DESIGN CONSIDERATIONS FOR *TABLE-TOP* FELs*

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Abstract

Refinements in laser technology (few-cycle pulse generation, chirped pulse amplification) combined with supercomputer-based plasma simulations have brought the discipline of relativistic laser-matter interaction to a new level of predictability. This was recently demonstrated by the generation of brilliant electron bunches with energies on the 0.1-1-GeV-scale. Our plan is to utilize such laser-accelerated electron beams to realize table-top FELs. The essential feature of those electrons is their ultra-high beam current of up to few 100 kA in 10 fs. Such high currents make small-period undulators realistic, which require less electron energy for the same FEL wavelength. Together with low emittance and relatively large Pierce parameters the undulator length for reaching SASE saturation should be as small as only meter-scales. In this paper we present our first basic design considerations based upon start-to-end simulations including 3d PIC codes and GENESIS 1.3. In contrast to large-scale XFELs, which will be dedicated user facilities, our aim is to deliver the proof-of-principle of table-top FELs, starting from the VUV to the X-ray range.

The present paper will give a short overview of the basic design-considerations for *table-top* FELs, while a more detailed manuscript will be submitted to Nucl. Instrum. Methods A.

LASER-PLASMA ACCELERATORS

The year 2004 marked a breakthrough in the field of laser-plasma accelerators [1]. Three independent groups demonstrated the acceleration of electrons up to relativistic energies with quasi-monoenergetic distributions. There are different mechanisms for laser-plasma accelerators. Here we focus on the so-called "bubble regime", which was theoretically predicted by one of us (MtV). A laser-pulse with a pulse duration smaller than the plasma wavelength is focused upon a gas jet, where due to its ponderomotive force plasma electrons are kicked away (in transverse direction), leaving an electron-free cavity - the so-called "bubble" - behind the laser pulse. These electrons return to the axis some micrometer behind the laser, where due to the enhanced space charge electrons are scattered into the bubble. Due to the absence of negative charges inside the bubble, the captured electrons experience a strong electrical field gradient of up to TV/m generated by the inertial positive ion background. Due to the strong acceleration field the necessary acceleration distances can be as small as millimeters. Besides this downscaling in size, bubble acceleration delivers high-current beams. Typically about $10^{9\ldots10}$ electrons are captured into the bubble, as found both experimentally and from scaling laws [2]. As can be seen in Fig. 1 the length of the bubble stem is in the order of a few microns only. Therefore, beam currents of the order of $100kA$ can be reached. The diameter of the bubble stem allows to realize very small source sizes.

Utilizing (discharge) capillaries instead of gas-jets allows longer acceleration distances (cm-scale due to laser guiding beyond the Rayleigh length) and even smaller energy spreads (due to the so-called de-phasing, which causes faster electrons to be slowed down and slower ones to be accelerated) [3]. It is thus expected that the energy spread for 100 MeV is about 2 percent, but 0.2 percent for 1 GeV. By capillaries maximum electron energies reached today are 1.2 GeV [4]. Normalized emittances are as good as from classical accelerators.

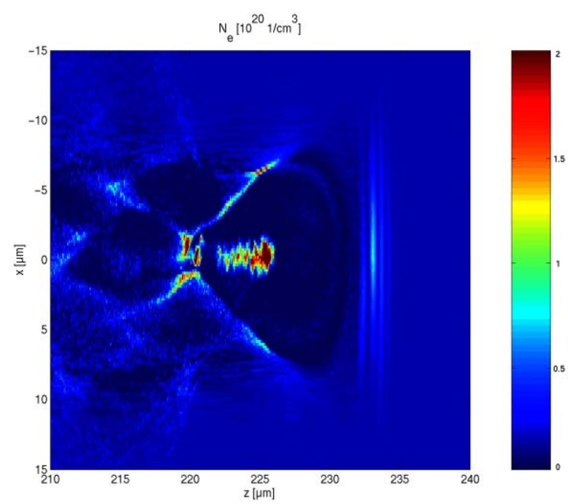

Figure 1: Snap-shot from PIC simulation of bubble acceleration: electron density map, propagation direction z. The typical length scale is the plasma wavelength, thus micrometers. The "bubble" behind the laser can trap nC charge, thus yielding electron beam currents on the scale of 100 kA.

CONDITIONS FOR *TABLE-TOP* SASE FELS

The construction of laser-plasma accelerators as described above clearly allow a table-top electron *accelerator*. For realizing a table-top FEL one also requires a table-

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top *undulator*. Here we present simplest quantitative arguments, which are complemented by *GENESIS 1.3* simulations. The basic scaling parameter within SASE FEL theory is the so-called Pierce or FEL parameter [5, 6], which reads for the one-dimensional and *ideal* case (neglecting energy spread, emittance, diffraction, and time-dependence)

$$\rho = \frac{1}{\gamma}\left[\frac{I}{I_A}\left(\frac{\lambda_u A_u}{2\pi\sigma_x^2}\right)^2\right]^{1/3} \tag{1}$$

Here $E_{beam} = \gamma mc^2$ is the electron beam energy, I the beam current, $I_A = 17kA$ the Alfven-current, σ_x the beam diameter and $A_u = a_u[J_0(\zeta) - J_1(\zeta)]$ (planar undulator), whereby $a_u^2 = K^2/2$, $\zeta = a_u^2/(2(1+a_u^2)))$, and J's are Bessel functions. The gain length, which is the e-folding length of the exponential amplification, is

$$L_{gain,ideal} = \frac{\lambda_u}{4\pi\sqrt{3}\rho} \tag{2}$$

In presence of energy spread, emittance, and diffraction a correction factor Λ is introduced [6]. The gain length then reads

$$L_{gain} = L_{gain,ideal}(1+\Lambda). \tag{3}$$

The undulator length should be at least as large as the saturation length, which is the length that SASE needs for reaching the maximum micro-bunching and reads with saturation and noise power P_{sat}, P_n, and the coupling factor $\alpha = 1/9$

$$L_{sat} = L_{gain}\log(\frac{P_{sat}}{\alpha P_n}) \approx 15 L_{gain}. \tag{4}$$

The saturation power scales as

$$P_{sat} \sim \left(\frac{1}{1+\Lambda}\right)^2 (I\cdot\lambda_u)^{4/3}. \tag{5}$$

The wavelength of an FEL amounts to

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left[1+\frac{K^2}{2}\right], \tag{6}$$

with λ_u being the undulator period and K the undulator parameter ($K = 0.9\cdot\lambda_u[cm]\cdot B_0[T]$, whereby B_0 is the magnetic field strength on the undulator axis). Thus, for reaching the same wavelength λ a shorter undulator period allows using less energetic electrons.

In the following Tab. 1 and Fig. 2 we compare two cases: DESY's TTF2 case in the so-called *femtosecond mode* [7] and our proposed scenario at the MPQ, both operating at a wavelength of 25-30 nm:

One major difference lies in the given currents, highlighted by Fig. 2, where the saturation length according to Eq. (4) and the Λ correction factor are plotted for both cases as a function of I. One can see the importance of the ultra-high current in the table-top case. The smaller undulator period allows a smaller beam energy, hence decreasing the saturation length. However, in order to keep the Pierce parameter large enough for compensating the relatively large energy spread and for maintaining a large output power, a strongly increased beam current is mandatory: the large I keeps the degrading Λ small enough and allows a high output power according to Eq. (5).

Table 1: Parameters for the comparison between DESY's femtosecond-mode TTF2-case and our table-top proposal, where the output values are taken from *GENESIS* simulations.

Parameter	**TTF2 (fs)**	**MPQ**
current	1.3 kA	160 kA
norm. emitt.	6 mm· mrad	1 mm· mrad
energy	461.5 MeV	130 MeV
energy spread	0.04 %	0.5 %
und. period	27.3 mm	3 mm
wavelength	30 nm	25 nm
Pierce par.	0.0016	0.0117
sat. power	0.66 GW	5 GW
sat. length	19 m	0.45 m

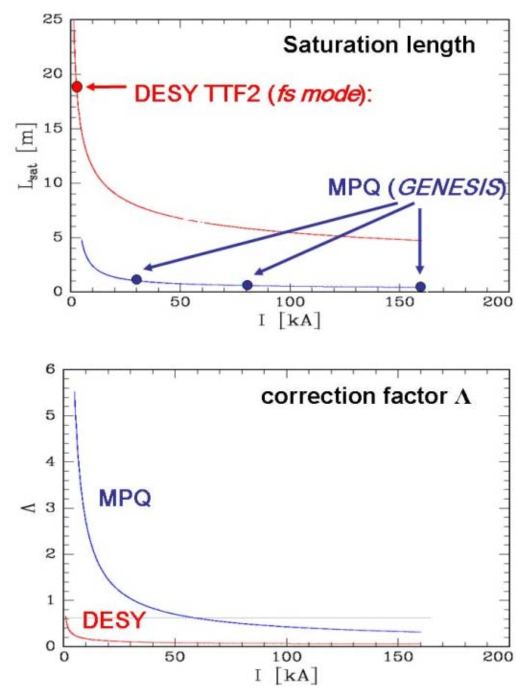

Figure 2: Saturation lengths (Eq. 4) and correction factor Λ for the two cases given in Tab. 1 as a function of electron beam current I: DESY's TTF2 (red curve) and MPQ (blue). The red circle is taken from [7], the blue ones from *GENESIS* runs. It is seen that the MPQ case is in a range, where the I-scaling is very weak ($I^{-1/3}$, according to Eq. 1). The ultra-high current also allows keeping the degradation Λ small enough.

CONCLUSIONS

We have presented a rough sketch of basic arguments on the realizability of *table-top* FELs based upon laser-plasma accelerators. The main aspect is the much higher beam current with comparative emittances, but larger energy spreads. The latter are compensated by the increased Pierce parameter. The ultra-high beam currents allow reducing the total undulator length to meter-scales and maintaining comparable output powers. In this paper we have addressed only a table-top SASE VUV FEL, but will soon submit a much more detailed manuscript which entails *GENESIS* simulations of a table-top XFEL that needs an undulator of only three meters. In this forthcoming paper we will also address questions of space charge, Coherent Synchrotron Radiation, and wakefields as well as issues of beam transport and focusing between capillary and undulator. First analytical estimates and simulations have revealed that all these effects play no significant role for the VUV case discussed above.

Table-top XFELs would open new areas of application due to their small-scale size, such as in hospitals for diagnostics.

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