BEAM DYNAMICS OF THE FRANZ BUNCH COMPRESSOR USING REALISTIC FIELDS WITH A FOCUS ON THE REBUNCHER CAVITIES

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Abstract

The ARMADILLO bunch compressor design being finalized at IAP is capable of reaching a longitudinal pulse compression ratio of 45 for proton beams of 150 mA at 2 MeV. It will provide one nanosecond long proton pulses with a peak current of 7.7 A. The system guides nine linac micro bunches deflected by a 5 MHz RF kicker and uses four dipole magnets – two homogeneous and two with field gradients – to merge them on the target. For longitudinal focusing and an energy variation of ± 200 keV two multitrack RF cavities are included. ARMADILLO will be installed at the end of the Frankfurt Neutron Source FRANZ [1] making use of the unique 250 kHz time structure. This contribution will provide an overview of the layout of the system as well as recent progress in component design and beam dynamics of the compressor.

THE ARMADILLO BUNCH COMPRESSOR

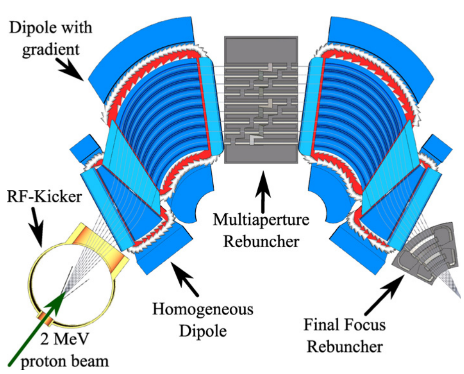

Figure 1: Design of the ARMADILLO. See [2] for details.

The rebuncher on the symmetry axis of the ARMADILLO compressor (Fig. 2) has to feature nine separate apertures with different longitudinal offset so all bunches arrive on time. The quarter-wave resonator operates at the half harmonic 87.5 MHz of the 175 MHz linac.

Fig. 3 shows the final focus cavity operating at 175 MHz. The design is able to provide an effective voltage of 250 kV for longitudinal focusing and an energy variation of ± 200 keV at 9.8 kW power consumption. The cavity requires a broad gap (21 cm) due to the onset of bunch merging within the rebuncher. Shorting bars were introduced to avoid RF leakage into the second half of the bunch compressor which is favoured due to the broad aperture. A temperature rise of 12°C was calculated with CST Multiphysics Studio for bars of 3 mm width assuming copper as material and using beam losses (about 0.6%) from particle tracking simulations as well as RF losses from CST Microwave Studio. Accordingly the bars should require no additional cooling.

Further details on the cavity design can be found in [3].

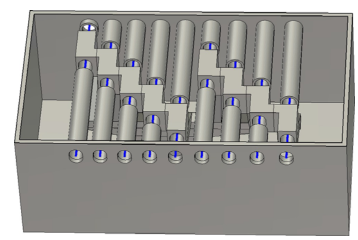

Figure 2: Multiaperture rebuncher cavity design.

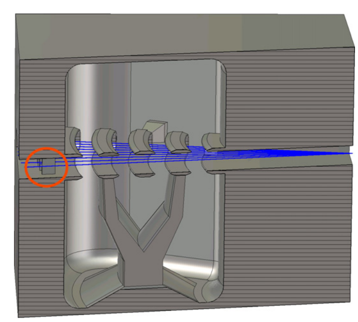

Figure 3: Final Focus cavity with shorting bars.

Optimization of beam dynamics

Each trajectory of the ARMADILLO has six adjustable parameters, the edge angles on entry and exit of the second and third dipole magnets and the voltages within the multiaperture and the final focus rebuncher. Due to the low spacing between trajectories, it was decided not to vary the edge angles on the homogeneous dipole magnets. Additionaly the particle distribution provided by the linac can be adjusted with three quadrupole tripletts and a CH rebuncher. The compressor geometry itself was considered as fixed.

To find optimal parameters that fulfill the requirements an automated approach has been chosen using the particle swarm optimization (PSO) algorithm [4]. For each value of the cost function evaluated by the algorithm, a LORASR [5]

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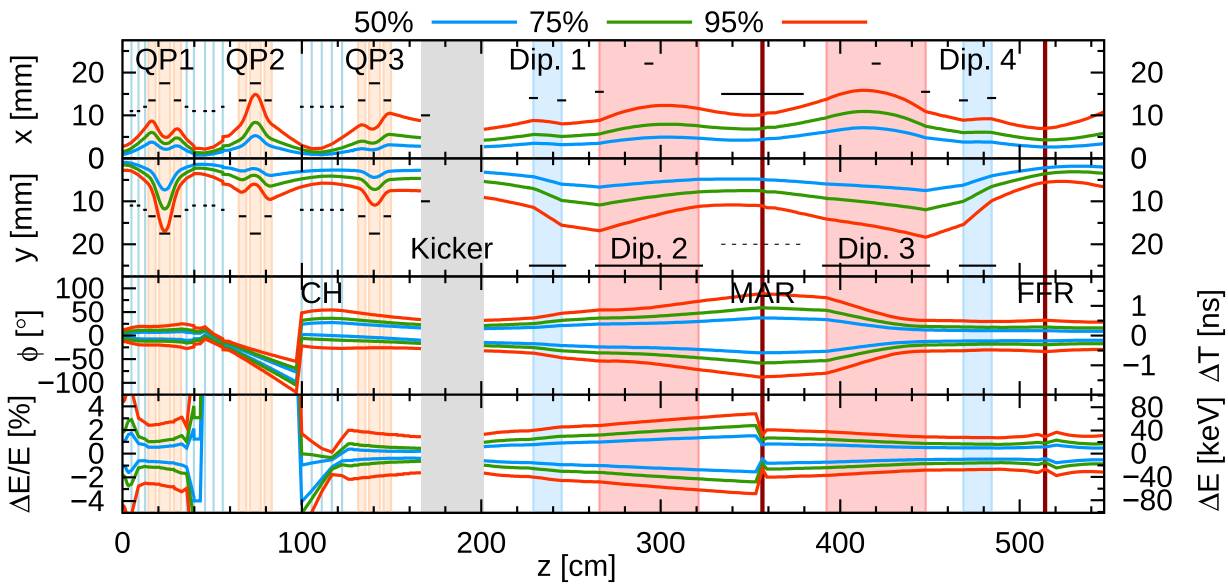

Figure 4: Beam dynamics in the FRANZ linac and the adjoining bunch compressor on the fifth trajectory. Areas where apertures were included in the PSO cost function are marked by horizontal black lines.

run for the given parameter set is performed and evaluated by

$$f = \left(\frac{x_{\rm rms}}{x_{\rm rms}^{\rm req}}\right)^2 + \left(\frac{y_{\rm rms}}{y_{\rm rms}^{\rm req}}\right)^2 + \left(\frac{\tau_{\rm rms}}{\tau_{\rm rms}^{\rm req}}\right)^2 + \left(\frac{\Delta E_{\rm rms}}{\Delta E_{\rm rms}^{\rm req}}\right)^2 .$$

Variables affixed with req are the requirements for the corresponding quantities on the target: transverse dimensions $x_{\rm rms}^{\rm req} = y_{\rm rms}^{\rm req} = R_{\rm target}/2 = 5\,\rm mm$, pulse length $\tau_{\rm rms}^{\rm req} = 1\,\rm ns$ and energy spread $\Delta E_{\rm rms}^{\rm req}/E = 5\%$. The filling degree k of every component is included by adding terms of the form $1 - \tilde{f}(k)$. For $\tilde{f}(k)$ a modified Fermi function with $\mu = 1$ is used, which rises linearly after it has reached 0.9 to avoid solutions with large filling degrees being rated equally.

To reduce the number of parameters per optimization run, first the fifth bunch compressor trajectory is optimized together with the linac. Afterwards the other trajectories are optimized with fixed linac settings.

The main challenge for setting the linac for the compressor is avoiding high particle losses on the kicker plates (20 mm minimum distance) as well as keeping the beam small enough until it can be focused again on the first edge of the second dipole. At the settings shown in Fig. 4, losses are below 4%. Within the second and third dipole magnets the dominating effect in the deflecting plane is weak focusing. The edge angles chosen by the algorithm provide focusing in the vertical plane. The beam focus within the multiaperture rebuncher is required due to the limited horizontal space available.

A main contribution to the longitudinal compression within the third dipole comes from dispersion effects. The beam passes the second dipole defocused longitudinally. Due to the different bending radii slower, trailing particles get a kick in negative direction, leading particles are deflected in opposite direction. In front of the third magnet the beam arrives with a tilt, leading to a compression within the magnet because of transit time differences.

Averaged over the trajectories—without considering the beam merging—a transverse beam spot size of $\langle x_{\rm rms}\rangle = \pm 5.4\,\rm mm$ and $\langle y_{\rm rms}\rangle = \pm 3.4\,\rm mm$ was achieved. Energy spread $\langle \Delta E_{\rm rms}/E\rangle = \pm 0.9\%$ as well as pulse length $\langle \tau_{\rm rms}\rangle = 0.5\,\rm ns$ of the PSO solution are well below the required values. For the multiaperture rebuncher a linear rise of the effective voltage from $115\,\rm kV$ on the longest to $145\,\rm kV$ on the shortest trajectory was found to be optimal. For the final focus rebuncher the optimal setting uses constant longitudinal focusing with $112\,\rm kV$ on all trajectories. The required dipole edge angles differ up to $22\,^\circ$ from those given by the bunch compressor geometry.

After finding an appropriate setting for the ARMADILLO parameters, the LORASR calculations provide a good starting point for a detailed analysis. Especially when using realistic, simulated field geometries instead of the paraxial, first-order models within LORASR, additional effects emerge. Some effects for the homogeneous magnets were already presented in [2]. In the following, we will take a closer look on the rebuncher cavities.

THE PIC-CODE BENDER

At IAP, the Particle-in-Cell(PIC)-Code BENDER is under development. It can be used to track particle distributions in electromagnetic field geometries generated from various sources like CST Suite. Space charge is included using an integrated Multigrid or BiCGStab solver for Poisson's equation. It was used for the tracking simulations in the following sections.

THE MULTIAPERTURE REBUNCHER

The small distance between trajectories and the displaced drift tubes lead to horizontal components within the electric fields in the gaps. This leads to a fan-out of the beam because trailing particles are deflected in opposite direction than leading particles. The deflection is strongest on trajectories 2,3,4,7 and 8 – up to ± 5 mrad for particles on axis at a gap length of 35 mm.

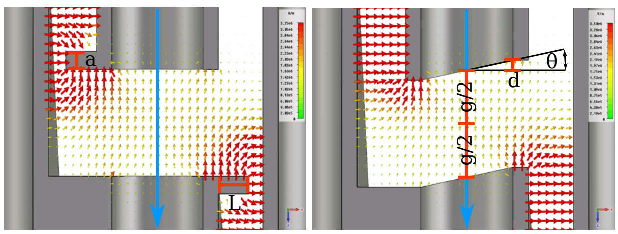

Figure 5: Two different approaches to reducing the deflecting field component within the gaps of the multiaperture rebuncher: bulges and slanted gaps.

Two different approaches to reducing the deflection were studied: bulges on the drift tube sides and slanted drift tubes. For the multiaperture rebuncher, bulges only reduce the deflection by 60%. Fig. 6 shows that decreasing the power loss by increasing the gap size and reducing the deflection to acceptable values by bulges is not possible.

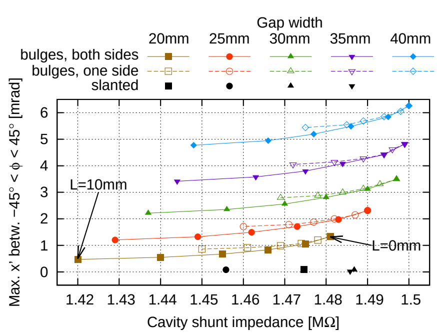

Figure 6: Shunt impedance vs. deflection for cases shown in Fig. 5. Bulge length L varies from 0 mm to 10 mm.

By using slanted drift tubes it was possible to reduce the deflection of particles on axis down to ± 0.3 mrad using angles θ from 4° at 20 mm gap length up to 17° for 35 mm. Shunt impedance for the model with slanted gaps is 1% to 7% lower than in the unmodified case. Further work will focus on the influence of the slanted gaps on beam quality.

THE FINAL FOCUS-REBUNCHER

The beam dynamics within the cavity was studied without space charge using homogeneous distributions first. In the longitudinal plane the BENDER simulation shows good agreement with LORASR. Fig. 7 shows the beam in the horizontal plane after transport through the cavity. On the inner trajectories there is no RF defocusing due to absent horizontal field components – as can be seen in comparison with the calculation without cavity ("Drift"). On the outer trajectories however, particles near drift tube sides get a kick, as shown in Fig. 7 for a small and a large distance between the beam axis and the drift tube sides.

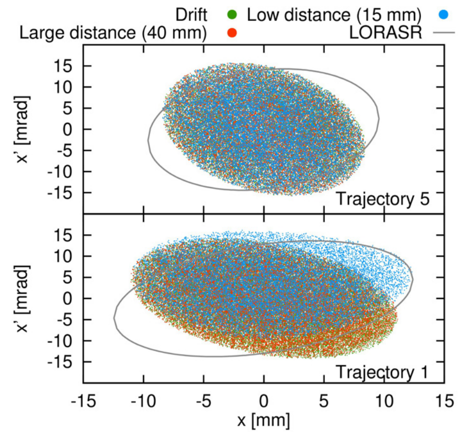

Figure 7: Emittance equivalent homogeneous distribution after transport through the final focus-rebuncher for different distances between trajectory and drift tube side.

Because of the broad aperture, top and bottom of the drift tubes mounted from the bottom of the cavity differ in potential, especially in the center. Thus, vertical electric fields form within the drift tubes, leading to vertical deflection of the bunch center of 1.9 mrad on outer and 2.6 mrad on inner trajectories. Bunch merging simulations however show no decrease in current on the target due to this effect.

CONCLUSIONS

The current ARMADILLO geometry provides feasible beam dynamics after optimization with the PSO algorithm. Beam dynamics studies using realistic fields for the multitrack rebuncher cavities show additional effects compared with LORASR calculations. Particle deflection in the multiaperture rebuncher can be reduced using slanted gaps.

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