Study in the High-Average Current, High-Brightness Electron Sources:
Diamond Amplified Photo-cathode and Multiple Cathode system

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Contents

Motivation of the DAP

Metallic Photo-cathodes

Photo-cathode material	QE	λ (nm)	Operational lifetime	Vacuum (Torr)
Cu	0.014%	266	Very long	10^{-7}
Mg	0.06%	266	Very long	10^{-7}

Semiconductor Photo-cathodes

Photo-cathode material	QE	λ (nm)	Operational lifetime	Vacuum (Torr)
Cs_2Te	4~20%	260	Hours-months	$<10^{-9}$
CsK_2Sb	3~10%	~530	Hours	$<10^{-9}$
Ga As (Cs)	1~10%	~750	Hours	$<10^{-11}$

- Metallic cathodes.
  - Low QE, low average current, long lifetime
- Semi-conductor photo-cathodes.
  - High QE, sensitive to contamination, short lifetime.

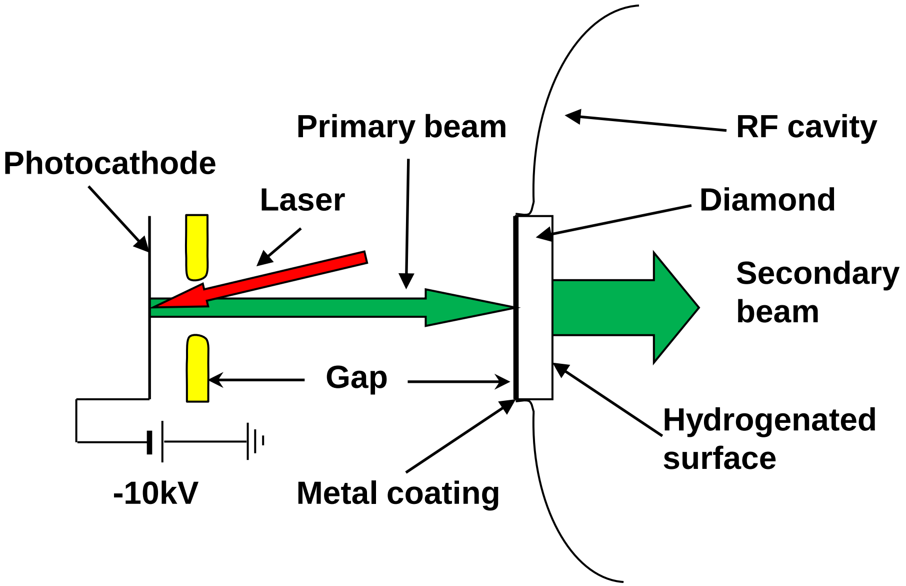
Diamond Amplified Photo-cathode Concept

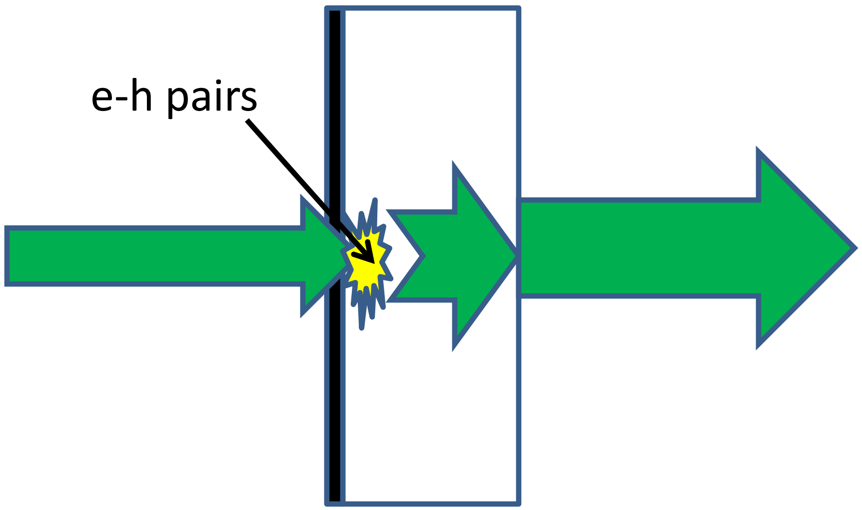
I. Traditional photo-cathode generate primary beam. Primary electrons penetrate the metal coating and generate electron-hole pairs in diamond.

II. Electron-hole pairs are separated by the RF electric field at appropriate RF phase.

III. Secondary electrons drift through diamond.

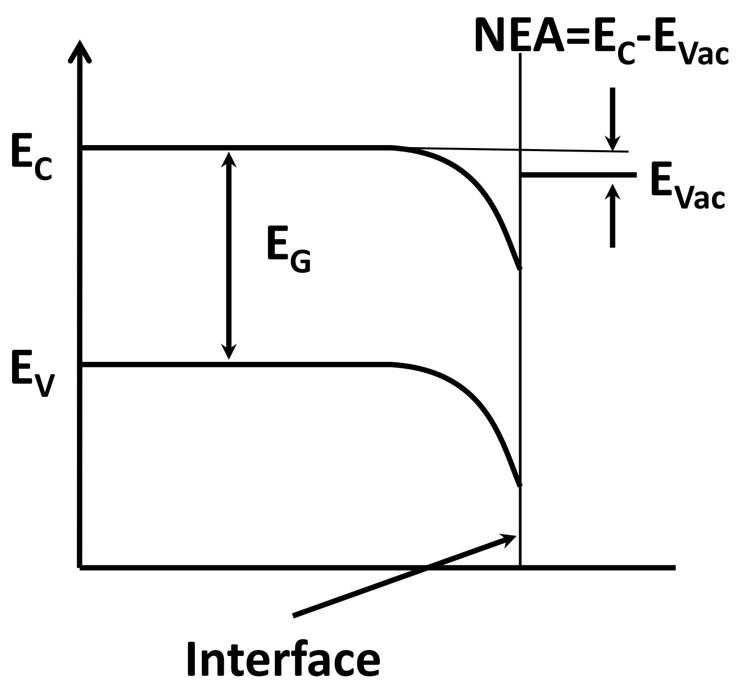
IV. Secondary electrons are emitted from the hydrogenated Negative Electron Affinity (NEA) surface.





Why diamond?

- Wide band gap (5.47eV). Easy to demonstrate Negative Electron Affinity (NEA).
- The hardest material. Free standing very thin films.
- The highest thermal conductivity. Handles high power in a thin film.
- The very high mobility and saturation velocity ($2.7\times10^{5}m/s$). Applicable for high-frequency RF cavities

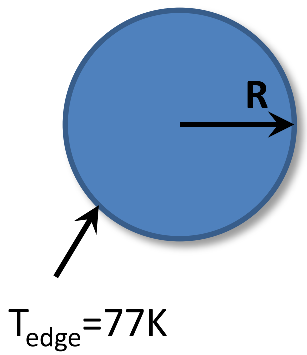


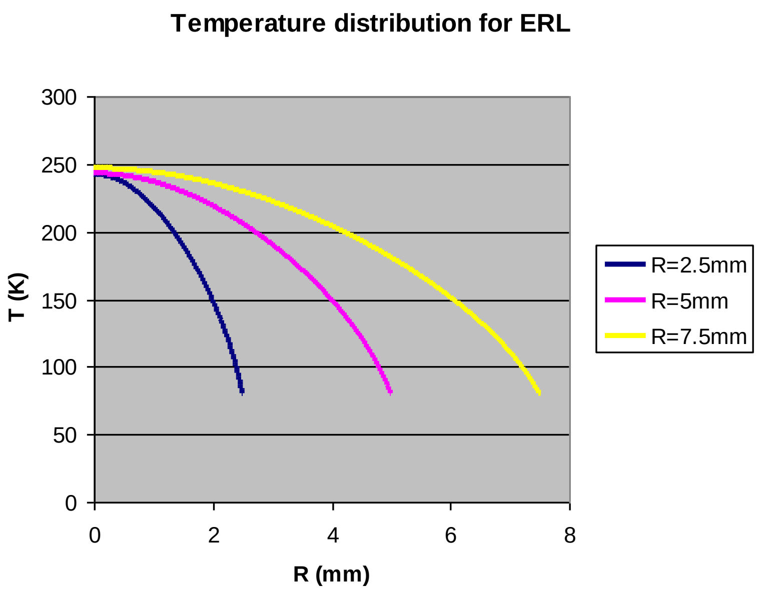
The concept of NEA surface

Thermal analysis

The BNL ERL project:

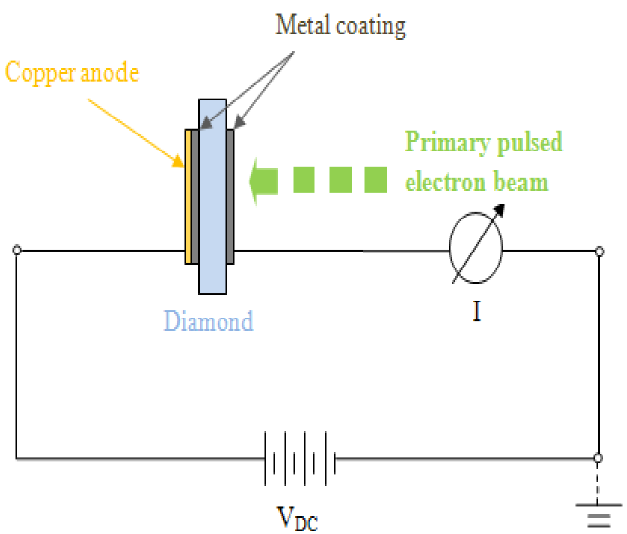
Charge	1.42 nC/bunch
Repetition frequency	703 MHz
Primary electron energy	10 keV
Diamond thickness	30 µm
Al thickness	800 nm
Peak RF field on cathode	15 MV/m
SEY	300
Temp. on diamond edge	80 K
Primary electron pulse length	10 deg

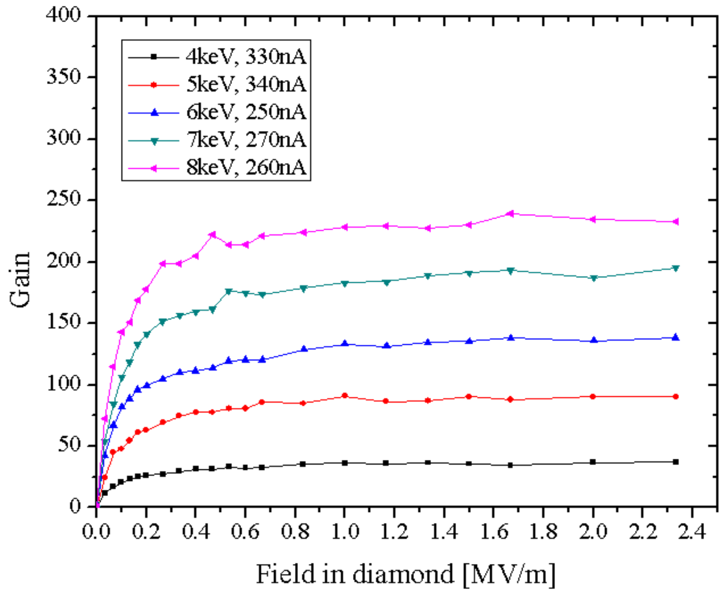


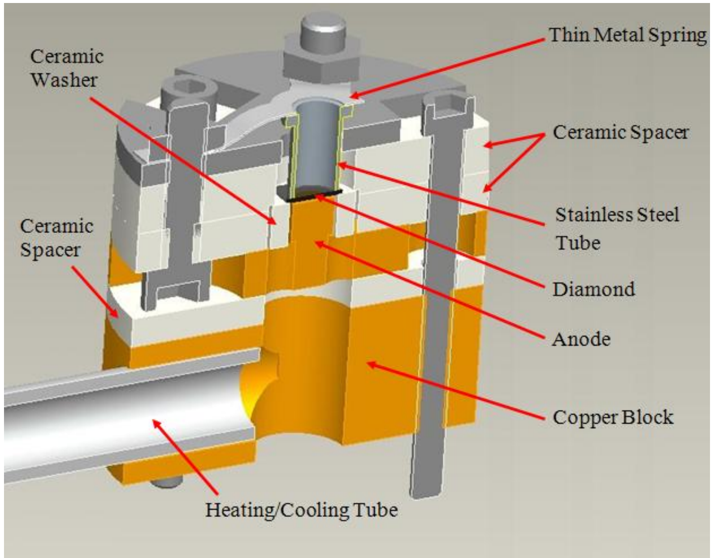


R (mm)	2.5	5	7.5
Primary power (W)	33	33	33
Secondary power (W)	40	40	40
RF power (W)	0.05	0.7	3.4
Replenishment power (W)	0.03	0.03	0.03
Total power (W)	74	74	77

Transmission Mode Measurement

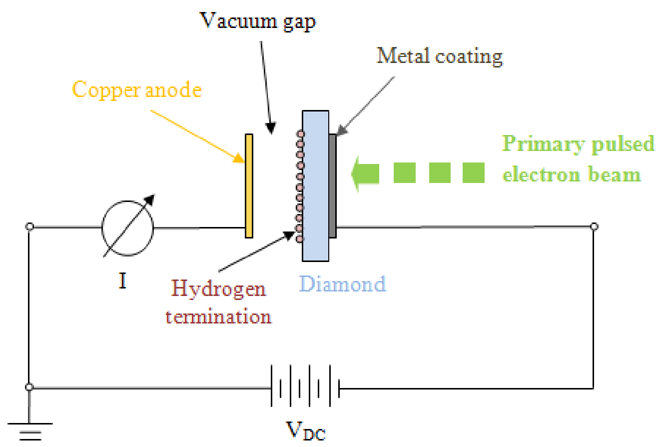






I. Single-crystal, high-purity, synthetic diamonds greatly reduce electron and hole trapping in the diamond's bulk.
II. Gain vs. field does not vary with the primary electron density.
III. The saturation gain is independent of temperature.
IV. Diamonds are very robust.
V. Can handle very large current densities (>100mA/mm^2).

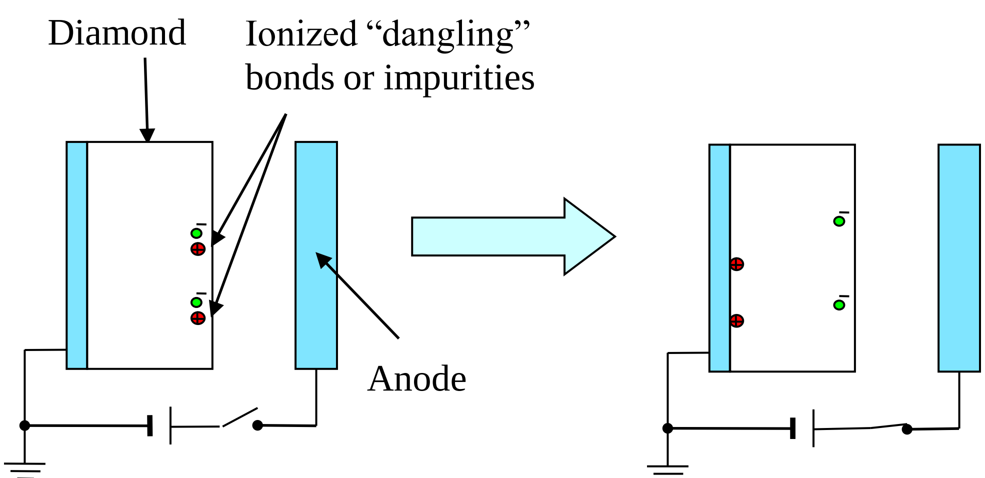
Emission Mode Measurement



A vacuum gap in between the copper anode and the hydrogenated diamond surface.

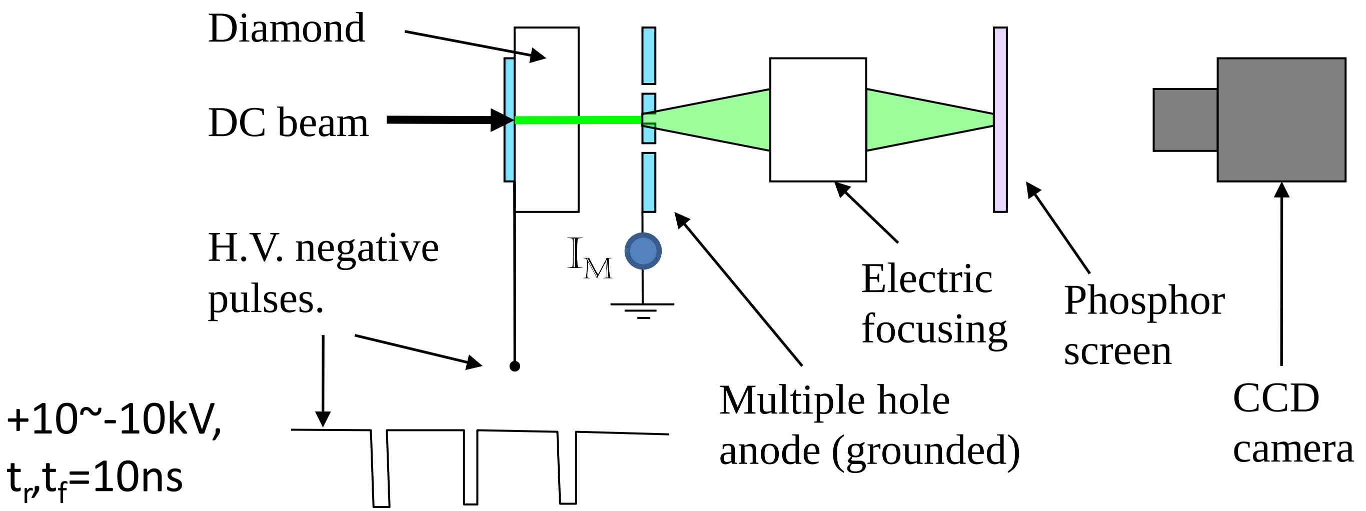
•DC voltage
•Pulsed beam

Poor emission result

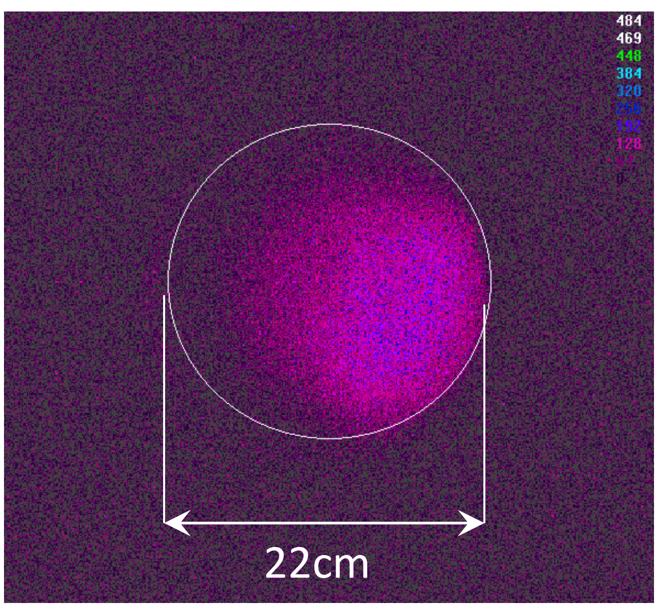


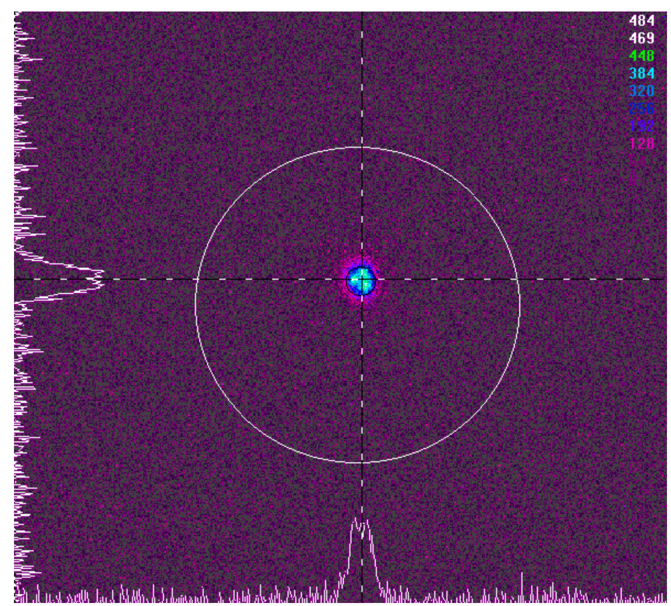
DC field shielding due to surface imperfection.

(ms scale)



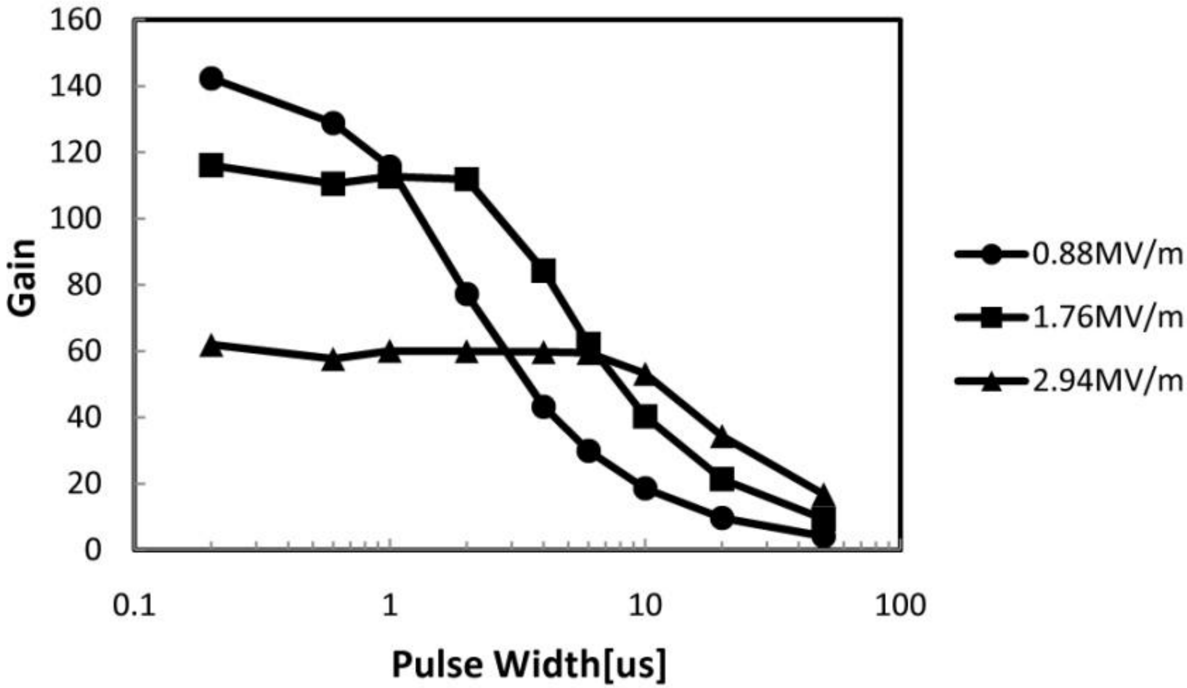
$$Gain = \frac{I_M}{I_P \times DutyCycle}$$





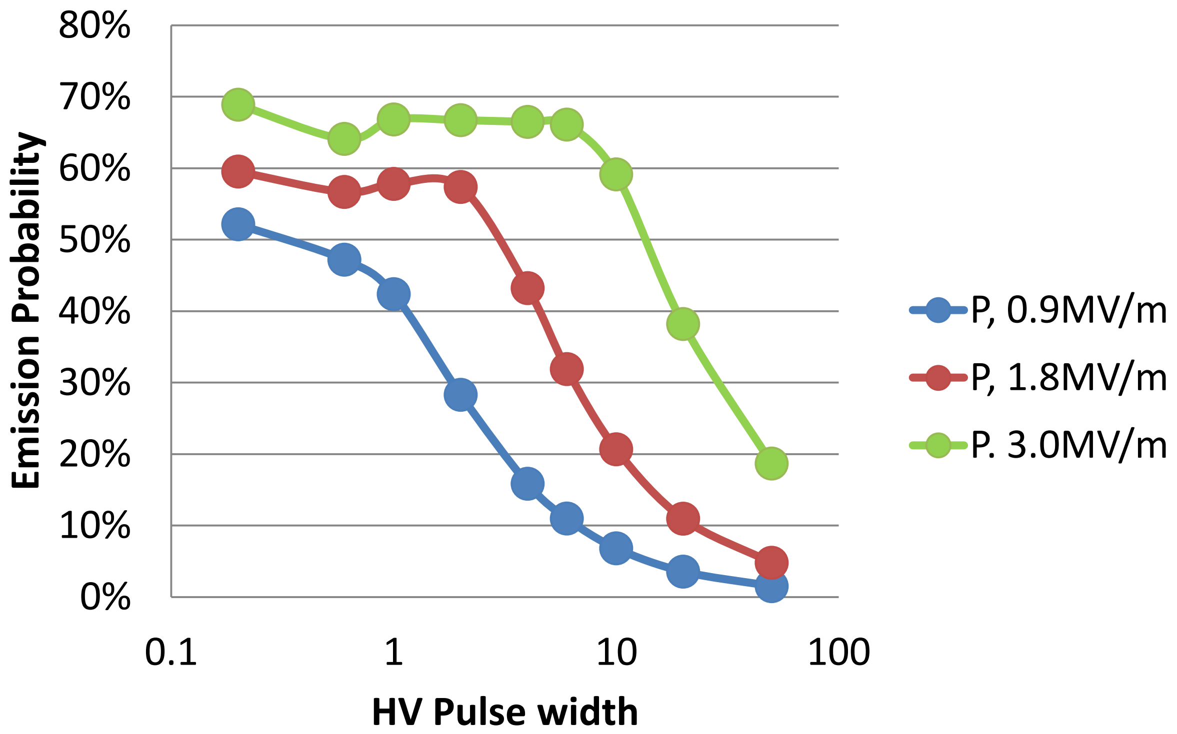
Important parameters

The hydrogenation system was later improved.



Maximum gain: 140

$$P_{Emission} = \frac{Gain_{Emission}}{Gain_{Transmission}}$$

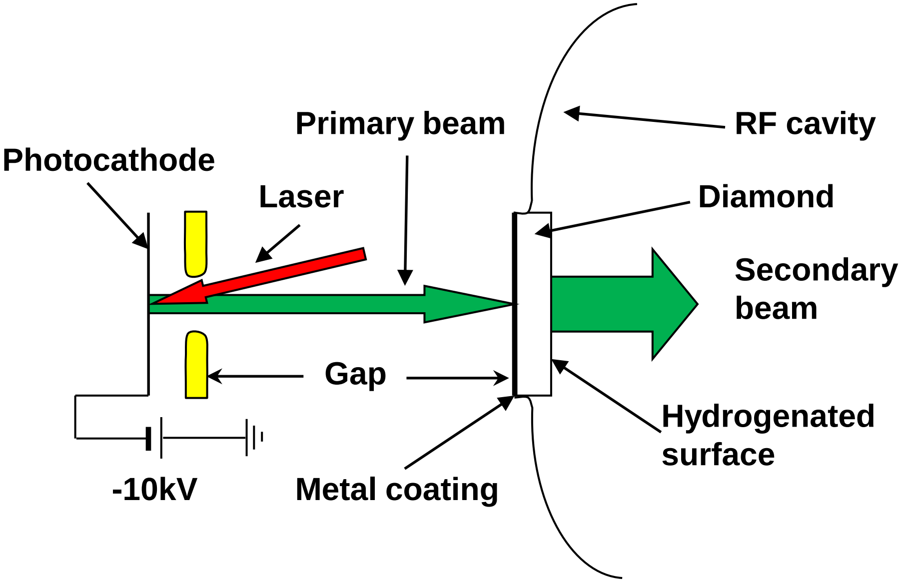


H-surface emission probability: 67%

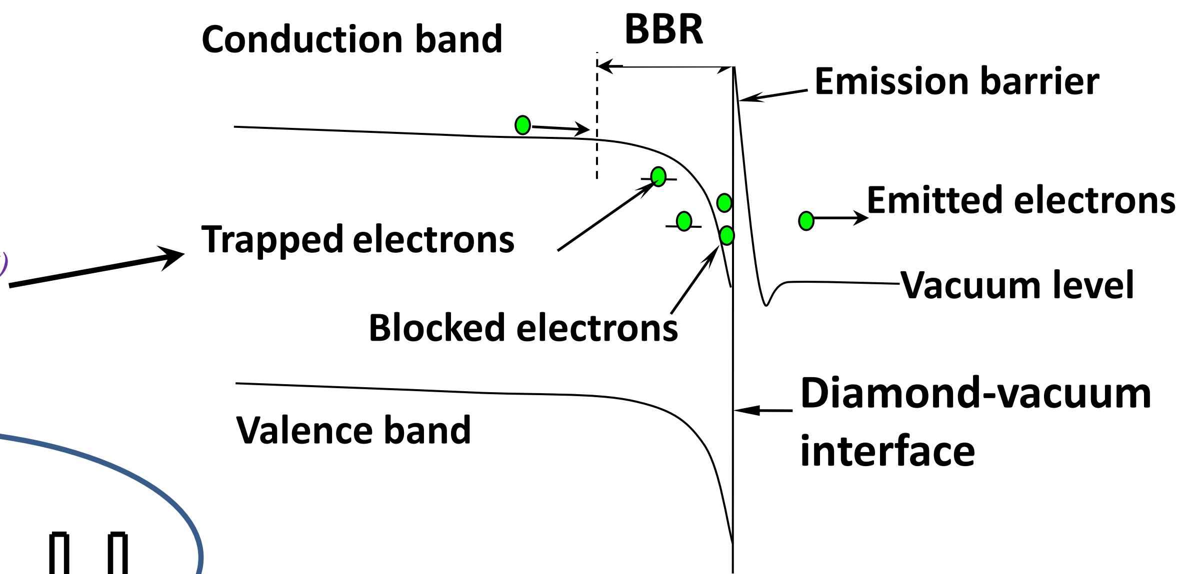
Maximum current density: 70 µA/mm^2
Maximum bunch-charge: 500 pC / mm^2
Extremely robust. Transport in air.

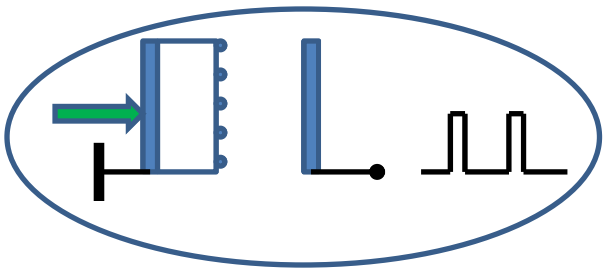
Emittance and RF cavity tests

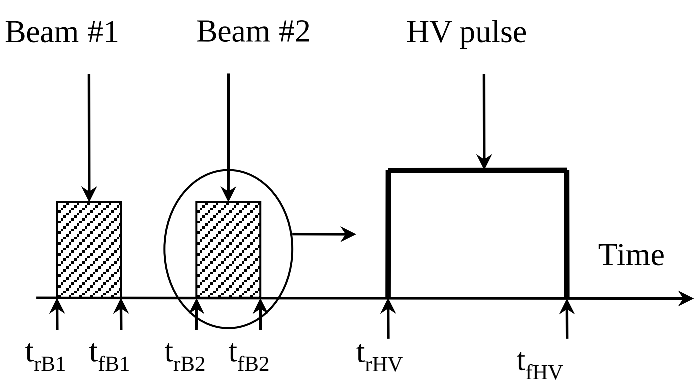
- The emittance measurement is being measured in our test setup. The thermal energy of the secondary electrons is estimated at about 0.1 eV.
- The RF cavity test will be done in a 112 MHz SRF cavity, with the following scheme.

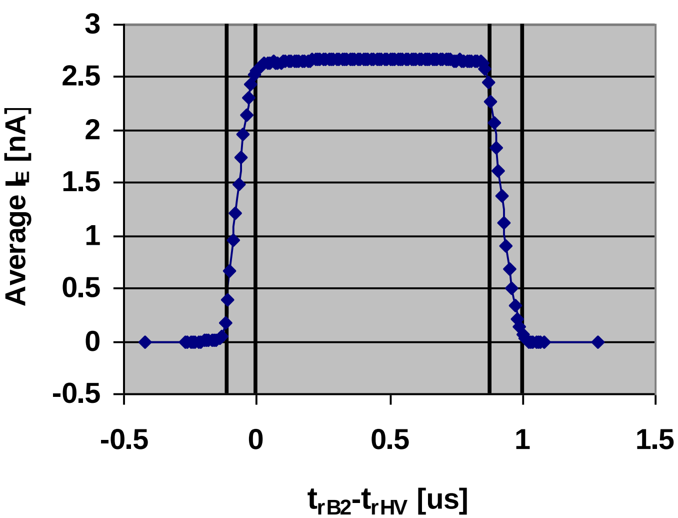


Detrapping of the H-surface trapped electrons



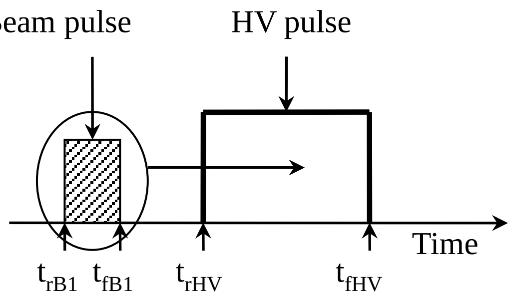


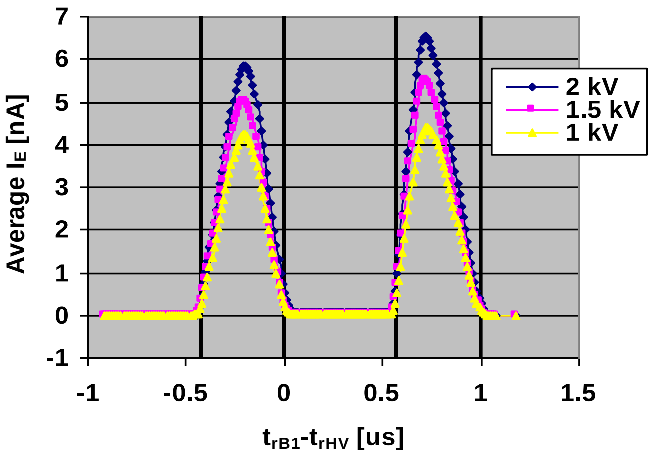


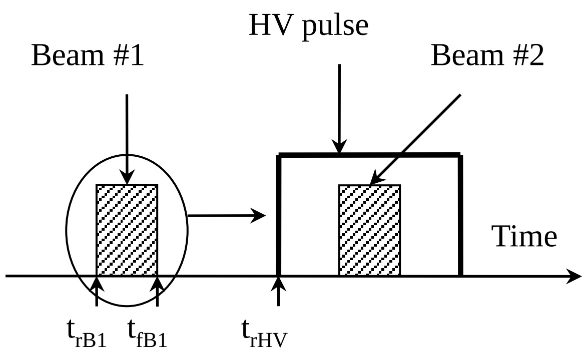


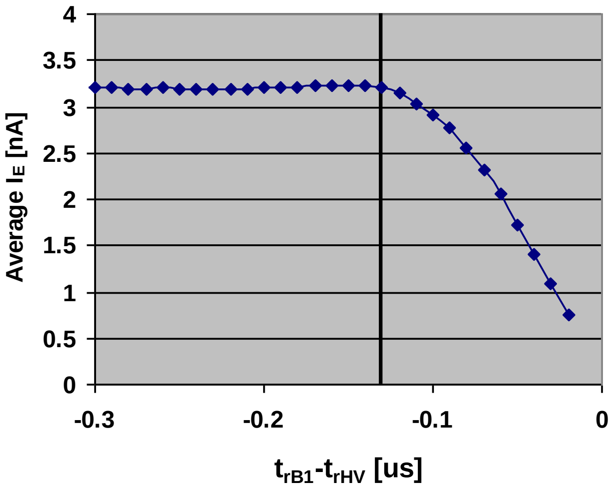
G_{top}=90

$\tau_{B1}=\tau_{B2}=0.1\ \mu s$, $\tau_{HV}=1\mu s$, $V_{HV}=1$ kV



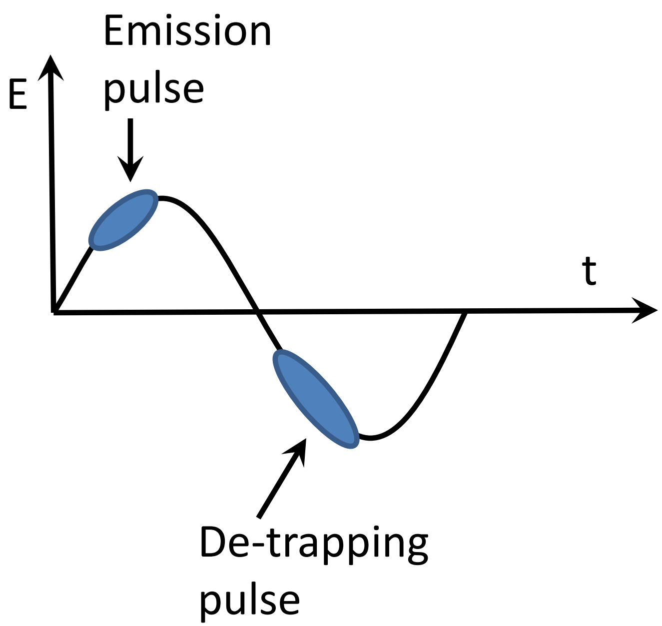


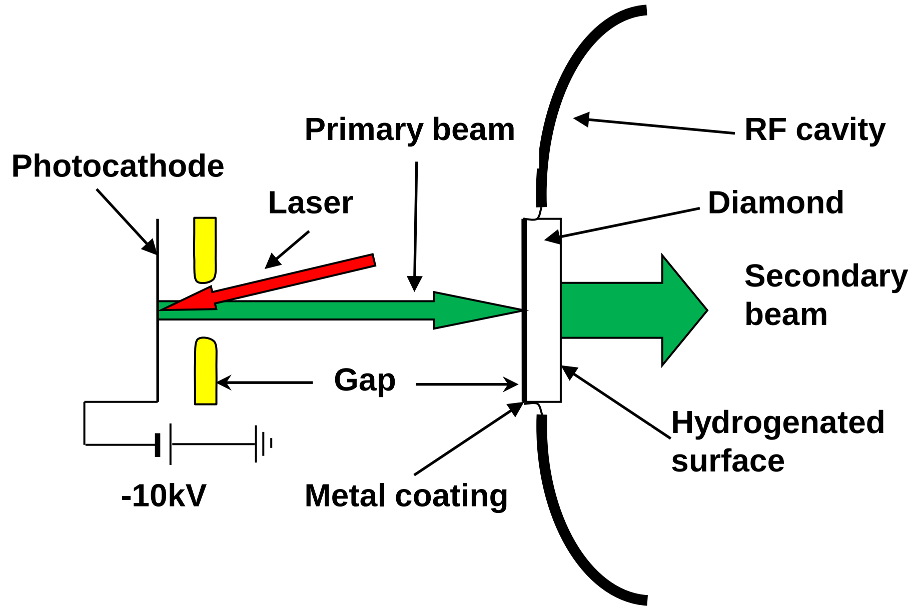




1. The stopped electrons are dominated by the trapped electrons.
2. Holes must be sent to H-surface to recombine with the trapped electrons.
3. The recombination of the trapped electron with hole is very fast. (ns scale or less)

De-trapping approaches



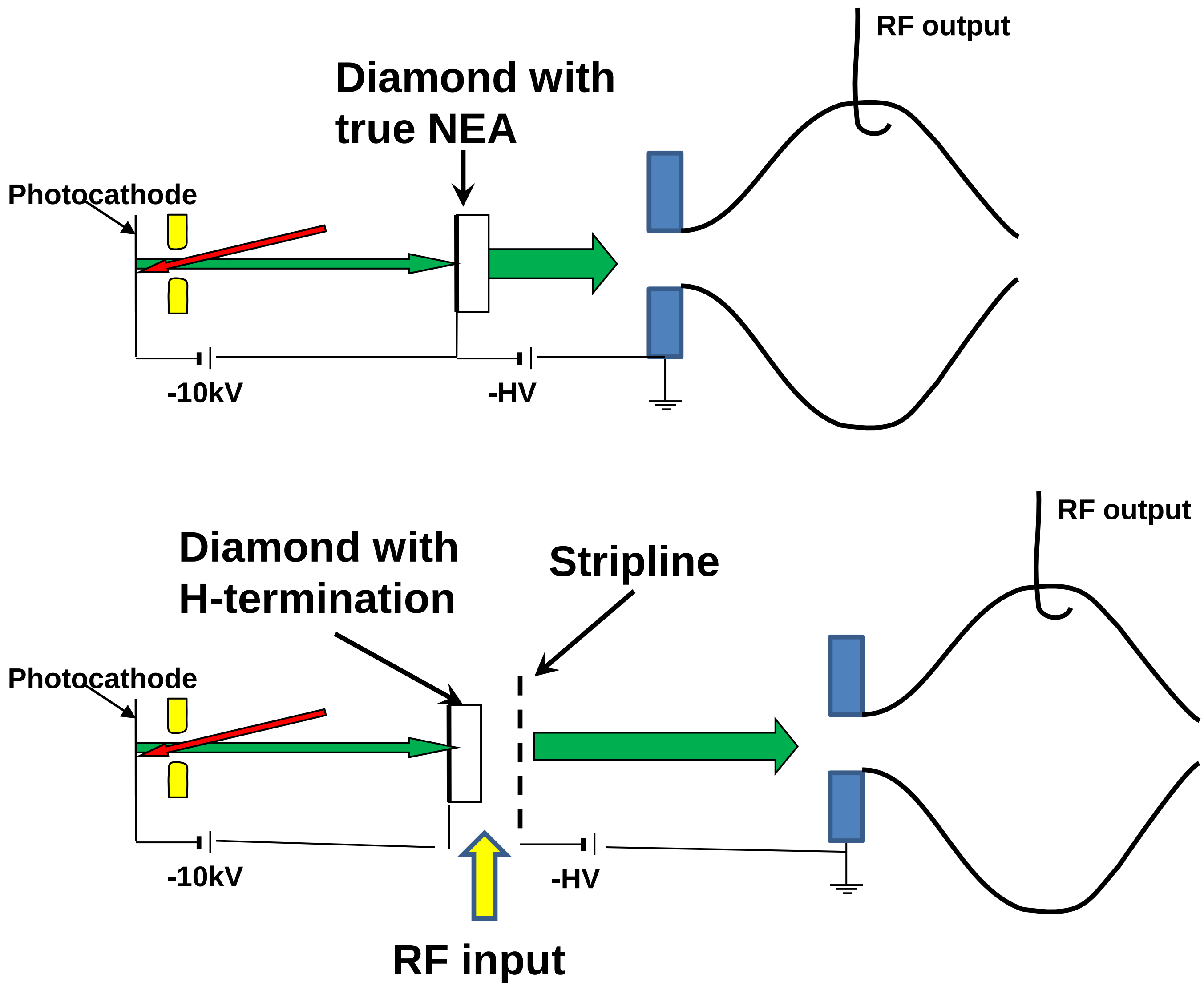


- Sending de-trapping primary beam in the electron decelerating phase.
- Ohmic contact on the M-surface. More heat.
- Other alkali element termination, such as Li. Possibly true NEA, may be used in DC gun. As much robust as H-termination or better.

Possible applications

- **The high average-current, high brightness electron beams with long lifetime can be used in:**
  - **Electron cooling of hadron accelerators**
  - **Energy-Recovery Linac (ERL) light sources**
  - **Ultra-high-power Free-Electron Lasers (FELs)**
  - **High efficiency RF power sources**
  - **Many others**

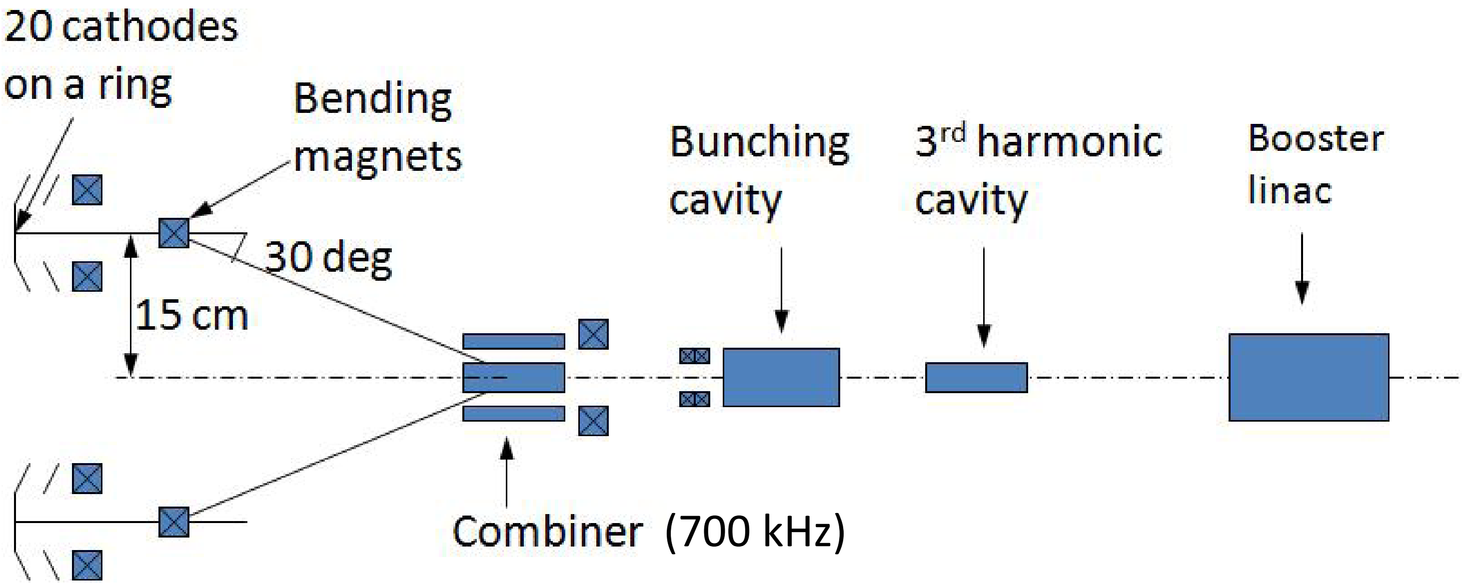
Possible application in high efficiency Klystron



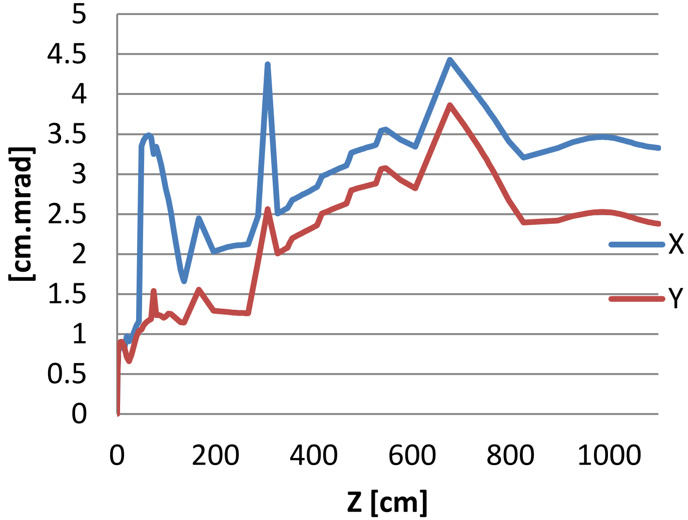
Multiple-Cathode (Gatling Gun) system

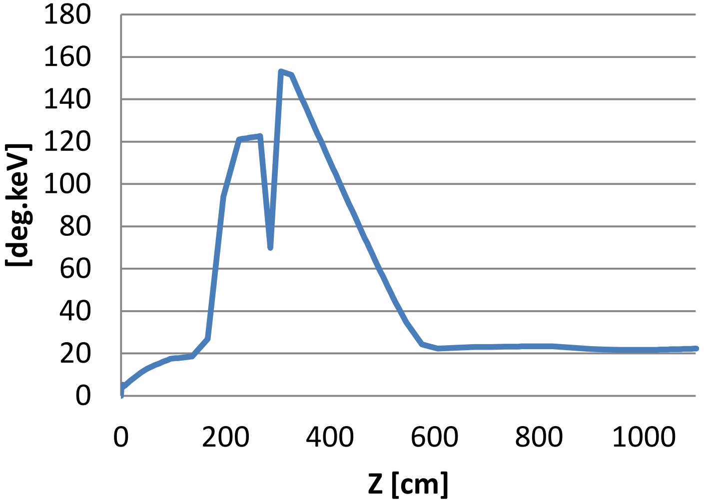
The eRHIC project requires a polarized electron source with:

- *High average current (~50 mA), state-of-art: a few mA.*
- *Bunch charge of 3.5 nC, repetition frequency of 14 MHz.*
- *Short bunch (~3 mm) at 10MeV.*
- *Small normalized emittance of 20 ~ 40 μm.*
- *Energy spread of ~1% at 10 MeV.*



2D simulation results





2D results:

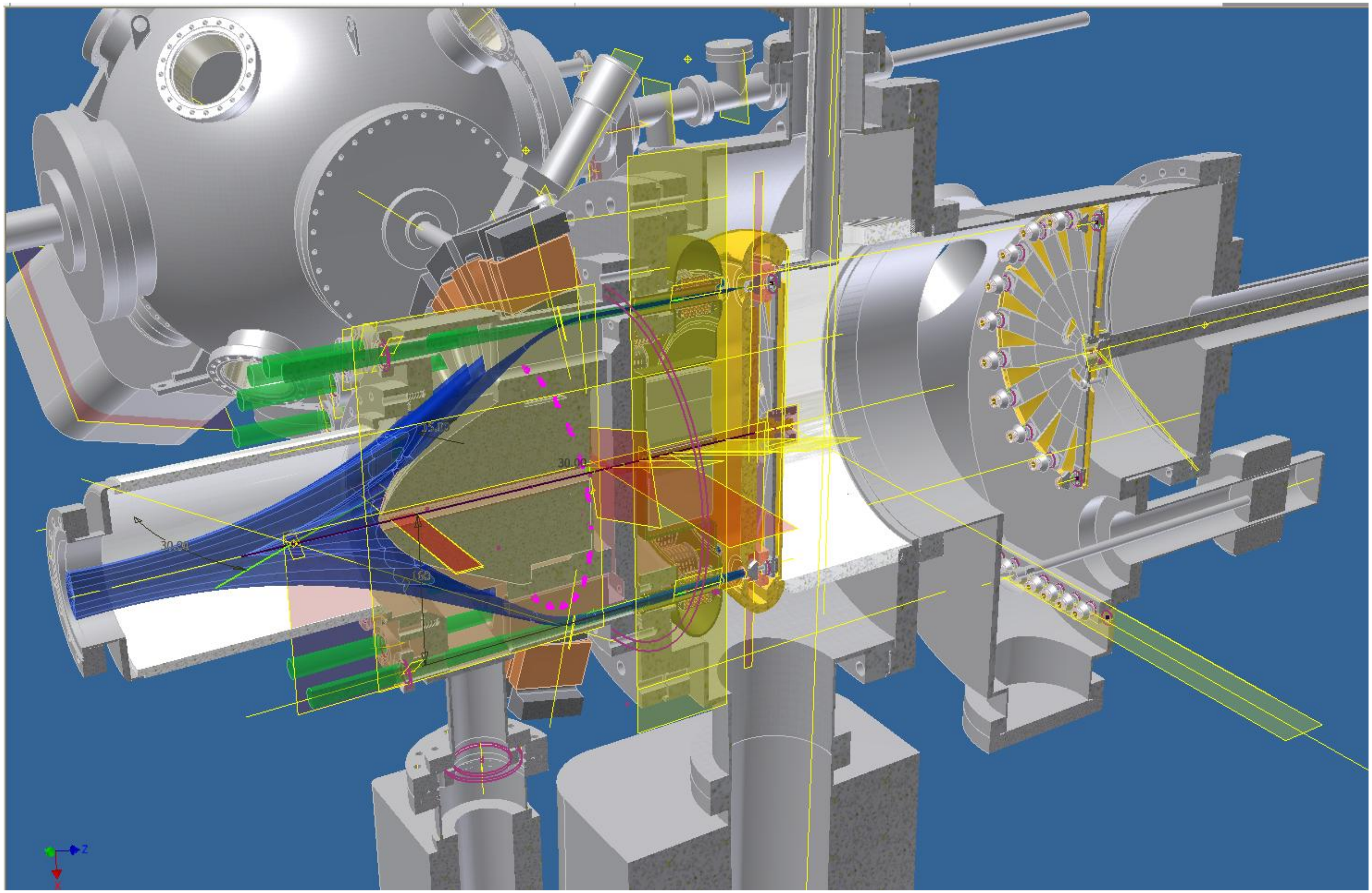
ε_X =33 mm.mrad

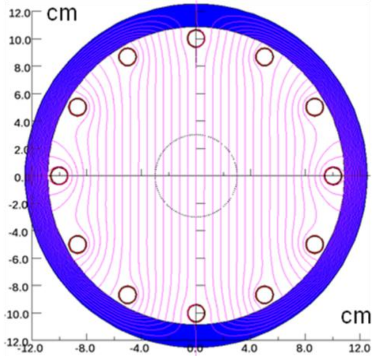
ε_Y =23 mm.mrad

ε_Z =22 mm.mrad

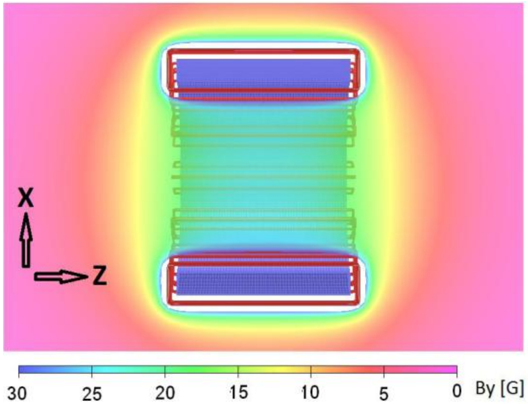
σ_Z=5.3 mm @ 10 MeV (can be 2 mm)

Sectioned View of GGun, From left, Green –indicate Laser, Blue-indicate electron beam paths. Near center is the cathode shroud and anode, and to the right is the cathode magazine.

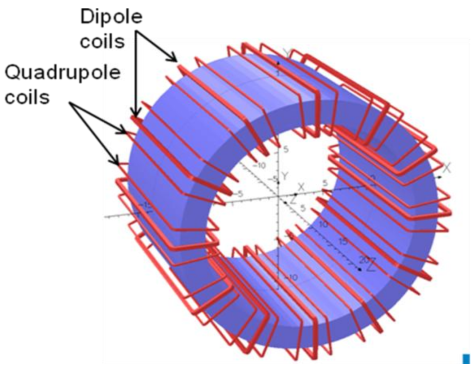




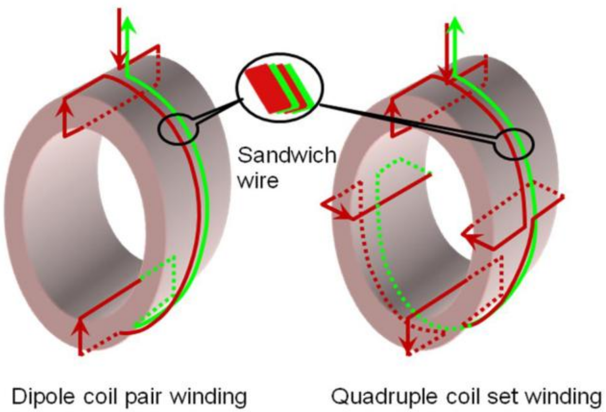
$R_{good\ field}$ ($B_{sextupole} < 5 \times 10^{-4}$) > 3cm



Bending Field on cross-section

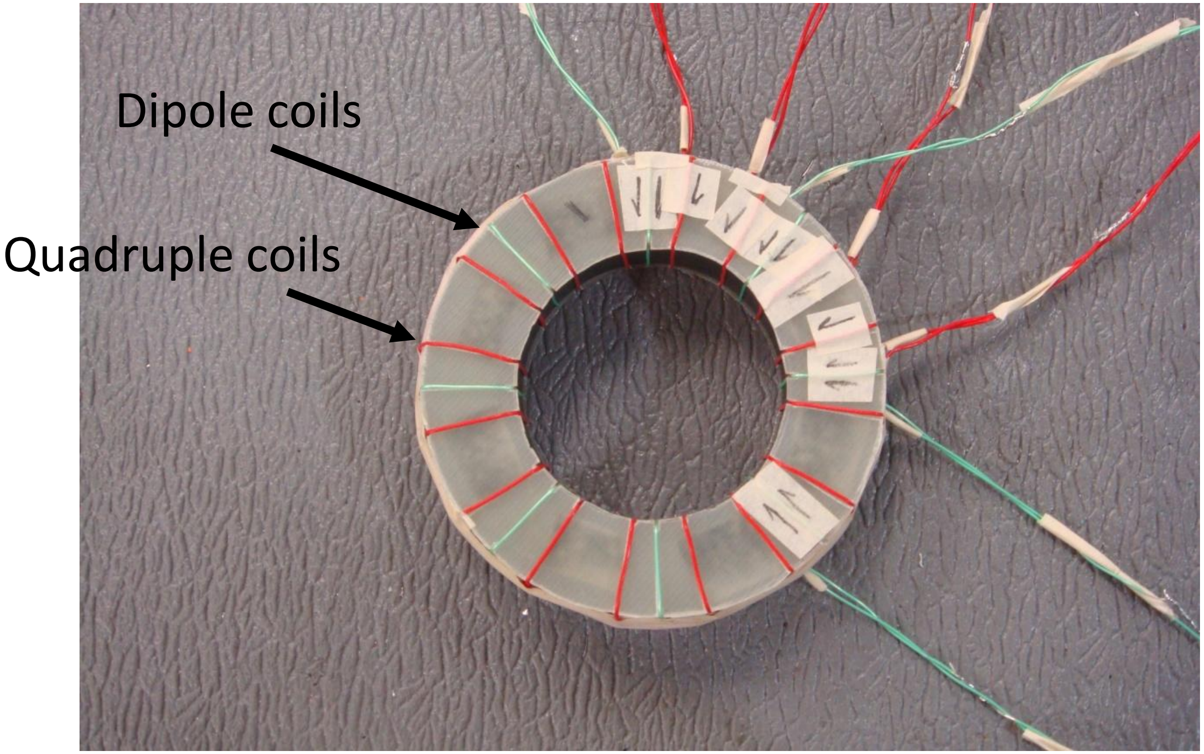


Combiner with dipole and quadrupole coils



Dipole and quadrupole windings

The peak dipole current on each dipole coil is 135.5 A to bend the 200 kV beam by 30°. The total power loss in dipole coils is about 600 W. A water cooled coil can easily handle this power density. The peak quadrupole current on each quadrupole coil is 2.4 A (power is negligible) to keep the beam round during bending.



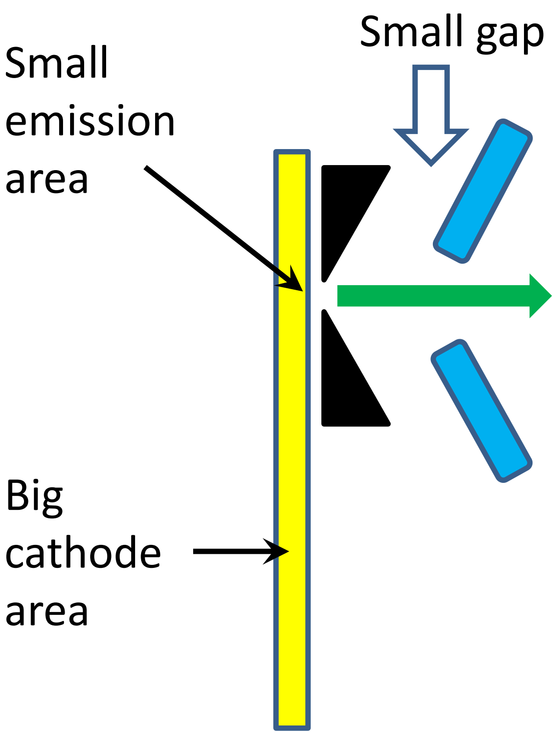
Simple Combiner prototype

Tests based on the simple combiner prototype proved that the dipole and quadrupole fields are independent. The radius of the range with constant dipole field (within the measurement error) is larger than 60% of the core for a 4 sets coils winding.

Challenges of the Gatling gun

- How to achieve and maintain the ultra-high vacuum in the whole system with so many insertions?
- Can the cathode plate holds up 200 kV voltage?
- How to minimize the outgassing of the wall due to the electron beam?
- How to minimize the emittance growth due to the combining mechanism?
- Are the operation of each cathode independent each other?

Another possible approach obtaining high-current, long-lifetime polarized beam



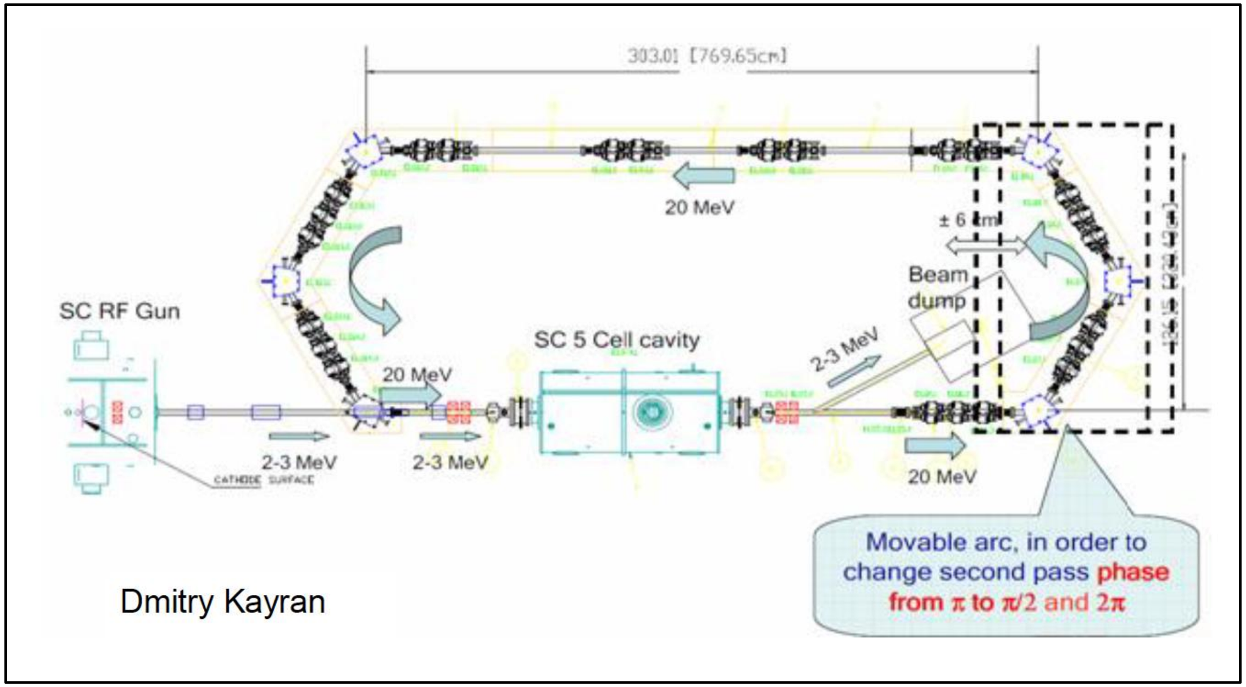
Advantages of this type of cathode:

1. High field gradient with low voltage. High current density.
2. High beam quality due to small emission area, on-axis beam, many optical options on transport line.
3. Effectively very long lifetime due to the large cathode area, the masking technique, and less degassing from the beam.
4. Overcome the local heating problem. Temperature rise gradient is ~ a few deg / second.

Overview of SRF projects

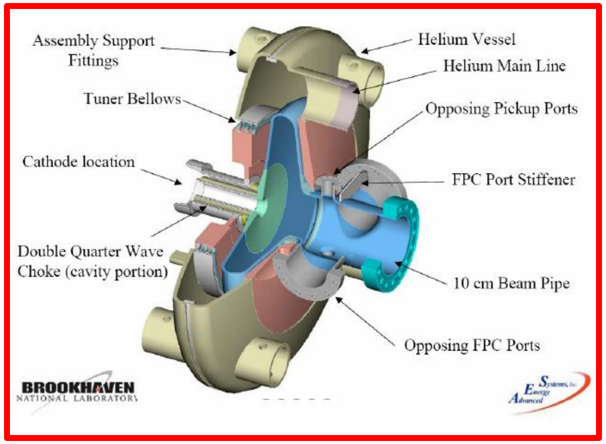
- Superconducting RF R&D activities at Collider-Accelerator Department are directed toward: 1) improving performance of RHIC, 2) developing technologies related to eRHIC, 3) developing high-current, high-bunch charge ERLs, 4) international collaborations (LHC, SPL).
- Energy Recovery Linac (ERL) prototype uses 704 MHz SRF gun* and 5-cell HOM-damped linac cavity*.
- 56 MHz quarter wave resonator (QWR)* serving as a storage cavity for RHIC.
- 112 MHz QWR SRF gun* for photocathode (multi-alkali and diamond amplified) development and Coherent electron Cooling Proof-of-Principle (CeC PoP) experiment.
- Five-cell 704 MHz BNL3 cavity for future applications such as eRHIC and SPL.
- 28 MHz QW accelerating cavity for RHIC.
- QW crab cavities for eRHIC and LHC.
- Small half-cell 1.3 GHz GaAs photocathode SRF gun* for production of polarized electron beams.

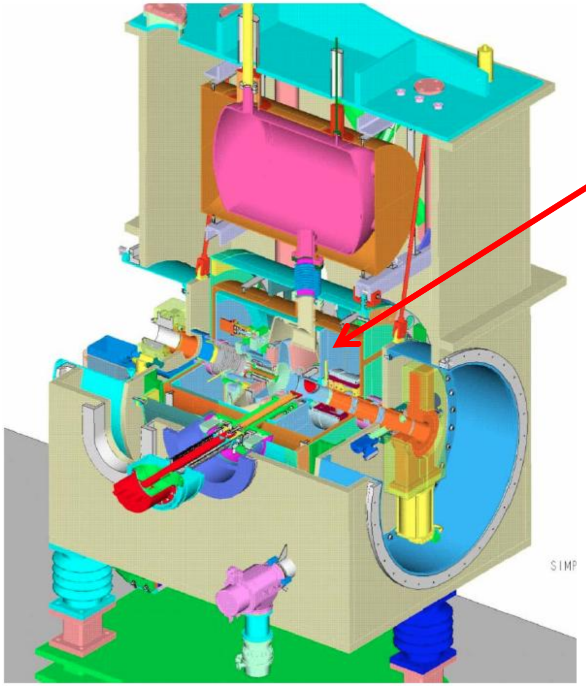
by courtesy of Sergey Belomestnykh



- The Energy Recovery Linac (ERL) is a small prototype to develop technologies relevant for future applications (eRHIC):
  i. high average current (up to 0.5 A) SRF electron gun
  ii. high charge per bunch (5 nC) SRF electron gun
  iii. photocathodes (multi-alkali) and lasers capable to produce high-intensity beams
  iv. high-performance HOM-damped SRF cavities for ERL
  v. beam optics and instrumentation
  vi. study beam dynamics and emittance preservation techniques in ERL
- SRF cavities operate at 704 MHz.
- This project is funded mostly by Navy
- The first beam is anticipated by the end of 2011.

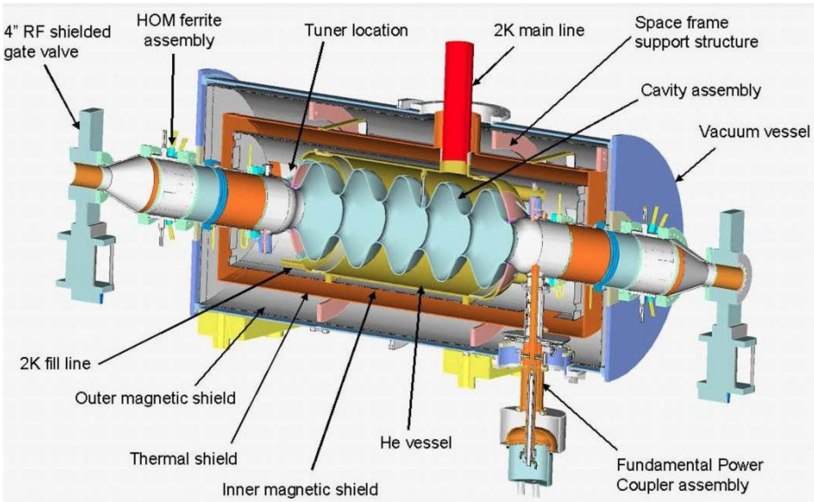
704 MHz SRF gun for ERL



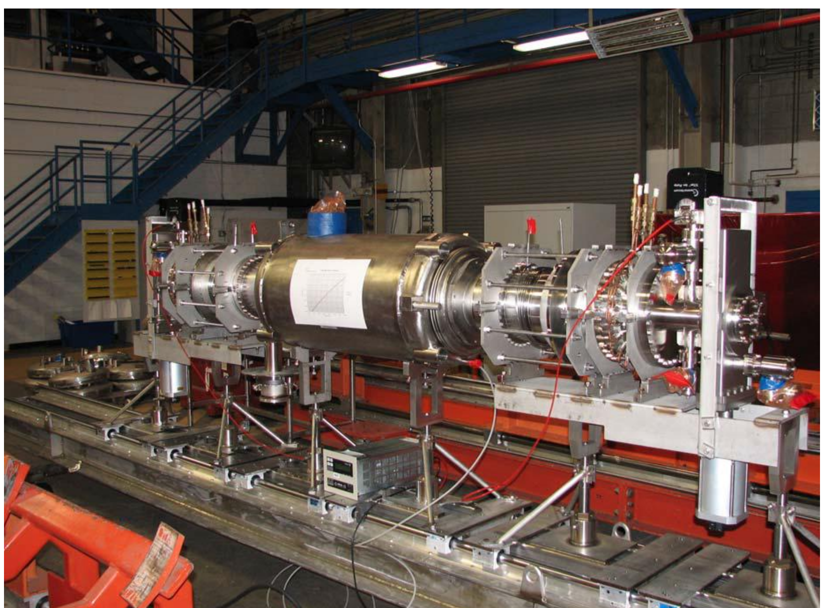


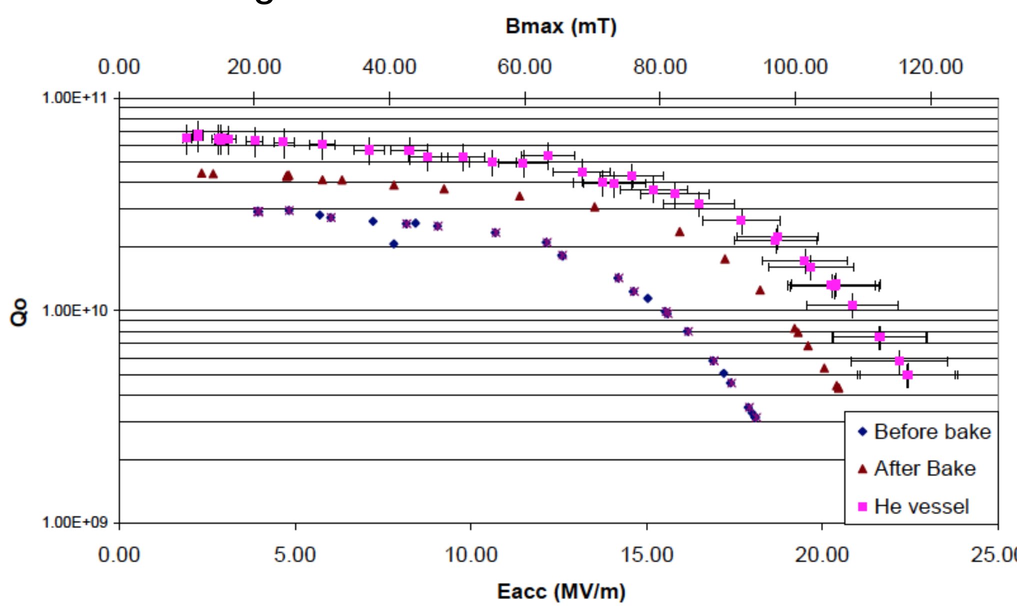
- The 704 half-cell SRF gun has two Fundamental input Power Couplers (FPCs) allowing to deliver 1 MW of RF power to 0.5 A electron beam.
- HOM damping is provided by an external beamline ferrite load with ceramic break.
- The gun and its cryomodule were designed and fabricated by AES.
- FPCs are manufactures by CPI/Beverly.
- The gun cavity was tested in a vertical cryostat last year.
- The plan is to finish the cryomodule assembly in Oct. of 2011, following by the gun installation in ERL and cold test.

704 MHz five-cell BNL1 cavity for ERL

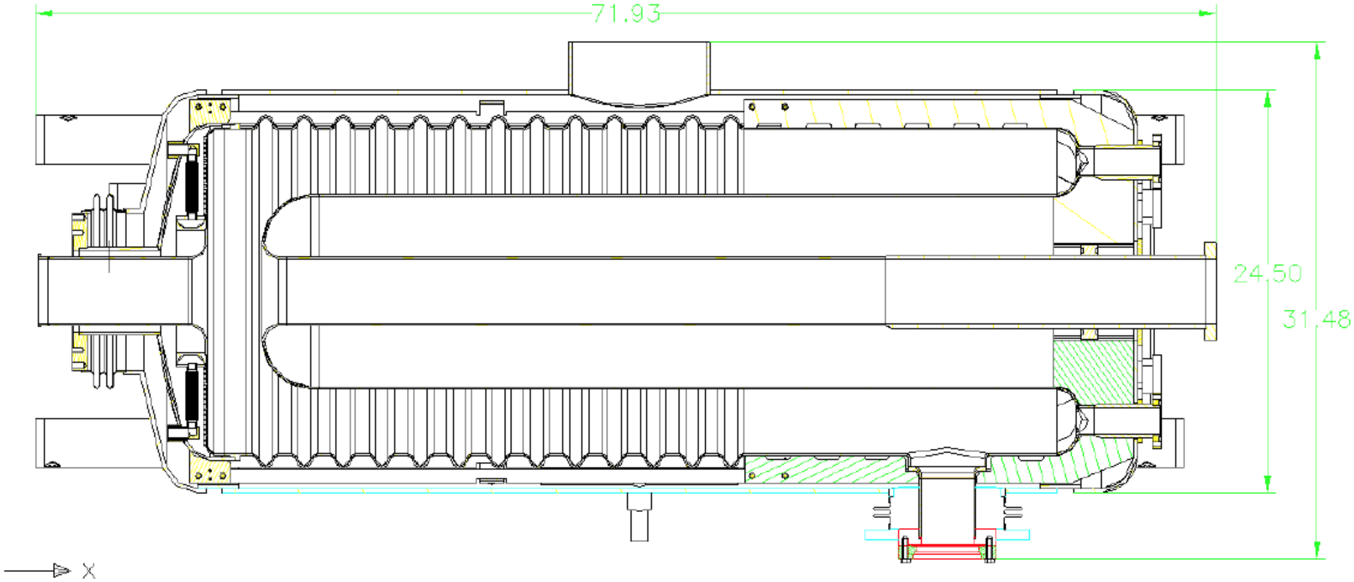


- 704 MHz BNL1 cavity shape was optimized for HOM damping by beamline ferrite loads located outside the cryomodule.
- The five-cell cavity and cryomodule were fabricated by AES.
- The cavity demonstrated excellent performance in vertical tests.
- The cryomodule has been tested and is awaiting beam.



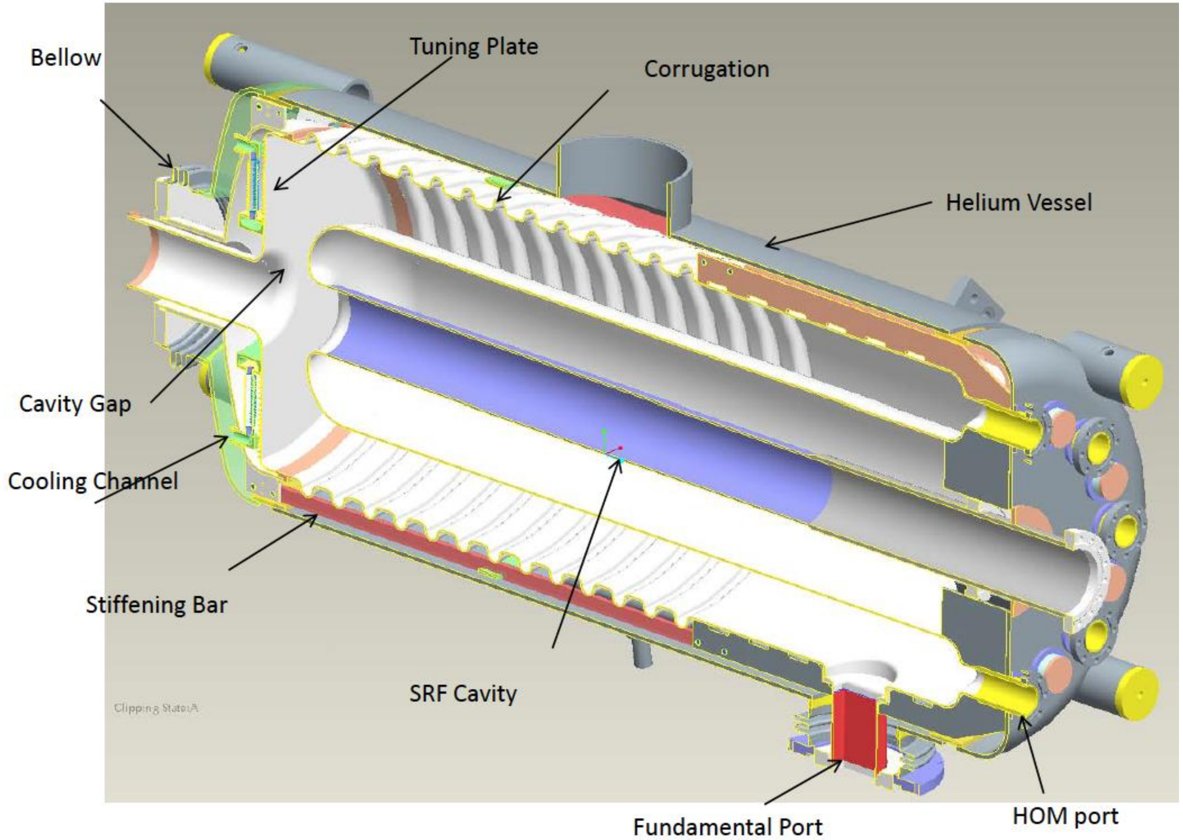


56 MHz storage cavity for RHIC



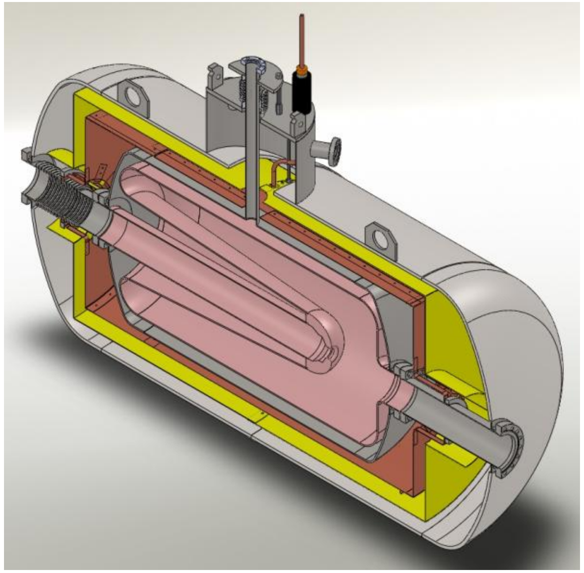
- The purpose of this QWR is to provide a larger RF bucket (5 times larger than that of 197 MHz cavities) for particles, which should result in higher luminosity of RHIC by: direct adiabatic capture from 28 MHz system, better preservation of longitudinal emittance, elimination beam spillage in satellite buckets, improving luminosity by allowing shorter beat function at the IP.
- This is a “storage” cavity, that is it does not have large tuning range to follow the large frequency change during acceleration from injection energy to energy of experiment and is turned on only after that for re-bucketing.
- One 56 MHz cavity will serve both RHIC rings. It will be the first superconducting RF system in RHIC.

56 MHz storage cavity for RHIC (2)



- The cavity is funded as an Accelerator Improvement Project (AIP).
- Presently the project is at the end of the design phase / beginning of the fabrication phase.
- The cavity is already on order from Niowave, Inc. The expected delivery date is Oct. 30th, 2011.
- The cryomodule is designed to be compliant with the ASME Pressure Vessel Code.
- The cryomodule and axillary components (FPC, HOM couplers, fundamental damper) will go out for bids soon.
- The cavity will be processed at the joint BNL/AES BCP and HPR facility.
- Clean room assembly will be at BNL.
- The goal is to install it in RHIC for operations in 2013.

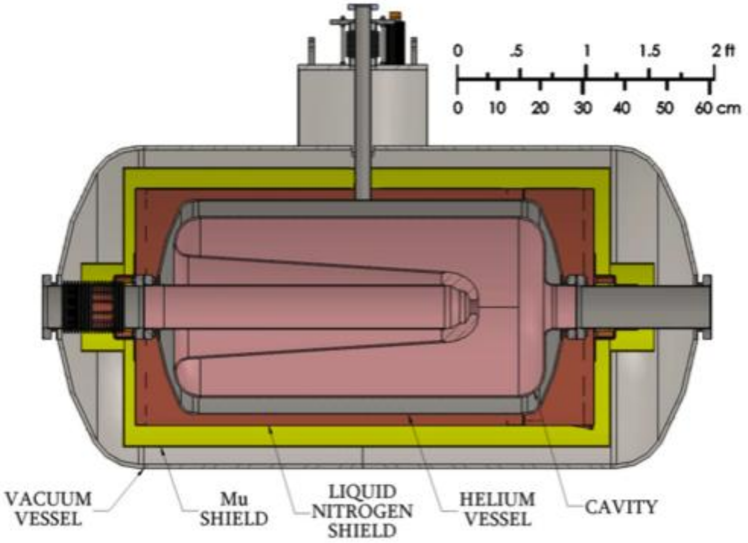
112 MHz QWR SRF gun

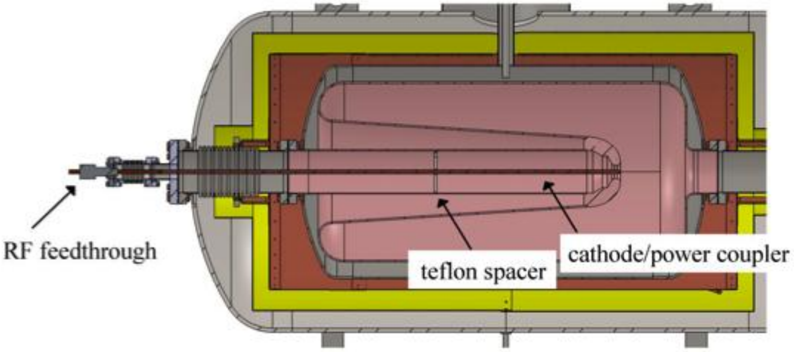


- Superconducting 112 MHz QWR was developed for electron gun experiments by collaborative efforts of BNL and Niowave, Inc..
- Design, fabrication, chemical etching, cleaning, assembly and the first cold test were done within the framework of DOE SBIR program.
- Why 112 MHz?
  - ✧ Low frequency: long bunches ➔ reduced space charge effect.
  - ✧ Short accelerating gap: accelerating field is almost constant.
  - ✧ Superconducting cavity: suitable for CW, high average current beams.
  - ✧ Cathode does not have to be mechanically connected to SRF structure: flexibility in cathode types.
  - ✧ Simulated emittance of ~3 mm×mrad at 2.7 MeV

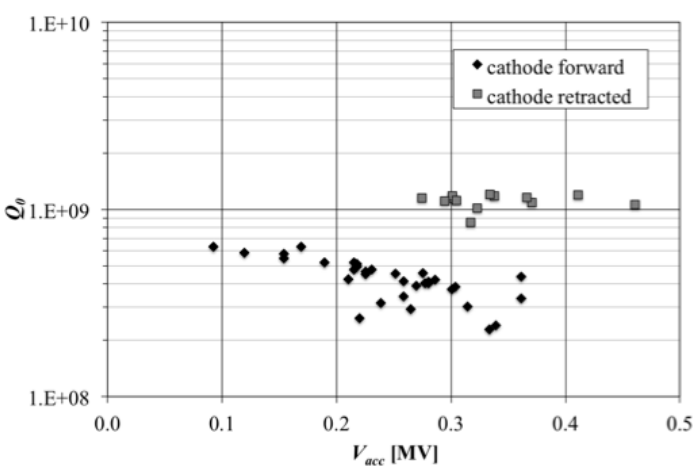
112 MHz cryomodule features

- Cryomodule features:
  - ✧ Nb quarter wave cavity
  - ✧ Stainless steel helium vessel
  - ✧ Superinsulation
  - ✧ LN2 thermal shield
  - ✧ Magnetic shield
  - ✧ Low carbon steel vacuum vessel
- Simple copper rod was used as a combined-function cathode/power coupler.



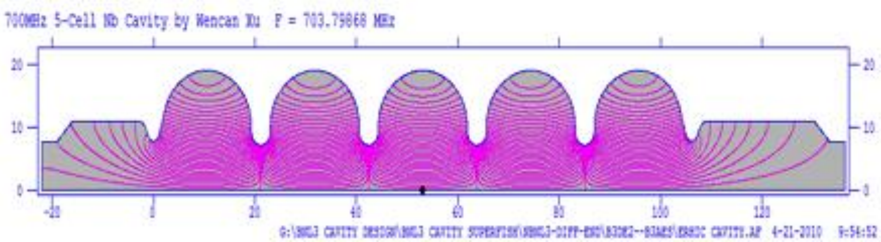


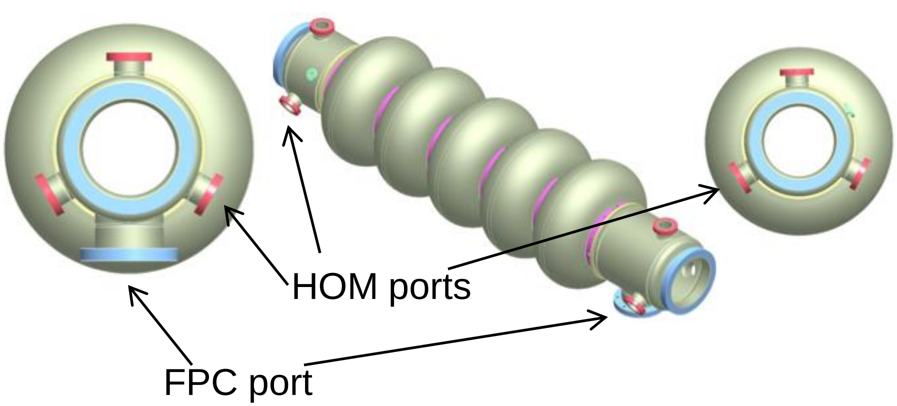
112 MHz SRF gun cold test & plans



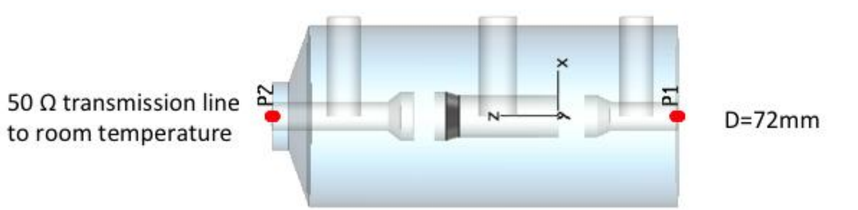
- First cold test was successfully performed at Niowave, Inc. in December of 2010.
- This gun is now a baseline option electron gun for the Coherent electron Cooling Proof-of-Principle (CeC PoP) experiment at BNL, which is funded by DOE, now in preparation phase. The experiment is scheduled for FY2013/FY2014.
- For CeC PoP, the gun will require some hardware upgrade/modification.
- Also, we are applying for funding to study different photocathodes using this gun.

Five-cell 704 MHz BNL3 cavity



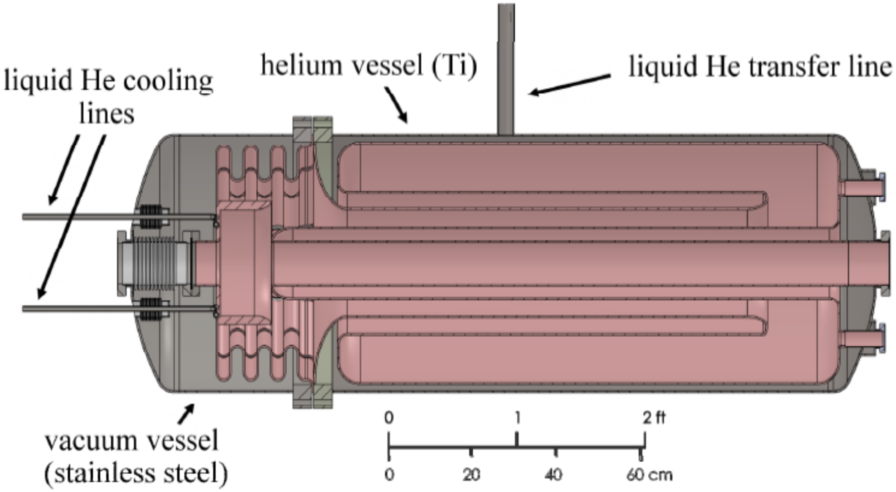


High-pass filter of the HOM coupler



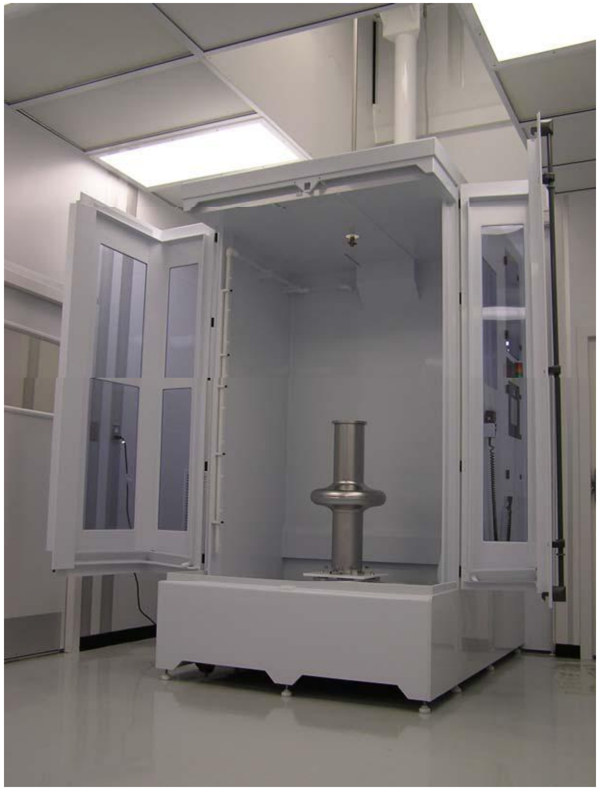
- This is a high-beam-current five-cell cavity with new scheme of HOM damping.
- The cavity development is supported by DOE as contribution to SPL at CERN.
- AES is doing mechanical design and fabrication of copper prototype and niobium cavity.
- Our aspirations are to make the cavity “universal” enough to be considered for other projects, in particular eRHIC and ESS.
- It has an optimized geometry for fundamental mode as well as HOMs.
- Three HOM couplers at each beam pipe provide very efficient HOM damping.
- The copper model should be ready in Sept., the niobium cavity – early next year.
- Further plans include HOM studies, vertical testing, designing a cryomodule.

28 MHz QW accelerating cavity for RHIC



- This cavity has unique, “folded” QWR geometry, providing compactness.
- If successful, it will be the lowest frequency SRF cavity in operation.
- Advantages:
  - ✧ one SRF cavity will replace two normal conducting 28 MHz cavities – reduced number of cavities
  - ✧ QWR geometry is smaller, hence fewer number of HOMs – reduced effective beam impedance
  - ✧ Reduced RF & AC power requirements
  - ✧ LHe is readily available in RHIC tunnel
- Challenges:
  - ✧ large (200 kHz or 1% of operating frequency) tuning range
  - ✧ complicated cavity shape
- Funded by DOE’s SBR grant to Niowave, Inc. Now in the first year of Phase II.

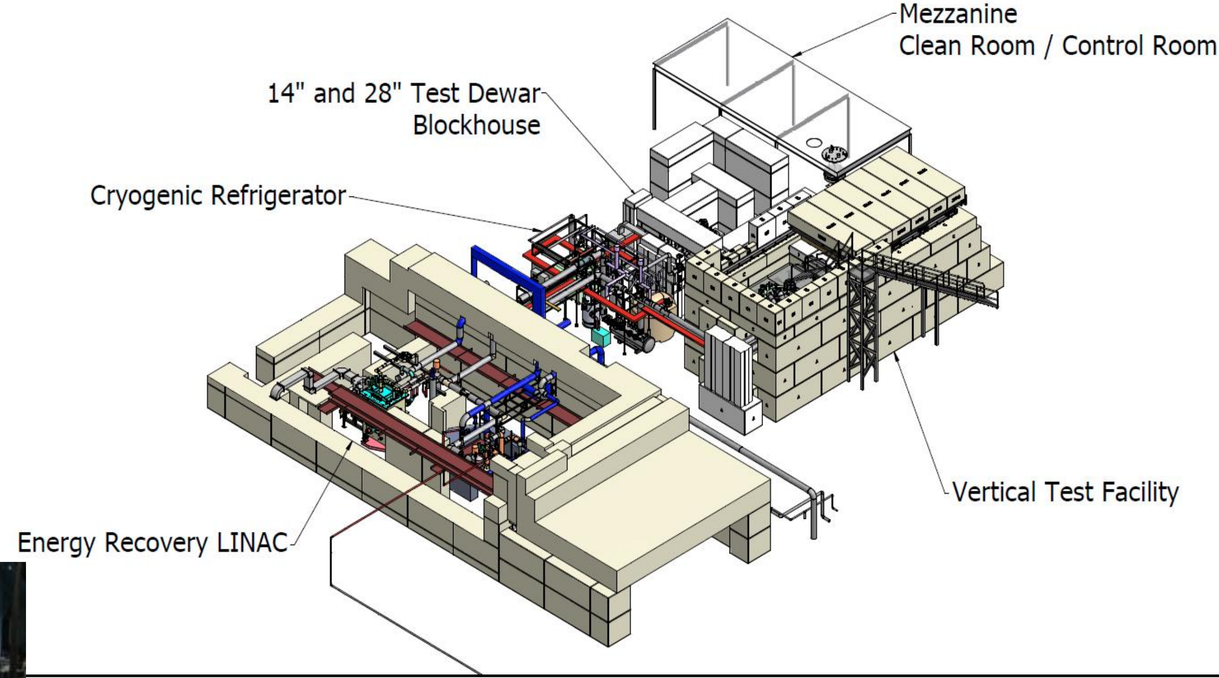
SRF facilities for cavity processing



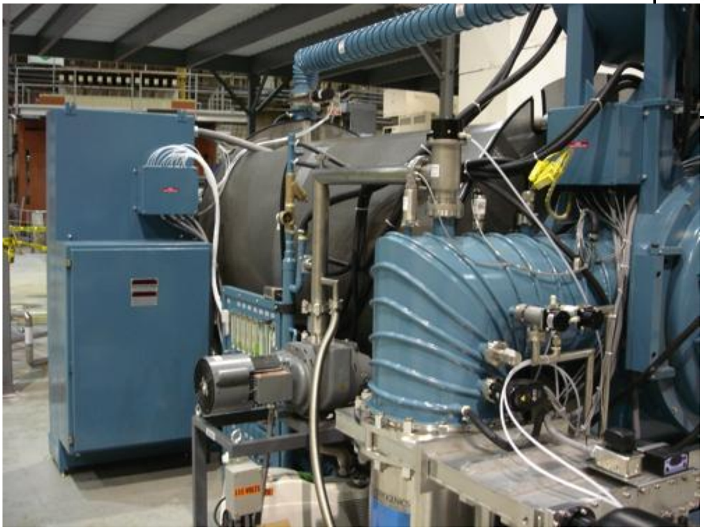
- To achieve good performance, preparation of the SRF cavities involves several important steps:
  - ✧ The cavity surface must be free of manufacturing defects. Usually about 150 μm of material is etched out by Buffered Chemical Polish (BCP) process to remove the damaged layer.
  - ✧ Any residual particulate contamination is removed by High Pressure water Rinsing (HPR).
  - ✧ All subsequent cavity preparations are done in Class 100 or better clean room environment to facilitate particulate-free assembly.
- For the first two steps, we have built a joint BNL/AES facility at AES.
- At C-AD, we have a Vertical Test Facility (VTF), allowing us clean preparation of the cavities for vertical tests, baking the cavities in a 800°C vacuum oven, and performance testing in vertical dewars coupled with a dedicated refrigeration system.
- The whole complex of the testing facilities in Building 912 is now in its final phase of construction/commissioning.

SRF facilities at C-AD

Layout of Accelerator R&D Facility in Building 912



800°C vacuum oven for cavity baking



Summary

- It has been demonstrated experimentally that the DAP is a strong candidate for high-current, high-brightness, long lifetime cathode. It has many potential important applications.
- The "Gatling gun" multi-cathode system can possibly raise the beam current beyond the state-of-art current. It is especially important for the polarized beam. But this technique has many challenges.
- The status of the BNL SRF cavities has been introduced.

Thank you!

Electron injector systems been designed and studies

- “Gatling gun” injector system.
- DC electron cooling system for the RHIC Low Energy e-cooling.
- CEC electron beam injector.
- 112 MHz SRF cavity beam line.
- RHIC e-cooling injector employing SRF cavities.
- RHIC e-cooling injector employing normal conducting RF cavities.
- BNL ERL beam line.
- A compact SRF gun and booster linac system for emittance compensation study.
- Studied the photo-cathode RF gun system of the Accelerator Test Facility at BNL.
- …

Patent

United States Patent #: 7227297, entitled “Secondary emission electron gun using external primaries”

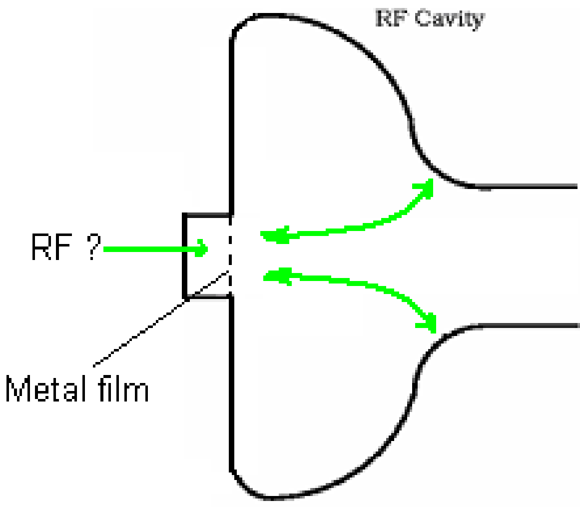
Publication list

1. X. Chang, I. Ben-Zvi, A. Burrill, et al., “Electron beam emission from a Diamond-Amplifier Cathode”, Phys. Rev. Lett. 105, 164801 (2010).
2. X. Chang, Ilan Ben-Zvi, Jörg Kewisch, “Emittance compensation of compact superconducting guns and booster linac”, Phys. Rev. ST Accel. Beams, 9, 044201 (2006).
3. I. Ben-Zvi, X. Chang, V. Litvinenko, et al., “Generating high-frequency, rotating magnetic fields with low harmonic content”, Phys. Rev. ST Accel. Beams, 14, 092001 (2011)
4. E. Wang, I. Ben-Zvi, X. Chang, et al., “Systematic study of hydrogenation in a diamond amplifier”, Phys. Rev. ST Accel. Beams, 14, 061302 (2011).
5. …

- **The metal layer**
  - RF penetration of the metal film of the diamond cathode.

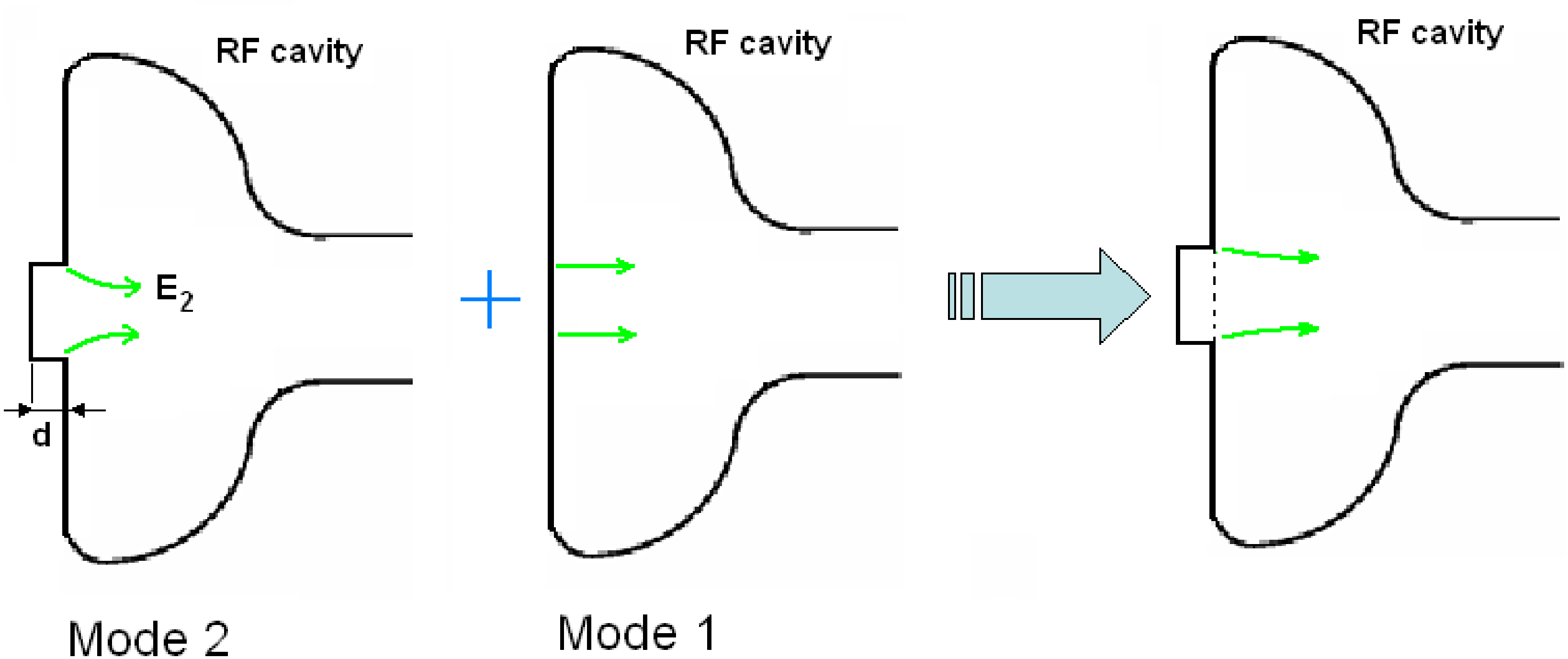
$$\delta_{Al} = \sqrt{\frac{2}{\mu\omega\sigma_{Al}}} \approx 3.1\mu m \qquad (Al,\ f_{RF} = 700\,MHz)$$

$$t_{Al} << \delta_{Al}$$



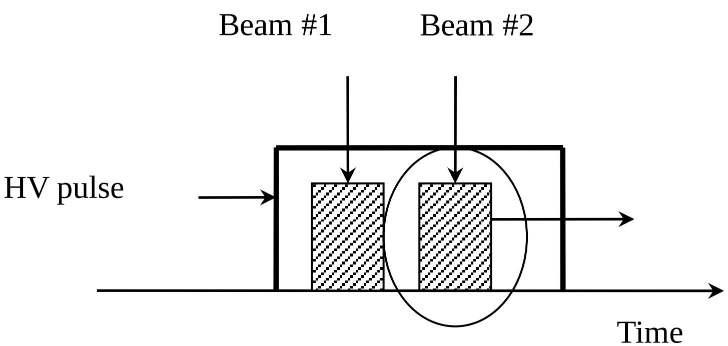
It is demonstrated that the RF penetration through a very thin metal film is negligible.

Schematic explanation of the poor RF transmission through a thin metal film

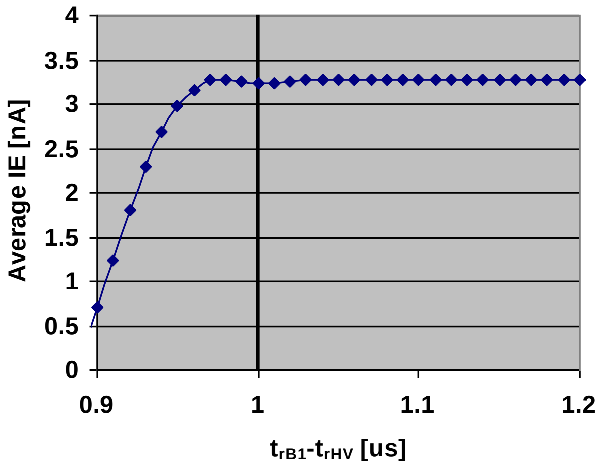


Assume E_2=1kV/m, E_{2T}=10V/m ⇒ I_{RF} ~4A ⇒ E_1~300kV/m ⇒ Penetration~1/300

$$R_S = \frac{1}{\sigma\delta} \qquad E = \frac{I}{\pi r^2 \varepsilon_0 \omega}$$



Beam #1
Beam #2
HV pulse
Time



Average IE [nA]
4
3.5
3
2.5
2
1.5
1
0.5
0
0.9
1
1.1
1.2
t_{rB1}-t_{rHV} [us]

3.5nC, final bunch length of 3.6 mm