A PROPOSAL FOR INCREASING THE ENERGY OF THE FERMI@ELETTRA LINAC

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Abstract

FERMI@Elettra is a soft X-ray, fourth generation light source facility in the last phase of its construction stage at the Elettra Laboratory in Trieste, Italy [1].

It will be based on a seeded FEL, driven by the existing normal conducting linac that is presently expected to operate at 1.5 GeV. Two different FEL lines will produce very short coherent photon pulses (25-200 fs) in the UV and soft X-ray region (100-4 nm). FEL1 will cover 100-20 nm, FEL2 20-4 nm [2].

Here a possibility to extend the FERMI spectral range capability down to the water window (1.0-2.0 nm) is presented. The suggested upgrading foresees the increase of the linac energy up to 2.4-2.5 GeV, leaving untouched the existing undulator chains and the overall length of the accelerator.

INTRODUCTION

A detailed description of the FERMI linac can be found in [3]. Recent revisions of the machine capability have fixed its operating energy at 1.5 GeV. This has allowed the extension of the FEL2 spectral range from the original design of 10 nm down to the 4 nm (300 eV) in the present setup [4]. With the current undulator chains and machine parameters, the FEL1 operation would be quite relaxed, with the possibility to go down to 10 nm, beyond the 20 nm requested, with a 1.2 GeV beam and a deflection parameter K=1. For FEL2, the present parameters (4 nm @1.5 GeV, K=1) are quite stringent, with a fast drop of the photon production below 4 nm. Table 1 summarizes the main linac and undulator parameters.

Table 1: Main Electron Beam and Radiator Parameters

e-beam parameter	***Short bunch***	***Long bunch***
Energy (GeV)	1.5	
Charge (nC)	0.3	0.8
Peak current (A)	2000	900
Bunch length (fs-full width)	200	700
Slice norm. emitt. (μmrad)	≤ 1.0	
Undulator parameters	***FEL1***	***FEL2***
Period length (mm)	55	35
Minimum gap (mm)	10	
K param. @20 nm, 1.2 GeV	1.7	
K param. @10 nm, 1.2 GeV	1.0	
K param. @4 nm, 1.5 GeV		1.0

The lower limit of 4 nm is fixed by the e-beam energy and the particular period chosen for the final radiators of the FEL2 line, 35 mm. However by only operating with the third harmonic emission, at a power level well below that of the fundamental one (~0.1-0.5%), it would be possible to reach shorter wavelengths up to the water window. For this reason, also stimulated by the high interest expressed from the users community to extend the operation in the wavelength region of 300-1000 eV, the possibility of increasing the present linac energy up to 2.4-2.5 GeV has been considered. Indeed, with 2.4 GeV, and a deflection parameter K=1.0 for the FEL2 radiators, it would be possible to go down to 1.6 nm in fundamental.

The proposed solution for boosting the e-beam energy to the above mentioned levels, is to add a very compact X-band linac segment (~1 GeV @12 GHz) in the high energy region of the present machine, after dismounting the last three existing structures and redeploying the S-band power released from this modification for the remaining plants. The peculiarity of the proposal is that the new layout will leave unchanged the total length of the linac and the space requirements in the machine tunnel. Furthermore, using a progressive approach, it could be easily implemented in the existing context, thus minimizing the cost and impact on the main accelerator. The main reason for using X-band technology is the possibility of increasing the energy gain per meter, with less RF energy per pulse, compared to the S-band systems now used. The growth of interest in this technology, enabling a very compact 4th generation photon sources, is currently recognized worldwide. The huge amount of work carried out in the last 15 years, in the framework of the linear collider project at SLAC [5], has contributed to the development of many X-band components, such as power sources, accelerating structures, waveguide systems, etc. Even though these components, at present, represent the know how of a few labs (SLAC, KEK), and are not readily available on the market, certainly an increase in their demand will draw the attention of industry, subsequently increasing the availability and lowering the cost.

Several X-band structures have already shown reliable operation at gradients up to 65-70 MV/m, with extremely low RF breakdown rates (< 0.1fault per hour) [6]. Moreover, recent proposals foresee their use not only at high gradients, for very compact linacs, but also at low gradients, to have very high repetition rate machines (up to hundreds of kHz) [7].

For FERMI, considering the beam characteristic and the space available for modifications, two types of X-band structures, developed and tested in early 2000's for the SLAC collider, have been considered: the T53, with a length of 53 cm, $2/3\pi$ phase advance, 7 mm average iris diameter and the H60, with a length of 60 cm, $5/6\pi$ phase advance and 9 mm average iris diameter. Even though the first has a better RF-to-beam efficiency, the second is more attractive for its larger iris aperture, particularly important in containing the negative effects of the short range wake fields on the beam optical quality.

PRESENT LINAC LAYOUT AND SUGGESTED UPGRADE

The linac layout is shown in Fig. 1: in a) the present configuration and in b) the suggested energy upgrade.

The low energy part of the machine is a quite standard segment, including a 5 MeV high brightness photo-cathode gun, two 3.2 m long structures, S0A-S0B, powered from the same klystron (TH2132A with 45 MW peak power) and seven 4.6 m long, constant gradient sections, C1-C7, paired two per klystron. The first two sections bring the beam energy up to 100 MeV and C1-C7 further increase the beam energy up to 520-530 MeV. C8 is a 3.2 m long supplementary structure, included in the layout, but not yet installed on the machine. It will share with C7 the K6 RF source, contributing a 50 MeV energy gain. A short X-band accelerating structure is installed between C2 and C3 for linearizing the beam phase space before the compression. It will be operated in decelerating mode with a negative energy gain of -20 MeV. The internal geometry of the above mentioned structures is of SLAC-type, with irises diameters ranging from 18 to 25 mm. They are operated at moderate gradients, ~15 MV/m, not limited by RF breakdown, but by the available RF power.

The high energy segment of the linac is based on seven high gradient S-band structures (S1-S7), 6.2 m long, $3/4\pi$ nose-cone Backward Travelling Wave (BTW). Each one is equipped with a double-cavity Sled system and a dedicated 45 MW klystron plant. These structures have already been operated at gradients up to 24-25 MV/m, corresponding to 140-150 MeV energy gain/section, with acceptable reliability. The main drawback is their relatively small iris aperture, 10 mm in diameter, that increases the wakefield strengths, which negatively effects the energy spread and projected beam emittance. For this reason they have been arranged in the high energy region of the machine, mainly after the second bunch compressor, paying particular care to the beam steering and centering. C9 is like C8 and not installed yet.

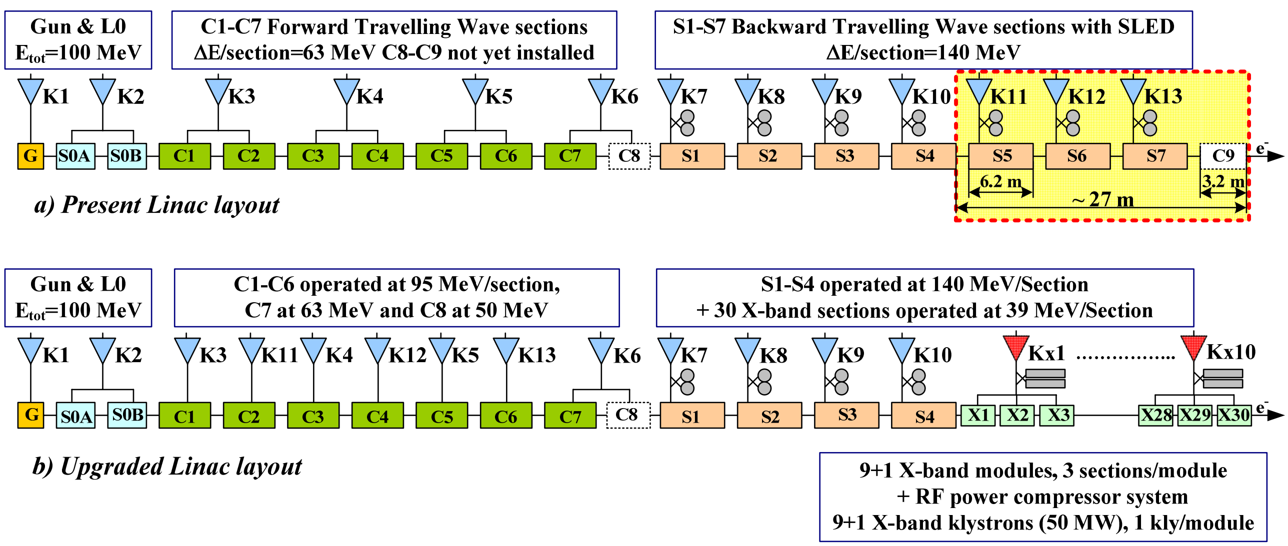

Figure 1: Present (a) and upgraded (b) linac layouts.

To increase the beam energy, while leaving unchanged the overall dimension of the accelerator, we propose to dismantle the last three BTW sections and to replace them with a very compact X-band linac. Considering the overall length of the S structures and the relative intra-sections, the total space left available is roughly 23 m, that goes up to 27 m, if we also consider the space already foreseen for C9, that, with this upgrade, is made unnecessary. The new high gradient linac segment will be composed of 9+1 X-band modules, each one with three H60 structures, 60 cm/structure, powered by one XL5 klystron (50 MW, 1.5 µsec), through a pulse compression system. The overall length of a module will be 2 m and three of them will fit in the current space of one S-section. 20 m in total are requested for installing all the modules, leaving available the remaining 7 m for the optics, diagnostics and vacuum components. To maximize the energy gain per meter, we plan to operate the H60 structures at an unloaded gradient of 65 MV/m, a value that has already been demonstrated feasible and reliable for this kind of structure. With negligible beam loading and a flat RF pulse of ~60 MW/structure, this gradient allows about 39 MeV energy gain/section [8] resulting in 117 MeV for each X-band module. Considering the filling time of a structure (100 ns) and 20 % total losses in the waveguide circuit, with 50 MW-1.5 µsec RF pulse from the klystron, we need a power compression factor of roughly 4.3, a value at present achievable with several different systems, Barrel Open Cavity (BOC), Beating Modes Cavity (BMC) [9], or a dual-moded Sled II.

Considering that each "old S-structure" is replaced by three new X-band modules, the net energy gain reached is over 200 MeV per structure. Moreover, the three S-band klystrons dismounted from the previous locations, K11, K12 and K13, can be redeployed on C2, C4 and C6 respectively (see Fig. 1). Allowing each C section to operate with its own RF power source, greatly increases its energy gain, from the present 63 MeV/section (measured) up to 95 MeV/section, while still maintaining the operating gradients at reasonable levels (~ 20 MV/m). The RF power required at the section input in this case is 37 MW [10]. Table 2 summarizes the expected linac energy, operating on crest, in the present situation and with the proposed energy upgrading.

Table 2: Linac Energy Budgets

	Energy gain on crest (MeV)	
Type of struct.	*At present*	*With energy upgr.*
L0	100	100
X-band lin.	-20	-20
C1-C6	378 (63 x 6)	570 (95 x 6)
C7	63	63
C8	50	50
S1-S4	560 (140 x 4)	560 (144 x 4)
S5-S7	420 (140 x 3)	-
C9	50	-
X1-X30	-	1170 (39 x 30)
Total	***1.601***	***2.493***

STRUCTURE SELECTION AND SHORT-RANGE WAKEFIELD

The selection of the best design for the X-band structure is quite difficult, because it has to match several requirements, frequently conflicting with each other. The choice of operating gradient, is generally based on cost optimization, space available, etc. To minimize the space and the number of RF sources needed, it is necessary to choose structures with small iris apertures, which improve the RF-to-beam efficiency. However, this increases the strength of the short-range wakefields, that impose severe limits on the minimum iris apertures to preserve the small beam emittance requested.

As an example, in terms of costs for our energy range, we have estimated that ±1 mm change of the iris radius represents a 10-15 % change in the total RF budget.

Among the possible solution now available, the H60 represent a starting point, still to be improved, with an acceptable balance between pros and cons. A comparative analysis, between the X and S band structures, of single bunch induced energy spread and emittance growth has been performed. The data have been evaluated both for the long bunch and short bunch operating modes and the results are reported in Table 3. The values are quite similar in terms of energy losses, but the X-band structure shows a better performance in emittance growth. Preliminary beam dynamics simulations performed with LiTrack [11] are also shown in Fig. 2.

CONCLUSION

A proposal for increasing the linac energy of the FERMI@Elettra FEL, using the X-band technology, has been discussed. This will extend the spectral range of the facility up to the water window, with great advantages for the user community. Preliminary evaluations in terms of beam dynamics and wakefield effects are promising, but they have to be confirmed with more extensive studies. Also the structure design has to be carefully checked, optimizing its performance and project costs.

Table 3: Energy Loss and Emittance Growth Per Cavity

	Short bunch		*Long bunch*	
Total energy loss	X_{band}	S_{band}	X_{band}	S_{band}
@ 0.6 GeV	0.4E-4	2.2E-4	1.3E-4	9.1E-4
@ 1.0 GeV	0.2E-4	1.3E-4	0.8E-4	5.5E-4
@ 1.4 GeV	0.2E-4	0.9E-4	0.6E-4	3.9E-4
Rel. emitt. growth	X_{band}	S_{band}	X_{band}	S_{band}
@ 0.6 GeV	<1E-6	2.7E-4	0.7E-5	3.8E-3
@ 1.0 GeV	<1E-6	1.6E-4	0.4E-5	2.3E-3
@ 1.4 GeV	<1E-6	1.2E-4	0.3E-5	1.6E-3

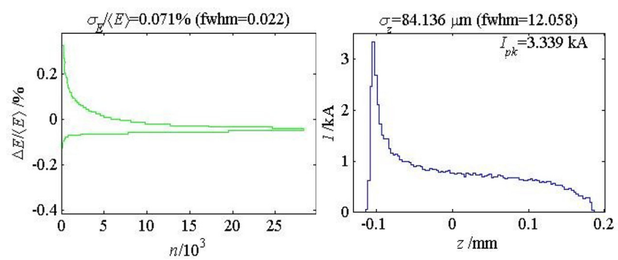

Figure 2: Energy and current distribution in the bunch at the linac exit (E=2.4 GeV).

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