Diamond amplifiers for photocathodes

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The motivation

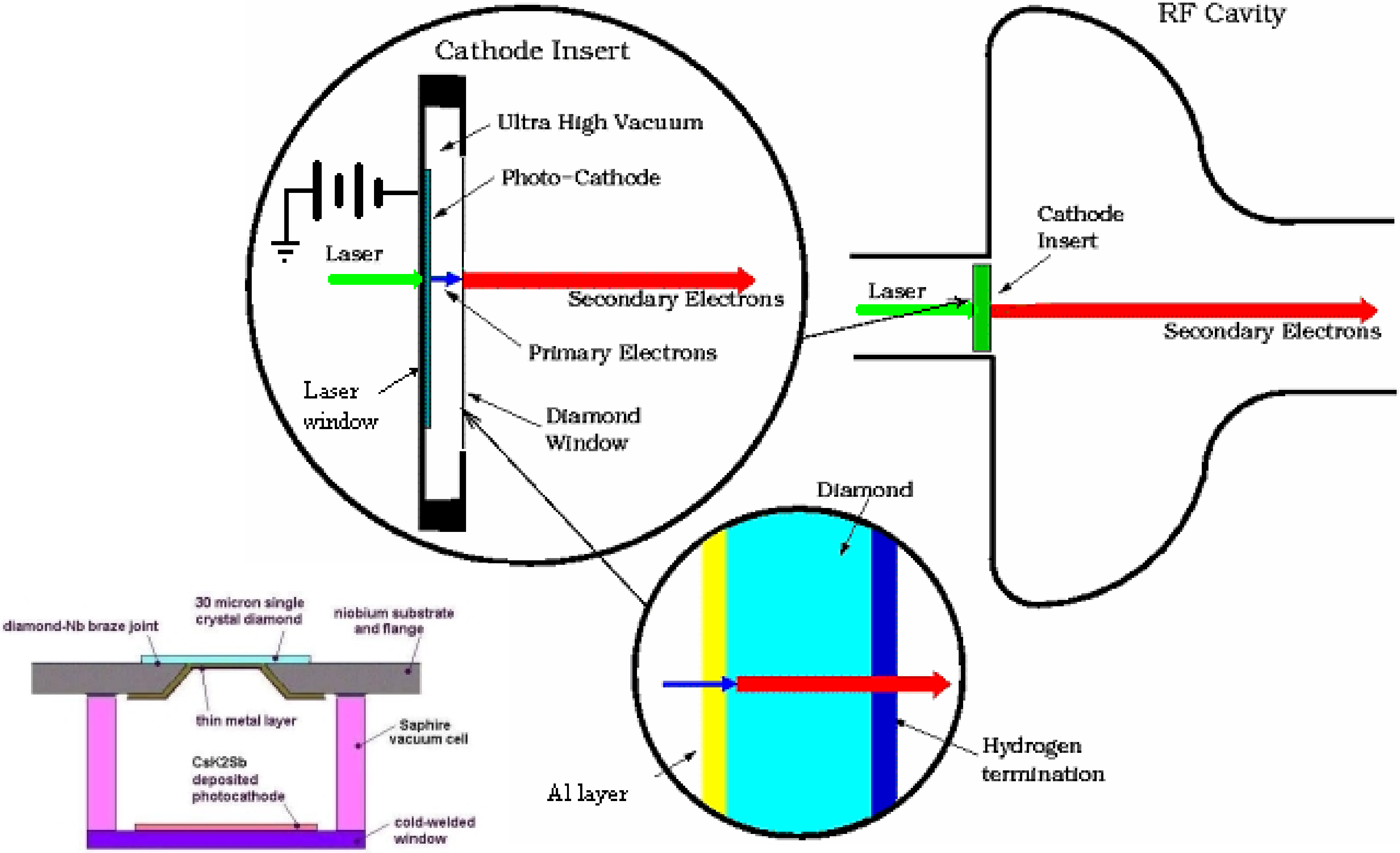
- Photocathodes allow emission of high charge in a short time, controlled by a laser.
  - Good match for RF guns
  - Large bunch charge (e.g. AWA)
  - Allow control of 3-D electron bunch shape
- Found just about anywhere
- Problem: Trade-off between robustness and quantum efficiency. Gave lasers a bad name…

New solution:

- Use secondary emission to “amplify” the charge emitted by the photocathode.
- Layout: Place a diamond thin film (~30μm) between photocathode and acceleration space.
- The multiplication depends on the energy of the “primary” electrons: ~13 eV/e-h pair.

The diamond amplified photocathode

- Photocathode produces primary electrons, amplification in diamond by secondary emission.
- The diamond window may hold an atmosphere to provide simple transport of the capsule.
- The diamond window will protect the niobium (or any other gun metal) from the cathode material
- The diamond will protect the cathode (long life)
- The secondary emission coefficient is very high
- The emittance and temporal spread are very low
- High current & low laser power due to amplification

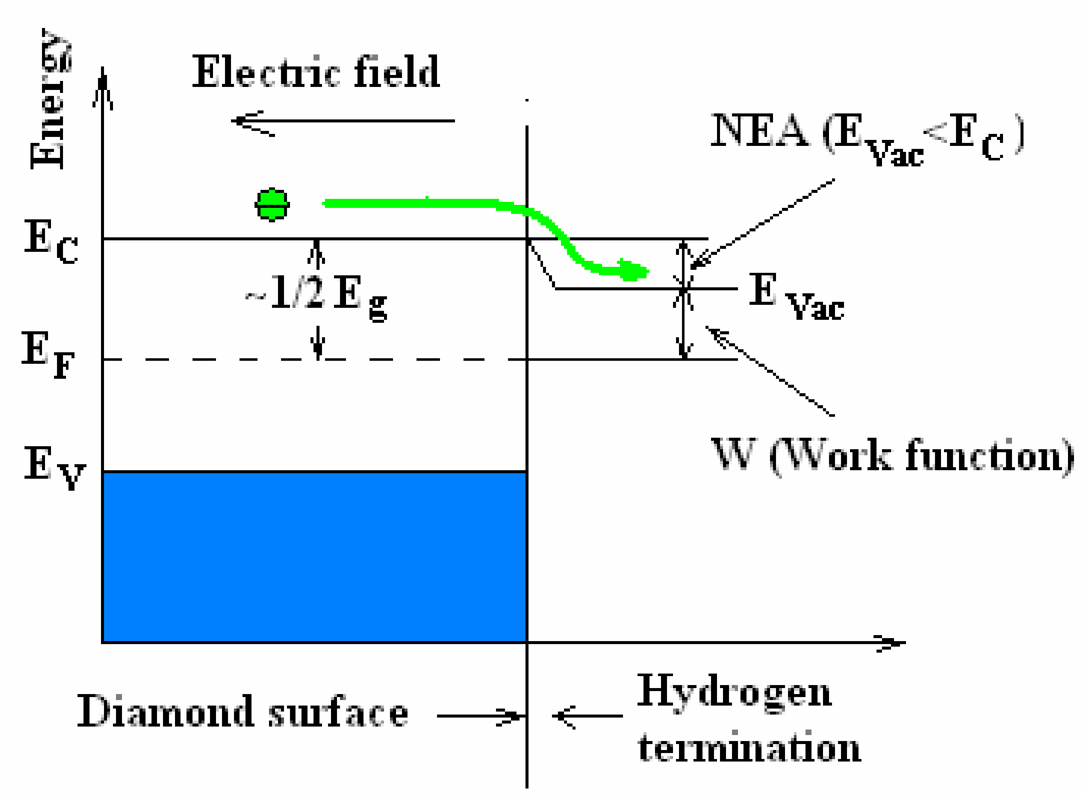


Schematic diagram of a secondary emission amplified photoinjector

Many possible applications

- High average current electron guns
  - – RF guns, both SRF and NC
  - – DC guns
- Lasertrons
- Imaging
- For use in high-power FELs, two-beam accelerators, terahertz radiation, etc.

Diamond’s negative electron affinity



The Fermi levels of the diamond and of the termination materials (hydrogen or alkaline elements) are aligned. Since the termination material has a relatively low work function, and then the vacuum level can be lower than the bottom level of the diamond’s conduction band.

The current replenishment layer

- Need good electrical conductivity for return current (holes and RF shielding)
- Need low stopping power to transmit most of the energy of the primaries
- Need good ohmic and thermal contact to the diamond
- Aluminum is a good choice for the bulk, with titanium / platinum ohmic contact

- The impurity problem
  - Impurities: Boron (p-type), Nitrogen (n-type), Hydrogen (n-type), Phosphorus (n-type), Lithium (n-type) and Sodium (n-type).
  - Heating and background current:
    - Electrons in the diamond's conduction band (n-type) behave like secondary electrons. Thus they generate extra heat and a background current.
    - Holes on the valence band (P type) only generate the extra heat.
  - Charge carrier trapping and field shielding problem:
    - Impurities and grain boundaries can trap charge carriers therefore attenuate the RF field inside diamond and finally affects the conduction of the secondary electrons.

The thickness of the diamond

- In principle, a thick diamond is desired for various reasons: strength, thermal conductivity…
- The optimized bunch launch phase < 35° .
- Initial phase of secondary electrons > 5° .
- That results a drift time ~30° , or ~120 ps.
- The saturated electron drift velocity at a field > 2MV/m is 2.7×10^5 m/s (independent of temperature).
- This leads to a diamond thickness ~30µm.

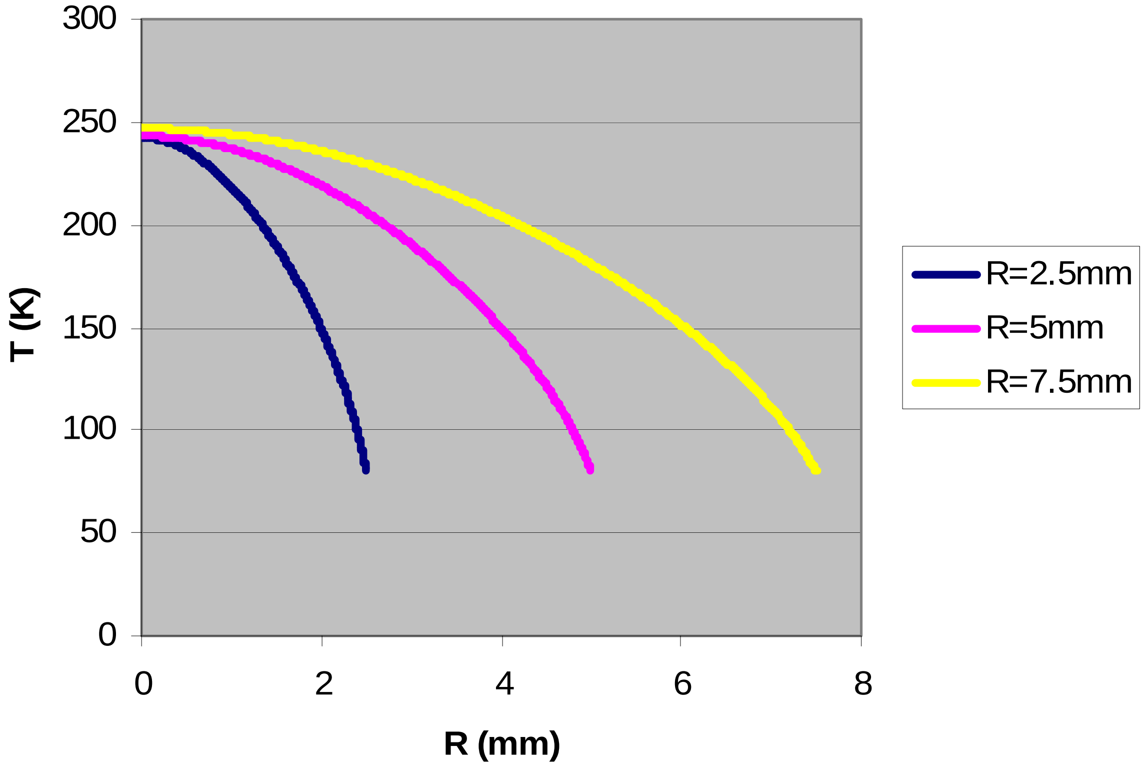
Sources of heat

- Source in the diamond layer:
  - Stopping the primary electrons.
  - Transport of the secondary electrons through the diamond under the RF field.
  - Motion of the impurity induced free electrons in the diamond conduction band (Nitrogen doping) and holes in the valence band (Boron doping) driven by the RF field.
- Sources in the metal layer:
  - Resistive heating by the replenishment current.
  - RF shielding currents.

- Low charge, high current set of parameters

Charge	1.42 nC/bunch
Repetition frequency	703 MHz
Radius	~5 mm
Primary electron energy	10 keV
Diamond thickness	30 µm
Al thickness	800 nm
Peak RF field on cathode	15 MV/m
SEY	300
Temperature on diamond edge	80 K
Primary electron pulse length	10 deg

Temperature distribution for ERL



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

Timing, broadening

Transit time through a 30 microns diamond:

$$T_{delay} \approx \frac{t}{V_{drift}} \approx \frac{30x10^{-6}}{2.7x10^{5}} \approx 110\,ps \approx 28\,\text{degrees}\,@\,704MHz$$

A delta function of primary electron pulse is stopped in about 200nm.
The secondary electron bunch will have a spread of~ 100nm
100nm/Drift velocity=$1*10^{-7}/2.7*10^{5}$~0.4ps

The mobility dependence of the electric field may enlarges this very slightly. Thus the cathode is quite prompt.

The number of elastic collisions is about $5x10^4$.

Emittance

Experiments in reflection mode show that the energy spread of the secondary electrons from NEA diamond is sub eV, leading to a small rms normalized emittance of less than 2 microns. In transport through A thick diamond we must consider the energy input from the field. Under a high electric field, at equilibrium, the energy loss rate to the bulk must equal energy gain rate from the field, leading to the following:

$$\left(\frac{d\overline{W}}{dt}\right)_e + \left(\frac{d\overline{W}}{dt}\right)_L = -eE_0 v_e - \frac{\overline{W}(T_e)-\overline{W}(T_L)}{\tau_W} = 0 \qquad \tau_W = \lambda_i / v_e \qquad v_e = \sqrt{2\overline{W}(T_e)/m_e}$$

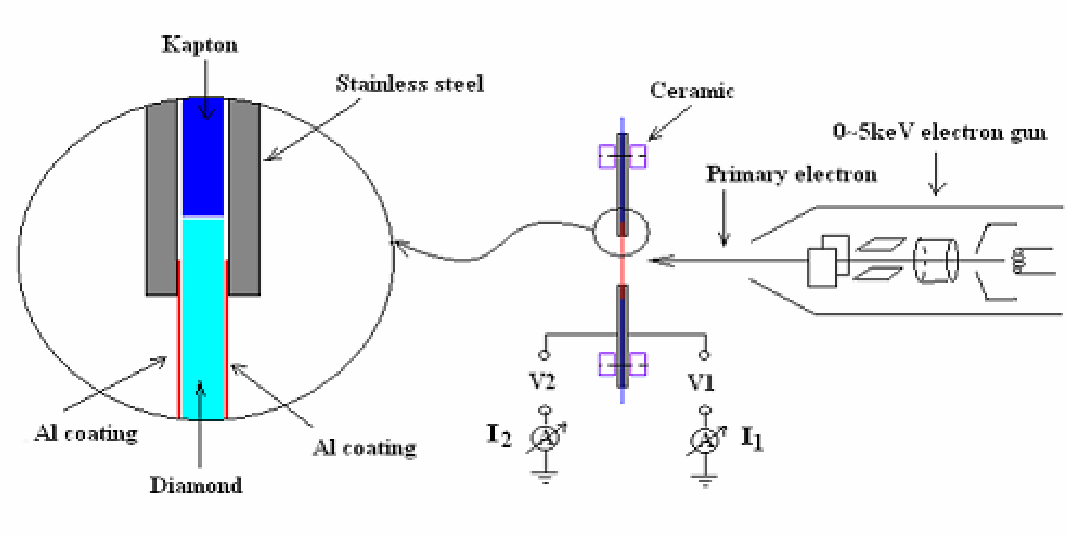
W(Te), W(TL) are the electron thermal energy and lattice thermal energy.
From M.P. Seah and W.D. Dench:

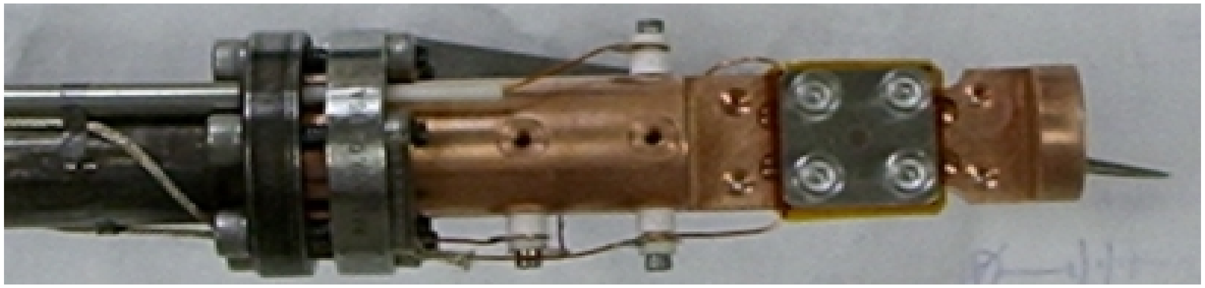
$$\lambda_i = \left[538 E_r^{-2} + 0.41\left(a_m E_r\right)^{\frac{1}{2}}\right] a_m$$

a_m= 0.1783 nm. E_r is the electron’s energy above the Fermi level.

Solving at $E_0 = 10MV/m$ we get $T_e \approx 0.4eV$

Electron and hole transmission measurements





Hydrogenation

Requirements:

Acid etch sample to remove all impurities- metal, graphite, carbon

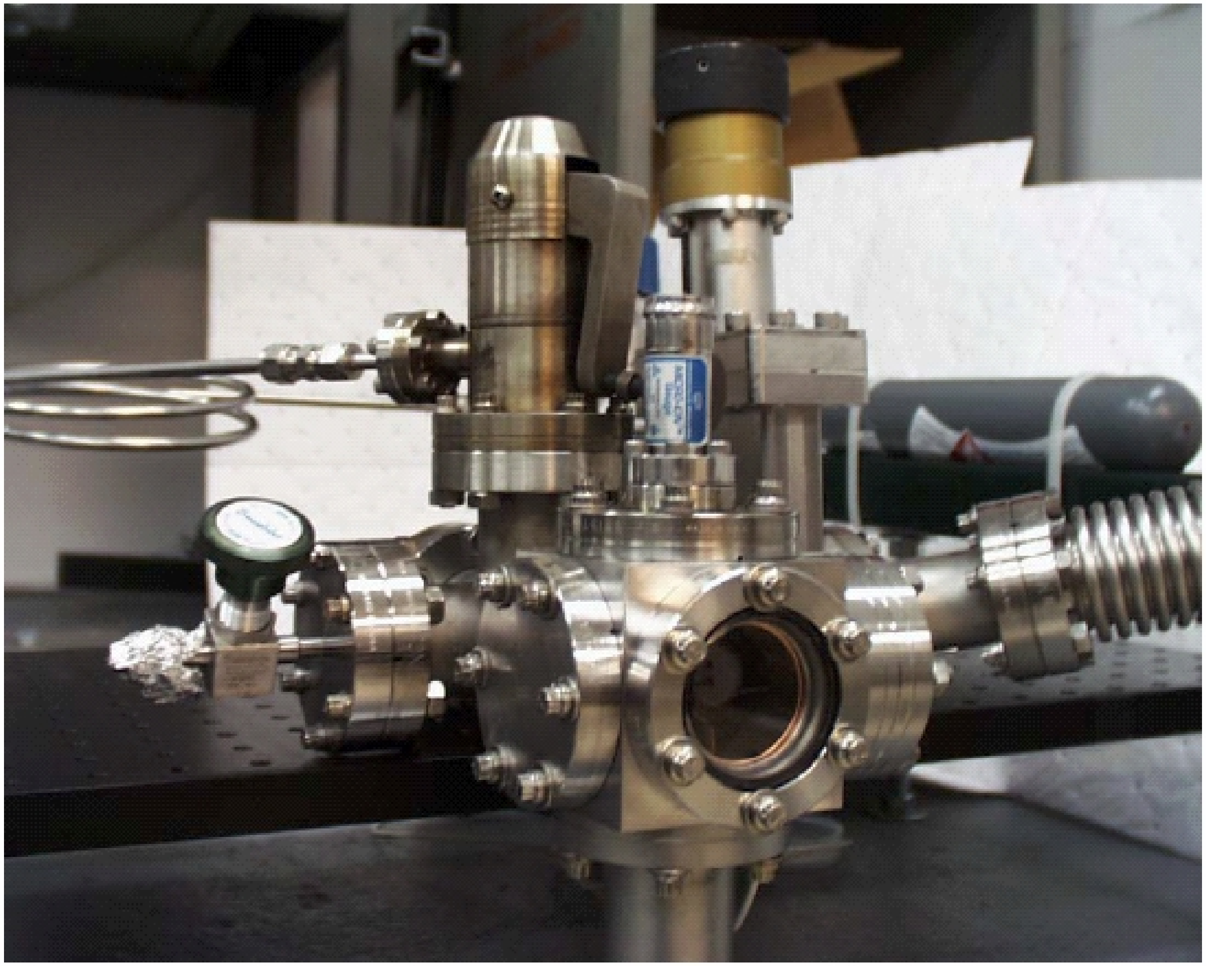
Sample to be heated to > 800 C to remove impurities and free dangling bonds

High vacuum

10^{-6} Torr H_2

W filament to be heated to > 1800 C

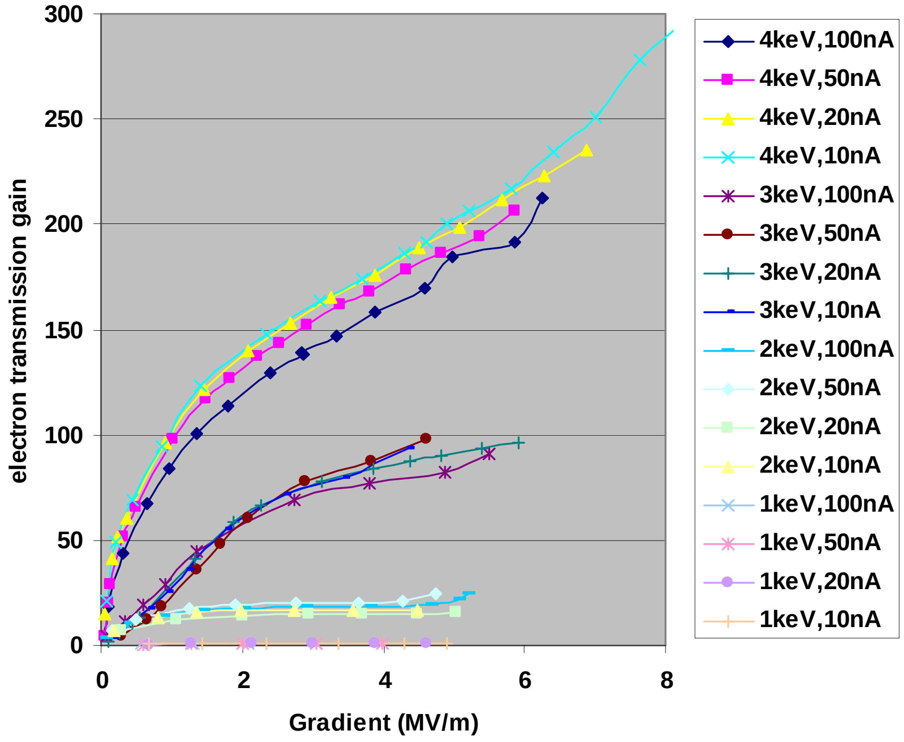
Capable of Photoemission measurements



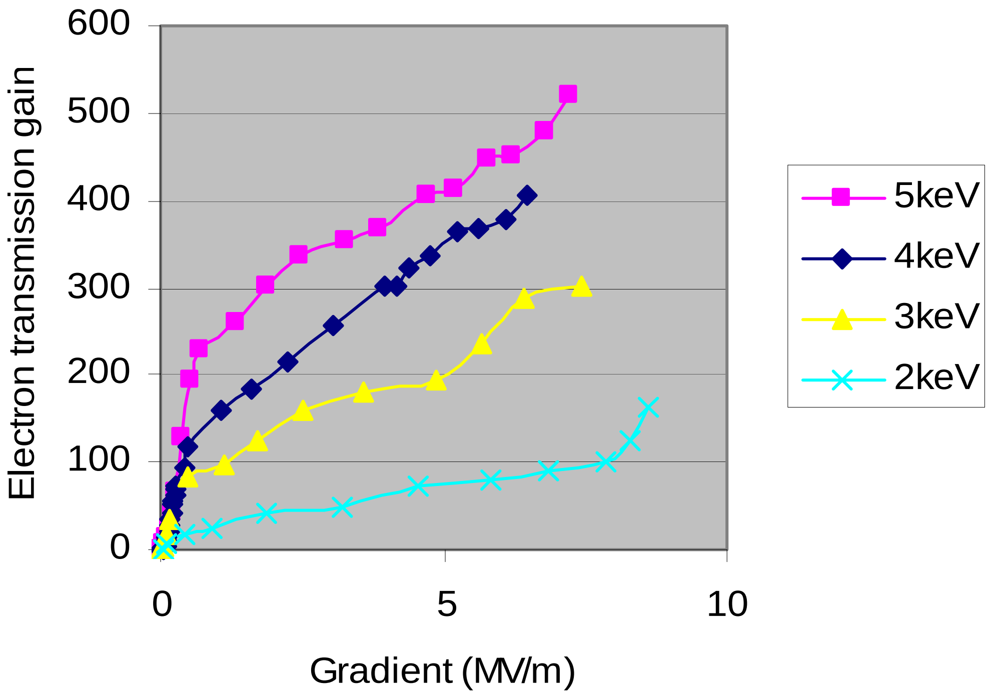
Status: Assembled, being pumped

•Transmission in natural type II A diamond

$3X2.6X0.16mm^3$, N 60ppm

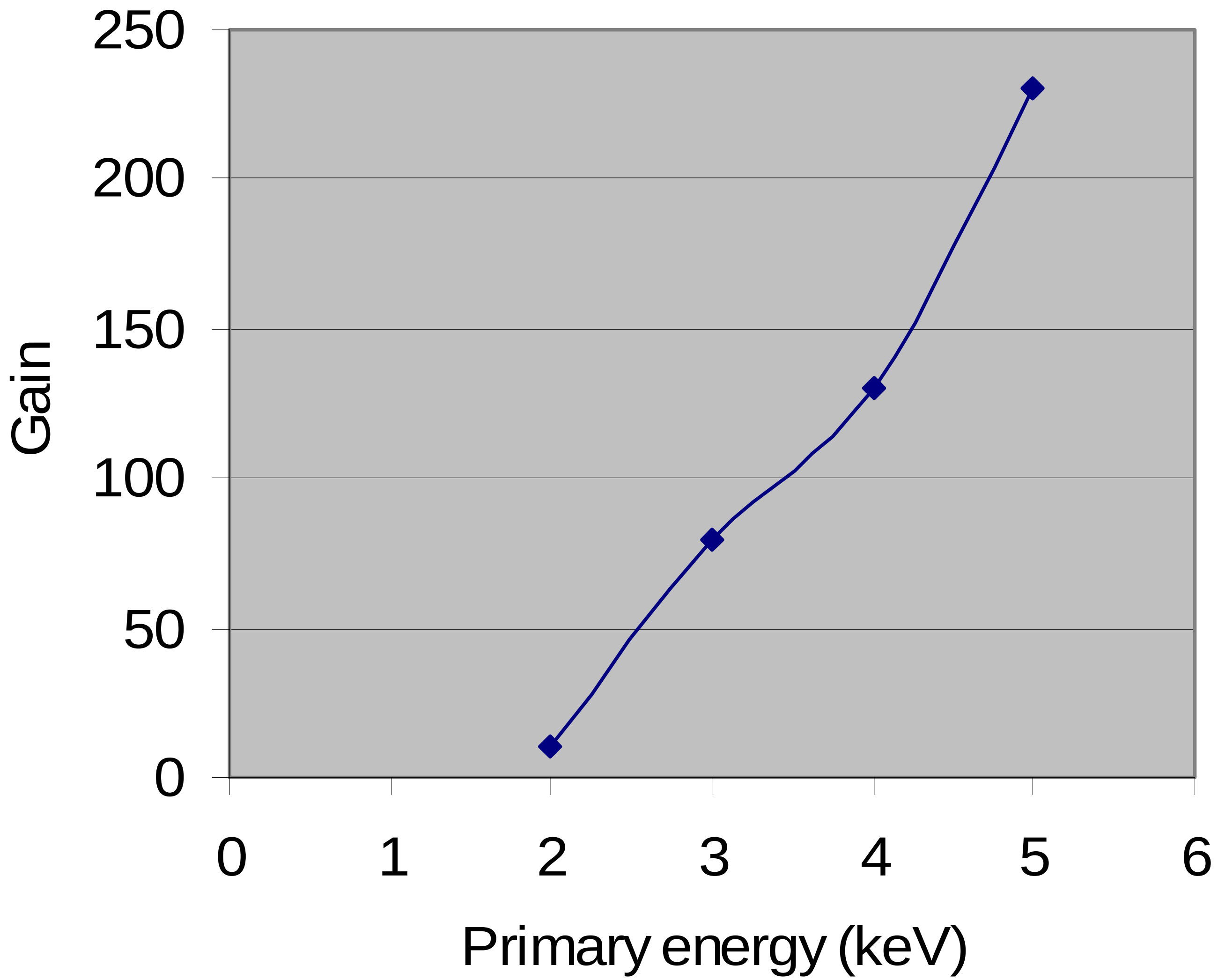


Room temperature

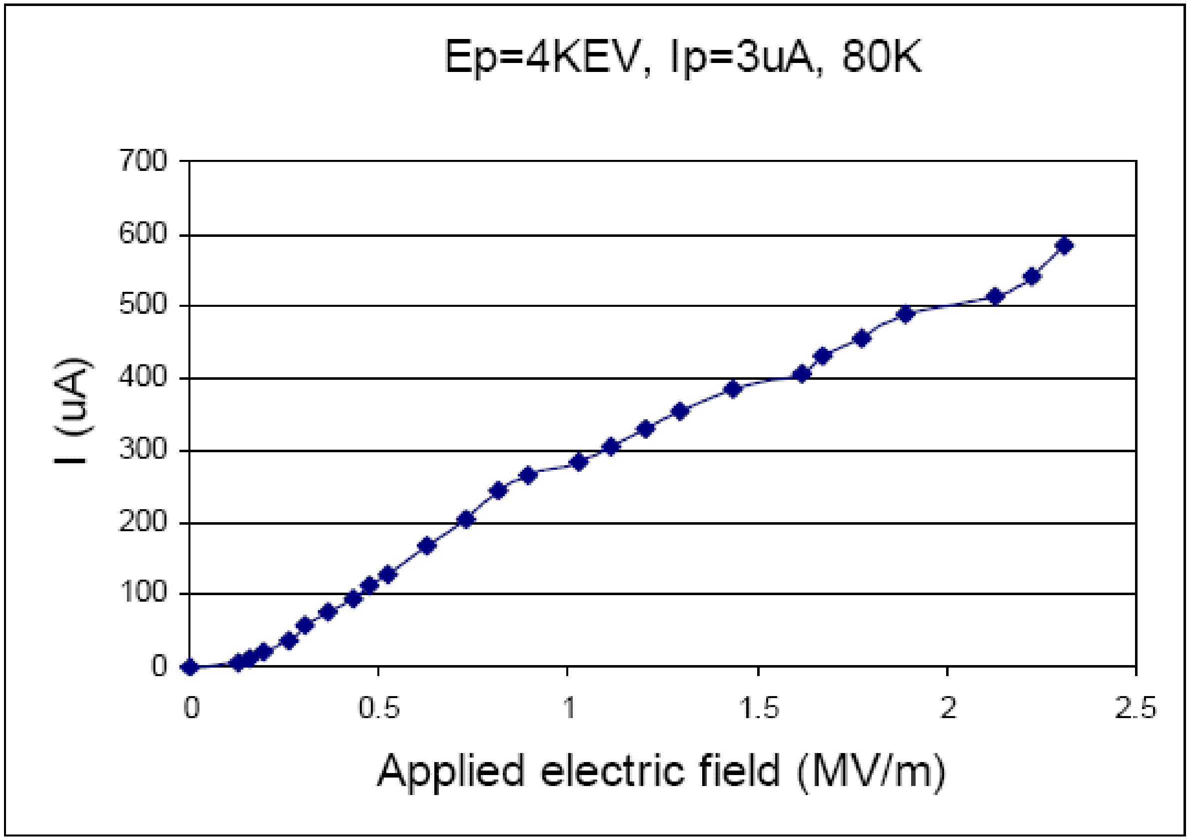


Liquid nitrogen temperature

Slope: 13 eV / electron-hole pair, as expected

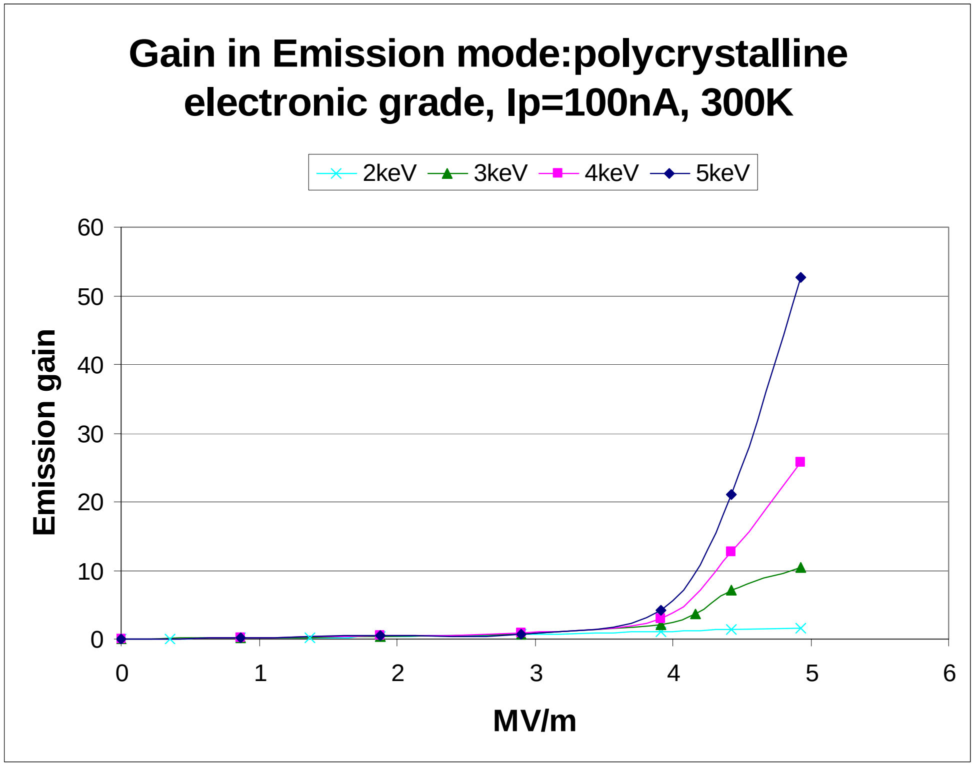


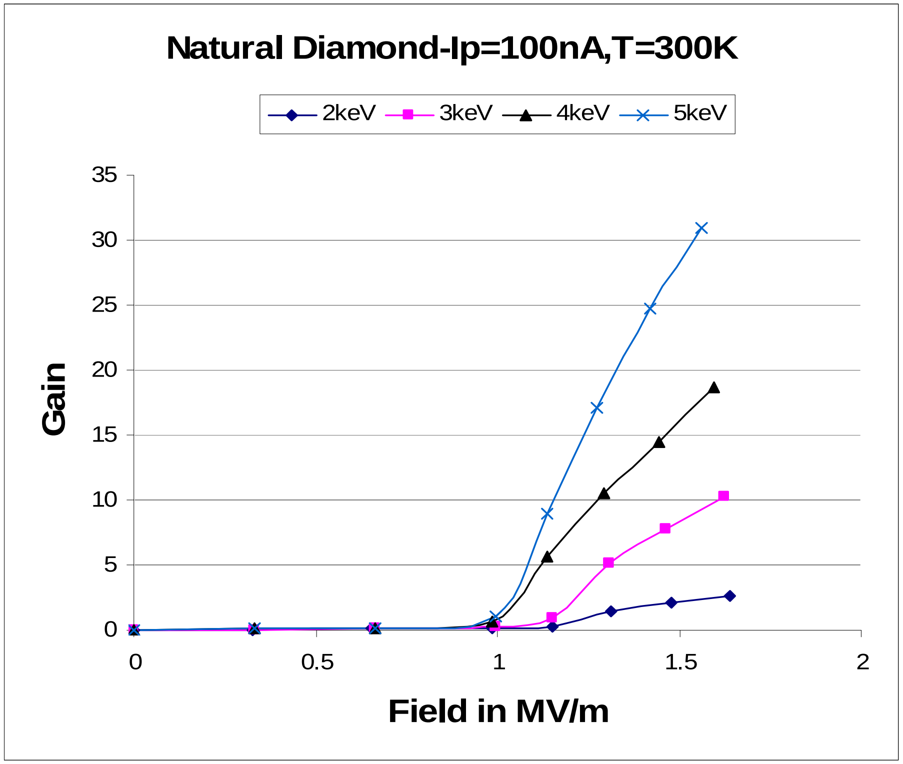
High Current Performance



Max. current obtained 0.58 mA, limited by the power supply
Current density of .82 A/cm^2

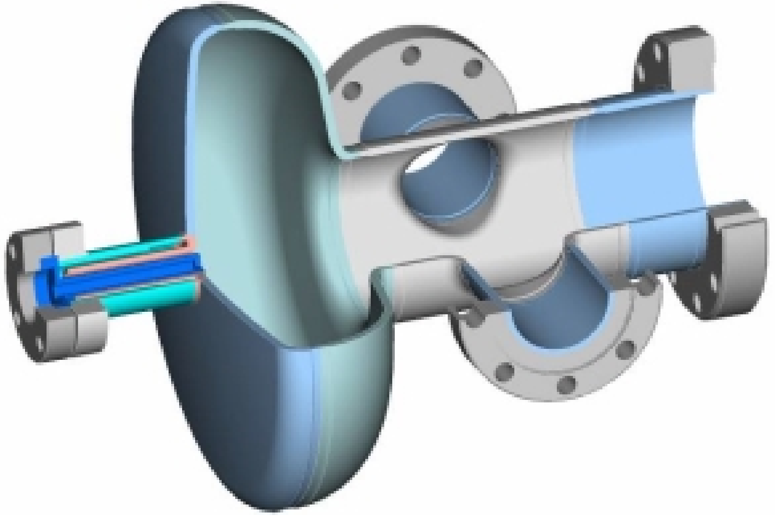
Gain in Emission mode From Hydrogenated samples



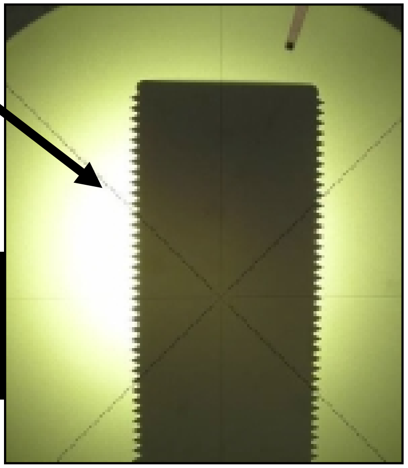


Gain of 50, still increasing W/ field, further investigation underway

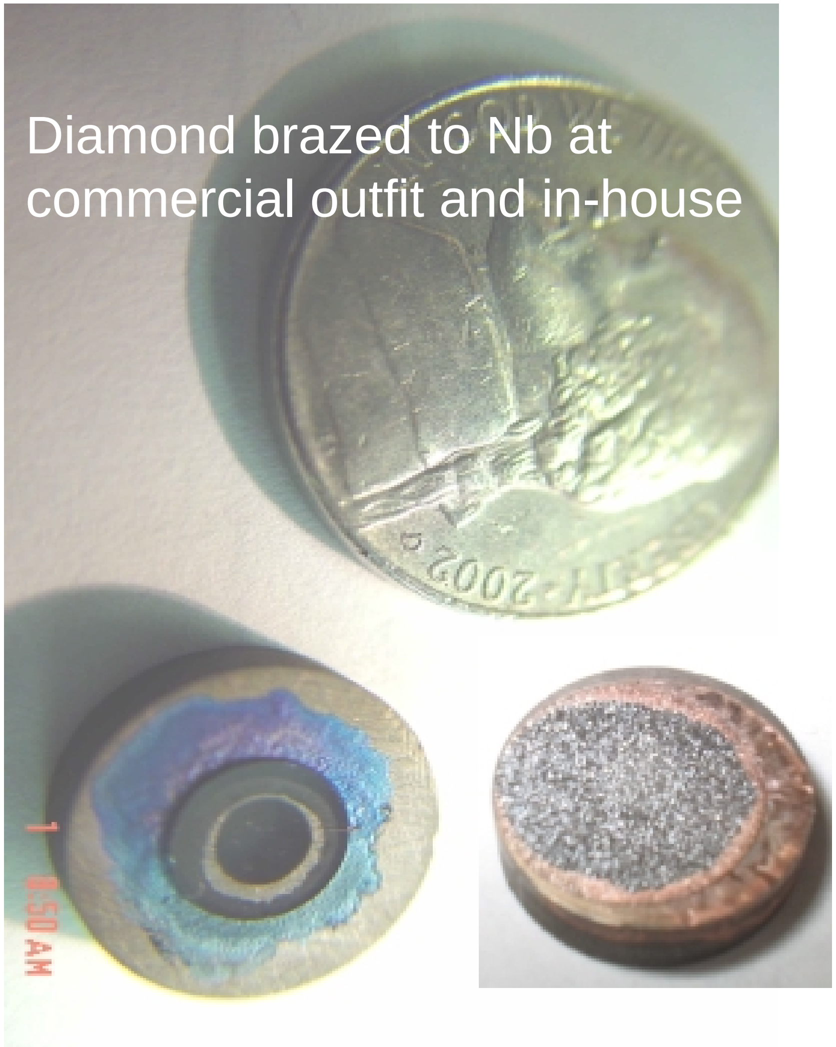
Testing in RF gun

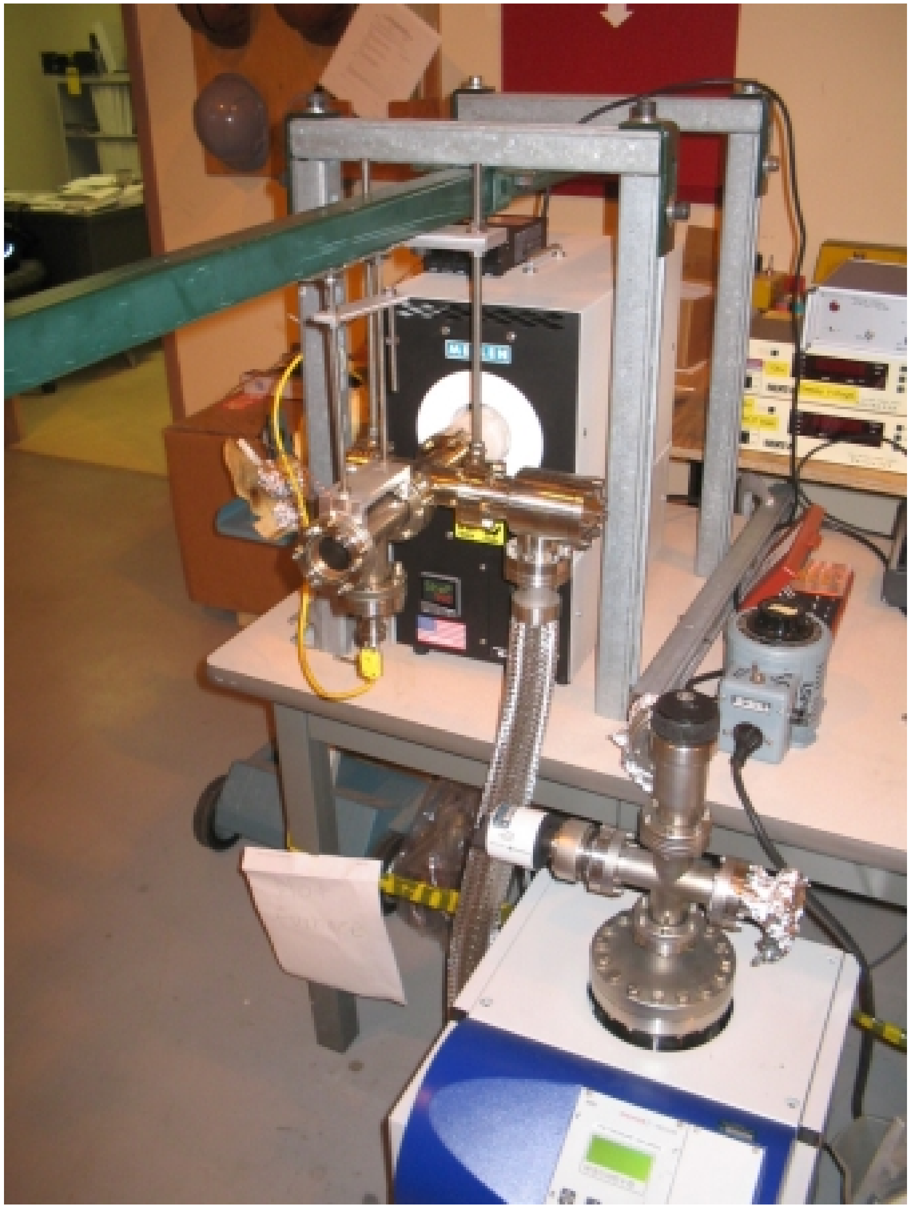


Diamond can be attached to the insert for RF testing



Oven and Nb-Diamond braze photograph


Diamond brazed to Nb at commercial outfit and in-house



Achievements & Future Plans

- Improve sample quality V
- Produce ohmic contacts V
- Use thinner sample
- Measure electron transmission V
- Hydrogenize and measure emission V
- Measure temporal response
- Measure thermal energy
- High charge / current measurement
- Temperature dependence
- Fabricate transparent photocathode
- RF test in SRF 1.3 GHz gun
- Capsule design, fabrication and test

Thanks and acknowledgements

Thanks for people associated with the BNL project:

- Andrew Burrill , Xiangyun Chang, Jacob Grimes, Peter Johnson, Jörg Kewisch, David Pate, James Rank, Triveni Rao, Zvi Segalov, John Smedley, YongXiang Zhao
- Support by DOE / NP, BNL / director's Office and DOD / ONR