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# CONSIDERATIONS ON A FEL BASED ON LEP SUPERCONDUCTING CAVITIES

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*Abstract*

After the scheduled shut-down of LEP, 2.7 GV of superconducting accelerating cavities at the frequency of 352 MHz will become available for other uses. One of the possibilities would be to build a linear accelerator delivering a beam suitable as a driver for a Free Electron Laser in the VUV and soft X-rays spectral region, where numbers of interesting applications exist. Some preliminary calculations made in this note 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 electron beam and using state-of-the-art technology for the wiggler and the injector. Technological limits and possible extension are also briefly discussed.

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# CONSIDERATIONS ON A FEL BASED ON LEP SUPERCONDUCTING CAVITIES

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## I. Scientific applications of the FEL

The Free Electron Laser realized with the superconducting cavities of LEP can be optimized in a wavelength range between about 2 to 10 nm. In this region exist a number of applications, listed for example in the report of the VUV FEL at the TESLA Test Facility (DESY) [1] and also in the proceedings of workshops for the Linear Coherent Light Source FEL (LCLS) project at Stanford [2,3]. They include single and multi photon excitations of atoms and ions, spectroscopy of clusters and radicals, dynamics of photo chemistry, photo electron spectroscopy in solids, non-linear x-ray scattering, etc. We do not intend to go any further into all these possibilities but concentrate here on the one application for which the CERN FEL is particularly well suited, namely the x-ray microscopy of biological samples in the water window.

The spectral range between the wavelengths between the K-edge of oxygen at 2.3 nm and the one of carbon at 4.4 nm is called water window. 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. This makes it possible to obtain a good contrast of biological samples imbedded in water.

The characteristics of the FEL based on the superconducting LEP cavities can be optimized for frequencies lying in the water window. Furthermore the high intensity short pulses and the high coherence of the emitted radiation makes this device suitable for single shot x-ray imaging of biological samples. The dose necessary to obtain a good resolution is quite high and leads to the destruction of the sample. By using a very short X-ray pulse of only a few ps length 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 in the order of 30 nm can be obtained. It is also possible to obtain three-dimensional images by taking views at different angles. To do this in a single shot a beam splitter is used which could consist of a crystal-like structure in which the orders of the diffracted light are emitted in different directions.

There is also some interest to go to a wavelength region around 1 nm which is just below the water window. Good phase contrast can still be obtained and the K adsorption edges of F, Na and P can be covered.

The source energy necessary for the mentioned resolution of 30 nm lies between 10 and 100 μJ. With the performance listed below, the CERN FEL can deliver an energy of about 2 mJ which is well adapted to this type of application.

## II. FEL parameters

A FEL in the VUV or soft X-ray region of the spectrum can not rely on the existence of high-reflectivity, high-power mirrors or of conventional laser sources. Therefore the FEL oscillator configuration (with mirrors) and the amplifier configuration (with external input source) are ruled out.

The one remaining possibility is the Self Amplified Spontaneous Emission (SASE) regime of a single-pass, high-gain FEL [4]. In such a device, a high current, low emittance electron beam is injected into a long wiggler, and generates by spontaneous emission a photon beam at a wavelength $\lambda_0$ determined by the electron energy and the wiggler period and field. The interaction between the photon and the electron beams in the wiggler leads eventually to the bunching of the electron beam on the scale of the wavelength $\lambda_0$, and to an exponential amplification of the photon beam intensity up to a saturation value orders of magnitudes above the spontaneous emission level.

Both of the projects cited above (TTF FEL - DESY [1] and LCLS - SLAC [2,3] are based on this concept. In order to evaluate the possible parameters of a LEP cavities driven FEL, 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 $\lambda_w$ is the wiggler period, $\gamma$ is the electron beam energy (in $mc^2$ units) and $a_w$ is the so called wiggler parameter, defined as: $a_w = e/mc^2 \, B_w\lambda_w/(2^{3/2}\pi)$, where $B_w$ is the wiggler magnetic field strength. In first approximation, the gain per unit lenght, saturation length and emitted power at saturation can be easily calculated using a 1-D FEL model [5]. The gain of the FEL is described by the fundamental 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 in fact 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 $L_G = \lambda_w / 4\pi\sqrt{3}\,\rho$.

The ρ parameter gives also power extraction efficiency from the electron to the photon beam at saturation ($P_{ph} \sim \rho P_{beam}$). The possible effects having a negative influence on the performance which are not included in the above equations are:

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

Considering eqs. 1-2 it can be shown that a higher electron beam energy allows to reach shorter wavelengths, but in general at the expense of a reduced efficiency and gain. The effective scaling is complicated since:

- Increasing the energy, the reduced real emittance by adiabatic damping decreases the beam size, increasing the current density $J$.
- A planar wiggler has natural focusing in the vertical plane only. By proper shaping of the pole faces, focusing can be introduced also in the horizontal plane. In such a case the 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, for instance by tilting the wiggler poles. A FODO lattice can be thus superimposed to the wiggler field. While this enhances the 1-D gain, diffraction losses and emittance velocity spread increases. A tradeoff between these effects defines the optimum β.

Some of the 3-D effects can be included in the model (namely, energy spread and emittance velocity spread), while the exact assessment of the influence of diffraction losses is better done through numerical simulations. The relevant parameter in this case is $D = L_R / L_G$.

In Fig. 1 and 2 are plotted the 1-D values of ρ and $L_G$ as a function of the beam energy for the TTF nominal radiation wavelength, the upper and lower wavelengths of the water window, and the 1 nm case.

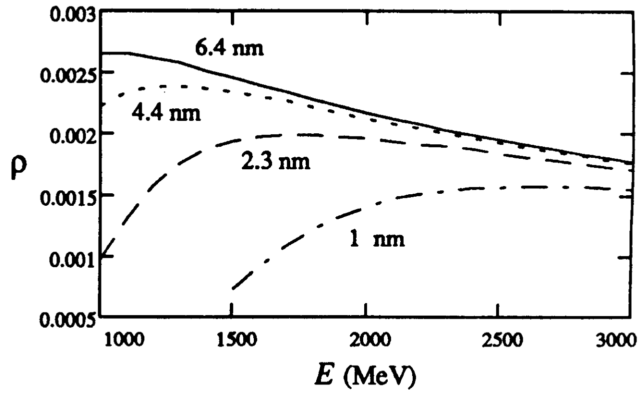


*Figure 1.The fundamental FEL parameter ρ as a function of electron beam energy for optimized wiggler parameters and different laser wavelengths.*

The wiggler parameters have been chosen in order to minimize $L_G$ for each value of the energy (maximum $B_w$ and minimum $\lambda_w$), and β has been scaled in such a way as to keep the diffraction parameter $D$ roughly constant for all cases ($3.1 < D < 3.8$).

The 3-D effects described above are not included in the calculations, but an evaluation of the reduction factor coming from points 1 and 2 is plotted in Fig. 3. Since $D$ is almost constant in all cases, the diffraction losses should give roughly the same fractional reduction for $L_G$. This reduction should be of the order of 25 % (simulations made for TTF [1,6]).

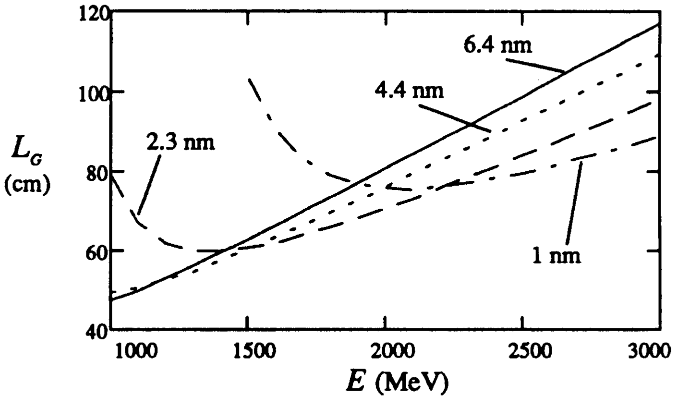


*Figure 2. 1-D gain length as a function of electron beam energy for optimized wiggler parameters and different laser wavelengths.*

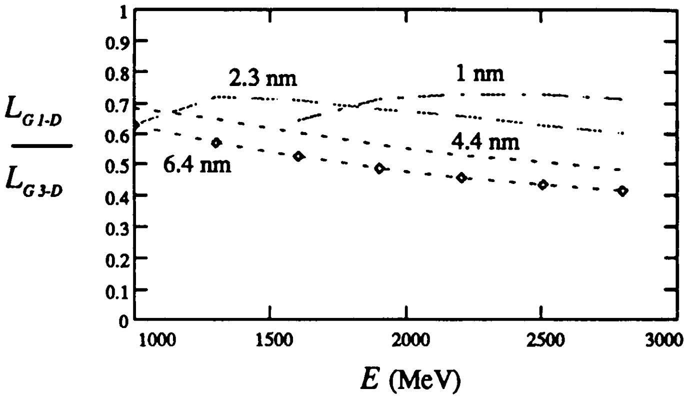


*Figure 3. 3-D Gain reduction factor (only energy and emittance velocity spread included) as a function of electron beam energy for optimized wiggler parameters and different laser wavelengths.*

From figures 1, 2 and 3 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 problems in the realization of such a long wiggler (including more stringent tolerances). As an example, possible parameter sets for a FEL at 2.3 nm and 4.4 nm have been calculated using the modified 1-D model. As before, the $\beta$ function has not been optimized, but rather chosen in such a way as 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 [6].

The results are summarized in Table I, where they are compared to the nominal parameters of the TTF proposal. The values of the saturation length given in parenthesis should be considered as merely indicative. It must be remmembered that such parameters are not optimized. To do so a full numerical simulation study would be needed. As a check of the validity of these evaluation, a 3-D simulation using the NUTMEG code [7] has been carried out with the parameters given in Table I for the CERNFEL 4.4 option. The results of this simulation, given in Fig. 4, are in reasonable agreement with the predictions.

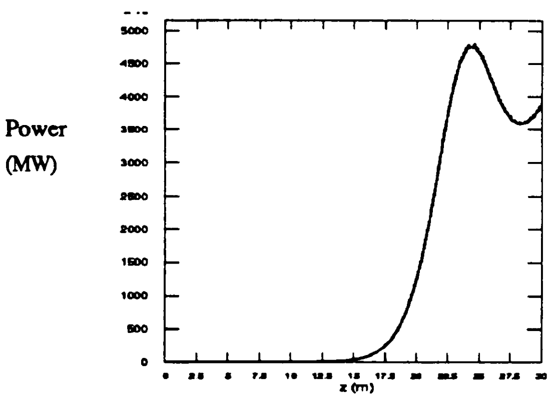


*Figure 3. 3-D simulation results using the NUTMEG code, for the CERN FEL 4.4 parameter set. The radiation power is plotted as a function of the wiggler length. Saturation occurs slightly before 25 m of wiggler. The power at saturation is slightly less than the expected 5 GW.*

TABLE I

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

| Variable | | Units | TTF | CERNFEL 4.4 | CERNFEL 2.3 |
|---|---|---|---|---|---|
| Beam energy | $E$ | GeV | 1 | **1.5** | **1.5** |
| Wavelength | $\lambda_o$ | nm | 6.4 | **4.4** | **2.3** |
| Wiggler period | $\lambda_w$ | mm | 27 | **30** | **26** |
| Wiggler gap | $g$ | mm | 12 | 12 | 12 |
| Wiggler field | $B_w$ | Gauss | 4970 | **5980** | **4400** |
| Average Twiss function | $<\beta>$ | m | 3 | **4** | **2.2** |
| Beam size (rms) | $r_b$ | mm | 0.055 | **0.053** | **0.039** |
| Norm. emittance (rms) | $\varepsilon_n$ | $\pi$ mm mrad | 2 | 2 | 2 |
| Peak electron current | $I$ | A | 2490 | 2490 | 2490 |
| Energy spread | $\sigma_\gamma/\gamma$ | $10^{-3}$ | 1 | 1 | 1 |
| Bunch length | $\sigma_z$ | µm | 50 | 50 | 50 |
| Gain length | $L_G$ | m | 1 | **1.3** | **1** |
| Saturation length | $L_S$ | m | < 25 (18.4) | **< 30 (23.3)** | **< 25 (16.2)** |
| Saturated power | $P_{sat}$ | GW | 4 | **~ 5** | **~ 5** |
| Energy per pulse | $E_{sat}$ | mJ | | | |

As discussed in section I, there is some interest in reaching a wavelength of about 1 nm. By considering the figures 1,2 and 3, it seems possible to do so, by increasing the electron beam energy to 2 - 2.5 GeV. The wiggler in this case would be longer, and, since the sensitivity to field errors (scaling as $1/\rho$) is increased in such a case, that could be a problem. Therefore, it would be advisable to improve, if possible, the beam characteristics, increasing the beam current or decreasing the transverse emittance. In alternative, or if some interest would arise to go even further in wavelength (in the 0.15 nm region, for example), one possibility would be to use a resonant harmonic generation scheme [8], in which a first wiggler, resonant at a subharmonic, is used to develop bunching at such wavelength, and a second one, tuned at the fundamental, makes it possible to generate power at the desired frequency. In this case, anyway, the output power level would be smaller.

## III. Technical Considerations

The main components of the SASE FEL are :

1. A radio-frequency photoinjector.
2. A number of magnetic chicanes to compress the electron bunches.
3. A electron linear accelerator.
4. A long wiggler.

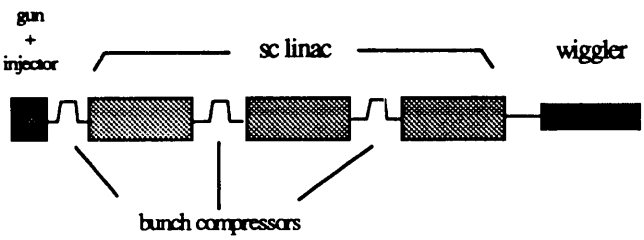


*Figure 4. Schematic layout of a SASE FEL.*

The basic difference between the TTF and CERN layouts is the electron linac.

In both cases the linac is based on superconducting technology, but in our case the frequency is lower (352 MHz instead of 1.3 GHz) and the accelerating gradient is lower as well (6 MV/m against the TTF design value of 15 MV/m). The final beam energy, anyway, could be in our case considerably higher (maximum 2.7 GeV instead of 1 GeV). These differences determine also the possible differences in the other components.

*a) Linac and beam parameters.* In principle a lower frequency could enable us to mantain a lower longitudinal emittance, i.e., 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 important at low energy, where the acceleration can be made in normal conducting cavities where very high fields can be obtained. The transverse emittance at the gun exit is in TTF equal to 1 $\pi$ 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 likely cancel this advantage.

The lower frequency could determine also a different time structure of the beam. The pulse length and the repetition rate will be in the end limited by beam loading either in the injector or in the linac. It must be noted tha the FEL parameters are single bunch quantities, and will not be affected by the pulse time structure and repetition rate, but the average radiation power will be.

*b) Bunch compression.* The bunch compression is obtained by introducing a correlated energy spread from head to tail of the bunches by a proper phasing of the rf cavities. The bunch are then compressed in a magnetic chicanes. This can be 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 exact value of the final energy spread will depend on the exact arrangement of the compression stages and on the injection energy in the sc linac; for the reasons given before, a value of 0.1 % for the rms energy spread seems to be conservative in our case.

*c) Photo-injector.* In the case of TTF the photocathode gun (~ 6 MeV) is normal conducting , and is followed by a accelerating section (15 MeV), also normal conducting Both have the same frequency of the sc linac. While thi seems to be a natural choice for TTF, in the CERN case a 352 MHz gun is probably not the best solution, since the transverse emittance is mainly limited by space charge in the gun, and an accelerating field as high as possible is needed. 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 a charge of 1 nC 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.

*d) Wiggler.* In TTF the chosen technology for the wiggler is the hybrid solution (permanent magnet material + iron poles). This seems to be a technically sound choice, since for short wiggler periods like the ones needed in the VUV and soft X-ray region, itmakes 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 $\beta$ function range of values given in Table I (2 to 4 m for a 1.5 GeV beam) can be easily obtained in our case. For instance in the CERNFEL 4.4 example, $\beta = 4$ m can be obtained using F and D sections constituted of 5 periods each, alternated with "neutral" sections of 35 periods. The gradient is ~ 17 T/m, obtained with a tilt angle of $\alpha = 10^{\circ}$. In such case the cell length would be 2.4 m, and $\beta_{max} = 5.3$ m, while $\beta_{min} = 2.8$ m. The tilt angle and the gradient could still be increased, in order to optimize $\beta$ for maximum gain or saturated power.

The optimization method followed in this paper for the wiggler field and period is the same as the one followed in the TTF design, i.e., for a given beam energy and radiation wavelength, we choose between the possible values of $B_w$ , $\lambda_w$ by taking the couple with the highest possible $B_w$ for a given gap. The minimum gap is determined by resistive wall effects. This procedure minimizes the 1-D gain length.

In Table I we have therefore presented different values for 4.4 nm and 2.3 nm. If the FEL has to be tunable in this frequency range, one should fix the period and change the wiggler field in operation by increasing the gap, or choose an intermediate value for the couple $B_w$ , $\lambda_w$ 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.

## IV. Conclusions

A FEL based on LEP superconducting cavities could allow to reach the spectrum region of the "water window", where X-ray microscopy of biological samples is of particular interest. In this wavelength range the FEL parameters can be optimized for an electron beam energy of ~ 1.5 GeV and state-of-the-art beam characteristics (current, emittance and energy spread).

A further extension in energy would allow us to reach even shorter wavelength, but in such a case an improvement of beam characteristics is probably necessary.

The optimization of the FEL parameters and the exact determination of the radiation power output would need a more detailed study of the FEL components, namely for the acceleration and compression of the electron bunch, beside some numerical simulations of the FEL process.

## V. Acknowledgement

We would like to thank H. Winick of SLAC for his help and many suggestions.

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