BUNCH COMPRESSOR FOR INTENSE PROTON BEAMS†

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Abstract

The Frankfurt Neutron Source FRANZ is under construction at IAP. The ARMADILLO bunch compressor, as a part of it, is composed of a 5 MHz electric kicker, a magnetic dipole chicane and rf-rebunching cavities. The design phase of the bunch compressor has reached the final stage. A 175 MHz 2 MeV proton linac forms 100 ns long beam pulses consisting of nine micro bunches with 150 mA. Deflected by the 5MHz kicker, the micro bunches are guided on different paths to arrive within 1 ns at a n-production target. Due to high space charge forces rebuncher cavities are included. The peak current at the target is expected to be in the range of several amperes in a 1 ns proton pulse, which is equivalent to a longitudinal pulse compression ratio of 45. A new code specific for complex magnetic multi aperture system and for high current applications has been developed. Hardware designs according to the beam dynamics results are in progress. Improved 3D magnetic and electric fields will be applied in the future beam dynamics studies including high space charge forces. The preliminary designs and the beam dynamics studies will be presented in this contribution.

INTRODUCTION

FRANZ is an unique combination of a 150 mA-175 MHz-linac and an 1 ns-bunch compressor. The detailed layout, design parameters, planned experiments and applications can be found in [1, 2]. FRANZ is characterized by a high integrated neutron flux produced by very short intense proton pulses at high repetition rates. It is well suited as a test stand for novel accelerator technology, development of high current beam diagnostics, as well as for high precision (n, γ)-cross section measurements with astrophysical relevance as well as for high power target development. For the Time of Flight (TOF) measurements a *rms* pulse width shorter than 1 ns and a maximal *rms* energy spread of $\pm 5\%$ at the highest possible intensity is required. A Li-target with $R = 10$ mm is chosen as a reasonable compromise.

ARMADILLO

A bunch train of nine micro bunches arrives with a repetition rate of 250 kHz at the entrance of the bunch compressor (Fig. 2). Periodic deflection by a 5 MHz rf-kicker guides the micro bunches into an *Arc Magnetic Dipole Chicane with Large Aperture Longitudinal Focusing Cavities* (Fig. 1). The ARMADILLO is based on Mobley's buncher

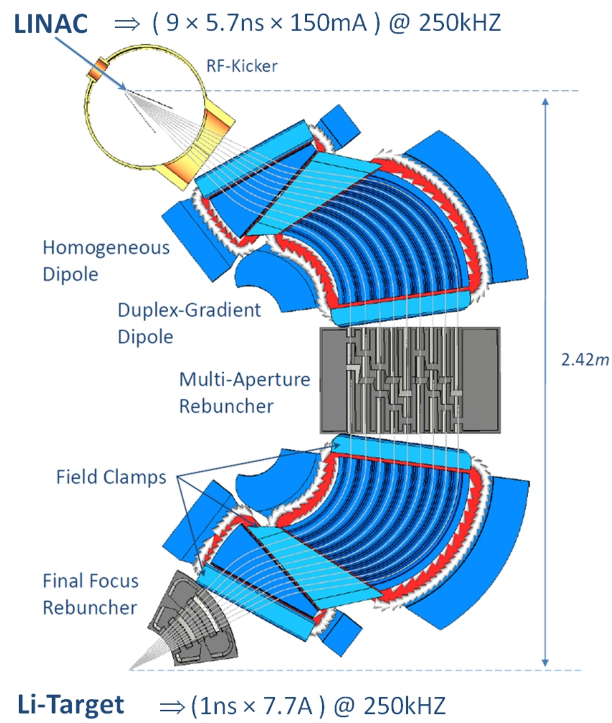

Figure 1: The ARMADILLO consists of an rf-kicker, a dipole chicane and two rebuncher cavities.

system [3]. A more detailed discussion of the geometrical concept and crucial differences to the classical concept was given in a previous contribution [4].

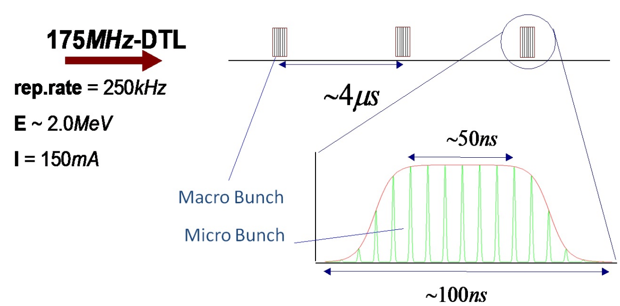

Figure 2: Proton pulse structure at the entrance of the ARMADILLO.

Passing the chicane the micro bunches compensate their longitudinal distances and arrive simultaneously at the neutron production target. In the transverse planes the beam dynamics is controlled by weak and edge focusing of the dipoles. Due to the high space charge forces rebuncher cav-

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ities are needed for longitudinal beam dynamics. In order to minimize dispersion effects the first rebuncher is located at the symmetry axis of the dipole chicane, while the second rebuncher is positioned in front of the final focus. The final focus rebuncher provides the final 1 ns-pulse length as well as the option to vary the final pulse center energy. The design and concepts of these unique cavities is discussed in [5].

MAGNETS

The magnetic dipole chicane guides the micro bunches on trajectories with a path difference given by the bunch center velocity and the linac frequency ($\beta\lambda = 112.5\,\mathrm{mm}$). The dipoles are arranged symmetrically, where the symmetry axis is defined by the line perpendicular to the shortest connection $L = 2420.0\,\mathrm{mm}$ between entrance and exit focus. The first homogeneous sector dipole with an average flux density of $B_1 = 515.0\,\mathrm{mT}$ is needed for linear separation of the trajectories and for keeping their tranverse distances almost constant. In addition to its main duty, it provides a momentum exchange between the transverse planes. The relatively big gap induces a large fringing field, which is undesired for beam dynamics. Additional field clamps and shims reduce the fringing field integral from $K = 1.034$ to $K = 0.098$ (Fig. 3).

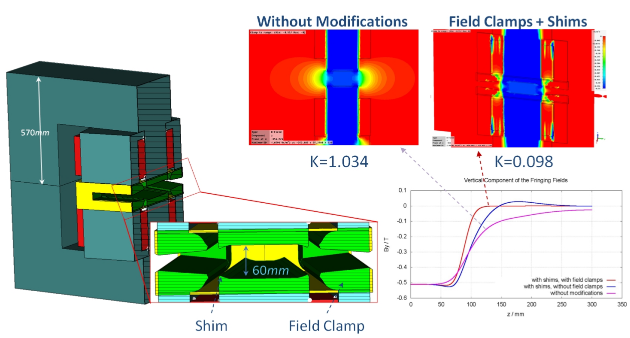

Figure 3: Fringing field integral is reduced by field clamps and shims.

By feeding these 3D-field distributions into the *Particle in Cell* (PIC) transport code, specifically written for the ARMADILLO, one achieves a significant improvement in the beam dynamics. The bunch center motion is closer to the ideal trajectory, which is defined by transport through a constant field with hard edge approximation (Fig. 4). Differences, especially in the vertical plane, can be explained by the transverse field gradients ($\partial B_x/\partial y$) and ($\partial B_y/\partial y$), which are not included in the first order paraxial approximation (Fig. 5). Vertical field gradients are increased by shimming the edges. These effects have to be studied in details using improved magnet designs.

A preliminary design for the duplex-gradient dipole is proposed (Fig. 6). The individual flux density for every trajectory, defined by differences in gap height, leads to a global horizontal gradient, which causes a longitudinal compression of the macro bunches. An additional reverse oriented gradient on every trajectory results in a transverse focusing of the micro bunches. For the central trajectory a magnetic flux density of $509.2\,\mathrm{mT}$ is needed, with a maximum field difference of $92.6\,\mathrm{mT}$ from the central to the outermost trajectory.

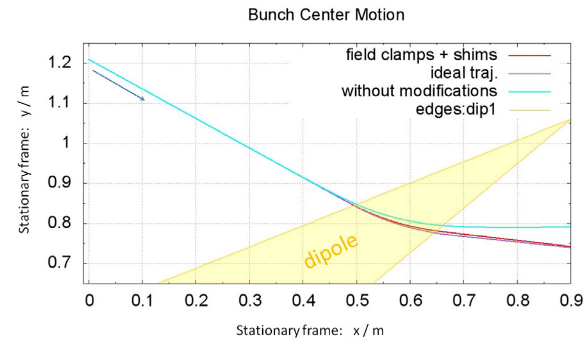

Figure 4: Comparison: realistic external 3D-field distribution of the first dipole applied to the PIC-code versus ideal trajectory defined by constant field and hard edge approximation. Improvements in magnet design lead to a convergence to the ideal trajectory.

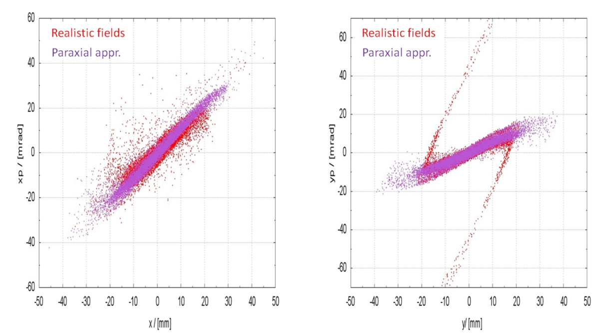

Figure 5: Transport through a realistic field distribution of the improved magnet design (red) compared to first order paraxial approach with the same fringing field integral (purple). The core and the slope of the particle distribution fit very well. Aberration in the vertical plane are caused by vertical field gradients, which are increased by shimming the edges.

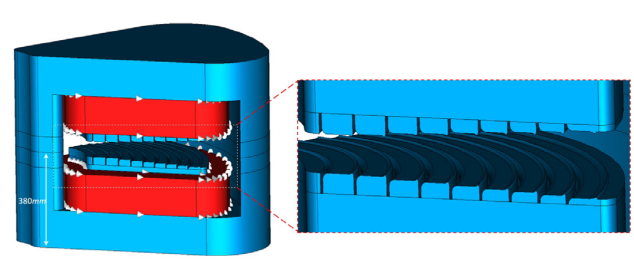

Figure 6: Preliminary design of the duplex-gradient dipole.

BEAM DYNAMICS - SPACE CHARGE EFFECTS

Single bunch beam dynamics are carried out by the *Particle Swarm Optimization* (PSO)[6] algorithm, applied to LORASR simulations. A solution is found with less than 5% losses at *Full Space Charge Forces* (FSCF) (Fig. 7).

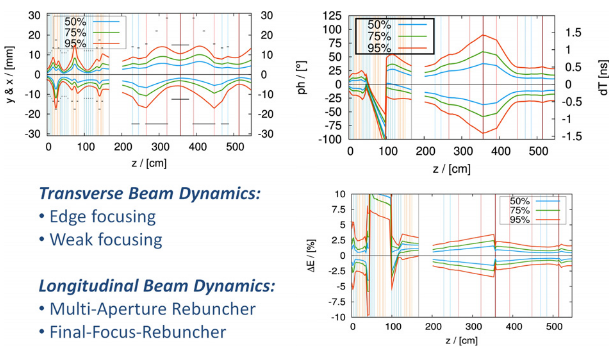

Figure 7: PSO-result for the central trajectory. The transverse dimensions of the micro bunch are significantly smaller than the given apertures (black bars). In principle a 1ns micro bunch with an energy spread less than ±5% is possible at the exit of ARMADILLO.

The space charge effects are studied by merging realistic particle distributions along the last 300 mm to the final focus with the PIC-code. Results are summarized in Fig. 8 and Tab. 1. All beam profiles in all projections are well characterized by a Gaussian fit. 95.5% of the particle distribution is expected within the $2 \cdot \sigma$-radius. Furthermore the $2 \cdot \sigma$-width is also equal to the *rms* width of the pulses. Merging at *full space charge force* can still meet the requirements. The 95% radius of the transverse beam spot is expected to be at least 10% smaller than the radius of the Li-target, while the *rms* energy spread of the merged macro bunch is roughly half of the required value. Therefore the *rms* pulse length is just roughly 15% shorter than the required 1ns.

A better beam quality can be reached by *Space Charge Compensated* (SCC) merging, provided by a *Space Charge Lens* [7]. The beam size will be reduced up to 25%. The final energy spread is decreased almost to 50% compared to the transport with full space charge forces. The longitudinal *rms* emittance is significantly reduced by 25%. The peak current of the compressed proton macro bunch is increased by 30% up to 9.2 A with an *rms* pulse width of 0.63 ns.

CONCLUSIONS

The ARMADILLO bunch compression concept is presented. In principle it is able to reach a longitudinal compression ratio of 45. The major challenge of this system is to handle the high space charge forces. Single bunch and multi bunch beam dynamics results are in face of full space charge force still promising to satisfy the requirements. A

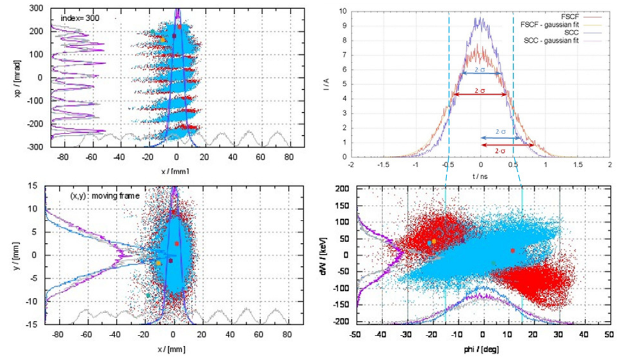

Figure 8: Merging: Projections at the Li-target. Transport with *Full Space Charge Forces* (FSCF, red and violet) compared to *Space Charge Compensated* (SCC, blue) transport. The longitudinal coordinate ϕ is given by the rf-phase at 87.5 MHz. Grey lines are the initial beam profiles, when merging is started.

Table 1: Beam Quality at the Target

		FSCF	SCC	rel. change
$2 \cdot \sigma_x$	mm	7.86	6.92	-12%
$2 \cdot \sigma_y$	mm	8.90	7.02	-21%
$2 \cdot \sigma_{\Delta T}$	ns	0.84	0.63	-25%
$2 \cdot \sigma_{\Delta W}$	keV	104.6	55.5	-47%
$\epsilon_{rms,x}$	π mm mrad	12.767	12.608	-1%
$\epsilon_{rms,y}$	π mm mrad	0.542	0.536	-1%
$\epsilon_{rms,z}$	π ns keV	1.883	1.410	-25%

space charge compensated transport provided by a Space Charge Lens could even increase the beam quality at the target. Preliminary designs and improvements in magnet design are proposed. Optimization of the hardware and the complementary code, developed specifically for the ARMADILLO geometry, has to be continued.

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