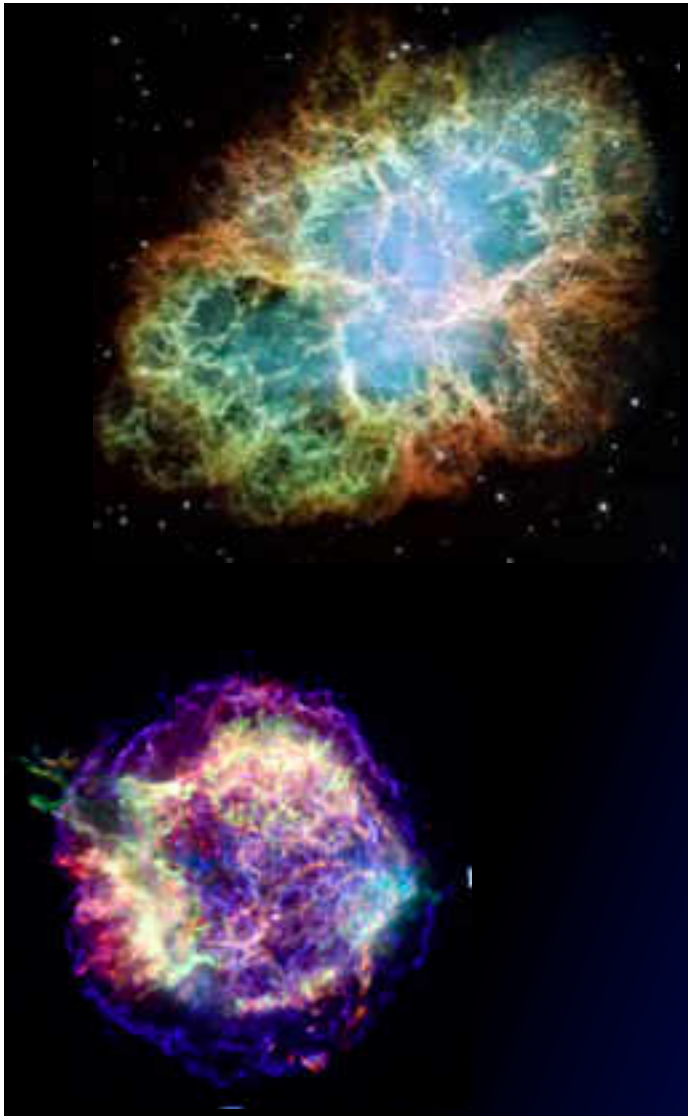


Digital FDIRC

a Focused Differential
Internal Reflection Cherenkov
imaged by SiPM arrays

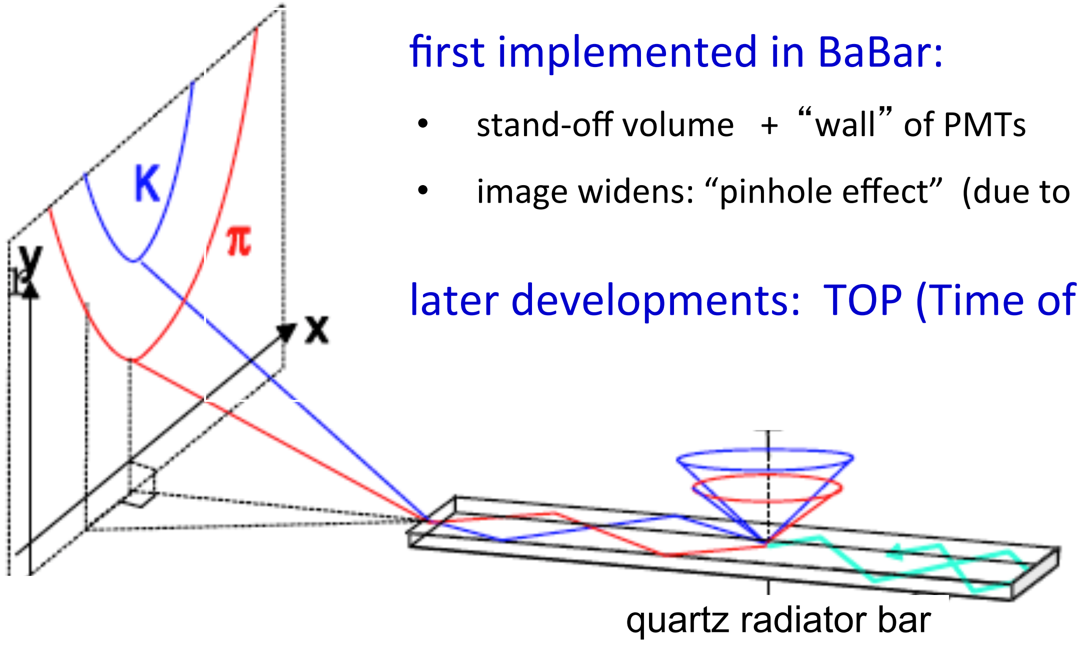
Pier Simone Marrocchesi

Univ. of Siena and INFN Pisa

FRONTIER DETECTORS FOR FRONTIER PHYSICS
13° Pisa Meeting on Advanced Detectors
24-30 May 2015 - *La Biodola, Isola d'Elba*

A

DIRC: Detection of Internally Reflected Cherenkov light



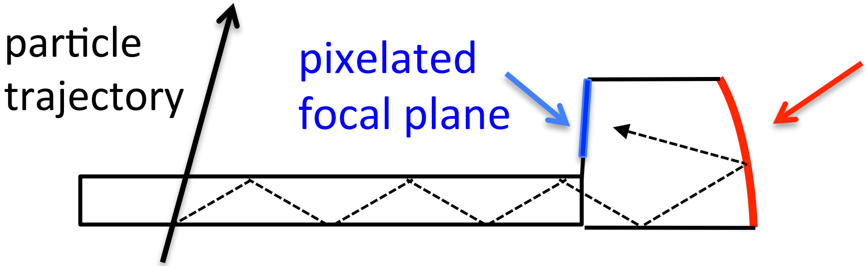
first implemented in BaBar:

- stand-off volume + "wall" of PMTs
- image widens: "pinhole effect" (due to finite width of quartz bar)

later developments: TOP (Time of Propagation), etc...

B

A **focalization scheme** is introduced: FOCUSING DIRC (**FDIRC**)



Focusing block:
spherical or cylindrical mirror

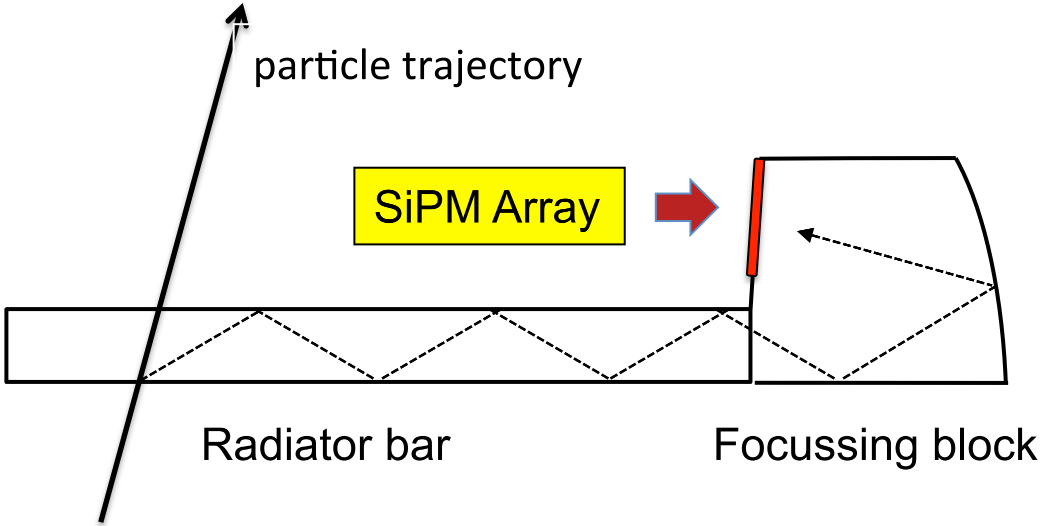
Focal plane instrumented either with:

- ☐ pixelated photosensors (e.g. MAPMT, HPD, MCP):
  - Limited number of pixels
  - Large pixel size
- ☐ or fiber bundles coupled to pixelated photosensors → Low light trapping efficiency

this talk

Digital FDIRC

FDIRC with high resolution SiPM array



Focal plane instrumented with a **mosaic of SIPM arrays**:

- small pixels (mm^2 or sub-mm^2)
- large number of sensors (~10^3)
- photon counting

Possible applications

High Energy Physics:

- PID @ a few GeV momenta (e.g.: π/K separation as in BABAR, BELLE, PANDA)

Astroparticle Physics:

- Charge identification of cosmic ray nuclei
- isotopic separation in cosmic rays (for space/balloon borne experiments)

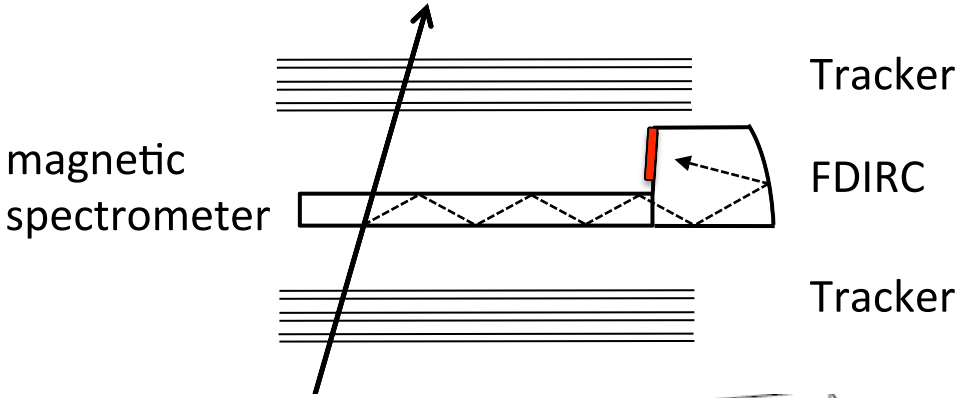
Isotopic separation by momentum + velocity (FDIRC) measurements

For not too large total-particle momenta P (~ tens of GeV/c) an accurate measurement of β can provide an adequate mass separation for fully stripped ions of atomic number Z and mass A: $\left(\frac{\sigma_M}{M}\right)^2 = \left(\frac{\sigma_{P_T}}{P_T}\right)^2 + \left(\gamma^2 \frac{\sigma_\beta}{\beta}\right)^2$

CONCEPT

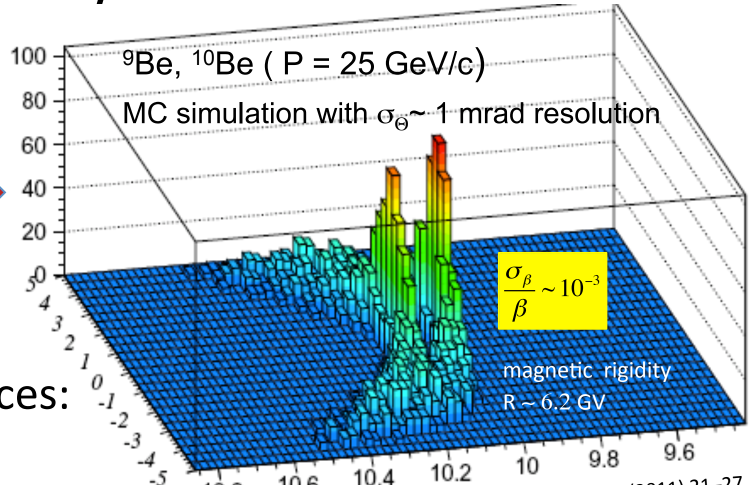
FDIRC embedded in a magnetic spectrometer:

- non destructive measurement of β
- track measured **before** and **after** FDIRC
- **large photostatistics** ~ Z^2 for **charged ions**



Example: $\Delta\Theta_c$ difference in Cherenkov angles for ^{9}Be, ^{10}Be ions with P = 25 GeV/c is $\Delta\Theta_c \sim 11$ mrad

A mass separation better than 0.2 a.m.u. can be achieved with an angular resolution of σ_Θ= 1.5 mrad and σ_P/p ~ 1 %



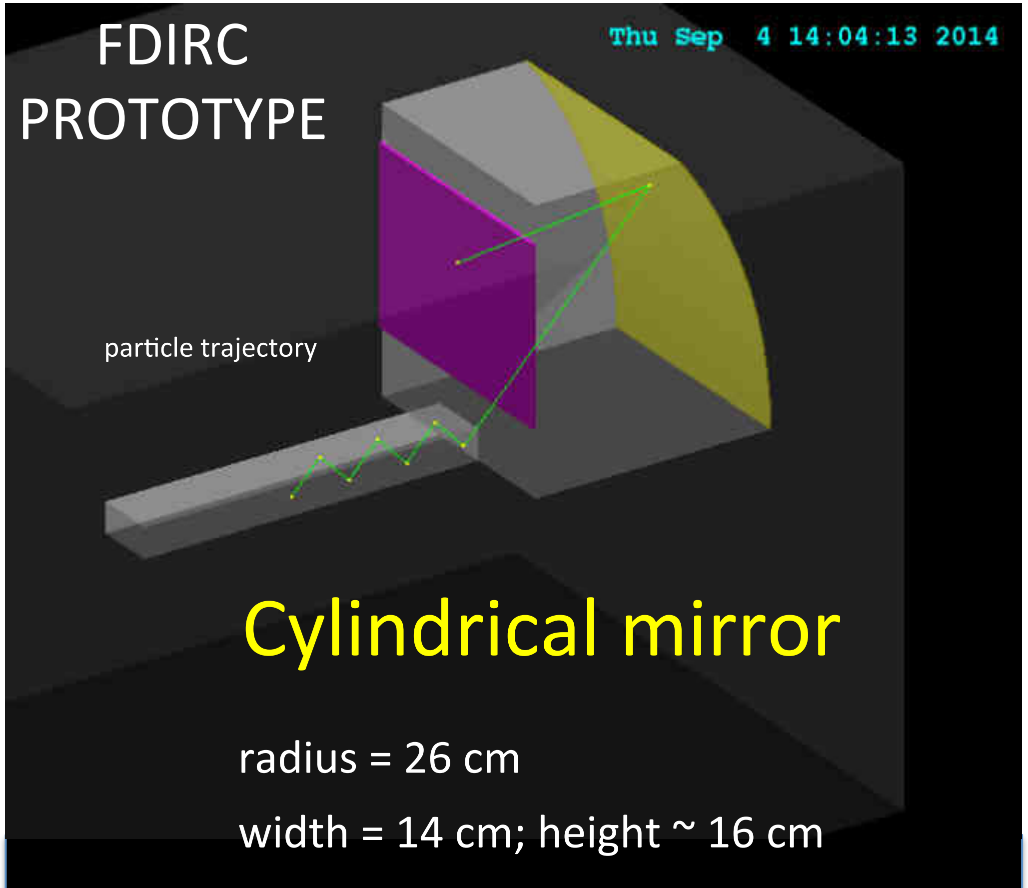
P. S. Marrocchesi et al., Astroparticle Physics 35 (2011) 21–27

Not easy to achieve: σ_Θ is affected by several error sources:

FDIRC
- geometry/optics
- chromatic dispersion along the optical path
- bar imperfections (surface and angles)
- pixel size, etc...

$\oplus$ tracking angular error

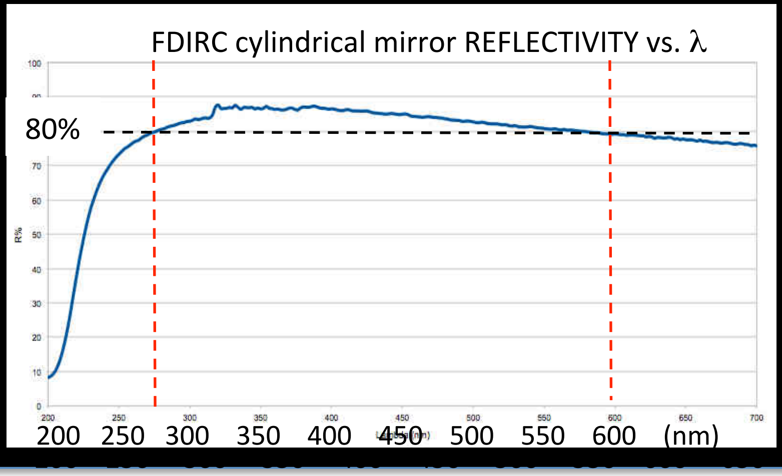
Quartz radiator bar



Cylindrical mirror

radius = 26 cm

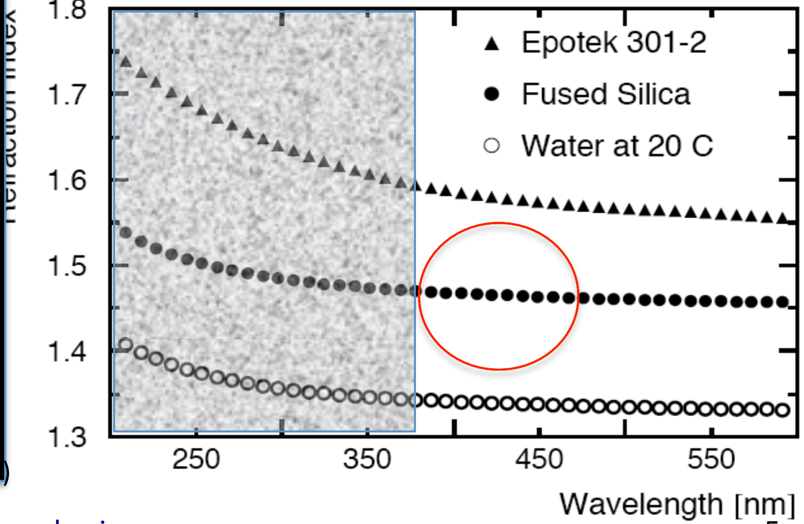
width = 14 cm; height ~ 16 cm



- Fused Silica (SiO_2) radiator bar
- 3 spare short bar segments from BaBar
- 17.25 mm (thickness) x 35 mm (width)
- 200 mm (long)

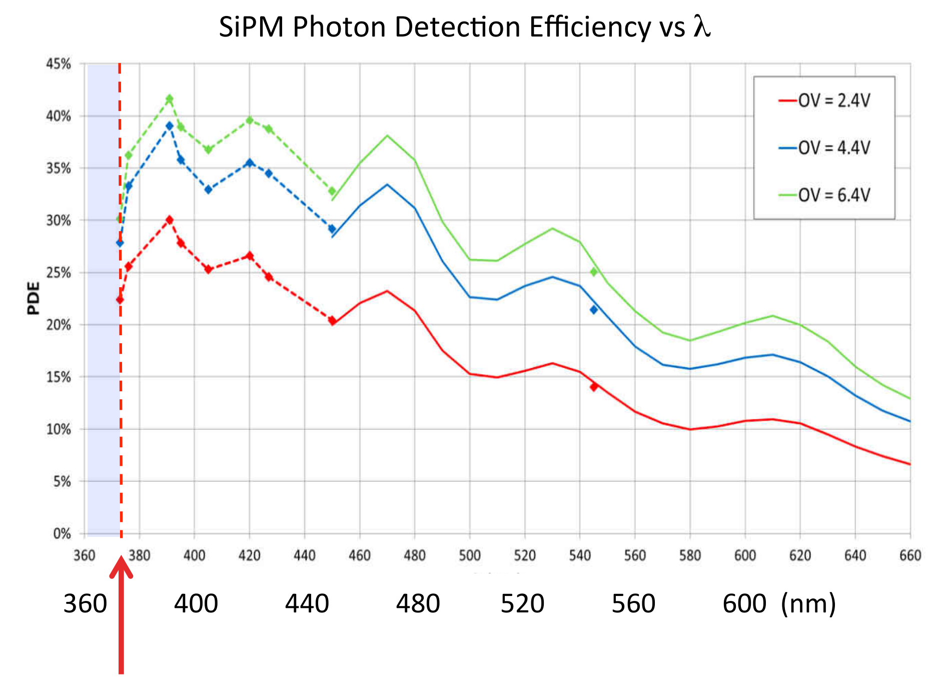
Dispersion relation in the radiator:

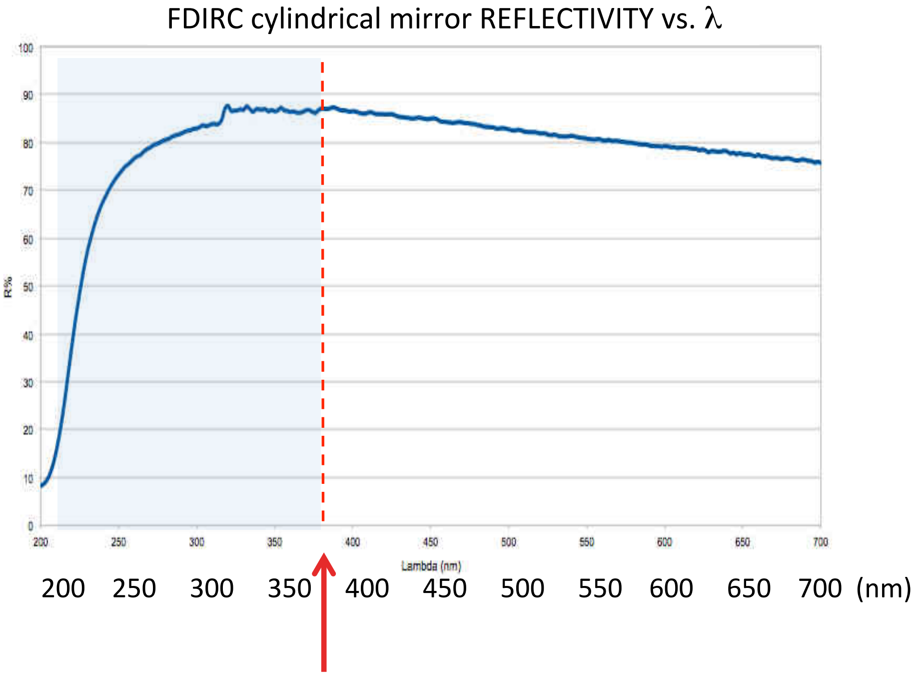
- **above ~ 370 nm (PDE cutoff)**
  n(λ) is almost constant vs. λ
- n ~ 1.47 at 435 nm



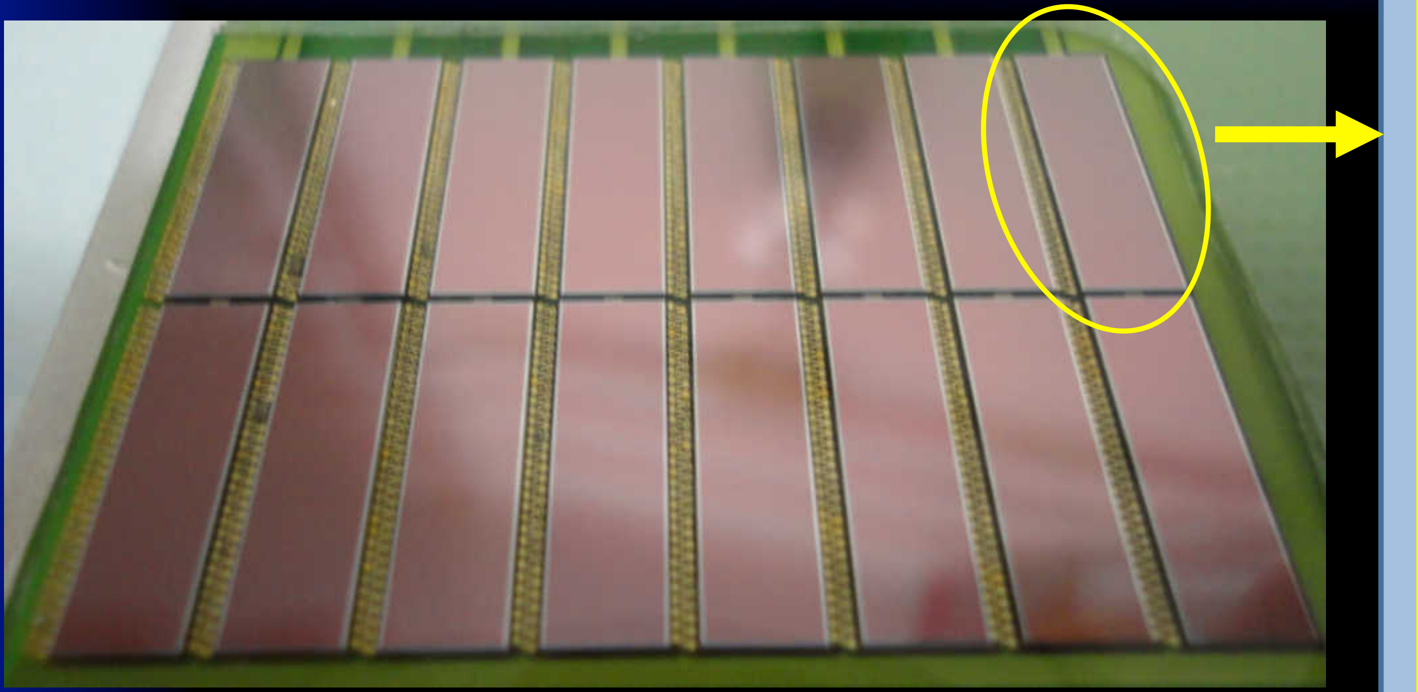
Chromatic dispersion vs. bandwidth

- Cherenkov light yield ~ $1/\lambda^2$ → grows in the UV
- in SiO_2 radiator, the rate of change of the index of refraction vs. wavelength $dn(\lambda)/d\lambda$ is larger in the UV: angular resolution (chromatic term) gets worse
- tradeoff between light yield and bandwidth: in our case **mirror reflectivity** and **photon detection efficiency (PDE) of SIPM** limit the effective bandwith to ~ $370 < \lambda < 600$ nm

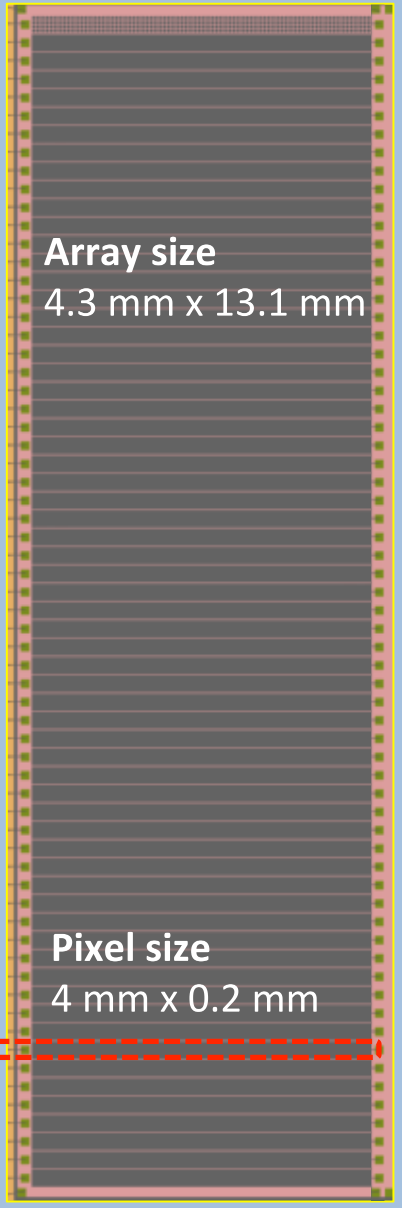

SiPM Photon Detection Efficiency vs λ


FDIRC cylindrical mirror REFLECTIVITY vs. λ

FOCAL PLANE (4.3 cm x 2.7 cm)

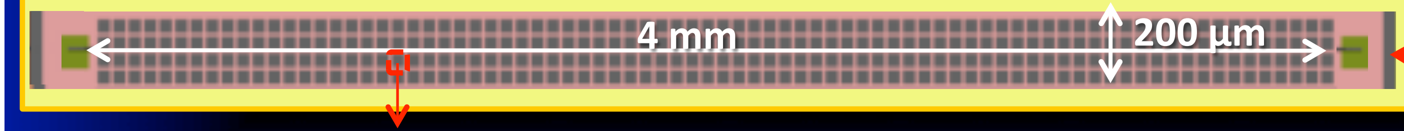


Array of 64 SIPMs



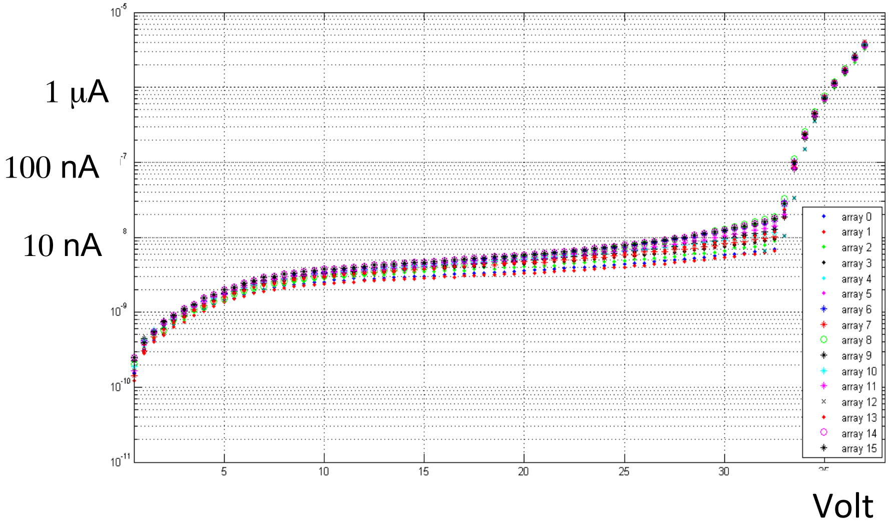
- Each **Array**: 64 pixels (SiPM sensors)
  inter-pixel gap 10 µm
- Each **Pixel** : 4mm x 200 µm = 0.8 mm^2 SiPM
  4 x 100 micro cells

16 SiPM Arrays
(1024 SiPMs)

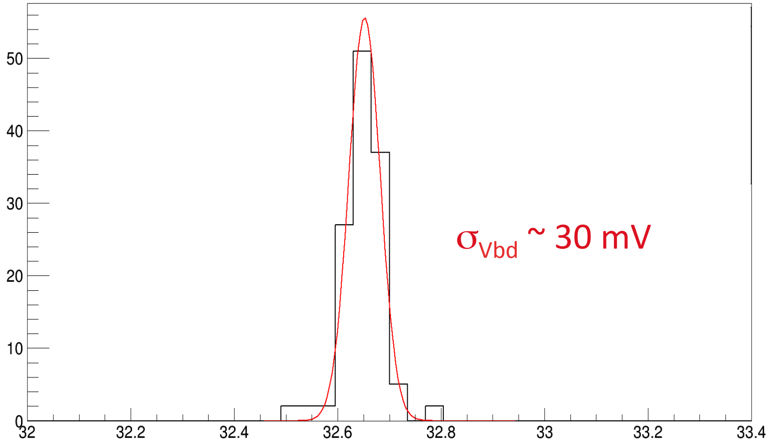


Micro cell
47.5 µm X 40 µm

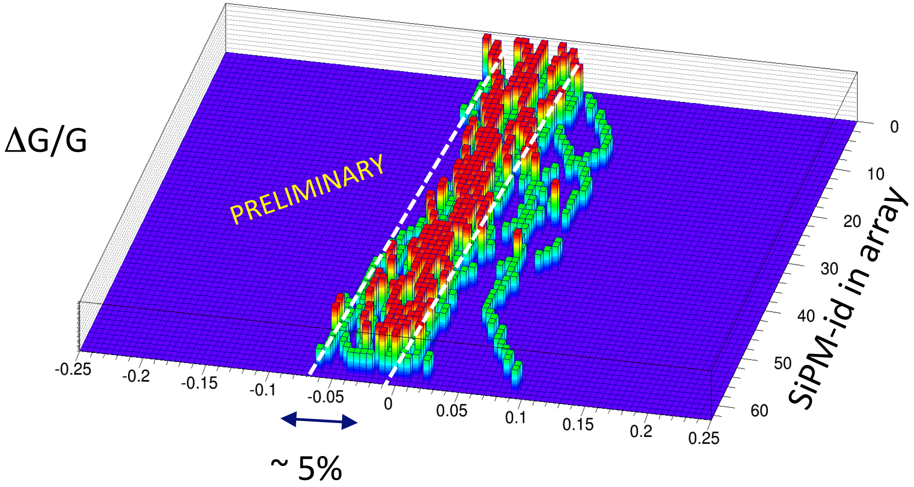
Characterization of 16 SiPM arrays (1024 SiPM)



I-V curves for 16 arrays



Breakdown Voltage (V_{bd}) spread at fixed temperature T ~ 22°C for 16 arrays

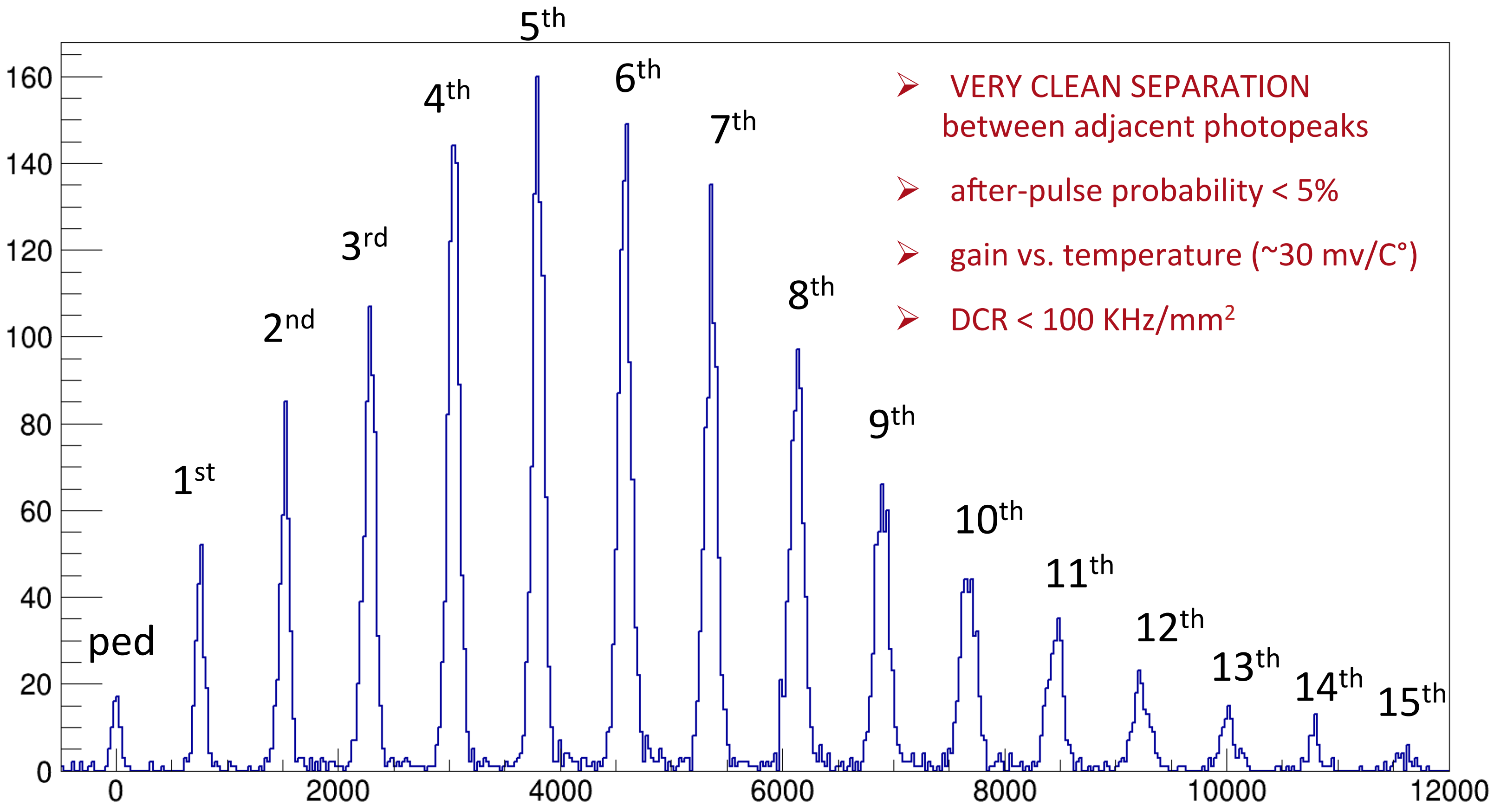


Gain spread ΔG/G at fixed temperature for ~10^3 channels (the gain spread of the FE electronics is FOLDED in)

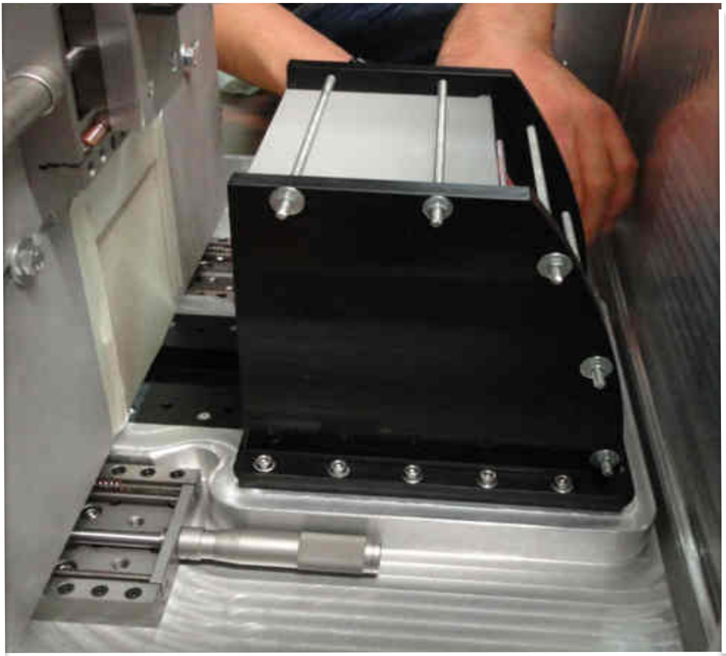
A real Photon Counting Device at room temperature !

NUV-SiPM arrays developed at FBK-Trento

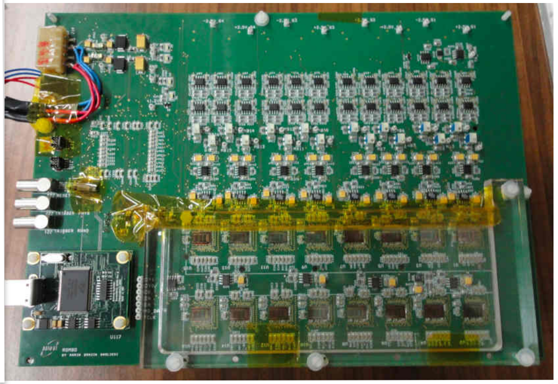
- designed for SPIDER2 R&D project under INFN funding
- delivered in December 2014

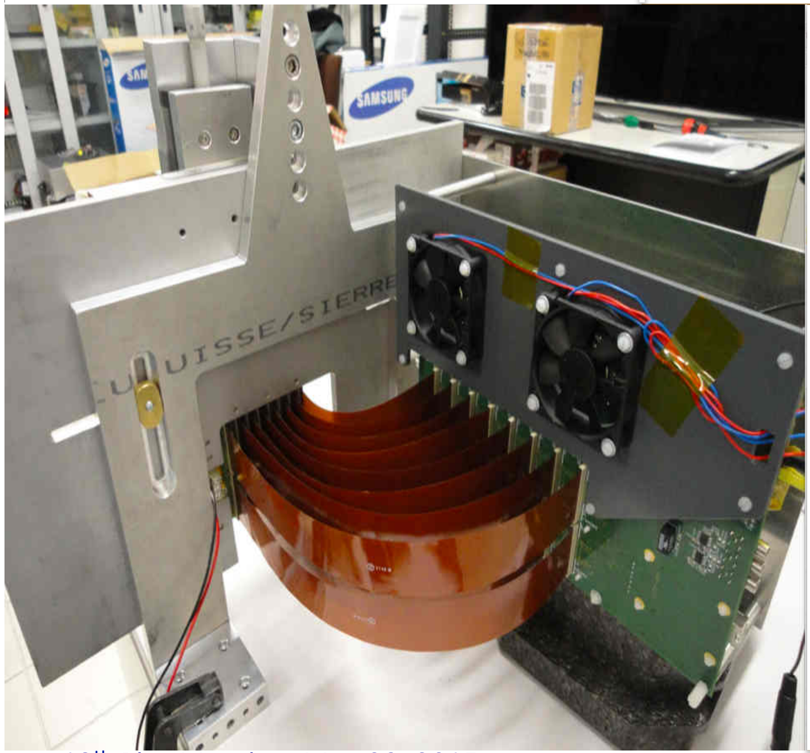


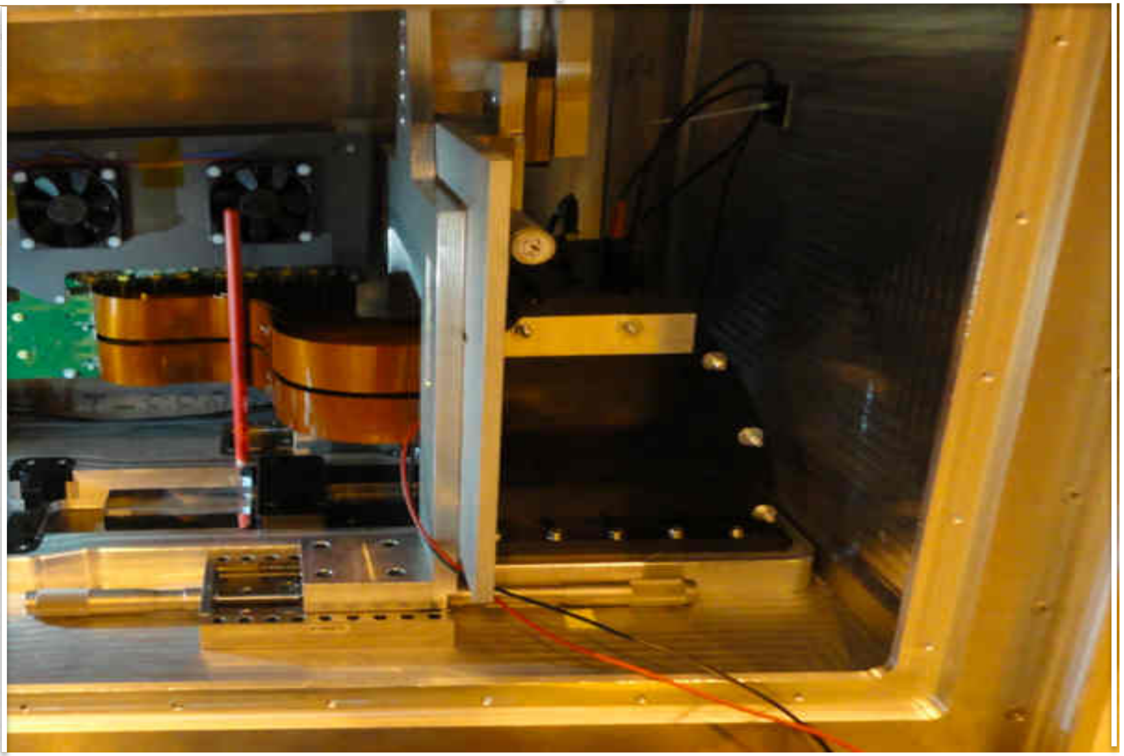
- ➢ VERY CLEAN SEPARATION between adjacent photopeaks
- ➢ after-pulse probability < 5%
- ➢ gain vs. temperature (~30 mv/C°)
- ➢ DCR < 100 KHz/mm^2



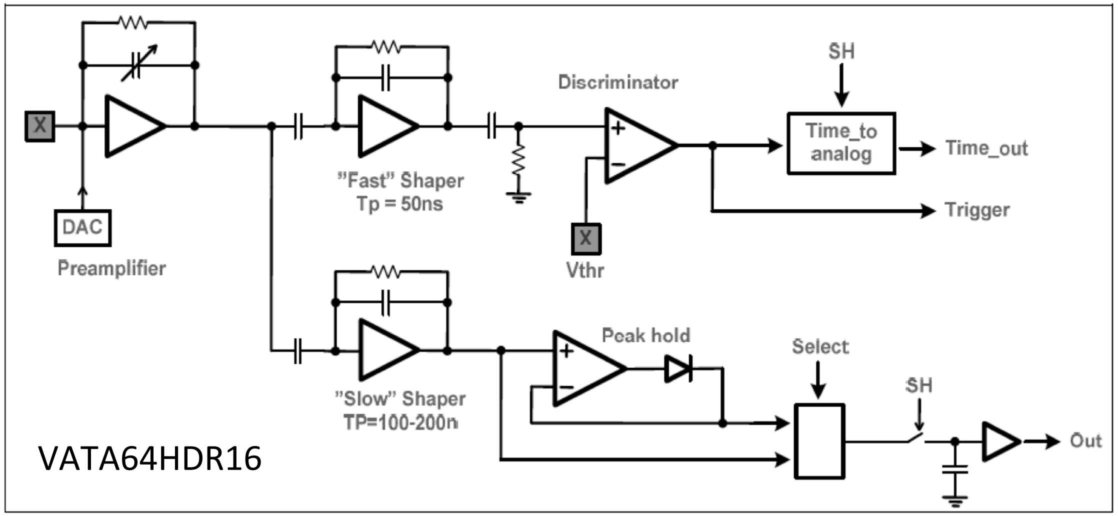
Prototype Construction in Siena/Pisa







Front End electronics and readout of 1024 SiPMs



M.G. Bagliesi et al., Nucl.Phys.B (Proc.Suppl.) 215:344-348, 2011

Custom ASIC VATA64HDR16:

- autotrigger mode / external trigger
- adjustable threshold / channel
- programmable slow shaper 50 – 300 ns
- Peak&Hold device → pulse height
- fast shaper + TAC → time measurement (~ 160 ps resolution)

2014: FDIRC readout board (1024 chns) developed in Siena/Pisa

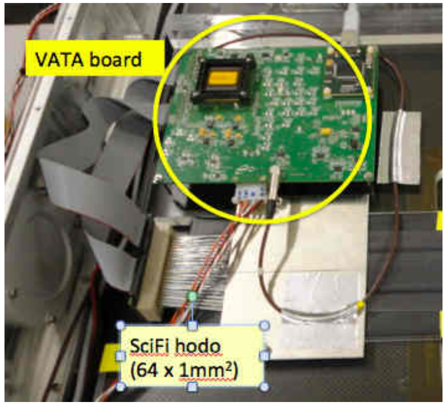
- **16 VATA chips**
- 16 bit ADCs
- 1024 SIPM digitized signals
- 1024 time stamps
- autotrigger + 2 external triggers: random/physics
- USB-2 connection to PC

2009/10: development of custom ASIC for SIPM readout (64 channels)

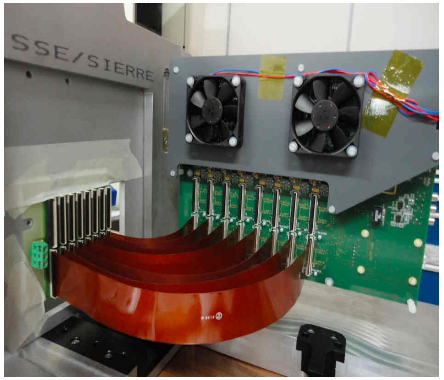
jointly funded by INFN (SPIDER project) and GM-IDEAS

- 64 pulse height measurements
- 64 time measurements
- **custom SIPM r/o board (64 chns)**

2011 SciFi hodoscope with SIPMs

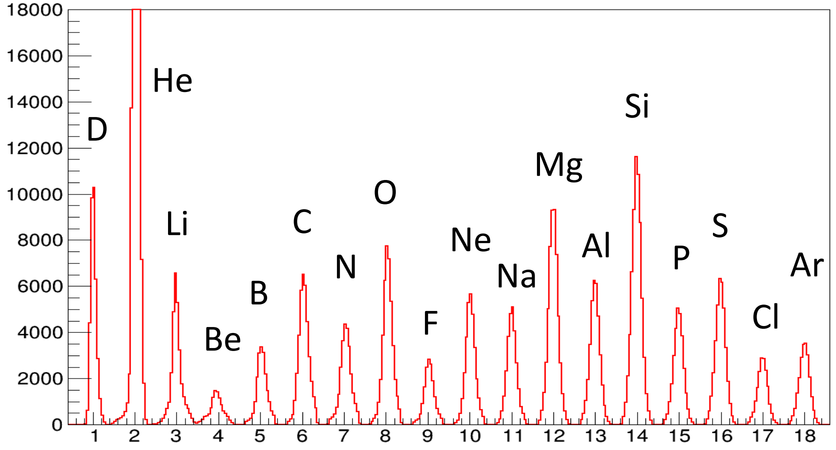


2013:
Scintillation Fiber hodoscope
(1 VATA)
@CERN beam test



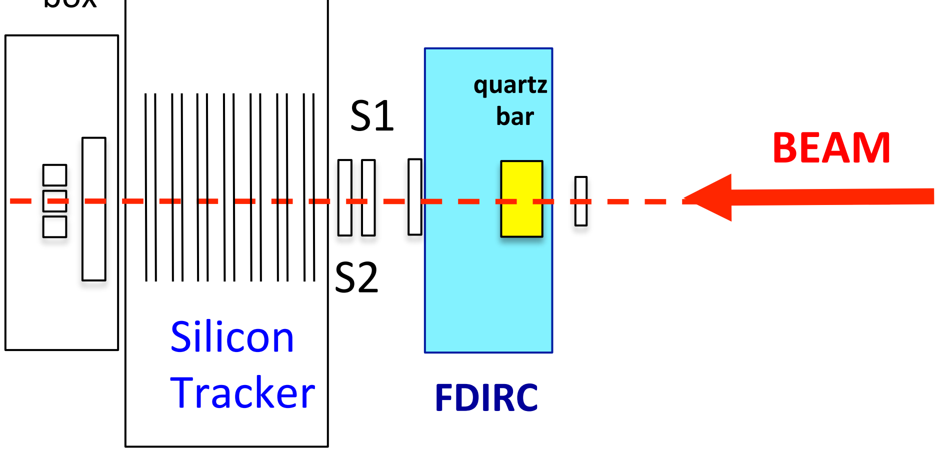
2014:
FDIRC prototype
(16 VATA)

- to test isotopic separation → need a LOW ENERGY ion beam (P < few tens of GeV/c)
- However, in March 2015 we had the opportunity of a parasitic beam test at CERN SPS (H8) primary Ar beam → internal target → ion fragments with A/Z=2: ^{2}H, ^{4}He, ... , ^{34}Cl, ^{36}Ar
- available beam energies (13, 19, 30 GeV/n) too large: **no chance for isotopic separation** by $\Delta\beta$ measurements. Nevertheless we decided to test the performance of the FDIRC prototype:



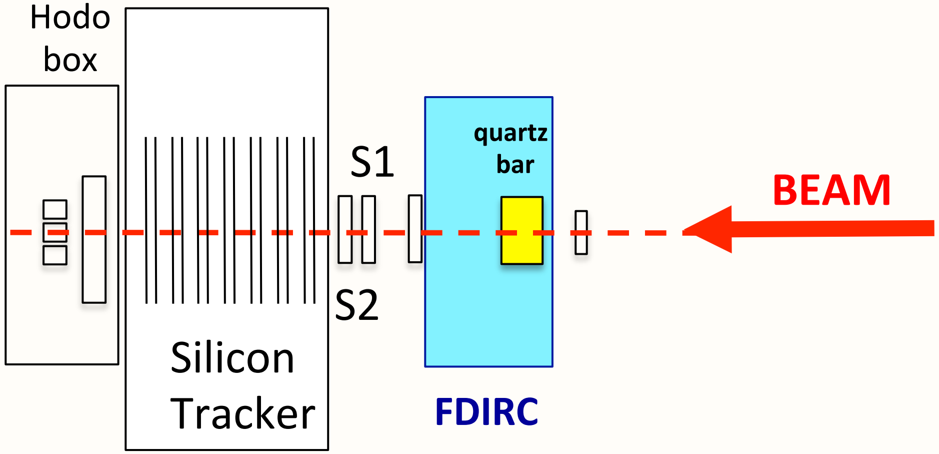
charge tagging by Silicon Tracker

Beam Test Layout



- Silicon Tracker identifies beam particles (+ interact. products in FDIRC)
- CHARGE-TAGGING: up to 14 independent dE/dx samples: 4 Si pixel layers + 10 Si strip layers

CERN 2015 Ion Beam Test Layout


Hodo box

Silicon Tracker

S1

S2

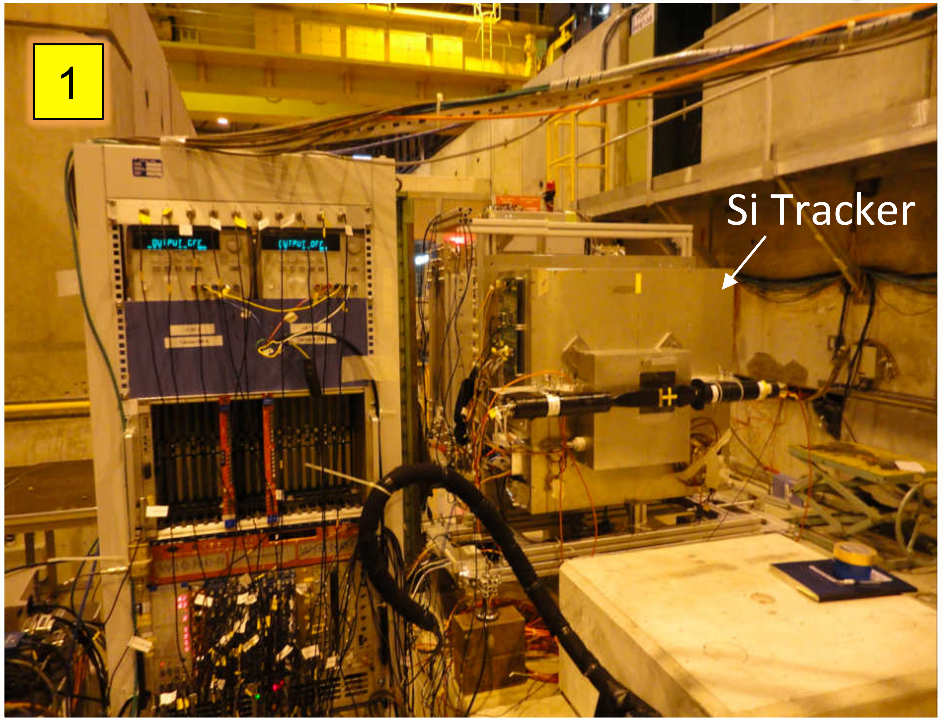
quartz bar

FDIRC

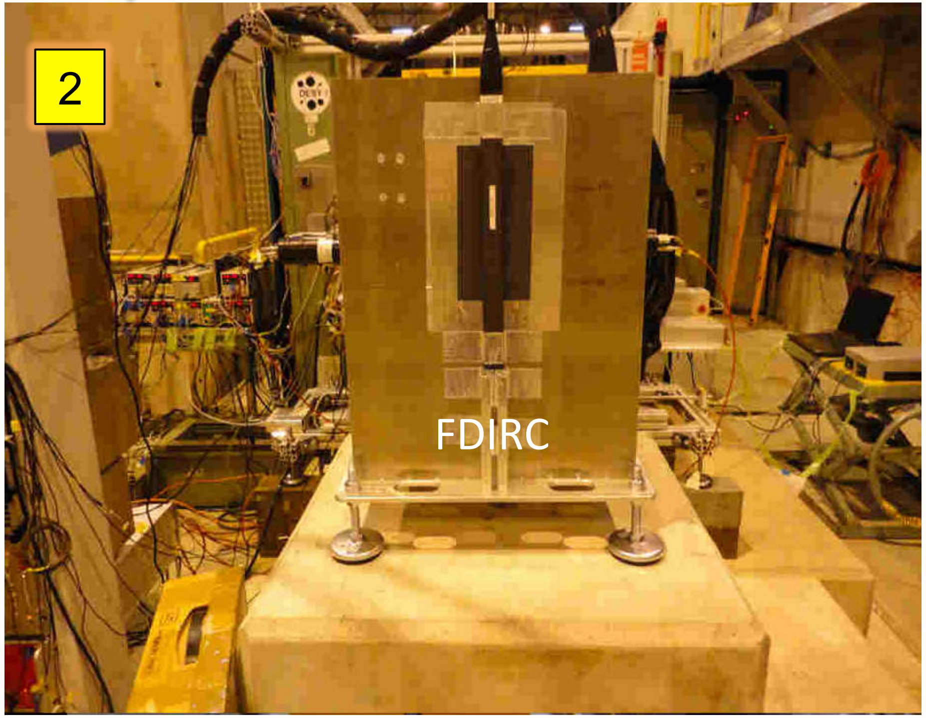
BEAM

March 2015, SPS H8 beam line

data: ~ 9 10^6 triggers collected



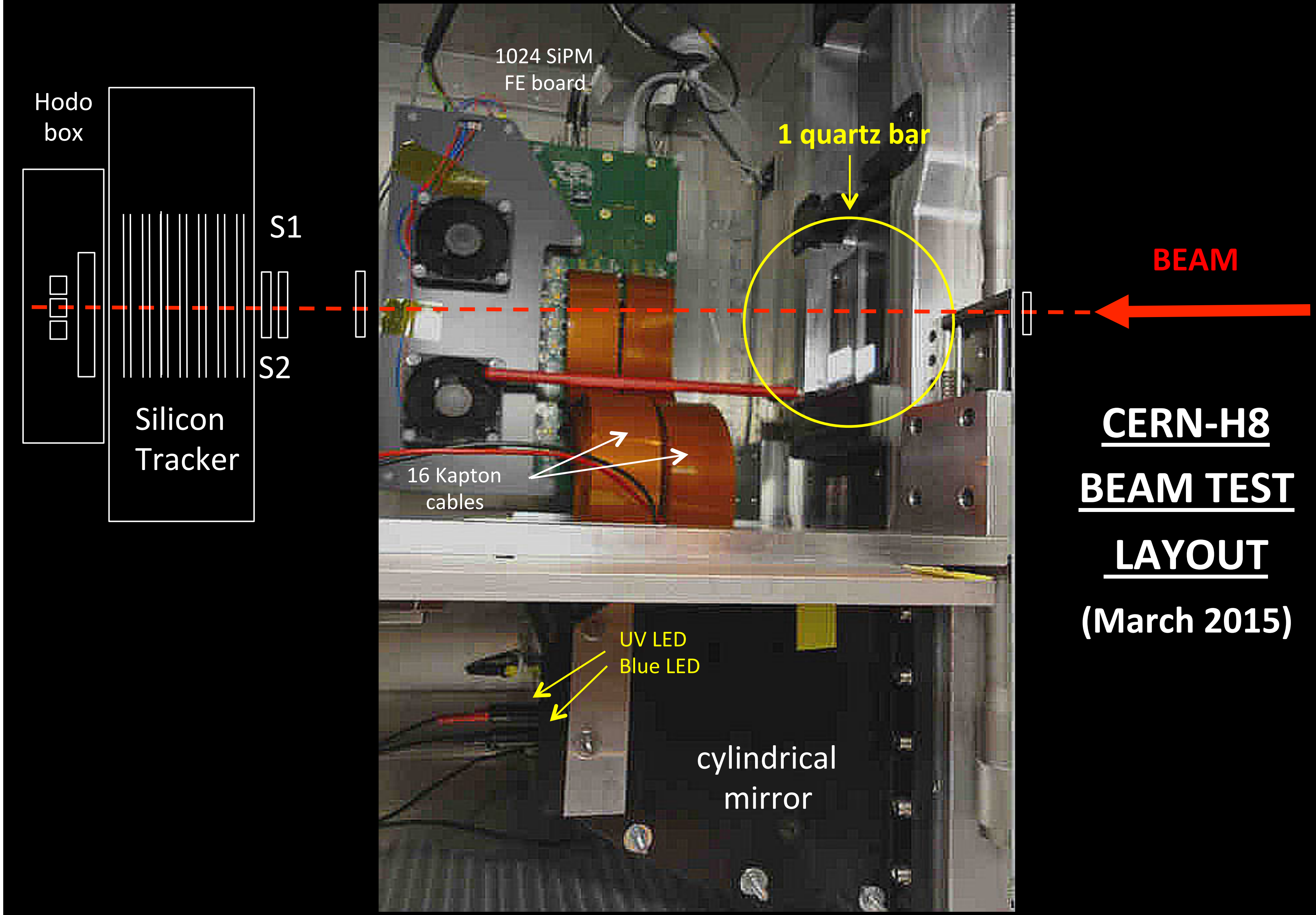
beam line after TRACKER installation



beam line after FDIRC installation

CERN-H8 BEAM TEST LAYOUT

(March 2015)

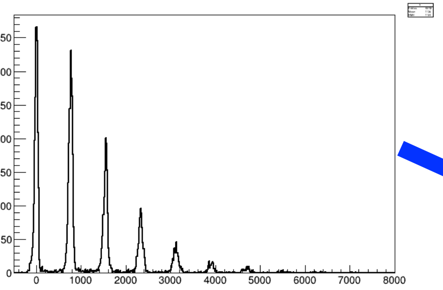


FDIRC Signal and Background subtraction

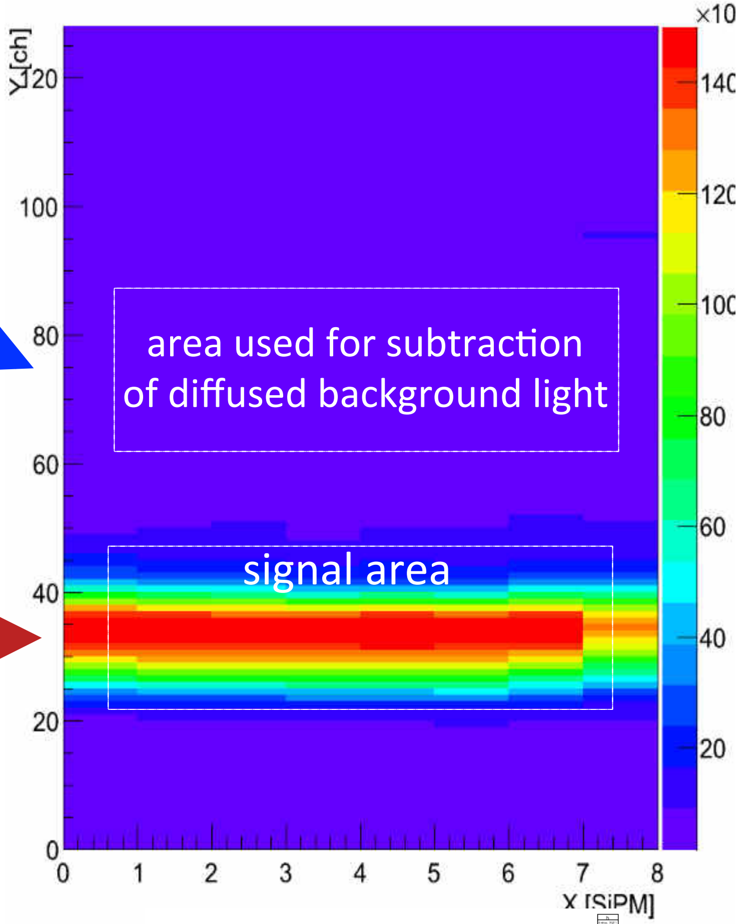
❑ Diffused light background:

reflected light: mainly from the lateral walls of the mirror

- small (~ 5 %)
- from Cherenkov light
  → proportional to Z^2
- measured with beam triggers

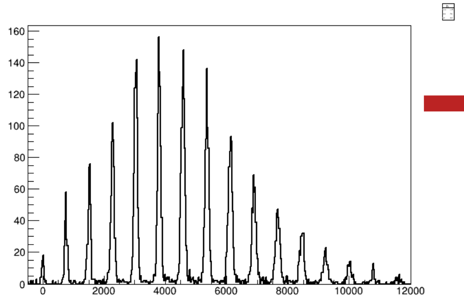


in a region with same area but far away signal region.



❑ Cherenkov signal:

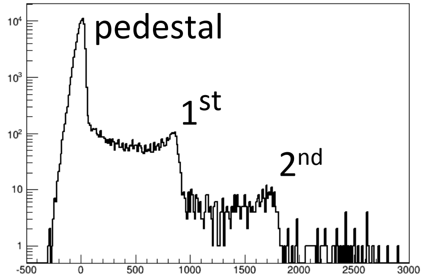
- from signal illuminated band
- well below SIPM saturation



❑ Dark count background:

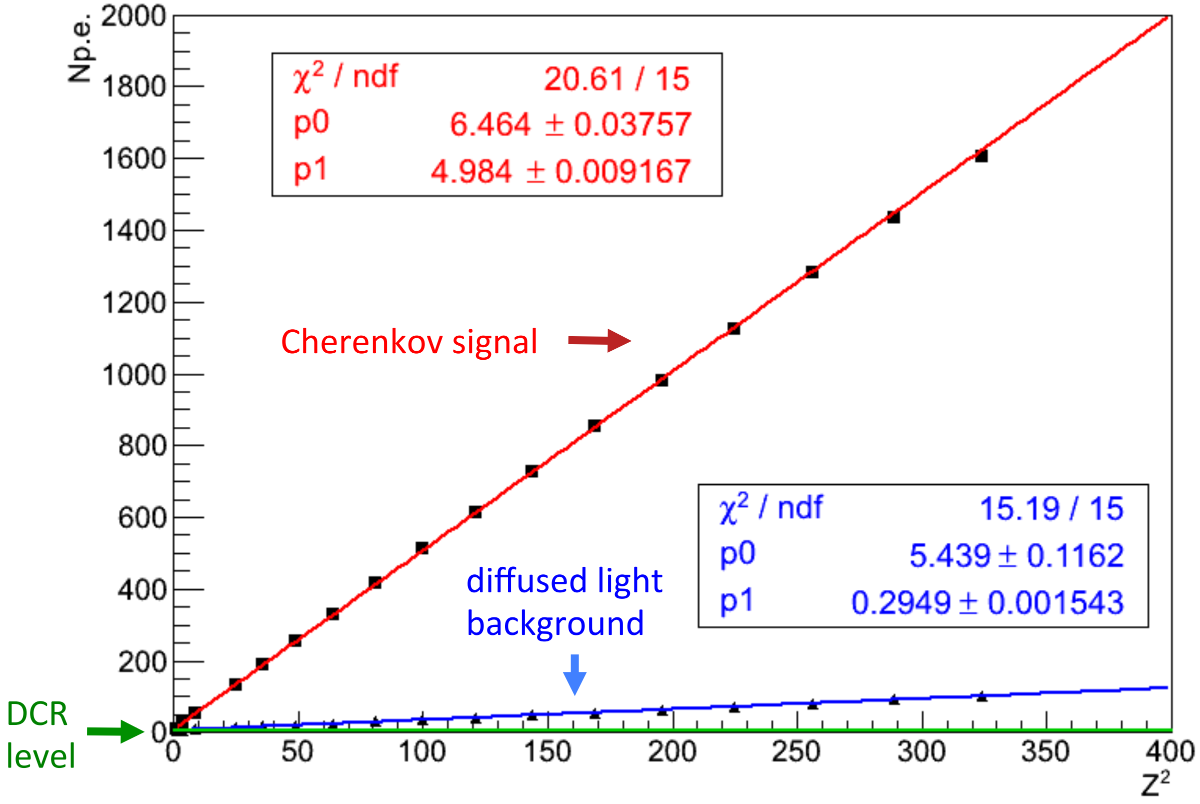
due to **SiPM dark count rate** (DCR)

- does not depend on atomic number Z
- measured with random triggers (off spill: no beam triggers)
- very small (%) due to excellent performance of SiPM arrays



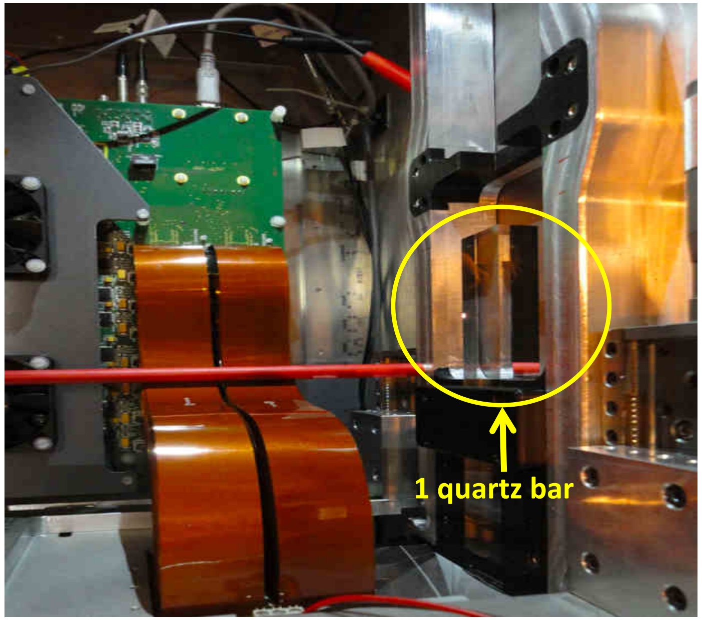
Z^2 dependence of Cherenkov (integrated) signal

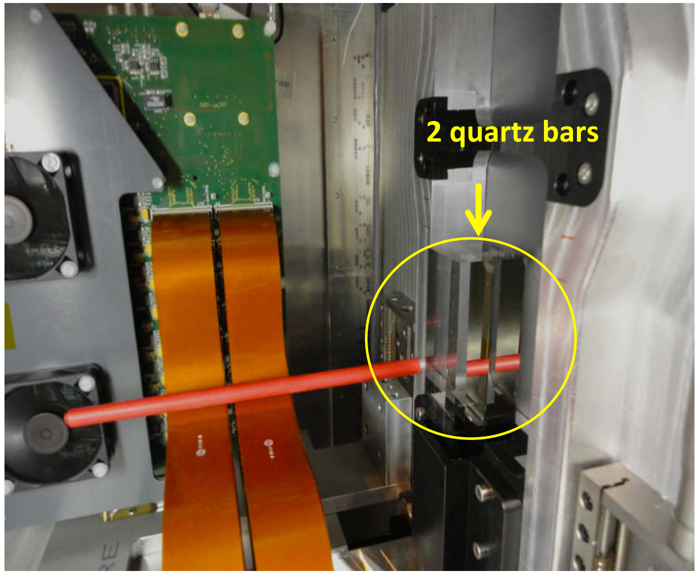
- INTEGRAL measurement: use **Cherenkov light yield** ~ Z^2 to identify chemical elements by their CHARGE Z



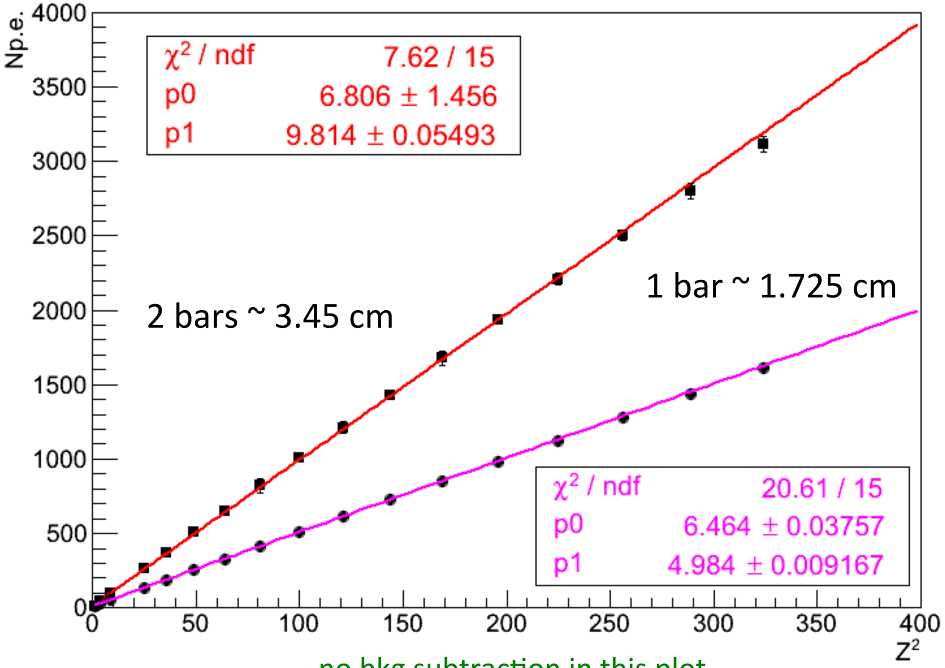
The mosaic of 16 SiPM arrays covers ~ 1/3 of the focal plane. Active area is ~68% of instrumented area (cracks among arrays). For Z=1 particle: ~ 5 p.e. in region covered by SiPM arrays → ~ 22 p.e.on the whole focal plane (ideal seamless mosaic).

Integrated Cherenkov light from 2 radiators of different thickness





Z^2 dependence of Cherenkov signal

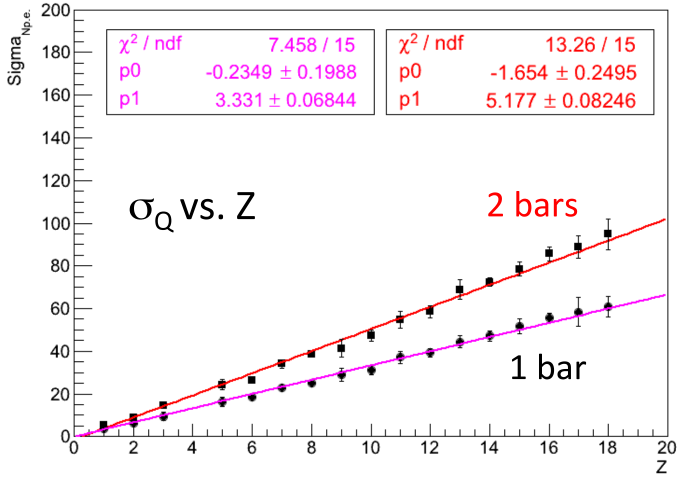


no bkg subtraction in this plot

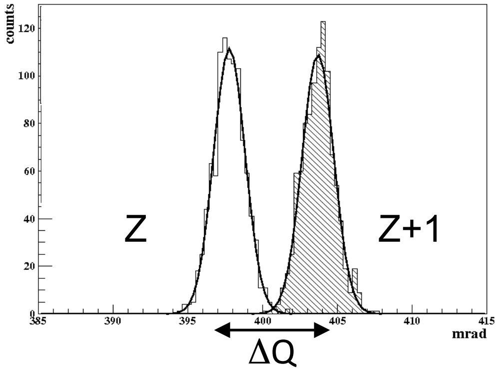
- scales linearly with radiator thickness
- NO SATURATION effects in the radiator as well as in the photosensors: each SiPM has 400 micro-cells and max photopeaks with 2 bars for Argon are < 50 → well below SIPM saturation

Charge separation: Photon counting

- Integrated Cherenkov signal $Q(Z) \sim N_{pe} Z^2$
- $\sigma_Q^2 \sim N_{pe} Z^2 + \sigma^2_{electronics} + \ldots$
- σ_Q dominated by Poissonian photostatistics: scales $\propto N_{pe}^{1/2}\, Z$ i.e. **linear in Z**


linear Z dependence of σ_Q

☐ **Charge separation** $\equiv \sigma_Q / \Delta Q$

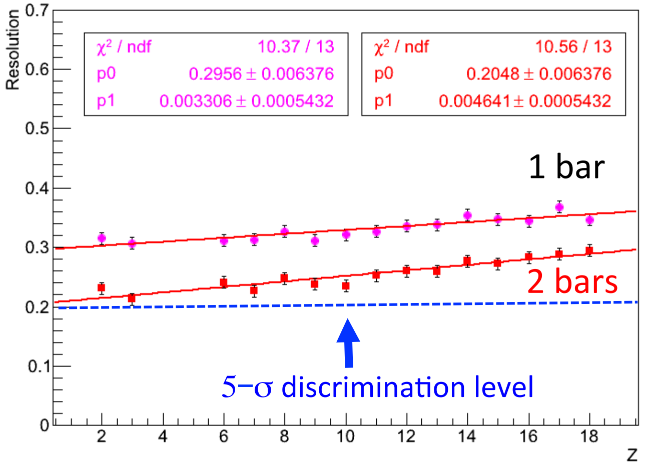


For two adjacent ions with $\Delta Z = 1$:

$\Delta Q = Q(Z+1) - Q(Z) = (2Z+1)\, N_{pe}$

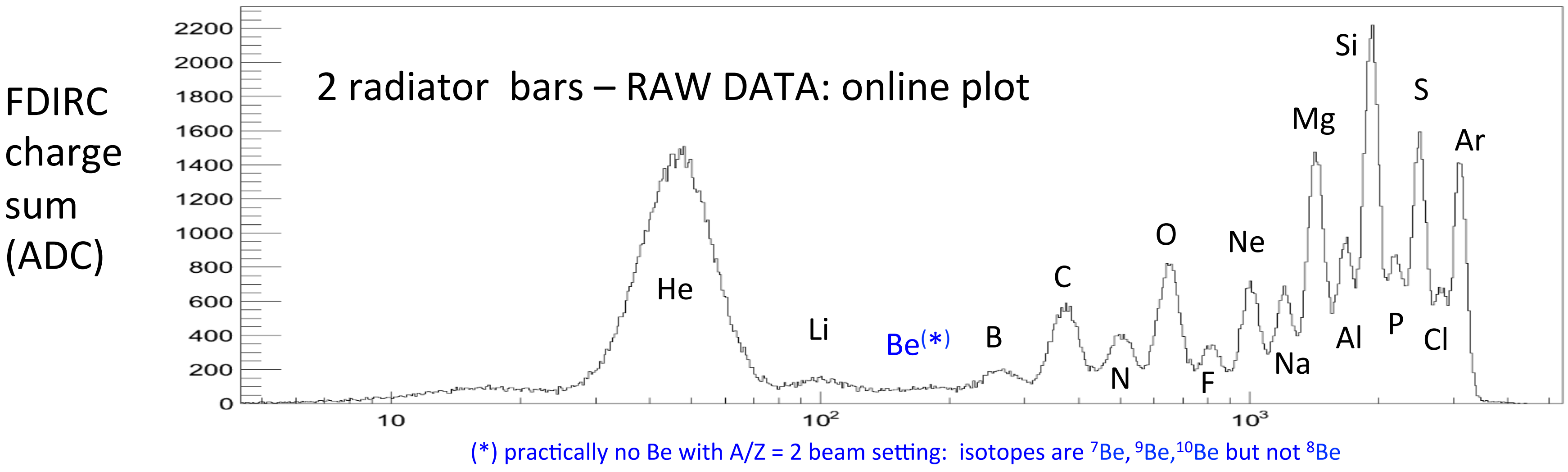
$$\frac{\sigma_Q}{\Delta Q} \propto \frac{1}{2\sqrt{N_{pe}}}$$

If purely Poissonian then charge separation should be independent of Z.
Residual linear Z dependence is observed in the data.

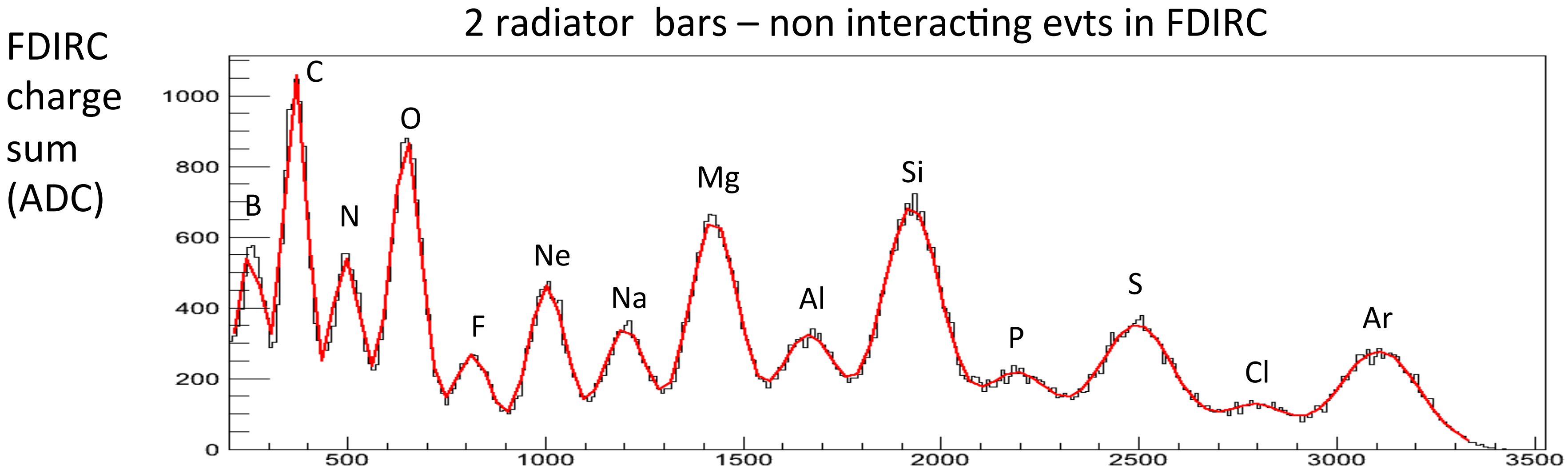

charge separation vs. Z

LEGENDA: Z = atomic number = charge of fully stripped ion
N_{pe} = number of p.e. for Z=1 charge

Charge identification by FDIRC (integral measurement)

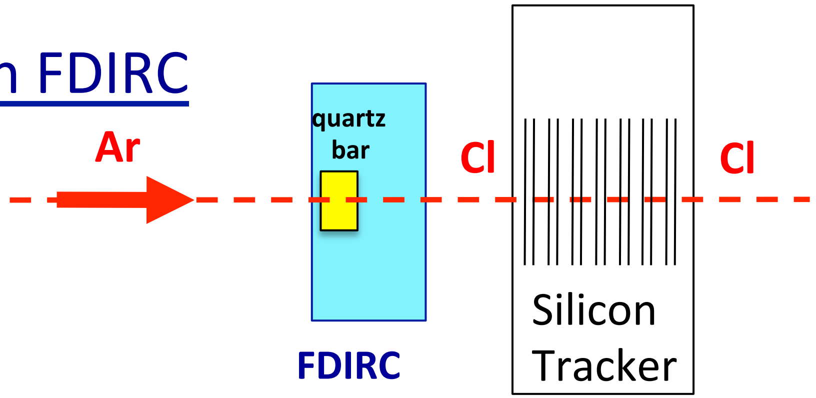


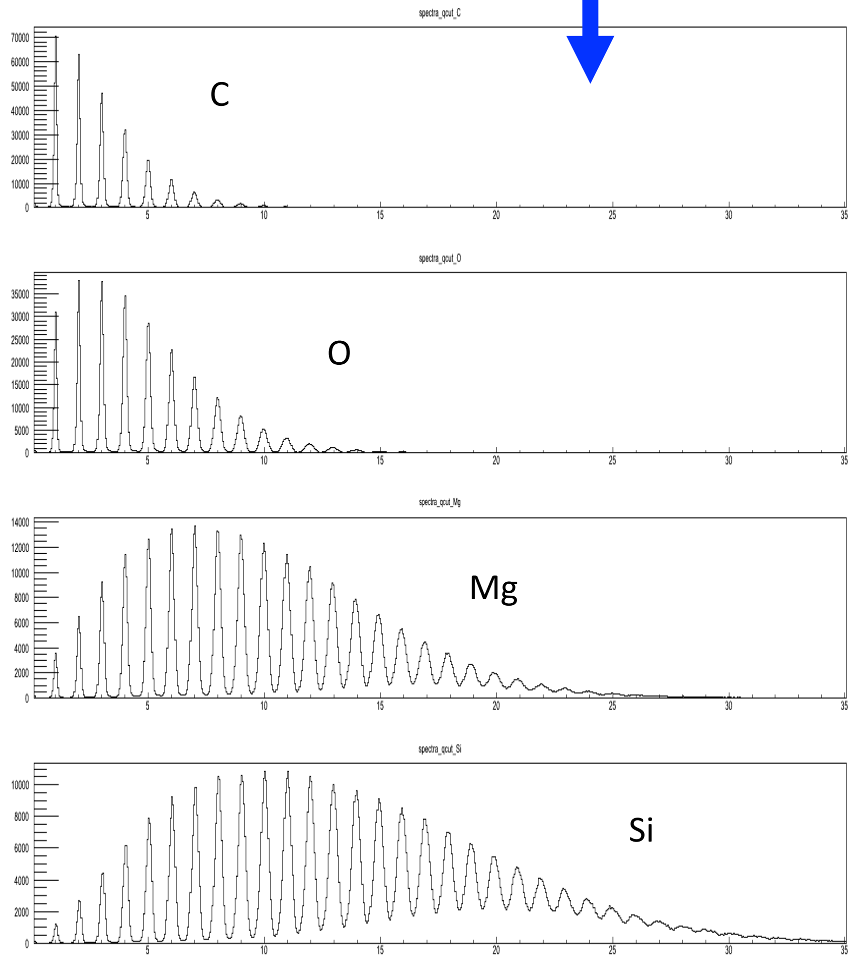
(*) practically no Be with A/Z = 2 beam setting: isotopes are ^{7}Be, ^{9}Be, ^{10}Be but not ^{8}Be

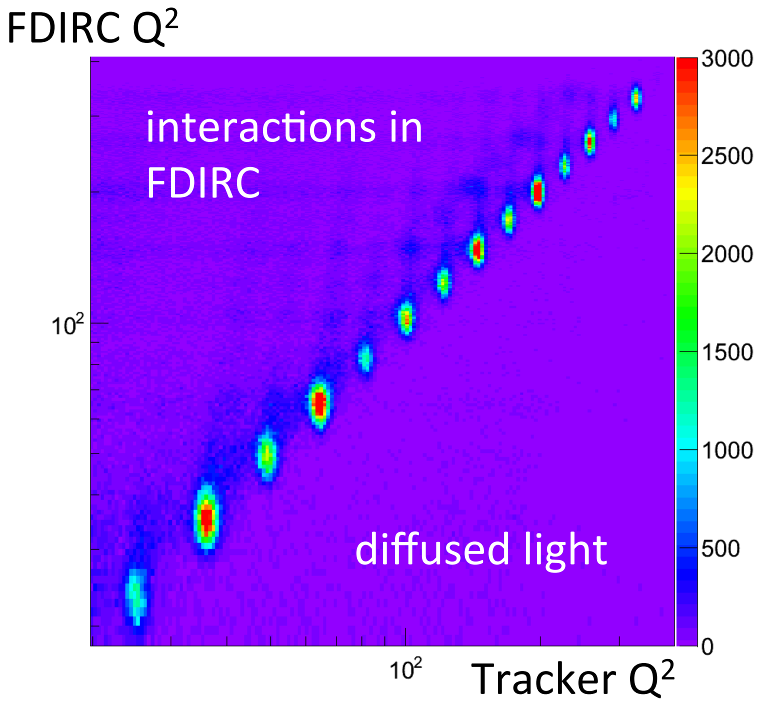


❑ Selection of non-interacting nuclei in FDIRC

Photopeak spectra for non-interacting ions:
C, O, Mg, Si   with 2radiator bars







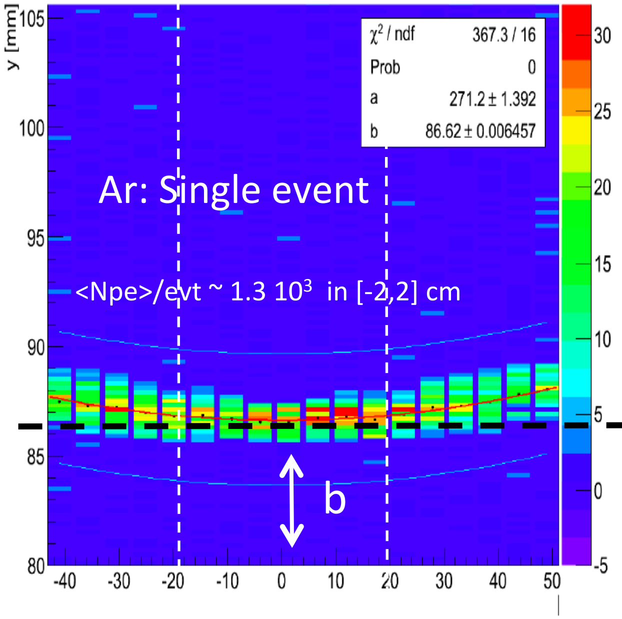
Use charge tagging from Tracker (downstream FDIRC): impose the same charge.

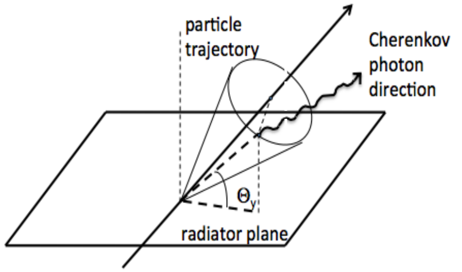
Cherenkov pattern fit: MC simulation vs beam test data

- DIFFERENTIAL measurement : fit Cherenkov pattern and measure FDIRC angular resolution.
- For tracks at normal incidence on the radiator the focal plane (FP) pattern is hyperbolic.

Geant4 simulation: 30 GeV/n Ar

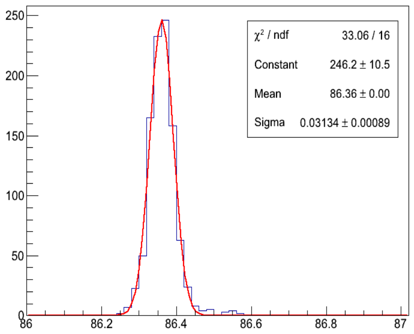
(beam center shifted on the left as at beam test)



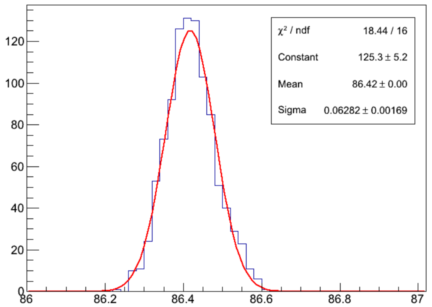


Θy is conserved during propagation along the bar

- Dead areas among SiPM arrays implemented in the simulation. In total 68% of instrumented FP area is active.
- fit FP pattern event-by-event:
  - → Cherenkov angle Θ_y
  - → apex of hyperbola (b parameter)



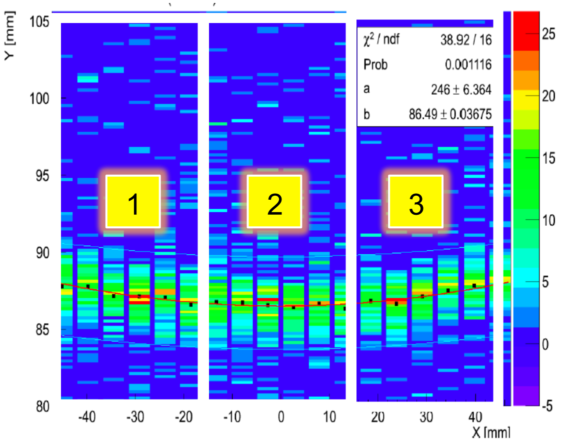
MC simulation:
fitted **b parameter**
σ_b~ 31 μm for Ar



beam test data:
fitted **b parameter**
σ_b~ 63 μm for Ar

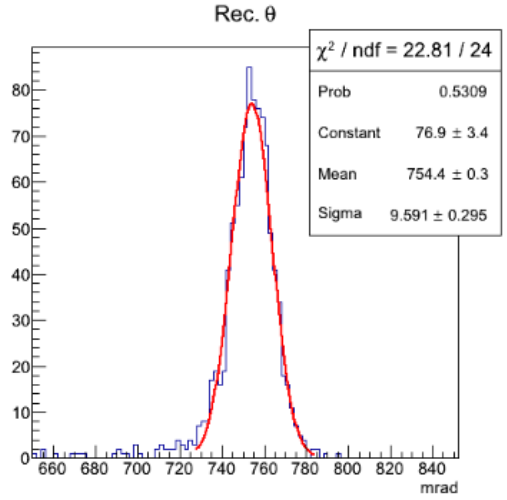
Beam data fit to b-parameter is ~ **2 times larger than MC.**
However: geometry + bar imperfections affecting light propagation along the bar are not simulated as well as diffused light background.

Cherenkov angle fit: MC simulation vs beam test data

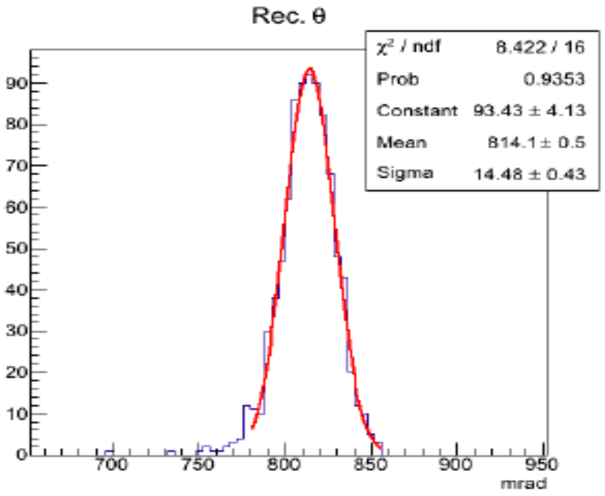


The SiPM instrumented area (4.3 cm x 2.7 cm) covers only ~ 1/3 of the Cherenkov pattern for tracks at normal incidence.

- Take data at 3 different positions moving the focal plane along the X-axis
- select events within a "narrow beam" (8 mm x 10 mm) using tracking info
- data stitching from 3 evts at different positions → cover x: [-5, +4] cm
- angular fit "event-by-event" → reconstruct Cherenkov angle Θ



Ar: MC simulation
fitted **Cherenkov angle**
σ_Θ~ 9.6 mrad for Ar



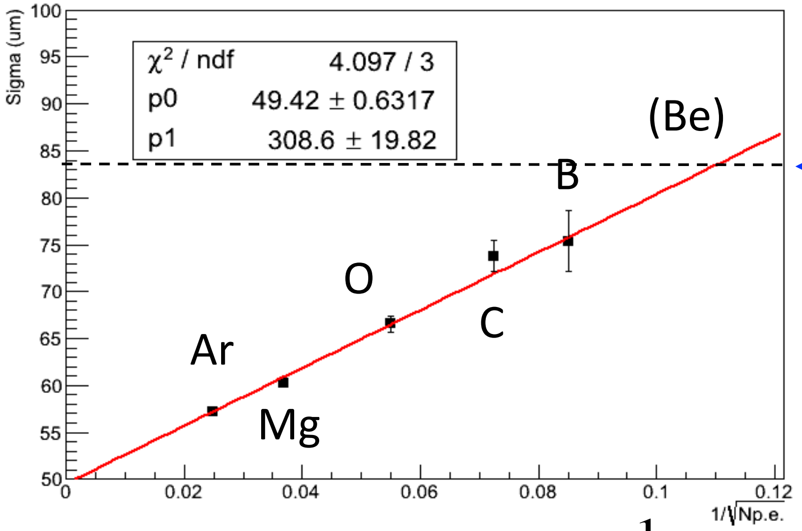
Ar: beam test data
fitted **Cherenkov angle**
σ_Θ~ 14.5 mrad for Ar

Beam data angular resolution is ~ 1.5 larger than MC.

Of course, "stitching" 3 different events is just a poor approx.of having a larger instrumented area.

Be isotopes mass separation for P < 30 GeV/c ?

- ☐ To achieve σ_M = 0.2 amu (i.e. 5-σ mass separation) for ^{10}Be/^{9}Be → $\sigma_M/M < 0.02$ → σ_θ ~ **1.5 mrad**
- ☐ **Difficult → needs larger mirror aperture and larger FP coverage. How about apex parameter b?**

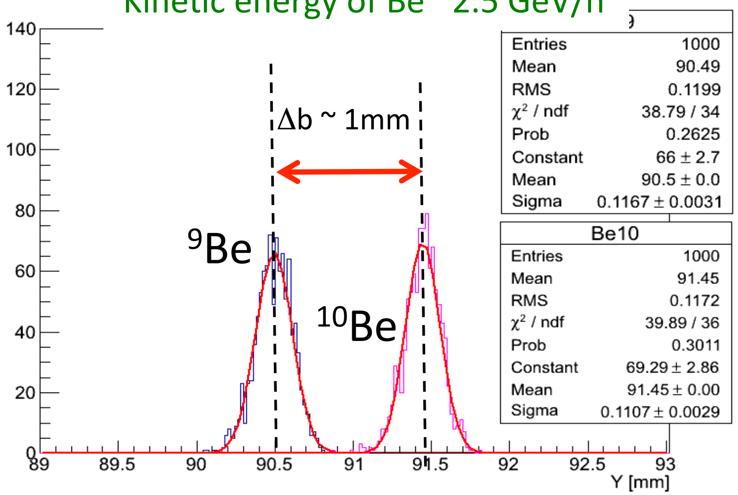


error on b-parameter vs $\dfrac{1}{\sqrt{N_{pe}}}$

- Extrapolation of beam test data to Be gives σ_b~ 85μm
- This is possible because SiPM size is small (200μm) along y.
- Δb ~ 1mm distance on the focal plane for the two Be isotopes with 31.5 GeV/c total particle momentum (at normal incidence).

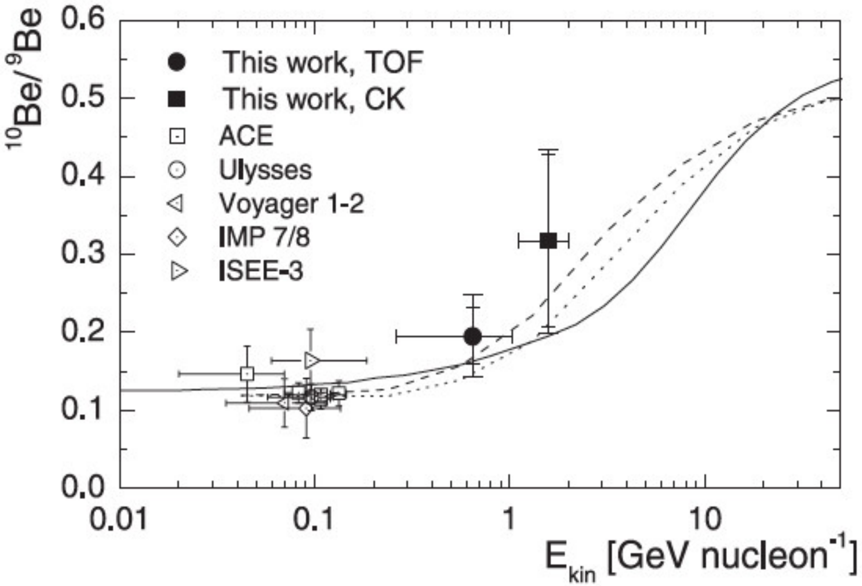
- **Simulated b-parameter distributions for ^{9}Be and ^{10}Be** at 31.5 GeV/n total momentum (7.9 GV).
- The difference in Cherenkov angles is ~7.7 mrad
- The difference in b-parameter Δb~ 1mm
- [-2,+2] cm instrumented area as in beam test.
- **track at normal incidence**

Kinetic energy of Be ~2.5 GeV/n



Cosmic $^{10}Be/^{9}Be$ Isotopic Ratio

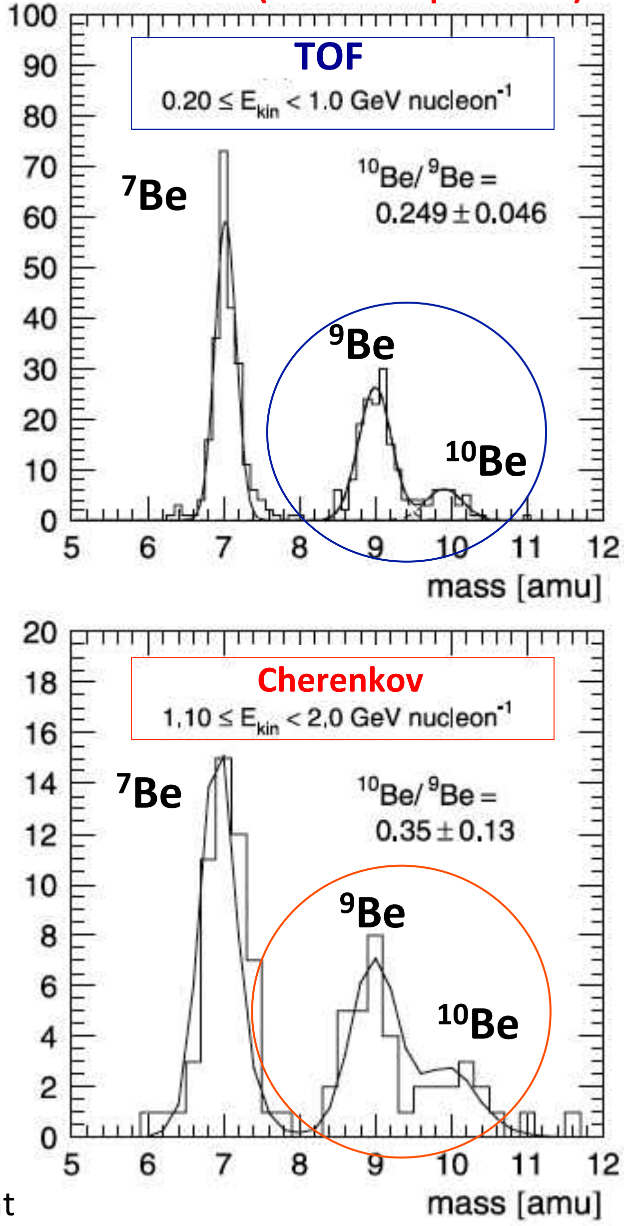
- ^{10}Be decays to stable ^{9}Be isotope
- "radioactive clock" to measure propagation time in the galaxy: very important for astrophysics models
- few measured points vs kinetic energy per nucleon
- need better accuracy + extension above 2 GeV/n



T. Hams et al., The Astrophysical Journal, 611:892–905, 2004

^{10}Be/^{9} Be isotopic ratio measurement by ISOMAX (balloon experiment with magnetic spectrometer) in the energy interval 0.2 < E_{kin} < 2.0 GeV/n

ISOMAX (balloon experiment)



Conclusions

- Good beam test performance of our first prototype of FDIRC with SiPM readout
- Outstanding performance of the SiPM arrays
- Ion beam test data are very useful to study detector's full dynamic range
- Preliminary analysis presented (2 months after beam test) → more to come...
- Proof-of-principle for isotope separation requires lower beam momentum

- ^{10}Be/^{9}Be measurement is not easy.
- Effect of the incident track angle vs. mass resolution has to be studied.
- Requires 1-2% momentum resolution from magnetic spectrometer at 30 GeV/c.
- Quartz bars + coverage of focal plane with SiPM array are expensive.

(no meal is for free...)

Authors

P.S. Marrocchesi(a), M.G. Bagliesi(a), G. Bigongiari(a), S. Bonechi(a), P. Brogi(a), P. Maestro(a), F. Morsani(b), C. Piemonte(c), F. Stolzi(a), J.E. Suh(a), A. Sulaj a)

(a) University of Siena and INFN Pisa
(b) INFN Sezione di Pisa
(c) Fondazione Bruno Kessler (FBK), Trento