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 \(\sim 10\,\text{mA}\) of protons at \(\sim 1\,\text{GeV}\) with unprecedented reliability, and should not add significantly to the cost of the power station.

<table>
<thead>
<tr>
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<th>Energy 1 GeV</th>
<th>Current 10 mA</th>
<th>Cost (&lt;!&lt;!! 1,\text{Bn})</th>
<th>Reliability in principle</th>
<th>Exists</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclotron</td>
<td>N (?)</td>
<td>Y (?)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Synchrotron</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
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<td>LINAC</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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<td>Y</td>
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<tr>
<td>FFAG</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
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</table>

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

**KEK - KURRI**

**EMMA**

**PIP**
- Proton Isotope Production
- Up to 28 MeV protons
- Carol Johnston (FNAL) and David Bruton (Huddersfield)

Roger Barlow (IIAA, Huddersfield)
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 $\sim 1\text{nA}$
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....
Anticipate increasing demand for neutrons - the ESS will not be enough (and ILL will close)
So plan ISIS upgrade:
180 kW → multi-MW
New linac! 70 MeV → 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
Scaling and non-scaling versions

Two pumplet patterns

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

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

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

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\textsuperscript{2}
Continued by Yaxi Liu\textsuperscript{3}

Studies continue: latest by Feizi and Ranjbar\textsuperscript{4}

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

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

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


\textsuperscript{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)
8 cm diameter Target is 0.9 cm W + 4 cm U + 2 cm Be
(Be gets neutrons from low energy $\gamma$s)
100 MeV electrons gives $4 \times 10^{14}$ neutrons/s/mA, (compare 1 GeV protons give $\sim 2 \times 10^{17}$ neutrons/s/mA)
With $k_{\text{eff}} = 0.98$ that gives $0.25 MW_{\text{Th}}/mA$
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
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

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Conclusions

FFAGs are a promising design for an ADS driver
Not currently being developed as such
But machines being discussed/designing currently could readily 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.