CLIC Breakdown Workshop

Ion Current from Breakdowns in RF Structures

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Outline

-Set-up

-Measurements

- General observations

-Results

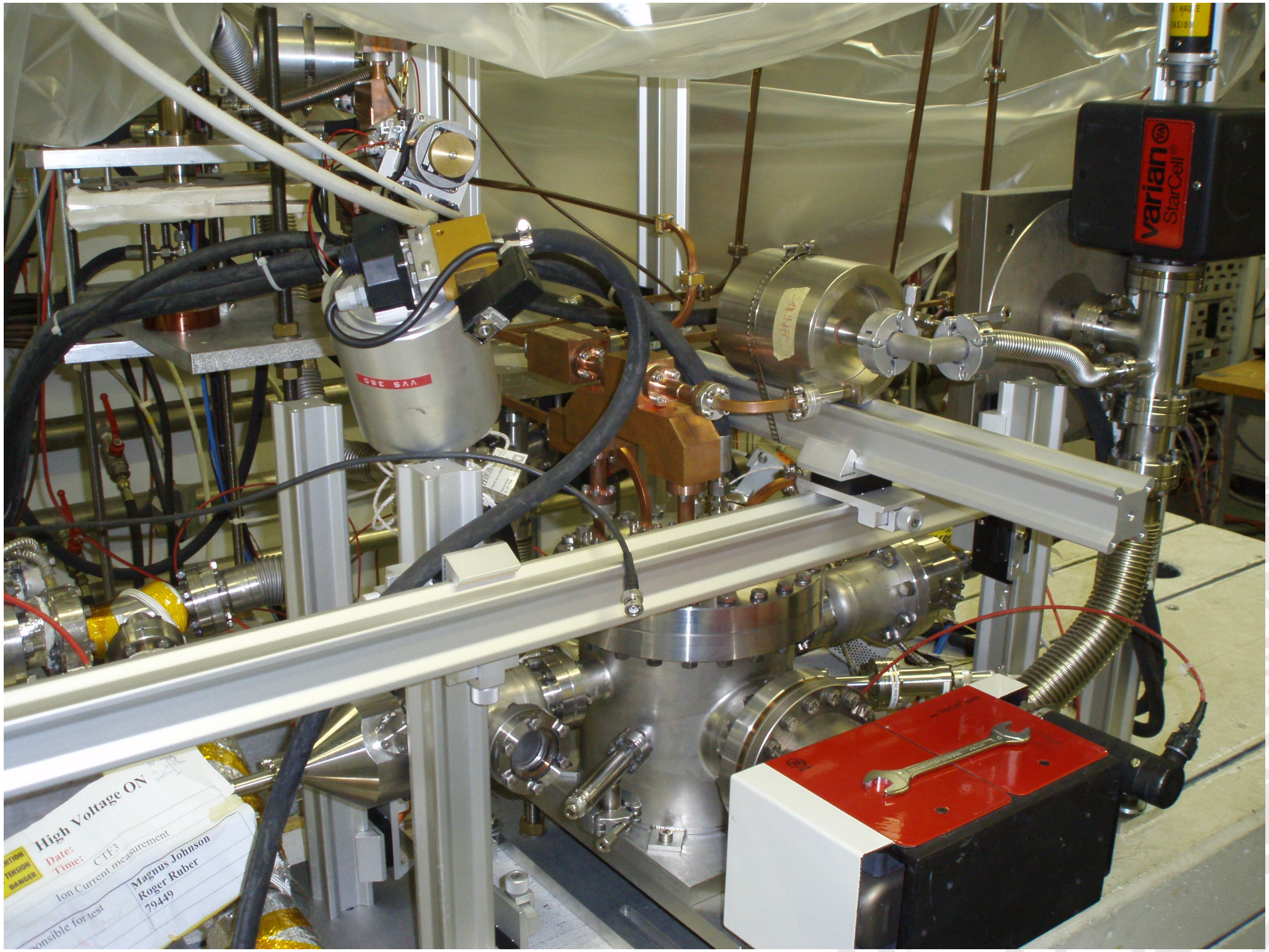
- Analytical calculations: results and limitations
- Estimations of breakdown site size

-Surface analysis of FC

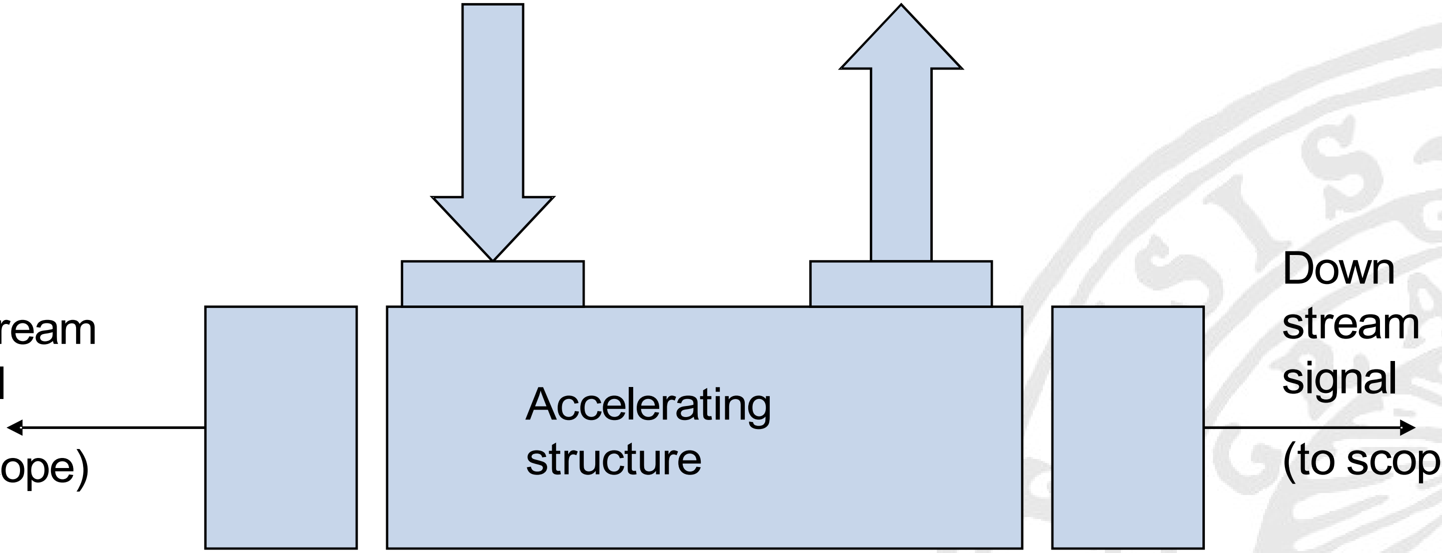
- Results, comparison with ion current measurements

-Conclusion

30 GHz test-stand



Setup



RF in

RF out

Up stream signal

(to scope)

Accelerating structure

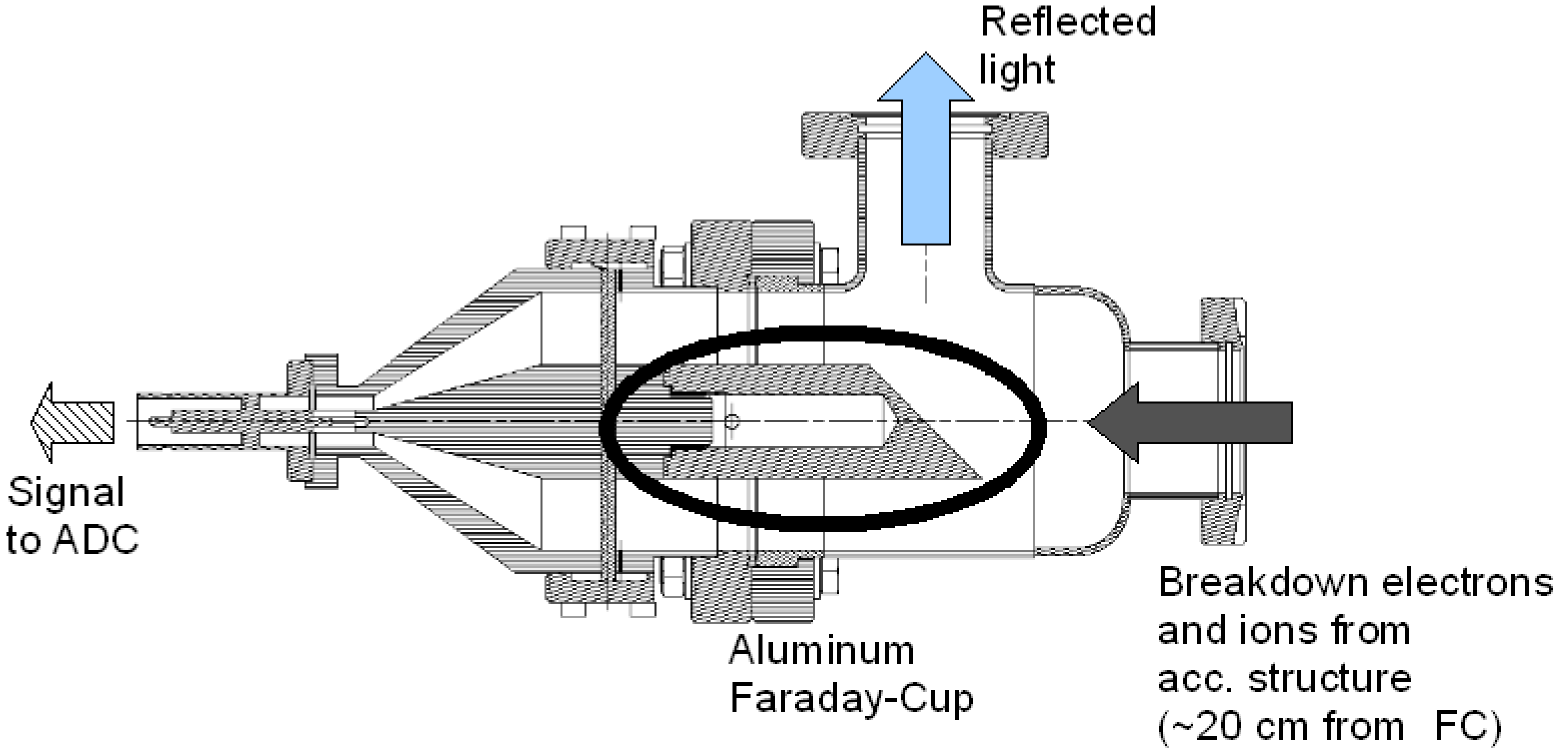
Down stream signal

(to scope)

‘Upstream’ FC

‘Downstream’ FC

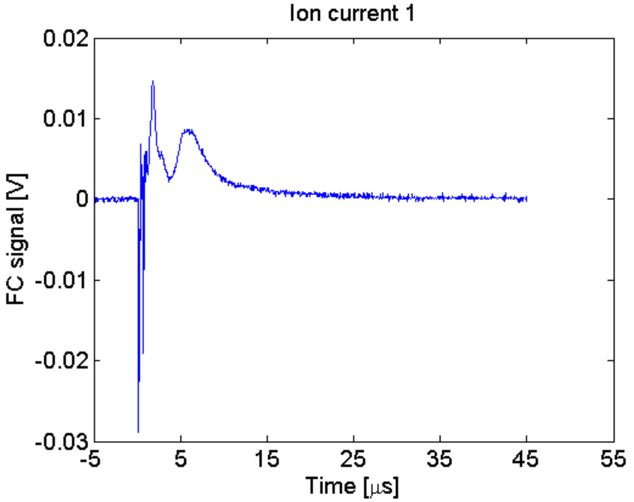
Faraday-Cup


Reflected light
Signal to ADC
Aluminum Faraday-Cup
Breakdown electrons and ions from acc. structure (~20 cm from FC)

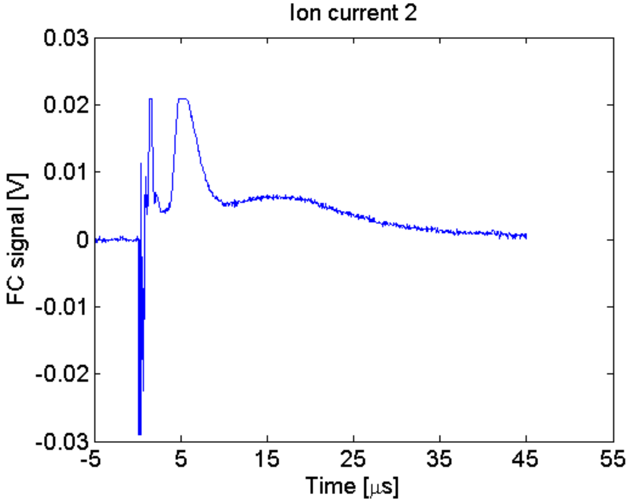
Measurements

- Data acquired in 2007:
  - August 20th – October 8th (**HDSthick**)
  - November 1st – December 14th (**NDSthick**)
- **6700** ion current events recorded
  - Significant ion currents detected after 40% of breakdown events (overall).

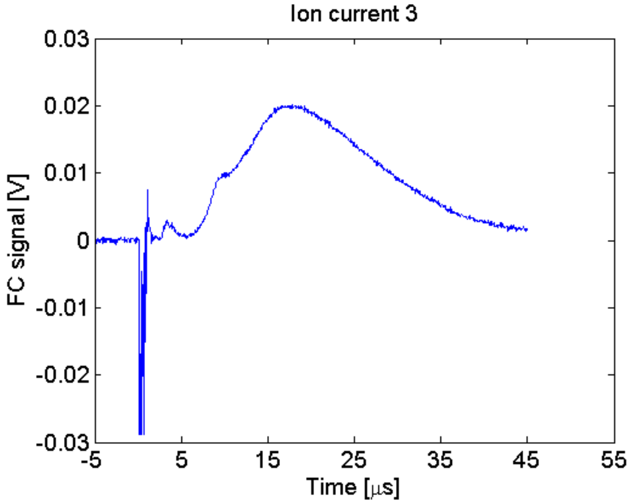
Sample ion currents



Ion current 1



Ion current 2



Ion current 3

- Triggered on e$^-$ signal
- 5 μs delay
- Ion currents detected on 30-70% of all breakdown events.
- No obvious dependence on RF, conditioning time etc....

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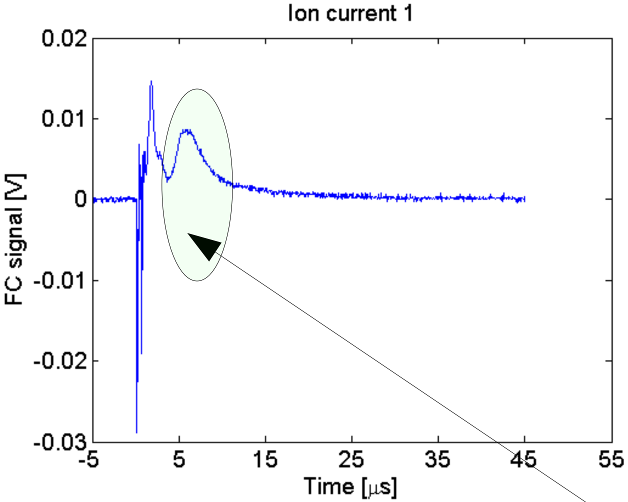
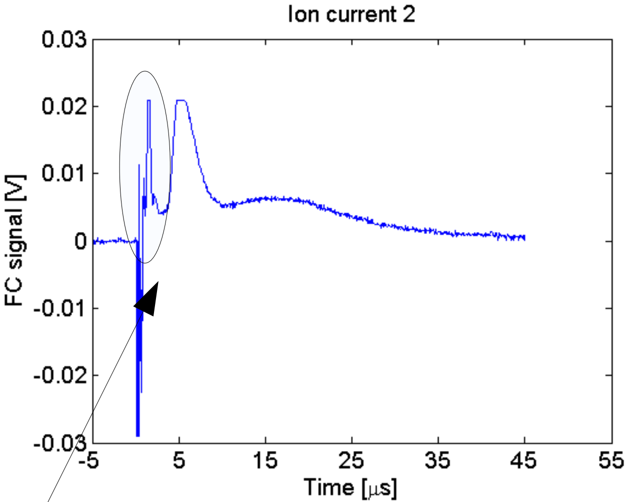
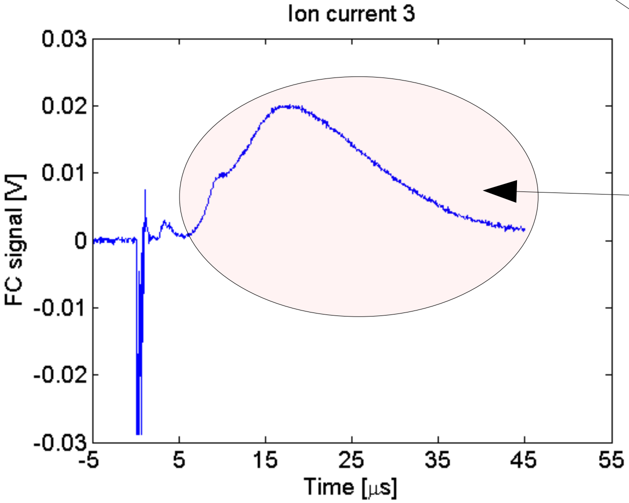
Sample ion currents







- “Fast” signal
- “Medium” signal
- “Slow signal”

Multiple ionization states?

Multiple ion spices?

Multiple breakdown sites?

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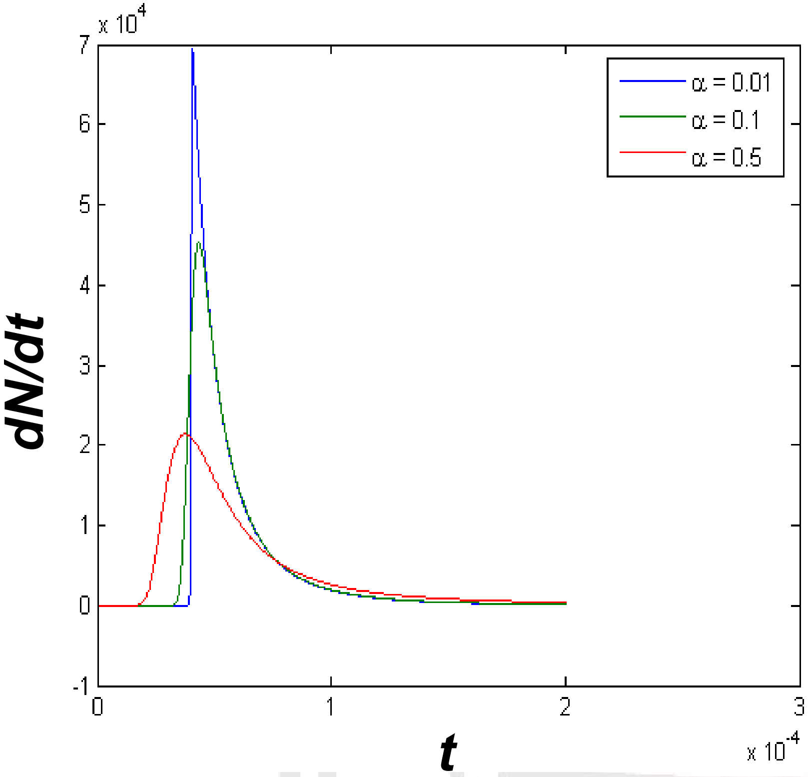
Analytical calculations – Coulomb explosion

Arrival time spectrum from hot Coulomb explosion:

$$\mathbf{dN/dt} = f\,(\,N_0,\ \alpha,\ t_s,\ t\,)$$

(Ziemann NIM. A 575 (2007))

- $\mathbf{N_0}$ = number of particles in sphere.
- **α** = relative importance Coulomb forces vs thermal motion, allows for calculation of temperature **T**
- $\mathbf{t_s}$ = arrival time of fastest ions from cold distribution. Determine time of peak.
- **t** = time



Theory - Applied

How does this fit measured ion currents?

Fit of events with one peak works well.

Events with several peaks can be fit with a simple sum.

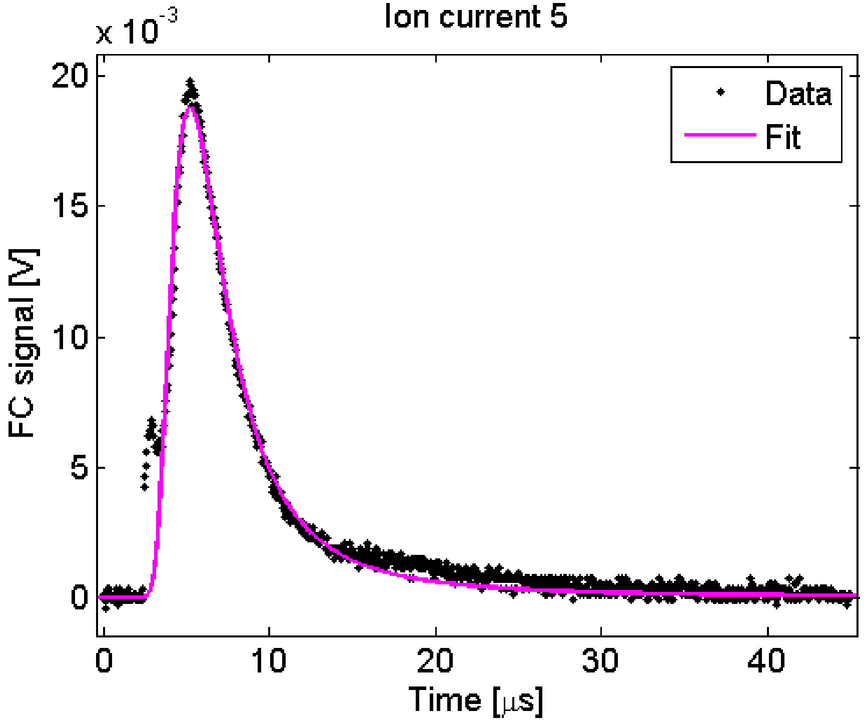
Theory *does not* work for different masses/charge states....

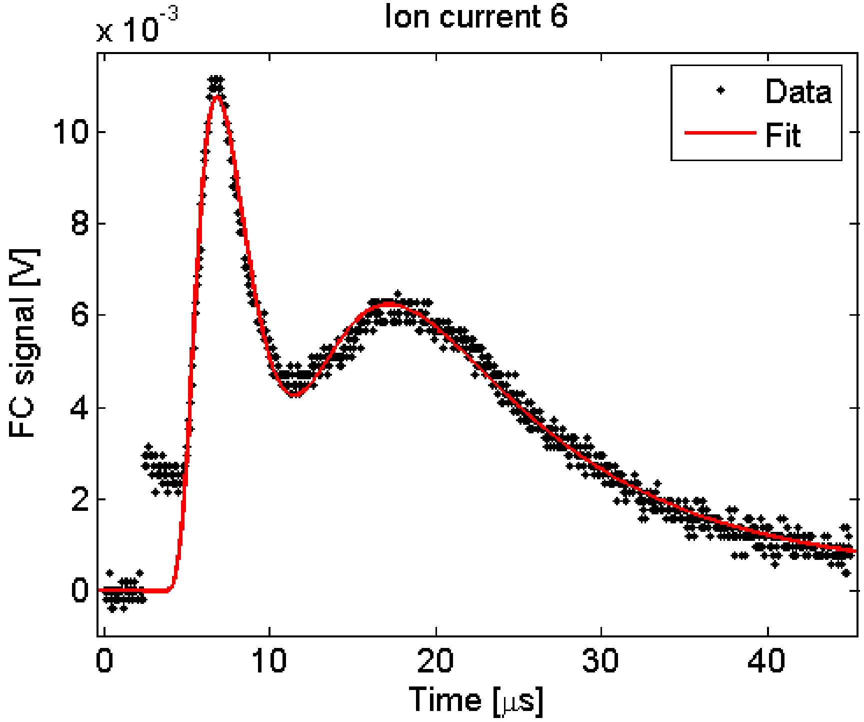
....which we maybe see in the measurements....

....thus need

- *Simulations
- *Experimental means to measure charge-mass ratio (e.g dipole magnet)

Theory - Fit





$N0 = 1.32 *10^{10}$
$\alpha = 0.4128 \rightarrow T = 900\,000$ K
ts =5.2 μs

$N0_1 = 1.61*10^{10}$ ts1 = 19 μs
$N0_2 = 0.75*10^{10}$ ts2 = 6 μs
$\alpha_1 = 0.52 \rightarrow T = 115\,000$ K
$\alpha_2 = 0.27 \rightarrow T = 312\,000$ K

Results – breakdown site size

- Average number of particles reaching FC per ion current event **$\sim 10^{10}$**.

- **10^{13}** ions in each breakdown site (FC covers 1/1000 of total solid angle).

- This is equivalent of a copper cube with **5** µm side.

XPS result

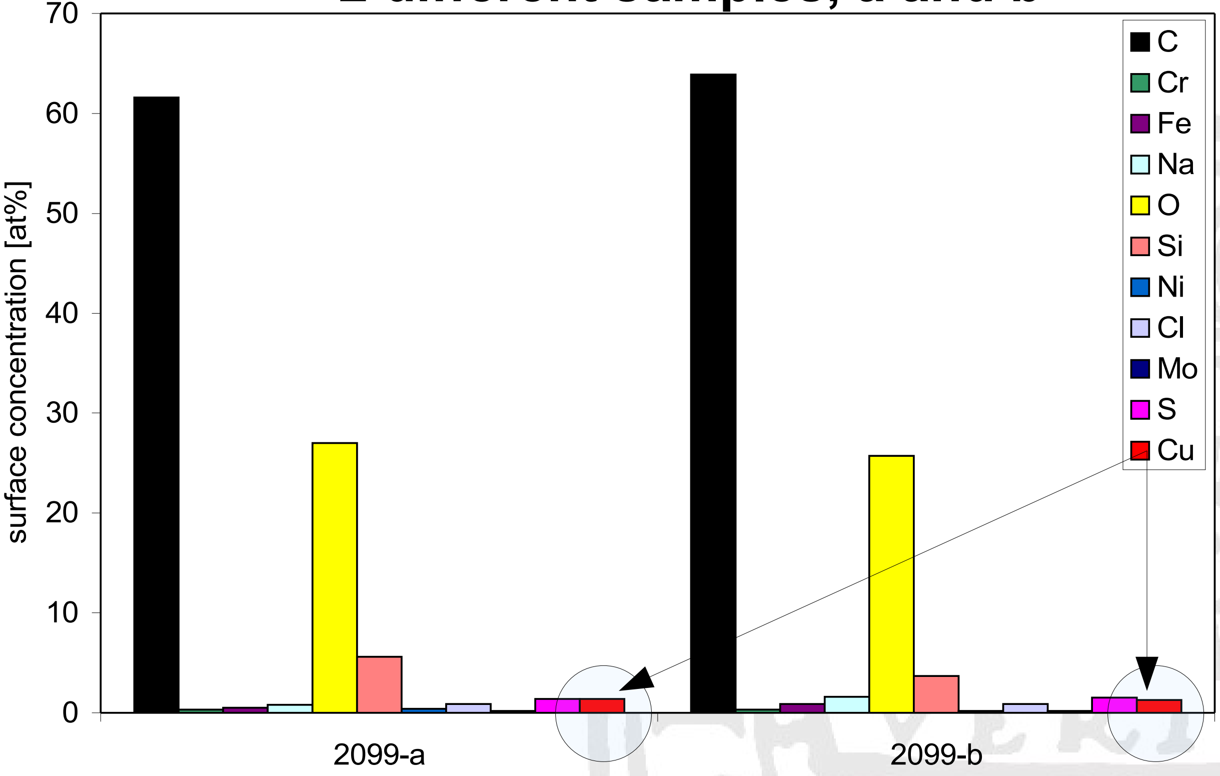
Where is the copper?

Visual inspection of FC:
no copper.

Bulk sensitive analysis:
no copper.

Surface sensitive analysis, XPS:
copper!
(thanks Mauro, Delphine and Luigi!)

“Upstream” FC,
2 different samples, a and b



Comparison XPS – number of particles

XPS analysis:

We still see some of the bulk material

- Assume a nm thick layer of copper (could be 0.3 – 3 nm), homogeneously distributed on FC surface
- → **$8*10^{-12}$ kg copper / mm^2**
  (Again: Thanks Mauro!)

Ion current measurements:

Mean number of ions per ion current event

- ≈ 10^{10} ions (assuming singular ionized)

Assume 10^6 ion current events (total for all copper structures)

- → **$1.38*10^{-12}$ kg copper / mm^2**

Conclusions

Ion current events have 3 components

- “Fast”, “Medium” and “Slow”
  - Multiple breakdown sites?
  - Multiple ion spices?
  - Multiple ionization states?

Hot Coulomb explosion theory gives nice fits...

- ...but does not describe multiple ion spices or ionization states
  - -Simulations needed (*work in progress*).
  - -Add spectrometer to 30 GHz test stand?

Amount of copper seen on FC with XPS is consistent with estimations from ion current measurements

Fin

Arrival time spectrum – hot Coulomb explosion

Arrival-time spectrum *dN/dt* given by:

$$\frac{dN}{dt} = \frac{3N_0\alpha^2}{\sqrt{\pi}\,t_s}\left(\frac{t_s}{t}\right)^2 V_2\left(\frac{1}{\alpha}, \frac{1}{\alpha}\frac{t_s}{t}\right),$$

where the function V_2 with input arguments *w* and *s* is given by:

$$V_2(w,s) = \frac{s}{2}e^{-s^2} - \frac{s+w}{2}e^{-(s-w)^2} + \frac{\sqrt{\pi}}{2}\left(s^2 + \frac{1}{2}\right)(erf(s) - erf(s-w)).$$

$$N_0 = \frac{4\pi\rho R^3}{3}$$

N_0: Number of particles in initial sphere,

ρ: the number density of initial sphere,

R: the radius of initial sphere.

3 free parameters:

$$\alpha = \sqrt{2}\sigma / v_s,$$

$$\sigma = \sqrt{kT/m}$$

α: RMS width of thermal velocity distribution divided by v_s,

k: Boltzmanns constant,

T: the temperature of the initial charge distribution,

m: the mass of the ions.

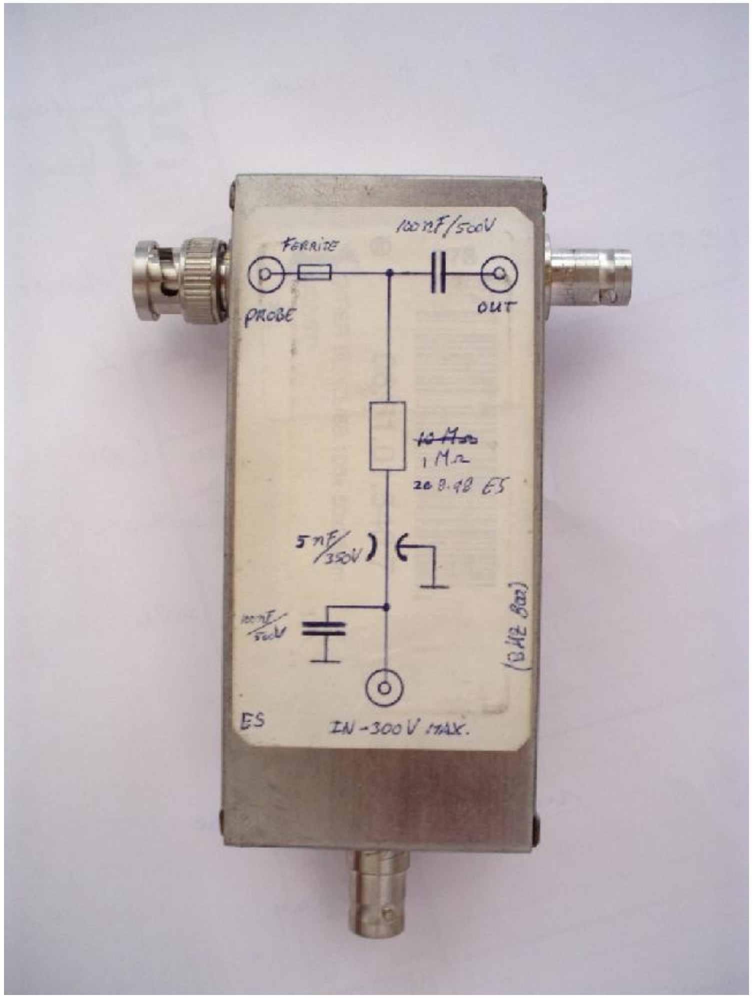
$$t_s = L / v_s$$

t_s: arrival time of the fastest ions from cold distribution,

L is the distance from the detector to the Coulomb explosion,

v_s is the velocity of the fastest ions from a cold Coulomb explosion

HV bias box



FC (left) sees a high-pass filter with cut-off frequency of 1.5 Hz

HV (bottom) sees a low-pass filter with cut-off frequency of 1.5 Hz

Signal out (right) is decoupled by a capacitance, and has 0 bias voltage.

Cu and Mo properties

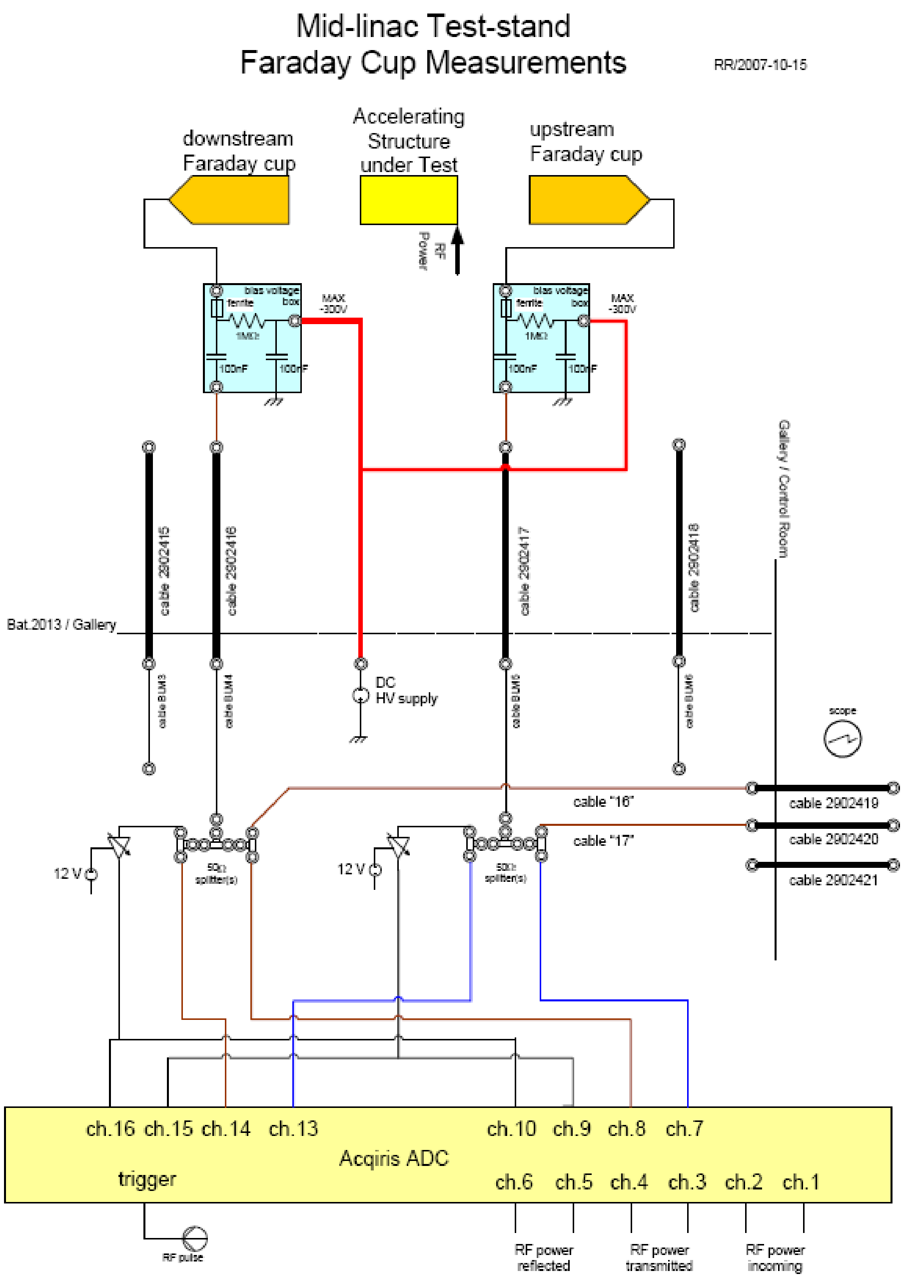
- Boiling point
  - Cu: 2855 **[K]**
  - Mo: 5830 **[K]**
- Heat of vaporization
  - Cu: 4.75 **[MJ/kg]**
  - Mo: 6.83 **[MJ/kg]**
- Energy per RF pulse ~ 1 **[J]**
  - enough to vaporize order of 1 mg material
  - 1 mg copper corresponds to a sphere with radius R=0.3 **[mm]**
- Ionization energy
  - Cu: E_{ion} = 7.478 **[eV]**
  - Mo: E_{ion} = 7.099 **[eV]**
- Temperature needed to ionize Cu:

$$E_{ion}=(3/2)*k_B*T_{ion}$$

$$\rightarrow T_{ion} = 2*E_{ion}/(3*k_B)$$

$$\approx 100\ \mathbf{[kK]}$$

Signal Schematic



Mid-linac Test-stand
Faraday Cup Measurements

RR/2007-10-15