EMMA DIAGNOSTIC LINE

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Abstract

EMMA (Electron Machine with Many Applications) is a prototype non-scaling electron FFAG to be hosted at Daresbury Laboratory. NS-FFAGs related to EMMA have an unprecedented potential for medical accelerators for carbon and proton hadron therapy. It also represents a possible active element for an ADSR (Accelerator Driven Sub-critical Reactor). This paper will summarize the design of the extraction / diagnostic transfer line of the NS-FFAG. In order to operate EMMA, the energy recovery linac ALICE shall be used as injector and the energy will range from 10 to 20 MeV. Because this would be the first non-scaling FFAG, it is important that as many of the bunch properties are studied as feasible, both at injection and at extraction. To do this, a complete diagnostic line was designed consisting of a tomography module together with several other diagnostic devices including the possibility of using a transverse deflecting cavity. Details of the trajectory correction as well as the diagnostics are also presented.

INTRODUCTION

Both the EMMA injection and extraction lines have already been designed [1, 2]. In this paper we look at the trajectory correction in both lines together with vertical steerers for the purpose of painting the EMMA phase space. The idea of phase space painting is to explore the acceptance of FFAGs as much as possible. This should be around 3 mm rad for EMMA or roughly three orders of magnitude with respect to the ALICE emittance. However, some recent studies [3] have shown that the predicted acceptance may not hold for every operational energy between 10 to 20 MeV.

We also look at the dedicated diagnostics line to be implemented at the extraction stage of the EMMA ring. The purpose of this line is to give as good as possible characterisation of the bunch exiting the EMMA ring. This is crucial to furthering our understanding of NS FFAGs and their highly non-linear dynamics.

TRAJECTORY CORRECTION

Injection

After the main ALICE linac, electron bunches travelling to EMMA will be at an energy ranging from 10 to 20 MeV. Just before the ALICE outward arc, the bunch is taken out of the ALICE lattice with a single dipole magnet and sent down the injection line. The dispersion generated by this dipole is closed with a reverse dipole bend in the dogleg. The bunch then goes through a tomography section where the transverse emittance may be measured and the transverse phase space reconstructed. The tomography module serves also to keep the beam size low and under good control for injection into the ring. For adequate phase reconstruction it is important to maintain a well corrected trajectory through this section. The strict requirements on the injection process also necessitate fine control over the trajectory as it passes the vertical painting steerers. It was initially envisaged to use the 3 dipoles as part of the correction scheme, but this was disregarded as limiting the flexibility of the system. The position of the dipole corrector magnets was optimised based on the minimisation of the trajectory at the key points in the line, and over several random seeds. The final positioning had to take into account the positioning of other element positions that had been defined. Differing numbers of correctors were also investigated, with the optimisation favouring 4 correctors. The positions of these correctors in the injection line are given in Figure 1. The trajectory is measured by the 7 YAG screens and 6 BPMs, placed at the beginning of every dipole.

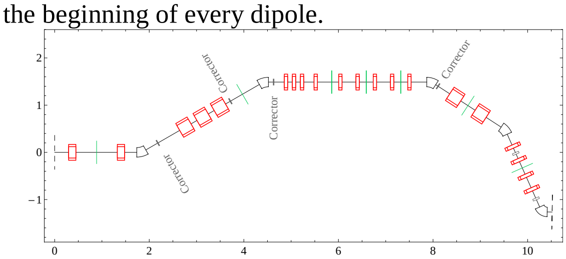

Figure 1: Positioning of EMMA injection line correction scheme.

Analysis of the efficiency of the correction scheme shows, Figure 2, that the maximum required kick is 7.5mrad, and that the trajectory is corrected to better than 1mm in all cases. The increase in dispersion is also small in both planes.

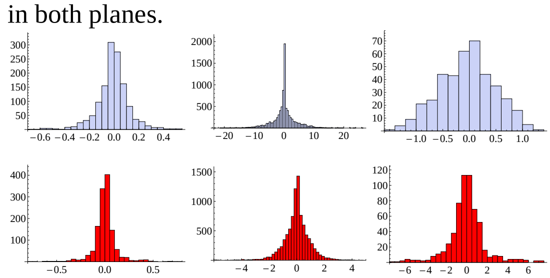

Figure 2: Injection line trajectory correction analysis.

Extraction

After circulation in the EMMA ring, the bunch is extracted via two kickers followed by an extraction septum. The extraction line has a similar layout to the injection line in terms of a dogleg, followed by a tomography section. As the engineering layout of the extraction line was less well developed, there was more flexibility on positioning of the corrector magnets. To maintain consistency with the injection line, the same corrector magnet design was assumed, and again 4 correctors provided the best balance between flexibility and cost. The layout of the extraction line and the positioning of the correctors is shown in Figure 3. Again the trajectory is measured by BPMs placed at the entrance to every dipole, as well as the 3 YAGs in the tomography section.

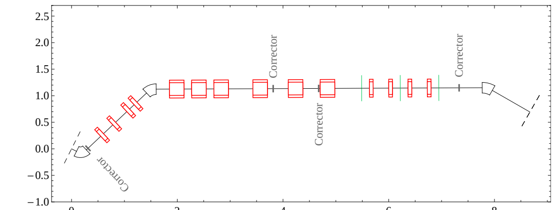

Figure 3: Positioning of EMMA extraction line correction scheme

Analysis of the efficiency of the correction scheme shows that similar to the injection line the maximum required kick is less than 7.5mrad. The trajectory error is smaller than the injection line due to better placement of the correctors.

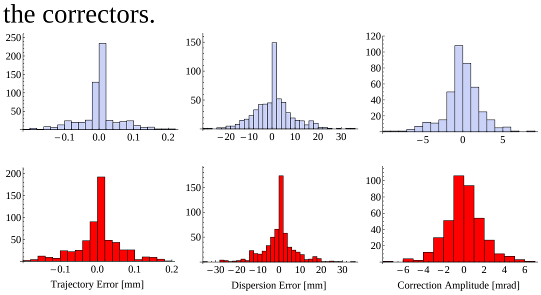

Figure 4: Extraction line trajectory correction analysis.

VERTICAL PAINTING STEERERS

Injection

Figure 5 shows the phase advance in the final straight of the EMMA injection line. It starts at the exit of the last dipole in the injection line and ends at the exit of the septum. The crosses either side of the short drifts represent the entry and exit points of the quadrupoles.

Due to engineering constraints, it is not possible to place the steerers exactly 90 degrees phase advance apart. Therefore the next best thing was to place them 60 degrees apart, namely roughly at locations at 1.02 m and 1.65 m from the exit of the last dipole, as shown in the figure above. Now, the displacement required at the exit of the septum covers the vertical septum aperture (22 mm), hence, if we start with the centroid in the middle, we require the steerers to give an 11 mm excursion.

The relevant component of the transport matrix for the kick given at the first steerer is R_{34} and is given by

$$R_{34} = \sqrt{\beta_1 \beta_2}\,\sin\Delta\mu$$

Assuming y_1 and y_1' are both zero at the location of the first kicker (so the beam is on-axis) and the kicks are represented by Δ_1 and Δ_2, respectively, we are left with the following equations to be solved

$$y_2 = R_{34}\Delta_1,\quad \Delta_2 = R_{44}\Delta_1$$

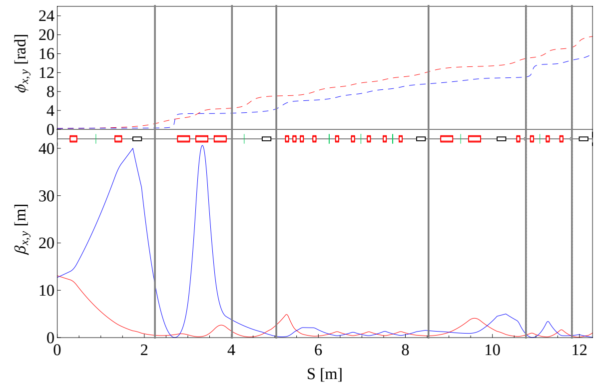

Figure 5 Twiss parameters in the horizontal (red) and vertical (blue) planes in the EMMA injection line, showing the corrector positions (gray lines) as well as the vertical steerers (gray, dashed).

from which we have

$$\Delta_1 = \frac{y_2}{R_{34}} = \frac{y_2}{\sqrt{\beta_1\beta_2}\,\sin\Delta\mu}$$

and

$$\Delta_2 = \frac{R_{44}y_2}{R_{34}} = \frac{y_2(\cos\Delta\mu - \alpha_2\sin\Delta\mu)}{\beta_2\sin\Delta\mu}$$

So, for the vertical plane we have β_1 = 3 m, β_2 = 0.5 m and α_2 = -0.4, hence R_{34} = 1.061 m and R_{44} = 2.07. This means Δ_1 is given by Δ_1 = 10.4 mm rad or 7.1 Gm at 20 MeV and so Δ_2 = 14.7 Gm at the same energy. So the steerers are specified at 17 Gm if contingency is added.

Extraction

Figure 6 shows the phase advance in the first straight of the EMMA extraction line. It starts at the exit of the extraction septum and ends at the entrance of the first dipole in the extraction line. The crosses either side of the short drifts represent the entry and exit points of the quadrupoles. The two steerers are located approximately 90° phase advance (in the vertical plane), one being located 0.6 m from the exit of the septum and the next being located at 1.4 m.

Therefore, using the same equations we have the following - bearing in mind that we now wish the beam to move in the opposite direction to earlier at the entrance of the EMMA ring:

For the vertical plane we have β_1 = 2 m, β_2 = 0.25 m and α_2 = 0.5, which means Δ_1 is given by Δ_1 = - 15.6 mm rad or -10.7 Gm at 20 MeV and so Δ_2 = 15.1 Gm at the same energy. So the two steerers in the extraction line can be specified as identical to those in the injection line which is 17 Gm**.**

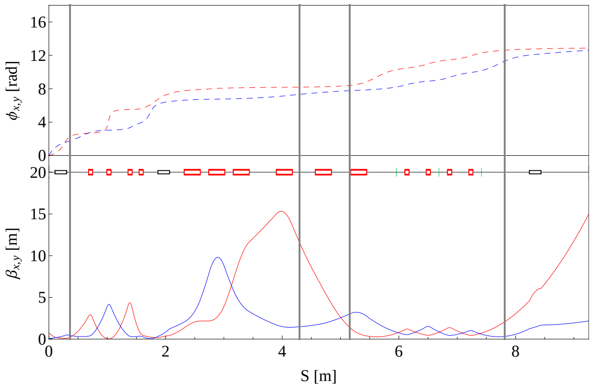

Figure 6 Twiss parameters in the horizontal (red) and vertical (blue) planes in the EMMA extraction line, showing the corrector positions (gray lines).

DIAGNOSTICS LINE

It is vital to be able to diagnose as much as possible of the six dimensional phase space of the electron bunch exiting the EMMA ring. To this end, the following diagnostics line has been designed. This consists of:

- Tomography module;
- Transverse deflecting cavity;
- Spectrometer dipole.

With these tools it is possible to make the following measurements:

- Transverse projected emittance (tomography module);
- Projected slice emittance and bunch length (one screen in the tomography module and TCD to provide streak);
- Energy and energy spread (spectrometer at the end of the line);
- Slice energy spread (spectrometer and TDC to provide streak).

As the bunch passes through the TDC, it receives a transverse kick. This transverse kick is a function of the longitudinal position along the bunch, *z*, and is approximately given by

$$\Delta x'(z) = \frac{eV_0}{pc}\sin(kz+\varphi) \approx \frac{eV_0}{pc}\left(\frac{2\pi}{\lambda} z\cos\varphi + \sin\varphi\right)$$

where V_0 is the peak voltage, p is the beam's longitudinal momentum in the structure, φ is the RF phase (0 ≡ zero crossing) and λ is the RF wavelength. Therefore, the resulting displacement at the screen is given by

$$\Delta x(z) \approx \frac{eV_0}{pc}\sqrt{\beta_d\beta_s}\sin\Delta\mu\left(\frac{2\pi}{\lambda} z\cos\varphi + \sin\varphi\right)$$

If we take the mean over all values of z and assume $\langle z\rangle = 0$, the transverse offset at the screen is

$$\langle\Delta x\rangle = \frac{eV_0}{pc}\sqrt{\beta_d\beta_s}\sin\Delta\mu\sin\varphi$$

Similarly, the beam size on the screen is

$$\sigma_x \equiv \left\langle\left(x-\langle x\rangle\right)^2\right\rangle^{\frac{1}{2}} = \sqrt{\sigma_{x_0}^2 + \sigma_z^2\beta_d\beta_s\left(\frac{2\pi eV_0}{\lambda pc}\sin\Delta\mu\cos\varphi\right)^2}$$

where σx is the nominal beam size on the screen (when the deflecting voltage is zero and the bunch is un-streaked). It may be seen that the second term in the expression for the beam size above is purely due to the deflection. Hence, for a meaningful resolution it should be that this term dominates the expression for the beam on the screen. Therefore we should have the following

$$eV_0 \geq \frac{\lambda}{\pi\sigma_z\,|\sin\Delta\mu\cos\varphi|}\sqrt{pcm_0c^2\frac{\varepsilon_N}{\beta_d}}$$

where we have used $\sigma_{x_0} = \sqrt{\beta_s\varepsilon_N/\gamma}$ with $\gamma = pc/m_0c^2$ and m_0 is the electron rest mass. Therefore, if we apply this formula to the desired EMMA parameters [4] ($\varepsilon_N = 3\mu m$, $\sigma_z = 4\,ps = 1.2mm$, $\beta_d = 10m$, $pc = 20MeV$) for a *1.3 GHz* cavity with a phase advance from cavity to screen of only 45°, we obtain that the peak deflecting voltage (eV_0) must be greater than *0.13 MV.*

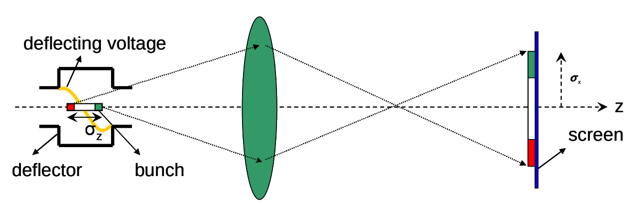

Figure 7: Physics of transverse deflecting cavity with interspersed quadrupoles.

CONCLUSIONS

The diagnostic line for the EMMA NS FFAG was specified together with two doublets of steerers either side of the ring for the purposes of painting the phase space of an EMMA bunch.

REFERENCES

[1] B.D. Muratori et al, "Injection and Extraction for the EMMA NS-FFAG", EPAC'08, Genoa, July 2008.

[2] S.L.Smith et al. "EMMA, the World's First Non-Scaling FFAG Accelerator", these proceedings.

[3] S.I. Tzenov (2008) Talk presented at FFAG'08, Manchester, September 2008.

[4] M. Röhrs et al. (2007) 'Time-Resolved Phase Space Tomography at Flash Using a Transverse Deflecting RF-Structure', Proceedings of PAC'07.