Particle Accelerators and Thorium Energy

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“A reactor needs an accelerator like a fish needs a bicycle...”
Spallation
Spallation: a two stage process

First stage:
Successive hard collisions between incident particle and target nucleons leading to emission of fast neutrons

*Intra-nuclear cascade models*

Second stage:
Decay of excited remnant nucleus by emission of low energy particles or of heavy nuclei by fission.

*Evaporation models*
Cascade neutrons are produced predominantly in the forward direction, with energies up to those of the incident protons.

“Evaporation” and “fission” neutrons (at significantly lower energies, <20MeV) are essentially isotropic.

From: Bauer, 2005
<table>
<thead>
<tr>
<th>Process</th>
<th>Example</th>
<th>Yield</th>
<th>Energy Deposition MeV/n</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT Solid Target</td>
<td>400keV deuterons on tritium in titanium target</td>
<td>4x10^{-5} n/d</td>
<td>10000</td>
</tr>
<tr>
<td>Deuterium Stripping</td>
<td>35MeV deuterons on liquid lithium</td>
<td>2.5x10^{-3} n/d</td>
<td>10000</td>
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<tr>
<td>Electron bremsstrahlung photoneutrons</td>
<td>100MeV electrons on U-238</td>
<td>5x10^{-2} n/e</td>
<td>2000</td>
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<tr>
<td>Fission</td>
<td>U-235(n,f)</td>
<td>1 n/fission</td>
<td>180</td>
</tr>
<tr>
<td>Spallation</td>
<td>800 MeV protons on lead</td>
<td>~20 n/proton</td>
<td>30</td>
</tr>
</tbody>
</table>
Spallation: an efficient process
Global Spallation Neutron Sources

- ISIS 200kW
- PSI (1.8MW)
- SNS (1 MW)
- J-PARC (1MW)
Introducing...
The European Spallation Source

Featuring
Professor Sir Patrick Stewart, OBE
Chancellor, University of Huddersfield

5MW
(Construction begins 2013 in Lund, Sweden)
Spallation Neutron Spectrum

Thermal neutrons:
\(^{238}\text{U}, \, ^{241}\text{Am}\) capture more than fission

Fast neutrons:
\(^{238}\text{U}, \, ^{241}\text{Am}\) fission more than capture

Thermal fission breeds actinides - fast fission destroys them
Applications of accelerator driven systems

- Transmuting selected isotopes present in nuclear waste (e.g., actinides, fission products) to mitigate the need for geologic repositories.

- Producing fissile materials for use in conventional critical or novel sub-critical reactors by irradiating fertile precursors (*Ferficon* – see Roger Barlow tomorrow)

- Generating electricity and/or process heat – Thorium fuelled ADS systems
1b€ European project to build an ADSR for transmutation and waste management (2015-2023)

SC Linac, 600 MeV, 2.5 mA
57 MWth reactor
Pb-Bi eutectic target/coolant
Fuel (MOX) loading from underneath
Examine transmutation of waste
ADSR or Energy Amplifier

- Subcritical ADSR core
- Extracted proton beam
- Spallation target
  - Spallation neutrons
- High energy, high current proton accelerator
  - Fraction of power, $f$ (~5%), fed back to accelerator
- Energy extraction with efficiency $\eta$ (~40%)
- Power, $(1-f)$, fed to the Grid
Jacobs Engineering’s ADTR™

ADTR™ COMPLEX

- 1500MW(Th)/600MW(e)
- 59te MOX fuel, 10 year refuelling
- Vessel dimensions 9.5m diameter, 20m high
- Molten lead coolant and spallation target
- Decay heat removed by natural convection on shutdown
- System operates at atmospheric pressure
The (thermal) power output of an ADSR is given by

\[ P_{th} = \frac{N \times E_f}{\nu} \cdot \frac{k_{eff}}{1-k_{eff}} \]

with

- \( N \) = number of spallation neutrons/sec
- \( E_f \) = energy released/fission (~200MeV)
- \( \nu \) = mean number of neutrons released per fission (~2)
- \( k_{eff} \) = criticality factor (<1 for ADSR)

Assuming:

\( P_e = 0.4 \times P_{th} \)

\( N \) varies approximately linearly with the energy of the protons, delivering ~24 neutrons per proton at 1 GeV for a lead spallation target

and noting

\[ P_{acc} (MW) = I_p (mA) \times E_p (GeV) \]

\[ P_{acc} = 1.04 \cdot P_{el} \cdot \frac{k_{eff}}{1-k_{eff}} \]

or

\[ G = \frac{P_{el}}{P_{acc}} = 0.96 \cdot \frac{1-k_{eff}}{k_{eff}} \]
Accelerator power
Potential ADSR electrical power output

\[ P_{\text{acc}} = 1.04 \cdot P_{\text{el}} \cdot \frac{k_{\text{eff}}}{1-k_{\text{eff}}} \]

*For lead spallation target*
Time evolution of the criticality value, $k_{\text{eff}}$

Coates, Parks (Univ. of Cambridge)
Evolution of power output after switch-off

Coates, Parks (Univ. of Cambridge)
Potential ADSR electrical power output

*For lead spallation target
Potential energy amplifier gain

\[ G = \frac{P_{el}}{P_{acc}} = 0.96 \cdot \frac{1 - k_{eff}}{k_{eff}} \]

*For lead spallation target

K_{eff} values in this range can be used but control rods must be an intrinsic component of the reactor control system.

*For lead spallation target
Cyclotrons
*High Current (<A) Low Energy (600MeV)*
*Continuous beam*

Synchrotrons
*Low Current (<mA) High Energy (TeV)*
*Pulsed Beam*

Linacs
*High Current, High Energy*
*Pulsed or continuous beam*
*Large and relatively expensive*
## Technology readiness assessment (US)

| Category                          | Performance                                                                 | Reliability                                                                 | RF Structure Development and Performance | Linac Cost Optimization | Reliability                                                                 | Cost Optimization | Reliability                                                                 | Performance                                                                 | Reliability                                                                 | Beam Delivery | Performance                                                                 | Reliability                                                                 | Performance                                                                 | Reliability                                                                 | Performance                                                                 | Reliability                                                                 | Instrumentation and Control | Performance                                                                 |
|-----------------------------------|------------------------------------------------------------------------------|------------------------------------------------------------------------------|------------------------------------------|-------------------------|------------------------------------------------------------------------------|------------------|------------------------------------------------------------------------------|------------------------------------------------------------------------------|------------------------------------------------------------------------------|----------------|------------------------------------------------------------------------------|------------------------------------------------------------------------------|------------------------------------------------------------------------------|------------------------------------------------------------------------------|------------------------------------------------------------------------------|------------------------------------------------------------------------------|-----------------------------|------------------------------------------------------------------------------|}

<table>
<thead>
<tr>
<th>Category</th>
<th>Transmutation Demonstration</th>
<th>Industrial-Scale Transmutation</th>
<th>Power Generation</th>
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<tbody>
<tr>
<td>Front-End System</td>
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<tr>
<td>Accelerating System</td>
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<td>RF Plant</td>
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<td>Beam Delivery</td>
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<td>Target Systems</td>
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<tr>
<td>Instrumentation and Control</td>
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<td>Beam Dynamics</td>
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<td>Reliability</td>
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<td>Green: “ready”, Yellow: “may be ready, but demonstration or further analysis is required”, Red: “more development is required”.</td>
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*Fermilab*
There is need for:

1. development and demonstration of highly reliable high-current proton injector systems;

2. advancing the state-of-the-art in accelerator systems, including linacs and RF systems;

3. improved understanding of beam loss mechanisms, emittance and halo growth;

4. development of highly reliable and fault tolerant accelerator systems and accelerator components.
An alternative approach?

**Fixed Field Alternating Gradient Accelerators (FFAGs)**

- Cyclotron: *isochronous orbit*
- Synchrotron: *constant closed orbit* *varying magnetic field*
- FFAG: *varying closed orbit* *fixed magnetic field*

Japanese approach (Mori)

Our approach (Barlow et al)
EMMA – The world’s first ns-FFAG

ns-FFAGs should be much smaller, cheaper and easier to operate than any existing accelerators and are ideally suited to ADSR, proton therapy and many other applications.

Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA


In a fixed-field alternating-gradient (FFAG) accelerator, eliminating pulsed magnet operation permits rapid acceleration to synchrotron energies, but with a much higher beam-pulse repetition rate. Conceived in the 1950s, FFAGs are enjoying renewed interest, fuelled by the need to rapidly accelerate unstable muons for future high-energy physics colliders. Until now, a ‘scaling’ principle has been applied to avoid beam blow-up and loss. Removing this restriction produces a new breed of FFAG, a non-scaling variant, allowing powerful advances in machine characteristics. We report on the first non-scaling FFAG, in which orbits are compacted to within 10 mm in radius over an electron momentum range of 12-18 MeV/c. In this strictly linear-gradient FFAG, unstable beam regions are crossed, but acceleration via a novel serpentine channel is so rapid that no significant beam disruption is observed. This result has significant implications for future particle accelerators, particularly muon and high-intensity proton accelerators.
EMMA – The world’s first ns-FFAG
Multiple FFAG proton injection

Multiple injection:
- mitigates against proton beam trips and fluctuations
- homogenises power distribution across ADSR core

*Patent taken out on multiple injection*
Summary

- Accelerator-driven spallation provides a non-invasively switchable and controllable source of neutrons with a suitably hard \((E_n > 10 \text{ MeV})\) spectrum.

- Accelerator driven systems could be utilised for nuclear waste management and/or power generation, with thorium as the ideal fuel and waste matrix.

- For such systems \(K_{\text{eff}}\) should ideally be maintained at \(~0.985\), restricting the energy amplifier gain to \(~60-70\). (Though higher \(K_{\text{eff}}\) and Gain are possible.)

- For power generation the total accelerator(s) power should approach 10MW.

But:

- Significant R&D is required to deliver accelerator technology with appropriate reliability.

- ns-FFAG accelerator systems may ultimately provide the best (ie cheapest, smallest, simplest and most reliable) ADS drivers – but much R&D is needed.

\[\text{\ldots and perhaps fish do need bicycles!!!}\]
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