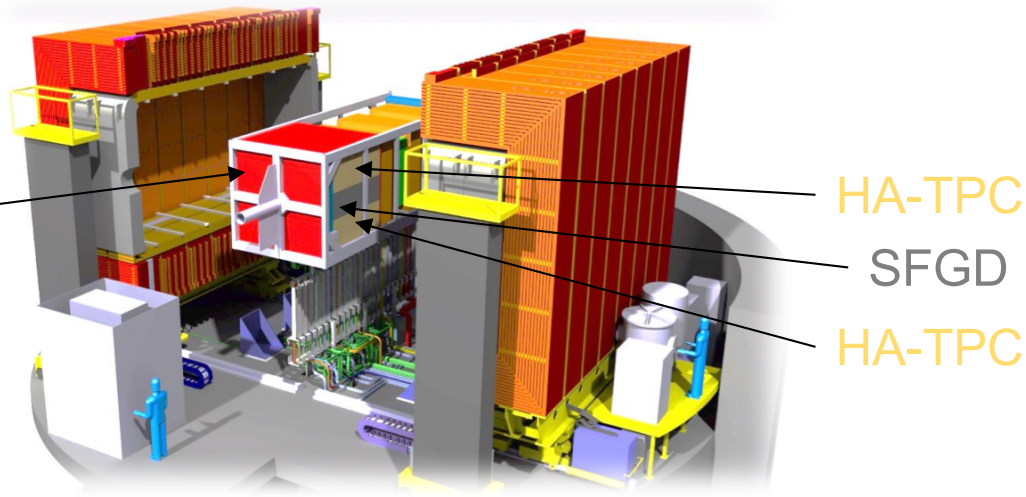
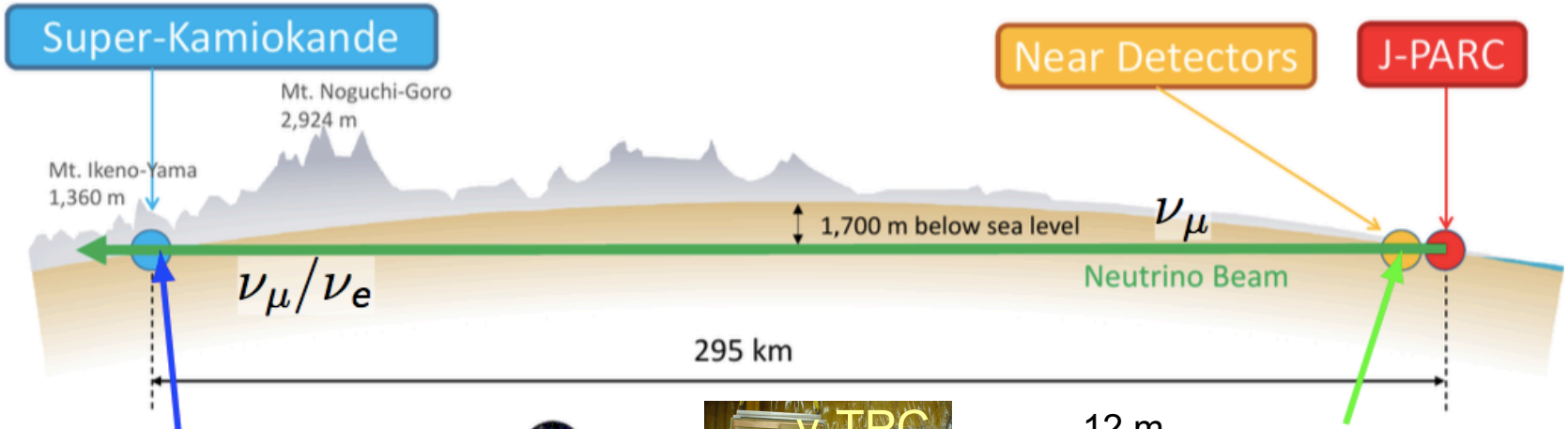
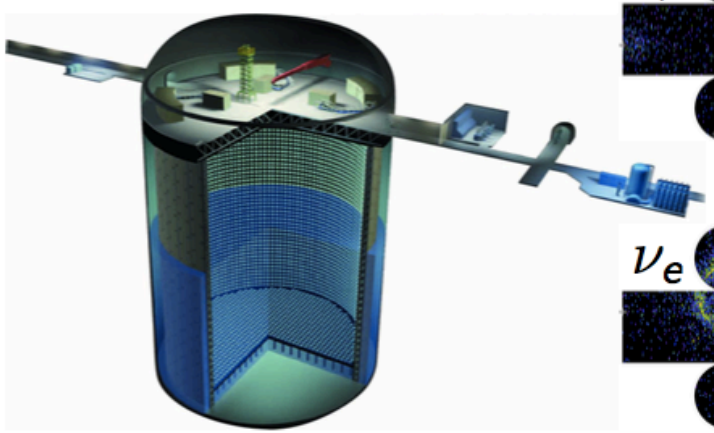
DEVELOPMENT OF RESISTIVE MICROMEGAS TPCs FOR THE T2K EXPERIMENT

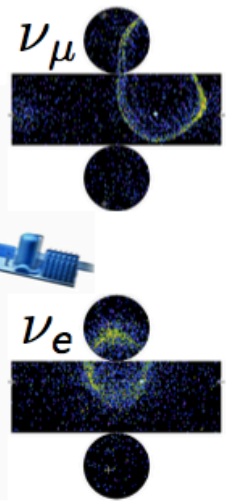


A. Delbart, on behalf of the ND280/HA-TPC collaboration,
CEA-Saclay/DRF-IRFU, Univ. Paris – Saclay

THE T2K EXPERIMENT
THE ND280 NEAR DETECTOR

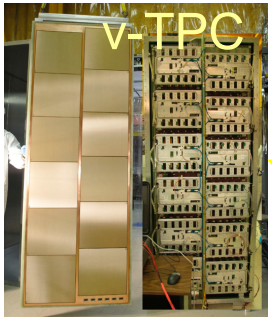


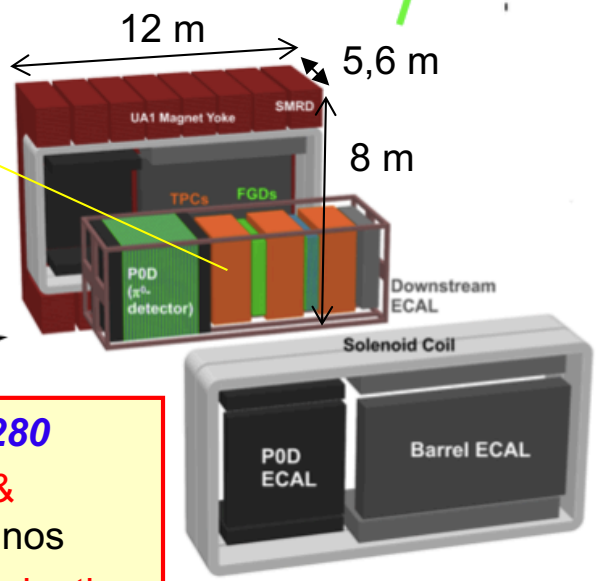




Super-Kamiokande (SK)

22.5 kt → ~200 kt (Hyper-K)





ND280

Goal of ND280

Measure the flux & spectrum of neutrinos

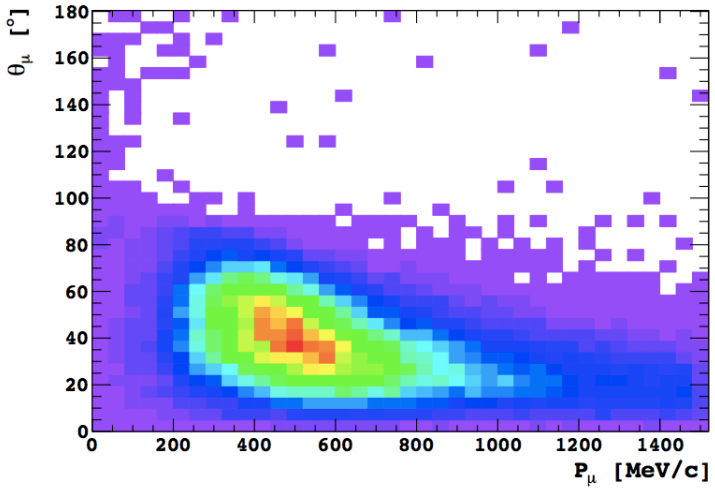
Measure ν_e contamination

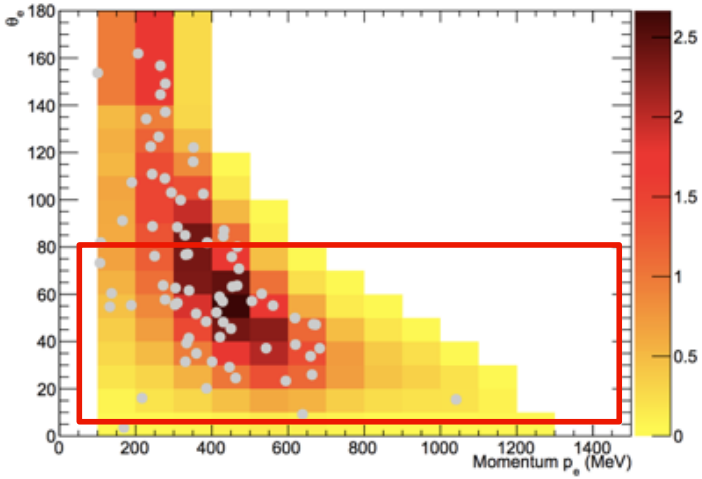
The goal of T2K-II phase (2022-) data taking after main ring upgrade is to measure δ_{CP} at 3σ thanks to a decrease in systematic errors in ND280 from 6% to 4%.

T2K/ND280 PERFORMANCES & LIMITATIONS NEED FOR AN UPGRADE

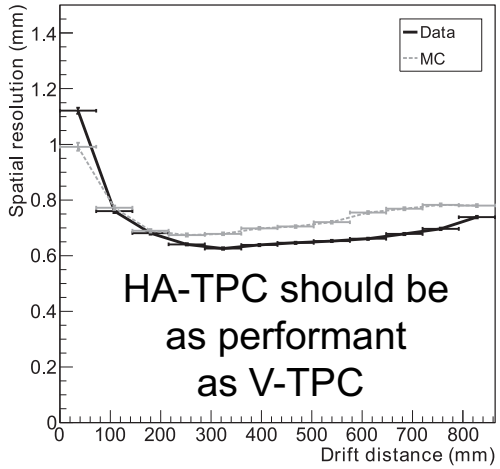
T2K v-TPC : NIM A659 (2011) p106-135
ND280 upgrade TDR : arXiv:1901.03750v1

Reconstructed momentum and angle for μ selected at ND280 (left) and e- selected at SK

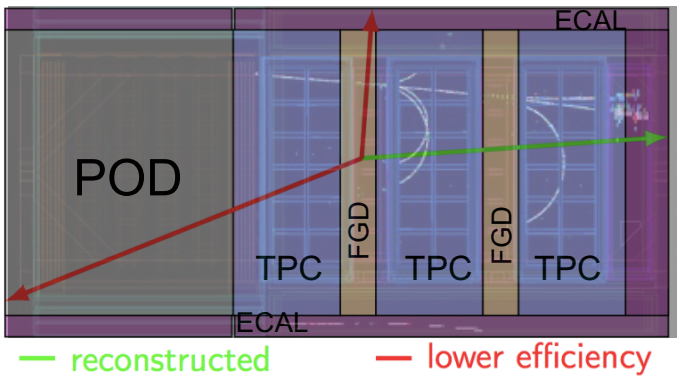


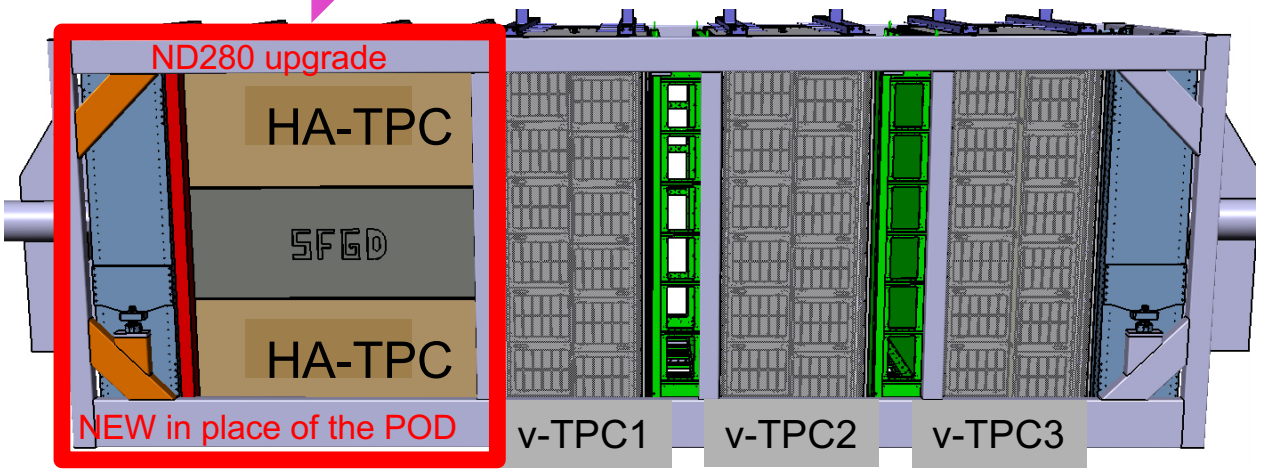


V-TPC spatial resolution 6.9x9.7 mm² pads



Current ND280 → Proposed ND280 upgrade



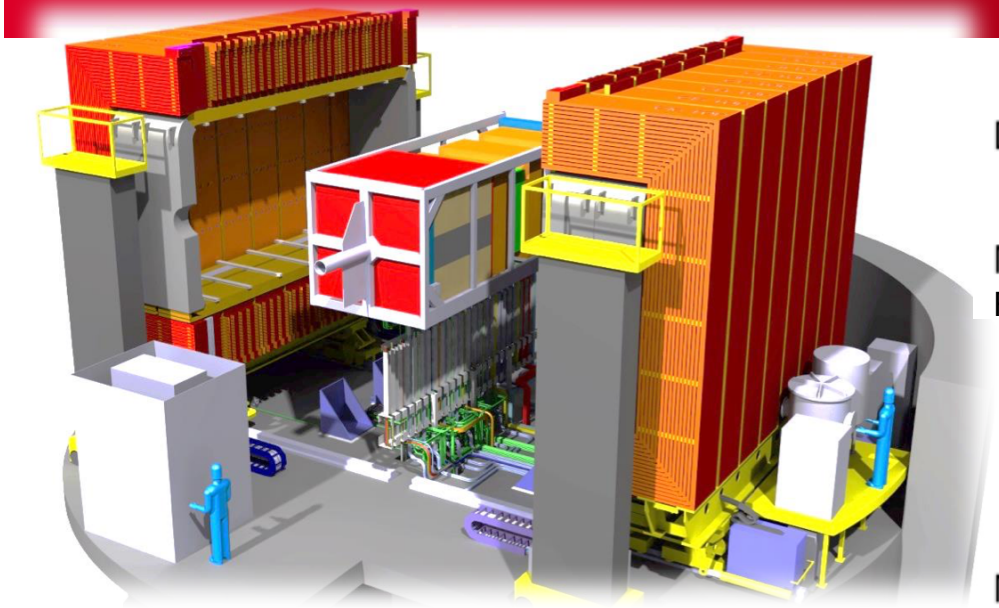


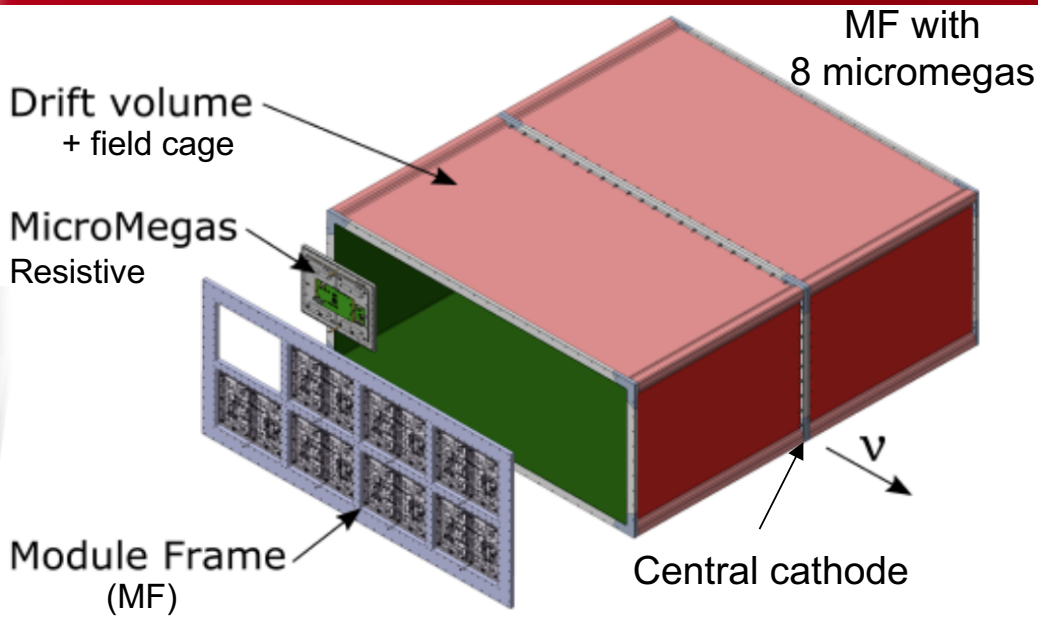
Good acceptance only for forward tracks

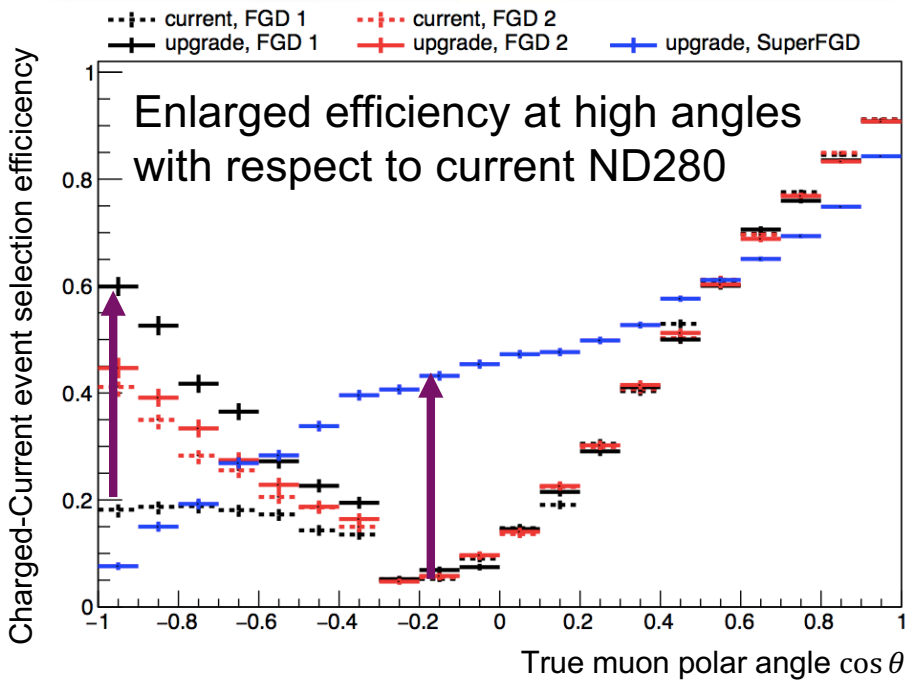
+ 6 TOF planes surrounding the new tracker

T2K/ND280 UPGRADE

HA-TPCS







Parameter	Value (HA-TPC)	V-TPC
Overall x × y × z (m)	2.0 × 0.8 × 1.8	0.85 x 2.2 x 1.8
Drift distance (cm)	90	
Magnetic Field (T)	0.2	
Electric field (V/cm)	275	
Gas Ar-CF_4-iC_4H_{10} (%)	95 - 3 - 2	
Drift Velocity $cm/\mu s$	7.8	
Transverse diffusion ($\mu m/\sqrt{cm}$)	265	
Micromegas gain	1000	
Micromegas dim. z×y (mm)	340x420	340x360
Pad z × y (mm)	10 × 11	7x10
N pads	36864	124272
el. noise (ENC)	800	
S/N	100	
Sampling frequency (MHz)	25	
N time samples	511	

RESISTIVE BULK-MICROMEGAS WITH DIAMOND-LIKE CARBON LAYER

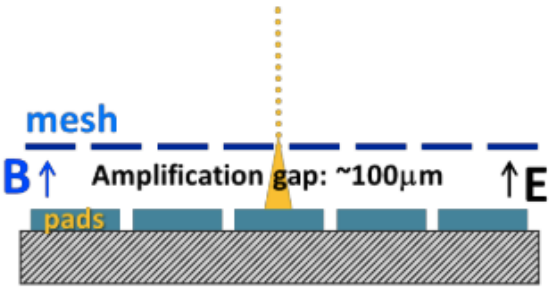
ILC/TPC R&D: P. Colas et al.

Ref: M.S. Dixit *et al. NIM* A518, p. 721, 2004

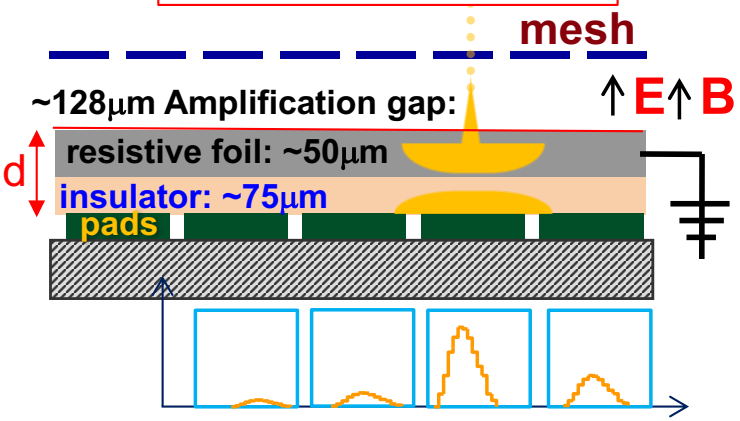
Choice of the Resistive foil technology for the HA-TPC micromegas readout

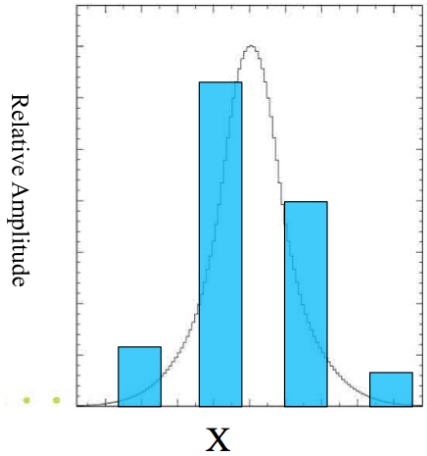
- Charge spreading which should enable keeping the ~600 μm spatial resolution with larger pads and improves it at short drift distance → less electronic channels, cost reduction
- ASIC spark protection no longer needed → more compact FEE, maximize HA-TPC acceptance
- Encapsulated mesh @ GND + insulating layer → potentially lower track distorsions & better S/N

Standard bulk-mm



Resistive-bulk-mm





2-D RC network

$$\rho(r,t) = \frac{RC}{2t}\exp\left[-\frac{-r^2RC}{4t}\right]$$

R- surface resistivity
C- capacitance/unit area

Gaussian spreading as a function of time with :

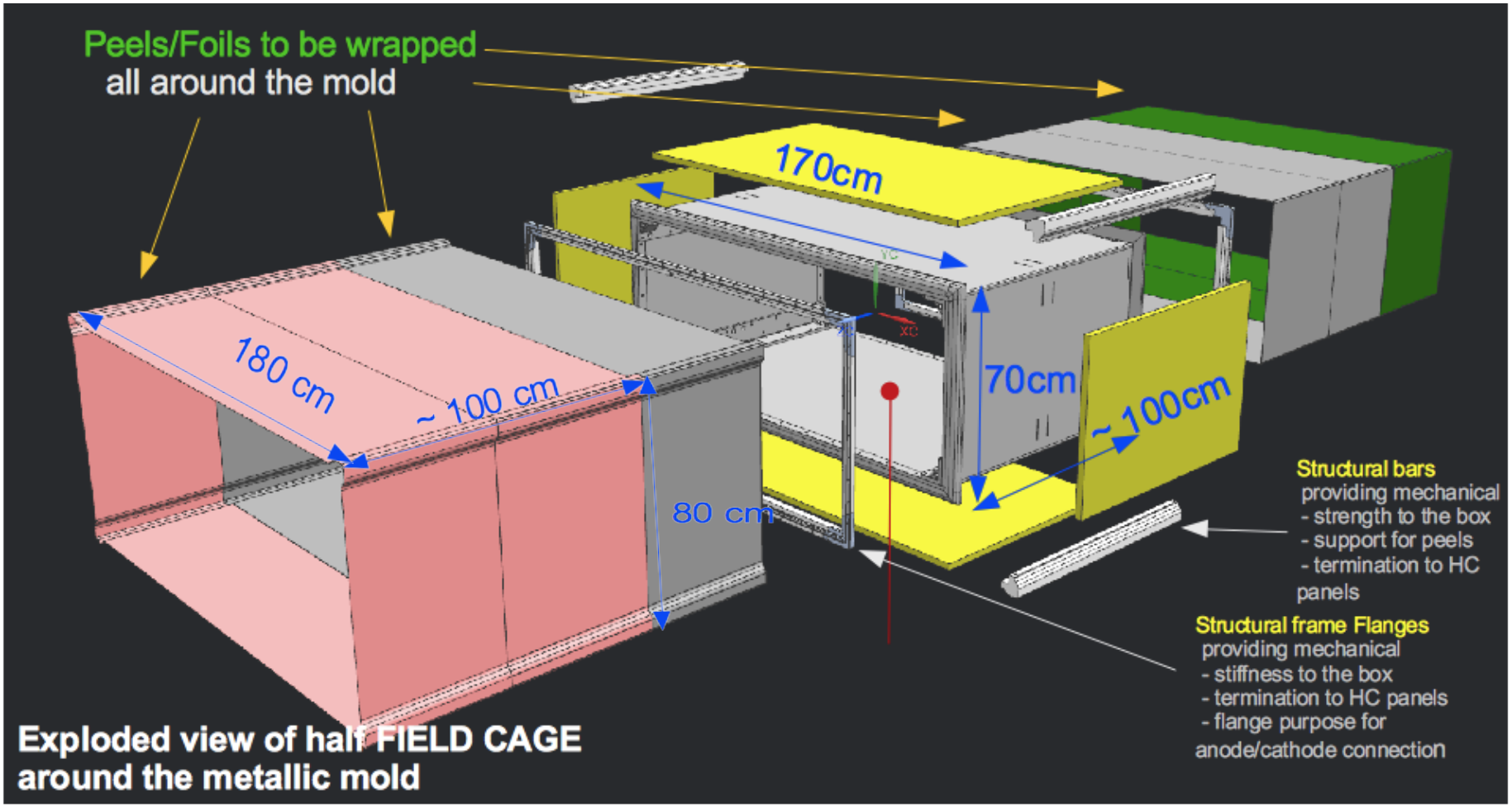
$$\sigma_r = \sqrt{\frac{2t}{RC}} \qquad \begin{cases} t \approx shaping\ time\ (few\ 100\ ns) \\ RC_{[ns/mm^2]} = \dfrac{180\ R_{[M\Omega/\blacksquare]}}{d_{[\mu m]}/175} \end{cases}$$

For pads of ~11x10 mm^2, the Kapton foil resistivity could be **around** $0.4\ M\Omega/\blacksquare$ and glue thickness **~75 μm** for a good charge spreading (σ~ 2,6 mm) (spark protection to be checked)

TPC CAGE DESIGN & CONSTRUCTION

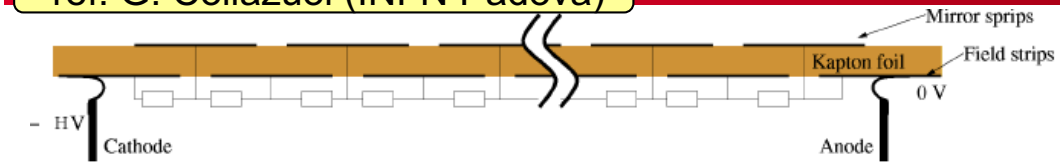
ref: G. Collazuol (INFN Padova)

To keep $\Delta E/_E \leq 10^{-4}$ confined at <1cm from FC walls, the TPC cage requirements are :
Cathode flatness better than 0.1mm, Micromegas plane flatness better than 0.2 mm,
Cathode/Anode planes parallel to within 0.2mm, Field Cage walls flatness better tham 0.3mm
Voltage divider resistors matched within rms ~ 0.1%



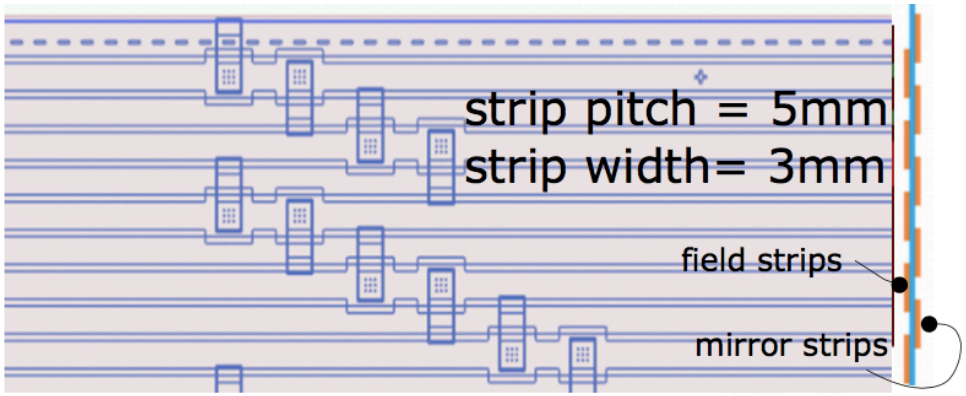
TPC CAGE
FEA & ELECTRIC FIELD SHAPING

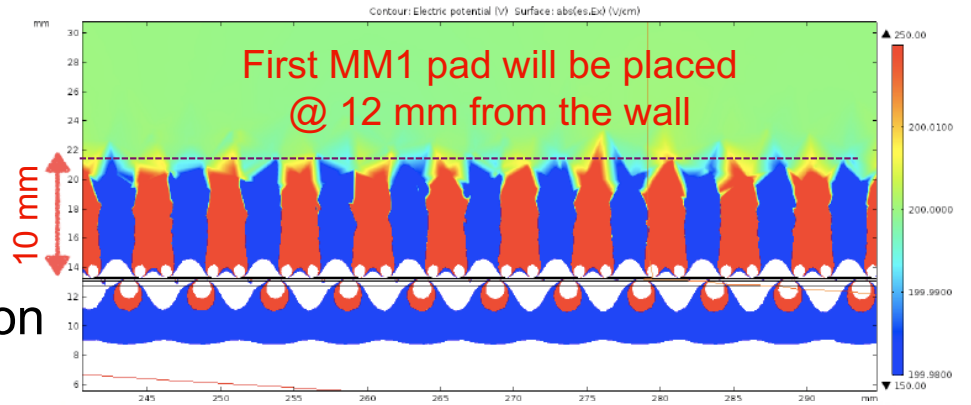
ref: G. Collazuol (INFN Padova)



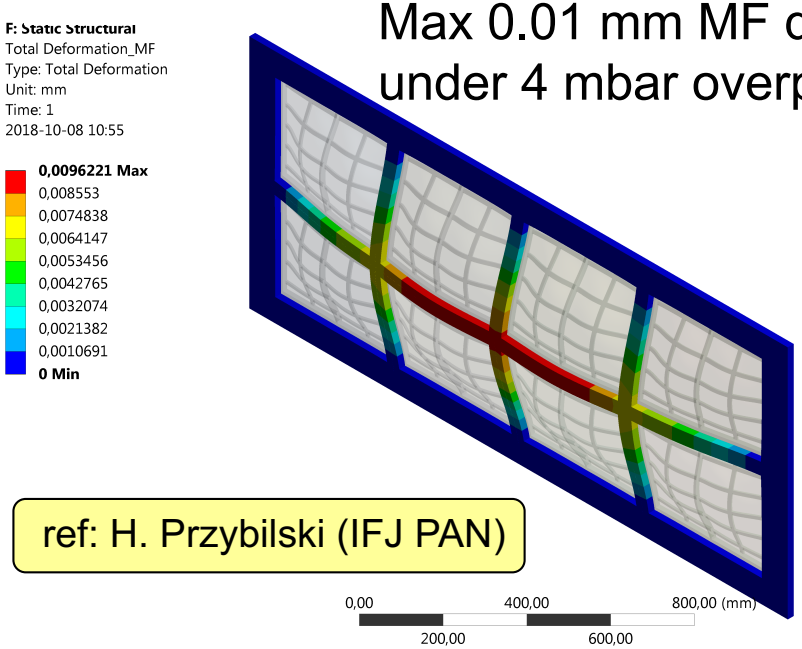
Layer of the wall	Material	thickness d d (mm)	average X_0 (mm)	d/X_0 (%)
1 (inner layer)	Double layer strip foil (+glue)	0.05		
	→ Copper strips	~0.005	14.3 (Cu)	~0.07
2	Aramid Fiber Fabric (Twaron)	2.0	~240	0.70
3	Aramid honeycomb panel (Nomex)	25	14300	0.17
4	Aramid Fiber Fabric (Twaron)	2.0	~240	0.70
5	Kapton tape (+glue)	0.125	285	0.04
6 (outer layer)	Aluminized Mylar (+glue)	0.05		
	→ Aluminum layer	0.01	89 (Al)	~0.02
Total		~30		~1.6

Thin & low Z composite materials

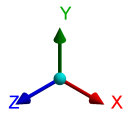


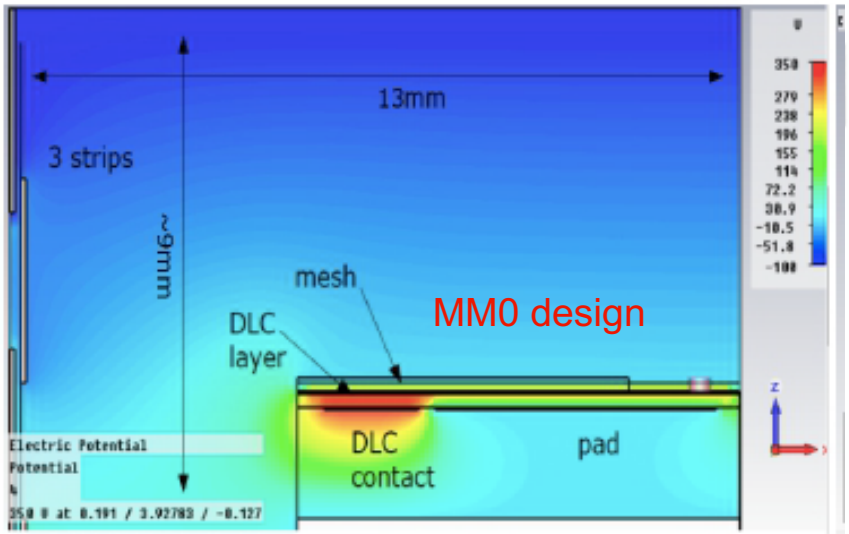


Max 0.01 mm MF deformation under 4 mbar overpressure



ref: H. Przybilski (IFJ PAN)

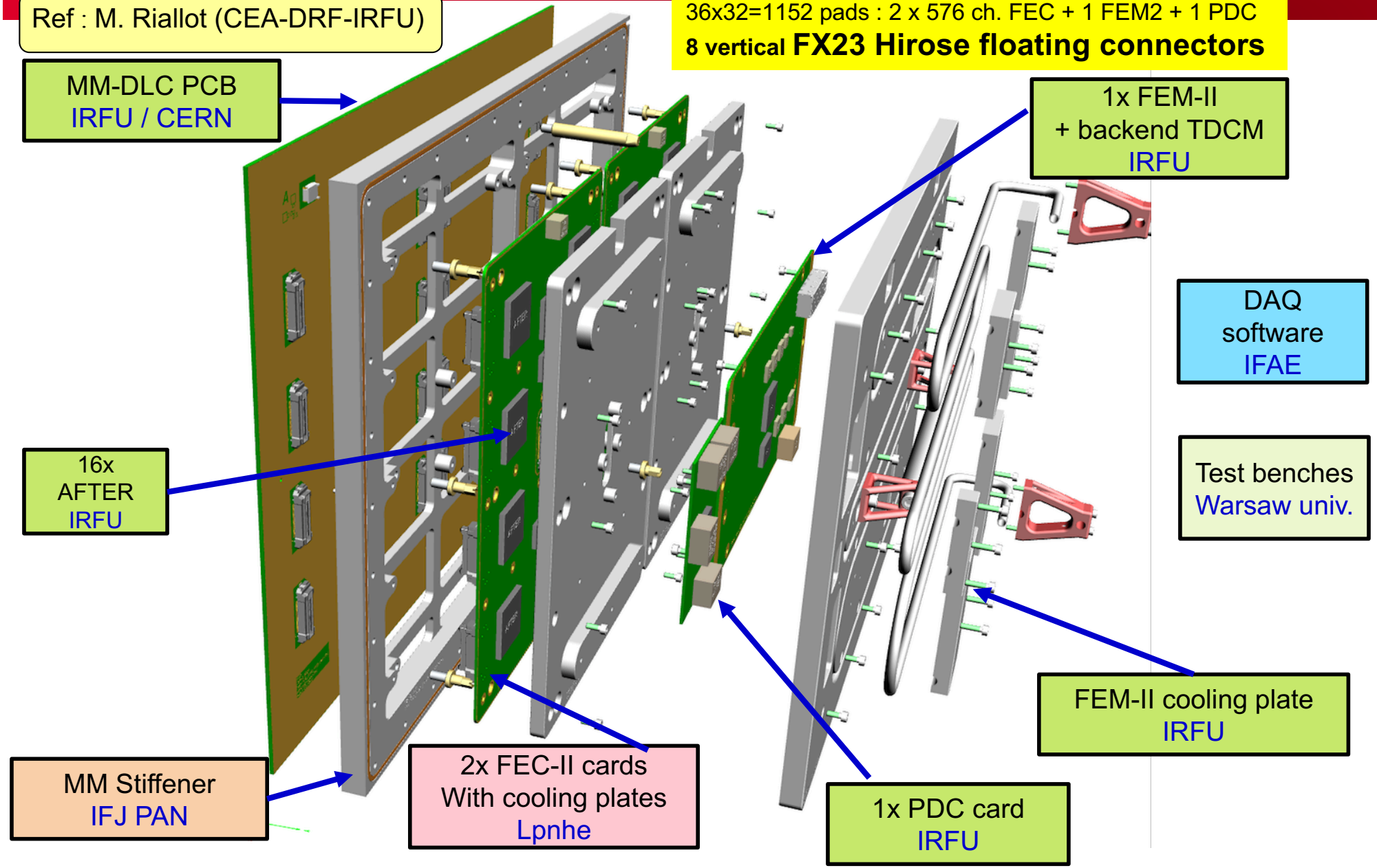




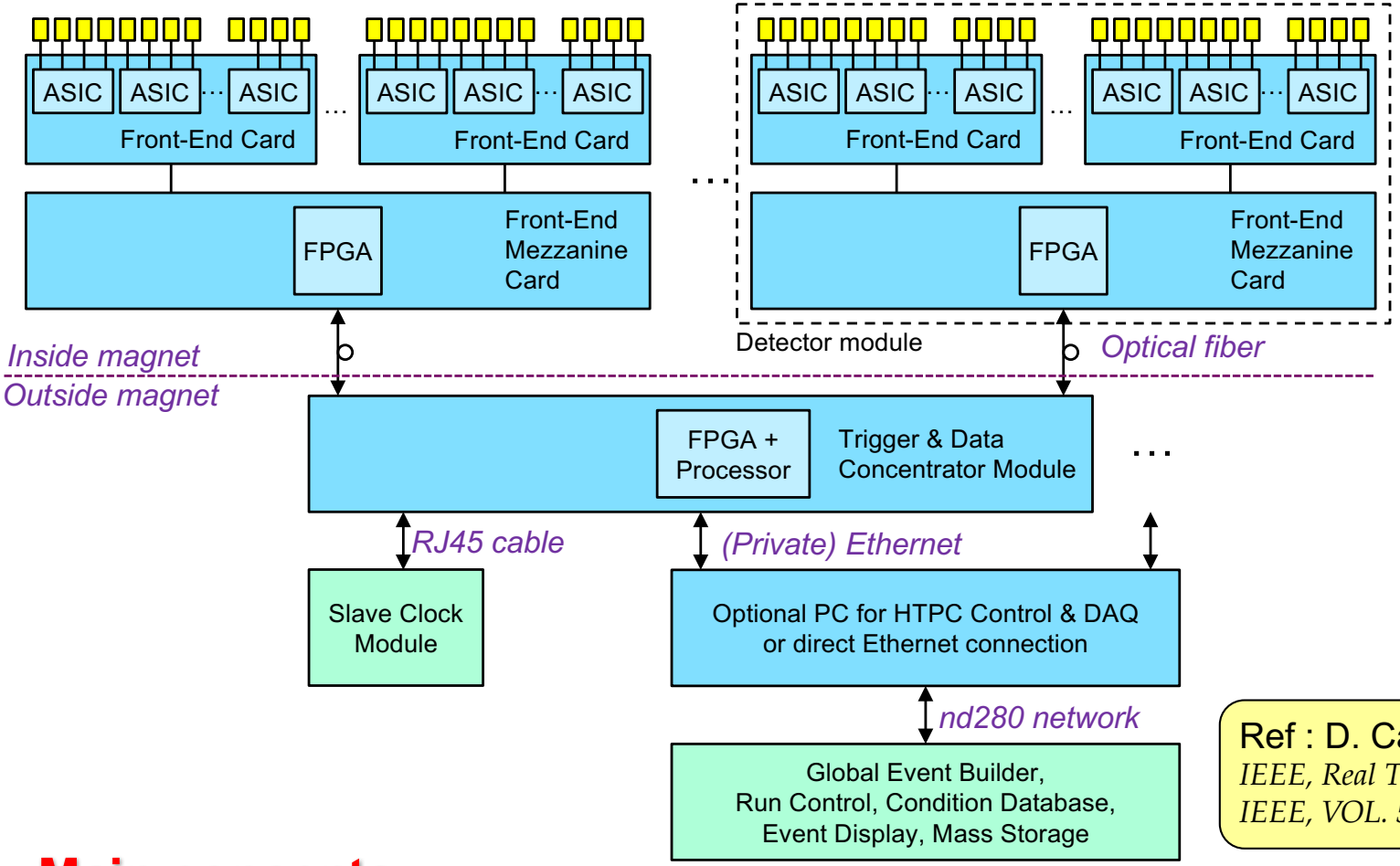
RESISTIVE BULK - MICROMEGAS MODULE

Ref : M. Riallot (CEA-DRF-IRFU)

36x32=1152 pads : 2 x 576 ch. FEC + 1 FEM2 + 1 PDC
8 vertical FX23 Hirose floating connectors



HA-TPC READOUT ELECTRONICS
A NEW AFTER-BASED ARCHITECTURE



36.864 detector pads

512 AFTER (72 channels)

64 FECs (8 ASICs each)

32 FEMs (1 drives 2 FECs)

2 TDCMs (1controls 16 FEMs, i.e. 1 TPC)

1 PC (controls 2 TDCMs)

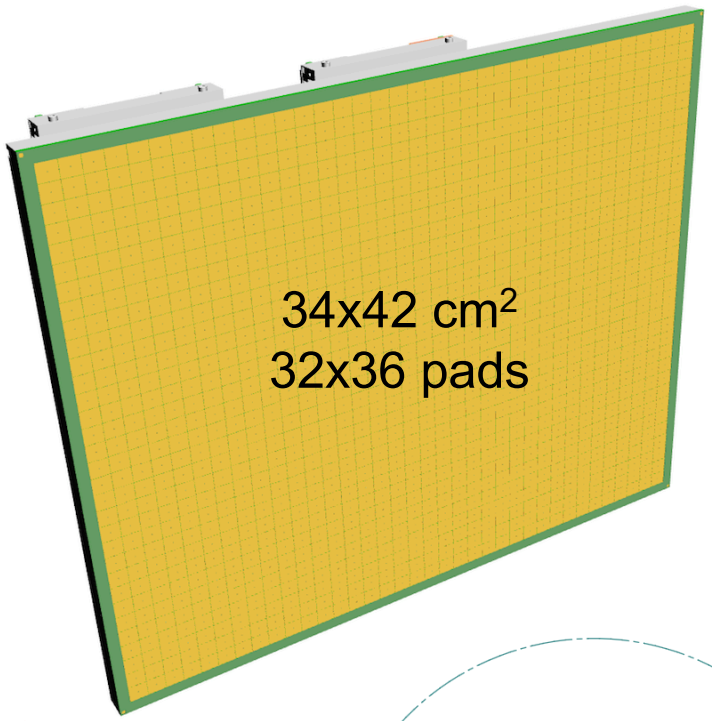
Ref : D. Calvet (CEA-DRF-IRFU)
IEEE, Real Time 2018, arXiv 1806.07618
IEEE, VOL. 55, NO. 3, JUNE 2008

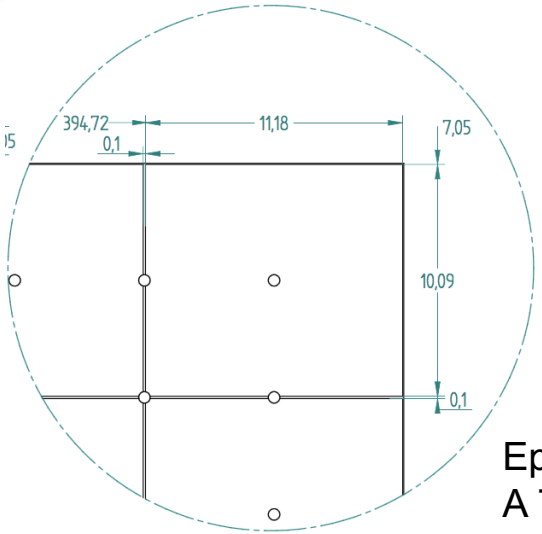
Main concepts

- AFTER chip designed for T2K (511 bucket SCA sampling@25 MHz, 120fC-600 fC, 100ns-2µs peaking time)
- New FEC with 8 AFTER chips which digitizes pad signal with an 8 ch. ADC (minimum dead time of 3.3 ms)
- FEM provides control (&trigger), synchronization, data aggregation, data buffering & data zero suppression
- The TDCM is a generic clock and trigger distributor and data aggregator (FPGA+2 xilinx CPU+1 GB DDR3)

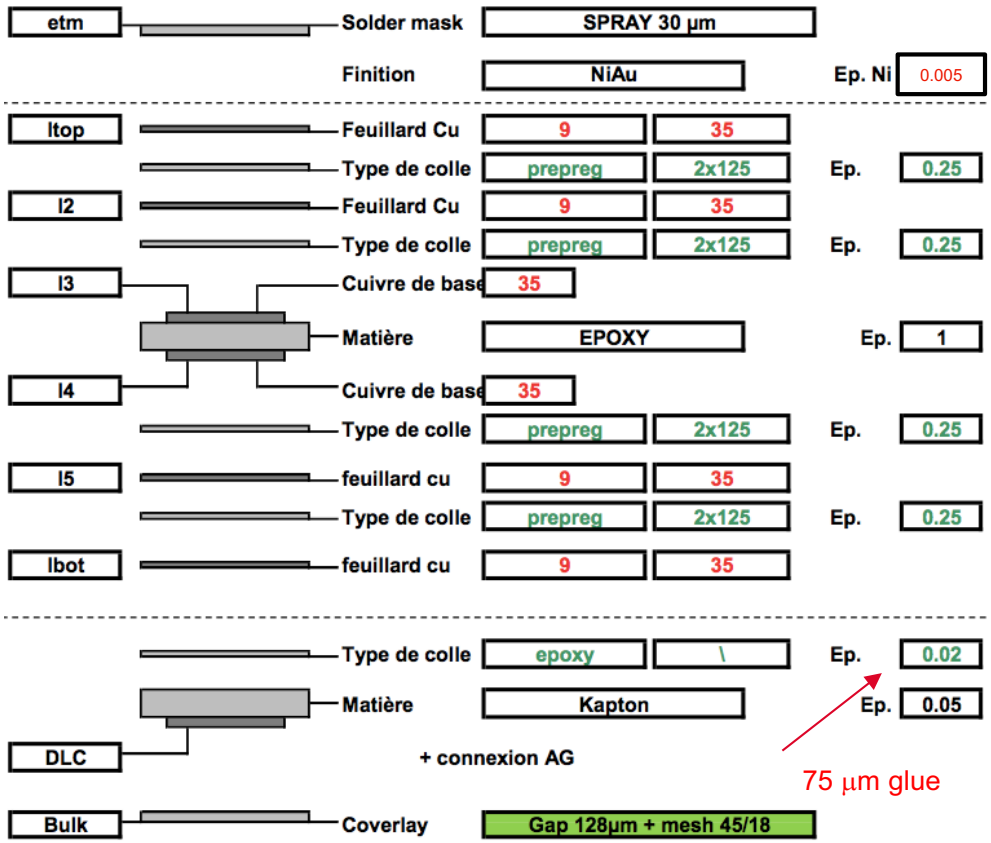
FULL-SIZE MM-DLC PCB DESIGN

ref: CERN/IRFU : B. Mehl, R. de Oliveira, O. Pizzirusso (CERN-EP-DT-EF)





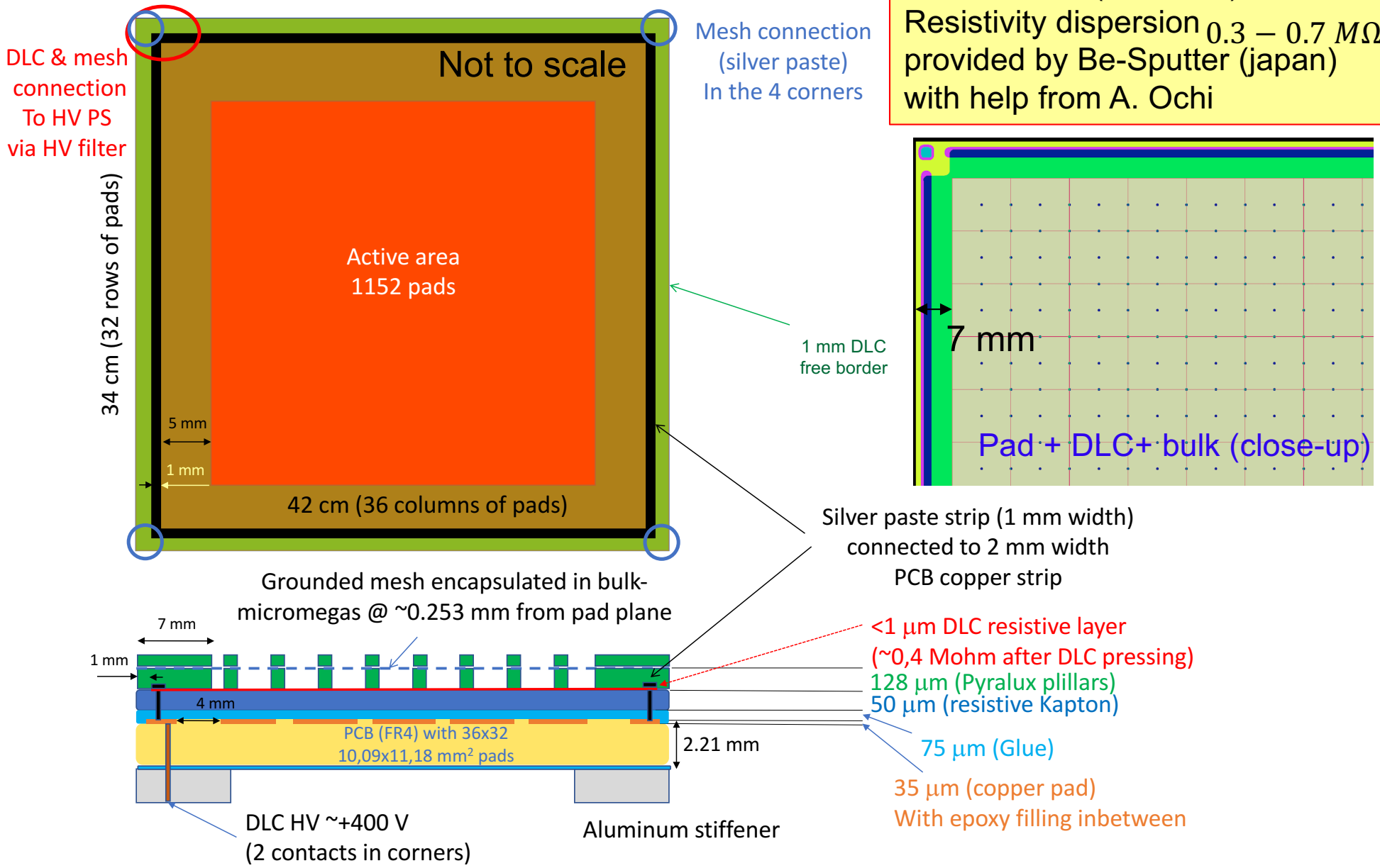
PCB design thickness : 2.21 mm



Epoxy (~0,02 mm) is used to fill the gap between copper pads
A 75 µm thick glue layer is used for the 50 µm Kapton+ $0.4\ M\Omega/\blacksquare$
DLC pressing → same process as for the MM0-DLC3

FULL-SIZE MM-DLC DESIGN
DLC+BULK-MICROMEGAS

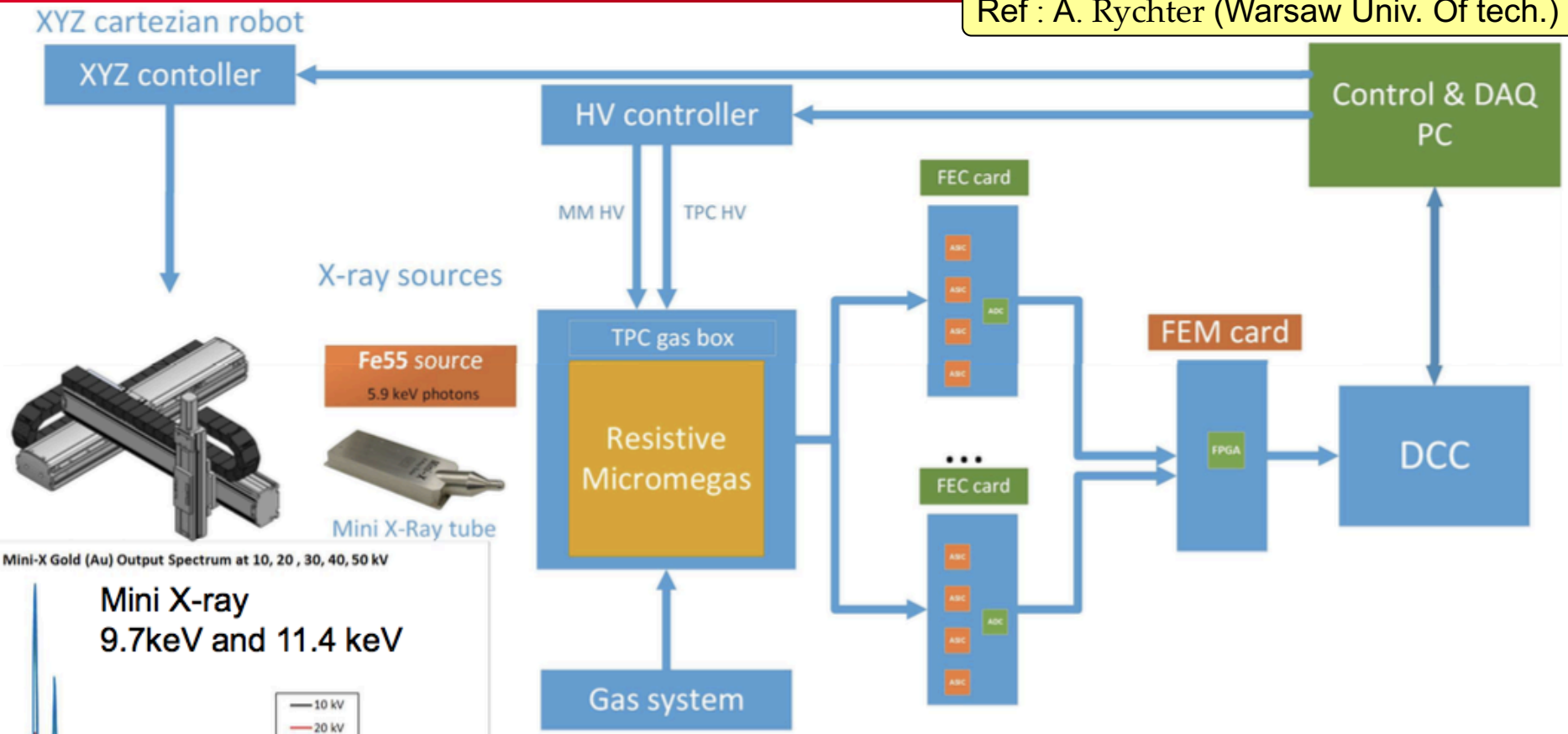
7 x DLC foils (1x0.6 m^2) at CERN
Resistivity dispersion $0.3 - 0.7\ M\Omega/\blacksquare$
provided by Be-Sputter (japan)
with help from A. Ochi

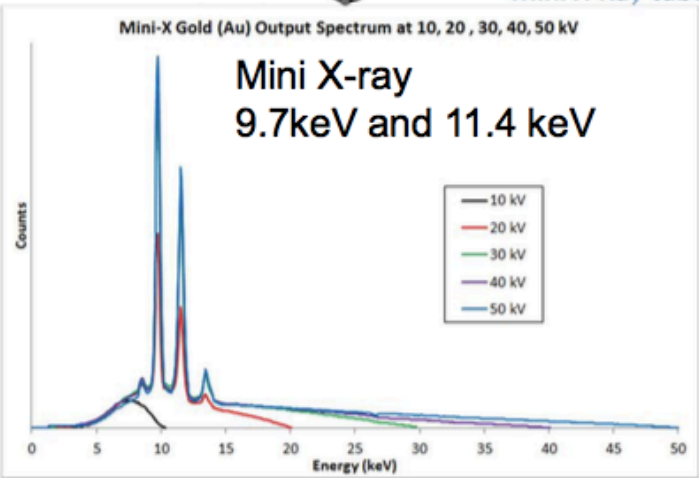


MM MODULE TESTBENCH FOR PRODUCTION QA/QC

Warsaw University of Technology

Ref : A. Rychter (Warsaw Univ. Of tech.)





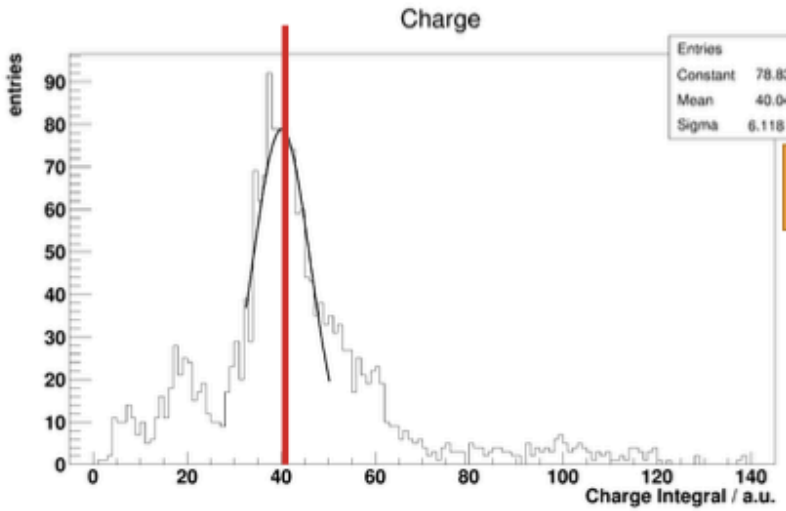
Main goal of the testbench is to measure, verify and calibrate:

- Quality(find dead pads),
- Mapping for all MM modules of :
  - Signal amplitude/gain
  - Energy resolution
  - Assess spread of the signal–verify spatial resolution.
  - Need to scan the active surface with a strong radioactive source or small X-ray lamp.

GAS MONITORING CHAMBERS

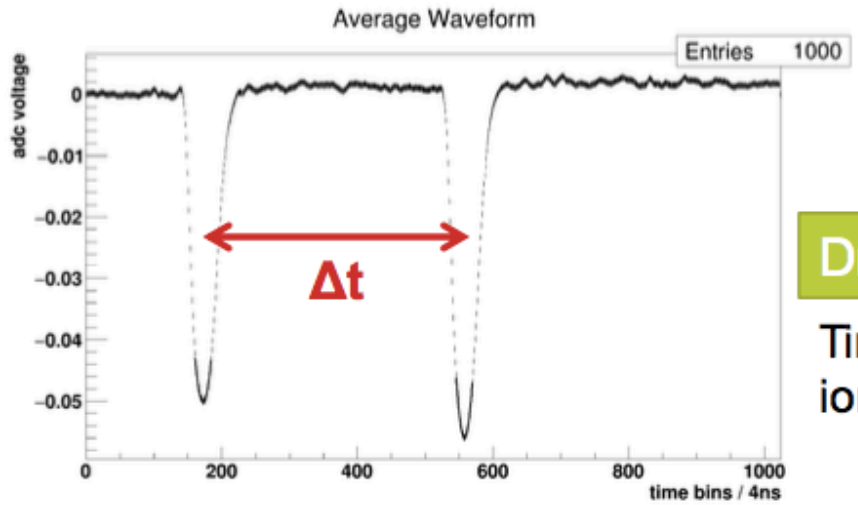
Ref : P. Hamacher-Baumann (RWTH aachen univ.)

- Two identical chambers for supply and return gas
- Sequential measurement of drift velocity and gain



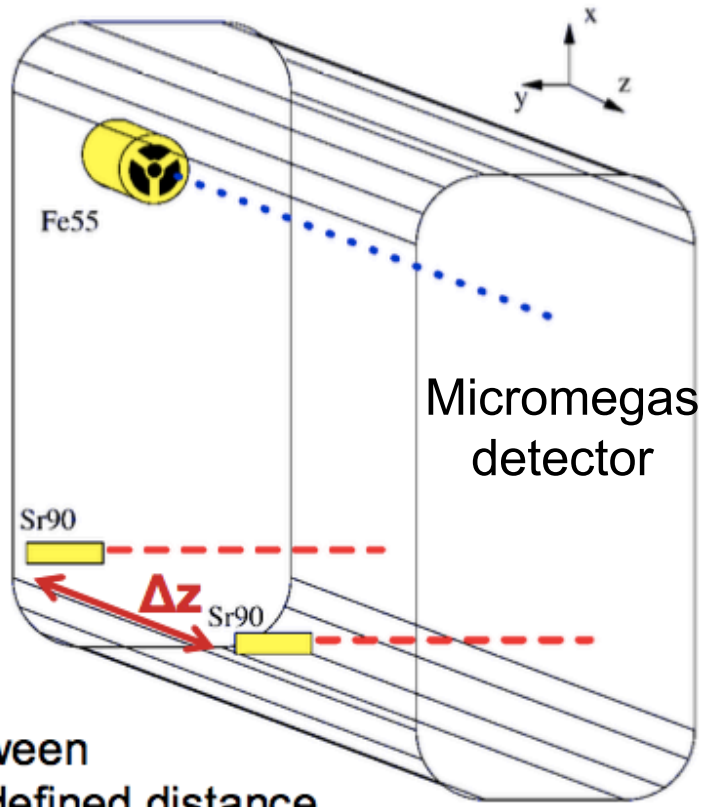
Gain Measurement

Detected charge from defined deposition

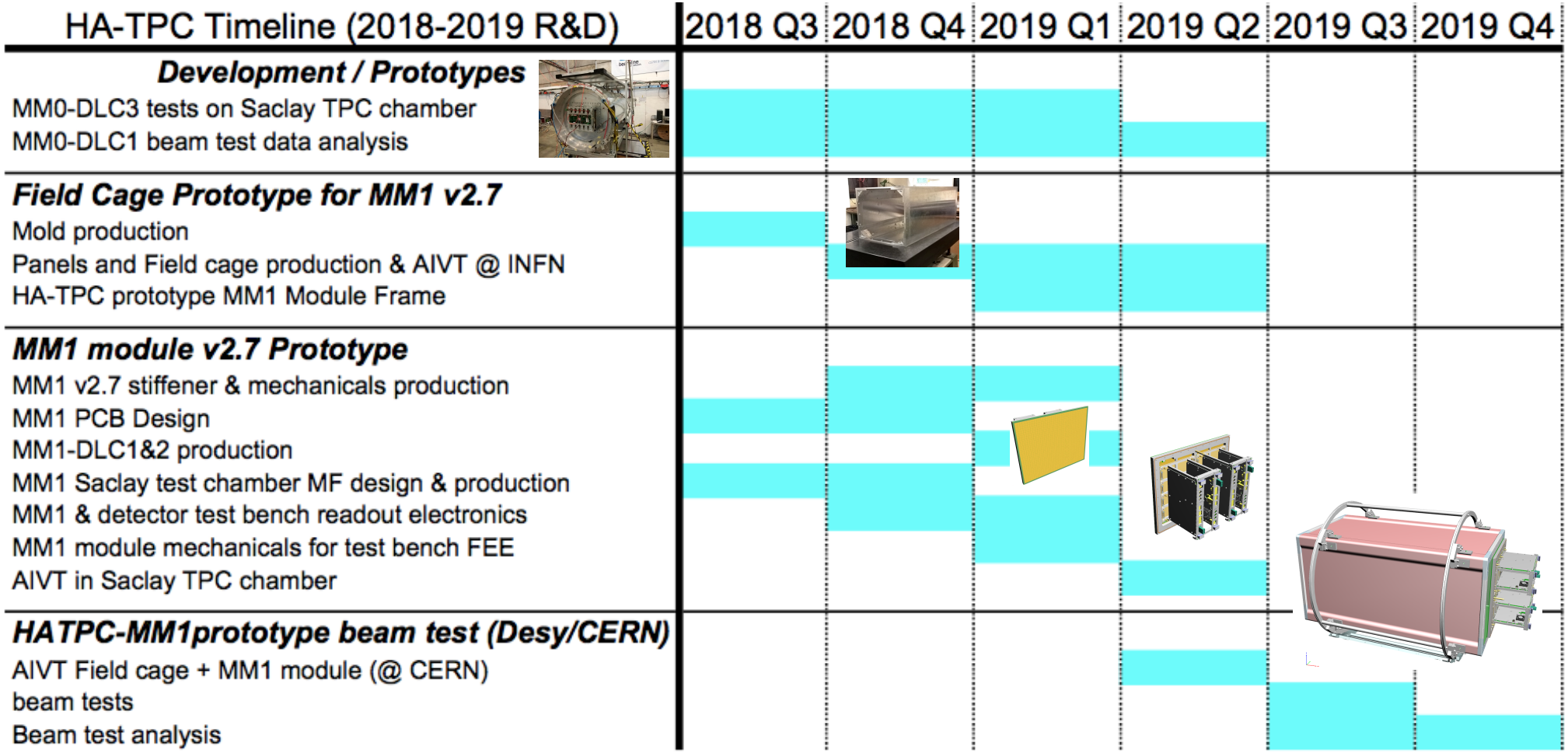


Drift Velocity

Time difference between ionization tracks of defined distance



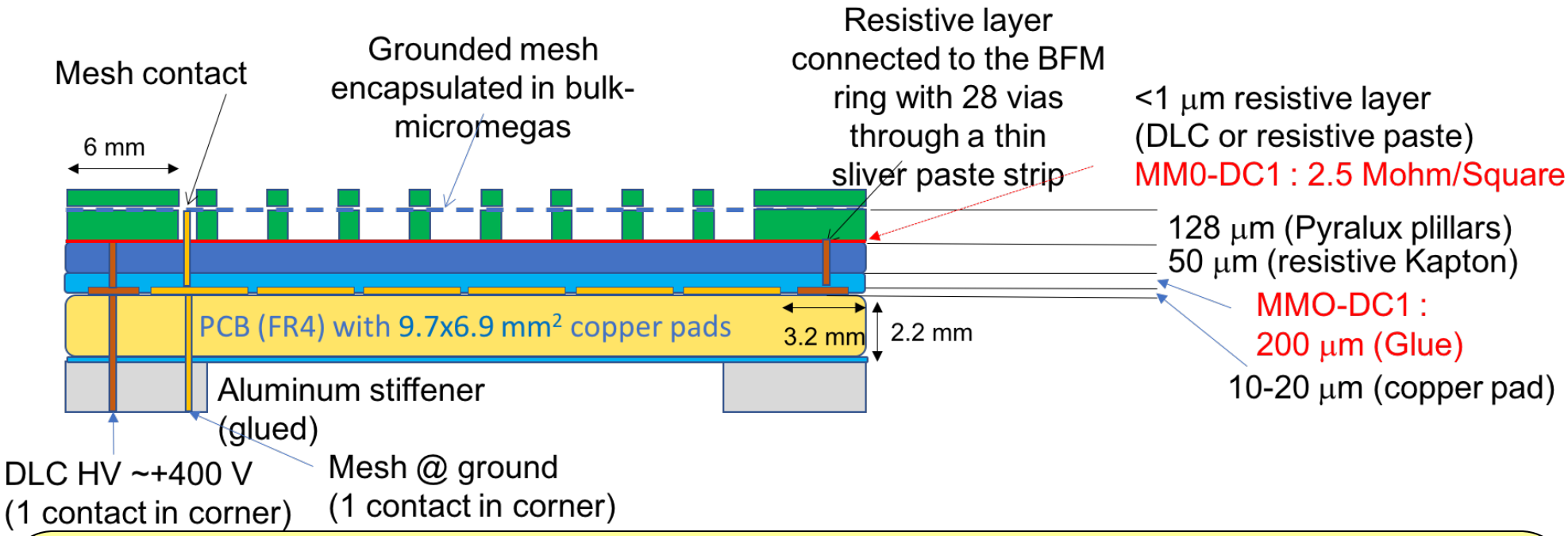
HA-TPC TIMELINE & MILESTONES 2018-2019 R&D



MM0 resistive bulk-micromegas on HARP TPC beam test @ CERN/PS-T9 : sept 2018
HA-TPC prototype with MM1 resistrive bulk-micromegas AIVT @ CERN : may 2019
Test beam in 0.2T magnet at DESY : 10-24 june 2019

THE MM0 RESISTIVE BULK-MICROMEGAS
MM0 PROTOTYPE BASED ON V-TPC MM-PCB

Use of the same micromegas PCB as current T2K TPCs : 1726 pads, 34x36 cm^2
Use of the same Front-End Electronics & DAQ as for current T2K TPCs
Add resistive-layer at positive voltage with mesh at GND → use of a new metallic stiffener



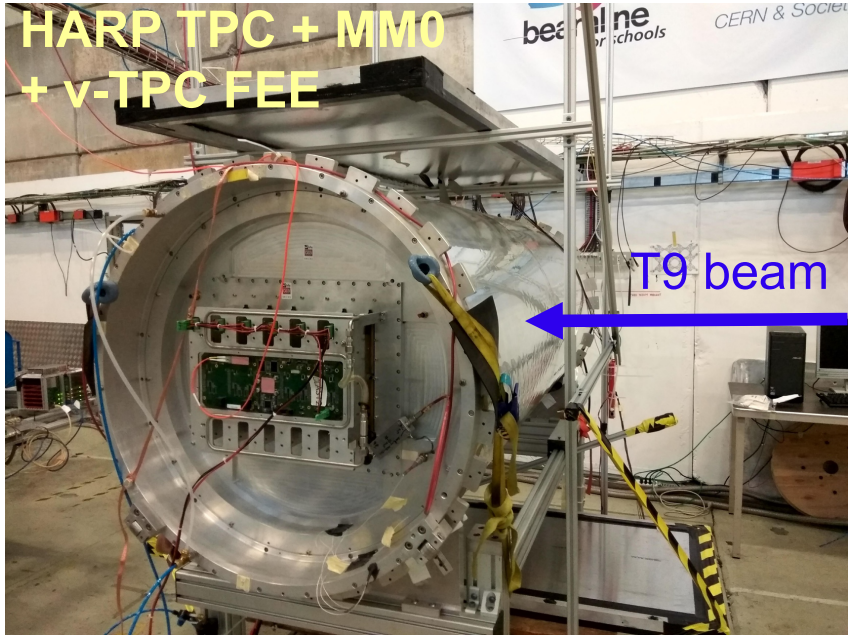
GOALS of the prototypes

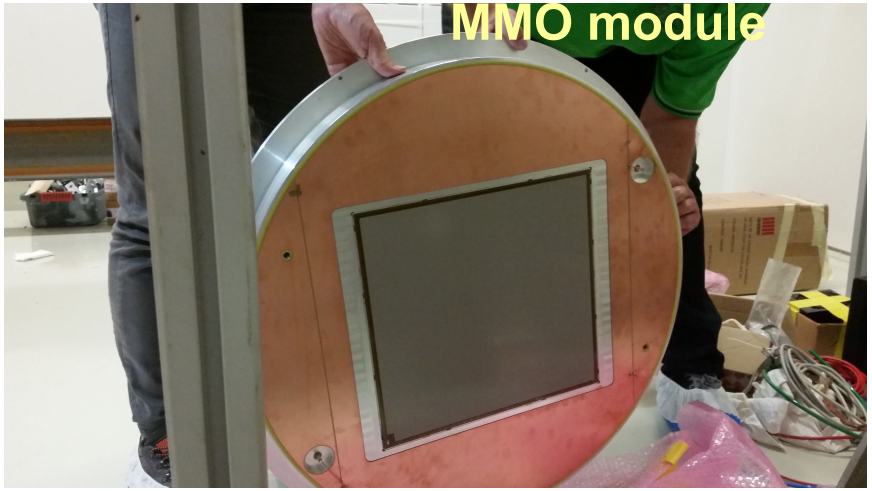
Define the resistive layer technology (DLC or ink paste) & its specifications (resistivity & glue thickness)
Define the most efficient PCB segmentation in accordance with the measured charge spreading

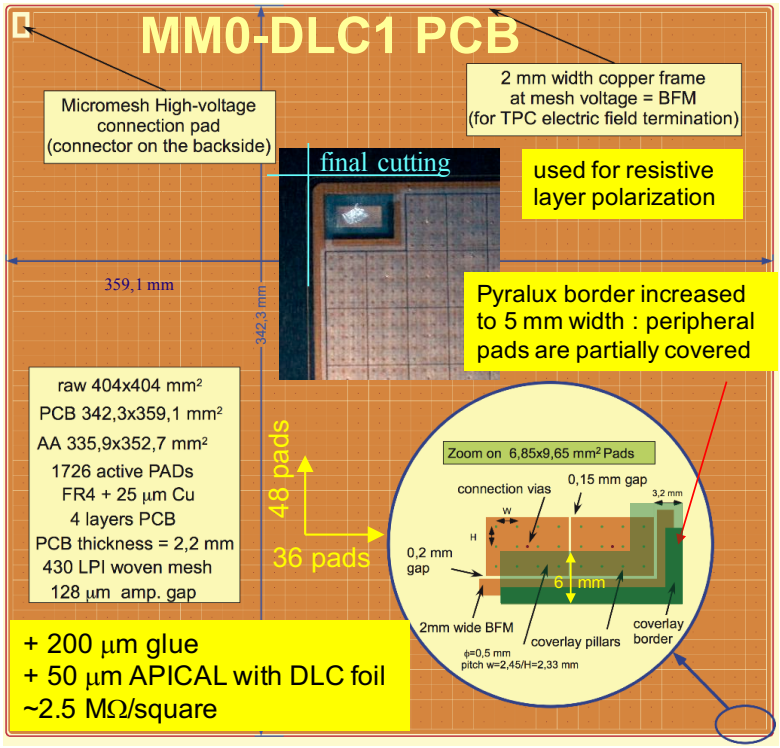
USE of the prototypes

2 prototypes produced in 2018 : MM0-DLC1&2 . A MM0-DLC3 with ~400 kOhm/Square was just produced
Measure Pad Response Function in Saclay mini-TPC chamber with cosmics
Beam test of prototype MM0-DLC1 on the HARP TPC at CERN august 22 – sept 5 – on-going analysis

RESISTIVE MICROMEGAS MODULE MM0 TEST BEAM @ CERN/PS-T9 SETUP







RESISTIVE MICROMEGAS MODULE MM0
TEST BEAM @ CERN/PS-T9 (AUGUST-SEPT 2018)

Gas volume : HARP TPC

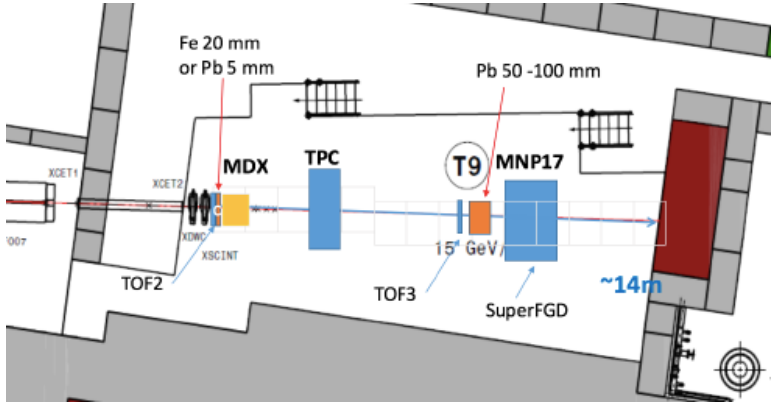
- 1.5 m drift distance / 25 kV (166 kV/cm)
- 25 l/h Argon(95%)/CF4(3%)/isobutane(2%)

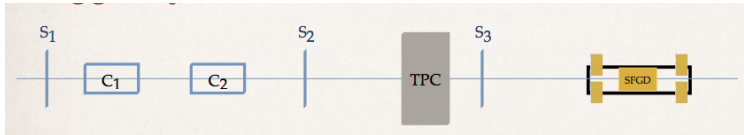
Detector : MM0 module

- Micromegas module MM0 with $2.5\ M\Omega/\blacksquare$ DLC
- horiz. x vert. = 36 x 48 pads
- each pad 0.97 x 0.69 cm
- nominal MM voltage 340 V (up to 380 V)
- V-TPC FEE: Sampling time 80 ns (12.5 MHz)
- nominal peaking time 600 ns

Data taking

- Cosmic trigger with 2 plastic scintillators +MPPC
- Fe55 source for 5.9 kEv X-rays
- Beam : $0.5,\ \pm 0.8,\ 1,\ 2$ GeV/c momentum

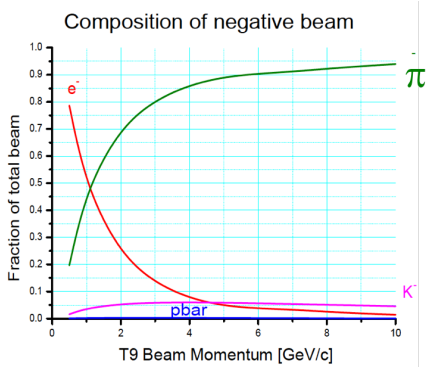


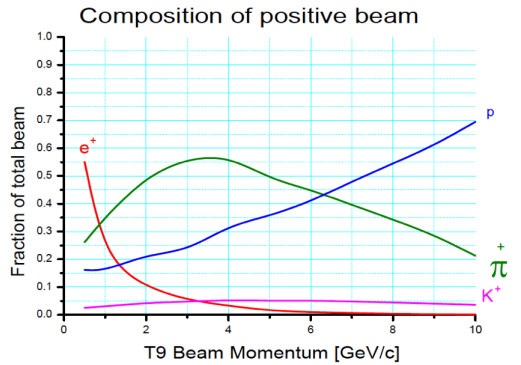


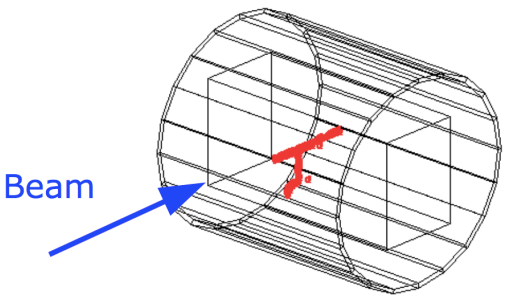
π, e, p trigger

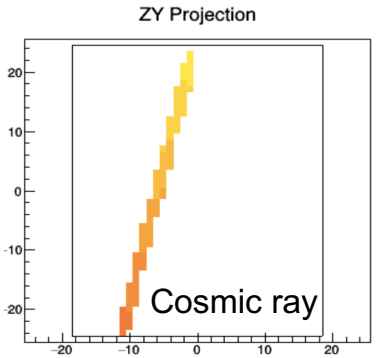
Particle	Selection
Electrons	Scintillators + Cherenkov
Protons (+Kaons)	S1(delayed) * S2 (delay proton TOF between S1 and S2)
Pions (+ muons)	Scintillators * protons * electrons
Cosmic ray	from the scintillators panels (only out of spill)

+ ^{55}Fe X-ray source in the middle of the cathode





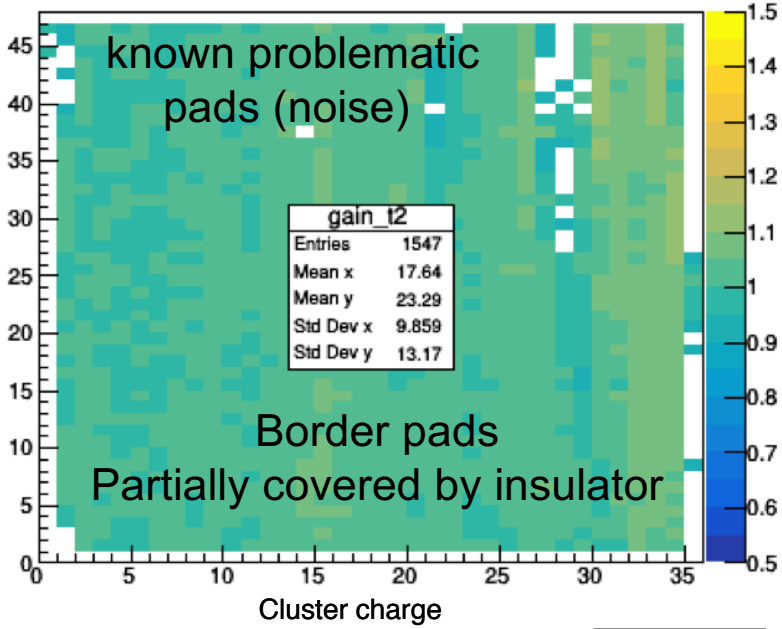




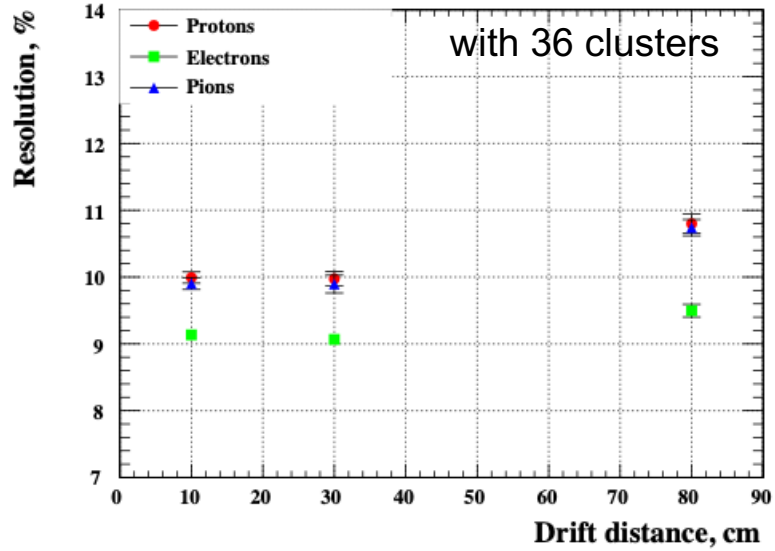
PRELIMINARY RESULTS : DE/DX RESOLUTION
MICROMEGAS GAIN

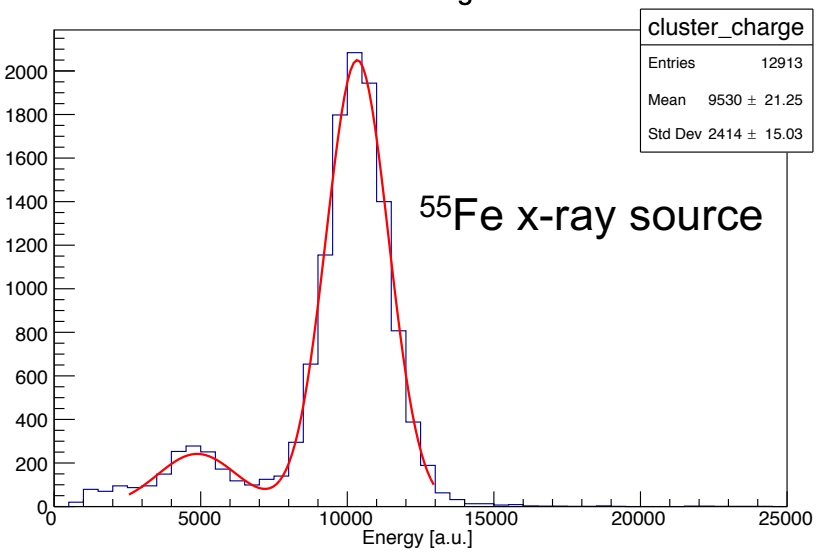
Ref : TPC beam test analysis group

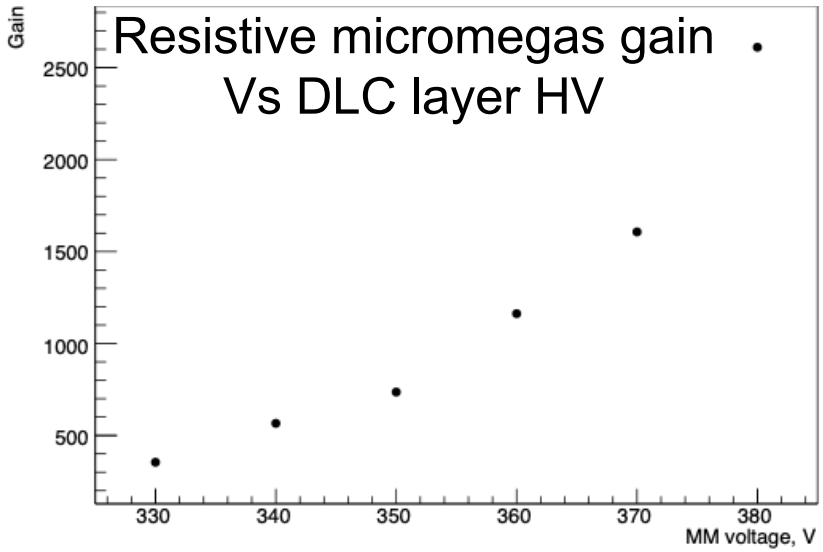
Gain uniformity ($Q_{pad}/Q_{pad\ average} \geq 0.93$)



dE/dx resolution vs. Drift distance using truncated mean method

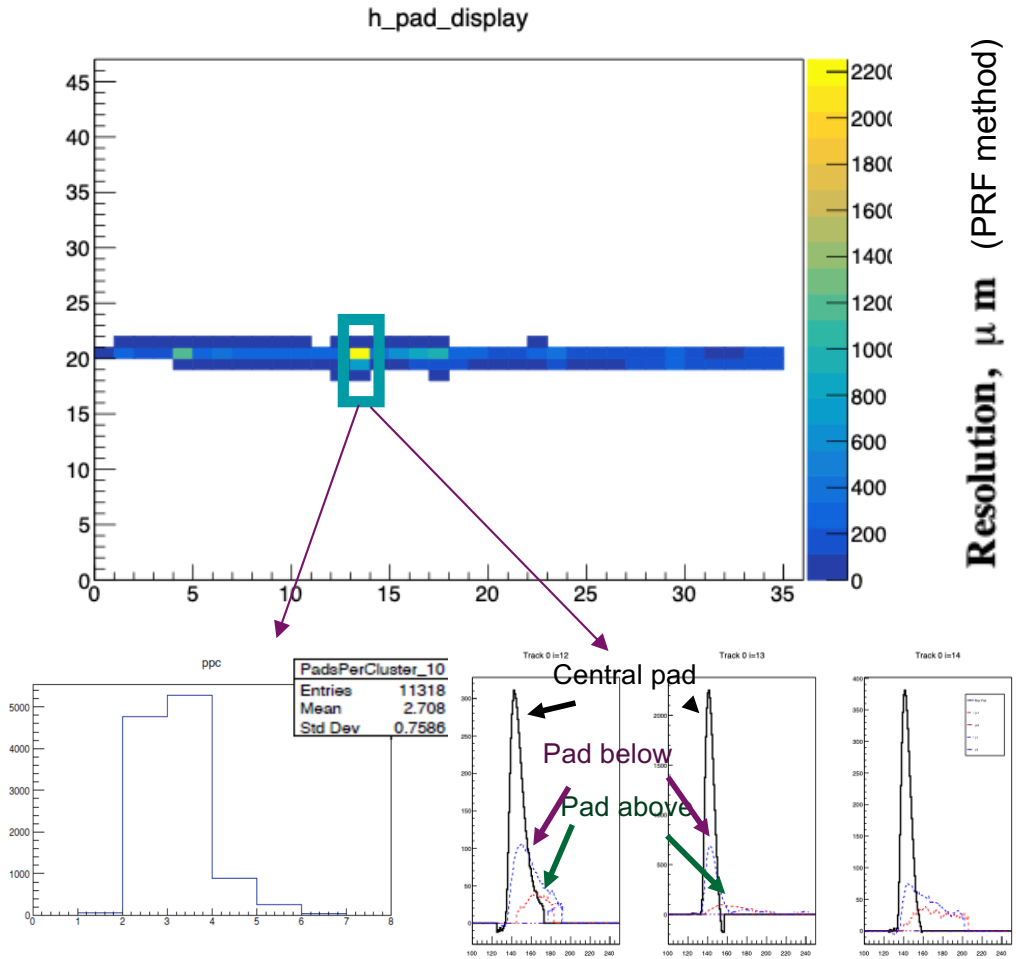






PRELIMINARY RESULTS : SPATIAL RESOLUTION VS DRIFT DISTANCE

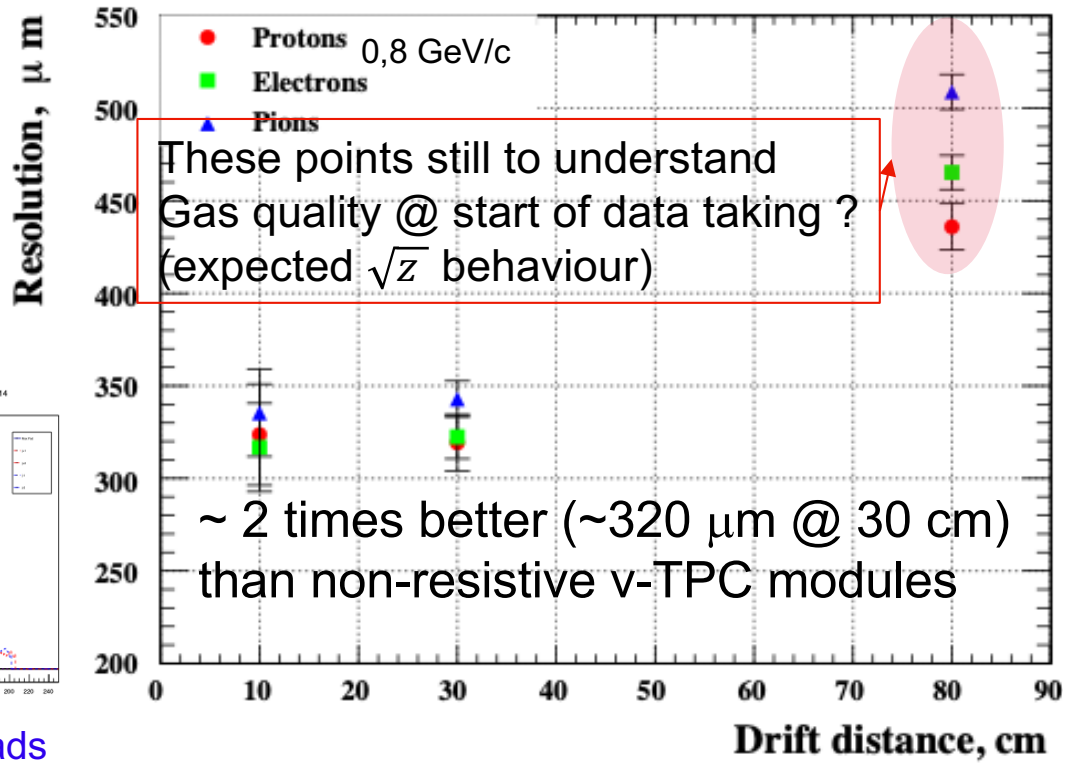
Ref : TPC beam test analysis group



Spread over 2.7 pads ~1.8 cm

Waveforms on adjacent pads

MM0-DLC resistive bulk-micromegas
6.9 x 9.7 mm^2 pads
with 2.5 $M\Omega/\blacksquare$ DLC



Seems to have margin for going from MM0 6.9 x 9.7 mm^2 to MM1 10.09 x 11.18 mm^2 pads by decreasing the resistivity to $\sim 0.4\ M\Omega/\blacksquare$ (trade-off btw charge spreading & spark protection)

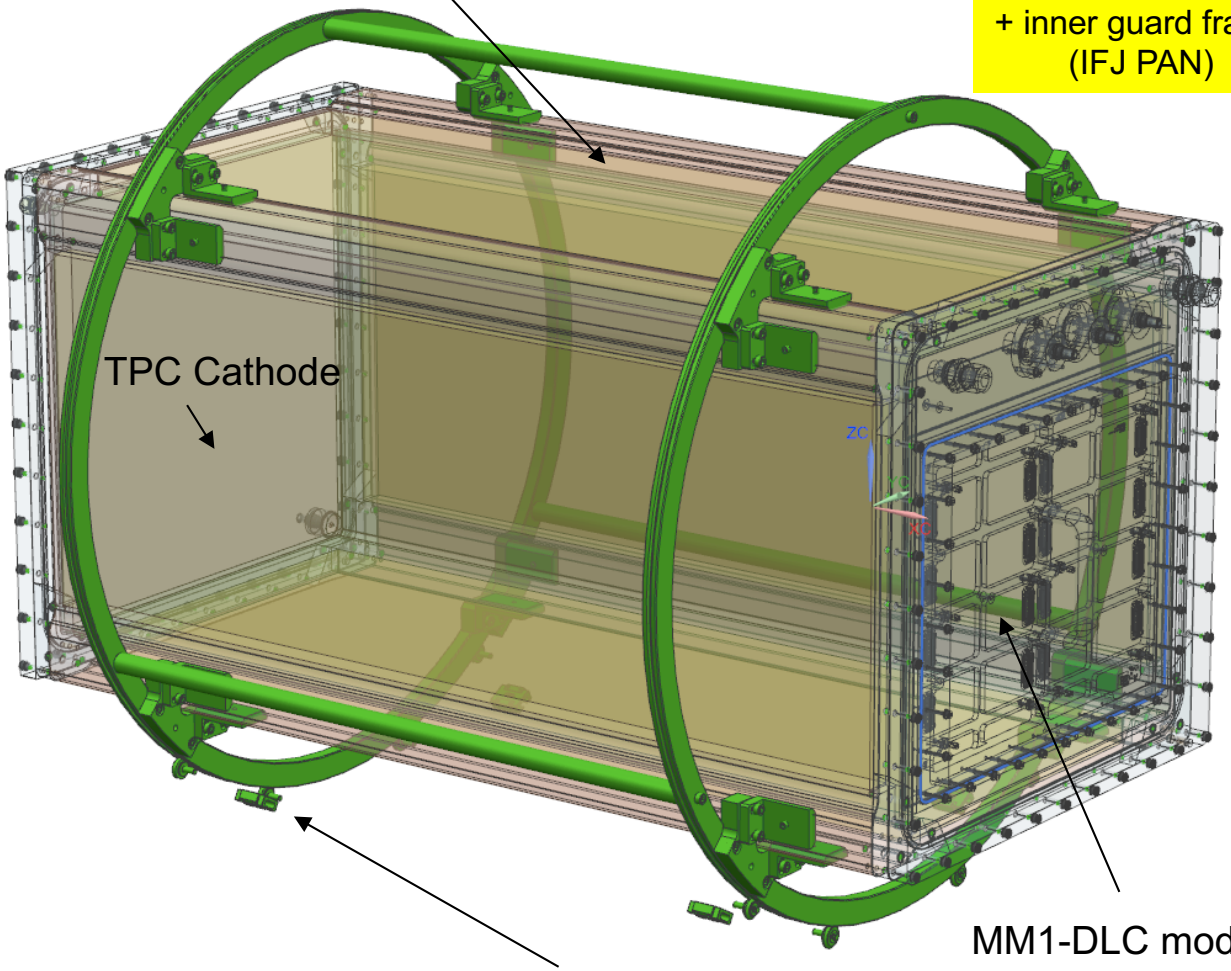
HA-TPC 2019 PROTOTYPE TO BE MOUNTED IN PCMAG MAGNET FOR BEAM TEST @ DESY AREA 24/1

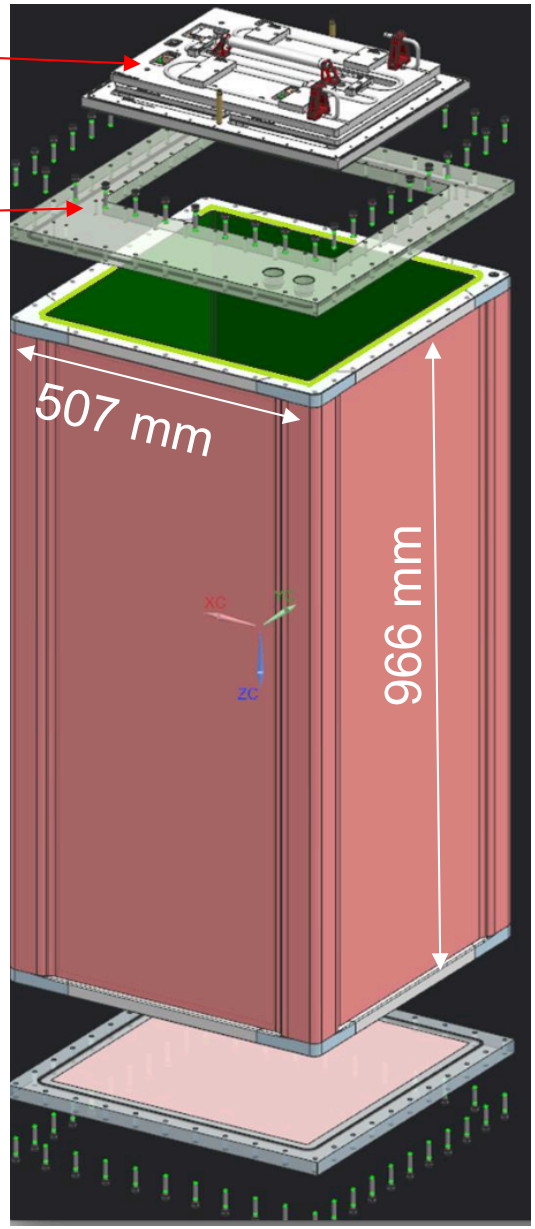
Ref : G. Collazuol (INFN Padova)

Field cage + cathode (INFN)

MM1-DLC1 module
+ 4x ARCv1 cards (IRFU/CERN/LpnHe)

Module Frame
+ inner guard frame
(IFJ PAN)

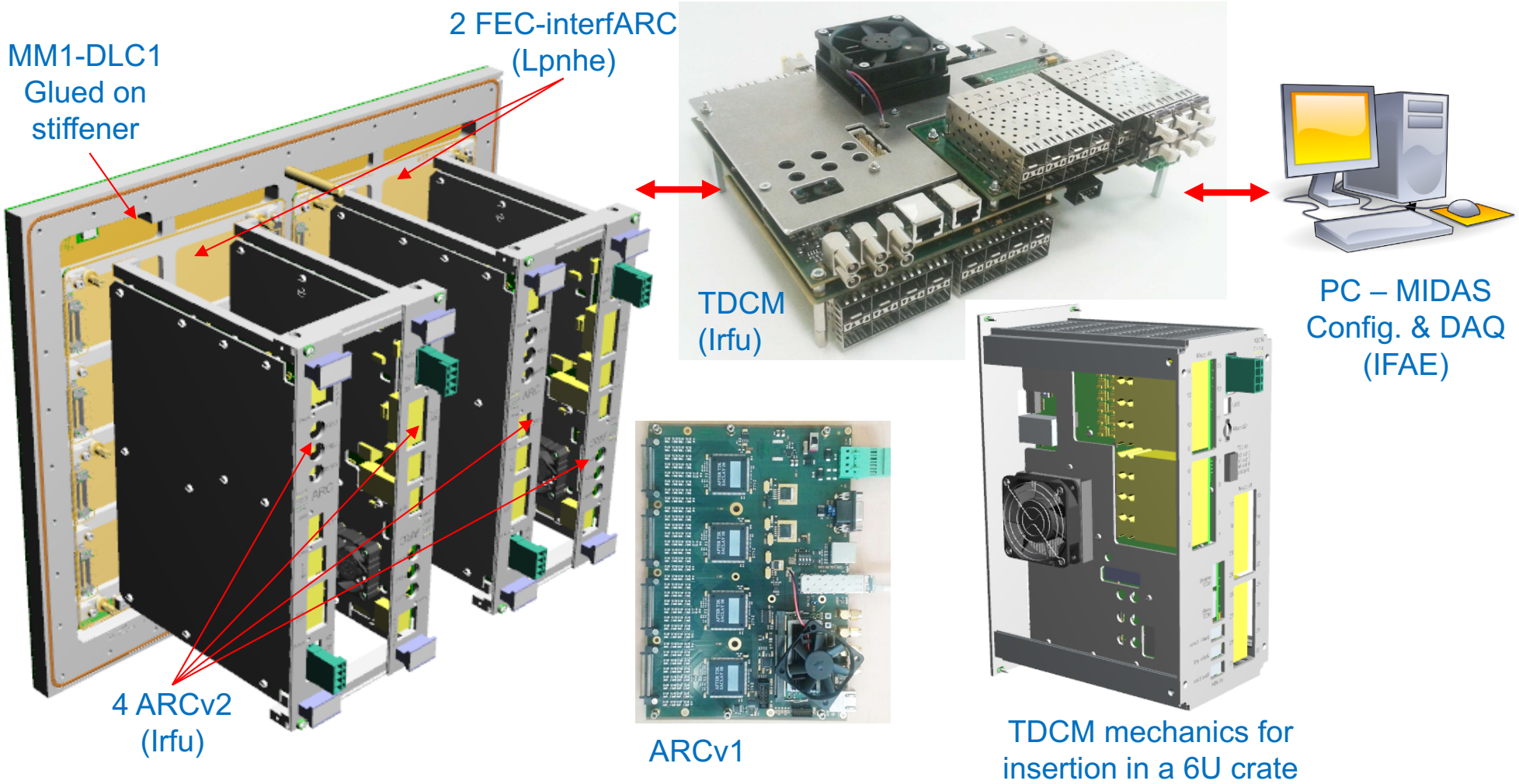




Supporting frame to mount in DESY/ILC-TPC magnet (operated @ 0.2 T)

HA-TPC FULL-SIZE MM MODULE PROTOTYPE READOUT ELECTRONICS FOR BEAM TESTS

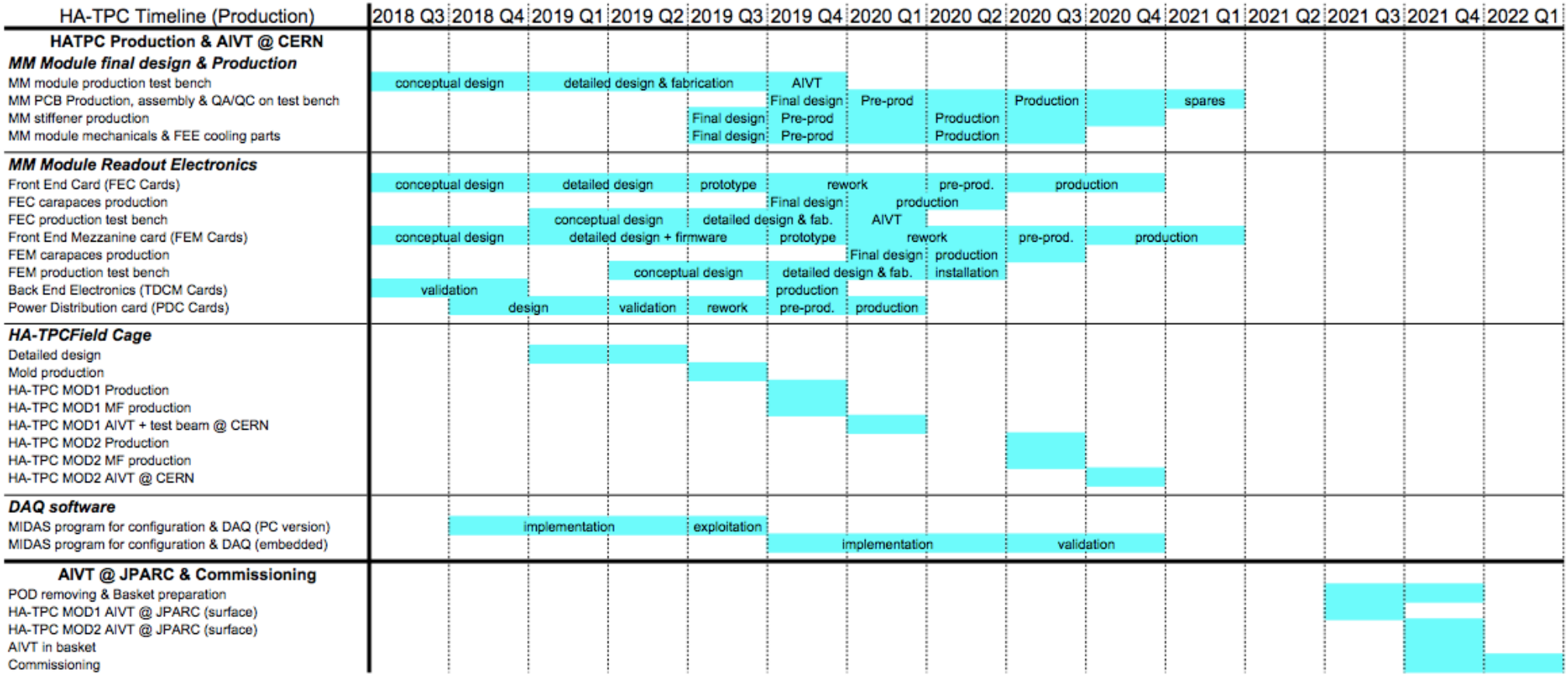
Ref : D. Calvet (CEA-DRF-IRFU)



Description

- Front-end: 4 x 288-channel ARCv2-AFTER (minor corrections compared to ARCv1)
- Back-end: TDCM (bare metal command interpreter) + PC running MIDAS for configuration and DAQ

HA-TPC : PROSPECTIVES
2019-2021 DETAILED DESIGN & PRODUCTION



PRRs for start of production : june-october 2019
HA-TPC 1 ready : march-june 2020
HA-TPC 2 ready : january 2021

CONCLUSION & PERSPECTIVES

- The tests of a resistive bulk-micromegas module on CERN/PS-T9 beam showed a 2 times better spatial resolution while keeping the dE/dX capabilities in control (9-10% with only one module track length). Analysis is on-going to investigate the effects of the DLC resistivity non-uniformity and of lower shaping times.

- A prototype of a HA-TPC field cage equipped with a full-size resistive bulk-micromegas module will be tested with beam at DESY in june 2019.

- The T2K / ND280 near detector upgrade development is on-going. The 2 new HA-TPCs design will be soon fixed and production should start in october this year for a completion scheduled for march 2021.

- Not covered in this talk but of great importance : HA-TPC gas system, HA-TPC FEE cooling, ND280 upgrade sub-detectors mechanical integration and cabling in basket (HV, LV, cooling, FEE datas, …).

More details in the ND280 upgrade TDR (SPSC-TDR-006) :
http://cds.cern.ch/record/2653463/files/SPSC-TDR-006.pdf?version=1

BACKUP SLIDES

Thank you for your attention

THE AFTER ASIC

❖ Mean features

Input current polarity: positive **or** negative

72 analog channels

4 charge ranges: 120 fC, 240 fC, 360 fC & 600 fC

16 peaking time values: 100 ns to 2 µs

511 analog memory cells / channel

Fsampling: 1 MHz to 50 MHz; Fread: 20 MHz

Slow Control (SPI protocol); Test inputs (calibration & test)

❖ Main requirements

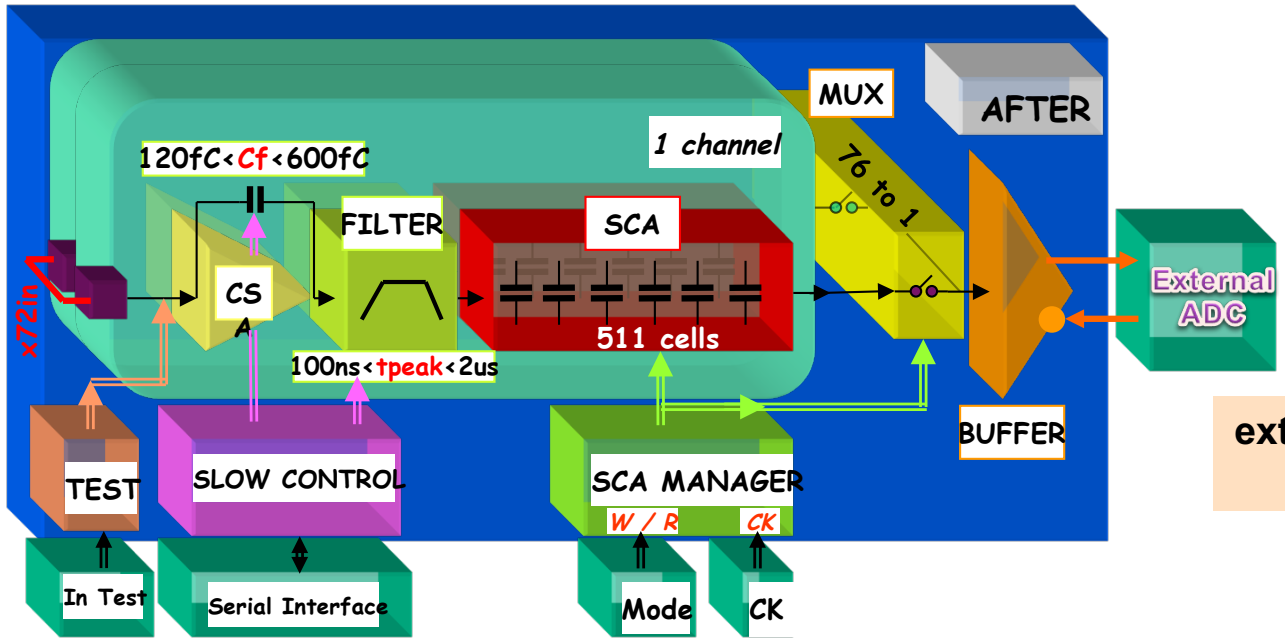
MIP/Noise: 100

Output Dynamic: 2V/10 MIPs

I.N.L: 1% 0-3 MIPS; 5% 3/10 MIPs

Minimum Ionizing Particle:

MIP: 12 fC to 60 fC



external 12-bit ADC [AD9229]

Ref: P. Baron, IRFU MPGD workshop, CEA, Saclay 6-8 dec. 2011

IRFU/ SCA BASED ASIC FAMILY (AMS CMOS 0,35 MM)

	T2K/TPC (2007)	General Electronic for TPC GET (2009)	DREAM For CLAS12 (2011)
Parameter	**AFTER**	**AGET**	**DREAM**
Polarity of detector signal	Negative or Positive	Negative or Positive	Negative or Positive
Number of channels	72	64	64
External Preamplifier	No	Yes; access to the filter or SCA inputs	Yes; access to the filter or SCA inputs
Charge measurement			
Input dynamic range/gain	120 fC; 240 fC; 360 fC; 600 fC	120 fC; 240 fC; 1 pC; 10 pC /channel	50 fC; 100 fC; 200 fC; 1 pC /channel
Sampling			
Peaking time value	100 ns to 2 µs (16 values)	50 ns to 1 µs (16 values)	50 ns to 1 µs (16 values)
Number of SCA Time bins	511	512	512
Sampling Frequency (WCk)	1 MHz to 100 MHz	1 MHz to 100 MHz	1 MHz to 50 MHz
Triggering			
Discriminator solution	No	Leading edge	Leading edge
HIT signal		OR of the 64 discriminator outputs in LVDS level	OR of the 64 discriminator outputs in LVDS level
Threshold Range		5% of the dynamic range	5% of the dynamic range
Threshold value		(3-bit + polarity bit) common DAC + 4-bit DAC / channel	(7-bit + polarity bit) DAC common to all channels
Readout			
Readout frequency	20 MHz	25 MHz	Up to 20 MHz
Channel Readout mode	all channels	All, hit or selected	all channels excepted those disabled
SCA cell Readout mode	all	1 to 512	Triggered columns only
Trigger rate			Up to 20kHz (4 samples read/trigger).
Counting rate	< 0.3 Hz / channel	< 1 kHz / channel	< 50 kHz / channel
Power consumption	< 8 mW / channel	< 10 mW / channel	< 11 mW / channel
Status	Production	Test of first prototype: Under test. Functionality has been tested successfully	Test of first prototype: Under test.
Noise 120 fC; 200 ns peaking time	370 e- + 14.6 e- / pF (measured)	550 e- + 14 e- / pF (measured)	685 e- + 2.3 e- / pF (simulated)

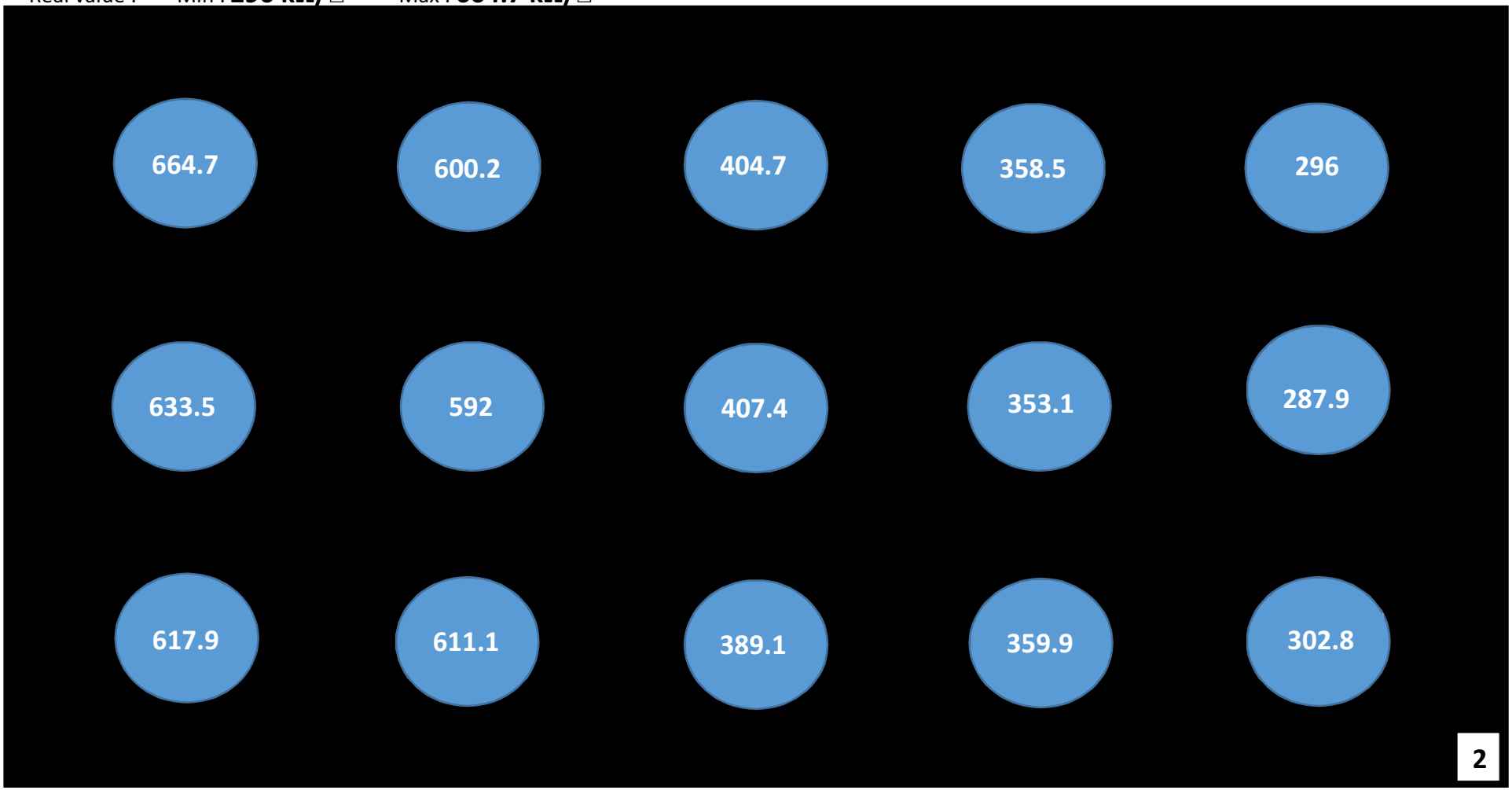
Ref: P. Baron, IRFU MPGD workshop, CEA, Saclay 6-8 dec. 2011

EXAMPLE OF DLC FOIL RESISTIVITY (FOIL 2)

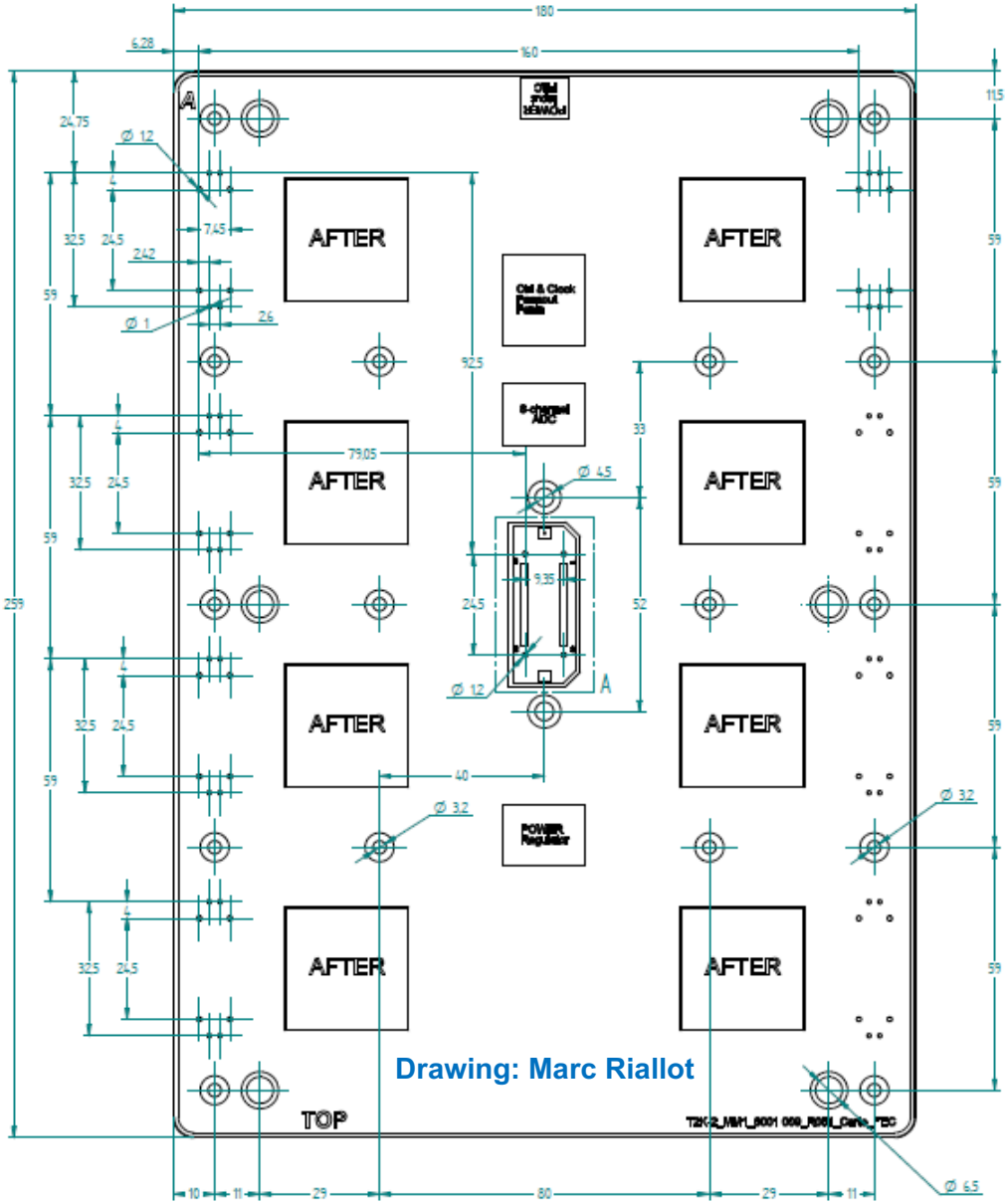
Theoretical value **500 kΩ/□**

Foil size : 100x61cm

Real value : Min : **296 kΩ/□** Max : **664.7 kΩ/□**



FEC CONCEPTUAL DESIGN



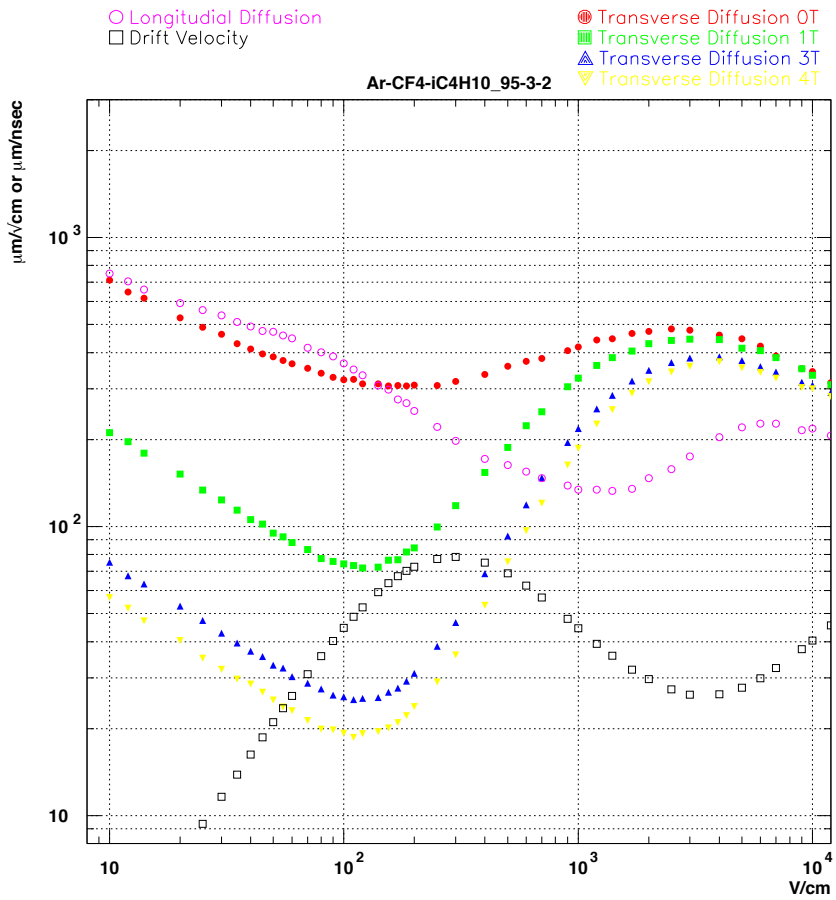
Main components

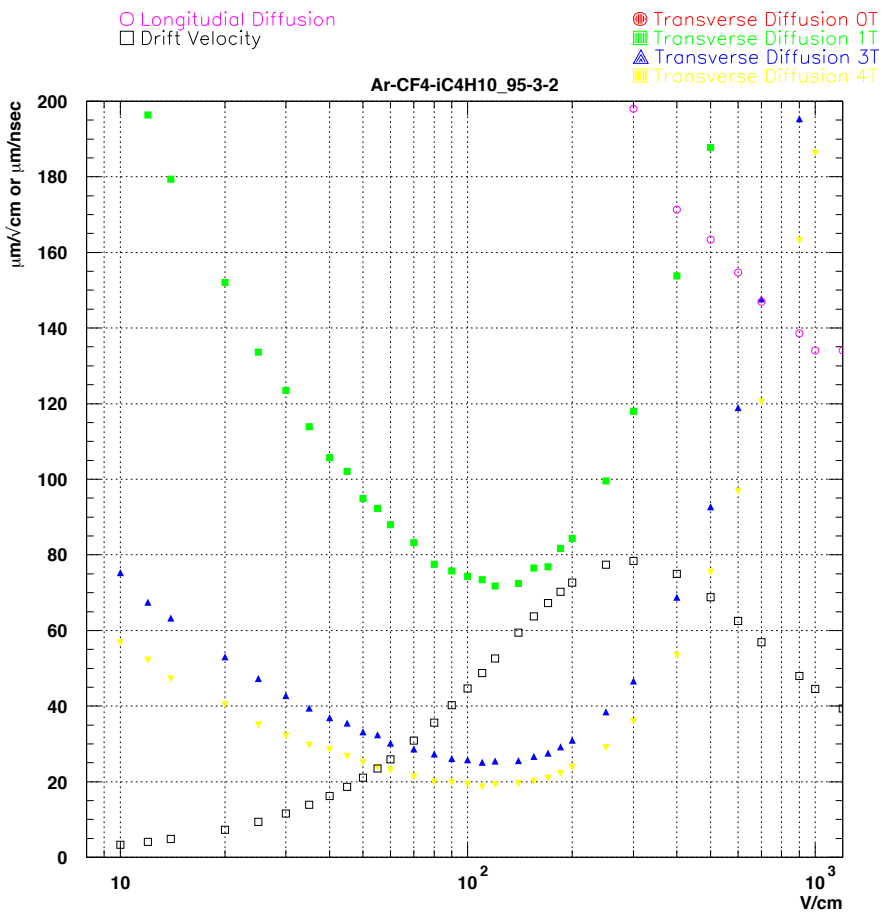
- 8 AFTER chips
- No spark protection diodes, only one capacitor link per channel
- On-board small logic for signal distribution
- Octal-channel ADC 12 bit (e.g. AD9637), clocked at 12.5 MHz
- Calibration pulser, e.g. 16-bit DAC + analog swith + injection capacitor
- On-board voltage/current/temperature/serial number chip, e.g. Maxim DS2438
- 4.2 V to 5.5 V single power supply via FEM connector and/or cable connector
- Anticipated power consumption: ~2.5 A

Ref : D. Calvet (CEA-DRF-IRFU)
J-M Parraud (In2P3/LpnHe)

T2K GAS MAGBOLZ SIMULATIONS

Ref : www-hep.phys.saga-u.ac.jp/ILC-TPC/gas/

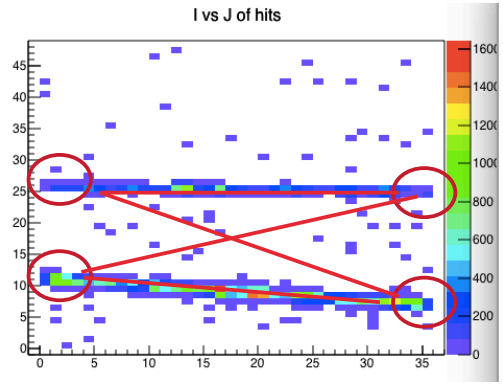


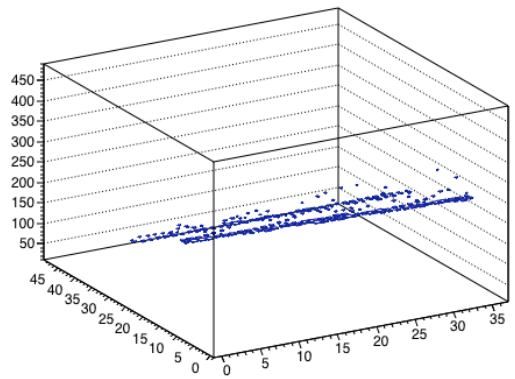


TRACK RECONSTRUCTION

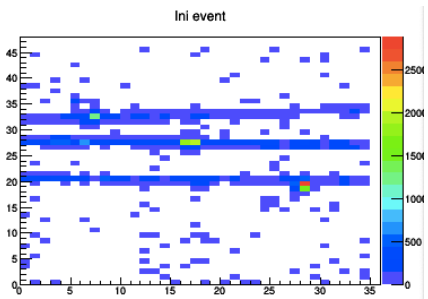
Ref : TPC beam test analysis group

- Look for clusters at the left and right side of the detector
  clusters are selected with relatively high threshold to suppress noise
- Study all possible tracks from clusters combinations
- Define the box in 3D space: X, Y, T
- Take all the waveforms in pads inside this box
- Select the "good" tracks:
  - Enough number of pads and columns
- Main advantage:
  - Very simple!
  - Severe noise suppression
  - Possibility to select multiple tracks in the event

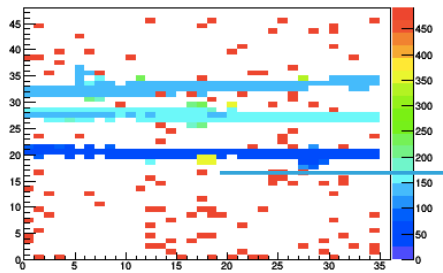




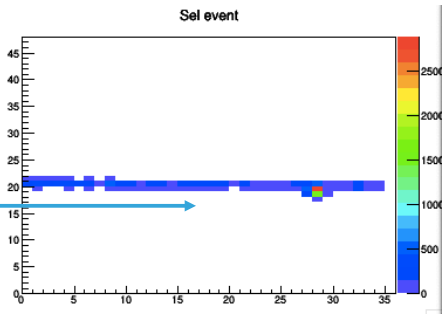
Display with charge:



Display with time:



Selected track:

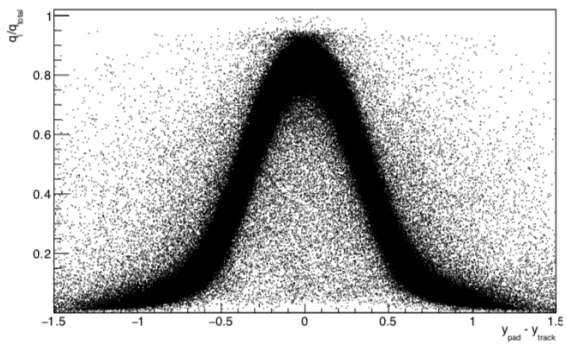


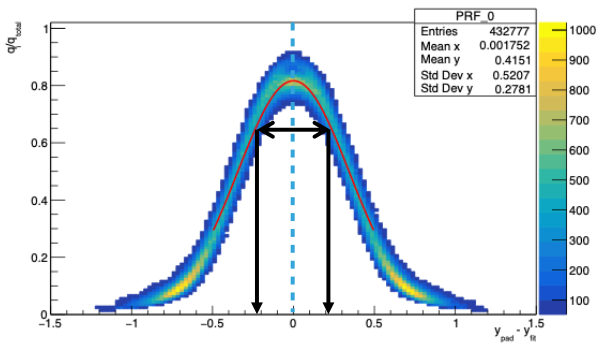
PRF

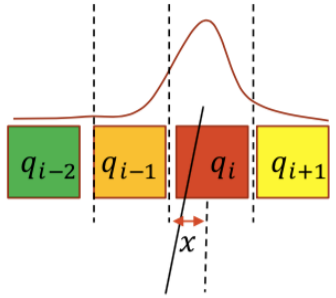
Ref : TPC beam test analysis group

- Reconstruction of the track position was done with the Pad Response Function (PRF)
- Consider the PRF uniform for all the pads estimate it form:

PRF scatter plot:







$$PRF(x_{track} - x_{pad}) = \frac{q_{pad}}{q_{cluster}}$$

Ref: A. Bellerive *et al. Proc. of* 2005 International Linear Collider Workshop - Stanford, U.S.A. (*LCWS05*, 2005)

- Based on the measured charge ratio we reconstruct the track position

- with minimisation of

$$\chi^2 = \sum_{column} \left[\frac{a - PRF(y_{track} - y_{pad})}{\sigma_a} \right]^2 \quad a = q_i/q_{total} \quad \sigma_a = \sqrt{q_i}/q_{total}$$

- We perform several iterations of "estimation PRF –> track position extraction" until the track fit quality stops improving