

A COMMERCIAL MeV-UED INSTRUMENT BASED ON A 2.5 CELL RF-PHOTOGUN*

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Abstract

Current research in quantum, nano, and energy materials requires information about material structure on the atomic scale in space and time. These materials show a variety of ultra-fast phenomena such as light absorption, structural changes, phase transitions, thermal or non-thermal melting, all of which happen on the ps or sub-ps scale and involve position changes on the Ångström scale. In this contribution we present the conceptual design for the RI-Bornite instrument, which allows ultra-fast electron diffraction using Mega-electron-volt electron beams (MeV-UED). For this instrument we use a warm (copper) 2.5-cell RF-photogun with a replaceable Cu photocathode. A single Ti:Sa fs-laser system drives both the pump beam (266 nm, ca. 1 μJ/pulse) and the probe beam (800 nm, several mJ/pulse). The system is designed to reliably reach 100 fs temporal resolution. The current sample chamber is optimized for solid-state samples and includes the option for sample cooling and a load-lock. Future versions will allow experiments on liquid or gaseous samples. We present the main design considerations, electron beam dynamics simulations, and the engineering design.

INTRODUCTION

MeV ultra-fast electron diffraction (MeV-UED) is a powerful technique in the field of material science, chemistry, biology, physics and related fields. It provides deeper insights into processes on the atomic scale which happen on ultra-short time scales (fs) like phase transitions, light absorption or structural changes in quantum, nano and energy materials.

We present the conceptual design study for the first commercial MeV-UED system.

A MODULAR ROBUST INSTRUMENT

Our design focusses on a robust design reliably achieving sub 100 fs temporal resolution and allowing future upgrades. The electron beam is created in a 2.5 cell RF-electron gun by a UV laser pulse (50 fs, 256 nm). The electron beam is focused using a single solenoid and an aperture allows reduction of dark current. In this paper we show the sample chamber for solid samples which includes the beam path for the IR pump laser and mechanical stages for sample positioning. Two detectors are located in the far-field with an adjustable distance up to 5 m. We are considering

a hybrid pixel detector (PSI, Jungfrau) and a scintillation detector based on an electron-multiplied CCD camera. The instrument includes the RF-klystron and low-level RF (LLRF) system as well as the fs laser system and an EPICS based control system. This allows controlling the e-beam, the laser beam, the sample and acquiring the data. Data analysis can be done by one of the many open-source codes for diffraction.

The configuration and parameters described in Figure 1 and Table 1 are the design goals for a basic instrument. Optional upgrades which are foreseen in the design include:

- Gaseous or liquid samples
- Optical Parametric Amplifier (OPA)
- Electron pulse compression
- Solenoids for focussing the e-beam at the sample or the detector
- Two separate lasers for pump and probe with delays up to μs and dedicated synchronization

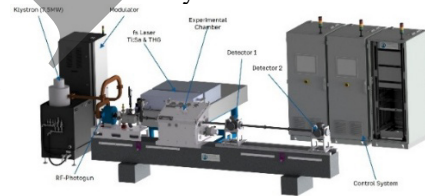


Figure 1: CAD model of the MeV-UED instrument.

Figure 2 shows a schematic overview. The Ti:Sa laser beam is split into the probe beam which is frequency triplet to 257 nm and used to generate the electrons from a Cu-photocathode in the electron gun. The pump beam is guided via a motorized delay line, enters the sample chamber and is directed onto the sample via a mirror. The sample stage is adjustable in x / y, Rx / Ry.

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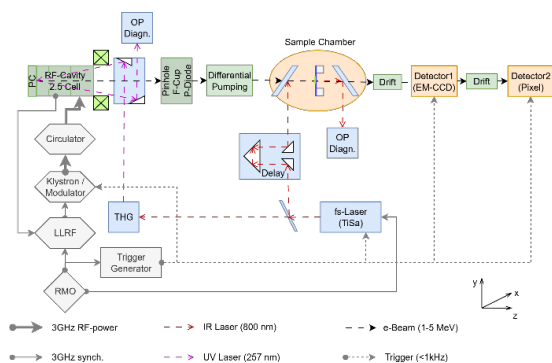


Figure 2: Schematic overview of the MeV-UED System.

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Table 1: Design Goal of a Basic Instrument

Parameter	Design Goal
Time Resolution:	100 fs
Electron Energy	3 - 7 MeV (optimized for 5 MeV)
Rep. Rate	Up to 1000 Hz possible
Bunch Charge	~ 60 fC (ca. $4 \cdot 10^5$ electrons) for best t-resolution ~ 3 pC (ca. $2 \cdot 10^7$ electrons) for single-shot experiments
Detectors	Ca. 1M Pixels, $75\mu\text{m}$ pixel size, <2 kHz read out rate Scintillator screen read out by EM-CCD (1M pixel, $13\mu\text{m}$, <50 fps)
Spot diameter @ sample (RMS)	ca. $160\mu\text{m}$
Laser energy per pulse	5 mJ/pulse
Laser energy range	800 nm (Ti:Sa)
Delay range	1 ns, 100 fs/step
Sample environment	Room temperature solid sample mounted on motorized stages.
Single-shot capability	Possible
Momentum resolution	ca. $<0.05\text{ \AA}^{-1}$
Delivery time	ca. 20 months
Software	Experiment control and data acquisition included. Data analysis not included.

2.5 CELL RF-PHOTOGUN

The electron gun uses a 2.5-cell S-band design (Figure 3) based on brazed copper parts. The photocathode is a copper stub, which can be replaced after venting the gun. The 1st full cell contains a pick-up for measurement of the RF-field and regulation via the low-level RF system (LLRF). The second cell is connected to a symmetric RF coupler. The combination of two RF-ports with two pump ports symmetrizes the RF-field in this cell. The gun is fed by the klystron (up to 7.5 MW, $1.5\mu\text{s}$ pulse length). It allows maximum fields of 120 MV/m at the PC. To avoid excessive dark currents the design foresees operation at ca. 80 MV/m under normal conditions.

The in-coupling of the PC-laser happens from the front. It uses adjustable all-metal mirrors located downstream of the gun inside the UHV. This achieves a near normal laser incidence on the PC and thus a round spot.

The gun is currently in fabrication and will be tested in 2027.

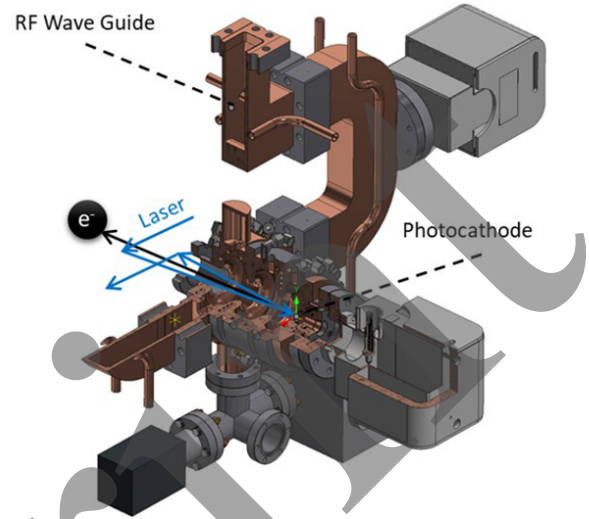


Figure 1: 2.5 cell RF-gun

ELECTRON BEAM DYNAMICS

We used ASTRA [1] and GPT [2] to investigate the electron beam dynamics and optimize emittance and temporal resolution. To benchmark our simulations, we compare this 2.5 cell gun with the 1.6 cell gun operated successfully at SLAC [3] since many years.

Figure 4 shows the RMS-spot size of the electron beam vs. beam propagation (z) for three different electron energies. After the PC the spot size grows due to the intra-bunch Coulomb repulsion. The solenoid ($z \sim 0.4\text{ m}$) focuses the beam onto the sample position. The aperture ($z \sim 0.57\text{ m}$) only slightly clips the main beam but massively attenuates background by field emission. The sample is located near the e-beam focus ($z \sim 1.16\text{ m}$). Here the e-beam spot size is between ca. $50 - 100\mu\text{m}$ depending on the electron energy.

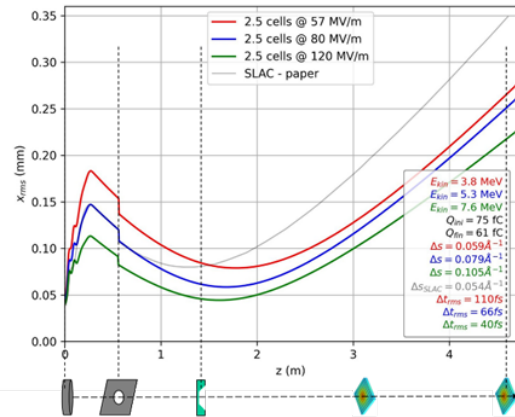


Figure 2: Electron beam diameter vs. distance to photocathode for various field strength of the 2.5-cell gun in comparison to the SLAC [3] gun (grey line).

High fields at the PC lead to rapid acceleration to relativistic energies and thus reduce the Coulomb repulsion resulting in smaller spot sizes on the sample. The electron energy can be varied between ca 3.8 and 7.6 MeV. The higher the energy, the thicker a sample can be penetrated.

Figure 5 shows the emittance ϵ_n vs. beam propagation. After the PC the emittance decreases because of the acceleration in the RF-field, at the aperture it is reduced by ca. 20% by clipping off-energy and high-angle electrons, see Figure 6, middle row ($z = 0.57$ m).

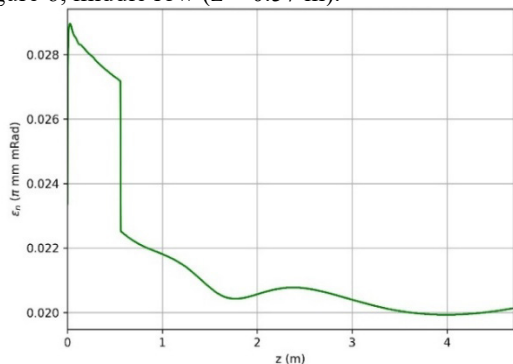


Figure 3: Normalized transverse emittance along the e-beam.

Phase space plots of the electrons are shown in Figure 6.

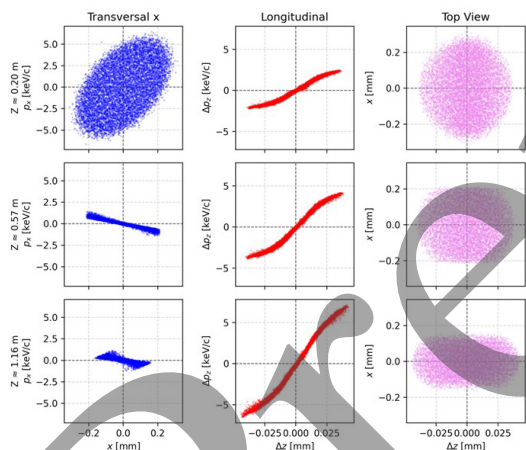


Figure 4: Phase space of the electrons at three positions ($z = 0.2$ m immediately after the gun, $z = 0.57$ m position of pinhole, and $z = 1.16$ m sample position).

SAMPLE CHAMBER

The sample chamber shown in Figure 7 is a general purpose chamber. It is designed for solid samples and allows installation of relatively bulky custom equipment placed on bread boards. Access during such installation is provided through a large lid on the top, allowing two persons to work inside the chamber. Spare flanges allow installing additional pumps, feedthroughs, etc. Samples mounted on the standard flag style sample holder, or similar, can be introduced via a load-lock. This load lock also features a storage rack holding five sample plates with several samples (SiN membranes, 3 mm TEM grids, etc.) per plate. The samples can be mounted on electron transparent membranes (SiN, graphene, etc.) or the standard TEM grids.

The laser is fed into the chamber from the back side where a long-distance microscope also allows *in-situ* sample observation. Additional ports allow user adaptation for sample cooling, electrical contacts and other optional features. Inside the chamber the sample can be positioned in the electron focus and can be rotated around the x- and y-axis to meet the Bragg diffraction condition for single crystalline samples.

For the laser beam the focus and overlap with the electron beam is detected using a fluorescent screen mounted on a sample plate and the long-distance microscope.

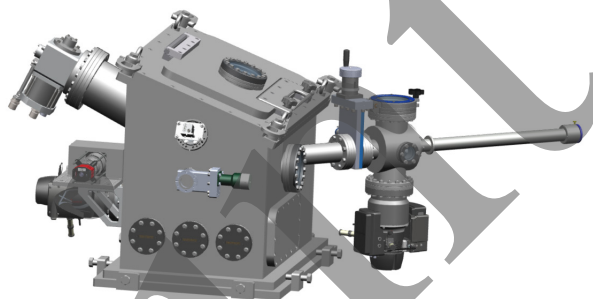


Figure 5: Sample chamber seen along the e-beam path showing load lock (right), large lid for access (top), cryocooler (top left) and long-distance microscope (bottom left).

The sample chamber can be adapted for each user depending on specific requirements of the experiment and the infrastructure.

CONCLUSION

We demonstrate the suitability of a 2.5 cell RF gun for MeV-UED. This provides a narrow ($x_{\text{rms}} < 100$ μm), low emittance ($\epsilon_n = \text{ca. } 0.2 \pi \text{ mm mRad}$) beam with variable energy of ca. 3.5 – 7.5 MeV and sub 100 fs temporal resolution.

Providing the instrument as a fully commercial device installed and tested at the customer site will open the technique of MeV-UED to users who have so far not been able to conduct such experiments on their most interesting sample due to limited availability of such a system.

ACKNOWLEDGEMENTS

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