DESIGN, CONSTRUCTION AND OPERATION OF THE DUTCH RF-PHOTOGUNS

S.B. van der Geer, M.J. de Loos, Pulsar Physics, The Netherlands
W.P.E.M. Op 't Root, W. van Dijk, W. van Hemmen, G.J.H. Brussaard, O.J. Luiten,
Department of Applied Physics, Eindhoven University of Technology, The Netherlands
W. Knulst, M.J.W. Vermeulen, Opto-electronic Materials,
Delft University of Technology, The Netherlands

Abstract

Three different S-band RF-photoguns have been constructed by Eindhoven University of Technology in the Netherlands: A 1.5-cell, a 100-Hz 1.6-cell, and a 2.6-cell. They share a design concept that differs from the 'standard' BNL-gun in many aspects: Individual cells are clamped and not brazed, saving valuable manufacturing time and allowing damaged parts to be replaced individually. The inner geometry employs axial incoupling, inspired by DESY, to eliminate any non-cylindrically symmetric modes. Elliptical irises, identical to a 2.6-cell design of Strathclyde University, reduce the maximum field on the irises and thereby reduce electrical breakdown problems. The manufacturing process uses single-point diamond turning based on a micrometer-precise design. The overall precision is such that the clamped cavities are spot-on resonance and have near-perfect field balance without the need for any post-production tuning. Operational performance of the three Dutch RF-photoguns will be presented.

INTRODUCTION

The design process of the 2nd generation RF-photogun described here started from an earlier 2.6-cell version [1]. The typical production method of RF-photoguns at that time—and it still is—involved an iterative manufacturing procedure for the individual cells and/or post-production adjustments after brazing. Such adjustments were necessary, because the required resonant frequency and field-balance are significantly affected by changes in the overall geometry on micrometer scale. Recently however, these tolerances came within reach of the both the numerical modeling and the manufacturing process. Pioneered in the 1st generation 2.6-cell RF-photogun was micrometer-precise design of the inner dimensions combined with single-point diamond turning manufacture. It was proven that this combination fully eliminated the need for any adjustments or corrections.

The cells of the 1st generation 2.6-cell Dutch RF-photogun were still conventionally brazed together. This is risky and undesired: Heating the high-purity copper can easily cause small deformations, which in turn can affect the resonant frequencies and field-balance. Furthermore, traces of solder can easily reach the inner surface causing breakdown problems later on. Finally, having brazed everything together, there is no simple way to repair the device in case it gets damaged. The 2nd generation Dutch RF-photoguns therefore use a different approach: The individual cells and the cathode plate are all mechanically clamped together, eliminating the need for brazing altogether. This procedure thereby avoids the risk of deformations during the brazing and allows for an individual cell and/or cathode plate to be replaced.

OVERALL DESIGN

The overall mechanical construction of the three 2nd generation Dutch RF-photoguns is schematically shown in figure 1. Depicted is the 1.5-cell version, with all typical features of our new RF-photoguns. Shown are the individual copper parts and the cathode plate, all clamped together inside a stainless steel vacuum vessel. A bucking coil, cooling channels, and axial incoupling (not shown) complete the design.

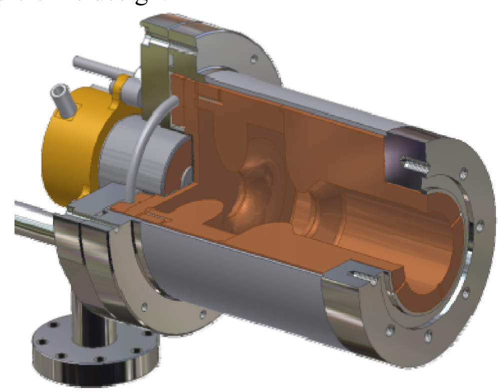

Figure 1: Schematic design of the 1.5-cell 2nd generation Dutch RF-photogun.

Inspired by the Alpha-X RF-photogun [2]—having inner dimensioned designed by the same 'Pulsar' team—the typical 'BNL' irises with circular cross-section have been replaced by irises with an elliptical shape. This results in a 10–20% lower field at the irises and it has the advantage that potential breakdown damage, most likely to occur at the location of highest field-strength, is now at the easily replaceable cathode and not on the irises.

During several conferences and workshops there has been ongoing discussion about the new design. Is the micrometer precise design and manufacture of the 1st generation RF-photogun reproducible? Has the clamped design sufficient electrical contact? Will there be microscopic cracks and, if so, will they cause breakdown problems? These questions will be answered in the next sections, based on low and high-power tests of our three new RF-photoguns.

1.5-CELL

The 1.5-cell RF-photogun is tailor made for the production of 'pancake' electron bunches with a charge in the order of 100 pC or less, to be used for the generation of terahertz radiation via various schemes of coherent transition radiation [3-4]. As such, the design criteria for the inner dimensions differ slightly from the more usual design aiming at extracting more charge during several picoseconds. In the 'pancake' regime the image charge fields must be much smaller than the accelerating gradient during photoemission and this is particularly relevant for the extraction of `ellipsoidal' bunches [7]. To get the highest possible fields at the cathode during extraction, the length of the first half cell was shortened.

After fabrication the 1.5-cell RF-photogun was first tested at low power using a network analyzer. The measurements were performed in ambient conditions at room temperature. In figure 2 the measured absorption is show, together with two fitted Lorentz curves. From the fit it follows that the resonance frequency of the π-mode is at 2.9979 GHz, and that the loaded quality factor is 5100. Also shown is the electric field distribution of the π-mode, measured with the bead-ball method. It shows that the combined design and manufacturing process has a precision better than 5 μm.

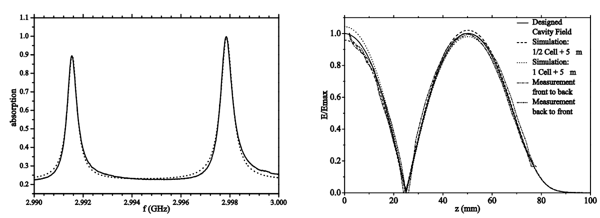

Figure 2: Frequency scan of the 1.5-cell RF-photogun showing two resonant frequencies, measured at 20 °C in air (top); Relative electrical field profile (bottom).

The conditioning of the RF photogun is fully automated: The forward RF power increases linearly with time until a breakdown occurs, which is detected by a sudden change in the reflected RF power. Whenever a breakdown is detected the forward RF power is immediately removed and kept zero during 10 seconds. Subsequently, RF power is slowly increased to the level at which the breakdown occurred via an analog RC-filter with a time constant of 20 seconds. Finally, the training program resumes the linear increase of the RF power 200 seconds after the breakdown occurred.

Using the above mentioned method the RF-photogun was conditioned to an electric field of 76 MV/m at the cathode in ~10^6 shots at 3-Hz repetition rate. This corresponds to accelerated electrons with an energy of 3 MeV. The pressure in the cavity was typical 10^{-8} mbar during conditioning, occasionally increasing to 10^{-7} mbar after breakdown. Preliminary measurements of a 2.8 MeV bunch result in a transverse rms emittance of 1 μm at 70 pC.

2.6-CELL

The 2.6-cell RF-photogun is the e^- source of a laser wakefield experiment being constructed at Eindhoven University of Technology. Electron bunches are externally injected into a plasma channel just after a powerful laser pulse has created an accelerating plasma wave [5]. In order to get trapped by the accelerating plasma wave, the injected electrons must have sufficient energy, preferably well over 5 MeV. For this reason an additional cell was added compared to the 1.6-cell design. This increases the nominal output energy to 6.7 MeV, while the maximum fields at the irises is kept below 100 MV/m.

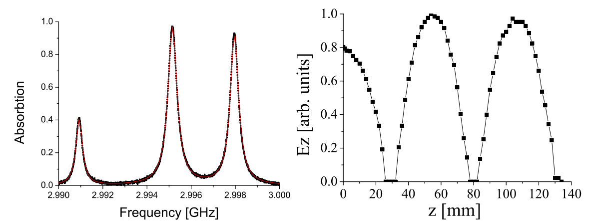

Figure 3: Frequency scan of the 2.6-cel RF-photogun (left) and field-profile of the π-mode (right).

The 2.6-cell photogun has been characterized using the same methods and equipment as the 1.5-cell photogun. The measured low power absorption with the Lorentz fits for the 3 modes are show in figure 3. The central frequency of the π-mode used for acceleration is 2.9976 GHz with a loaded quality factor of 6555. Also shown is the corresponding electric field measurement.

Conditioning, as applied to the previously described 1.5-cell RF-photogun, is currently being performed.

HIGH REPETITION RATE 1.6-CELL

At the Delft University of Technology a project has been started to extend their pulsed photolysis and radiolysis measurement equipment into the (sub)picosecond time regime. The materials under investigation will be excited by either an ultrashort laser or a relativistic electron pulse. The properties of generated excitations and charge carriers will be detected by time-resolved THz conductivity and absorption or reflection spectroscopy based on the pump-probe technique. Eventually, the results will contribute to the improvement of the performance of, for instance, solar cells [6] and light-emitting diodes.

The design of the Delft RF-photogun is based on the requirements for ultrafast pulsed radiolysis using relativistic electrons pulses: 1- the pulse duration $\tau \approx 1$ ps, 2- the charge per pulse $Q \approx 1$ nC, 3- the electron pulse diameter at the sample $d \approx 1$ mm, 4- the pulse repetition frequency $f \approx 100$ Hz, 5- the electron energy $E \approx 5$ MeV.

The results of the 1st generation RF-photogun [1] have indicated that point 1 and 2 are in reach with this design without the use of additional compression techniques. Space-charge induced lengthening of our 1-nC target bunch can be lowered by increasing the beam radius.

However, in return path length differences between the central and outer electrons increase the pulse length again. Based on simple model of space charge in the pancake regime [7] and modeling electron beam trajectories a minimum bunch length is obtained for a radius of $r \approx 4$ mm at the cathode surface. By redesigning the cathode surface and introducing a hollow structure, path length differences can be compensated to some extend [2].

The 1.5 and 2.5-cell RF-photoguns are designed to operate at low pulse repetition frequency. The application in Delft requires a large number of electron pulses to acquire a full pump-probe scan up to 1 ns. Therefore, we have designed our setup to operate at a maximum pulse repetition frequency of 100 Hz. This parameter is set by the available power of moderate-sized klystron tube (Thales TH2157A) and pulsed high-voltage source (ScandiNova Solid State Klystron Modulator type K1). Consequently, this causes high average power dissipation in the RF-photocavity of about 1.5 kW (RF input pulse specifications to cavity: $f = 100$ Hz, $P_{peak} = 10$ MW, $\tau = 3$ µs, 50% reflection). Therefore, the temperature control of the cavity is serving two purposes: 1- Keeping the cavity constantly at the desired operating temperature to keep the resonant frequency of the cavity steady. 2- During operation the heat has to be removed, while in standby status the cavity has to be heated.

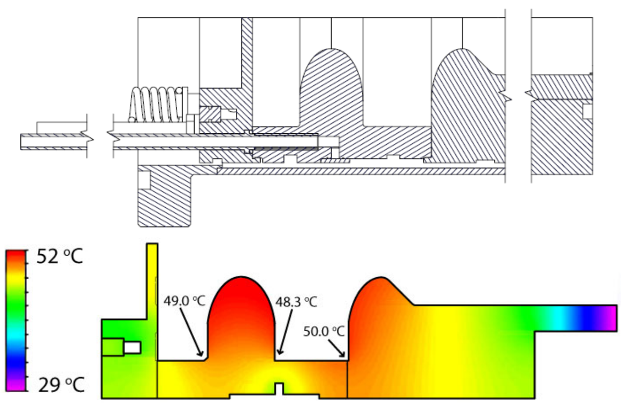

Figure 4: Detail of cross section of 1.6-cell. Cooling water channel with pipe connection and springs to clamp cavity (top). Temperature modeling of cavity with extra cooling channel (bottom).

The cooling water channels are designed so that there is a minimum temperature difference between the two cells, preferable less than 1 K. Any temperature difference increases the field imbalance. To achieve this, we had to introduce an additional ring cooling channel at the position of the iris in the central cavity section (see figure 4). As a consequence, we could no longer clamp the cavity together by bolts and had to use springs instead. These springs are put under tension when the stainless steel cavity housing is closed by its flange. A numerical modeling program (Algor) is used to calculate the resulting temperature profile of the RF-photogun at full operation power (see figure 4). The heat dissipation at the surface of the internal cavity walls that was put into the model was obtained from the surface integration of the electric field profile calculated by the RF design program. Three cooling points were used in the model at the positions of the three water cooling channels. The inlet cooling water temperature was set to 20 °C. The model showed that the operating temperature at full power is 50 °C and confirmed that the temperature difference is about 1.5 K.

After finishing the manufacturing the resonant frequencies and field profile are measured (see Figure 5). The π-mode resonant frequency and loaded quality factor measured at 20 °C and in air are $f_0 = 2.99780$ GHz and $Q_L = 6890$. The electric field profile measurement shows that the field imbalance is better than 0.95:1.00 between the 0.6:1.0 cell. This year the Delft RF-photogun will be put into operation, so that more test results of high-power RF test and cooling will become available.

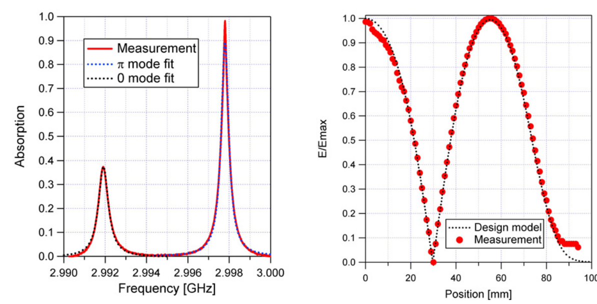

Figure 5: Frequency scan of the 1.6-cell RF-photogun showing two resonant frequencies, measured at 20 °C in air (left); Relative electrical field profile (right).

CONCLUSION

All three 2nd generation Dutch RF-photoguns have good field-balance and spot-on resonance, implying that the design and manufacturing process is sufficiently accurate and reproducible. Elimination of the risky and time-consuming brazing process did not affect the operation of our new RF-photoguns in any way.

REFERENCES

[1] F.B. Kiewiet, Generation of ultra-short, high-brightness relativistic electron bunches, PhD thesis Eindhoven University of Technology (2003).
[2] De Loos, M.J., et al., PRST-AB 9, (2006), 084201.
[3] W. P. E. M. Op 't Root, et al., PRST-AB 10, (2007), 012802.
[4] P. W. Smorenburg, W. P. E. M. Op 't Root, and O. J. Luiten, Physal. Review B 78, (2008), 115415.
[5] W. H. Urbanus, W. van Dijk, S. B. van der Geer, G. J. H. Brussaard, and M. J. van der Wiel, J. Appl. Phys. 99, (2006), 114501.
[6] Trinh, M.T., et al., Nano Letters 8(6), p. 1713, (2008).
[7] Luiten, O.J., et al., Physical Review Letters 93, (2004), 094802.