# A High Voltage DC GUN for a High Brightness Beams Test Facility

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***on behalf of the HB$^2$TF collaboration***

**Carlos Hernandez Garcia** – ***JLAB (agreement n. 21-T001 25-6-2019)***

**19th October 2023**

# HB$^2$TF

**High-brightness electron beam sources are** critical elements in the path to the success of upcoming projects, such as linac-based light sources and industrial-scale UV lasers.

Disparate needs are driving injector design in different directions: high beam power for IR and UV FELs, low transverse emittances for linac-based x-ray light sources, and emittance aspect-ratio control for linear colliders.

The present proposal is related to **the development of a High Brightness Beams Test Facility (HB$^2$TF) at the INFN-LASA laboratory**.

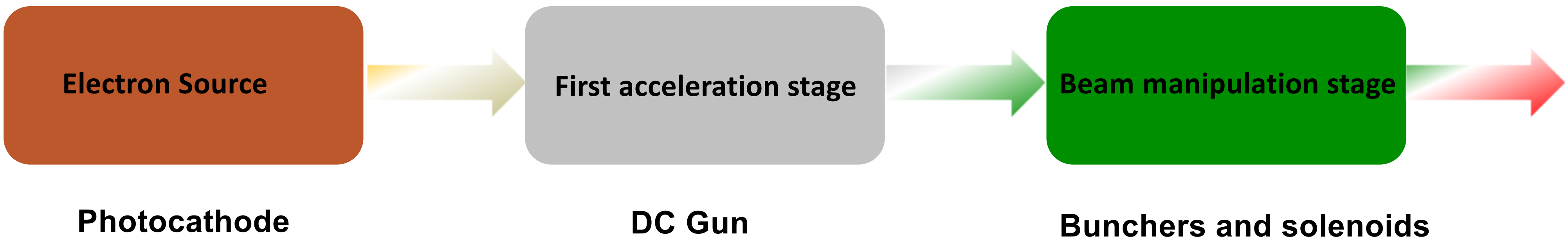
The proposal is aimed to pool different experiences and capabilities so far available in research groups at the LASA laboratory along with the contribution from accelerator groups in other INFN sites and in foreign labs.

# HB$^2$TF in a nutshell

The proposal to **develop a High Brightness Beams Test Facility (HB$^2$TF) at the INFN-LASA laboratory** has been approved by INFN-CSN5 for the period 2023-2025. HB$^2$TF aims to provide **a high power and high brightness CW beam**. The beam will provide different bunch charges at different repetition rate and energies.
This impressive flexibility is part of the originality of the facility and will allow the usage of the beam for some advanced experiments.

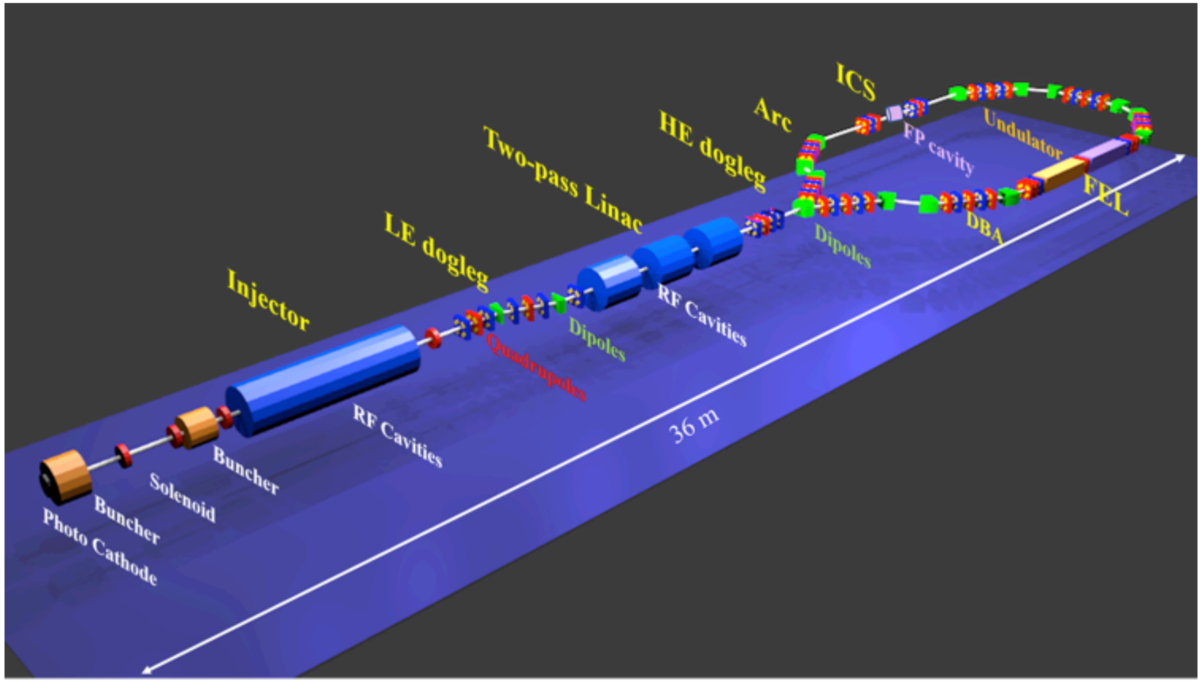
Under these assumptions, the facility is composed of different elements that can be grouped into the following sections:

- An electron source.
- A first acceleration stage (DC).
- A beam manipulation and transport stage.



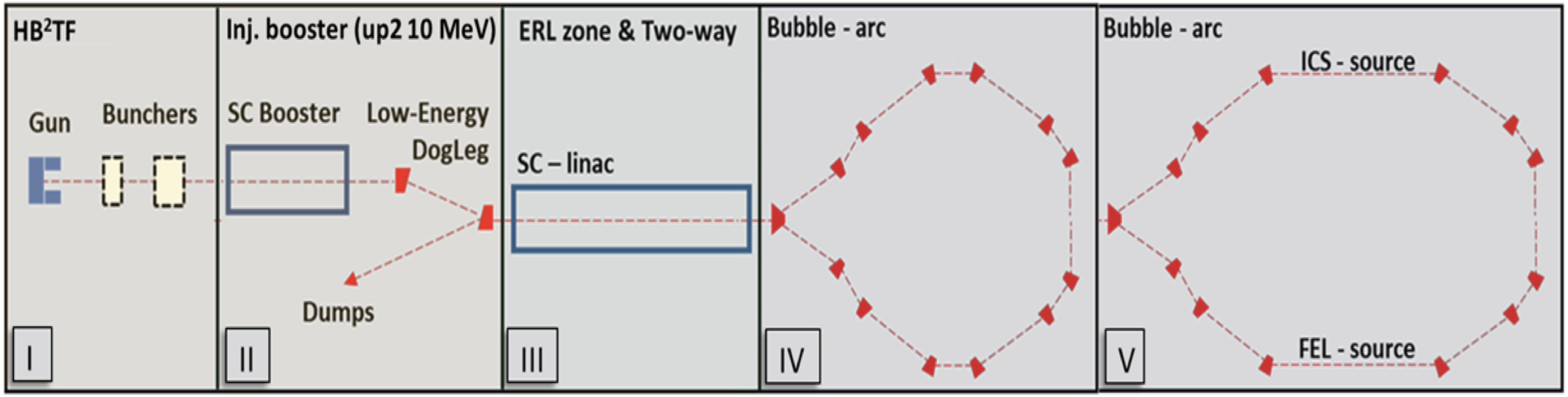
# HB$^2$TF: First Step toward a Milan High Brightness Facility

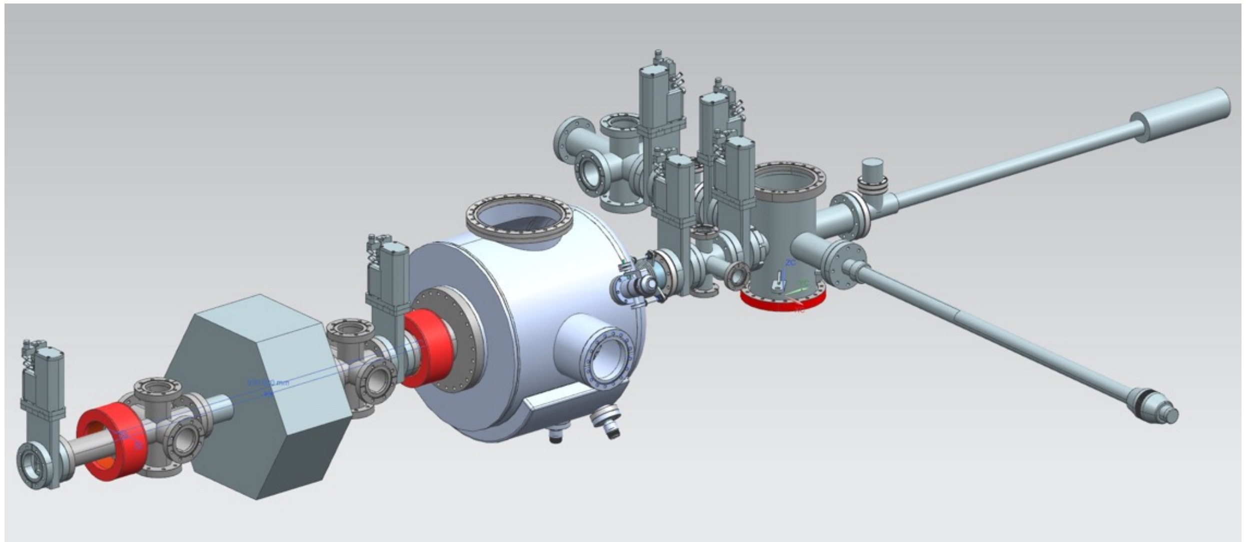
| Parameter | two-pass acc. | ERL |
|---|---|---|
| Energy (MeV) | 80 | 45 |
| Bunch charge (pC) | 100 | 100 |
| Repetition rate (GHz for CW operation) | $0.9286\ 10^{-3}$ | 0.9286 |
| Average Current (mA) | $5\ 10^{-3}$ | 5 |
| Beam power @ dump (W) | $22.5\ 10^{3}$ | 400 |
| $\varepsilon_{n,x,y}$ (mm – mrad) | < 1.6 | < 1.6 |
| Energy spread (%) | < 0.2 | < 0.2 |




*BriXSinO general layout. From left: injector with DC gun, bunchers and radiofrequency cavities. Low-energy (LE) dogleg with quadrupoles in red and dipoles in green. Two-way (or ERL zone) SC linac that can be operated in the two-pass two-way acceleration or ERL mode. High-energy (HE) dogleg. Recirculating loop (Arc), made by Double Bend Achromats (DBA), hosting the light sources and bringing back the beam to the two-way zone. On left branch of the arc: Fabry-Pérot (FP) cavity with Inverse Compton Scattering (ICS) source. On right branch of he arc: Free-Electron Laser (FEL).*

# HB²TF: First Step toward a Milan High Brightness Facility



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# HB2TF– Machine Optimized Layout

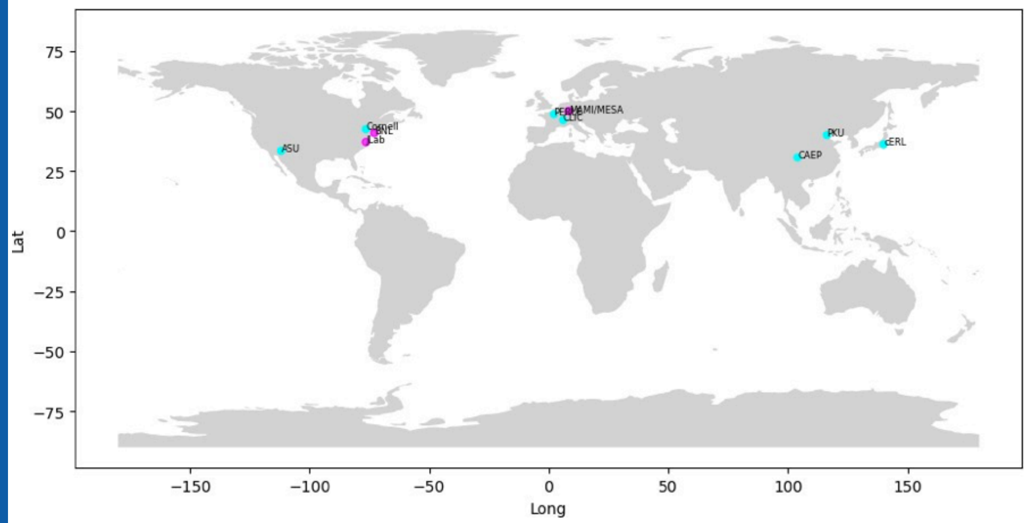
HB2TF is based on a DC-gun with a maximum acceleration field of 350 kV/m. However, we have chosen to work at 300 kV/m to be conservative and due to the effectiveness of the scheme. Downstream of the DC-gun, the two RF sub-harmonic bunchers are set with a maximum peak field of 2.7 MV/m.

The apparatus under development currently ends with the second buncher. In our simulations, we considered an RF SC linac booster that accelerates the beam to 4.5 MeV. This value is ideal for low energy injection in ERLs and provides adequate mitigation of space charge effects.

The main beam line data for the simulated WP, including the laser pulse shaping, 4 solenoids peak field along the line and the injector booster, which present design is based on three 2-cell SC cavities bERLinPro like, are reported in the table below. The first solenoid is the one dedicated to the emittance compensation, the following three are needs to control the beam size, together with focusing effects of the two bunchers.

| |
|---|
| **Bunch extraction:** |
| $Q_b = 50$ [pC]; $\sigma_{x,y} = 650$ [μm]; $\tau_{laser} = 18$ [ps] (rise-time = 1ps) |
| **DC-gun:** |
| $\Delta V$=300 kV/m |
| **The two Bunchers:** |
| $E_p = 2.7$ MV/m |
| $\Phi_{inj\_1} = -31°$, $\Phi_{inj\_2} = -35°$ |
| **SC inj. booster (three two-cells):** |
| $E_p = 11.5$ MV/m |
| $\Phi_{inj\_1} = -25°$, $\Phi_{inj\_2} = 21°$, $\Phi_{inj\_3} = 0.0°$ |
| **beam-line solenoids peak fields [T]:** |
| $B_{z\_1} = 0.0276$, $B_{z\_2} = 0.0172$, $B_{z\_3} = 0.0128$, $B_{z\_4} = 0.0246$ |

# HV DC GUN Worldwide

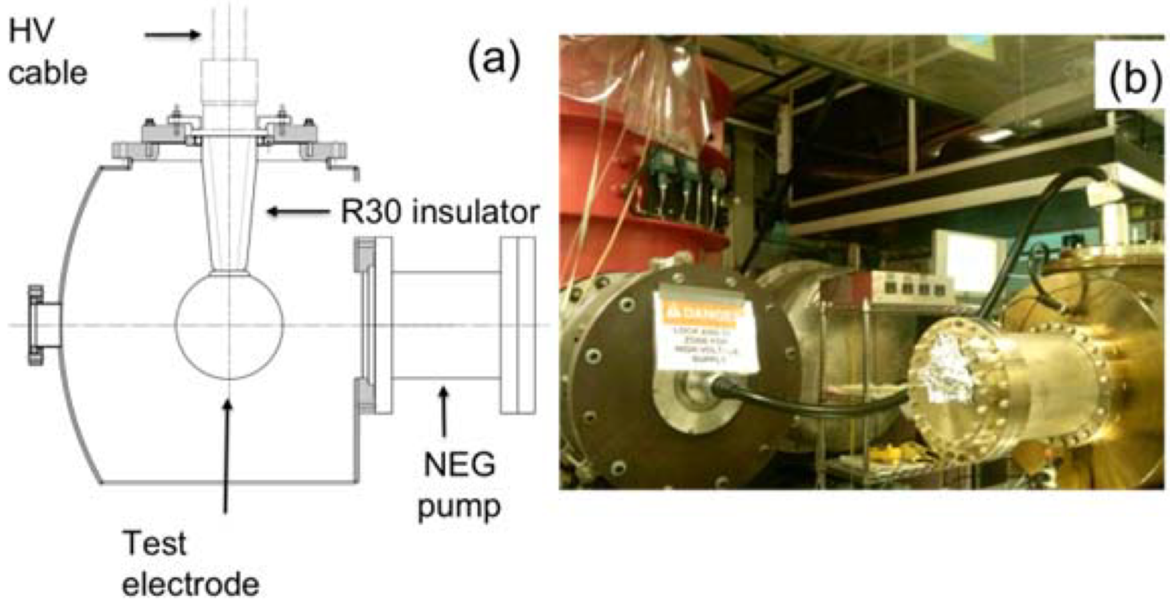



| Place | Specifications |
|---|---|
| | |
| CEBAF (USA) | Operating<br>130-200 kV<br>CW<br>0.07 mA |
| MAMY (Germany) | Operating<br>100 kV<br>CW<br>0.1 mA |
| MESA (Germany) | Commissioning<br>100-150 kV<br>CW<br>0.15 mA |
| EIC (USA) | R&D |
| | 300 kV |
| | Pulsed |
| | 4.5 A (peak current) |
| LEREC (USA) | 375 kV<br>20 mA |
| ILC (Japan ?) | Proposed |
| | 200-300 kV |
| | Pulsed |
| | 4.8 A (peak current) |
| CLIC (Switzerland) | Proposed<br>140 kV<br>Pulsed<br>9.6 A |
| PERLE (France) | Proposed |
| | 350 kV |
| | CW |
| | 20 mA |
| CEBAF e+ (USA) | Conceptual |
| | 350 kV |
| | CW |
| | 10 mA |
| Arizona State University (USA) | Cryocooled |
| | 200 kV |
| CAEP (Chna) | 500 kV |
| Heracles Cornell | 200 kV |
| | 10 mA |
| Peking University (China) | 100 kV |
| | Coupled to SRF Gun |
| LHeC Polarized | 220 kV |
| LHeC Unpolarized | 350 kV |
| CBeta Cornell (USA) | 250 kV |
| | 100 mA |
| cERL (Japan) | 450 kV |
| | 1 mA |
| RHIC (USA) | 375 kV |
| | 20 mA |

# HV DC GUN Characteristics

Recent worldwide interest in developing bright accelerator-based light sources has renewed efforts to operate dc high voltage photoguns at considerably higher voltages (up to 500 kV or more).
At Jefferson Lab, an inverted-geometry ceramic insulator approach has been adopted, where the term “inverted” describes an insulator that extends into the vacuum chamber serving as the cathode electrode support structure. This represents an alternative to designs that employ large cylindrical insulators with long metal electrode support tubes passing through the insulator bore.

The inverted-insulator design helps to reduce field emission because there is considerably less metal biased at high voltage. However, the inverted-geometry ceramic insulator introduces a new problem compared to other photogun designs, namely, how to effectively apply high voltage to the cathode electrode without encountering high voltage breakdown across the relatively small inverted insulator.



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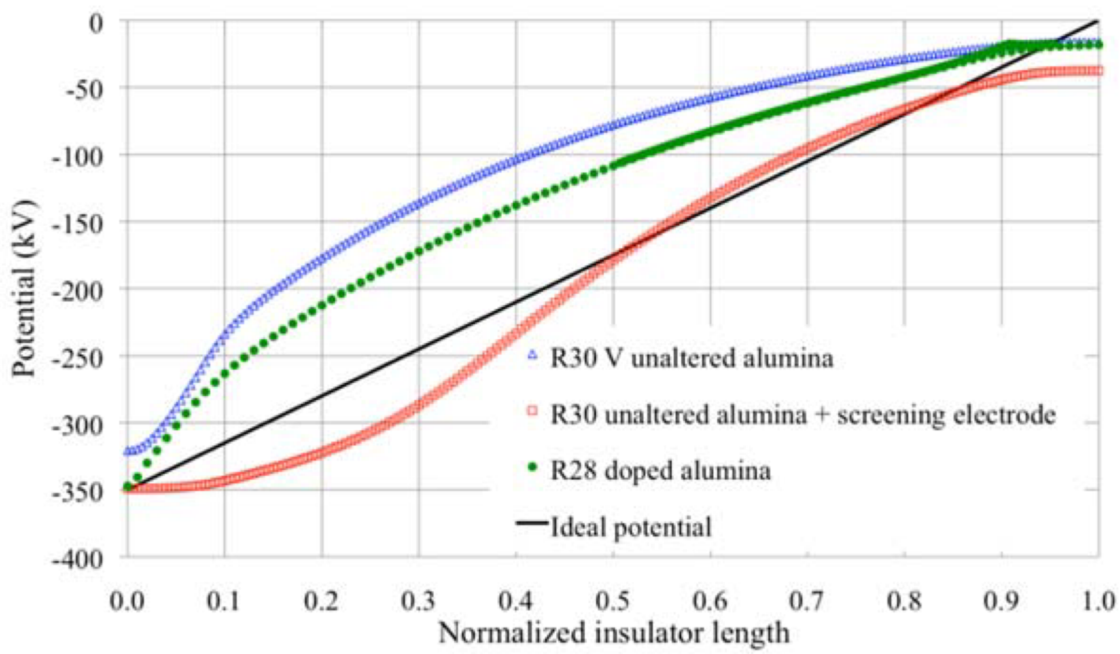
# HV DC GUN Characteristics

**It is prudent to engineer high voltage insulator/electrode configurations to obtain a uniform potential gradient across the length of the insulator**

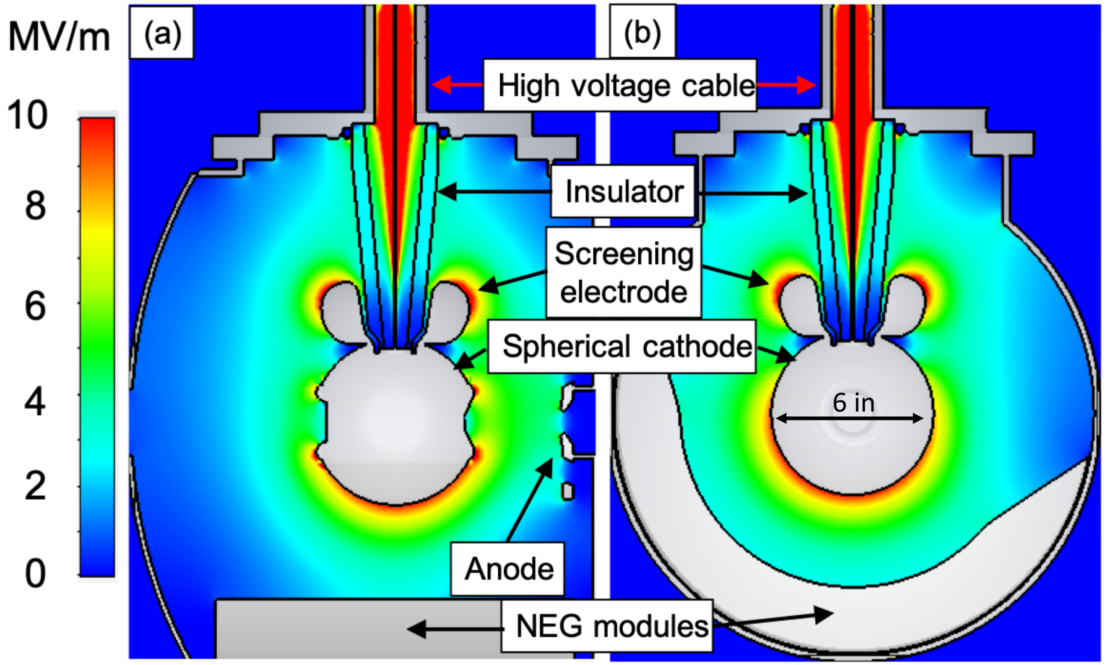
*A. S. Pillai and R. Hackam, "Modification of electric field at the solid insulator-vacuum interface arising from surface charges on the solid insulator", J. Appl. Phys, Vol. 54, pp. 1302-1313, 1983.*




*Credit: C. Hernandez-Garcia, M. Poelker, and J. Hansknecht*
*Thomas Jefferson National Accelerator Facility*
*12000 Jefferson Ave*
*Newport News, VA 23606, USA*

# Electrostatic design principles are based on the following requirements:

Electron gun electrostatic fields at 350 kV




Side view

Front view looking from anode

- No field emission, to provide long photocathode lifetime.
  - Electrode shape and size designed for 10 MV/m max at 350kV
  - Polished electrodes
  - High voltage conditioning
- No high voltage insulator breakdown (i.e., arcing)
  - Design triple junction shield
- Radially symmetric electric field in the anode-cathode gap to minimize beam deflection.
  - Intrinsic gun design makes this difficult to achieve

Credit: C. Hernandez-Garcia, and G. Palacios-Serrano
Under Non-Proprietary User Agreement No. 21-T001 between Jefferson Science Associates, LLC, and Istituto Nazio nale di Fisica Nucleare (INFN)



Jefferson Lab

# Triple junction shield design principles: where vacuum metal and insulator meet

## To reduce risk of breakdown along the insulator:

- Minimize gradient along the insulator
- Minimize gradient at triple junction
- Make the potential along the insulator as linear as possible

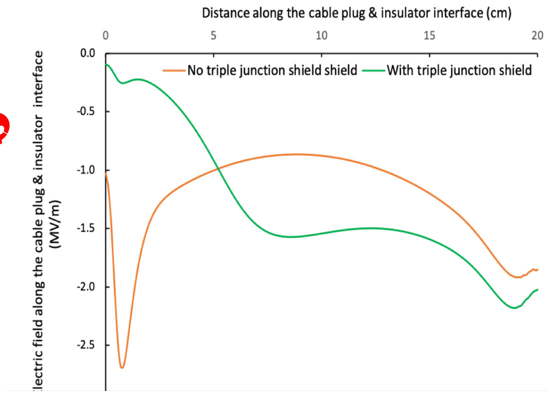
## To reduce risk of field emission:

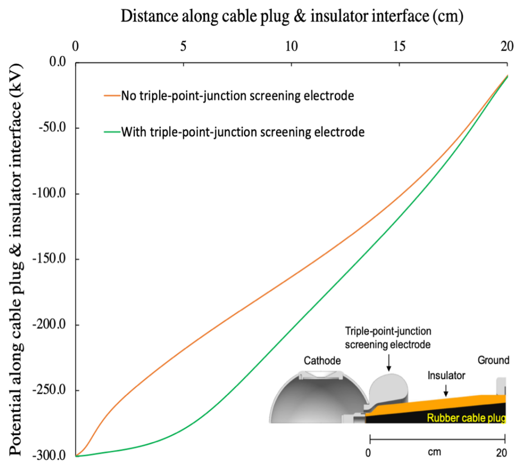
- Adjust height and cusp radius to maintain 10 MV/m max at 350kV

## To minimize distortions to gradient in anode-cathode gap:

- Keep outermost radius smaller than ball electrode radius

ADJUSTING SHAPE AND SIZE
IT'S AN ITERATIVE PROCESS




Credit: C. Hernandez-Garcia, and G. Palacios-Serrano
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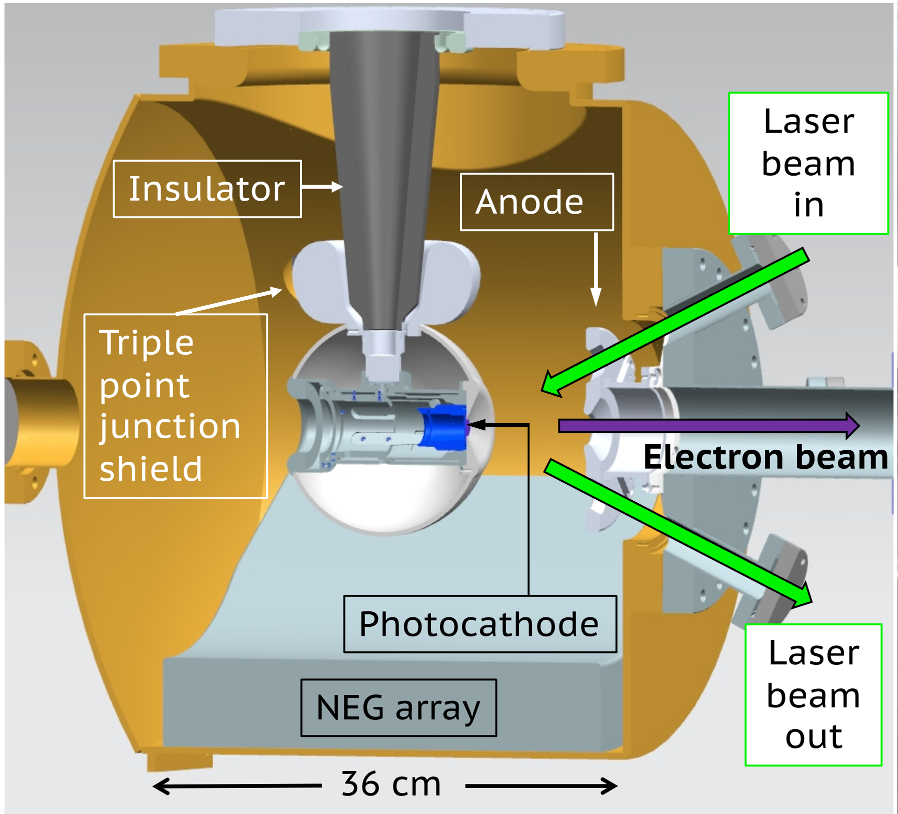
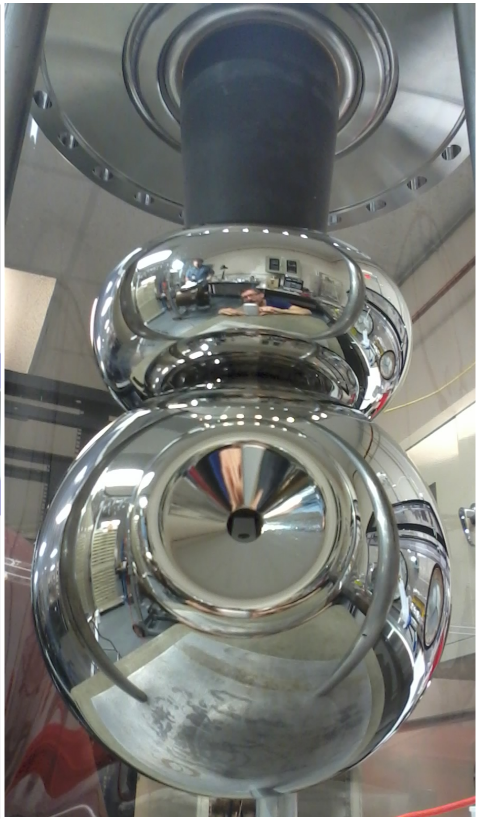
# The engineering design evolves from the electrostatic optimization



- The vacuum chamber was vacuum fired to 400 C for hundreds of hours to minimize outgassing
- The anode and mounting flange allow for laser to illuminate the photocathode at 25 deg
- The ceramic insulator is doped to drain charge for minimizing arcing
- The ball cathode and triple junction shield are barrel polished in corncob to < 100 nm rms surface roughness for minimizing field emission*



Credit: C. Hernandez-Garcia, and G. Palacios-Serrano
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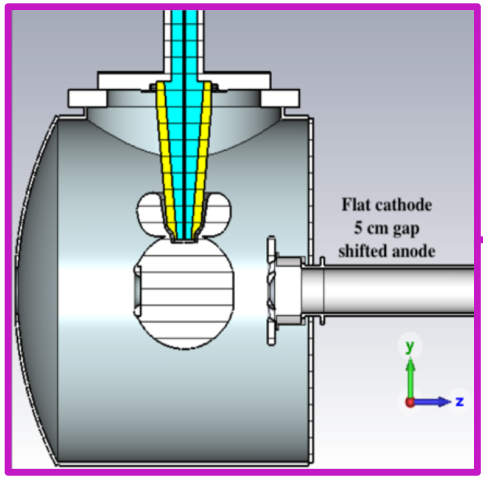
# HB2TF Current Activities – DC Gun cathode

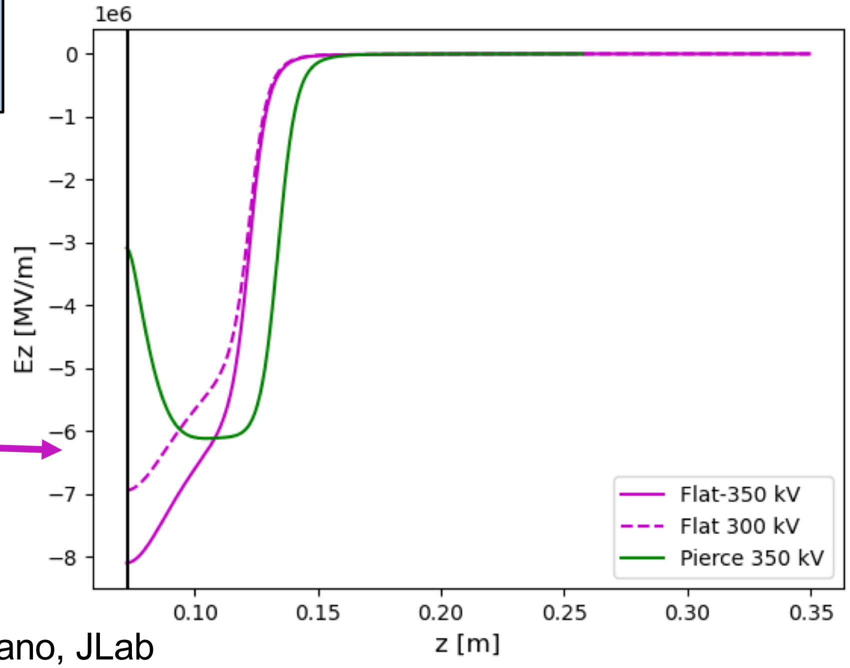
The Flat-cathode Ez profile works very well.

We tested some different cases:

1. ΔV = 250 kV (as BriXSinO gain case) not in the fig.
2. ΔV = 350 kV (maximum gain case)
3. ΔV = 300 kV (most reasonable operative gain case)
   **The one we are going to use as reference value**

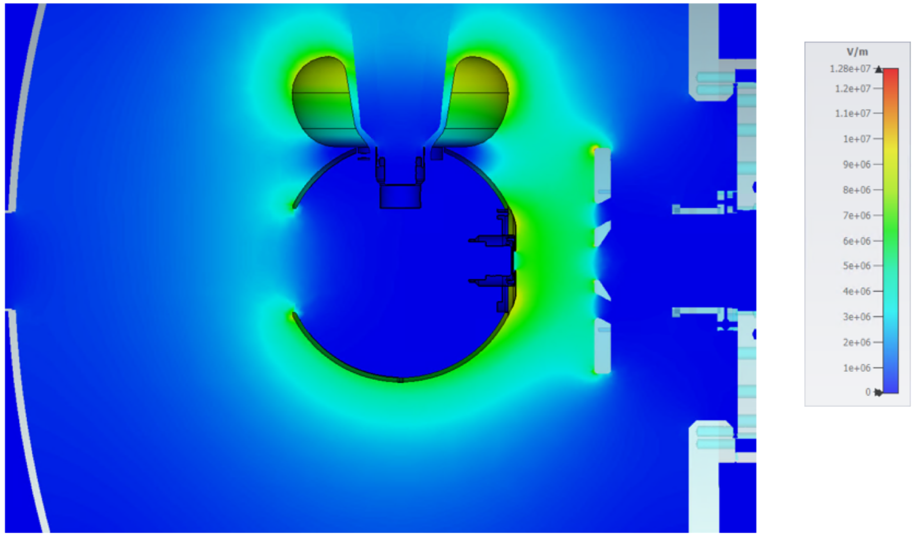


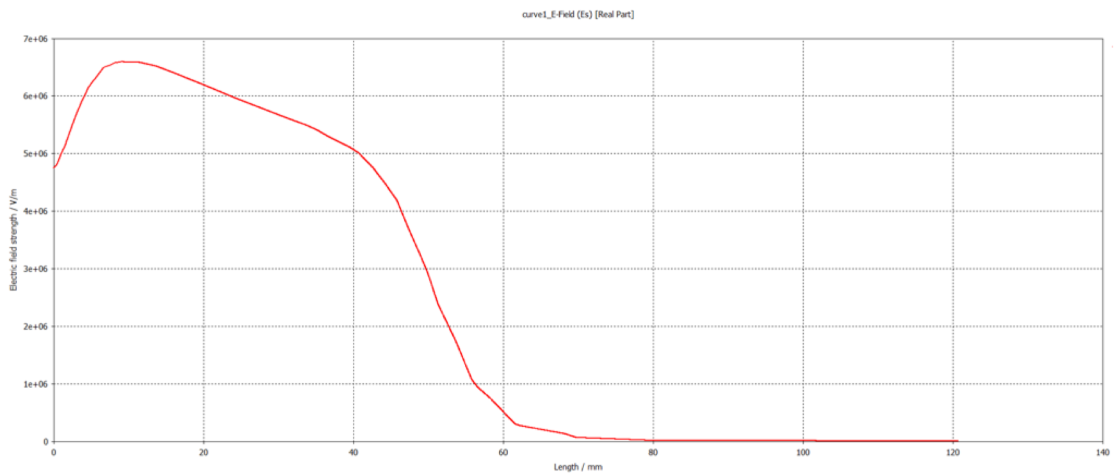

Flat-cathode 300 kV




Model by G. Palacios-Serrano, JLab

# Electrostatic Computations

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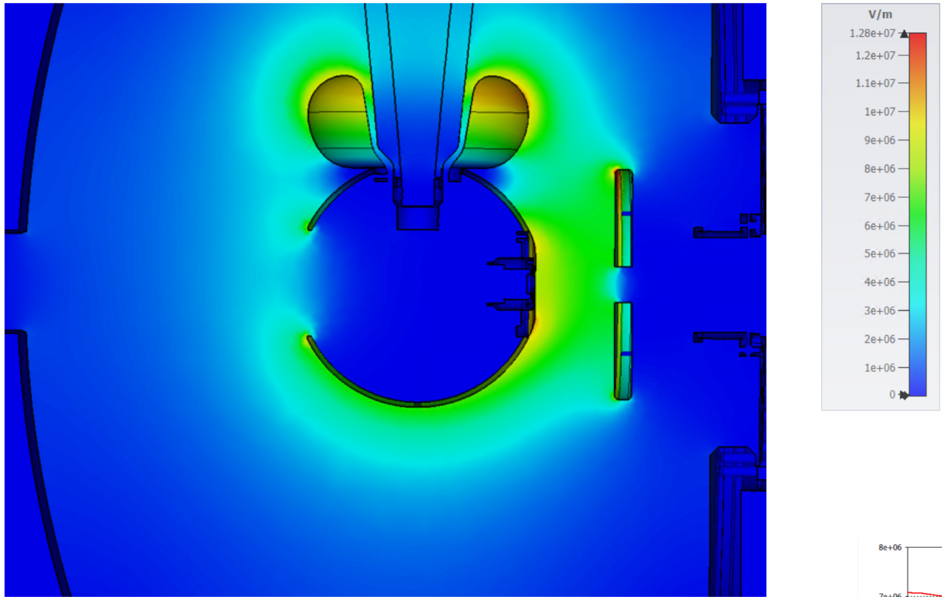
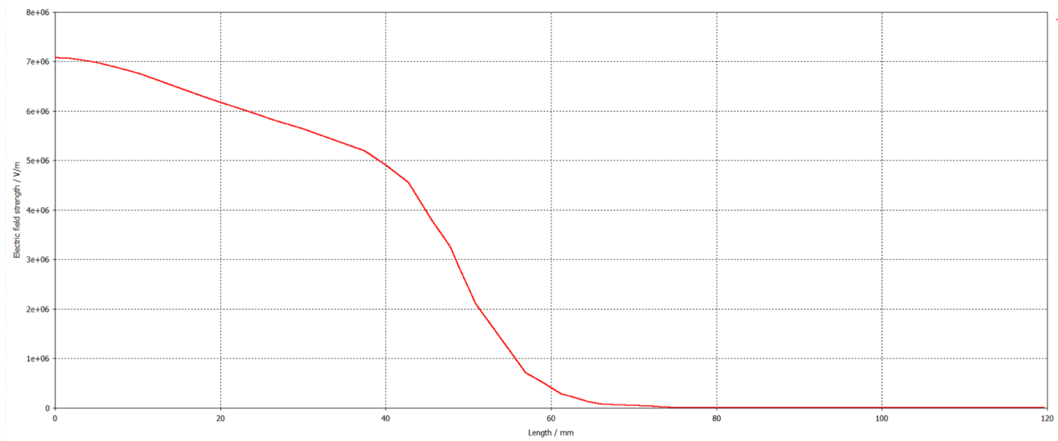
# Electrostatic Computations



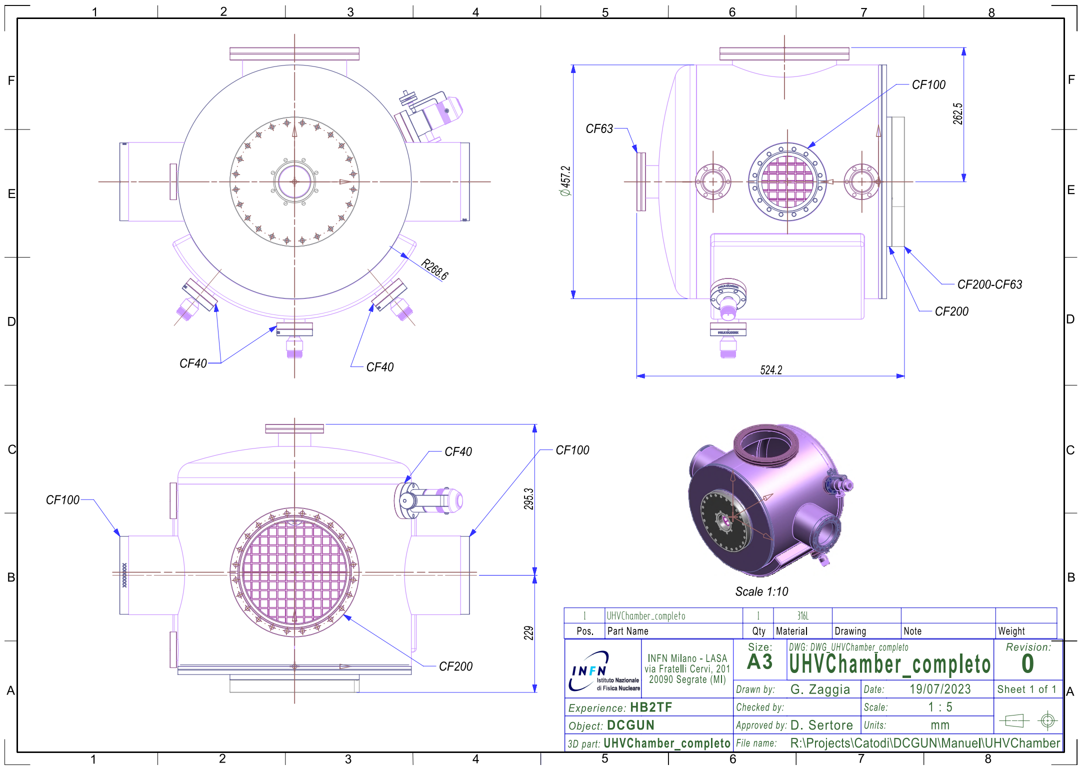
# HB2TF Current Activities – DC Gun Vacuum Chamber

- JLAB has provided 3D drawings of the full DC gun
- INFN started a set of activities aimed to design a new vacuum chamber that prevents asymmetries as the actual one.
- Some optimization cycles based on vacuum and electrostatic analysis have been performed to reach the final mechanical design reported below.

Vacuum performances have been defined and a final configuration has been frozen.

The main modification on the chamber has been the one that removed the couple of lateral 45° pipes for laser entry. They will not allow to have the solenoid as close as we need to the cathode. The laser will enter on the beam axis through a devoted box (a solution that has been already verified on a small model)

The materials and the processing have been defined.



# HB2TF Current Status DC Gun Inverted Insulator

The DC Gun Inverted Insulator is one of the most critical components of the Injector. It is dedicated to provide the input path for the HV Voltage.

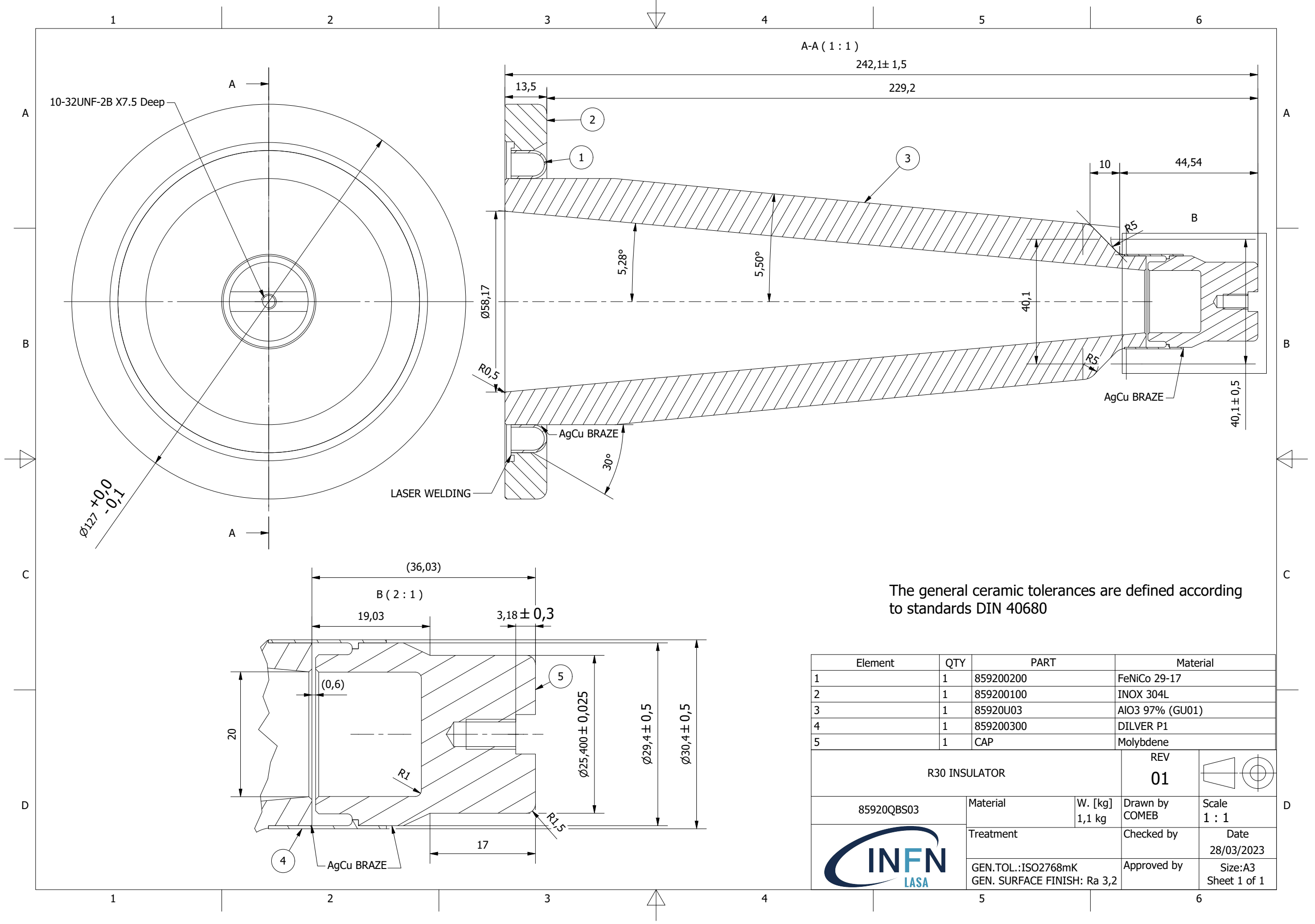
Jlab uses components from a small supplier in France BUT immediately when we asked a quote for more identical elements it results that the company has been closed or, at least, was no more involve din this business. The bad new is that Jlab does not have the intellectual property of this element and they do not have any engineered drawing.

We contacted a lot of companies in Europe and in the US but it was quite impossible to get an involvement in the subject.

At least we got some interest from the Company MORGAN ADVANCED MATERIALS – Germany and after an iteration lasted nearly 5 months we provide them an engineering drawing of the insulator and they quoted the realization of a first set of units.

The good news is that this piece belongs to INFN while the bad news are related to the costs.

# HB2TF Current Status DC Gun Inverted Insulator



# Main HV Power Supply

The experiment has been designed to consider a power supply able to:

- Deliver at least 350 kV (up to 400 kV may provide a safer margin)
- Deliver up to 5 mA (to cope the beam current required).

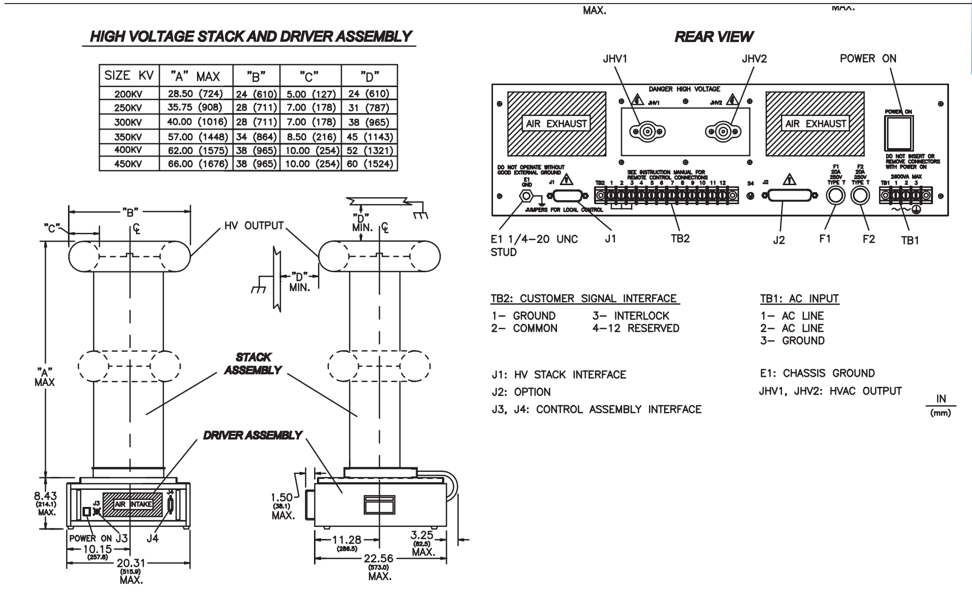
In January 2023 we asked quotes at the following companies:

- XP-Power (USA with local representative)
- FUG (Germany)
- Heinzinger (Germany)
- Teslaman HV Power Supply (China)
- Genvolt (UK).

**We get a positive answer only from XP-Power** ! The other companies were not able to provide a product at least similar to the one we requested.

**A direct contact with the company in USA let us to understand that there is an improved model available at stock (model OS 450N03.0-2) 0-450KV, 3mA, Negative Polarity, 230VAC 1PH input, arc count and quench included, Air Insulated Open Stack DC Power supply**

# Main HV Power Supply




| SIZE KV | "A" MAX | "B" | "C" | "D" |
|---|---|---|---|---|
| 200KV | 28.50 (724) | 24 (610) | 5.00 (127) | 24 (610) |
| 250KV | 35.75 (908) | 28 (711) | 7.00 (178) | 31 (787) |
| 300KV | 40.00 (1016) | 28 (711) | 7.00 (178) | 38 (965) |
| 350KV | 57.00 (1448) | 34 (864) | 8.50 (216) | 45 (1143) |
| 400KV | 62.00 (1575) | 38 (965) | 10.00 (254) | 52 (1321) |
| 450KV | 66.00 (1676) | 38 (965) | 10.00 (254) | 60 (1524) |

**Today the Power Supply has been delivered from USA to Italy and we are ready to install**

# Thanks for your attention !