Alternative designs for ADSR drivers
FFAGs and electron linacs

EUCard2 Workshop on ADS, CERN

Roger Barlow

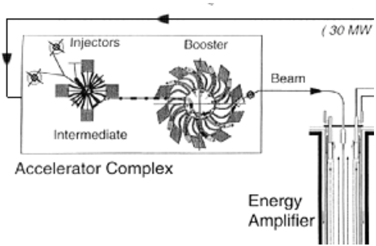
Int. Inst. for Accelerator Applications
The University of Huddersfield

8th February 2017

Contents

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.

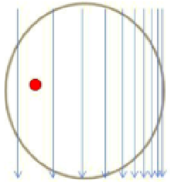
As particle energy increases, field increases

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

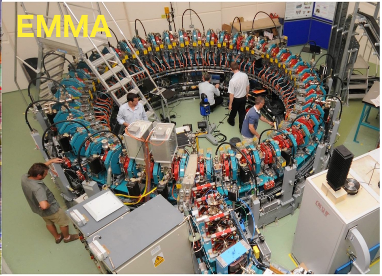
Optics changes during acceleration

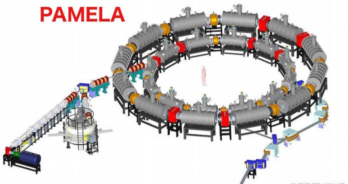
- Tune varies. Hit resonances - but survive

Can be made isochronous

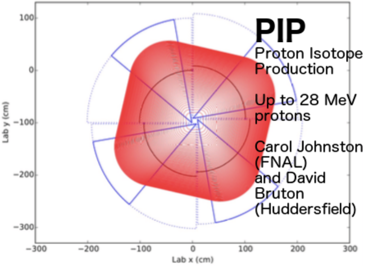
- Fixed frequency
- CW operation
- High mean current

Real and proposed FFAGs



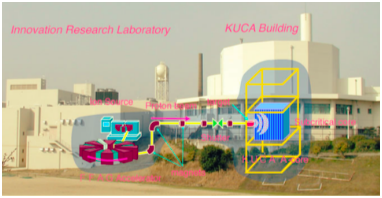


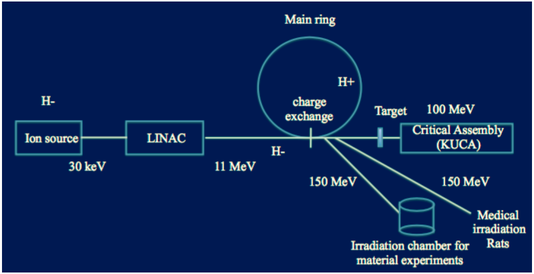
Proposed Proton/Carbon therapy FFAG



KURRI

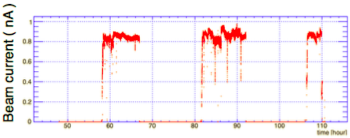
Will also be covered in Dr Song Hyun Kim's talk - but he will concentrate on target KUCA (Kyoto University Critical Assembly)



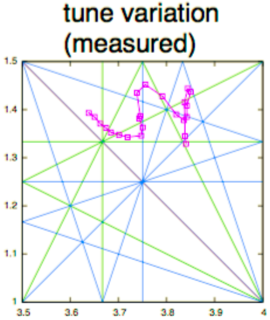


150 MeV proton FFAG ring
Producing useful beams
Current $\sim 1nA$

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?)

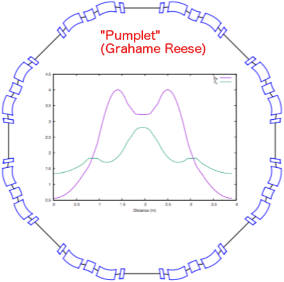
Neutrons pulsed - complementary to ESS

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)

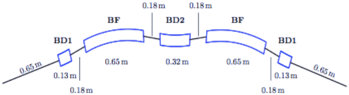
FFAG or RCS? FFAG preferred (high rep rate, more beam power, high momentum acceptance, large horizontal emittance possible, magnets can be SC or permanent.)
2 FFAG designs: pumplet and spiral DF

Pumplet

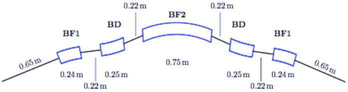
Scaling and non-scaling versions



Two pumplet patterns



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



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

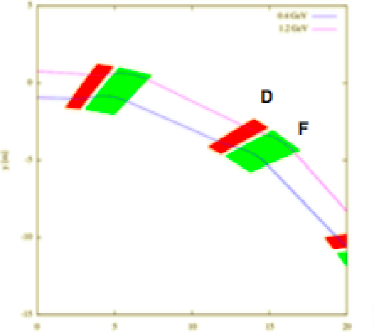
Model	Structure	Energy (MeV)	R_{inj}(m)	ρ_{inj}(m)	$\hat{\beta}_h$	$\hat{\beta}_v$	$\hat{D}_h$	Q_h	Q_v
Pumplet-1	fDFDf	3-10	4.974	0.91	4.68	2.72	0.71	3.20	2.72
Pumplet-2	dFDFd	3-10	4.974	0.91	4.00	2.81	0.67	3.40	2.82
RCS	dFDFd	3-10	4.974	2.40	2.90	7.20	0.65	3.22	2.73
Pumplet-3	fDFDf	800-3200	52.0	7.60	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

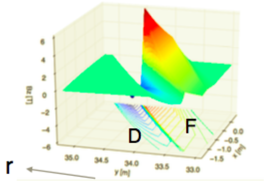
Pumplet FFAG designs compare well with RCS for MW proton spallation source

Spiral DF

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

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





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

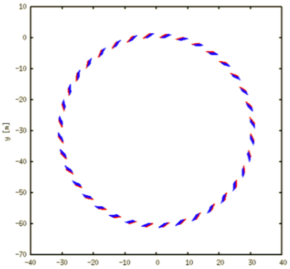
Momentum ratio 3

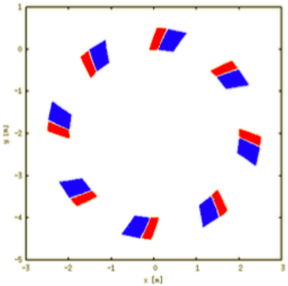
$\zeta = 20^\circ$

$k = 3$

Radius: 2.1 - 2.6 m

1.1 m straight





Main ring

0.4 - 3 GeV

Momentum ratio 4

$\zeta = 58^\circ$

$k = 50$

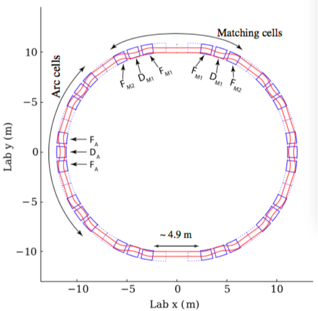
Radius: 30.2 - 31.0 m

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

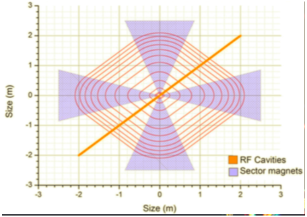
[1] J M Garland et al, Normal-conducting scaling fixed field alternating gradient accelerator for proton therapy, PRSTAB **18** 094701 (2015)

HEATHER

HElium ion Acceleration for radioTHERapy

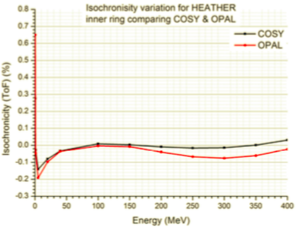
Jordan Taylor, Rob Edgecock, Carol Johnstone

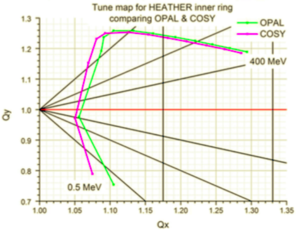
900 MeV He^{2+} or 450 MeV H_2^+. Not explicitly high current

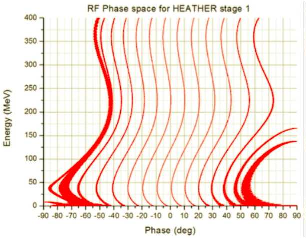


Ring 1: Superconducting ring, 2.5 m radius 0.5 to 400 MeV in 350 turns

Large phase acceptance



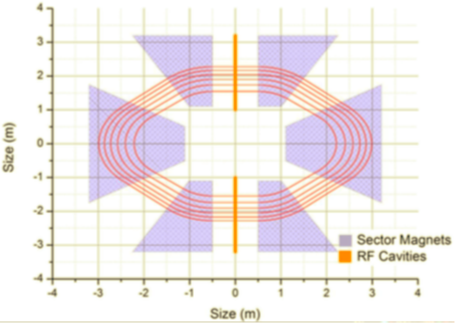


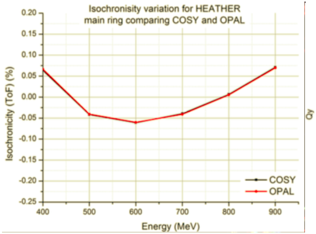


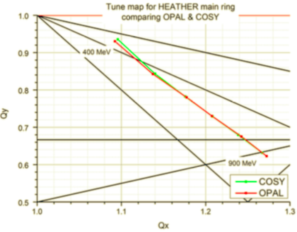
HEATHER Ring 2

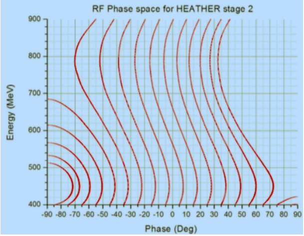
8 identical magnets
Racetrack gives space for extraction etc
Good isochronicity and phase acceptance. Does not cross integer resonance

Adaptable for higher currents and energies



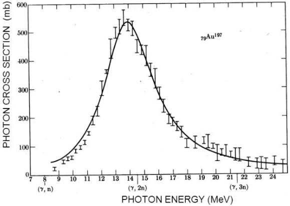






Electrons?

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.

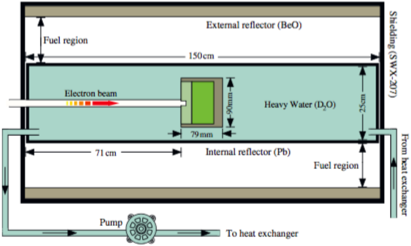
---

[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

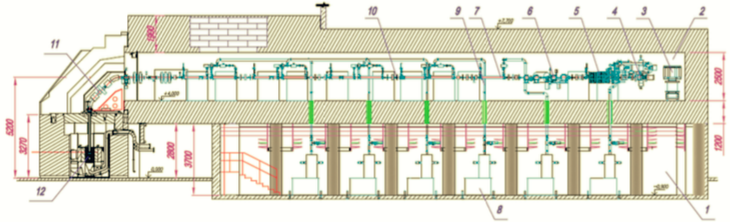


Taken from Feizi and Ranjbar

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.