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 a 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 systems 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 $R = 10\,\mathrm{mm}$ is chosen as a reasonable compromise.

From the viewpoint of an accelerator physicist the following two questions are most interesting with respect to high current applications:

- ○ Where are the limits of conventional accelerator technologies?
- ○ Are there alternative concepts?

Most important sub-projects of FRANZ in addition to the ARMADILLO are related to these questions:

- High repetition rate beam forming: E×B chopper [3].
- High current cw RFQ [4].
- Coupled RFQ-IH combination [5].
- DTL-concepts: IH [6], CH [7], Multi-Aperture Rebuncher [8].
- Alt. beam focusing device: Space Charge Lens [14].
- Non destructive diagnostics: beam tomography [15].

BUNCH COMPRESSION CONCEPTS

In principle a *transit time difference* between the front and the backmost part of bunch is the only way to compress longitudinally. This effect can be attained either by an *energy difference* within the bunch or by a *path length difference* in a chicane or a combination of both concepts. In the most common concept the head of the bunch is decelerated by an rf-cavity, while the tail of the bunch is accelerated. The required energy difference $\Delta W_{\pm}$ to merge the macro bunch is defined by the velocity β of the bunch center relative to the speed of light and the ratio between the macro bunch length ΔL to the focus length L:

$$\Delta W_{\pm} = \left(\frac{1}{\sqrt{1-\beta^2\left(1 \pm \frac{\Delta L}{2L}\right)^2}} - \frac{1}{\sqrt{1-\beta^2}} \right) \cdot W_{p,0} \tag{1}$$

, whereby $W_{p,0}$ is given by the rest energy of the accelerated particle. Due to limited space in the experimental hall, L has to be less than 4 m, which leads to an energy variation five times higher than the required energy spread within the macro bunch.

Therefore an alternative concept (Fig. 1) is considered, which is based on Mobley's concept [9] for the production of short intense monoenergetic ion pulses. Horizontally defocused by an rf-deflector, the first part of the bunch passes a horizontal focusing dipole with a longer path length than the hindmost part of the bunch. Due to the transit time difference all parts arrive at the same time on the target. For a linear operation with sinusoidal kicker voltage

$$U(t) = U_0 \cdot \sin(\omega t + \phi_0) \tag{2}$$

the macro bunch has to be fitted on the linear flank of the voltage rise, e.g. the ratio of the macro pulse length $\Delta T = 45.7\,\mathrm{ns}$ to the kicker period $T = 2\pi/\omega = 200\,\mathrm{ns}$ has to be small enough:

$$\frac{(\Delta T/2)}{(T/4)} \lesssim \frac{\pi}{4} = \phi_0 \quad . \tag{3}$$

In the worst case scenario, the energy gain of the first micro bunch is given by the change of potential with the transit

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time through the kicker $t_k = L_k/(\beta \cdot c)$:

$$\begin{aligned} \Delta W &= q\Delta U = q \cdot |U(t_k) - U(0)| \qquad (4) \\ &= qU_0 \cdot \left| \sin\left(\frac{2\pi}{T}\frac{L_k}{\beta c} + \phi_0\right) - \sin(\phi_0) \right| \end{aligned}$$

With a worse case maximal voltage $U_0 = 250\,\mathrm{kV}$, a kicker length $L_k = 0.2\,\mathrm{m}$ and the same macro bunch parameters the maximal energy gain by the rf-kicker is estimated in order of $(\Delta W/W)_{max} = 2.3\%$. More accurate *Particle In Cell (PIC)* calculation including realistic shape of the kicker and space charge forces result in a smaller energy variation of the micro bunches. Nevertheless Mobley's system yields an order of magnitude lower energy spread as the compression concept due to energy difference.

A combination of both concepts is commonly used for high energetic (several GeV) electron beams [11]. Applying this scheme to the defined parameters leads to twice the energy variation than the pure Mobley-concept.

In addition to this effect the energy spread caused by space charge forces is not negligible. For planned experiments an energy variation $\Delta W/W \lesssim 5\%$ in one nanosecond intense proton pulses at high repetition rate is required. For this reason Mobley's bunch compression system remains as the only reasonable concept for the given requirements. The main challenge of this work is to adapt the well proven concept, which was built several times in the 60's for ion beam current in the μA range [10], and expand the system to handle a 1000 times more intense current at moderate geometrical size.

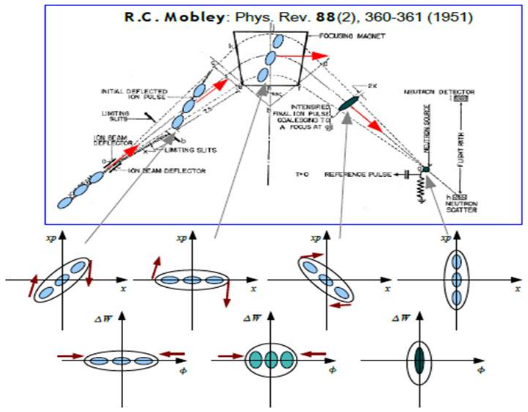

Figure 1: Classical Mobley-buncher concept: path length differences between the head and the tail cause the biggest transit time difference for the outermost part of the bunchs.

ARMADILLO

At the Frankfurt neutron source FRANZ, a bunch train of nine micro bunches arrives with a repetition rate of 250 kHz at the entrance of the bunch compressor (Fig. 3). Periodic deflection by a 5 MHz rf-kicker guides the micro bunches into an *<u>Ar</u>c <u>Ma</u>gnetic <u>Di</u>pole Chicane with <u>L</u>arge Aperture <u>Lo</u>ngitudinally Focusing Cavities* (Fig. 2). A more detailed discussion of the geometrical concept and crucial differences to the classical concept was given in a previous contribution [12].

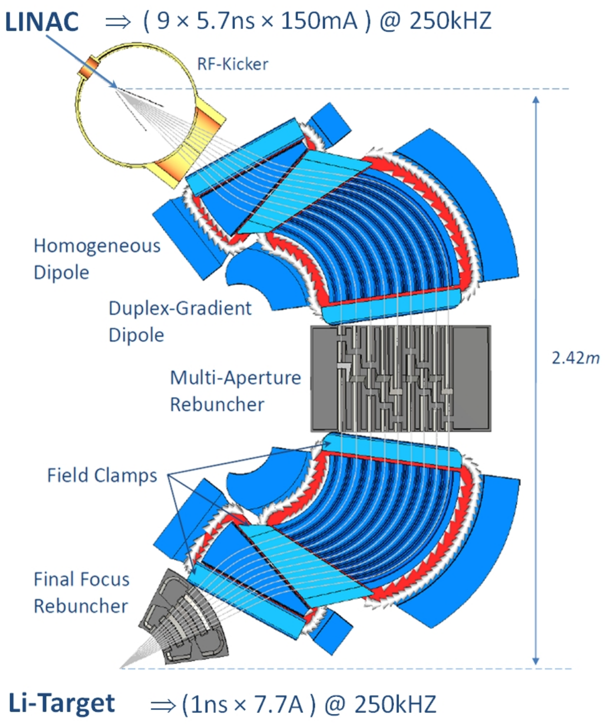

Figure 2: The ARMADILLO consists of an rf-kicker, a dipole chicane and two rebuncher cavities.

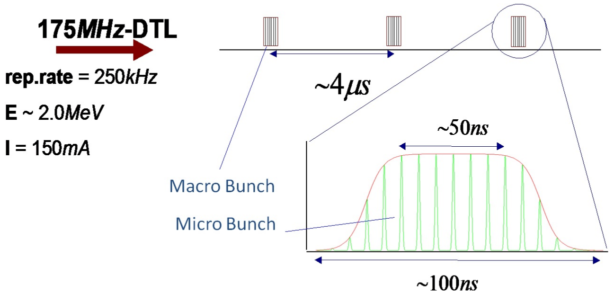

Figure 3: Proton pulse structure at the entrance of the ARMADILLO.

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 cavities are needed for longitudinal beam dynamics. In order to minimize dispersion effects the first rebuncher (Fig. 4) 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 (Fig. 4) 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 [8].

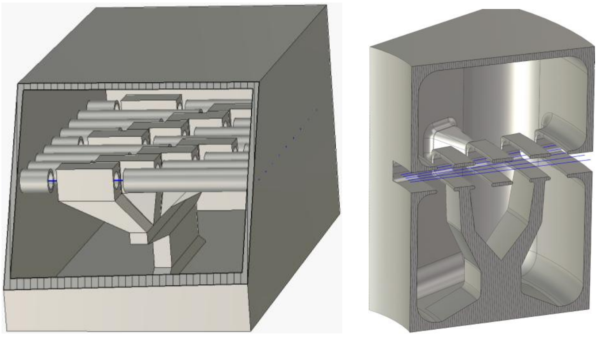

Figure 4: *Multi-Aperture Rebuncher* (left): Due to the high space charge forces, the phase spread at the symmetry axis of the bunch compressor is in the magnitude of ±90° in respect of the linac frequency 175 MHz (see Fig. 10). In order to avoid aberration the rebuncher is operated at the half harmonic of the linac frequency, 87.5 MHz. Furthermore only half of the longitudinal distance between the bunches remains at the position of the rebuncher. Therefore geometrical shifts of the gaps are necessary to compensate the phase shifts. The effective voltage is individually choosen for every trajectory, depending on the length of the trajectory. The voltage distribution (110 to 160 kV) can be roughly tuned by shifting the stem in transverse direction. The *Final Focus Rebuncher* (rigth) allows for the 1 ns pulse length at the target as well as for an energy variation ±200 kV of the final bunch.

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 ($\beta\lambda = 112.5$ mm). The dipoles are arranged symmetrically, where the symmetry axis is defined by the line perpendicular to the shortest connection $L = 2420.0$ mm between entrance and exit focus. The first homogeneous sector dipole with an average flux density of $B_1 = 515.0$ 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. 5 + 6).

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 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. 7). 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. 8). Vertical field gradients are increased by shimming the edges. These effects have to be studied in detail using improved magnet designs.

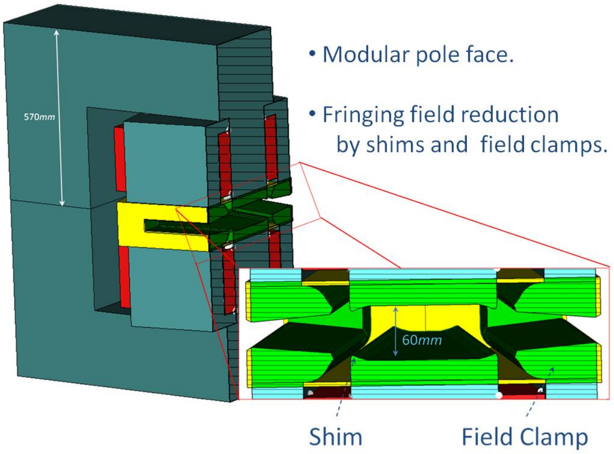

Figure 5: Dipole 1: Improvements of the magnet design for the beam dynamics.

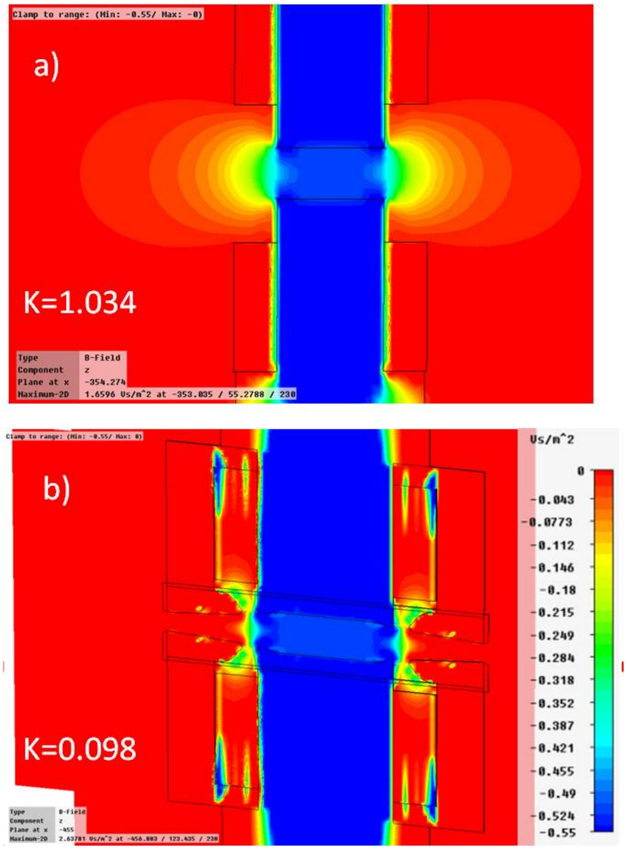

Figure 6: Dipole 1: Fringing field integral K, evaluated for the central trajectory, is reduced by field clamps and shims: a) without modifications, b) with shims and field clamps.

A preliminary design for the duplex-gradient dipole is proposed (Fig. 9). The individual flux density for every

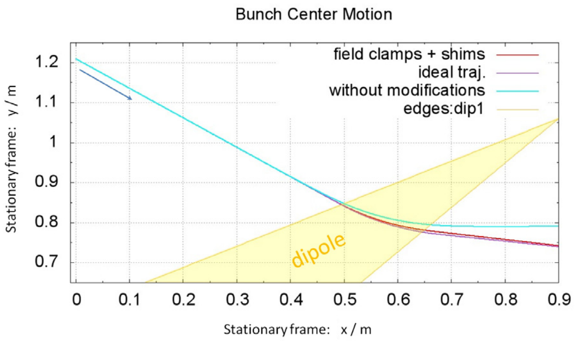

Figure 7: Comparison: realistic external 3D-field distribution of the first dipole applied to the PIC-code versus ideal trajectory defined by constant field and hard edge approximation. Improvements in magnet design lead to a convergence to the ideal trajectory.

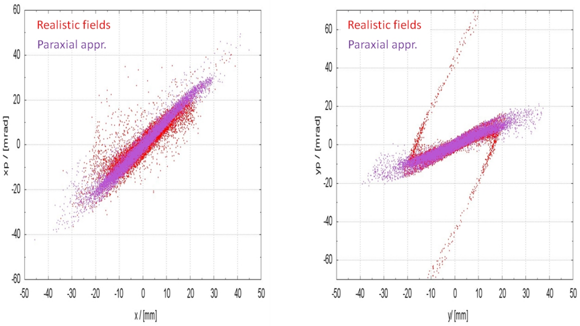

Figure 8: Transverse projections at the end of the trace in Fig. 7: Transport through a realistic field distribution of the improved magnet design (red) compared to first order paraxial approach with the same fringing field integral (purple). The core and the slope of the particle distribution fit very well. Aberration in the vertical plane are caused by vertical field gradients, which are increased by shimming the edges.

trajectory, defined by differences in gap height, leads to a global horizontal gradient, which causes a longitudinal compression of the macro bunches. An additional reversely 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 mT is needed, with a maximum field difference of 92.6 mT from the central to the outermost trajectory.

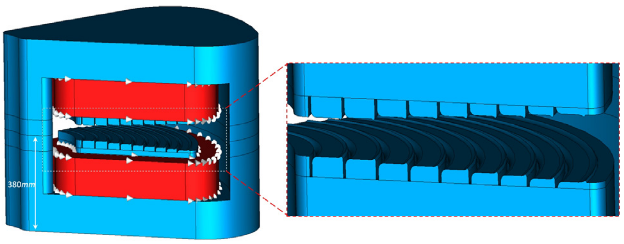

Figure 9: Preliminary design of the duplex-gradient dipole.

BEAM DYNAMICS - SPACE CHARGE EFFECTS

Single bunch beam dynamics are carried out by the *Particle Swarm Optimization* (PSO)[13] algorithm, applied to LORASR simulations. A solution is found with less than 5% losses at *Full Space Charge Forces* (FSCF) (Fig. 10).

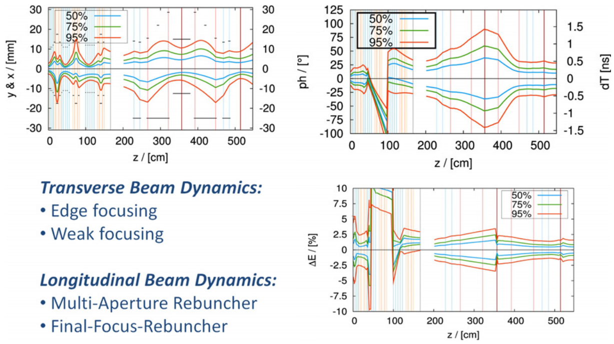

Figure 10: PSO-result for the central trajectory. The transverse dimensions of the micro bunch are significantly smaller than the given apertures (black bars). In principle a 1 ns micro bunch with an energy spread less than ±5% is possible at the exit of ARMADILLO.

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. 11 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 corresponds well to the *rms* width of the pulses. Merging at *full space charge forces* can still meet the requirements. The 95% radius of the transverse beam spot is expected to be at least 10% smaller than the radius $R = 10$ mm 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* [14]. 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

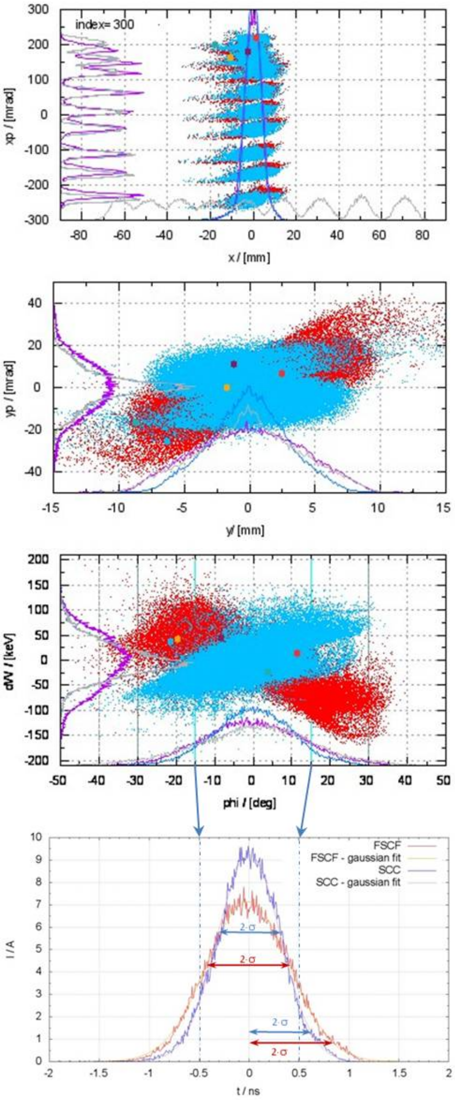

Figure 11: Merging: Projections at the Li-target. Transport with *Full Space Charge Forces* (FSCF, red and violet) compared to *Space Charge Compensated* (SCC, blue) transport. The longitudinal coordinate ϕ is given by the rf-phase at 87.5 MHz. Grey lines are the initial beam profiles, when merging is started.

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 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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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%

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