New Horizons for TPCs, 5th to 9th of October 2020
Video workshop from Santiago de Compostella

Charge spreading with a Resistive-Capacitive coating

Paul Colas

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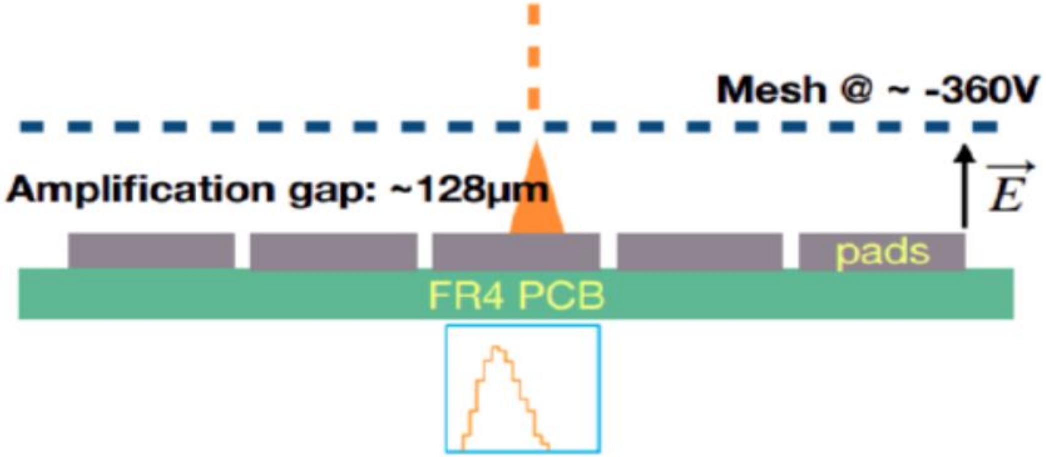
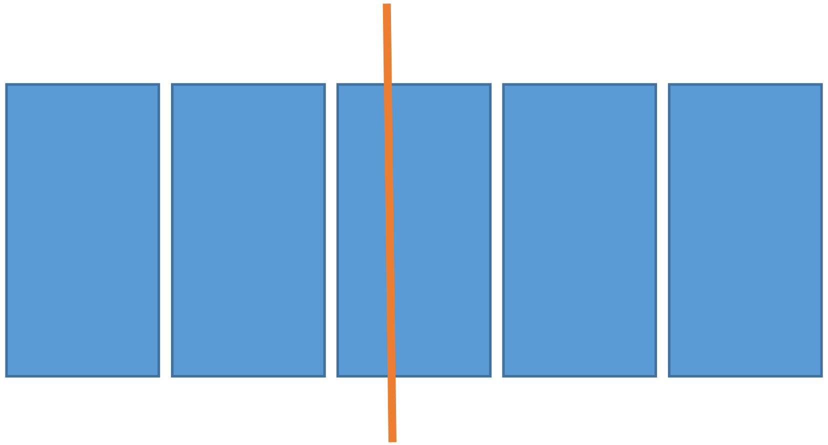
Introduction to charge spreading

- Typical r.m.s. diameter of a Micromegas avalanche : 15 to 25 µm (dominated by diffusion in the amplification gap). This is much less than the pad width, typically 1-10 mm.
- A track segment usually hits only 1 pad (unless sufficient diffusion in the drift space)
- This leads to w/√12 resolution (870 µm for 3mm pads, 2.9 mm for 10mm pads!)





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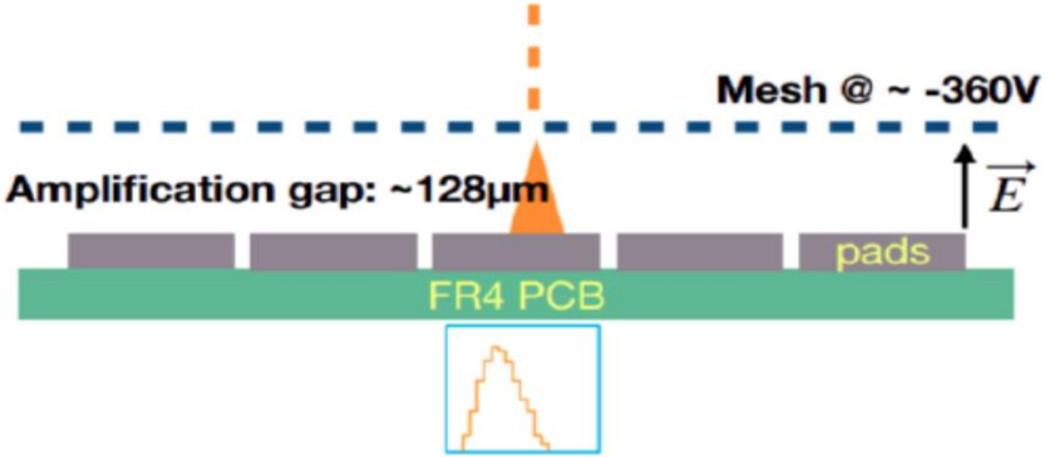
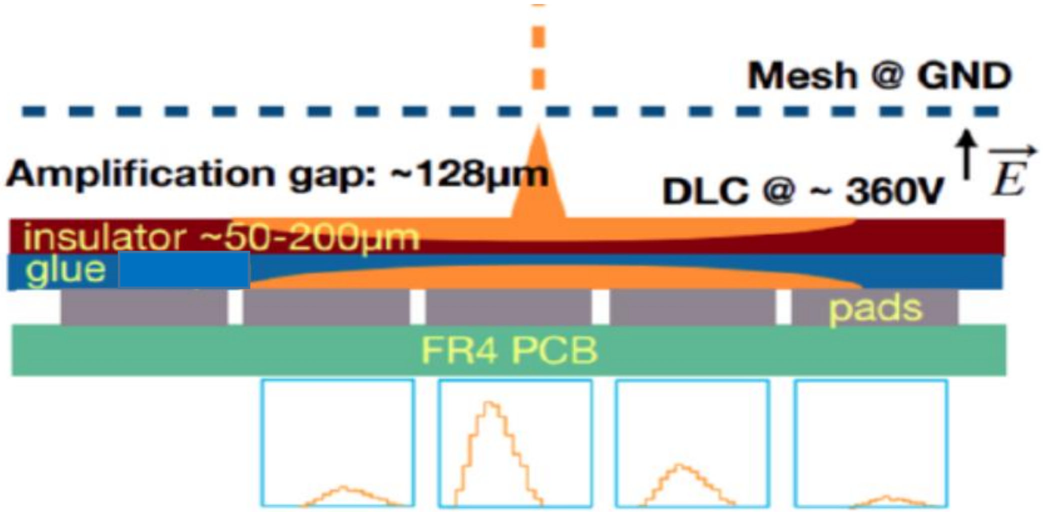




- Need to spread the charge to share the signals between several pads
- This can be done with a resistive-capacitive continuous network.
- This also helps in protecting against sparks

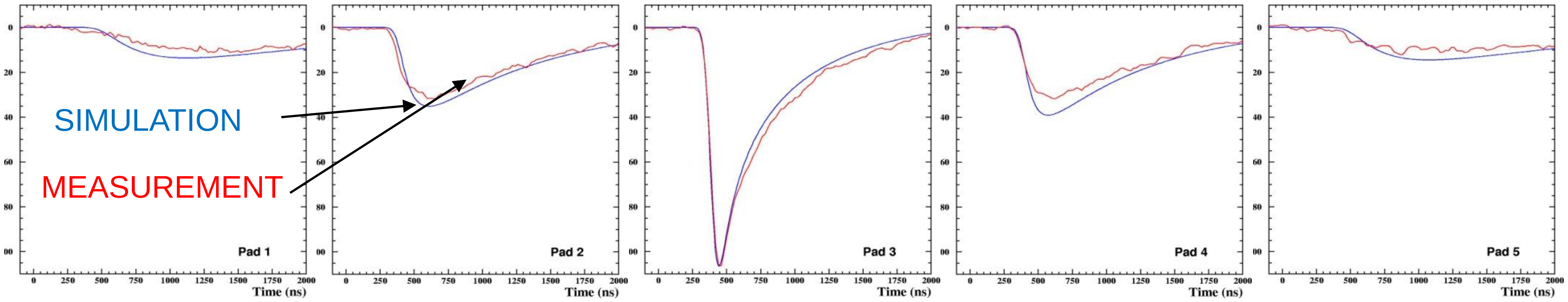
One way of analysing the charge spreading (assumes infinite and thin resistive layer on top of a dielectric) is to consider it as a 2D resistive-capacitive network (2D analog of a transmission line) obeying the 2D telegraphist equation.

$$\frac{\partial\rho}{\partial t}=\frac{1}{RC}\left[\frac{\partial^2\rho}{\partial r^2}+\frac{1}{r}\frac{\partial\rho}{\partial r}\right]\Rightarrow\rho(r,t)=\frac{RC}{2t}e^{\frac{-r^2RC}{4t}}$$

assuming rotation symmetry and $\rho\to0$ at $r\to\infty$ boundary conditions .
Solution : 2D gaussian charge distribution with $\sigma=\sqrt{(2t/RC)}$.

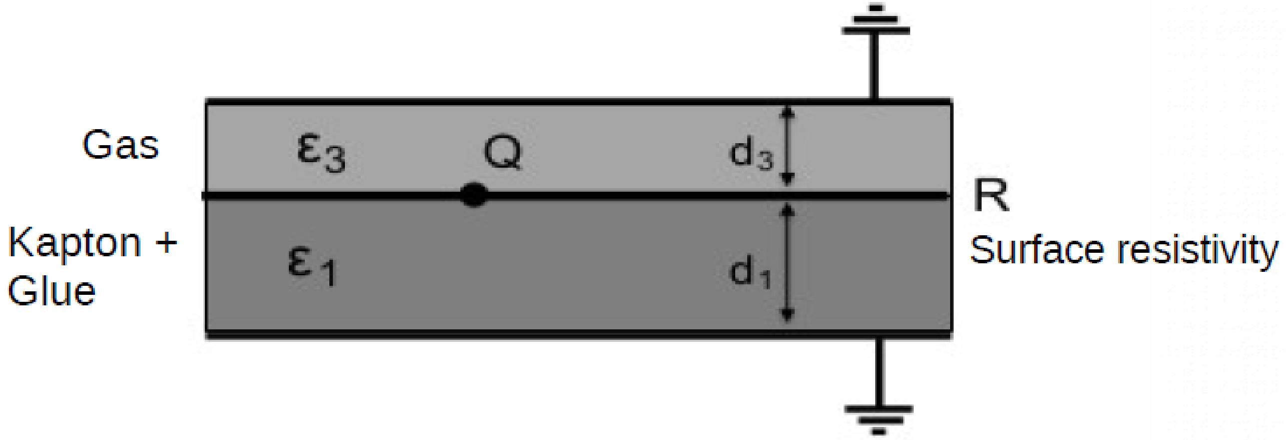
Typical spread is given for t~peaking time of the electronics (200 ns)
The smaller RC, the larger the spread. Neighbouring pads see delayed and wider signals

M.S.Dixit and A. Rankin NIM A566 (2006) 281

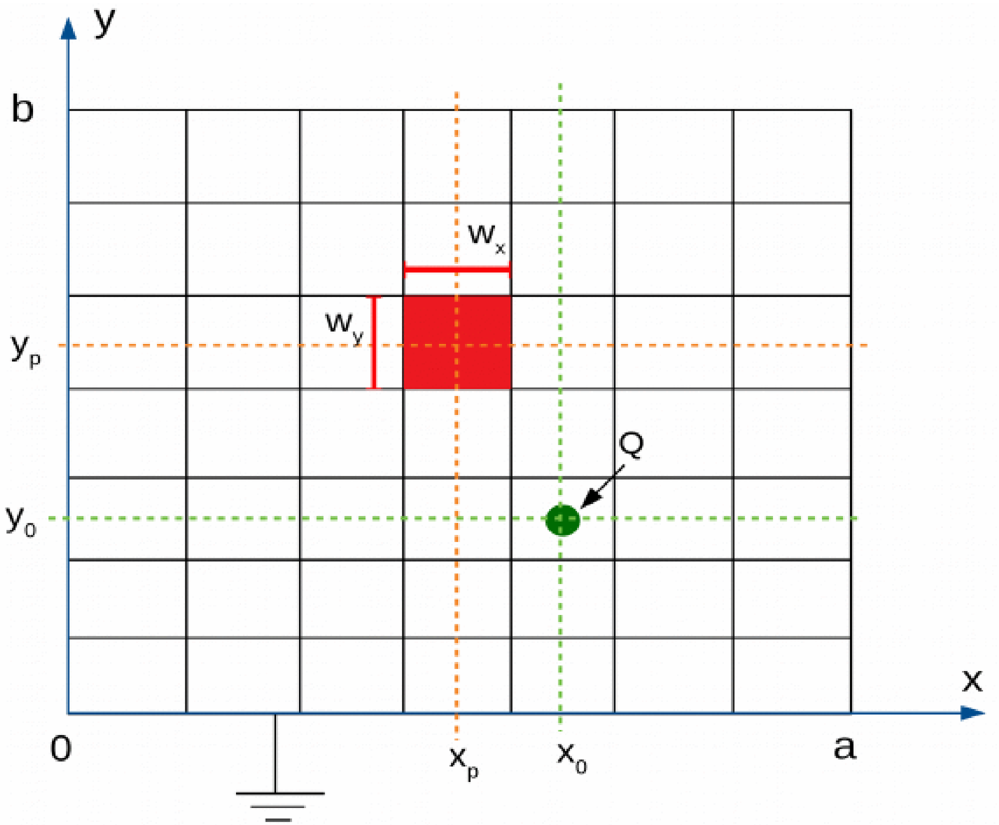


Calculation of induced charge

W. Riegler



The avalanche is close to the DLC surface



Specifications of T2K and ILC ERAM module

Parameter	ERAM module for:	
	T2K	ILC
Number of pads in Horizontal direction	36	72
Number of pads in Vertical direction	32	24
a (Horizontal length of Module)	40.2 cm	21.6 cm
b (Vertical length of Module)	32.3 cm	16.8 cm
w_x (Horizontal length of Readout pad)	11.18 mm	3 mm
w_y (Vertical length of Readout pad)	10.09 mm	7 mm
d_1 (Distance b/w Resistive layer and Readout pads)	250 μm	125 μm
d_3 (Distance b/w Resistive layer and Mesh)	120 μm	120 μm
R (Surface resistivity of Resistive layer)	400 kΩ/square	2.5 MΩ/square
ε_1 (Permittivity of d 1 region)	$4 \times \varepsilon_0$	$4 \times \varepsilon_0$
ε_3 (Permittivity of d 3 region)	ε_0	ε_0

Induced charge

Assume a charge appears on the DLC surface at t=0 at point x_p , y_p and calculate induced charge at point x_0 , y_0 at time t
The problem is similar to a critically damped membrane with fixed boundary on a rectangle.

$$Q^{ind}(x_0, y_0, t) = \Theta(t)\frac{16Q}{\pi^2}\sum_{\alpha=1}^{\infty}\sum_{\beta=1}^{\infty}\frac{\sin\left(\alpha\pi\frac{w_x}{2a}\right)\sin\left(\alpha\pi\frac{x_p}{a}\right)\sin\left(\alpha\pi\frac{x_0}{a}\right)}{\alpha}\frac{\sin\left(\beta\pi\frac{w_y}{2b}\right)\sin\left(\beta\pi\frac{y_p}{b}\right)\sin\left(\beta\pi\frac{y_0}{b}\right)}{\beta}h(k_{\alpha\beta}, t)$$

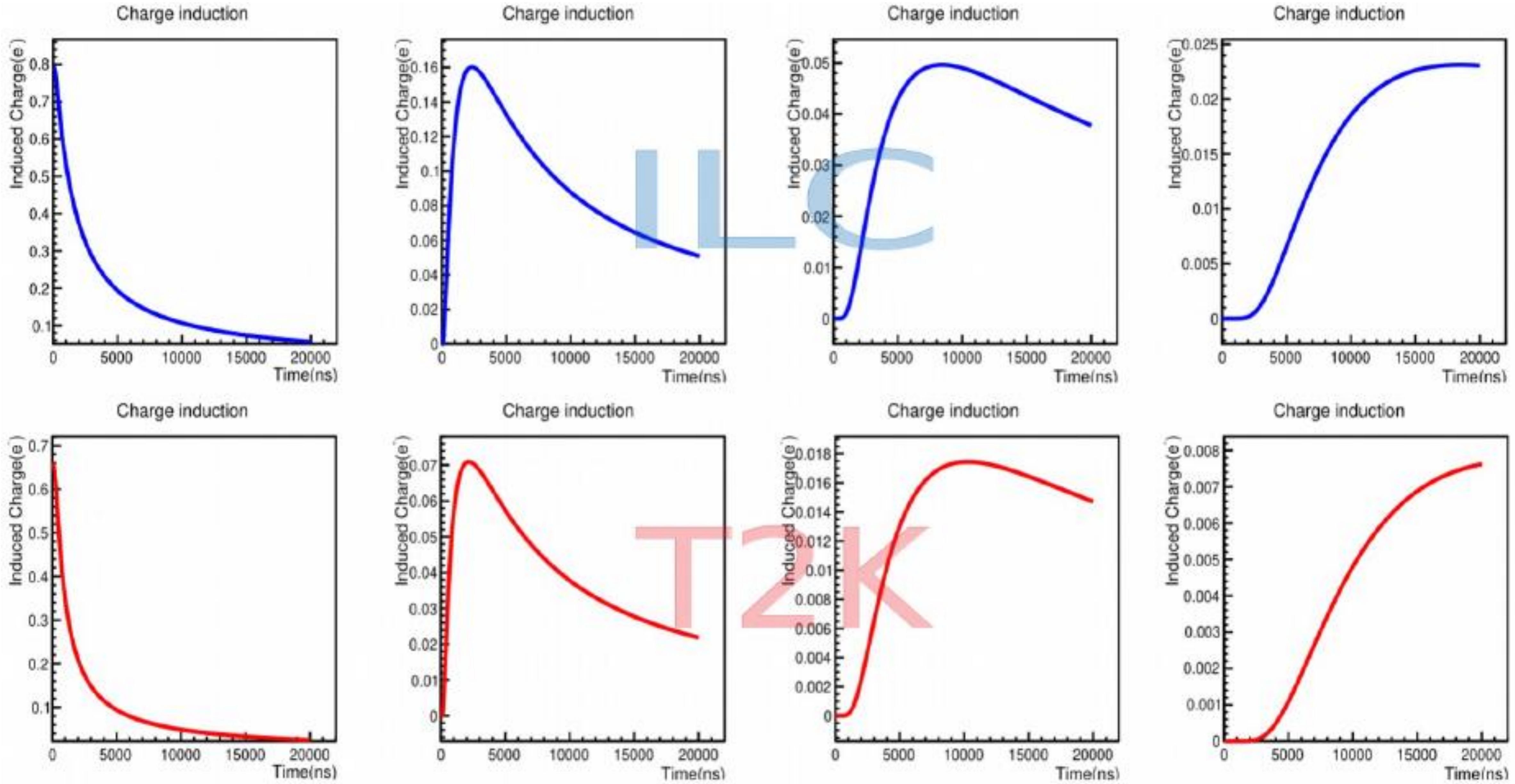
with $k_{\alpha\beta} = \pi\sqrt{\frac{\alpha^2}{a^2} + \frac{\beta^2}{b^2}}$ and

$$h(k, t) = \frac{\varepsilon_1\, e^{-t/\tau(k)}}{\varepsilon_1 \cosh(kd_1) + \varepsilon_3 \coth(kd_3)\sinh(kd_1)} \qquad \tau(k) = \frac{R}{k}\left(\varepsilon_1 \coth(kd_1) + \varepsilon_3 \coth(kd_3)\right) \qquad (1)$$

A full simulation is possible starting from this point charge solution,
by adding :
Electron ionization
Avalanche creation, and its fluctuation
Ions going back to the mesh
In a quasistatic way
And convolute by electronics response

W. Riegler

See D. Janssens, WG4 on Monday



Leading pad

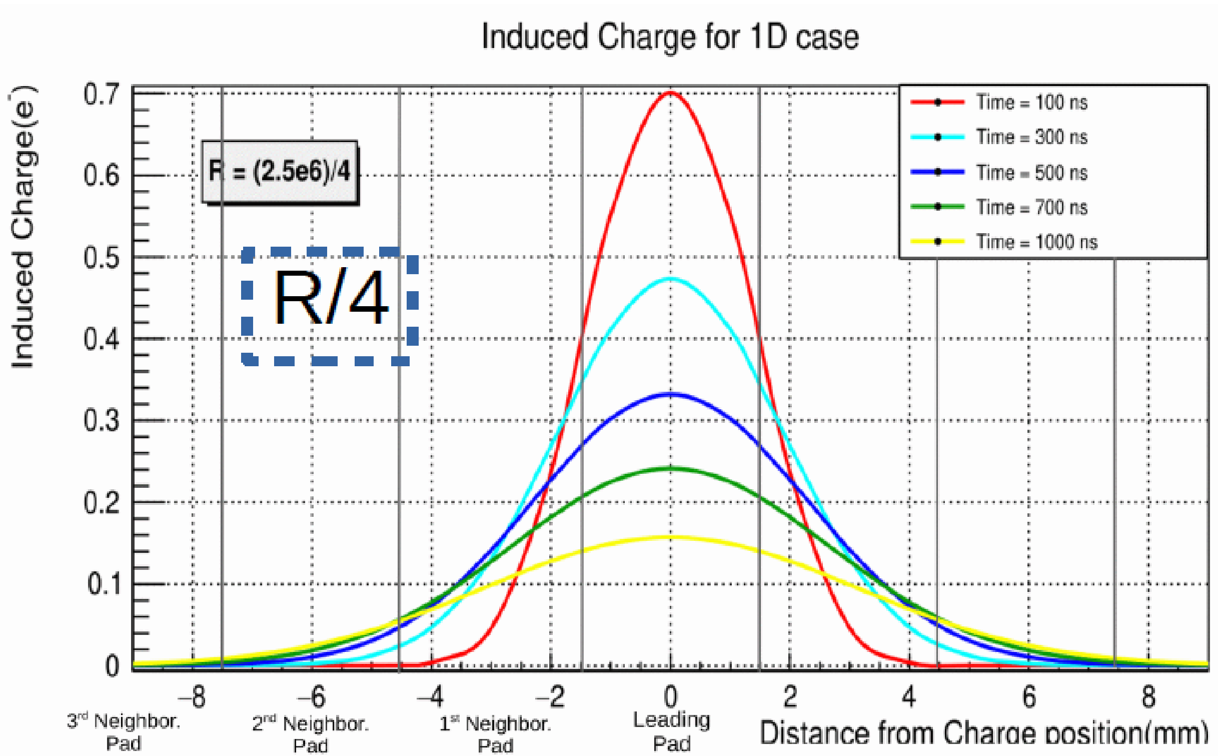
1st neighbour

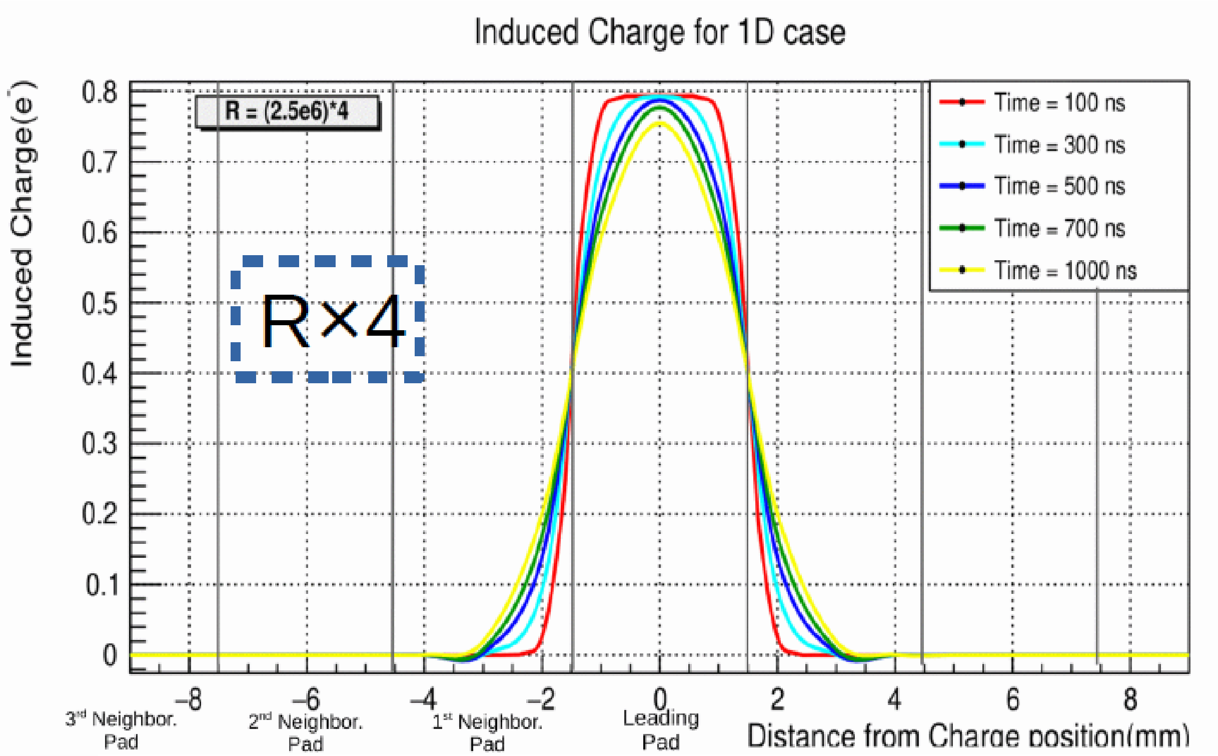
2nd neighbour

3rd neighbour

T2K pads ~3 times wider than ILC and RC~3 times smaller

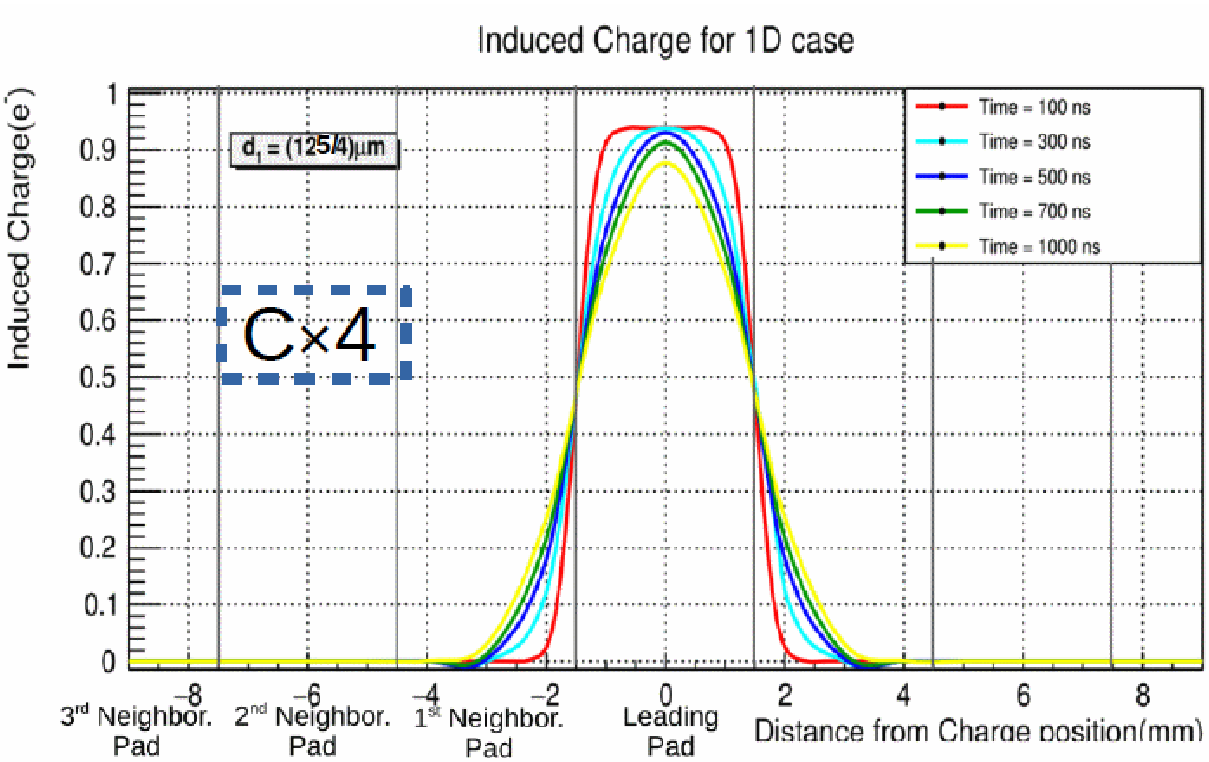
$Q^{ind}(x, t)$ plots with varying Surface resistivity (R).

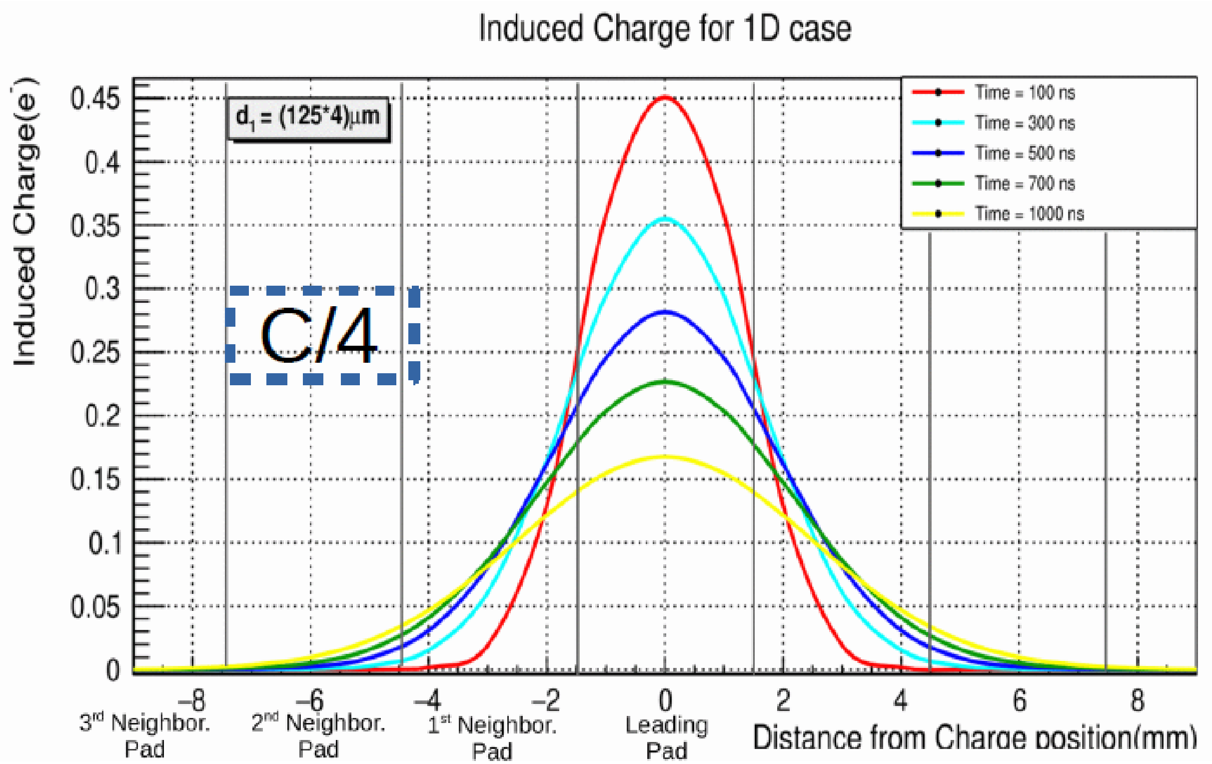




- Vary RC value by changing R.
- Lower RC implies more charge spreading.

$Q^{ind}(x, t)$ plots with varying Insulation thickness (d_1).

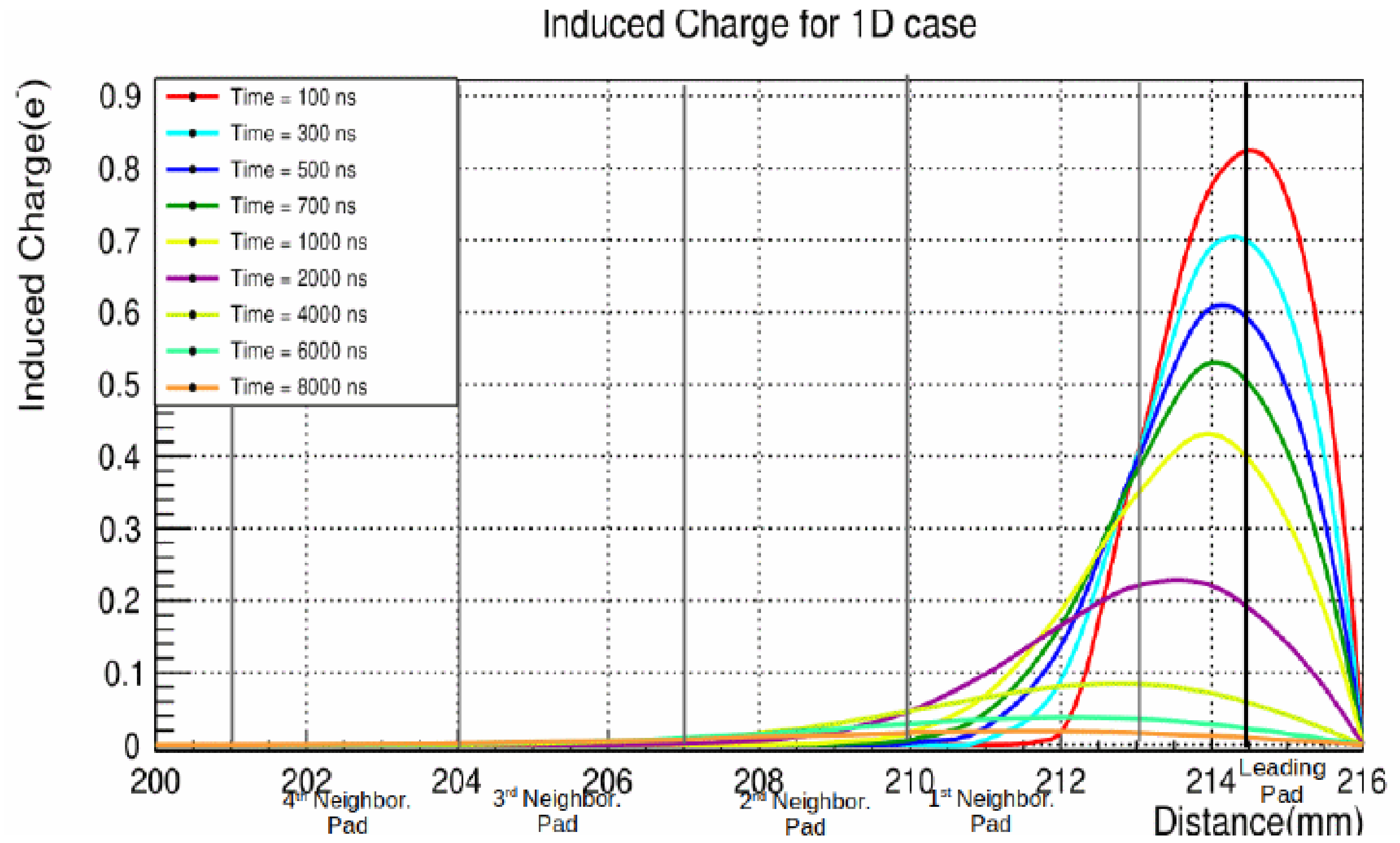




- Vary RC value by changing C.
- Capacitive coupling of resistive foil to pad plane also varies, thus signal strength.

S. Joshi

Edge effects



S. Joshi

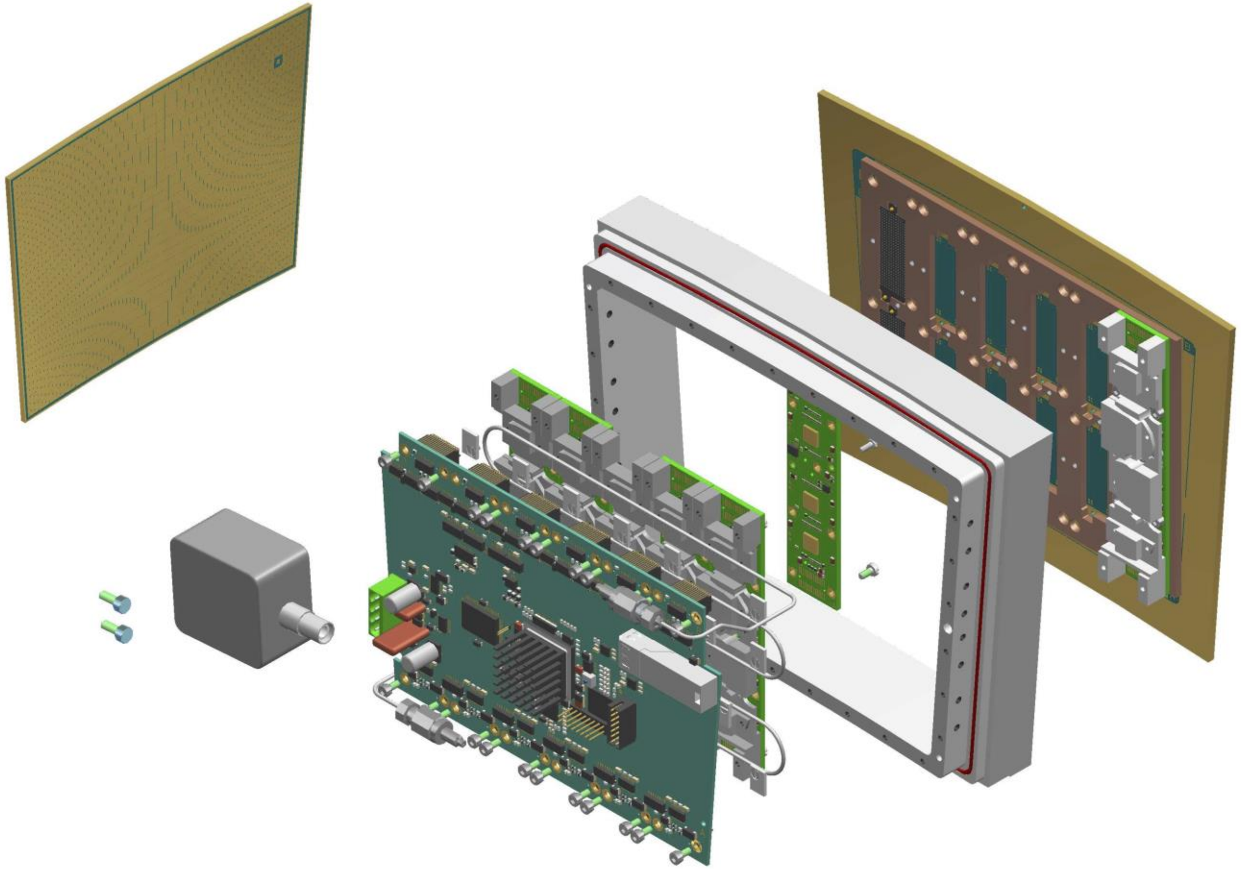
Charge spreading varies as $1/\sqrt{RC}$: minimize RC to spread more.

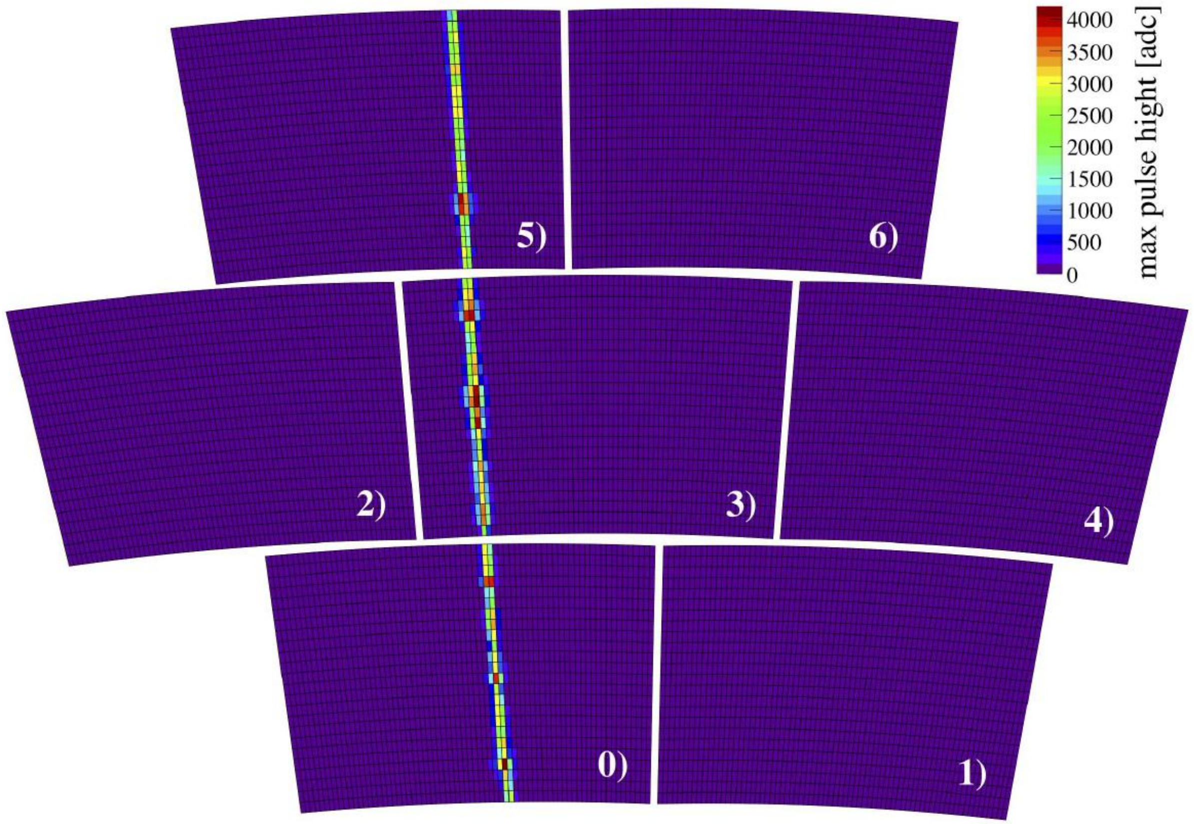
However the signal is proportional to the relative capacitive coupling to pad wrt mesh :
$Q^{ind} = Q_0 \, C_1/(C_1+C_3)$.

This factor is between 0.67 and 0.80 for 120 µm to 250 µm insulator.

So there is a trade-off between spreading, sensitivity to small signals, and stability of operation if it is too close to the breakdown limit (this is not the case for ILC and T2K).

ILC module

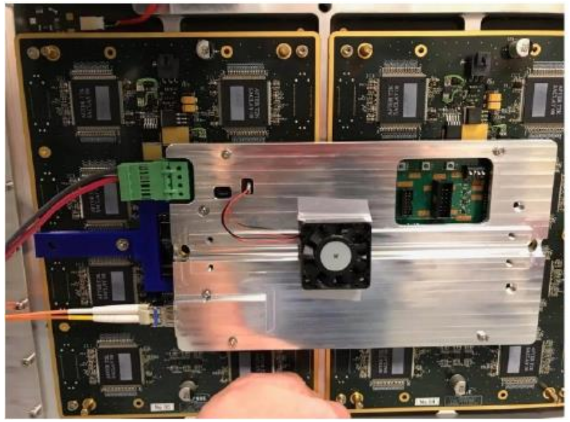


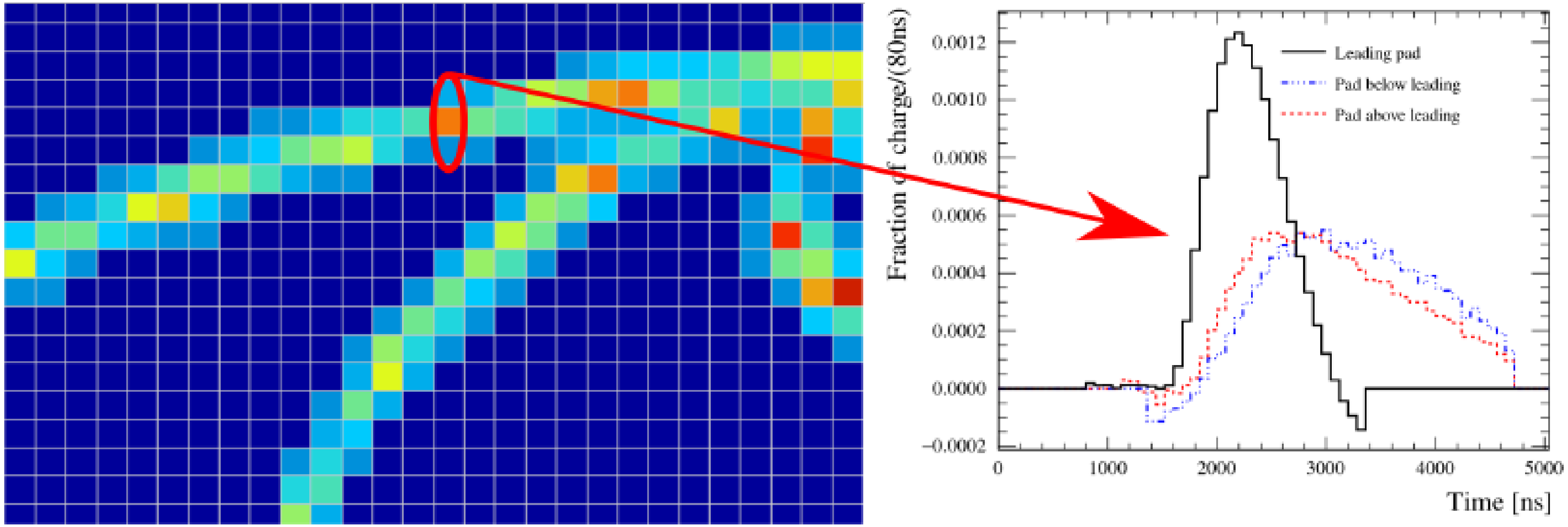


Electron beam track
taken at DESY
Drift : 5 cm

T2K/ND280 module

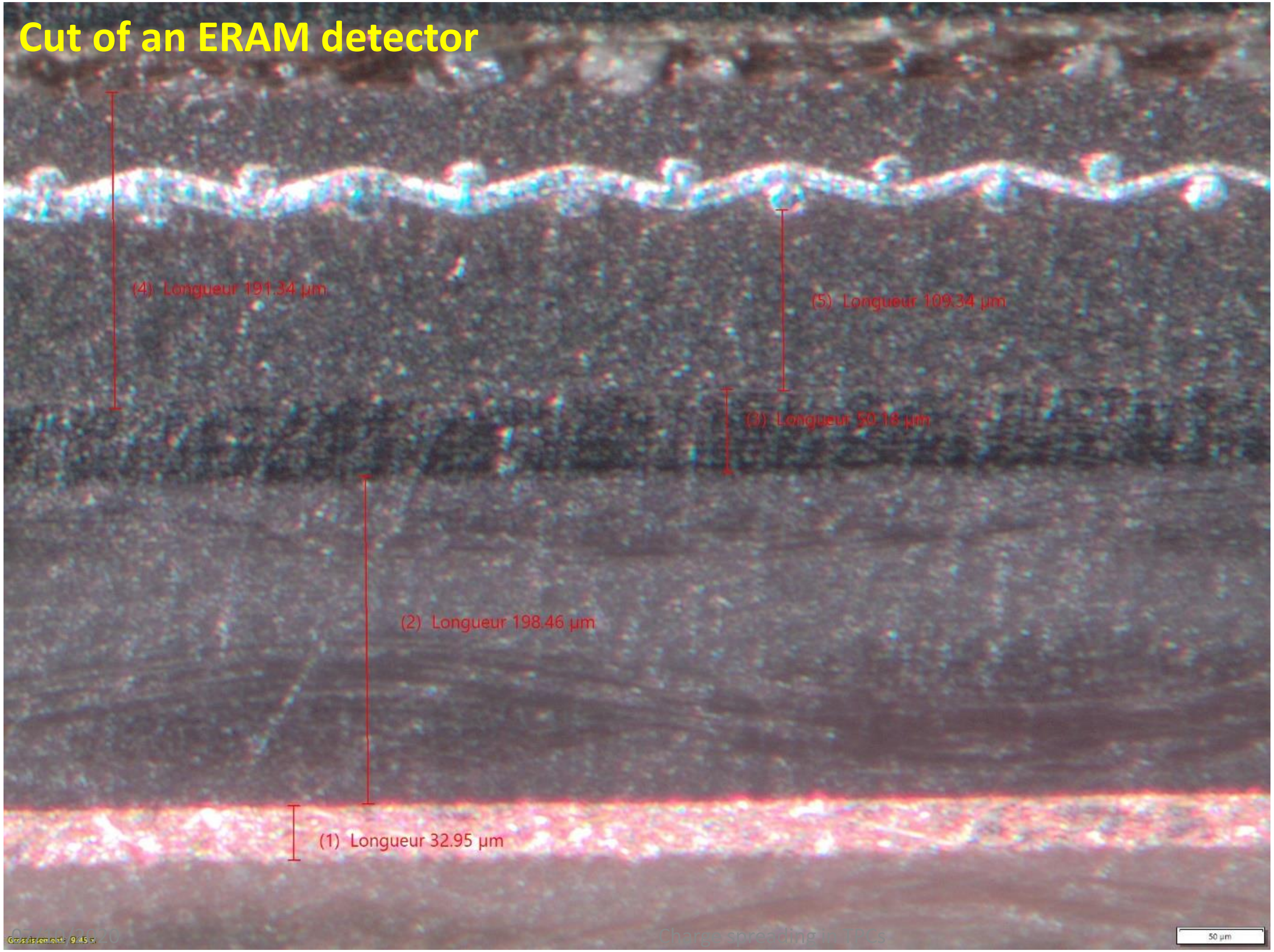
(See talk by C. Giganti on Friday)





Cut of an ERAM detector

O. Pizzirusso,
R. De Oliveira



Mesh

Photo-imageable
film (for pillars)

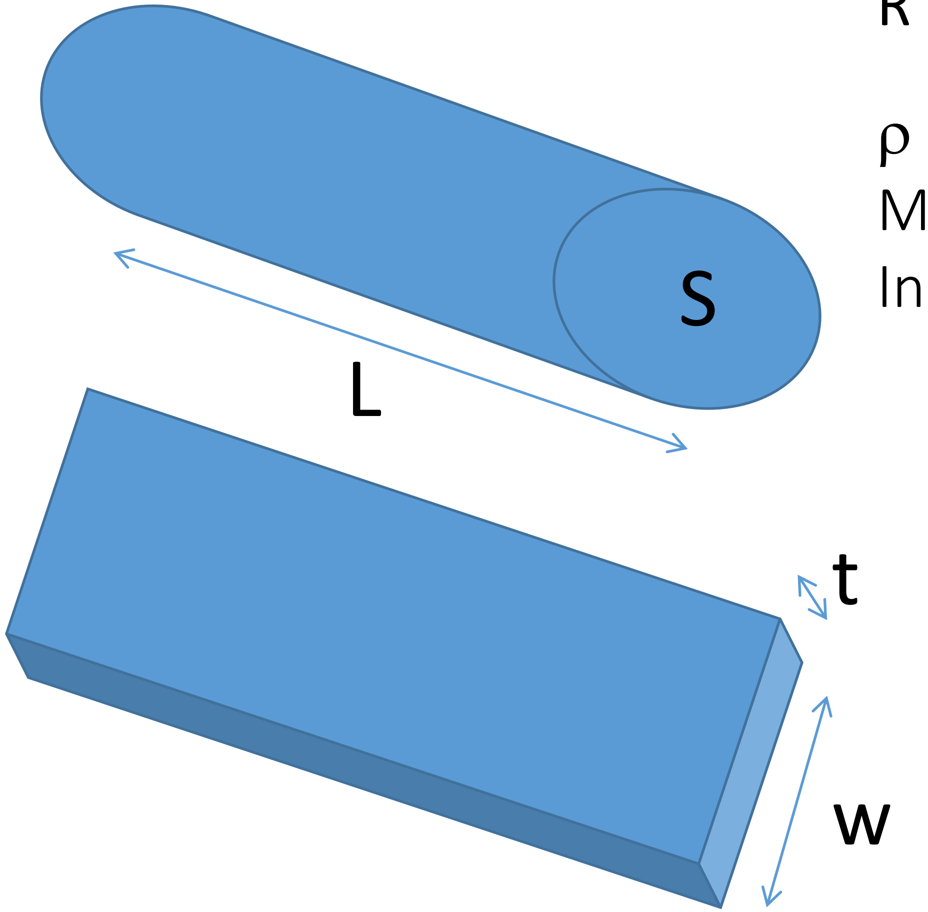
DLC-coated kapton

Glue (prepreg)

Copper pad 35 µm

PCB

Resistive materials : surface resistivity



$R = \rho\ L/S$

ρ : bulk resistivity

Metal : 10^{-6} - $\mathbf{10}^{-5}$ Ω.cm

Insulator >10^{17} Ω.cm

$R = \rho\ L/wt$

Flat layer: t small

Square L=w

Surface resistivity $R = \rho/t$

Units : Ohm per square

Materials :

Ex: AlSi (Cermets),

amorphous hydrogeneted silicon

carbon-loaded kapton

Si_xN_y

Ruthenium oxyde

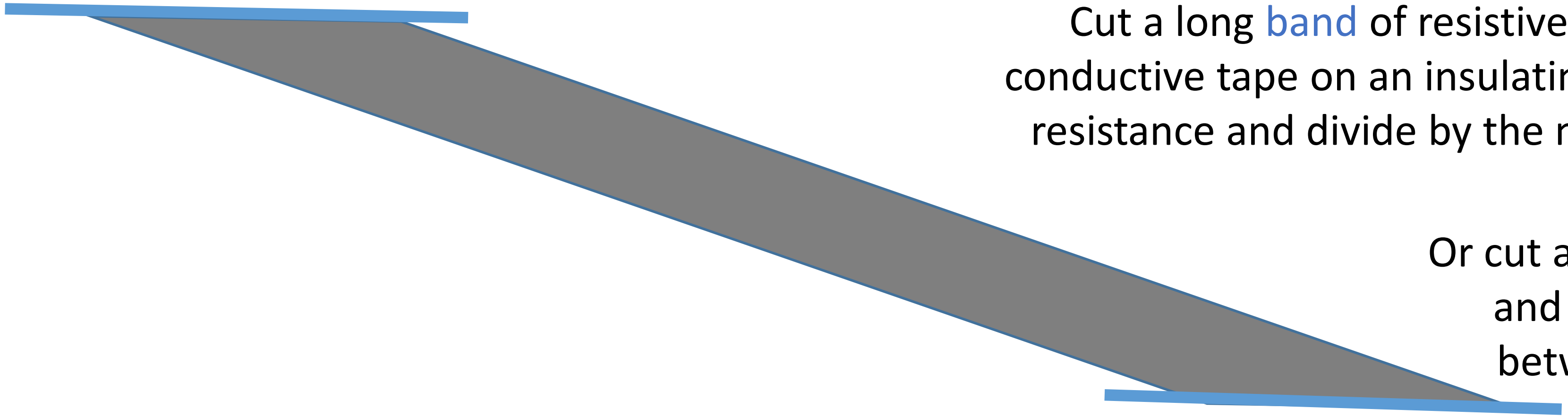
Diamond-Like Carbon (DLC)

Thickness : 100 nm to few microns

(even 50 µm for CLK)

We use 2.5 MΩ/□ for ILC (3mm pads) and 200 kΩ/□

Measurement techniques



Cut a long band of resistive. Hold it both ends with conductive tape on an insulating surface, measure the resistance and divide by the number of squares L/w.

Or cut a square of resistive film and measure the resistance between 2 conductive lines

Circular probe

(for example ETS model 803B)

Measure the resistance between 2 rings

$$\rho_s = \frac{(D_1 + D_2)}{(D_2 - D_1)} \pi R_m \text{ Ohms/sq}$$

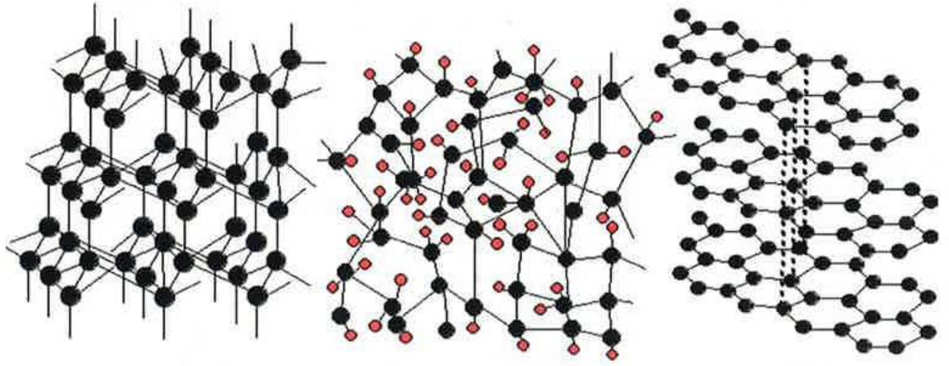
D_1 = Outside Diameter of inner ring

D_2 = Inner Diameter of outer ring

R_m = Measured resistance in ohms

CERN probe

What is DLC?



Diamond

DLC

Graphite

sp^3 bounds

Amorphous with H, both sp^2 and sp^3

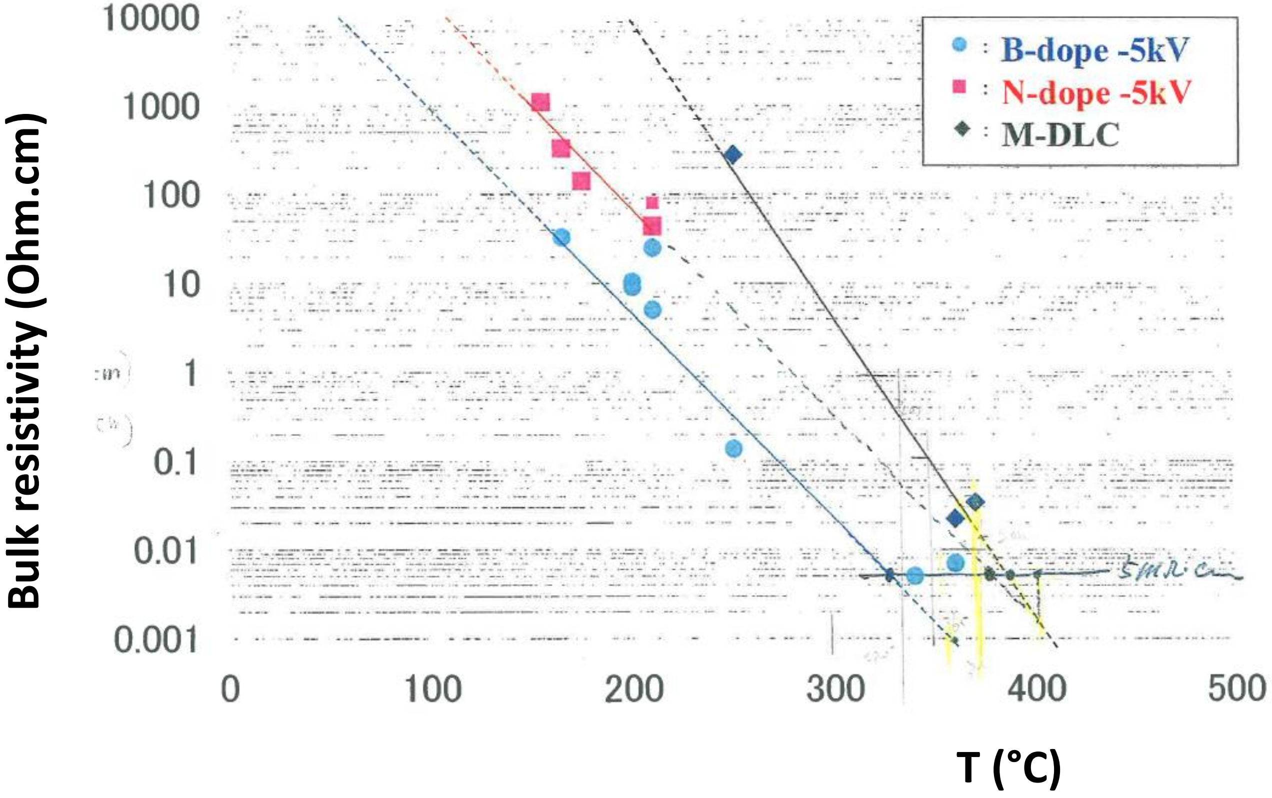
sp^2 bounds

- Diamond-like Carbon
- Properties
  - Electric : resistive
  - Mechanical : hardness, anti-corrosion protection, solid lubricant
- Applications in MPGD
  - Charge spreading anode: deposited on an insulating substrate makes a continuous resistive-capacitive network, evenly spreading the charge, improving point resolution by allowing a barycenter between pads or strips
  - Anti-spark protection (O(1 to 10 or 100) MΩ/□). Needs several microns to get to low enough resistivity for T2K (400 Kohm/sq)
- Other applications
  - Fuel cell battery component

Two fabrication techniques for DLC

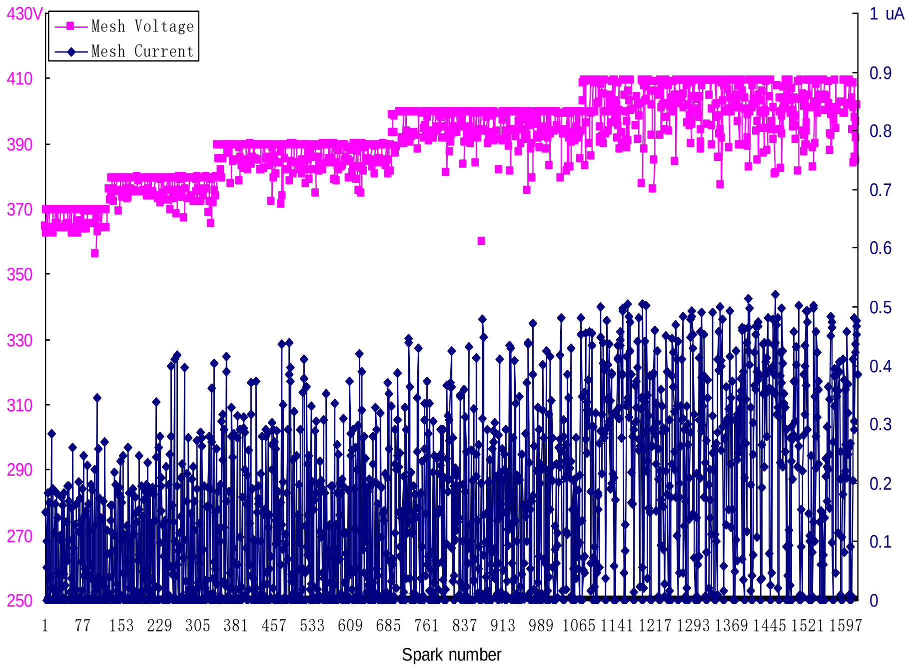
- Sputtering : use an argon plasma to vaporize a graphite target
  - BE-sput company in Kyoto (contact by Atsuhiko Ochi). Successfully produced resistivity in the range 0.4-several 10 Mohm per square.
  - Production also in USTC China (contact Yi Zhou)
- Plasma Assisted ion deposition : use a methane plasma in a high E field to deposit carbon on the substrate. Deposition rate 5-10 µ/hour. Need ~2 microns for 400 Kohm/sq (T2K requirement)
  - PAI company in Kyoto

With the PIA technique, bulk resistivity below 10^{-2} Ω.cm requires temperatures in excess of 350 °C

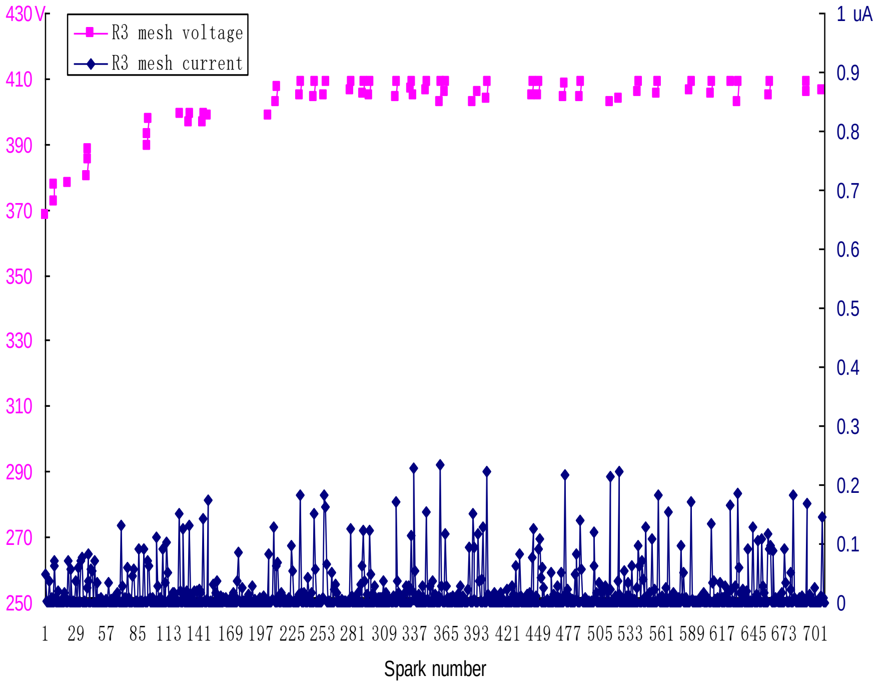


Different sparking behaviours of standard and resistive detector:

Standard SLHC2(@10KHz):



Resistive R3(@wide beam,15KHz):



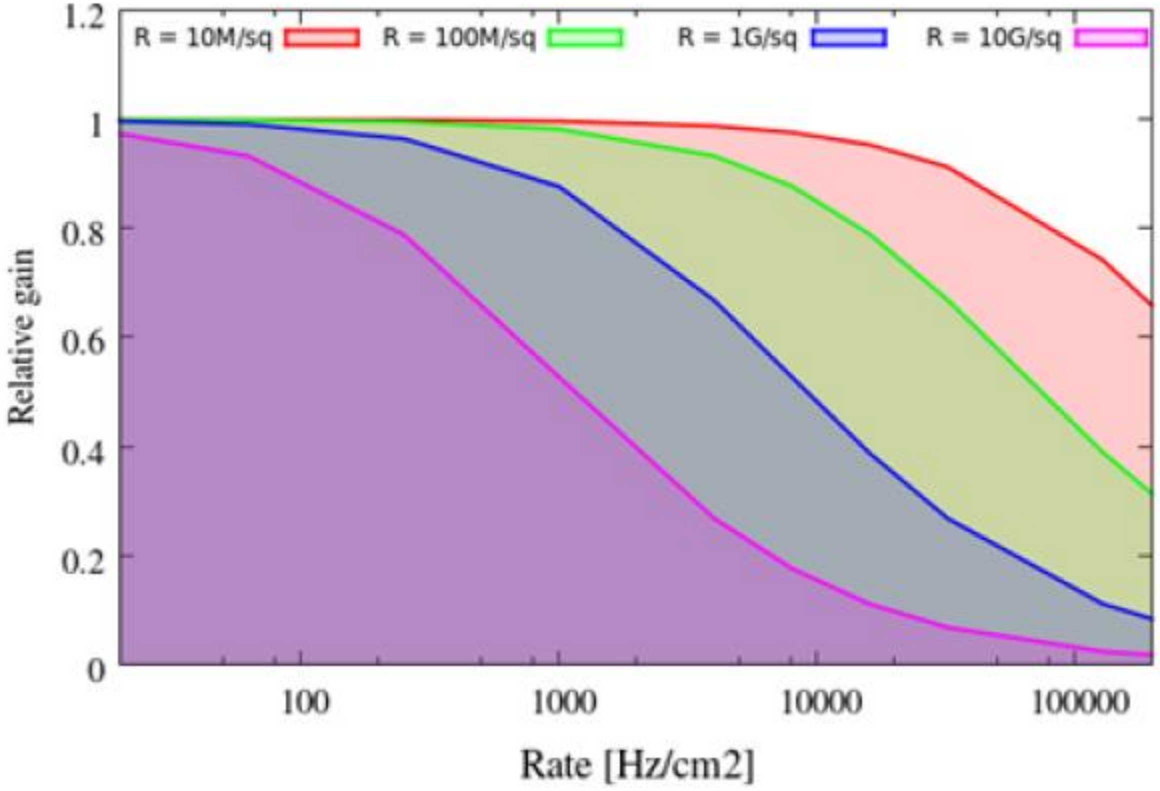
S. Wu

SLHC2: HV=400 V (Gain ~3000): current when sparking < 0.4 μA
voltage drop< 5%

R3: HV=410 V (Gain ~3000): current when sparking < 0.2 μA
voltage drop<2%

RATE CAPABILITY

Resistive layers slow down the detector, as the charge remains some time on the anode. They degrade slightly the rate capability.



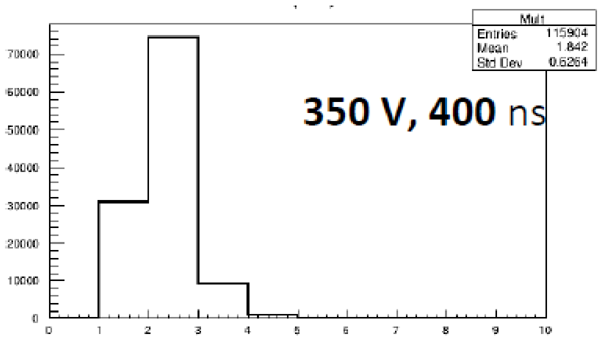
Simulation by J. Galan

D. Attié et al., JINST (2013), 'A piggyback Micromegas'

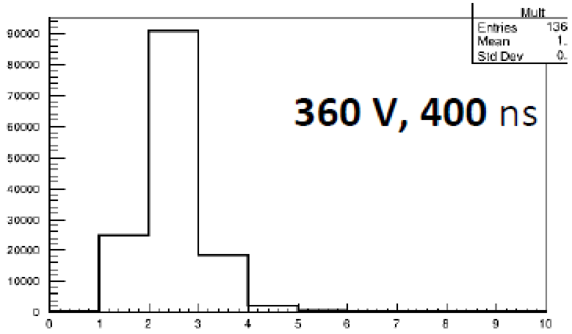
For 10 MΩ, there is a 20% gain drop at 100 kHz/cm2

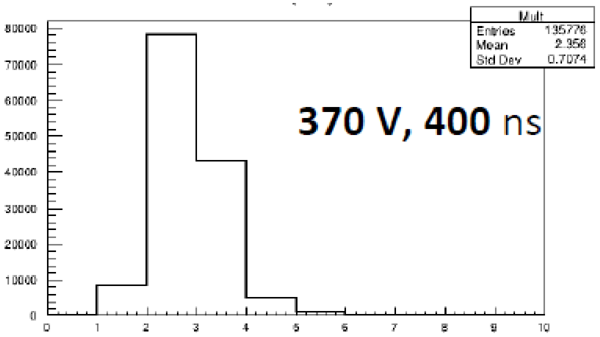
Cluster size distributions
evolution with amplification voltage

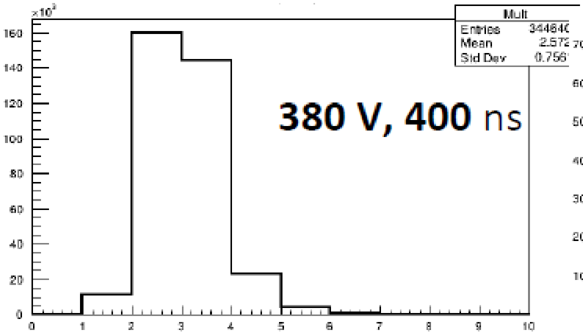
T2K MM1-DLC2 (75µm+50)
Cosmics

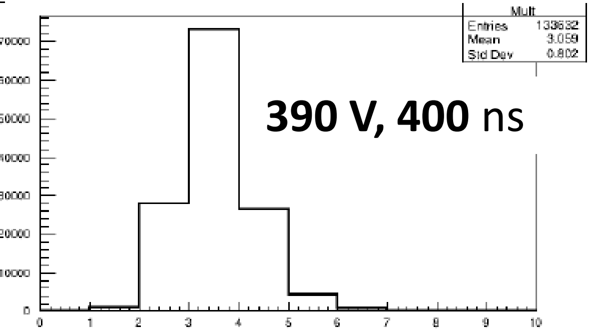


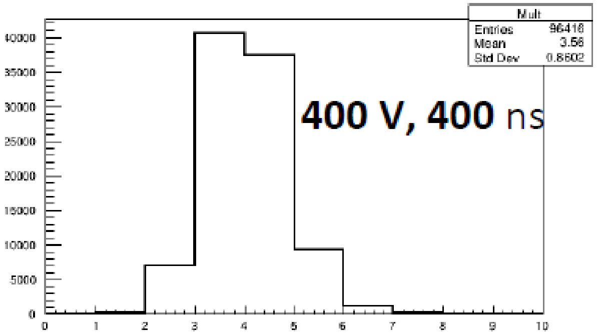
0 1 2 3 4 5 number of pads







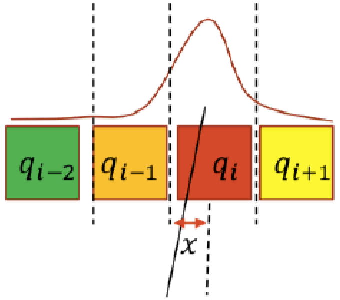




S. Hassani

Pad Response function

2D distribution :
Charge fraction vs Xpad-Xtrack

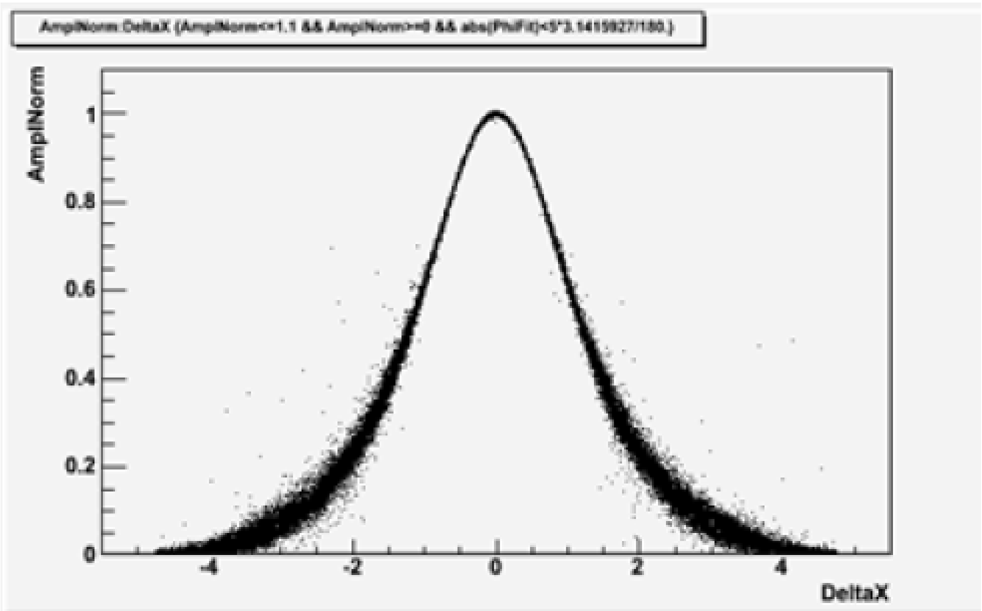


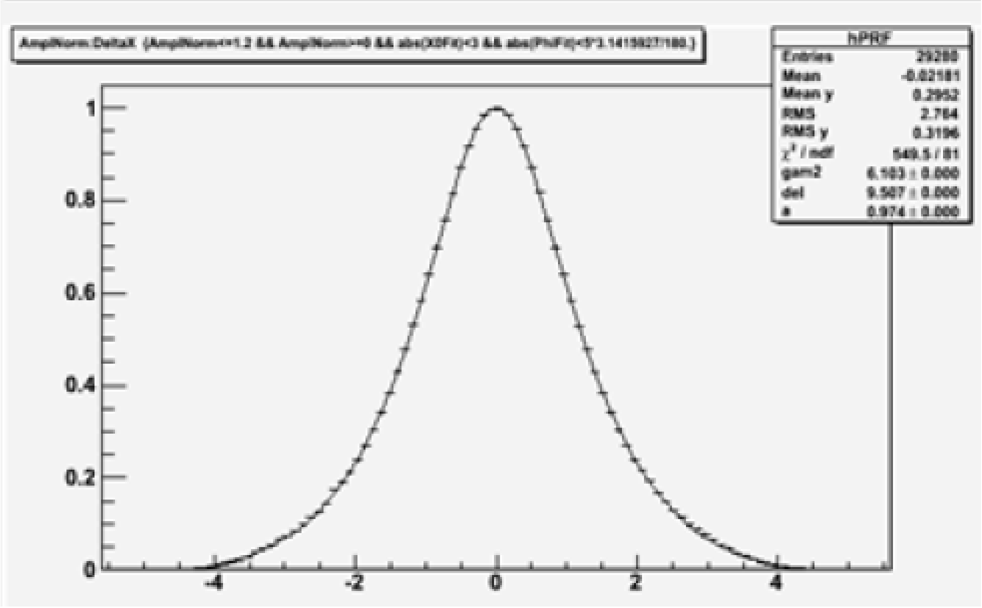
Fit a parameterization to the profile, for i

$$PRF(x,r,w) = \frac{\exp[-4\ln 2(1-r)x^2/w^2]}{1+4rx^2/w^2}$$

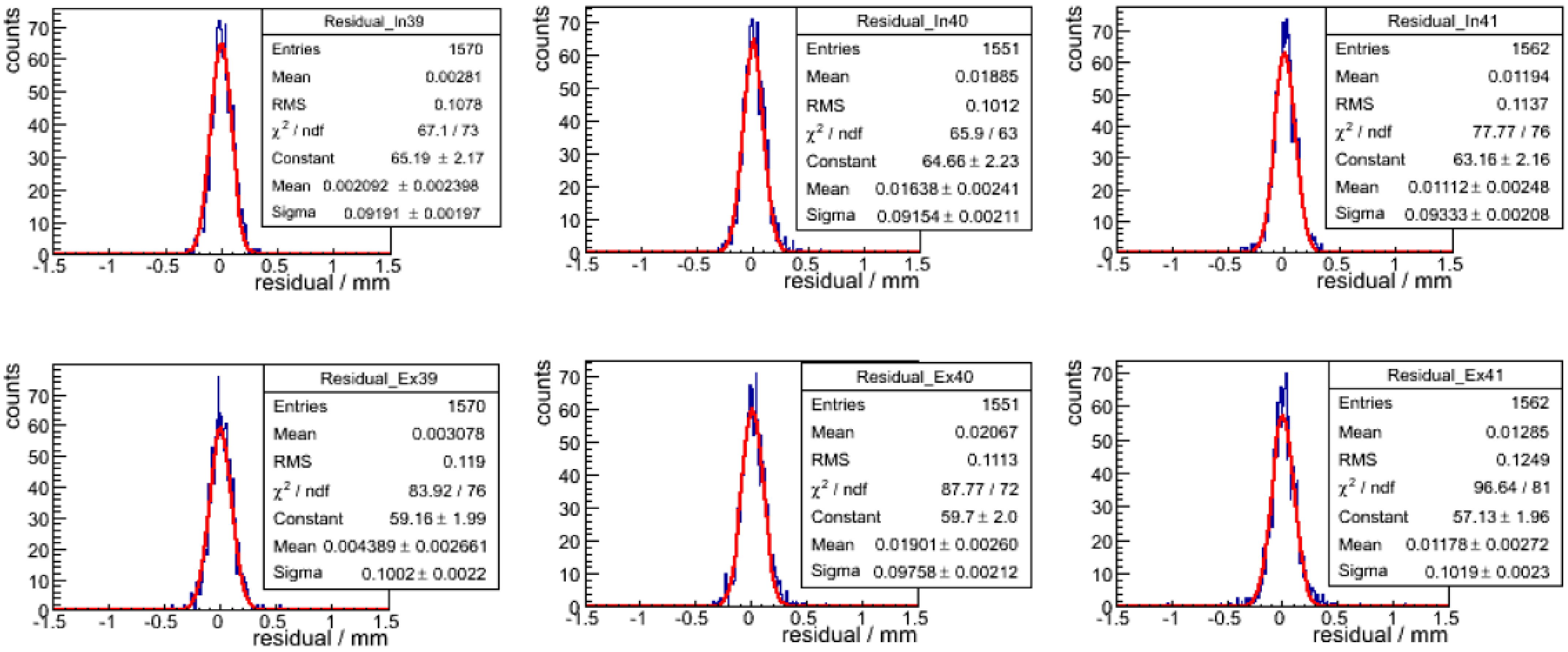
Use the Pad Response Function to obtain the track postion in each padrow from the charge fraction

Re-fit the track and iterate





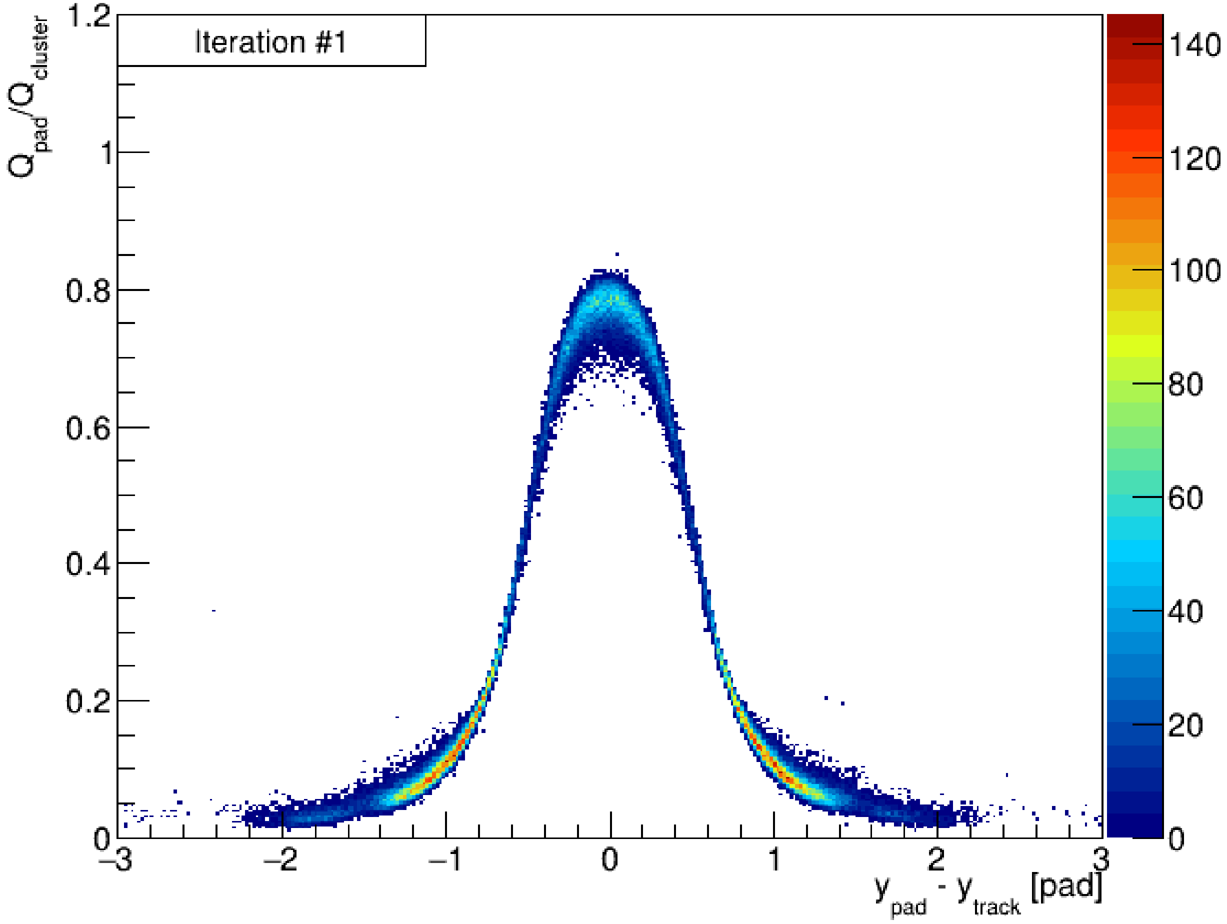
Residuals of the fitted track (after iterations)



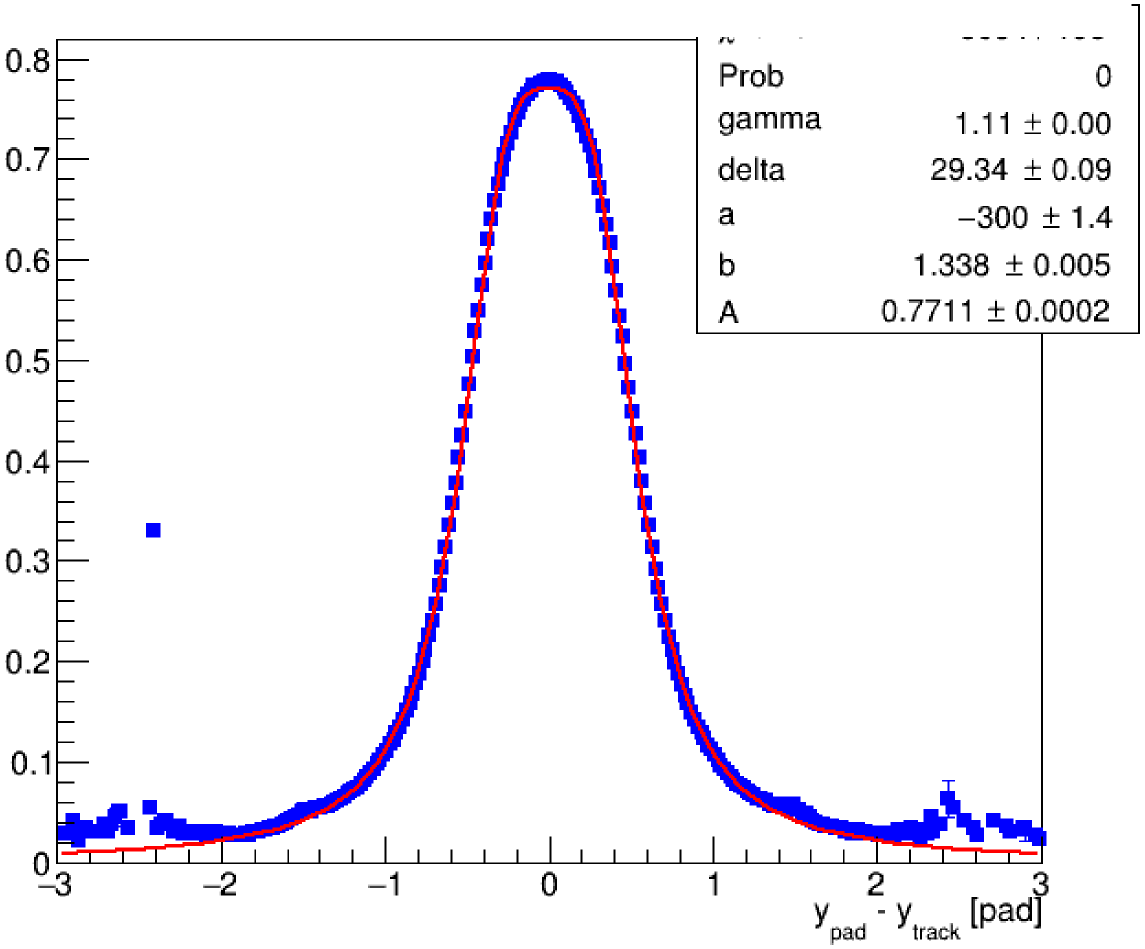
Take the geometrical mean between resolution including and excluding the hit in question to get an unbiased result

T2K beam test data

PRF Calibration column #24



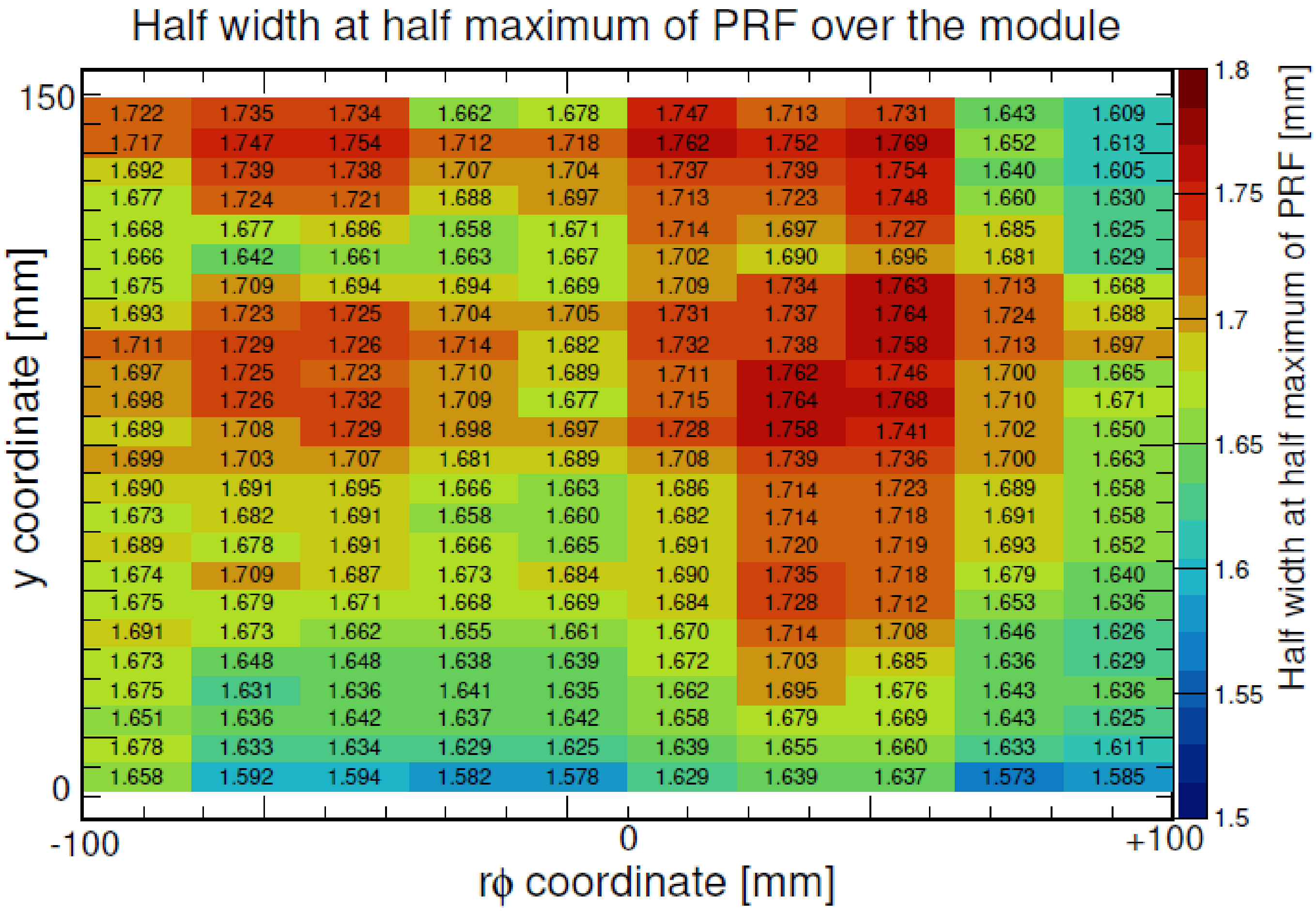
Fit to the profile using the ratio of 2 4th order Polynomials



M. Lehureaux

Uniformity of the charge spreading

T. Ogawa
ILC



Half width at half maximum of PRF over the module

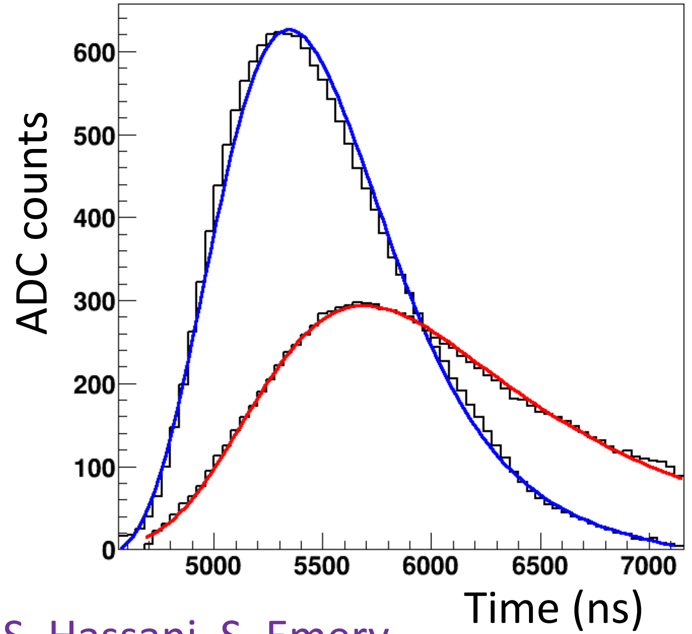
1.722	1.735	1.734	1.662	1.678	1.747	1.713	1.731	1.643	1.609
1.717	1.747	1.754	1.712	1.718	1.762	1.752	1.769	1.652	1.613
1.692	1.739	1.738	1.707	1.704	1.737	1.739	1.754	1.640	1.605
1.677	1.724	1.721	1.688	1.697	1.713	1.723	1.748	1.660	1.630
1.668	1.677	1.686	1.658	1.671	1.714	1.697	1.727	1.685	1.625
1.666	1.642	1.661	1.663	1.667	1.702	1.690	1.696	1.681	1.629
1.675	1.709	1.694	1.694	1.669	1.709	1.734	1.763	1.713	1.668
1.693	1.723	1.725	1.704	1.705	1.731	1.737	1.764	1.724	1.688
1.711	1.729	1.726	1.714	1.682	1.732	1.738	1.758	1.713	1.697
1.697	1.725	1.723	1.710	1.689	1.711	1.762	1.746	1.700	1.665
1.698	1.726	1.732	1.709	1.677	1.715	1.764	1.768	1.710	1.671
1.689	1.708	1.729	1.698	1.697	1.728	1.758	1.741	1.702	1.650
1.699	1.703	1.707	1.681	1.689	1.708	1.739	1.736	1.700	1.663
1.690	1.691	1.695	1.666	1.663	1.686	1.714	1.723	1.689	1.658
1.673	1.682	1.691	1.658	1.660	1.682	1.714	1.718	1.691	1.658
1.689	1.678	1.691	1.666	1.665	1.691	1.720	1.719	1.693	1.652
1.674	1.709	1.687	1.673	1.684	1.690	1.735	1.718	1.679	1.640
1.675	1.679	1.671	1.668	1.669	1.684	1.728	1.712	1.653	1.636
1.691	1.673	1.662	1.655	1.661	1.670	1.714	1.708	1.646	1.626
1.673	1.648	1.648	1.638	1.639	1.672	1.703	1.685	1.636	1.629
1.675	1.631	1.636	1.641	1.635	1.662	1.695	1.676	1.643	1.636
1.651	1.636	1.642	1.637	1.642	1.658	1.679	1.669	1.643	1.625
1.678	1.633	1.634	1.629	1.625	1.639	1.655	1.660	1.633	1.611
1.658	1.592	1.594	1.582	1.578	1.629	1.639	1.637	1.573	1.585

$\sigma = \mathrm{sqrt}(2t/RC)$

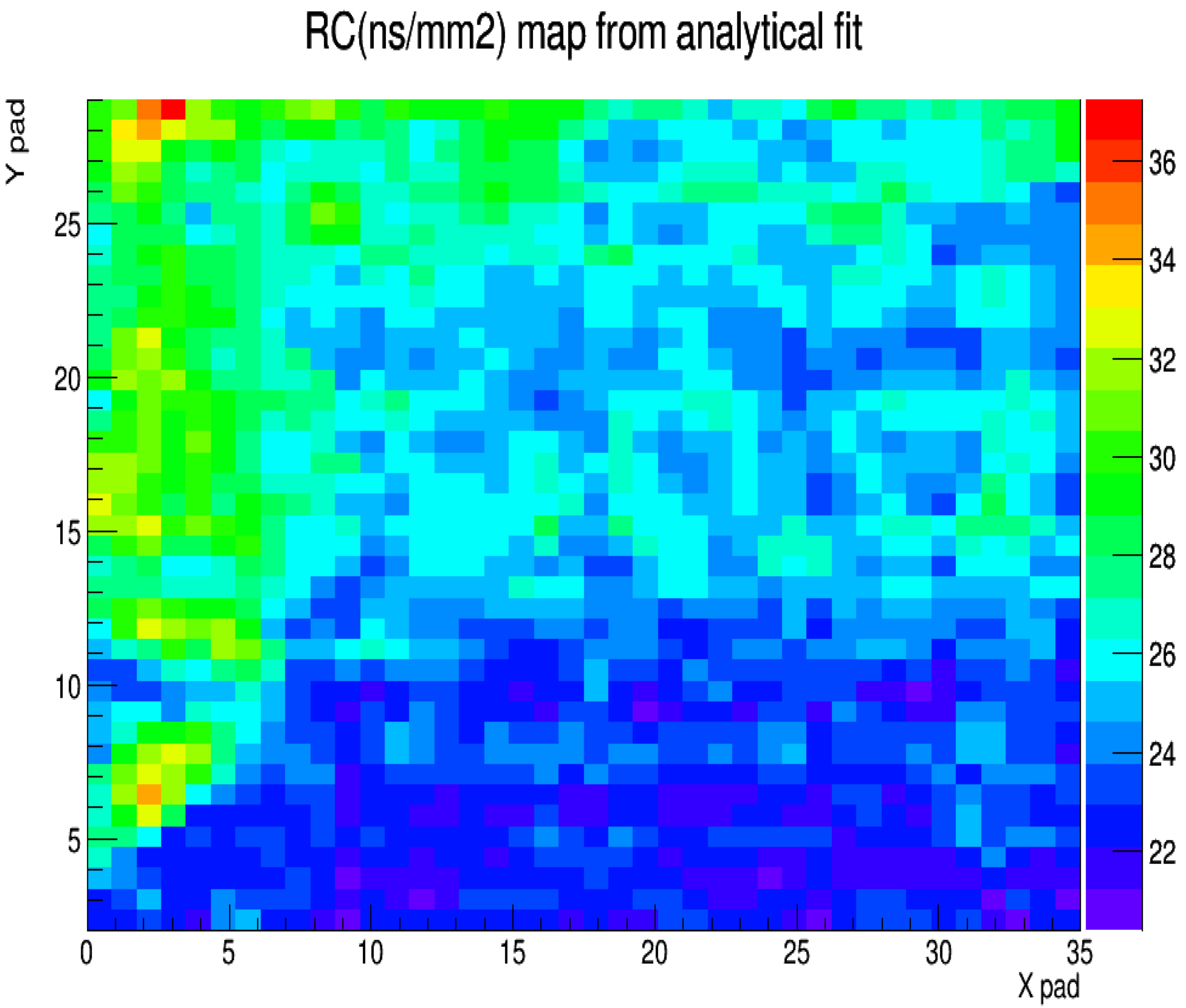
The PRF width is very uniform : 1.6 to 1.7mm

An RC map can be obtained from a fit to the waveforms (T2K)

The electronic response is fitted to the leading pad waveform, and RC is fitted to the convolution of the response by the expected signal shape in the two neighbouring pads. Note that both amplitude and time are sensitive to the track position (G. Collazuol).

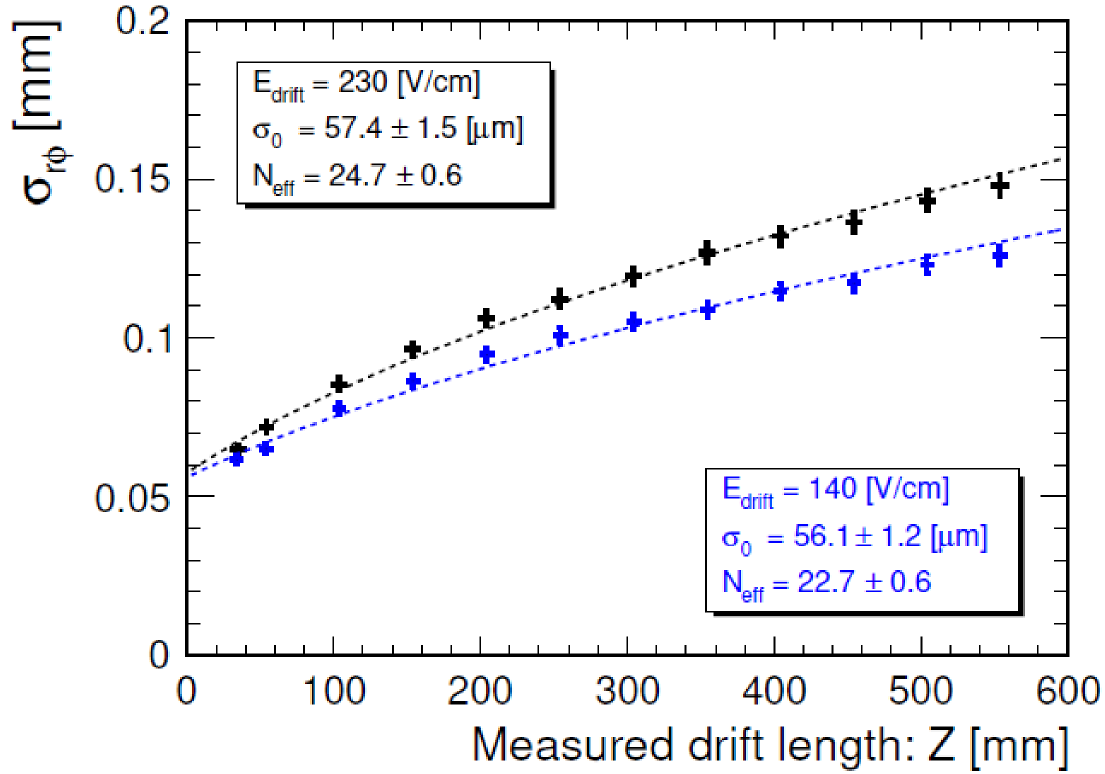


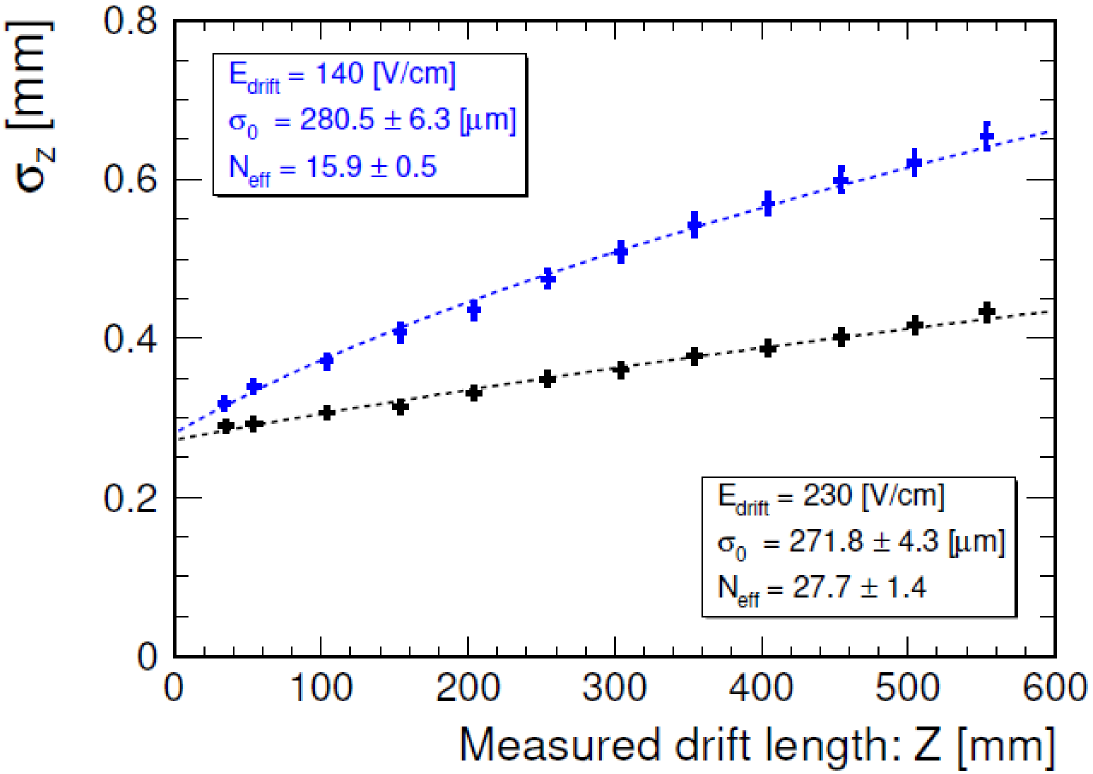
S. Hassani, S. Emery


RC(ns/mm2) map from analytical fit

Position resolution

T. Ogawa, S. Ganjour, ILC





Resolution at zero drift distance : 60 µm with 3mm pads.
Gain by a factor of 14 with respect to w/√12 !

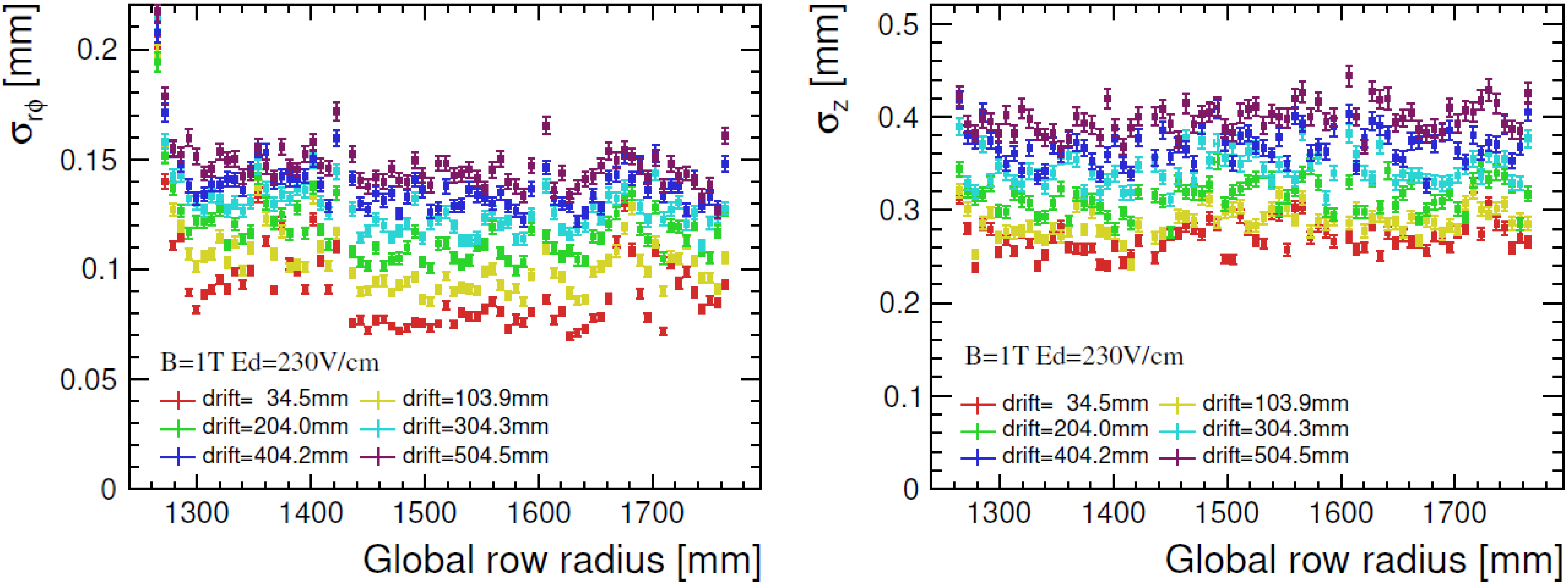
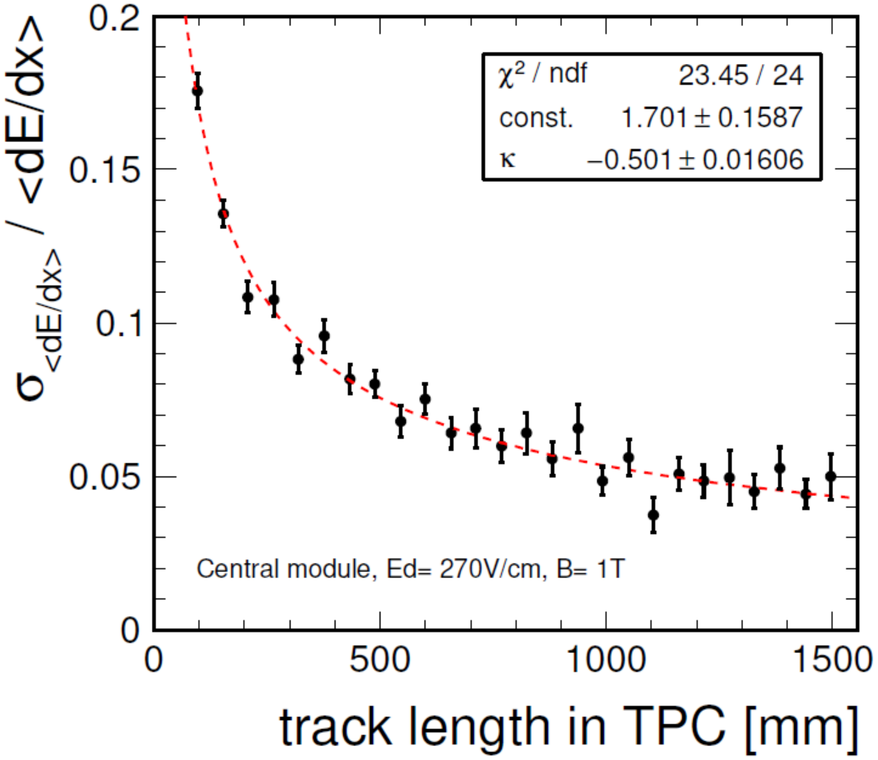


Figure 9: The distributions of the spatial and z resolution for different drift lengths over all pad-rows in three modules with the track reconstruction using those modules.

dE/dx measurement



5 % resolution for 1.2 m tracks

Scales as sqrt(track length)

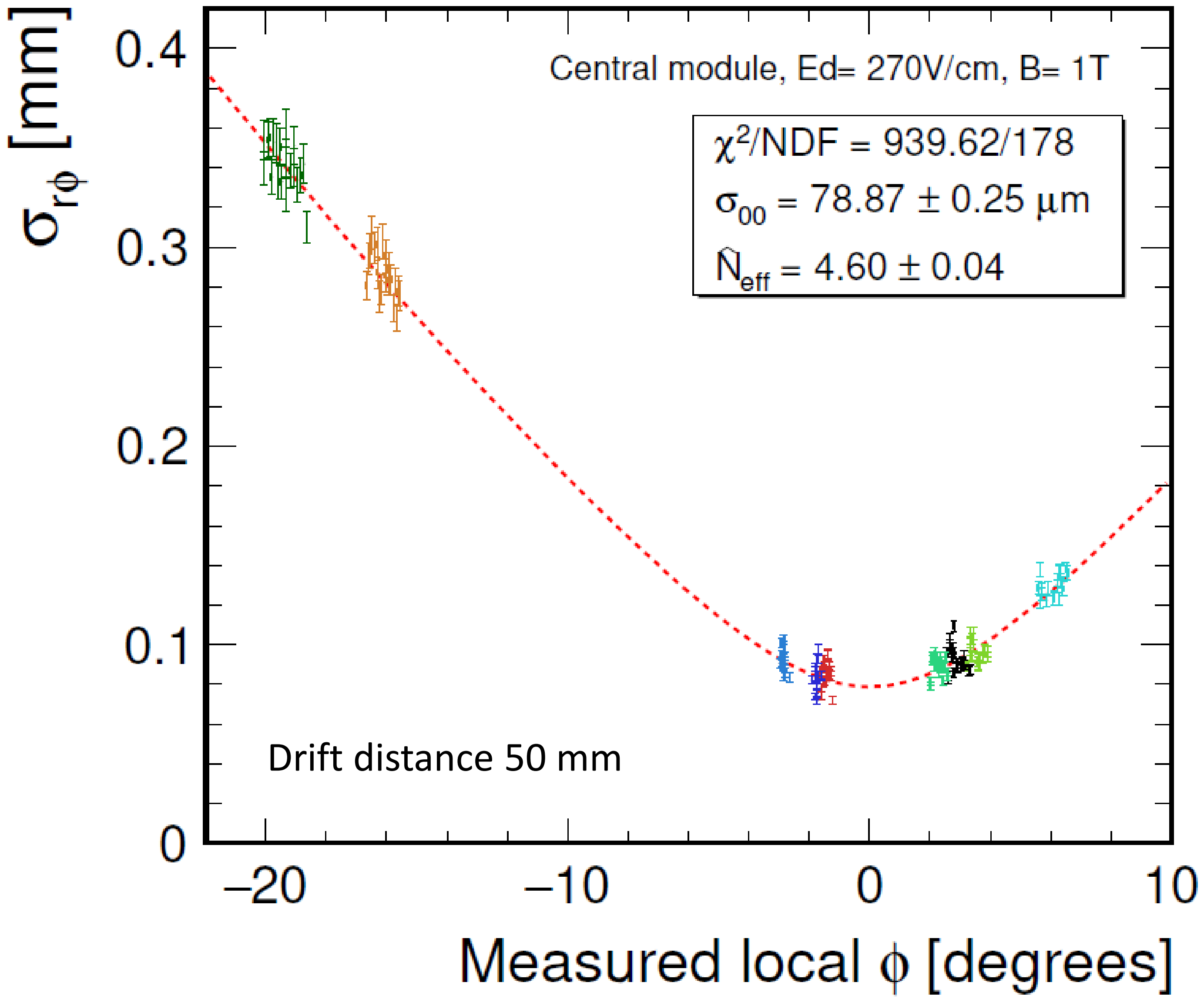
T. Ogawa

Track angle effect

Pad height

$$\sigma^2_{r\phi 0} = \sigma^2_{r\phi 00} + \frac{h^2 \cdot \tan^2\phi}{12\hat{N}_{\text{eff}}}$$

Effective number of clusters per padrow



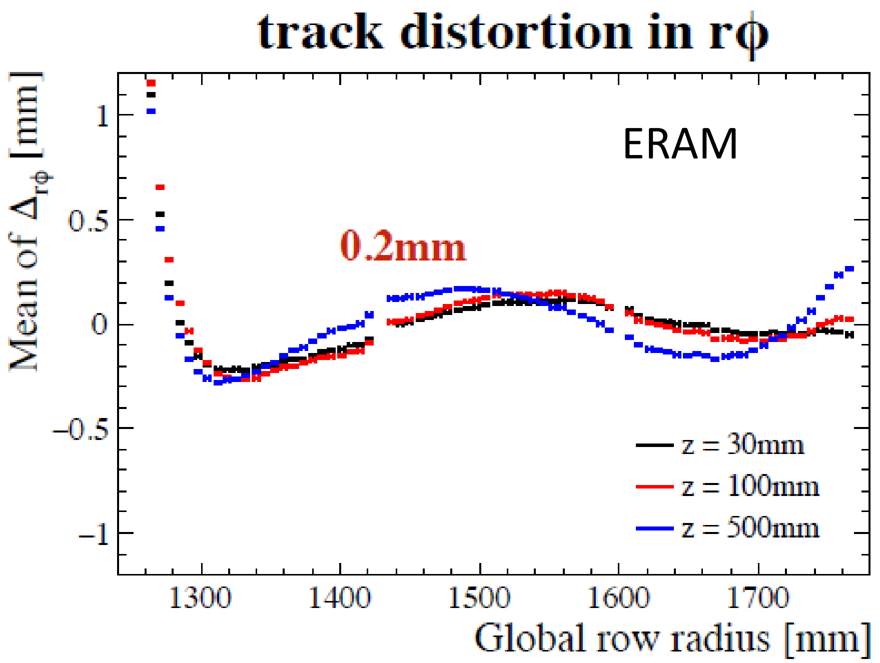
Drift distance 50 mm

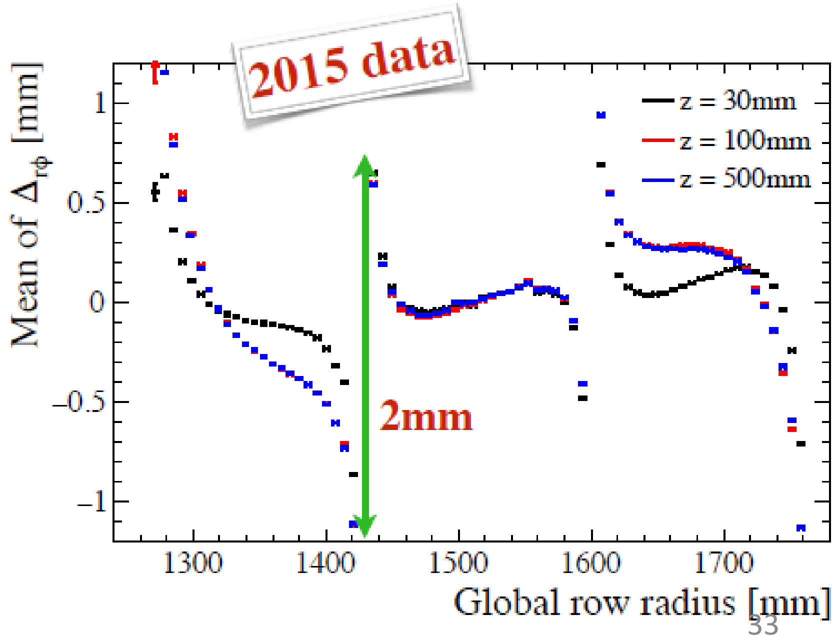
Mitigation of distortions

The ERAM scheme allows the mesh to be at ground, while the resistive coating is at a positive high voltage.
As the frames are necessarily grounded, this provides a much better equipotential surface at the endplate level.

As a consequence, distortions are suppressed by an order of magnitude.

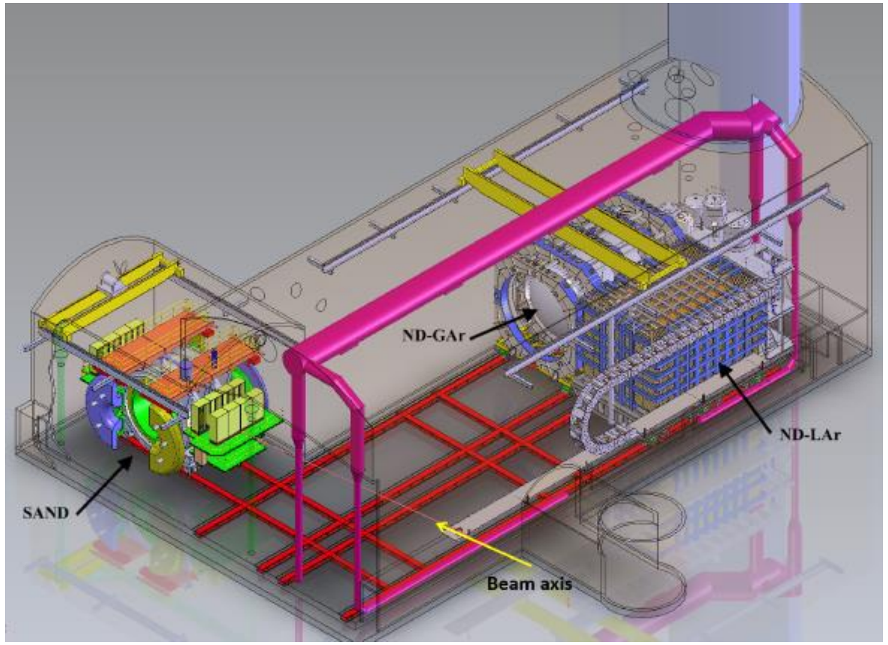
This also brings a large flexibility as this allows to have a module at a different voltage, or even switched of, without affecting the neighbours.

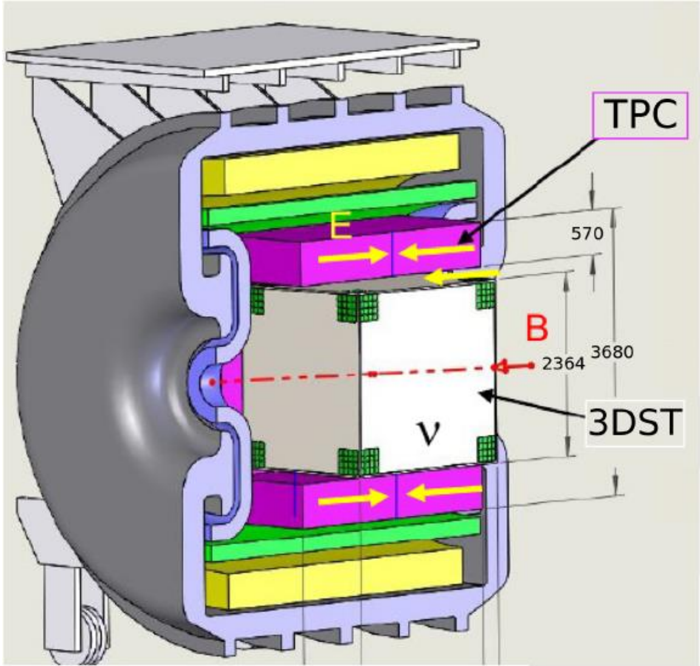


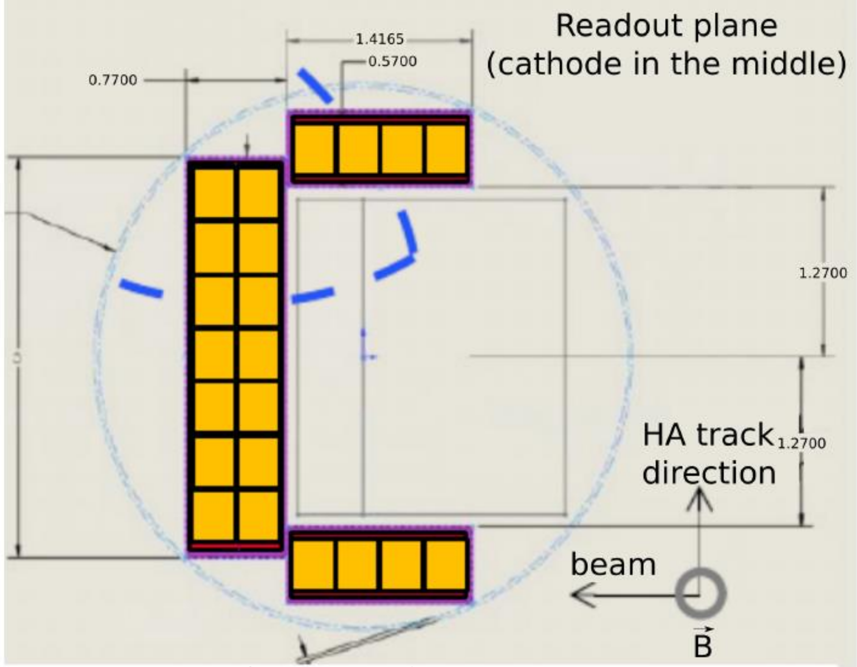


Future

A Micromegas TPC with a resistive anode is one of the options of SAND (the DUNE near detector), surrounding a 3D Scintillator Tracker and centered on the beam axis, in the KLOE magnet.







Compared to T2K / ND280:
Higher momentum beam
and Hydrogen-rich target
(no Fermi motion smearing)
-> better space resolution
and segmentation

Conclusions

- The ERAM structure (Encapsulated Resistive Anode Micromegas) is a good way of improving
  - resolution and cost-effectiveness
  - detector stability
  - distortion mitigation
  - flexibility
- There are already several applications in progress of ERAM-equipped TPCs