OPTIMISATION STUDIES OF THE PLANNED PAUL SCHERRER INSTITUTE ELECTRON GUN TEST FACILITY

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1. INTRODUCTION

An RF gun with a laser driven photocathode is regarded as a possible pre-injector for the light source presently under study at PSI (Swiss Light Source)[1]. One of the main features of the proposed machine is an optional operating mode at extremely low emittance. The relatively modest beam lifetime expected in this regime could be partially compensated by fast and frequent fillings of the ring, based on a single shot on-axis injection of the full charge bunches (≈ 5 nC).

In a more classical mode of operation with relaxed emittance performance, the longer beam lifetime will lead to relatively long delays between the successive fillings of the ring. It is envisaged to make use of the injector, during this "dead time", for driving Free Electron Laser experiments, which necessitates the production of very bright electron beams.

In order to generate electron bunches suitable for both purposes, the use of a photocathode RF gun is regarded as an adequate solution. Within this context, we started investigating possible performance of a gun similar to that installed at CERN in the CLIC Test Facility [2]. It consists of a cylindrical 1/2 + 1 cell RF cavity operated at 3 GHz in a TM010 π- mode. The results of beam dynamics simulations in such a gun were previously reported [3,4]. These predicted beam characteristics then served as input data for the optimisation of a single pass FEL amplifier operated in the so-called Self Amplified Spontaneous Emission mode [5]. A summary of this study is presented here.

The principle of the SASE FEL [6,7] is based on the constructive interference between a bunch of electrons and a transverse electromagnetic wave, all along their path through an undulator. Starting from the spontaneous emission at the undulator entrance, the radiation is further amplified by the beam itself as they propagate in synchronism down the undulator. If the electron density is high enough and the bunches sufficiently long, the amplitude of the radiated wave grows exponentially until it reaches saturation (steady state regime). With short bunches, one can enter another regime called "superradiance", where the saturation is removed [8,9].

The possibilities of driving SASE FEL's are investigated within an electron beam energy range from 4 MeV at the gun exit, up to 100-200 MeV after acceleration through the SLS LINAC. Proper combinations of the electron beam and undulator characteristics should permit the production of high power radiation, from the Far-Infra-Red down to the Vacuum-Ultra-Violet region.

2. ELECTRON BEAM CHARACTERISTICS

For our FEL optimisation, we will assume that the electron bunches are produced by a photocathode RF gun similar to that used at CERN in the CTF. Beam dynamic simulations inside the gun were performed [3,4] by means of the particle tracking code PARMELA [10]. The graph in figure 1 shows the computed normalised emittance versus peak current at the gun exit. For the relativistic and cylindrically symmetric Gaussian bunches of electrons considered here, the normalised RMS emittance is defined as : $\varepsilon_n = \gamma \sigma_r \sigma_\theta$, where γ is the Lorentz factor, σ_r and σ_θ are the RMS bunch radius and divergence. The characteristics of the bunches emitted off the photocathode were adjusted as follows:

- Initial phase *, $\phi_0 = 6$ degrees;
- RMS bunch radius, $\sigma_{r0} = 3$ mm;
- RMS bunch duration, $\sigma_{t0} = 2$ ps.

The bunch charge was varied within $0 < q_0 < 1$ nC, so as the peak current density ** off the photocathode would not exceed 750 A/cm^2. For the field of 100 MV/m, the final value of γ was found to be around 8 and the relative energy spread below 0.5%.

Setting the initial phase to a small value ($\phi_0 = 6$ degrees) results in a significant bunch length compression in the gun. With 1 nC of charge, final peak currents up to 800 A, four times the initial value I_0, are thus obtained in 0.6 mm (4σ) long bunches; the corresponding normalised RMS emittance is 20 mm.mrad. As shown in figure 1, lower values of emittance are achieved at the expense of reduced charges per bunch and lower peak currents.

These particular initial conditions were found to be optimum with regards to the ratio of the peak current to normalised emittance. However, with less emphasis on the emittance performance, much higher charges in longer bunches could be easily produced, when necessary. Computed and first experimental results obtained at CERN [3], tend to prove that one order of magnitude larger charges ($q_0 > 10$ nC) can be extracted off a CsI photocathode and fully transferred to the gun exit. Typically, one should be able to achieve the same levels of final peak current (up to 800 A) in 1 cm (4σ) long bunches, with a normalised emittance of about 100 mm.mrad and a relative energy spread around 1%.

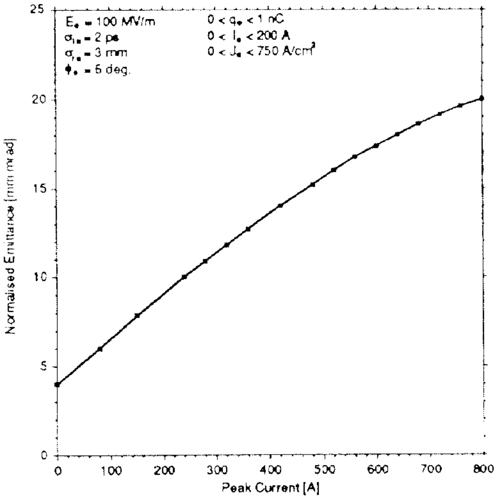

Figure 1 : Normalised emittance versus peak current at the gun exit, computed with PARMELA.

3. UNDULATOR CHARACTERISTICS

The undulator is characterised by its period length, λ_u and its dimensionless potential vector

$$K = \frac{e B_u}{\omega_u m_o c^2} \approx 0.934 \, B_u[\mathrm{T}] \, \lambda_u[\mathrm{cm}] \qquad (1)$$

where $\omega_u = 2\pi c / \lambda_u$, B_u is the RMS value of the magnetic field on the undulator axis †, c is the velocity of light, e and m_0, the electron charge and rest mass. Typical undulator parameters for FEL applications are $0.3 < K < 3$, with period lengths of a few centimetres and $B_u < 1$ Tesla.

Helical and linear undulators naturally provide transverse focusing of the beam. The helical undulator focuses equally in both transverse directions and the wavelength of the natural betatron oscillation is

$$\lambda_{\beta u} = \sqrt{2} \, \gamma \lambda_u / K . \qquad (2)$$

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* The initial phase is the RF phase at the time the electron bunch center leaves the photocathode.

** The peak current density is defined as $J = I / (2\pi\sigma_r^2)$, where $I = q / \sqrt{2\pi} \, \sigma_t$ is the peak current.

† For a helical undulator, $B_u = B_{peak}$; for a linear one $B_u = B_{peak} / \sqrt{2}$.

A conventional linear undulator focuses only in the direction of the magnetic field (perpendicular to the wiggle plane). Focusing in the other direction usually is achieved by adding a quadrupole component to the field or by shaping the magnet poles with parabolic curvature [11]. With both methods it is possible to obtain equal focusing in the two directions and a betatron wavelength again given by (2).

In these conditions, a cylindrically symmetric bunch, matched to the undulator, will approximately conserve its initial radius and therefore its current density. This is achieved when the beam envelope at the undulator entrance has a waist with:

$$\sigma_r^2 = \varepsilon_n \lambda_{\beta u} / 2\pi\gamma = \varepsilon_n \lambda_u / \sqrt{2}\, \pi K. \tag{3}$$

At high beam energy, λ_{β_u} tends to be very large, limiting the value of ρ. It is then convenient to provide additional focusing inside the undulator ($\lambda_\beta < \lambda_{\beta u}$) in order to improve the FEL efficiency. This is not relevant for the energy range considered here ($8 < \gamma < 400$). Within these limits, the condition $\lambda_\beta = \lambda_{\beta u}$ is quite appropriate and we will assume that it is fulfilled.

4. SASE FEL THEORY

In the SASE regime, the two basic elements which define the FEL system are the injected beam and the undulator. Their characteristics will fully determine the properties of the radiated wave.

The wavelength of the radiation, λ is given by the FEL synchronism condition:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+K^2\right). \tag{4}$$

Another fundamental quantity is the FEL dimensionless parameter

$$\rho = \left(\frac{1}{16\pi I_A}\right)^{1/3} \left(\frac{G K \lambda_u}{\gamma}\right)^{2/3} \left(\frac{I}{\lambda_\beta \varepsilon_n}\right)^{1/3}, \tag{5}$$

where $I_A = 17000$ A and I is the electron peak current; for a helical undulator $G = 1$ while for a linear one $G = J_o(\zeta) - J_1(\zeta)$, where $\zeta = K^2 / 2\,(1+K^2)$ and the J's are Bessel functions ($0.5 < G < 1$);

According to the 1-D theory (cold beam and no diffraction effects), the FEL performance can be expressed in terms of ρ. The radiated power grows exponentially through the undulator with a (e - folding) gain length

$$L_G = \lambda_u / (4\sqrt{3}\,\pi\rho); \tag{6}$$

it saturates in a path length

$$L_{sat} = \lambda_u / \rho \approx 22\, L_G, \tag{7}$$

at a power level

$$P_{sat} = \rho\, P_{beam}, \tag{8}$$

where $P_{beam} = I\,E / e$ and $E = \gamma m_0 c^2$ is the beam energy in eV.

The 1-D theory remains a good approximation for a real beam with non-zero emittance and energy spread, provided that the following additional conditions are fulfilled:

a) $r_1 = 2\sigma_E / \rho \leq 1$ (energy spread less than the gain bandwidth),

b) $r_2 = 4\pi\, \varepsilon_n / \lambda\gamma \leq 1$ (emittance matching of the electronic and optical beams),

c) $r_3 = \lambda L_G / \pi\sigma_r^2 \leq 1$ (optical guiding and negligible diffraction effects);

σ_E is the relative energy spread of the beam.

If the preceding conditions are not all satisfied, the FEL efficiency is less than predicted by the 1-D theory.

Introducing the bunch-undulator matching condition (3), one finally obtains:

$$\rho[\%] = 0.94 \frac{K}{\gamma} \left(\frac{G^2 \lambda_u I[A]}{\varepsilon_n}\right)^{1/3}. \tag{9}$$

and the 1-D limits can now be rewritten:

a') $$r_1 = \frac{2\sigma_E}{\rho} \leq 1;$$

b') $$r_2 = \frac{4\pi\varepsilon_n}{\gamma\lambda} = \frac{8\pi\gamma\varepsilon_n}{\left(1+K^2\right)\lambda_u} \leq 1;$$

c') $$r_3 = \frac{\lambda L_G}{\pi\sigma_r^2} = 28.6\left(\frac{1+K^2}{\gamma I[A] G^2 r_2^2}\right)^{1/3} \leq 1.$$

Furthermore, combining b') with c'), one gets:

bc') $$1 < \frac{1+K^2}{G^2} \leq 0.043\, \gamma I[\text{kA}].$$

The last relation bc') gives, for a fixed energy, the current threshold below which the 1-D conditions b') and c') cannot be both satisfied.

At low energy and consequently long radiation wavelength, the most critical limitation comes from condition c'): maintaining the diffraction effects at reasonable level requires a short gain length (high ρ value) together with a bunch radius large enough to properly overlap the radiated wave. On the other side, the transverse bunch dimensions are limited by condition b') on the emittance. This finally leads to severe constraints on the current: from bc'), one finds that about 3 kA are needed for a γ of 8 ($E \approx$ 4 MeV). At such a low electron beam energy, the emittance requirements ($r_2 \approx 1$) are relatively modest. It should be noted that an excessively small emittance ($r_2 < 1$) would tend to increase the current threshold.

At high energy, the situation is somewhat inverted: while the current requirements are relaxed, the production of short radiation wavelengths imposes severe constraints on the emittance.

The amplification-saturation process previously described is known as the steady state regime of the high gain FEL amplifier. This theory holds provided that the bunch properly overlaps the radiated pulse along the entire interaction path. Yet, the resonance condition requires the path difference between the bunch and the radiated pulse, over an undulator period, to be equal to the radiation wavelength and, consequently, the slippage length, accumulated over the N_u periods of the undulator, to be $S = N_u\, \lambda$. Therefore, the steady state theory, considered so far, will only apply under the condition that the slippage is much shorter than the bunch length ($S << L_b$).

In the opposite case, when the bunch is shorter than the slippage length, one enters different regimes, so-called "weak and strong superradiance" [8,9].

5. FEL OPTIMISATION

In our preliminary estimates of possible SASE FEL's, we used the following assumptions :

- the electron bunches are generated by a photocathode gun as described before and the beam quality (peak current, normalised emittance, absolute energy spread) essentially is preserved after acceleration through the LINAC up to 50 - 100 MeV;
- the electron beam dimensions are well matched to the undulator and $G \approx 1$;
- the conditions are such ($r_1 \approx r_2 \approx r_3 \approx 1$) that the 1-D theory can be applied.

5 . 1 *Infra-Red FEL (50 MeV < E < 100 MeV)*

In table 1-a, are listed typical working conditions of possible SASE FEL's at electron beam energy around 50 and 100 MeV. The results were obtained with the short bunch characteristics described in figure 1.

For each energy, 50 and 100 MeV, the first column corresponds to the shortest achievable radiation wavelength, 1.4 and 0.57 µm, within the 1-D limits ($r_1 \approx r_2 \approx 1$); thus, up to about 60 MW of peak power are expected from quite realistic undulator parameters ($\lambda_u \approx$ 2.5 cm, $B_u \approx$ 0.3 T and a total length of 5 - 10 m).

The two other columns show that the FEL efficiency can be largely improved at the expense of a relatively small increase in radiation wavelength: with the largest expected peak current of 800 A, about 400 - 600 MW are predicted from 2.5 - 5 m long undulators, at wavelengths of 2.5 and 1.2 µm, respectively.

	a)				b)	
γ	100.		200.		8.	
I [A]	300.	800.	200.	800.	800.	800.
ε_n [μm]	11.	20.	9.	20.	150.	100.
σ_E[%]	< .2	< .5	< .15	< .3	< 1.	< 1.
K	0.5	1.0	0.8	1.4	0.5	0.5
λ_u[cm]	2.2	2.5	2.8	3.4	2.5	1.6
B_u[T]	0.24	0.42	0.31	0.44	0.21	0.33
L_{sat}[m]	5.7	2.7	8.7	4.7	0.85	0.55
λ [μm]	1.4	2.5	0.57	1.25	245.	157.
P_{sat}[MW]	60.	375.	65.	585.	100.	100.
ρ [%]	0.4	0.94	0.32	0.73	3.	3.
r_1	< 1.	< 1.	< 1.	< 1.	< .35	< .35
r_2	1.	1.	1.	1.	1.	1.
r_3	1.	0.84	1.	0.76	1.7	1.7
s[mm]	0.36	0.27	0.18	0.17	8.5	5.6

Table 1: typical SASE FEL operating conditions; **a)** E = 50 and 100 MeV; **b)** E = 4 MeV

Within this energy range, the electron beam emittance is essentially the limiting factor for generating short wavelengths.

A further acceleration up to 200 MeV would make possible the production of wavelengths down to the VUV domain ($\lambda \approx 0.1$ µm); however, this would require much longer undulators ($L_{sat} \approx 25$ m).

5.2 Low Energy FEL (E = 4 MeV)

Table 1–b shows examples of FEL using the electron beam at the exit of the gun ($E \approx 4$ MeV). These results were again obtained in applying the 1-D theory, although the conditions were not fully satisfied ($r_3 \approx 1.7$). At such a low energy, the limitation does not come from the emittance any more, but from the current. Precise estimates would require 3-D simulations; however, the FEL efficiency should not be affected too dramatically. Thus, we anticipated typically 100 MW of peak power in the 150 - 250 µm range with undulators shorter than a meter.

These estimates will be approximately correct if the bunches will be long enough ($L_b > 1$ cm), so that the propagation effects remain insignificant. Producing the same peak current in shorter bunches should make possible the observation of the superradiant regimes.

Realising the electron beam-to-undulator matching at low energy might be an issue since this requires very small values of the β-function at the undulator entrance ($\beta_{min} < 10$ cm).

6. Conclusions

A photocathode RF gun similar to that used at CERN in the CTF appears to be an adequate source of electrons for serving our two-fold purpose: FEL drive and SLS injection. We expect a beam quality which is well suited for operating SASE FEL's with wavelength ranging from 200-100 µm at the gun energy of 4 MeV, down to 0.5 µm (resp. 0.1 µm) after acceleration through the SLS LINAC up to 100 MeV (resp., 200 MeV). At 4 MeV, with predicted bunch length shorter than 1 mm (4σ), it should be possible to observe the superradiant regimes.

Our study was here mainly oriented towards the generation of high current density without any magnetic compression system. The emittance blow-up then essentially results from the space charge effects inside the gun. Another approach would consist in operating with longer bunches inside the gun and providing a further magnetic compression. Provided that one corrects for the emittance blow-up due to the time dependence of the RF fields [7], one could significantly improve the emittance performance and therefore obtain shorter wavelength than reported above for electron beam energy of 50 - 100 MeV.

On the other hand, with relaxed emittance requirements, the production of bunches suitable for injection into the SLS should not pose any serious problems, even in the most demanding (5 nC per bunch) "single shot on-axis" filling mode.

Amongst the present day technology components, different types of laser and photocathode have the potential to fulfil the requirements. The possibility of simply converting the CTF gun into a thermionic RF gun is also investigated [12]. A test facility, is under construction at PSI, in order to experiment with the various alternatives.

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8. References

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