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AN X-BAND ULTRA-HIGH GRADIENT PHOTOINJECTOR*

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Abstract

High brightness beams appealing for XFELs and UEM essentially imply a high current and a low emittance. To obtain such beams we propose to raise the accelerating voltage in the gun mitigating repealing Coulomb forces. An ultra-high gradient is achieved utilizing a short-pulse technology. We have designed a room temperature X-band 1,5 cell gun that is able to inject 4 MeV, 100 pC bunches with as low as 0.15 mcm normalized transverse emittance. The gun is operated with as high gradients as 400 MV/m and fed by 200 MW, 10 ns RF pulses generated with Argonne Wakefield Accelerator (AWA) power extractor. We report results of low RF power tests, laser alignment test results, and successful gun conditioning results carried out at nominal RF power.

A CONCEPT FOR HIGH GRADIENT GUN

High brightness beams appealing for XFELs and UEM essentially consist of a large number of electrons in a small phase space volume, i.e. a high peak current [1-3]. When such beams are generated from the cathode, there is a strong space charge force, which elongates the bunch and reduces its brightness. An optimal solution is to raise the accelerating voltage in the gun to mitigate repealing Coulomb forces. However, the maximum gradient is limited by the effects of RF breakdown. The uniqueness of the Euclid's proposal is its utilization of a ultra-high gradient and a short-pulse technology at room temperature. The probability of RF breakdown and pulse heating temperature are reduced as the RF pulse length decreases [4-5]. We present a development of an electron ultra-high gradient photoinjector (UHGPI) operating with short RF pulse, 10 ns scale.

RF AND ENGINEERING DESIGN

The proposed 11.7 GHz gun is a 1,5 cell overcoupled resonator with the perforated iris in-between cells in order to sustain strong coupling factor (Fig. 1). The Q-factor is slightly below 200 to accommodate 9 ns RF pulse. The gun has a coaxial feeder. The field structure is shown in the Fig. 2. The simulated and measured S_{11} parameters are shown in the Fig. 3 and the Fig. 4 respectively. We note a good agreement for design and low-power measurements. Results of bead pull measurements performed with special ferromagnetic bead, moved along axial magnetic field, are plotted in the Fig. 5.

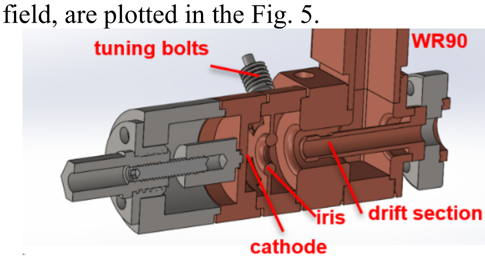

Figure 1: Engineering design of UHGPI.

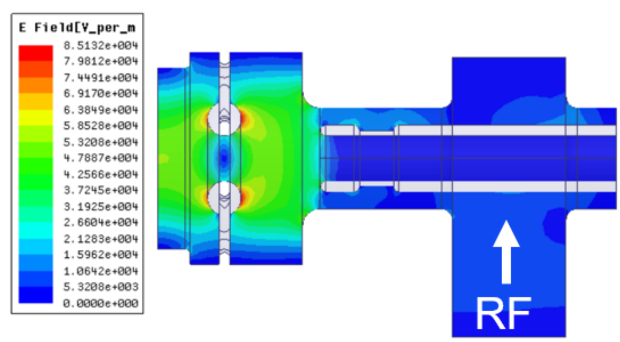

Figure 2: Field structure in gun at 11.7 GHz.

We designed and fabricated a 0.55 T solenoid for beam emittance compensation (Fig. 6). The solenoid has the B-field length 110 mm. Solenoid position and field distribution were optimized by ASTRA code to obtain the best achievable emittance compensation which could be reached using of an additional 8-cell brazeless linac tested at AWA one year ago [6]. The linac was assumed to provide slightly more than 100 MV/m gradient. Results of emittance simulations along the UHGPI are shown in the Fig. 7. In this Figure the shaded blue, grey, and orange rectangles indicate the locations of the TW-gun, solenoid and linac section. The yellow shaded area shows the incoming UV laser beam being focused on the cathode. More information about beam dynamics simulations can be found at this conference presentation [7]. A list of the projected parameters is represented at the Table 1.

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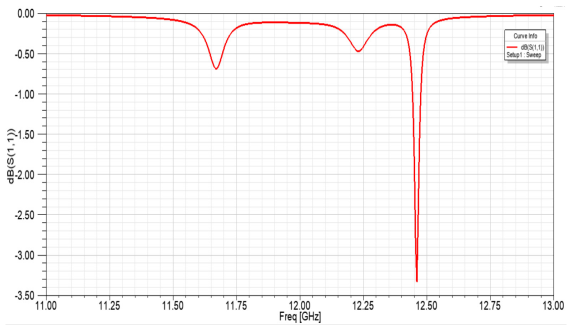

Figure 3: S_{11} simulation.

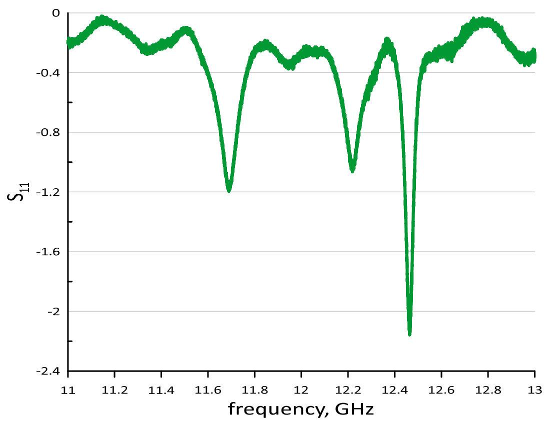

Figure 4: S_{11} measurement.

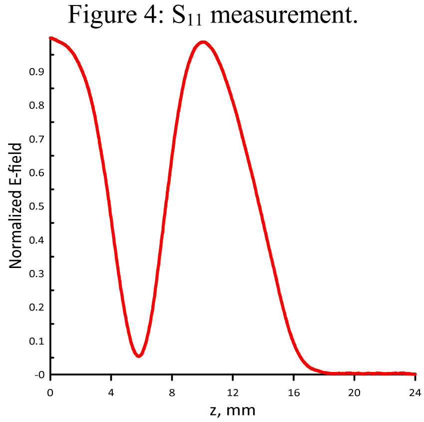

Figure 5: Bead pull measurement result at 11.7 GHz.

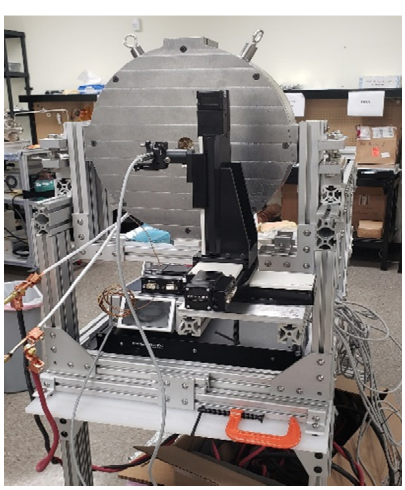

Figure 6: Gun solenoid.

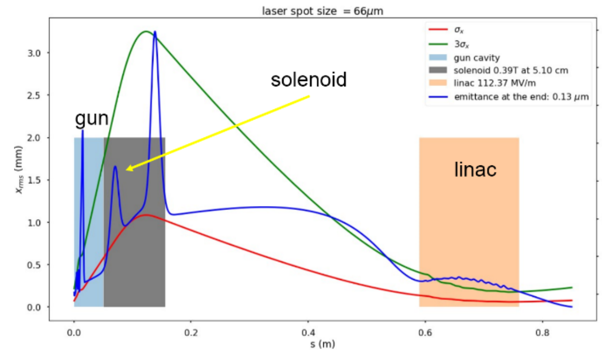

Figure 7: Evolution of the RMS beam size (red) and emittance (blue) along gun beamline.

Table 1: Projected Gun Parameter List

Parameter	Value
Frequency	11.7 GHz
Mode quality	180
Mode separation	250 MHz
Pulse length	9 ns (3 ns flat top)
Cathode field	300-400 MV/m
Bunch charge	100 pC
Bunch radius at cathode	70 μm
Bunch length	4 ps
Normalized emittance	150 nm
Energy spread	2.5×10^{-3}

BEAMLINE DESIGN

A beamline configuration is different for every of three experiments planned for the UHGPI. In the experiment #1, where we planned to carry out a high-gradient test and to measure a dark current, the scheme of the experiment includeed the gun itself only, because that time we did not plan to inject laser induced bunches. The beamline included a YAG screen and was assembled at the zone#3 at AWA. This experiment completed and results are described in the next paragraph. During the experiment #2, scheduled for this May, we plan to inject laser induced bunches so that the scheme has additional components: double cross in which we will install YAG and mirrors for UV launching and a spectrometer to measure energy of the particles. A full beamline assembly will include: a gun solenoid with power supply and chiller, a YAG screen, an ICT and BPM, a laser transmission line consisted of optical mirrors in the double cross, a linac for maximum emittance compensation, a spectrometer for bunch energy measurements, and a "pepper-pot" for emittance characterization (Fig. 8). In the Fig. 9 one can see a linac which will be installed behind the gun. The mentioned 100 MV/m linac was fabricated in frames of another DoE grant and tested at high power level at AWA. The considered full assembly will be used in the experiment #3 to be carried out in fall of 2021. In this final experiment we plan to show as small emittance as possible.

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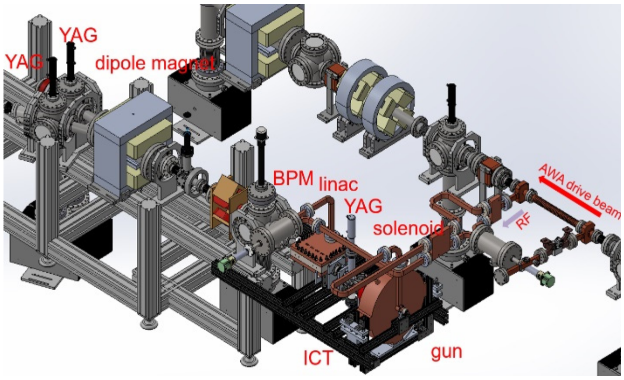

Figure 8: Beamline design for experiment #3.

In the experiment #3 we will use the mentioned 100 MV/m linac which will be fed from the same AWA power extractor as the gun itself. This requires means to share RF power among the gun and the linac as well as to provide in-phase conditions for them. In order to embody this task, we envisaged using RF network which implied that RF power from the extractor will be split and delivered by means of two independent RF waveguide lines to the gun and to the linac correspondingly (Fig. 9). For that purpose, we had to elaborate two key components, a variable power splitter and a phase shifter, in order to guarantee in-phase acceleration of bunches in the gun as well as in the linac. These components were designed. The phase shifter (Fig. 10a) is based on a so-called "trombone" principle so that the phase changes by means of a waveguide sliding section moving in vacuum. To provide sliding, an actuator is used. This solution provides small enough field enhancement, almost linear dependence of the inserted phase on actuator position, and broadband low reflection for all actuator positions. Bragg reflectors prevent leakage of RF power through the sliding contact.

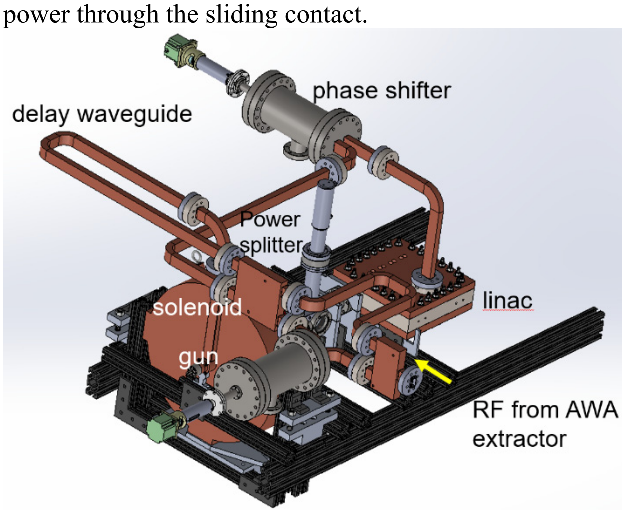

Figure 9: RF transmission line feeding gun and linac.

Another necessary RF component for the experiment #3 is the mentioned variable power splitter (Fig. 10b). The idea of the power splitter, which allows to obtain an arbitrary power ratio at the outputs, is based on super positioning of two equal signals with different phases. In dependence on the controllable mutual phase one can obtain an arbitrary power ratio. The incident power is split by means of a symmetrical T-splitter, in one arm we place the described phase shifter and combine powers again in the -3 dB coupler. A key component is the -3 dB coupler which was designed to provide low reflection and power loss in a broad frequency band.

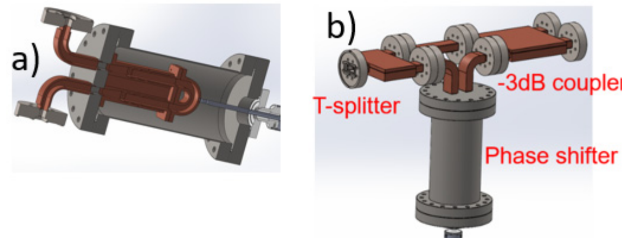

Figure 10: Broadband RF components: a – phase shifter, b – power splitter.

HIGH-POWER TEST AT AWA

At AWA we tested a prototype of our gun (Fig. 11). In viewpoint of RF design the prototype and the final gun are the same. AWA power extractor delivered up to 300 MW power. This allowed to reach 350 MV/m accelerating field on cathode [8]. During test we observed strong dark current loading regime, but the gun quickly conditioned away. It only took 70 k pulses for a full condition. Back to 200 MV/m to 250 MV/m region, no measurable dark current. We looked for reflection RF signal at bidirectional coupler. After conditioning we did not observe any change in reflection that allowed to conclude that no RF breakdown regime was established, at least plasma concentration was very low. We plan to inspect gun surface in order see if there are fingerprints of a breakdown.

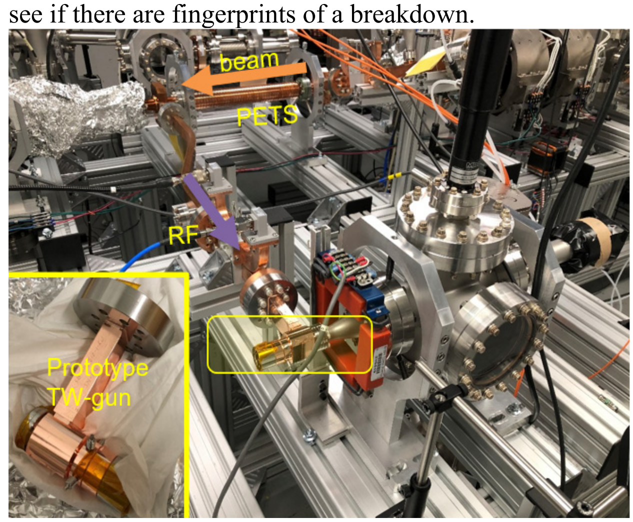

Figure 11: High-gradient test setup at AWA.

CONCLUSION

High-gradient gun design promises an exceptionally low beam emittance (less than 0.15 mm×mrad). As high as 350 MV/m gradient achieved with a short RF pulse (9 ns full duration, 3 ns flat top) preserved from breakdown and large dark current. This was confirmed at AWA experiment with 300 MW power extraction structure. Full-scale high-power experiments scheduled for this Spring (experiment #2) and fall of this year (experiment#3).

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