DAEδALUS

New Cyclotrons for ν Physics

You can get a copy of these slides at:
http://www2.lns.mit.edu/~conrad/Conrad_FNAL_2013.pdf

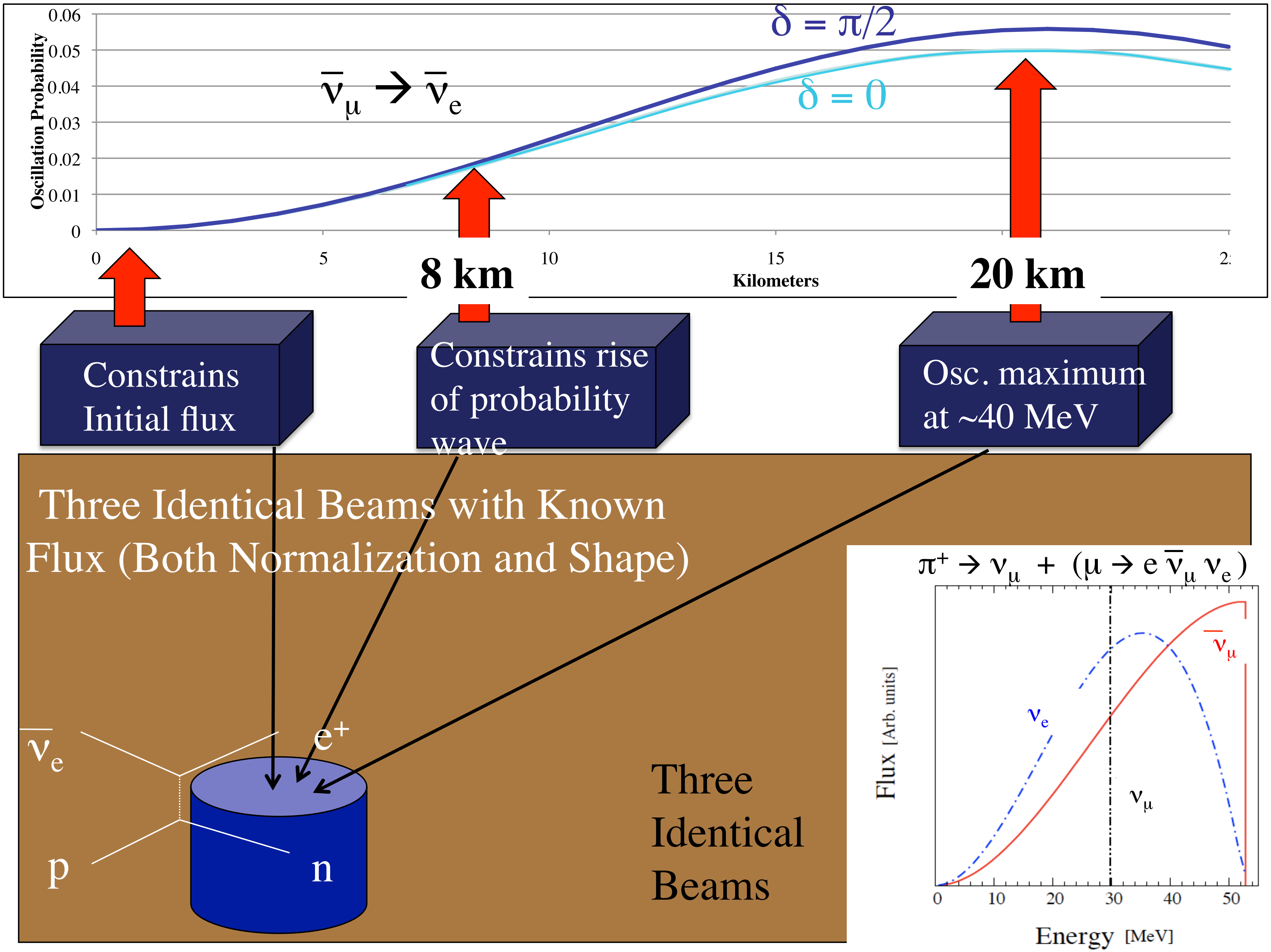
Janet Conrad, MIT
Fermilab, Nov 21, 2013

1. PHYSICS CONTEXT
2. THE COLLABORATION
3. THE ISODAR SOURCE
4. THE DAEδALUS SOURCE

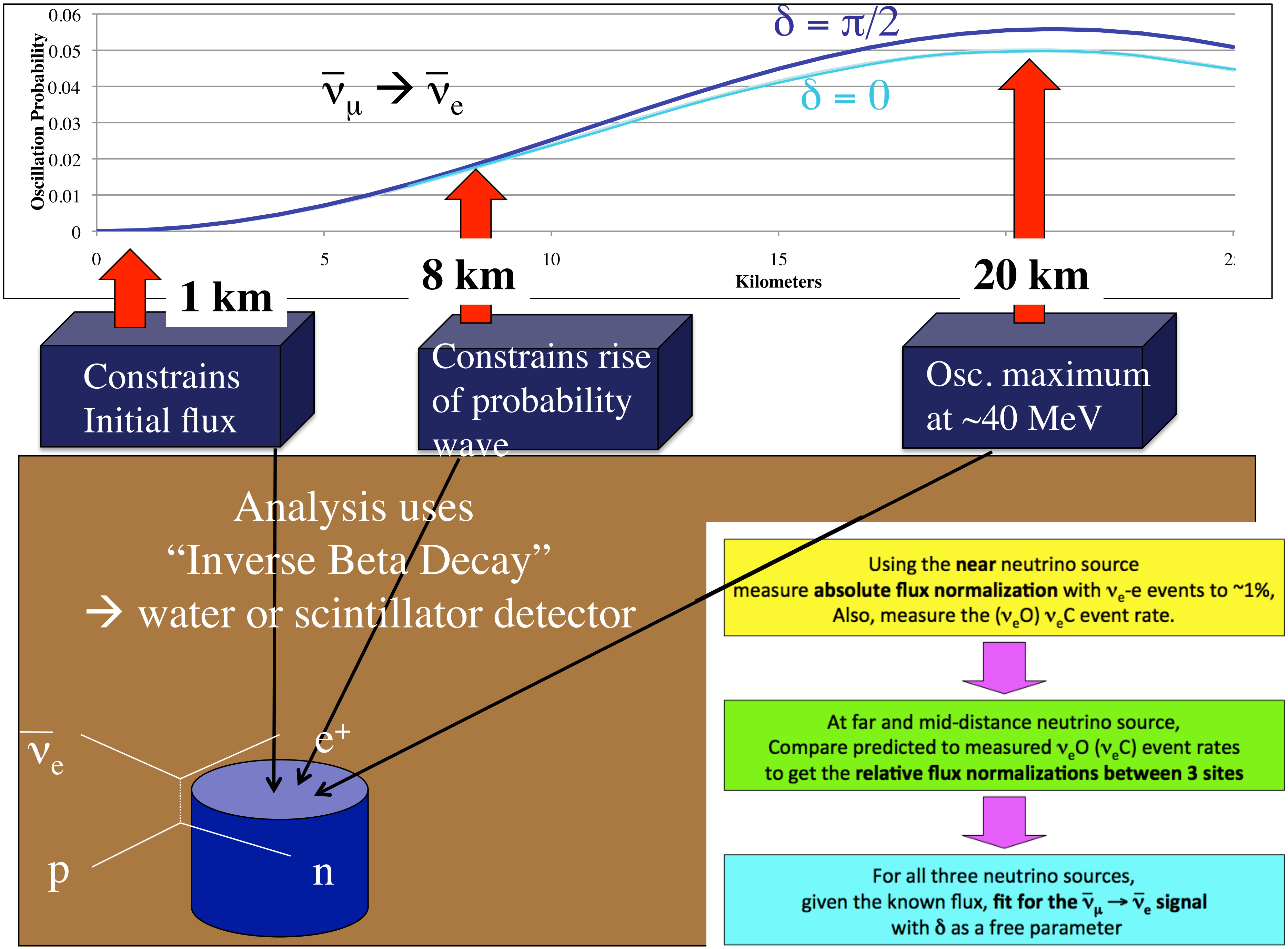
1. ν Physics Context
2. The Collaboration
3. The IsoDAR Source
4. The DAEδALUS Source

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

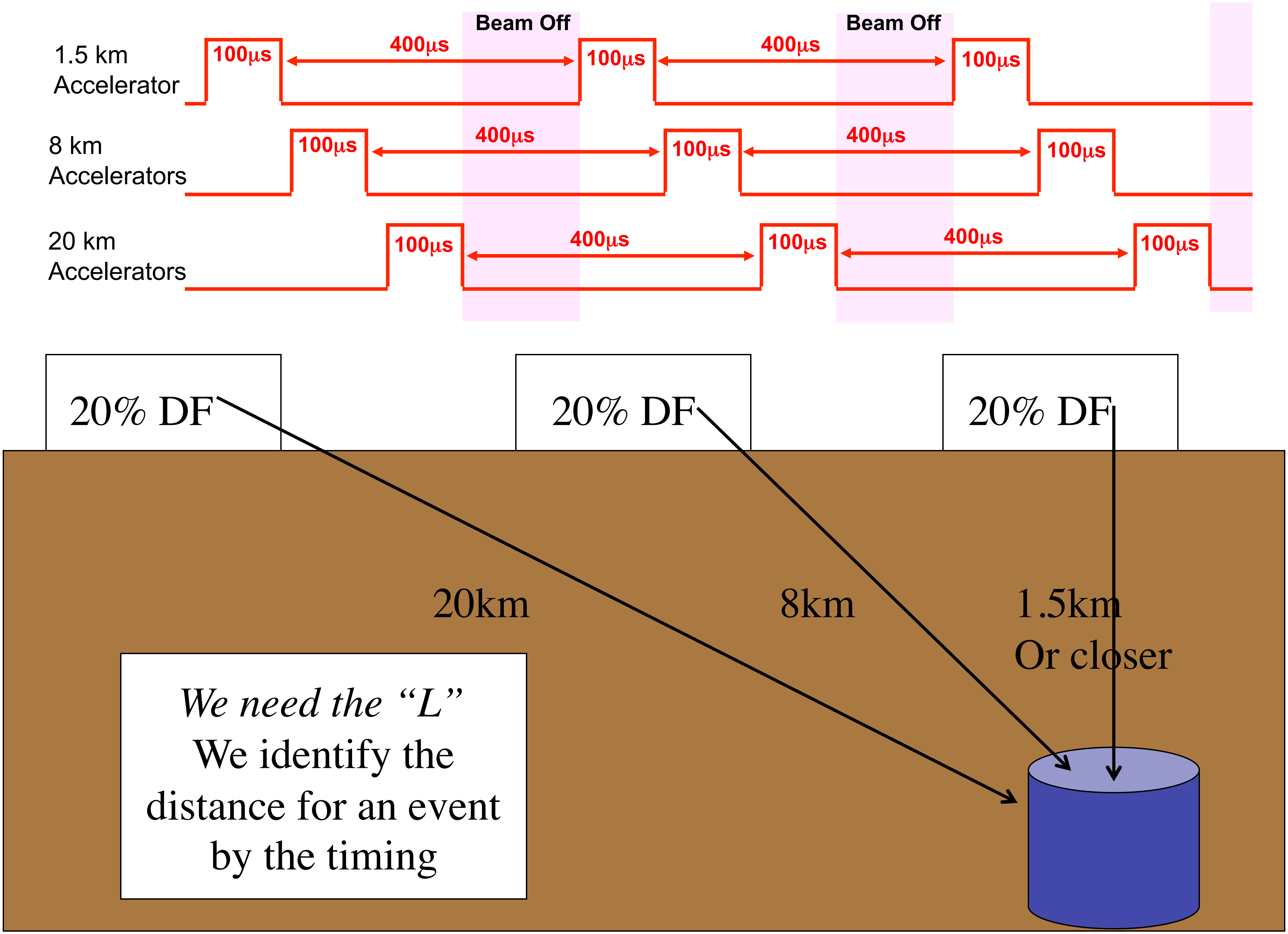
Use *decay-at-rest (DAR) neutrino beams*,
and one of the planned ultra-large detectors
with free protons (H_2O, oil)
to search for CP violation in the neutrino sector



Oscillation Probability
0.06
0.05
0.04
0.03
0.02
0.01
0
δ = π/2
δ = 0
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
0
5
10
15
Kilometers
8 km
20 km
Constrains Initial flux
Constrains rise of probability wave
Osc. maximum at ~40 MeV
Three Identical Beams with Known Flux (Both Normalization and Shape)
$\bar{\nu}_e$
e^+
p
n
Three Identical Beams
$\pi^+ \rightarrow \nu_\mu + (\mu \rightarrow e\, \bar{\nu}_\mu\, \nu_e)$
Flux [Arb. units]
ν_e
ν_μ
$\bar{\nu}_\mu$
0
10
20
30
40
50
Energy [MeV]

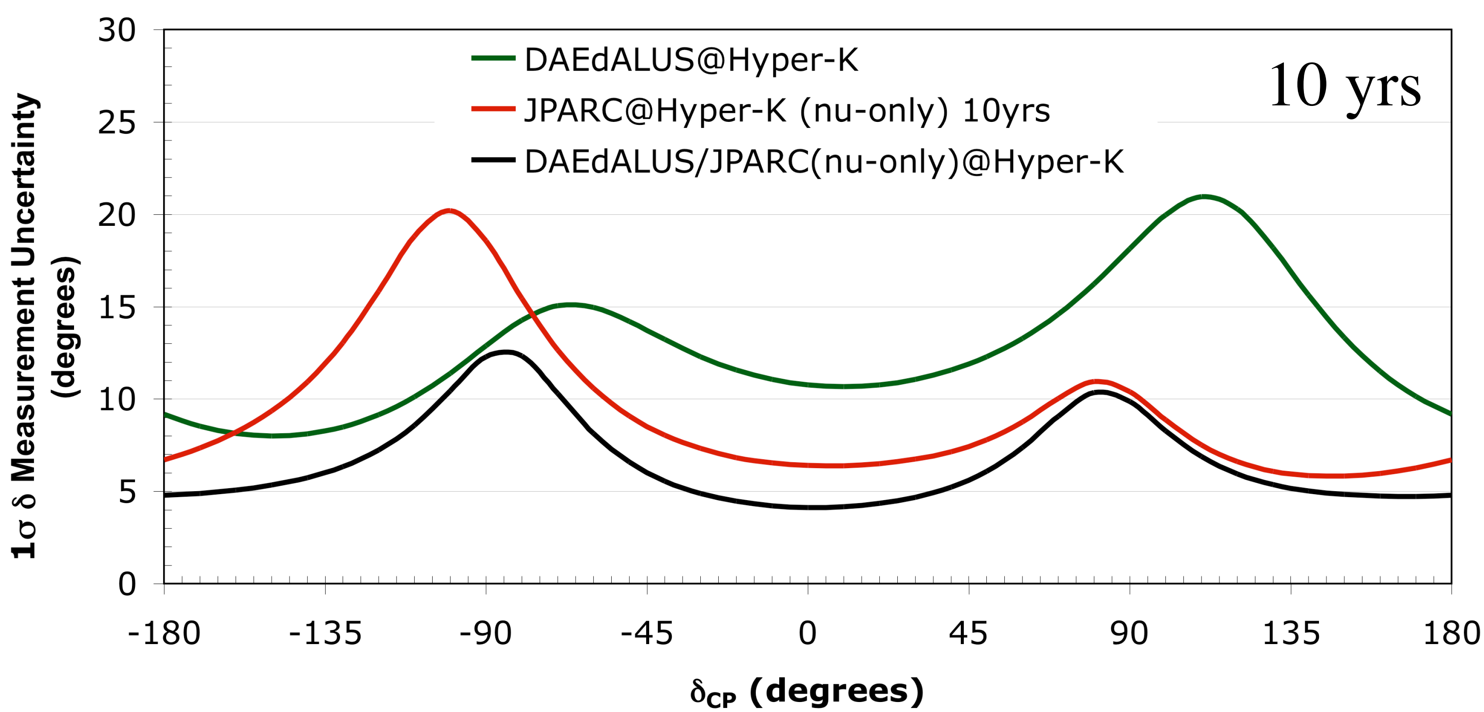


sources using high
statistics



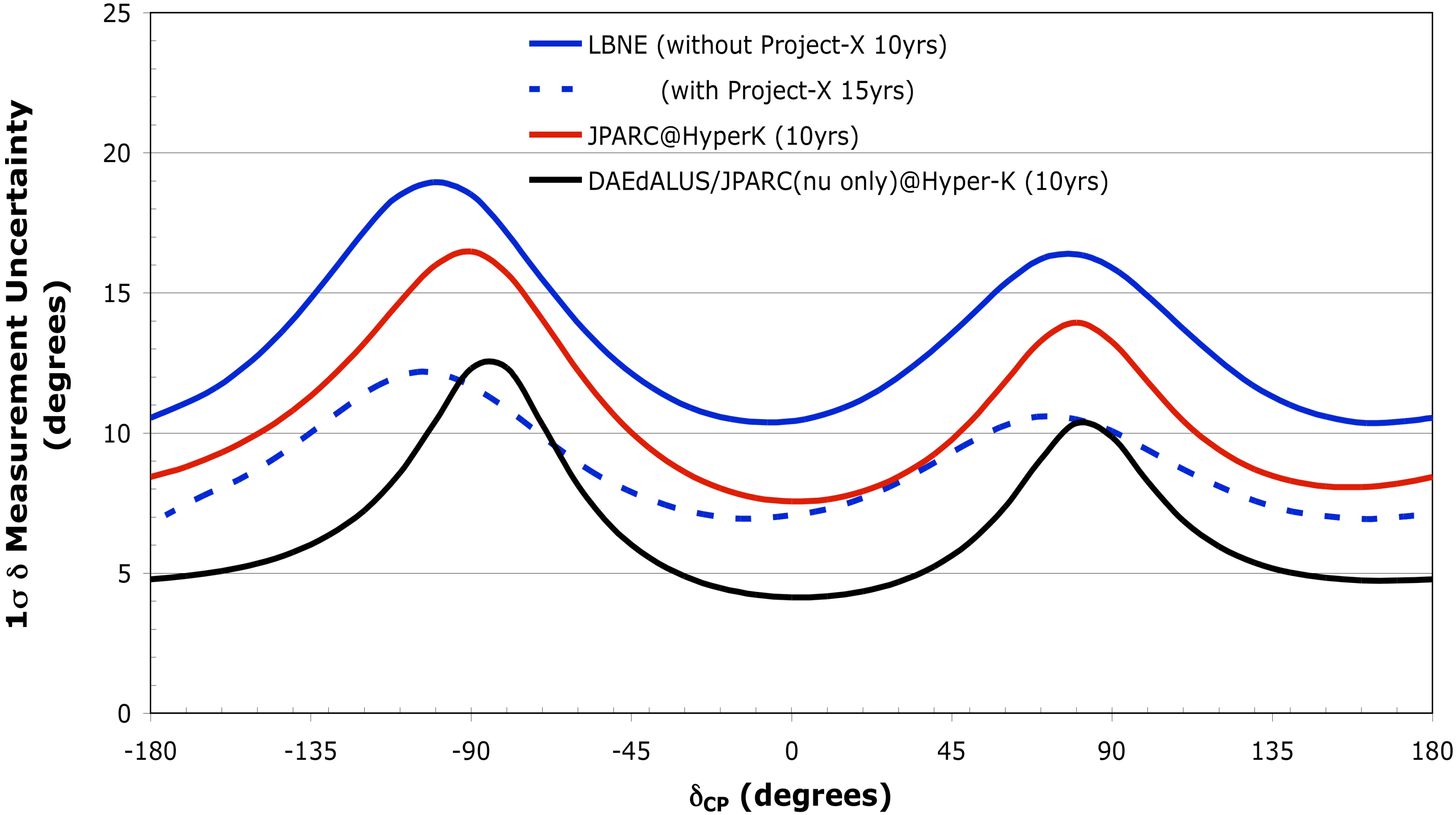
Beam Off
Beam Off
1.5 km Accelerator
100μs
400μs
100μs
400μs
100μs
8 km Accelerators
100μs
400μs
100μs
400μs
100μs
20 km Accelerators
100μs
400μs
100μs
400μs
100μs
20% DF
20% DF
20% DF
20km
8km
1.5km Or closer
We need the "L"
We identify the distance for an event by the timing

- Daeδalus has good CP sensitivity as a stand-alone experiment.
  - Small cross section, flux, and efficiency uncertainties
- Daeδalus can also be combined with long baseline ν-only data to give enhanced sensitivity, i.e. Hyper-K
  - Long baseline experiments have difficulty obtaining good statistics for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ which DAEδALUS can provide
  - Daeδalus has no matter effects and can help remove ambiguities.



arXiv:1307.2949

δ_{CP} Sensitivity Compared to Others

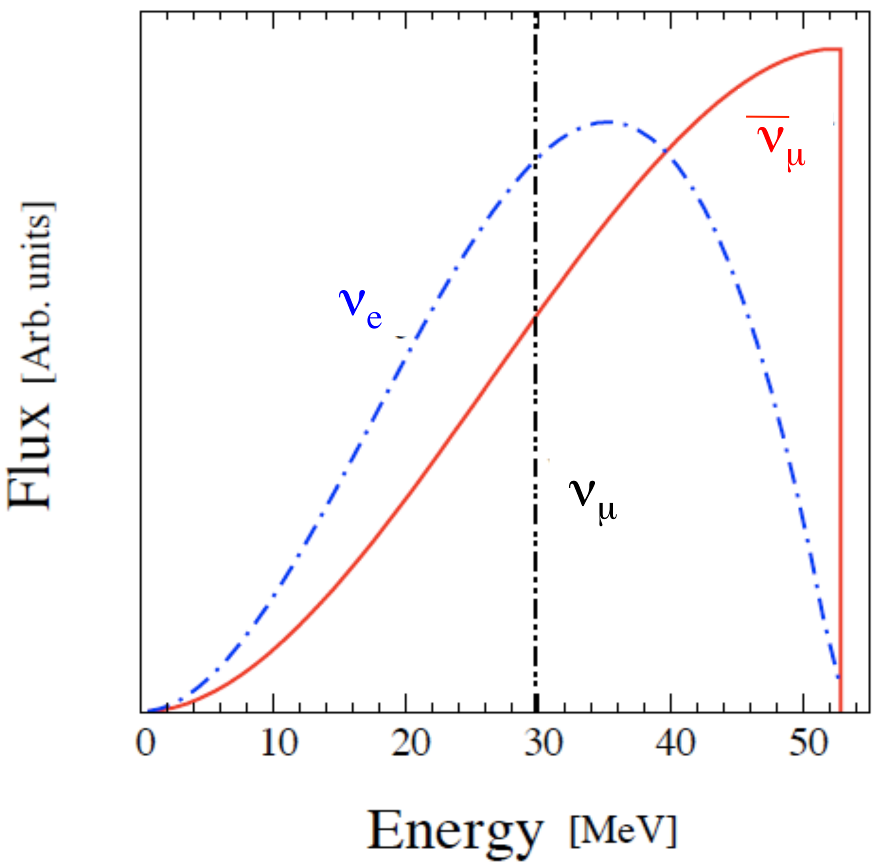


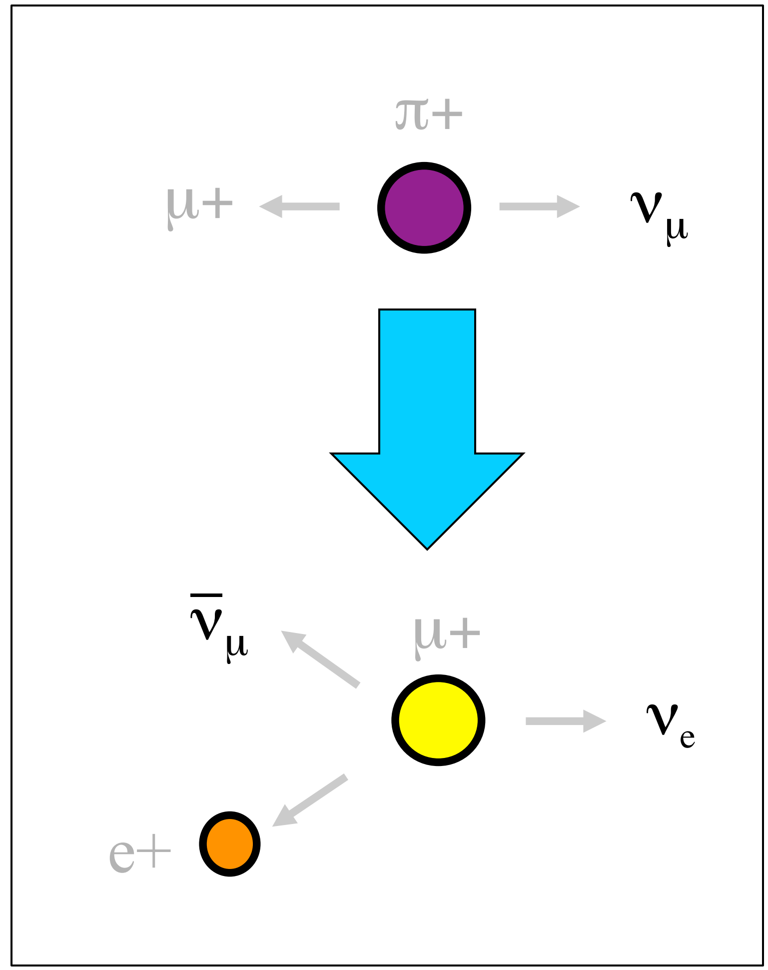
"What makes this program unique?"

DAEδALUS

1. Tracing the oscillation wave is a unique approach to CP studies.
2. Beam energy and flavor content well defined
3. Very low $\bar{\nu}_e$ intinsic background
   - Due to compact target/dump design with little π^- decay-in-flight backgrounds
   - Energy implies no Kaon production
   - Better geometry than DAR setups at spallation facilities
4. Very short baseline ⇒ no matter effects
   - No mass hierarchy dependence
   - Unaffected by propagation NSI effects
5. The complementary nature is what makes combining with conventional beam data so powerful

What do we need to produce
Pion/muon decay-at-rest?





Production data on p+Be target…
(Similar for carbon, which we will use)

	Produced Hadron	Exclusive Reaction	M_X (GeV/c^2)	$\sqrt{s_{thresh}}$ (GeV)	E^{beam}_{thresh} GeV	KE of beam (MeV)
wanted	π^+	$pn\pi^+$	1.878	2.018	1.233	295
Not wanted	π^-	$pp\pi^+\pi^-$	2.016	2.156	1.54	602
	π^0	$pp\pi^0$	1.876	2.011	1.218	280
	K^+	$\Lambda^0 pK^+$	2.053	2.547	2.52	1582
	K^-	ppK^+K^-	2.37	2.864	3.434	2496
	K^0	$p\Sigma^+K^0$	2.13	2.628	2.743	1805

We want to be well above threshold to produce a lot of π+ but near or below threshold for π- (which we then capture)

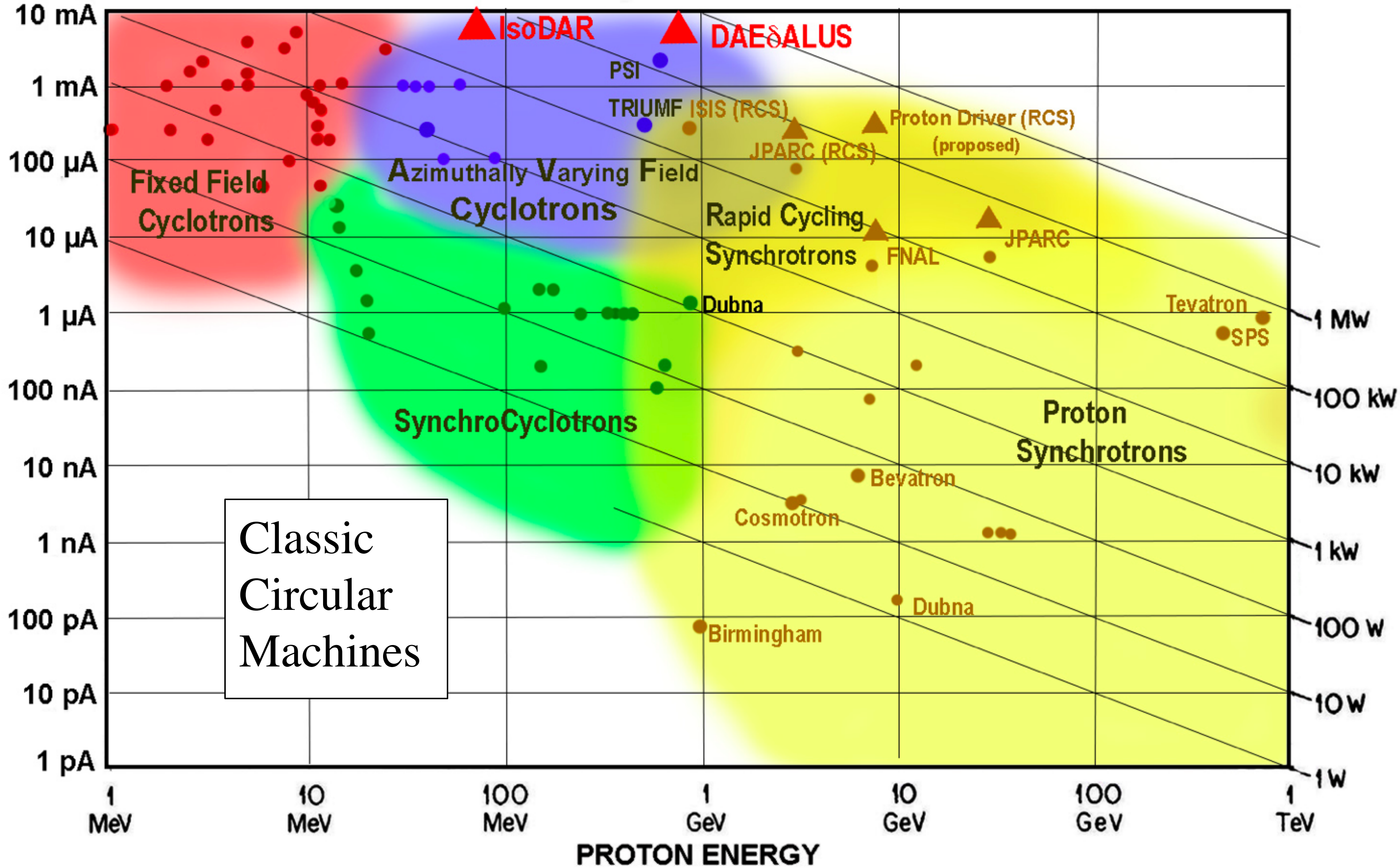
800 MeV is a good choice…
(Used at ISIS, LAMPF, others)

Some thoughts about the DAEδALUS beam so far...

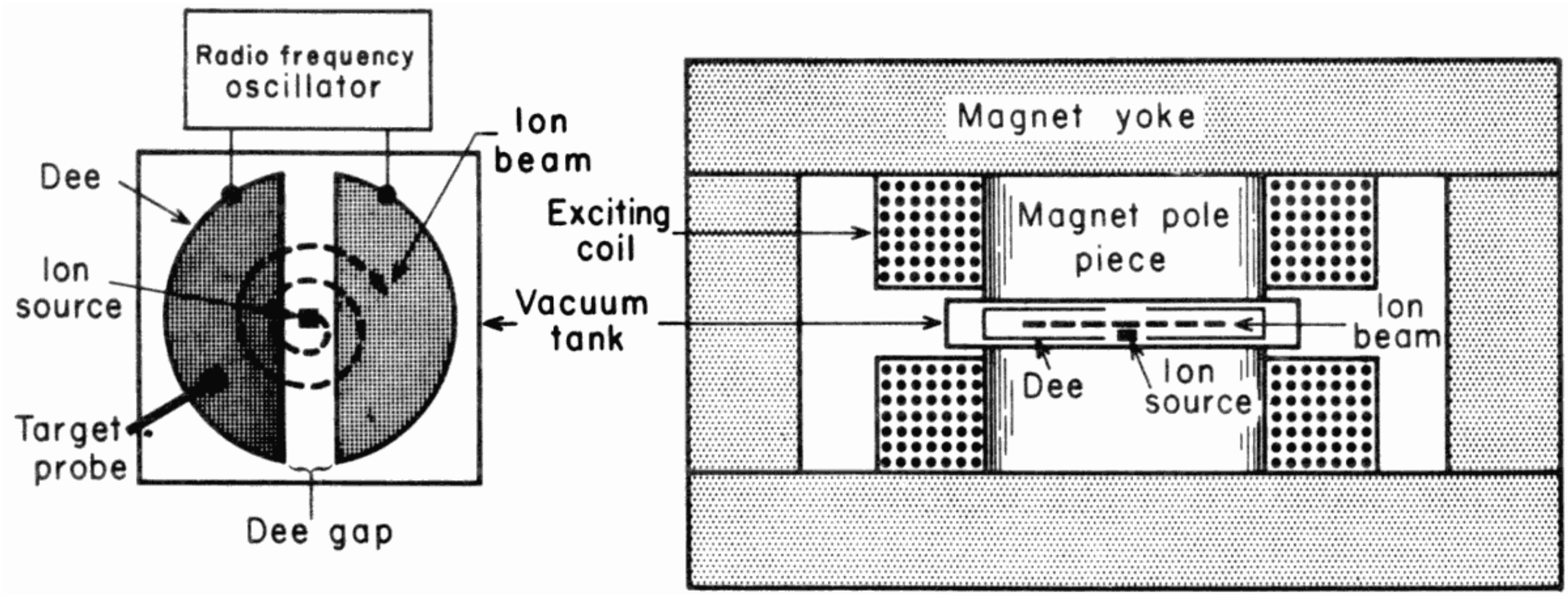
1. The needs are driven by requirements for pion/muon DAR
2. We need multi-MW proton beams
3. Kinetic energy of ~800 MeV seems optimal
4. Beams can be CW (on/off need, but on >1 μsec timescales)
5. If we can produce multiple beams, we can use multiple targets
6. The beams will hit target faces with very large surface area.
7. We want the machines to be relatively inexpensive

These points cause one to look at cyclotrons running H2+…

Look at circular accelerators,
since linacs are expensive



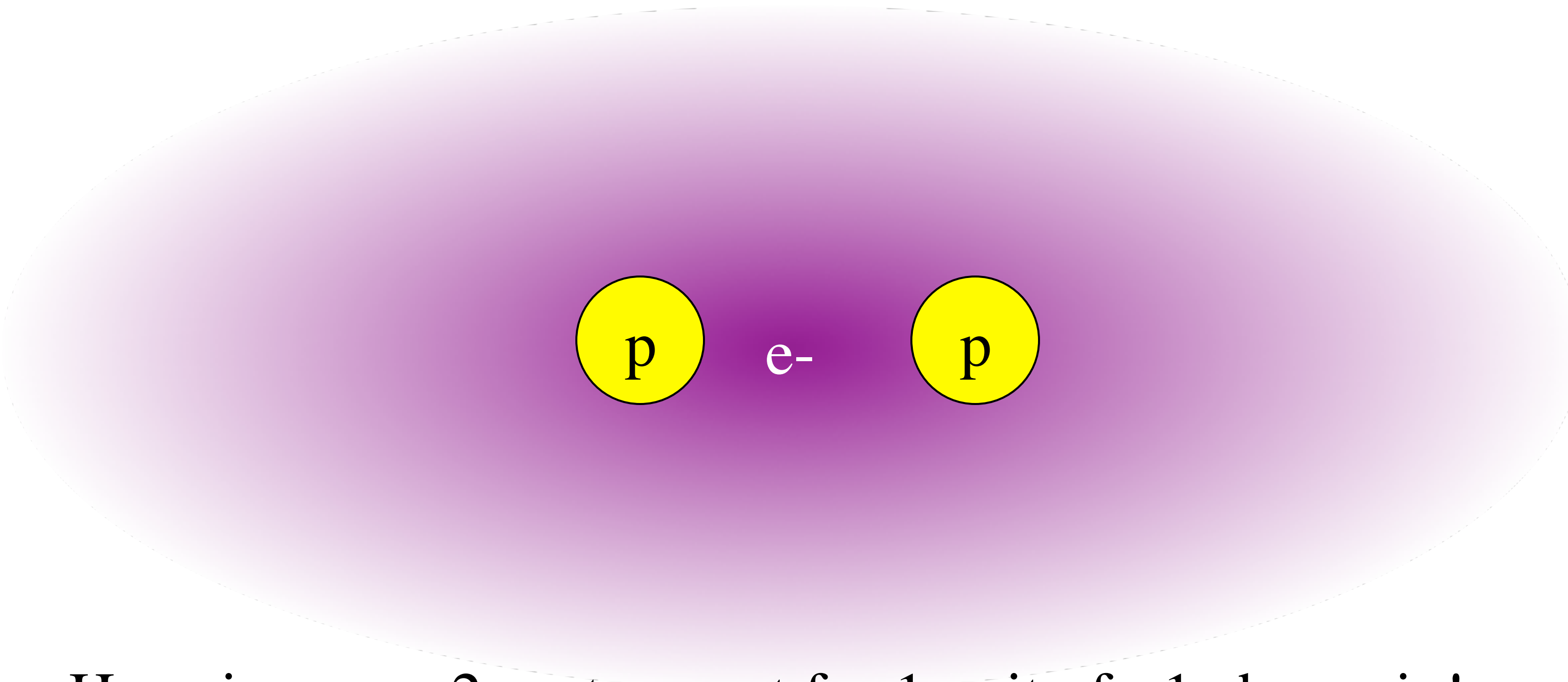
Use Cyclotrons to produce the 800 MeV protons!



Inexpensive,
Practical below ~1 GeV
Good for ~10% or higher duty factor
Typically single energy
Taps into existing industry

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

We plan to accelerate H_2+

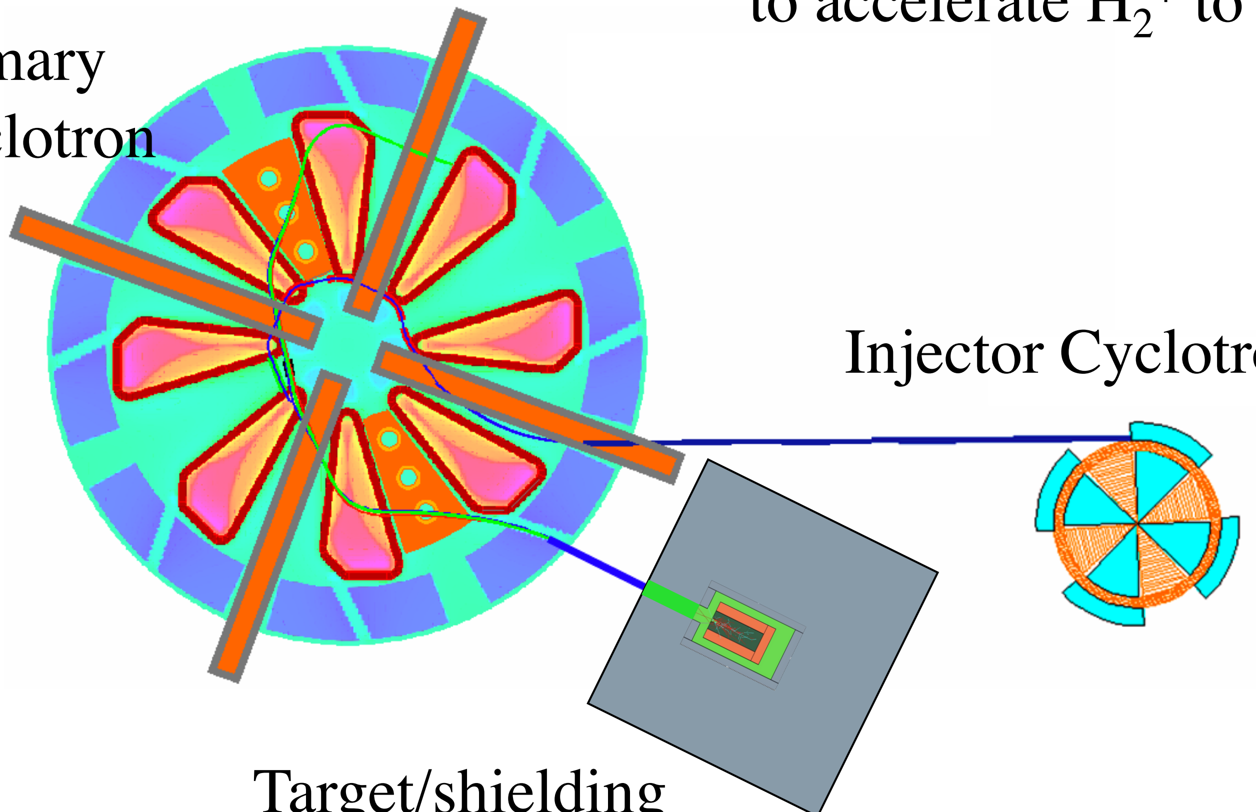


H_2+ gives you 2 protons out for 1 unit of +1 charge in!

Reduces the space charge effects at injection…

Clean to extract at 800 MeV by stripping the electron w/ a foil.
Can strip off multiple beams.

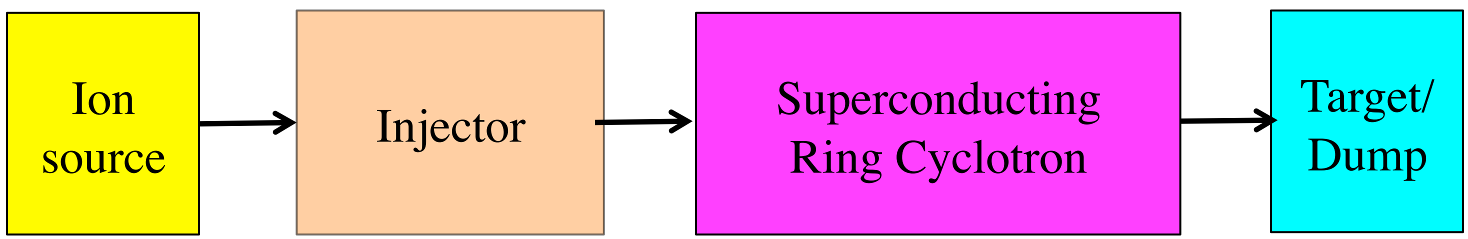
Uses Multiple "Accelerator Units"
constructed of cyclotrons
to accelerate H_2^+ to 800 MeV/n



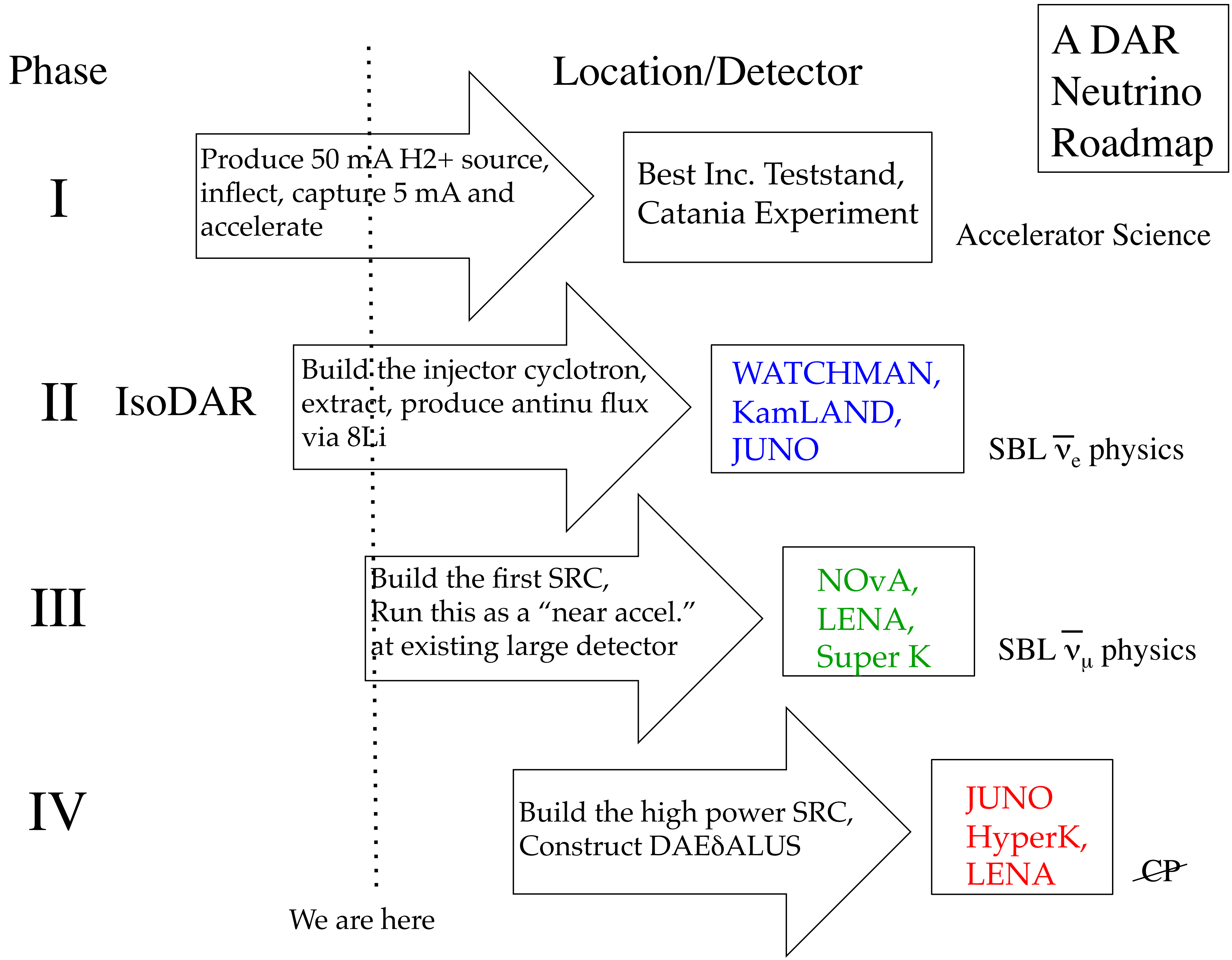
The result is a decay-at-rest flux
That can be used for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ searches

The "plug-and-play design" of accelerator unit

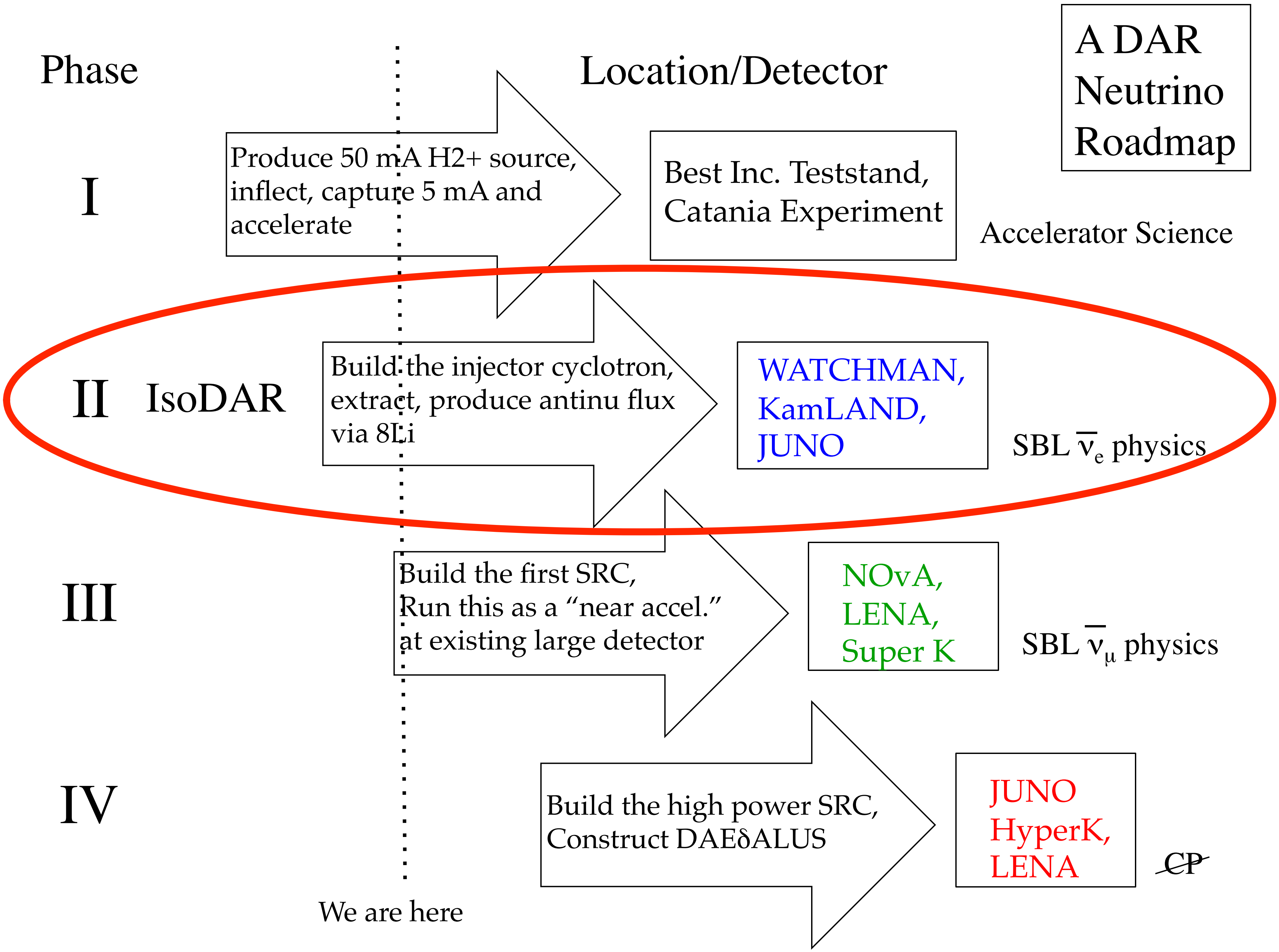
modular → cheaper
multiple units → cheaper



Leads to an obvious multiphase development plan.
Our goal: produce excellent physics at every phase.



A DAR Neutrino Roadmap
Phase
Location/Detector
I
Produce 50 mA H2+ source, inflect, capture 5 mA and accelerate
Best Inc. Teststand, Catania Experiment
Accelerator Science
II
IsoDAR
Build the injector cyclotron, extract, produce antinu flux via 8Li
WATCHMAN, KamLAND, JUNO
SBL $\bar{\nu}_e$ physics
III
Build the first SRC, Run this as a "near accel." at existing large detector
NOvA, LENA, Super K
SBL $\bar{\nu}_\mu$ physics
IV
Build the high power SRC, Construct DAEδALUS
JUNO HyperK, LENA
CP
We are here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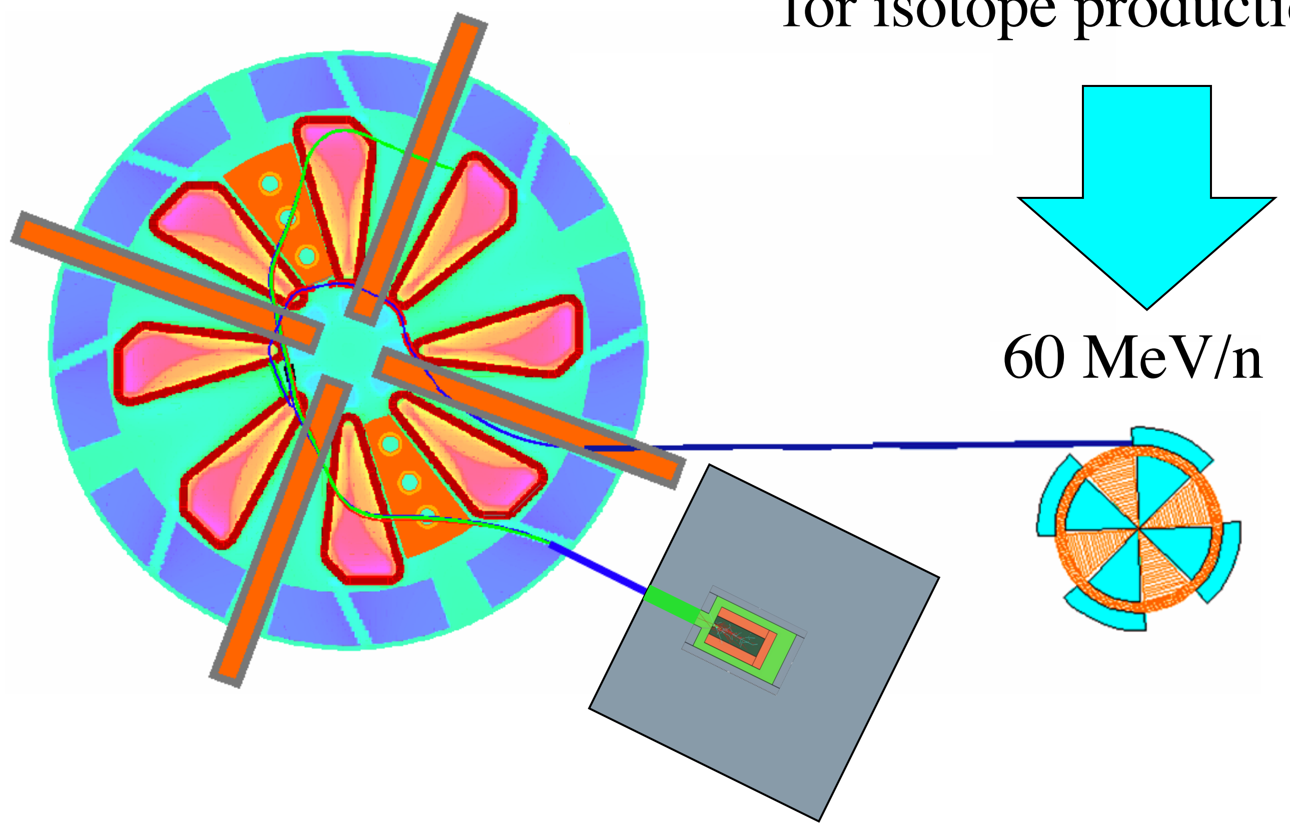
Cyclotrons of the same energy as our injector are already used for isotope production



Medical isotopes produced by 60 to 70 MeV cyclotrons

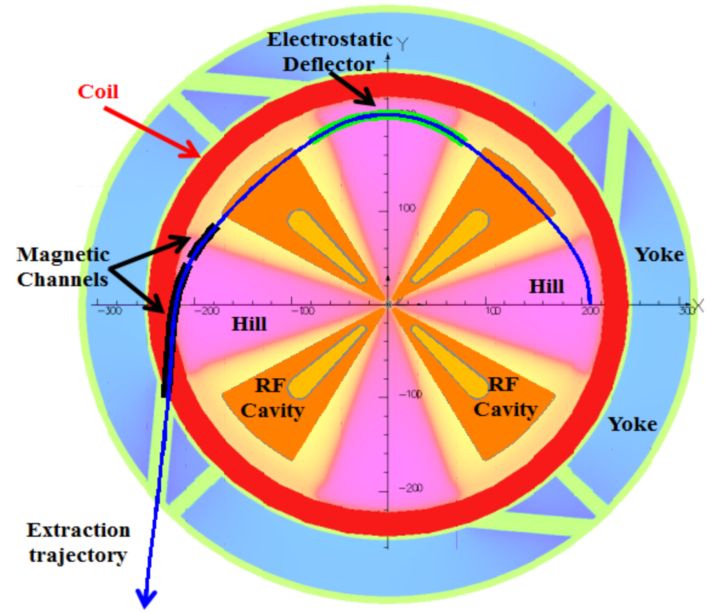
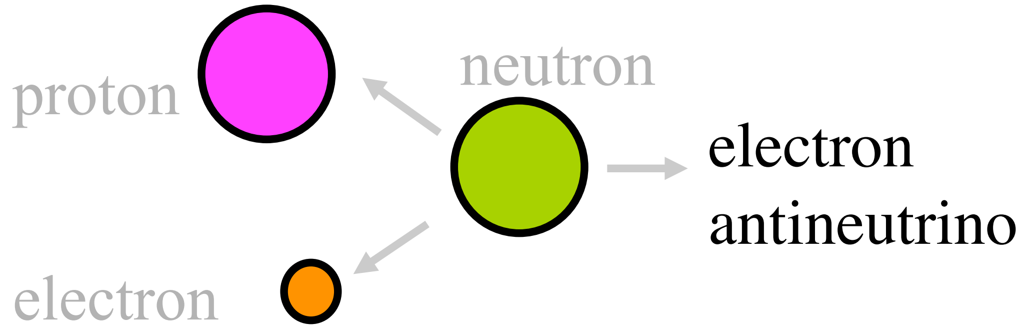


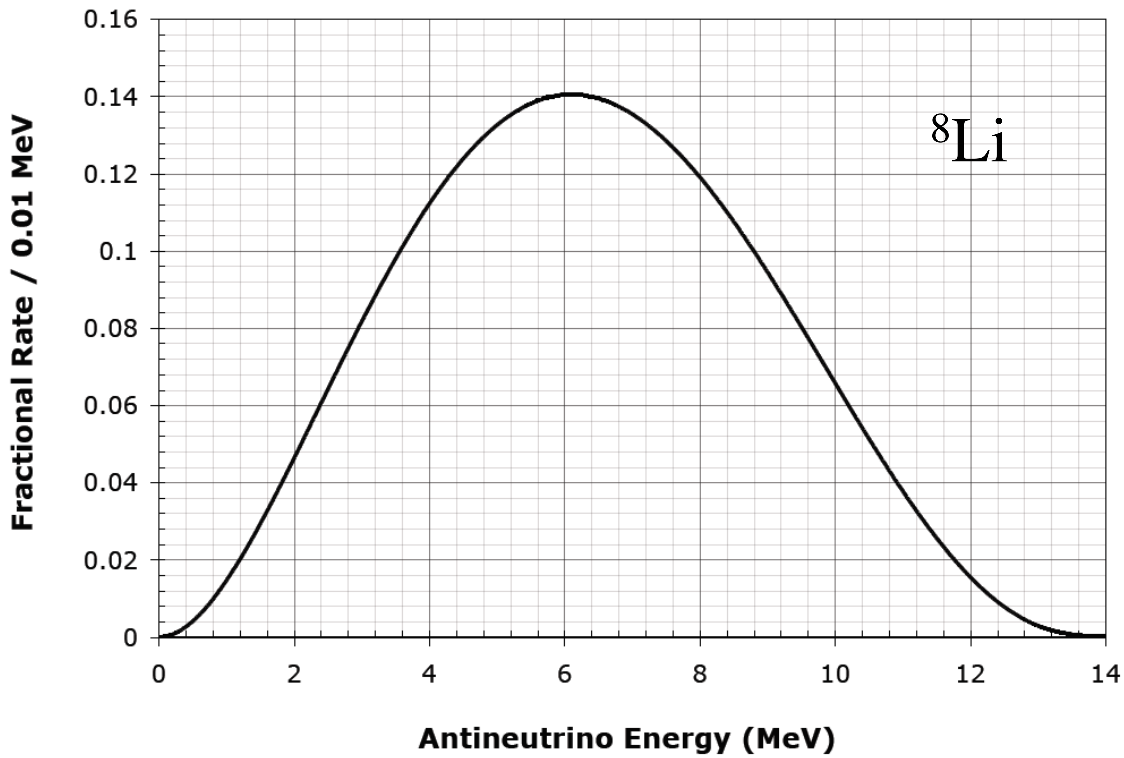
Table 3: Medical isotopes relevant to IsoDAR energies, from Ref. [23].

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 ^{82}Rb, a potassium analogue This isotope is also directly used as a PET isotope for heart imaging.

What can we do with Isotope decay-at-rest in neutrino physics?

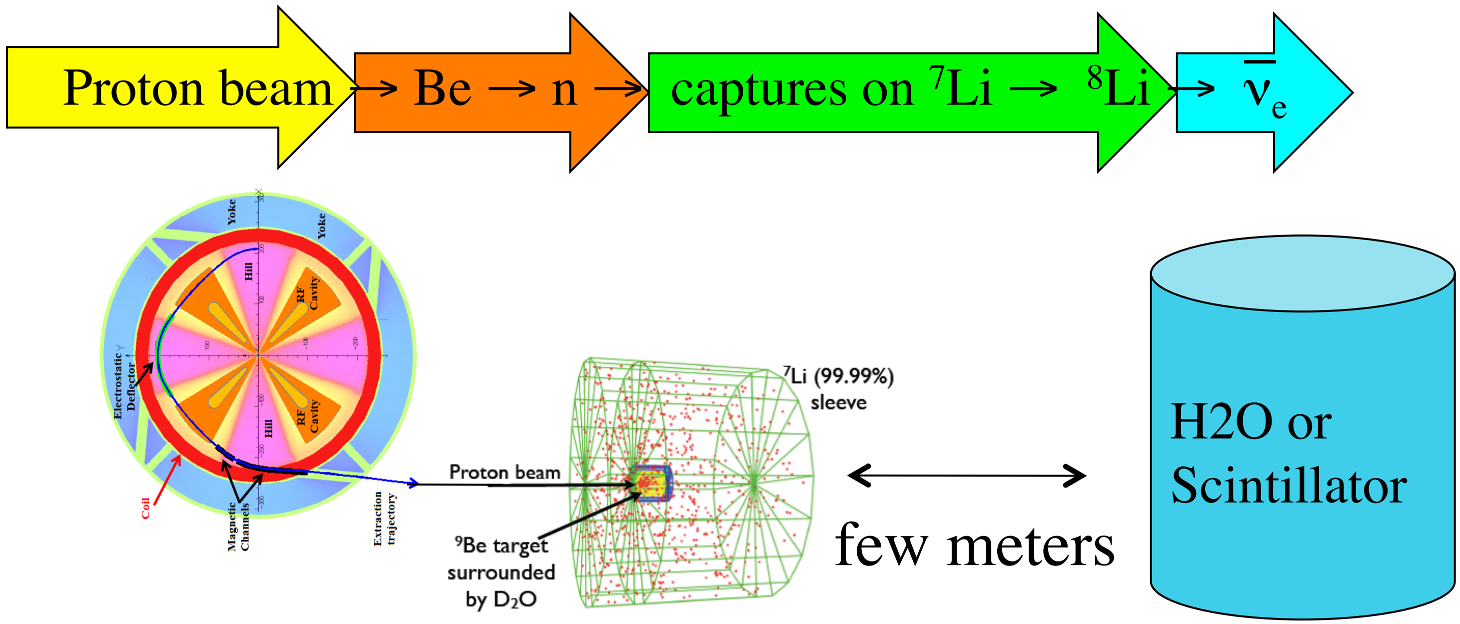


Will produce a
Very pure $\bar{\nu}_e$ beam



But only a few isotopes have endpoints > 3 MeV, above environmental backgrounds that affect detectors.

e.g.
$^{8}\text{Li} \rightarrow {}^{8}\text{Be} + e + \bar{\nu}_e$



Requirements IsoDAR of system:

1. Produce a lot of thermal neutrons (*e.g*. p on Be target)

2. Intensity of flux will require ~ 600 kW

3. If ^{8}Li is used (since 1 sec. lifetime) Continuous Wave (CW) is fine,
   low DF does not help you, but experiment MUST BE UNDERGROUND.

4. Low energy of antineutrinos → machine needs to be underground.
   Therefore we require a small size machine to fit.

The first group to pair with us was KamLAND,

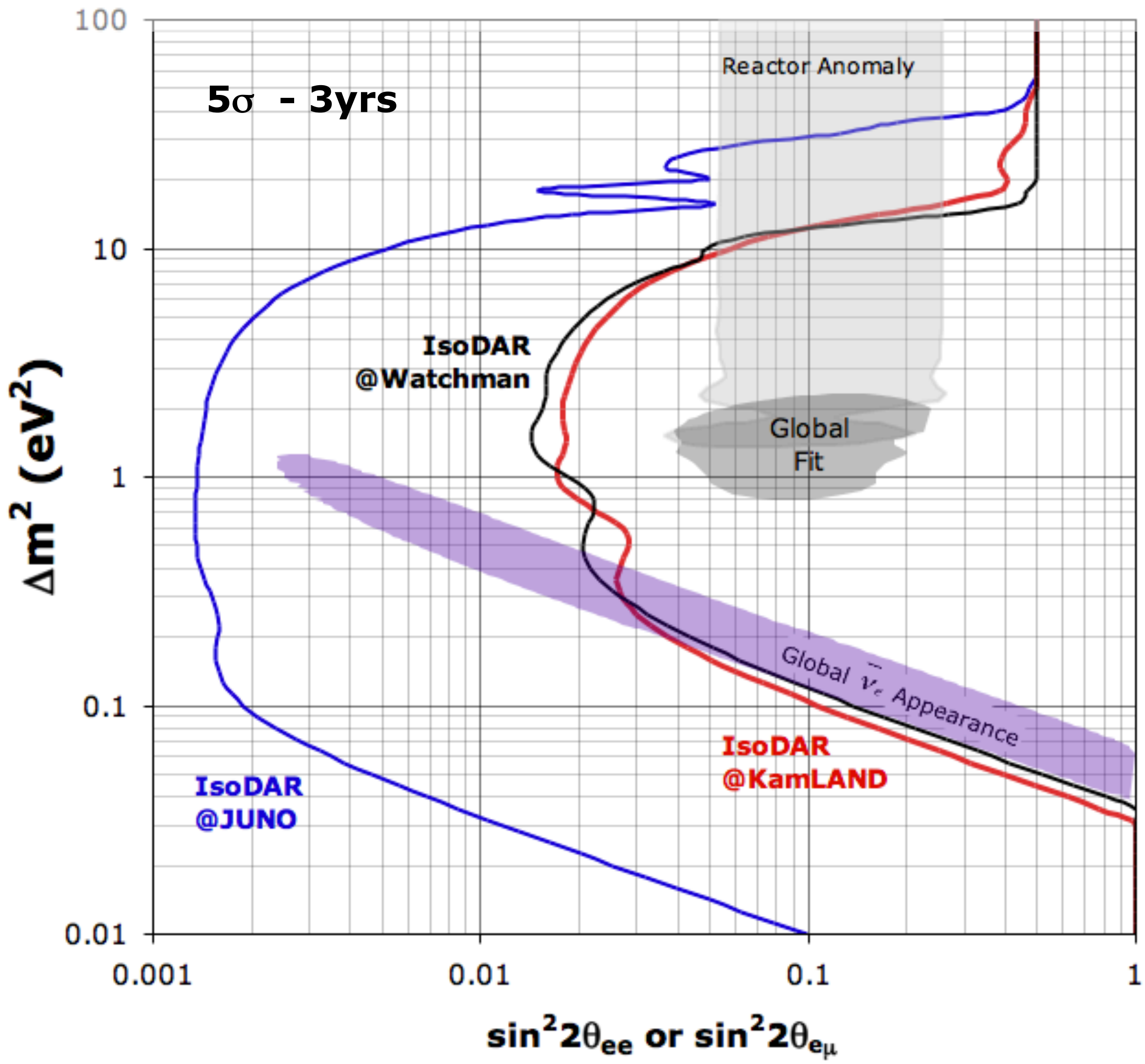
(and we continue to work toward a Baseline Design Report for Kamioka.)

Accelerator	60 MeV/amu of H_2^+
Current	10 mA of protons on target
Power	600 kW
Duty cycle	90%
Run period	5 years (4.5 years live time)
Target	^{9}Be surrounded by ^{7}Li (99.99%)
$\overline{\nu}$ source	^{8}Li β decay ($\langle E_\nu \rangle$=6.4 MeV)
$\overline{\nu}_e$/1000 protons	14.6
$\overline{\nu}_e$ flux	1.29×10^{23} $\overline{\nu}_e$
Detector	KamLAND
Fiducial mass	897 tons
Target face to detector center	16 m
Detection efficiency	92%
Vertex resolution	12 cm/$\sqrt{E\ (\mathrm{MeV})}$
Energy resolution	6.4%/$\sqrt{E\ (\mathrm{MeV})}$
Prompt energy threshold	3 MeV
IBD event total	8.2×10^5
$\overline{\nu}_e$-electron event total	7200

20% of Avogadro's number of electron antineutrinos

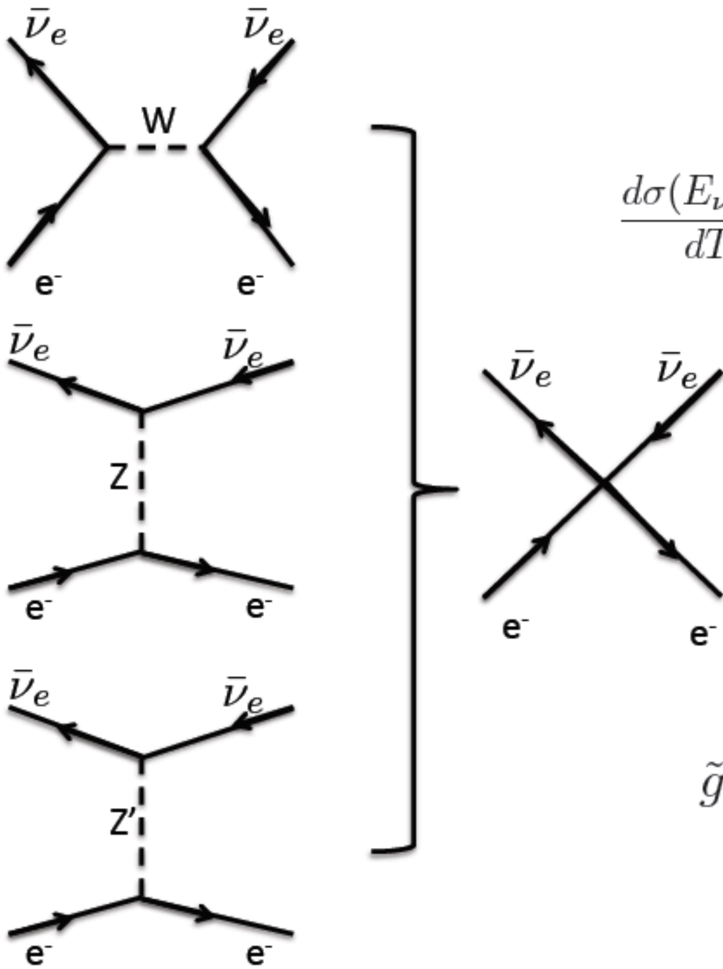
Example 1: IBD sample-- study high Δm^2 anomalies

IsoDAR Combinations with Various Detectors



- IsoDAR @ **Watchman** or **KamLAND**
  - Full coverage of "Global Fit region" and "Reactor Anomaly" for $\Delta m^2 < 10 eV^2$
- IsoDAR @ **JUNO**
  - Full coverage of "Global $\overline{\nu}_e$ Appearance" region

Example 2: $\bar{\nu}_e$ – e sample: search for nonstandard interactions (NSIs)



$$\frac{d\sigma(E_\nu,T)}{dT} = \frac{2G_F^2 m_e}{\pi}[(\tilde{g}_R^2 + \sum_{\alpha\neq e}|\epsilon_{\alpha e}^{eR}|^2) + (\tilde{g}_L^2 + \sum_{\alpha\neq e}|\epsilon_{\alpha e}^{eL}|^2)\left(1 - \frac{T}{E_\nu}\right)^2 - (\tilde{g}_R\tilde{g}_L + \sum_{\alpha\neq e}|\epsilon_{\alpha e}^{eR}||\epsilon_{\alpha e}^{eL}|)m_e\frac{T}{E_\nu^2}]$$

$$\tilde{g}_L = g_L + \epsilon_{ee}^{eL} \qquad \tilde{g}_R = g_R + \epsilon_{ee}^{eR}$$

The heart of the Intensity Frontier Philosophy!

"What makes this program unique?"

IsoDAR

1. Known flux shape since single beta decay (unlike reactors)
2. Higher energy than sources or reactors (endpoint 13 MeV)
   - Well above the 3 MeV environmental backgrounds
   - Very low systematic uncertainties
   - High flux and low systematics allows precision $\bar{\nu}_e$ - e scattering
3. Flexible location
   - Can bring source to detector (unlike reactors)
   - Combined with higher energy gives better L/E coverage
4. Long runs are possible (unlike sources) with no interfacing with company or lab schedules

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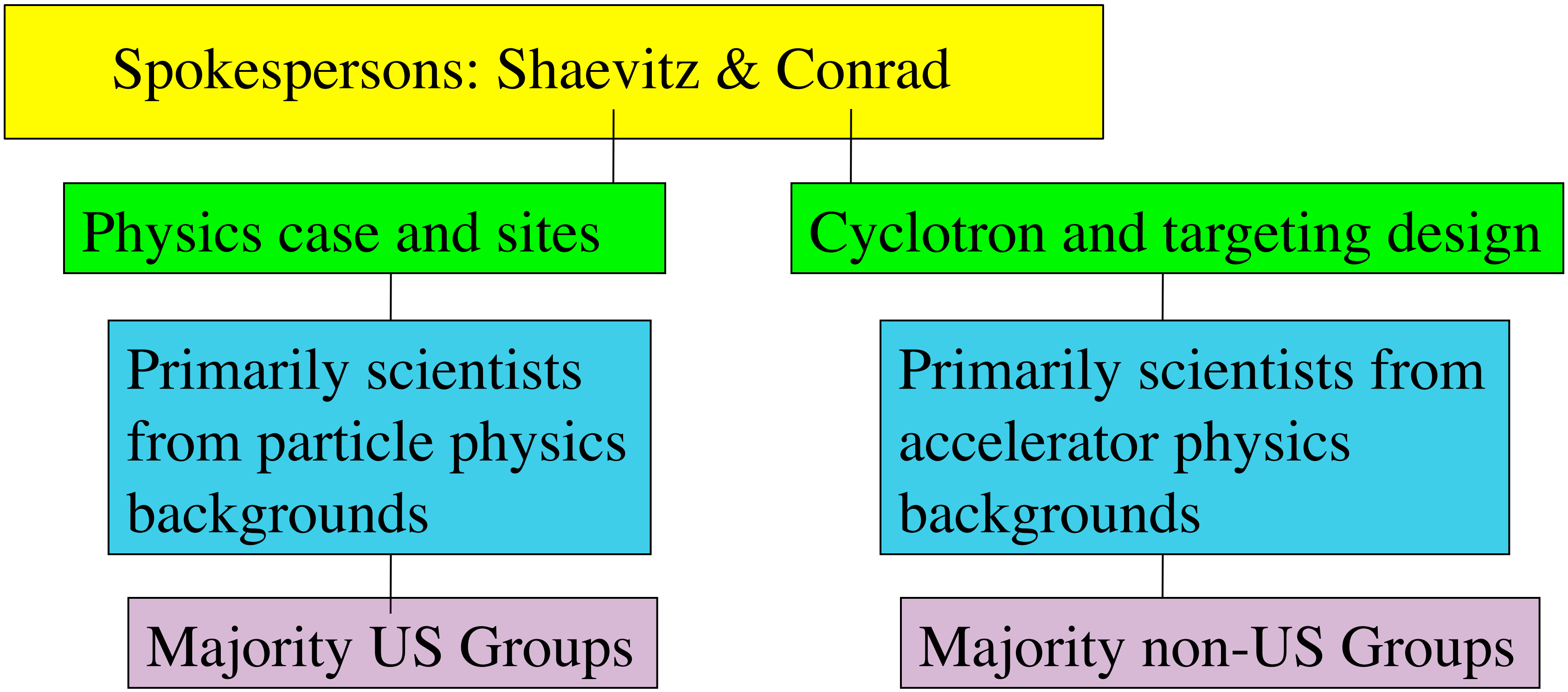
4. The DAEδALUS Source



Both “tracks” report in the same bi-weekly meetings, so there is a lot of exchange between them.

DAEδALUS
Which US Groups Are Involved Now?

Very Active,
Ramping Up,
Low Level,
but interested

Amherst College
Columbia University
Duke University
Lawrence Livermore National Laboratory
Los Alamos National Laboratory
Massachusetts Institute of Technology*
Michigan State University*
New Mexico State University
University of California, Berkeley (Nuclear Engineering)
University of California, Irvine
University of California, Los Angeles
University of Maryland*
University of Tennessee

* group includes experienced accelerator scientists

Very Active
Ramping Up
Low Level,
but interested

DAEδALUS
Which Non-US Groups Are Involved Now?

Generally interested:

The Cockcroft Institute for Accelerator Science & the University of Manchester*
University of Huddersfield*
Imperial College London
LNS-INFN (Catania)*
Paul Scherrer Institut*
RIKEN*
Tohoku University*

* group includes experienced accelerator scientists

Where are the major foreign cyclotron laboratories?

(★ Part of the DAEdALUS group)

INFN – H2+ Cyclotrons (Calabretta)

PSI– Simulations (Adelmann)

RIKEN – SRC design, ES&H in Japan (Okuno)

From Accelerators for America's Future:

"The United States, which has traditionally led the development and application of accelerator technology, now lags behind other nations in many cases, and the gap is growing. To achieve the potential of particle accelerators to address national challenges will require sustained focus on developing transformative technological opportunities...."

This is quite true for cyclotrons!

If Fermilab is serious about being "stewards of accelerator physics," then you ought to be excited about this university based, US program

An important point:
We are discussing machines industry can (and would like) to build.
This affects the practicality & costs!

Very Active
Ramping Up
Low Level, but interested

What Cyclotron Companies are Involved?	Location	Comment
AIMA	European	
Best Cyclotron Systems, Inc.	US & Worldwide	General interest
IBA	US & Worldwide	
Sumitomo Heavy Industries	Japan	Interest is in Japan-based program

So far the role of these companies has been as collaboration members, not as contractors.

Papers on arXiv (not including conference proceedings)

17) Electron Antineutrino Disappearance at KamLAND and JUNO as Decisive Tests of the Short Baseline Antinu-mu to Antinu-e Appearance Anomaly, J.M. Conrad, M.H. Shaevitz, October 2013, arXiv:1310.3857, accepted to PR Brief Reports.

16) Cyclotrons as Drivers for Precision Measurements, A. Adelmann, J. Alonso, W.A. Barletta, J.M. Conrad,M.H. Shaevitz, J. Spitz, M. Toups, L.A. Winslow, July 2013, arXiv:1307.3658, submitted to Advances in High Energy Physics.

15) Precision antielectron neutrino-electron Scattering Measurements with IsoDAR to Search for New Physics, J.M. Conrad, M.H.Shaevitz, I Shimizu, J. Spitz, M. Toups, L.A. Winslow, July 2013, arXiv:1307.5081, submitted to PRD.

14) Whitepaper on the DAEδALUS Program, C. Aberle et al., July 2013, arXiv:1307.2949.

13) Cost-effective Design Options for IsoDAR, A. Adelmann et al., October 2012, arXiv:1210:4454.

12) Beam Dynamics Simulation for the High Intensity DAEδALUS Cyclotrons
J.J. Yang, A. Adelmann, W. Barletta, L. Calabretta, J.M. Conrad , September 2012 arXiv: 1209.5864, published in NIM.

11) Relevance of IsoDAR and DAEδALUS to Medical Radioisotope Production
J. Alonso, September 2012, arXiv:1209.4925.

10) Engineering Study of Sector Magnet for the DAEδALUS Experiment
J. Minervini, M. Cheadle, V. Fishman, C. Miller, A. Radovinsky, B. Smith, September 2012, arXiv: 1209:4886

Papers on arXiv (not including conference proceedings)

9) Modelling challenges of the high power cyclotrons for the DAEδALUS project, A. Adelmann, August 2012, arXiv:1208.6587

8) Multimegawatt DAEδALUS Cyclotrons for Neutrino Physics, M. Abs et al., July 2012, arXiv:1207.4895

7) An Electron Antineutrino Disappearance Search Using High-Rate 8Li Production and Decay A. Bungau et al., May 2012, arXiv:1205.4419, published in PRL, chosen as a highlight.

6) Measuring Active-to-Sterile Neutrino Oscillations with Neutral Current Coherent Neutrino-Nucleus Scattering A.J. Anderson et al. Jan 2012 arXiv:1201.3805, published in PRD.

5) Short-Baseline Neutrino Oscillation Waves in Ultra-Large Liquid Scintillator Detectors Sanjib Kumar Agarwalla, J.M. Conrad, M.H. Shaevitz, May 2011, arXiv:1105.4984, published in JHEP

4) Coherent Neutrino Scattering in Dark Matter Detectors, A. J. Anderson et al. March 2011, Sept 2011, arXiv:1103.4894, published in PRD.

3) A Study of Detector Configurations for the DUSEL CP Violation Searches Combining LBNE and DAEdALUS, The DAEδALUS Collaboration, Aug 2010, arXiv:1008.4967.

2) Expression of Interest for a Novel Search for CP Violation in the Neutrino Sector: DAEdALUS J. Alonso et al. , June 2010, arXiv:1006.0260.

1) A New Method to Search for CP violation in the Neutrino Sector also called Multiple Cyclotron Method to Search for CP Violation in the Neutrino Sector, J.M. Conrad, M.H. Shaevitz Dec 2009 arXiv:0912.4079, published in PRL

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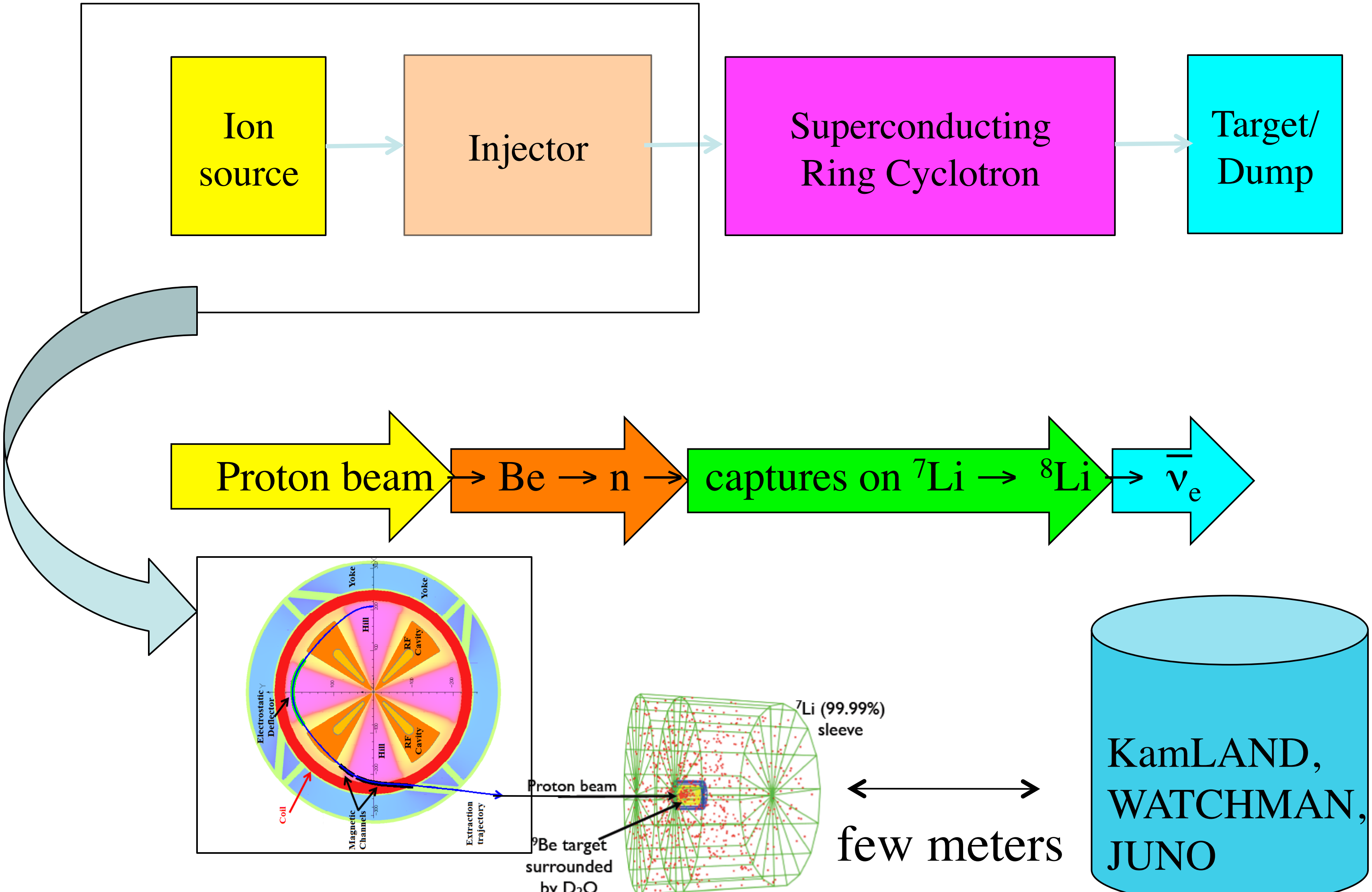
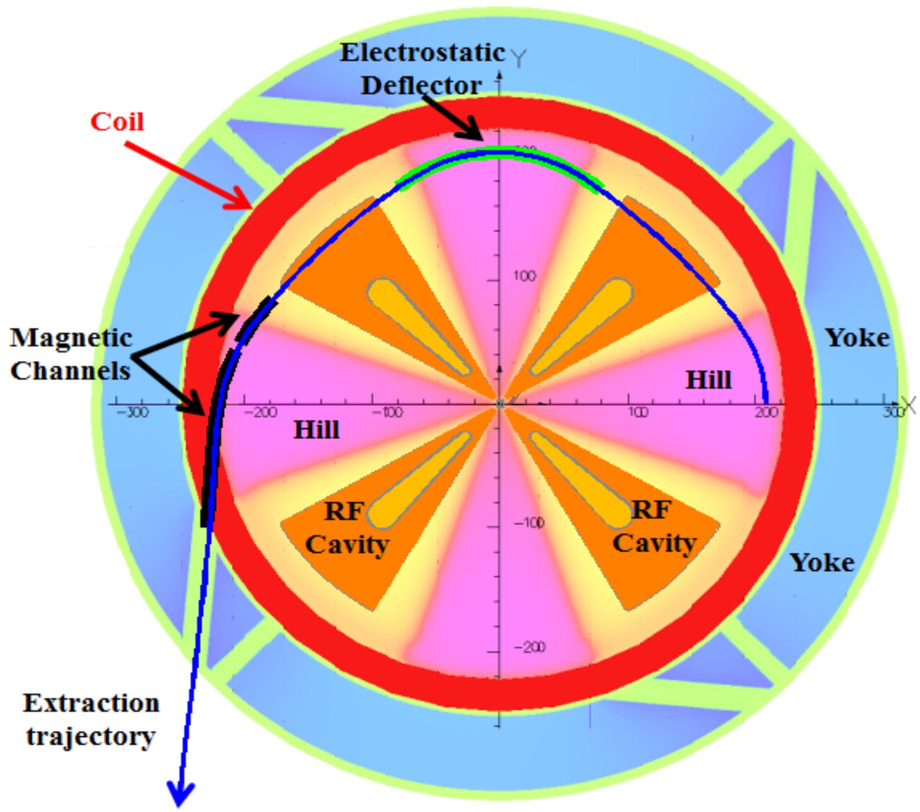
IsoDAR: A physics program that facilitates DAEδALUS development



The cyclotron driver…



5 mA of H2+…
x10 total protons
of "on-market" machines
(x5 the electrical current)

E_{max}	60 MeV/amu
E_{inj}	35 keV/amu
R_{ext}	1.99 m
R_{inj}	55 mm
$< B >$ @ R_{ext}	1.16 T
$< B >$ @ R_{inj}	0.97 T
Sectors	4
Hill width	28 - 40 deg
Valley gap	1800 mm
Pole gap	100 mm
Outer Diameter	6.2 m
Full height	2.7 m
Cavities	4
Cavity type	$\lambda/2$, double gap
Harmonic	4th
rf frequency	32.8 MHz
Acc. Voltage	70 - 240 kV
Power/cavity	310 kW
ΔE/turn	1.3 MeV
Turns	95
ΔR /turn @ R_{ext}	> 14 mm
ΔR/turn @ R_{inj}	> 56 mm
Coil size	200x250 mm^2
Current density	3.1 A/mm^2
Iron weight	450 tons
Vacuum	$< 10^{-7}$ mbar

Cost-effective Design Options for IsoDAR

arxiv: 1210.4454

Are cyclotrons Really the best Option for Isotope Decay-at-Rest?

Assessment

- Good (green)
- Moderate (yellow)
- Bad (red)

	60 MeV Compact Cyclotron	RFQ/Separated Sector Cyclotron	LINAC, 30 MeV, 40 mA	Modified Beta Beam Design	New Detector at Existing Beam
1. Cost	Good	Moderate	Bad	Moderate	Bad
2. $\bar{\nu}_e$ rate	Good	Good	Good	Bad	Good
3. Backgrounds low	Good	Good	Good	Good	Moderate
4. Technical risk	Moderate	Moderate	Moderate	Moderate	Good
5. Compactness	Good	Moderate	Bad	Good	Moderate
6. Simplicity u'ground	Good	Moderate	Moderate	Bad	Moderate
7. Reliability	Good	Good	Good	Bad	Good
8. Value to other exps	Good	Good	Good	Bad	Bad
9. Value to Industry	Good	Moderate	Moderate	Bad	Bad

Since writing the "cost-effectiveness" article:

Question: *Should the IsoDAR cyclotron run deuterons instead?*

Pros:

- This does not change the central region design (same q/m)
- But the ion sources are well proven
- The magnet can be smaller – same flux for 40 MeV/n beam
  smaller radius = easier to install and less expensive.
- The 7Li sleeve can be smaller.

Con:

- Deuterons cause significant activation – machine & line, so there will be
  added cost and challenge in shielding & maintenance
- Less data to benchmark 8Li production expectations

Our group is continuing to investigate this, but H2+ is favored

IsoDAR Compared to Existing Similar Cyclotrons

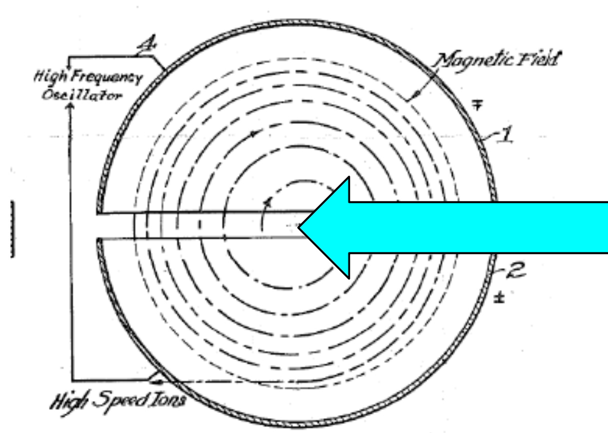
We claim we will be able to produce
~10 mA of protons @ 60 MeV
when commercial machines (IBA, Best) produce
~1 mA of protons @ 70 MeV

How do we achieve this?

Rather than one single order-of-magnitude improvement, there are four related issues to solve…

1. Space charge
2. Intensity of ion source
3. Inflection
4. Protection of the electrostatic septum

1) Accelerate more particles for same level of space charge effects



Present machines inject p or H^-

We inject H_2^+

A measure of the strength of space charge Is the generalized perveance:

$$K = \frac{qI}{2\pi\varepsilon_0 m\gamma^3\beta^3}$$

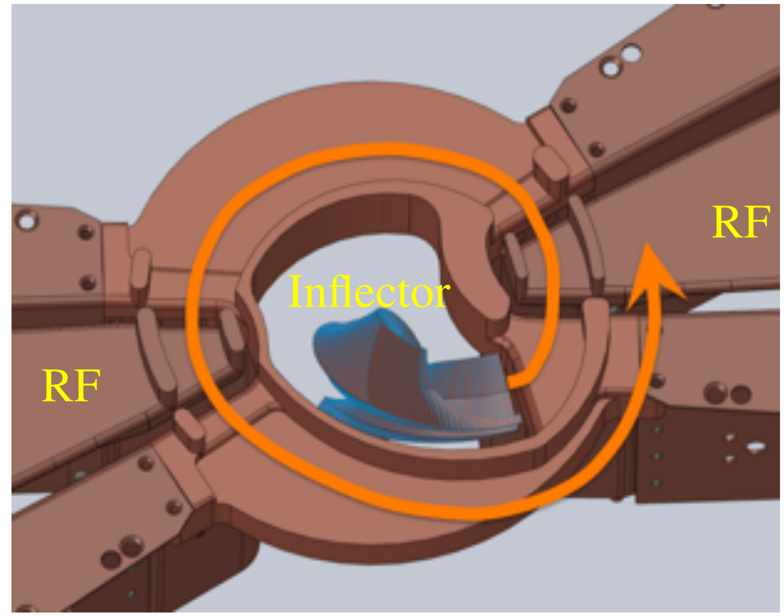
Comparing perveance at injection:

5 mA, 35 keV/n of H2+ = 2 mA, 30 keV of p (already achieved in commercial cyclotrons)

2) Push the envelope of H_2^+ intensities from ion sources

Most ions are lost in the first "turn"

To capture 5 mA we will need between 35 and 50 mA injected, depending on the efficiency for bunching, inflection & RF.



This is not unusual for a p source, but is high for an H_2^+ source. This is at the edge of what has been done…

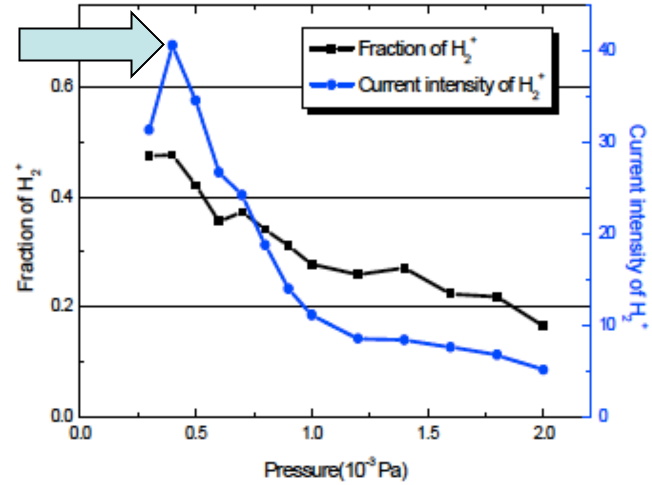
~40 mA ion source examples… (and there are more)

Proceedings of IPAC2013, Shanghai, China MOPFI035

PRELIMINARY RESULTS OF H_2^+ BEAM GENERATED BY A 2.45 GHZ PERMANENT MAGNET ECR ION SOURCE AT PKU*

Yuan Xu, Shixiang Peng#, Haitao Ren, Jie Zhao, Jia Chen, Tao Zhang, Ziheng Wang, Yuting Luo, Zhiyu Guo and Jiaer Chen, SKLNPT & IHIP, School of Physics, Peking University, Beijing 100871, China
Ailin Zhang, School of Physics, UCAS, Beijing 100049, China

Can run 50 mA but is pulsed, not CW.
Interesting because design is similar to VIS source we have been using in our teststand.



Testing of a H_2^+-enriched ion source for deuterium simulation

M. D. Williams and K. N. Leung
Lawrence Berkeley Laboratory, Berkeley, California 94720
G. M. Brennen and D. R. Burns
McDonnell Douglas Astronautics Co., St. Louis, Missouri 63166

(Presented on 12 July 1989)

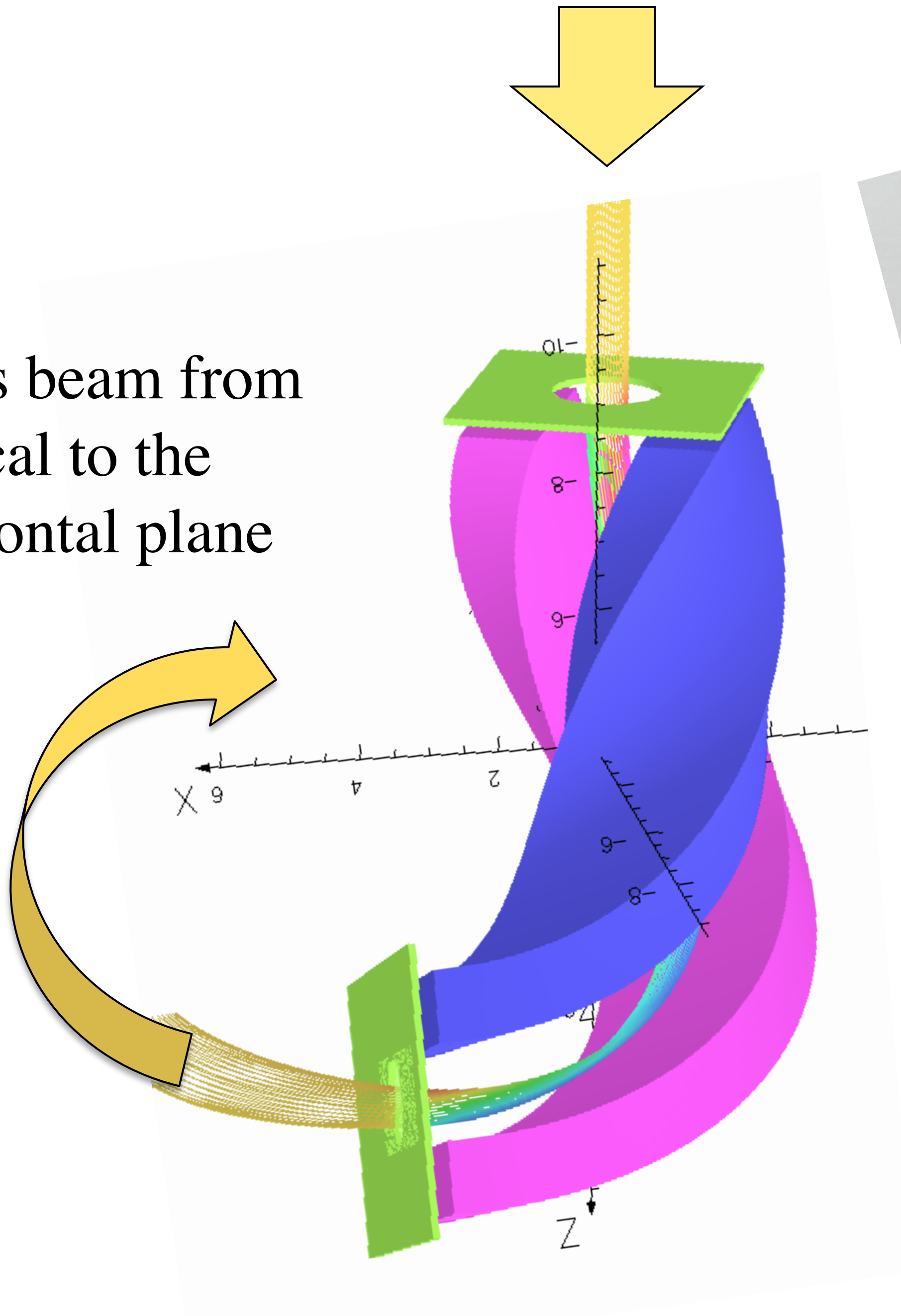
We have tested a McDonnell Douglas short milticusp plasma generator, designed to generate a positive hydrogen ion beam which is enriched with H_2^+ ions. Initial testing shows that the prototype source is capable of producing a positive hydrogen ion beam with H_2^+ percentage greater than 85%. The total ion-current density was 56 mA/cm^2. For a higher current density of 110 mA/cm^2, the percentage of H_2^+ ions is approximately 73% as measured by a magnetic deflection spectrometer. A comparison between tungsten and lanthanum hexaboride cathodes shows that tungsten filaments can provide better performance.

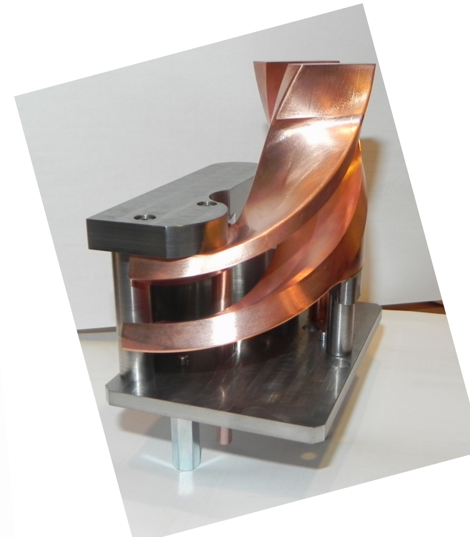
An interesting question for the ion source community!

3) Develop an unusually large spiral inflector (H_2^+ rigidity)

The beam enters axially, through a conducting "spiral inflector"

Takes beam from vertical to the horizontal plane



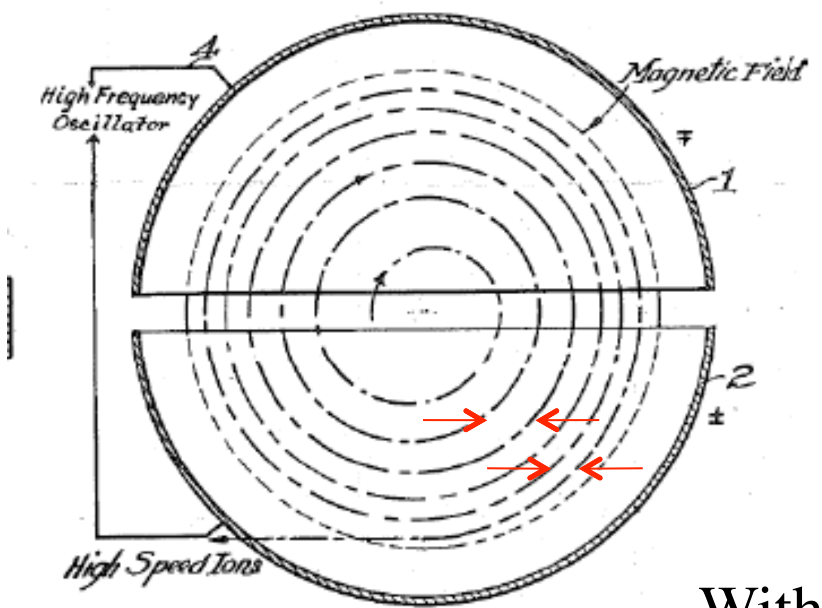


Tricky to design:

- B field effects
- neutralization

designed by MIT Postdoc Daniela Campo

This is an iterative R&D process

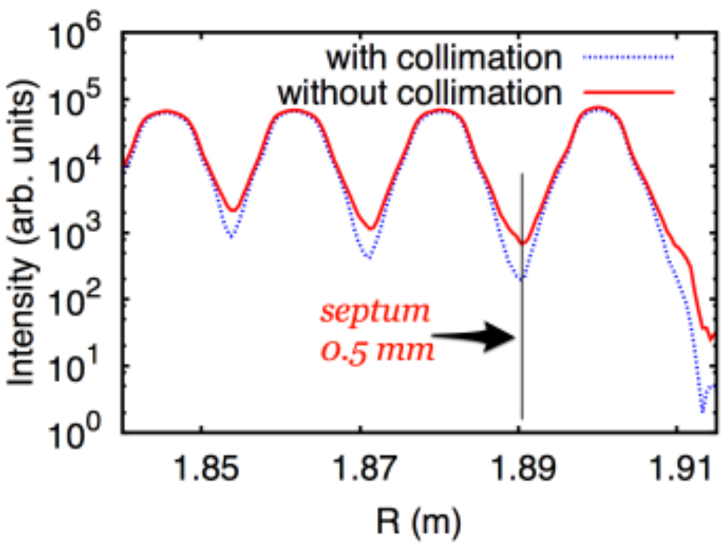


4) Avoid beam losses on the electrostatic extraction septum (protecting with a stripper foil, removing 5 μA of beam)

Without the foil:

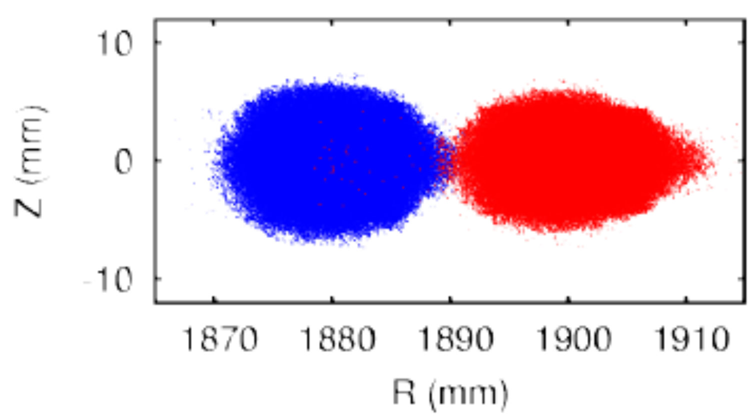
In the final four turns…

Intensity vs. position

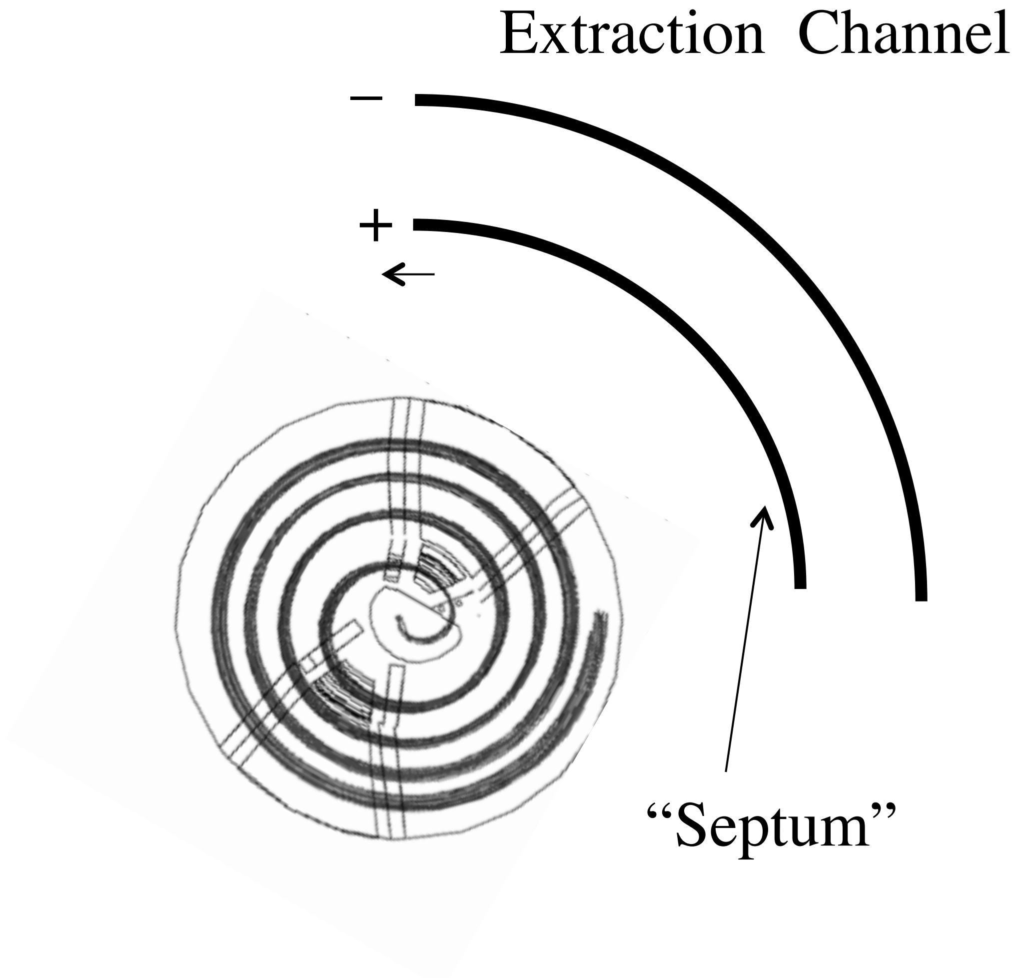


In the final two turns…

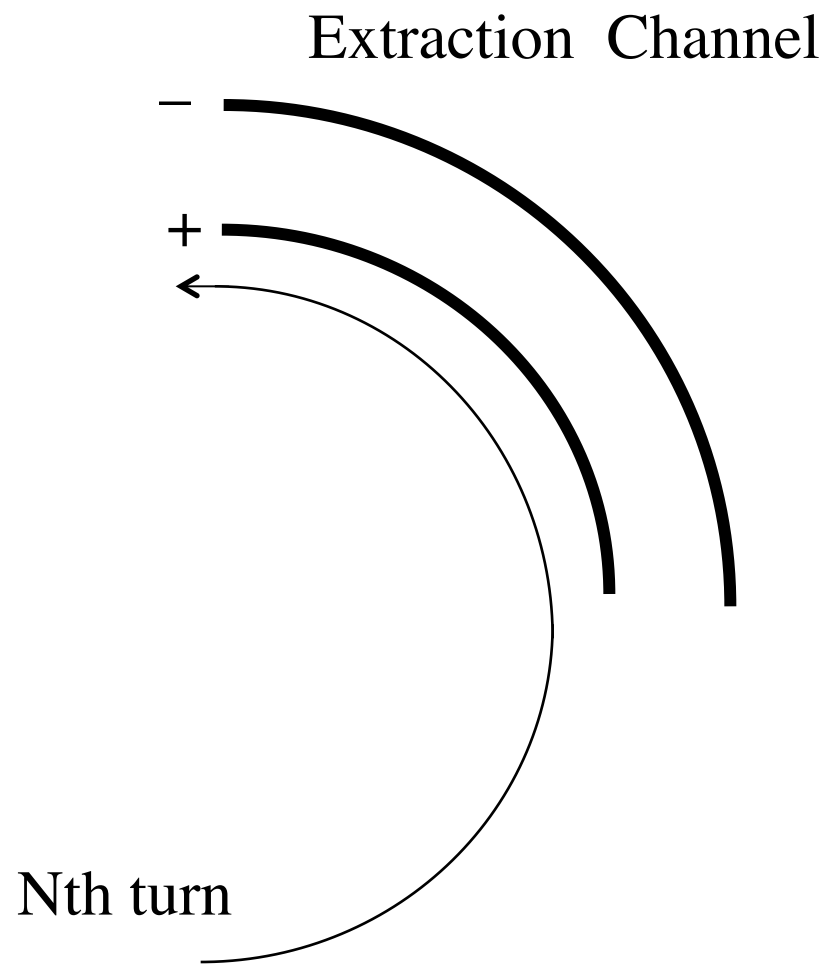
Beam spot vs. position



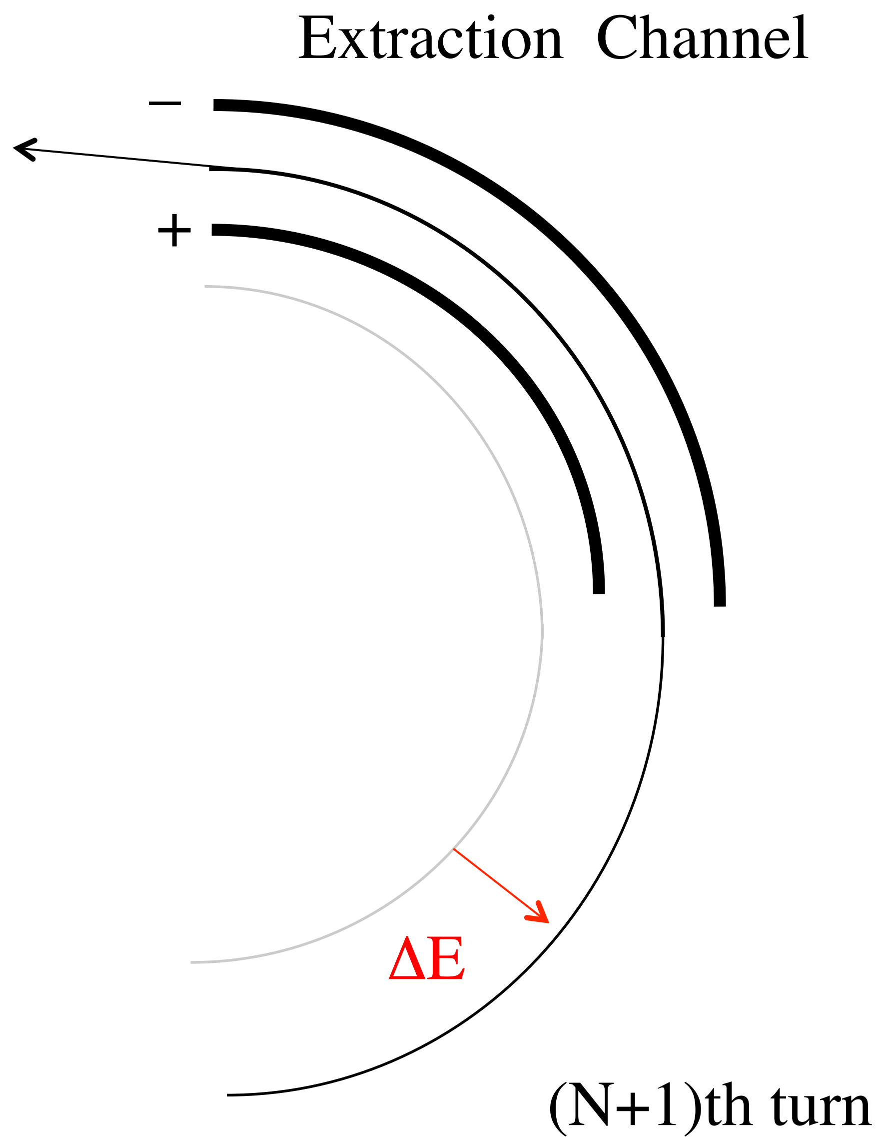
Extraction Process



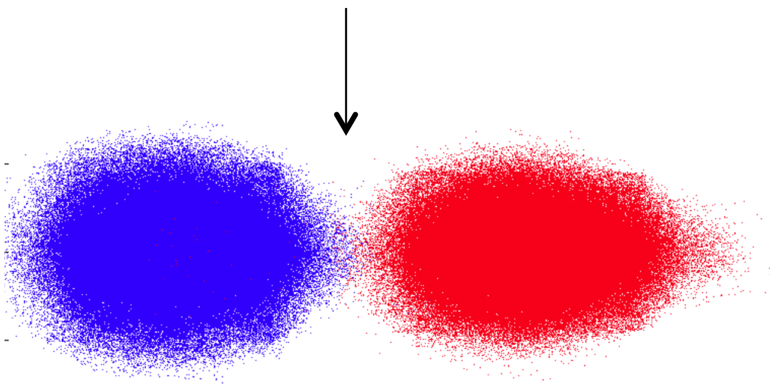
Extraction Process



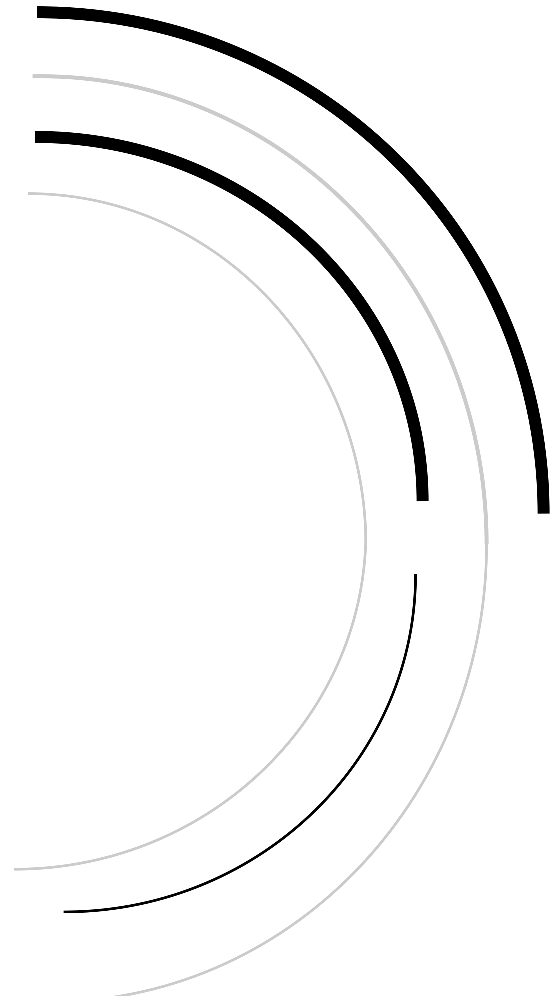
Extraction Process



Extraction Process



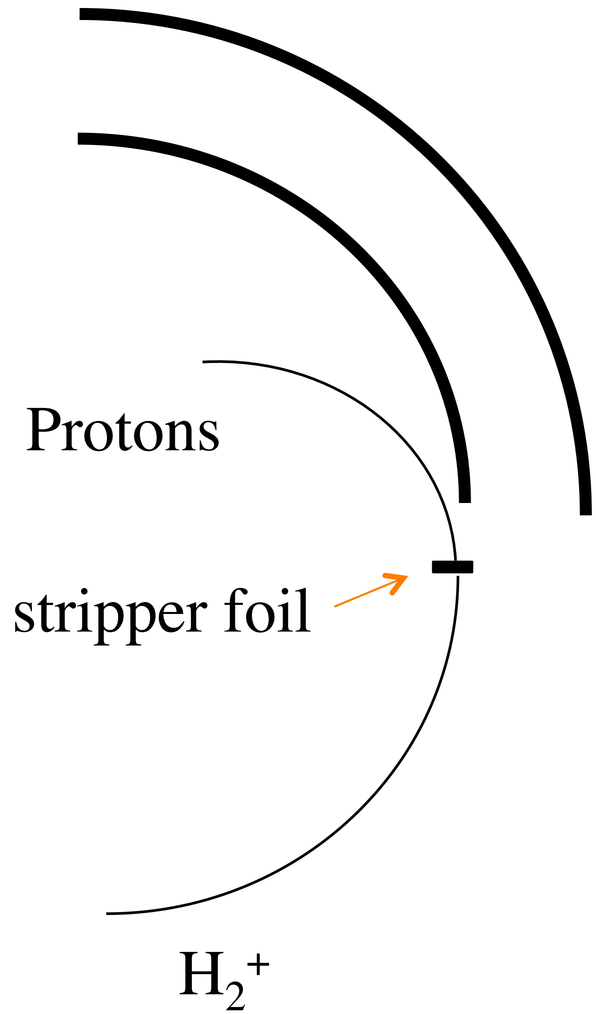
~.02% intercepted
on septum



"Problem"
(120 W max)

Extraction Process

Notice protons
cross the
cyclotron
to exit!
That's ok!



Progress on the 4 problems…

1. Space charge

From OPAL simulations: http://arxiv.org/abs/arXiv:1209.5864,

"Large-scale particle simulations show that the injector cyclotron is a space charge dominated cyclotron and that a 5mA beam current can be extracted with tolerable beam losses on the septum."

BUT – this has an assumption for the inflected beam.

We are replacing this with inflected beam matching measurements point 3

2. Intensity of ion source

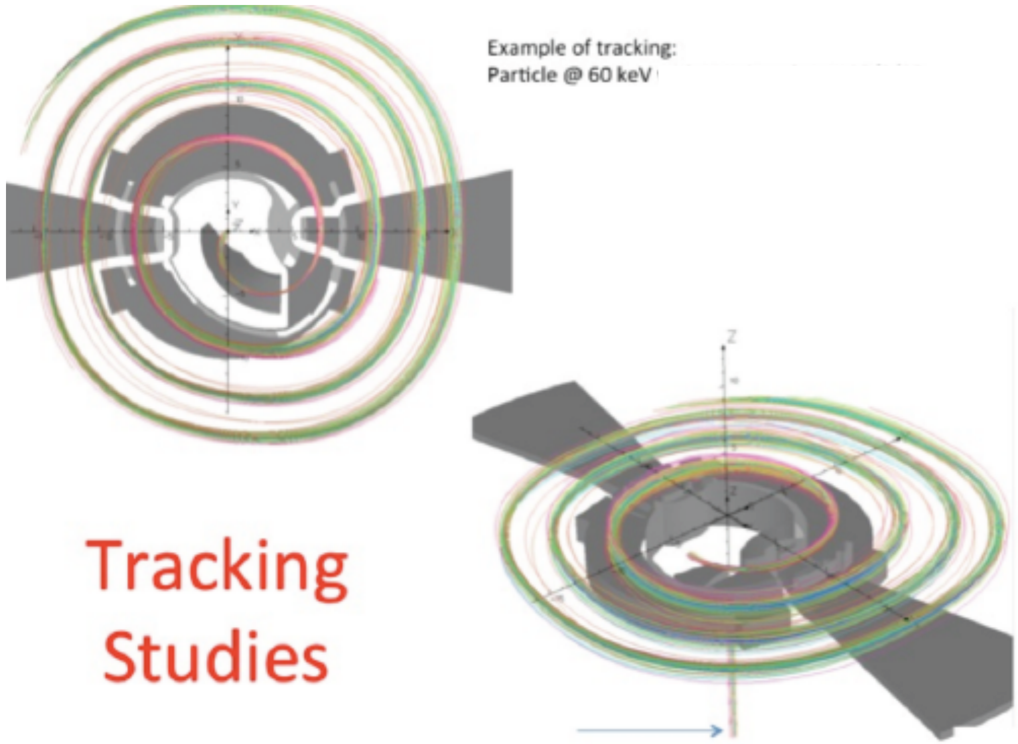
Working with ion source experts. Regarded as solvable.

3. Inflection

Performing Experiments – Next few slides on R&D program

4. Protection of the electrostatic septum

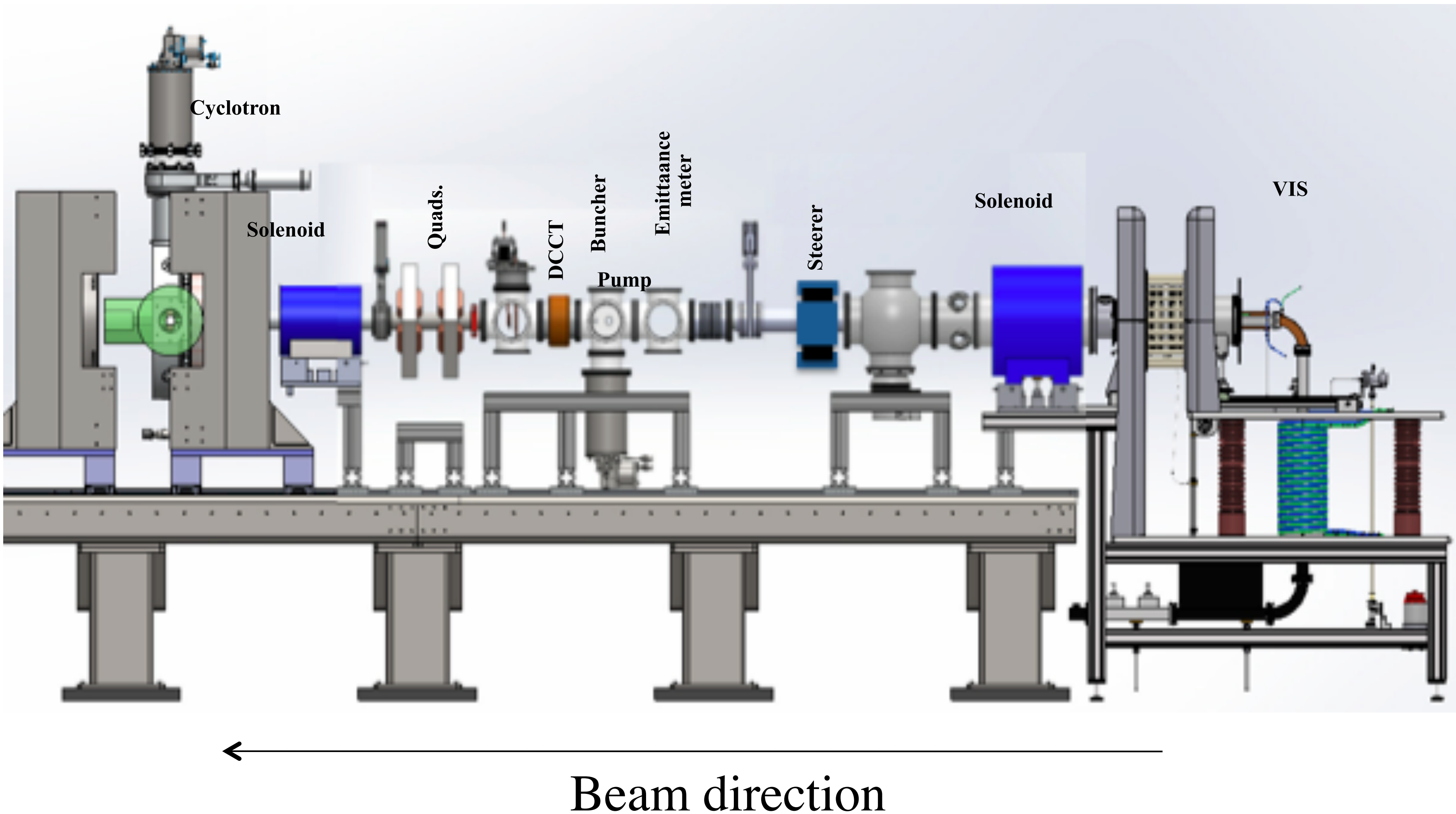
Now completing OPAL simulations to demonstrate this



Main R&D question: How much beam can we accelerate?
and what is its quality?

- A simulations question –
  - INFN-Catania – single particle simulation
  - MIT & PSI – including space charge
- And an experimental question…

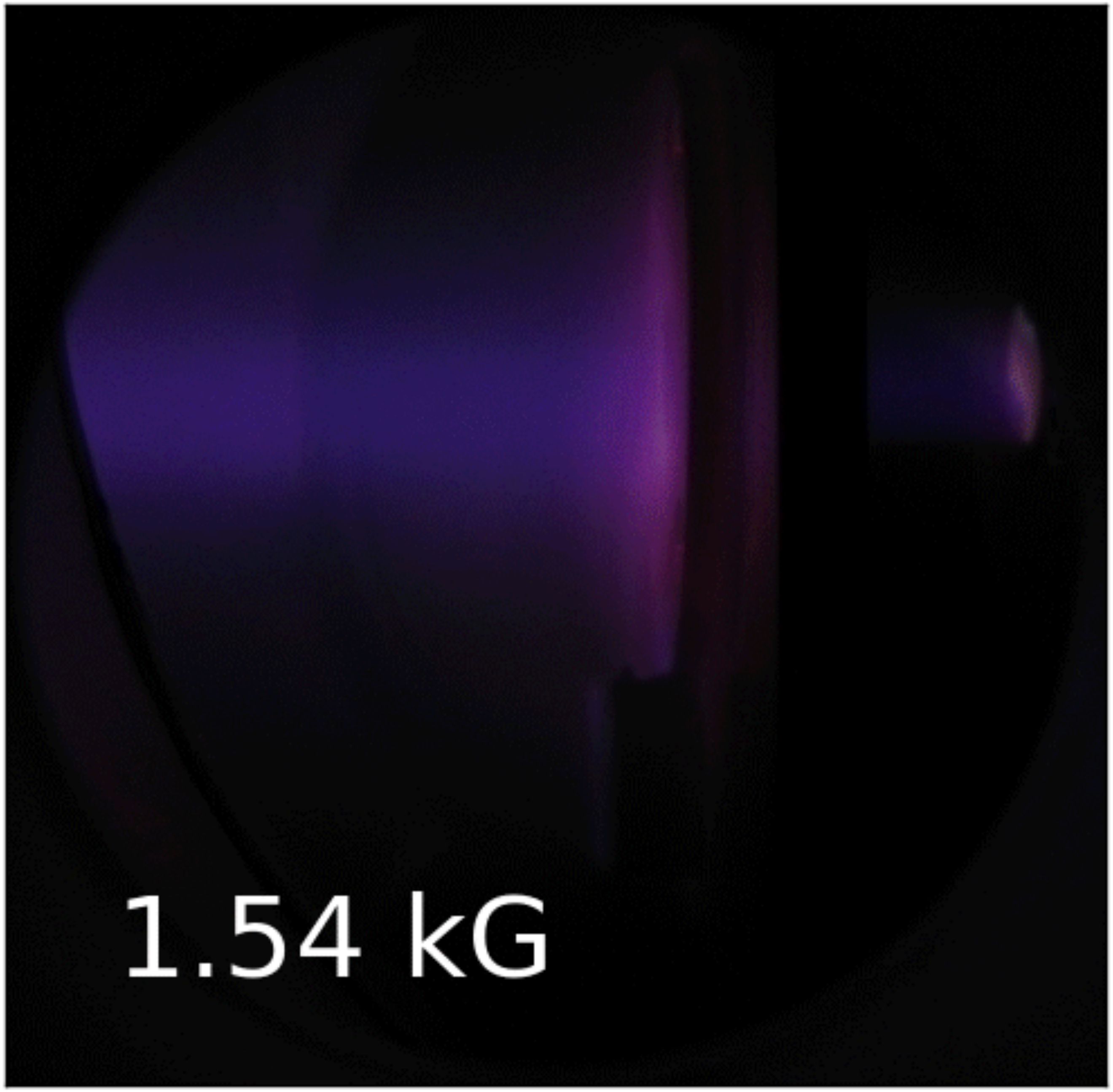
Beam to now being characterized at Best Cyclotrons, Inc, Vancouver (Best Cyclotron Systems, INFN-Catania, and MIT -- NSF funded)



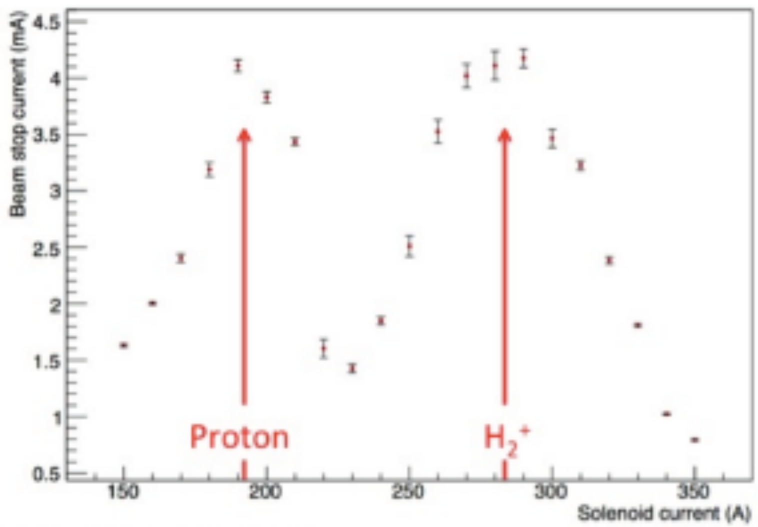
Just finished Part I of run

Commissioning, characterizing the ion source and beam

The source has 2 principle components:
Protons, H2+



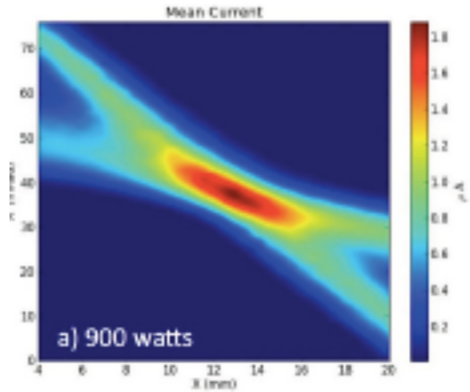
Beam Stop (mA) vs Solenoid (A)



600 watts Microwave power
40 kV extraction potential

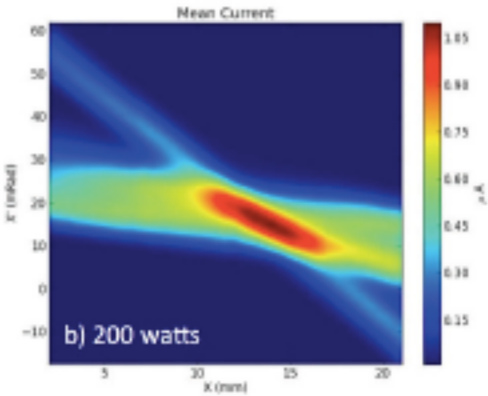
Emittance Plots

$\varepsilon_{norm} \approx 0.4\,\pi$ mm-mrad



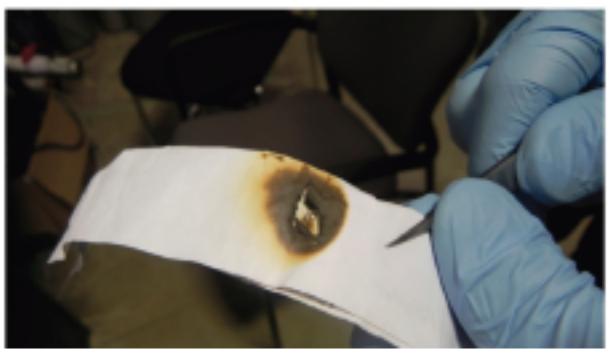
Note total current scale change

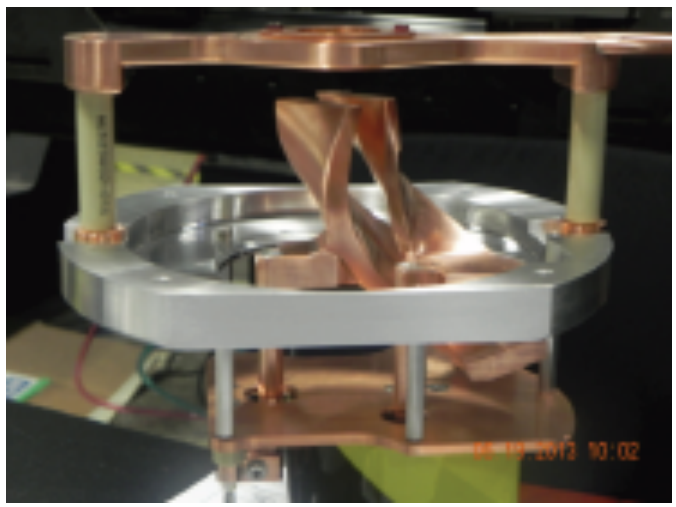
Solenoid current: 270 A (2.1 kG)

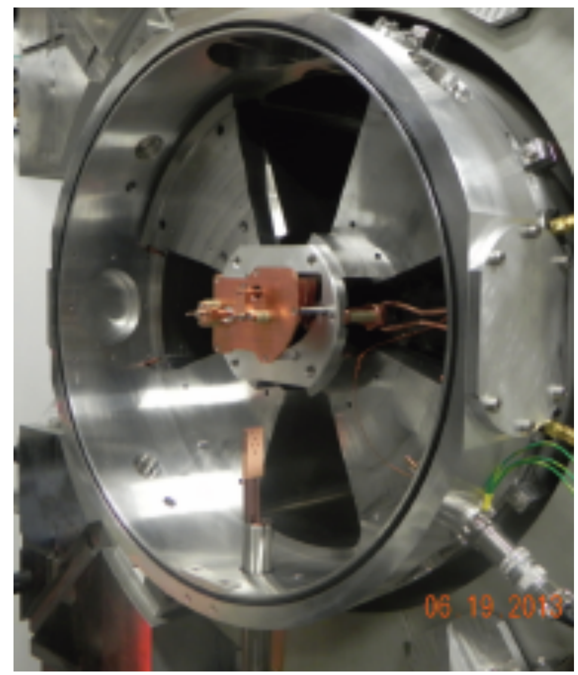


Note proton ellipse weaker

First Beam in Cyclotron!







Ready to go for Run II, starting in Feb.

Our next steps after completion of Best Teststand studies:

1) Bring the upstream line to 35 to 50 mA
2) Iterate on the spiral inflector
3) Capture and accelerate up to 7 MeV

→ Cannot run at 7 MeV at the Vancouver site so studies will move to Catania, Italy

Scientific Goals: Demonstrate high intensity injection.

Practical goal: Produce equipment that can move directly to the first IsoDAR program

* The "front end"
* The inflector
* Diagnostic equipment

Agreement signed yesterday!

Remainder of equipment will be paid for & owned by Best, which will refit front end for alphas, and produce isotopes.

COST / BENEFIT COMPARISON

FOR

45 MEV AND 70 MEV CYCLOTRONS

MAY 26, 2005

Conducted for:

U.S. Department of Energy
Office of Nuclear Energy, Science, and Technology
Office of Nuclear Facilities Management
19901 Germantown Road
Germantown, MD 20874

Conducted b

JUP
Technical, Security, and

Suite 900, Westfi
2730 University B
Wheaton, MD 20

Costs: <u>Working with companies on estimate.</u>
But can scale from a DOE-sponsored study on a 2 mA, 70 MeV proton machine.

EXECUTIVE SUMMARY

A cost/benefit study was conducted by *JUPITER* Corporation to compare acquisition and operating costs for a 45 MeV and 70 MeV negative ion cyclotron to be used by the Department of Energy in the production of medical radioisotopes. The study utilized available information from Brookhaven National Laboratory (BNL) in New York and from the University of Nantes in France, since both organizations have proposed the acquisition of a 70 MeV cyclotron. Cost information obtained from a vendor, Advanced Cyclotron Systems, pertained only to their 30 MeV cyclotron. However, scaling factors were developed to enable a conversion of this information for generation of costs for the higher energy accelerators.

Two credible cyclotron vendors (IBA Technology Group in Belgium and Advanced Cyclotron Systems, Inc. In Canada) were identified that have both the interest and capability to produce a 45 MeV or 70 MeV cyclotron operating at a beam current of 2 mA (milliamperes).

The results of our analysis of design costs, cyclotron fabrication costs, and beamline costs (excluding building construction costs) resulted in total acquisition costs of:

- $14.8M for the 45 MeV cyclotron, and
- $17.0M for the 70 MeV cyclotron.

Annual operating cost estimates for a 70 MeV cyclotron ranged between $1.9M and $1.1M; the large uncertainty is due to the lack of specificity in available data in comparing costs from BNL and the University of Nantes.

Overall power requirements (exclusive of facility heating and air conditioning) were estimated to be:

- 560 kW for the 45 MeV cyclotron, and
- 831 kW for the 70 MeV cyclotron.

Operational lifetime is expected to be in excess of 30 years for the main components of the accelerator.

Considerable scientific and economic benefits are gained in using the 70 MeV cyclotron compared to use of the 45 MeV cyclotron in terms of the variety and quantity of isotopes that can be produced. Selected examples of benefits in isotope production are discussed.

This is a simpler machine. Ours will cost more because machine is larger.

An important point…

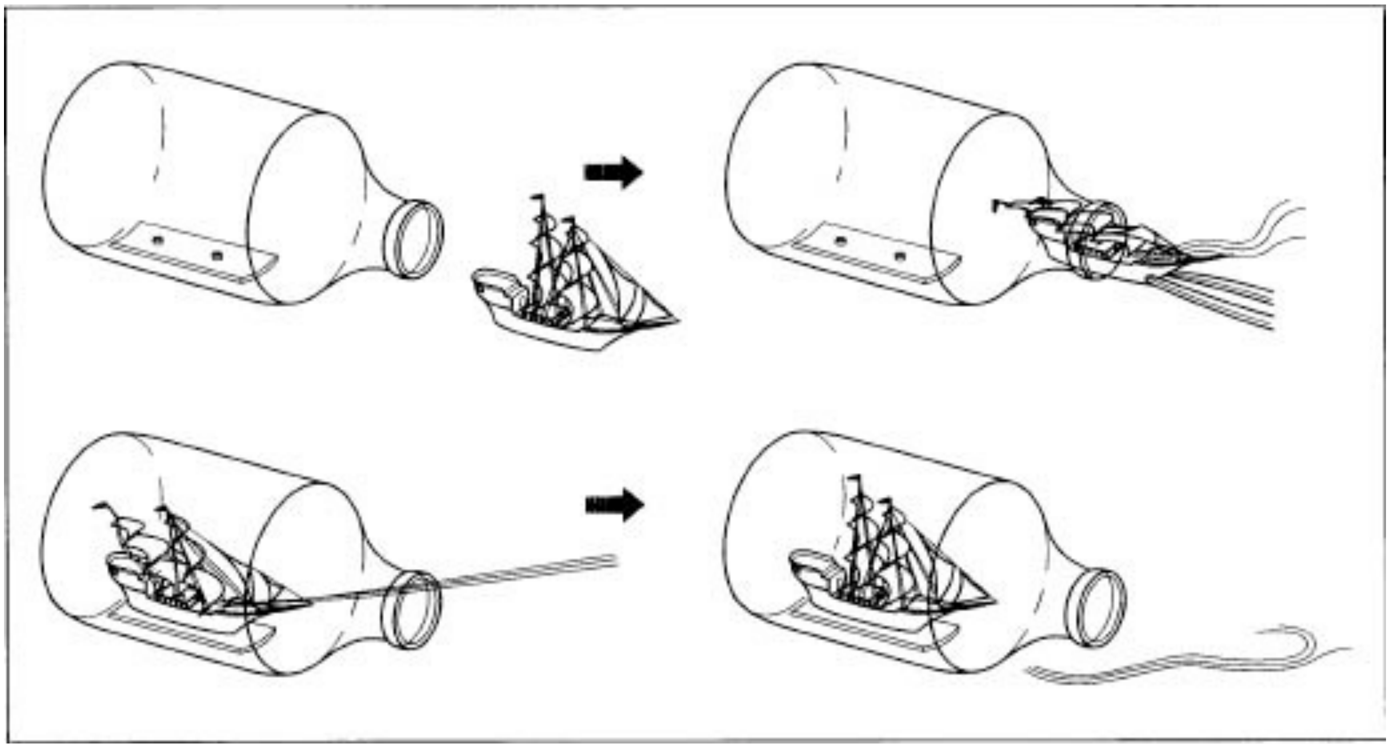
$17M = DOE estimate is for a 2 mA, 70 MeV cyclotron,
installed by industry.

24M CHF = cost of PSI Injector II, 2.5 mA, 72 MeV
not including beamlines.

The cost of cyclotrons has gone down significantly with time, because these are industrial products.

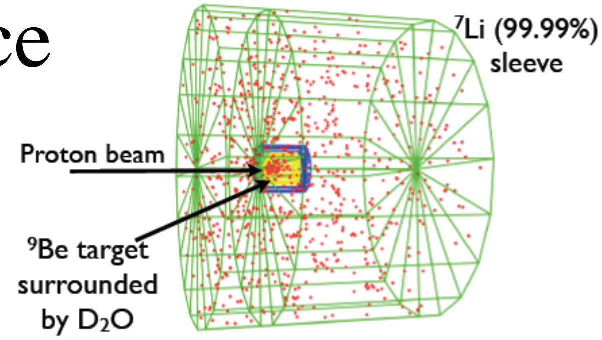
Our estimate based on scaling is ~$25-30M for the cyclotron
But what we really want is funding
to do an engineering-based estimate of our machine.

A major difference between IsoDAR and existing machines: the proposed underground installation!



1. Space for installation/layout of power supplies/etc
2. Distance from accelerator to source
3. Shielding issues in a mine

Challenges of the neutrino source



The sleeve -- Use 7Li or FLiBe?

…Under study!

FLiBe = LiF + BeF2 in a 2:1 mixture

(50 kg 99.99% pure are at MIT reactor for study now)

Simulations say you need about 3 tons.

Molten Salt Reactors use 10's of tons of FLiBe:

Higher Purity

100 m^3 of flibe will contain about 30 tonnes of 99.995% ^{7}Li with previous cost estimates being from 120 to 800 $/kg. Even several

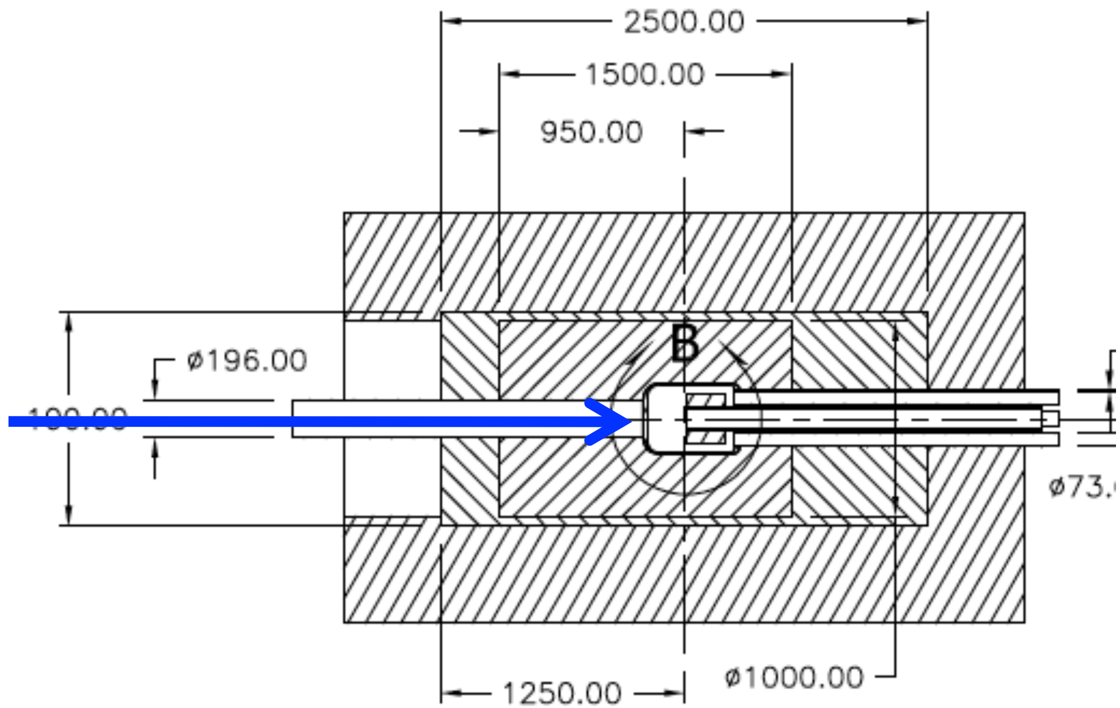
Nuclear Engineering and Design
Volume 240, Issue 6, June 2010, Pages 1644–1656

Molten salt reactors: A new beginning for an old idea

David LeBlanc[a,b,*]

Needs more study.

Target design concept (Bartoszek Engineering):
Embedded in the sleeve,
Beam can be painted across the initial Be target -- 2 cm
Bragg peak is in cooling water
(600 kW -- painted to become 2 kW/cm^2)



Downstream Be target for neutrons enhances rate considerably

Need a very simple system for target removal,
as this must be performed in a mine.

Other R&D:

Activation studies -- Activate rock from Kamioka site
at MIT reactor.
Track radioactive decay with time.
Necessary to specify shielding.

Comparing to PHITs (Japanese (RIKEN) choice
-- equivalent to FNAL's use
of MARS)

Technically-driven schedule

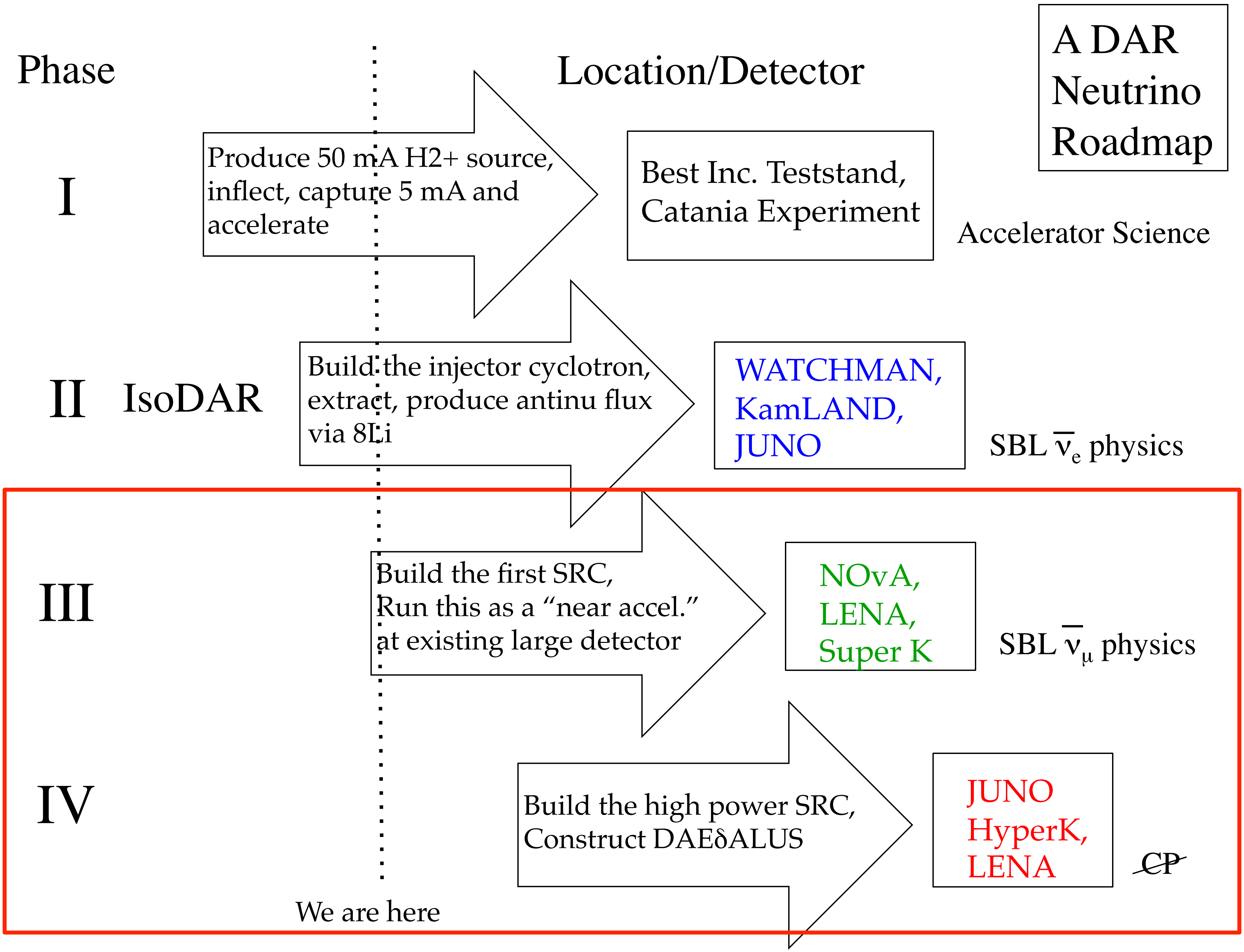
If, by summer 2015:

The R&D at the Catania site is fully successful,
We understand all siting/activation issues
We have been funded to complete the BDR

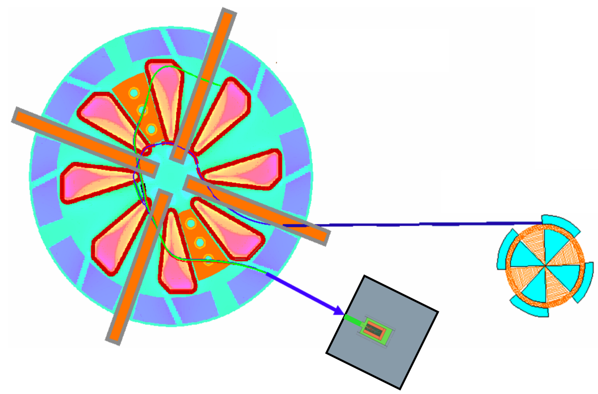
And we have funding in hand to engineer and build…

Then we can be commissioning and running
IsoDAR in 2018

1. ν Physics Context
2. The Collaboration
3. The IsoDAR Source
4. The DAEδALUS Source

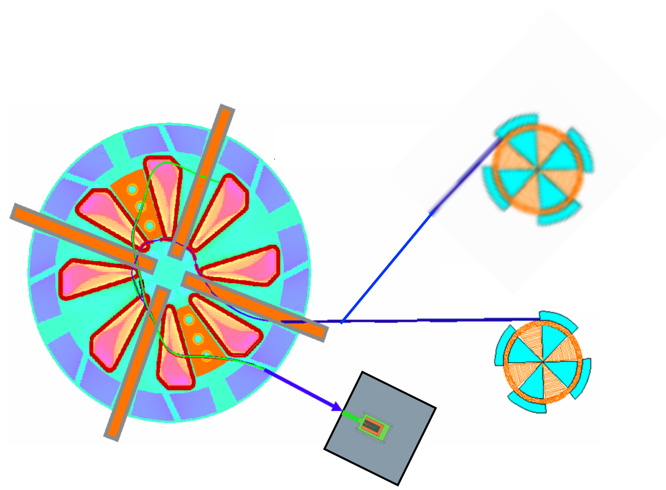

A DAR Neutrino Roadmap
Phase
Location/Detector
I
Produce 50 mA H2+ source, inflect, capture 5 mA and accelerate
Best Inc. Teststand, Catania Experiment
Accelerator Science
II IsoDAR
Build the injector cyclotron, extract, produce antinu flux via 8Li
WATCHMAN, KamLAND, JUNO
SBL $\bar{\nu}_e$ physics
III
Build the first SRC, Run this as a "near accel." at existing large detector
NOvA, LENA, Super K
SBL $\bar{\nu}_\mu$ physics
IV
Build the high power SRC, Construct DAEδALUS
JUNO HyperK, LENA
CP
We are here

Developing two systems for the CP experiment…



The "standard" system

For positioning near a big underground detector

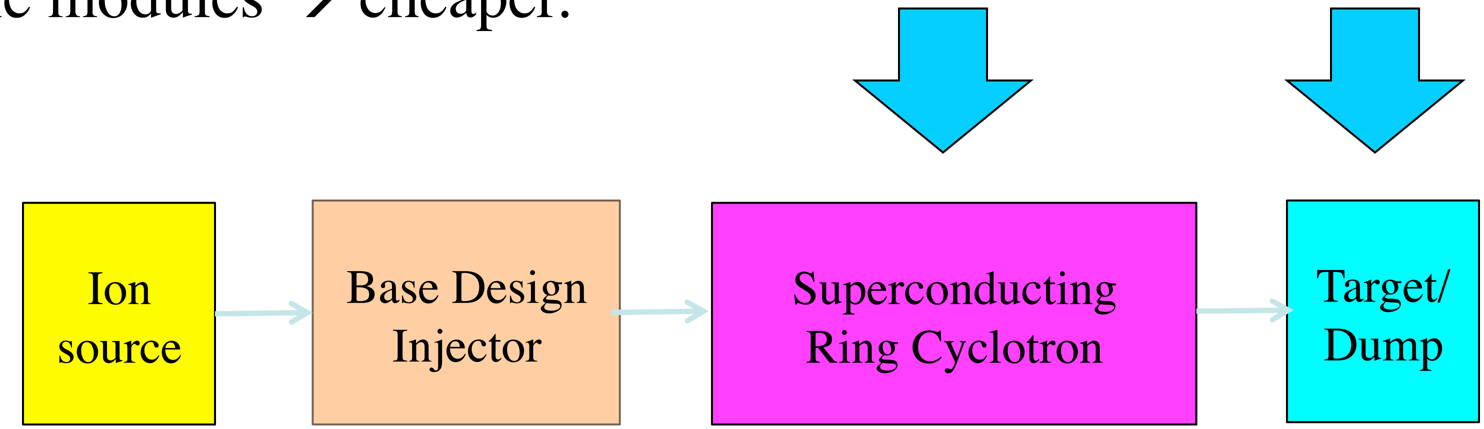


And then a high-power system

For positioning as much as 20 km away from the detector

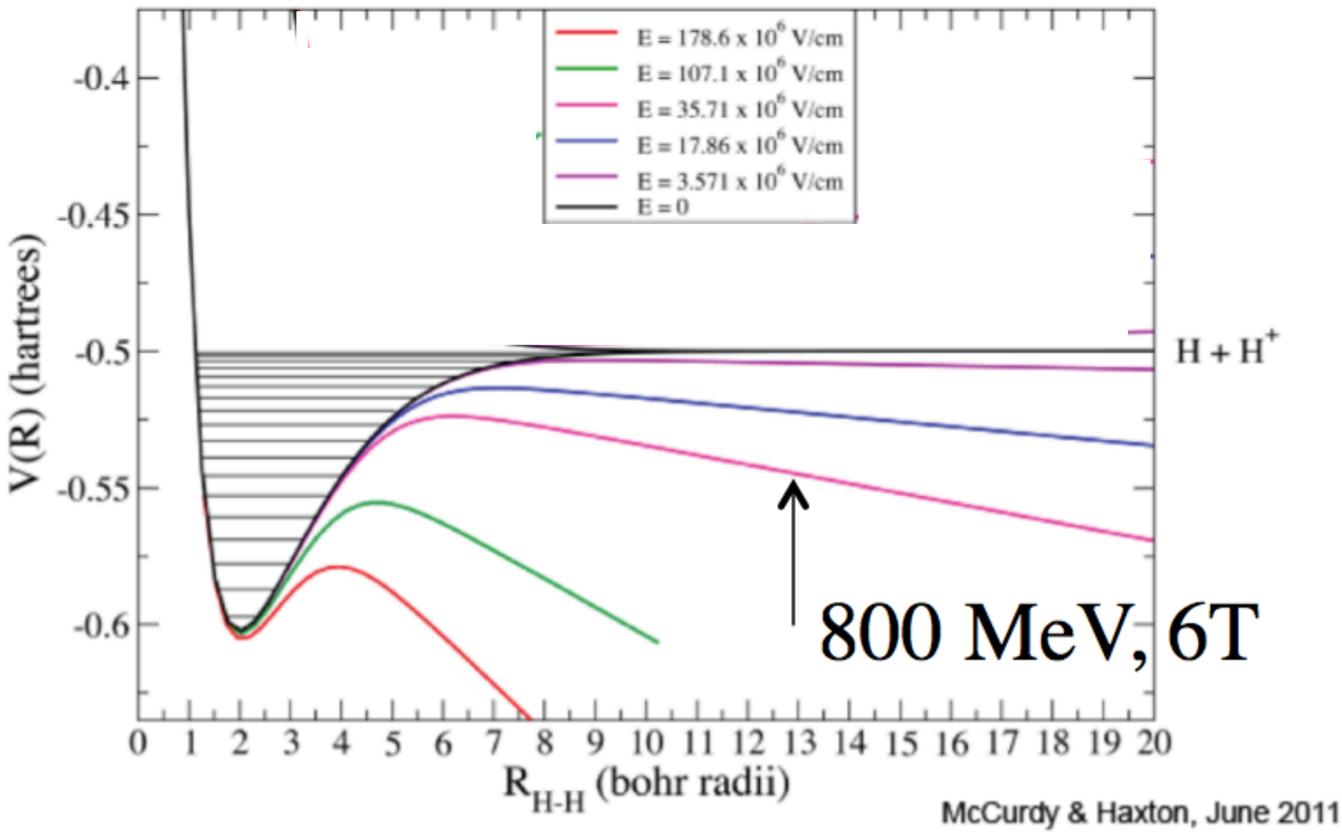
New in Phases III and IV

multiple modules → cheaper.



For the most part,
the same design as for IsoDAR,
but with an important new
ion-related issue…

Important question for the beam in the 800 MeV SRC (not IsoDAR): Lorentz stripping of the H2+ ions?



Should be OK as long as high vibrational states are eliminated before acceleration

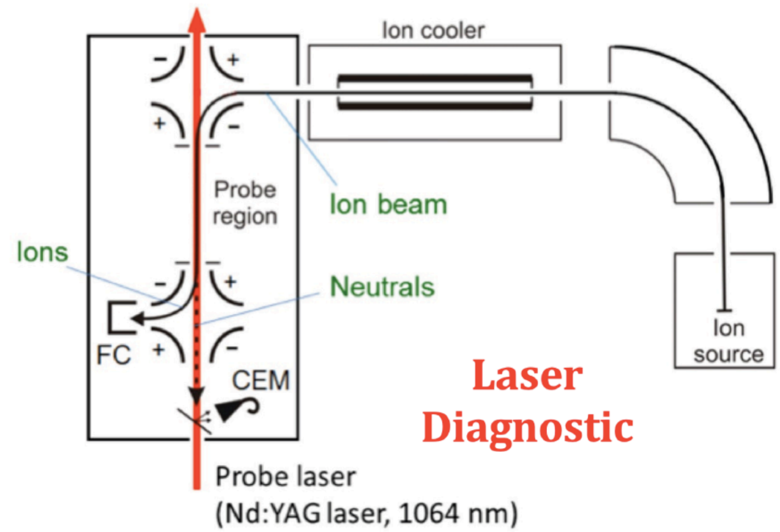
(Note we could not use H- because it would Lorentz strip!)

How to remove the high vibrational states?

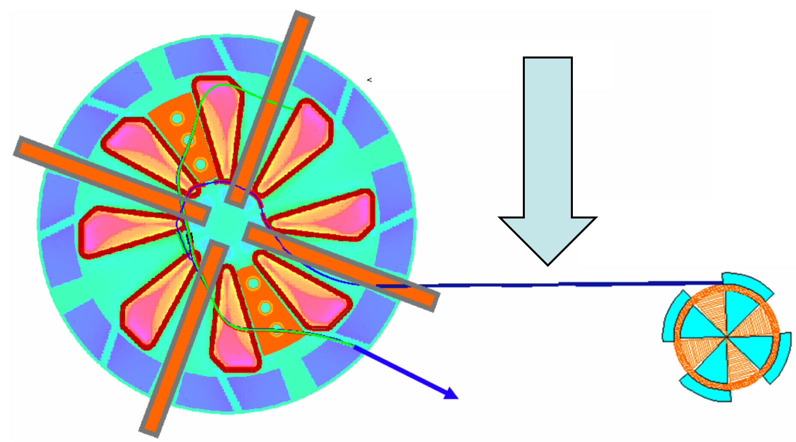
Option 1:
Remove them at the ion source via collisional dissociation with a noble element (exothermic for v>4)

$$H_2^{+*} + He \Longrightarrow HeH^{+} + H_o$$

ORNL Teststand

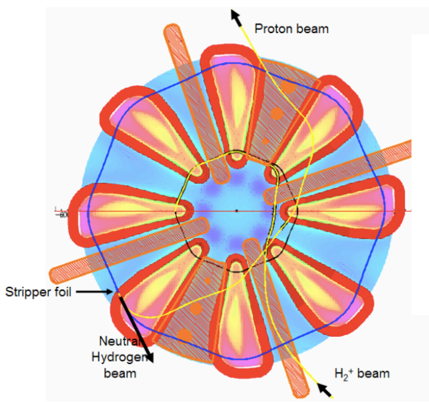


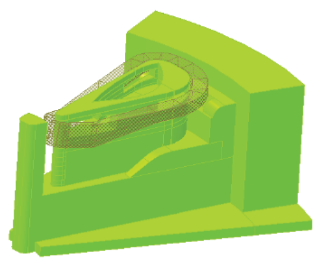
Option 2:
Run the 60 MeV beam through a 25T magnetic field.
(New option now under study)

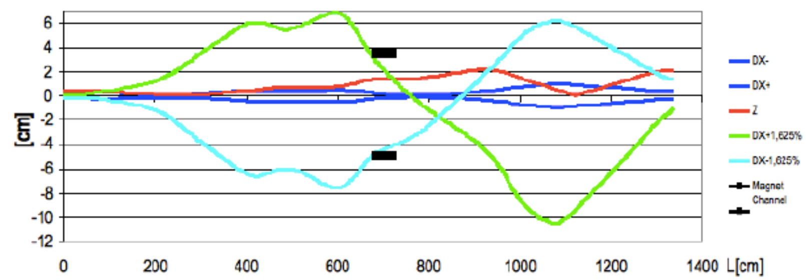


Status of design of the superconducting cyclotron: (DSRC)

1st iteration design completed with 8 sectors

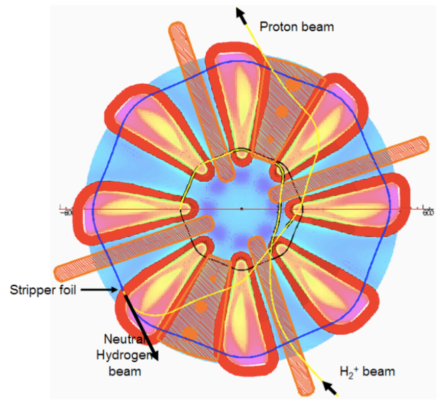


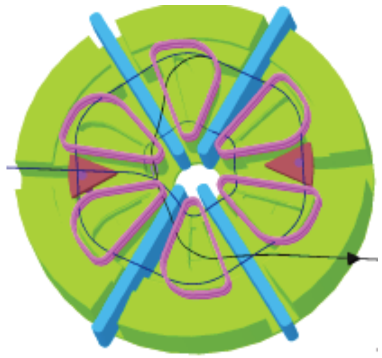




Many papers are on web. Reviews completed.
And the results led us to….

Move from an 8 sector design … to six sectors



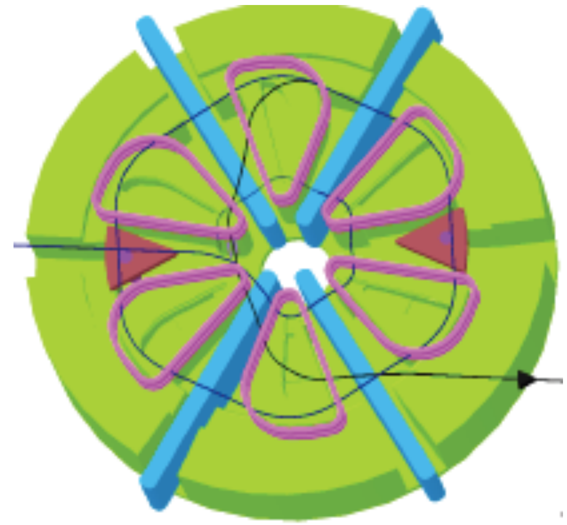


Why? The coil shape.
We were concerned about slipping/quenching
unless we had extremely tight clamping → too much risk.
(also, this magnet turns out to be cheaper)

In rethinking the design, we ended up with, essentially,
the RIKEN SRC magnet design!

Comparison DSRC vs RIKEN-SRC

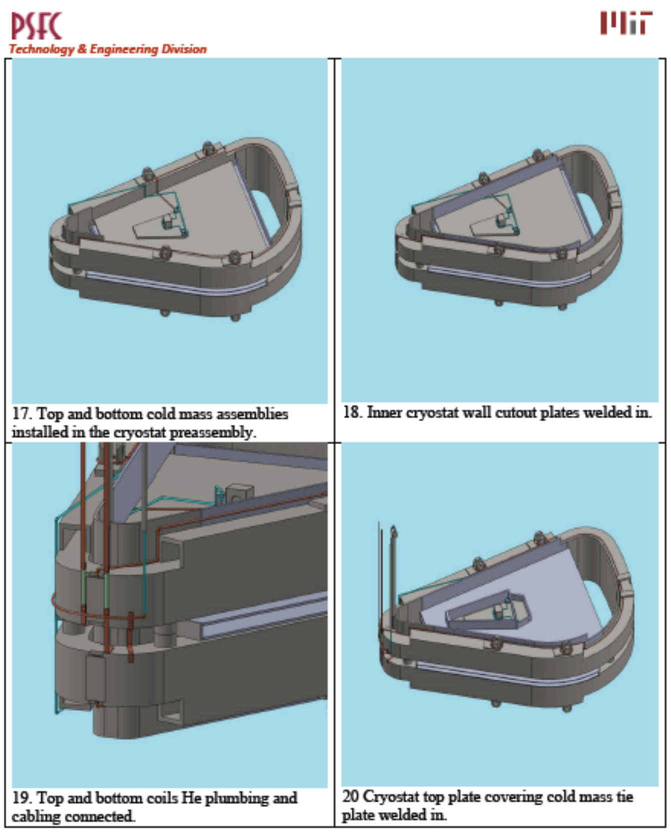
Basic	**DSRC**	**Riken-SRC**	**units**
Max field in the hill	4.72	3.8	T
Max field on the coil	4.27	4.2	T
Stored energy	166	235	MJ
Coil size	31x16	21x28	cm^2
Coil circumference	10.82	10.86	m
Magnetomotive force	3.37	4	MAtot/sector
Current density	34	34	A/mm^2
Height	6	6	m
Length	7.3	7.2	m
Weight/sector	830	800	tons
Additional magnetic shielding	0	3000	Ton/total
Magnetic foces			
Expansion	1.8	2.6	MN/m
Radial shifting	2.05	0.36	MN
Azimuthal shifthing	0.0595	0	MN
Vertical	7.07	3.3	MN
Main Coil			
Operational current	4800	5000	A
Layer per turn	16x22	22x18	
Cooling	Indirect forced cooling	Bath cooling	
Maddock stabilized current	Tbd in a further study stage	6665	A
Other Components			
SC trim	No	4	Sets
NC trim x turn	No	22	Pairs
Valley field	0.65	0.04	T
Gap for thermal insulation	50	90@min	mm
Extraction method	Stripper foil	Electrostatic channel	

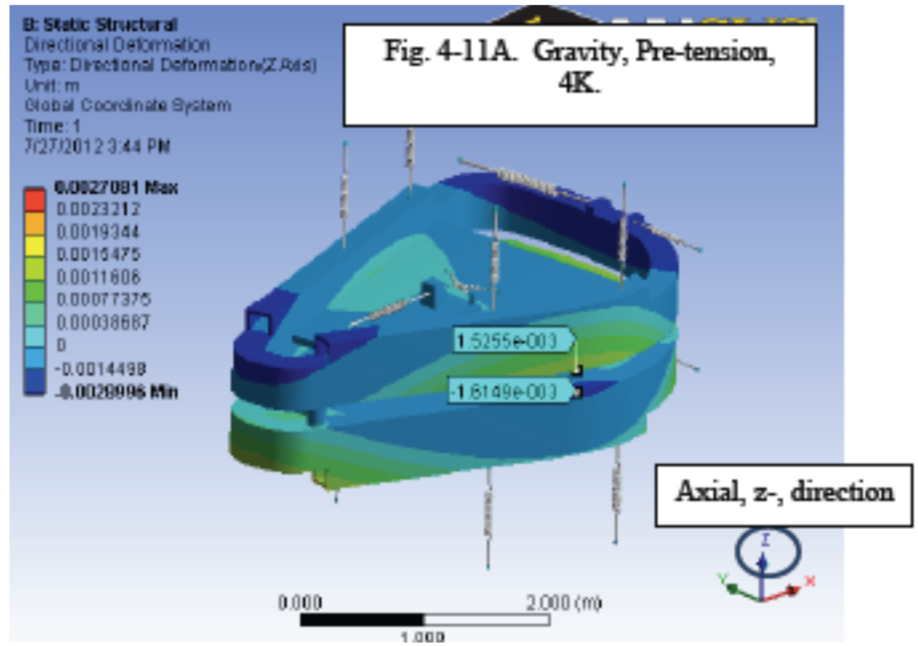


A lot of knowledge on what's needed already (Thanks to our RIKEN collaborators)

Engineering Study of 6 Sector Magnet for the Daedalus Experiment, http://arxiv.org/abs/1209.4886

Engineering design,
Assembly Plan,
Structural analysis,
Cryo system design





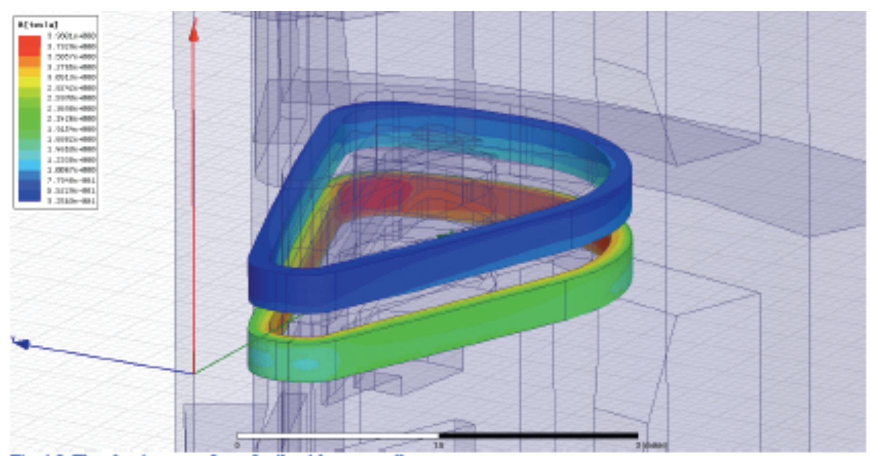


Fig. 4-9. Flux density on surface of coils with upper coil current zero.

The SRC Magnet is the cost driver for the DAEδALUS system.

Costing by Minervini group
Sanity check: compare to RIKEN cost – get good agreement.

Other components can be costed from PSI and RIKEN experience (in come cases we are re-using their components!)

Sanity check: scaling PSI to modern costs…
(cost of RIKEN Magnet)/(cost of PSI SRC)*total PSI cost

Bottom line, for the first standard system… ~$130M

With this said we are seeking funding for improved engineering and a better estimate.

November 11, 2013

To: Steve Ritz, Chair, P5

From: Janet Conrad, Steve Holmes and Mike Shaevitz

Subject: Cost Assumptions for MW-class Cyclotrons

At the P5 Meeting at Fermilab you heard a divergence of opinion on the projected costs of MW-class cyclotron facilities. Through a series of discussions since that meeting we have come to a common understanding on several aspects of the costs of such facilities, and we wish to share these with the committee as they will factor into your considerations of future programs.

1. $130M is a plausible estimate, in 2013 dollars, for the procurement of an 800 MeV/1 MW cyclotron from industrial vendors.

2. If this were built in the US at a "greenfield" site, the cost of the building and supporting infrastructure would be of the same order as cyclotron procurement costs. Also, execution within the US as a DOE project, would add roughly an additional 50% to a formal Total Project Cost.

3. The Collaboration did not quote a cost for buildings and infrastructure for DAEdALUS, as was noted on the slide. The accelerators are most likely to be installed at a mine site rather than a "greenfield" site. The collaboration believes there will be substantial savings through the utilization of preexisting infrastructure at mine sites that house the underground detector– therefore the actual cost of supporting infrastructure can only be estimated once the site is determined.

4. The current estimates are based on extrapolations from existing systems that are of limited accuracy. The development of a more reliable estimate will require an engineering/cost study for an actual facility.

Can we get an industrial vendor? Why yes!

RIKEN Construction by Sumitomo Heavy Industry

The Movie!

Our design was
originally developed for ADS technology

L. Calabretta, Utilization and reliability of high power proton accelerators, NEA Workshop.
L. Calabretta, D. Rifuggiato, M. Maggiore, V. Shchepounov, A superconducting ring cyclotron to deliver high intensity proton beams, in: EPAC 2000, Vienna, Austria, 2000.

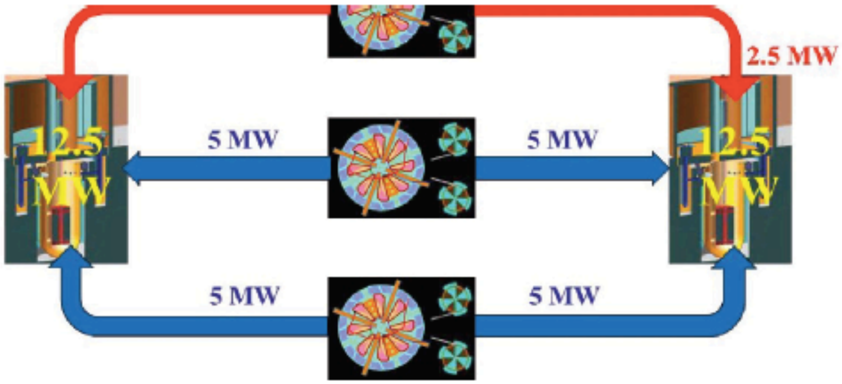
Development in this direction continues!

MW-CLASS 800 MeV/n H_2^+ SC-CYCLOTRON FOR ADS APPLICATION, DESIGN STUDY AND GOALS*

F. Méot, T. Roser, W. Weng, BNL, Upton, Long Island, New York, USA
L. Calabretta, INFN/LNS, Catania, Italy; A. Calanna, CSFNSM, Catania, Italy

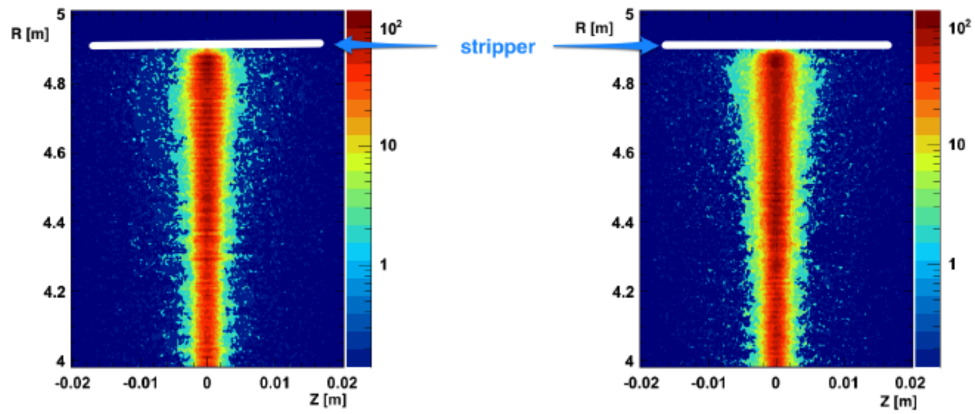
Abstract

This paper addresses an attempt to start investigating the use of the Superconducting Ring Cyclotron (SRC) developed for DAEδALUS experiment for ADS application [1, 2], focusing on the magnet design and its implication for lattice parameters and dynamic aperture performance.



H2+ allows us to strip beam with a foil to extract

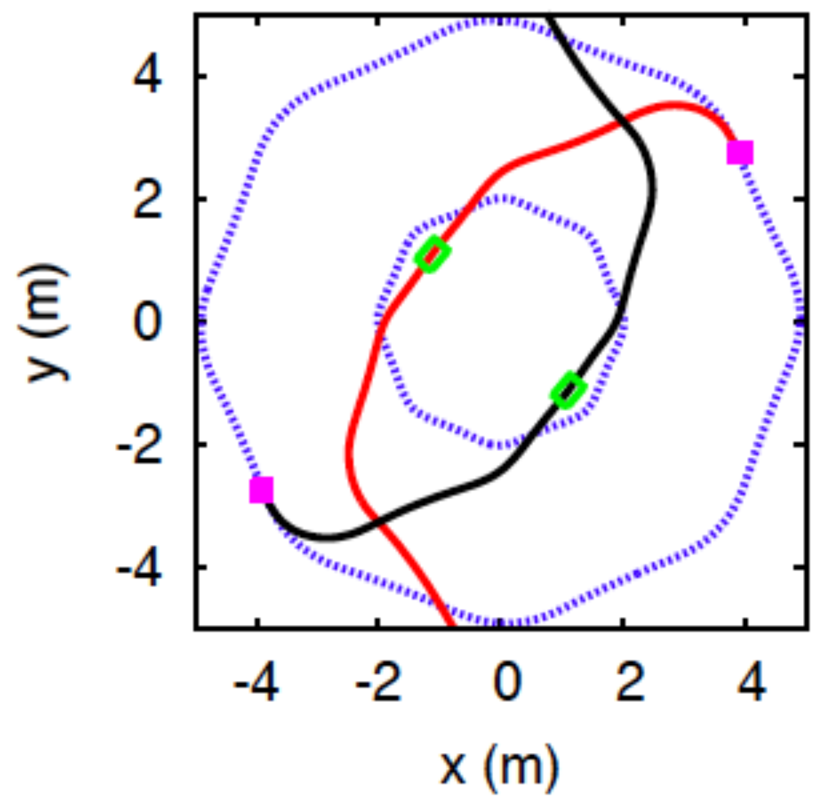
Projection
In vertical
plane



Projection
In radial
plane

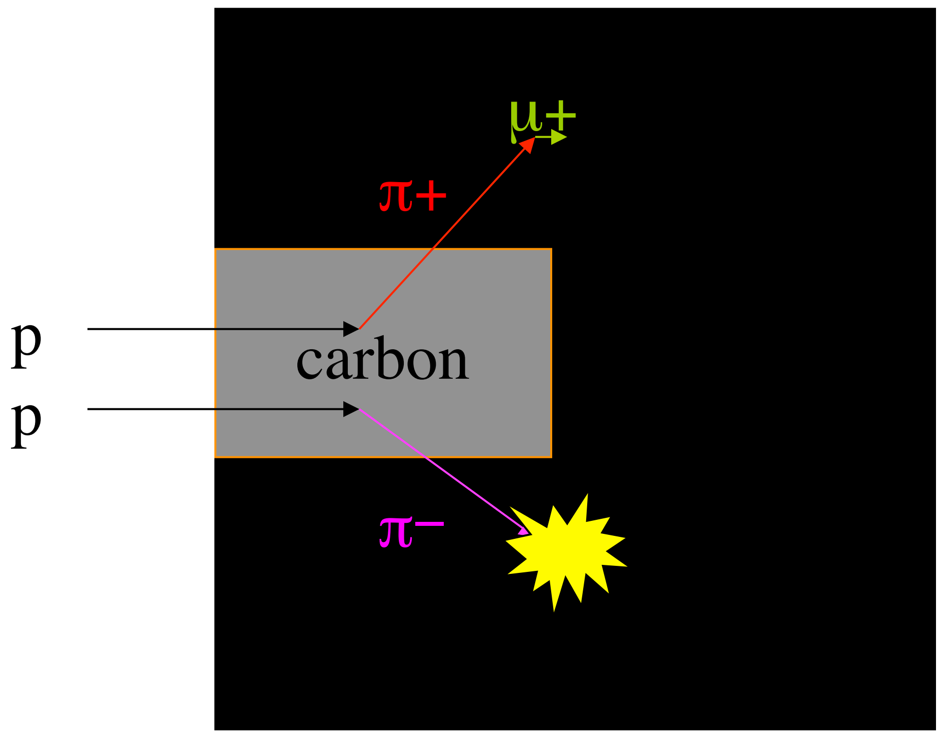
Extraction trajectories
(2 are shown)
cross the cyclotron,

But do not interfere with
the circulating bunches



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

Light target embedded in a heavy target

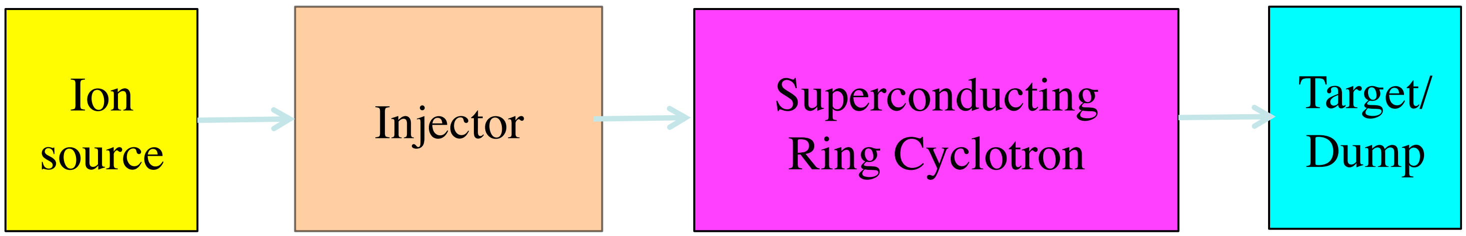


Also,
no upstream
targets!!!

Targets are above ground (not in a mine)

Studies on the target are available on the arXiv.

On DAEδALUS…



…We are presently thinking about:

1) IsoDAR R&D program, plus…
2) Characterizing vibrational spectrum of the H2+
   & demonstrating removal of high vibrational states
3) Next round SRC design → Prototyping SRC sector magnet
4) Full (start-to-end) simulation of beam dynamics using the OPAL code
   and latest experimental results

CONCLUSION

Conclusions from our P5 presentation…

DAEδALUS / IsoDAR Summary

- DAEδALUS is a program to develop a new resource for Neutrino Physics.
  - The goal is to produce small sized and relatively inexpensive cyclotron-based decay-at-rest neutrino sources.
- This frees the program from being forced to match detectors to accelerator sites and opens up interesting new physics opportunities.
  - Therefore, the development of these new, smaller sources should be a priority for our field.
- This is a phased program with physics output at each stage
  - IsoDAR experiment is the second phase.
  - Full DAEδALUS for CP measurements as the final phase
- We request that P5 endorse our development program with the goal to move rapidly forward with a
  1. A first demonstration IsoDAR system built before the end of this decade
  2. A full DAEδALUS set-up potentially installed in the 2020's.

You can get a copy of these slides at:
http://www2.lns.mit.edu/~conrad/Conrad_FNAL_2013.pdf

THANKS!