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RE-EXAMINATION OF THE WORKING POINT FOR THE SPARC INJECTOR AND SASE FEL

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Abstract

Because the SPARC injector is to provide an uncompressed beam to the SASE FEL, the SASE performance is not as robust as one may like. In order to address an improved working point for this injector/FEL system, we examine two issues. The first is the specific proposal of obtaining increased current out of the injector. It is shown that previous proposals for increasing the current based on deformation of the injected bunch distribution do not yield good performance because of limitations due to longitudinal space charge. An alternative scheme based on adding charge to the beam by keeping the injected pulse length and beam density constant is shown to work well. The predictions of HOMDYN and PAMRELA are examined, and start-to-end simulations of both the baseline 1 nC design and a 1.7 nC high current design in an undulator close to that being discussed now are performed. It is shown that the high charge design produces a qualitative advantage in the SASE FEL performance, by moving the FEL working point away from a diffraction-dominated regime. This observation motivates the second issue, which is the general approach to improving the FEL performance by minimizing diffraction effects on gain. We then discuss the general approach to mitigation of diffraction in order to produce a small 3D gain length. Particular emphasis is placed on the possibility of shortening the undulator period, which must be accompanied by reduction of the undulator gap.

1 INTRODUCTION

The SPARC photoinjector is, in its baseline, uncompressed design, intended to have state-of-the-art performance, with a peak current of around I_p=85 A, and a normalized rms emittance below $\varepsilon_n \approx 0.6$ mm-mrad[1]. While this type of beam has unprecedented brightness, and serves as a first test of LCLS-like injector conditions (the Ferrario scenario[2]), it is not optimum for driving a single-pass SASE FEL at 155 MeV with wavelength $\lambda_r \approx 500$ nm, as promised in the SPARC proposal. The problems associated with driving an FEL with this type of beam have become clearer in the recent past, motivated in no small part by the desire to shorten the undulator length needed. It is clear, for instance, that focusing the beam more strongly does not produce notably better gain, while also producing a much worse level of misalignment tolerances. The suggestion of stronger focusing arose in part from the desire to scale the performance of the VISA FEL[3], which had lower energy (71 MeV) quite strong focusing ($\beta \approx 30$ cm v. 16 m in SPARC), a shorter undulator period ($\lambda_u = 2$ cm v. 3 cm in SPARC), a narrower gap (5 mm v. 9 mm in SPARC), higher beam current ($I_p \approx 250$ A, compressed from 55 A after the injector) and larger emittance in the lasing portion of the beam ($\varepsilon_{n,x(y)} = 4$ (2.1) mm-mrad).

With all of these parameters in VISA pointing towards higher gain, it is not clear to the casual observer which enables the much shorter gain length reported in VISA (19 cm) as opposed to the baseline design of SPARC FEL (80 cm). One immediately notices, however, that the current in the SPARC case is anomalously low; in fact if SPARC FEL is built as presently designed, it would be the first saturating FEL to *not* use a compressor to increase the current. This point is clarified if one examines the expression for the three-dimensional gain length of a SASE FEL given by Ming Xie for SPARC parameters, as essentially only one term is driving the deviation from 1D gain behavior — diffraction. In order to beat diffraction in a SASE system, one has two choices: 1) decrease the 1D gain through the current density (thus increasing the ρ-parameter, and 2) increasing the electron beam size, so as to decrease the effects of diffraction. A combination of the two choices would of course be the most desirable, and such a scheme is what we study in this note. Before we discuss the effects of this type of change in electron beam parameters, let us first review the options we have for increasing the beam current.

The first is intriguing, but a bit risky, and that is to use velocity bunching for partial compression, while attempting to control the emittance compensation process. This option has both physics risk and increased cost attached to it, as the technique is completely unproven, and also requires significant investment in solenoids for downstream linac sections in the SPARC injector.

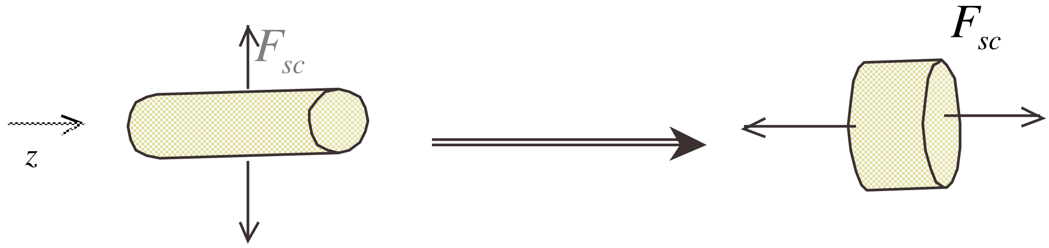


Figure 1. Geometry for constant charge, constant bunch volume deformation, which produces larger launch current.

2 INCREASED CURRENT THROUGH BUNCH DEFORMATION

The second proposal, which was discussed by M. Quattromini and C. Ronsivalle in an ENEA-INFN beam dynamics meeting, is to deform the beam launched at the cathode keeping the beam charge constant. Maintenance of emittance compensation requires keeping the beam plasma frequency constant[4], and therefore the beam density and the beam volume constant as well. Thus in increasing the launched current by shortening the laser pulse length σ_z, we must increase the radius of the bunch as $\sigma_r \propto \sigma_z^{-1/2}$. This scheme produces two notable effects: 1) the emittance increases (in the lowest order approximation it should grow as the launched current, $\varepsilon_n \propto \sigma_r^2 \propto \sigma_z^{-1} \propto I_L$), and 2) the deformation of the bunch produces debunching through *longitudinal* space-charge effects. This effect is shown schematically in Fig. 1, where we see that the exercise of constant charge/volume deformation of the bunch converts what was a "cigar-like" bunch shape, where the aspect ratio $A \equiv \sigma_r / \sigma_z$ is less than unity (at nominal design it is 0.5), to one where $A > 1$. When this ratio increases much beyond one, the space-charge field becomes increasingly longitudinal, and stays "turned on" longer, before the bunch shape in its rest frame becomes cigar-like, and the space-charge again becomes radially dominated. It is important to note that the relative elongation is always expected to rise under this deformation, because the longitudinally "defocusing" field gradient is in any case initially roughly the same for all cases, and with $A > 1$ the defocusing is integrated for a longer time. The dependence of the aspect ratio on the launch current is particularly discouraging in this regard,

$$A = \frac{\sigma_r}{\sigma_z} \propto \frac{1}{\sigma_z^{3/2}} \propto I_L^{3/2}, \tag{1}$$

so A may increase unacceptably very soon beyond the present design current.

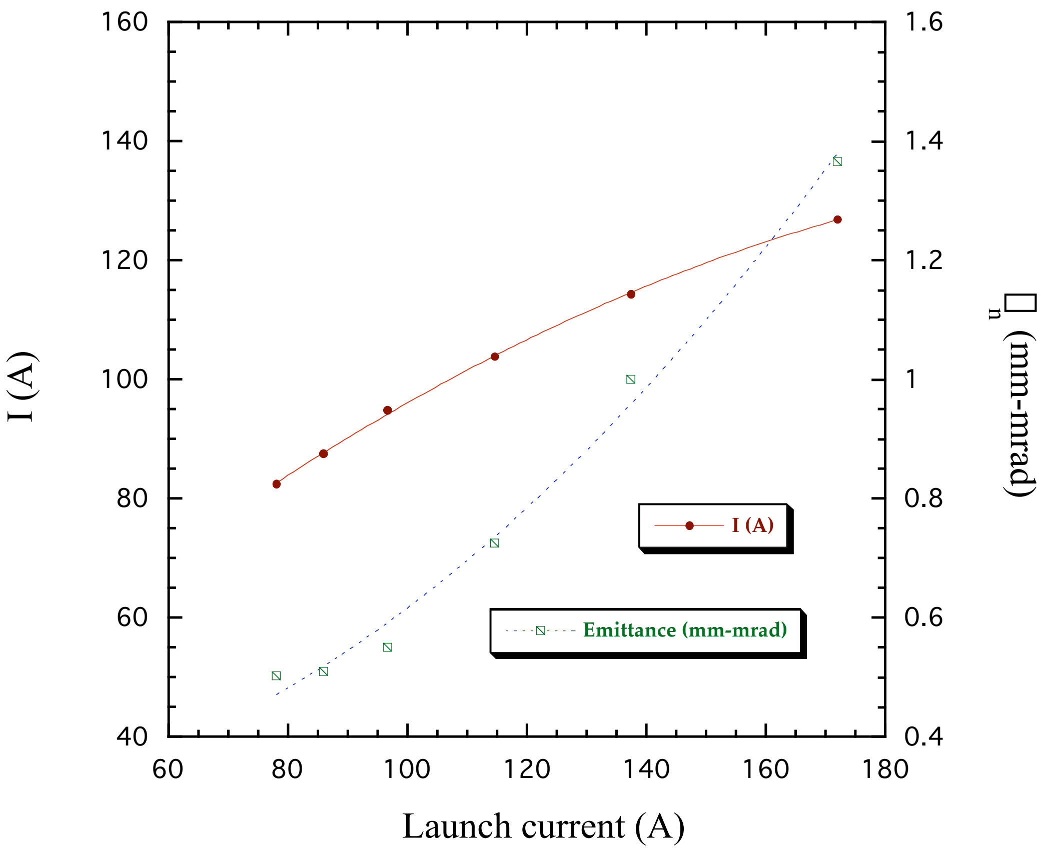


Figure 2. Final peak current and emittance from HOMDYN, using deformation scheme illustrated in Fig. 1, varying launch current around nominal SPARC working point (86 A launch current) using bunch deformation.

A short HOMDYN study (with the charge kept at 1 nC, and nominal bunch radius of 1 mm, bunch length of 11.63 ps taken as reference design numbers) has been performed that illustrates the performance of the beam under the deformation scheme that is intended to raise the current. It can be seen in Fig. 2 that once the launch current exceeds 100 A or so, the debunching effect asserts itself. In addition, the emittance growth is strong at higher launch currents, as emittance compensation is degraded by the turning of the field lines from radial to longitudinal at low beam energy.

This beam behavior is not too encouraging, and the usual benchmark of calculating the Xie saturation length (for the beam cooperation-length slice in the longitudinal bunch center) shown in Fig. 3 displays that in fact, little or no advantage is obtained from trying to increase the current in this fashion. The current growth is simply not robust enough to boost the gain significantly, and for very short launched beams, the performance is in fact degraded. Thus we are led consider other ways to increase the current, and therefore the 1D gain length.

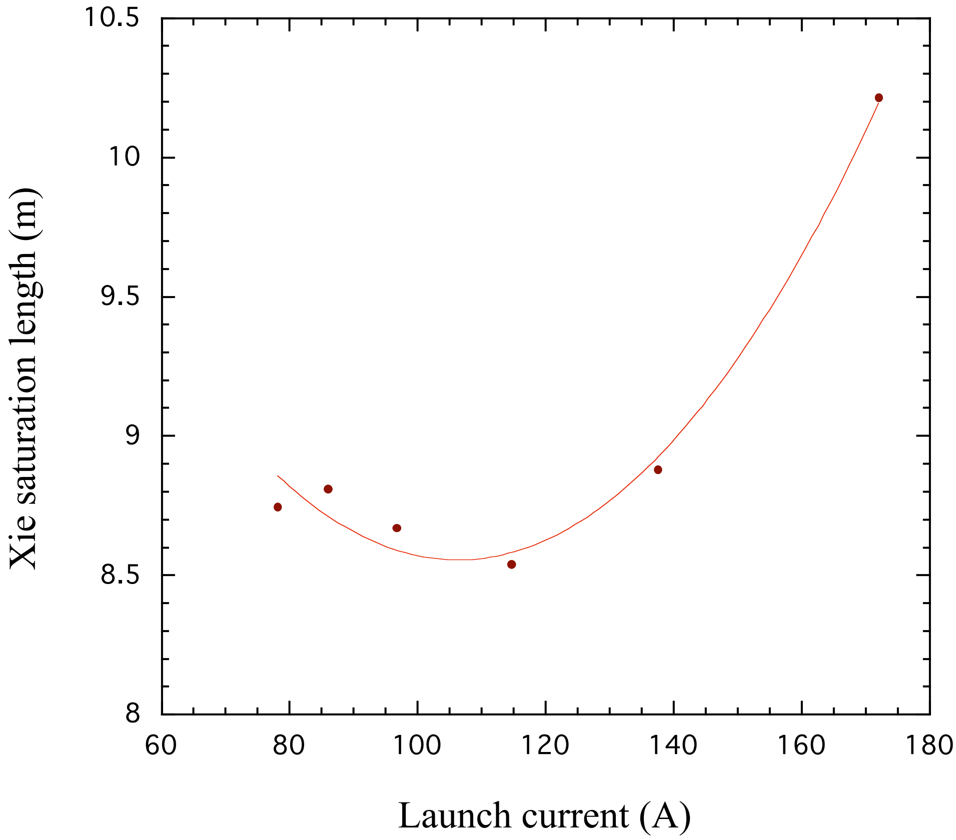


Figure 3. Saturation length using 3 cm period, *K*=2 undulator from HOMDYN, using deformation scheme illustrated in Fig. 1, varying launh current around nominal SPARC working point (86 A launch current) using bunch deformation.

Figure 4. Geometry for constant bunch length, constant bunch density scheme for production of larger launch current, with increase in total charge.

3 INCREASED CURRENT THROUGH LARGER CHARGE/BUNCH RADIUS

In fact, we have considered in detail a modified scheme for current enhancement, in which the beam pulse length σ_z and density are held constant, while the total charge is increased by expansion of the radial beam size. This scheme, displayed schematically in Fig. 4, implies that the charge and rms bunch radius are related by $\sigma_r \propto Q^{1/2}$, and thus the bunch aspect ratio scales as

$$A \propto Q^{-1/2}/\sigma_z \propto I_L^{1/2} \qquad (2)$$

This scaling with increased launch current is much more forgiving, and, as we shall see, allows to evade the transition to debunching. Higher currents are therefore enabled.

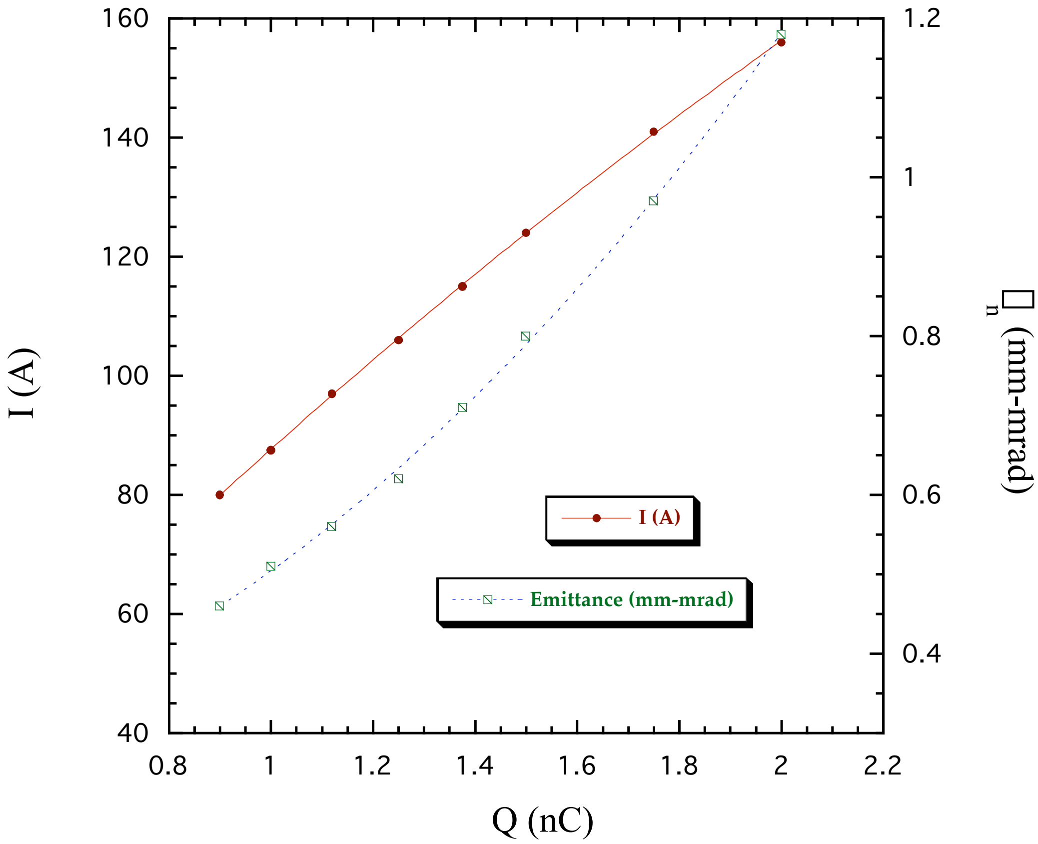


Figure 5. Final peak current and emittance from HOMDYN, using additional charge scheme for enhancing the current illustrated in Fig. 4.

This scheme produces extremely good results, with enhancement of the HOMDYN (averaged over the bunch length) current, achieved at the expense of moderate emittance growth, as can be seen from Fig. 5. The final HOMDYN-averaged peak current achieved over the range from 80 A to 156 A is nearly linear in the launched charge. Again performing the Xie analysis for the central beam slice, we see in Fig. 6 that a dramatic downwared change in the saturation length, from nearly 8.8 m to around 7.5 m, is predicted when the beam charge exceeds 1.5 nC or so. Before we discuss the reasons for this change, we first examine a working point above the predicted transition to higher FEL performance, at 1.7 nC, using PARMELA. This new working point is compared to the baseline 1 nC design. A slice analysis is displayed to show the details of the beam performance in both cases.

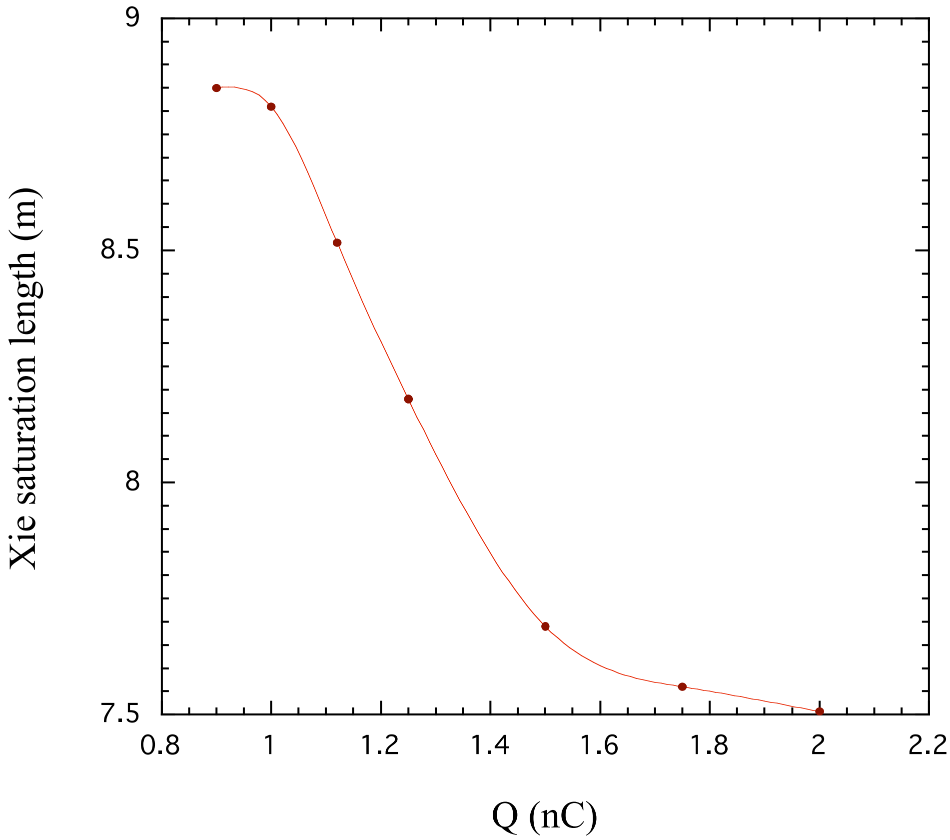


Figure 6. Saturation length using 3 cm period, *K*=2 undulator from HOMDYN, using deformation scheme illustrated in Fig. 1, varying launh current around nominal SPARC working point (86 A launch current) using bunch deformation.

4 PARMELA SIMULATION OF INCREASED CURRENT WORKING POINT

The baseline working point in the PARMELA analysis has a 1 mm hard edge radius for the beam, a pulse length of 11.6 psec, and 1 nC of charge. The more promising working point changes the hard-edge radius from 1 to 1.3 mm, and therefore from 1 nC to 1.7 nC. Simulations with and without the standard 1 psec rise time were performed, but only the phase spaces with the rise time effects included were used in the subsequent GENESIS analysis of the SASE FEL performance.

The emittances and beam size evolution from the cathode through the undulator for these cases are shown in Fig. 7. It is seen that, as predicted, the behavior in all cases is similar, as the added-charge scheme preserves well the transverse plasma frequency of the beam. This is especially true in this scheme as opposed to bunch deformation, as there is much less space-charge driven lengthening, which noticeably changes the beam plasma frequency, and thus the emittance compensation dynamics.

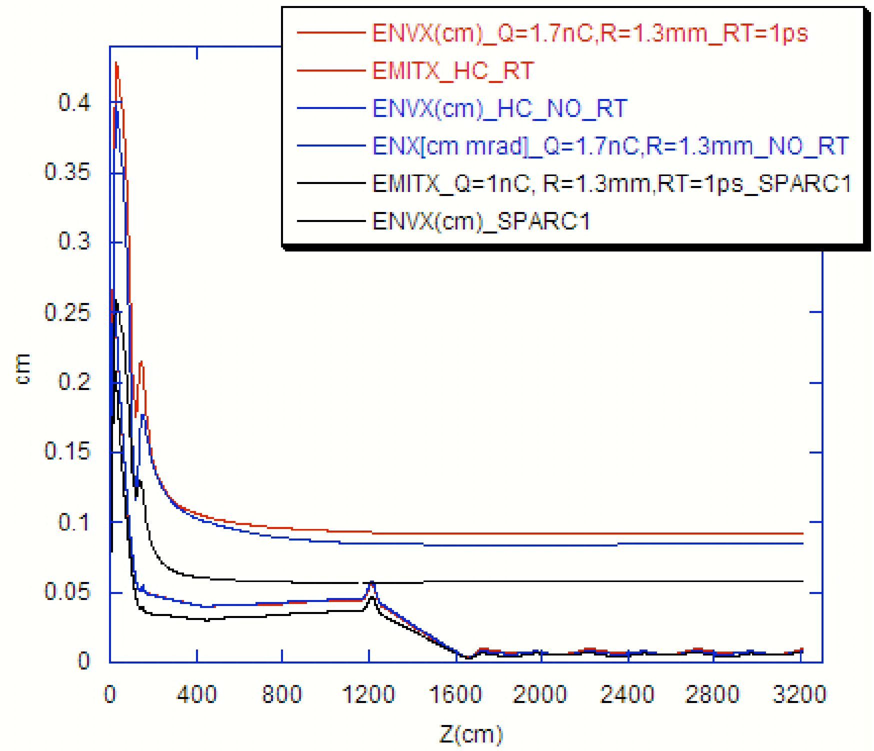


Figure 7. Bunch size and emittance evolution in three cases: baseline 1 nC design (SPARC1); 1.7 nC, 1.3 mm bunch radius case without (HC_NO_RT) and with (HC_RT) rise time included.

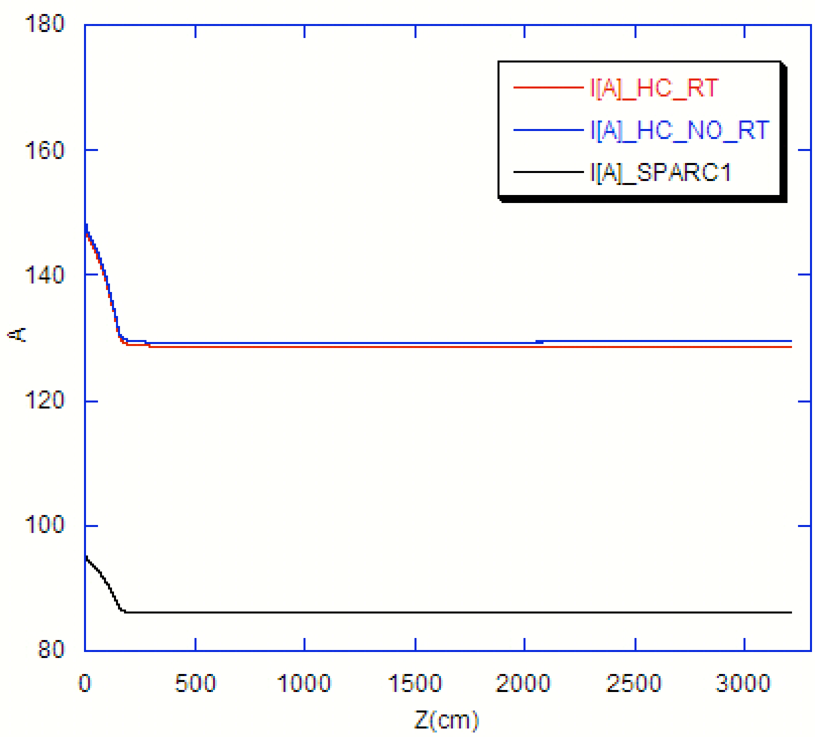
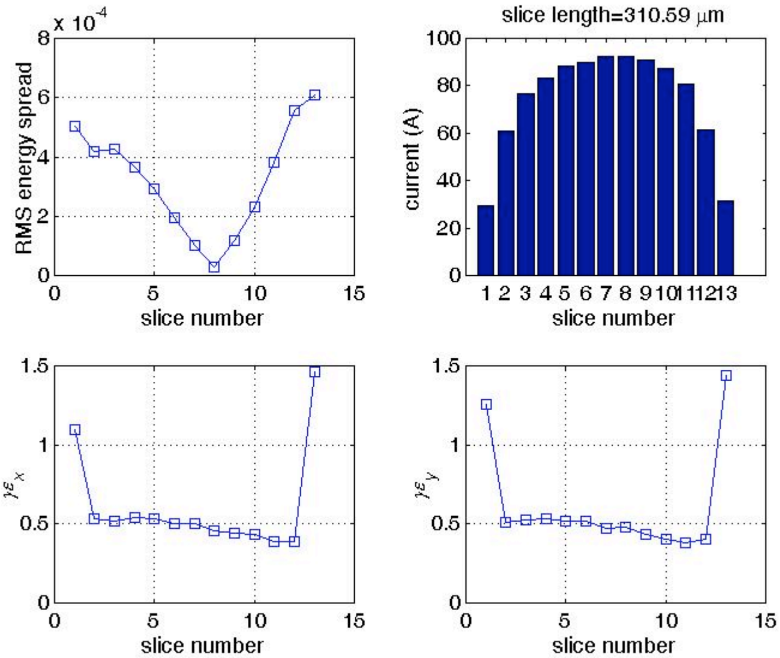
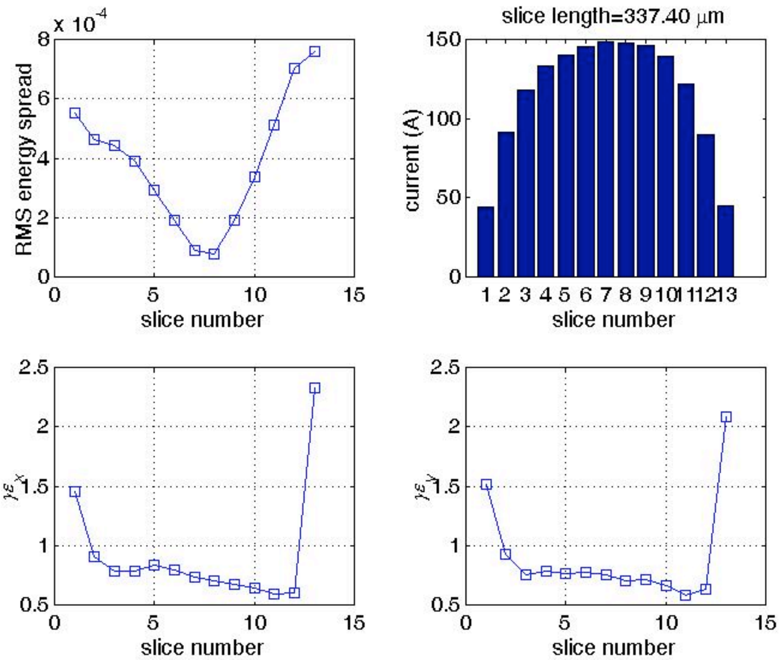


Figure 8. Beam current evolution in three cases: baseline 1 nC design (SPARC1); 1.7 nC case without (HC_NO_RT) and with (HC_RT) rise time included.

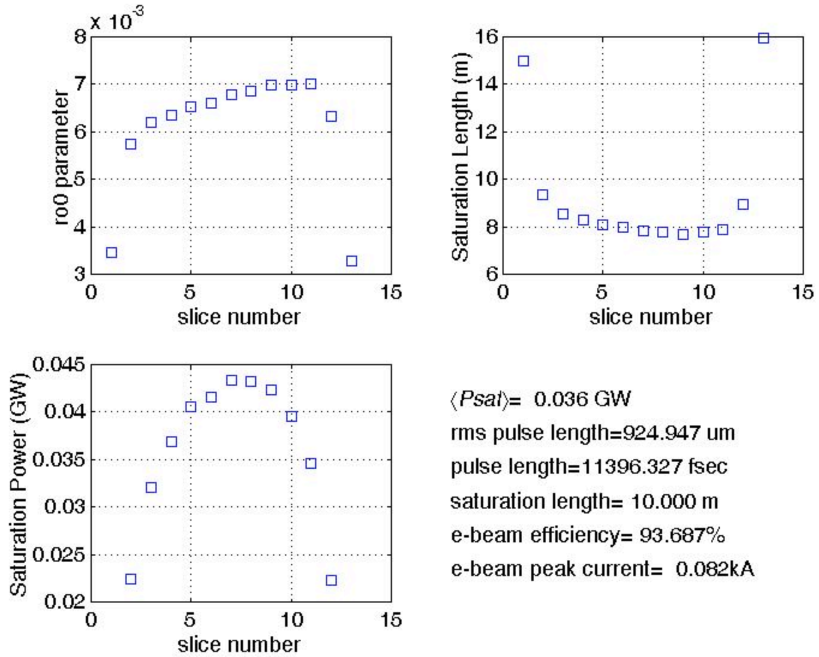


(a)

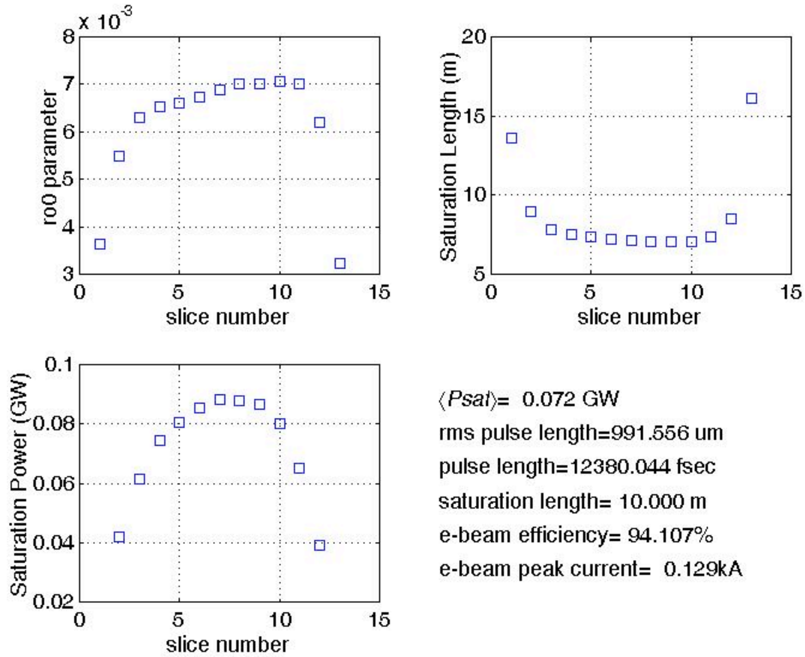


(b)

Figure 8. Slice analyses for the (a) 1 nC, and (b) larger charge/radius (1.7 nC) cases.



(a)



(b)

Figure 9. Slice analysis of SASE FEL predicted performance, analyzing PARMELA output (rise-time included), in (a) baseline 1 nC case, and (b) larger charge/radius 1.7 nC case.

The slice analyses of direct beam parameters are shown in Figs. 8 and 9. In Fig. 8, it can be seen that the peak current is increased from 89 A to 150 A in going from 1 to 1.7 nC, for a ratio of almost exactly 1.7! Further, the slice emittance in the core of the beam does not rise even by this factor, going from around 0.5 mm-mrad to 0.75 mm-mrad. The Xie analysis shown in Fig. 9 indicates that the saturation length for these cases should decrease from 8 m in the low charge case, to 7 m in the high charge case. The enhanced performance is also illustrated in the doubling (*i.e*. more than 1.7) of the predicted SASE power.

5 SASE FEL PERFORMANCE AT INCREASED CURRENT WORKING POINT

The PARMELA output phase space that was analyzed in Figs. 8 and 9 was then used as input in a model undulator calculation using GENESIS to complete the start-to-end modeling process. Here we take a slightly enhanced undulator design (one presently under discussion), with 2.8 cm period, and *K*=2.1, still with 1.6 m beta-function, and no gaps, to simply understand the FEL itself. In the 1 nC case (Fig. 10), we see saturation in roughly 8.8 m (it is a bit difficult to rigorously define saturation in the case where portions of the beam saturate at different points in the beam line). In the 1.7 nC case (Fig. 11), the FEL saturates in around 7.6 m, and achieved more than 3 times the final energy.

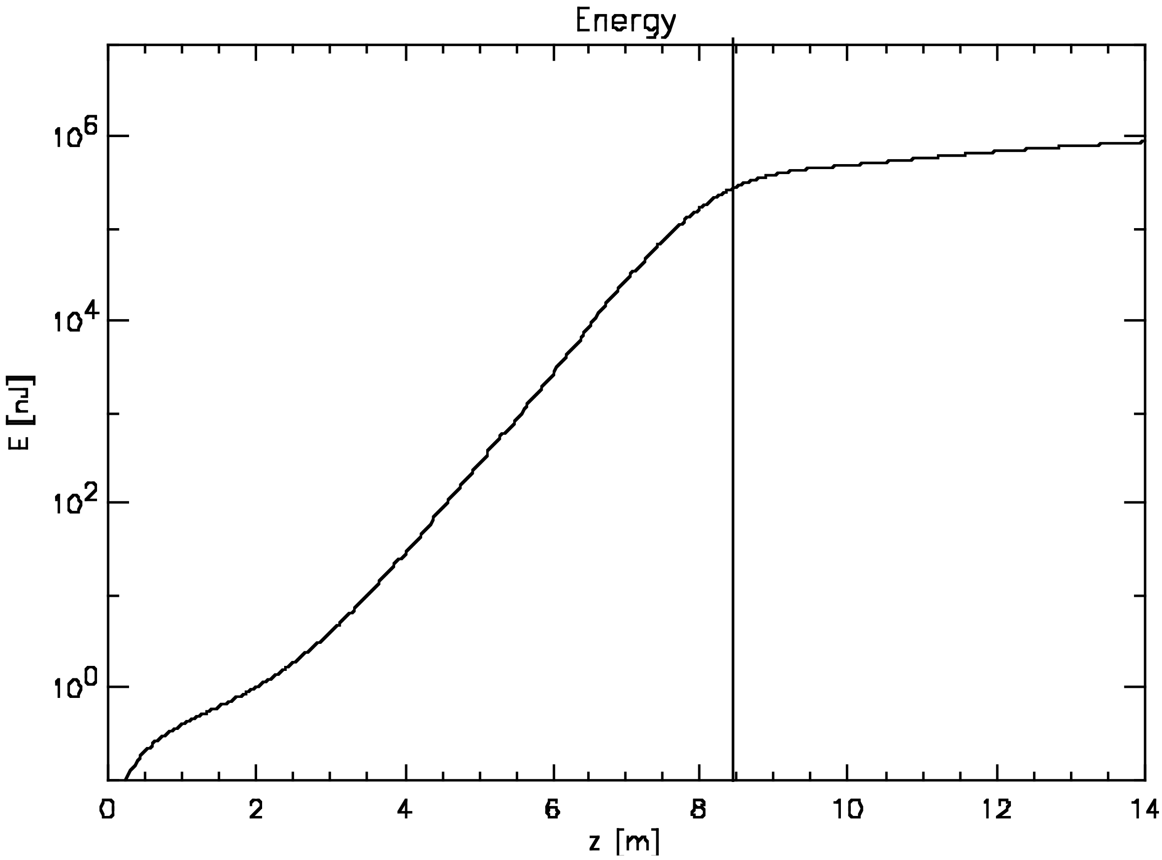


Figure 10. GENESIS simulation of baseline 1 nC case, using PARMELA output as input.

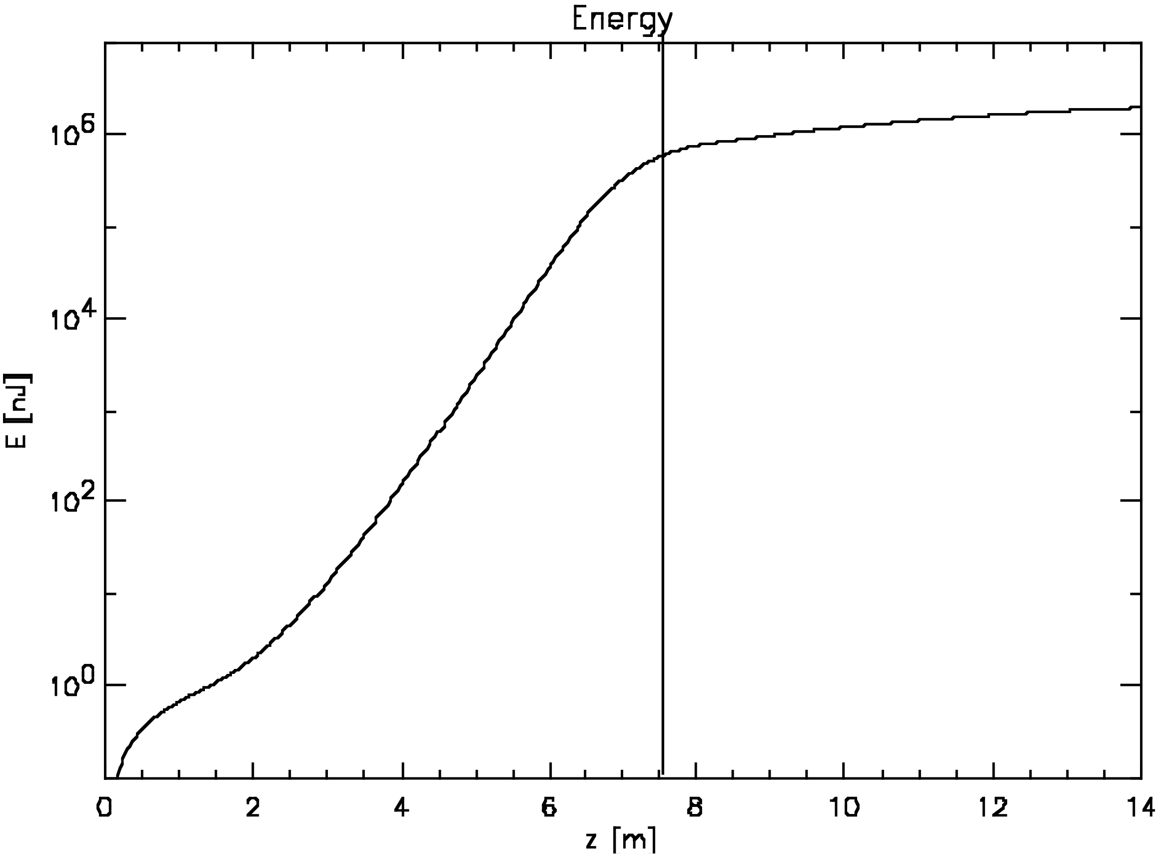


Figure 11. GENESIS simulation of 1.7 nC case (with rise-time), using PARMELA output as input.

It can be seen that higher performance of the injector and FEL can be achieved with this type of current-enhancement scheme. The technical risk associated with this proposal is small, as SPARC has specified both laser energy and cathode size with an overhead of at least a factor of 5! Thus one may expect that the current can be raised in the SPARC injector in such a way that the performance of the FEL, including the effects of emittance degradation, is enhanced. Of course, the current and emittance are only two parameters which effect the beam

6 SCALING OF OTHER BEAM AND UNDULATOR PARAMETERS FOR ENHANCED FEL PERFORMANCE

The implications of what was learned about possible changes to the FEL undulator design extend beyond those of simply increasing the current in a viable way, as discussed above. The curious behavior exhibited in Fig. 6, where a transition between a nearly 9 m saturation length and one near 7.5 m implies that we have an effect with a strong signature that is ameliorated in the higher charge cases. In fact, one can identify this effect as being due to diffraction. In order to see this, we introduce a discussion motivated by M. Xie's analysis. There are several relations that should be reviewed to make a quantitative analysis of the scaling of FEL performance with various parameters.

We begin with the one-dimensional FEL scaling laws[5], starting with the definition of the 1D gain parameter,

$$\rho_{1D} = \left[\left(\frac{I}{I_A}\right)\left(\frac{\lambda_u K \cdot JJ(K)}{4\pi}\right)^2\left(\frac{1}{\beta\varepsilon_n}\right)\left(\frac{1}{\gamma^2}\right)\right]^{1/3}, \tag{3}$$

where the undulator wavelength λ_u is related to the resonant on-axis FEL wavelength by

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left[1+\frac{K^2}{2}\right]. \tag{4}$$

The other parameters of interest are the undulator strength parameter $K = eB_0\lambda_u/2\pi m_e c$ (which does not exceed 3 for the designs of interest, and so the function $JJ(K)$ is near unity), the current I which is normalized to $I_A \cong 17$ kA, the normalized rms beam emittance ε_n, and the beta-function β.

Among other parameters, the 1D gain parameter is related to the the 1D gain length, by

$$L_{1D} = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{1D}}. \tag{5}$$

Thus, a desired short gain length is obtained by decreasing λ_u and/or increasing ρ_{1D}. M. Xie's work that generalizes the 1D theory to three dimensions is based on a fit to a large simulation set, up to third order in parameters which describe three distinct effects that may degrade thegain: diffraction, beam emittance, and beam energy spread. At low energy, and with uncompressed photoinjector sources, it is generally the rule that only diffraction matters in the performance of a SASE FEL; this is the case for the SPARC FEL design.

Under these conditions, Xie's fit is very simple, with a single correction to the 1D gain

$$L_g \cong L_{1D}\left[1+0.45\left(\frac{L_{1D}}{Z_R}\right)^{0.57}+\ldots\right]. \tag{6}$$

where the Rayleigh range of the emitted coherent radiation is written as

$$Z_R = \frac{4\pi\sigma_x^2}{\lambda_r} = \frac{4\pi\beta\varepsilon_n}{\lambda_r\gamma}. \tag{7}$$

We are taking an approximate picture here that the beam is round, $\sigma_x \cong \sigma_y$, and of constant size, even though the focusing is of alternating gradient form. Thus the value of β is taken to be approximately constant. It should be noted that in the baseline SPARC design, if we take the emittance to be 2 mm-mrad, we have $L_{1D} = 23.6$ cm, while $Z_R = 13.2$ cm, and the 3D gain length is increased dramatically by diffractive effects, to 38.5 cm.

If we concentrated for the moment on only the ratio of the 1D gain length to the Rayleigh length that controls the correction to the gain length, we have the following scaling:

$$\frac{L_{1D}}{Z_R} \propto \frac{\lambda_u^{1/3}}{I^{1/3}K^{2/3}(\beta\varepsilon_n)^{2/3}}, \qquad (8)$$

where we have assumed the “programmatic boundary conditions” that the energy and the radiation wavelength are to be held constant. Further, under these assumptions, the undulator strength is related to the undulator wavelength, and

$$\frac{L_{1D}}{Z_R} \propto \frac{\lambda_u^{1/3}}{I^{1/3}\left[\frac{4\lambda_r}{\lambda_u}\gamma^2 - 2\right]^{1/3}(\beta\varepsilon_n)^{2/3}} \propto \frac{\lambda_u^{2/3}}{I^{1/3}(\beta\varepsilon_n)^{2/3}} \propto \frac{\lambda_u^{5/3}}{I^{1/3}\varepsilon_n^{2/3}}, \qquad (9)$$

where in the final relation we assume that K is large, and have also inserted in the end the implicit dependence of the focusing on the undulator strength, $\beta \propto \lambda_u/K \propto \lambda_u^{3/2}$ (for K large). We have therefore the preference that λ_u is short, which is strongly reinforced by the λ_u dependence found in L_{1D} as well. In addition, we have the remarkable dependence on the beam size, which should be larger in order to mitigate this 3D correction. Thus under certain circumstances, an increase in the emittance or the beta function In fact, if one looks at the original UCLA/LANL high gain experiment[7], as the charge was increased, the current did not increase much, but instead the emittance grew. If one plots the 1D gain length as a function of charge in this experiment, it is seen (in Fig. 12) that the dependence is weak; the beam brightness does not improve much, and in fact degrades near the maximum charge (2.3 nC). On the other hand, because the diffraction is so dominant in this experiment (12 micron radiation), the Rayleigh range falls dramatically as a function of the charge, and the 3D gain length falls as well, in agreement with the data on final SASE energy.

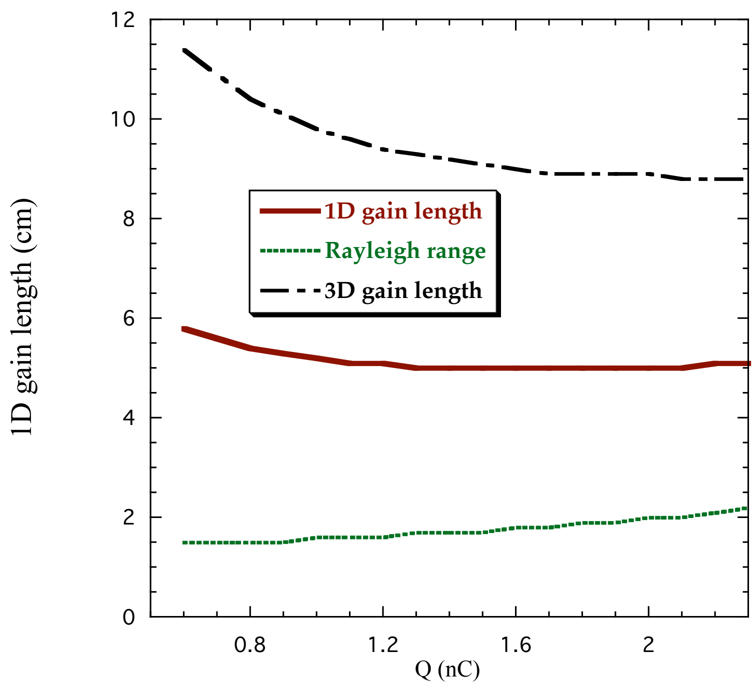


Figure 12. The 1D gain length, 3D gain length, and the Rayleigh range as a function of charge in the UCLA/LLNL 12 micron high gain SASE FEL experiment.

While it is clear that by moving the working point to higher charge, the gain length and saturation length can be made shorter due to a moderately smaller 1D gain length and a *much* smaller Rayleigh range, it is worth asking whether the other parameters that are displayed in Eq. 8 should be changed as well. It is clear that strengthening the focusing without changing other parameters is not very productive, as it exacerbates the diffraction term. On the other hand, one is tempted to decrease λ_u. Unfortunately, this implies, because one is dealing with magnets that are of fixed strength, that the gap g must be changed in order to give the correct value of the undulator strength. The relevant relation is

$$K \cong 3.2\lambda_u(\text{cm})\exp\left[-5.08g/\lambda_u + 1.54(g/\lambda_u)^2\right]. \tag{10}$$

The bias inherent in this scaling is that we will lose strength linearly with λ_u without the gap effects. Fortunately, the present design is so relaxed in this regard that we may (as we must, to obtain constant λ_r) actually increase K while decreasing λ_u over a limited range. As an example, we show the gain length as a function of charge (using the current/emittance scaling given by HOMDYN) for two cases: λ_u=3 cm with g=10 mm and $\beta = 1.6$ m, and λ_u=2.5 cm period with g=6.6 mm and $\beta = 1.22$ m. It can be seen in Fig. 13 that the performance of the shorter wavelength undulator is convincingly better.

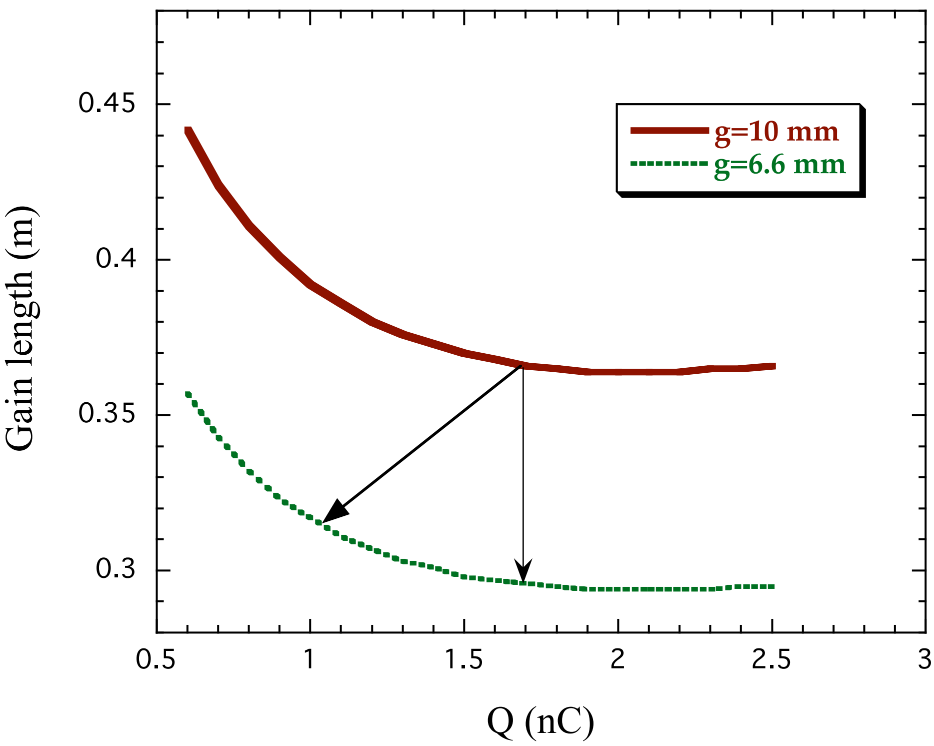


Figure 13. The 1D gain length as a function of charge for the SPARC FEL, for gaps of 10 mm (λ_u=3 cm) and 6.6 mm (λ_u=2.5 cm).

Some comparisons between working points in the 10 mm gap and the 6.6 mm gap cases are worth mentioning. First, if one works at the enhanced current point (1.7 nC), the increase in performance in going to the smaller from the larger gap, as measured by the relative decrease in the gain length, is notable: L_g decreases by 19%. This working point change is shown in Fig. 13 by a vertical arrow. It should also be emphasized that we may always revert to the baseline 1 nC point with the shorter undulator period of λ_u=2.5 cm, and still achieve a shortening of the gain length by 14% over the 1.7 nC, λ_u=3 cm case (changing both parameters, the angled arrow in Fig. 13). Perhaps most impressively, by proceeding *only* with changes in the undulator (λ_u = 3 cm $\rightarrow$ 2.5 cm), and remaining at the 1 nC working point, we can reduce L_g by 25%.

7 SOME HARDWARE CONSIDERATIONS

There are two obvious questions concerning the implementation of the two recommendations given for improving the SASE FEL working point in SPARC. The first is that one must have the capability to produce more charge, through a larger radius laser beam with either more power or improved quantum efficiency. For the SPARC gun design the cathode is not an issue; it is much larger than the baseline spot size of 1 mm radius. Likewise the laser is specified presently with a large overhead, one that is based on extremely conservative assumptions concerning the quantum efficiency. Thus one may conclude that obtaining 70% more current should not present a problem for the SPARC photoinjector system.

The second experimental consideration concerns the scaling of the undulator gap to smaller size. This question involves knowledge of a detailed design of the undulator and its vacuum system, which does not presently exist. It suffices to examine two recent successful SASE FEL undulators, from the VISA and LEUTL experiments. The VISA undulator[7] had a gap of 6 mm, and a free vertical aperture for the beam of 5 mm, with a much wider horizontal aperture. The LEUTL undulator had a gap of 9.3 mm, with a round beam pipe of inner diameter 6 mm. Thus, contingent on a well-designed vacuum scheme for the gap region, a gap of even 6.6 mm in the case of the SPARC undulator seems entirely within reason. Since it is apparent that changes in the undulator design may be even more important than those in the injector which enhance the current, the closing of the gap, and concomitant shortening of λ_u, should be investigated seriously, including all hardware (vacuum, magnetic, diagnostic) issues at the engineering design level. It may be foreseen that the vacuum and diagnostic issues are the most challenging, but their solution is certainly not without reasonable, feasible approaches, as *e.g.* the VISA experience clearly shows. It should also be noted that the VISA experiment had an ambitious undulator and vacuum design, and succeeded well at lower energy (smaller beam) than SPARC. Likewise, it is relevant to note that the LEUTL was not designed specifically for the needs of the SASE experiment, and therefore should not be considered an optimum point to scale from. Similar comments hold for their vacuum pipe choice; it was not the result of a long design process, but rather an expedient choice that did indeed work. To extrapolate from this design to SPARC, assuming that it leads to an optimized experiment, is also without strong rationale.

8 ACKNOWLEDGEMENTS

The authors would like to acknowledge beneficial discussions with, Luca Giannessi, Marcello Quattromini, Concetta Ronsivalle and Luca Serafini.

9 REFERENCES

[1] SPARC Preliminary Technical Design Report, INFN-LNF, April 2003.

[2] M. Ferrario et al., “HOMDYN Study For The LCLS RF Photo-Injector”, Proc. of the 2nd ICFA Adv. Acc. Workshop on “The Physics of High Brightness Beams”, World Scientific (2000).

[3] A. Tremaine, et al., "Experimental Characterization of Nonlinear Harmonic Radiation From a Visible SASE FEL at Saturation", *Phys. Rev. Lett.* **88,** 204801 (2002)

[4] J.B. Rosenzweig and E. Colby, "Charge and Wavelength Scaling of RF Photoinjector Designs", *Advanced Accelerator Concepts* p. 724 (AIP Conf. Proc. 335, 1995).

[5] R. Bonifacio, L. Narducci, and C. Pellegrini, *Opt. Comm.* **50** (1984) 373

[6] M. Xie, “Design optimization for an X-ray Free Electron Laser driven by SLAC linac”, Proc. of PAC-95, Dallas 1995.

[7] M. Hogan, et al., "Measurements of Gain Larger Than 10^5 at 12μm in a SASE FEL", *Physical Review Letters,* **81** 4867 (1998).

[8] R. Carr et al, “Visible-infrared self-amplified spontaneous emission amplifier free electron laser undulator”. *Phys. Rev. ST Accel. Beams* **4**, 122402 (2001).