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To cite this article: Dietrich Habs 2007 J. Phys.: Conf. Ser. 58 447

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# Advanced Photonics for SPARC or other FAIR projects

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**Abstract.** We describe how short-pulse high-intensity lasers and laser generated ion-, electronand table-top XFEL-beams may contribute in the future to SPARC or the FAIR project at GSI.

# 1. Introduction

High-power short-pulse lasers and their applications are a fast developing field. At the MPQ at Munich a so-called Petawatt Field Synthesizer (PFS) [1] is developed, which uses optical parametric amplification for chirped pulses to deliver with 10 Hz repetition rate laser pulses of 5 fs duration, 500 TW at 1.2  $\mu$ m wavelength. In this overview we describe expected future developments based on this PFS. On the other hand, the Facility for Antiproton and Ion Research (FAIR) [2] at GSI has a setup phase of many years. In this way many new synergy effects may occur between both fields. If a table-top X-ray free electron laser (TT-XFEL) can be realized, it will have a large impact on high resolution spectroscopy and cooling of highly charged ions.

# 2. Lasers and brilliant laser generated particle and photon beams

# 2.1. Lasers

The PFS uses optical parametric amplification to generate high-power laser pulses of short duration. Here high quality pump beams with very good spatial and time properties are required. The pump beam is amplified in Yb:YAG crystals pumped with efficient diode lasers reaching 20 J in the green. The chirped pulse finally is compressed to 5 fs and is carrier-envelope stabilized. In contrast to former petawatt lasers employing laser amplification the new system has a repetition rate of 10 Hz, while the former systems provided only a few shots per hour. In the more long-term future the ELI laser system [3] is planned within the European road map (ESFRI) which will deliver exawatt pulses with 0.03 Hz or petawatt pulses with 1 kHz. Also the longer much more intense pump laser of the PSF is of interest for many applications like ion acceleration.

# 2.2. Laser generated particle and photon beams

2.2.1. Laser electron acceleration. During the interaction of intense short laser pulses with a gas having typical densities of  $10^{18}-10^{19}$  atoms/cm<sup>3</sup>, monochromatic electron beams are produced via bubble acceleration [4]. Here the laser pulse pushes the electrons aside and leaves a "bubble" of ions behind. The electrons return to the ion bubble after half a plasma oscillation and get injected into the bubble by wave breaking. In the ion cloud the laser field is rectified and

intense electron bunches are accelerated to some 100 MeV [5]. An improved scheme focuses the laser into the plasma enclosed in a capillary [6]. Here the electrons first get started like in a usual bubble acceleration, but later the capillary guides a broader laser pulse and thus leads to a further acceleration without further wave breaking and continuous injection of electrons. In this way electron energies up to 1.2 GeV have been observed with very good beam quality [6]. Probably with the intense very short pulses of the PFS laser more stable intense electron beams will be obtained, because the nonlinear phase of self-focusing and self-shortening before the bubble regime is avoided.

2.2.2. Laser ion acceleration: While laser ion acceleration from the backside of foils has been pursued for many years [7] only recently monochromatic ion beams could be realized [8,9]. New target concepts have been developed to reach much higher ion energies. For ion energies in the GeV/u range [10] the threshold for this new "radiation-pressure dominated" regime scales with the target thickness. Very thin targets and laser beams with a very good contrast ratio are required. Since recently significant progress in improving the contrast ratio to  $10^{11}$  has been achieved at different laser facilities, this method looks very promising.

2.2.3. High harmonics generation. The generation of high harmonics with high-power lasers on surfaces is a very efficient method, where up to the  $800^{th}$  harmonic has been observed in accordance with theory [11]. Very recently this could be extended to the  $3000^{th}$  harmonic. The harmonics add up coherently to a very short intense pulse and may be used in pump-probe experiments with other laser pulses.

2.2.4. Table top X-FEL (TT-XFEL) or  $\gamma$ -FEL. After the observation of very intense, highenergetic, high-quality laser-generated electron beams with typical currents of 100 kA the idea was put forward [12,13] to inject such an electron beam into an undulator and to operate an X-FEL. This is now pursued by several laser laboratories. The electron currents are much larger than in classical FELs and lead to reduced requirements on energy spread and transverse emittance for achieving FEL operation. Also the necessary undulator length is much reduced. Thus we calculate with the GENESIS 1.3 FEL code [14] that a 3m long undulator delivers  $10^{12}$ photons at 2.5 Å with a peak brilliance of  $10^{32}$  photons/(s mm<sup>2</sup>mrad<sup>2</sup> 0.1% BW) for a 0.9 GeV electron beam. While classical FELs are limited to photon energies of about 10 keV by quantum fluctuations, the laser-driven FELs hold promise to operate also at significantly higher photon energies up to 10 MeV.

#### 3. Laser ion acceleration and application at FAIR

In principle it appears possible to reach in a few years by laser acceleration monochromatic heavy ion beams with up to 35 GeV/u as planned for FAIR. The energy stored at FAIR in a storage ring reaches several kJ at the maximum ion intensity. With high-repetition lasers (typically 10 Joule per shot, rates of 1 kHz and conversion efficiencies of 10% for ion acceleration) it will be possible to fill such a ring within a few seconds by stacking. The advantages of laser acceleration would be that injection could occur at the required final energy, thus avoiding the reduced duty factor due to ramping. Since the maximum number of ions which can be stored due to the tune shift scales with  $\gamma^3$  [15], typically 10–10<sup>4</sup> more ions could be stored. Presently this maximum number is limited by the space-charge limit for ions at the injection energy, because the rings have to be used to debunch the high-intensity ion bunches for coincidence experiments. If this technique would be successful, it could lead to a total decoupling of the rings and a more efficient operation.

#### 4. Table top X-FEL (TT-XFEL) or $\gamma$ -FEL and applications for FAIR

The X- or  $\gamma$ -FEL has many applications: laser cooling, high resolution X-ray spectroscopy, nuclear spectroscopy after resonant nuclear excitation, coherent nuclear excitations, density and

temperature measurement for studying warm, dense matter in plasma physics.

#### 4.1. Laser cooling

In the past we used closed transitions of Li-like ions for laser cooling with a frequency-doubled Ar-ion laser at 257 nm. In a storage ring we can match the transition energy of the stored ion by Doppler-boosting the 257 nm wavelength in a counter-propagating mode. We recently have demonstrated this laser cooling for relativistic  $C^{3+}$  ions in the Experimental Storage Ring ESR [16]. Only ion intensities below  $10^8$  could be cooled, but we reached the lowest beam temperatures. The typical cooling-laser intensity was 50 mW. Due to the tunability of a table-top X-FEL H-like ions could be cooled in storage rings for all beam energies, but also ions in traps could be cooled. H-like ions have a significantly longer lifetime in storage rings compared to Li-like ions. Due to the saturation intensity  $I_{sat} = 2\pi^2 \hbar c/(3\lambda^3 \tau)$  with wavelength  $\lambda$  and lifetime  $\tau$  in the rest frame, the saturation intensity for heavier H-like ions is that large that even the large peak powers of a X-FEL do not lead to saturation broadening. The FEL has a comparable cooling power like the present frequency-doubled Ar-ion laser.

# 4.2. Coherent $\gamma$ -quantum optics

For energies below 100 keV and targets cooled to He-temperature, recoil-free Mößbauer transitions may be excited with the FEL. Since the wave function of the excited nucleus cannot be assigned to a specific nucleus it is described as a delocalized bosonic exciton [17]. Present synchrotron light sources can deliver at most one exciton per every 100th shot. One still observes interesting phenomena like speed-up of the nuclear decay or beating in the decay curve. We expect new phenomena when we excite many excitons in a single shot. We expect a strong broadening of the transition line width proportional to the number of excitons. Also the coherent intense X-FEL photons may lead to a saturation broadening. This interaction of a bosonic laser field with a bosonic exciton field will allow to produce many new exotic phenomena.

# 4.3. Nuclear spectroscopy with TT-XFEL

Rare radioactive nuclei can be deposited on a nano-tip after rest gas cooling. With the  $\gamma$ -FEL focused down to 100 nm we reach a very high luminosity, which results in an excitation of every radioactive nucleus when exciting at 5–6 MeV with highly overlapping level density. The deexcitating  $\gamma$ -transitions can be observed with Ge detectors. The spin of the levels can be deduced from the angular distribution of the  $\gamma$ -rays, since the  $\gamma$ -FEL is 100 % polarized. With this technique the level structure and level width of rare nuclei can be studied at much smaller intensities compared to other techniques proposed for FAIR.

#### 4.4. Warm dense matter in plasma physics

At FAIR it is planned to produce extended warm dense matter by heating with intense ion beams. Here the X-FEL may be used to probe the density and temperature of warm dense matter. From the Doppler broadening of resonantly excited nuclear transitions the temperature may be deduced, which is difficult to obtain otherwise e.g. from Thomson scattering.

#### 5. Ultra-high field physics

There is a large interest in studying the physics at ultra-high fields. At the Schwinger limit, for fields of  $1.3 \times 10^{18}$  V/m, a break-down of the quantum vacuum into  $e^+e^-$  pairs is predicted. The properties of the vacuum are very little understood [18]. In astrophysics the overall energy density of the vacuum has been deduced from deviations from the linearity in Hubble expansion and cosmic microwave background (WMAP) to 4 GeV/m<sup>3</sup>. On the other hand theoretical predictions range from  $10^{124}$  GeV/m<sup>3</sup> for a cutoff of the vacuum zero-point fluctuations at the Planck scale to  $10^{-121}$  GeV/m<sup>3</sup> at the Hubble length scale for the Casimir effect [19]. This is described as "the most embarrassing problem of theoretical physics" [18]. From QCD we know that the vacuum has strongly correlated complex vacuum fluctuations. Thus exploring the properties of the vacuum is a challenging task. At lower energies QED seems to do extremely well. Ultra-high field physics can be realized in H-like heavy ions. Another approach is to generate fields beyond the Schwinger limit by coherent harmonic focussing of laser light [19]. An interesting approach to study the eigenmodes of the vacuum is to study highly accelerated systems. Here the system emits Unruh radiation.

#### 5.1. Coherent harmonic focusing

The idea of producing intense high harmonics from surfaces has been extended in theoretical studies to reflections from a curved solid surface to achieve also a coherent spatial focusing [20]. Also a flying plasma mirror may be realized to do this focusing [21]. In this way the Schwinger field strength or Schwinger intensity can be reached when focusing the PFS laser. With the ELI laser even much larger fields can be realized.

#### 5.2. Production of $e^+e^-$ pairs

It is interesting to study the pair production in intense laser fields. Here it was recently predicted that at rather moderate laser intensities of  $10^{20}$  W/cm<sup>2</sup> and a wavelength of 1  $\mu$ m,  $10^{19}$  virtual  $e^+e^-$  pairs per cm<sup>3</sup> are theoretically produced [22], which may be identified in interferometric measurements.

#### 5.3. Unruh radiation

Recently we have studied the signatures of the Unruh effect from electrons accelerated by ultrastrong laser fields [23]. The Unruh photons are created in pairs, whose polarization is perfectly correlated. For accelerating fields close to the Schwinger limit the photons have typical energies in the 100 keV range. The Unruh intensity strongly increases with acceleration and thus should become detectable at these accelerations, which are 6 orders of magnitude larger compared to other schemes, where unsuccessful measurements have been proposed until now. In this way we may study the eigenmodes of the vacuum.

#### Acknowledgments

This work was supported by DFG under Contract No. TR18.

#### References

- [1] http://www.attoworld.de/research/PFS\_1.html
- [2] FAIR Baseline Technical Report 2006 GSI
- [3] Mourou G et al 2006 Extreme Light Infrastructure (ELI) http://loa.ensta.fr/Extreme\_Light\_Infrastructure/EliWeb1.html
- [4] Puhkov A and Meyer-ter-Vehn J 2002 Appl. Phys. B74 355
- [5] Geddes C G R et al 2004 Nature **431** 538
- [6] Geddes C G R et al 2006 Anomalous Absorpt. Conf. (unpublished) submitted to Science
- [7] Schreiber J et al 2006 Phys. Rev. Lett.  $\mathbf{97}$ 045005
- [8] Hegelich B M et al 2006 Nature **439** 441
- [9] Schwoerer H et al 2006 Nature 439 445
- [10] Esirkepov T et al 2005 Phys. Rev. Lett. 92 175003
- [11] Dromey B et al 2006 Nature Physics 2 456
- [12] Habs D et al 2005 AIP Conf. Proc. 802 6
- [13] Gruener F et al 2006 Design considerations for table-top FELs http://adweb.desy.de/mpy/FLS2006/proceedings/index.htm Phys. Rev. Lett. submitted
- [14] Reiche S 1999 Nucl. Instrum. Methods A **429** 243
- [15] Möhl 1988 Proc. of the Worksh. on Cryst. Beams GSI Report 89-10 108
- [16] Schramm U. et al 2006 AIP Conf. Proc. 821 501
- [17] van Bürck U 1999 Hyperfine Interact. 123/124 483
- [18] Fraser G 2006 The New Physics for the 21st Century (Cambridge: University Press)
- $[19]\,$  Hollands S and Wald R M 2004  $Preprint\ {\rm gr-qc}/0405082 {\rm v1}$
- [20] Gordienko S et al 2005 Phys. Rev. Lett. 94 103903
- [21]Bulanov S V et al 2003 Phys. Rev. Lett.  $\mathbf{91}$ 085001
- [22] Blaschke D G et al 2006 Phys. Rev. Lett. 96 140402
- [23] Schützhold R, Schaller G and Habs D 2006 Phys. Rev. Lett. 97 accepted for publication