Space-charge + Isochronous, AVF cyclotron = Vortex motion. Good!
- Needs to be carefully matched, though! + Collimators



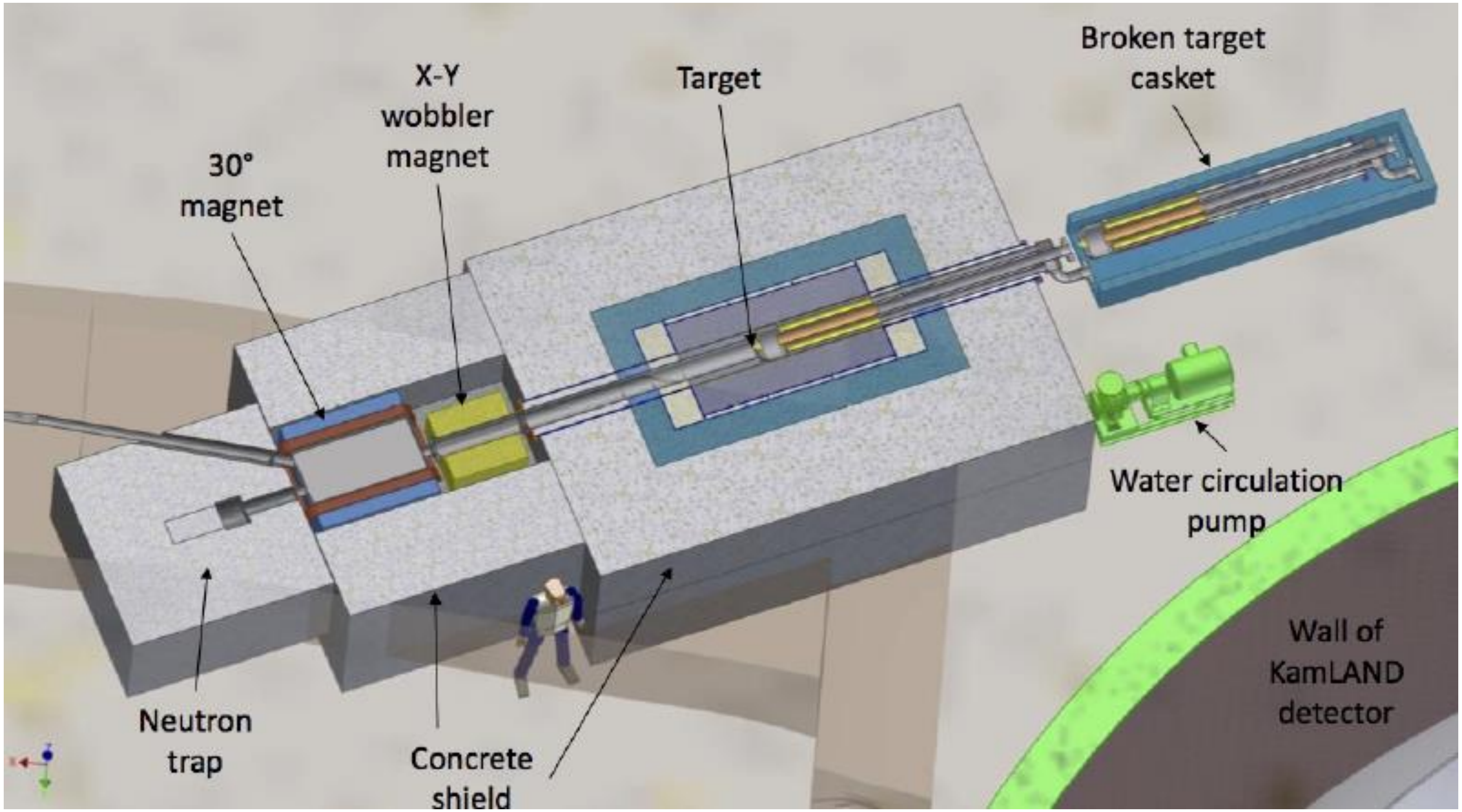


IsoDAR Driver: Target I

- Beryllium target with lithium-beryllium sleeve
- 600 kW painted across face ~ 16 cm diameter (~3 kW/cm^2)
- Considerable progress on optimization of shape and Li-Be mixture



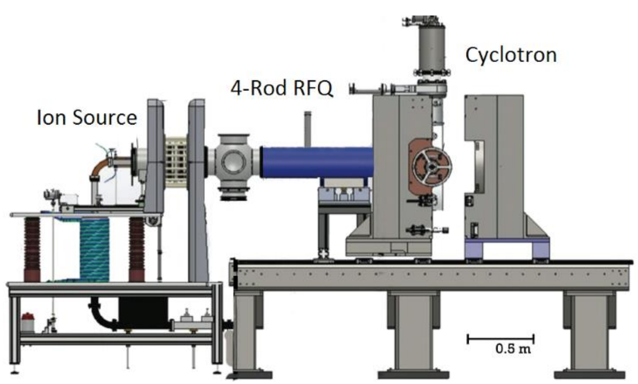
IsoDAR Driver: Target II

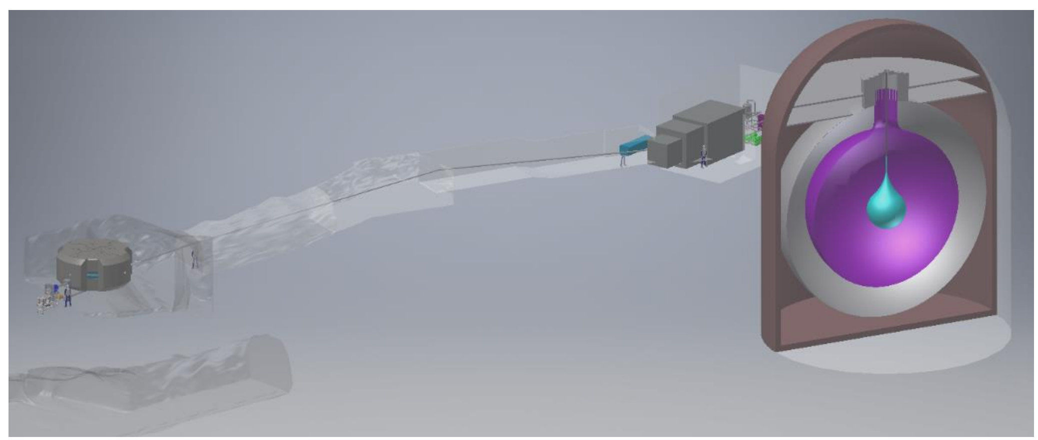


NSF funded target study on the way at Columbia University!

IsoDAR – Current Status

- Full Proposal due in fall 2018 (NSF encouraged)
- Path to proposal:
  - Conventional Facilities CDR in collaboration with KamLAND
  - Determine siting at KamLAND (new option came up!)
  - Full set of start-to-end simulations (have all the parts)
  - Frozen proton driver design
- In parallel: RFQ-DIP. First ever demonstration of direct injection from RFQ into compact cyclotron → Will determine path for LEBT





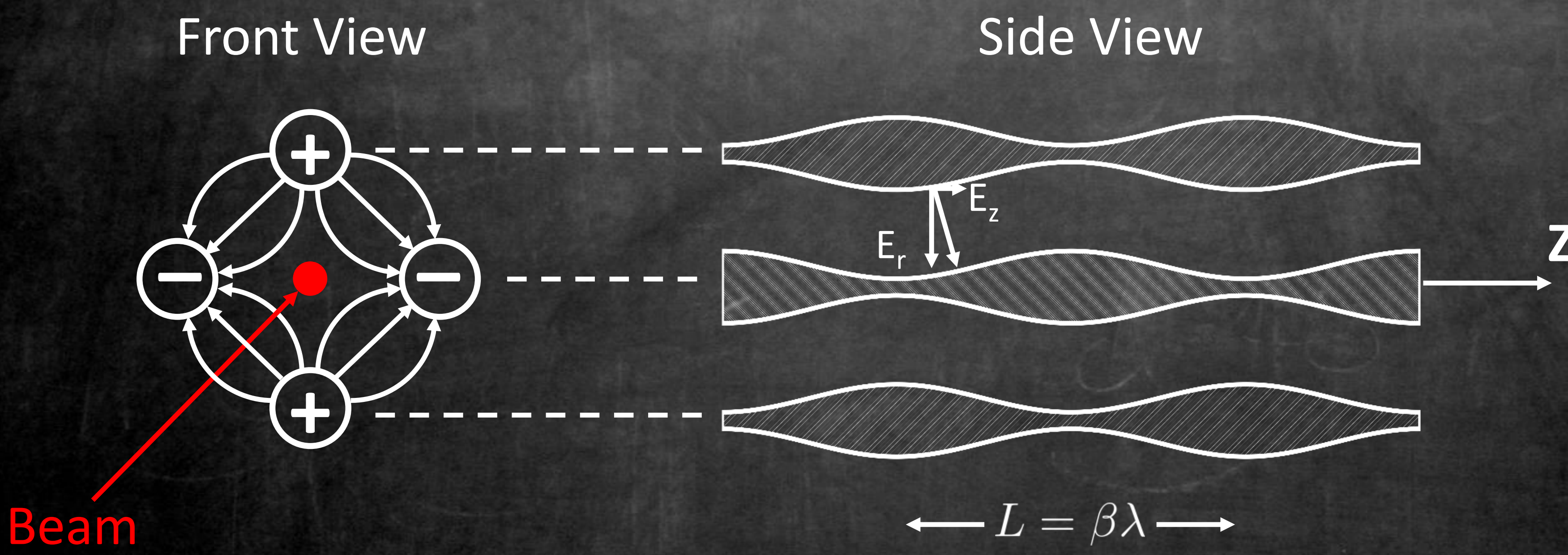
Conclusion / Outlook

- Decay-At-Rest presents some great opportunities!
- As for example demonstrated by COHERENT
- JSNS^2 will have first data by the end of 2018
- In addition there are several proposals in various design stages:
  - KPipe
  - DAEδALUS
  - IsoDAR
- Cyclotrons are a possible alternative for proton driver
- Full proposal for IsoDAR to be submitted to NSF in fall 2018….stay tuned!

Thank You!
(Bon Appétit :)

π^+ μ^+ K^+ ^{A}X

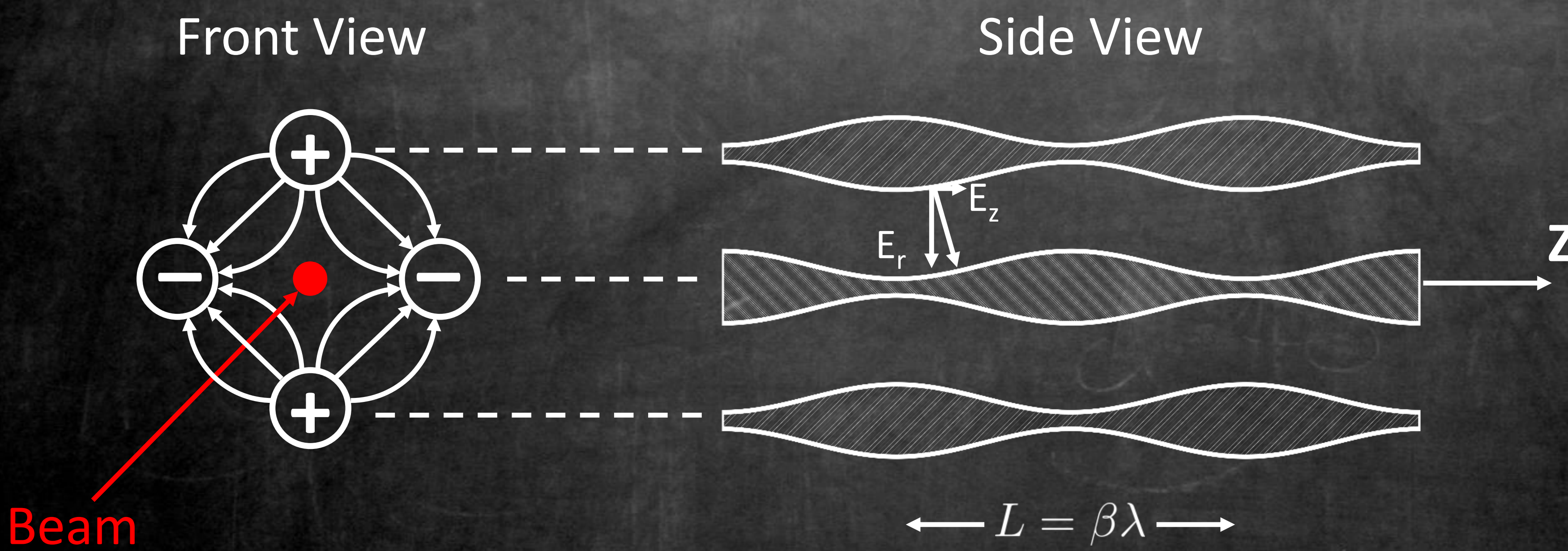
RFQ General Principle

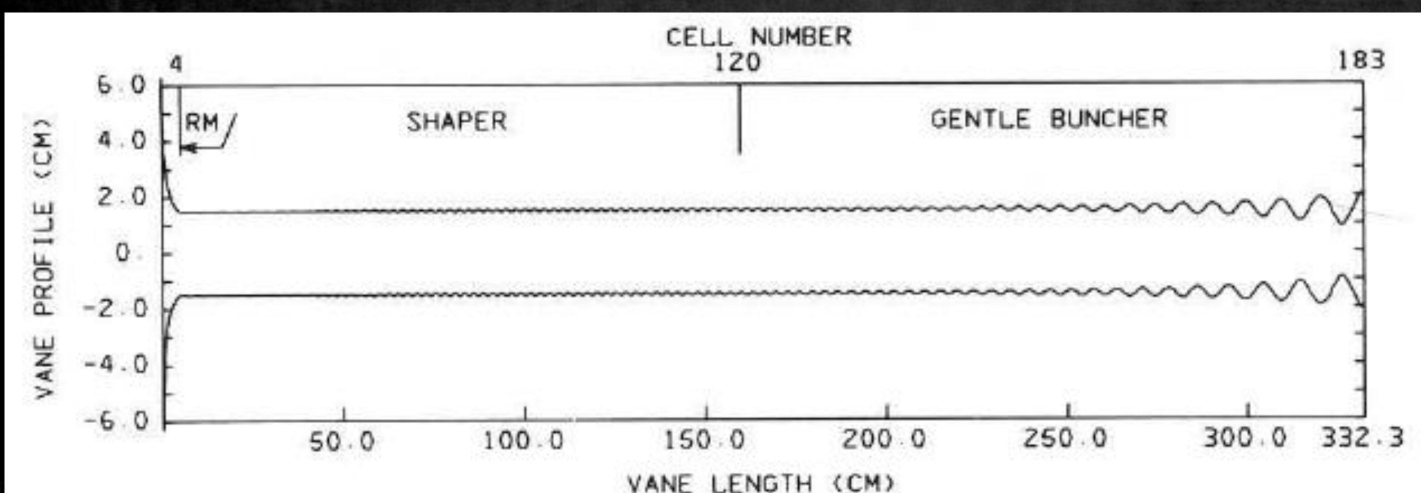


$$V(t) = V_{max} \cdot \cos(\omega_{RF} \cdot t - \Phi_S)$$

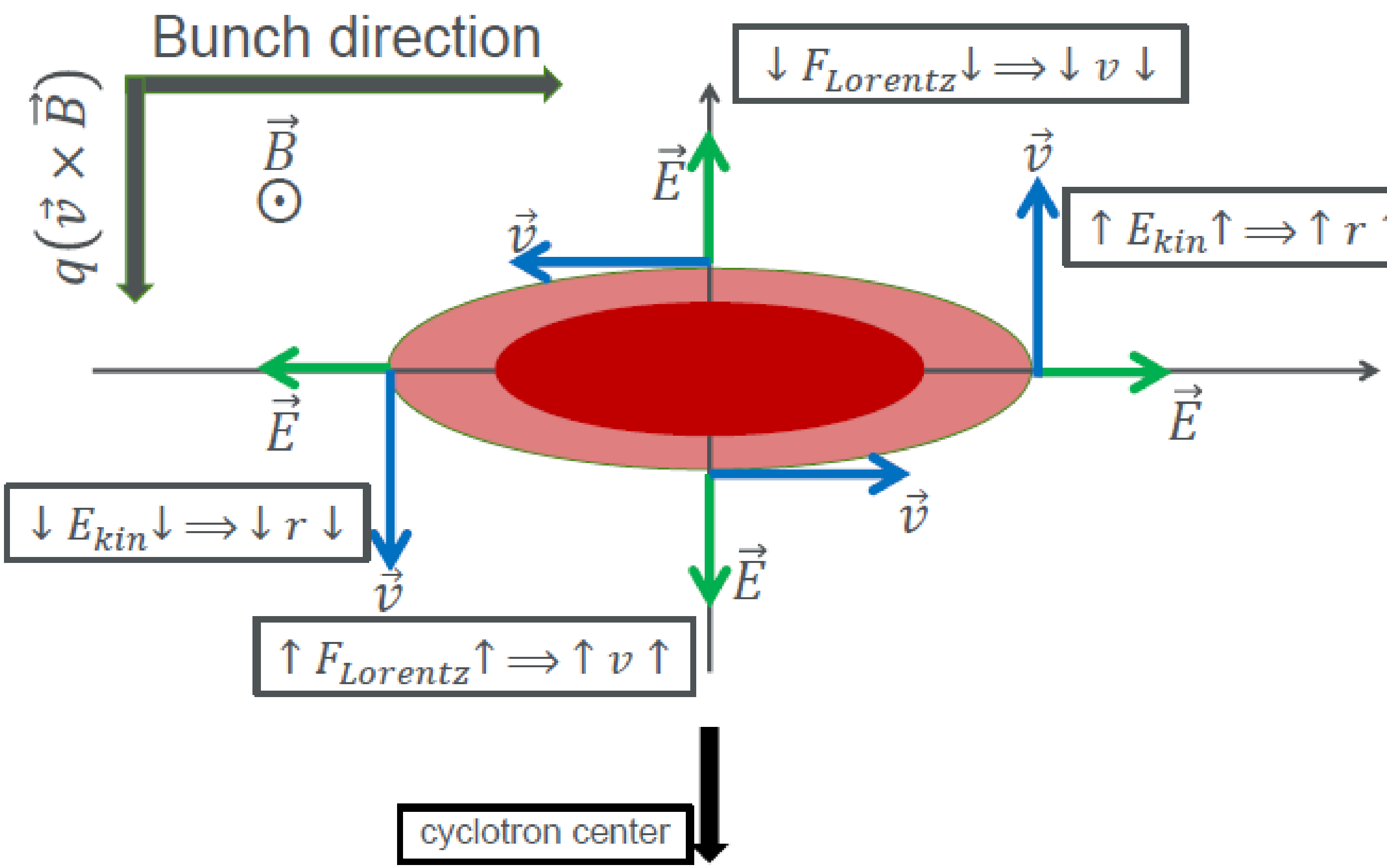
- Continuous focusing like in a series of alternating F/D Electrostatic quadrupoles
- Wiggles lead to acceleration and bunching (RF bunching similar to cyclotron)
- Same frequency as cyclotron

RFQ General Principle





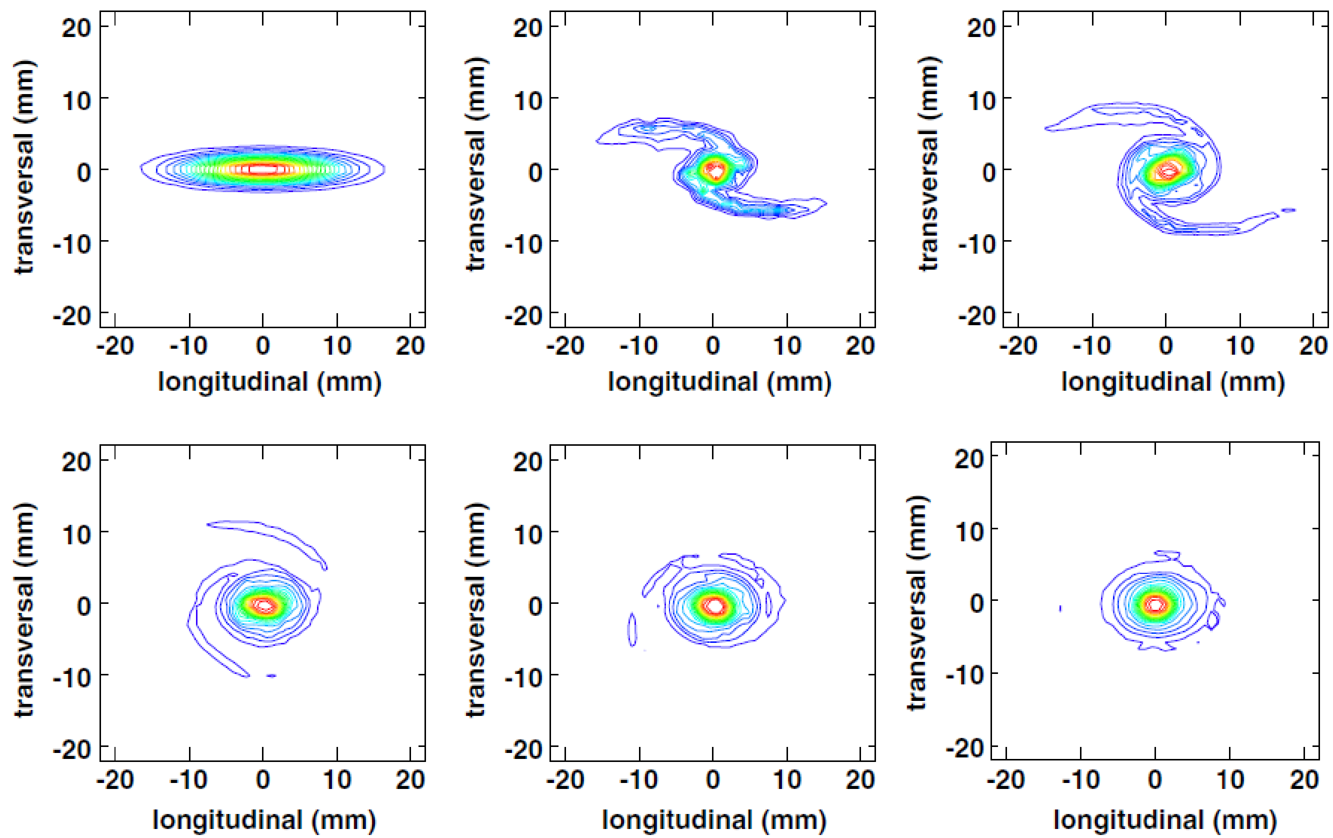
Vortex Motion Principle



Courtesy of Wiel Kleeven (Cyclotrons 2016)

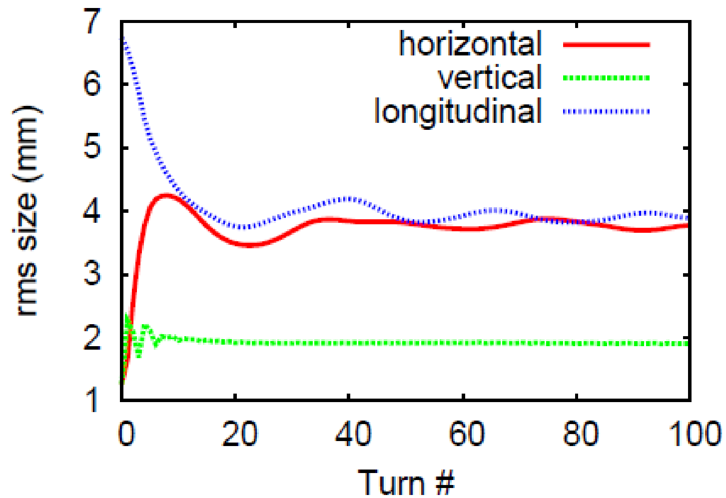
Vortex Motion PSI Injector II

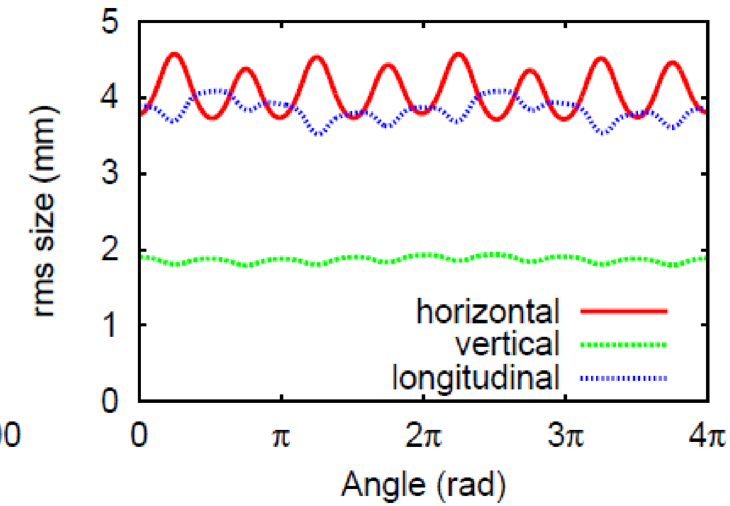
- If the beam is initially well matched, it curls up into a tight ball with only a bit of halo.
- It is circular in x-y (mid plane of cyclotron)
- This has been seen at PSI Injector II and reproduced in OPAL:



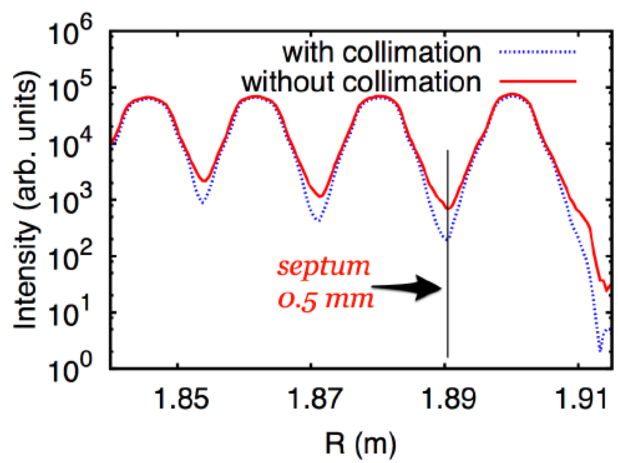
Vortex Motion IsoDAR/DIC

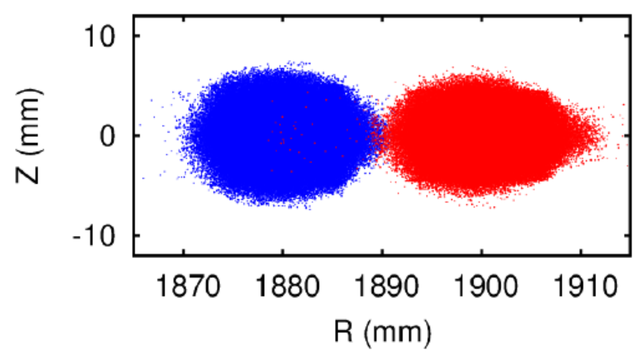
- Starting at 1.5 MeV/amu (JJ.Yang 2012) a nice round beam shape develops





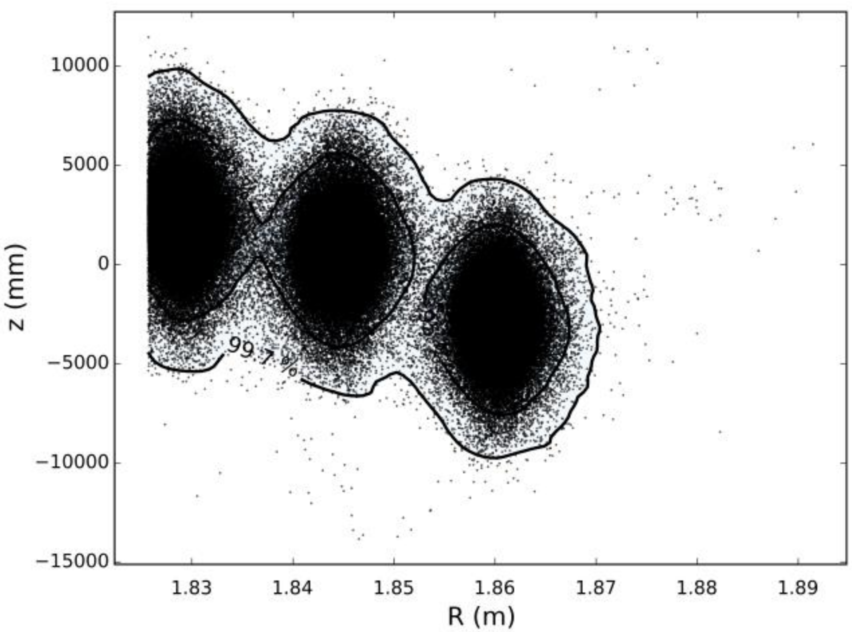
- Beam power on septum <110 W

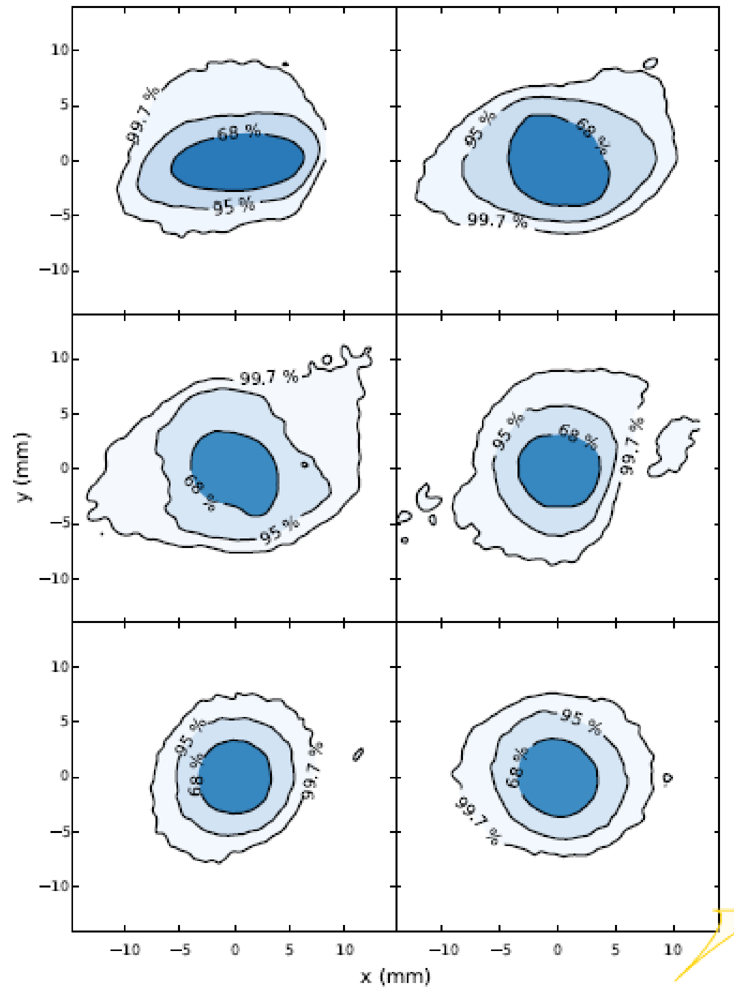




Vortex Motion in the IsoDAR Cyclotron

- Starting at 192 keV/amu (within the first turn) (J. Jonnerby, 2016)
- Vortex motion happens for our H_2^+ beam
- Beam separation not yet fully sufficient, but work in progress





Costs for the source, to be proposed to NSF

These costs do not include contributions via base grants.
Costs do include project management and EDIA

Cost Estimate for the cyclotron:

Our present estimate, with the help of IBA (a Cyclotron Co.)

$18.2 M – not including university-based manpower,
i.e. cost to NSF

with 33% contingency: $24.2 M

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 b

Suite 900, Westfi
2730 University B
Wheaton, MD 20

Does that cost estimate make sense?

DOE-sponsored study on a 2 mA proton machine.

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.

There are differences, but this sets a rough scale.

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.

Cost estimates for the medium energy transport:
$0.16M, or with 33% contingency, $0.24M

Cost estimates for the target/sleeve:

Target: $6.2 M, with 33% contingency, $8.3M
Sleeve: $5M, with 100% contingency, $10M

Other costs: 1.5M, with 33% contingency, $2.1M
(Controls, interface to conventional facility, etc.)

Total cost, with contingency: $44.8M

Kpipe - Background:

- Small outer-veto layer
- beam-timing
- two-pulse signal
- reduce cosmic ray background rate