R&D OF THE 17 MeV MYRRHA INJECTOR*

D. Mäder†, M. Basten, D. Koser, H. C. Lenz, N. F. Petry, H. Podlech, A. Schempp,
M. Schwarz, M. Vossberg, IAP, Goethe Universität Frankfurt, Germany
C. Zhang, GSI Helmholtzzentrum, Darmstadt, Germany

Abstract

MYRRHA is designed as an accelerator driven system (ADS) for transmutation of long-lived radioactive waste. The challenge of the linac development is the very high reliability of the accelerator to limit the thermal stress inside the reactor. With the concept of parallel redundancy the injector will supply a cw proton beam with 4 mA and 17 MeV to the main linac. The new MYRRHA injector layout consists of a very robust beam dynamics design with low emittance growth rates. Sufficient drift space provides plenty room for diagnostic elements and increases the mountability. Behind a 4-Rod-RFQ and a pair of two-gap QWR rebunchers at 1.5 MeV the protons are matched into the CH cavity section. A focussing triplet between the rebunchers ensures an ideal transversal matching into the doublet lattice. Each of the 7 room temperature (RT) CH structures has a constant phase profile and does not exceed thermal losses of 29 kW/m. The transition to the 5 superconducting (SC) CH cavities with constant beta profile is at 5.9 MeV. For a safe operation of the niobium resonators the electric and magnetic peak fields are defined below 25 MV/m and 57 mT respectively.

MOTIVATION

For the development of the MYRRHA injector and all of its components the reliabilty is a key issue [1, 2]. Based on the error studies for the current injector design an enhanced version with an optimized matching section and a doublet focusing lattice has been developed [3]. The beam emittance and particle losses regarding the error studies could be further reduced.

Failures need to be detected very fast and localized accuratley to avoid unnecessary shut downs and in case to reduce the MTTR (mean time to repair). Phase probes are placed between every cavity. Additional drift space in the rebuncher section and in the transition section to the SC cavities is reserved for beam position monitors, a faraday cup, two pairs of steering magnets, halo collimators, vacuum pumps and gate valves.

RESULTS

A Monogan M-1000 ECR ion source by Pantechnik[1] and the LEBT developed at SCK-CEN deliver the 4 mA proton beam to the following injector section shown in Figure 2 [4]. Because of the high accelerating gradients SC cavities are favourable and should be used to the greatest possible extend. Figure 1 illustrates the gap voltages and the energy gain in the CH section of the injector. In the current accelerator configuration 17.3 MeV are reached at the end of the injector.

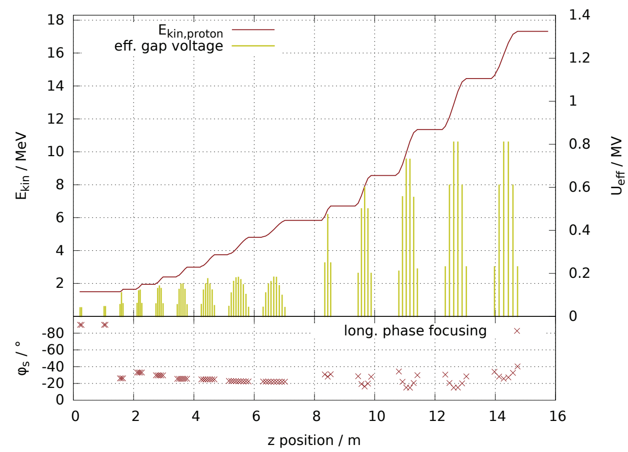

Figure 1: The kinetic proton energy after the 4-Rod-RFQ is $W_p = 1.5$ MeV and increases up to $W_p = 17.3$ MeV at the end of the CH section (upper graph, in red). The effective voltages of the gaps are plotted in yellow. In the lower graph the gap phase configuration of the RT constant phase structures and the SC constant β structures is visualized.

A few particles losses after the 4-Rod-RFQ, which don't occur in the beam simulations, can be expected empirically. To protect the clean niobium surfaces inside the SC structures, RT CH structures are used up to the transition energy of 5.9 MeV. Additionally constructing CH cavities for lower beam energies is a challange because of the slow particle velocities and the related small cell length and should be avoided for a reliable linac [5].

The CH cavities of the injector are based on the optimized geometries of the consolidated injector design [6]. They are adjusted for phase, energy and the gap number. A prototype RT CH cavitiy with a constant phase profile has been built and is currently being tested at IAP in Frankfurt [7, 8]. The 217 MHz SC demonstrator CH structure for the SHE-Linac at GSI is currently under development at IAP [9]. It is based on the design of the SC constant β CH cavities for MYRRHA with 176.1 MHz and serves as a prototype for MYRRHA, too.

Matching Section

Three different electrode modulations of the MYRRHA 4-Rod-RFQ were used for the beam dynamics of various injector designs, which were developed in the last three years. The CH section of the new injector design consists of a flexi-

* Work supported by the EU, FP7 MAX contract number 269565
† d.maeder@iap.uni-frankfurt.de
[1] http://www.pantechnik.com

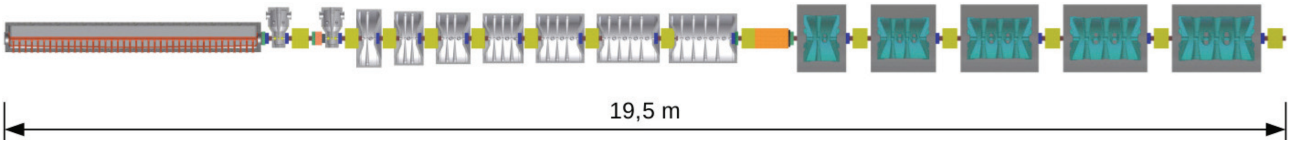

Figure 2: Cross sectional scheme of the components of the MYRRHA injector (without source and LEBT). The 4 m long 4-Rod-RFQ is followed by nine RT cavities (grey) and five SC cavities (blue). The quadrupol lenses (yellow), collimators and a lot of diagnostic devices are in between.

ble matching system, which is able to adjust the proton beam of all of the three RFQ output distributions for the following accelerating cavities. The matching system consists of two rebuncher cavities with two gaps each and an effective voltage of 80 kV and 90 kV, respectively. Detailed studies of the rebuncher geometry result in the use of two QWR cavities [10]. In this case the dissipated power of the QWR is 46 % lower than the dissipated power of a appropriate spoke cavity. In addition the compact geometry of the QWR is an advantage for the mountability of adjacent diagnostics and the quadrupole triplet lens, which is mounted in between the QWR structures. With the triplet lens the proton beam is matched transversally into the doublet lattice.

Doublet Lattice

In the previous injector designs a triplet focusing lattice was used for transversal focusing. With the use of 13 quadrupol doublets the distance between the accelerating cavities could be reduced with benefits for the longitudinal beam dynamics. Furthermore the magnitude of the 3σ beam envelope of the doublet lattice compared to the triplet lattice is smaller, which reduces the particle losses inside the magnets. The mean emittance growth rate in the transversal planes of the CH section is $\Delta\epsilon_{n,x,y,rms} = 18.9\,\%$ (Figure 3) and the absolute transversal emittance at the injector exit amounts to $\epsilon_{n,x,rms} \cong \epsilon_{n,y,rms} = 0.247$ mm mrad.

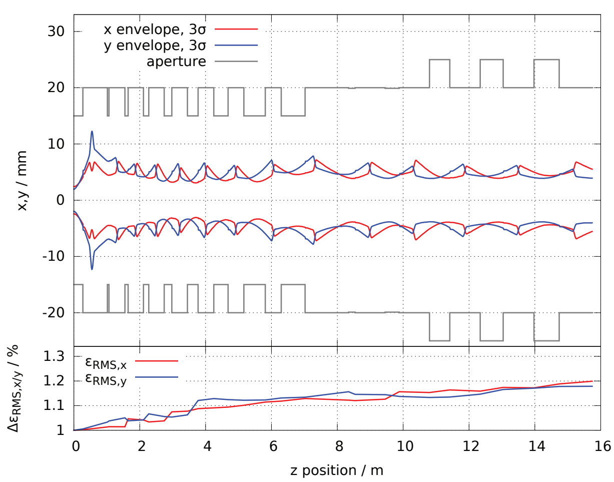

Figure 3: The periodic doublet lattice focuses the beam and ensures a small fill factor of the aperture. For an apropriate transversal focusing in the longer drift of the transsition section the beam envelope widens to $r_{beam,3\sigma} \approx 8.5$ mm.

In the injector two types of doublet lenses with pole shoe lengths of 4 and 5 cm are used. Magnetic field gradients at a maximum of 45 T/m are suffucient to focus the beam. The magnetic flux density at the pole shoe tip is $B_{max} = 0.99$ T.

Longitudinal Beam Dynamics

After the two rebuncher cavities of the matching section the particle bunch is focused longitudinally by the negative phase of the accelerating cavities. The low effective voltage in the first RT CH cavities successively increases with a higher number of gaps per cavity to achieve a constant phase advance per structure period (σ_z)(Table 1).

Table 1: Effective Voltage and Longitudinal Phase Advance per Structure Period of the Injector Cavities

Cav. No.	Eff. Volt.	Long. Ph. Adv.
Reb. 1	80 kV	52.0 °
Reb. 2	90 kV	55.8 °
CH 1	224 kV	55.2 °
CH 2	360 kV	72.1 °
CH 3	516 kV	67.3 °
CH 4	660 kV	71.4 °
CH 5	826 kV	75.5 °
CH 6	1140 kV	74.3 °
CH 7	1110 kV	74.7 °
CH 8	970 kV	71.5 °
CH 9	2.0 MV	75.8 °
CH 10	3.0 MV	72.3 °
CH 11	3.3 MV	70.5 °
CH 12	3.3 MV	76.8 °

In the optimization process of the longitudinal beam dynamics it proved to achieve the lowest emittance growth rates with $\sigma_z \approx 75\,°$. The longitudinal 3σ beam envelope steadily decreases until the long drift of the transition section (Figure 4).

The low energy spread in this section is beneficial for a minimal divergence of the particle beam. With an average negative phase of $\phi_{CH8} = -29.5\,°$ in the first SC cavity the beam is focused. At the exit of the CH section the beam is narrow in phase and energy spread again (Figure 5). The longitudinal emittance growth rate of the CH section is $\Delta\epsilon_{n,z,rms} = 10.65\,\%$ resulting in an absolute output emittance of $\epsilon_{n,z,rms} = 0.707$ ns keV.

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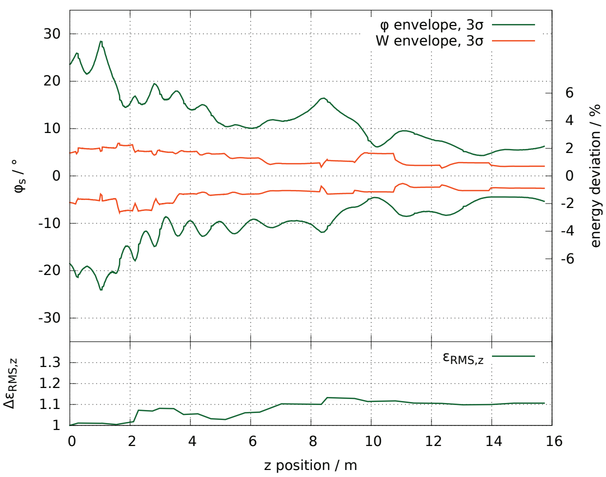

Figure 4: The longitudinal 3σ envelopes for the phase and energy spread of the beam (upper graph) with longitudinal RMS emittance growth rate (lower graph).

Comparison to Previous Designs

Since the release of the MAX reference design of the MYRRHA injector in 2012 based on KONUS beam dynamics, a completly revised injector design with improved beam dynamics could be found. Because of shorter (but more) cavities, smoothly increasing accelerating voltages and a nearly constant phase advance the beam quality is increased. The emittance growth rates in every plane are reduced (Table 2) and the particle tail formation in the longitudinal distribution is suppressed (Figure 5).

Table 2: Emittance Growth Rates of the Old and the New Reference Design in Comparison

Parameter	Ref. Des. 2012	Ref. Des. 2014
$\Delta\epsilon_{n,x,rms}$	26.8 %	19.9 %
$\Delta\epsilon_{n,y,rms}$	25.9 %	17.6 %
$\Delta\epsilon_{n,z,rms}$	38.0 %	10.6 %

CONCLUSION

The new injector design for MYRRHA is optimized for a high realiability with conservative accelerating gradients and a lot of reserved drift space for diagnostic elements. Additionally the beam quality could be significantly improved with very small emittance growth rates during the transport in the CH section. Including displacement, rotation, phase and voltage errors a high particle transmission of 99.9 % could be reached [3]. The presented design provides improvements in all aspects and will be used as the new reference design for the MYRRHA injector.

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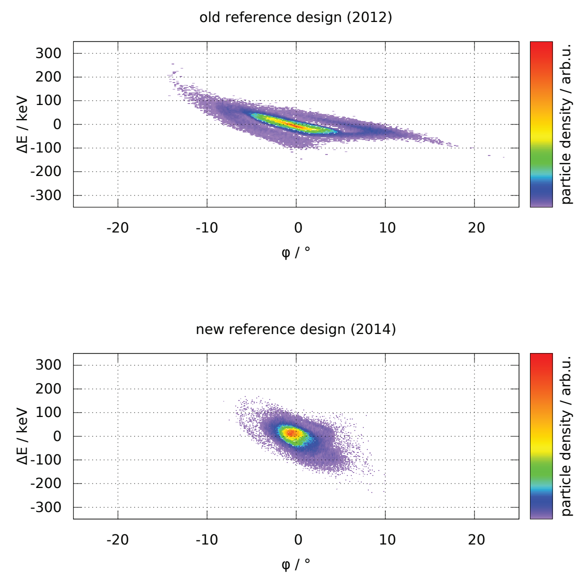

Figure 5: Longitudinal particle beam output distributions.

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