Diamond secondary emitter status & plans

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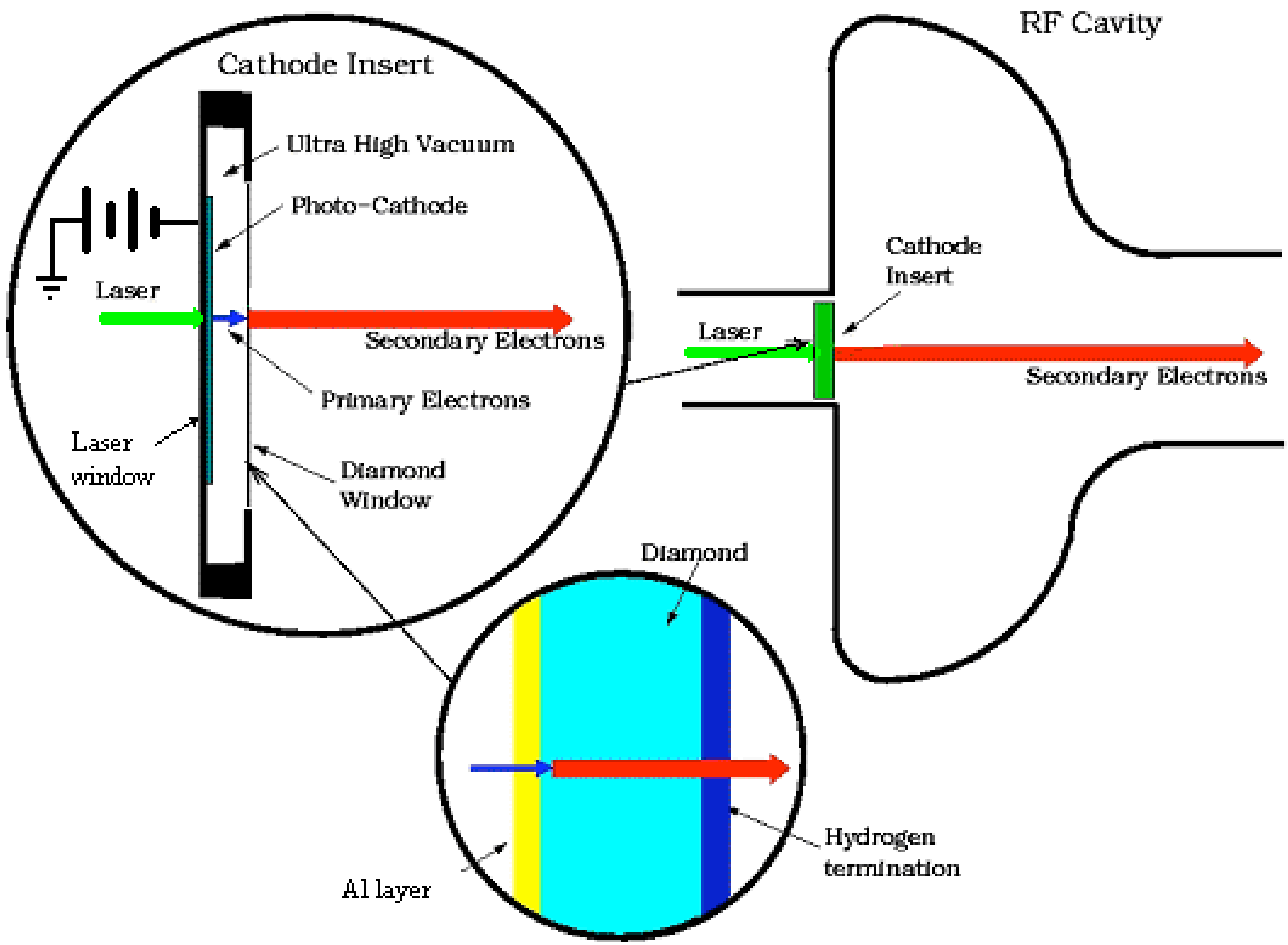
What is desired in a cathode of a CW, high brightness injector?

- Timing by a laser
  - short pulse
  - good control
- Small emittance
- High CW current capability
- Compatibility with a superconducting gun
  - Highest possible accelerating field
  - CW operation with negligible cavity losses

What is desired in a cathode of a CW, high brightness injector?

- High quantum efficiency
  - Make laser small and simple
- Hermetically sealed in ultra-high vacuum
  - Should not contaminate gun
  - Should not be contaminated by gun
  - Long lived
  - Simple field installation open to air, no load-lock mechanism
- Fast response time of the emission



Schematic diagram of a secondary emission amplified photoinjector

The diamond amplified photocathode

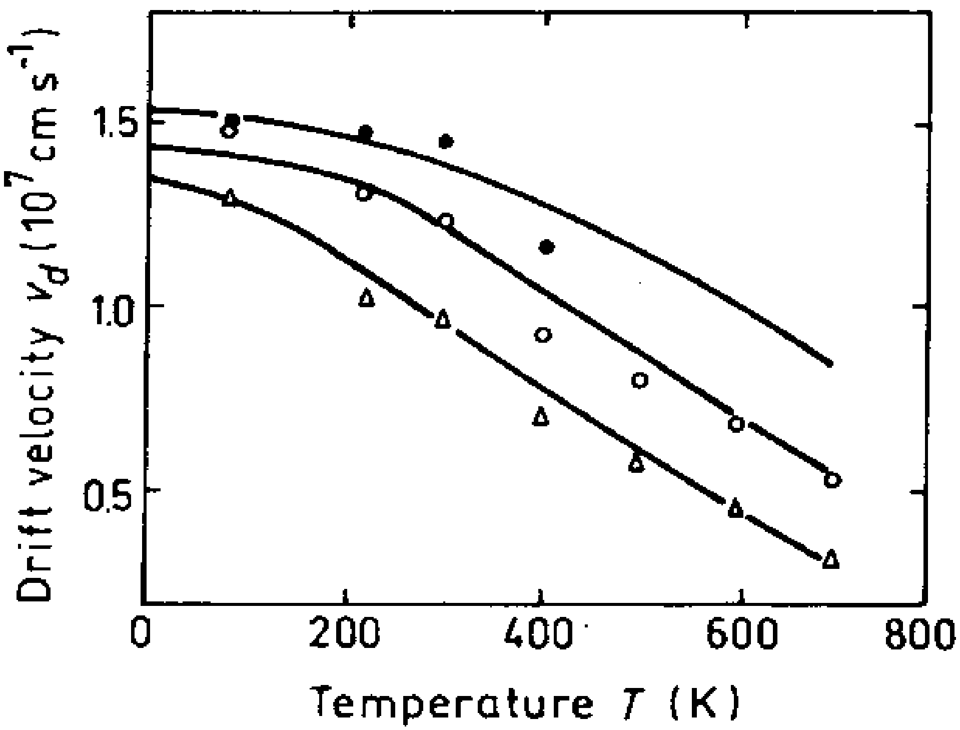
- Photocathode produces primary electrons, amplification in diamond by secondary emission.
- The diamond window may hold an atmosphere to provide simple transport of the capsule.
- The diamond window will protect the niobium (or any other gun metal) from the cathode material
- The diamond will protect 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

Diamond properties

Crystal structure	Diamond	Breakdown field	10^6-10^7 V/cm
Number of atoms in 1 cm^3	$1.764 \cdot 10^{23}$	Mobility electrons	$\leq 2200\ cm^2V^{-1}s^{-1}$
Debye temperature	1860 K	Mobility holes	$\leq 1800\ cm^2V^{-1}s^{-1}$
Density	3.515 g/cm^3	Electron thermal velocity	$\sim 10^5\ m\ s^{-1}$
Dielectric constant (10^2-10^4 Hz)	5.7	Melting point (@ p=125kbar)	4373 °C
Lattice constant	3.567A	Specific heat	$0.52\ J\ g^{-1}\ °\ C^{-1}$
		Thermal conductivity	6-20 $W\ cm^{-1}\ °C^{-1}$
		Thermal expansion, linear	$0.8 \cdot 10^{-6}\ °C^{-1}$
		Saturated electron drift velocity	$2.7 \cdot 10^7$ cm/s

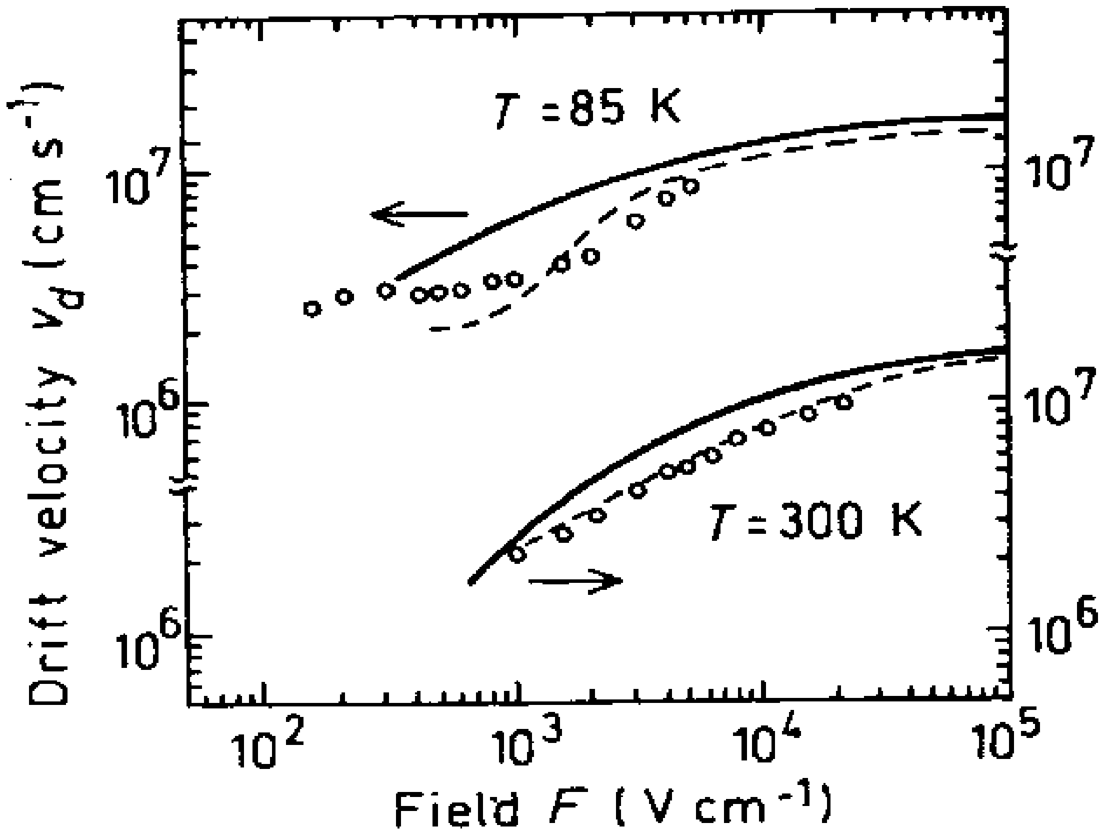
Best orientation for NEA: [1,1,1]

Electron mobility vs. temperature



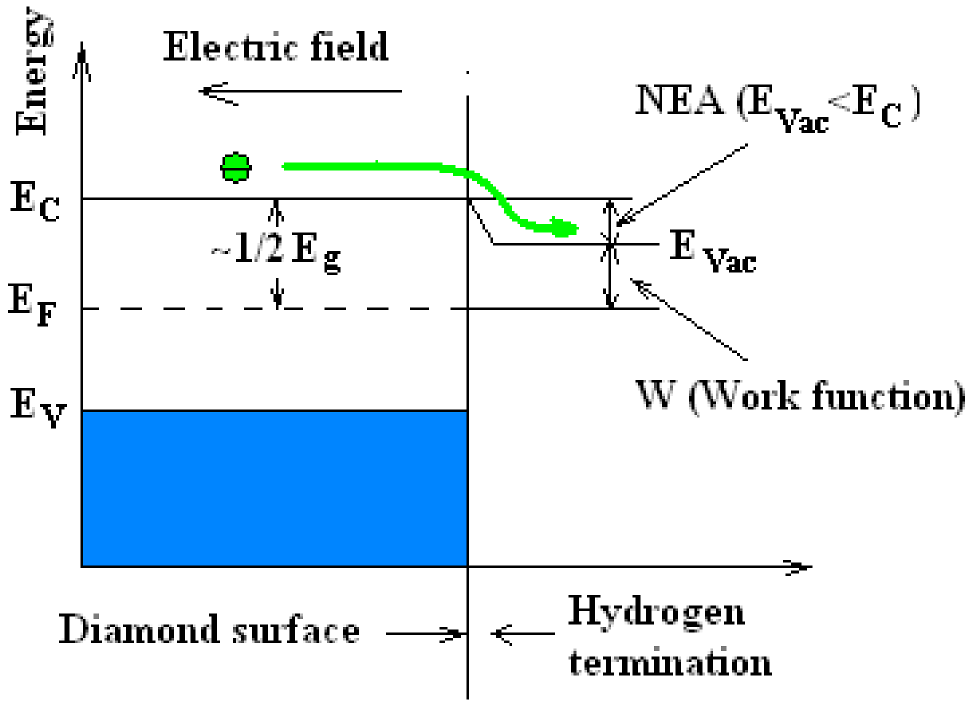
Electron mobility as a function of temperature in natural diamond. Saturated electron drift velocity is 2.7×10^5 m/s.

Mobility vs. field



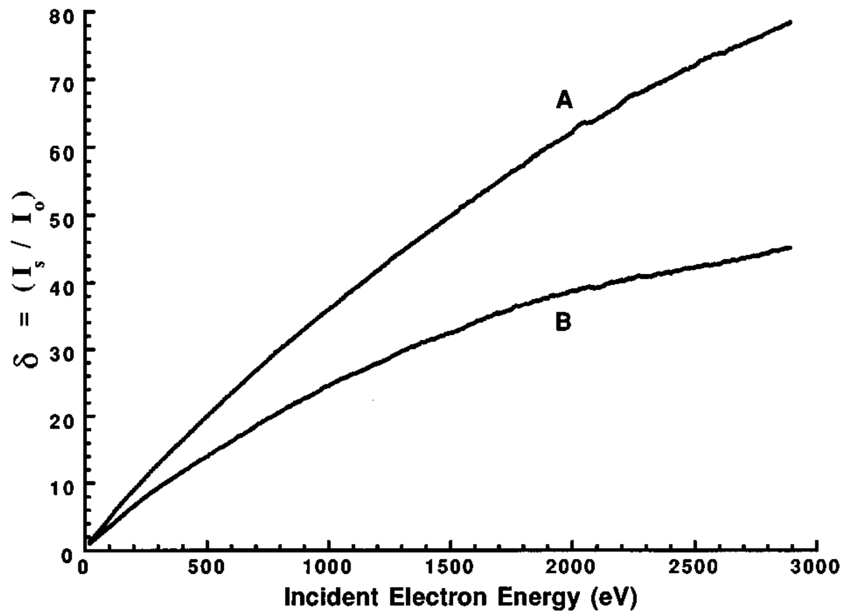
Field dependence of the electron drift velocity.
Solid lines: F||(111). Dashed lines: F||(100)

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.

¶UThe hydrogenated surface.



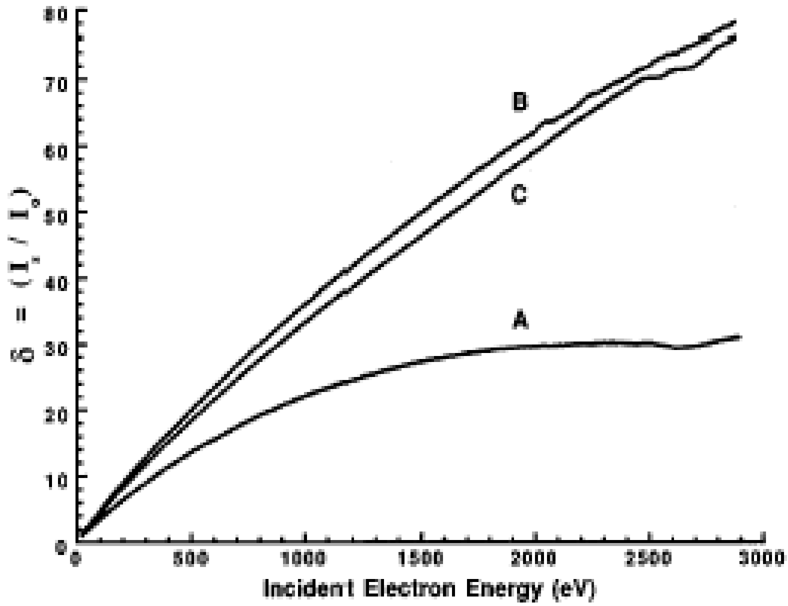
SEY measurement for reflection mode. (A) After exposure to a saturated atomic-hydrogen. (B) After heating to 900°C

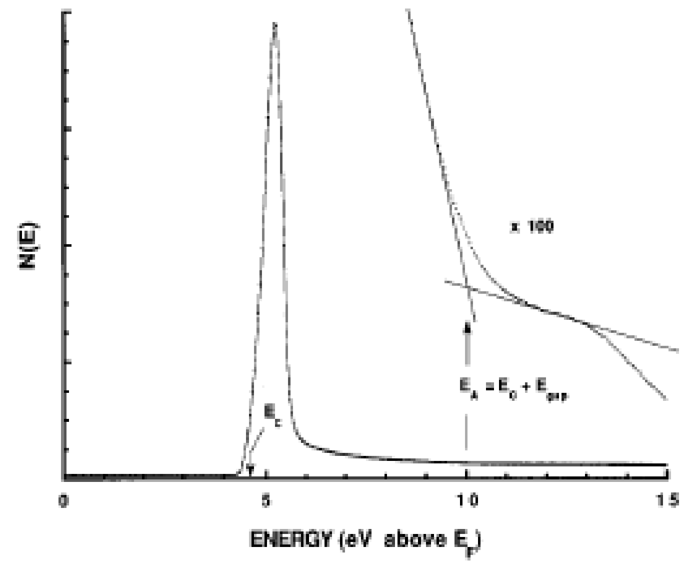
A. Shih, J. Yater, P. Pehrsson, J. Butler, C. Hor, and R. Abrams

J. Appl. Phys., Vol. 82, No. 4, 15 August 1997

It is expected that almost all the secondary electrons produced would come out from the diamond for our transmission mode.
We will assume SEY to be about 300 at 4keV for our transmission mode.

Secondary emission in doped diamond, transmission mode





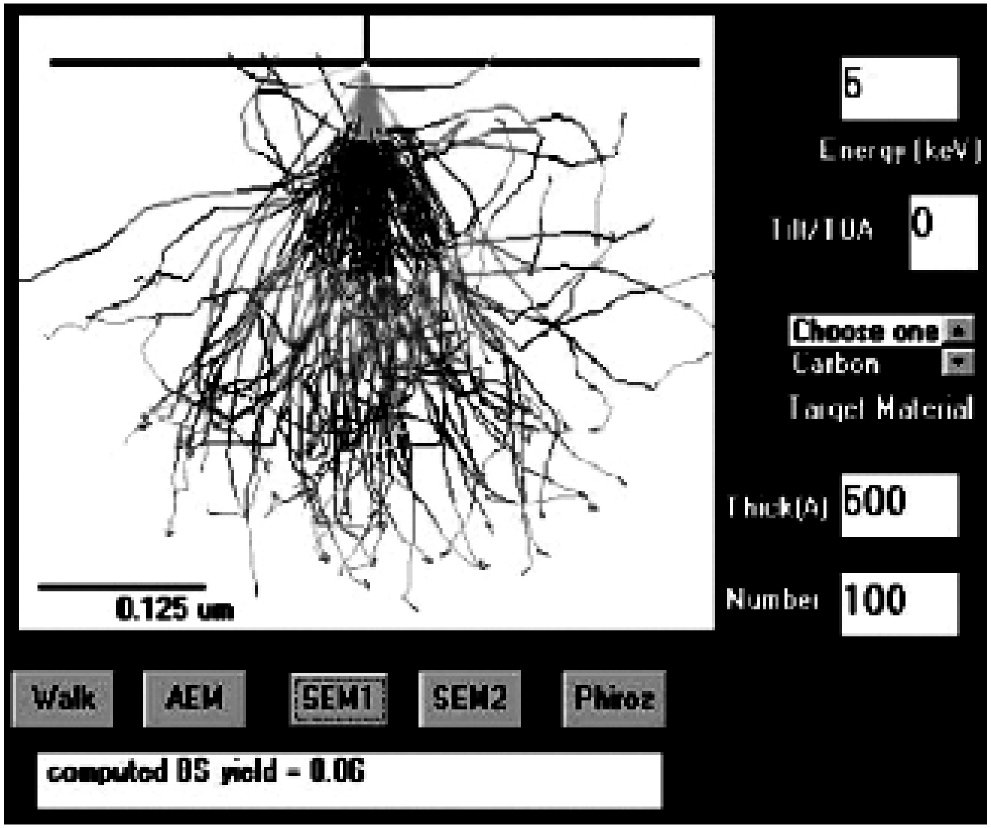
SEY from samples with different B-doping levels.
(A) High doping, B) Medium doping, (C) Low doping.

SEED for medium doping

A large secondary emission coefficient (over 80) and very narrow (sub eV) energy spread of the secondaries, good for a normalized emittance of better than 2 microns.

Penetration depth in diamond

Monte Carlo simulation of a 5kev electron beam scattering in diamond. The electrons stop at a few hundreds nm.



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

Electron transmission

Good secondary electron generation and transmission across a thick sample was demonstrated for a good quality diamond. It became clear from poor samples that trapping of electrons is a major concern, thus we require the highest purity and crystal quality diamonds.

- 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 priciple, a thick diamond is desired for various reasons: strength, thermal conductivity etc.
- 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 ~32μm.

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.

Rough estimate of temperature increase

Assume 50 watts of power dissipated uniformly through the diamond.
Let the outer diameter of the diamond be clamped at 100 K.
We further assume a t=30μm thick diamond and 1000 W/mK thermal conductivity independent of temperature in the resultant range.
Then the temperature rise to the center of the cathode is:

$$T(r) = T(R) + \frac{\overline{P}}{4kt}\left(R^2 - r^2\right)$$

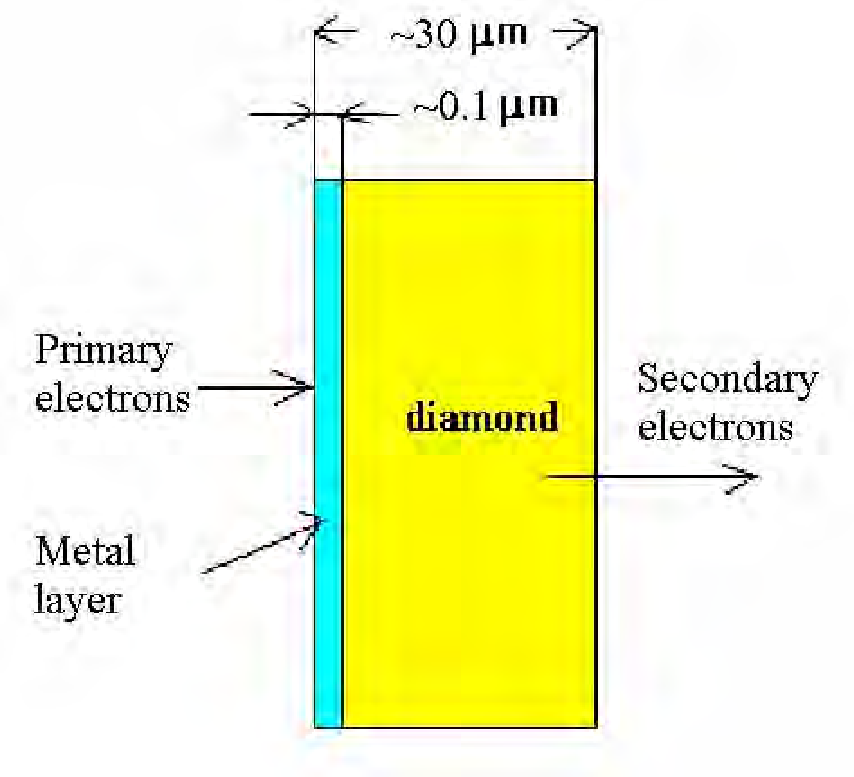
Precise calculation must take into account the temperature dependence of the electric resistivity and thermal conductivity.

Primary and transport heat, 0.5A

Primary electron current:
(use SEY of 250 and 4 KeV injection)
500 mA /250=2 mA

Primary electron power:

The peak field in the cavity is expected to be 30 to 40 MV/m.
At the time of emission,
at 30° phase, it is 15 to 20 MV/m. In the diamond, due to the dielectric constant of 5.7, the field will be about 3 MV/m.

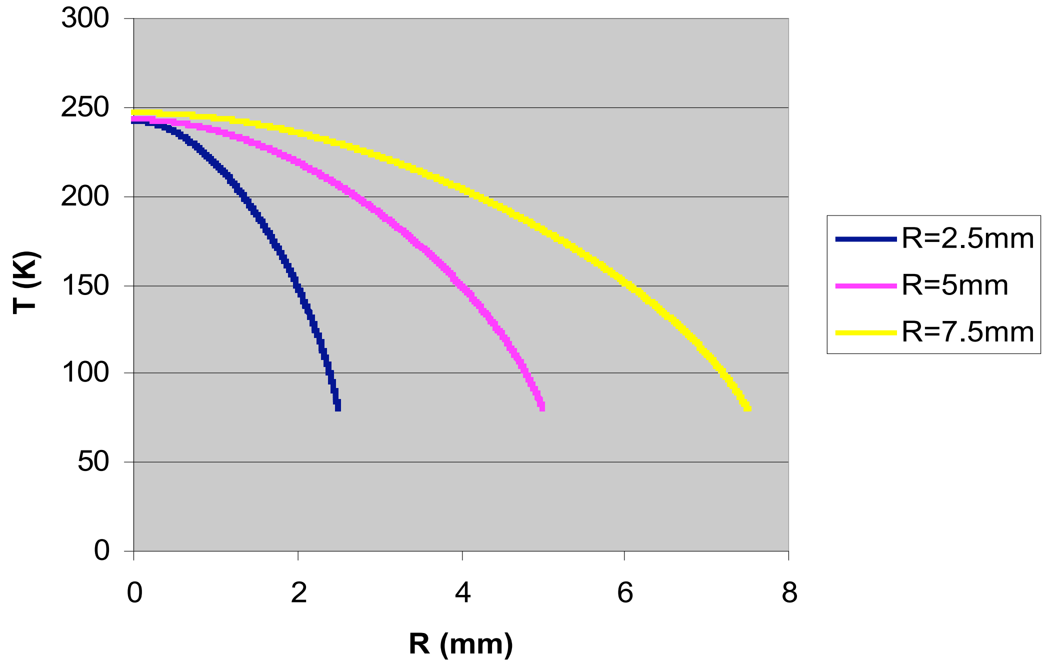


Energy loss in transport, at 3 MV/m in the diamond:

¶ULow 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 •ïm
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:

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

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:

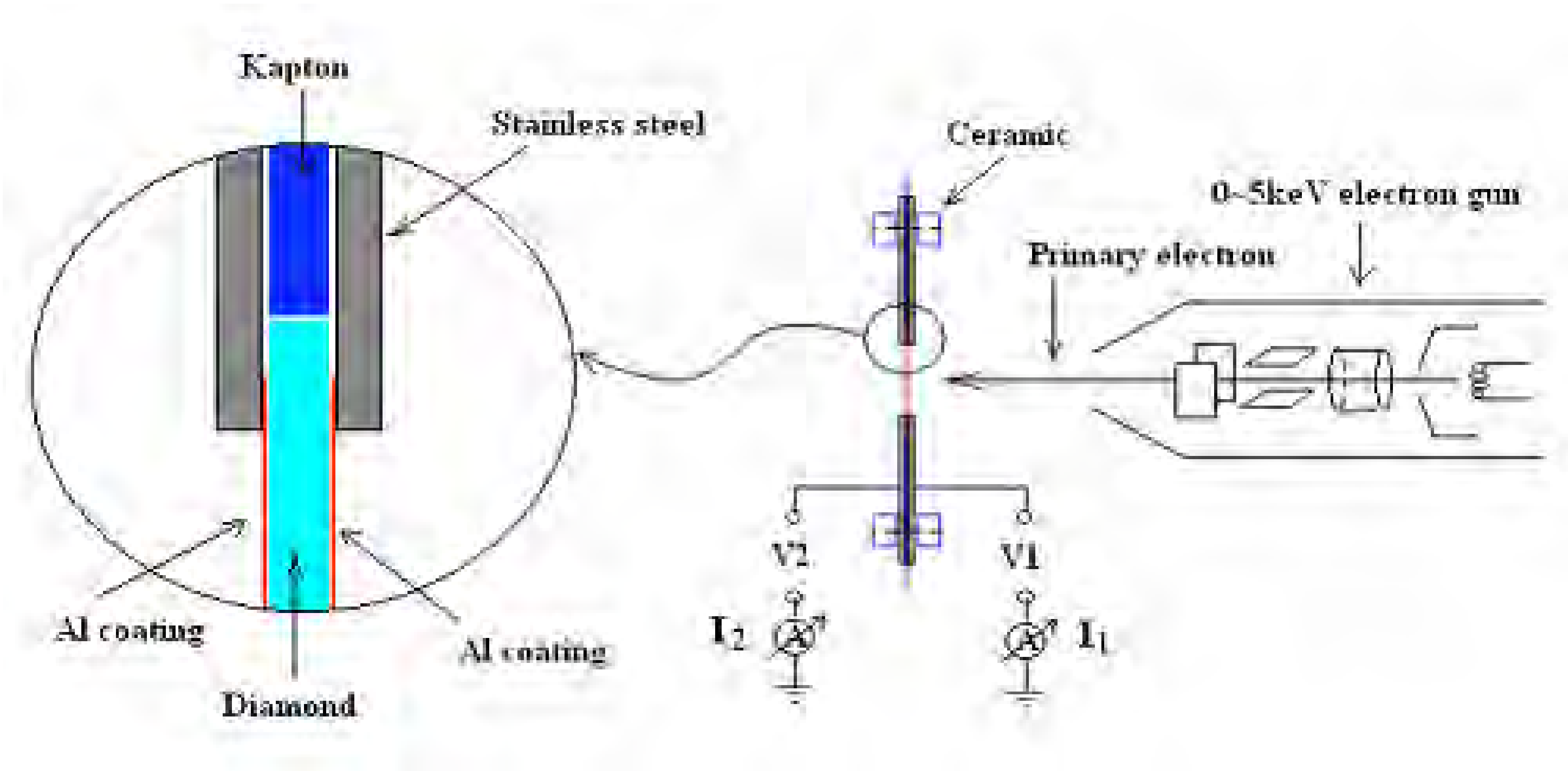
$$\left(\frac{d\overline{W}}{dt}\right)_e + \left(\frac{d\overline{W}}{dt}\right)_L = -eE_0 v_e - \frac{\overline{W}(T_e) - \overline{W}(T_L)}{\tau_W} = 0 \qquad \tau_W = \lambda_i / v_e \qquad v_e = \sqrt{2\overline{W}(T_e)/m_e}$$

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

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



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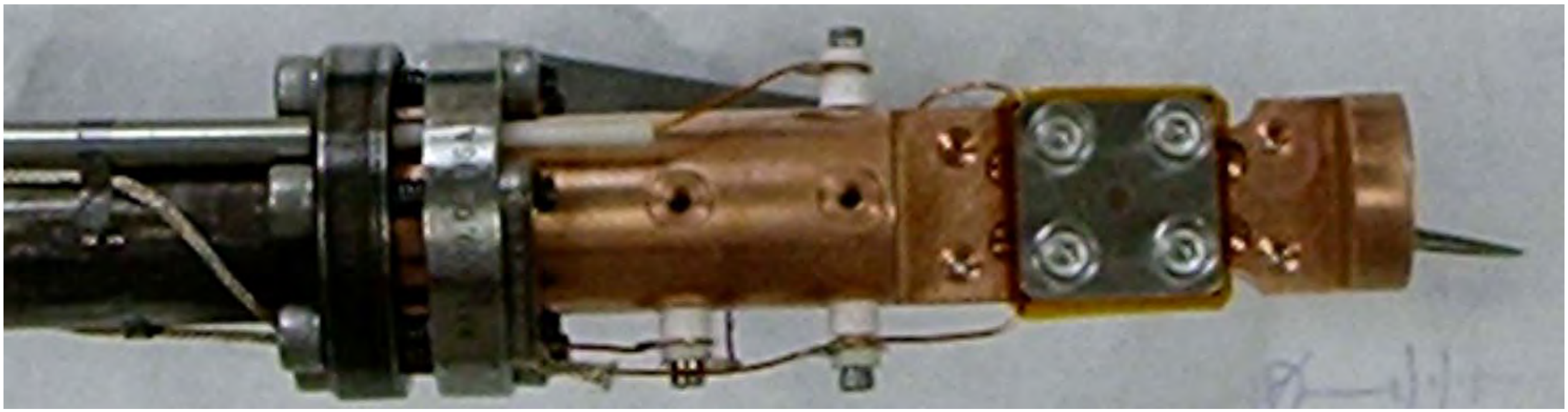
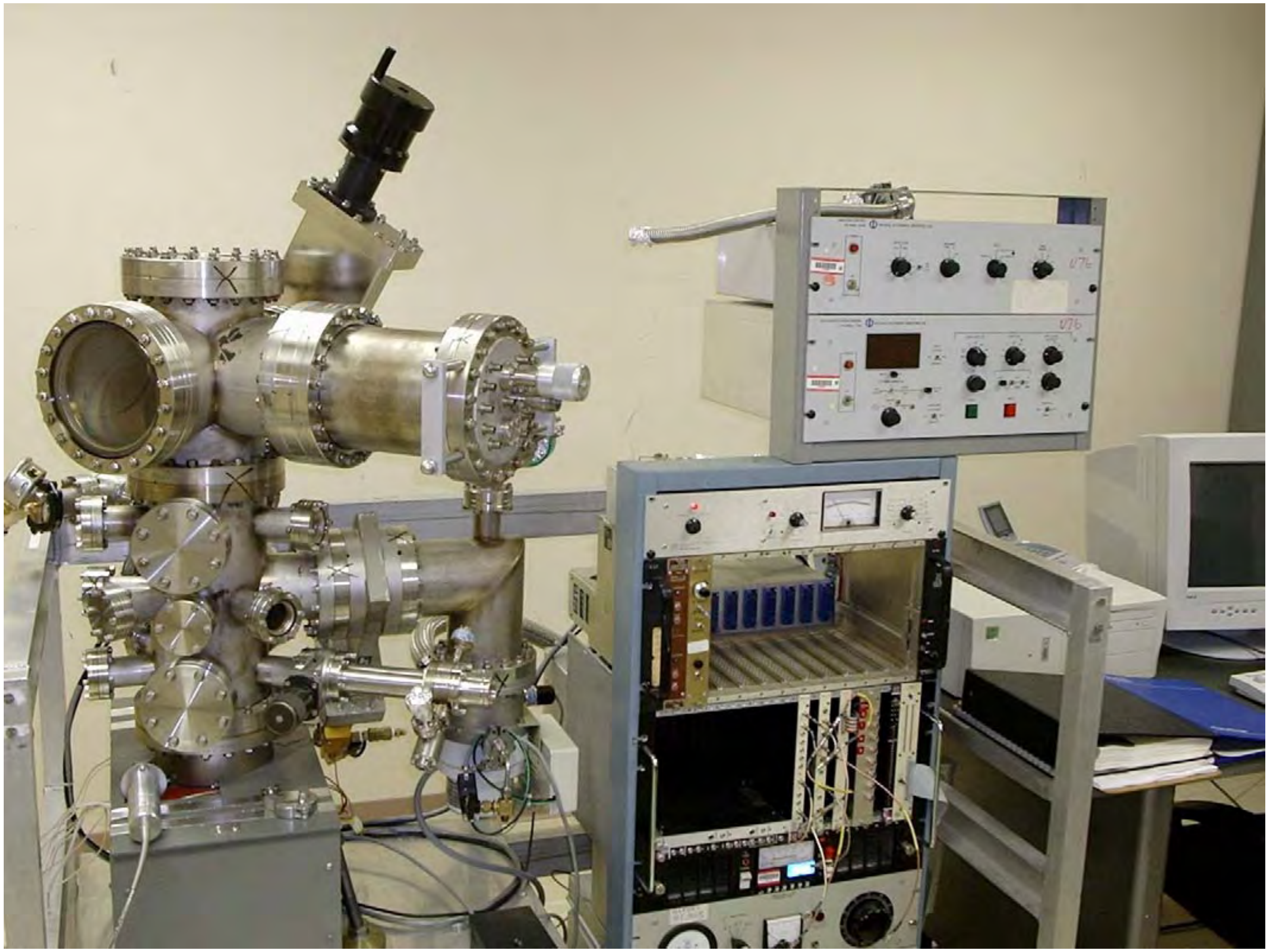
The sample holder



Experiments



Hydrogenation

Requirements:

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

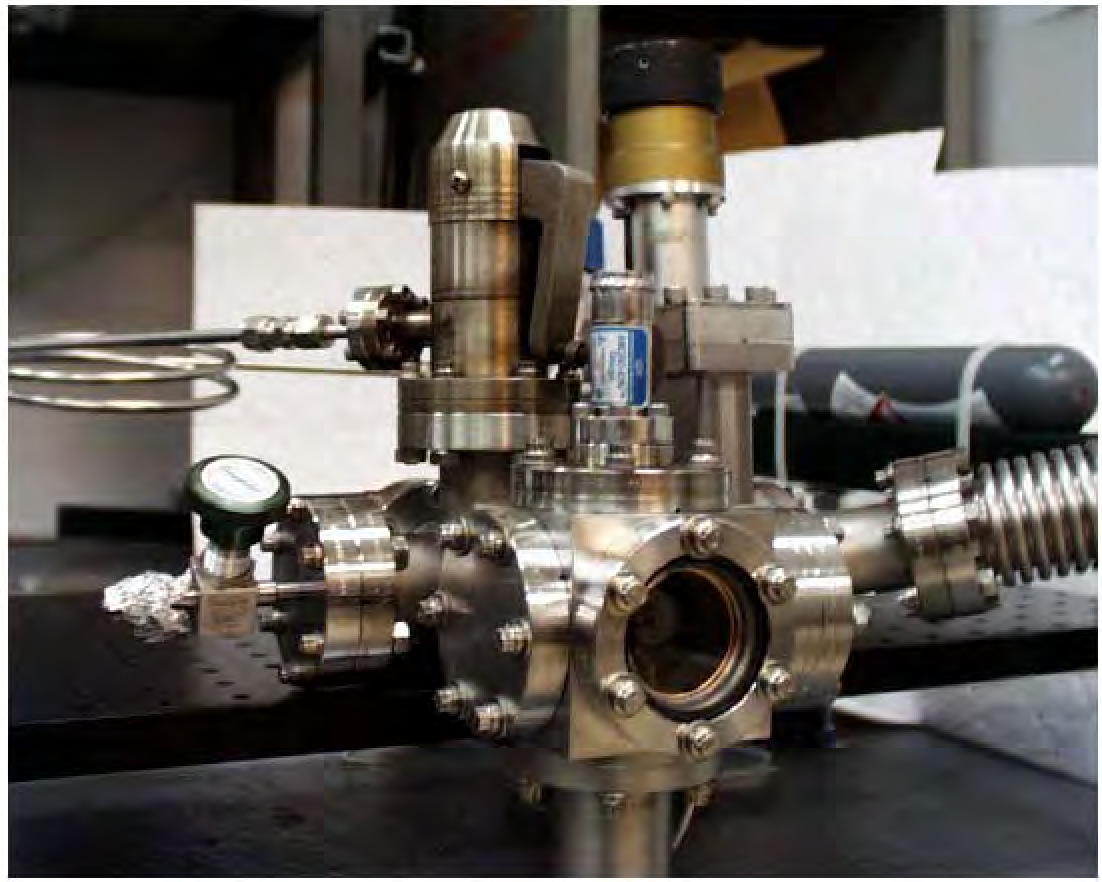
Sample to be heated to > 800 C to remove impurities and free dangling bonds

High vacuum

10^{-6} Torr H_2

W filament to be heated to > 1800 C

Capable of Photoemission measurements



Status: Assembled, being pumped

Cathode For Primary Electrons

QE of 2 and 10% @ 545 & 352 nm

Uniformity over the emitting area

Current density of 250 mA/cm^2 delivered from 100 μm diameter spot

Life time in deposition chamber

Present Status

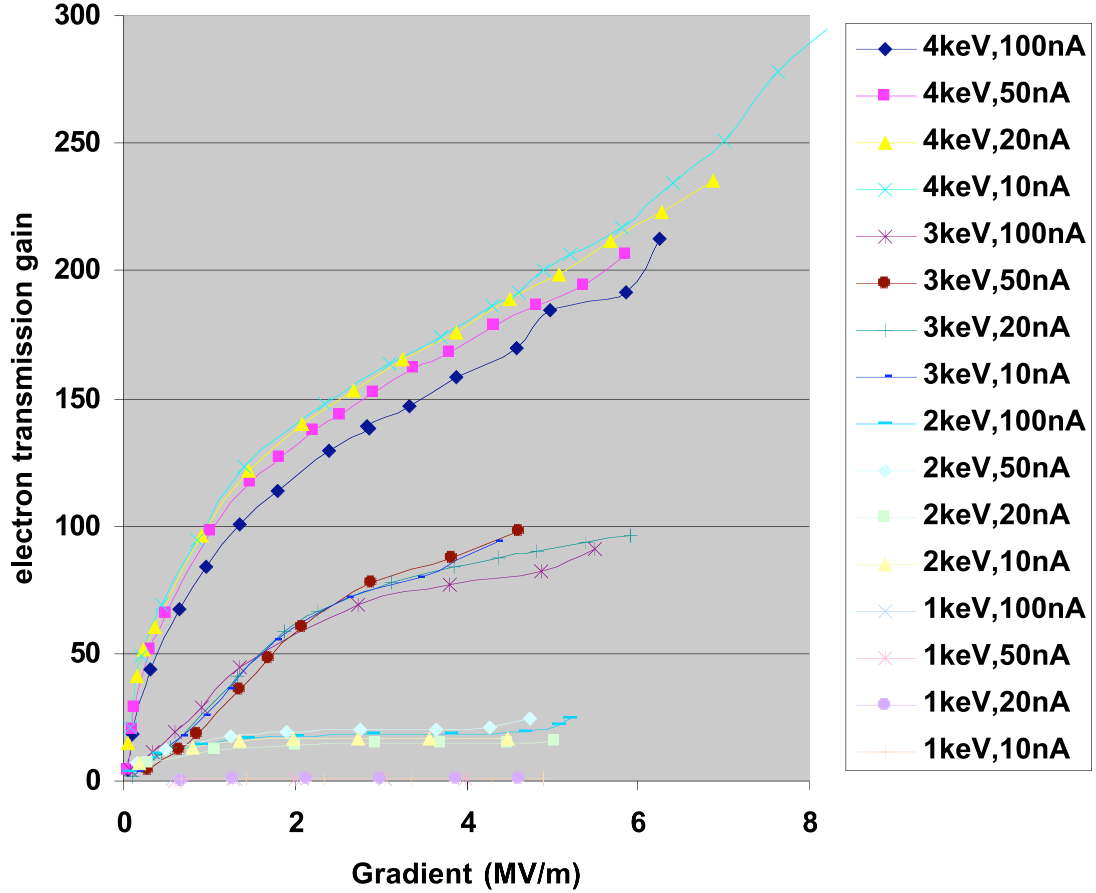
High current generation with excimer and vanadate lasers: measurements limited by space charge, power supply and detector

Deposition system for transmission cathodes

Most recent result: 4% QE @ 545 nm.

•Natural type II A diamond

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



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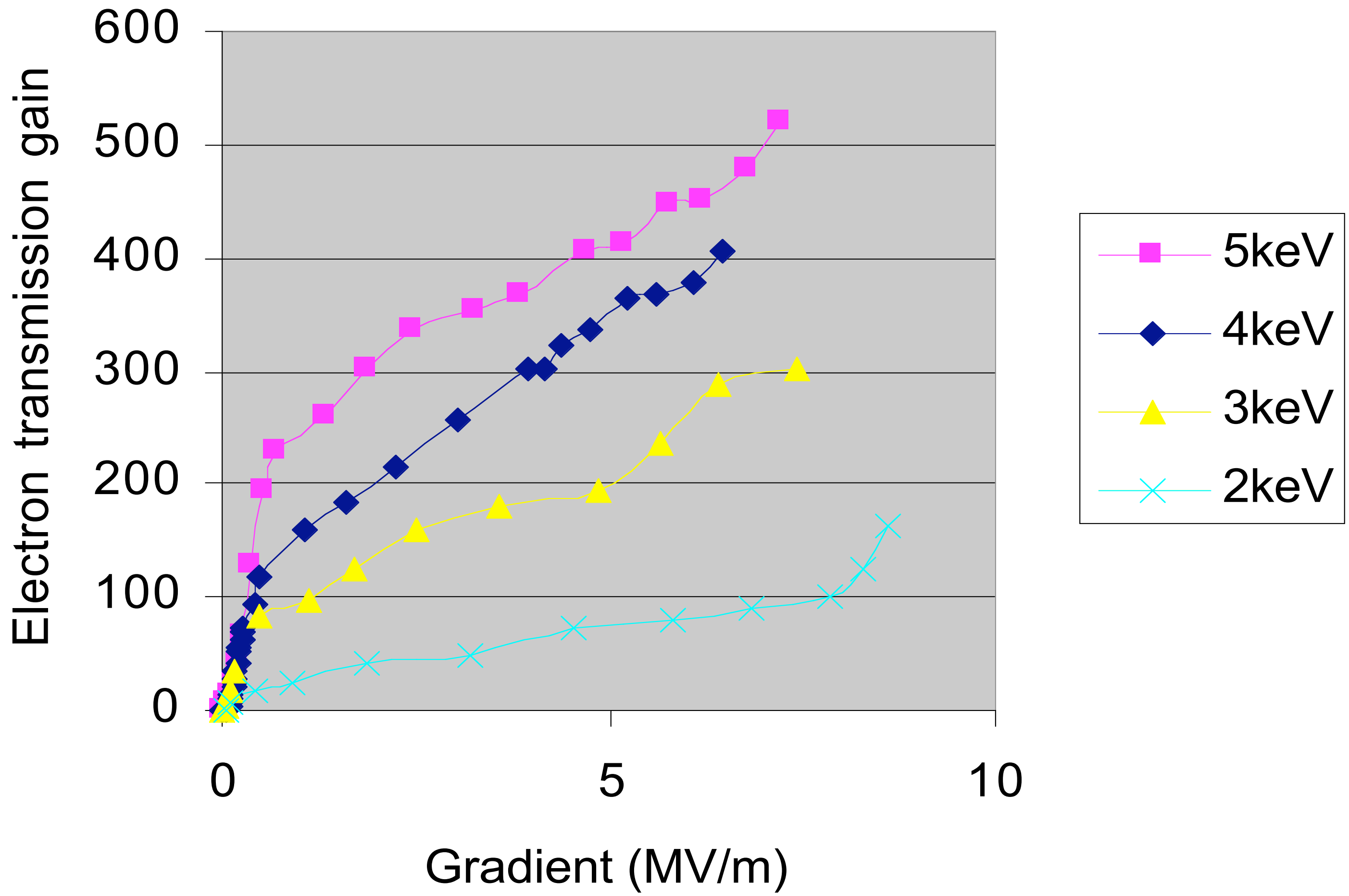
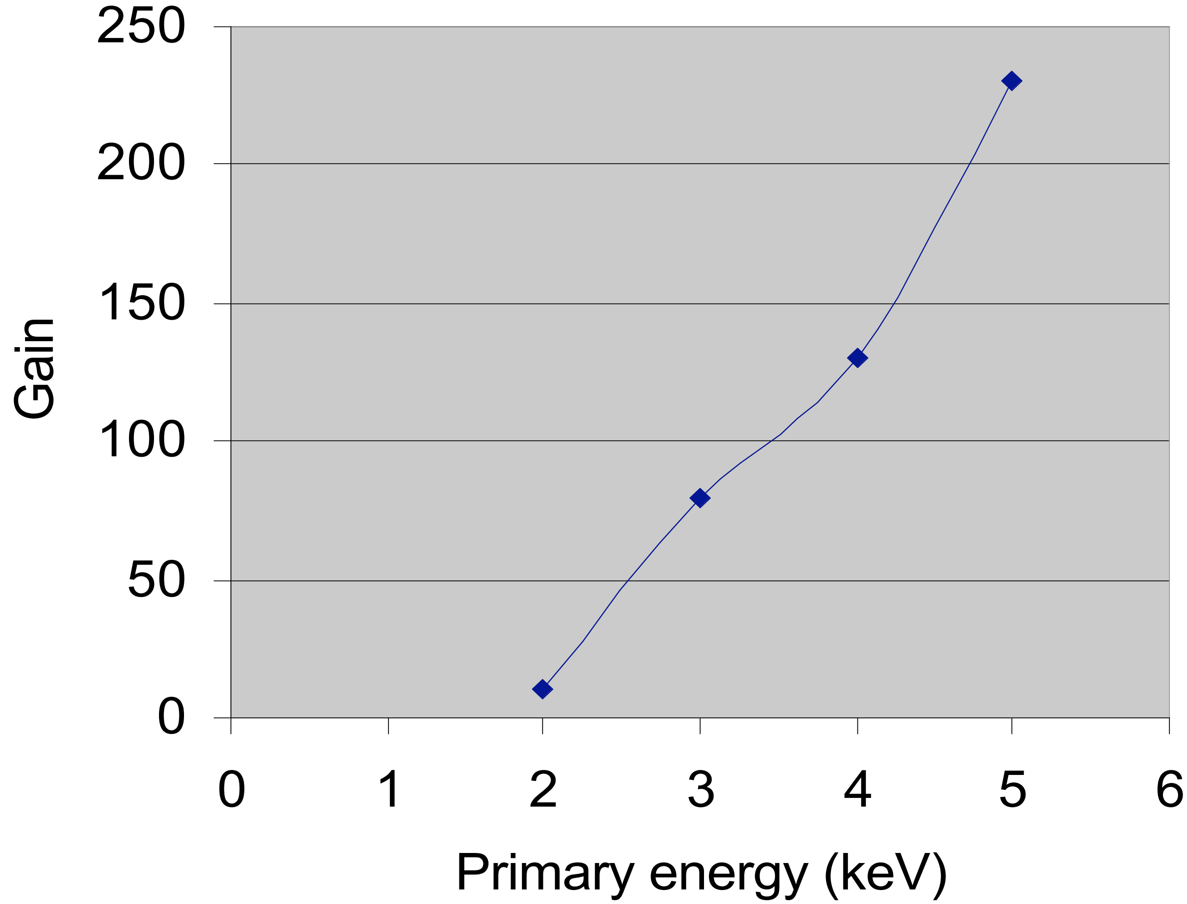
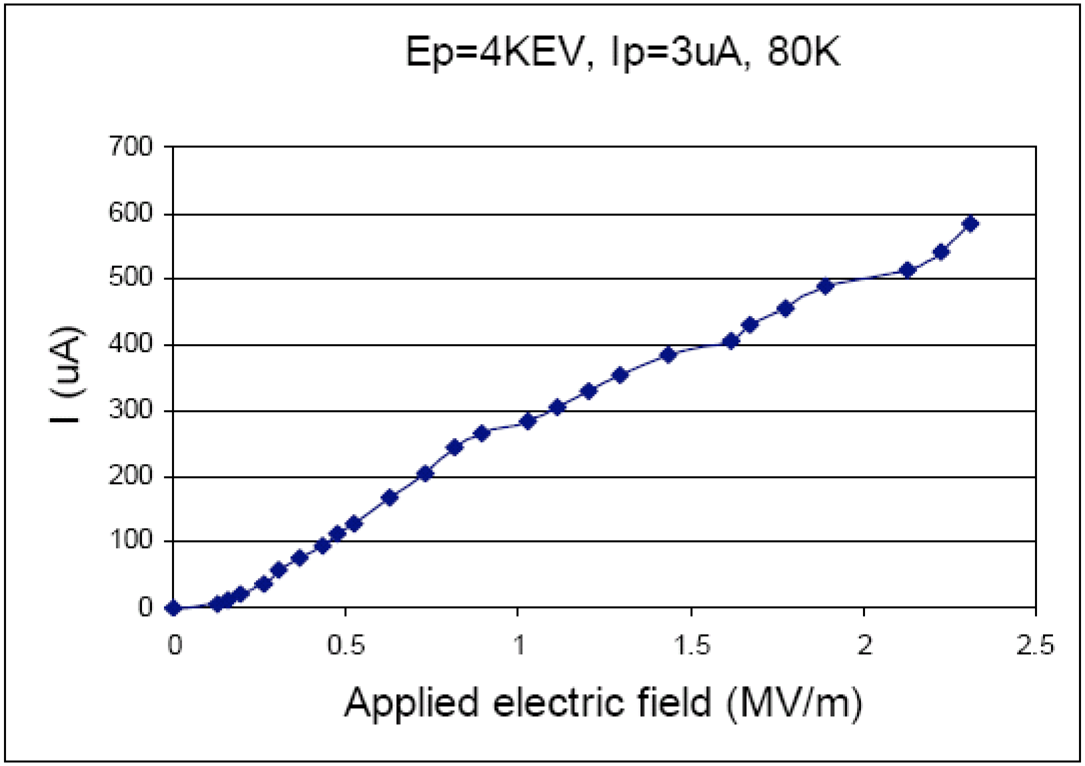
80K



Electron transmission gain
600
500
400
300
200
100
0
0
5
10
Gradient (MV/m)
5keV
4keV
3keV
2keV

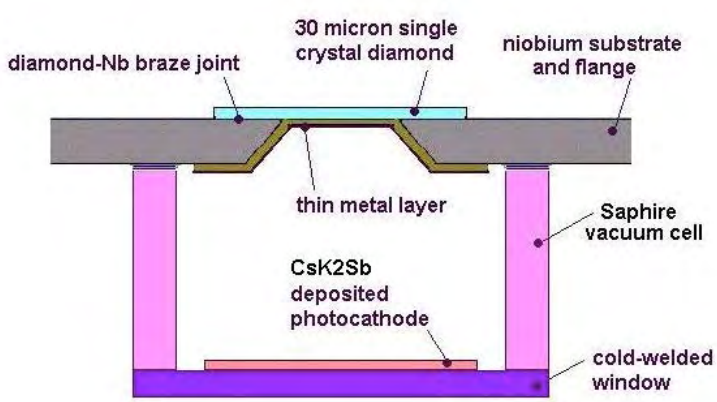

250
200
150
100
50
0
Gain
0
1
2
3
4
5
6
Primary energy (keV)

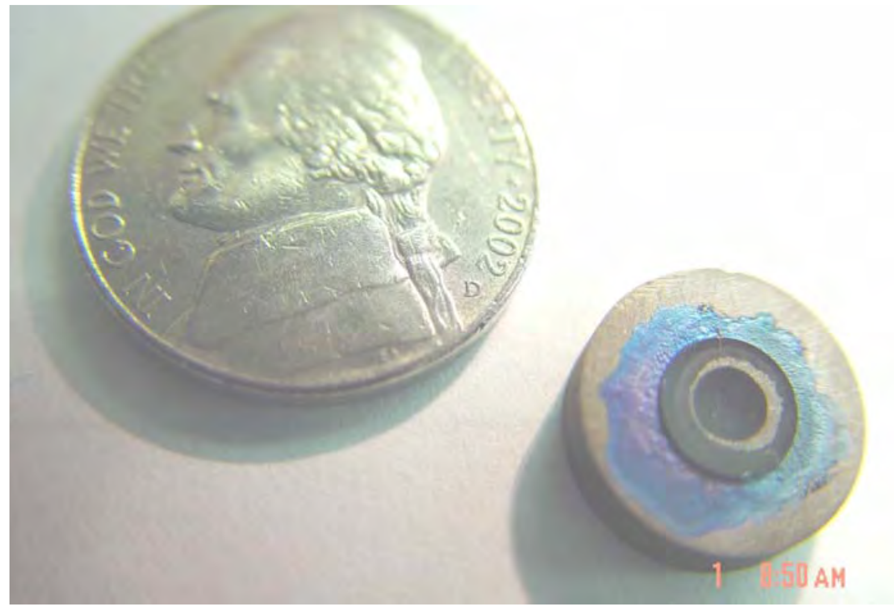
High Current Performance



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

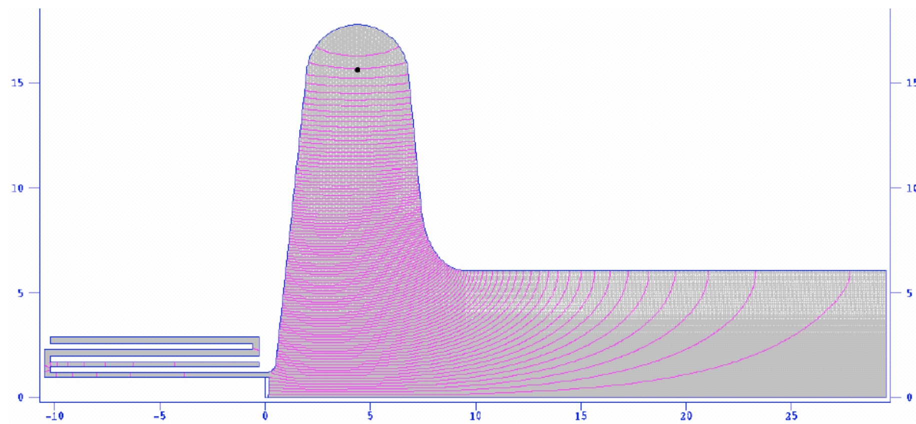
Capsule fabrication

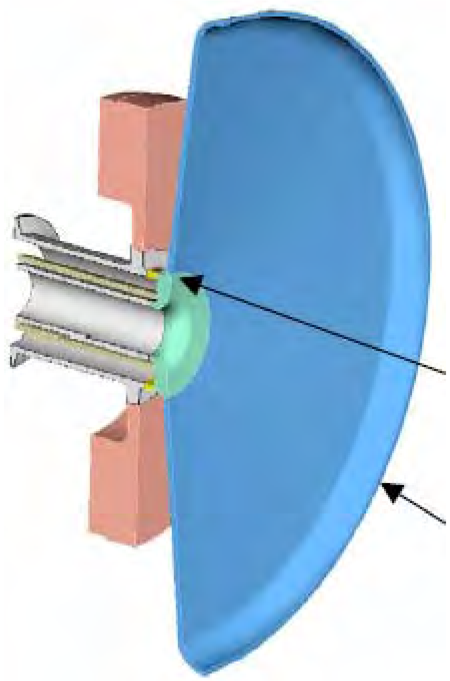




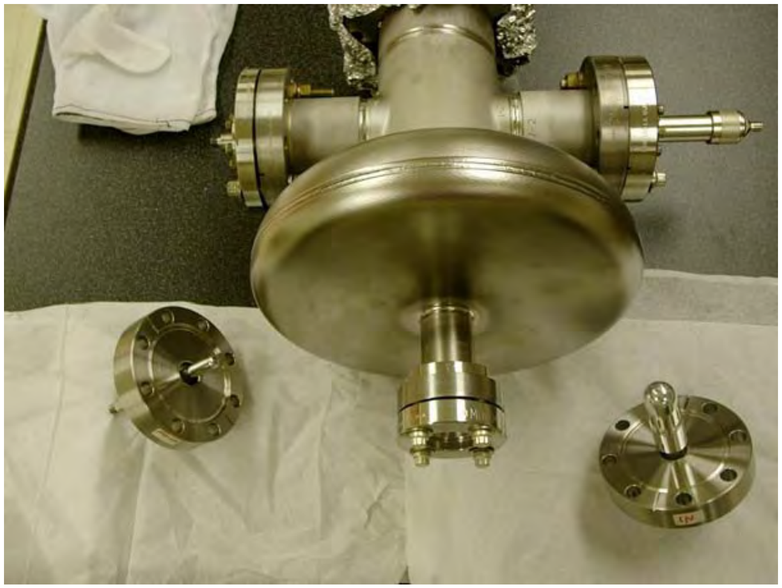
Brazing of a few samples successful. We are working on the subsequent polishing process (requires bracing the diamond), EDM process etc.

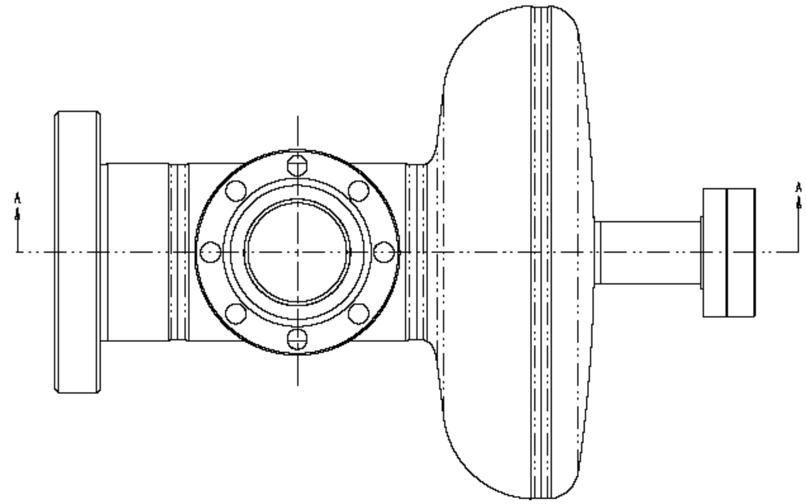
Insertion into the SRF gun

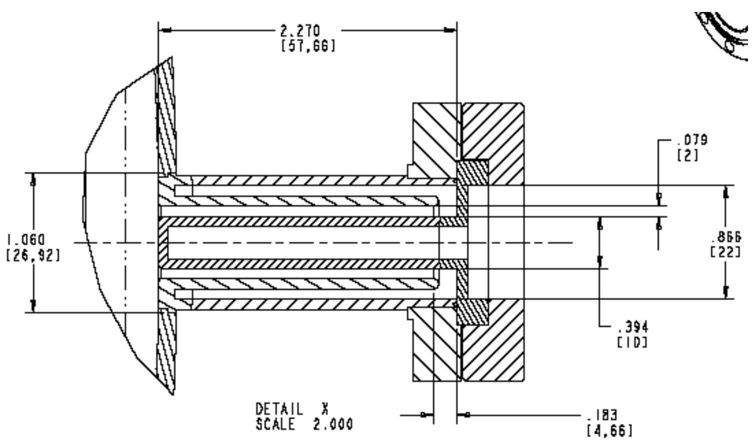




Modification of 1.3 GHz gun for testing diamond capsules







Future Plans

- Improve sample quality V
- Produce ohmic contacts V
- Use thinner sample
- Measure electron transmission V
- Hydrogenize and measure emission V
- 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

Summary

- Simulations and experiments show the feasibility of the diamond amplified photocathode.
- We measured transmission current through various diamond samples, all quite thick. The amplification of primary current is greater than 200, depending on the primary energy.
- We made progress brazing diamonds to niobium for the sealed capsule preparation.
- Initial emission into vacuum results.

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

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