ALPA WORKSHOP

Applying Laser-driven Particle Acceleration: Using Distinctive Energetic Particle and Photon Sources

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WS101-1: Laser driven electrons for X-ray backscatter imaging

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High Power Lasers of 10-100’s TW capable of achieving relativistic intensities >10¹⁸ Wcm⁻² are rapidly developing worldwide and such systems are ideal for producing pencil like beams of ~0.05 - 1 GeV electrons. One application which can take full advantage of such electrons is single sided X-ray backscatter imaging[1] – “X-ray Radar”.

To deliver penetrating imaging, a narrow electron beam is generated in a suitable gas convertor, sent through the intervening air and strikes the target. As the e-beam passes through the target it generates X-rays and some of these are backscattered[2] and can escape. Using a time resolved X-ray detector, the depth at which the X-ray were emitted can be determined. If the beam is them scanned across the region of interest a 3D image can be formed.

The requirements for both a suitable laser driven e-beam and detector will be explored as well as considering the potential image quality with material depth. Demonstration images obtained using the Gemini laser will be reviewed and the future potential of such systems to deliver high penetration single images will be discussed.


The development of ion acceleration techniques based on ultra-intense lasers has been advancing rapidly due to the dramatic progress of laser systems capable of delivering increasingly higher power laser pulses. Based on these developments, laser-driven acceleration is now moving from pure scientific exploration to applications. In this context, the primary accelerating process known as Target Normal Sheath Acceleration (TNSA) represents a robust mechanism to accelerate light ions from laser interaction with thin foil targets [1].

Here, an overview is given about the ion acceleration activities ongoing at the Intense Laser Irradiation Laboratory within the TNSA regime [2].

Specifically, the activity with a 200 TW laser aims at establishing a beam-line of > 10 MeV protons coupled with a beam transport line that will provide an advanced test facility for the development and exploitation of laser-driven ion sources [3].

In parallel, a 10 TW laser beam-line is designed to serve as a practical platform for the assessment and development of a compact few MeV proton beam-line to perform Particle Induces X-ray Emission (PIXE) in ambient air, and to produce single-dose specific amounts of radioactive isotopes for biomedical imaging within suitably devised integrated high-yield microfluidic-based setups.

A description of the main components is given, including the laser, the beam transport lines, the interaction chamber, and the diagnostics. A review of the main results obtained so far is reported, including details of the laser-plasma interaction and ion beam characterization.
Figure 1: Lay-out of ILIL-PW system comprising the main multi-pass amplifier, compressor, and target area [2].


Particle acceleration in dielectric microstructures powered by infrared lasers, termed \textit{dielectric laser acceleration} (DLA), is a new and promising area of advanced accelerator research. The idea of using lasers to accelerate subatomic particles dates back even before the coinage of the word “laser.” However the technology to make such accelerators did not exist until more recently. With the advent of efficient solid state lasers and a rich variety of nanofabrication techniques developed by the semiconductor industry, scientific research in photonic devices, optical waveguides, and metamaterials for myriad uses (including particle acceleration) has garnered much interest in recent years. An active international community has developed working on photonic structure based particle acceleration, including government laboratories in both the United States and in Europe, as well as university groups in Israel, US, Germany, Japan, and Taiwan. In the last few years, the first demonstrations of particle acceleration have been conducted using such devices in experiments at both relativistic and subrelativistic energies [1-4], and compatible photonic systems for coupling of laser light and nanotip field emission sources have been developed [5]. Techniques using the laser field itself to provide transverse focusing and confinement of the particles have been proposed and are now being implemented into prototype experimental designs [6]. And waveguides based in silicon nitride have been found to provide a suitable architecture for delivery of ultrashort laser pulses to an on-chip accelerator [7]. An extensive international effort is underway to combine these approaches to make a working tabletop prototype accelerator [8].

Applications for a compact accelerator with target energies in the 1-20 MeV range (see conceptual illustration in Fig. 1), such as medical radiation oncology or ultrafast electron diffraction (UED) could provide compelling near term uses for a DLA based system. The operating principles are similar in some ways to conventional radio-frequency accelerators, but scaled down in operating wavelength and size by 5 orders of magnitude. This change of scale opens up a plethora of new areas of investigation and incorporates fields of study (material science, advanced photonics, laser science, nanofabrication) that are outside the usual framework for conventional accelerators as well as other advanced schemes such as plasma accelerators. The potential for sub-fs pulse structure and high repetition rates (1-50 MHz) for DLA also distinguishes it and may lead to very different operating regimes for light sources based on DLA. The evolving understanding of operation in this regime could lead to attosecond science developments for understanding atomic and molecular processes on short time scales. Links to other modern accelerator concepts may result: DLAs could tie in with conventional and plasma based schemes as ultra-high resolution monitoring devices. We will provide an update on new developments in this area of research and present results from a recent workshop held at SLAC to explore the variety of applications for this technology.
Figure 2: Conceptual illustration of a portable chip-based electron accelerator driven by a high repetition rate solid state fiber laser. Such a device could be used as a university-scale source of multi-MeV electrons or employed via robotic manipulation for radiation oncology treatment.


The ELIMED (ELI MEDical and multidisciplinary applications) beamline for transport and dosimetry of laser-accelerated ion beams has been completed by LNS-INFN (Catania, I) and installed as a part of the ELIMAIA (ELI Multidisciplinary Applications of laser-Ion Acceleration) beamline at ELI-Beamlines (Dolní Brezany, CZ).

The beamline will be able to focus, select and transport proton and carbon beams up to 250 MeV and 70 AMeV, respectively, down to the sample irradiation point, which is located in air about 9 meters far from the laser-target interaction point. A picture of ELIMED after its installation in July 2018 is shown in Figure 1.

In order to deal with peculiarities of non-conventional, laser-accelerated ion beams, such as ultrahigh dose-rates (up to $10^9$ Gy/min), non-monochromatic spectra (up to 100% bandwidth) and large angular divergence (tens of degrees), innovative transport and dosimetric solutions have been designed, realized and preliminary tested with laser driven proton beams. Such devices are based on permanent quadrupoles and electromagnetic dipoles (for focusing and energy selection, respectively) and by a dual-gap ionization chamber coupled with a Faraday cup, ad-hoc designed to minimize recombination effects coming from the high dose rates which are crucial for an accurate determination of the absorbed dose by the irradiated sample.

Cancer treatment with particle beams (hadrontherapy) arguably represents an appealing prospective for future applications of ELIMED beamline [1, 2]. To validate the feasibility of clinically sound laser-driven beams, preliminary in-vitro radiobiology experiments are necessary. This is because cellular response to ionizing radiation is profoundly influenced by the spatio-temporal distribution of DNA lesions along radiation tracks. Hence, the unprecedented physical regimes that can be achieved by such beams warrant verification that biological effectiveness at tumour cell killing is at least the same as that offered by conventionally accelerated beams, as most recent literature seem to confirm. Furthermore, the recent findings [3] that conventionally accelerated short-pulsed, ultra-high dose rate (exceeding 40 Gy/s) photon and electron irradiation may lead to an increased sparing of normal tissue (paving the way to the so-called FLASH radiotherapy), adds interest to test such a behavior also with optically accelerated particles, where such physical features are greatly magnified. The first radiobiology experiment at ELIMED is expected at the beginning of 2020, after a preliminary phase where all dosimetric devices will be characterized and the absolute dosimetry protocol defined.

We shall investigate the biological response along the ELIMED beamline using two cell lines, both from human breast tissue: highly metastatic MDA-MB-231 cells and the normal epithelial MCF-10A cells. The use of a breast model system stems from the growing interest in treating breast cancer by protontherapy. Reduction of normal-tissue damage, e.g., radiation-induced cardiovascular disease, has been identified as a key advantage for using beamlines such as ELIMED.
represent the main rationale. Cell survival by clonogenic assay, the golden standard to measure cellular radioresponse in terms of loss of proliferative ability will be studied, together with cytogenetic and biomolecular assays such as cellular premature senescence, chromosome aberrations, □-H2AX foci induction and gene expression profiling. Our group has a consolidated expertise in working with cell lines, and in particular with those from breast tumor, exposed to photons, electrons and particle radiation at conventional accelerating facilities, which would enable us to compare previously obtained results for such endpoints [4, 5] with those obtained at ELIMAIA. Moreover, our group has investigated the radiobiological effectiveness of both ultrashort laser-driven electron bunches at the Intense Laser Irradiation Laboratory (ILIL) of the National Institute of Optics of the CNR (Pisa, Italy) as well as laser-driven protons accelerated at the Laboratoire pour l'Utilisation des Lasers Intenses (LULI, Palaiseau cedex, France) [6, 7, 8].

[8] Lamia D; Russo G et al., Monte Carlo application based on GEANT4 toolkit to simulate a laser-plasma electron beam line for radiobiological studies, Nuclear Instruments & Methods in Physics Research Section A, 786, (2015), 2015.03.044

Figure 3: Photo of the ELIMAIA accelerator section (left) and of the ELIMED beam transport (collection, energy selection, transport and focusing and dosimetry) in November 2018, just after the installation in the RP3 hall at ELI-Beamlines (CZ)
WS101-5: Laser-driven proton beams for precise nanoparticle synthesis and cultural heritage diagnostics

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The advent of high-power ultra-short lasers has opened up the field of laser-driven particle acceleration, in particular proton and electron acceleration. The investigation of these laser-accelerated beams and its use is currently challenging many research laboratories worldwide, in particular for the improved characteristics of these sources such as compactness, versatility and tunability. As such, this new acceleration technique has a strong potential of being employed in diverse applications.

Currently, the main applications for laser-accelerated protons include astrophysics[1], being used as bright ultra-short neutron source [2], in medicine [3] or as injector for large scale accelerators [4]. High-intensity lasers and their secondary sources have also a strong potential in Materials Science applications [5]. Recently, some interesting applications in this field have been emerging, e.g. the use of these sources for application in picosecond metrology [6], taking benefit of the short bunch duration. These secondary sources have also a strong benefit for stress testing materials, both, using electrons [7] or protons [8], in particular if the materials to be stressed needs to be employed in a harsh environment. Laser-driven protons are potentially also usable as diagnostics in the Cultural Heritage, in particular the Particle-Induced X-Ray Emission (PIXE), where the intense, short and large proton beam should allow for a quicker analysis of the artifacts [9]. Another recent application is the use of laser-generated protons for Advanced Material Synthesis, profiting from the quick and intense heating generated by the laser-accelerated protons which provides ideal conditions for a short, and therefore more precise, nucleation phase in a Laser-Driven Proton Ablation synthesis process [10].

In this talk I will present different applications using laser-generated protons in Material Science embracing several domains such as Cultural Heritage and Advanced Material Synthesis, and where the characteristics of laser-accelerated particles are of advantage.

[1] B. Albertazzi et al., Laboratory formation of a scaled protostellar jet by coaligned poloidal magnetic field, Science 346, (2014); 325


WS101-6: Development of intense, pulsed ion beams for studies of defect dynamics and materials processing very far from equilibrium

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We use the BELLA petawatt laser [1] to accelerate ions to multi-MeV energies at a repetition rate of up to 1 Hz [2]. Ion acceleration is now routinely conducted at BELLA in parallel to the main program on laser-plasma acceleration of electrons. With laser intensities in the 1019 W/cm2 regime at our current beamline, we find ion intensities up to 1012 ions/shot with low divergence and peak proton energies of ~7 MeV. When transported to a second target, ion pulses can then drive the formation and annealing dynamics of defects [3] and simulations predict that they can uniformly heat materials to temperatures of >1 eV, well into the warm dense matter regime [4].

For lower ion energies and intensities, we operate an induction linac (NDCX-II, [5]), which delivers 2 to 10 ns long pulses of ~1011 protons or helium ions at 1 MeV into a few mm2 spots at a repetition rate of ~1/min. Ion intensities can be selected for materials processing, to form desired defect structures or to drive desired phase-transitions. We present results from ion acceleration and materials processing experiments and simulations [2, 4, 5]. We then discuss the status and prospects for some specific near-term applications e. g. in color center synthesis for spin qubits in diamond [6] as well as the implementation of a short focal length beamline for laser intensities >1021 W/cm2 and the quest for much higher proton energies (>100 MeV).

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WS101-7: Computer simulation of possible materials modification effects by very high-flux accelerated ions

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Ion implantation is a widely used tool in materials research and industry. For instance, doping of semiconductors is routinely carried out by ion implantation, making the field essentially a multi-billion dollar industry. In this talk, I focus on comparing the differences between laser-driven and conventional ion acceleration with respect to the physics of ion irradiation of materials. Laser ion acceleration essentially opens up a new regime of peak fluxes for materials modification, one where the ion-induced collision cascades can overlap in both space and time, something which essentially never occurs during use of conventional ion accelerators. This flux regime is, however, not entirely unprecedented: during electrical arc discharges, similar fluxes are present, in a limited time and space domain [1]. The laser ion irradiation involves a very wide energy range, which also differs strongly from the conventional accelerator condition.

Thanks to these differences, laser-driven ion acceleration would open up several new interesting physics regimes for exploration. The much wider energy spread of laser-driven ion bunches compared to conventional ion irradiation may actually offer advantages of practical value. In fact, in modern materials processing quite often “box-like” ion implantation depth profiles are desired, and to achieve these, the implantation is split up into several stages that utilize different ion energies. Laser acceleration could at least in principle achieve the same goal with a single “shot” – although this would require achieving a fairly well-defined, controllable ion energy profile with the laser-driven scheme.

Comparison with the arc plasma modification, on the other hand, indicates that laser-driven acceleration with similarly high fluxes could open up a new materials modification regime. The laser-acceleration could have the advantage over arcing that one could use any ion-material combination – arcing is limited to using the same material for both the implanted ions and the material to be implanted. Moreover, the laser acceleration would be more controllable and the ion flux densities could be better tuned. Also a regime slightly below the “heat spike overlap” regime could be very interesting from a basic science point of view, as it would allow studying materials modification in a regime where there is very little time for thermally driven defect migration. The combination of very high flux density and little time for defect migration could allow for making new kinds of metastable thin films.

Developing the study of radiation-condensed matter interactions to different scales of time and space, with advanced detection techniques, to understand real-time defect formation and oxidation processes occurring under irradiation in biological systems are very challenging. In fact, the two past decades have been an encouraging period in the development of pulse radiolysis capabilities that has reversed an earlier trend of decline in number and accessibility. The new technology based on photocathode electron guns accelerators, has emerged and spawned a large new generation of fast accelerator facilities. These installations in Brookhaven (US), at Orsay (France) in Tokyo and Osaka (Japan) are developing advanced experimental techniques and making sophisticated experiments available to a larger community of researchers. New inaccessible research area such as, direct effect, solvation dynamics of electron in alcohol and high temperature spur reactions were well studied. Nevertheless, important domains remains unreachable for example the observation of the redox reactions before solvation in water or the charge localization in biosystems occurring in subpicosecond range. Moreover, the processes induced by ionizing radiation concern several applications. Nuclear energy, from upstream to downstream of the cycle and radiobiology and radiotherapy are concerned by the chemical effect of the ionizing radiation. For these applications, a thorough knowledge of physical and chemical processes of radiation effects in the objective to master and to control the operation of equipment’s, ensuring the safety and performance is needed.

Up to now the time resolution of the energetic electron pulse available is not, enough short and it can be improved. The best time resolution of electron pulses with enough charge (more than 0.2 nC) is limited to picosecond. Femtosecond time resolution of energetic electron beam coupled with specific laser spectroscopy can be very helpful to study subpicosecond reactions occurring during the direct effect and also during the scavenging of electron and hole in water before the hydration process. The energy of the electron ranging from a few MeV and 20 MeV, must be mono-energetic.

In addition, the fast and ultrafast ion beams are not available for pulse radiolysis. The earliest physiochemical processes induced by high LET (Linear energy transfer) are studied only with microsecond time resolution by using mainly the heavy ion beam produced by cyclotrons. A high number of studies need ion beam (mainly Proton and Alfa beam) with high energy (from 20 MeV to 100 MeV) with a time resolution of less than 1 ns. These new tools of pulsed electron and heavy ion beams are indeed to face the new challenges in radiation chemistry and radiation damage.
Beams of energetic ions are finding application in multiple cutting edge technologies ranging from hadrontherapy to semiconductor device manufacture/metrology. To date, however, ion interactions in matter have been dealt with in a manner similar to those of electrons/photons, with attention primarily being paid to the energy, E, lost over path length, dx, giving the stopping power $S(E) = - dE/dx$. The obvious distinction is of course that ion stopping in matter exhibits a Bragg peak. In both scenarios the expected cell death or material damage are then generally extrapolated from empirical studies of dose deposition. For ions it is not immediately clear that this is the correct approach as it masks a critical phase of the interaction. When ions are incident on matter they generate dense tracks of ionisation that rapidly evolve. Exactly how this evolution, which occurs on femtosecond and picosecond timescales, determines the nascent radiation chemistry is still largely unknown.

Recently we have demonstrated that laser driven ion accelerators can provide an ultrafast tool for studying this inherently multiscale regime with temporal resolution $< 0.5$ ps [1,2]. Here we present novel results that show a marked difference in the solvation dynamics for electrons generated due to the passage of fast electrons/X-rays and protons ( $>10$ MeV) in water. We discuss the role of nano-cavitation during ion radiolysis in H$_2$O and the potential for modified dose-depth curves on ultrafast timescales.

References


One of the pressing demands in our western society is the safety and maintenance of our nuclear legacy. In Germany the dismantling, safe processing and storage of nuclear waste have resulted in a multi-national research program. One of the findings was that nondestructive testing methods and material selective imaging of compound large objects is possible using thermal and fast neutrons. They also identified that a powerful, safe, and compact neutron source would be required.

Since the advent of ultra-intense lasers many applications have been investigated using the unique parameter of laser-driven secondary sources. Recently, we have demonstrated the realization of a short-pulse laser-driven neutron source with beam intensities orders of magnitude above earlier attempts. Those sources can lead to a compact and potentially mobile neutron source with a large number of applications.

I will present the underlying mechanism of creating an intense pulsed and highly directed beam of neutrons using ultra-intense lasers and the recent experimental results using laser systems in the US and in Europe. Furthermore, I will focus on a few examples of using such sources for applications that are either important for the security of our countries or will have large economical potential in industrial applications. These range from the remote sensing of illicit nuclear material in cargo to the non-destructive analysis of large civil constructions using compact laser systems.
The acceleration of ions using high power lasers is attracting significant interest as an alternative source for future therapeutic applications, and several projects worldwide (including the UK-wide A-SAIL project) are devoted to developing laser-based accelerator technologies and assess their promise for future medical use.

In this context, a key area of research is the investigation of the biological effects, in cell and tissue models, of the short bursts of ions produced by laser-driven sources. This activity serves a dual purpose: on one hand, any future use of laser-accelerated ions will require prior validation of their biological effects on appropriate models; on the other hand, by exploiting these unique beam properties, one can access unexplored regimes of radiation interaction with living systems.

In experiments carried out the dose required to trigger meaningful effects on cell samples has been either fractionated in a number of consecutive pulses, or delivered as a single pulse exposure, typically depositing ~Gy doses at dose rates exceeding 109 Gy/s.

The work of the A-SAIL consortium has focused so far on this second approach, which is more appropriate to the type of laser sources available for our activities, but is also, arguably, more suited to reveal any high dose rate effects. The talk will review the approaches taken for adapting cell exposure techniques to the non-conventional environment of a large laser facility, and will discuss the results of recent experiments carried out on large laser systems such as GEMINI and VULCAN at the Rutherford Appleton Laboratory.
WS101-12: Perspectives of laser driven particle acceleration in radiation oncology

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Fundamental advances in radiation oncology including tumor molecular assessment, volumetric imaging, technical developments, and introduction of combined approaches (e.g., radiosensitisation, radio-immunotherapy) have lead to substantial improvements in the therapeutic index. The implementation of precision medicine, such as genomics, radiomics, and mathematical modelling open the possibility to personalised radiotherapy adaptation and treatment. Further emerging methods under intensive preclinical research offer additional benefit such as, high dose-rate synchrotron broad-beam radiation therapy (SBBR), microbeam radiation therapy (MRT) (1) and ultra-high dose-rate radiation therapy (so called “FLASH” effect). The recent development of high power lasers allows laser driven particle acceleration (LDPA) with main characteristics of ultra-high beam intensity, small beam size and the potential of particle and energy range selection. With the laser based technique the promising results by FLASH, SBBR and MRT achieved on in vitro and small animal studies (mice, rats, mini pigs), furthermore on tumor bearing veterinary patients such as cats and dogs potentially transferable into human investigation could be available on wider basis for radiation oncology. The laser research facilitated as well as the exploitation of novel binary approach of boron proton capture enhanced proton radiation. Seeking for neutron free fusion the boron proton capture reaction have been proposed for densely ionizing additional dose delivery, occurring at the end of spread out Bragg peak (SOBP) at a proton energy of ca 700 KeV resulting in 3 alpha particles (2). Another promising modality is the Boron Neutron Capture Therapy (BNCT), which requires special neutron facility, which could be theoretically provided with the development of laser based thermal- epithermal neutron beams. The biomedical application group at ELI-ALPS has established and validated a vertebrate biological model with reliable quantitative endpoints for extensive preclinical investigations on very high energy electron (VHEE) / VHEE based photon/ and laser driven proton sources for MBT, SBBT and FLASH radiation development (3). The recent achievements in radiation oncology, the clinical potential of the laser based approaches will be presented and guidelines for in vitro radiobiology experiments using zebrafish embryo model at LDPA facilities will be proposed.

The ELI-ALPS project (GINOP-2.3.6-15-2015-00001) is supported by the European Union and co-financed by the European Regional Development Fund. The project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement no 654148 Laserlab-Europe.
Figure 4: One figure representing the key content and message of your presentation is highly appreciated. Ideally you can use the above drawing canvas.


Radiation therapy is a cornerstone of cancer management in which ionizing radiation is used to deposit energy in the cancer tumor. The improvement of spatial dose distribution in the target volume by minimizing the dose deposited in the healthy tissues and organs have been a major concern during the last decades that is reached when using proton beams. The possibility to produce energetic protons of relevance for therapy has triggered strong interest in laser community that questions on the feasibility of laser plasma accelerators approach. In parallel of the research on the quest of high protons, the study of radiation biology is very interesting due to the unique irradiation conditions they can produce, in terms of peak current and duration of the irradiation.

We will present the implementation of a beam transport system optimized for in vitro irradiation of biological samples [1]. A set of four permanent magnet quadrupoles is used to transport and focus the beam, efficiently shaping the spectrum and providing a large and relatively uniform irradiation surface. Real time, absolutely calibrated, dosimetry is installed on the beam line, to enable shot-to-shot control of dose deposition in the irradiated volume. Results of cell sample irradiation are presented to validate the robustness of the full system. Laser-plasma-based particle accelerators are able to emit pulsed proton beams at extremely high peak dose rates (~10^9 Gy/s) during several nanoseconds with a high repetition rate in the range of (0.1 to 10 Hz).

The effect of such extremely high proton dose rates on highly resistant human glioblastoma cell lines, SF763 and U87-MG, was compared to conventionally accelerated protons and X-rays [2]. No significant difference was observed in DNA double strand breaks generation (γH2AX foci detection) and cells killing. The variation of the repetition rate of the proton bunches produced behavior of the radio-induced cell susceptibility in HCT116 cells only. This feature appeared to be related to the presence of the PARP1 protein and an efficient parylation process.
Figure 5: Effect of PARP1 inhibition on cell survival oscillation in response to the variation of the delay between LDP bunches. (A) Western Blot detection of the PARP1 protein and parylation in total protein extracts from HCT116 WT cells left untreated, treated 10 min with 1 mM hydrogen peroxide (H₂O₂) or treated one hour with 200 nM Olaparib before H₂O₂ treatment. (B) HCT116 WT cells were left untreated (black circles) or treated one hour with 200 nM Olaparib (white circles) and were then exposed to five bunches of LDP (3.5±0.77 Gy). Each data point represents the mean of three replicates obtained in two independent experiments. Comparisons of the cell survival were performed using by two way ANOVA multiple comparisons test (Tukey’s multiple comparisons test).


Very intense hard X-ray beams (1.5 μm X-ray source size, 5 μJ-50 μJ/shot in the 30 keV- 40 keV band, 50 mrad x 50 mrad divergence, critical energy for the X-ray spectrum of 30 keV) have been generated through ultra-relativistic self-guiding over long gas jet length (cm range). I will describe the experiments realized with our new laser facility (delivering up to 7J in 18 fs at 2.5 Hz on target) and I will discuss the empirical scaling laws we have obtained correlating the X-ray photon number to the laser and gas jet parameters. Our scaling indicates that a 40 keV X-ray beam with energy of 1 mJ range per shot can be produced with a driving laser with power in the 1 – 2 PW range. The X-ray source has been operated at the nominal 2.5 Hz repetition rate giving an average power in the 12 μW-125 μW range in the 30 keV-40 keV spectral band.

High throughput X-ray phase contrast imaging and 3D phase contrast tomography of various objects have been realized. We demonstrated that the phase contrast imaging was giving the possibility to see transparent very small objects (10 μm to 300 μm diameter range) embedded inside inhomogeneous and anisotropic thick (absorbing) environment. We will present the experimental demonstration and discuss the potential for non-destructive imaging. There is a need for a stand-alone system dedicated for plants and seeds screening available on production sites. I will present our funded program in Canada in developing high throughput X-ray phase contrast plant imaging and screening using LWFA-based X-ray sources (30 keV-80 keV). This effort is realized through an initiative led by the Global Institute for Food Security (GIFS) at the U of Saskatchewan that aims to establish the correlation between the phenotypic expression of a plant and its adaptation to biotic and abiotic environmental stress.
Thomson backscattering X-ray sources are a promising way of generating high-brilliance X-ray pulses. Using a laser-wakefield-accelerated (LWFA-), ultrashort, ultrahigh-current relativistic electron bunches as a scattering medium for the laser field, such a source could potentially be very compact and would afford a high degree of control over the X-ray parameters. The shock-front injection approach to LWFA yields narrowband electron bunches with adjustable energy and multi-kA peak currents in a mm-scale accelerator, which exhibit emittance parameters close to the best conventional accelerators. This makes such bunches an ideal scattering target. We show that by controlling the electron energy, we can tune the X-ray energy over a wide range of parameters\(^1\). Likewise, by moving the scattering point along the axis of an LWFA, we can choose the scattering energy regardless of the final electron energy, giving an even greater range of freedom. We also show that X-rays from such a backscatter source can be used for imaging and that their penetration through different materials scales with energy.

By producing two independently tuneable electron bunches from a single laser shot, we demonstrate how a dual-color X-ray source with variable pulse delay could be constructed\(^2\). Finally, we will show how we can further improve the source brilliance by tailoring the scattering laser pulse to yield as narrowband pulses as possible with a given electron spectrum.


\[\text{[2]}\] Wenz et al., Dual-energy electron beams from a compact laser-driven accelerator, Nat. Photon., (2019) DOI: https://doi.org/10.1038/s41566-019-0356-z