HIGH REPETITION RATE ELECTRON INJECTORS FOR FEL-BASED NEXT GENERATION LIGHT SOURCES

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Abstract

Several laboratories concentrate their efforts on the development of high repetition rate FEL-based next generation light sources. One particular concept under development at STFC Daresbury Laboratory specifies high brightness electron bunches with a charge of 0.2 nC which arrive with a repetition rate of up to 1 MHz. As emittance of the bunches should not exceed 1 mm·mrad, traditional grid modulated thermionic injectors, similar to the ones used at ELBE or FELIX, may not be used. We consider three options of high repetition rate injectors based on photocathode guns - a high voltage DC gun, a 3½-cell superconducting RF gun and a normal conducting VHF gun, recently proposed at LBNL. We analyse practical injector schemes for all three guns and provide the results of beam dynamic simulations. We also discuss the photocathodes which may be used in each gun, as this critical component defines achievable beam parameters and operational efficiency of the injectors.

INTRODUCTION

High brightness electron beams which are required for the operation of next generation light source may be delivered by three types of electron injectors – a high voltage DC photocathode gun, a very high frequency NCRF gun and a SRF gun. The first two options deliver relatively low energy (500-750 keV) beams and require additional velocity bunching and acceleration with a booster to an energy of 10 MeV in order to inject into the main linac. A SRF gun delivers beams with the required energy without additional acceleration. However, this leads to less flexibility in emittance compensation at different bunch charges. We consider the injectors for operation in CW mode with high beam repetition rate with a bunch charge of 200 pC as is the case for the UK's New Light Source (NLS) project [1].

Simulations

Beam dynamic simulations have been carried out for the three guns considered using ASTRA through the injector system to 10 MeV, then through the first module of the main linac to 120 MeV. Initial thermal emittance was included in all the simulations.

The main linac module consists of eight 9-cell TESLA-type 1.3 GHz superconducting cavities. All cavities except the first have been set to provide an average accelerating gradient of 17 MV/m and a phase of -20° to provide a beam with the necessary longitudinal phase space profile for the bunch compression system. There are two quadropoles to match the beam from the injector into the main linac. The injector parameters were optimised using a multi-objective genetic algorithm with a non-dominated sorting approach.

HIGH VOLTAGE DC GUN

High voltage DC guns with GaAs photocathodes illuminated with laser light of wavelength 532 nm are used at a number of laboratories worldwide to feed energy recovery linac (ERL) based FELs. These include TJNAF [2] and Daresbury Laboratory [3]. An extra high voltage gun is under development at Cornell University [4]. Originally designed for operation at high (up to 100 mA) average currents, DC guns may be relatively easily adopted for operation at low (typically less than 1 mA) currents specific for NLS.

One disadvantage of DC guns is that the field strength on the cathode is restricted to 10-12 MV/m in order to minimise field emission. This rules out obtaining high emission current density and limits the minimum beam size at given bunch charges. However, the low energy spread of emitted electrons from GaAs photocathodes allows high brightness beams to be produced.

GaAs based photocathodes require XHV vacuum conditions to avoid surface contamination which restricts the cathode lifetime. Under ideal vacuum conditions the operational life time is defined by ion back-bombardment, which is proportional to the total extracted charge. Experiments have shown that the maximum charge extracted does not exceed a few hundred coulombs [5] which means that for an average current of 0.2 mA the operational life time will be at a level of 1–2 months. This is acceptable as modern guns are equipped with integrated load-lock photocathode preparation facilities [6] that allow replacement of the photocathode within half an hour and reduce the possibilities of vacuum contamination.

Alkali photocathodes operating in visible light are more stable to vacuum contaminations than GaAs [7]. For example, their lifetime in the presence of oxygen is two orders of magnitude higher than GaAs. However, their resistance to ion back-bombardment is not known, and investigation of their operation in DC photocathode guns is now in progress at Daresbury.

Simulations

A 500 keV DC electron gun with a focussing electrode was modelled in CST Studio/POISSON [8] and the on-axis field map was used as an input to ASTRA. The initial laser pulse used has a 4 mm diameter flat-top transverse profile and a 20 ps flat-top longitudinal profile.

DC guns provide electron bunches with a temporal profile similar to that of the initial laser pulse but quickly

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lengthen during acceleration, therefore a buncher cavity is required to reduce the bunch length to less than 2 mm.

Solenoids are located on either side of the buncher to provide transverse focussing and emittance compensation. A booster module increases the energy of the beam from the 500 keV of the gun to a level around 10 MeV for injection into the main linac. A superconducting module containing two 9-cell TESLA-type cavities operating with peak gradients of lower than 10 MV/m is appropriate for this purpose. Figure 1 shows the evolution of emittance along the injector and Fig. 2 shows the slice emittance of the beam at the exit of the injector.

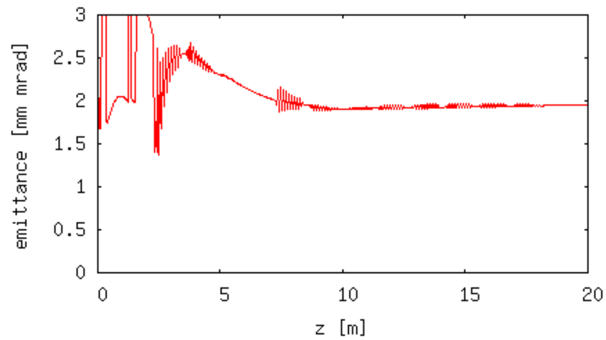

Figure 1: Evolution of emittance along the DC injector.

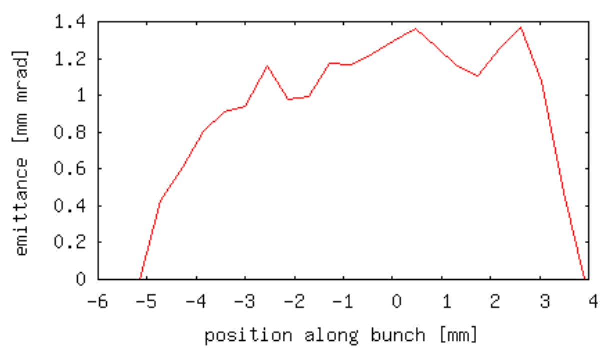

Figure 2: Slice emittance at the exit of the DC injector.

NORMAL CONDUCTING VHF GUN

An interesting design of a high repetition rate gun has been proposed by LBNL [9]. A normal conducting copper cavity is driven with a frequency of around 100 MHz and is able to deliver bunches over a broad range of repetition rates, varying from a few hertz to the RF driving frequency. The cavity is based on mature normal conducting technology but requires installation of a dedicated RF power supply. The total RF power required for accelerating of the beam to 750 keV should be about 100 kW. This corresponds to a maximum field strength on the cathode of 20 MV/m. Operation at relatively low frequencies allows significant reduction in the power density dissipated in the gun walls to 10 W/cm^2, which significantly simplifies the cooling system. The gun uses K_2CsSb or similar alkali-antimonide photocathodes which operate at a wavelength of 532 nm and require extra high vacuum, which can be provided by an array of NEG strips installed on the periphery of the gun cavity.

Simulations

Since the gun delivers bunches with a similar profile and energy to DC guns, a similar injector layout can be used, with the addition of an extra solenoid and a bucking coil to zero the magnetic field on the cathode. The higher field strength allows a smaller laser spot to be used than in the DC case. The following simulations use a laser pulse with a 2 mm diameter flat-top transverse profile and a 20 ps flat-top longitudinal profile with rise and fall times of 2 ps. Figure 3 shows the evolution of emittance along the injector and Fig. 4 shows the slice emittance of the beam at the exit of the injector.

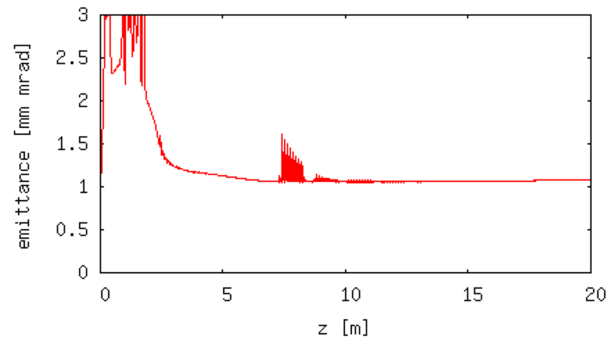

Figure 3: Evolution of emittance along the VHF injector.

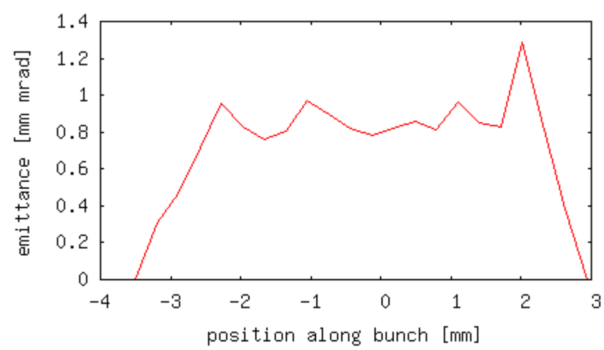

Figure 4: Slice emittance at the exit of the VHF injector.

SUPERCONDUCTING RF GUN

Studies of a suitable 3½-cell SRF gun have been carried out at Daresbury Laboratory [10]. The gun consists of two cavities: a 1½-cell launch cavity with a proposed design largely adopting the TESLA cavity shape, and an adapted Cornell 2-cell booster cavity [11]. The cavities are placed in one cryomodule and are fed via individual RF couplers. If the gun is operated at high repetition rate, an optional High Order Mode (HOM) absorber may be installed between the cavities. The beam pipe diameters are widened to allow the HOMs to propagate and are then absorbed by a broad band absorber [12] consisting of a series of ferrite and ceramic plates which can absorb over 200 watts of RF power over a frequency range of 1 to 40 GHz. Further assessment of the geometry has to be carried out to evaluate the HOM excitation and extraction.

The absence of ohmic losses in SRF cavities provides an option for delivering high beam current with significantly less RF power than for an equivalent normal conducting gun. The hard limit is therefore the maximum power of CW RF source available at 1.3 GHz L-band klystrons are able to provide over 160 kW CW, with an IOT equivalent capable of rising to 90 kW pulsed.

For a beam energy of 10 MeV, the power required is easily achievable with a standard IOT amplifier. An output beam power of 2 kW simplifies the RF input coupler scheme which often restricts the maximum beam power of SRF accelerating systems. If the gun operates at the frequency of the main linac, it easily integrates with the RF and cryogenic infrastructure and does not require non-standard RF power supplies.

At 1 MHz, existing laser systems are not able to drive metallic photocathodes so alkali photocathodes have to be considered. A SRF gun using Cs_2Te photocathodes is under commissioning at FZD [13] and a SRF gun using K_2CsSb photocathodes is under development at BNL [14] to operate in CW mode with an average current of 0.5 A.

Simulations

Operating at 50 MV/m peak field strength, the 3½-cell gun accelerates electrons to 10 MeV, thus no additional accelerating modules are required before the main linac. A buncher cavity is not required as the SRF gun alone can provide electrons with an rms bunch length lower than 2 mm. The laser pulse used in the ASTRA simulations has a 1 mm diameter flat-top transverse profile and a 20 ps flat-top longitudinal profile with rise and fall times of 2 ps. Fig. 5 shows the evolution of emittance along the injector line and Fig. 6 shows the slice emittance of the beam at the exit of the injector.

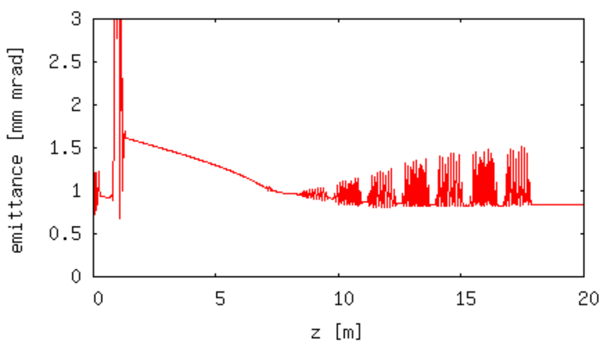

Figure 5: Evolution of emittance along the SRF injector.

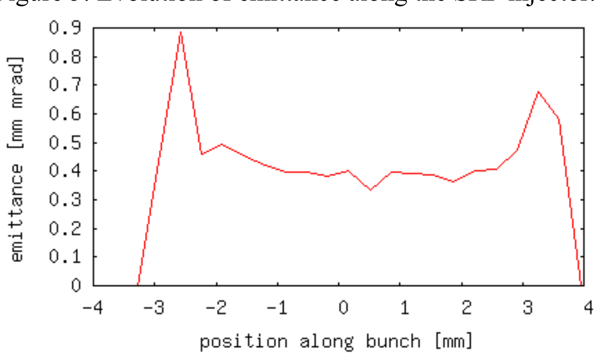

Figure 6: Slice emittance at the exit of the SRF injector.

JITTER

An important aspect of FEL-based light sources is synchronisation, particularly when multiple sources are used such as in pump-probe experiments or in HGHG schemes where the FEL interacts with light from an external laser. Any instability of the RF phase and amplitude of the various cavities causes the arrival time of the electron bunches to differ. An analysis was carried out on the contribution to arrival time jitter in the VHF gun case. For phasing instabilities, the buncher contributes 5.1 ps per degree and the first cavity 1.0 ps per degree. Any instability of the gradients in the cavities contributes a minor amount, only 0.1 ps for each percent offset. The largest contribution comes from the buncher phase jitter. Since the injector layout is the same, the DC gun jitter follows these trends however, since the SRF gun does not require additional bunching and boosting modules, the jitter is solely determined by that of the drive laser.

SUMMARY

The results of beam dynamics simulations of the proposed injector designs are summarised in Table 1. As may be seen the best beam parameters are delivered by the SRF gun, though development of the particular design requires extensive R&D.

Table 1: Beam parameters at the exit of the injectors.

	DC	VHF	SRF
Projected emittance (mm·mrad)	1.95	1.08	0.84
Slice emittance (mm·mrad)	1.2	0.8	0.4
Bunch length (mm)	1.72	1.3	1.67
Longitudinal emittance (keV·mm)	295	115	198
Beam energy (MeV)	120	117	118

ACKNOWLEDGMENTS

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