

TEST OF A DC-PHOTOGUN INJECTOR FOR THE LIGHTHOUSE FACILITY

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Abstract

Worldwide there is a push for producing medical isotopes using particle accelerators rather than fission reactors. Here we report on the operation of the beam test facility (BTF), set up and operated at the RI site in Bergisch Gladbach, Germany, comprising a dc-photogun designed for producing ^{99}Mo in the Lighthouse facility and commissioned by the Institute for Radio Elements (IRE, Belgium). The gun is based on the successful CBETA design by the Cornell University. The existing design has been reworked and integrated with a fully automatable photocathode production facility (PPF) designed for series production and exchange of photocathodes (PC).

INTRODUCTION

The BTF has been set up as a test bed to qualify the injector for the demanding requirements implied by the operational needs of the Lighthouse project [1]. These included (Fig. 1): The development and consistently stable operation of a 1.3 GHz laser at 515 nm wavelength, of an adjustable intensity between a few mW and 40 W of output power and support for the generation of high-contrast pulse patterns ranging from 100 ns at up to 10 kHz to cw operation; a DC high voltage (HV) system continuously delivering up to 40 mA at 350 kV to a photo cathode (PC) in the gun chamber [2]; an integrated PC Production Facility (PPF) with a deposition chamber allowing fully automated preparation of one PC per day with a quantum efficiency of at least 5 %; an emittance compensating section and a beam diagnostic section are installed behind the gun chamber for qualification and quantification of the beam parameters. Beam diagnostics include: insertable view screens with an attached CCD for transversal beam evaluation, three beam position monitors (BPM), evaluated by units of Libera Spark EL¹, ICT and NPCT², read out by a digit500 from Instrumentation Technologies (IT), a Faraday cup (FC) and two beam loss detectors (BLD) connected to a Libera BLM, both a product delivered by IT; a FPGA-based trigger system to produce the desired laser patterns and necessary trigger signals for the laser- and the beam diagnostics; a control system employing a Siemens CPU for equipment control and machine protection. It communicates via OPC UA with a Siemens WinCC OA SCADA for the GUI, archive and alert management.

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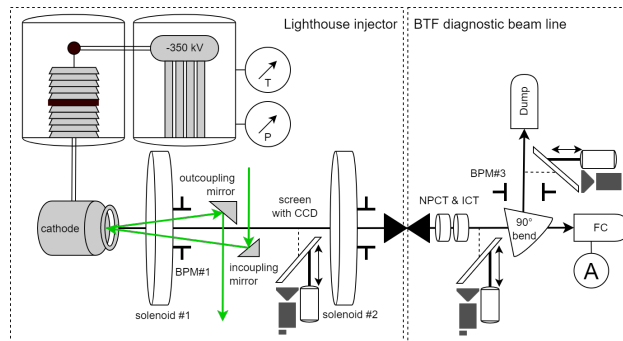


Figure 1: Overview of the BTF. The diagnostics beamline would have been replaced by the first SRF accelerating module.

Unfortunately, the project has been terminated by the customer half-way through the commissioning process, effectively halting further activities at the BTF. We here report on the commissioning status as of March 2023.

PHOTOCATHODE PREPARATION

The PPF was designed, build and tested for the fully automated handling and production of CsK₂Sb PCs and their transfer between load lock, MBE and gun chamber within the same UHV system. Up to five pucks, 2" in diameter, and each labelled with a unique QR code, can be handled at a time.

A CsK₂Sb PC is obtained from an uncoated puck by sequential deposition of elements using thermal effusion cells and monitoring the deposition process with the help of a quartz micro balance and an in-situ QE measurement. For better control of the evaporation rates and to prevent the alkali metals from evaporating already during the vacuum bake out (typically 175 °C) In-K and In-Cs alloys are prepared in an inert gas atmosphere using an attached glove box before being filled into the evaporators.

Figure 2 shows the PC deposition process on a stainless steel puck at 100 °C. The sequential coating steps follow a recipe from Cornell³ and consist of first growing 20 nm of Sb, then K and finally Cs onto the puck while following the QE measurement. This process consistently results in PCs with a final QE above 5 %.

INSULATION GAS

Because of the global warming potential (GWP) factor > 25,200 for SF₆ gas [3] and an atmospheric longevity of about

³ Luca Cultrera, Cornell University, internal communication

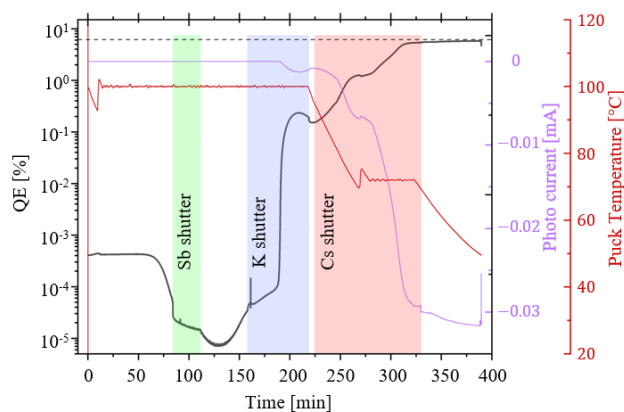


Figure 2: The process of PC coating is manually optimized for maximum QE yield (black line, in-situ measurement).

3,200 years, we decided to use NOVECTM4710 from the manufacturer 3M as an alternative insulation gas promoted with a lower GWP of 2,090⁴. At the beginning of the project, this insulation gas was the best proven alternative to SF₆ gas. This insulation gas requires a mixture of 10 to 20 % NOVECTM with dry natural gases like N₂ or O₂. Prior to using these new insulation gases, we did chemical compound reaction tests with all contact materials of the HV-power supply, especially for the organic compounds. It is known that NOVECTM disintegrates in a chemical reaction with water. So particular care was taken to remove humidity from the vessel to the highest degree possible, e. g. by evacuation to below 1 mbar before filling with NOVECTM. In operation the insulation gas worked without problems up to 450 kV. In the beginning we saw a reduction in the gas concentration from about 20.1 % to 18.9 % over the course of 2 months, which slowed to a rate of approximately -0.3 % per month in the past 2 months. We cannot tell whether this is the result of a gas compound reaction or a measurement problem.

Unfortunately, 3M will discontinue the manufacturing of all fluoro-polymers such as NOVECTM by the end of 2025, requiring qualification of other alternatives to SF₆ gas.

We plan to test operation of the high voltage in the same tank with pure dry N₂ at 3 to 4 bar pressure in the near future.

COMMISSIONING RESULTS

High Voltage Commissioning

Conditioning of the high voltage was performed using a 5 MΩ load resistor.

After filling the vessel to 3 bars of NOVECTM gas, the HV has then been stabilized at 380 kV, providing sufficient headroom for beam operation at 350 kV. We have also shortly reached the design voltage of 450 kV, but not without intense vacuum activities in the gun chamber. We never detected high voltage instabilities that did not correlate with an increase of the gun chamber pressure, nor current draw or

effects on pressure or temperature of HV-tank during the operation up to 450 kV.

Beam Operation

Set points for the solenoids and the dipole were taken from beam optics calculations. Note that space charge effects are not negligible in such a setup. In the final facility, this was to be accommodated by extraction of 20 to 30 ps long pulses being compressed to a few ps by a harmonic buncher (not part of the BTF), and by keeping the emittance compensation as compact as possible, placing the first SRF module only ≈ 1.3 m downstream of the PC. In the BTF, we allowed the beam to spread to a 100 mm opening of the beam dump.

Fine-tuning of beam focusing was performed using the beam profile visualization from the view screens, see Fig. 3. These also allowed centering the beam through the two solenoids. This process was sufficient to steer the beam with very low losses through the beam current monitors and onto a FC mounted in straight direction behind the dipole magnet.

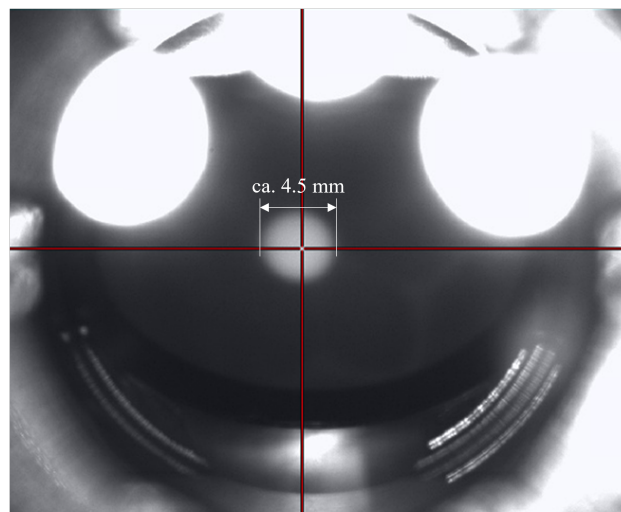


Figure 3: Electron beam spot ($E=350$ keV) at an illuminated screen, located between the emittance compensation section and the dipole magnet.

When directing the beam onto the beam dump located behind the dipole magnet, we experienced significant pressure increase already at average beam currents well below 1 mA. An imperfect steering into the dump was confirmed through temperature measurements upstream of the dump entrance. At this point, scintillator-based beam loss detectors helped to identify that the beam was indeed entering the dump slightly off-axis. We then used an iterative approach to optimize the deflection angle of the dipole magnet together with a steerer magnet to symmetrize the beam losses when wiggling the beam relative to the nominal position.

In an attempt to establish cw operation at up to 40 mA of beam current, the necessary increase of average beam current was approached in two ways: In one approach, we fixed the laser power to keep the bunch charge at around

⁴ https://www.3mdeutschland.de/3M/de_DE/p/d/b40006511/

30 pC required for the specified cw current of 40 mA. Here we started with laser pulse trains of 1 μ s at 10 Hz repetition rate, corresponding to a duty cycle of 10^{-5} . From there we increased the pulse train length up to 1 ms and also increased the frequency. During this run we observed a degradation of the quantum efficiency (see next section) which was not corrected for. We also did not adjust the beam focussing. On November 30, 2022, this approach reached a duty cycle of 80 % with a pulse current of around 28 mA, resulting an average beam current of 22.4 mA and average beam power of 7.8 kW. At this power level we experienced high voltage arcing in the gun chamber, which we ascribe to the increased vacuum pressure caused by beam induced outgasing in the beam dump.

In a second approach, we set the duty cycle to 100 % (permanently pulsing at 1.3 GHz) but slowly increased the laser output power. Again, the focusing elements were held constant. Following this procedure, on November 22, 2022 we measured a cw current around 13.5 mA at 350 keV, before an increase in vacuum pressure produced a high voltage arcing in the gun chamber. After such arcing in the gun chamber we often observed a reduction of the QE by 2 to 3 %, imposing a practical limit to the number of attempts possible before the need for exchanging the PC.

QE Dependence on Laser Power

While increasing laser power on the PC and monitoring the extracted photo-current, we observed that the resulting QE dropped from an initial ≈ 9 % at approximately 100 mW to about 2 % at roughly 7 W, see Fig. 4. We found this dependency to be reversible and reproducible, excluding an effect of degradation. The photo-current has been measured at two different locations using different techniques, giving confidence that its behaviour is not an artifact. Note also, that for the short pulses used, we have been able to extract a pulse current close to 60 mA, not even exploiting the full laser power available (7 W out of 10 W on the cathode).

CONCLUSION

Within a relative short time span of effectively a few weeks only, we have demonstrated that the BTF is in good condition to reach its design goals. In Detail:

- We have operated the HV up to 450 kV with no indication of discharge activities in the HV-tank. Stable operation was attained up to 380 kV, which has proven sufficient for the nominal operation at 350 kV. Stabilizing the voltage at even higher levels may require purging of a process gas, such as Helium, which is implemented on the gun chamber, but has not yet been tested.
- With the attached PPF, around 10 PCs have been produced in a semi-automated procedure, with a reproducibly high quantum efficiency around 7 to 8 % for low laser powers. The PPF has proven the potential

for a fully automated transport and production of PCs,

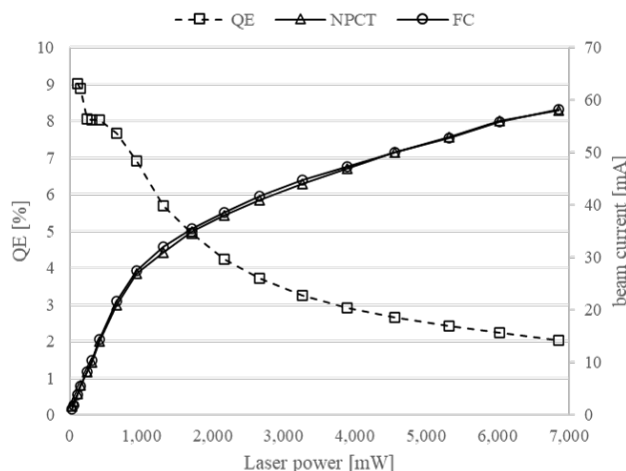


Figure 4: Quantum efficiency (QE, dashed line) of a PC as a function of applied laser power. Beam current as measured at the NPCT and the FC agree qualitatively (the FC reading is known to be inaccurate in absolute terms and has been scaled to meet the NPCT readings). Beam energy is at 150 keV, pulse length at 100 μ s.

including their exchange in the gun chamber, without reduction of the initial QE.

- Beam operation at 350 kV was performed up to an average beam current of 22.4 mA, marking more than the half-way point of the 40 mA design goal. To further increase the power we may need to reduce the backflow of desorbed gas from the close-by beam dump. This can be achieved by a bake-out at higher temperature than performed so far (limited to 90 °C because of the current monitors in the same vacuum section), or by additional pumping capacity or by applying bias voltage of a few hundred volts to the anode, thus trapping ions before they enter the gun chamber.

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