INJECTOR LINAC FOR THE MESA FACILITY*

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Abstract

In this paper we present several possible configurations of an injector linac for the upcoming Mainz Energy-recovering Superconducting Accelerator (MESA) [1] and discuss their suitability for the project.

INTRODUCTION

The Institute for Nuclear Physics (IKPH) at Mainz University is successfully operating and developing the 1.6 GeV microtron cascade MAMI for more than 30 years [2] which is a key qualification for the upcoming project MESA. This facility is a small superconducting (sc) recirculating CW electron accelerator for particle physics experiments in the energy range of 100-200 MeV.

MESA is designed for two modes of operation:

1. the energy recovery mode in which the accelerator will provide a beam current of up to 10 mA at 105 MeV for an internal target experiment with multi-turn energy recovery
2. an external beam mode where a polarized beam of 150 μA at up to 205 MeV (155 MeV in stage 1) will be provided on an external target.

The main linac will provide an energy gain of 50 MeV/pass by using four TESLA like structures. MESA is designed to fit inside existing buildings of the IKPH. Funding for MESA has been granted in 2012.

DESIGN GOALS

The goal is to design an injector linac which delivers as good beam characteristics as the MAMI injector ILAC (up to 100 μA at 3.5 MeV [3]), but at 5 MeV and up to 10 mA. The characteristics for the longitudinal phase space measured at the ILAC are $\Delta\psi \leq 3^\circ$ and $\Delta T = 4\,\mathrm{keV}$ [4]. The generation of halo has to be minimized. The injector must be shorter than 15 m.

CONSIDERATIONS ON THE INJECTOR

Electron bunches of 7.7 pC (unpolarized) and 0.115 pC (polarized) are produced by electrostatic sources (100 kV) driven by RF synchronized lasers. Even tiny contributions (10^{-4}) from out of phase electrons, which may result e.g. from stray light, are not acceptable for the external experiment. Therefore a chopper system is foreseen for the low bunch charge injection path, eliminating the source of halo. The chopper will consist of two circular deflecting RF resonators and a solenoid [5], which has proven to reliably remove halo at MAMI.

To achieve a high longitudinal capture efficiency two buncher cavities are implemented, one at the fundamental, one at the 2nd harmonic of the injector as described in [6]. This configuration produces a linear phase space distribution of the beam at the entrance of the first linac section.

Since in energy recovery mode the MESA beam is dumped at injection energy, the beam energy should be below 10 MeV to avoid the production of neutrons and long-lived radioisotopes.

For the injector linac two structure types can be taken into account:

1. a normal conducting (nc) bi-periodic on axis coupled structure which is in operation at MAMI at different frequencies for years [3, 7]
2. a superconducting TESLA like structure [8] which will be used for the MESA main linac (BBU and HOM damping have not been addressed yet).

A nc structure can be operated at an electric field gradient of roughly 1 MV/m. Allowing for some space for polarisation manipulation, chopping, bunching, beam diagnostics and focussing the final energy of 5 MeV could be achieved with an injector of roughly 12 m length. This would meet the spacial constraints. The injector should consist of a graded-β section for bunch forming and a couple of constant beta sections for acceleration. Such a configuration is well-known at IKPH from the MAMI ILAC [3]. A version scaled to the frequency of 1.3 GHz of the sc TESLA modules is studied.

A TESLA structure can be operated below 7 MV/m without field emission even under bad conditions [9]. Field emission must be avoided, since it is a major cause for beam halo in the injector [10]. With a module of 1 or 2 TESLA structures at $\leq 7\,\mathrm{MV/m}$ an injector energy of 5 to 10 MeV can be achieved. Low energy particles undergo a large phase slip in a $\beta = 1$ structure which may result in an emittance blow up due to the particles slowing down and experiencing space charge [11]. It is therefore not desirable to inject at 100 keV into the sc sections, thus a graded-β section should precede a $\beta = 1$-section. Since it is quite complex to develop a sc graded-β we adopt the development of the nc injector to form, what we call a "hybrid injector". Such a hybrid injector is considerably shorter and less demanding in terms of radio frequency (RF) power, than a nc injector and is the second injector type studied.

* Work supported by the German Federal Ministry of Education and Research (BMBF) and German Research Foundation (DFG) under the Cluster of Excellence PRISMA

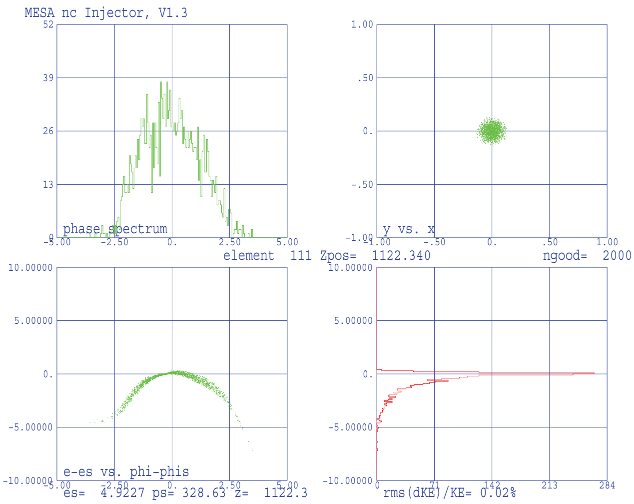

Figure 1: Longitudinal phase space at the end of the nc injector V1.3. The low energy tail of the particle distribution can lead to problems with the main linac sc modules.

NORMAL CONDUCTING INJECTOR

A graded-β is followed by booster sections at β_j =const, with β_j being the mean of β_{particle} at input and exit of the particular section j. This choice of β_j lets particles slip to more positive or negative phases depending on $\beta_{\text{particle}} \gtrless \beta_j$. So the beam phases at the input and exit of the sections are nearly the same. If the starting phases are chosen right, a longitudinal FODO structure is introduced, which also acts on the transverse planes [12] supporting external focussing.

In a first design approach, using PARMELA [13] with space charge, the output energy of the graded-β section of the injector is taken from the ILAC. Due to the larger λ_{RF} the number of cells is much lower than at the ILAC, the beam can only undergo a quarter synchrotron period and leaves the section longitudinally diverging. This divergence spoils the bunch length achieved before in the following drift space. Optimisation using amplitude & phase of the bunchers and the linac sections leads to the results given in Tab.1 configuration V1.3 as best solution. But it does not meet the desired bunch length and the particle distribution has a strong low energy tail (see Fig.1) which can lead to problems with the sc modules of the main linac.

In a next step the graded-β section is lengthened to the number of cells of the ILAC so the bunch leaves the section convergent. The exit energy is much higher now, so only 2 booster sections are needed. The phase space of the beam improves considerably (Tab. 1, V2.4), the tail nearly vanishes. The design meets the design goals fully, unfortunately the RF-power needed by each section (incl. beam loading) is larger than available power sources can deliver.

Now as 3rd step the booster sections are redesigned to stay below 30 kW maintaining the phase space (Tab. 1, V3.1). The overall RF-power consumption drops by 4%. In this design the booster sections 3&4 reach $\beta \approx 1$, so they can be replaced by two $\beta = 1$ sections without negative influences on the phase space (Tab. 1, V4.1). In order to profit from the higher transit-time factor at low β the exit energies of sections 1&2 are lowered. Together with raising the number of cells in sections 3&4, the accelerating gradient of all sections can be decreased by 9%, so the RF-power consumption decreases by another 4.5%. If the phase advance per cell of the graded-β section is changed from $0.7°$ to $0.3°$ the phase space of this injector V4.4 even improves compared to V4.1: no tail in energy distribution is visible and bunch length is shorter (see Fig.2). This design is now regarded as reference design for the nc injector.

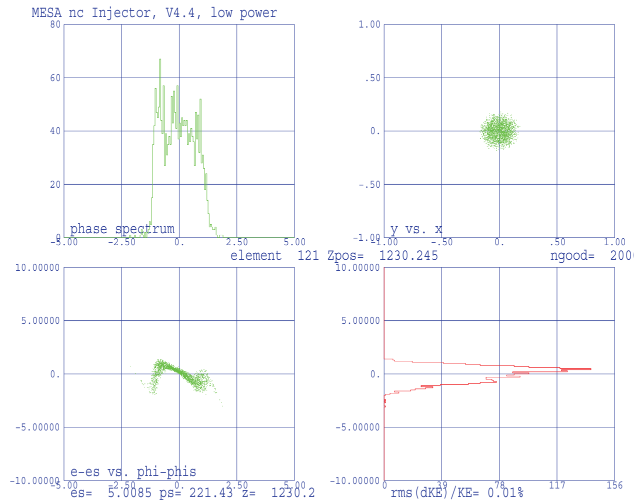

Figure 2: Longitudinal phase space after the last accelerating section of the nc injector V4.4. This design is the reference design for the normal conducting injector.

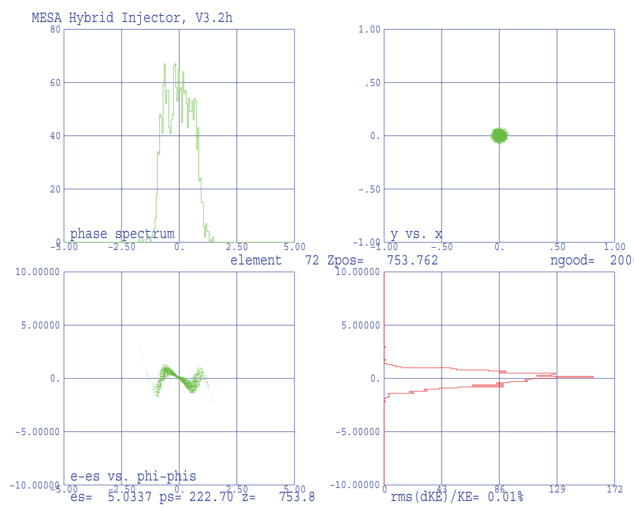

Figure 3: Longitudinal phase space at the end of the hybrid injector V3.2h. This design is the reference design for the hybrid injector.

HYBRID INJECTOR

The initial design ideas foresees the short graded-β section to be followed by a 2x9-cell cryomodule as proposed

ISBN 978-3-95450-122-9

Table 1: Selected configurations of a normal conducting and a hybrid injector representing different stages of the design process. Configurations V4.4 and V3.2h are regarded as reference configuration for the respective design.

		nc injector					hybrid injector			
configuration name:		V1.3	V2.4	V3.1	V4.1	V4.4	V1.4h	V2.2h	V3.2h	V3.3h
Sec 1	# cells	15	33	33	33	33	15	15	33	33
	$\Delta\psi$ [°/cell]	0.7	0.7	0.7	0.7	0.3	0.7	0.3	0.3	0.3
	β_{first}	0.599	0.589	0.589	0.589	0.585	0.599	0.587	0.585	0.585
	β_{last}	0.889	0.966	0.966	0.966	0.957	0.889	0.884	0.957	0.957
	T_{out} [MeV]	0.627	1.416	1.416	1.416	1.257	0.634	0.627	1.38	1.256
Sec 2	# cells	19	41	25	25	29	9	9	9	9
	β_2	0.946	0.982	0.979	0.979	0.977	1.0	1.0	1.0	1.0
	T_{out} [MeV]	1.513	3.341	2.605	2.605	2.492	2.762	5.099	5.034	5.017
Sec 3	# cells	43	35	25	25	29	9	–	–	–
	β_3	0.983	0.995	0.99	1.0	1.0	1.0	–	–	–
	T_{out} [MeV]	3.257	5.009	3.807	3.802	3.744	5.020	–	–	–
Sec 4	# cells	31	–	25	25	29	–	–	–	–
	β_4	0.993	–	0.995	1.0	1.0	–	–	–	–
	T_{out} [MeV]	5.015	–	5.012	5.008	5.009	–	–	–	–
$\epsilon_{\text{z,rms}}$	[deg-keV]	1.265	0.484	0.49	0.487	0.409	0.618	0.64	0.309	0.332
$\epsilon_{\text{z,100\%}}$	[deg-keV]	68.02	11.53	11.91	11.78	8.15	21.95	21.94	8.56	8.11
$\Delta T/T_{\text{rms}}$	[%]	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
$\Delta\psi_{\text{rms}}$	[°]	1.22	0.84	0.85	0.84	0.71	0.93	0.94	0.56	0.63
$\Delta\psi_{\text{total}}$	[°]	±3.6	±2.3	±2.3	±2.3	±2.1	±2.6	±2.6	±1.7	±2
E_{acc}	[MV/m]	1	1	1	1	0.91	2.85	5.75	4.65	4.79
$P_{\text{RF,total}}$	[kW]	100	100	96	96.2	91.6	71	71.8	74.2	72.1
T_{end}	[MeV]	5.02	5.01	5.01	5.01	5.01	5.02	5.1	5.03	5.02
L_{total}	[m]	11.34	10.83	11.42	11.45	12.1	7.33	6.3	7.35	7.33

for the main linac (V1.4h). Due to the higher field gradient in the sc structure phase focussing is stronger and leads to a more compact phase space than compared to the nc injector V1.3. Switching over to only one sc 9-cell resonator (V2.2h) with increased gradient has no negative influence on the phase space and reduces investment costs. To further improve the phase space the short graded-β is changed to the long one with a phase advance of 0.3°. The bunch length now reduces by ca 35% and is as short as 1.7° (see Fig. 3 & Tab.1, V3.2h). Adopting the low power graded-β of V4.4 of the nc injector leads to slightly worse phase space (V3.3h). Therefore the hybrid injector V3.2h is seen as reference design for the hybrid injector.

DISCUSSION

Both injector designs are suitable for MESA and deliver competitive longitudinal phase spaces. One has to carefully look into the technical implications, to decide which design is to choose. Pros for the hybrid injector are: smallest longitudinal phase space, shortest setup, lowest RF-power consumption. The cons are: SRF is a new and demanding technology, SRF modules are more expensive than nc RF sections, our existing cryoplant might be overcharged with main linac *and* injector cryomodules. Pros for the nc injector are: established technology, turning and milling can be done in house, no additional load on cryoplant. The cons are: long setup, high RF-power consumption, larger longitudinal phase space. At the moment no decision can be taken, the nc injector is regarded as basic design and the hybrid as option.

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