DAEδALUS

ANDES Workshop
April 11, 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

Collaboration Resources:

DAEδALUS co-spokespersons:

- Janet Conrad, MIT
- Mike Shaevitz, Columbia

Accelerator Team:

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

Thx to:

- Georgia Karagiorgi, Columbia

Outline

- Premise for DAEδALUS experiment
- Description of experiment
- Sensitivity studies
- Complementarity between DAEδALUS and LBNE
- Accelerator requirements/options for DAEδALUS
- Design progress
- Outlook
- Summary

Neutrino Oscillation and δ_{CP}

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

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) = \; & \sin^2\theta_{23} \sin^2\theta_{13} \sin^2\Delta_{31} \\
& + \sin\delta \; \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \; \sin^2\Delta_{31} \sin\Delta_{21} \\
& + \cos\delta \; \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \; \sin\Delta_{31} \cos\Delta_{31} \sin\Delta_{21} \\
& + \cos^2\theta_{23} \sin^2\theta_{12} \; \sin^2\Delta_{21}
\end{aligned}
$$

CP terms | mixing angle terms | L/E-dep. mass-splitting terms

CP-violating interference terms

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

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

Neutrino Oscillation and δ_{CP}

Assuming we measure θ_{13} at reactor experiments in the near future
(global fits suggest $\sin^2 2\theta_{13}$=0.06±0.04, near-future reactor experiment sensitivity 0.005)

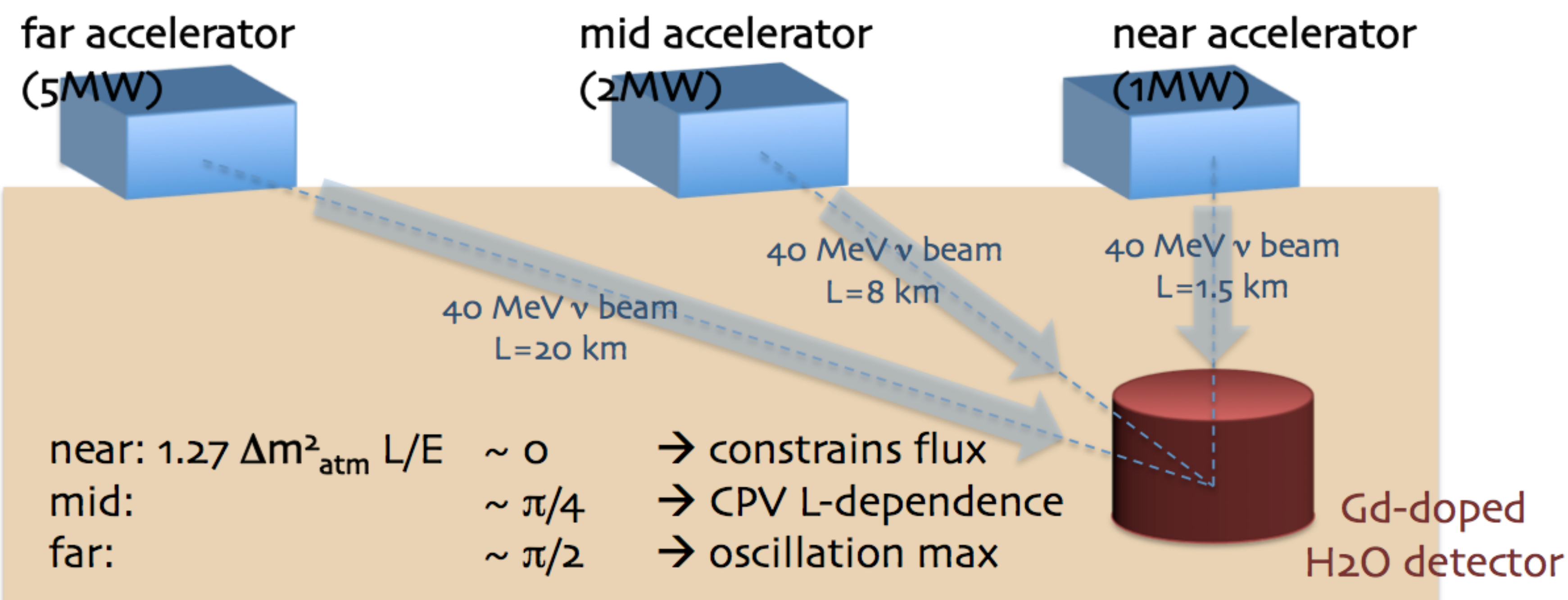
Conventional approach: LBNE
Use neutrino and antineutrino beams over long baselines: $\delta \rightarrow -\delta$

DAEdALUS:
Use antineutrino-only beam over short baselines: L-dependence of CP-violating interference terms

avoids complication of matter effects!

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

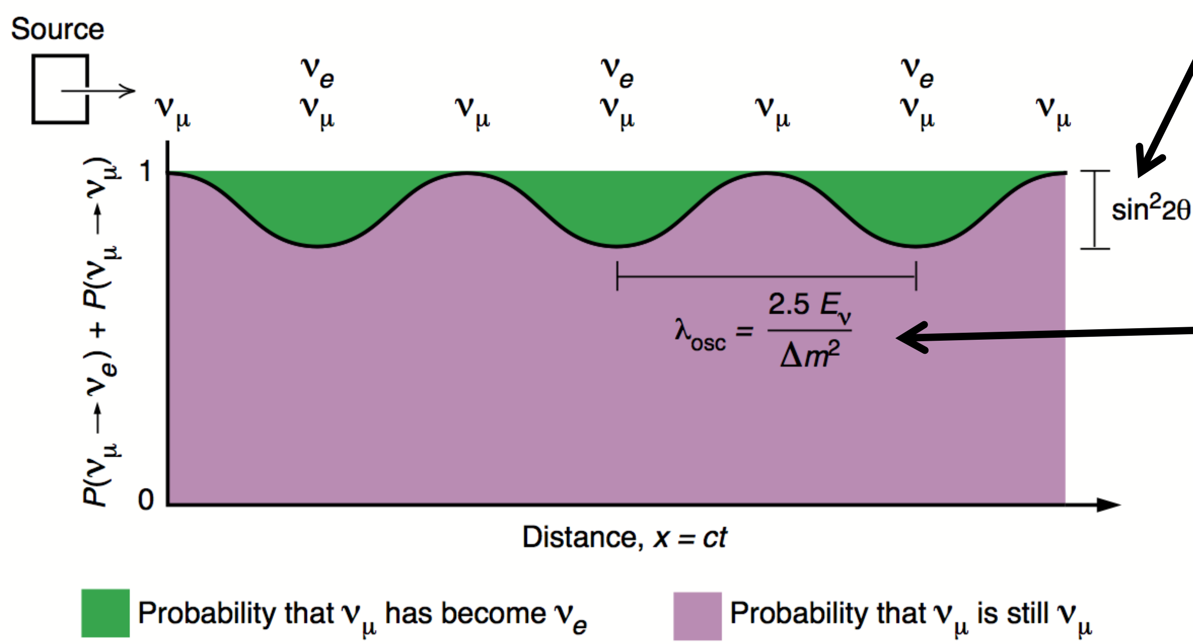


DAEδALUS

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

Oscillations of Neutrinos

θ = mixing angle

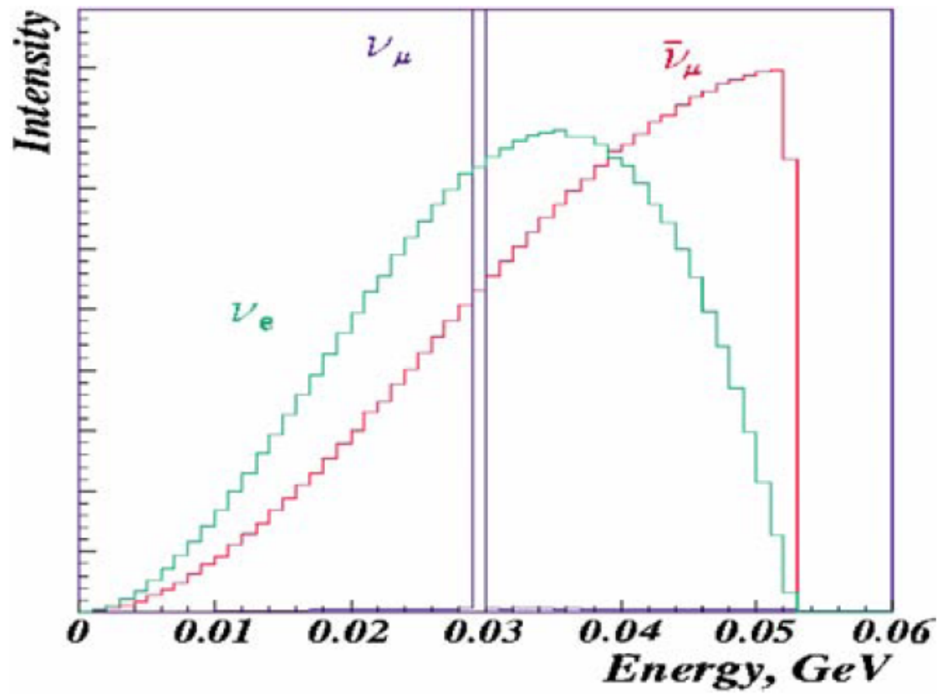


λ = oscillation frequency

NOTE: $\lambda/E \sim 1/\Delta m^2$

Decay At Rest Source

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



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

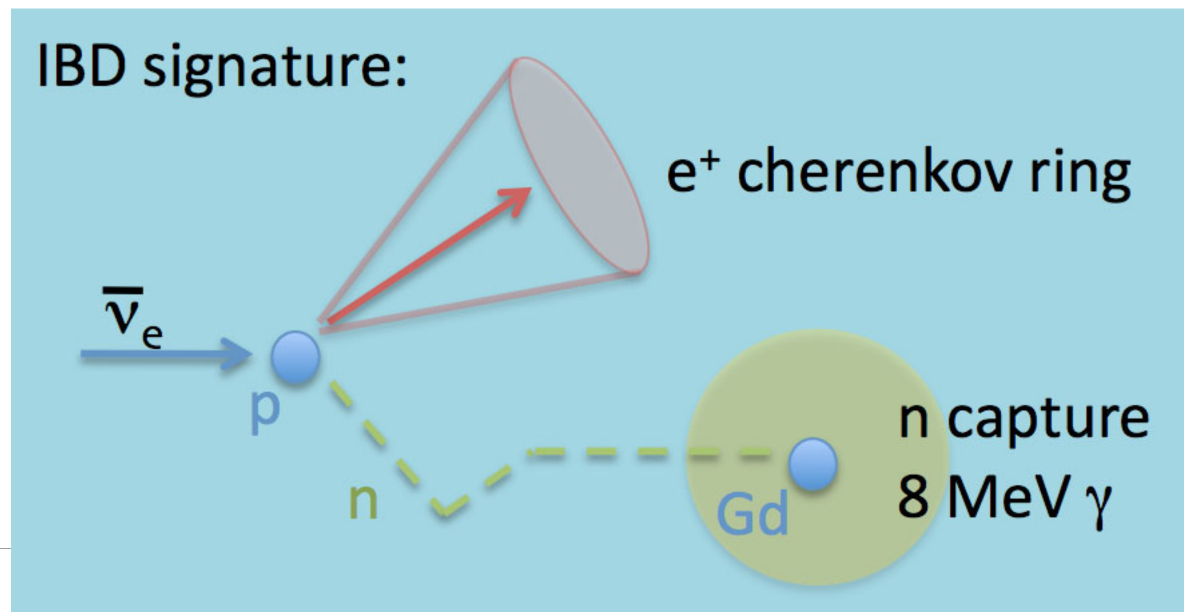
  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

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

DAEδALUS

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%



DAEδALUS

Sensitivity Comparisons

Complementarity with LBNE:

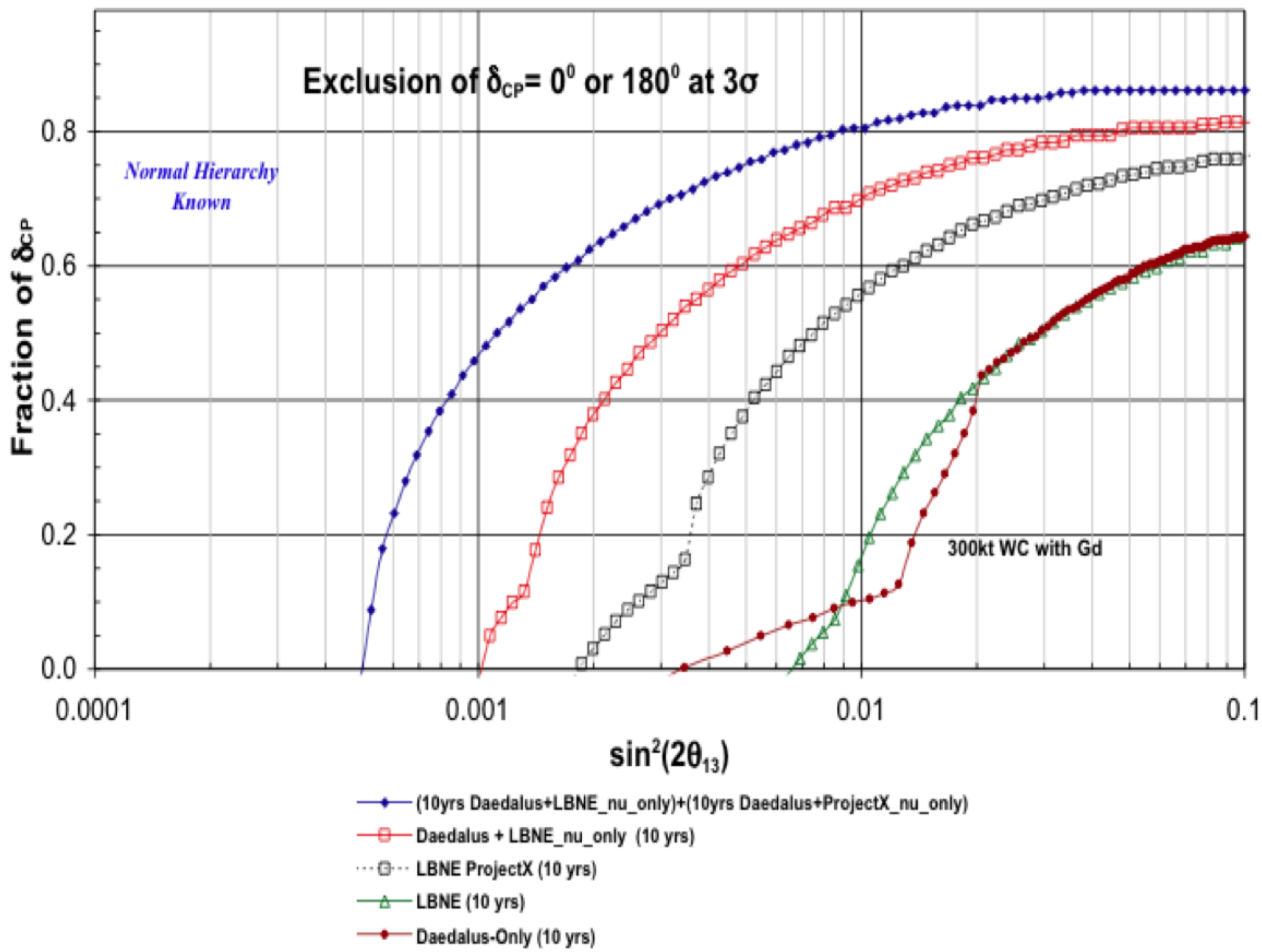
Four scenarios:

1) LBNE only	10yr run	n+nbar
2) DAEdALUS only	10yr run	nbar only
3) LBNE+ProjectX	10yr run	n+nbar
4) LBNE + DAEdALUS concurrent running		
LBNE:	10yr run	n only
DAEdALUS:	10yr run	nbar only
5) DAEdALUS+LBNE	10yr run	
followed by		
DAEdALUS+ProjectX	10yr plan	

Quantifying measure:

Fraction of dCP space where dCP=0 or 180 (no CP violation) can be excluded at 3 sigma

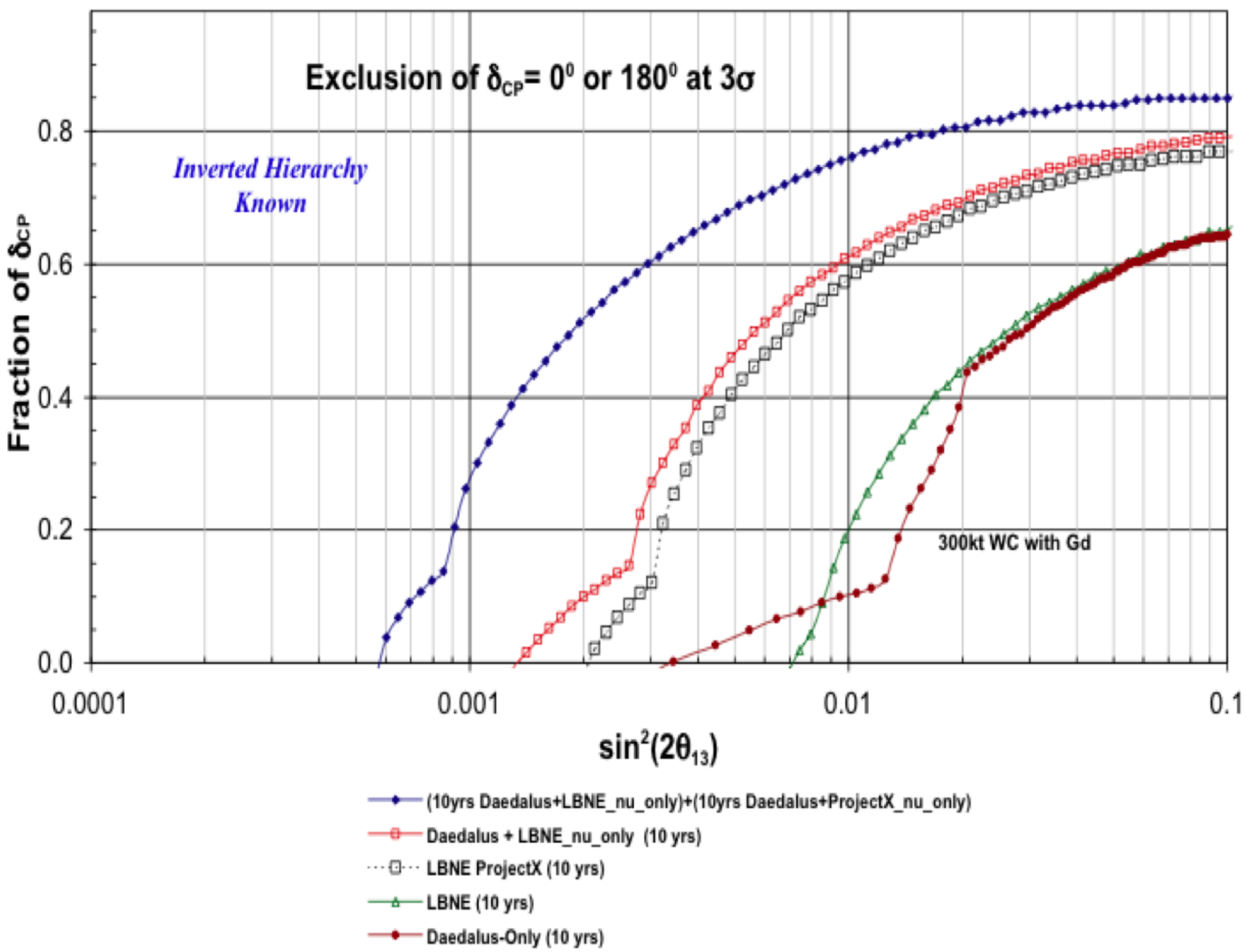
Sensitivity Comparisons



Normal Hierarchy

DAEδALUS

Sensitivity Comparisons

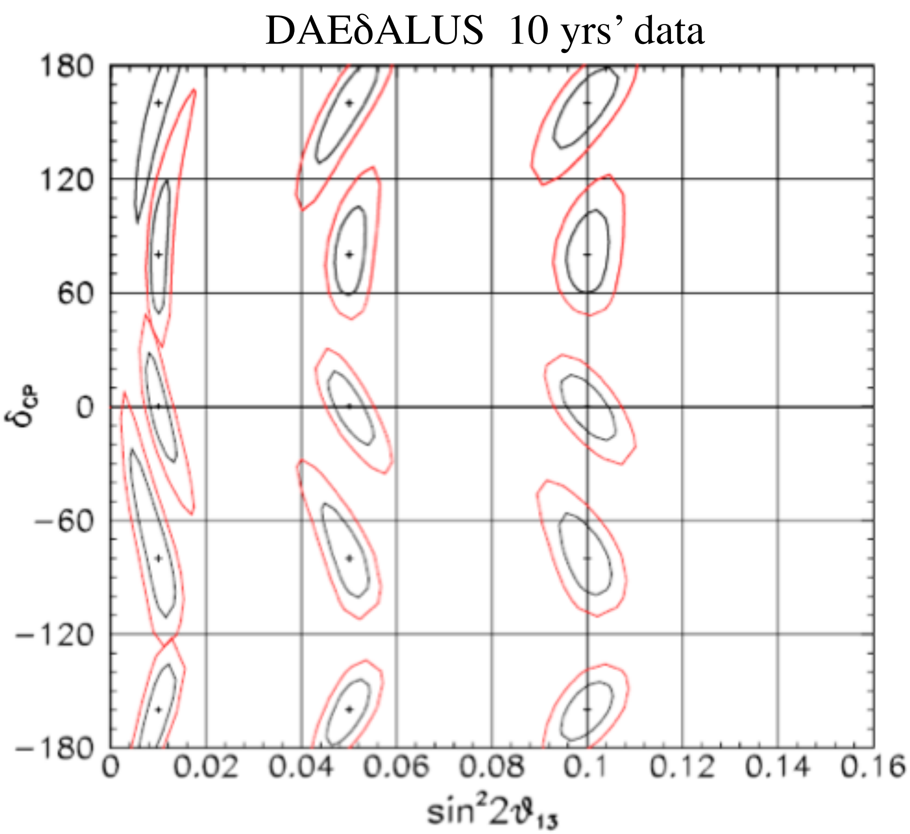


Inverted Hierarchy

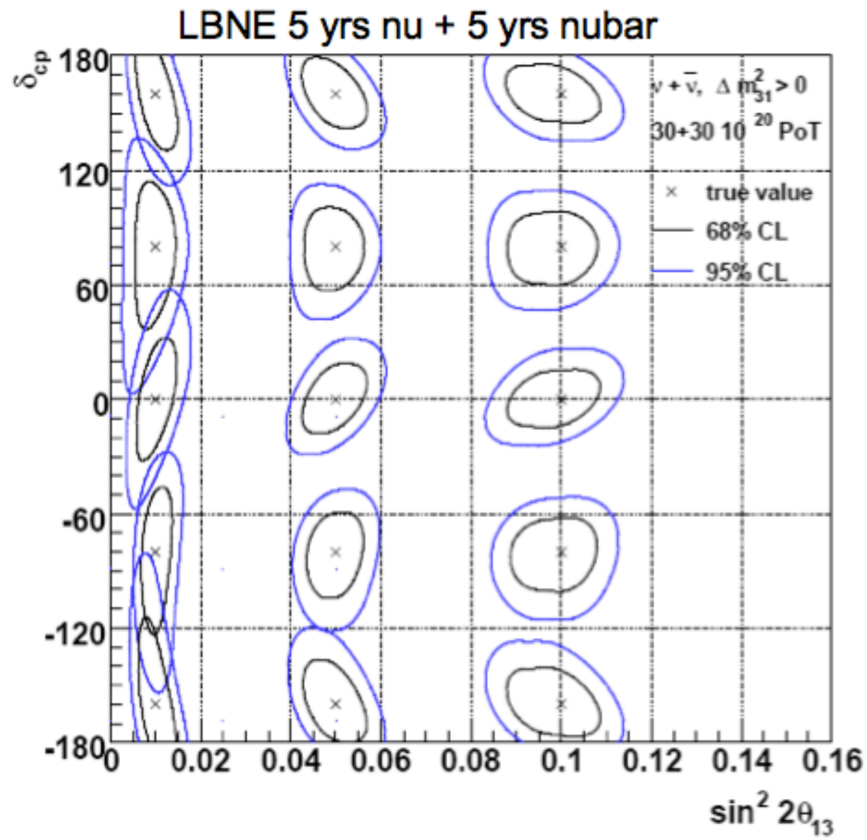
DAEδALUS

Sensitivity Comparisons

DAEδALUS



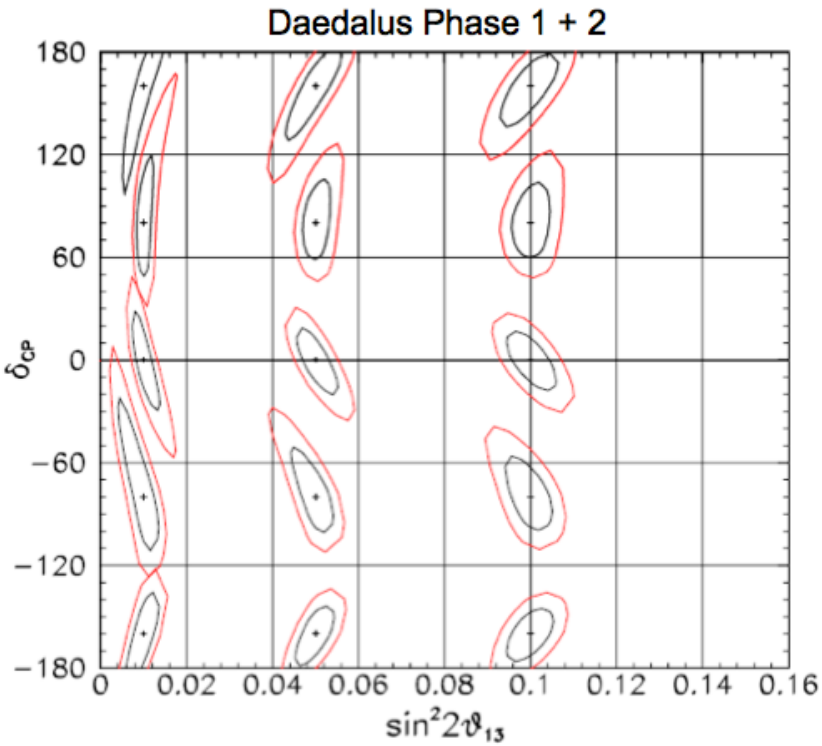
LBNE



Synergistic Combination

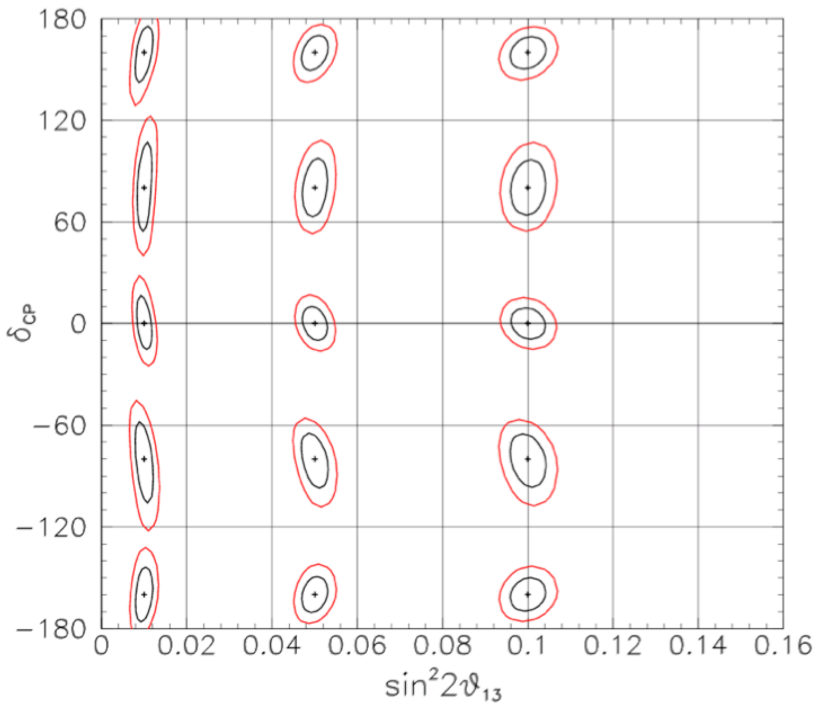
DAEδALUS alone

(10 year data collection)



DAEδALUS + LBNE

(10 yr DAEδALUS + 10 yr LBNE ν only)



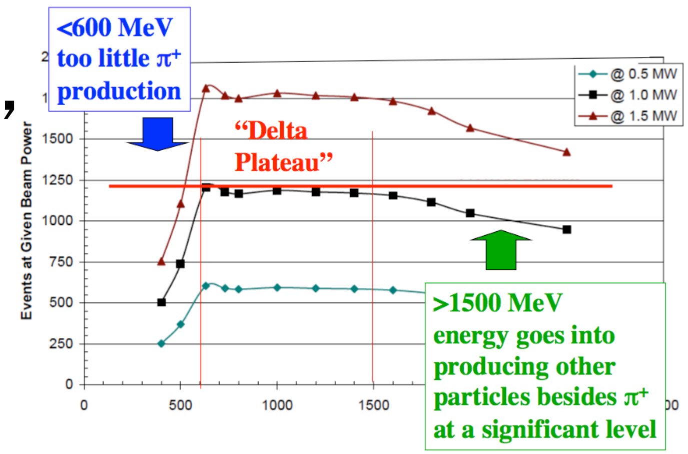
DAEδALUS

Accelerator Requirements

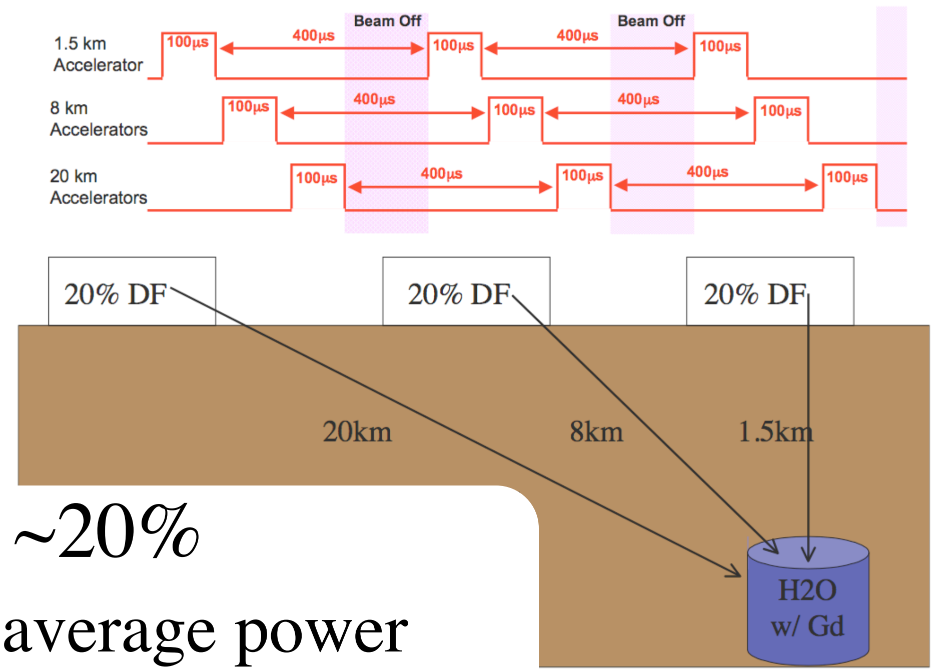
Can they be built?

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)



Accelerator Requirements



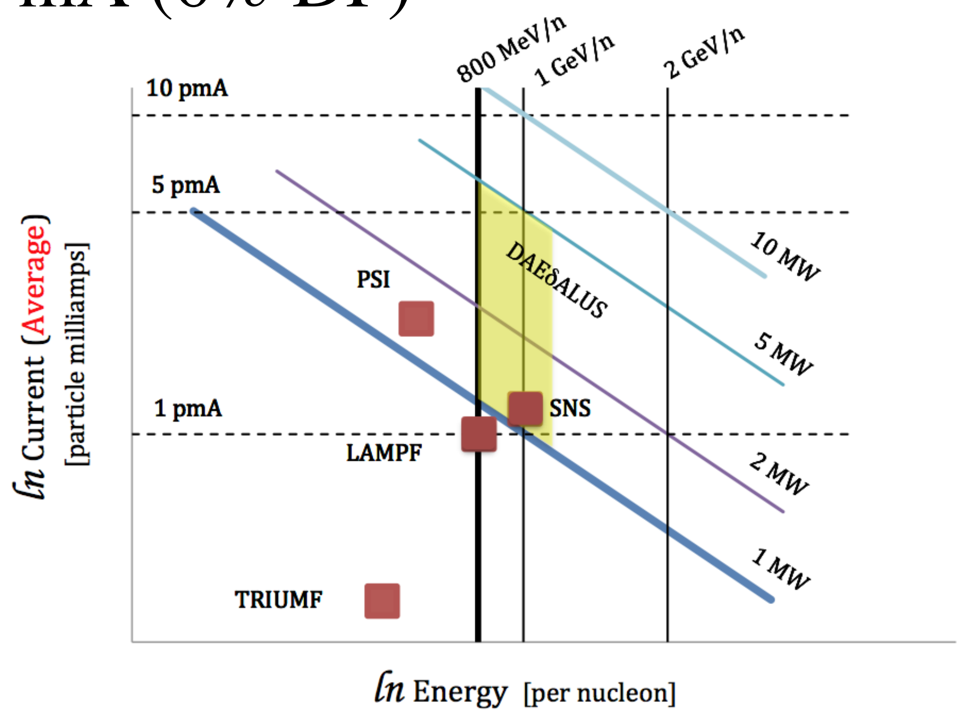
- Beam Power:
  - 1.5 km site: 1 MW average
  - 8 km site: 2 MW average
  - 20 km site: 5 MW average
- Accelerator Duty Factor: ~20%
  - Instantaneous power is ×5 average power
  - Can be optimized as time structure is fairly arbitrary
- High Reliability: both running & handling
- Cost: As low as possible

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)



DAEδALUS

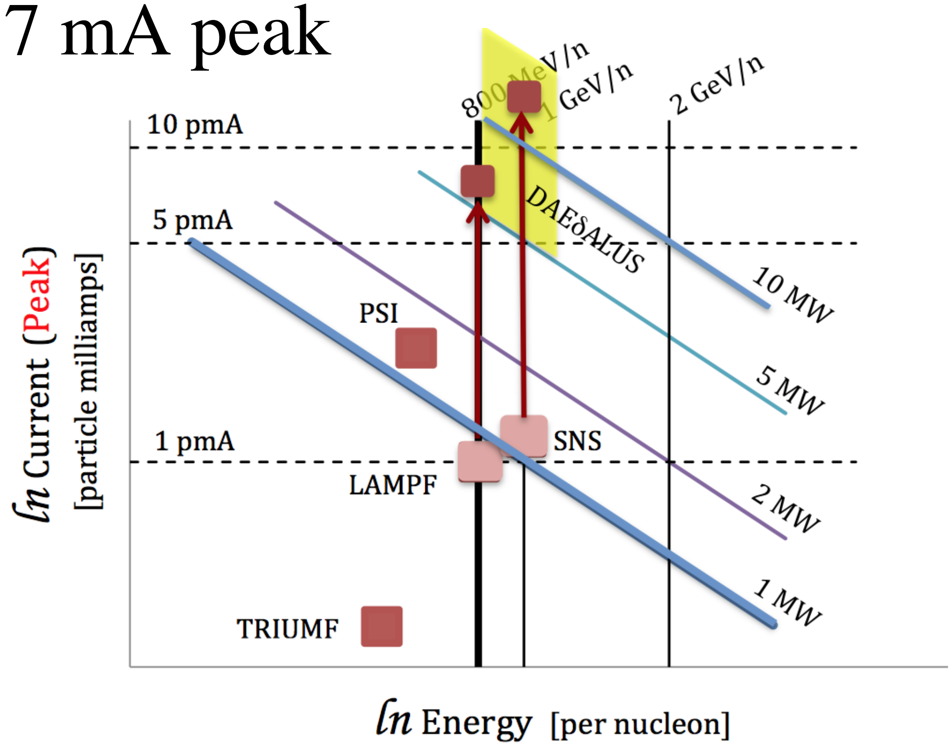
Our Needs vs. Existing Machines
(Peak Power Needs)

- 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



DAEδALUS

Issues with High Intensities

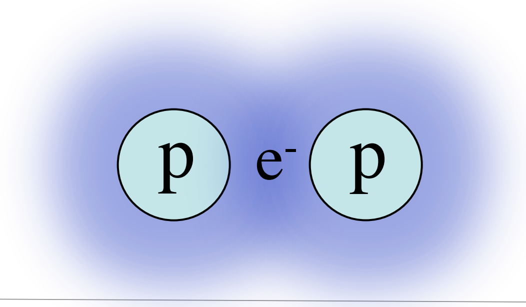
- Beam Loss
  - Thermal power damages components
    - E.g. 0.1% of 1 MW beam (1 kW) will cause problems
  - Activation causes problems for maintenance
    - SNS Specification: < 1 watt/meter of uncontrolled loss along length (~ 600 meters) of accelerator
- Space-charge Emittance Growth
  - Makes controlling 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

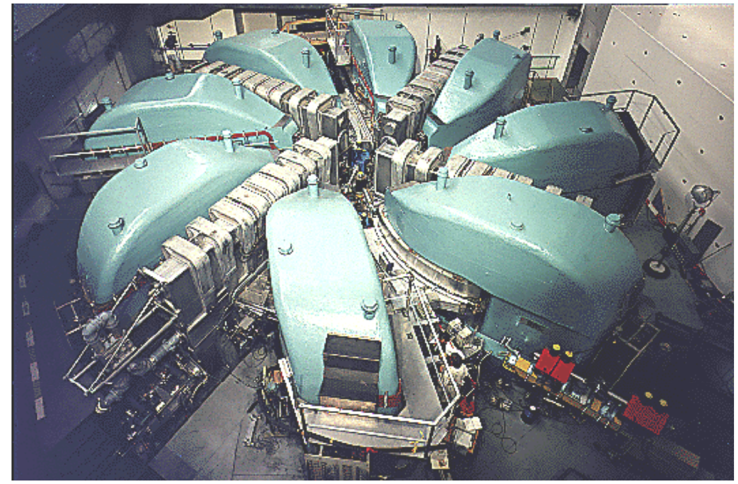
Technologies explored

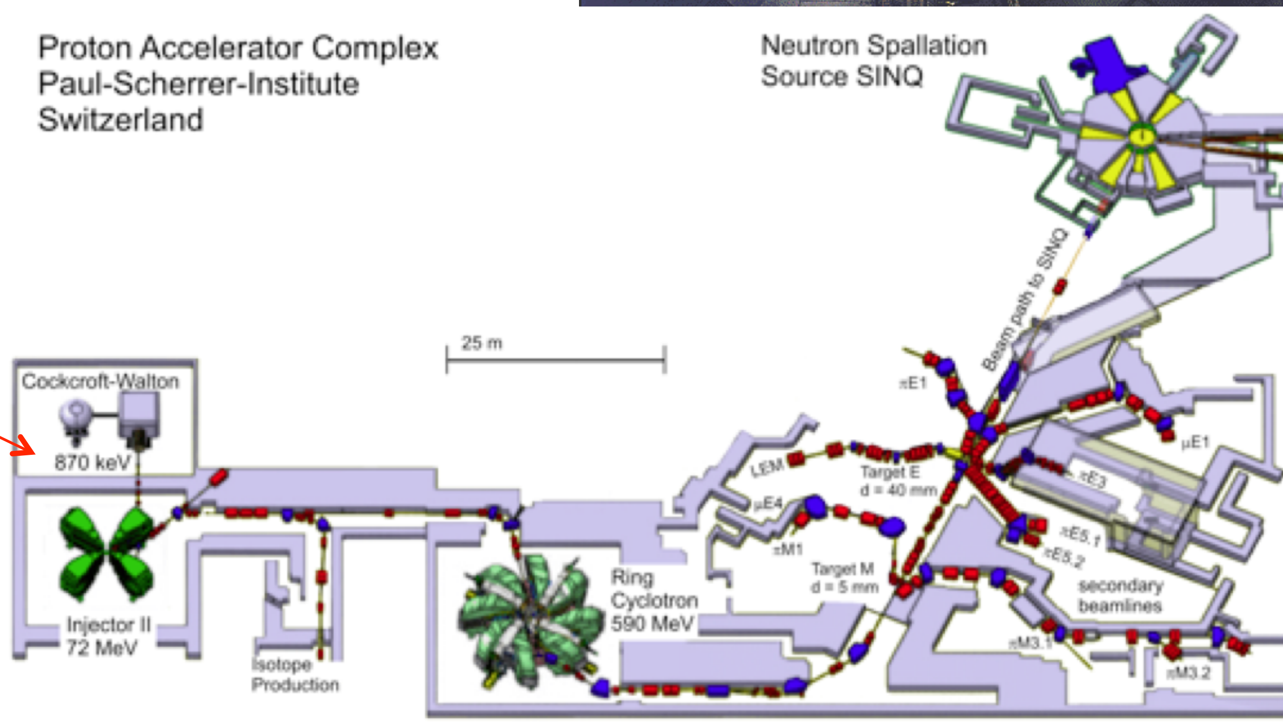
- Linacs
  - Cleanest of technologies,
    but there are issues of size and cost
- Cyclotrons
  - Compact Superconducting (proton) Cyclotron
  - Stacked (proton) Cyclotron
  - H_2^+ Cyclotron -- reduces many problems related to beam loss and extraction compared to other designs



Cyclotron Experience

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

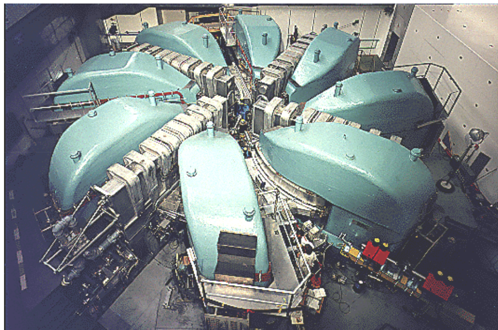


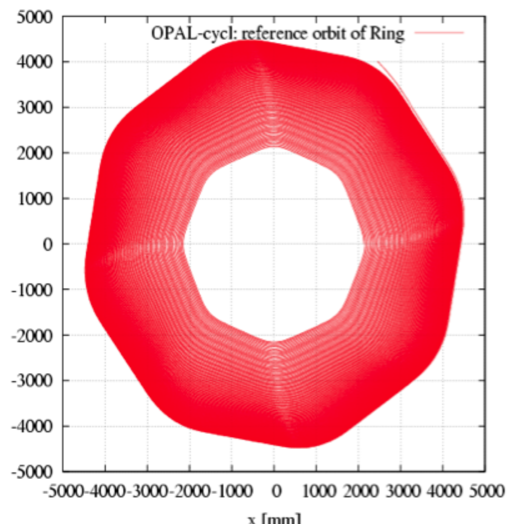


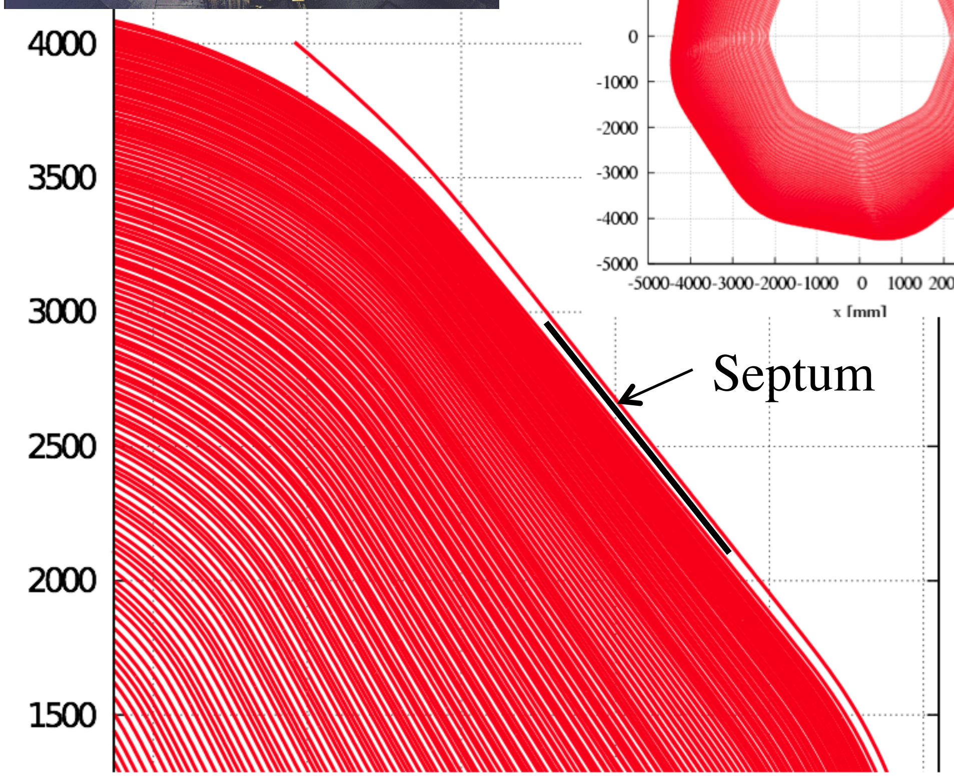
Very high
Injection energy

DAEδALUS

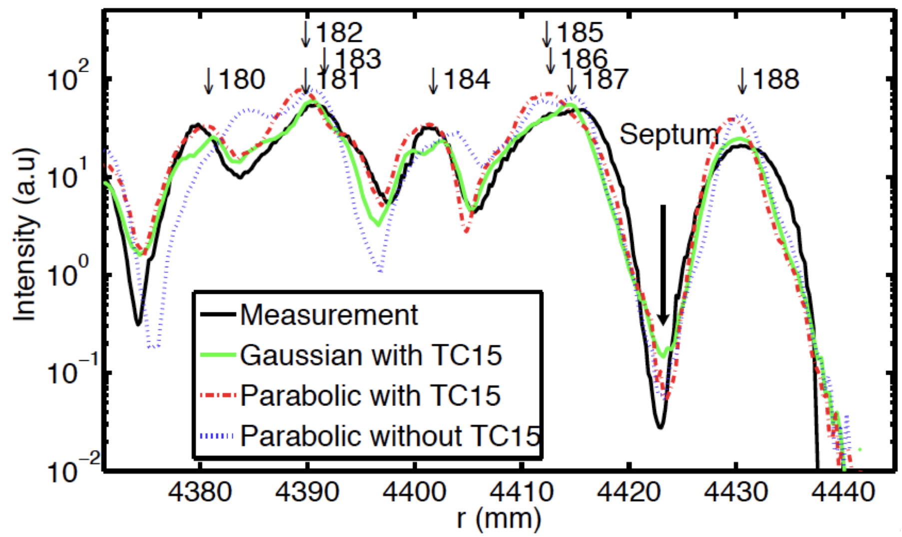
Beam at High Energy End





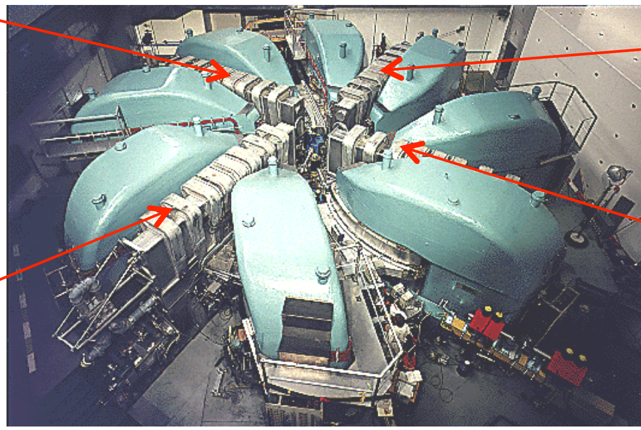


- Turns get closer together as radius increases
  - Must play resonances to get turn separation
  - Septum intercepts beam!
  - PSI achieves 99.98% extraction efficiency!



DAEδALUS

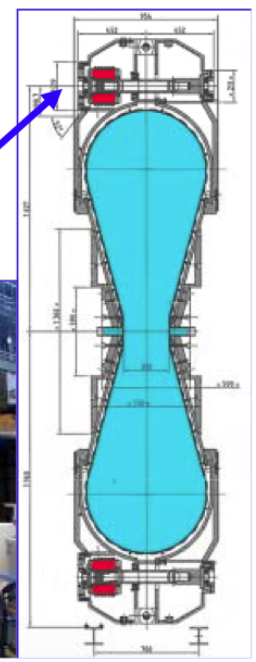
Also Must Have Very Large RF System



- High accelerating voltage promotes larger turn separation
  - ΔE = 2 MeV/turn
  - 500 kV/cavity

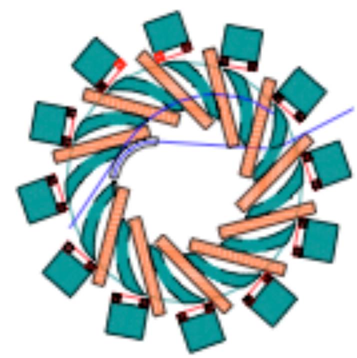
resonator inside

hydraulic tuners



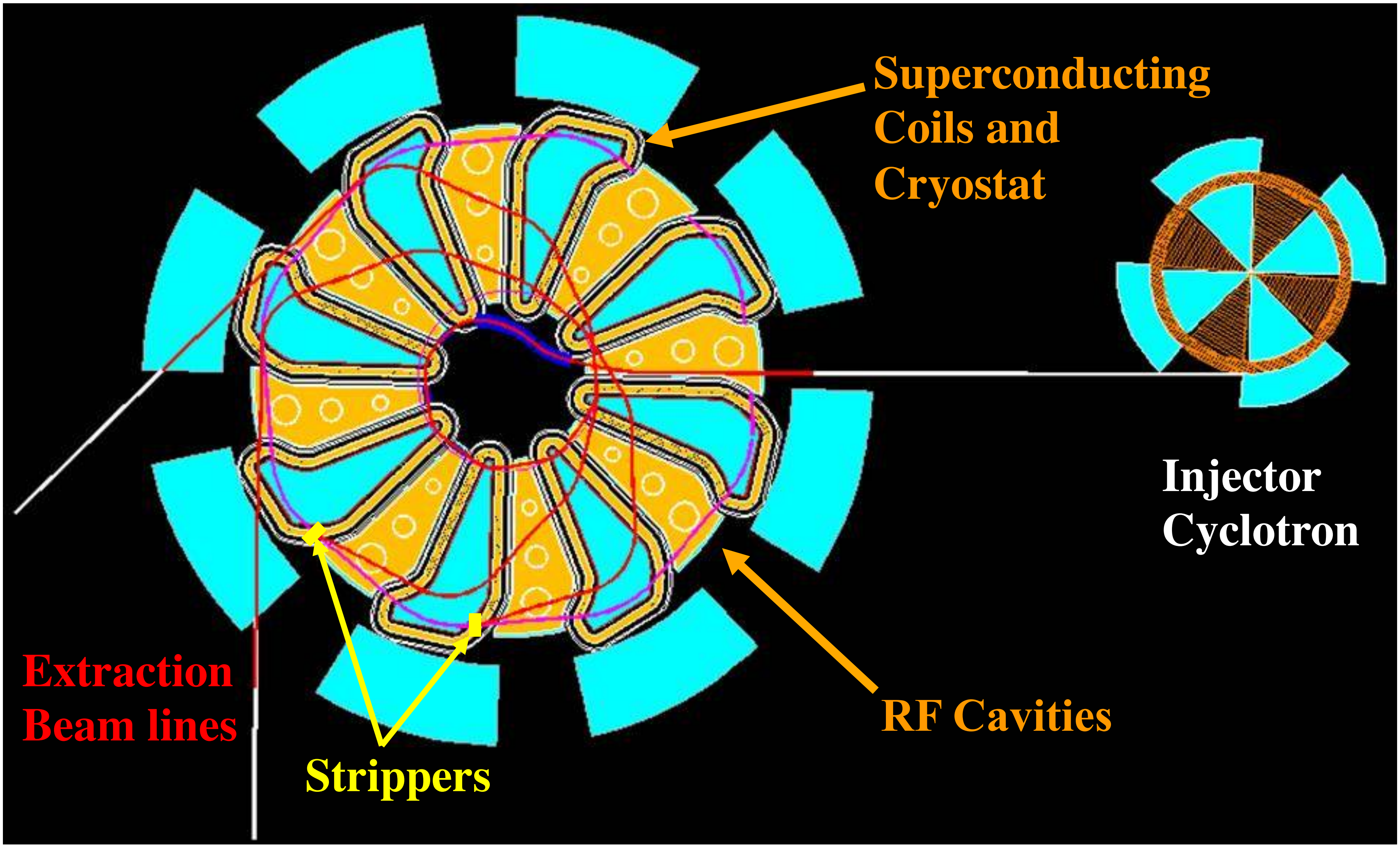
H_2^+ Ring Cyclotron
Promising Design from 1990's

- Concept proposed by Carlo Rubbia ~1994
- Initial designs done by Luciano Calabretta, Catania
  - Reports in European Particle Accelerator Conference
    - Calabretta et al: PAC 99 & EPAC 2000
- 1 GeV, ~6 mA
- High rigidity for H_2^+
  - Superconducting magnets reduce consequences
- Clean extraction (via stripping)
  - Substantially less RF requirements



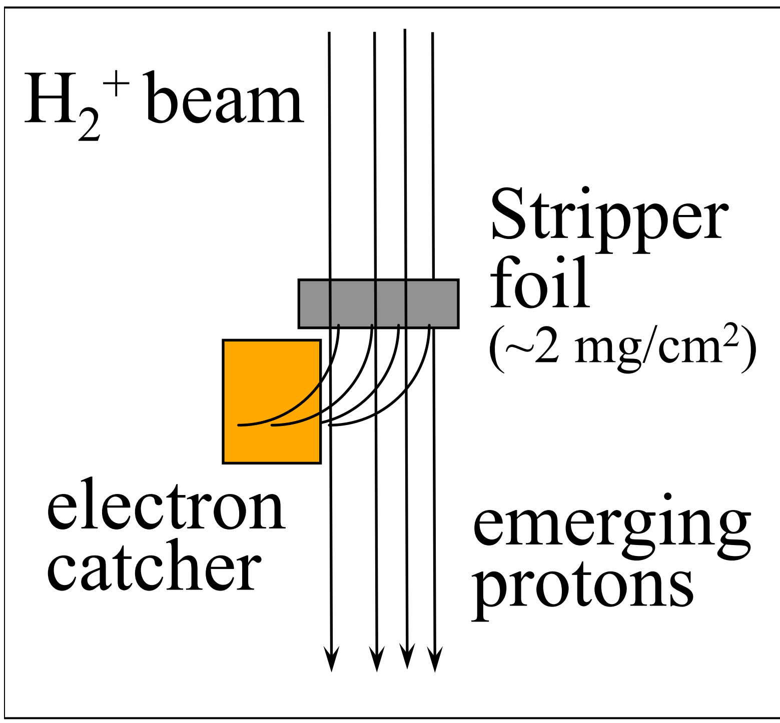
DAEδALUS

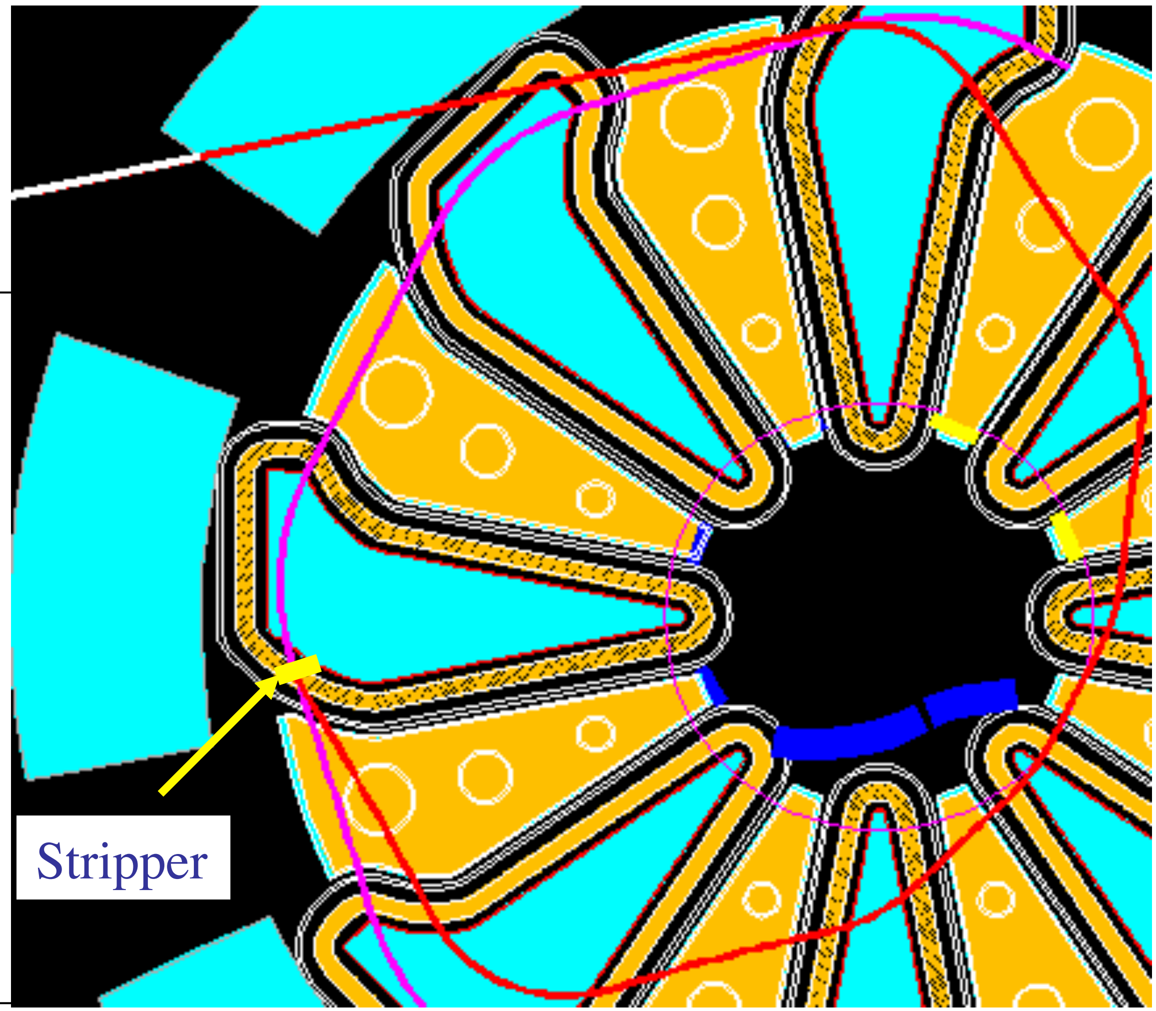
Injector Cyclotron delivers ~ 50 MeV/n H_2^+ beam to Ring Cyclotron
800 MeV/n beam stripped at outer radius,
Proton orbits designed to cleanly exit machine



Stripper Considerations

Stripper position is chosen to achieve:
- Beam extraction
- Good beam envelope
- No interference with injection devices
- Magnetic Field positive





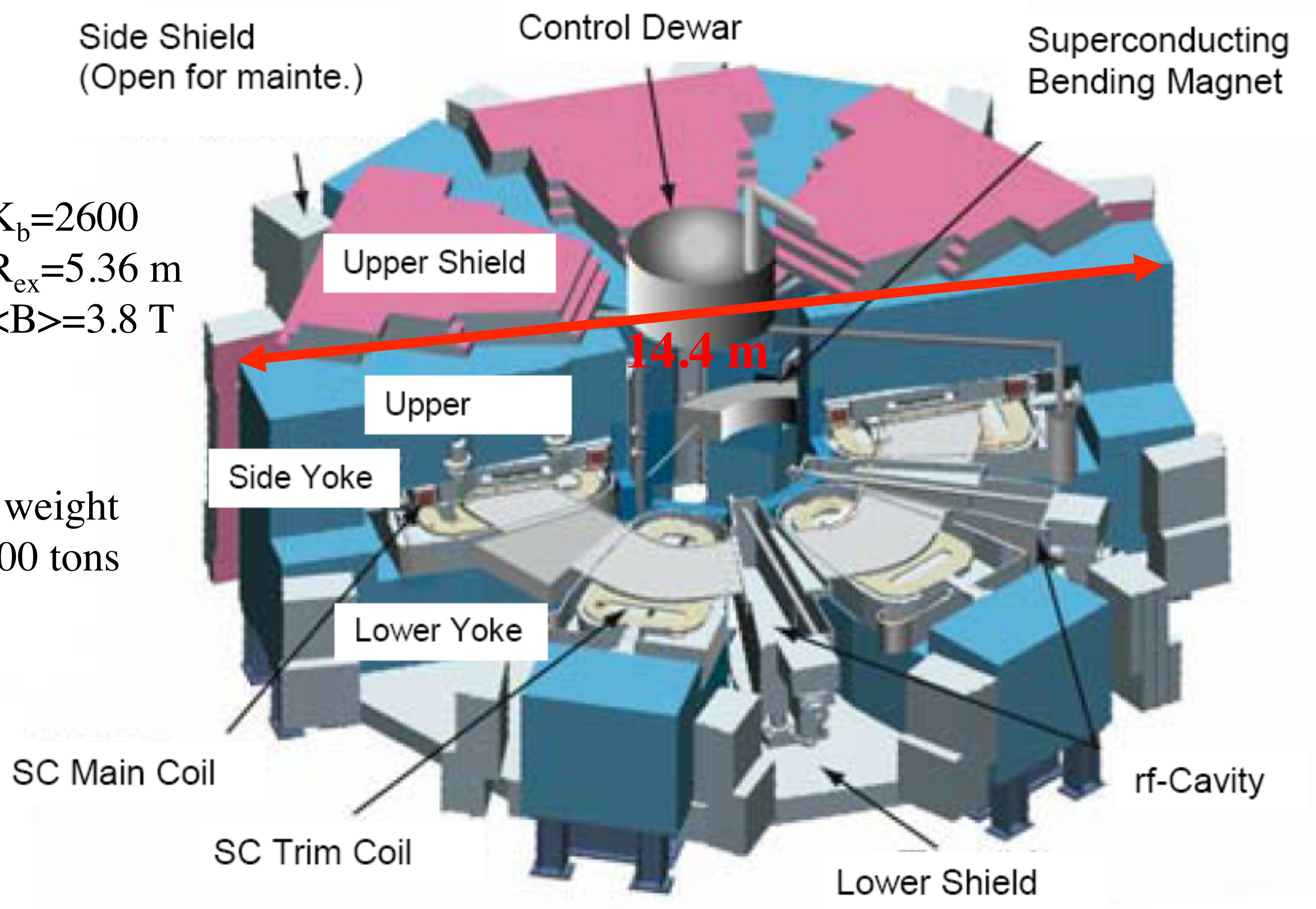
Cyclotron Characteristics

- Both cyclotrons are isochronous
  - Revolution frequency independent of energy/radius (fixed RF frequency)
  - Allows for continuous beam (highest current)
- Injector cyclotron ~similar to commercial machines (IBA, EBCO isotope-production)
- Ring cyclotron ~similar to superconducting RIKEN (heavy-ion) cyclotron

RIKEN Superconducting Ring Cyclotron (SRC)

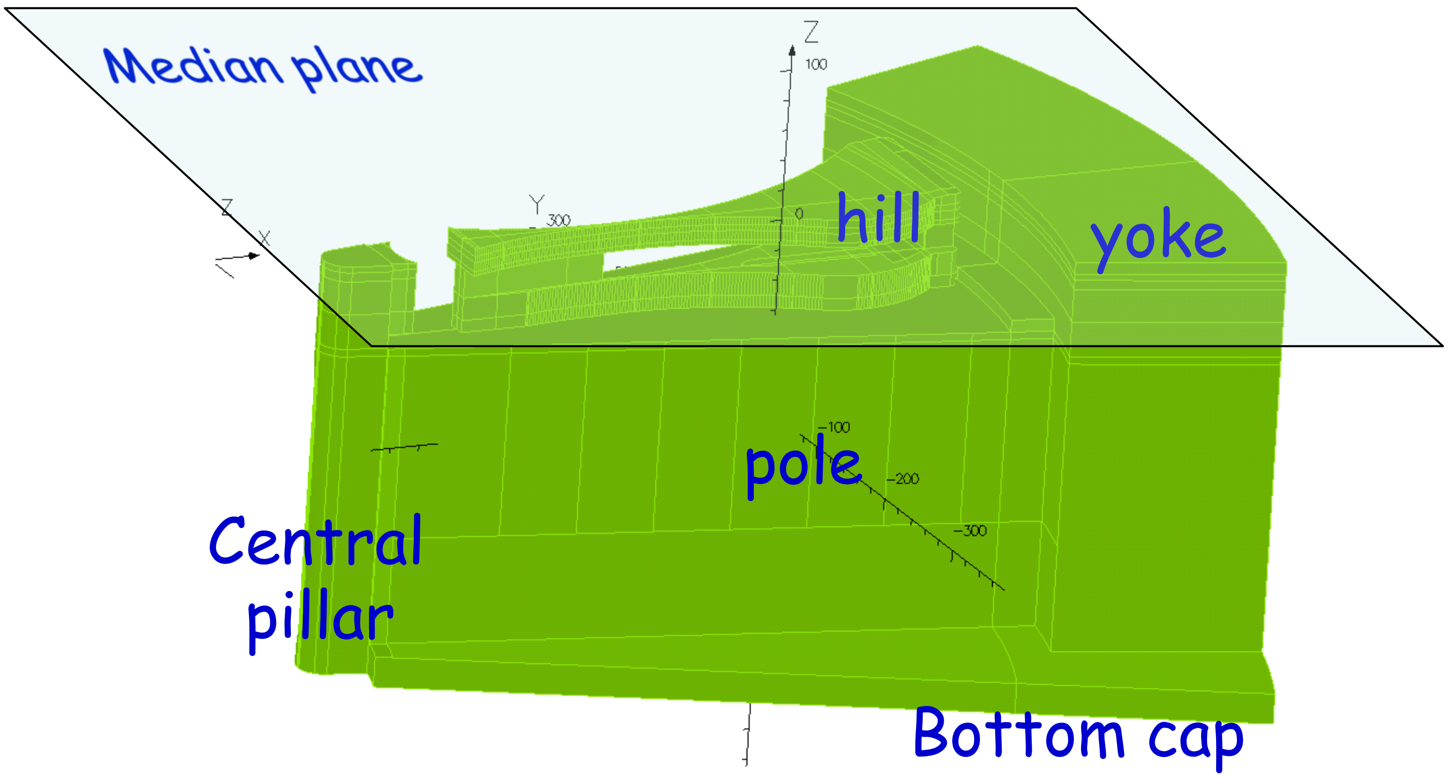
K_b=2600
R_{ex}=5.36 m
<B>=3.8 T

Iron weight
8000 tons



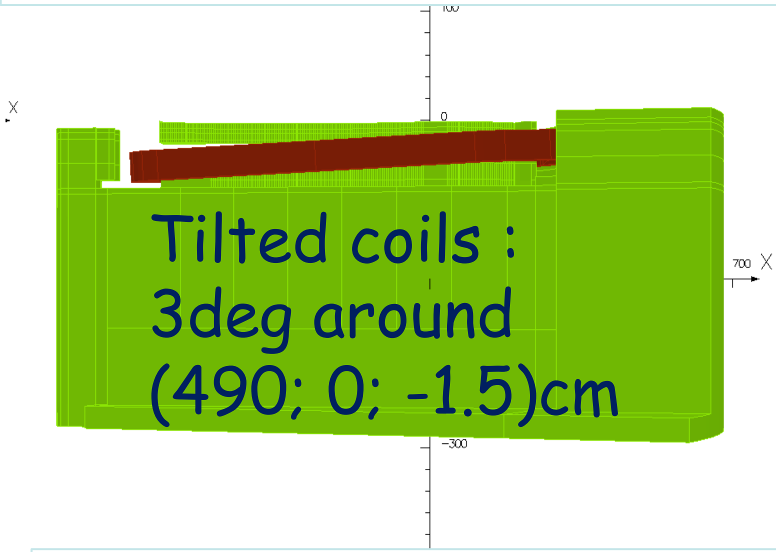
FERROMAGNETIC STRUCTURE

Bottom half of one octant

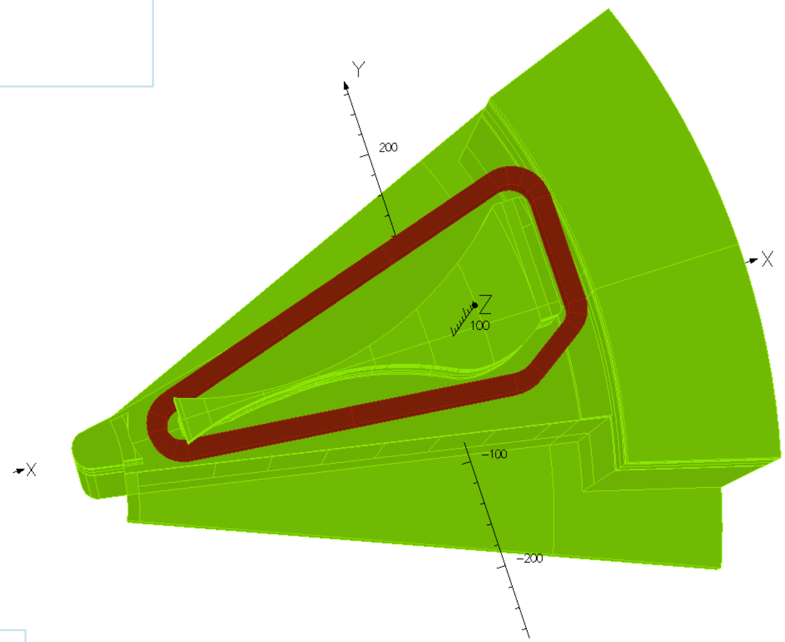


IRON WITH COILS

Current density 5200A/cm2
Area 16x27cm2



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

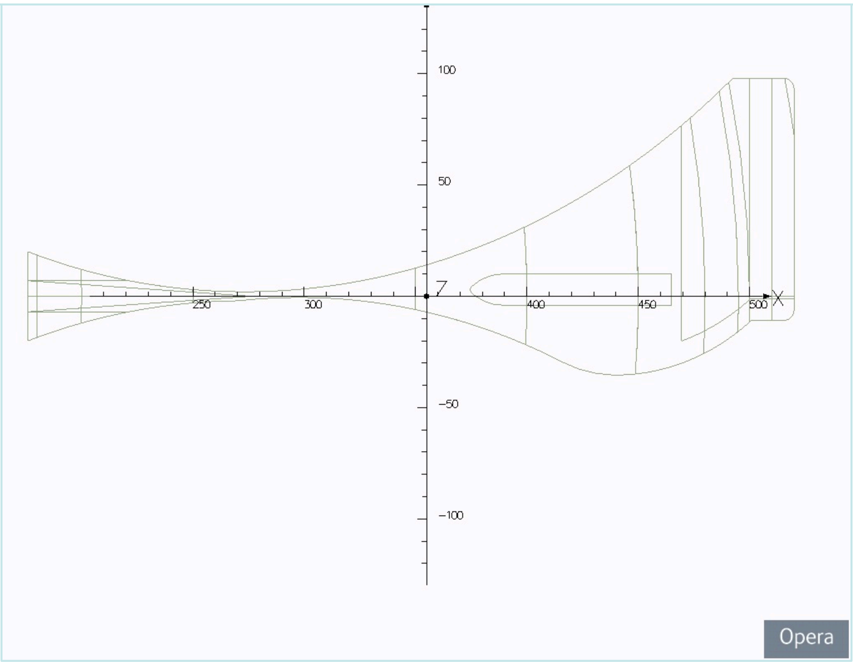


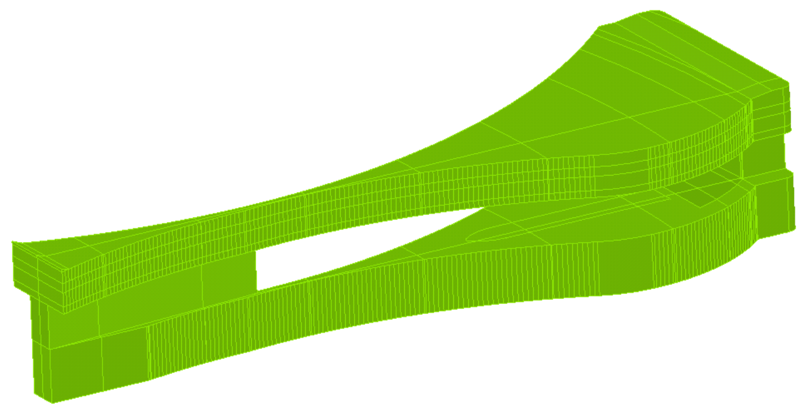
Total radius 688cm
Semi-height 280cm

Minimum distance
iron-coil 7.5cm

HILL DETAILS

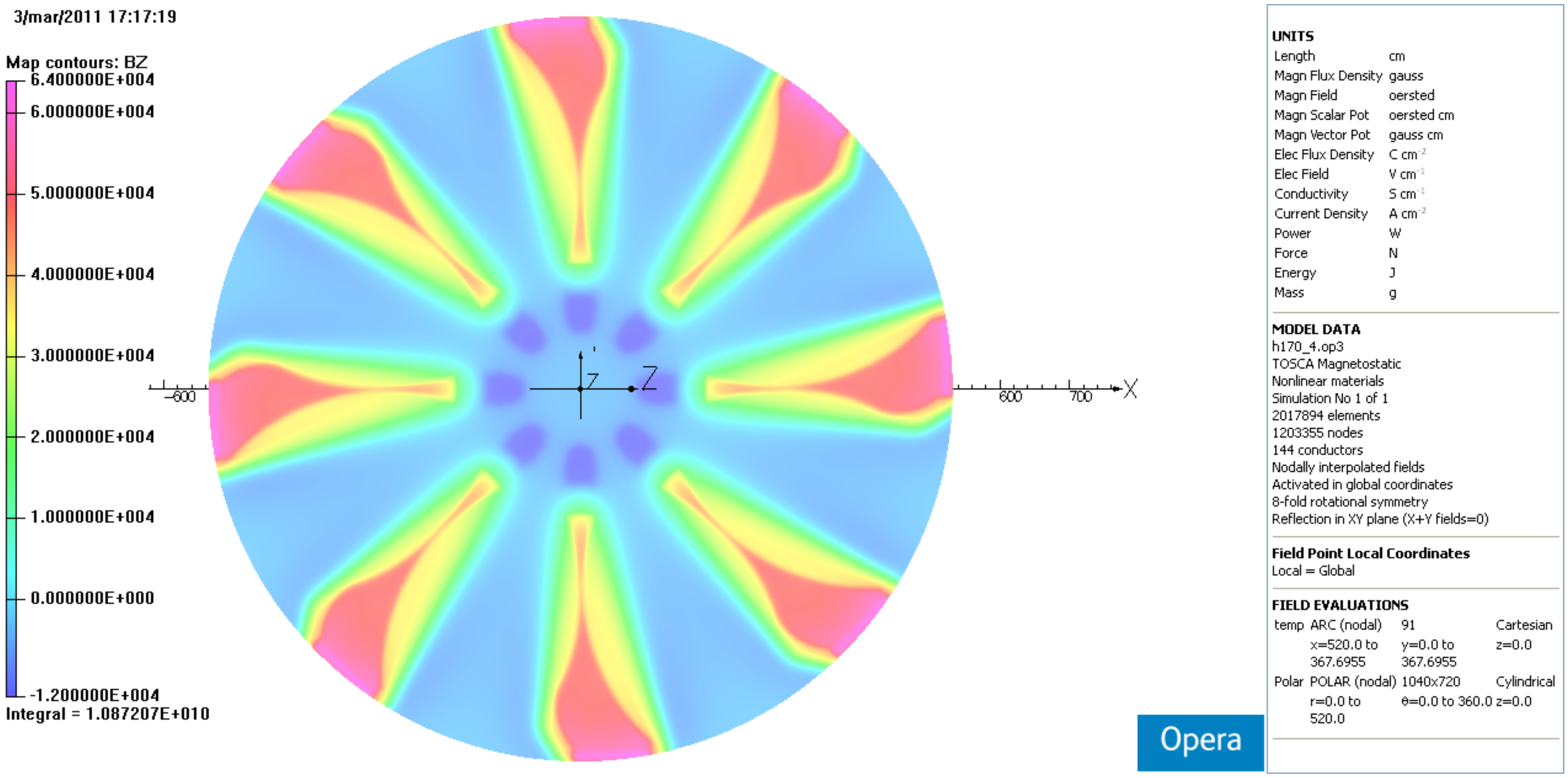
View of the hill from the top



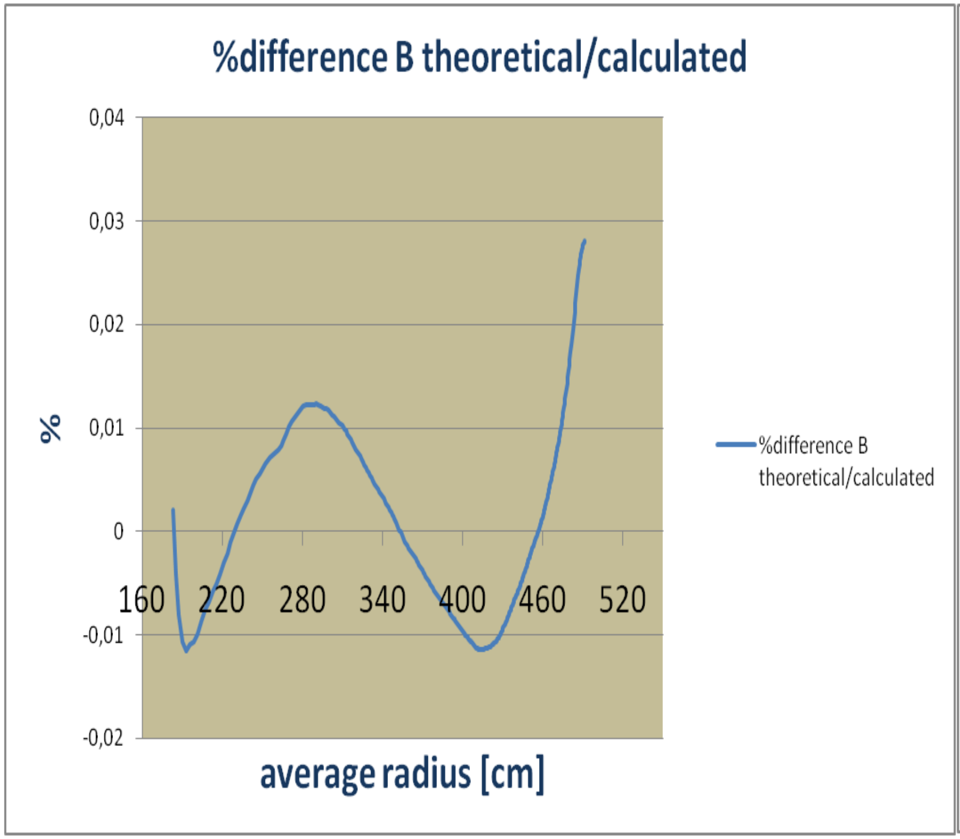


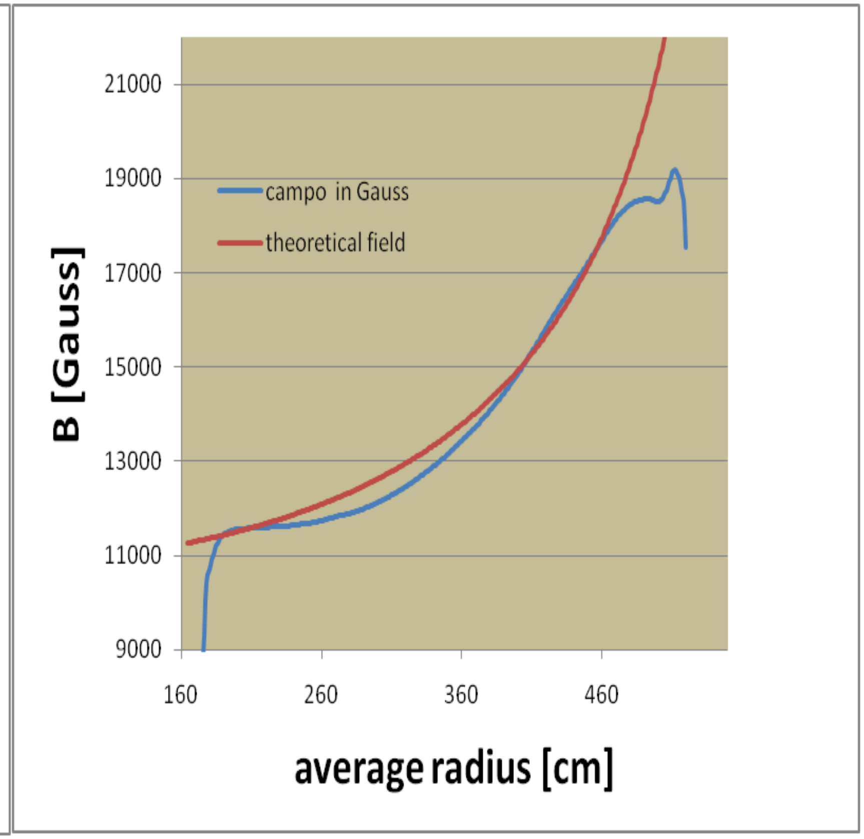
Variable gap:
3cm total at 176;
6cm total at 180cm up to 500cm;
3cm total from 510cm to 520cm

RESULTS: FIELD ON THE MEDIAN PLANE



RESULTS: COMPARISON WITH THEORETICAL ISOCHRONOUS FIELD

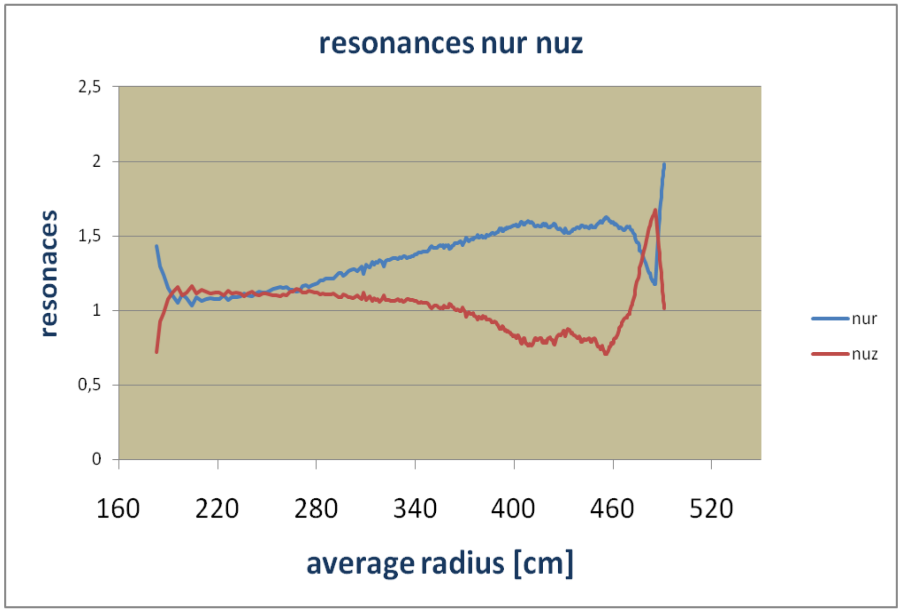


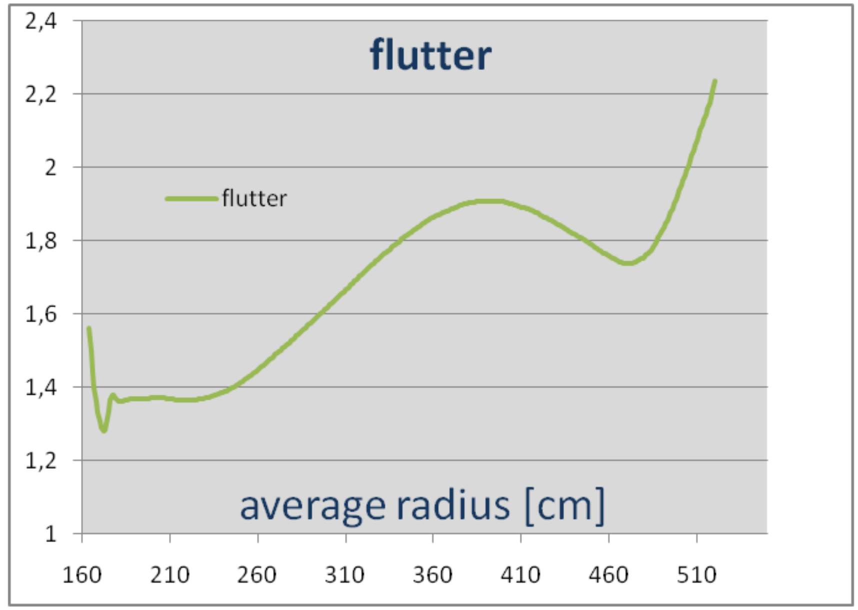


DAEδALUS

Last closed orbit at energy >800MeV

RESULTS: RESONANCES AND FLUTTER





ν_z = 0.5 most dangerous resonance **AVOIDED**

DAEδALUS

Status of Design

- Beam dynamics studies well underway
  - Collaboration between Catania, PSI
- Magnet engineering needed
  - Estimates of force containment, cryostat
- RF systems not yet developed
- Injection cyclotron, ion source still to be developed

As of Today…

Our View…

- No show-stoppers have been seen
- Design looks feasible
- Good concepts and ideas for systems not yet developed
  - Stripping extraction has been conceptualized
  - RF systems viewed as challenging, but do-able
  - Ion source tests for H_2^+ show excellent results
  - Inflection tests into low-energy cyclotron planned
    - Alternate injection schemes with less technical risk are available (e.g. RFQ for pre-acceleration)

Prospects

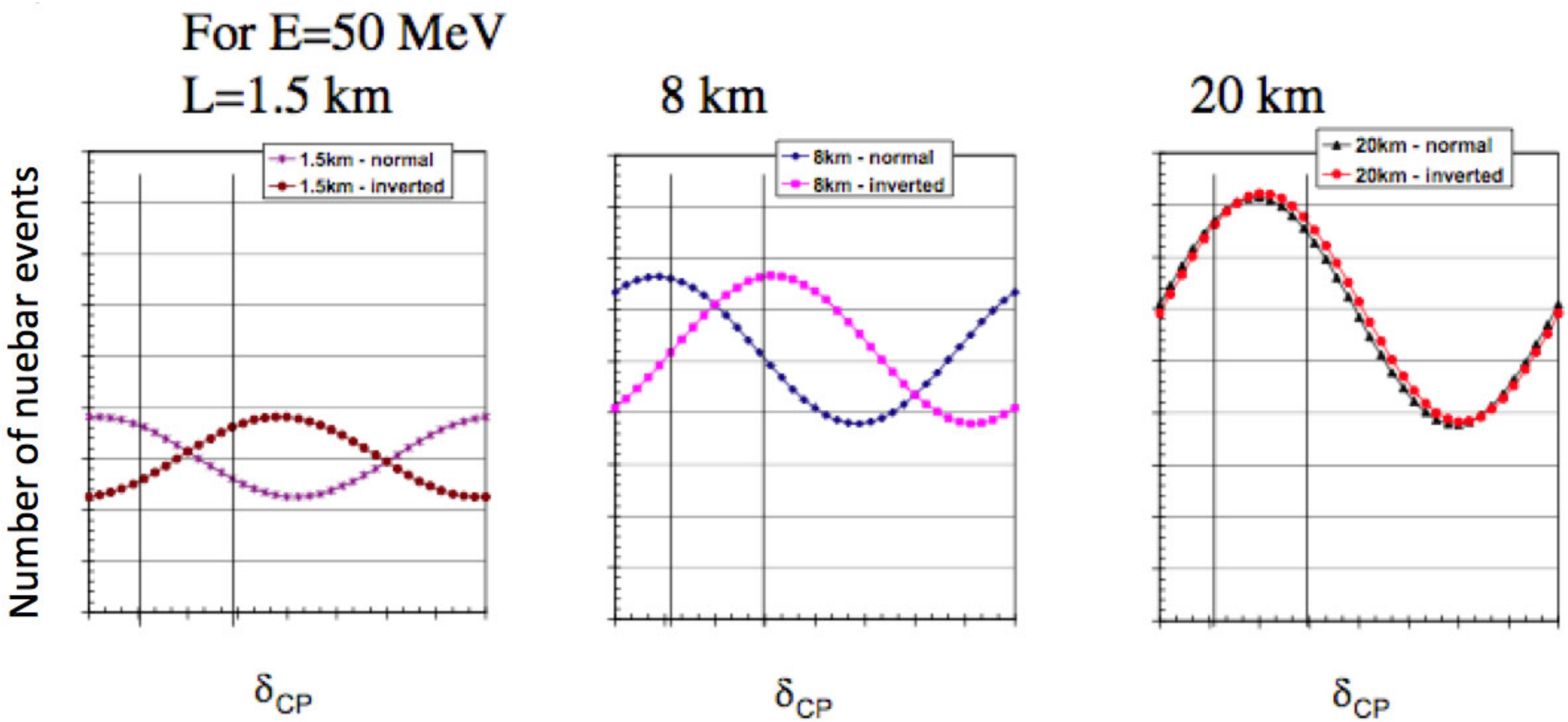
- Critical yet will be cost-determination
- Our plan is to have rough cost numbers in ~1 year

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!

Sensitivity Studies



near: $1.27\ \Delta m^2_{atm}\ L/E$ ~ 0
mid: ~ $\pi/4$
far: ~ $\pi/2$

DAEδALUS