UK Developments Towards Accelerator-Driven Systems

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&
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Supported by EPSRC Basic Technology Grant EP/E032869/1
Daresbury
‘Energy Amplifier’ (Rubbia)

Pb/Bi coolant

Rubbia et al., CERN/AT/93-47 (ET), CERN/AT/95-44 (ET) 
also MSR option: C.D.Bowman, NIM A320, 336 (1992)
ADSR as an ‘Energy Amplifier’

10MW Accelerator

Extracted proton beam

Subcritical ADSR core

Spallation target

Spallation neutrons

Spallation neutrons

1550MW Thermal Power

15% of power, \( f \sim 5\% \), fed back to accelerator

fraction of power, \( f \sim 5\% \), fed back to accelerator

energy extraction with efficiency \( \eta \sim 40\% \)

20 MW electrical

High energy, high current proton accelerator

power, \((1 - f)\), fed to the Grid

600 MW Electrical Power

Reactor part costs about \( \sim 2-3 \) billion to construct

Fuel is ‘sort-of’ free
To meet a constraint of a 10MW proton accelerator we need $k_{\text{eff}} > 0.985$.
THOREA Organisation

- www.thorea.org
- Roadmap document on ADSR development for UK
- 3-stage programme focusing on high-current, reliable proton driver
- lead-cooled fast reactor, Th cycle
MEGAPIE (SINQ Facility, PSI)

Ran successfully for 4 months in 2006

700 kW, CW, liquid Pb-Bi
First Pb-Bi spallation target

‘Makes future licensing simpler’

<table>
<thead>
<tr>
<th></th>
<th>Megapie</th>
<th>XT-ADS target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coolant / target</strong></td>
<td>liquid Pb-Bi</td>
<td>liquid Pb-Bi</td>
</tr>
<tr>
<td><strong>Beam energy</strong></td>
<td>595 MeV</td>
<td>600 MeV</td>
</tr>
<tr>
<td><strong>Beam current</strong></td>
<td>1.4 mA max</td>
<td>3 mA</td>
</tr>
<tr>
<td><strong>Lifetime</strong></td>
<td>4 months</td>
<td>9 months</td>
</tr>
<tr>
<td><strong>Accumulated charge</strong></td>
<td>2.8Ah</td>
<td>20Ah</td>
</tr>
<tr>
<td><strong>Target diameter</strong></td>
<td>Ø20 cm</td>
<td>Ø10 cm</td>
</tr>
<tr>
<td><strong>Accumulated charge / m²</strong></td>
<td>90 Ah/m²</td>
<td>2500 Ah/m²</td>
</tr>
<tr>
<td><strong>Beam interface</strong></td>
<td>window</td>
<td>windowless</td>
</tr>
</tbody>
</table>
Funded and recruiting right now; construction 2015-1029

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

Useful proton source in its own right
Replaces BR2 isotope reactor

(JAEA plan similar project at JPARC)

Abderrahim et al., *Nuclear Physics News, Vol. 20, No. 1, 2010*
Subcritical Reactor Studies

Table 1: The basic parameters for ADSR experiment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor output power</td>
<td>~10 W</td>
</tr>
<tr>
<td>Neutron multiplication factor</td>
<td>≤ 100</td>
</tr>
<tr>
<td>Beam power</td>
<td>≤ 0.1 W</td>
</tr>
<tr>
<td>Beam energy</td>
<td>100 - 150 MeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>≤ 1 nA</td>
</tr>
</tbody>
</table>

Y.Ishi et al., ‘PRESENT STATUS AND FUTURE OF FFAGS AT KURRI AND THE FIRST ADSR EXPERIMENT’, IPAC’10

Also RACE and TRIGA/TRADE planned experiments, e.g. Gabrieli, D'Angelo, Nucl. Eng. Design, 239, 2349 (2009)
Proof-of-principle proton FFAG (KURRI test ADSR, Japan)

Proof-of-principle ns-FFAG (EMMA experiment, UK)

FFAG Particle Dynamics – James Jones, James Garland (University of Manchester) (in conjunction with Cockcroft Institute and STFC Daresbury Laboratory)
ADSR Research in the UK: Core/Target Options

Geoff Parks, Ali Ahmad, Leo Goncalves

Fast spectrum (lead-cooled)

Thermal spectrum (water-cooled)

Power flattening with multiple targets
GEANT4 general particle transport code modified to model simultaneous spallation and fuel evolution

C. Bungau et al., STUDY ON NEUTRONICS DESIGN OF AN ACCELERATOR DRIVEN SUBCRITICAL REACTOR’, IPAC’10

Also work by L. Goncalves at Cambridge - http://agenda.hep.manchester.ac.uk/conferenceDisplay.py?confId=1550
UK civil research reactor
100 kW, ~1m³ core

$^{235}$U plate fuel

Coupled to 230 MeV proton cyclotron via solid W target

ICIS – 25mm x ~6m (to final quad)

180 deg irradiation tube - 145mm x ~2.5m (to final quad)
The Fission Reaction Dies Out When The Accelerator Stops?

“An ADS drives nuclear reactions that will stop if the proton beam from the accelerator stops”
Nuclearinfo.net

“If the particle beam is switched off, it is impossible for the fuel to enter a chain reaction and cause a meltdown. Instead, the rate of fission will immediately begin to slow and the fuel will eventually cool down and die out”
COSMOS magazine

Courtesy of David Coates, Cambridge
Critical and ADS Shut-down

**Critical – Control Rod Insertion**

1) Has an inherent reduction in the reactivity of the system as a direct consequence of the action
2) Intrusive – requires a clear path

**ADS- Accelerator Trip**

1) No associated inherent reduction in the reactivity of the system
2) Non intrusive
3) The system must be sub-critical for this to work

The ADS trip requires the reactor to be sub-critical and remain sub-critical to be effective

Courtesy of David Coates, Cambridge
ADS operating modes to compensate for reactivity variations:

1) Use rods to continually flatten the reactivity variations and maintain fixed $k_{\text{eff}}$

2) Use fixed rods to set maximum $k_{\text{eff}}$ and use the accelerator to compensate for reactivity movements

Note: The bare reactor is critical and requires rods to achieve sub-critical operation
Thorium Reactor – Post Shutdown Criticality Increase

Criticality ($k$) vs. Time (days) for different keff values:

- keff 0.9990
- keff 0.9980
- keff 0.9970
- keff 0.9960
- keff 0.9950
- keff 0.9940
- keff 0.9930
- keff 0.9920
- keff 0.9910
- keff 0.9900
- keff 0.9898
- keff 0.9895
- keff 0.9890

Criticality ($k$) increases over time as the reactor approaches criticality.
Thorium Reactor – Post Shutdown Power Increase

Point in time at which the accelerator is switched off

The analyses are discontinued at the point at which the reactor reaches criticality.
Thorium Reactor – Post Shutdown Time to Criticality

Time (days) vs. keff
ADTR

- 1st demonstration of ADSR
- Reactor kinetic studies (load-following)
- Source-jerk $k_{eff}$ measurement (ADTR concept)
- Fuel irradiation measurements
**KUCA at KURRI**

**Figure 1.** KUCA core configuration of ADS experiments (Reference core)

**Fig. Side view of ADS core in KUCA A-core**
UK Civil Research Reactors closed:

**Harwell**: Dido, Pluto, GLEEP

**Winfirith**: SGHWR, Nester, Dimple

**Scottish Universities**: UTR300

**ICI**: TRIGA….. etc.

Remaining facility:

**Imperial College**: Consort
CONSORT Reactor

Power: 100kW (max thermal)
Type: Open pool
Moderator: Light water (coolant)
Fuel: MTR Type
Excess Reactivity: 1.5% max at 100kW
Commissioned: 1965
Control Absorbers: Four: 1 Safety Rod (Cd); [rod worth ~2%]
                        2 Coarse Rods (Cd) [rod worth ~2%]
                        1 Fine Rod (SS) [rod worth ~0.5%]
Licensee: Imperial College of Science, Technology & Medicine
**CONSORT History**

1963  
Government funding secured

1964 - 1965  
Construction and commissioning  
(designed by Imperial College Nuclear Power Group with GEC; constructed by W.E. Chivers Ltd)

1965  
9th April first criticality established  
(Nuclear Site Licence No. 7B issued December 1968)

1965 - 1983  
Operated as a stand alone centre for University of London

1983 - 1997  
Centre for Analytical Research in the Environment (Imperial College of Science Technology & Medicine)

2005  
40th Anniversary

1965 - 2008  
Continual operations (academic, R&D and commercial/industrial applications)

2008  
31st March planned cessation of operations

2009 (Nov)  
Return to critical operations
ADS Coupling Issues
**Aims:**
- 1\textsuperscript{st} demonstration of ADSR at significant power
- Reactor kinetic studies (load-following)
- Source-jerk $k_{\text{eff}}$ measurement (ADTR concept)
- Fuel irradiation measurements

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**Core Layout**

- **Proton Beam**
- **RB Coarse (Cd)**
- **RF Fine (SS)**
- **RS Safety (Cd)**
- **RA Coarse (Cd)**

---

- Insert C/F rods to 60cm: $k_{\text{eff}}=0.9872+/-.0009$
  - MCNPX multiplication is 68.4 (nout/nin)
Approximate parameters

Assuming $k=0.98$

<table>
<thead>
<tr>
<th>$E$ (MeV)</th>
<th>$I$ (uA)</th>
<th>Target (kW)</th>
<th>Reactor (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>230</td>
<td>50</td>
<td>11.5</td>
<td>100</td>
</tr>
<tr>
<td>230</td>
<td>5</td>
<td>1.5</td>
<td>10</td>
</tr>
<tr>
<td>230</td>
<td>1</td>
<td>0.23</td>
<td>2</td>
</tr>
</tbody>
</table>

Bruker (ACCEL) COMET
3.4 m diam, 90 ton, 0.8 uA @ 250MeV
U9-Mo and U$_3$Si$_2$ Fuels

![Graph of U235 Enrichment vs Volume Aluminium for U9-Mo Fuel Meat](image1)

![Graph of Al Volume vs Keff for U9-Mo Fuel Meat](image2)

![Graph of Al Volume Fraction vs Keff for U3Si2](image3)
Rod Worths

- Rod A
  - % Reactivity vs. Withdrawal /cm for U-Al (●) and U-9Mo (△)

- Safety Rod
  - % Reactivity vs. Withdrawal /cm for U-Al (●) and U-9Mo (△)

- Rod B
  - % Reactivity vs. Withdrawal /cm for U-Al (●) and U-9Mo (△)

- Fine Rod
  - % Reactivity vs. Withdrawal /cm for U-Al (●) and U-9Mo (△)
Target Concept

Vacuum 100 mm 50 mm 60 mm
Al collar around W plug
Reactor tank wall
First fuel element
Air circulation
Cooling water circuit in Al vacuum pipe

Concrete

p +

Vacuum

p +

Water coolant/moderator

(Removable) Cd Control Rod

Al collar around W plug

50 mm 100 mm

Table 5: Neutron yields from different targets using incident protons scaled from existing simulations to deliver \times 13 n as desired for CONSORT. The current required for CONSORT is compared to that achieved in proposed in the case of TRADE. Lower energy protons result in an impractical target power, whilst the use of GeV protons is discounted because of the size and capital cost of the accelerator, irrespective of the achievable current. A tws MeV high current proton cyclotron is under development by ENEA/IBA, but is not yet demonstrated. We note that there is significant discrepancy in the expected \times 7 Li and \times 7 Be yield between the quoted values from Culbertson et al. and those of Kononov et al. The current required for CONSORT is compared to that achieved in proposed in the case of TRADE. Lower energy protons result in an impractical target power, whilst the use of GeV protons is discounted because of the size and capital cost of the accelerator, irrespective of the achievable current. A tws MeV high current proton cyclotron is under development by ENEA/IBA, but is not yet demonstrated. We note that there is significant discrepancy in the expected \times 7 Li and \times 7 Be yield between the quoted values from Culbertson et al. and those of Kononov et al.

<table>
<thead>
<tr>
<th>Target</th>
<th>E /MeV</th>
<th>n/p</th>
<th>I /\mu A (ach.)</th>
<th>I /\mu A (req.)</th>
<th>Power /W</th>
<th>p/s</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>2.8</td>
<td>0.0009</td>
<td>1000</td>
<td>2000</td>
<td>5600</td>
<td>1.25 \times 10^{16}</td>
<td>Culbertson et al. (2004)</td>
</tr>
<tr>
<td>Be</td>
<td>30</td>
<td>0.019</td>
<td>60 to 250</td>
<td>96</td>
<td>2885</td>
<td>6.01 \times 10^{14}</td>
<td>Abbas et al. (2009)</td>
</tr>
<tr>
<td>W</td>
<td>140</td>
<td>0.75</td>
<td>(200-300)</td>
<td>2.4</td>
<td>336</td>
<td>1.50 \times 10^{13}</td>
<td>Herrera-Martinez et al. (2007)</td>
</tr>
<tr>
<td>W</td>
<td>230</td>
<td>1.8</td>
<td>0.8 to 1.0</td>
<td>1</td>
<td>230</td>
<td>6.25 \times 10^{12}</td>
<td>this work</td>
</tr>
<tr>
<td>Pb</td>
<td>1000</td>
<td>20</td>
<td>N/A</td>
<td>0.09</td>
<td>90</td>
<td>5.625 \times 10^{11}</td>
<td>Hilscher et al. (1998)</td>
</tr>
</tbody>
</table>
Where do the neutrons go?

Graph: 

- $n/p$ vs. Target Thickness [cm]
- Curves for different conditions

Diagram: 

- Water (to fuel)
- Irradiation Tube
- Particles: n, p

In the diagram:

- 1: Irradiation Tube
- 2: Particles
- 3: Target Thickness

Water

The Cockcroft Institute
of Accelerator Science and Technology
Thermalisation in the Simple Model

Through 8.5 Cm water (Distance to Core)

From Target
Needs development of compact neutron instrumentation
Accelerator Requirements

Proton Energy ~ 1 GeV gives >20 spallation neutrons per proton.

For 1GW thermal power:

- Need $3 \times 10^{19}$ fissions/sec (200 MeV/fission)
- $6 \times 10^{17}$ spallation neutrons/sec ($k=0.98$ gives 50 fissions/neutron)
- $3 \times 10^{16}$ protons/sec

Current 5 mA. Power = 5 MW

Reliable! Spallation target runs hot. If beam stops, target cools and stresses and cracks: no more than 3 trips per year – but this is a controversial number

Compare:

PSI cyclotron: 590 MeV, 2mA, 1MW

ISIS synchrotron: 800 MeV, 0.2mA, 0.1 MW

Several trips per day
Proton Driver Alternatives

- **Cyclotron**
  - Energy limited in classical cyclotron
  - Power perhaps achievable, but difficult
  - Reliability not good enough

- **Synchrotron**
  - Can’t yet achieve currents (RCS?)
  - More complicated (ramping magnets), therefore reliability probably low

- **Linac**
  - Can meet power requirements (e.g. 2x ESS)
  - May be reliable enough (loss of module okay)
  - But too expensive for commercial use

- **FFAG**
  - Can deliver currents in principle
  - Still quite large
  - Simpler than synchrotron
  - First proton FFAGs only built recently at KEK

(JAEA and MYRRHA demonstrators propose linac)
Proton Driver Performance

PSI Parameters: [2.2mA, 1.3MW] → [3mA, 1.8MW]
Synergies with UK HPPA Programme

- UK has a significant role in a number of high power proton accelerator projects – ESS, Neutrino Factory etc.
- IOP Proton Workshop -
- ISIS Upgrade - ADSR target/core studies?

1) Replace ISIS linac with a new ~180 MeV linac (~0.5MW)

2) Based on a ~3.3 GeV RCS fed by bucket-to-bucket transfer from ISIS 800 MeV synchrotron (1MW)

3) RCS design also accommodates multi-turn charge exchange injection to facilitate a further upgrade path where the RCS is fed directly from an 800 MeV linac (2 – 5 MW)

courtesy of J. Thomason (RAL)
Front-End Test Stand

FETS to test H\(^{-}\) sources, LEBT, RFQ and two-stage beam chopper
- 324 MHz linac based on Toshiba klystron
- Pulse repetition frequency 50 Hz
- Peak current \(\sim 60\) mA
- Pulse duration \(\sim 400\) \(\mu\)s
- Chopping 70%

Courtesy of C. Prior, ASTeC/RAL/Oxford

S. Lawrie et al. IPAC’10
High-Power Cyclotron Options – see Luciano’s Talk

<table>
<thead>
<tr>
<th>Accelerated Species</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>H+</td>
<td>Simpler ion source</td>
<td>Poor extraction efficiency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Auto-extraction limited to 85%?</td>
</tr>
<tr>
<td>H-</td>
<td>Stripping extraction</td>
<td>Lorentz stripping</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gas stripping</td>
</tr>
<tr>
<td>H2+</td>
<td>Stripping extraction</td>
<td>Lorentz stripping</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gas stripping</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Complex extraction path</td>
</tr>
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</table>

Favoured option: H2+
Calabretta et al., INFN-Catania
arxiv:1107.0652

<table>
<thead>
<tr>
<th>Rext</th>
<th>4.9m</th>
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<tbody>
<tr>
<td>&lt;B&gt;ext</td>
<td>1.88T</td>
</tr>
<tr>
<td>Bmax</td>
<td>&lt; 6.3 T</td>
</tr>
<tr>
<td>V</td>
<td>0.5-1 MV/turn</td>
</tr>
<tr>
<td>dE</td>
<td>3.6 MeV/turn</td>
</tr>
</tbody>
</table>
nsFFAGs

- Rapid acceleration
- Large acceptance
- Good dynamic range (factor 4-5 in momentum)
- Much smaller magnets
- EMMA Proof-of-principle being commissioned at Daresbury Laboratory

10-20 MeV \( e^- \), 42x FD, \( \sim 16 \)m

1 bunch @ 20 Hz, 20-40pC

Injected bunch 4/7 around the ring; rest of ring now being connected up.
ALICE and EMMA at Daresbury Laboratory

- Nominal Gun Energy: 350 keV
- Injector Energy: 8.35 MeV
- Max. Energy: 35 MeV
- Linac RF Frequency: 1.3 GHz
- Max Bunch Charge: 80 pC
- Emittance: 5-15 mm-mrad
Cyclotrons

PSI Cyclotron
590 MeV
2.2 mA, 1.3 MW
From the Cyclotron onwards

- **Cyclotron**
  *Isochronous*
  *(varying mag. field)*

- **Synchrotron**
  *Const. closed orbit*
  *(varying mag. field)*

- **FFAG**
  *Varying closed orbit*
  *(const. mag. field)*
- Orbit offsets are proportional to the dispersion function:
  \[ \Delta x = D_x \times \frac{\delta p}{p} \]

- To reduce the orbit offsets to ±4 cm range, for momentum range of \( \frac{\delta p}{p} \sim \pm 50\% \) the dispersion function \( D_x \) has to be of the order of:
  \[ D_x \sim \frac{4 \text{ cm}}{0.5} = 8 \text{ cm} \]

Narrowly-spaced orbits mean time-based extraction must be used in most cases
- Pulsed kicker/septum magnets
Possible Applications of ns-FFAGs

Neutrino Factory
e.g. NIM A 503, 301 (2003)

PAMELA Non-Scaling FFAG for Proton/Carbon Therapy
K. Peach et al., IPAC’10, www.jacow.org
70-250 MeV p
110-450 MeV/u C
1 kHz

DAEδALUS: Neutrinos via Stopped Pions
PRL 104, 141802 (2010)

Talks by M. Shaevitz & K. Scholberg at this conference

Subcritical Thorium-Fuelled Reactor
CERN AT/93-47
The EMMA Project

- BASROC – British Accelerator Science and Radiation Oncology Consortium

- CONFORM – The first project
  - **Build EMMA – the first non-scaling FFAG accelerator**
  - Design PAMELA – Hadron Therapy Machine

- Funded by Research Councils Basic Technology Grant
  - April 2007 -> March 2011
  - GBP 7.47 M (approx. $12.2M)

- International collaboration
  - Brookhaven, FNAL, LPSC Grenoble, TRIUMF
  - (UK) **Cockcroft Institute**, John Adams Institute, Science&Technology Facilities Council
## Project Milestones

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
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</thead>
<tbody>
<tr>
<td>Project start</td>
<td>Apr 2007</td>
</tr>
<tr>
<td>Major procurement contracts</td>
<td>May 2007 – Aug 2009</td>
</tr>
<tr>
<td>Off line build of modules</td>
<td>Oct 2008 – 15&lt;sup&gt;th&lt;/sup&gt; Jun 2010</td>
</tr>
<tr>
<td>Installation in Accelerator Hall</td>
<td>Mar 2009 - Sep 2009</td>
</tr>
<tr>
<td>Test systems in Accelerator Hall</td>
<td>Jul - Oct 2009</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; Beam down the Injection line</td>
<td>26&lt;sup&gt;th&lt;/sup&gt; Mar 2010</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; Beam through 4 sectors</td>
<td>22&lt;sup&gt;nd&lt;/sup&gt; Jun 2010</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; Circulating beam in EMMA</td>
<td>16&lt;sup&gt;th&lt;/sup&gt; Aug 2010</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; Accelerated beam in EMMA</td>
<td>Sep 2010</td>
</tr>
<tr>
<td>EMMA Experiments</td>
<td>Sep 2010 – Mar 2011</td>
</tr>
<tr>
<td>UK Basic Technology Grant completed</td>
<td>Mar 2011</td>
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# EMMA Structure and Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Energy range</td>
<td>10 – 20 MeV</td>
</tr>
<tr>
<td>Lattice</td>
<td>F/D Doublet</td>
</tr>
<tr>
<td>Circumference</td>
<td>16.57 m</td>
</tr>
<tr>
<td>No of cells</td>
<td>42</td>
</tr>
<tr>
<td>Normalised acceptance</td>
<td>$3\pi$ mm-rad</td>
</tr>
<tr>
<td>Frequency (nominal)</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td>No of RF cavities</td>
<td>19</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>1 - 20 Hz</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>16-32 pC</td>
</tr>
<tr>
<td>Cavity Voltage</td>
<td>2.3 MV/turn</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>5-20 Hz</td>
</tr>
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</table>
Flexible EMMA Design

(1) Rapid acceleration with large tune variation (natural chromaticity)

(2) Serpentine acceleration (results from parabolic ToF)

(3) Map the transverse and longitudinal acceptances.
Different Lattice Configurations are Needed

<table>
<thead>
<tr>
<th>Lattice</th>
<th>ToF minimum</th>
<th>Resonances crossed</th>
<th>3ν_y=1</th>
<th>ν_y+2ν_y=1</th>
<th>ν_y-2ν_y=0</th>
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<td>070221d</td>
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<td>070221f</td>
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<td>070221g</td>
<td>15.5 MeV</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>070221h</td>
<td>14 MeV</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>070221i</td>
<td>15.5 MeV</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

retune lattice to vary resonances crossed during acceleration

Time of Flight vs Energy

retune lattice to vary longitudinal Time Of Flight (TOF) curve, range and minimum
**EMMA Cell**

- **Low Energy Beam**
- **High Energy Beam**

**Dimensions:**
- **Long drift:** 210 mm
- **F Quad:** 58.8 mm
- **Short drift:** 50 mm
- **D Quad:** 75.7 mm

**Features:**
- 42 identical doublets
- Beam stay clear aperture
- Independent slides
EMMA Layout

RF distribution
17 hybrid and phase shifter
waveguide modules

Injection Septum 65°
Kicker

Kicker

RF Cavities
x 19

YAG Screen

Septum & kicker
power supplies

Extraction Septum 70°
Kicker

Septum & kicker
power supplies

Wall Current Monitor

EMMA RING

YAG Screen

D Quadrupole x 42
F Quadrupole x 42
BPM x 81
16 Vertical correctors
### Major Challenge: Injection and Extraction

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum beam deflection</td>
<td>105</td>
<td>mrad</td>
</tr>
<tr>
<td>Horizontal good field region</td>
<td>± 23</td>
<td>mm</td>
</tr>
<tr>
<td>Minimum vertical gap at the beam</td>
<td>25</td>
<td>mm</td>
</tr>
<tr>
<td>Horizontal deflection quality</td>
<td>± 1</td>
<td>%</td>
</tr>
<tr>
<td>Minimum flat-top (+0, -1%)</td>
<td>≈ 5</td>
<td>ns</td>
</tr>
<tr>
<td>Field rise/fall time (100% to 1%)</td>
<td>&lt; 50</td>
<td>ns</td>
</tr>
<tr>
<td>Kicker magnet repetition rate</td>
<td>20</td>
<td>Hz</td>
</tr>
</tbody>
</table>

![Diagram of injection and extraction system with kicker magnets and septum]
Acceleration Results

Fixed Energy Measurement (Equivalent Momentum)

Beam pos (mm)

cell tune

Typical Measurements During Acceleration Of A Bunch
Acceleration Properties Using Fixed Energy Measurements

Direct E meas. on extraction line

- Beam pos (mm) vs. Cell
- Beam pos (mm) vs. Momentum (MeV/c)
- Cell tune vs. Momentum (MeV/c)
- Momentum (MeV/c) vs. Phase (degree)
Fast vs Slow Acceleration (ongoing simulations)

Measurements in Aug/Sep

0.16 MV/turn

1.6 MV/turn
Experimental Plan

- Cross individual and multiple resonances by performing variable speed synchrotron oscillations. Vary injection point to cross difference resonances and RF voltage to vary the speed at which resonances are crossed.

R. Baartman and G. Guignard developed a theory of resonance crossing. For integer resonance crossing the betatron amplitude growth is:

$$\Delta A = \frac{\pi}{\sqrt{Q_T}} \beta \frac{B_n}{B}$$

Where $Q_T$ is the tune change per turn at the crossing point, $\beta$ is the average beta function in the ring, $B$ is the average magnetic field and $B_n$ is the $n^{th}$ harmonic component of the field errors.

Zgoubi single particle simulations were carried out where one integer resonance was crossed, indicated by vertical lines in the plot to the left. Zgoubi simulations indicate a good agreement with Baartman formula thus far. Experimental data is keenly awaited.
Thankyou