Design Study of Table-Top Free-Electron-Lasers ◇

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There is a new boom in laser plasma physics, where the generation of intense quasi-monoenergetic electron bunches up to the GeV range has been achieved [1,2,3,4]. Another new development are kilometer-long X-ray free-electron lasers (XFELs) that are expected to deliver photon beams with unprecedented peak brilliance. Our task is to combine both fields with the prospect that laser-plasma accelerator-based FELs are of only meter-scale and could thus open new possibilities in *clinical* diagnostics such as phase-contrast imaging (PCI) or Small-Angle-X-ray-Scattering (SAXS) [5]. Both techniques have been investigated at large-scale synchrotrons and our group is co-proposer for a future study at the ESRF synchrotron in Grenoble. Our design of a table-top XFEL is expected to deliver the same photon flux per second as available at the biomedical beamline at ESRF [6].

The mechanism for the generation of intense (nC charge) quasi-monoenergetic electron pulses by laser-plasma accelerators requires an ultrashort, high-intensity laser-pulse with a length shorter than the plasma wavelength (μm-scale). Due to the ponderomotive force, plasma electrons are blown out transversely, leaving an electron-free zone - the *bubble* - behind the laser pulse [7]. These electrons return to the axis after half a plasma oscillation, thus determining the size of the bubble on the order of the plasma wavelength. Typically about $10^9 ... 10^{10}$ electrons are captured into the bubble, hence delivering ultra-high currents of the order of 100 kA. Due to the inertial positive ion background, these electrons experience a strong longitudinal electric field gradient of up to TV/m.

An FEL requires an undulator which is an arrangement of magnets with an alternating transverse magnetic field. Electrons in an undulator are forced on a sinusoidal trajectory and can thus couple with a co-propagating radiation field. The induced energy modulation yields a current modulation from the dispersion of the undulator field. This modulation is called micro-bunching expressing the fact that the electrons are grouped into small bunches separated by a fixed distance. Therefore, electrons emit *coherent* radiation with a wavelength equal to the periodic length between the micro-bunches. In a *Self-Amplification of Spontaneous Emission* (SASE) FEL, there is no initial radiation field and the seed has to be built up by the spontaneous (incoherent) emission [8].

All our detailed FEL-studies are based on simple estimates from 1d FEL-theory [9] as well as extensive full SASE FEL simulations utilizing the same FEL code *GENESIS* [10] as used for all FELs across the world. Our current design values are given in Tab. 1. Our design study of table-top FELs can be seen as the first which not only gives quantitative results but also includes disturbing effects, such as space-charge and induced resistive wall wakefields.

Parameter	TT-VUV-FEL	TT-XFEL
current	50 kA	160 kA
norm. emittance	1 mm· mrad	1 mm· mrad
energy	150 MeV	1.74 GeV
energy spread	0.5 %	0.1 %
wavelength	32 nm	0.25 nm
undulator length	0.8 m	5 m
FEL power	2.0 GW	58 GW

Table 1: Parameters of our first test case of a table-top VUV FEL as well as a table-top X-ray FEL with a 5-mm-period undulator of different lengths.

Our group has already started the development of a short-period undulator and miniature focusing device [11]. The shorter the undulator period the lower the required electron energy for reaching a certain FEL wavelength and the larger the tolerance of the FEL process against energy spread and emittance. We have therefore built an undulator with the world's shortest period (5 mm). Fig. 1 shows the energy- and angle-resolved undulator radiation spectrum measured at the Mainz Microtron (MAMI), demonstrating a sufficient undulator quality as even the fourth harmonic is visible, though the critical harmonic number scales with K^3 and in our case $K = 0.4$. Furthermore, the amplitudes and widths of the spectral lines is well in agreement with the theoretical expectation.

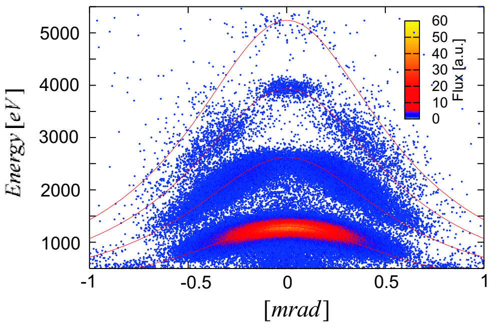

Fig. 1: Undulator radiation spectrum of our 5-mm-period undulator measured at MAMI with a beam energy of 855 MeV. The lines indicate the theoretical expectation for the angular dependence of the photon energy. One can see up to the forth harmonic of the fundamental energy around 1 keV.

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