FLASH simulations that model laser-driven plasma experiments aiming to study second order Fermi acceleration at the GSI Helmholtz Centre for Heavy Ion Research

K.Moczulski[1],A.Scopatz[1], T. Campbell[2], C. A. J. Palmer[5], C. D. Arrowsmith[2], A. Blazevic[3], D. Schumacher[3], M. Metternich[3], H. Nazary[3], P. Neumayer[3], V. Bagnoud[3], O. Karnbach[2], C. Spindloe[4], A. F. A. Bott[6], S. Sarkar[2], A. R. Bell[2], A. A. Schekochihin[2], R. Bingham[4], S. Feister[7], F. Miniati[2], D. Q. Lamb[8], B. Reville[9], G Gregori[2], P. Tzeferacos[1,2]

[1]University of Rochester [2]University of Oxford [3]GSI Helmholtz Centre for Heavy Ion Research [4]Rutherford Appleton Laboratory [5]Queens University Belfast [6]Princeton University [7]California State University Channel Islands [8]University of Chicago [9]Max Planck Institute for Nuclear Physics

Abstract: Non-thermal particles are common in the Universe and are observed in solar winds, supernova remnants, gamma ray bursts, and elsewhere. One of the methods used to explain how the particles are accelerated is the second order Fermi mechanism. While less efficient than diffusive shock acceleration, the ubiquitous nature of magnetized turbulence makes second order Fermi[1] an important process. Magnetized turbulence can cause stochastic particle acceleration to non-thermal velocities, with the Hillas limit typically being used as the upper bound on such acceleration. With the combination of high-powered laser systems and particle accelerators it is possible to use magneto-hydrodynamical scaling to understand this astrophysical phenomenon. We present FLASH MHD simulations used to interpret laser-driven plasma experiments that aim to reproduce second order Fermi acceleration at the GSI Helmholtz Centre for Heavy Ion Research. The experiments aim to demonstrate the second order Fermi acceleration process in stochastic magnetic fields. The simulations results are compared to the experimental measurements in an attempt to characterize the turbulent magnetized plasma responsible for the non-thermal particle acceleration.

GSI Facility: The experiment took place at GSI Helmholtz Centre for Heavy Ion Research facility in Germany[2]. In order to generate a plasma with stochastic magnetic fields the experiment employed two laser beams, nhelix (Nanosecond High Energy Laser for heavy Ion eXperiments) and phelix (Petawatt High Energy Laser for heavy Ion eXperiments). The lasers generate a pair of asymmetric colliding flows by ablating two plastic (CH) grooved targets, which are separated by 1.95 mm. To measure particle acceleration, Calcium ions are launched through the interaction region, accelerated by the UNILAC (Universal Linear Accelerator) device. The experimental setup is shown in Figure 1. The top laser (nhelix) has a wavelength of 1064 nm, while the bottom laser (phelix) has a wavelength of 1053 nm. Each beam deposits 50-60 J of energy onto each target, with a spot size of 200 µm. The pulse duration is 10 ns, with a 3 ns rising edge, a 4 ns plateau, and a 3 ns falling edge. The lasers have a 40° angle of incidence.

FLASH Simulations of the GSI experiments: FLASH[3] is a multi-physics[4], parallel, adaptive mesh refinement (AMR), finite-volume Eulerian radiation hydrodynamics and magneto-hydrodynamics (MHD) code, developed by the Flash Center for Computational Science [https://flash.rochester.edu] at the Department of Physics and Astronomy of the University of Rochester. In this work, we use FLASH to model the GSI experiments and help interpret their outcomes.

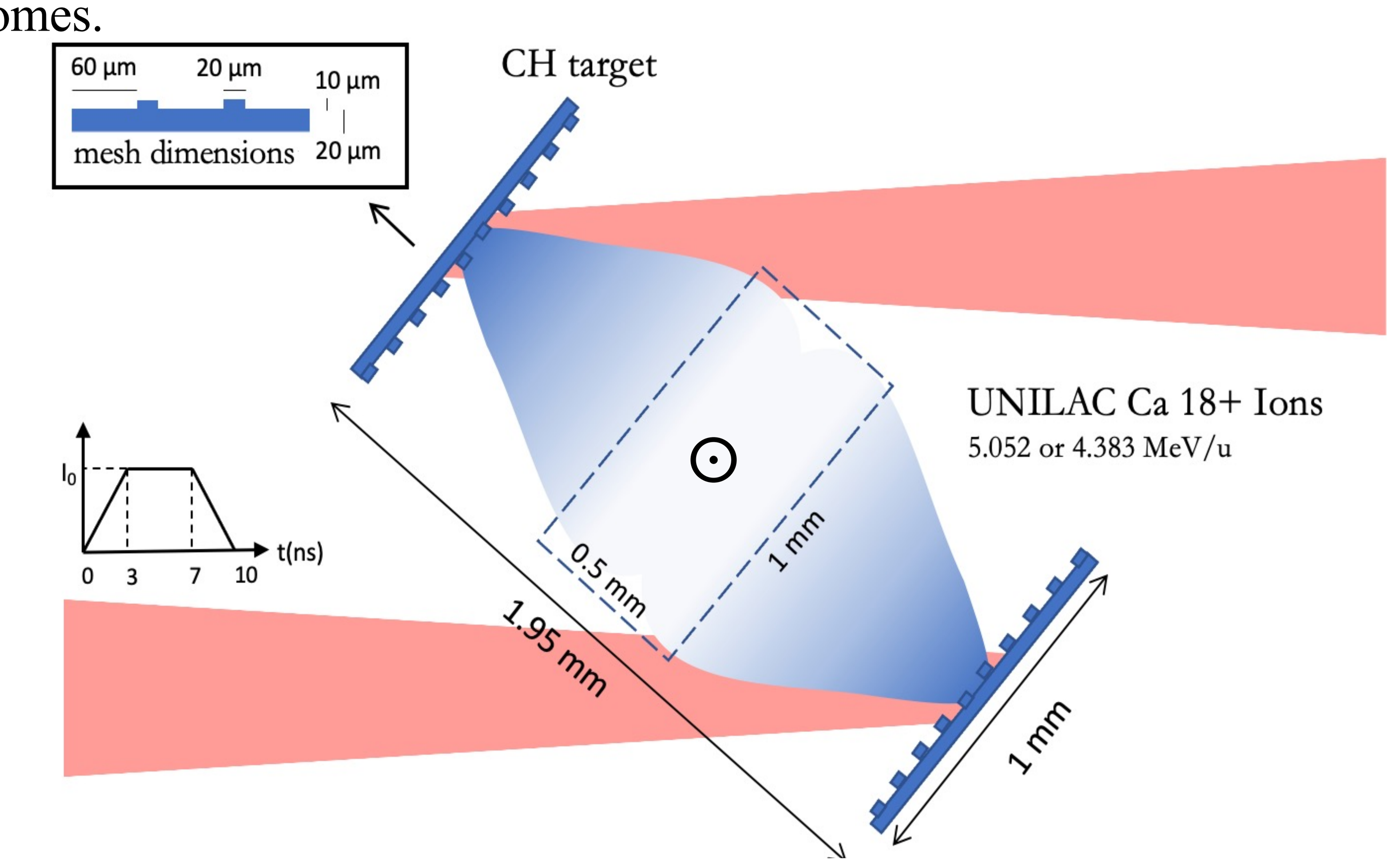
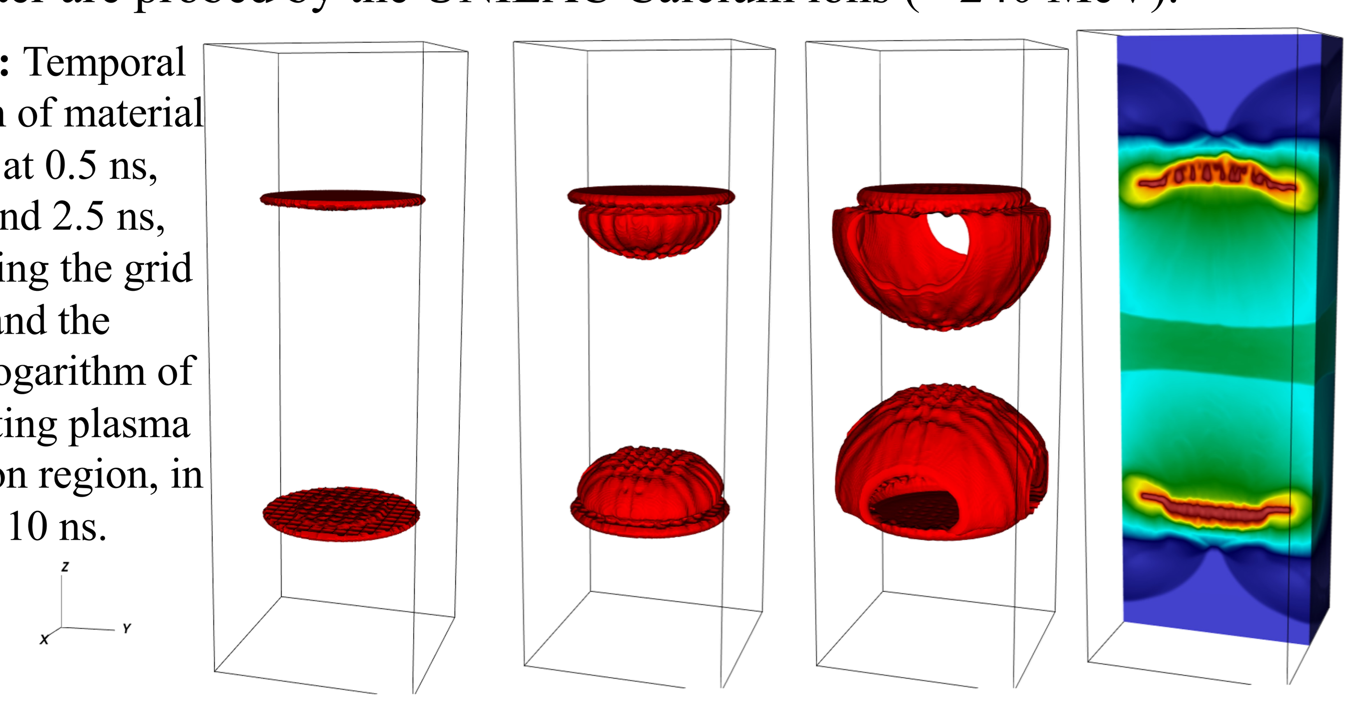


Figure 1: Setup of the GSI experiment. The top beam denotes the nhelix laser while the bottom beam is the phelix laser. The box in the center is the region where the UNILAC-accelerated Calcium ions traverse.

To model the experiments, we initialized a pair of CH target foils 1.95 mm apart and illuminate them with laser beams whose parameters match those of nhelix and phelix. The grooves in the CH targets reproduce the machined targets used in the experiments and are rotated by 30° with respect to one another. The lasers ablate the targets, creating a pair of counter-streaming flows that maintain the grid patterns (Figure 2) and carry Biermann battery-generated magnetic fields. At ~ 2.7 ns after the lasers are turned on, the two flows collide in the center of the domain to create an interaction region with stochastic magnetic fields (Figure 3). The latter are probed by the UNILAC Calcium ions (~ 240 MeV).

Figure 2: Temporal evolution of material contours at 0.5 ns, 1.5 ns, and 2.5 ns, maintaining the grid pattern, and the density logarithm of the resulting plasma interaction region, in g cm^{-3} at 10 ns.



Collisionality: As FLASH is an MHD code, it does not model kinetic effects and cannot accurately capture counterstreaming ion-ion interactions unless they are in the collisional regime. To ensure we are within such a regime, we compute the inter-jet mean free path[5] of the Carbon ions outside of the interaction region and the collisional mean free path within the interaction region, normalized to the interaction region thickness (Figure 4). At early times, the inter-jet mean free path of the Carbon ions is greater than the interaction region, resulting in counter-streaming. This phase only lasts for ~ 2 ns after collision, promptly entering the collisional regime after that - which is well described by the code. The inter-jet and collisional mean free paths remain much smaller than the interaction region size at late times.

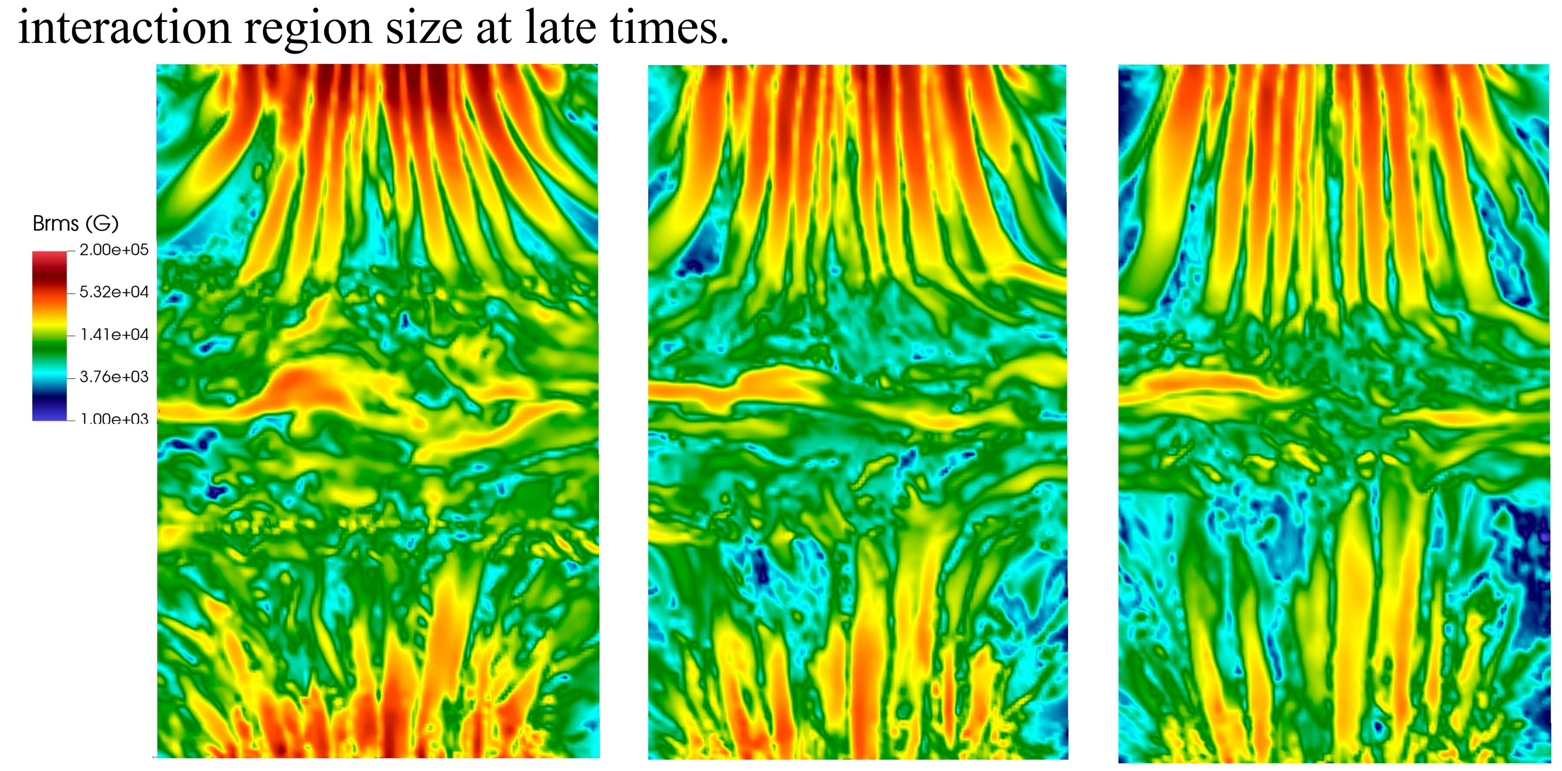


Figure 3: RMS magnetic field in Gauss as a function of time in the FLASH simulations, at 15 ns (left), 20 ns (center), and 25 ns (right).

Comparison to the experimental results: As seen in Figure 5, the FLASH simulation results start to match plasma conditions attained in the experiments (temperature and density) for t > 15 ns. On account of the short (~ 2 ns) duration of collisionless counterstreaming of the Carbon ions, FLASH initially overpredicts the plasma temperature and density of the interaction region, and underpredicts the interaction region thickness. While this effect is dynamically relevant to the experiment at early times, the properties align when the experiments record the Calcium ion acceleration, after 10 ns.

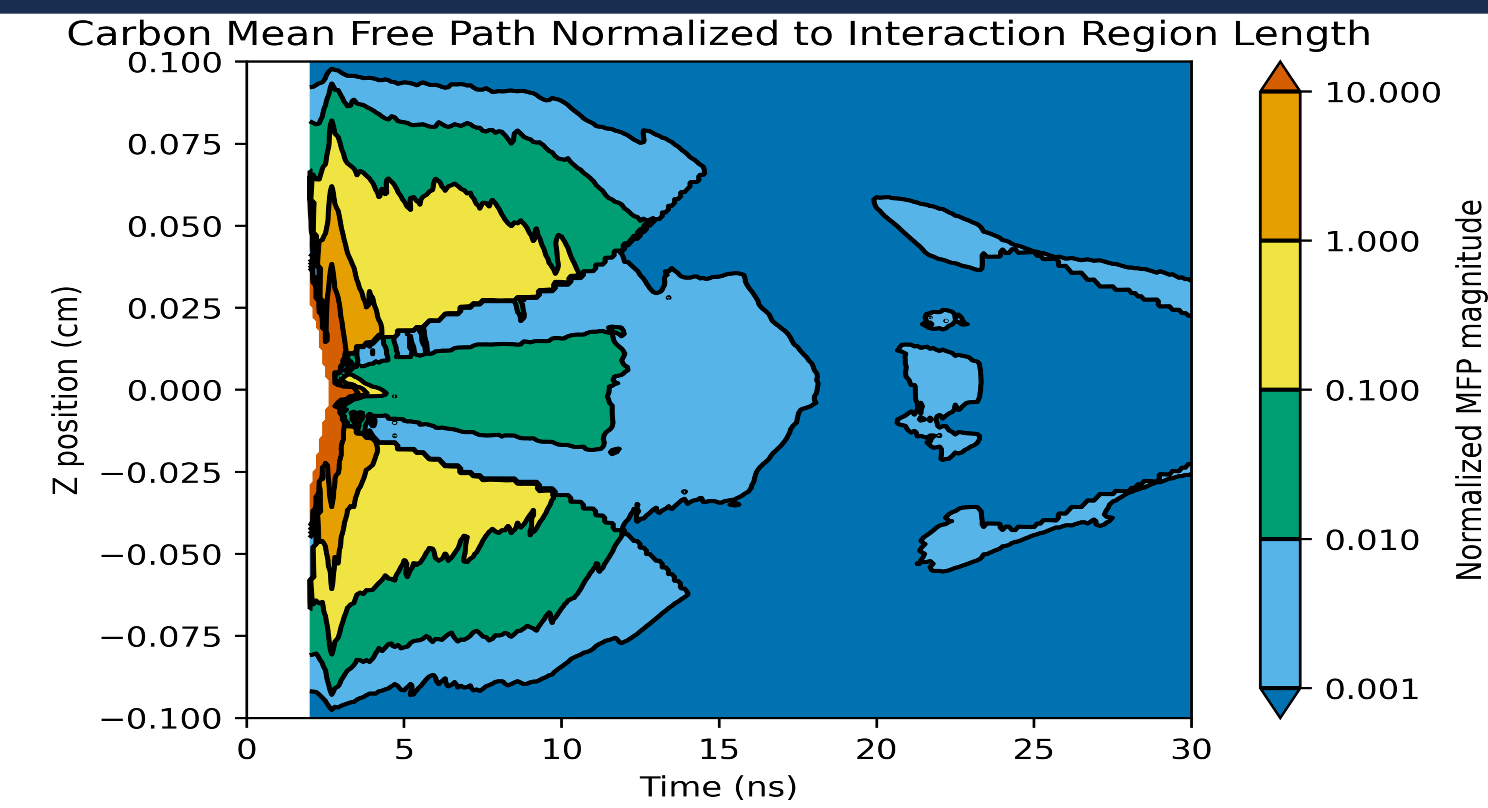


Figure 4: Carbon ion inter-jet mean free path outside of the interaction region and the thermal Carbon ion mean free path within the interaction region as a function of time and space (along the line of centers connecting the two targets).

Figure 3 shows the magnetic field structure in the FLASH simulation at 15 ns, 20 ns, and 25 ns. The magnetic field is generated by the laser-target Biermann battery, which is advected and subsequently compressed at the midplane. To account for any magnetic field generation due to the ion Weibel instability during the first instances of the jet interaction, we calculate the Weibel growth rate[6] and find $\gamma_W \sim 6 \times 10^{-8}$ s^{-1}. Since the counter-streaming phase is only ~ 2 ns, this is insufficient time to generate Weibel filaments. This is consistent with most of the magnetic fields present in the interaction region plasma originating from Biermann battery.

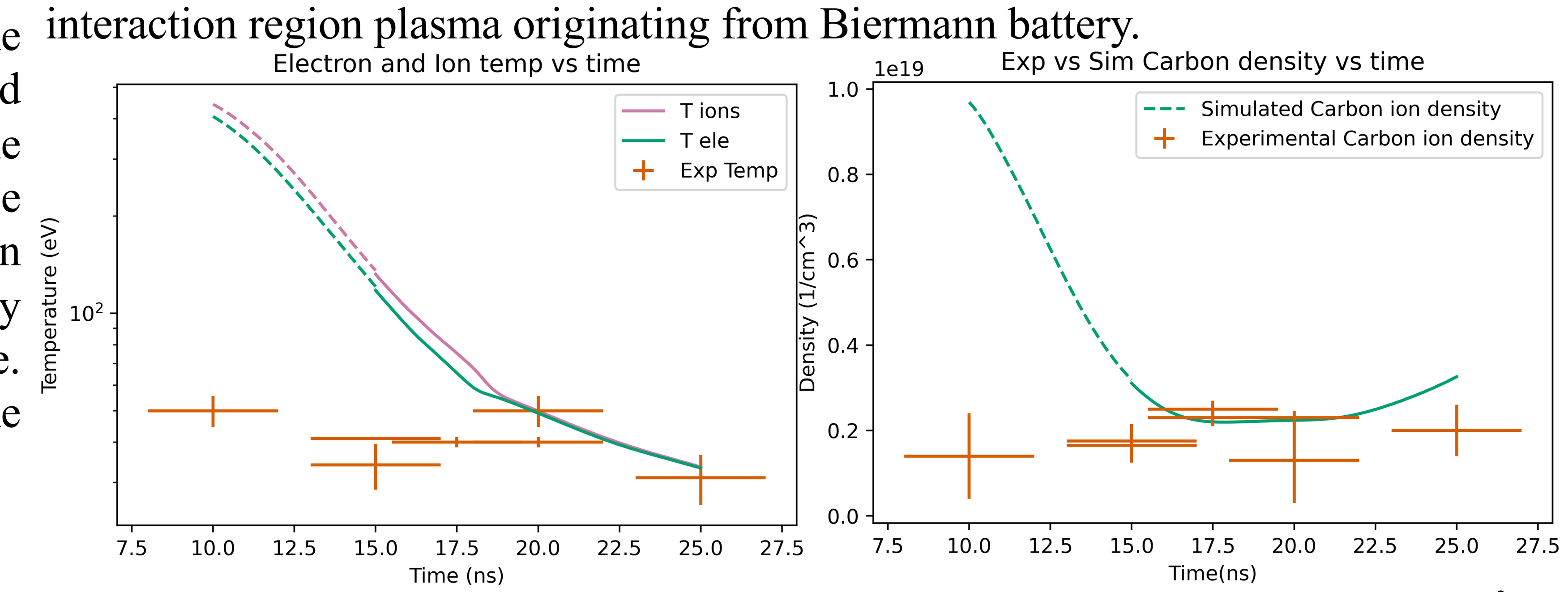


Figure 5: Simulated electron and ion temperatures in eV (left) and carbon ion densities in cm^{-3} (right), compared against the experimental results.

For the simulated plasma properties, we recover an energy diffusion of the Calcium ions due to Fermi acceleration of the order of

$$\left(\frac{\Delta E}{E}\right)_B = 3\times 10^{-4}\left(\frac{Z_b}{18}\right)\left(\frac{u}{250\ \mathrm{km/s}}\right)\left(\frac{B}{100\ \mathrm{kG}}\right)\left(\frac{E_b}{240\ \mathrm{MeV}}\right)^{-1}\left(\frac{L\ell_B}{2\ \mathrm{mm}^2}\right)^{1/2},$$

where u and B are the RMS values of the velocity and magnetic field, respectively, and ℓ_B is the correlation length of the magnetic field. The experimental results show also a significant upshift in the Calcium ion spectra that is of the order of $(\Delta E/E)_{\mathrm{upshift}} \sim 8\times10^{-4} - 3\times10^{-3} > (\Delta E/E)_B$. The likely explanation for the large upshift is the lower hybrid drift instability[7]. This is caused by a global vorticity in the interaction region that the stochastic magnetic fields align with. The resulting density gradients point radially outward, creating an environment which is unstable to lower-hybrid waves and a longitudinal electric field which can further accelerate the ions.

References:

1. Petrosian, *Space Science Reviews,* **173,** 535, 2012.
2. Bagnoud et al., *Applied Physics B,* **100**, 137, 2010.
3. Fryxell et al., *The Astrophysical Journal Supplement Series,* **131,** 273, 2000.
4. Tzeferacos et al., *High Energy Density Physics,* **17**, 24, 2015.
5. Trubnikov, *Reviews of Plasma Physics,* **1**, 105, 1965.
6. Ryutov et al., *Physics of Plasmas,* **21**, 032701, 2014.
7. Davidson, *Physics of Fluids,* **21**, 1375, 1978.

We would like to thank the operators and technicians of the GSI Helmholtz Centre for Heavy Ion Research, specifically those who assisted on the UNILAC accelerator, the Z6 experimental hall, and the PHELIX and NHELIX lasers. The Flash Center acknowledges support by the U.S. DOE NNSA under Awards DE-NA0002724, DE-NA0003605, DE-NA0003842, DE-NA0003934, DE-NA0003856, and Subcontracts 536203 and 630138 with LANL and B632670 with LLNL; the NSF under Award PHY-2033925; and the U.S. DOE Office of Science Fusion Energy Sciences under Award DE-SC0021990.