EMMA, THE WORLD'S FIRST NON-SCALING FFAG ACCELERATOR

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Abstract

EMMA, the Electron Model with Many Applications, was originally conceived as a model of a GeV-scale muon accelerator. The non-scaling (ns) properties of resonance crossing, small apertures, parabolic time of flight (ToF) and serpentine acceleration are novel, unproven accelerator physics and require "proof of principle". EMMA has metamorphosed from a simple "demonstration" objective to a sophisticated instrument for accelerator physics investigation with operational demands far in excess of the muon application that lead to technological challenges in magnet design, rf optimisation, injection and extraction, and beam diagnostics. Machine components procured in 2008-09 will be installed March-August 2009 leading to full system tests September-October and commissioning with electrons beginning November 2009.

APPLICATIONS OF NS-FFAGS

FFAGs are like cyclotrons in that they accelerate without increasing the magnetic fields however to reduce magnet apertures they implement alternating gradient focussing. They were first proposed in the middle of the last century and demonstrations were made at that time with electrons [1,2,3,4]. Recently renewed attention has been given to the application of this type of accelerator, with proton acceleration being achieved at KEK [5]. So far these machines have been based on the scaling principle where the betatron tunes and orbit shape are kept constant during acceleration. In the late 1990s, motivated by consideration of the very rapid acceleration requirements for muons, the non-scaling concept was proposed. This new configuration achieves a more compact orbit by allowing the betatron tunes to vary throughout the acceleration. Initial designs did this using simple cells with purely linear magnets [6,7]. Serpentine acceleration demonstrated a mode of operation which allowed acceleration with constant RF frequencies over more than a factor of 2 in momentum [8,9]. These properties make ns-FFAGs a very attractive option for muon acceleration and for a diverse range of other applications. The PAMELA (Particle Accelerator for MEdicaL Applications) project is evolving the concept to produce a design for a proton and light ion accelerator for cancer therapy [10]. A ns-FFAG has also been adopted as apart of the baseline design of a Neutrino Factory [11] and they are being investigated as a possible options for an accelerator driver for subcritical reactors [12]. The applications of ns-FFAGs are being pursued actively within the CONFORM project, which holds a multi-million pound grant funding the construction of EMMA, the design study for PAMELA [13,14] and the study of wider reaching potential applications.

EMMA REQUIREMENTS

Although the physics of ns-FFAGs has been studied extensively, EMMA, an electron based demonstrator will provide an economic test-bed of this novel acceleration concept. The overall design of the EMMA ring has been driven from its roots as a demonstrator for an ns-FFAG for muon acceleration.

EMMA will be used to make detailed study and verification of the predictions and theories which underpin the ns-FFAG concept, such as, rapid acceleration with large tune variation (natural chomaticity) and serpentine acceleration. It will also be important to carefully map both the transverse and longitudinal acceptance. To do so EMMA must accommodate several machine configurations obtained varying both RF and magnet parameters as illustrated in Figure 1 [15]. These studies will require:-

- Full aperture injection and extraction at all energies
- Ability to run at fixed energy
- Independently variable dipole and quadrupole fields
- Variable RF frequency, amplitude and phase in all cavities.
- Mapping of longitudinal and transverse acceptance with the probe beam.
- A machine heavily instrumented with diagnostics.

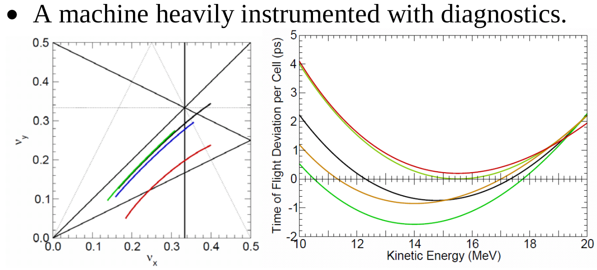

Figure 1: Left, single cell tunes for different lattice configurations. Right, varying the energy of the minimum time of flight.

These requirements along with the challenging constraints of a compact lattice and the overall budget for the project have driven the accelerator design and the specification of its technical systems.

DESCRIPTION OF EMMA

The main parameters for EMMA are given in Table 1. It is a so called linear ns-FFAG based on a doublet cell with linear magnetic fields provided by displaced quadrupoles. It has a high periodicity of 42 which is matched closely to the requirements for muon acceleration. The normalised acceptance of 3mm is scaled with the cell lengths to give the equivalent level of nonlinearities experienced within a typical 30 mm

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acceptance of a muon ring. Acceleration is provided by 19, 1.3 GHz RF cavities.

Table 1: EMMA Parameters

Energy range	10 to 20 MeV
Cell	Doublet
Number of cells	42
RF	19 cavities; 1.3GHz
Cell length	394.481mm
Ring circumference	16.57m
Normalised transverse acceptance	3 mm
Repetition rate	1 - 20 Hz
Bunch charge	16 - 32 pC

The energy range of 10-20 MeV provides a credible factor of 2 acceleration across an affordable energy range where the electrons are highly relativistic. With the specified bunch charge it should be possible to obtain accurate readings from the EMMA diagnostics systems while avoiding unwanted effects such as excessive beam loading and space charge.

The compact ring layout is shown in Figure 2 and an EMMA cell is illustrated in Figure 3. The cell length is 394.481 mm consisting of magnetic lengths QD 75.699 mm, QF 58.782 mm, a short drift of 50 mm and long drift 210 mm. The long drifts are required for RF cavities, kicker magnets, septum magnets, diagnostics devices and vacuum pumping.

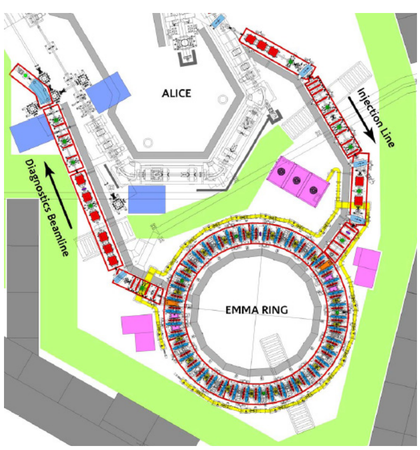

Figure 2: EMMA Layout

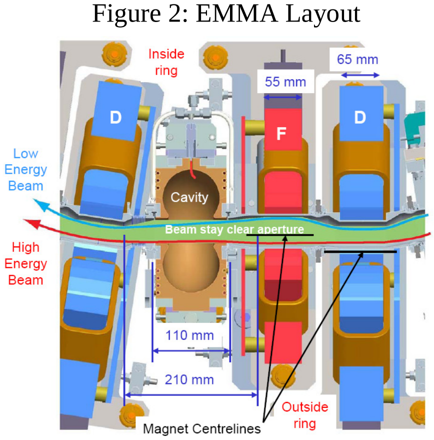

Figure 3: EMMA Doublet Cell

ACCELERATOR PHYSICS

The accelerator physics of the EMMA ring has already been extensively described elsewhere [15]. In this paper we would like to highlight recent analytic studies which use the EMMA ring to demonstrate a synchro-betatron approach for the description of the dynamics of particles in a ns-FFAG, based on a Hamiltonian formalisation. Figure 4 show the phase stability of the standard EMMA ring, for the central trajectory obtained applying this formulation [16].

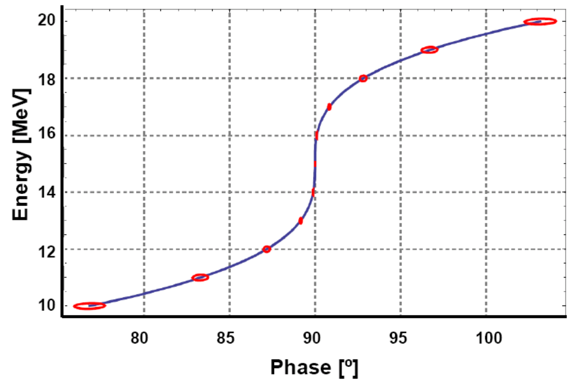

Figure 4: Phase stability of the standard EMMA ring, for the central trajectory at H0 = 0. The errors are given as 0.1MeV in energy and 1.3^{o} in phase.

Injection and extraction have been studied extensively to understand the relationship between the requirement to meet the experimental aims of EMMA and the specification of the pulsed magnets [17].

EMMA HARDWARE

Injection and Extraction

The ALICE accelerator delivers 10 to 20 MeV electrons to EMMA in a single 16-32 pC bunch. The injection line from ALICE is shown in Figure 5. As well as transporting beam and matching it to the EMMA ring it includes an extensive suite of diagnostics designed to characterise the beam [18, 19]. The line ends with a 65^{o} septum followed by 2 ring kickers. The large injection angle is necessary to avoid the complexity of the beam passing through variable fringe fields in the ring quadrupoles, since the magnets are translated to change the dipole field component of the quadrupoles.

The exploration of the full EMMA acceptance of 3mm rads with the 5-10 mm-mrad emittance ALICE probe beam will be done by a combination of horizontal and vertical phase space painting. The vertical painting is carried out by two corrector magnets towards the end of the transport line. The horizontal painting is achieved by using the two injection kickers inside the ring.

Extraction is initiated with two ring kickers followed by a 70^{o} septum, the extracted beam is characterised in the diagnostics line, which is extensively equipped with diagnostics devices as illustrated in Figure 6 [19].

Figure 5: ALICE to EMMA injection line

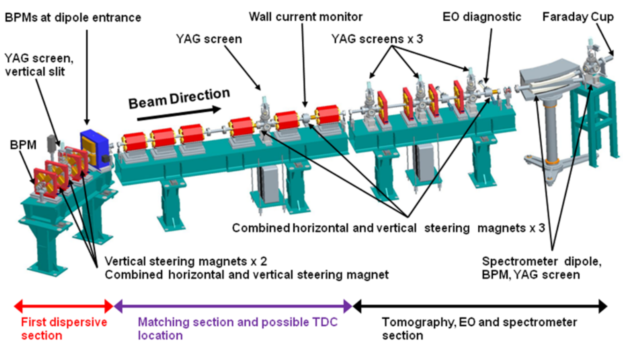

Figure 6: Layout of the EMMA extraction diagnostics line.

Pulsed Magnets

The challenging designs of the pulsed injection and extraction magnets, shown in Figure 7, are described in [20]. The septum magnet has to deliver 77° maximum deflection, with large vertical acceptance whilst minimizing the stay end fields. The laminations for the septum magnet are manufactured and the assembly and testing of the system will take place in-house.

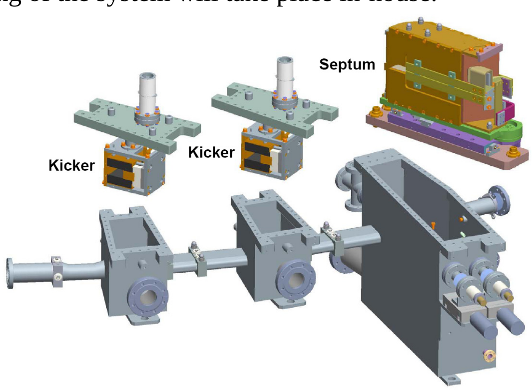

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Figure 7: In-house design of injection septum and kickers exploded from the vacuum chamber. Extraction is a mirror configuration.

The kicker magnet parameters are summarised in Table 2. The power supply specification is very demanding, including the need to switch the kickers in one turn, <50ns and provide a wide range of amplitudes. The requirements result in a very fast rate in change of current and optimised pre and post pulse currents to less than +/-1% of the peak current. A prototype kicker has been manufactured, tested and supplied to APP who have been awarded the contract to supply the power supplies, that will be matched to the kicker load. Initial test results are very encouraging.

Table 2: Main kicker magnet parameters.

Maximum beam deflection	105	mR
Horizontal good field region	± 23	mm
Minimum vertical gap at the beam	25	mm
Horizontal deflection quality	± 1	%
Minimum flat-top (+0, -1%)	≥5	ns
Field rise/fall time (100% to 1%)	50	ns
Kicker magnet repetition rate	20	Hz

Magnets

Although EMMA is a very compact accelerator covering a footprint of <6m diameter there are 156 magnets required for its accelerator ring, injection line and diagnostics line, Figure 7. By far the most challenging are the ring quadrupoles.

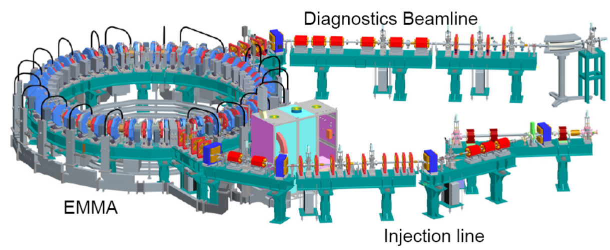

Figure 7: EMMA ring containing 42 F and D magnets.

The design of the short EMMA quadrupoles is extensively discussed in [20]. Figure 3 shows an EMMA quadrupole doublet located to the right of an RF cavity. There are field clamp-plates at either end of the doublet to prevent the end field penetrating into the straight section components. To reduce the variation in strengths between the ring magnets, the azimuthal positions of clamp plates are adjusted during the magnet measurements, providing a strength uniformity of $1{:}10^4$. The assembly of the quadrupoles on to the girders has now commenced. All 84 ring quadrupole magnets have been assembled, thermally and mechanically tested. Figure 8 shows a complete EMMA girder assembly with magnets and RF cavities. The final 16 quadrupoles are undergoing field measurements and are due for delivery in May.

Figure 8: EMMA Girder Assembly

Radio Frequency Systems

The RF system is described in detail in [21]. The 19 cavities in the EMMA ring are distributed in every other cell except for the injection and extraction regions. The parameters of the cavities are presented in Table 3 and shown in Figure 9.

Table 3: EMMA cavity parameters.

Parameter	Value
Frequency	1.3 GHz
Theoretical Shunt Impedance	2.3 MΩ
Realistic Shunt Impedance (80%)	2 MΩ
Q_0	23,000
R/Q	100 Ω
Tuning Range	-4 to +1.5 MHz
Accelerating Voltage	120 kV
Total Power Required (with 30% losses in distribution)	90 kW
Power required per cavity	3.6 kW

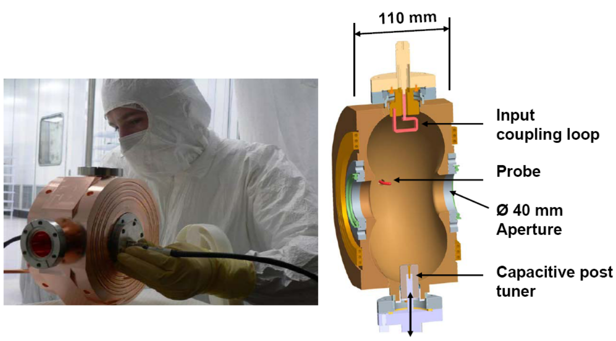

Figure 9: RF Cavity

The cavities are normal conducting single cell re-entrant cavity design optimised for high shunt impedance within the constraints of the compact EMMA lattice and beam aperture requirement. The high loaded Q values necessary to achieve the maximum voltages were achieved through tight control of the manufacturing process that included chemical etching. Measurements have been made on each of the 16 cavities so far delivered and the frequency bandwidth is greater than the 5.5 MHz specified.

The power source is a CPI IOT model CHK51320W. An evaluation of the IOT under pulsed conditions has proven it can meet the EMMA power requirements over the frequency range required. Production of the RF waveguide system which uses 17 hybrid and phase shifter waveguide modules to split the RF power in a cascade type system is manufactured. To evaluate amplitude and phase stability issues for the EMMA RF system, low level RF control system tests have been conducted, using 2 cavities, a Q-Par Angus hybrid module and a IOT. Initial results show phase stability (0.009°) and amplitude stability (0.006%), well within specification levels. A tender will be issued shortly for the EMMA system.

DIAGNOSTIC DEVICES

The electron beam diagnostic requirements for EMMA are provided by a number of devices. The multifunction instrumentation will provide all the positional information required to accurately and comprehensively understand the beam properties within the injection line, accelerator and diagnostics line. The devices include beam position monitors (BPM), wall current monitors (WCM), optical YAG screens, wire scanners, faraday cups and an electro-optic device [22] to measure longitudinal profile of the extracted beam.

The BPM electronics system has to deliver 50 μm resolution across the full horizontal acceptance and is by far the most challenging system. A locally mounted RF coupler takes its input from two opposite button pickups and amplifies these. By using coupler striplines and delay cables, these two signals are separated in time, then the two button BPM signal pulses some 12nS apart are multiplexed into the same output cable. These signals are then passed down a single high quality coaxial cable to the electronic detector card located in the EMMA rack room, outside of the accelerator shielding.

The design of this detector card is complete; Figure 10 shows the prototype electronics under test. Work is now progressing to move the design onto a VME style card that will take the inputs, from X and Y plane for each BPM from two coupler cards.

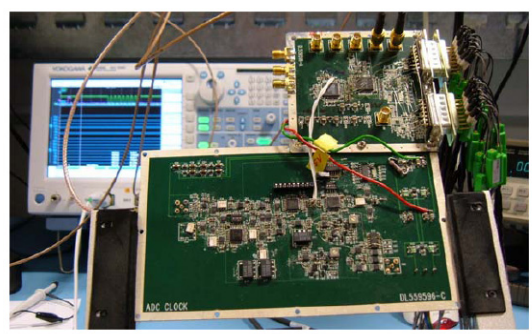

Figure 10: BPM RF Detector, clock control and ADC

STATUS AND PLANS.

Overall Status

The installation of EMMA within the ALICE accelerator hall is taking place in parallel to the operation of ALICE for accelerator and photon science R&D. The spring 2009 shutdown saw extensive cabling work and installation of the EMMA extraction dipole within the ALICE beam transport system. The injection line to EMMA is currently being installed and is expected to be commissioned with beam during the summer. The ring girder build off line is underway. Installation of these modules in the accelerator hall will take place over the coming summer, allowing the services, cabling, electrical and controls work to progress in parallel. It is expected that EMMA will be ready for commissioning with beam in late 2009.

Commissioning Plans

Commissioning an accelerator proceeds through a number of clearly defined stages, progress usually being dependent on the previous step being completed; however some iteration is also usually required. After the hardware is fully tested, the key activities will be operating the control system to manipulate and control the electron beam and particularly setting up the diagnostics and its associated data acquisition software (DAQ), controls and hardware. Initially, it will be necessary to ensure we can transport the beam in the machine to whichever location we want. Next, it is vital that we can measure all the bunch properties we desire so as to have as full a characterisation of the bunch's six dimensional phase space as possible. This goes hand-in-hand with ensuring that the machine itself is set up to be as close as possible to its designed operational parameters, such as making sure dispersion free straights are as described. There is a separate, dedicated paper on commissioning at this conference [23].

The Experiments

Accelerator physics experiments that could be carried out on this demonstrator to help prove the major principles of this type of ns-FFAGs are described [23]. It lists individual experiments covering the measurement and characterisation of both transverse and longitudinal dynamics at fixed energies and during acceleration. These would be carried out for the range of lattice configuration, the characteristics of which have been defined to deliver the EMMA experimental aims [15]. Completion of these experiments will be a fundamental step in proving the concept of ns-FFAGs, a promising candidate accelerator for a broad range of future applications.

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