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LOW EMITTANCE PHOTO-INJECTORS

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Abstract

Photon colliders require high charge polarized electron beams with very low normalized emittances, possibly lower than the actual damping rings design goals ($\sqrt{\varepsilon_{nx} \cdot \varepsilon_{ny}} \approx 10^{-7}$ m). Recent analytical and numerical efforts in understanding beam dynamics in rf photoinjectors have raised again the question whether the performances of an RF electron gun based injector could be competitive with respect to a damping ring. As a matter of discussion we report in this paper the most recent results concerning low emittance photoinjector designs: the production of polarized electron beams by DC and/or RF guns is illustrated together with space charge compensation techniques and thermal emittance effects. New ideas concerning multi-gun injection system and generation of flat beams by RF gun are also discussed.

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1 INTRODUCTION

The research and development of high current low emittance photoinjectors (high brightness) has been driven in the last decade mainly by Free Electron Laser (FEL) applications. Beams with emittance lower than 1 µm ($\varepsilon_{nx} = \varepsilon_{ny}$) with peak current of some kA are required for example for the new x-ray FEL SASE projects [1], [2]. In figure 1 measured emittance versus time is reported for bunched beams of approximately 1 nC charge [3]. Despite the tremendous improvement in emittance reduction since the introduction of RF guns [4] and the emittance compensation technique [5], in the last years the barrier of 2 µm [6] has not yet been breached, even if slice emittance measurements, that is the relevant parameter for FEL applications, close to 1 µm have been recently reported [7].

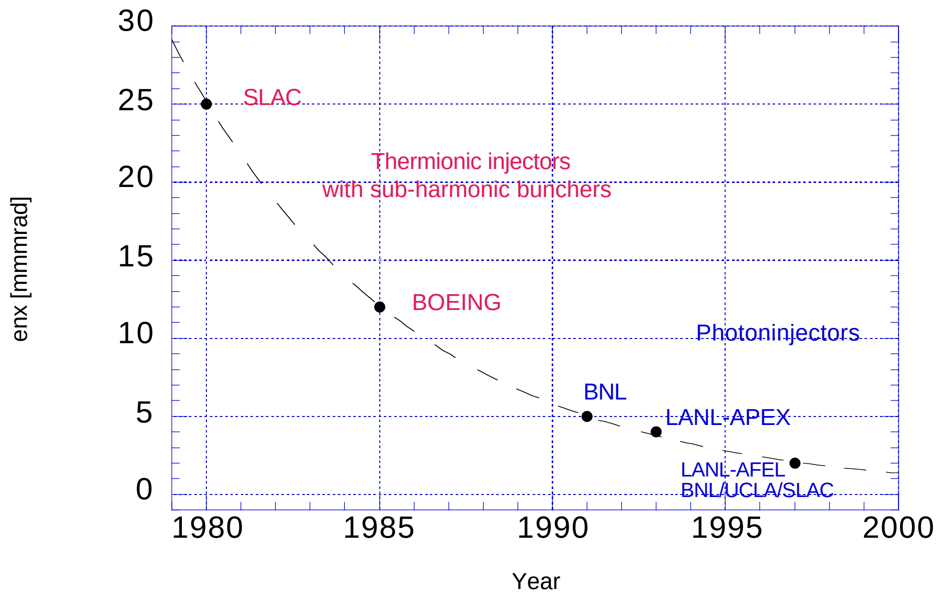

Fig. 1: Measured emittance (rms normalized) from the leading thermoionic and RF photocathode injectors [3]

These measurements were done with a spatially uniform but temporally Gaussian charge distribution. Simulations show that if the temporal distribution is also uniform lower values can be reached [8]. The effort under way in this direction mainly at DESY and SLAC and the dedicated gun test facilities under commissioning are expected to break through the 2 µm barrier in the next years. In addition new design studies have recently lowered the expected correlated emittance to 0.3 µm for a 1 nC beam [9].

In the context of a Photon Collider project the problem is even more challenging. Photon colliders require in fact high charge polarized electron beams with very low normalized emittances, possibly lower than the actual damping rings design goals ($\sqrt{\varepsilon_{nx} \cdot \varepsilon_{ny}} \approx 10^{-7}$ m) [10]. The recent analytical and numerical efforts in understanding beam dynamics in RF photoinjectors have raised again the question whether the performances of an RF electron gun based injector could be competitive with respect to a damping ring. As a matter of discussion we report in this paper the most recent results concerning low emittance photoinjector designs. Space charge compensation techniques and thermal emittance effects are discussed in section 2 in the context of FEL applications. In section 3 new ideas about the generation of flat beams by RF gun are reported. The production of polarized electron beams by DC and/or RF guns is illustrated in section 4 together with a discussion on multi-gun injection system.

2 STATE OF THE ART RF PHOTOINJECTORS DESIGN

In a photoinjector electrons are emitted by a photocathode, located inside an RF cavity, illuminated by a laser pulse so that the bunch length and shape can be controlled on a picosecond time scale via the laser pulse. The emitted electrons are rapidly accelerated to relativistic energies thus partially mitigating the emittance growth due to space charge force effects. Nevertheless the phase dependent focusing forces that the electrons experience in the RF field [11] result in an RF induced emittance growth. In order to keep this effect small the transverse and longitudinal bunch dimensions have to be kept small. The increased particle densities lead, in turn, to increased space charge forces thus compensating partially the beneficial effects of the high gradients available in RF cavities. Since the early '80 was clear that the space charge induced emittance growth in an RF gun is partially correlated and can be reduced by a simple focusing scheme invented by B.Carlsten [5]. The space charge in fact acts to first order as a defocusing lens, the strength of which varies over the bunch length. The force is strongest in the middle slice of the bunch and decreases towards both ends. Therefore a fan-like structure appears in the phase space. After a focusing kick is applied by means of an external solenoid, the fan slices distribution tends to close in the following drift space until a minimum phase space area is reached, corresponding to a partially re-alignment of bunch slices. A residual emittance growth is nevertheless left in practical cases, caused by non linear space charge fields within the bunch [12]. In order to avoid additional space charge emittance growth in the subsequent beam line, the emittance minimum has to be reached at high beam energy so that space charge forces are sufficiently damped. The beam has to be properly matched to the following accelerating sections (booster) in order to keep under control emittance oscillations and obtain the required emittance minimum at the booster exit.

A fully theoretical description of the emittance compensation process [13] has demonstrated in fact that in the space charge dominated regime, i. e. when the space charge collective force is largely dominant over the emittance pressure, mismatches between the space charge correlated forces and the external focusing gradient produce slice envelope oscillations that cause normalized emittance oscillations. It has been shown that to damp emittance oscillations the beam has to be matched properly at injection into any accelerating section, according to the following conditions:

$$\sigma' = 0 \qquad (1)$$

implying a laminar waist at injection and:

$$\gamma' = \frac{2}{\sigma}\sqrt{\frac{\hat{I}}{2I_0\gamma}} \qquad (2)$$

giving the matched accelerating field for a standing wave structure.
The laminar regime extends up to an energy given by:

$$\gamma = \sqrt{\frac{2}{3}}\frac{\hat{I}}{I_o \varepsilon_{th} \gamma'} \qquad (3)$$

where ε_{th} is the thermal emittance, I_o = 17 kA the Alfven current, $\hat{I}$ the peak current and $\gamma' = \frac{eE_{acc}}{m_e c^2} \approx 2E_{acc}$, E_{acc} being the accelerating field.

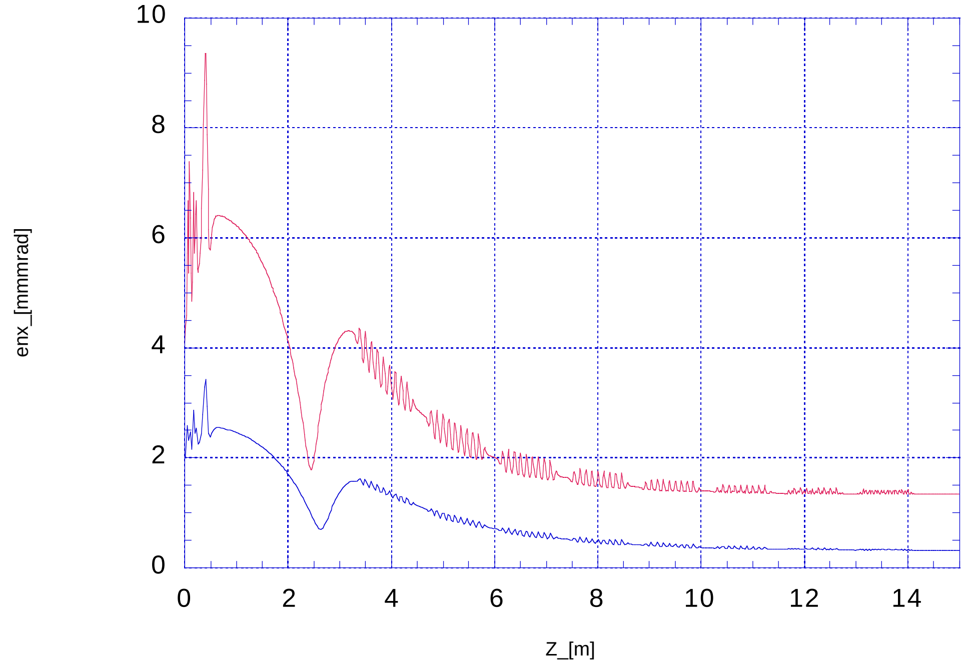

Fig. 2: RMS normalized emittances for 1 nC (lower line) and 3.2 nC (upper line) cases, for the TESLA facility}

As a consequence of such a theory the definition of injector has to be extended up to an energy high enough to exceed the laminar regime. The beam enters then in the so called emittance dominated regime, where trajectory cross overs dominate over space charge oscillations and the total normalized emittance remains constant in an ideal accelerator. With the expected TESLA/FEL injector parameters $\hat{I}$ =50 A, E_{acc}=12 MV/m and an estimated [14] thermal emittance of 0.74 µm for a CsTe cathode with UV excitation, the transition occurs at 66 MeV.

Following the previous matching condition a new working point very suitable to damped emittance oscillations has been recently found [9] in the context of the LCLS FEL project [2]. The correlated emittance can be damped at the level of 0.3 µm at 160 MeV for a uniform charged cylindrical bunch. This working point can be easily scaled [15] to any frequency or charge design. In addition in this configuration the location of the solenoid can be shifted downstream of the gun cavity exit opening a new possibility also for high brightness superconducting rf guns. Scaling this results to TESLA frequency 1.3 GHz and charge 3.2 nC would results in an emittance close to 1 µm.

Unfortunately the total emittance is given by two contributions:

$$\varepsilon_n = \sqrt{\varepsilon_{cor}^2 + \varepsilon_{th}^2} \tag{4}$$

The so called thermal emittance, i.e. the uncorrelated emittance resulting from the cathode emission process, results to be a fundamental limitation to the achievable minimum emittance. By means of a simple model 14] thermal emittance contribution can be estimated according to the following relation:

$$\varepsilon_{th} = \frac{R}{2\sqrt{3}}\sqrt{\frac{2E_{kin}}{m_o c^2}} \tag{5}$$

where E_{kin} is the electron kinetic energy as emitted by the photocathode, 0.55 eV for CsTe cathode. With R=1.5 mm laser spot radius eq.(5) gives ε_{th}=0.74 μm. Thermal emittance measurements are not yet available but a careful investigation is under way [16].

High voltage pulsed guns, called also pulsed photodiodes [17], are also under development: in these devices high fields are achieved by using a very short (nsec) pulsed gradient (1 GV/m) across a gap of 1 mm. Experimental results with beam are soon expected, but the beam energy gain is too low to overcome space charge effects and a design study for matching this beam into an accelerating structure is still in progress in order to evaluate the final emittance at high energy.

3 FLAT BEAM INJECTORS

An injector for a linear collider must provide a flat beam ($\varepsilon_{n,y} << \varepsilon_{n,x}$) in order to suppress beamstrahlung at the Interaction Point. But a production of a flat beam directly from the cathode surface would increase the difficulties for emittance compensation, easily achieved by means of a symmetric solenoid as discussed in the previous section. A very useful transformation of a round beam into a flat beam and vice versa has been recently proposed [18] by means of simple linear beam optics adapter. This transformation is possible with a magnetized beams as produced by an rf gun with a cathode embedded in a solenoid field [19]. At the exit of the gun/solenoid system the beam has an angular momentum given by:

$$p_\vartheta = \frac{1}{2} e B_{z,c} R_c^2 \tag{6}$$

where $B_{z,c}$ is the on cathode magnetic field and R_c the laser spot radius. Both transverse planes are thus coupled by the beam rotation. Such rotation can be arrested by a suitable choice of a skew quadrupole triplet that in addition changes the emittance ratio according to the following relations:

$$\frac{\varepsilon_x}{\varepsilon_y} = 1 + \frac{2\sigma_r^2}{\beta^2 \sigma_{r'}^2} \tag{7}$$

for a beam with rms size σ_r and rms angular spread $\sigma_{r'}$. The final emittance ratio is thus simply variable by adjusting the free parameter:

$$\beta = \frac{2p_o}{eB_{z,c}} \quad (8)$$

via the on cathode magnetic field (p_o being the particle momentum). Design studies based on this scheme [20] show that for a 0.8 nC charge one can obtain ε_{nx}=1.1 10^{-5} m and ε_{ny}=3 10^{-8} m with an emittance ratio of about 370. Additional studies are under way for a better understanding of the space charge effects when the transformation is applied at low energy. A first successful demonstration of this method was recently achieved at the A0 experiment at FNAL [21].

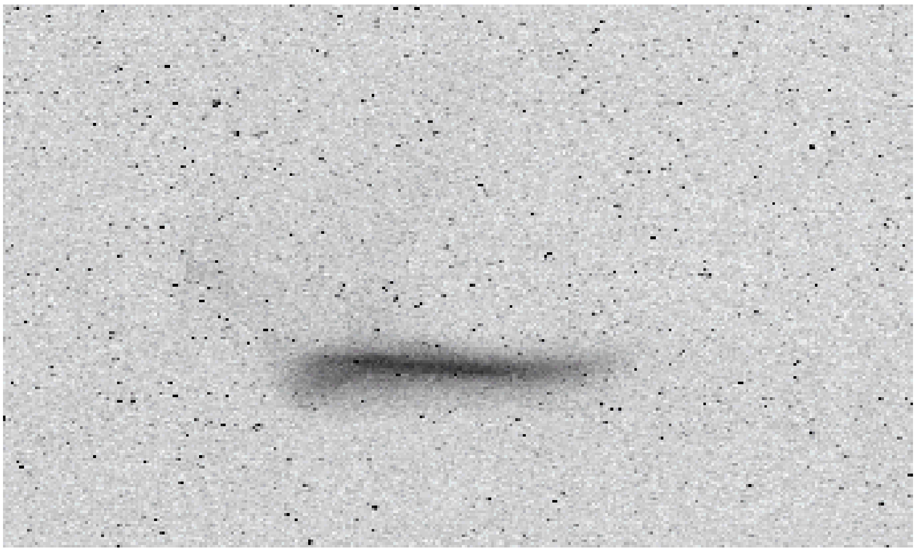

Fig. 3: Beam profile on OTR screen 1.2 m downstream of the third skew quadrupole at FNAL A0 flat beam experiment.

In Fig. 3 the beam image downstream the third quadrupole is shown and it has been verified that the beam remains flat as it drifts farther downstream, an important experimental achievement that demonstrate the effectiveness of the linear beam optics adapter also in the context of RF photoinjector. The measured ratio of emittances is about 50 with ε_{nx}=0.9 μm and ε_{ny}=45 μm for a 1 nC beam. Additional experiments are foreseen in the near future to optimize the emittance compensation process.

4 POLARIZED ELECTRON INJECTORS

There are no fundamental reasons that disable the production of polarized electron beams by means of an RF gun. There are unfortunately technical problems that are not yet solved [22]. The main limitations come directly from cathode performance. While for unpolarized electron sources CsTe cathodes are a mature technology with a high quantum efficiency QE=10 % with UV illumination and a life time longer than one month under operating conditions of 10^{-9} Torr pressure [23], semiconductor GaAs cathodes have still some problem to overcome before being adopted in an RF gun. QE drops in few hours if high vacuum conditions are not satisfied: 10^{-10} Torr under operation, a very difficult task for an RF gun due to the distance between the cathode location and the vacuum port. For this reason DC guns, where a short gap is located inside a large metal vacuum chamber, are preferred as polarized electron source. Low frequency rf guns or open rf structure like Plane Wave Transformer, have been suggested as a possible structure to house GaAs cathode because of their large apertures that facilitate the cavity evacuation[24], but experimental results are not yet achieved. Efforts are under way to solve the following additional problems [24]:

- Overcoming the cathode charge limit, at the moment limited by a current density J_c of 4 A/cm^2 for an extraction field of 1.8 MV/m and a laser pulse 2 nsec long, well below the space charge limit. However, there is ongoing work that indicates that this limit may be substantially raised by using special superlattice structures and special doping patterns. In addition the charge limit for sub-ns pulses has not been explored[25].

- Reducing the cathode time response, a 10 ps long electron bunch is now produced by a 1 ps long laser pulse.

- Increasing the polarization from 80 % up to 95 %, so to improve the collider luminosity and extend the physics reach.

- Reducing dark currents and cathode back bombardment, that damage the cathode.

With the state of the art GaAs cathode technology the parameters available for an ultra low emittance rf gun, suitable to substitute electron damping ring in a linear collider project , could be the following: thermal emittance should not be higher than 0.2 μm implying a laser spot radius of 1.5 mm (from eq. (5) assuming 0.025 eV the electron kinetic energy as emitted by the GaAs photocathode, see [26] for a more appropriated discussion about thermal emittance computation in this context). Considering an L-band structure with an on cathode peak field of 60 MV/m and a 20 ps long bunch, and assuming a (pessimistic) linear extrapolation at higher field of the cathode charge limit resulting in J_c =130 A/cm^2 at 60 MV/m, the available current shall not exceed 10 A, corresponding to a 0.2 nC charge per bunch. A higher bunch charge as required for the TESLA collider, 3.2 nC charge per bunch, could be obtained by combining several beams by dispersive funnel. Such a multi-gun option has not yet been investigated in details. However to provide 3 nC charge with the constrains discussed above one would need 15 independent injectors. And any bunch superposition can be done when each bunch energy is high enough to exceed the space charge dominated regime, in order to avoid emittance growth due to the increasing charge. Such a scheme seems too complicated to be a realistic alternative to the electron damping ring.

5 CONCLUSIONS

The state of the art low emittance polarized flat beam injectors based on rf gun, is not yet a mature technology to be competitive with electron damping rings. Nevertheless technological development are increased in the last years and new ideas are growing. A more dedicated experimental study of a polarized electron rf gun design in combination with the flat beam experiment would be of great interest for the linear collider projects. The resulting emittance could be low enough to simplify at least the damping ring design.

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