Experimental and numerical studies on laser-generated spin-polarized particle beams

P. Gibbon[1,2], Z. M. Chitgar[1], C. Zheng[1], P. Fedorets[1], A. Lehrach[1,5], X. F. Li[1,6], M. Büscher[1,3]

[1] *FZ Jülich, Germany;* [2] *KU Leuven, Belgium;* [3] *HHU Düsseldorf, Germany;* [5] *RWTH Aachen, Germany;* [6] *Jiao Tong University Shanghai, China;*

Spin-polarized particle beams are already used for a wide range of applications in nuclear, particle and material physics to probe the structure of matter at the subatomic level. Such sources offer the means to gain insight into quantum chromodynamics, nuclear reactions and symmetry violations, and can in principle even yield enhanced fusion cross-sections in reaction channels of interest [1]. Given the rapid advances in laser-driven particle acceleration over the past 3 decades, attention has recently turned to the question of whether polarized particle beams can also be accelerated via a compact laser-plasma scheme while preserving a high degree of net beam polarization. Experiments by the Jülich team have previously demonstrated that an unpolarized proton source is not polarized during the interaction when subjected to laser acceleration from the rear of a foil target at multi-mJ energies [2], prompting the recent series of campaigns to accelerate a *pre*-polarized ion source using the PHELIX laser system at GSI Darmstadt to accelerate ^{3}He and ^{4}He ions [3].

The polarization of the laser-driven ^{3}He ion beam within a few MeV can be analyzed by secondary scattering in a deuterated foil target, simultaneously observing the Rutherford scattering of ^{3}He ions and the deuterium-^{3}He fusion reaction, the later one showing whether the laser-driven ^{3}He ion beam is polarized when the pre-polarized ^{3}He gas target is utilized [4]. A very first test of the preservation of the nuclear polarization of ^{3}He inside a laser-induced plasma was made in the summer of 2021 at the PHELIX laser facility at GSI/Darmstadt - see Fig. 1. For this purpose a ^{3}He polarizer based on the Metastability Exchange Optical Pumping (MEOP) method was used to achieve a polarization value of more than 70%, after which the ^{3}He can be compressed and stored at pressures of 3 bar with a lifetime exceeding 100 h, permitting transportation within a cage equipped with permanent magnets. A system of pneumatic valves and a compressor then serves to compress the polarized ^{3}He up to 30 bar and a very fast piezo valves determines the gas pulse that leaves a supersonic nozzle. In such a way the target densities of 4×10^{19} atoms/cm^{3} are attained for interaction with

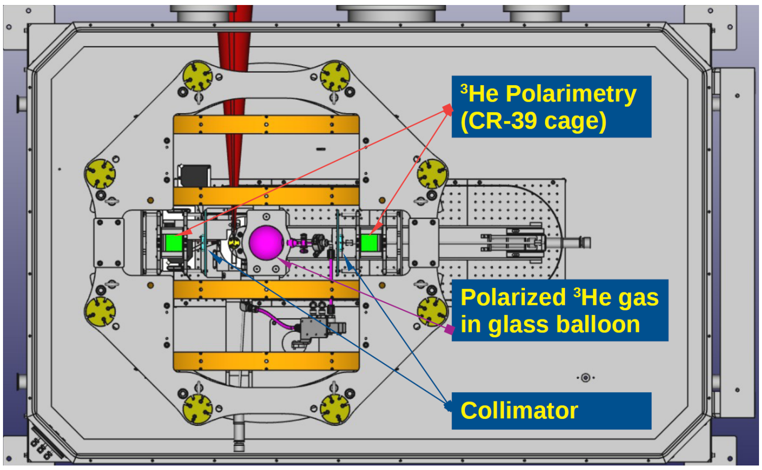

Figure 1: PHELIX Experiment Setup

the PHELIX laser beam.

After ionizing the polarized ^{3}He atoms into ions and accelerating them to a few MeV [3] the $^3He^{2+}$ ions must pass a collimator before they reached the nuclear-reaction polarimeter (green). Based on the known analysing powers of the fusion reaction $^3\vec{He}+d \rightarrow ^4 He+p$, both protons as well as $^4He^{2+}$ ions are registered with stacks of CR-39 plates. The helium ions with Z=2 are stopped in the first layer, but due to the high Q-value of the fusion reaction (18.4 MeV) the protons travel through two layers before they are stopped too. Due to the different tracks produced by both types of particle, they can be identified and their fraction measured as function of the scattering angle.

Since the polarimeter is only able to detect transverse polarization, the ^{3}He beam accelerated perpendicular to the laser beam needs to be polarized along the laser beam axis, which is realized by activating the Helmholtz coils (orange) along the PHELIX beam direction. There are two polarimeters installed at different distances to the gas-jet target, giving double cross-check measurements of the beam polarization. To minimize systematic errors, the beam polarization can be flipped by reversing the direction of the current in the Helmholtz coils. In this case, the asymmetry should also flip between the top and bottom sides in the polarimeter.

Preliminary measurements with the complete polarized gas-jet target and detection system yielded up to 8000 alpha-particle counts on the CR-39 plates, with a left-right asymmetry of $\simeq 160$ and statistical error $\sim \sqrt{N} \simeq 90$. While this an encouraging result, it is clear that the $^3He^{2+}$ ion flux collected by the detector is still too low to confidently pronounce this as a polarized ion source! Nevertheless the analysis thus far provides an important proof-of-principle that each stage in this complex experiment could be successfully executed.

In order to assess and optimize the efficiency of the ^{3}He ion acceleration and preservation of spin polarization, 2D PIC simulations using EPOCH code [5] have been performed for the PHELIX laser parameters, *i.e* an intensity of $1.38 \times 10^{19}\,\mathrm{W\,cm^{-2}}$ with $1.053\,\mu$m wavelength and a pulse duration of 0.8 ps FWHM. The laser pulse is focused from the left boundary down to a focal waist of $25.7\,\mu$m (FWHM) in the centre of the gas-jet target. Two simulations were performed using $1.5 \times 1.3\,\mathrm{mm}^2$ and $2.0 \times 2.0\,\mathrm{mm}^2$ boxes filled with helium-3 gas at $4.75 \times 10^{19}\,\mathrm{cm}^{-3}$, discretized by a computational grid with a resolution of $0.04\,\mu$m in each dimension and around 1 particle per cell. The particle weighting shape function in the simulation is a fifth order (B-Spline). For both simulations a round target is used with a super-Gaussian density profile, so that the density falls off smoothly, avoiding a sharp edge. The simulation box in both cases is large enough to avoid substantial particle loss and spurious space-charge effects at the boundaries. The effective lengths of the targets in the above mentioned simulations are ~ 0.5 mm and ~ 1 mm, respectively.

Figure 2(a,c), shows the averaged kinetic energy per cell of accelerated $^3He^{2+}$ ions together with the laser-axis lineout of the ^{3}He gas target number density in the beginning of the simulation (blue line), number density of accelerated $^3He^{2+}$ (green line) and longitudinal electric field E_x (red line) at time $t = 10$ ps, Fig. 2(b,d), for both simulations. Generally there are two main mechanisms responsible for the acceleration: (a) ions which are accelerated at $\pm 90^\circ$ to the laser

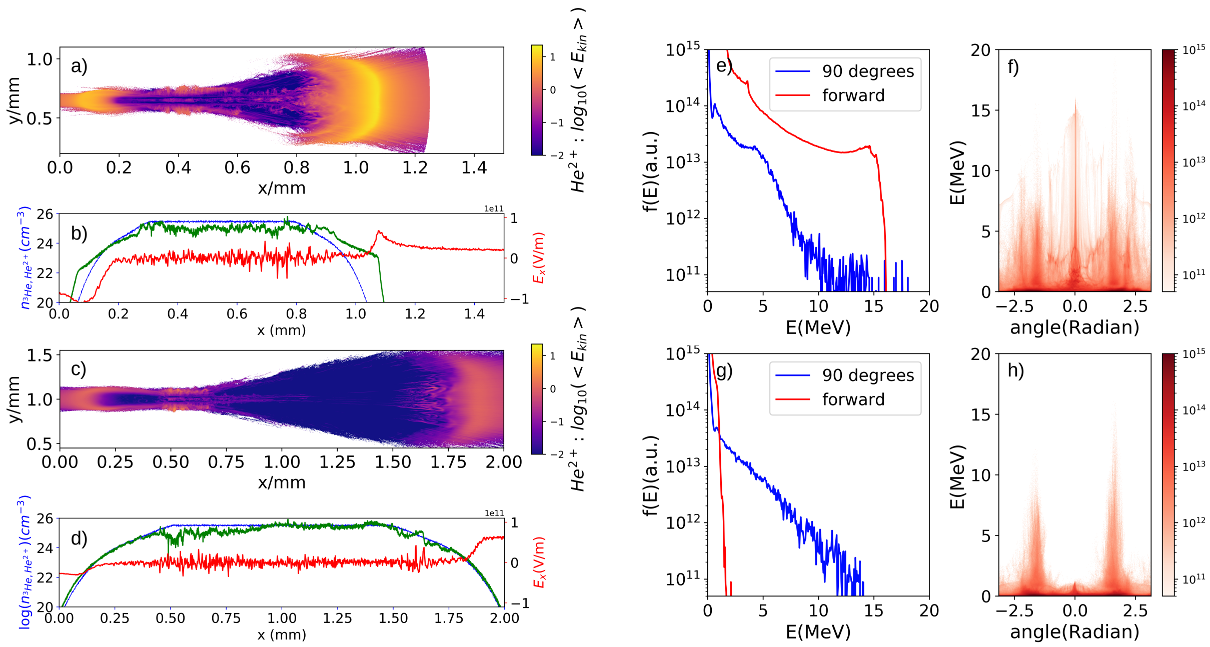

Figure 2: 2D simulations of $^3He^{2+}$ ion acceleration with EPOCH at $t = 10$ ps for gas jet diameters of 0.5 mm and 1 mm, showing: mean kinetic energy of $^3He^{2+}$ ions in MeV (a,c); lineouts of $^3He^{2+}$ number density (green line), longitudinal electric field E_x (red line), and initial number density of ^{3}He gas (blue line), for target lengths of 0.5 mm and 1 mm, respectively (b,d); ion energy spectra for short (e) and long (g) targets, selected in the forward (red line) and $\pm 90°$ (blue line) directions; angular distribution of accelerated ions, where the scale represents the number of the $^3He^{2+}$ ions (f,h). The number density plots are on a logarithmic scale.

axis, creating a channel, (b) those blown off the trailing edge of the target in forward direction. In the latter case, the $^3He^{2+}$ density plot and longitudinal electric field profile are consistent with a TNSA-like mechanism, consistent with previous experimental studies [6]. The acceleration direction can be identified more clearly via the angular distribution plot, Fig. 2(f,h), which reveals the three main acceleration directions, *i.e.* $\pm 90°$ and the forward direction with a half-angle $< 30^o$. For the shorter target, the forward acceleration dominates because a substantial portion of the laser energy passes through the jet, sustaining a strong longitudinal electric field at the trailing edge.

According to the energy spectra acceleration in the $\pm 90°$ (blue line) is insensitive to the target length of the target with a cutoff at ~ 12 MeV, all other parameters remaining the same. However, the forward acceleration (red line) is highly dependant on the target length: ions get accelerated up to ~ 15 MeV for the shorter target, while only ~ 2 MeV for the longer target, although this may not yet have reached saturation. Further simulations at other gas densities suggest that there is an optimal gas jet diameter beyond which laser depletion and filamentation prevent significant forward acceleration and reduce the channel length over which radial acceleration is observed. More detailed analysis of these findings will be presented elsewhere.

The polarization dynamics of the $^3He^{2+}$ ions was examined with a new spin-tracking module added to EPOCH, based on the solution of the T-BMT equation [7]. With this module it is possible to track the spin evolution of the $^3He^{2+}$ ions exposed to the laser and plasma-generated magnetic fields. The simulation starts with polarized ^3He gas target with a polarization of $S_x = 1$ and $S_y = S_z = 0$. Figure 3 shows the spin evolution $\langle S_x \rangle$ and during the acceleration process for 15 ps along with the average energy of the ions. With the higher energy gain, *i.e.* 0.5 mm target (hollow circle markers), polarization falls off faster by 0.1% for the forward ions and 0.4% for radially accelerated ones, while the longer target (solid square markers) results in a 0.04% decrease in the forward direction and 0.1% in the radial direction. These are both negligible compared to experimental typical losses over several shots (in a day) and one can conclude that the spin polarization is conserved during the acceleration process, regardless of emission direction.

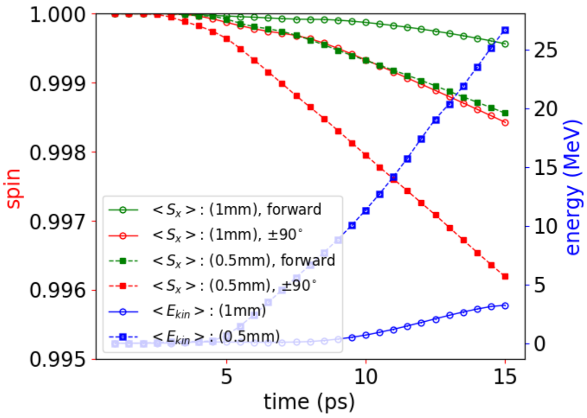

Figure 3: spin (green line for forward and red line for radial direction) and energy evolution (blue lines) of accelerating $^3He^{2+}$ ions. Hollowed circle marker represents the longer target, and solid square is the shorter one.

In summary, we have successfully demonstrated full deployment of a new targetry and detection system for laser acceleration of spin-polarized MeV ion beams. Preliminary analysis of alpha particle asymmetry generated by fusion reactions with deuterated foils indicate that the ion flux needs to be enhanced by $3-4\times$ to be confident of the efficacy of this polarized source [8]. Simulations suggest that there is negligible polarization degradation due to the acceleration process for this laser-target configuration, and that the flux might be increased by up to an order of magnitude by matching the gas jet dimensions and density to favour forward acceleration. Improvements to the polarimetry diagnostic system are also being implemented to improve the detection statistics for a follow-up campaign with the PHELIX laser.

References

[1] R. Engels *et al.*, in Proc. Science, 23rd Spin Physics Symposium (SPIN2018), Ferrara, Italy (2018). https://doi.org/10.22323/1.324.0031/

[2] N. Raab, M. Büscher *et al.*,Phys. Plasmas **21**, 023104 (2014).

[3] I. Engin, Z. M. Chitgar, *et al.*, Plasma Phys. Control. Fusion, **61** 115012 (2019).

[4] P. Fedorets, C. Zheng, *et al.*, Instruments, **6**, 18 (2022).

[5] Arber, T D *et al.*, Plasma Phys. Contr. Fusion **57**, 1/–26 (2015).

[6] L. Willingale *et al.*, Phys. Rev. Lett. **96**, 245002 (2006); A. Lifschitz *et al.*, New J. Phys. 16, 033031 (2014).

[7] X. F. Li, P. Gibbon, A. Hützen, M. Büscher et al., Phys. Rev. E **104**, 015216 (2021).

[8] C. Zheng *et al.*, 'Polarimetry for high intensity polarized ^3He generated in laser-plasma interaction', in preparation (2022).