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ABSTRACT

This report describes the manufacturing design process of electron gun and RF modulator, which is the main deliverable of the JRA project IRME (WP16). Special emphasis is put on the key components of gun and modulator developed in close cooperation of the partners from IAP and RTU. Finally, an outline of the planned performance tests is presented.

ARIES Consortium, 2021

For more information on ARIES, its partners and contributors please see <http://aries.web.cern.ch>

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Executive summary

In this report we present the manufacturing design of the electron gun and power modulator built in task 16.3 of WP16. After a brief introduction, summarizing the requirements and the design work, the staged experimental and engineering approach towards the final manufacturing design of electron gun and modulator is described in detail.

1. Introduction

Within the framework of ARIES WP16, a prototype RF modulated electron gun was built for integration into an electron lens for space charge compensation of ion beam by an overlapping electron beam. Therefore, it may help to increase the intensity of primary beams, especially in low energy booster synchrotrons like the SIS18 and SIS100 at GSI/FAIR or the PS at CERN, which are limited in intensity by transverse space charge at low energies. To meet the requirements for these facilities it is important to provide stable electron beam properties. A high effort was put in a robust and flexible design with high reliability of the key components. It was also important to develop a design in a framework which enables the possibility for the partners of the ARIES collaboration to procure all parts of the electron source easily, cost-effectively and by European industry supplier.

For an effective space charge compensation the generated electron beam needs to follow transverse and longitudinal beam profile of the ion bunch structure. As case of application, the requirements on the electron gun for GSI/FAIR are considered and can be summarized as followed:

- maximum currents of 10 A
- Gaussian or (homogeneous) profile with round or (elliptical) shape in the x-y plane
- modulation option to cover a broad frequency range according to the changing bunch length (min. bunch length of about 200 ns, max. bunch length of about 2 μ s, DC beam during injection) and changing repetition rate during acceleration to follow the ion bunches

Especially the modulation option with respect to required beam currents and resulting extraction voltages represented a major challenge in the design of the electron gun. The modulation by a grid which is placed close to the cathode and therefore reduces the needed voltages (max. 3 kV) to suppress the electron current was chosen to be the most suitable solution. The conceptual layout of gridded gun and modulator are presented in MS53 [1].

In this report the iterative process of the engineering design and the manufacturing of the prototype electron gun TE² (tungsten electron emitter) as well as the power modulator designed and built at RTU are described.

2. Engineering Design and Manufacturing of Electron Gun

The strategy to use hot tungsten as electron emitter (described in MS56 [2]), makes the electron gun as robust as possible. On the other hand the surface temperature has to be in the range of 2800 K and cannot be provided by indirect heating using a tungsten filament. Therefore, a direct novel heating using a plasma stream was developed. Modification of a common plasma generator for intense hadron beams, were made. A method was invented to control a directed energy transfer from the plasma to the tungsten cathode. The R&D efforts took into account the interaction of the cathode and the plasma in first step only.

2.1 DESIGN STEPS OF THE TUNGSTEN ELECTRON EMITTER (TE²) GUN

The tungsten emitter and the grid electrode were designed and manufactured to be integrated in the extractor of the original volume type ion source. The tungsten cathode, the grid as well as the assembled extractor part are shown in Figure 1.

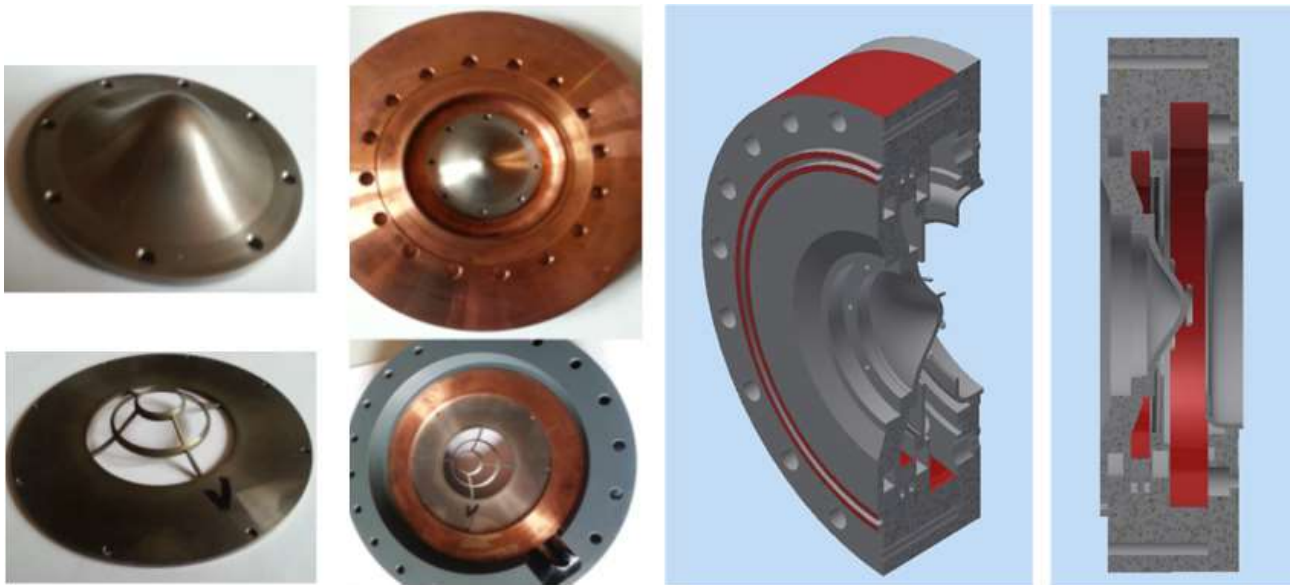


Figure 1: Pictures of tungsten cathode and grid (left). They were purchased from industry and delivered with a purity factor of 99.98%. CAD model of the extractor part (mid and right).

Volume type ion sources are used in different accelerator applications at the Institute of Applied Physics (IAP) since several years. It is a proven design and therefore, spacing and design of several parts is already optimized regarding high voltage breakdowns (~30 kV), vacuum conditions and outside isolation.

Due to its flexible design it is possible to adapt changes and modifications quickly, and it allows to study main challenges in the engineering of the new electron gun such as the modification of distances, heat contact, electrical conductivity and vacuum separation between the plasma generator and the extraction system by the tungsten cathode (copper-tungsten contact). The energy transfer

from plasma to cathode was also optimized. The iterative process included the adaption of the geometry of the plasma generator and the heat transfer to the cooling system, to prevent the risk of copper melting. The grid-cathode distance was optimized sequentially regarding the RF-impedance and heat transfer to the grid, which should be as small as possible.

All parts of TE² (except cathode and grid) were manufactured in the workshop of the IAP. The results of completed design studies are summarized in the following sections.

2.2 CATHODE HEATING

In order to study the cathode heating of TE² and the performance of the designed electron gun a dedicated test bench was installed including several diagnostic tools (see Figure 2). Besides the investigation of heating mechanisms and temperature distribution over the cathode by the use of a pyrometer, the water cooling system was monitored as well as the vacuum pressure.

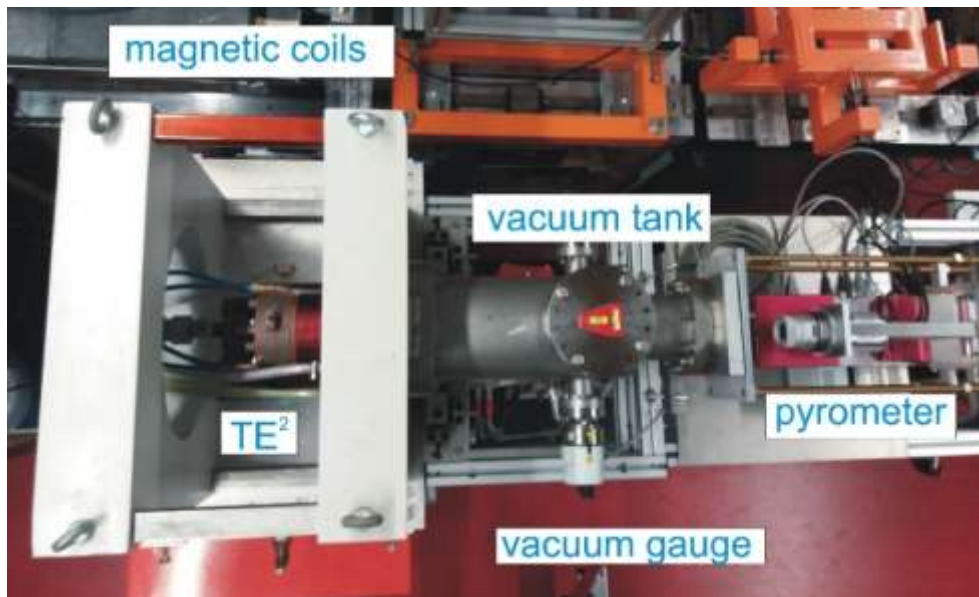


Figure 2: Test stand for temperature measurements.

At the beginning of the experiments, TE² was aligned in an axial magnetic field of Helmholtz-Coils. This was important to study the influence of the magnetic field on the direct heating procedure and the thermal emission of electrons in presence of a strong magnetic field. TE² is equipped with a correction solenoid to adjust the local magnetic field distribution near the tungsten cathode. Later it is planned to install also a magnetic quadrupole to extract intense electron beams with an elliptic instead of a round cross section.

During heat-up, pyrometric measurements of the cathode temperature were carried out (see Figure 3). The presented temperature has to be multiplied by a correction factor of approx. 1.78 considering the emissivity $\varepsilon = 0.1$ of tungsten at melting temperature (3695 K). This results in a realistic temperature T of approx. 2321 K.

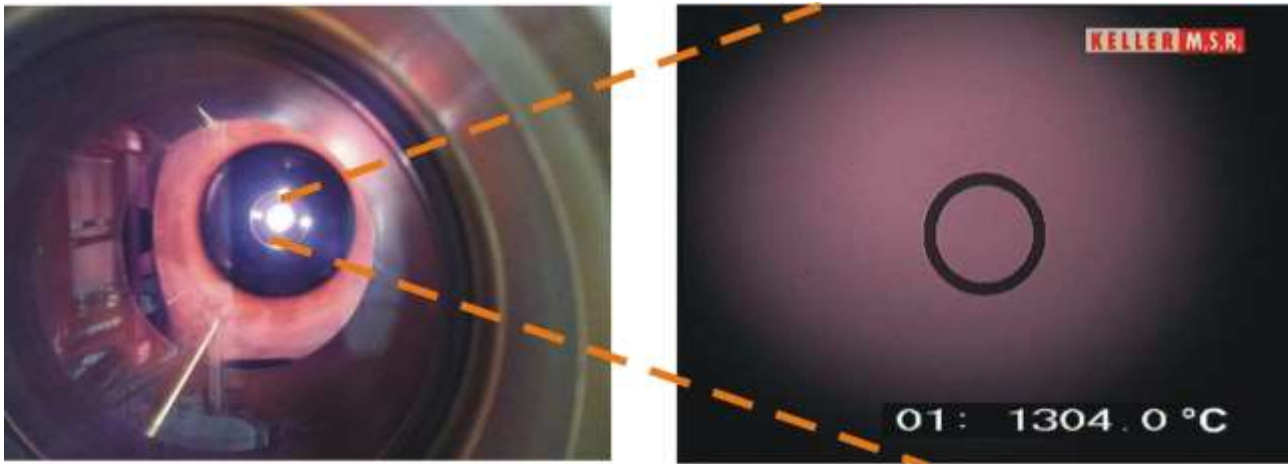


Figure 3: Photo of the cathode heat-up (left), pyrometric measurement (right). Temperature calibration was set to the emissivity $\varepsilon = 1$ (black body radiation).

During the experiments the temperature was varied up to the melting point in order to prove system performance at critical temperatures. Cooling and vacuum system remained stable. After inspection small tungsten drops were found on the cathode flange and a small area of the cathode was melted. On the contrary, copper parts and insulators showed no damage, which demonstrated the reliability of the whole system.

To achieve the required current density of 3.2 A/cm^2 the cathode must be heated to a temperature of approx. $T = 2800 \text{ K}$, given by theoretical and numerical predictions. Therefore, it is justified to state that the cathode is capable to deliver the required electron currents of up to 10 A for the described heating method.

The influence of the direct heating on the temperature distribution on the cathode was measured as well. Figure 4 shows the results of these measurements before (left) and after (right) maintenance of the plasma generator when the filament was replaced by a new one.

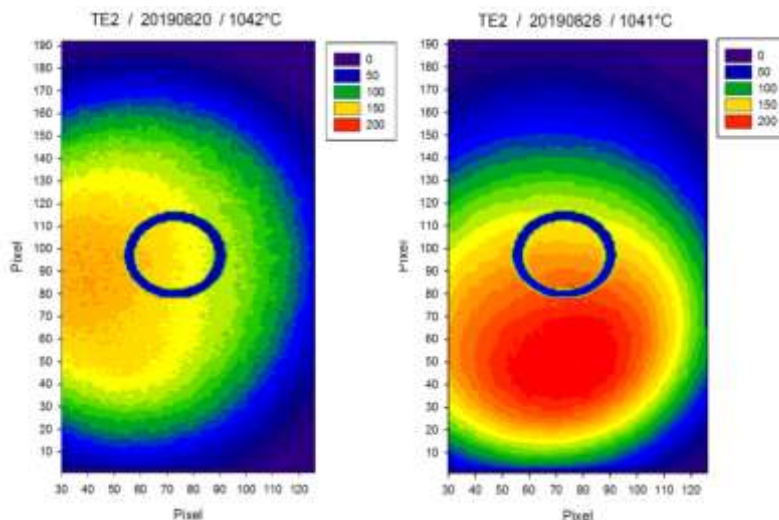


Figure 4: Temperature distribution on the cathode for different filaments.

It was observed that the temperature distribution is influenced by the geometry of the plasma generator and the alignment of TE^2 within the Helmholtz-coils. A template will be designed in the future to provide a good reproducibility in the performance after a maintenance of TE^2 .

Besides these considerations, also vacuum conditions and cooling performance of the device could be investigated. While the heating power for the cathode was carefully increased at the beginning of the experiment, degassing of the vacuum chamber was observed. It disappeared after desorption of the inner surface contaminations, comparable to the behaviour observed during conventional baking routines. During operation, the temperature of the vacuum chamber was found to be about $\Delta T = 30^\circ\text{C}$ above room temperature, while the temperature of the water-cooled electrodes remained constant at $T = 20^\circ\text{C}$ (for water temperature of 18°C and water pressure of 6 bar).

2.3 GRID HEAT-UP AND IMPEDANCE

Since the grid is positioned very close to the cathode, a major interest was the amount of heat transferred from cathode to grid. The cathode position could be varied by installing different spacers between cathode and cathode holder resulting in a changing distance between cathode and grid of 18 mm as maximum and 5 mm as minimum. During the experimental campaign no heat-up of the grid could be observed.

The grid electrode is modulated by a power modulator described in section 3. of this report. The main challenge for the RF modulation is posed by the grid-cathode capacitance. As a result of this the expected impedance changes about a factor of 17 over the waveform bandwidth of 6.5 MHz. In order to determine the grid capacitance over the required frequency range, it was measured with a network analyser in vacuum (Figure 5, green).

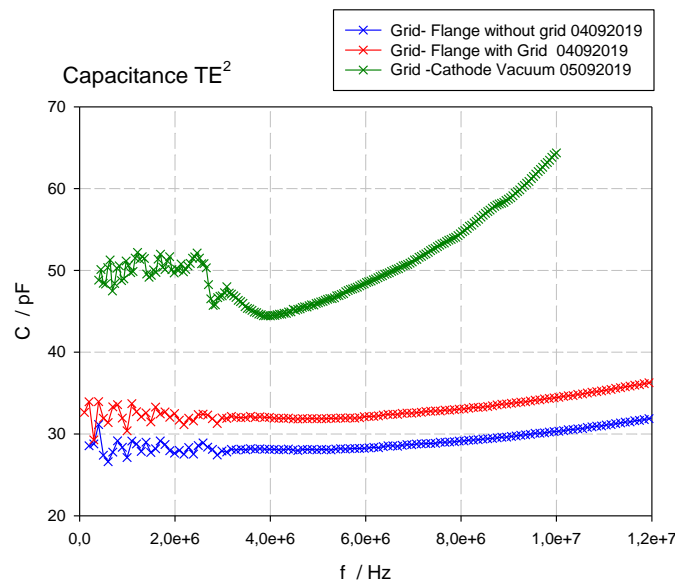


Figure 5: Capacitance measurements of the cathode-grid system (distance $d = 18$ mm)

The values were in the expected range defined for the modulator design. An intensive exchange with our partners from RTU was and is the basis for the success of the development.

2.4 GUN MAGNET

The gun has to be positioned in the centre of a solenoid where the magnetic field is considered to be homogeneous with a maximum field of $B_z = 0.6$ T on axis. The solenoid was designed and manufactured by European company Scanditronix Magnet AB, Sweden and provided by GSI as partner of WP16 (see Figure 6). The magnet parameters are presented in Table 1.

Maximum magnetic field on axis	0.60 T
Nominal current	457 A
Voltage	77 V
Solenoid length	408 mm
Aperture diameter	200 mm
Turns	360
Good-field-region in longitudinal and radial direction	35 mm

Table 1: Mechanical and electrical parameters of the electron gun solenoid.

After delivery the properties of the solenoid were checked. Minor changes of the insulator were needed to transfer the TE² gun from the Helmholtz-coils to the solenoid.

While the Helmholtz configuration was superior for prototyping of the electron gun in an early stage because of an easy access to the components, the solenoid provides the magnetic field strength needed for reaching the final parameters of the of IRME gun. The integration of TE² in the solenoid is essential for the first extraction of electron beams.

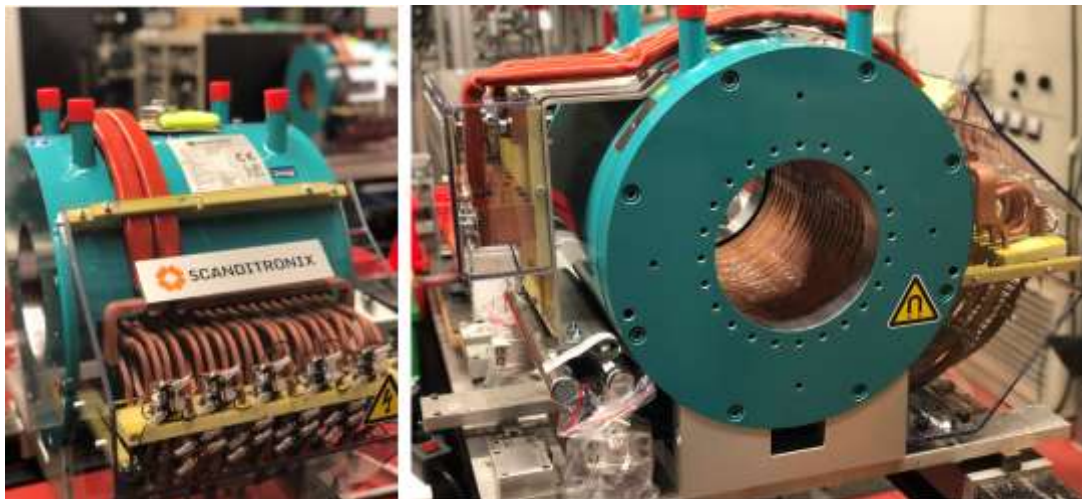


Figure 6: Picture of the Gun solenoid manufactured by Scanditronix.

2.5 TE² ELECTRON GUN

Because of the promising experimental results described previously as well as the robust and flexible design, it was decided to use the TE² design as the final layout for the IRME electron gun.

The layout of its electrode system and magnetic field is based on the conceptual design of the electron gun outlined in the MS53 report [1]: The cathode has a radius of 26.5 mm, the minimum distance between grid and cathode is designed to be 3 mm and the distance between cathode and anode is designed to be 20 mm. But both parameters may be varied if necessary. The layout of the grid was designed according to the final layout described in MS53 [1] and is going to replace the tungsten grid presented in Figure 1. The whole electron lens set-up is designed for extraction voltages up to 30 kV.

According to numerical simulations using CST Particle Studio, a maximum current of 8.4 A is expected for the previously defined cathode-to-grid and cathode-to-anode distances and for a cathode heating temperature 2800 K which results in approx. 3.2 A/cm² according to Richardson's law. Although the design current of 10 A is not predicted for the current layout of the extractor, the Schottky-effect which is not considered within the numerical simulation modifies Richardson's-law and the current density could be increased. This has to be investigated experimentally. Further numerical simulations are performed in parallel to the experiments to evaluate the performance of the electron gun.

The current design status of TE² of the electron gun as technical drawing and assembled part is shown in Figure 7.

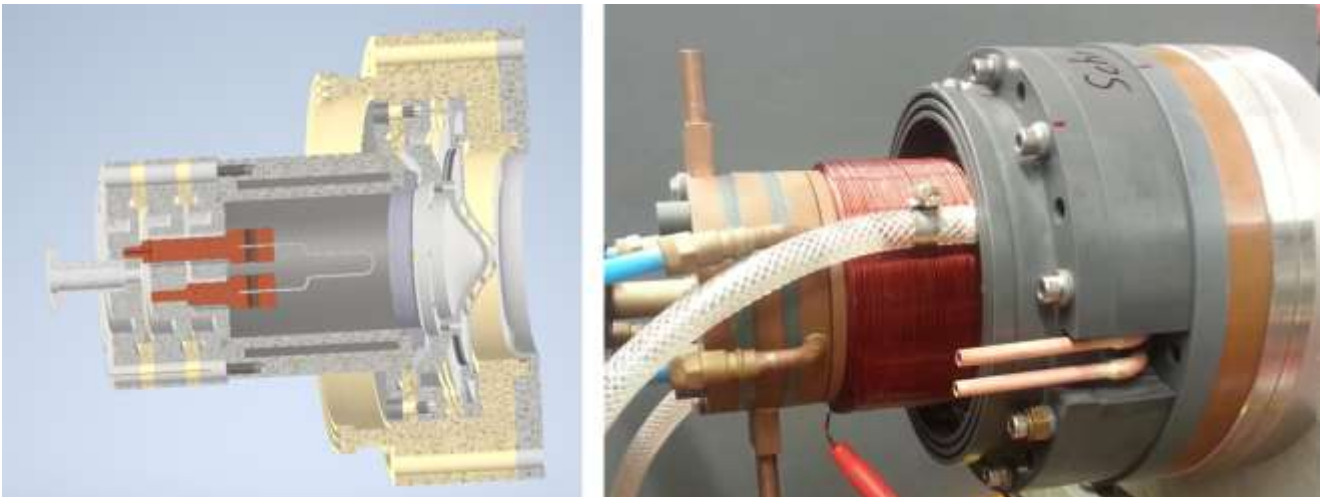


Figure 7: Technical drawing (left) and picture (right) of the electron gun TE²

3. Engineering Design and Manufacturing of Power Modulator

3.1 DESIGN STEPS OF THE POWER MODULATOR

The modulator was developed in parallel to the construction of TE² and the experiments on the test bench. The partners of RTU were involved regularly in the experimental campaigns at IAP. A risk minimisation was provided by sharing the results and adapt further steps after discussions with experts from RTU.

As briefly described in the introduction, the requirements of the modulation are very challenging: The electron beam needs to be RF modulated at a bandwidth of several MHz with time varying amplitude ranging from DC to fully modulated, while the transverse size needs to be continuously adapted to the adiabatically shrinking ion beam.

The design parameters are summarized in Table 2.

Extraction voltage	< =30 kV
Arbitrary waveform	Gaussian (normal, double, flat-topped)
Modulation voltage, peak-to-peak	0 - 3200 V
Waveform frequency sweep	400 - 1000 kHz
Waveform frequency sweep period	~ 150 ms
Modulation bandwidth	6.5 MHz
Amplitude compression ratio during the frequency sweep	0.4 - 1
Grid-cathode capacitance (measured)	100 - 125 pF

Table 2: Electrical parameters of the electron gun power modulator.

A review of available information sources revealed that, apparently, nobody has yet designed a linear amplifier producing up to 3 kV output voltage for an arbitrary waveform with a first harmonic frequency sweep from 400 kHz to 1000 kHz at a bandwidth of 6.5 MHz, while the load impedance is changing by a factor of 17 over the bandwidth.

Due to these challenging requirements, just like that of the electron gun, an iterative engineering approach was chosen. In the initial step, small scale modulator prototypes based on vacuum valve technology were built. Based on the first results the design of the modulator was changed to that of a multi-level RF inverter. This successful strategy was published on the IEEE 60th International Scientific Conference on Power and Electrical Engineering [3].

3.2 WORKING PRINCIPLE AND MANUFACTURING DESIGNS TOWARDS FINAL LAYOUT

Based on previous research and the initial designs (details can be found in [3]), the topology for the final modulator was chosen to be a semiconductor multi-level RF inverter feeding the grid-cathode

capacitance from a distance by a twisted pair high voltage feeder. Multi-level inverters potentially offer high performance with respect to the output signal. Figure 8 sketches the working principle of such a device.

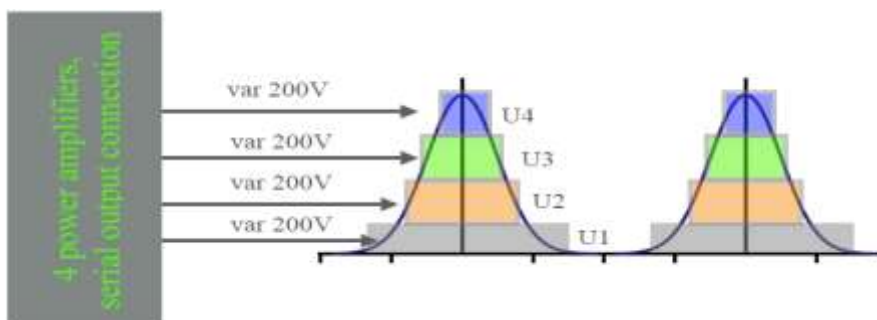


Figure 8: Working principle of a multi-level RF inverter amplifier.

In the final modulator design 26 RF inverters will be connected in series providing an output signal up to 150 V each. They are switched on or off according to generate the prescribed waveform. For smoothing of the waveform an output signal filtering is used.

The first test version of a four-level RF inverter to study the principle is shown in Figure 9.



Figure 9: First test version of four-level RF inverter.

After working principle was confirmed, an upgraded, second version of the multi-level modulator was built.

A picture of this upgraded version, its electrical circuit and the corresponding output waveform are shown in Figure 10.

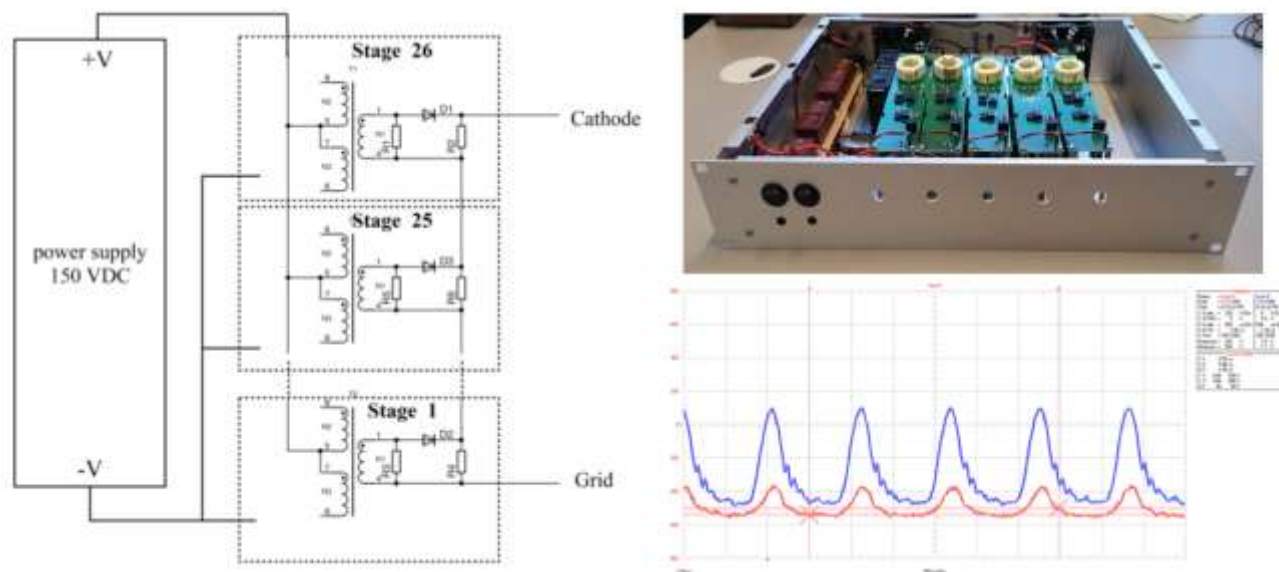


Figure 10: Electrical circuit of the multi-level RF-Inverter (left) and second version of the four-level modulator (top right) as well as its output waveform (bottom right).

3.3 POWER MODULATOR TESTS AT GOETHE UNIVERSITY FRANKFURT

The modulator used in the tests was a four-level prototype of the final multi-level amplifier design as presented previously. This prototype was capable of delivering up to 800 V output voltage. The modulator with its signal generator is now controlled via optical fibres, such that operation on a HV platform is possible. The experimental set-up is shown in Figure 11.

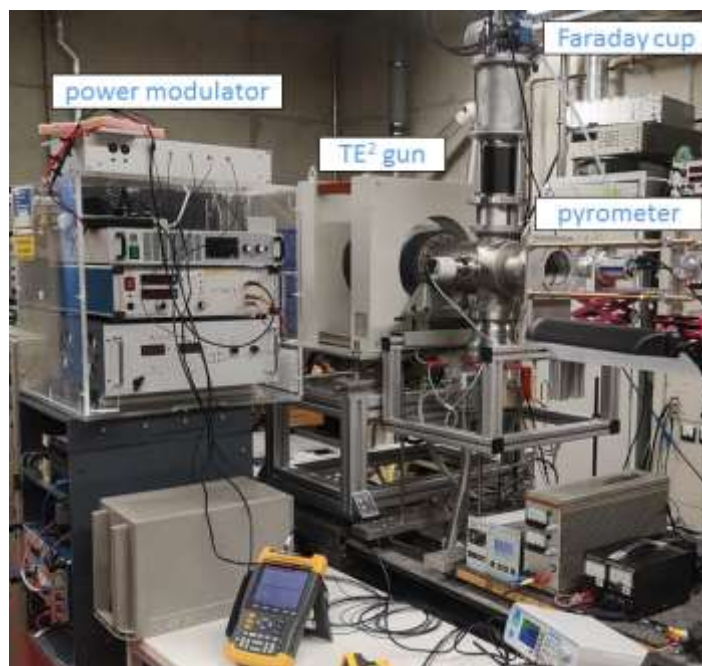


Figure 11: Second version of four-level RF inverter connected to the grid of the TE² electron gun.

During joint experiments of RTU and IAP in Frankfurt several tests were executed to check the performance of the multi-level modulator:

The HV waveform was tested with cold cathode while the modulator output was connected to the grid. The required output waveform was in principle generated, but some influence of parasitic capacitances could still be observed.

With cathode heated to 2800 K, the modulation was tested in presence of an electron cloud emitted by the cathode. In a second step, those electrons were trapped between cathode and grid, so that the modulator had to do work to shift the electrons back and forth. No negative influence of the modulator was observed in the presence of an electron density around the grid, the high temperature of the cathode or the leakage current over the grid flange.

In order to improve the output waveform the latest design version is again being upgraded: The 26 individual stages are electrically separated by isolated individual power sources (see Figure 12).

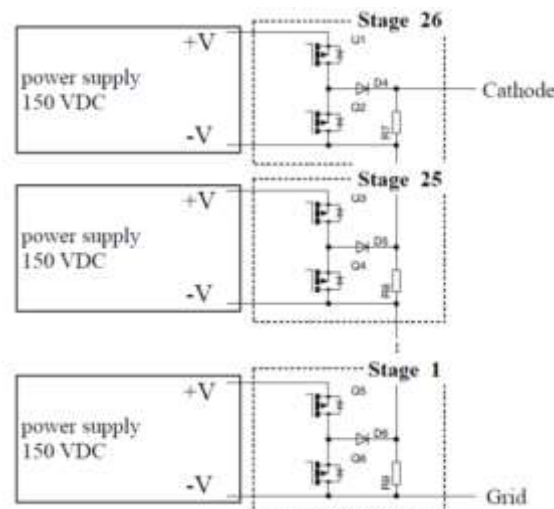


Figure 12: Electrical circuit of the latest version of multilevel RF-Inverter.

While this comes at the price of a more complicated design with respect to the power supply, it clearly delivers an improved curve shape of the output signal as presented in Figure 13.

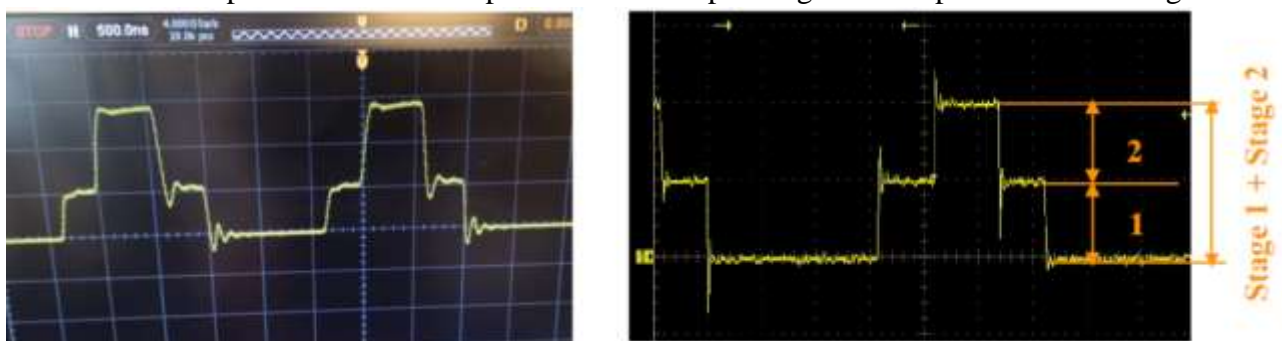


Figure 13: Comparison of output waveforms between second (left) and latest version (right) of power modulator.

4. Conclusion and Future Plans

The developed TE² source fulfils the basic functionality to produce the defined beam parameters within WP16. Engineering and construction of critical parts were successfully finished. The key components for TE² as a source for intense, RF-modulated electron beams for application in electron lenses are the direct cathode heating system developed at University Frankfurt in combination with the unique modulator developed at RTU.

To provide experiments with extracted modulated intense electron beams a dedicated test stand is needed. It is planned by the collaborators to assemble the test stand including beam diagnostics at IAP instead of CERN. IAP offers the possibility to provide a dedicated laboratory for task 16.4 and the implementation of the experimental campaign under supervision of CERN. This modification in the project strategy has to be done because of the COVID-19 pandemic. All partners were forced to adapt their schedules and resources for risk minimization and to avoid exchange of staff and hardware (safety requirements).

Together with CERN and the other partners of WP16 it was decided to extend the existing test bench for TE² development by a high voltage terminal to provide beam extraction and transport experiments. For a detailed study of the beam dynamic several non-interceptive beam diagnostics will be installed and energy recovery will help to save operational costs.

In a first step the electron gun will be integrated electrically isolated into the solenoid and the high voltage platform for powering the gun will be assembled. Very careful beam extraction at low intensities will be performed to test the performance of the extraction system of TE² and the instrumentation.

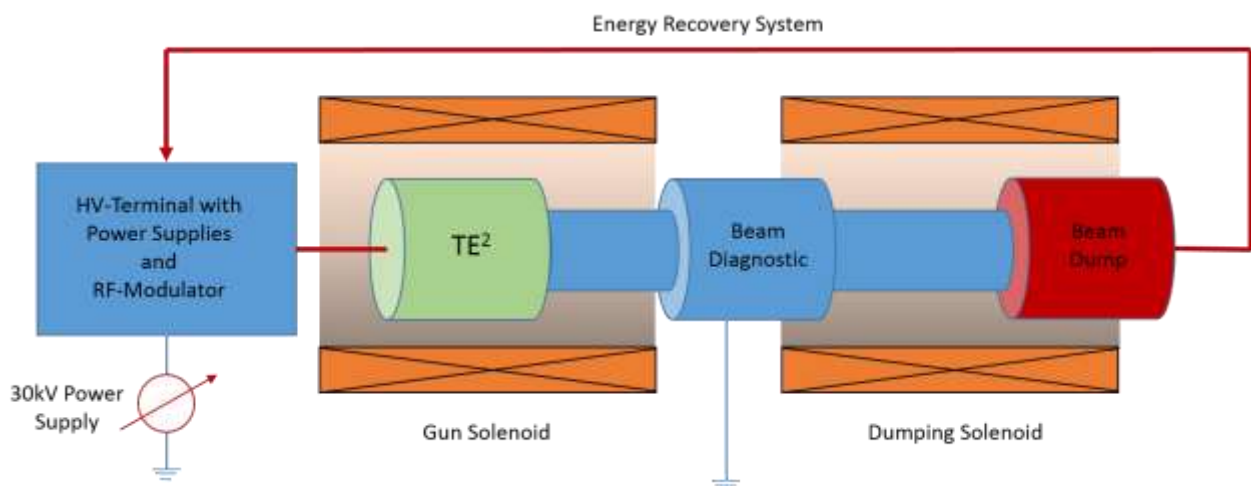


Figure 14: Electrical scheme of the high voltage platform for powering the electron gun.

The beam intensity will be increased sequentially after experiments on electron beam extraction and comparison with theoretical and numerical prediction. Therefore, a beam dump for electron current measurement and controlled power deposition will be installed. An energy recovering system recycles

the beam power of about 300 kW for the beam loading within the TE² extraction system. A schematic overview of the planned setup is shown in Figure 14.

In parallel the final 26-level RF-modulator will be manufactured at RTU. As soon as high-current extraction from the TE² gun becomes routinely, the final modulator will be used for modulation of the electron beam.

In a far future it might be possible to extend the test stand by a two meter long transport channel embedded in an axial magnetic field. It enables beam dynamic experiments and study of the self-demodulation of the space charge dominated electron beam.

The planned activities will provide a close collaboration of the accelerator laboratories GSI/FAIR and CERN as well as the Universities of Frankfurt and Riga in the field of electron lenses beyond ARIES. The project will thus strengthen the accelerator infrastructure in Europe.

5. References

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Annex: Glossary

Acronym	Definition
IRME	Intense RF-Modulated Electron beams
TE ²	Tungsten Electron Emitter
SCC	Space Charge Compensation
SIS18	Synchrotron at GSI/FAIR with rigidity of 18 Tm
SIS100	Synchrotron at GSI/FAIR with rigidity of 100 Tm
PS	Proton Synchrotron at CERN