DESIGN OF A NORMAL CONDUCTING L-BAND PHOTOINJECTOR

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Abstract

For the successful operation of an X-ray free electron laser the injector must be robust and able to provide high quality beams. In this paper we present the design of a normal conducting L-band photoinjector which is based on the successful DESY/PITZ gun, but with improved cavity geometry. The result of beam dynamics simulations predicts that a beam with a normalised transverse emittance of less than 0.7 mm mrad at 1 nC can be produced. With an expected repetition rate of at least 1 kHz, this gun meets the requirements of the first stage injector for the UK's New Light Source project.

INTRODUCTION

A user driven new generation light source project, UK's New Light Source (NLS) project, was launched in April 2008 [1]. Since then, user's requirements for the NLS facility were summarised and the Science Case was published in October 2008 [2]. The NLS facility will be a linac based free electron laser (FEL). The baseline specification in the Science Case requires a repetition rate of 1 kHz and an FEL photon energy ranging up to 1 keV. For the fulfilment of the baseline specification, an L-band normal conducting photoinjector is designed. This injector consists of an L-band normal conducting photocathode gun and 8 TESLA type superconducting cavities. This injector is similar as the FLASH injector [3], but the gun is modified for a high repetition rate operation. The cell lengths of the gun cavity are optimised for low emittance beam generation even with a relatively low RF field. The cooling water channel is a bit improved for higher cooling capacity. With the new gun geometry, operation parameters are optimised at several bunch charge cases.

INJECTOR DESIGN

We started our gun design from PITZ Gun4 which was successfully tested at PITZ [4] and will be installed at FLASH injector end of this year [5]. The PITZ gun was tested with 50 kW average RF power; i.e., 63 MV/m maximum RF field (for 7.2 MW peak power), 10 Hz repetition rate, and 0.7 ms RF pulse length. To fulfil the NLS injector requirements, 1 kHz repetition rate, the maximum RF field is decreased to 50 MV/m. This low RF power operation allows one RF window (instead of two like PITZ) between the RF source and the gun cavity. In addition, the cavity deformation due to the non-uniform temperature rise caused by the RF heating will be reduced and dark current issues will be relaxed.

To generate high quality beams while decreasing the RF field strength, the gun cavity geometry was modified. For the RF field distribution calculation for the cavity, SUPERFISH [6] was used. Electron beam dynamics was calculated with ASTRA [7] for several first and second cell lengths of the gun cavity while optimising the laser beam shape and size as well as the focusing solenoid position and field strength. For ASTRA simulations, 100,000 macro-particles were used. The result is shown in Fig. 1. In addition to finding a low transverse emittance, low dark current from the gun cavity has been considered. When the emission phase gets closer to the zero phase, the momentum distribution of the dark current is separated from that of electron beams [8].

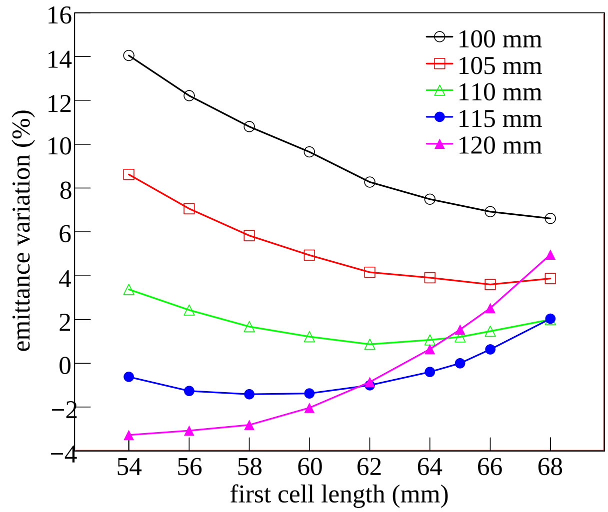

Figure 1: Normalised transverse emittance as a function of the first cell length for different second cell lengths.

Beam and Dark Current Dynamics in RF Gun

To generate a beam with a small transverse emittance, the electric field during the beam emission should be strong. The strong field accelerates quickly the beam, generated at the cathode, so that the beam degradation due to space charge force is minimised. With fixed maximum electric field strength, the electric field during the electron emission can be increased by increasing the emission phase close to 90° [9]. However, when the emission phase is shifted towards 90°, dark current generated at the vicinity of the cathode has a similar energy distribution as the beam. When we operate RF guns with high emission phase, it is difficult to separate the dark current from the beam [8]. For this gun design, the first cell length was optimised so as to minimise the beam emittance while keeping the dark current to be separated from the beam as much as possible. The first cell length was set to 65 mm and this is the same as the PITZ gun. The second cell length was optimised with the same way and set to 115 mm. This is 5 mm shorter than as the PITZ gun. With the cell lengths, the normalised transverse beam emittance after gun is 0.33 mm mrad for 0.2 nC bunch charge. Figure 1 shows the emittance

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variation depending on the lengths of the first and second cells. The emittance variations are referred to the emittance for the case of the 65 and 115 mm for the first and second cells, respectively. For the simulation in Fig. 1, 0.2 nC bunch charge was used. The emission phase variation as functions of the cell lengths is shown in Fig. 2. For the cell lengths selected here, the emission phase is about 44°.

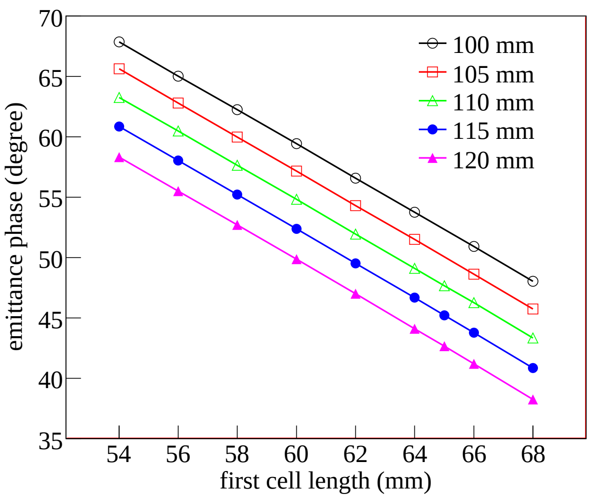

Figure 2: Beam optimum emission phase for highest beam energy as functions of cavity cell lengths.

RF Heating

The average RF power of the gun will be about 70 kW; i.e., 4.5 MW peak RF power, 1 kHz repetition rate and 16 μs RF pulse length. The maximum localised temperature rise caused by the average RF heating is estimated about 40°C [10]. The additional temperature during an RF pulse is estimated about 3.4°C [10]. This temperature rise is in a safe operation region.

Cathode and Thermal Emittance

For an electron beam generation, a Cs_2Te cathode will be used. Cs_2Te cathodes have been used at FLASH and PITZ for many years. This cathode has a long life time of typically several months [11], a moderate thermal emittance [12] and a response time of about 0.1 ps [13]. The homogeneous quantum efficiency (QE) is one of attractive factor [11].

For the ASTRA simulations in this study, the kinetic energy of emitted electrons is assumed to be 0.7 eV. This electron kinetic energy generates a thermal emittance of 0.48 mm mrad for an initial beam radius of 1 mm, which is the same as the laser beam radius.

Cathode Laser

A Cs_2Te cathode needs a UV laser to generate electron beams by photoemission. The laser wavelength should be about 262 nm like the FLASH laser [3]. For the ASTRA simulations, a uniform distribution is assumed for the temporal and radial directions. For the radial direction, the distribution has a sharp edge. For the temporal flat-top distribution, a finite rise/fall time of 2 ps from 10% to 90% of the peak value is assumed. For different bunch charges, the laser pulse length is changed with 2 ps step, which can be achieved with a multicrystal birefringent pulse shaper [14].

Focusing Solenoid

Focusing solenoids were designed with POISSON [6] so that there is no saturation in the yoke. A bucking solenoid is positioned behind the cathode to compensate the field tail at cathode (see Fig. 3). The main focusing solenoid is located at 235 mm from the cathode. This optimum solenoid position is found after 5 mm position scanning with beam dynamics simulation.

Accelerating Cavities

As a part of injector, 8 accelerating cavities are used for further electron beam acceleration. These cavities will be the same type as the other accelerating cavities of the NLS facility. For ASTRA simulations, the field distribution of the TESLA cavity was used [15].

The centre of the first cavity is located at 3.6 m from cathode. This cavity location was optimised with beam dynamics simulation with the 0.2 nC bunch charge case. Then, the cavity location was fixed for other bunch charge beam optimisation. If the cavity location is used as a free parameter for different charge simulation, the location should be shifted downstream for lower charge beam cases and upstream for higher charge beam cases. However, the cavity location is difficult to change during operation and set to be fixed for the optimisation here.

For an electron beam with 0.2 nC, the first four cavity were set to have 11 MV/m gradient and the last four have 20 MV/m. For different charge cases, the cavity gradients were divided as three groups. The first cavity was separated from other cavities. The second, third, and fourth cavities were grouped together. The last four cavities were grouped as one. The RF phase of the all cavities was set to the same value. But, the phase was optimised for different bunch charge cases. See Table 1 for more detail.

SUMMARY

As an injector of the UK's New Light Source facility, an L-band normal conducting photoinjector was designed and optimised. The injector will be able to operate with 1 kHz repetition rate and to produce low emittance beam as required by the baseline specification of the NLS facility. For several bunch charge cases, from 1 pC to 1 nC, beam parameter optimisation was done with ASTRA. These simulation results are used for the start-to-end simulation of the NLS machine [16].

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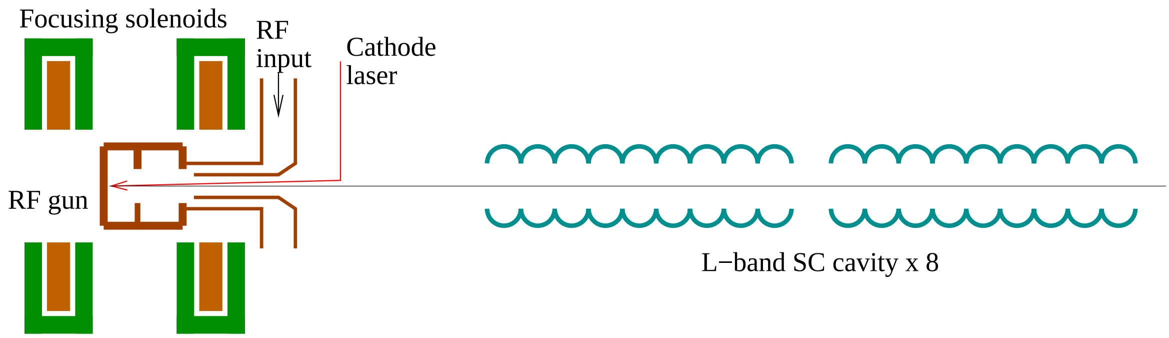

Figure 3: Layout of L-band normal conducting photoinjector.

Table 1: Machine and beam parameters. For ASTRA simulation, 100,000 macro-particles were used.

	Parameters	1 pC	10 pC	50 pC	100 pC	200 pC	500 pC	1 nC
Laser	length (ps)	2.7*	8	8	10	12	16	20
	radius (mm)	0.1	0.13	0.28	0.38	0.48	0.66	0.88
	thermal ε (mm mrad)	0.0478	0.0621	0.134	0.182	0.229	0.315	0.421
Solenoid	max field (T)	0.1887	0.1901	0.1929	0.1925	0.1939	0.1937	0.1943
Linac	C1 grad (MV/m)	1	1	5	7	11	11	13
	C2-C4 grad (MV/m)	7	7	8	8	11	8	11
	C5-C8 grad (MV/m)	20	20	20	20	20	20	20
	C1-C8 phase (deg)	-20	-20	-20	-20	-20	-26	-30
Beam	projected ε (mm mrad)	0.052	0.071	0.165	0.225	0.304	0.439	0.680
	central slice ε (mm mrad)	0.048	0.067	0.162	0.219	0.299	0.423	0.599
	beam size (μm)	35	53	99	178	177	239	223
	length FWHM (ps)	2.5	8	10	12	15	20	25
	$\Delta E/E$ at centre	2.6E-5	7.6E-5	9.0E-5	1.1E-4	1.5E-4	2.4E-4	3.5E-4
	mean E (MeV)	108.9	109.0	116.2	118.3	120.6	118.3	125.4

* The laser temporal distribution for the 1 pC case is Gaussian instead of flat-top.

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