HIGH CHARGE PHIN PHOTO INJECTOR AT CERN WITH FAST PHASE SWITCHING WITHIN THE BUNCH TRAIN FOR BEAM COMBINATION

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Abstract

The high charge PHIN photo-injector was developed within the framework of the European CARE program to provide an alternative to the drive beam thermionic gun in the CTF3 (CLIC Test Facility) at CERN. In PHIN 1908 electron bunches are delivered with bunch spacing of 1.5 GHz and 2.33 nC charge per bunch. Furthermore the drive beam generated by CTF3 requires several fast 180 deg phase-shifts with respect to the 1.5 GHz bunch repetition frequency in order to allow the beam combination scheme developed at CTF3. A total of 8 sub-trains, each 140 ns long and shifted in phase with respect to each other, have to be produced with very high phase and amplitude stability. A novel fiber modulator based phase-switching technique developed on the laser system provides this phase-shift between two consecutive pulses much faster and cleaner than the base line scheme, where a thermionic electron gun and sub-harmonic bunching are used. The paper describes the fiber-based switching system and the measurements verifying the scheme. The paper also discusses the latest 8nC charge production and cathode life-time studies on Cs2Te.

INTRODUCTION

PHIN photo-injector was developed in collaboration with LAL, CCLRC and CERN as an alternative to the thermionic source for CTF3 drive beam [1-2]. Table 1 shows the achieved and nominal parameters as well as the CLIC goals. A detailed description of the commissioning needed to reach nominal parameters can be found in [3]. Here we report on the latest development work towards the full feasibility of the system including phase-coding for beam combination and the study of charge scaling towards CLIC requirements.

PHASE-CODING

One of the main goals of CTF3 is to demonstrate the beam combination, which provides the high power to feed the 12GHz two-beam accelerating structures tested for CLIC [4]. Several fast 180 deg phase-shifts with respect to the 1.5 GHz bunch repetition rate are needed over the 1.2μs long train in order to allow the beam combination scheme using a 1.5GHz RF deflector. A total of 8 sub-trains, each 140 ns long and shifted in phase with respect to each other, have to be produced with very high phase and amplitude stability.

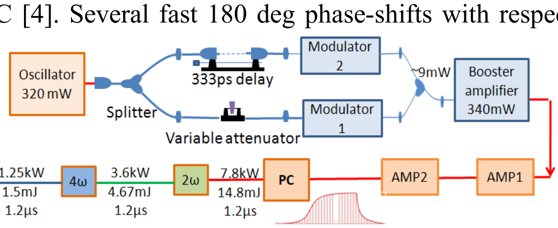

Fig.1: Laser chain with phase-coding

Table 1. Injector parameters for PHIN and for the future CLIC drive beam

	Achieved	Nominal	CLIC
Charge per bunch (nC)	8.1	2.3	8.4
Train length (μs)	1.2	1.2	140
Number of sub-pulses	8	8	24x24
Norm. emittance (π-mm-mrad)	14 (at 2.3nC)	<25	<100
Energy spread	0.7%	<1%	<1%
Energy (MeV)	5.5	5.5	50
Charge stability (r.m.s)	1-2%	<0.25%	0.1%
UV laser pulse energy (nJ)	500	370	1500
Typical cathode lifetime at QE>3%	>40h	>50h	>150

The currently used thermionic gun uses sub-harmonic bunching and fast RF phase-switches to achieve the time structure required [5]. However the sub-harmonic bunching produces unwanted charge in the supposedly empty RF buckets, which in turn causes radiation and efficiency losses during combination. This could prove to be a limitation for CLIC long train operation. Also due to the bandwidth limit of the phase-switch, the transition between opposite phases takes place over several bunches.

Laser

As short bunches are produced directly from the laser pulses in PHIN, fiber modulator based phase-switching on the laser itself provides a clean solution for the beam combination. With this scheme 180^{o} phase-shift (respect to 1.5GHz) can be achieved between two consecutive pulses without satellites. Phase-coding incorporated into the laser system described in [3] is shown on Fig.1. The IR output of 1.5 GHz Nd:YLF laser oscillator is injected into a fiber and split on two arms containing two fast fiber optics modulators driven by 7.1 MHz square waves signal synchronized with laser frequency. The modulators select the odd and even sub-trains after the oscillator, while an optical path delay and an attenuator set the phase difference and amplitude balance between them. In detail the phase-coding system is described in [6]. After recombination of the train, the time structure shown in Fig.2 is produced for the amplification window of the burst mode amplifiers. An accuracy of 0.2 ps in time and 0.4% in amplitude was achieved, limited by the manual adjustability of the delay line and the noise arriving from the laser oscillator.

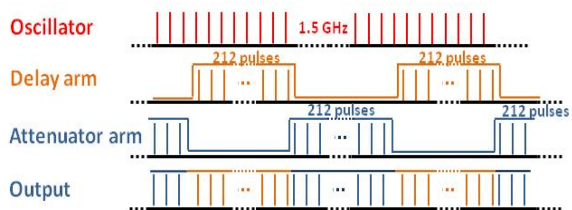

Figure 2. Timing structure created by the phase-coding showing odd and even sub-trains with 180deg phase difference.

The signal is then amplified to 200mW using a fiber amplifier (Fianium FPA-320mW) to bring the power level back to the oscillator's level and coupled back into the rest of the laser chain, bypassing the solid state pre-amplifier used in the past. Switching was verified on the laser system by the use of streak camera after full amplification at the IR and second harmonic stage. Extinction ratios of 1:300 were achieved from the modulators in the IR, which improves further in the UV due to the non-linear conversion process. This provides satellite free switching well below the 1:100 contrast requirement.

Beam Dynamic Measurements

Fig.3. shows the diagnostic beamline of PHIN. To further check the time-structure of the produced phase-coded beam, a Cherenkov target (300µm thick aluminium coated Sapphire plate) was installed in the same place as the OTR screen. Moveable screen and target allows either

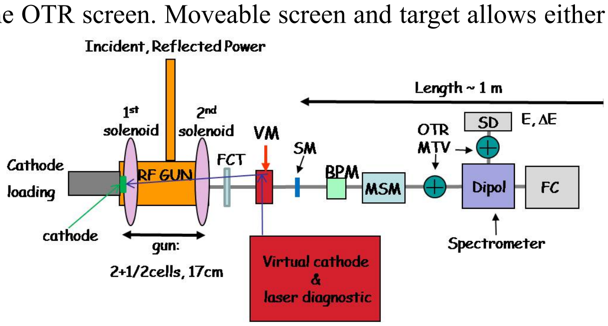

Figure 3. Layout of beam diagnostics
FCT: Fast current transformer; VM: Vacuum mirror; SM: Steering magnet; BPM: Beam position monitor; MSM: Multi-slit Mask; OTR: Optical transition radiation screen; MTV: Gated cameras; SD: Segmented dump; FC: Faraday cup

beamsize, emittance or the Cherenkov measurement. Figure 4. shows the measurements carried out with the Cherenkov-light transported back to the streak-camera in the laser room. The clean phase-shift (180deg at 1.5GHz) can be seen with no measurable satellites.

Extensive emittance and energy measurements were carried out in the past [7]. Our aim here was to measure these parameters along the bunch train with the phase-coded beam. Gating time was set to 100ns to see the changes from odd to even sub-pulses. No degradation of beamsize, emittance or energy was observed along the train due to the phase-coding [6]. A fast current transformer installed after the gun is capable of measuring with <1% accuracy the charge variation induced by changing the balance between the arms of the phase-coding.

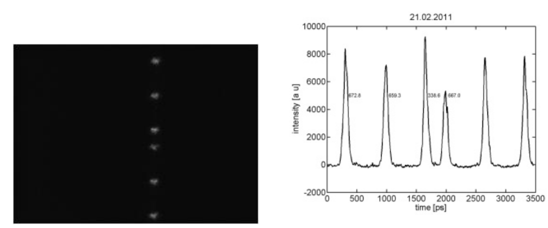

Fig.4. 333ps switching between two consecutive bunches measured with the Cherenkov-radiation. Fast amplitude variations are due to laser oscillator noise.

CATHODE

Saturation effect due to space charge at the cathode was observed in previous experiments [3], limiting the extractable charge/bunch to 4.4nC. This effect was investigated and overcome by using a larger laser beamsize on the cathode and by optimization the laser beam transport to accommodate for this. The CLIC drive beam injector has to deliver a nominal 8.4nC/bunch at 500MHz repetition rate with 140µs long bunch-trains at 50Hz. To understand the scaling, which would be required for a future photo-injector, the aim was to produce ~8nC charge/bunch in PHIN. The lifetime depending on number of bunches, bunch charge and vacuum conditions were also investigated as change over time of the cathodes can be a disadvantage of the photo-injector compared to the thermionic source.

High charge production

Cs_2Te cathodes have a long tradition at CERN with a dedicated photo-emission lab, producing and studying photo-cathodes for high brightness electron sources [8]. In the past Cs_2Te has shown the ability to produce >10nC charge in a single bunch in CTF2 facility with a 100MV/m gradient gun [9]. In PHIN with the 85MV/m gradient, charge was limited to 4.4nC in the past due to saturation. According to Travier's [10] estimation for maximum extractable charge (Q_{max}) for a photo-gun:

$$Q_{max}[nC] = E_{ac}[MV/m] \cdot \sigma^2[mm]/20.2 \qquad (1)$$

, where E_{ac} is the acceleration gradient in the gun, σ is the rms beamsize of the laser beam on the cathode. Using a simple saturation model:

$$Q_{extr}(E_l) = Q_0(E_l)\cdot \exp\left(\frac{-QD_0(E_l)}{QD_{sat}}\right) \qquad (2)$$

,where Q_0 and QD_0 is the maximum charge and charge density extractable with given quantum efficiency and beamsize with no saturation at E_l laser energy on the cathode. QD_{sat} is the saturation parameter. From previous experiment $QD_{sat}=QD_{max}\cdot 0.43=25.2\text{nC/mm}^2$ can be determined. With a larger 1.4mm sigma beamsize no saturation was expected at the given energy levels, which was confirmed and allowed us to reach 8nC bunch charge. The beamsize is however limited to this value due to beam transport, although the cathode has 16mm of clear aperture.

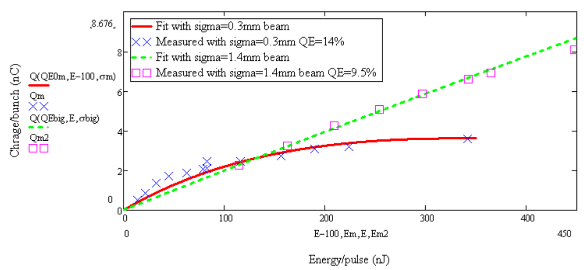

Fig 5. Measured charge/bunch as a function of beam size and laser energy with measured and fitted values

Cs2Te lifetime measurements

With the excellent 10^{-11}mbar vacuum in the DC gun of the photo-emission laboratory, the lifetime was >350h with QE still remaining over 8% [9].

However in the RF gun the dynamic vacuum levels are ~$4\cdot10^{-9}$ mbar peaking to ~$2\cdot10^{-8}$ mbar in some cases during and after breakdowns. The laser energy and the charge (FCT) were measured for every shot over 40 hours of continuous operation. QE as a function of the vacuum/ train-length and bunch charge has been studied (Fig.6.). Initial measurements show a correlation between vacuum level and lifetime. Degradation process of the vacuum needs to be understood and appears to be dependent on the extracted charge. With all cathodes we have observed a fast drop of QE in the first 2-3 hours. In this particular case this was followed with 1/e lifetime of >110 hours at

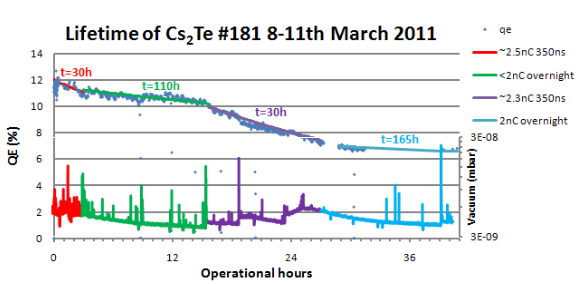

Fig.6.: Cathode lifetime measurement showing 1/e lifetime and vacuum conditions

2nC bunch charge and vacuum levels at ~$4\cdot10^{-9}$ mbar and significantly worse at >2.3nC bunch charge at ~$6\cdot10^{-9}$ mbar.

CONCLUSION

PHIN photo-injector delivers the full specifications to provide an alternative to the CTF3 thermionic drive beam injector. Recently demonstrated fiber-optic modulator based phase-coding provides clean switching between two consecutive bunches and thus overcomes the losses introduced in the currently used sub-harmonic bunching and RF phase-switching scheme on the thermionic source. Beam dynamics measurements show no significant difference between the odd and even sub-trains.

Lifetime studies for Cs_2Te cathodes have been carried out with unusually high average currents and the scaling of the charge to the nominal CLIC value of 8 nC/bunch was demonstrated. A clear correlation with vacuum degradation was shown. Further studies of the lifetime dependence on beam parameters and an improvement of the vacuum conditions are planned for future runs as well as tests of Cs_3Sb cathodes responsive to green light.

Laser development to produce long train of 140µs with nominal average power levels for CLIC will continue in the next two years.

REFERENCES

[1] G. Geschonke, A. Ghigo, "CTF3 design report" CTF3 note 2002-047, CERN; CERN/PS 2002-008(RF); LNF-02/008 (IR).

[2] H. Braun et al, "The Photo-Injector Option for CLIC: Past Experiments and Future Developments", Proc. of PAC (2001), Chicago

[3] M.Petrarca et al., "Performance of the PHIN high charge photo injector", Proc. of IPAC, Kyoto, Japan, (2010) THPEC032, 4124

[4] C.P.Welsch et al., "Longitudinal beam profile measurements at CTF3 using a streak camera", (2006) JINST 1 P09002

[5] P.Urschütz et al., "Beam dynamics and first operation of the sub-harmonic bunching system in the CTF3 injector", Proc. of EPAC, Edinburgh, Scotland, (2006), 795

[6] M.Csatari Divall et al. "Fast phase switching within the bunch train of the PHIN photo-injector at CERN using fiber-optic modulators on the drive laser" Nucl. Instr.& Meth. A (submitted)

[7] O. Mete et al., "Production of long bunch trains with 4.5µC total charge using the PHIN photo-injector" (in progress)

[8] G. Suberlucq, "Development and production of photo cathodes for the CLIC Test Facility", Free Electron Lasers (1996), p. II-131, 1997 Elsevier Science B.V.

[9] E. Chevallay et al., "Photo-cathodes for the CERN CLIC Test Facility", KEK APAC (1998) TH4046 972

[10] C. Travier et al., Nucl. Instr.& Meth. A, 340 (1994) 26-39