DAEδALUS

A Phased Physics Program Using Decay-at-Rest Neutrino Beams

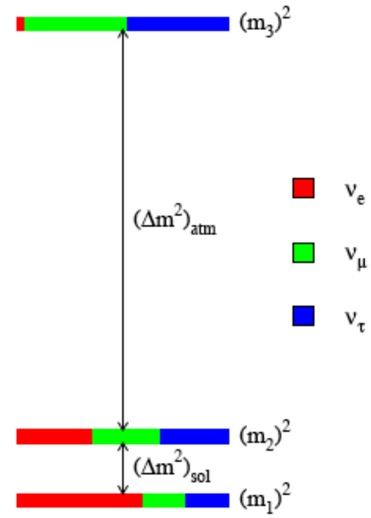
NuFact 2012
Janet Conrad, MIT

A two-part talk:

1. The design for the ultimate goal: CP Violation

2. Phased progression
   Especially showcasing:
   The IsoDAR sterile neutrino program (Phase II)

The oscillation of muon-flavor to electron-flavor at the atmospheric Δm^2 may show CP-violation dependence!



in a vacuum…

$$
\begin{aligned}
P = \quad & (\sin^2\theta_{23}\sin^2 2\theta_{13})\ (\sin^2\Delta_{31}) \\
& \mp \sin\delta\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin^2\Delta_{31}\sin\Delta_{21}) \\
& + \cos\delta\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}) \\
& + (\cos^2\theta_{23}\sin^2 2\theta_{12})\ (\sin^2\Delta_{21}).
\end{aligned}
$$

We want to see if δ is nonzero

terms depending on mixing angles

terms depending on mass splittings

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

Our plan: Use $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$
and exploit the L/E dependence in absolute rates

in a vacuum…

$$\begin{aligned} P = &\qquad\qquad (\sin^2\theta_{23}\sin^2 2\theta_{13})\ (\sin^2\Delta_{31}) \\ &\mp \sin\delta\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin^2\Delta_{31}\sin\Delta_{21}) \\ &+ \cos\delta\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}) \\ &\qquad + (\cos^2\theta_{23}\sin^2 2\theta_{12})\ (\sin^2\Delta_{21}). \end{aligned}$$

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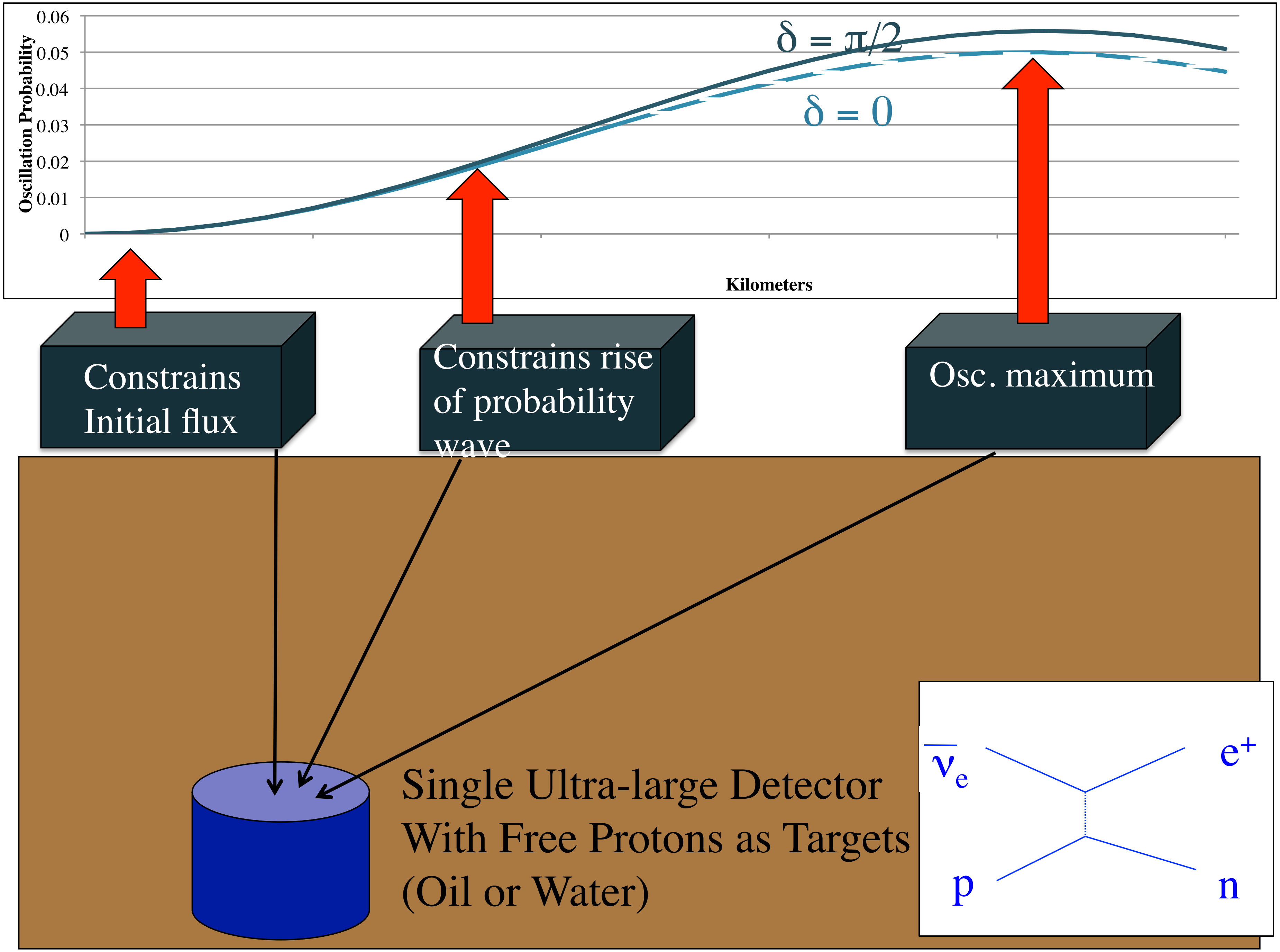


0.06
0.05
0.04
0.03
0.02
0.01
0
Oscillation Probability
Kilometers
δ = π/2
δ = 0
Constrains Initial flux
Constrains rise of probability wave
Osc. maximum
Single Ultra-large Detector
With Free Protons as Targets
(Oil or Water)
$\bar{\nu}_e$
e^+
p
n

Measurement strategy:

Using the **near accelerator**
measure **absolute flux normalization** with ν-e events to ~1%,
Also, measure the ν_eC event rate.

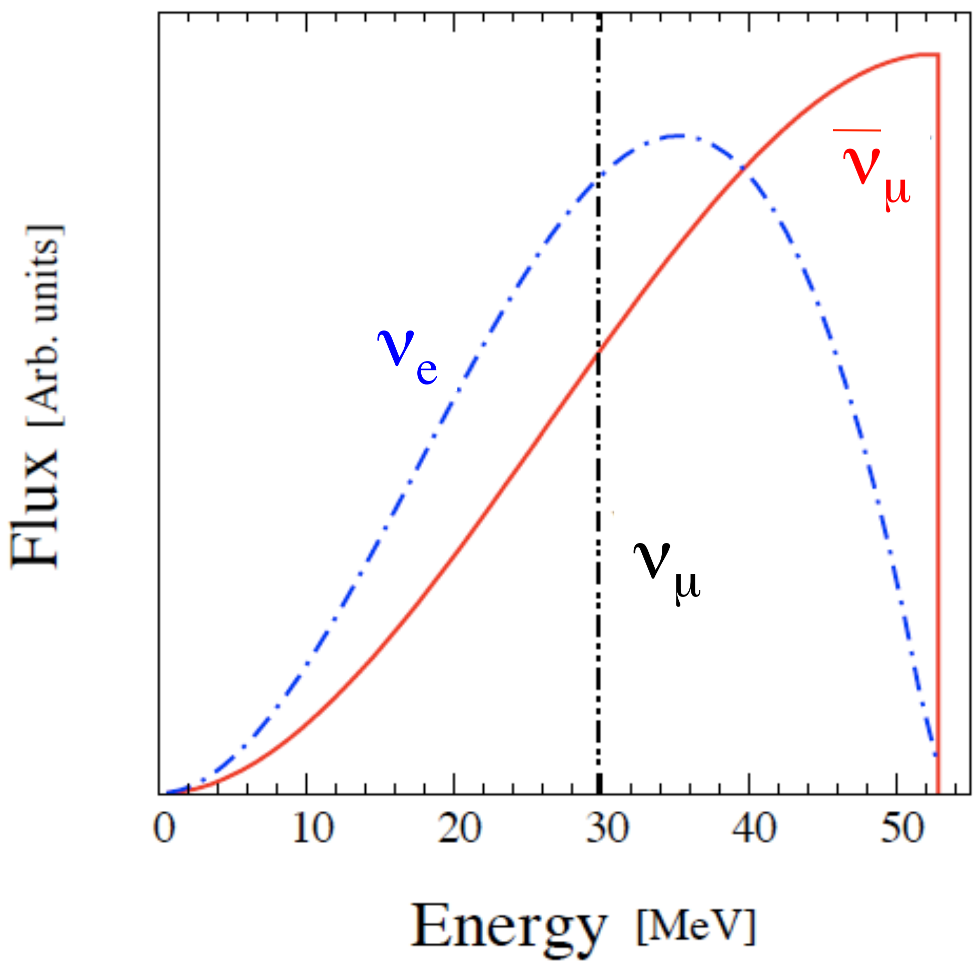
At far and mid accelerator,
Compare predicted to measured ν_eC event rates
to get the **relative flux normalizations between 3 accelerators**

In all three accelerators,
given the known flux, **fit for the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal**
with free parameters: $\boldsymbol{\theta_{13}}$ **and** $\boldsymbol{\delta}$

A really nice
low-energy beam:
A π/μ beam stop

A π^+ decay-at-rest beam:

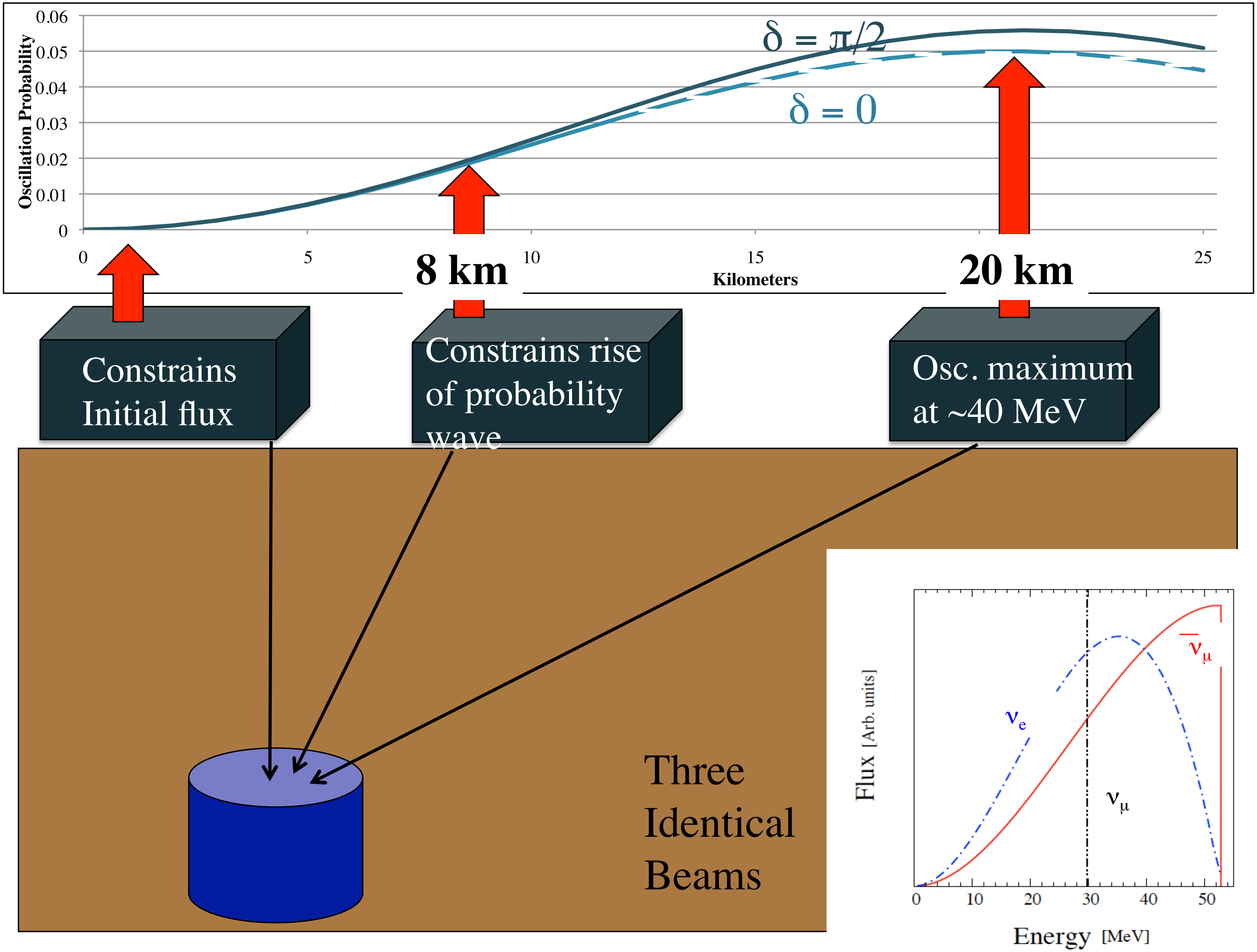
$$p+C \rightarrow \pi^+ \rightarrow \nu_\mu + \mu^+ \\ \hookrightarrow e^+ \bar{\nu}_\mu \nu_e,$$



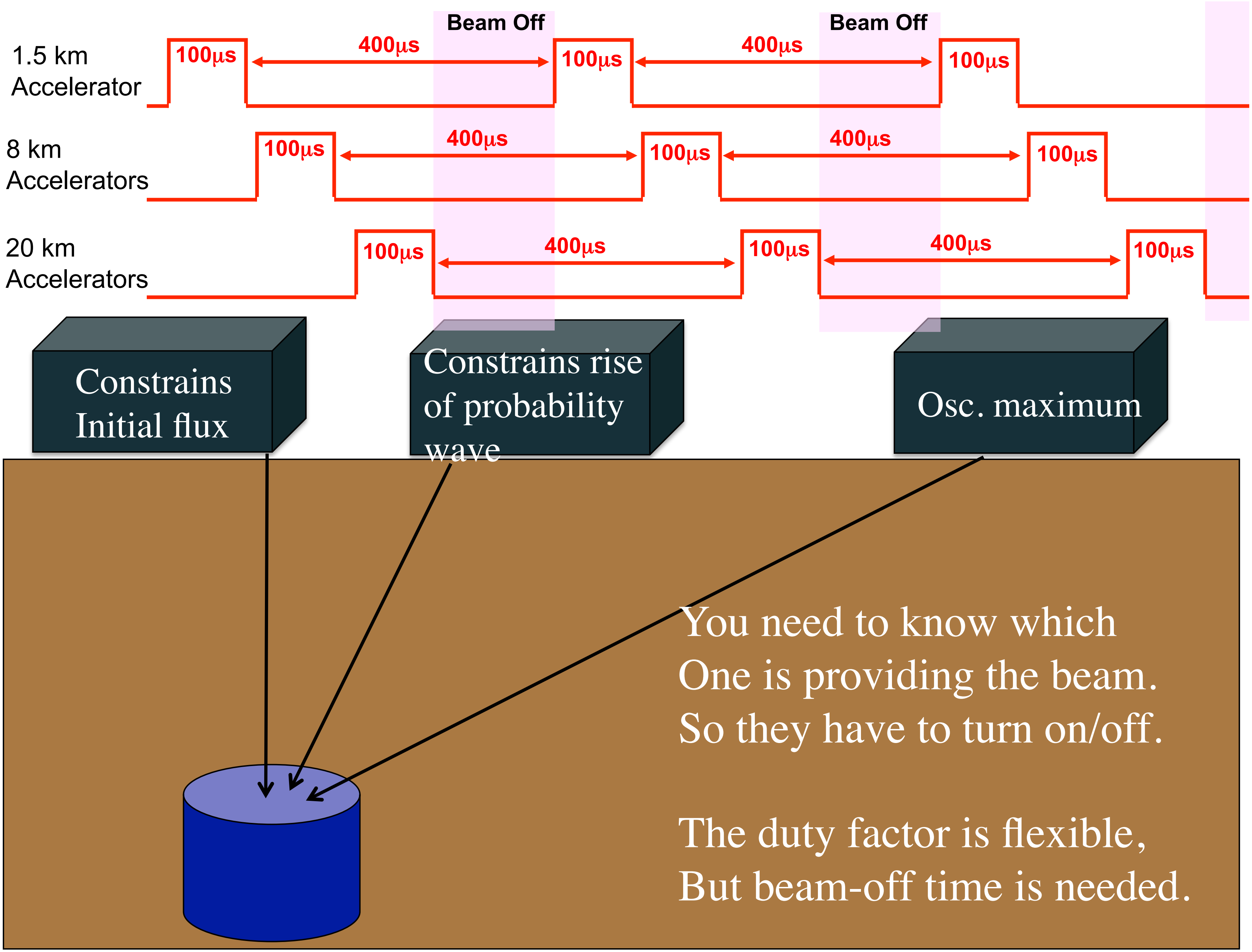
Shape driven by nature!

Only the normalization varies from beam to beam

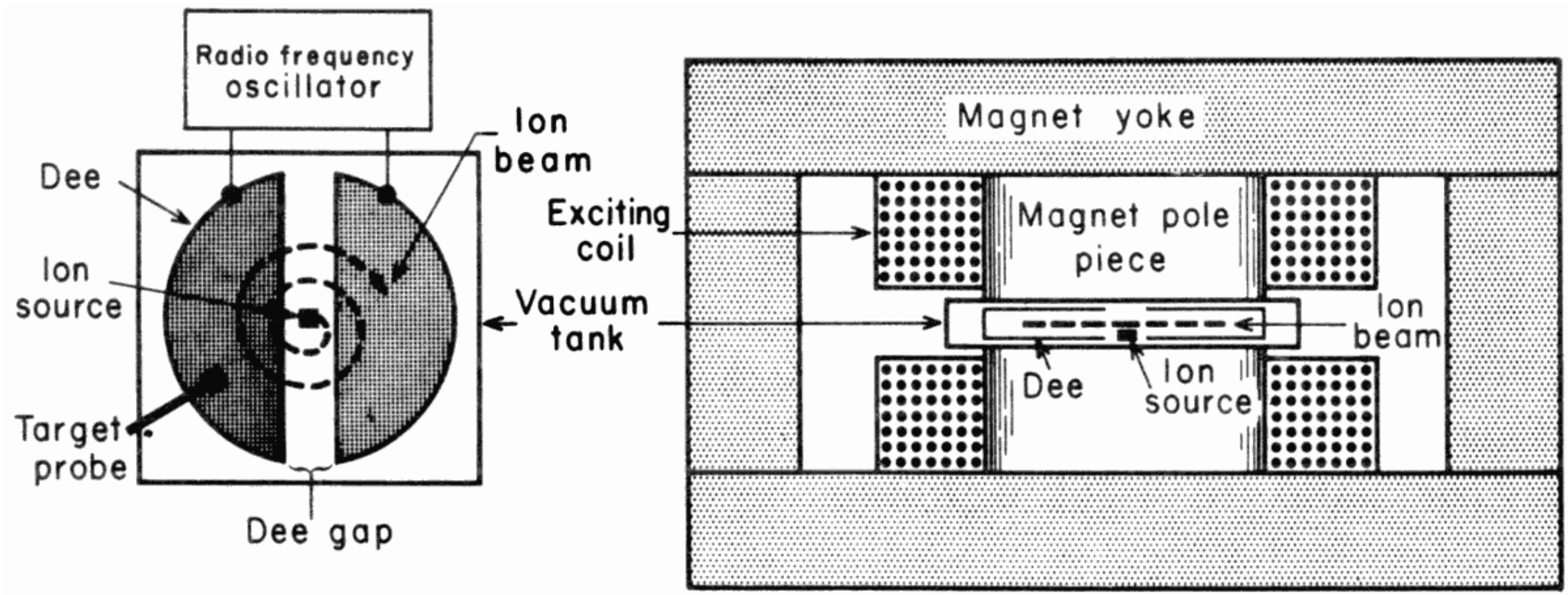
A great place to search for
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



Oscillation Probability
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
25
Kilometers
δ = π/2
δ = 0
8 km
20 km
Constrains Initial flux
Constrains rise of probability wave
Osc. maximum at ~40 MeV
Three Identical Beams
Flux [Arb. units]
Energy [MeV]
0
10
20
30
40
50
ν_e
ν_μ
ν̄_μ


Beam Off
Beam Off
1.5 km
Accelerator
8 km
Accelerators
20 km
Accelerators
100μs
400μs
Constrains
Initial flux
Constrains rise
of probability
wave
Osc. maximum
You need to know which
One is providing the beam.
So they have to turn on/off.
The duty factor is flexible,
But beam-off time is needed.

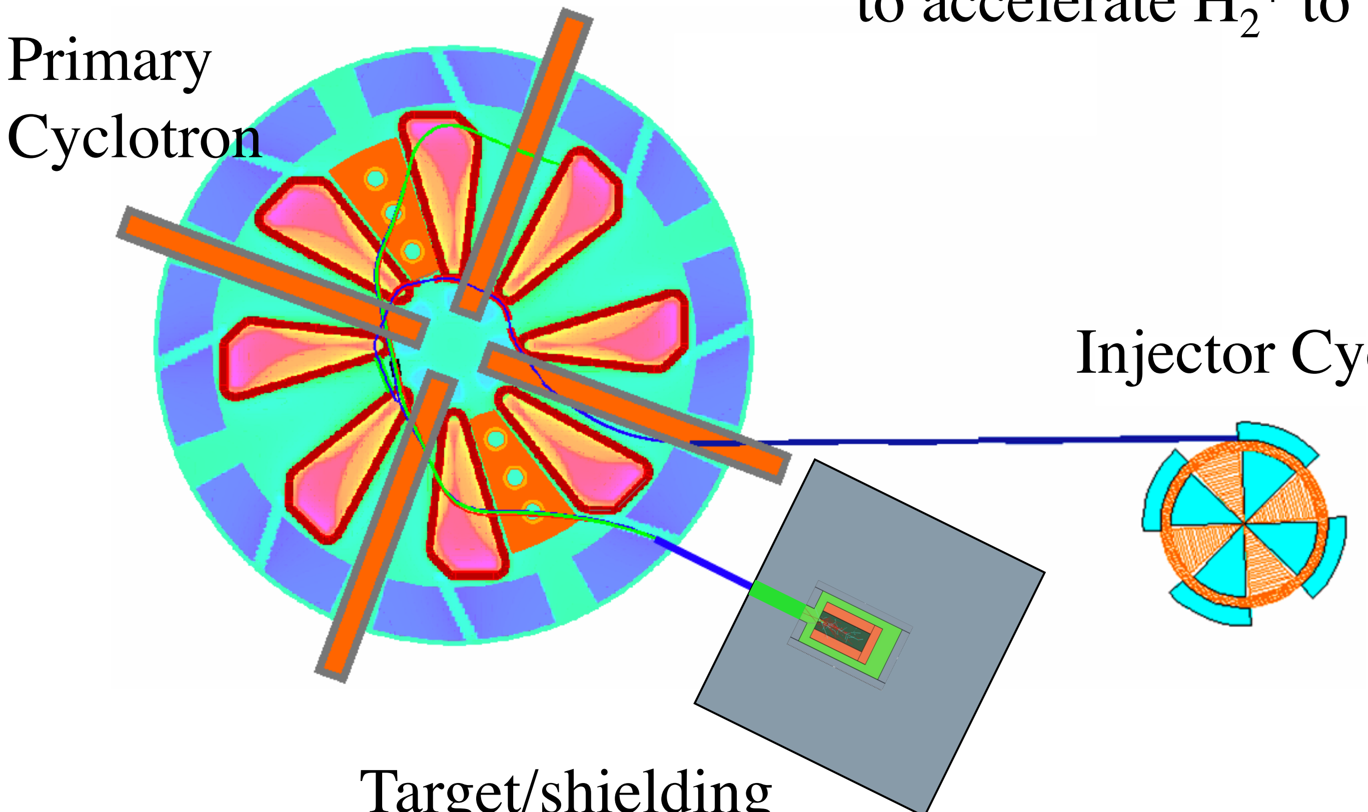
Use Cyclotrons to produce the 800 MeV protons!



Inexpensive,
Only practical below ~1 GeV
(ok for us!)
Only good if you don't need
short timing structure (ok!)
Typically single energy (ok!)
Taps into existing industry

An "isochronous cyclotron" design:
magnetic field changes with radius
Allowing multibunch acceleration

Uses Multiple "Accelerator Units"
constructed of cyclotrons
to accelerate H_2^+ to 800 MeV



The result is a decay-at-rest-flux
That can be used for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ searches

Multimegawatt DAEδALUS Cyclotrons for Neutrino Physics

M. Abs[j], A. Adelmann[b,*], J.R. Alonso[c], W.A. Barletta[c], R. Barlow[h], L. Calabretta[f], A. Calanna[c], D. Campo[c], L. Celona[f], J.M. Conrad[c], S. Gammino[f], W. Kleeven[j], T. Koeth[a], M. Maggiore[e], H. Okuno[g], L.A.C. Piazza[e], M. Seidel[b], M. H. Shaevitz[d], L. Stingelin[b], J. J. Yang[c], J. Yeck[i]

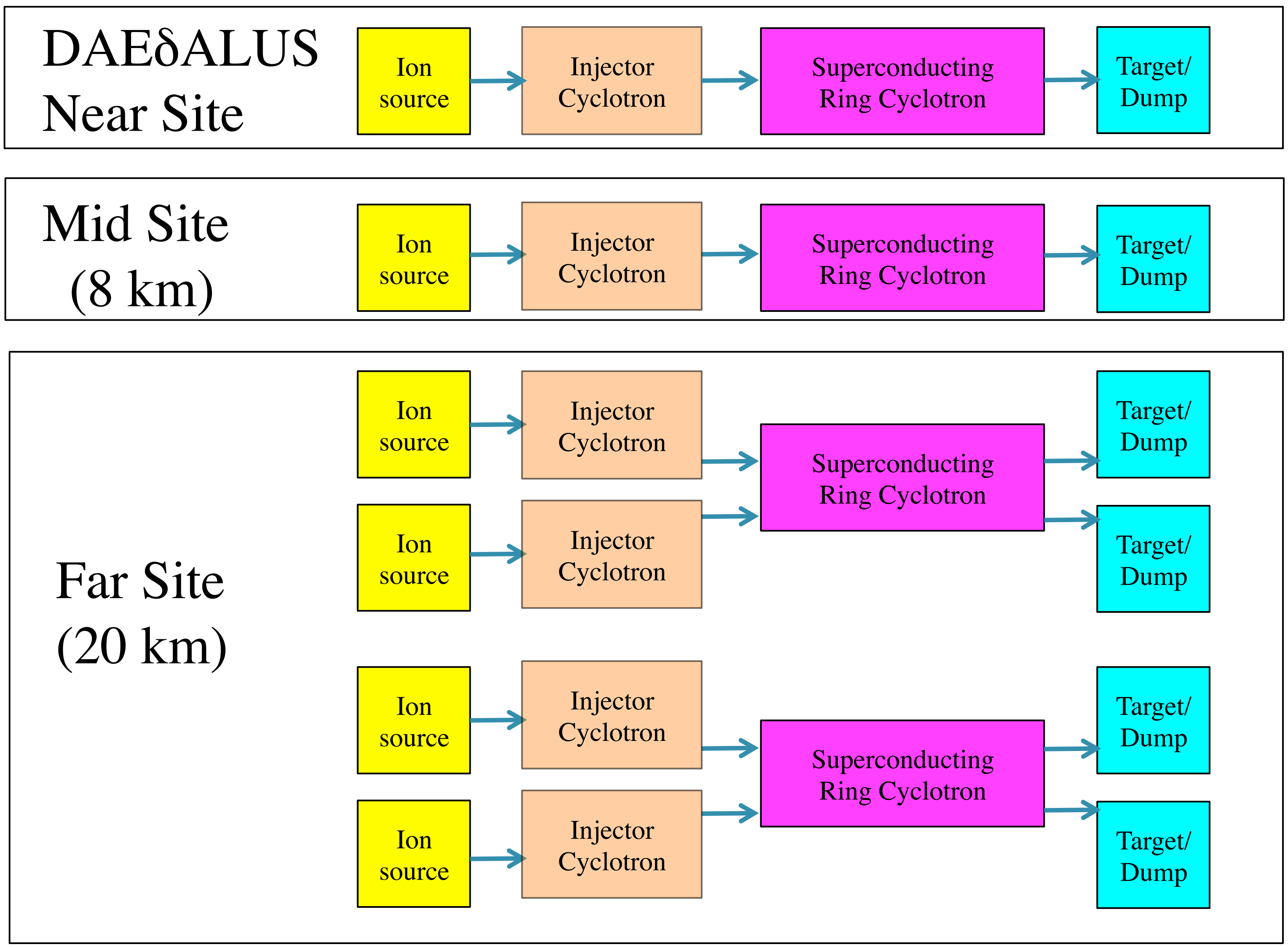
[a] *Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, Maryland, 20742*
[b] *Paul Scherrer Institut, CH-5234 Villigen, Switzerland*
[c] *Department of Physics, Massachusetts Institute of Technology*
[d] *Columbia University*
[e] *Istituto Nazionale di Fisica Nucleare - LNL*
[f] *Istituto Nazionale di Fisica Nucleare - LNS*
[g] *Riken*
[h] *Huddersfield University, Queensgate Campus, Huddersfield, HD1 3DH, UK*
[i] *IceCube Research Center, University of Wisconsin, Madison, Wisconsin 53706*
[j] *IBA-Research*

In this paper we address the most challenging questions regarding a cyclotron-based high-power proton driver in the megawatt range with a kinetic energy of 800 MeV. Aspects of important subsystems like the ion source and injection chain, the magnet design and radio frequency system will be addressed.

Precise beam dynamics simulations, including space charge and the H_2^+ stripping process, are the base for the characterization and quantification of the beam halo–one of the most limiting processes in high-power particle accelerators.

To be submitted to NIM

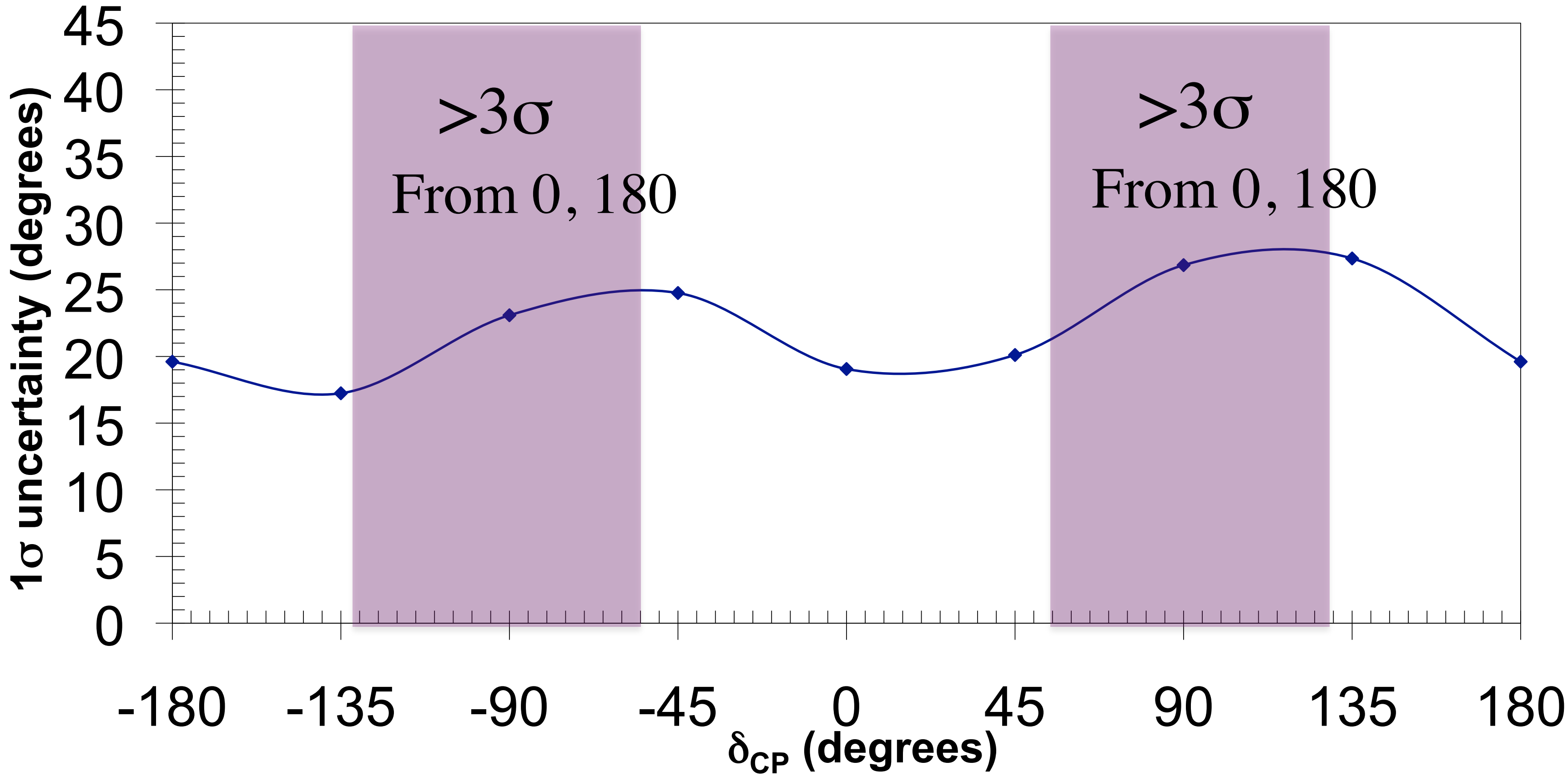
Design Principle: “Plug-and-play”



Where can we run?

LENA is an outstanding possibility!

Coverage of CP violation Parameter at LENA, 10 years



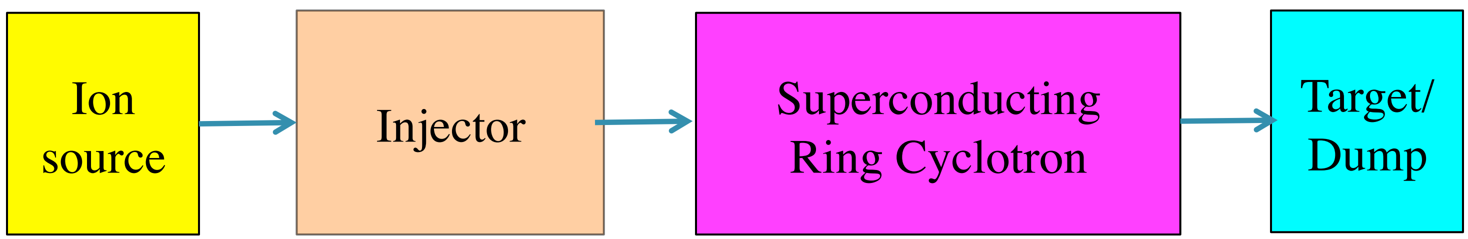
This gets even better if it can be played against a conventional beam!

A two-part talk:

1. The design for the ultimate goal: CP Violation

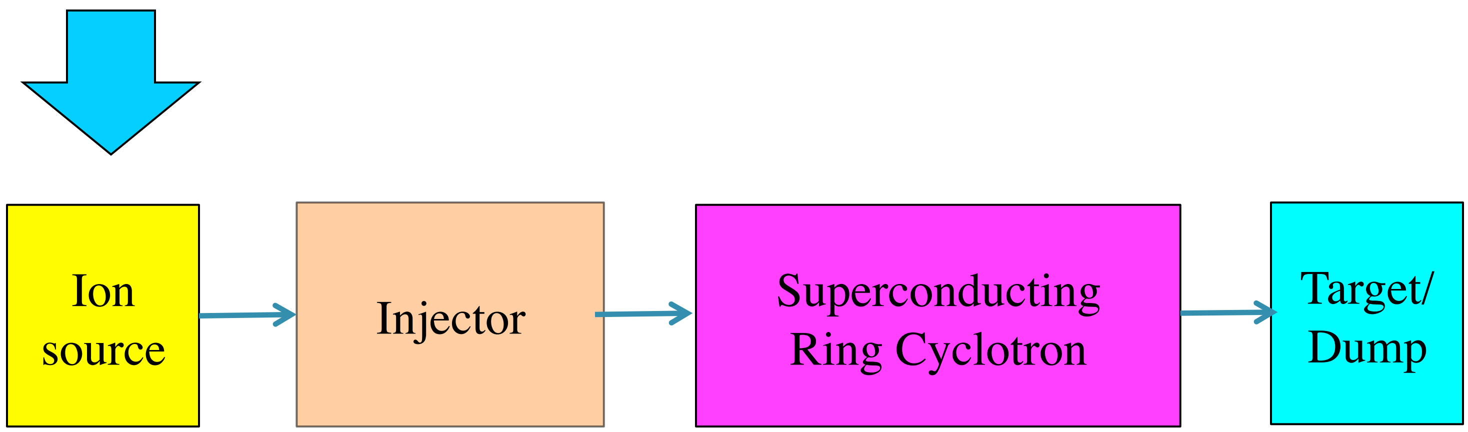
2. Phased progression
   Especially showcasing:
   The IsoDAR sterile neutrino program (Phase II)

The "plug-and-play design" of what we are building



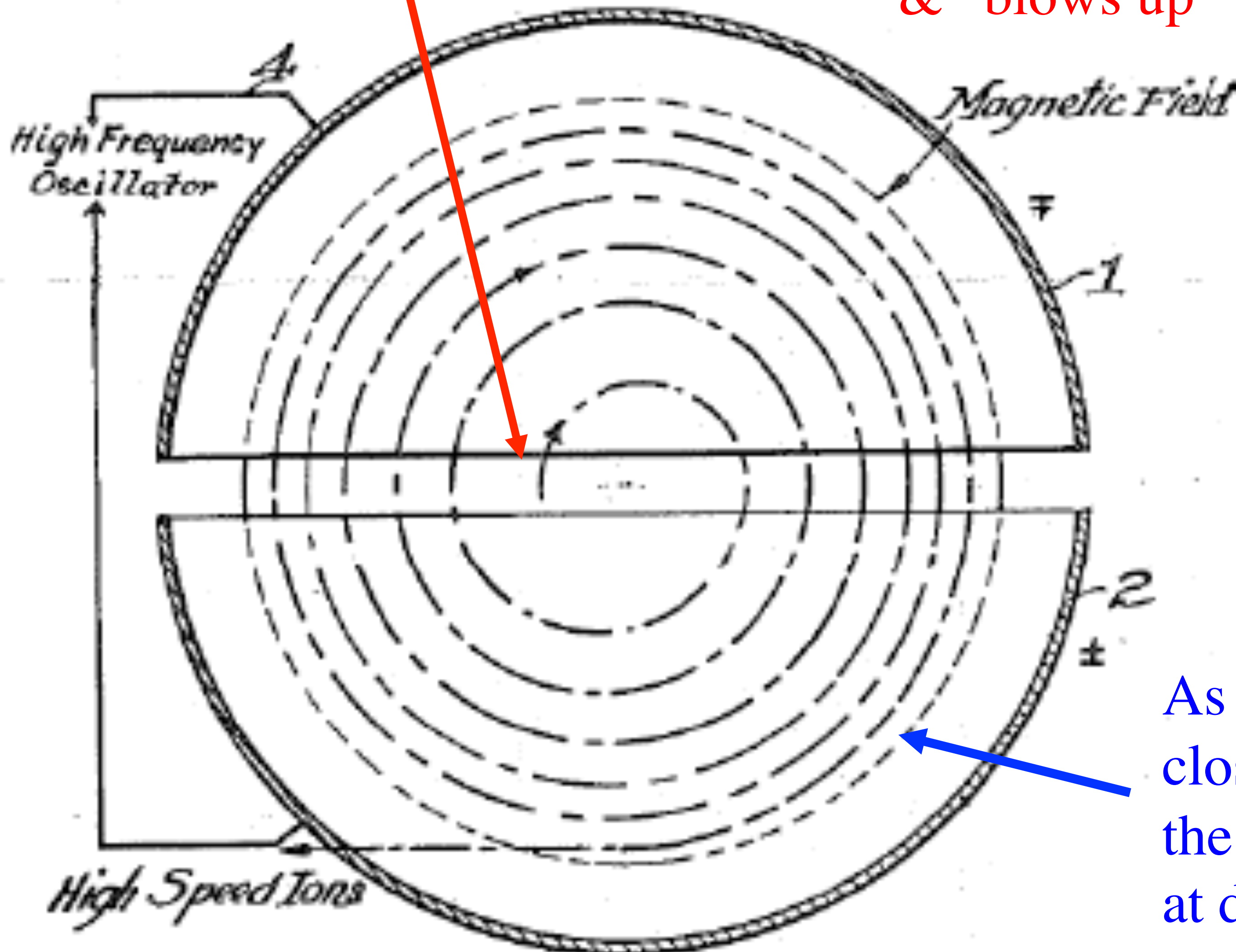
Leads to an obvious multiphase development plan

Phase I: The Ion Source



The big issue…

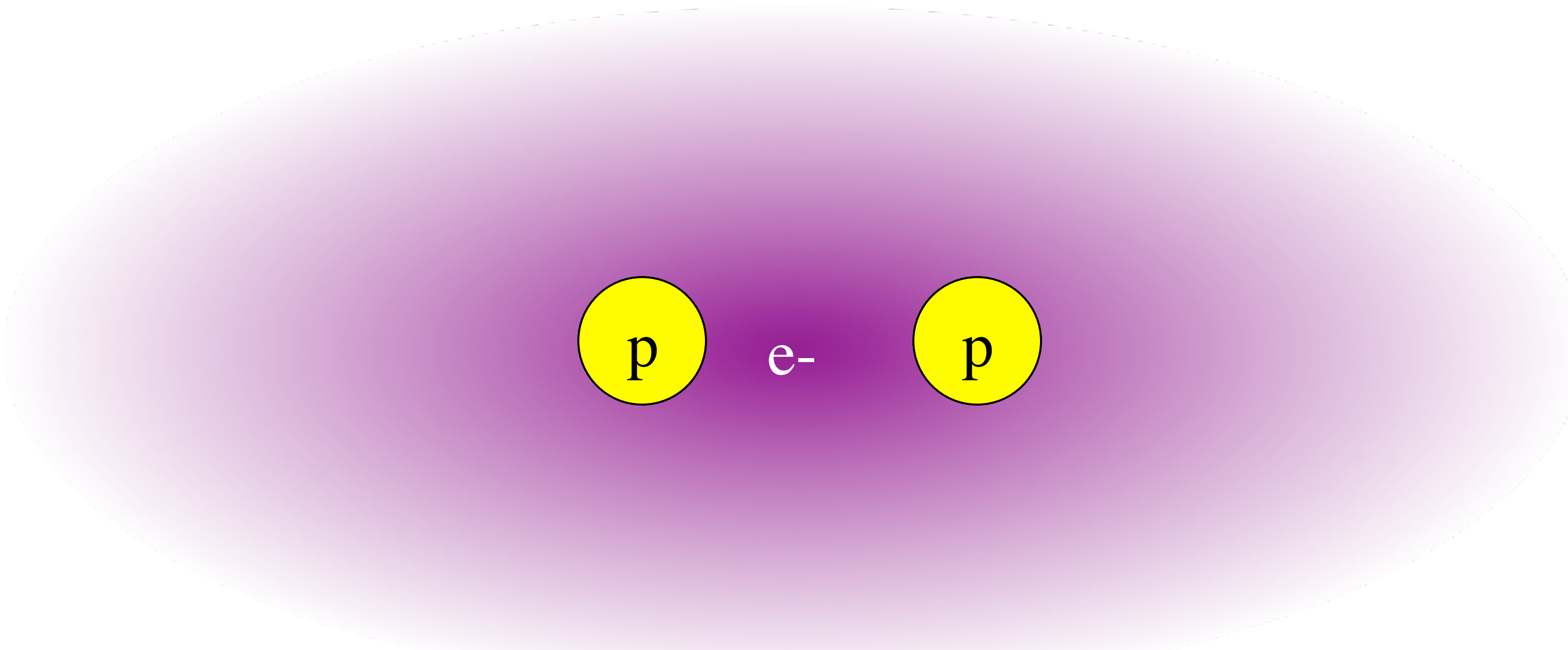
If you inject a lot of charge here, it repels & "blows up"



As radii get closer together, the bunches at different radii interact

Why H_2+ ???

To reduce the “space charge” at injection…

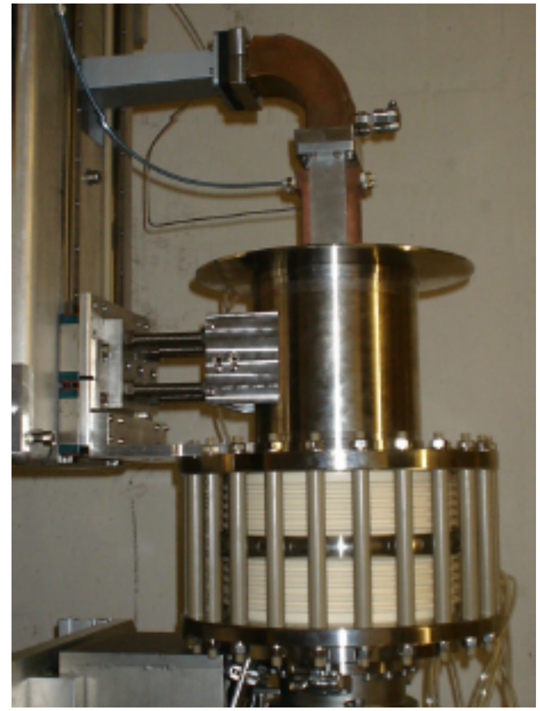


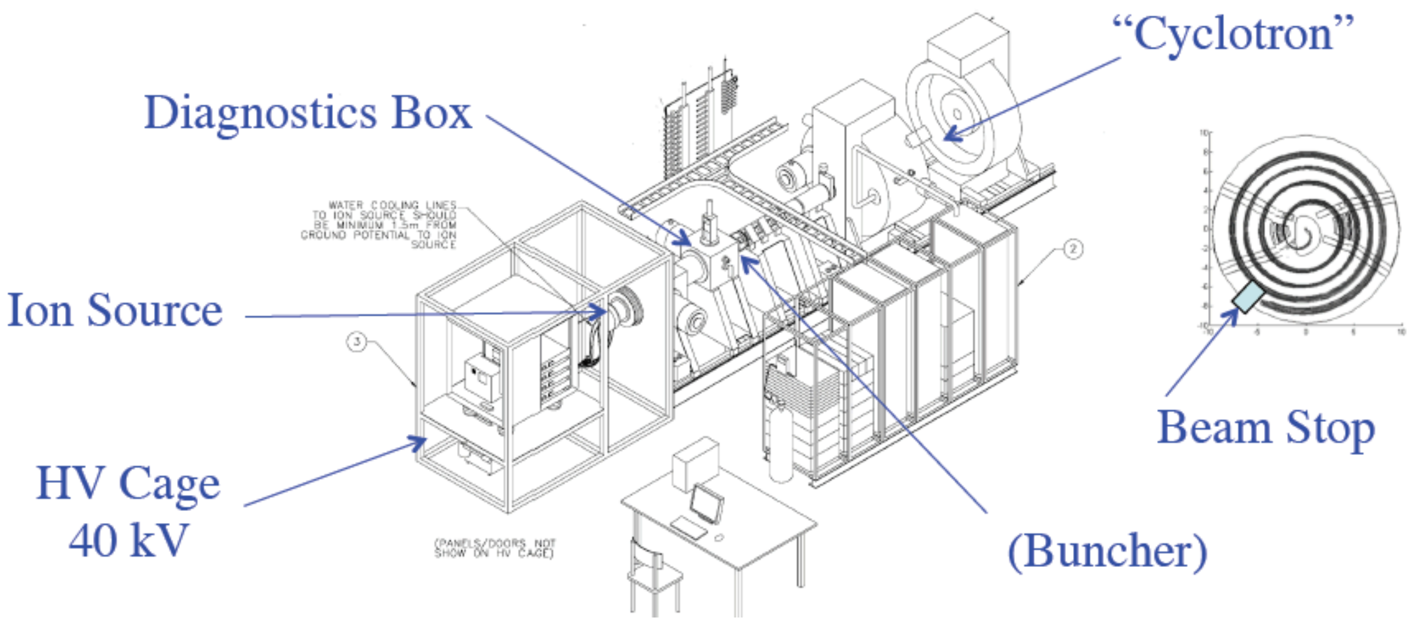
H_2+ gives you 2 protons out for 1 unit of +1 charge in!

Simple to extract! Just strip the electron w/ a foil

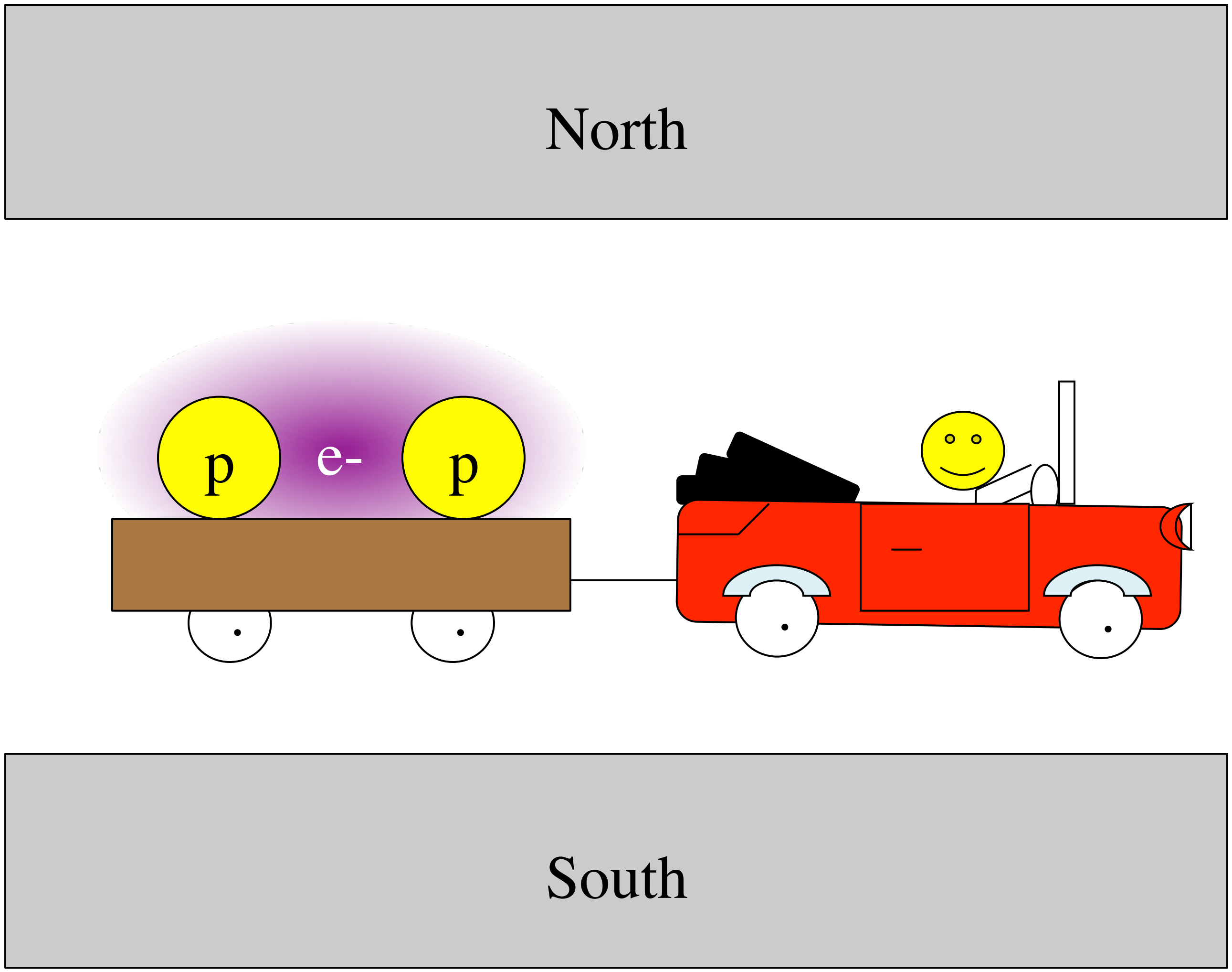
Ion Source:
By our collaborators at INFN Catania.
Produces sufficient H_2^+!

Beam to be characterized at
<u>Best Cyclotrons, Inc</u>, Vancouver
This winter   (NSF funded)
Test results to be available by
Cyclotrons'13 Conference, Sept 2013, Vancouver

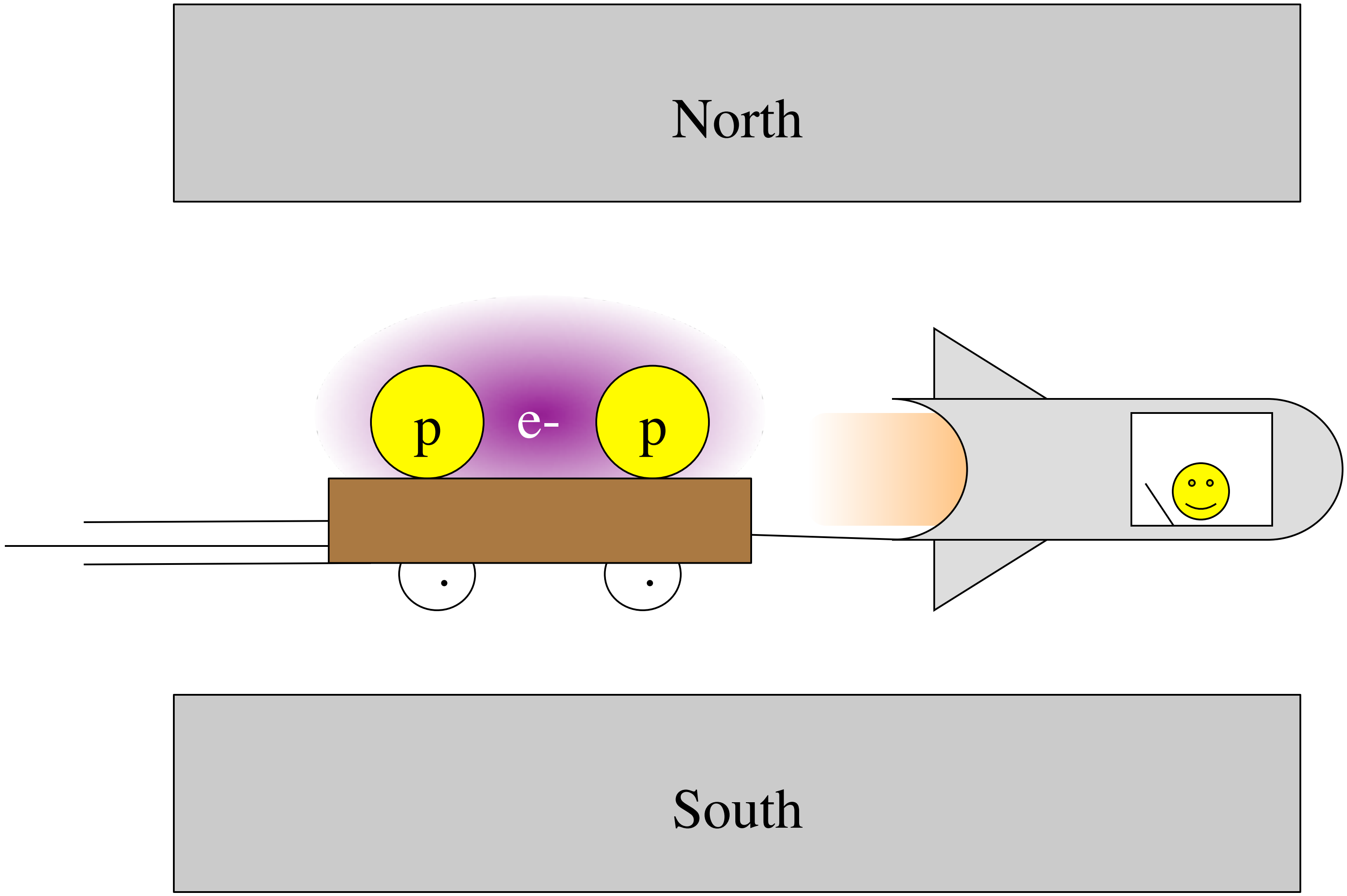




Ions in the low-energy cyclotron…

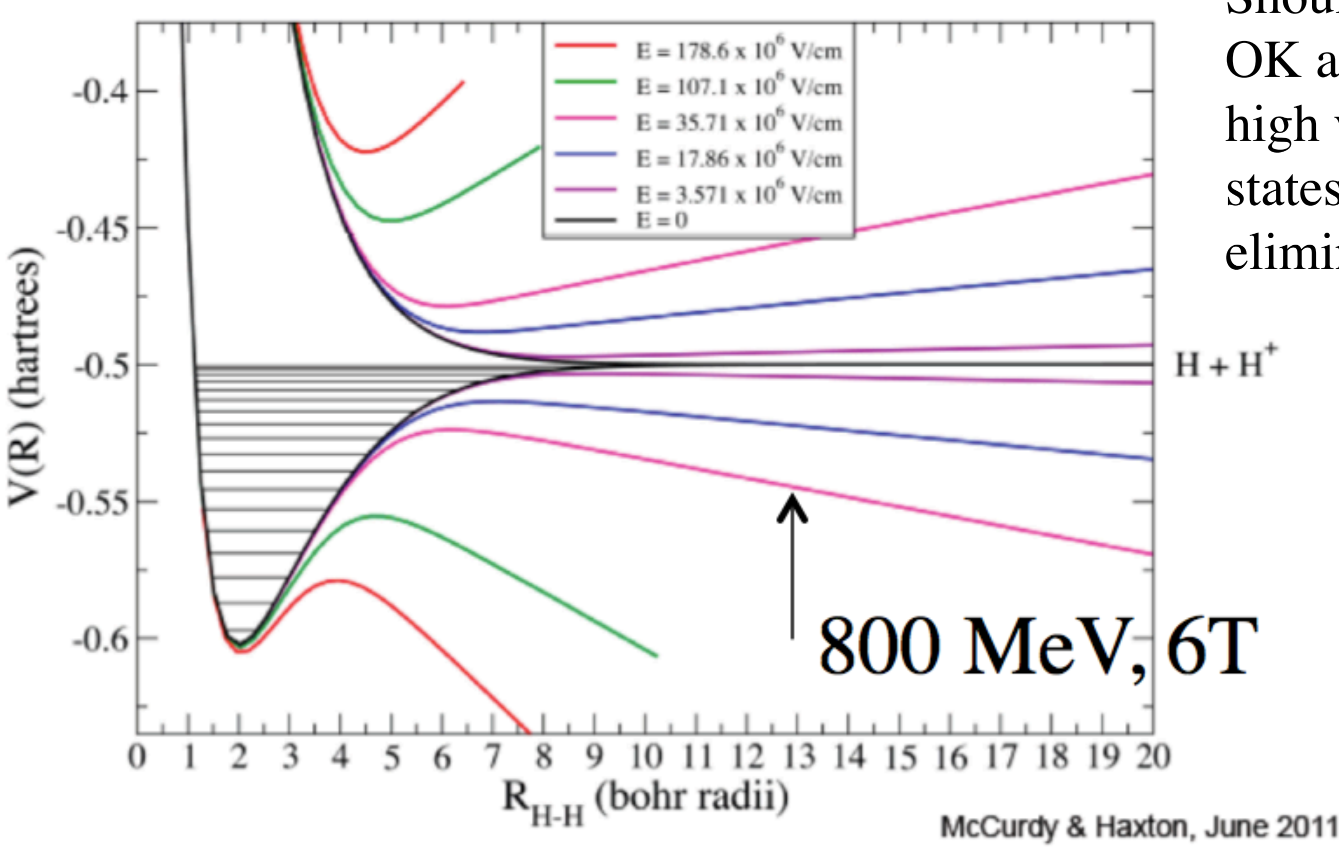


In the high-energy cyclotron (800 MeV)



H_2^+ will "see" high B and also significant E fields (relativity at work!)

Important question for the beam in the 800 MeV SRC:
Lorentz stripping of the ions?

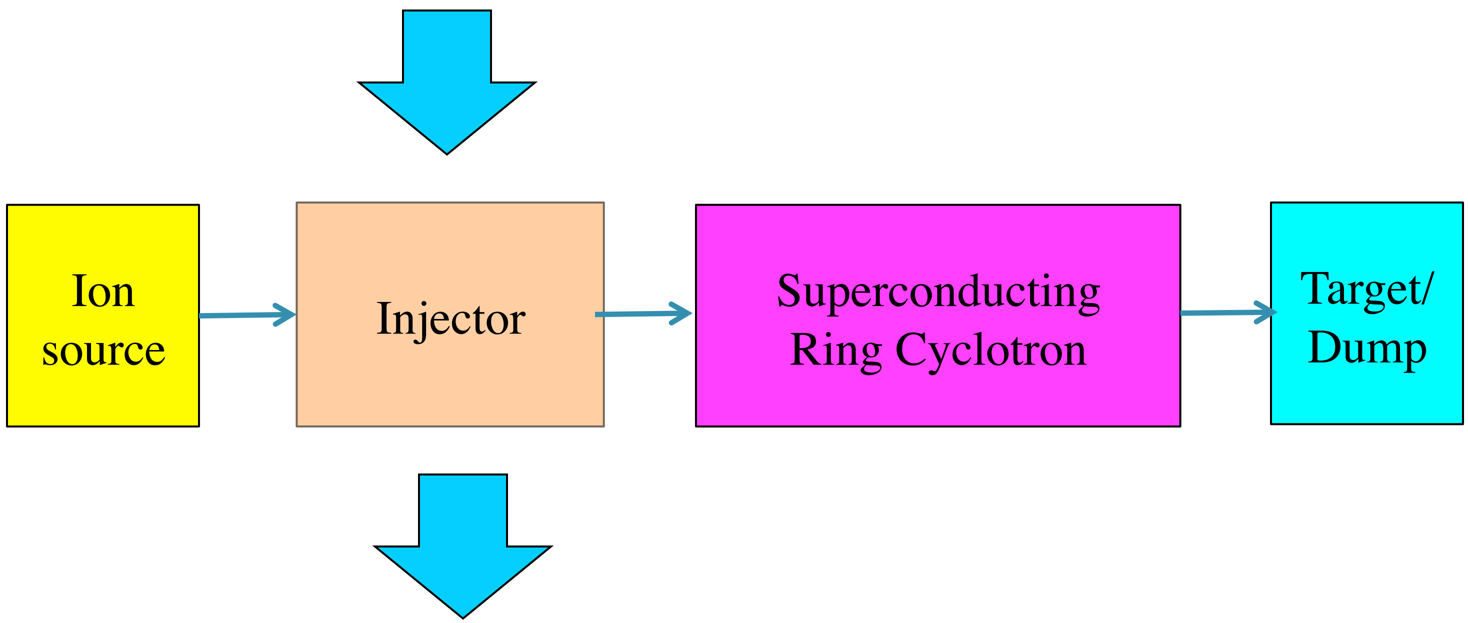


Should be OK as long as high vibrational states are eliminated

We are doing tests at Oakridge to study vibrational states from ion soures

So: some important questions remain for DAEδALUS,
But we have a workable ion source for a

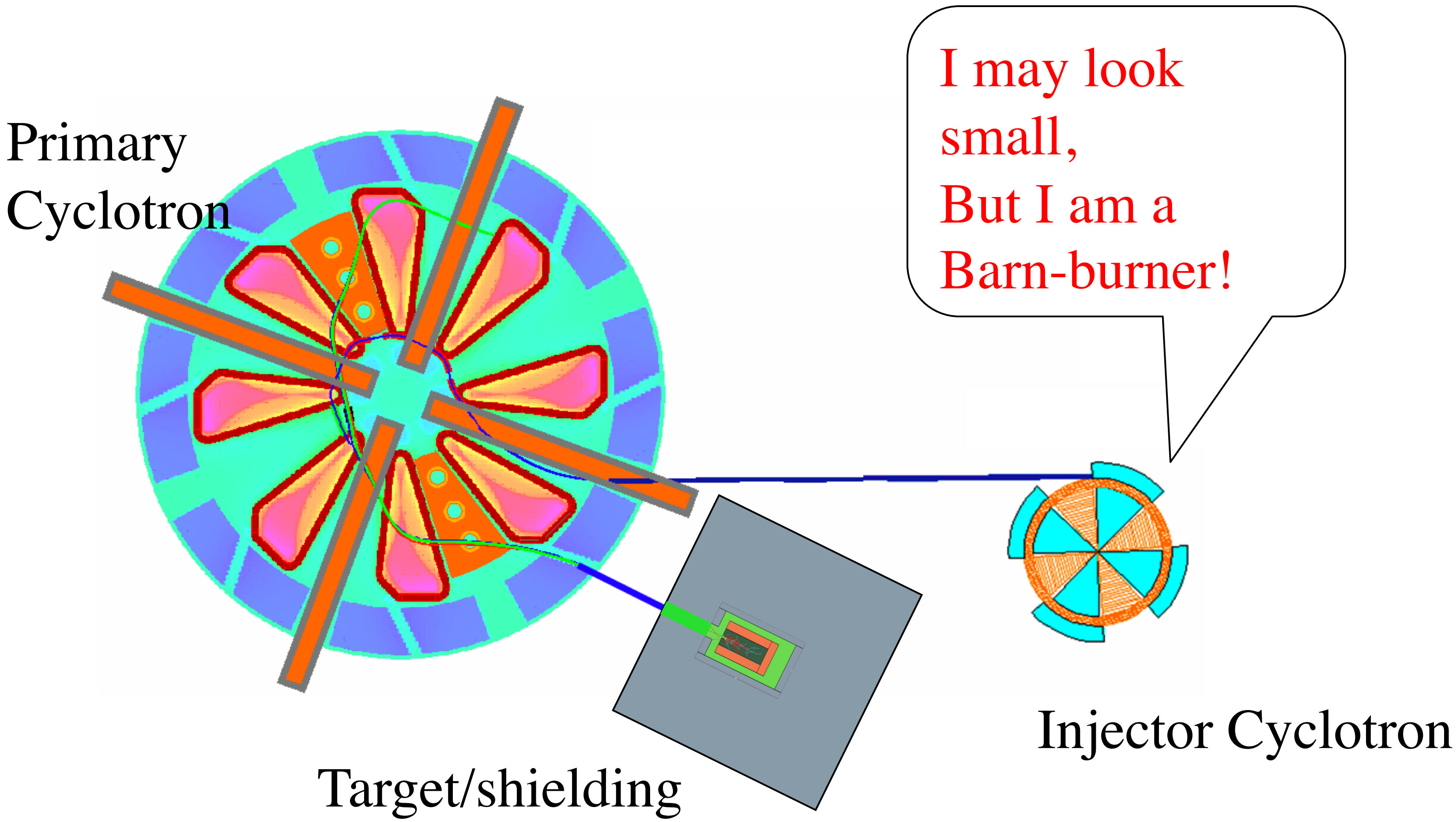
Phase II



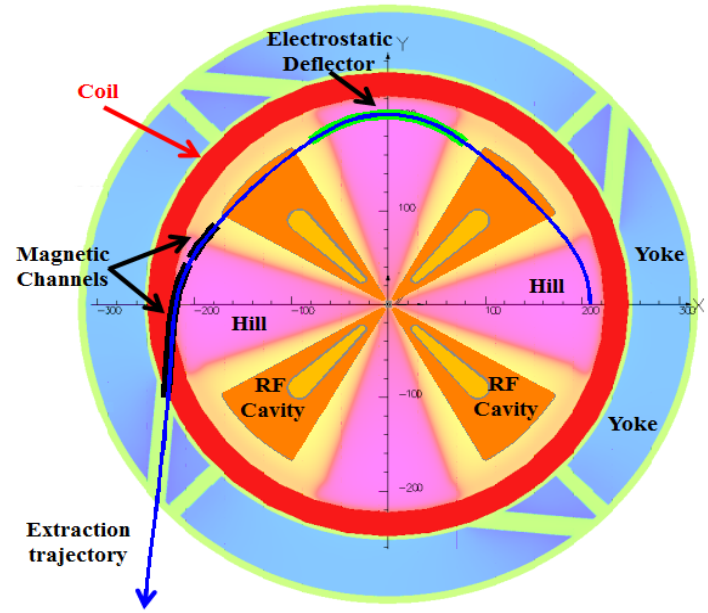
IsoDAR:

A sterile neutrino experiment
On its own!

Do not be deceived…

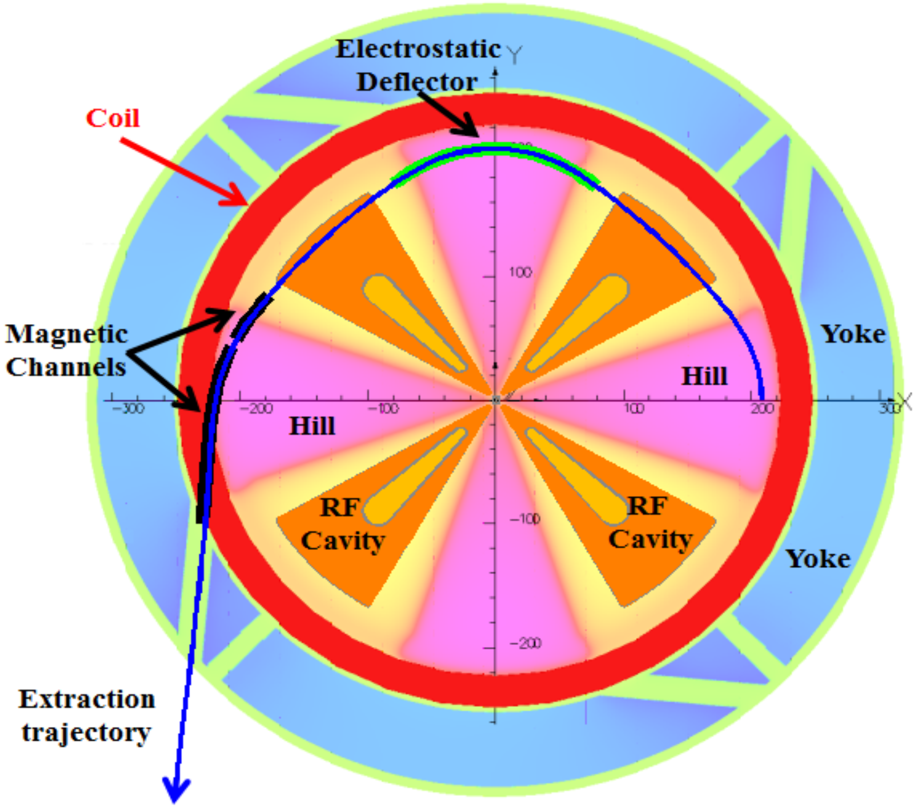


Base Design Injector
60 MeV/n @ 5 mA of H_2^+



~1 mA p machines are made
By industry (IBA, BEST)
For isotope production

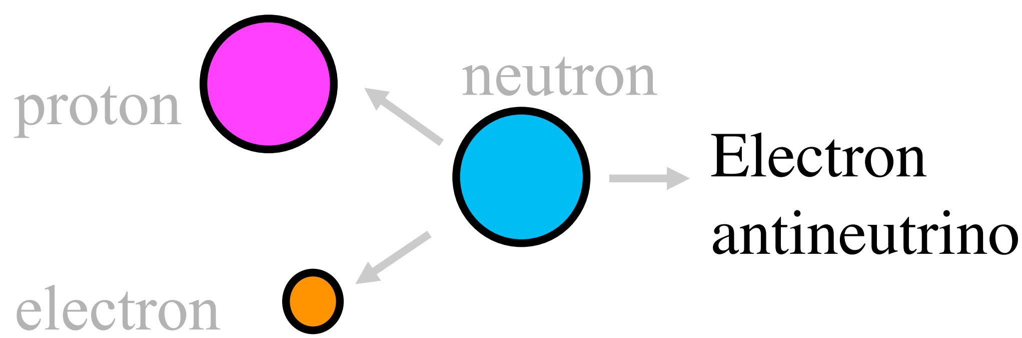
Isotope	half-life	Use
^{52}Fe	8.3 h	The parent of the PET isotope ^{52}Mn and iron tracer for red-blood-cell formation and brain uptake studies.
^{122}Xe	20.1 h	The parent of PET isotope ^{122}I used to study blood brain-flow.
^{28}Mg	21 h	A tracer that can be used for bone studies, analogous to calcium
^{128}Ba	2.43 d	The parent of positron emitter ^{128}Cs. As a potassium analog, this is used for heart and blood-flow imaging.
^{97}Ru	2.79 d	A γ-emitter used for spinal fluid and liver studies.
^{117m}Sn	13.6 d	A γ-emitter potentially useful for bone studies.
^{82}Sr	25.4 d	The parent of positron emitter ^{81}Rb, a potassium analogue This isotope is also directly used as a PET isotope for heart imaging.



At 60 MeV/n,
We can use this to
Make isotopes
That beta decay
At rest…

IsoDAR

This can produce
A lot of beam!



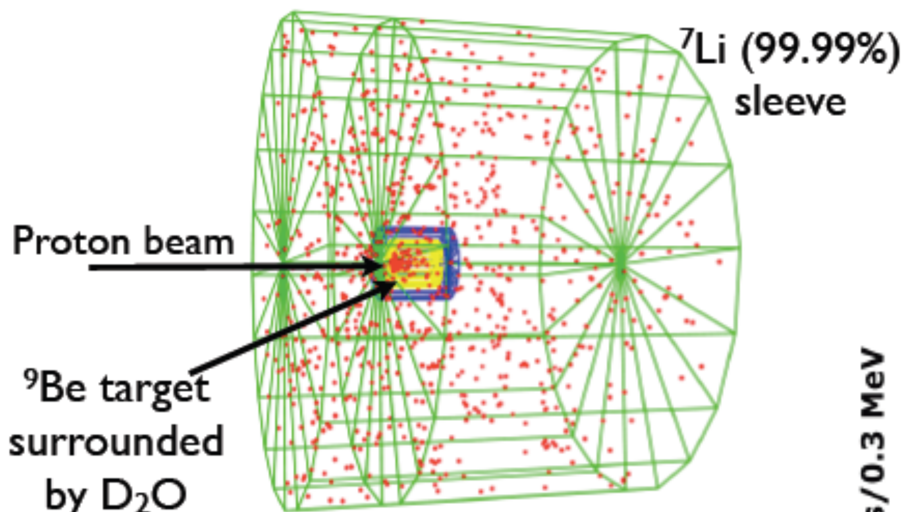
arXiv.org > hep-ex > arXiv:1205.4419

Search or Article-id

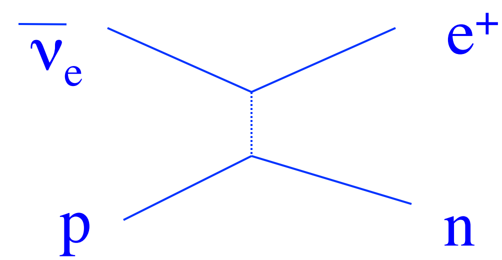
High Energy Physics - Experiment

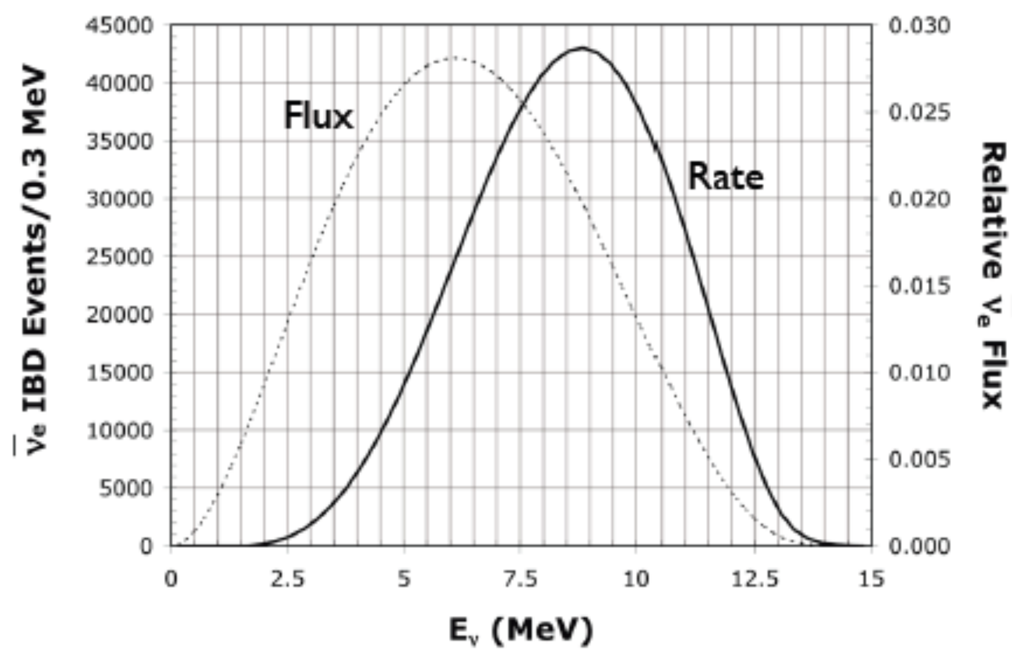
An Electron Antineutrino Disappearance Search Using High-Rate 8Li Production and Decay

A. Bungau, A. Adelmann, J.R. Alonso, W. Barletta, R. Barlow, L. Bartoszek, L. Calabretta, A. Calanna, D. Campo, J.M. Conrad, Z. Djurcic, Y. Kamyshkov, M.H. Shaevitz, I. Shimizu, T. Smidt, J. Spitz, M. Wascko, L.A. Winslow, J.J. Yang

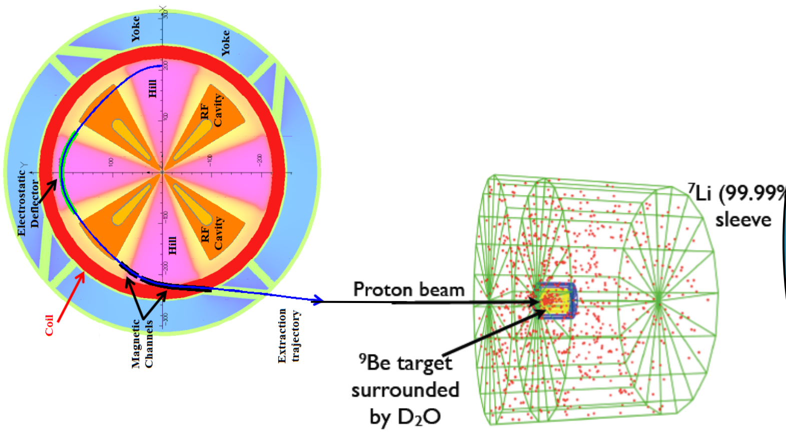


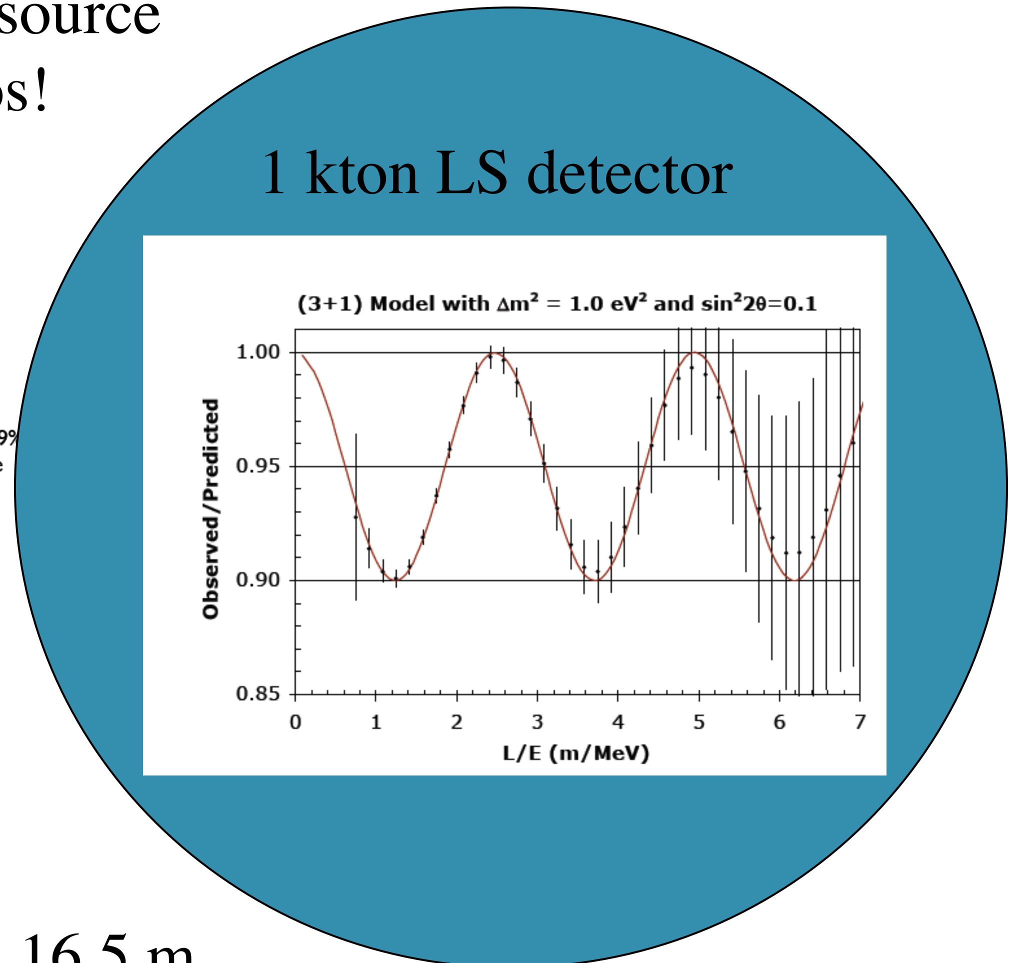
In liquid scintillator





Use this low-energy pure $\overline{\nu}_e$ source
To search for sterile neutrinos!



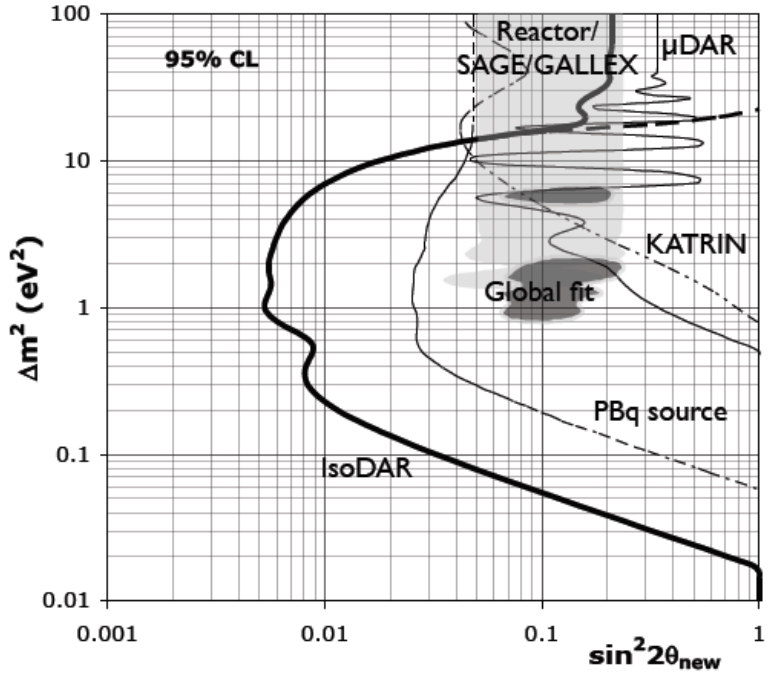


16.5 m

Potential locations: KamLAND and SNO+

Outstanding sensitivity!

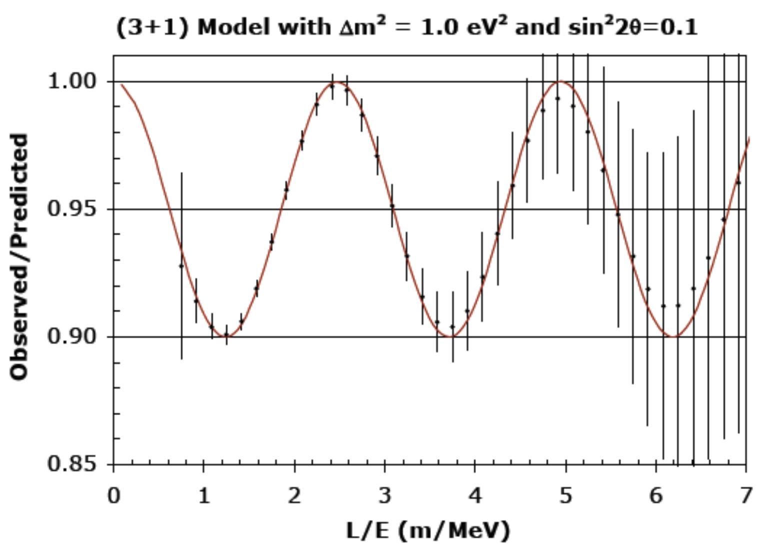
> 5σ in <2 years of running

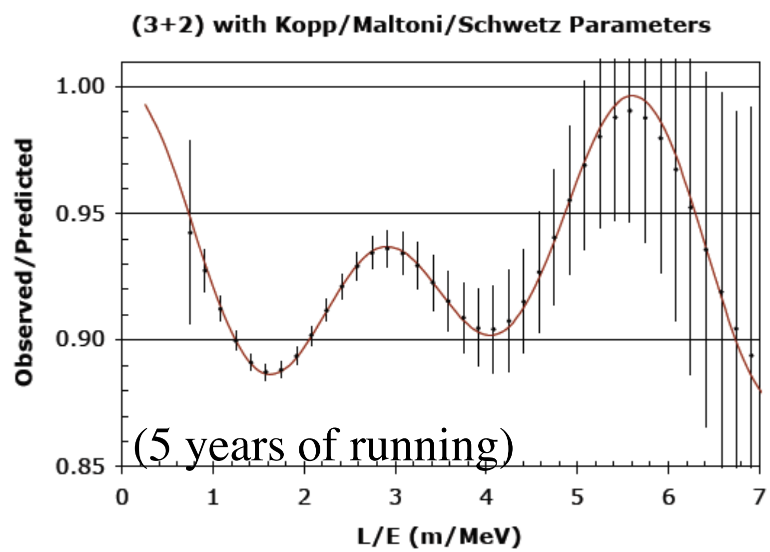


Ability to discriminate between models!

3+1

3+2





Along with sterile neutrino searches…

Searches for new particles produced in dump

Studies of antineutrino-electron scattering

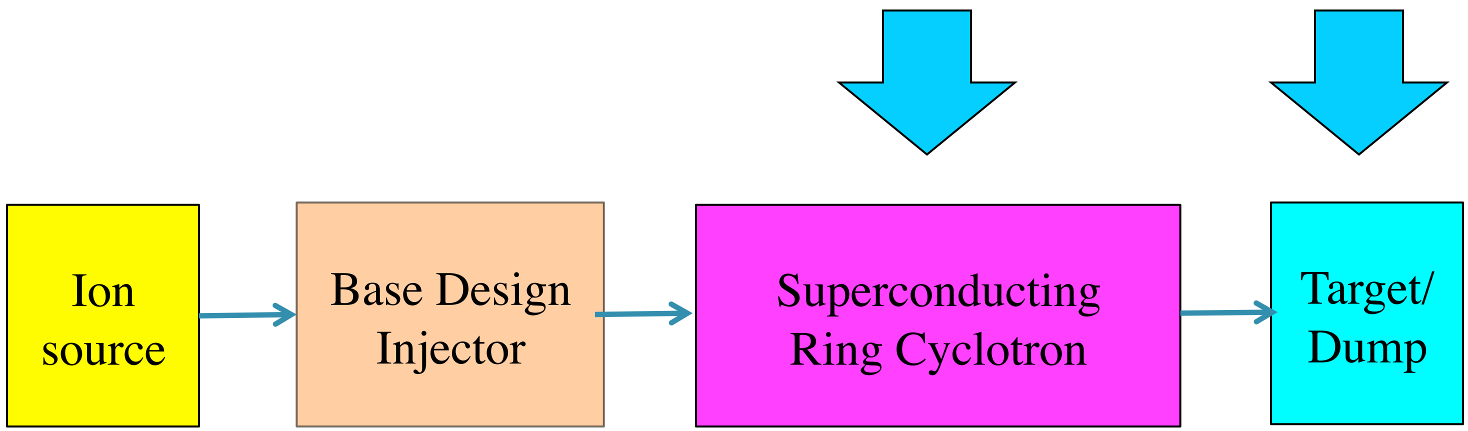
More ideas welcome!

The science capability is outstanding.

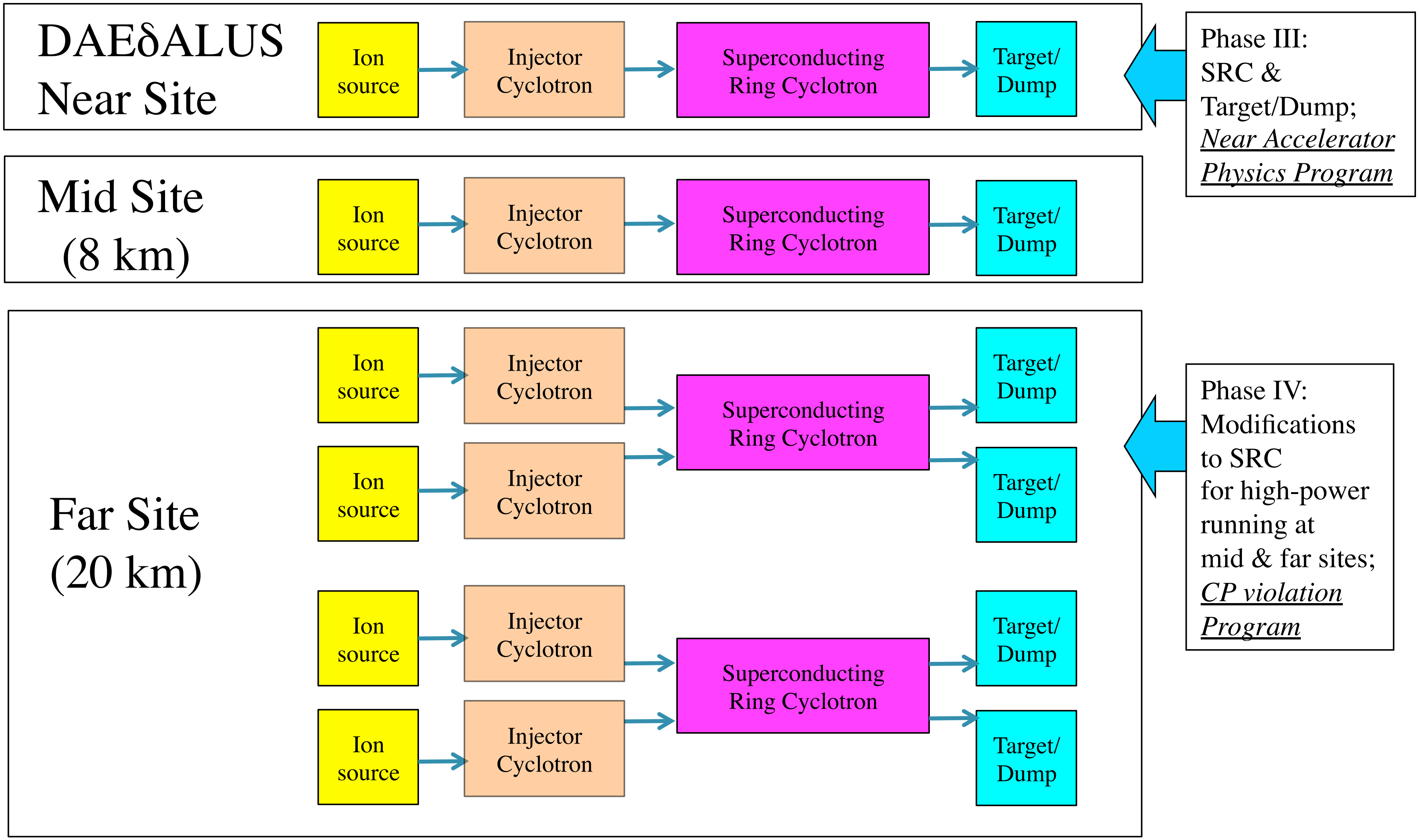
This is of interest to the medical isotope industry!

This moves DAEδALUS forward!

Phases III and IV



Establish the “standard” system
And the the high-power system


DAEδALUS
Near Site
Ion source
Injector Cyclotron
Superconducting Ring Cyclotron
Target/ Dump
Phase III:
SRC &
Target/Dump;
Near Accelerator Physics Program
Mid Site (8 km)
Ion source
Injector Cyclotron
Superconducting Ring Cyclotron
Target/ Dump
Far Site (20 km)
Ion source
Injector Cyclotron
Superconducting Ring Cyclotron
Target/ Dump
Phase IV:
Modifications to SRC for high-power running at mid & far sites;
CP violation Program

The most challenging aspect:
The Superconducting Ring Cyclotron

Original design

Multi Megawatt DAEδALUS Cyclotrons for Neutrino Physics

M. Abs[j], A. Adelmann[*,b], J.R. Alonso[c], W.A. Barletta[c], R. Barlow[h], L. Calabretta[f], A. Calanna[c], D. Campo[c], L. Celona[f], J. M. Conrad[c], S. Gammino[f], W. Kleeven[j], T. Koeth[a], M.Maggiore[e], H. Okuno[g], L.A.C. Piazza[e], M. Seidel[b], M. Shaevitz[d], L. Stingelin[b], J. J. Yang[c], J. Yeck[i]

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[b]*Paul Scherrer Institut, CH-5234 Villigen, Switzerland*
[c]*Department of Physics Massachusetts Institute of Technology*
[d]*Columbia University*
[e]*National Institute of Nuclear Physics - LNL*
[f]*National Institute of Nuclear Physics - LNS*
[g]*Riken*
[h]*Huddersfield University, Queensgate Campus, Huddersfield HD1 3DH, UK*
[i]*IceCube Research Center, University of Wisconsin, Madison, Wisconsin 53706*
[j]*IBA-Research*

For ADS/thorium reactor applications,
see web for our talk at

ThEC
THORIUM ENERGY CONFERENCE 2011

Our proposed 800 MeV cyclotron
is very similar to the existing Riken, Japan, cyclotron

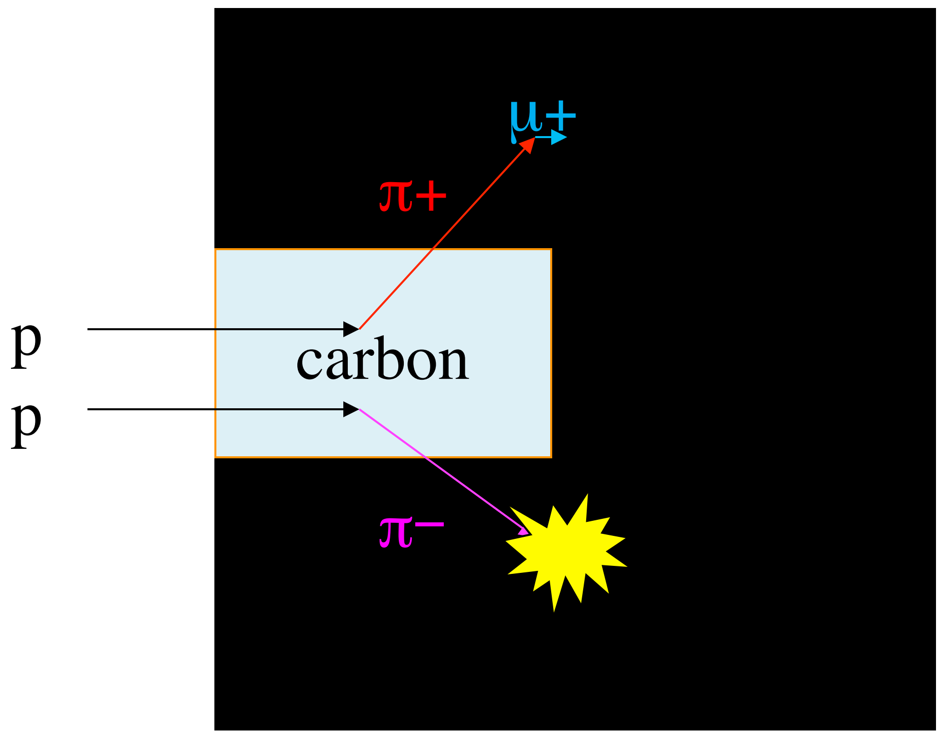
Table 5: Comparison of main parameters for DSRC with those for RIKEN-SRC

Basic Parameters	DSRC	RIKEN-SRC	Unit
Maximum field on the hill	6.05	3.8	T
Maximum field on the coil	6.18	4.2	T
Stored Energy	280	235	MJ
Coil size	30× 24 or 15× 48	21× 28	cm^2
Coil Circumference	9.8	10.86	m
Magnetomotive force	4.9	4	MAtot/sector
Current density	34	34	A/mm^2
Height	5.6	6.0	m
Length	6.9	7.2	m
Weight	≤450	800	ton
Additional magnetic shield	0	3000	ton/total
Magnetic Forces			
Expansion	1.87 or 1.8	2.6	MN/m
Vertical	3.7	3.3	MN
Radial shifting	2.7	0.36	MN
Azimuthal shifting	0.2	0	MN
Force on the pole	tbd	630	MN
Main Coil			
Operational current	5000	5000	A
Layer × turn	31×16	22×18	
Cooling	Bath cooling	Bath cooling	
Maddock Stabilized Current	6345	6665	A
Other Components			
SC trim	no	4	sets
NC trim× turn	no	22	pairs
Stray field in the SRC valley region	0.01	0.04	T
Gap for thermal insulation	40	90@min.	mm
Extraction method	Stripper foil	Electrostatic channel	

Our first engineering design will be available from…
MIT-PFSC Technology and Engineering Division
… this autumn

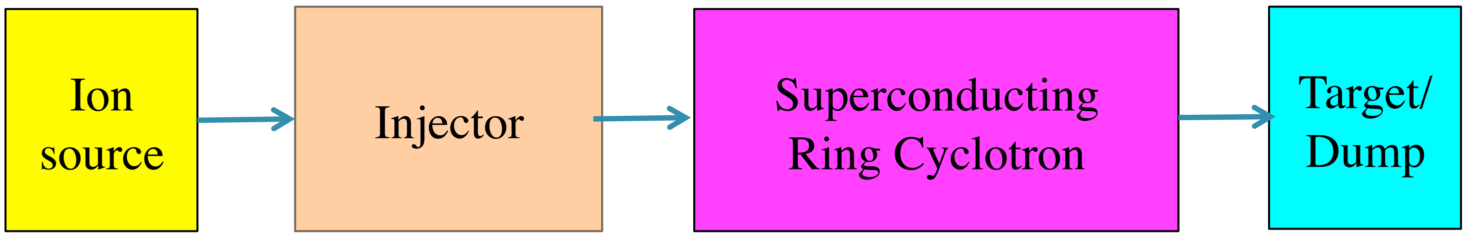
We will use 1 MW targets (we can use multiple targets)
Design is well understood from past DAR experiments…

Light target embedded in a heavy target



Also,
no upstream
targets!!!

Summary…



Existing Prototype, Tests Funded & Ongoing.

Advanced Design, Proposing A physics Program: **IsoDAR**

Now undergoing 1st Engineering Design.

Least Advanced, But based On past designs

Conclusions

DAEδALUS

Is…

A phased program with strong physics along the way
(especially the IsoDAR sterile neutrino search!)

Being brought to you by an international collaboration
of accelerator and particle physicists,
with input from Industry

Other Slides

Some other useful articles (beyond those already highlighted)…

arXiv:1205.5790 [pdf, ps, other]

Target Studies for the Production of Lithium8 for Neutrino Physics Using a Low Energy Cyclotron
Adriana Bungau, Roger Barlow, Michael Shaevitz, Janet Conrad, Joshua Spitz
Comments: 3 pages, 6 figures, IPAC 2012
Subjects: **Accelerator Physics (physics.acc-ph)**; Nuclear Experiment (nucl-ex)

arXiv:1205.5528 [pdf, ps, other]

Simulations of Pion Production in the DAEδALUS Target
Adriana Bungau (1), Roger Barlow (1), Mike Shaevitz (2), Janet Conrad (3), Joshua Spitz (3), Tess Smidt (3) ((1) University of Huddersfield, (2) Columbia University, (3) Massachusetts Institute of Technology), for the DAEδALUS Collaboration
Comments: 3 pages, 3 figures, IPAC 2012
Subjects: **Instrumentation and Detectors (physics.ins-det)**; High Energy Physics - Experiment (hep-ex); Nuclear Theory (nucl-th)

arXiv:1107.0652 [pdf]

Preliminary Design Study of High-Power H2+ Cyclotrons for the DAEdALUS Experiment
L. Calabretta, L. Celona, S. Gammino, D. Rifuggiato, G. Ciavola, M. Maggiore, L.A.C. Piazza, J.R. Alonso, W.A. Barletta, A. Calanna, J.M. Conrad
Subjects: **Accelerator Physics (physics.acc-ph)**; High Energy Physics - Experiment (hep-ex)

Our next talk on the cyclotron designs will be in August at…

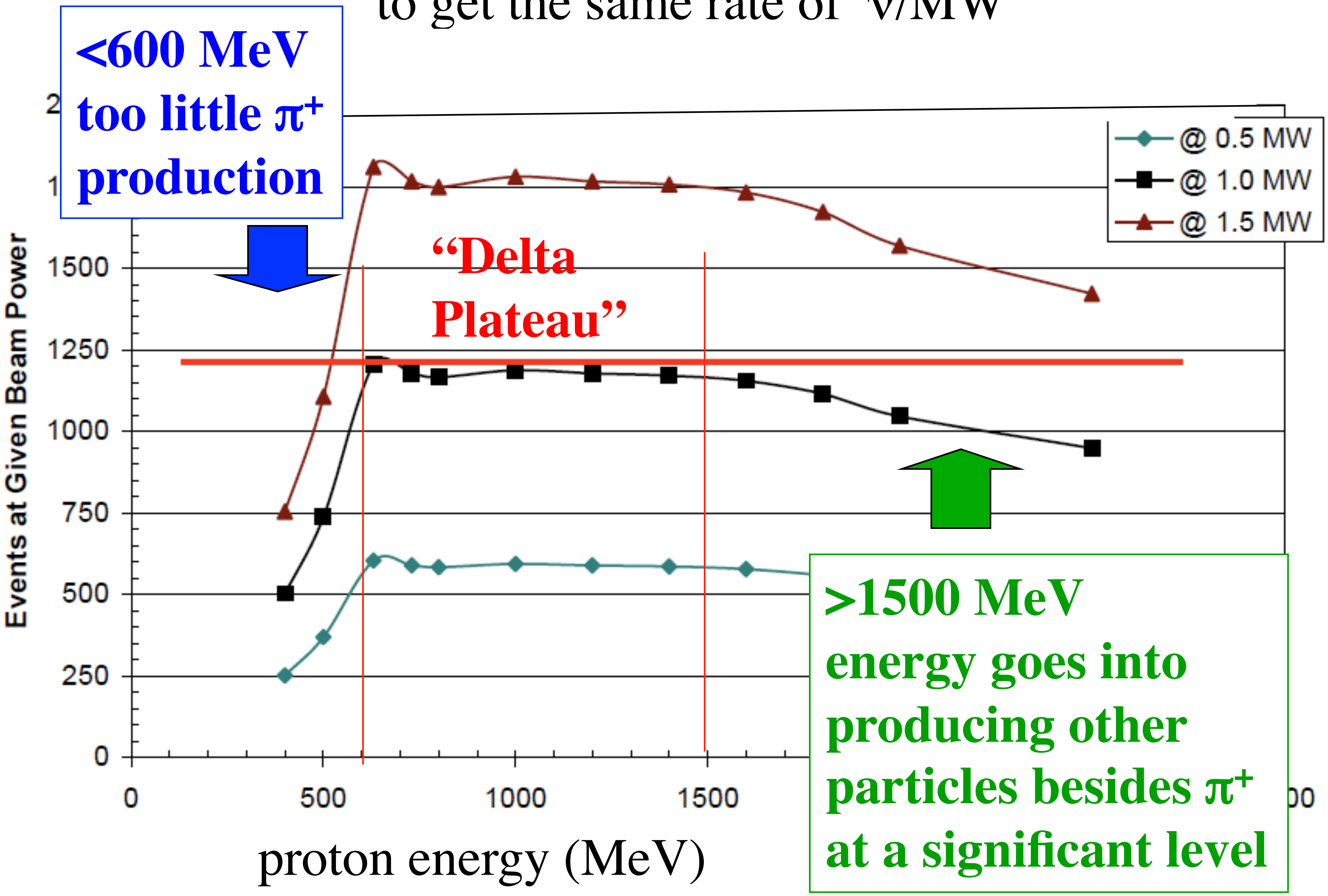
CAARI 2012

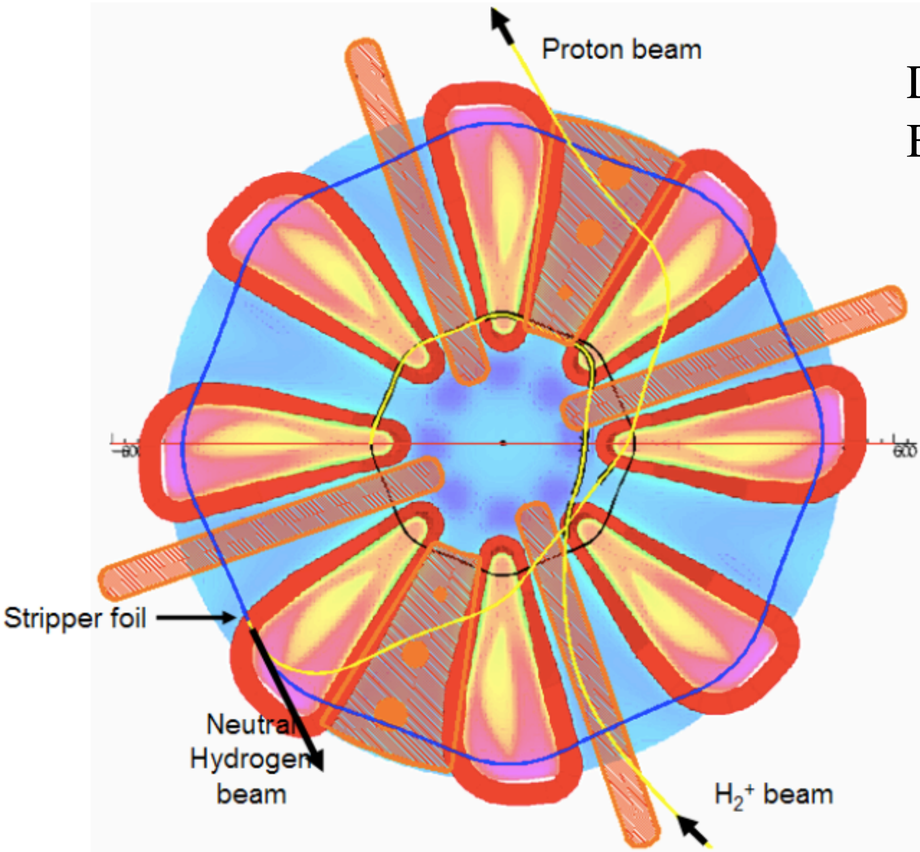
22nd International Conference on the Application of Accelerators in Research and Industry

Invited Talk By Jose Alonso

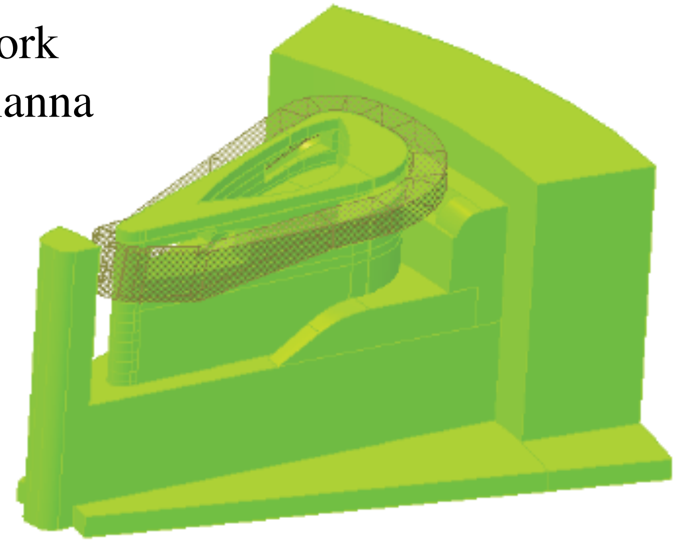
What proton energy is required?

There is a "Delta plateau" where you can trade energy for current to get the same rate of ν/MW





Design work
By A. Calanna



Beam envelope,
No energy spread,
1% spread