NEW INJECTOR FOR THE EMMA NS-FFAG RING

B.D. Muratori, STFC Daresbury Laboratory, ASTeC & Cockcroft Institute, UK

Abstract

EMMA is the world′s first non-scaling FFAG which has recently demonstrated acceleration in the serpentine channel. At present, the electron beam is injected into EMMA from the ALICE accelerator. However, funding will be redirected to an Electron Beam Test Facility (EBTF) in the near future, therefore, in order to continue the broad portfolio of planned experiments required to characterize non-scaling FFAGs, it essential to consider an alternative injector. The paper looks at some possible alternatives and how the required beam for injection into EMMA can be achieved.

THE NEED FOR A NEW INJECTOR

The EMMA experiment has been extremely successful and a new type of acceleration was demonstrated in April 2011 and published later that year [1]. It should be possible to apply this new type of machine in three main distinct areas. The first is for medical applications such as proton or hadron therapy - this is the subject of the PAMELA project which constitutes a natural follow-on from the EMMA accelerator [2]. The second application consists of using a ns-FFAG as an accelerator for a charged particle beam to send into an active element for an accelerator driven sub-critical reactor (ADSR). Finally, the last planned application is to use a ns-FFAG as a muon accelerator, both for MICE [3] or for a muon collider [4]. Because there are so many applications, there is a very strong incentive to try to learn as much as possible about the properties of ns-FFAGs and the physics behind them. In particular, it is very important to be able to study the relationship between the real machine and the various existing models - all of which are broadly similar but also subtly different. Due to a possibility of not continuing ALICE operation beyond March 2013, it is important to find other injector options for EMMA in order continue further research on ns-FFAGs, as this is the only available in the world so far. A summary of all known possibilities is given here together with an initial evaluation of each.

The easiest location to insert the new injector is just after the start of the present ALICE to EMMA injection line [5], in the tomography straight, after the dogleg, as shown in Fig. 1. The space requirements mean that the injector should be between 5 and 6 m long in order to fit comfortably in the same location as EMMA is currently located.

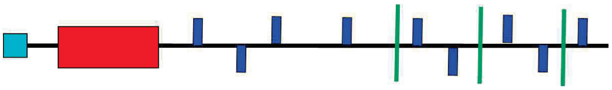

Figure 1: New Injector layout for EMMA: gun - blue, booster - red, quadrupoles - dark blue, YAG screens - green.

REQUIREMENTS

Most of the desired parameters for running EMMA are very similar to the ALICE ones for day to day operations and this is one of the reasons why ALICE was chosen as an injector for EMMA. The main required beam parameters for EMMA are listed briefly in the Table 1 below. The better the energy spread of the bunch coming from the new injector, the more precisely all the experiments can be done on EMMA.

Table 1: Main EMMA Injector Parameters

Parameter	Units	Value
Normalized transverse emittance	μm	$5-10$
Bunch length	ps	$4-10$
Bunch charge	pC	$40-80$
Beam energy	MeV	$10-20$
Energy spread	keV	< 20

DIFFERENT TYPES OF INJECTOR

There are several possibilities for injectors for EMMA. These range from a complete re-use of existing equipment to an entirely new injector. A typical injector consists of a gun, some solenoids to focus the beam, a buncher cavity and a booster cavity to accelerate the beam to relativistic energies. As far as electron guns are concerned, there are three main choices: RF gun, DC gun and thermionic gun. The booster cavity can be either super-conducting, as is the case on ALICE, or normal conducting. Very roughly, the difference between the two is that super-conducting cavities require a lot of overhead for the operation of the cryogenics which has to be left on all the time even when beam is not being run but it does lead to lower RF power losses leading to higher gradients and longer pulses being available. Super-conducting cavities also have an extreme damping of higher order modes. Below, we look at each main option in more detail.

RF gun and booster: An example of this set-up is the PITZ facility in DESY Zeuthen [6]. This is difficult to apply as an EMMA injector because there has never been an RF gun at Daresbury Laboratory so it would have to be purchased new. Further, an RF gun requires a UV laser to be operated and this would also have to be purchased new. Therefore, this option is discounted.

DC gun and booster: A typical layout for a DC gun is the ALICE injector. If the booster is super-conducting, then this is identical to continued ALICE operation. This is unlikely to happen due to the priority for ASTeC and Daresbury Laboratory being EBTF and CLARA [7, 8]. Therefore and as an alternative, the ALICE set-up was considered again, but this time feeding into a normal conducting booster cavity. This option will be further considered and modelled in detail below.

Thermionic gun and booster: There is the possibility of re-using the old SRS thermionic gun and linac [9, 10]. The SRS gun is an 80 kV triode gun with a peak intensity of at least 0.35 A and a bunch length of 1 ns, after two cavity choppers for a charge of less than 0.4 nC. Such a bunch would be very hard for the EMMA kickers to cope with as the bunch would no longer be short enough to be considered point-like, given the kicker pulse, and therefore an additional disruption would have to be taken into account. This gun was always operated in conjunction with a 3 GHz, $10 - 15$ MeV 2 m, $2\pi/3$ mode travelling wave linac. This linac has a total of 77 cells and is divided into three sections. The first 11 cells for a variable phase velocity buncher where the electrons, injected at 80 kV from the gun are accelerated to around 2 MeV and in the process are collected into bunches riding close to the peak of the accelerating field [10]. Cells 12 to 58 form the main accelerator for the bulk of the energy gain, the $\pi/3$ acceleration mode with 3 cells to the wavelength is used. Cells 59 to 77 are close pitched and form a lossy load section where left-over microwave power is absorbed. The linac also has two solenoids surrounding it in order to give additional focusing to the beam. The best performance ever of this linac gave an energy spread of ± 0.5 %, which, at 15 MeV is an order of magnitude worse than that delivered to EMMA at present (0.05 %).

Unfortunately, there are several things which are not optimal with this solution. Firstly, the choppers that were used in the SRS are essential in order to get a bunch length which is suitable for injection into EMMA and, even then, it is not ideal. This means that a considerable extra length of transfer line is required and this is very unlikely to fit in the present EMMA location. An attempt was made to introduce an additional buncher cavity in front of this linac to reduce the need for choppers and further reduce the bunch length but this led to multipacting. Secondly, the linac represents a single cavity with only two RF controls, namely, phase and voltage, despite the fact that it has three distinct sections, so there is very little control of the beam.

INJECTOR MODELLING

Some initial modelling at 80 pC was done using the space charge code ASTRA so as to get a better idea of the requirements of such an injector. As a starting point, it was assumed that the gun from ALICE and its beamline matching into the superconducting booster were available, this is described in [11] in detail. However, unlike ALICE, the booster was taken to be normal conducting. Several examples could have been chosen for such a normal conducting cavity but for the purposes of this model, a cavity based on the PITZ normal conducting booster was taken [6]. This is a 1.3 GHz standing wave, 14 cell accelerating cavity. From a modelling point of view, the fact that the booster cavities are super-conducting or not does not make too much difference qualitatively. However, as shown below, the fact that only one cavity was chosen restricts the achievable parameters.

The variables used to match the non-relativistic 350 keV beam into the first booster cells were: the buncher power, the second solenoid strength and the cavity phase. ASTRA was run many times, then, a plot of the scaled versions of all the six main parameters at the exit of the booster was made versus run number. The first solenoid strength is fixed due to a restricted aperture in the buncher which means that the beam is slightly over-focused at this location. In this way, it is easy to compare and see which run is the most favourable and what the trade-offs are. This plot is shown in Fig. 2, it represents 5 sets of 10 runs and the buncher power is decreased from 2.4 to 1.9 MV/m in steps of 0.1 MV/m, starting from the left, from one set to the next and the second solenoid is increased within a set from 170 G to 260 G in steps of 10 G, again starting from the left. From Fig, 2, it is possible to see that the best energy spread is achieved for the highest buncher power and the lowest second solenoid strength, but, at the expense of transverse emittance. However, it is unrealistic to have a buncher power higher than 2.3 MV/m, already this being rather high. It is possible to have a similar effect on the beam by trading off buncher power versus linac off-crest, by going to $-10\,^{\circ}$ instead of on-crest but, here too it is not sufficient to achieve the required energy spread within the existing limits of all the components. Less than $-10\,^{\circ}$ degrees off crest leads to a blow-up of the Twiss parameters and hence aperture problems, so cannot be done. Another possibility is to lower the gun gradient which would naturally lead to a smaller buncher power, however, this would lead to increased space charge problems. The main properties of the best run from Fig. 2 (# 301) are shown in

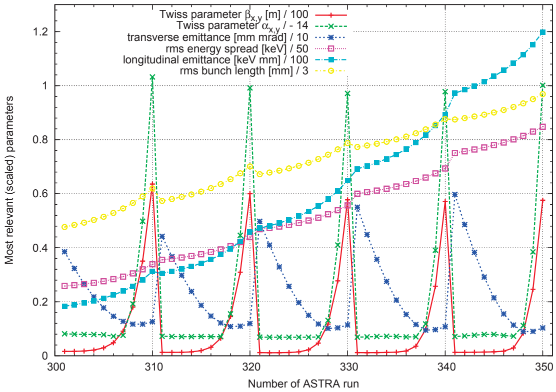

Figure 2: Multi-parameter plot at the exit of the booster.

Fig. 3, for the bunch dimensions and for emittances, below. The results for the parameters of the main components in the injector are summarized in Table 2 below. It is instructive to compare the output parameters at the exit of this booster with those modelled at the exit of the ALICE super-conducting booster and this is done in Table 3 below from which it can be seen that longitudinal emittance and bunch length are much easier to control if the booster consists of two cavities rather than just one. This means that it would be nice to match into a cavity consisting of just a few cells before the main booster cavity used above. This would give two additional parameters in the optimization, namely the gradient and phase of the additional cavity.

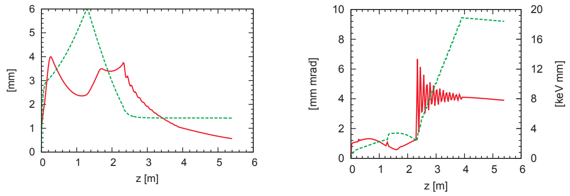

Figure 3: Left: Beam size (red) and bunch length; Right: transverse (red) and longitudinal emittance.

Table 2: Proposed Injector Parameters

Parameter	Units	Value
Laser spot size	mm	4.0
Laser pulse length	ps	28
Bunch charge	pC	80
Gun voltage	kV	350
1^{st} Solenoid	G	330
Buncher gradient	MV/m	2.4
Buncher phase	deg.	-90
2^{nd} Solenoid	G	170
Cavity gradient	MV/m	11.0
Cavity phase	deg.	0

Table 3: Design parameters at the exit of the booster with the ALICE and single normal conducting cavity set-ups.

Parameter	Units	ALICE Val.	New Val.
Energy	MeV	8.0	10.0
Emittance (N)	mm mrad	2.0	4.0
Bunch length	mm	1.3	1.5
E. spread (rms)	keV	7.7	13
L. Emitt. (N)	keV mm	10	18
$\beta_{x,y}$	m	39	1.0
$\alpha_{x,y}$		-5.9	-1.2

CONCLUSIONS

From the ASTRA models it can be seen that the suggested injector layout, together with the settings summarized in Table 3 should be capable of delivering the required beam parameters for EMMA operation. However, the parameters are not as good as those achieved using the ALICE injector as it is at present. This is essentially due to the booster consisting of two accelerating cavities in ALICE whereas the model presented here only has one. Therefore, the best scenario would be to have two cavities for the booster rather than just one. This could be achieved in several ways: the first is to have an EMMA type cavity or two before the 14 cell accelerating structure, the second is to divide the 14 cell linac into two. Another option would be to build a cavity based on a novel idea from Siemens [12]. Such a cavity would have phase and voltage control and be well suited to the EMMA requirements and would also be an opportunity for Siemens to test the idea.

ACKNOWLEDGEMENTS

Discussions with Deepa Angal-Kalinin, Phil Atkinson, Scott Berg, Fay Hannon, Stephen Hill, David Holder, James Jones, Peter McIntosh, Julian McKenzie, Boris Militsin, Andy Moss, Hywel Owen, Yuri Saveliev, Alan Wheelhouse and Peter Williams are gratefully acknowledged.

REFERENCES

[1] S. Machida et al. 2012, “Acceleration in the linear nonscaling fixed field alternating gradient accelerator EMMA”. *Nature Physics,* **N8**, *243247 (2012).*

[2] PAMELA Design Team (2011). “PAMELA Design Report”.

[3] IDS-NF Collaboration (2011). “International design study for the neutrino factory”.

[4] K. Yonehara (2012). “Research and Development Toward a Future Muon Collider”. These proceedings.

[5] B.D. Muratori et al. (2011). “EMMA Injection and Extraction”. Proceedings of IPAC11.

[6] G. Asova et al. (2010). “Status of the Photoinjector Test Facility at DESY, Zeuthen Site”. Proceedings of IPAC10.

[7] D. Angal-Kalinin et al. (2012). “Optics Design and Layout for the Electron Beam Test Facility at Daresbury Laboratory”. These proceedings.

[8] J. Clarke et al. (2012). “CLARA: A Proposed New FEL Test Facility for the UK”. These proceedings.

[9] Instruction Manual for 10/15 MeV Injector Linear Accelerator. Radiation Dynamics Limited.

[10] D.J. Thompson et al. (1975). “Design Study for a Dedicated Source of Synchrotron Radiation”. Daresbury Laboratory.

[11] B. Muratori and Y. Saveliev (2008). “ALICE (ERLP) injector design”. Proceedings of EPAC08.

[12] O. Heid and T. Hughes (2010). “Compact Solid State Direct Drive RF Linac”. Proceedings of IPAC10.