IsoDAR@YEMILAB and its next-generation proton cyclotron

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Huddersfield University

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Contents

Neutrinos - a history of surprises

We thought they were massless.
That turned out to be wrong

We assumed that any mixing would be small (like for quarks).
That turned out to be wrong.

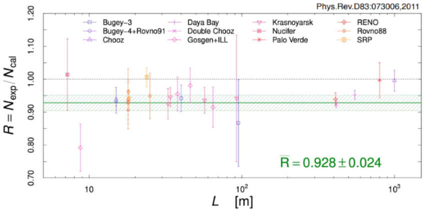
We still don't know whether they are Dirac particles
(like neutral electrons so 4 components:$\nu_L, \nu_R, \overline{\nu}_L, \overline{\nu}_R$)
or Majorana particles
(2 components: $\overline{\nu}_L \equiv \nu_R$)

What else?

Need to study neutrinos with an open mind.
And there are hints...

The Neutrino Anomalies

- LSND anomaly: Excess of $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations
- MiniBoone anomaly: Excess of $\nu_\mu \to \nu_e$ oscillations - at lowest energies
- The Gallium anomaly: Gallex and SAGE calibrations using ν_e sources from electron capture see only $87 \pm 5\%$ of expected rates
- The Reactor anomaly: too few $\overline{\nu}_e$ seen at short distances from reactors



Pointing towards

Further 'sterile' neutrino(s)? Or neutrino decay?? Or ???

Neutrino Oscillations

Simple two-flavour version, ν_e and ν_μ

Start with a ν_e. This is a mixture

$$|\nu_e >= \cos\theta|\nu_1 > + \sin\theta|\nu_2 >$$

Each component develops as $e^{-i(Et-px)/\hbar}|\nu_i >$

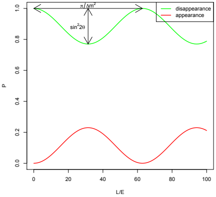
approximating $L \equiv x = ct, E = pc + \frac{m_i^2 c^4}{2E}$ this becomes

$$\cos\theta e^{-im_1^2 c^3 L/2E\hbar}|\nu_1 > + \sin\theta e^{-im_2^2 c^3 L/2E\hbar}|\nu_2 >$$

Rotating back to the e, μ states and taking $|\mathrm{Amplitude}^2|$ gives probability

$$P_{\nu_e \to \nu_e}(L) = 1 - \sin^2 2\theta \sin^2 \left[(m_1^2 - m_2^2)c^3 L/4E\hbar\right]$$

$$P_{\nu_e \to \nu_\mu}(L) = \sin^2 2\theta \sin^2 \left[(m_1^2 - m_2^2)c^3 L/4E\hbar\right]$$



Important point

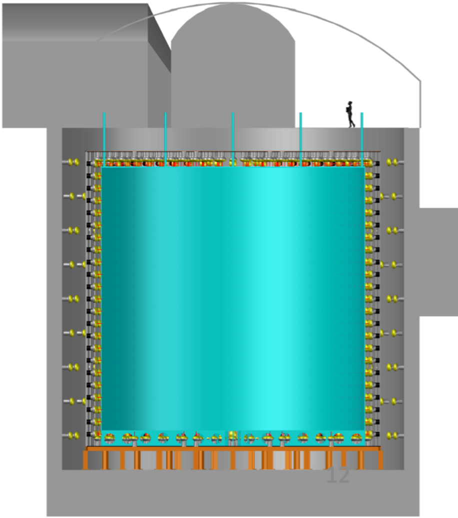
Oscillations are functions of L/E. Need to vary them and measure them!

The LSC detector

Large Scintillation Counter
2,500 tons of liquid scintillator, loaded with gadolinium, surrounded by phototubes
Detect inverse beta decay (IBD)

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

Prompt signal from positron track (gives energy)
Delayed signal from gadolinium (n, γ) so *very* clean
L and E measured, event by event
2,000,000 IBD events over 5 years

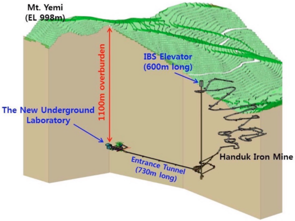


Plus further physics program: axion searches, νe elastic scattering, etc.

YEMILAB

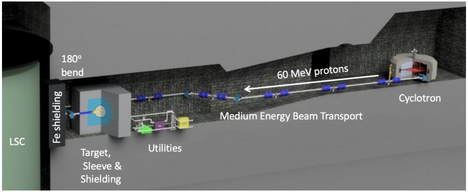
Neutrino Physics Opportunities with the IsoDAR Source at Yemilab, J. Alonso, *et al.*, Phys Rev D **105** 052009. (2022)

Handuk iron mine under Mt Yemi, Korea



Lab contains several experiments

3.5x3.5 m tunnel you can drive a truck through, all the way down



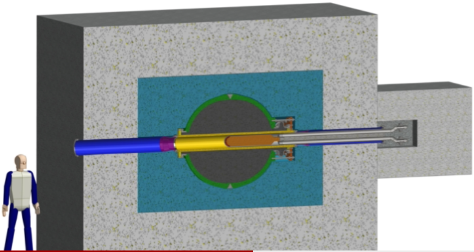
The target

A. Bungau *et al. Optimizing the* $^{8}\mathrm{Li}$ *yield for the IsoDAR Neutrino Experiment*
Journal of Instrumentation 14 P03001 (2019)

2-stage process: Be target enclosed in Li sleeve

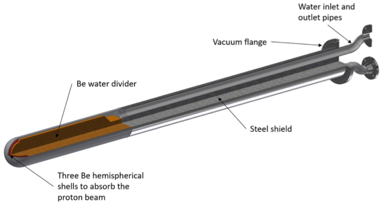
1. High current proton beam on ^{9}Be target produces neutrons
2. Neutrons on $^{7}\mathrm{Li}$ give $^{8}\mathrm{Li}$, which β decays ($\tau = 0.8$ s) giving $\overline{\nu}_e$with mean energy 6.4 MeV
   (IsoDAR = 'Isotropic Decay at Rest')

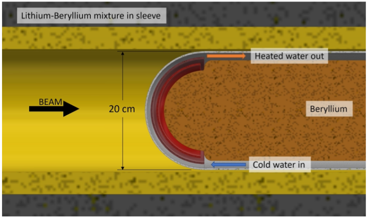
Target is 99.99% pure $^{7}\mathrm{Li}$ as $^{6}\mathrm{Li}$ eats neutrons
Sleeve is Be/Li: Li packed with small Be spheres. After much optimisation, can achieve 0.019 $^{8}\mathrm{Li}$ per incident proton. And we need $\sim 10^{23}$ per year

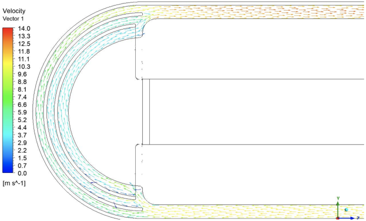


"The Torpedo": Challenging engineering!

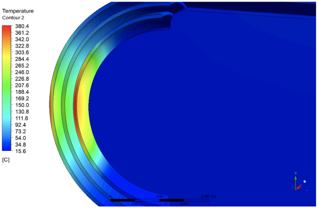
600kW cooled by heavy water. Many numerical studies needed







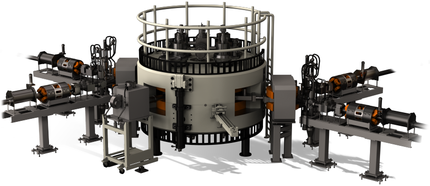
Beryllium Temperature:



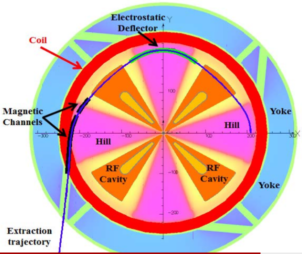
Several targets probably needed during lifetiime of experiment

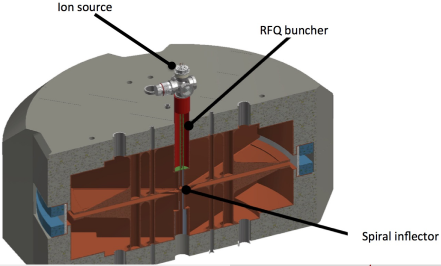
The IsoDAR cyclotron

Machines for medical isotope production (e.g. IBA Cyclone30, 0.6 mA at 30 MeV, Cyclone70 1 mA at 70 MeV)

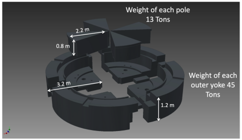


The IsoDAR cyclotron needs 10x more power: 10 mA of 60 MeV protons:





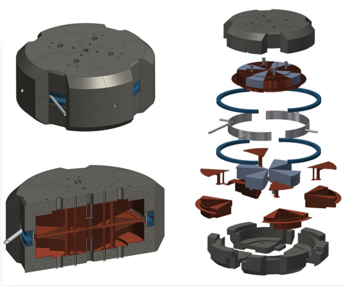
The Magnet



∼ 1 Tesla sector cyclotron Coil 4.95 m diameter - just fits into the tunnel (diagonally)

Cyclotron design

Parameter	Value
Ion accelerated	H_2^+
Max Energy	60 MeV/amu
Extraction radius	1.99 meters
Average magnetic field	1.16 tesla
Number of sectors	4
RF frequency	32.8 MHz
Accel. Voltage	70 – 240 kV
ΔE/turn	(ave) 1.7 MeV
Turns	95
Outer diameter	6.2 meters
Iron weight	450 tons

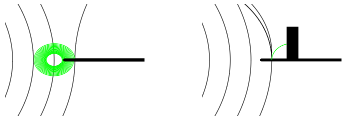


So what's so special?

H_2^+ and the accelerated ion

Modern cyclotrons use H^- rather than H^+ for extraction by stripping
Increasing interest in H_2^+ as an alternative

1. Binding energy is 2.8 eV as opposed to 0.7 eV, so more robust under strong electric (RF) and magnetic (Lorentz stripping) field
2. Space charge effects (important at low energies) are reduced because the mass is doubled. Characterised by Generalised Perveance $K = \frac{qI}{2\pi\epsilon_0 m_0 c^3 \beta^3 \gamma^3}$
3. Extraction can be done without the convoy electrons damaging the stripping foil



Incidentally can also accelerate D^+, He^{2+}, C^{6+}

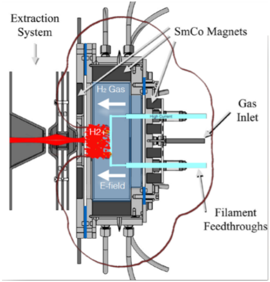
Ion Source Status

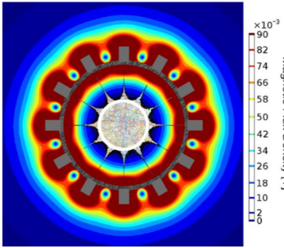
New Commissioning Results of the MIST-1 Multicusp Ion Source

D.Winklehner et al J. Phys.: Conf. Ser. 2244 012013 (2022)

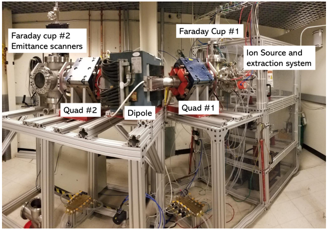
Multicusp Ion source MIST-1 optimised for H_2^+

SmCo permanent magnets to confine plasma





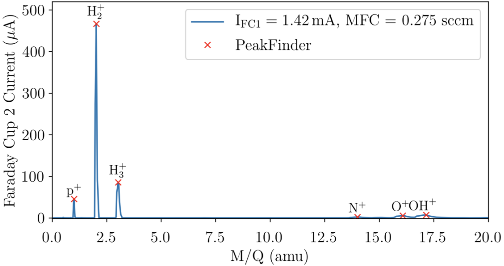
And the prototype ion source really exists



Ion source performance

Achieved

- H_2^+ beam current density of $\sim 10mA/cm^2$,
- $\sim 80\% H_2^+$ fraction
- Extrapolated H and V emittances of 0.05 π-mm-mrad (RMS, normalized) after extraction.



This does not yet meet requirements, but is well on the way

Advantages of an RFQ as the LEBT

Instead of solenoids or quads

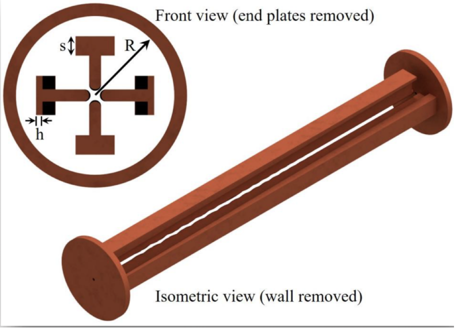
Ion source is DC.

On injection to cyclotron, particles entering within 10° of the correct RF phase are accelerated. All others are lost.

Buncher may give factor ~ 2 improvement,

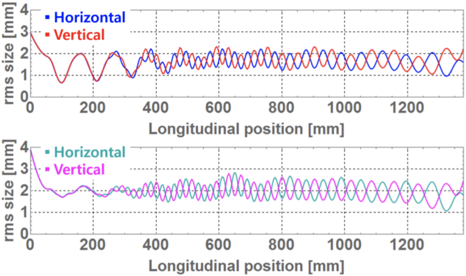
Not treated as a problem as energies are low. But means 50 mA source needed for 5 mA beam current

Solution: use RFQ as LEBT. Focuses+bunches+accelerates



RFQ status

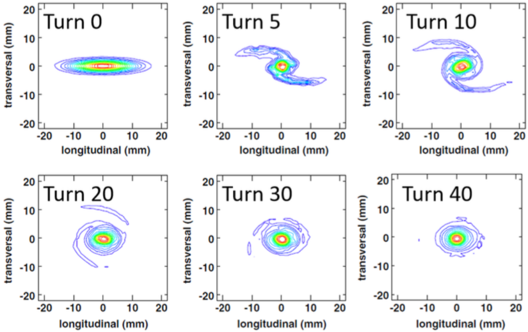
4 rod split-coaxial design. 1.4m long, operates at 32.8 MHz (very low frequency! Matched to cycloton)
Consumes modest 12.25 kW
Accelerates from 15 keV to 70 keV
Collection efficiency 97%. with longitudinal re-buncher at the end
Encouraging simulations (using TRACK code: 10 mA and 20 mA shown)



Design being finalised. Construction approved.

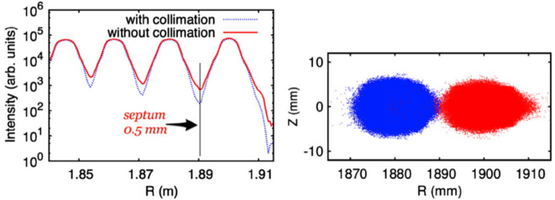
Cyclotron Design

Modern simulation software (OPAL) gives understanding of bunch dynamics in cyclotrons (space charge repulsion, field inhomogeneities, inter bunch effects,..) including spiral inflector
Established by use in PSI injector II and other machines. Shows 'vortex motion' mixing T and L emittance, driven by space charge.

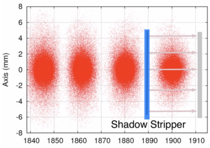


Using Vortex motion

Central collimators give clean beam separation for high energy orbits.



Control losses and enable shielded septum between outermost bunch orbits



So can extract with electrostatic septum rather than stripping (becomes plan B)

Of 600kW beam power, only 100W on septum

Applications: Medical Isotopes

Highlighting these among many uses for such machine

Production of medical isotopes with (relatively) small cross sections:

60 MeV protons on natural Gallium target (^{69}Ga and ^{71}Ga) gives 50 Ci/week $^{68}\mathrm{Ge}$

$^{68}\mathrm{Ge}$ decays to $^{68}\mathrm{Ga}$ - a positron emitter

Like widely used Mo/Tc system used for imaging except

- PET not SPECT so better imaging
- Half life of $^{68}\mathrm{Ge}$ is 270 d so "cow" lasts for 1 year not few days
- $^{68}\mathrm{Ga}$ half life 68 min not 6 h: don't send patients home radioactive

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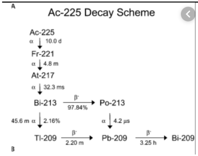


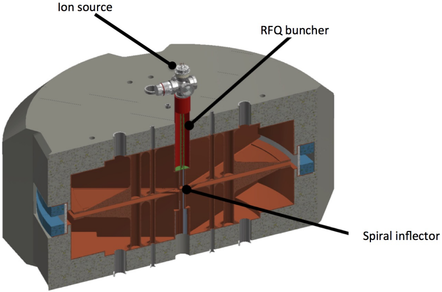
$^{225}\mathrm{Ac}$ radiotherapy α emitter

4 α particles, enormous LET, range 50 microns, so powerful targeted dose.

Make by 60 MeV protons on thorium. Estimate could get 200 mCi/hour so 5 hours gives as much as current world production

Conclusions

The IsoDAR design is a game changer
Increase the power of low energy cyclotrons by an order of magnitude.
Many applications - including ADSR injectors
(and solve the sterile neutrino question)



Design, development, optimisation and funding bids continue...

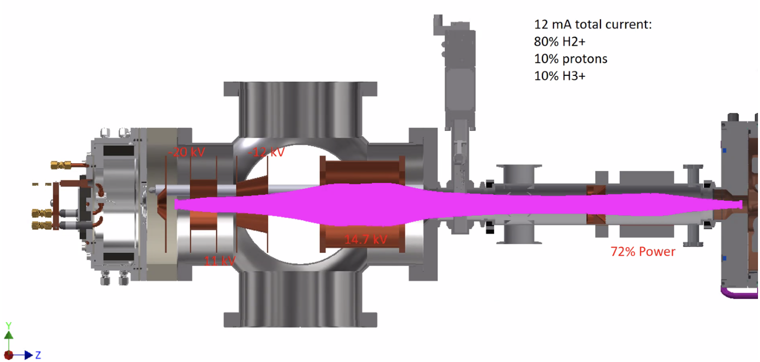
Thanks to everyone for the pictures : Andreas Adelmann, Dan Winklehner, Jared Huang, J J Yang, Janet Conrad, Joe Smolsky, Mike Shaevitz and the rest of the IsoDAR collaboration

Backup slides

TABLE 1. Comparison of IsoDAR with commercial cyclotrons

Parameter	IsoDAR	IBA C-30	IBA C-70
Maximum energy (MeV/amu)	60	30	70
Beam current (milliamps)	10	1.2	0.75
Pole radius (meters)	1.99	0.91	1.24
Outer diameter (meters)	6.2	3	4
Iron weight (tons)	450	50	140
Elect. Power reqd. (megawatts)	2.7	0.15	0.5

Backup slides



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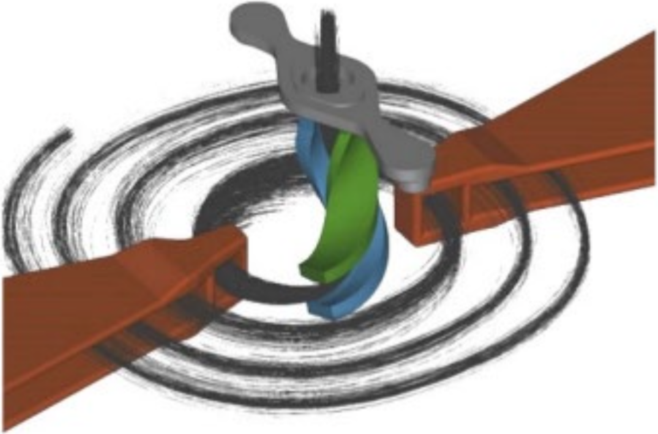

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