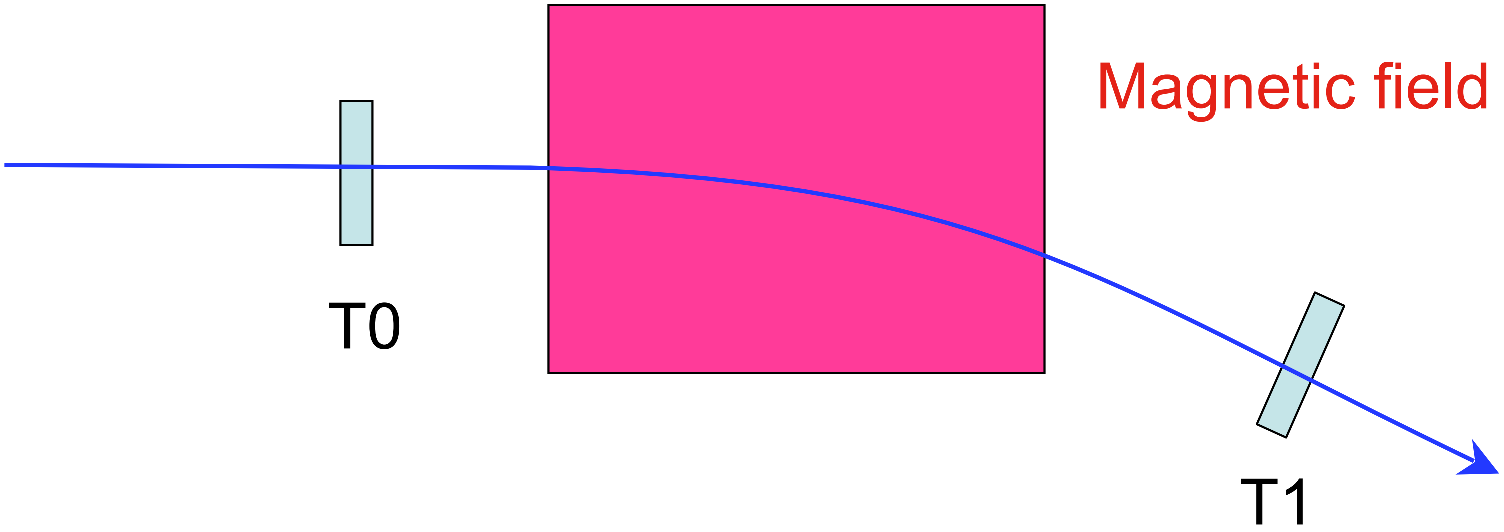
Time of Flight

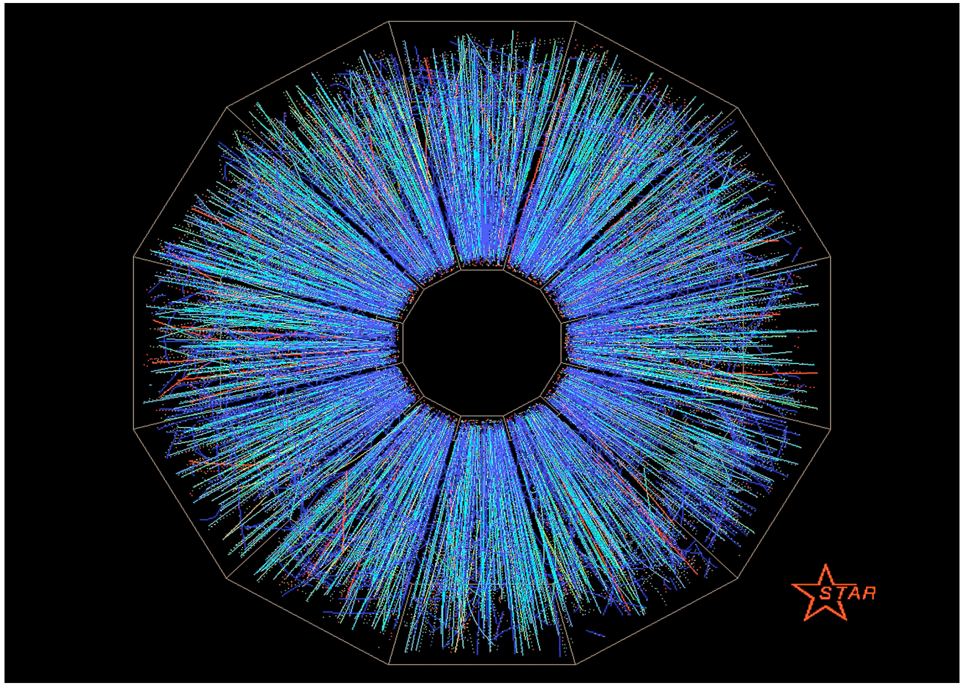
- The TOF system of the ALICE experiment
- The Multigap RPC as a TOF detector
  - Space charge limited avalanche growth
  - NINO ASIC - an ideal front-end amplifier/discriminator

Charged particle follows curved path in magnetic field, curvature ~ momentum (mass, velocity)



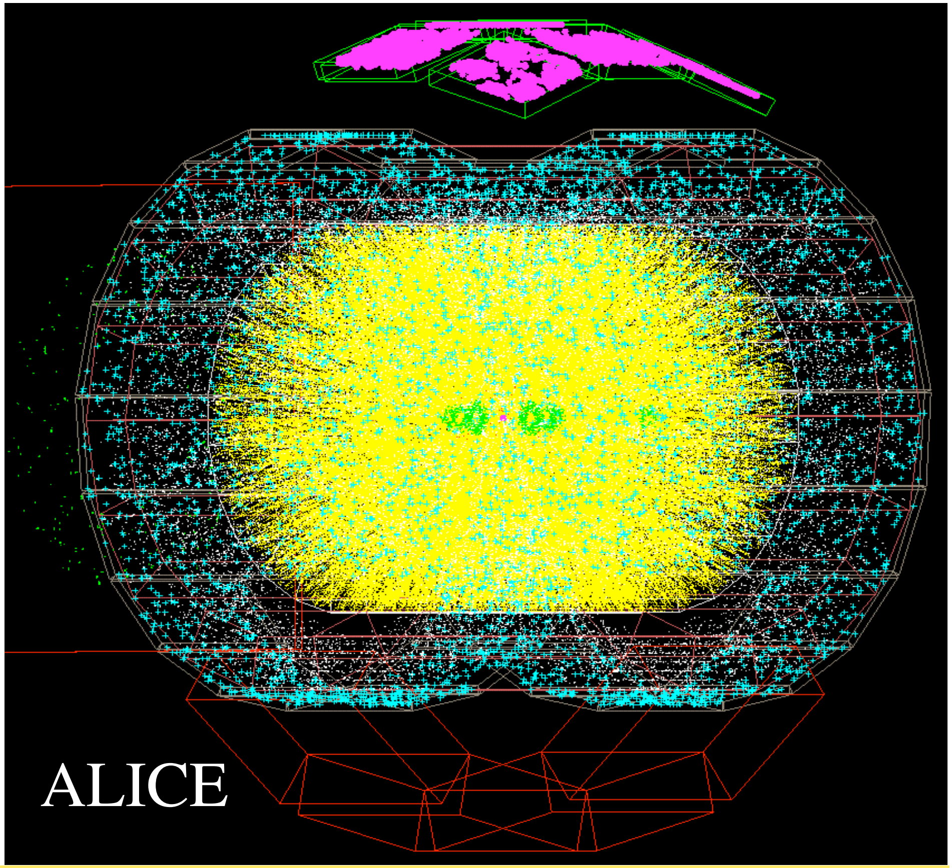
However if velocity can be measured accurately by time-of-flight of particle from T0 to T1, then the mass can be calculated.

Why bother identifying particles?
Helps us understand complex heavy ion collisions

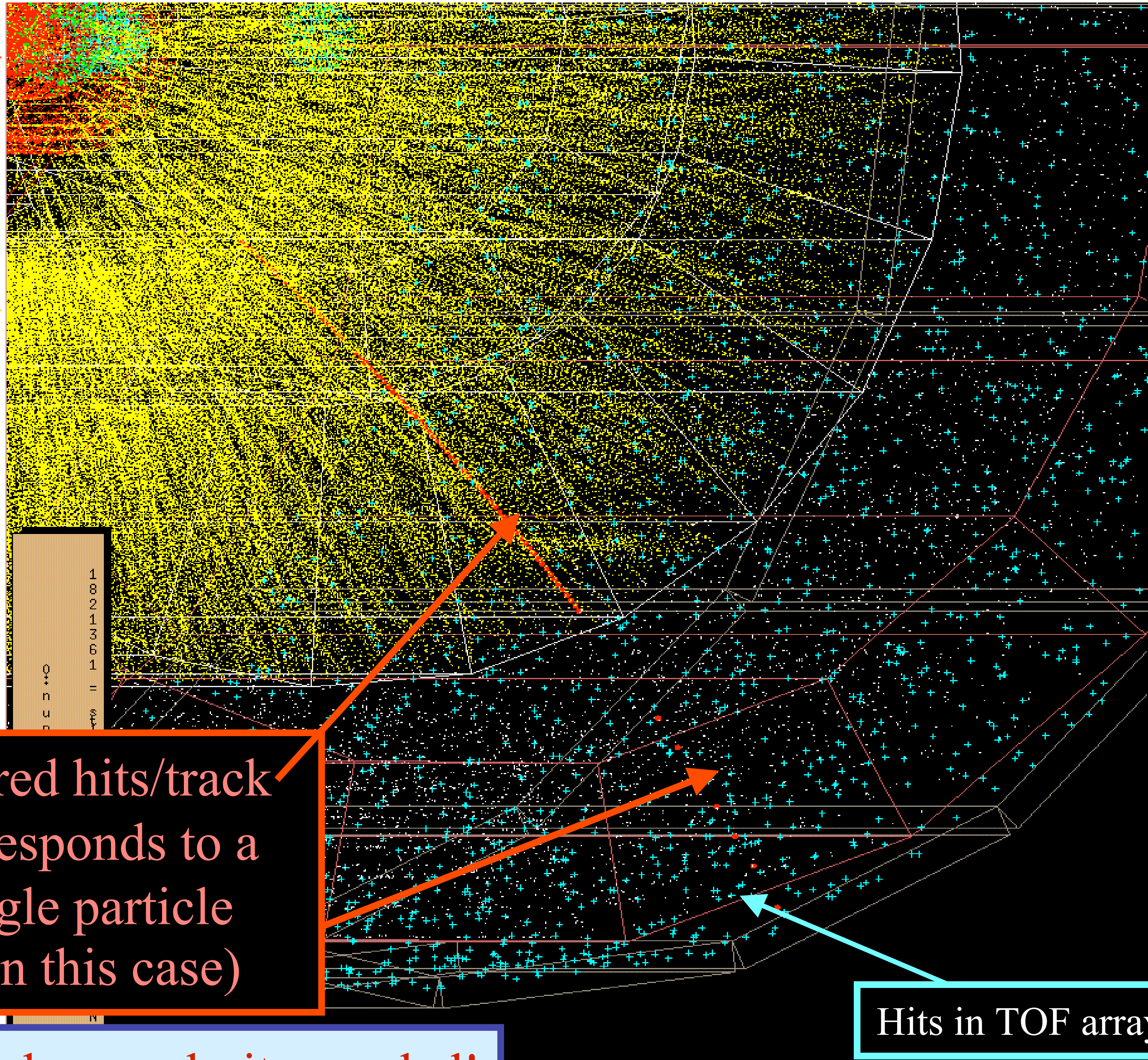


Au + Au at RHIC

Simulated Pb-Pb at LHC



Question: How do we make sense of this?
Answer: Identify each particle - or at least as many as possible.



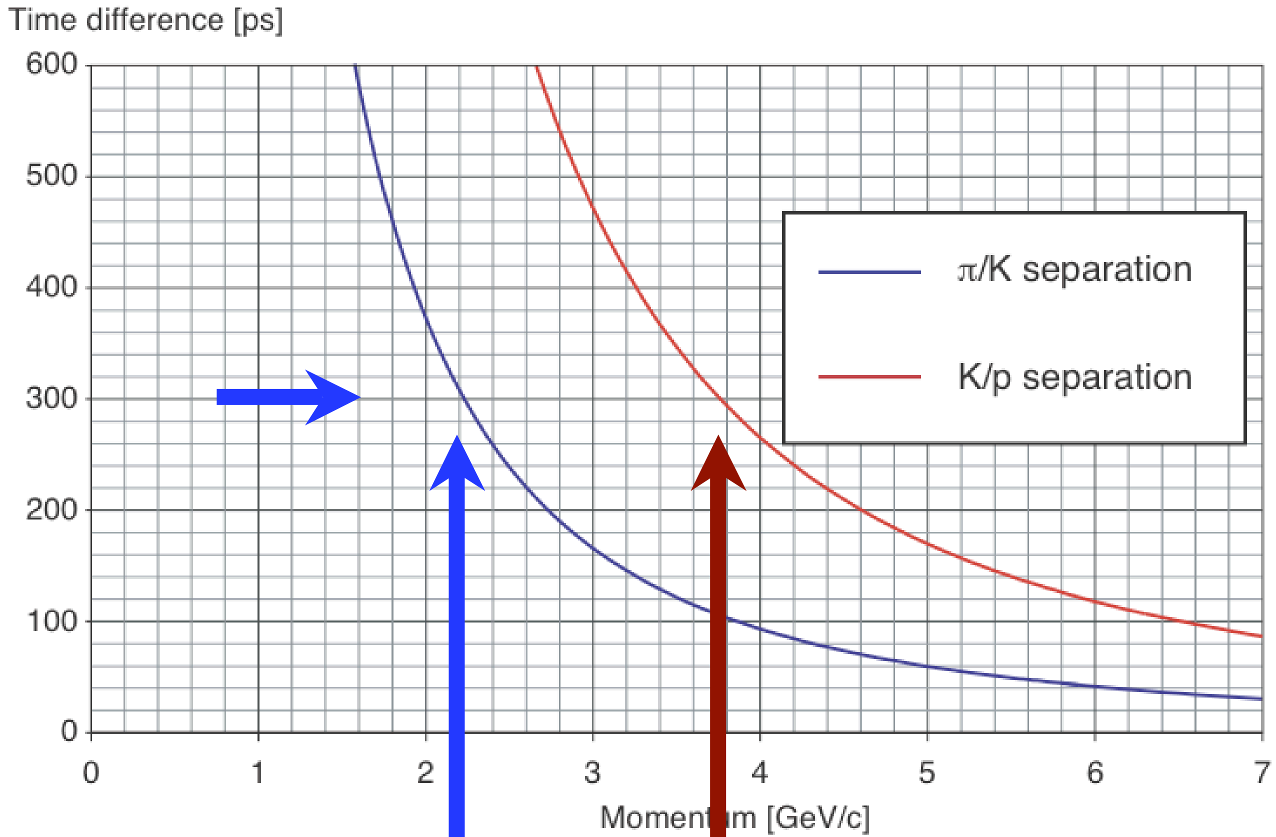
TOF with very high granularity needed!

Time difference = distance /(difference in velocity)

$$\Delta t_{1-2} = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) = \frac{L}{c}\left(\sqrt{1 + m_1^2c^2/p^2} - \sqrt{1 + m_2^2c^2/p^2}\right) \approx \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$

For example if time resolution of TOF is 100 ps 3σ separation equivalent to 300 ps difference

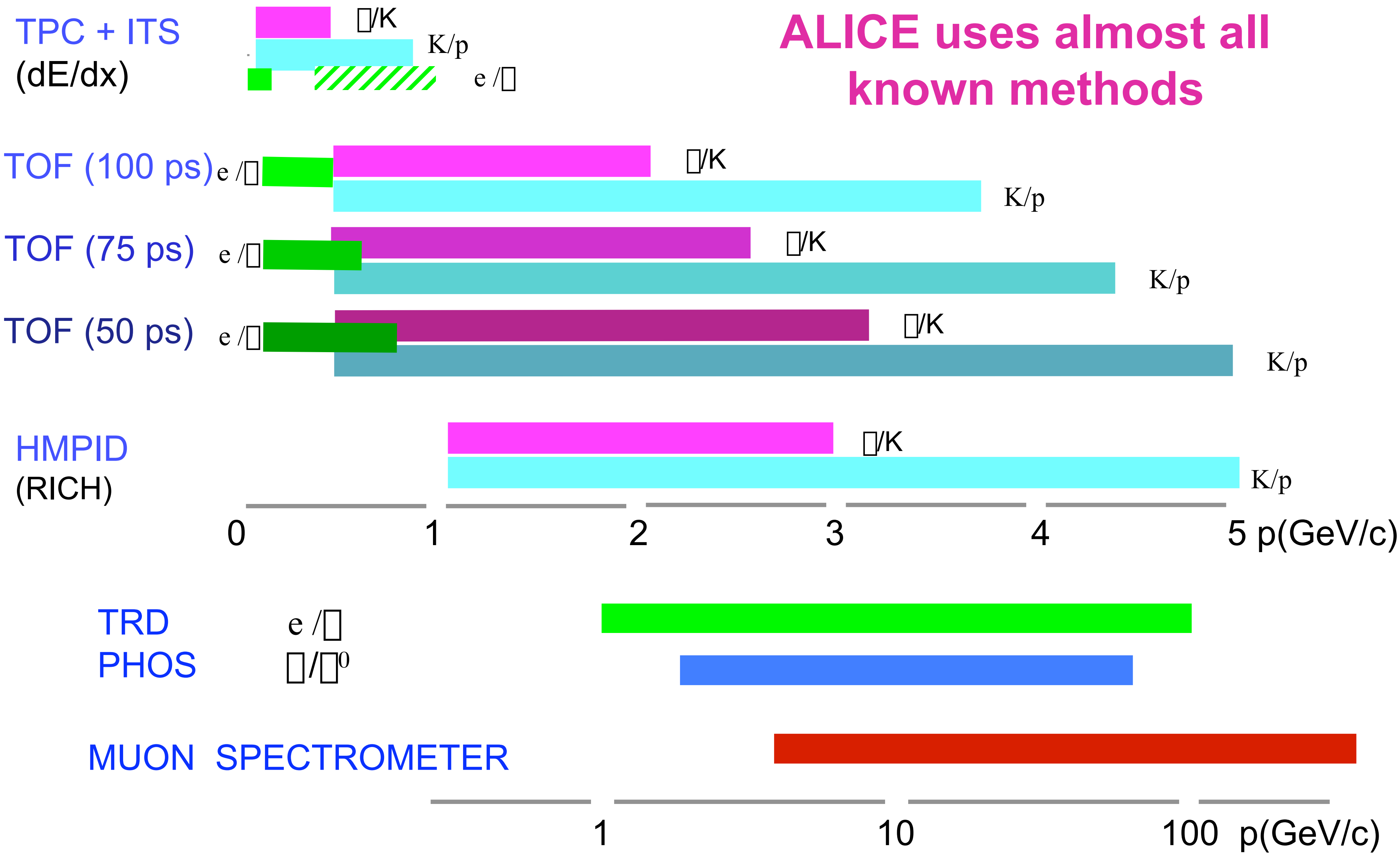
TIME DIFFERENCE AT 4 m (i.e. ALICE TOF)



π/K up to 2.2 GeV/c

K/p up to 3.7 GeV/c

Particle Identification in ALICE

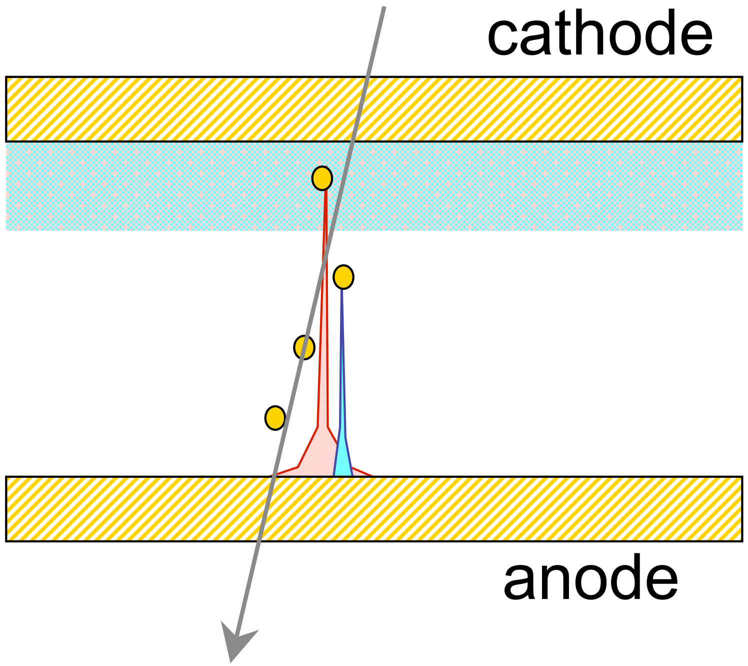


So what are the principle requirements for the ALICE TOF?

- Segmentation (easy and low cost)
- Time resolution - better than 100 ps
- Rate capability in excess of 50 Hz/cm^2

160,000 channels, each of ~ 10 cm^2 area
Has to be a gaseous detector - scintillators and phototubes prohibitive cost

→ MULTIGAP RESISTIVE PLATE CHAMBER



Electrons avalanche according to Townsend

$$N = N_o\, e^{\alpha x}$$

Only avalanches that traverse full gas gap will produce detectable signals - only clusters of ionisation produced close to cathode important for signal generation.

Avalanche only grows large enough close to anode to produce detectable signal on pickup electrodes (must be within 25% of distance closest to cathode if work at $\alpha D \sim 20$ (max avalanche has 10^8 electrons)

Time jitter proportional to: gap size/drift velocity

So (a) only a few ionisation clusters take part in signal production

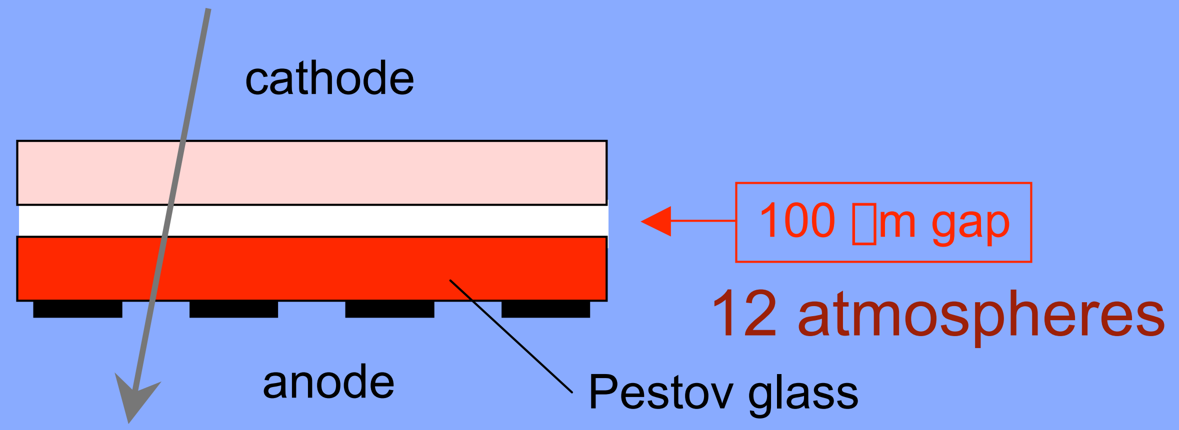
(b) size matters (small is better)

We have known for many years the important of size

Example: Pestof chamber (~1970)

30 years ago Y. Pestov informed us of the importance of size with his Pestof chambers - gas gap of 100 micron gives time resolution ≈ 50 ps. This is also first example of resistive plate chamber

Glass electrode and metal electrode



Excellent time resolution ~ 50 ps or better!

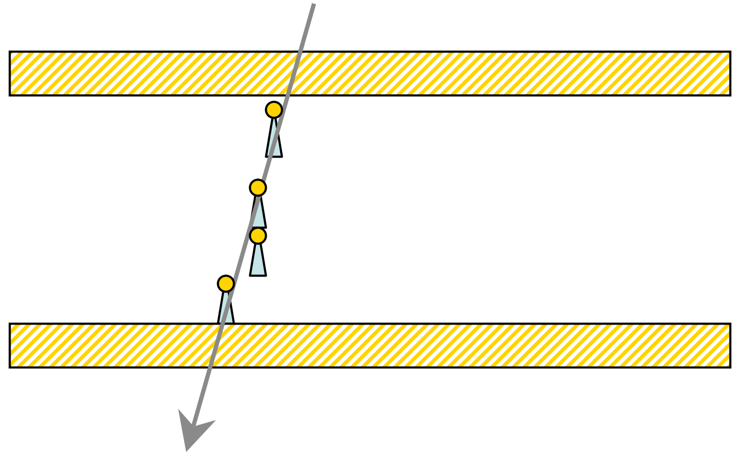
But long tail of late events
Mechanical constraints (due to high pressure)
Non-commercial glass
Needs very special gas mixture

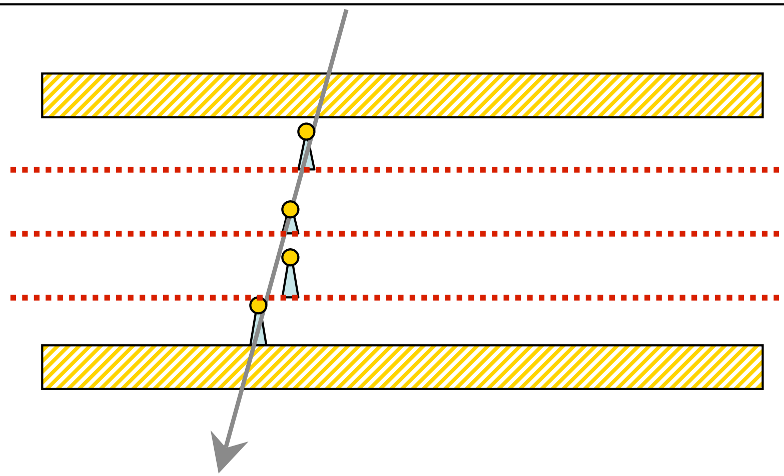
Gas detector at atmospheric pressure (Pestov at 12 atm) needs large gas gap to have high efficiency

Question: Can we increase gas gain such that avalanche produces detectable signal immediately?

(a) Need very high gas gain (immediate production of signal)

(b) Need way of stopping growth of avalanches (otherwise streamers/sparks will occur)

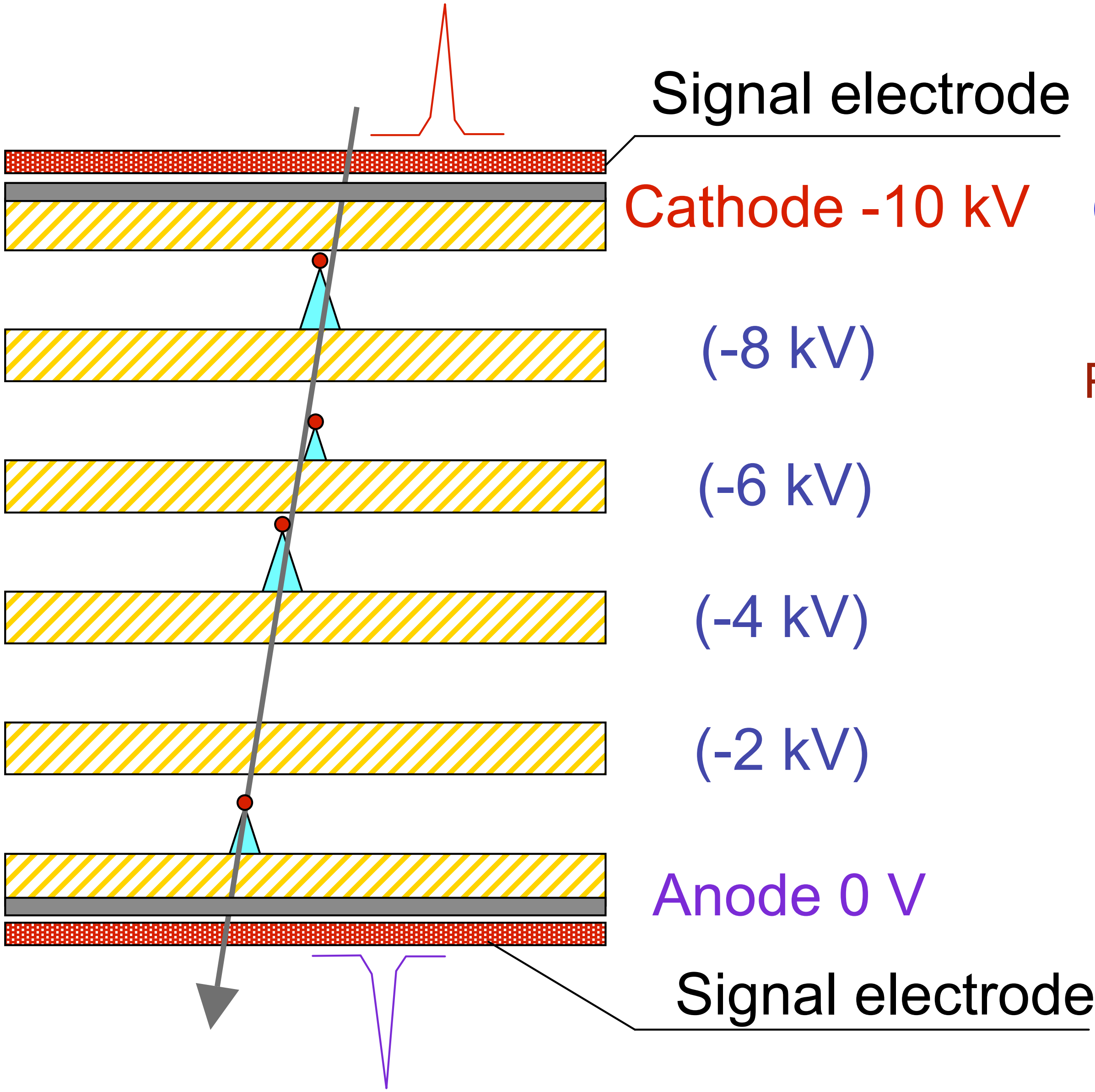




Answer: add boundaries that stop avalanche development. These boundaries must be invisible to the fast induced signal - external pickup electrodes sensitive to any of the avalanches

From this idea the Multigap Resistive Plate Chamber was born

MULTIGAP RESISTIVE PLATE CHAMBER

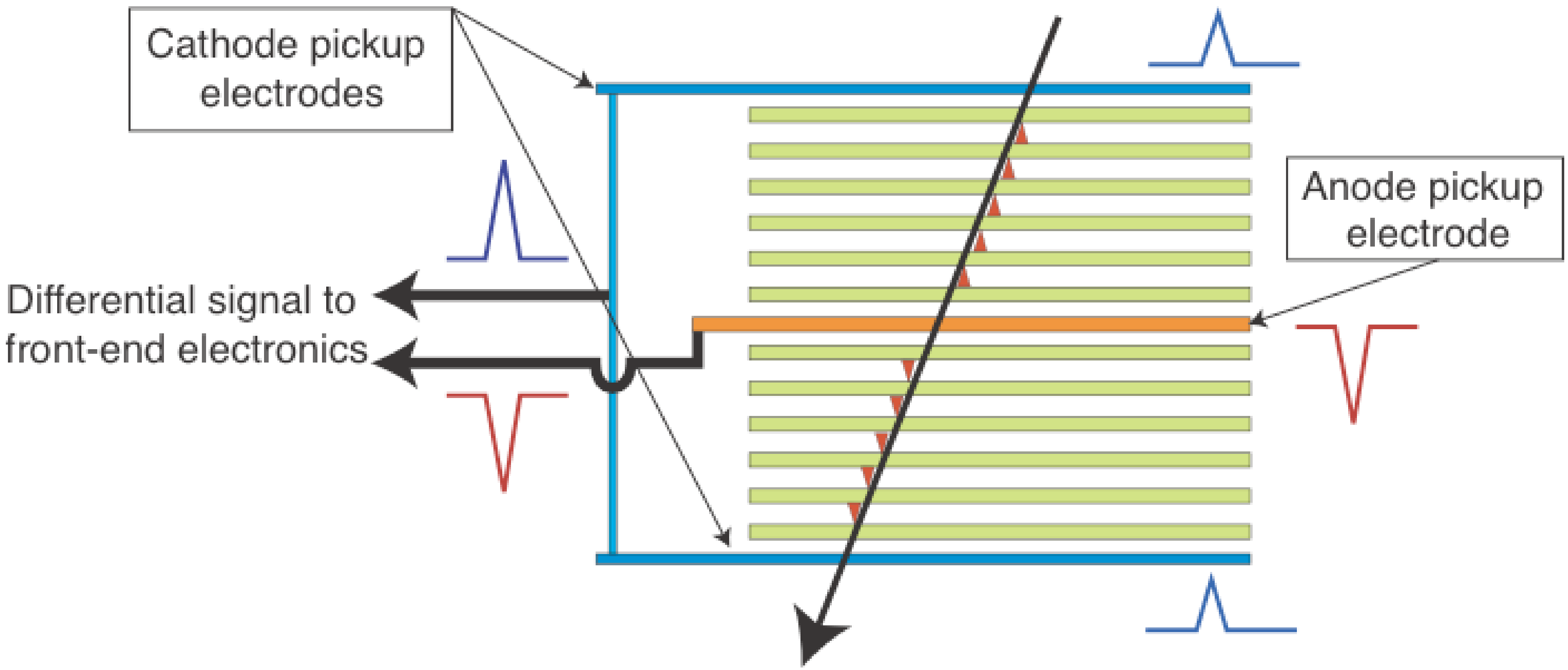


Stack of equally-spaced resistive plates with voltage applied to external surfaces (all internal plates electrically floating)

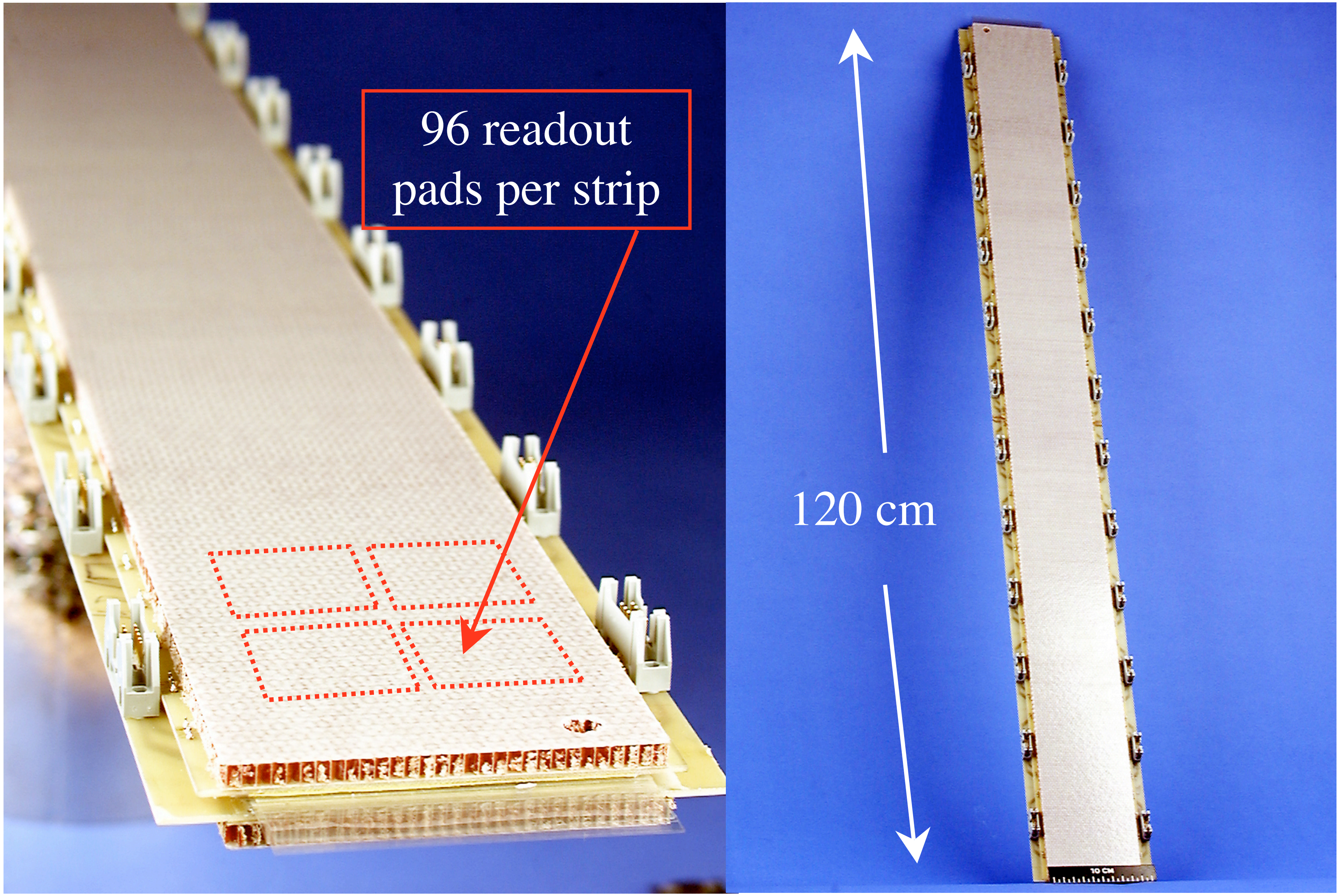
Pickup electrodes on external surfaces (resistive plates transparent to fast signal)

Internal plates take correct voltage - initially due to electrostatics but kept at correct voltage by flow of electrons and positive ions - feedback principle that dictates equal gain in all gas gaps

ALICE-TOF has 10 gas gaps, each of 250 micron width
Built in the form of strips, each with an active area of 120 x 7 cm^2, readout by 96 pads (each 2.5 x 3.5 cm^2)



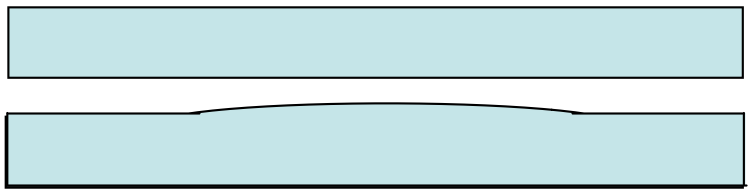
ALICE TOF STRIP



Good timing needs small gas gaps - this is the reason for gaps of 250 micron

Need a certain thickness of gas - so that we have something for through-going charged particles to ionise - this is the reason for the 10 gaps (2.5 mm total)

Gas gaps of small size need to be constructed with very tight mechanical tolerance to have uniform field

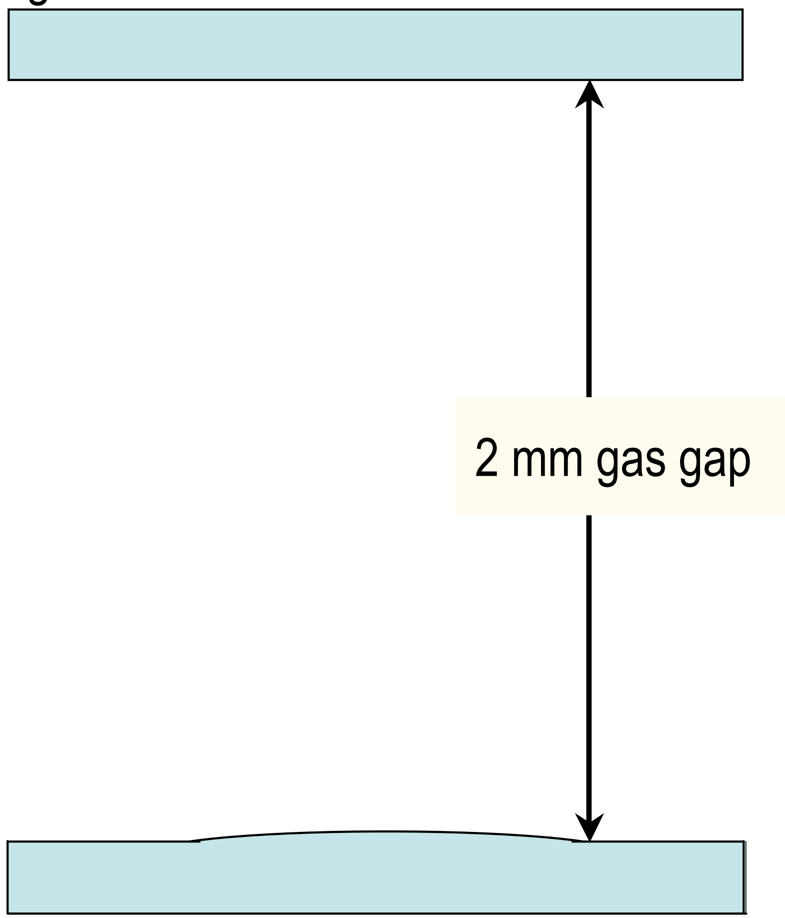


250 μm gas gap

25 μm bump 10% increase in E field

QUESTION : CAN WE BUILD 1500 m^2 OF GAP WITH ULTRA PRECISE TOLERANCE?

QUESTION : WHAT TOLERANCE IS NEEDED??

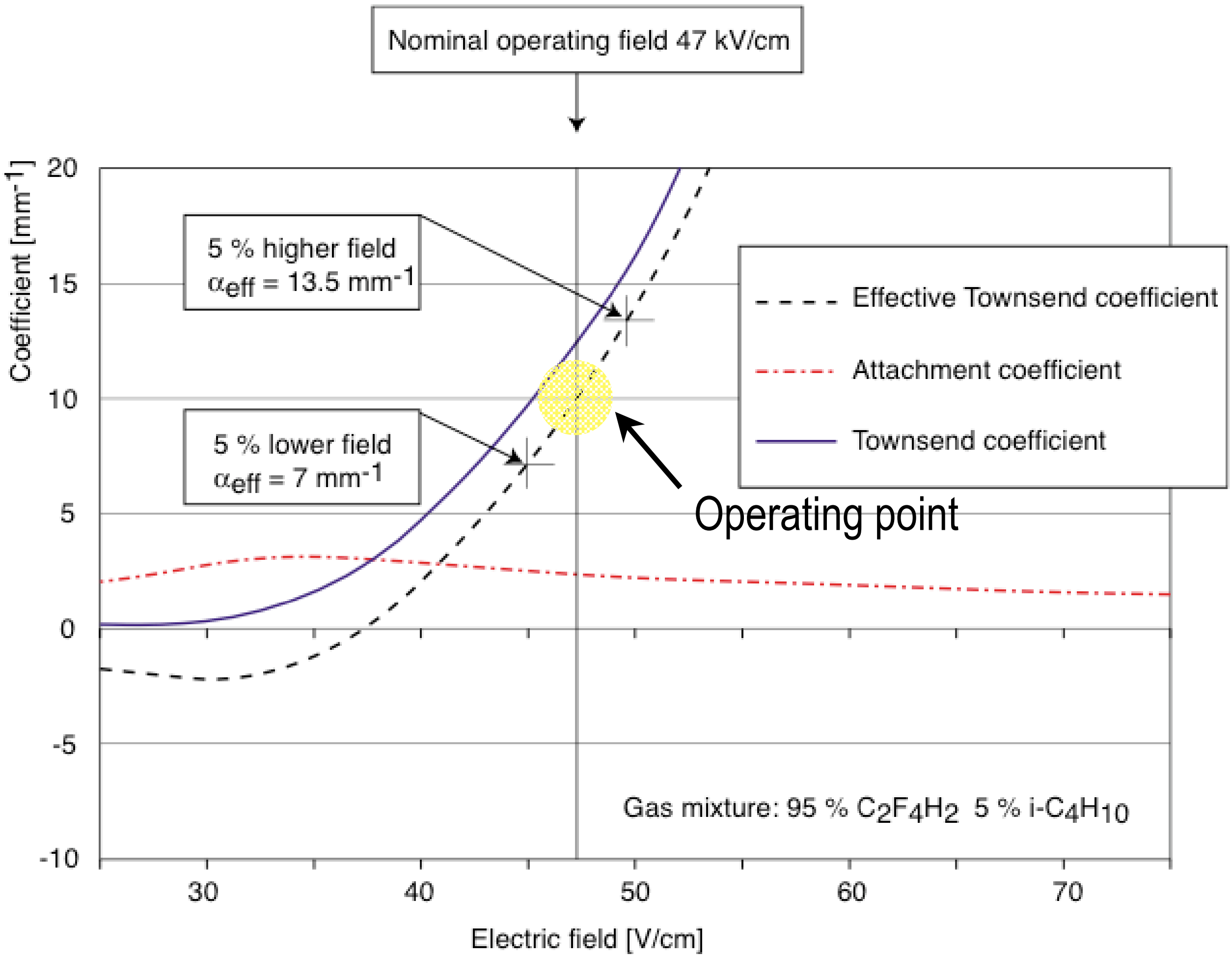


25 μm bump only 1% increase in E field

Use MAGBOLTZ to get value of and dependence on applied voltage

2 mm gas gap

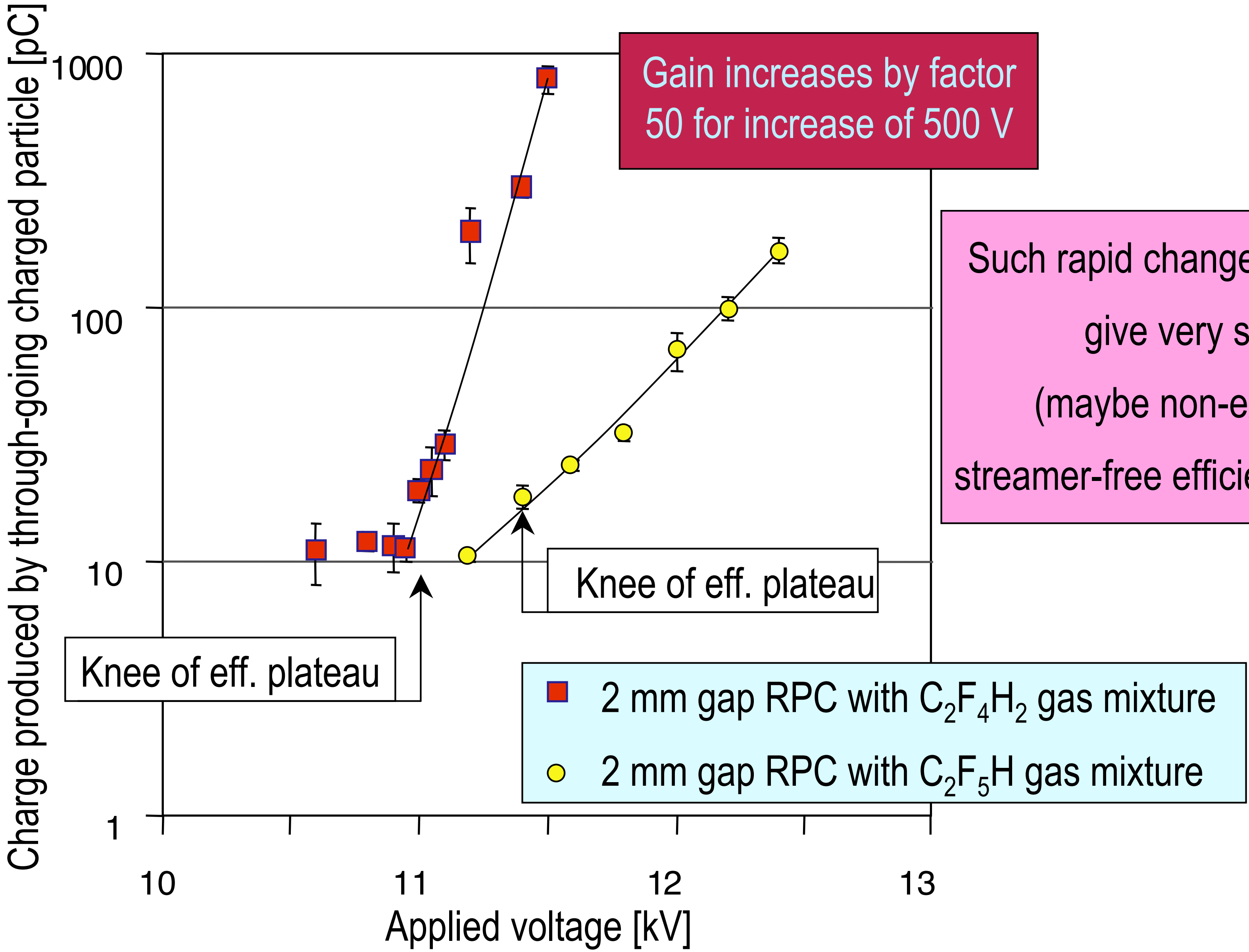
$_{effective}$ =



Order of magnitude change in gas gain for less than 200 V change in applied voltage

- Big variation in gain with small change in field
- Very short streamer-free plateau
- Very sensitive to change in gap size
- 20 micron is 1% change of field (i.e change in applied voltage of 100 V)

Measure TOTAL charge of 2 mm RPC



Such rapid change in gain will give very short (maybe non-existent) streamer-free efficiency plateau

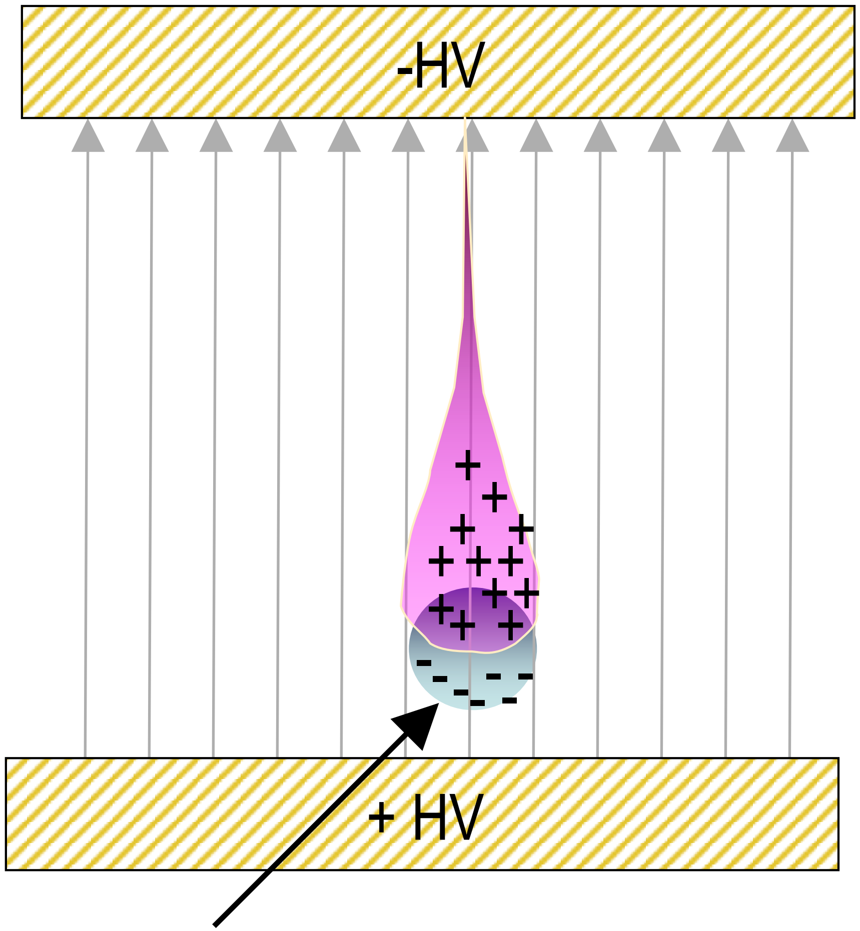
We have seen that 2 mm RPC has large variations in gain for small changes in voltage and gap width.

WHAT ABOUT THE ALICE TOF MRPCs?

Question: Surely gaps of 250 micron are going to be even more sensitive to changes in voltage and gap width?

Answer: avalanche growth in small gas gaps dominated by space charge effects

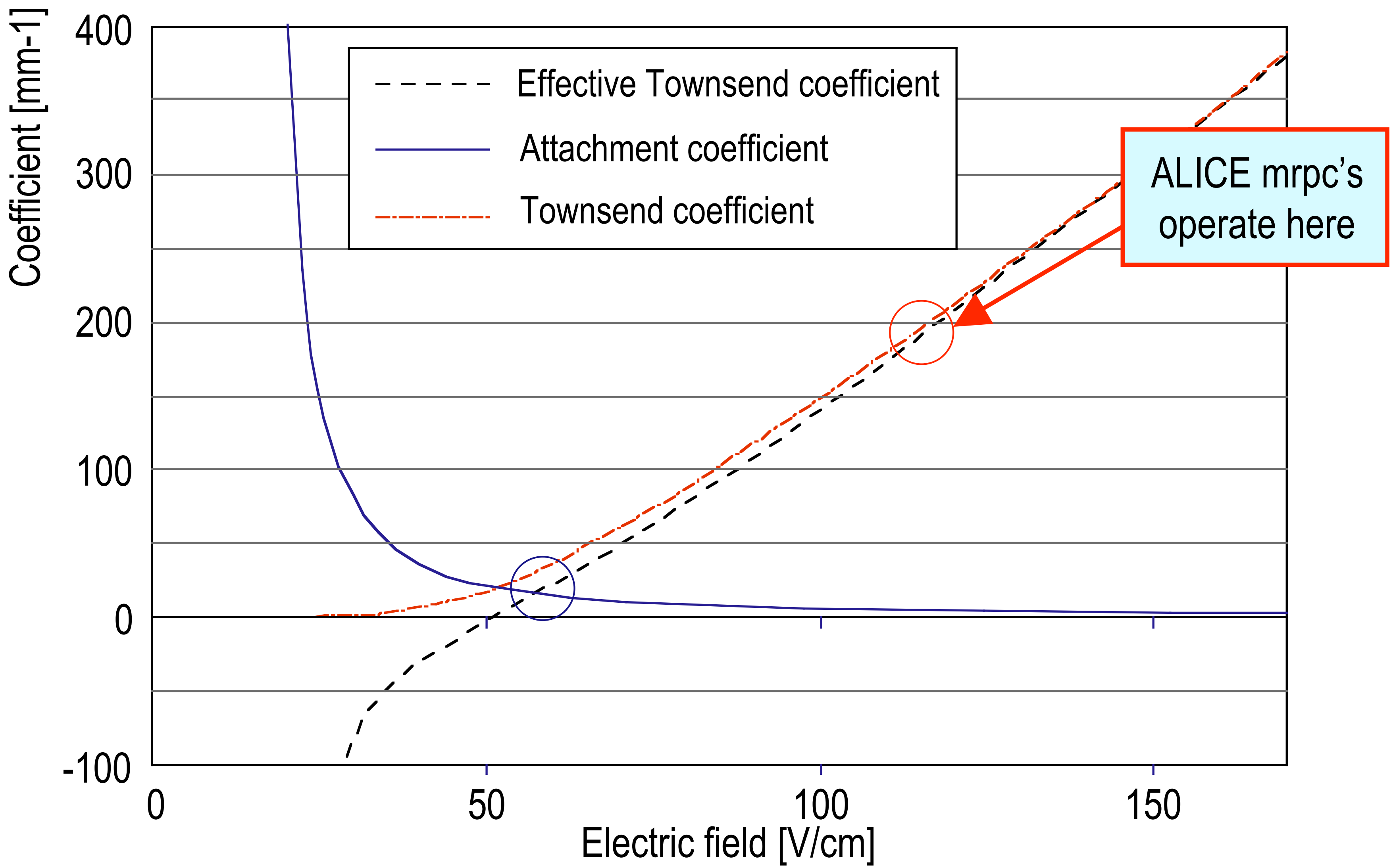
Growth of avalanche limited by space charge of positive ions



Low field region due to space charge

Every time an ionising collision creates an electron, there is also a positive ion created. Since the positive ion is heavy - it is stationary in time scale of avalanche formation. The charge of these positive ions reduces the electric field seen by the electrons in the 'head' of the avalanche. i.e. Gas gain is reduced - so avalanche grows to certain size and then growth slows down.

Magboltz output for 90% $C_2F_4H_2$, 5% SF_6 and 5% i-C_4H_{10}

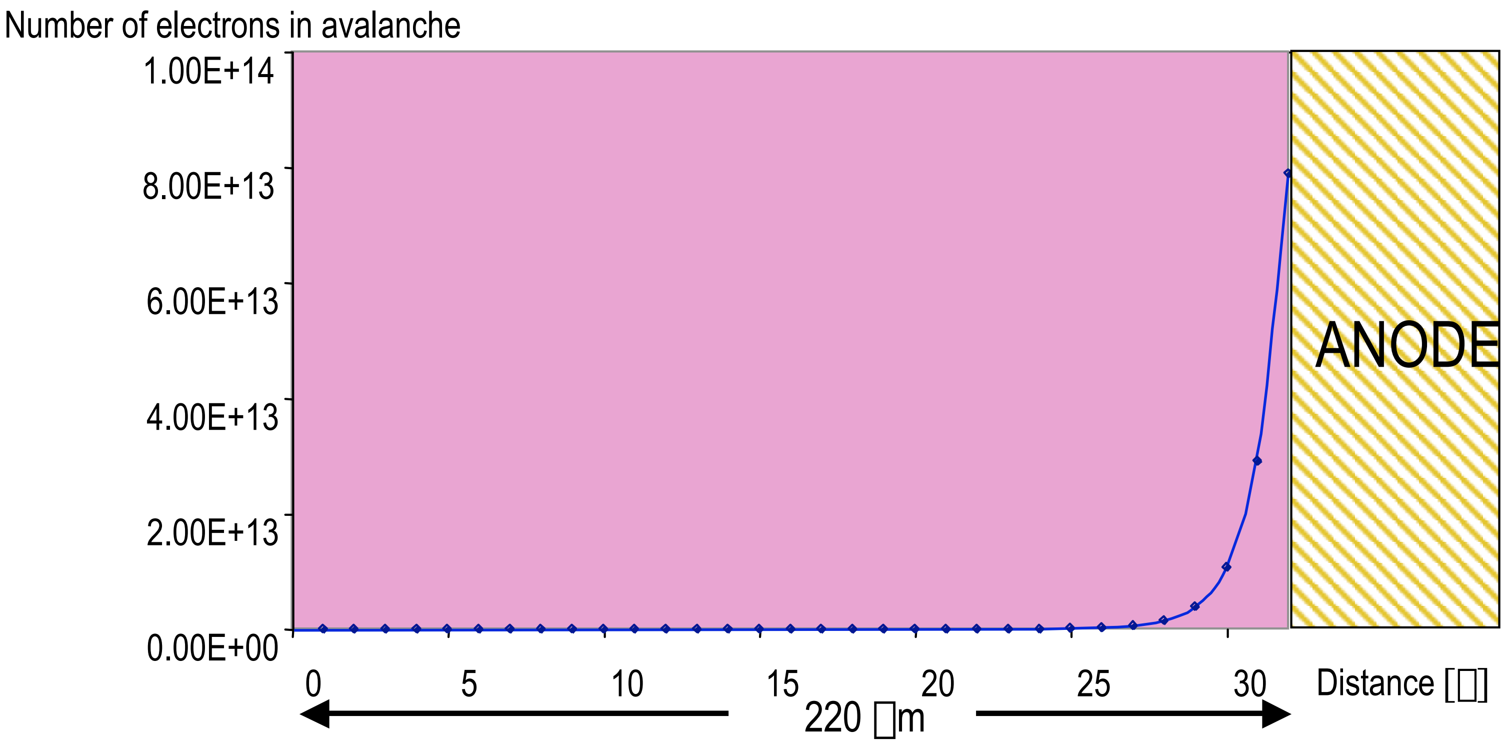


Use MAGBOLTZ program to predict Townsend coefficient and attachment coefficient in gas mixture 90% $C_2F_4H_2$, 5% iso-C_4H_{10} and 5% SF_6.

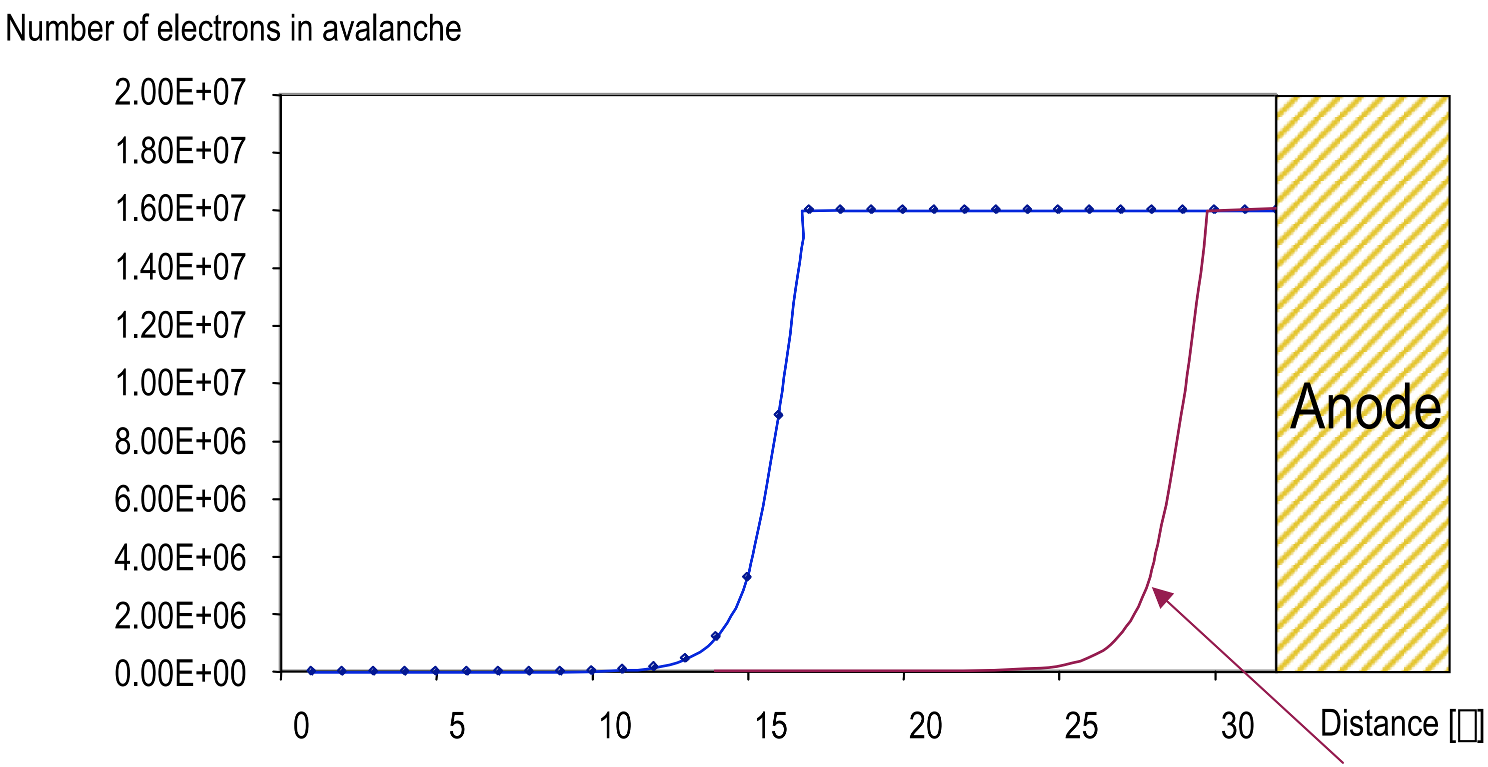
Result □ = 173.4 mm^{-1} and □ = 5.8 mm^{-1} for a 220 micron gap MRPC

i.e. □ = 6 □m

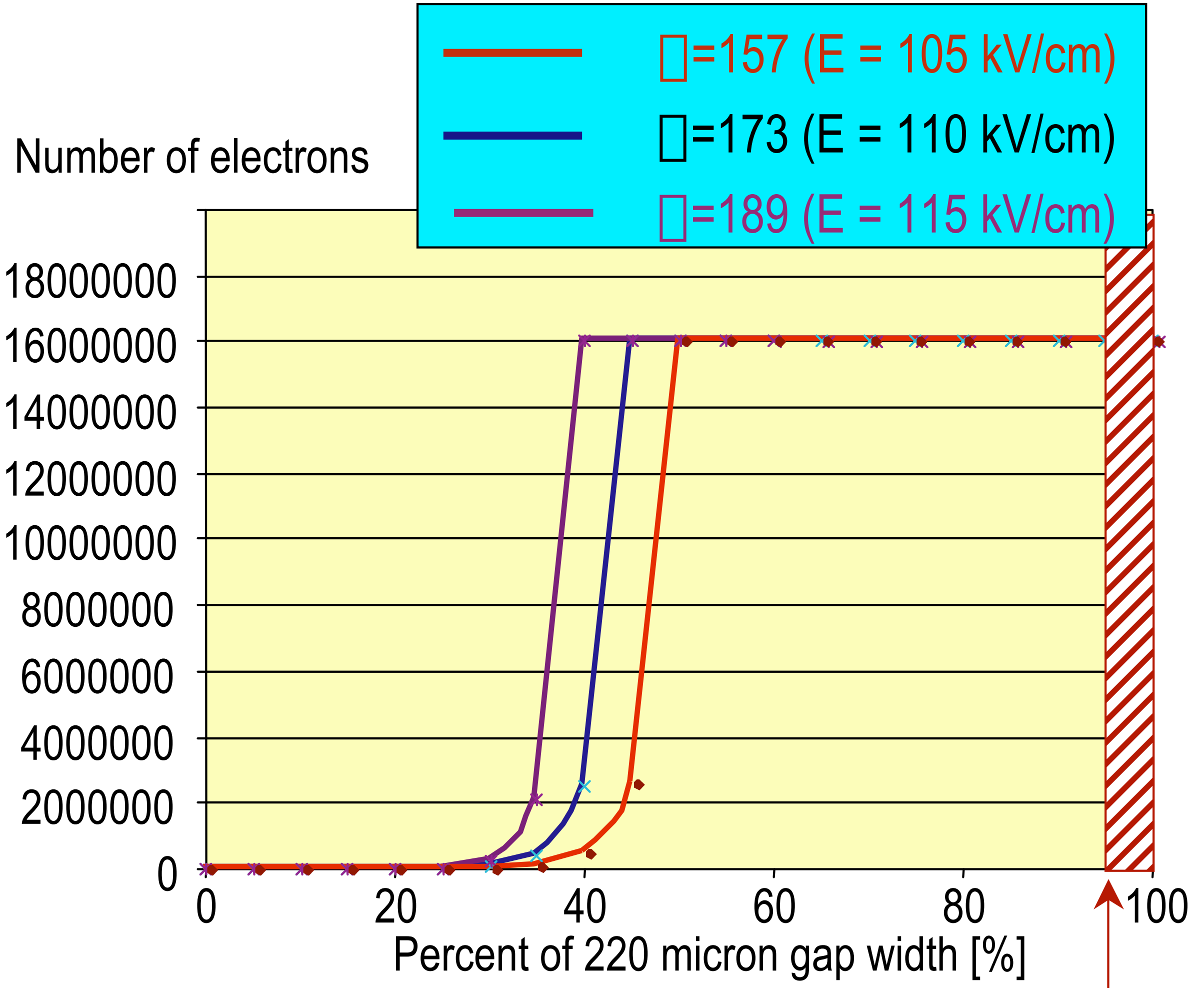
Single electron avalanching across 220 □m gap would produce ~10^{14} electrons !



Add 'space charge' limitation as saturation at 1.6 10^7 electrons



Even avalanches that start half way across gap can produce detectable signals



Vary applied voltage by ±5 %

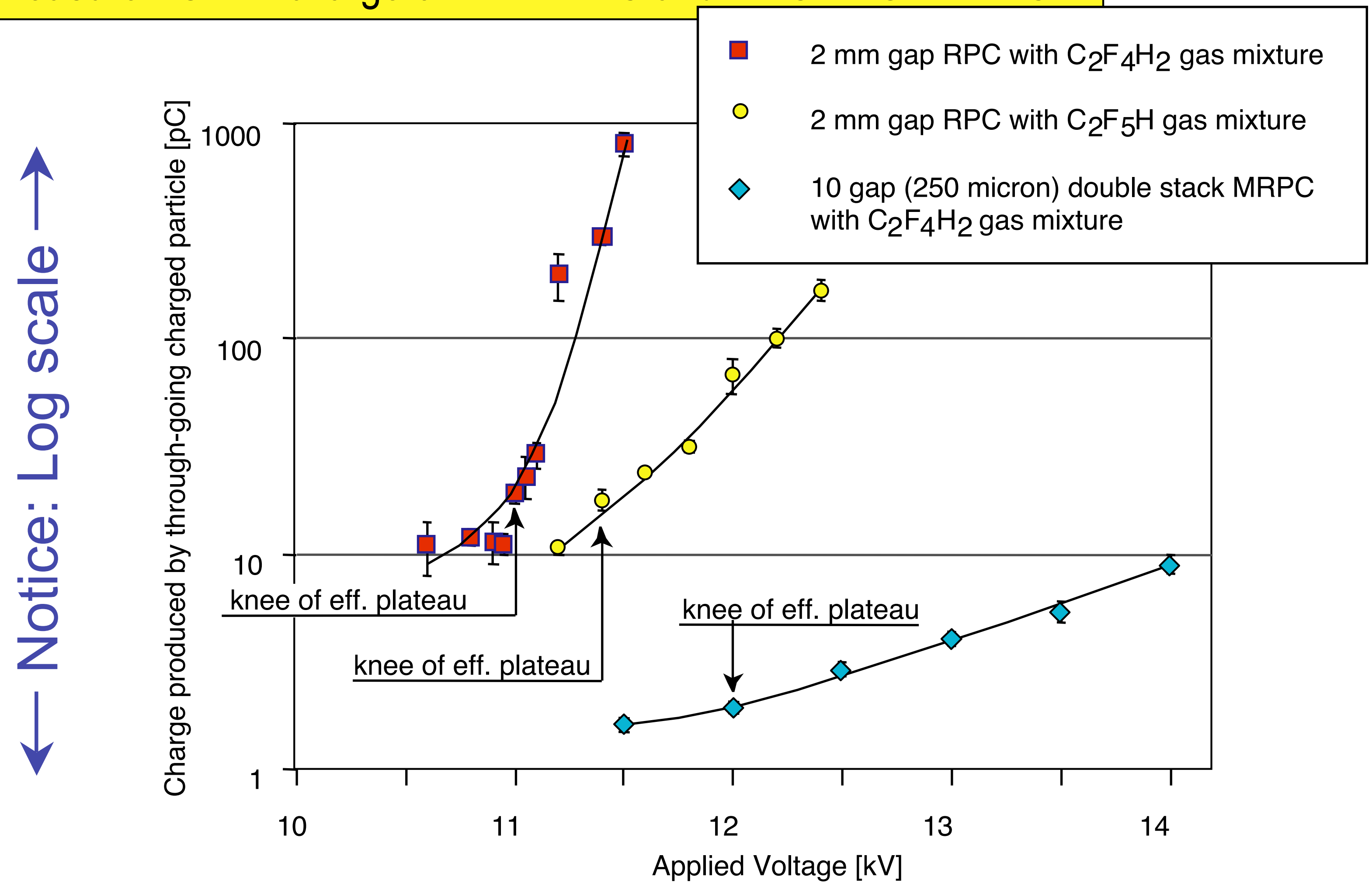
Example: if voltage fixed but gap size reduced by 5% E field 5% higher (avalanche follows purple line - but gap now ends at 95% of gap width

If the 5% change in electric field caused by gas gap size changing by 5% then effect shown above almost completely cancels !

NON CRITICAL GAP TOLERANCE FOR GAS GAIN…

Note: fast signal / total signal should be much larger than for Townsend type avalanche

Measure TOTAL charge of 2 mm RPC and ALICE-TOF MRPC



N.B.

(a) observe how slow gain changes with voltage (factor 5 / 2 kV)

(b) MRPC (ALICE TOF) average total charge ~ 2 pC (good rate capability)

If we want to have a gaseous detector with good time resolution, we are forced to build parallel plate devices with (many) small gas gaps.

Gas avalanches in small gas gaps are dominated by space charge; this limits avalanche growth.

Small dependence on gap size and applied voltage

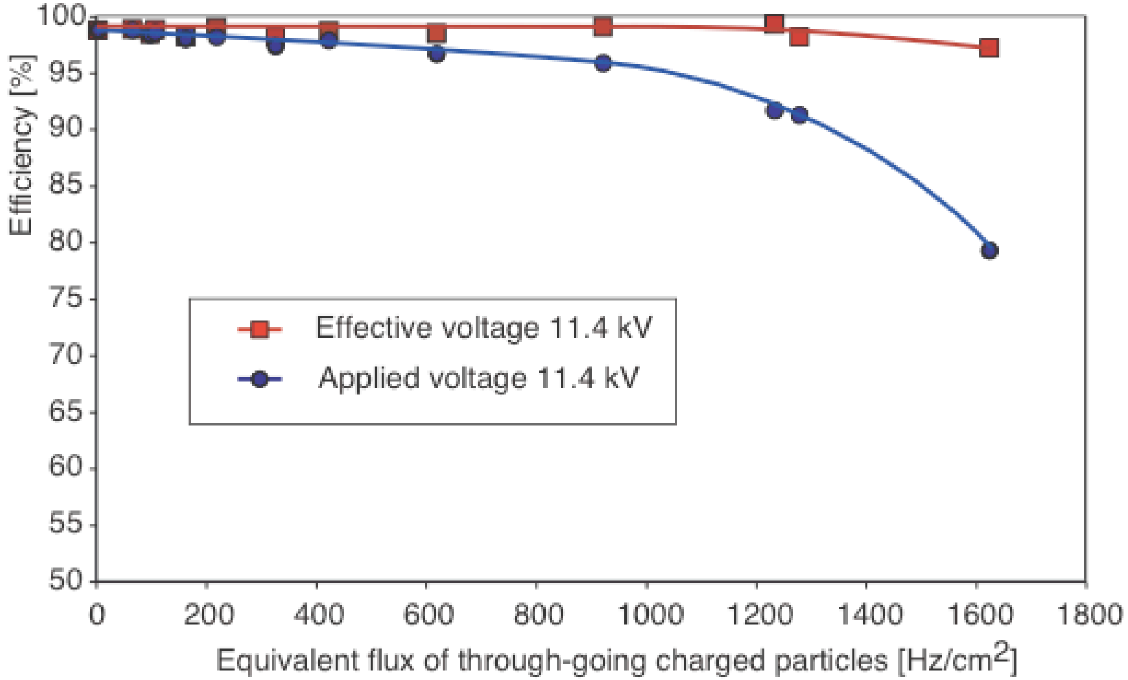
Low amount of total charge produced

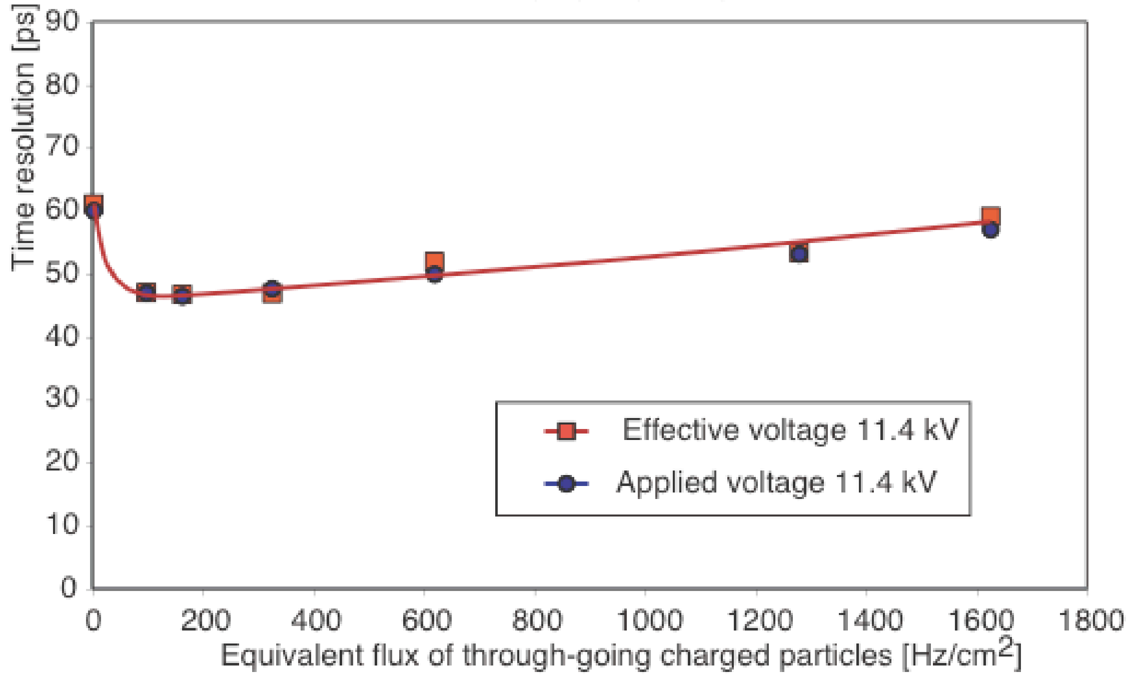
Easy to build

Excellent rate capability

Test of 220 micron 10 gap MRPC at GIF CERN

Effective voltage : increase voltage across stack as current drawn by MRPC increases to compensate for voltage drop across resistive plates.. But anyway rate capability in excess of 1 kHz/cm^2 .. Excellent for resistive plate chamber



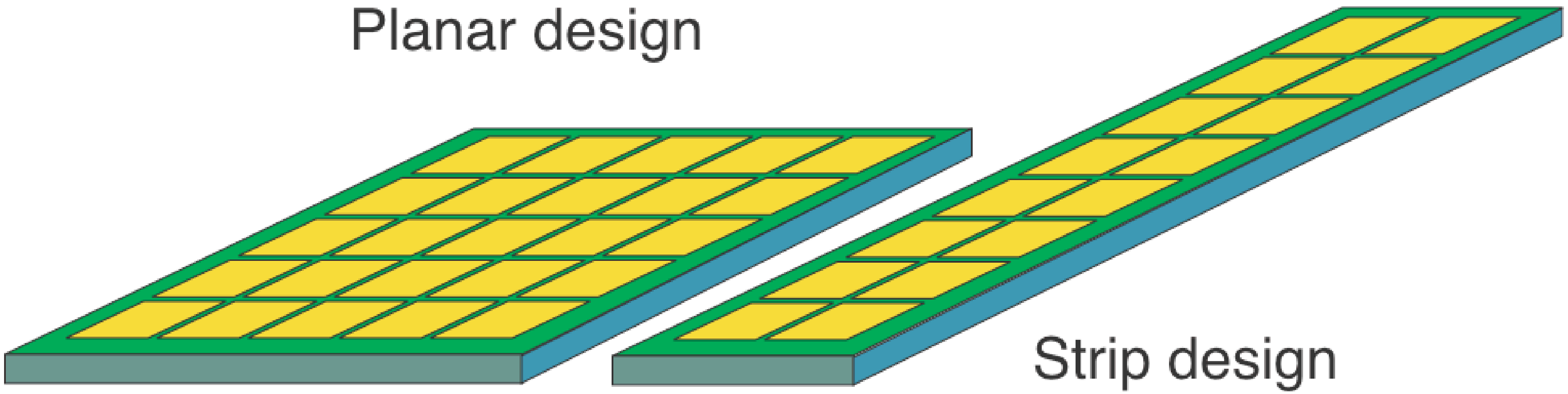


Front-end electronics

Exceptional timing precision requires exceptional front-end electronics

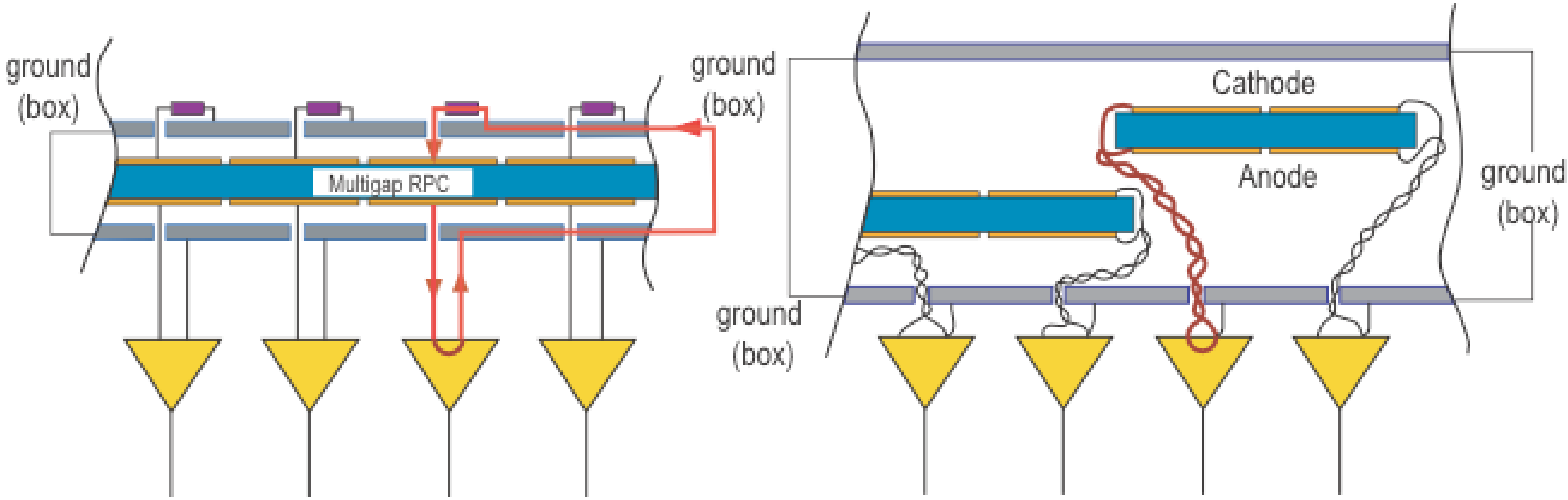
Fast
Low-noise
Sensitive
Low-power

Minimise noise : good detector design as well as good electronics. Consider the case of the planar versus the strip MRPC detector



Strip has some advantages concerning the geometry but very large advantage for the readout

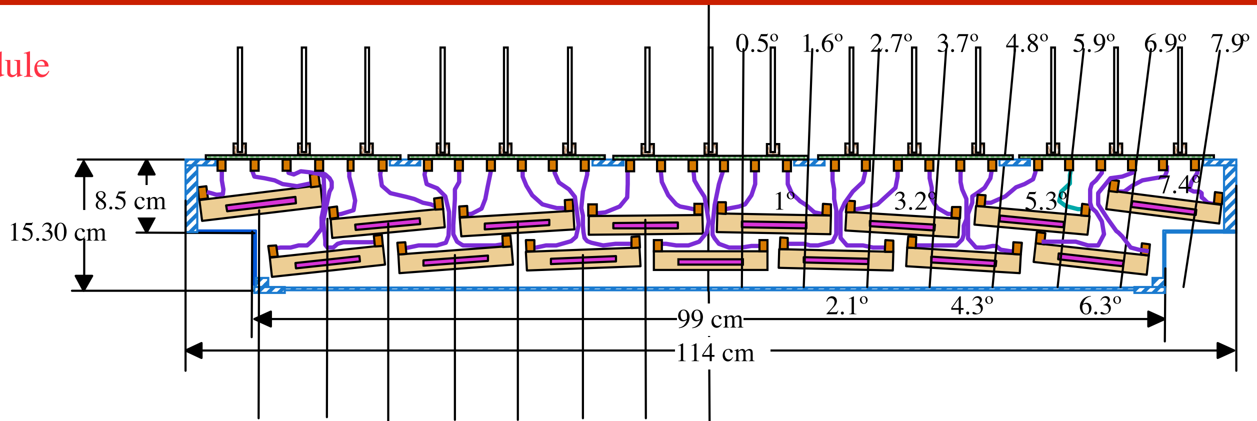
Big reduction in noise if care is taken with the signal return



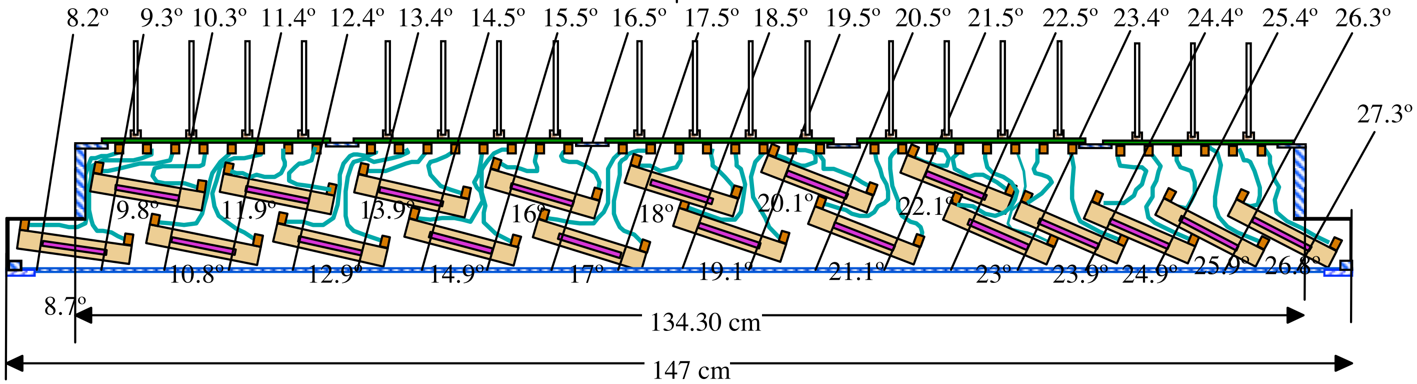
The signal is induced on the anode and cathode pickup pads - current flows from anode pad through amplifier and returns to cathode pad. The strip design allows the use of a transmission line (twisted pair cable) to connect this 'signal generator' to the amplifier - otherwise return path is via the outside grounding box (therefore sensitive to all the noise in the ground). In reality this is a key ingredient to substantially reducing the noise and improving the time resolution - however the selected amplifier for the initial tests (Maxim 3760) is single-ended and cathode signal are grounded at input of amplifier.

Detector made of strips allows us to have detector normal to incoming particles in r-phi plane - good geometric reasons for this but also allows differential readout

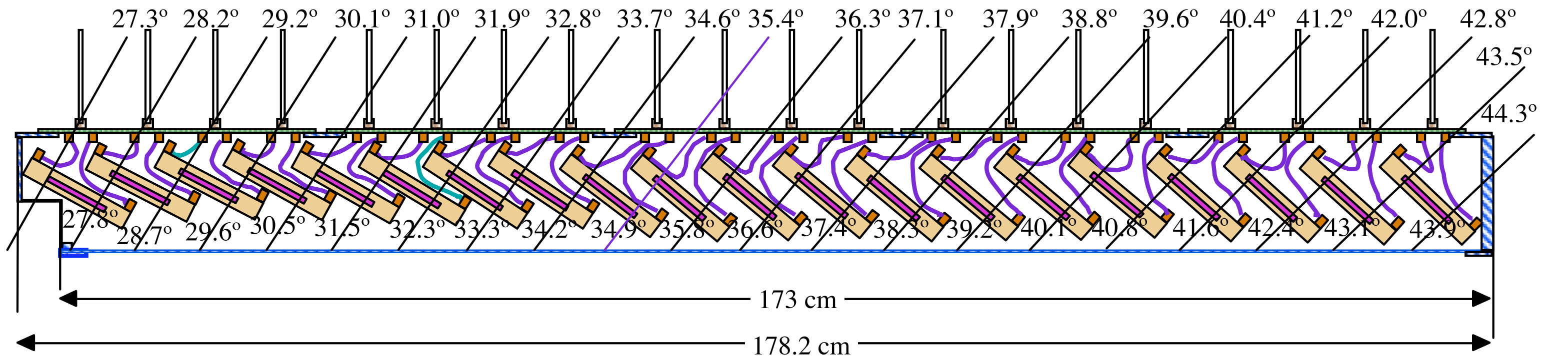
Central module



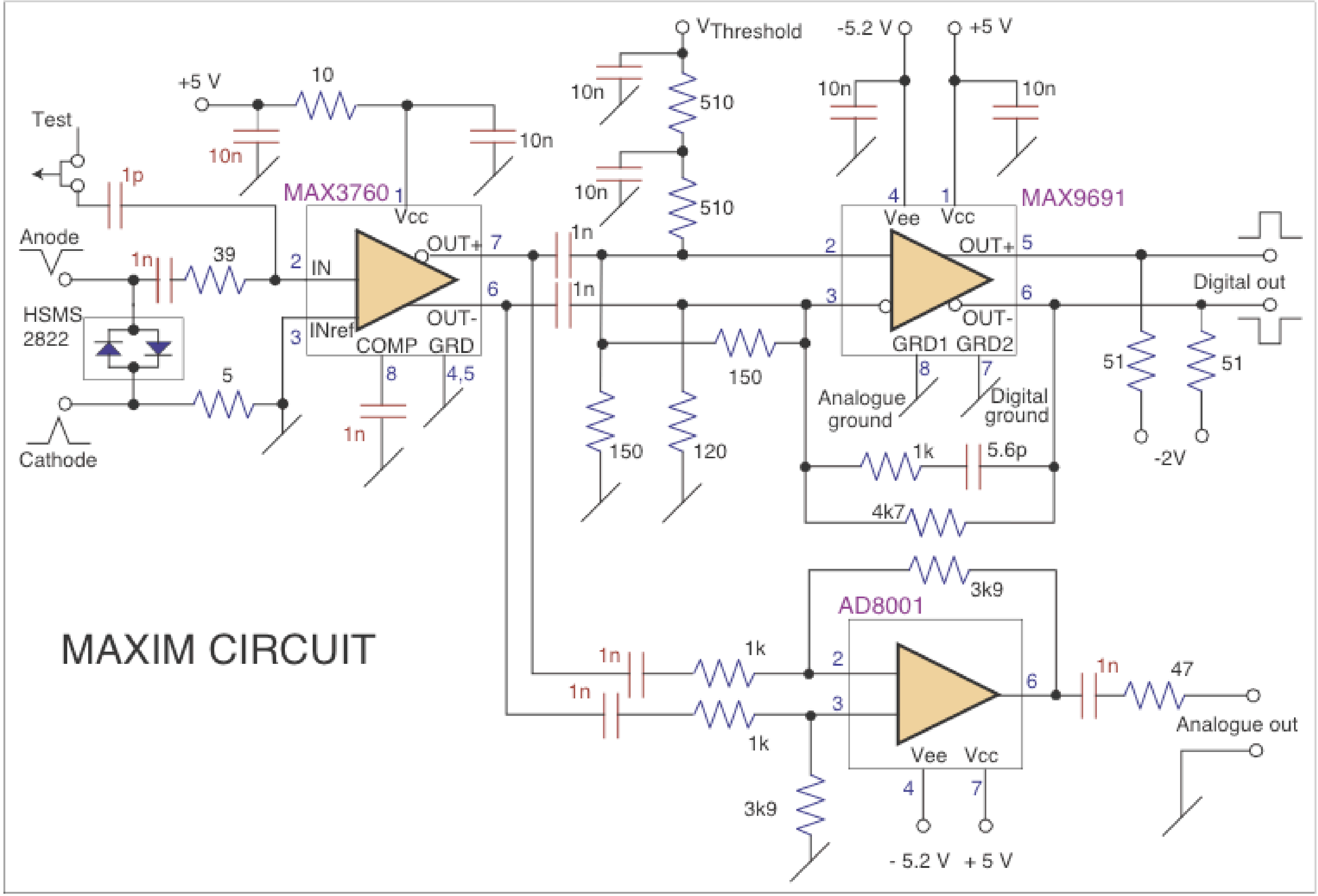
Intermediate module



Outer module



MAXIM 3760 used for much of the TOF R&D



MAXIM CIRCUIT

GOOD POINTS OF MAXIM SOLUTION

- Fast
- Low input impedance (but used a feedback system)

NOT SO GOOD POINTS OF MAXIM SOLUTION

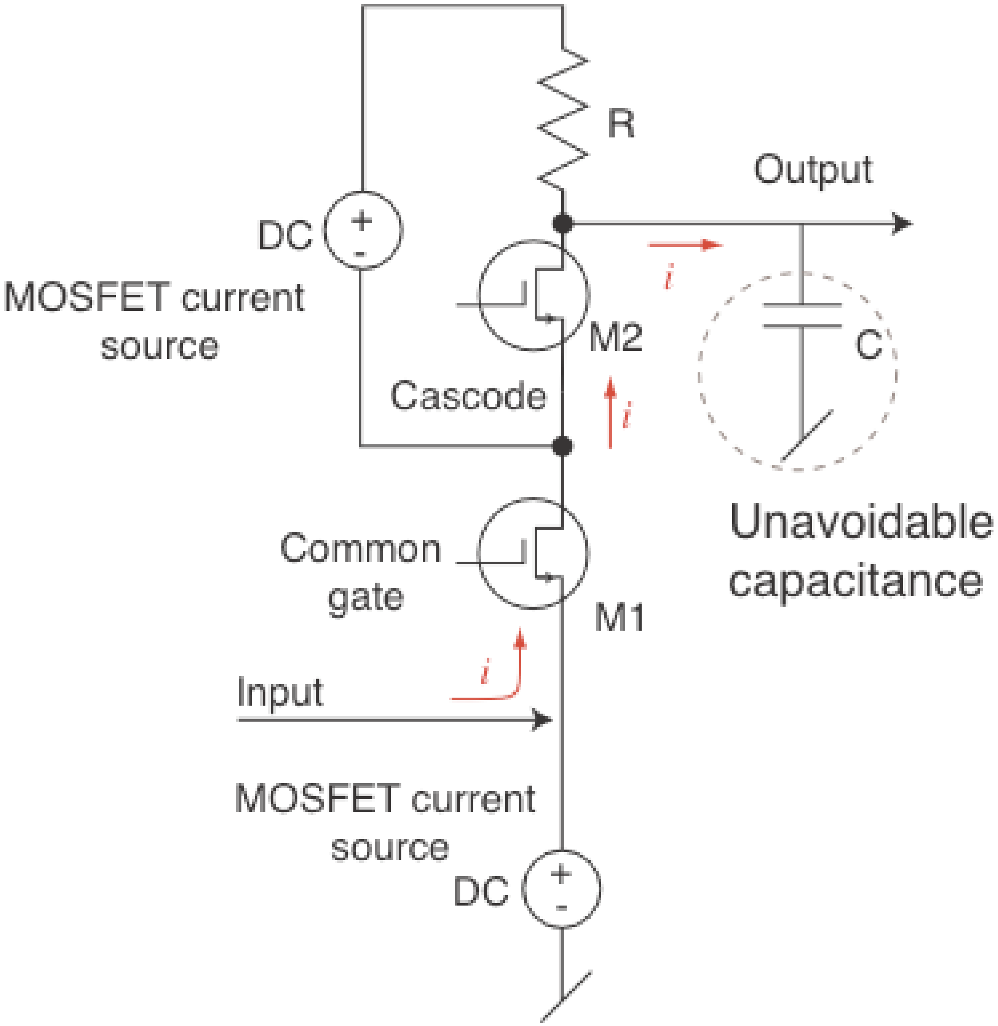
- High power (300 W/m^2 for ALICE TOF ARRAY)
- Not differential input
- Measurement of input charge by TOT not implemented
- Cost ($4.- for MAXIM 3760 if 200,000 ordered)

At end of 2001 decide to start development of suitable amplifier+discriminator+time-over-threshold ASIC in 0.25 μm technology

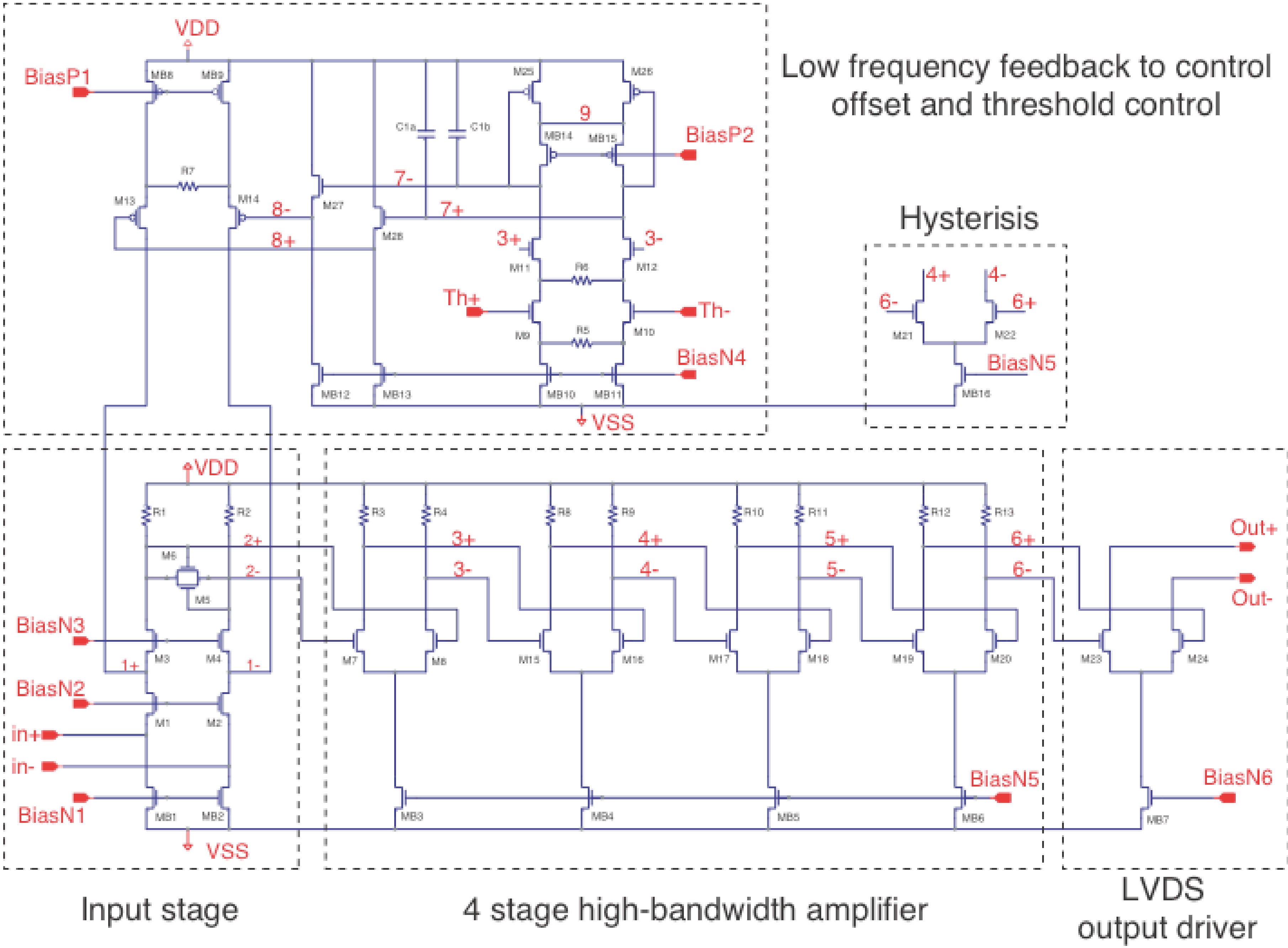
- Differential input
- Designed to be coupled to transmission line
- Fast (1 ns peaking time) to minimise jitter
- Differential design throughout to minimise cross-talk, etc
- Low power (less than 50 mW/channel was the target)
- Time-over-threshold measurement of input charge

THE NINO ASIC

1/2 of input circuit



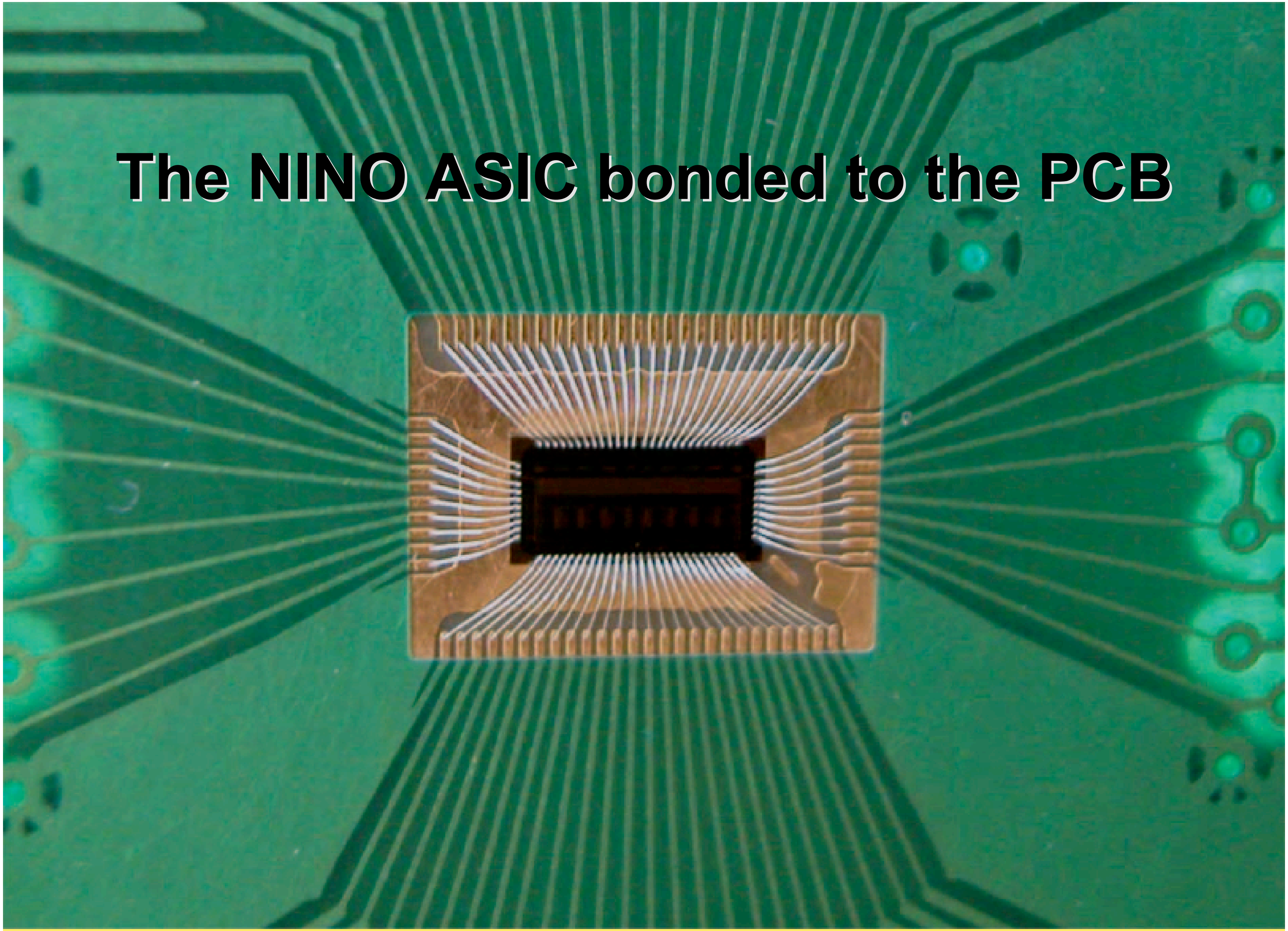
- oThe input current flows through the two transistors and charges the capacitor at the output (need to minimise C for maximum voltage)
- oTrailing-edge of voltage pulse at output has RC time constant
- o The impedance seen at the input is mainly the $1/g_m$ of the input transistor.
- oThe advantage of this configuration is the high bandwidth with excellent stability due to the absence of feedback element.


Low frequency feedback to control offset and threshold control
VDD
BiasP1
BiasP2
9
7-
7+
8-
8+
3+
3-
Th+
Th-
BiasN4
VSS
Hysterisis
4+
4-
6-
6+
BiasN5
VDD
BiasN3
BiasN2
in+
in-
BiasN1
1+
1-
2+
2-
3+
3-
4+
4-
5+
5-
6+
6-
Out+
Out-
BiasN5
BiasN6
VSS
Input stage
4 stage high-bandwidth amplifier
LVDS output driver

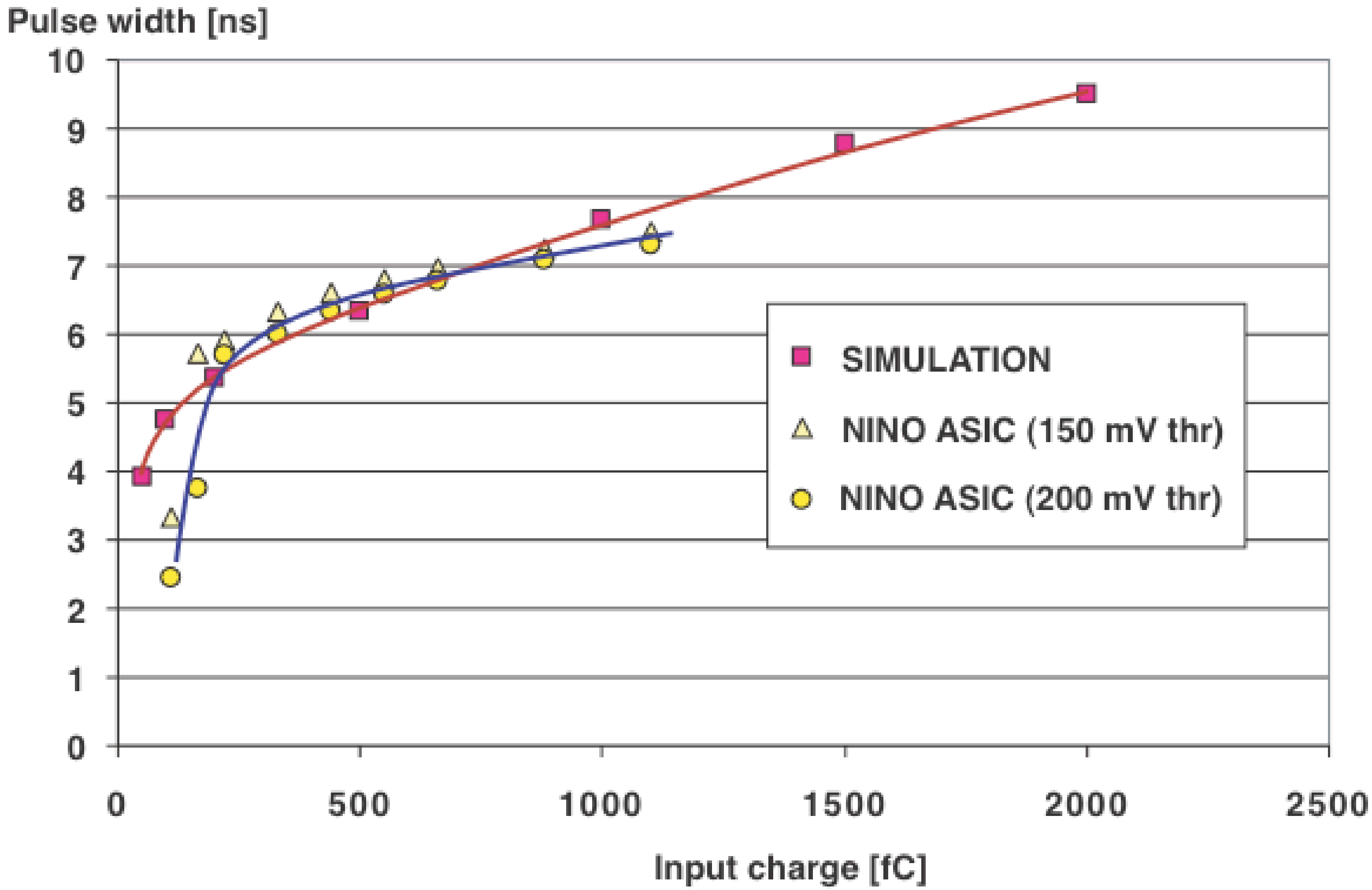
Even though it is a ‘straight forward’ circuit a lot of thought has gone into making it perfect - i.e. completely stable, independent of process variations, applied voltage, temperature… Do not have time to discuss these issues here but do have time to acknowledge the team

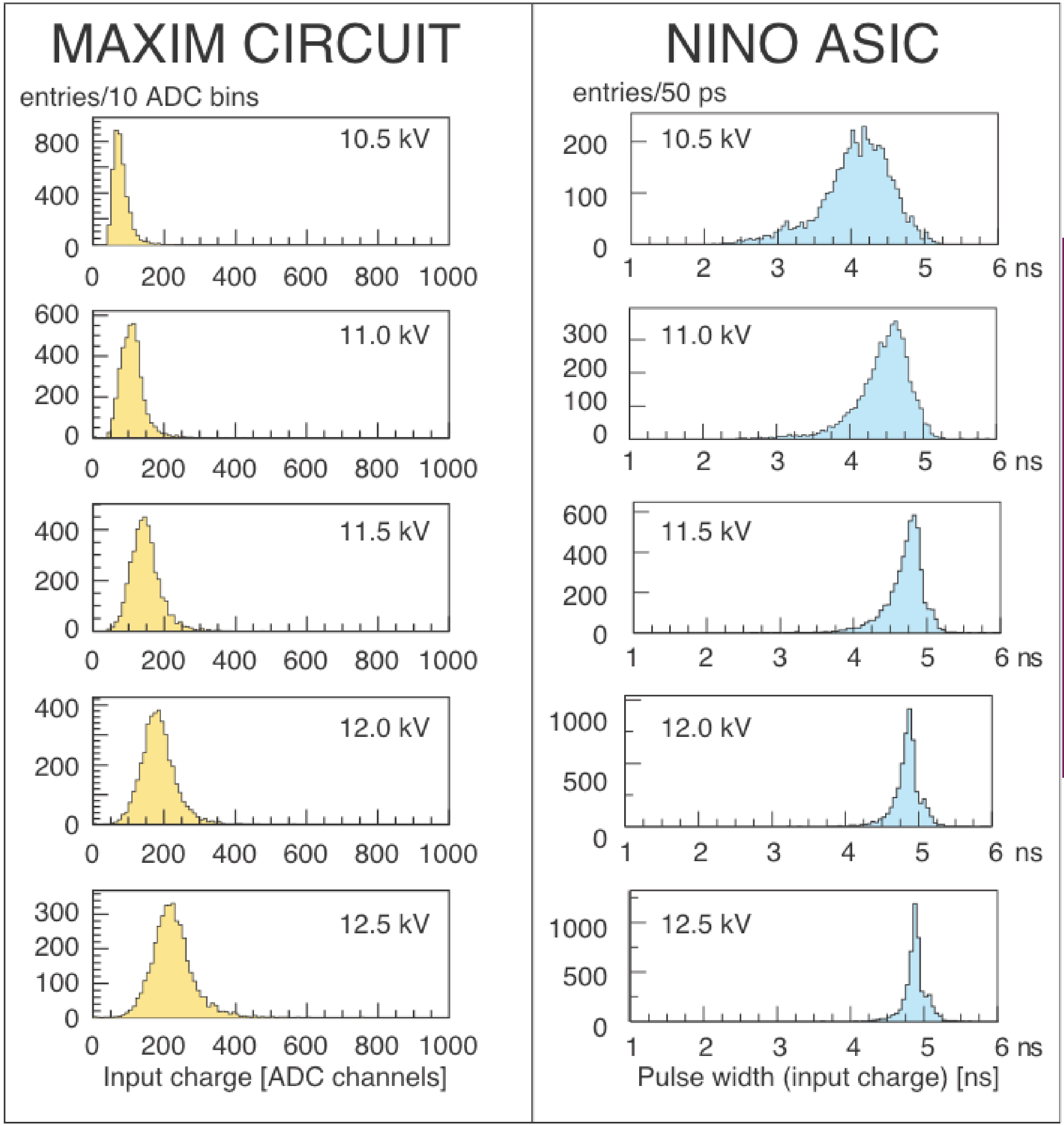
•A. Zichichi	
•H. Wenninger	
•P. Jarron	conceptual design
•F. Krummenacher	circuit design
•F. Anghinolfi	layout on silicon
•E. Ousenko	testing of ASIC

The NINO ASIC bonded to the PCB

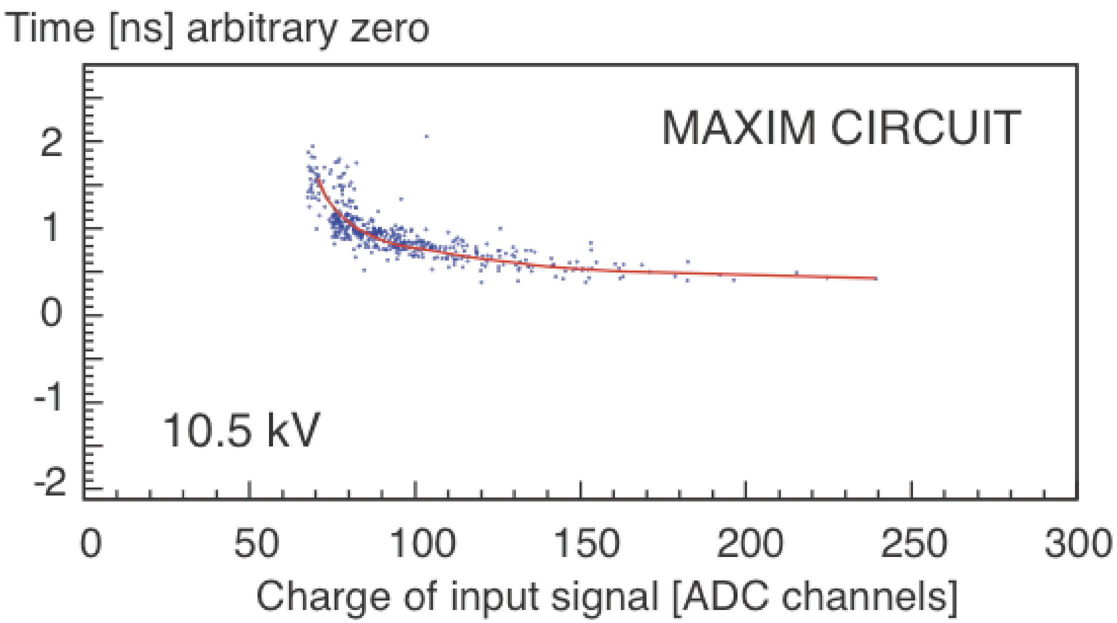


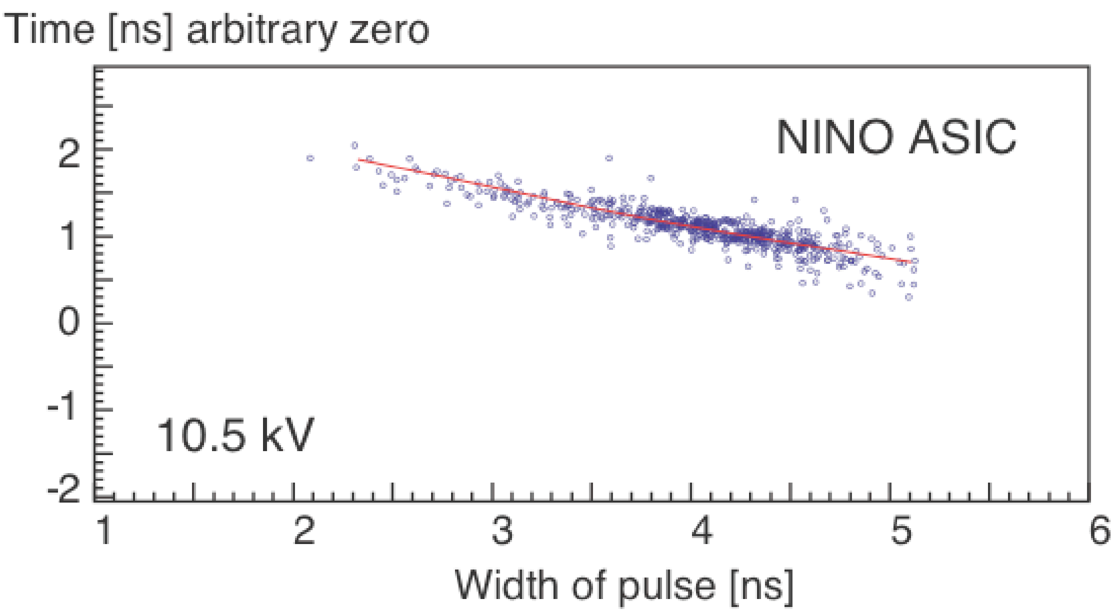
Width of output pulse related to input charge - non linear





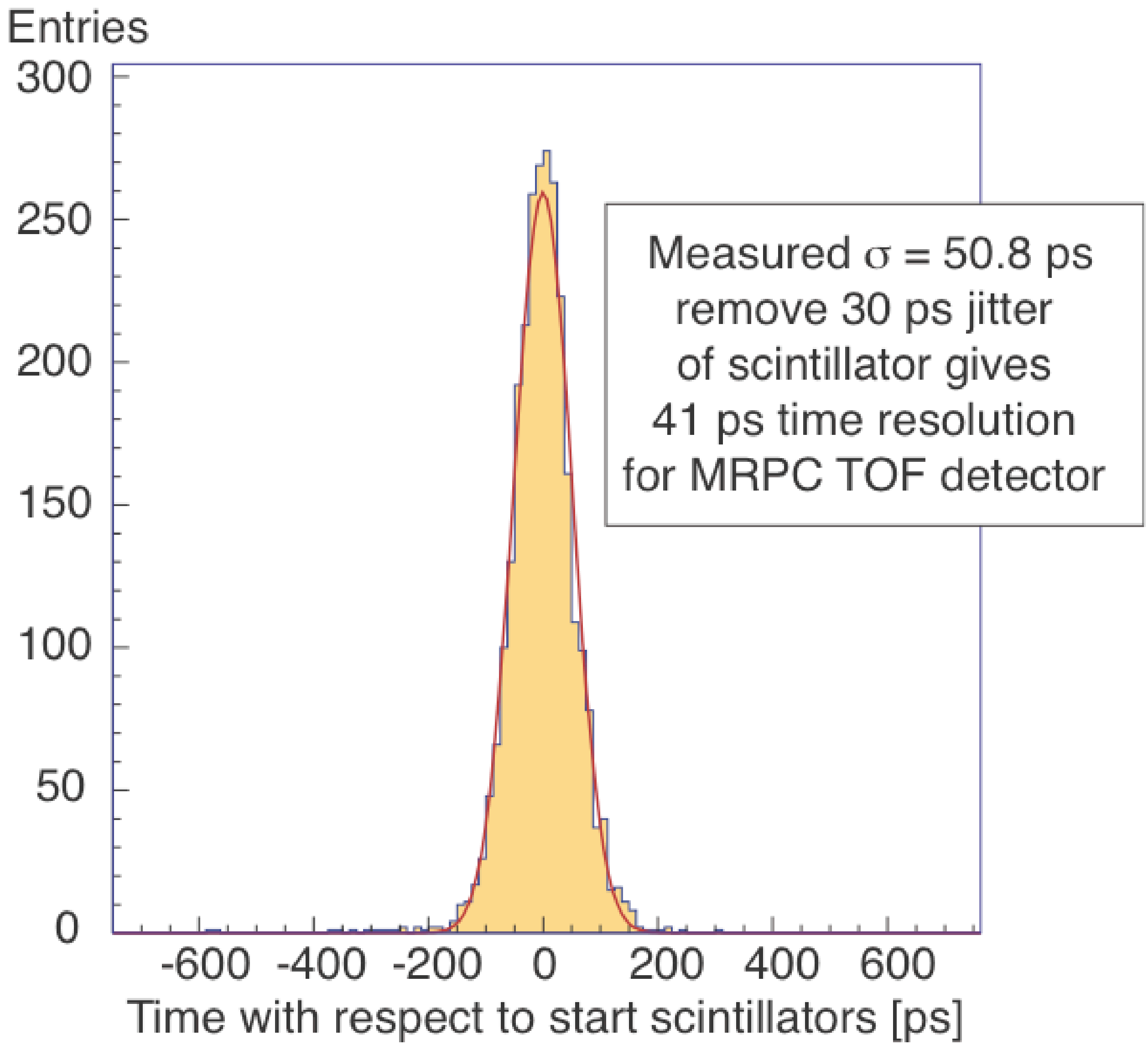
NINO ASIC expands the dynamic range for small input charge



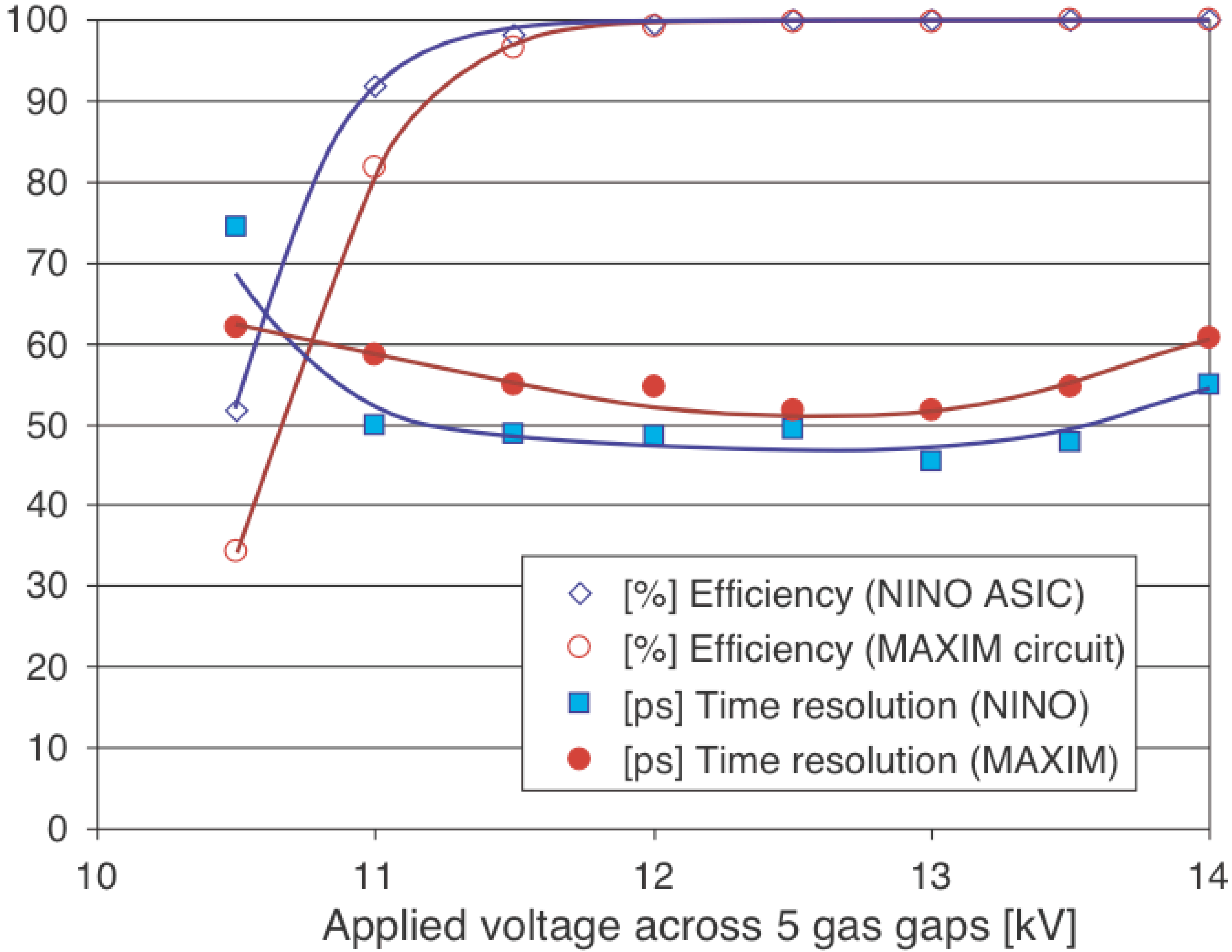


Correction very steep at small pulse heights

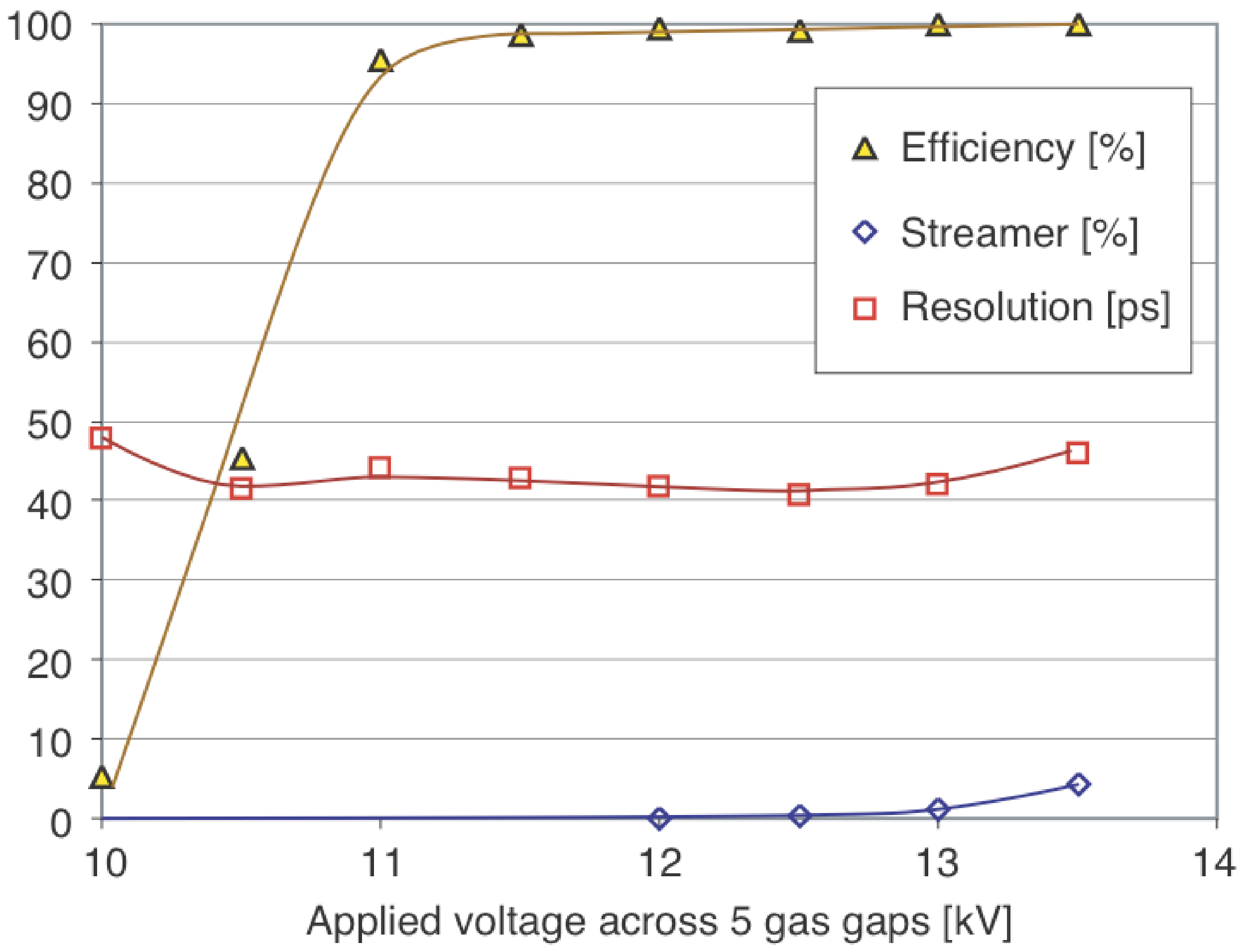
Typical corrected time spectrum measured on-line in test beam



Both circuits set to 60 fC threshold - NINO has better efficiency for small signals (maybe due to differential input); also NINO has improved time resolution.



Use HPTDC readout - this is a new ASIC developed by the CERN MIC group - 25 ps bins - gives a time stamp to hit and then puts in buffer - technique without dead-time



Note on the 41 ps time resolution
This is a combination of many factors

1.	HPTDC 15 ps time resolution (but measurement shown is difference between two channels)	21.2 ps
2.	Beam spot 1 cm in size 50 ps/$\sqrt{12}$	14.4 ps
3.	NINO ASIC + cables, etc	20 ps
4.	MRPC time resolution	25 ps

TOTAL $(21.2^2 + 14.4^2 + 20^2 + 25^2)^{1/2} = 41$ ps

Measured time resolution understood - it will be very difficult to reduce this by much

Things that I have not discussed

- Edge effects - readout pads of 2.5 x 3.5 cm^2
  34% of detector area within 2.5 mm of boundary
  - Double hit probability
  - Degradation of time resolution
- Ageing (no problem for ALICE)
- Gas studies

Summary 1

Requirements for the TOF array for the ALICE experiment are completely satisfied with the Multigap RPC

a) efficiency ~ 99.9 %

b) time resolution < 50 ps (actual time resolution in ALICE experiment will be larger than this (e.g. jitter in T0)

c) easy to segment (sharp boundaries between cells)

d) excellent rate capability

e) excellent non-ageing properties

Summary 2

The NINO ASIC
has been designed for our application
so it is no surprise that it is an ideal
front-end

The STAR detector

- Small prototype test of TOF array built using 6 gap MRPC with 220 micron gaps - only 56 elements readout
- Radial distance 220 cm
- Pad size 31.5 x 63 mm^2
- Time resolution of TOF system is 85 ps but start system had worse timing (85 ps and 140 ps)
- π/K 2σ separation up to 1.6 GeV/c
- K/p 2σ separation up to 3 GeV/c

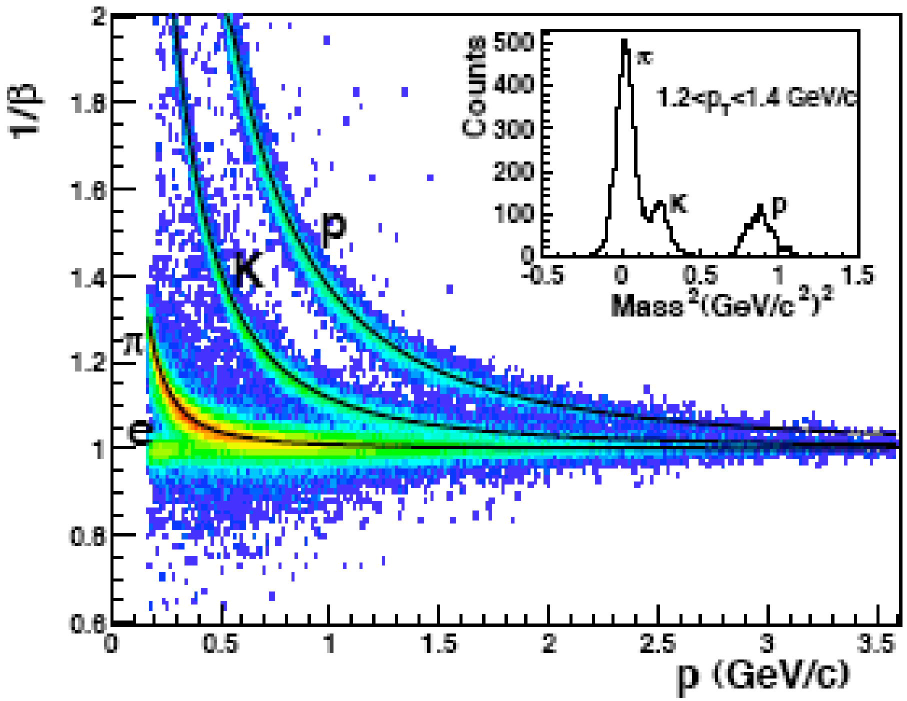


FIG. 1: 1/β vs. momentum for $\pi^{\pm}$, $K^{\pm}$, and p($\bar{p}$) from 200 GeV d+Au collisions. Separations between pions and kaons, kaons and protons are achieved up to $p_T \simeq 1.6$ and 3.0 GeV/c, respectively. The insert shows $m^2 = p^2(1/\beta^2 - 1)$ for $1.2 < p_T < 1.4$ GeV/c. Clear separation of π, K and p is seen.

STAR already producing physics with this prototype

arXiv:nucl-ex/0309012 v1 15 Sep 2003

Pion, kaon, proton and anti-proton transverse momentum distributions from p+p and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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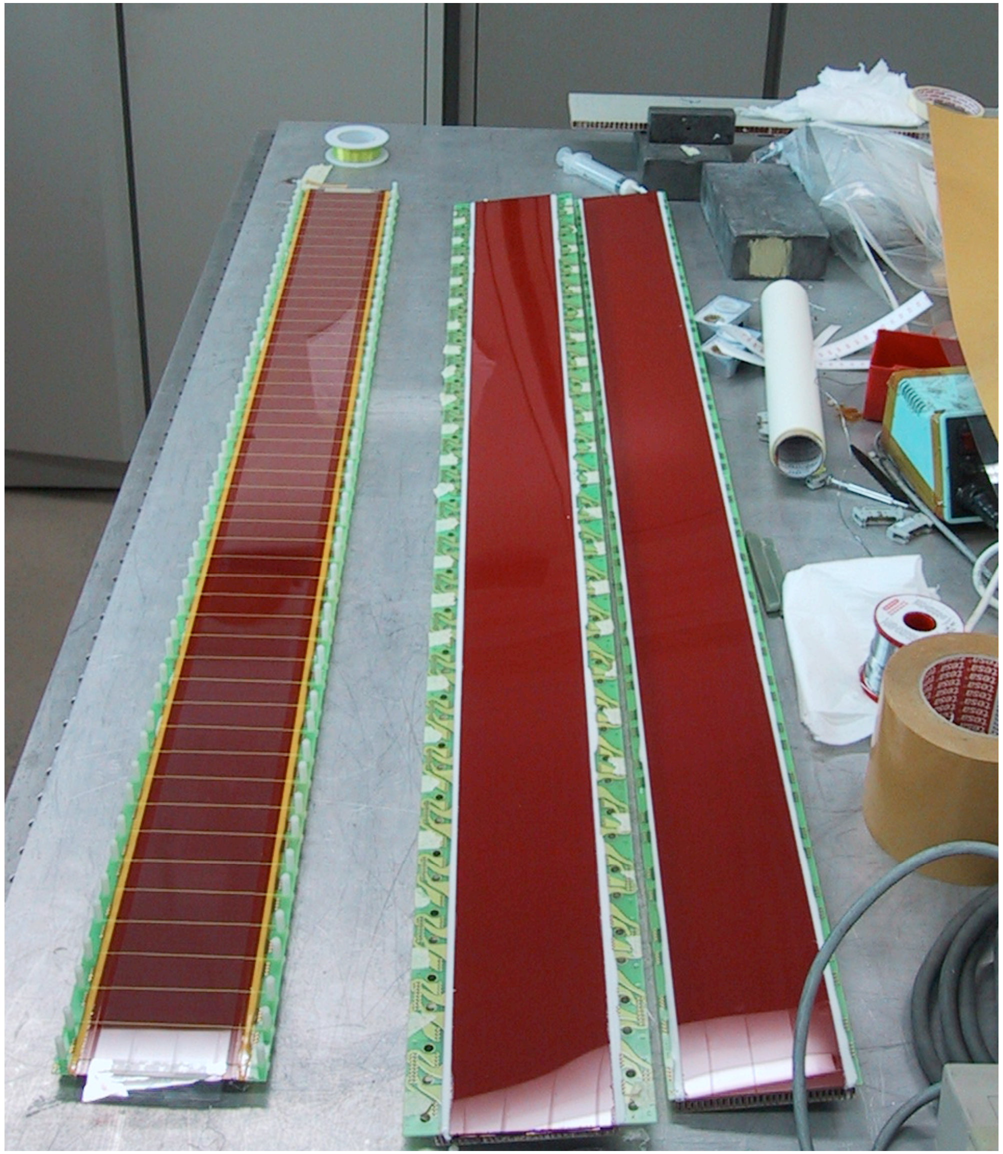


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