Alternative designs for ADSR drivers FFAGs and electron linacs

EUCard2 Workshop on ADS, CERN

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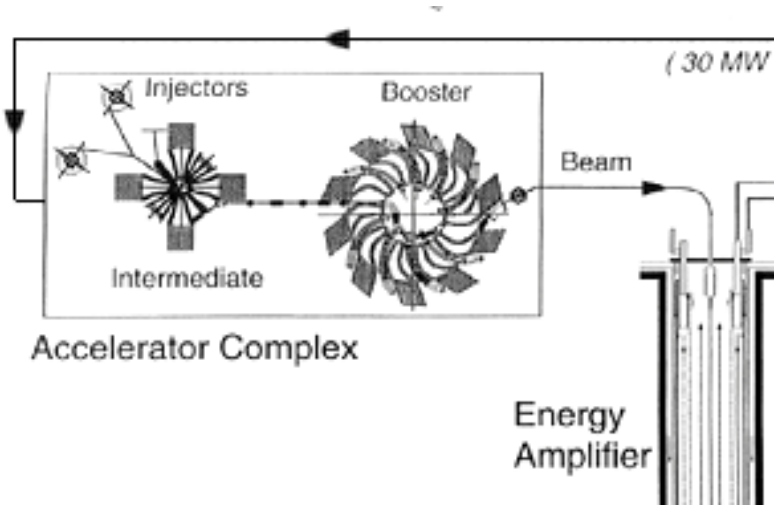
Why an FFAG?

ADS driver must deliver $\sim 10\mathrm{mA}$ of protons at $\sim 1\mathrm{GeV}$ with unprecedented reliability, and should not add significantly to the cost of the power station.



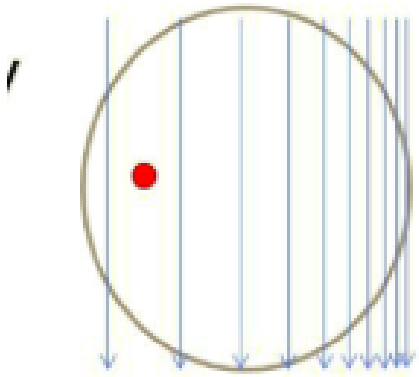
	Energy 1 GeV	Current 10 mA	Cost $<<$ 1Bn	Reliability in principle	Exists
Cyclotron	N (?)	Y (?)	Y	Y	Y
Synchrotron	Y	N	Y	N	Y
LINAC	Y	Y	N	Y	Y
FFAG	Y	Y	Y	Y	N

The proton nsFFAG is the only design that definitely ticks all these boxes.

Unfortunately no-one's built one yet

What is an nsFFAG?

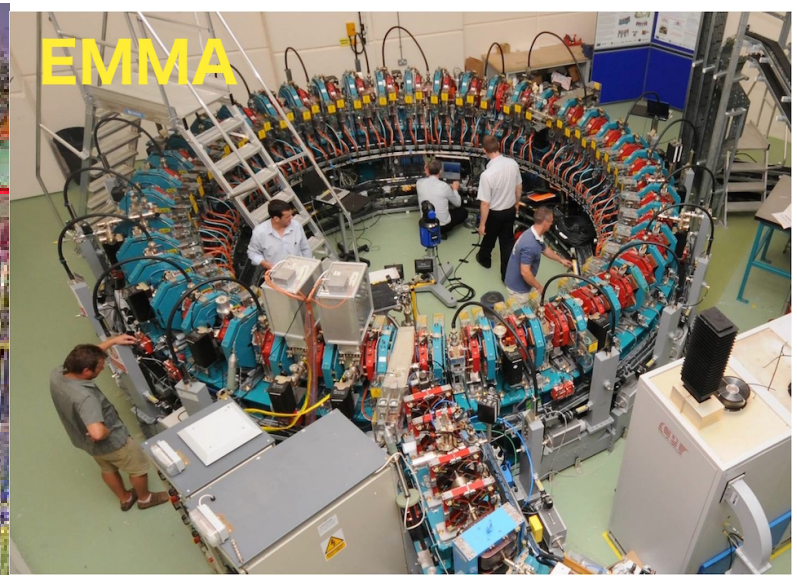
'A cyclotron from the outside but a synchrotron from the inside'
DC magnets (hence -FF-)
B field varies significantly with radius.
As particle energy increases, field increases
Acceleration is *fast* - not limited by magnet inductances.
Beam pipe more compact than for a cyclotron
Field gradients provide strong focussing (- AG).
Large dynamic aperture and low losses.

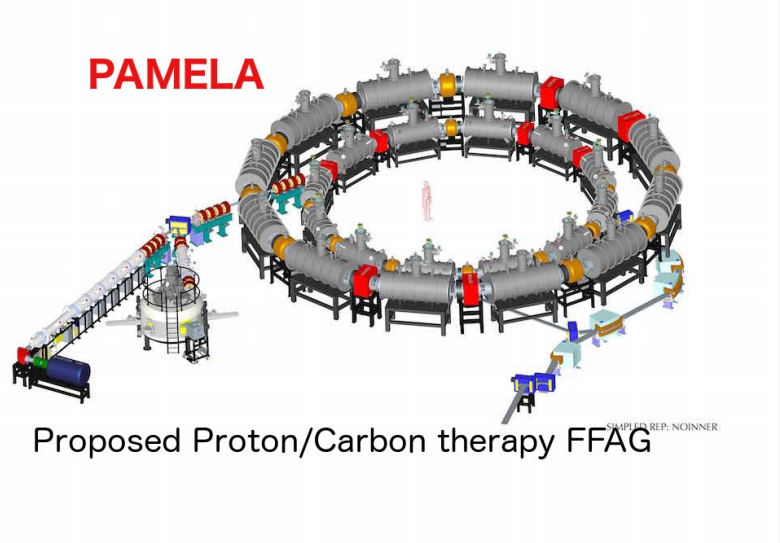


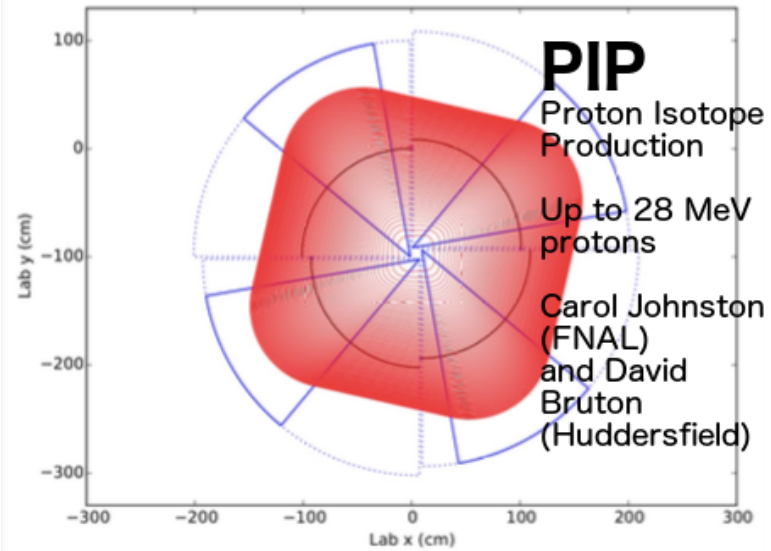
Conventional (scaling)
Field variation gentle $B \propto R^k$.
Optics unchanged through acceleration cycle.
- Tune constant: avoid resonances
Not isochronous
- Need to sweep frequency
- Pulsed operation
- Limited mean current

Nonscaling
Field variation steep
Optics changes during acceleration
- Tune varies. Hit resonances - but survive
Can be made isochronous
- Fixed frequency
- CW operation
- High mean current

Real and proposed FFAGs

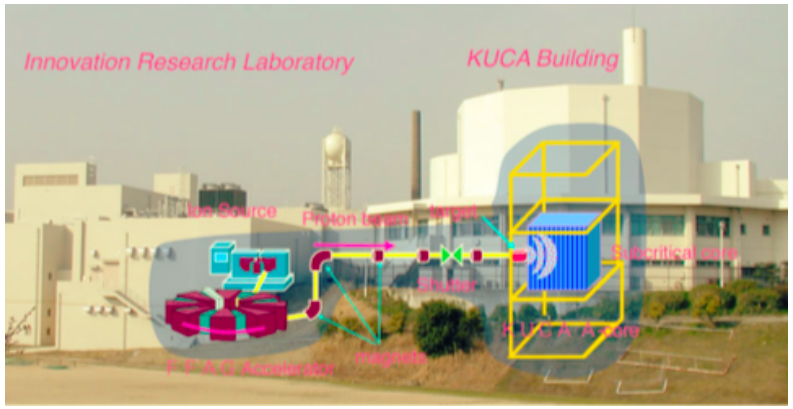


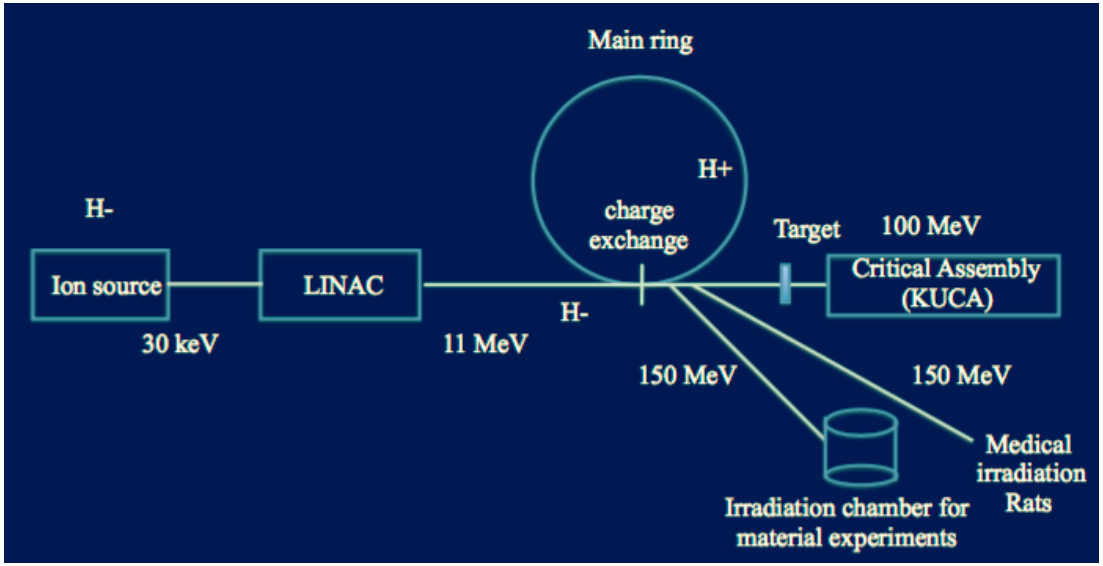




KURRI

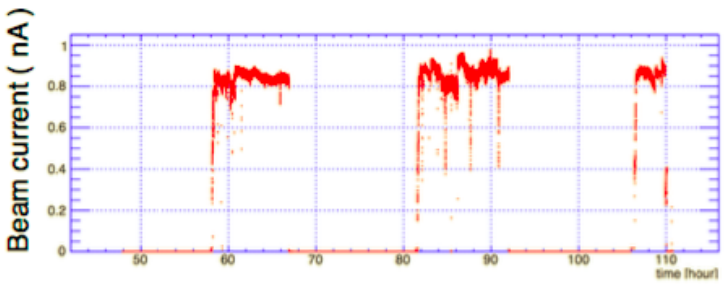
Will also be covered in Dr Song Hyun Kim's talk - but he will concentrate on target KUCA (Kyoto University Critical Assembly)



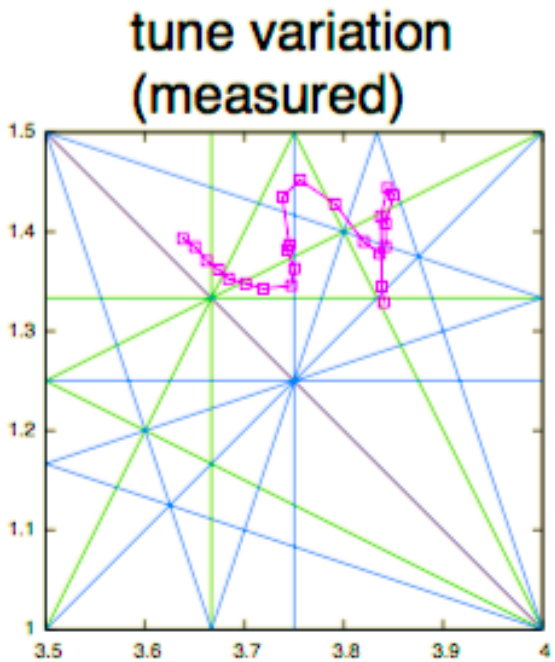


150 MeV proton FFAG ring
Producing useful beams
Current $\sim 1nA$

From Y Ishi's talk at FFAG16



Nice steady 1 nA currents



Measured tune - varies with energy.
Seems odd given scaling FFAG rationale

Recent problems with coolant leak in RFQ....

RAL-ASTeC

From Chris Prior's talk at FFAG16

Anticipate increasing demand for neutrons - the ESS will not be enough (and ILL will close)
So plan ISIS upgrade:
180 kW $\rightarrow$ multi-MW
New linac! 70 MeV $\rightarrow$ 180 MeV (800 MeV?)

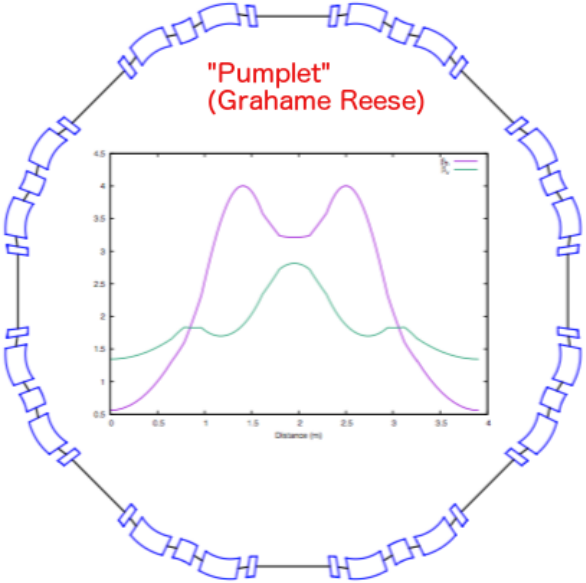
Neutrons pulsed - complementary to ESS

Upgrade 800 MeV synchrotron to 3.2 GeV.
15-20 year timescale. Time to develop small (2.6-5 m radius) test ring before main ring(25-50 m radius)

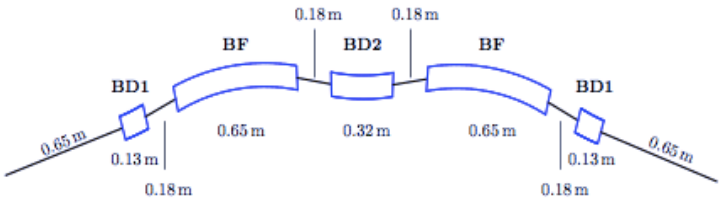
FFAG or RCS? FFAG preferred (high rep rate, more beam power, high momentum acceptance, large horizontal emittance possible, magnets can be SC or permanent.)
2 FFAG designs: pumplet and spiral DF

Pumplet

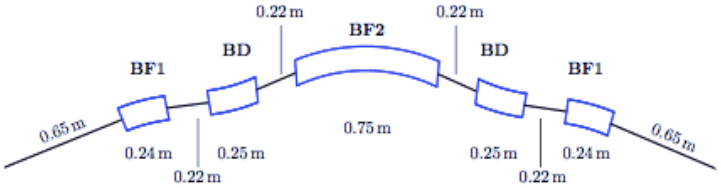
Scaling and non-scaling versions



Two pumplet patterns



Od(-)oF(+)oD(-)oF(+)od(-)O



Of(+)oD(-)oF(+)oD(-)of(+)O

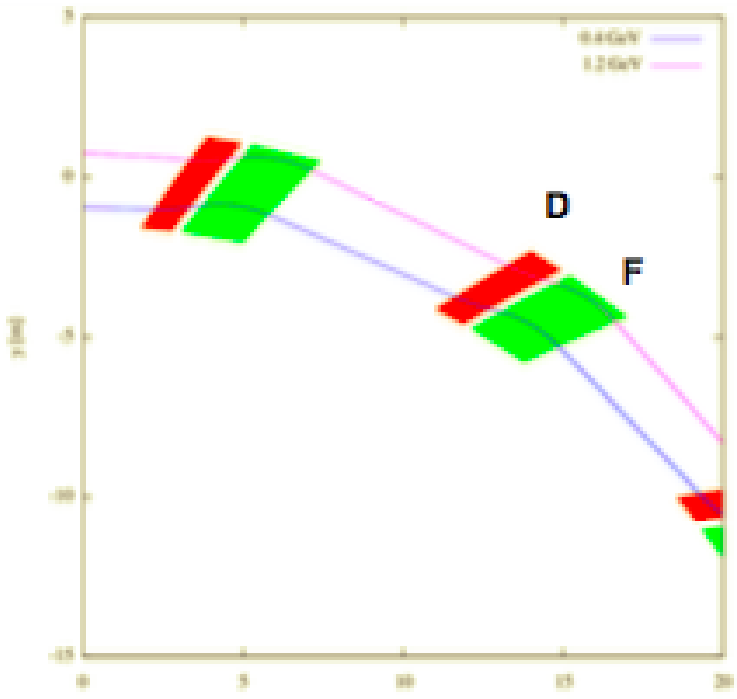
Model	Structure	Energy (MeV)	$R_{\rm inj}$(m)	$\rho_{\rm inj}$(m)	$\hat{\beta}_h$	$\hat{\beta}_v$	$\hat{D}_h$	Q_h	Q_v
Pumplet-1	fDFDf	3-10	4.974	0.91	4.68	2.72	0.71	3.20	2.72
Pumplet-2	dFDFd	3-10	4.974	0.91	4.00	2.81	0.67	3.40	2.82
RCS	dFDFd	3-10	4.974	2.40	2.90	7.20	0.65	3.22	2.73
Pumplet-3	fDFDf	800-3200	52.0	7.60	19.80	10.62	1.36	9.21	7.38
Pumplet-4	dFDFd	800-3200	52.0	7.60	14.93	8.72	1.32	9.21	7.38
RCS	dFDFd	800-3200	52.0	24.60	15.69	8.53	1.04	9.24	7.80

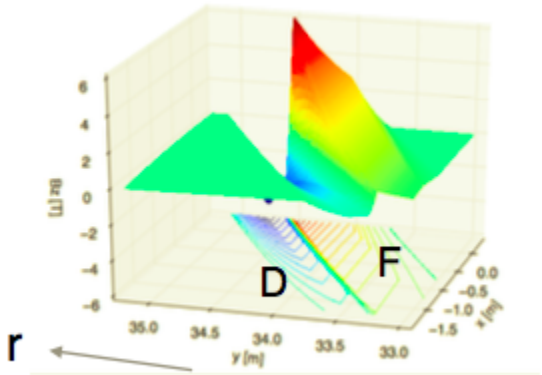
Pumplet FFAG designs compare well with RCS for MW proton spallation source

Spiral DF

Sharp edge between D and F (negative field). Large flutter f.

$$B(r,\theta) = B_0 \left(\frac{r}{r_0}\right)^k [1 + f\cos(N\theta - N\tan\zeta \ln(r/r_0))]$$

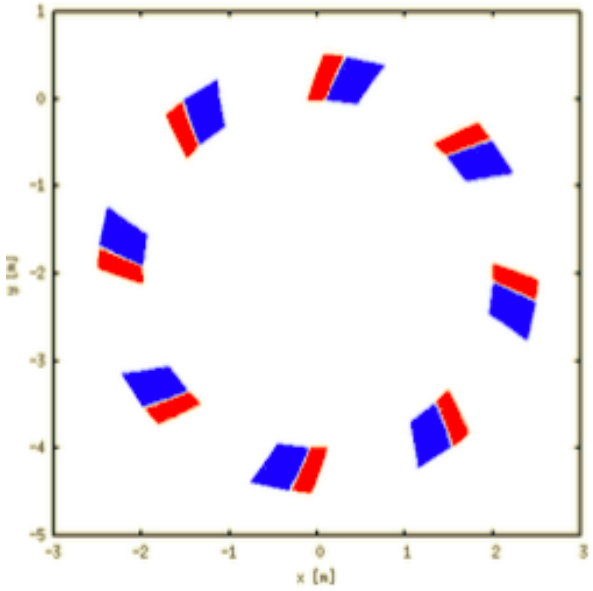


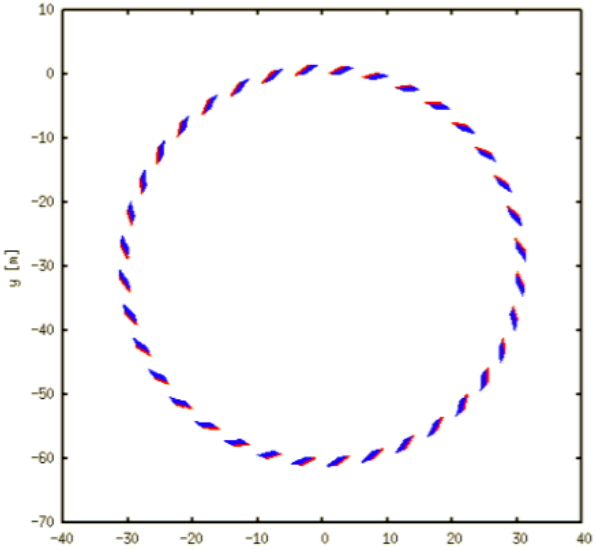


Combines features of radial and spiral FFAGs - compact and versatile
Developed by Shinji Machida
Magnet model under study

Spiral DF

Test ring
3-27 MeV
Momentum ratio 3
$\zeta = 20^\circ$
$k = 3$
Radius: 2.1 - 2.6 m
1.1 m straight



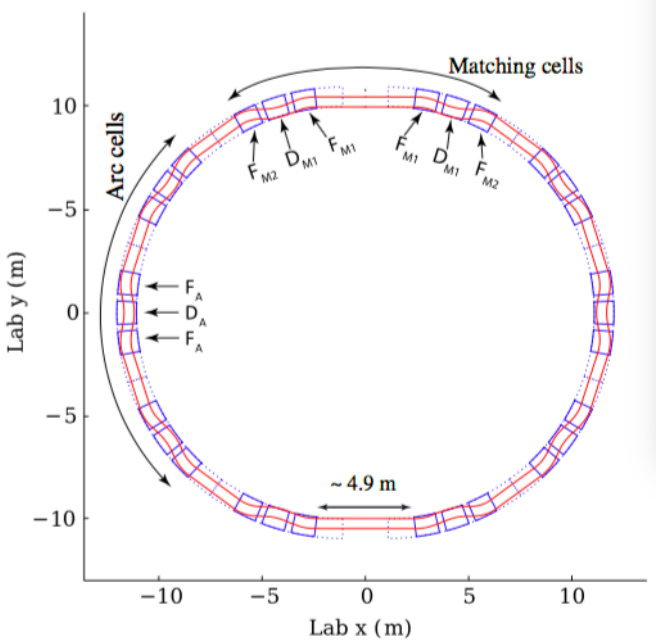


Main ring
0.4 - 3 GeV
Momentum ratio 4
$\zeta = 58^\circ$
$k = 50$
Radius: 30.2 - 31.0 m
3.6 m straight

Medical Accelerators - can they be adapted for ADSRs?

Maybe

Protons (and other ions) at 230 -300 MeV
E.g. NORMA[1] 70 - 250 MeV Scaling FFAG. RF frequency changes by factor 2.6 over cycle. Accelerates 1 bunch at a time.



High current machine should be CW not pulsed
Even then:
1) Activation scales with current.
2) Space charge may be a problem, but early studies suggest manageable
3) Injection and extraction may be difficult. Especially extraction

[1] J M Garland et al, Normal-conducting scaling fixed field alternating gradient accelerator for proton therapy, PRSTAB **18** 094701 (2015)

HEATHER

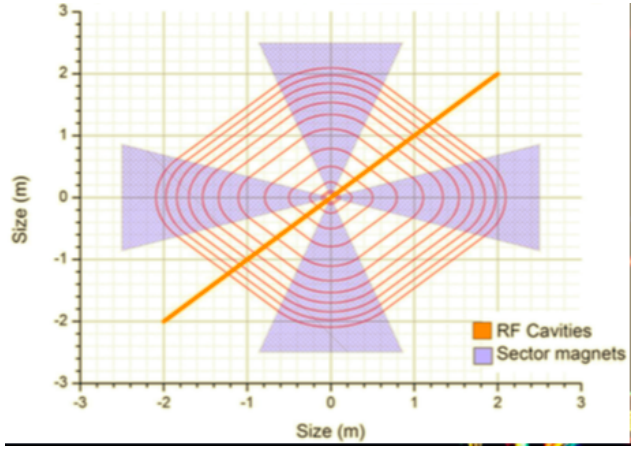
HElium ion Acceleration for radioTHERapy

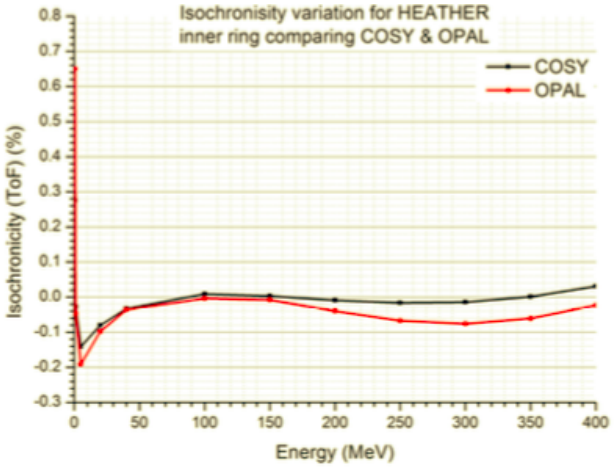
Jordan Taylor, Rob Edgecock, Carol Johnstone

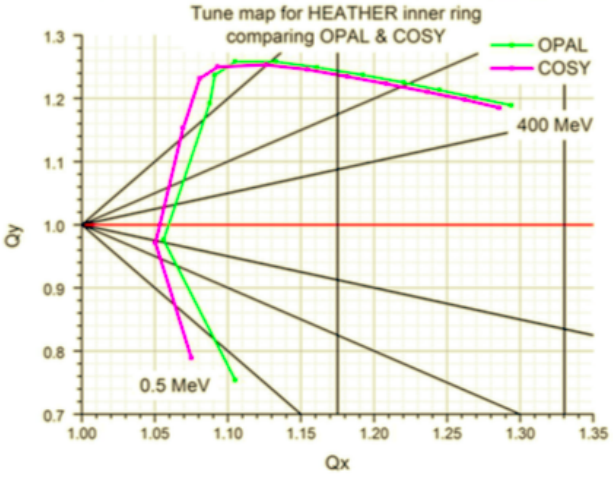
900 MeV He^{2+} or 450 MeV H_2^+. Not explicitly high current

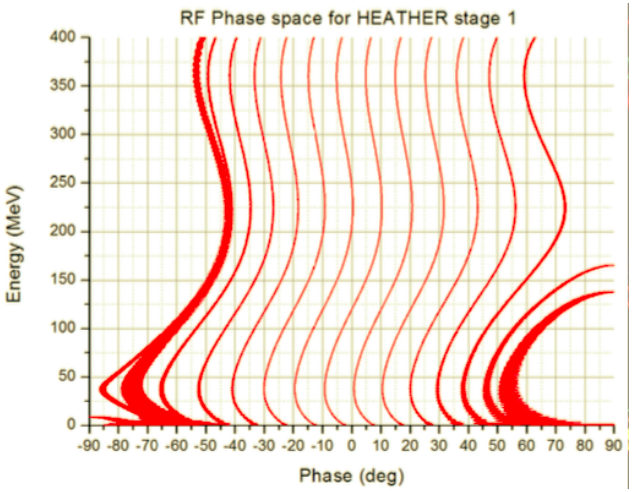
Ring 1: Superconducting ring, 2.5 m radius 0.5 to 400 MeV in 350 turns

Large phase acceptance





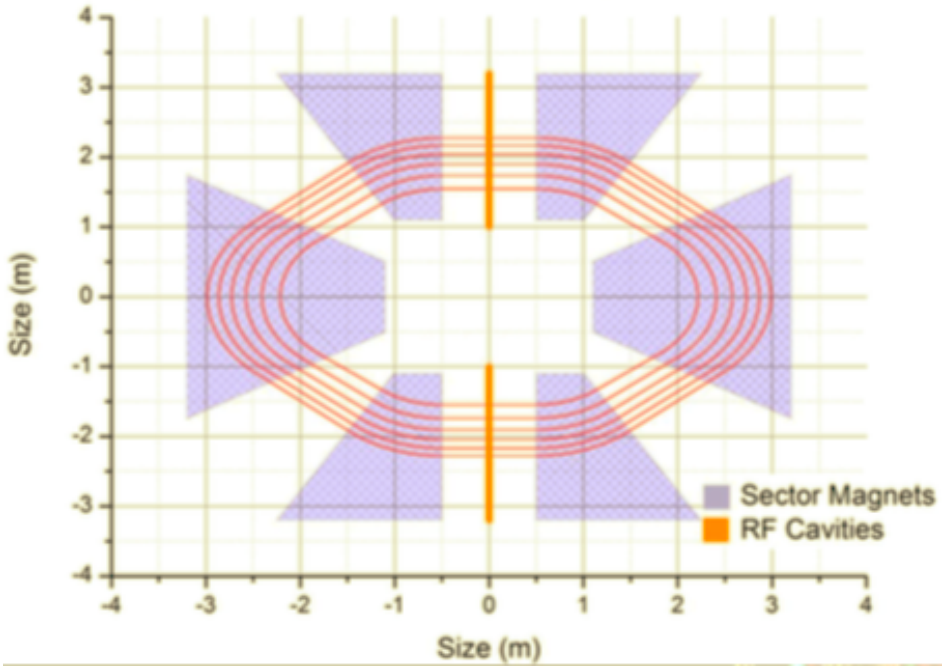


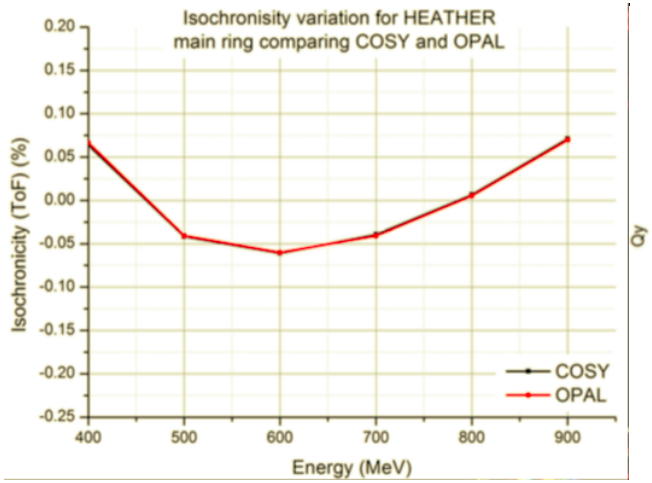


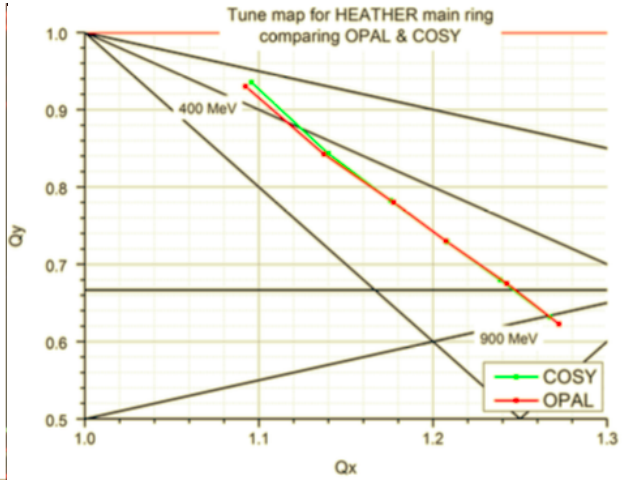
HEATHER Ring 2

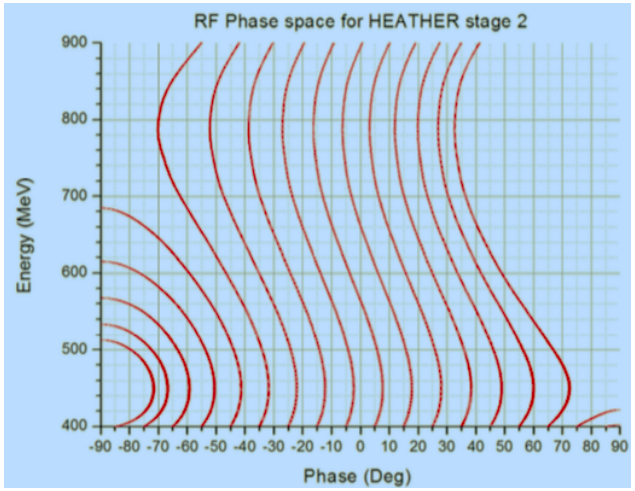
8 identical magnets
Racetrack gives space for extraction etc
Good isochronicity and phase acceptance. Does not cross integer resonance

Adaptable for higher currents and energies



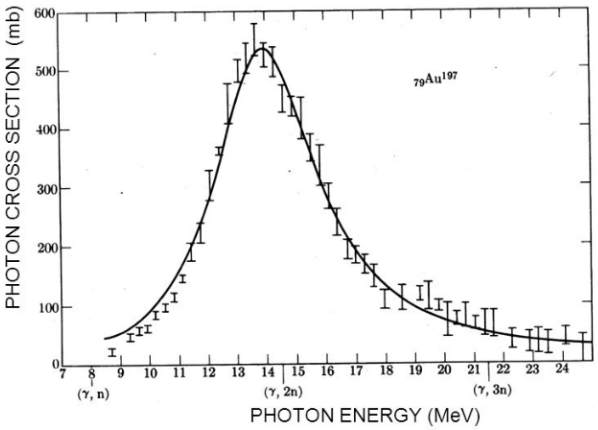






Electrons?

Proposed by Abalin [2]
Continued by Yaxi Liu [3]
Studies continue: latest by Feizi and Ranjbar[4]



Two stage process:
1) Electrons make Bremsstrahlung photons
2) Photons make neutrons through (γ, n) reactions on the giant dipole resonance

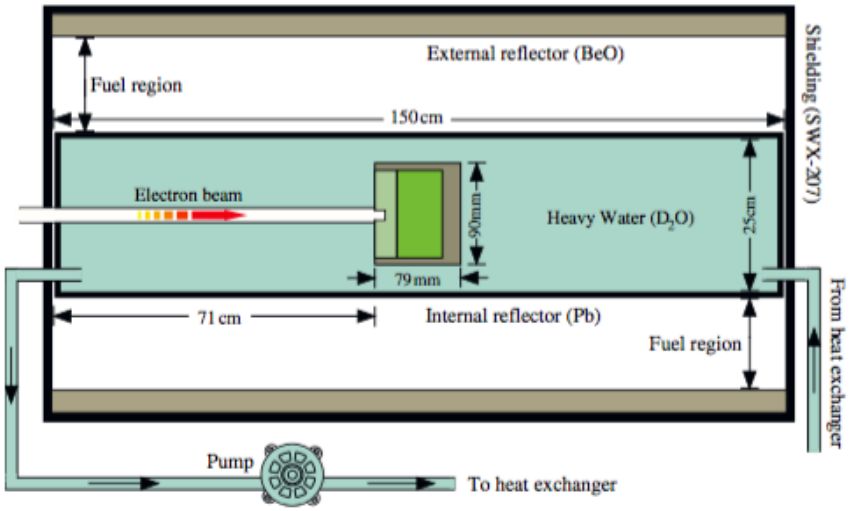
Dipole resonance is broad. Peak occurs when $\lambda \sim r_{nucleus}$ - so don't want energy too high.

[2] S.S. Abalin et al., Conception of electron beam-driven subcritical molten salt ultimate safety reactor, AIP publishing, U.S.A. (1995).

[3] Y. Liu, A study on the feasibility of electron-based accelerator driven systems for nuclear waste transmutation, Ph.D. Thesis, North Carolina State University (2006).

[4] H. Feizi and A.H. Ranjbar,Developing an Accelerator Driven System (ADS) based on electron accelerators and heavy water, J. Inst 11 P02004 (2016)

ADSR deslgn

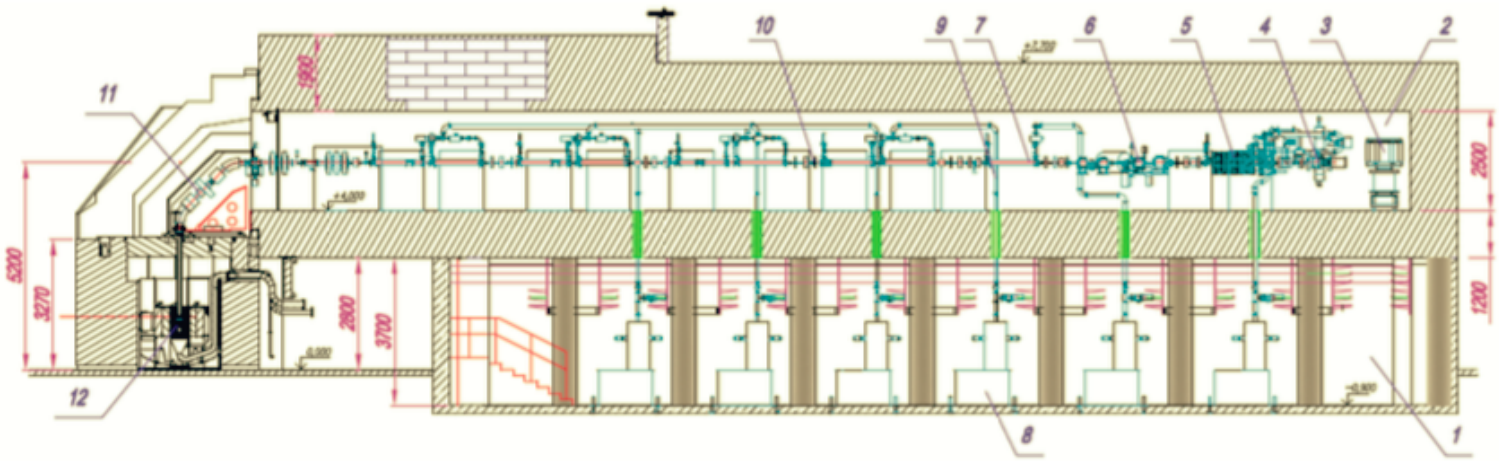


Taken from Feizi and Ranjbar

8 cm diameter Target is 0.9 cm W+4 cm U+ 2 cm Be
(Be gets neutrons from low energy γs)
100 MeV electrons gives 4×10^{14} neutrons/s/mA, (compare 1 GeV protons give $\sim 2 \times 10^{17}$ neutrons/s/mA)
With $k_{eff} = 0.98$ that gives $0.25 MW_{Th}/mA$
Need beam current of thousands of mA. Achieved - but in storage rings.
Peak neutron energy around 0.1 eV due to coolant/moderator D_2O.
Target needs cooling $\rightarrow$ moderation $\rightarrow$ thermal neutrons

KIPT

Being built at Kharkov[5]



100 kW, 1 mA of 100 MeV electrons. (Nothing to be gained by higher energy)
Tungsten or Uranium target
2-3 10^{14} neutrons/sec
131-192 kW thermal power
So you need 1000 of these for a *small* power reactor or incinerator

[5] A Y Zelinsky et al, NSC KIPT Neutron Source On The Base Of Subcritical Assembly Driven With Electron Linear Accelerator, IPAC13. And Yousry's talk yesterday.

Conclusions

FFAGs are a promising design for an ADS driver
Not currently being developed as such
But machines being discussed/designed currently could readily be be adapted for ADS use

Electron beams can provide some interesting neutron sources where fluxes required not so high, but very much a niche market.