A POSSIBLE FEL BASED ON LEP SUPERCONDUCTING CAVITIES

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Abstract

After the LEP shut-down, 2.7 GV of superconducting cavities at the frequency of 352 MHz will become available for other uses. For instance, they can be used to drive a Free Electron Laser (FEL) in the VUV and soft X-rays spectral region. Some preliminary calculations show the feasibility of such a device. In particular some GW of peak power can be obtained in the "water window" part of the spectrum, for a 1.5 GeV beam and using state-of-the-art technology for the wiggler and the injector. Technological limits and possible extension are also briefly discussed.

1 SCIENTIFIC APPLICATIONS

The FEL realized using the LEP cavities can be optimized in a spectral region between about 1 to 10 nm [1]. In this region exist a number of applications, (see e.g. the report of the VUV FEL at the TESLA Test Facility (TTF - DESY) [2] and the proceedings of workshops for the Linear Coherent Light Source FEL (LCLS) at Stanford [3,4]).

We intend to concentrate here on the application for which the CERN FEL is particularly well suited, namely the X-ray microscopy of biological samples in the "water window", i.e., the spectral range between the the K-edge of oxygen at 2.3 nm and the one of carbon at 4.4 nm. In this range the wavelength is too long to be absorbed by the oxygen of the water but short enough to be absorbed by carbon, making it possible to obtain a good contrast of biological samples imbedded in water. The high intensity short pulses and the high coherence of the FEL radiation makes this device suitable for single shot X-ray imaging of biological samples. The dose necessary to obtain a good resolution is high and leads to the destruction of the sample. By using a very short X-ray pulse (a few ps) an image of the sample can be made before it is destroyed. It is therefore possible to study initially live specimens. Thanks to the spatial coherence of the FEL radiation, holography is a suitable method for imaging. Resolutions of the order of 30 nm can be obtained.

There is also some interest to go to the 1 nm wavelength region. Good phase contrast can still be obtained and the K adsorption edges of F, Na and P can be covered. The minimum energy needed for the mentioned resolution of 30 nm lies between 10 and 100 µJ. The proposed CERN FEL can deliver an energy of about 2 mJ which is well adapted to this type of application.

2 FEL PARAMETERS

A FEL in the soft X-ray region of the spectrum can not rely on high-reflectivity, high-power mirrors or on conventional laser sources. Therefore both the FEL oscillator (mirrors) and the amplifier (external input source) configurations are ruled out. The remaining possibility is the Self Amplified Spontaneous Emission (SASE) regime of a single-pass, high-gain FEL [5].

Both the TTF FEL - DESY [2] and LCLS - SLAC [3,4] projects are based on this concept. In the following, we will take as a reference the DESY proposal, assuming in particular similar performances for all the equipment other than the superconducting accelerating cavities. As a first guess, we will assume that the electron beam parameters at injection into the wiggler would be the same, except for the energy (2.7 GeV maximum instead of 1 GeV). In a FEL, the output wavelength is given by:

$$\lambda_0 = \lambda_w \frac{1 + a_w^2}{2\gamma^2} \qquad (1)$$

where λ_w is the wiggler period, γ is the electron beam energy (mc^2 units) and a_w is defined as: $a_w = e/mc^2\, B_w \lambda_w/(2^{3/2}\pi)$, where B_w is the wiggler magnetic field. In first approximation, the gain per unit length, saturation length and emitted power at saturation can be easily calculated using a 1-D FEL model [6]. The gain of the FEL is described by the parameter ρ, scaling as:

$$\rho \propto \gamma^{-1} J^{\frac{1}{3}} B_w^{\frac{2}{3}} \lambda_w^{\frac{4}{3}} \qquad (2)$$

where J is the electron peak current density. The growth of the radiation field before saturation is given by the expression $P = P_0 \exp(z / L_G)$, where z is the distance along the wiggler and the gain length L_G is defined as $L_G = \lambda_w / 4\pi\ 3^{1/2} \rho$. The parameter ρ gives also the power extraction efficiency at saturation ($P_{ph} \sim \rho\, P_{beam}$). The possible detrimental effects are:

- Energy spread effects: not all of the electrons are exactly in resonance with the radiation and the gain is reduced. The effect is small if $\sigma_\gamma / \gamma \leq \rho$.
- Emittance effect: betatron motion in the wiggler introduces also a velocity spread. The effect can be neglected if $\varepsilon_n < \lambda_0 \gamma / 4\pi$.
- Diffraction of the photon beam decreases the coupling with the electron beam. The reduction is small if $D = L_R / L_G \geq 1$, where $L_R = 4\pi \varepsilon_n \beta / \gamma \lambda_0$ is the Rayleigh length and β the average betatron amplitude.

From equation (1) and (2), it can be shown that a higher electron beam energy allows shorter wavelengths to be reached, but in general at the expense of a reduced efficiency and gain. The scaling is complicated, since:

- Increasing the energy reduces the real emittance leading to a smaller beam size, higher current density J and hence a somewhat higher gain.
- In general a wiggler behaves as a weak constant focusing channel. In order to increase the current density J, and hence the gain, additional focusing can be introduced. A FODO lattice can be superimposed to the wiggler field. While this enhances the 1-D gain, diffraction losses and emittance velocity spread increases. A trade-off defines the optimum β.

In Fig. 1 the 1-D values of L_G are plotted as a function of the beam energy for different wavelengths. The wiggler parameters have been chosen in order to minimize L_G for each value of the energy and β has been scaled to keep the diffraction parameter D roughly constant for all cases ($3.1 < D < 3.8$). The 3-D effects are not included in the calculations, but an evaluation of the reduction factor coming from energy spread and emittance gives values between 0.5 and 0.8 for all cases.

The evaluation of diffraction losses is better done through numerical simulations. This reduction should be of the order of 25 % (simulations made for TTF [2,7]).

From Fig. 1 one can conclude that a FEL in the water window region is optimized for a beam energy of about 1.5 GeV. Increasing the beam energy above this value would somewhat increase the emitted power ($\propto \rho\, P_{beam}$) but at the expenses of a much longer wiggler. The main concern here is not cost, but the realization of such a long wiggler (including more stringent tolerances).

As an example, possible parameters for a FEL at 2.3 nm and 4.4 nm have been calculated using the modified 1-D model (including energy spread and emittance). As before, the β function has not been optimized, but rather chosen to obtain roughly the same value for D in all cases. Diffraction effects have been taken into account by linearly scaling the gain length, saturation length and output power taking as a reference the results of the TTF FEL simulations [7].

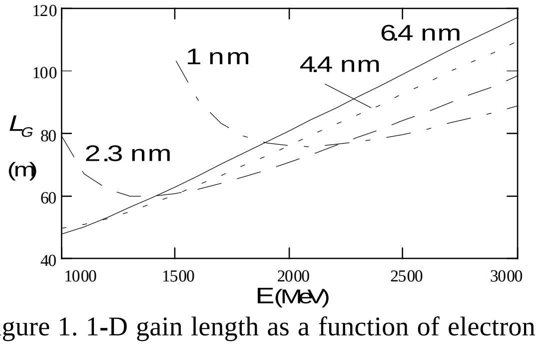

Figure 1. 1-D gain length as a function of electron beam energy for optimized wiggler parameters and different laser wavelengths.

Table 1 - The TTF - FEL parameters compared with two possible sets of parameter for a LEP cavities FEL in the water window.

Variable		**Units**	**TTF**	**CERN** FEL 4.4	**CERN** FEL 2.3
Beam energy	E	GeV	1	**1.5**	**1.5**
Wavelength	λ_o	nm	6.4	**4.4**	**2.3**
Wiggler period	λ_w	mm	27	**30**	**26**
Wiggler field	B_w	Gauss	4970	**5980**	**4400**
Average beta	$\langle\beta\rangle$	m	3	**4**	**2.2**
Beam size (rms)	r_b	mm	0.055	**0.053**	**0.039**
Emittance (rms)	ε_n	π m rad	$2\ 10^{-6}$	$2\ 10^{-6}$	$2\ 10^{-6}$
Peak current	I	A	2490	2490	2490
Energy spread	σ_γ/γ	10^{-3}	1	1	1
Bunch length	σ_z	µm	50	50	50
Gain length	L_G	m	1	**1.3**	**1**
Saturation length	L_S	m	< 25	**< 30**	**< 25**
Saturated power	P_{sat}	GW	4	**~ 5**	**~ 5**
Energy per pulse	E_{sat}	mJ	1.7	**~ 2**	**~ 2**

The results are summarized in Table 1, where they are compared to the nominal parameters of the TTF proposal. It must be remembered a full numerical simulation study would be needed for a real optimization. As a validity check, a 3-D simulation using the NUTMEG code [8] has been carried out with the parameters of the CERNFEL 4.4 option. The results of this simulation in (Fig. 2) are in reasonable agreement with the predictions.

As discussed in section 1, there is some interest in reaching the 1 nm region. It seems possible to do so by increasing the electron beam energy to 2 - 2.5 GeV (see Fig. 1). The wiggler would be longer, and, since the sensitivity to field errors ($\propto 1/\rho$) is increased, that could be a problem. Therefore, it would be better to improve the beam characteristics, (increasing the beam current or decreasing the transverse emittance). As an alternative, or if some interest would arise to go even further in wavelength (in the 0.15 nm region, for example), one could use a resonant harmonic generation scheme [9]. In this case, anyway, the output power would be smaller.

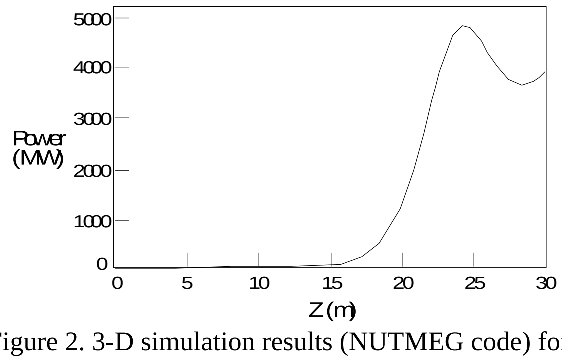

Figure 2. 3-D simulation results (NUTMEG code) for the CERN FEL 4.4 parameter set. The radiation power is plotted as a function of the wiggler length.

3 TECHNICAL CONSIDERATIONS

The main components of the SASE FEL are: 1) A RF photo-injector. 2) Magnetic chicanes to compress the bunches. 3) An electron linac. 4) A long wiggler.

The basic difference between the TTF and CERN layouts is the electron linac. Both linacs are superconductive, but in our case the frequency is lower (352 MHz instead of 1.3 GHz) and the field gradient is lower as well (6 MV/m against 15 MV/m). The maximum beam energy, anyway, could be in our case considerably higher (2.7 GeV instead of 1 GeV). These differences influence also the the other components.

1) *Linac and beam parameters.* In principle a lower frequency could enable us to maintain a smaller energy spread for a given bunch length. In TTF the energy spread is determined by the correlated spread introduced for the compression (from 2 mm at the gun exit to 50 μm at the end of the linac) and by the growth due to space charge forces, RF field non-linearity and single-bunch longitudinal wakefields. Both the non-linearity and the wakefields are lower in 352 MHz cavities. Space charge forces are only important in the photo-injector. The transverse emittance at the gun exit is 1 π mm mrad, which is at the limit of present technology.

A margin of a factor 2 is given for the emittance growth in the linac. This seems to be quite conservative, since beam dynamics simulations have shown a growth at the percent level, and should provide some margin for the obtainable emittance at the gun exit. Again, the main source is given by transverse wakefields. These will be smaller in our case, but the longer linac length will be likely to cancel this advantage.

2) *Bunch compression.* The bunch compression is done in different stages, thus optimizing the final bunch length and energy spread. A layout adapted to our case would need to be studied. The final energy spread will depend on the exact arrangement of the compression stages and on the injection energy in the linac; for the reasons given before, a value of 0.1 % for the rms energy spread seems to be conservative in our case.

3) *Photo-injector.* In the case of TTF the RF gun (~ 6 MeV) is normal conducting , and is followed by a accelerating section (15 MeV), also normal conducting. Both have the same frequency as the superconducting linac. While this seems to be a natural choice for TTF, in the CERN case a 352 MHz gun is probably not the best solution. A higher harmonic of 352 MHz can be used, the choice being based on the maximization of the bunch charge and the minimization of the emittance.

For 1 nC bunches, an S-band gun may give better performances than an L-band one. The injector should provide an energy high enough to minimize the space charge forces in the first bunch compressor.

4) *Wiggler.* In TTF the chosen technology for the wiggler is the hybrid solution (permanent magnets + iron poles). This seems to be a technically sound choice, since for short wiggler periods it makes it possible to reach higher fields in comparison to electromagnets.

Superconducting wigglers could give a higher field still but, apart from costs, they pose a number of problems, including the superposition of a FODO lattice to the wiggler field. This could be obtained in a hybrid wiggler by tilting the wiggler poles in an alternate fashion. This arrangement introduces a quadrupolar field component added to the sinusoidal wiggler field. Horizontal focusing or defocusing sections of the wiggler can thus be obtained, and they can be alternated with sections with plane pole faces (essentially neutral with respect to focusing), obtaining a FODO-like lattice.

The average β function range given in Table 1 can be easily obtained in our case. For instance in CERNFEL 4.4, β = 4 m can be obtained using F and D sections of 5 periods each, alternated with “neutral” sections of 35 periods. The gradient is ~ 17 T/m (tilt angle $\alpha = 10^o$). The cell length would be 2.4 m, and β_{MAX} = 5.3 m, while β_{MIN} = 2.8 m. The tilt angle and the gradient could still be increased, in order to optimize β for maximum gain or power. If the FEL has to be tunable in a frequency range, one should fix the period and change the wiggler field by increasing the gap, or choose an intermediate value for the couple B_w , λ_w and change the electron beam energy to tune the FEL. These procedures will reduce somewhat the performances, and a detailed study is needed for the optimization.

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