FARICH option for the PID system of the Super C-Tau Factory project.

Alexander Barnyakov

on behalf of BINP group of SCT-collaboration

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- **SCTF project overview**
- **R&Ds status in BINP**
- **PID system**
  - **FARICH technique progress**
  - **FARICH with dual aerogel radiator concept**
- **Summary**

22 August 2023

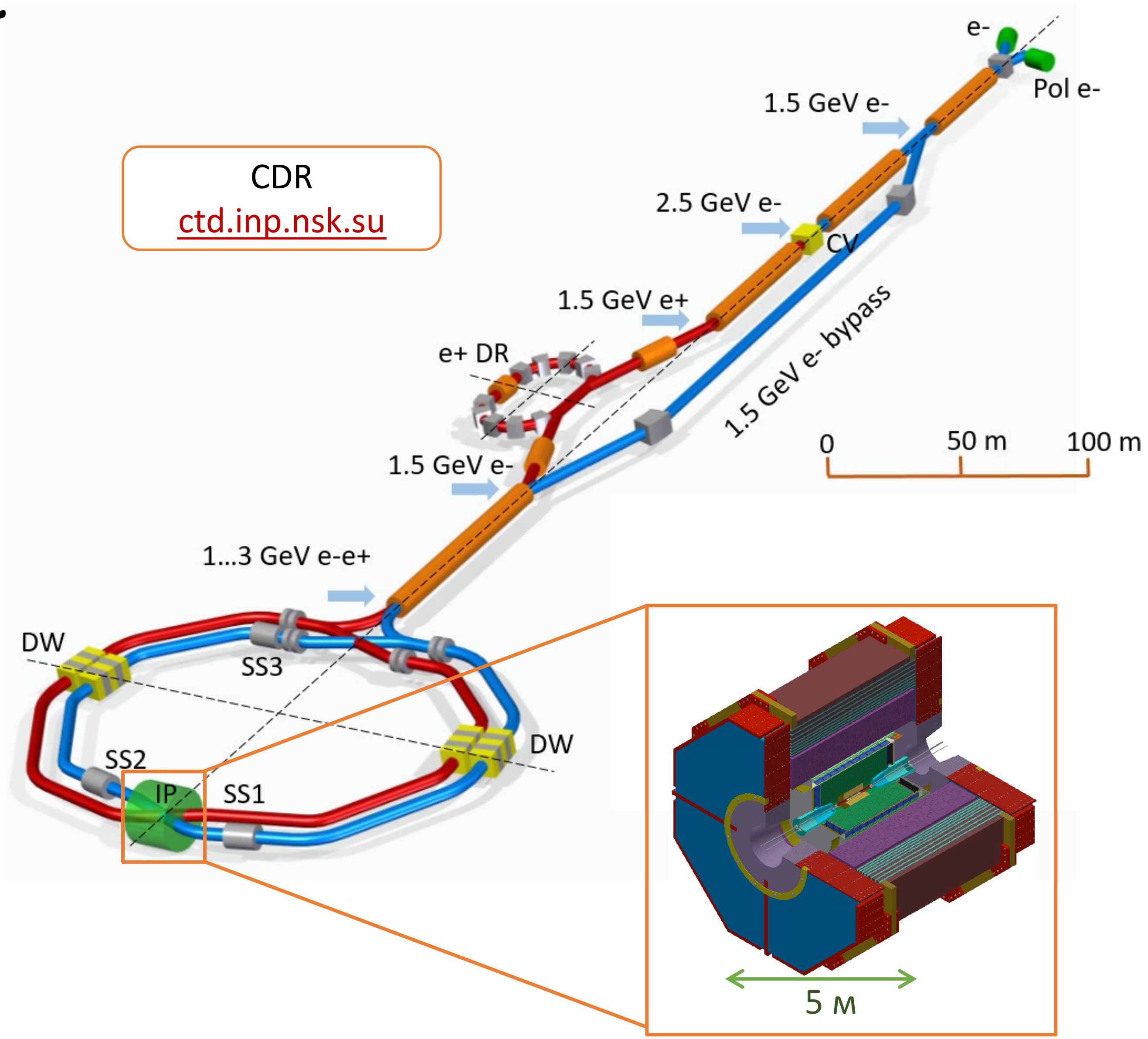
University of Chinese Academy of Sciences, Beijing, China

中国科学院大学

University of Chinese Academy of Sciences

The SCT experiment

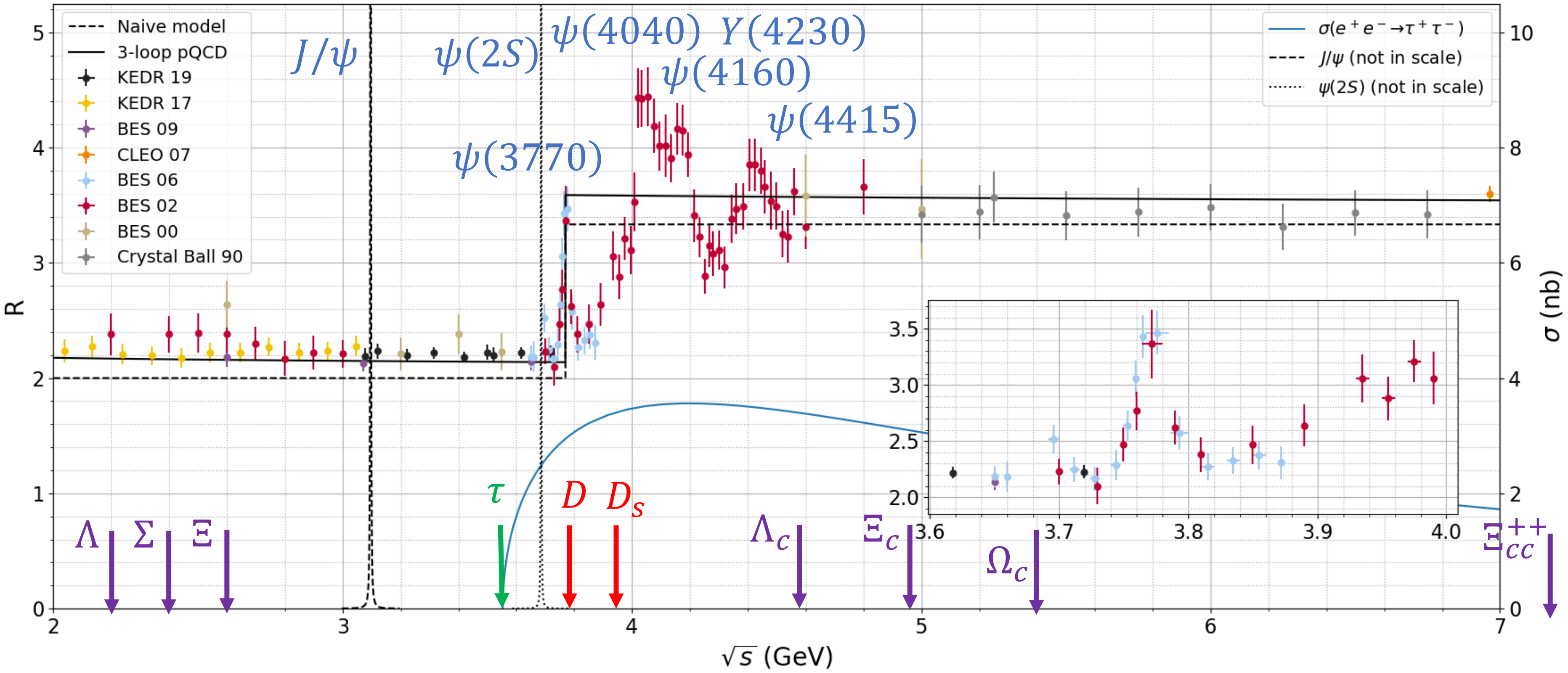
- Super charm-tau factory is e+e− collider, dedicated to precision study of properties of charm-quark, τ-lepton, study of strong interactions, search of BSM physics
  - Beam energy from 1.5 (1.0) to 3.5 GeV
  - Luminosity $\mathcal{L} = 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ @ 2 GeV
  - Longitudinal polarization of the e^- beams
- Experiments will be conducted using state-of- the-art general purpose detector
  - Tracking (including low p_t)
  - Calorimetry (high resolution, fast, π^0/γ sep.)
  - PID system:
    - π/K – separation up to 3.5 GeV/c
    - μ/π – separation up to 1.5 GeV/c



The SCT energy range

$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma_0(e^+e^- \to \mu^+\mu^-)}$$

Threshold production of nonrelativistic particles provides best conditions for their comprehensive study



$\mathcal{L} = 10^{35}\ \text{cm}^{-2}s^{-1}$

A one-year dataset

$2E$, GeV	Events recorded
3.1	$10^{12}\, J/\psi$
3.69	$10^{11}\, \psi(2S)$
3.77	$10^{9}\, D\bar{D}$
4.17	$10^{8}\, D_s\bar{D}_s$
3.55 ÷ 4.3	$10^{10}\, \tau\,\tau$
4.65	$10^{8}\, \Lambda_c^+\Lambda_c^-$

SCT Physics in a nutshell

Input for B meson studies at LHCb and Belle II

- ✓ Measurement of the strong phases of D decay amplitudes
- ✓ Measurement of absolute branching fractions
- ✓ Searches for rare and forbidden decays of the charm quark
- ✓ CP violation in charm
- ✓ …

charm

QCD

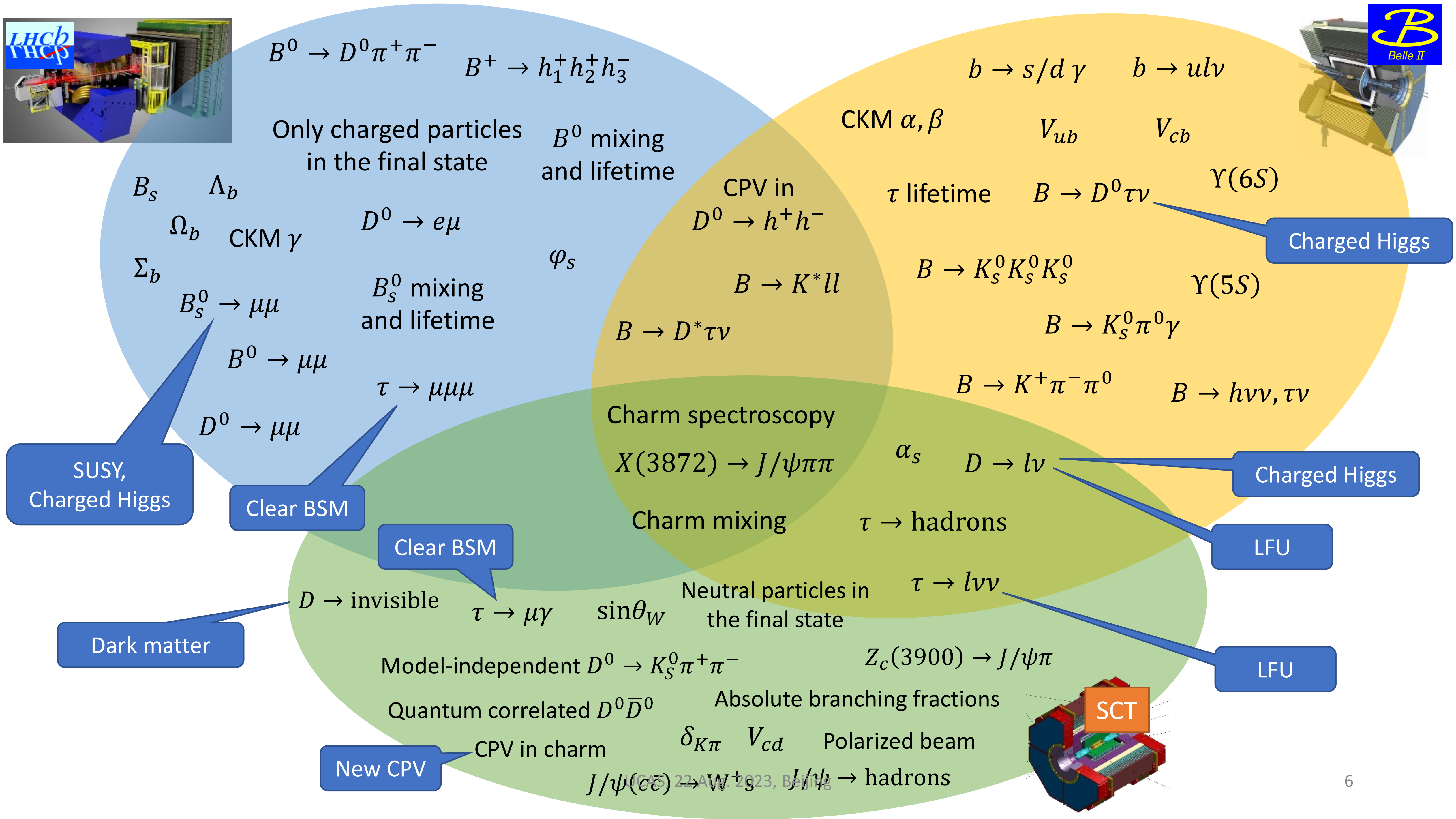
- ✓ Physics of highly-excited quarkonium
- ✓ Molecular states
- ✓ Baryon interaction at threshold
- ✓ Search for glueballs in decays of J/ψ and $\psi(2S)$
- ✓ …

tau

Test of the electroweak sector of the SM

- ✓ Precision measurement of the τ lepton properties
- ✓ Michel parameters, tests of lepton universality
- ✓ Precision measurement of hadronic τ decays
- ✓ Search for CP and T violation in τ decays
- ✓ …

QCD, α_s, V_{us}. Test of the electroweak model, searches for non-standard contributions



$B^0 \to D^0\pi^+\pi^-$
$B^+ \to h_1^+h_2^+h_3^-$
Only charged particles in the final state
B^0 mixing and lifetime
B_s
Λ_b
Ω_b
CKM γ
Σ_b
$D^0 \to e\mu$
φ_s
$B_s^0 \to \mu\mu$
B_s^0 mixing and lifetime
$B^0 \to \mu\mu$
$\tau \to \mu\mu\mu$
$D^0 \to \mu\mu$
SUSY, Charged Higgs
Clear BSM
$b \to s/d\,\gamma$
$b \to ul\nu$
CKM α, β
V_{ub}
V_{cb}
$\Upsilon(6S)$
τ lifetime
$B \to D^0\tau\nu$
Charged Higgs
$B \to K_S^0K_S^0K_S^0$
$\Upsilon(5S)$
$B \to K_S^0\pi^0\gamma$
$B \to K^+\pi^-\pi^0$
$B \to h\nu\nu, \tau\nu$
CPV in $D^0 \to h^+h^-$
$B \to K^*ll$
$B \to D^*\tau\nu$
Charm spectroscopy
$X(3872) \to J/\psi\pi\pi$
Charm mixing
α_s
$D \to l\nu$
Charged Higgs
$\tau \to$ hadrons
LFU
$\tau \to l\nu\nu$
LFU
Clear BSM
$D \to$ invisible
Dark matter
$\tau \to \mu\gamma$
$\sin\theta_W$
Neutral particles in the final state
Model-independent $D^0 \to K_S^0\pi^+\pi^-$
$Z_c(3900) \to J/\psi\pi$
Quantum correlated $D^0\bar{D}^0$
Absolute branching fractions
SCT
$\delta_{K\pi}$
V_{cd}
Polarized beam
New CPV
CPV in charm
$J/\psi(c\bar{c}) \to W^+s$
$J/\psi \to$ hadrons

On some accelerator R&Ds progress

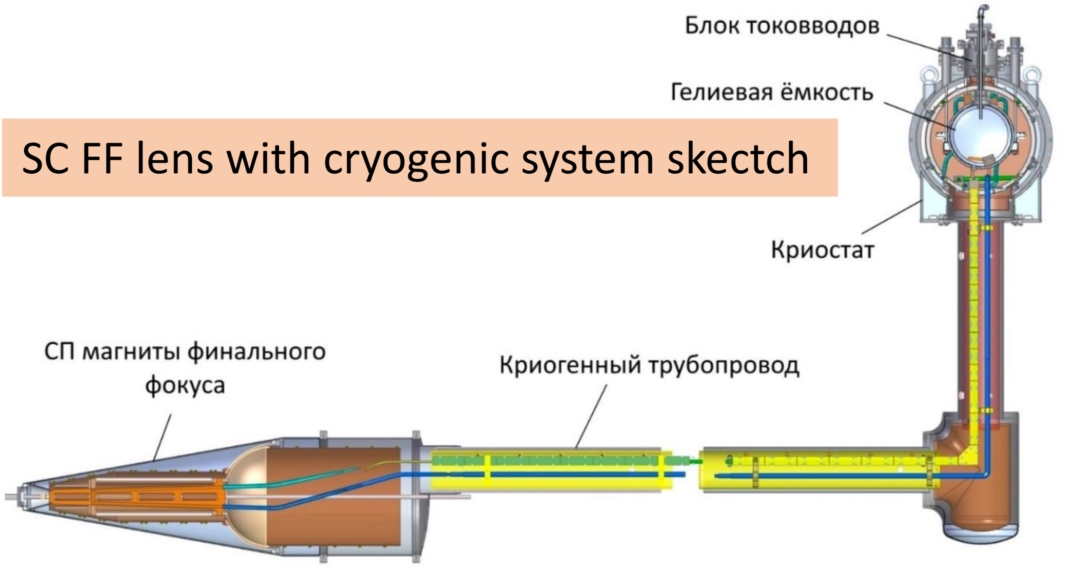
“Reliable” parameters of the collider

E(MeV)	1500	2000	2500	3000	3500
Π(m)	935.874				
F_{RF}(MHz)	350				
2θ(mrad)	60				
β_x^*/β_y^* (mm)	100/1				
$\varepsilon_y/\varepsilon_x$(%)	10	0.5	0.5	0.5	0.5
I(A) / N_b	2.9 / 941	1.64 / 983	2.5 / 983	2.7 / 983	2.9 / 974
$N_{e/bunch}\times10^{-10}$	6	3.25	5	5.3	5.8
U_0(keV)	91	288	504	820	1266
V_{RF}(kV)	750	2000	3000	3900	5000
ν_s	0.0108	0.0152	0.0166	0.0172	0.018
δ_{RF}(%)	1.3	1.83	1.97	1.97	1.98
$\sigma_e\times10^3$ (SR/IBS+WG)	0.27/0.9	0.36/1.1	0.5/1.2	0.5/1.2	0.6/1.3
σ_s(mm) (SR/IBS+WG)	3.6/17	4.7/15	6/14	7/14	8/14
ε_x(nm) (SR/IBS+WG)	2.0/2.9	3.5/3.5	5.5/3.2	7.9/4.1	11/5.7
$L_{HG}\times10^{-35}(cm^{-2}s^{-1})$	0.29	0.4	1	1	1
ξ_x/ξ_y	0.003/0.03	0.002/0.06	0.002/0.08	0.002/0.065	0.002/0.05
$\tau_{Touschek}$ (s)	304	304	302	560	1100
$\tau_{Luminosity}$ (s)	12000	5000	3000	3200	3500

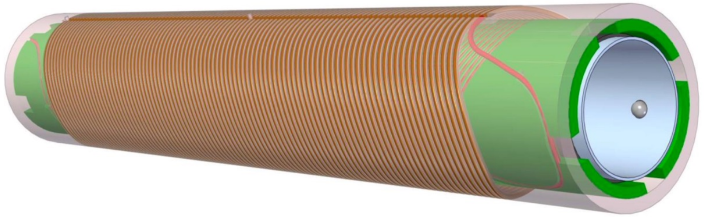
2022:
– Reliable structure of the collider was developed
– Touschek lifetime ~300 s
– $L = 0.3 \div 1.0 \cdot 10^{35} cm^{-2}s^{-1}$

–It is necessary to check IBS and beam-beam effects with help of simulation
– Possibility of prototyping is considered now

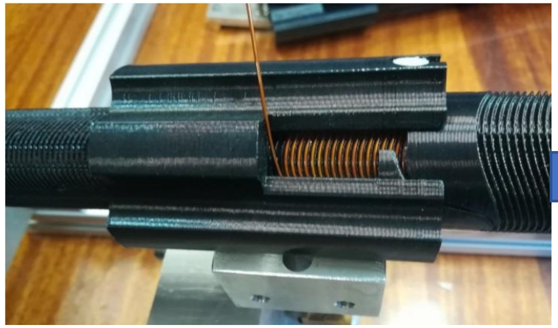
Final Focus lens prototyping

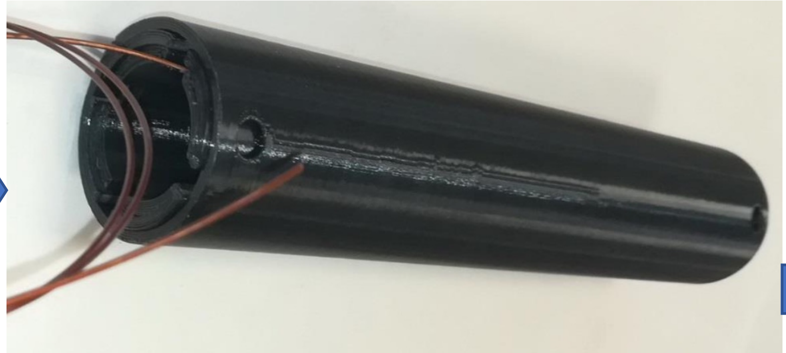


SC FF lens with cryogenic system skectch



Concept design of SC FF lens
Direct Double Helical (DDH) technology
2 concentric coil at 2 cylinders



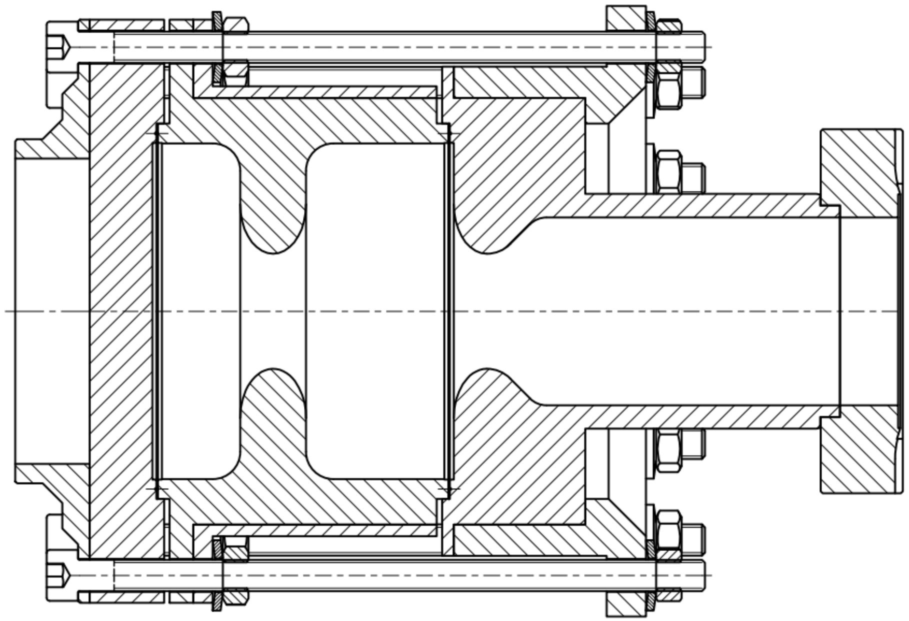


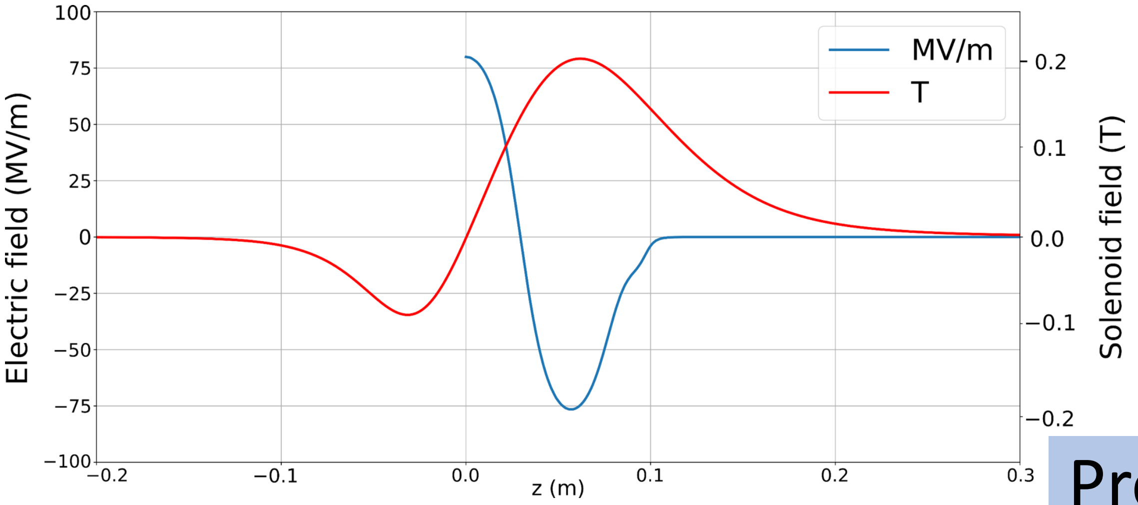
2022:

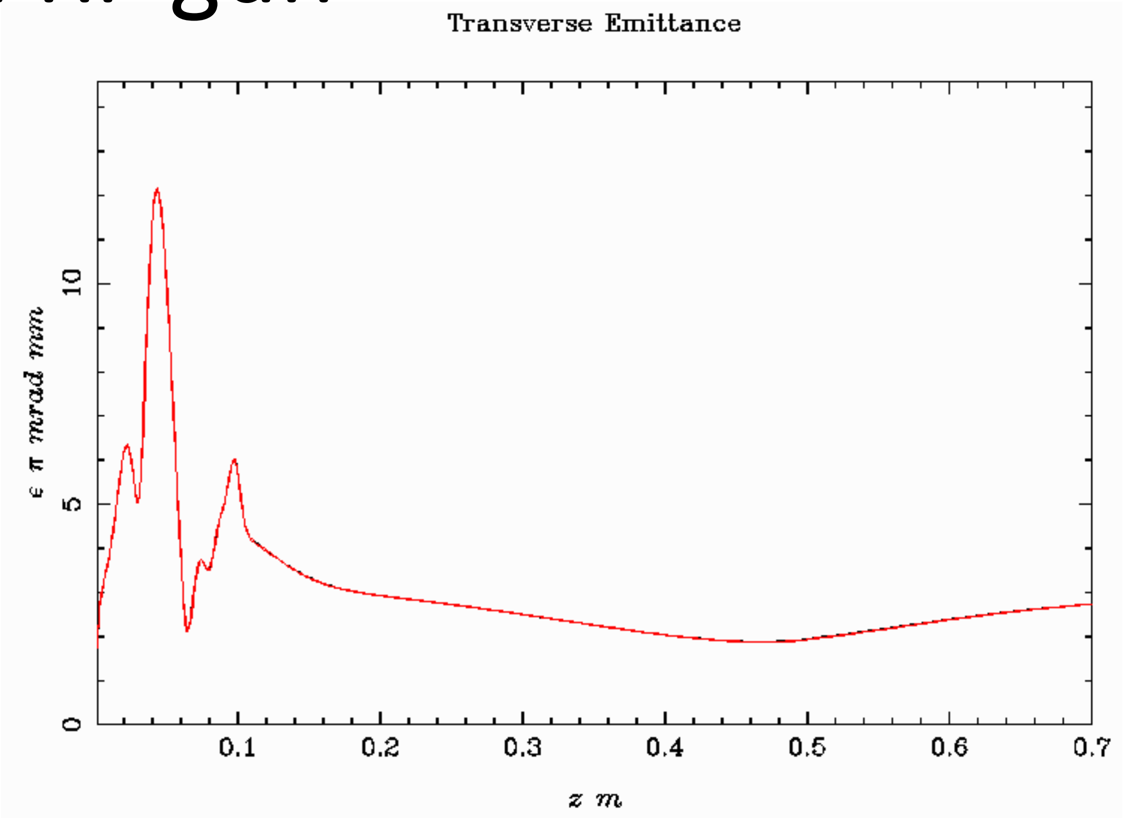
- Cryogenic system for FF lens is designed
- Project of SC FF lenses:
  - Compensated coil
  - Screen coil
  - SC coils production technology
  - Thermal loads calculation
  - Safety system
  - Coil holders calculation
  - Magnetic fields of FF lens calculation
  - First prototype of FF lens is under production
  - Testbench for magnetic measurements with FF lens is prepared
- Procedure of mechanical uncertainties measurements with high accuracy (~50 um) for FF lens assemblage is considered

Production and magnetic tests are expected until the end of 2023

Electron RF gun





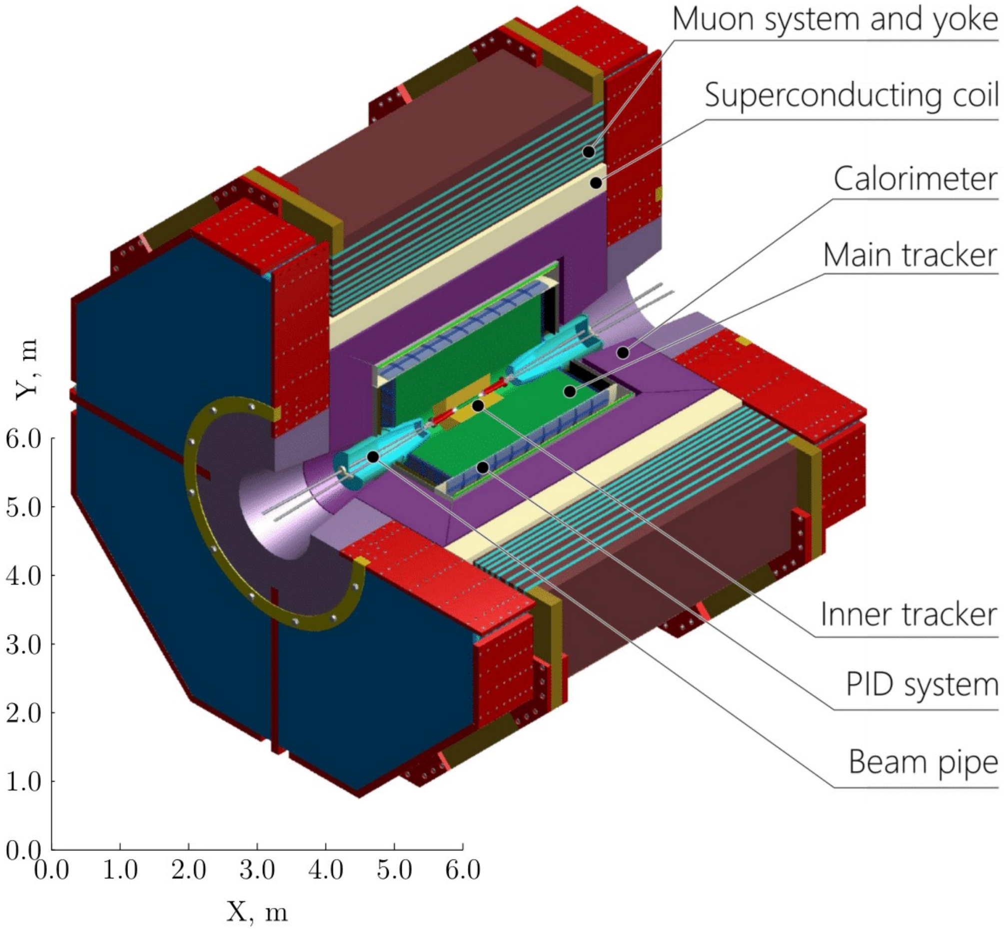


Field at cathode	80 MV/m
Bunch charge	1.5 nC
Beam energy	3.5 MeV

Production and first test until the end of 2023!

On some detector R&Ds progress

Detector concept



Momentum resolution $\sigma_p \leq\ 0.4\%$ at $1 GeV/c$

Very symmetric and hermetic

Able to detect soft tracks ($p_t \geq 50\ MeV/c$)

- Inner tracker should be able to handle 104 tracks/cm2s

Very good PID: $\mu/\pi/K$

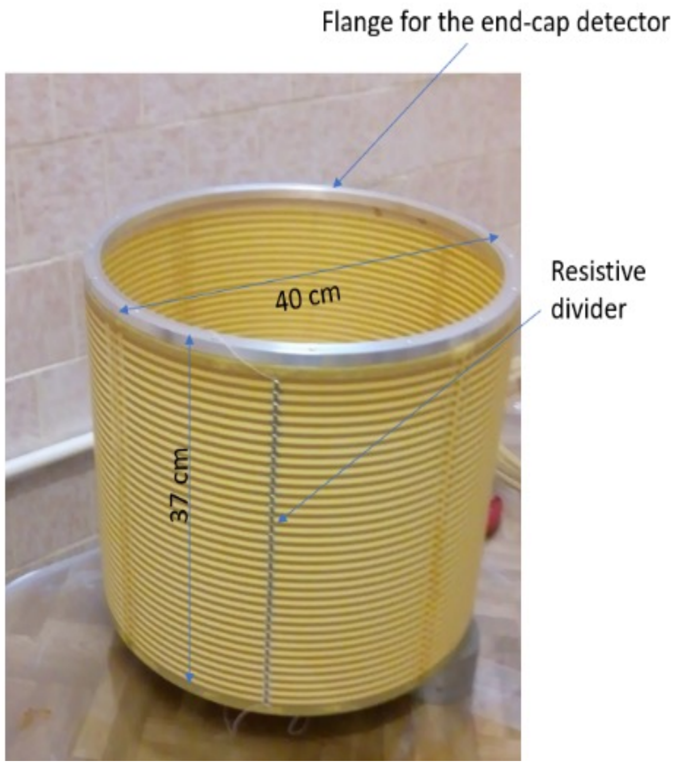
- π/K up to 3.5 GeV/c, e.g. for $D\bar{D}$ mixing
- μ/π up to 1.5 GeV/c, e.g. for $\tau\ \rightarrow\ \mu\gamma$ search
- dE/dx better than 7% for PID below 0.6 GeV/c

Able to detect γ from 10 MeV to 3.5 GeV, good π^0/γ separation

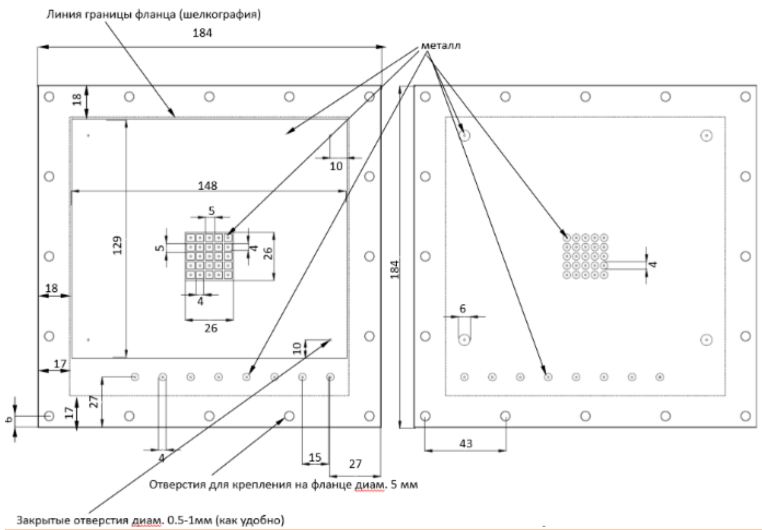
- Calorimeter energy resolution $\sigma_E \lesssim 1.8\%$ at 1 GeV
- Calorimeter time resolution $\sigma_t \lesssim 1$ ns

Efficient "soft" trigger
Ability to operate at high luminosity, up to 300 kHz at J/ψ

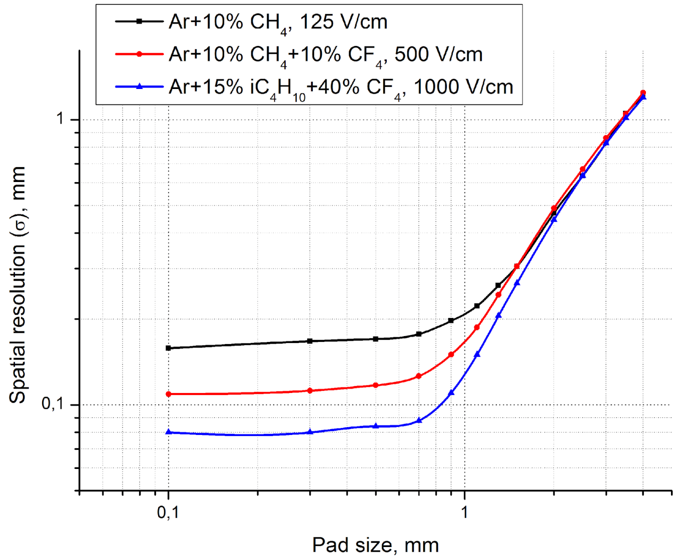
TPC with readout based on GEM



Gas volume with HV divider



Sketch of readout PCB:
25 pads $4 \times 4\ mm^2$



Plans:

- 2023:
  - Prototype production
- 2024:
  - Tests with prototype
  - Full simulation package for IT based on TPC-GEM

- IT prototype based on TPC-GEM project:
  - Investigate different gas mixtures
  - Test various MPGD options for readout (GEM + muRWELL or GEM + Thick RWELL),
  - To compare different options of RO electronics
- Some nodes of prototype still are under production
- Dependence of spatial resolution on RO structure pixel size is investigated with help of calculations. Optimal pixel size for several gas mixtures is 0.7÷1.0 mm.

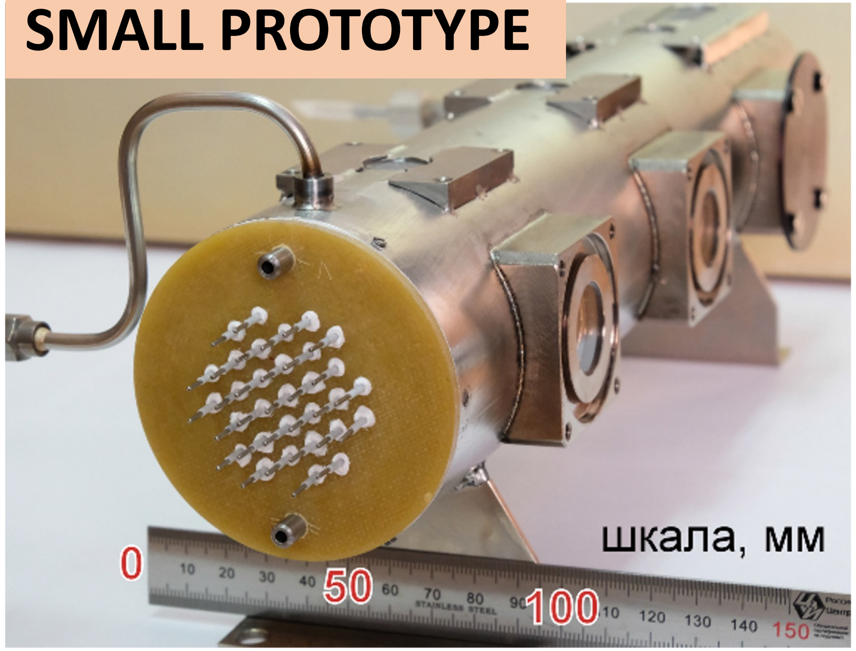
Drift Chamber with hexogonal cells

Characte-ristics	Detector				
	CLEOIII	BaBar	BESIII	BelleII	SCTF
B,T	1.5	1.5	1.0	1.5	1.5
N_{cells}	9796	7104	6796	14336	10903
Shape	Square	Hex.	Square	Square	Hex.
Anode wire d, mkm	W 20	W 20	W 25	W 30	W-Re(3 %) 25
Field wire d, mkm	Al 110	Al 120	Al 110	Al 126	Al 100, 125
Size mm × mm	14×14	18×12	12×12 16×16	7×7 10×10	$\sim 14 \times 14$
Gas mixture	He/C_3H_8 60/40	He/iC_4H_{10} 80/20	He/C_3H_8 60/40	He/C_2H_6 50/50	He/C_3H_8 60/40
V_{anode}, B	1900	1930	2200	2300	$\sim$ 2000
T/D, ns/mm	$\sim 300/7$	$\sim 500/9$	$\sim 350/8$	$\sim 350/8$	$\sim 350/7$
σ_p/p, %	0.32	0.48	0.5	-	$\sim$ 0.35
$\sigma_{dE/dx}$, %	5.7	7.5	6.0	$\sim$ 6	$\sim$ 6.9
σ, μm	110	120	120	$\sim$ 100	$\sim$ 100

https://doi.org/10.1016/j.nima.2021.165490

DC prototypes

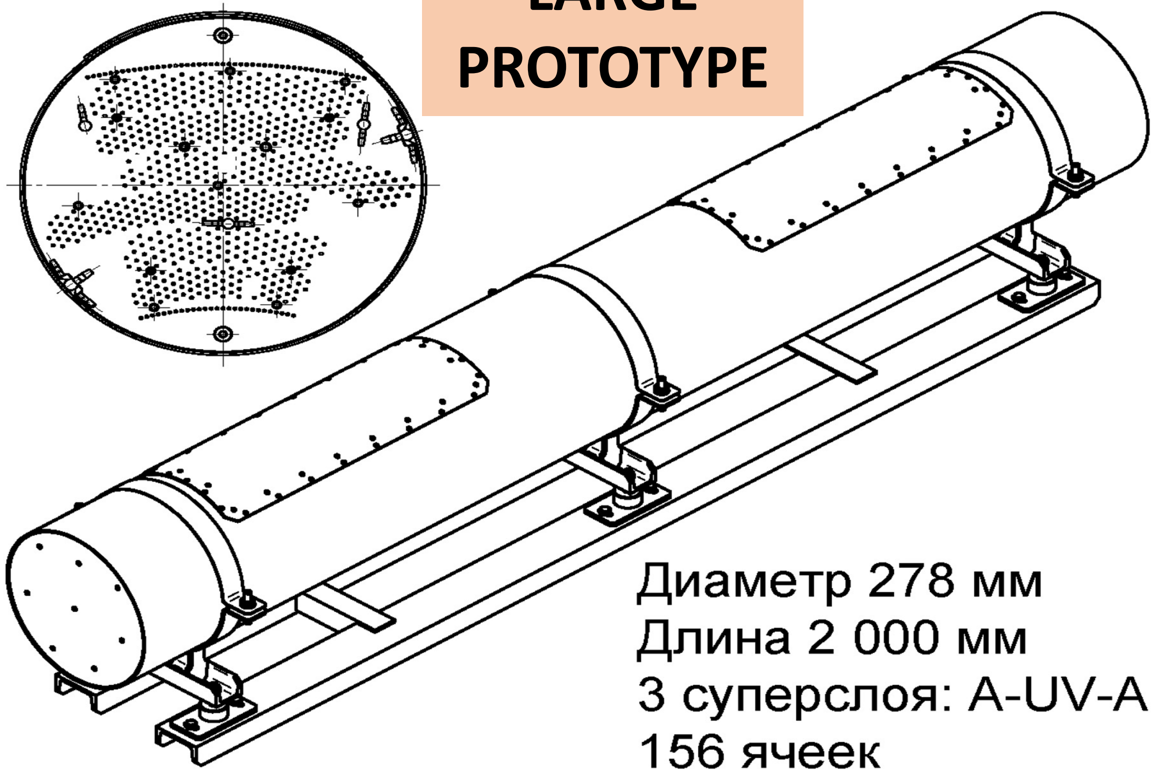
SMALL PROTOTYPE



Small prototype:

- Diameter – 70 mm
- Length – 300 mm
- 7 hexagonal cells
- Launched in operation in 2022

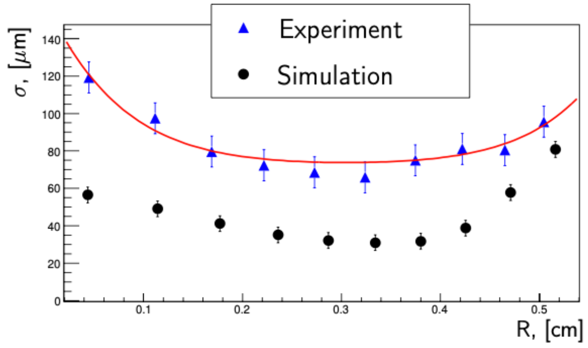
LARGE PROTOTYPE



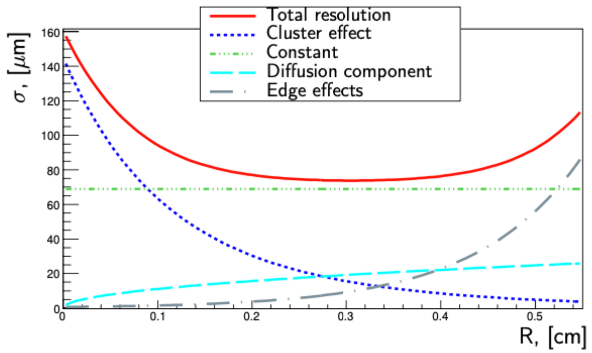
Large prototype:

- Diameter – 278 mm
- Length – 2 000 mm
- 3 superlayers: A-UV-A
- 156 hexagonal clls
- Design is developed
- Production in 2023-2024.

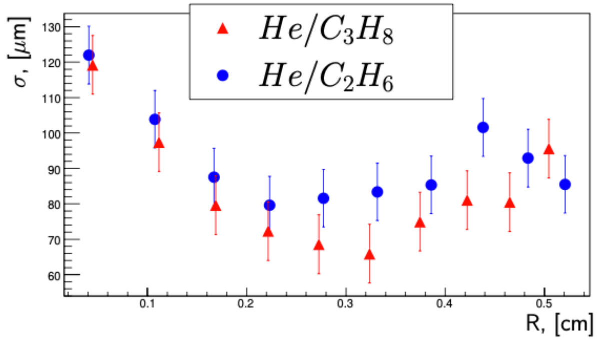
Spatial resolution measurements with small prototype



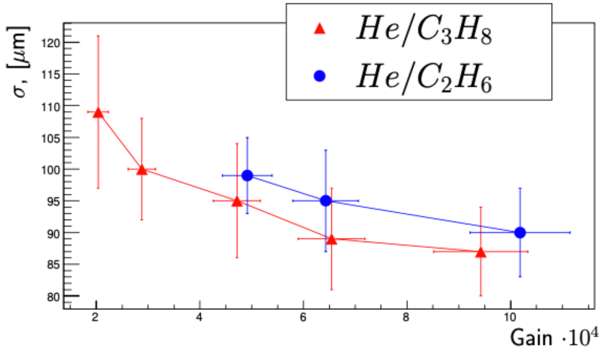
Full spatial resolution for He/C3H8 mixture



Contribution of each component to resolution



The spatial resolution comparison for He/C_3H_8 and He/C_2H_6 at $7 \cdot 10^4$



The average spatial resolution for He/C_3H_8 and He/C_2H_6 at the different gas gains

$$\sigma(r) = \sqrt{\sigma_{cl} + \sigma_{dif} + \sigma_{edge} + \sigma_0}$$

σ_{cl} - cluster effect, σ_{dif} - diffusion component, σ_{edge} - edge effects, σ_0 - constant (contributions from electronics, wire arrangements, pressure, temperature)

For He/C_3H_8:

$\bar{\sigma} = 109 \pm 12$ μm at $2 \cdot 10^4$

$\bar{\sigma} = 100 \pm 8$ μm at $3 \cdot 10^4$

$\bar{\sigma} = 95 \pm 9$ μm at $5 \cdot 10^4$

$\bar{\sigma} = 89 \pm 8$ μm at $7 \cdot 10^4$

$\bar{\sigma} = 87 \pm 7$ μm at 10^5

For He/C_2H_6:

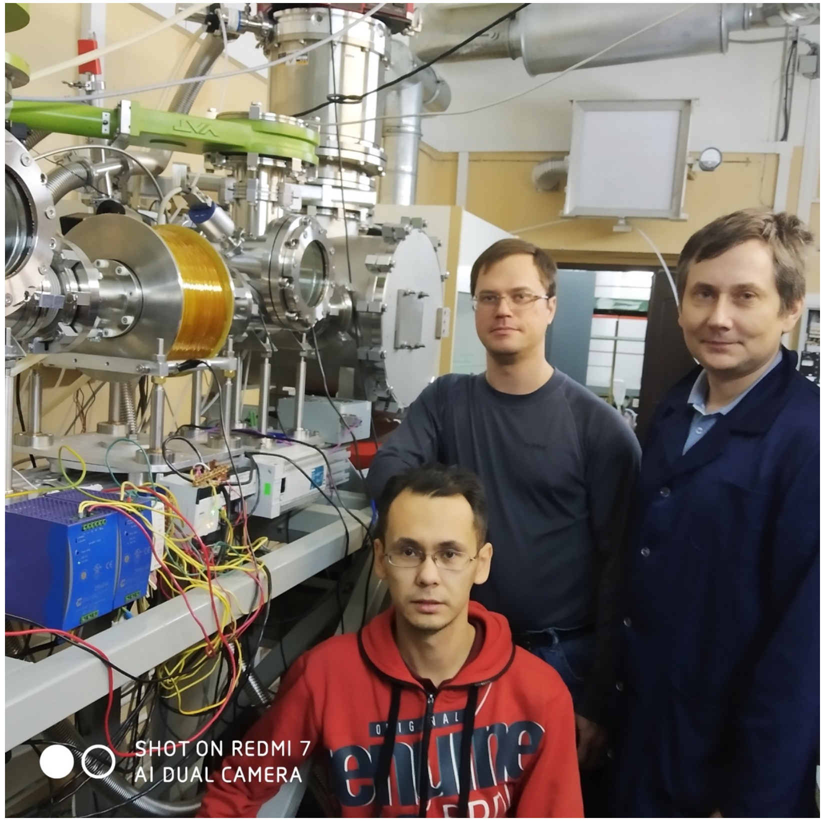
$\bar{\sigma} = 99 \pm 6$ μm at $5 \cdot 10^4$

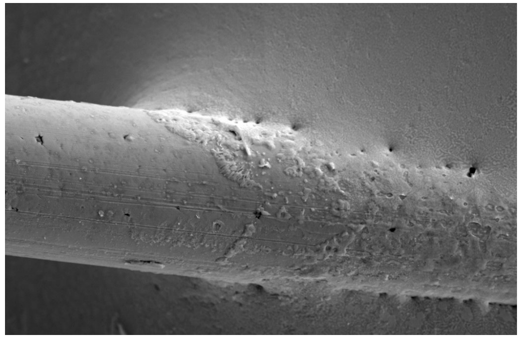
$\bar{\sigma} = 95 \pm 8$ μm at $7 \cdot 10^4$

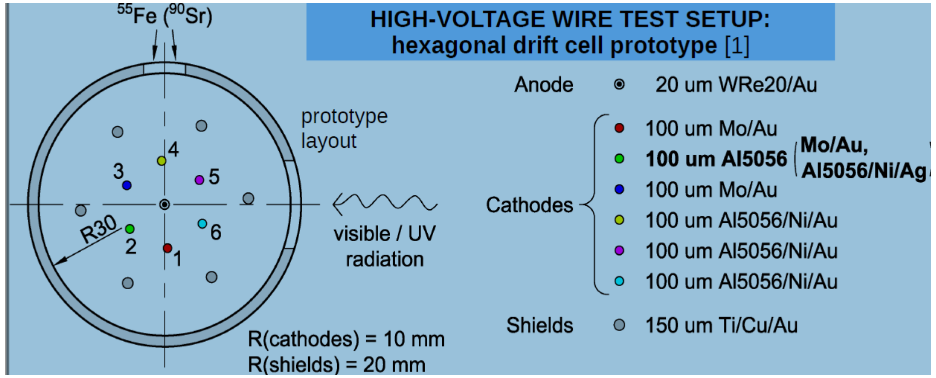
$\bar{\sigma} = 90 \pm 7$ μm at 10^5

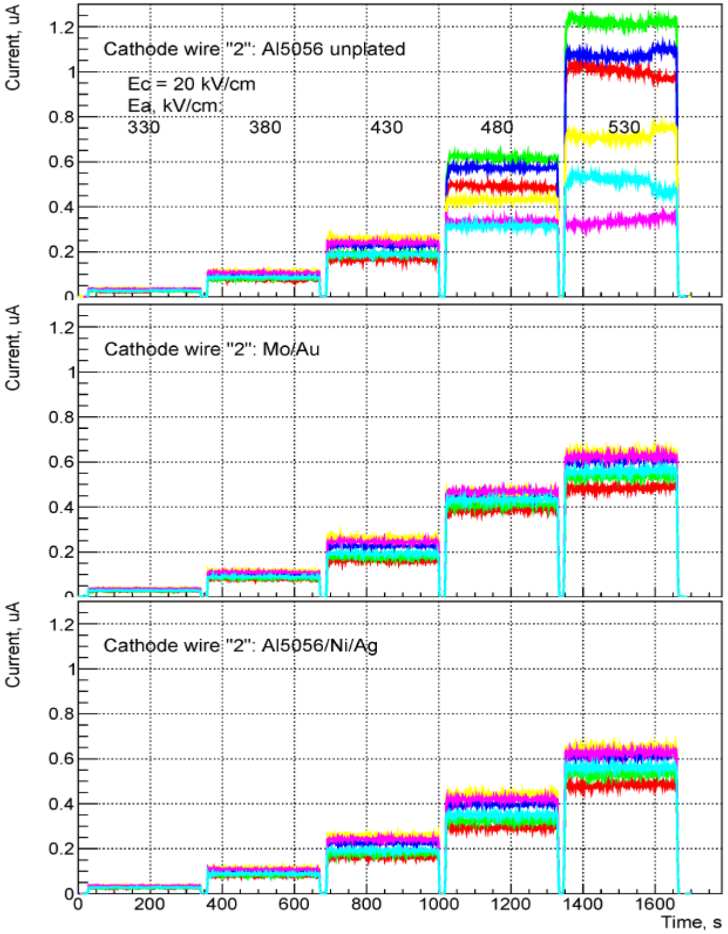
Target spatial resolution is achivable in our DC design!!!

Magnetron sputtering setup







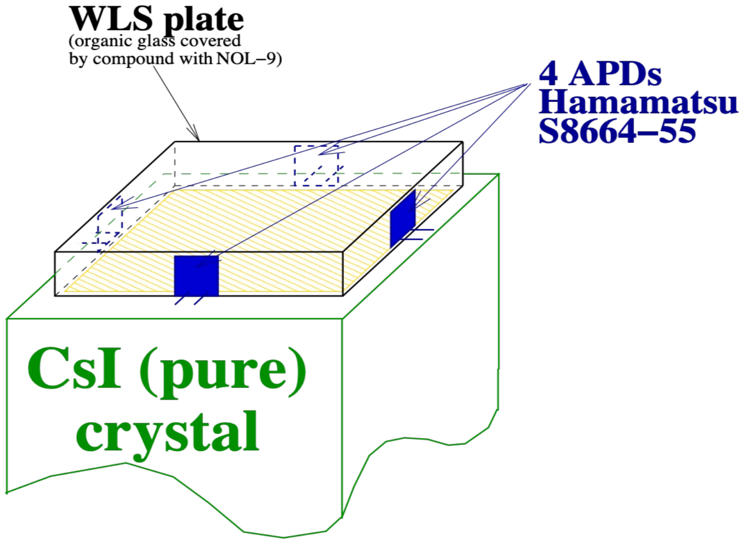


2022:

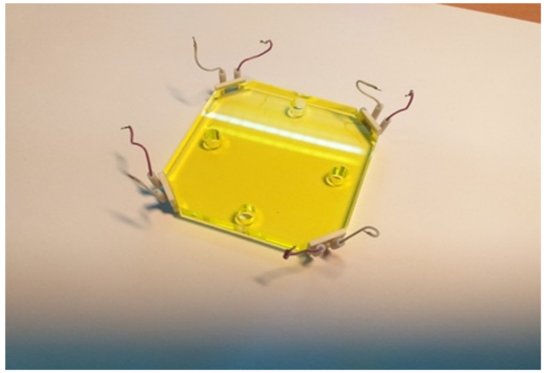
- Stable procedure of sputtering for Ni, Ag (or Au) 40 и 50 um at wires (Al) was found:
  - thickness – up to 70 нм
  - speed – 4 m/min.
- Au spends – 10÷15 g/km for 10 nm thick layer, but recycling of some amount of Au is possible
- There are no overheating and mechanical properties changes effects after sputtering process
- The cover provide easy soldering process and suppress SEE from cathode wire surface
- About 600 m Aluminum wires with ø4 um and ø50 um were covered and delivered to Italy to be tested by MEG2 experiment group

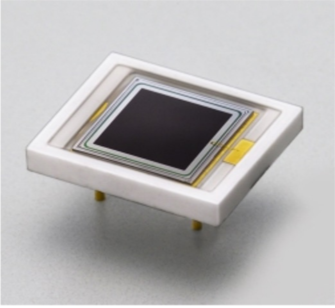
Leakage current of cathode wire irradiated by γ from ^{55}Fe (E_{cath}=const; E_{an}=var)

Prototype of pureCsI-calorimeter



PMMA with NOL-9





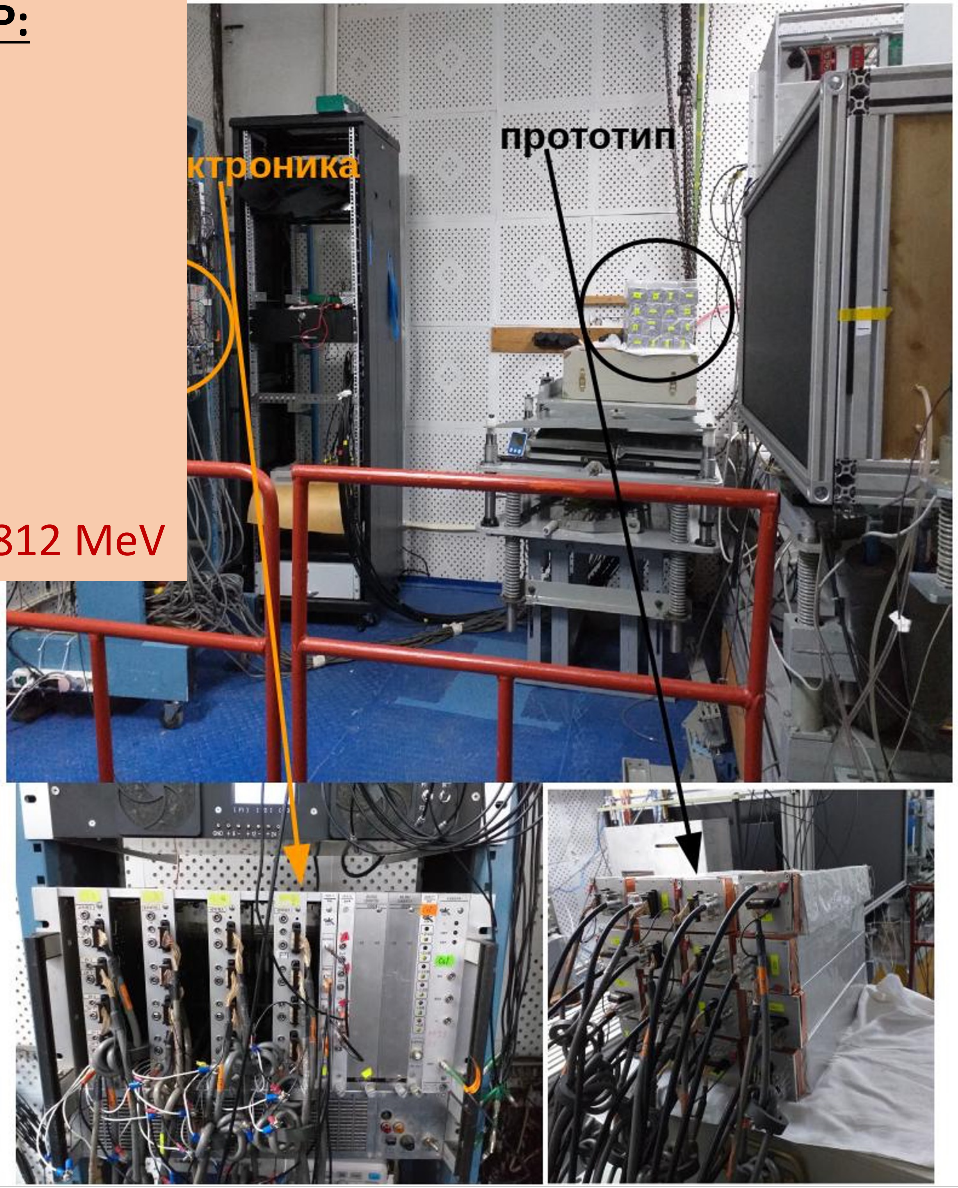
Hamamatsu
APD S8664-55

pCsI calorimeter concept

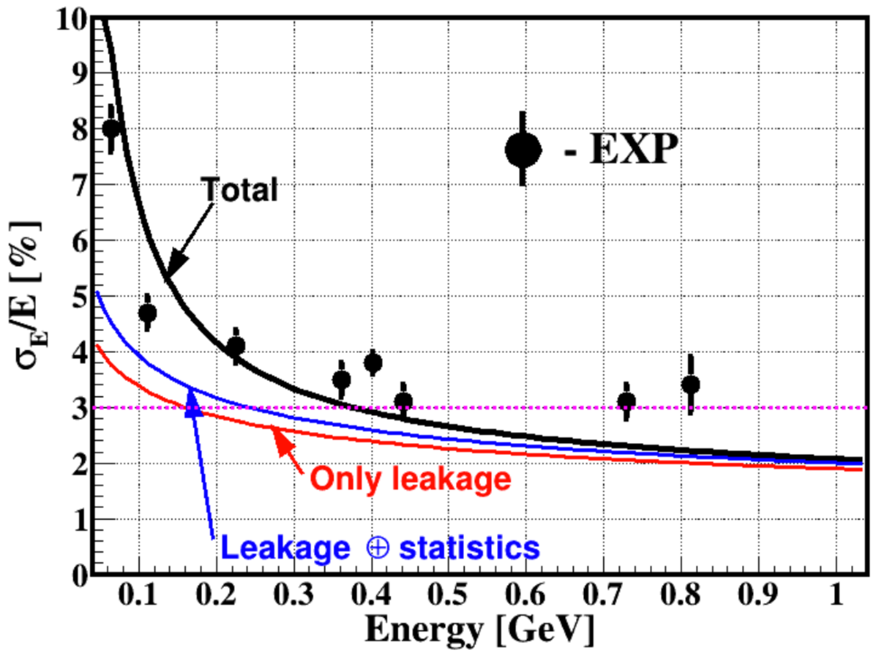
TBeam June 2023 at the BINP:

CBS gammas were used for energy resolution calibration:

- Two laser modes:
  527 nm & 1064 nm
- Five beam energies:
  1.9, 2.5, 4.5, 4.75 GeV
- Eight CBS edges for calibration:
  64, 111, 225, 361, 402, 441, 730, 812 MeV



pureCsI-calorimeter protype: beam test results



Stat = 0.63%

Elec = 0.54%

- The results are still preliminary!!!
- Some improvement are expected after fine calibration procedures

$$\frac{\sigma_E}{E} = \frac{1.9\,\%}{\sqrt[4]{E[GeV]}} \oplus \frac{Stat}{\sqrt{E[GeV]}} \oplus \frac{Elec}{E[GeV]}$$

$$Stat = 100\,\% \cdot \sqrt{\frac{F}{S[ph.e/MeV] \cdot N_{APD} \cdot 1000}}$$

$$Elec = 100\,\% \cdot \frac{ENE[MeV] \cdot \sqrt{N_{crys}}}{1000}$$

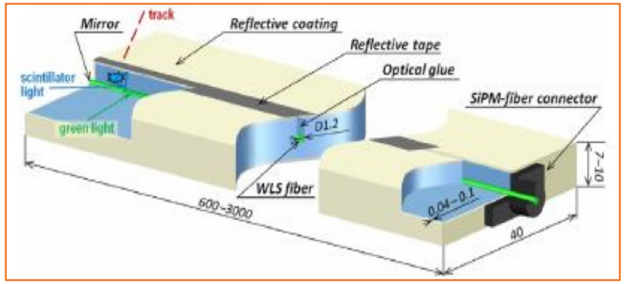
F = 1.69 ± 0.04

$S \cdot N_{APD}$ = 42 ph.el./MeV

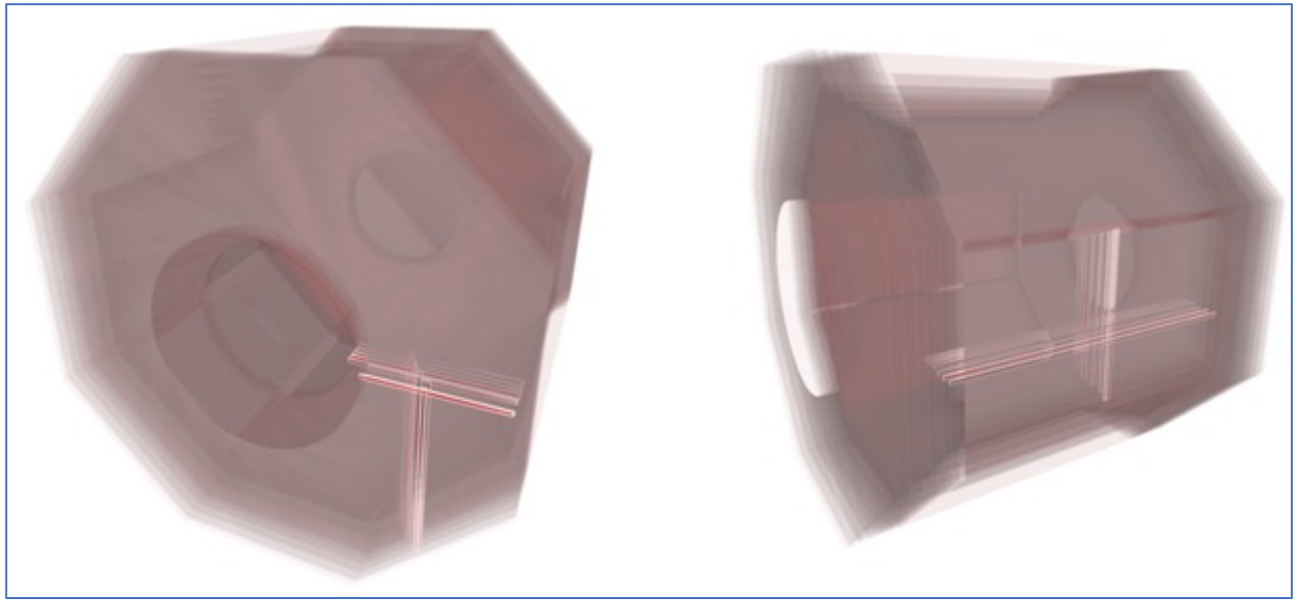
ENE = 1.7 MeV

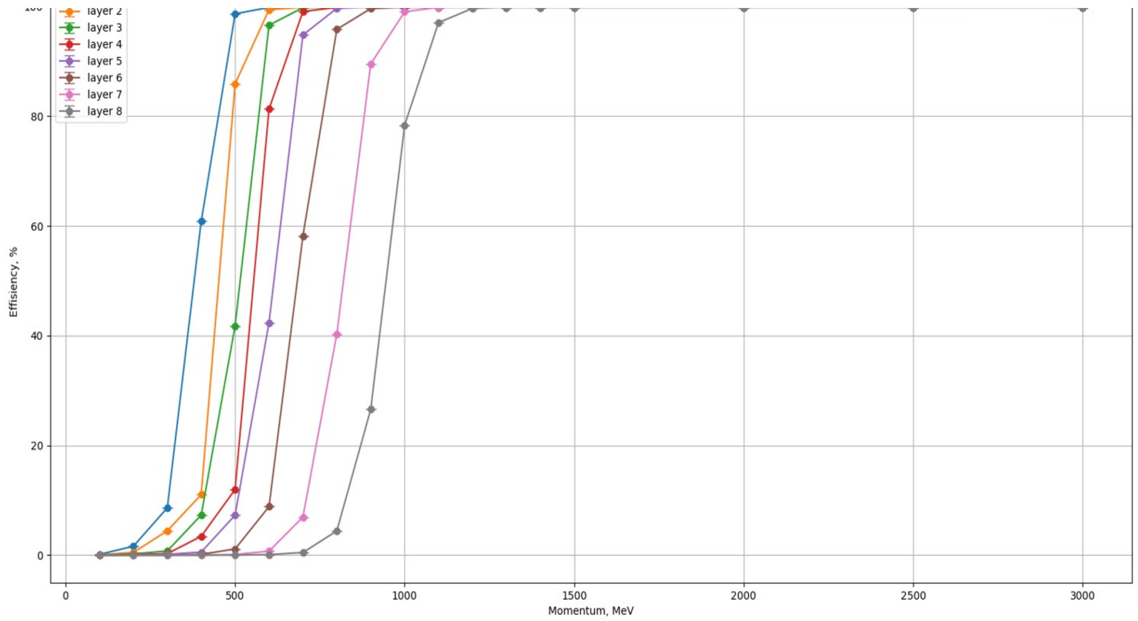
N_{crys} = 10 – number of crystals in the 1 GeV cluster

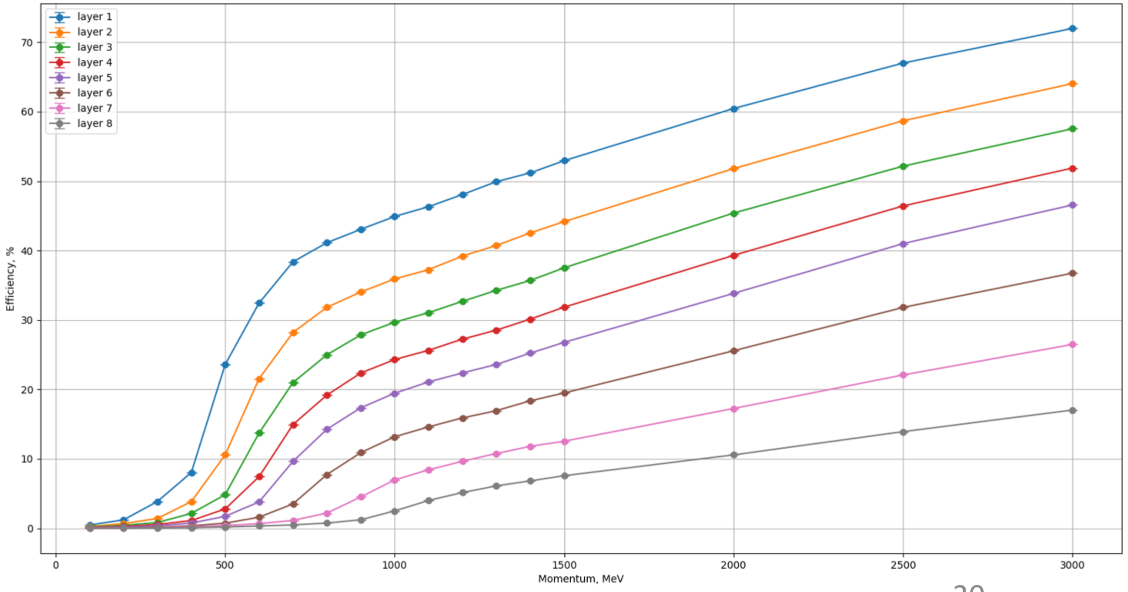
Muon system: scintillator with WLS fibers and SiPMs



SW for simulation:
MU system totally implemented in AURORA framework.

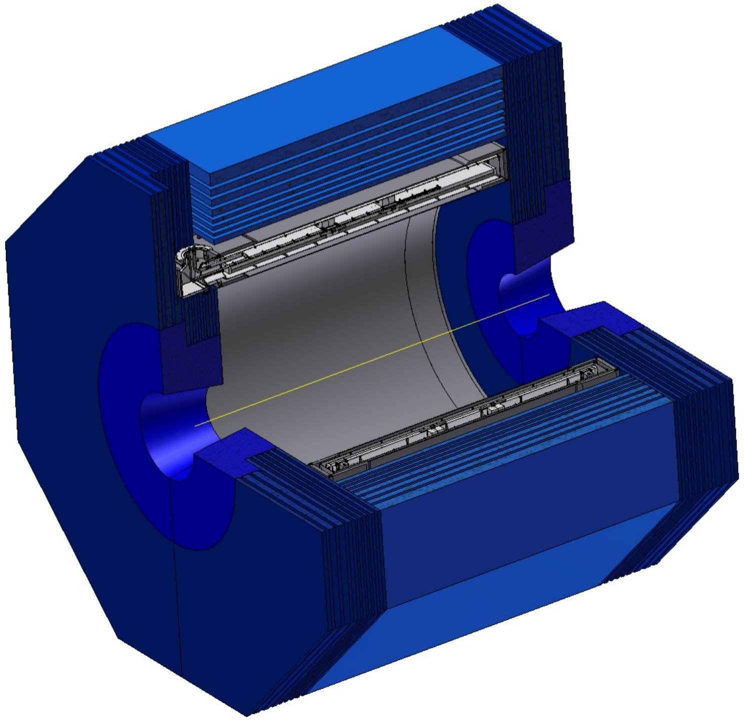


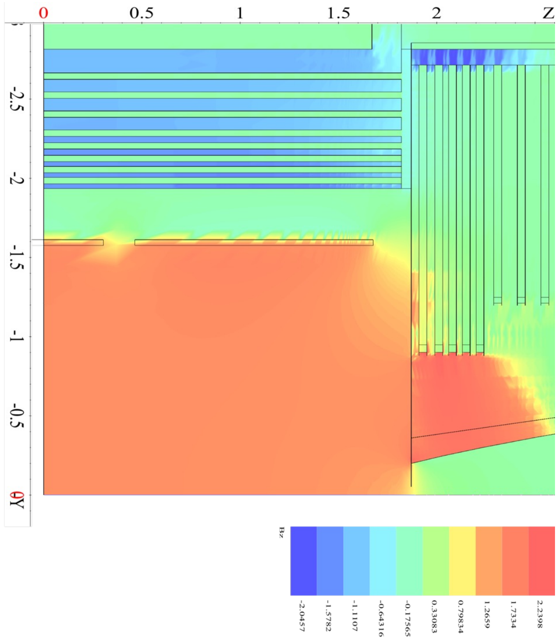


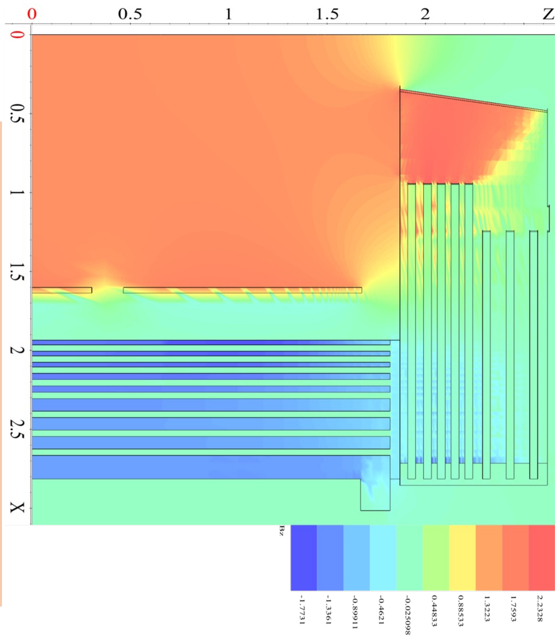


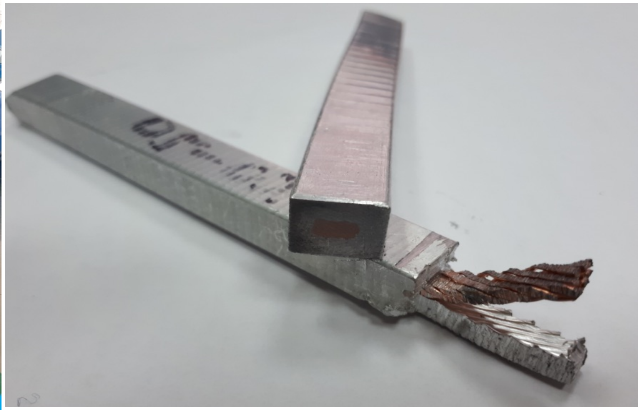
Plans:
We need to find new modern solution to realized this concept:
- Scintillators – ?
- WLS fibers – ?
- SiPM – ?

Magnetic system









2022

- Design is well done:
    - Three coils made solenoid
    - Supports, hangs, holders, cryotubes, …
- Main calculations are performed
    - Magnetic fields
    - Mechanical loads

<u>SC cables designed for PANDA</u>

- Several meters were produced and tested
- Technology of long strands (>1 km) production are under development
- We have enough high purity Al for SCTF magnet production (2x3.5 km & 1x1.5 km of cables)
- The similar cables will be used in SPD (NICA) project.

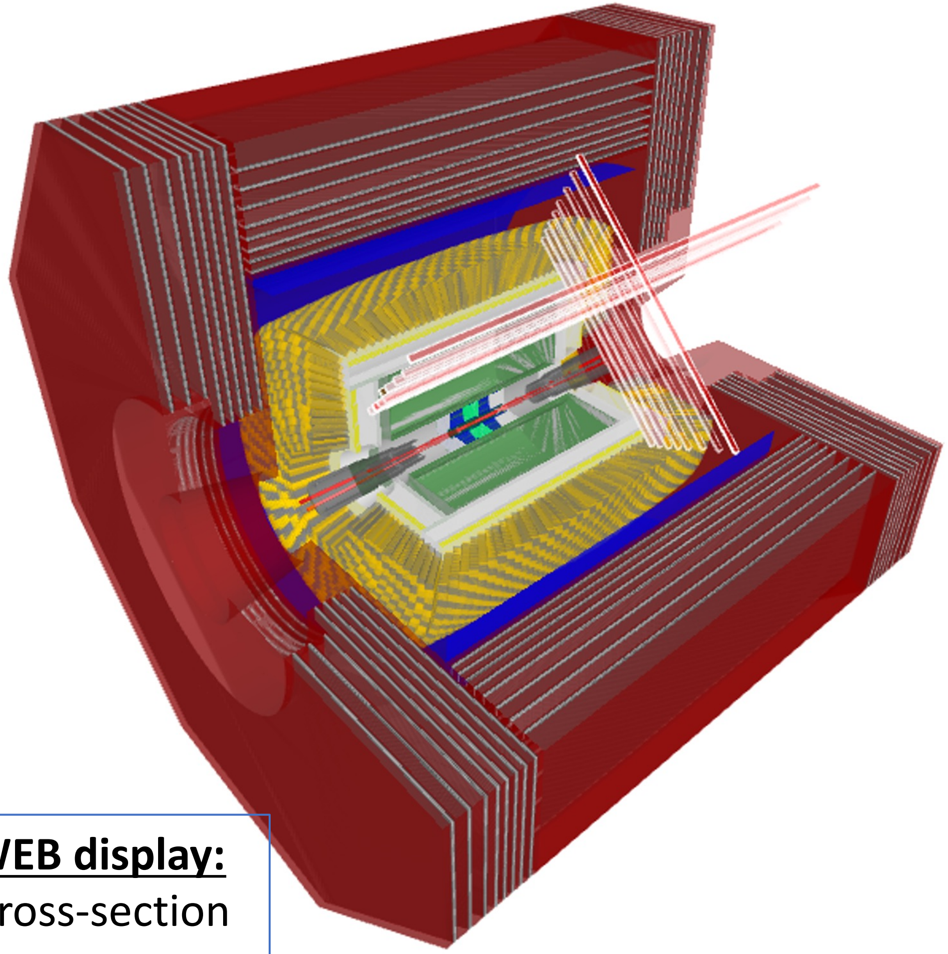
Soft Ware for the project

SW is available now for users of BINP clusters and as an image of virtual PC for external users

Aurora Framefork

Release 2.1.0 (December 2022):

- Blocks interaction, system of configuration and linking
- Event generators
- Geometry description (DD4Hep)
- Digitization
- Reconstruction
- Parametric simulation
- Instrumentation (visualization, tests,..)

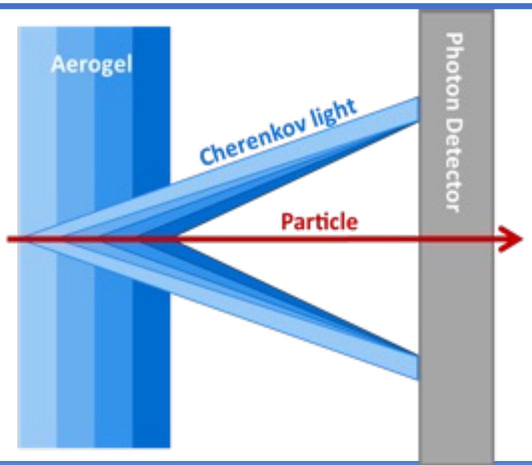


Detector WEB display:

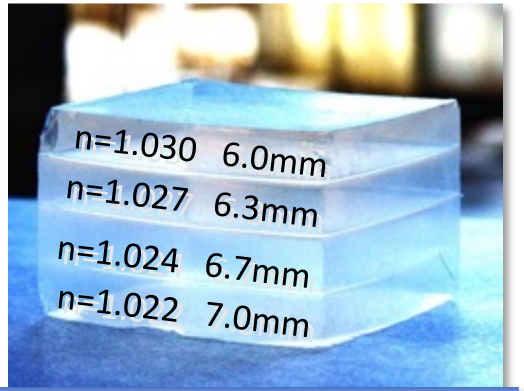
- Detector cross-section
- Hits in MU system

FARICH – 19 years of R&Ds (since 2004) and only 12 for SCTF project (since 2011)

FARICH technique



The first 4-layer monolithic sample

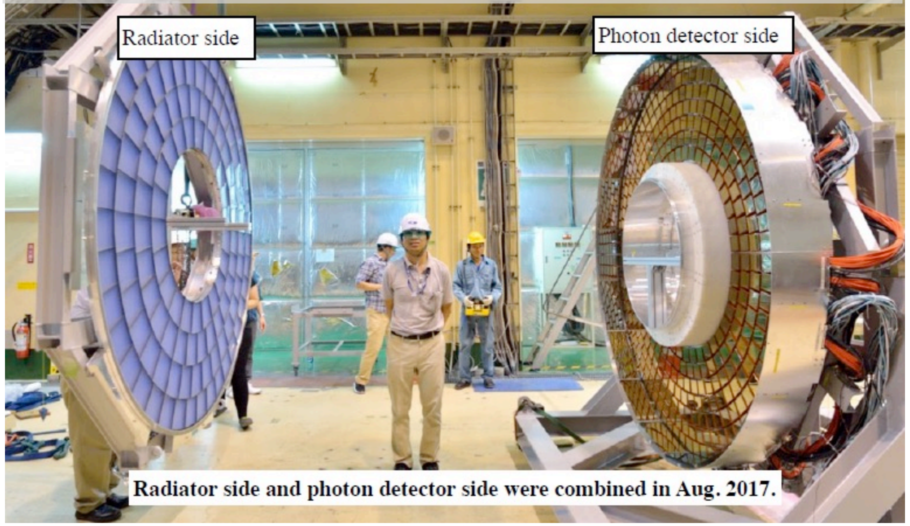


Increase N_{pe} due thickness increase without $\sigma_{\Theta c}$ degradation

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

2004÷2005

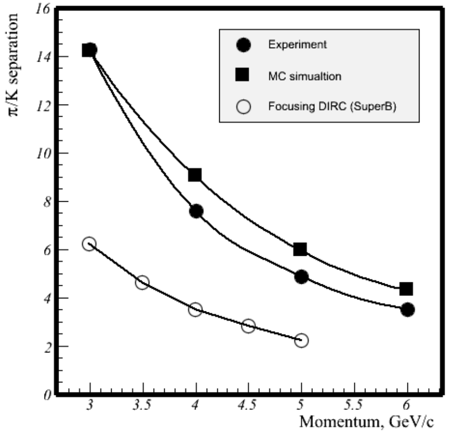
The Belle II (ARICH) is the first application of the method

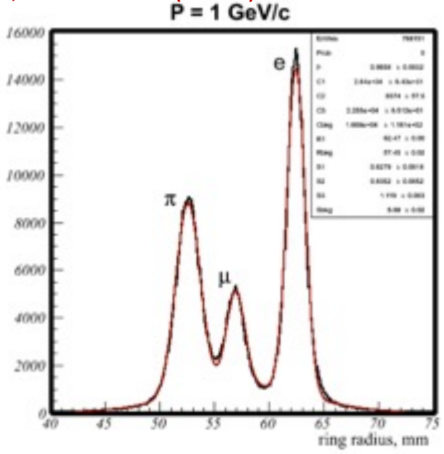


2017

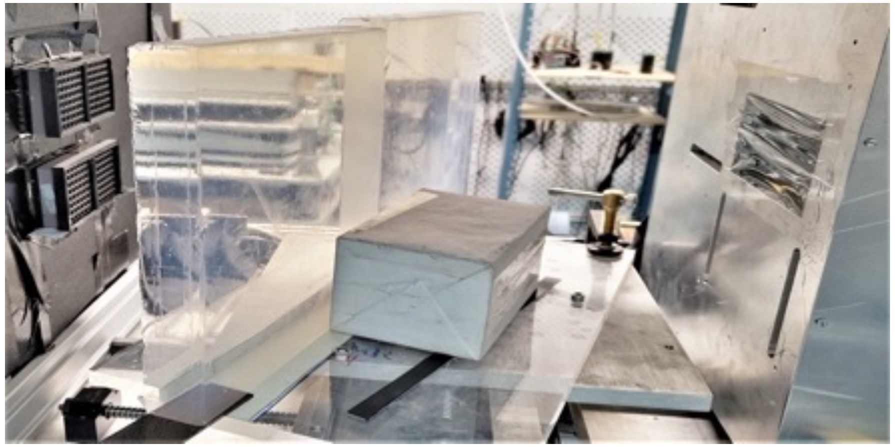
Excellent PID capability were shown at CERN beam test in 2012

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



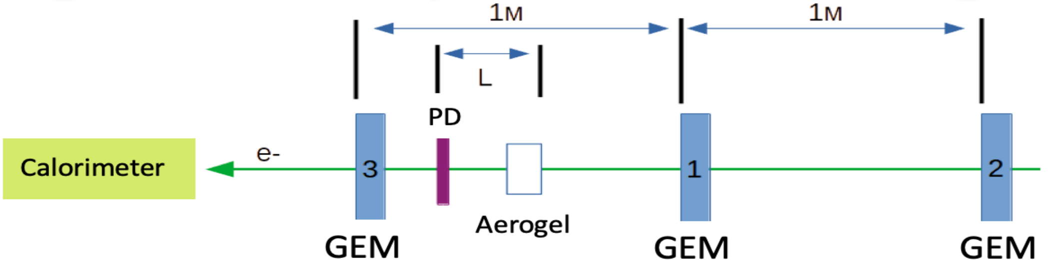


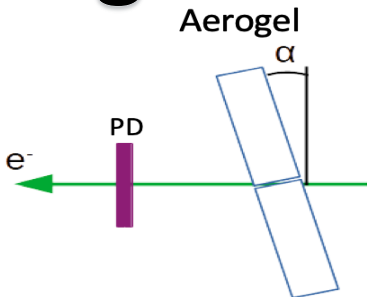
Two 4-layer focusing aerogel blocks
230x230x35 mm



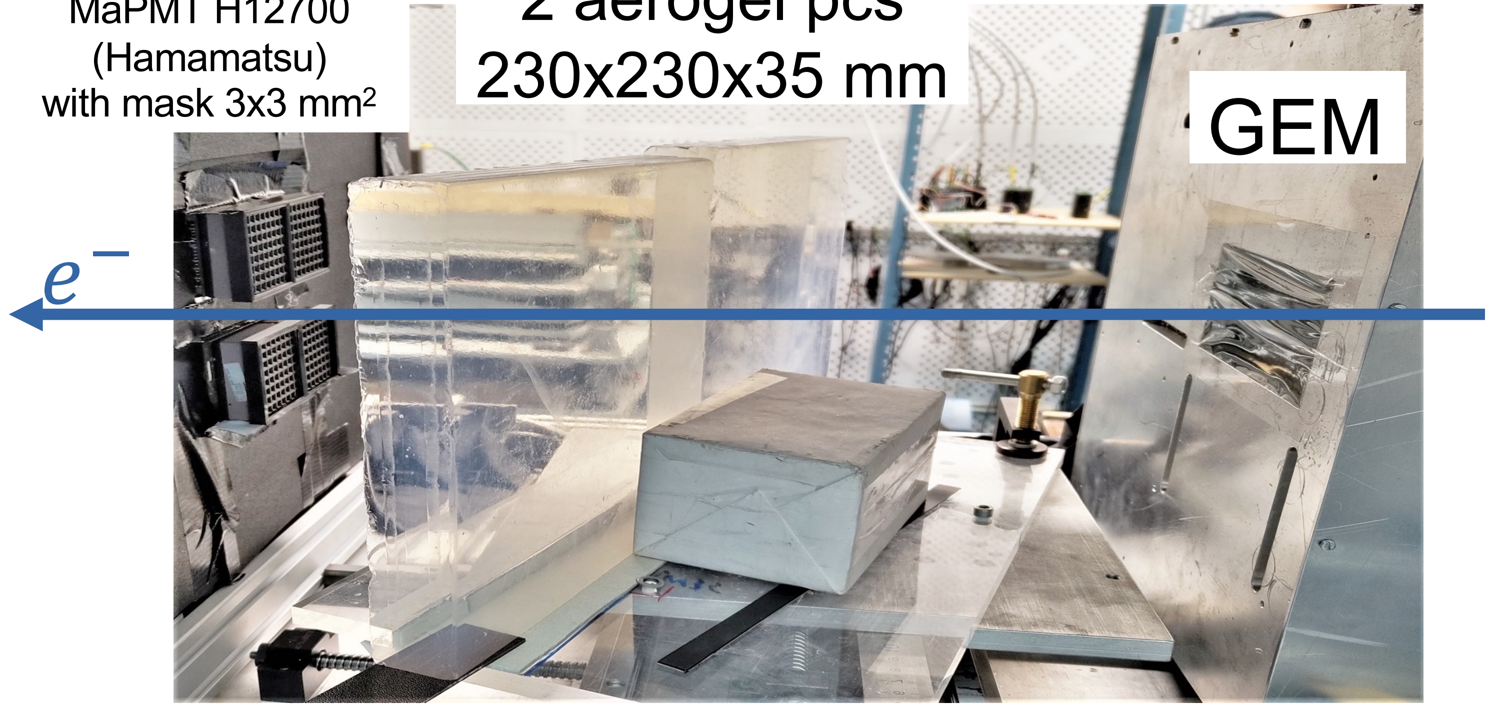
2022÷2023

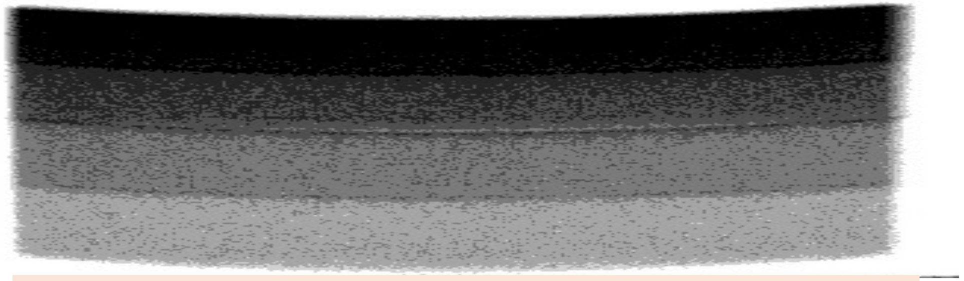
The largest 4-layers focusing aerogel samples



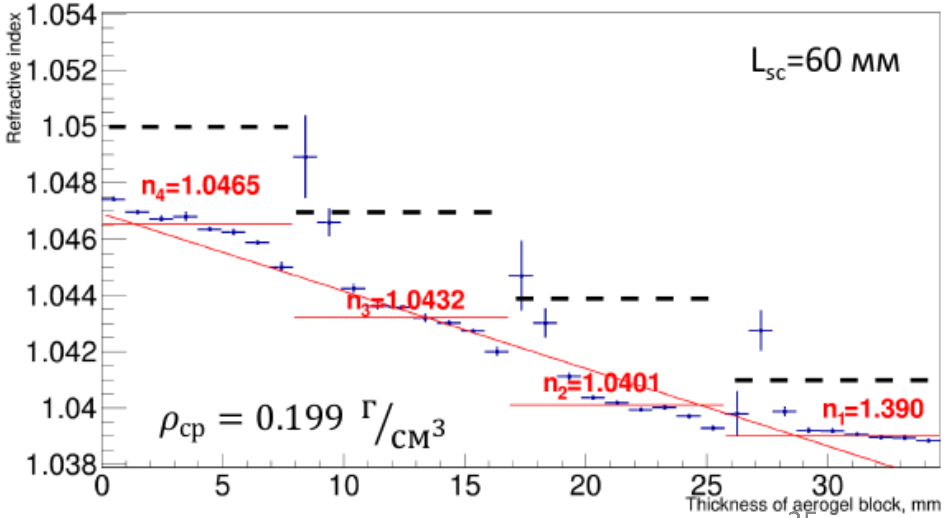


MaPMT H12700
(Hamamatsu)
with mask 3x3 mm²





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

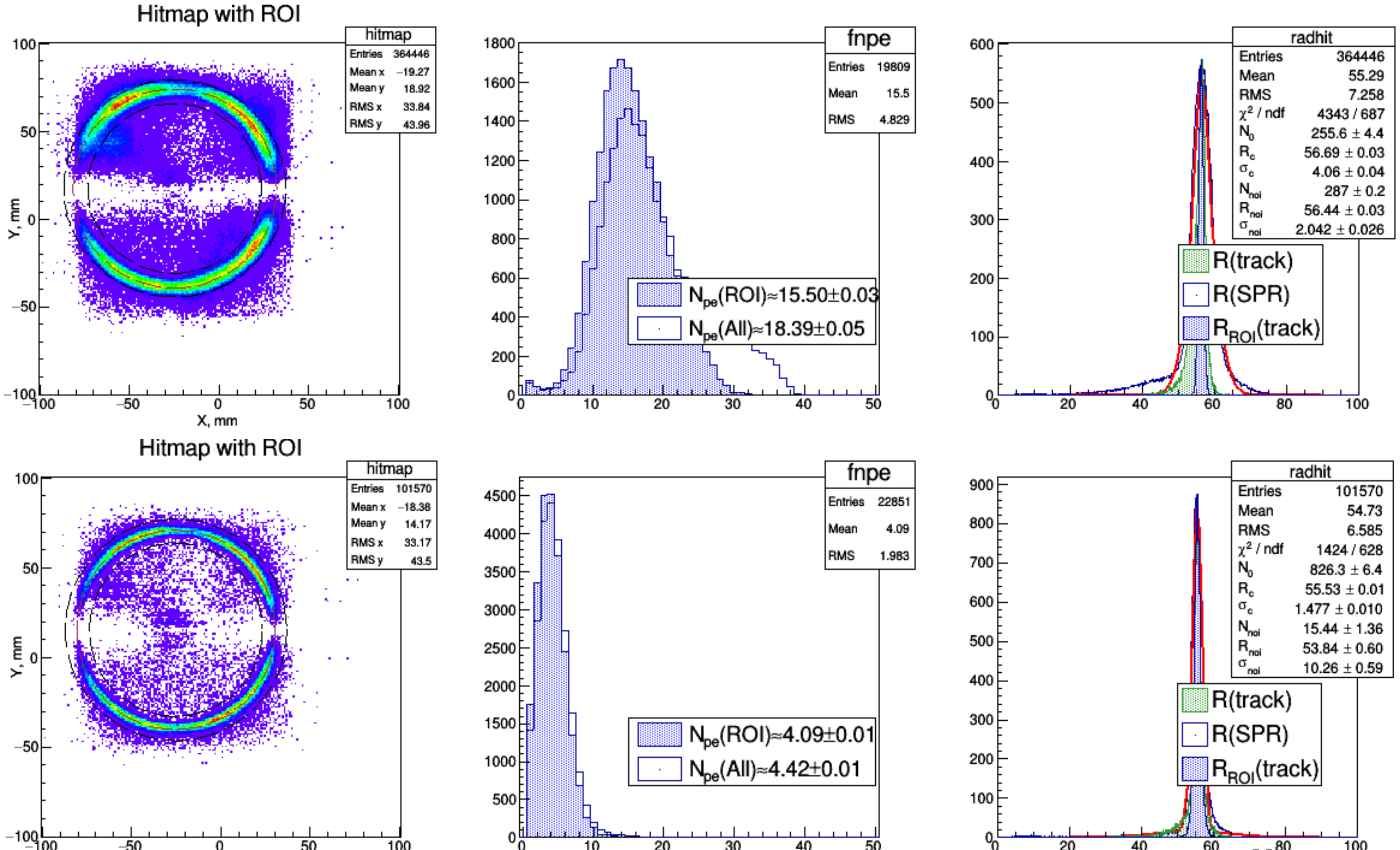


Single photon Cherenkov angle resolution is investigated with relativistic electrons at BINP beam test facilities ”Extracted beams of VEPP-4M complex”.

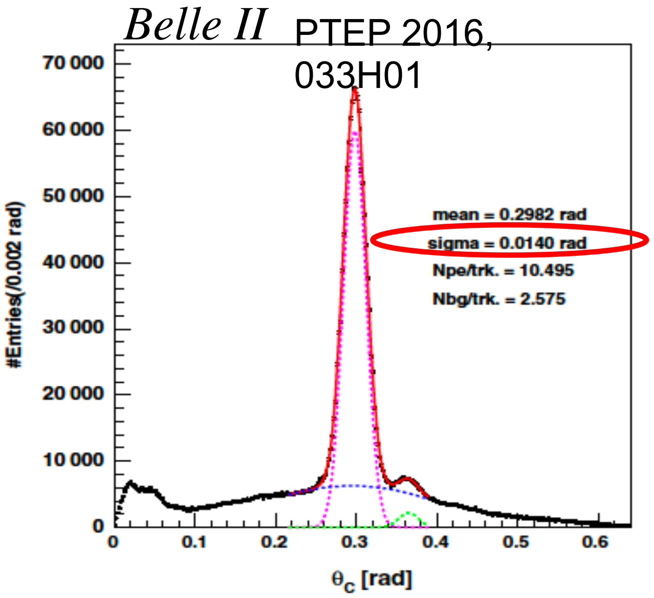
Beam test results

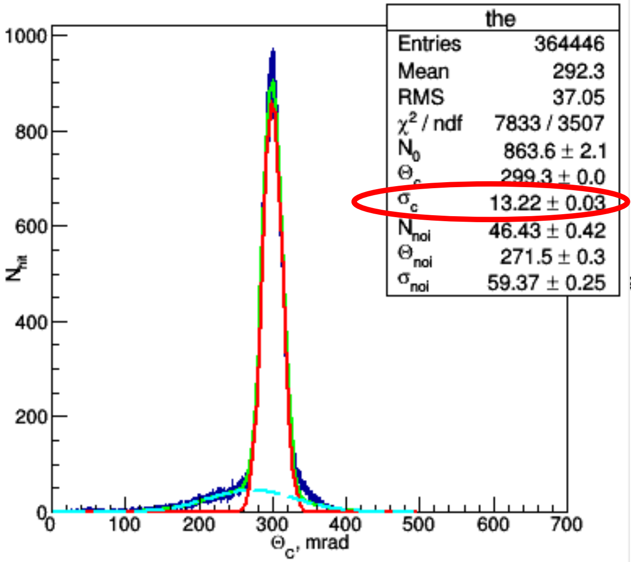
Pixel 6x6 mm
Geom.Eff. ~ 80%

Pixel 3x3 mm
Geom.Eff. ~ 20%

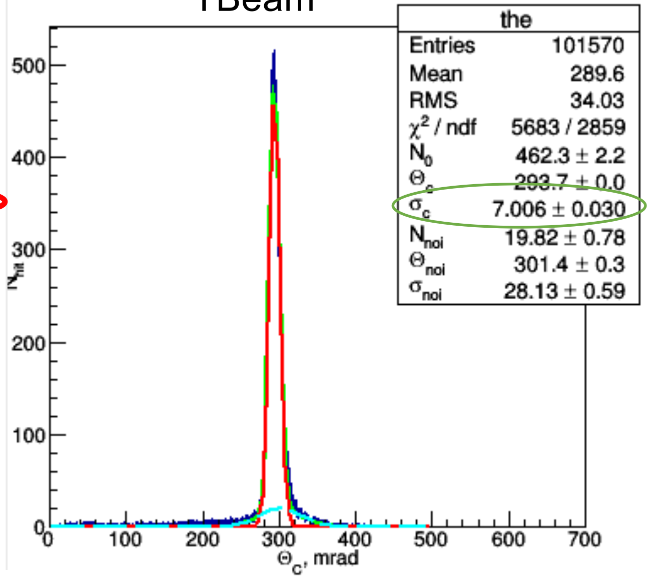


Cherenkov angle Single Photo-Electron (*SPE*) resolution

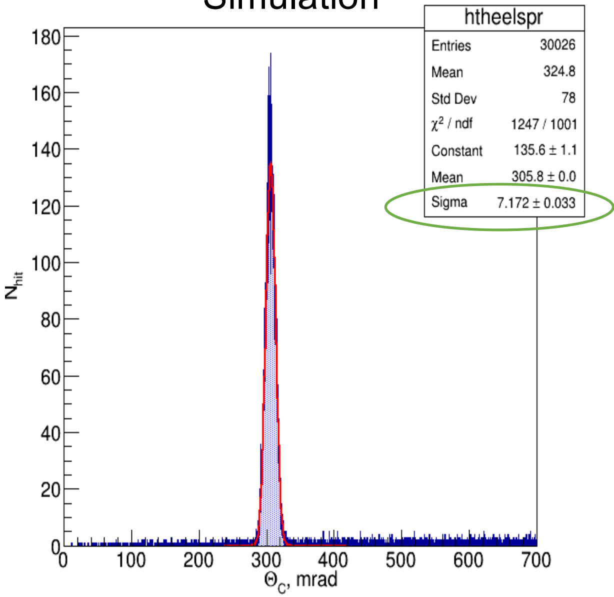




TBeam



Simulation

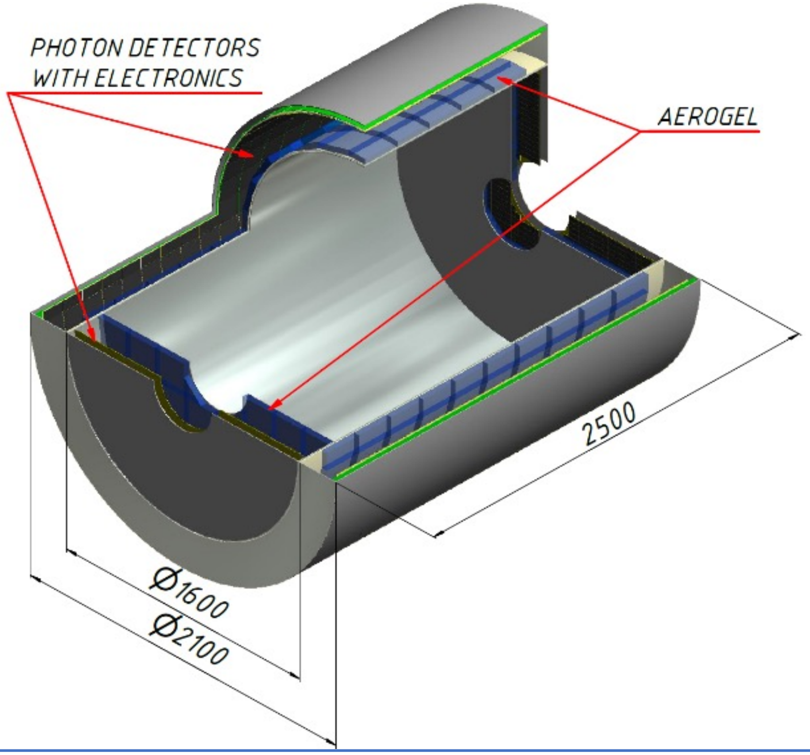


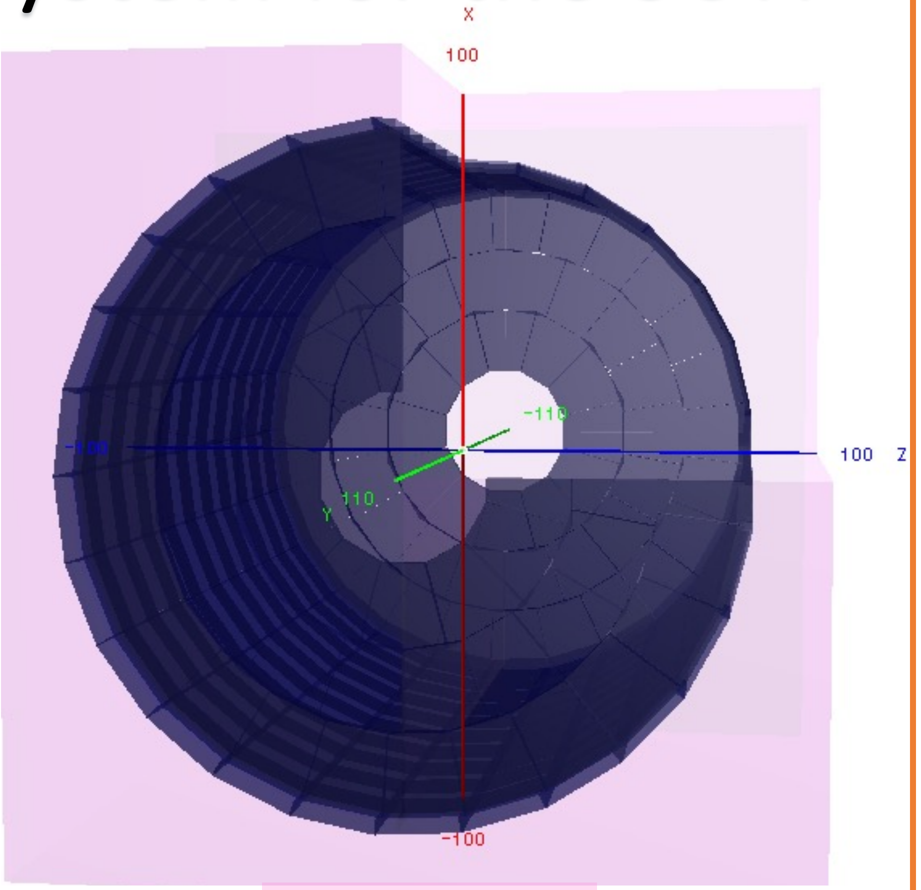
Aerogel: 20+20 mm (Chiba Univ.)	4-layers (Novosibirsk) –>	–	4-layers (ideal profile)
n(400nm): 1.045 +1.055	1.039 ÷ 1.046	–	1.041 ÷ 1.050
Pixel: 5x5 mm	6x6 mm	3x3 mm	3x3 mm

Geom.Eff. ~ 90%	Geom.Eff. ~ 80%	Geom.Eff. ~ 20%
$N_{pe} \approx 10.5$	$N_{pe} \approx 16$	$N_{pe} \approx 4$

The excellent single photon Cherenkov angle resolution ~7÷8 $mrad$ was achieved with the 4-layer focusing aerogel tiles with dimensions 23x23x3.5 cm for the first time in 2022!!!
This circumstance allows us to consider the FARICH detector design based on 4-layer focusing aerogel tiles with large dimensions (23x23x3.5 cm).

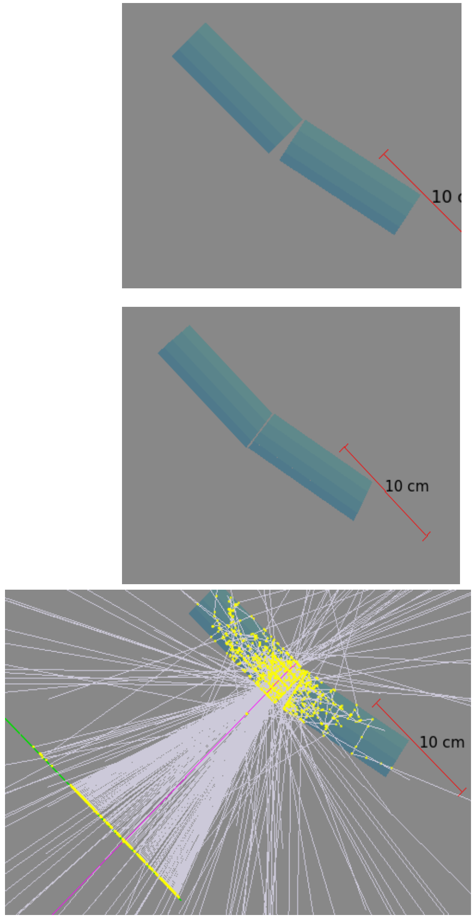
FARICH system for the SCTF





Aerogel layout

GEANT4 simulation of edge effects

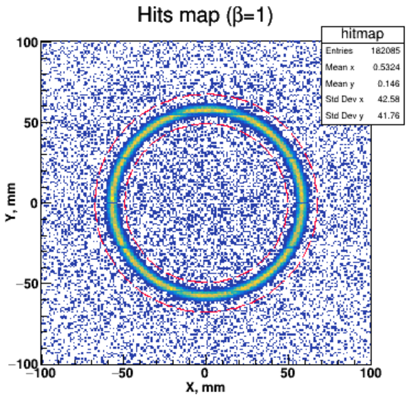


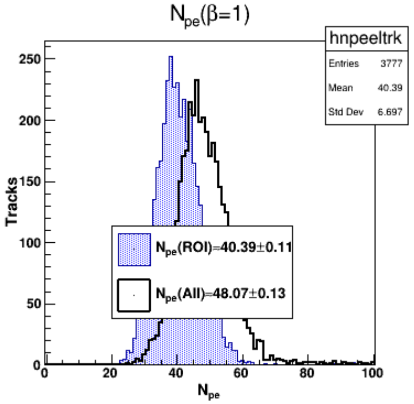
- Proximity focusing RICH
- 4-layer focusing aerogel
  - n_{max} = 1.05 (1.07?), total thickness 35 mm
  - $S_{aer} = 15\ m^2$
- 21 m^2 – total area of photon detectors
  - SiPMs – barrel part (16 m^2)
  - MCP-PMT – endcap parts (4 m^2)
- ~10^6 pixels 3x3 mm^2 with pitch 4 mm

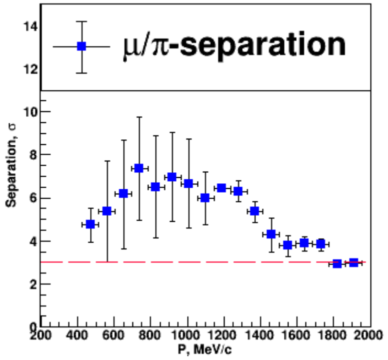
SHAPE	Δ, mm	Aerogel size, mm			
		200	100	75	50
Parallelepiped	6	0.86	0.74	0.62	0.5
Trapezoidal	1	0.96	0.94	0.92	0.9

FARICH edge effects: simulation & experiment

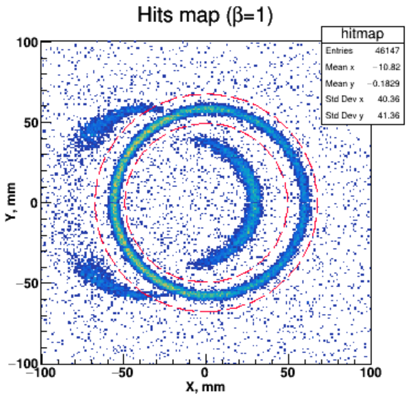
Parallelepiped shape aerogel G4sim

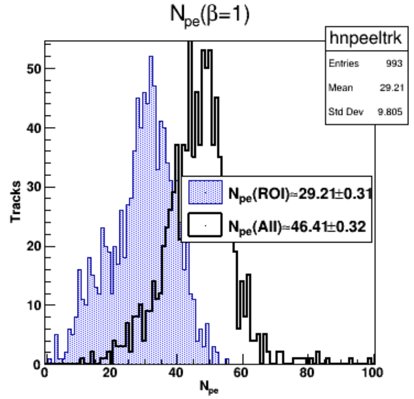


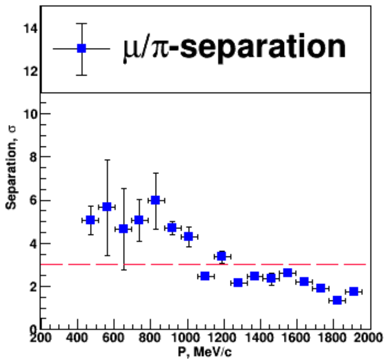




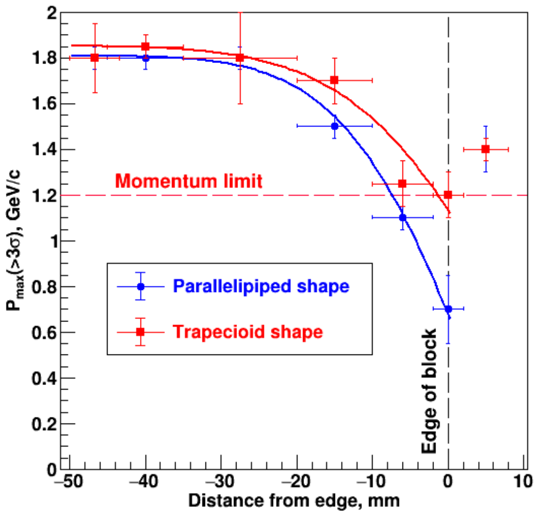
Tracks are in a midle of aerogel tile

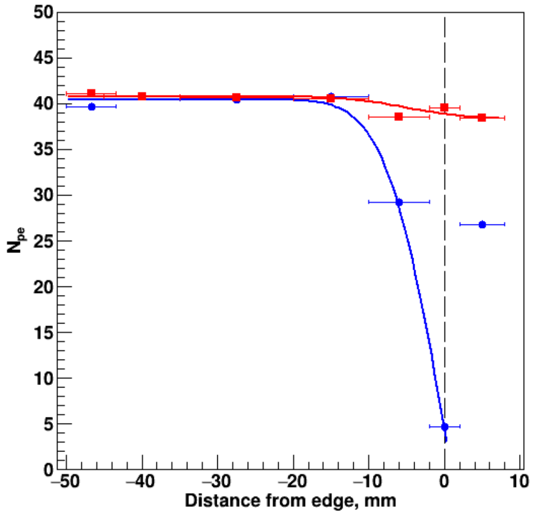




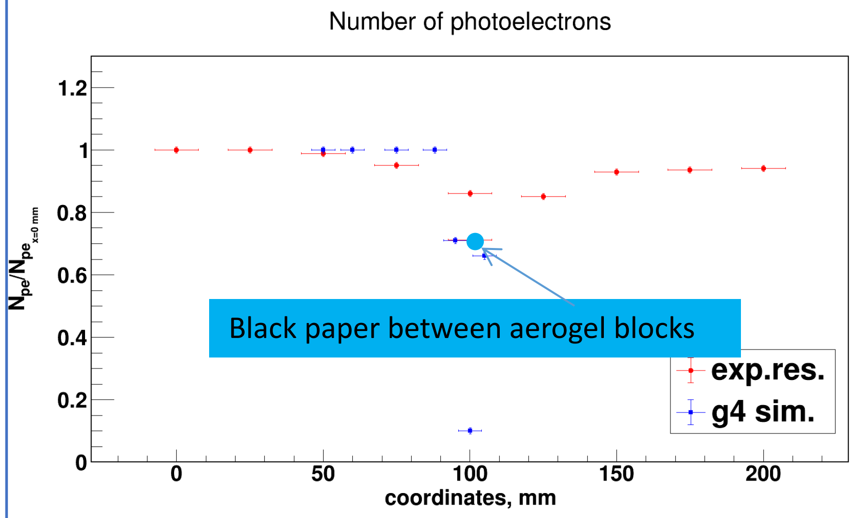


Tracks are in 6±4 mm from aerogel tile edge





Beam test & sim. results



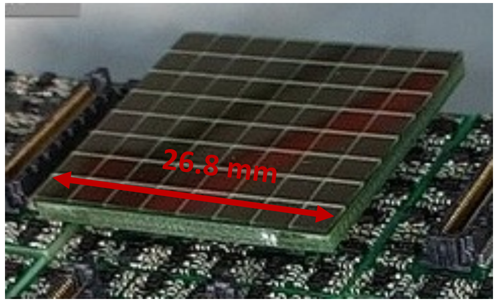
Photon detector options

Due to axial magnetic field the SiPM is only one possible candidate for the cylindrical part of the FARICH system!!!

For the endacp regions there are three options of photon detectors.

SiPM arrays

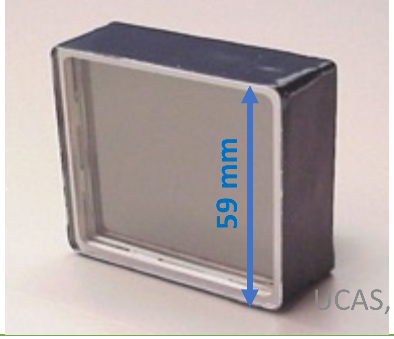
- There are several manufacturer in the world including China.
- There is no comercially available SiPM arrays produced in Russia for the moment, but some R&Ds are going now.
- Estimated cost of such detector option is about 100$/cm^2
- It is required to develop and produce special R/O electronics and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



KETEK PA3325-WB-0808
(BroadCom, USA)

MCP-PMT

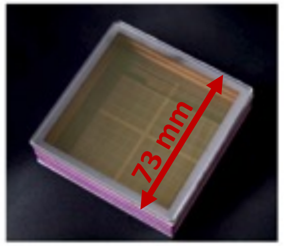
- There are several manufacturer in the world including China.
- There is no comercially available position-sensitive MCP-PMTs produced in Russia for the moment, but R&Ds are going now in (Baspik&Ekran FEP).
- There is a very large spread of prices for rectangular position-sensitive MCP-PMT. The best 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

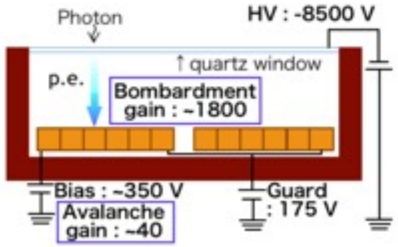


Planacon XP85112
8x8 pixels with 6x6 mm
Cost: 15 k\$

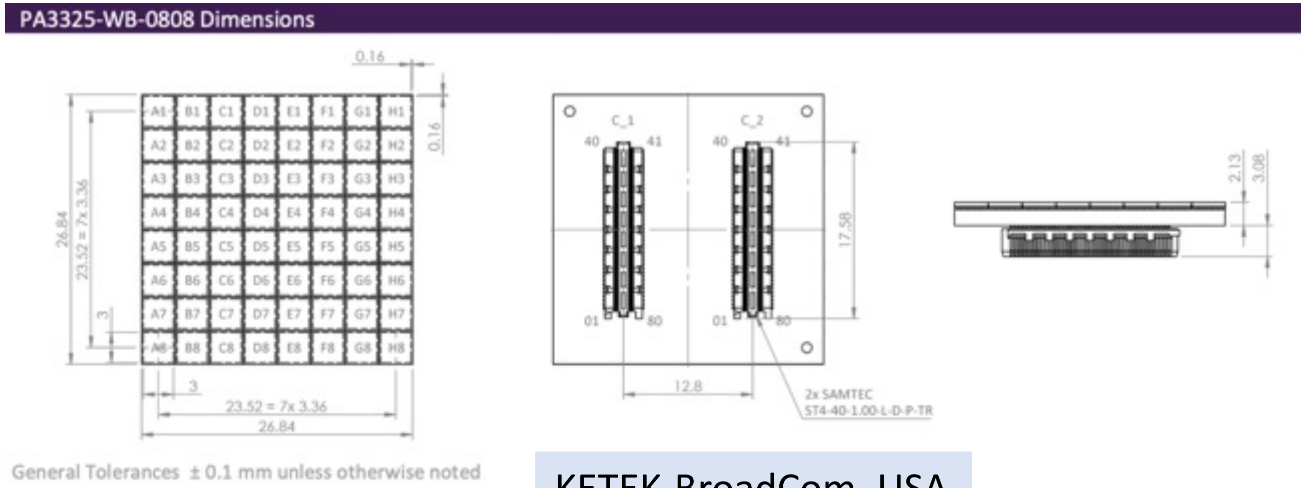
HAPD

- 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.

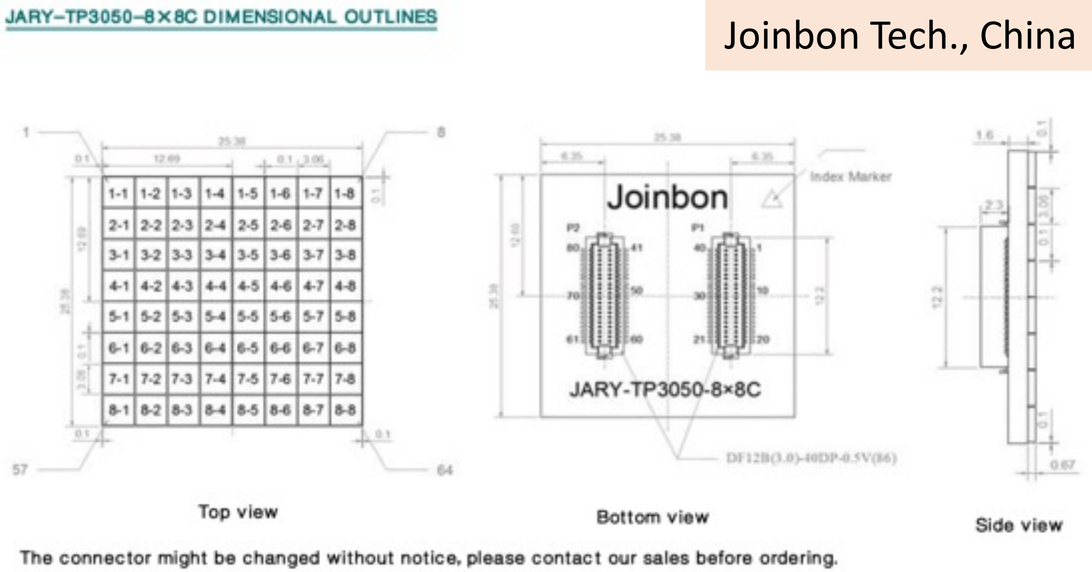




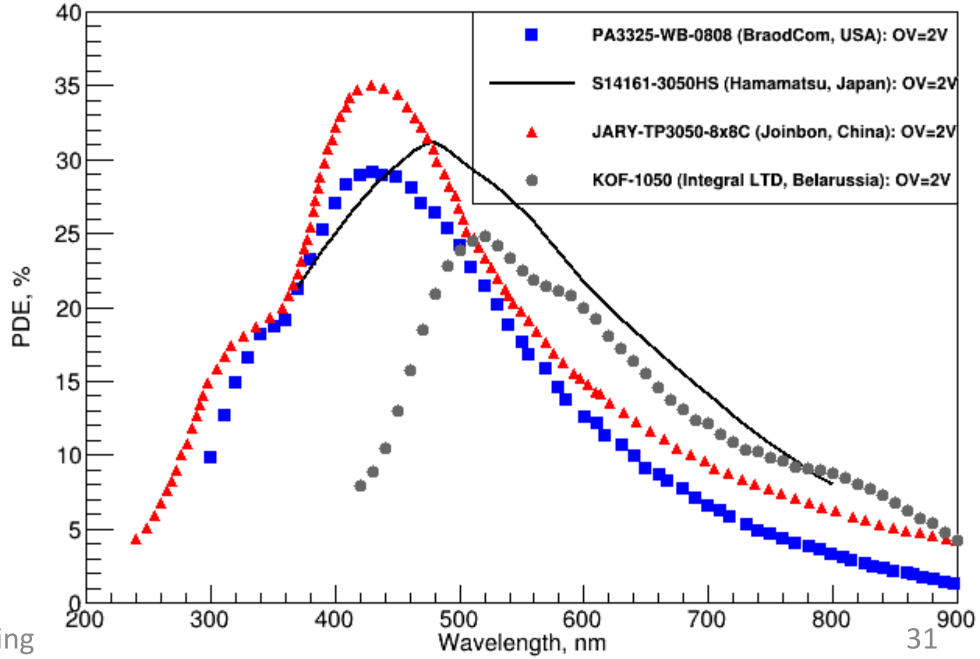
SiPM array option



KETEK-BroadCom, USA

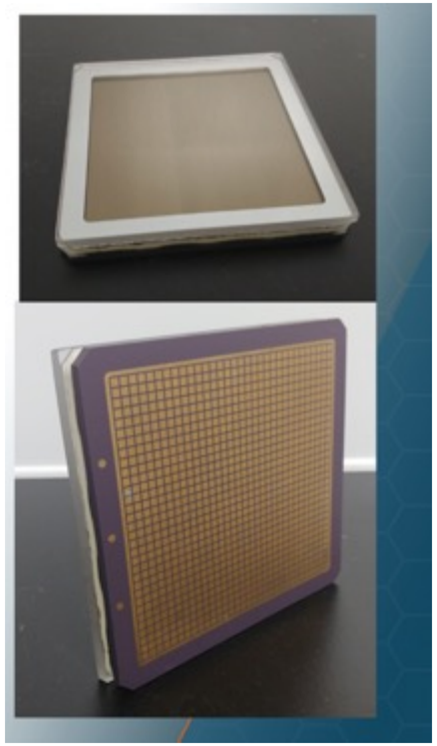


Joinbon Tech., China



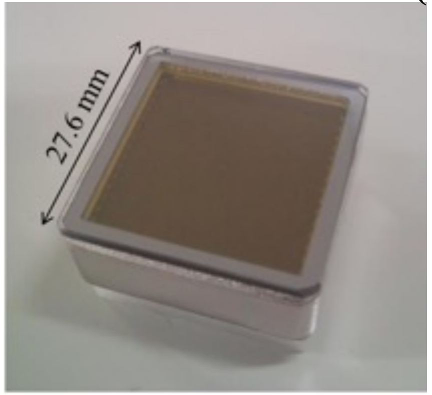
- Endcaps: 2x2490 SiPM arrays 2.7x2.7 cm^2
- Barrel: 18 000 SiPM arrays 2.7x2.7 cm^2
- 1 470.7k pixels with 3x3 mm^2
- Geometrical Efficiency $\frac{S_{detect}}{S_{total}} \approx 76 \div 80\%$
- Highly effective cooling sysytem is required!

Position-sensitive MCP-PMT

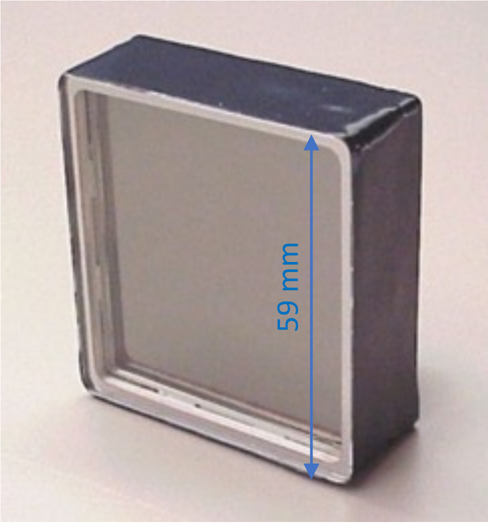


HRPPD (Income)
10x10 cm; pixel 2.5x2.5 mm

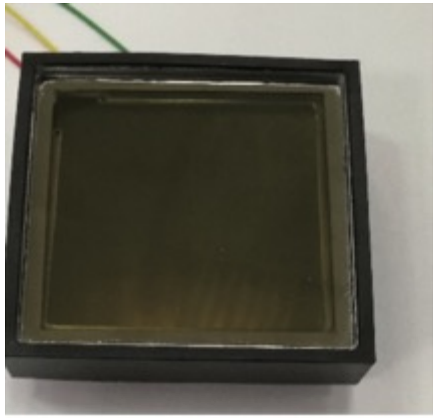
Hamamtsu R10754-016-M16(N)

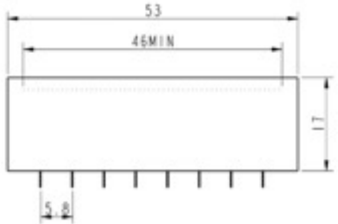


4x4 pixels with 5x5 mm

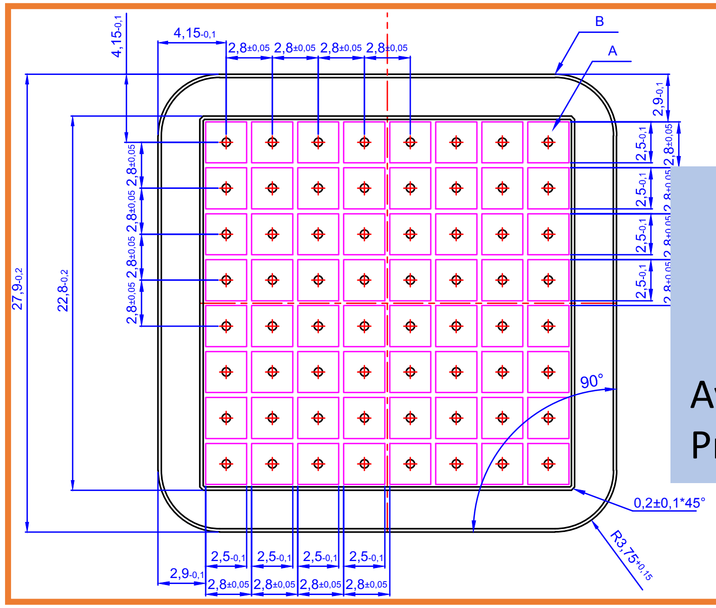


Planacon XP85112
8x8 pixels with 6x6 mm





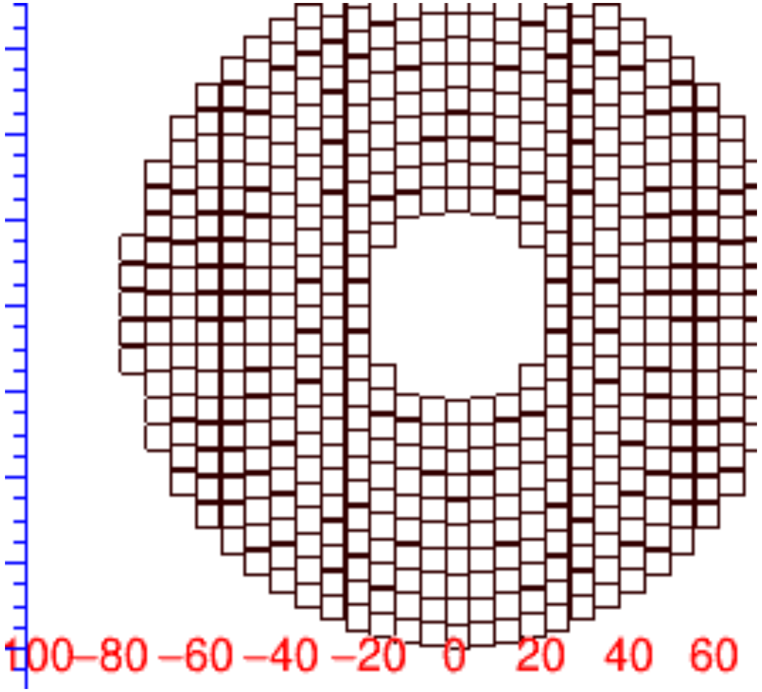
NNVT (China)

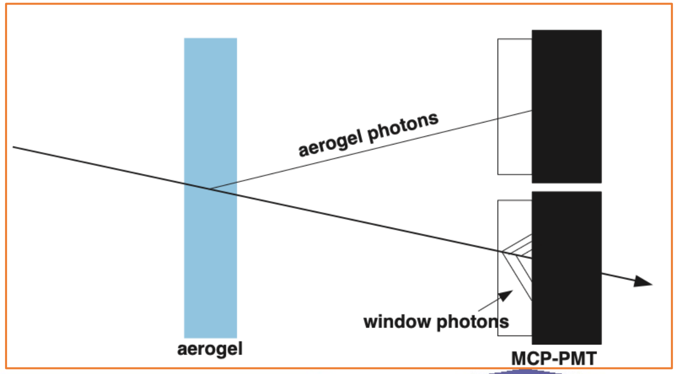


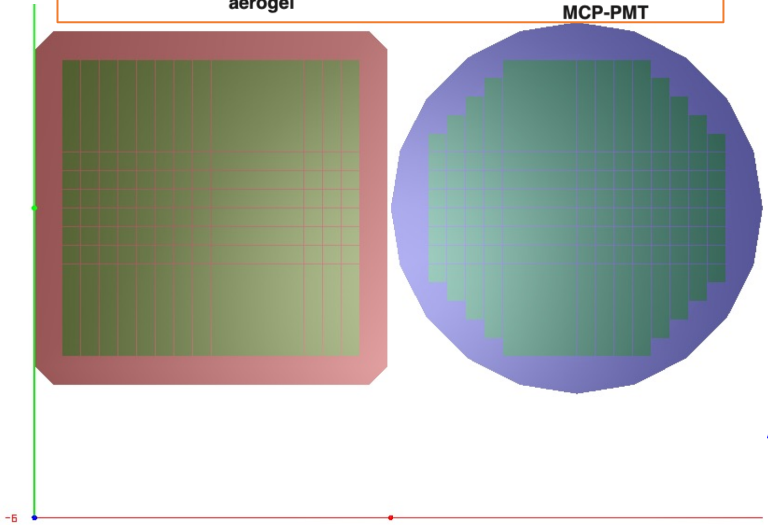
Collector plane of MCP-PMT
Concept of Ekran FEP
(Summer 2022)

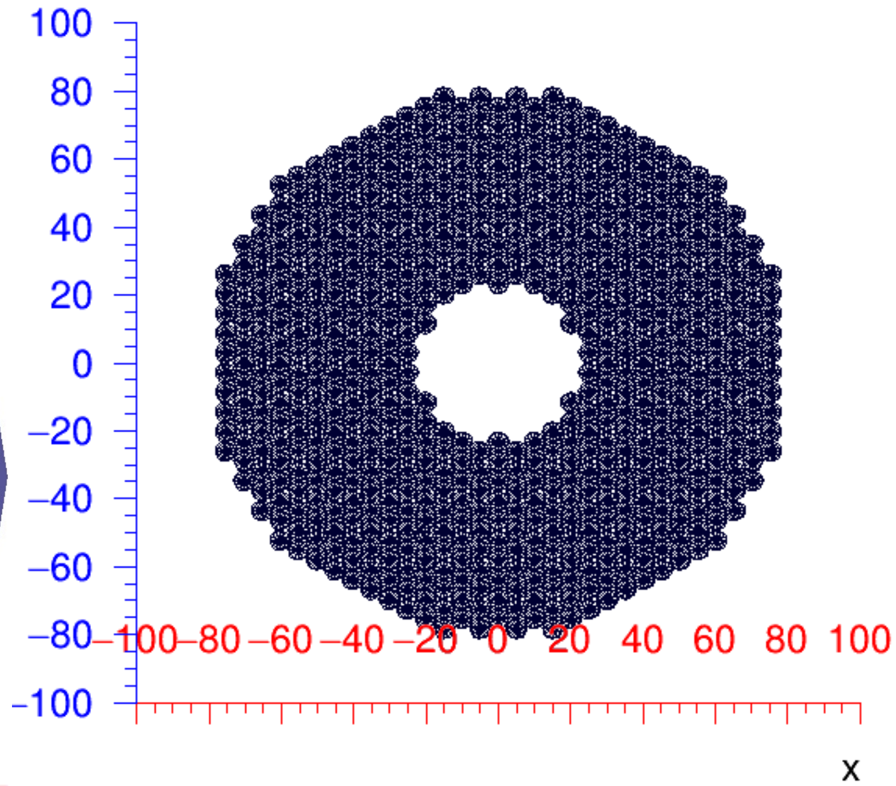
Availabilty: until end of 2023?!
Price: until end of 2023?!

Round vs Square MCP-PMT for the RICH









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

$$Eff = \frac{516 \cdot 5{\times}5}{S_{endcap}} = \frac{12900\ cm^2}{18850\ cm^2} \approx 0.68$$

16x16=256 pixels 2.9x2.9 mm

$$Eff = \frac{516 \cdot 256 \cdot 0.29{\times}0.29}{S_{endcap}} = \frac{11109\ cm^2}{18850\ cm^2} \approx 0.59$$

594 PMTs Ø58 mm (PC Ø50 mm) –>

$$Eff = \frac{594 \cdot \pi \cdot 2.5^2}{S_{endcap}} = \frac{12370\ cm^2}{18850\ cm^2} \approx 0.65$$

216 pixels 2.9x2.9 мм

$$Eff = \frac{594 \cdot 216 \cdot 0.29{\times}0.29}{S_{endcap}} = \frac{11444\ cm^2}{18850\ cm^2} \approx 0.57$$

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

expected FARICH performance

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

- $GE^{exp} \approx 0.59$
- $N_{pe}^{expect} = \frac{16 \cdot 0.6 \cdot 0.59}{0.8 \cdot 0.8} \approx 8.8pe$ (for $\beta = 1$)
- $\sigma_{tr}^{\theta} = \frac{\sigma_{SPE}^{\theta}}{\sqrt{N_{pe}}} = \frac{7 \div 8\ mrad}{\sqrt{8.8}} = 2.3 \div 2.7\ mrad$

Round shape MCP-PMT

- $GE^{exp} \approx 0.57$
- $N_{pe}^{expect} = \frac{16 \cdot 0.6 \cdot 0.57}{0.8 \cdot 0.8} \approx 8.5pe$ (for $\beta = 1$)
- $\sigma_{tr}^{\theta} = \frac{\sigma_{SPE}^{\theta}}{\sqrt{N_{pe}}} = \frac{7 \div 8\ mrad}{\sqrt{8.5}} = 2.4 \div 2.7\ mrad$

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: $\frac{\theta_C^{\pi} - \theta_C^{K}}{\sigma_{tr}^{\theta}} = \frac{309 - 299}{2.5} = 3.9\sigma$

R/O electronics cost estimation

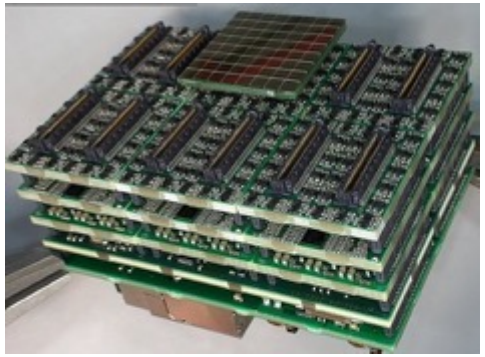
There are two modern approaches in development of specialised R/O electronics:

- 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)

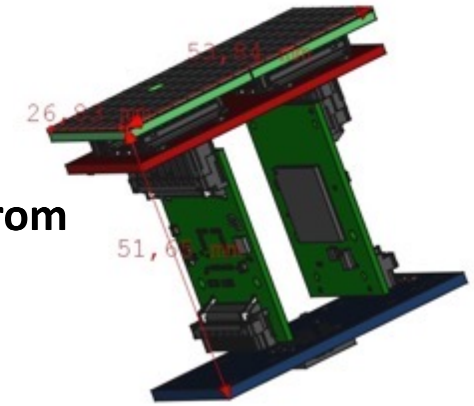
It was designed and produced by GSI group inspired by experience with DiRICH board.
One module readouts 6 SiPM arrays with 8x8 pixels (3x3 mm).
Dimensions: 81x54x50 mm.
It worked in Germany until the 2022.
It doesn't work in Russia.
Power consumption: ~55mW/chan



TOFPET-II (PetSys)

Ready to use solution

One ROM readout 2 SiPM;
One DAQ board combine info from 8 ROMs
Dimensions: 54x26x52 мм



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

Both options are not available for us, we are looking for new solution!

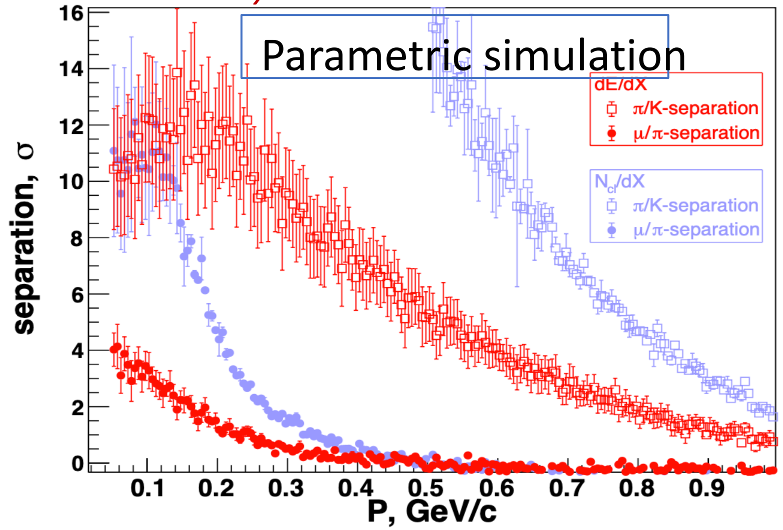
FARICH with dual aerogel radiator

PID options for $\boldsymbol{\pi}/\boldsymbol{K}$ – separation

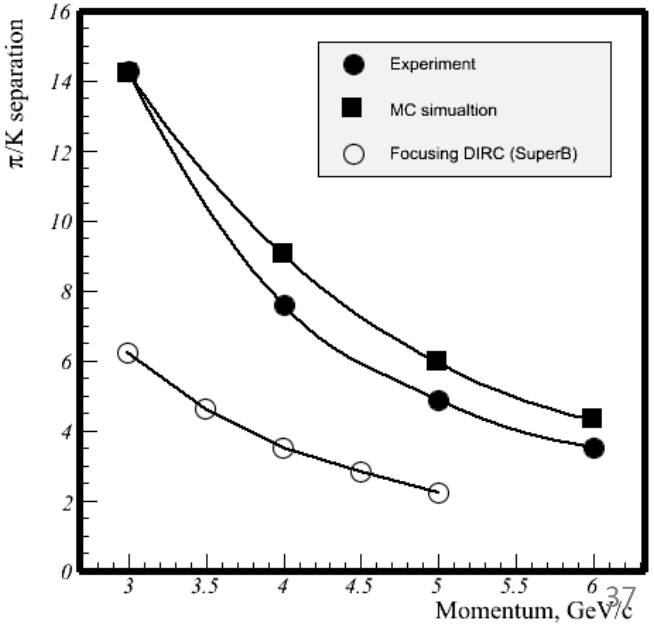
- dE/dx
  - $\frac{\sigma_{dE/dx}}{\langle dE/dx \rangle} \le 7\% \rightarrow \ge 3\sigma$ up to 0.6 GeV/c
  - $\frac{\sigma_{N_{cl}/dx}}{\langle N_{cl}/dx \rangle} \le 4\% \rightarrow \ge 3\sigma$ up to 0.9 GeV/c
- Focusing Aerogel RICH (FARICH)

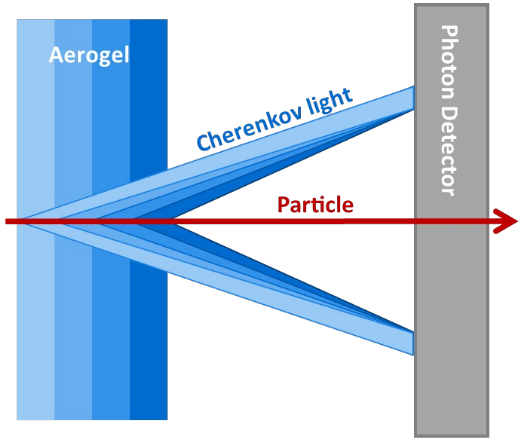
(4 layer @ n_{max}=1.05) → ≥ 3σ from 0.5 to 6 GeV/c

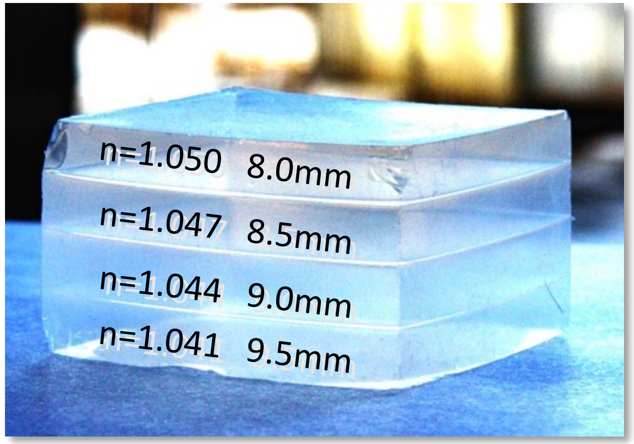
A.Yu. Barnyakov et al 2020 JINST **15** C04032



A.Yu. Barnyakov, et al., NIM A 732 (2013) 35

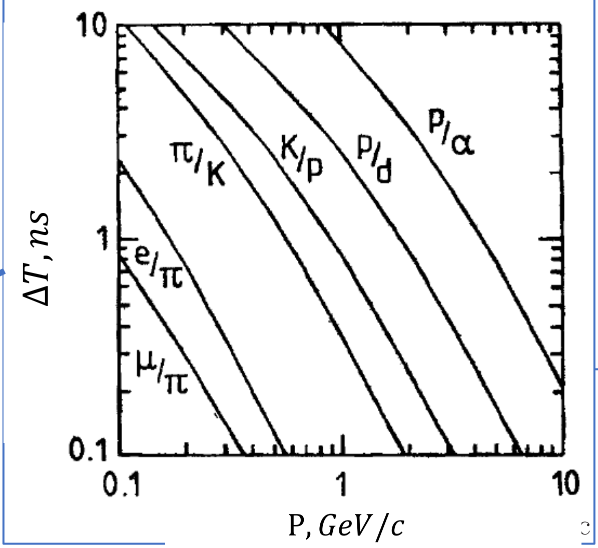






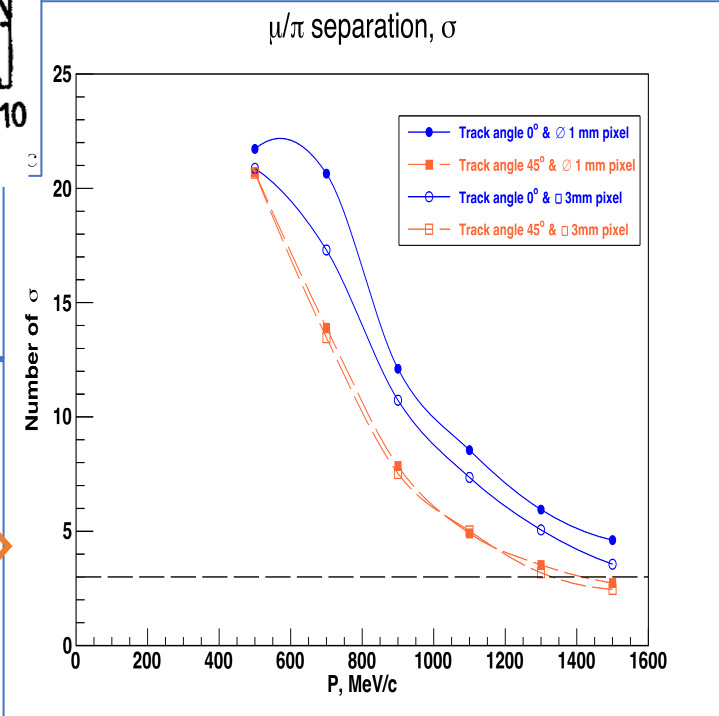
PID options for μ/$\boldsymbol{\pi}$ – separation

- $^{dE}/_{dx}$
  - $\frac{\sigma_{dE/dx}}{\langle dE/dx \rangle} \approx 7\% \rightarrow \geq 3\sigma$ up to 0.15 GeV/c
  - $\frac{\sigma_{N_{cl}/dx}}{\langle N_{cl}/dx \rangle} \approx 4\% \rightarrow \geq 3\sigma$ up to 0.25 GeV/c
- **TOF** with σ_t ≈100 ps $\rightarrow \geq 3\sigma$ up to 0.2 GeV/c, e.g. Chernkov light from entrance window of MCP-PMT
- **FARICH** (4-layer, n_{max}=1.05) $\rightarrow \geq 3\sigma$ from 0.5 to 1.5 GeV/c



FARICH with dual aerogel radiator is proposed to provide μ/π – separation for 0.2≤P≤0.5 GeV/c

Results of parametric simulation tuned with results of beam test campaign in 2021:
– SPR(β = 1, ■3 mm)= 1.63 mm
– SPR(β = 1, ⌀1 mm)= 1.36 mm

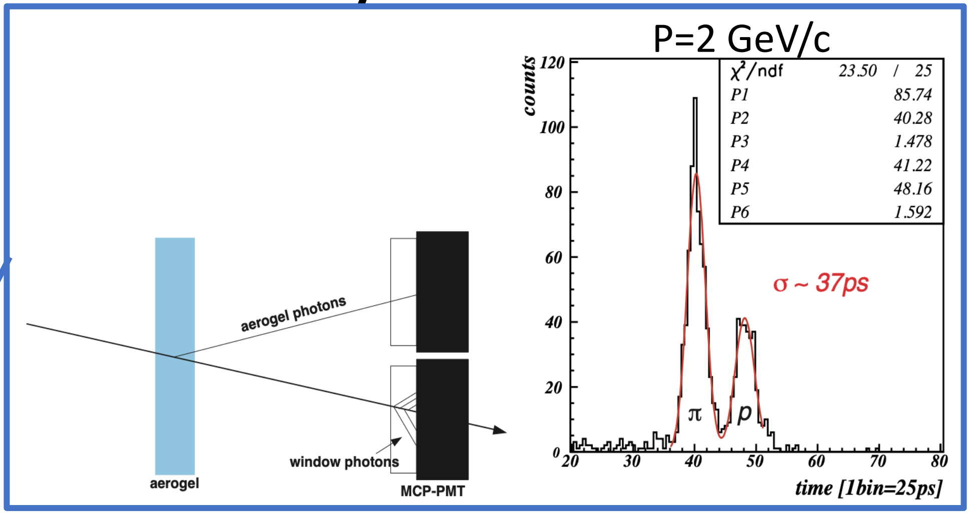


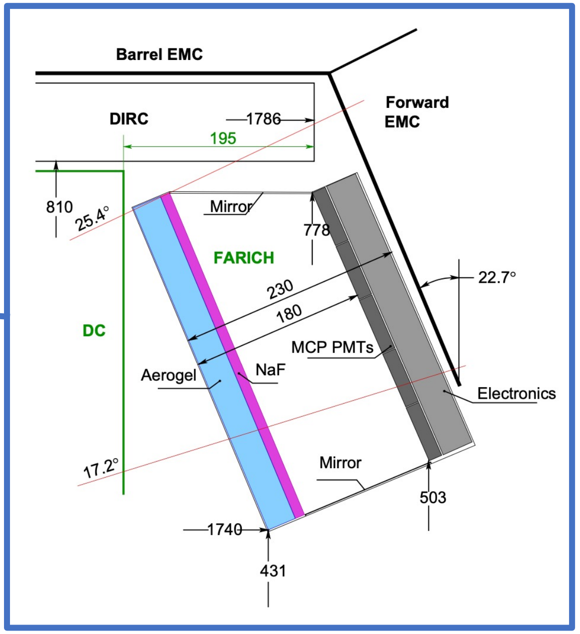
A.Yu.Barnyakov et al., NIMA 1039 (2022) 167044

RICH with dual radiators is not very new idea!

- Liquid + Gas:
  - RICH – DELPHI
  - CRID – SLD
    - C_6F_{12}(n=1.278@190nm) + C_5F_{10}(n=1.00174@190nm)
- Aerogel + Gas:
  - HERMES
  - RICH1 – LHCb
    - Aer.(n=1.03@400nm) + C_4F_{10}(n=1.00137@400nm)
- Aerogel + Crystal:
  - RICH+ToF – SuperB:
    - Aer.(n=1.05@400nm) + Quartz (n=1.47@400nm)
  - FARICH – SuperB:
    - 3-layer aer. n_{max}=1.07@400nm + NaF (n=1.33@400nm)
- Aerogel + Aerogel:
  - FARICH – SCTF:
    - 4-layer aer. n_{max}=1.05@400nm + aer (n=1.12@400nm)

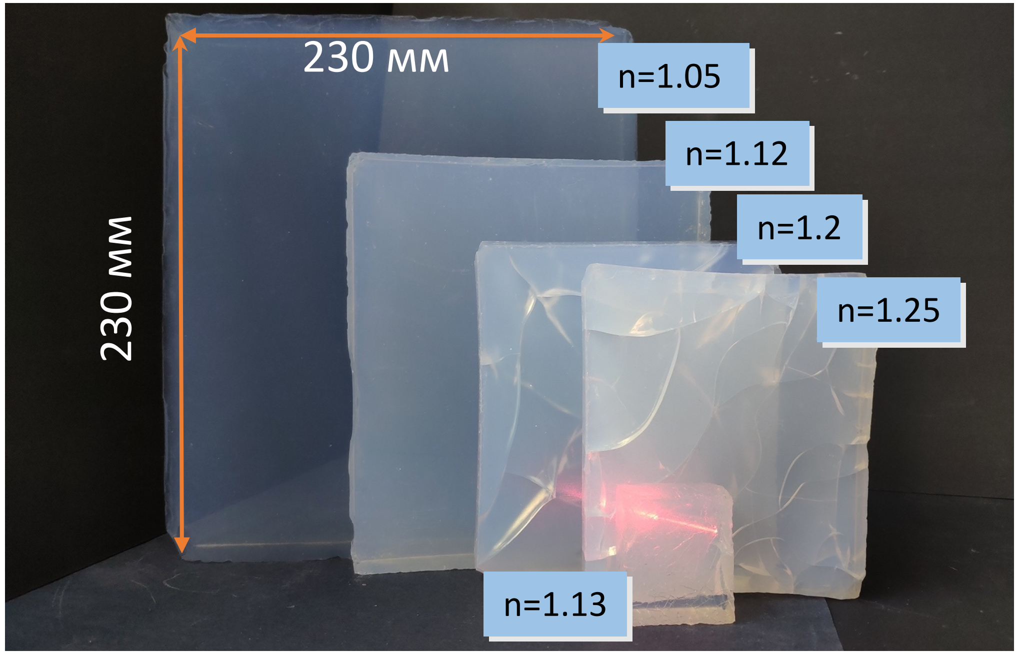
Aerogel is material with easy tunnable refractive index!

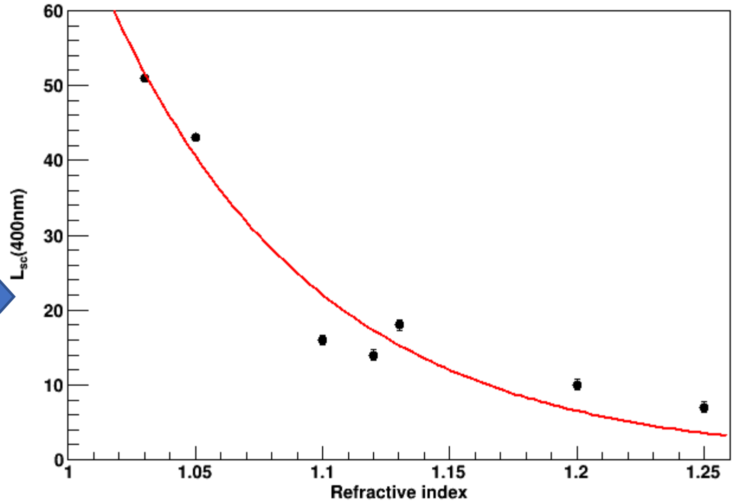




Aerogels with high optical density

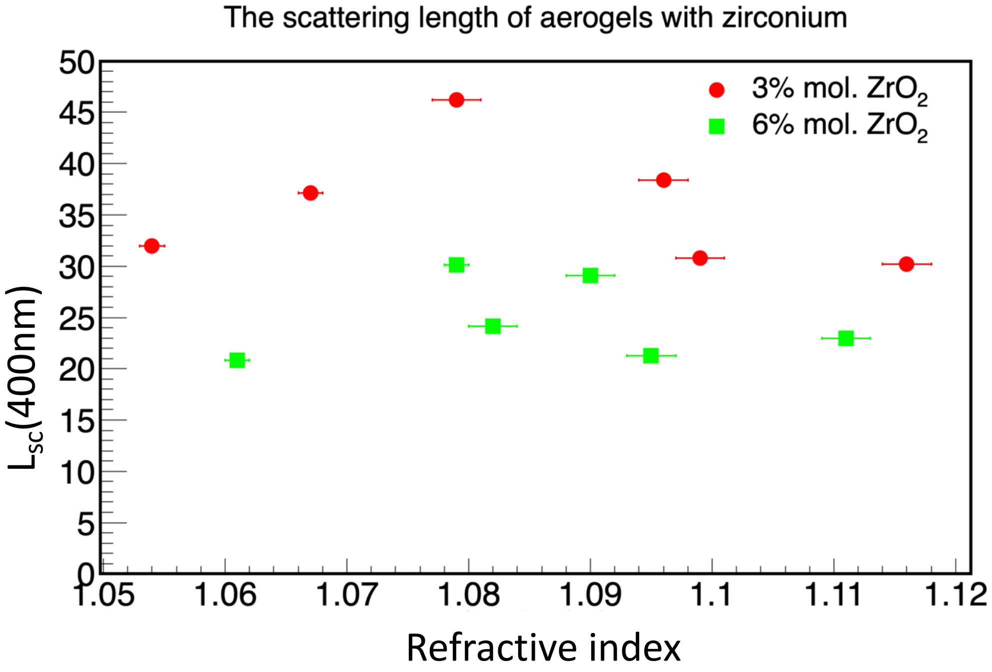
Sintering approach

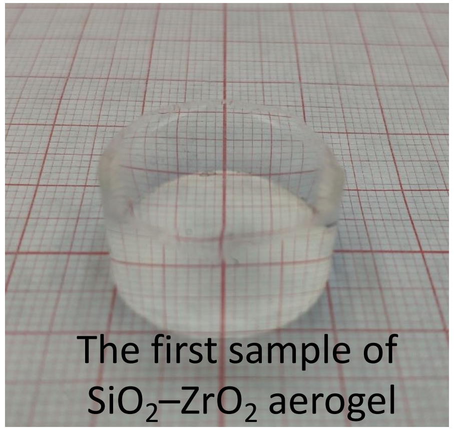




The main flaw of this approach

ZrO_2 addition approach



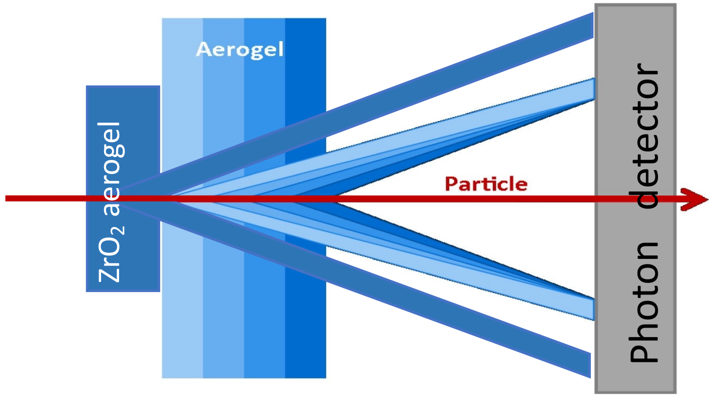


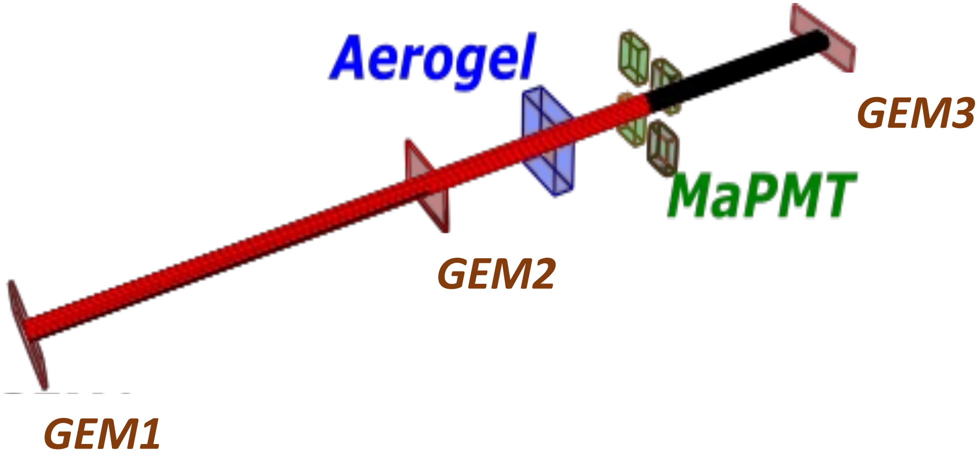
The first sample of SiO_2–ZrO_2 aerogel

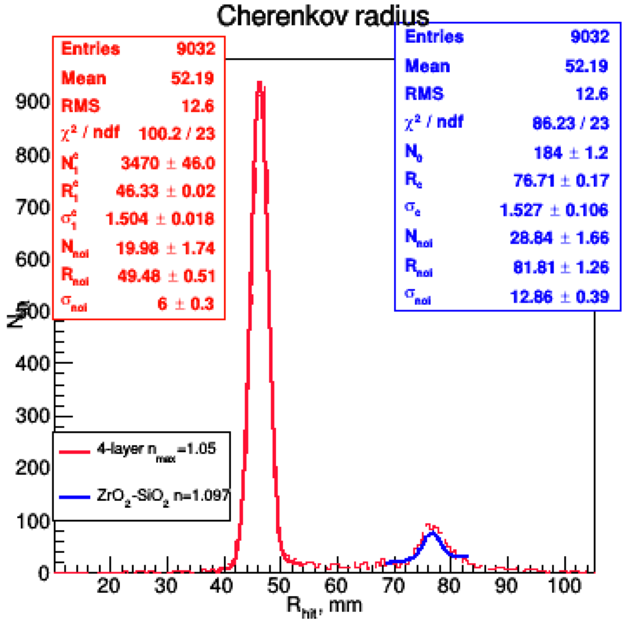
The addition of small amount (0.03÷0.06 mol) of ZrO_2 in SiO_2 based aerogel alow us to produce highly transperant aerogels with high optical density:

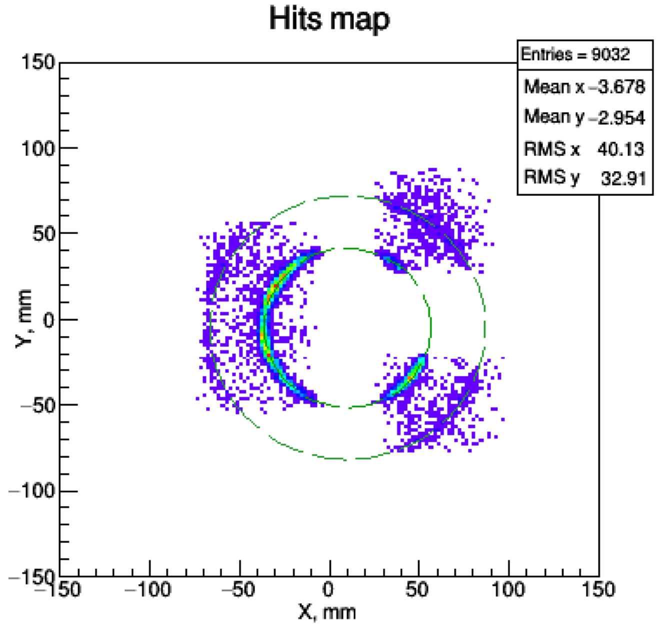
- Refractive index up to n=1.12
- Rayleigh light scattering length L_{sc}(400nm) up to 30 mm

Beam tests results of FARICH with dual radiator









ZrO_2–SiO_2 aerogel:

Thickness 12 mm & ø20 mm;

L_{sc}(400nm)=21±0.5 mm;

4-layer SiO_2 aerogel:

100x100x35 mm;

L_{sc}(400nm)=37±0.3 mm;

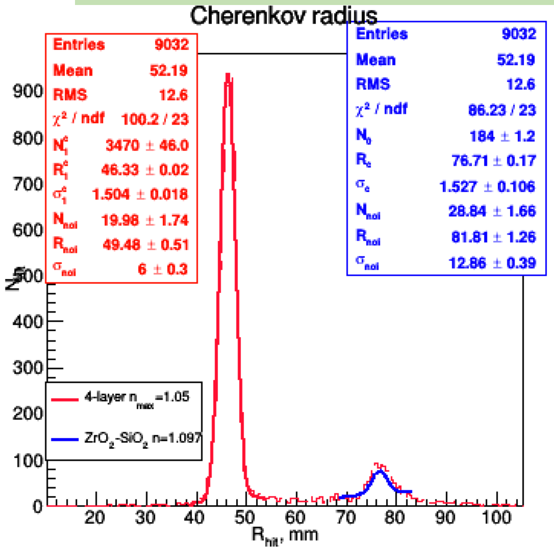
Photon detector

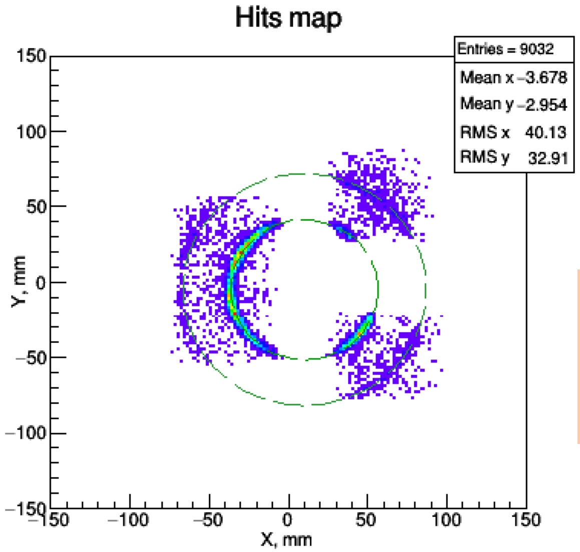
4 MaPMT H12700 (Hamamatsu);

256 pixels with 3x3 mm size;

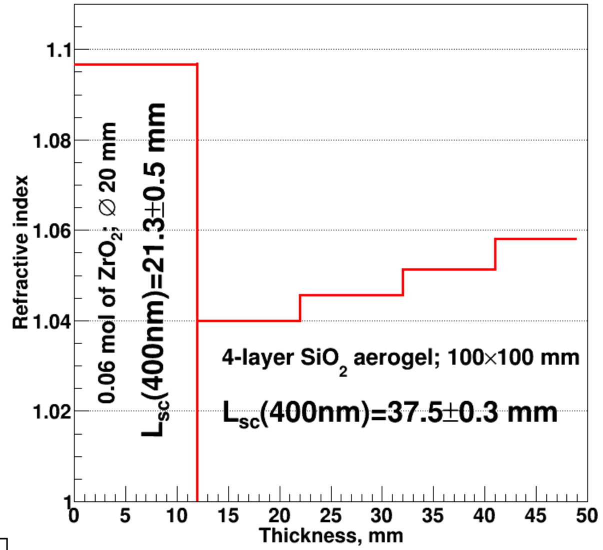
G4 simulation vs beam test results

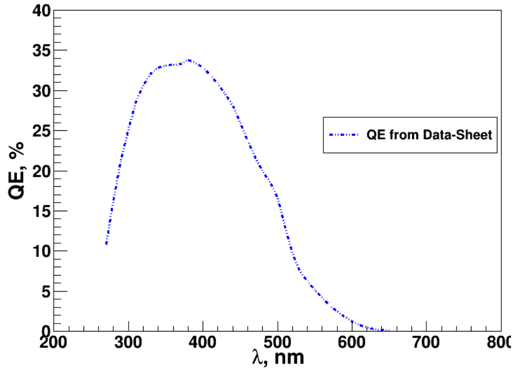
TBeam results





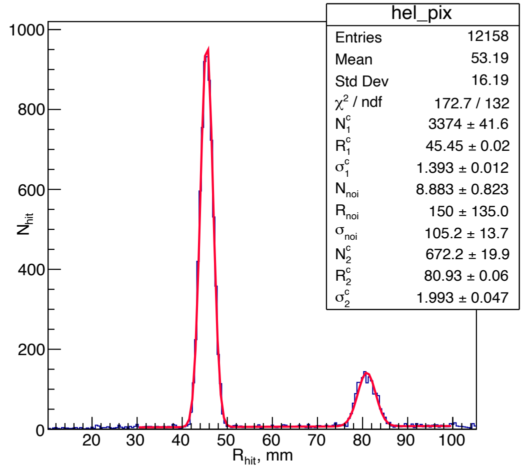
Optical parameters for G4 simultion

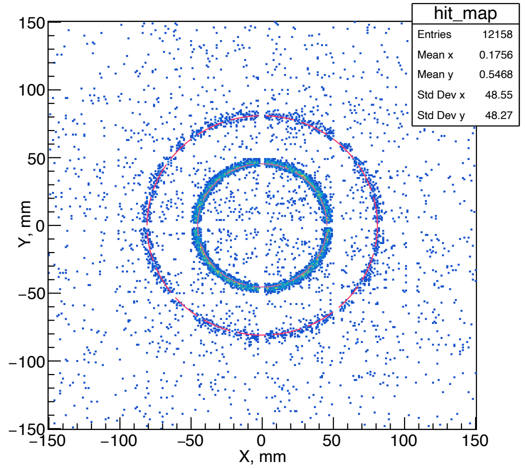




- PDE for H12700 from data-sheet
- Pixel 3x3 mm with pitch 6mm
- Focal distance L=172 mm

G4 simulation results

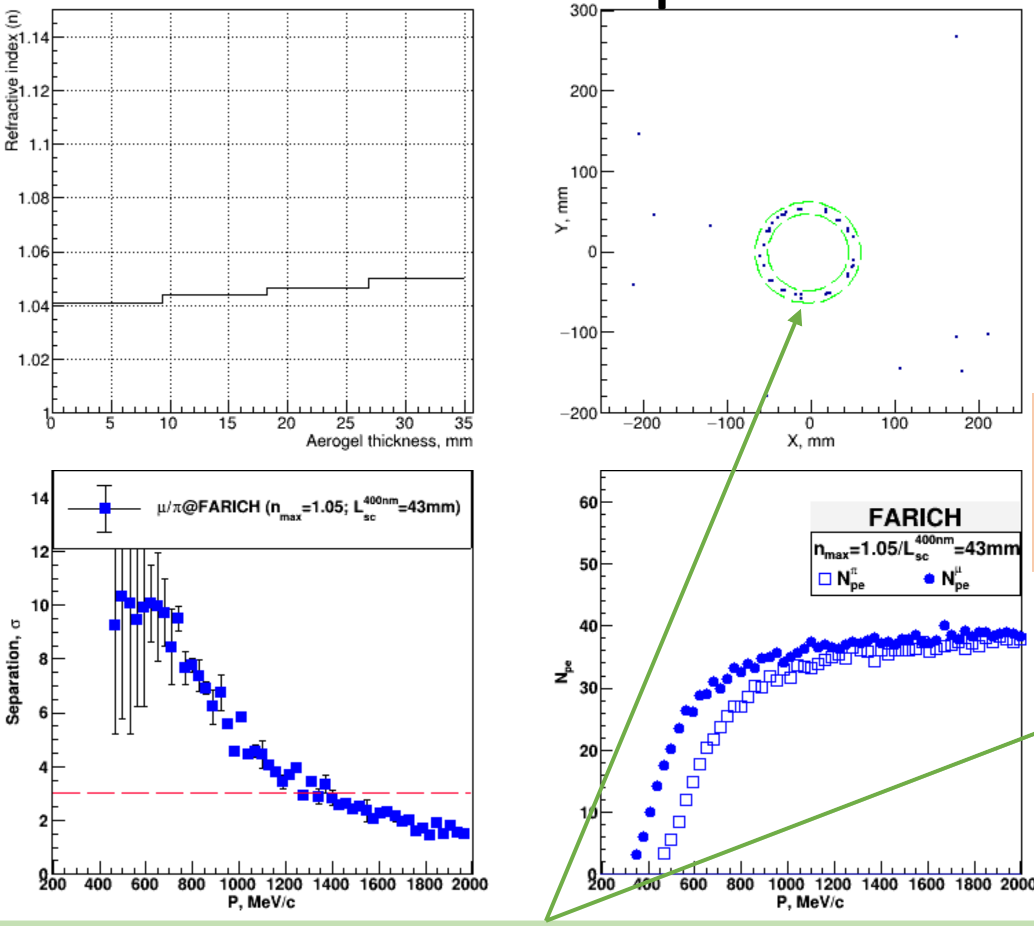




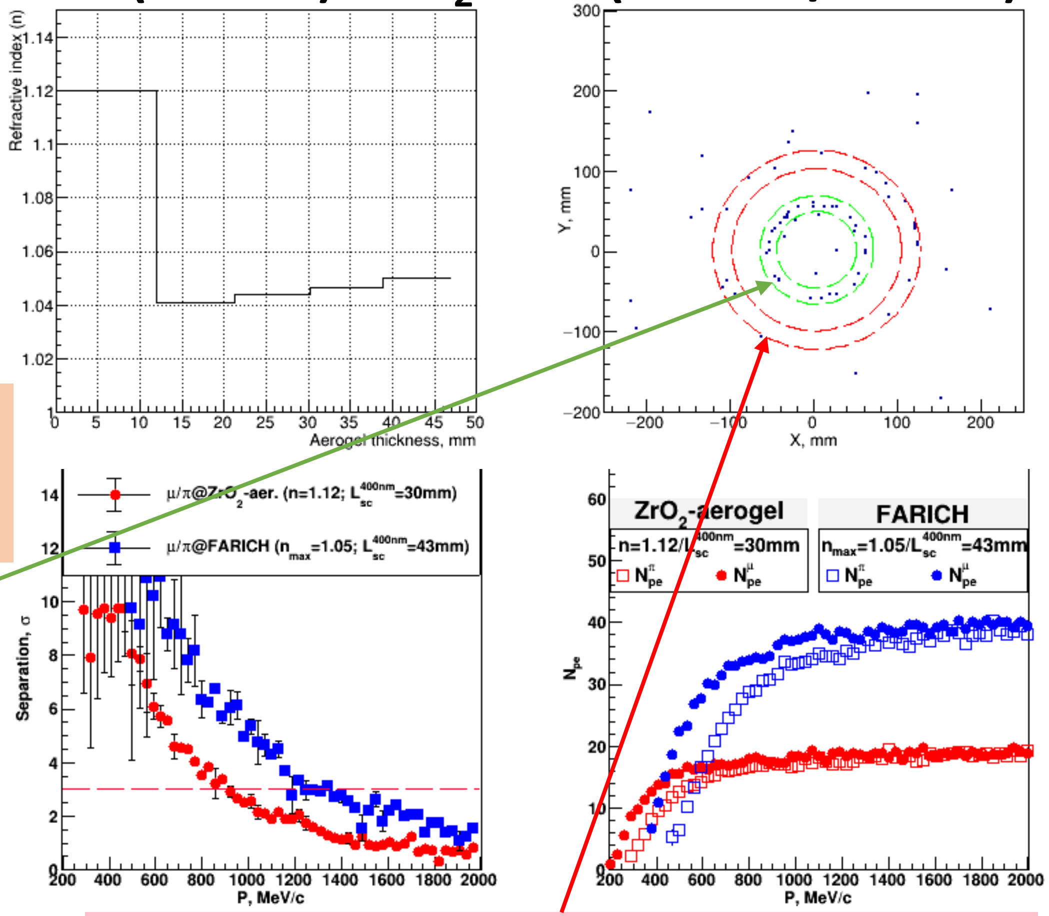
The main difference between G4sim and TBeam is a photon small angle scattering effect on aerogel surfaces and inside. These effects have not implemented in G4sim yet.

μ/π-separation via G4 simulation

FARICH: "ideal" n profile



FARICH (“ideal”)+ZrO_2–aer. (n =1.12/12 mm)



$$N_\sigma = \frac{\bar{R}_C^{\mu} - \bar{R}_C^{\pi}}{\left(\sigma_R^{\pi} + \sigma_R^{\mu}\right)/2}$$

$$(\mathbf{L_f} - \mathbf{t_{Zr}} - \mathbf{t_{Fa}}) \cdot \frac{\sqrt{\left(n_{Fa}^{min\,2} - 1\right) - \frac{m^2}{p^2}}}{\sqrt{\frac{m^2}{p^2} + 1}} \le R_{Fa} \le (L_f - t_{Zr}) \cdot \frac{\sqrt{\left(n_{Fa}^{max\,2} - 1\right) - \frac{m^2}{p^2}}}{\sqrt{\left(n_{Fa}^{max\,2} - 2\right) + \frac{m^2}{p^2}}}$$

$$(L_f - t_{Zr}) \cdot \frac{\sqrt{\left(n_{Zr}^{2} - 1\right) - \frac{m^2}{p^2}}}{\sqrt{\frac{m^2}{p^2} + 1}} \le R_{Zr} \le L_f \cdot \frac{\sqrt{\left(n_{Zr}^{2} - 1\right) - \frac{m^2}{p^2}}}{\sqrt{\left(n_{Zr}^{2} - 2\right) + \frac{m^2}{p^2}}}$$

Summary

- R&Ds on detector and collider subsystems of the SCTF project are carried out at the BINP. Several other Russian institutions also take part in this activity as well
- Some fundings for the R&Ds on the project in 2023-2025 are provided by Russian government
- PID system based on FARICH technique is the main option for the SCTF project
  - In 2022-2023 the possibility to produce 15 m2 of “focusing” aerogel Cherenkov radiators with target parameters was demonstrated
  - Recent progress in high opticaly dense aerogel production with help of ZrO2 dope allows us to consider new design of FARICH detector with dual aerogel radiator which able to provide exccelent μ/π – separation from 0.2 up to 1.5 GeV/c
  - For further progress of the FARICH technique it is necessary to develop photon detector options and compatible R/O electronics
- In modern conditions we faced with some issues which are able to delay realization of the SCTF project

Back up slides

Advantages of the SCT factory

1. Threshold production of τ leptons and charmed hadrons
   - Well-defined initial state
   - Low multiplicity of particles
   - Kinematic constraints

2. Longitudinal polarization of the electron beam
   - Boosted sensitivity to $\mathcal{CP}$ violation in baryons and τ leptons
   - Measuring the Weinberg angle

3. Coherent $D^0\overline{D}^0$ pairs
   - Measuring charm mixing and $\mathcal{CP}$ violation with unique techniques
   - Measuring phases of the decay amplitudes

4. Full event reconstruction
   - Superior background suppression
   - Measuring absolute branching fraction of charmed hadrons

LFV and CPV with tau

$\tau \to \mu\gamma$

- Allowed in several BSM scenario, including SUSY, leptoquarks, technicolor, and extended Higgs models
- $\mathcal{O}(10^{-9})$ – reachable upper limit at SCT for the branching of $\tau \to \mu\gamma$
- Requires excellent π/μ separation

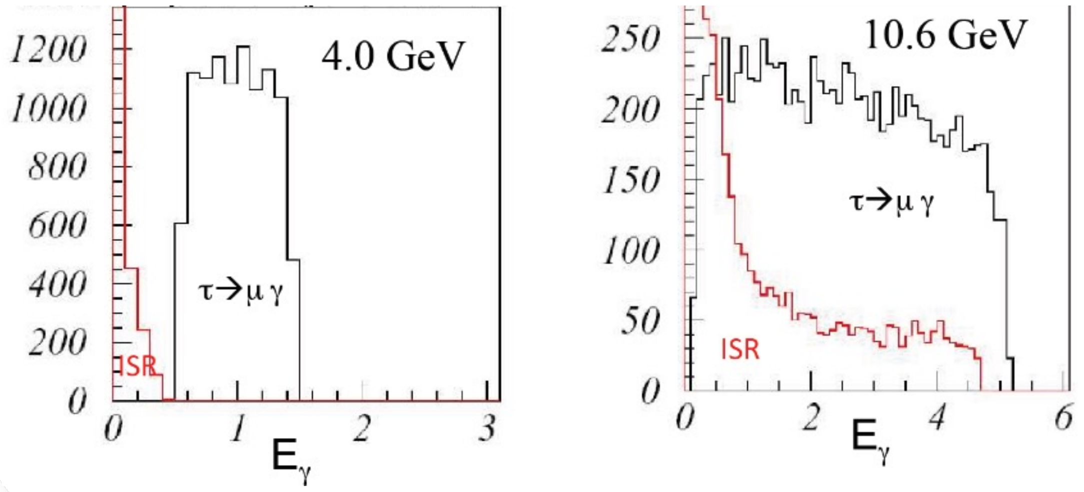
CP symmetry breaking

- CPV in tau production

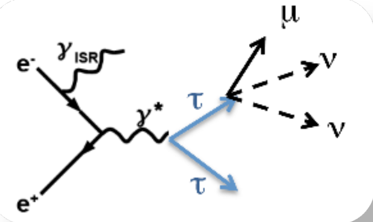
$$J_{EM} \propto F_1\gamma^\mu + \left(\frac{i}{2m_\tau}F_2 + \gamma^5 F_3\right)\sigma^{\mu\nu}q_\nu$$

  - Current limit: $|d_\tau| \lesssim 10^{-17}\ e\cdot\text{cm}$
  - Tau EDM with polarized electrons: $\sigma(d_\tau) \sim 10^{-20}\ e\cdot\text{cm}$
- CPV in tau decays (e.g., $\tau \to K\pi\nu_\tau$)

ISR photon background [arXiv:1206.1909 [hep-ex]]

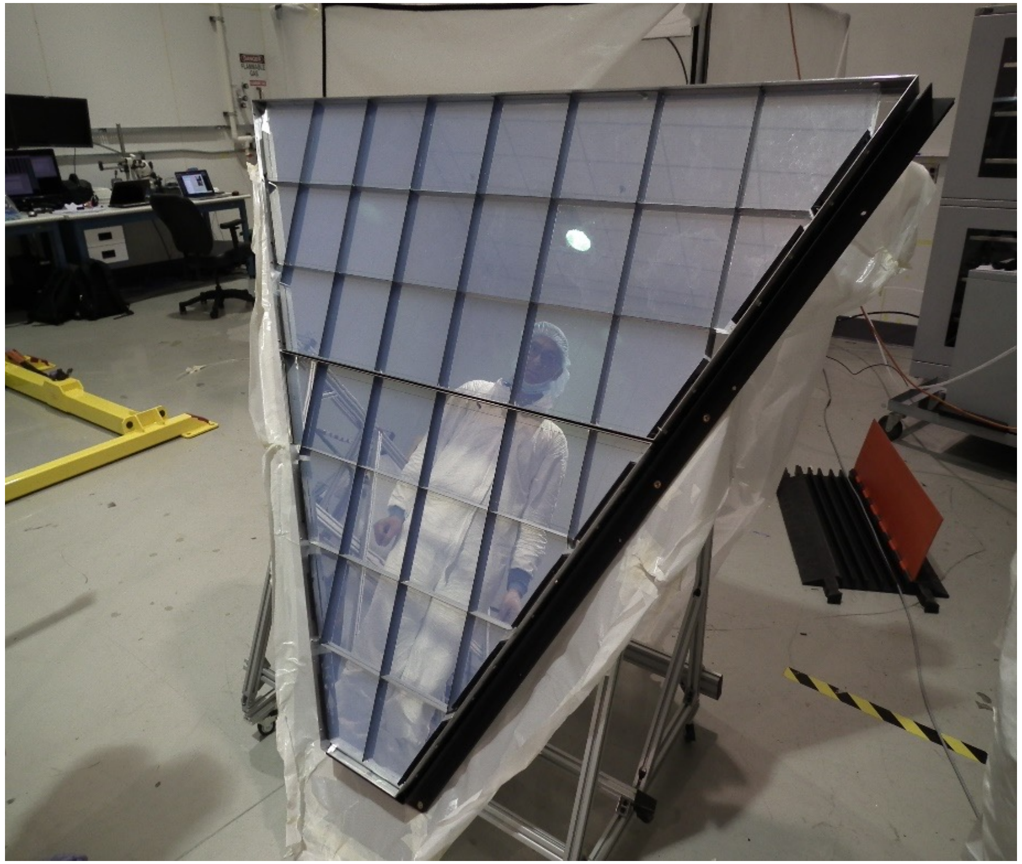


Beam polarization is essential for these measurements [PRD 51 (1995) 5996]



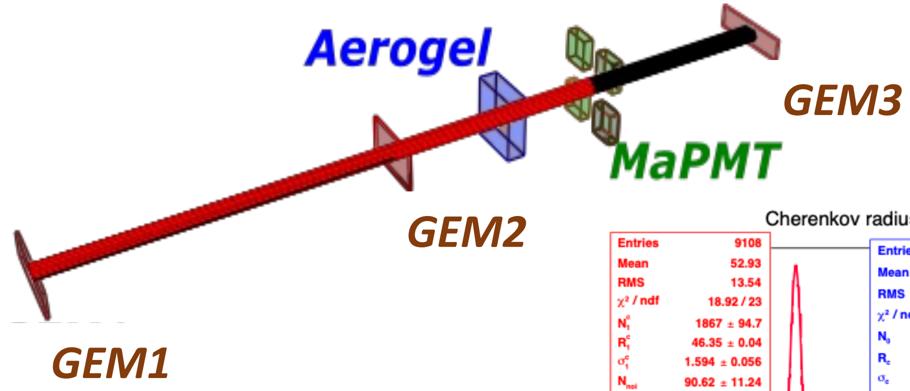
History of aerogel radiators in Novosibirsk

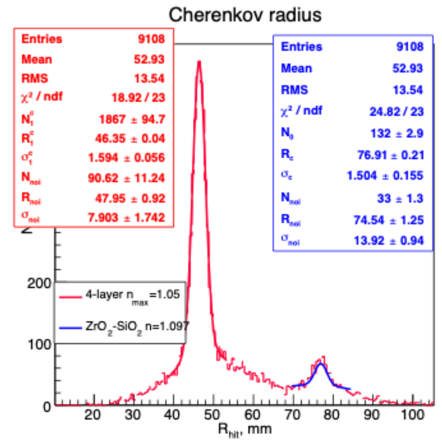
- **KEDR ASHIPH** system (VEPP-4M – BINP):
  - π/K-separation in the momentum range 0,6÷1,5 GeV/c.
  - Aerogel $n = 1{,}05$ (V~1000 L).
- **SND ASHIPH** system (VEPP-2000 – BINP):
  - π/K-separation in the momentum range 300÷870 MeV/c.
  - Aerogel $n = 1{,}13$ (V~9 L).
- **DIRAC-II** (PS – CERN):
  - π/K-separation in the momentum range 5,5÷8,0 GeV/c.
  - Aerogel $n = 1{,}008$ (V~9 L).
- **AMS-02** aerogel RICH (ISS):
  - Search for antimatter, study of cosmic rays.
  - Aerogel $n = 1{,}05$ (S~1 m^2).
- **LHCb** aerogel RICH (LHC – CERN):
  - π/K-separation in the momentum range 5,5÷8,0 GeV/c.
  - Aerogel $n = 1{,}03$ (S~0,5 m^2), aerogel tile 20x20x5 $см^3$.
- **CLAS-12** aerogel RICH (J-Lab):
  - π/K- & K/p-separation at level 4σ with several momentum GeV/c.
  - Aerogel $n = 1{,}05$ (S~6 m^2), aerogel tile 20x20x2-3 $см^3$.

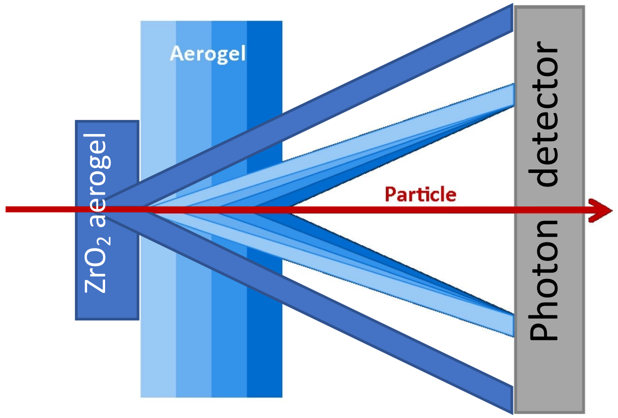


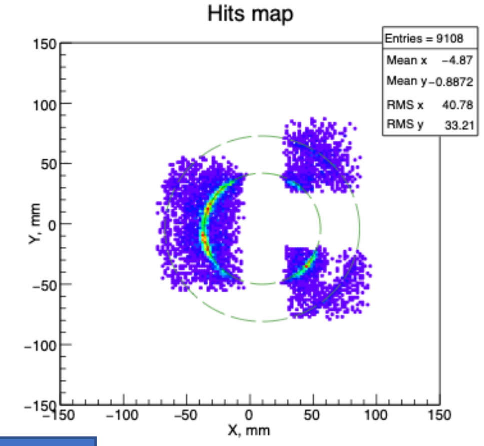
Beam tests with FARICH in 2021-2022 at BINP

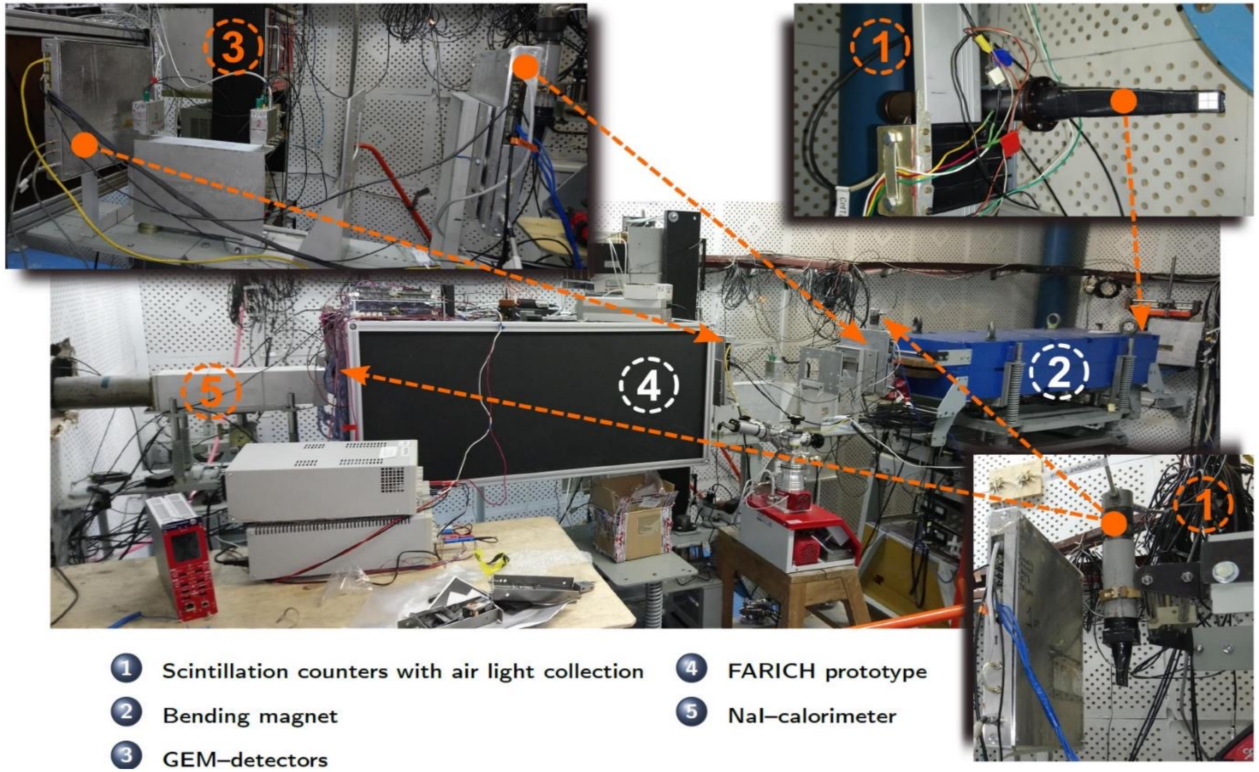
- Electrons with E=2 GeV are used
- 4 MaPMTs (H12700 from Hamamatsu with pixel 6x6 mm) were used with different masks to reduce effective pixel size:
  - Ø1 mm to investigate contribution from aerogel itself
  - 3x3 mm to measure realistic Single Photon Resoulution (SPR)
- Three GEMs are used at beamline:
  - ✓ Two before aerogel sample and one behind
  - ✓ It allows us to restore Chernekov angle for each detected photon and mitigate multiple scattering affects at beam-line.







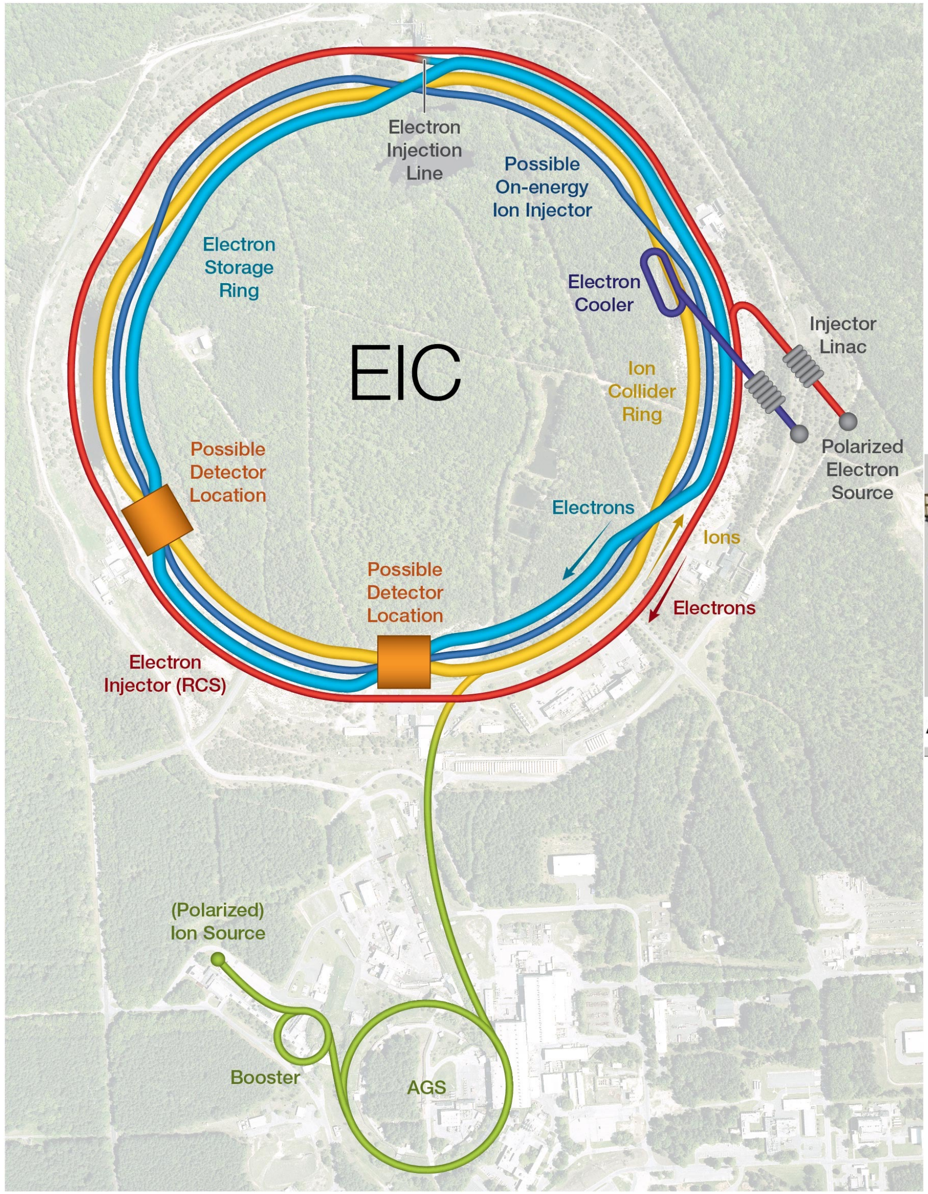




G N Abramov et al 2014 JINST **9** C08022

RICH with Fresnel lens

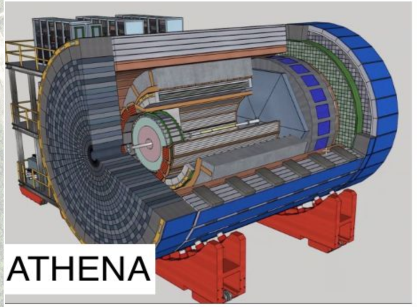
EIC project



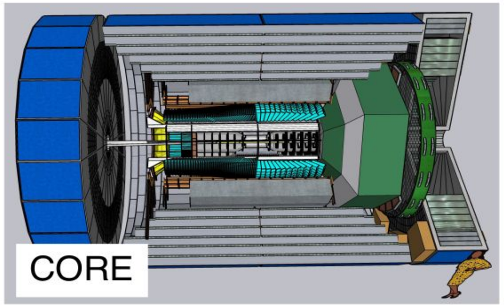
Key EIC Characteristics (parameters)

- **High particle collision rate** $L = 10^{34} cm^{-2} s^{-1}$ $\left(\int L\,dt = 100 fb^{-1}/year\right)$
- **Large center-of-mass energy range** $E_{CM} = 20 \div 140\ GeV$
  - **electrons** $2.5 \div 18\ GeV$
  - **protons** $40 \div 275\ GeV$ $(ions\!: Z/A \times E_p)$
- **Polarized beams** of electrons and ions $(up\ to\ 70\%)$
- **Large range of ion species** $(p \to U)$
- At least one **large-acceptance detector**
- **Projected budget:** $\approx \$2.4\ billion$ – **Start date:** ≈ 2031

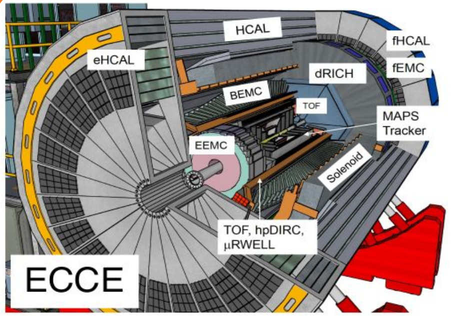
EIC detector proposals



- **backward**
  proximity-focus RICH
- **central**
  high-performance DIRC
  AC-LGAD TOF
- **forward**
  dual-radiator RICH



- **backward**
  AC-LGAD TOF
- **central**
  high-performance DIRC
- **forward**
  dual-radiator RICH



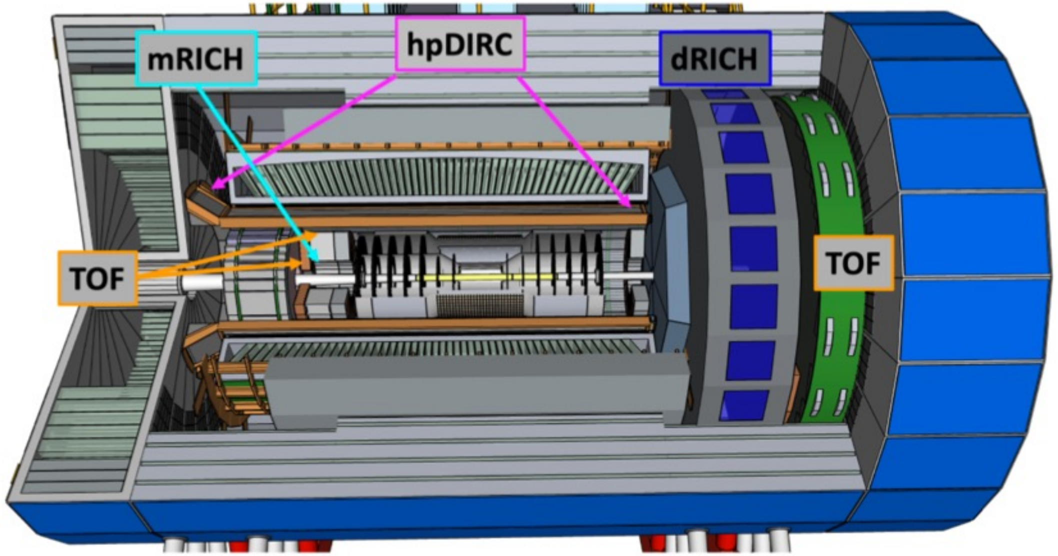
- **backward**
  modular RICH
  AC-LGAD TOF
- **central**
  high-performance DIRC
  AC-LGAD TOF
- **forward**
  dual-radiator RICH
  AC-LGAD TOF

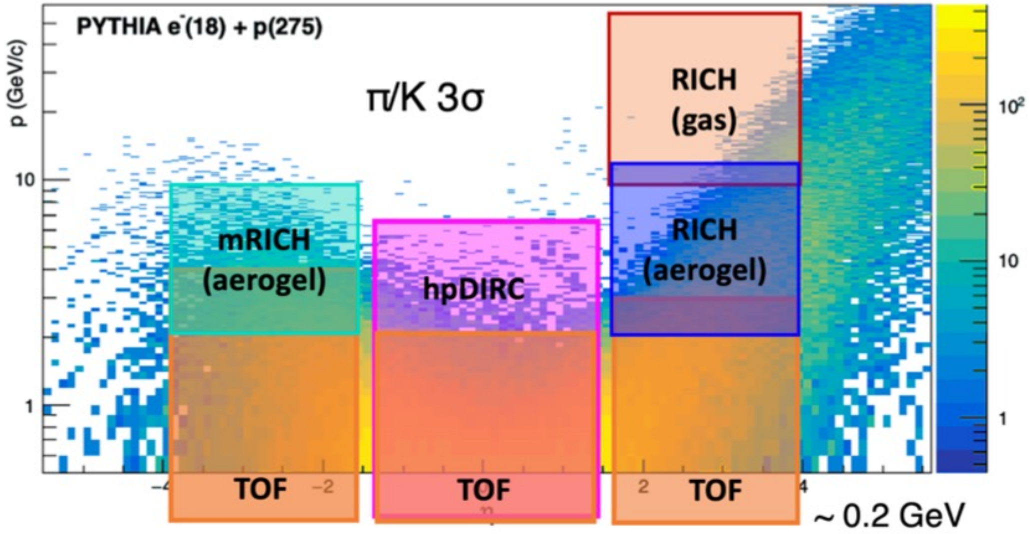
Almost approved concept since begin of 2022

6

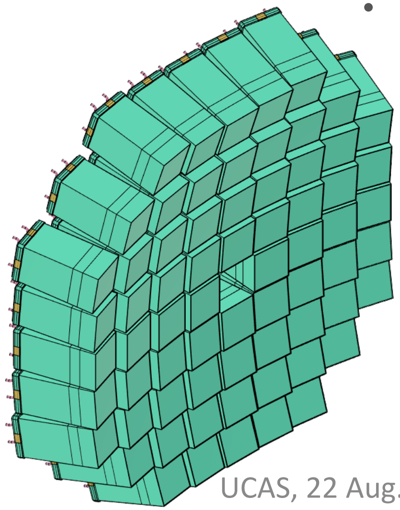
ECCE-PID & mRICH system concepts

ECCE = EIC Comprehensive Chromodynamics Experiment





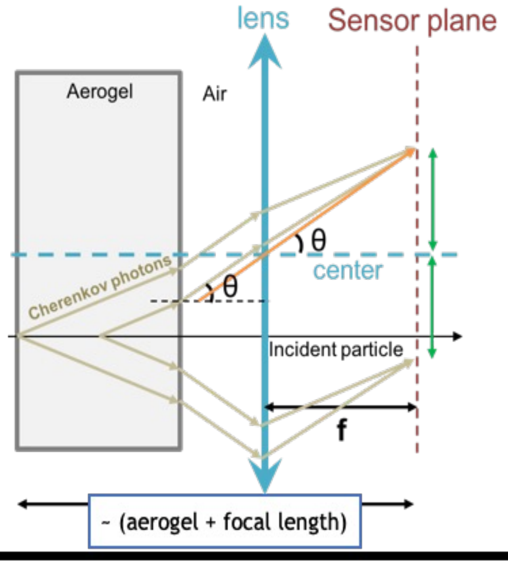
- **Physics requirements**
  - pion, kaon and proton ID
  - over a wide range $|\eta| \leq 3.5$
  - with better than 3σ separation
  - significant pion/electron suppression
- **Momentum-rapidity coverage**
  - forward: up to 50 GeV/c
  - central: up to 6 GeV/c
  - backward: up to 10 GeV/c
- **Demands different technologies**
- **Cherenkov detectors:**
  - dRICH = dual RICH (aerogel + gas)
  - hpDIRC = high-performance DIRC (synthetic fused silica)
  - mRICH = modular RICH (aerogel + Fresnel lens)

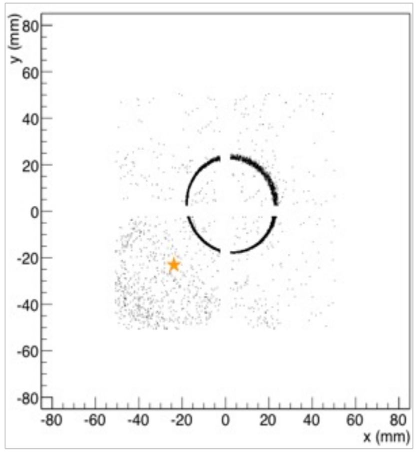


68 modular counters oriented to IP:
– aerogel n=1.03 100x100x40 mm^3
– acrylic Fresnel lens with focal distance 6”
– position sensitive photon detector HRRPD (MCP-PMT) or SiPM arrays

Aerogel RICH with Fresnel lens

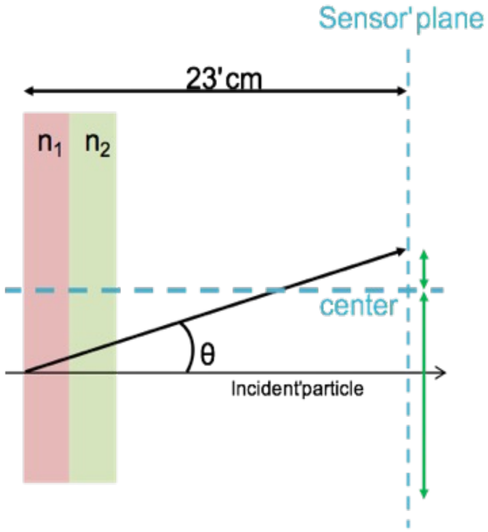
Lens-Based mRICH Design

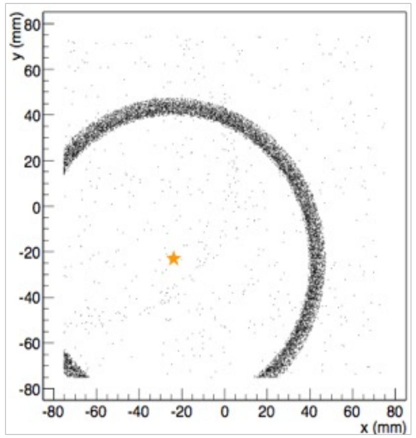




- 9 GeV/c pion beam incident at third quadrant (**star**) in simulation
- Ring image is **shifted toward the central region** on the sensor plane

Two-Layer Proximity Focusing Design (BELLE-2 ARICH)

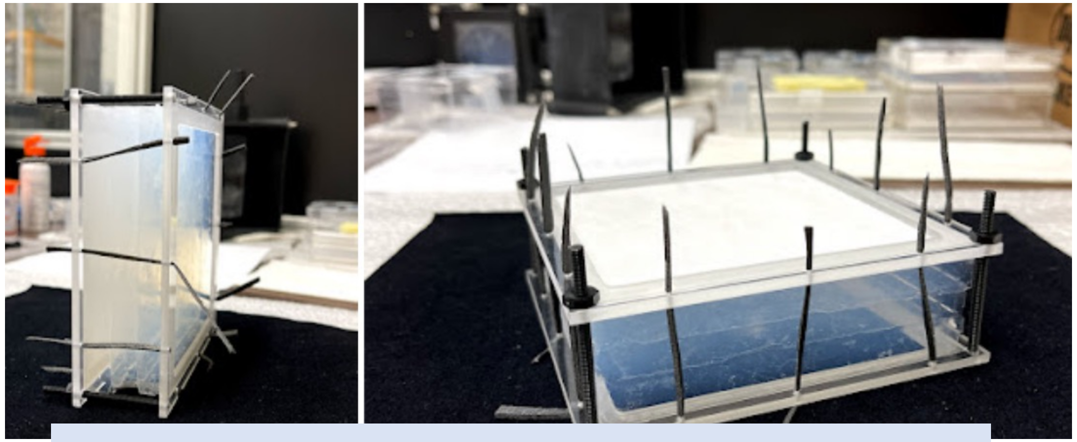




- 9 GeV/c pion beam incident at third quadrant (**star**) in simulation
- Ring is centered at point of incidence

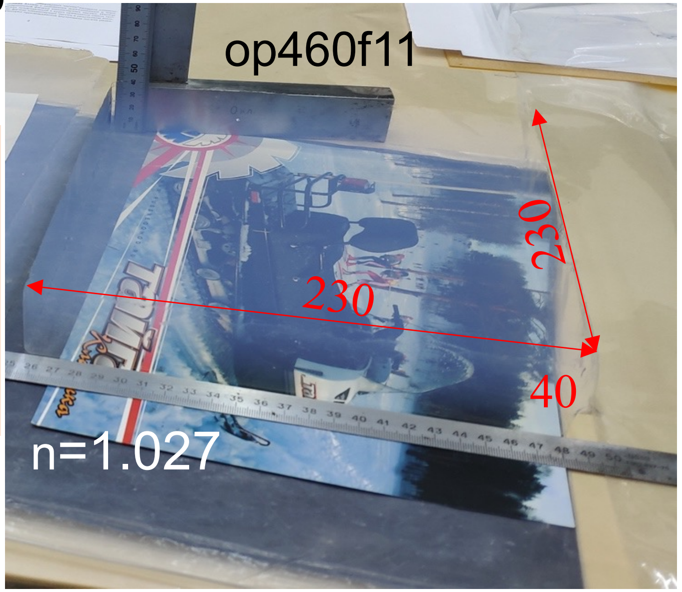
Such approach allows us to improve Cherenkov angle resolution and optimize photo detectors area!

The thick aerogel for mRICH – EIC project



FermiLAB 2021: stack of three 1 cm thickness blocks with n=1.03 from Chiba University

BINP 2022: single block 23x23x4 cm with n=1.027 from BIC

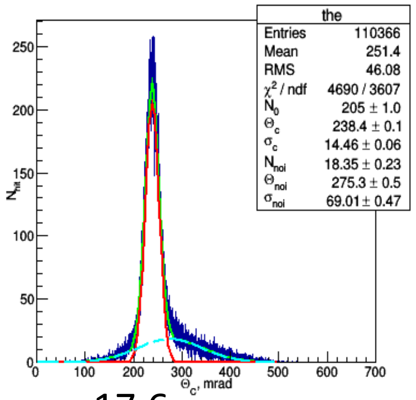


- In both cases there is no reason to make the aerogel thickness more than $(1 \div 2) \cdot L_{sc}$:

$$N_{out} = N_0 \frac{L_{sc}}{h}\left(1 - e^{-\frac{h}{L_{sc}}}\right), \qquad L_{sc} \sim \lambda^4$$

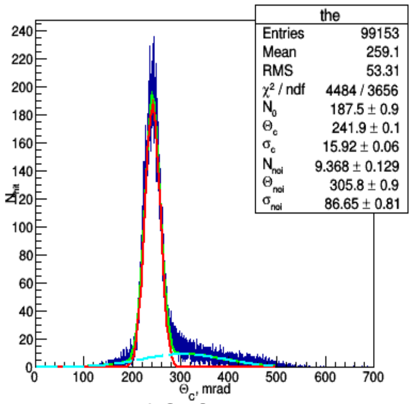
- In case of approach “stack” the additional Cherenkov photons loss is occurred due to reflectance and scattering on the additional surfaces
- There are two not cut off surfaces in aerogel
  - “Optical surface” – it contacts only with air during the production
  - “Bottom” – it contacts with metallic frame during the production processes
- Several configuration of the aerogel Cherenkov radiators were tested with relativistic electron beams at BINP beam test facilities in 2022.

Cherenkov angle single photon resolution (SPR)



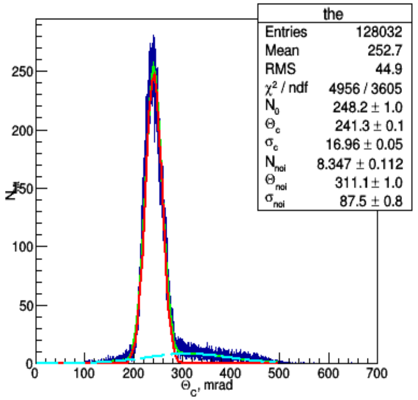
17.6 mm

457f4



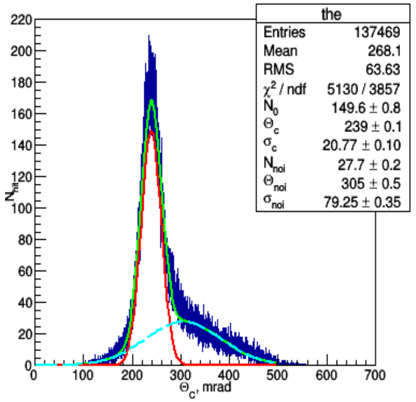
19.0 mm

457f3



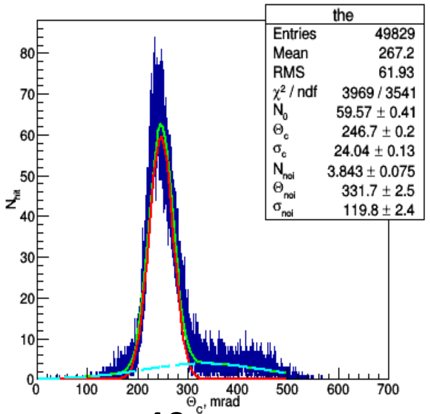
30.0 mm

460f4_3



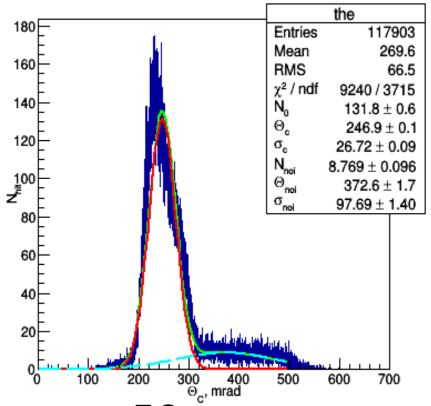
19.0+17.6 mm

457f3+457f4



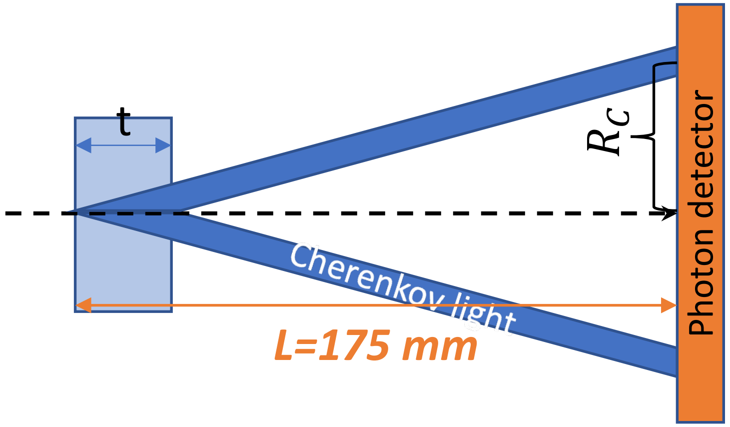
40. mm

460f11_22



50. mm

460f15_3



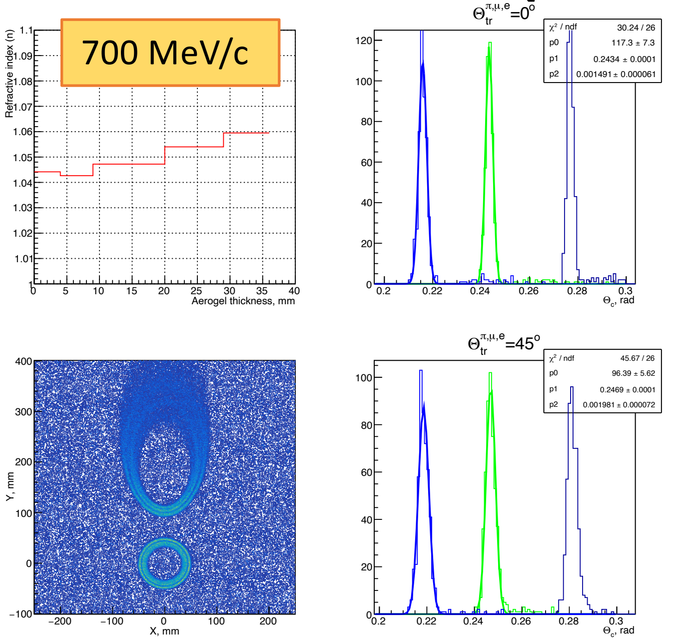
	457f4	457f3	460f4_3	457f3_f4	460f11_22	460f15_3
t/L, mm	17.6/185	19.0/175	30.0/185	36.6/185	40.0/185	50.0/185
$\sigma_{\theta_C}^{SPR}$, mrad	14.46±0.06	15.92±0.06	16.96±0.05	20.8±0.1	24.0±0.1	26.7±0.1
N$_{pe}$ *** – 60% of the ring**	4.01±0.01	4.16±0.01	7.69±0.02	5.51±0.02	8.22±0.03	8.05±0.02
$\sigma_{\theta_C}^{trk} = \frac{\sigma_{\theta_C}^{SPR}}{\sqrt{N_{pe}}}$,mrad	7.2	7.8	6.1	8.9	8.4	9.4
$\sigma_{R_C}^{ROI}$, mm	1.11±0.03	1.08±0.04	1.20±0.02	1.33±0.06	1.35±0.04	1.37±0.07
$\sigma_{\theta_C}^{R} \approx \frac{1}{n^2}\frac{\sigma_{R_C}}{L - t/2}$	5.9	6.15	6.65	7.5	7.7	8.1

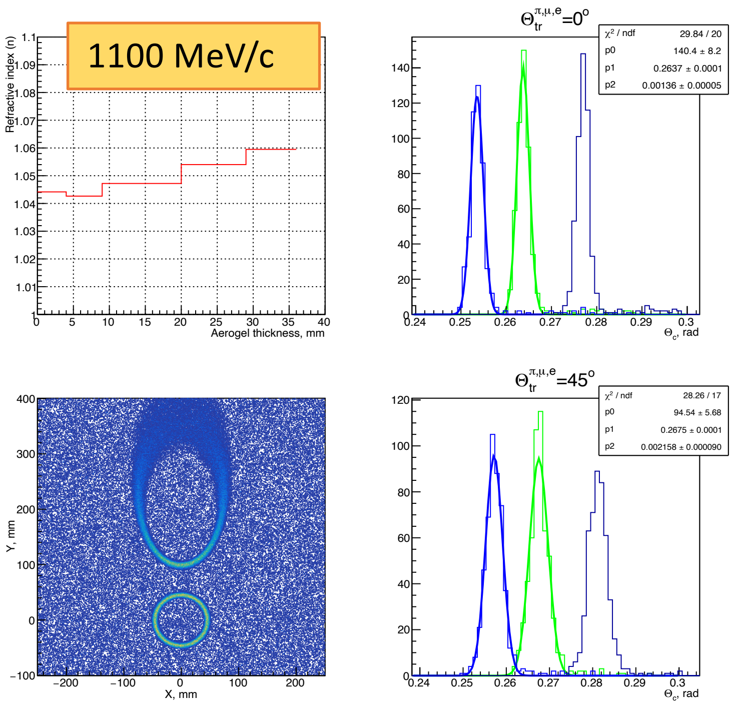
$$\theta_C^R = arctan\left(\frac{R_C}{L - t/2}\right),$$

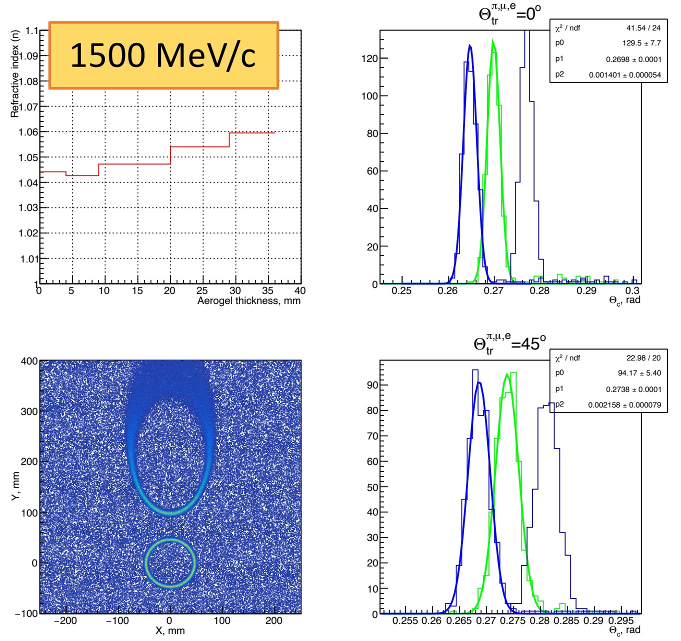
$$\sigma_{\theta_C}^R = \cos^2\theta_C\left(\frac{1}{L - t/2}\right)\cdot\sqrt{\sigma_{R_C}{}^2 + \tan^2\theta_C\cdot(\sigma_L^2 + \sigma_t^2)} \approx \frac{1}{n^2}\frac{\sigma_{R_C}}{L - t/2},$$

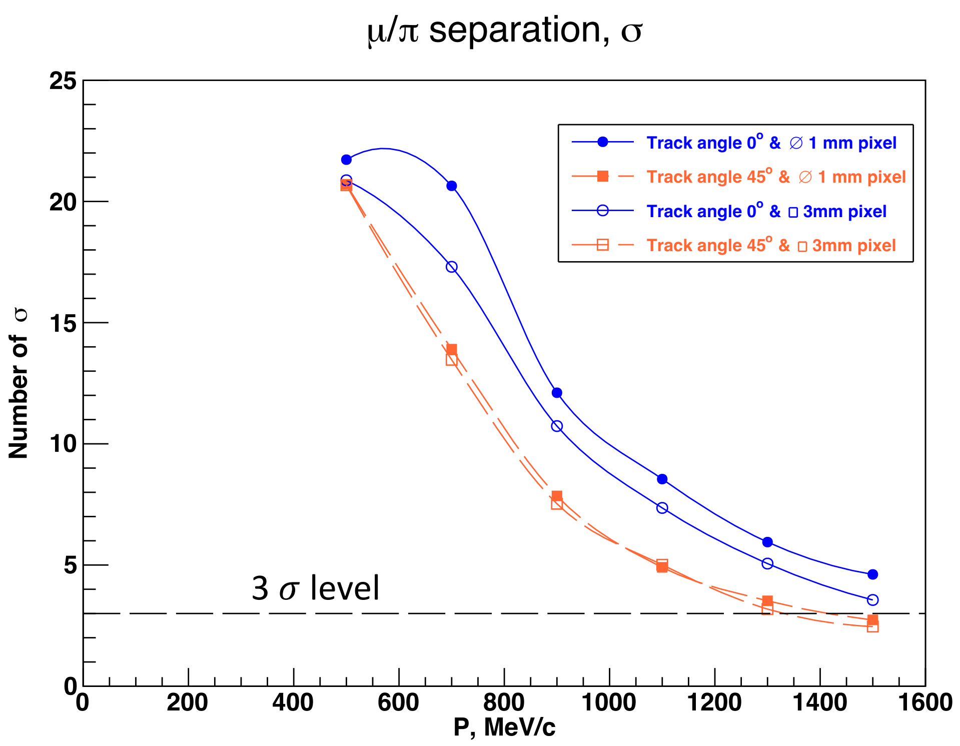
How much effect from Fresnel lens is expected?!

Expected e/μ/π – separation with FARICH up to 1.5 GeV/c









To estimate μ/π-separation capability in wide momentum range results of parametric simulation were used:

- Refractive index profile approximation for aerogel sample *453f4* and its focusing distance *L=160 mm*
- Simulation was performed for track angles *0º* and *45º*.
- Number of photoelectrons for relativistic particles (beta=1) is equal to 39 (was taken from G4 simulation).
- Single Photon Resolution (SPR) for relativistic particles SPR(■3 mm) =1.63 mm and SPR(ø1 mm)=1.36 mm (was taken from beam test results).

Quality of particles separation is determined as:

$$N_\sigma = \frac{\bar{\theta}_1 - \bar{\theta}_2}{(\sigma_1 + \sigma_2)/2}.$$