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Towards swift ion bunch acceleration by high-power laser pulses at the Centre for Advanced Laser Applications (CALA)

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ABSTRACT

Laser-driven acceleration of ions has inspired novel applications, that can benefit from ion bunch properties different from conventionally (non-laser based) accelerated particle beams. Those differences range from extremely short bunch durations, broad energy spectra, large divergence angles and small source sizes to ultra-high ion bunch densities. So far, the main focus of research has been concentrating on the physics of the interaction of intense laser pulses with plasmas and the related mechanisms of ion acceleration. Now, the new Centre for Advanced Laser Applications (CALA) near Munich aims at pushing these ion bunches towards applications, including radiation therapy of tumors and the development of heavy ion bunches with solid-state-like density. These are needed for novel reaction mechanisms ('fission-fusion') to study the origin of heavy elements in the universe and to prepare for related studies at the upcoming EU-funded high-power laser facility ELI – Nuclear Physics in Bucharest.

1. Introduction: properties of laser-accelerated ion bunches

About 15 years ago, it was realized that short, high-power laser pulses can accelerate ions to high energies in the range of some tens of MeV, if the laser is focused on a thin solid foil target down to a small spot of some micrometers [1–3], exceeding the relativistic laser intensity threshold of 1.37×10^{18} W/cm^2, at which electrons start to get accelerated to relativistic energies within a few laser cycles. These electrons leave the target and, as a consequence, a massive electric field with gradients in the order of TV/m emerges, that drives the ion acceleration. The ions emerging from this laser-solid interaction exhibit some very specific features, which are fundamentally different from the ion bunches provided by conventional accelerators. These features are [4–6]:

- A mixed radiation field consisting of different, target-dependent ion species with variable charge states as well as relativistic electrons, neutrons and X-rays.
- A very broad energy spectrum, depending on the underlying acceleration mechanism with a bandwidth from 10–20% up to 100%, while the ion bunch durations are very short (in the order of some picoseconds) right after the target. This yields longitudinal emittances of below 1×10^{-4} eVs, which is competitive to conventional accelerators.
- A very small normalized transverse emittance of below 0.01 mm mrad (compared to about 1 mm mrad in conventional accelerators [7]). This is resulting from the ion bunch originating from a small, micrometer source size and the (at present still rather) large divergence half angles ranging from two [8] up to some tens of degrees.

The target normal sheath acceleration mechanism (TNSA) is nowadays the most prominent laser ion acceleration mechanism, as it dominates the laser-plasma interaction at laser intensities below 10^{22} W/cm^2 and is thus accessible with existing laser systems. For higher intensities, as promised by upcoming next-generation laser systems, the radiation pressure acceleration mechanism (RPA) becomes increasingly relevant, which promises a narrower energy spread and a more efficient conversion of laser energy to ion energy [5].

As protons are always present in form of surface contaminants even at metal foils, they are the most intensively studied laser-

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accelerated ion species. Typical proton numbers achieved in the experiments range from 10^6–10^8/(msr × 1%E_{kin}). Using adequate ion beam optics to refocus these proton bunches both spatially and temporally, very high proton fluxes in the order of about 10^{12}–10^{14} protons/(cm^2 × ps × 1%E_{kin}) can be achieved with maximum proton energies approaching 100 MeV [9,10]. The ongoing developments of new Petawatt-class laser systems promise to surpass these energies soon, as the maximum proton energy scales with the laser energy and the laser intensity, respectively [11].

2. Laser-driven ion acceleration at CALA

Laser-driven ion acceleration will be one of the central research topics at the new Centre for Advanced Laser Applications (CALA) in Garching near Munich, which is currently built and will be operated by the two universities in Munich: the Ludwig-Maximilians-Universität München (LMU) and the Technische Universität München (TUM). After the civil construction works have recently been finished, the ATLAS 300 laser will be moved from the Laboratory for Extreme Photonics (LEX Photonics) to CALA and upgraded from 300 TW to a 3 PW laser system, the ATLAS 3000.

The ATLAS 3000 laser is Ti:sapphire based (*A*dvanced *T*i:sapphire *LAS*er) and will provide 60 J pulse energy within a pulse duration of 20 fs at a repetition rate of 1 Hz. Focused down to a small spot with a radius of a few micrometers, intensities above 10^{22} W/cm^2 can be achieved. With this laser system, Munich will play a leading role in the investigation of laser-driven ion acceleration, particularly with regard to applications of this unique particle source.

The preparations for the experiments at CALA already started years ago. Especially, LEX Photonics and the ATLAS 300 laser have been extensively used for technological development of high repetition rate components for future experiments and applications. Fig. 1 shows the designed experimental setup for laser-based heavy ion acceleration at CALA. Most of these components have already been routinely used at LEX Photonics. Advanced expertise has been gained in target production and positioning: our group in Munich shows world-leading capability in fabrication of free-standing diamond-like carbon (DLC) foils [12] as well as of near-critical-density carbon-nanotube-foam (CNF) targets [13]. Levitating spheres in a Paul trap have been used by our group to investigate truly isolated, mass-limited targets [14]. The requirements of high-repetition-rate laser-driven ion experiments, accompanied by the demand of a high number of targets, are faced by the application of the droplet method for the efficient production of a large amount of thin plastic foils with thicknesses between a few nanometers up to micrometers [15]. Furthermore, a target wheel has been designed to provide an accurate positioning of a high number of targets at a repetition rate up to 1 Hz [16].

A major obstacle for high-repetition-rate experiments is the diagnostics for the laser-accelerated ions, since the environment in laser-plasma experiments is very hostile for any kind of electronic detectors due to the massive electromagnetic pulse generated as a consequence of the laser-plasma interaction [17,18]. Our group investigated the usage of pixelated semi-conductor detectors as online detectors for laser-accelerated protons for the first time [19,20] and recently employed the CMOS-based RadEye1 detectors successfully in an advanced setup for the simultaneous, high-repetition-rate detection of both laser-accelerated ions and electrons in experiments performed at LEX Photonics. Moreover, new concepts for in-line pulse cleaning and contrast measurement are investigated and ion beam optics have been prepared for beam guidance and focusing.

All these efforts, especially for gaining high-repetition-rate capability, have been done following the main goal for laser-driven ion acceleration at CALA: preparing this unique particle source for applications.

3. Applications of laser-driven ion acceleration: two examples

Many ideas for applications of laser-accelerated ion bunches will be explored at CALA. Most of them – but not all – will have medical background: for example, the suitability of these ion bunches for medical radiography is investigated, also involving the co-generated X-rays. Ionoacoustic tomography will be investigated at CALA as a potential new diagnostic tool for further development and characterization of the ion bunches, but also for range verification measurements in ion beam radiotherapy [21]. In the following, two further examples for applications at CALA will be sketched in more detail: laser-driven ion bunch radiotherapy (LIBRT) and the fission-fusion reaction mechanism, relevant for astrophysical nucleosynthesis investigations.

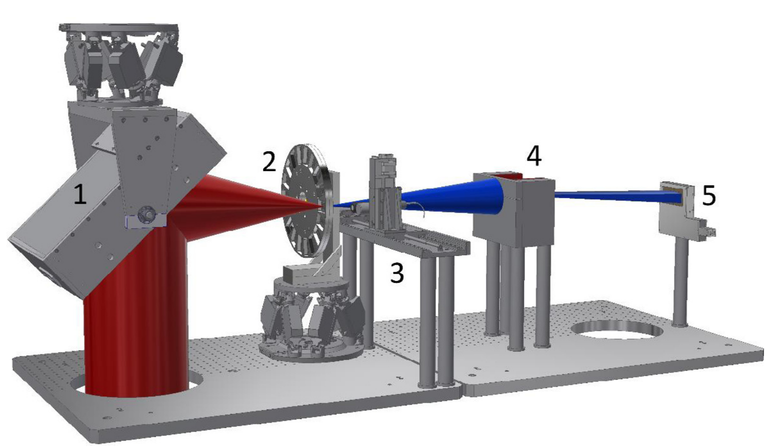

Fig. 1. Planned experimental setup for laser-driven ion acceleration experiments at CALA. The laser (red) hits a hanging f/2 parabola (1), that can be positioned precisely using a 6-axis hexapod. The parabola focuses the laser onto thin foil targets, provided by an automated, 1 Hz nano-target positioning system (2). A microscope (3) ensures together with a confocal sensor that the targets are exactly placed in the focus. An ion bunch (blue) is accelerated from the target foils and finally detected in the chosen diagnostics, in this case a magnetic wide-angle spectrometer (4), that deflects ions according to their velocity to different positions. These are recorded by RadEye1 CMOS pixel detectors in an aluminum housing (5), that functions as electromagnetic pulse (EMP) shielding. Most of these components have already been successfully tested and routinely used at the Laboratory for Extreme Photonics. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.1. Cancer therapy using laser-accelerated ions: LIBRT

Cancer therapy using light ions promises a better dose conformity and superior healthy tissue sparing compared to the more common photon therapy using energetic X-rays. Contrary to photons and electrons, ions deposit most of their energy at the position of the well-known Bragg peak, which is arbitrarily adjustable by choosing the energy of the penetrating ions and can be located deep inside the body. Thus, especially tumors in the vicinity of critical structures like in the head and deep-seated tumors can potentially be treated in a more effective way.

Albeit their ion bunch characteristics contrast those from conventionally accelerated ions in current clinical use [22], the utilization of laser-accelerated ions for laser-driven ion bunch radiotherapy (LIBRT) must be considered. For example, the non-monoenergetic spectrum and the large divergence angles can be beneficial for radiotherapy, as a simultaneous irradiation of larger areas in different depths becomes conceivable. Current and near term efforts will concentrate on the study of such new possibilities, that emerge from laser-driven ion bunches, complementing conventional technology.

First steps paving the way for LIBRT have already been taken, as the suitability of short, laser-accelerated proton bunches for inducing DNA damage in radiobiological cell experiments has been shown by our group [23] and others [24]. Next steps will be tackled at CALA: the generation of protons with energies of above 100 MeV and the subsequent irradiation of tumors in small animals.

3.2. Generation of extremely neutron-rich isotopes for astrophysics – the fission-fusion reaction mechanism

The second example for an application of laser-driven ion bunches at CALA are preparatory experiments for heavy ion acceleration towards the realization of the novel fission-fusion reaction mechanism [25]. This mechanism exploits the uniquely high density of laser-driven ion bunches to generate extremely neutron-rich isotopes close to the waiting point at the magic neutron number of N = 126 in the rapid neutron capture nucleosynthesis process (r-process) [26]. This process is known to be responsible for the production of heavy elements like gold, uranium or thorium. A detailed understanding of the r-process, however, requires the investigation of the nuclear properties of extremely neutron-rich isotopes, in particular those near this N = 126 waiting point, like their lifetimes and masses.

The production of these neutron-rich isotopes close to the N = 126 waiting point is far from being accessible using conventional acceleration techniques. Even state-of-the-art existing, upcoming or planned radioactive ion beam facilities like FAIR (at GSI/Darmstadt, Germany) or FRIB (at the NSCL of Michigan State University, USA), while also striving for reaching the N = 126 isotope region, will hardly be able to access the area relevant for the r-process, being about 15 neutrons away from the last presently known isotope. The fission-fusion mechanism benefits from the unprecedentedly high, solid-state like density of the laser-accelerated heavy ion bunch right after the target, exceeding typical ion bunch densities from conventional accelerators by up to about 14 orders of magnitude. If such a highly dense bunch of fissile, heavy ions, laser-accelerated from a first ‘production target’, hits a second ‘reaction target’, made of the same fissile material, closely spaced about 0.1 mm behind the production target to avoid dilution of the fission fragment density by Coulomb explosion, the fission-fusion reaction can start. Basically, it consists of two steps: first, fission of the heavy ions is induced, resulting in heavy and light fission products. Second, the fusion of two light, neutron-rich fission fragments resulting in even more exotic (=extremely neutron rich) isotopes near the desired magic neutron number N = 126 [25]. This second step is exclusively possible due to the ultra-high density of the ion beam and the resulting light and heavy fission fragments.

Fig. 2 visualizes the reaction scheme of the fission-fusion mechanism. Thorium (^{232}Th) is chosen as the heavy ion material due to its low radioactivity and its stability in the vacuum conditions needed for laser-driven ion acceleration (10^{-6}–10^{-5} mbar). An additional layer made of polyethylene could be added to both the production and the reaction target to maximize the fission yield of the ^{232}Th atoms. The ions accelerated from the production target by the laser pulse impinge upon the reaction target, where the thorium ions fission into heavy products centered around $\langle A_H \rangle = 139$ ($\langle Z_H \rangle = 55$, $\langle N_H \rangle = 84$) and light products with $\langle A_L \rangle = 90$ and $\langle Z_L \rangle = 38$ ($\Delta A_{L,FWHM} = 14$, $\Delta A_{L,10\%} = 22$). This second stage of the reaction, the fusion between two light fission fragments, will finally result in neutron-rich fusion products close to N = 126.

Estimating the fission-fusion reaction yield per shot, even high laser pulse energies of up to 300 J (as envisaged for the upcoming Extreme Light Infrastructure – Nuclear Physics (ELI-NP) facility in Bucharest, Romania) will end up with only a few (1–2) fusion products per laser shot in the relevant mass range A≈180–190, assuming conventional electronic stopping of the accelerated projectiles (fission fragments) in the reaction target [25]. This directly points to the necessity of research towards an increased laser repetition rate, like already foreseen for CALA with an 1 Hz operation. Moreover, also the ion stopping power may be significantly reduced by collective effects in the target due to the high density of the incoming ion bunch [27]. This could be considered in a simplistic way like the ion bunch acting as a snow-plough: the first ions of the bunch already remove all the target electrons, screening the subsequent ions from the electronic stopping in the first layers of the targets. This allows the ions accelerated from the production target to penetrate the reaction target much deeper, resulting in a highly increased number of light fission products. Assuming a stopping power reduction by a factor of 100, Ref. [25] calculated the resulting yield of neutron-rich fusion products to be in the range of 10^4 per laser shot. Clearly, such potential collective effects need to be experimentally addressed and quantified.

The proposed fission-fusion reaction mechanism requires in its first (fission) stage to (laser-) accelerate the ions from the production target to beyond the fission barrier, typically around 7 MeV per nucleon. In the second (fusion) reaction step, the fragment energies should be decelerated (via energy loss in the reaction target) to about 2–3 MeV/u for optimum fusion conditions. This motivates the additional polyethylene target layers visible in Fig. 2. In

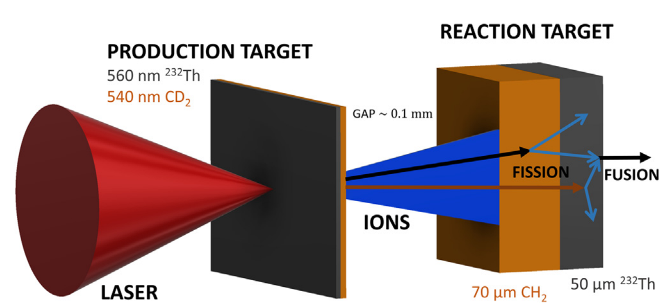

Fig. 2. Fission-fusion reaction scheme: The laser beam is focused onto the production target, where it accelerates thorium, carbon and deuterium ions to energies of about 7 MeV/u. The thorium ions (black arrow) are fissioning in the polyethylene layer of the reaction target, while the deuterium ions (orange arrow) induce fission of the thorium atoms at rest, contained in the reaction target. The close distance between the two targets (about 0.1 mm) avoids a dilution of the ultra-high density of the fission fragments by Coulomb explosion. The light fission fragments finally fuse, generating extremely neutron-rich isotopes close to the waiting point at N = 126 in the r-process. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Ref. [25], it was proposed to apply the radiation pressure acceleration (RPA) mechanism to accelerate the heavy ions from the production target to about 7 MeV/u, as this laser acceleration mechanism promises (in contrast to the more 'conventional' target normal sheath acceleration scheme) quasi-monoenergetic ion energies as well as a higher laser energy conversion efficiency. Using the 1D RPA model described by Robinson et al. [28], they estimated the needed laser pulse intensity to 1.2×10^{23} W/cm^2 and, thus, the required dimensionless vector potential to $a_L = 167$ for a laser wavelength of 800 nm.

At CALA, intensities in the range of 10^{22} W/cm^2 ($a_L \approx 50$) will be reachable, about one order of magnitude less than the optimum conditions described above. However, the ATLAS 3000 provides a unique possibility for the investigation, characterization and further optimization of laser-driven acceleration of heavy ions. This is necessary preparatory work for experiments at future facilities with even more powerful lasers, as presently under construction at the ELI-NP project in Bucharest. With the planned 2×10 PW system, intensities of above 10^{23} W/cm^2 will be possible, sufficient for fission-fusion experiments [29].

4. Conclusion

A number of specific, new applications benefit from the unique properties of laser-accelerated ion bunches. Even though these properties differ in many regards from those of conventionally accelerated ion bunches, these special features of this novel ion source potentially open up entirely new approaches to research areas in physics, radiation chemistry, biology and medicine. The specificity of the laser-driven sources will require a similarly unconventional thinking also from the application point of view to become revolutionary in a large number of research fields.

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