Diamond detectors R&D at LAL

V. Kubytskyi, S. Liu, D. El Klechen, P. Bambade,
C. Rimbault, F. Bogard, F. Wicek, D. Jehanno

ADAMAS, 3-4 December, 2015

Our principal DS activity

Beam halo measurements at ATF2. Vertical and horizontal DSv.

ATF2 is prototype of **Final Focus System for ILC.** FFS to validate local chromaticity correction and to **focus the beam at** nanometer **level at the IP.**

Goals of ATF2

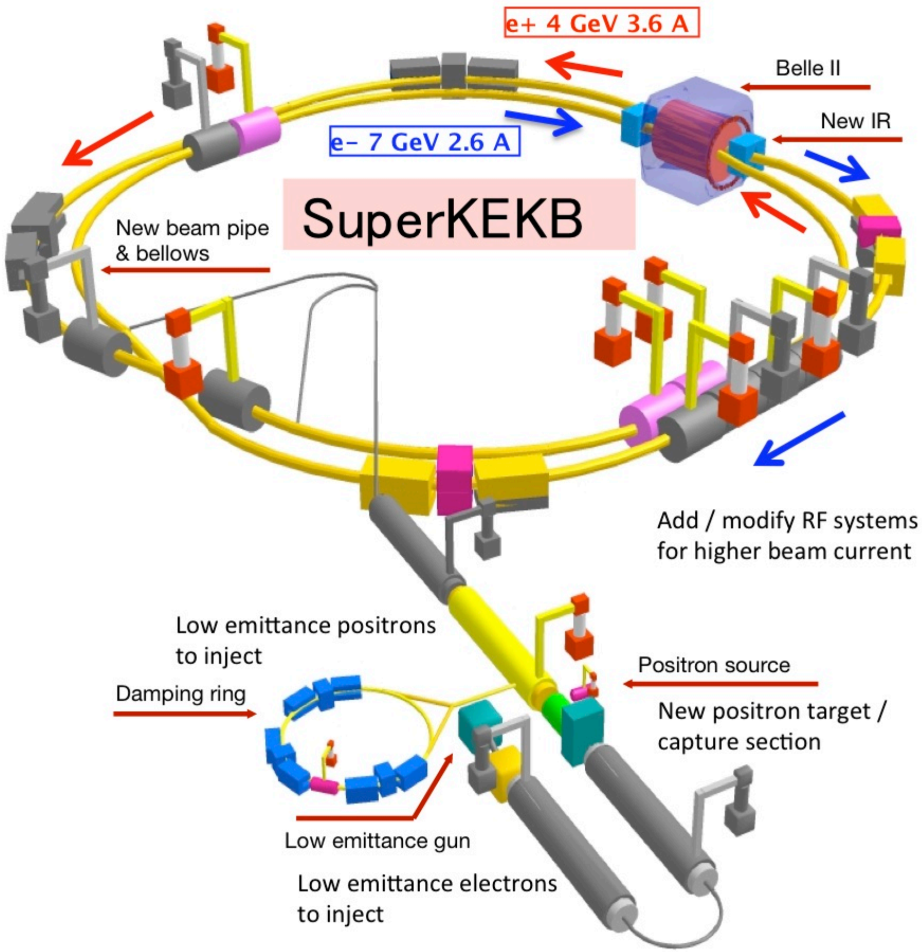
- ***goal 1—achieving the 37 nm design vertical beam size at the IP***
- ***goal 2—stabilizing the beam at that point at the nanometer level***

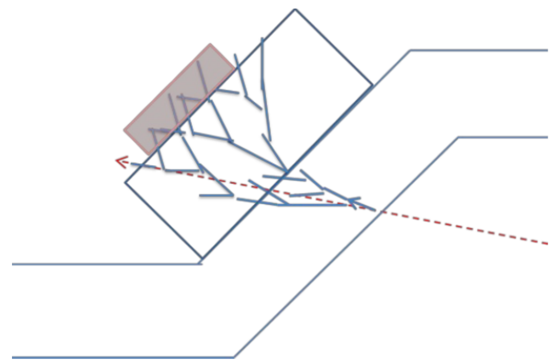
ILC and ATF2 Comparison

Parameter	ILC	ATF2
Beam Energy [GeV]	**250**	**1.3**
Energy Spread (e^+/e^-) [%]	**0.07/0.12**	**0.06~0.08**
Final quad – IP distance (L^*) (SiD/ILD detector) [m]	3.5/4.5	1.0
Vertical beta function at IP (b^*_y) [mm]	0.48	0.1
Vertical emittance [pm]	**0.07**	**12**
Vertical beam size at IP (s^*_y) [nm]	**5.9**	**37**
L^*/b^*_y (~natural vertical chromaticity, SiD/ILD detector)	**7300/9400**	**10000**

To investigate beam effects we need large dynamic range -> Diamond Sensor

Fast Luminosity monitoring at SUPERKEKB





Signals each 4 ns!

“Window” in the beam-pipe with DS on top of it.

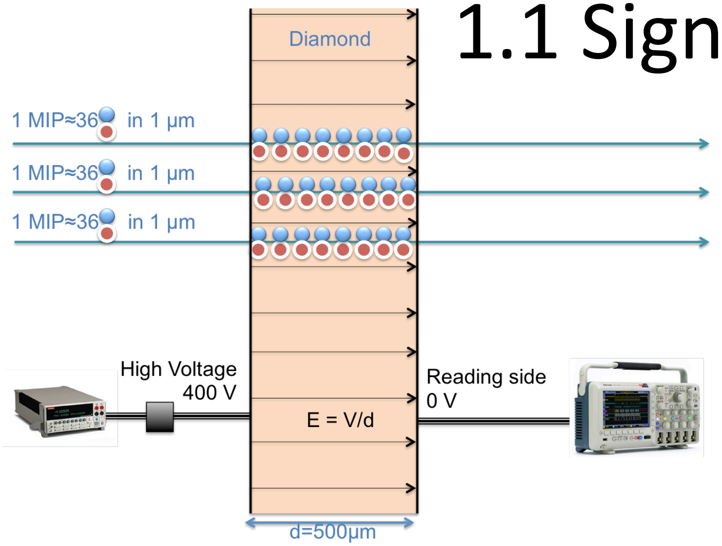
- PhD of Dima Klechen ;
- Complicated data acquisition by D. Jehanno

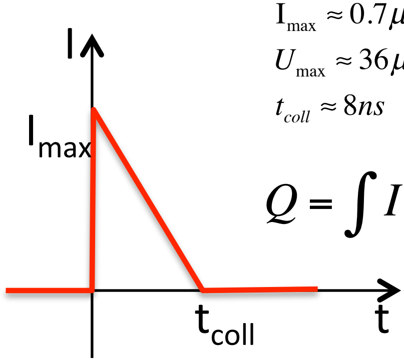
Outline

1. Few electrons
   - signals
   -calibration
   -1,2,3 electrons

2. What if N electrons is large?
   - rough estimations
   - measurements
   - model and results

1.1 Signals from single electron

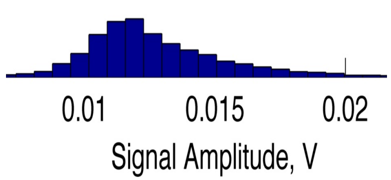




$$I_{max} \approx 0.7 \mu A$$
$$U_{max} \approx 36 \mu V$$
$$t_{coll} \approx 8 ns$$

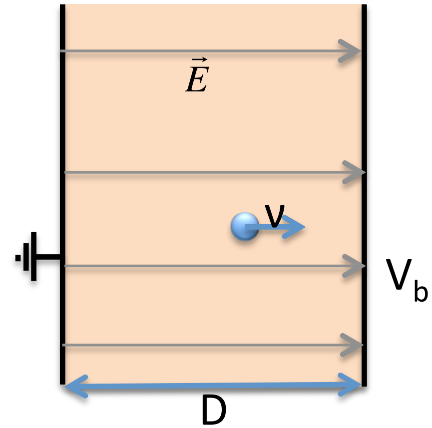
$$Q = \int I\, dt \approx 2.9\, fC$$

With charge amplifier:



Shockley-Ramo theorem

works for many electrodes configuration



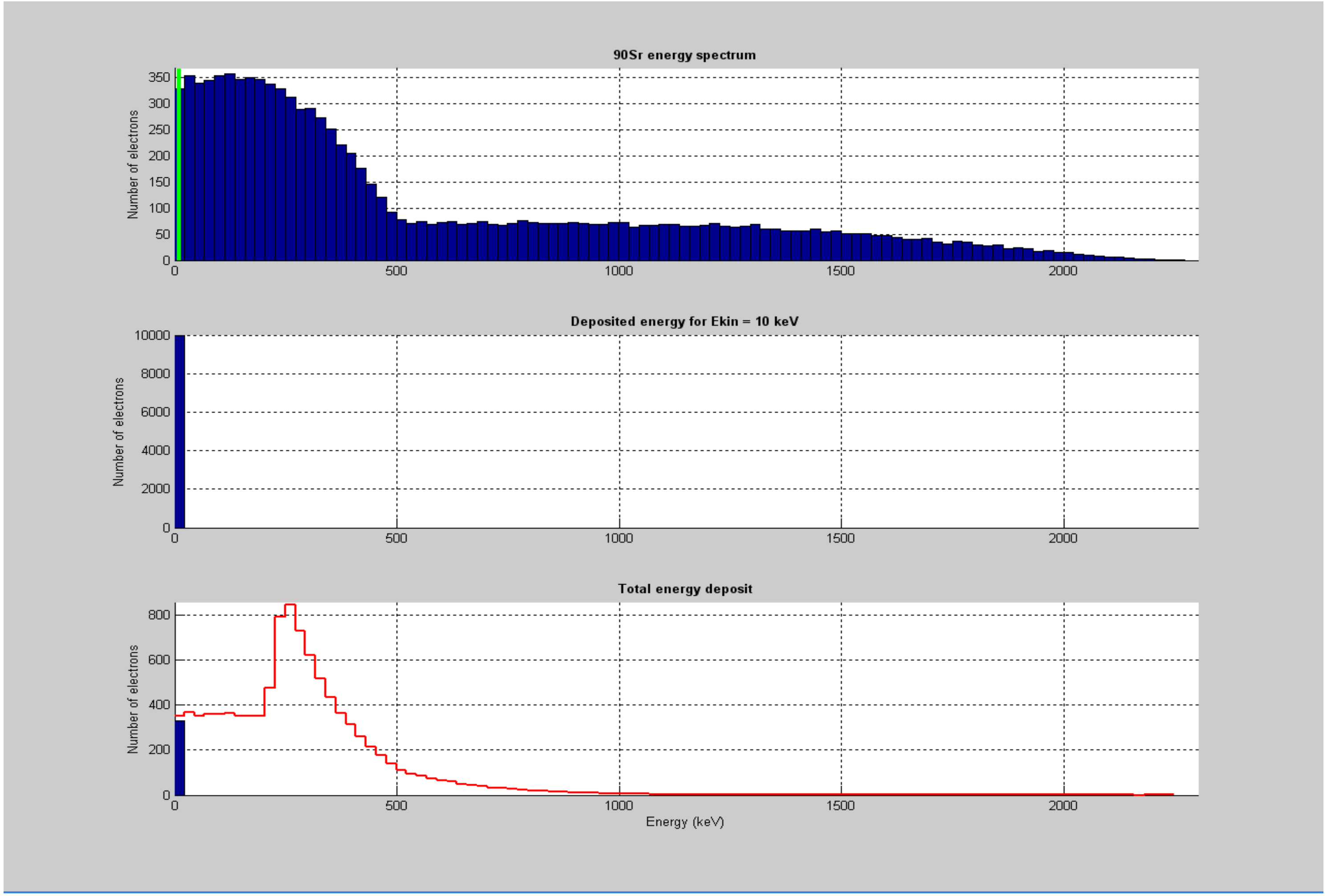
$$I(t) = -\frac{q}{V_b}\vec{E}(x(t))\vec{v}(t)$$

In parallel plate geometry el. field

$$\vec{E}(x(t)) = \frac{V_b}{D}$$

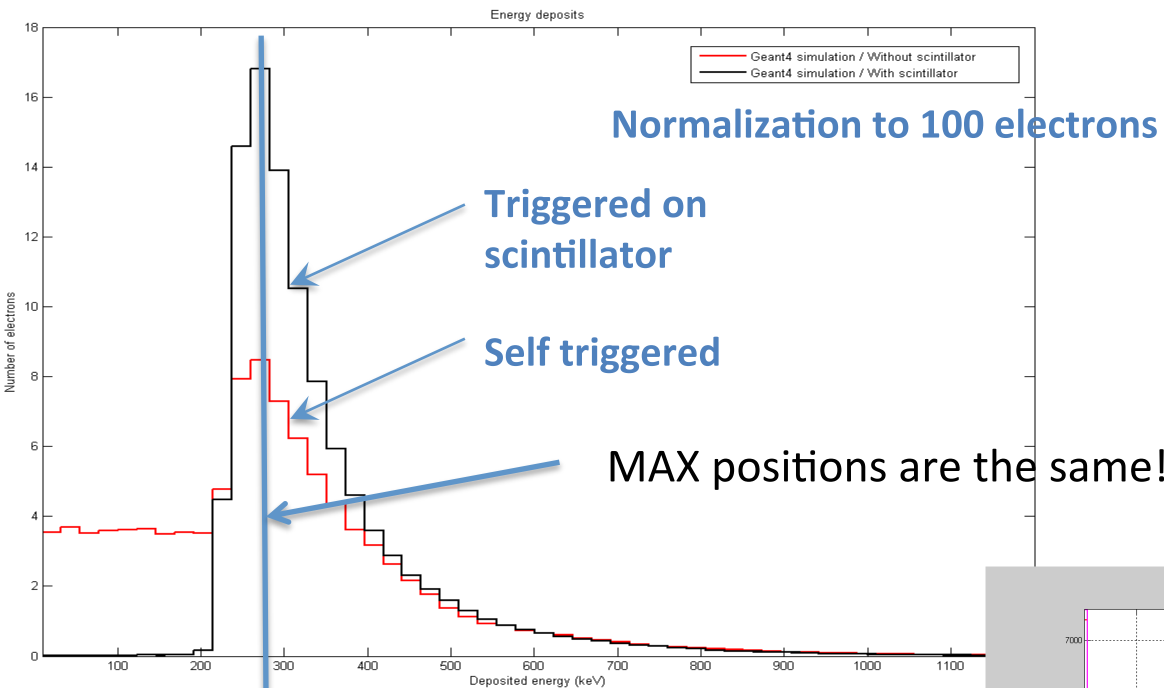
$$I(t) = -\frac{q}{V_b}\frac{V_b}{D}v = -\frac{qv}{D}$$

1.2 Fast calibration of DS with Sr90

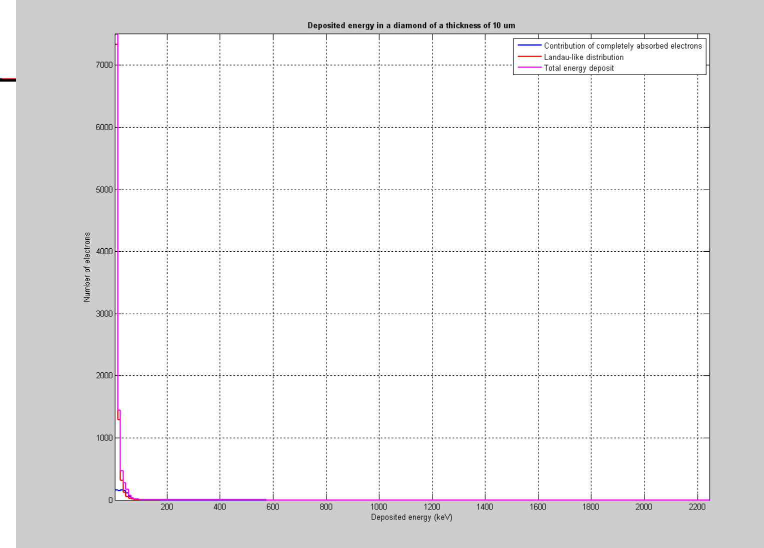


Internship of B. Cabouat

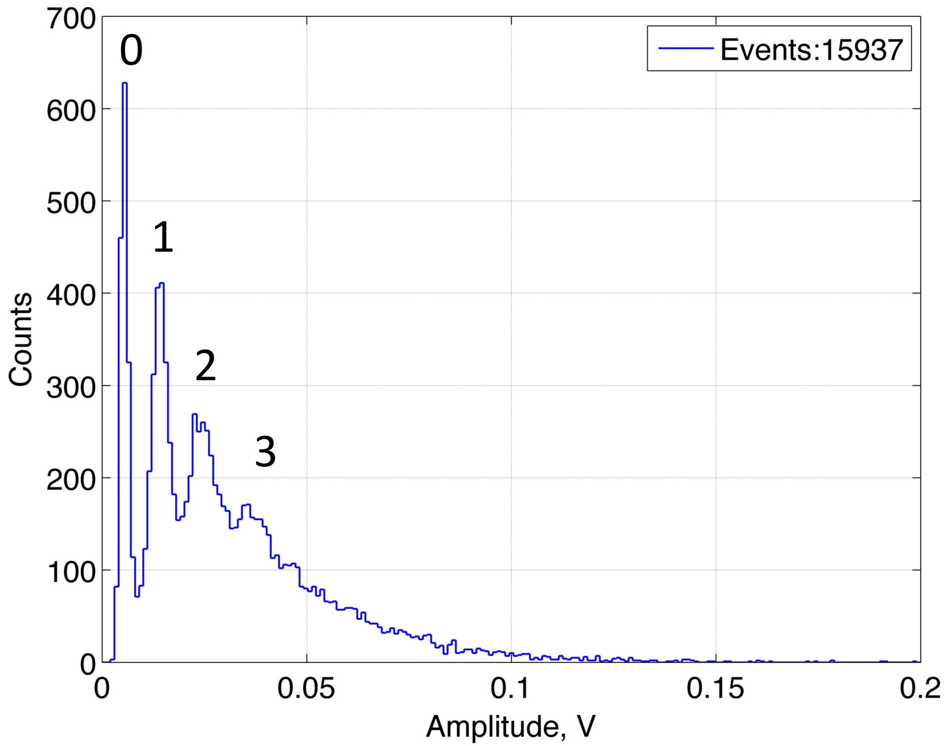
1.2 Comparison self triggering vs triggering on scintillator

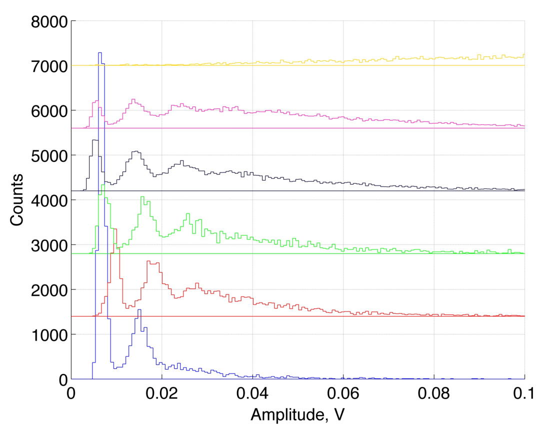


Role of thickness



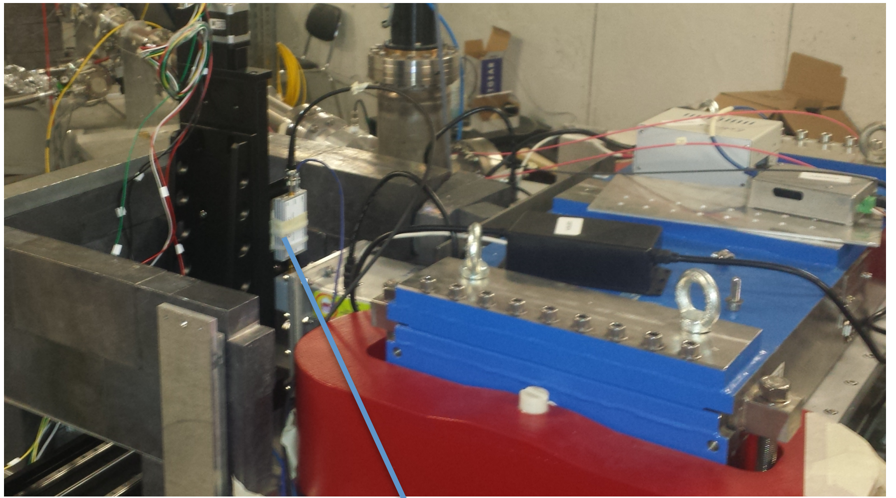
1.3 Measurements by DS of 1, 2, 3 electrons at LEETECH

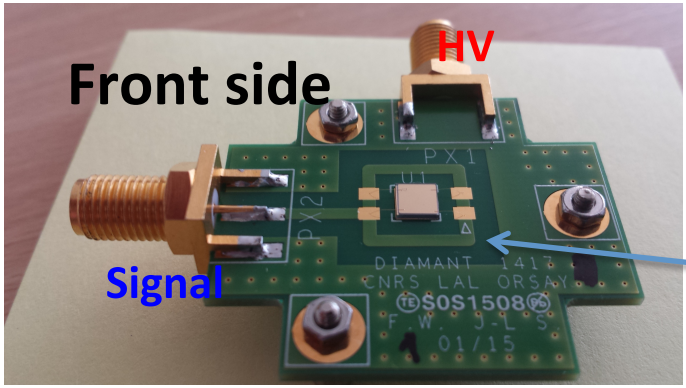


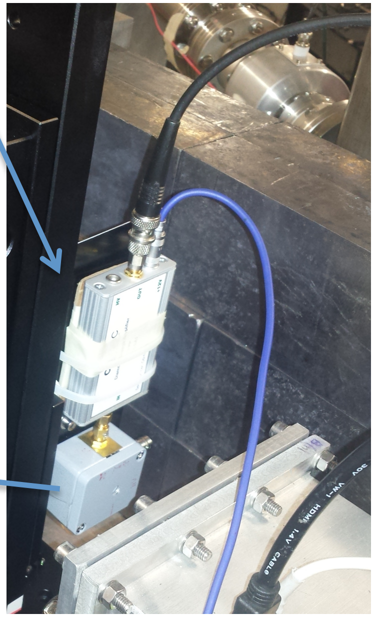


Different openings of collimators

PHIL: 10^9 electrons of 3.5 MeV



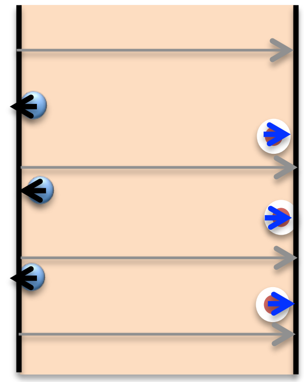




2.What if N mip is large? Rough estimations.

Space-charge

Suppose volume charge is screened, Contribution of charges near surface to the electric field?



$$E = \frac{\sigma}{\varepsilon\varepsilon_0} \approx 7\cdot 10^{-3} N_{mip}, or$$

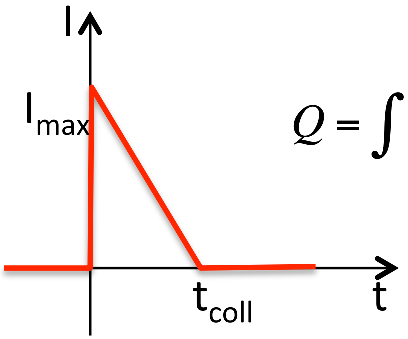
$$\Delta V \approx 3.6\cdot 10^{-6} N_{mip}$$

$$N_{mip} = 10^6;\ \Delta V \approx 3.6V$$

$$N_{mip} = 10^7;\ \Delta V \approx 36V$$

$$N_{mip} = 10^8;\ \Delta V \approx 360V\ ??$$

Voltage drop due to charge collection



$$Q = \int I\, dt \approx 2.9\, fC$$

$For\ 1e^-$

$I_{max} \approx 0.7\mu A$

$U_{max} \approx 36\mu V$

$t_{coll} \approx 8ns$

Standard diamond
4mm*4mm*500um
Spatial distribution of incident electrons is homogeneous

$$U \approx N_{mip}\cdot 36\mu V$$

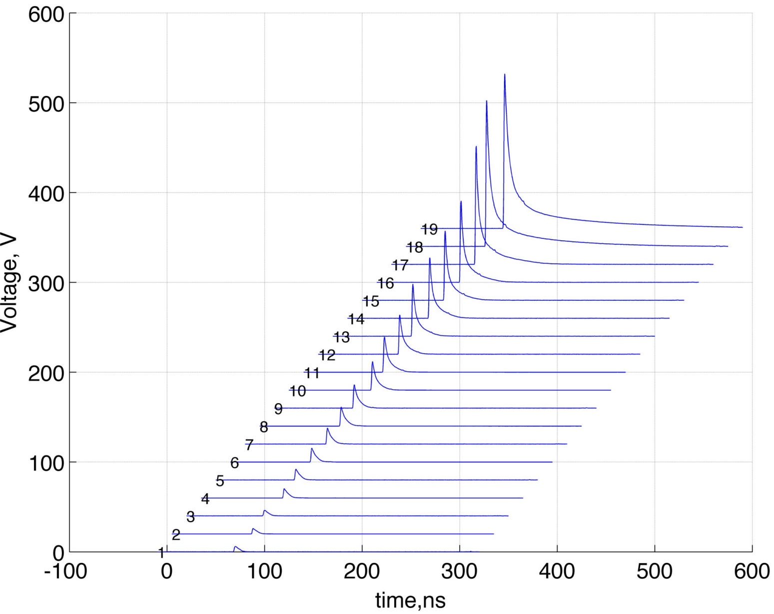
$$N_{mip} = 10^6;\ U \approx 36V$$

$$N_{mip} = 10^7;\ U \approx 360V\ ??$$

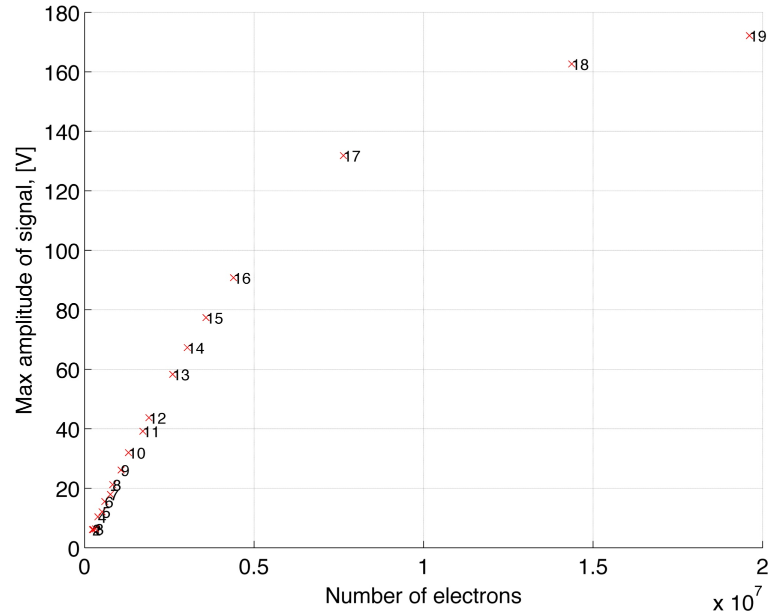
$$N_{mip} = 10^8;\ U \approx 3600V\ ??\ not\ possible$$

Charge collection must be nonlinear!
For more quantitative description we need numerical modelling.

2.1 What if N mip is large?

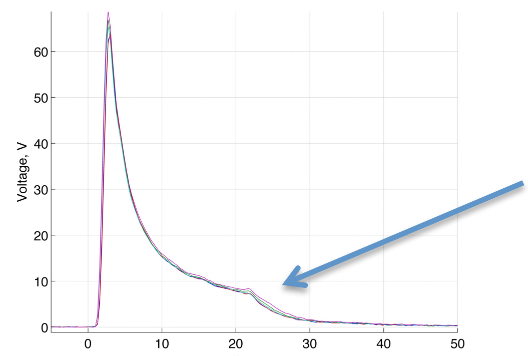


Waveforms for different number of incident electrons.



Max amplitude of signal as a function of collected charge. Measure of linearity of the DS reponse.

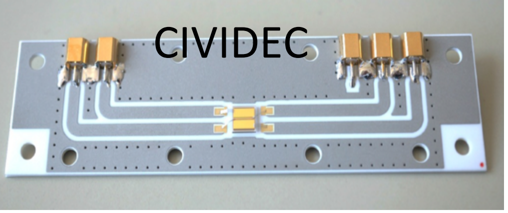
Measured with DS in air, placed at the exit of PHIL beampipe. By changing the laser intensity on the photocathode we change the number of accelerated electrons.

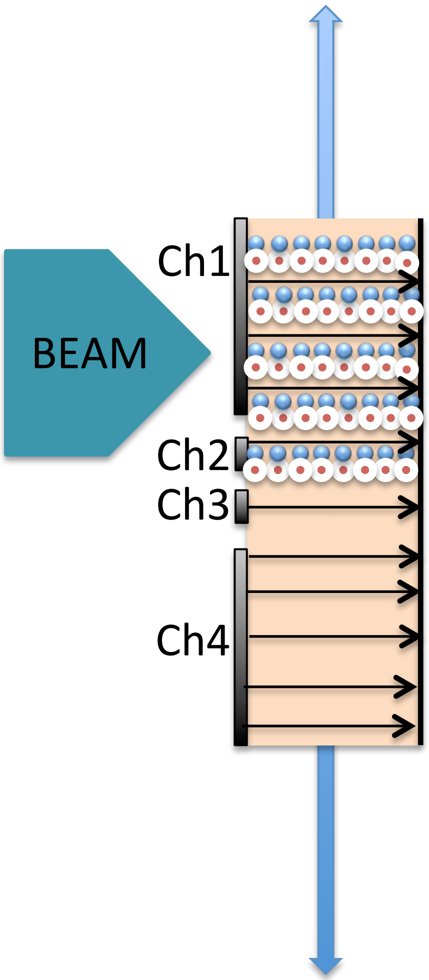


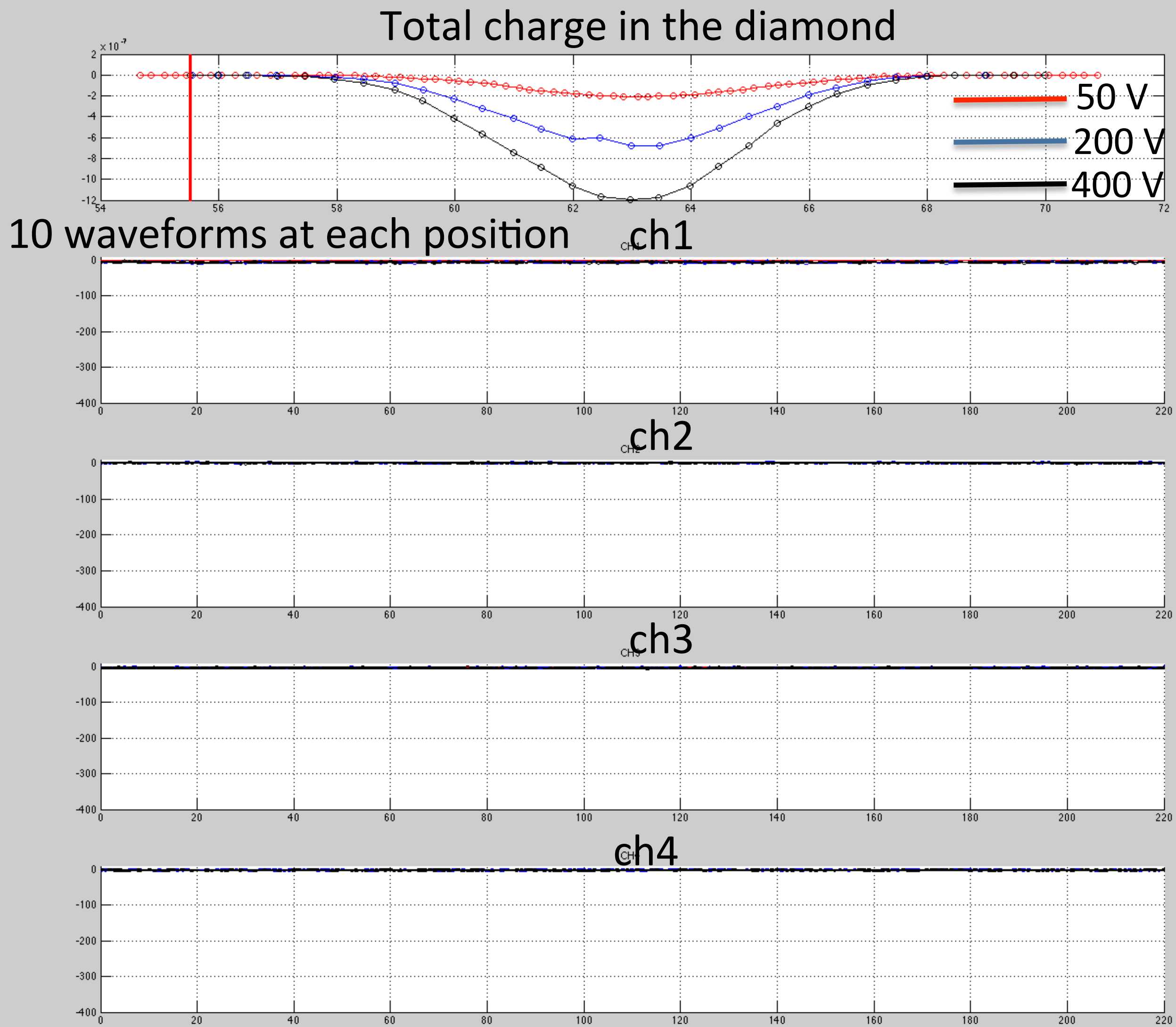
Characteristic step at the end of charge collection

Two possible effects: space-charge, and voltage drop on the reading electrode due to large current.

2.1 Signals measured at ATF2

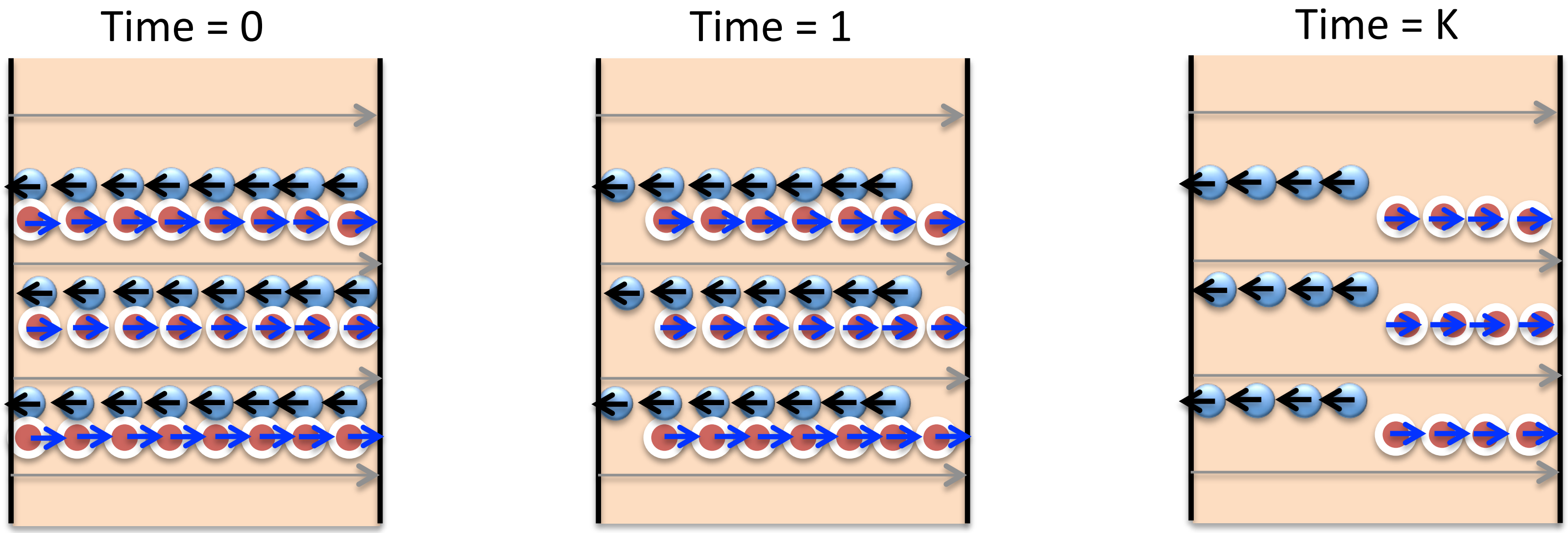






S.Liu et al, *In vacuum diamond sensor scanner for beam halo measurements in the beam line at the KEK Accelerator Test Facility*, publication in preparation NIMA 2015.

2.2 Modeling of charge collection in 1D



Motion of electrons and holes in external electric field create current on electrode.

Parameters:

-number of incident particles

-biased voltage

-diamond thickness

Variables:

$$n(x,t);\ p(x,t)$$

$$J_n(x,t);\ J_p(x,t)$$

$$E(x,t)$$

Material parameters (Pomorski et al.)

Mobilities

μ_e = 1300..3100 [cm^2/Vs]

μ_h = 2300 [cm^2/Vs]

Saturation velosities

v_sat_e = $1.9*10^7$ [cm/s]

v_sat_h = $1.4*10^7$ [cm/s]

Lifetimes

τ_e = 300 ns

τ_h = 300 ns

2.2 Modeling of charge collection in 1D

Standard approach in semiconductor device modeling is solution of Drift-diffusion equations.

$$\frac{\partial J_n}{\partial x} - q\frac{\partial n}{\partial t} = \frac{n}{\tau_n}, \quad \textbf{where} \quad J_n = qn\mu_n E + qD_n\frac{\partial n}{\partial x},$$

$$\frac{\partial J_p}{\partial x} + q\frac{\partial p}{\partial t} = -\frac{p}{\tau_p}, \quad \textbf{where} \quad J_p = qn\mu_p E - qD_p\frac{\partial p}{\partial x},$$

$$E(x,t) = -\frac{V}{d} - \frac{q}{\varepsilon_0 d}\int_0^d\int_0^x (p-n)\,dx'\,dx + \frac{q}{\varepsilon_0}\int_0^x (p-n)\,dx'$$

Variables:

$n(x,t);\ p(x,t)$

$J_n(x,t);\ J_p(x,t)$

$E(x,t)$

+ initial conditions (concentrations proportional to Nmip)
+ appropriate boundary conditions

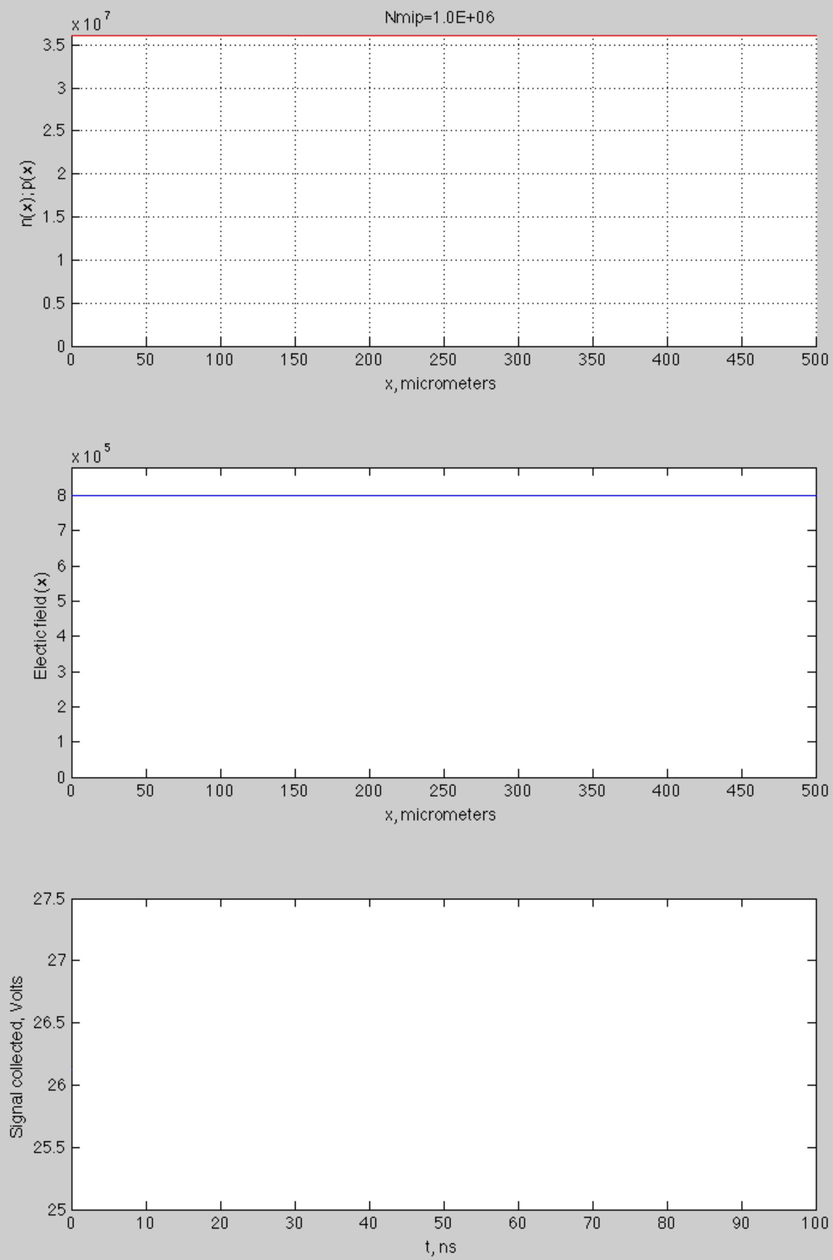
We use Scharfetter-Gummel Discretization:

$$J(x_{i+1/2},t) = v\frac{n(x_i,t) - \exp(-v\Delta x / D)n(x_{i+1},t)}{1-\exp(-v\Delta x / D)}$$

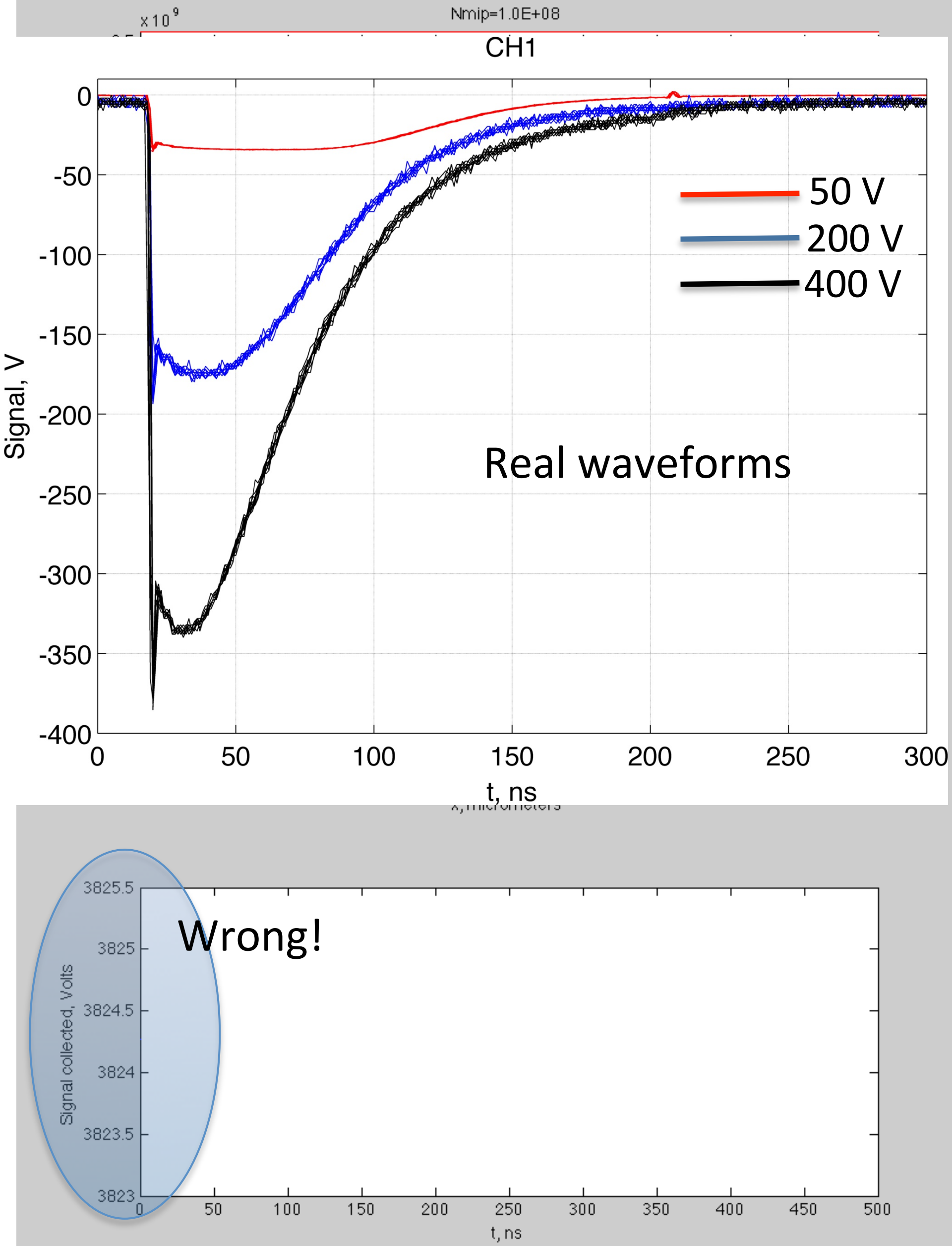
Solving for each time moment (by Runge-Kutta method) gives the evolution of charge densities $n(x,t);\ p(x,t)$

2.3 Examples

Nmip=1e6

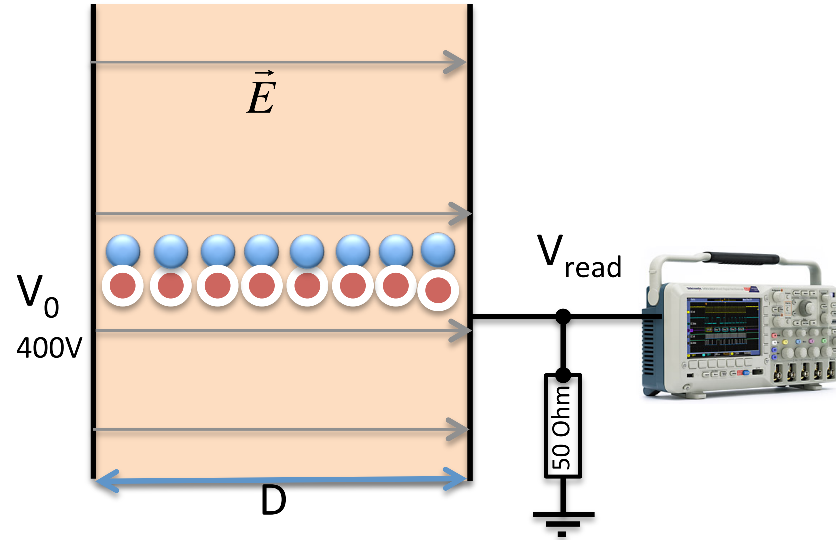


Nmip=1e8



2.4 Taking into account the voltage drop

$$E(x,t) = -\frac{V}{d} - \frac{q}{\varepsilon_0 d}\int_0^d \int_0^x (p-n)\,dx'\,dx + \frac{q}{\varepsilon_0}\int_0^x (p-n)\,dx'$$



$$V = V_0 - V_{read}$$

For Nmip 1-1e5 $V_{read} << V_0$

For Nmip=1e6 and V_0=400V V_{read} 25 V

Which is not the case when signal is large, and system behaves self-consistently:
-large **I** -> large **V_{read}**->small **V**->slow collection (small **I**) *and inverse*
-small **I** -> small **V_{read}**->large **V**->fast collection (large **I**)

$$V_{read} = f(I(V_{read}))$$

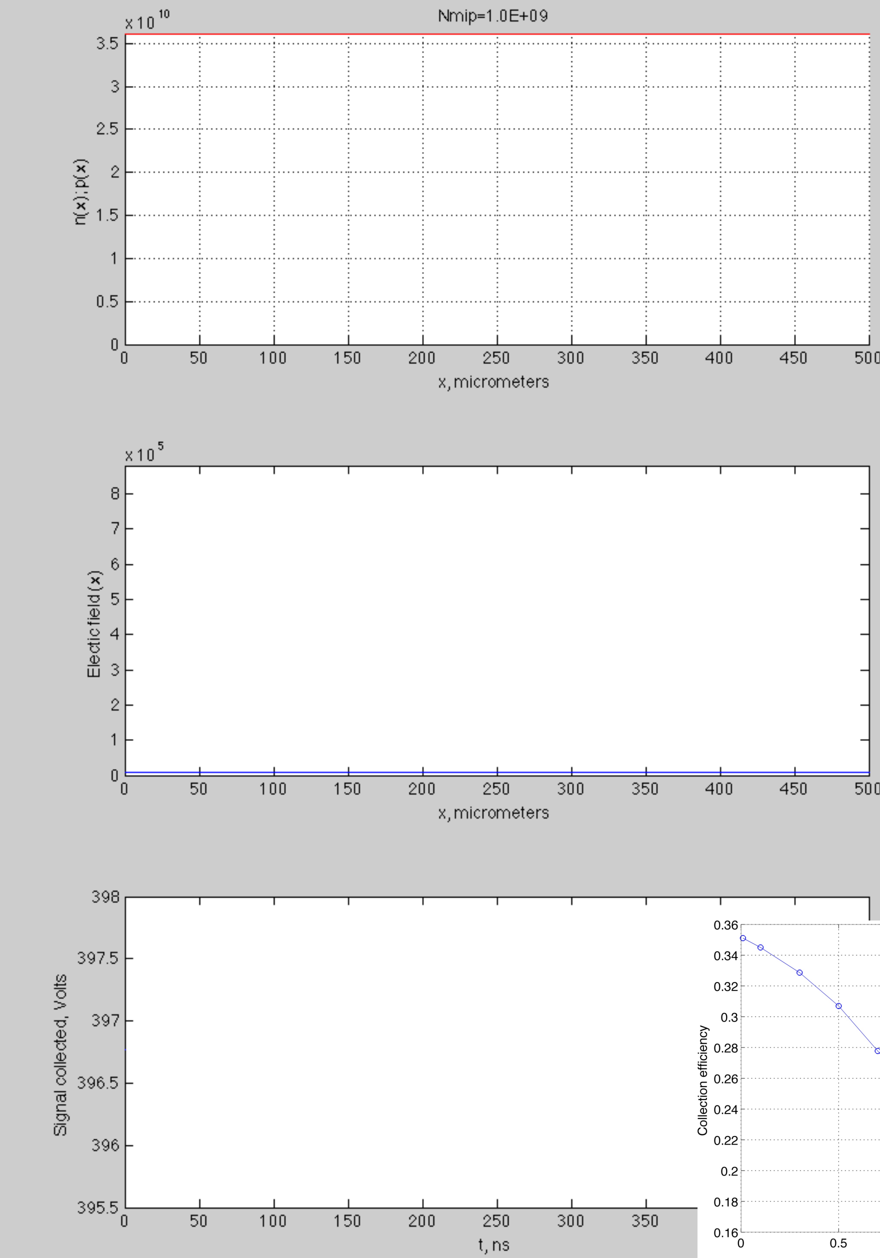
We solve this equation at each time step to find settled regime V_{read}

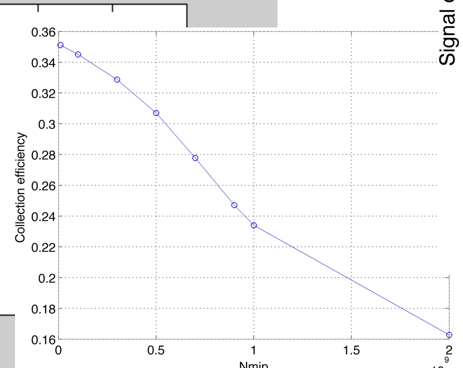
This significantly slows down the modeling speed

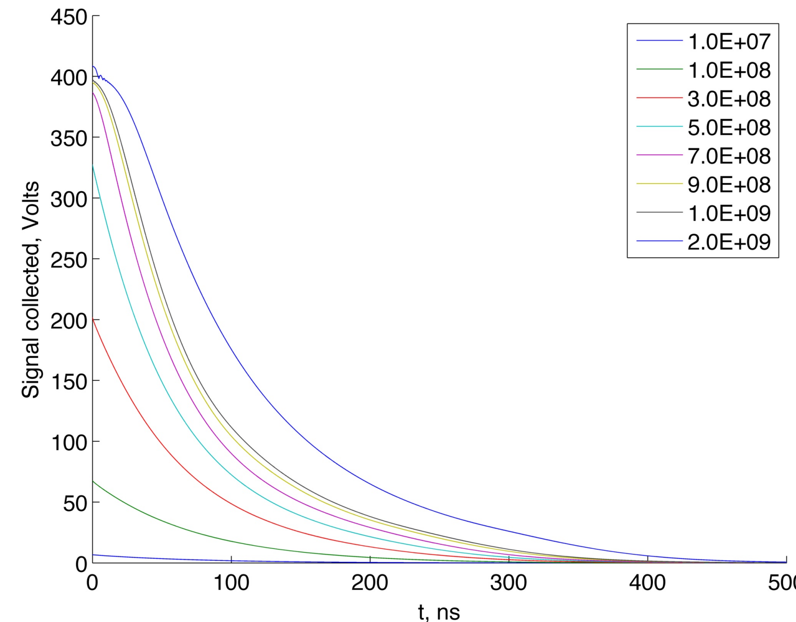
V Kubytskyi et al., *Modeling / measurement comparison of signal collection in diamond sensors in extreme conditions,* Proceedings of IPAC2015,787-790, MOPHA007, Richmond, VA, USA.

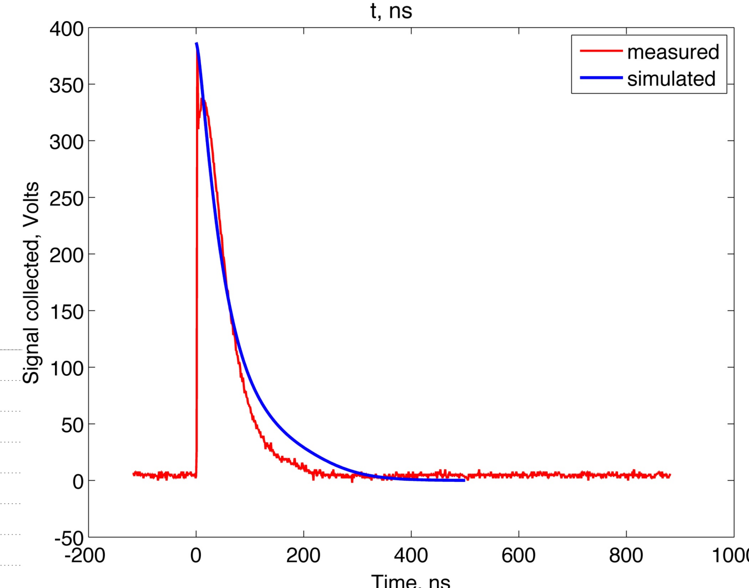
2.5 Results

Nmip=1e9

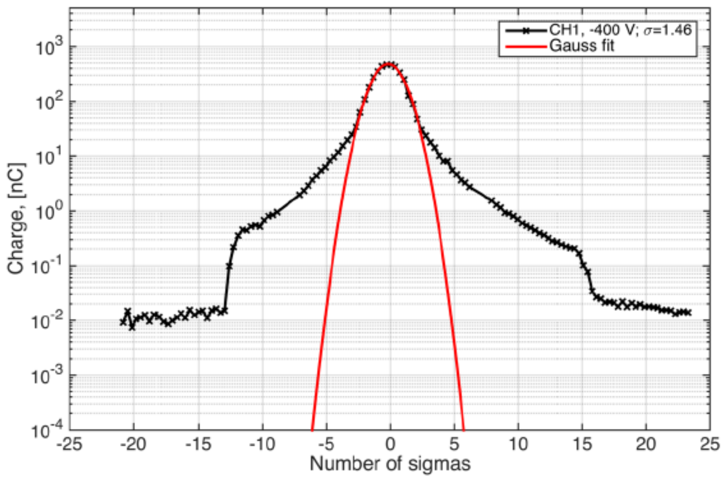


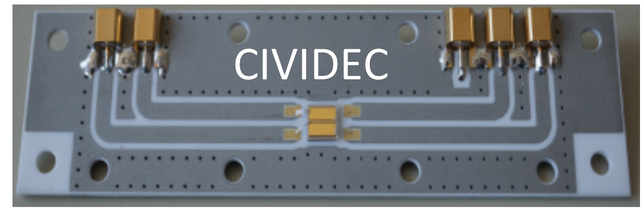




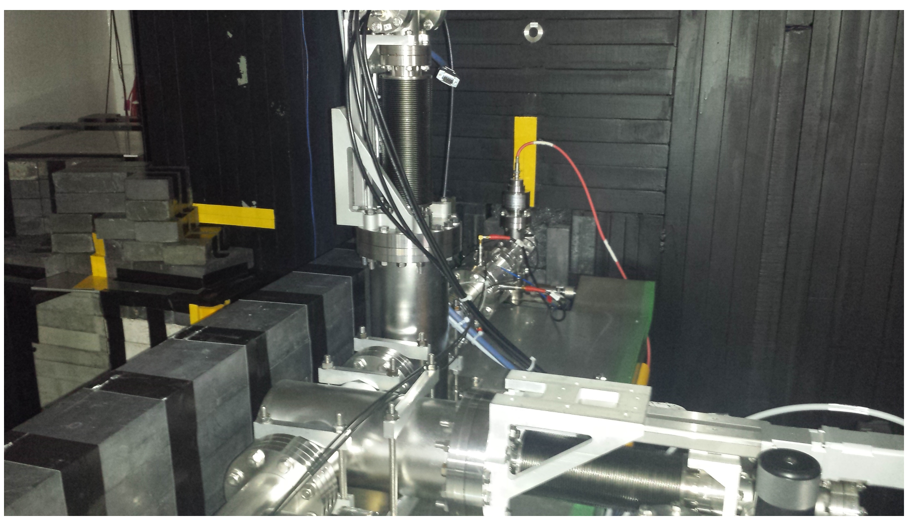


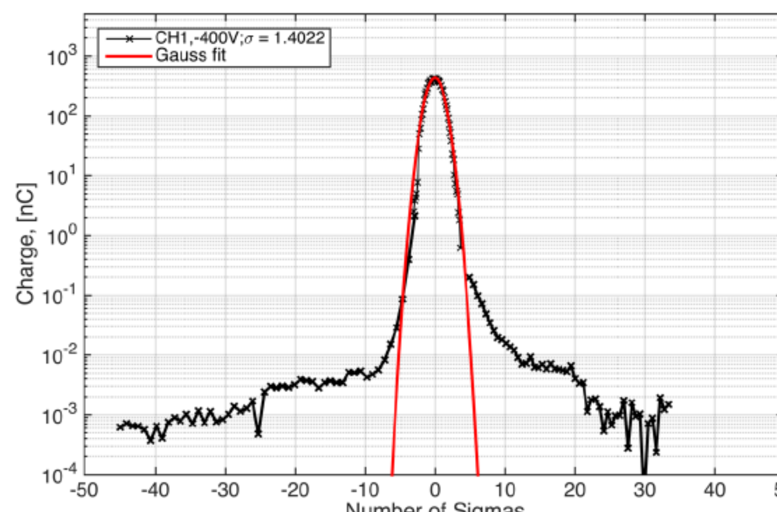
3. Beam Halo measurements with DSv at ATF2





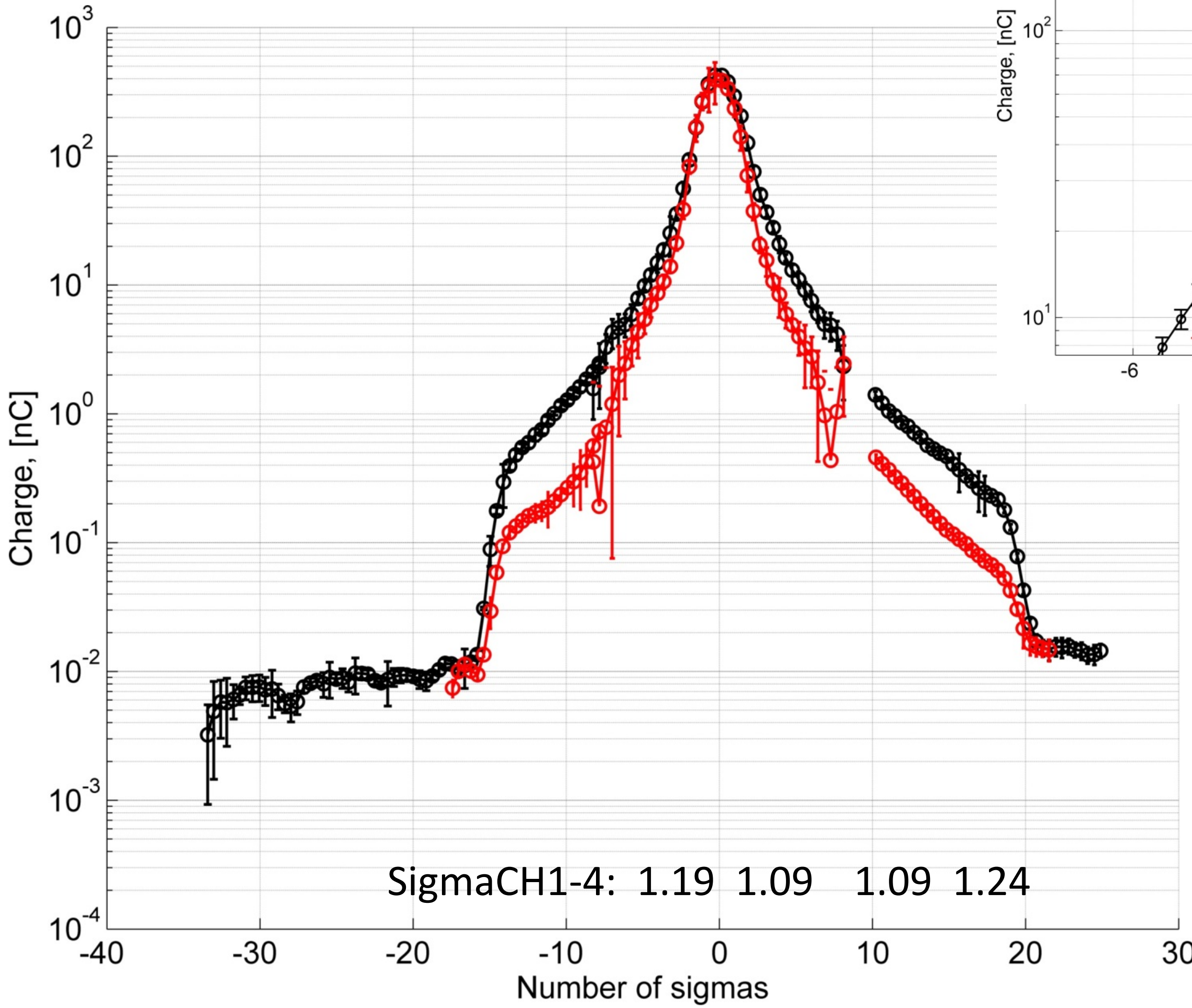
Horizontal and vertical
4 channels DS from CIVIDEC.

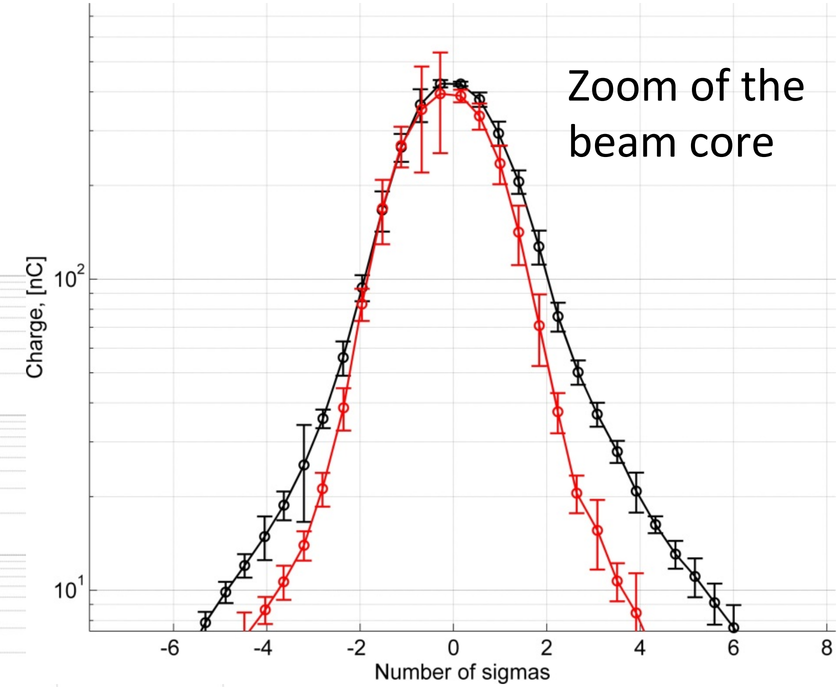




Vacuum level

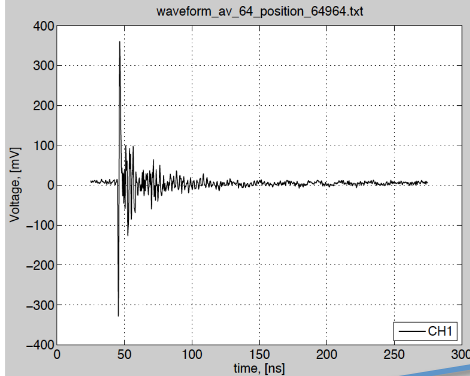
Red 4.84e-7 Pa
Black 13.5e-7 Pa

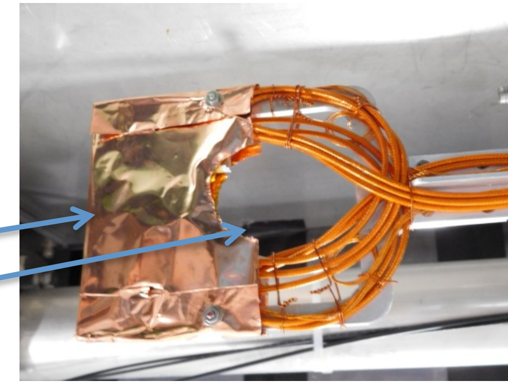




Pickup questions.
Vertical DS.

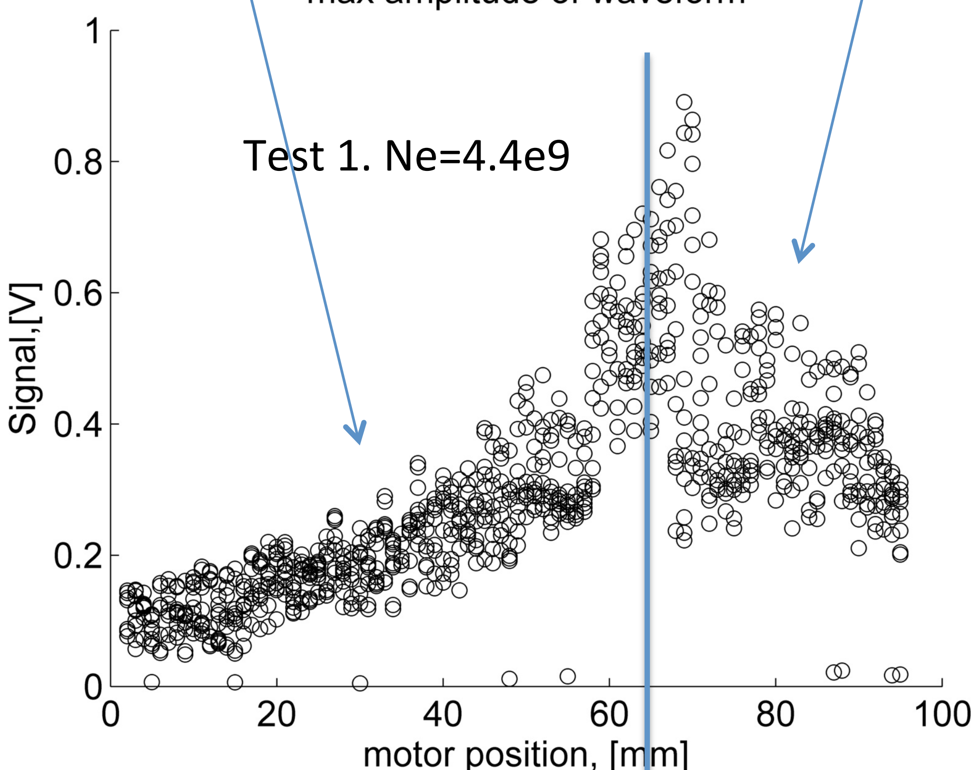
No HV applied to DS

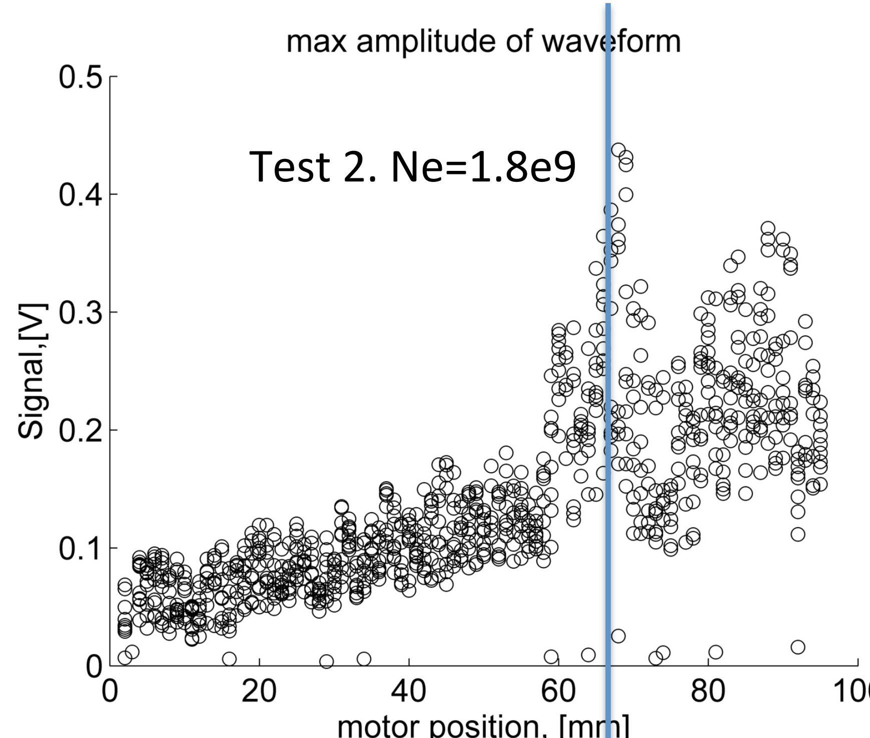




Shielding closed

Shielding open





BEAM CORE

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Summary

- A fast calibration procedure for DS of arbitrary thickness was developed.
- We demonstrated for the first time the capability of DS to differentiate one, two and tree electrons.
- We identified two regimes of charge collection.
  -The first corresponds to 1-10^6 MIPs, in this case the externally applied electric field is negligibly perturbed by space-charge effects during the separation of the electron/hole clouds.
  -The second corresponds to intensities larger than 10^7 MIPs, where the space-charge effects significantly slow down the charge collection due to large concentrations of electron/hole pairs in the DS volume.
- A dynamic range of 10^6 was obtained, allowing simultaneous measurement of both beam core and beam halo transverse distribution. Diagnostics of background sources in the nanometer beam size measurement instrumentation at the interaction point of ATF2 (KEK, Japan).