Development and First Beam Generation of A Conduction-Cooled SRF Photogun for MeV Ultrafast Electron Diffraction and Microscopy

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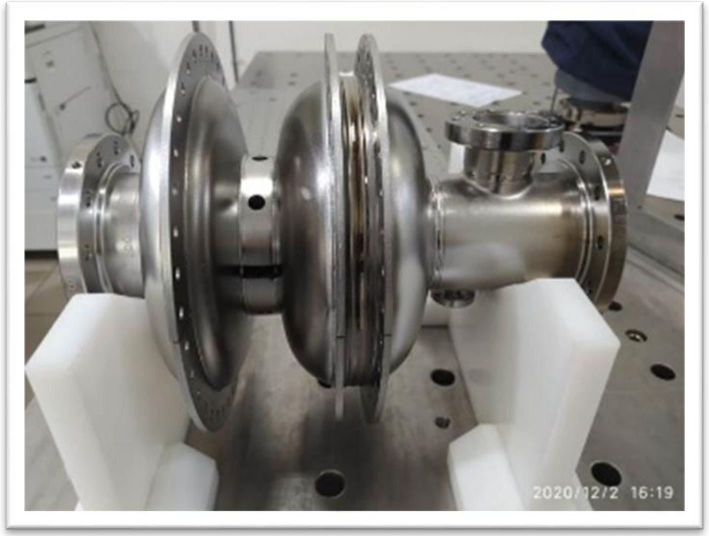
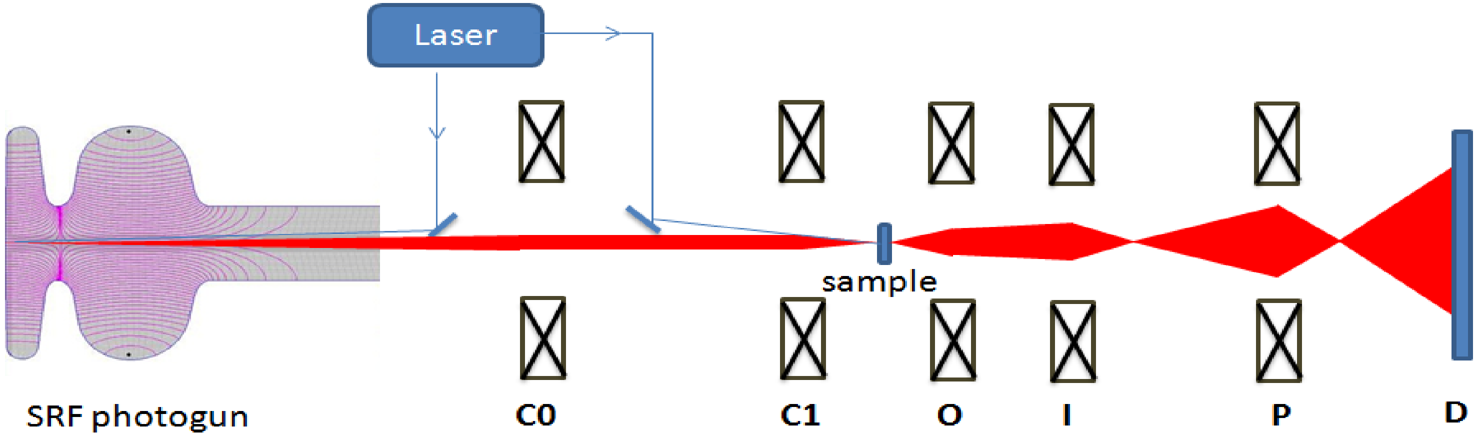
Outline:

1. *Introduction to the project*
2. *Design and Fabrication (cavity, cryostat, LLRF)*
3. *Testing Results (cryogenic, RF, Beam)*
4. *Plans and conclusions*





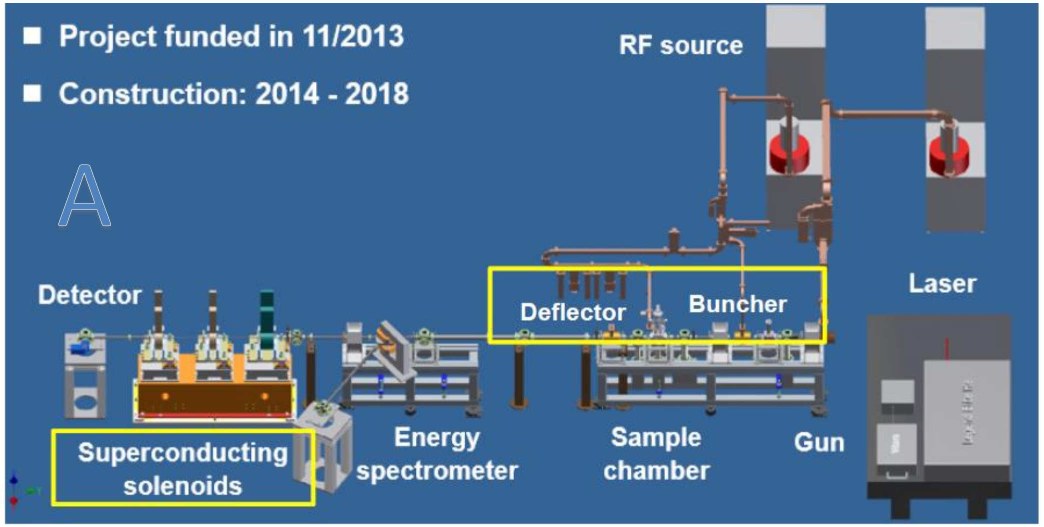
Introduction: MeV UEM/UED

- *Ultra-fast electron diffraction/microscopy based on MeV beam which greatly reduce the challenges of the sample preparation, also suppresses the space charge effect at higher bunch charges*

- *Stringent requirements on energy spread:*
  - *UED: $dE/E \sim 10^{-4}$, $\sigma_t \sim 10s'$ fs, $< 10^6$ electrons*
  - *UEM: $dE/E \sim 10^{-6}$, σ_t ~ps-ns, $>10^6$ electrons (single shot or stroboscopic)*

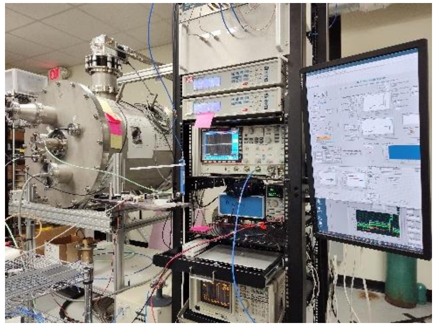
- *Current UED facilities are based on NC guns (see A):*
  - *Large facility + high power RF needed (expensive)*
  - *Timing jitter 10~100fs*
  - *Repetition is <1000 pps*

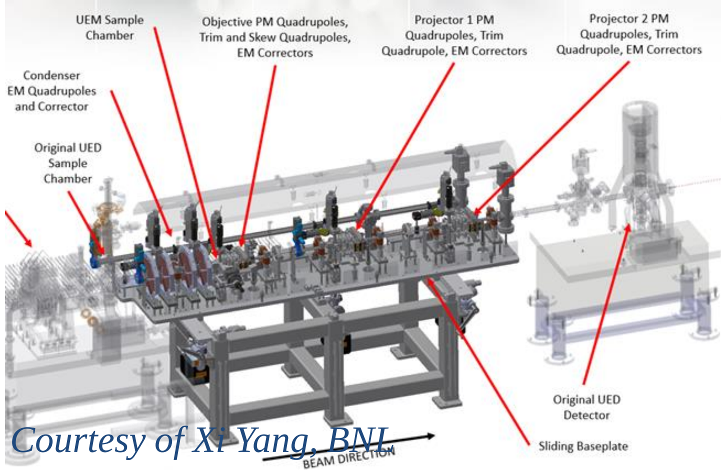
- *Conduction cooled Nb_3Sn SRF photo-gun (see B):*
  - *4K operation temperature (Nb_3Sn)*
  - *2W cryocooler is required ($80K, affordable)*
  - *CW operation (high throughput)*
  - *Smaller footprint, 10W RF power only*
  - *Higher stability*



Courtesy of Dao Xiang, talk at IPAC19

B



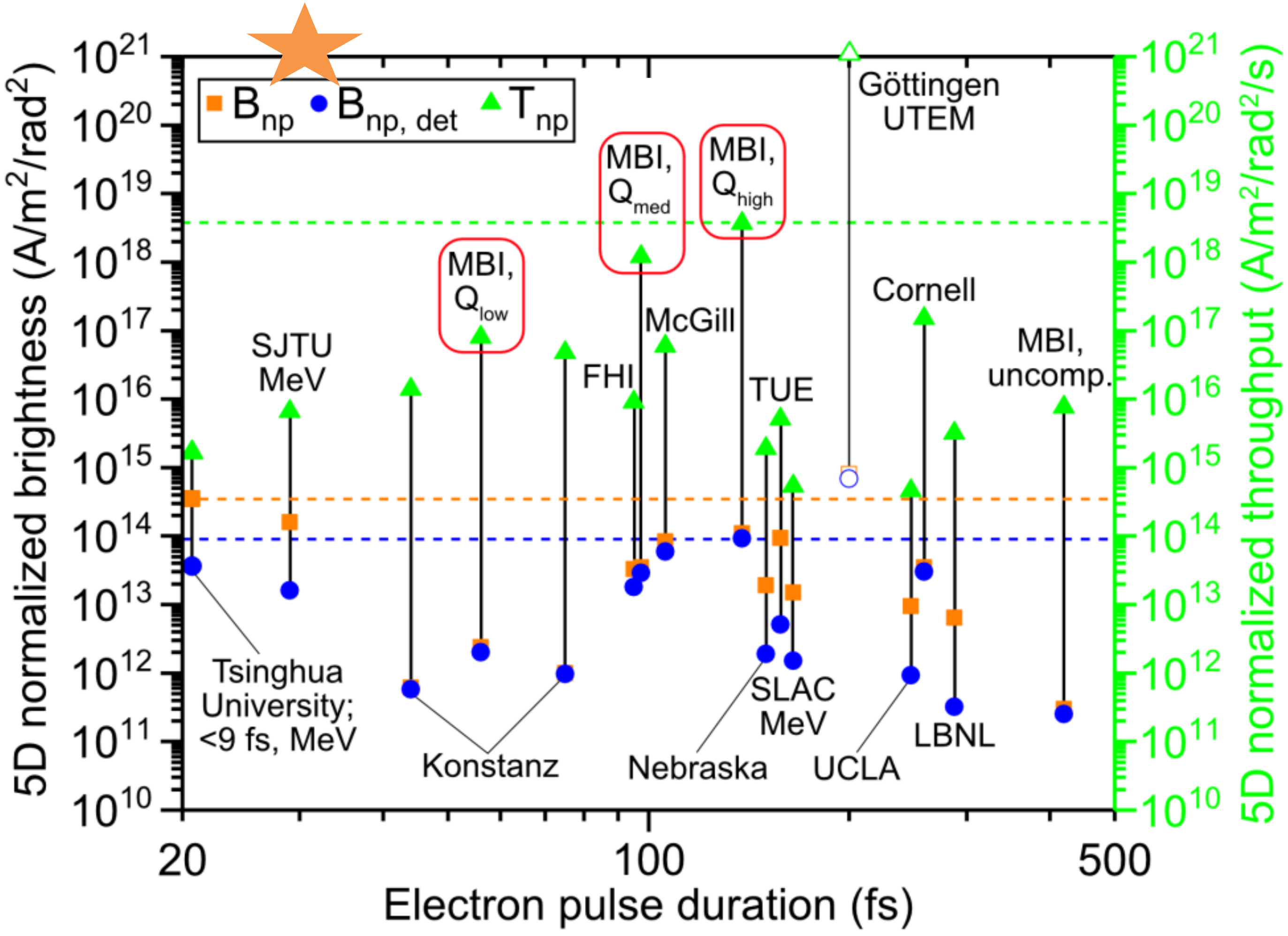


Courtesy of Xi Yang, BNL

SRF photo-gun based UEM/UED facility

Ultimate Goal

CC-SRF enabling
MeV HT-HB



High-throughput, high-brightness, ultrashort 90 keV electrons at 40 kHz

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(Dated: January 7, 2026)

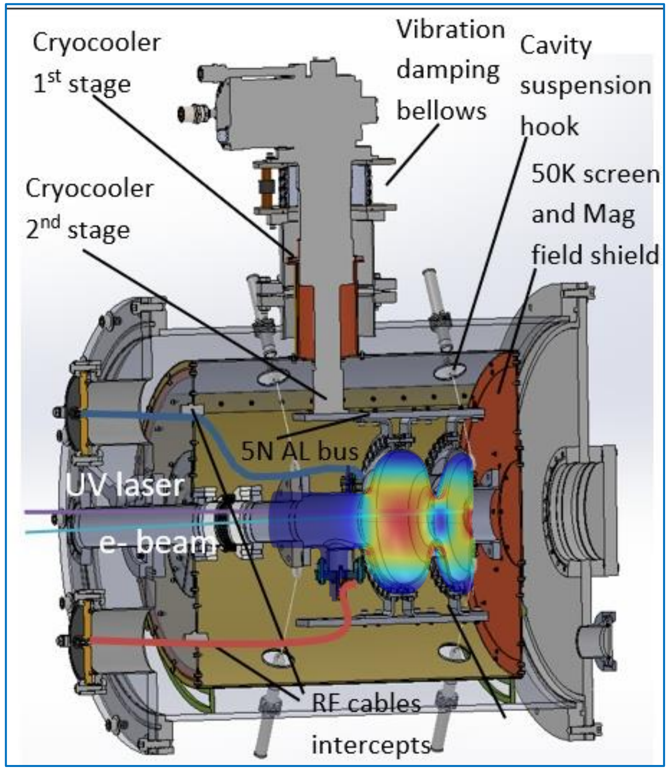
$$T_{\mathrm{np,det}} = f_{\mathrm{rep}} \cdot \mathrm{DQE} \cdot B_{\mathrm{np}},$$

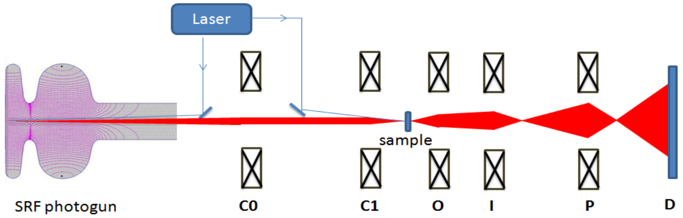
$$B_{np} = \frac{Q}{\sqrt{2}\,\pi^{5/2}\,\epsilon_n^2\,\sigma_t}.$$

https://arxiv.org/pdf/2601.02597

Introduction: CC-SRF photogun for MeV UEM/UED

1. The gun geometry was optimized to minimize dE/E while keeping acceptable energy gain (1.6 MeV)
2. Field on the cathode is 20 MV/m (E_{acc}=10 MV/m)
3. One cryocooler should be sufficient for cooling Nb_3Sn gun
4. **Required Q_0=1e10 at operating gradient**
5. Cryomodule design is required to provide enough cooling and sufficient magnetic field insulation





Gun parameters

Parameter	Value	
Application	UED	UEM
Beam energy	1.655MeV	1.655MeV
Charge	5fC	500fC
Laser pulse length, rms	6.4fs	6.4fs
Laser spot size	36um	180um
Beam bunch length, rms	167fs	741fs
Beam emittance	6.6nm	39nm
Energy spread (relative)	1.3e-5	6.4e-5
Frequency,	1.3 GHz	
Length	1.45cell (166.54mm)	
Q0 at 4° K (Rs = 20 nΩ)	1.16×10^{10}	
R/Q	176.9 Ω	
Geometry factor	232 Ω	
Wall Power dissipation	0.9 W	
E on axis	20 MV/m	
E max	23.5 MV/m	
B max	43.3 mT	
E acc	10 MV/m	

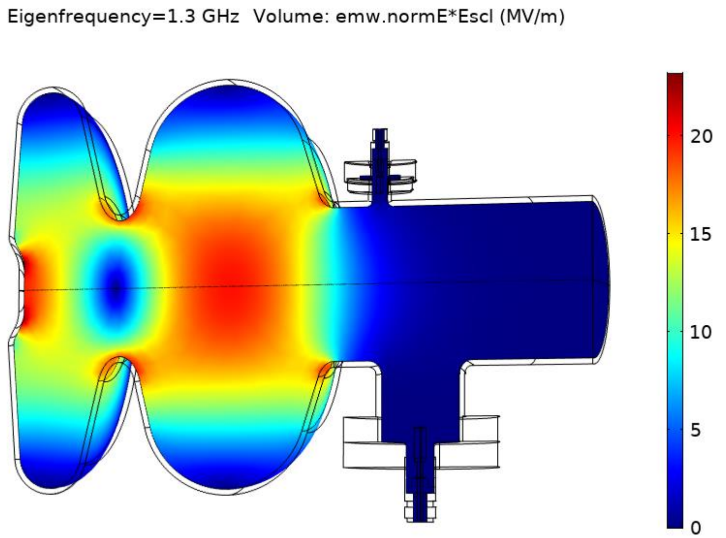
II. Design and Fabrication (cavity, cryostat, LLRF)

RF Design

1. *Maximum energy gain and min energy spread of the beam corresponds to different RF phases*

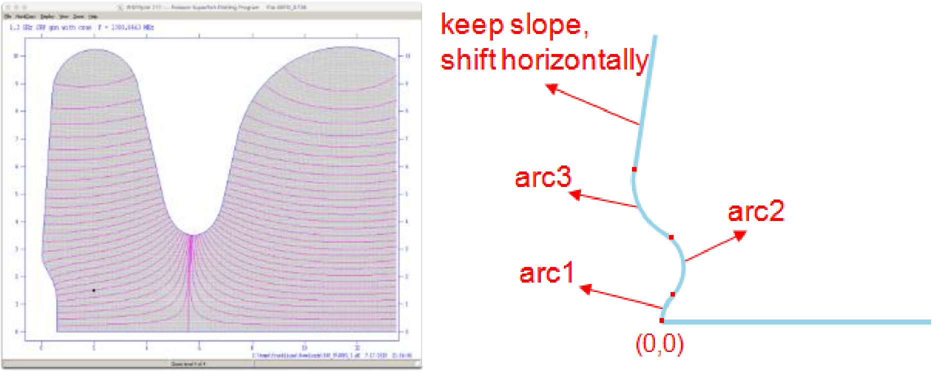
2. *Cavity nose section was optimized to minimize the spread while keeping acceptable energy gain.*

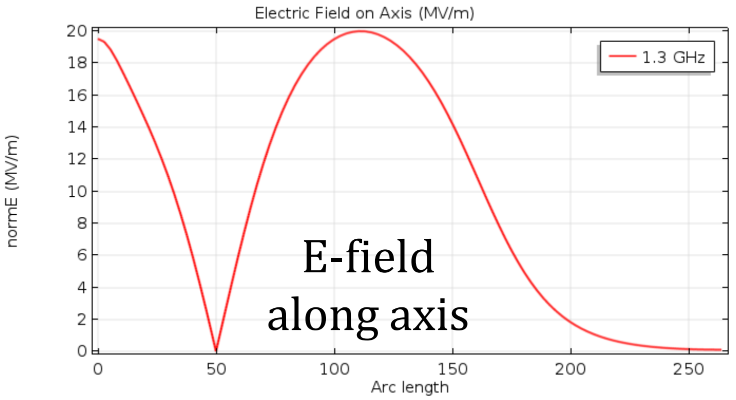
E-field

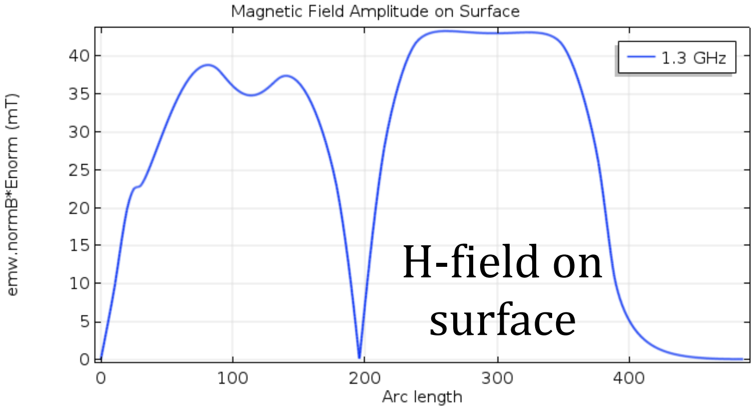


RF parameters

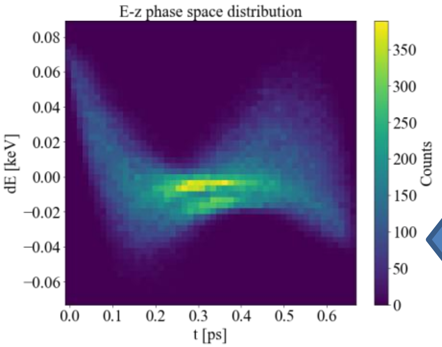
Parameter	Value
Frequency,	1.3 GHz
Length	1.45cell (160mm)
Q_0 at 4°K (Rs = 20 nΩ)	1.16×10^{10}
R/Q (critical coupling)	176.9 Ω
Geometry factor	232 Ω
Wall Power dissipation	0.9 W
$E_{on\ axis}$	20 MV/m
E_{max}	23.5 MV/m
B_{max}	43.3 mT
E_{acc}	10MV/m
Beam energy	1.6MeV

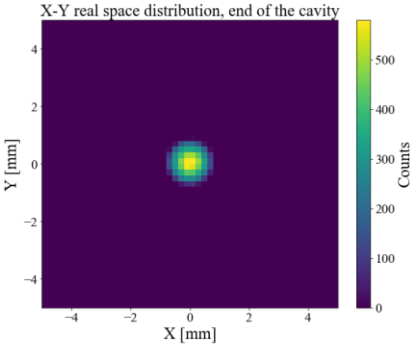


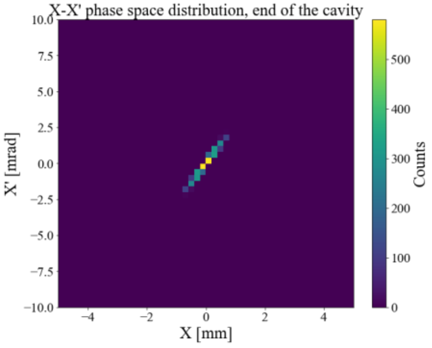




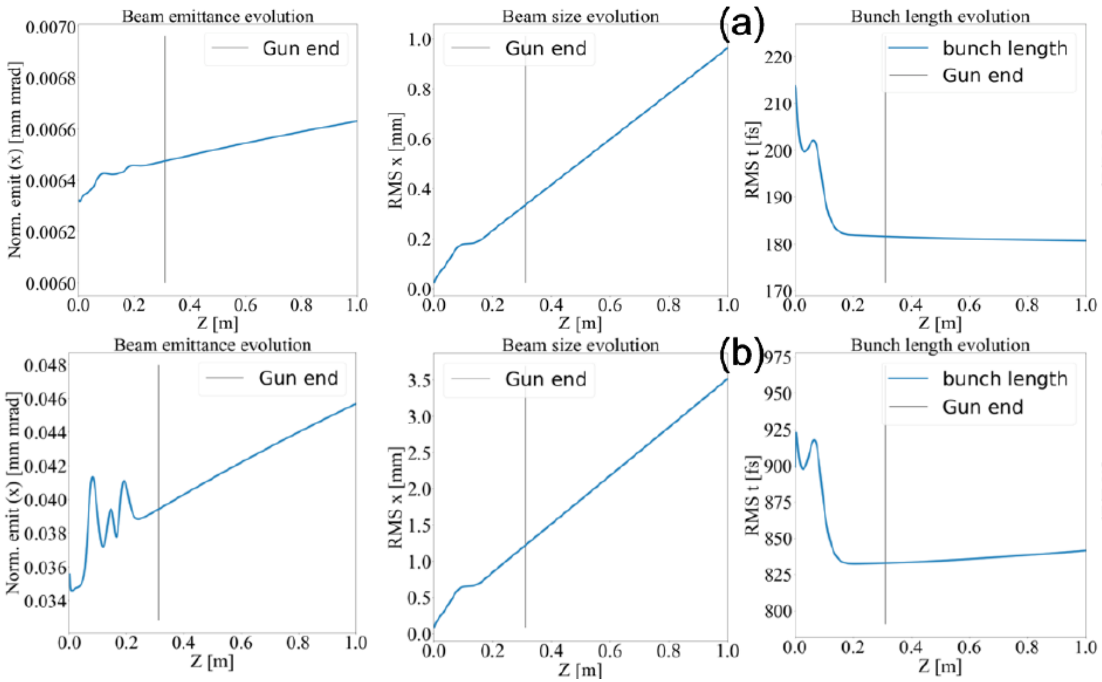
Beam dynamics



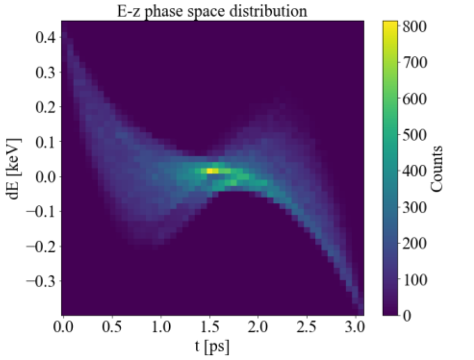


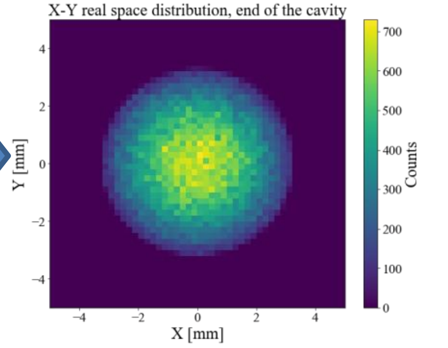


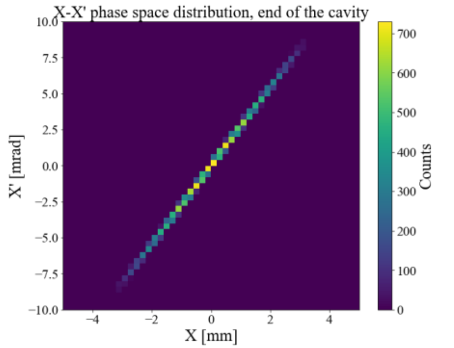
(a) Beam Simulation (UED Application, 5fC)



(b) Beam Simulation (UEM Application, 0.5pC)







Parameter	*Value*	
Application	*UED*	*UEM*
Beam energy	*1.655MeV*	*1.655MeV*
Charge	*5fC*	*0.5pC*
Laser pulse length, rms	*6.4fs*	*6.4fs*
Laser spot size	*36um*	*180um*
Beam bunch length, rms	*167fs*	*741fs*
Beam emittance	*6.6nm*	*39nm*
Energy spread (relative)	*1.3e-5*	*6.4e-5*

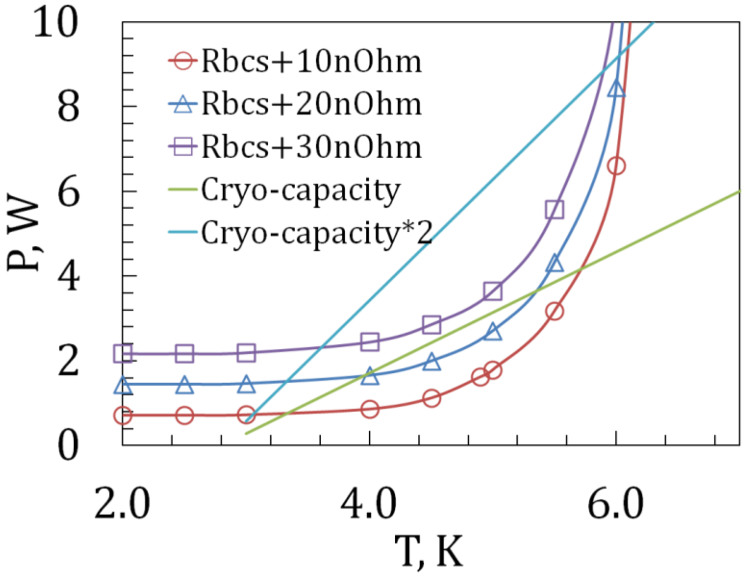
Thermal Analysis and Conduction Cooling

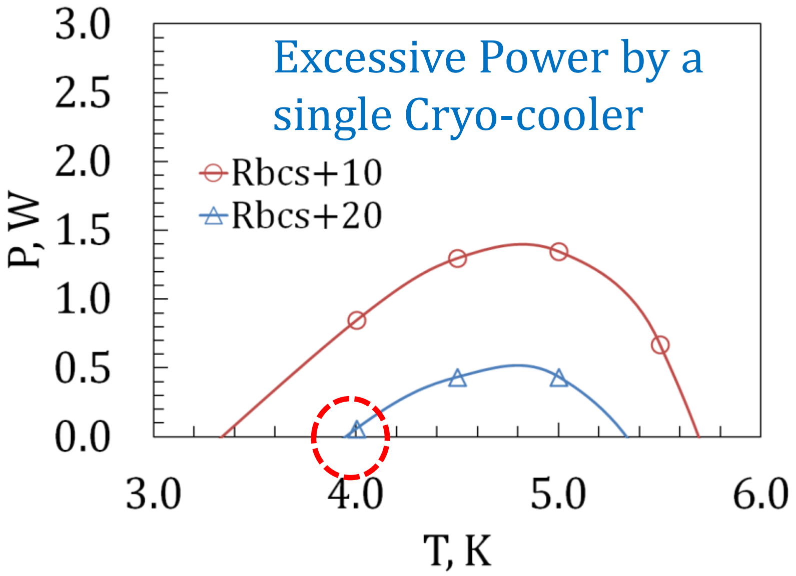
1. *Thermal modeling was done for different cryocooler temperatures to find stable operation regimes for the case of Eacc=10MV/m (1.6MeV beam)*

2. *Dissipated power in the gun along with the capacity of the cryocooler are presented below.*

3. *In the ideal case (Rbcs+10nOhm) with no additional heat from radiation or conduction the gun will stabilize at 3.5K. 1.5W of cryocooler capacity is still available to accommodate the other sources of heat*

4. *In the case of Rbcs+20nOhm, the gun will stabilize at 4K with additional cryocooler capacity of 0.5W.*

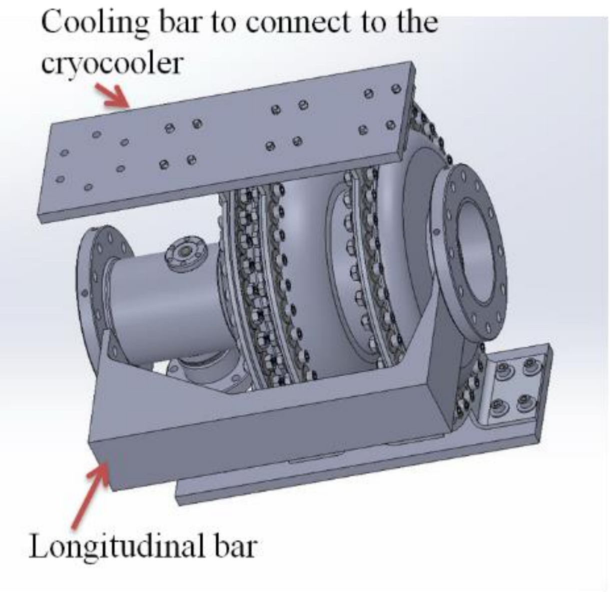


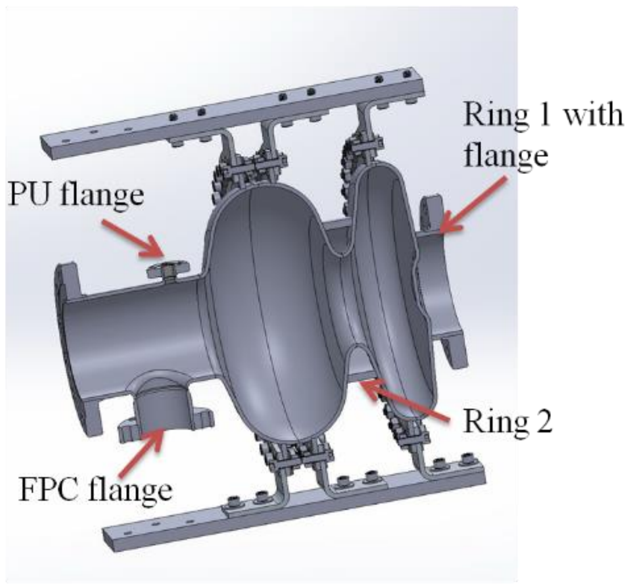


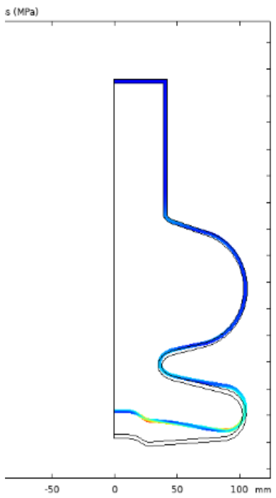
Engineering Design

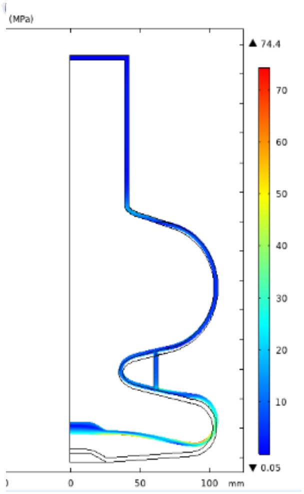
The three key parameters:

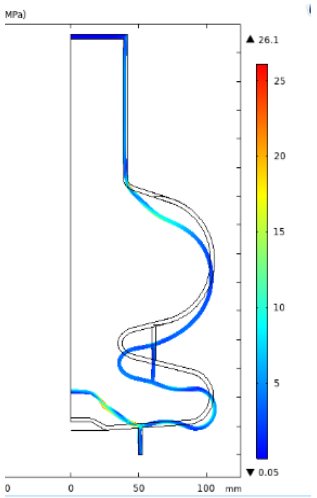
- mechanical stresses >> 0.21MPa
- Lorentz Force Detuning (in case of pulsed mode operation)
- dF/dP (for the case that the cavity will be tested at the Vertical Test Stand first before the Nb_3Sn coating)

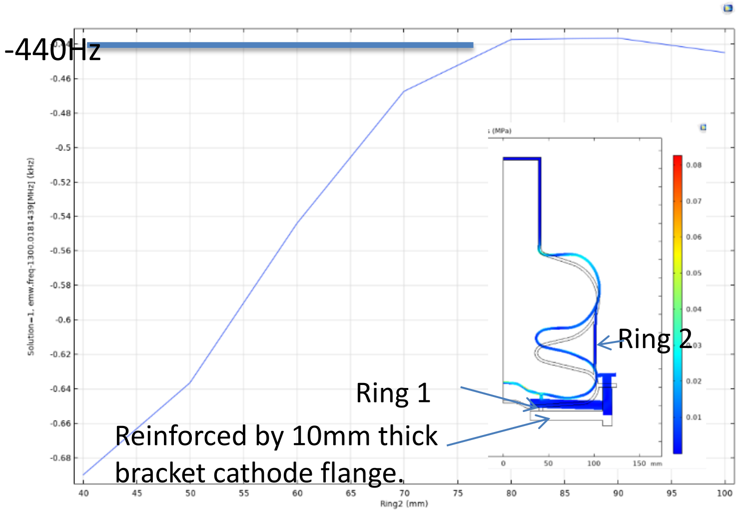


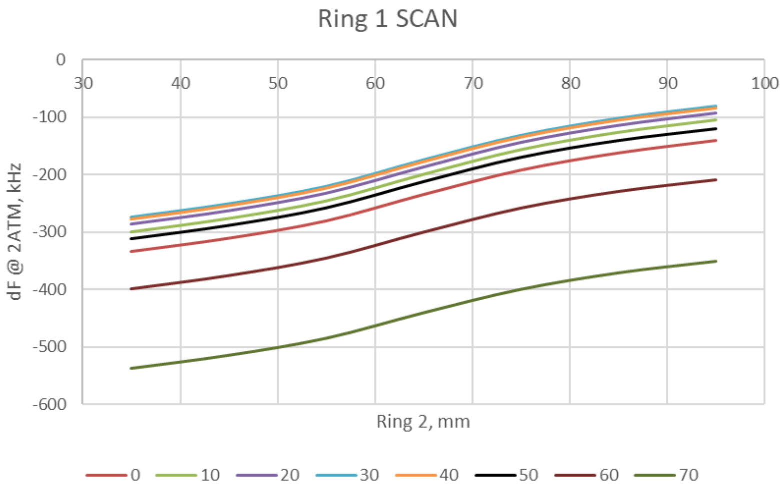



No enforcement


The link ring between cells

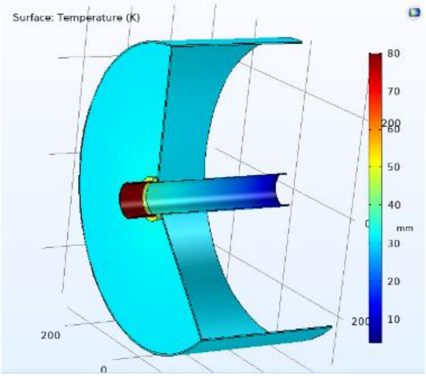

Backwall ring and the link ring





Cryomodule design

1. *Cryomodule was developed to host the photogun*
2. *It is based on conduction cooling approach and is cooled by one Sumitomo cryocooler (CC)*
3. *1st stage of the CC is used as a thermal intercept and cools down a copper thermal radiation screen.*
4. *There is a 1mm thick magnetic screen (A4K) on top of the radiation screen*
5. *The cavity is supported by 8 Kevlar strips (k=0.05W/m/K)*
6. *The total power to the cavity is less than 0.2W, while the intercept has a heat flow of 20W*



Temperature distribution in the copper thermal shield connected to the beam pipe.

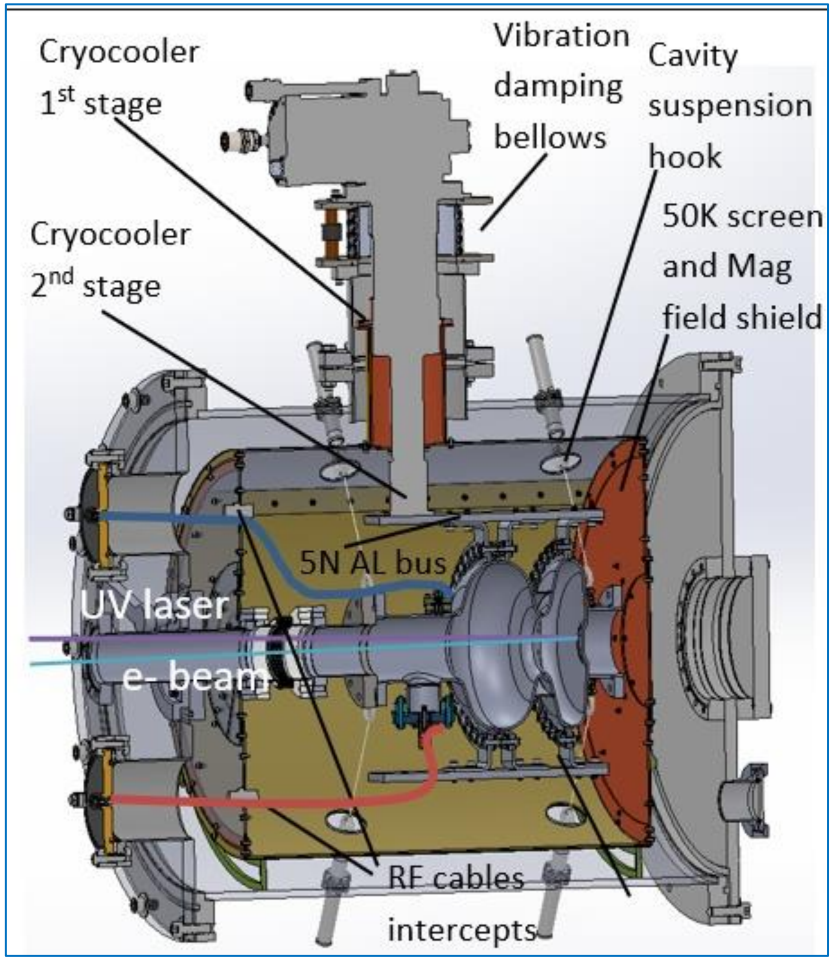
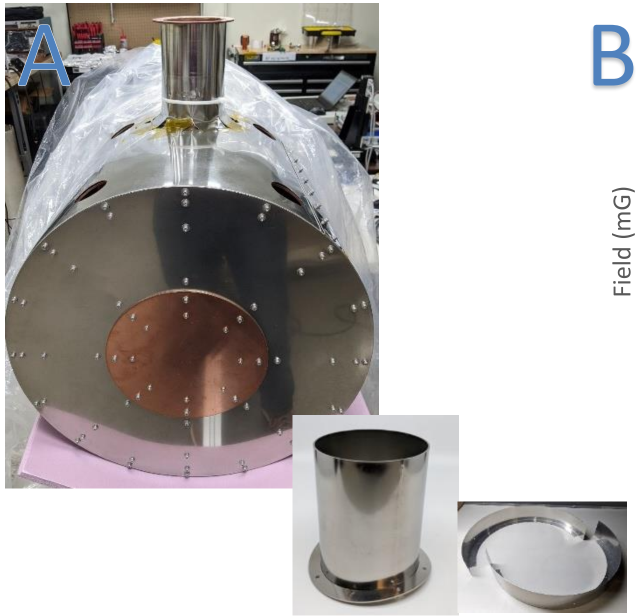
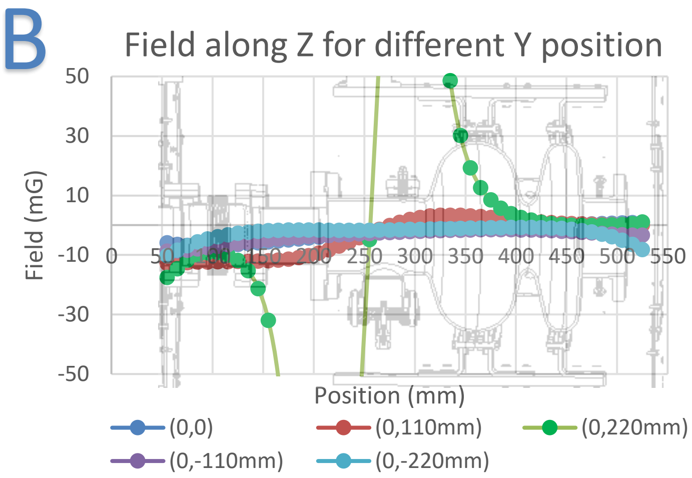


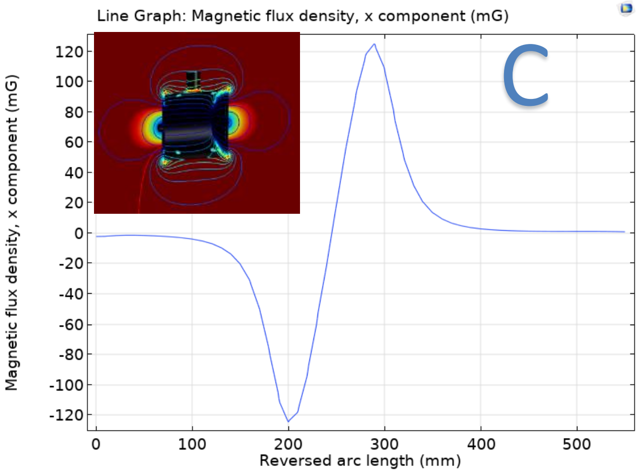
Table 1. Static heat load to 30K and 4K zones in UEM cryomodule.

	Radiation	Beam pipe	Suspension	RF cables	Total
30K zone	2 W	17 W	NA	0.8 W	20 W
4K zone	0.01 W	0.03 W	0.05 W	0.05 W	0.14 W

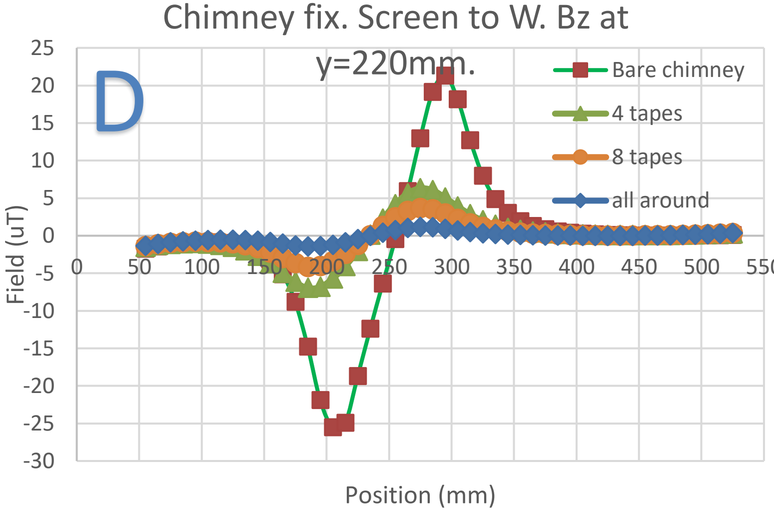
Magnetic shield in the cryomodule





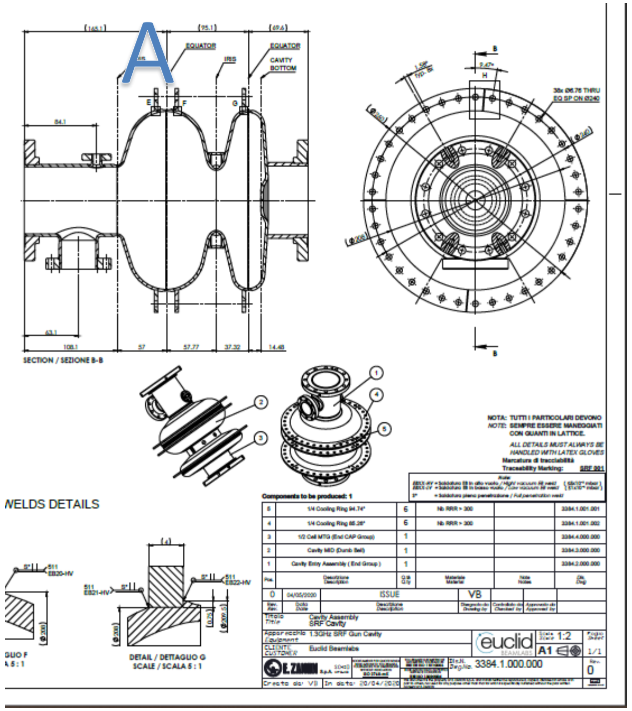


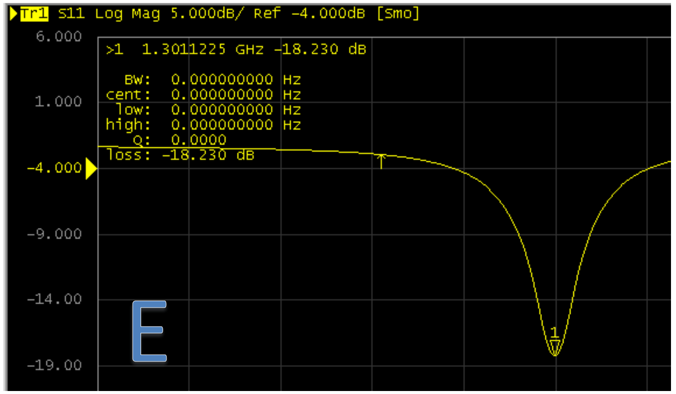
1. *Initial magnetic field measurements identified a gap in the magnetic shielding (see B) between the chimney and the cylindrical body (see A and B).*
2. *The results correlates with Comsol model (see C).*
3. *Nevertheless, the field in the cavity region (R=110mm, Z=(250;500)) is below 10mG at room temperature for A4K screen (See B).*
4. *A patch from Mu-metal foil (see C) reduced the field penetration at R=220mm down to 10mG (D).*

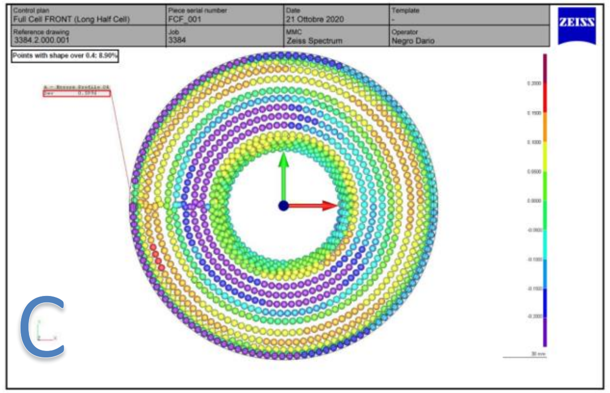


SRF GUN Fabrication

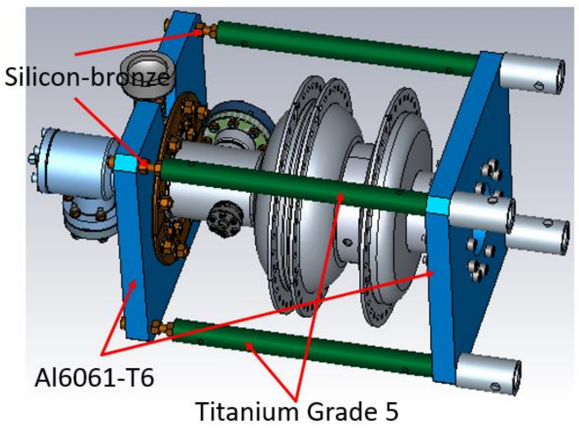
1. *Conduction cooled SRF photogun drawings were produced (see A)*
2. *Half cells were die-pressed from copper first, then from pure RRR300 Niobium (see B)*
3. *The Half cells were inspected by CMM and are within the tolerances (see C)*
4. *The cavity manufacturing is complete (see D). The sizes are within the tolerances. Target frequency is 1301.1MHz (see E). It will be tuned upon arrival.*

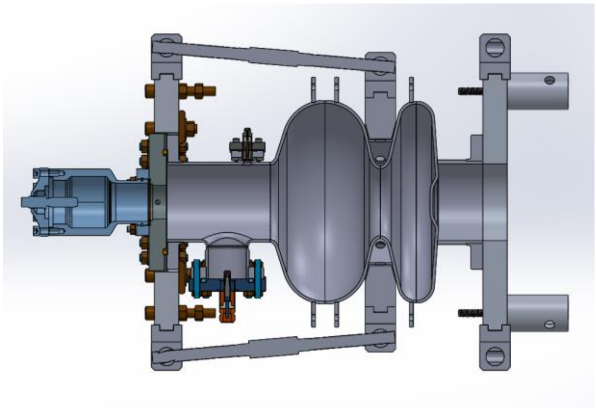


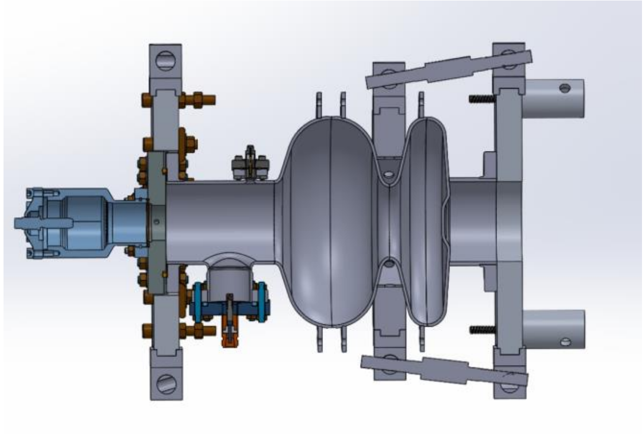


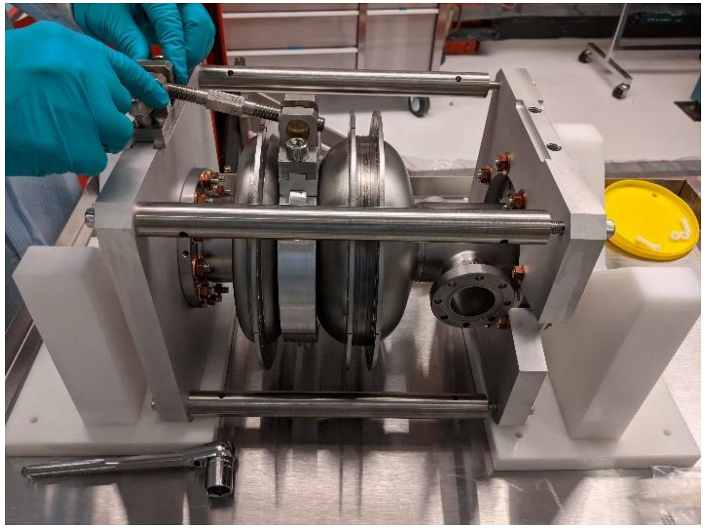


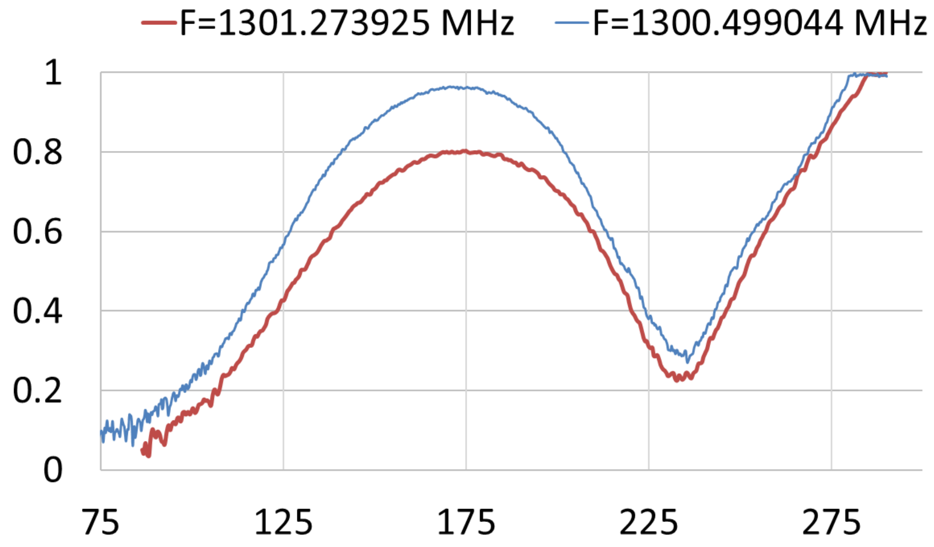
SRF photogun: Post Fabrication Frequency Tuning



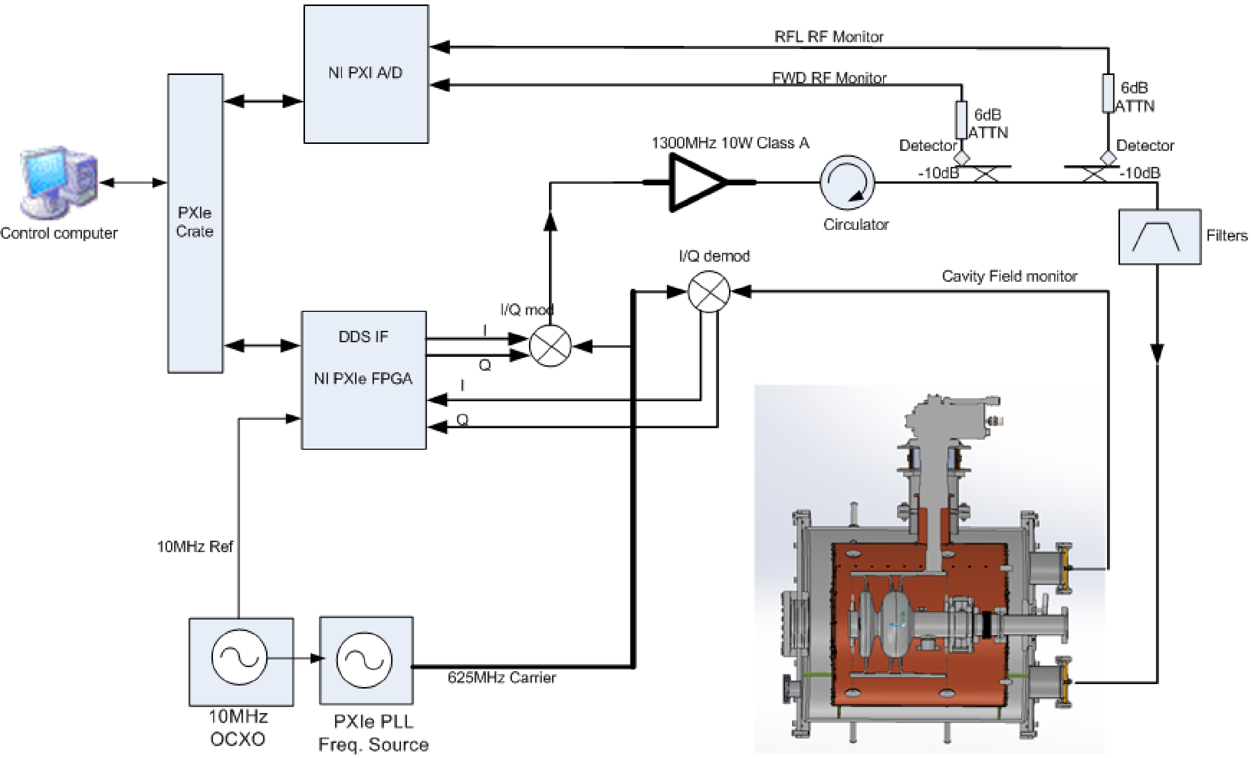




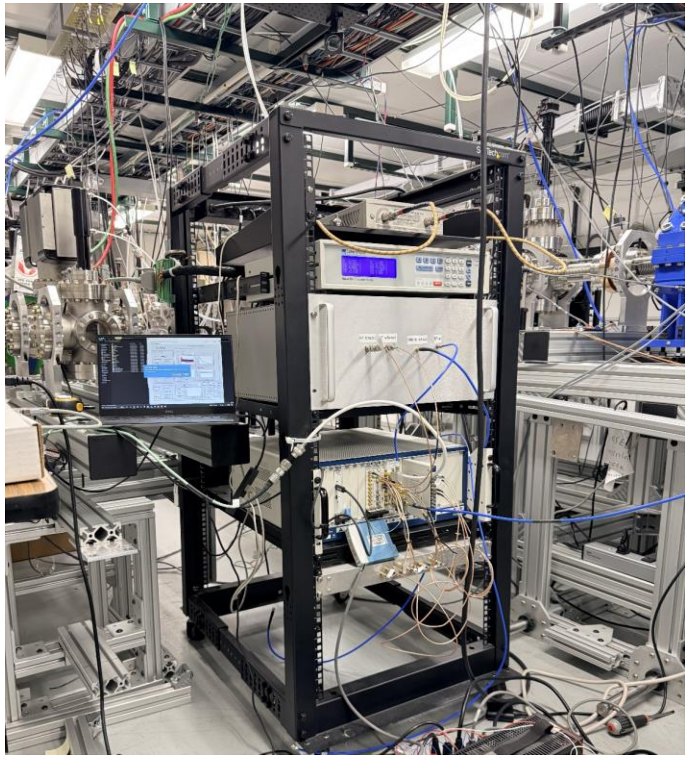


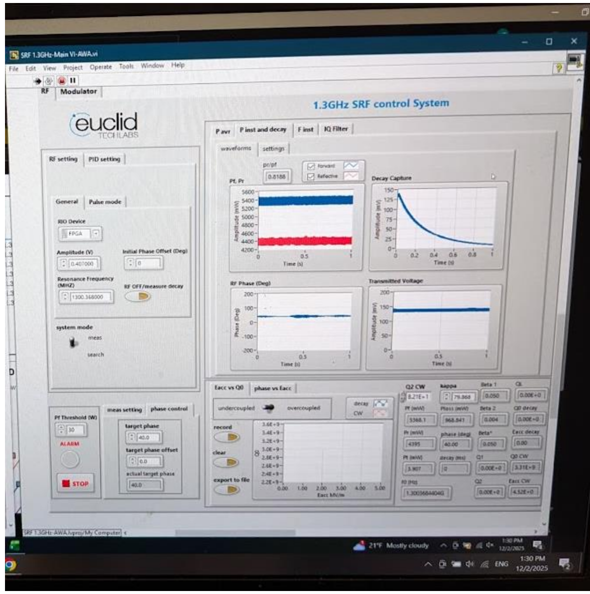


LLRF Design

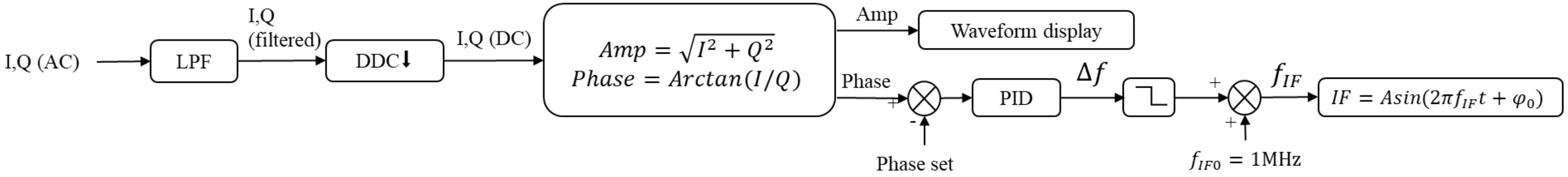


RFL RF Monitor
FWD RF Monitor
NI PXI A/D
PXIe Crate
Control computer
6dB ATTN
6dB ATTN
1300MHz 10W Class A
Detector
Detector
-10dB
-10dB
Circulator
Filters
I/Q demod
Cavity Field monitor
I/Q mod
DDS IF
NI PXIe FPGA
I
Q
I
Q
10MHz Ref
10MHz OCXO
PXIe PLL Freq. Source
625MHz Carrier





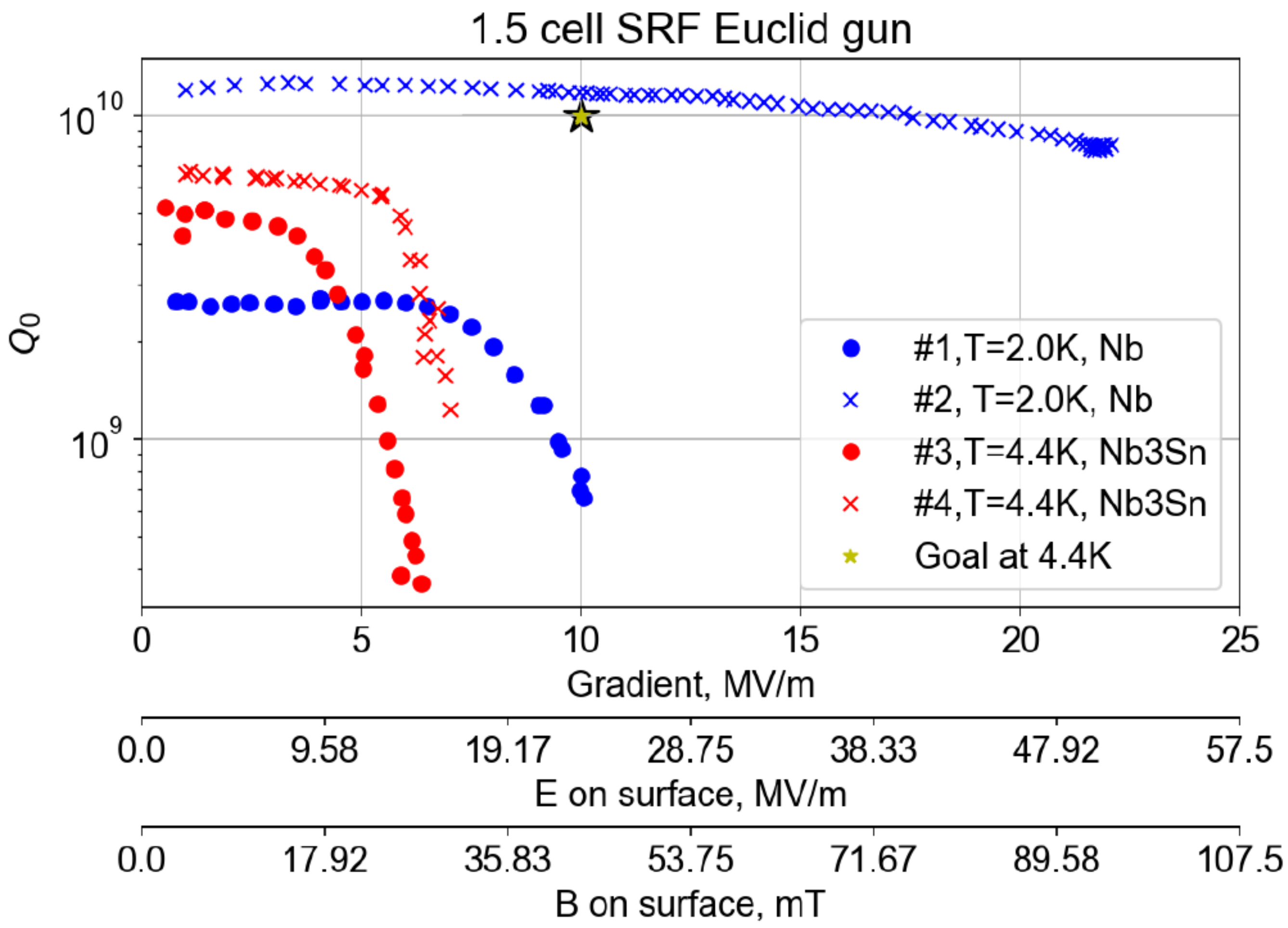
1.3GHz SRF control System
euclid



I,Q (AC)
LPF
I,Q (filtered)
DDC⬇
I,Q (DC)
$Amp = \sqrt{I^2 + Q^2}$
$Phase = Arctan(I/Q)$
Amp
Waveform display
Phase
Phase set
PID
Δf
f_{IF}
$IF = Asin(2\pi f_{IF} t + \varphi_0)$
$f_{IF0} = 1\text{MHz}$

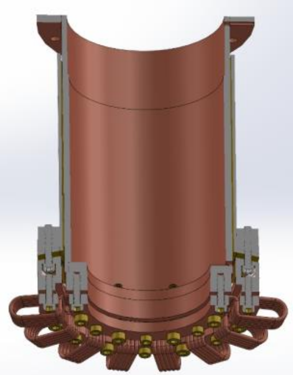
III. Testing Results (cryogenic, RF, Beam)

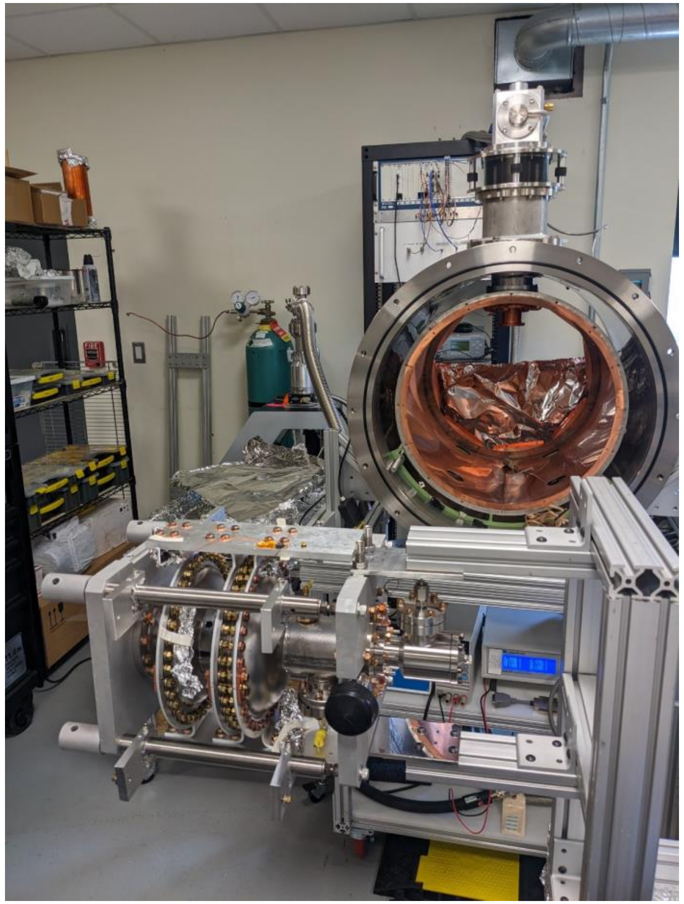
Summary of SRF Gun He Vertical Tests

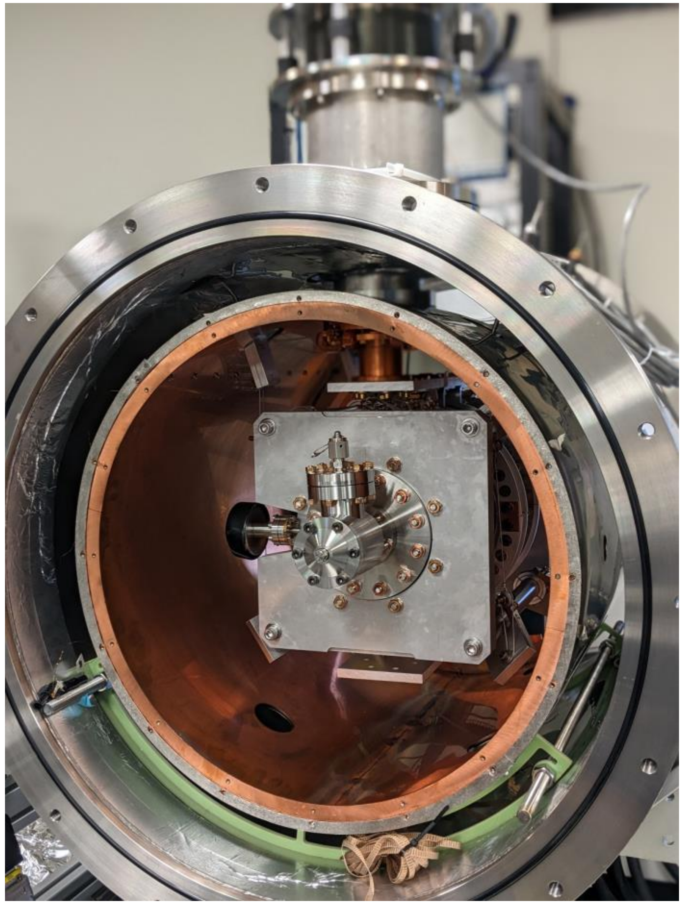


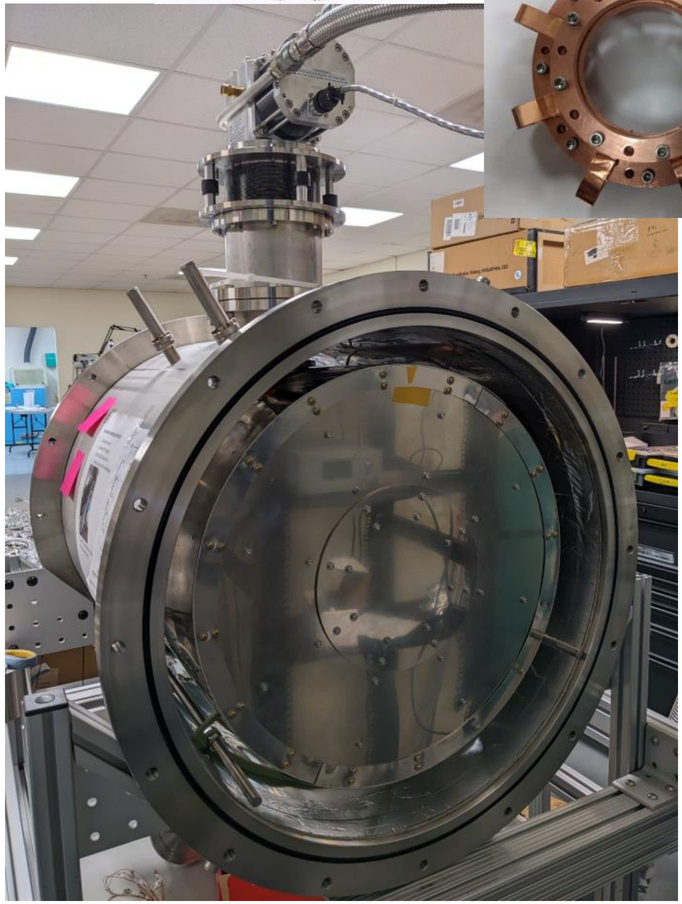
euclid BEAMLABS

Cryomodule integration at Euclid

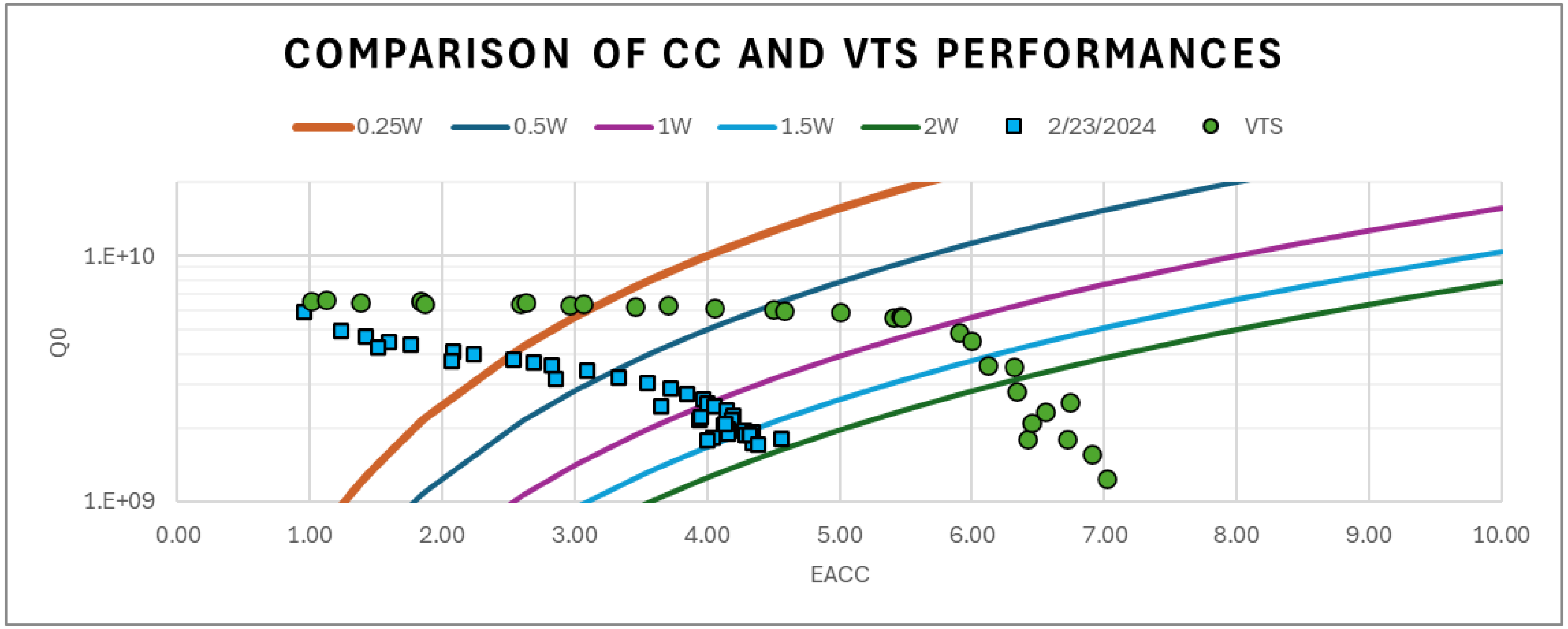


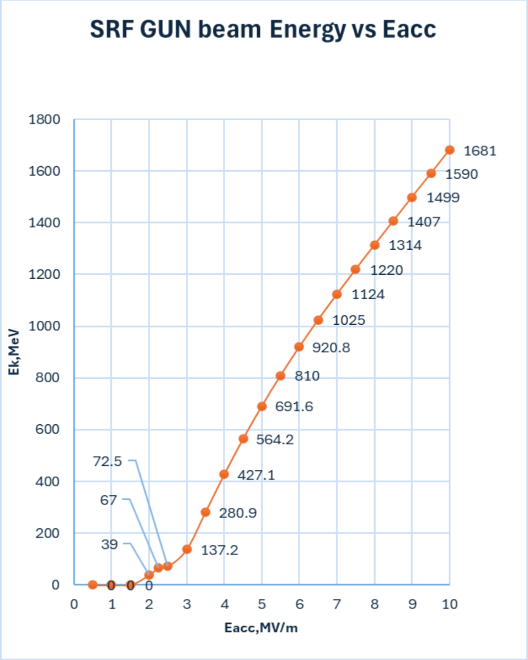






Cryomodule Tests at Euclid



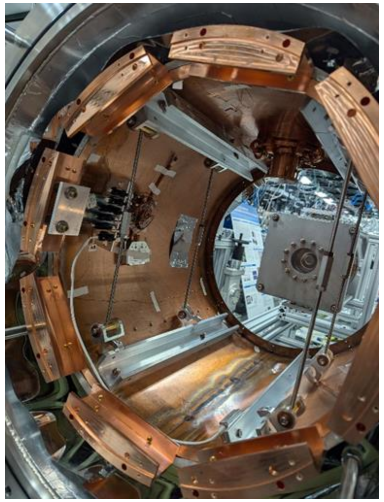
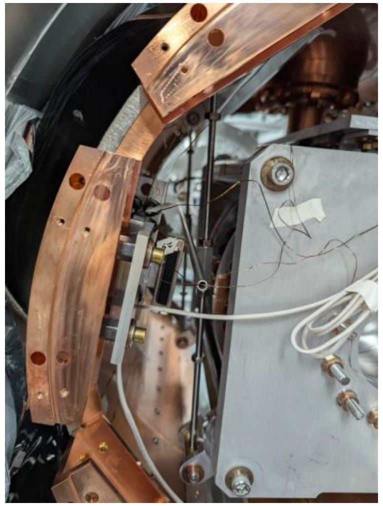
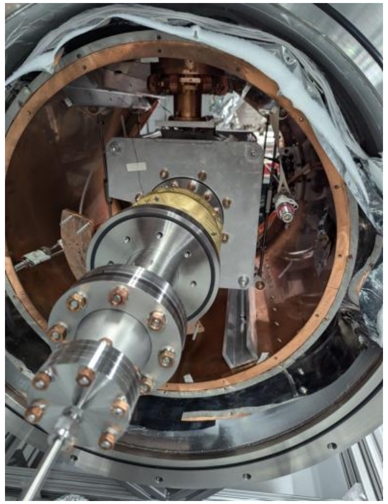


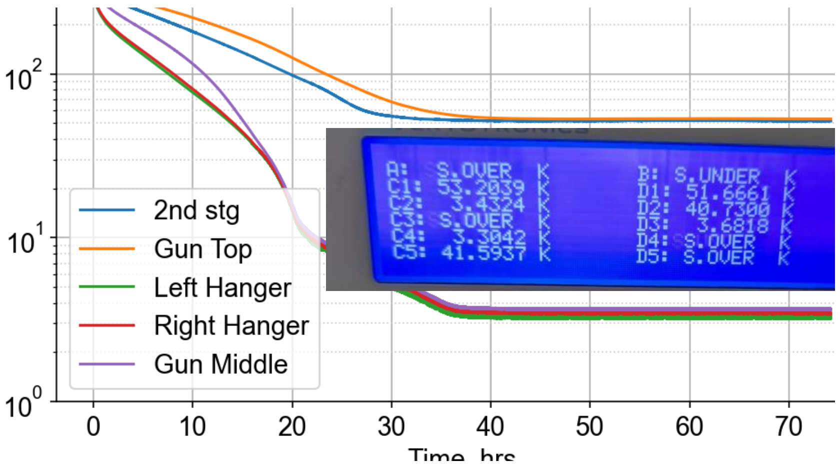
Where	What	Configuration	Date	F, MHz	1st T, K	1st, W	2nd T, K	2nd, W	gun mid	dT,	braid ring	U char	Front Barrel	dT barrel	BP	Q0	Eacc	Comments
ETL	GUN	Polished AL links, cntrld CD18K+-2K	2/22/2024	1300.3	28.2	10.64	3.4	1.22	4.25	0.85	nan	nan	nan	nan	nan	5.92E+09	4.56	Final Euclid data collection done right
ETL	GUN	Polished AL links, cntrld CD18K+-2K	2/21/2024	1300.3	27.25	5.37	3.4	1.22	4.25	0.85	nan	nan	nan	nan	nan	6.90E+09	4.44	QvsE ongoing LLRF refining
ETL	GUN	Polished AL links, cntrld CD18K+-2K	2/14/2024	1300.3	27.19	5.02	3.2	0.92	3.92	0.72	nan	nan	nan	nan	nan	5.12E+09	3.83	QvsE ongoing LLRF refining
ETL	GUN	Polished AL links	1/12/2024	1300.3	27.9	9.02	3.6	1.51	3.95	0.35	nan	nan	nan	nan	nan	2.94E+09	4.22	QvsE ongoing LLRF refining
ETL	GUN	Polished AL links	1/5/2024	1300.3	27.8	8.47	3.5	1.36	3.86	0.36	nan	nan	nan	nan	nan	2.95E+09	4.63	QvsE ongoing LLRF refining
ETL	Info	freezed	1/5/2024	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan	compressor freezed, outdoor temp was beow -30
ETL	GUN	lished AL links, Gun Evaced, MLI everyw	1/2/2024	1300.3	27.54	7.02	3.38	1.19	3.68	0.3	nan	nan	nan	nan	nan	3.00E+09	2.28	POLISHED AL BUS. First results, did not push too far
ETL	Info	Vacuum pumped	12/19/2023	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan	Vacuum pumped to e-8 at ETL clean room to resolve BD issue
ETL	CM	CM w MLI on G10	12/1/2023	nan	26.59	1.48	2.78	0.31	nan	nan	29.08	nan	31.59	5	nan	nan	nan	MLI on Barrel added. End caps w MLI form 3/22/2023
ETL	GUN	GUN LOCKED->BD	11/9/2023	1300.4	38.06	46.71	3.3	1.07	4.62	1.32	38.06	nan	47.42	9.36	nan	2.00E+09	nan	Locked first time but gas discharge.
ETL	GUN	CD4 same as CD3	5/15/2023	1300.5	37.3	44.94	3.14	0.84	4.35	1.21	37.37	nan	44.85	7.55	nan	3.24E+09	nan	simple warm up Q0=3e9
ETL	GUN	CD3, taped hangers	4/26/2023	1300.4	38.51	47.69	3.02	0.66	4.37	1.35	35.19	nan	44.4	5.89	nan	5.00E+09	nan	Q0 measured by decay. 1e9 improved to 5e9 w controoled CD taau=226ms. Tap
ETL	GUN	CD2: AL RF cables w DC blocks	4/5/2023	1300.4	29.97	19.51	3.64	1.57	5.03	1.39	nan	nan	nan	nan	nan	nan	nan	Smaller RF cables AL OD w SS ID reduced power by 1W confirme
ETL	GUN	CD1, MLI on Caps. White RF cables	3/22/2023	1300.4	30	19.65	4.15	2.31	5.15	1	35.75	nan	44.67	14.67	nan	nan	nan	MLI on end caps only: Cap T reduced 55 to 45K. Estimate the 1st st
ETL	CM	CM w SS sheet, G10	3/9/2023	nan	31.5	26.24	3.06	0.72	nan	nan	38.91	nan	55.5	24	nan	nan	nan	SS sheet. Temperature on 1st stage reduced from 36.3K to 31.5K, c
ETL	CM	New Chimney, no foil, G10	2/15/2023	nan	36.2	42.12	3.3	1.07	nan	nan	49.6	nan	95	58.8	nan	nan	nan	New chimney installed. AL foil removed. 40W to 1st stg
FNAL	GUN	VTS 4	7/21/2022	1300.1	nan	nan	nan	nan	4.4	nan	nan	nan	nan	nan	nan	6.60E+09	6.5	Nb3Sn 2nd coating. Cage assebl monitored by VNA.
FNAL	GUN	VTS3	1/6/2022	1302.1	nan	nan	nan	nan	4.4	nan	nan	nan	nan	nan	nan	5.00E+09	6	Nb3Sn 1st coating. Tuned to be 1300.0 MHz. Overtighten by 2MHz, c
FNAL	GUN	VTS2	09/31/2021	1303.3	nan	nan	nan	nan	2	nan	nan	nan	nan	nan	nan	1.00E+10	22.5	Cleaned with new nozzle. 10um additional BCP. No tuning.
FNAL	GUN	VTS1	7/16/2021	1303.5	nan	nan	nan	nan	2	nan	nan	nan	nan	nan	nan	3.00E+09	10	BCP 140+40. Poor HPR - not everything cleaned - Bad QvsE. BCP
ETL	CM	CM w AL foil, bad chimney	11/4/2020	nan	28.63	12.91	2.55	-0.02	nan	nan	nan	nan	50.65	22.02	nan	nan	nan	First CM CD. AL Foil. Sleds. 2nd stag 0W, 1st stage 10W estimated

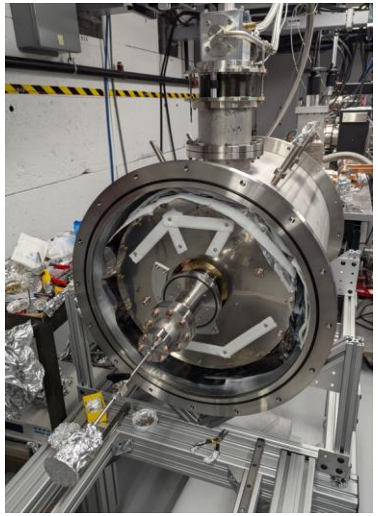
euclid BEAMLABS

Cryomodule Upgrade at AWA

- The first cooldown of the fully loaded SRF photogun was carried out on Dec. 9th, 2024. The base plate intercept is 55K. Grade 2 Ti bolts were used which resulted in a large temperature difference between the cold head of the cryocooler and cavity (dT=2.2K). To solve this unexpected issue, we replaced the Ti screws with Brass screws.
- The 2nd cool down test was carried out on March 31, 2025. The temperature difference between the cold head of the cryocooler and cavity was successfully reduced to <0.8K. During the cooldown process, we observed some instabilities, which was later attributed to the bad vacuum inside cavity.
- We pumped the gun and remeasured it again. The Q value was still in the low 10^9 level. We found surprisingly high residual magnetic field in some components, including 700mG of RF cables, 500mG of a DSUB connector, 400mG of 18-8 nut and 316 studs for the hanger. The RF cables were then degaussed to 30mG. All bolts were changed to Grade 5 Ti and brass nuts which zeroed the residual magnetic fields. The DSUB50 connector was removed, replaced by the direct wire solider connections. We also polished the aluminum bus bar and the 2nd stage of cold head with polishing paste. The PEEK DC blocks moved to the 50K screen.
- In the 4th cooldown in May 2025, **<u>We achieved the lowest temperature and smallest thermal leakage ever: 3.3K at the cold head and 3.43K at the Aluminum Bar and 3.68K at middle of the cavity body.</u>**

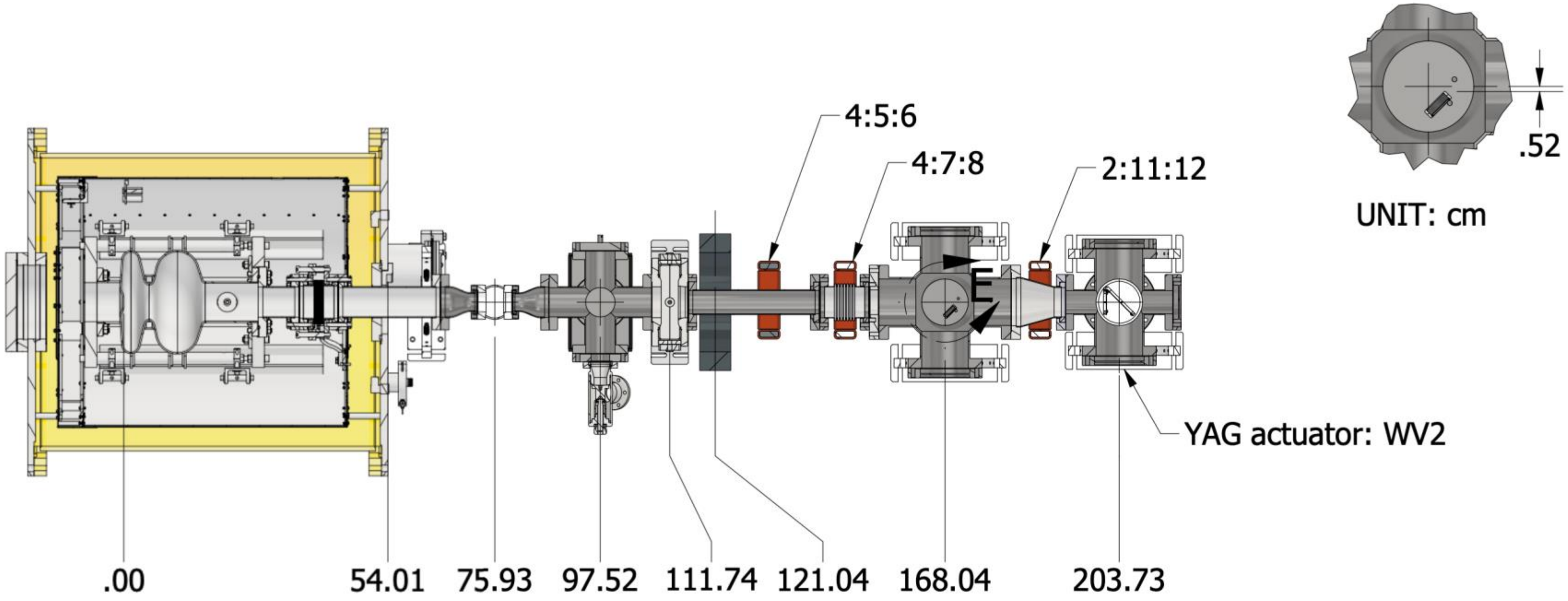





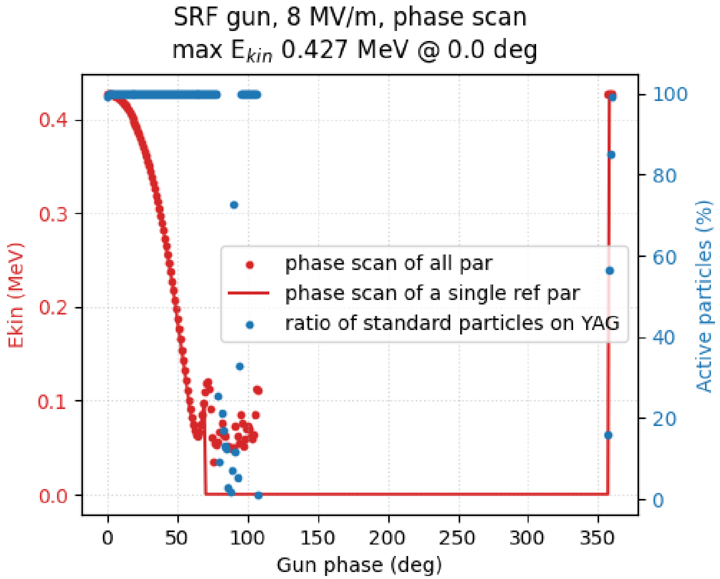


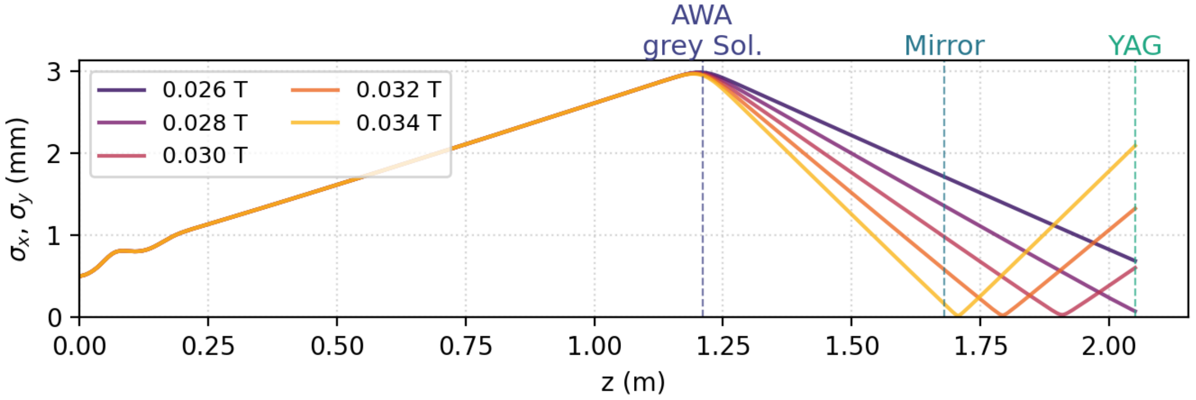



Beamline and Beam Tracking

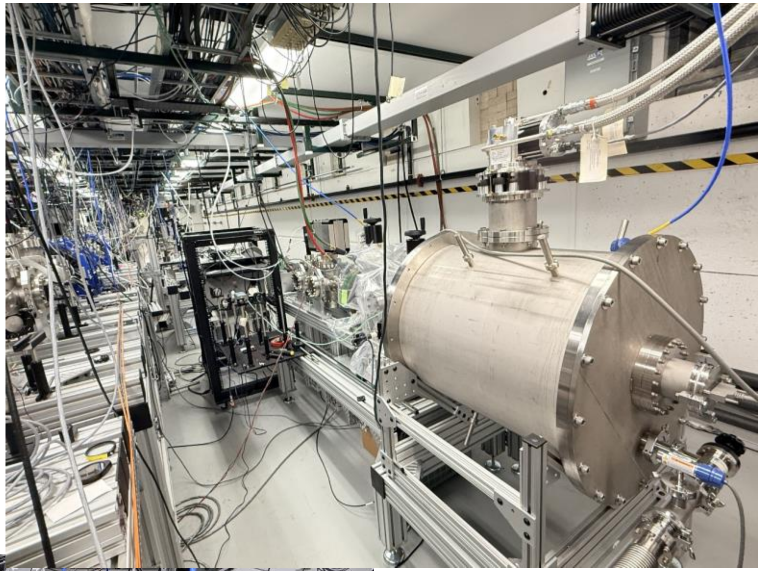
Basic params in Astra:
- Laser σ_x: 0.5 mm
- Laser pulse duration (FWHM): 300 fs
- Charge: 500 fC
- SRF gun gradient on cathode: 8 MV/m
- Space charge is included.
- Schottky effect is NOT included.

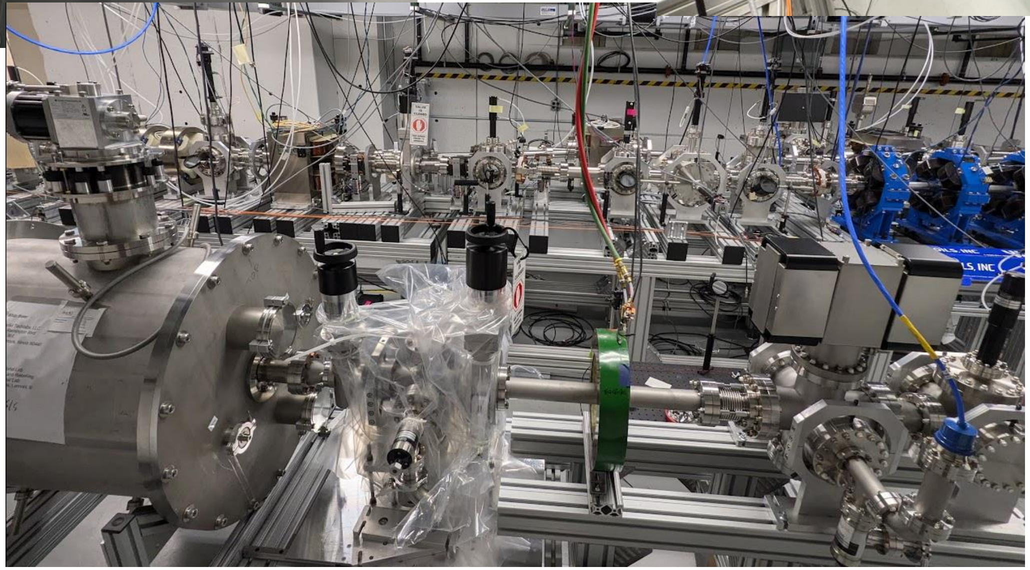




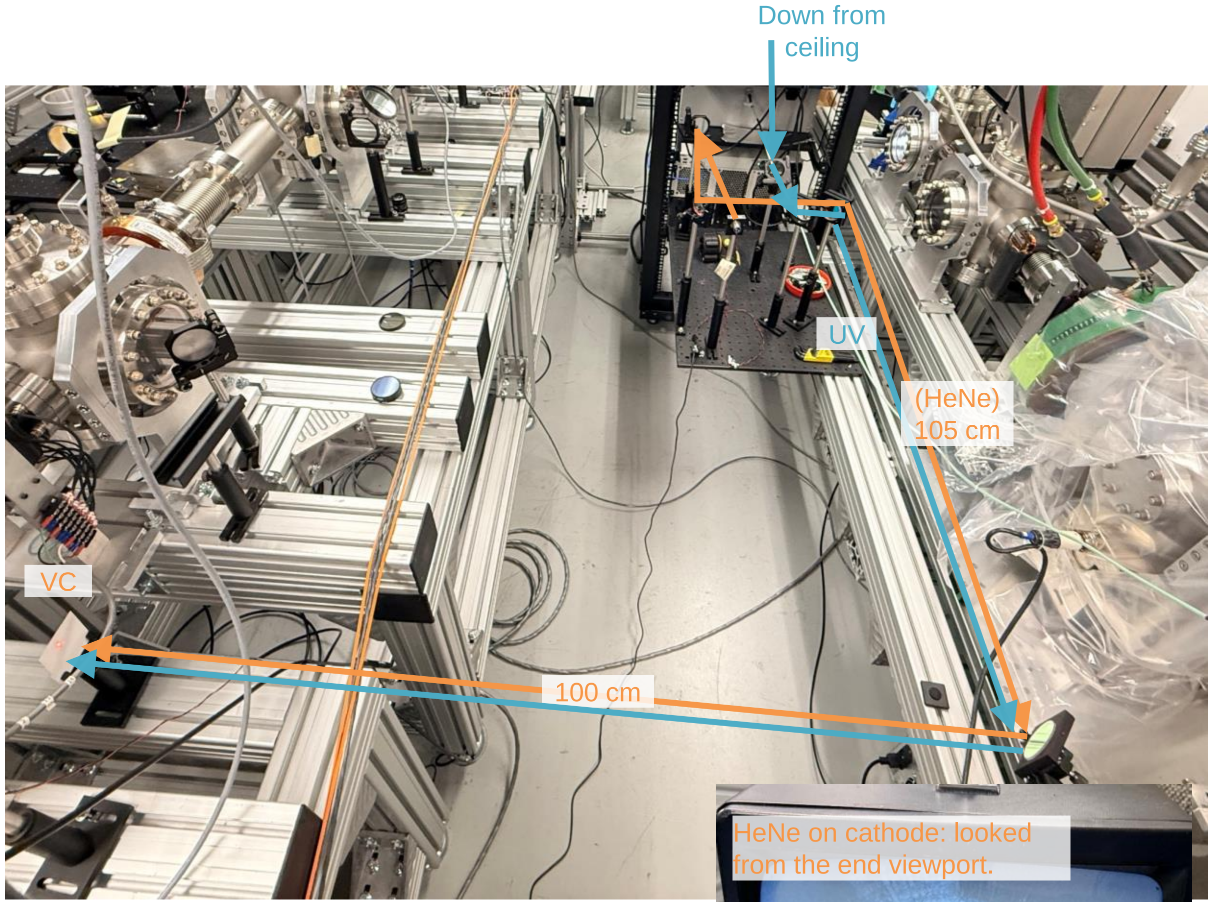


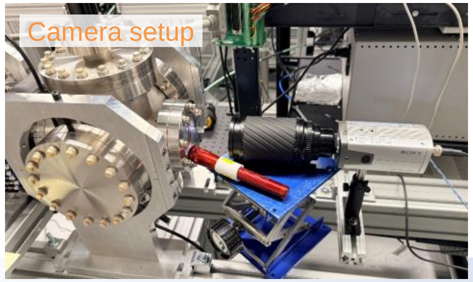
Beamline Installation at ANL



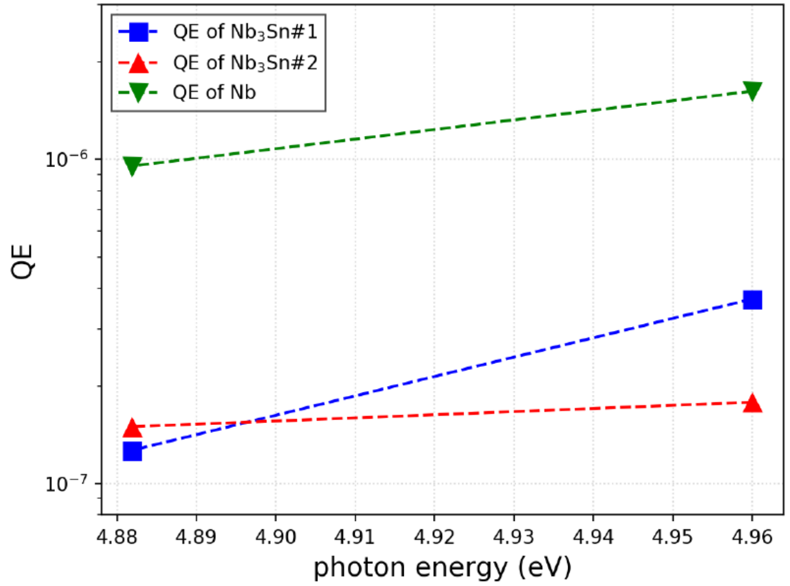


Laser Setup

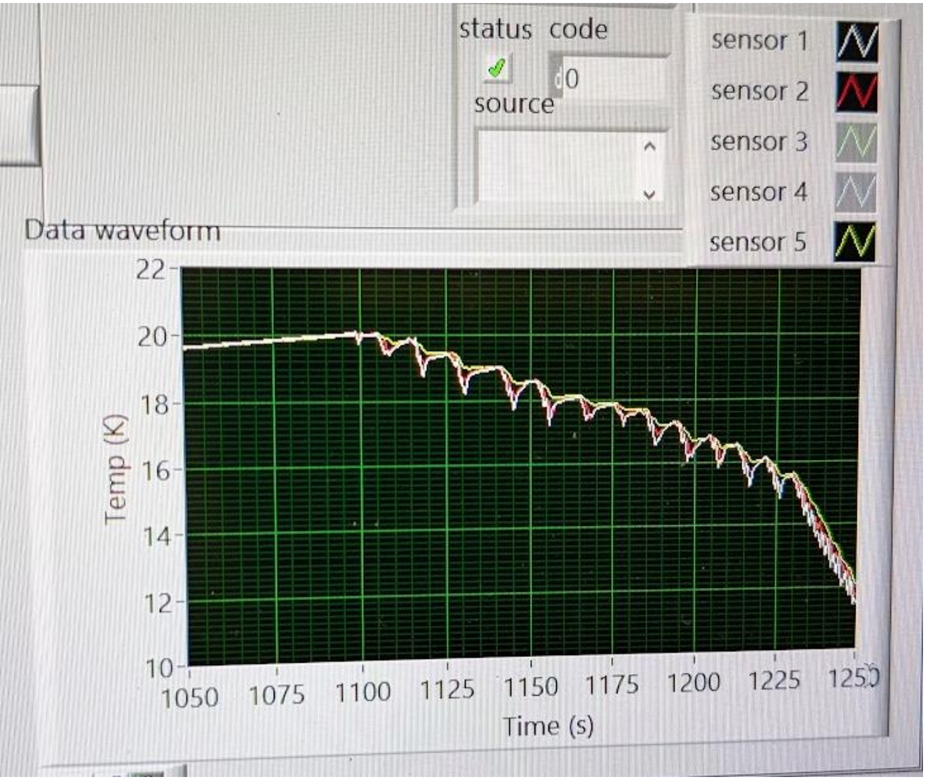


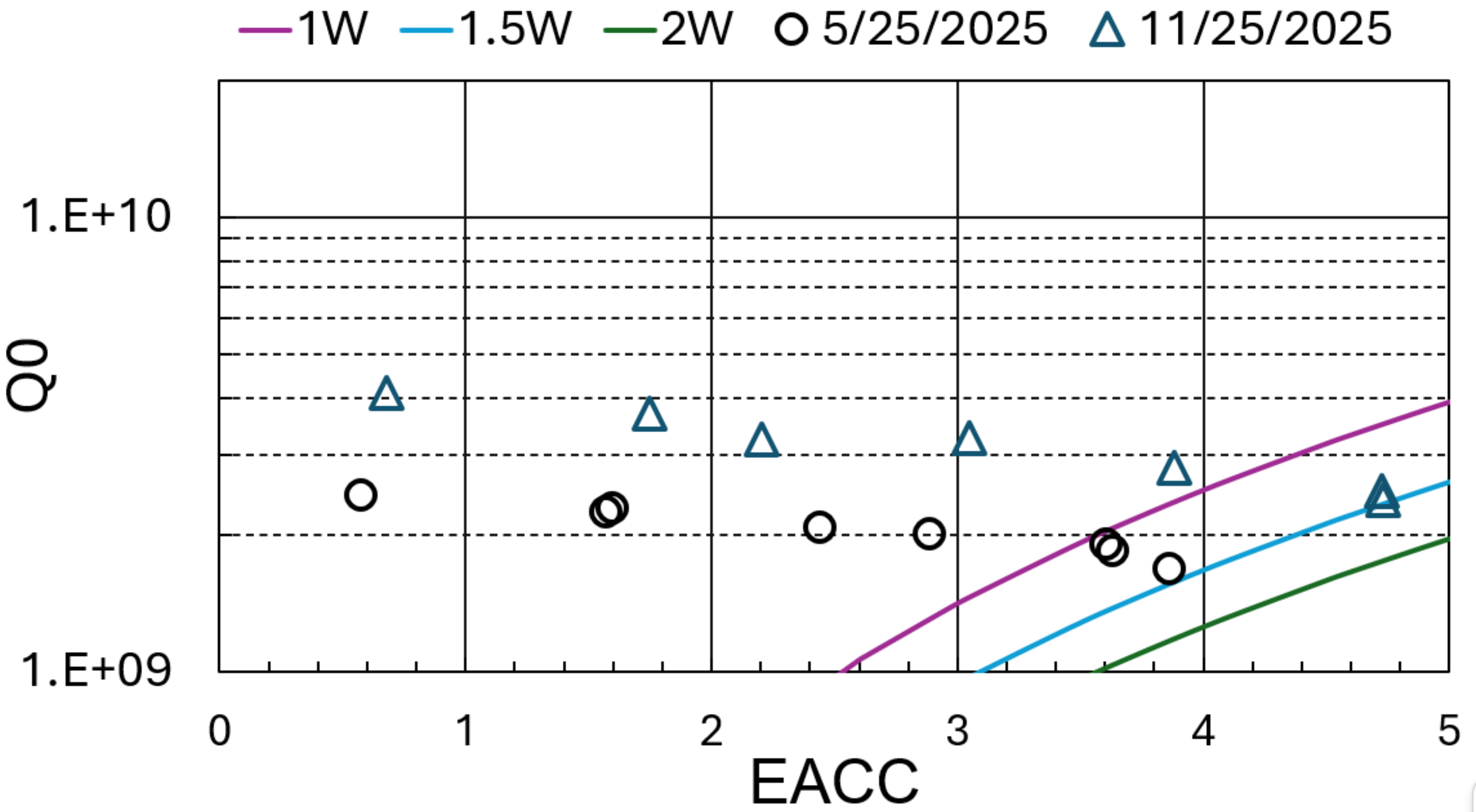


QE of Nb3Sn at RT

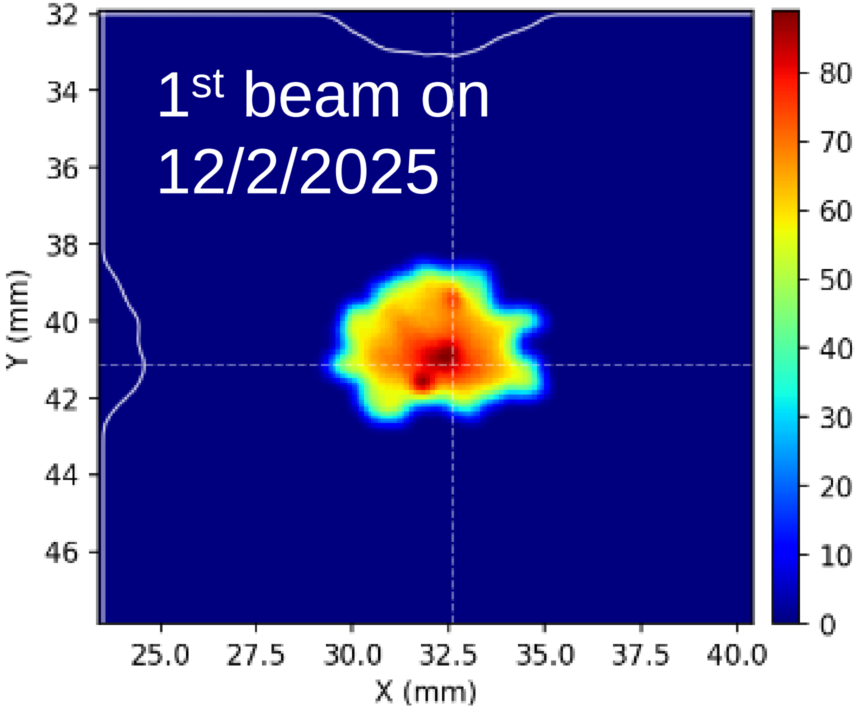


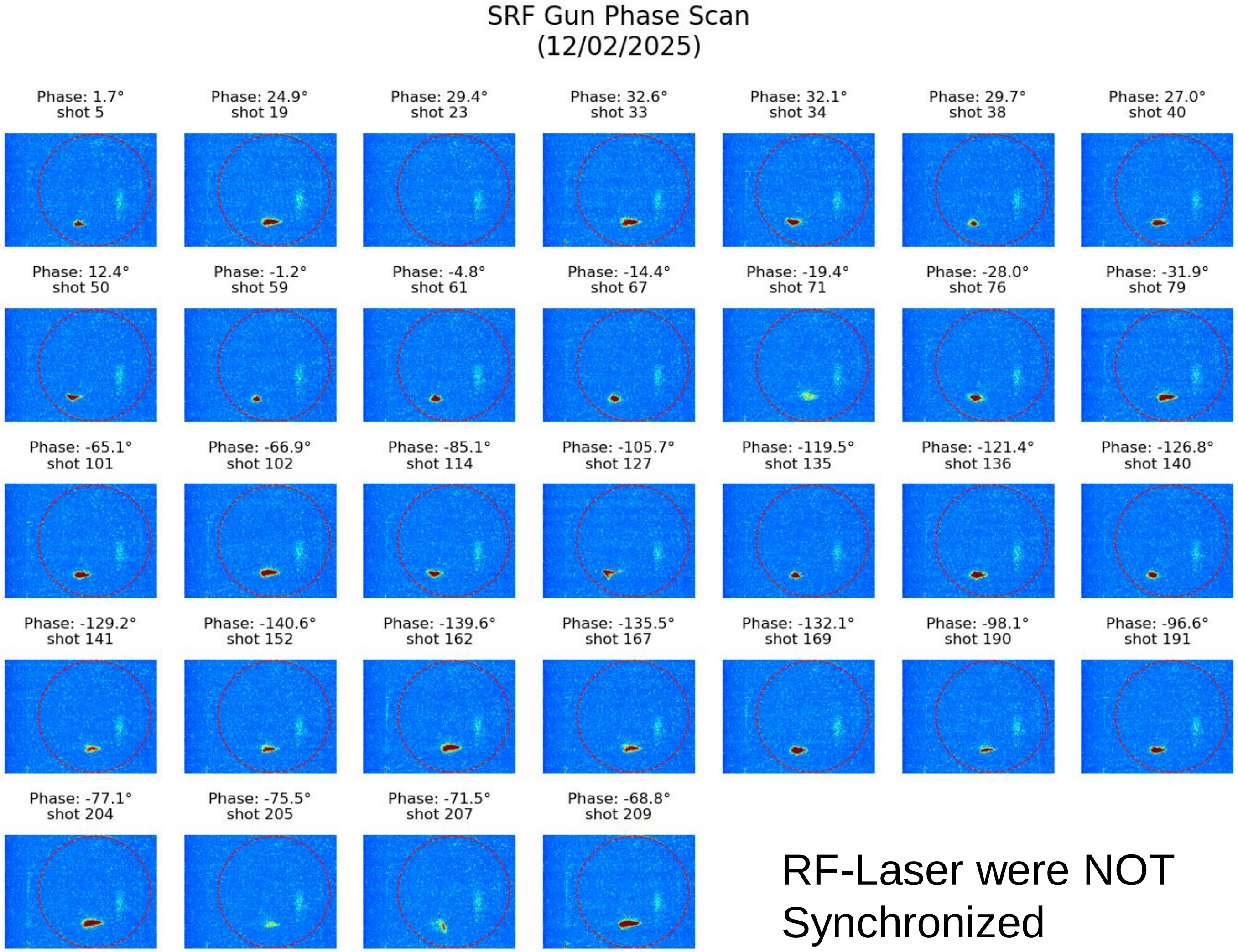
Controlled Cooled down and Q scan before the Beam Test





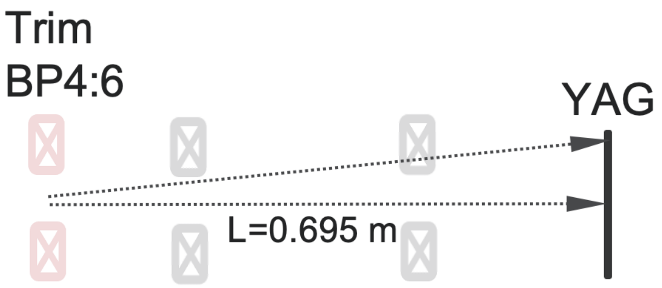
1st Beam from CC-SRF Photogun





RF-Laser were NOT Synchronized

Beam Energy Estimation from CC-SRF Photogun

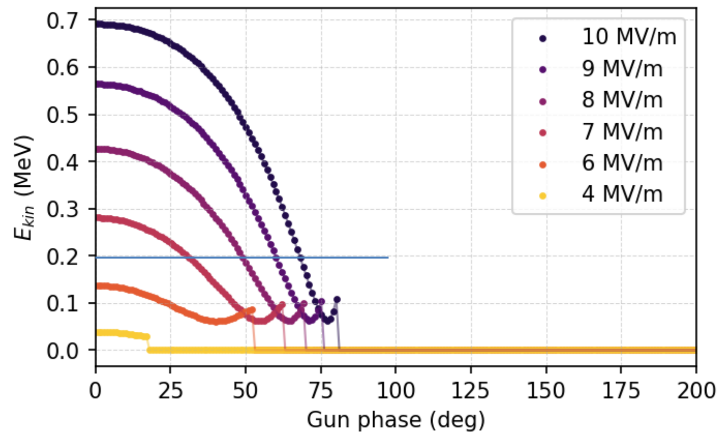


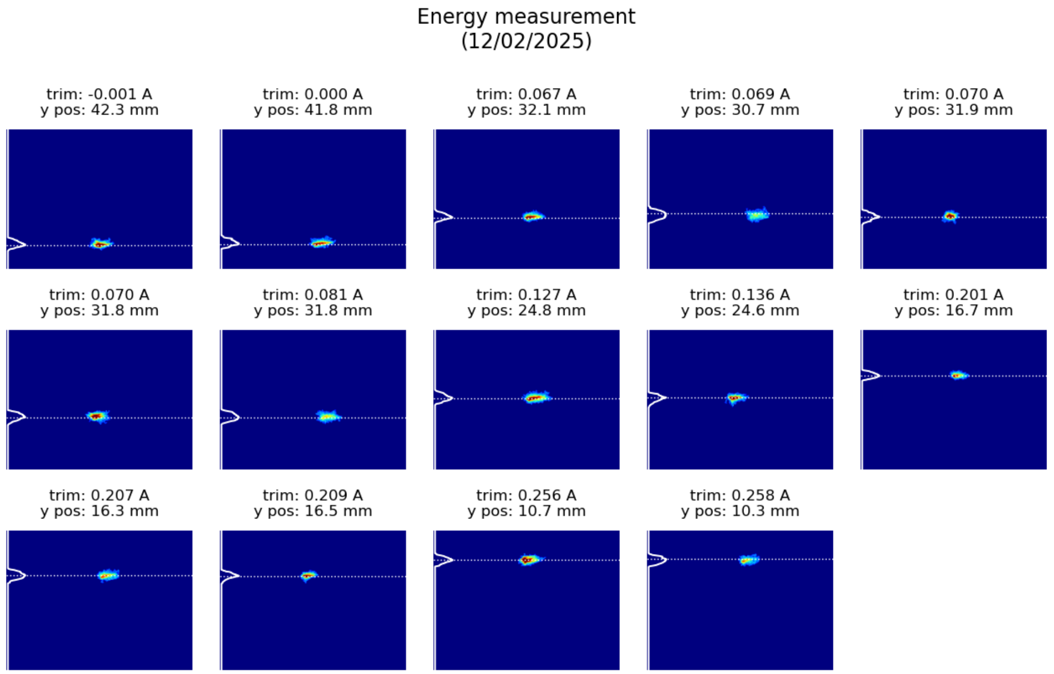
Given that, $\theta = \frac{q}{p}\int B dl$,

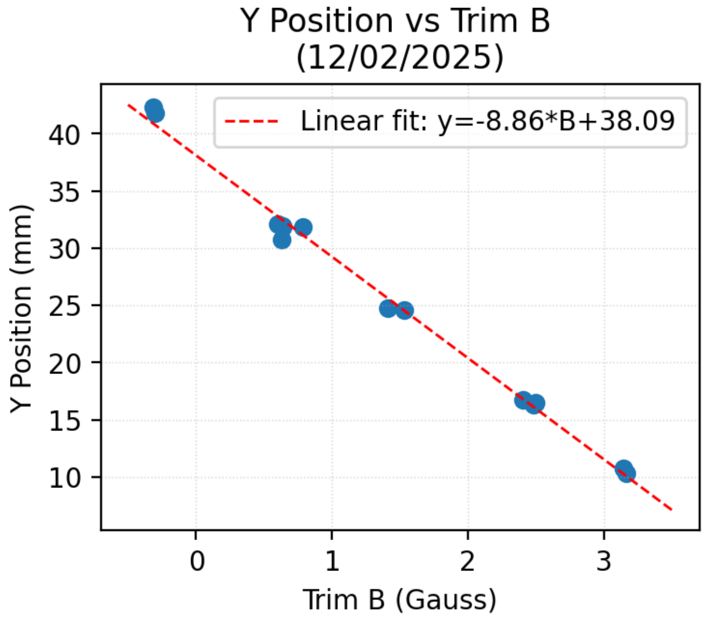
so have, $P[GeV/c] = 0.2998\frac{\int B dl}{\theta}$

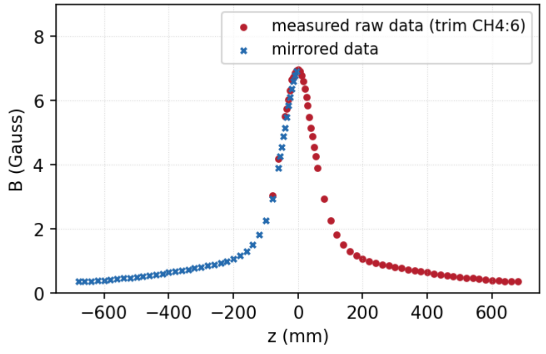
$E = \sqrt{p^2 + (mc^2)^2}$

$E_{kin} = E - mc^2 \approx 190\ keV$





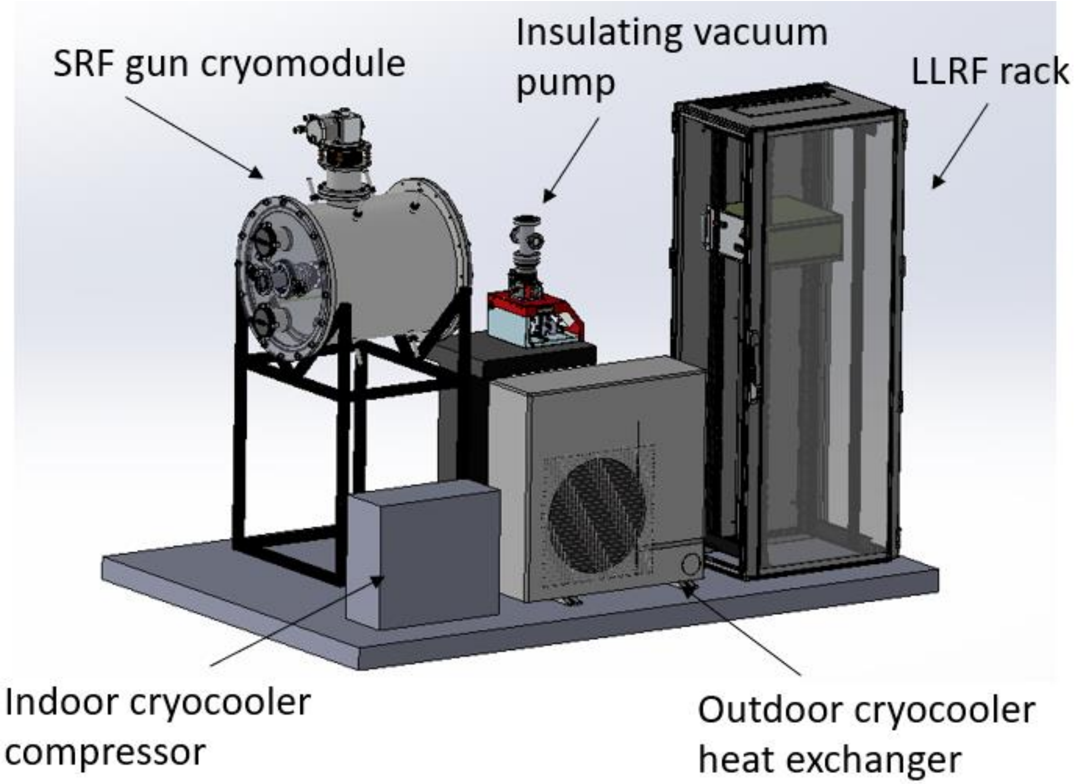




IV. Plans and Conclusion

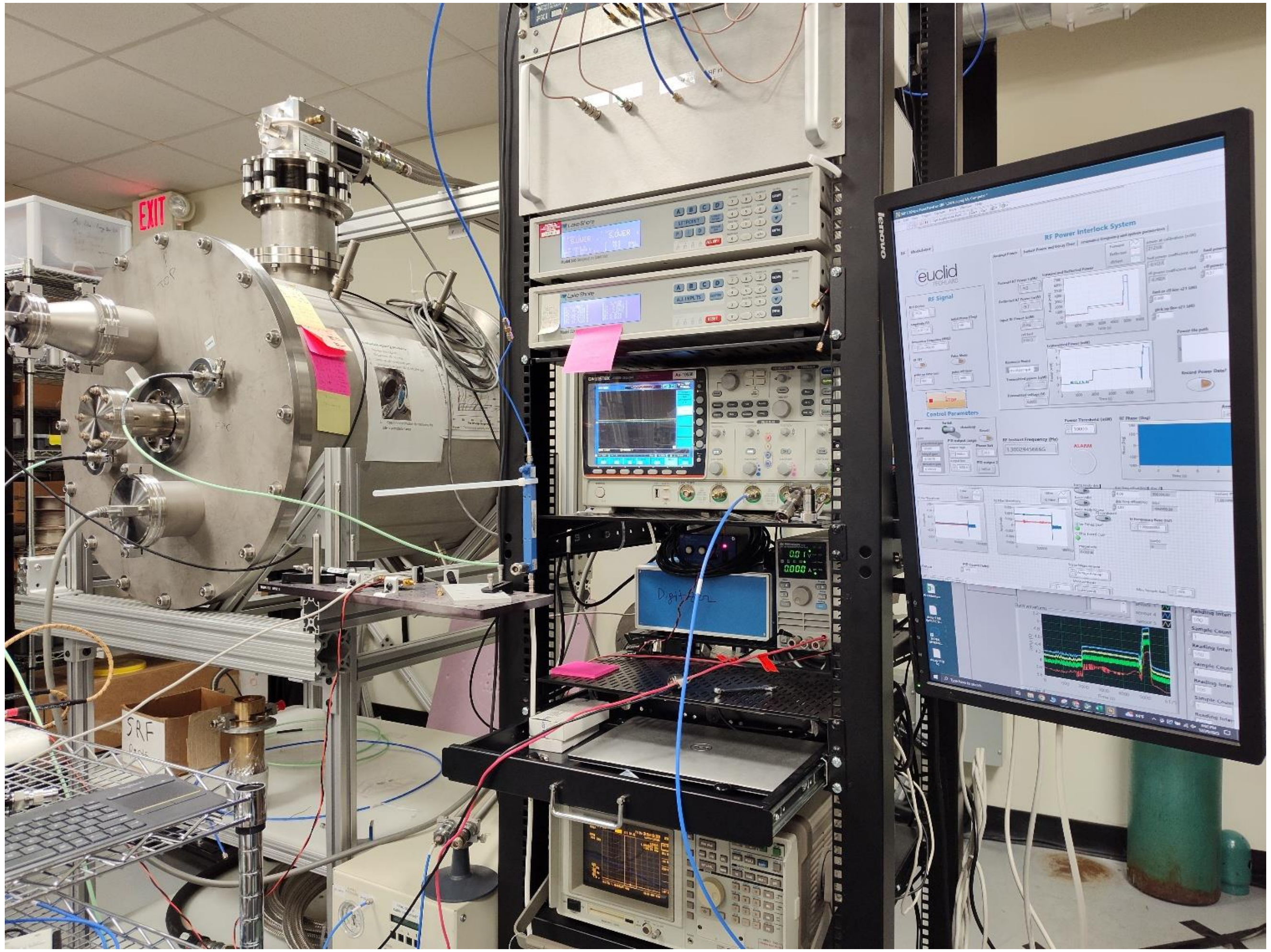
Next Plan

- ➢ Seeking funding for a new Nb3Sn coating
- ➢ Establish a CW UED demonstrator



Conclusion

- Successful demonstration of photoemitted beam out of a conduction cooled SRF photogun validates this concept and technical approach.
- This first step opens up an avenue toward a throughput high brightness MeV UED/UEM/STEM facility.
- Technical challenges remain but mostly resourced limited, no technical showstopper.



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