EMMA
the World's First Non-Scaling FFAG Accelerator

Susan Smith STFC Daresbury Laboratory
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• What are ns-FFAGs? and Why EMMA?
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• EMMA goals and requirements
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INTRODUCTION
Project Overview

**BASROC** (The British Accelerator Science and Radiation Oncology Consortium, BASROC)

- **CONFORM** project (CONstruction of a Non-scaling FFAG for Oncology, Research, and Medicine)
- 4 year project April 2007 – March 2011
- 3 parts to the project
  - EMMA design and construction ~ £6.5m (~$9M)

**Electron Model for Many Applications (EMMA)**
  - PAMELA design study TH4GAC03, “Pamela Overview”, Ken Peach
  - Applications study
Applications of ns-FFAGs

Neutrino Factory

TU1GRC04 “FFAG Designs for the IDS…”, Scott Berg

High power proton driver

Proton & Carbon Therapy

TH4GAC03 “Pamela Overview”, Ken Peach

Dedicated Muon Source

Sub-critical Thorium Reactor

TU6PFP029 C. Bungau et al
WHAT ARE NON-SCALING FFAGS? WHY EMMA?
Scaling FFAGs

- **Fixed Fields** => Rapid acceleration
- **Alternating Gradient** => Reduced magnet apertures compared to cyclotron
- Large 6D acceptance
  - High average and peak beam currents
- Beam can be extracted at a number of energies
- **Fixed tunes**
- Fixed orbit shape (largely increases with radius)
- **Variable time of flight**
Non-scaling FFAG

• Born from considerations of very fast muon acceleration
  – Breaks the scaling requirement
  – More compact orbits ~ X 10 reduction in magnet aperture
  – Betatron tunes vary with acceleration (resonance crossing)
  – Parabolic variation of time of flight with energy
    • Factor of 2 acceleration with constant RF frequency
    • Serpentine acceleration

• Can mitigate the effects of resonance crossing by:-
  – Fast Acceleration ~15 turns
  – Linear magnets (avoids driving strong high order resonances)
    • Or nonlinear magnets (avoids crossing resonances)
  – Highly periodic, symmetrical machine (many identical cells)
    • Tight tolerances on magnet errors dG/G <2x10^{-4}

Novel, unproven concepts which need testing
Electron Model => EMMA!
Muon Acceleration Model

• EMMA was originally conceived as a model of a 10-20 GeV muon accelerator

• Designed to demonstrate that linear non-scaling optics work and to make a detailed study of the novel features of this type of machine

• Variable tunes with acceleration

• Parabolic variation of time of flight with energy
  - Serpentine acceleration
THE INTERNATIONAL COLLABORATION
EMMA International Collaboration

• EMMA design is an international effort and we recognise and appreciate the active collaboration from:
  – Brookhaven National Laboratory
  – Cockcroft Institute UK
  – Fermi National Accelerator Laboratory
  – John Adams Institute UK
  – LPSC, Grenoble
  – Science & Technology Facilities Council UK
  – TRIUMF
EMMA GOALS AND REQUIREMENTS
EMMA Goals

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

(2) Serpentine acceleration (results from parabolic ToF)

(3) Map the transverse and longitudinal acceptances.

Graphs courtesy of Scott Berg BNL
Lattice Configurations

Understanding the NS-FFAG beam dynamics as function of lattice tuning & RF parameters

- Example: retune lattice to vary resonances crossed during acceleration

Time of Flight vs Energy

- Example: retune lattice to vary longitudinal Time of Flight curve, range and minimum

Graphs courtesy of Scott Berg BNL
Accelerator Requirements

- Injection & extraction at all energies, 10 - 20 MeV
- Fixed energy operation to map closed orbits and tunes vs momentum
- Many lattice configurations
  - Vary ratio of dipole to quadrupole fields
  - Vary frequency, amplitude and phase of RF cavities
- Map longitudinal and transverse acceptances with probe beam

EMMA to be heavily instrumented with beam diagnostics
LAYOUT AND LATTICE
ALICE

Accelerators and Lasers In Combined Experiments

Parameter | Value
---|---
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

EMMA

TU5RFP083 “Progress on ALICE Commissioning…” Yuri Saveliev

EMMA May 2009

Susan Louise Smith
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<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 transverse 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 per single bunch</td>
</tr>
</tbody>
</table>
EMMA Ring

RF distribution
17 hybrid and phase shifter waveguide modules

Extraction Septum 70°
Kicker
Kicker

Septum & kicker power supplies

Wire Scanner
Wall Current Monitor
EMMA RING

YAG Screen
Wire Scanner

RF Cavities x 19

YAG Screen

D Quadrupole x 42
F Quadrupole x 42
BPM x 82
16 Vertical correctors

90kW IOT racks

Injection Septum 65°
Kicker
Kicker

Septum & kicker power supplies
EMMA Ring

RF distribution
17 hybrid and phase shifter waveguide modules

Extraction Septum 70°
Kicker
Kicker

Septum & kicker power supplies

~ 5 m

Injection Septum 65°
Kicker
Kicker

RF Cavities x 19

YAG Screen

D Quadrupole x 42
F Quadrupole x 42
BPM x 82
16 Vertical correctors

90kW IOT racks

Instrumentation:
Wire Scanner
YAG Screen
Wall Current Monitor
D Quadrupole x 42
F Quadrupole x 42
BPM x 82
Kicker
Power Supplies

EMMA May 2009

Susan Louise Smith
EMMA Ring Cell

- 42 identical cells
- Cell length 395 mm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Long drift</td>
<td>210 mm</td>
</tr>
<tr>
<td>F Quad</td>
<td>58.8 mm</td>
</tr>
<tr>
<td>Short drift</td>
<td>50 mm</td>
</tr>
<tr>
<td>D Quad</td>
<td>75.7 mm</td>
</tr>
</tbody>
</table>

Beam stay clear aperture

Low Energy Beam

High Energy Beam
EMMA Ring Cell

42 identical cells
Cell length 395 mm

<p>| | |</p>
<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
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<td>Long drift</td>
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<tr>
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<td>50 mm</td>
</tr>
<tr>
<td>D Quad</td>
<td>75.7 mm</td>
</tr>
</tbody>
</table>

Low Energy Beam

High Energy Beam

Magnet Centre-lines

Beam stay clear aperture
A 6 Cell Girder Assembly

- F Magnet
- D Magnet
- Cavity
- Location for diagnostics
- Ion Pump
- Girder
- Beam direction
MAGNETS & MAGNET CHALLENGES

Talk TU1RAI02 Neil Marks, “Non-Scaling FFAG Magnet Design Challenges”
Ring Quadrupole Magnets

Requirements / Design

• Adjust dipole & quadrupole components independently
  – Mount magnets on independent radial linear slides
• Fields identical in every cell despite kickers and septum
  – Field clamps at cell entrance face of QD & exit face of QF
• Very large good field region for range of orbits
  – Optimised pole profile
Prototype Ring Magnets

- Good field gradient quality requirement is ± 1.0% over a good gradient region of
  - QF  +15.8, -32.0 mm
  - QD  -56.0, -9.9 mm
Production Quadrupole Status

- Magnet construction is complete
- QF x 34 delivered
- QD x 34 delivered
- Field measurements are in progress on the remaining 16 magnets
- Complete delivery scheduled for the end of May
Injection & Extraction

- Large angle for injection (65°) and extraction (70°) very challenging !!
- Injection/Extraction scheme required for all energies (10 – 20 MeV)
- Many lattices and many configurations of each lattice required
- Very limited space between quadrupole clamp plates for the septum and kickers construction

Extensive 3D magnet modelling conducted to minimise the effect of stray septum fields on circulating beam
Injection Region

Kicker

Septum 65°
Septum Design

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum beam deflection angle</td>
<td>77 degrees</td>
</tr>
<tr>
<td>Maximum flux density in gap</td>
<td>0.91 T</td>
</tr>
<tr>
<td>C core magnet gap height</td>
<td>22.0 mm</td>
</tr>
<tr>
<td>Internal horizontal beam 'stay-clear'</td>
<td>62.5 mm</td>
</tr>
<tr>
<td>Turns on excitation coil</td>
<td>2</td>
</tr>
<tr>
<td>Excitation half-sine-wave duration</td>
<td>25 µs</td>
</tr>
<tr>
<td>Excitation peak current</td>
<td>9.1 kA</td>
</tr>
<tr>
<td>Excitation peak voltage</td>
<td>900 V</td>
</tr>
<tr>
<td>Septum magnet repetition rate</td>
<td>20 Hz</td>
</tr>
</tbody>
</table>

- Inject/Extracts from 10-20 MeV
- For all lattice configurations
Kicker

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum beam deflection</td>
<td>105</td>
<td>mR</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>

- Inject/Extracts from 10-20 MeV
- For all lattice configurations (Amplitude range including polarity changes)
- Explore the large EMMA horizontal acceptance
- Correction initial horizontal trajectory during acceleration
## Kicker Magnet, Fast Switching

Kicker Magnet Power Supply parameters

With compact design and require:

- Fast rise / fall times **35 nS**
- Rapid changes in current **50kA/μS**
- Constraints on pre and post pulses

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet length</td>
<td>0.1m</td>
</tr>
<tr>
<td>Field at 10MeV (Injection)</td>
<td>0.035T</td>
</tr>
<tr>
<td>Field at 20MeV (Extraction)</td>
<td>0.07T</td>
</tr>
<tr>
<td>Magnet Inductance</td>
<td>0.25μH</td>
</tr>
<tr>
<td>Lead Inductance</td>
<td>0.16μH</td>
</tr>
<tr>
<td>Peak Current at 10/20MeV</td>
<td>1.3kA</td>
</tr>
<tr>
<td>Peak Voltage at Magnet</td>
<td>14kV</td>
</tr>
<tr>
<td>Peak Voltage at Power Supply</td>
<td>23kV</td>
</tr>
<tr>
<td>Rise / Fall Time</td>
<td>35nS</td>
</tr>
<tr>
<td>Jitter pulse to pulse</td>
<td>&lt; 2nS</td>
</tr>
<tr>
<td>Pulse Waveform</td>
<td>½ Sinewave</td>
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</table>

Prototype R&D led to a contract with APP for production units which are due for deliver end of June
DIAGNOSTICS
## Diagnostics (1)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Device</th>
<th>Number</th>
<th>Required resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam position</td>
<td>4 button BPM</td>
<td>2/plane/cell in ring 4 in injection 3 in extraction</td>
<td>50 μm</td>
</tr>
<tr>
<td>Beam profile</td>
<td>OTR / YAG screens</td>
<td>2 in ring, 6 in injection &amp; extraction line</td>
<td>20-30 μm pixel size</td>
</tr>
<tr>
<td>Beam profile</td>
<td>Wire scanners</td>
<td>2 in ring</td>
<td>10 μm</td>
</tr>
<tr>
<td>Beam current</td>
<td>Wall current monitor</td>
<td>1 WCM</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 scope</td>
<td></td>
</tr>
<tr>
<td>Phase</td>
<td>WCM</td>
<td>As above</td>
<td>10°</td>
</tr>
<tr>
<td>Transmission</td>
<td>WCM</td>
<td>As above</td>
<td>2%</td>
</tr>
</tbody>
</table>
## Diagnostics (2)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Device</th>
<th>Number</th>
<th>Required resolution</th>
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</thead>
<tbody>
<tr>
<td>Bunch charge</td>
<td>Faraday cup</td>
<td>1 at injection, 1 at extraction</td>
<td>2%</td>
</tr>
<tr>
<td>Beam loss</td>
<td>Beam loss monitor</td>
<td>4 in ring</td>
<td>2%</td>
</tr>
<tr>
<td>Momentum</td>
<td>BPMs and TOF from WCMs</td>
<td>Already included elsewhere</td>
<td>100 keV</td>
</tr>
<tr>
<td>Emittance</td>
<td>Tomography diagnostic</td>
<td>Injection &amp; extraction lines</td>
<td>10%</td>
</tr>
<tr>
<td>Extracted momentum</td>
<td>Spectrometer</td>
<td>1 (diagnostics line)</td>
<td>1%</td>
</tr>
<tr>
<td>Longitudinal profile</td>
<td>Electro-Optic system</td>
<td>1 (diagnostics line)</td>
<td>&lt;1 ps</td>
</tr>
</tbody>
</table>
DIAGNOSTICS BEAMLINE LAYOUT

FR5REP109 Bruno Muratori

BPMs at dipole entrance

Wall current monitor

EO diagnostic

Faraday Cup

YAG screen, vertical slit

YAG screen

Combined horizontal and vertical steering magnets x 3

Combined horizontal and vertical steering magnets x 2

Vertical steering magnets x 2

Spectrometer dipole, BPM, YAG screen

Beam Direction

First dispersive section

Matching section and possible TDC location

Tomography, EO and spectrometer section
Electron Beam Position Monitors

• The BPM electronics system has to deliver 50 μm resolution over a large aperture

• Locally mounted coupler cards
  – Amplifies signals from opposite buttons, coupler and strip line delay cables give a 12 ns delay, signals combined in single high quality coax

• Detector card in rack room outside of shielded area
  – Prototype tested and moving to a VME style card design

Prototype Coupler

RF Detector, Clock Control and ADC
• Standard vacuum chambers each covering 2 cells are being constructed at VG Scienta

• 12 chambers are delivered

• Remaining chamber are scheduled to be delivered in May
RADIO FREQUENCY
RF Requirements

• Voltage:
  – 20 - 120 kV/cavity essential, based on 19 cavities
  – Up to 180 kV/cavity desirable (future upgrade)

• Frequency:
  – 1.3 GHz, compact and matches the ALICE RF system
  – Range requirement 5.6 MHz

• Cavity phase:
  – Remote and individual control of the cavity phases is essential
Normal conducting single cell re-entrant cavity design optimised for high shunt impedance

Parameter | Value
---|---
Frequency | 1.3 GHz
Theoretical Shunt Impedance | 2.3 MΩ
Realistic Shunt Impedance (80%) | 2 MΩ
Q₀ (Theoretical) | 23,000
R/Q | 100 Ω
Tuning Range | -4 to +1.6 MHz
Accelerating Voltage | 120 kV
Total Power Required (Assuming 30% losses in distribution) | 90 kW
Power required per cavity | 3.6 kW
Cavity Construction

- Manufacture of prototype cavities and 19 production cavities completed by Niowave
- High quality manufacture including electron beam welding of body to reduce distortion
- Chemical etching adopted to improve Q (Qo 18,500 to 20,400)

Exceeds EMMA specification
RF Source

- A single 100kW (pulsed) IOT supplying the 19 RF cavities distributed around EMMA
- VIL409 high power RF amplifier system in 3 racks
- Tested to ensure required bandwidth
- Software and system tests are in progress
- Delivery scheduled for July 2009
Cascade RF Distribution

- 17 hybrid and phase shifter modules located around the EMMA ring in a cascade configuration splitting the RF power equally to 19 cavities
- Manufacture by Q-Par Angus is complete, tests in progress
- Delivery scheduled for June 2009
Low Level RF

- Stability of the accelerating field is provided by the LLRF
- Includes hardware and software to optimise the **amplitude** and **phase** during operation and for the **frequency** of operation to be set
- LLRF tests have been completed using:
  - CPI IOT at power level 5 kW
  - 2 EMMA cavities
  - Power split equally using a 3 dB hybrid and phase shifter waveguide module
    - Amplitude stability 0.006% (spec. 0.3%)
    - Phase stability 0.009° (spec. 0.3°)

**System required by September for full tests in October 2009**
ASSEMBLY STATUS
Off Line Assembly

Injection Line Modules

6 Cell Ring Module
1/7th of Circumference
ALICE Accelerator Hall

EMMA injection line

First 6 cell girder
EXPERIMENTS
Experiments

- Examine effects of resonance crossing and the importance of which resonance is crossed;

- **Measurement of TOF**, and minimum of TOF by changing the frequency until no synchrotron oscillations are seen and calculating the TOF from the frequency;

- Look at relationship of TOF to lattice parameters and tune and tune versus energy using BPM readings;

- **Map longitudinal & transverse phase**;

- **Benchmark lattice properties** achieved to the simulations;
  - Study the variation of “all parameters” to lattice properties;
  - Interpretation of BPM readings;
  - Examine phase space at injection by changing septum and kicker settings to validate models;
  - Scan aperture in phase space with a pencil beam to paint the full acceptance of the EMMA ring (both longitudinally and transversely);
  - Explore acceptance with and without acceleration;
  - Benchmark measured dynamic aperture with and without acceleration against the simulations
SCHEDULE
## Schedule

<table>
<thead>
<tr>
<th>Activity</th>
<th>Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off line build of modules</td>
<td>Oct 2008 - Aug 2009</td>
</tr>
<tr>
<td>Installation in ALICE Accelerator Hall</td>
<td>Mar - Sep 2009</td>
</tr>
<tr>
<td>Test systems in Accelerator Hall</td>
<td>Jul - Oct 2009</td>
</tr>
<tr>
<td>Injection line ready for beam</td>
<td>Aug 2009</td>
</tr>
<tr>
<td>EMMA ring ready for beam</td>
<td>31st Oct 2009</td>
</tr>
<tr>
<td>1st beams in to EMMA</td>
<td>Nov 2009</td>
</tr>
</tbody>
</table>
SUMMARY
Summary

- Design phase of the project is complete
- Procurement is underway with major contracts placed
- Major components started to arrive in October 2008,
- Off-line build is in progress at Daresbury and installation of the ALICE to EMMA injection line is underway
- Will commission the injection line in late August
- Plan to deliver 1st electrons into the ring in November

A key aim is to:-

Show non scaling FFAG acceleration works, compare results with the theoretical studies and gain real experience of operating such accelerators

The next step will be to apply the lessons learnt to new applications!
Acknowledgements

Neil Bliss &

All the team

– STFC, Cockcroft Institute & John Adams Institute staff
– International Collaborators
– Commercial suppliers