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>
<th></th>
<th>Energy 1 GeV</th>
<th>Current 10 mA</th>
<th>Cost ( \ll 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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<tr>
<td>LINAC</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>FFAG</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
</tbody>
</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

KEK - KURRI

EMMA

PAMELA

Proposed Proton/Carbon therapy FFAG

PIP

Proton Isotope Production
Up to 28 MeV protons
Carol Johnston (FNAL) and David Bruton (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 $\sim 1nA$
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....
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

<table>
<thead>
<tr>
<th>Model</th>
<th>Structure</th>
<th>Energy (MeV)</th>
<th>$R_{\text{inj}}$ (m)</th>
<th>$\rho_{\text{inj}}$ (m)</th>
<th>$\beta_h$</th>
<th>$\beta_v$</th>
<th>$\hat{D}_h$</th>
<th>$Q_h$</th>
<th>$Q_v$</th>
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<tbody>
<tr>
<td>Pumplet-1</td>
<td>fDFDf</td>
<td>3-10</td>
<td>4.974</td>
<td>0.91</td>
<td>4.68</td>
<td>2.72</td>
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<td>dDFDd</td>
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<td>2.90</td>
<td>7.20</td>
<td>0.65</td>
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<td>7.60</td>
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<td>1.36</td>
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<tr>
<td>RCS</td>
<td>dDFDd</td>
<td>800-3200</td>
<td>52.0</td>
<td>24.60</td>
<td>16.69</td>
<td>8.53</td>
<td>1.04</td>
<td>9.24</td>
<td>7.80</td>
</tr>
</tbody>
</table>

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

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

$$B(r, \theta) =$$

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

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 \((\gamma, n)\) 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.

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\(^4\)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 $0.25 \text{MW}_{Th}/mA$
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

Taken from Feizi and Ranjbar
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

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 adapted for ADS use

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