First High-Gradient Results of UED/UEM SRF Gun at Cryogenic Temperatures*

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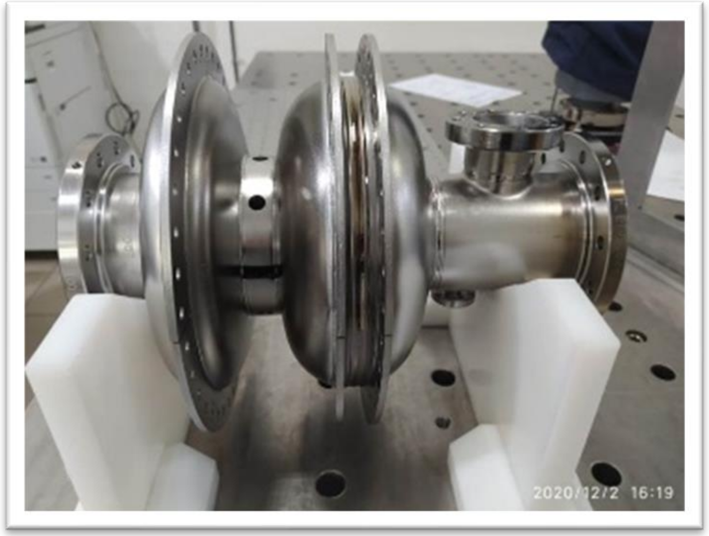
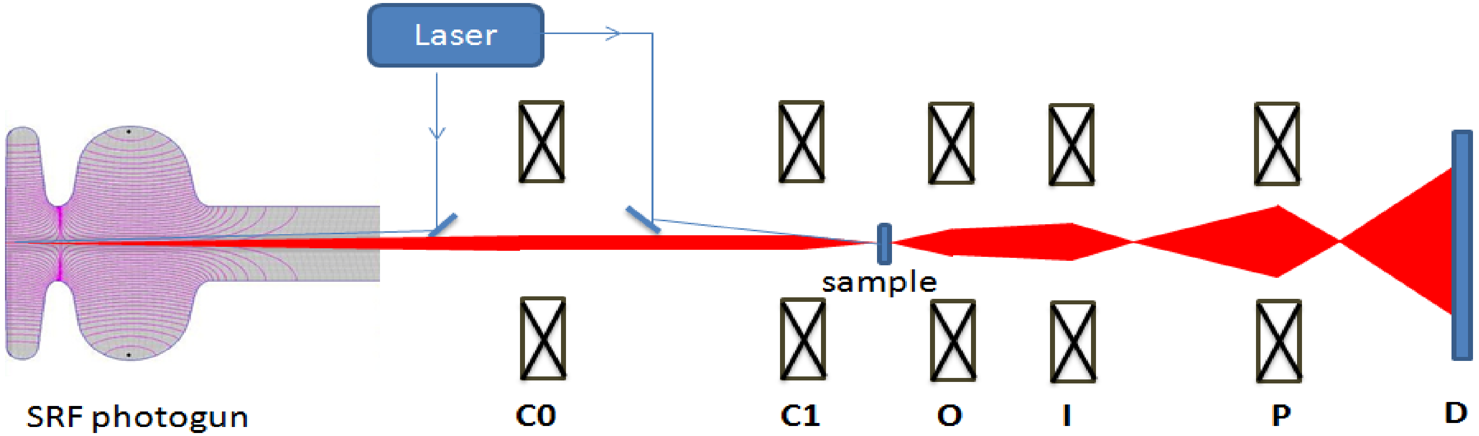
*Work supported by US DOE SBIR grant DE-SC0018621

Outline:

1. *About Euclid*
2. *Introduction to the project*
3. *SRF GUN components*
4. *Cryogenic Results*
5. *Plans and conclusions*

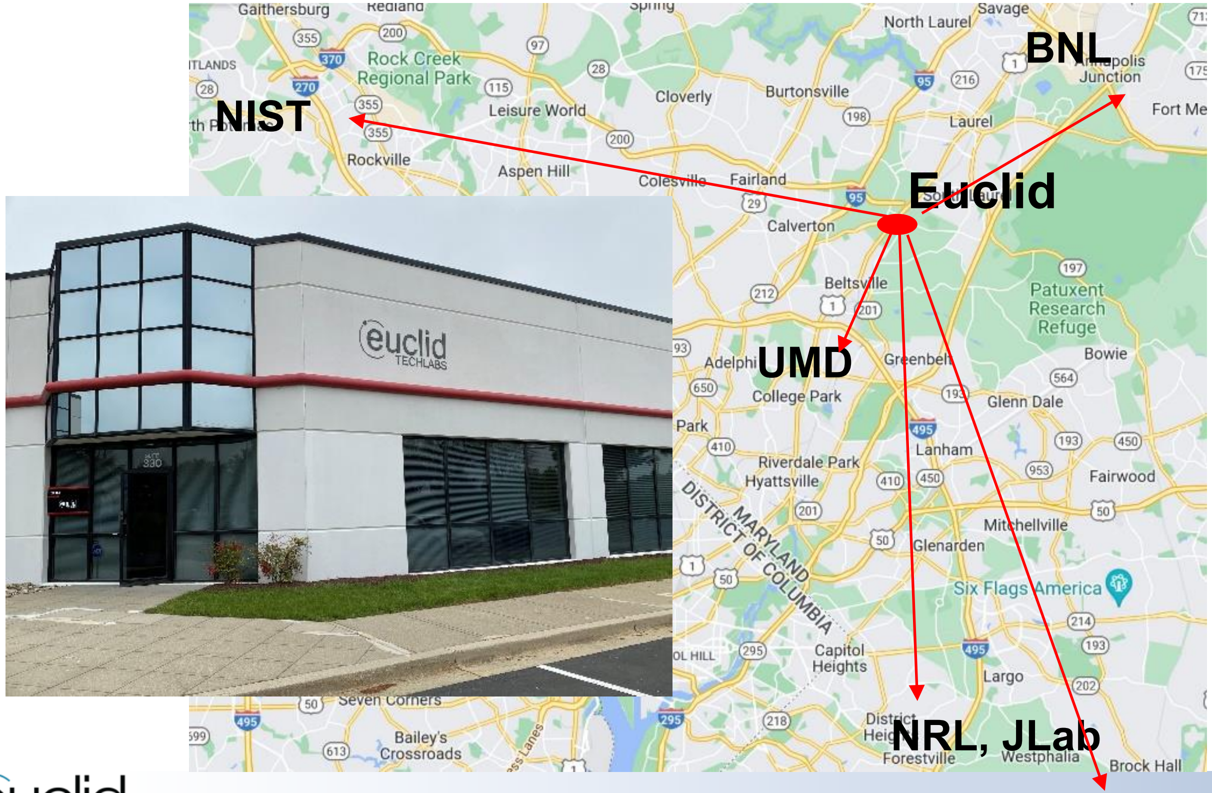


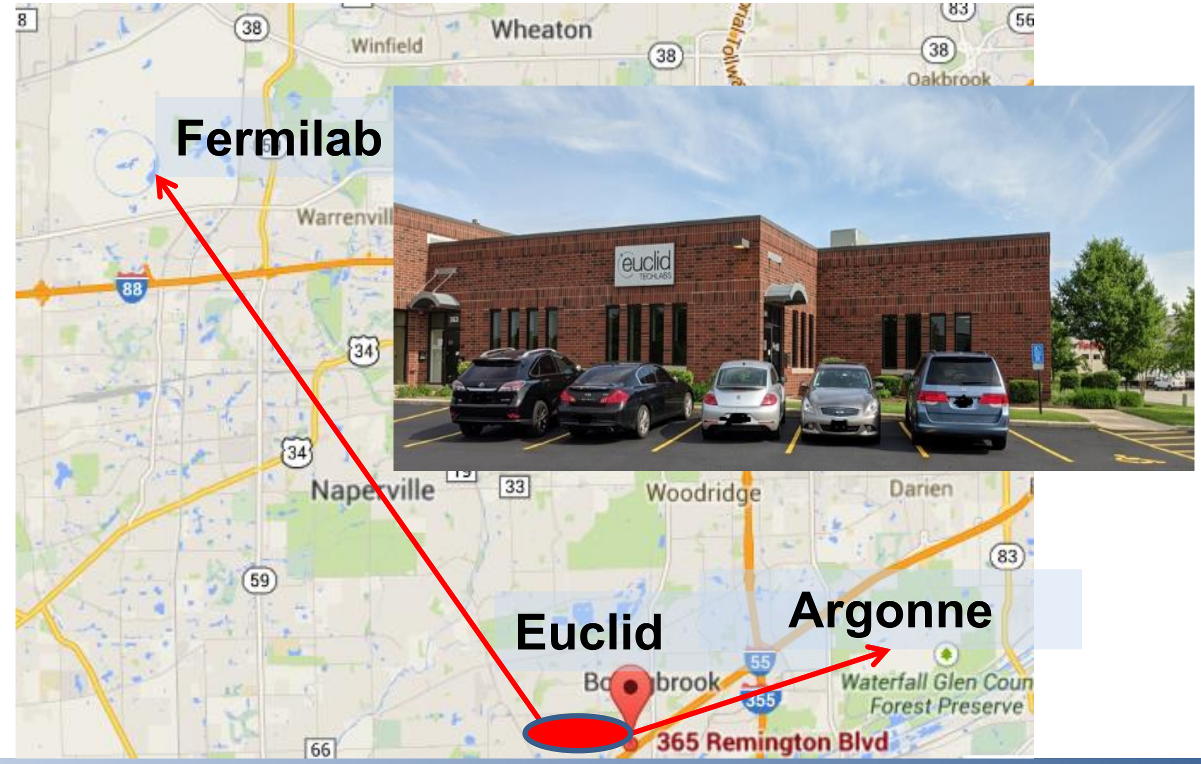


Euclid Techlabs/Euclid Beamlabs

Euclid has developed expertise and products in several innovative technologies: time-resolved ultra-fast electron microscopy; ultra-compact linear accelerators; electron guns with thermionic, field emission or photo-emission cathodes; fast tuners for SRF cavities; advanced dielectric materials; HPHT and CVD diamond growth and applications; thin-film for accelerator technologies.

- www.euclidbeamlabs.com. Find us on Facebook and LinkedIn!
- Two labs: Beltsville, MD (material science lab). Bolingbrook, IL (accelerator R&D lab)
- Tight collaborations with national labs and universities: FNAL, ANL, Jlab, LBL, SLAC, LANL, NIST, NIU, IIT, CERN, etc.





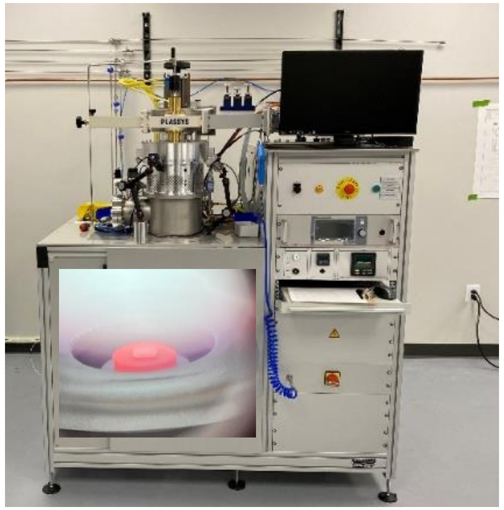
Products & Capabilities Snapshot

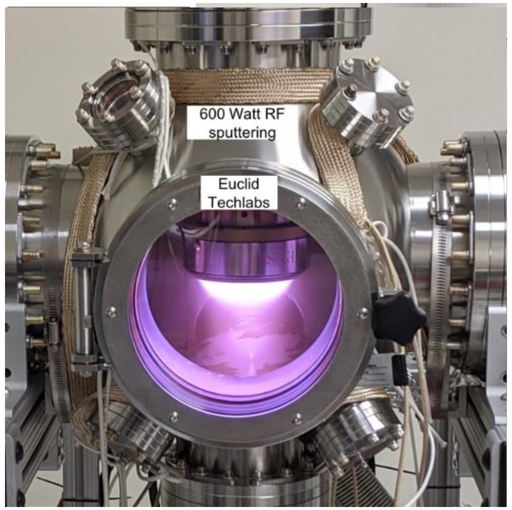
Products

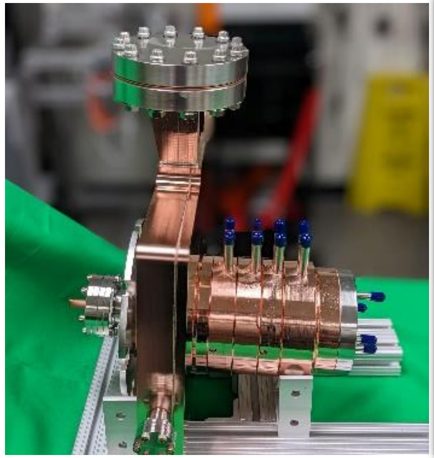
- UltraFast Pulser (UFP™) for TEM
- Dislocation free (HPHT&CVD) diamond for Xray optics
- Compact X-Ray Source
- NCRF and SRF electron sources
- Low loss ceramics (linear and non-linear)
- LINAC
- RF window
- In flange BPM

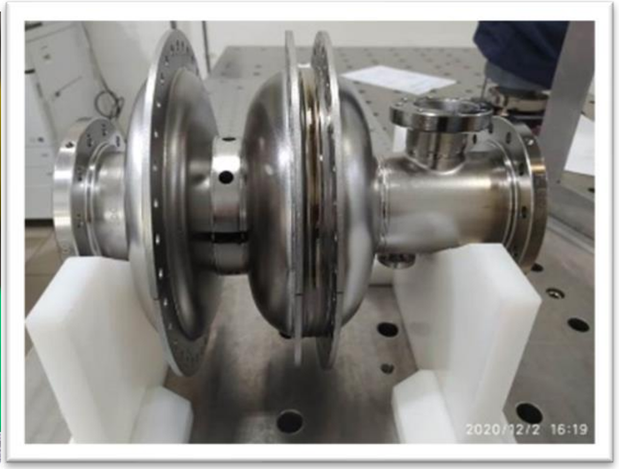
Capabilities

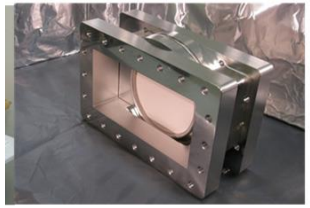
- Femtosecond Laser Ablation System
- Thin Film Deposition Lab
- EM/RF Testing Lab
- Radiation Shielding/Testing Lab
- Cryogenic 4K measurements
- Custom designs and consulting











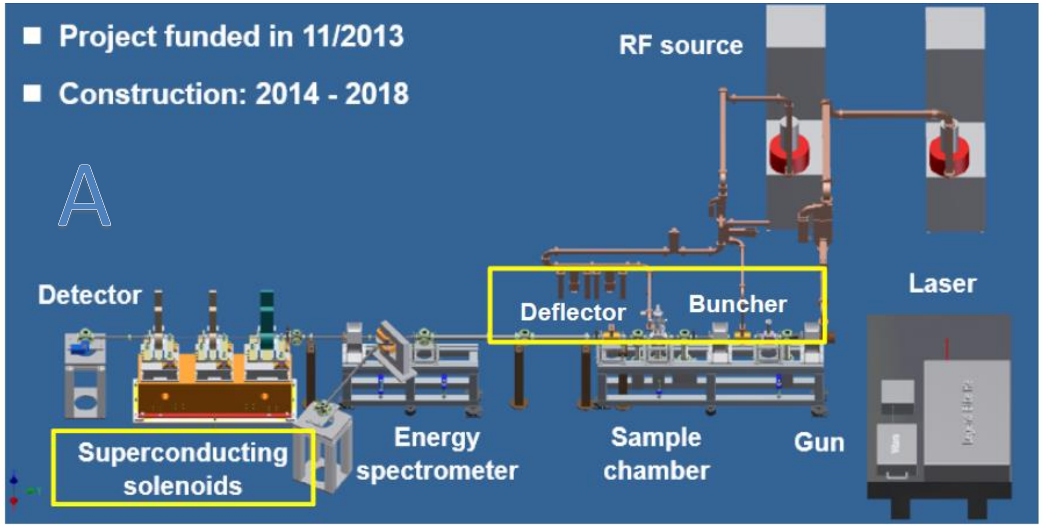
Introduction: UEM/UED

- *Ultra-fast electron diffraction/microscopy based on MeV beam which greatly suppresses the space charge effect at high bunch charges – next level of beam quality!*

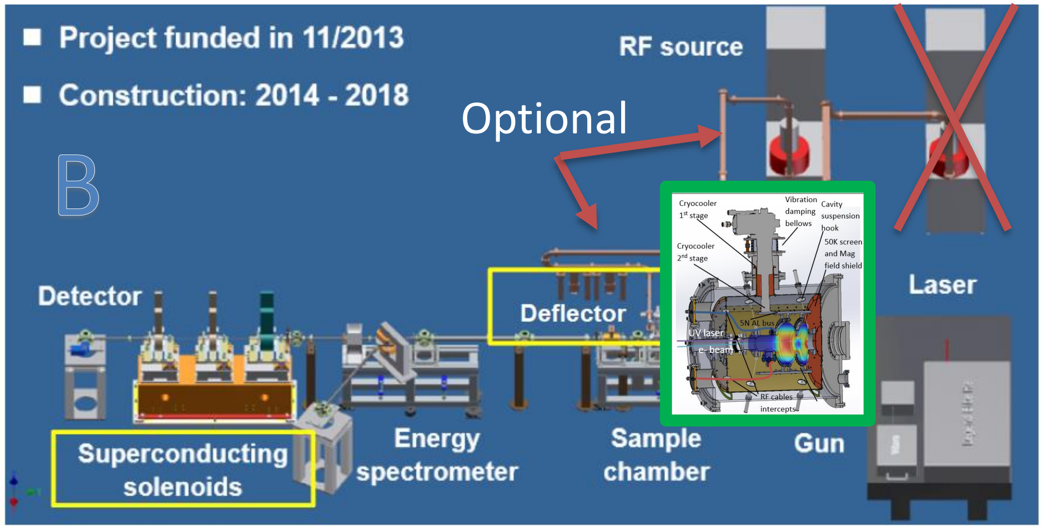
- *Stringent requirements on energy spread:*
  - *UED: $dE/E \sim 10^{-4}$, $\sigma_t \sim$10's fs, <500 fC*
  - *UEM: $dE/E \sim 10^{-5}$, $\sigma_t \sim$ps-ns, >500 fC*

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

- *Conduction cooled Nb_3Sn SRF photo-gun (see B):*
  - *4K operation temperature (Nb_3Sn)*
  - *2W cryocooler is required ($50K, relatively cheap)*
  - *CW operation*
  - *Smaller footprint, 10W RF power only*
  - *Higher stability*



Courtesy of Dao Xiang, talk at IPAC19

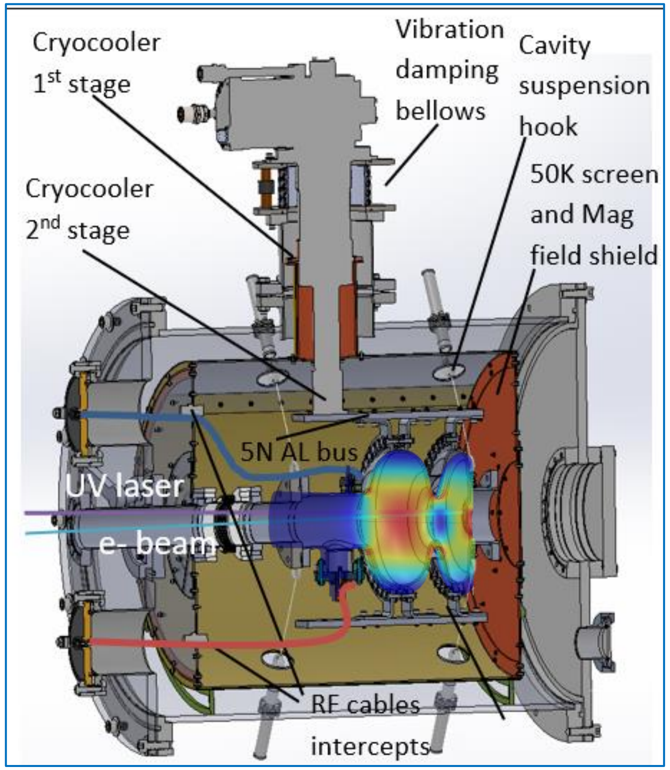


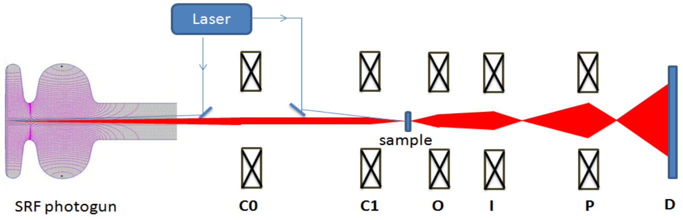
SRF photo-gun based UEM/UED facility

Introduction: 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 E_{acc}=10 MV/m**
5. Cryomodule design is required to provide enough cooling and sufficient magnetic field insulation

R.Kostin et al.," Conduction cooled SRF photogun for UEM/UED applications", UED 308081, 23-rd ATF user meeting, 2020.



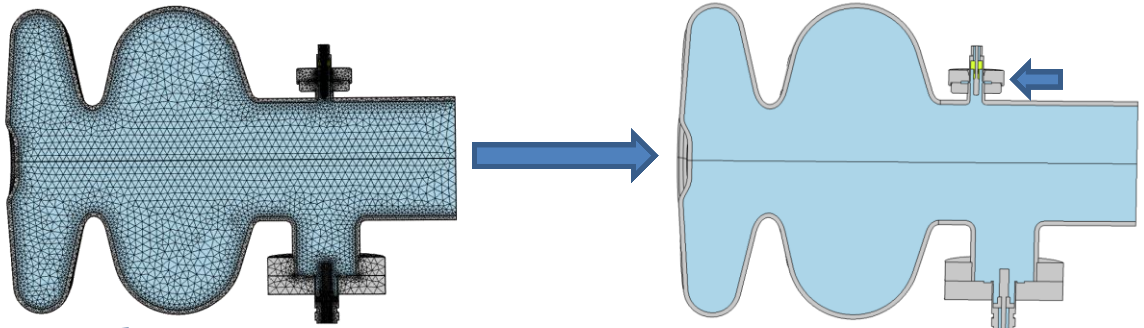


Gun parameters

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	

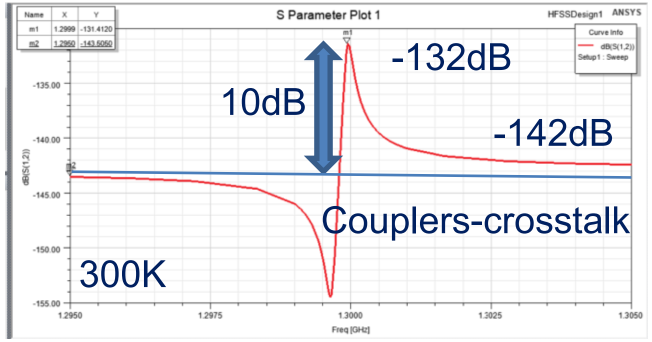
SRF photogun: couplers

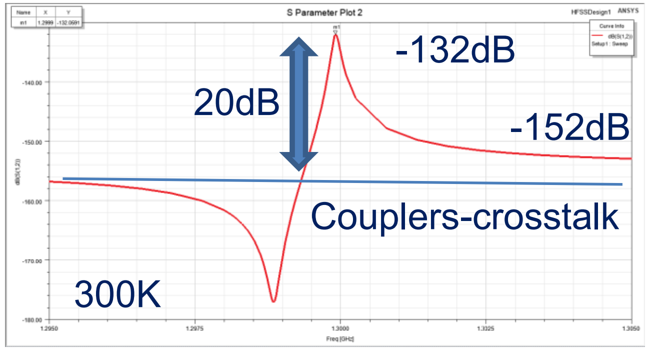
1. *The couplers were developed:*
   - *Iterative vendor's feedback → fine model*
   - *Drawings generated*
   - *Standard Titanium flanges (AL diamond seal)*
   - *Cu screw-on antennas (easy tuned if needed)*
   - *Ordered from Kyocera*
2. *Couplers were optimized in Comsol (Eigen-solver):*
   - *FPC: N-type, Qext=2.1e10 (370 mW)*
   - *PK: SMA-type, Qext=1.7e11 (40 mW)*
3. *Couplers crosstalk was investigated in HFSS:*
   - *Pick-up was moved closer to the gun*
   - *Signal-to-noise increased from 10dB to 20dB*
   - *Crosstalk filtering (34dB signal)*
4. *Qext measured as expected – fine model paid off*

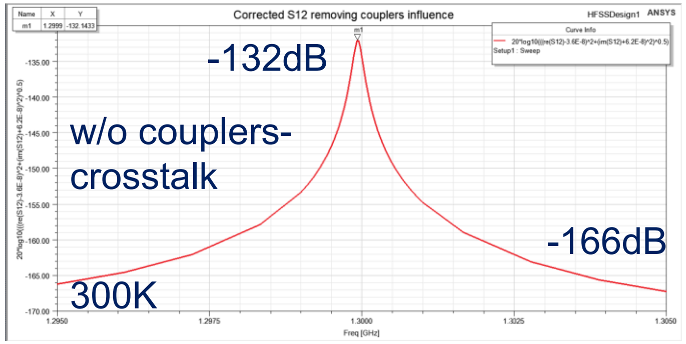


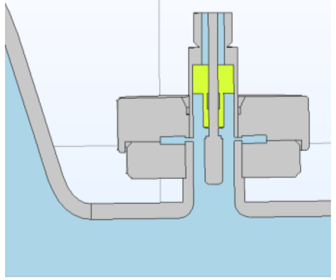
Tesla Beam pipe

Moved pick-up

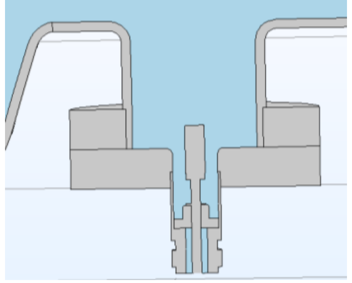








SMA pick-up



N-type FPC

SMA pick-up

N-type FPC

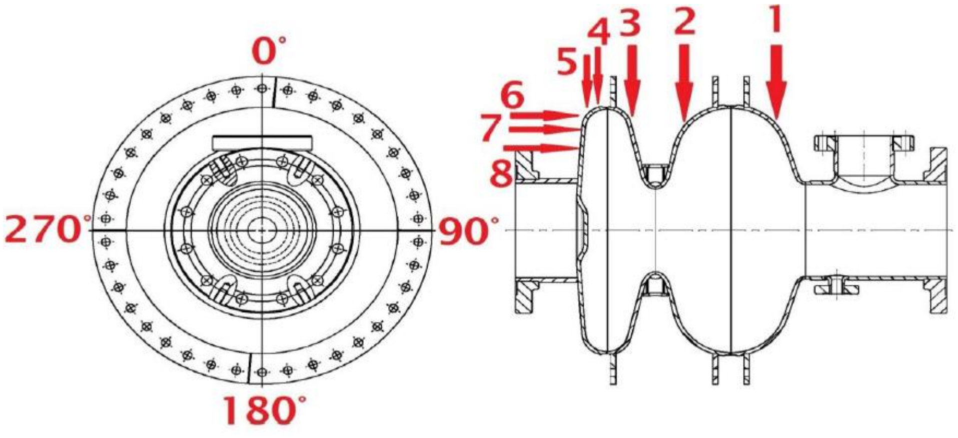
euclid BEAMLABS

SRF photogun: processing

1. *The cavity thickness was measured after manufacturing and found to be around 2.9 mm thick*
2. *Cavity processing consisted of:*
   - *150 um rotational BCP*
   - *800 C bake for 3 hrs*
   - *40 um BCP*
3. *Fairly uniform surface processing hitting the ~200 um target*
4. *Cavity received manual HPR before the fist 2 K test*
5. *Frequency shift due to BCP is -1.02 MHz (twice lower than expected for 200 um layer removal)*

AS received

After BCP



Measured points

Position	0°	90°	180°	270°
1	2,89	2,89	2,87	2,89
2	2,92	2,91	2,86	2,90
3	2,81	2,79	2,77	2,78
4	2,78	2,82	2,81	2,80
5	2,85	2,84	2,84	2,78
6	2,84	2,83	2,83	2,80
7	2,88	2,87	2,87	2,84
8	2,88	2,88	2,88	2,88

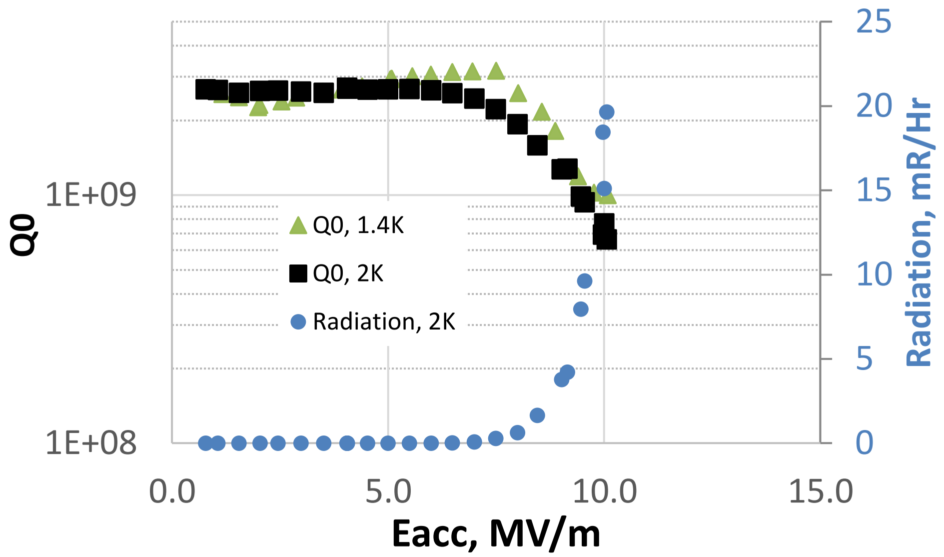
Thickness as manufactured

Point	0	90	180	270
1	229	193	211	192
2	276	294	254	261
3	223	195	219	208
4	212	222	238	208
5	228	231	246	193
6	204	170	200	197
7	185	187	206	160
8	164	168	202	180

Layer removed by BCP

Cryogenic test #1: Pure Nb at 2K

1. *SRF gun was tested at 2K.*
2. *Magnetic field in the Dewar is around 1mG.*
3. *The operating gradient of 10MV/m has been reached*
4. *No MP observed up to the operating gradient of 10MV/m.*
5. *Q0=2.6E9 at low fields. Q degradation after 7 MV/m due to field emission.*
6. *Field emission observed - cavity is not properly cleaned?*
7. *The gun was tested at 1.4K and no much difference in Q0, meaning BCS not a dominating factor, but the residual resistance.*
8. *Several quenches happened during the test. We were power limited (bad coupling, as the Q0 was lower than expected).*
9. *Probably different nozzle is needed to clean the 1st cell.*
10. *Cavity was stressed during the cleanroom assembly, F0=1303.48MHz is higher than expected.*
11. *Pi/2 mode was also tested (field in the 1st cell primarily): similar results, meaning that the 1st cell need more cleaning.*

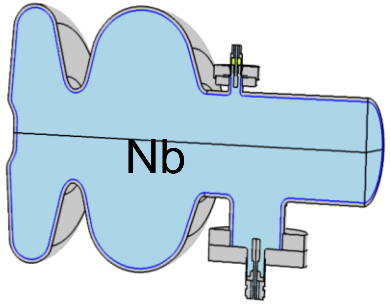


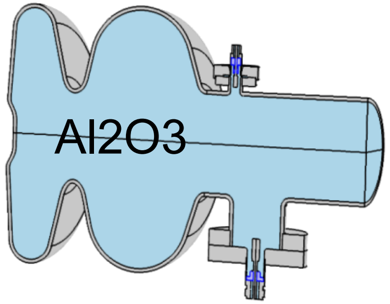
Losses in the gun investigation.

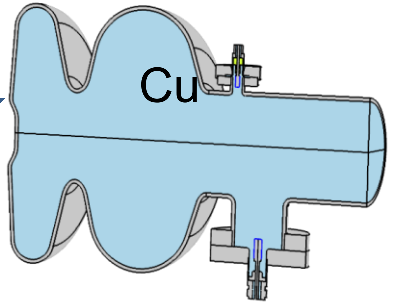
1. *Losses in the gun were investigated once again*
2. *Only close coupler ports (potential reflections in the feedthroughs?) result in field distribution with higher losses: Q0=3.5E9 (2.6E9 measured)*
3. *The main losses are in FPC body.*
4. *Beam pipe flange, pick-up feedthrough, Al_2O_3 windows and Cu pins do not contribute much in this regime.*
5. *Reflections from feedthroughs were ruled out as Q_{ext1}=2E10 as expected during the test.*
6. *Surface processing is suspected to be the main reason of low Q0.*

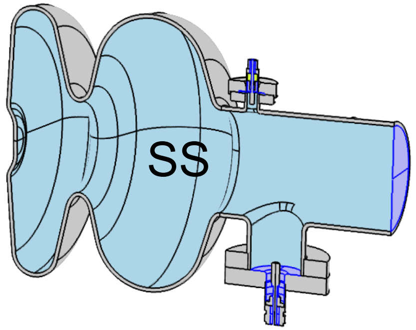
Material	Losses, mW Open	Losses, mW Short	Q0 Short
Nb (cavity, Rs=10nOhm)	370	370	2.3E10
+ Al2O3 (tanδ=1e-4)	0.03	12	2.2E10
+ Cu (antenna, σ=5.8E7)	1.6	5.8	2.18E10
+ SS (feedthroughs and BP flange, σ=0.1E7)	21.6	2023	3.5E9
P_FPC	363.5	NA	NA
P_PK	48.2	NA	NA

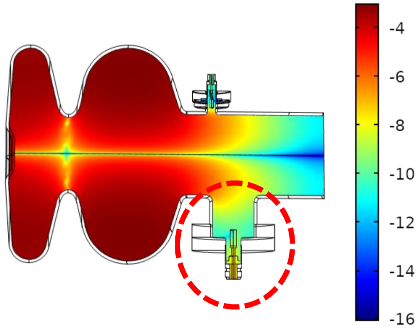
Losses

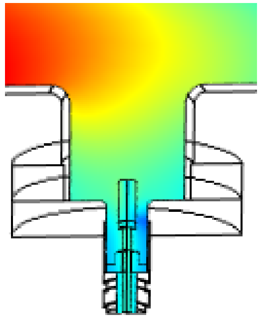












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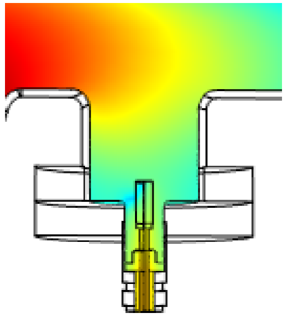
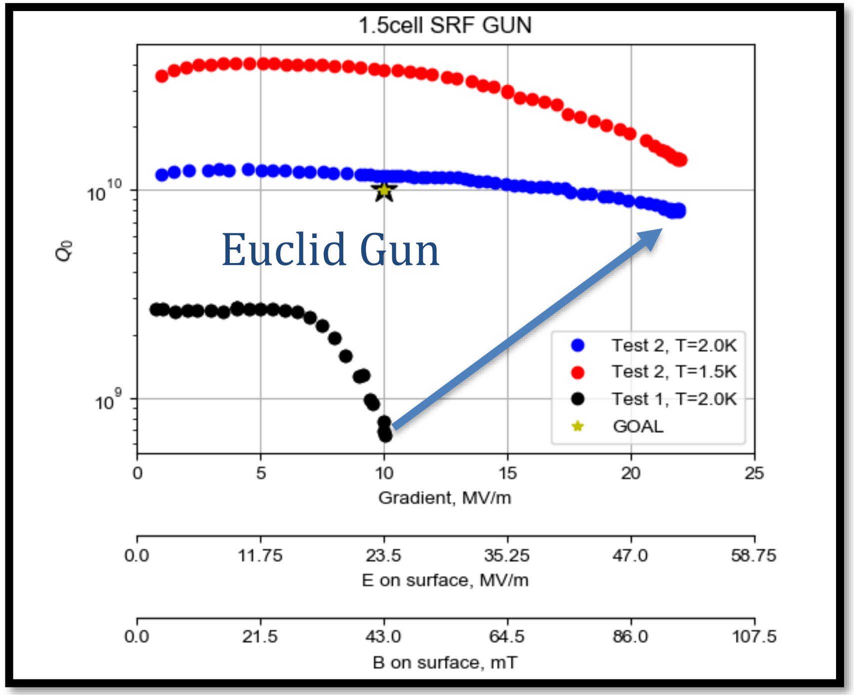
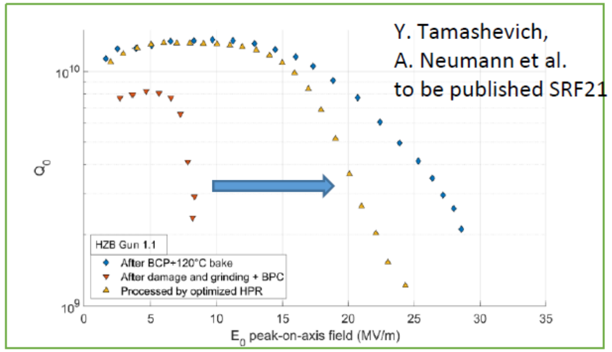


SHORT

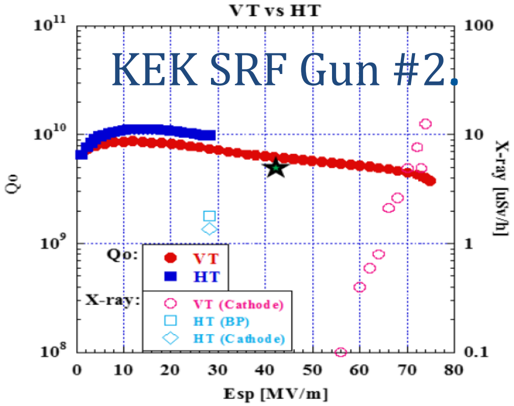
Cryogenic test #2: Pure Nb at 2K

1. *Cleaning procedure:*
   - *10 um BCP*
   - ***Automatic HPR with a new nozzle***
   - *US bath*
2. *SRF gun was tested at 2K and 1.5K.*
3. *The gun frequency 1303.26 MHz (-0.22 MHz), no tuning*
4. *Q0=1.2E10 at low fields*
5. ***The operating gradient of 22MV/m has been reached @ Q0=8E9 :***
   - *Ez_pk=44 MV/m*
   - *Esp=51.7 MV/m*
   - *Bsp=95.26 mT*
6. *No MP, no field emission.*
7. *Euclid gun in comparison with similar projects:*
   - *HZB 1.3GHz 1.4 cell: Ez_pk=35MV/m @ Q0=2E9*
   - *KEK 1.3GHz 1.5cell: Esp=75MV/m @ Q0=4E9*
8. *Key milestones has been reached by test #2:*
   - *The gun performance satisfies the requirements*
   - *The gun is ready for Nb_3Sn deposition*
   - *Successful cleaning procedure has been established.*





HZB gun 1.1

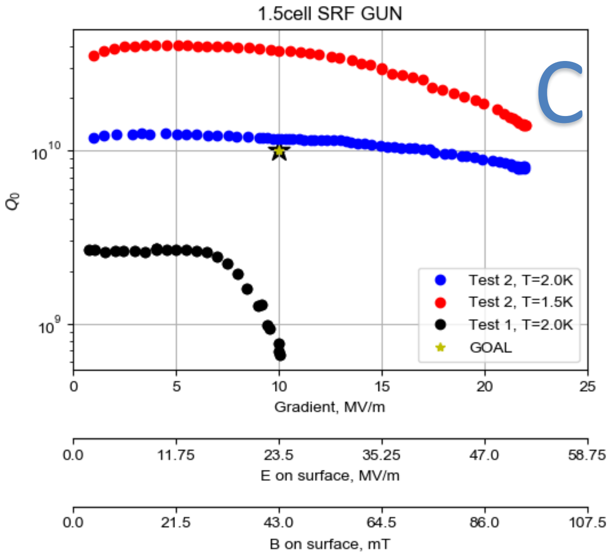


T.Konomi. "Overview on worldwide development of SRF-gun cavities", SRF21 talk.

Conclusions

1. Euclid is developing an MeV 1.3 GHz SRF photogun for UED/UEM.
2. The cryomodule was developed and successfully cooled down to 2.5K.
3. Magnetic shielding was upgraded reducing the field below 5mG at room temperature.
4. LLRF control similar to one delivered to Fnal-IARC is developed.
5. SRF gun was manufactured and was within the tolerances (see B).
6. The Nb gun was tested in vertical test stand (C):
   - 1st test (2K) reached 10 MV/m, but Q0 was low ~1e9. Field emission was observed.
   - 2nd test (2K) reached E_{acc}=22 MV/m (while 10 MV/m is req-d) and Q0=1E10
7. The pure Nb gun passed the quality check and is ready for the next step: Nb_3Sn deposition.

R.Kostin et al., "Status of Conduction Cooled SRF Photogun for UEM/UED", proc. of IPAC21, TUPAB167.



Future plans

1. Nb_3Sn coating to obtain high Q0 at 4K, followed by test in liquid helium.
2. Test of the Nb_3Sn gun at Euclid using conduction cooled cryomodule.
3. Demonstration of 10 MV/m of accelerating gradient as required to get 1.6MeV beam.
4. Delivery of the system to BNL and commissioning.
5. Integration of the system with the BNL EUM/EUD beamline.
6. Beam generation by UV laser and beam quality studies.
7. UED/UEM sample measurements.

THANK YOU!

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Yimei Zhu, Erdong Wang

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