

# Accelerators for ADSRs

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# Contents

Thorium fuelled ADSR systems require high power proton beams, beyond the capacity of existing machines.

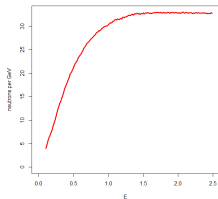
- Review of the requirements for energy, current, and reliability
- Comparison with the performance of current and proposed Linacs
- The proposed DAE $\delta$ ALUS MultiMegawatt Cyclotron
- The proposed nsFFAG

# Beam requirements

Probably largely covered by previous speakers

Protons obvious beam particle. Electrons easier but much less effective.  
No compelling advantage for ions

Neutron-per-proton-energy plateaus at 1 GeV, making it obvious choice.



For mid-range power plant (1 GW thermal) and  $\beta = 0.98$  (safe and sensible?) need 10 mA of 1 GeV protons – 10 MW.

$$\frac{0.010}{e} \times \frac{30}{2.5} \times \frac{1}{1 - 0.98} \times 200 \cdot 10^6 \times e = 1.2 \cdot 10^9 \text{ Watts}$$

# Why only .98?

- slide added at the last minute

## The protactinium problem

During running of a Thorium ADSR, Thorium is converted into Uranium via Protactinium



and a dynamic equilibrium is reached for Pa and U.

If the accelerator is switched off, the first and third steps stop. But the second continues (mean life 27 days). So the concentration of  $^{233}\text{U}$  *increases* after operation stops.

This increases the criticality,  $\beta$ , over a period of weeks.

The amount depends on the design – analyses I've seen give a boost around 1%.

So  $\beta \geq 0.99$  are not 'deterministically' safe.



# Comparison with existing/planned machines

We're not there yet

Machine	Energy GeV	Current mA	Power MW
PSI	0.59	2	1.2
ESS	2.0	2.5	5
CSNS-II	1.6	0.125	0.2
SNS	1	1.4	1.4
MYRRHA	0.6	3.5	2.1
ISIS	0.8	0.2	0.16

Some spallation sources below 1 GeV due to cost

Some spallation sources above 1 GeV due to space charge problems(?)

# Reliability

and a commercial power station

Limit of 3 trips/year often quoted but too demanding (See DOE white paper). But reliability needs to be much better than currently achieved.

- Simple design
- Careful analysis
- Redundancy
- Under-rating
- Graceful failure
- Planned maintenance

Hostile environment - need shutdown for maintenance. But long downtimes not acceptable, even when scheduled.

Ideal - run with 3 accelerators. One under maintenance, two operating, but if one drops out the other can manage.

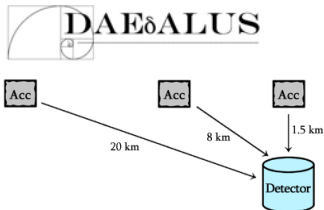
Huge cost of 3 linacs – consider cyclic accelerators.



# DAE $\delta$ ALUS

Decay At rest Experiment for  $\delta_{CP}$  At a Laboratory for Underground Science

A neutrino oscillation experiment using 3  $\bar{\nu}_\mu$  sources and one  $\bar{\nu}_e$  detector  
800 MeV proton accelerators (each 20% duty cycle) at distances of 1.5, 8  
and 20 km, with powers of 1.0, 1.6 and 4.8 MW.



Propose the multi-megawatt  
DAE $\delta$ ALUS Superconducting Ring  
Cyclotron (DSRC): 800 MeV  
protons. Accelerate  $\text{H}_2^+$  ions with  
stripping extraction.

Design very applicable for ADSRs

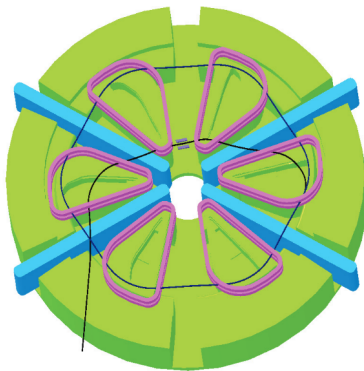
# The cyclotron complex for the DAE $\delta$ ALUS experiment

A. Calanna <sup>1</sup>, D. Campo <sup>1</sup>, J. M. Conrad, L. Calabretta, F. Meot, M. Tahar Haj:  
Cyclotrons2013

Cyclotron accelerating  $H_2^+$  ions  
to 1.6 GeV, giving 4 mA of  
800 MeV protons.

Extraction done by stripping.  
(Path shown)

Injection cyclotron up to 60  
MeV/amu, clean extraction  
with two electrostatic  
deflectors,





# The choice of particle: $H_2^+$

Stripping extraction needed for main cyclotron as orbits are very close.



Binding energy  $2.75\text{eV} \gg 0.75\text{eV}$  for  $H^-$ ,  
so much more stable and easier to handle.

## Other Advantages

Also reduces effects of space charge (very important). Simulations show that the injector cyclotron is space charge dominated, but 5 mA achievable.

Space charge effects can be quantified using the generalised perveance,  
$$K = \frac{qI}{2\pi\epsilon_0 m\gamma^3\beta^3}$$
 so effect for  $H_2^+$  is halved.

## Disadvantages

Needs better vacuum:  $10^{-8}$  rather than  $10^{-7}$  torr.

Needs high field strength, hence superconducting magnet.

# Source and injector

## The Source

Require 50 mA of  $\text{H}_2^+$ . Versatile Ion Source (VIS), designed and built at INFN-LNS (Catania) achieves several mA. Other possibilities under study. Experimental tests with the source, and the matching of the beams from it, currently under way at BEST cyclotrons, in Vancouver.

## The Injector

The DAE $\delta$ ALUS Injector Cyclotron (DIC) will accelerate 5 mA of  $\text{H}_2^+$  ions up to 60 MeV/amu. 4 sectors, diameter 6.2 m, 2.7 m high. Field (conventional magnet) increases from 1.075 to 1.16 T.

Injection with spiral inflector. Four 49.2 MHz double-gap RF cavities accelerate the bunches in 107 turns. Bunches extracted conventionally, as separation 2 cm. Isochronism better than  $5 \times 10^{-4}$ .

Injection energy 70 keV (35 keV/amu), gives the same generalised perveance as commercial cyclotrons.

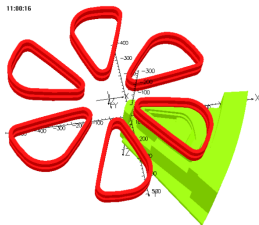


# The main cyclotron

## The DAE $\delta$ ALUS Superconducting Ring Cyclotron (DSRC)

Six superconducting sector magnets are used, with current densities of  $3400\text{A}/\text{cm}^2$ . (Earlier design had 8, didn't leave enough room for RF)

Four single-gap copper cavities, 3m high and 8.8m long. 49.2 MHz (6th harmonic),  $Q = 37,500$ . Gives acceleration from 2.0 to 4.0 MV per turn. Similar to those of the PSI cyclotron, hence credible. May be possible to add two double-gap cavities.



Extraction by thin ( $2\text{mg}/\text{cm}^2$ ) pyrolytic graphite foil, a few  $\text{cm}^2$  in size. Stripping of  $\text{H}_2^+$  needs study but should be OK. Electrons stop on copper shield. . Hope for pulse width  $< 1\text{ms}$  to ensure foil temperature  $< 2500\text{K}$ . Based on SNS, anticipate foil lifetimes of several months.

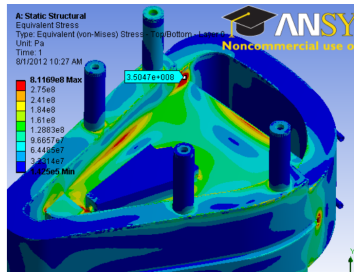


# The magnets

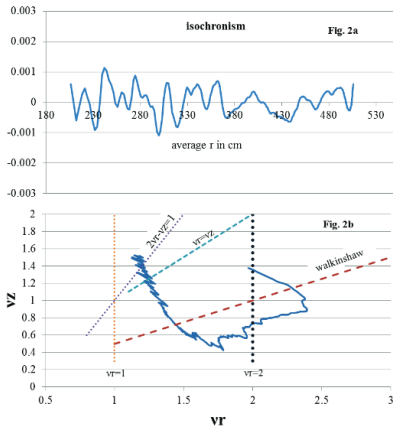
Cryostat made of iron and stainless steel. Enormous forces analysed with OPERA: stainless steel plates connect opposite segments. Design similar to the existing RIKEN SRC, hence the parameters in general credible.

8-sector magnet solution problematic. Developed 6-sector alternative.  $34 \text{ A/mm}^2$ , Constant cross-section  $31 \times 16 \text{ cm}^2$ . Space for 4 RF cavities and injection+extraction.

Preliminary engineering study done. Modelling for the conductor, high temperature superconductor and copper current leads for the magnet, structural design of magnet cold mass, cryostat and warm-to-cold supports, cryogenic design of the magnet cooling system, and magnet power supply.



# Lattice properties



Isochronicity 0.05% is adequate, focussing sufficient in both planes.  
Walkinshaw resonance is crossed rapidly, and should not lead to beam losses (more studies needed).

# DAE $\delta$ ALUS outlook

Simulations with space charge now being done (using OPAL) for 6 sector model. Surprises not expected as 8 sector model behaved well.

Injector on its own could provide interesting neutrino source (IsoDAR). Possibilities being strongly pursued. Would provide valuable experience of high currents and low (60 MeV) energies.

This could be another instance where the demands of particle physics push technology forward - blazing the trail for the benefit of the applications who follow.

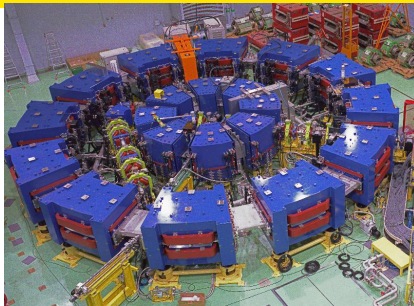
# The FFAG

## Fixed Field Alternating Gradient Accelerator

Bending field increases  
with  $R$

Looks to us like a  
cyclotron but particles  
see it as a synchrotron.

Gradient gives focussing  
Counterbends with  
opposite gradient



Invented and abandoned in the 1950's. Not the way to the energy frontier.

Revived in the 1990's. Gives cyclotron currents with synchrotron focussing  
and fast acceleration.



# The nsFFAG

non-scaling Fixed Field Alternating Gradient Accelerator

Conventional (scaling) FFAG has slow  $B(R) \propto R^k$

Optics does not change during acceleration

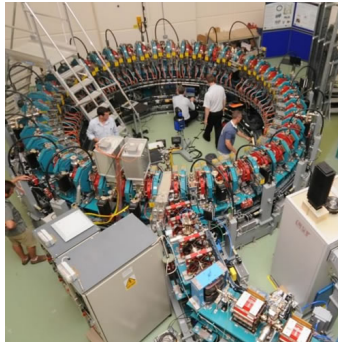
Hence tune does not change

Hence resonances can be avoided

Why avoid resonances?

If acceleration is fast,  
they don't hurt

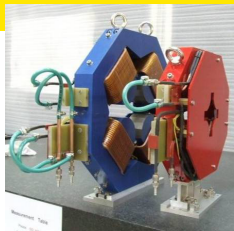
Build EMMA to test the  
idea





# EMMA: The Electron Machine with Many Applications

formerly The Electron Machine for a Muon Accelerator

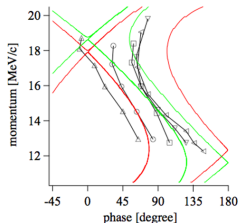


10 - 18 MeV electron accelerator

84 quadrupole magnets.

Built at Daresbury Laboratory, UK

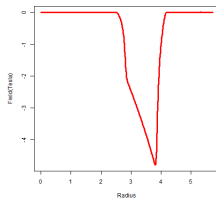
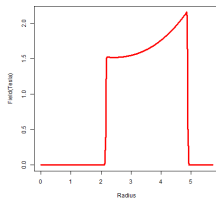
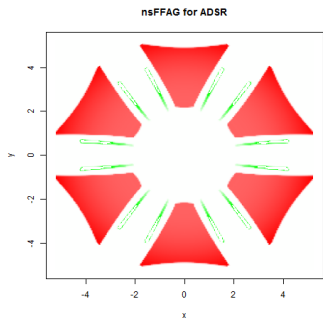
Success! Store and accelerate electrons



# An nsFFAG for ADSR

Very important disclaimer

Field map produced by Carol Johnstone, who gets any credit going Rudimentary tracking and analysis by me, to whom any blame is due.



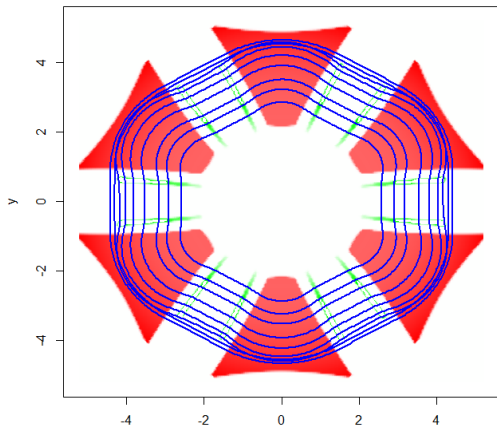
6 bending magnets, 12 small counterbends. 10 m diameter.



# Reference Orbits

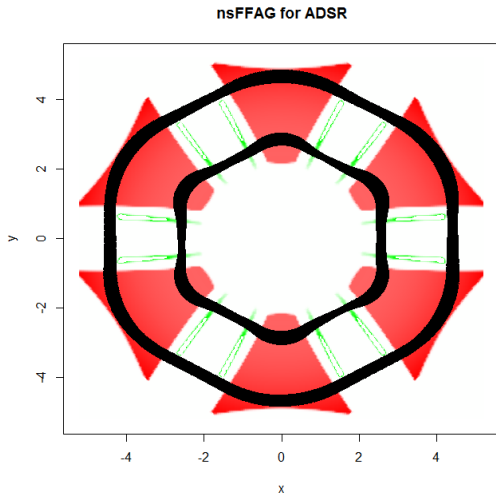
From 100 MeV to 1 GeV

nsFFAG for ADSR



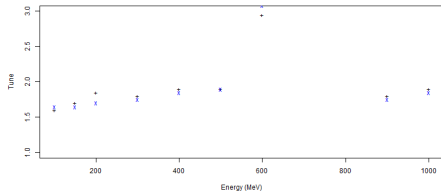
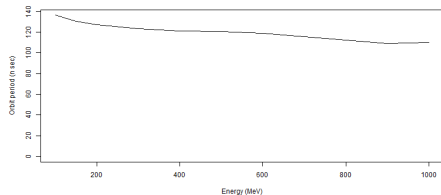
# Acceptance

Very generous, especially at low and high energies. Plot shows orbits spread about reference by 10 cm and 50 mrad



## Period and tune

Period is fairly constant with energy. Not strictly isochronous but enough to enable serpentine acceleration.



Tune is also fairly flat - which is a bonus.

## Outlook

Looks promising but needs a little more optimisation and a lot more study

# Conclusions

Cyclic accelerators (Cyclotrons or FFAGs) are possible solutions to the ADSR requirements.

Cheaper than Linacs, and multiple-accelerator systems may be affordable

Several designs are progressing from different groups...

Stay tuned!