A high resolution Timing Counter for the MEG II experiment

M. De Gerone
on behalf of the MEG II Collaboration

Frontier Detectors for Frontier Physics
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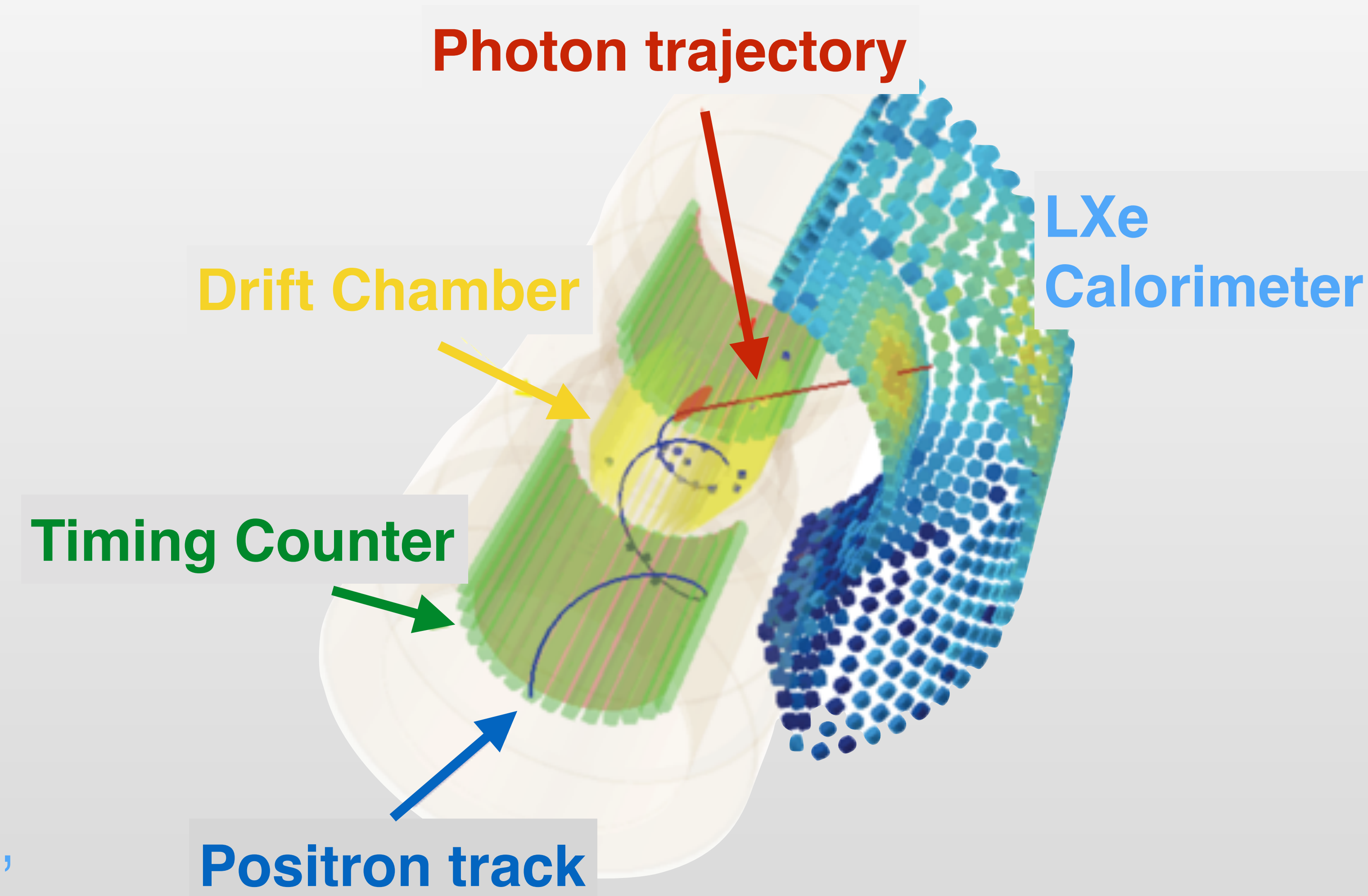
Summary

- The MEG and MEG II experiments in a nutshell
- The new Timing Counter R&D
  - Basic principles: pixelated structure and multiple hits timing
  - Pixel studies and optimization
  - Detector design
- Beam test results

The MEG experiment in a nutshell

- Looks for cLFV $\mu^+ \rightarrow e^+ + \gamma$ decay
- Tiny signal in huge background ($BR(\mu \rightarrow e\gamma) < 5.7 \times 10^{-13}$)
- Needs extremely high reso on signal kinematic variables:
  - Energies & Direction (**LXe**, **Drift Chambers**)
  - Time (**Timing Counter**, **LXe**)



- $E_\gamma = E_{e^+} = 52.8$ MeV
- $\Delta t_{e\gamma} = 0$
- $\Delta\Omega_{e\gamma} = 180°$

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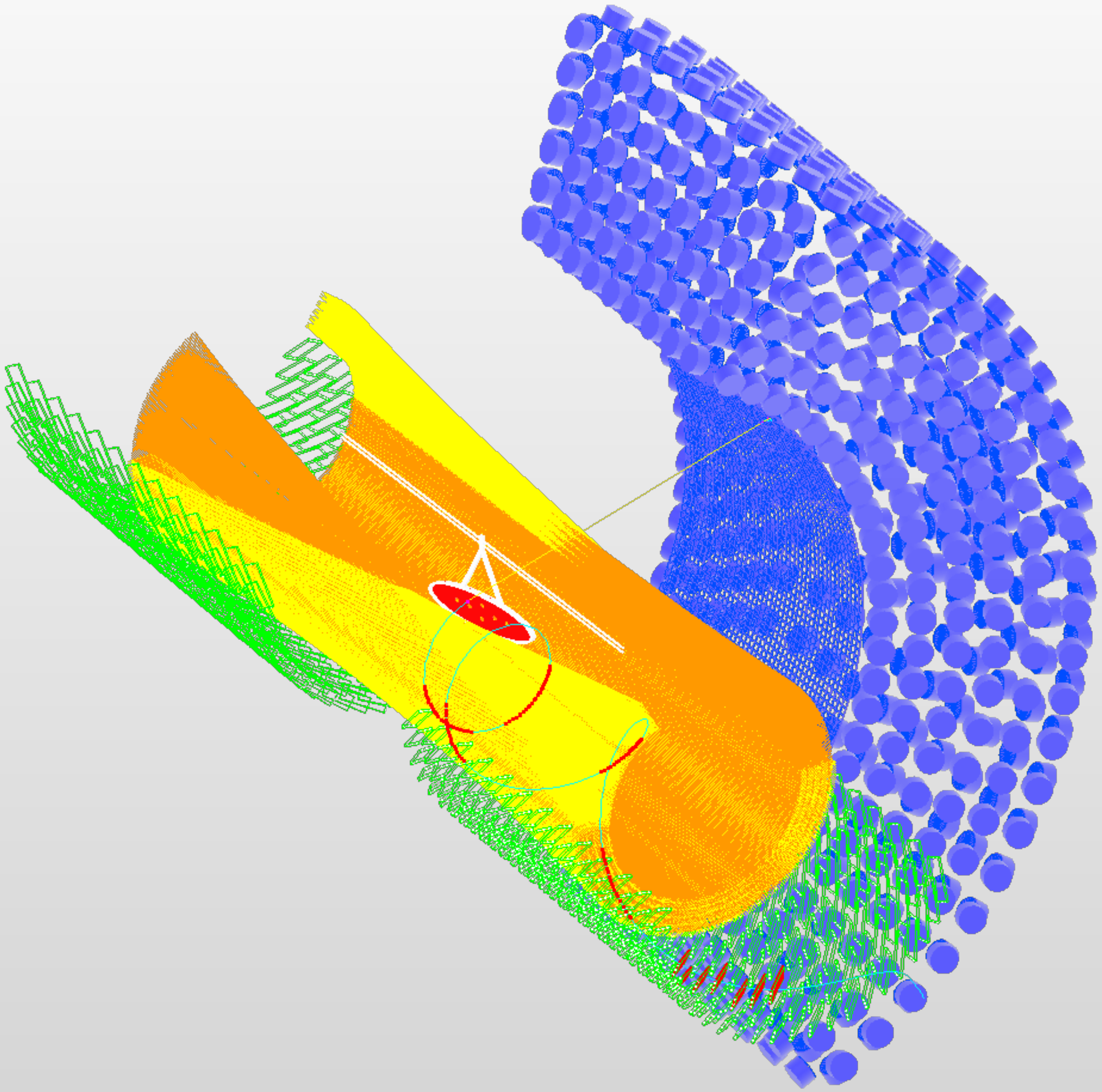
The MEG upgrade: MEG II

- Usage of existing infrastructure:
  - cryostat, magnet, beam line, CW accelerator for calibrations
- Full redesign of Drift Chamber system
- Modification in LXe inner face readout devices (PMT ⇒ SiPM)
- **New Timing Counter design**
- A new TDAQ system
- First engineering run this year!



A lot of contribution this week!
(IDs: 1, 10, 136, 142, 143, 144, 172, 174, 178, 208, 343, 383, 393, 403)

The Pixelated Timing Counter: basic ideas

- Arrays of **15 scintillating bars** readout by **PMTs**
- Time reso: **~65/70ps**, possible improvements:
  - **PMTs not optimal** (B field and He environment)
  - **Large scintillators** (40x40x800 mm^3) imply **low granularity**, uncertainty in z impact point, large multiple scattering and spread of optical photons paths

The Pixelated Timing Counter: basic ideas

Goals:

- **reach the same time resolution with smaller modules**
- **use more than 1 hit for timing evaluation (reso scales as 1/√N$_{hit}$)**

$$\sigma^2 = \frac{\sigma^2_{\text{single}}}{N_{\text{hit}}} + \frac{\sigma^2_{\text{inter pixel}}}{N_{\text{hit}}} + \sigma^2_{\text{MS}}\,(N_{\text{hit}})$$

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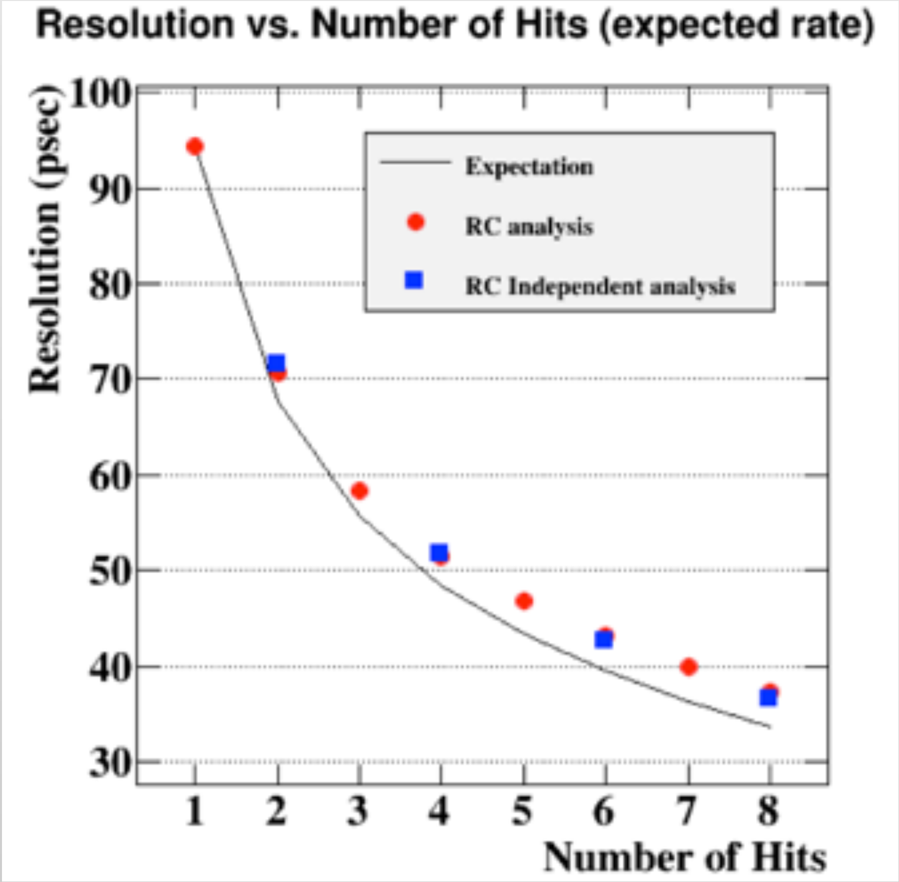
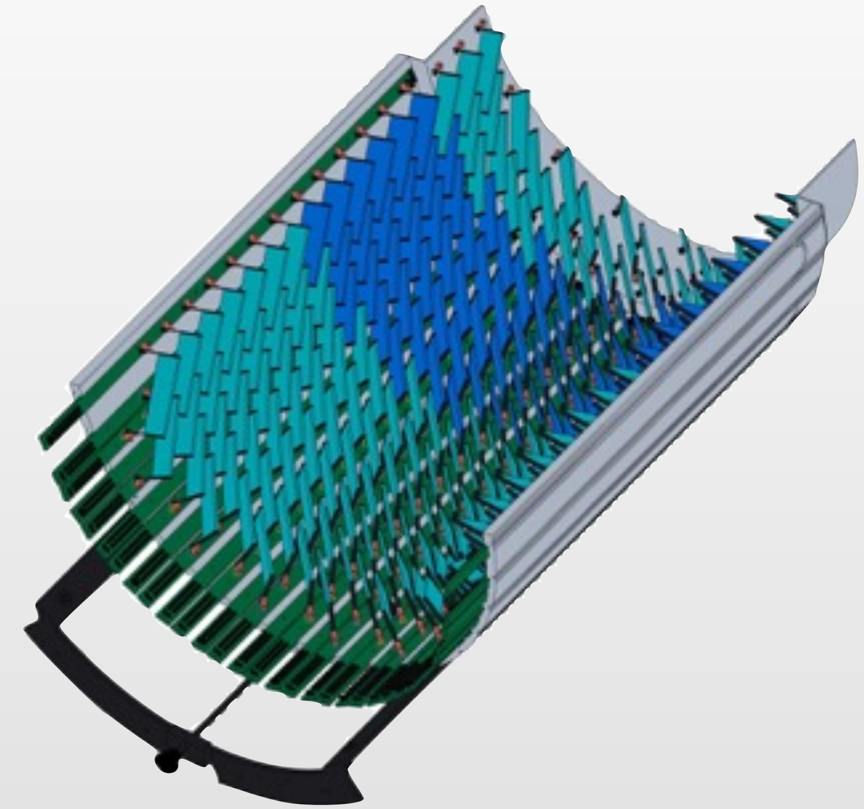


The Pixelated Timing Counter: basic ideas



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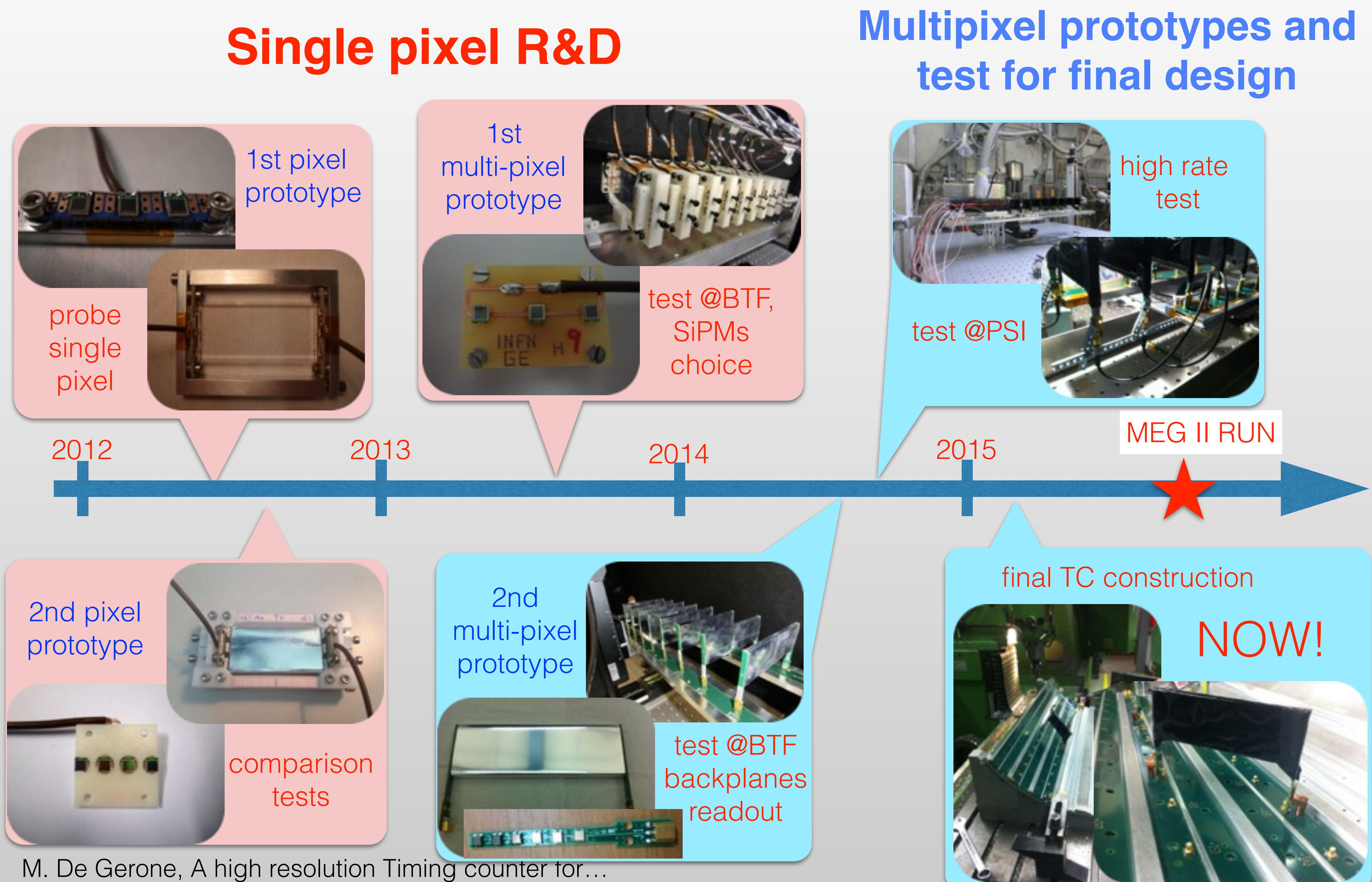
- **Higher granularity**: hundreds (2 x 256) of **small scintillator plates** (120x50x5 mm^3) read-out by **SiPMs**.
- **Good single pixel resolution improved with multiple hits**
- **Thinner** (5mm) **scintillators** for less multiple scattering
- Less pile-up also with higher beam intensity

A 3 years long R&D…



Single pixel R&D

A lot of items to be tested and compared…here, (some of) the main ones:

- **SiPMs comparison** (noise, PDE, temperature dependence, resolution);
- **SiPMs connection**: series vs parallel;
- **scintillator and counter geometry** (pixel sizes, number of SiPMs);
- implementation in final detector.

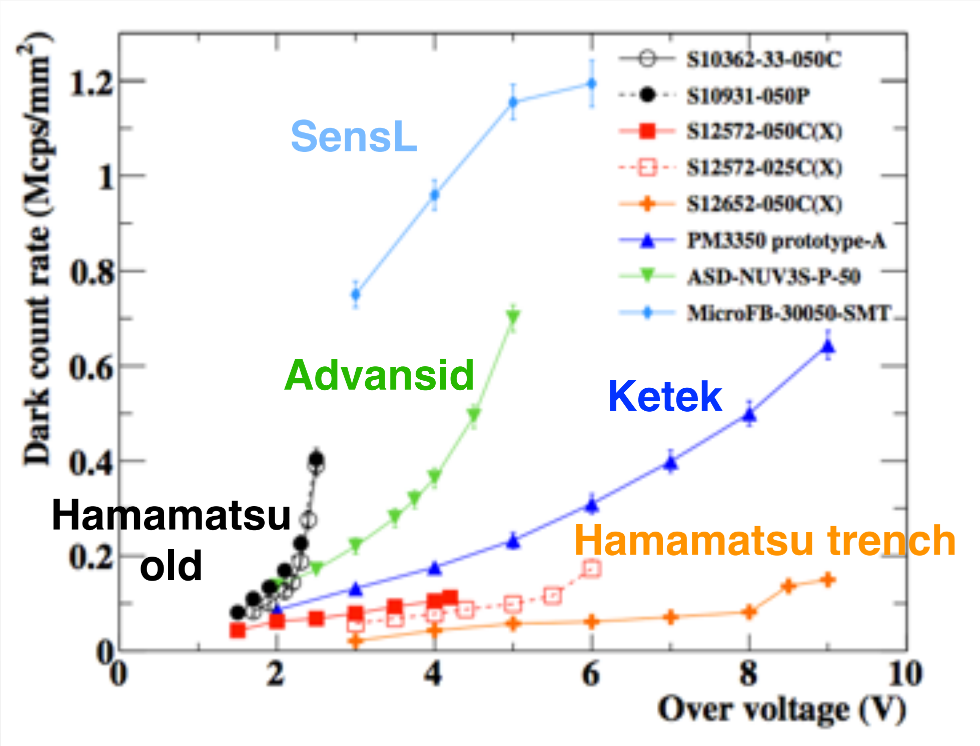
Manufacturer	Model number	Type[a)]	
HPK	S10362-33-050C	Conventional (Old) MPPC	Ceramic package
	S10931-050P		Surface mount type (SMT) package
	S12572-050C(X)[b)]	New (standard-type) MPPC	Metal quench resistor
	S12572-025C(X)[b)]		25 μm pixel
	S12652-050C(X)[b)]	Trench-type MPPC	Metal quench resistor
	3X3MM50UMLCT-B[b)]		Improved fill factor
AdvanSiD	ASD-NUV3S-P-50[b)]	NUV type	SMT package
KETEK	PM3350 prototype-A[b)]	Trench type	–
SensL	MicroFB-30050-SMT	B-series	With fast output. SMT package

[a)] Sensor size of all the samples is 3×3 mm^3. Pixel pitch is 50 μm unless specified.
[b)] Not version of commercial product. Under development.

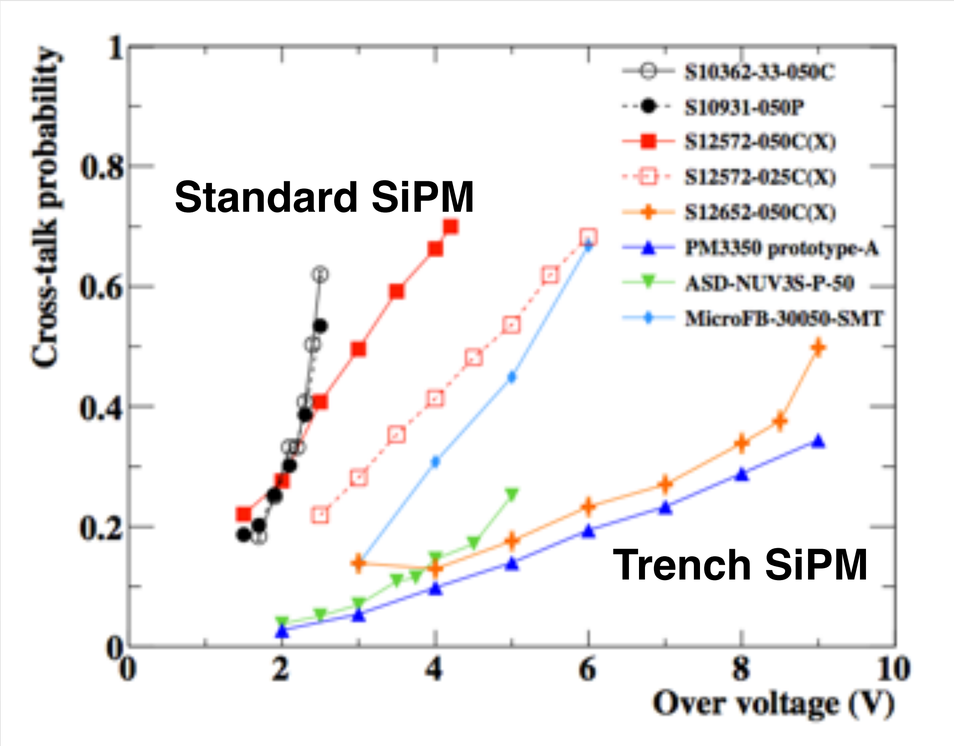
All tests led as a function of OV in thermal chamber with controlled temperature (std: 23°C)

Single pixel R&D: SiPM comparison

Dark count rate: evaluated with random trigger in a fixed time window. **New Hamamatsu** and **trench type** models show best result



Crosstalk probability: strongly suppressed by **trench type** model & **Advansid** devices.



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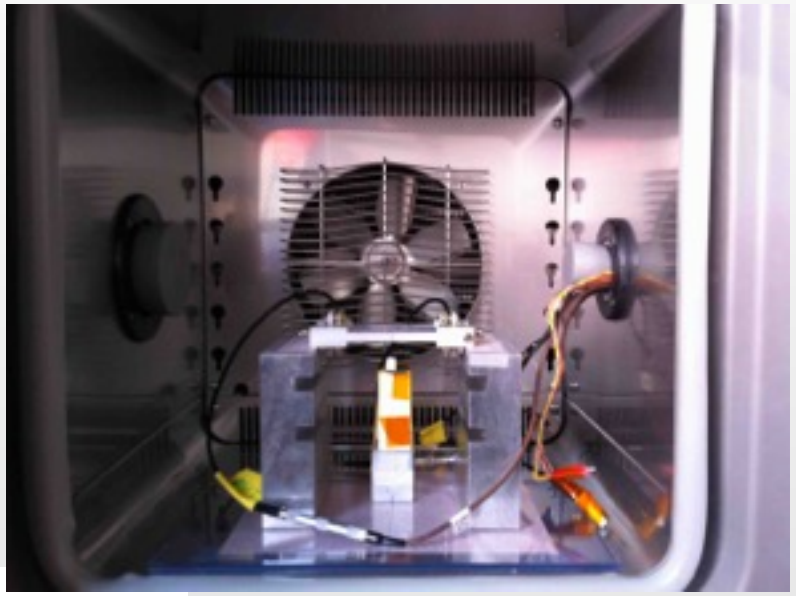
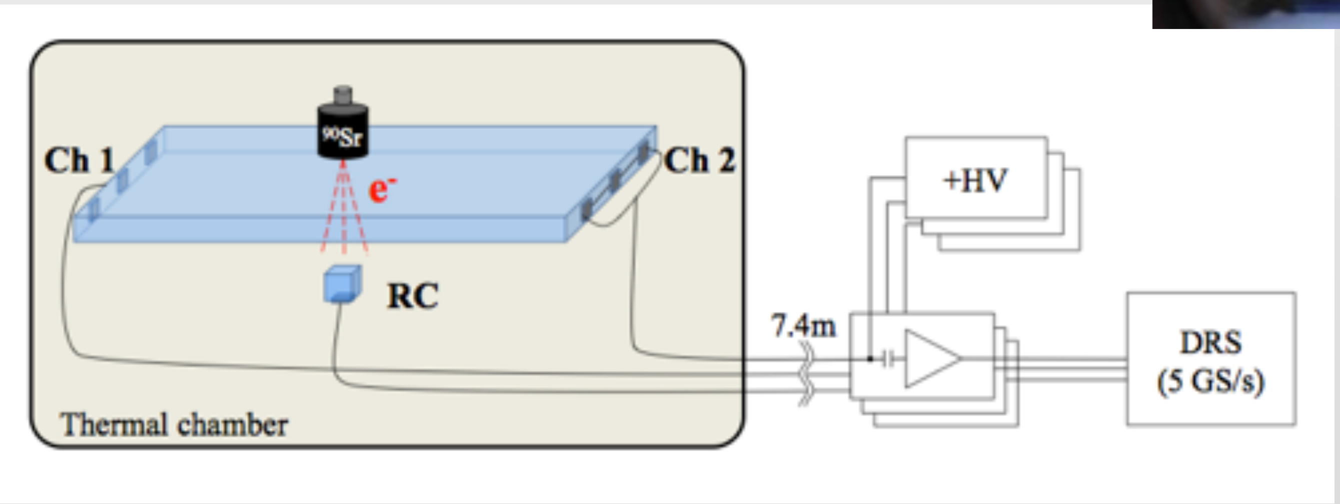
Single pixel R&D: SiPM comparison

Standard setup for timing measurement:

- 60 x 30 x 5 mm^3 scintillator equipped with 4 SiPMs arrays (series).
- Reference counter (RC) for trigger and T_{ref}.
- ^{90}Sr source (E<2.28 MeV).
- Read out: amplifier (G~20, BW~600MHz) + DRS evaluation board v4, dynamic range (-0.1, 0.9)V.



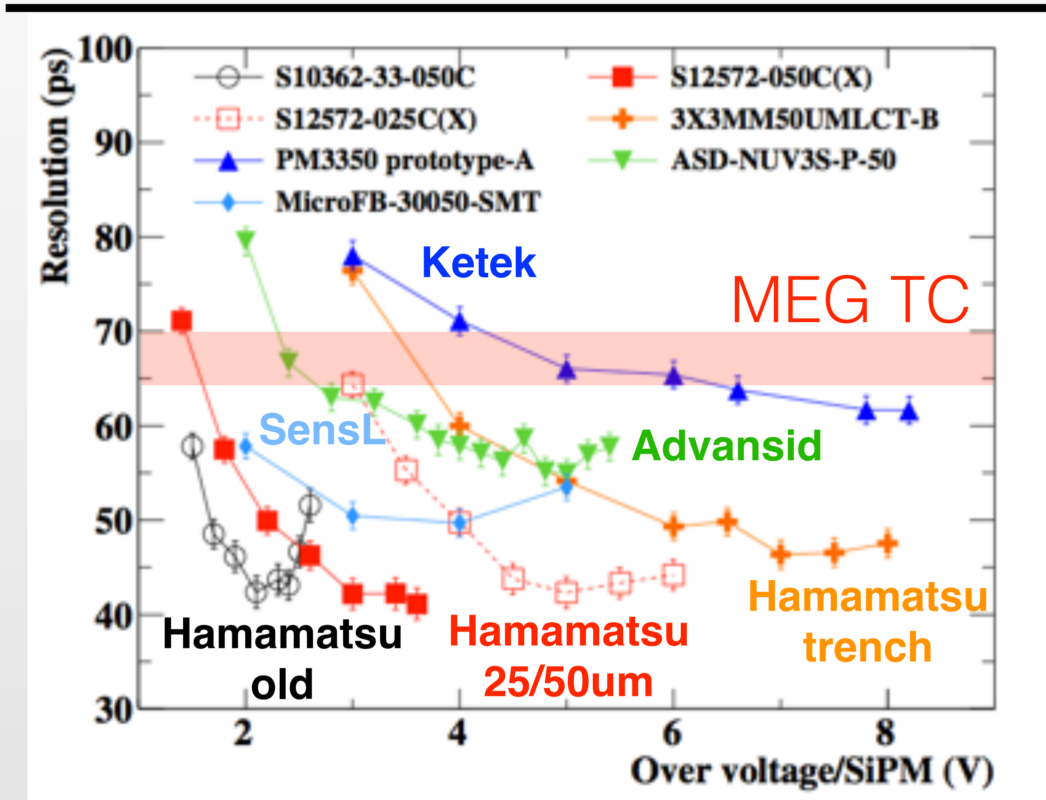


Time resolution is evaluated as the width of: $\Delta t = t_{ref} - \frac{t_1 + t_2}{2}$

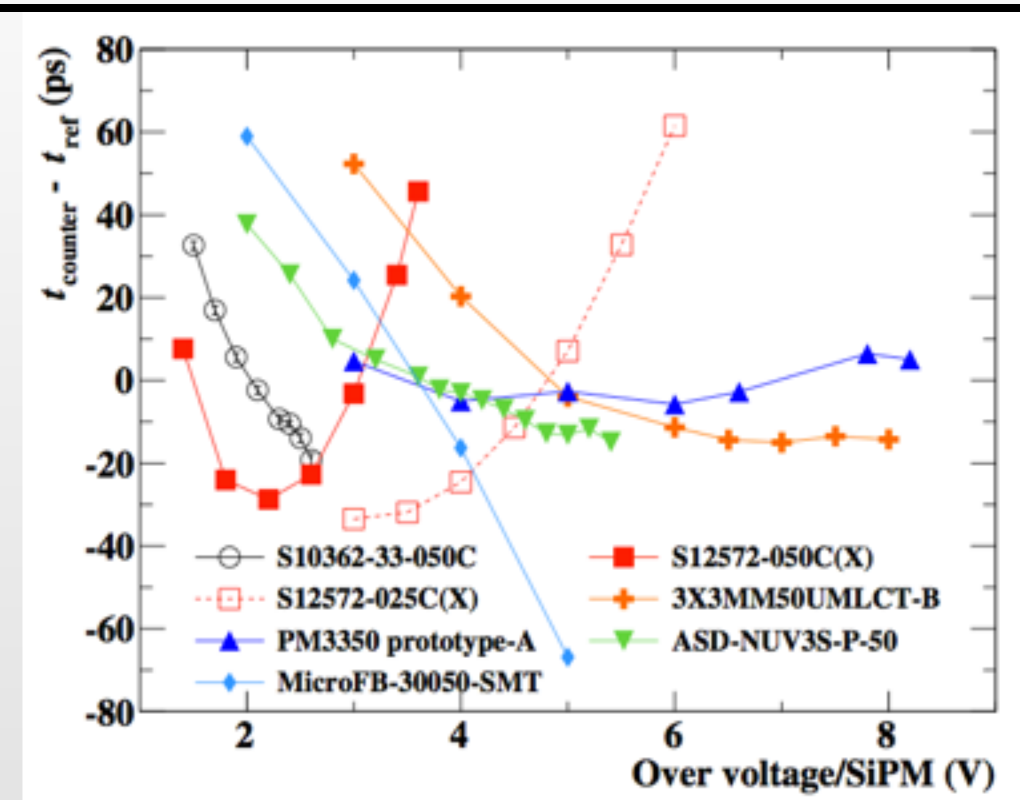
RC reso (28ps) is calculated in dedicated runs and subtracted from overall resolution.

We checked also the **stability of Δt** as a function of overvoltage and **temperature**

Single pixel R&D: SiPM comparison



Best time reso with **Hamamatsu** device…but almost all devices work better than previous TC bar.



Advansid and **trench** devices are **more stable** as a function of over voltage and temperature.

HPK old	HPK new	HPK new 25um	HPK trench	Ketek	Advansid	SensL
2.5	5.5	2.8	0.1	0.1	0.2	0.8

Temperature coefficient: ps/°C

Temperature stability is a crucial parameter for our detector: $\Delta T \rightarrow \Delta V_{BD} \rightarrow \Delta V_{OV}$

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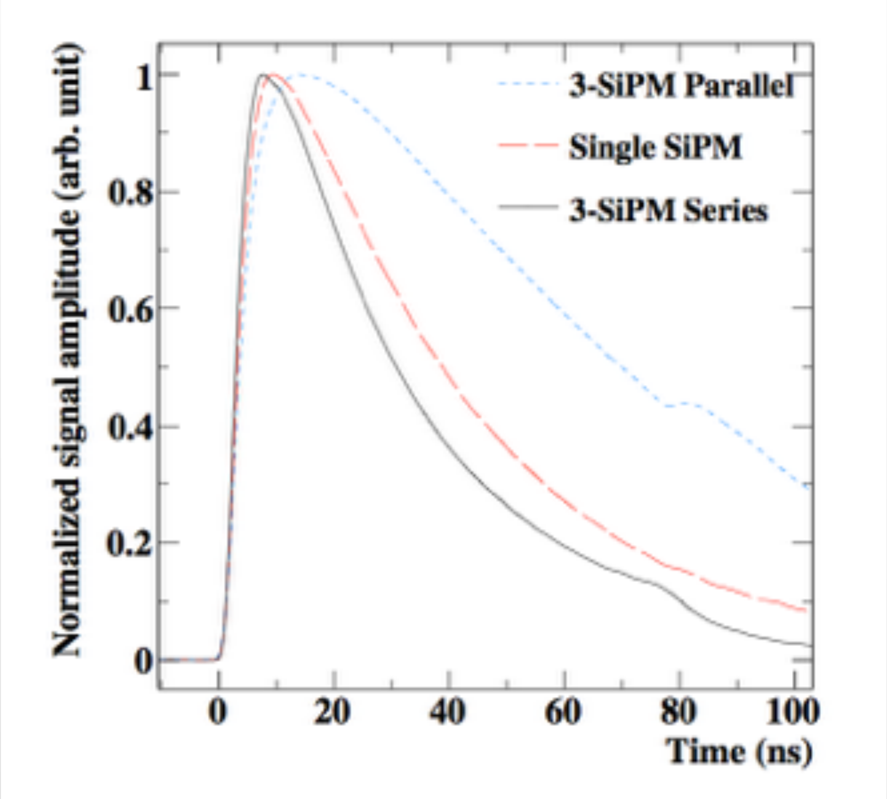
Series vs parallel

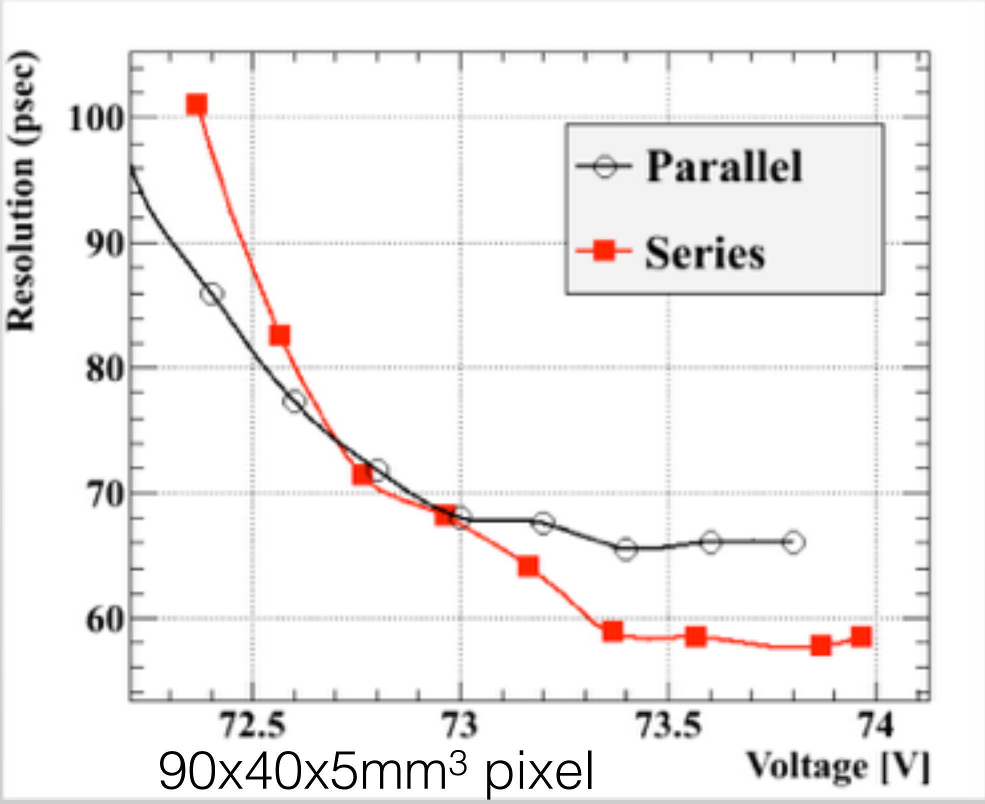
Series connection:

- OV adjustment between SiPMs with different V_{BD}
- reduced capacitance → narrower pulse
- **better time resolution**
- higher bias voltage

Parallel connection:

- lower bias voltage
- OV not adjusted
- increased capacitance → wider pulse
- **poor time resolution**





$90x40x5mm^3$ pixel

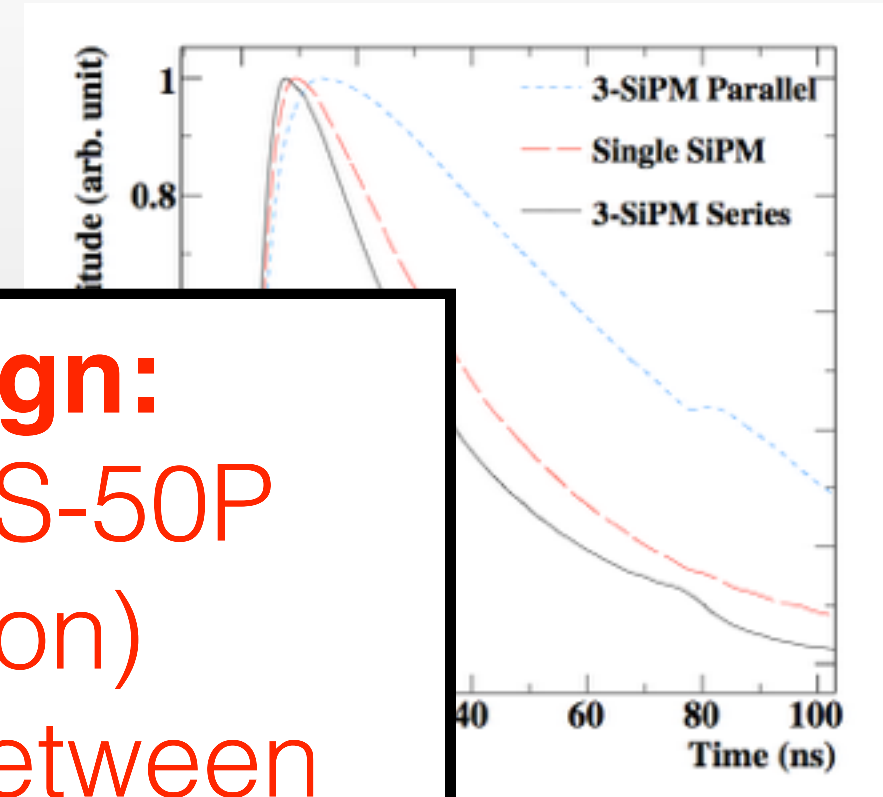
Series vs parallel

Series connection:

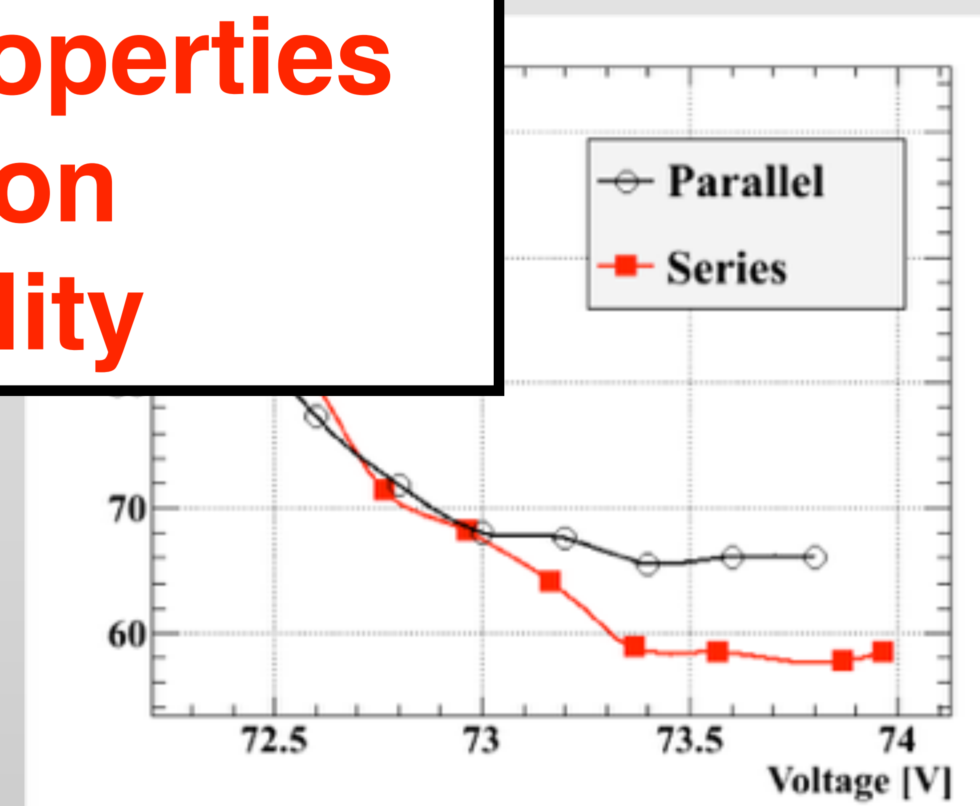
- OV adjustment between SiPMs with diffe
- reduced pulse
- **better ti**
- higher b

Parallel conn

- lower bia
- OV not a
- increased capacitance → wider pulse
- **poor time resolution**

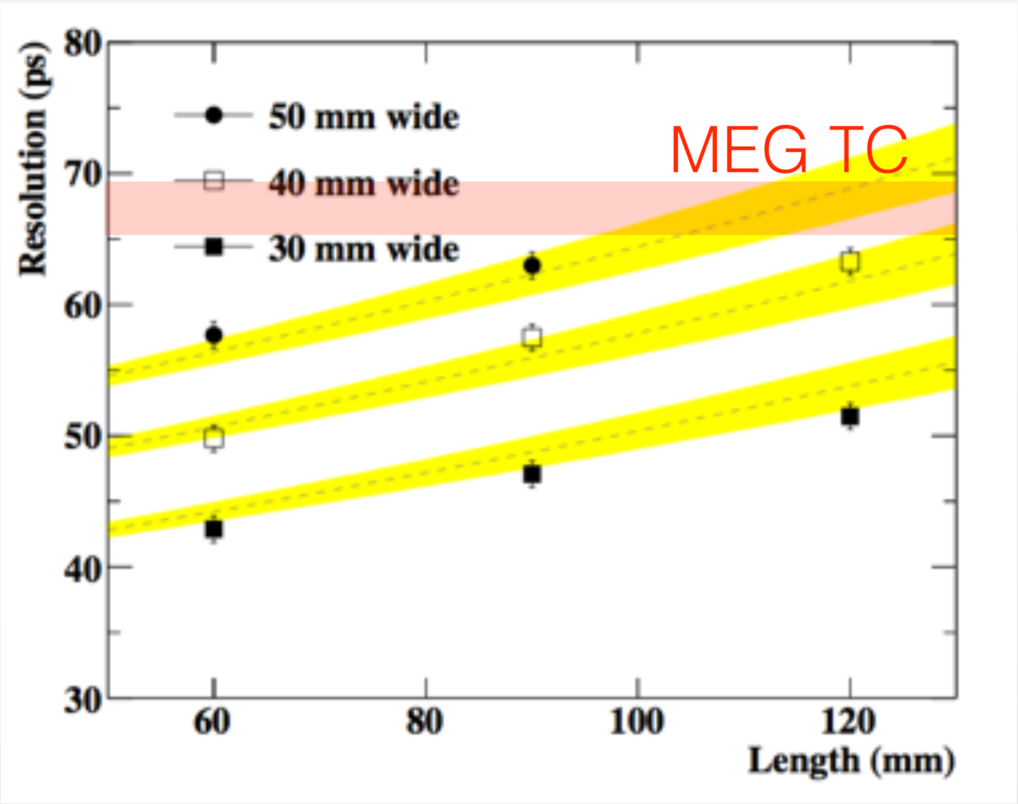


Final array design:
6 SiPM ASD-NUV3S-50P
(series connection)
best compromise between
intrinsic SiPMs properties
time resolution
thermal stability



Single pixel R&D: scintillator

Measurements with 4 SiPMs array in series connection (HAMAMATSU S10362-33-050C).



Properties	BC418	BC420	BC422	BC422Q
LY(%Anthracene)	67	64	55	19
Rise time (ns)	0.5	0.5	0.35	0.11
Decay time (ns)	1.4	1.5	1.6	0.7
Wavelenght (peak, nm)	391	391	370	370
Attenuation length (cm)	100	110	8	8
Resolution (ps)	48±2	51±2	43±2	66±3

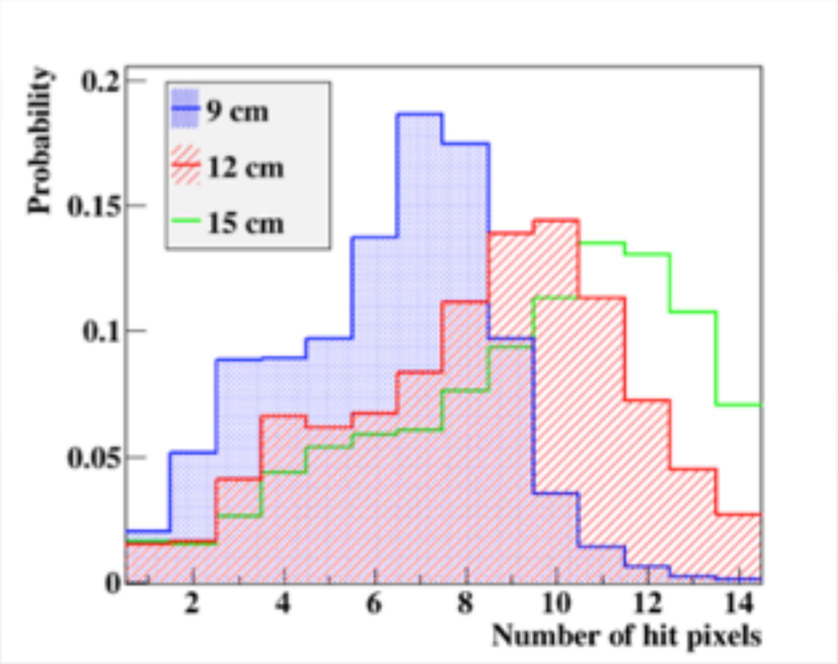
measured with 60 x 30 x 5 mm^3 pixels

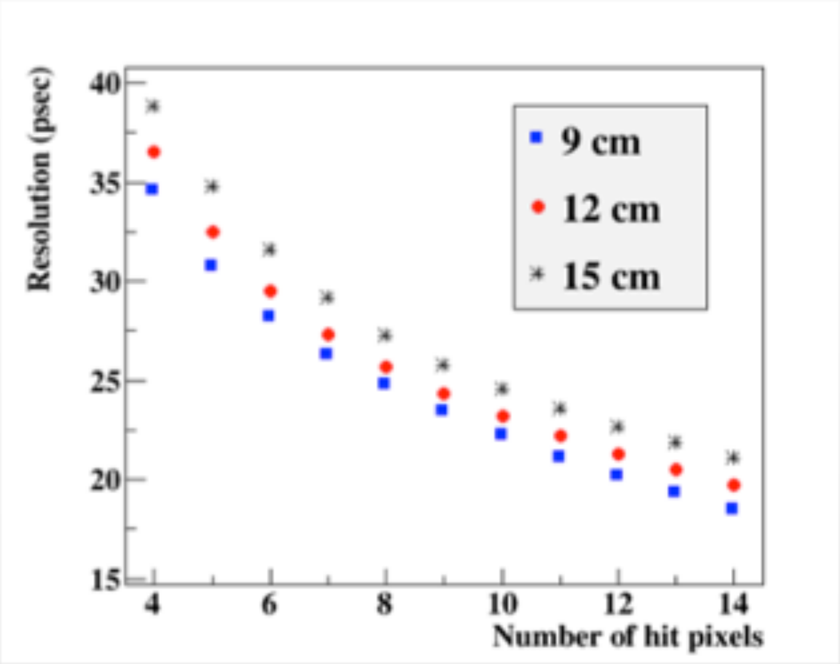
All the configurations showed a **resolution better than 70ps** (same as old TC reso).
The final choice is done taking into account many factors:

- intrinsic single pixel resolution
- expected number of hits
- efficiency
- number of channel
- costs

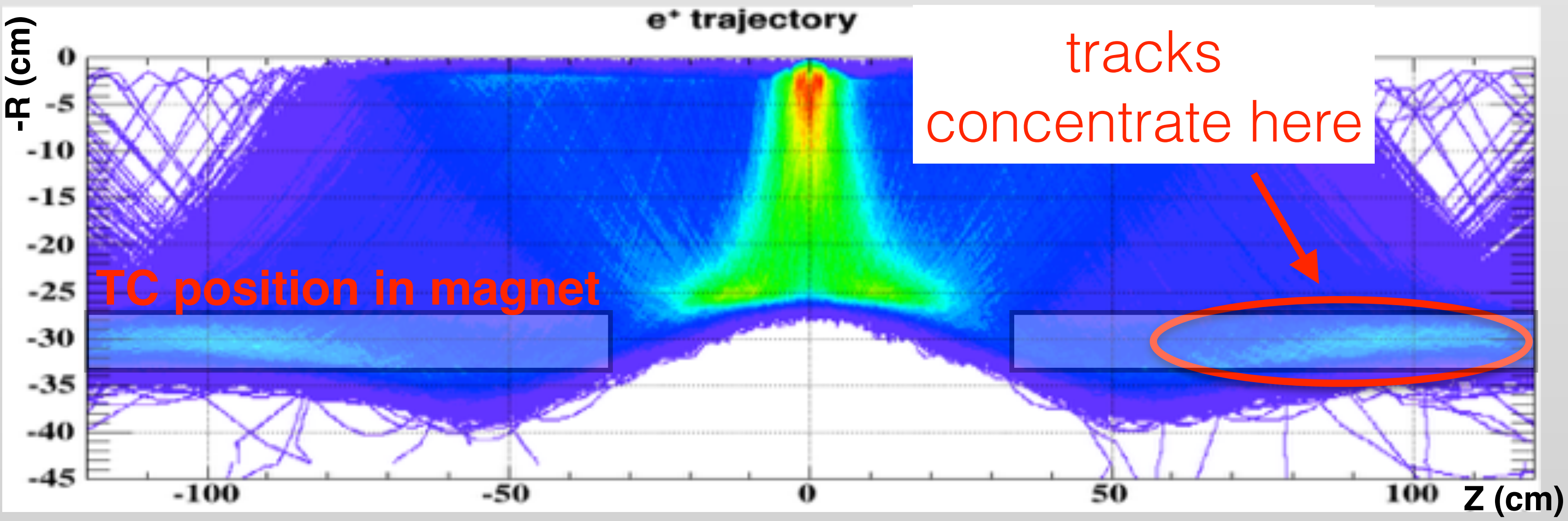
Numbers to be evaluated on Monte Carlo simulation…

(few) MonteCarlo results





120mm length pixel is the best compromise between hit multiplicity, time resolution and number of channels.

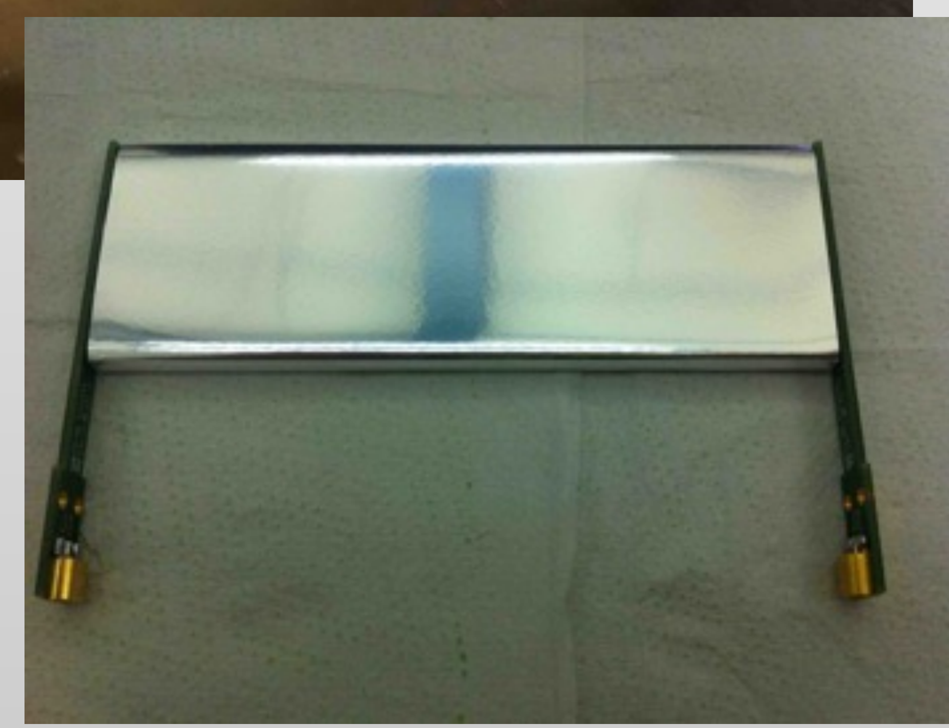


tracks envelope in a gradient magnetic field (MEG COBRA magnet)

different pixel height (40 or 50 mm) increases efficiency

Final pixel design

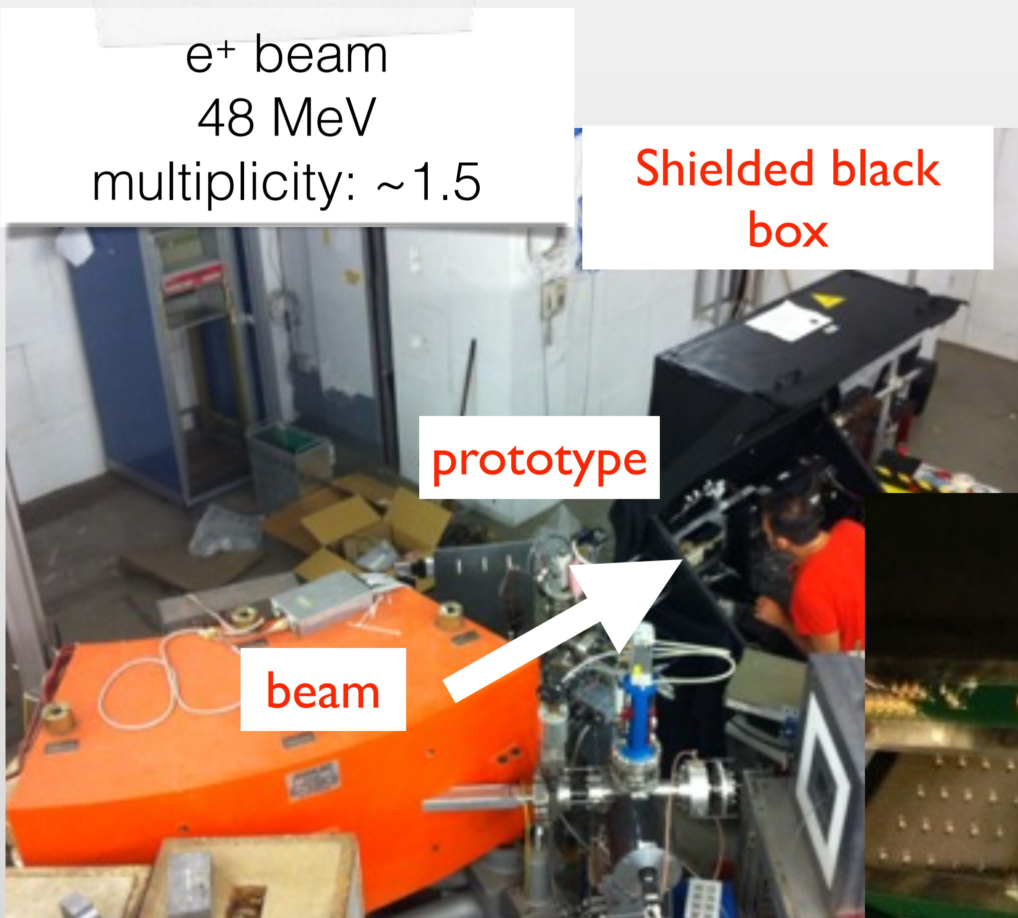
- Double side read-out with **6 SiPMs (ASD-NUV3S-P) array** mounted in series connection on a PCB:
    - increase sensor coverage;
    - small material budget along positron trajectories: **PCBs act also as frame**.
- **120 x 50 (40) x 5 mm^3 fast plastic scintillator (BC422)** coupled with optical cement, wrapped with reflector (3M mirror).
- Impact time and position reconstructed with sum / difference of single array time.
- **MCX connector for backplane plugging** (no cables on TC).



Proving multi hit @BTF

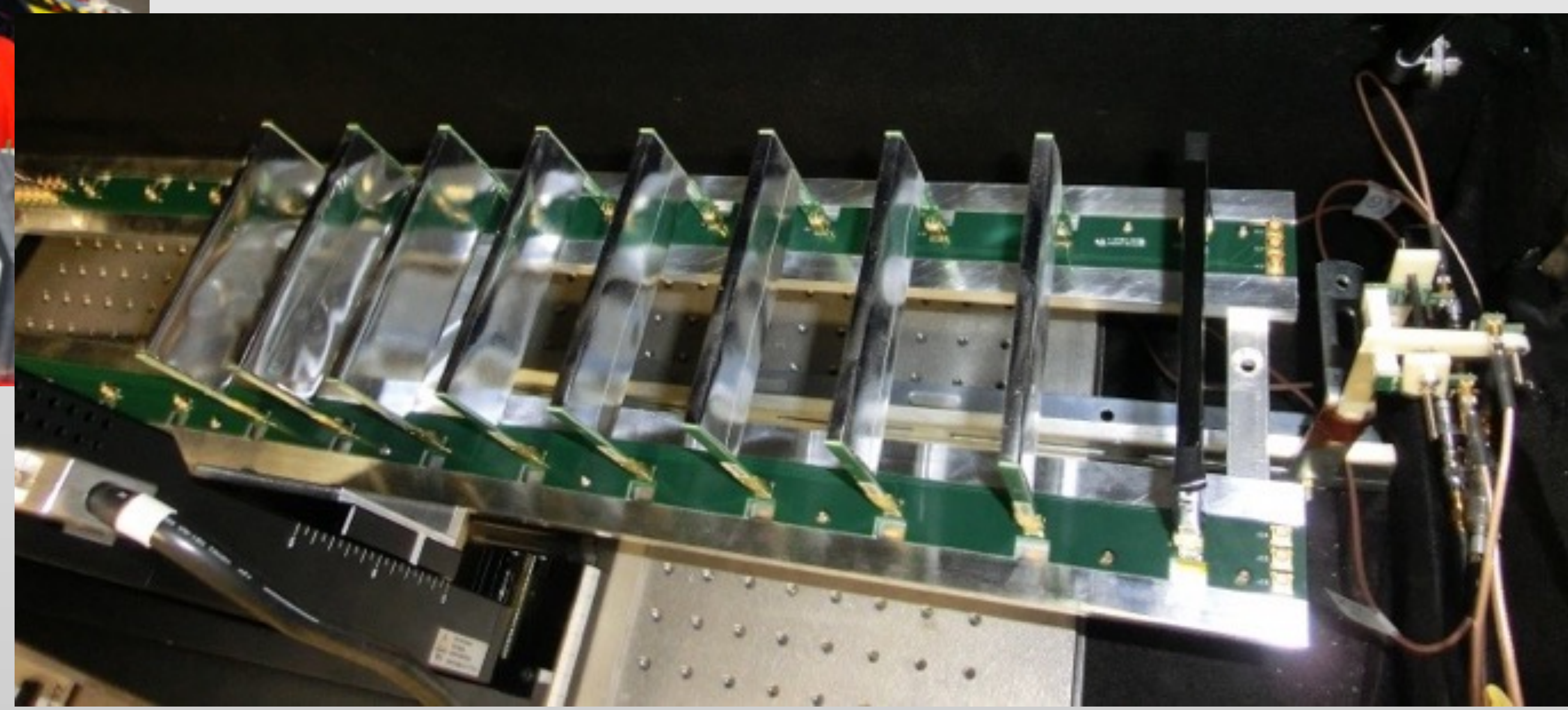
Resolution improves combining more hits: $\sigma^2 = \frac{\sigma^2_{\text{single}}}{N_{\text{hit}}} + \frac{\sigma^2_{\text{inter pixel}}}{N_{\text{hit}}} + \sigma^2_{\text{MS}}\left(N_{\text{hit}}\right)$

Tested under beam @BTF (Frascati, IT) in 2013 and 2014 with different setups.



2014 configuration

- **6 SiPMs series + PCB**
- **120 x 50 x 5mm^3 pixels**
- **backplanes**



Beam tests @BTF: results

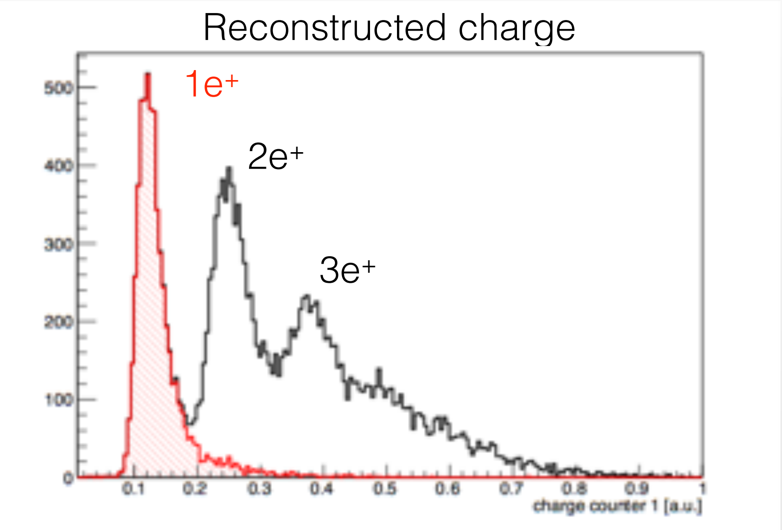
Time resolution evaluated as the width of

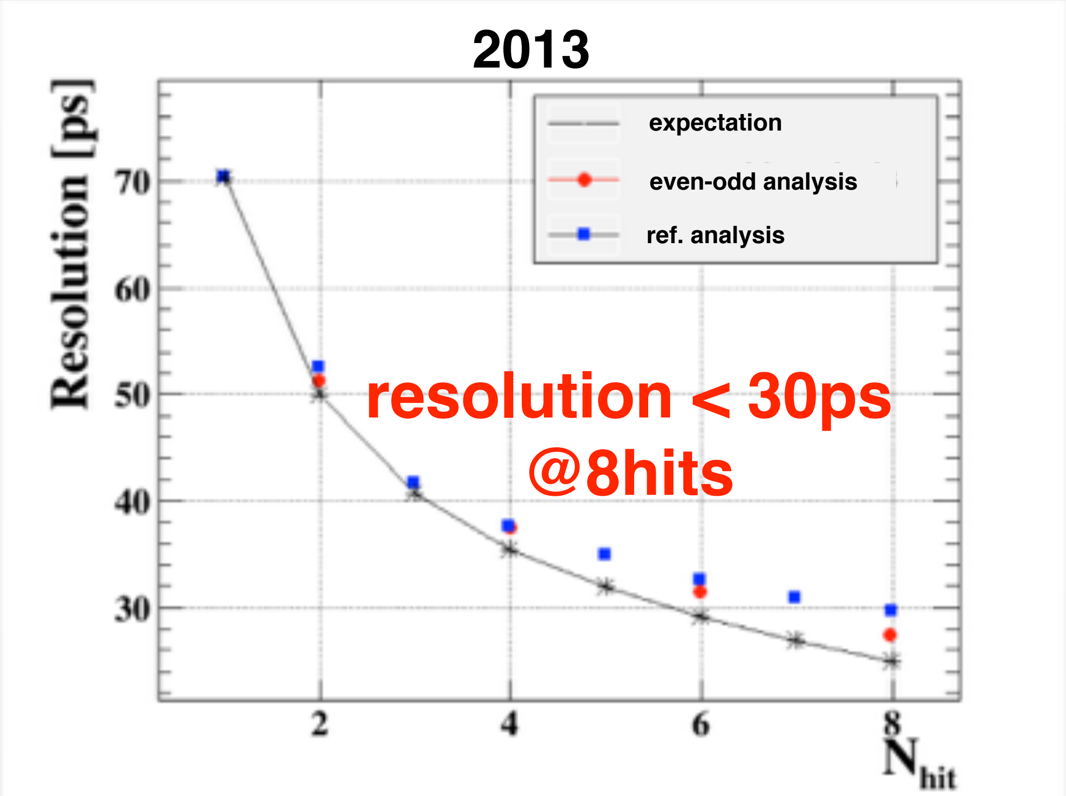
$$\Delta T(N) = T_{ref} - \frac{1}{N}\sum_{i=1}^{N} T_i$$

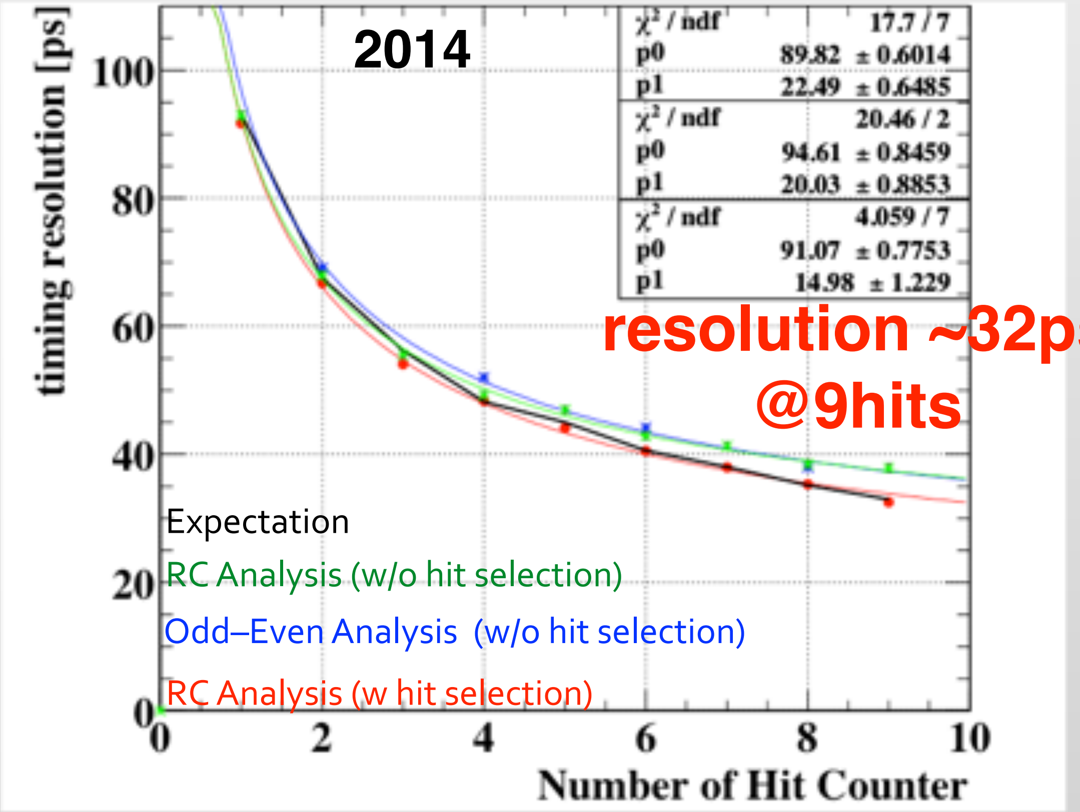
RC analysis

$$\Delta T(N) = \frac{1}{\sqrt{2}}\left[\frac{1}{N/2}\sum_{j=1}^{N/2} T_{a_j} - \frac{1}{N/2}\sum_{i=1}^{N/2} T_{b_i}\right]$$

Odd/even analysis





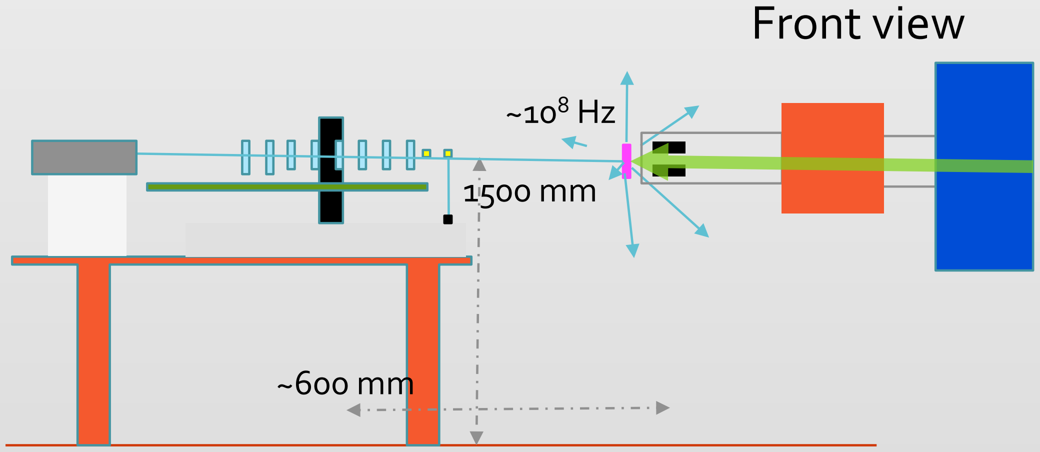


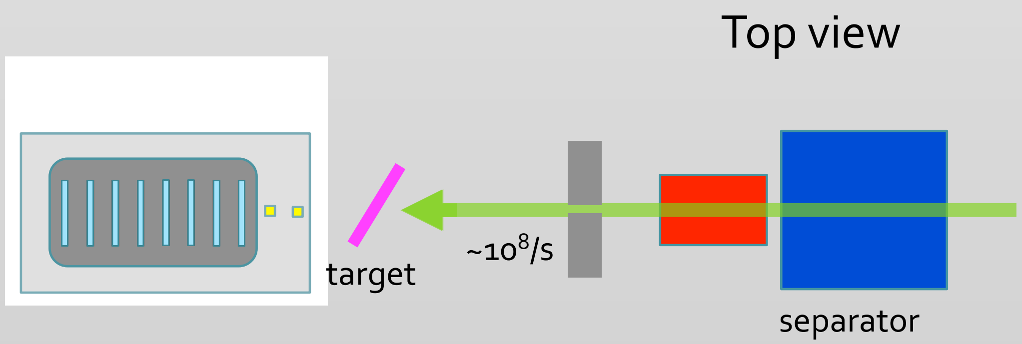
Differences due to:

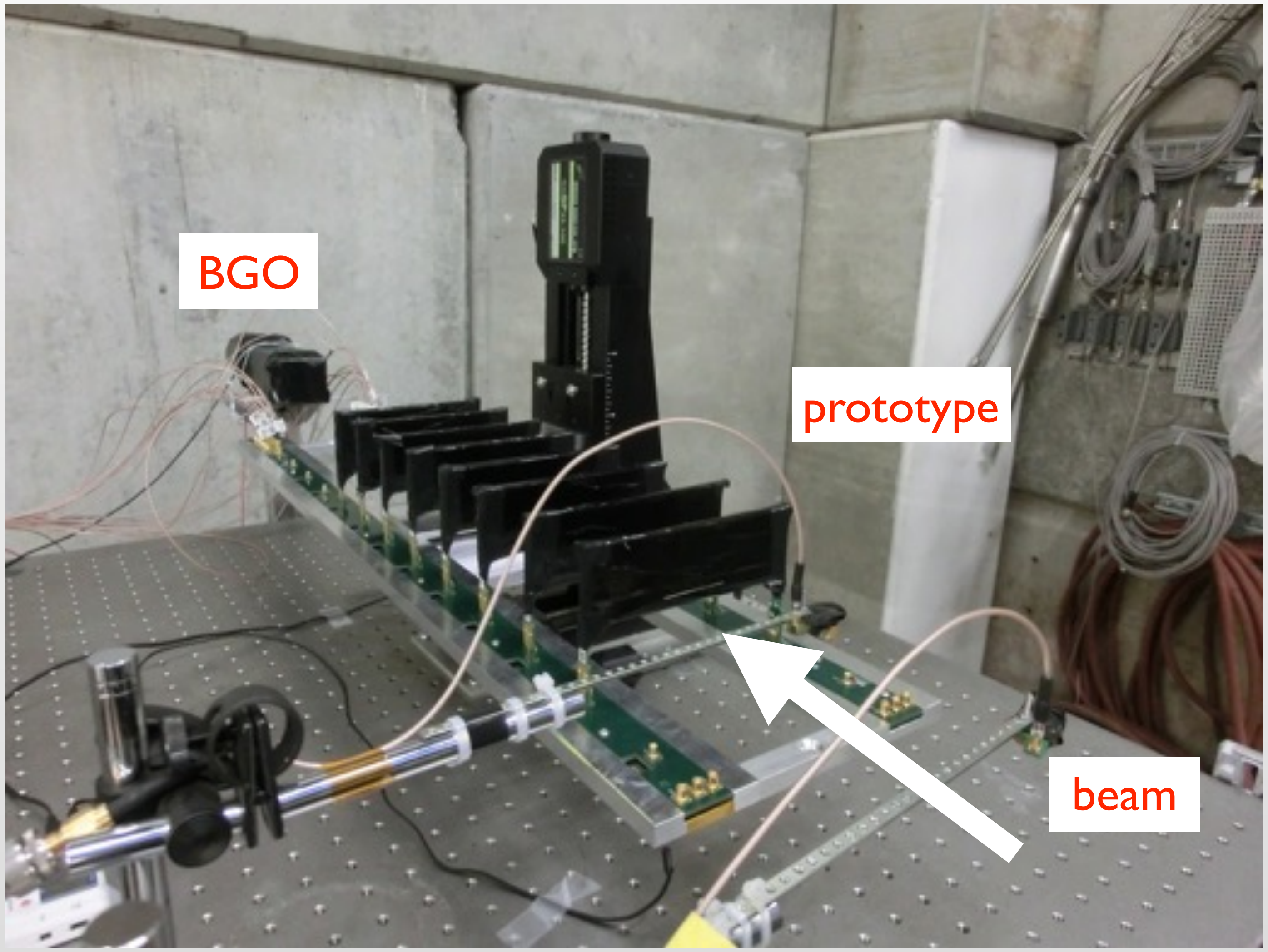
- Longer pixel (120mm vs 90mm)
- Different SiPM model

Beam test @Paul Scherrer Institute

- **e^+ from Michel decay**
- **hit rate as expected in MEG II**





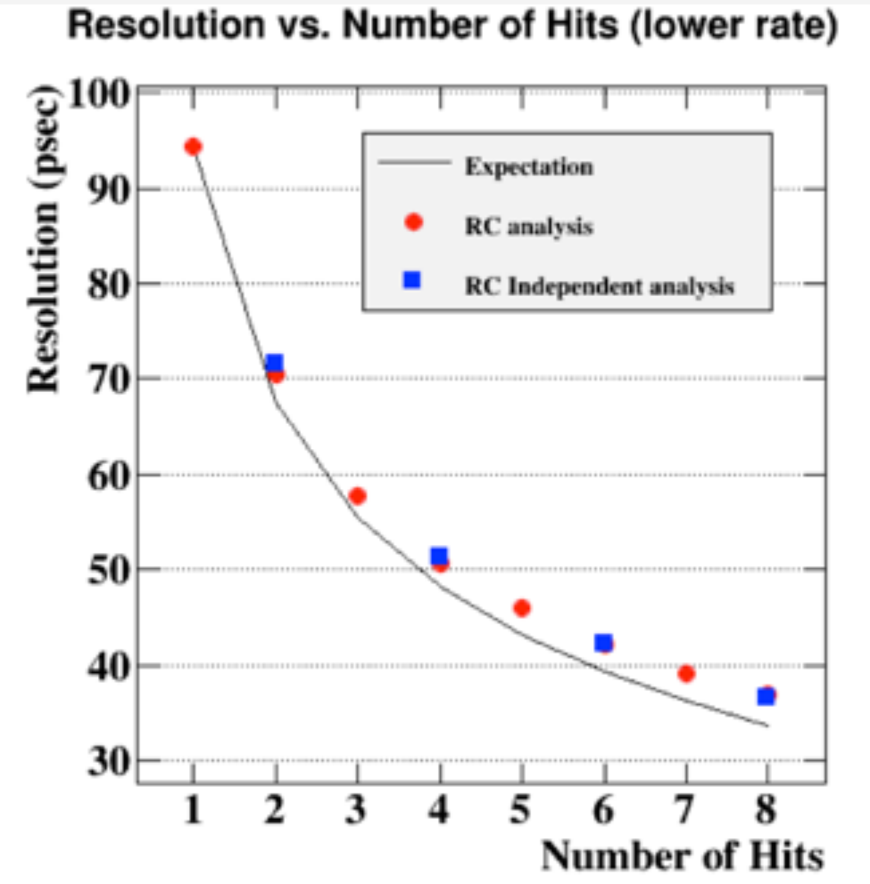


μ-beam (πe5@PSI), ~10^8Hz DC beam

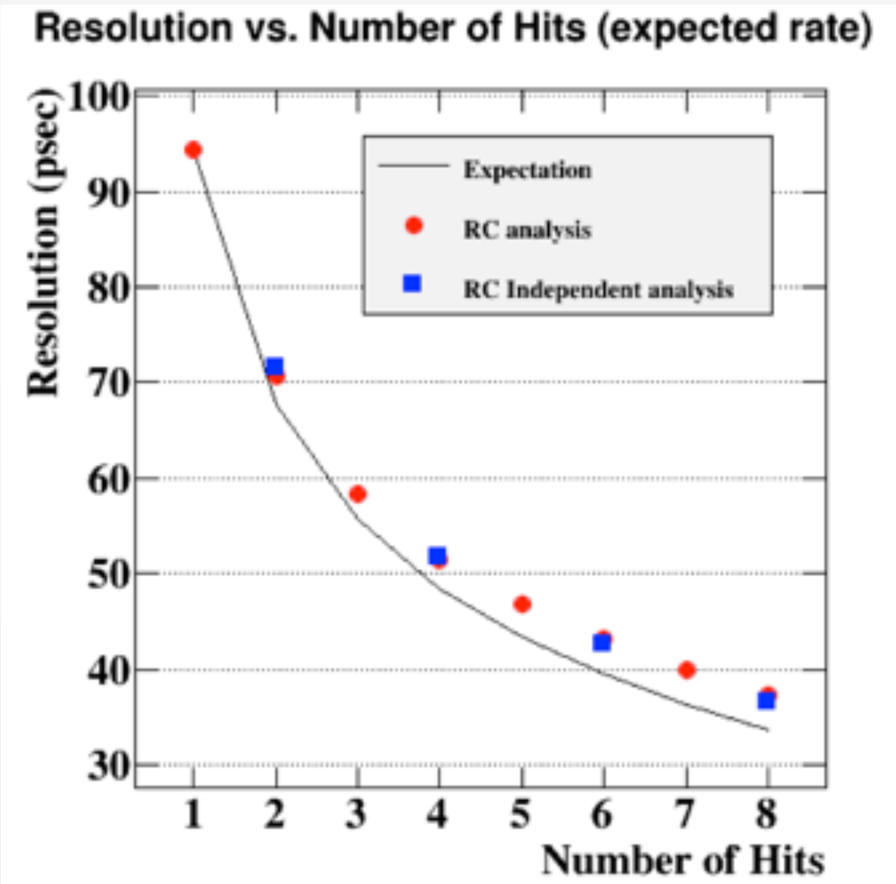
- **8 counters** mounted on **backplanes**
  - 6 120x40x5mm^3 + 2 120x50x5mm^3
  - **final pixel layout**
- 2 RC counters (trigger/selection)
- BGO calorimeter (beam monitoring)

Beam test @PSI: results

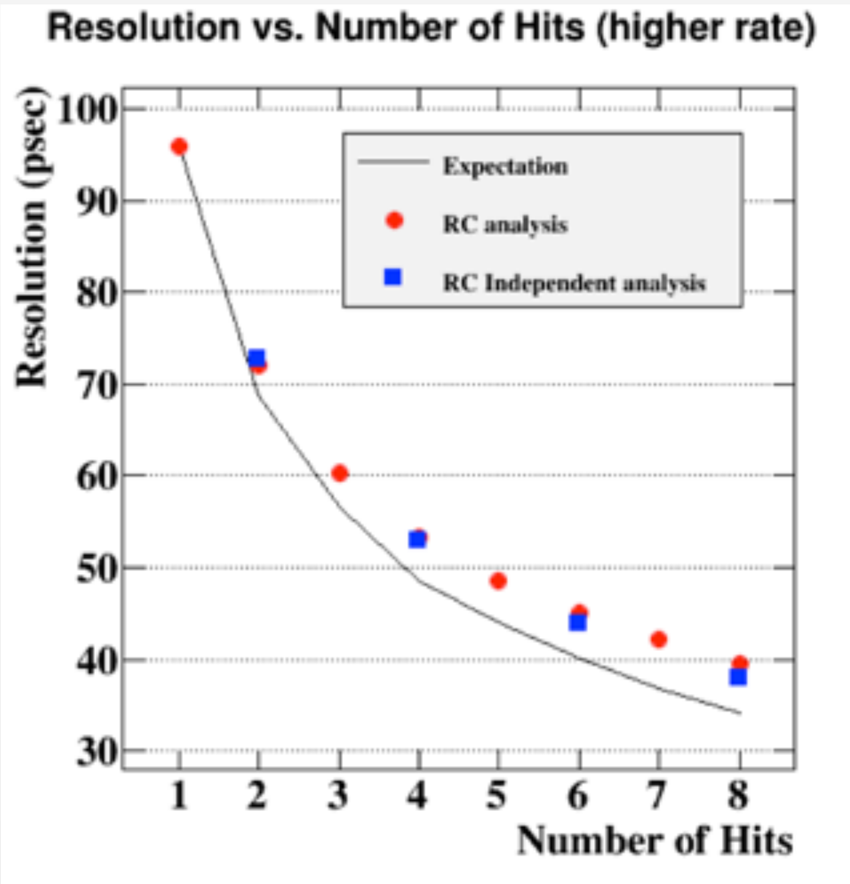
20-60KHz



50-150KHz (MEG expected)



90-290KHz

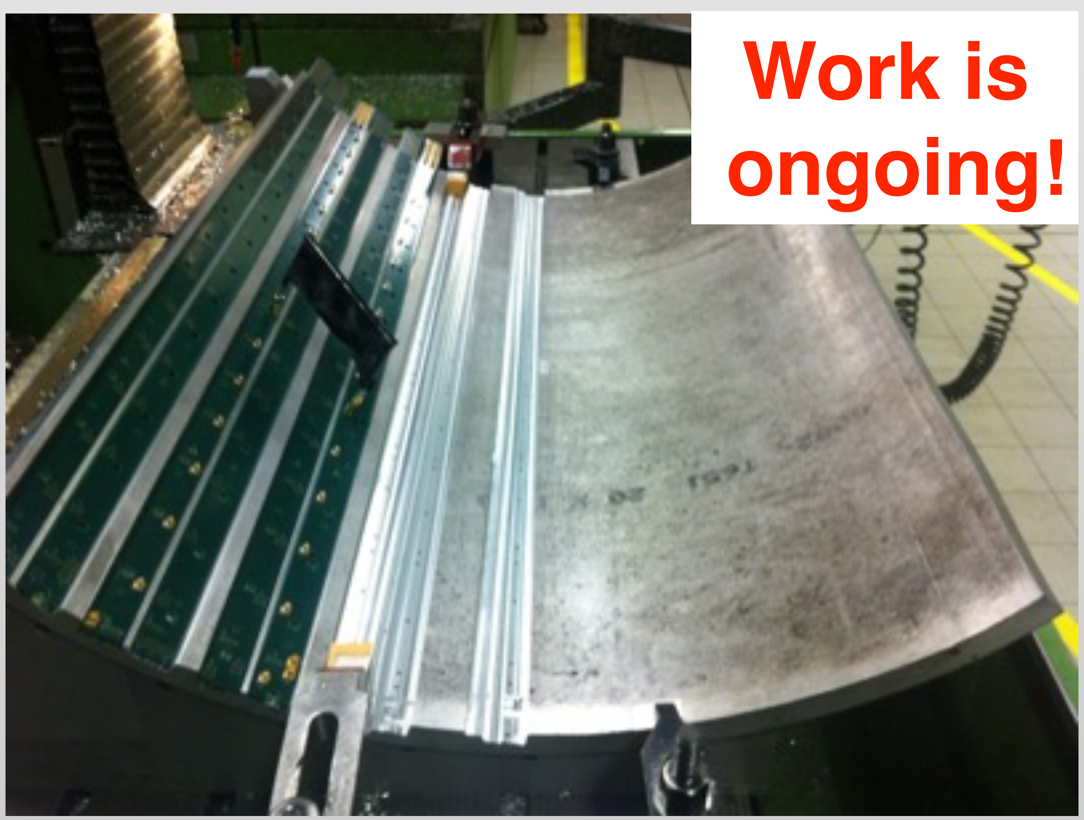


Resolution does not depend from beam rate in the range ~20-300 kHz.

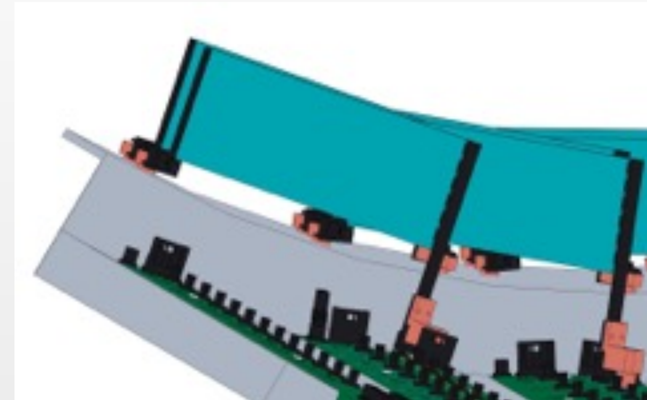
~35ps resolution was found at the expected MEG II rate (~150 kHz).

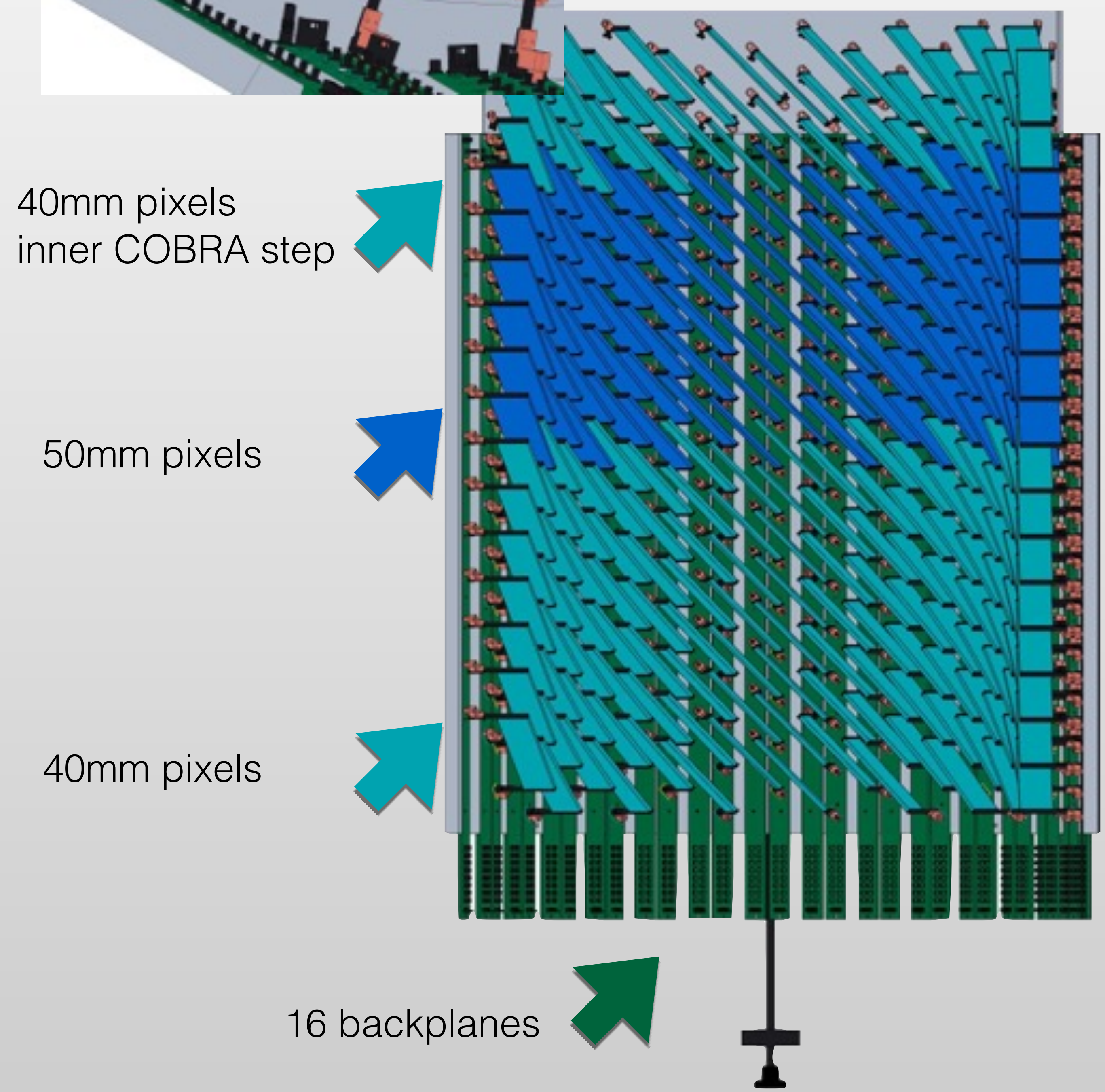
Final detector layout

- 256 **pixels** connected to **backplanes**
- **different heights** in different TC regions.
- optimized layout (fit mechanical constraints from magnet and DCH).
- expected reso ~30/35ps



Work is ongoing!

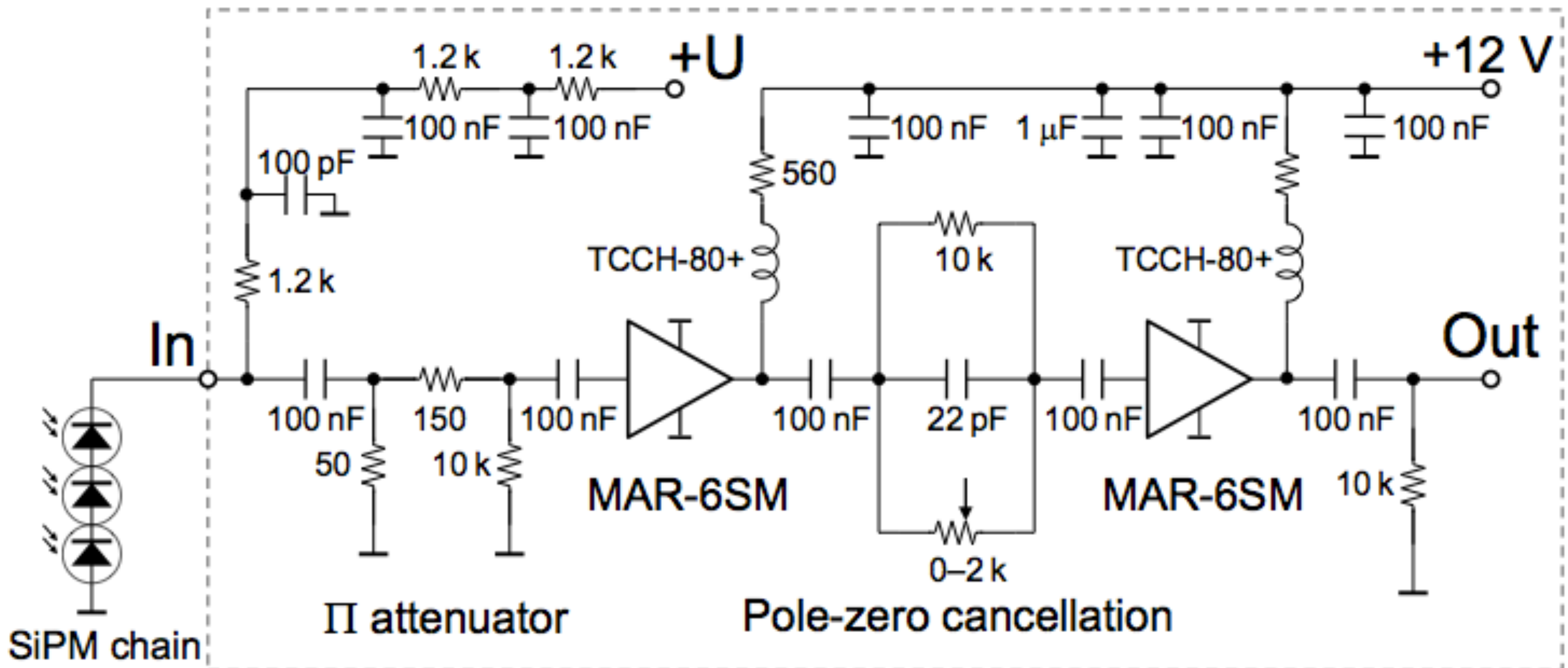




Conclusion and next steps…

- We upgraded the MEG Timing Counter experiment, developing a new detector based on hundreds of scintillator tiles with SiPMs readout.
- An improvement in time reso is expected thanks to good single pixel resolution and multiple hits events.
- A 3 years long R&D led to a 120x50(40)x5 mm^3 pixel, equipped with 6-SiPMs arrays in series connection.
- Prototype were tested under beam, proving a time resolution of ~30-35ps @8hits (x2 better than previous TC)
- The final detector is currently under construction.
- Next step: MEG engineering run 2015.

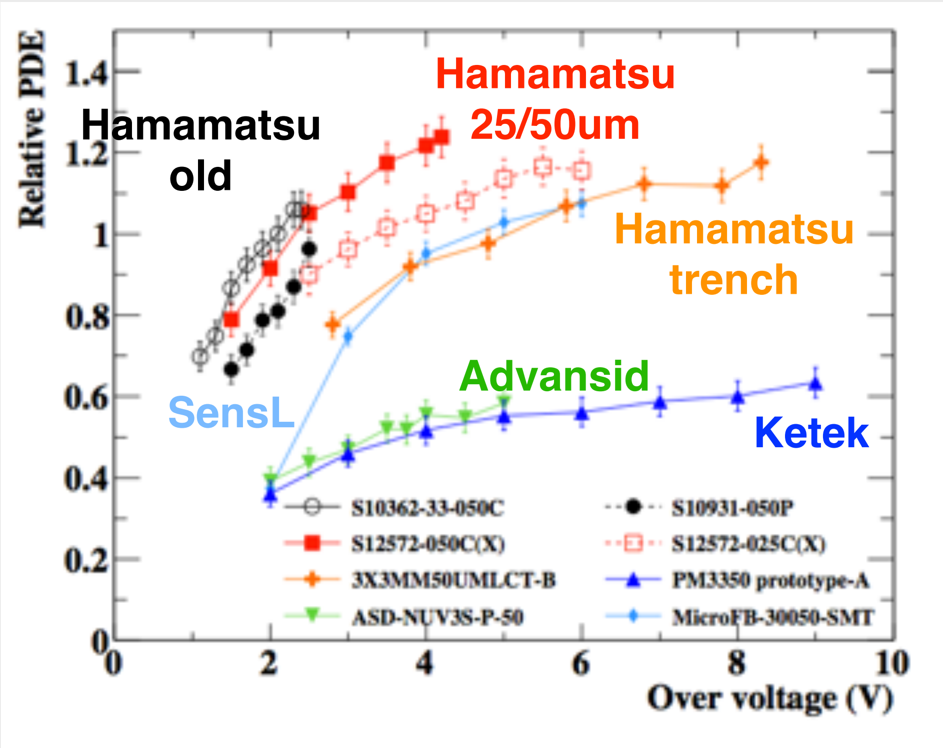
Back up



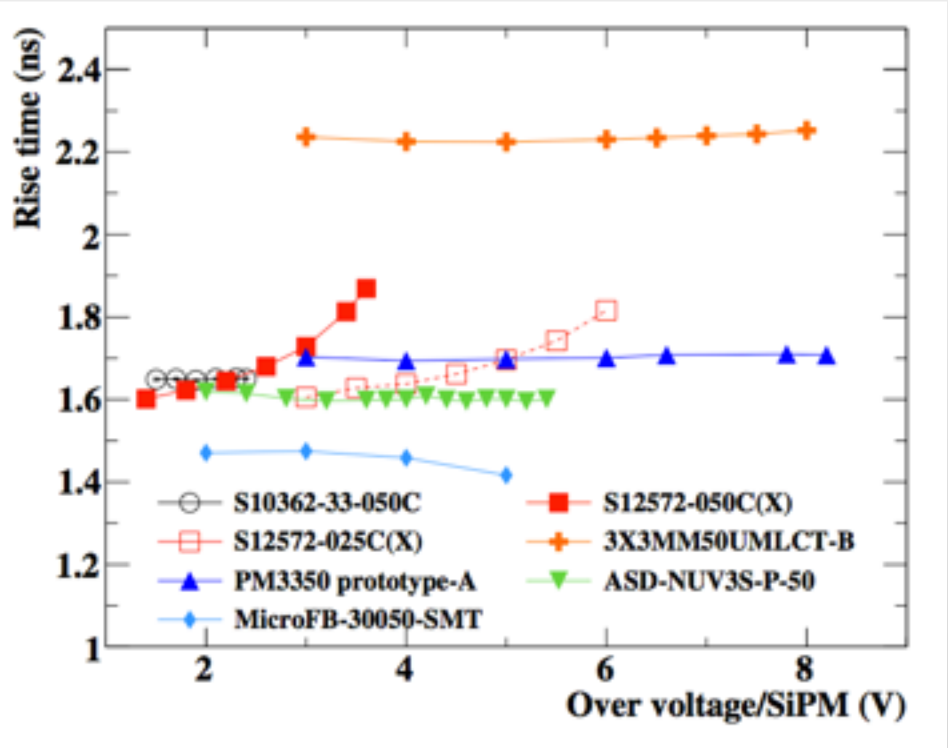
A. Stoykov (Paul Scherrer Institute)

SiPM comparison: PDE, rise time

PDE: light from a LED (λ~400nm). Relative PDE is calculated from P(N=0) with a correction for accidental coincidences of dark counts.



Rise Time: 10-90% time from waveform analysis



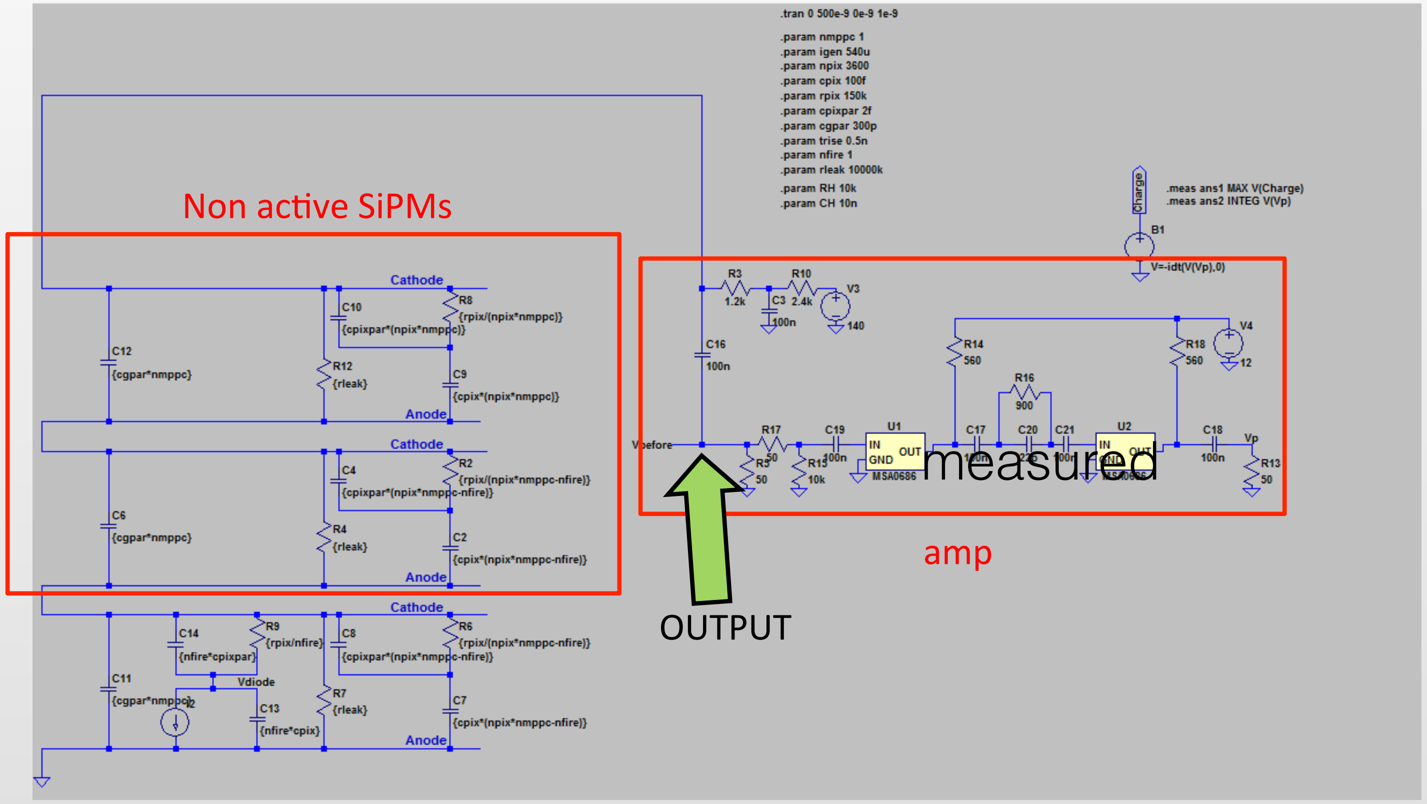
Series vs parallel

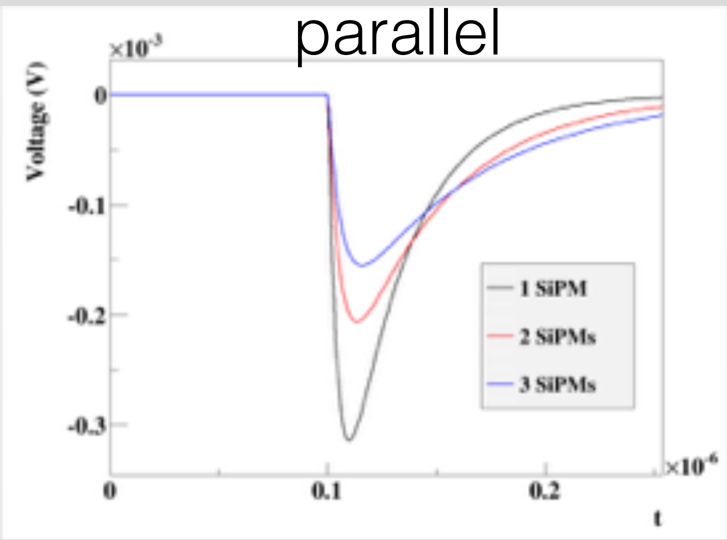
Series connection:

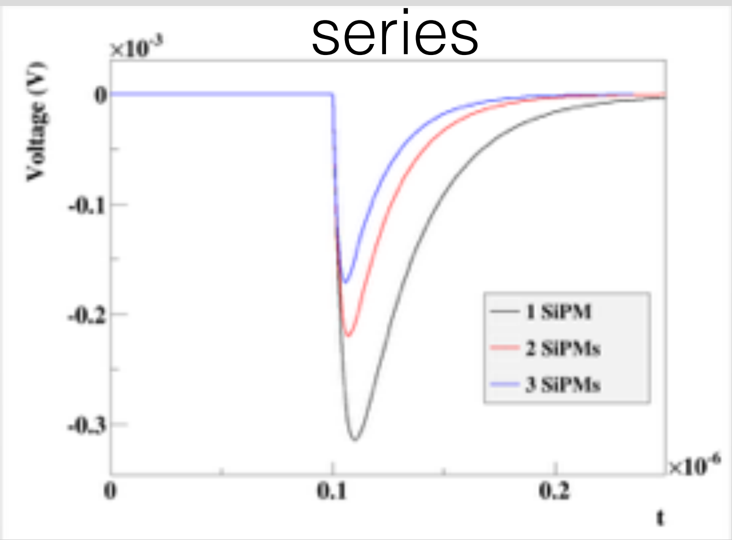
- OV adjustment between SiPMs with different V_{BD}
- reduced capacitance → narrower pulse
- **better time resolution**
- higher bias voltage

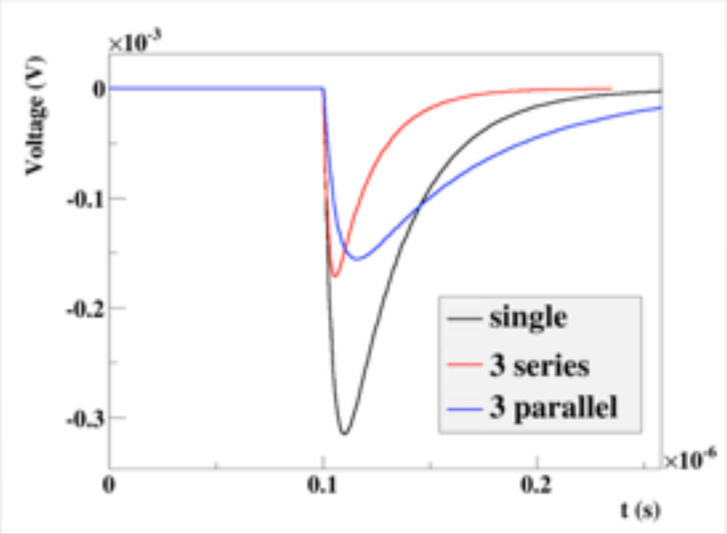
Parallel connection:

- lower bias voltage
- OV not adjusted
- increased capacitance → wider pulse
- **poor time resolution**



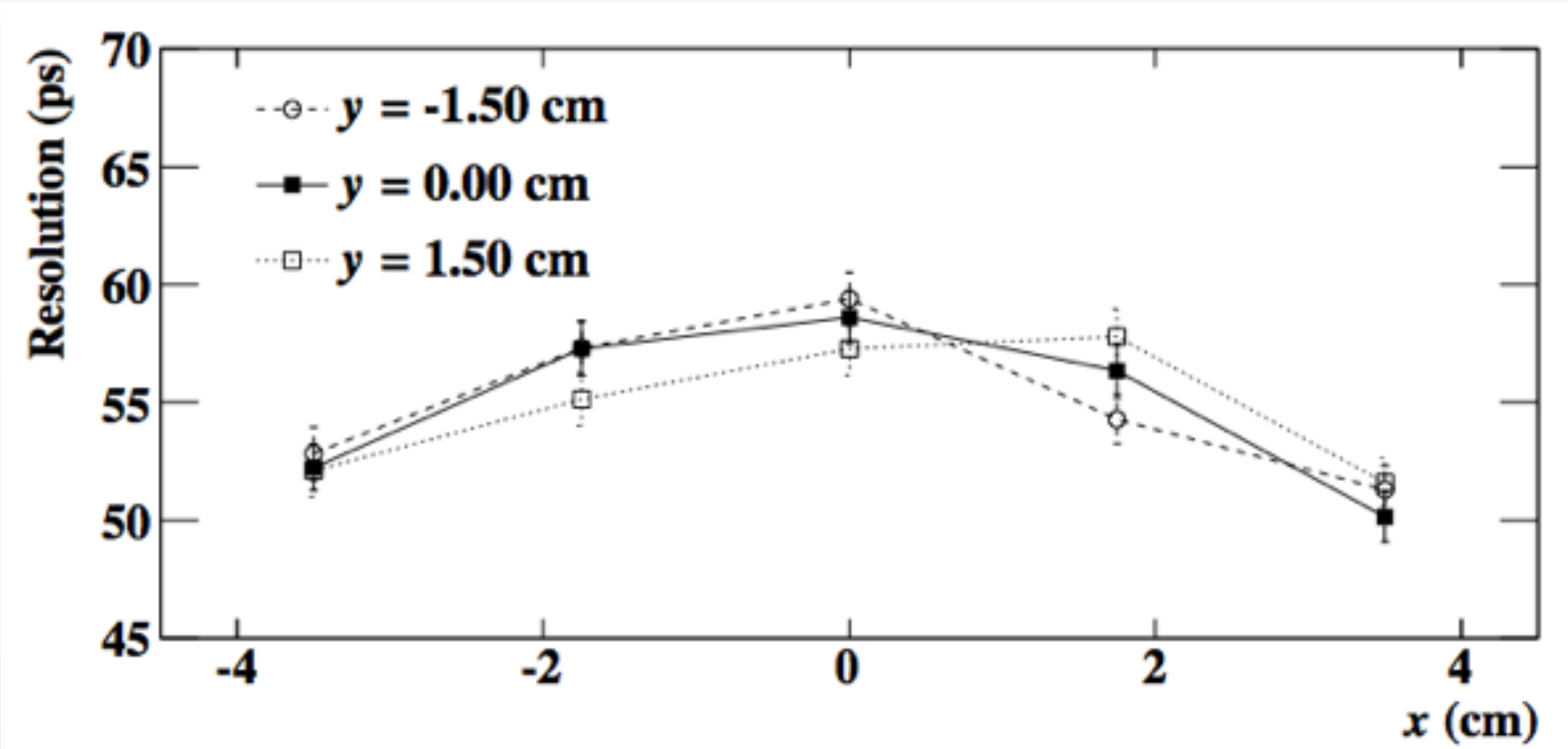


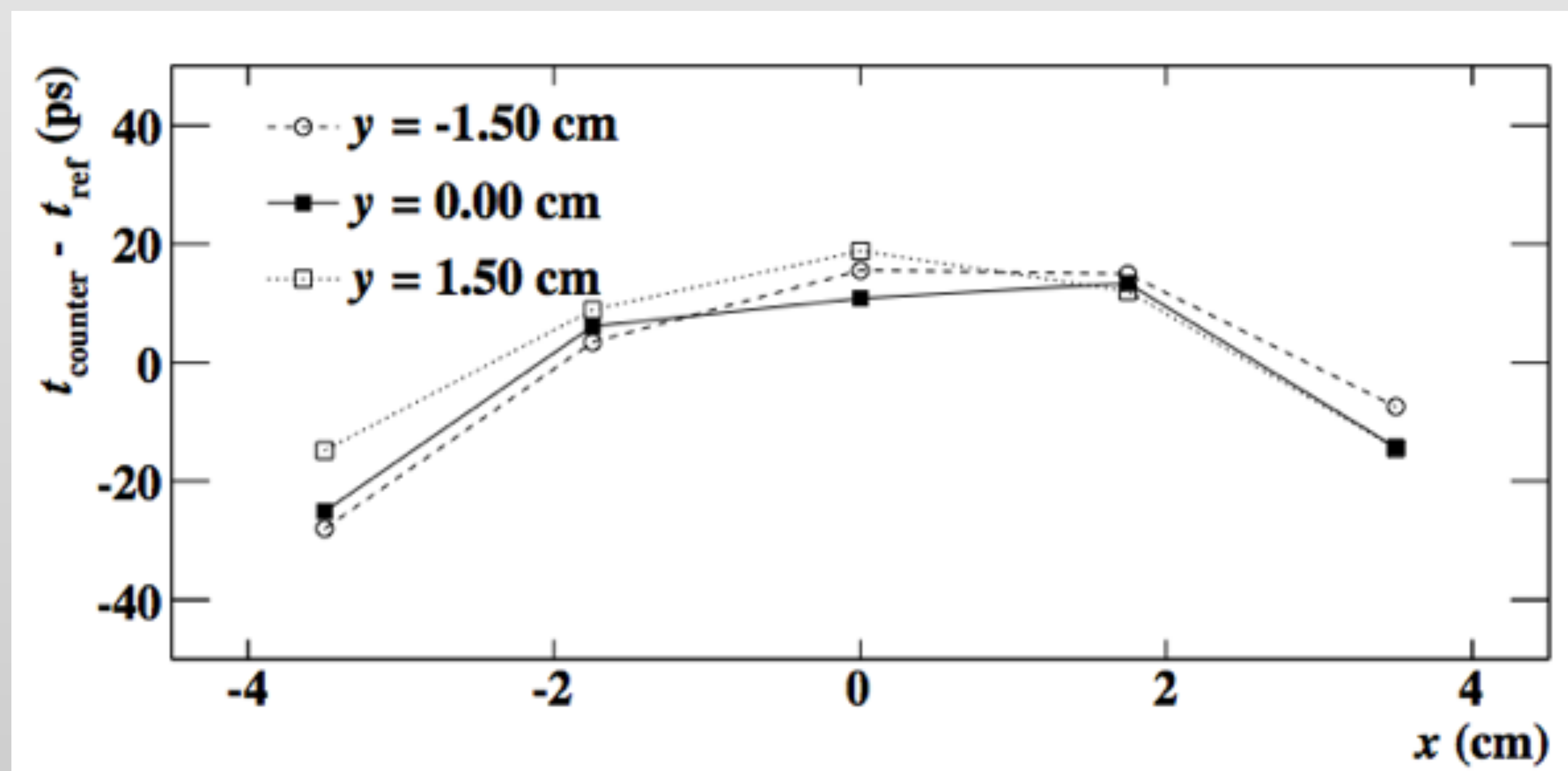




SPICE simulation by D. Kaneko

Position dependence





Probing the multi hit scheme

Time resolution improves combining time measured by many pixels:

$$\sigma^2 = \frac{\sigma^2_{\rm single}}{N_{\rm hit}} + \frac{\sigma^2_{\rm inter\ pixel}}{N_{\rm hit}} + \sigma^2_{\rm MS}\left(N_{\rm hit}\right)$$

Tested under beam with prototypes at BTF (Frascati, IT), PSI (Villigen, CH)

BTF (2013, 2014):

- 50MeV positron,
- very low rate (~50Hz),
- provisional pixel setup

→ Confirm multiple hit scheme
Test of backplane

PSI:

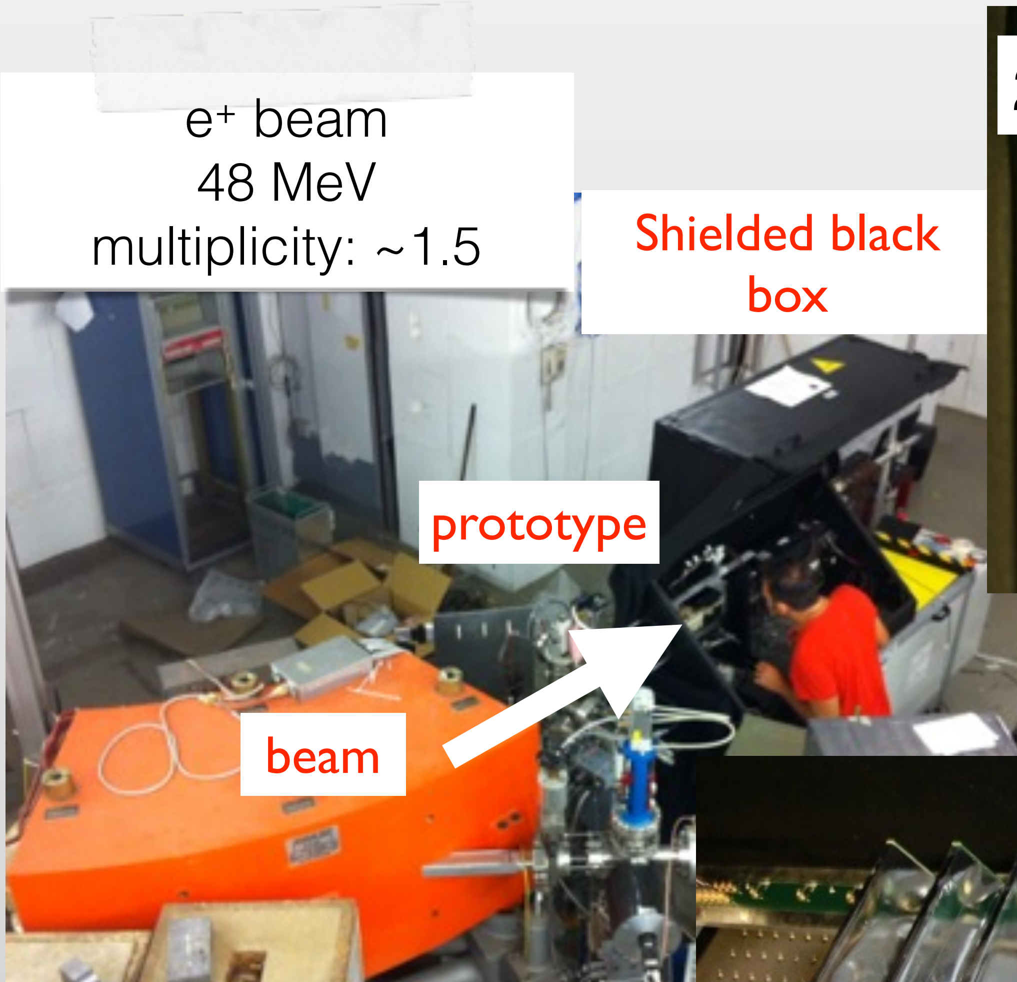
- MEG II environment,
- positrons from μ decay,
- high beam rate (MEG II expected: ~100kHz/pixel)

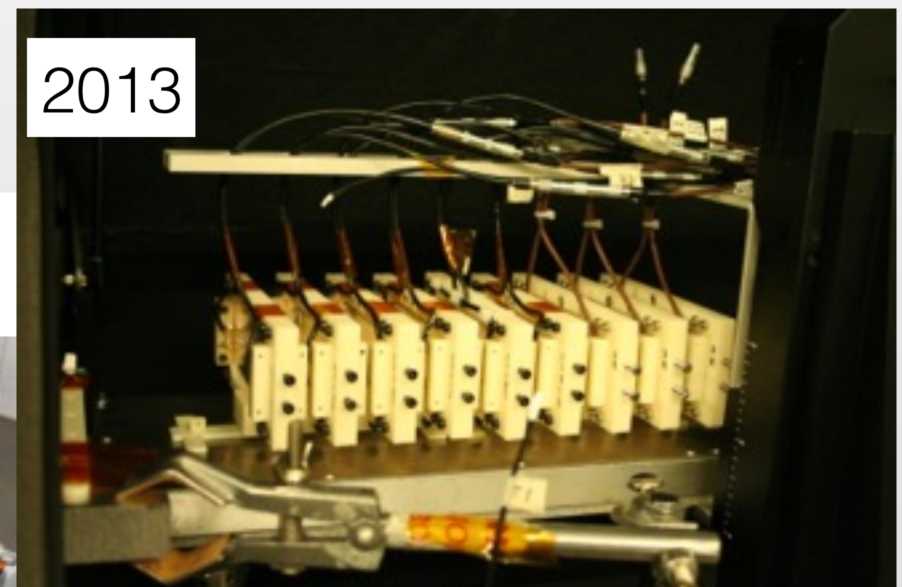
→ Final pixel layout
High rate environment

Proving multi hit @BTF

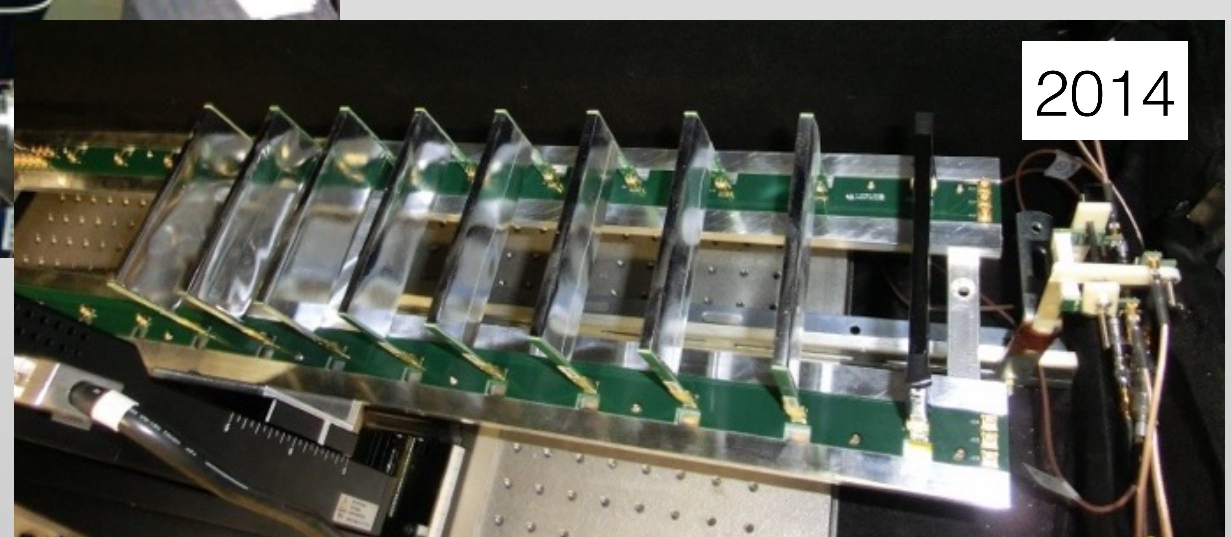
Resolution improves combining more hits: $\sigma^2 = \frac{\sigma^2_{\text{single}}}{N_{\text{hit}}} + \frac{\sigma^2_{\text{inter pixel}}}{N_{\text{hit}}} + \sigma^2_{\text{MS}}(N_{\text{hit}})$

Tested under beam @BTF (Frascati, IT) in 2013 and 2014 with different setups.





- **4 SiPMs series + PCB**
- **90 x 50 x 5mm³ pixels**
- **cables, no backplanes**
- **check multi-hit**



- **6 SiPMs series + PCB**
- **120 x 50 x 5mm³ pixels**
- **backplanes**

Calibration

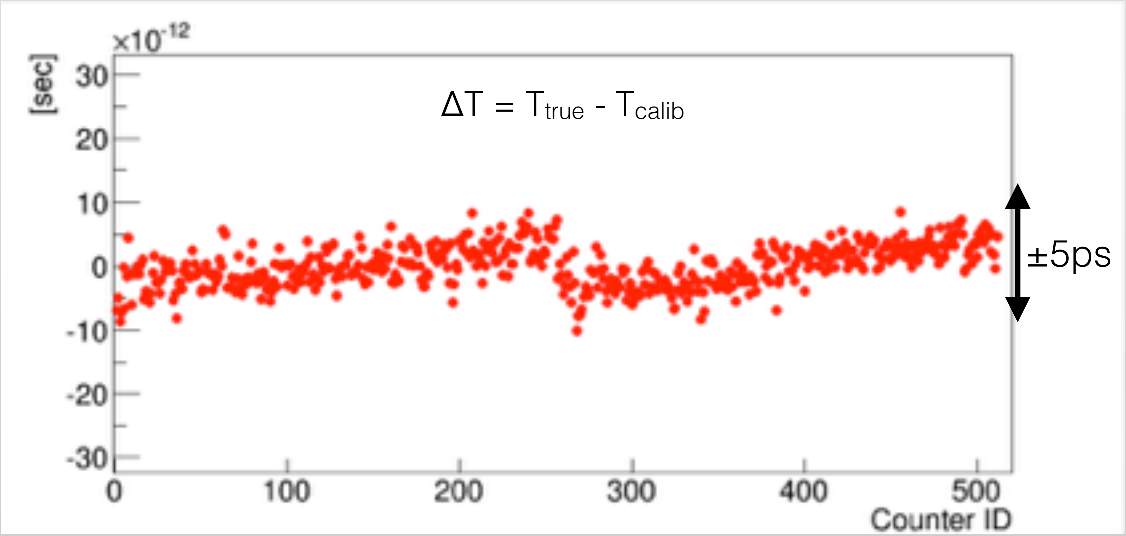
We are developing 2 independent ways for pixel inter-calibration based on **Michel data** and **laser calibration**.

Michel

Developed on MC:

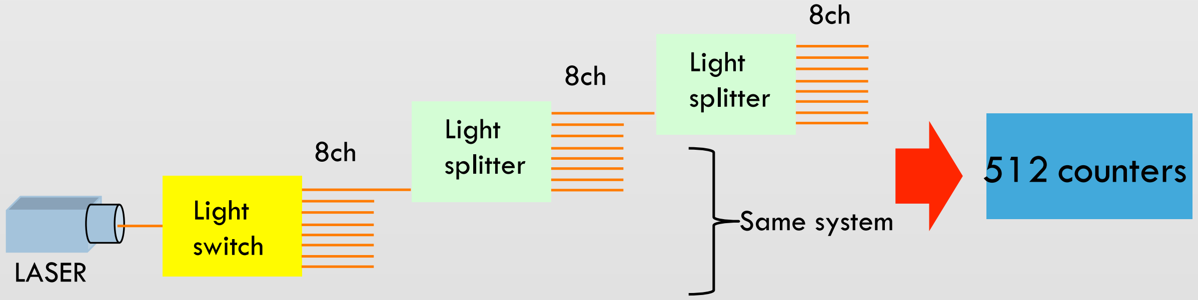
- Analysis with clustering and tracking;
- TOF between counters calculated from tracking
- Time offset is calculated by minimizing χ^2;
- Tested adding a random time offset (5ns RMS)

$$\chi^2 = \sum_i^{N_{ev}} \sum_j^{N_{hit}} \left(\left(T_{ij} - \left(T_{0i} + TOF_{ij} + \Delta T_j \right) / \sigma \right) \right)^2$$



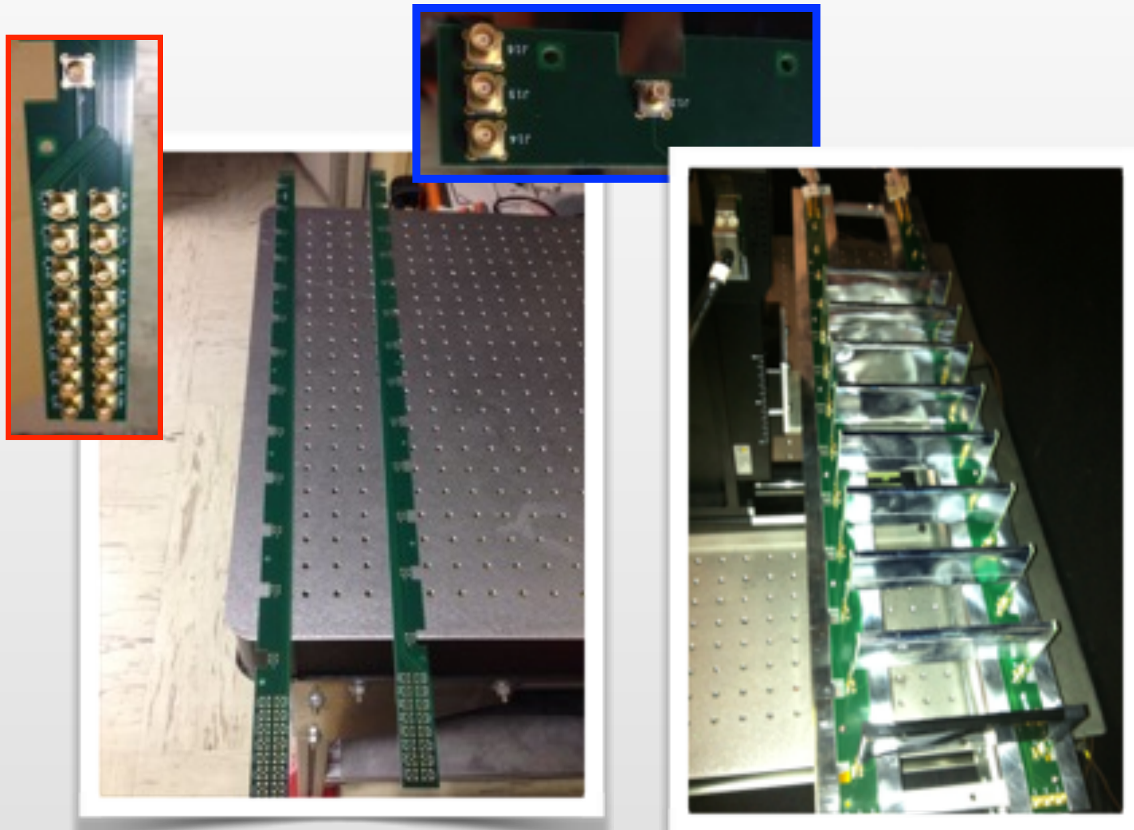
Laser

Sending a synchronous light pulse to all the pixels.

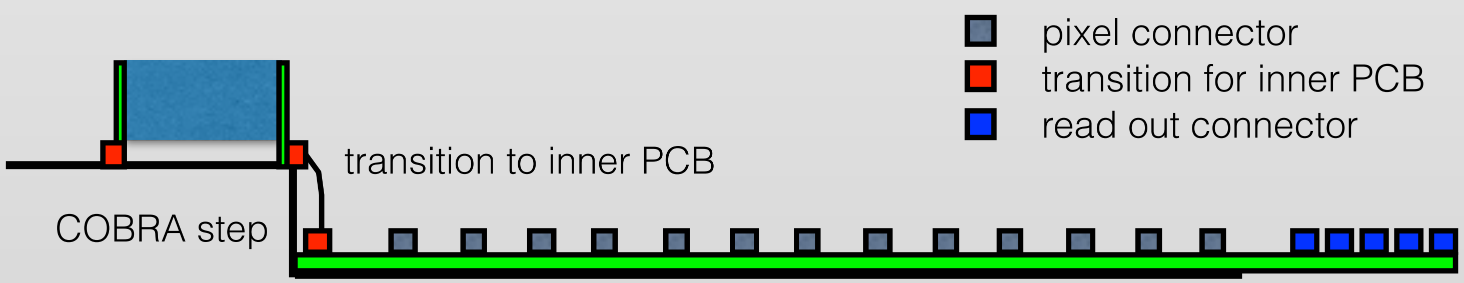


- Hamamatsu ps laser (MODEL??)
- A chain of optical splitters is used to divide the light signal then
- light is injected in the pixel by means of an optical fiber coupled to the scintillator
- independent from other detector

Backplanes



Pixels are connected to the BPs by means of MCX connectors and fixed to the main structure through the thermal connection.
BPs usage (940x25x5.5mm^3) avoid large number of cables on TC (>500).
In the inner region there is not enough room: pixels are mechanically connected to the structure using thermal blocks, while a coaxial cable connect them to the BP.
We need 4 different BP layout (for pixel positioning)

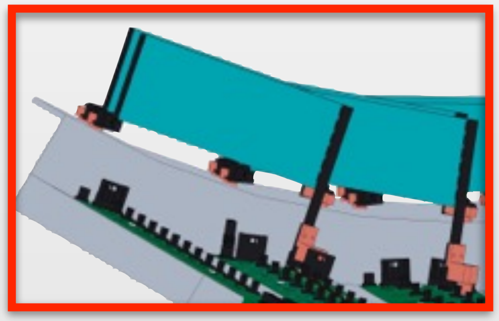


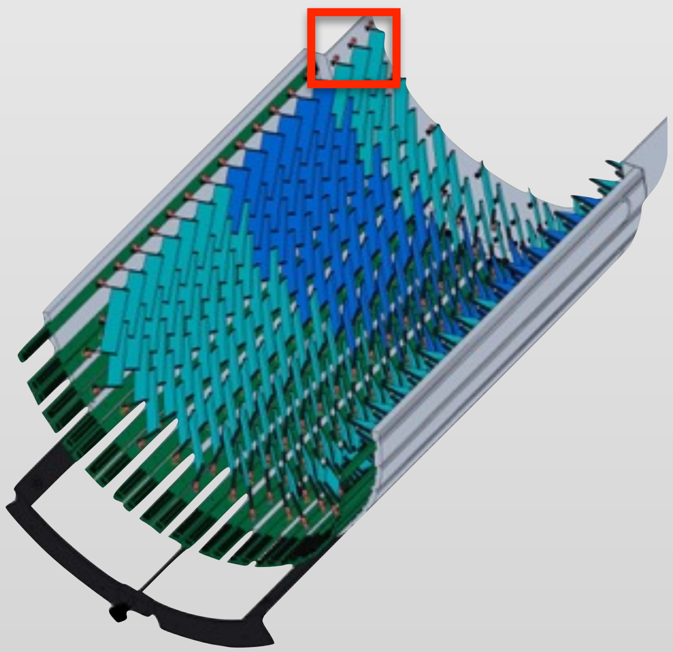
Successfully tested at BTF and PSI in 2013 and 2014.

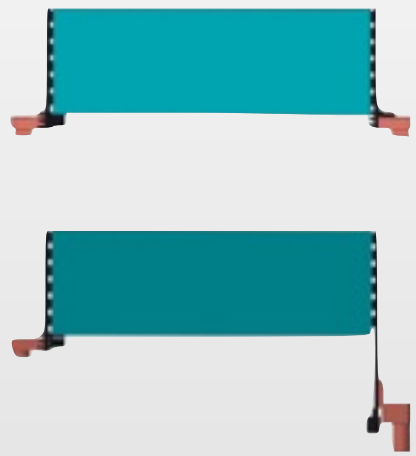
New Timing Counter overview

Pixels have different sizes and frame in different detector region

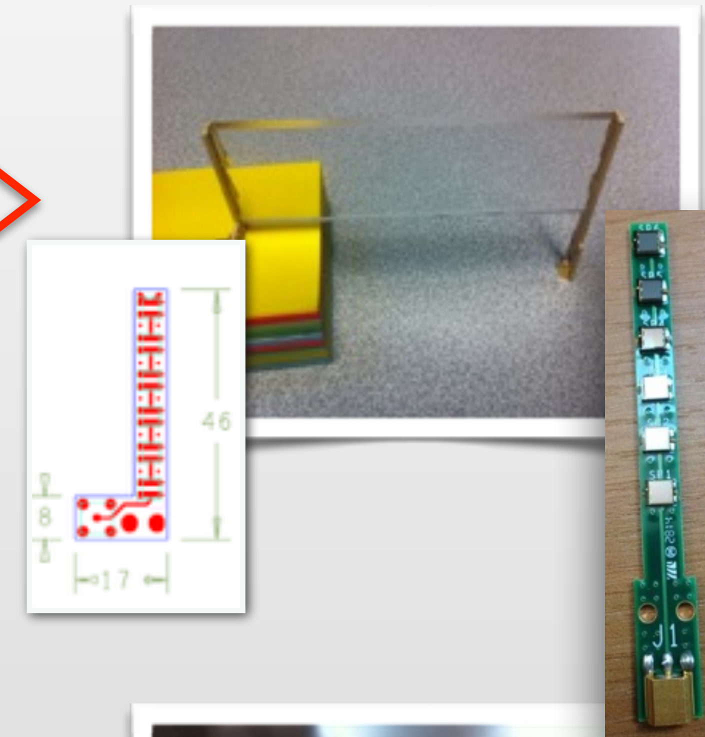
zoom of the inner region

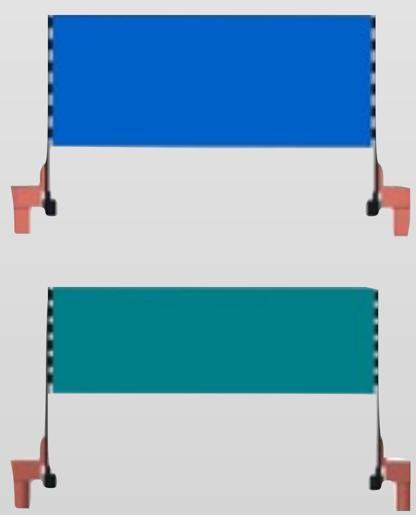






40mm height, PCB “L” shaped to fit inner COBRA step



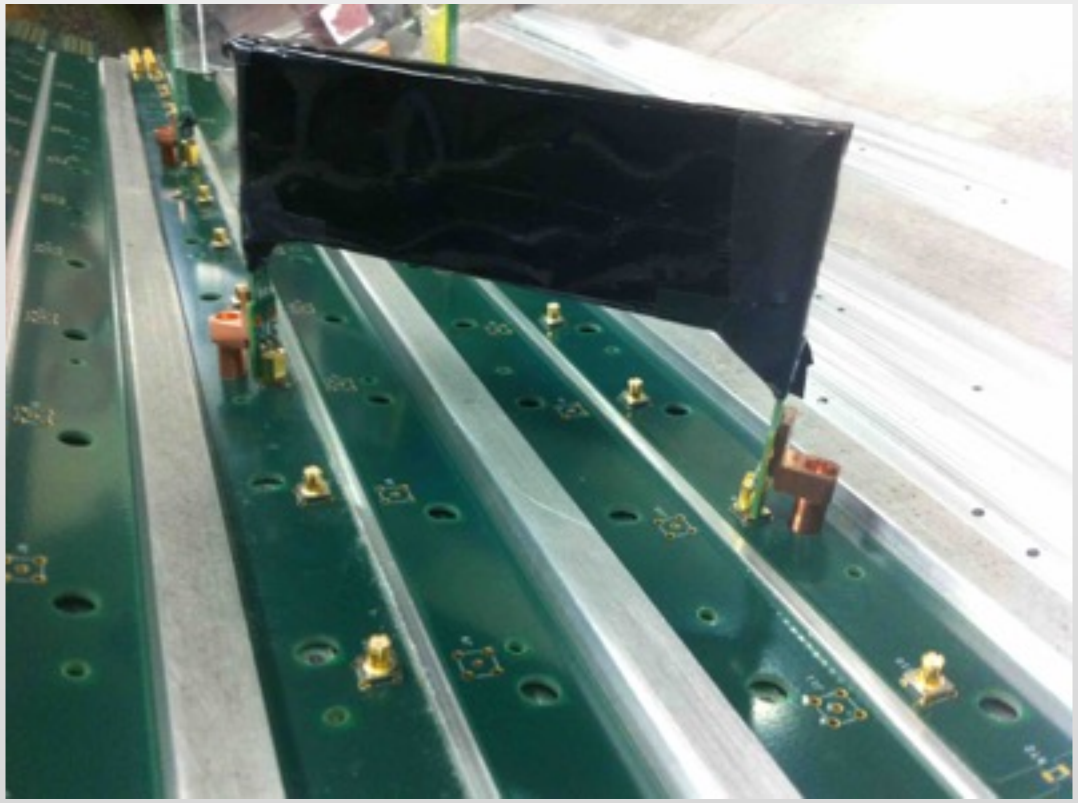


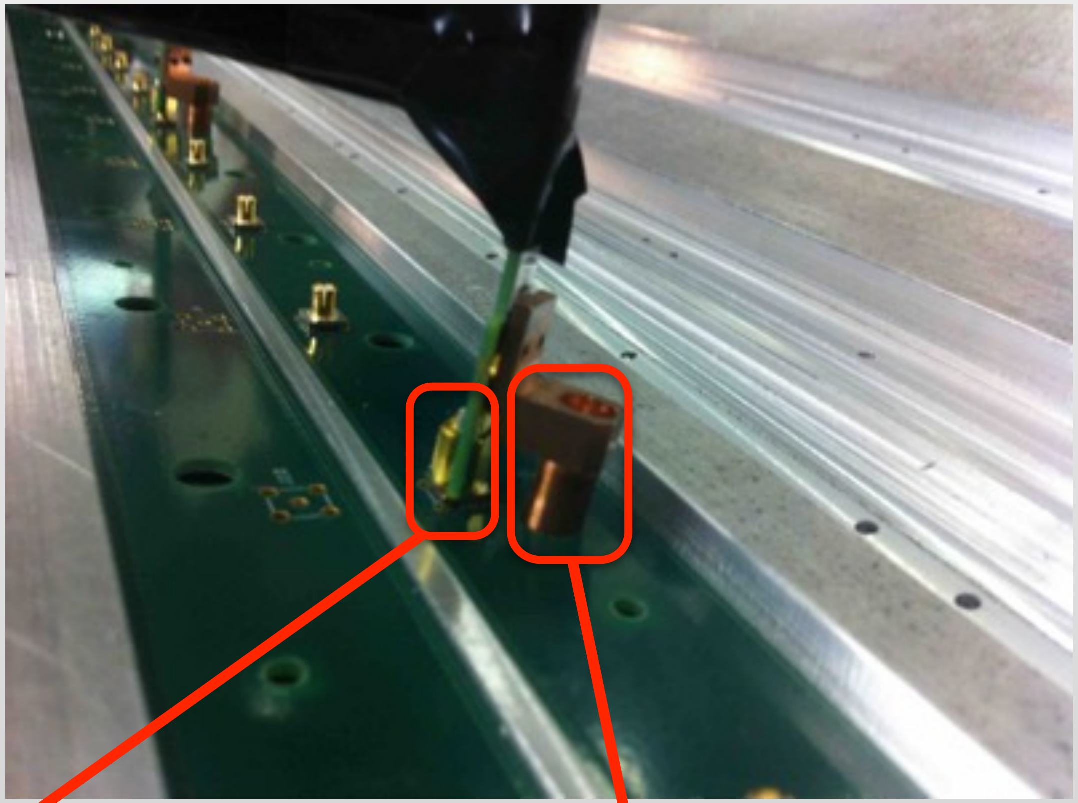
40 or 50mm height, “standard” pixel design

All configurations have been built and tested

TC structure: pixel mounting

The pictures show an example of pixel mounting





MCX connector

Copper block for thermalization and mechanical support