OVERVIEW OF FEL INJECTORS

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Abstract

Future light sources based on high gain free electron lasers, require the production, acceleration and transport up to the undulator entrance of high brightness (low emittance, high peak current) electron bunches. Wake fields effects in accelerating sections and in magnetic bunch compressors typically contribute to emittance degradation, hence the injector design and its operation is the leading edge for high quality beam production and for the success of the future light sources. DC and RF guns, photo-cathode materials, laser pulse shaping and sub-ps synchronization systems are evolving towards a mature technology to produce high quality and stable beams. Nevertheless reduction of thermal emittance, damping of emittance oscillations and bunch compression are still the main issues and challenges for injector designs. With the advent of Energy Recovery Linacs, superconducting RF guns have been also considered in many new projects as a possible electron source operating in CW mode. An overview of recent advancements and future perspectives in FEL injectors will be illustrated in this talk.

INTRODUCTION

After the successful demonstration of exponential gain in a Self Amplified Spontaneous Emission Free Electron Laser (SASE-FEL) at UCLA and LANL and the operation up to saturation with the LEUTL (500 nm), TTF_II (93 nm) and VISA (800 nm) experiments, including harmonic generation at HGHG, a number of short wavelength SASE-FEL projects have been funded or proposed world wide, oriented as user facilities. The choice of FEL radiation wavelength ranges from 100 nm down to 1 Angstrom (LCLS and XFEL) and the adopted linac technology is based on normal conducting (S-band or C-band) or superconducting accelerating structures (L-band), see Fig. 1.

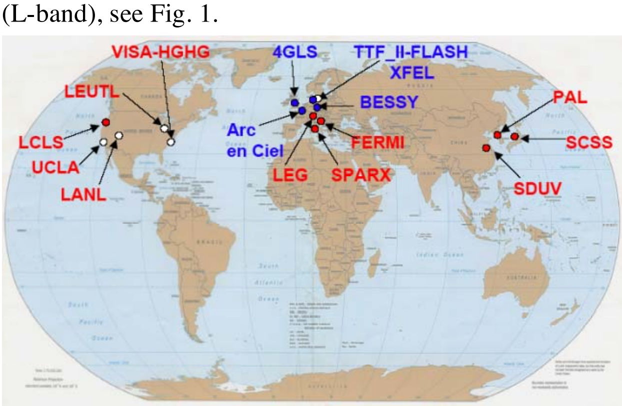

Figure 1: IV generation synchrotron light sources based on short wavelength FEL world distribution. Red and blue lables: FEL projects based on normal conducting or superconducting technology respectively. White circles: first SASE demonstrative experiments.

The optimization of the FEL parameters is quite a complicated task [1] but the main requirement for the electron beam in order to achieve short wavelength radiation in a reasonable long undulator (30-100 m) is clear: high transverse brightness and low energy spread (~0.1 %). Transverse beam brightness is defined hereafter with the approximated [2] expression:

$$B_{\perp} \approx \frac{2I}{\varepsilon_{n,x}\varepsilon_{n,y}}$$

where I is the bunch peak current and ε_n is the bunch transverse normalised emittance. The expected transverse brightness for electron beams driving short wavelength SASE FEL facilities is of the order of $10^{15} - 10^{16}$ A/m^2. High brightness beam essentially means high bunch charge density (with peak currents of several kA) and low emittance (~ 1 μm). The difficulties to achieve such a high quality beam are partially mitigated by the fact that the FEL resonance condition implies that electrons slips back in phase with respect to photons by one radiation wavelength λ_r per undulator period λ_u. Hence radiation amplification occurs on a scale length of the slippage length $L_s=N_u\lambda_r$, where N_u is the number of undulator periods, tipically much shorter than the bunch length so that bunch slice parameters are important. Wake fields effects in accelerating sections and in magnetic bunch compressors typically contribute to emittance degradation, hence the injector design and its operation is the leading edge for high quality beam production and for the success of the future light sources. DC and RF guns, photo-cathode materials, laser pulse shaping and sub-ps synchronization systems are evolving towards a mature technology to produce high quality and stable beams. In particular the technique termed "emittance compensation" [3] has been experimentally verified in many laboratories and theoretically well understood [4]. It is important to emphasize that high charge density beams experience two distinct regimes along the accelerator, depending on the laminarity parameter ρ defined as the ratio between the space charge and the thermal emittance ε_{th} terms in the transverse envelope equation:

$$\rho = \left(\frac{I}{\gamma\gamma' I_A \varepsilon_{th}}\right)^2$$

where I_A is the Alfven current, and γ'~2Eacc_[MeV] is the normalised gradient. When $\rho >> 1$ the transverse beam dynamics is dominated by space charge effects, the typical injector regime. Correlated emittance oscillations are observed in this regime [4], caused by the different local current along the bunch and by finite bunch length effects. In this case special matching condition should be adopted (invariant envelope [4]) to properly damp the residual correlated emittance oscillations. By accelerating the beam, a transition occurs to the so-called emittance dominated regime, when $\rho << 1$, in this case the transverse beam dynamics is dominated by the emittance and correlated effects are not anymore observed. In case of bunch compressor systems are foreseen along the linac space charge effects might become important again and the transition from space charge to emittance dominated regime shift at higher energy, see Fig. 2. In this case the whole linac behaves like a long injector [5] and the same matching techniques [4,5] should be adopted also at higher energy.

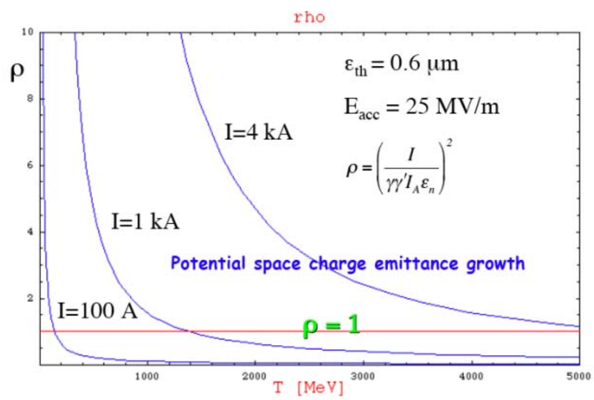

Figure 2: Laminarity parameter ρ versus beam energy T for different beam currents. Notice for example that a 1 kA beam is space charge dominated up to 1 GeV.

In the next sections the state of the art of normal conducting and superconducting injectors will be briefly discussed taking some representative case as examples. For a more detailed and systematic analysis, not limited by conference proceeding requirements, see [6] and [7].

HIGH PEAK BRIGHTNESS INJECTORS

As shown in Fig. 3 the brightness achieved so far by the operating injectors is not sufficient to drive short wavelength SASE FEL experiments, thus requiring additional bunch compression schemes downstream the injector in order to reach the 10^{15} A/m^2 threshold.

As one can notice from the plot, the brightness increases with the gun operating frequency, with a record well in excess of 10^{14} A/m^2 achieved at ATF [8], obtained with an 1.6 cells S-band photo-injector, a widely used RF gun design shown in Fig. 4. In a RF photo-injector in fact, electrons are emitted by a photo-cathode located inside an RF cavity that is illuminated by a laser pulse, so that the bunch length and shape can be controlled on a picosecond time scale via the properties of the laser pulse. The emitted electrons are rapidly accelerated to relativistic energies, thus partially mitigating the emittance growth due to space charge force effects. Operation at higher frequency allows higher peak field in the RF cavity as it is desirable. The ATF results confirm the expected performance of a photoinjector after a long operating experience and improvements of the facility like the use of Mg cathode with QE=0.25 % to reduce the laser load compared to the Cu cathodes with typical QE<0.1 %, high gradient in the cavity (> 130 MV/m), good alignement and stability of the driving laser and RF system.

Sumitomo Heavy Industries SHI results [9] are very important since they have demonstrated the advantages of using laser pulse shaping to reduce non-linear space charge effects in the beam. With a 10 ps flat top laser pulse with rising time shorter than 1.5 ps, produced by a femtosecond Ti:Sa laser system equipped with a liquid crystal spatial light modulator pulse shaper (LCM), they have measured at 14 MeV an emittance of 1.3 μm at 1 nC charge, a reduction of a factor 2 with respect to a Gaussian electron distribution.

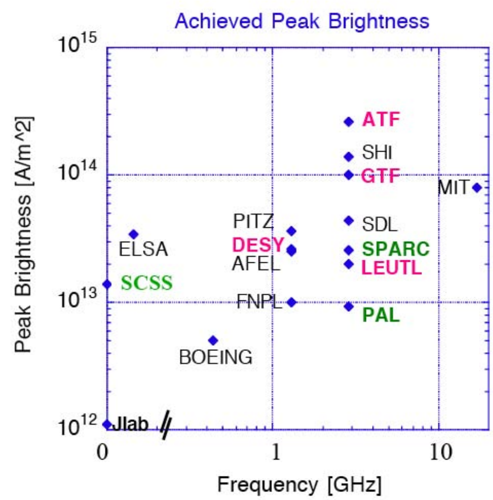

Figure 3: Achieved peak brightness versus gun frequency. Red labels: results achieved with ρ<1, black labels: measurements performed at low energy ρ>1, green labels: preliminary results of new facilities. DC guns are indicated as 0 frequency.

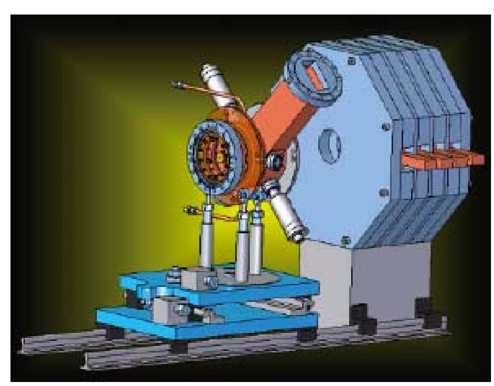

Figure 4: 1.6 cells S-band gun cavity of the BNL/SLAC/ /UCLA design with solenoid.

A 1.6 cells S-band gun design is foreseen also for the LCLS experiment [10], the first X-ray SASE FEL, whose commissioning will begin in January 2007 and whose expected brightness is $2x10^{14}$ A/m^2 at 135 MeV. The LCLS gun test facility GTF despite operating in a not fully optimised layout, has demonstrated the possibility to achieve the LCLS required brightness, at least in the low charge (0.2 nC) operating mode. Several modification has been adopted for the final LCLS photoinjector [11], including laser pulse shaping and axial injection, increased mode separation, suppression of RF dipole and solenoid quadrupole field components.

A very similar photoinjector has began in March 2006 its commissioning stage: the SPARC project at INFN Frascati [12,13].

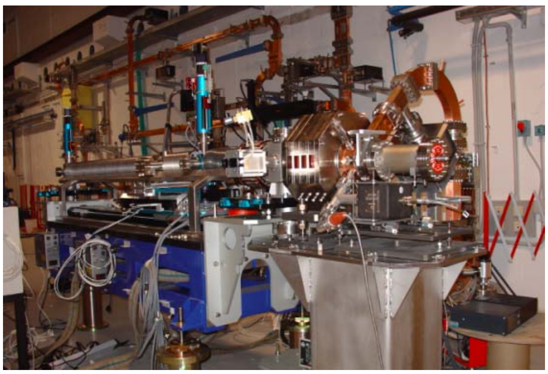

Figure 5: 1.6 cells S-band gun cavity with solenoid and movable emittance meter installed in the SPARC hall.

The peculiarity of this project is the possibility to test different laser pulse shaping techniques (based on DAZZLER and LCM) with an advanced diagnostic techniques, the so called movable emittance meter device [14], that gives the possibility to investigate the emittance compensation process along the 2 m long drift at the exit of the RF gun. One of the goal of the SPARC experiment is to confirm the theoretical prediction of a new working point for an optimal matching with the subsequent booster [15]. Preliminary results obtained so far with a not yet optimized machine operation, in particular without pulse shaping, are very encouraging showing the possibility to achieve a brightness of $4x10^{13}$ A/m^2 at 5.5 MeV. The possibility to compare simulations with experimental data [14] as a function of the beam position in the drift have also shown that when the beam waist is obtained at 1.5 m, where the booster will be located, the emittance minimum is found at 1.8 m as expected from the optimal working point. Operation with laser pulse shaping is foreseen in July.

L-band photoinjectors despite the lower peak field achievable (< 60 MV/m) and hence a lower expected peak brightness are able to generate long electron bunch trains (~ 800 μs with MHz repetition rate) in long RF pulses with low emittance, as required to drive pulsed (10 Hz) superconducting RF linac. In addition high QE cathodes like Cs_2Te (very sensitive to high peak field) can be used in this case, thus reducing the required laser pulse energy. The DESY injector is now routinely able to produce 20 ps long bunches with 1 nC Gaussian charge distribution and emittance of 2.1 μm at 100 MeV. The high injector stability (certainly more important than unstable peak performances) achieved at DESY allowed the successful operation of the 13 nm SASE FEL experiment FLASH, a very remarkable and unique result. At the PITZ gun test facility even better performances have been obtained (emittance ~ 1.1 μm) with a flat top longitudinal profile, very close to meet the requirements for the X-FEL user facility.

In the early stage of the commissioning a photoinjector can be affected by many problems since its performances are strongly dependent on the uniformity and pointing stability of the laser beam, the Quantum Efficiency (QE) of the cathode, the dark currents when peak field exceeds 100 MV/m and in some case RF breakdown. For the reasons listed above a completely different and more conventional choice has been done for the SCSS injector that is recently entered in the commissioning stage with very interesting results [16]. A single crystal CeB_6 thermionic cathode inserted in a high voltage (500 kV) pulsed gap has been adopted as electron source. The advantage of this choice is the possibility to generate a stable beam in terms of charge, energy and pointing stability with uniform current distribution. The drawback is that only a 10 MV/m accelerating field can be generated in the 5 cm long gap, thus allowing only a low charge density beam generation in along pulse. Further manipulation of the beam is then necessary in order to achieve the required brightness by means of a sub-harmonic buncher, a chopper and a booster cavity before injecting the beam in S-band capture sections followed by a C-band linac, as shown if Fig. 6.

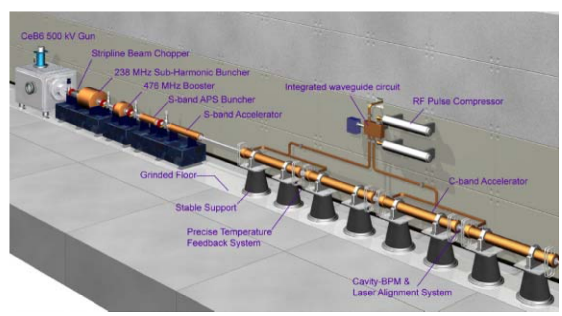

Figure 6: Layout of the SCSS thermionic injector.

Nevertheless, as reported in [16], with this injector the SCSS group has been able to reach very competitive results at 50 MeV: 110 A peak current with rms normalised emittance of 3 μm (slice emittance < 2 μm) corresponding to an achieved brightness of ~ 3 10^{13} A/m^2. The exponential gain at 50 nm observed in the SCSS undulator means also that at least one slice of the bunch has even better brightness. The SCSS is the first SASE FEL driven by a thermionic injector.

Another alternative design is subject of investigation at the Low Emittance Gun Project LEG at PSI [17]. The idea in this case is to generate an ultra-low thermal emittance beam (~ 0.05 μm) by means of cathode field emission process and to prevent space charge induced emittance growth with a strong acceleration immediately after the emitters with a high voltage pulsed diode, followed by a 1.6 cells cavity and a linac. Preliminary simulations [18] show that with a careful beam matching to the subsequent accelerating structure an emittance lower than 1 μm can be obtained at 200 MeV. Two possible choices for this cathodes are under investigation: field emitter arrays (FEA) and single needle cathode electron sources. FEA can give a high current density (~ 10^{12} A/mm^2) while a needle cathode (ZrC, HfC) would have the possibility to temporally modulate the electron beam through laser pulse assisted emission. To overcome the main observed drawbacks: non-uniform emission and arc breakdown, a conditioning process on FEA has been developed at PSI and tests are under way.

VELOCITY BUNCHING

Since the impact of magnetic compressors on the beam quality is a relevant and compelling topic, with the tendency to have serious emittance growth due to coherent synchrotron radiation effects in bends, a new method able to compress the bunch at moderate energies (tens of MeV), using rectilinear trajectories, and integrated in the emittance compensation process, has been proposed [19]. This scheme, named *velocity bunching,* has the following characteristics: although the phase space rotation in this process is still based on a correlated velocity chirp in the electron bunch, in such a way that electrons on the tail of the bunch are faster (more energetic) than electrons in the bunch head, this rotation does not happen in free space but inside the longitudinal potential of a traveling RF wave which accelerates the beam inside a long multi-cell traveling wave (TW) RF structure, applying at the same time an off crest energy chirp to the injected beam. This is possible if the injected beam is slightly slower than the phase velocity of the RF wave so that, when injected at the crossing field phase (no field applied), it will slip back to phases where the field is accelerating, but at the same time it will be chirped and compressed. The key point is that compression and acceleration take place at the same time within the same linac section, actually the first section following the gun, that typically accelerates the beam, under these conditions, from a few MeV (> 4) up to 25-35 MeV.

Table 1: Velocity bunching experiments

	BNL	UCLA	DUV-FEL	UTNL	LLNL
Charge [nC]	0.04	0.2	0.2	1	0.2
Length [ps]	0.37	0.39	0.5	0.5	<0.3
Compression Ratio	6	15	>3	>13	10
Reference	[20]	[21]	[22]	[23]	[21]

A fully optimized dedicated photo-injector for application of the velocity bunching technique still does not exist: one of the missions of the SPARC project is indeed to design and commission such a system.

HIGH AVERAGE BRIGHTNESS INJECTORS

With the advent of proposed superconducting energy recovery linacs (ERL) dedicated to production of radiation [24] that operate at high average current (high duty factor), the demand for high peak and high average brightness, pushes the injector community to consider also the possibility of using a superconducting RF photoinjector. In the past, for an implementation of SRF guns it was always assumed that one needs strong focusing inside the gun, near the photocathode. This assumption has been partially driven by relatively low achievable gradient in SRF guns. A solution which avoids use of solenoid fields in transverse beam control near the cathode, has been proposed in [25] using recessed cathode to enhance transverse RF component on the cathode surface. Experimental test have demonstrated that this solution is not enough to prevent space charge emittance growth downstream the gun exit. The improvement in superconducting cavity fabrication allows today accelerating gradient higher than 30 MV/m, corresponding to peak field of 60 MV/m [26]. An alternative scheme in which rf focusing is not required can today be considered. A very attractive approach has been proposed at BNL [27]. The basic idea is to illuminate with UV laser the back wall of the superconducting Nb cavity accelerating in this way photo-emitted electrons. An optimized configuration has been proposed in [28], in which the working point described in [15] has been scaled to an L-band SC gun design.

Another proposed scheme is to excite a TE magnetic mode inside the cavity, as shown in Fig. 7, that focuses the electron beam and prevents the increase of the transverse emittance [29].

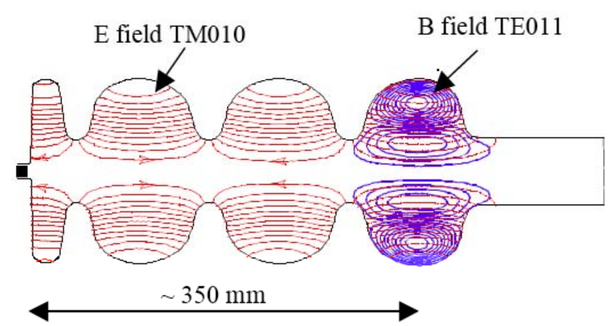

Figure 7: Electric field of the accelerating TM010 mode (red lines) and magnetic flux of the solenoidal TE011 mode in 3.5-cell L-band superconducting FZR cavity.

Operation with high average beam current requires photocathodes having enhanced quantum efficiency. When superconductor is used as a photoemitter, high QE minimizes the thermal load on the superconducting surface. More generally, high QE implies that one may keep the size and cost of the high duty cycle laser system used to illuminate the photocathode within reasonable limits. It has been recently proposed to use lead as a photocathode deposited on the back wall of the gun cavity. Preliminary measurements [30] show a QE =1.7 10^{-3} for a lead cathode illuminated by a 213 nm laser.

The extreme case of ampere class superconducting guns is discussed in [31]. These devices require careful control of the higher order mode trapping and are specifically designed with wide beam tubes so to facilitate damping of unwanted trapped HOM.

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