FARICH option for the PID system of the SPD experiment.

Alexander Barnyakov

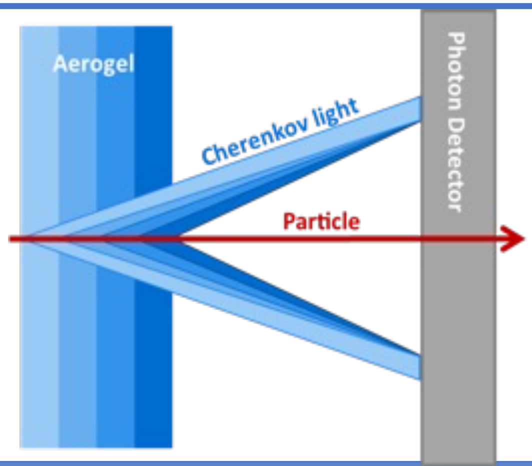
BINP group

- Introduction to FARICH technique
- Recent beam test results & aerogel performance
- Photon detection options
- Future R&D's steps
- Summary

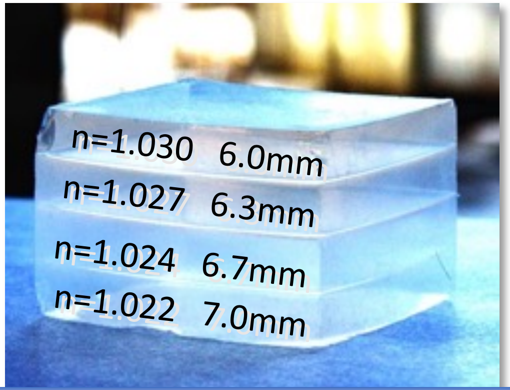
SPD Collaboration meeting, 23-27/10/2023, Samara

Introduction to FARICH technique

FARICH technique



The first 4-layer monolithic sample

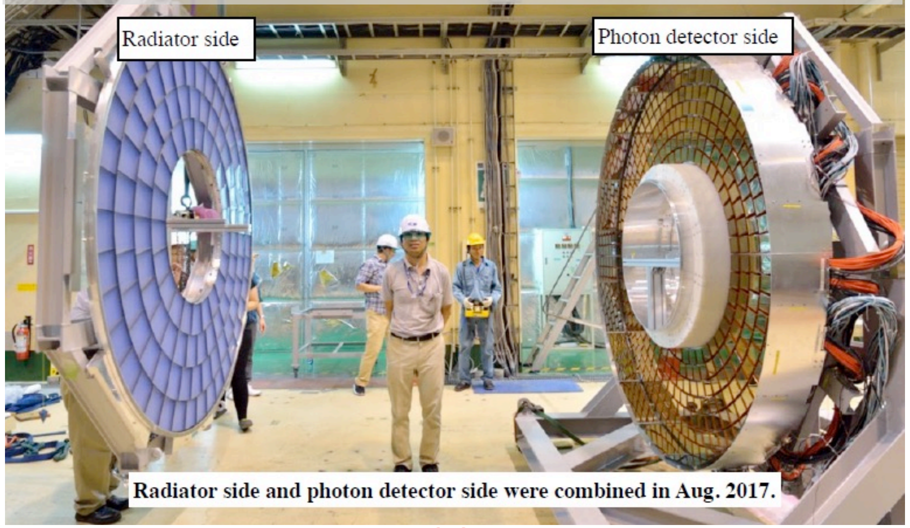


Increase N_{pe} due thickness increase without $\sigma_{\Theta c}$ degradation

T.Iijima et al., NIM A548 (2005) 383 and A.Yu.Barnyakov et al., NIM A553 (2005) 70

2004÷2005

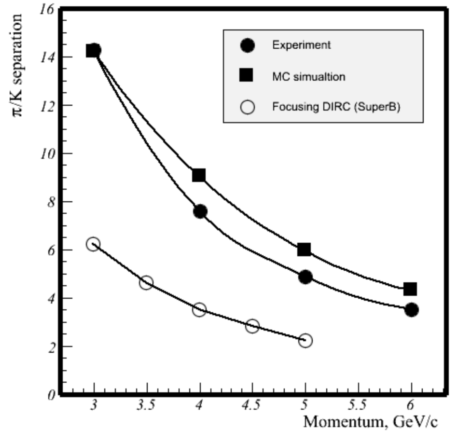
The Belle II (ARICH) is the first application of the method

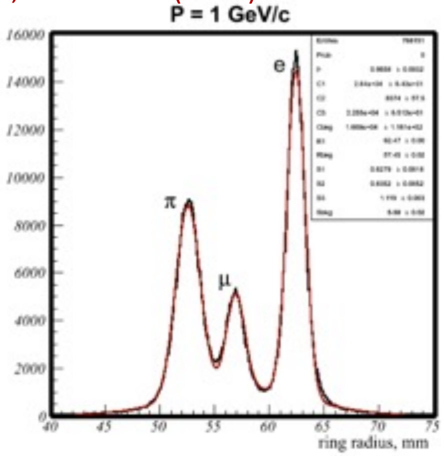


2017

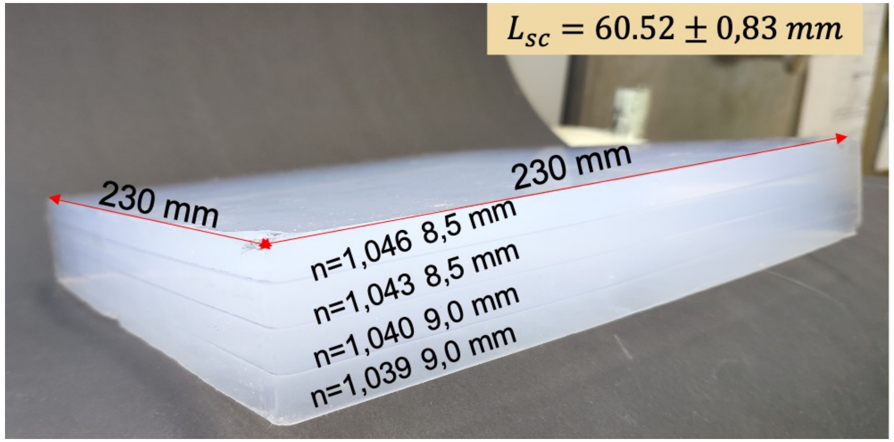
Excellent PID capability were shown at CERN beam test in 2012

A.Yu. Barnyakov, et al., NIM A 732 (2013) 352



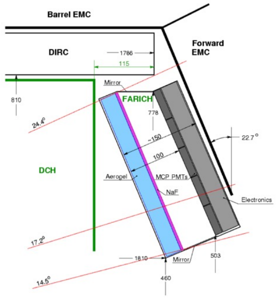


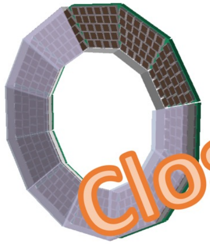
Two 4-layer focusing aerogel blocks
230x230x35 mm



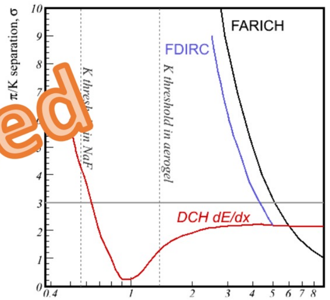
2022÷2023

FARICH proposals



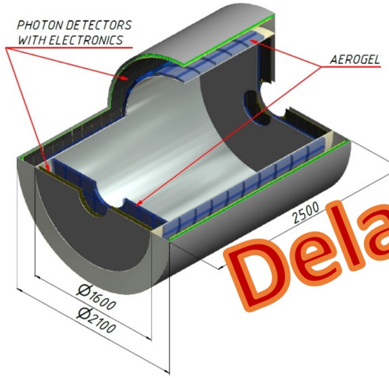


Closed

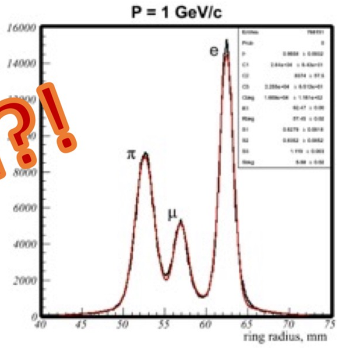


SuperB Forward RICH

PID: π/K up to 6 GeV/c
Radiator: 4- or 2-layer aerogel + NaF PD: MCP PMT



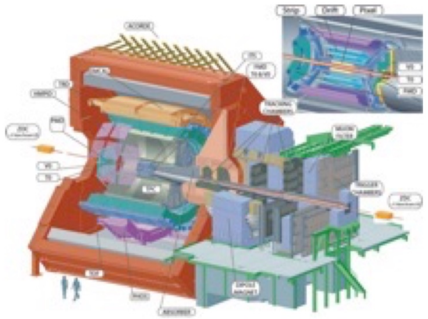
Delayed?!



FARICH for Super Charm-Tau Factory

PID: μ/π up to 1.7 GeV/c
$21 m^2$ detector area (SiPMs) ~1÷2 M channels

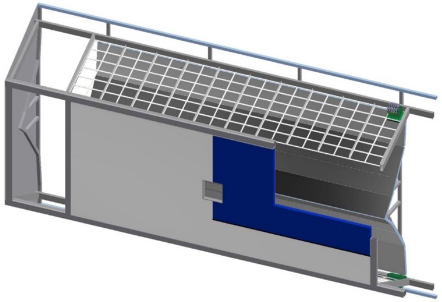
Closed



FARICH for ALICE HMPID upgrade

PID: π/K up to 10 GeV/c, K/p up to 15 GeV/c
$3 m^2$ detector area (SiPMs)

Delayed?!



Forward Spectrometer RICH for PANDA

PID: π/K/p up to 10 GeV/c
$3 m^2$ detector area (MaPMTs or SiPMs)

Main motivations to use FARICH in colliding beam experiments

- Reliable π/K–separation up to P=5÷8 GeV/c.
  - reliable $D^{\pm}(D^0)$ reconstruction in experiments with 2E=27 GeV.

A.Yu. Barnyakov et al., NIM A732 (2013) 352

- μ/π–suppresion at the level of $\frac{1}{50\div100}$ up to momentum 1.5 GeV/c.
  - improve detection efficiency of $J/\psi \rightarrow \mu\mu$

A.Yu. Barnyakov et al., NIM A766 (2014) 235.

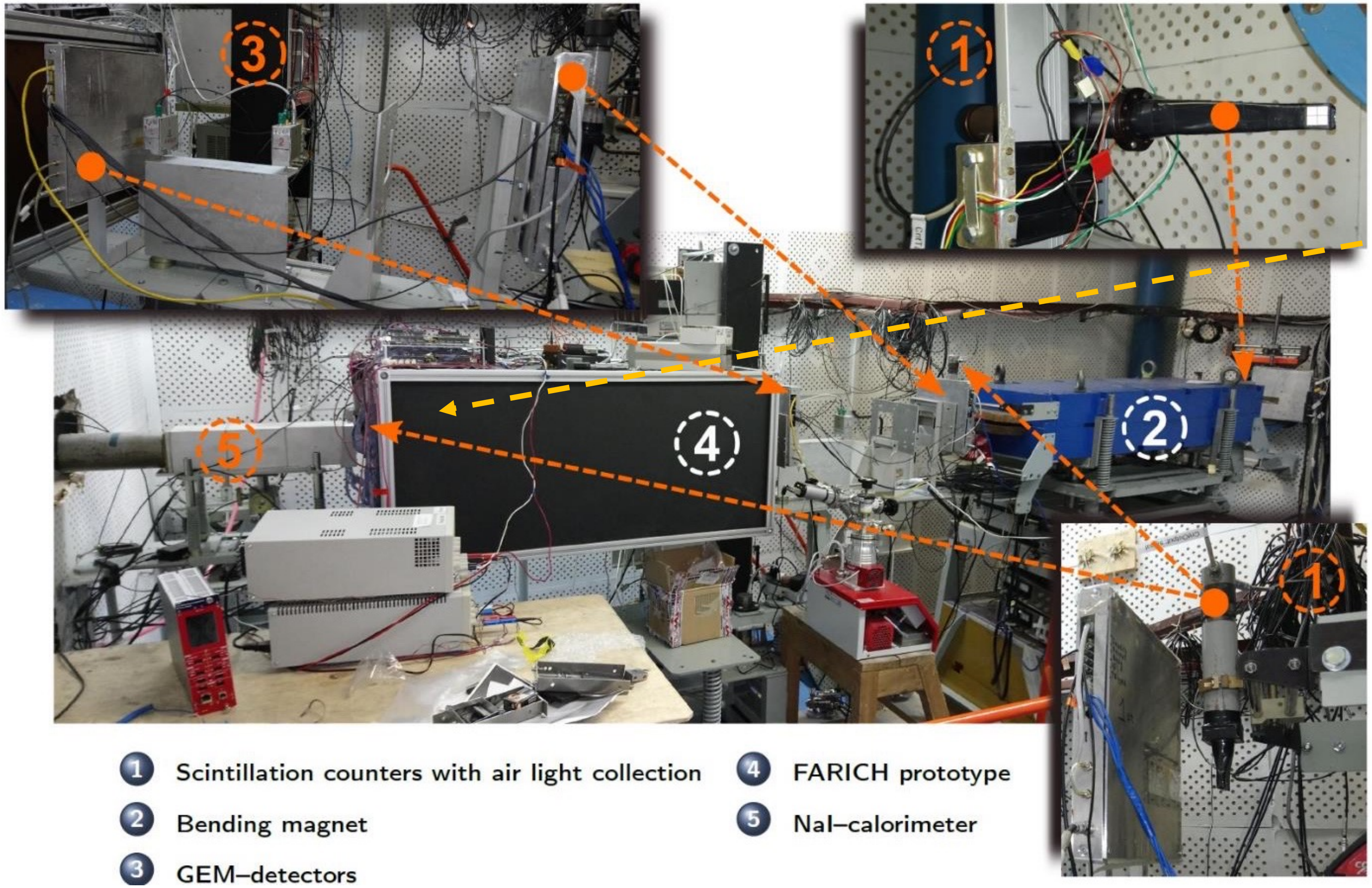
- Direct prcise charged particle velocity measurements
  - independent momentum mesurements with $\frac{\sigma_P}{P} = 1 \div 2\%$

A.Y. Barnyakov et al. NIM A598 (2009) 169–172

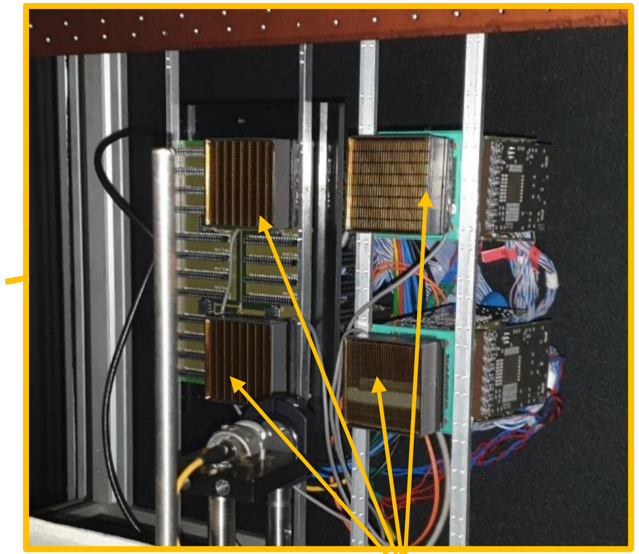
Recent beam test results & Aerogel performance

BINP beam test facility

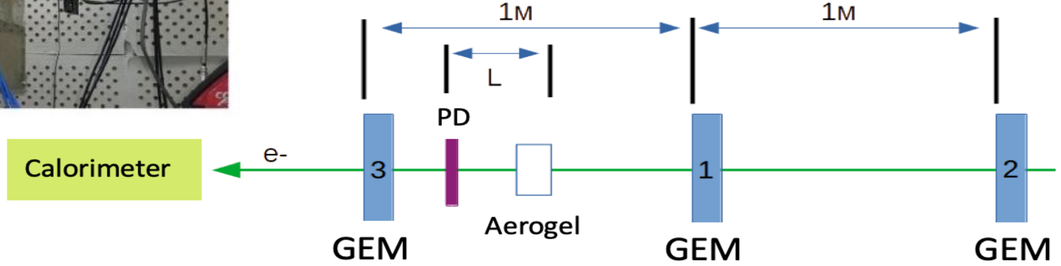
Example disposition of equipment in experimental hall (15/03/2018)



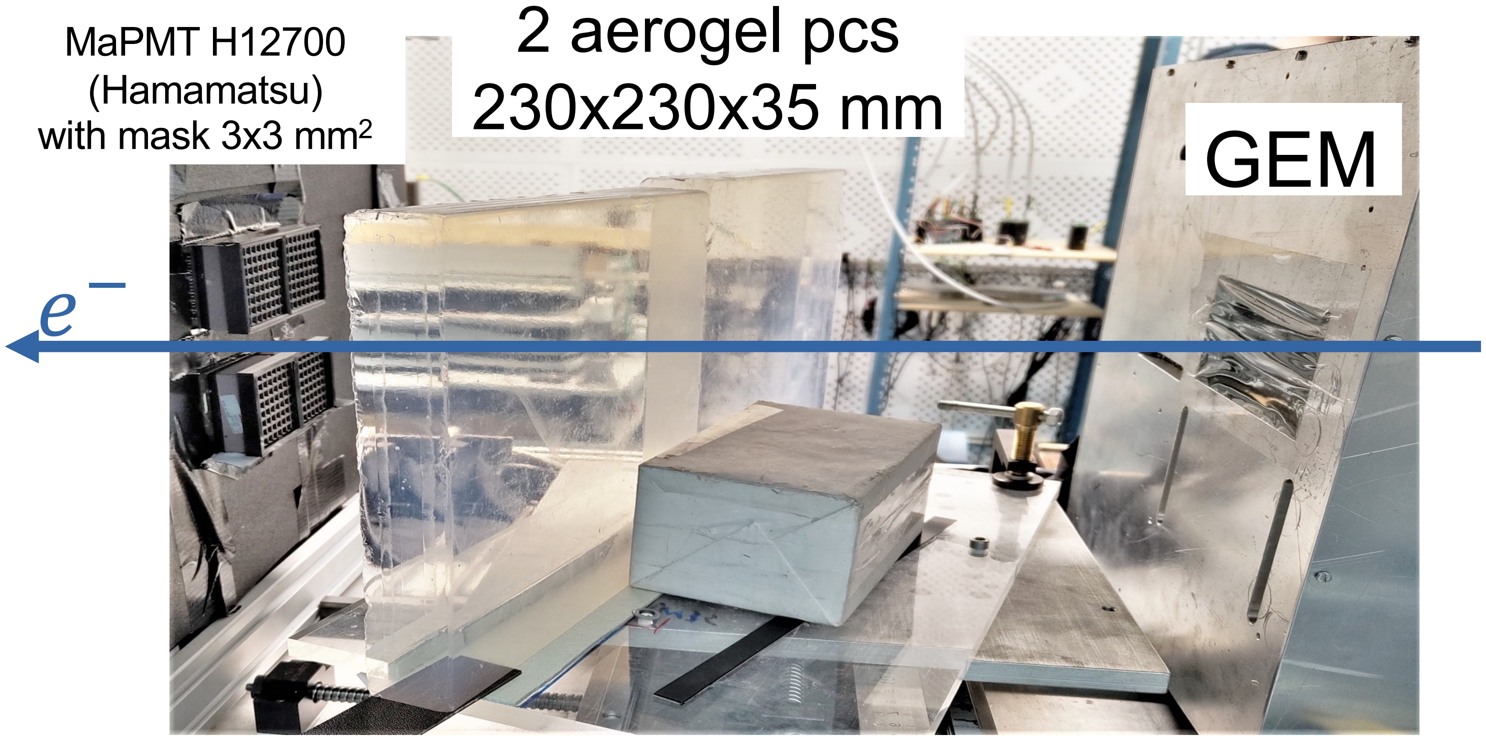
1. Scintillation counters with air light collection
2. Bending magnet
3. GEM–detectors
4. FARICH prototype
5. NaI–calorimeter



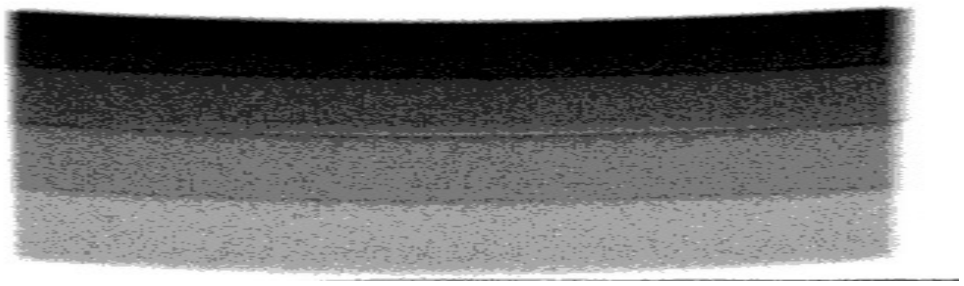
*G N Abramov et al 2014 JINST **9** C08022*



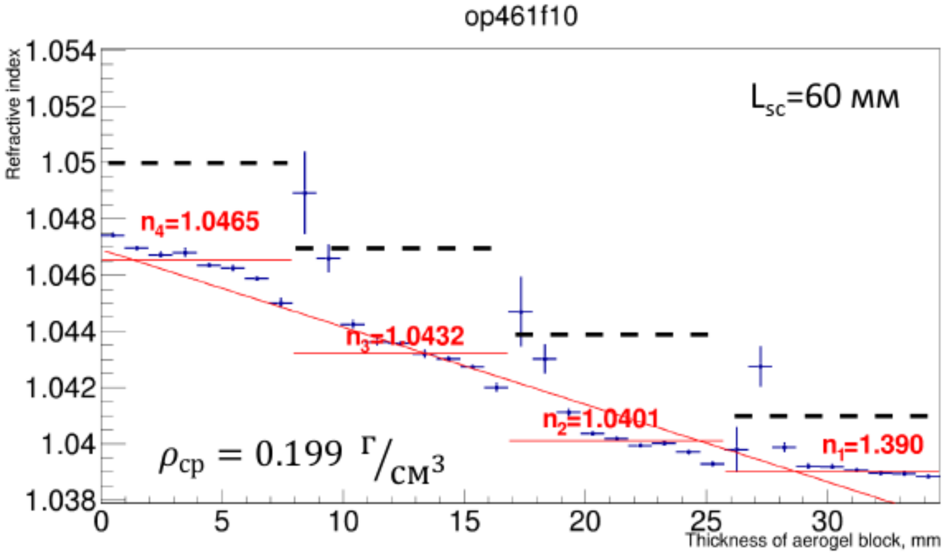
The largest 4-layer focusing aerogel samples were produced in Novosibirsk and tested at BINP in 2022-2023



Single photon Cherenkov angle resolution is investigated with relativistic electrons at BINP beam test facilities ”Extracted beams of VEPP-4M complex”.

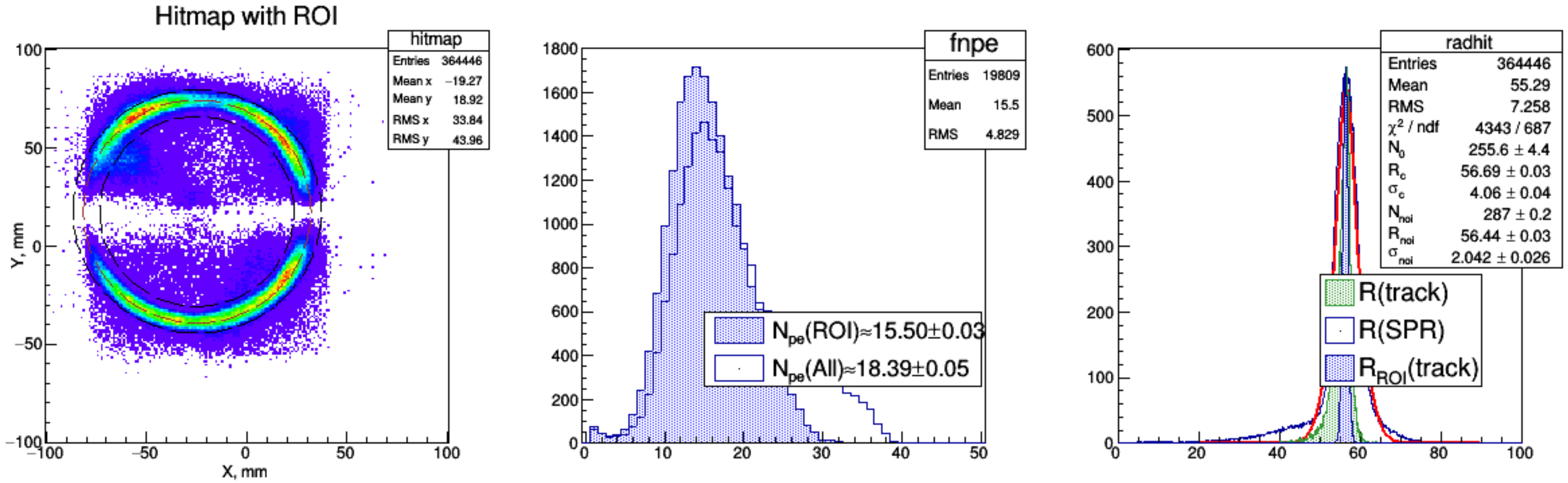


Refractive index profile is measured with help of didgital X-ray setup at the BINP.

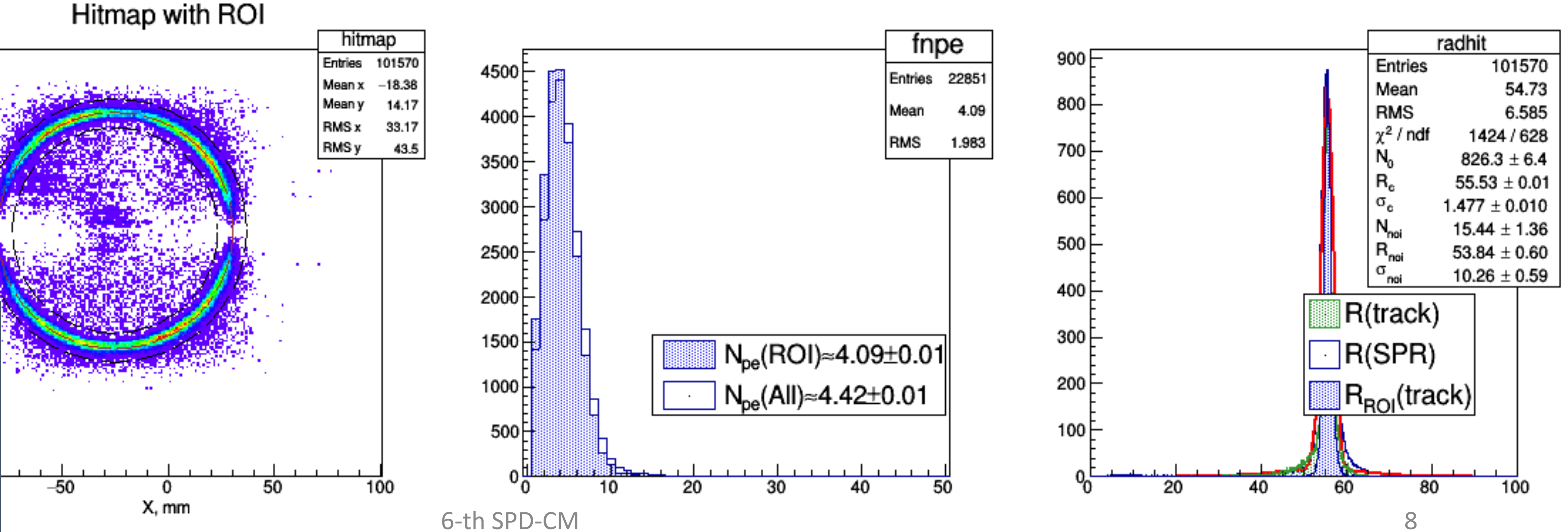


Recent beam test results

Pixel 6x6 mm
Geom.Eff. ~ 80%



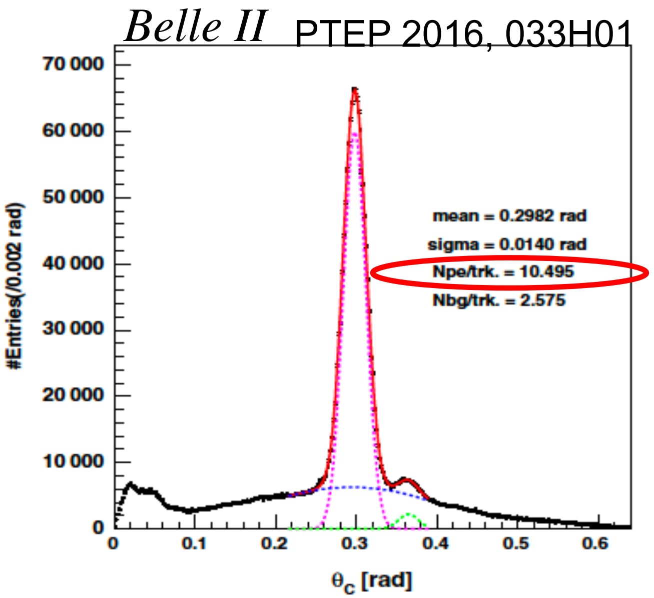
Pixel 3x3 mm
Geom.Eff. ~ 20%

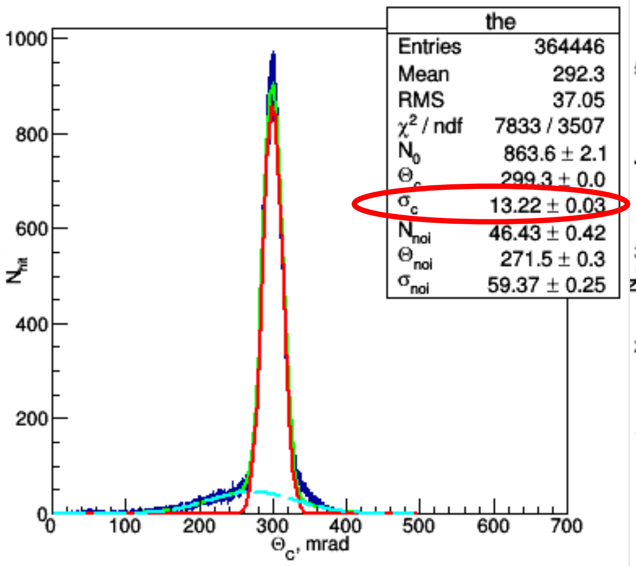


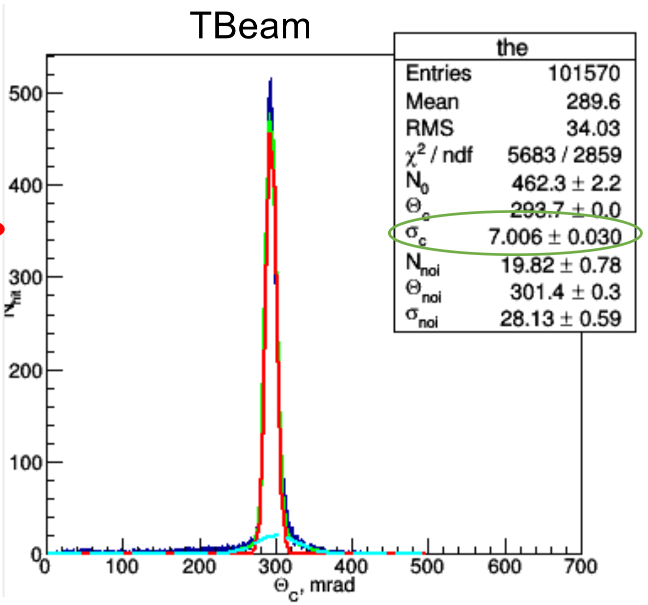
Main results:

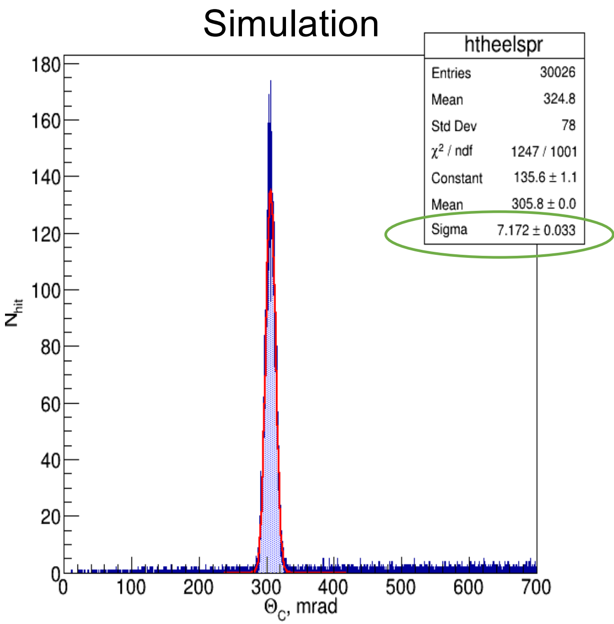
- $N_{pe} \approx 16$ (~ 0.8 of Ring)
- $\sigma_\theta^{1pe} \approx 13.5\ mrad$ (■ 6mm)
- $\sigma_\theta^{1pe} \approx 7.5\ mrad$ (■ 3mm)

Cherenkov angle Single Photo-Electron (*SPE*) resolution







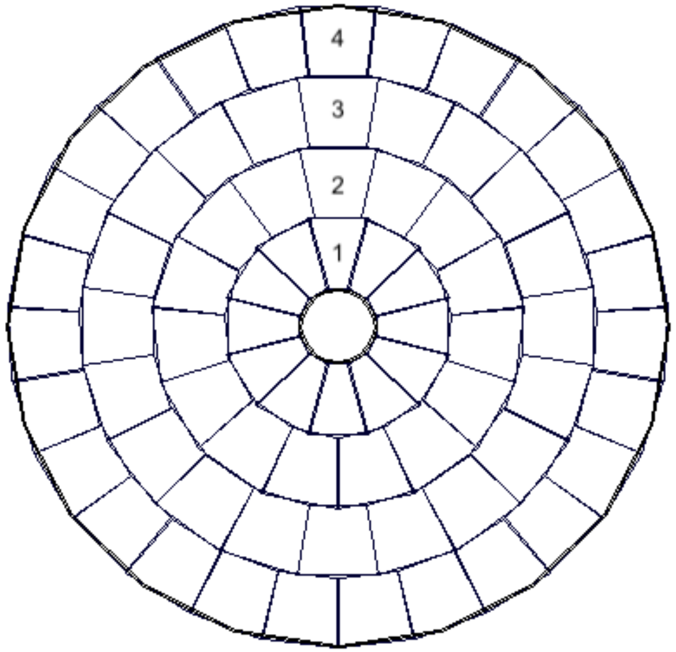


	Belle II		TBeam	Simulation
Aerogel:	20+20 mm (Chiba Univ.)	4-layers (Novosibirsk) –>	–	4-layers (ideal profile)
n(400nm):	1.045 +1.055	1.039 ÷ 1.046	–	1.041 ÷ 1.050
Pixel:	5x5 mm	6x6 mm	3x3 mm	3x3 mm
	Geom.Eff. ~ 90% $N_{pe} \approx 10.5$	Geom.Eff. ~ 80% $N_{pe} \approx 16$	Geom.Eff. ~ 20% $N_{pe} \approx 4$	

- Beam test results are in good agreement with MC simulation and corresponds to goals: μ/π–separation up to P≥1.2 GeV/c & π/K–separation up to P≥4.5 GeV/c
- Beam test results demonstrate better PID capabilities than that were demonstrated with ARICH prototype earlier

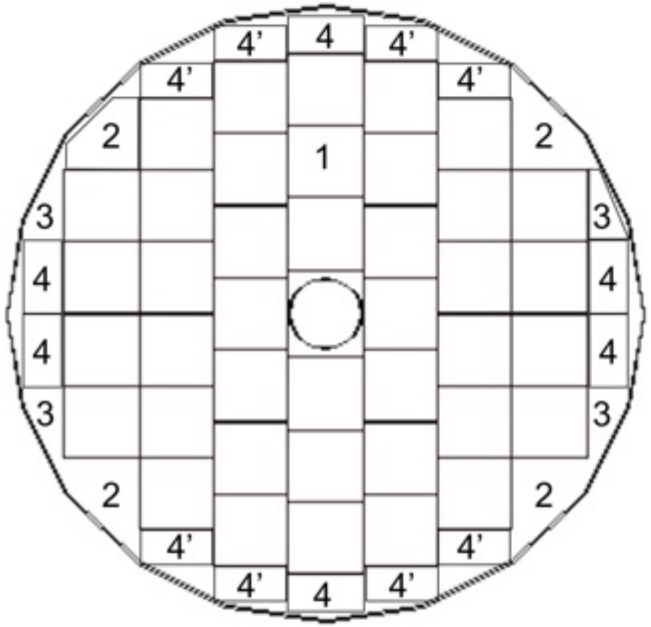
Dimensions of focusing aerogels 23x23x3.5 cm allow us to design the full-scale FARICH systems for the future particle physis experiments.

Aerogel



1 – 12 tiles x S=0.5•(5.6 + 15.6)•18.5 = 159.0 sq.cm
2 – 15 tiles x S=0.5•(12.2+20.2)•18.5 = 299.7 sq.cm
3 – 20 tiles x S=0.5•(15.0+20.8)•18.5 = 331.15 sq.cm
4 – 27 tiles x S=0.5•(15.2+19.6)•18.5 = 321.9 sq.cm

S(aer)/S(total)=21717.8/22383.8=0.97



1 – 40 tiles x S=20•20=400 sq.cm
2 – 4 tiles x S=20•20–0.5•10•12=340 sq.cm
3 – 4 tiles x S=0.5•(12+5)•20=170 sq.cm
4 –14 tiles x S=20•10=200 sq.cm

S(aer)/S(total)=20840/22383.8=0.93

For two endcap FARICH detectors it is required:

– 136 ”good” aerogel tiles 23x23x3.5 cm (5.44 m^2);
– Produce, select and characterise ~2×136 aerogel tiles with help of digital X-ray setup and other laboratory satnds including electron beam test facilities* at BINP;
– Cutt off 136 tiles in 4 different trapziodal shapes;

Cost estimate: 72MRUR = 0.85M€
2.5÷3 years

– 106 ”good” aerogel tiles 23x23x3.5 cm (4.24 m^2);
– Produce, select and characterise ~2×106 aerogel tiles with help of digital X-ray setup and other laboratory satnds including electron beam test facilities* at BINP;
– Cutt off 106 tiles in 2 rectangular and 2 trapziodal shapes;

Cost estimate: 56MRUR = 0.66M€
2÷2.5 years

≥30%

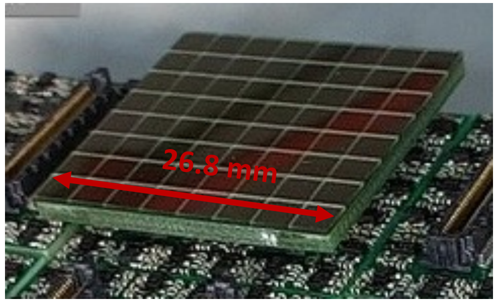
Photon detection options

Photon detector options

Due to axial magnetic field in endcap region of the detector only limited opations of the photon detectors are able to detect very low intensity Cherenkov radiation produced in aerogel

SiPM arrays

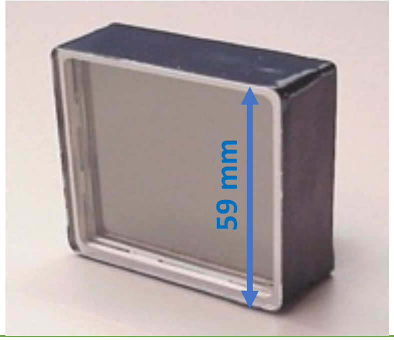
- There are several manufacturer in the world including China.
- There is no comercially available SiPM arrays produced in Russia for the moment, but some R&Ds are going now.
- Estimated cost of such detector option is about 100$/cm^2
- It is required to develop and produce special R/O electronics and cooling system to operate with SiPMs in SPD detector conditions



KETEK PA3325-WB-0808 (BroadCom, USA)

MCP-PMT

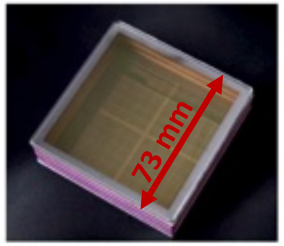
- There are several manufacturer in the world including China.
- There is no comercially available position-sensitive MCP-PMTs produced in Russia for the moment, but R&Ds are going now in (Baspik&Ekran FEP).
- There is a very large spread of prices for rectangular position-sensitive MCP-PMT. The best price is about 200$/cm^2
- PDE is not so high, it is limited by photoelectron collection efficiency (~60%) and geometrical efficiency is worse than for SiPM option.
- Specialised R/O elctronics is already developed for other experiments and could be adopted for the SPD experiment requirements
- There is no such a big problem with intrinsic noise rejecion in comparison with SiPM option

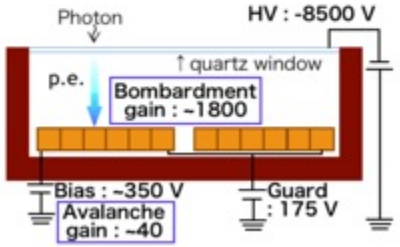


Planacon XP85112
8x8 pixels with 6x6 mm
Cost: 15 $k$$

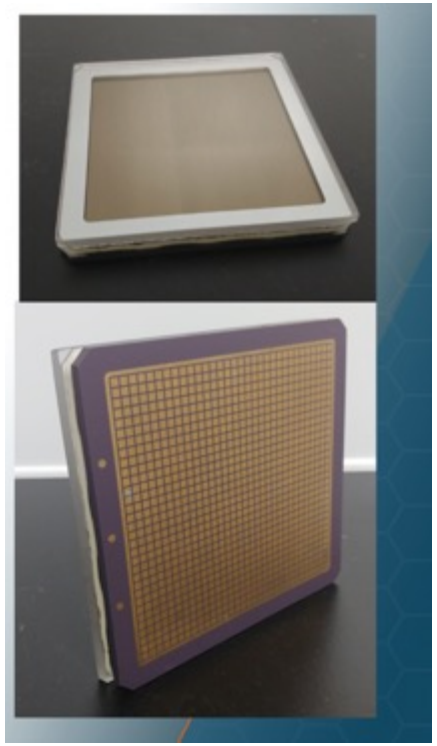
HAPD

- Only Hamamtsu produced such devices for the Belle II experiment and now it doesn't produced anymore!
- There is no comercially available HAPDs in Russia for the moment, but R&Ds are going now in ISP SB RAS.
- Price – ???
- Expected PDE of such devices will less than for SiPM option but signficantly (1.5 times) higher than for MCP-PMT option.
- Expected gain is about $1 \div 2 \cdot 10^5$
- Development of specialised R/O elctronics is needed. It is possible to adopt some Belle II ARICH system expirience.





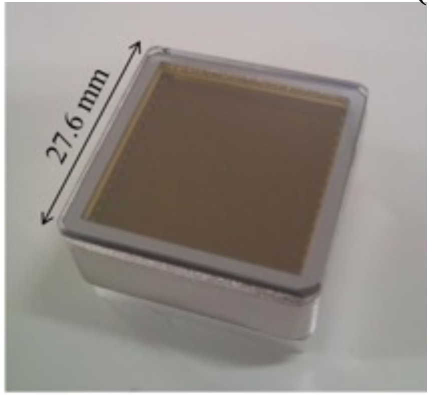
Position-sensitive MCP-PMT



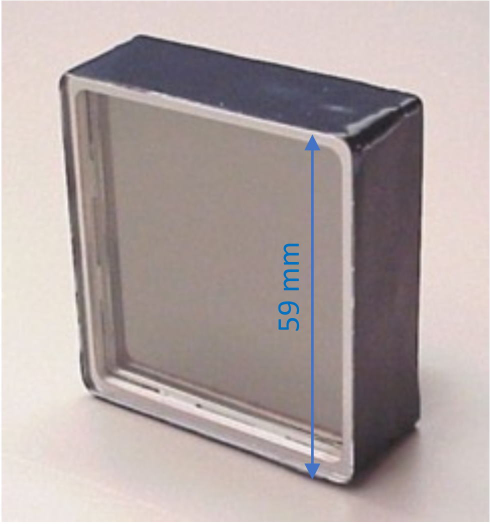
HRPPD (Income)
10x10 cm; pixel 2.5x2.5 mm
Cost: ~20 k\$

The best current price is
200\$/cm²

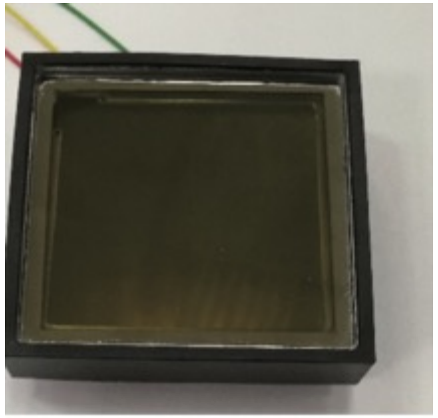
Hamamtsu R10754-016-M16(N)

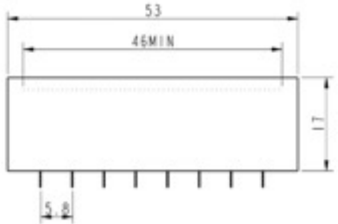


4x4 pixels with 5x5 mm
Cost: 900 k¥

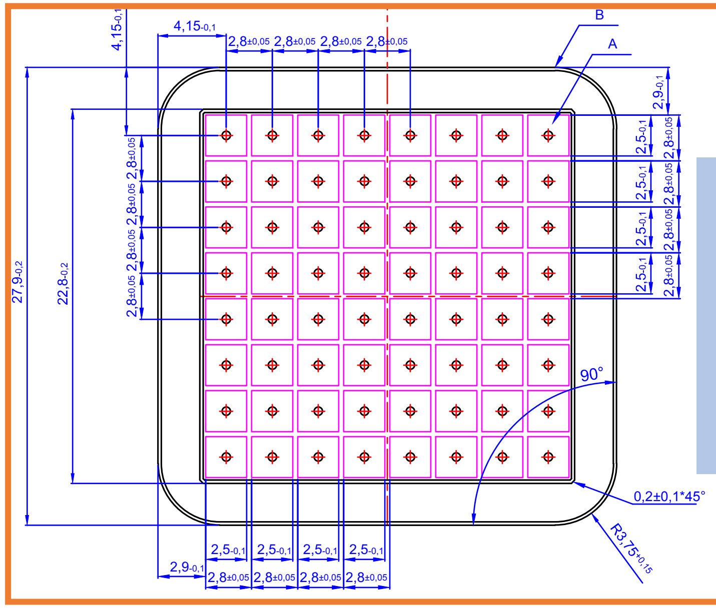


Planacon XP85112
8x8 pixels with 6x6 mm
Cost: 15 k\$





NNVT (China)
Cost: 18 k€

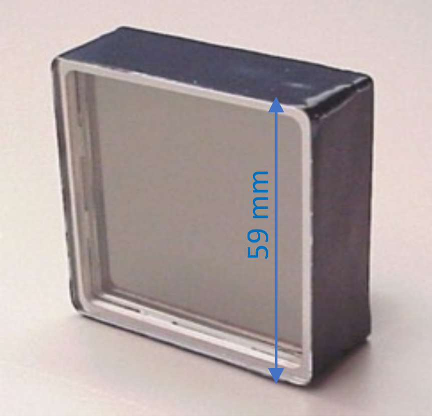


Collector plane of MCP-PMT
Concept of Ekran FEP
(Summer 2022)

Not available yet!!!
COST???

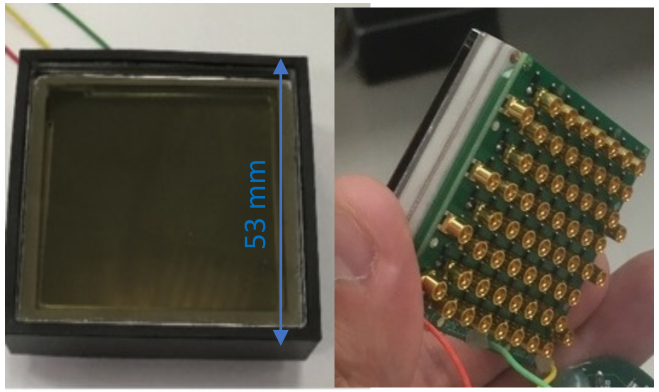
Option 1: "Conservative" or "ready to GO"

MCP PMT available from vendors:



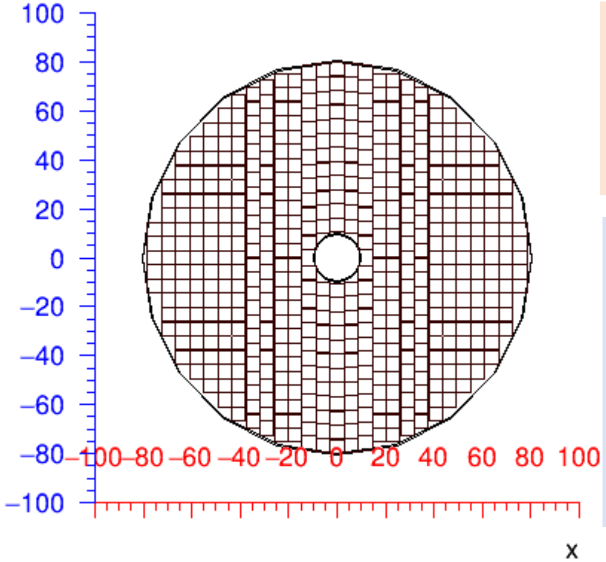
Planacon XP85112 (USA)

8x8 pixels with 6x6 mm



NNVT N6021 (China)

8x8 pixels with 5.9x5.9 mm

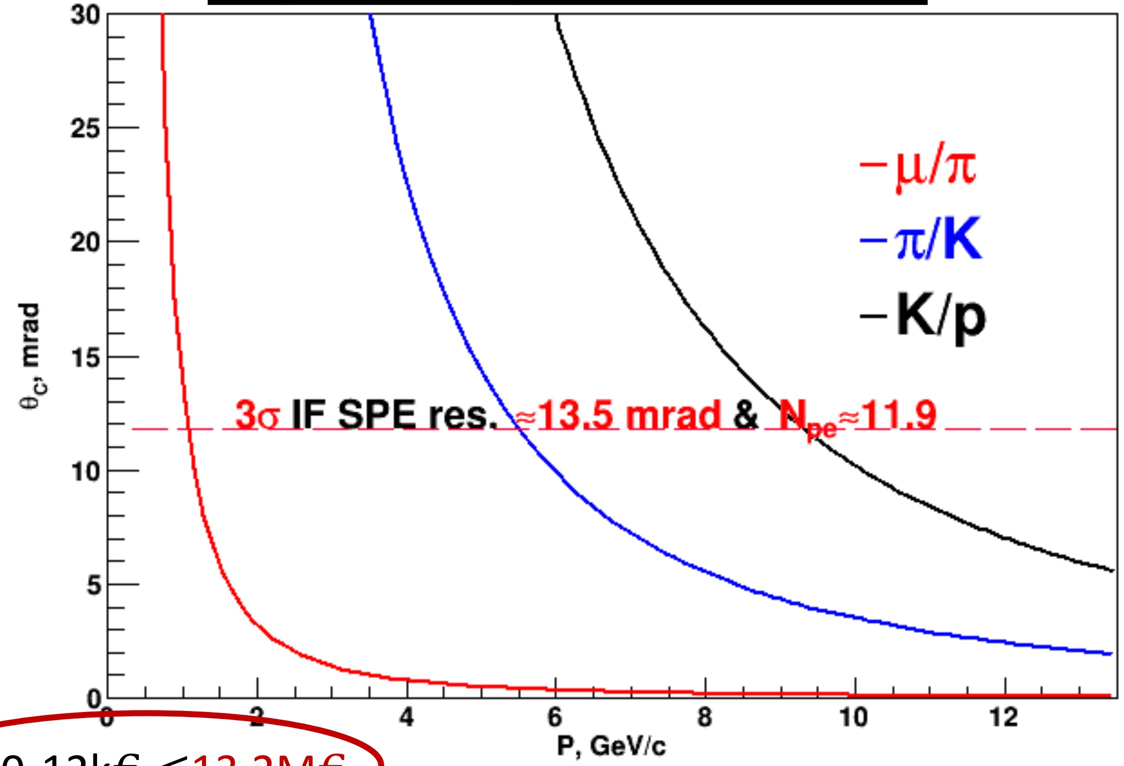


2x548 PMTs:
- 2x35kPixels
- Pixel 6x6 mm

Cost estimate: 1100•12k€ ≤13.2M€

Existing FEE aka DiRICH (GSI):
- 1 DiRICH board per each 6 PMTs
- 2x100 DiRICHs per 2 end-caps
- 2x100 optical links to DAQ sys.
- 10÷20 TRB3 interfaces

Expected performance:

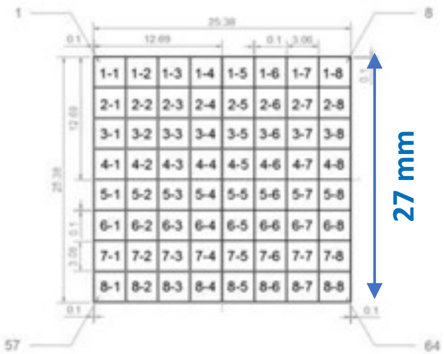


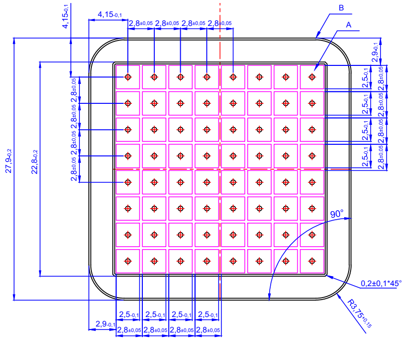
- π/K–separation up to 5 GeV/c
- μ/π–separation up to 1.1 GeV/c
- K/p–separation from 3 to 9 GeV/c

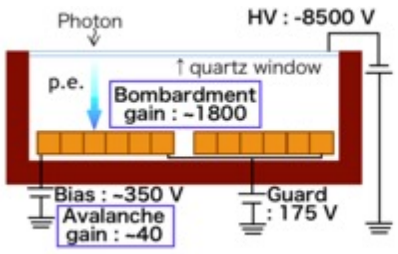
Cost estimate: 70kChan•6÷13 € ≈ 0.42÷0.91M€

Option 2: “Progressive” or “3x3mm pixel challenge”

Suitable PDs with 3x3mm pixels are still under development





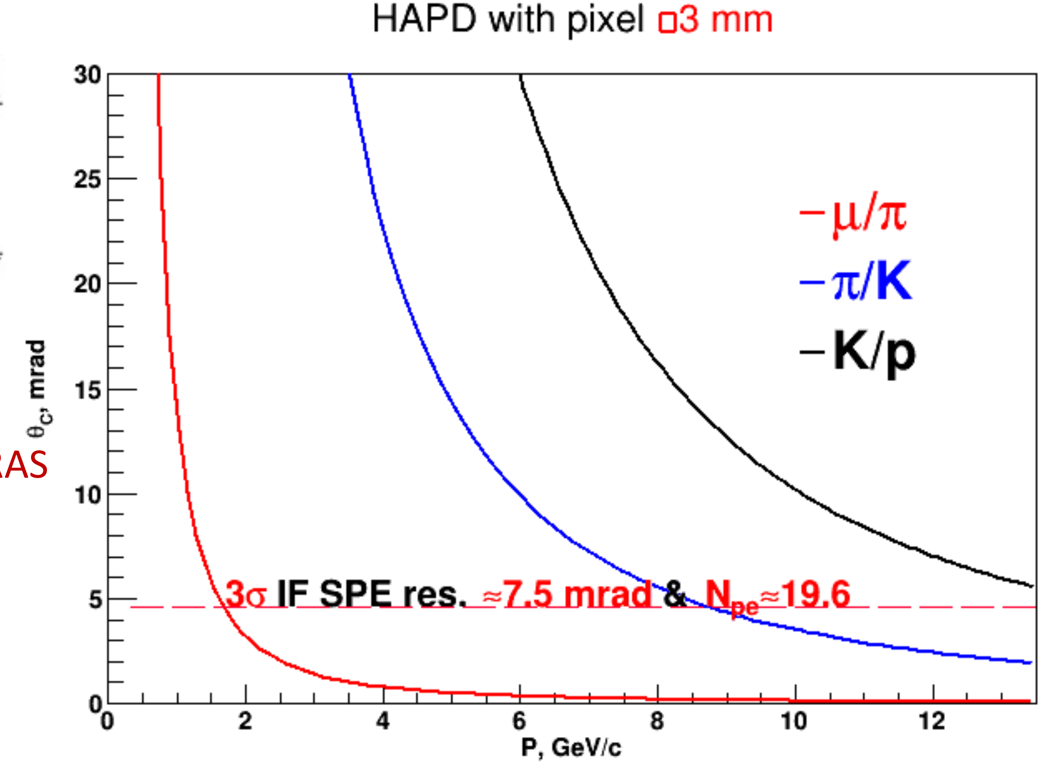


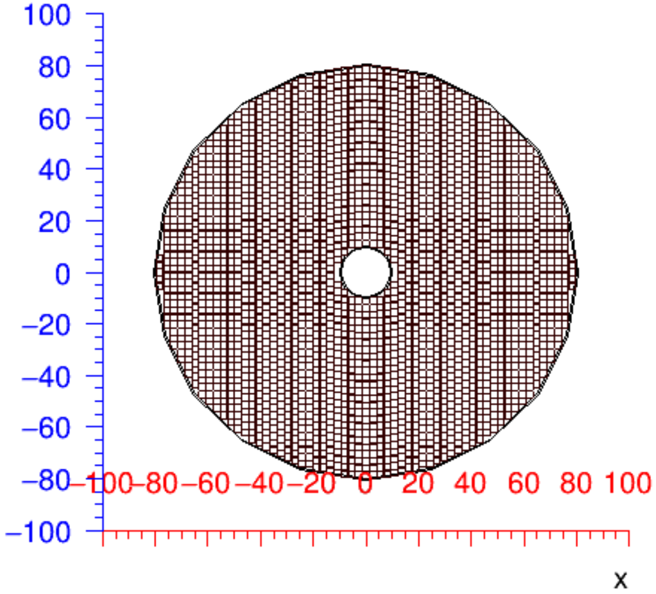
SiPM arrays, Joinbon (China)
64 3x3mm pixels, PDE~40%
DCR ~1÷2·10^6 cps/ch.@300°K

MCP PMT, Ekran FEP (RU)
64 2.5x2.5mm pixels
Still under R&D

HAPD is very attractive
Possible R&Ds are under consideration with ISP SB RAS

Expected performance:





2x2600 PMTs:
- 2x166.4kPixels
- Pixel 3x3 mm

Specialazed FEE is required!!!
- FaRICH-Auslese-System (GSI) – design inspired by DiRICH approach to readout of SiPM arrays or MCP PMTs with 3x3mm pixels?!
- ASICs developed at BINP for SR detector to readout Hybrid Photo Detectors?!

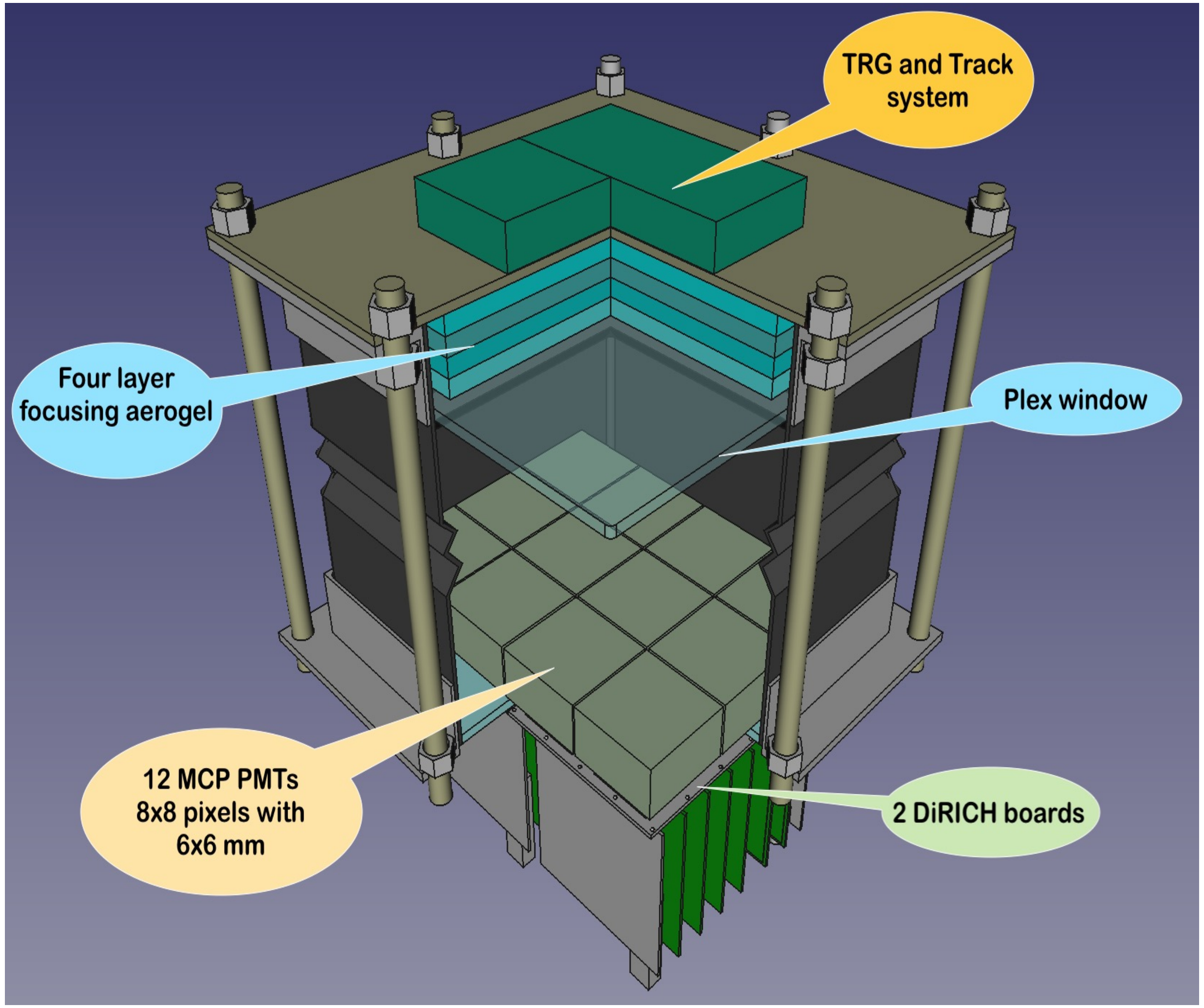
- π/K–separation up to 8.5 GeV/c
- μ/π–separation up to 1.7 GeV/c
- K/p–separation from 3 to 14 GeV/c

Cost estimate: 2•166.4kChan•6€ ≈ 2M€?

Future R&D's steps and expectations

FARICH prototype with full-ring detection

- To demonstrate real PID capabilities of FARICH based on modern solutions.
- We need 8÷12 MCP PMTs with size ~5x5 cm to provide photon detection area S≈15x15 cm.
- We have at BINP FEE to readout up to 18 MCP PMTs (18•64=1152 pixels) by means of DiRICH boards and TRB-3 interface.
- Time performances and ToF approaches should be tested too. Jitter of this FPGA-TDC from GSI declared better than 40 ps.
- This FARICH prototype could be tested with mixed hadron beams or with cosmic rays to demonstrate PID cpabilities.



Aerogel R&Ds

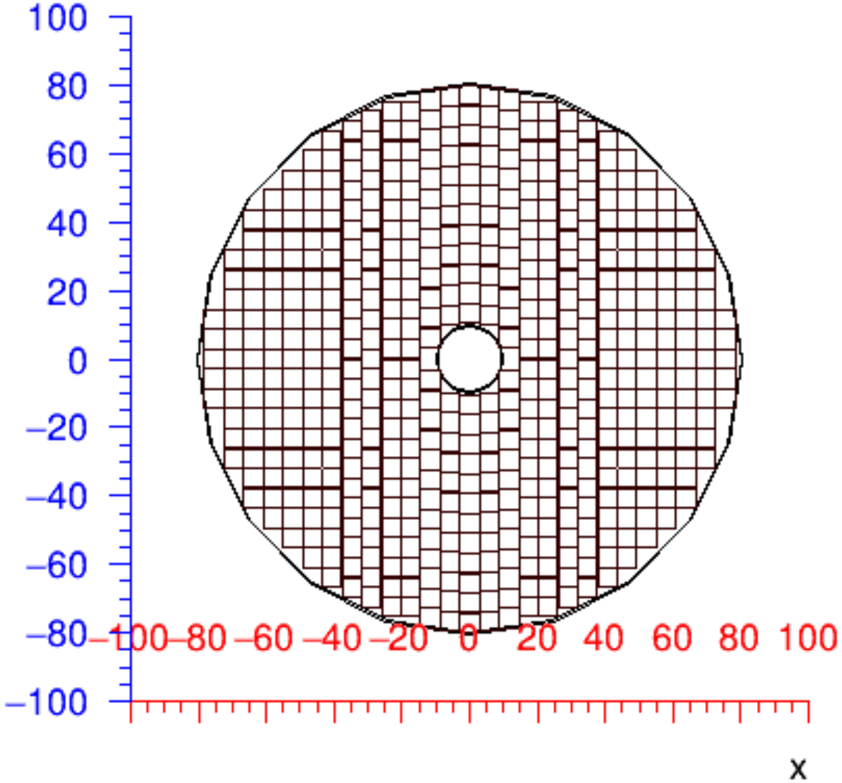
- Mass production issues:
  - Replicability of target optical and mechanical parameters
  - Cutting and other mechanical tooling development
- Hydrofobization of aerogels:
  - Novosibirsk production procedure alows us to produce thick aerogel samples up to 50mm with high optical transperancy but they are hydrophilic
  - There are several approaches how to hydrofobizeied aerogels but with some degradation of optical transperancy
  - Some compromise between hydrofobicity and optical transperancy could be very useful from mpoint of view of real system production and operation
- ???

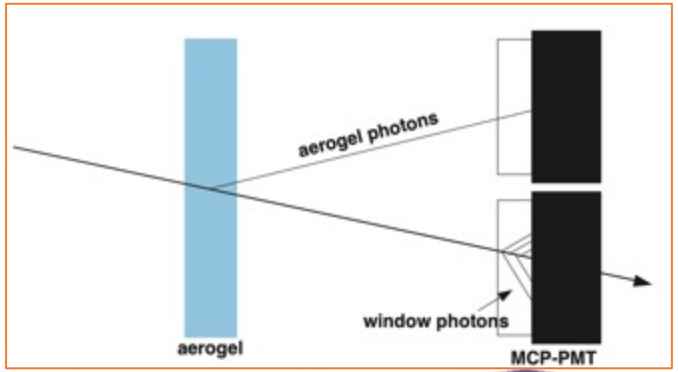
Photon detrectors R&Ds

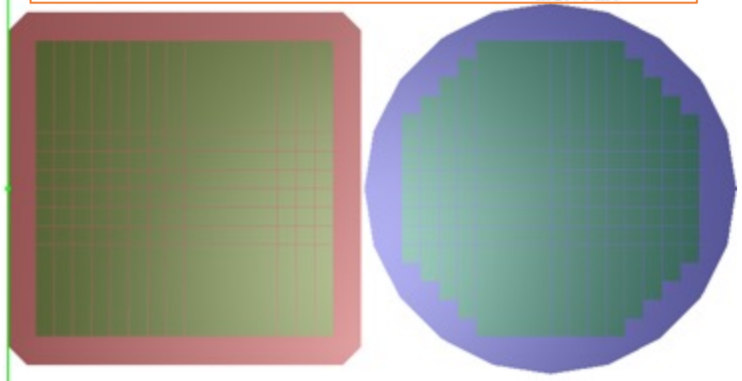
The most part of the system cost is the price of PDs even if it will be decreased by two times due to production in Russia. Two possibilities could be considered from point of view of price decrease:

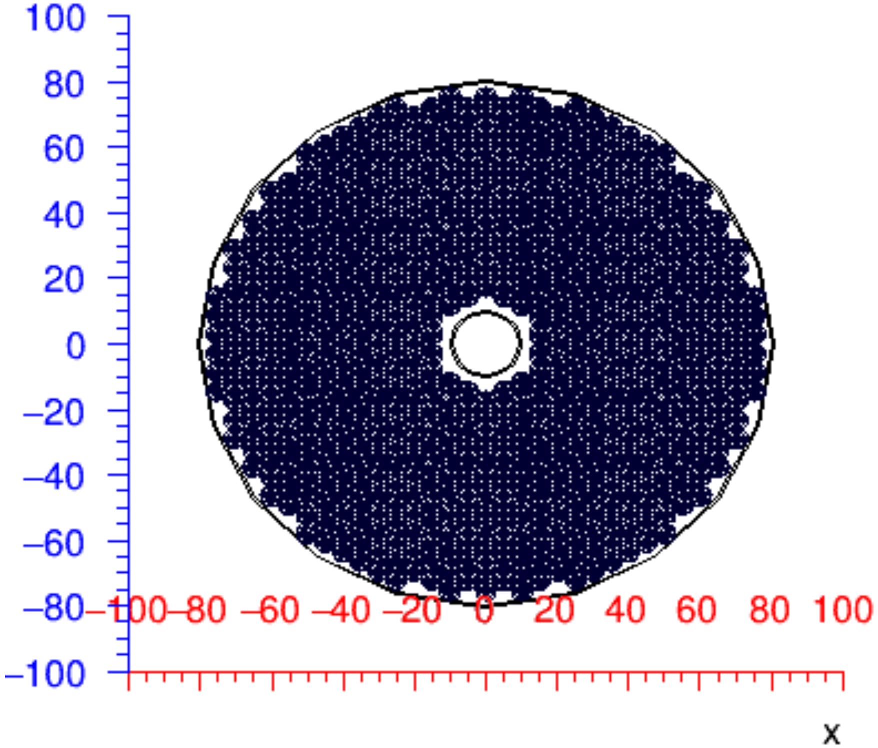
- Round shape MCP PMTs
- Hybrid MCP based PMTs

Round vs Square MCP-PMT for the RICH









548 PMTs ■ 58x58 mm (PC ■ 50x50 мм) –>

$$Eff = \frac{548 \cdot 5{\times}5}{S_{endcap}} = \frac{13700\ cm^2}{19792\ cm^2} \approx 0.69$$

16x16=256 pixels 2.9x2.9 mm

$$Eff = \frac{548 \cdot 256 \cdot 0.29{\times}0.29}{S_{endcap}} = \frac{11798\ cm^2}{19792\ cm^2} \approx 0.596$$

630 PMTs Ø58 mm (PC Ø50 mm) –>

$$Eff = \frac{630 \cdot \pi \cdot 2.5^2}{S_{endcap}} = \frac{12370\ cm^2}{19792\ cm^2} \approx 0.625$$

216 pixels 2.9x2.9 мм

$$Eff = \frac{630 \cdot 216 \cdot 0.29{\times}0.29}{S_{endcap}} = \frac{11444\ cm^2}{19792\ cm^2} \approx 0.58$$

Round vs Square MCP-PMT for the RICH (2)

To evaluate expected performance we can use recent FARICH beam test data:

- $N_{pe}^{H12700} \approx 16$
- $CE^{H12700} \approx 0.8$ – photoelectron collection efficiency ($CE^{MCP} \approx 0.6$)
- $GE^{TB} \approx 0.8$ – Geometrical Efficiency of Test Beam setup (GE^{exp} is determined by fill factor of photon detectors for the experimental setup)

$$N_{pe}^{expect} = \frac{N_{pe}^{H12700} \cdot CE^{MCP} \cdot GE^{exp}}{CE^{H12700} \cdot GE^{TB}}$$

Square shape MCP-PMT

- $GE^{exp} \approx 0.596$
- $N_{pe}^{expect} = \frac{16 \cdot 0.6 \cdot 0.596}{0.8 \cdot 0.8} \approx 8.94pe$ (for $\beta = 1$)
- $\sigma_{tr}^{\theta} = \frac{\sigma_{SPE}^{\theta}}{\sqrt{N_{pe}}} = \frac{7 \div 8\ mrad}{\sqrt{8.94}} = 2.3 \div 2.7\ mrad$

Round shape MCP-PMT

- $GE^{exp} \approx 0.58$
- $N_{pe}^{expect} = \frac{16 \cdot 0.6 \cdot 0.58}{0.8 \cdot 0.8} \approx 8.7pe$ (for $\beta = 1$)
- $\sigma_{tr}^{\theta} = \frac{\sigma_{SPE}^{\theta}}{\sqrt{N_{pe}}} = \frac{7 \div 8\ mrad}{\sqrt{8.7}} = 2.4 \div 2.7\ mrad$

μ/π @ 1 GeV/c: $\frac{\theta_C^{\mu} - \theta_C^{\pi}}{\sigma_{tr}^{\theta}} = \frac{292 - 278}{2.5} = 5.6\sigma$

π/K @ 6 GeV/c: $\frac{\theta_C^{\pi} - \theta_C^{K}}{\sigma_{tr}^{\theta}} = \frac{309 - 299}{2.5} = 3.9\sigma$

Hybrid MCP based Photon Detector (HMCPPD)

The idea:

- Vacume sealed device with Bialkali PC
- Equiped with 1 MCP
- Charge collected by p-i-n – diodes (one p-i-n – one pixel)
- P-i-N diods are readout by ASIC chip (SciCODE64 developed at BINP to readout 64 P-i-N diodes fired by SR gammas with energy 3÷30keV) –> The possiblity to readout HPDs produced at ISP SB RAS will be checked soon

Pros:

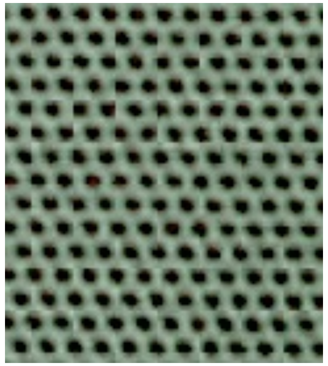
- S/N is much better than in SiPM
- HV ~1÷2kV instead 8÷10kV
- Less MCPs by two times than in standard MCP PMTs

–> cheaper?!

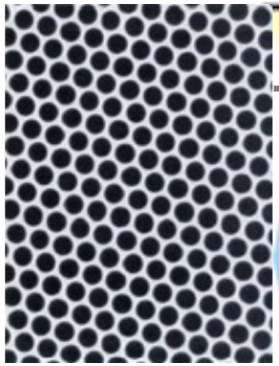
Cons:

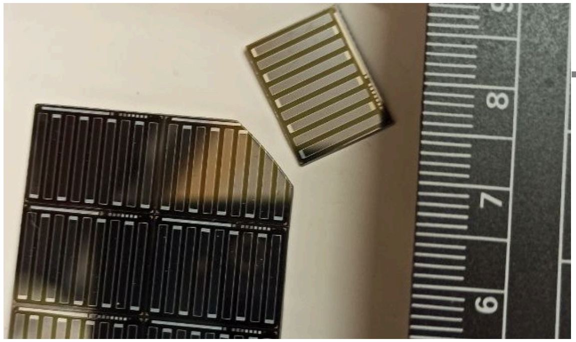
- CE≤85%
- Aditional R&D

Baspik (RU)
CE~60%



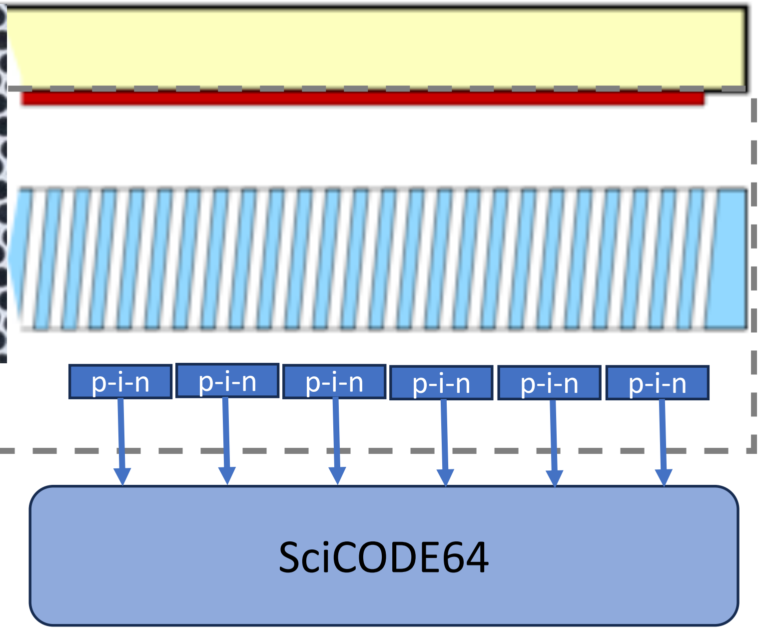
Photek (IR)
CE~83%





APD from ISP SB RA

Conceptual design:



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Summary

- PID system based on FARICH could be releable subsytem to provide π/K–separation up to 5÷8 GeV/c.
- The main cost contributions are estimated as follow:
  - Aerogel – 0.66÷0.85 $M€$
  - Photon Detectors – 13.2 $M€$ (4 m^2 – The largest area of MCP PMT based system in HEP)
  - R/O electronics – 0.42÷2 $M€$
  - Cooling system – 0.1 $M€$
  - HV supply – 0.1 (MCP-PMT)$M€$
  - Mechanics 0.1 $M€$
- Total cost estimation: 14.5÷16.35$M€$
- Additional R&D aimed on optimization of the system performances and its component costs is required. Sufficient efforts on R&D of photon detectors and R/O electronics are needed.
- It will take about 1 year for active R&Ds to optimise system design and production technologies + 3 years to create the FARICH system optimised for the experiment. Major time contributions are estimated as following:
  - Aerogel production – 1 year R&D to optimise mass production process of large focusing radiators + 2.5÷3 years for aerogel mass production
  - Photon detectors (PD) based on MCP – at least 1 year for R&D and 2÷3 years for mass production, characterization and selection processes
  - R/O electronics – about 1.5 years for R&D after development and designing of photon detectors + 1 year for mass production
  - Cooling system – 1 year for R&D after PD and R/O designing + 1 year for production

Summary (2)
(discussion)

The significant optimisation of the system cost could be expected after full-scale R&D

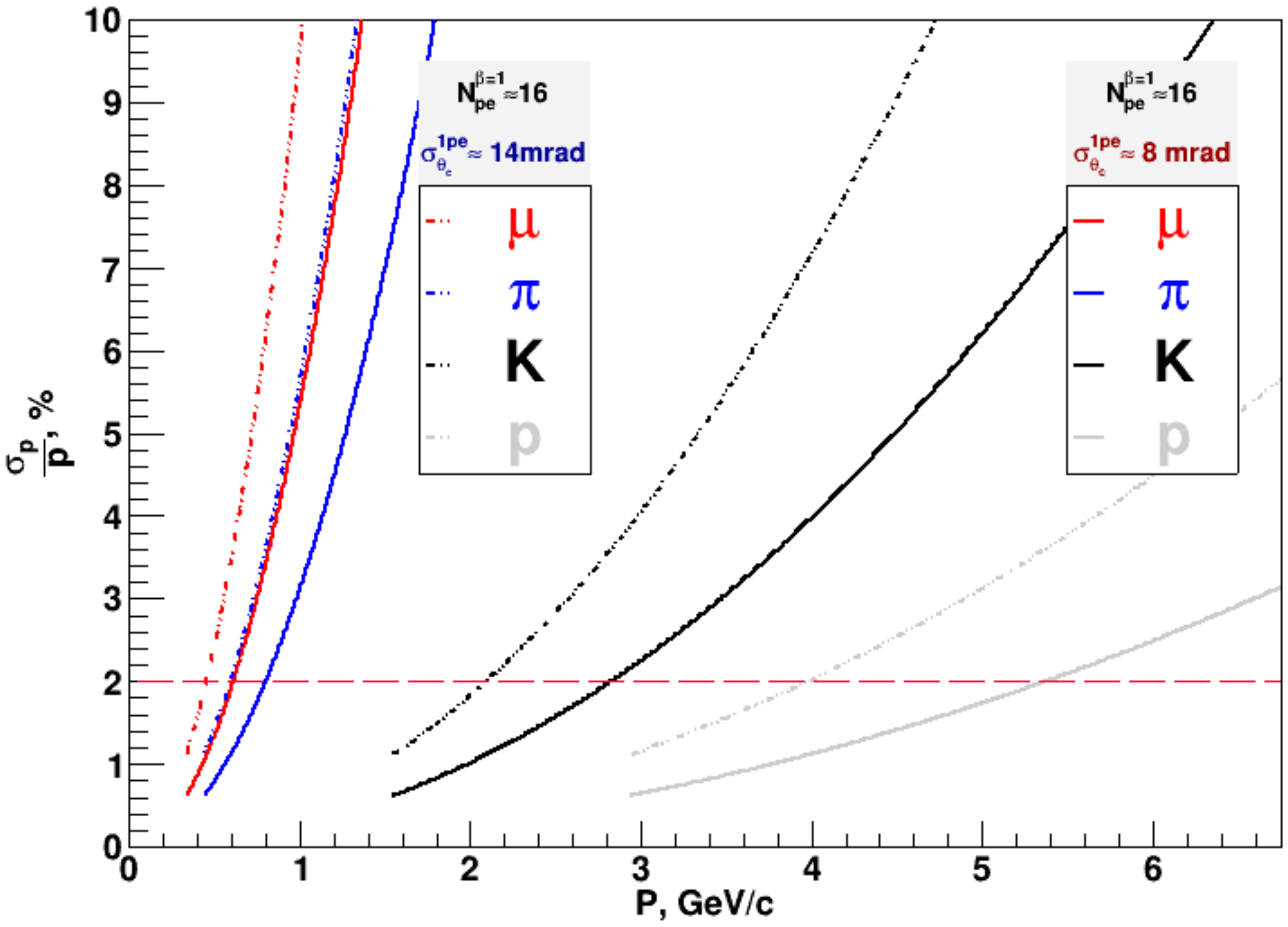
- Development of specialised R/O electronics can lead to reduce the cost of one channel from 17€$/chan$ to 5€$/chan$. It could help to save up to 1.5M€
- R&D for optimisation of aerogel production technology could save up to 20% of aerogel cost (0.1÷0.2M€)
- Close cooperation and joint R&D with photon detector manufacturers will improve the efficiency of photon detectors production, characterisation and selection processes and could lead to form the optimal cost of the each device and whole system as well.

Development of the full-scale simulation framework with capability to perform simulation of physics processes will help to figure out critical performances of the PID system and consequently it will open the possibility to consider any compromise optimisations of the system, such like reduce of the number of R/O electronics channels, number of the photodetectors and so on.

Back up

Momentum measurements with FARICH

$$\frac{\sigma_p}{p} = \gamma^2 \cdot \frac{\sigma_\beta}{\beta}$$



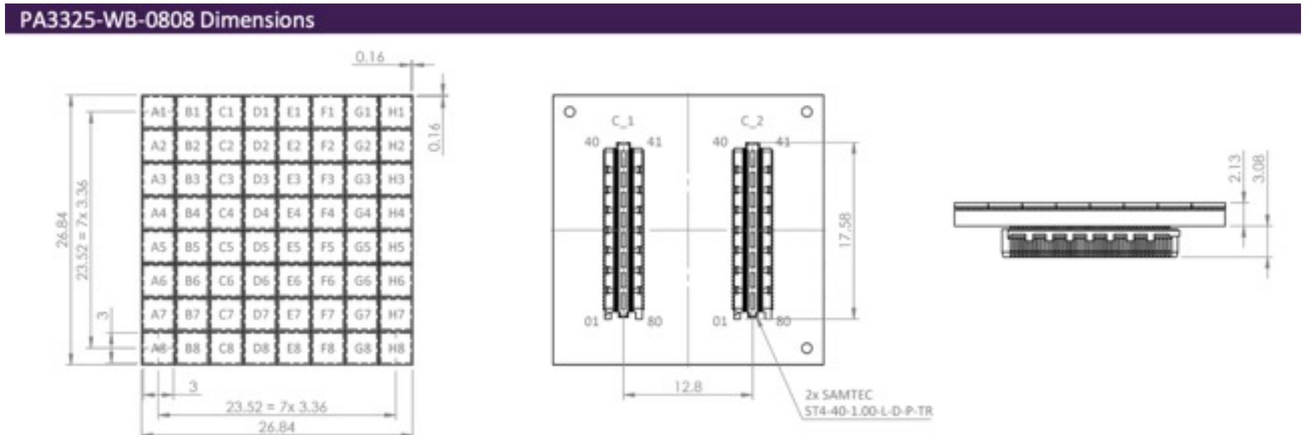
$$\frac{\sigma_p}{p} = \gamma^2 \cdot \tan\theta \cdot \sigma_\theta^{tr}$$

$$\sigma_\theta^{tr} = \frac{\sigma_\theta^{1pe}}{\sqrt{N_{pe}(p)}} = \frac{\sigma_\theta^{1pe}}{\sqrt{N_{pe}^{\beta=1}}} \cdot \frac{p\sqrt{n^2-1}}{\sqrt{p^2(n^2-1)-m^2}}$$

$$\frac{\sigma_p}{p} = \frac{p\sqrt{p^2+m^2}}{m^2}\sqrt{n^2-1} \cdot \frac{\sigma_\theta^{1pe}}{\sqrt{N_{pe}^{\beta=1}}},$$

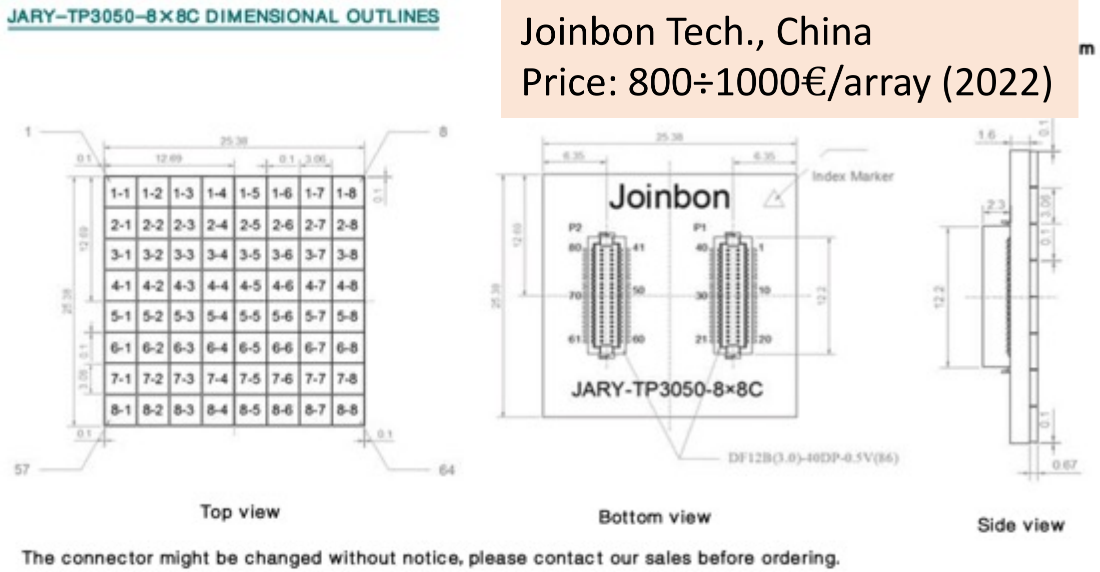
where m – particle mass, p – particle momentum, $n = 1.05$ – refractive index of aerogel, σ_θ^{1pe} and $N_{pe}^{\beta=1}$ are single photon Cherenkov angle resolution and number of detected photons per track correspondingly measured with relativistic electron beams.

SiPM array option



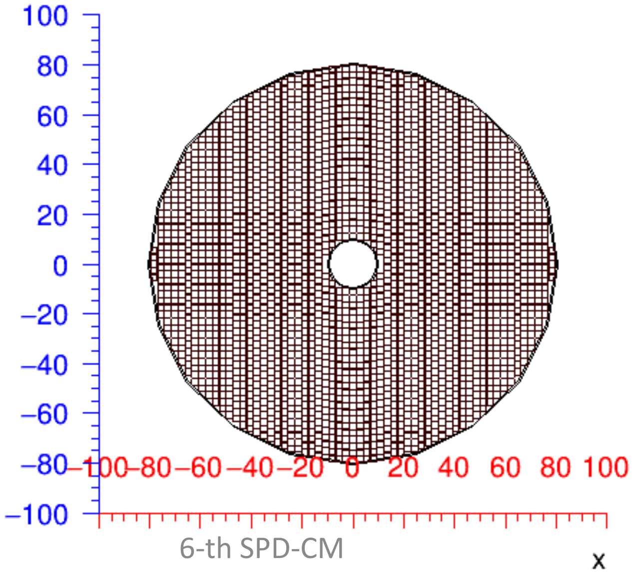
General Tolerances ± 0.1 mm unless otherwise noted

KETEK-BroadCom, USA
Price: 500÷650€/array (2020)



Joinbon Tech., China
Price: 800÷1000€/array (2022)

Two endcaps:
– 2x2624 SiPM arrays 2.7x2.7 cm^2
– 336k pixels with 3x3 mm^2
– Geometrical Efficiency $\frac{S_{detect}}{S_{total}} \approx 76\%$
– Highly effective cooling sysytem is required



Cost estimation:
– SiPM arrays ~4.2÷5.2 M€
– Additional cost for R&D and construction of special cooling system???

R/O electronics cost estimation

There are two modern approaches in development of specialised R/O electronics:

- ASIC (Application Specialised Integrated Circuits)
- FPGA (Field Programable Gate Arrays)

The differences in performance, power consumption and costs are not sufficient today!!!

FPG-TDC (GSI)

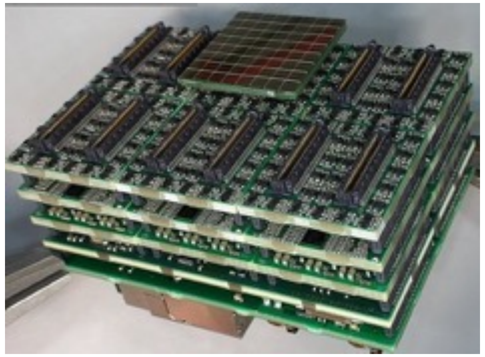
Unit	Article	Price per unit	Total price
2	DiRICH	4.917,00 €	9.834,00 €
	Additionally the export duty from Germany		150,00 €
	Total price		9.984,00 €

$\frac{9\,834€}{2\times384} \approx 13€/chan$ if N_{ch}<1000 (2019)

A system with 30kChannel (HADES):

$170k€/30k \approx 6€/chan$ (2017)

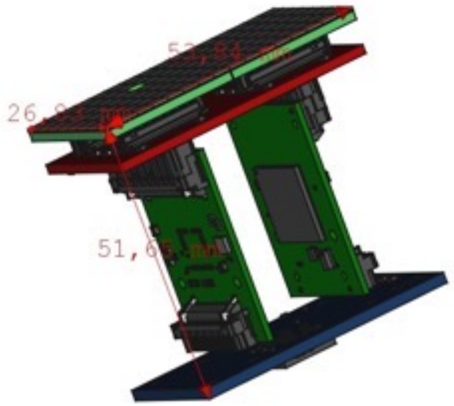
Power consumption: ~55mW/chan



TOFPET-II (PetSys)

The price of what you list (if based on ASIC_2,c) is

1	DAQ		8'000
1	clk&trg		5'000
1	FEB/D		5'376
8	FM128	1'579	12'632
TOT			31'008



$\frac{31\,008€}{8\times128} \approx 30€/chan$ if N_{ch}≤1000

A system with 100kChannel:

$5€/chan$ (2020)

Power consumption:

15mW/chan (ASIC) + DAQ (FPGA)~60mW/chan

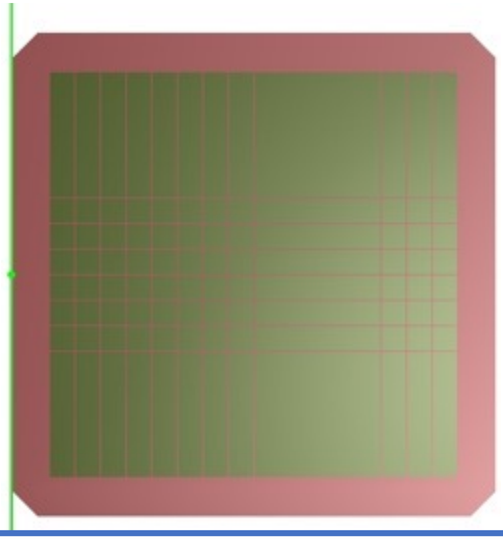
If we assume average price about $^{17€}/_{chan}$

Total cost: from $4.6M€$ (MCP-PMT option) to $5.7M€$ (SiPM option)

MCP-PMT option cost estimation

Square shape MCP-PMT

- **Major assumption:** MCP-PMT with 58x58 mm with 256 pixels 2.9x2.9 mm is $7.5k\$$ (based on the best price $200\$/cm^2$)
- For two endcaps 2x548 PMTs are needed
  $\rightarrow 2\times548\times7.5k\$ \approx 8.2M\$$
- **Additional cost???**:
  - R/O for $2\times548\times256 \approx 280kCh$.
  - Thermostabilization system



Round shape MCP-PMT

- **Major assumption:** MCP-PMT with ø58 mm with 216 pixels 2.9x2.9 mm is $5.5k\$$ (based on the best price $200\$/cm^2$)
- For two endcaps 2x630 PMTs are needed
  $\rightarrow 2\times630\times5.5k\$ \approx 7M\$$
- **Additional cost???**:
  - R/O for $2\times630\times216 \approx 272kCh$.
  - Thermostabilization system