π^+ μ^+ K^+ ${}^{A}X$

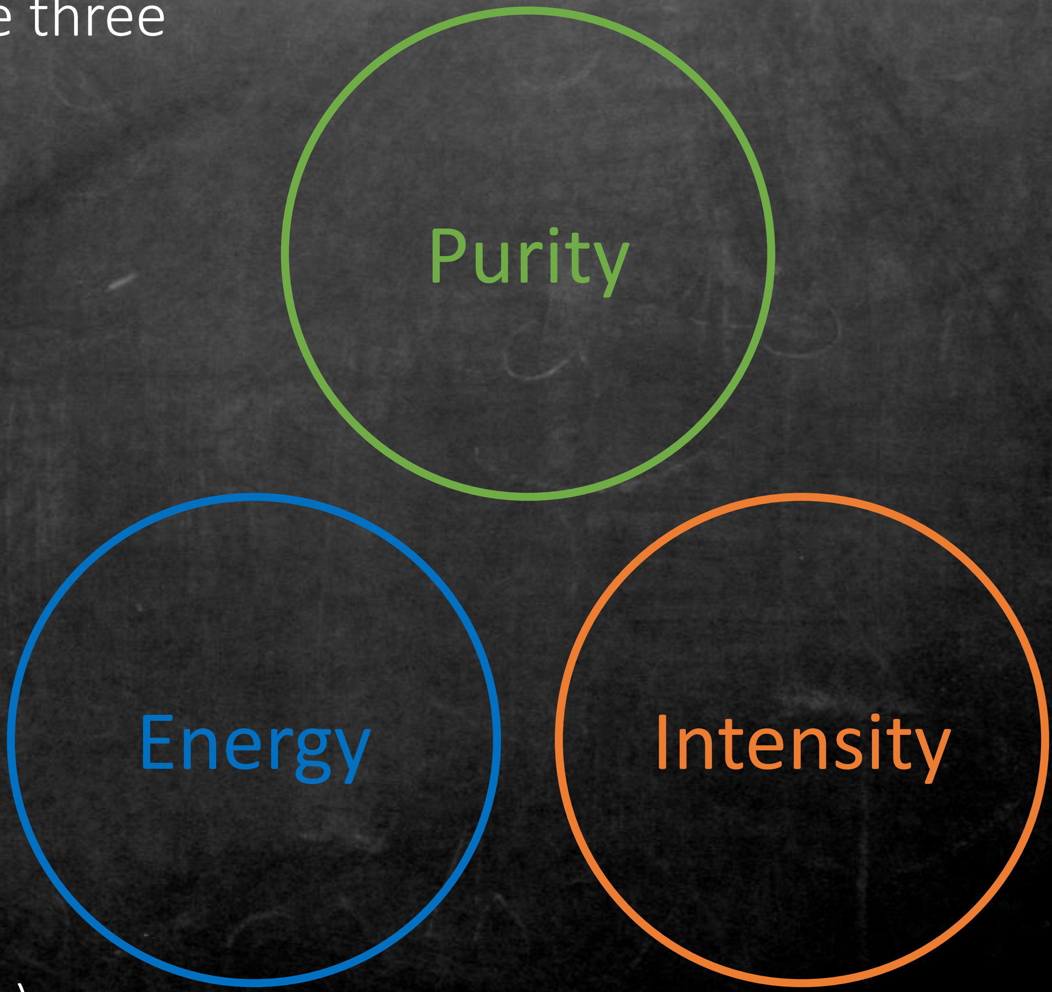
Neutrinos from Decay-At-Rest

Daniel Winklehner, MIT

CIPANP2018, Palm Springs, CA, 05/31/2018

Some Important Parameter Spaces

- In devising a new experiment, one might be interested in these three parameter spaces:
  - 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^+

$$\pi^+ \to \mu^+ \to e^+$$
$$\mu^+ \to \nu_e, \quad \pi^+ \to \nu_\mu, \quad \mu^+ \to \bar{\nu}_\mu$$

PiDAR
MuDAR

K^+

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

KDAR

$^A X$

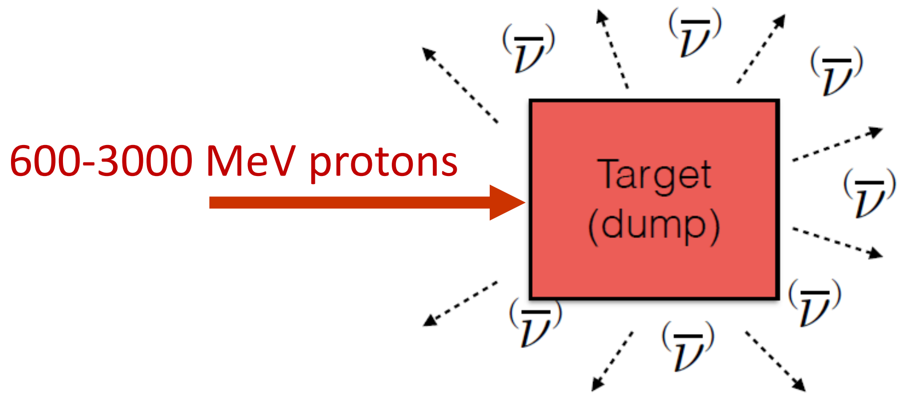
$$^{\mathrm{A}}_{\mathrm{Z+1}}\mathrm{X}' \to {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} + e^- + \bar{\nu}_e$$

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

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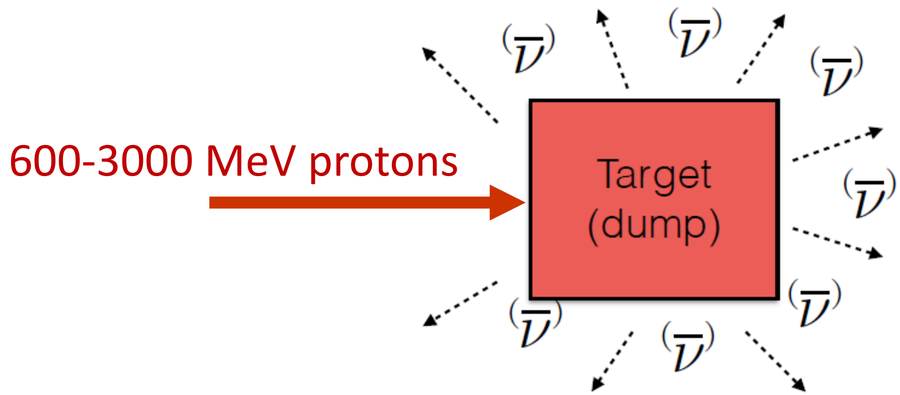

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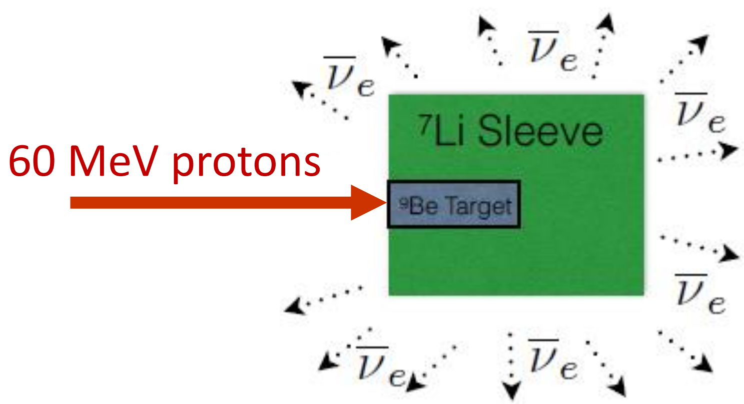


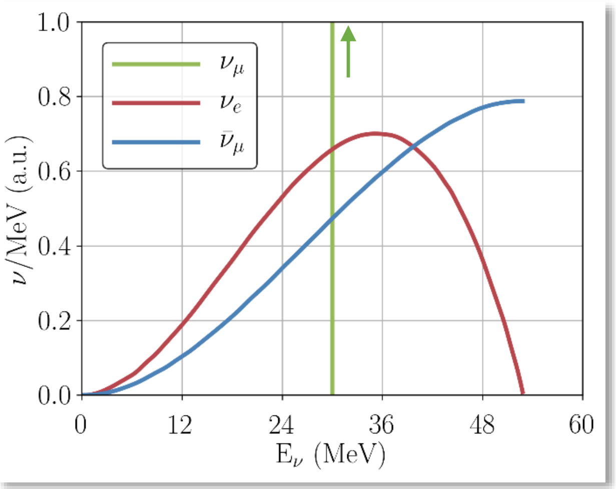
Decay-At-Rest – Energy Spectra

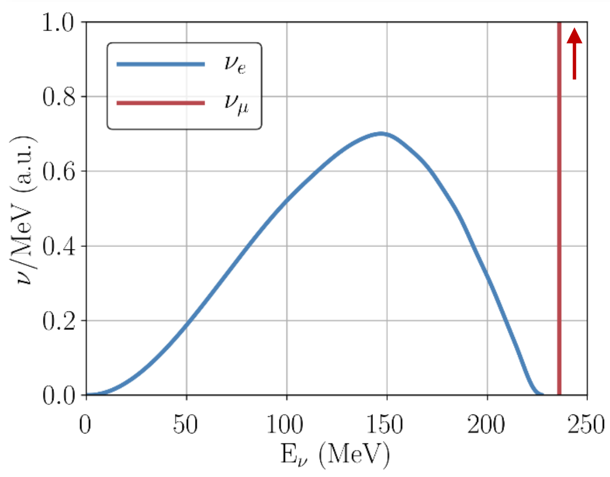
Energy

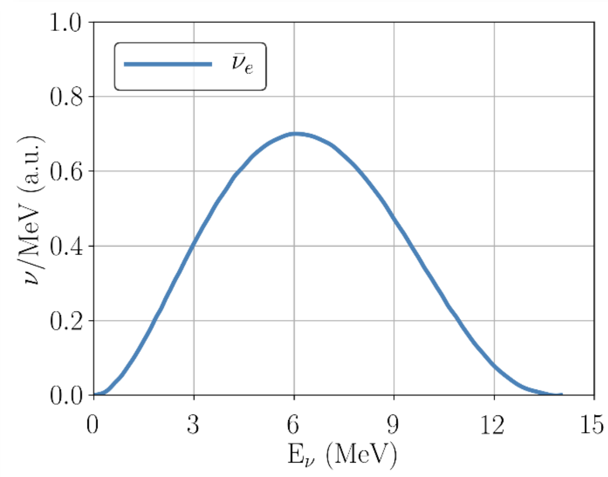
π^+ μ^+

K^+

${}^{A}X$







$$\pi^+ \to \mu^+ \to e^+ \quad (\pi^+ \hookrightarrow \nu_\mu;\ \mu^+ \nearrow \nu_e,\ \mu^+ \hookrightarrow \bar{\nu}_\mu)$$

$$K^+ \to \mu^+ + \nu_\mu$$
$$K^+ \to \pi^0 + e^+ + \nu_e$$
$$K^0_L \to \pi^- + e^+ + \nu_e$$

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

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

Decay-At-Rest – Detection

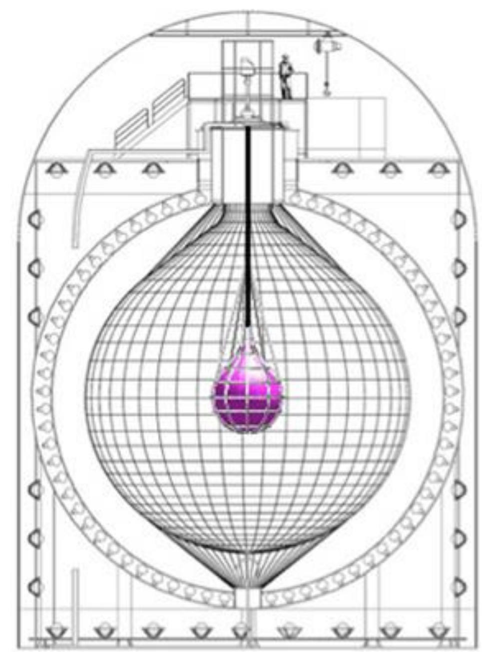
- In order to detect neutrinos we must decide:
  - The flavor(s) we are looking for
  - The type of interaction → Charged Current (CC) and Neutral Current (NC)
- Some examples of low energy interaction open to DAR neutrinos
  - NC: Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)
  - CC: At typical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

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

Want large number of protons available →

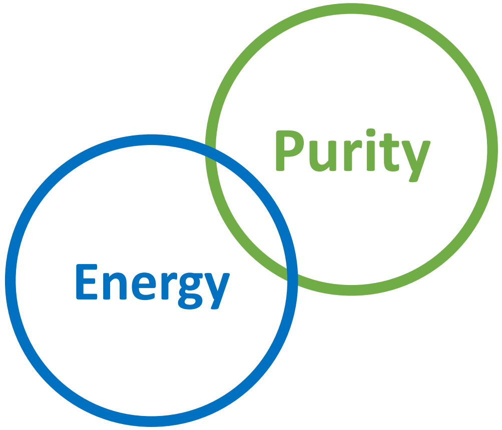
- Scintillator
- Gd-doped water-Cherenkov detector

  - 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 – 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)

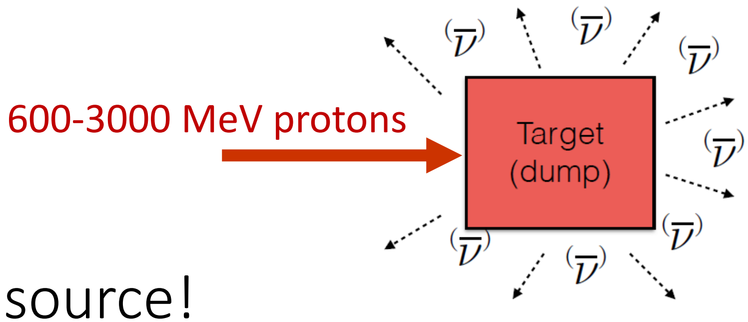
KDAR

- 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!
- Target design (cooling, activation → maintenance) is issue!
- There are a number of existing facilities, e.g.:
  - Spallation Neutron Source at Oak Ridge (SNS)
  - J-PARC Materials and Life Sciences Experimental Facility (MLF)
- In the second half of this talk, I will present you with another possibility: Cyclotrons

(Proposed) Experiments

π^+ μ^+ K^+ ${}^{A}X$

COHERENT

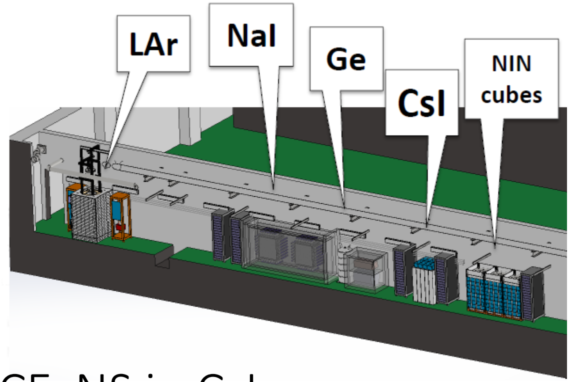
Running

- Talks during this meeting:
  - *Plenary this morning by Kate Scholberg*
  - *Next talk in this session by Ivan Tolstukhin [264]*

- In a nutshell:
  - Uses neutrinos from PiDAR/MuDAR at Oakridge SNS to measure Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

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

  - 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

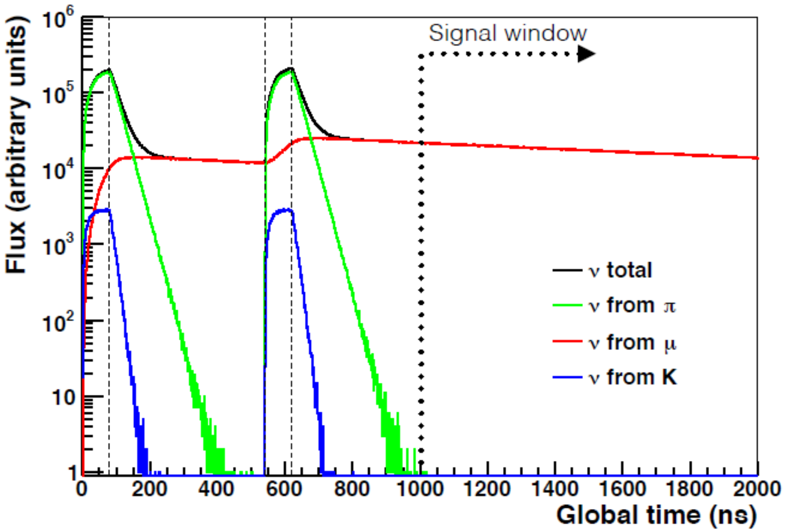
Under Construction

- 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
- 24 m from neutrino source
- 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: $\bar{\nu}_e + p^+ \rightarrow e^+ + n$

JSNS²

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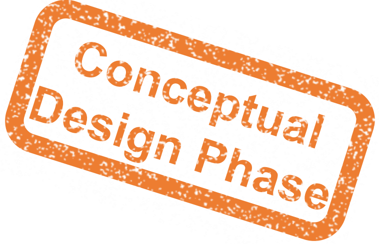
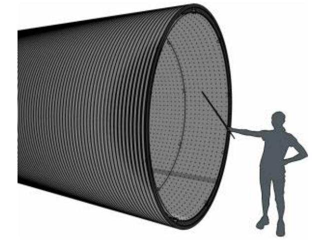
Expecting first results early next year!

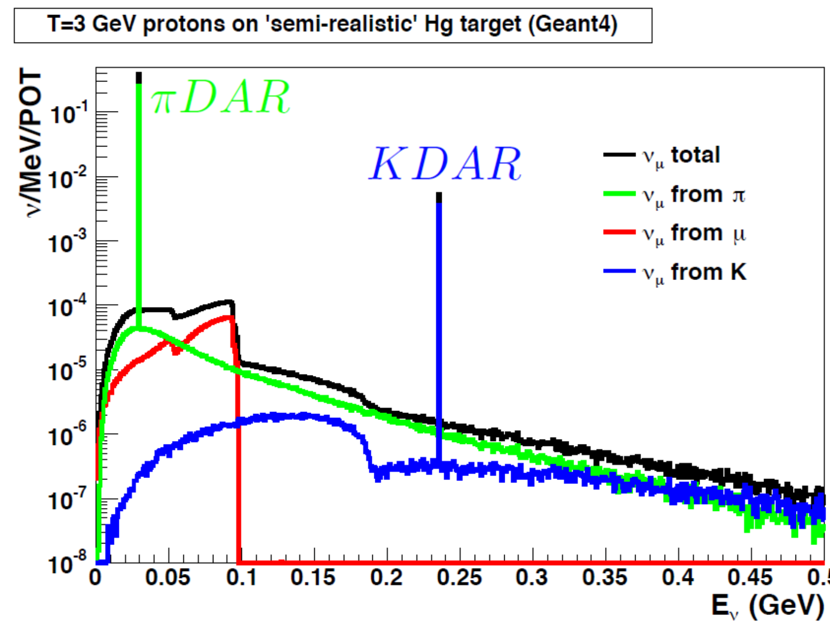
~~See talk by Joshua Spitz in NMNM tomorrow [301]~~

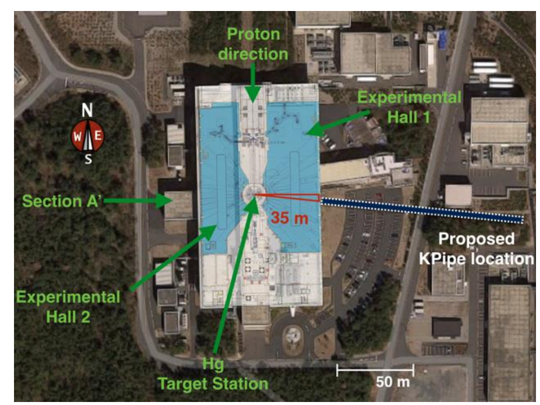
KPipe



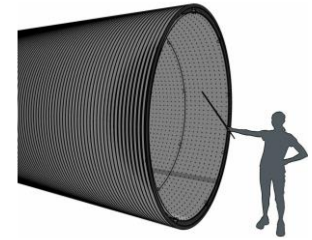


- Use 236 MeV ν_μ from KDAR
- L/E: With long detector (100-120 meters), filled with liquid scintillator, one can contain oscillation period for ν_S with mass splitting >1 eV^2
- To keep cost down, use industrial plastic chemical storage containers for vessel and instrument with 0.6% photocoverage (120k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



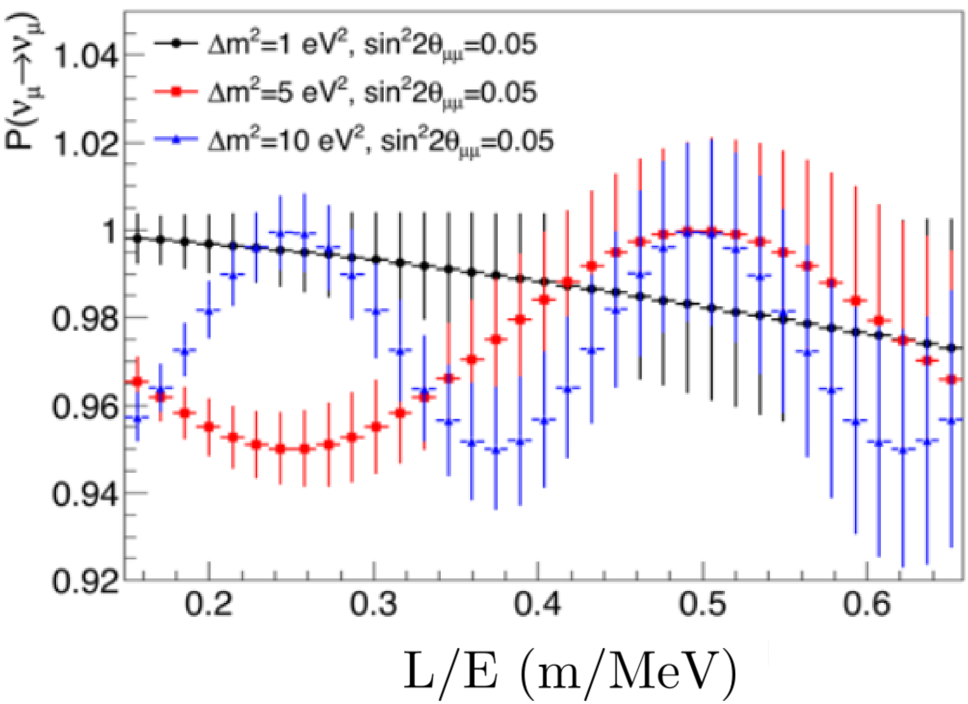


KPipe

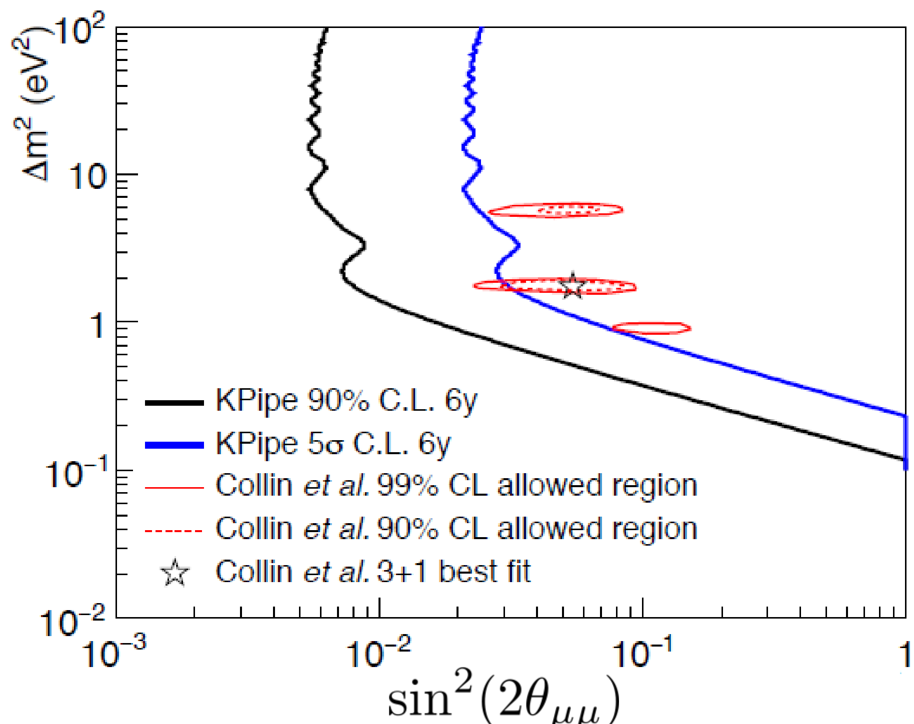


- Trace out oscillation curve in long detector
- High precision ν_μ disappearance search with minimal systematic uncertainties from cross-section and flux
- Cost: 5 M$, Decisive in 6 years of running.

Signal:

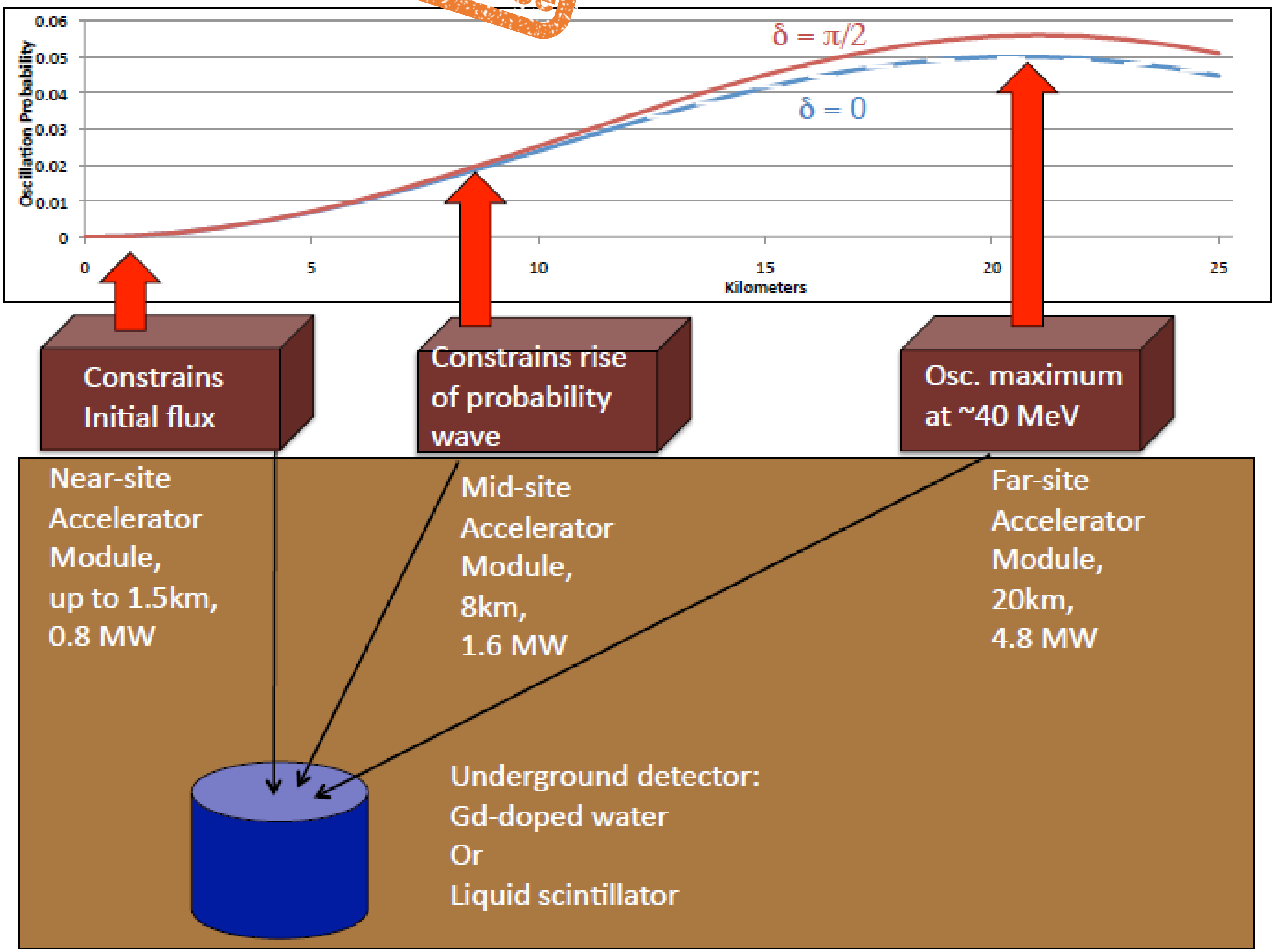


Sensitivities:



DAEδALUS

Conceptual Design Phase



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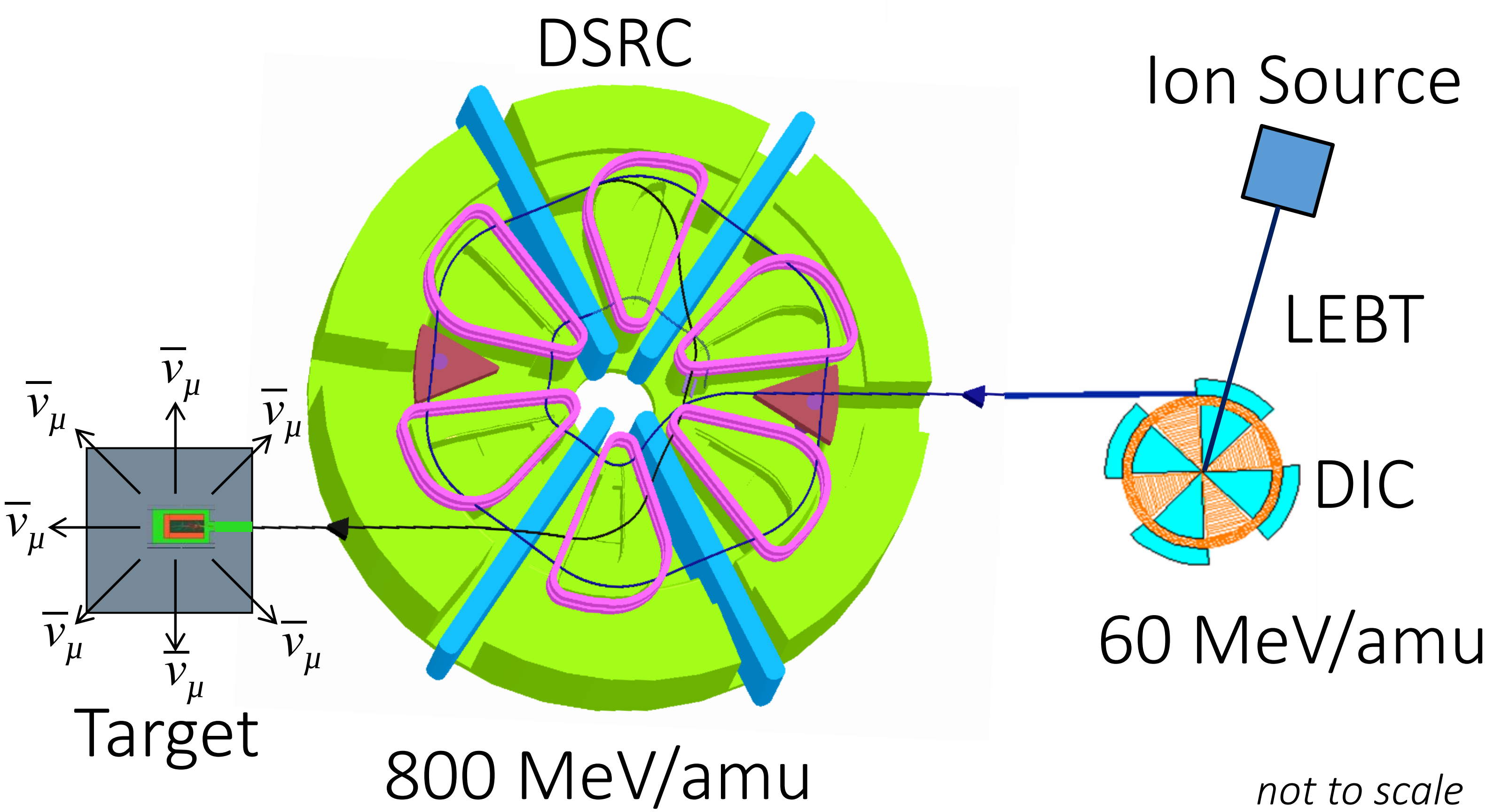
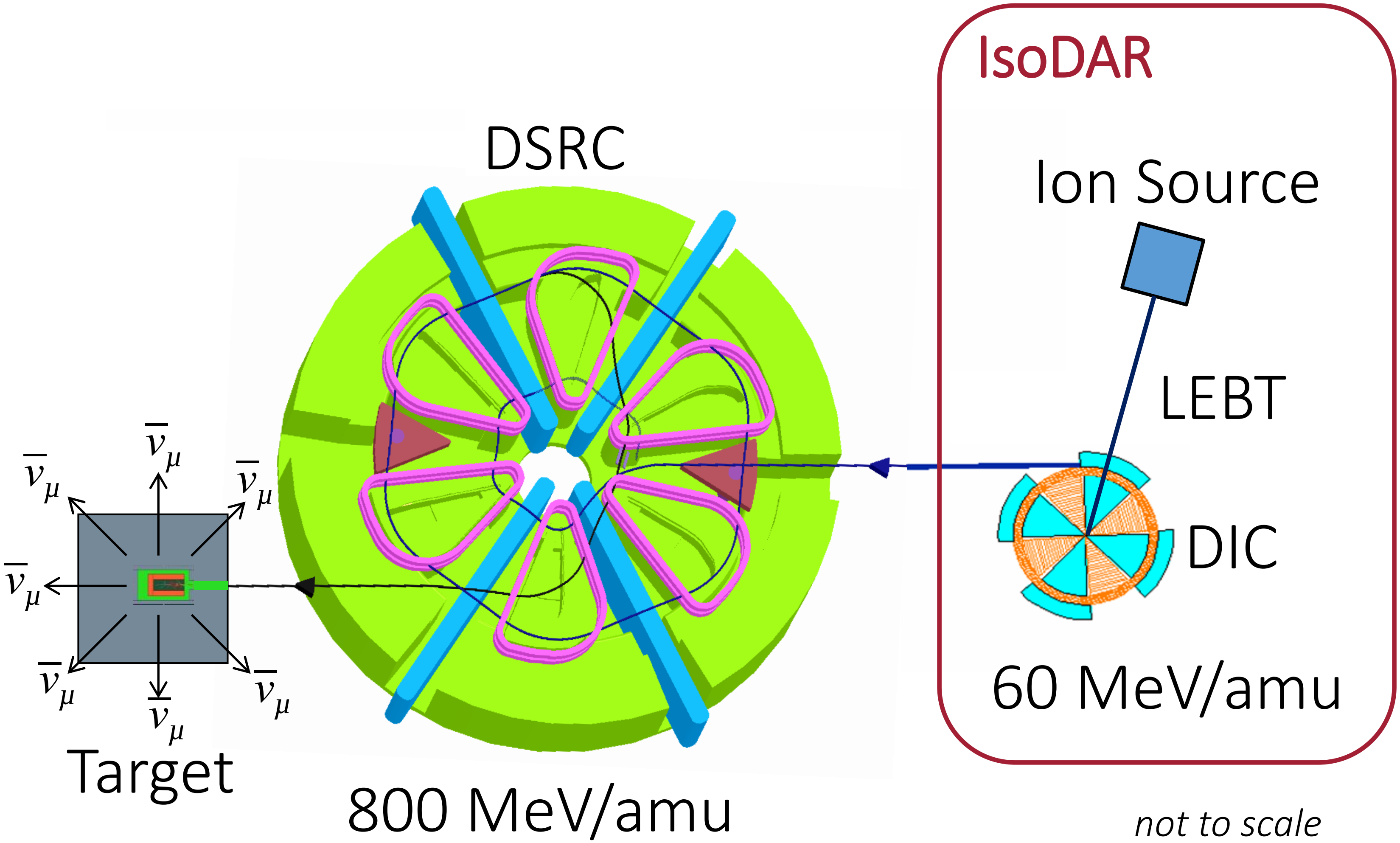


not to scale

DAEδALUS/IsoDAR



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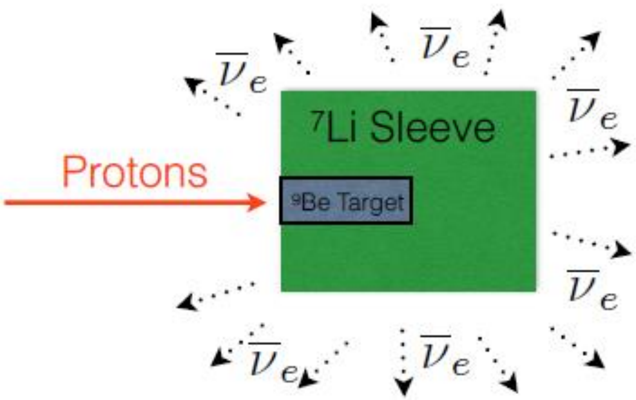
IsoDAR

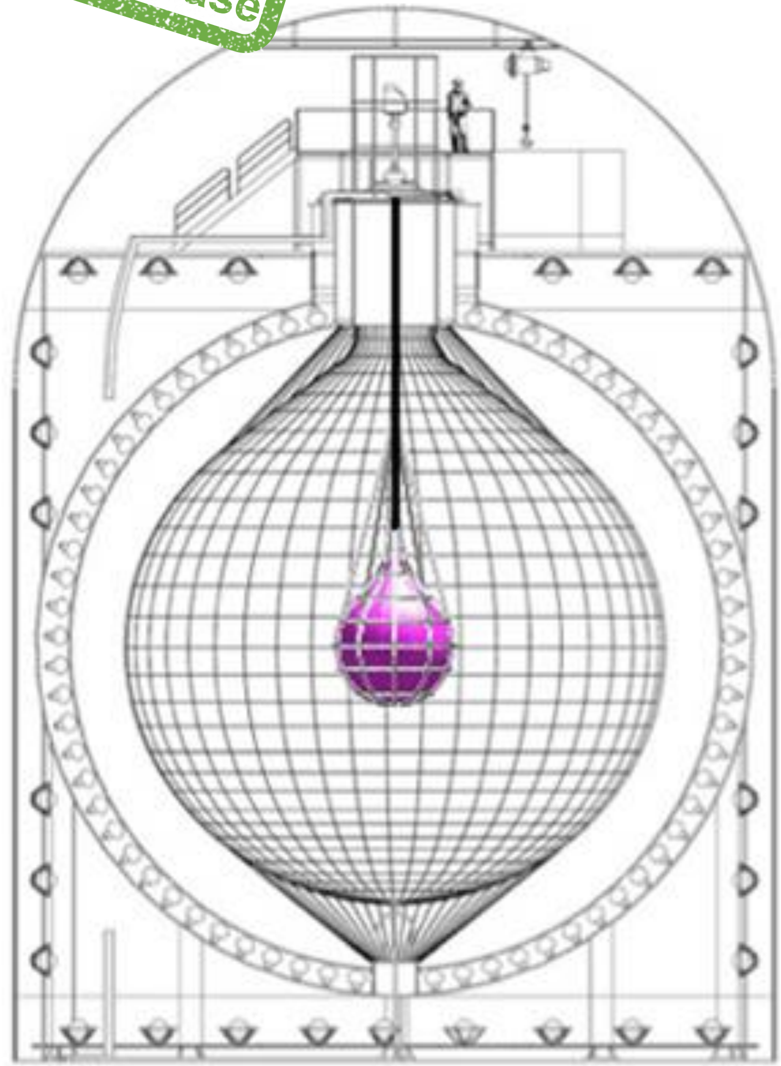
Search for sterile neutrinos through oscillations at short distances and low energy

Preliminary Design Phase

DAEδALUS IsoDAR

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





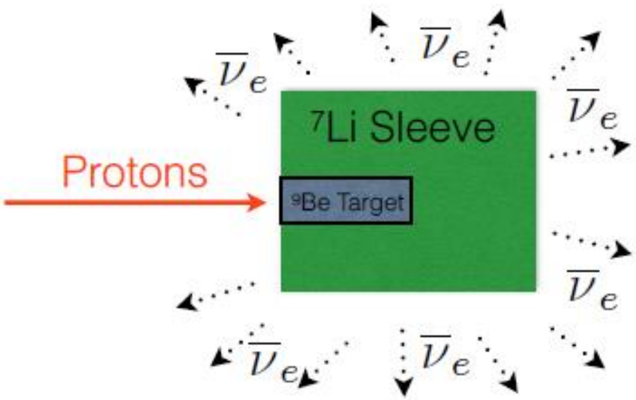
16.5 m

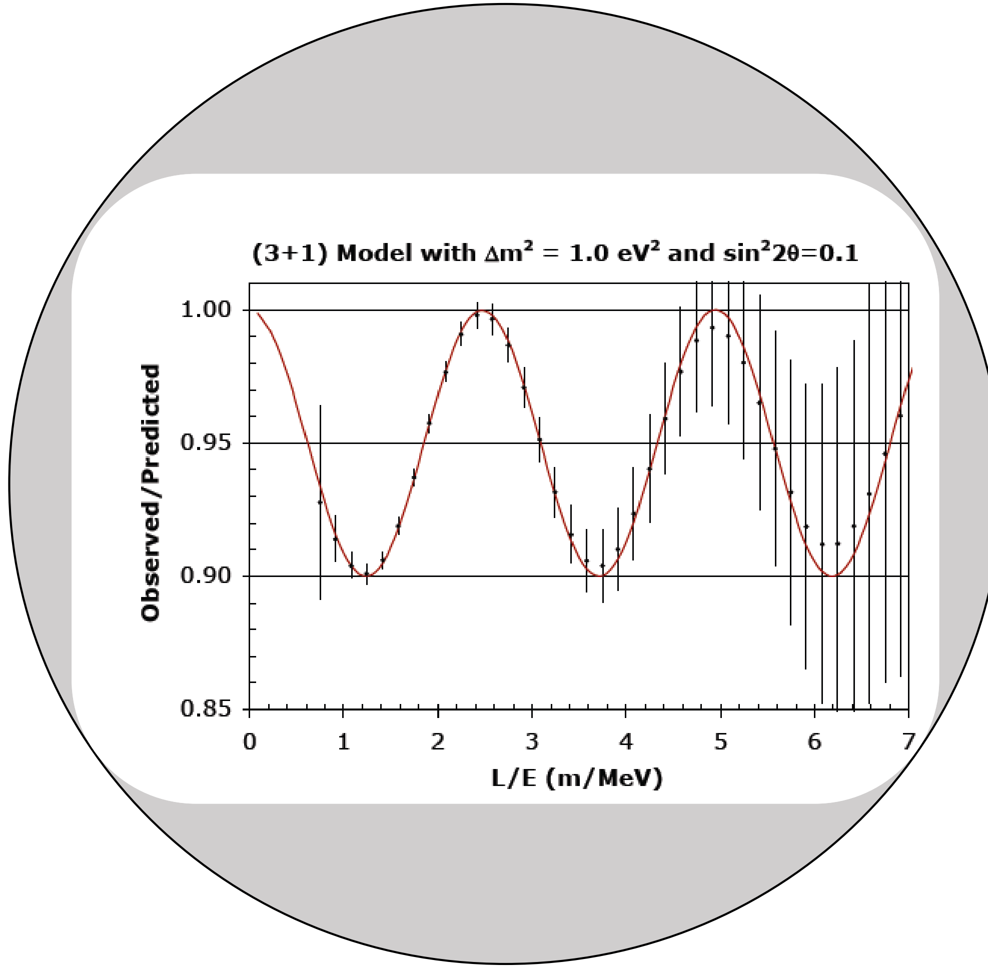
kton scale detector (e.g. KamLAND)

IsoDAR

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

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





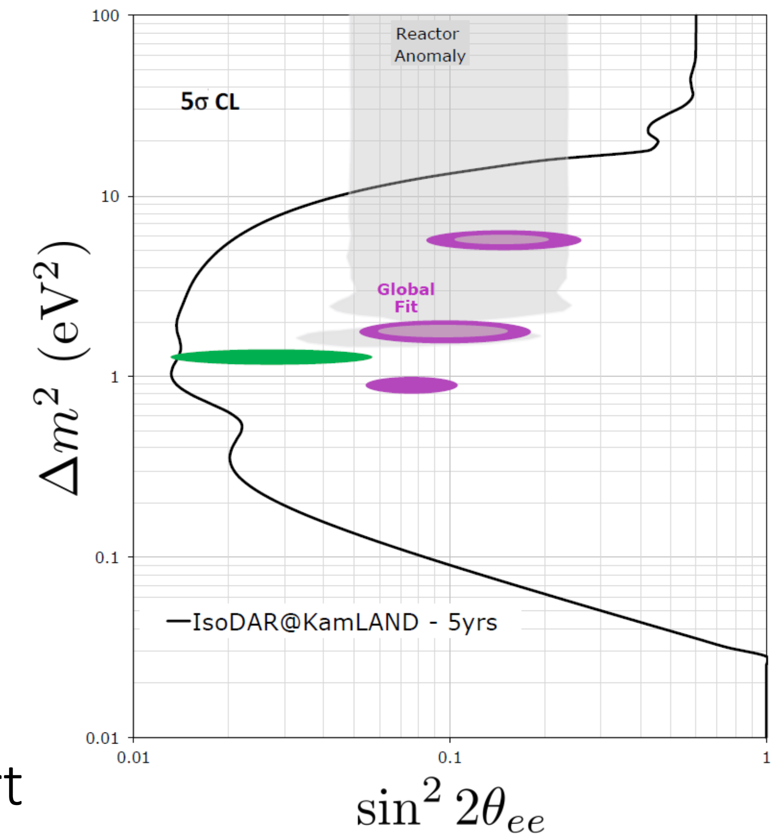
16.5 m

kton scale detector (e.g. KamLAND)

IsoDAR

DAEδALUS IsoDAR

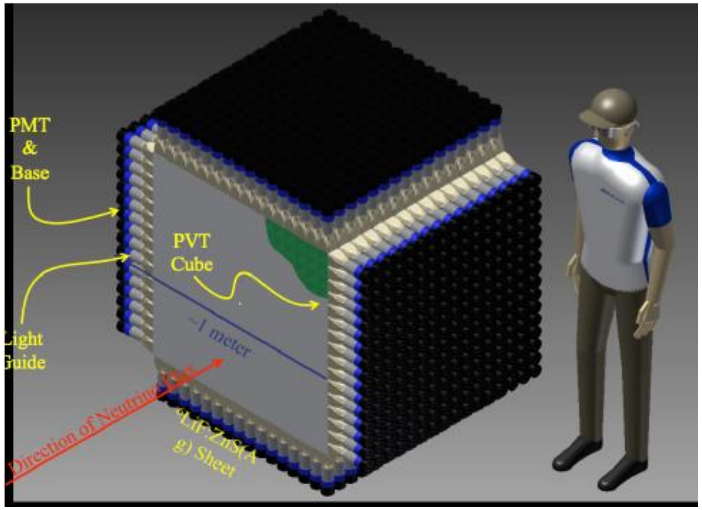
- High Statistics
- Well-understood beam
  - $^8\mathrm{Li}$ is virtually the only contributor to neutrino production
  - 0.016 neutrinos per incoming proton
- Fairly Compact neutrino source
  - Sleeve yields production volume ~ $\sigma_x = \sigma_y = 23$ cm, $\sigma_z = 37$ cm
- KamLAND detector resolution:
  - Vertex: $12\ \mathrm{cm}/\sqrt{\mathrm{E(MeV)}}$
  - Energy: $6.4\ \%/\sqrt{\mathrm{E(MeV)}}$
- Conceptual Design Reports: https://arxiv.org/abs/1511.05130 https://arxiv.org/abs/1710.09325
- Working on Technical Design Report



IsoDAR – A New Opportunity

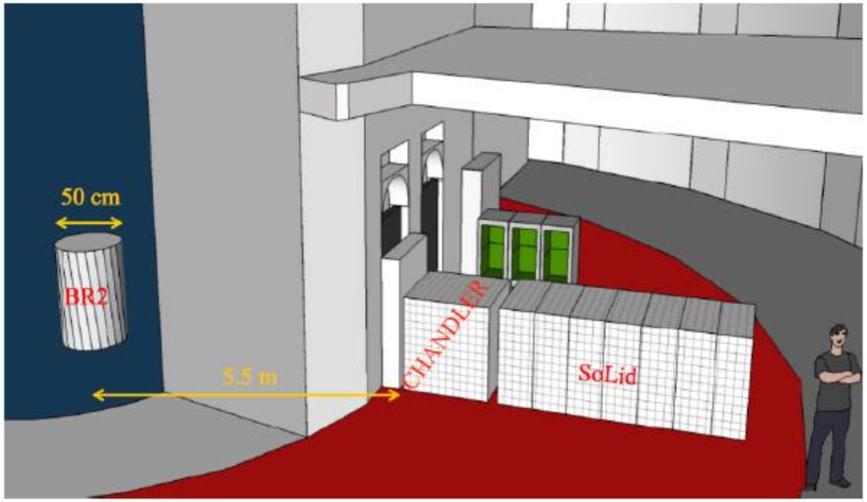
CHANDLER - Carbon Hydrogen Anti-Neutrino Detector with a Lithium Enhanced ROL

PVT Scintillator blocks with ^{6}Li neutron capture sheets coupled to ZnS scintillator
⇒ High efficiency IBD neutrino detector.



CHANDLER/SoLid at the BR2 Reactor in Belgium

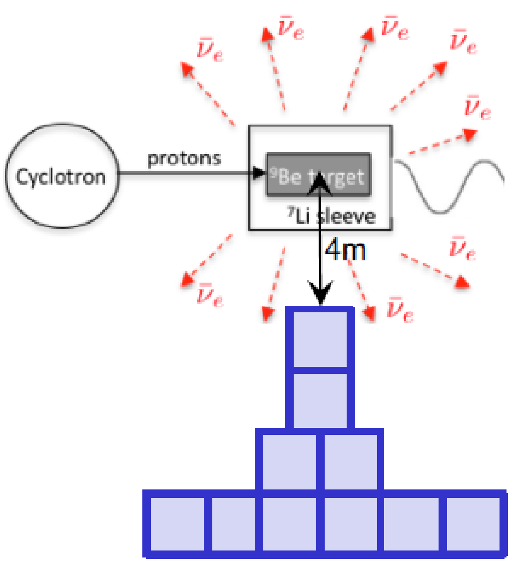
- BR2 is 60 MW research reactor
- Compact well-shielded core (d ~ 50cm)
- High flux (~1019 ν/s) from highly enriched 235U fission products
- Reactor hall allows baselines from 5.5m to 10m

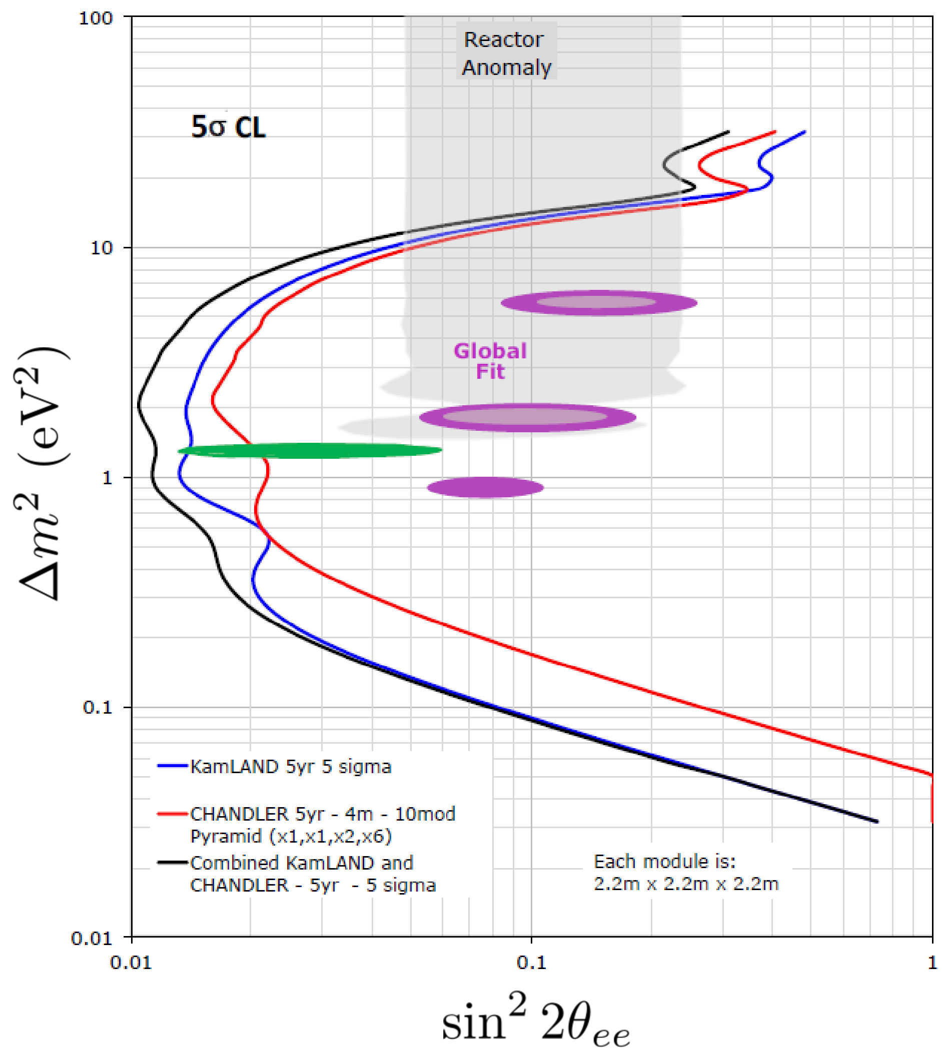


https://arxiv.org/abs/1303.3011

IsoDAR + CHANDLER

- Each block is 2.2^3 m^3
- 10 ton/block
- 10 blocks = 100 tons
- Three options:
  - IsoDAR + KamLAND
  - IsoDAR + CHANDLER
  - IsoDAR + Both





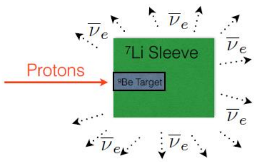
DAEδALUS
IsoDAR

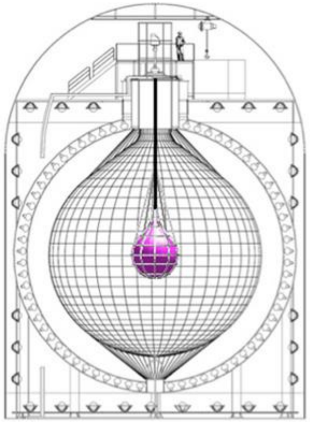
Cyclotron Proton Driver

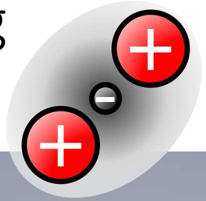
π^+ μ^+ K^+ ${}^{A}X$

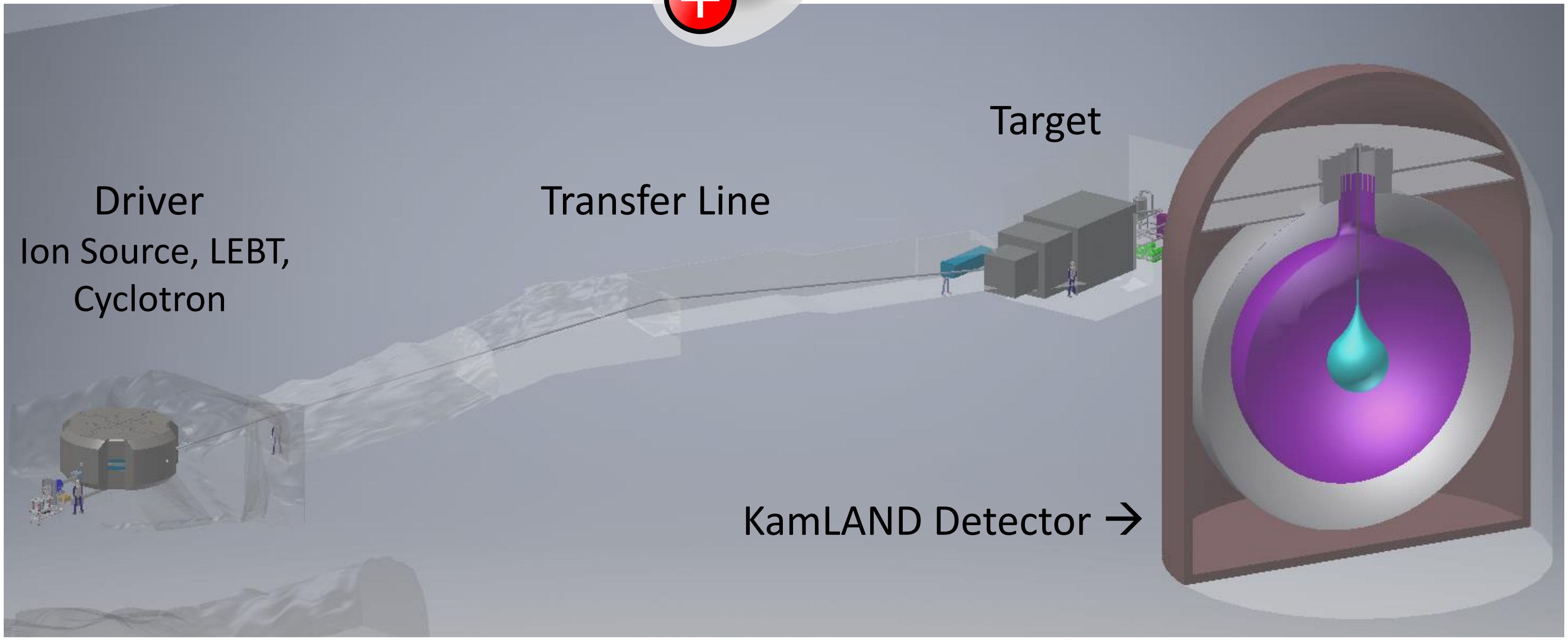
IsoDAR Driver: Overview

- 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



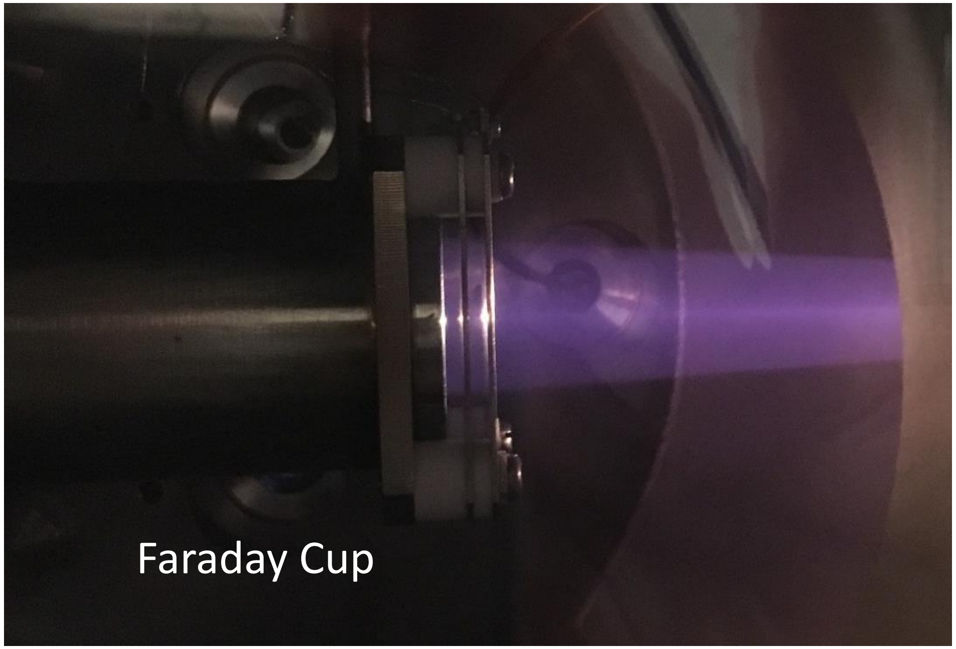


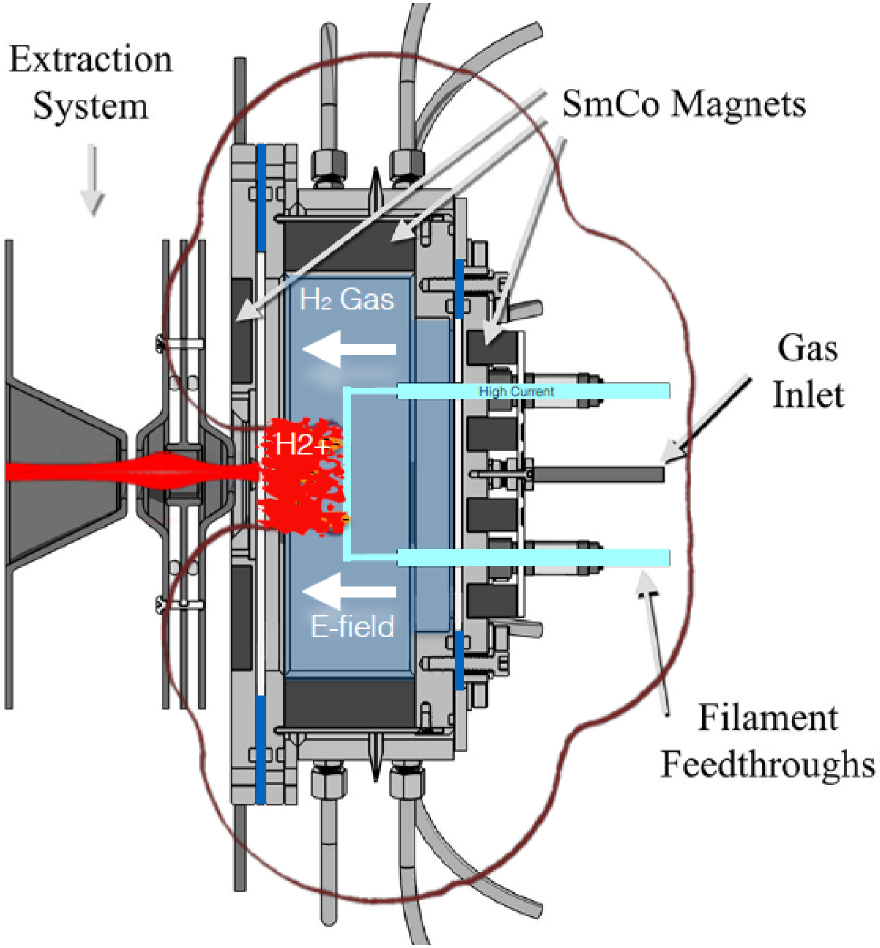




IsoDAR Driver: Ion Source

- Producing the H_2^+...



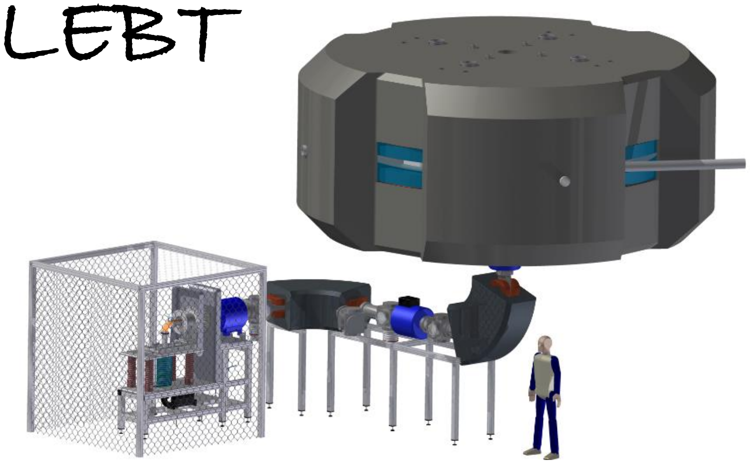


- Filament-Driven Multicusp Ion Source
- Based on: Ehlers and Leung: http://aip.scitation.org/doi/10.1063/1.1137452
- Currently commissioning at MIT

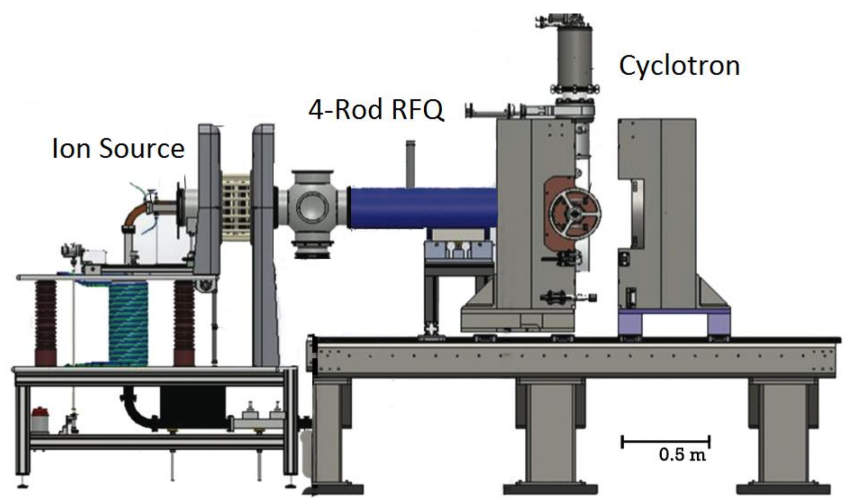
IsoDAR Driver: LEBT

DAEδALUS IsoDAR

RFQ-DIP

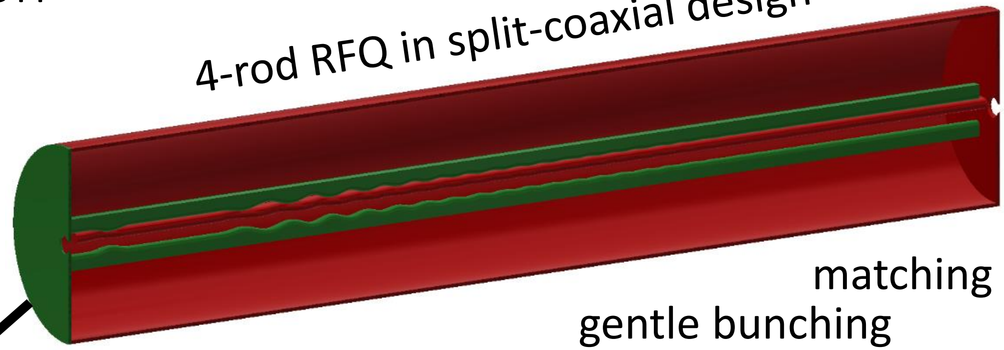


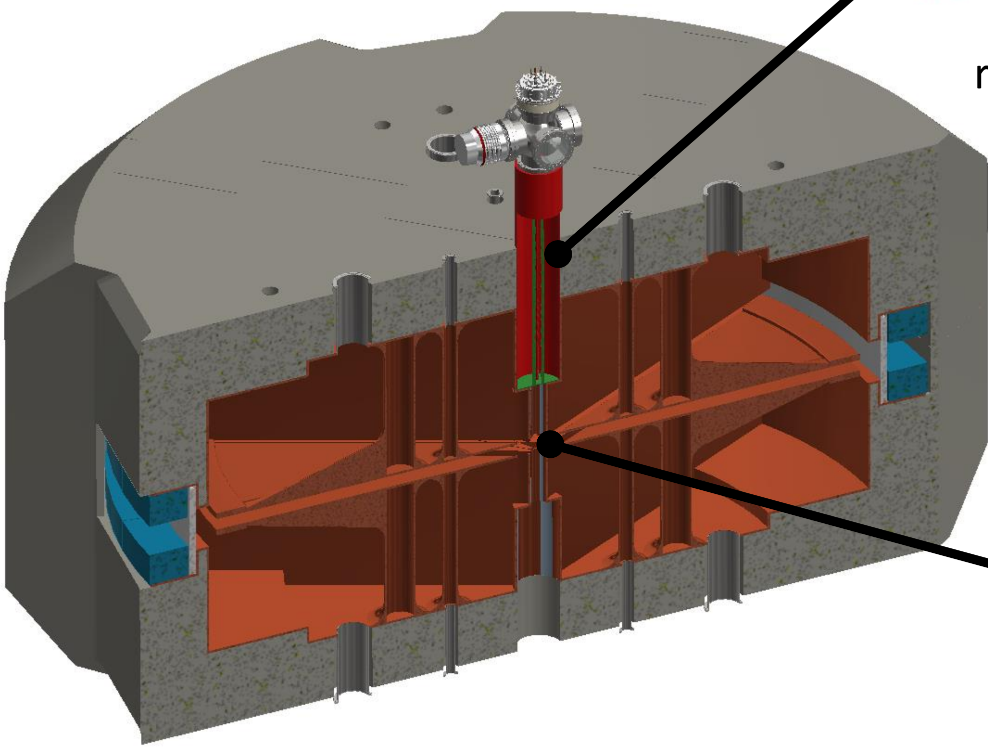
- Two options:
  - Conventional Low Energy Beam Transport (demonstrated experimentally)
    http://iopscience.iop.org/article/10.1088/1748-0221/10/10/T10003/pdf
  - Better: RFQ-Direct Injection Project (RFQ-DIP); NSF funded at ~1 M$
  - Why? http://dx.doi.org/10.1063/1.4935753
    - Highly efficient 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

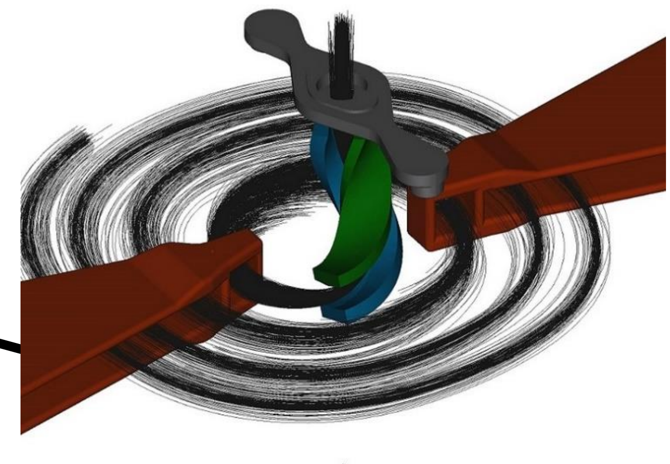


IsoDAR Driver: Cyclotron I

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

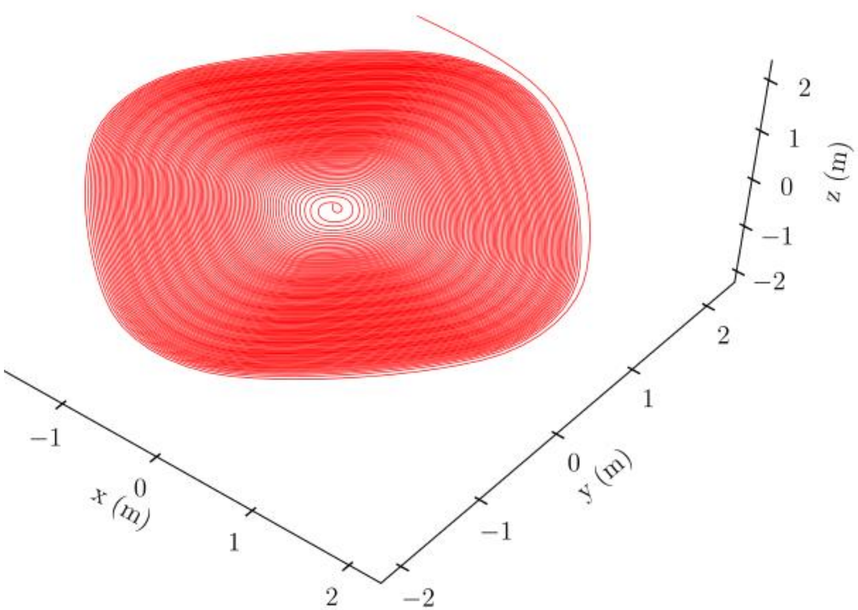


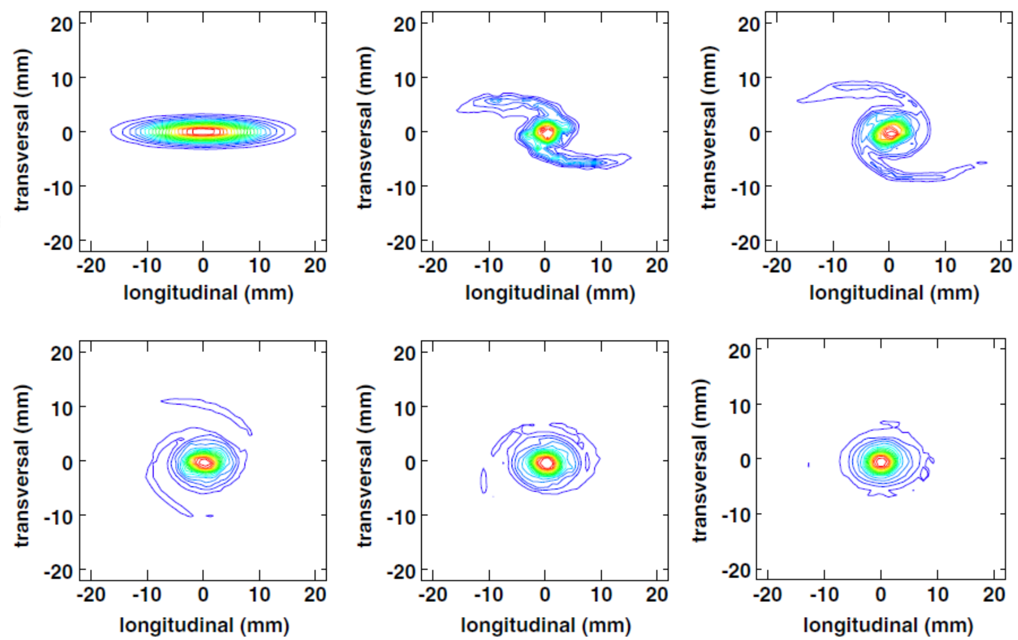




IsoDAR Driver: Cyclotron II

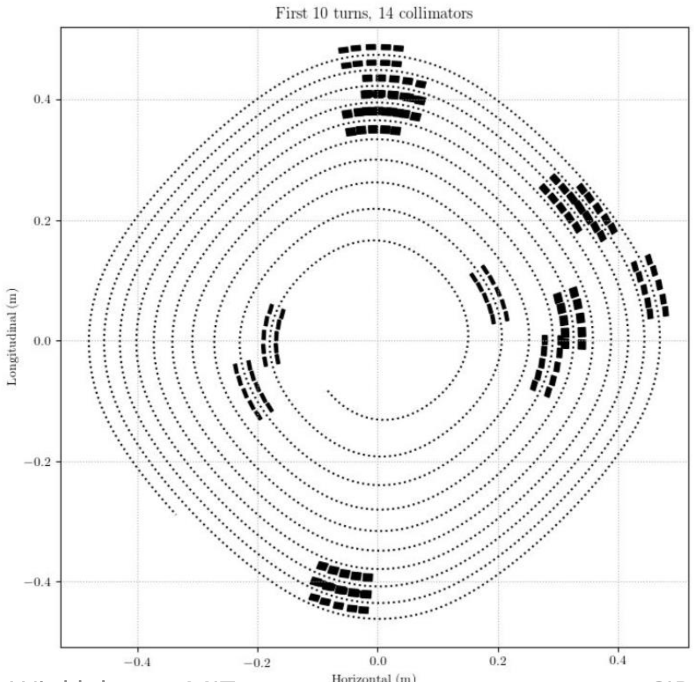
- Acceleration & Extraction. Space-charge again…
- Septum can tolerate about 200 W of controlled beam loss.
- If turn separation is small halo formation is large → big problem.
- Space-charge + Isochronous, AVF cyclotron = Vortex motion. Good!
- Needs to be carefully matched, though!

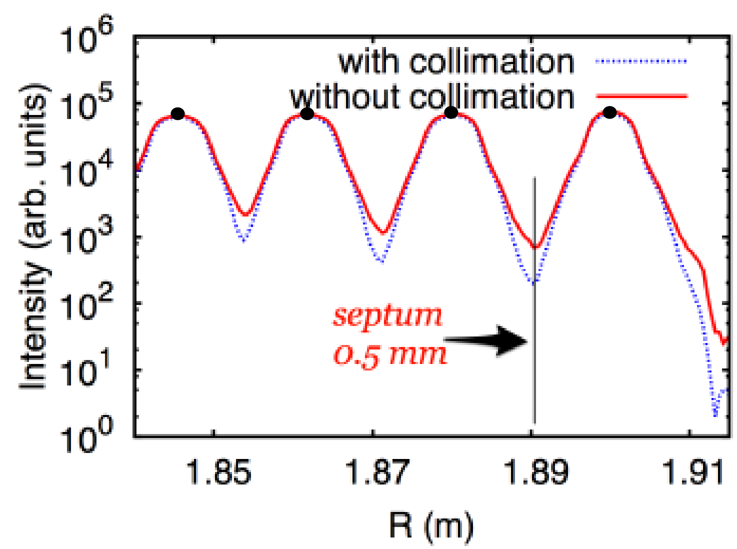




IsoDAR Driver: Cyclotron III

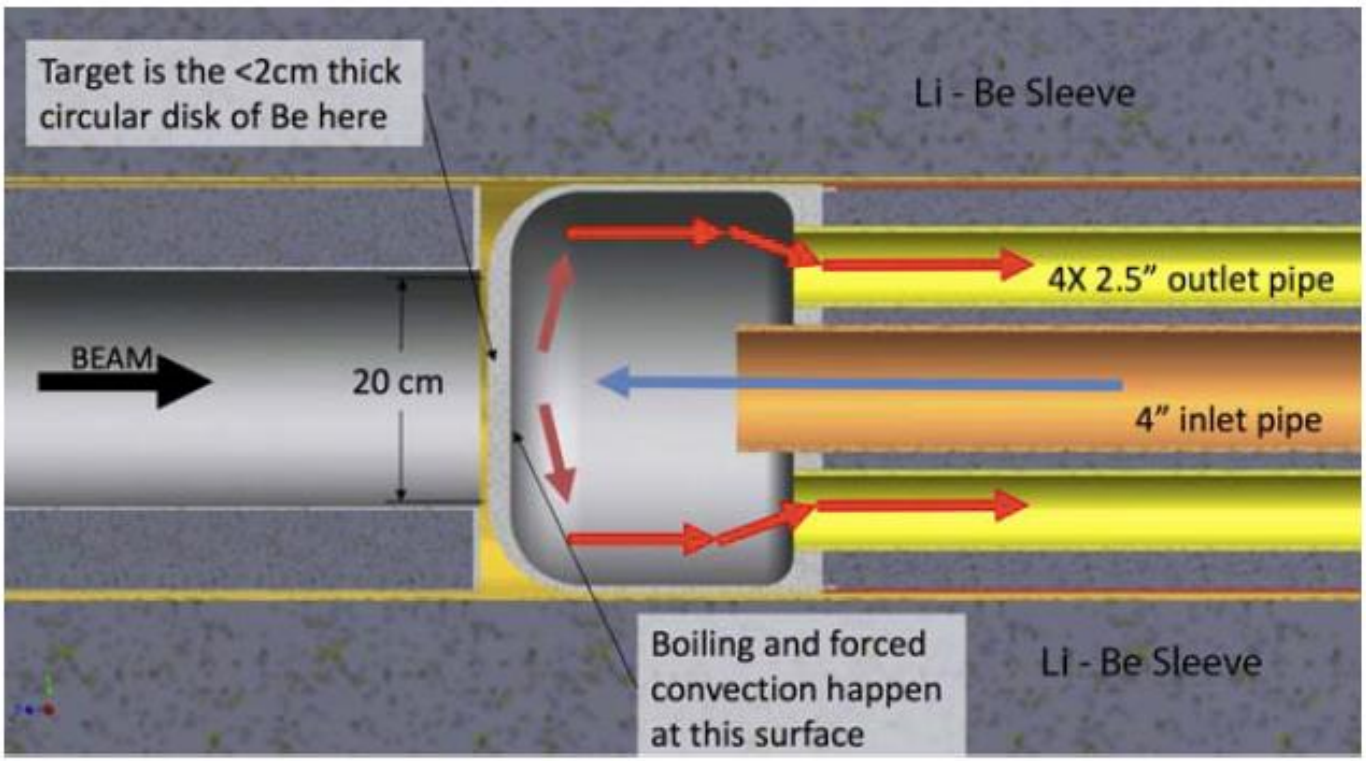
- Acceleration & Extraction. Space-charge again…
- Septum can tolerate about 200 W of controlled beam loss.
- If turn separation is small halo formation is large → big problem.
- Space-charge + Isochronous, AVF cyclotron = Vortex motion. Good!
- Needs to be carefully matched, though! + Collimators





IsoDAR Driver: Target I

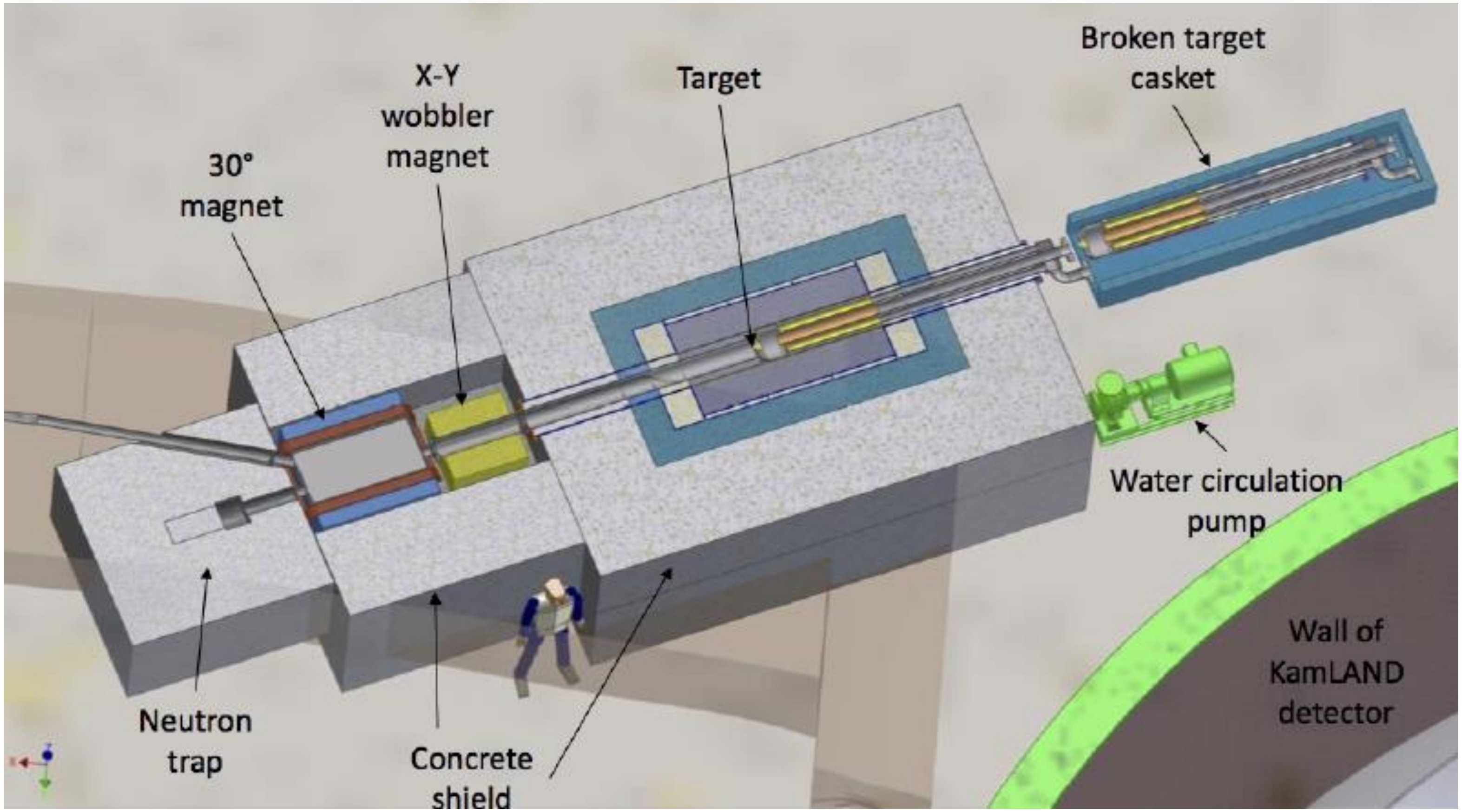
- Beryllium target with lithium-beryllium sleeve
- 600 kW painted across face ~ 16 cm diameter (~3 kW/cm^2)
- Considerable progress on optimization of shape and Li-Be mixture



IsoDAR Driver: Target II

DAEδALUS IsoDAR

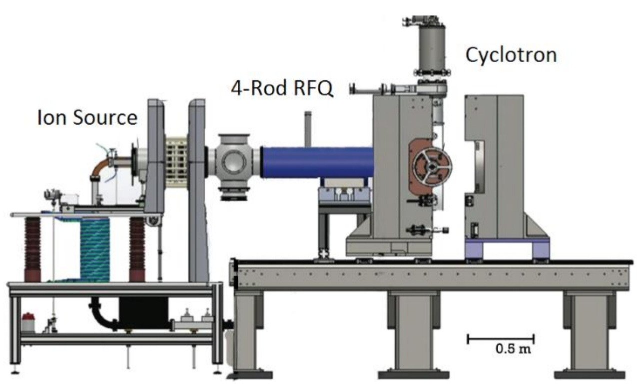
COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

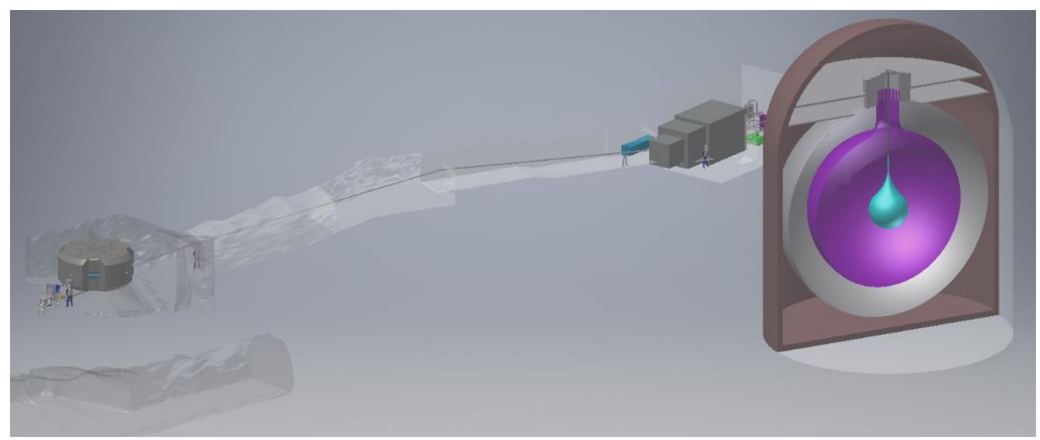


NSF funded target study on the way at Columbia University!

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





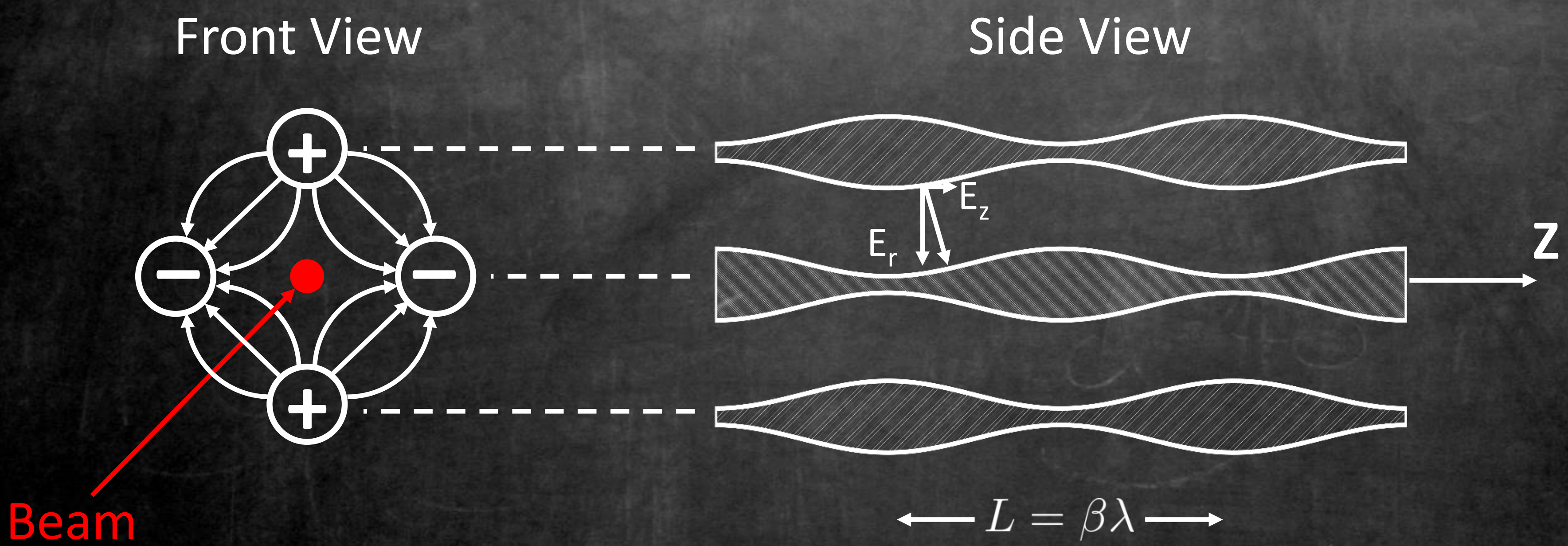
Conclusion / Outlook

- 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 this fall….stay tuned!

Thank You!

π^+ μ^+ K^+ ${}^{A}X$

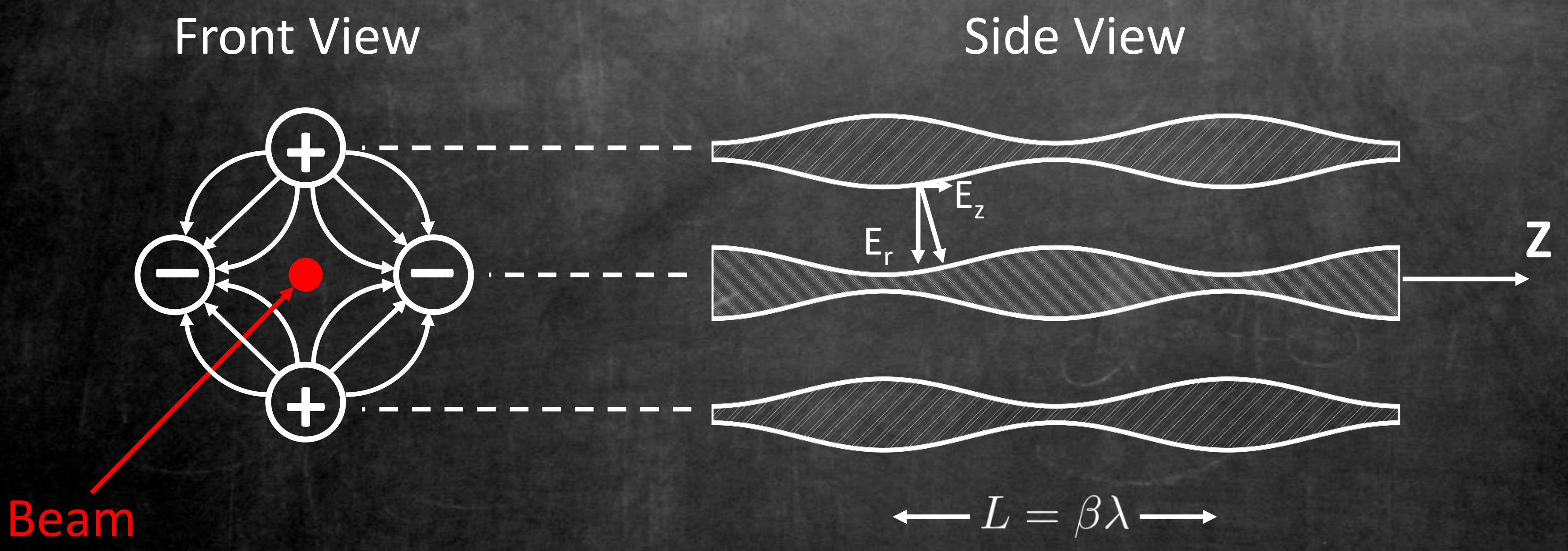
RFQ General Principle

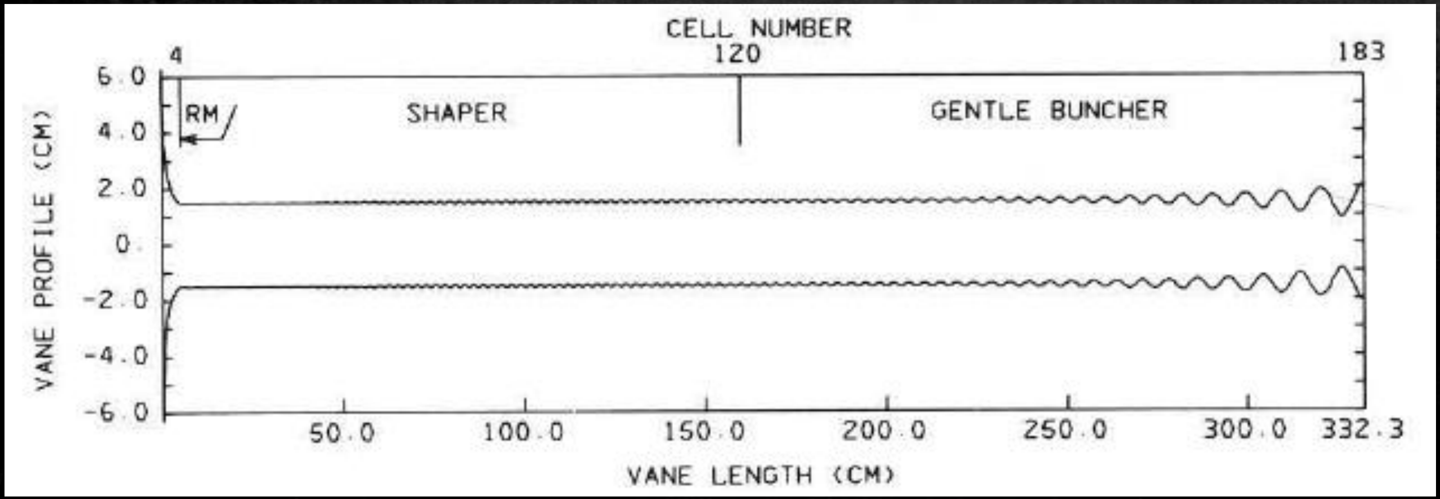


$$V(t) = V_{\max} \cdot \cos(\omega_{\mathrm{RF}} \cdot t - \Phi_S)$$

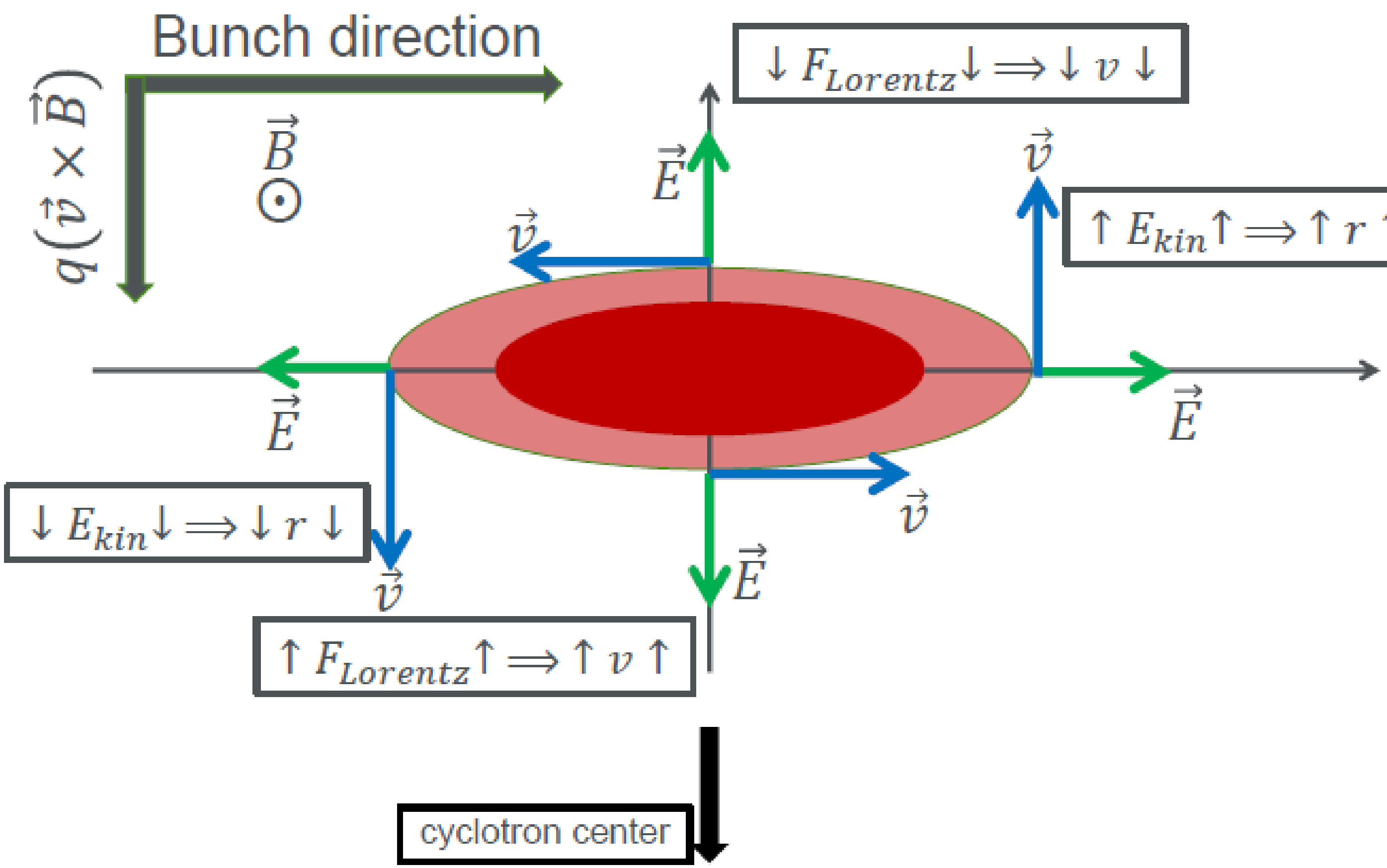
- Continuous focusing like in a series of alternating F/D Electrostatic quadrupoles
- Wiggles lead to acceleration and bunching (RF bunching similar to cyclotron)
- Same frequency as cyclotron

RFQ General Principle





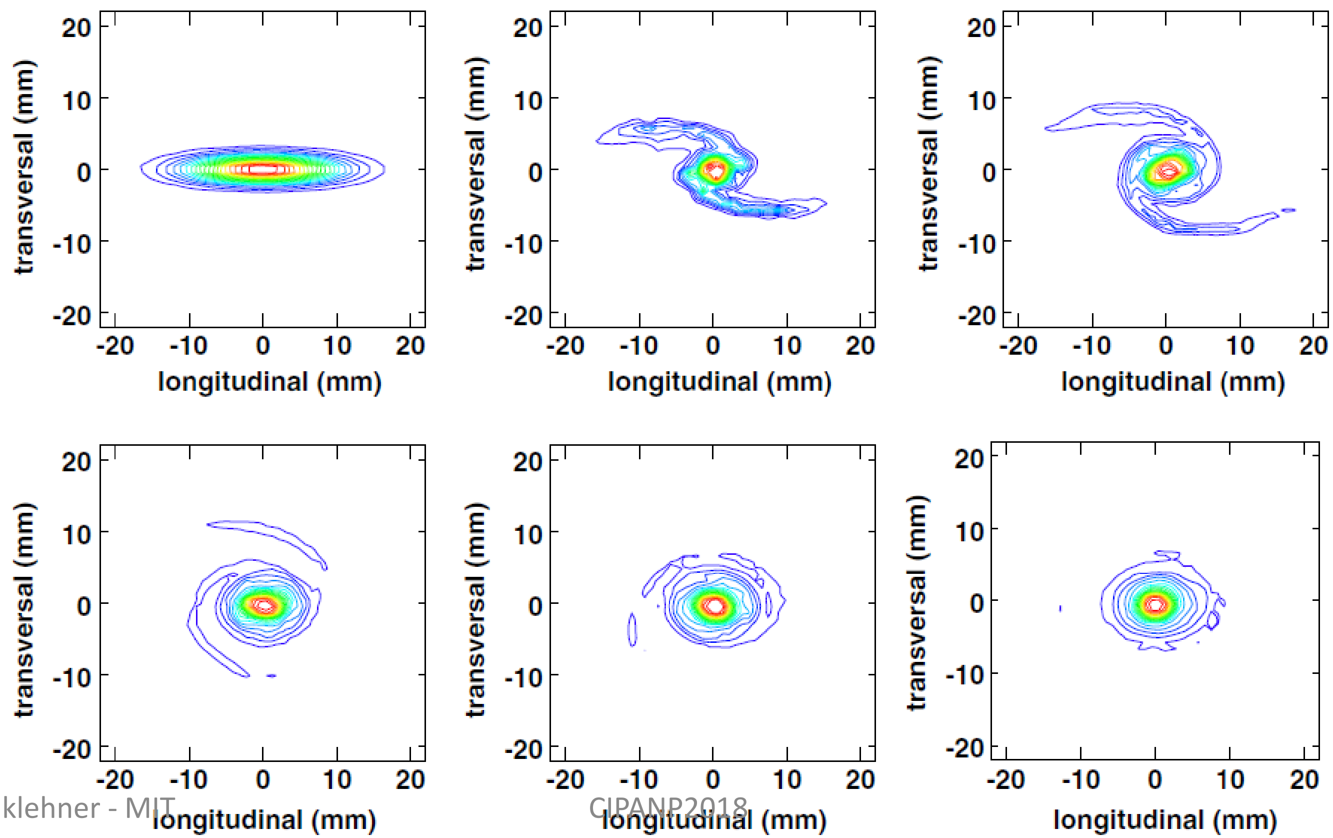
Vortex Motion Principle



Courtesy of Wiel Kleeven (Cyclotrons 2016)

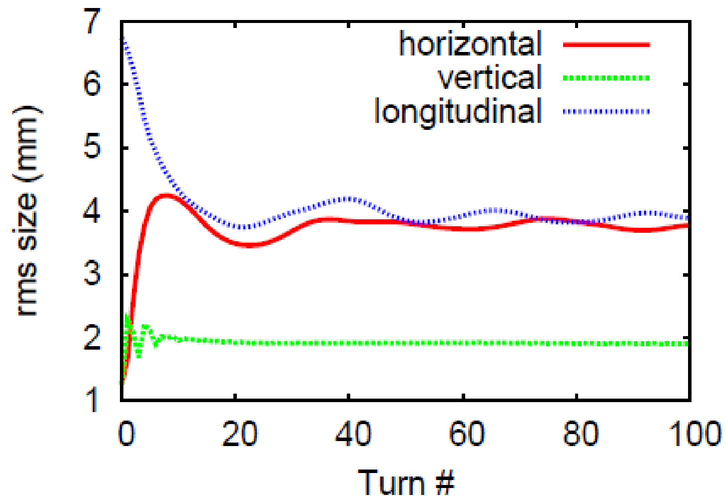
Vortex Motion PSI Injector II

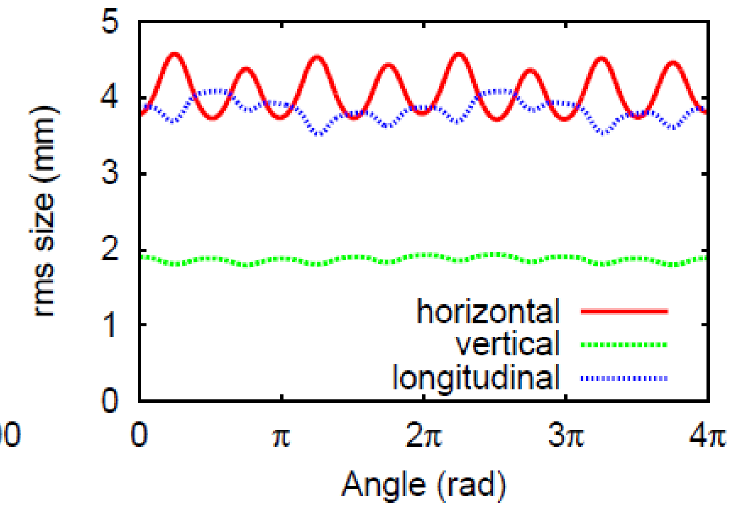
- If the beam is initially well matched, it curls up into a tight ball with only a bit of halo.
- It is circular in x-y (mid plane of cyclotron)
- This has been seen at PSI Injector II and reproduced in OPAL:



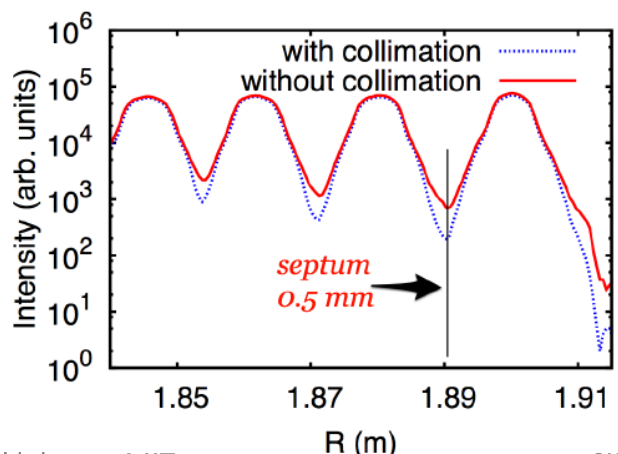
Vortex Motion IsoDAR/DIC

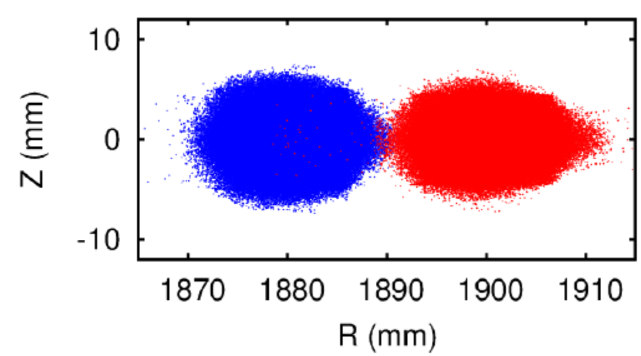
- Starting at 1.5 MeV/amu (JJ.Yang 2012) a nice round beam shape develops





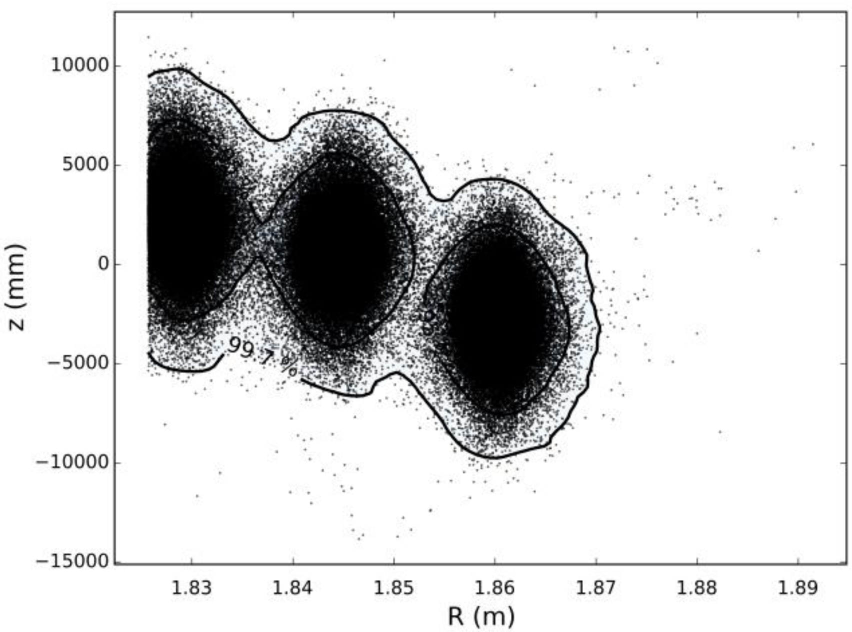
- Beam power on septum <110 W

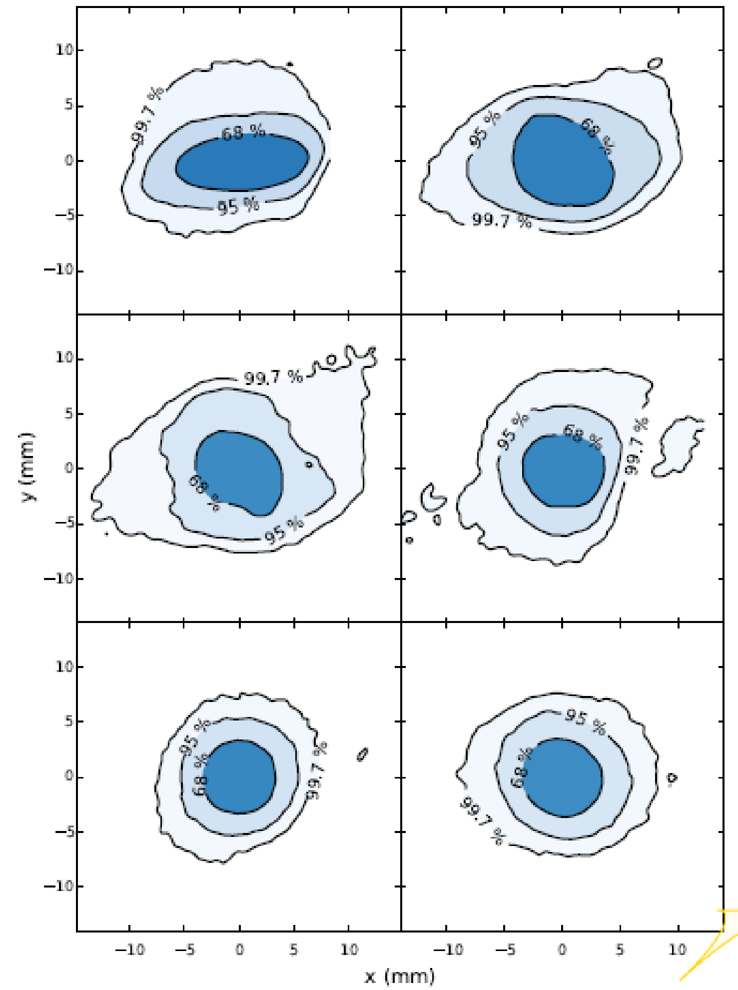




Vortex Motion in the IsoDAR Cyclotron

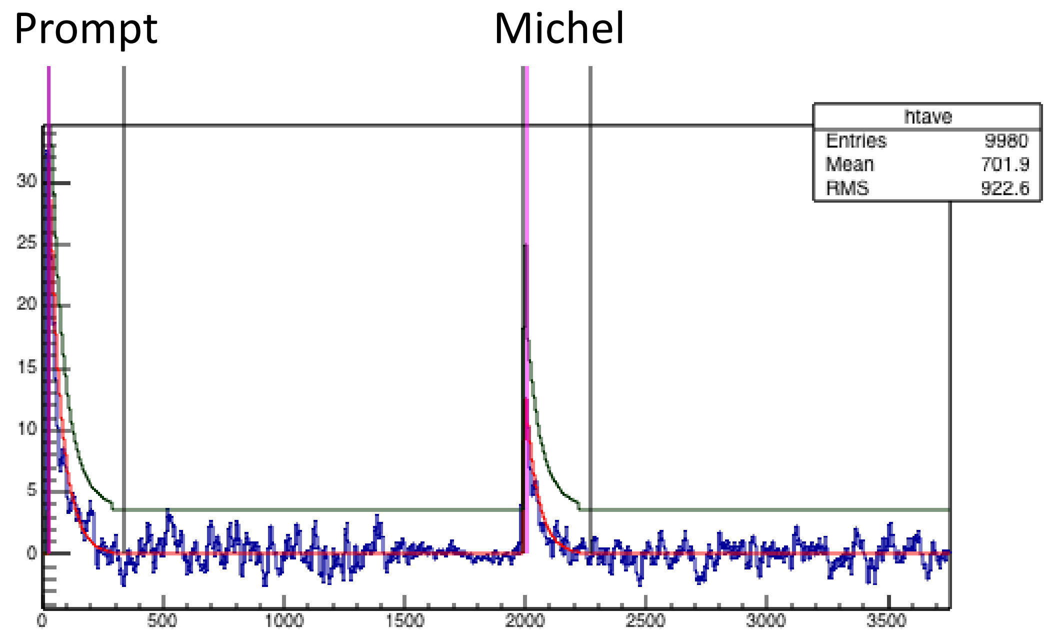
- Starting at 192 keV/amu (within the first turn) (J. Jonnerby, 2016)
- Vortex motion happens for our H_2^+ beam
- Beam separation not yet fully sufficient, but work in progress

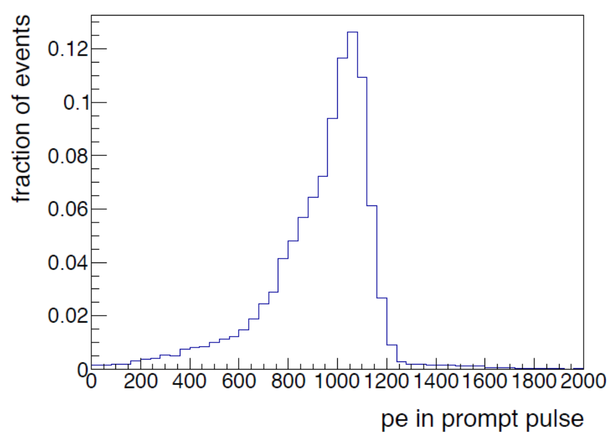


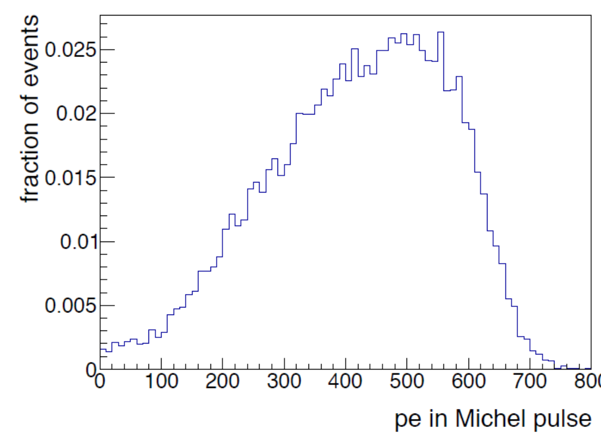


Kpipe - Background:

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

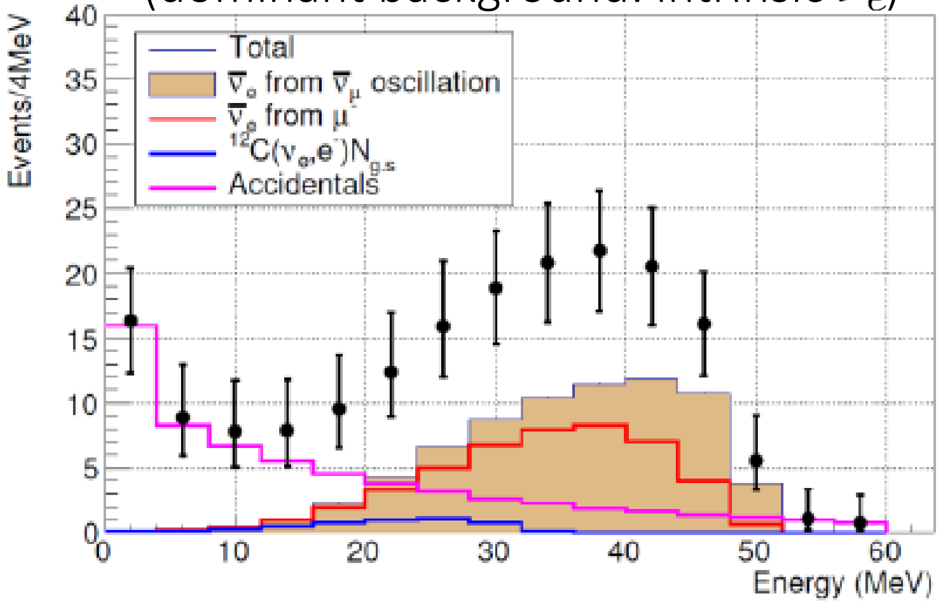




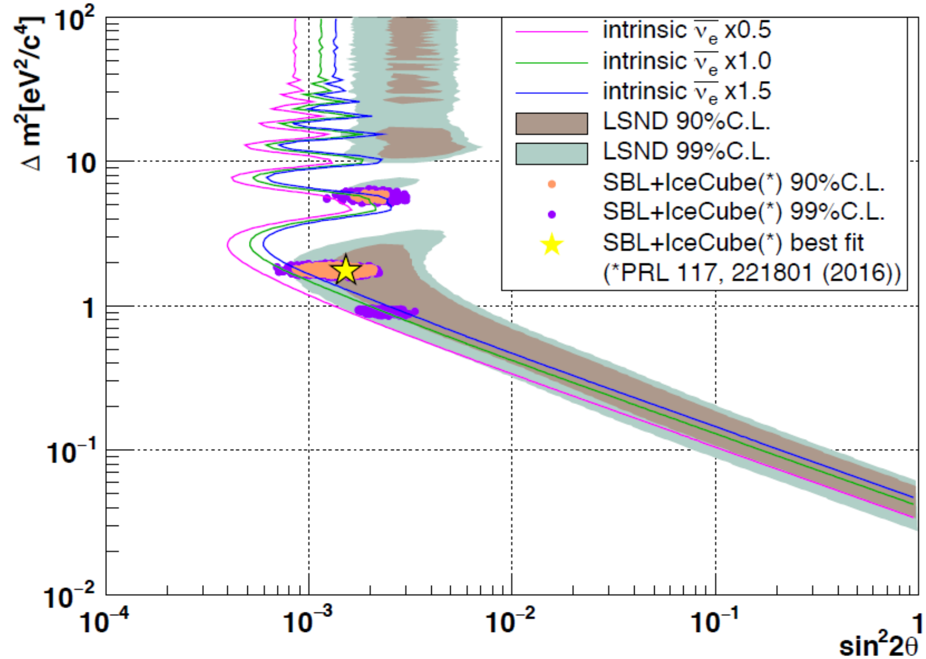


JSNS² - Spectrum & Sensitivity

(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