HIGH REPETITION RATE HIGHLY STABLE S-BAND PHOTOCATHODE GUN FOR THE CLARA PROJECT

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Abstract

Compact Linear Accelerator for Research and Applications (CLARA) is a 250 MeV FEL test facility under development at STFC Daresbury Laboratory [1]. The CLARA photo-injector will be based on a RF photocathode gun operating with metal photocathodes and driven by a third harmonic of Ti: Sapphire laser (266 nm). The injector will be operated with laser pulses with an energy of up to 2 mJ, pulse durations down to 76 fs RMS and a repetition rate of up to 400 Hz. In order to investigate performance of different photocathodes activated using different processes the gun will be equipped with a load-lock system which would allow fast replacement of the photocathodes. Duration and emittance of electron bunches essentially depends on the mode of operation and vary from 0.1 ps at 20 pC to 5 ps at 250 pC and from 0.2 to 2 mm·mrad respectively. Requirements for the stability of beam arrival time at the CLARA experimental area are extremely high and are in the range of tens of femtoseconds.

BASELINE ELECTRON SOURCE

The baseline electron source for CLARA will be based around that of the VELA (Versatile Electron Linear Accelerator), formerly known as EBTF (Electron Beam Test Facility), currently under commissioning at Daresbury Laboratory [2]. The electron gun is a 2.5 cell normal conducting S-band RF design, as shown in Fig. 1. This was originally intended for use on the ALPHA-X laser wakefield acceleration project [4]. The gun is operated with a copper photocathode driven by the third harmonic of a Ti: Sapphire laser (266 nm). The injector is operated with laser pulses with an energy of up to 2 mJ, pulse duration of 76 fs RMS and a repetition rate of 10 Hz. At a field gradient of 100 MV/m provided by a 10 MW klystron, the gun is expected to deliver beam pulses with an energy of up to 6.5 MeV. The length and emittance of the electron bunches varies with charge from 0.1 ps at 20 pC to 5 ps at 250 pC and from 0.2 to 0.5 mm·mrad respectively.

The photocathode is a polycrystalline, oxygen-free, copper disc [5], polished to 1µm roughness. It forms an integral part of the 2.5-cell gun cavity and is placed at the back wall of the first half-cell. Prior to installation the cathode is degreased by washing in acetone, ethanol and finally in de-ionized water (>10 MΩ). Carbon contamination is then removed from the surface by ozone cleaning. The gun is pumped down and baked to 150°C in order to achieve pressure in the region of 10^{-9} mbar. The emission area of the photocathode plate is locally baked to a temperature of 200°C to remove oxide. This activation procedure allowed us to reach a photocathode quantum efficiency of $1 \cdot 10^{-5}$ [6].

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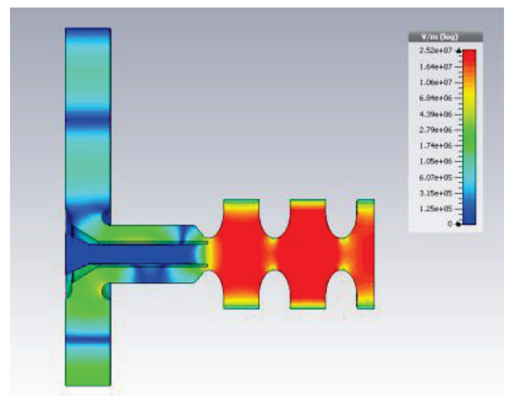

Figure 1: 3D CST calculation of electric field in the front-coupling 2.5 cell cavity (VELA/ALPHA-X gun design).

ADVANCED ELECTRON SOURCE

Further development of the CLARA electron source will be concentrated on design of a highly stable, high gradient and high repetition rate gun which would allow operation at a field of 120 MV/m at 100 Hz repetition rate and 100 MV/m at 400 Hz. Both 1.5 cell and 2.5 cell designs are presently under consideration.

Operational Field and Power

One of the limiting factors, which restrict performance of normal conductive RF guns, is the RF power, dissipated inside the cavity. Excess of this power leads to detuning of the gun and parasitic modulation of the amplitude and phase of the accelerating field. We estimate the operational power of the gun on the basis of existing designs. For a 1.5 cell option we select a high repetition rate design [7] with a well-developed cooling system. The proposed cavity is potentially able to operate with a maximum field of 100 MV/m within a 3 µs RF pulses at 1 kHz repetition rate. The maximum cathode field is restricted by the average power dissipated in the cavity, which exceeds 17 kW. For a 2.5 cell cavity, the required power may be estimated from the existing VELA gun cavity. The RF power required to reach a cathode field of

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Table 1: Pulsed and average RF power dissipated in the gun cavity.

Cavity design	100 Hz				400 Hz			
	100 MV/m		120 MV/m		100 MV/m		120 MV/m	
	Pulsed power, MW	Average power, kW	Pulsed power, MW	Average power, kW	Pulsed power, MW	Average power, kW	Pulsed power, MW	Average power, kW
1.5 cell	5.7	1.7	8.2	2.4	5.7	6.8	8.2	9.8
2.5 cell	10.0	3.0	14.4	4.3	10.0	12.0	14.4	17.3

100 MV/m is 10 MW and at repetition rate of 10 Hz the average dissipated power is 300 W.

The results of scaling these design parameters to the CLARA requirements of 100 Hz and 400 Hz repetition rate at two gun cathode fields 100 MV/m and 120 MV/m are summarised in Table 1. As may be seen, the 1.5 cell design is able to cover all possible operation modes utilizing the existing VELA RF station which can deliver both peak and average power of 10 MW and 10 kW respectively. The 2.5 cell design is only able to operate in the 100 Hz, 100 MV/m mode. For all other modes it will require an upgrade to the existing VELA RF station.

Gun Stability

Seeded FEL experiments which require interaction between an external several fs long laser beam with the electron pulse place extremely high demands on the stability of the RF field in the gun. Amplitude stability with a level of better than 10^{-3} will be provided with a feed forward on the basis of pick-up electrodes in the gun cavity. The jitter of the launching phase of the beam in the magnetic bunch compression mode should be less than 300 fs, which, in terms of the S-band RF phase, is 0.32°. The phase shift φ between RF source and the cavity field at a cavity detuning $\delta_f = f - f_0$ is defined by:

$$tg\,\varphi = -2Q_l\frac{\delta_f}{f_0}$$

where f_0 is the operation frequency of the cavity, $Q_l = Q_0/2$, the loaded quality factor, and Q_0 – own quality factor, which is typically equal to $1.2\cdot10^4$ for a normal conducting S-band cavity. At a frequency of 3 GHz, the phase shift of 0.32° is caused by a cavity detuning of $1.4\,kHz$. The typical thermal drift of S-band cavity resonance frequency is $df_0/dT = -50\,kHz/℃$. This gives us the requirements of peak to peak cavity temperature stability of 0.028°C. This is well below the typical performance of thermal stabilisation systems 0.1°C.

Cavity detuning due to a small mechanical deformation caused by the RF cavity heating is a dynamic process and the phase shift changes along the RF pulse following this detuning. For the single pulse modes, the required phase stability may be achieved by proper selection of the bunch launching time within RF pulse and introduction of slow feedback from arrival time monitors. For the multi-bunch operation mode of CLARA, the situation is complicated by the rise of the cavity temperature causing detuning, and consequently phase shift change along the RF pulse. For the S-band cavities this process is even more complicated, as the time, required for deformations to propagate along the cavity wall is comparable with the duration of the RF pulse. And thus, for cavity thermal analysis, the steady state approximation, typically used for analysis of long pulse L-band guns is not applicable. Very careful coupled transient analysis should be performed to satisfy the extremely high phase stability, requirements of CLARA.

Cavity Design

The RF cavity of the photoinjector must operate in both the 100 Hz regime with a cathode field of 120MV/m, delivering bunches of up to 6MeV energy and the less demanding 400Hz regime where the cathode field can be lowered to 100MV/m.

Two designs are under consideration: a 1.5 cell cavity as seen in the conventional S-band injector design [8] or a 2.5 cell design, similar to the VELA/ALPHA-X. Initial design simulations suggest that the gradient required to deliver a 6MeV beam using a 1.5 cell cavity may cause prohibitive cavity RF heating and resulting the drift of the resonance frequency. We believe that the 1.5 cell design is more flexible from beam dynamics point of view.

Two options of RF power coupling are being considered. One option is to use coaxial coupling. Coaxial coupling is advantageous as it conserves the axisymmetry of the RF field in the cavity. These coupling schemes may however require a complex engineering design and are also susceptible to multipacting. A coaxial coupler can either be implemented from the front or back of the gun. Front coupling, similar to the VELA/ALPHA-X design(see Fig. 1), is an established technology but may suffer from multipacting and heating issues.

The other option is to use side coupling with rectangular waveguides as on the LCLS gun [9]. This has the advantage of simplicity, but compromises the field symmetry in the cavity that is then transmitted to the beam. Two and four-coupler schemes are also considered to compensate the field asymmetry.

PHOTOCATHODE AND DRIVE LASER

The gun of the advanced electron source will be driven by the same Ti:Sapphire laser system operating at 400 Hz. The maximum laser pulse energy of 2 mJ and the pulse duration is 76 fs RMS results in a peak power of ~10 GW. As generated, 99% of the pulse energy is contained within a beam diameter of 20 mm and so the beam intensity is ~2 GW/cm^2. The intention is to focus the UV beam to a spot size of less than ~1 mm full width on the cathode,

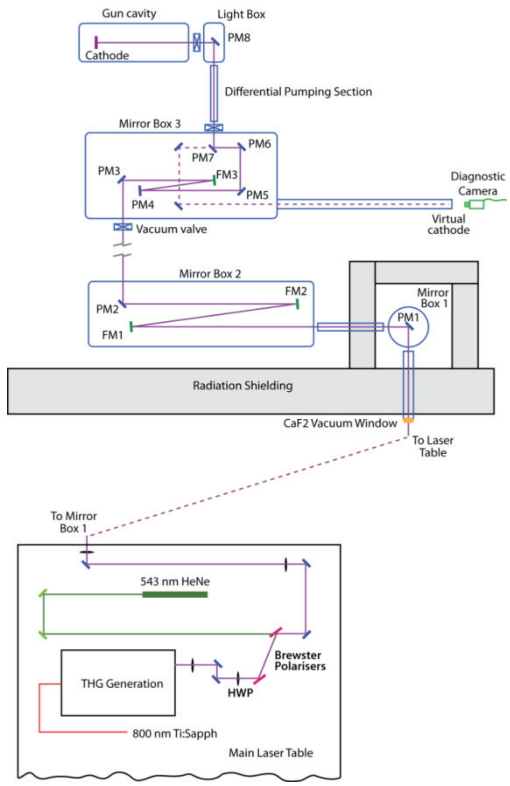

Figure 2: VELA/CLARA Laser transport system.

which will increase the beam intensity to nearly 1 TW/cm^2.

To prevent beam disruption through non-linear effects at high power, as much of the ~14 m long transport path as possible will be *in vacuo* with beam focussing achieved with mirrors instead of refractive optics. One air-to-vacuum window will be required in the laser room at the entrance to the vacuum system and this will be made from calcium fluoride to prevent two-photon absorption. The laser transport vacuum will be isolated from the gun vacuum by differential pumping so that no window will be required where the beam intensity is at its highest. See Fig. 2 for details.

The very high beam intensity also leads to the high risk of damage to the optics. All but the final mirror will have a standard ultra-fast, multi-layer dielectric coating with a high damage threshold. The final mirror sits in the injector vacuum chamber and has a simple protected aluminium coating on a copper substrate to prevent damage from accumulated electrical charge. The photon damage threshold of this mirror will be investigated experimentally on VELA.

Future developments will look at the use of higher quantum efficiency materials such as single-crystal Cu and metals such as Mg, Pb, Nb and eventually telluride based photocathodes. In order to investigate numerous photocathode materials the gun will be equipped with load-lock and transport system which will allow for easy delivery and interchange of photocathodes in the gun. The design of the photocathode plug will be chosen to provide reliable RF contact with the gun cavity. In order to keep compatibility with photocathode transport and preparation equipment already developed by other experimental group it has been decided to choose one of the existing plug design. Presently two designs are widely used: the DESY/INFN-LASA design developed in the framework of TESLA collaboration [10], which is now used at FLASH/PITZ, FNAL and LBNL, and the CERN-CTF3 design which is also used by PSI for the SwissFEL project.

The photocathode will be initially prepared in a dedicated preparation system based on the upgraded Vacuum Generators ESCALABII facility being set up at ASTeC. Preparation of metal photocathodes will include *ex vacuo* chemical and *in vacuo* thermal cleaning and surface processing with O_3 plasma in order to remove carbon contaminants. This procedure demonstrated good results during VELA commissioning. Surface analysis of the prepared photocathodes will be made with high resolution X-ray photoelectron and Auger spectroscopy. The prepared photocathodes will be transported to the accelerator hall in a vacuum vessel which will be attached to the gun load-lock system. and then inserted into the gun. This procedure will allow for maintaining the ultra-high vacuum conditions in the gun and replace photocathodes in tens of minutes. A load-lock system will also allow for investigation of a broad range of photocathodes in order to obtain materials for optimal CLARA performance as well as choices for future FEL facilities.

CONCLUSION

The analysis of the requirements to the ultimate performance gun for the CLARA facility leads to the 1.5-cell design equipped with a pickup electrodes, coaxial coupler and photocathode load-lock system. Very demanding phase stability in the gun requires a beyond state of the art temperature stability of the cavity and a local phase correction within the RF pulse.

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