Update on DAEδALUS and IsoDAR: Coupled cyclotrons for high intensity H_2^+ beam production

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Outline

Introduction

- 3-Page Neutrino Crash-Course
- DAEALUS & IsoDAR Facilities Overview

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- Challenges
- Recent Tests/Experiments
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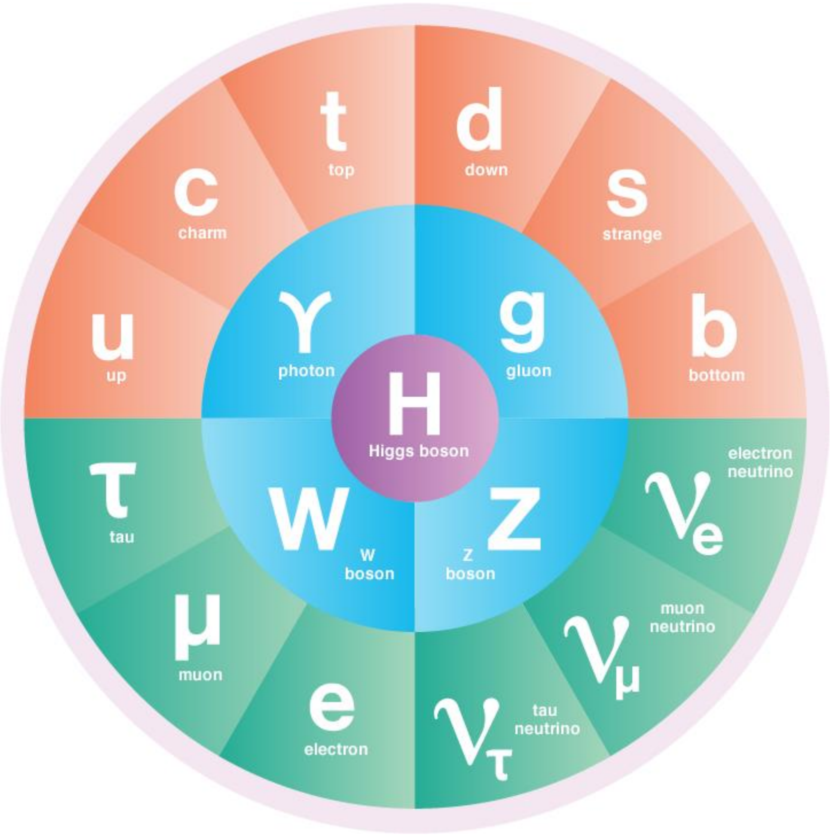
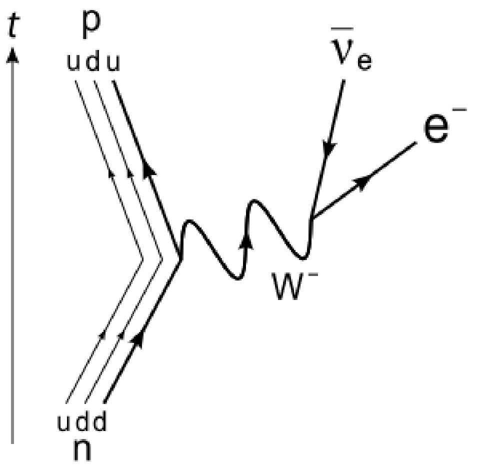
Neutrinos in the Standard Model



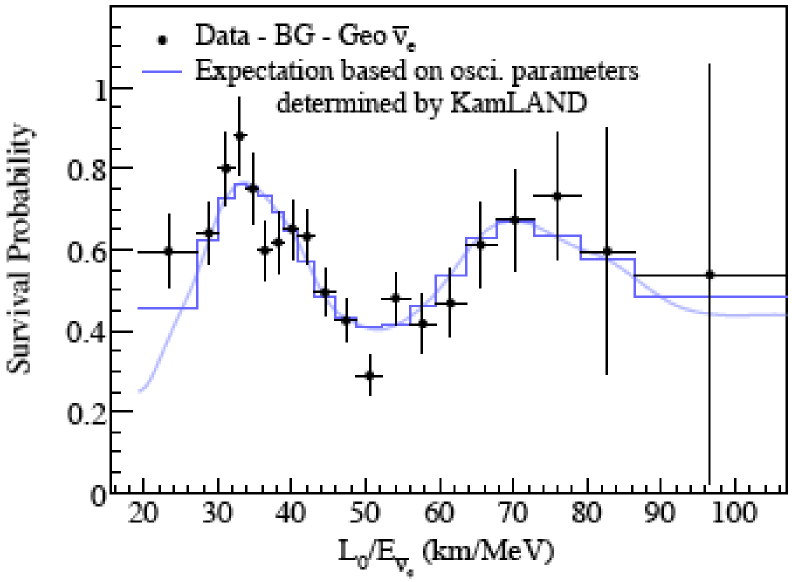
Source: symmetrymagazine.org

- Part of lepton weak doublets
- Three flavors (+ anti-particles)
- Only interact through weak force (CC, NC) (no e/m, no strong force, no mass)
- E.g.: Beta – decay:



Neutrinos Oscillations

- Seen 1998 in SuperK experiment
- Confirmation by SNO in 2001
- KamLAND measurements of electron antineutrino disappearance from a reactor (2003) (picture)



- Mixing:

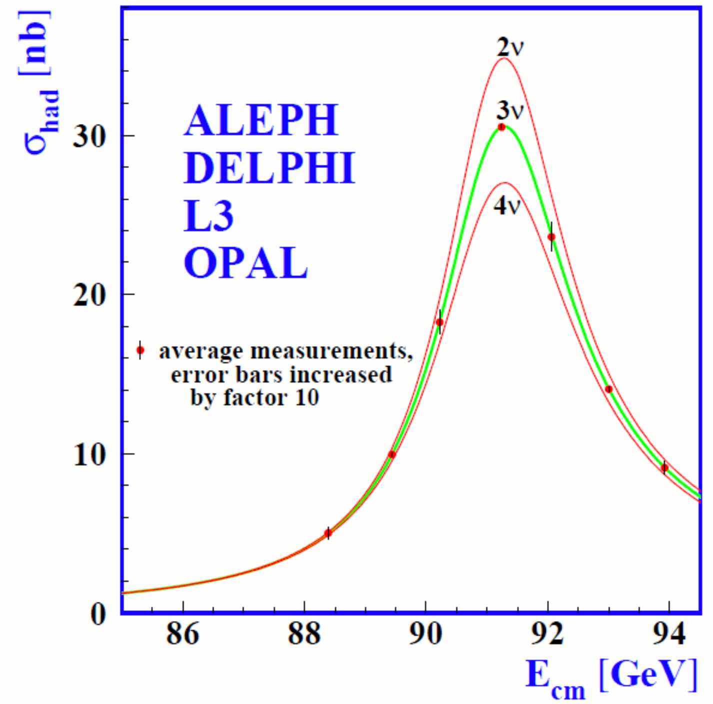
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

- Mass!
- CP violation?

Sterile Neutrinos

- The width of the Z boson shows us that there are only 3 flavors of neutrinos that interact via the weak force
- Reactor experiments indicate that there is a deficit in the electron flavored neutrinos
- Calibration source experiments confirm this
- Data from low L/E oscillation experiments observe ~3 sigma excess in ν_e and $\bar{\nu}_e$.
- Other type of neutrino could participate in oscillation → Sterile Neutrinos



Massachusetts Institute of Technology

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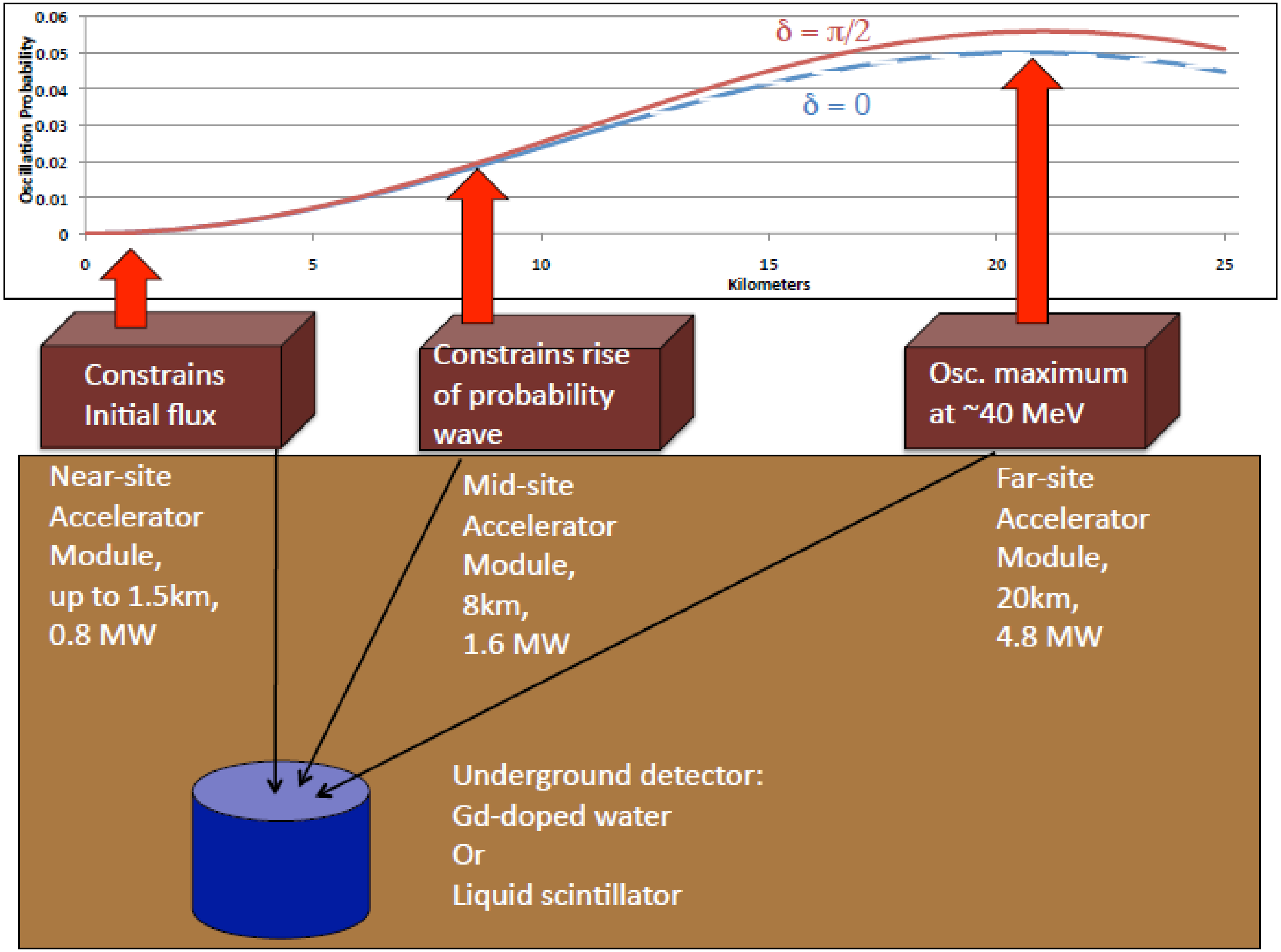
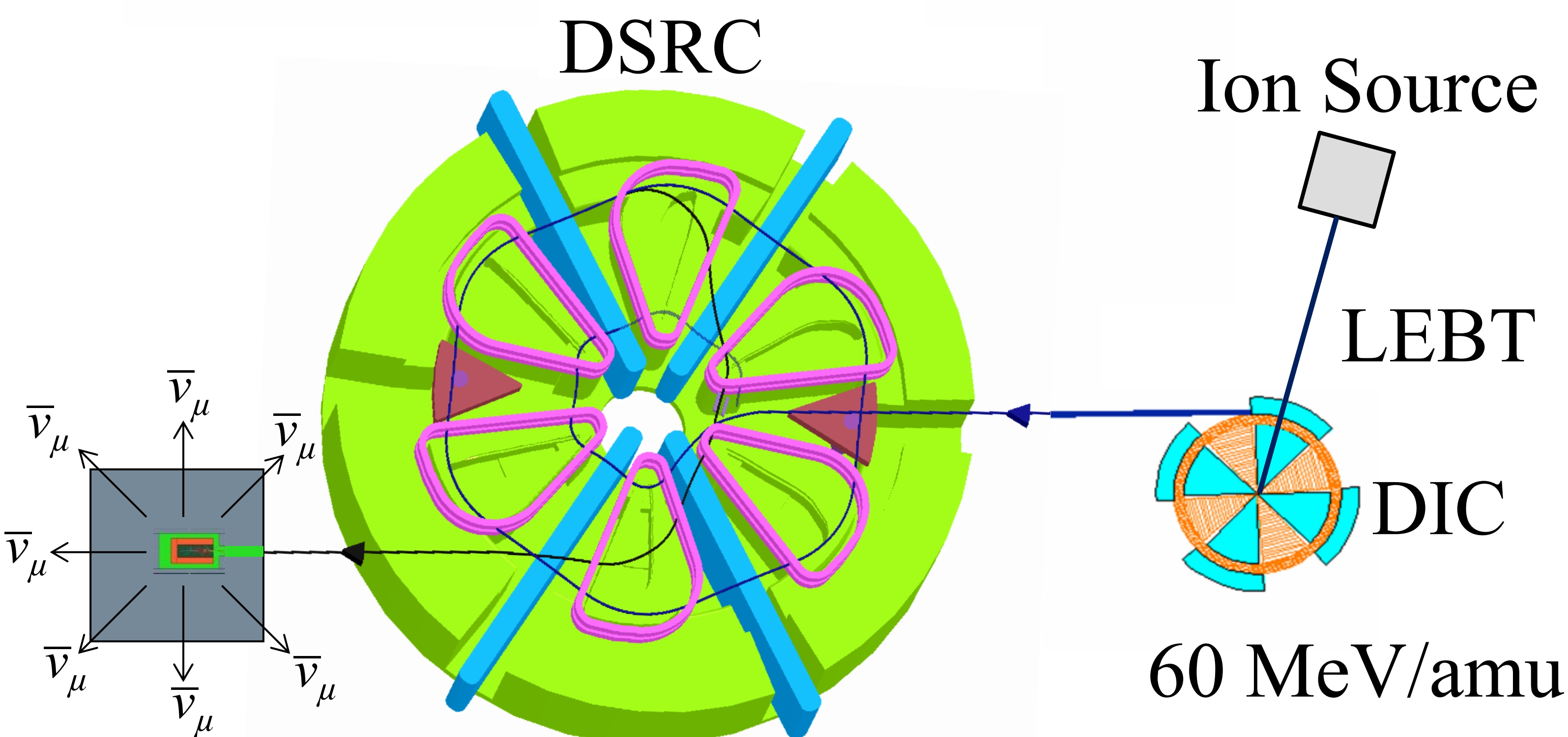
DAEδALUS – CP Violation – $\bar{\nu}_e$ appearance

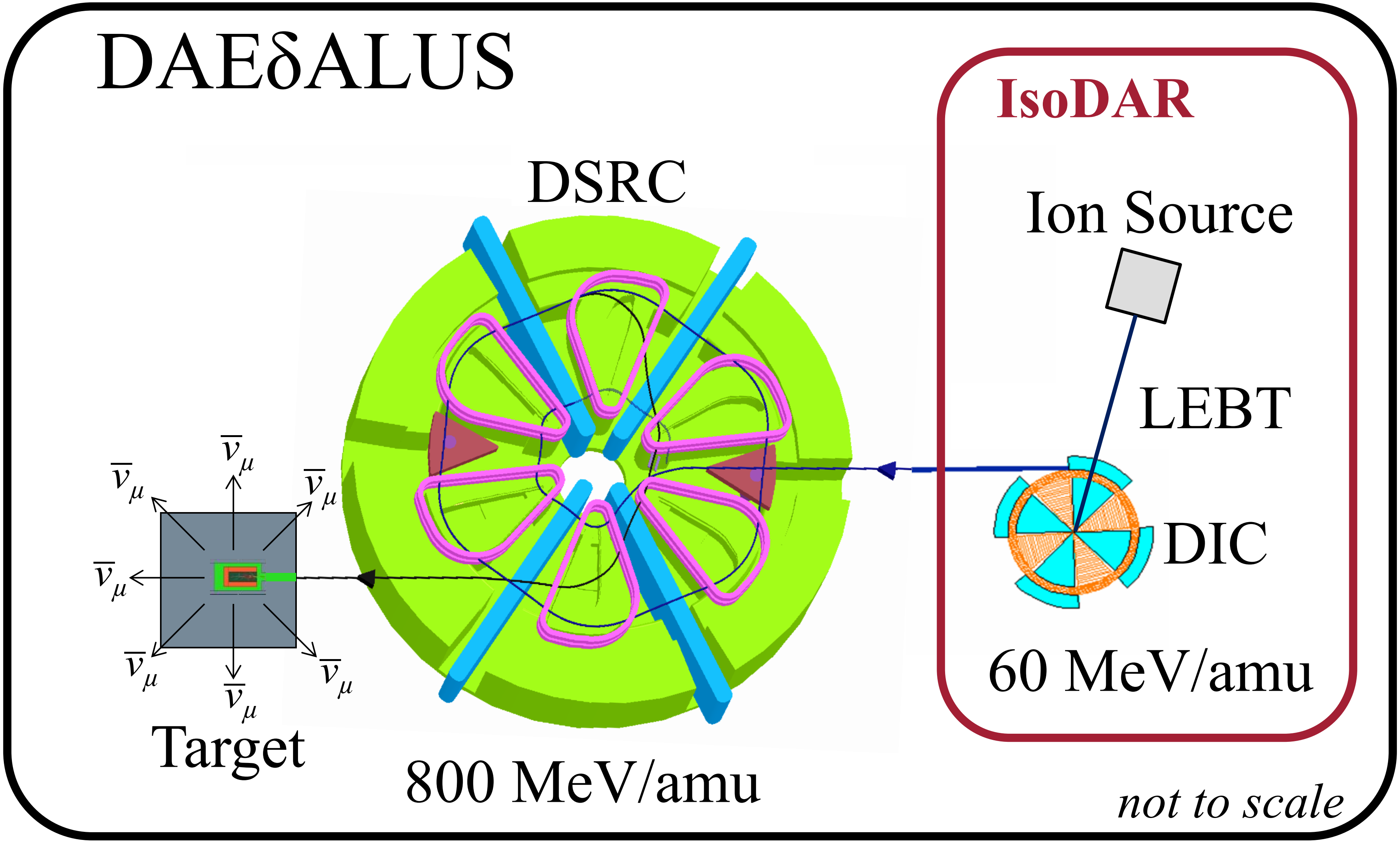


DAEδALUS Overview

DAEδALUS

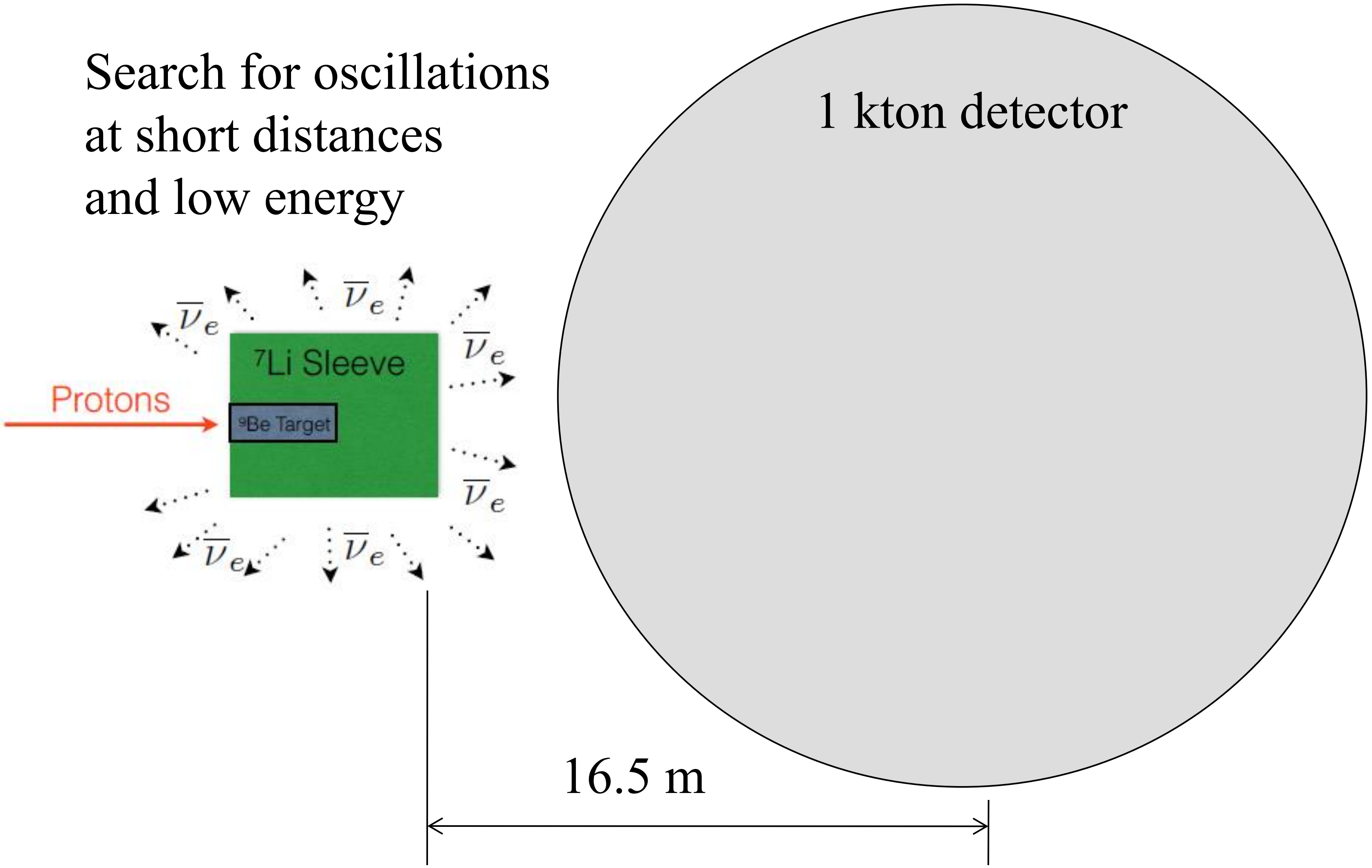


DAEδALUS + IsoDAR



IsoDAR – Sterile ν's – $\bar{\nu}_e$ disappearance

Search for oscillations
at short distances
and low energy



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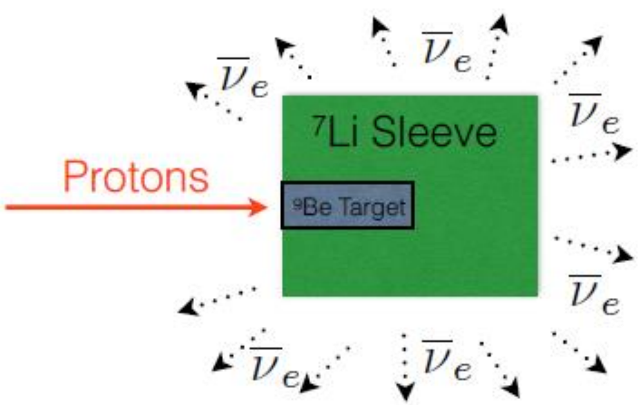

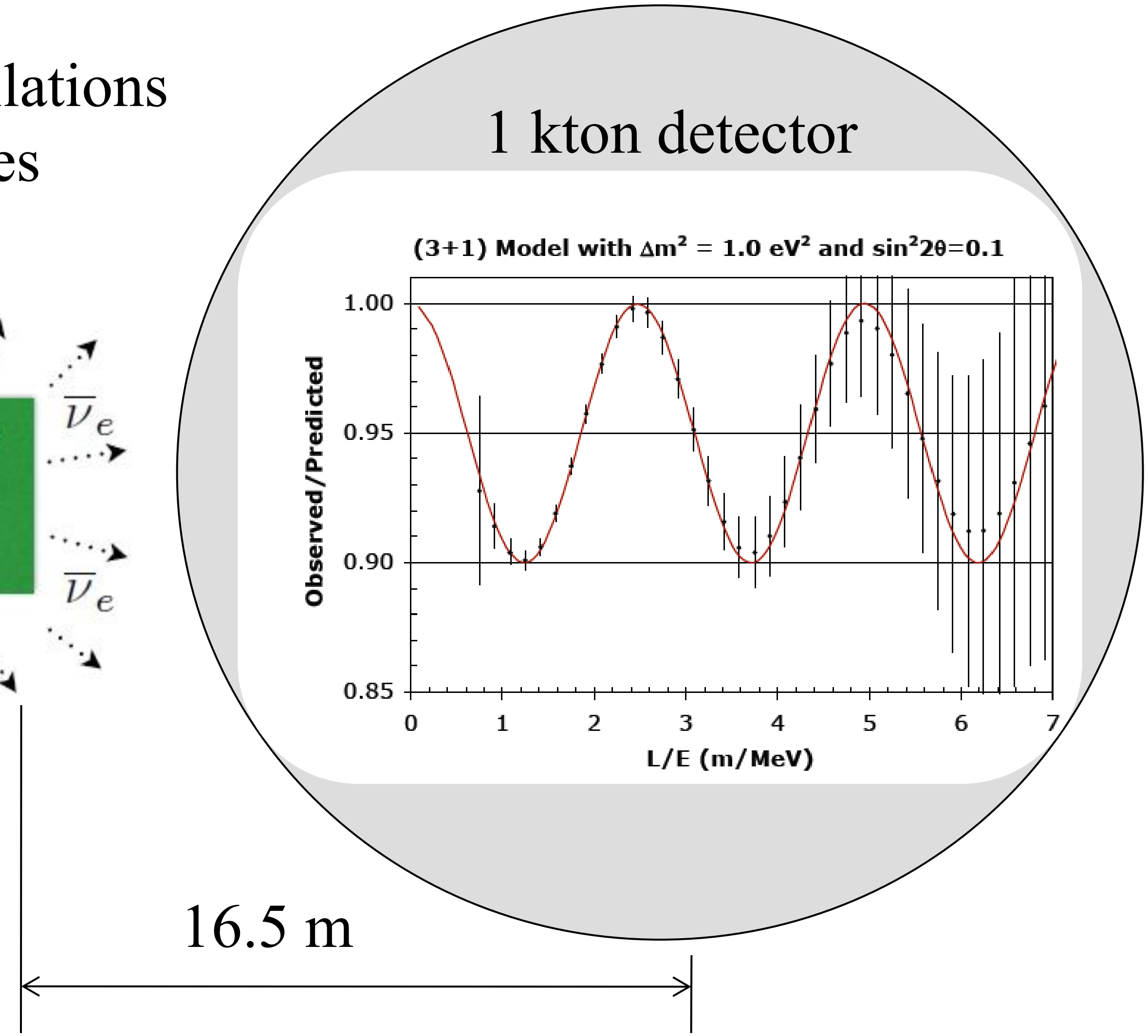

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Challenges

- In order to yield results within a reasonable time-frame, we would like to have 10 mA of protons on target for 5 years continuously.
- IsoDAR: 90% duty cycle, DAEδALUS: 20%.
  - Clearly targets are going to be an issue at 600 kW and 1.2 MW, respectively.
  - Columbia University and Bartoszek engineering are working on this, not part of this talk, but understood to be a challenge.

Challenges

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- IsoDAR: 90% duty cycle, DAEδALUS: 20%.
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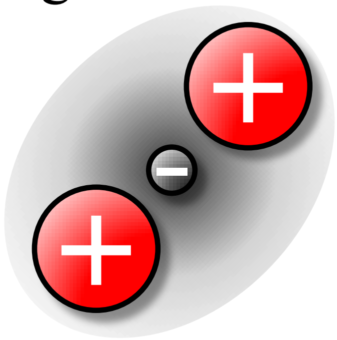
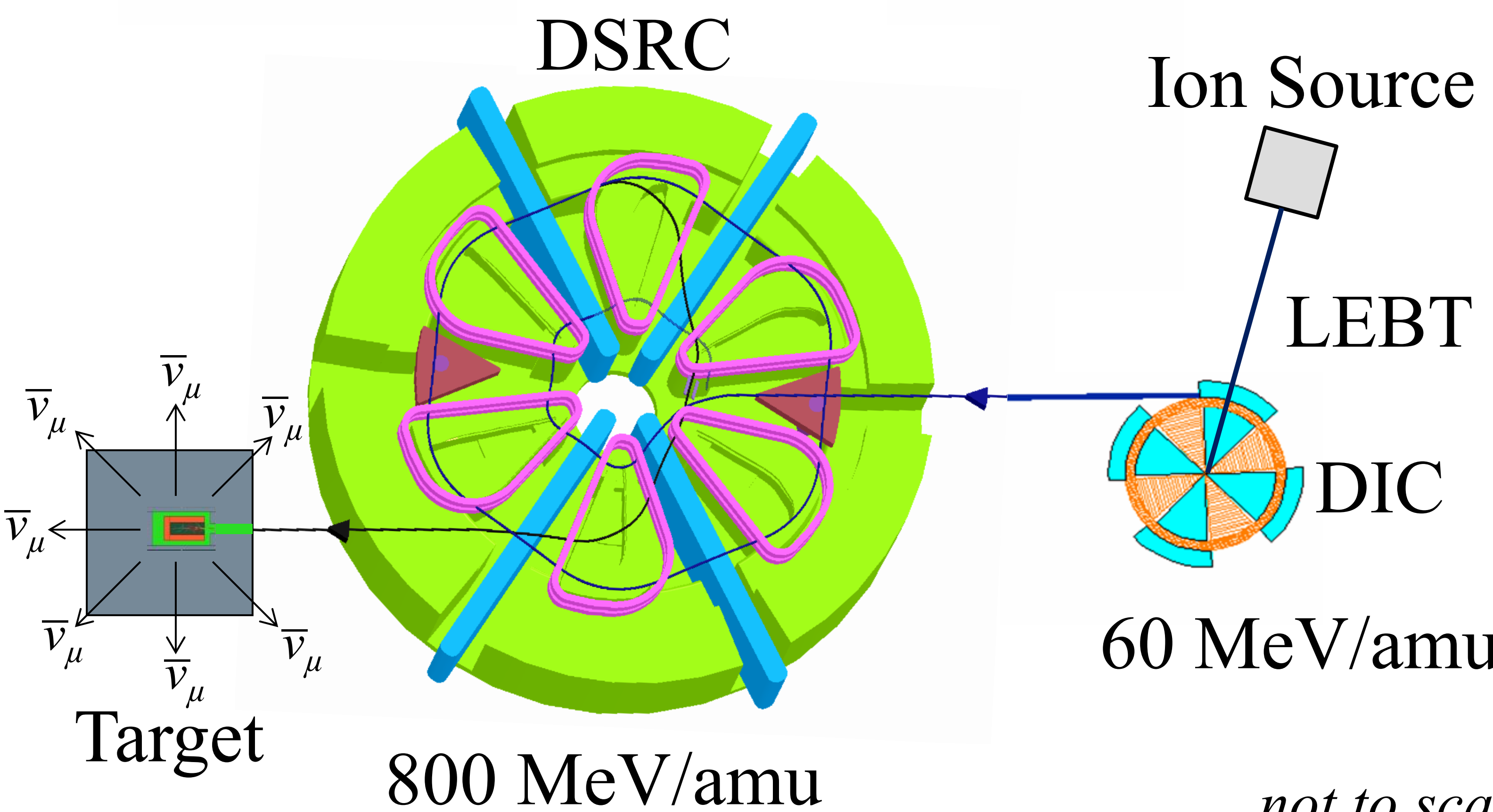
- Main Challenge to consider: Space Charge!
  - Mitigate by accelerating H_2^+
  - Half the electrical current for same particle current (protons after stripping)
  - Higher rigidity has to be accounted for.



Going from End to Start

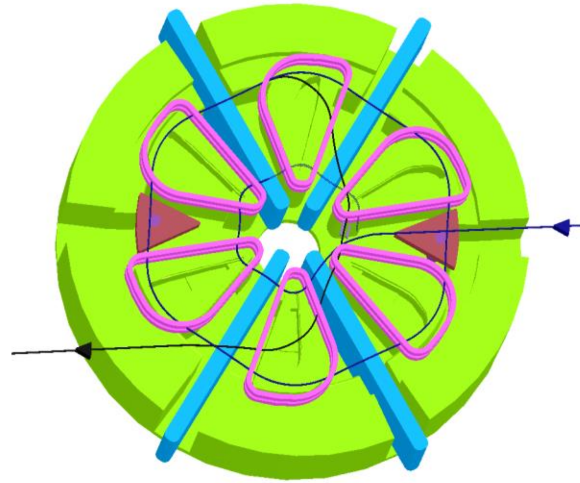
DAEδALUS

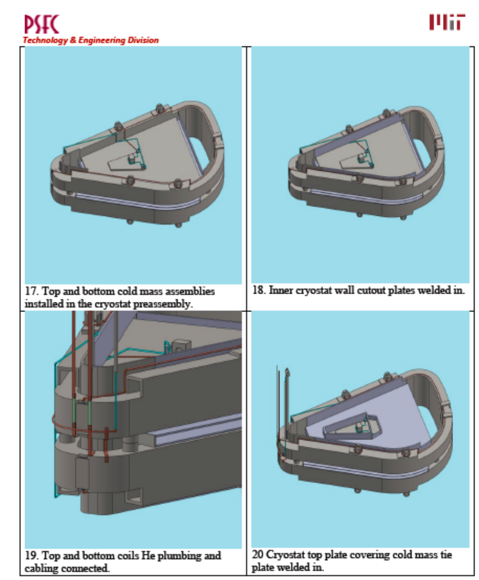


not to scale

DAEδALUS Superconducting Ring Cyclotron

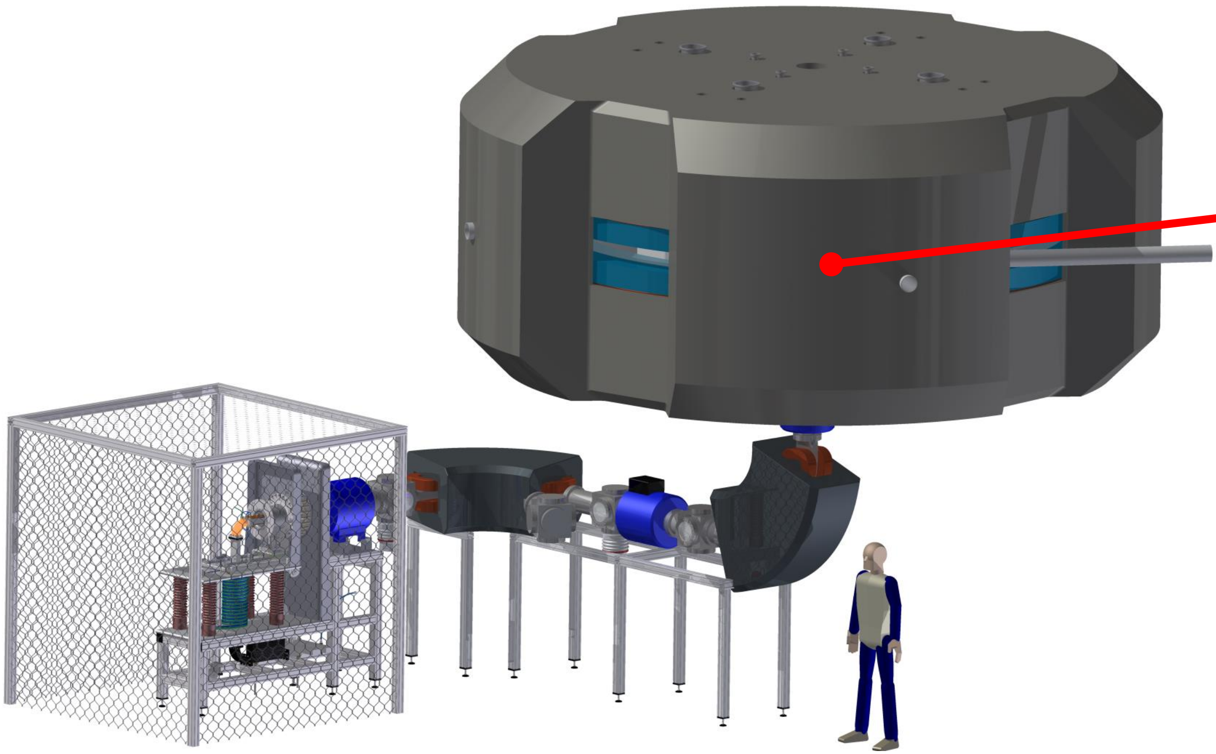
- Previously: 8 sector design
- Have solid beam dynamics calculations using OPAL for 8 sector. Stationary distribution develops, stripping extraction of H_2^+ yields excellent extraction efficiency.
- After magnet design study by PSFC (MIT) we changed design to 6-sector.
- 6-Sector beam dynamics pending.
- Main challenge: Vibrational states.

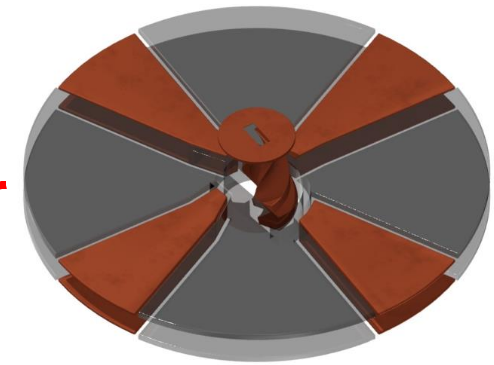


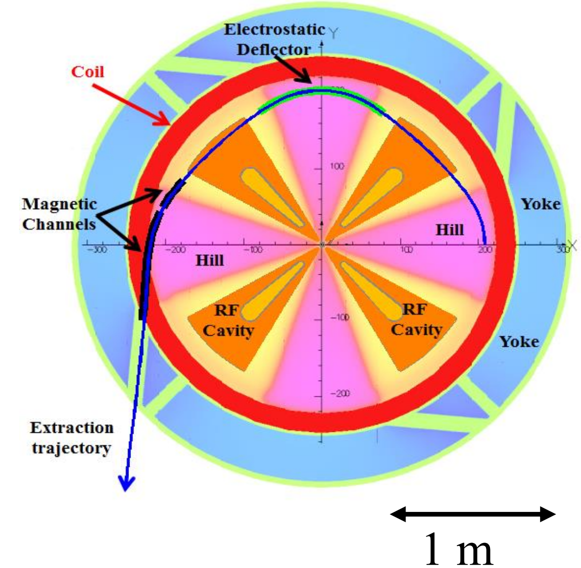


Parameter	Value	Parameter	Value
Ion	H_2^+	Injection	Radial
Cycl. Freq.	42.1 MHz	Harmonic	6
Cycl. Type	Ring	E_{max}	800 MeV/amu
Extraction	Stripping	$I_{cycl., extr.}$	5 mA avg.

Conceptual Layout of IsoDAR Driver



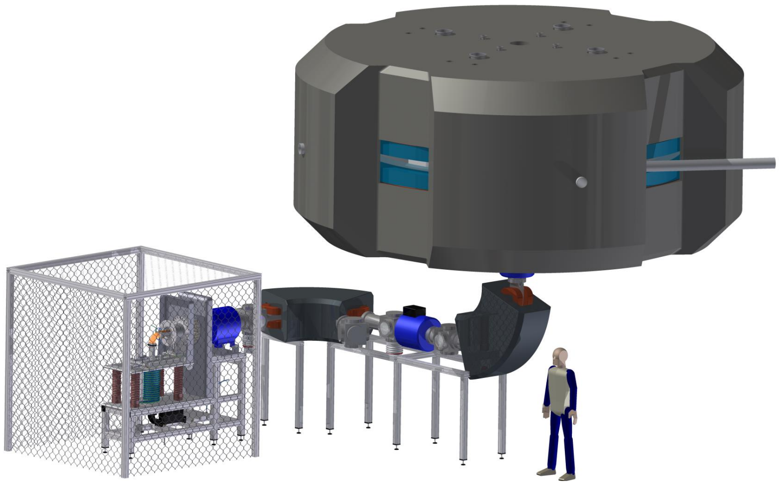




Parameter	Value	Parameter	Value
Ion	H_2^+	Ion Source	Multicusp
$I_{source, nom.}$	35 mA DC	Injection	Spiral Infl.
Cycl. Freq.	42.1 MHz	Harmonic	6
Cycl. Type	Compact	E_{max}	60 MeV/amu
Extraction	Septum	$I_{cycl., extr.}$	5 mA avg.

Immediate Concerns with High Intensity?

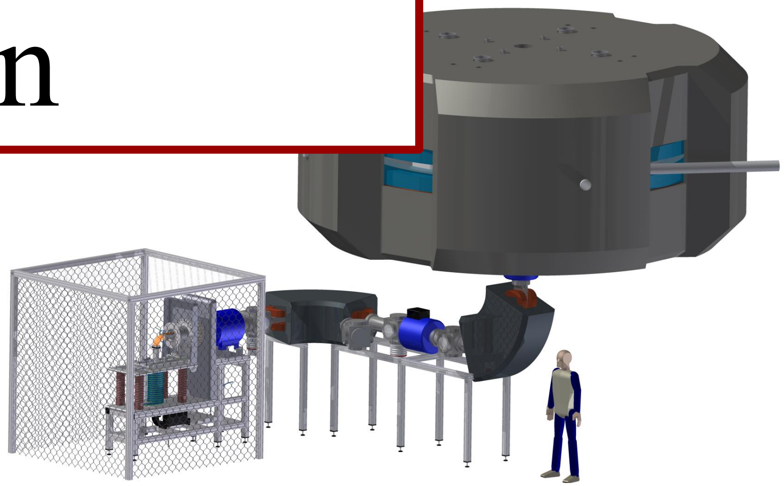
- 600 kW beam power
  → Worry about *uncontrolled* beam losses in the Cyclotron.
- 7 – 10% injection efficiency
  → Need 35-50 mA at injection to extract 5 mA.
- Space Charge in Cyclotron.
  - More Space Charge in Spiral Inflector.
  - Space Charge in LEBT.
  - Space Charge Compensation in LEBT?
- Can we transport that much without emittance becoming larger than acceptance?
- Can we produce that much in source?



Immediate Concerns with High Intensity?

- 600 kW beam power → Worry about *uncontrolled* beam losses in the Cyclotron.
- 5 – 10% injection efficiency → Need 50 mA at injection to extract 5 mA.
- Space Cha
  - More S
  - Space C
  - Space C
- Can we transport that much without emittance becoming larger than acceptance?
- Can we produce that much in source?

- Tests/Experiments
- Simulations
- Comparison



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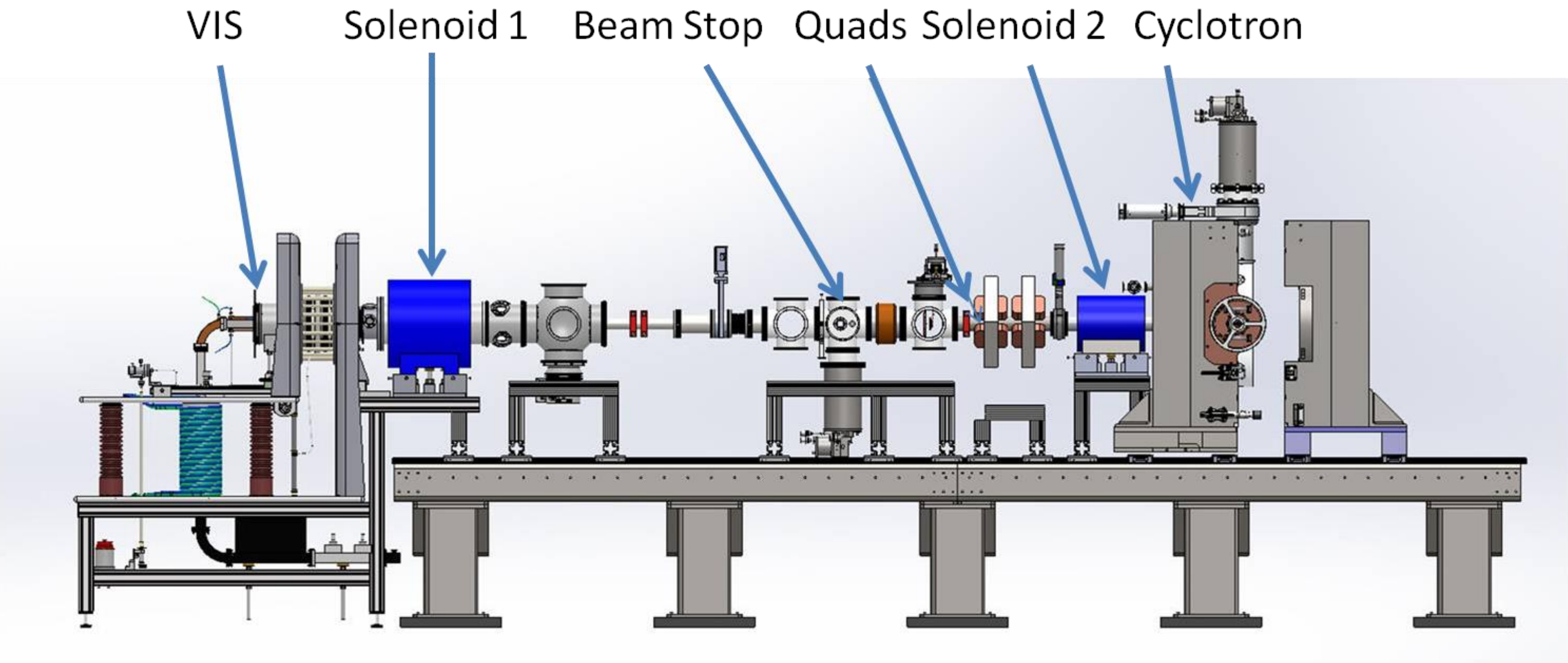
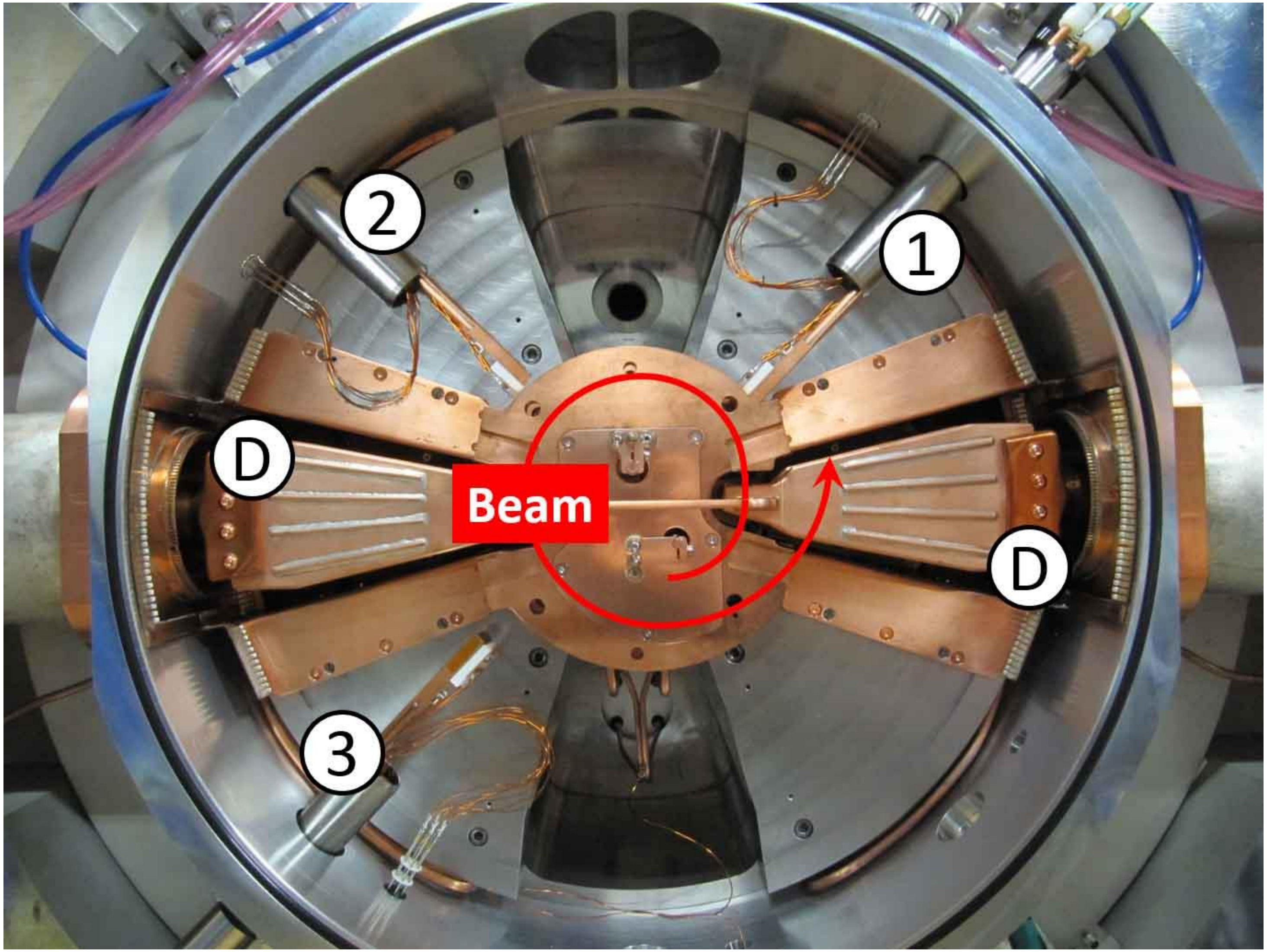
Injection Tests at Best Cyclotron Systems, Inc.



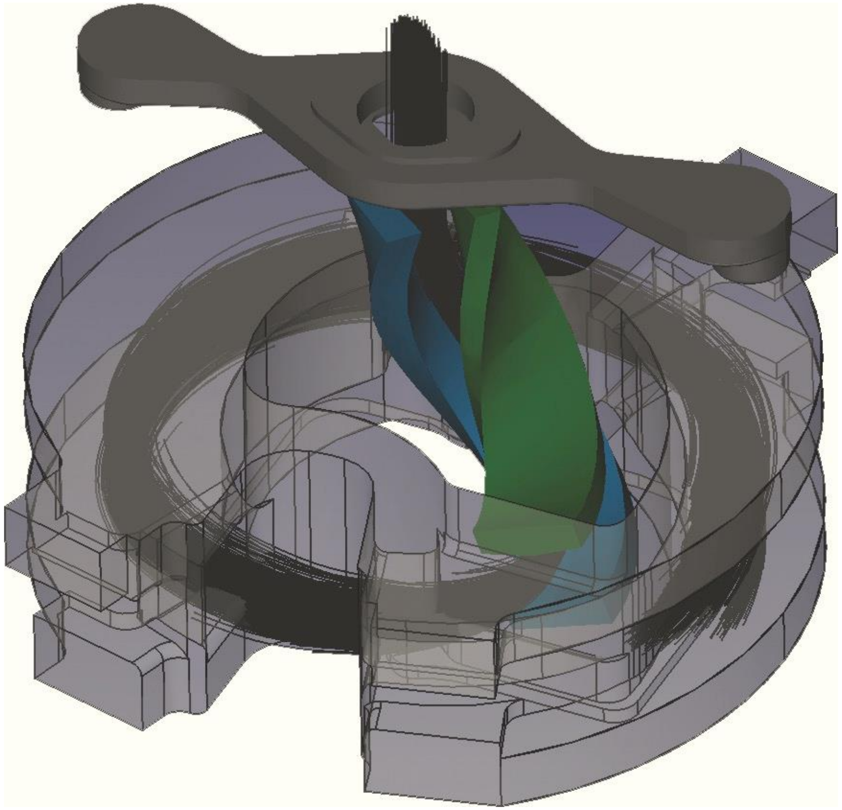
Versatile Ion Source (VIS) loaned from INFN
Cyclotron + Teststand provided by Best Cyclotron Systems, Inc. (BCS)

Injection Tests



Injection Tests

- First, look at beam through spiral inflector
- 8 mA before, 7.5 mA inside
  → 94% transmission
- Then accelerate
- Unfortunately, RF system did not manage to get to full power, only 50 out of 70 kV Dee voltage
- Measured beam currents on radial probes



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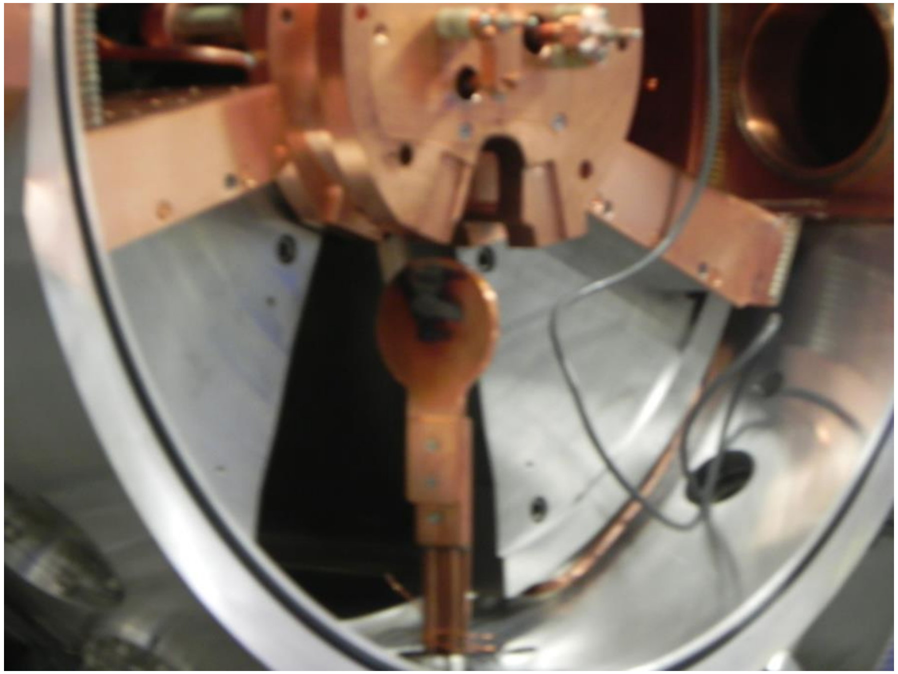
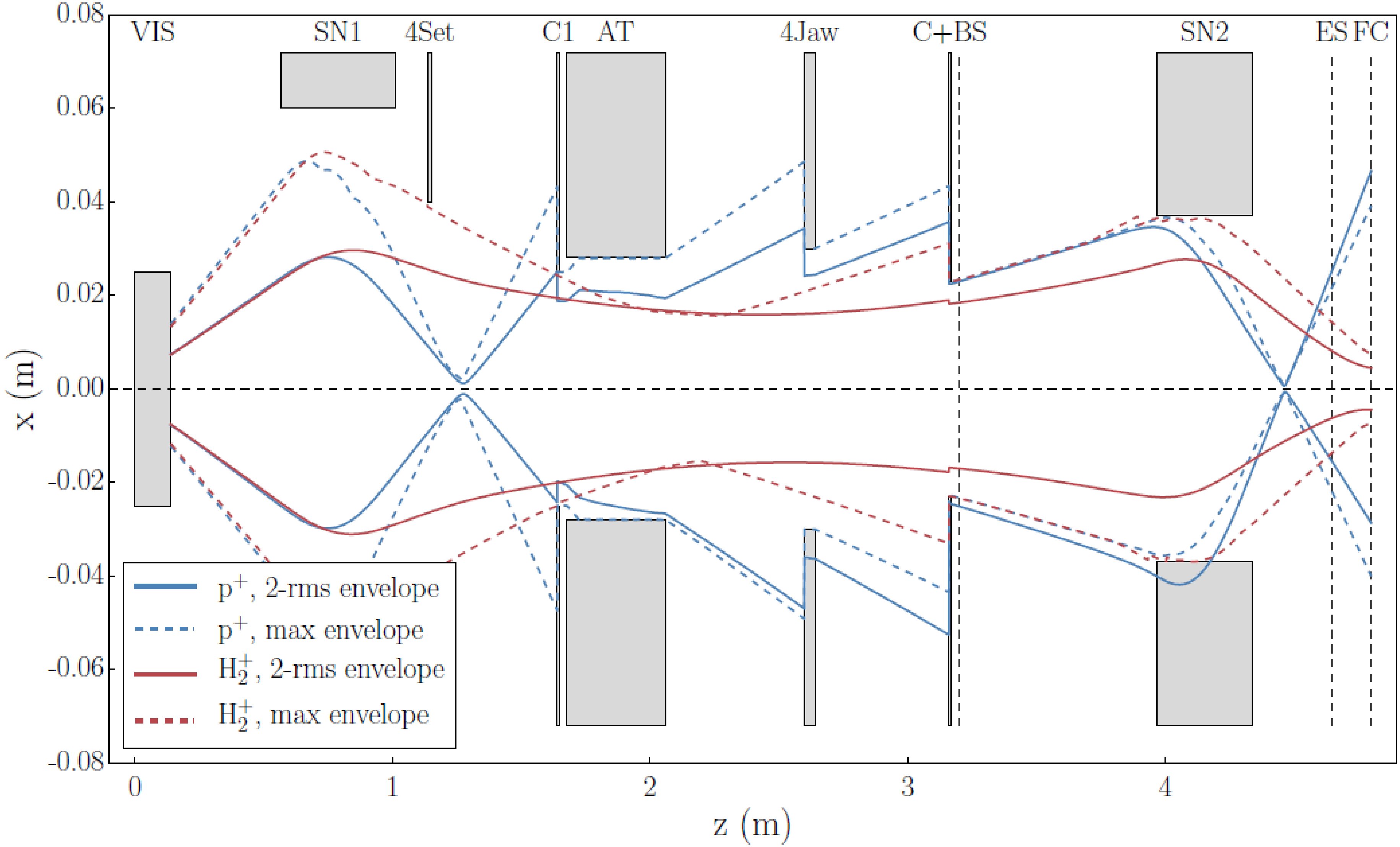


Accelerated 100 μA for four turns in test cyclotron @50 kV V_{Dee}

Good agreement of LEBT Simulations/Exp.



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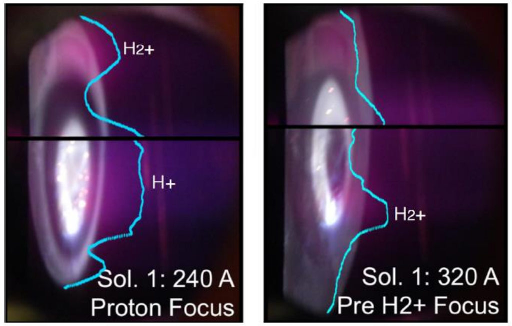
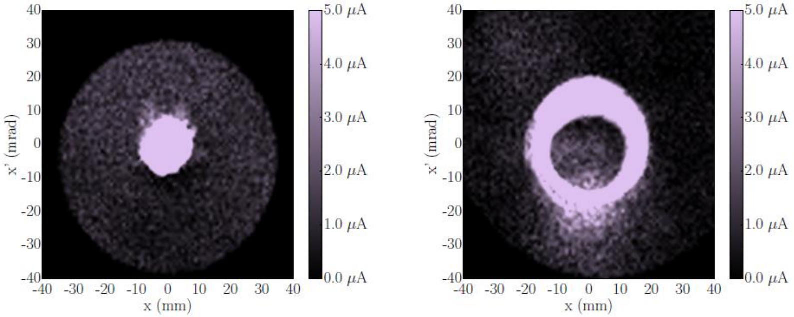
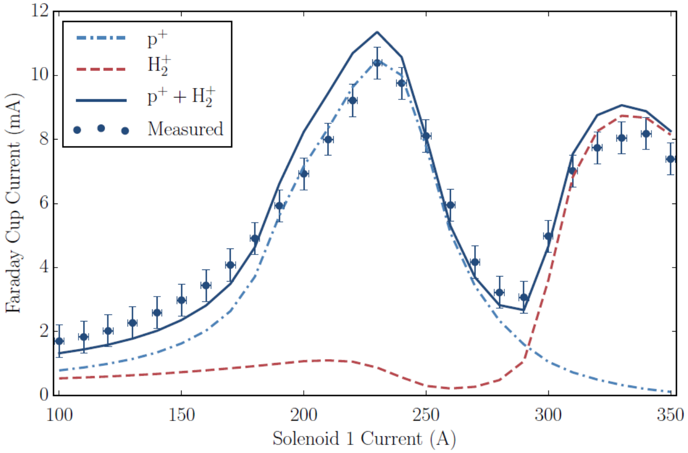
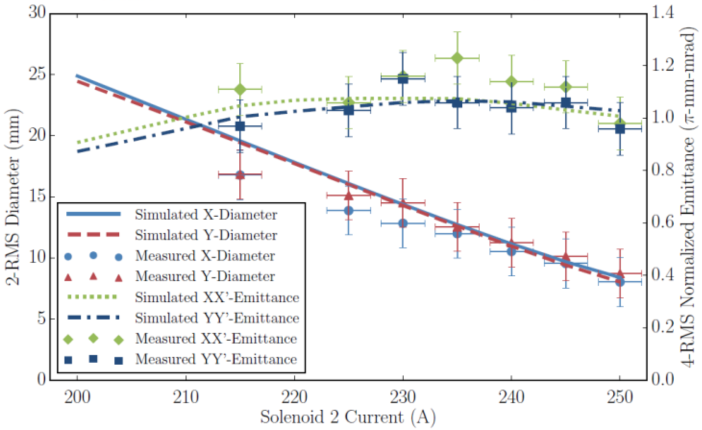


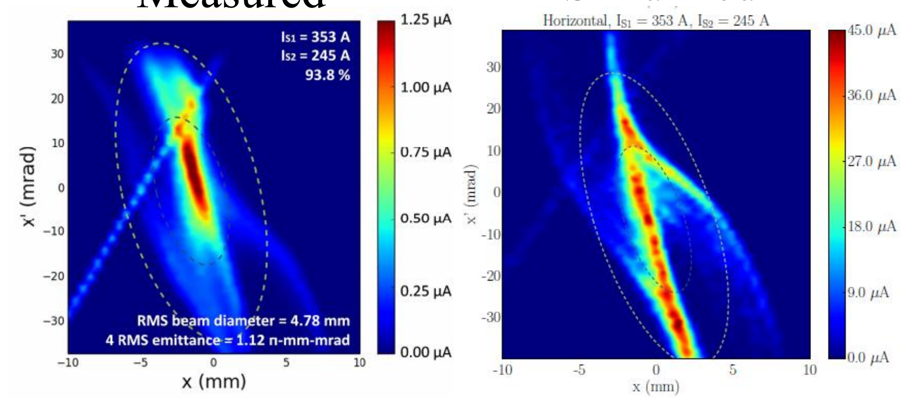






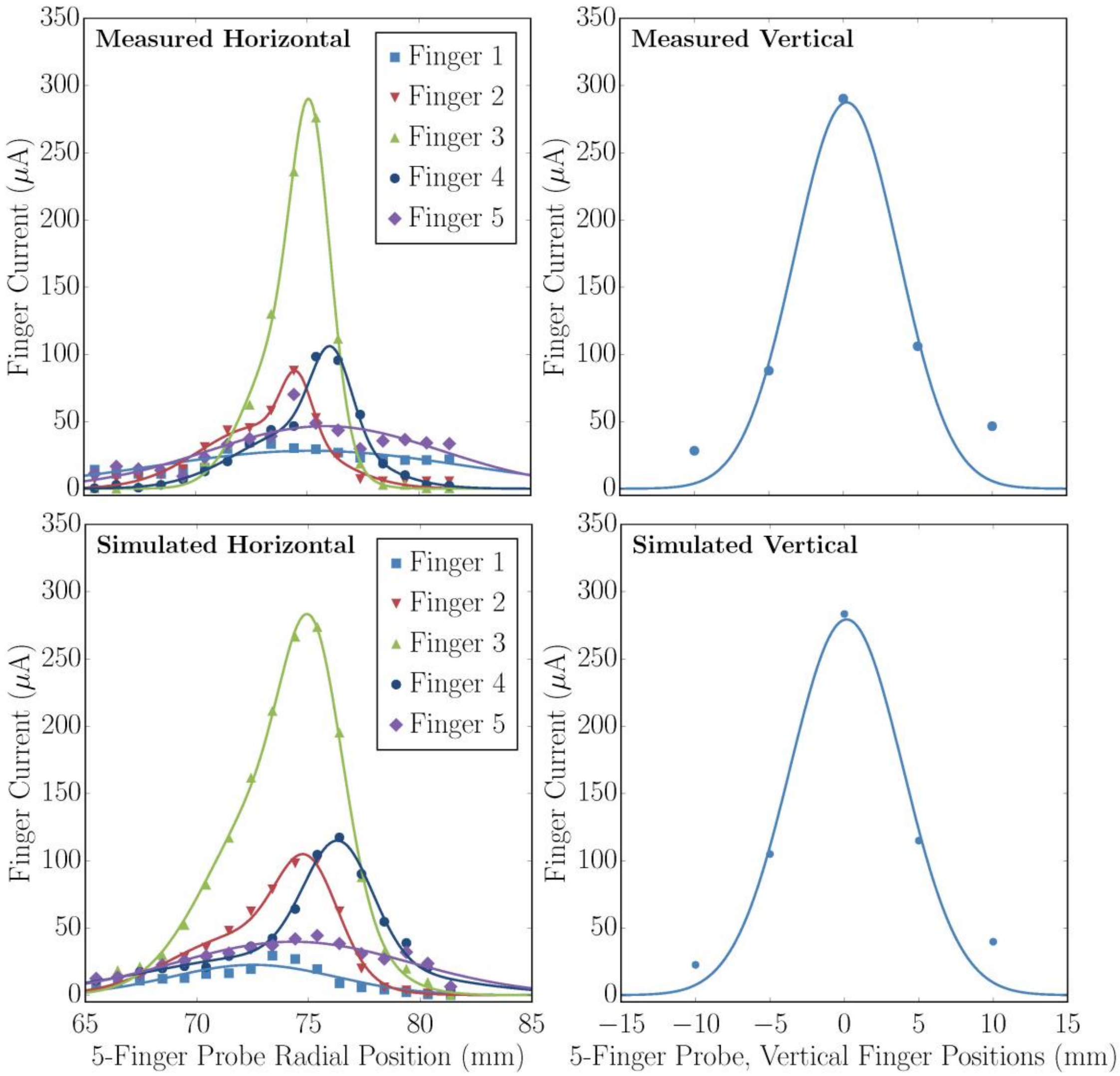
Measured

Simulated



Five Finger Probe

- At position of Probe 1
- Noticeable shoulder on the right, due to insufficiently accelerated ions
- Overall good qualitative agreement
- FWHM not in as good agreement, most likely due to probe geometry.



Summary of Tests

- We did beam tests with a slightly modified version of the IsoDAR Spiral Inflector at BCS in Vancouver.
- Showed > 95% transmission at 6-8 mA
- Showed ~1% acceptance (~100 μA) in RF bucket (due to reduced V_{Dee})
- Compares well with simulations.
- OPAL runs with up to 50 mA show reduction in Transmission + RF Capture from ~10% to ~5%. This will be addressed:
  - Final IsoDAR Spiral Inflector will be slightly larger.
  - Central region will have better vertical focusing.
  - Cyclotron will run 4 double gap cavities in 6^{th} harmonic.
  - Simulations can be tuned better to match highest intensity (for now, just used beam values from BCS tests to match results).
- Finally, close start-to-end gap by using spiral inflector results in main cycl.

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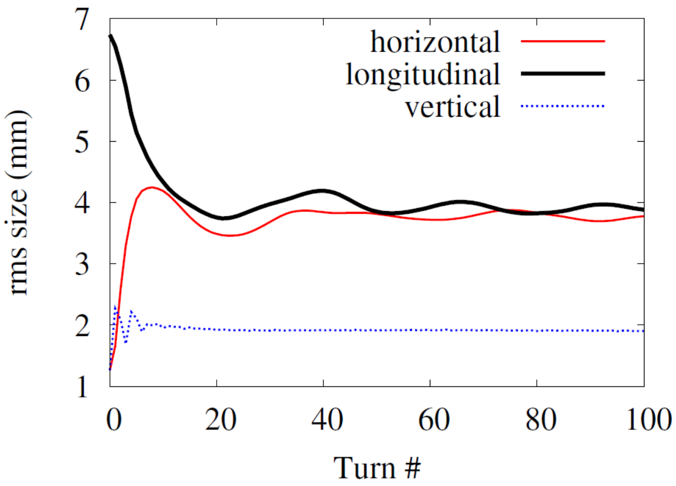
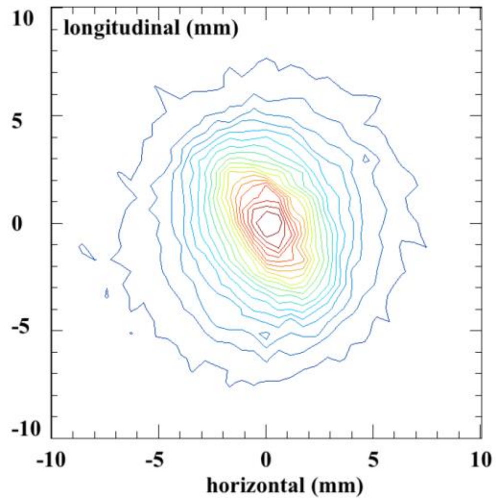
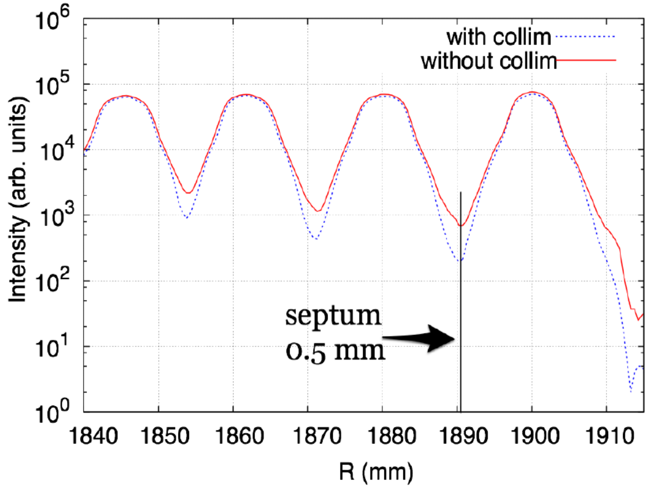
Previous Simulation Work

- Previously, we showed simulations using the PIC code OPAL (see tomorrow's talk by A. Adelmann) for both DIC and DSRC [Yang et al.]
- For the DIC these started at 1.5 MeV/amu.
- Showed formation of a stationary, almost round, horizontal particle distribution (vortex motion) from initially mismatched distribution,
- Showed good turn separation at extraction (beam losses on septum < 200 W)

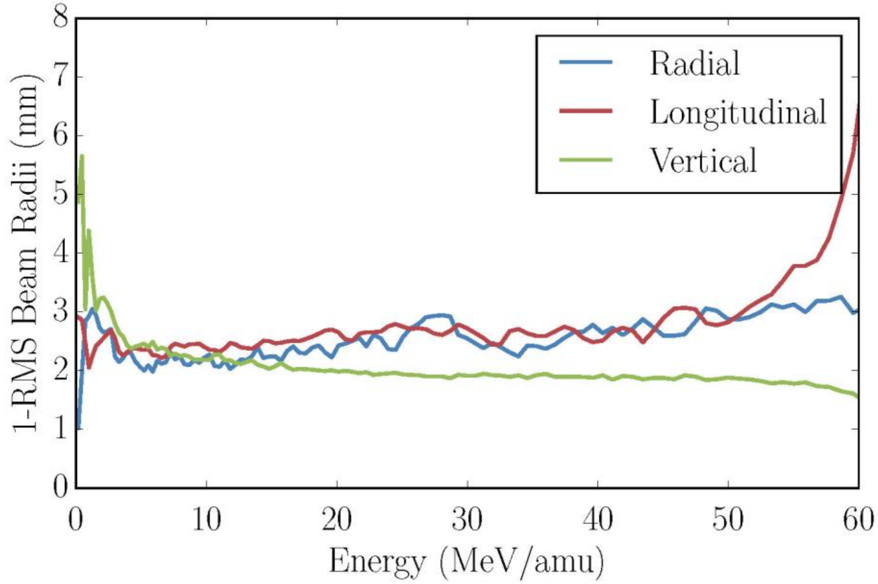






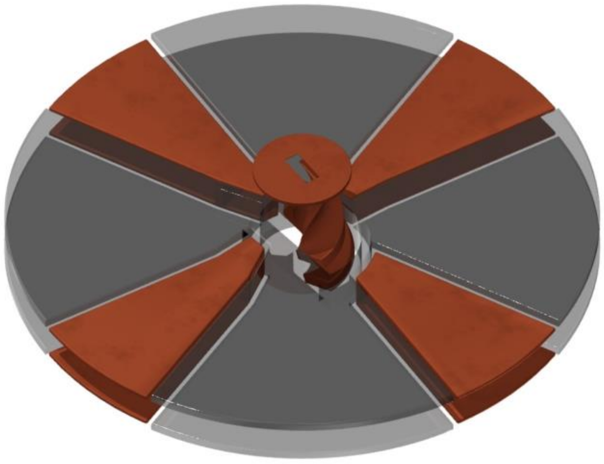
Current Simulation Work - DIC

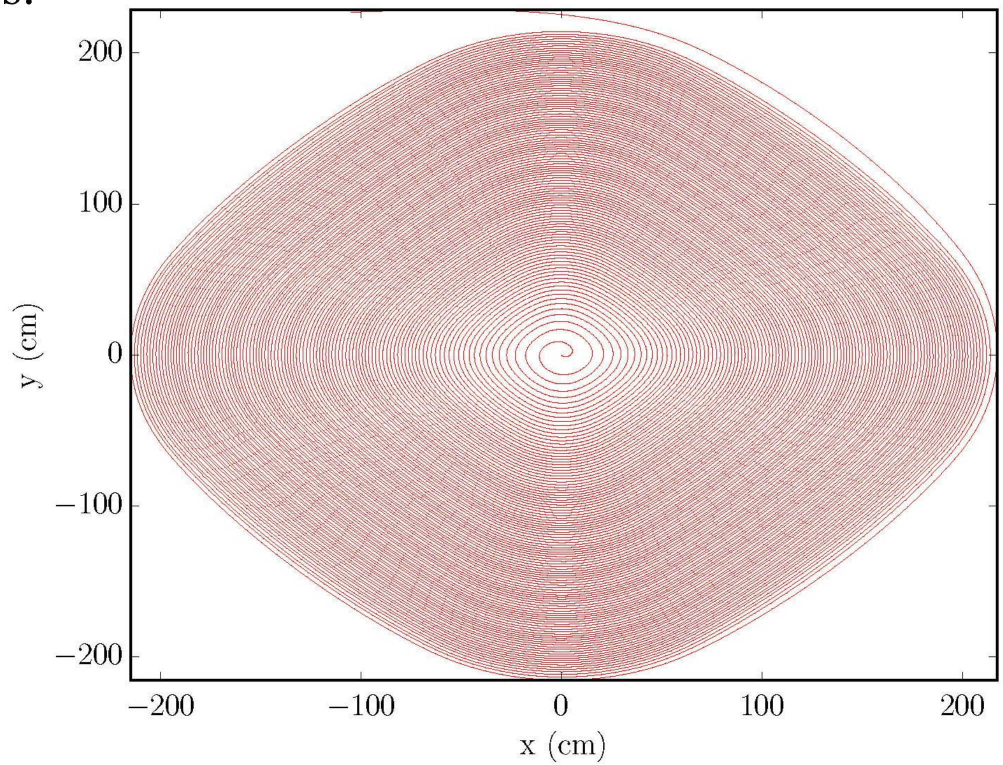
- Extension of previous work down to 193 keV/amu (Jakob Jonnerby: Masters Thesis, PSI/ETHZ)
- Similar behavior as before, but larger
- Collimators at ~3 MeV/amu cutting beam from 6.5 mA to 5 mA to clean up halo.
- Turn separation not as good as before, need to optimize collimator placement.
- Larger vertical size in very first turns. Gap of RF cavity 30 mm, barely fits through.



Current Simulation Work – Spiral Inflector

- Based on BCS Tests we are currently in the process of designing a new central region for the DIC/IsoDAR to match LEBT beam to cyclotron simulations.
- Spiral Inflector model by Grazia D'Agostino, INFN.
- Very preliminary, tedious process.
- First single particle results





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Next Steps

- This fall we are commencing the first phase of the RFQ study (funding obtained)
  - Simulations & Design
  - Build Test stand and RFQ
  - Commission and Test
- We will continue developing the OPAL injection simulations
  - Finish design of first iteration spiral inflector and central region
  - Continue systematic study of bunched beam injection into cyclotron and subsequent acceleration to full energy
  - Start-to-end simulations of both front end options
- Parallel: Target design (Columbia, Bartoszek Engineering)

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