High power cyclotrons for neutrino physics

IsoDAR @ KamLAND

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The IsoDar collaboration

- Spokespersons: J. Conrad (MIT) & M. Shaevitz (Columbia)
- Major institutional contributors
  - Neutrino physics: MIT, Columbia, U Michigan,
  - Cyclotron driver:
    - MIT, LNS Catania, PSI, IBA Inc. Best Cyclotrons
  - High power target:
    - Columbia, Bartosek Engineering, MIT
  - Siting issues:
    - RIKEN, Tohoku University
- Technical CDR:
  - arXiv:1710.09325v1 [physics.ins-det] 25 Oct 2017

Standard Model: 3 massless neutrinos in

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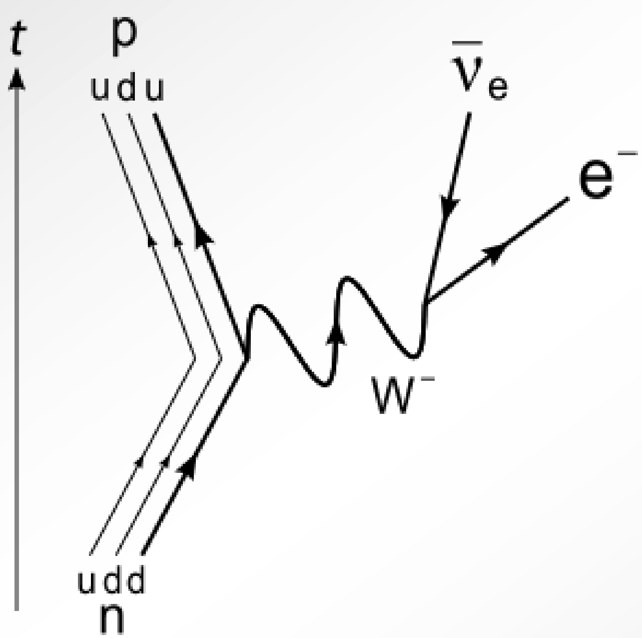
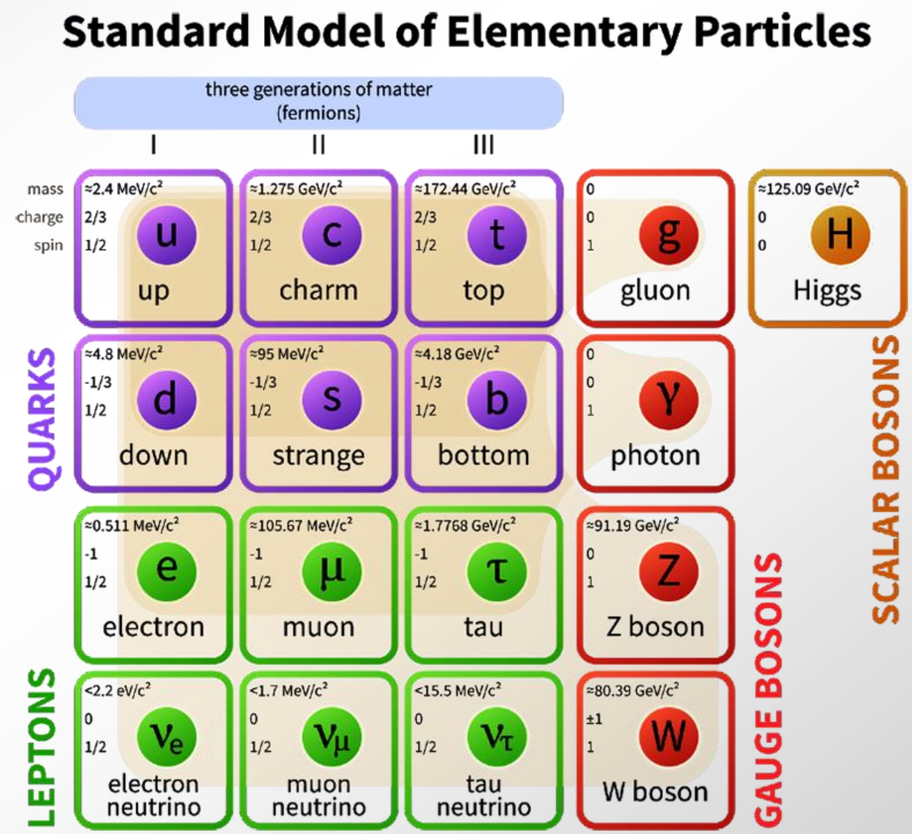
FACULTY OF ECONOMICS

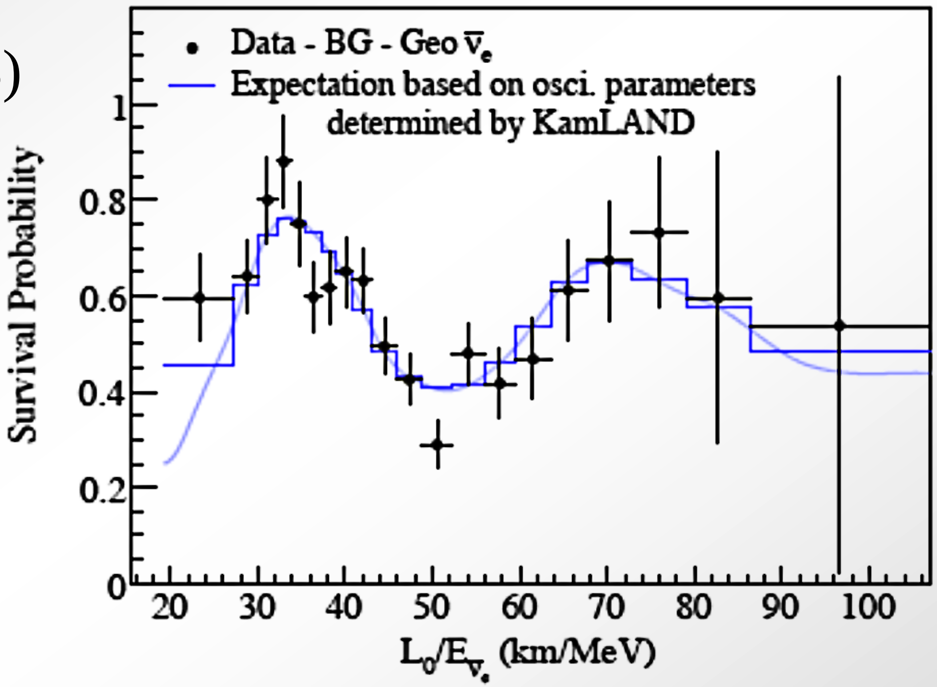
- Three ‘known’ neutrino flavors
- Part of lepton weak doublets
- Only interact via weak force
- Example: Beta-Decay:





EWSB gives neutrinos mass
=> Mass & flavor eigenstates mix

- First confirmed in SuperK (1998) now observed in many experiments
- Mass & Flavor eigenstates are not aligned
- => Mixing matrix U



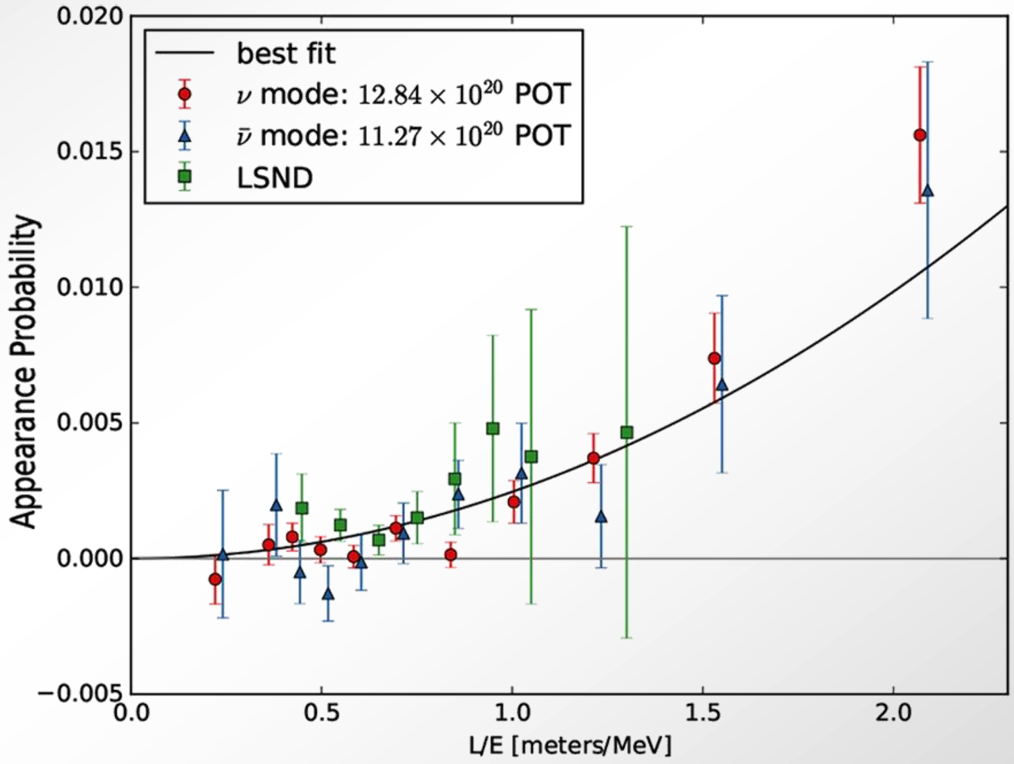
- U is a unitary matrix with 3 free parameters plus extra parameter $e^{i\delta}$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}s_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}c_{23} - s_{12}c_{23}s_{13}e^{i\delta} & s_{23}c_{13} \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij} \qquad c_{ij} = \cos\theta_{ij}$$

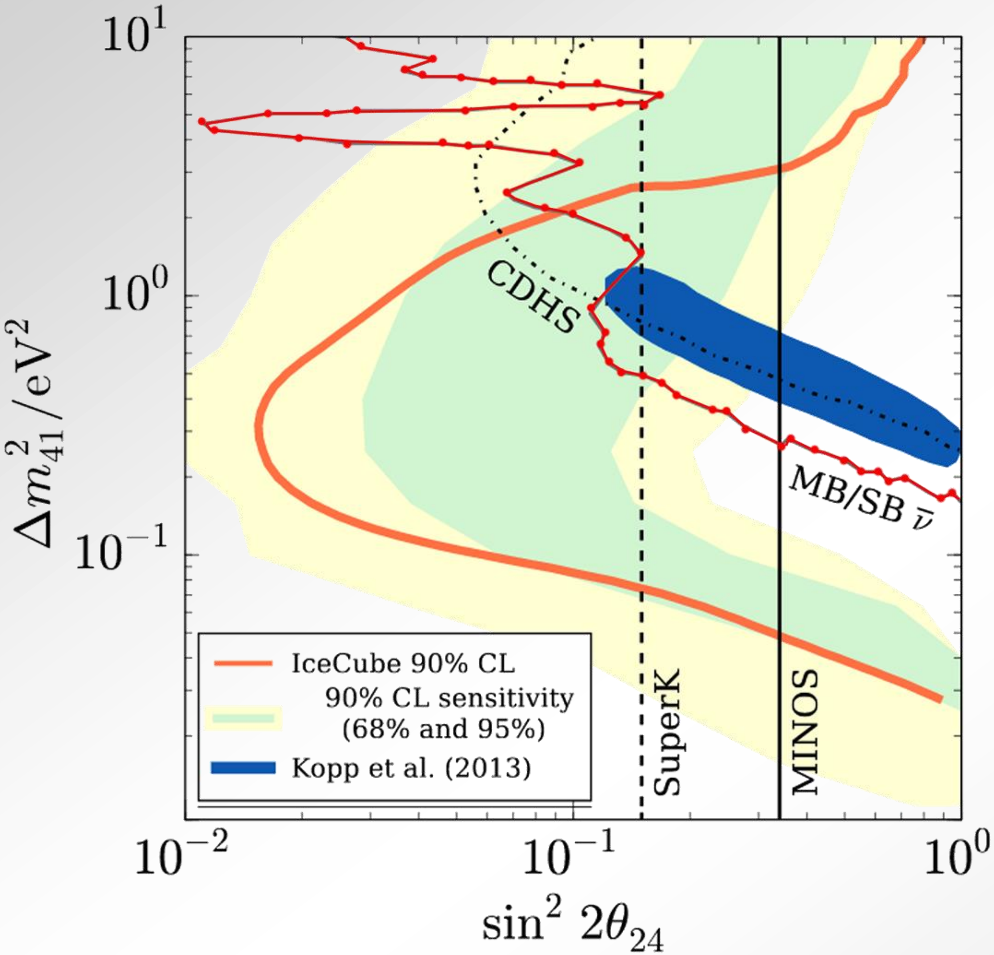
Anomalies observed in oscillation probabilities

- Heavy “sterile neutrino” that does not interact weakly might explain excesses of ν_e seen in MiniBoone & LSND experiments
  - LSND (3.8σ)
  - Mini-Boone (4.8σ)



A comparison between the L/E_ν^{QE} distributions for the MiniBooNE data excesses in neutrino mode (12.84×10^{20} POT) and antineutrino mode (11.27×10^{20} POT) to the L/E distribution from LSND [1].

A recent negative result?
Exclusion regions from the Ice Cube search



Ice Cube search
for light sterile neutrinos

90% (orange line) CL contour & bands containing ***68% (green)*** & ***95% (yellow) in simulated pseudo-experiments***.

Contours & bands are overlaid on *90% CL* exclusions from previous experiments MiniBooNE & LSND 90% CL allowed regions

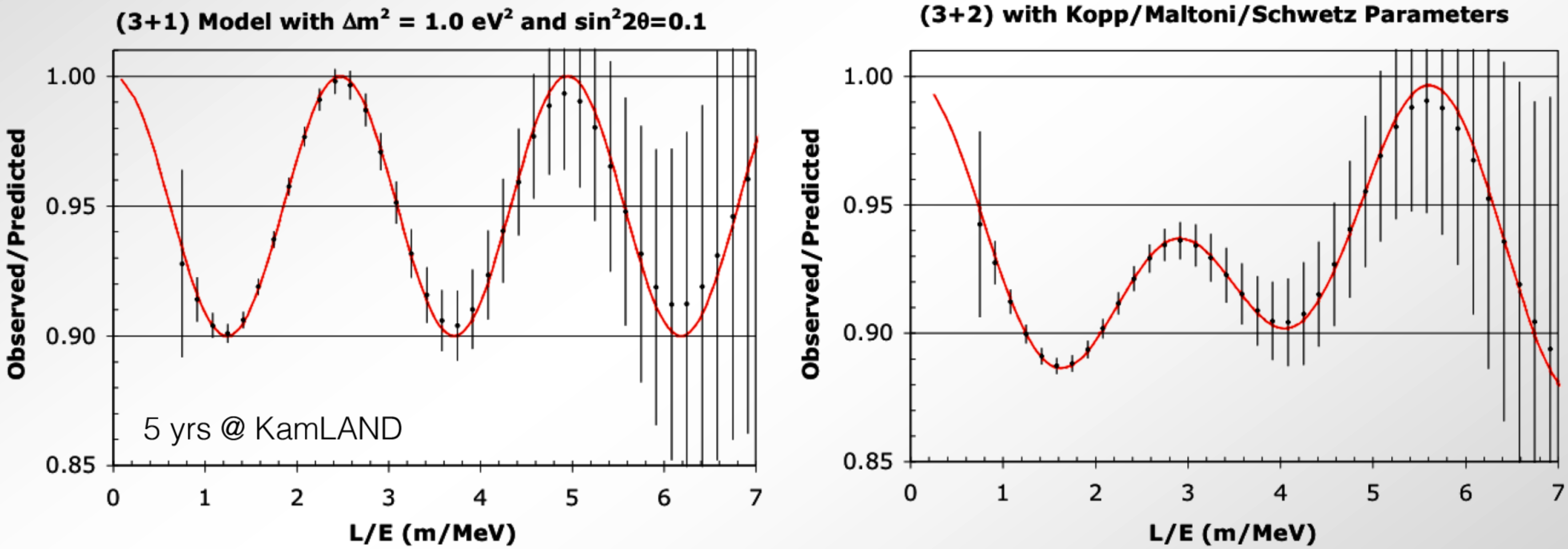
IceCube Collaboration
doi :10.1088/1742-6596/888/1/012023

Other null results in this parameter space:
MINOS, KARMEN, CDHS, OPERA

We need a definitive experiment
=> 5 to 10 σ measurement

❖ Distinguish between one & multiple sterile neutrinos
  - IsoDAR's high statistics & good L/E resolution provide potential for distinguishing (3+1) & (3+2) oscillation models

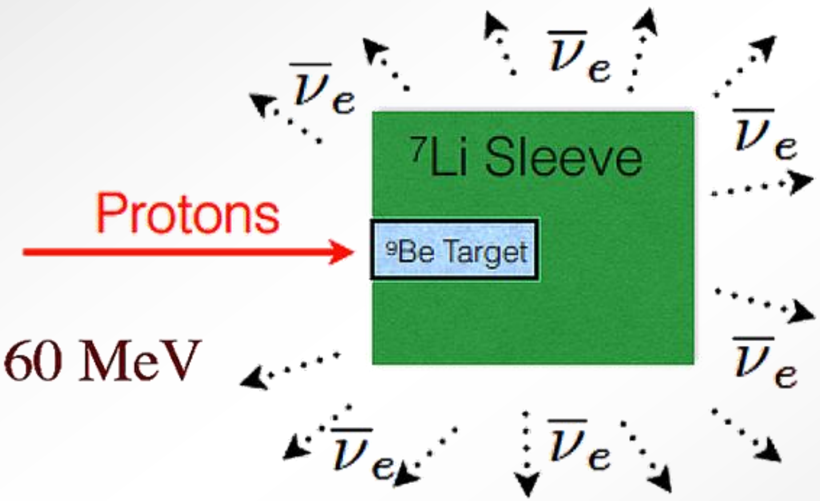
Observed/Predicted event ratio vs L/E, including energy and position smearing

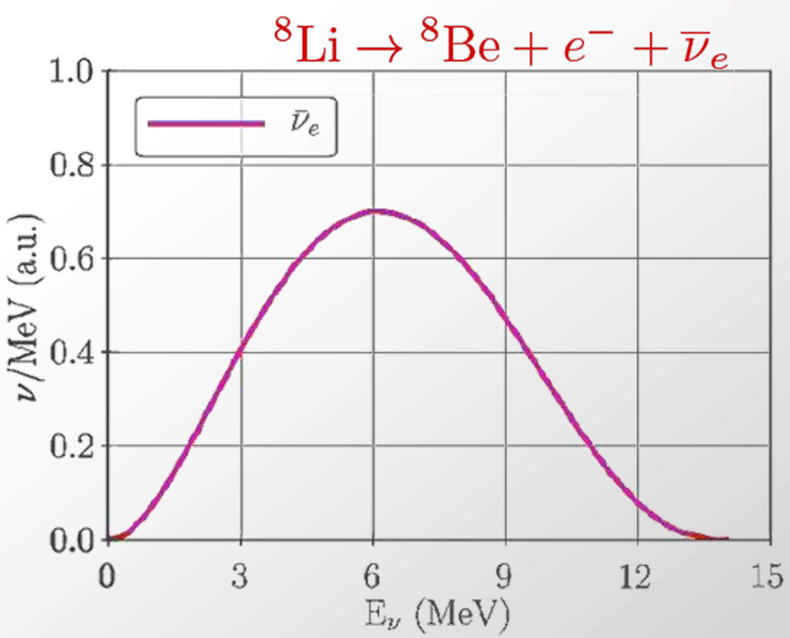


Hence, the IsoDAR proposal

IsoDAR:
Isotope Decay At Rest Neutrino Source

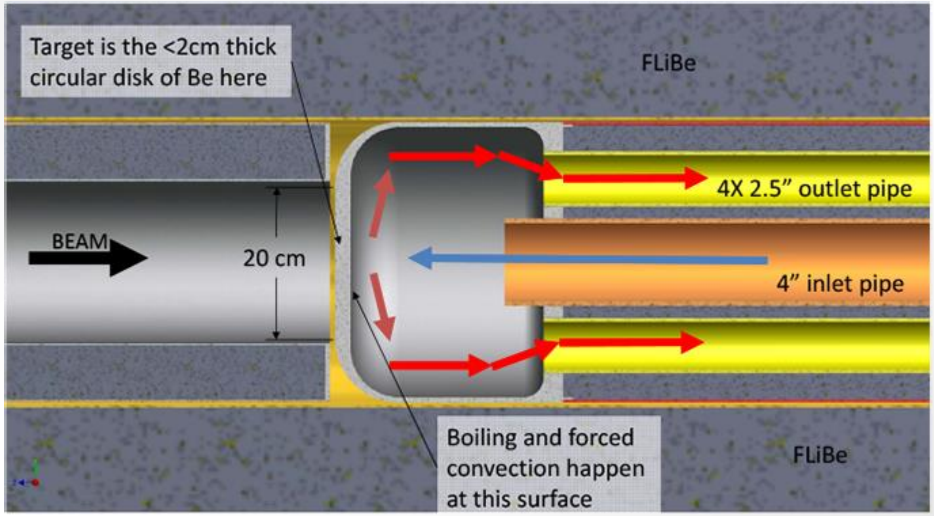
- Search for sterile neutrinos through oscillations at short distances & low energy
- Detect $\bar{\nu}_e$ by inverse beta decay
- Isotropic source of $\bar{\nu}_e$ through decay at rest of Li^8

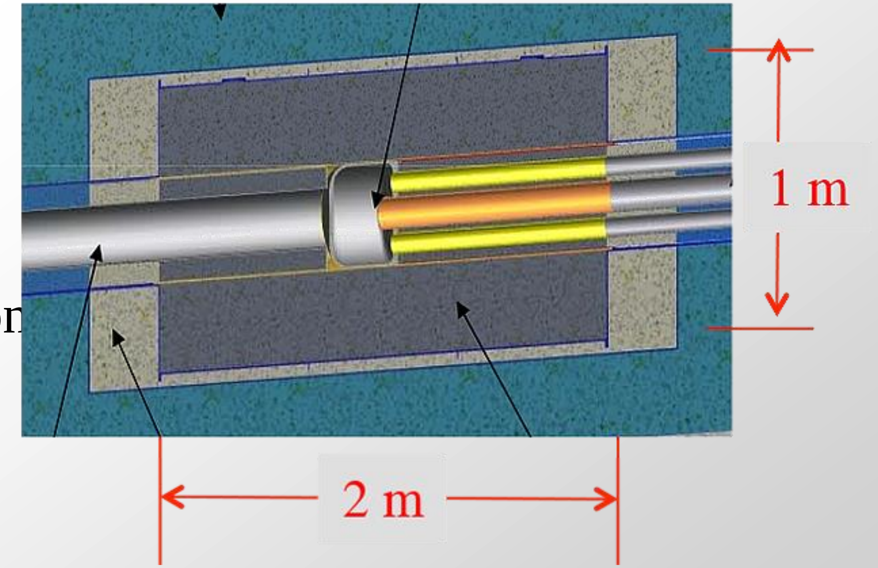




Characteristics of anti-neutrino source

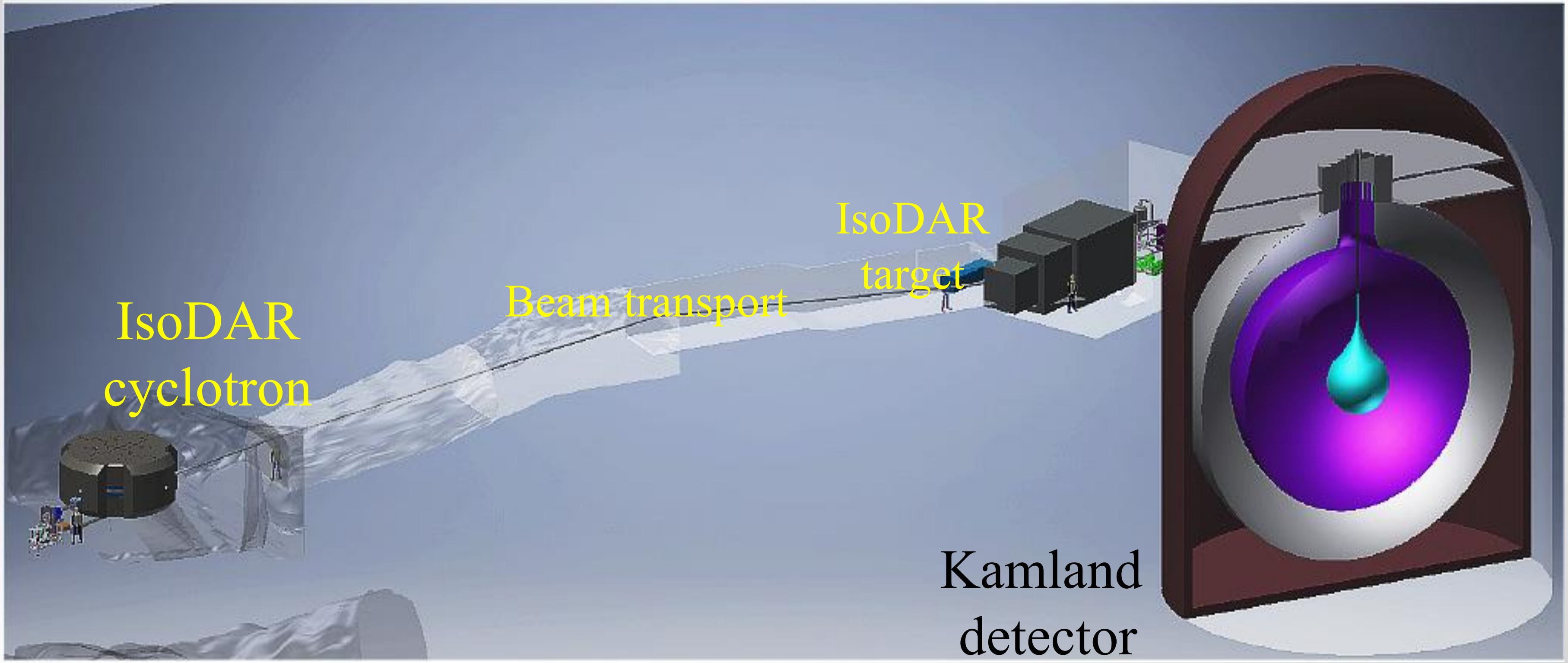
- Beam on Be target:
  - 10 mA of 60 MeV protons
- Neutron production
  - ~ 1 neutron/10 protons
  - => ~ 6 x 10^{15} neutrons/second
- Neutrino target: ^{7}Li + Be mixture
  - Size: 1 m diameter x 2 m long
  - Isotopic purity: 99.99% ^{7}Li\
  - Produces isotope of interest: ^{8}Li
- Antineutrino yield: ~ 0.02 ν_e / proton
  - =>1.2 x 10^{15} ν_e / second





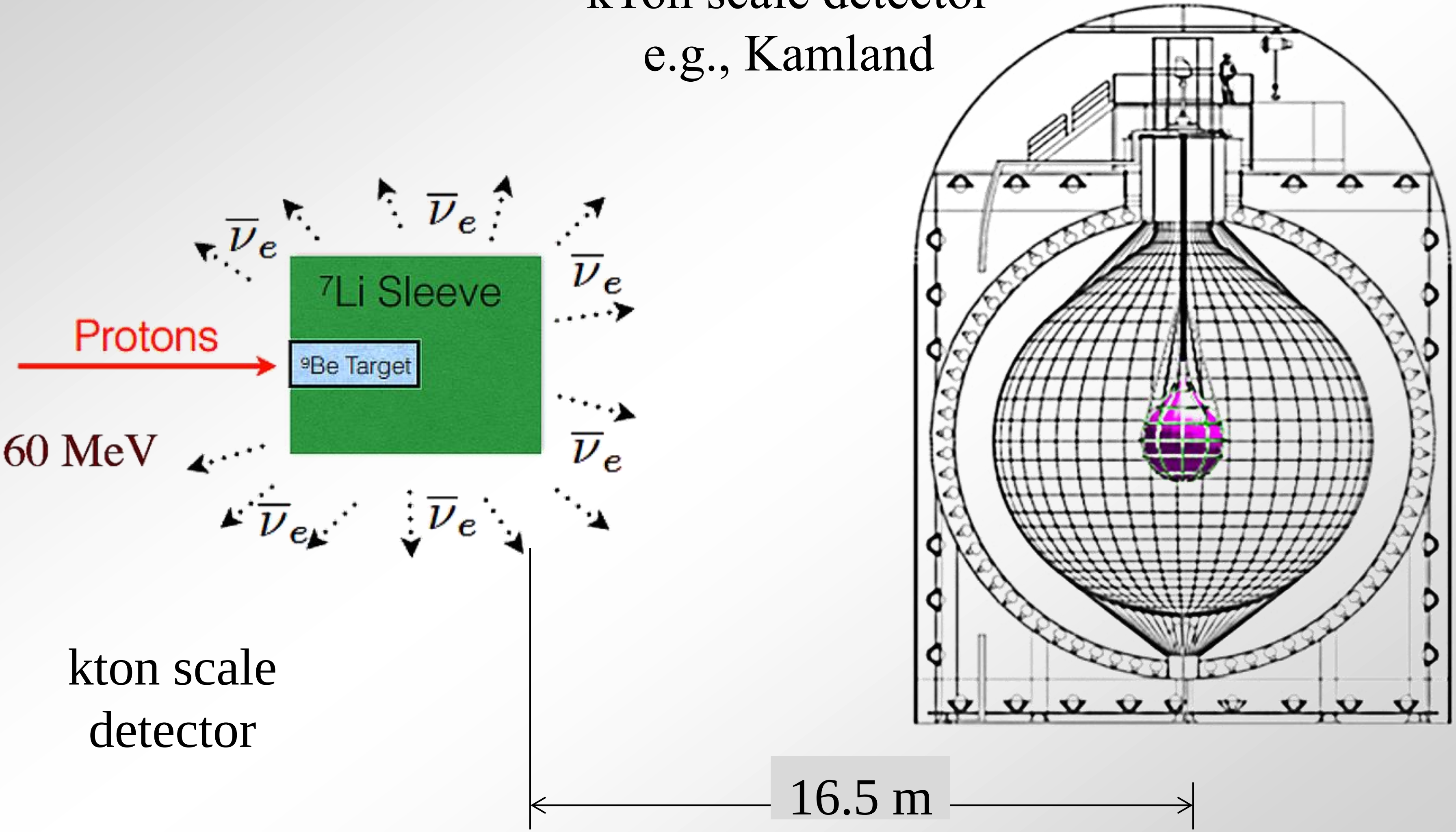
Complex optimization process

Conceptual layout in Kamioka mine



Schematic of IsoDAR target @ KamLAND

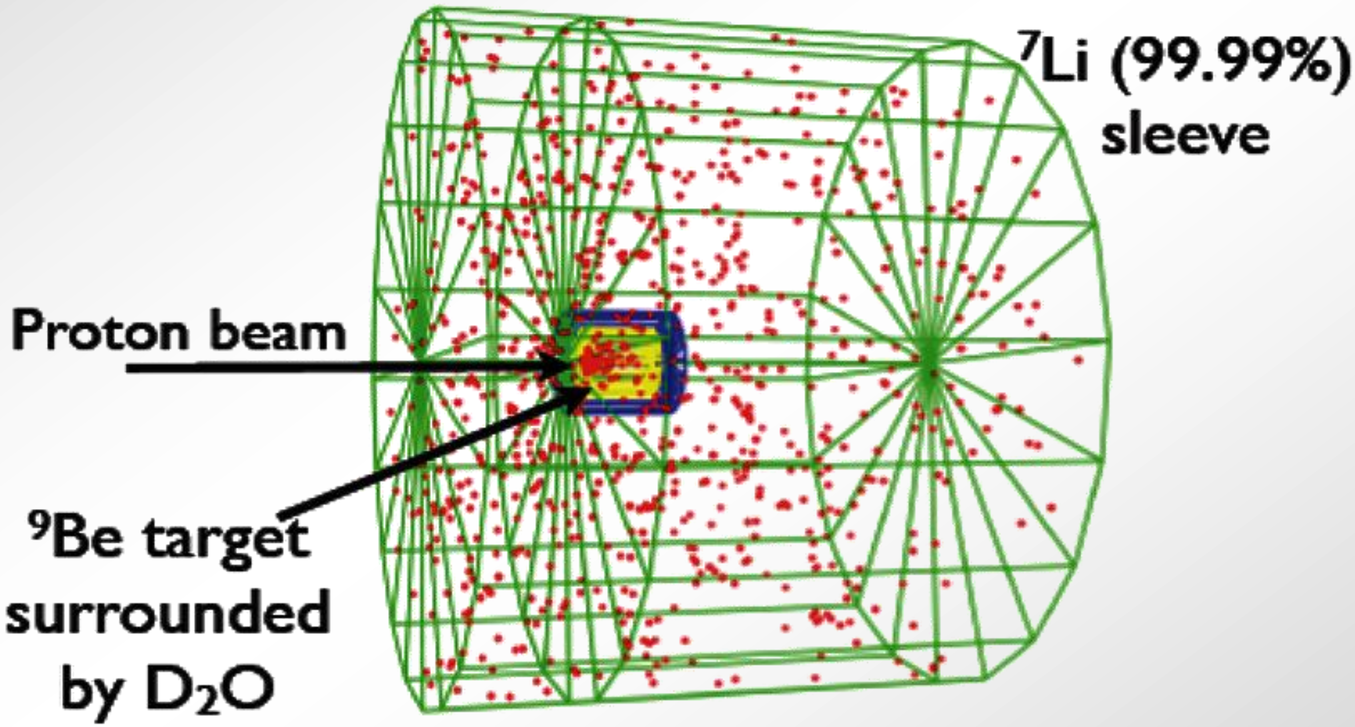
kTon scale detector
e.g., Kamland



kton scale
detector

What happens in the target…

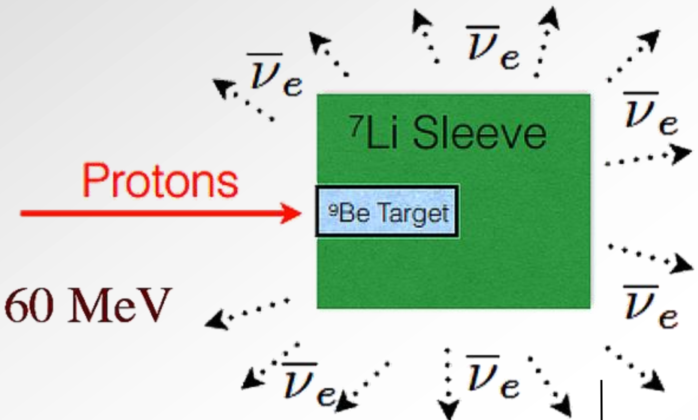
Proton beam → Be → n → captures on ^{7}Li → ^{8}Li → $\bar{\nu}_e$

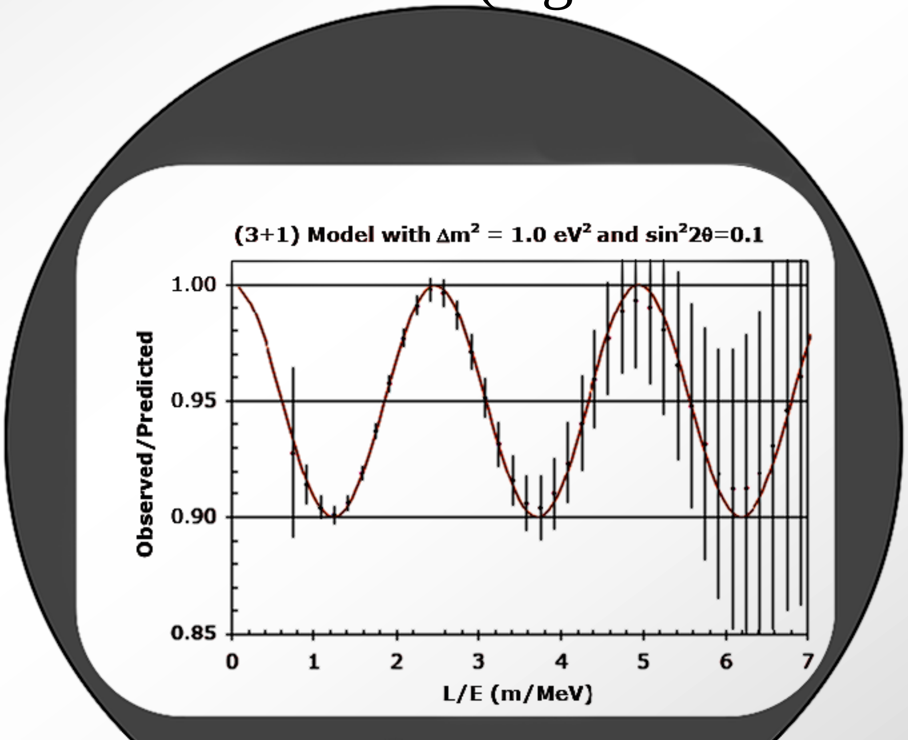


Optimizations done with GEANT4 & MARS

What we hope / expect to see with IsoDAR:
Multiple oscillations with the detector

kTon scale detector (e.g. KamLAND)



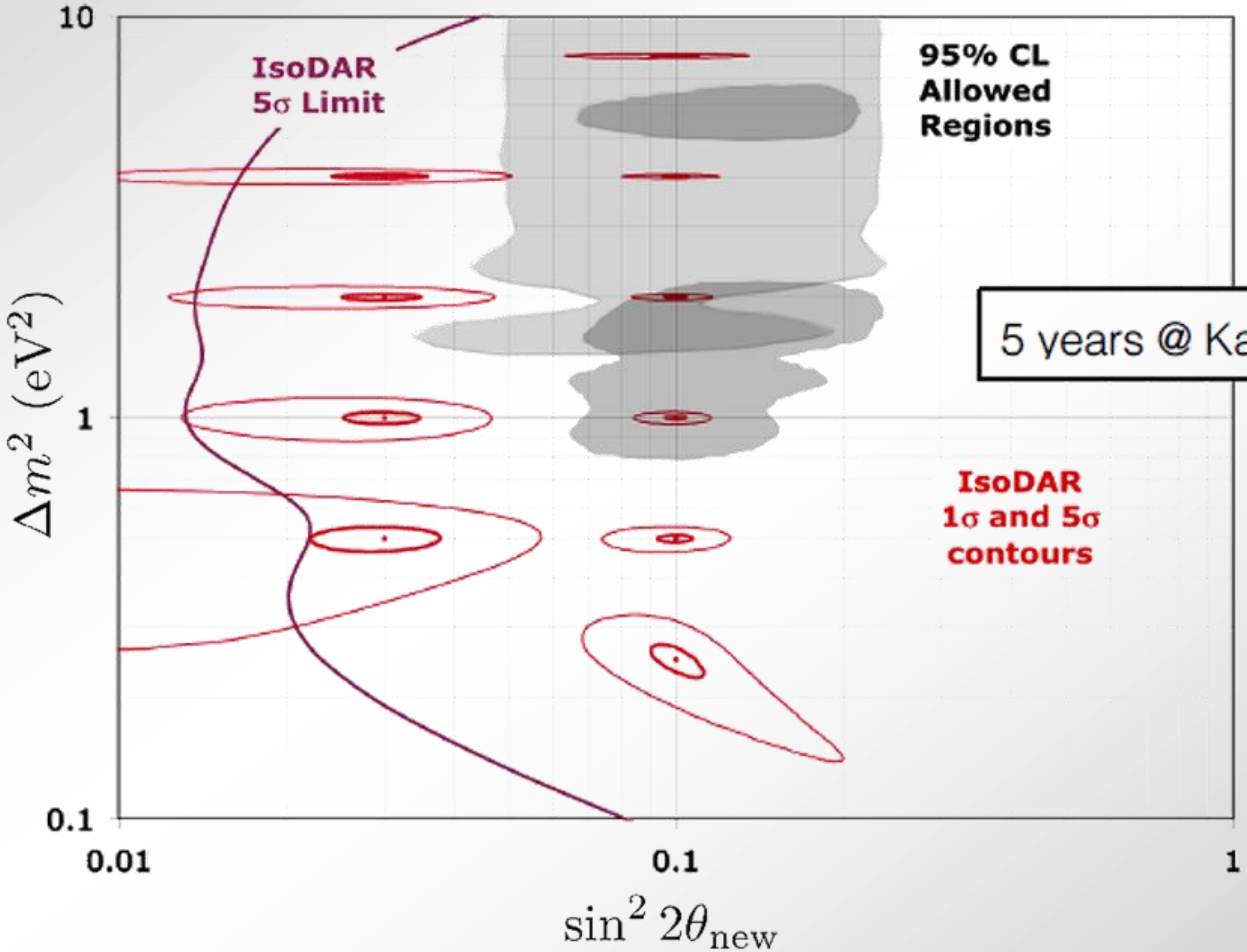


$$P_{osc.} = |\langle \nu_s | \nu_\mu(t) \rangle|^2 = \sin^2 2\theta \cdot \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

16.5 m

We must have the source close to a large detector

If we see a signal:
(assumes ~ 1 moles of anti-neutrinos)



5 years @ KamLAND

The challenge for the accelerator builder:
Produce ~10 moles of protons in a few years

Some simple arithmetic:

- 10 mA_p for 5 years at 80% availability = 11 moles of protons
- Inelastic neutron interactions inside LiBe sleeve => 0.06 neutrons / proton

  Only ~ 26% of interactions produce ^{8}Li

  => 1.3 x 10^{23} $\bar{\nu}_e$ in 5 years from the IsoDAR target
- Solid angle subtended by Kamland fiducial volume = 0.077

  $\Rightarrow$ 1.29 x 10^{21} $\bar{\nu}_e$ into the Kamland fiducial volume

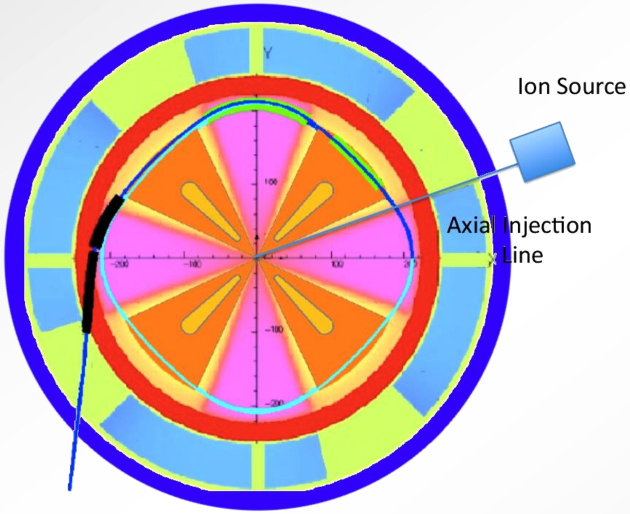
  @ 92% reconstruction efficiency => 8.2 x 10^5 IBD events
- Applying the 3 MeV energy threshold cut

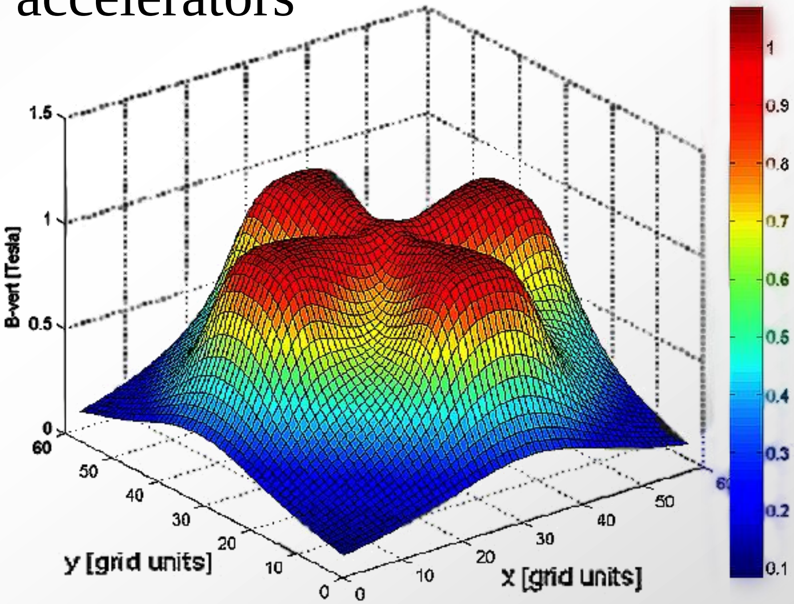
  => 7200 $\bar{\nu}_e$ events for physics analysis

But 10 mA is ~12x more than provided by commercial cyclotrons & 4x more that the PSI separated sector injector

Requirements on the IsoDAR cyclotron

- Be sufficiently compact to fit in the Kamioka mine shafts
  - Cannot be a separated sector design such as the PSI injector
- Provide 600 kW of protons to neutrino production target
- Be lower cost than alternative accelerators





Compact, Axially Varying Field cyclotrons are the most promising option

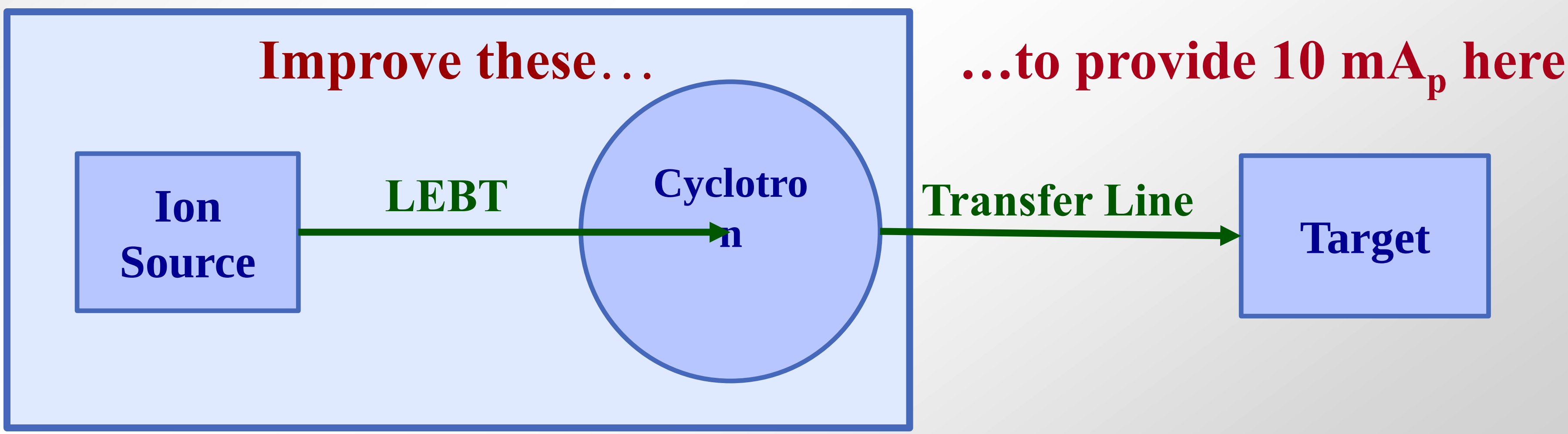
How can we improve the compact cyclotron design?
Control space charge at every stage

- Ion source
- Low Energy Beam Transport (LEBT)
- Cyclotron
  - Injection
  - Acceleration
  - Extraction

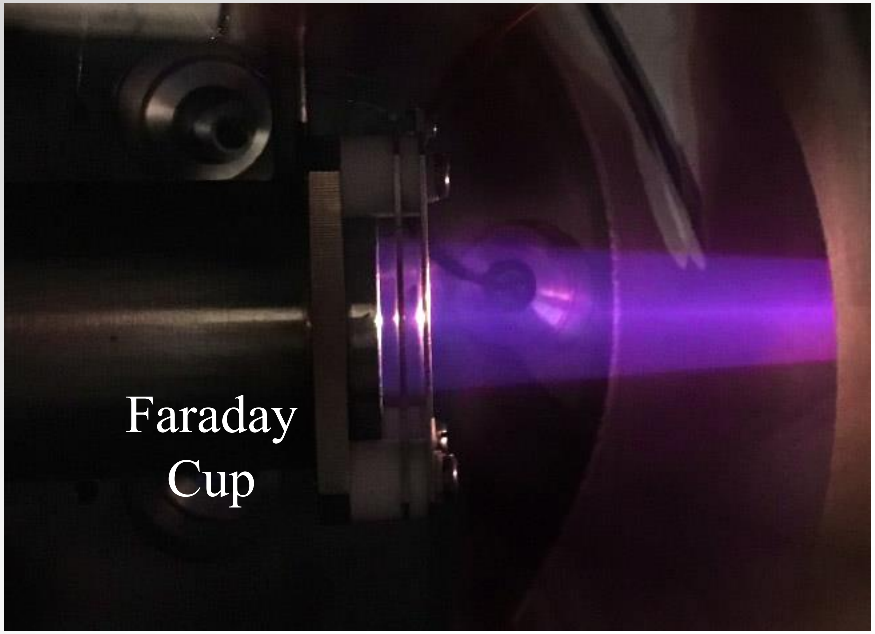
Generalized Perveance quantifies space charge forces:

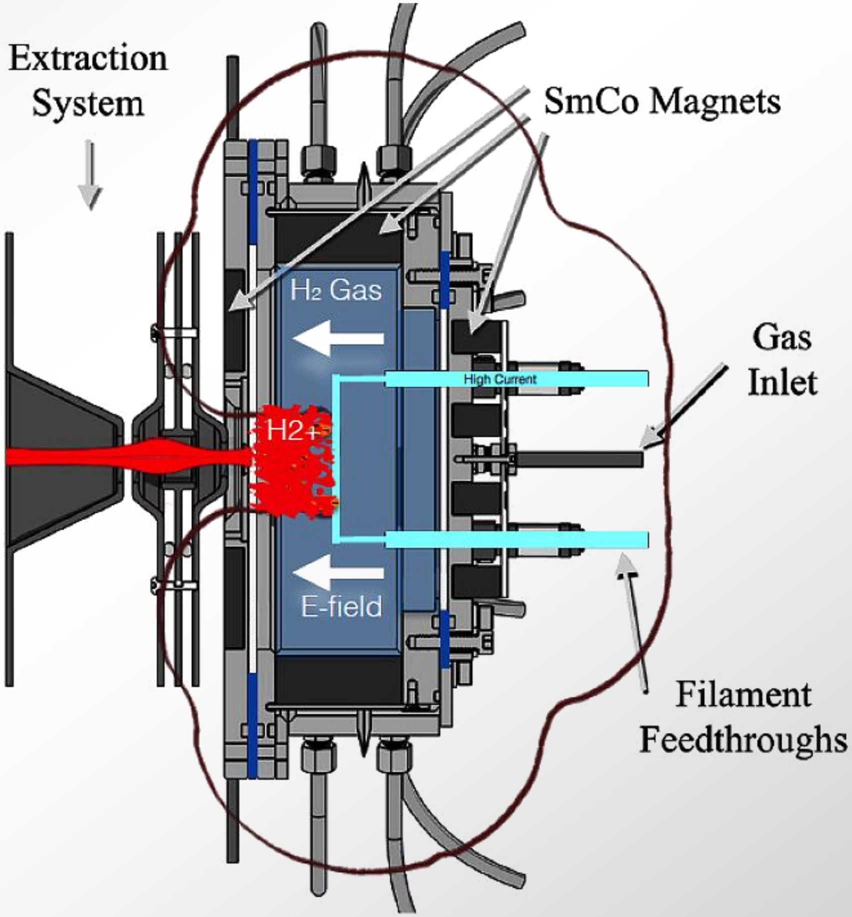
$$K = \frac{q\mathrm{I} \cdot (1 - \gamma^2 \mathrm{f_e})}{2\pi\epsilon_0 m_0 c^3 \gamma^3 \beta^3}$$

To increase I change m & E to keep K as low as possible



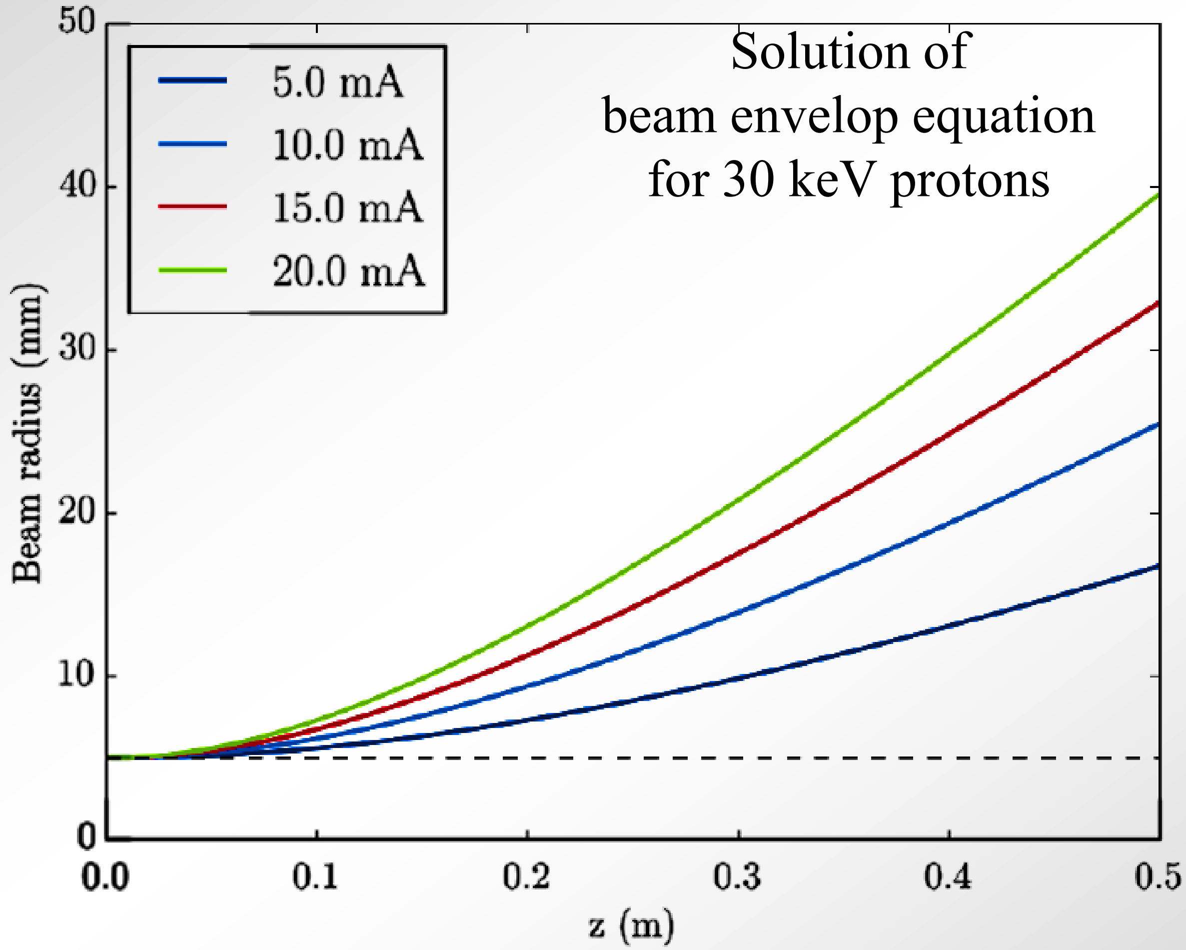
Building block 1: MIST-1 H_2^+ source





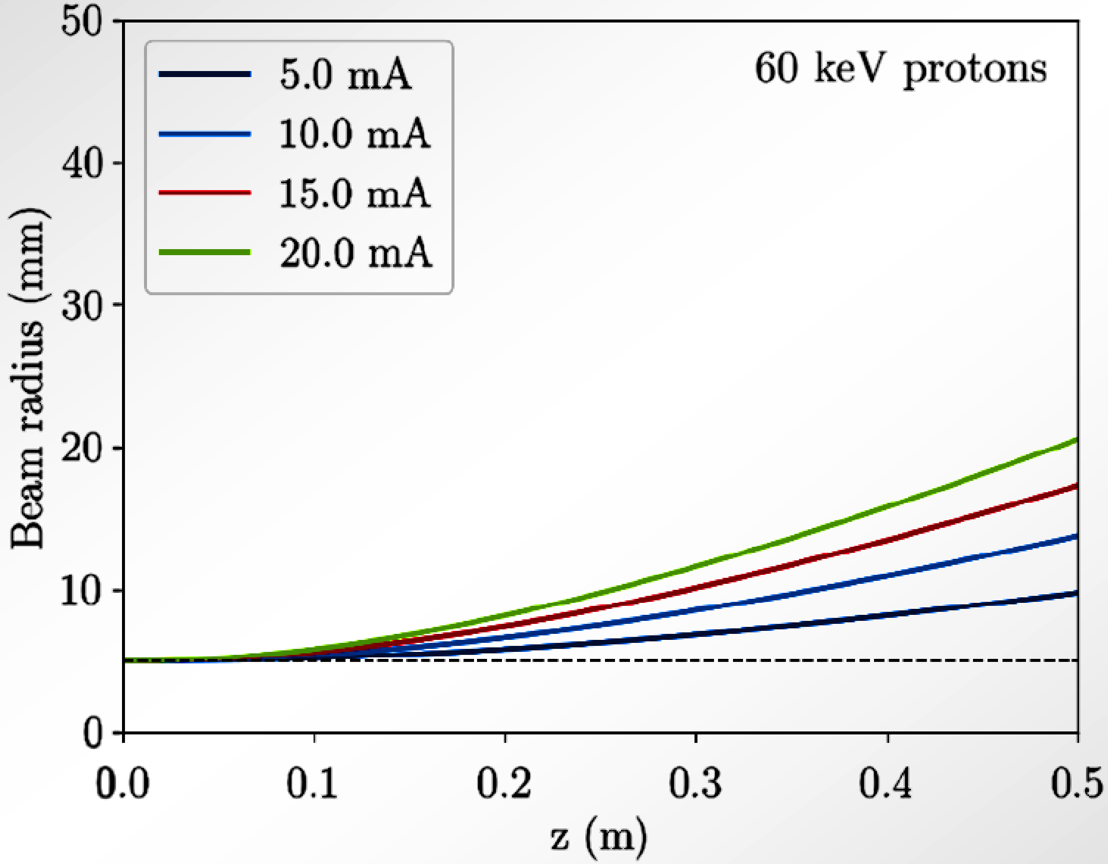
- Filament-Driven Multicusp Ion Source
- Based on: Ehlers and Leung: http://aip.scitation.org/doi/10.1063/1.1137452
- Operating at MIT (~35 mA/cm^2)

Space-charge makes injection difficult
in the LEBT (& in the spiral inflector)



Trying controlling expansion by increasing beam energy

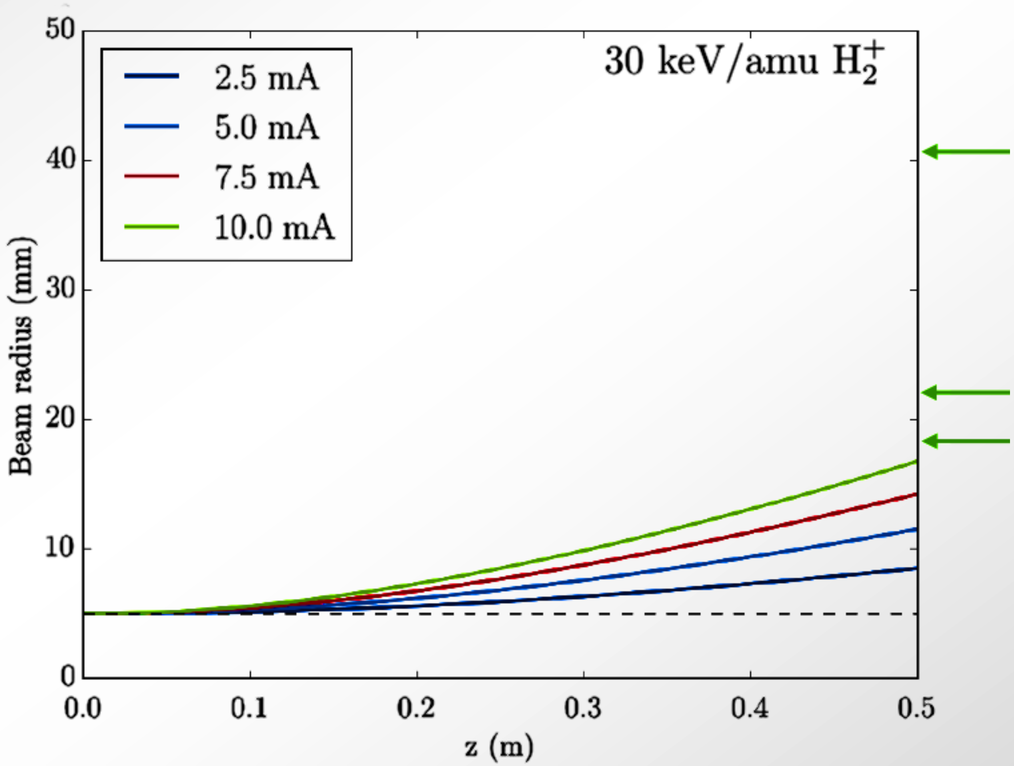
That helped



Next, try changing to a heavier ion

Innovation: Inject H_2^+

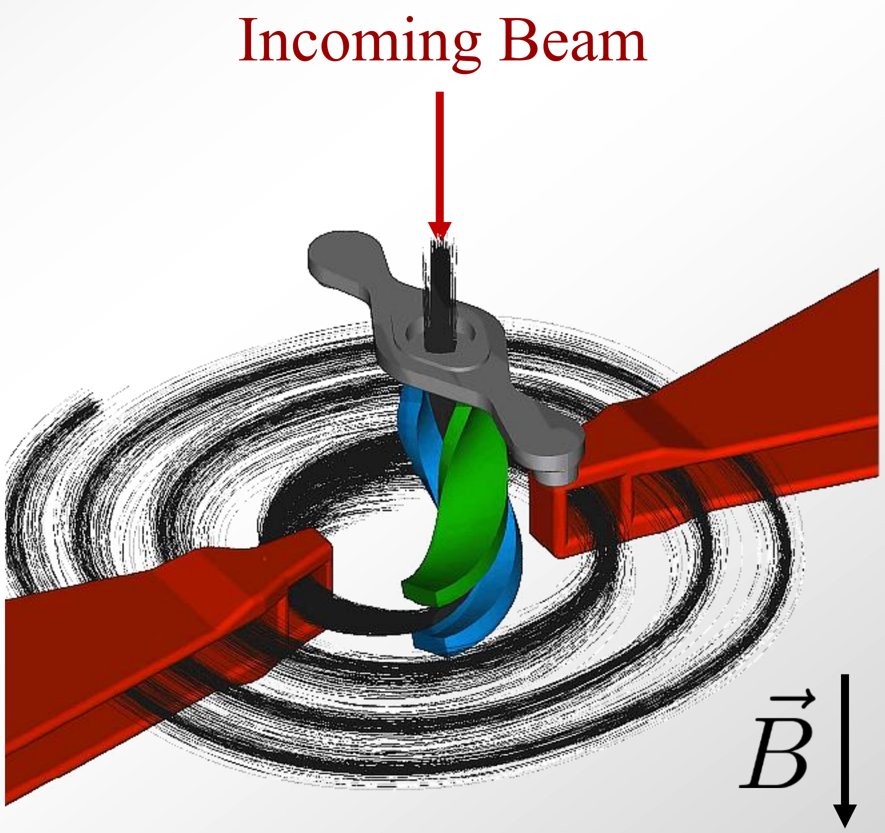
- Injects 2 protons for the charge of 1
- More difficult ion source but easier LEBT
  - Benchmark study with LLNL/LLNL WARP PIC code



Delivering beam to the cyclotron:
The spiral inflector

Key features:

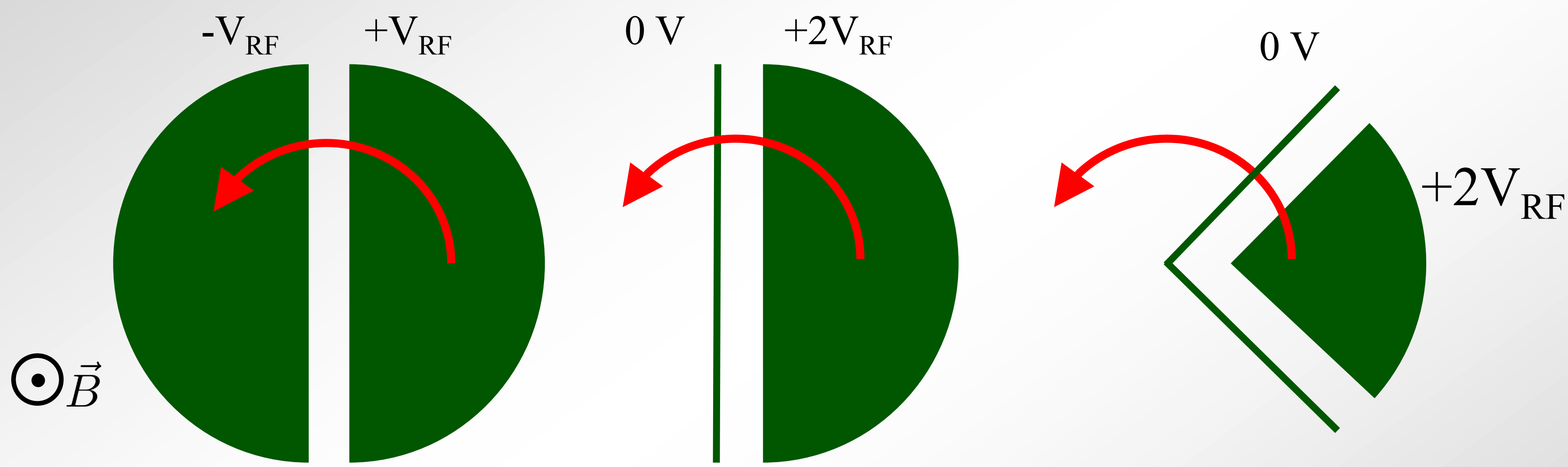
- Cyclotron Main B-Field
  - Uniform dipole at r = 0
- Electrostatic Field from Spiral Electrodes
  - Voltages must be manageable
  - Spacing must accept entire beam
- Combination guides particles into the horizontal plane
- Required upgrades to WARP & OPAL for precise simulation



Winklehner et al., *Realistic simulations of a cyclotron spiral inflector within a particle-in-cell framework*, **Phys. Rev. AB** *(Dec. 2017)*

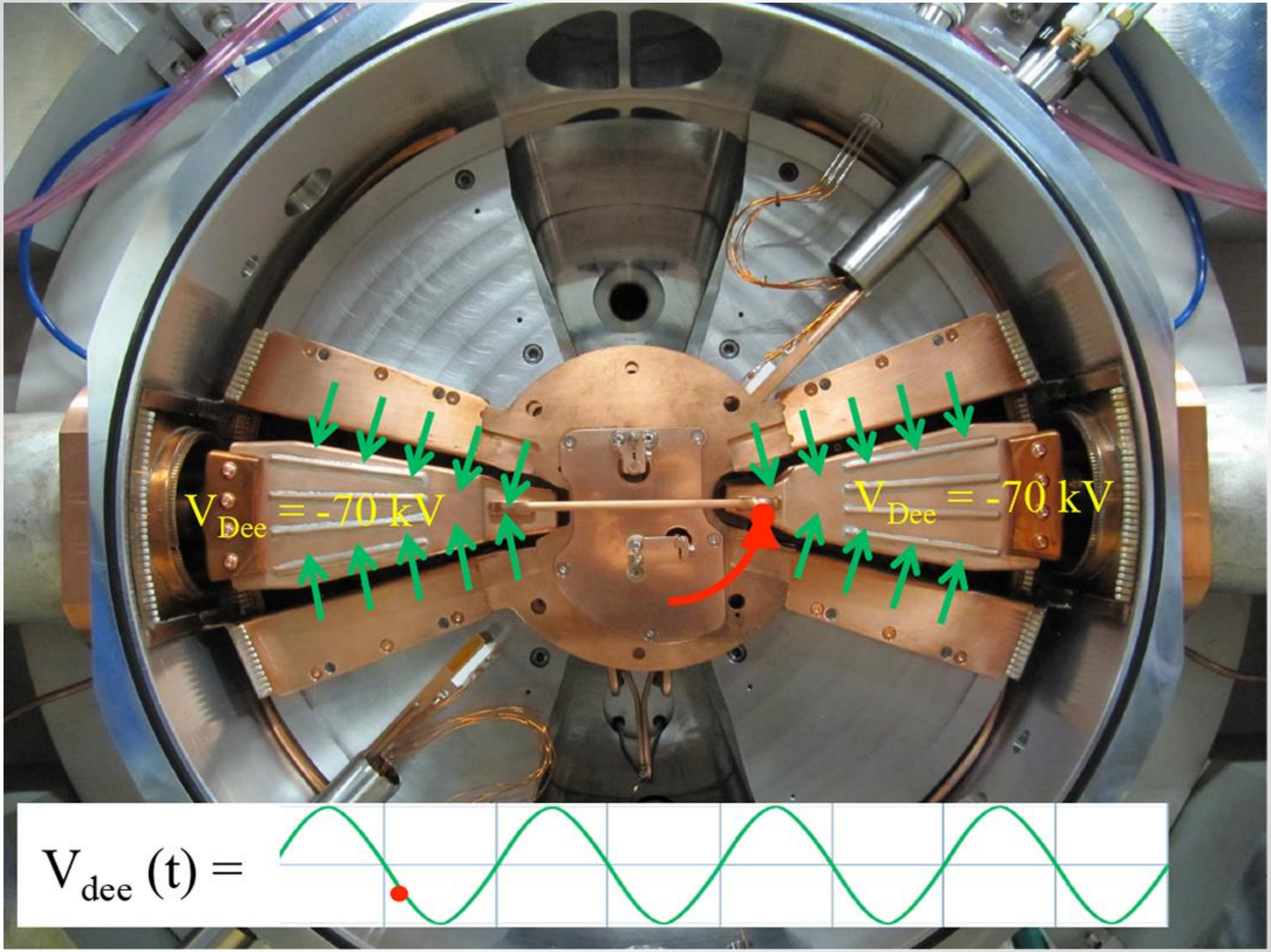
The Cyclotron: Dee doesn't have to be "D"-shaped
Higher energy gain per turn with harmonics

$$\omega = \frac{qB}{m} \qquad \omega = \frac{qB}{m} \qquad \omega = 2 \cdot \frac{qB}{m}$$

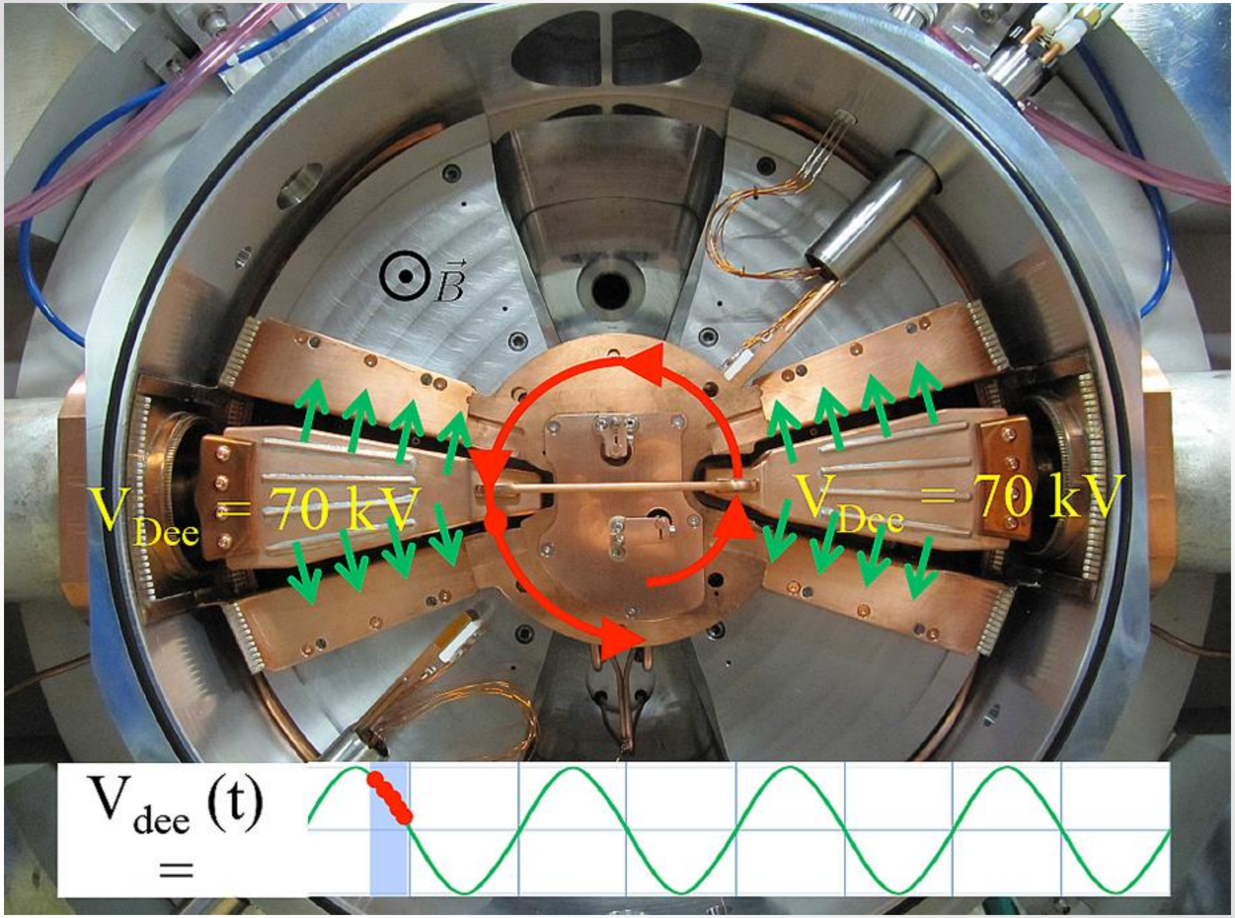


- In general: $\omega = h \cdot \frac{qB}{m}$, the RF frequency can be any integer multiple (harmonic) of particle frequency
- Dees can be made into double gap cavities with angle = 180/h

Acceleration (harmonic 6)

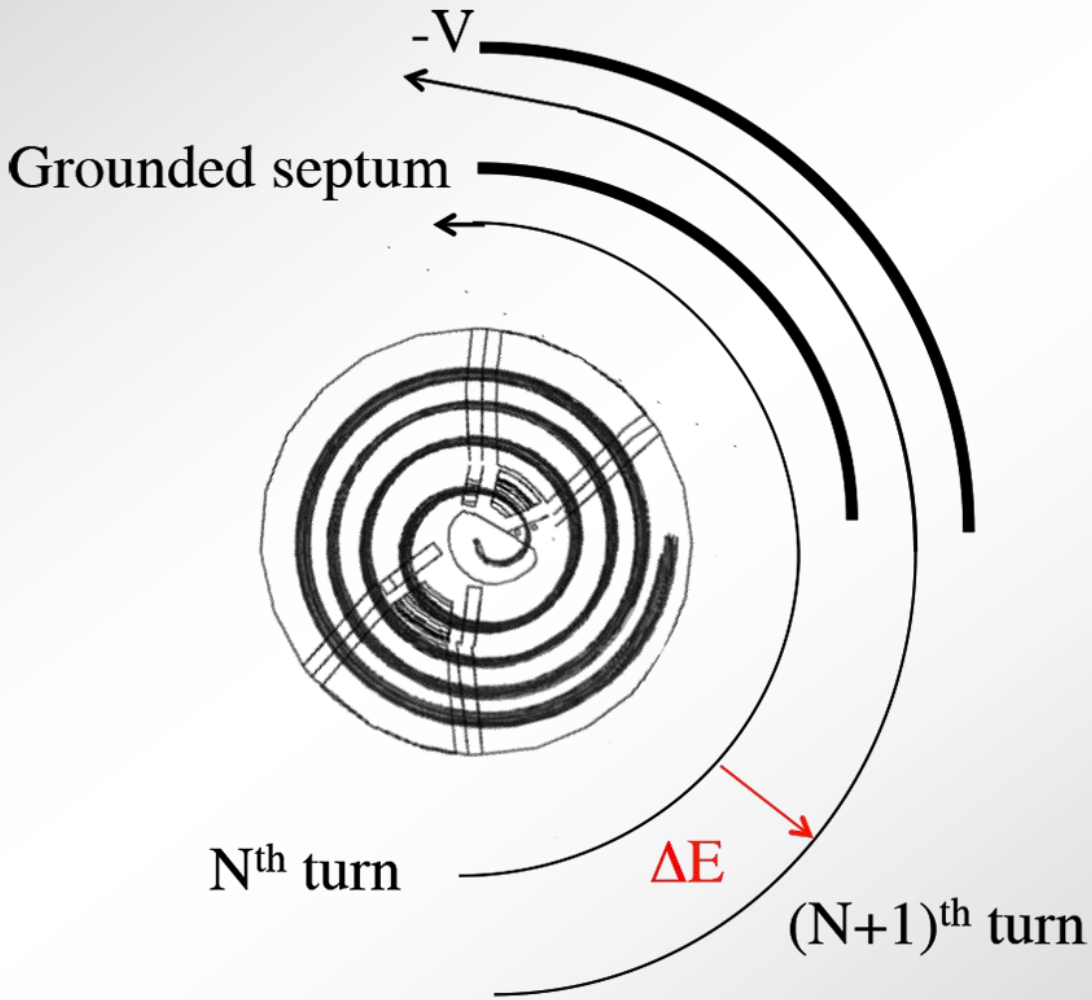


Only a narrow range of RF phase can be populated



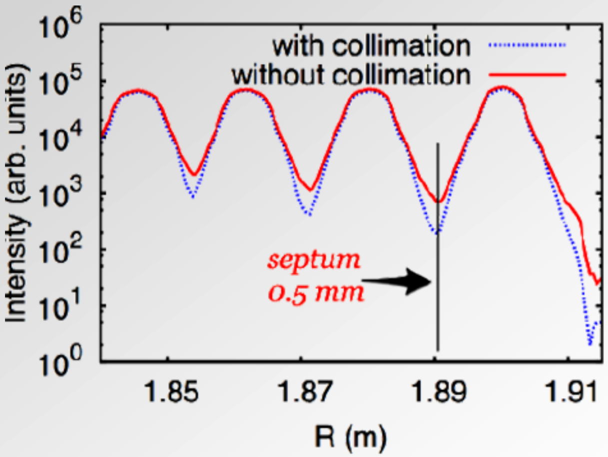
The rest of the injected beam will be lost in the cyclotron

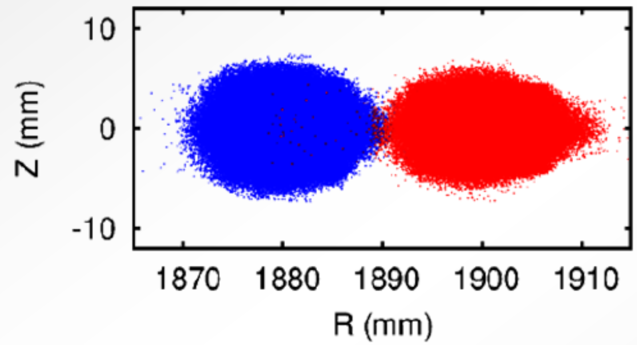
Jumping ahead:
Extraction from a compact cyclotron



Efficient extraction requires good turn separation

Beam loss in extraction => machine activation

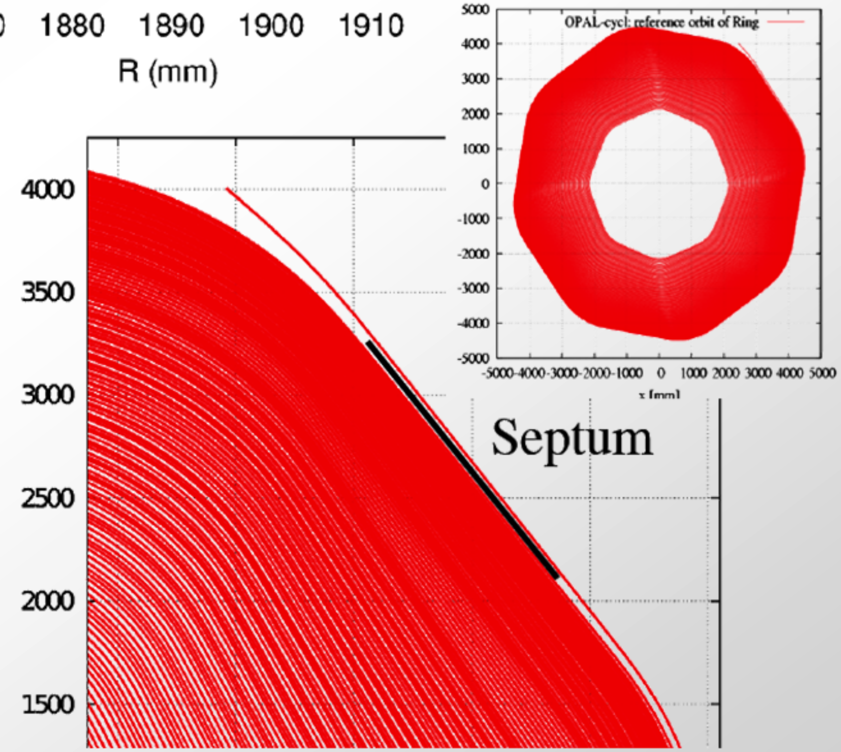




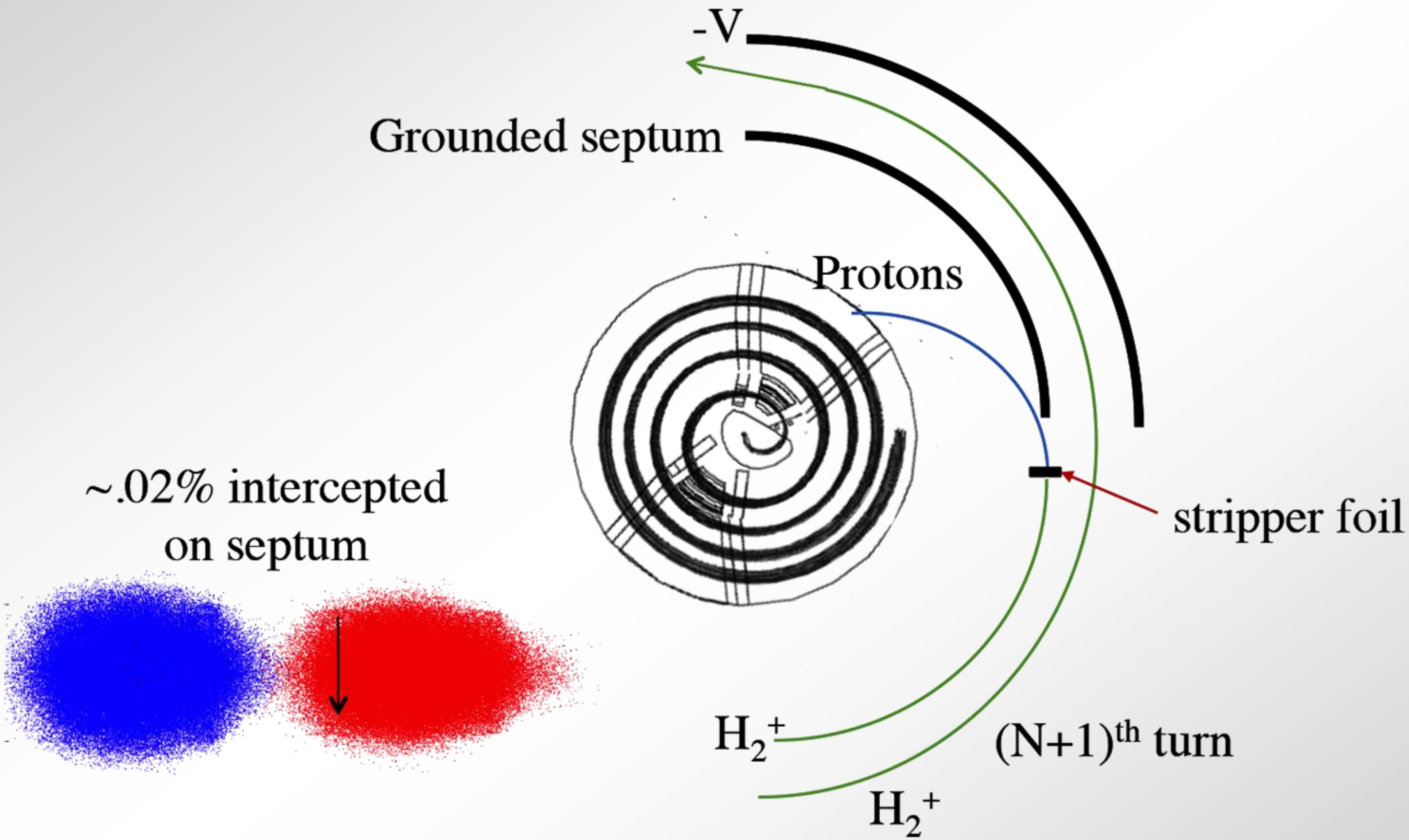
- Septum can only tolerate 200 W of beam losses

  => Maximize turn separation

- *Take advantage of H_2^+ beam => Protect septum with a foil!*



Cartoon of stripper foil protecting septum



But won't space charge cause bunches in adjacent turns to merge

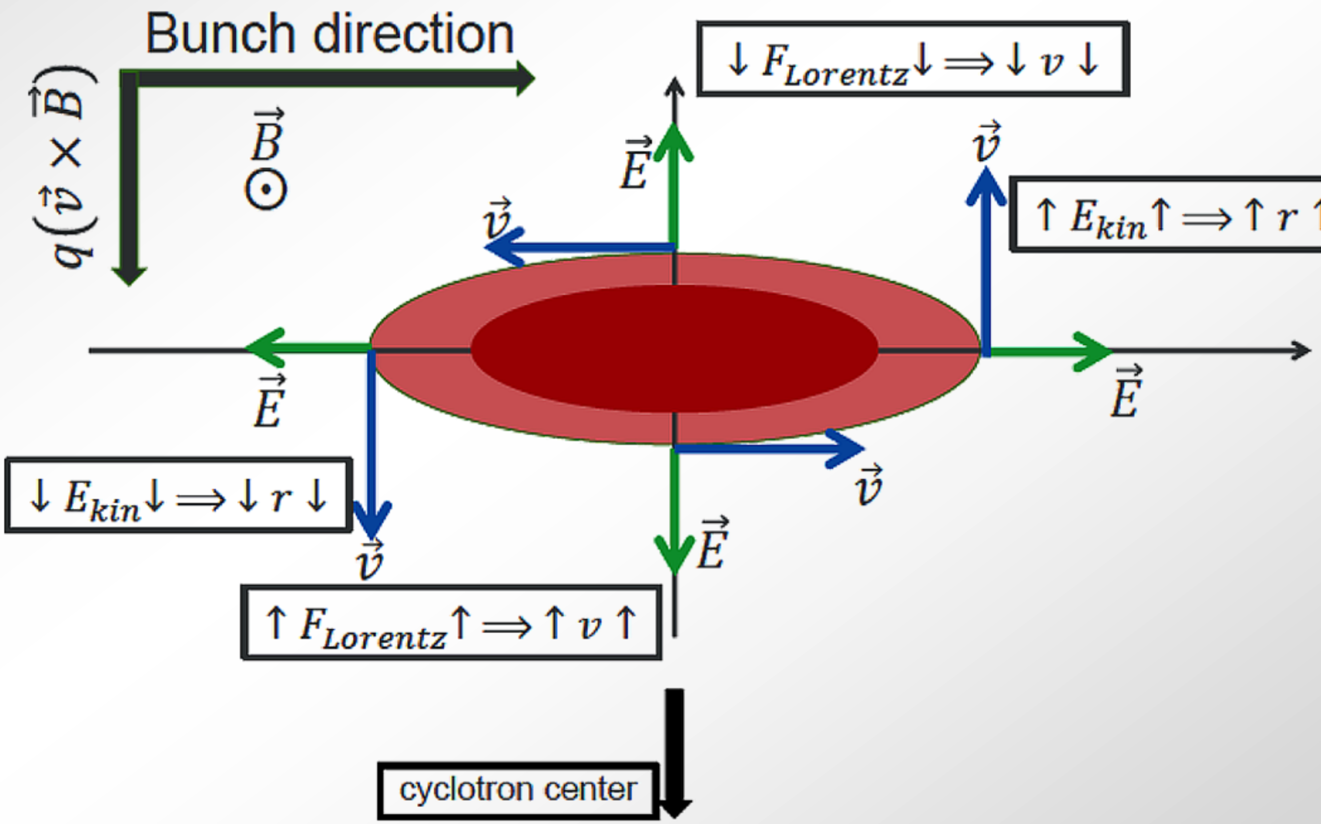
=> Limit to current in the cyclotron

We must maximize turn separation
& control beam size

- Step 1: Maximize Energy Gain/turn

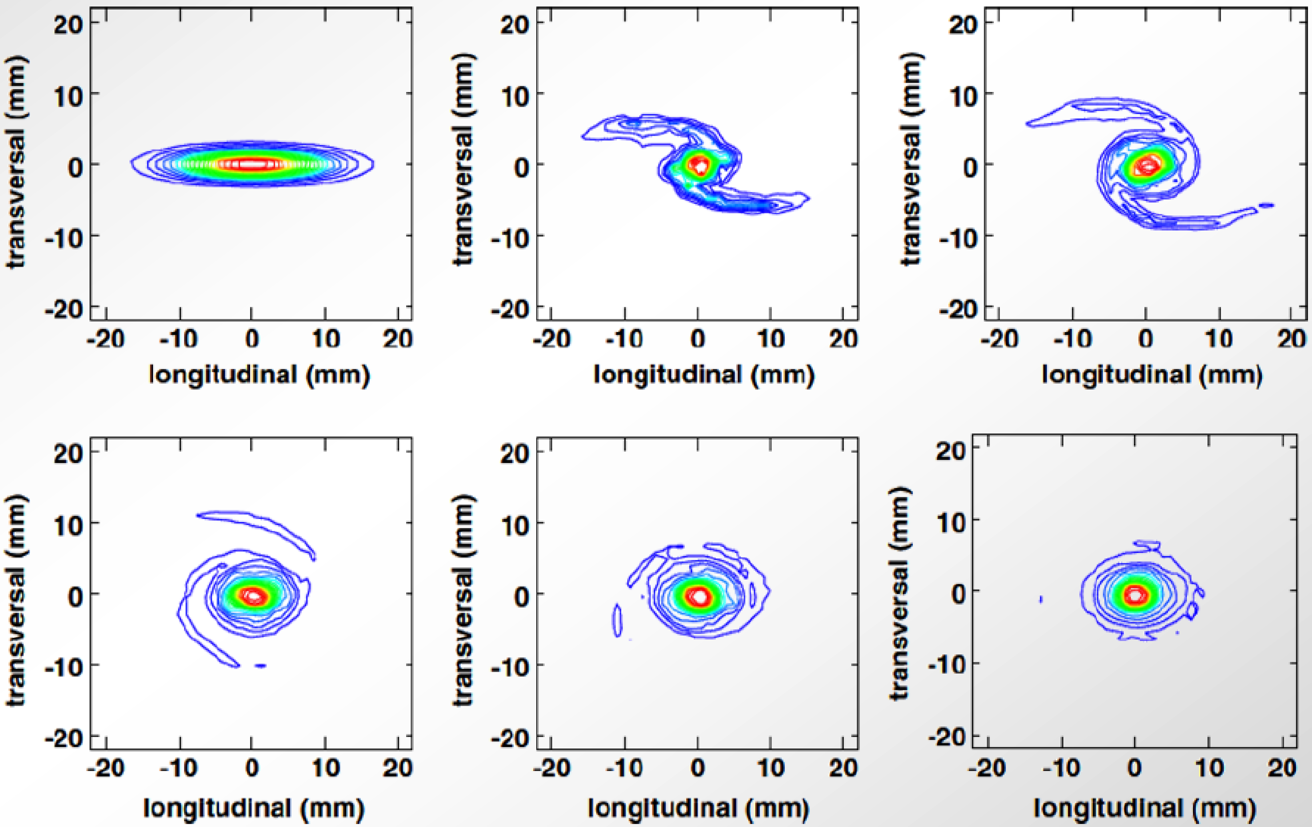
  250 kV per V_{dee} => 4 Dees (8 gaps) → 1 MeV/turn

- Step 2: Correct beam dynamics: Space charge =>Vortex Motion



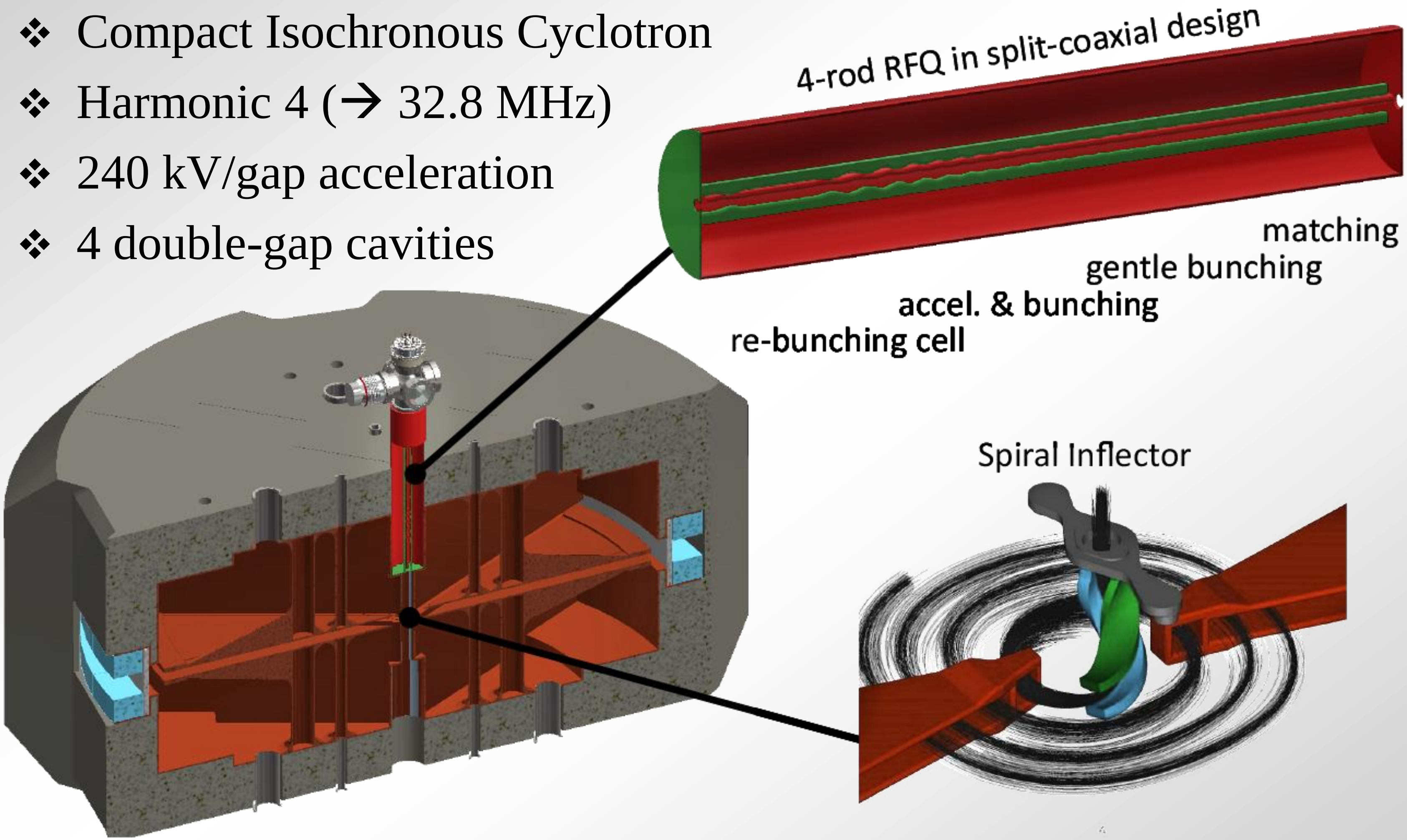
Simulation in upgrade to OPAL PIC code

- Observed in the PSI injector
  - => Simplistic estimates of current limits are not correct



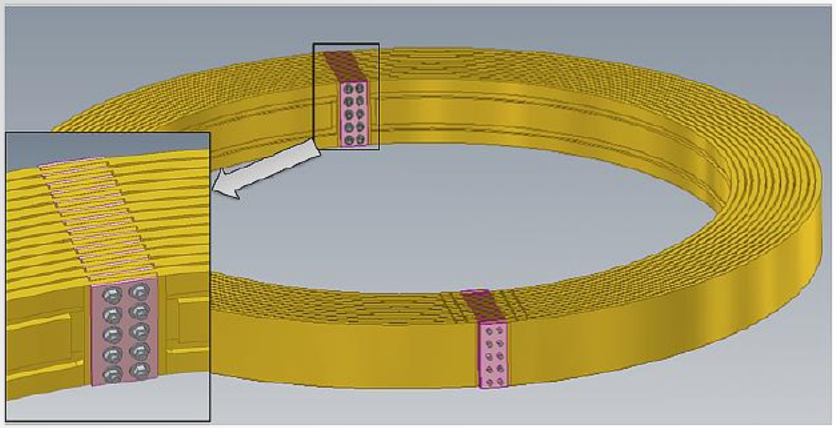
Final innovation in cyclotron design
Pre-bunch beam in LEBT using a RFQ

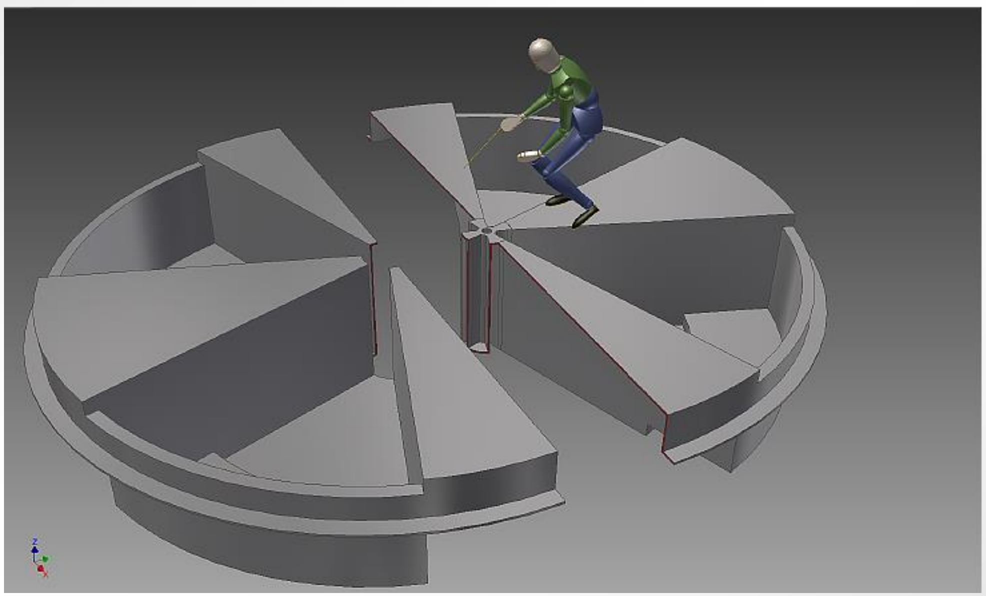
- Compact Isochronous Cyclotron
- Harmonic 4 (→ 32.8 MHz)
- 240 kV/gap acceleration
- 4 double-gap cavities

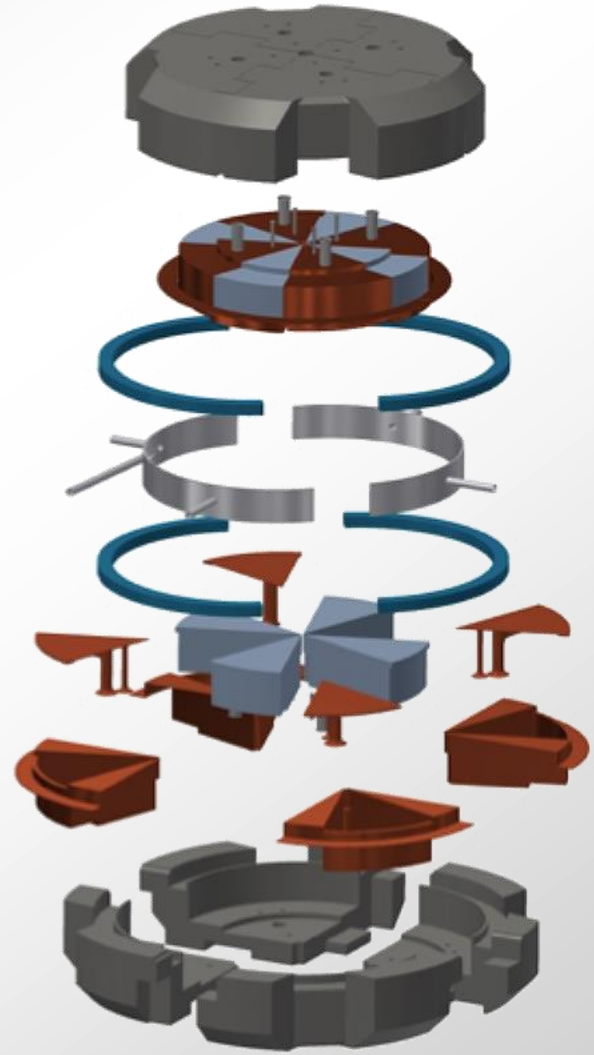


RFQ is in design and construction under an NSF grant

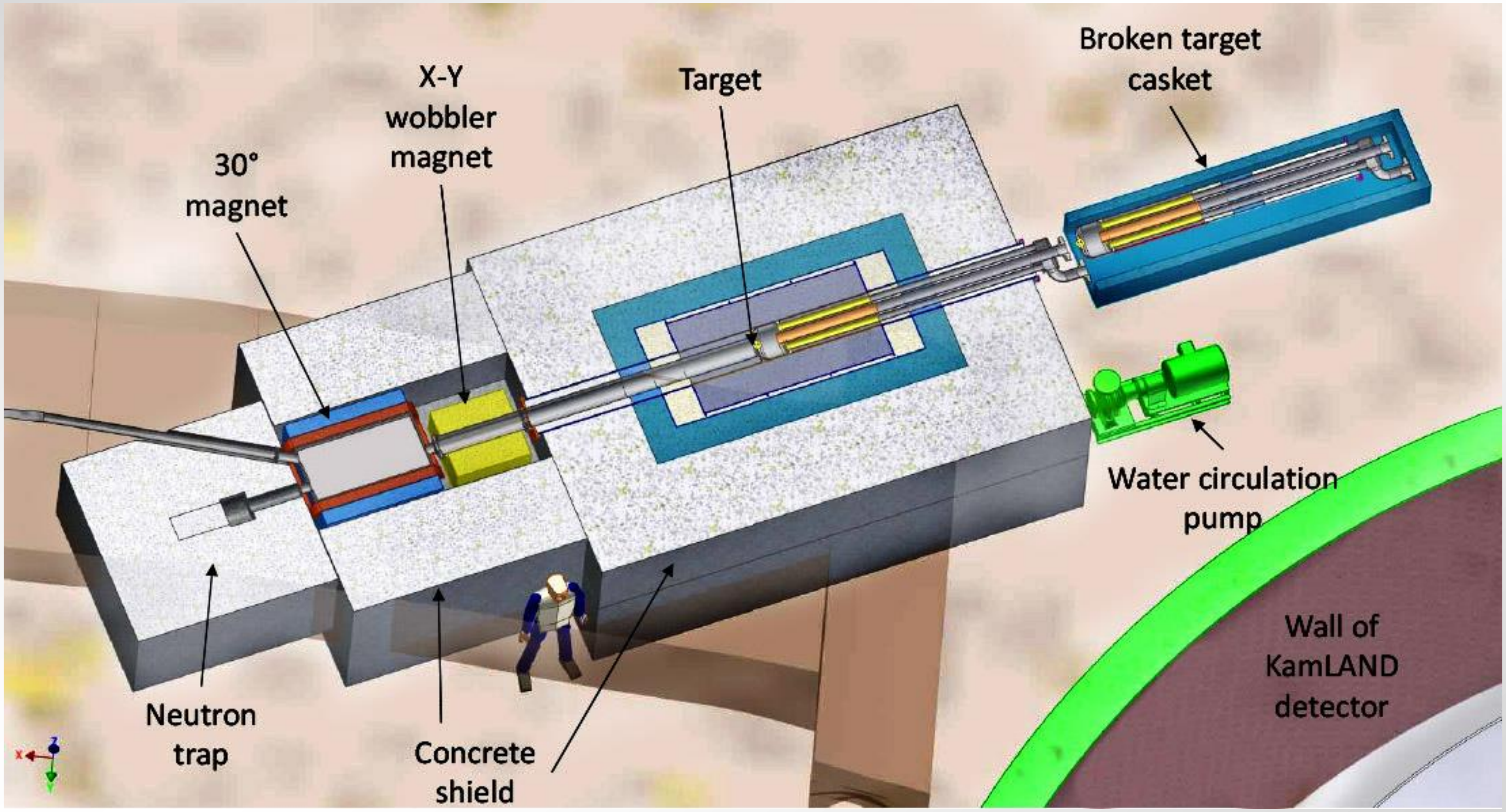
Assembling the cyclotron in a mine





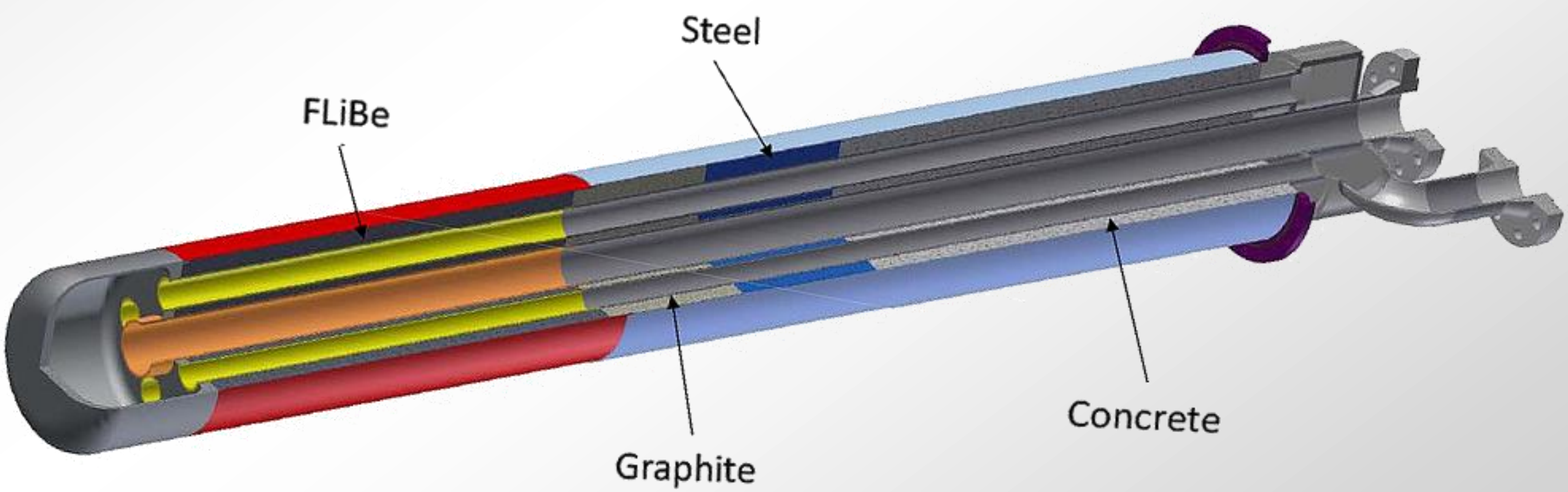


Presentation of Beam to Target

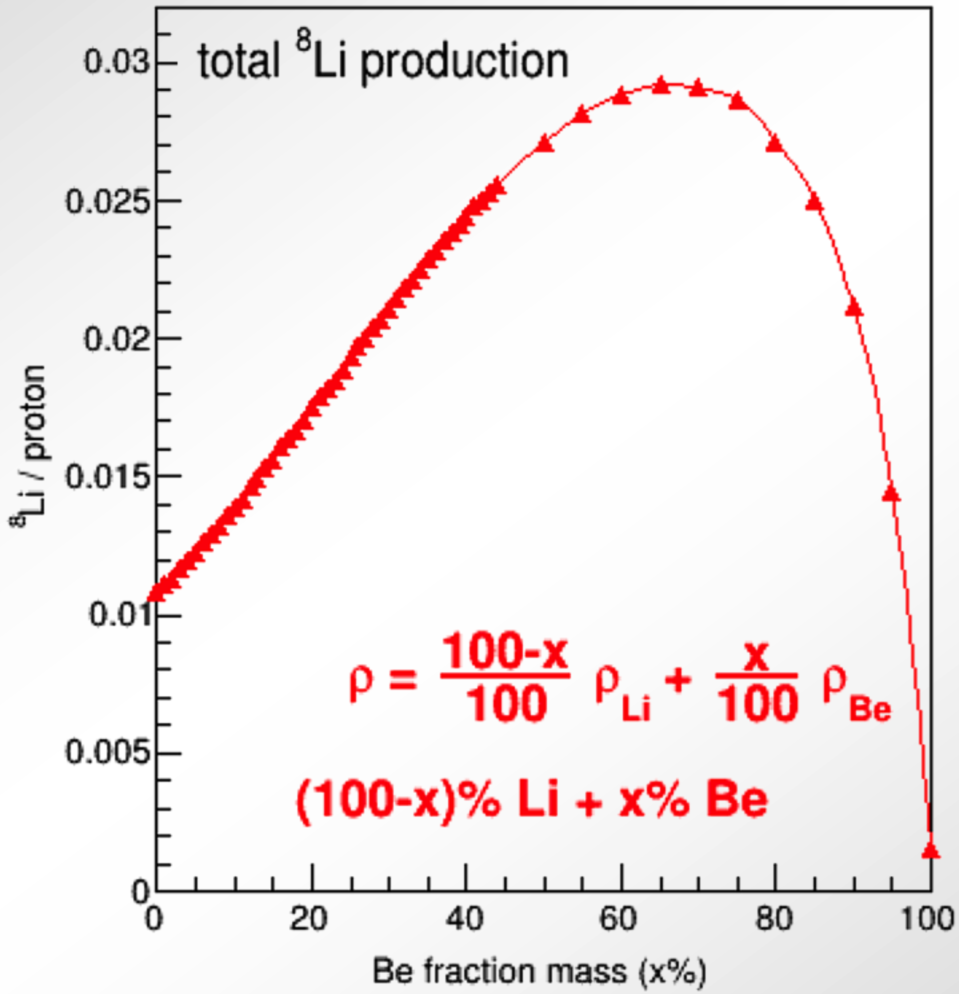


The “business” core of the target

- Must withstand high average heat & radiation loads
- Must be replaceable remotely (probably annually)
- Contains material to produce neutrons
- Contains material to breed ^{8}Li
  - Sleeve: 1000 kg of Be/^{7}Li mixture (75%/25%) with 99.99% pure ^{7}Li
  - Optimization of geometry & materials done with GEANT 4



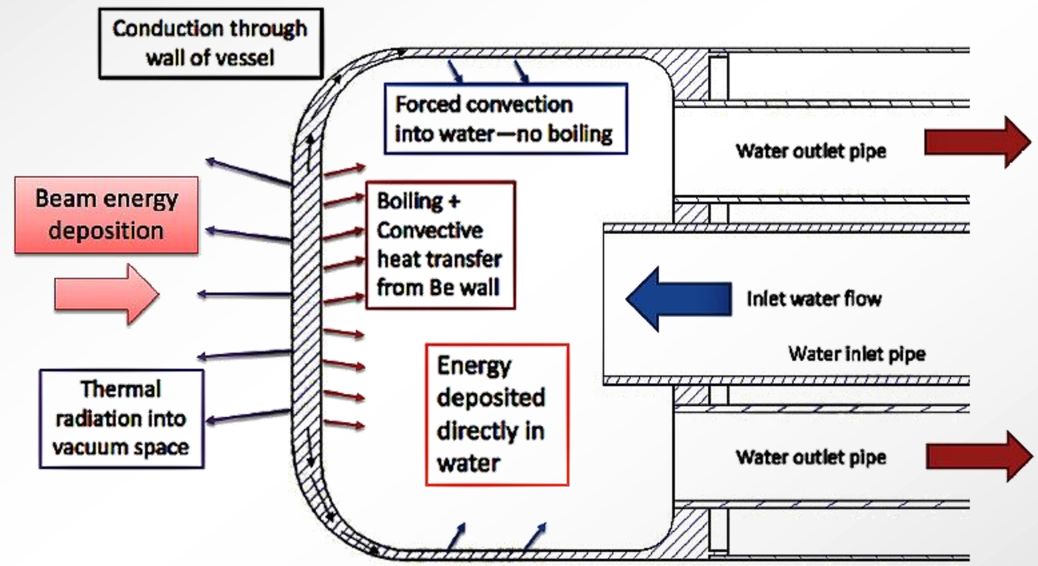
Example of target optimization with GEANT4: Yield of ^{8}Li for ^{7}Li + Be Mixtures



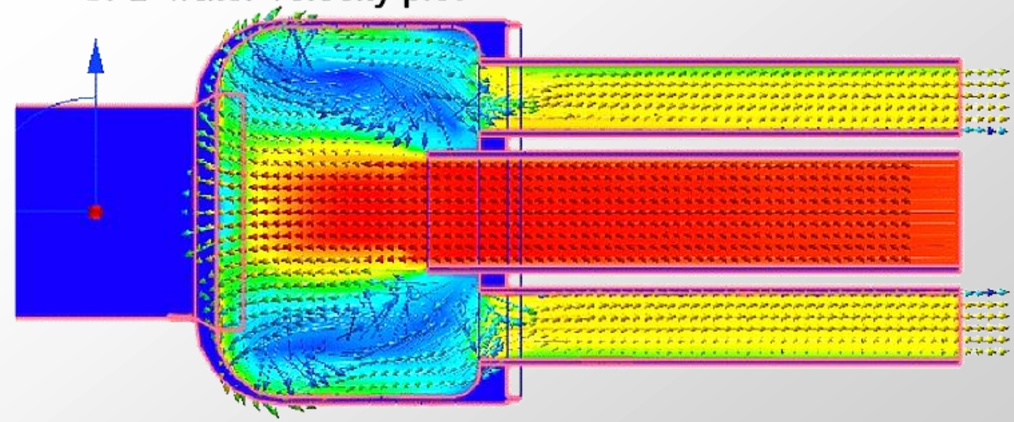
^{7}Li 99.995% enriched

Handling beam power is challenging
Thermal analysis of cooling Be target

- Computational fluid dynamic (CFD) simulations
  - Energy deposition of 300 kW in the Be, 300 kW in the water
  - Model convection, boiling & thermal radiation
  - Must keep water temp below 150-300° C
  - Input to mechanical stress calculations due to beam load & water pressure

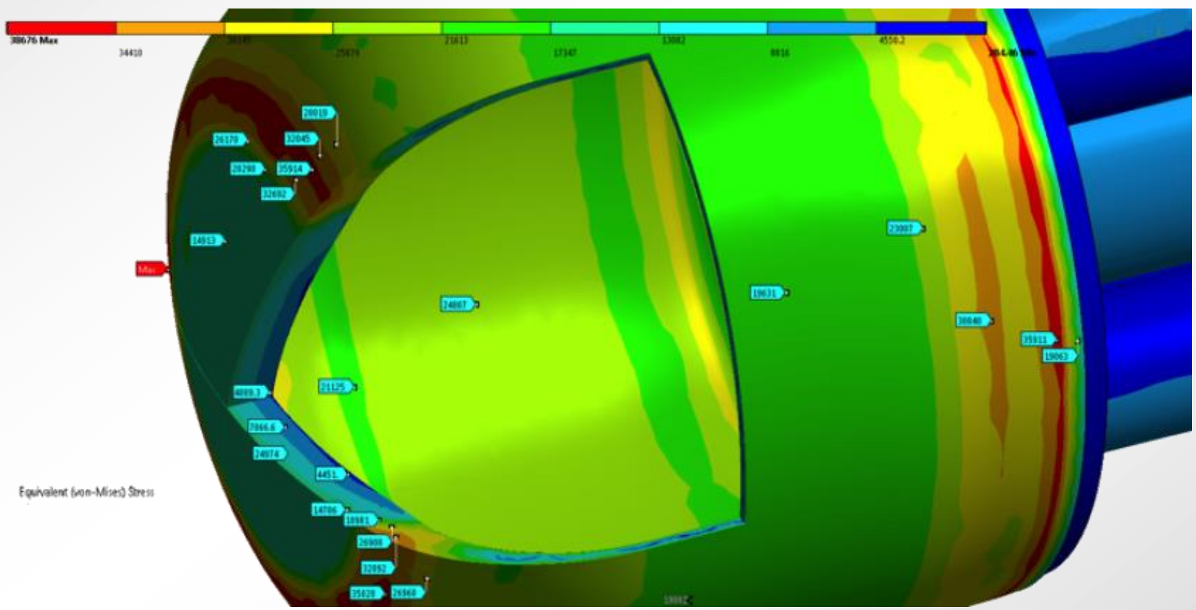


CFD water velocity plot



Target engineering is a work in progress

- How do we limiting stress in Be end-cap
  - What is the optimum shape?
  - What is the optimum beam power profile?
  - Should we use a wobbler to “paint” the target



Von Mises stress
at 204° C

- How do we fabricate a very homogeneous Be/7Li sleeve

Other technical issues / questions

- Shield the KamLAND experiment from high energy neutrons)
- Shield the cavern rock from activation
- Can the required enrichment of ^{7}Li be reduced?
- Is it possible to lessen beam power by moving the target from 16 m to 12 m from the KamLAND detector?
- What information does the mining company need to assign contractor and work crews to install equipment?
- What electrical power, cooling facilities, and support infrastructures are needed on-site?

IsoDAR summary and future

- We have a Cyclotron design concept
  - *Ion source* is suitable
  - *Spiral inflector* has been tested with beam
  - *RFQ* is in design stage & we are preparing call for tenders
    - Foresee testing with a 1 NeV cyclotron
- Engineering refinement of target design is funded by NSF
  - High power targets are challenging
- Technically driven schedule for KamLAND site preparation and deployment of IsoDAR: 3-4 years
  - Earliest experiment start with beam: 2022 - 2023
- Formal proposal in preparation for submission in Fall 2019
- Working with KamLAND to finalize the schedule

Thank you

Parameters for 16 meters to detector

Accelerator	60 MeV/amu of H_2^+
Current	10 mA of protons on target
Power	600 kW
Up-time	80%
Run period	5 years (4.5 years live time)
Target	^{9}Be surrounded by ^{7}Li (99.99%)
$\overline{\nu}$ source	^{8}Li β decay ($\langle E_\nu \rangle$=6.4 MeV)
$\overline{\nu}_e$/1000 protons	14.6
Total flux during run	1.29×10^{23} $\overline{\nu}_e$

Detector	KamLAND
Fiducial mass	897 tons
Target face to detector center	16 m
Reconstruction efficiency	92%
Vertex resolution	12 cm/$\sqrt{E\ (\mathrm{MeV})}$
Energy resolution	6.4%/$\sqrt{E\ (\mathrm{MeV})}$
Prompt energy threshold	3 MeV
IBD event total	8.2×10^5
$\overline{\nu}_e$-electron event total	7200