A HIGH-BRIGHTNESS PHOTO-INJECTOR FOR A FREE ELECTRON LASER PROPOSAL

S. JOLY, R. DEI-CAS, Cl. BONETTI, F. COÇU, J.P. DE BRION, J. FREHAUT, G. HAOUAT, A. HERSCOVICI, H. LEBOUTET and J. SIGAUD

Commissariat à l'Energie Atomique
B.P. N° 12
91680 BRUYERES-LE-CHATEL - FRANCE

Abstract : A photo-injector appears to be the best way to obtain very bright beams. The injector configuration was optimized by means of three different simulation codes. A photo-injector prototype is described, including the photocathode preparation system, the RF gun cavity, the RF amplifier, the laser illuminating the photocathode and the diagnostics to measure the beam characteristics.

Introduction

Free Electron Laser operation imposes severe constraints on the electron beam characteristics as high currents and small emittances must be obtained simultaneously. Consequently, the performance of the injector is of prime importance as the initial emittance is determined at the emission and cannot be reduced any further.

A low-temperature, high-current density cathode is needed to obtain a high brightness. Usual thermionic cathodes have too low current densities so very high bunching ratios are needed to reach high peak current and the emittance grows during this process. Photo-injectors have the advantage of producing partly bunched beams with large current densities ; the subsequent bunching will then be reduced along with the related deleterious bunching effects [1, 2]. The main mechanisms responsible for emittance growth in the photo-injector are space charge effects and RF dynamics. Space charge forces within a bunch can be reduced by increasing its dimensions involving low-frequency RF fields. Another reduction could follow if the electrons are accelerated to relativistic energies immediately after emission to take advantage of relativistic effects, requiring very high fields and thus high frequencies. These fields could be achieved if the photocathode is placed in a RF gun cavity as it can sustain higher surface fields than a DC diode. On the other hand, low-frequency RF fields would also minimize RF dynamics effects. Consequently, the frequency choice would result from simulation calculations of the electron bunch dynamics and from practical reasons.

The maximum charge a laser pulse can extract from a photocathode depends on the electric field at the cathode, on the illuminated cathode area by the incident laser and its intensity ; the cathode-anode distance could also play an important role. We have then to rely on simulation calculations to define the best conditions for the acceleration of electron bunches with the required properties (charge, energy, longitudinal and transverse emittances).

For future FEL photo-injectors, the electron energy should be around 4-5 MeV before magnetic compression occurs. However, just to study the different processes involved in the first tens of centimeters after emission, we restricted ourselves to a single RF gun cavity producing the highest possible accelerating electric fields with a minimum kinetic energy of 1 MeV. The main parameters are related to the incident laser flux (intensity, illuminated area, pulse width and shape), to the electric field (frequency, amplitude and phase relative to the laser pulse, longitudinal and radial dependences) and to the accelerating gap. A second cavity would then add about 3-4 MeV to the electron energy.

Photo-injector description

A schematic diagram of the photo-injector prototype is shown in fig. 1 ; following the cavity, two solenoid lenses help in transporting the electron bunches up to the diagnostics systems where their characteristics are measured.

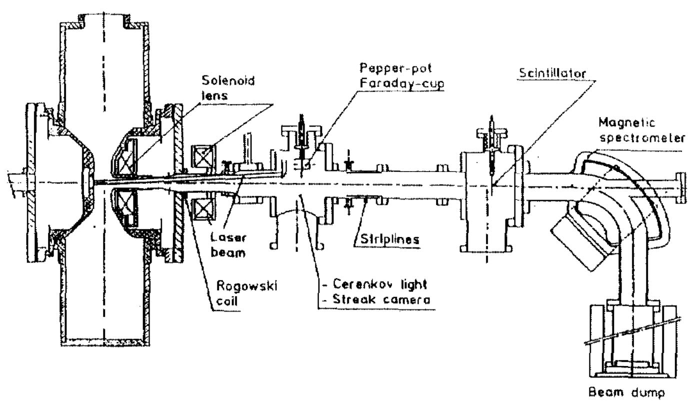

Figure 1 : Photo-injector prototype and electron diagnostics.

To limit the influence of the space charge effects on the bunch properties, the electron energy should be as large as possible immediately after emission, assuming the accelerating electric field is very important but the sparking breakdown would limit this value ; a minimum of 1 MeV is required. On the other hand, the accelerating gap should not be too large if a large charge ($q \gtrsim 10$ nC) is to be extracted. Therefore, the RF gun cavity has been designed to have a gap varying between 7 and 10 cm, by moving the anode nose only.

Two conditions were fulfilled in designing the shape of the cavity noses :
- to have the largest ratio for the electric field on the photocathode relative to the maximum surface field on the cavity wall ; a ratio as large as 0.86 was obtained by means of the SUPERFISH code [3],
- to have a linear dependence for the radial electric field as it would lead to lower emittance growth [4].

In fact, this dependence resulted from the first requirement. The resulting nose shapes are shown in fig. 2. The photocathode holder has a radius of 2 cm ; the largest electric field at the cathode surface is obtained for a cathode plane, out of the cathode holder, perpendicular to the cavity symmetry axis (fig. 2). An angle $\Theta_K < 90°$ would result in a small focusing component, because of the non vanishing radial electric field, at the expense of a smaller longitudinal electric component.

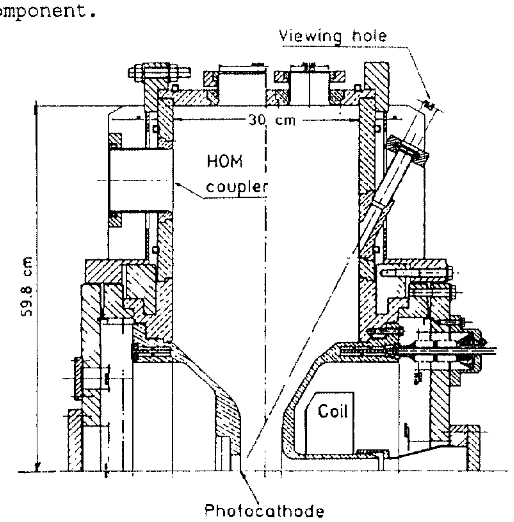

Figure 2 : RF gun cavity at 144 MHz ; the anode shape gives the largest electric field at the photocathode center.

The RF gun cavity has a calculated effective shunt impedance ZT^2 = 26.2 MΩ/m and a quality factor Q = 34 800 ; we expect a peak surface field of at least 15 MV/m. Great efforts are devoted to the nose machining conditions to enhance this value.

The cavity is manufactured in OFHC copper, an external stainless steel structure has been added to sustain atmosphere pressure ; it could also be used to change a little bit the accelerating gap and get the exact resonance frequency. The average power dissipated in the cavity walls would be around 20 kW ; they will be cooled down by water. With the expected flow, the maximum temperature will be around 38°C on the photocathode which is the hottest point for our cooling scheme.

Experiments at Los Alamos [2] showed that current densities as high as 600 A/cm^2 could be obtained using an cesium antimonide photocathode ; this material will be used here too. However, the preparation system as well as the RF gun cavity should sustain a vacuum of the order of 10^{-10} torr. After few hour use, the photocathode should be prepared again so the preparation system should be as automatic as possible. Such a system is under construction.

A cavity mode locker produces a micropulse train at 72.22 MHz and a Pockels cell defines the macropulse length of about 200 µs at a repetition rate of 1 to 20 Hz. The Nd-YAG laser beam passes through a KDP crystal (for frequency doubling) and then is directed on the photocathode.

The choice of the 144 MHz frequency results from the different requirements presented in the introduction ; it should also be a subharmonic of the main linac frequency, chosen to be 433 MHz. In fact, when the cathode-anode gap d is changed, the cavity resonance frequency will vary ; consequently, the RF generator should run between 144 MHz (for d = 7 cm) and 162 MHz (for d = 10 cm). The RF amplification chain is made of four components : a solid state amplifier (50 W) followed by three tetrode amplifiers with peak power of 3 kW, 80 kW and finally, 2.5 MW (TH 526 tube).

The transverse emittance of the bunch will be measured by the pepper-pot method using a copper, or a tantalum, plate for the beamlet holes and viewing screens or profile grids for the beamlet intensities. The beam current will be measured with a Faraday cup or a wall current monitor (Rogowski coil). A streak camera using the Cerenkov radiation (or transition radiation) emitted by a pure quartz plate will give the time distribution whereas the energy distribution will be measured in a double-focusing magnetic spectrometer. These diagnostics are presented in figure 1.

Simulation calculations

We used mainly the particle tracking code PARMELA [5], modified to take the electron emission mechanism into account, and the two dimensional model code ATHOS we developed [6], where the bunch is represented by disks and rings with cylindrical symmetry. External forces acting on the bunch result from the RF fields in the gun cavity and from the magnetic field generated by the lens at the cavity exit. Space charge forces and self-focusing magnetic fields constitute the internal forces generated by the bunch itself. The model tracks charges, initially distributed in cells, as they move under the influence of the external and internal forces and determines their positions and their velocities. The calculations are performed in the moving system and transformed in the stationary system where the beam characteristics are determined : energy, transverse emittance, energy spread, radial and temporal distributions. Calculations were also done with the code OAK [7]. The simulations were done for the RF gun cavity presented in figure 2, with an acceleration gap of 7 cm ; the electric field components were obtained from SUPERFISH.

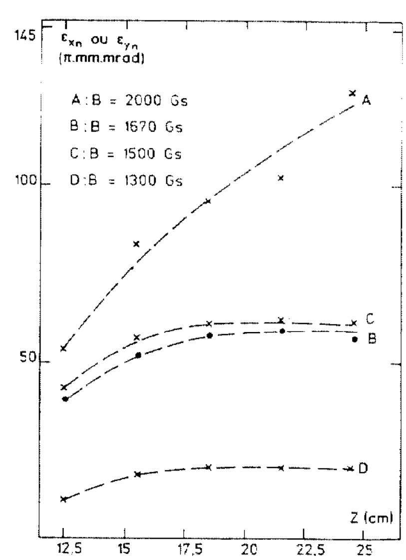

Figure 3 : Transverse emittance for different magnetic fields.

Figure 3 gives the normalized transverse emittance given by PARMELA as a function of the distance from the photocathode for different strengths of the magnetic field induced by the first lens ; the bunch contains 20 nC, the gaussian laser pulse has a width of 100 ps (FWHM) and the photocathode irradiated area has 1 cm^2. The energy-phase diagrams, at different positions and for two magnetic fields, are presented in figure 4.

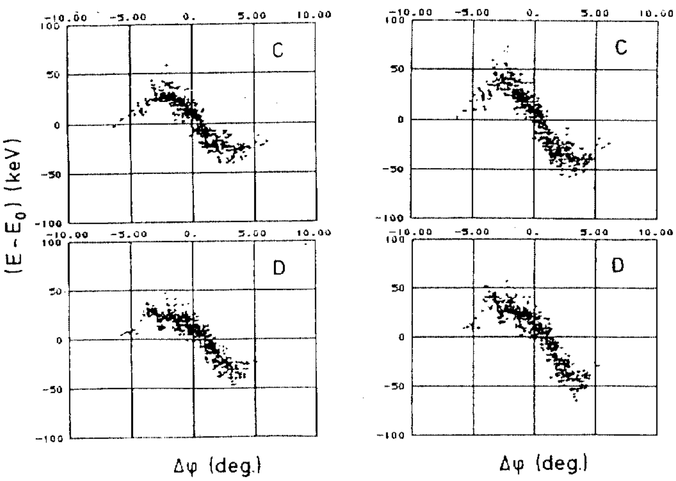

Figure 4 : Energy-phase diagrams at z = 12.5 cm (left) and z = 25.5 cm (right) for the fields given in figure 3.

Figure 5 gives the relative energy spread, as given by ATHOS, as a function of the electric field strength at the cathode for charges between 5 and 20 nC ; the radius R = 6 cm corresponds to an effective radius of the combined RF gun cavity and beam tube.

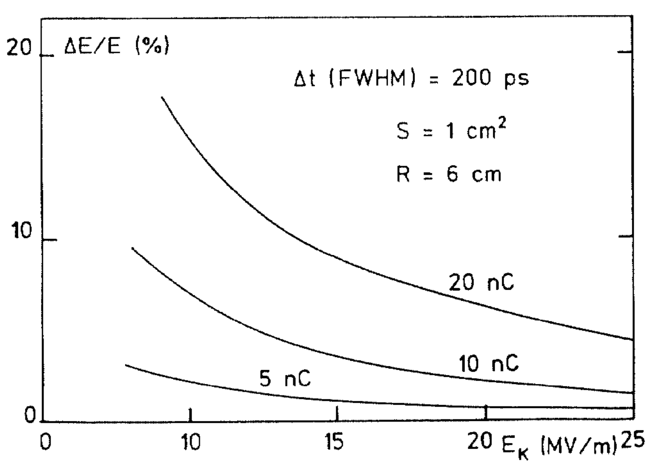

Figure 5 : Relative energy spread as a function of electric field on the cathode for different bunch charges.

Finally, the electron bunch dynamics, as calculated by OAK, is presented in figure 6 ; the bunch contains 20 nC, leaves the 1 cm^2 photocathode, where a maximum electric field of 20 MV/m is applied. A longitudinal magnetic field ranging from 900 Gs at the cathode to 1 000 Gs at z = 30 cm is applied ; the normalized emittance is given at two distances.

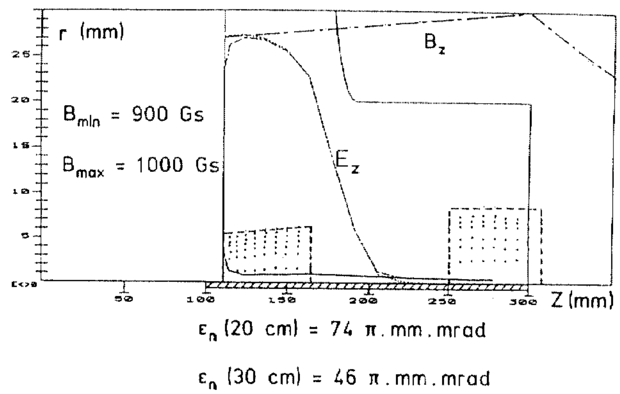

Figure 6 : Electron bunch dimensions and emittances under electric and magnetic fields at different positions.

Conclusion

The previous calculations show, primarily, a strong dependence of the beam characteristics (transverse emittance and energy spread) on the accelerating electric field ; the reduction in $\Delta E/E$ is very important when the field is increased from 10 to 15 MV/m, especially for important charges (see fig. 5). The transverse emittance drops also significantly. However, the results of these codes show large discrepancies as far as relative energy spread and transverse emittance absolute values are concerned, making experiments with the described photo-injector prototype a priority in the near future.

The different components of the photo-injector will be put togother in a 60 m^2 room, with 1 m thick concrete walls, except for the laser located in a building closeby. Experiments are scheduled at the beginning of the next year.

References

[1] J.S. FRASER et al., " A new high-brightness injector for free-electron lasers driven by RF linacs", Report LA-UR-85 - 3176.

[2] J.S. FRASER et al., "Photocathodes in accelerator applications" presented at the IEEE Particle Accelerator Conference, Washington D.C, March 16-19, 1987, pp. 1705 - 1709.

[3] K. HALBACH and R.F. HOLSINGER, Particle Accelerators, vol. 7, pp. 213-222, 1976.

[4] M.E. JONES and W.K. PETER, "Particle in cell simulations of the Lasertron", IEEE Trans. Nucl. Sci., vol. 32, p. 1794, 1985.

[5] K. CRANDALL and L. YOUNG, Los Alamos National Laboratory, private communication.

[6] F. COÇU et al., "Dynamique d'un faisceau intense d'électrons. Modélisation d'un injecteur pour le LEL-HF", Rapport PTN/827/87, Bruyères-le-Châtel.

[7] A. BUBROVIN, this conference.