DESIGN OF A 10-MeV PHOTOINJECTOR ACCELERATOR FOR ELFA*

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Abstract

This paper presents the design of an RF photoinjector that will provide the electron beam for the FEL project in Milan (ELFA). The goal of this project is to test the new regimes of superradiance with high gain. This FEL requires a pulsed beam with 80 nC per pulse; each pulse will be 200 ps long with a peak current of 400 A. The rms energy spread must be approximately 1% and the normalized transverse emittance less than 100 π $cm - mrad$. We have chosen the operating frequency to be 352 MHz so that the Lep2 superconducting accelerator structure can be used to accelerate the beam from the photoinjector to 10 MeV. This paper presents The main characteristics of this accelerator and the beam simulations obtained with PARMELA.

Introduction

The accelerator has been designed to generate, accelerate and transport a high-charge beam (80 nC), with pulses 200 ps long. The first part of this paper will briefly describe the different elements of the accelerator. The new technology of the photoinjector has been applied to this design to extract the 80 nC beam and a superconducting accelerator is used to accelerate the electrons up to 10 MeV. The second part of the paper will be dedicated to the most important aspects of the beam dynamics and to the solutions found for optimizing the emittance and the energy spread of the beam. Recent theoretical calculations have proved that the combined action of space charge forces and of focussing forces can reduce the transverse emittance [ref 1].

Numerical simulations show that with proper focussing the emittance increases in the first cell of the photoinjector and decreases in the drift region.

The Accelerator Design

As it has already been stated in the abstract, the FEL theory for this experiment requires a pulsed beam of 4 micropulses, each with 80 nC of charge which are 200 ps long and 2.8 ns apart [ref 2]. Generating and transporting this high-charge beam imposes strict conditions on the choice of the source and requires particular care in the design of the first accelerating section. Each bunch is generated by photoemission with a laser shot that determines the length and the charge of each electron pulse and the separation between pulses. With this type of source the beam is emitted directly inside the first cavity of the injector. Therefore, the design of the first cavity is very important for the dynamics of the particles. The final scheme consists of two accelerating sections having a resonant frequency of 352 MHz, that provide an energy gain of 3 MeV and 7 MeV respectively. Two drifts, the first between the accelerators and the second between the last accelerator and the wiggler, allow the installation of the diagnostic instruments, the injection of the photocathode laser beam, and the 3 mm radiation into the wiggler. Enough space remains for the cryostat. A focussing system on the injector reduces the effects of the space charge force and four quadrupoles, in the last drift, match the beam into the wiggler (fig 1).

The design of the injector and all the cavities parameters are chosen to minimize the emittance growth caused by the space charge and by the non linear

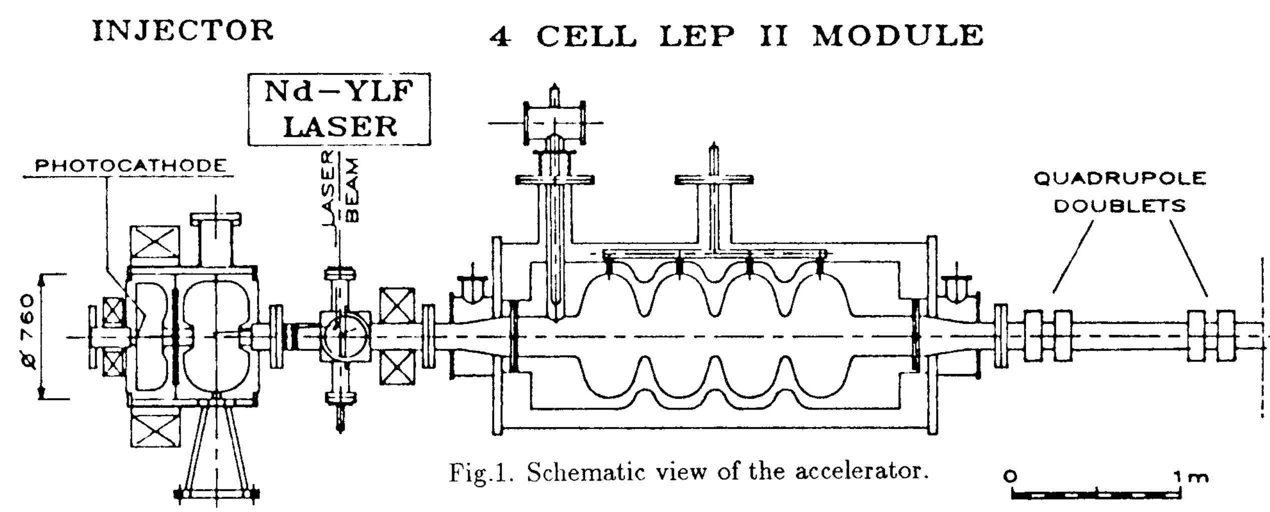

Fig.1. Schematic view of the accelerator.

*Work supported and funded by INFN, Italian Institute of Nuclear Physics, through a collaboration with Los Alamos National Laboratory under the auspicies of the US Department of Energy.

radial components of the rf accelerating field. The space charge forces are particulary strong when the particles are moving slowly. The injector consists of one short accelerating cell, one coupling cell ,and one full accelerating cell. We have compared two different shapes for the first cell. One has a flat wall which allows the highest accelerating gradient but no focussing forces. The other with a shaped wall provides rf focussing at the expense of the longitudinal component of the accelerating field. Beam dynamics simulations show that with the flat wall the values of energy spread and emittance are lower; we have made the final choice for this simpler shape. The coupling cell resonantly couples rf power from one accelerating cell to the other. With this configuration operating in $\pi/2$ mode, the relative amplitude of the rf fields in the two accelerating cells is fixed by the coupling constants between the coupling and the accelerating cells. A klystron having 1.6 MW of power can easily sustain a spatial average field gradient of 9.4 MV/m in the first cell and 5.6 MV/m in the second cell. Because the effects of the space charge forces are proportional to $1/\gamma^2$, it is advantageous to accelerate the beam to a high energy quickly; therefore, a higher accelerating gradient has been selected for the first cell of the photoinjector. A necessary aperture at the end of the first cavity forces the electric field lines to bend outward toward the nose, inducing a radial defocussing component of the rf field. The pattern of the field near the aperture is determined by the nose shape ,and the emittance is minimized when the forces are linear. A particular shape of the nose has been studied in which the radial component of the electromagnetic field satisfies this condition [ref 3]. Both the radial electric field and the space charge forces cause the beam to expand radially in the injector; therefore, a fundamental part in the design of the accelerator has been the focussing system. Two solenoidal focussing magnets placed over the first accelerating cell control the beam expansion and reduce the emittance growth. A third solenoid placed behind the cathode nulls the magnetic field on the photosensitive surface. These solenoids are adjusted to make the beam slightly convergent as it exits the injector. Another solenoid approximately halfway between the injector and the superconducting accelerator matches the beam into the superconducting cavities. The second accelerating section consists of 4 full niobium superconducting cavities of the Lep2 type resonating at the same frequency of 352 MHz [ref 4]. The structure is kept at 4.5 K°, at this temperature the power losses are almost negligible (40 W), so it is possible to achieve an accelerating gradient of 5 MV/m with a low power source. The total energy gain is 7 MeV.

A second drift of almost 3 m is necessary between the superconducting accelerator and the wiggler to place both the diagnostic instruments and the focussing system required to match the beam into the wiggler. Two quadrupoles doublets have been studied to provide a good match so that the beam parameters are conserved inside the wiggler.

The Beam Dynamics

In this section we will discuss the most important aspects of the beam dynamics. The results presented are for a single bunch and they have been obtained using the program PARMELA. In the simulations the charge distribution in the longitudinal direction is uniform, neglecting the raising time of 20 ps. However, two possible distributions of charge have been considered in the radial direction; the uniform and the gaussian distribution.

The transverse dimensions are determined by the laser spot and the cathode. The simulations showed that a cathode radius of 1.5 cm was optimum for both the gaussian and the uniform distribution. For the gaussian distribution, a σ_r of 1.2 cm was used. The total charge in the bunch is 80 nC, which means that a peak current of 400 A/cm^2 has to be extracted from the photocathode. With a photosensitive surface of 7 cm^2, the current density is lower than 60 A/cm^2 averaged over the photocathode.

The length of the beam at the generation has been selected to be 180 ps or 22° rf which gives a beam of 200 ps or 25° long at the end of the linac. The bunch lengthening occurs mainly in the injector and along the first drift where the space charge forces are strongest; however, more than 90% of the particles remain confined in 25° as required. The growth of the bunch length and of the energy spread have been further minimized by optimizing the injection phase of the beam in the first cell. The possibility of choosing the starting phase, however, is limited to a range of 10° because the length of the first cell and the accelerating gradients are fixed and the electrons have to reach the second accelerating cell in phase so they will not be decelerated. Just as the bunch is leaving the cathode, it forms a flat disk of charge next to a conducting surface (the cathode). The space charge produces an electric field that attracts the tail of the bunch back to the cathode whitout affecting the head of the bunch. The phase of the rf at injection is adjusted to partially cancel this effect by using the rising part of the rf field. The tail of the bunch sees a stronger accelerating field near the cathode than the head of the bunch. We have selected the injection phase at 53° for the reference particle. In the longitudinal phase space, though the beam is fairly long, the energy spread has been minimized by adjusting the relative phase of the rf in the different cells. The PARMELA simulations shows an rms energy spread of $\simeq$ 1% at the entrance to the wiggler. Furthermore, bunch lengthening only affects the head and the tail of the pulse so that most of the particles are confined in the required 25°.

The main problems in the first cell are the rf defocussing and the space charge effects, which cause the beam to enlarge in the radial direction. A large increase in beam size and emittance results. To minimize these effects, a higher accelerating gradient and a focussing system is used in the first cell. It has been analytically demonstrated that for a high current beam an appropriate magnetic field can help to remove the spatial correlation induced by the space charge forces [ref 1]. Numerical simulations show a progressive decrease of the transverse emittance along the first drift ,while a minimum is reached just before the entrance to the Lep2 cavities. However, in a previous design, the emittance value was doubled when the particles were accelerated in the four superconducting cells of the Lep2 type [ref 5]. This increase was probably due to the effect of the linear time-dependent rf fields that causes an emittance growth proportional to r^2. The beam was made smaller when the strength of the lens between the photoinjector accelerator and the Lep2 cavities was increased and the lens position was adjusted .

These adjustments reduce the beam size and the emittance at the exit of the Lep2 cavities from 59.2 π *cm mrad* to 38.5 π *cm mrad* when a gaussian distribution is used on the photocathode and from 46.4 π *cm mrad* to 16.7 π *cm mrad* when a uniform distribution is used. Table I reports the values of normalized emittance ϵ_n and energy spread $\Delta\gamma/\gamma$ relative to the different elements for a beam with a uniform distribution of charge.

TABLE I

Uniform beam parameters along the beam line

Element	Position(cm)	ϵ_n(π cm-mrad)	$\Delta\gamma/\gamma$(%)
Ent. Injector	0.	0.	0.
Exit Injector	63.8	65.4	1.36
Drift	128.8	37.5	1.94
Solenoid	138.8	35.7	2.03
Ent. Lep2	158.8	24.3	2.23
Exit Lep2	509.9	17.3	1.04
Drift	529.9	16.7	1.04

These values of emittance and energy spread remain approximately unalterated when the beam goes through the matching section. The computer code TRACE3D calculates the gradients of the quadrupoles magnetic field so that the dimensions of the beam are reduced ($x \simeq 0.5$ *cm* and $y \simeq 0.3$ *cm*) and the beam can enter the wiggler without changing the value of emittance and energy spread. Since the head and the tail of the beam have experienced different space charge forces from the center, some electrons are underfocussed or overfocussed by the quadrupoles doublets. At the end of the matching section a small halo of particles appears. This halo may have some effect on the FEL superradiance regime. A possible solution could be bending the beam line between the Lep2 cavities and the wiggler. The 3 *mm* radiation can then be injected easily into the wiggler for the FEL process. In addition, with the use of slits it is possible to scrape off the high and low energy tails of the electron beam. These tails occur at the head and at the tail of the beam and are responsible for the halo.

To investigate some of the possible variations on the proposed design we have analyzed the option of reducing the beam charge to 60 *nC*. In this case the emittance decreases $\simeq$ 20% and the energy spread goes from 1.05 % to 0.85 %, confirming that the space charge forces play a fundamental role in the evolution of the beam parameters. We have also considered the possibility of much higher gradients for the injector in order to achieve a lower value of emittance. Numerical results show that a quicker acceleration of the electrons reduces the emittance growth, particulary if the beam has a uniform distribution of charge. With high accelerating fields and the uniform distribution, a emittance of 11 π *cm mrad* can be obtained at the end of the accelerator.

The charge distribution seems to be a fundamental parameter in the physics design of this accelerator. In Table II the comparison between the final results obtained with the gaussian and the uniform beam, in the basic case, demonstrates the importance of generating the particles as uniformly as possible to avoid nonlinear space charge effects.

TABLE II

Beam parameters at the Lep2 exit

Beam parameters	Uniform	Gaussian
Bunch length(rf°)	25.9	27.2
Beam radius(cm)	0.9	0.8
Energy gain(MeV)	9.96	9.98
ϵ_n(π cm-mrad)	16.7	38.5
$\Delta\gamma/\gamma$	1.04	1.05

Conclusion

The physics design presented here shows that the theoretical requirements can be satisfied with both a gaussian and a uniform distribution of charge. However, the numerical results confirm the importance of a uniform distribution to get better values both of emittance and energy spread.

References

1. B. E. Carlsten, New Photoelectric Injector Design for the Los Alamos National Laboratory XUV FEL Accelerator , *Nucl. Instr. and Meth.*, A285 313-319 (1989).
2. R. Bonifacio, F. Casagrande, G. Cerchioni, L. De Salvo Souza and P. Pierini, *in Proceedings INFN int. School*, Varenna, June 1988.
3. M. E. Jones, W. K. Peter, *IEEE Trans. Nucl. Sci.*, NS-32, 1794 (1985).
4. P. Bernard et al., *Proceedings EPAC Conf.*, Rome, June 1988.
5. LASA(INFN, Milan), AT-1 (Accelerator and tecnology division, Los Alamos), The Photocathode Injector and the Superconducting Linac for the Elfa Project , *in Proceedings EPAC Conf.*, Nice, June 1990.

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