DAEδALUS

DPF-Providence
August 10, 2011
Jose Alonso
MIT

Decay
At rest
Experiment
for δ_{cp} studies
At the
Laboratory for
Underground
Science

Use *decay-at-rest neutrino beams*,
and the planned *300 kton H_2O detector* (Gd doped)
at the Deep Underground Science & Engineering Laboratory
to search for CP violation in the neutrino sector

DAEδALUS Concept

THESIS

- A new generation of cyclotron-based neutrino sources for decay-at-rest (from pi-mu chain) can become valuable research tools

TECHNOLOGY GOALS

- Compact
- Cost-effective
- Efficient, reliable, economical to operate

Collaboration Resources:

DAEδALUS co-spokespersons:

- Janet Conrad, MIT
- Mike Shaevitz, Columbia

Accelerator Team:

- Luciano Calabretta, LNS-Catania
- Bill Barletta, MIT
- Andreas Adelmann, PSI
- Jose Alonso, MIT

Thx to:

- Georgia Karagiorgi, Columbia

Outline

- Physics basis for DAEδALUS experiment
- Description of experiment
- Sensitivity studies
- Complementarity between DAEδALUS and LBNE
- Accelerator requirements/options for DAEδALUS
- Accelerator design based on H_2^+
- Status and planned work
- Summary

Neutrino Oscillation and δ_{CP}

Potential CP-violation in the lepton sector is accessible through:

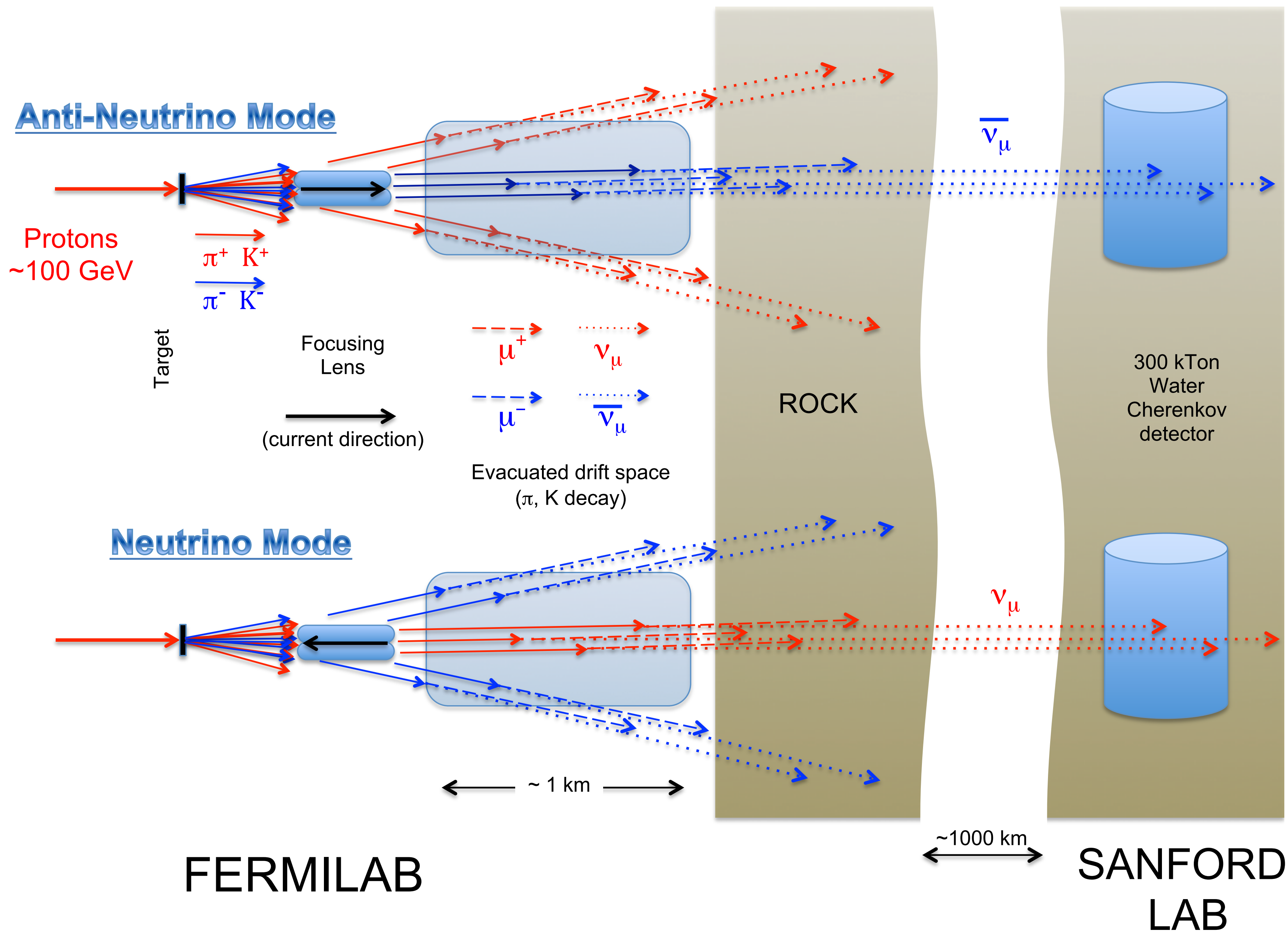
$P(\nu_\mu \rightarrow \nu_e) =$		$\sin^2\theta_{23}\,\sin^2\theta_{13}$	$\sin^2\Delta_{31}$
	$+\ \sin\delta$	$\sin 2\theta_{13}\,\sin 2\theta_{23}\,\sin 2\theta_{12}$	$\sin^2\Delta_{31}\sin\Delta_{21}$
	$+\ \cos\delta$	$\sin 2\theta_{13}\,\sin 2\theta_{23}\,\sin 2\theta_{12}$	$\sin\Delta_{31}\,\cos\Delta_{31}\,\sin\Delta_{21}$
	$+$	$\cos^2\theta_{23}\,\sin^2\theta_{12}$	$\sin^2\Delta_{21}$
	CP terms	mixing angle terms	L/E-dep. mass-splitting terms

CP-violating interference terms

$\delta \rightarrow -\delta$ for neutrinos $\rightarrow$ antineutrinos

$$\Delta_{ij} = \Delta m_{ij}^2\, L/4E_\nu$$

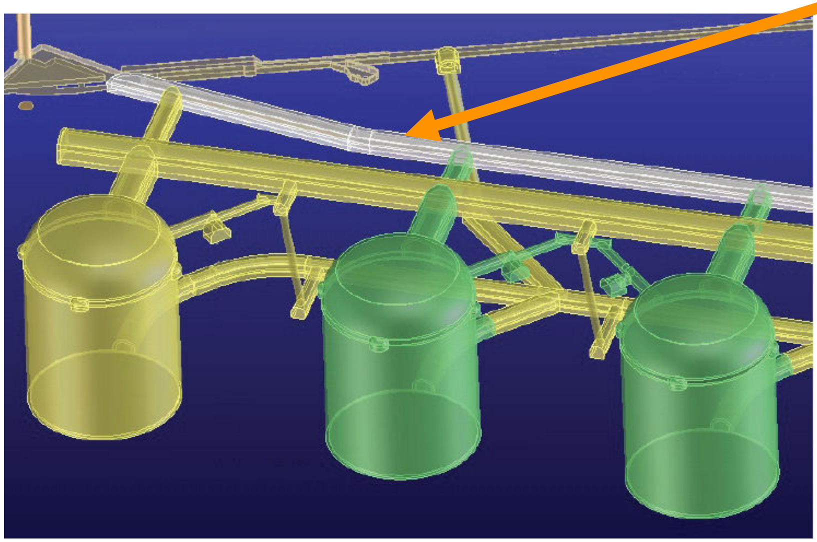
Long Baseline Neutrino Experiment (LBNE)

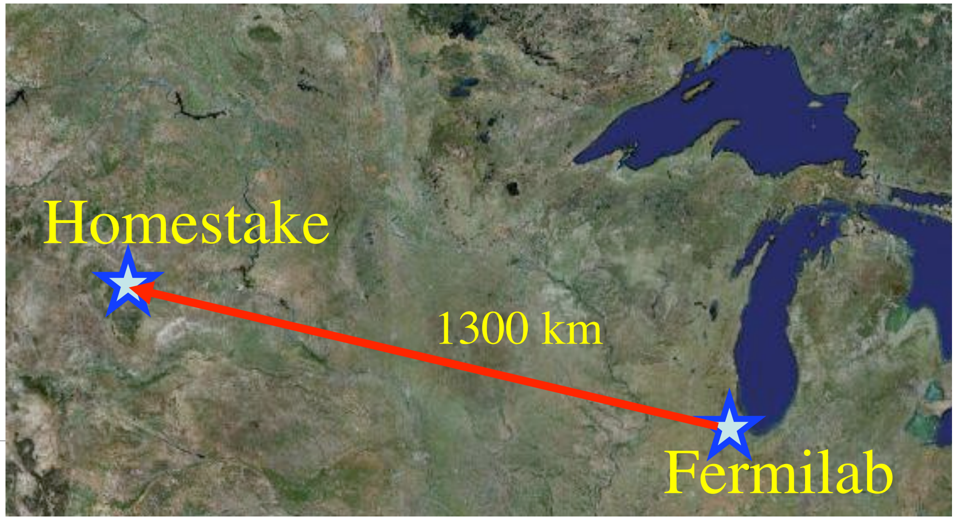


LBNE – Long Baseline Neutrino Experiment

Beam from Fermilab

Aimed at detectors in South Dakota





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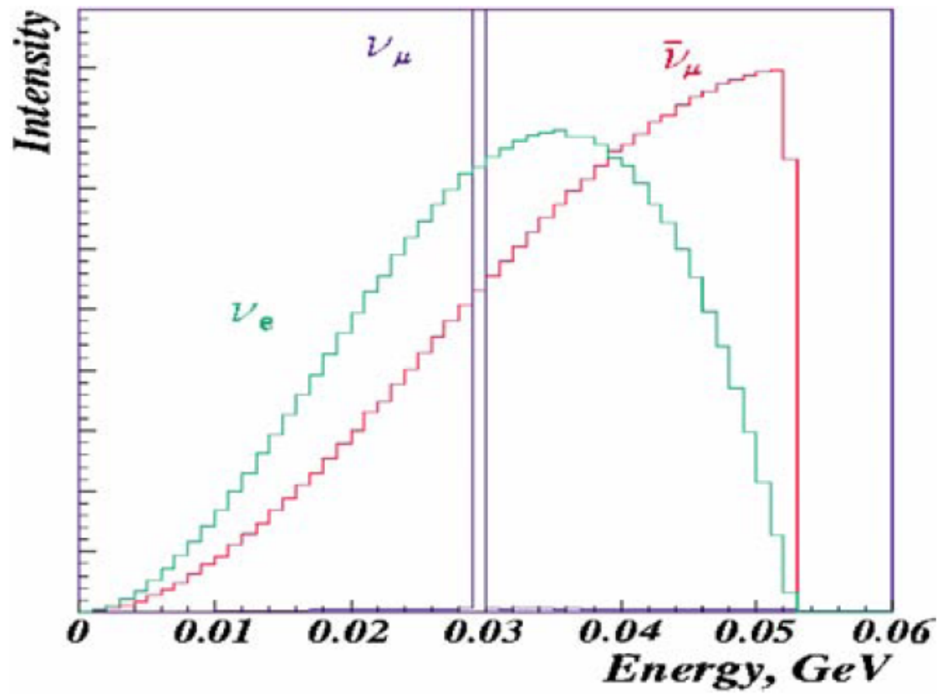
Decay-At-Rest Source

- 800 MeV proton beams
  - Produces pions at low velocity
- π^+ stopped, decay
  - (π^- absorbed)



- $\pi^+ \rightarrow \mu^+ \nu_\mu$

  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

- NO electron anti-neutrinos!
  - $\bar{\nu}_e$ contribution (π^- decay) is insignificant: $<10^{-2}\%$

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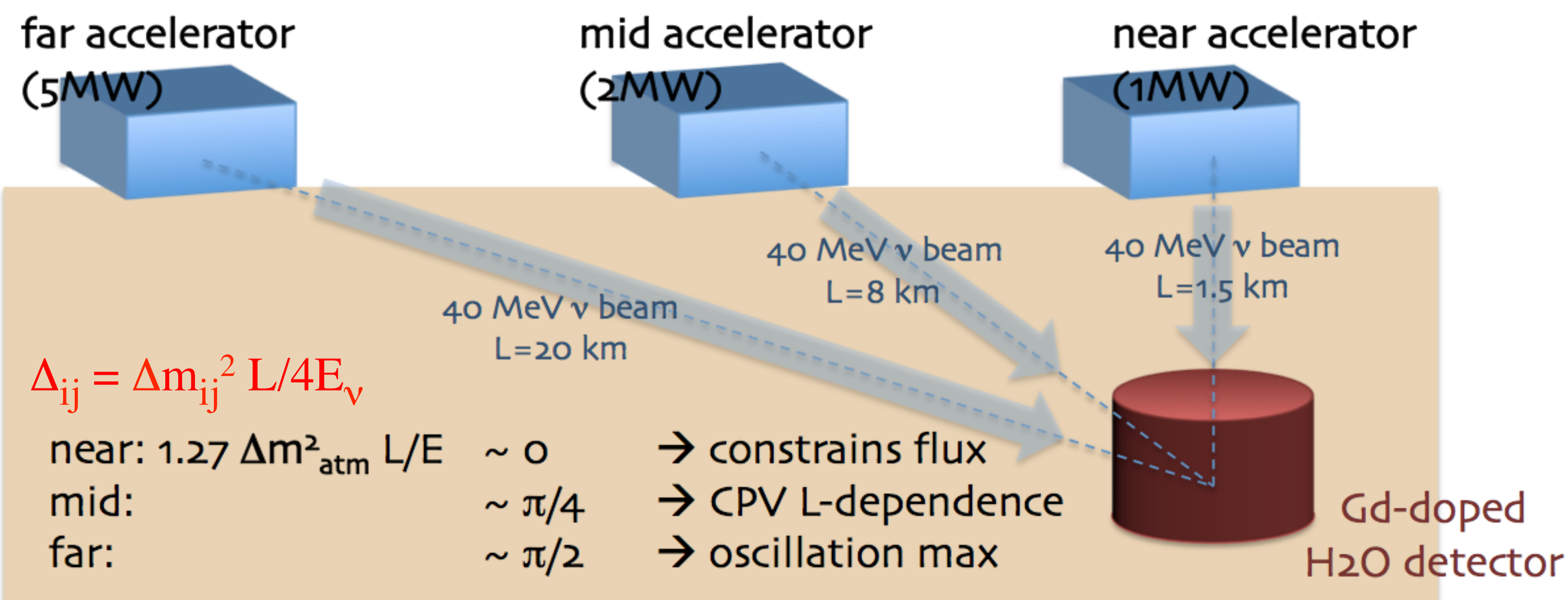
DAEδALUS Experiment

Uses multiple π+ and μ+ decay-at-rest neutrino beams,
and the planned 300 kton H_2O detector (Gd-doped)
at the Deep Underground Science & Engineering Laboratory



Nominally, $\sim 4\times10^{22}$ neutrinos/flavor/accelerator/year

DAEδALUS Experiment

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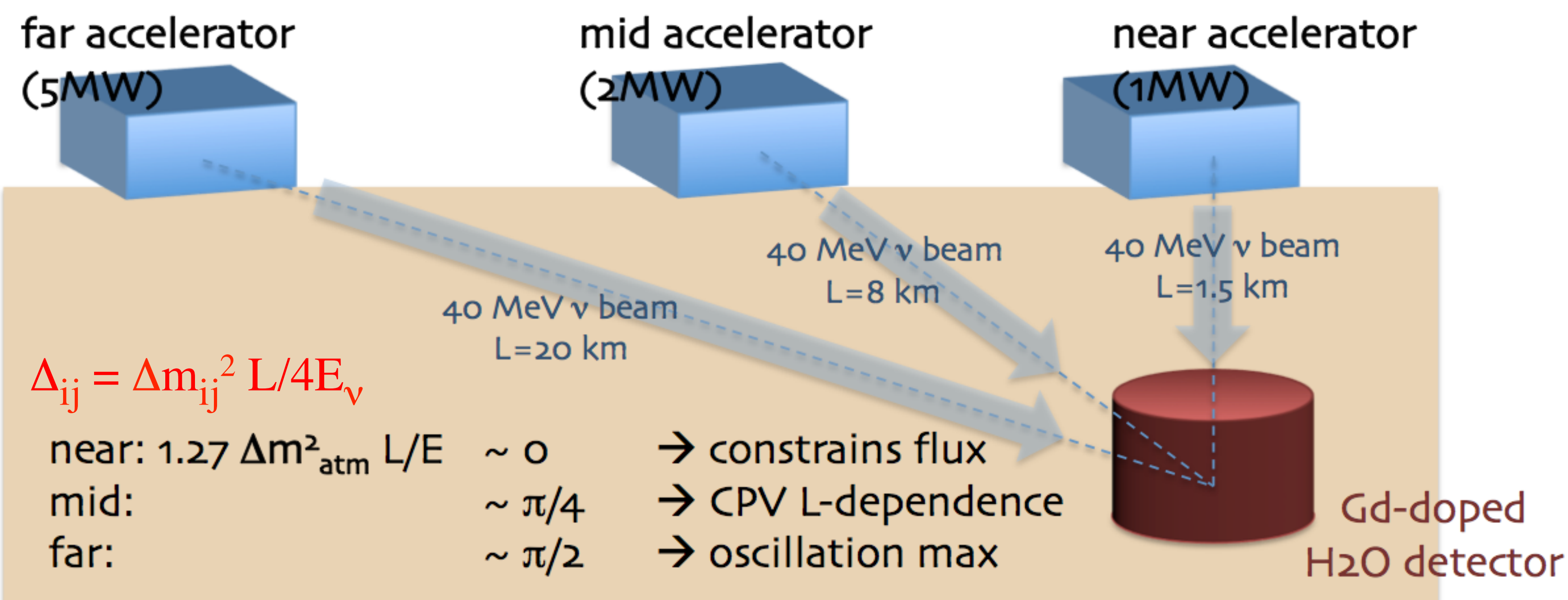
Short baseline minimizes matter effects



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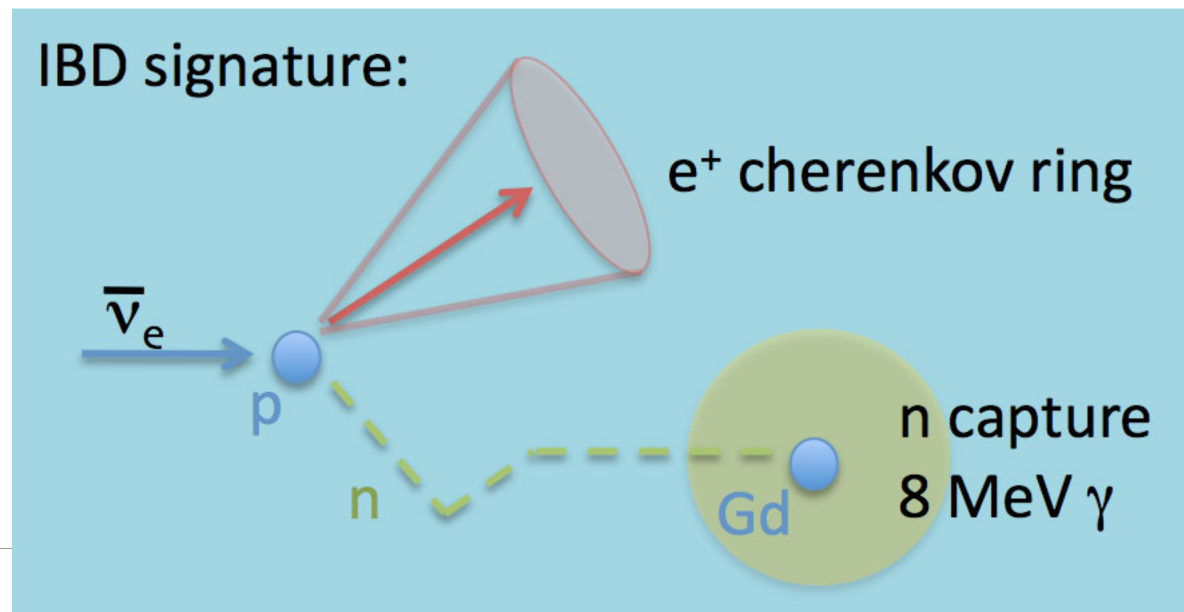
Nominally, ~4x10^{22} neutrinos/flavor/accelerator/year

Oscillation Signal

Look for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
via inverse-beta-decay (IBD):
$\bar{\nu}_e + p \rightarrow n + e^+$
Gd n capture efficiency ~67%



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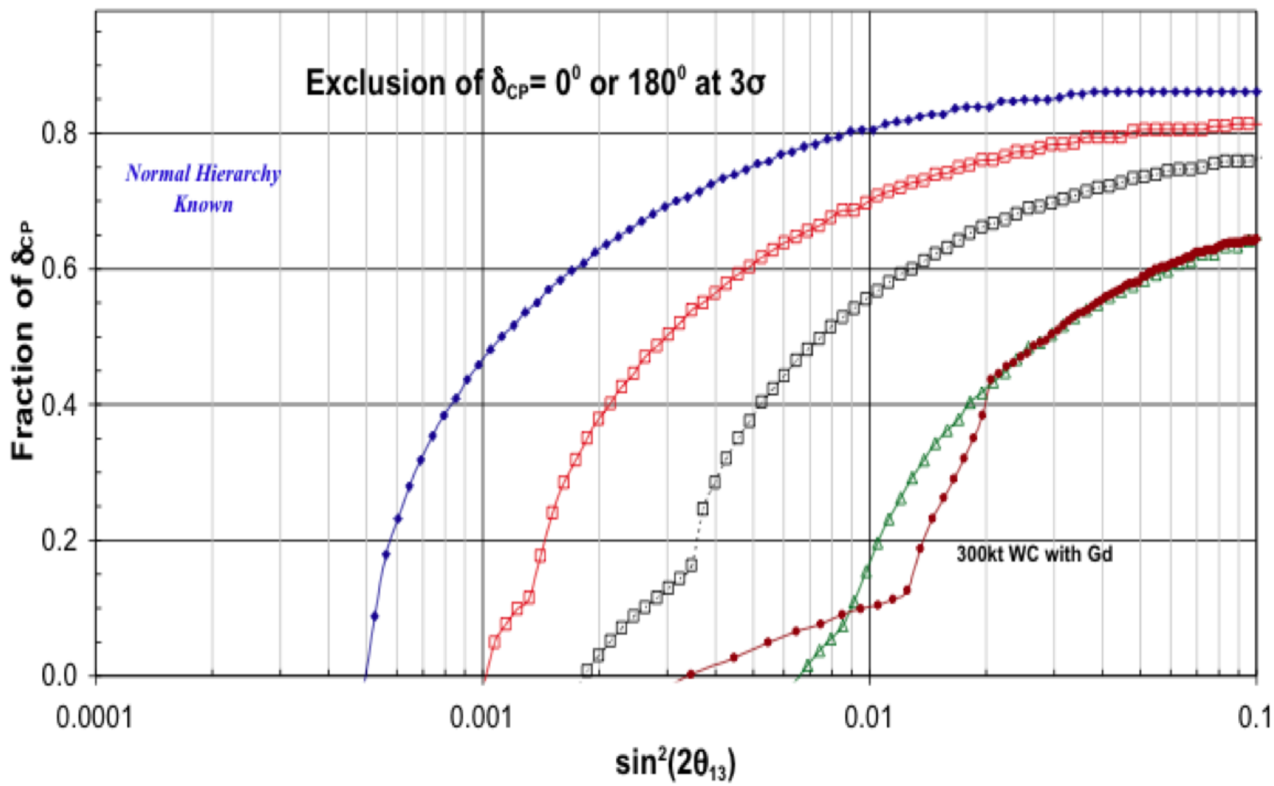
Sensitivity Comparisons

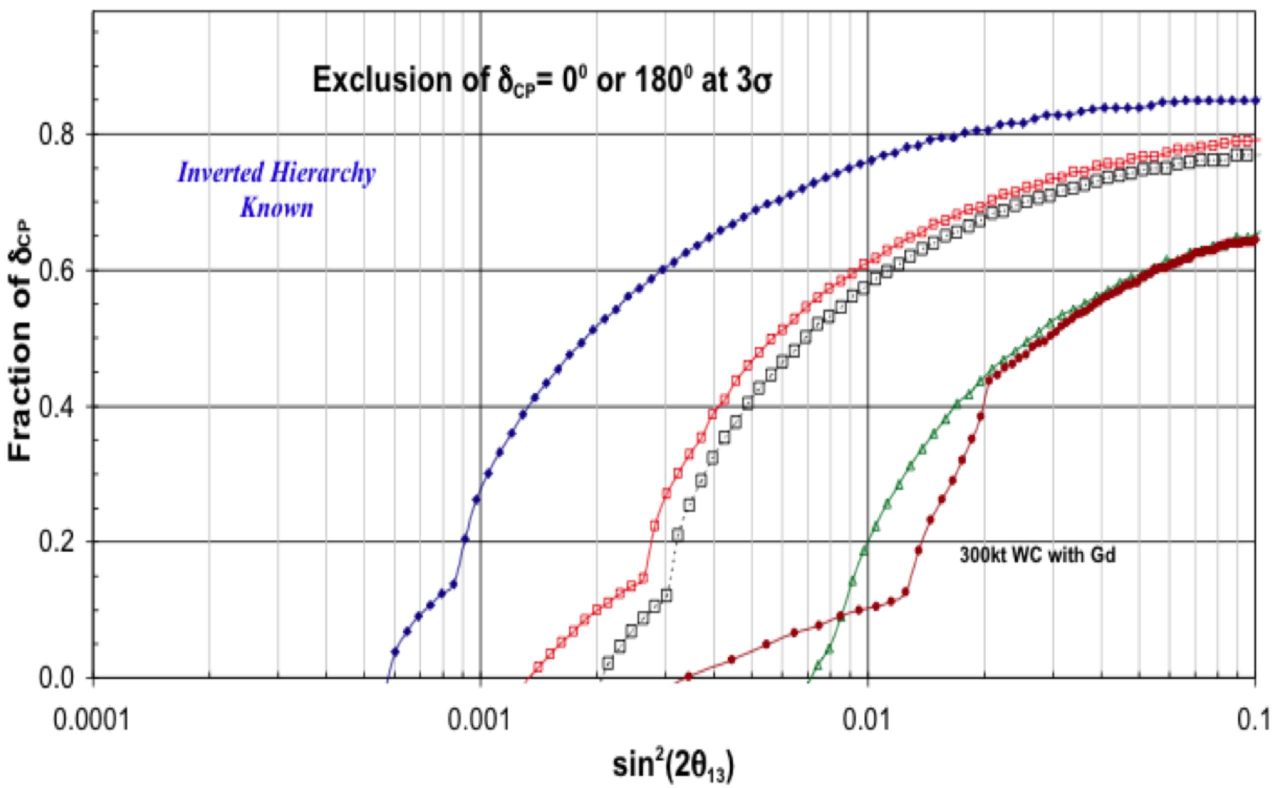


- DAEδALUS only – 10 years
- LBNE – 10 years
- LBNE-Proj X – 10 years
- DAEδALUS + LBNE ν only – 10 years concurrent running
- Additional 10 years concurrent ops of DAEδALUS + Proj X

Normal Hierarchy

DAEδALUS

Sensitivity Comparisons



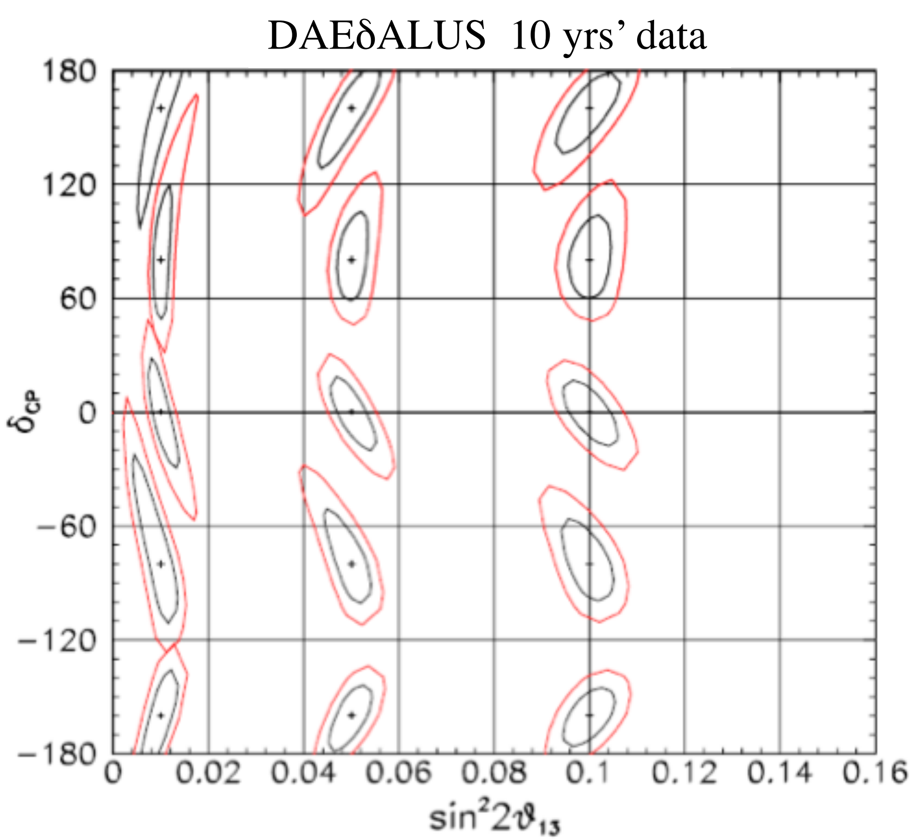
DAEδALUS only – 10 years
LBNE – 10 years
LBNE-Proj X – 10 years
DAEδALUS + LBNE ν only – 10 years concurrent running
Additional 10 years concurrent ops of DAEδALUS + Proj X

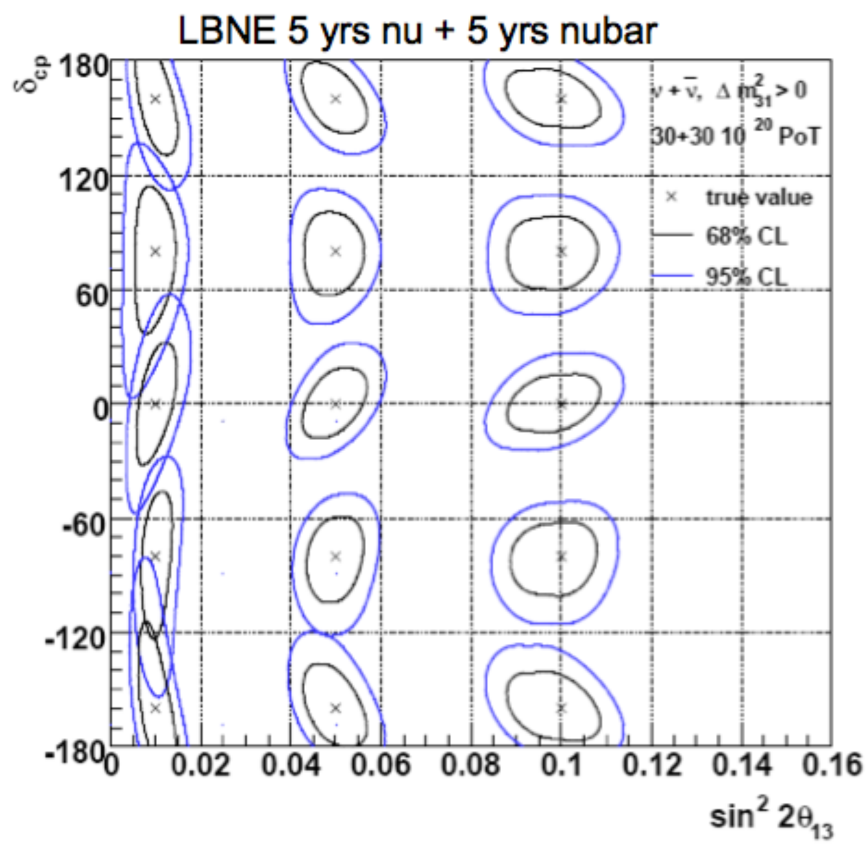
Inverted Hierarchy

Sensitivity Comparisons

DAEδALUS

LBNE

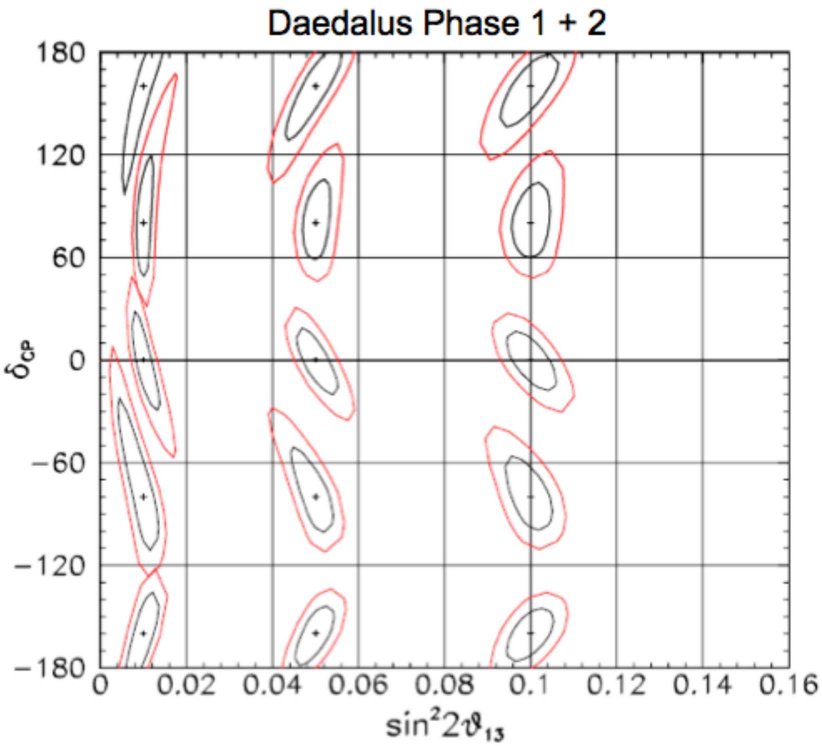




Synergistic Combination

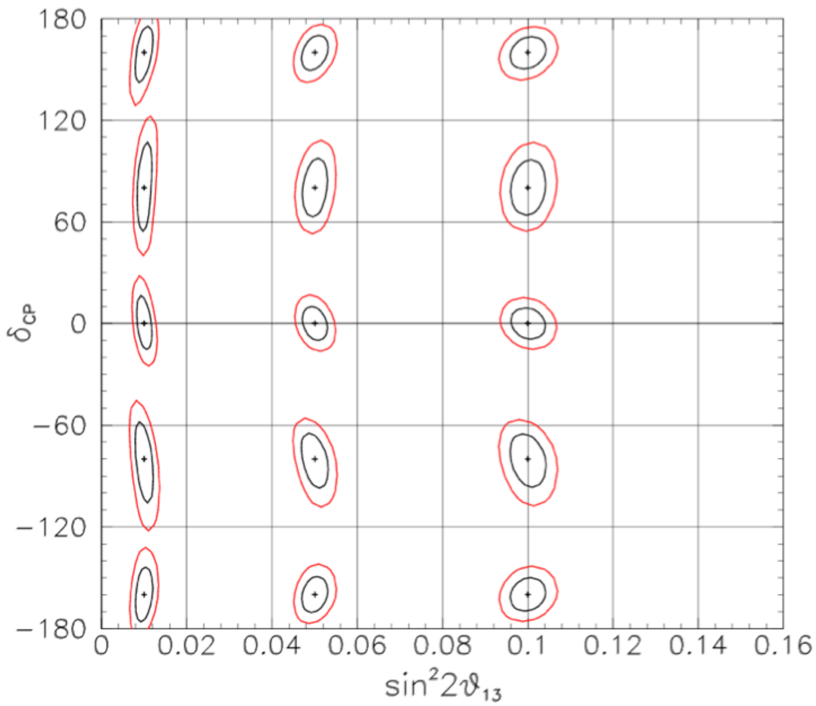
DAEδALUS alone

(10 year data collection)



DAEδALUS + LBNE

(10 yr DAEδALUS + 10 yr LBNE ν only)



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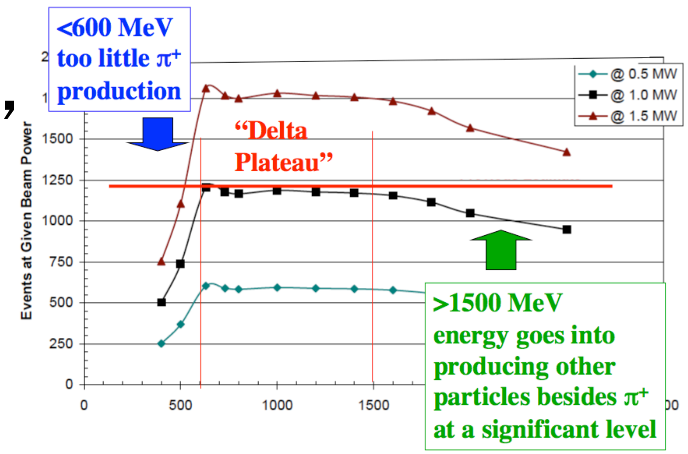
Accelerator Requirements

Can they be built?

Accelerator Requirements

- Beam on target: Protons
  - Most efficient beam for pion production
- Beam Energy: ~ 800 MeV
  - Produce pions in "delta plateau"
  - Optimize:
    - Nuclear mean free path (~ 15 cm)
    - Energy loss
    - Minimize decay in flight (π^- background)



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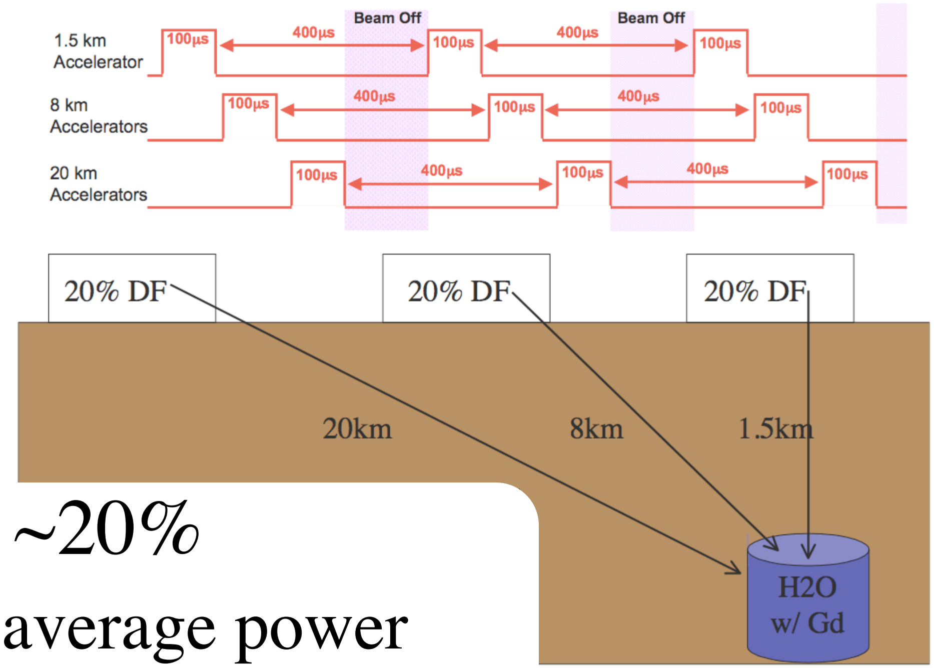
Accelerator Requirements



- Beam Power:
  - 1.5 km site: 1 MW average
  - 8 km site: 2 MW average
  - 20 km site: 5 MW average
- Accelerator Duty Factor: ~20%
  - Instantaneous power is ×5 average power
  - Can be optimized and time structure fairly arbitrary
- High Reliability: both running & handling
- Cost: As low as possible

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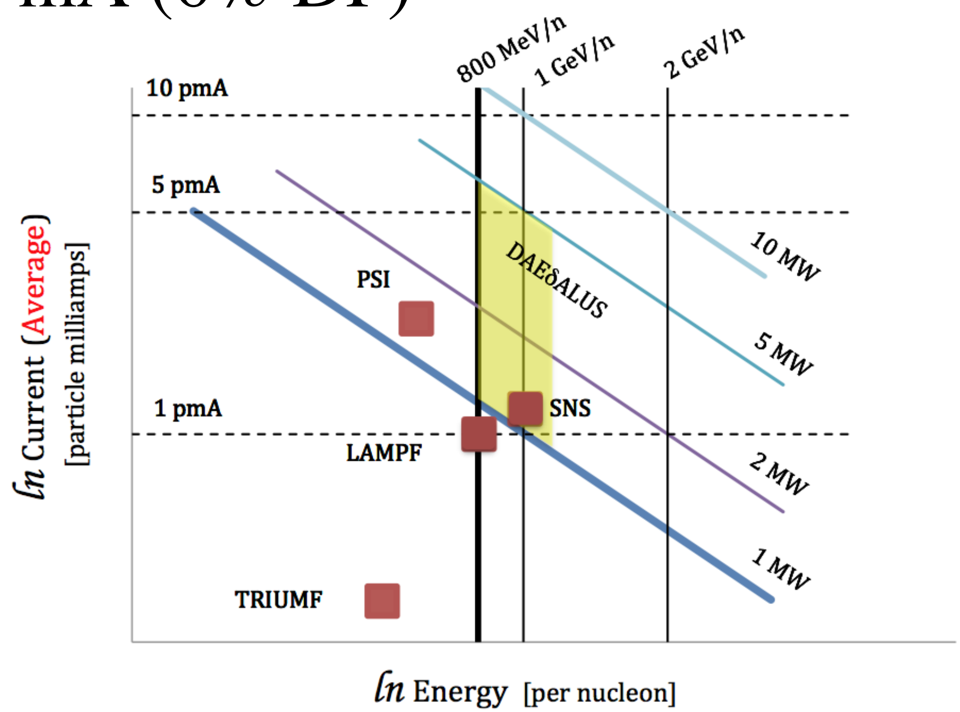
Our Needs vs. Existing Machines
(Average Power Needs)

- LAMPF (Linac): 800 MeV, 1 mA (12% DF)
- PSI (Cyclotron): 590 MeV, 2.2 mA (100% DF)
- SNS (Linac): 1 GeV, 1 mA (6% DF)

- DAEδALUS:

  Near ~ 1 mA (20% DF)

  Far ~ 5 mA (20% DF)



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Our Needs vs. Existing Machines

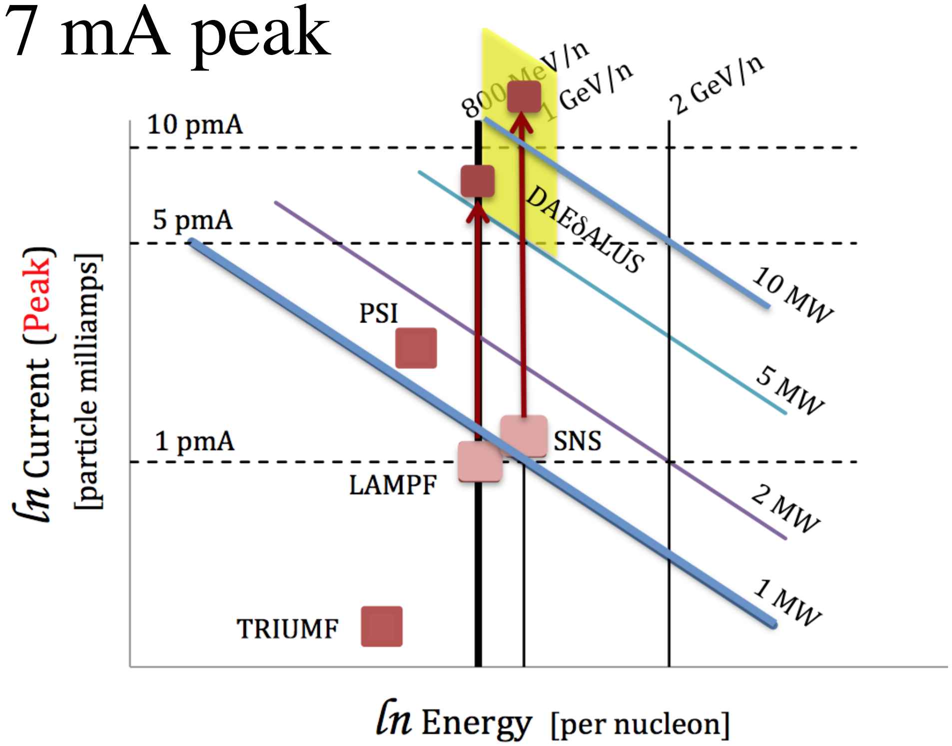
(Peak Power Needs)

- LAMPF (Linac): 800 MeV, 8 mA peak
- PSI (Cyclotron): 590 MeV, 2.2 mA
- SNS (Linac): 1 GeV, 17 mA peak

- DAEδALUS

  Near ~ 5 mA peak

  Far ~ 25 mA peak



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Issues with High Intensities

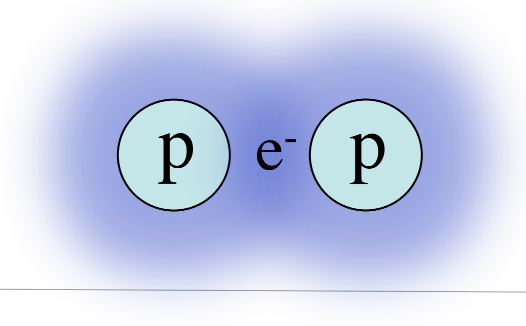
- Beam Loss
  - Thermal power damages components
    - E.g. 0.1% of 1 MW beam (1 kW) will cause problems
  - Activation causes problems for maintenance
    - PSI limits uncontrolled loss to 200 watts per cyclotron vault
- Space-charge Emittance Growth
  - Makes controlling beam loss more difficult
  - Primarily a problem at very low energies
    - current > few mA, at energy < 1 MeV

Design Considerations

- Low Energies
  - Very careful accelerator design for minimizing space-charge blowup
  - High brightness ion source
  - Good focusing, high acceleration rates
- High Energies
  - Careful beam handling for clean extraction
  - Large apertures, minimize chances of beam hitting anything

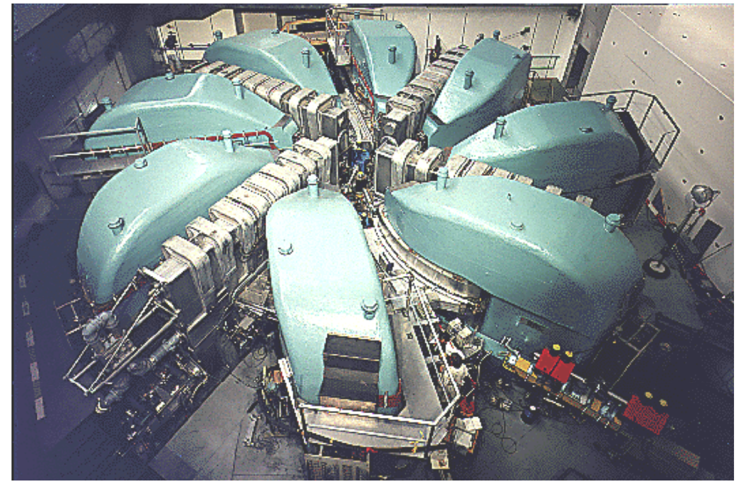
Technologies explored

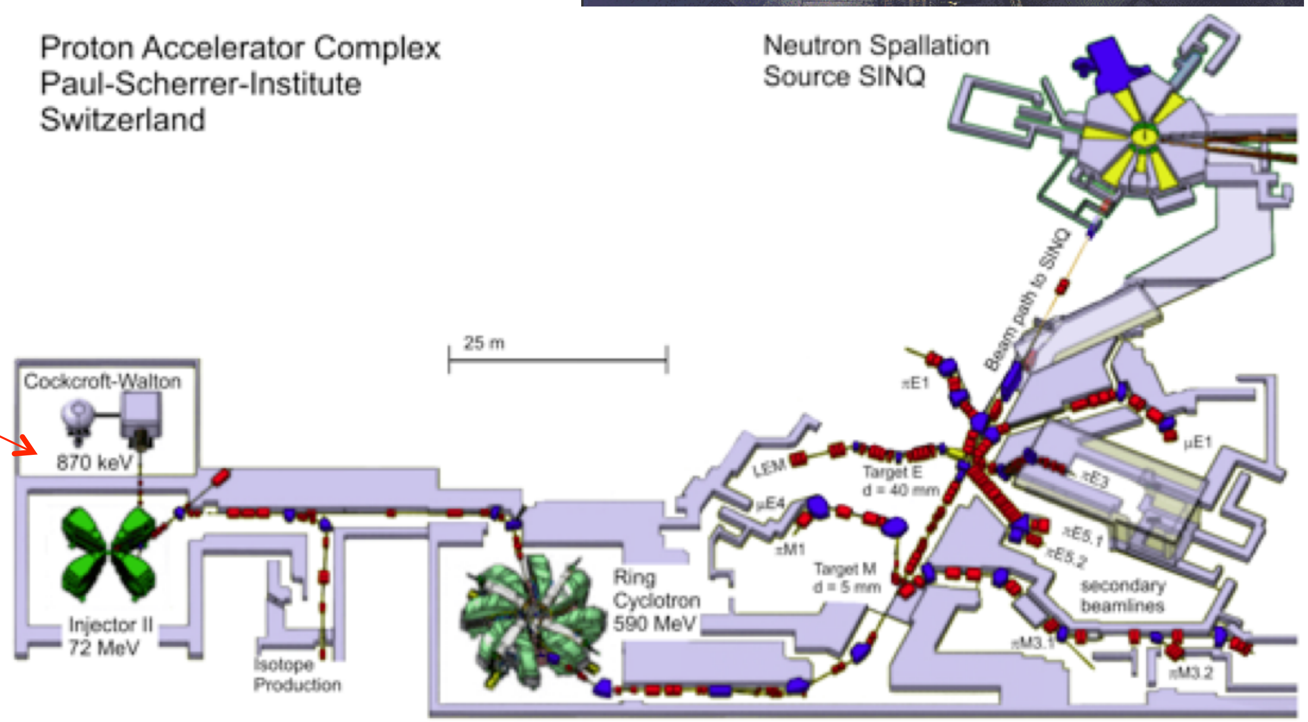
- Linacs
  - Cleanest of technologies
    - but there are issues of size and cost
- Cyclotrons
  - Superconducting (proton) Cyclotron
    - Extension of PSI
  - Stacked (proton) Cyclotron
  - H_2^+ Cyclotron -- reduces many problems related to beam loss and extraction compared to other designs



Cyclotron Experience

- PSI is most powerful in the world
  - 590 MeV protons
  - 2.2 mA
  - 1.3 MW





Very high
Injection energy

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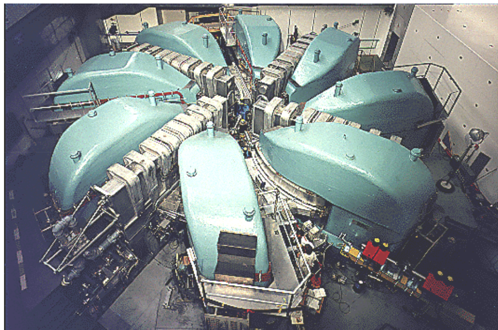
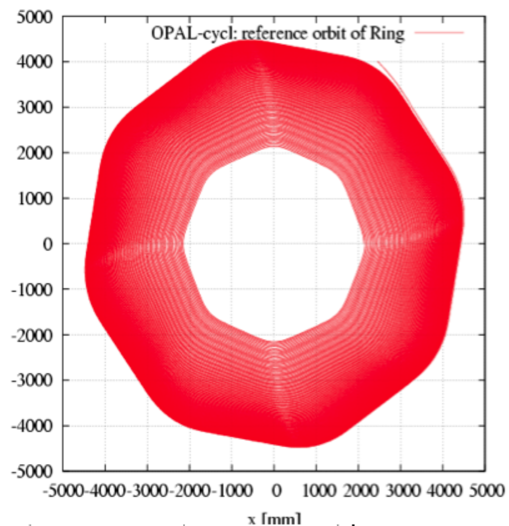
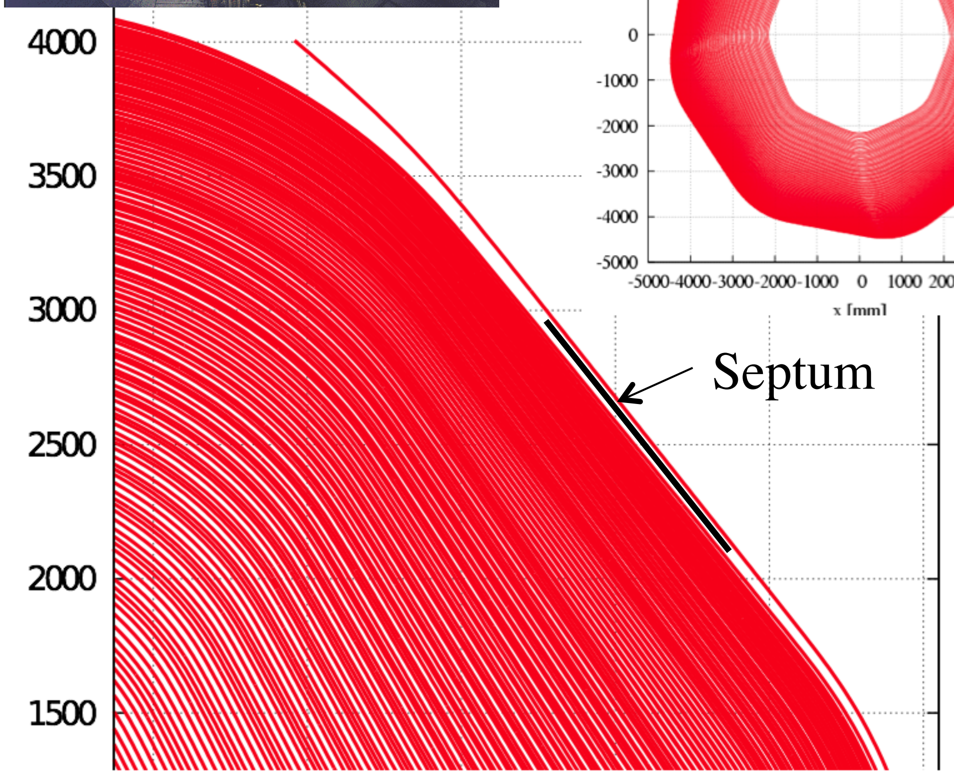
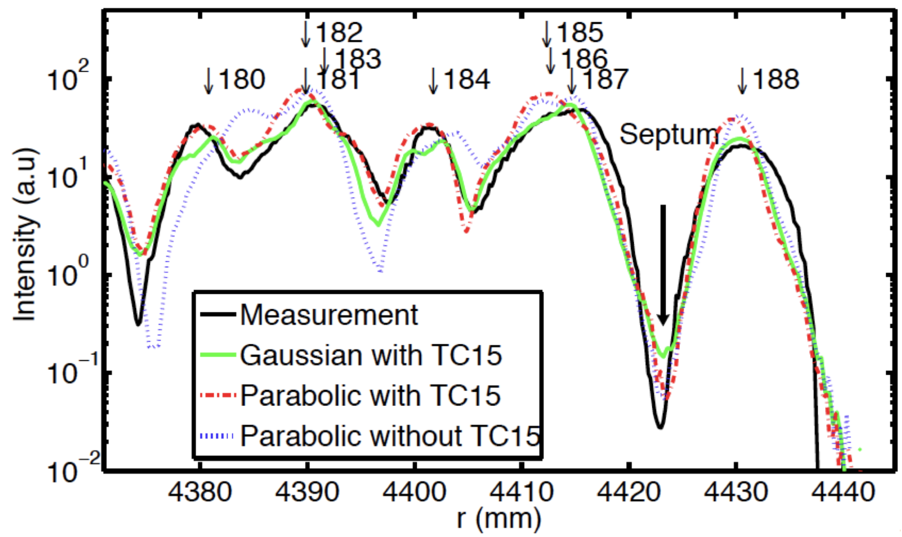
Beam at High Energy End



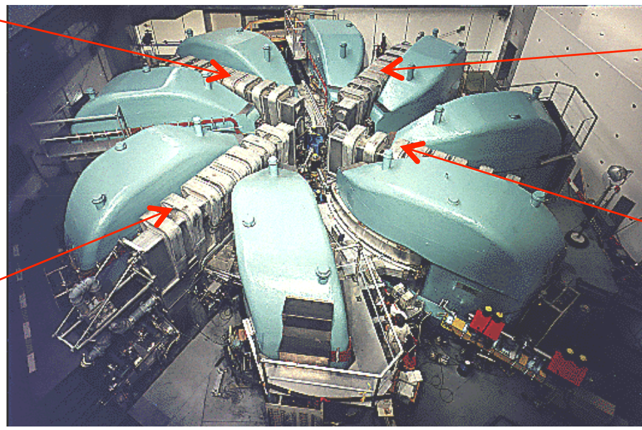




- Turns get closer together as radius increases
  - Must play resonances to get turn separation
  - Septum intercepts beam!
  - PSI achieves 99.98% extraction efficiency!



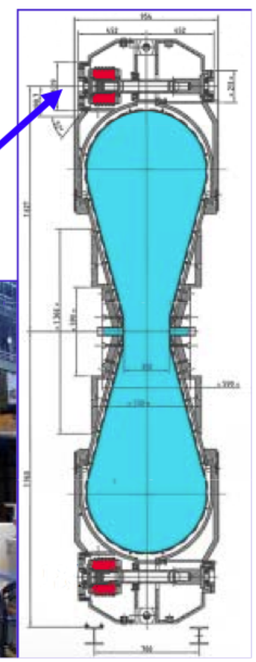
Also Must Have Very Large RF System



- High accelerating voltage promotes larger turn separation
  - $\Delta E = 2$ MeV/turn
  - 500 kV/cavity

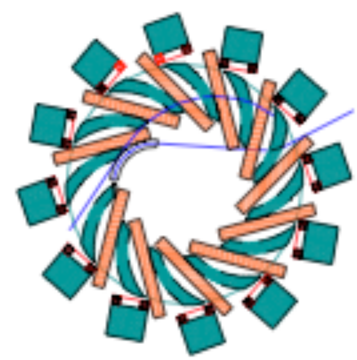
resonator inside

hydraulic tuners



H_2^+ Ring Cyclotron
Promising Design from 1990's

- Concept proposed by Luciano Calabretta, Catania
  - Response to C. Rubbia idea for high-power cyclotrons for ADS
  - Reports in European Particle Accelerator Conference
    Calabretta et al: PAC 99 & EPAC 2000
- 1 GeV, ~6 mA
- High rigidity for H_2^+
  - Superconducting magnets keep size reasonable
- Efficient extraction (via stripping)
  - Substantially less RF requirements
    no need for clean turn separation



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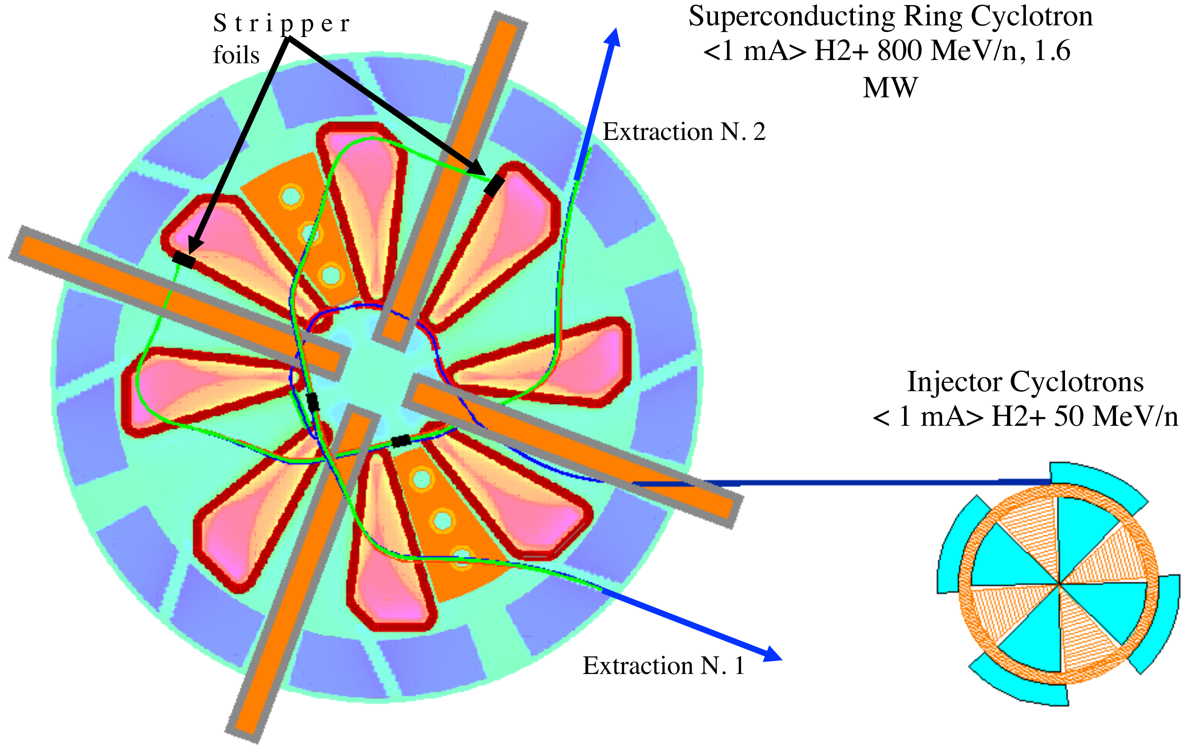
Status of Design

- arXiv: 1107:0652



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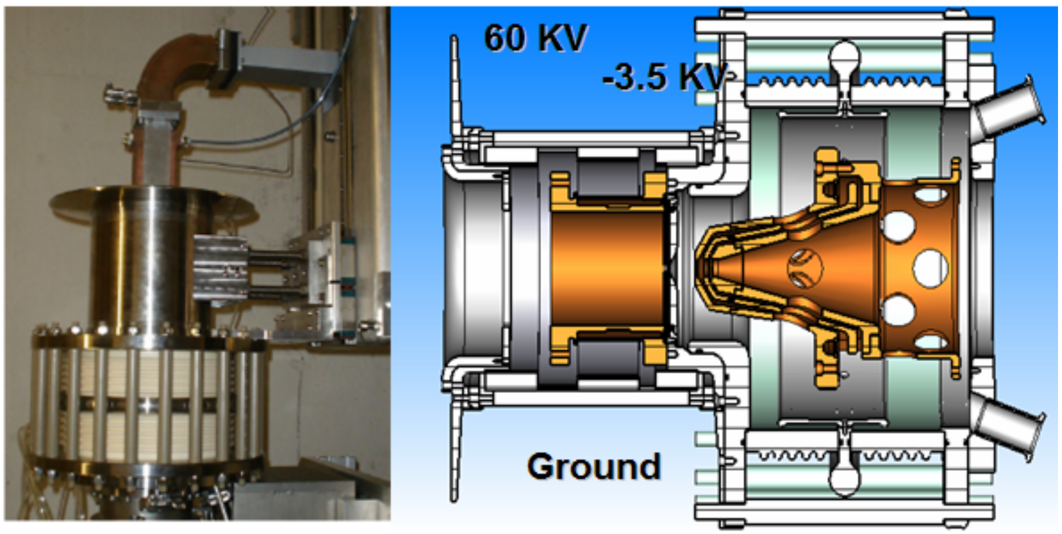
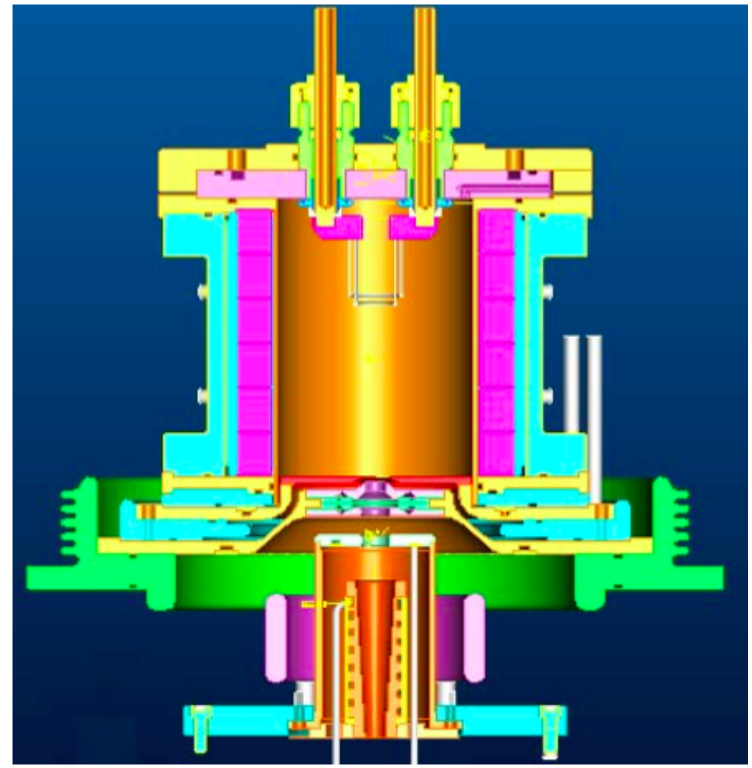
System Components

- Ion Source
  - High brightness H_2^+ options
    - Multicusp, microwave
- Injector Cyclotron
  - Axial injection
  - "Classical" extraction at 50 MeV/n
- Ring Cyclotron
  - Superconducting ($B_{max} \sim 6T$)
  - Stripping extraction
- Target/beam dump
  - Shaped graphite/copper/water-cooled
    - To absorb 5 MW

Ion Source Options



VIS – LNS-Catania



Multicusp – LBNL, Beijing

Either produces 20-50 mA (CW) H_2^+ with good emittance

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Ion Source Challenges

- Optimizing H_2^+ production
- Obtaining steady, reliable currents >30 mA

Ion Source Challenges

- Optimizing H_2^+ production
- Obtaining steady, reliable currents >30 mA
- Quenching of high ν (loosely-bound) vibrational states
  - 17 bound states
  - ν > ~8 (binding energy < ~ 1 eV) may undergo Lorentz stripping at high energies
  - ~ 10% of beam could be in these states
  - Mixing He, Ne in source plasma shown to adequately quench loosely-bound states
    - Must develop suitable diagnostic tools!

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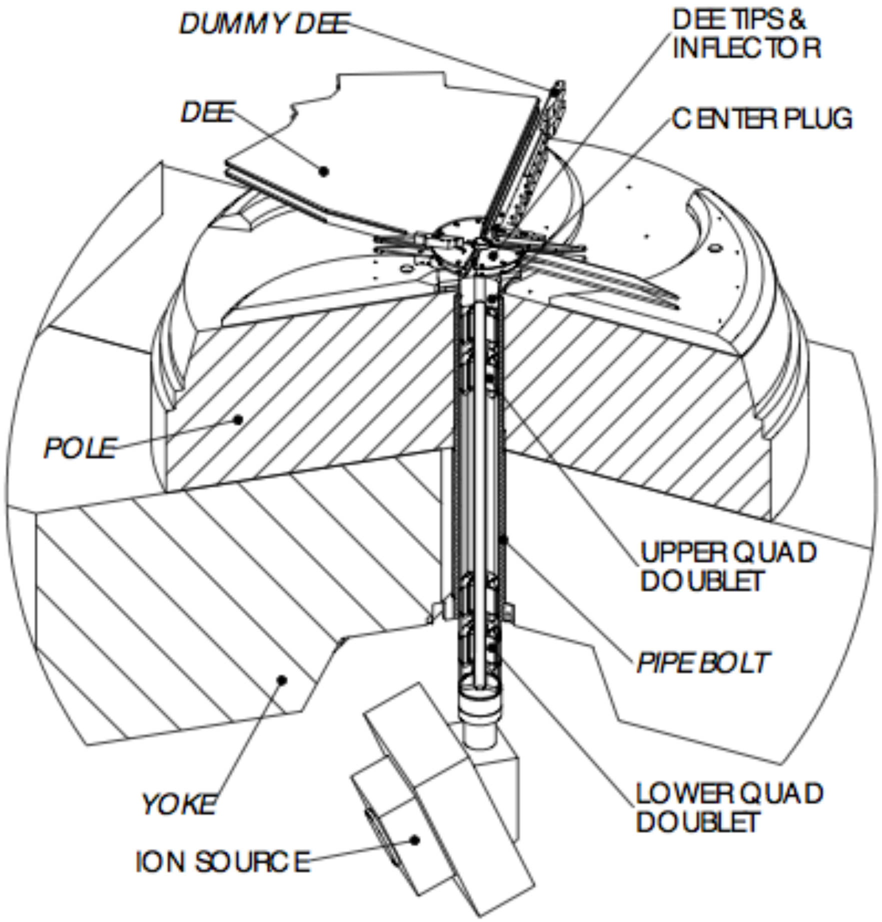
Injector Cyclotron



Axial injection channel

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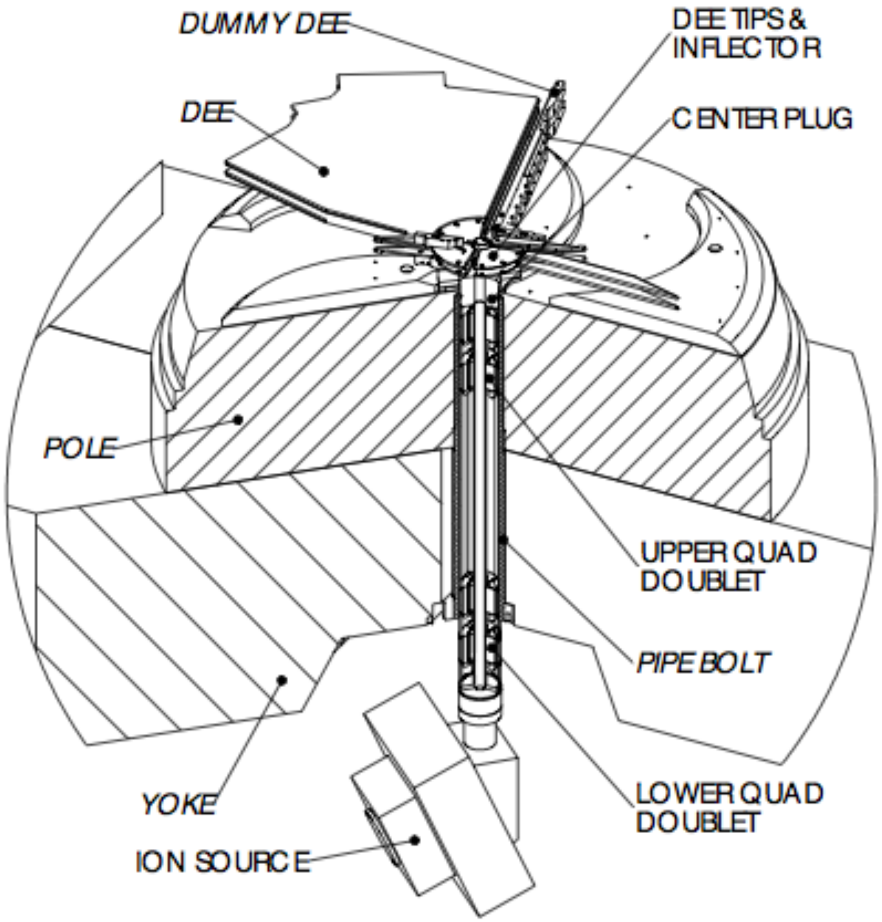
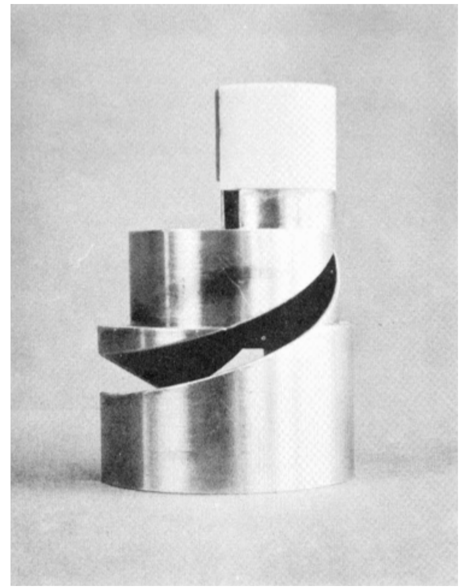
Injector Cyclotron



Axial injection channel



Spiral inflector

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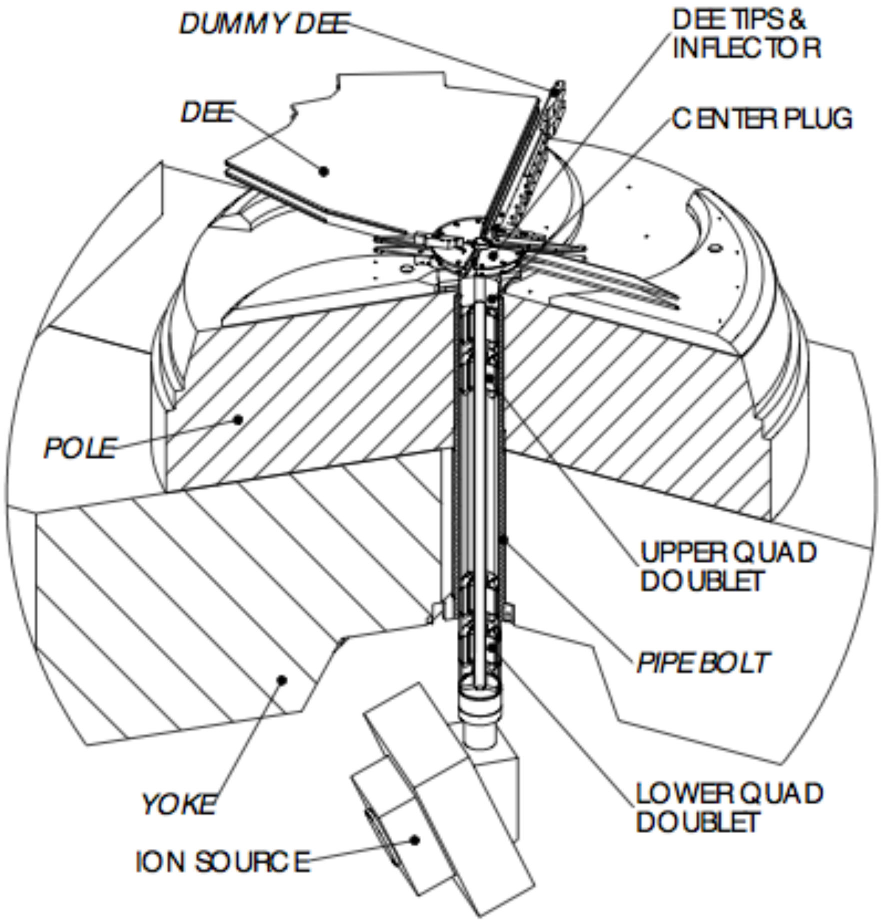
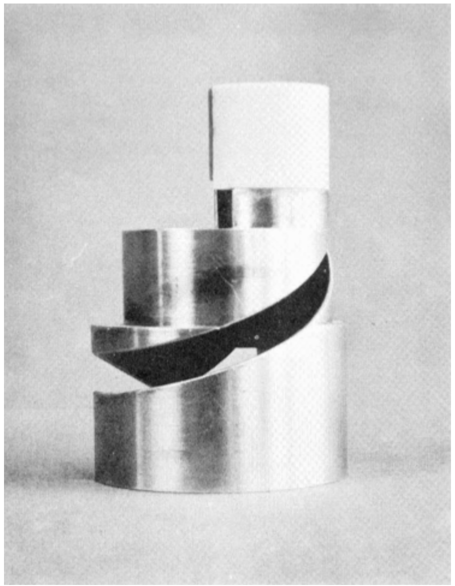
Injector Cyclotron

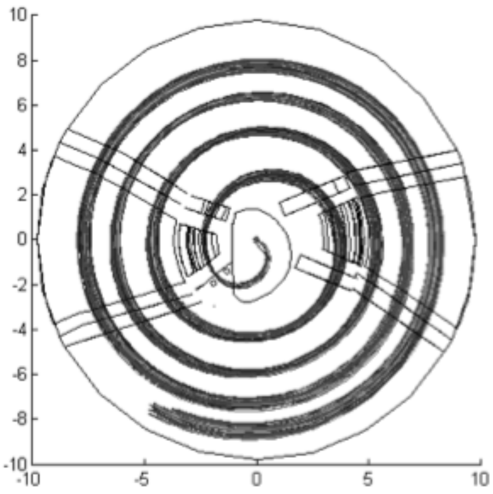


Axial injection channel



Spiral inflector

First captured orbits



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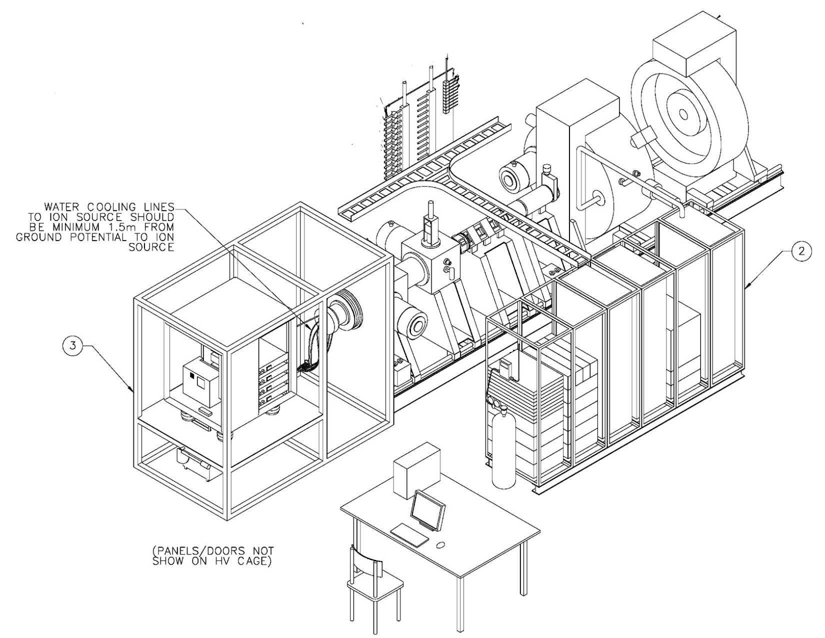
Injector Cyclotron Challenges

- Efficiency of capture
  - Space charge blowup
    - low energy
    - high current
- Excessive beam loss
  - Inject ~20 mA, capture ~3 mA
    - this considered "good"!
- Emittance growth
  - Problems in latter stages

Strategies

- Central Region tests
  - Collaborations with BEST Cyclotrons

    Vancouver, BC mfg isotope cyclotrons



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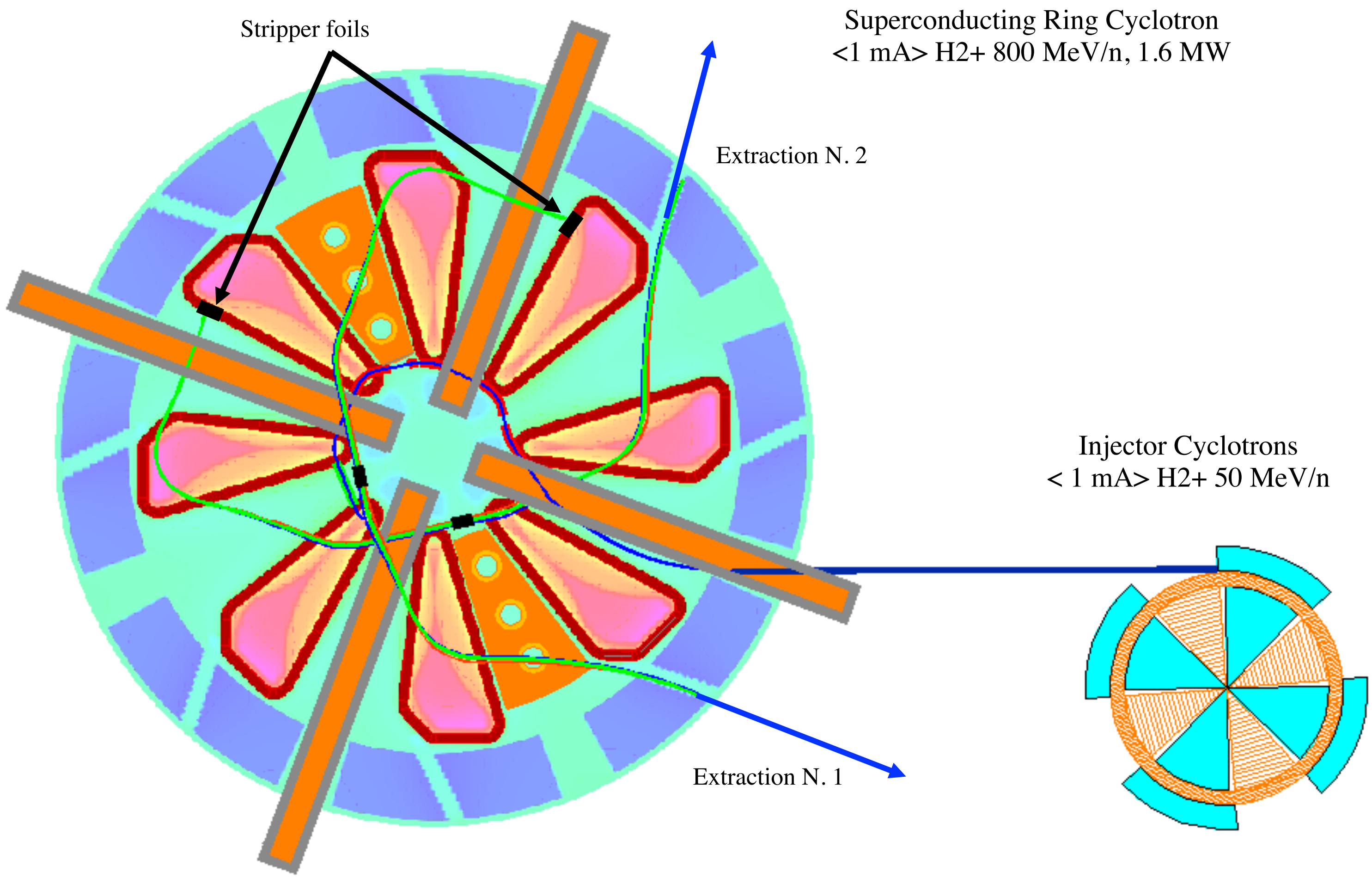
Superconducting Ring Cyclotron



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Cyclotron Parameters

Magnet – 8 sector

- 14 m steel diameter
- 4.9 m extraction radius
- 6.3 T B_{max}

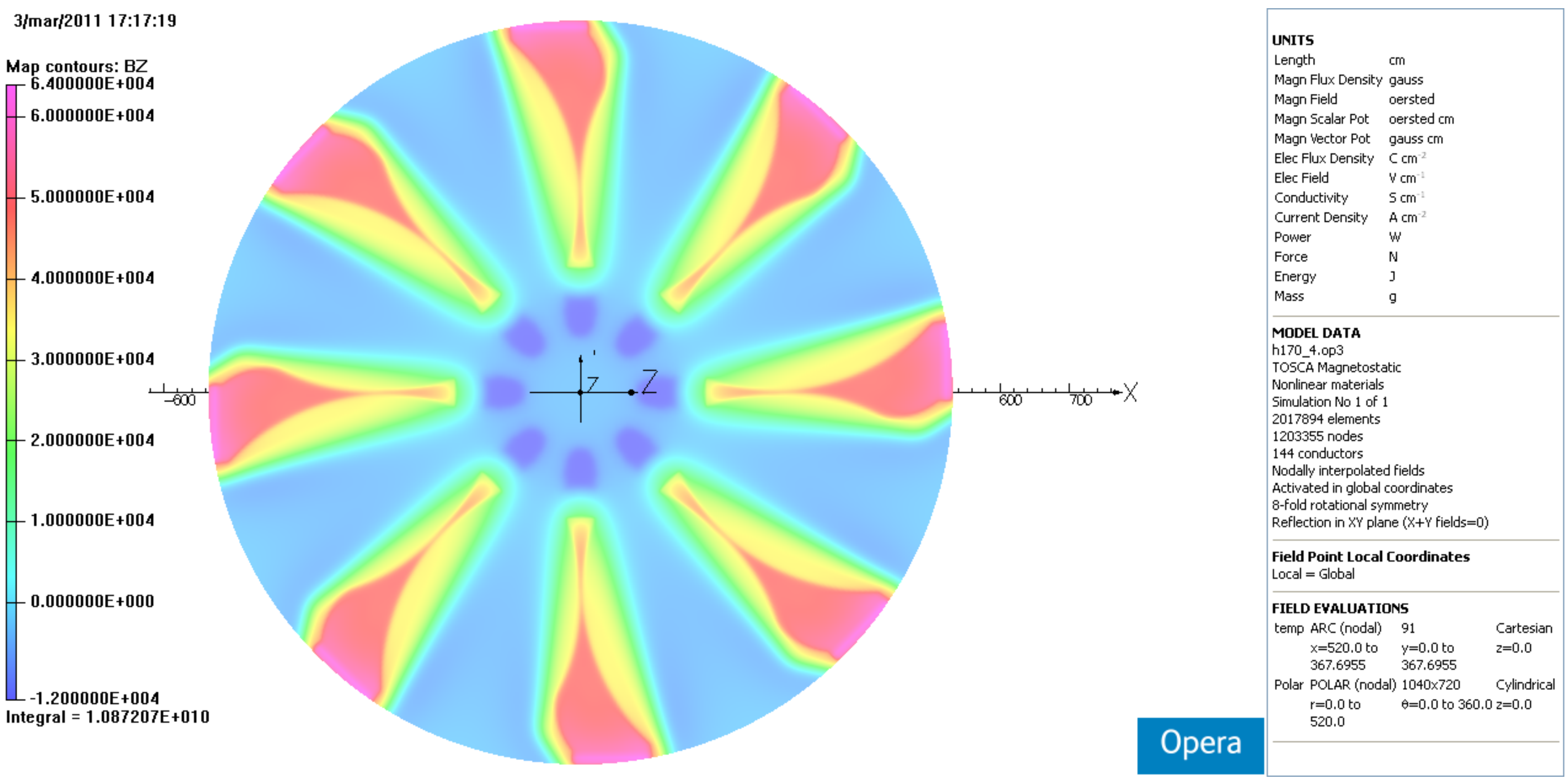
RF – 4 single-gap (PSI style)

- > 2 MeV energy gain/turn

Vacuum – $< 10^{-9}$ torr

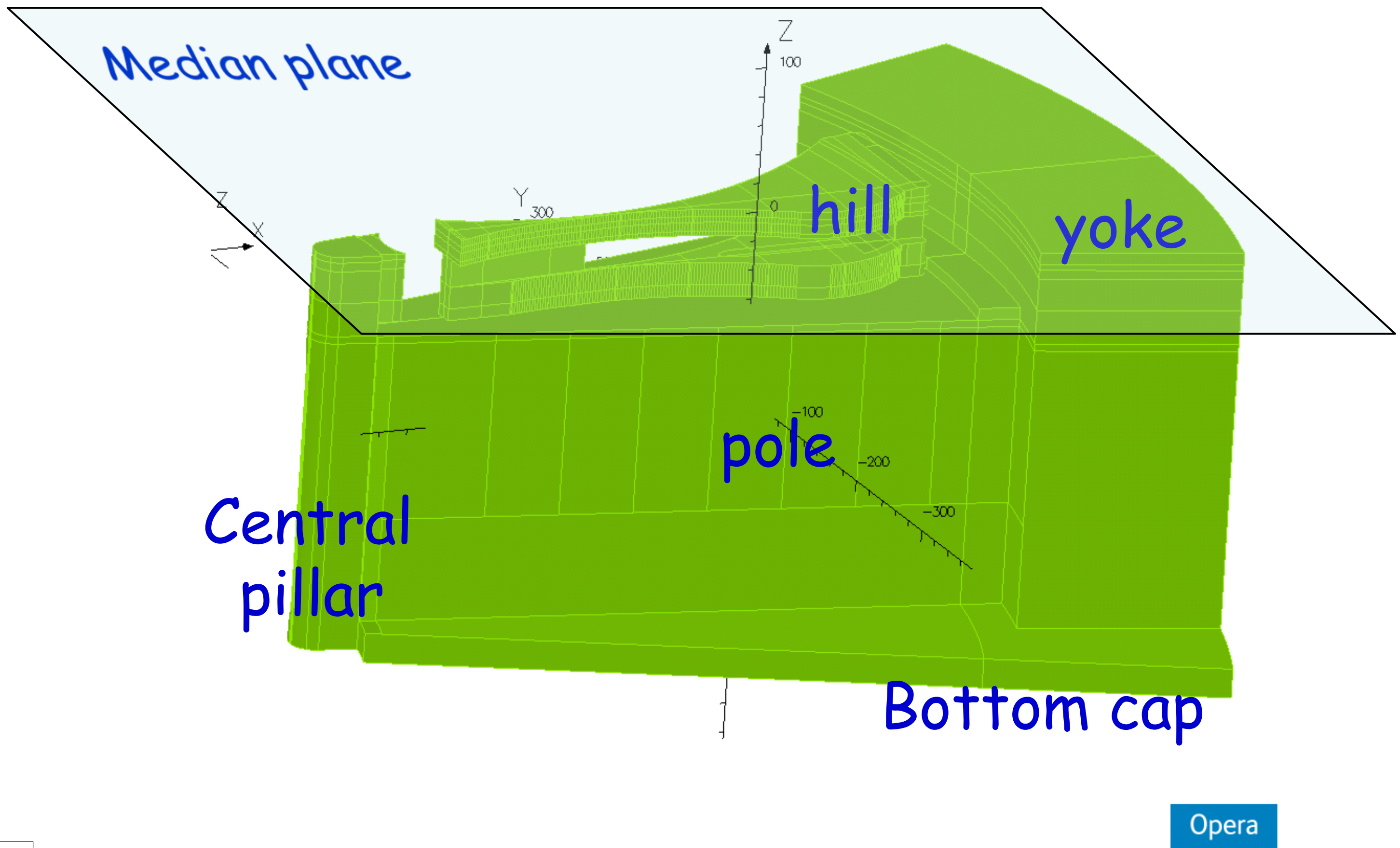
- avoid gas-stripping losses

FIELD ON THE MEDIAN PLANE



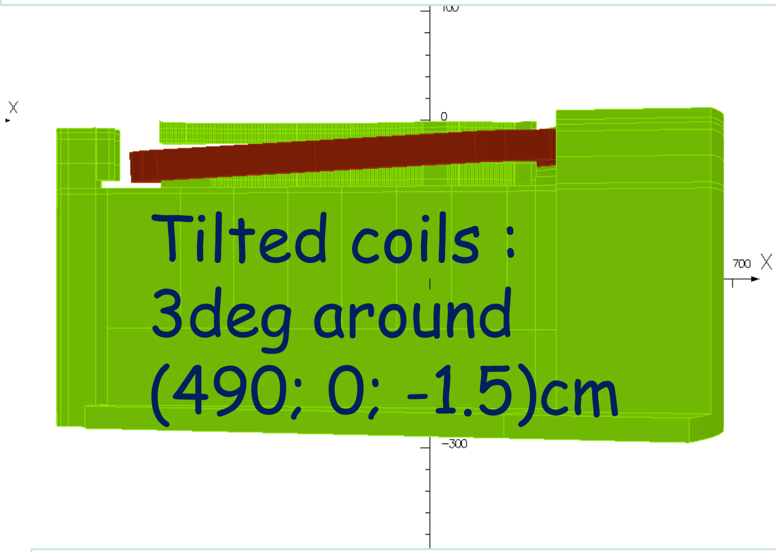
Iron Structure

Bottom half of one octant

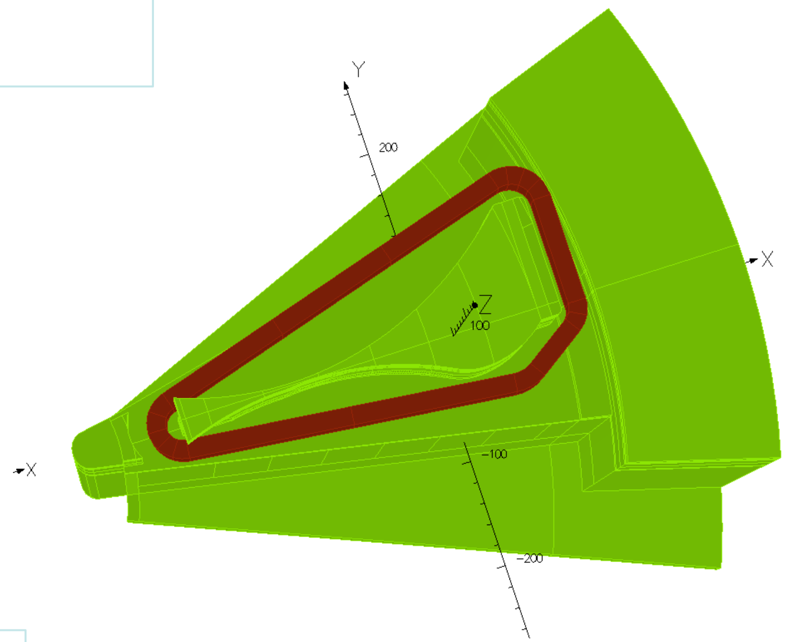


IRON WITH COILS

Current density 5200A/cm2
Area 16x27cm2



Tilted coils :
3deg around
(490; 0; -1.5)cm

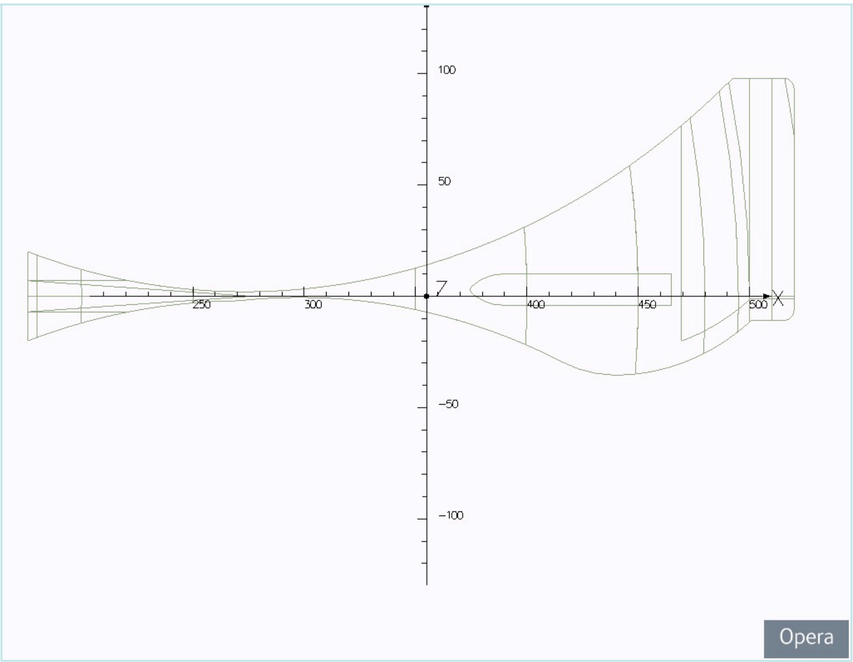


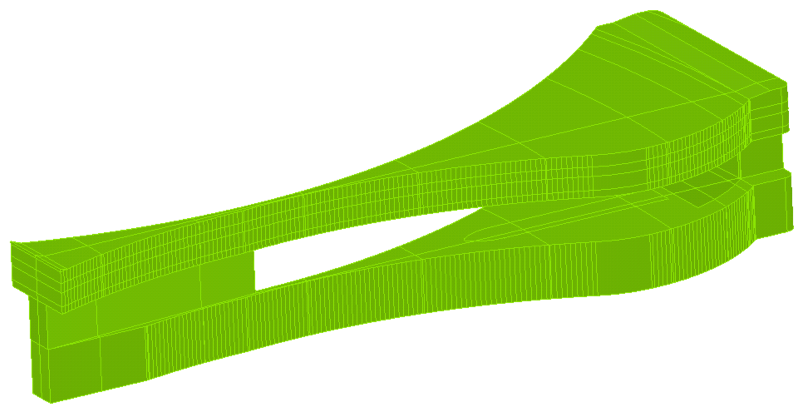
Total radius 688cm
Semi-height 280cm

Minimum distance
iron-coil 7.5cm

HILL DETAILS

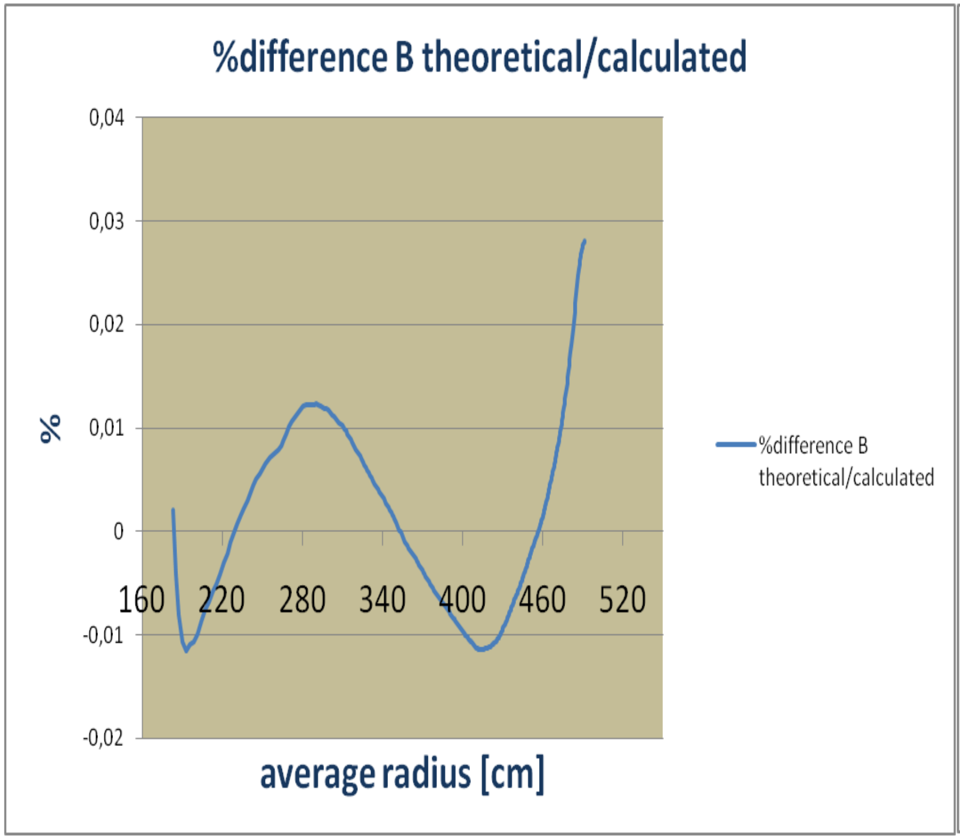
View of the hill from the top

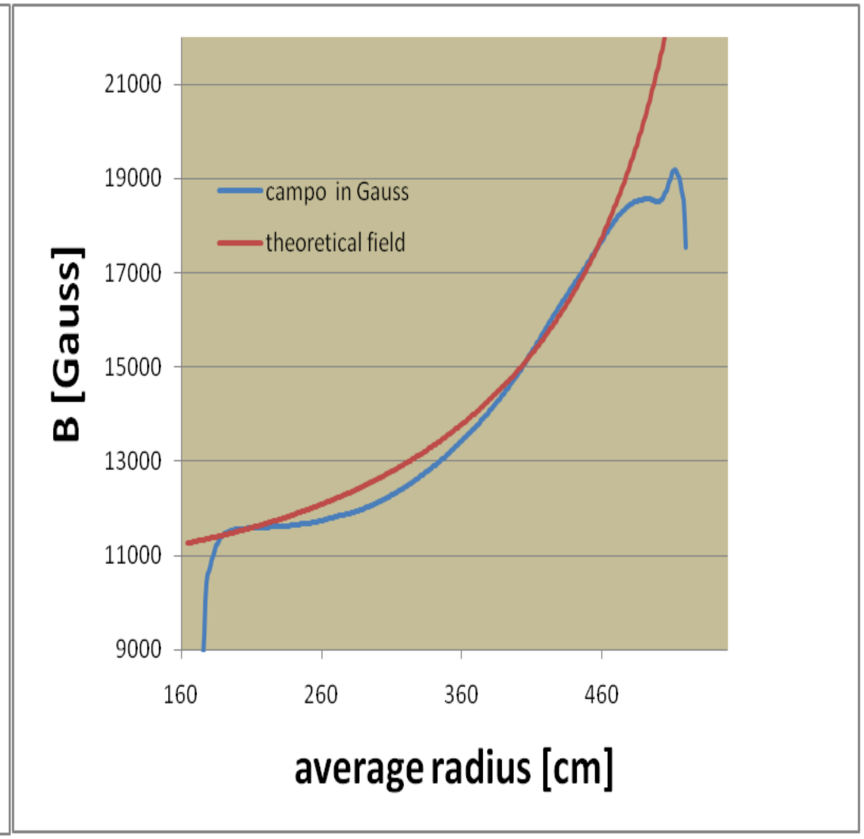




Variable gap:
3cm total at 176;
6cm total at 180cm up to 500cm;
3cm total from 510cm to 520cm

Beam Dynamics: Conformation to Isochronous Field





Last closed orbit at energy >800MeV

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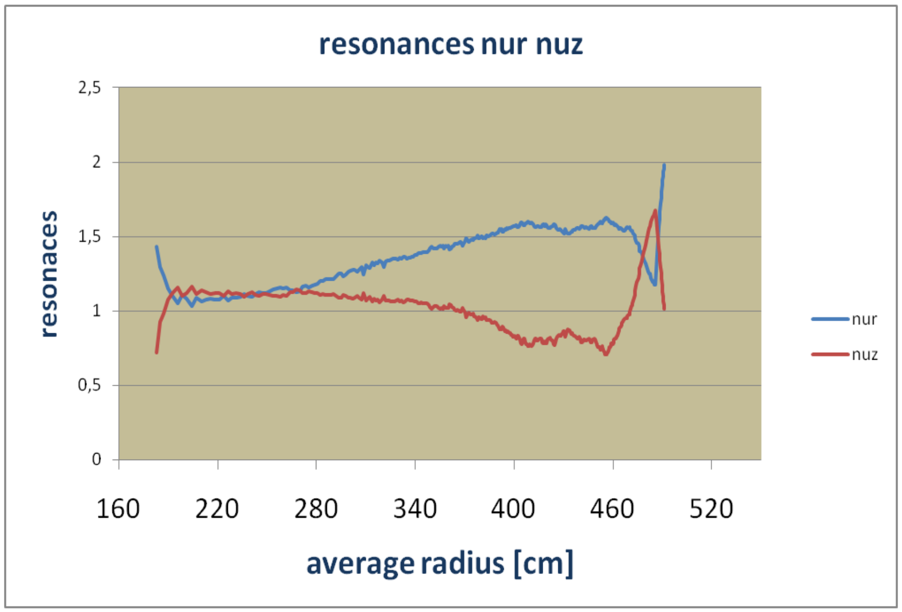
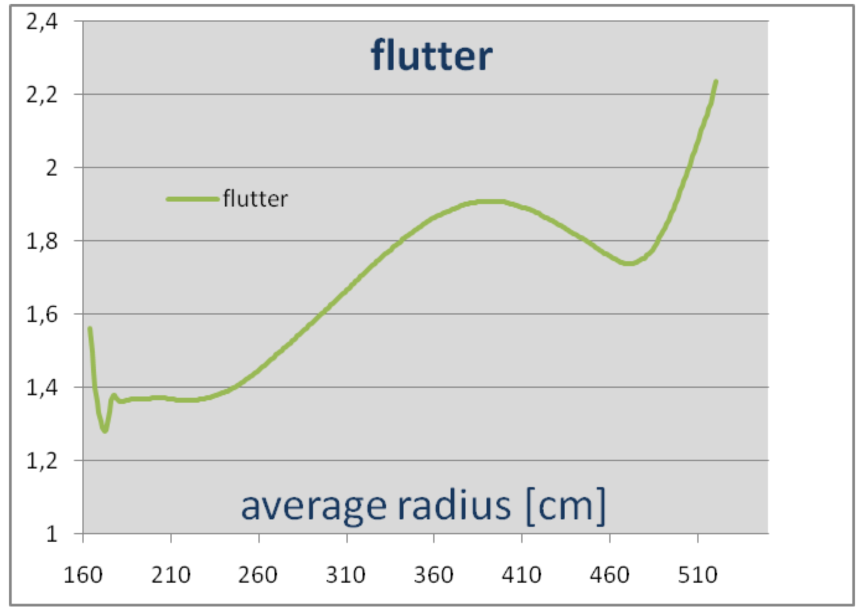
Beam Dynamics: Resonance Avoidance





ν_z = 0.5 most dangerous resonance **AVOIDED**

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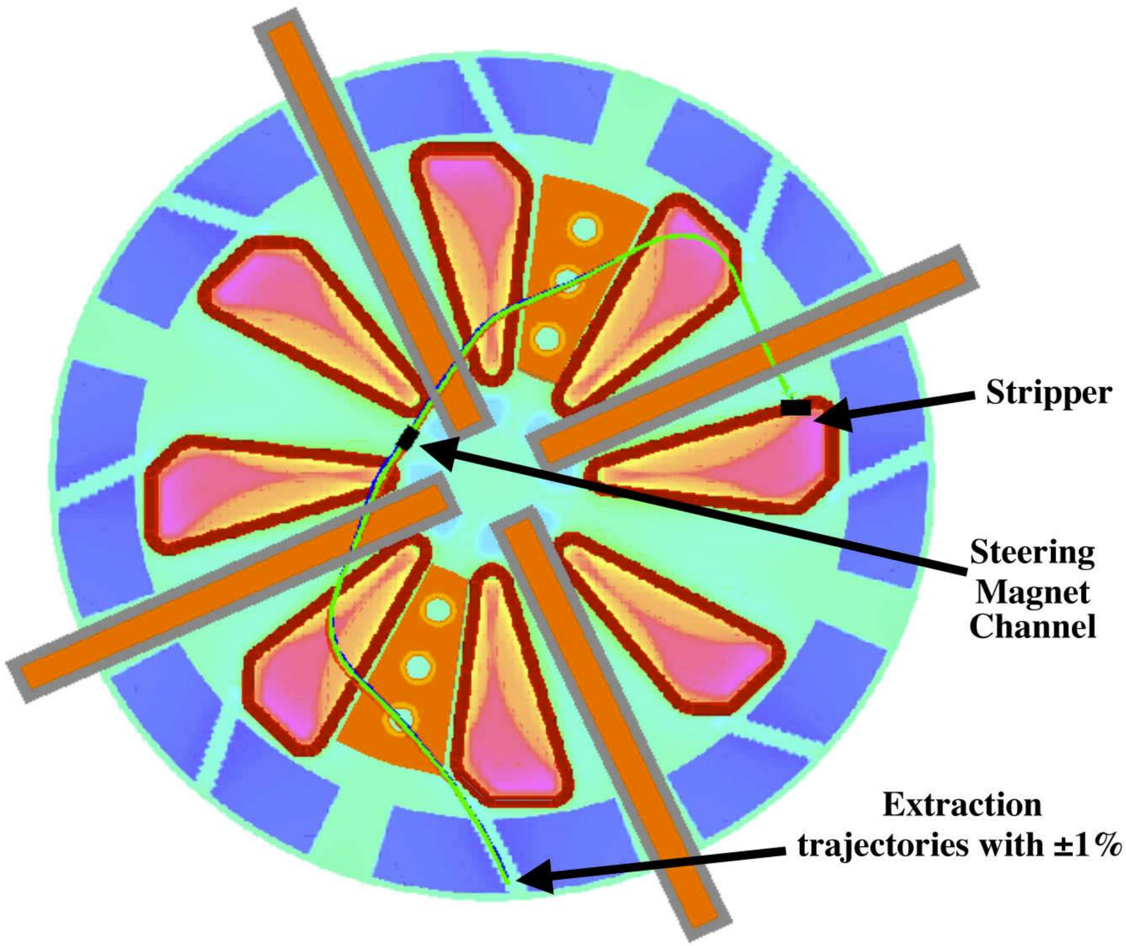
Stripping Extraction

-No need for turn separation
-Expect excellent efficiency



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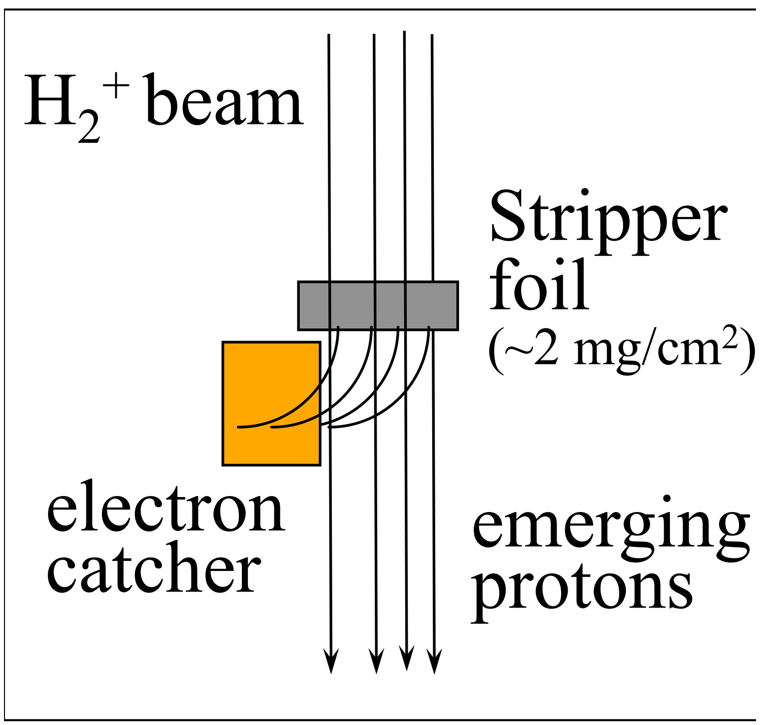
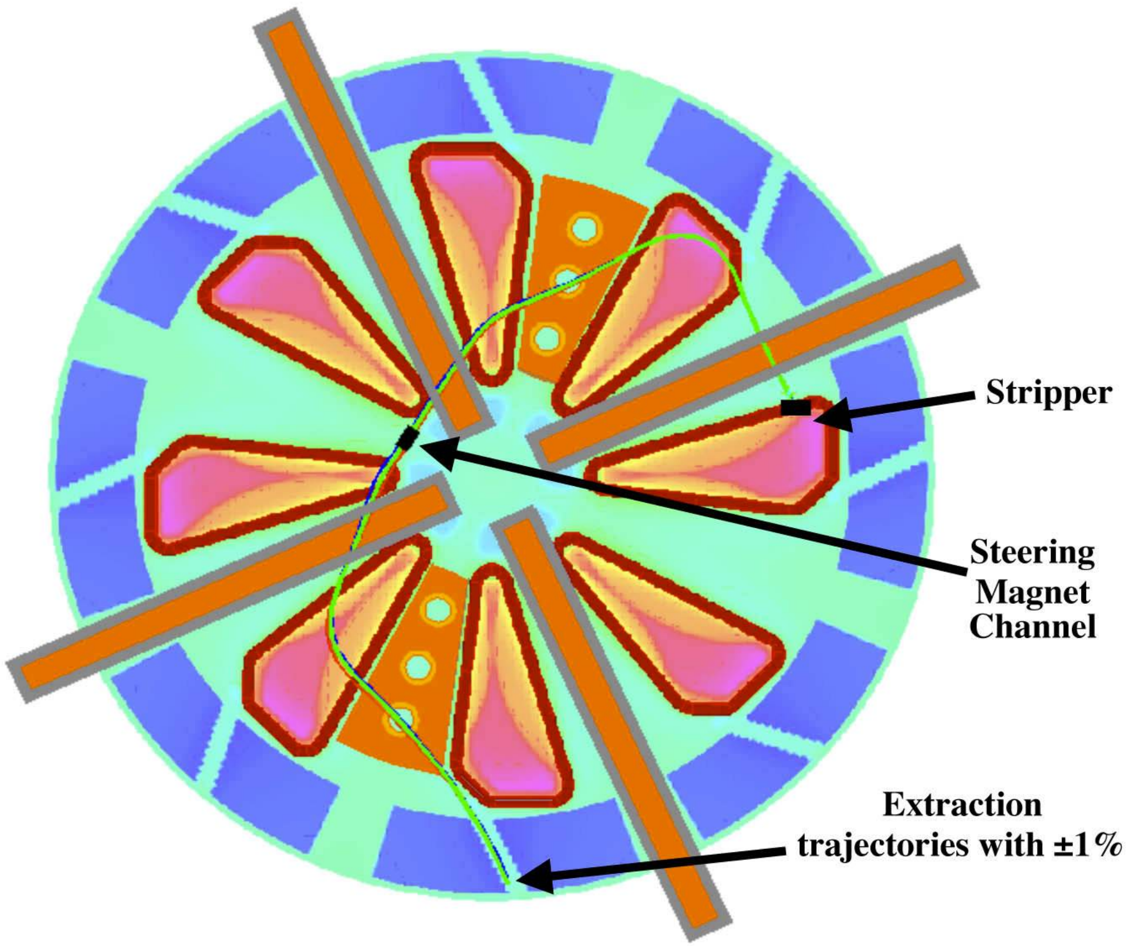




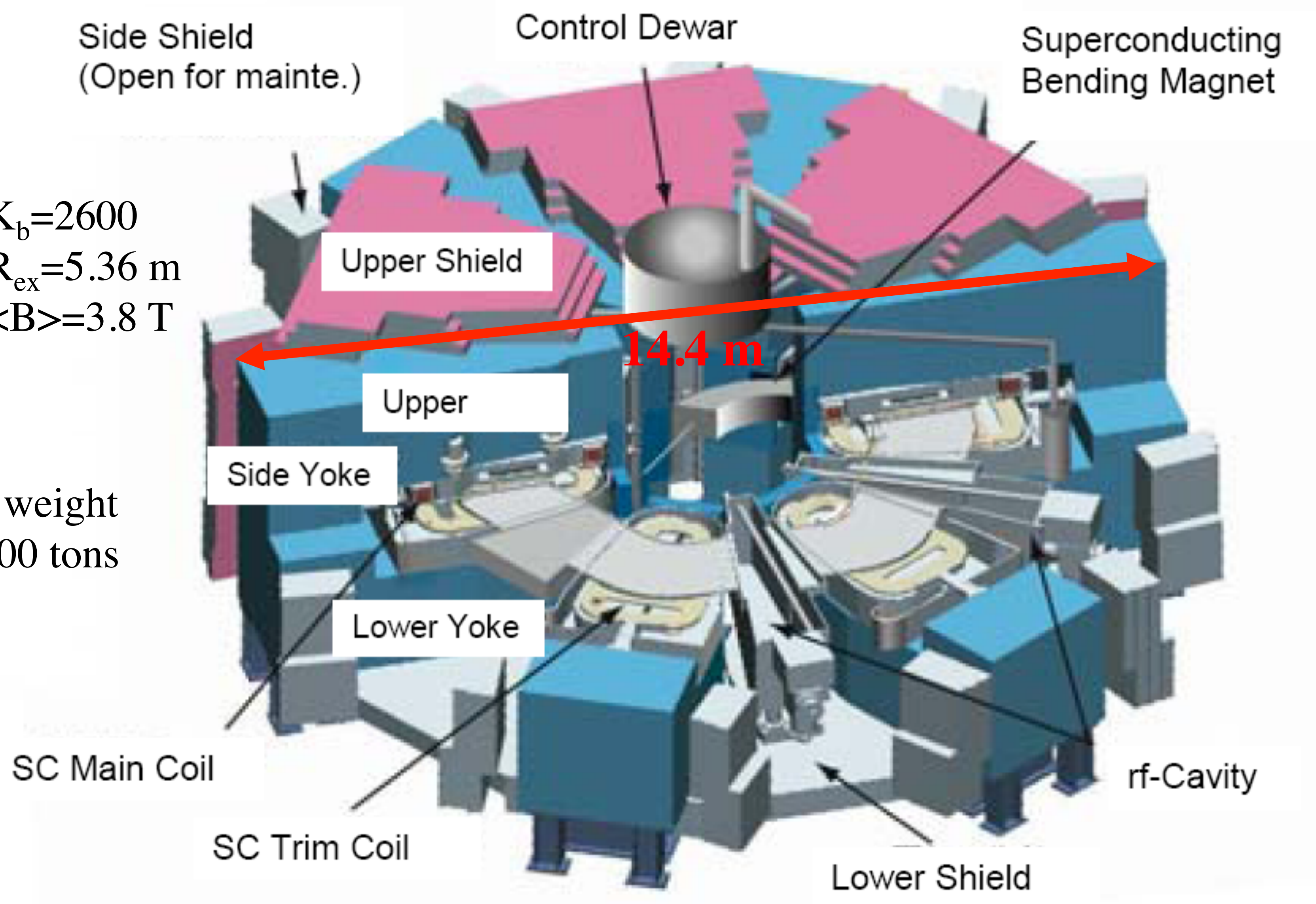
Ring Cyclotron Challenges

- Engineering design of magnet sector
  - Cryostat for containing hoop forces
  - Geometric conformation for isochronicity condition
- RF system design and integration
- Vacuum system
  - Achieve adequate vacuum to avoid gas stripping
- Extraction
  - Stripping several turns introduces momentum spread
  - Require ~2% acceptance in extraction channel

RIKEN Superconducting Ring Cyclotron (SRC)

K_b=2600
R_{ex}=5.36 m
<B>=3.8 T

Iron weight
8000 tons



Present Status of Design Efforts

- Beam dynamics work progressing well
  - Calabretta (LNS-Catania), Adelmann (PSI) leading significant modeling efforts
- Engineering studies expected in next months
  - SC magnet experts being contacted
- Ion source and Central Region tests
  - BEST collaborations
- Erice Workshop in late November
  - Assessment of viability and mapping of further R&D efforts

Goals

- Determination of feasibility of the technology
  - Development of complete straw-man design
- Establishment of base-line cost of the design

Timetable

- Rough cost within one year

Summary

- DAEδALUS experiment addresses interesting and timely questions in neutrino physics
- Accelerators being developed could be a revolutionary new compact, (relatively) inexpensive neutrino source, suitable for many experiments
  - and other ADS (Accelerator-Driven Systems) applications
- Our Collaboration is looking for new members!
  - Contact:
    - Janet Conrad <conrad@mit.edu>
    - Mike Shaevitz <shaevitz@nevis.columbia.edu>


Thank You!

H_2^+ Vibrational State Mitigation

$$H_2^+(v \geqslant 3) + He \rightarrow HeH^+ + H$$

$$H_2^+(v \geqslant 2) + Ne \rightarrow NeH^+ + H.$$

after Chupka & Russell (1968)

Diagnostic for optimizing quenching with noble gases in source plasma

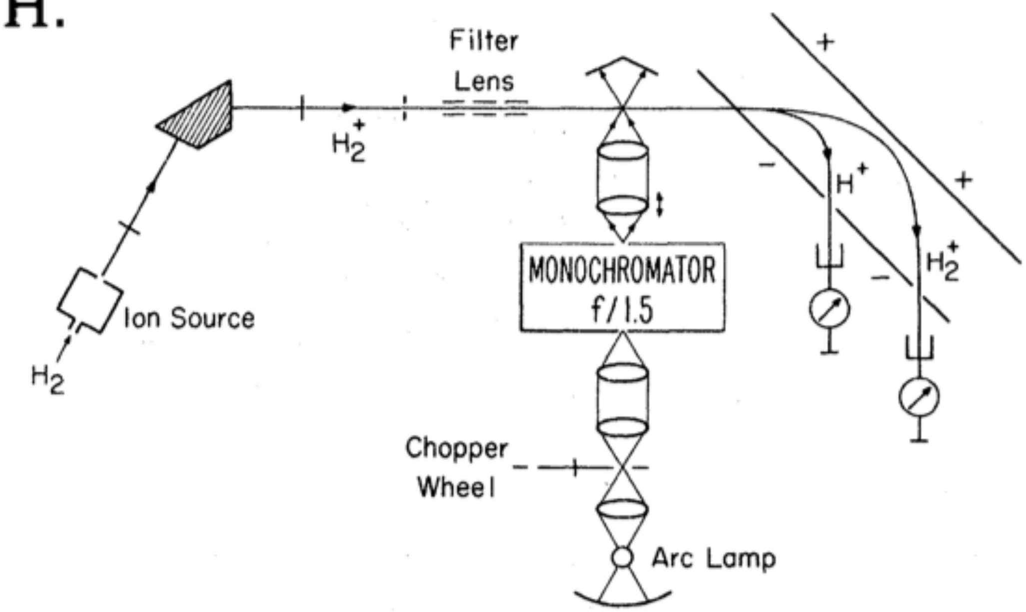


Photo-dissociation, after Von Busch & Dunne (1972)

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