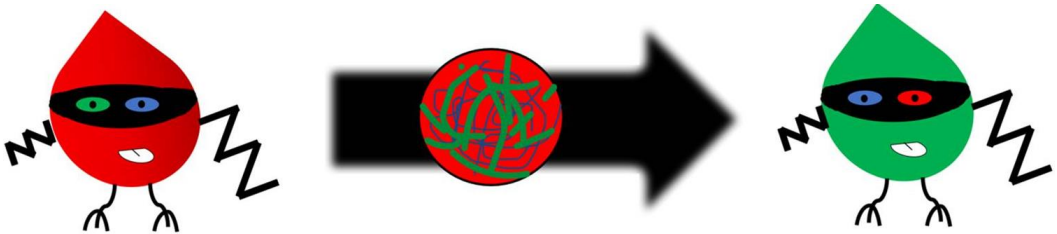
Applications of the high-Current IsoDAR Cyclotron from Neutrino Physics to Beyond

Loyd Waites

On behalf of the IsoDAR collaboration

Neutrino Oscillations

$$|U_{PMNS}| = \begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{pmatrix} \sim \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.36 & 0.56 & 0.71 \\ 0.42 & 0.60 & 0.68 \end{pmatrix}$$



$$|\nu_e\rangle \rightarrow |\nu_{1,2,3}\rangle \rightarrow |\nu_\mu\rangle$$

Neutrino Oscillations

$$|U_{PMNS}| = \begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{pmatrix}$$

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4 \sum_{j>i} \mathrm{U}_{\alpha i} \mathrm{U}_{\beta i} \mathrm{U}^*_{\alpha j} U^*_{\beta j} \sin^2 \left(1.27 \Delta m^2_{ij} \frac{L}{E} \right)$$

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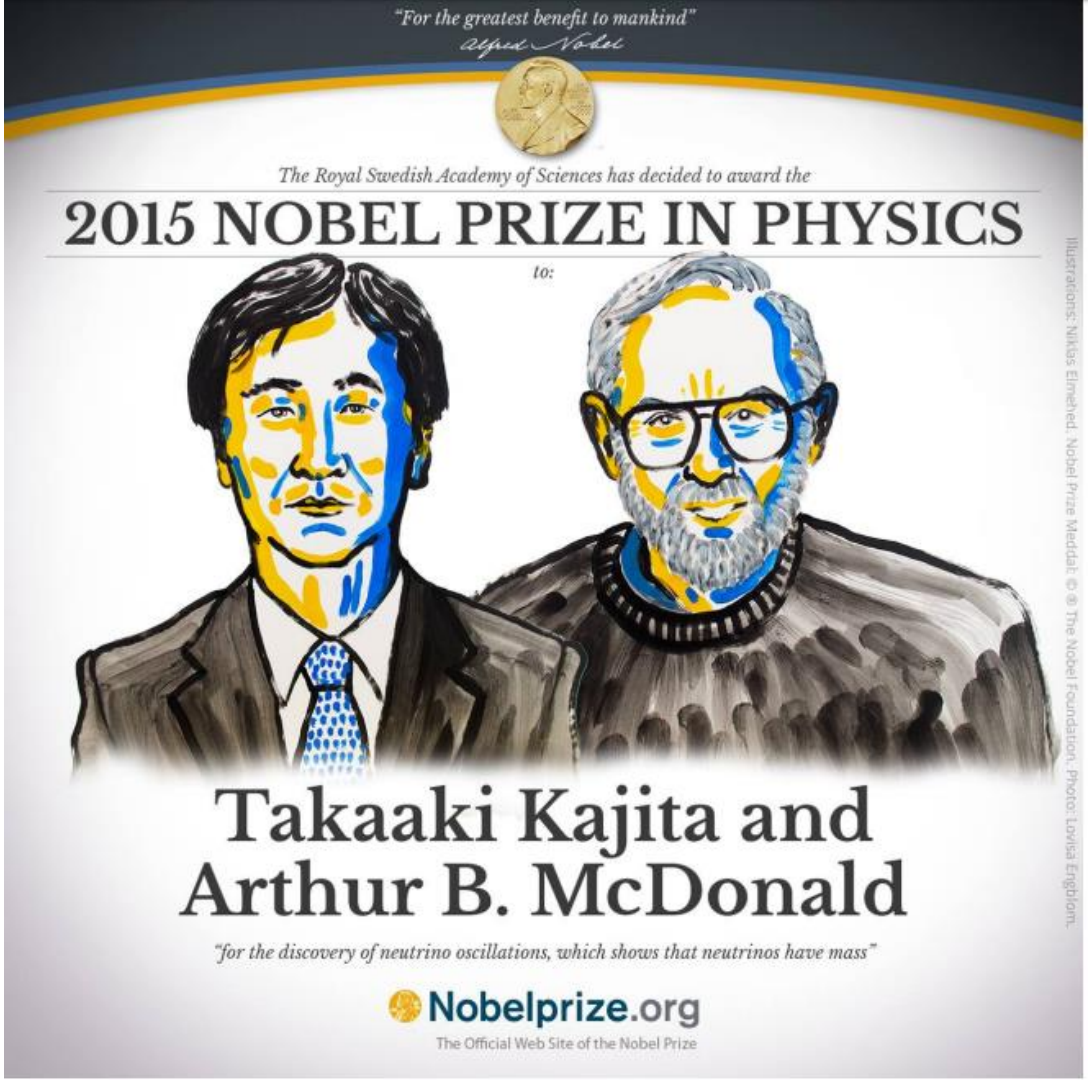

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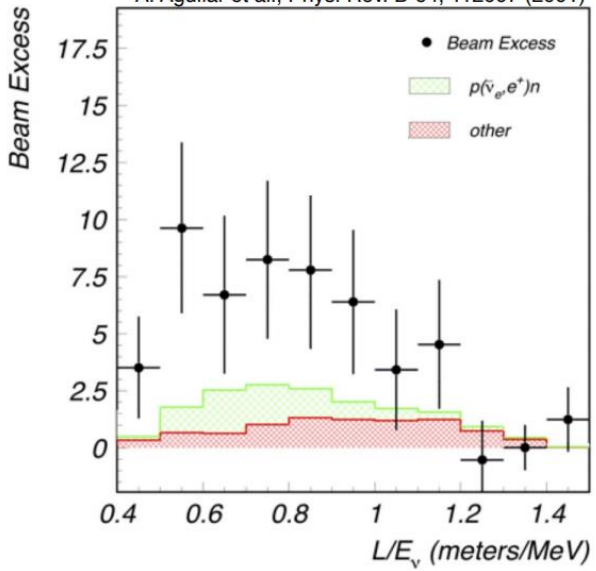
Oscillation Anomalies ($\nu_{\mu} \rightarrow \nu_e$ appearance)

LSND Anomaly

~3σ $\bar{\nu}_e$ excess in $\bar{\nu}_\mu$ beam

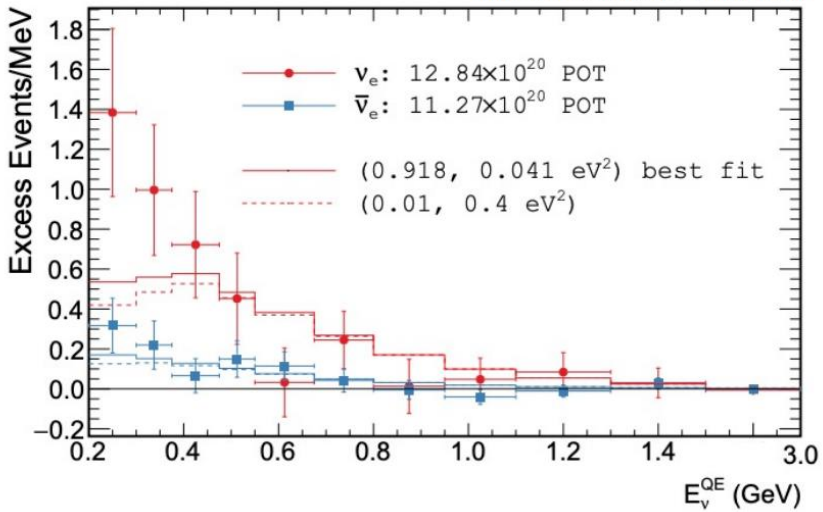
A. Aguilar et al., Phys. Rev. D 64, 112007 (2001)



MiniBooNE low energy excess

4.7σ $\overset{(-)}{\nu}_e$ excess in $\overset{(-)}{\nu}_\mu$ beam

Phys. Rev. Lett. 121, 221801 (2018)

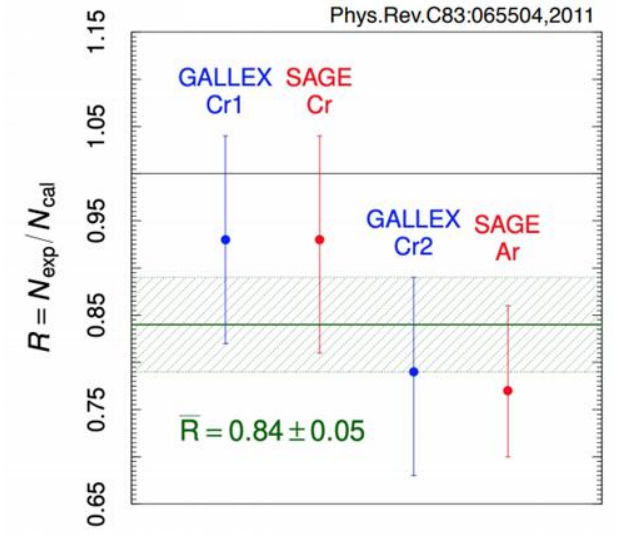


Oscillation Anomalies ($\nu_{\vec{e}} \rightarrow \nu_e$ disappearance)

The Gallium Anomalies

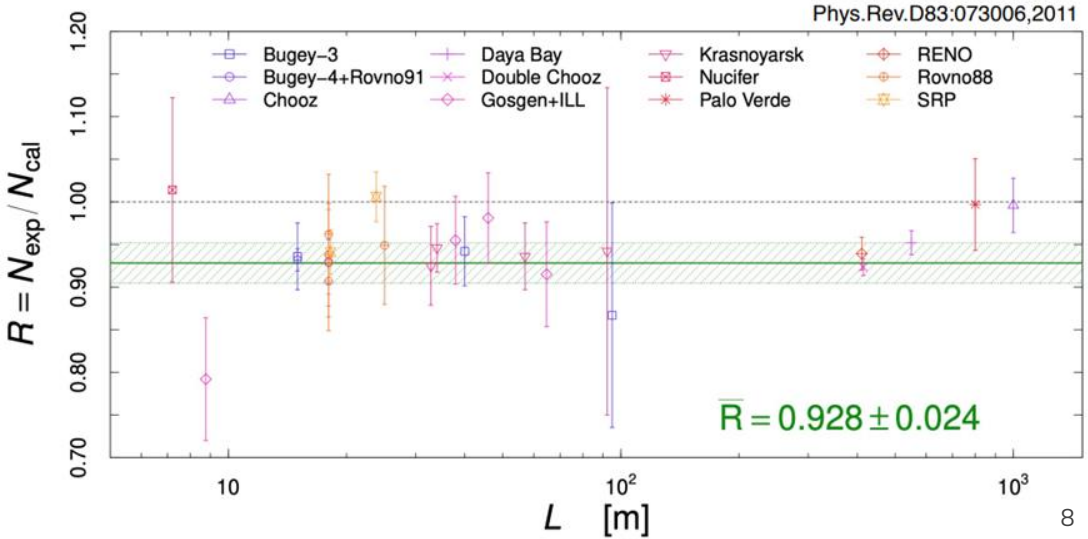
~2.3 - 3σ deficit observed in measured ν_e interaction rate

$$^{71}Ga + \nu_e \longrightarrow {}^{71}Ge + e^-$$



Reactor Anomaly

~3σ deficit observed in measured $\bar{\nu}_e$ interaction rate



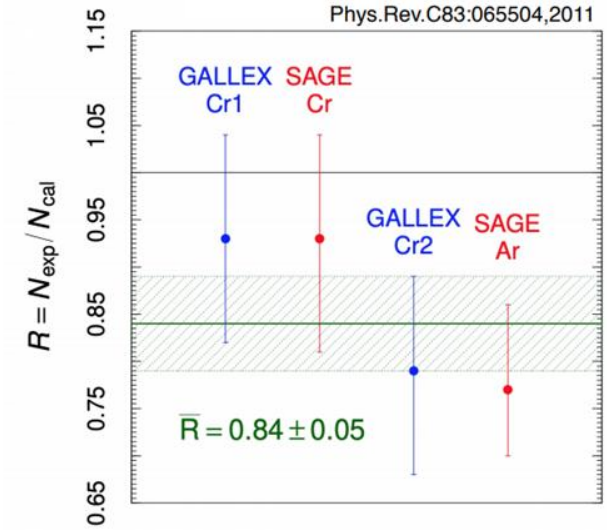
STERILE NEUTRINOS

Oscillation Anomalies ($\nu_{\vec{e}} \rightarrow \nu_e$ disappearance)

The Gallium Anomalies

~2.3 - 3σ deficit observed in measured ν_e interaction rate

$^{71}Ga + \nu_e \longrightarrow {}^{71}Ge + e^-$



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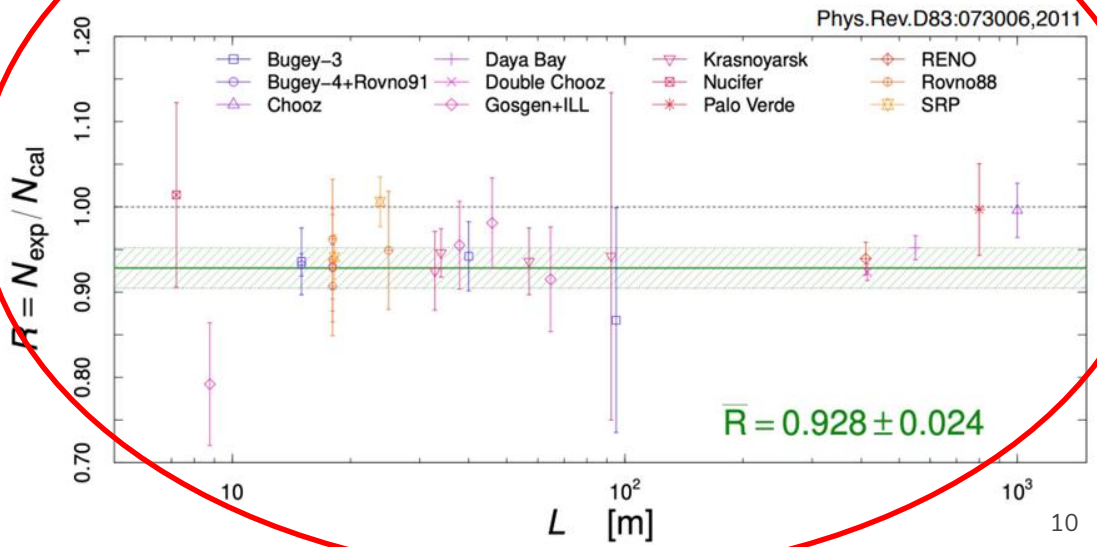
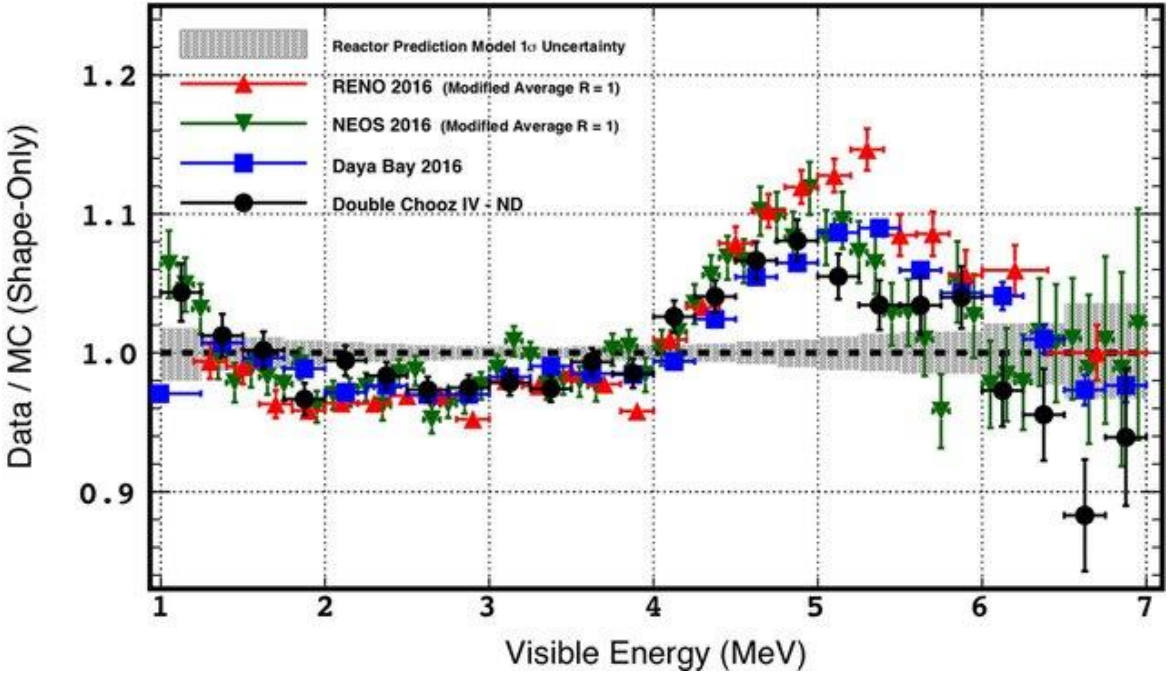
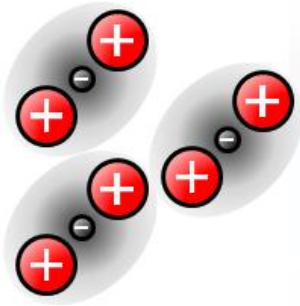


5 MeV bump

- Reactor Flux not well understood
- Anti-electron neutrino channel must be investigated using a well understood source

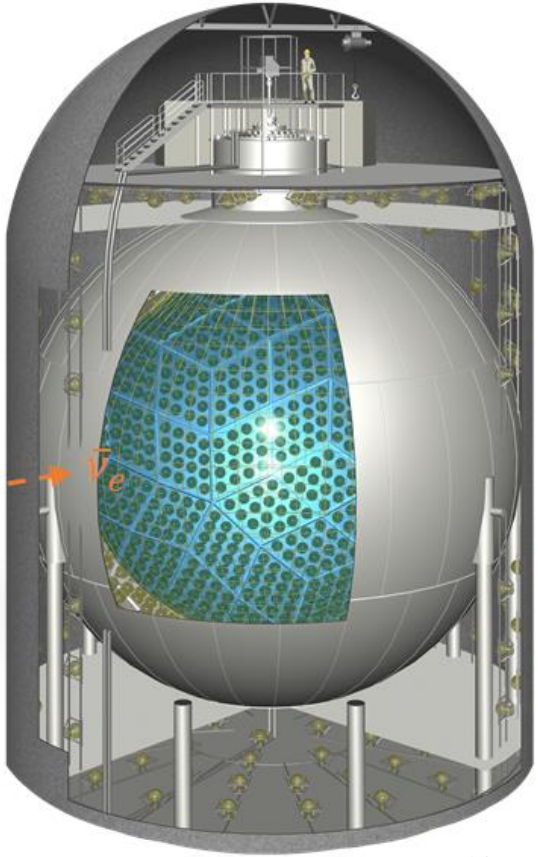


H_2^+ production → 60 MeV/amu acceleration → $\bar{\nu}_e$ production → IBD signal



Enter: IsoDAR

- "Neutrino light bulb"
- Isotropic anti-electron neutrino source
- Close proximity to detector



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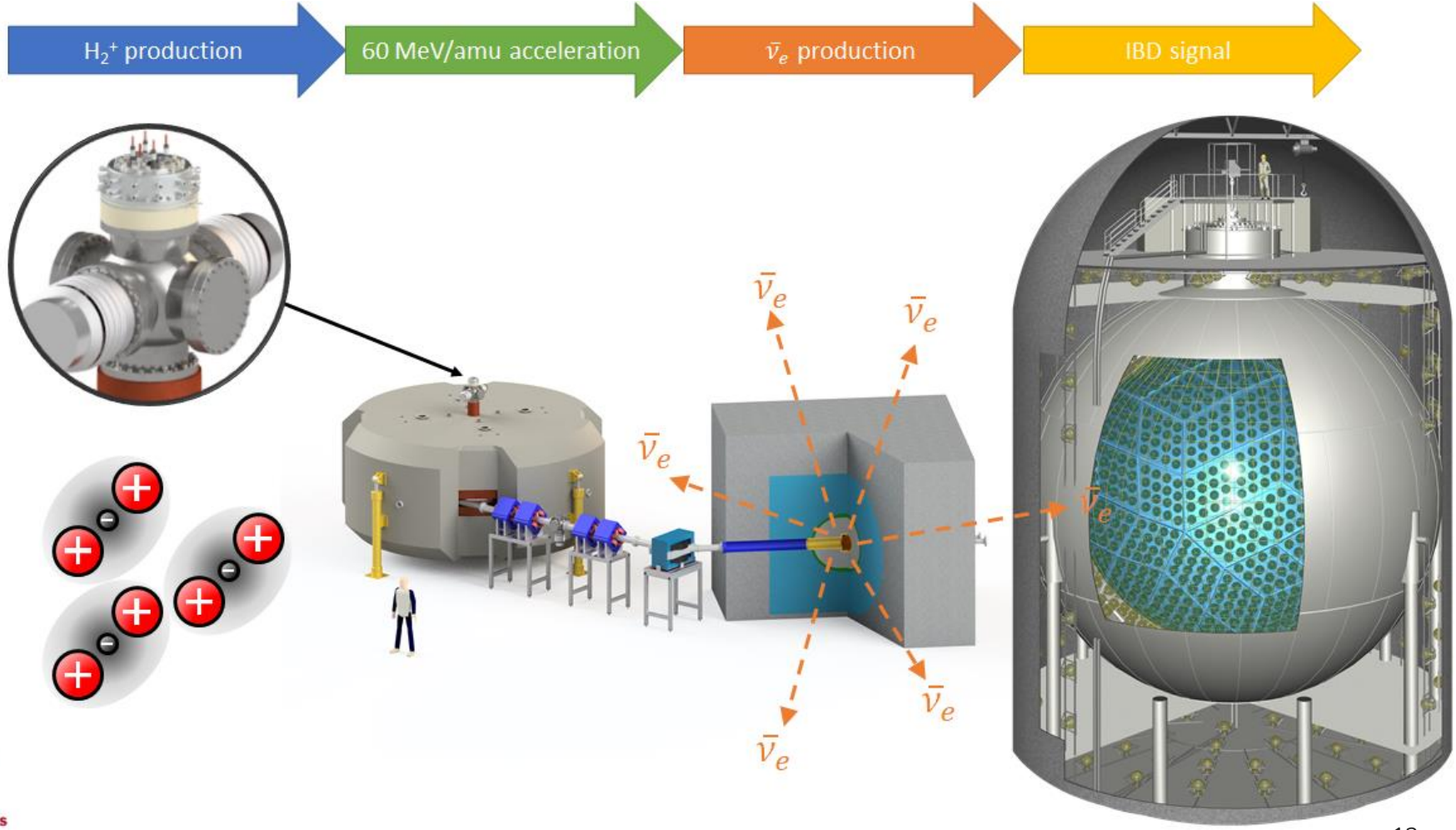

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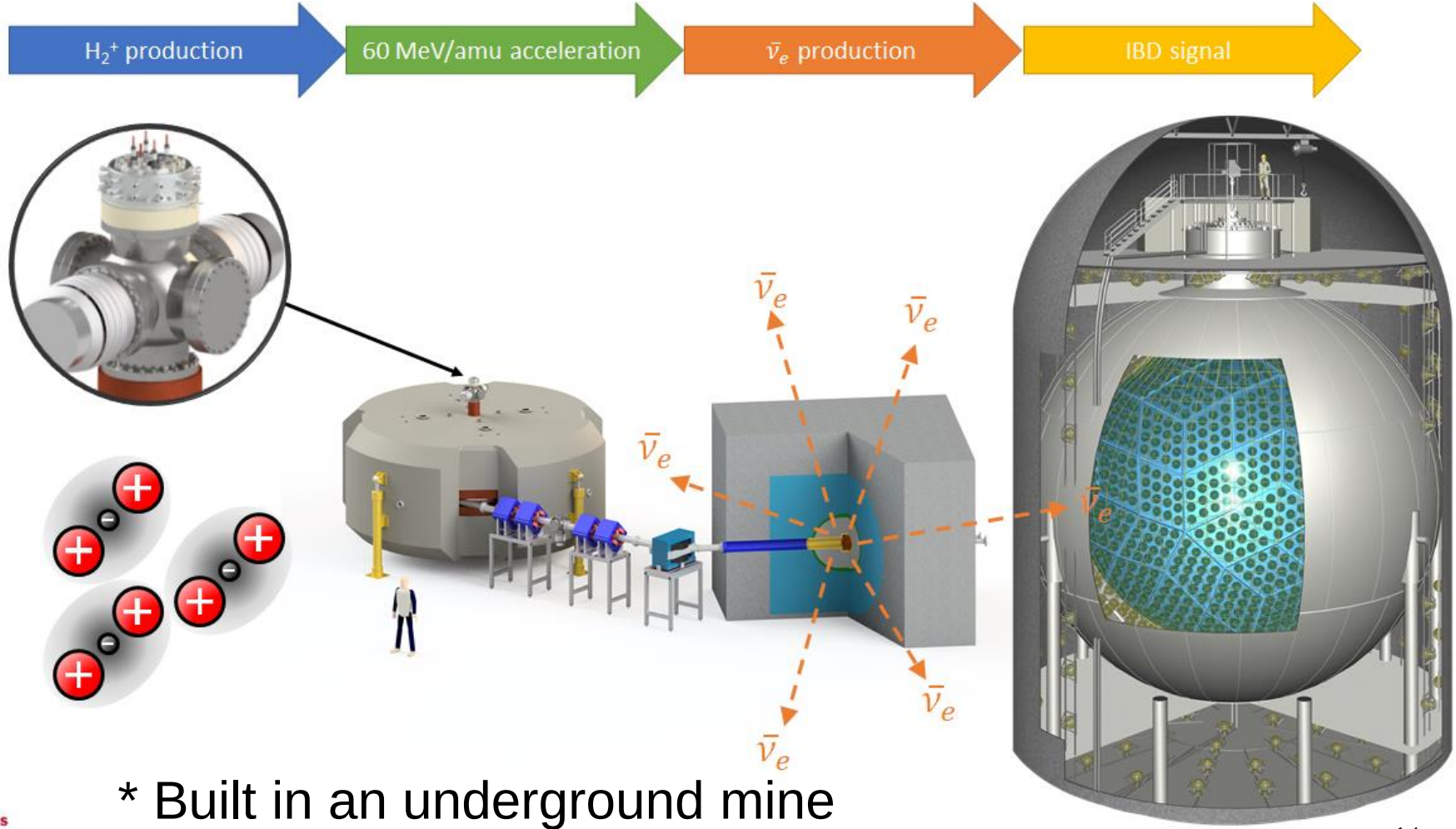

* Built in an underground mine

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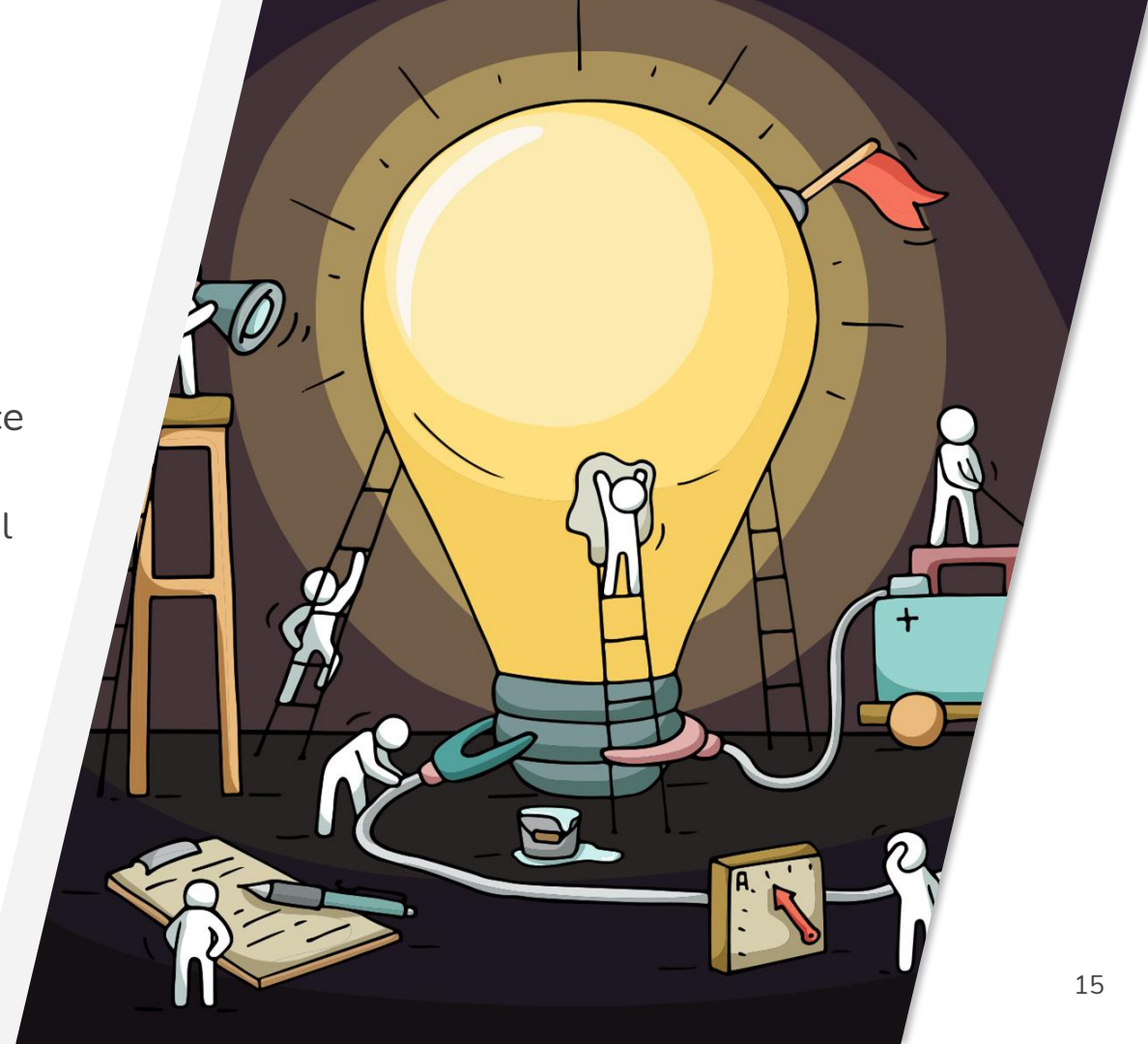
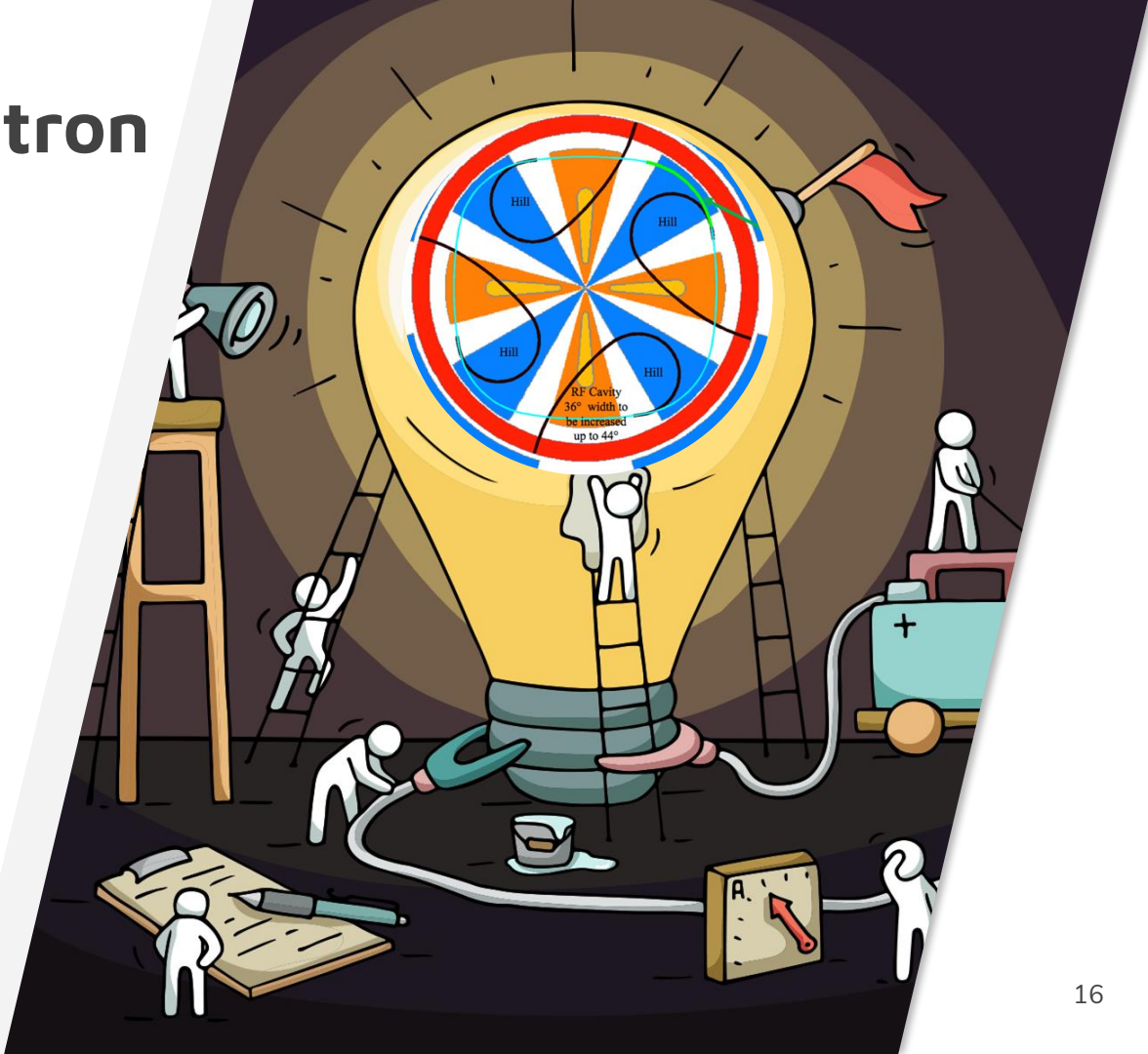
Innovation

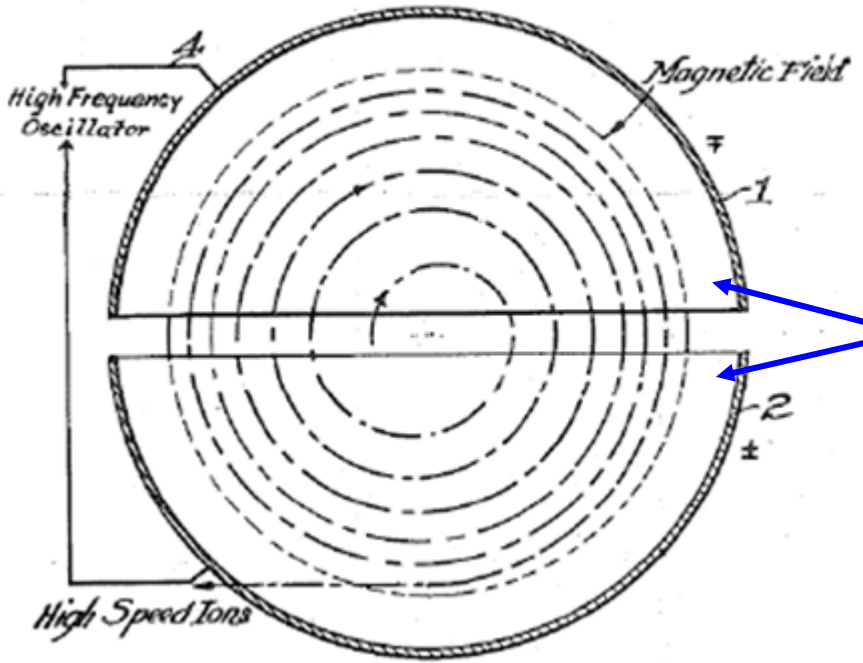
- Intense neutrino source requires intense proton source
- 10 mA beam current
  - 10X higher than commercial
- Built underground, at a reasonable cost



A New Cyclotron Design



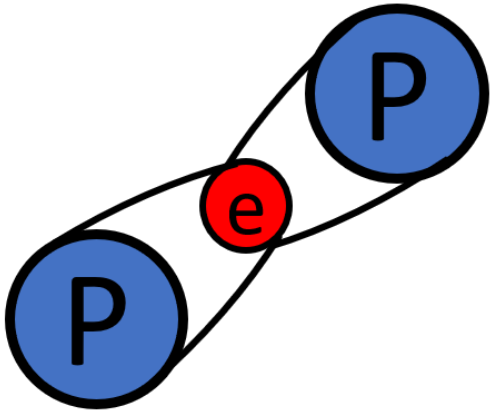
Cyclotrons

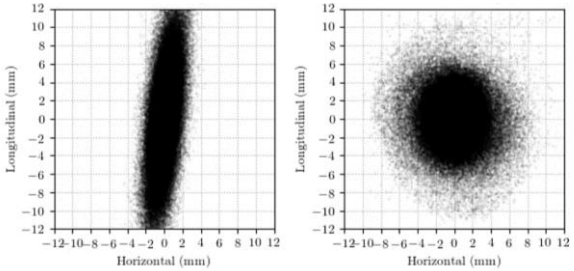


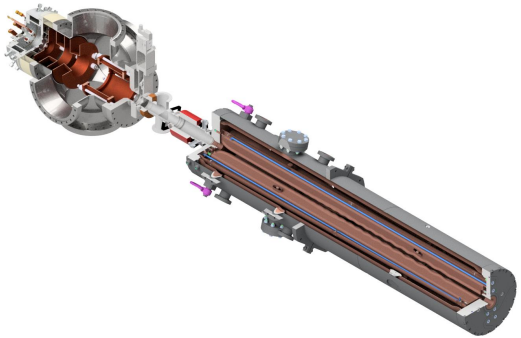
$$V(t) = V_{max} \cdot \cos(\omega_{RF} \cdot t - \Phi_S)$$

$$\omega_{RF} = \frac{qB}{\gamma m_0}$$

X B-field

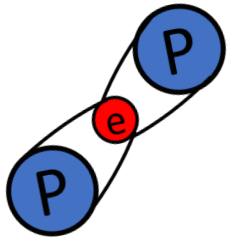






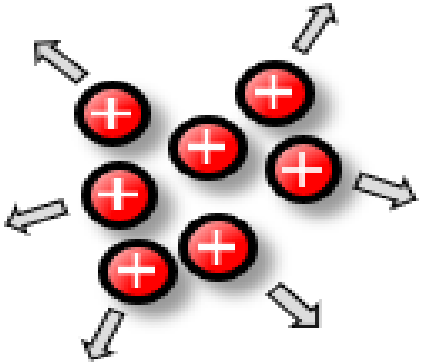
Three Breakthroughs to Higher Currents:

Use of H_2^+



PROBLEM

- High beam intensity + slow beam velocity
  - Space charge ⇨ emittance growth
- High impact of space charge in the low energy region

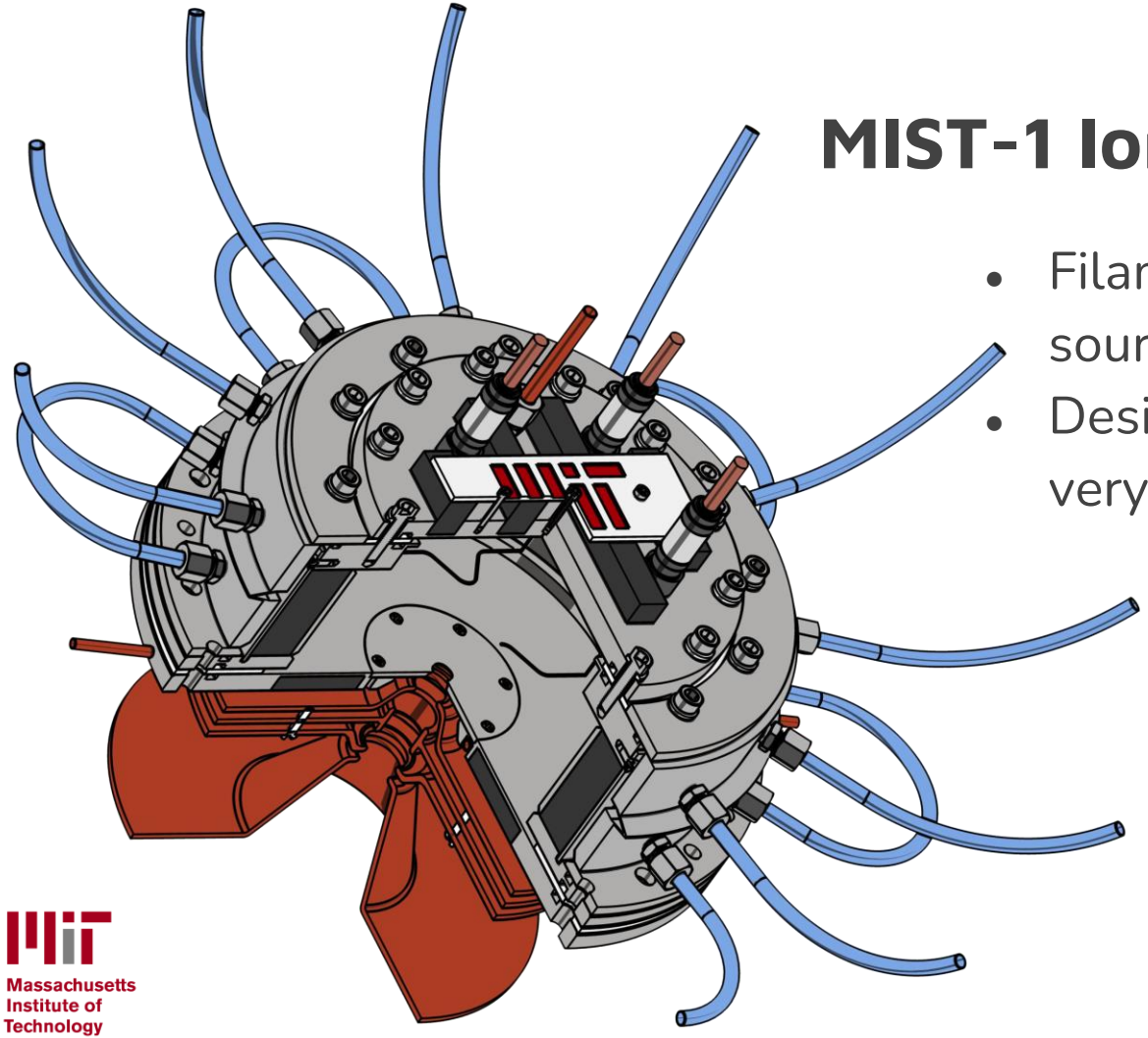


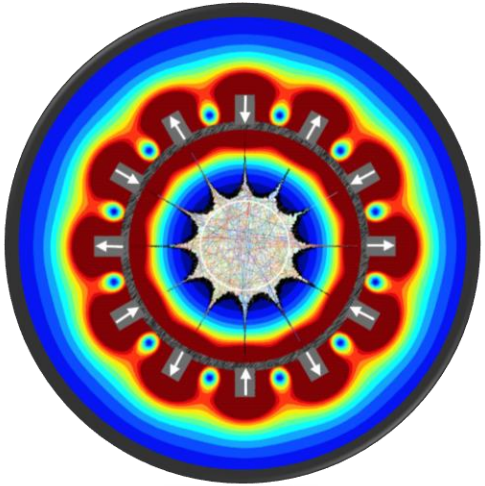
Solution

- H_2^+: Two units of charge for one in the low energy region
- Remove electron by stripping ⇨ two protons
- https://arxiv.org/abs/1807.03759

MIST-1 Ion Source

- Filament-driven, Multicusp Ion source
- Designed to maximize H_2^+ with very low emittance





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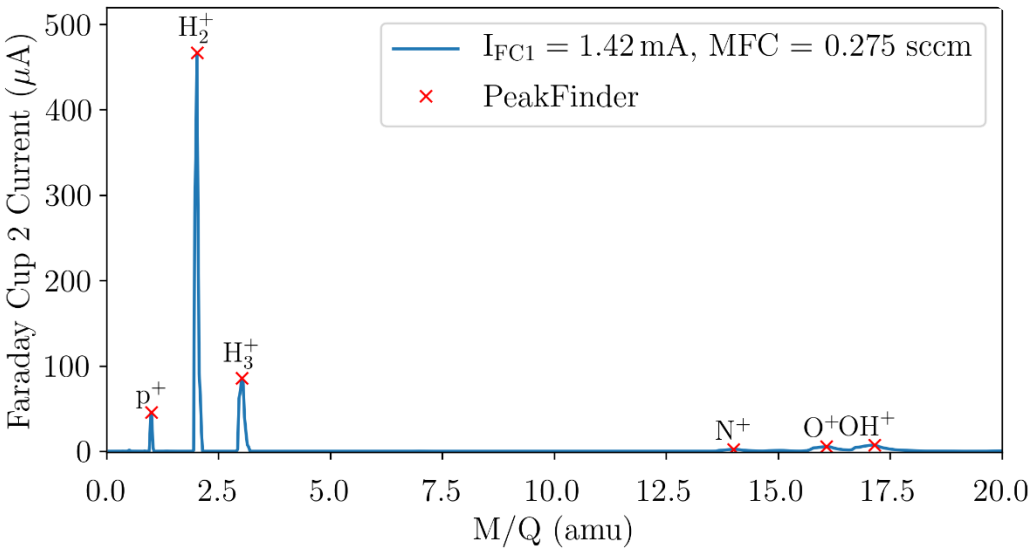
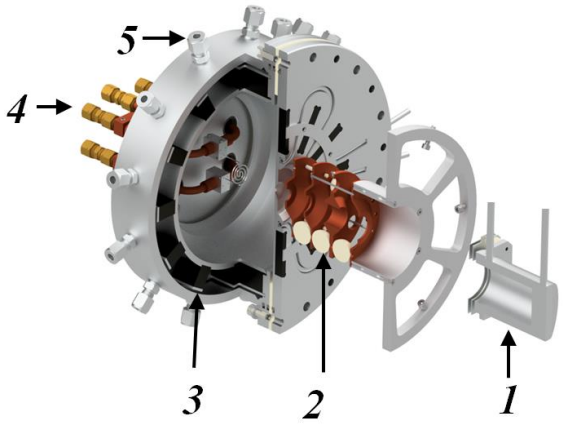
Experimental results

- Currently Commissioning at 25% power
- 80% pure H_2^+
- High quality beam emittance: 0.05 π-mm-mrad (RMS, norm.)
- Currently working to increase power





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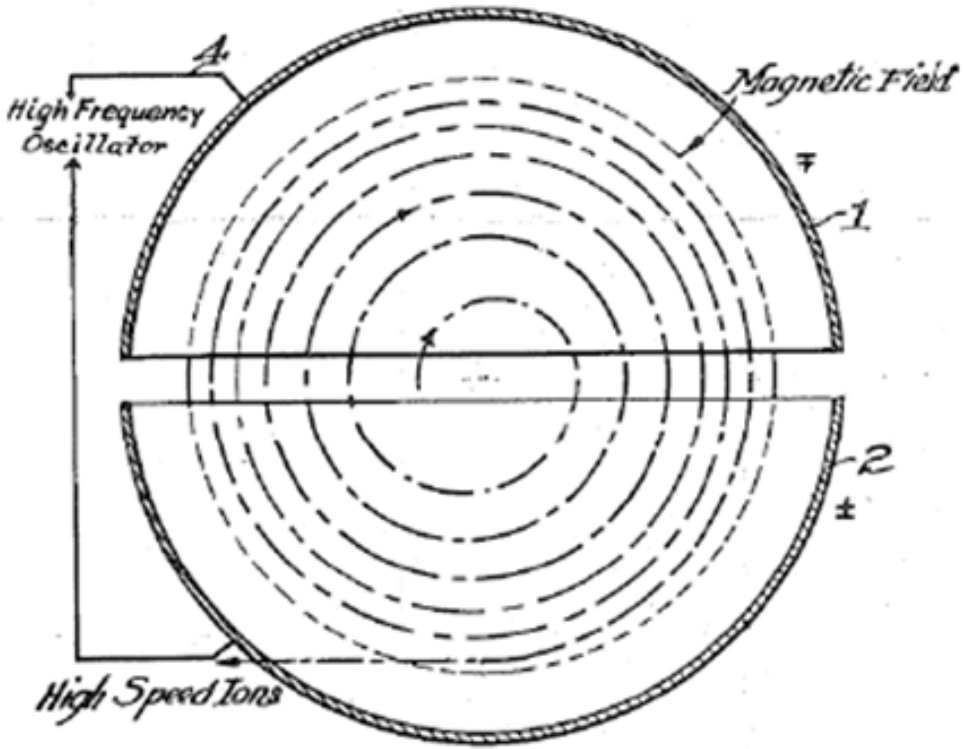
Vortex Motion



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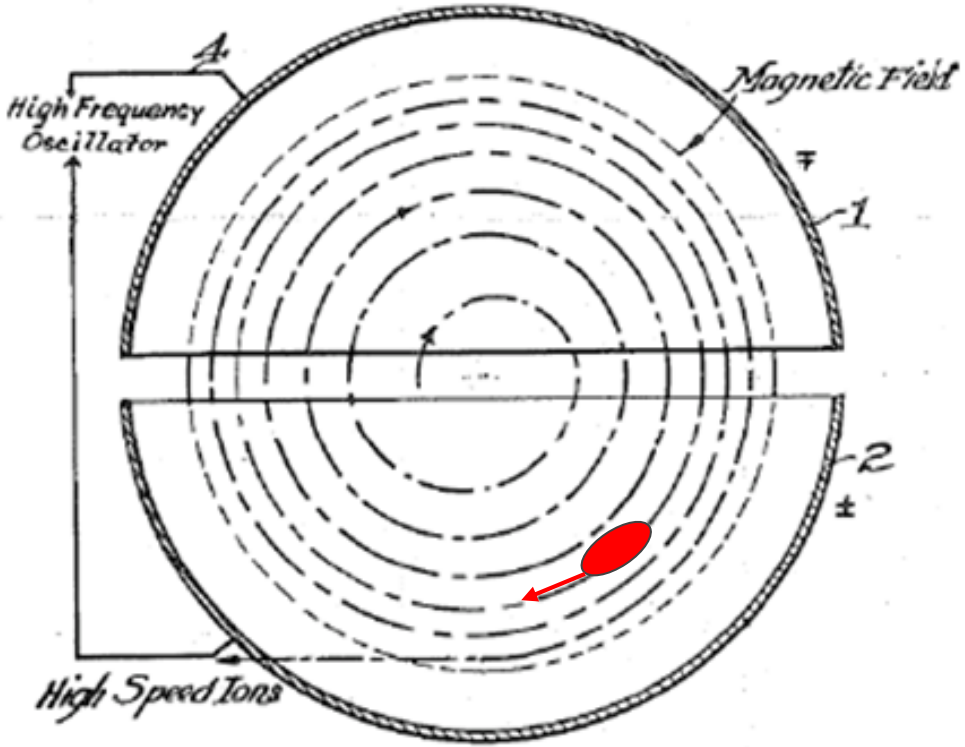
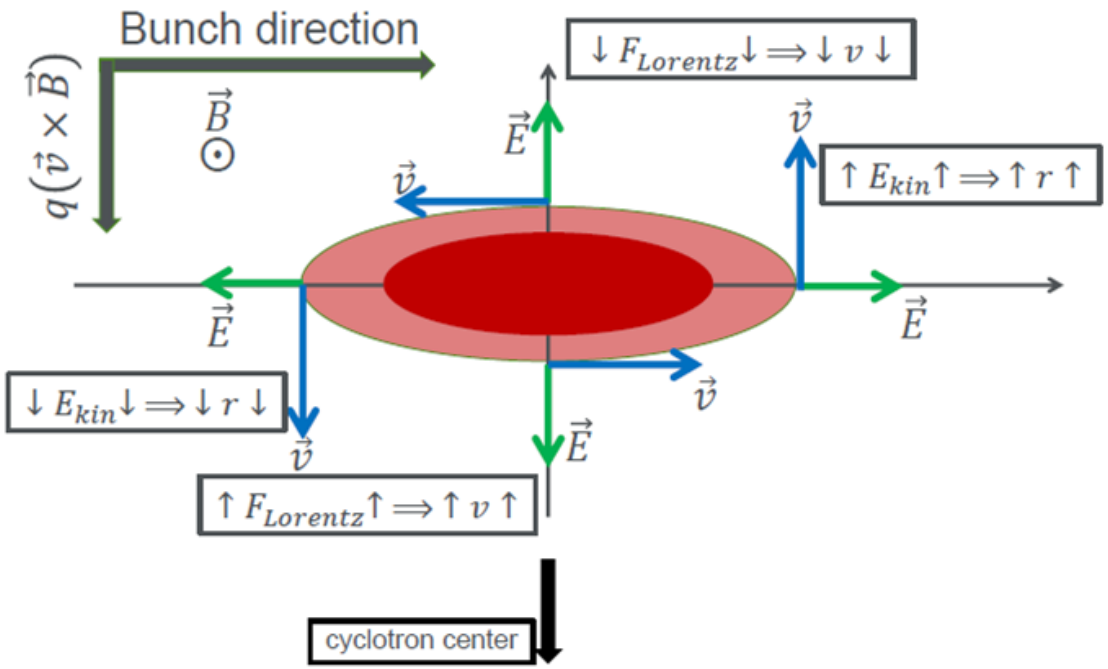
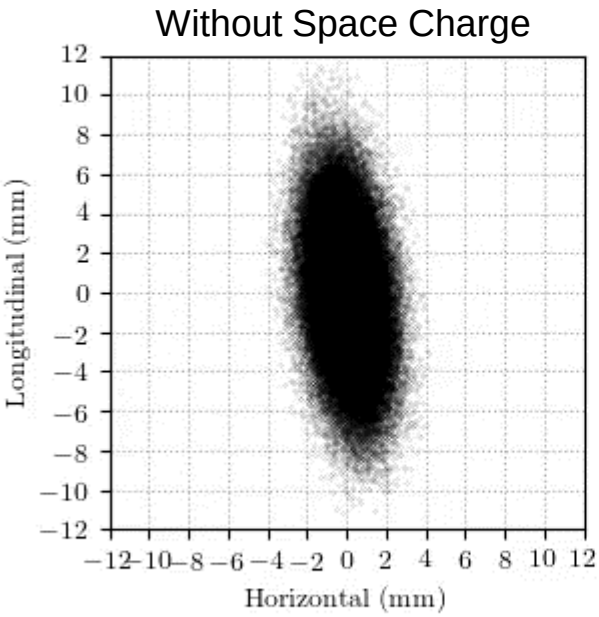
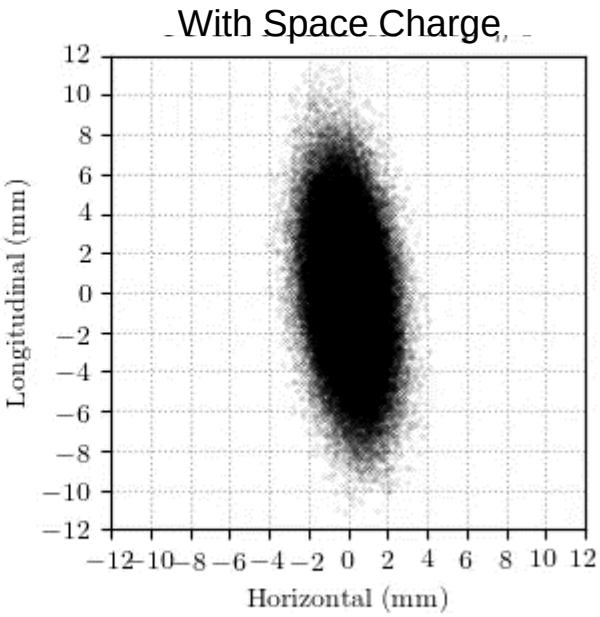


Vortex Motion




Without Space Charge
Longitudinal (mm)
Horizontal (mm)
12
10
8
6
4
2
0
−2
−4
−6
−8
−10
−12
−12 −10 −8 −6 −4 −2 0 2 4 6 8 10 12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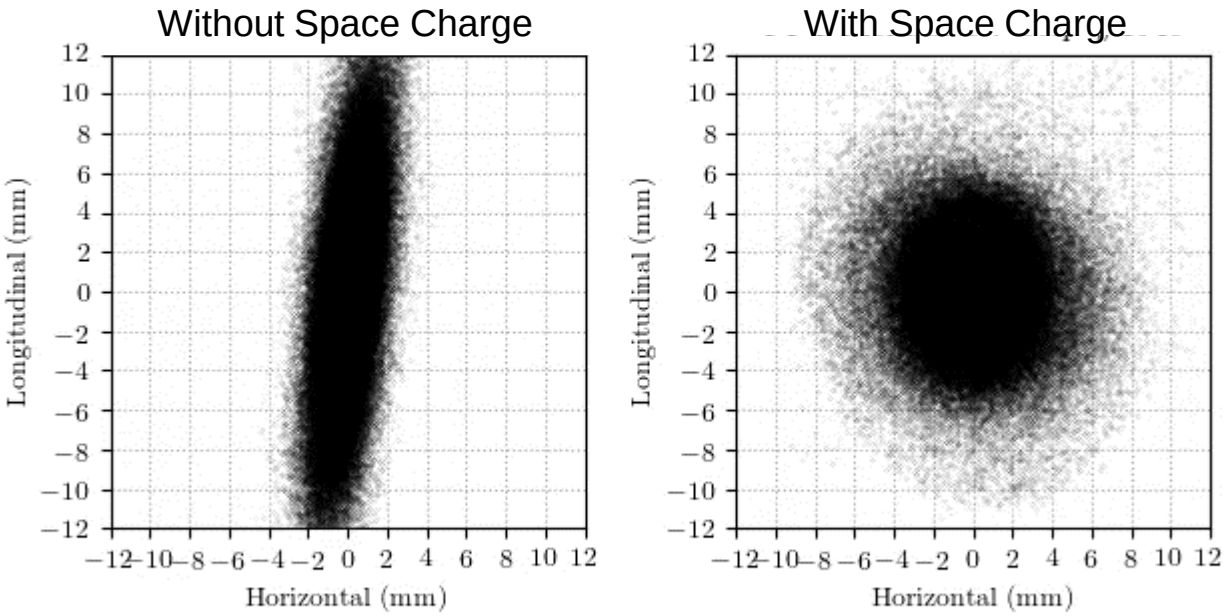
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Longitudinal (mm)
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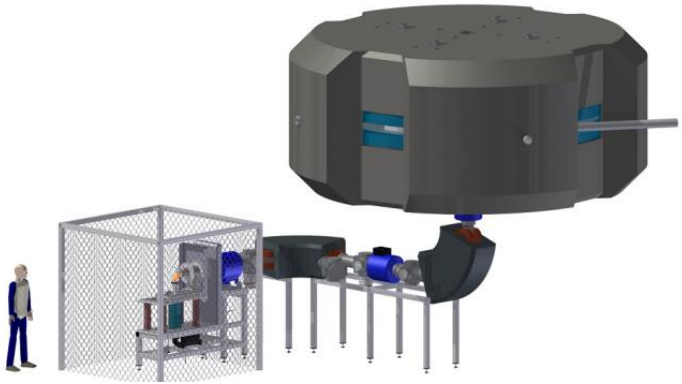
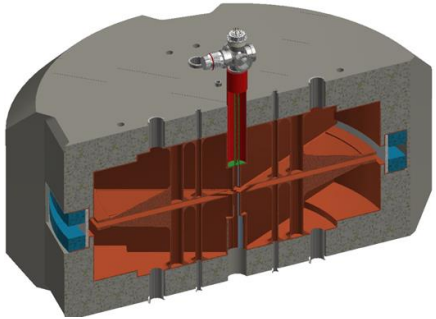
RFQ injection

- Replaces large LEBT
- Bunching allows for higher phase acceptance
- Significantly higher transmission





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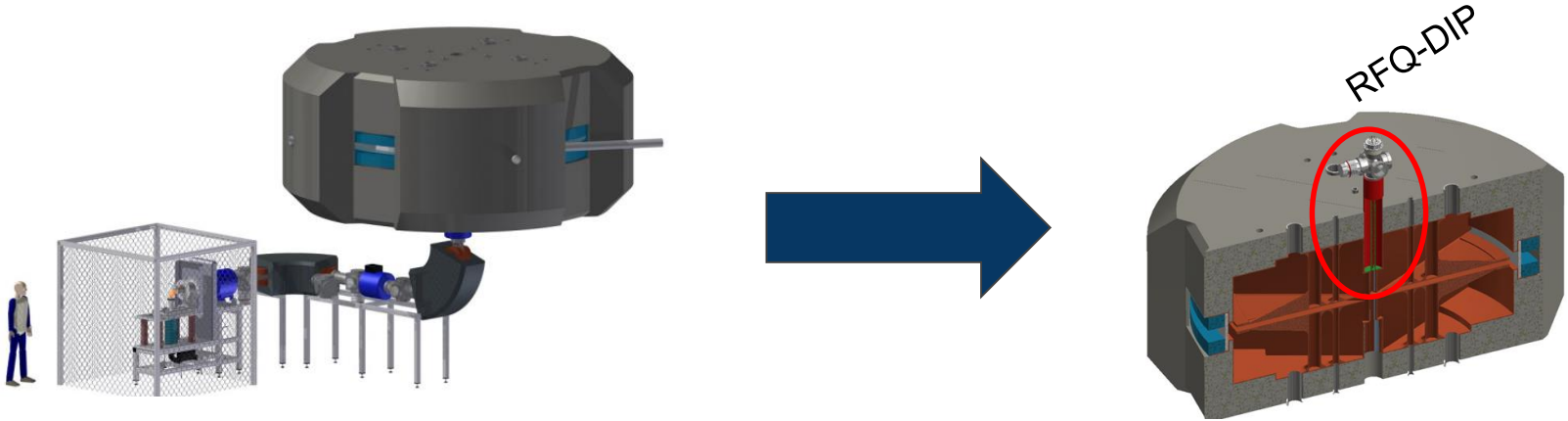
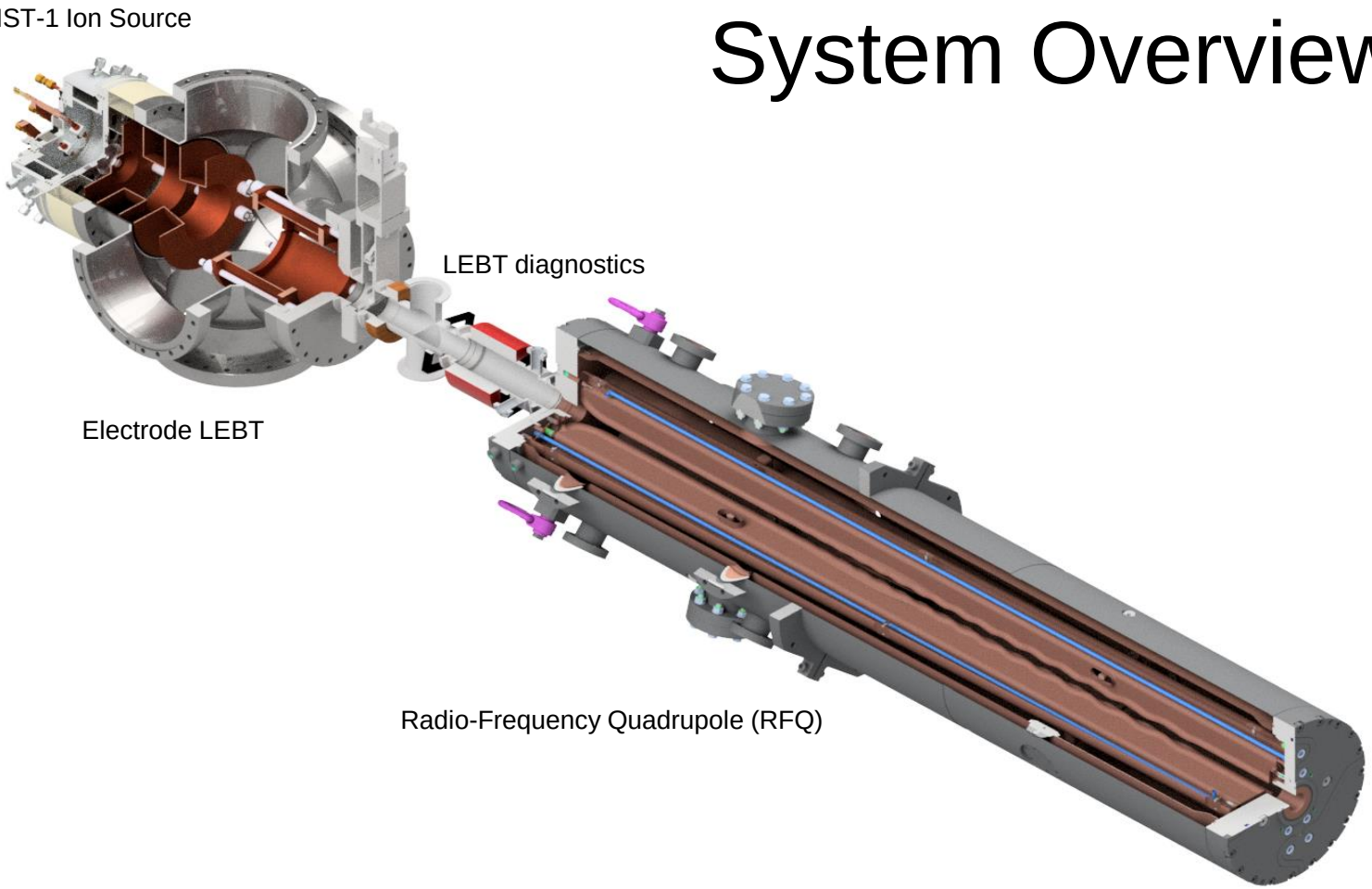


System Overview:



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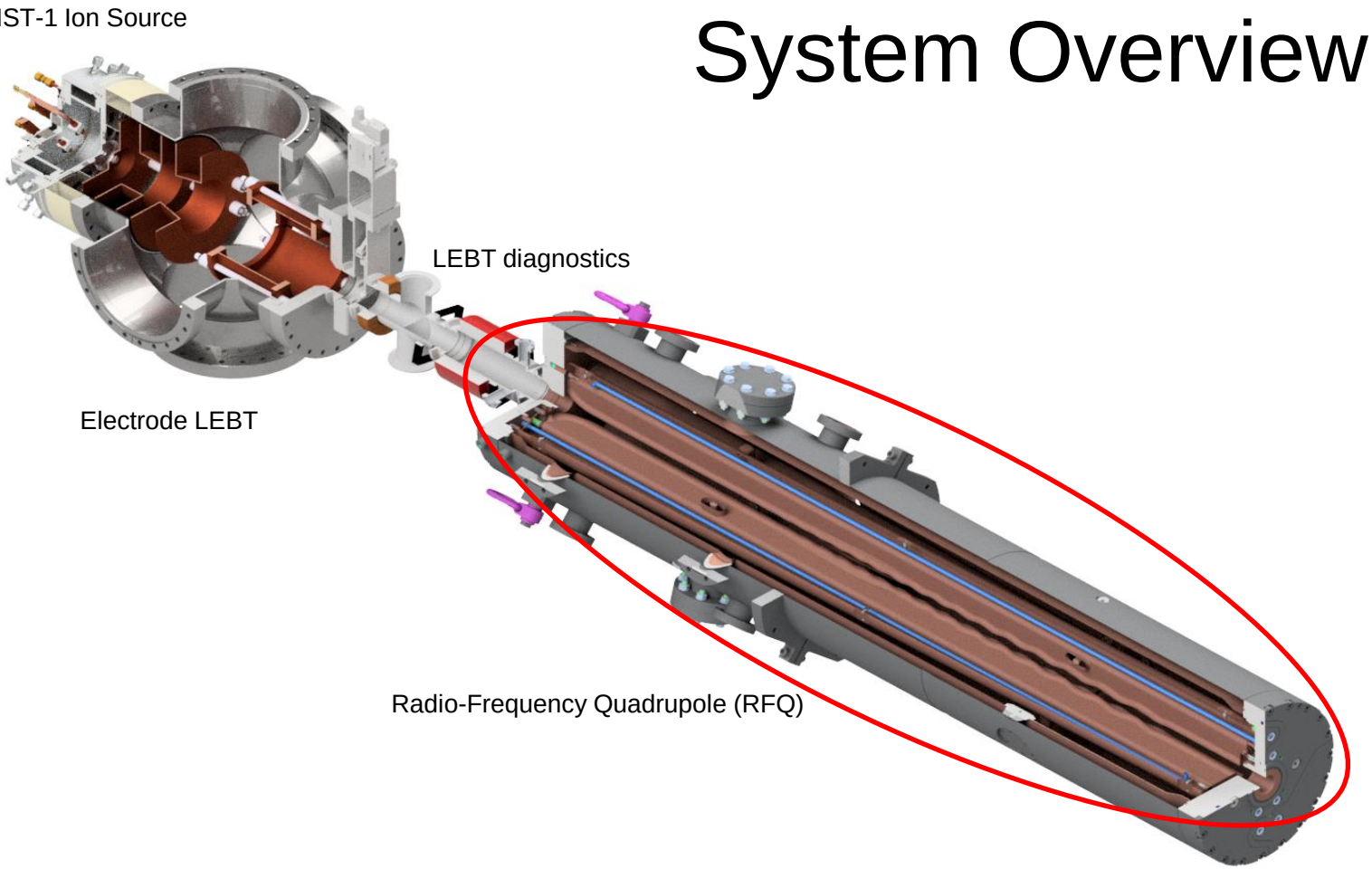
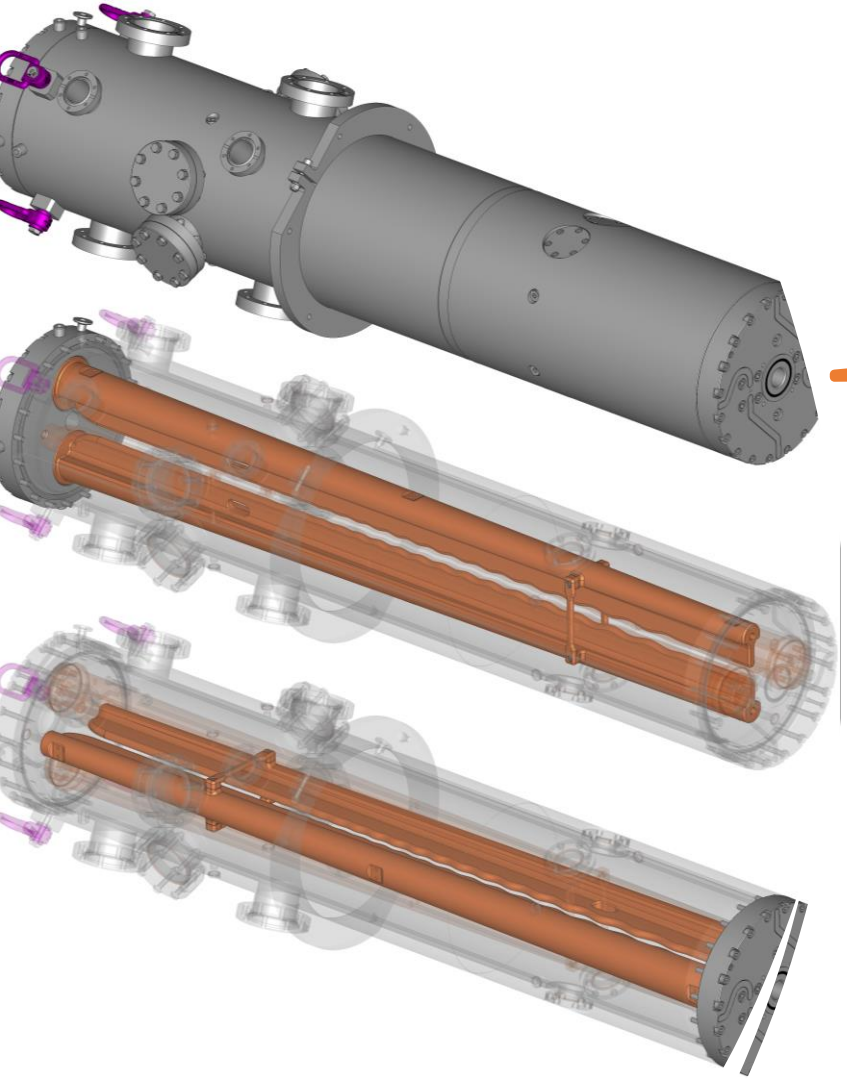


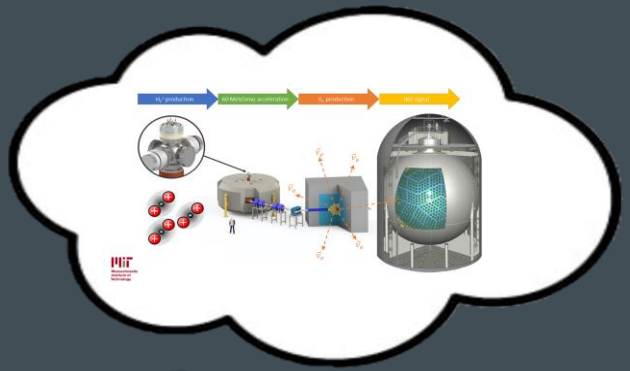


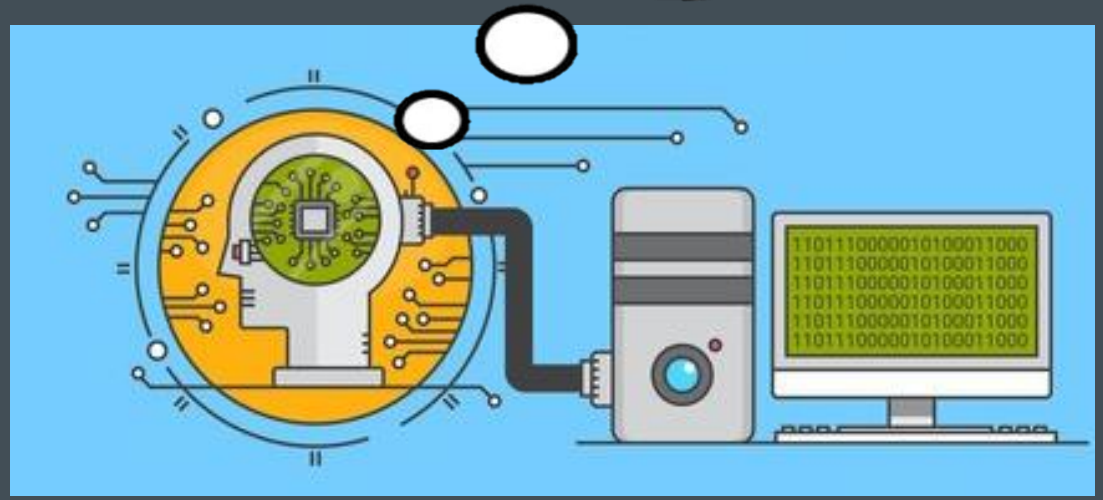
RFQ

- Electric Quadrupole (Split Coaxial)
  - Alternating voltage on vanes at RF
  - Vanes modulated for longitudinal effects
- Effects:
  - Acceleration
  - Bunching
  - Focusing

Use of Machine Learning

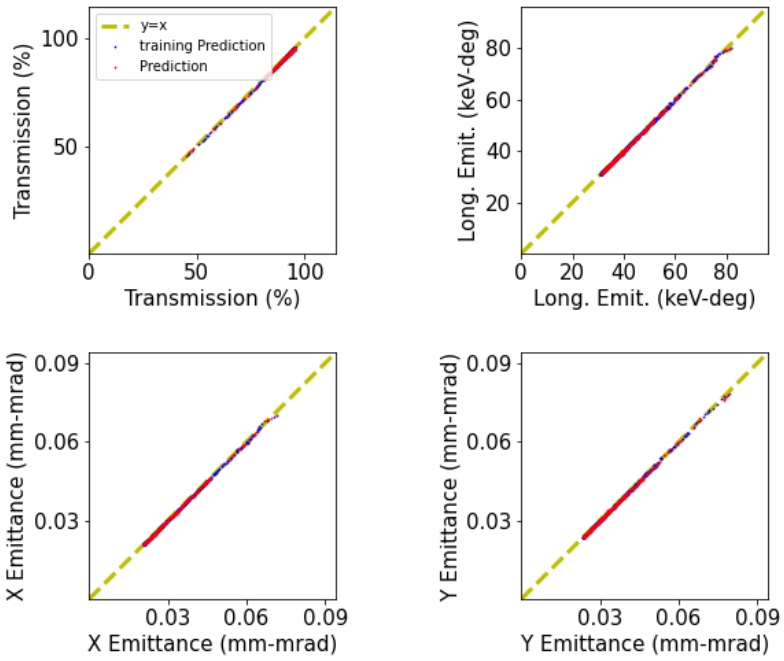
- Machine learning techniques to Model Accelerator System
  - Neural Networks
  - Polynomial Chaos Expansion
- Computational Speed Up
  - Sensitivity studies
  - Design Optimization

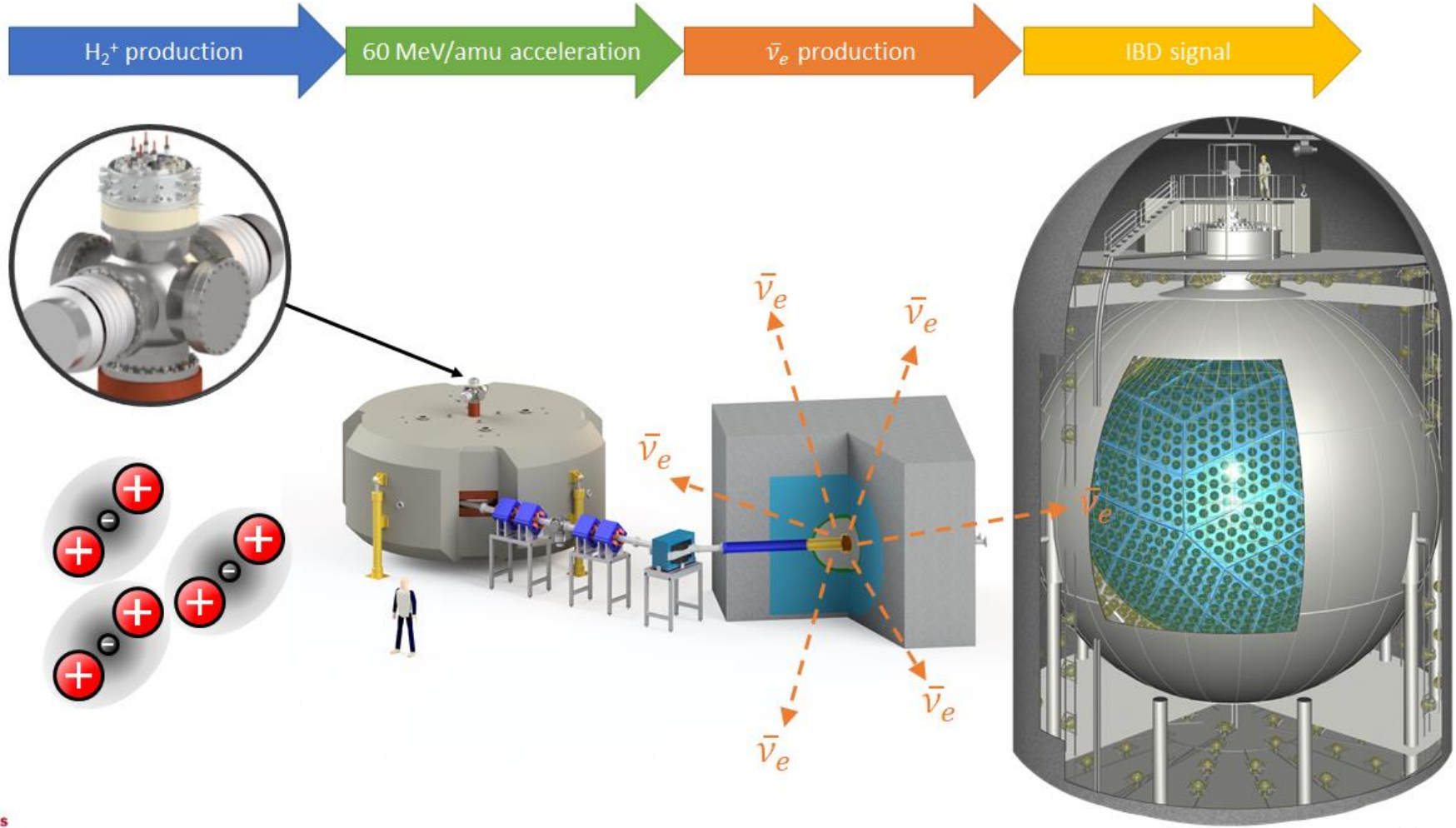




RFQ input parameters

- Neural Net able to reproduce RFQGen simulation at sub-percent level in
- Training data generated via RFQGen
    - Input of a series of varying input Twiss parameters
    - Output of Twiss parameters and transmission





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New Technology

- 3 Breakthroughs allow ground-breaking current and power
  - *note, PSI cyclotron, although 2.7 mA, is not compact
- Capable of applications beyond the scope of particle physics

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)	3.5	0.15	0.5

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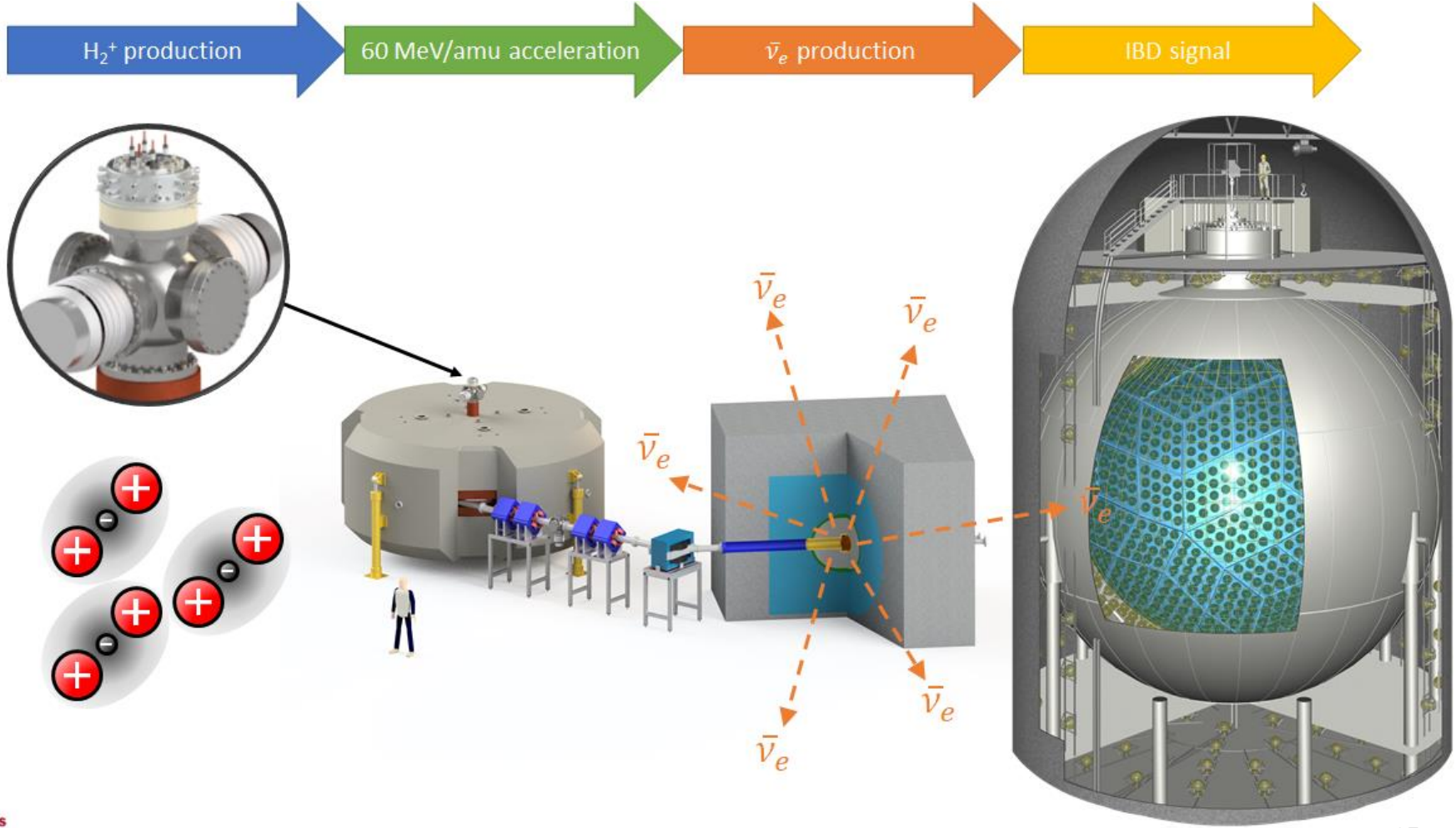

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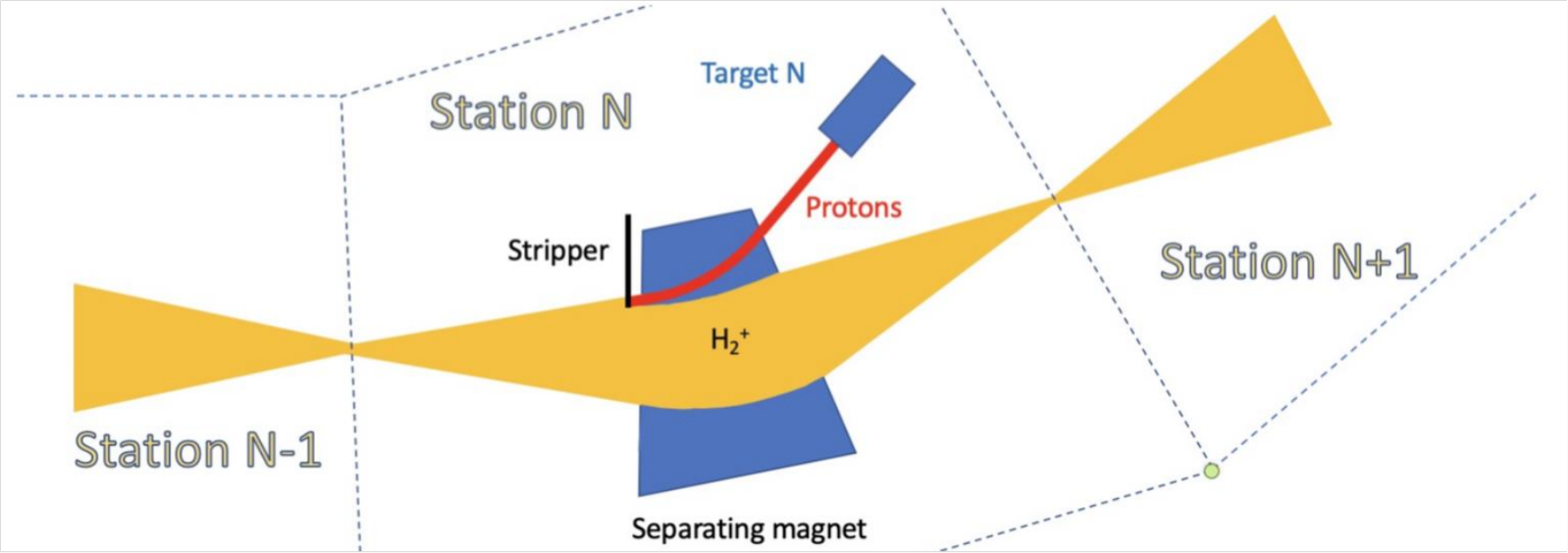
New Targets, New Applications

Target Limitations

600 kW beam vs. 60 kW Target

Target Management

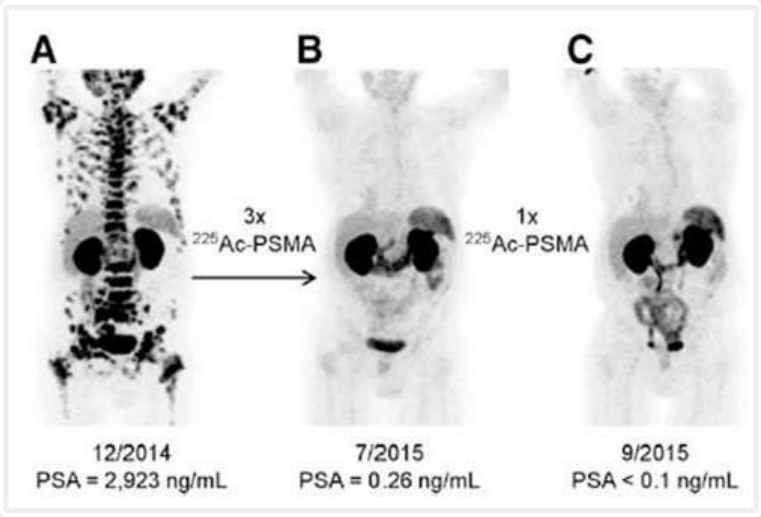
- Use of electron strippers to divide beam
- Can be done repeatedly



Example: ^{225}Ac

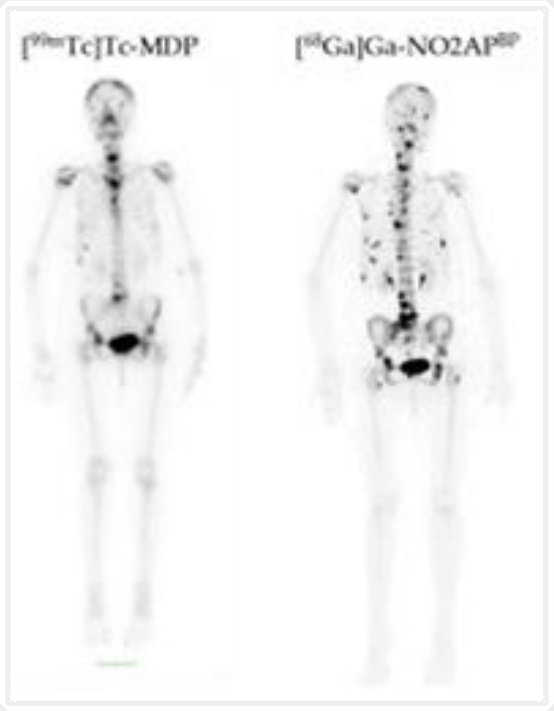
- Therapeutic alpha emitter (9.9 day half-life)
- Parent of chain to emit 4 X α ending with stable ^{209}Bi
- 50 μm radius of effect

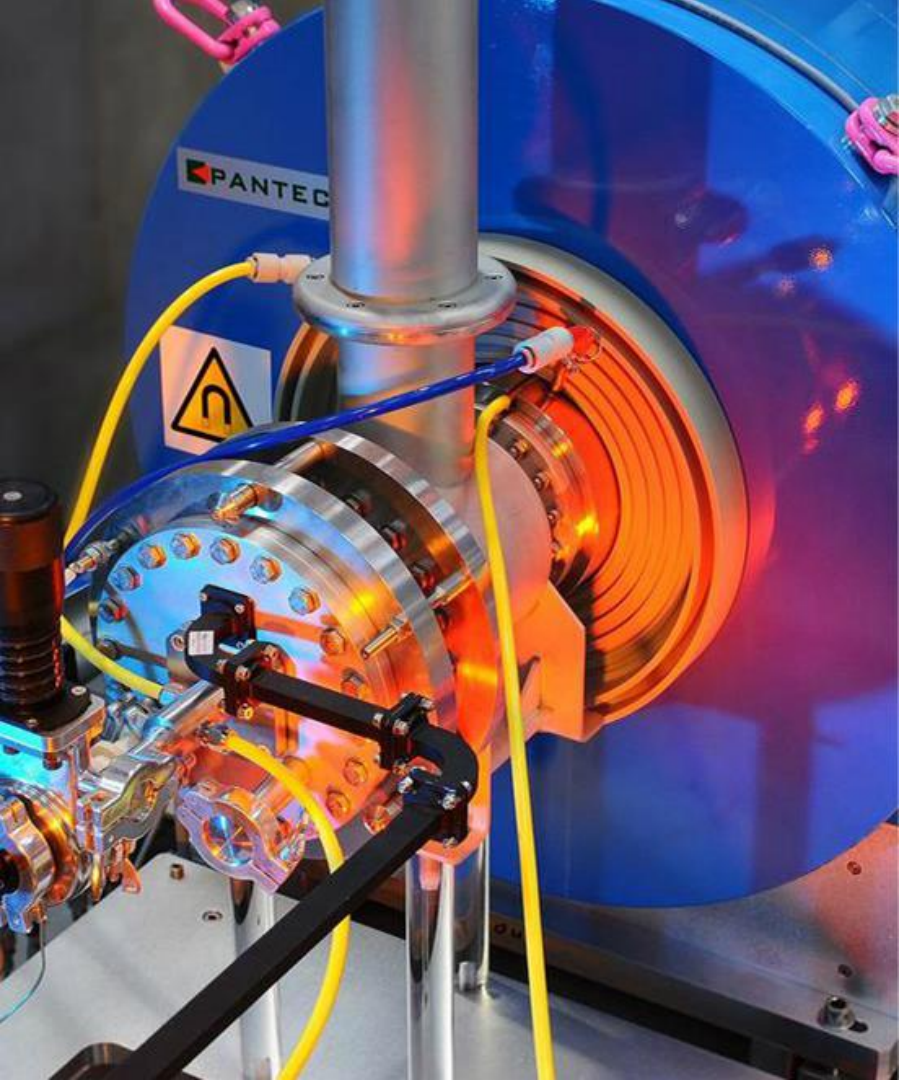
- BLIP and LANSCE at 100 μA would increase the world supply by 60 times (2012)
- IsoDAR production rate at 200mCi/hr



Example: $^{68}Ge/^{68}Ga$ Generator

- ^{68}Ge parent isotope (270 day half-life)
  - Decays to ^{68}Ga positron emitter (68 minute half-life)
- ^{99}Mo 66 hour half-life
  - ^{99m}Tc daughter 6 hour half-life
- 50 curies of ^{68}Ga parent /week
- Could eliminate need for rapid supply chain





Accelerating New Ions

- With minor tuning changes, can accelerate particles with the same charge/mass ratio
  - He^{++}, C^{6+} ,
  - There are commercially available ion sources for this (2.4 mA of alphas and 50 μA of C^{6+})
  - New Reactions

Conclusions

The requirements of an ambitious particle physics experiment have driven the development of new cyclotron technology. This development can grow beyond the scope of neutrino physics, and shift paradigms in the medical isotope community.

IsoDAR not only has the opportunity to change physics, but also has the opportunity to change lives.

Conclusions

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References:

- Slide 11: de Kerret, Hervé, et al. "Double Chooz θ13 measurement via total neutron capture detection." *Nature Physics* 16.5 (2020).
- Slide 17: Cirkel-Bartelt, Vanessa. "History of astroparticle physics and its components." *Living Reviews in Relativity* 11.1 (2008): 1-58.
- Slide 21: Kleeven, Wiel. "Some examples of recent progress of beam-dynamics studies for cyclotrons." *Proceedings of the 21st International Conference on Cyclotrons and their Applications, Zurich, Switzerland, 2016, WEA01*.
- Slide 30: https://www.iberdrola.com/innovation/machine-learning-automatic-learning
- Slide 39: Pfannkuchen, Nina, et al. "Novel radiolabeled bisphosphonates for PET diagnosis and endoradiotherapy of bone metastases." *Pharmaceuticals* 10.2 (2017): 45.
- Slide 40: Krtochwil JNM 2016 and 2017
- Slide 41: https://www.pantechnik.com/ecr-ion-sources/

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