PHIN photo-injector as the CLIC drive beam source

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Abstract. The Compact Linear Collider (CLIC) study proposes a multi-TeV, high luminosity, electron-positron linear collider in order to fulfill the current need for a lepton collider. The study has been started in the late 80s at CERN and currently is a joint effort with a collaboration of 40 institutes. An innovative scheme of high peak RF power production for the high accelerating gradient has been proposed for CLIC. The so called “two-beam scheme” consists of two beams that are running parallel to each other. One of the beams is to be accelerated for the collision experiments and called “the main beam”. The second beam of the CLIC scheme is “the drive beam” and will be employed for the power production. The quality of the main beam acceleration depends on the stability of the power that is generated by the drive beam. Therefore, the optimization of the drive beam production with the proper time structure and within the required beam dynamics tolerances is one of the most important accelerator physics aspects of the project. Currently in the conceptual level, the baseline design of the drive beam injector consists of a thermionic gun. This electron source has to be combined with a sub-harmonic bunching system in order to provide the required time structure of the drive beam. However, a big disadvantage of this scheme is the parasitic satellite bunches that are produced due to the sub-harmonic bunching system. PHIN photoinjector has been raised as another option in order to replace the existing thermionic gun of CLIC test facility (CTF3) and to form the bases of a source for the CLIC drive beam. The PHIN project is in the framework of the European CARE (Coordinated Accelerator Research in Europe) program.

1. Introduction

Within the CLIC study [1, 2], an RF system has been proposed by using normal accelerator cavities operating at 12 GHz, in pulses 239 ns long, with the nominal accelerating gradient of 100 MV/m. The implementation of such cavities would result a total machine length of 48 km for a 3 TeV centre of mass energy of colliding beams.

The choice of an optimum acceleration frequency is an essential item of optimization for the linear collider studies. This optimization is done concerning the RF power consumption and the achievable accelerating gradient. In the last fifty years, a significant number of research activities have been carried out under the assumption that the achievable accelerating gradient extends with the increasing RF frequency [3, 4]. The limitation comes from the phenomenon called RF breakdown and the early investigations has been done by Kilpatrick [5] in 1957. The RF breakdown is a localized dissipation of energy on the accelerating structure surface due to high electric or magnetic fields. The process causes distortions such as crater forming and melting on the structure surface. The experimental results confirm that the gradient limit increases
with the square root of the frequency in a range of 300 MHz to 3 GHz in agreement with the Kilpatrick criteria in Eq. (1),

\[ f[MHz] = 1.64 E^2[MV/m] e^{-\frac{8.5}{E[MV/m]}}, \]

where \( f \) is the RF frequency in MHz and \( E \) is the maximum electric field in MV/m.

The accelerating structure development is a crucial research activity within the CLIC study. The aspects of this research are studying the RF breakdown phenomenology and determining the limitations on the achievable accelerating gradient. The experiments focus on the RF frequency and pulse length dependence of the phenomenon as well as the impact of the material type and the surface treatment of the structures. The target structure should operate at low RF breakdown rates and remain undamaged against the inevitable RF breakdowns and RF heating. Among several designs, the candidate structure for CLIC has demonstrated an extremely low RF breakdown probability of less than one in \( 10^7 \) pulses. The tests have been done for 100 MV/m at the nominal pulse length. The mentioned accelerating structure can be seen in Figure 1.

![Accelerating Structure for CLIC](image)

**Figure 1.** An accelerating structure for CLIC that has been tested to 100 MV/m. Designed at CERN, the components were manufactured by KEK and the assembly and bonding as well as testing with high-power RF was done by SLAC (Courtesy SLAC).

## 2. Description of the CLIC General Layout

The general CLIC layout is shown in Figure 2. An innovative scheme of high peak RF power production for the high accelerating gradient has been proposed for CLIC. The so called “two-beam scheme” consists of two beams that are running parallel to each other. The overall CLIC parameters as indicated in the conceptual design studies in 2010 is given in Table 1.

One of the beams is to be accelerated for the collision experiments and called “the main beam”. For a linear collider providing the colliding beams of high charge and ultra-low emittance is essential to obtain high collision luminosity. This implies the requirement for an injection system that has been designed, efficiently. The lower part of the layout illustrates the injector system for the CLIC main beams. The pre-damping and the damping rings are shown as a part of the system. These rings have been designed to reduce the beam emittance of the high charged electron and positron beams. The circumference, therefore the design of the optical lattice of the damping rings can be accomplished by considering the beam parameters such as injection emittance, number of bunches in the bunch trains, bunch spacing and bunch charge. The necessary extraction emittance is obtained depending on the damping time, which determines the energy of the ring. More details on the damping ring design and issues can be found in reference [6]. The pre-damping rings of CLIC has been designed to receive a 2.86 GeV beam with a large emittance. They reduces emittance of electron and positron beams before the
Table 1. Overall CLIC parameters from 2010 conceptual design study.

| Parameter                                             | Value       |
|-------------------------------------------------------|-------------|
| Centre of Mass Energy (GeV)                           | 3000        |
| Main Linac RF Frequency (GHz)                         | 11.994      |
| Luminosity \( (10^4 cm^{-2}s^{-1}) \)                 | 5.9         |
| Linac Repetition Rate (Hz)                            | 50          |
| Number of Particles / Bunch                          | \(3.72 \times 10^9\) |
| Number of Bunches / Train                             | 312         |
| Bunch Separation (ns)                                 | 0.5         |
| Bunch Train Length (ns)                               | 156         |
| Beam Power / Beam (MW)                                | 14          |
| Unloaded / Loaded Gradient (MW/m)                     | 120 / 100   |
| Overall Two Linac Length (km)                         | 42.16       |
| Total Beam Delivery System Length (km)                | \(2 \times 2.75\) |
| Proposed Site Length (km)                             | 48.4        |
| Total Site AC Power (MW)                              | 415         |
| Wall Plug to Main Beam Power Efficiency (%)           | 7           |

injection to the damping rings. Damping rings produce the ultra-low emittance needed for the luminosity performance of CLIC [7, 8]. Some of the beam parameters before and after the pre-damping rings, and damping rings are given in the Table 2.

Additionally, further emittance reduction is possible by minimizing the emittance growth due to wake fields that are generated by the beam itself. The accelerating cavities of the main linac have been optimized in order to minimize this effect. Eventually, after the beam delivery system, the beam has the emittances of 1 nm rms and 40 nm rms, in the vertical and horizontal planes, respectively.

The second beam of the CLIC scheme is “the drive beam” and will be employed for the power production. The two-beam scheme should deliver a power of 275 MW per active accelerating
Table 2. The parameters for the CLIC main beams before and after the pre-damping rings.

|                          | Pre-Damping Rings | Damping Rings |
|--------------------------|-------------------|---------------|
| e⁻ Injected              | 4.7               | 4.5           |
| e⁺ Injected              | 6.4               | 4.1           |
| Bunch Population (10⁹)   | 1                 | 10            |
| Bunch Length (mm)        | 1                 | 0.5           |
| Bunch Spacing (ns)       | 0.5               | 312           |
| Energy Spread (%)        | 0.07              | 1             |
| Longitudinal Emittance (keV.m) | 2        | 0.5           |
| Horizontal Normalized Emittance (µm) | 100  | 6.10³         |
| Vertical Normalized Emittance (µm) | 100  | 5.10³         |

metre, which is necessary to produce the electric fields of 100 MV/m. The drive beam generation system can be seen in the upper part of the layout. The stability of the main beam acceleration depends on the stability of the power that is generated by the drive beam. Therefore, the optimization of the drive beam production with the proper time structure and within the required beam dynamics tolerances is one of the most important accelerator physics aspects of the project.

3. Power Generation for CLIC: Drive Beam and Its Injector Specifications

The two-beam acceleration scheme of CLIC Study proposes a unique power production technique. The scheme eliminates the utilization of the conventional klystrons which are not capable of providing high peak power required by the CLIC accelerating structures (275 MW/m), efficiently. This also prevents the additional underground building of a scheme with klystrons.

The drive beam consists of a high current (101 A), low energy (2.37 GeV) beam with a repetition rate of 12 GHz. The design specifications of drive beam is shown in Table 3. The high current is needed for the high peak power production in the so called “Power Extraction and Transfer Structures (PETS)” [9].

According to the CLIC scheme, the drive beam is generated as a long train (139 µs) of electron bunches. The separation between the individual bunches is 60 cm. This beam with a large bunch separation is accelerated up to 2.37 GeV in a linac with high efficiency, using the fully-beam-loaded acceleration mode [10]. In this mode, the most of the RF power is transferred to the beam so that the accelerating gradient in the end of the structure reduces nearly down to zero. Short RF structures are used in order to minimize the ohmic losses.

Table 3. The baseline parameters of the CLIC drive beam from the conceptual design studies (2010).

| Parameter                              | Value  |
|----------------------------------------|--------|
| Energy (decelerator injection) (GeV)   | 2.37   |
| Energy (final, minimum) (MeV)          | 237    |
| Average Current in the Pulse (A)       | 101    |
| Train Duration (ns)                    | 243.7  |
| Number of Bunches / Train              | 2922   |
| Bunch Charge (nC)                      | 8.4    |
| Bunch Separation (ns)                  | 0.083  |
| Bunch Length (rms) (mm)                | 1      |
| Normalized Emittance (rms) (mm mrad)   | 150    |
The drive beam linac is built by using normal conducting accelerating structures that operate at 1 GHz. Those structures are powered by the conventional klystrons. A series of rings are located in the drive beam generation system. These rings can be seen in Figure 2 as “delay loop” and two successive “combiner rings (CR1 and CR2)”\textsuperscript{1}. This system of three rings is designed to achieve the frequency multiplication of the drive beam in order to increase its peak current up to 101 A. This innovative technique is used to increase the beam current and it is called “the beam recombination”. In the delay loop, the 139 $\mu$s long bunch train is divided into 24 sub-trains with the length of 243.7 ns. The 500 MHz RF deflectors are used to separate the “even” and “odd” buckets to be transferred to the delay loop or toward CR1 and CR2 that are equipped with RF deflectors of 1 GHz and 3 GHz, respectively. The “even” buckets are delayed while they are circulating the delay loop. Then they are interleaved between the “odd” buckets by means of the combiner rings. After the whole procedure, the 24 sub-trains form a burst with the average beam current of 101 A. The time structure of the drive beam before and after the “beam recombination process” is shown in Figure 3.

![Figure 3. The schematic of the beam recombination and the time structure of the drive beam before and the beam recombination process.](image)

The drive beam system generates 24 of such bursts with the separation of 5.8 $\mu$s and sends them to the decelerators for the power production. A decelerator module houses PETS, quadrupoles and high power RF networks. The layout of the CLIC two-beam module can be seen in Figure 4-a. When the bursts of drive beam enters one of the PETS, it excites preferentially the synchronous mode by interacting with the impedance of the periodically loaded waveguide. In this way, a single PETS generates 12 GHz RF power and drives two accelerating structures of the main beam, as shown in Figure 4-b.

4. Photo-injector Option for the Drive Beam
A photoinjector is an electron source that uses laser pulses in order to extract electrons from the surface of a metallic or a semiconductor cathode. The electrons can escape the cathode surface provided that the laser pulses satisfies the energy to decrease the potential barrier of the surface. The cathode plug is placed in one end of an RF cavity. This RF cavity is used for the rapid acceleration of the electrons after the production. The photoinjectors are high brightness, low emittance electron beam sources. The theory and implementation of them date back to 80s.
A photo-injector option for CLIC drive beam has been also discussed during the early stages of the test facility studies [11]. The previous studies for the CLIC photo-injector can be found in the reference [12]. Indeed, there would be certain advantages of implementing an RF gun as the CLIC drive beam injector.

First of all, as a laser-driven system, a photo-injector can provide flexibility in manipulating the time structure of the beam. This manipulation is provided by a phase coding technique of a laser system. Moreover, in drive beam linac every second bucket is populated and the interleaving buckets are supposed to be empty. However, the parasitic charge in the supposedly-empty buckets is inevitable due to the bunching system. Those bunches are called "the satellite bunches". The charge in the satellite bunches can cause radiation problems and compromises the power production efficiency. The necessary time structure can be provided by a photo-injector without producing this parasitic charge.

A photo-injector can provide a beam with small transverse and longitudinal emittances compared to a thermionic gun. Therefore, the beam transportation and bunch length manipulation become easier throughout the machine. A photo-injector is capable of producing long electron pulse trains by ensuring the stability of the beam parameters within the defined tolerances.

The feasibility research on the implementation of a photoinjector as the current CTF3 and future drive beam source is the main objective of the commissioning of the PHIN photoinjector. During the PHIN commissioning, the produced electron beam has been characterized in terms of the longitudinal and transverse properties.

5. Instrumentation and Experimental Methods for PHIN

The PHIN photoinjector consists of a semiconductor photocathode, a laser system and the RF gun and a set of solenoids for focusing. The test-stand at CERN also houses a section with various instruments to measure the transverse and the longitudinal beam parameters with different techniques.

The measurement section has been equipped with the beam current monitoring instruments such as a fast current transformer, a beam position monitor, a wall current monitor and a Faraday cup. The OTR profiling has been widely used in the system in order to measure the size, the transverse emittance and the energy of the beam. A magnetic spectrometer has been installed in the beam line. In addition, the spectrometer set-up includes a segmented beam dump.

Figure 4. a) Schematic of the CLIC two-beam acceleration module. b) The illustration of two-beam acceleration.
The demonstration of the stability along the 1.3\(\mu\)s bunch train is one of the main focuses of the PHIN project. Therefore, the time-resolved measurements give the substantial results of the PHIN commissioning. In the beamline, the time resolved measurements were done by using gated-intensified CCD (Charge Coupled Device) cameras in order to be used for the OTR monitoring. The segmented dump monitors the energy and the energy spread as a function of time.

This section introduces the specifications of the building blocks for the PHIN photoinjector.

5.1. \(Cs_2Te\) Cathode Preparation for PHIN at CERN Photo-Emission Laboratory
The electrons of the PHIN photoinjector are extracted from a semiconductor \(Cs_2Te\) cathode, which is mounted on one end of a 2 + 1/2 cell RF gun. The cathode has been developed by the CERN photoemission laboratory and they have demonstrated a lifetime to allow > 100h run at a 3% quantum efficiency for a 262 nm laser wavelength [13]. Excellent vacuum conditions, below 10\(^{-11}\) mbar can be obtained by applying a bake-out at 300\(^\circ\)C to achieve this lifetime.

The cathodes are prepared by co-evaporation of \(Cs\) and \(Te\) on a copper plug. After the preparation, they have to be transferred from the photoemission laboratory to the experimental area. The cathode transfer chamber, the so-called “Transport Carrier” (or T.C.), is a mechanical device designed to receive and deliver up to four photocathodes, under Ultra High Vacuum conditions (U.H.V.), from the photo-emission laboratory to the PHIN photo-injector.

Before the measurements at the PHIN set-up, a bake-out at 130\(^\circ\)C has been done. The vacuum value of \(~3 \times 10^{-10}\) has been measured in the set-up without the RF and the beam. During the measurements a vacuum value of \(~10^{-9}\) mbar have been maintained in the existence of the RF and the beam.

5.2. Laser System
In order to provide the laser pulses for PHIN, initially a Nd:YLF oscillator produces laser pulses at a repetition rate of 1.5 GHz with an average power of \(P = 10\) W in a continues wave (CW) train.

![Figure 5. Layout of the laser system.](image)

The layout of the laser is shown in Figure 5. In the layout, after the pre-amplification, two additional amplification stages follow in order to increase the laser power from 10 W CW power to 9 kW of quasi continues wave (QCW) mean power.

The length of the pulse train can be adjusted between 50 ns and 170\(\mu\)s by using the Pockels cells [14, 15, 16]. The nominal pulse train length for the PHIN photoinjector is 1.27\(\mu\)s. The
PHIN laser has been designed to produce pulse trains at a repetition rate of up to \(50 \text{Hz}\). A temporal structure that consists of a macropulse repetition rate of \(1 - 5 \text{Hz}\) has been used during the measurements.

After the UV conversion the cathode is illuminated by the laser train of 1908 pulses (1.27\(\mu\text{s}\)) at the wavelength of 262 nm and with the energy of 370 \(\text{nJ/Pulse}\). This is the nominal energy in order to extract the bunch charge of 2.33 nC assuming the quantum efficiency of 3\%. The laser spot size on the photocathode can be changed within a range of 0.1 – 5 mm (4\(\sigma\)). The micropulse width of \(~6.5 (\pm0.41)\) ps (FWHM) has been measured for the UV laser.

During the commissioning runs a laser with the pulse train length of 200 – 1300 ns was used, alternatively, obtaining 300 – 1950 bunches. The laser spot sizes of 2, 3, 4 mm have been used for different measurements.

5.3. Design and Simulations for the PHIN RF Gun

The laser-driven PHIN RF gun consists of a 2 + 1/2 cell normal conducting S-band standing wave cavity [17]. The gun has been designed by LAL and it has been installed on the PHIN beamline at CERN. The design has been based on a previous prototype CERN RF gun. The previous design has been modified for the PHIN gun in order to provide the specifications that are needed by a possible CTF3 photoinjector. The specifications for the PHIN RF gun are summarized in the Table 4. The design of the RF gun aims to maximize the vacuum pumping speed which increases the dynamic vacuum. Therefore, a Non Evaporable Getter (NEG) thin film has been implemented on the wall of the anti-chamber that is placed around the cavity. A photograph of the PHIN RF gun is shown in Figure 6.

| Parameter                     | Value       |
|-------------------------------|-------------|
| RF Frequency (GHz)            | 2.99855     |
| RF Power (MW)                 | 30          |
| Gradient (MV/m)               | 85          |
| Vacuum Pressure (mbar)        | \(2 \times 10^{-10}\) |
| Beam Energy (MeV)             | 5.5         |
| Beam Current (A)              | 3.5         |
| Charge / Bunch (nC)           | 2.33        |
| Bunch Length (ps)             | 10          |
| Energy Spread (%)             | \(\pm1\)    |
| Normalized Transverse Emittance (mm mrad) | 25 |
| Pulse Length Duration (\(\mu\text{s}\)) | 1.27 |
| Vacuum Pressure (mbar)        | \(2 \times 10^{-10}\) |

The \(\pi\) resonance mode is used for the acceleration in the PHIN RF gun which corresponds to a frequency of 2.99855 GHz. This mode has been presented in Figure 7-a from the result of SUPERFISH simulation program. The on-axis electric field that is excited on the cavity is presented in Figure 7-b.

6. Experimental Results of the PHIN Commissioning

The PHIN photoinjector has been commissioned with the intermittent runs between 2008 and 2010 with a total beam time of 60 workdays. The studies led to an eventual success by fulfilling the design specification which are given in Table 5. The earlier results of the PHIN commissioning can be found in reference [18]. The latest commissioning measurements have been focused on
Figure 6. A photograph from the laser-driven PHIN RF gun that consists of a 2 + 1/2 cell normal conducting S-band standing wave cavity.

Figure 7. a) Illustration of the electric field in the cavity that is excited in the $\pi$-mode. The figure obtained as the result of the SUPERFISH simulation for the 2+1/2 cell normal conducting S-band standing wave PHIN cavity. b) The on-axis electric field that is excited in the PHIN RF gun for the $\pi$ mode.

In order to provide the drive beam requirements in terms of the time structure of the beam, a phase coding system has been developed and installed in the laser system. The details of the phase coding stage and the measurement on the phase coded electron beam will be soon presented in the International Particle Accelerators Conference (IPAC 2011) [20, 21].
Table 5. The specifications for the PHIN photoinjector.

| Parameter                  | Specification |
|----------------------------|---------------|
| **Laser**                  |               |
| UV Laser Pulse Energy (nJ) | 370           |
| Micropulse Repetition Rate (GHz) | 1.5         |
| Macropulse Repetition Rate |               |
| Train Length (ns)          | 1273          |
| **Electron Beam**          |               |
| Charge per Bunch (nC)      | 2.33          |
| Charge per Train (nC)      | 4446          |
| Current (A)                | 3.5           |
| Transverse Normalized Emittance (mm mrad) | 25          |
| Energy Spread (%)          | 1             |
| Energy (MeV)               | 5.5           |
| Charge Stability (% rms)   | 0.25          |
| **RF Gun**                 |               |
| RF Gradient (MV/m)         | 85            |
| RF Frequency (GHz)         | 2.99855       |
| Cathode                    | Cs$_2$Te      |
| Quantum Efficiency (%)     | 3             |

7. Conclusions
Throughout this paper the photoinjector concept has been introduced. The PHIN experimental set-up and a variety of accompanying beam diagnostics instrumentation have been described. The PHIN commissioning has been continued with the intermittent runs between 2008 and 2010. The experimental program has achieved the full characterization of the PHIN photoinjector for the short and the long bunch trains. The results table of the beam characterization measurements have been presented in comparison with the design specifications.

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