CTF3 3 GHz RF gun test at CERN

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Abstract

This PHIN note is the last deliverable provided by the JRA2-PHIN. It describes the first results obtained with the CTF3 photo-injector installed at CERN where an electron beam has been produced in November 2008.

The installation of the new photo-injector foreseen for the CTF3 Drive Beam has been completed on a dedicated stand-alone test bench in the CTF2 hall. The photo-injector operates with a 2.5 cell RF gun working at 3 GHz. A 30 MW modulator-klystron provides the necessary power to the RF gun in order to get an accelerating field of 85 MV/m. A UV laser beam at 262 nm illuminates the Cs_2Te photocathode. The Nd:YLF laser system consists of an oscillator, a preamplifier operating at 1.5 GHz and two powerful amplifier stages. The infrared radiation (1047 nm) produced at the source has its frequency quadrupled in two stages to obtain the UV light (262 nm). The synchronization between the RF and the laser is better than 1 ps. The train length for CTF3 is 1.272 μs. There are 1908 bunches in the train. Assuming a quantum efficiency of the photo-cathode of 3% and a laser energy of 370 nJ/pulse on the photo-cathode, the requested charge of 2.3 nC per bunch could be obtained. The first photoelectron beam in PHIN has been produced with smaller bunch charge but the results presented in this note show that the main objectives of the PHIN deliverable, as defined in 2003, have been reached.

1. Introduction

The CTF3 photo-injector was proposed to improve the injector of the existing facility at CERN. The goal is to replace the thermionic gun of the CTF3 Drive Beam injector by this PHIN photo-injector. The design was done in collaboration of three Institutes: CERN, LAL and RAL.

The laser system has been designed and purchased by RAL. The material was transferred to CERN in September 2006 but the system was not working with the requested performance. Unfortunately from this time, RAL was not anymore in position to provide further developments and support. Therefore the testing and development of the laser system was continued in collaboration between CERN, INFN Frascati, University of Milano and CEA of Saclay.

The RF gun has been designed and purchased by LAL. Within the framework of the JRA2-PHIN, LAL has built 2 RF guns, one for CTF3 and one for the NEPAL station in Orsay. Unfortunately the first one foreseen for CERN was not useable due to brazing problems. Therefore the RF gun foreseen for NEPAL was given to CERN following an agreement between both laboratories.

The Cs_2Te photocathode has been built by CERN and was stored for almost one year in the transport carrier. Summaries of these activities are given in [1] and [2].

2. The CTF3 laser system

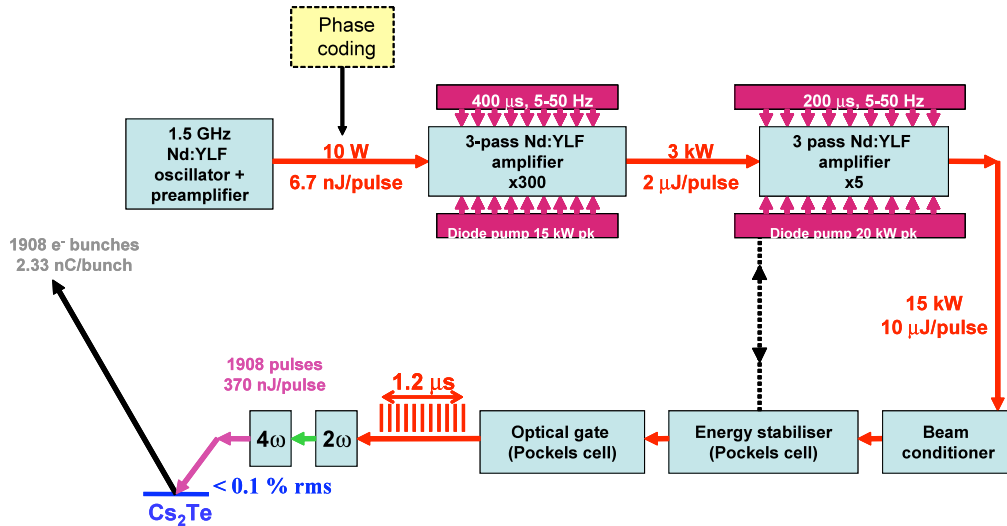A schematic layout of the laser system is given in Figure 1.

Figure 1: CTF3 photo-injector laser system

A Nd:YLF oscillator produces vertically polarized pulses at a repetition rate of 1.5 GHz (~ 666 ps between two consecutive pulses) with an average power P~300mW. The central wavelength is 1047nm and the pulse time width is ∼6 ps [3]. The pulses are amplified by a Nd:YLF "preamplifier" which brings the average power to 10W with the same pulse length and the same wavelength. After the oscillator there will be a special device called "Phase Coding" (not yet installed).

Then there are two powerful Nd:YLF amplifiers: the first amplifier is pumped by 5 slots of diode lasers symmetrically arranged around the rod. The diode pump peak power is 15 kW and its amplification window is ~ 400 μs. The measured output power is 3 kW as expected. The second amplifier is pumped by 5 diode arrays symmetrically arranged around the rod, the pumping peak power is 20 kW and its amplification window is ~200 μs starting with a delay of 200 ∓s from the trigger of the first amplifier. The measured output power is presently 6 kW, a factor 2.5 less compared to the nominal power. Both amplifiers are designed to work at a repetition rate of 5 to 50 Hz. A Pockels cell allows adjusting the length of the pulse train between 50 ns and 50 μs. The measured energy in the micro pulse in the laser room was 230 nJ in the UV. This UV laser beam has been directed to the photo-injector over the distance of ~ 8.5 m using a system of dielectric high reflectivity mirrors and one metallic mirror (in the vacuum chamber). Using a telescope consisting of two cylindrical lenses and one spherical lens (all made of quartz) it was possible to change the shape and size of the laser spot on the photo-cathode in the range of 1-10 mm. To monitor the shape and position of laser beam a small fraction of the laser beam was reflected with a quartz wedge positioned in front of the vacuum chamber to a "virtual" photo-cathode represented by a screen with fluorescent paper. The laser spot on this screen was visualised remotely using a video camera.

The nominal energy is 370 nJ, on the photo-cathode (see Figure 1), in order to obtain the bunch charge of 2.3 nC assuming a quantum efficiency of 3 %. The construction of the amplifiers, the conversion to UV and the synchronization to the laser system are described in references [3], [4], [5] and [6].

The "phase coding" is not yet installed. It will allow providing a special temporal distribution of sub-pulses. This is necessary to recombine these sub-pulses with a 1.5 GHz RF deflector, in order to divide by 2 the bunch spacing and therefore multiply by 2 the bunch frequency. It was initially designed by RAL but from September 2006, Milano University continued the job. Unfortunately large losses into the laser fibers demonstrated poor efficiency and prevented the system to be installed at present stage. The demonstration of the "phase coding" is reported in [7].

Concerning the feed-back stabilization system, it was foreseen to be implemented at the beginning of the PHIN project. However no specific development has been done and this remains under discussion.

3. The CTF3 RF gun

The RF gun design study made at LAL [8] has been optimized for the high charge.
Figure 2 shows a 2-D scheme used for SUPERFISH simulations. Also HFSS simulations have been performed for 3-D configuration.

The coupling factor β = 2.9 allows the gun to be at the critical coupling for the nominal beam current of 3.5 A. The electric field is kept symmetric around the beam axis by connecting 2 input couplers symmetrically in the horizontal plane.

The nominal accelerating gradient of 85 MV/m (loaded) requires a RF power of 30 MW. The unloaded gradient of 85 MV/m is obtained with a RF power of 14 MW. This was the experimental value used for the present very low charge of 0.1 nC. With 20 MW, the unloaded gradient could be raised up to 100 MV/m.

Due to the very long wave guides (~ 80 m) distribution between the modulator-klystron MKS14 and the RF gun, a RF pulse compressor has been installed upstream of the RF gun.
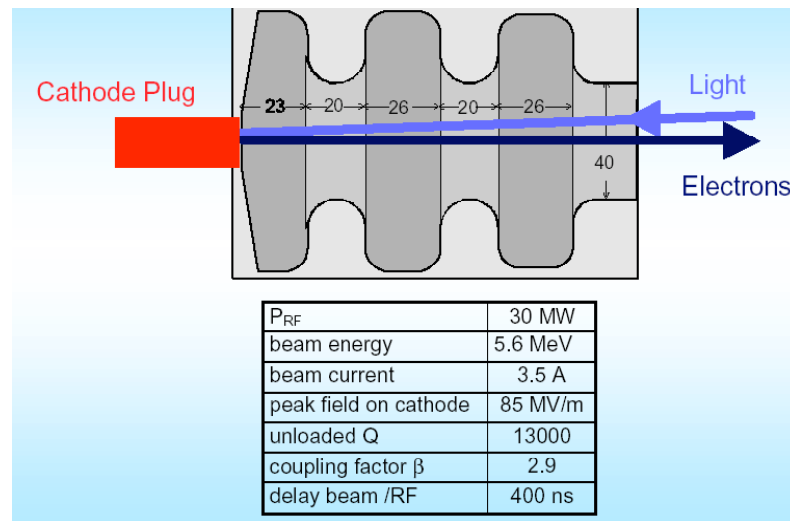

Figure 2: Geometry in 2-D for the CTF3 RF gun

Figure 3 shows a simplified 2-D layout with solenoids. The focusing solenoid close to the RF wave-guide requires a magnetic field of 0.27 T for the nominal conditions. The second solenoid is the bucking coil used to cancel the magnetic field on the photo-cathode. The construction of two RF guns is reported in [9].
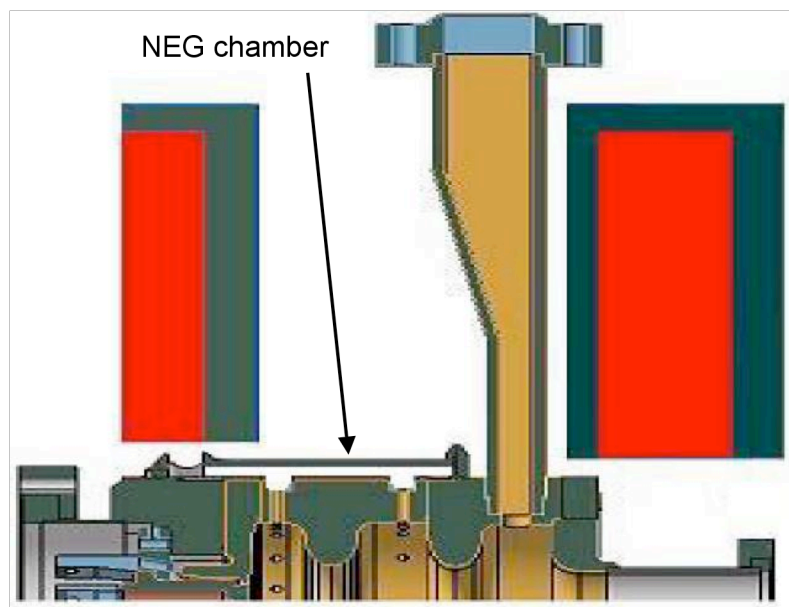

Figure 3: CTF3 RF gun with solenoids and NEG chamber

A critical parameter for high charge is the vacuum. Previous experiments, at CERN, show that the pressure inside the RF gun increases exponentially as a function of the total extracted charge. Simulations have been performed and shown that a value

below 10^{-10} mbar could be achieved. This assumes that there is no RF, no beam and the gun output is closed with a vacuum valve. In order to increase the pumping efficiency, 42 holes (diameter 4 mm) have been implemented between the cavity and the NEG chamber (see Figure 3).

Good operating conditions, for the dynamical vacuum, are obtained with the 5 ion pumps mounted around the gun.

4. The CTF3 photo-cathode

The photo-cathodes are produced in the CERN photoemission laboratory. After 4 years of shut-down, production of Cs_2Te photo-cathodes has been restarted. Measurements are performed in the photoemission laboratory before installing the photo-cathodes into the transport carrier. A Stylus profiler installed in the laboratory allows precise calibration of the Cs and Te film thickness deposited during the process. In the DC gun, a photocathode (No 167) was measured to have a quantum efficiency of 7 % in January 2008. This photo-cathode remained inside the transport carrier until November. Alignment tests were done using a copper photocathode, see Figure 4.
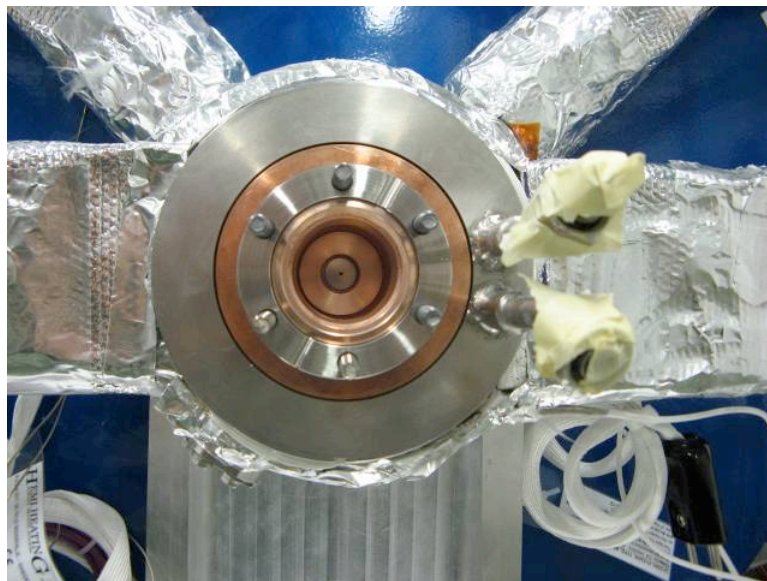

Figure 4: Alignment tests in the CTF3 RF gun

5. CTF3 goal and new PHIN parameters

When the JRA2-PHIN was proposed in 2003, the nominal CLIC accelerating frequency was 30 GHz. In 2007, this frequency has been changed to 12 GHz. Therefore the CTF3 parameters were adapted to this new value. The recombination factor of 5 changed to a factor of 4 in the Combiner Ring. The pulse length was reduced from 1548 ns to 1272 ns and the number of bunches changed from 2332 to 1908. The other parameters for the photo-injector remained unchanged. The PHIN

deliverable, in 2003, was based on a current measurement performed by a Faraday cup just downstream the RF gun.

Since this photo-injector is designed in view of a future and definitive installation on the CTF3 Drive Beam Linac, a more complete analysis of the beam parameters must be performed. The goal is to replace the present operational injector, based on thermionic gun, by the new photo-injector once its performance will be fully demonstrated (nominal bunch charge, beam emittances, phase coding system, laser stability and reproducibility).

6. Experimental results

A complete test beam line was designed and installed downstream of the RF gun on a dedicated stand-alone test bench in the CTF2 hall. The goal is to perform specific measurements to characterize the performance of the PHIN injector and not only the 3 GHz RF gun. The present layout is given in Figure 5.
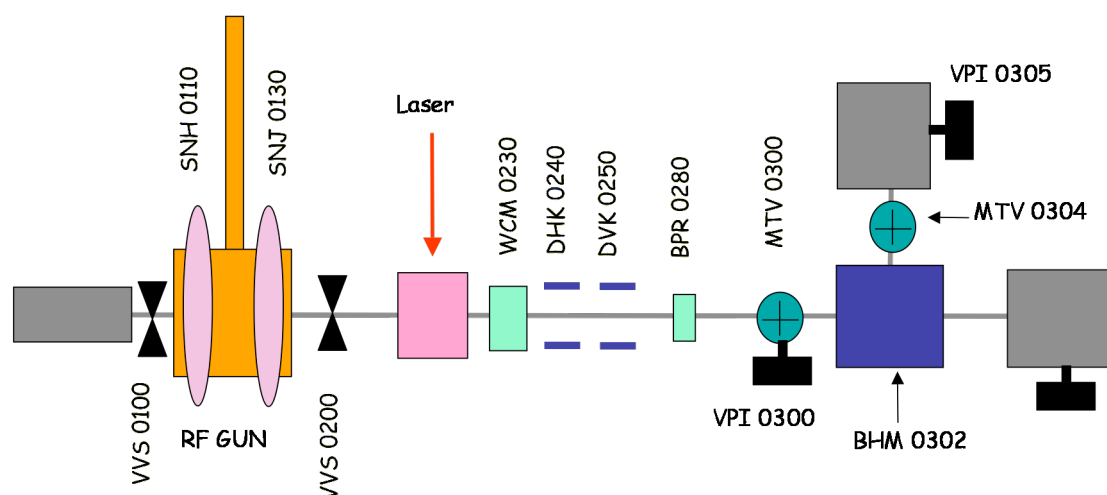

Figure 5: Layout of the PHIN installed into CTF2 hall
SNH, SNJ = solenoids, BHM=dipole, DHK/DVK= correctors, WCM= wall current monitor, BPR= Beam Position monitor, MTV= scintillator screens, VVS=vacuum valves, VPI= ion pumps

The first photoelectrons were produced in November 2008 and sent first to a ceramic screen labeled MTV 0300, then to MTV 0304. This allowed measuring the beam energy of 5.3 MeV. The beam size was measured to be 2 to 3 mm (FWHM). See Figure 6 and reference [10].
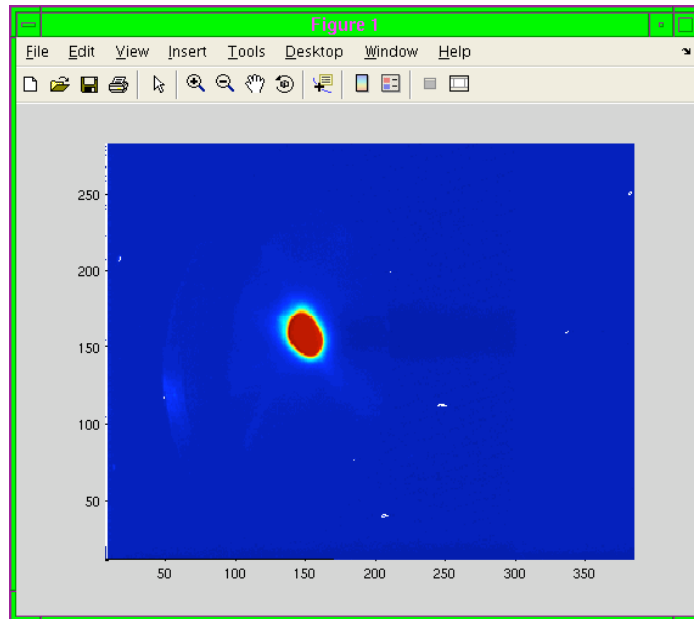
Figure 6: Electrons produced by the PHIN RF gun on MTV 0304

The beam parameters have been also measured with the Beam Position monitor BPR 0280 and the Faraday cup installed downstream of the dipole BHM 0302. The beam characteristics are shown in Figure 7. The experimental set-up in CTF2 is shown in Figure 8.

Figure 7: Signals from BPR (H, V, S) and Faraday Cup
Horizontal (Yellow), Vertical (Magenta), Sum (Red), FCU (green)
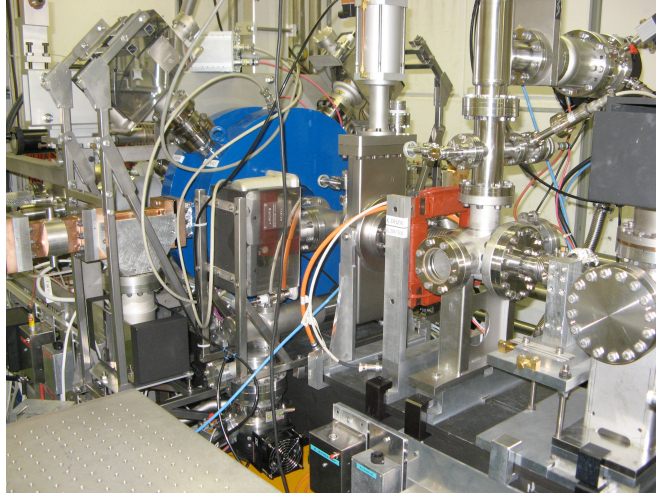Pulse length 1300 ns.

Figure 8: PHIN RF gun installed inside the blue solenoids

The experimental results obtained during a run of a few days in November 2008 are reported in Table 1 and compared with the PHIN Design parameters.

Table 1: Comparison between design parameters and measurements - PRELIMINARY

		PHIN Design	Achieved in November 2008
RF power (unloaded)	MW	13	13
Beam energy	MeV	5.6	5.3
Beam current	A	3.5	< 0.2
Number of bunches	-	1908	3000
Bunch spacing	ps	666.7	666.7
Bunch length	µs	1.3	2
Charge per bunch	nC	2.3	< 0.1
Repetition rate	Hz	5	0.8
Bunch length (FWHM)	ps	< 10	not measured
Energy spread (rms)	%	< 2	< 1
Normalized emittance	mm.mrad	< 25	9
Vacuum pressure in the gun	mbar	$< 2 \times 10^{-10}$	4×10^{-9}

All nominal beam parameters have been achieved, except the bunch charge.
For the bunch charge, a factor 23 is missing. The measured quantum efficiency is 0.6 %. Compared to the nominal value of 3 %, it is a factor 5. The other factor ~ 5 is explained by the missing laser energy in the micro-pulse received on the photo-cathode. Some other limitations, such as imperfect laser alignment on the photocathode, can explain partly the missing factor.
Concerning the emittance, some measurements have been performed with this low charge.
A method using slits has been tested. The different steps are shown in the Figure 9. This method is based on splitting the beam into beamlets with a slits mask in order to prevent the space charge dominancy of the beam. The emittance is calculated from the information out of the intensity profile of the beam image obtained from an OTR

screen with a CCD camera (MTV 0300 on Figure 5). The calculated value is 8.9 mm.mrad for the image in Figure 9.
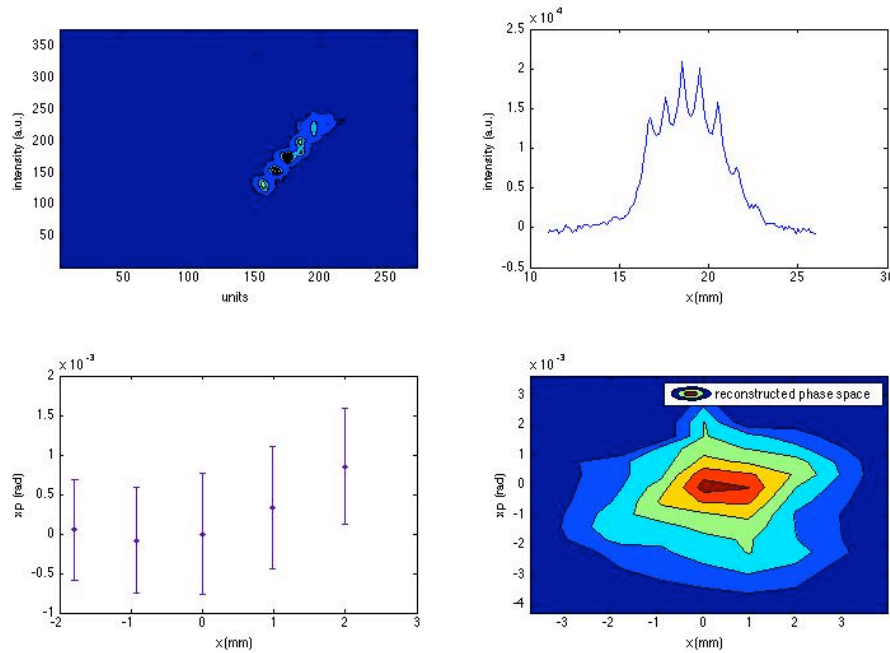

Figure 9: Emittance results based on the slits method.

The PARMELA simulations have given the emittance values between 5-6 mm.mrad for a range of focusing magnet settings shown in Figure10.
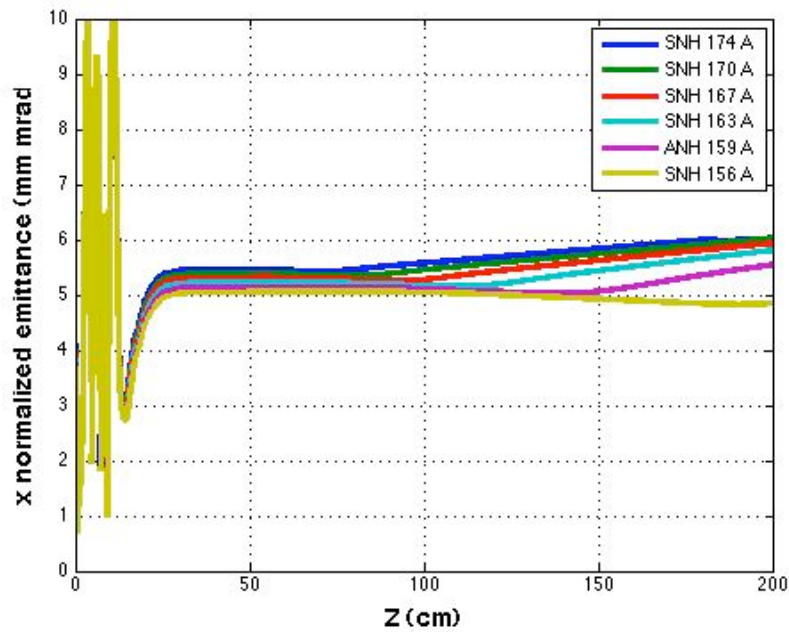

Figure 10: Normalized rms emittance along the beamline versus focusing currents.

Concerning the vacuum, the NEG inside the RF gun was not activated. However the achieved vacuum pressure (4×10^{-9} mbar) obtained in presence of the beam is already

good. A static vacuum pressure of 10^{-11} mbar has been obtained in the laboratory. It fulfills the specifications.

Las but not least, the stability of the PHIN electron beam was measured and found to be better than 5 %. Compared with previous experiments, this is an important achievement although the initial specification was 0.25 % rms. From with the present configuration and by implementing a fast feed-back, such value could be obtained in a future.

7. Summary

Concerning the laser system, the oscillator, the preamplifier and the two powerful amplifiers have been tested. Improvement of the second amplifier is necessary by changing the rod and the configuration of pumping. An agreement with a Russian laboratory has been found and a team will come to CERN for 6 weeks in April 2009. In collaboration with PHIN laser experts, they will try to get the expected performance from this second amplifier. The crystals for the second and fourth harmonic conversion process have converted the IR (1047 nm) to green (523 nm) and then to UV (262 nm) with high efficiency. The laser energy on the photocathode needs to be increased.

The poor quantum efficiency of the photocathode can be explained by the long storage time (almost one year). However a new photo-cathode is to be manufactured in order to reach the required bunch charge.

The measured RF parameters of the RF gun correspond to the ones expected.

In March 2009, three full weeks will be dedicated to perform further measurements and studies in order to improve the performance of the PHIN beam.

Although many difficulties were encountered for the PHIN CTF3 photo-injector, during the 5 years of design, construction and tests, a photoelectron beam has been produced validating the design of this photo-injector.

8. Acknowledgements

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