GENERATION OF SUB-FSEC, HIGH BRIGHTNESS ELECTRON BEAMS FOR SINGLE SPIKE SASE FEL OPERATION *

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Abstract

We present here the theory and computational modeling of beams in a new regime, where ~1 pC beams are strongly velocity bunched at low energy, and then compressed at the GeV level to ≤ fsec. This regime of operation produces beams with thermally dominated transverse emittance, and mitigates many problems associated with the nC-level operation. These problems include CSR induced instability and intra-undulator wakes. The resulting beams have extremely high brightness, enabling very high gain, efficiency, and single spike operation. We present here a detailed design example, that of the proposed SPARX FEL design.

INTRODUCTION

The idea has been recently suggested, and investigated in detail, of employing an ultra-short beam, as short as cooperation length and with very small charge [1] to drive short wavelength (i.e. X-ray) FELs [2] in the single spike regime. Such beams are predicted by scaling arguments to have very high brightness, and thus are indeed capable of driving short gain length FELs [3].

With short gain lengths come ever shorter cooperation lengths. Thus, in order to obtain single spike operation [4] *i.e.* with the beam length σ_z approximately equal to a cooperation length L_c — in such an X-ray FEL, the beam should indeed be ultra-short. We have therefore investigated the creation, through initial velocity bunching [5,6] at low energy and subsequent chicane bunching [7], of ultra-low-charge (pC scale) beams of sufficient quality to support strong FEL gain in two examples, the SPARX FEL [8]. In previous work using start-to-end simulations, we find that these beams can drive the FEL in single spike mode; one may therefore obtain SASE sources of coherent X-rays that have pulse lengths at or below 1 fsec. These modes are, further, accessible through changes only in running conditions, not in projected (i.e. not yet existing) hardware. In the context of SPARX, this work represents a refinement of that reported in Ref. 1.

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We re-examine the generation of such beams in more extreme cases. In order to do this, the process of electron beam creation and velocity bunching is simulated with PARMELA, while the final compression is modeled using ELEGANT. Finally, we verify the performance of the FEL systems using GENESIS 1.3. In this way, we use the most up to date accelerator lattice corresponding to that given in the SPARX Technical Design Report [9]. Further, we have optimized the transverse focusing during velocity bunching, to produce yet shorter beams than found in the analysis of Ref. 1, well below 1 fsec rms.

It should be noted that from the viewpoint of the beam, there are manifold advantages in operation with ultra-low charge. First, of course, is that ultra-short beams are possible, along with low emittances— in other words, high brightness electron beams naturally result from the photoinjector [10]. In addition, there are a number of problems which are almost entirely mitigated in this scenario, having to do with the beam's interaction with its environment. These issues, include coherent synchrotron radiation (CSR) [11] in the chicane compressor as well as surface roughness and resistive wall wakes in the undulator vacuum wall [12].

In comparison to other schemes, such as the slit-spoiler method [13], chirped pulses [14], enhanced SASE [15], the ultra-low charge option has decided advantages. First, none of these competing schemes mitigates the collective effects in the linac and compression systems in the way foreseen for the ultra-low chare scheme. In addition, the other schemes do not produce a near pedestal-free pulse. This may be a critical advantage in X-ray experimentation at free-electron laser facilities.

THE SPARX FEL

The SPARX FEL is presently undergoing a finalization in the design process, with the Technical Design Report due by October 2008. While the nominal design report of this FEL, which is envisioned to operate in a variety of scenarios from 1 to over 2 GeV to provide X-rays in the vicinity of the water window, is near 1 nC, there is great interest in pushing the performance of the SPARX system to ultra-short pulse performance.

Here, we examine two cases, a 1 pC scenario, as first examined in Ref. 1, and a 10 pC case which is provided in order to examine cases with higher peak power and total pulse energy. In both cases, the velocity bunching process was optimized with weaker solenoid focusing directly after the gun and in the linac section. This results in shorter beams and, in the end, more manageable emittance grown. These beams then are chicane compressed, after acceleration to 1.2 GeV, more than half the way to an energy of 2.095 GeV. We have applied very strong compression in order to probe the limits of this technique more deeply than was done in Ref. 1.

SPARX 1 pC case

The 1 pC case begins with excellent velocity bunching, with preservation of the thermal emittance $\varepsilon_n = 3.3\times10^{-8}$ m-rad, as opposed to the notable emittance growth shown in the analysis of Ref. 1. Further, the rms bunch length after velocity bunching to 127 MeV is only $\sigma_z = 4.7$ μm, as opposed to 9 μm found in Ref. 1, in which a waist with tight focus (the same as in the standard non-velocity bunched case) is employed. The relaxed focusing is clearly a better solution.

The ELEGANT simulations of acceleration and compression after velocity bunching show quite interesting performance. In contrast to the results of Ref. 1, significant effects due to CSR are noted during chicane compression, which produce large tails in the final longitudinal phase space distribution, as shown in Fig. 1.

These distortions are associated with a horizontal emittance growth to $\varepsilon_{nx} \cong 7.5\times10^{-8}$ m-rad, a bit higher than $\varepsilon_{nx} \cong 6.3\times10^{-8}$ m-rad found in the case analyzed in Ref. 1. On the other hand, the beam brightness is actually increased in the present case, as the peak current is predicted to exceed 740 A (Fig. 2), as opposed to the 260 A found in the case explored in Ref. 1.

The tails in the longitudinal phase space produced some pedestal around a very compact core of ~540 attosecond rms. This pedestal has negligible impact on FEL performance.

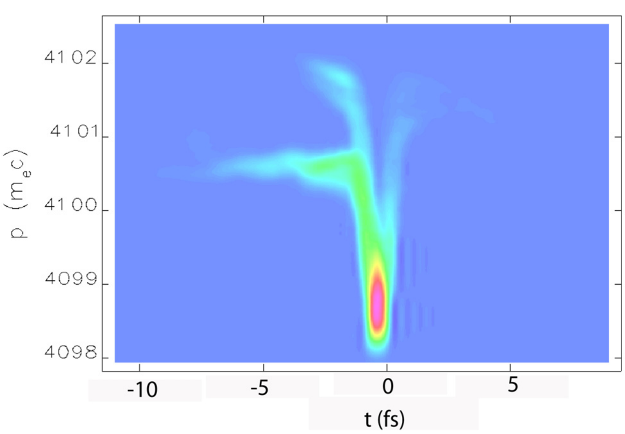

Figure 1. Longitudinal phase space at undulator entrance for SPARX 1 pC case.

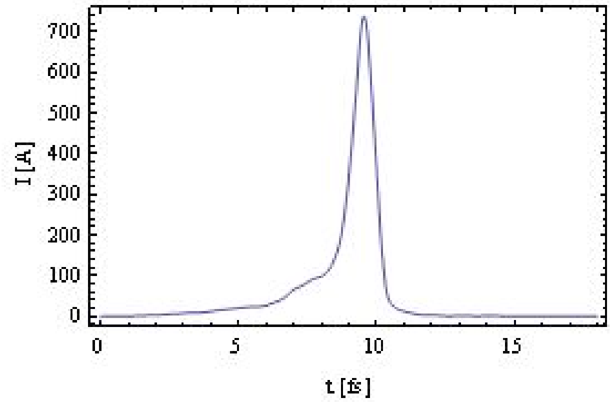

Figure 2. Current profile in SPARX 1 pC case.

The final predictions of the start-to-end model coming from GENESIS are shown for this case in Figs. 3-5. The simulations were performed for with an undulator wavelength λ_u =2.8 cm, having strength K=1.67. As seen in Fig. 3, a peak power of 1 GW is achieved in saturation, which has onset at only 24 m.

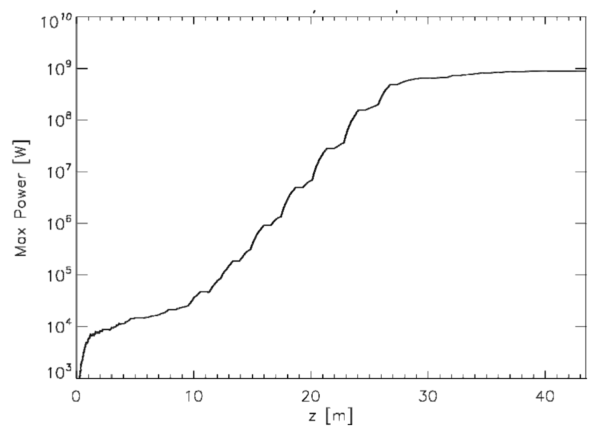

Figure 3. Evolution of peak FEL power along the undulator for SPARX 1 pC case.

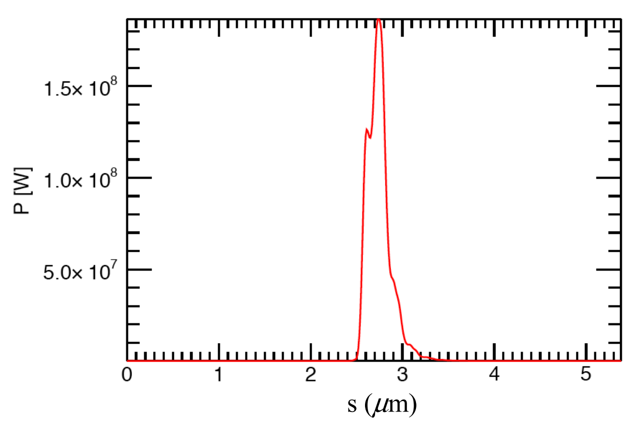

Figure 4. Peak FEL power as a function of *s* at saturation, SPARX 1 pC case.

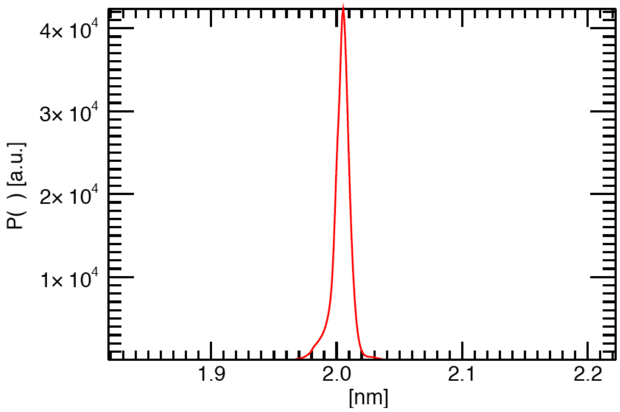

Figure 5. Saturation spectrum, SPARX at 1 pC.

Further, this essentially pedestal-free pulse achieves an rms length (Fig. 4) at saturation of 145 nm (484 attosecond), even shorter than the electron pulse. Thus one may, according to this design, shatter the fsec barrier at SPARX.

The rms spread in wavelength at saturation derived from the spectrum shown in Fig. 5 is only 0.046 nm, which yields a time-bandwidth product $\Delta\omega\Delta t = 1.67$, quite close to the Fourier transform limit. This is expected by the lack of significant structure in the temporal profile.

SPARX 10 pC case

If one prefers to relax the challenge in achieving ultra-fast pulses, while gaining in pulse energy and peak power, it is attractive to consider 10 pC operation. The 10 pC case velocity bunching presents a slightly higher than thermal emittance $\varepsilon_n = 1.05\times10^{-7}$ m-rad, with a final rms bunch length of $\sigma_z = 10.3$ μm, as expected from the $Q^{1/3}$ scaling predicted in Refs. 1 and 7. After acceleration and chicane bunching, the final phase space distribution obtained from ELE-GANT analysis is shown in Fig. 6; it has more notable tails than in the 1 pC case. These tails, produced by CSR effects are associated with a much more dramatic increase in the horizontal emittance, which rises to $\varepsilon_n = 7.6\times10^{-7}$ m-rad.

One still obtains very high brightness in this case, as the current profile (Fig. 7) associated with the phase space of Fig. 6 is predicted to exceed 3600 A ($\sigma_t = 1.1$ fsec), which is larger than the standard SPARX case.

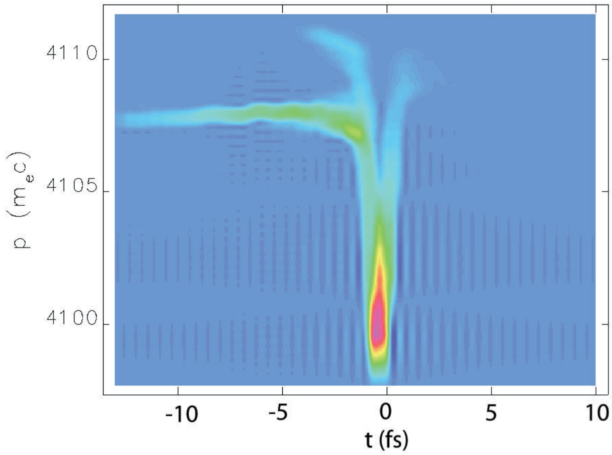

Figure 6. Longitudinal phase space at undulator entrance for SPARX 10 pC case.

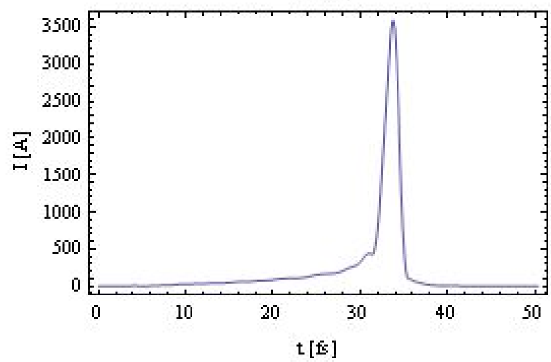

Figure 7. Current profile in SPARX 10 pC case.

The FEL performance is even more striking in this case, as the larger emittances are offset by much higher current and diminished diffraction effects. The peak power (Fig. 8) shows saturation withing 21 m, at the 10 GW level. The peak power as a function of distance along the bunch at saturation is shown in Fig. 9; it displays a sub-fsec (rms) pulse profile, even closer to transform limited than the 1 pC case.

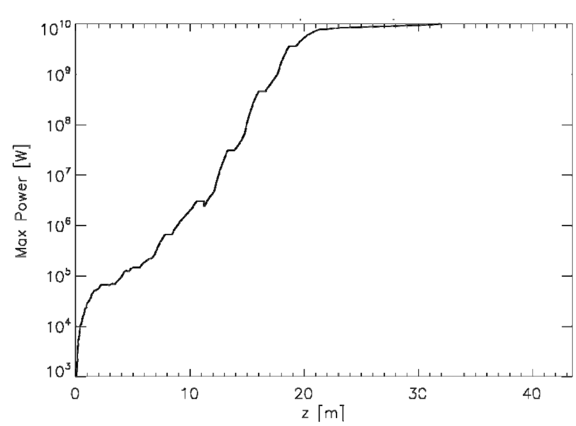

Figure 8. Evolution of peak FEL power along the undulator for SPARX 10 pC case.

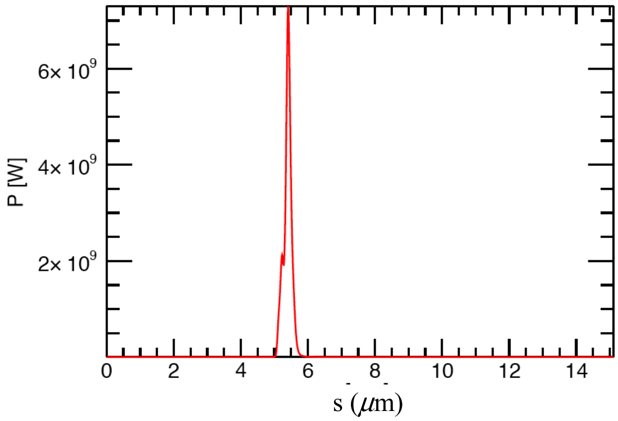

Figure 9. Peak FEL power as a function of *s* at saturation, SPARX 10 pC case.

DISCUSSION

There are also clearly challenges in using these types of pulses in the context of existing or modified injectors and accelerators. First, we note that the total dark current obtained in high field operation of S-band photoinjectors tends to be on the 1 nC level. Thus integrating detectors such as screens (particularly after the gun), will have some background issues. One may "clean up" the dark current using RF deflectors [1].

Just as interesting is the question of beam diagnostics; one must be able to measure very small values of ε_n and σ_t. After final comp-ression, beams should emit (in, e.g., CER/CSR from the final chicane dipole) coherent visible to IR light. The expected signal, despite the low charge, is quite robust, but difficult to interpret.

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