# High Voltage DC Breakdown of Technical Surfaces at PSI

F. Le Pimpec
R. Ganter
PSI

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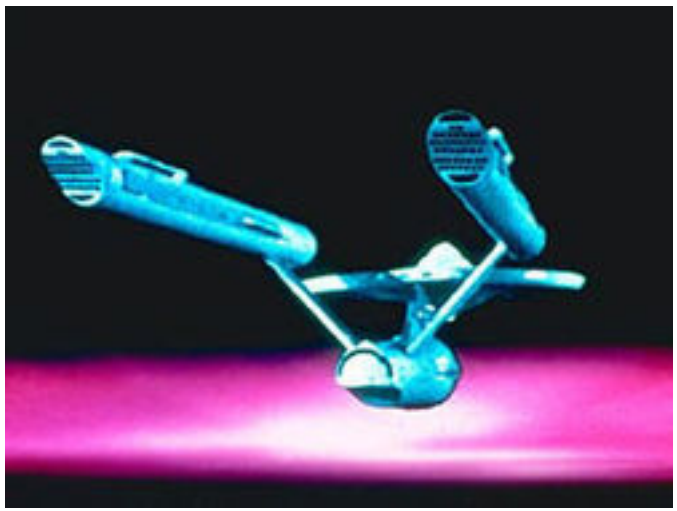
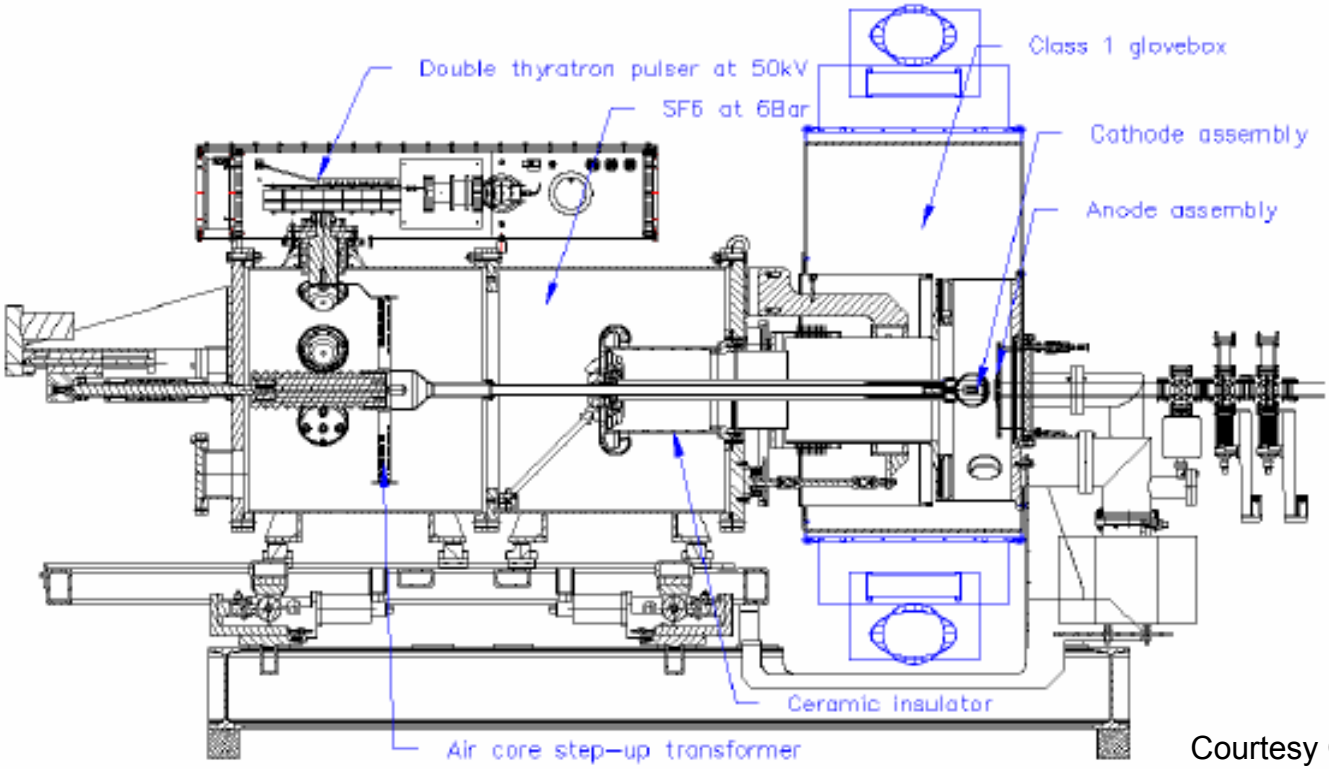
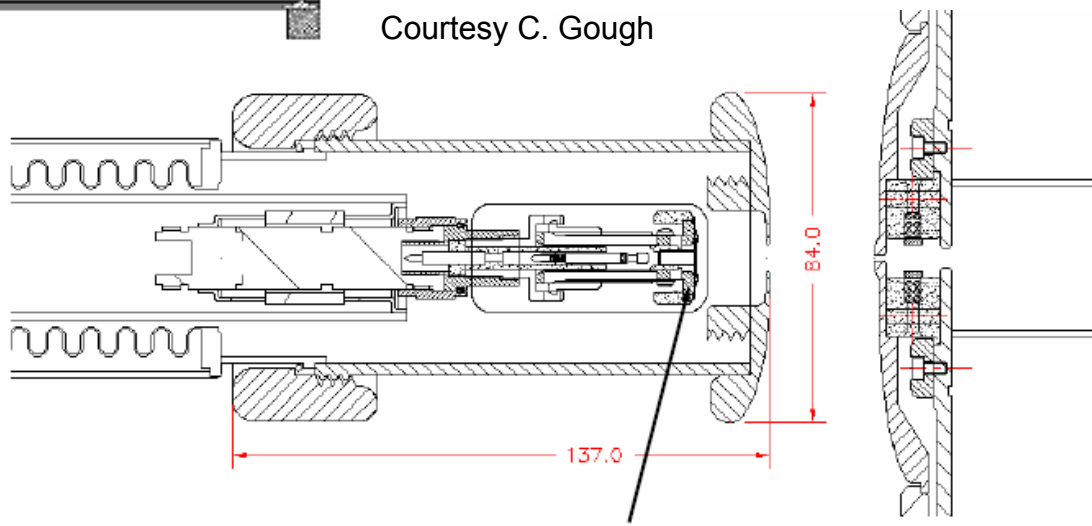
# "To boldly go where no man has gone before"






Building an e⁻ source of low emittance X-FEL application

Courtesy C. Gough




Substrate assembly mounted in cathode holder
External manipulator introduces cathode holder inside cathode assembly
Field emitting array is built into a 6mm silicon wafer

## (-)500 kV Pulser

- 250 ns FWHM pulse length
- Gap 1mm to 4mm

# What materials for the (broad) electrodes ?

- Take the literature (~100 years of research)
- Take the most cost efficient material found
- Mirror finish the material, prepare it, install it
- That should work !!!


| W.Diamond JVSTA 1998 | Cu | Ti | Al | N |
|---|---|---|---|---|
| No FE (MV/m)<br>1 mm gap | 70 | 60 | 85 | 9 |
| Breakdown (MV/m)<br>1 mm gap | 80 | 75 | 90 | 95 |

# Electrodes choice

| Elements | $SEY_{max}$ | $Atm/Ar_{inc}$ (@500eV) | Self Sputter rate @ 500 eV | Young Modulus GPA | Melting Point T °C |
|---|---|---|---|---|---|
| Cu | 1.3 | 2 (2.7) | > 1 | 110 | 1083 |
| Al | 1.0 | 1.05 (1.3) | < 1 | 69 | 660 |
| Au | 1.4 | 2.4 | > 1 | 78 | 1063 |
| Ti | 0.9 | 0.5 (0.6) | < 1 | 116 | 1668 |
| Mo | 1.25 | 0.6 (0.9) | < 1 | 329 | 2610 |
| Zr | 1.1 | 0.65 | < 1 | 68 | 1852 |
| Nb | 1.2 | 0.6 | < 1 | 105 | 2415 |
| Fe | 1.3 | 1 (SS 1.3) | ~1 | 200 | 1536 |

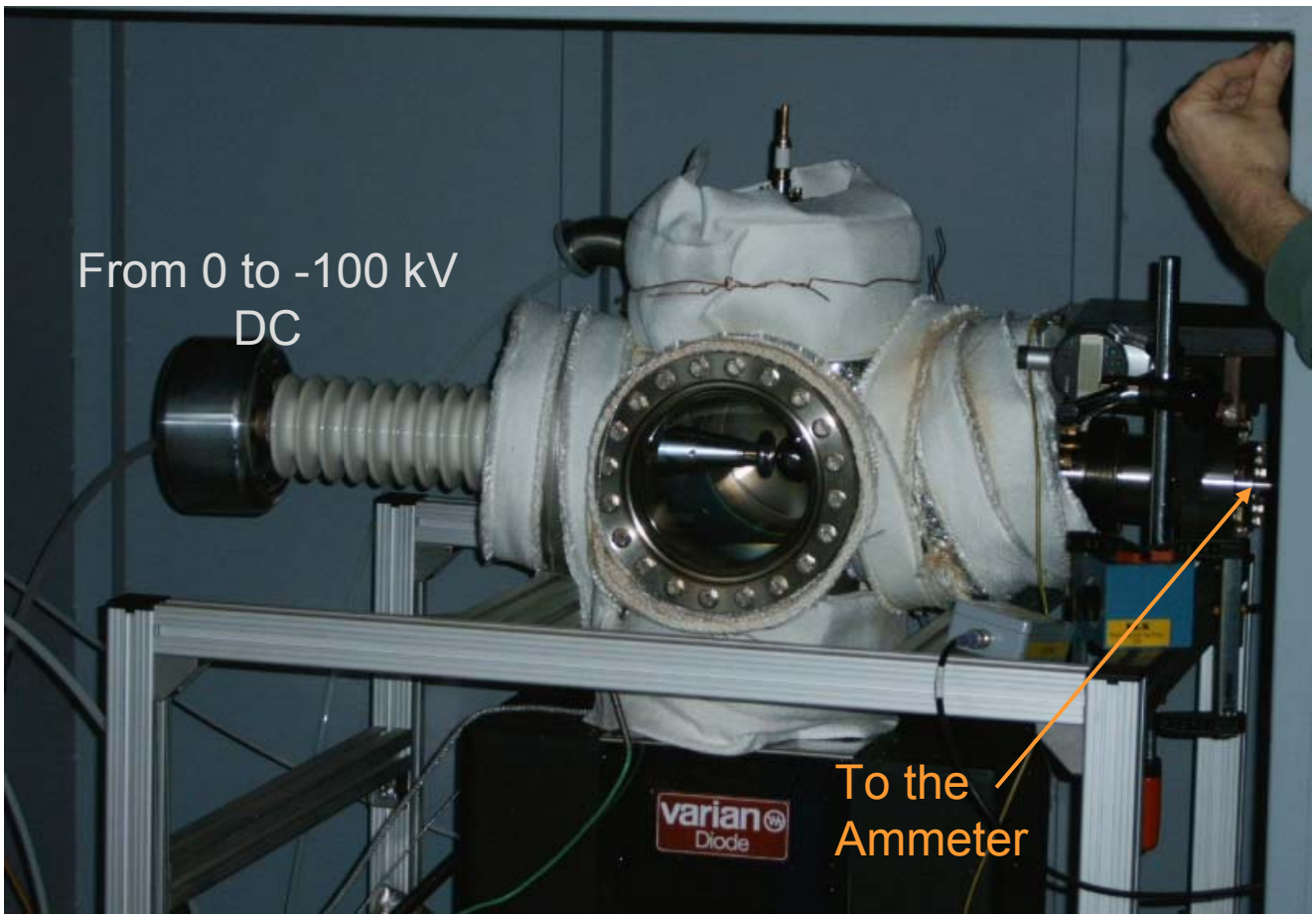
Cu material of choice for accelerators - excellent elect & therm cond

SS – Mo – W did give good results in RF induced breakdown (Au bad…)

Ti : “refractory” – good mechanical properties – low SEY – lousy elect & therm cond

# Dark Current test stand

Finding “quickly” a material and a process that could be used & implemented for the 500 kV pulser electrodes – Get a clue in how to process materials with HG




Flat disk cathode
Ra<0.2 (200nm)

Mushroom Anode
Ra<0.2 (200nm)

Mechanical comparator to measure the Gap between the electrodes

<P> ~$2.10^{-9}$ Torr after a light bakeout
Mid 10 scale after a more thorough bake

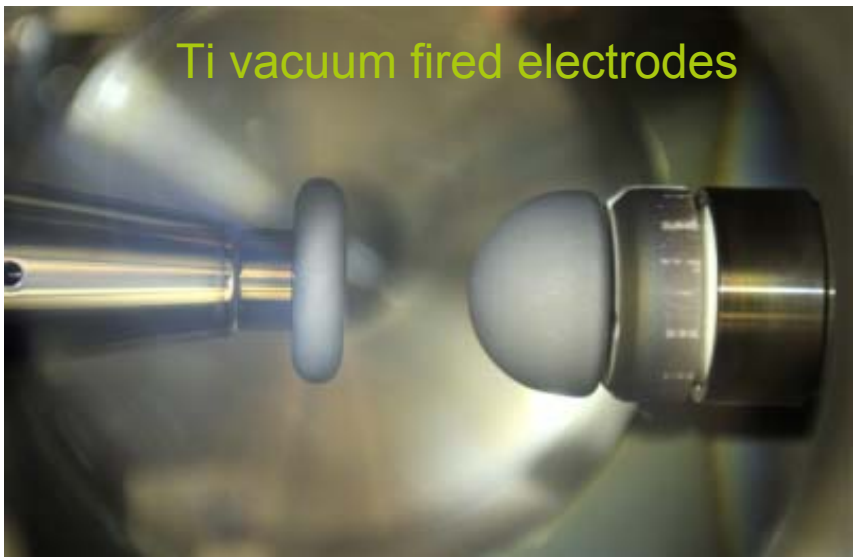
# Electrodes preparation and Installation

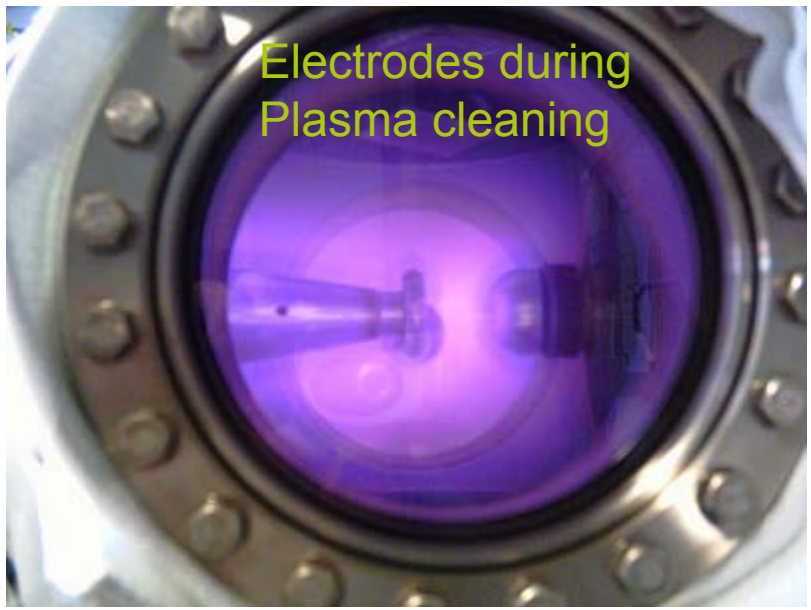
The electrodes are not mirror like finish, machining marks and “scratches” can be seen. All electrodes have been ultrasonically cleaned in an alcohol bath – Acetone was occasionally used beforehand !

Installation is done with normal UHV care – No clean room – *why being so cavalier ?*

After $N_2$/air venting system is fully baked at 170C for 24hour
After plasma glow discharge with noble gas (He , Ar); the IP is baked overnight

Overall P not significant if below ~$10^{-8}$ Torr



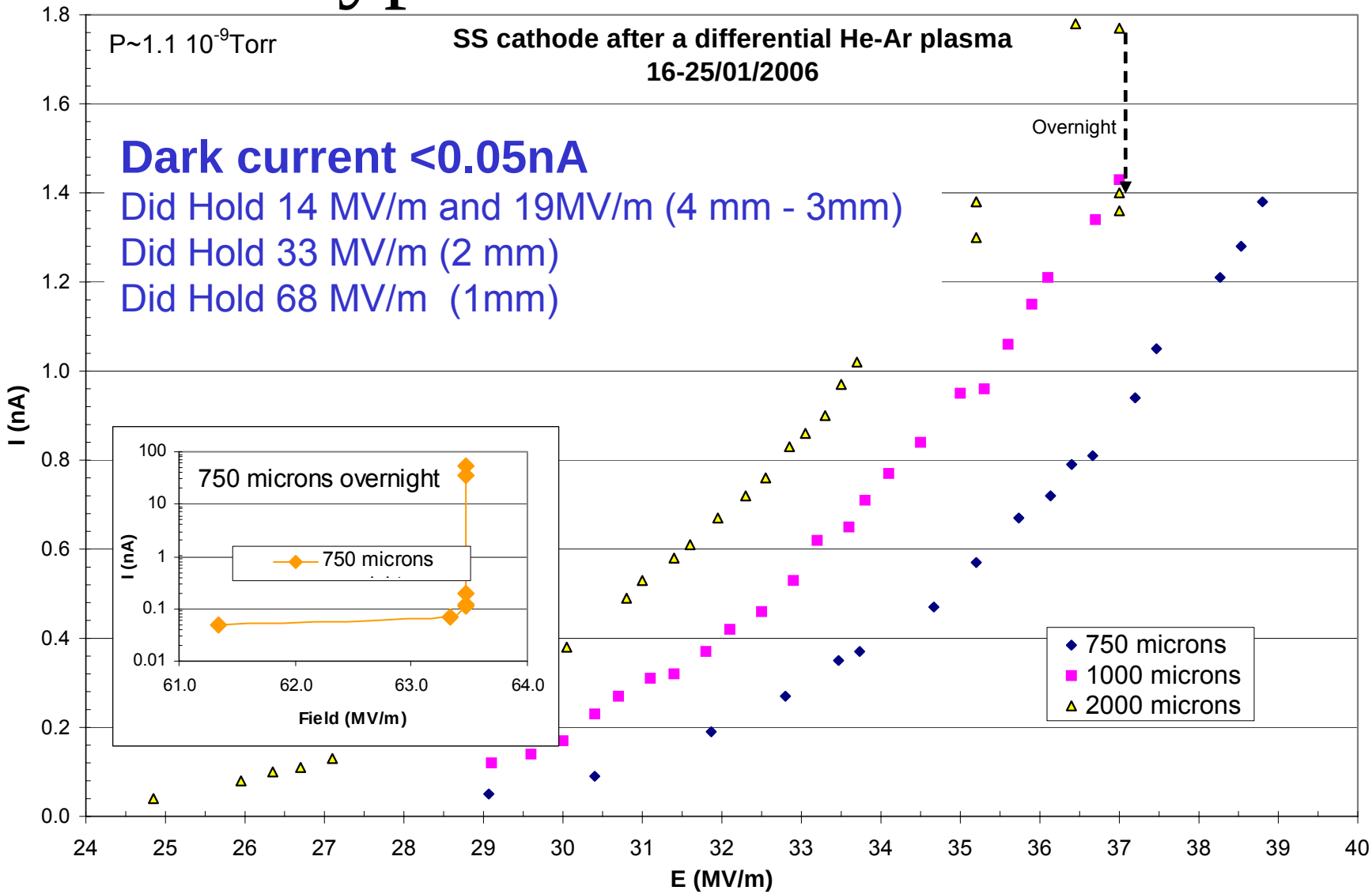
# Electrodes testing

| Cathode | Anode | As received | Plasma He - Ar | $n^{th}$ Plasma |
|---|---|---|---|---|
| SS | SS | Y | Y | "Y" |
| Al | Al | Y | Y | Y |
| Al mirror Fnshd | Al (sme as abv) | Y | Y | Y |
| Cu oxdzd | Cu oxdzd | - | Y | Y |
| Cu Polynox™ | Cu Polynox™ | Y | Y | - |
| Ti | Ti | Y | Y | Y |
| Mo (vac fired) | Mo (vac fired) | Y | Y (Ar) | Y |
| Ti (vac fired) | Ti(vac fired) | Y | Y (Ar) | Y |
| Cu mirror Fnshd | Mo (vac fired) | Y | Y (Ar) | Y |
| Nb | Nb | *Currently* | - | - |

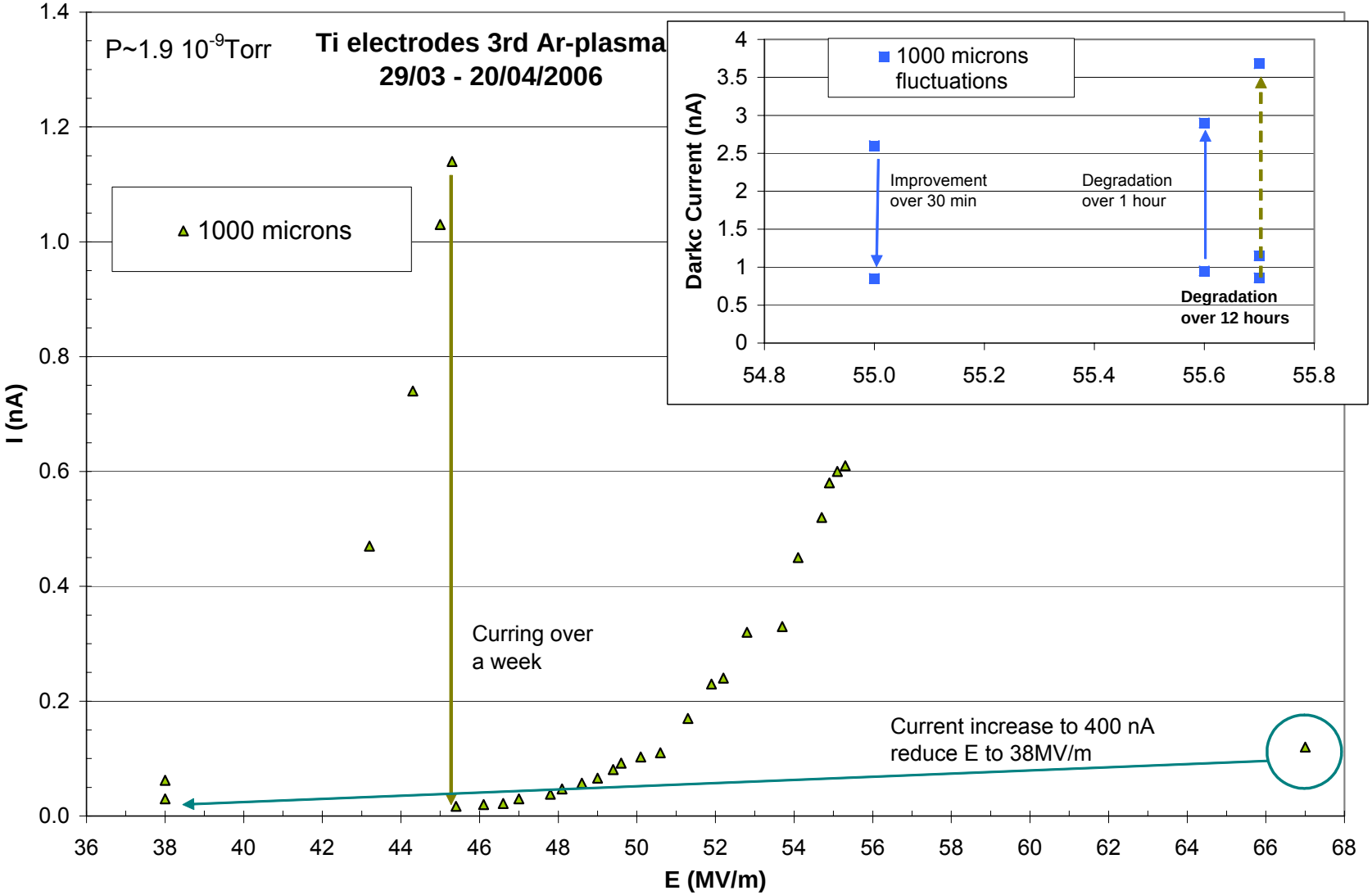
Pure material or alloy like CuZr, CuCrZr, TiAl?

Implant N to harden material (after all I have 100kV to do so) !

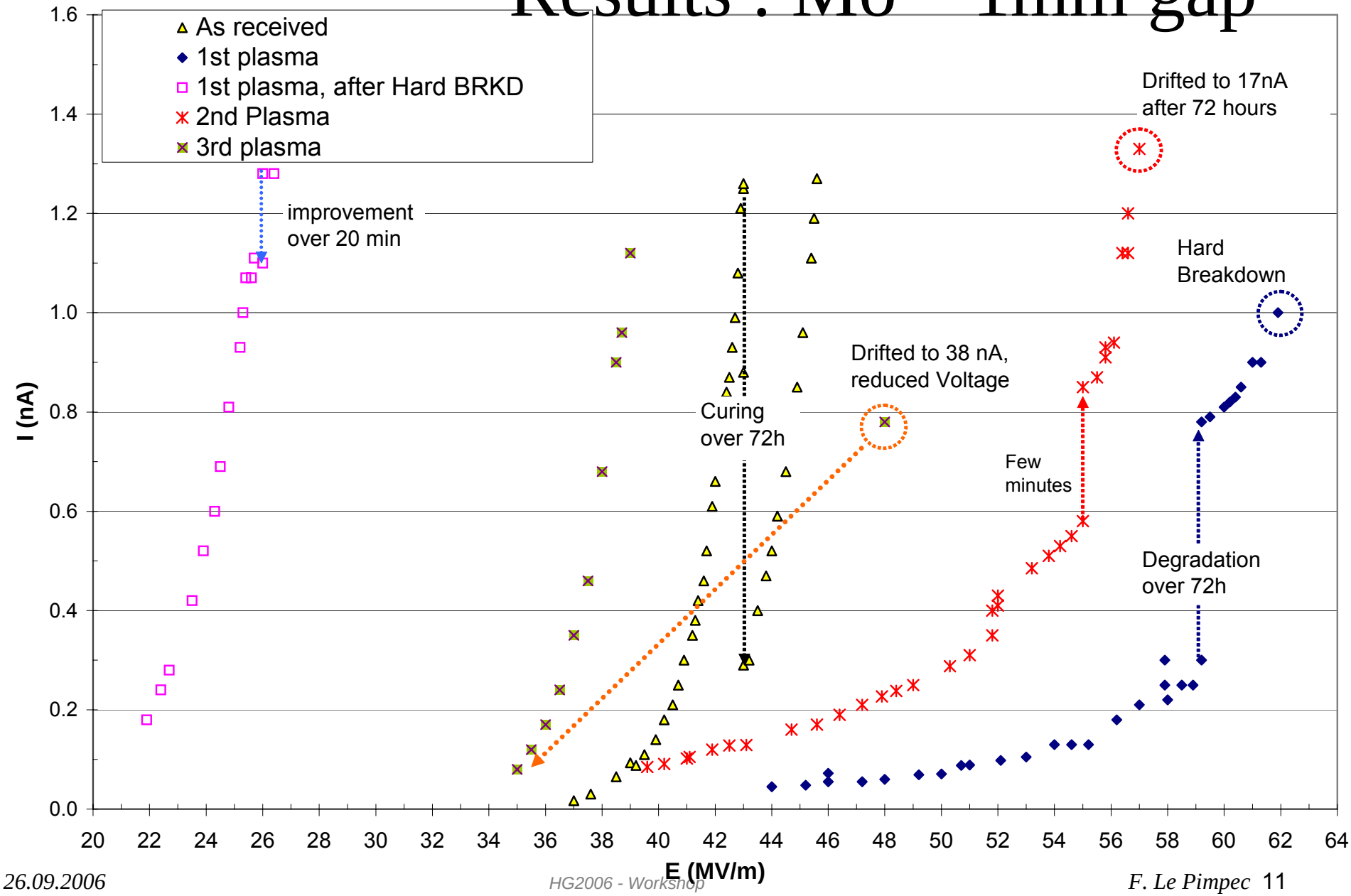
# Results : Typical – Al – SS - Cu



# Results : Ti


P~1.9 10-9Torr
Ti electrodes 3rd Ar-plasma
29/03 - 20/04/2006
1000 microns
Curring over
a week
Current increase to 400 nA
reduce E to 38MV/m
I (nA)
E (MV/m)
1000 microns
fluctuations
Darkc Current (nA)
Improvement
over 30 min
Degradation
over 1 hour
Degradation
over 12 hours

# Results : Mo – 1mm gap



# Results Summary : Before and After breakdown

## Stable Field (MV/m) Obtained at 1 mm Gap

| | Al - Al | | Al mirror finished - Al | |
|---|---|---|---|---|
| State / Dark Current | < 0.05 nA | 1 nA | < 0.05 nA | 1 nA |
| As Received | - | 7.5 | 36 (2 mm) | 29 |
| After Plasma | 52 | 30 | 73 (stable)<br>(92 at 750$\mu$m) | 31 |

Mirror finished Al cathode (Ra ≤ 3nm) - re-use of the damaged Al anode

Cu clean : cleaned with phosphoric acid solution

Cu – Mo : Cu is mirror finished - re-use of the damaged Mo anode (as it seems breakdown is cathode initiated (Al results))

| | Cu oxidized | | Cu clean | | Cu-Mo | |
|---|---|---|---|---|---|---|
| State / Dark Current | < 0.05 nA | 1 nA | < 0.05 nA | 1 nA | < 0.05 nA | 1 nA |
| As Received | - | - | 24 | 26 | 18.2 (*) | 13.8 (*) |
| After Plasma | 32 | 29.3 | 55 | 19 | 21.6 | 25.4 |

(*) at 3mm gap

# Results Summary 2: Before and After breakdown

## Stable Field (MV/m) Obtained at 1 mm Gap

Mo electrodes (Vac fired)

| Dark Current / State | < 0.05 nA | 1 nA |
|---|---|---|
| As Received | 37 | 45.2 |
| After Plasma | 44 | 61.3 |

Spark processing in order to get the gradient shown

Ti

Ti (vac fired)

| Dark Current / State | < 0.05 nA | 1 nA | < 0.05 nA | 1 nA |
|---|---|---|---|---|
| As Received | 50 | 46.6 | 29.6 | 32.5 |
| After Plasma | 63 | 67 (0.1nA) | 39 | 41.4 |

SS

best material so far

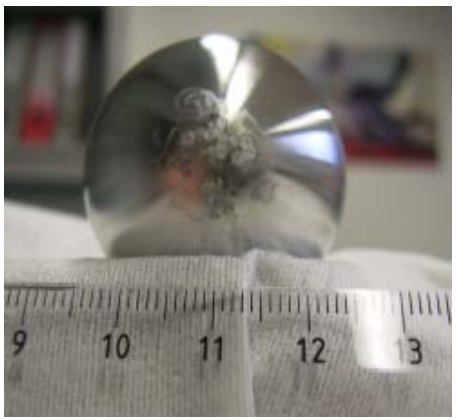
| Dark Current / State | < 0.05 nA | 1 nA |
|---|---|---|
| As Received | 40 | 42.5 |
| After Plasma | 68 | 35 |

Heating treatment tend to improve HV holding. A problem with a vacuum furnace, and you will get disappointing results.

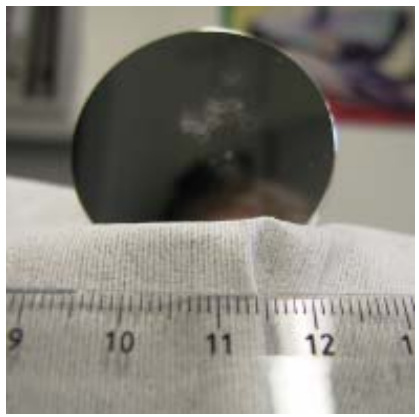
# Electrodes Damages


Mo (vac fired) cathode

Al anode

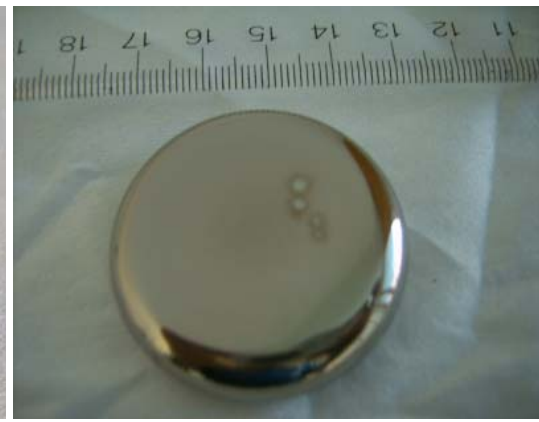


Al mirror finished cathode



Cu cathode

Ti cathode



# Damages on vacuum fired Mo


# Some criticism…

Data can be fitted with FN law - No Study of the β variation vs treatment !

$$I = A \cdot \frac{1.5 \cdot 10^{-6}}{\Phi} E_s^2 \cdot e^{\frac{10.4}{\sqrt{\Phi}}} \cdot exp\left(\frac{-6.83 \cdot 10^7 \Phi^{\frac{3}{2}}}{E_s}\right)$$

Sure but during treatment the work function will change. Φ varies with the chemistry and the crystal orientation, and on broad electrodes contaminants, what means comparing β then ?

Procedure used is repetitive and comparable, but the experiment is in some way not controlled !

True ! System looks stable (a day) and a breakdown might happen and cure itself or kill the electrodes when no one watch over ! – Cure : get a feedback ! We won't do it ! The pulser is the next "test stand" and will be fully interlocked

Surely there are some more…

# Electrode Processing : Conclusions

Patience over time is a key ingredient to get those field – current value drift from a given set point, can be important ! That doesn't lead necessary to breakdown …

For hard events, damages can be irreversible. No plasma recovery !!

| Material (at 1mm gap) | SUS/SS | Cu | Ti | Mo | Mo-Ti | Al | Nb |
|---|---|---|---|---|---|---|---|
| Furuta et al. (1 nA) | 36 | 47.5 | 88 | 84 | 103 | - | - |
| Diamond (no FE) | - | 70 | 60 | - | - | 85 | 92 |
| This work (<0.05 nA) | 68 | 55 | 63 | 44 | - | 73 | - |

Noble gas plasma looks like an efficient way to get or recover the gradient “without” dark current.
Other plasma can be efficient, but beware of the chemistry !

Combination of Mirror finished electrodes, and Noble plasma treatment should be a good combination to reach higher gradient (no great discovery there)

# Acknowledgement


- R. Betemps
- Kugler GMBH for providing the mirror finished surfaces