Status of drift chambers development at BINP

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Super Charm-Tau Factory

One of the main tools for studying the subatomic world are collider experiments

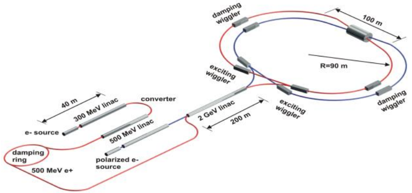
Currently, the Budker Institute of Nuclear Physics is developing the Super C-Tau Factory project

Which will allow to:

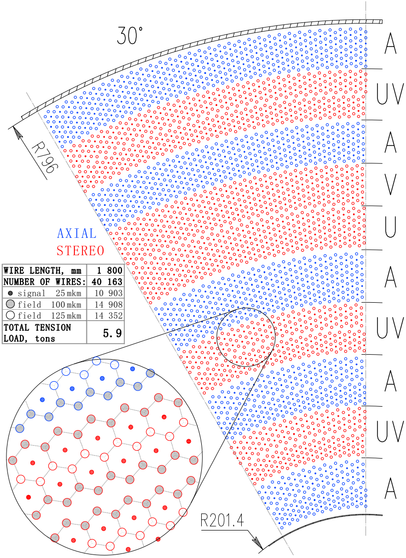
- study processes of c-quark and τ-lepton production;
- search for exotic particle states.

Which will:

- operate in the energy range from 2 to 6 GeV;
- have a luminosity of about $10^{35}\frac{1}{\text{cm}^2\times\text{s}}$.



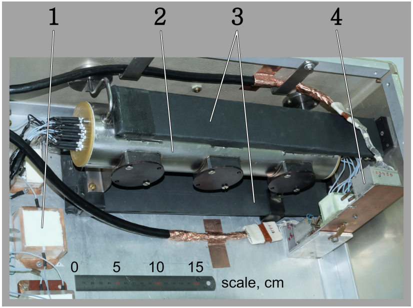
- Cell shape - hexagonal
- 41 cell layers, divided into 10 super layers
- Average radius - $\sim$ 7 mm
- Gas mixture - $He/C_3H_8 - 60/40$
- Gas gain - $\sim (5-7)\cdot 10^4$
- Anode voltage - $\sim$ 2 kV
- Average drift time - $\sim$ 350 - 400 ns
- $\sigma \sim 100\ \mu$m
- $\frac{\sigma_{dE/dx}}{dE/dx} \sim 7\ \%$



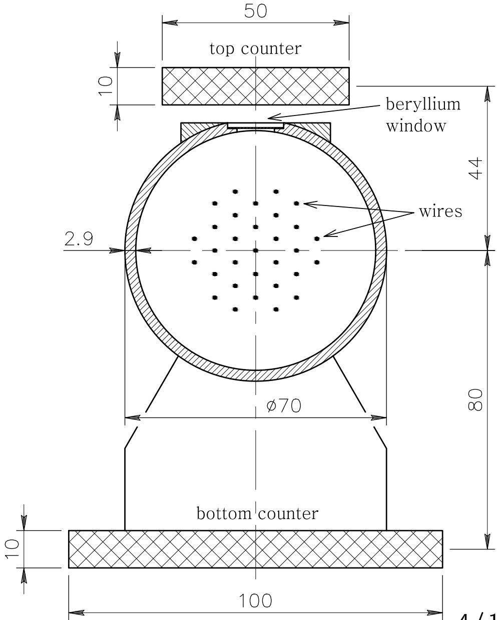
WIRE LENGTH, mm	1 800
NUMBER OF WIRES:	40 163
signal 25 mkm	10 903
field 100 mkm	14 908
field 125 mkm	14 352
TOTAL TENSION LOAD, tons	5.9

Small DC prototype

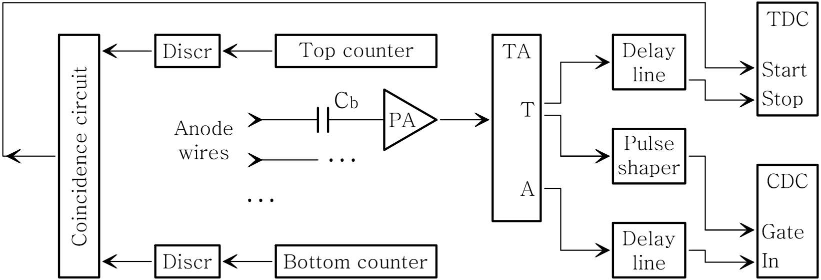
- Diameter - 70 mm
- Length - 300 mm
- 7 hexagonal cells
- Spatial resolution was measured in $He/C_3H_8 - 60/40$ and $He/C_2H6 - 50/50$ mixtures at various gas gains



Prototype photo



Small DC prototype



Block diagram of the prototype electronics

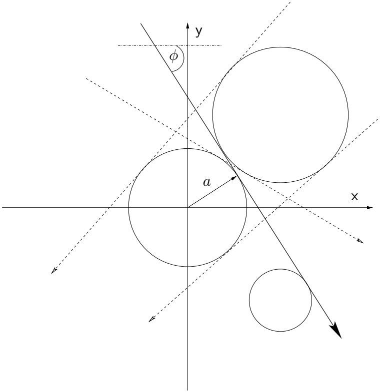
Track reconstruction algorithm

Track parameterization: $xsin(\phi) + ycos(\phi) - a = 0$

Search for the most suitable tangent lines. Then a numerical calculation of parameters in the vicinity of the found values is performed

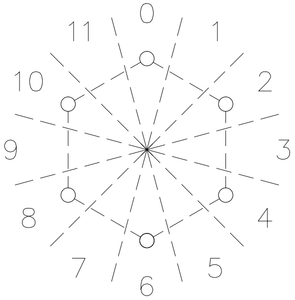
$$\chi^2(a, \phi) = \sum \frac{(R_i(a,\phi) - r_i)^2}{\sigma_i^2},$$

where $R_i(a, \phi) = |x_i sin(\phi) + y_i cos(\phi) - a|$

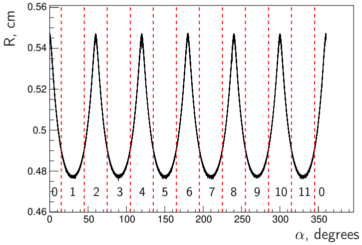


Tangent lines to two isochrones

Track reconstruction algorithm



Dividing the cell into 12 angular regions



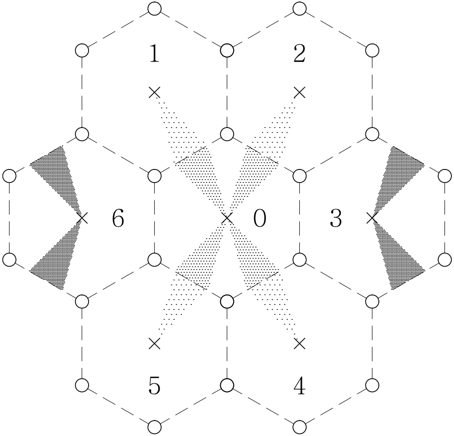
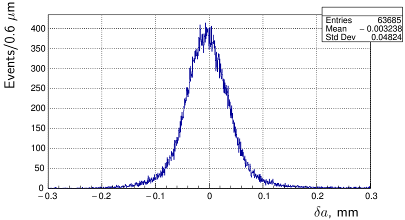
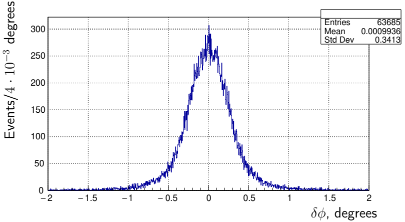


Diagram of region combination in cells

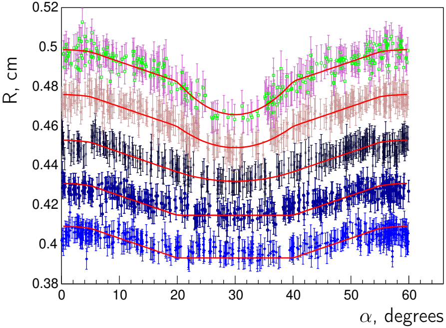
Experiment simulation



Deviation of parameter a from the real value (considering artificial shift)

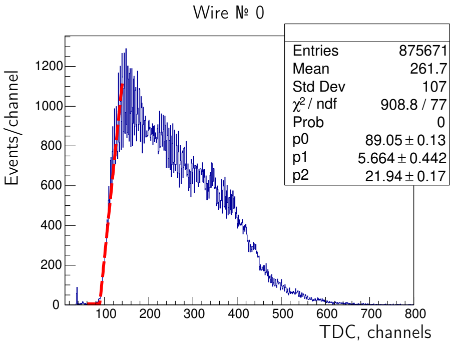


Deviation of angle ϕ from the real value



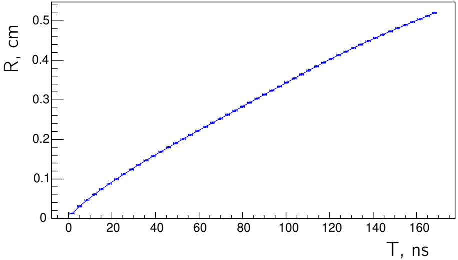
Isochrones as a function of azimuthal angle

Spatial resolution measurement

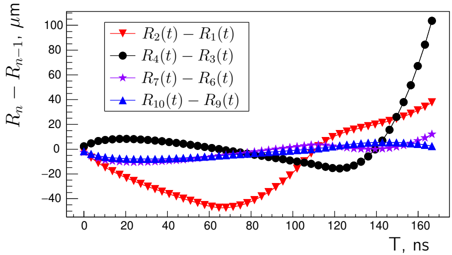


$\Longleftarrow$ Time spectrum for the central wire at gain $5 \cdot 10^4$ $(He/C_3H_8$, maximum drift time about 180 ns)

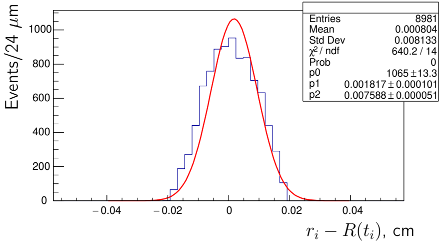
R(t) dependence in experiment at gain $7 \cdot 10^4$ (He/C_3H_8) $\Longrightarrow$

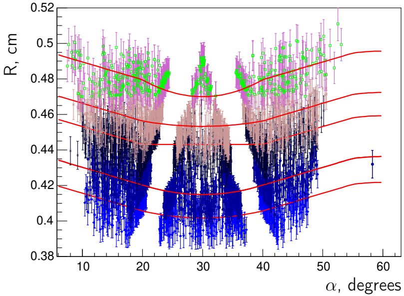


Spatial resolution measurement

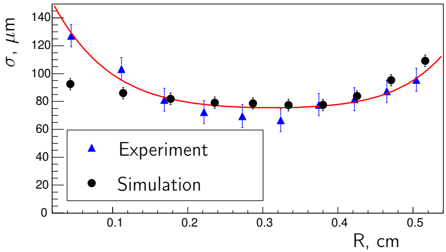


$\Longleftarrow$ Difference R(t) in two consecutive iterations

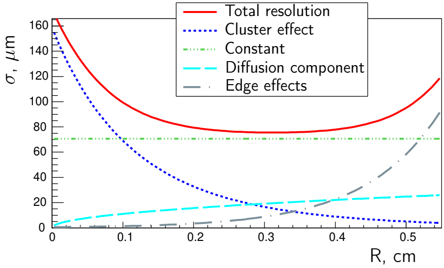




Spatial resolution measurement



Total resolution for He/C_3H_8 gas mixture at gain $7 \cdot 10^4$

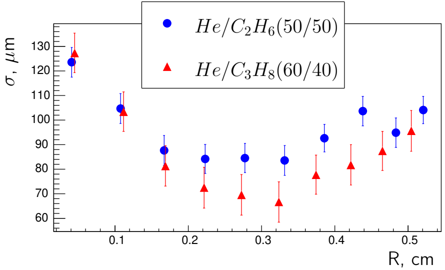


Contribution of each component to the resolution for He/C_3H_8 gas mixture at gain $7 \cdot 10^4$

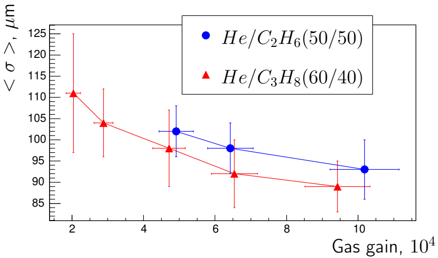
$$\sigma(r) = \sqrt{\sigma_{\text{cl}}^2 + \sigma_{\text{diff}}^2 + \sigma_{\text{edge}}^2 + \sigma_0^2}$$

σ_{cl} - cluster effect, σ_{diff} - diffusion component, σ_{edge} - edge effects, σ_0 - constant (contributions from time resolution (54 μm), mechanical inaccuracies (45 μm), pressure and temperature (4 μm))

Spatial resolution measurement



Comparison of resolutions for He/C_3H_8 and He/C_2H_6 at gain $7 \cdot 10^4$



Average resolution values for He/C_3H_8 and He/C_2H_6 as a function of gas gain

The paper on spatial resolution measurement with the small prototype was published in the NIM journal:

DOI: https://doi.org/10.1016/j.nima.2024.169419

Spatial resolution measurement

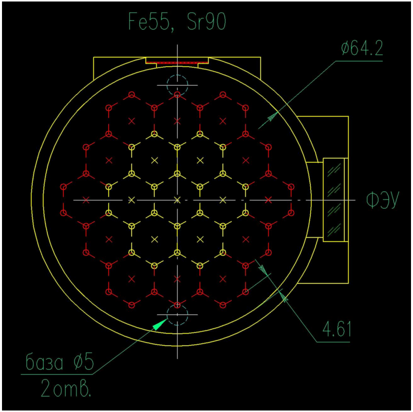
	He/C_3H_8 (60/40)		He/C_2H_6 (50/50)	
Gas Gain	N, 10^3	T, weeks	N, 10^3	T, weeks
$2 \cdot 10^4$	52	4	—	—
$3 \cdot 10^4$	73	3	—	—
$5 \cdot 10^4$	71	2	72	2
$7 \cdot 10^4$	84	2	97	2.5
10^5	94	2	96	2

Experiment parameters. N — number of events used in the analysis, T — data acquisition time

	He/C_3H_8 (60/40)	He/C_2H_6 (50/50)
Gas Gain	$< \sigma >$, μm	$< \sigma >$, μm
$2 \cdot 10^4$	111 ± 14	—
$3 \cdot 10^4$	104 ± 8	—
$5 \cdot 10^4$	98 ± 9	102 ± 6
$7 \cdot 10^4$	92 ± 8	98 ± 6
10^5	89 ± 6	93 ± 7

Experiment results

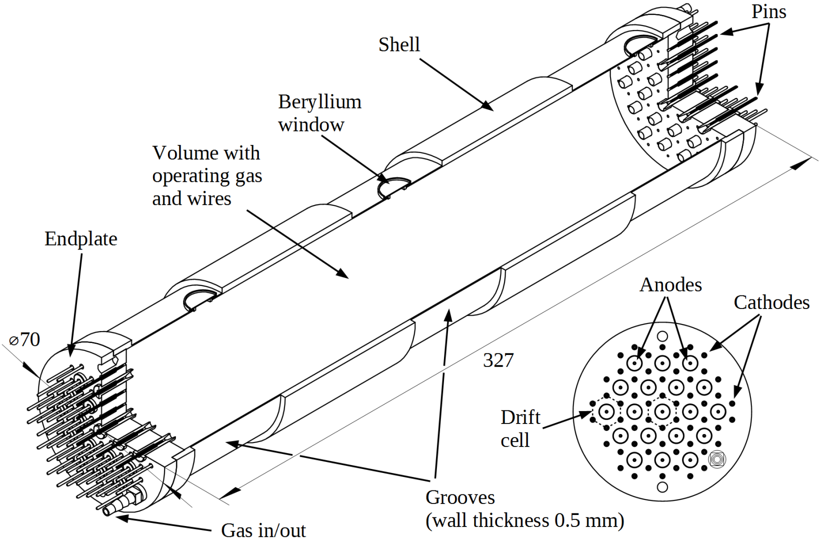
Methodical works. The prototype developing

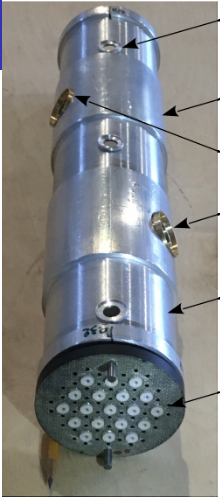


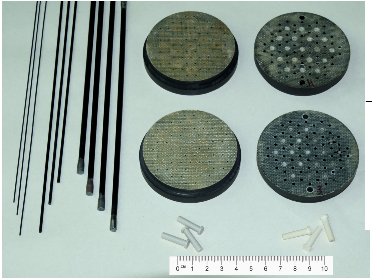
Wire structure design for the new prototype

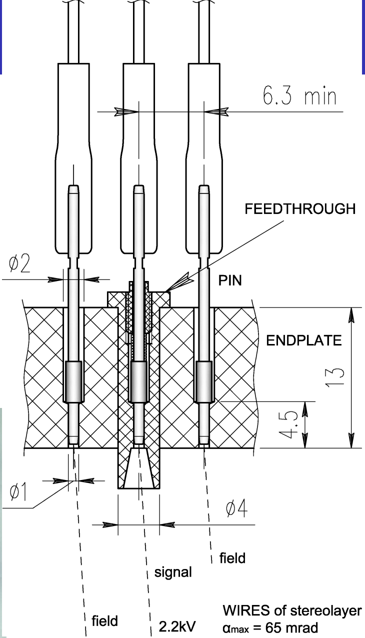
- Development of a second DC prototype with an additional cell layer for more "correct"resolution measurement and for measuring resolution at different angles using Sr_{90} isotope is underway

Methodical works. The prototype developing

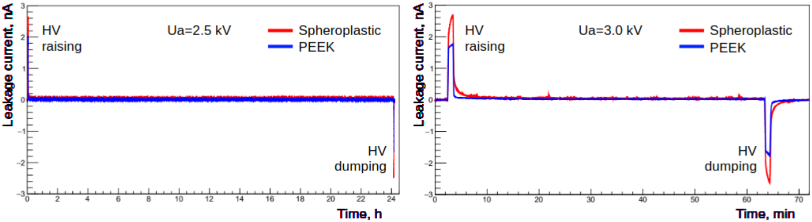



Be-window frame (3 pcs.)
Shell (body)
Quartz window frames
Groove: wall thickness 0.5 mm
Endplate



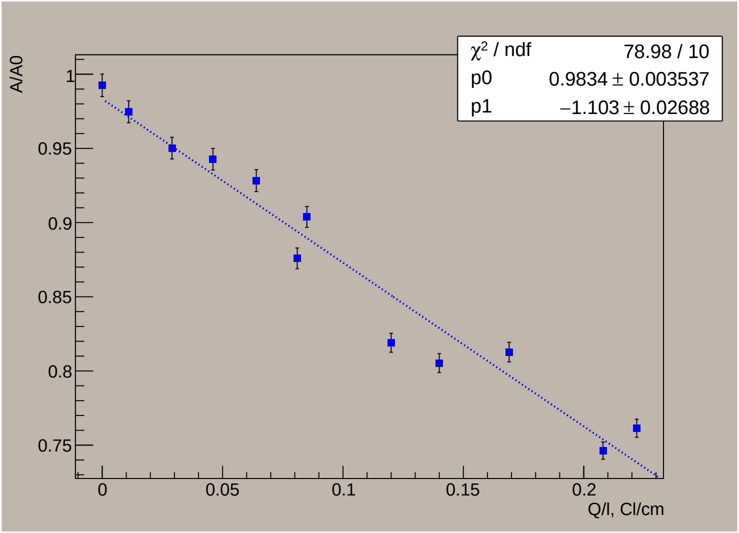

6.3 min
FEEDTHROUGH
PIN
ø2
ENDPLATE
13
4.5
ø1
ø4
field
signal
field
2.2kV
WIRES of stereolayer
α_{max} = 65 mrad

Methodical works. The pins electrical tests



- During charging from the HV, significantly less volume charge accumulates in samples with PEEK pins compared to spheroplastic material
- In the case of spheroplastic, the initial leakage current after voltage rise is about 2 times higher than in the case of PEEK, while the exponential relaxation times of the current are comparable in both cases
- Absence of electrical breakdowns
- The leakage current is equal to (50 ± 10) pA for spheroplastic and (20 ± 10) pA for PEEK $\Rightarrow$ $(1-3)$ pA per cell

Methodical works. The anode wire aging test



- The aging tests were done for He/C_3H_8 $60/40$ gas mixture measuring the average gas gain amplitudes with Fe_{55}
- The rate of aging test is (110 ± 3)%/(C/cm)

Summary

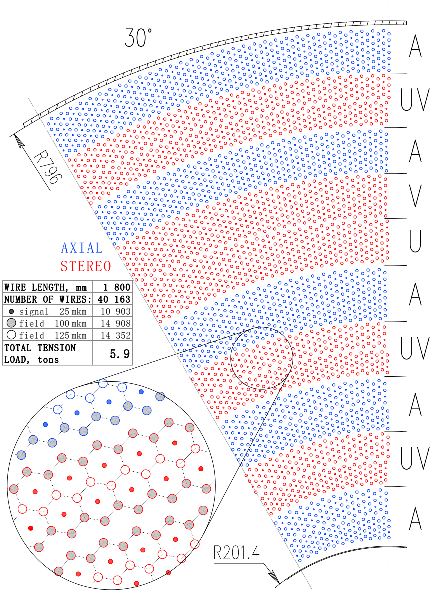
- The spatial resolution has been measured on the small DC prototype for He/C_3H_8 and He/C_2H_6 gas mixtures at various gas gains. The average resolution is less than 100 μm
- The new prototype has been developing with additional cell layer for studying the systematic uncertainties in the spatial resolution at different angles using Sr_{90} isotope
- The electrical properties of the two types (spheroplastic and PEEK) of pins have been studied for using in the endplates. The average current leakage is around (1-3) pA per cell
- The aging test of the anode wire has been carried out. The rate of aging test is about (110 ± 3)%/(C/cm).

Thank you for your attention!

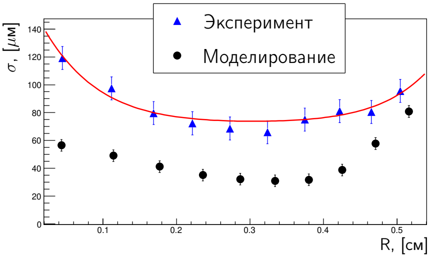
BACKUP

Drift Chamber

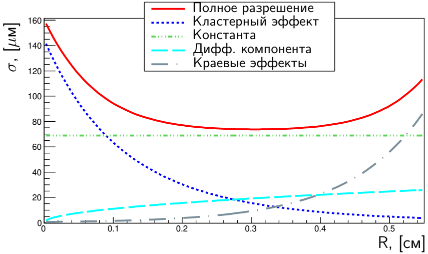
SUPER LAYER NUMBER	NUMBER OF MONO-LAYERS	NUMBER OF CELLS IN MONOLAYER	NUMBER OF CELLS	STEREO ANGLE, mrad	CELL SIZE r ± Δr, mm		RADIUS OF ANODE WIRE LAYER, mm
1	4	125	500	0	6.306	0.034	217.306
					6.644	0.007	227.100
					7.165	0.039	246.906
					7.549	0.009	258.035
2	4	157	628	+ 33.8	6.473	0.028	280.154
					6.747	0.006	290.136
				− 34.2	7.182	0.031	310.863
					7.486	0.007	321.938
3	4	189	756	0	6.564	0.024	341.986
					6.794	0.005	352.060
					7.140	0.026	371.992
					7.388	0.005	382.950
4	4	223	892	+ 48.9	6.603	0.020	405.941
					6.799	0.004	416.040
				− 49.3	7.104	0.021	436.741
					7.314	0.005	447.606
5	5	255	1275	0	6.651	0.018	467.570
					6.823	0.003	477.718
					6.968	0.001	488.097
					7.120	0.001	498.701
					7.274	0.001	509.535
6	4	287	1148	+ 63.1	6.741	0.016	533.350
					6.895	0.004	543.615
					7.026	0.001	554.088
					7.161	0.001	564.762
7	4	313	1252	− 63.4	6.778	0.015	584.801
					6.919	0.003	595.108
					7.039	0.001	605.606
					7.163	0.001	616.289
8	4	341	1364	0	6.768	0.014	636.220
					6.898	0.003	646.501
					7.007	0.001	656.957
					7.121	0.001	667.581
9	4	371	1484	+ 64.7	6.746	0.013	689.948
					6.865	0.003	700.185
				− 65.0	7.041	0.013	720.090
					7.165	0.002	730.775
10	4	401	1604	0	6.791	0.012	750.730
					6.902	0.003	761.027
					6.995	0.001	771.472
					7.091	0.001	782.061
TOTAL	41		10903				



WIRE LENGTH, mm	1 800
NUMBER OF WIRES:	40 163
● signal 25 mkm	10 903
field 100 mkm	14 908
○ field 125 mkm	14 352
TOTAL TENSION LOAD, tons	5.9



Total resolution for He/C_3H_8 mixture at gain $7 \cdot 10^4$



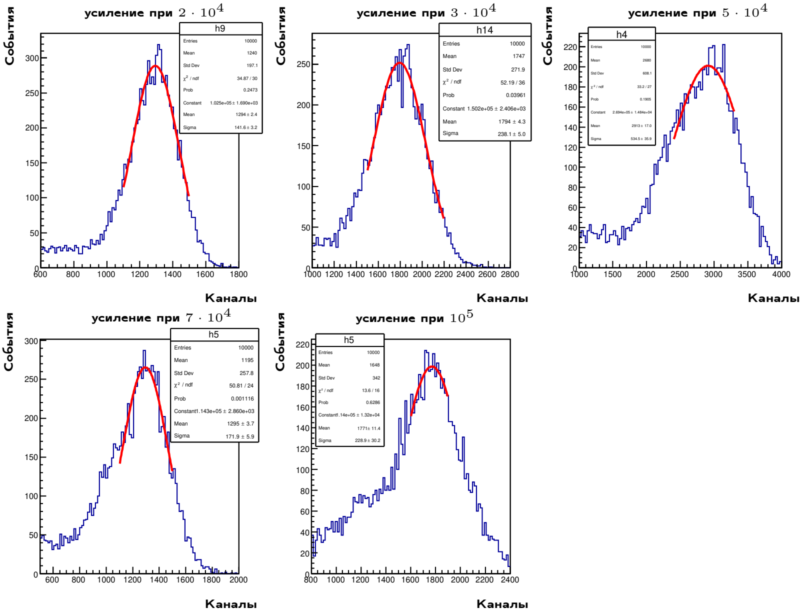
Contribution of each component to the resolution for He/C_3H_8 mixture at gain $7 \cdot 10^4$

$$\sigma(r) = \sqrt{\left(\frac{p_0}{r+p_1}\right)^{p_2} + (p_3\sqrt{r})^2 + (p_4 e^{p_5 r})^2 + p_6^2}$$

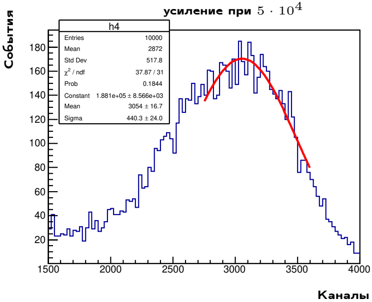
$p_0 - p_5$ free parameters

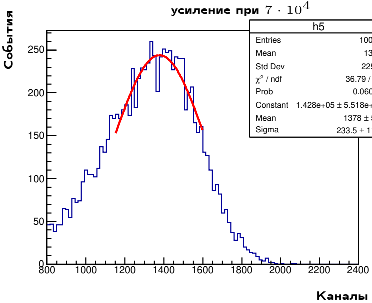
Parameter p_6 - σ_0 is associated with the contribution of electronics, mechanical inaccuracies, pressure, temperature. It was found by minimizing the quadratic difference between simulation and experiment

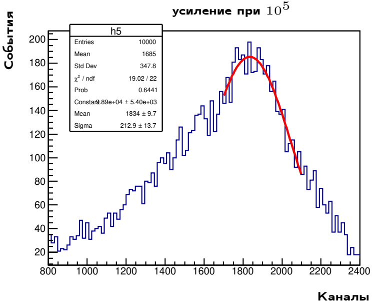
Gas gains for He/C_3H_8 gas mixture



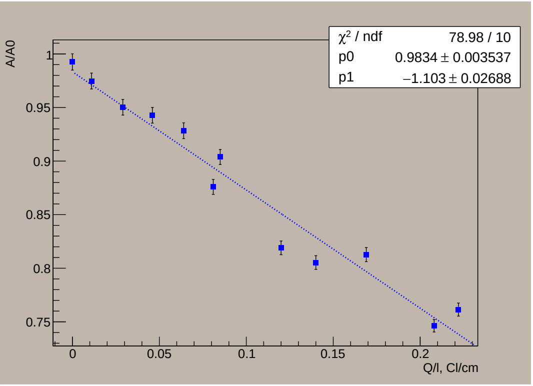
Gas gains for He/C_2H_6 gas mixture

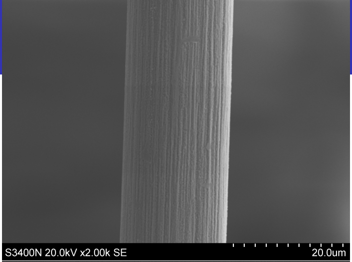


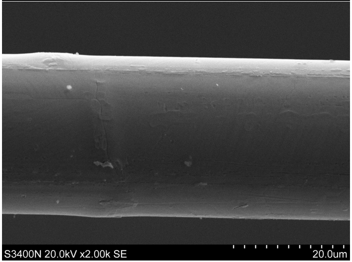




Methodical works







- The aging tests were done for He/C_3H_8 $60/40$ gas mixture measuring the average gas gain amplitudes with Fe_{55} for the samples from Institute of Modern Physics, Chinese Academy of Sciences
- The rate of aging tests is (110 ± 3)%/(C/cm)
- Right top figure is a surface in the wire, the right bottom figure shows the surface of a reference 25 microns wire

One of the project for CMD3 drift chamber

1.1 Внутренняя обечайка

Внутренняя обечайка представляет собой цилиндр. Параметры цилиндра:
$R_{in} = 20.$ мм
$R_{ou} = 20.2$ мм
Таким образом толщина $h_{in} = 0.2$ мм.
Длина цилиндра $L_{in} = 440$ мм.
Материал цилиндра: углепластик.
X_0 углепластика составляет $X_0^{CF} = 22.2$ см (в литературе также встречаются X_0^{CF}=24 см и $X_0^{CFPR} = 26.6$ см, взято консервативное значение).
На внутреннею сторону цилиндра приклеена алюминиевая фольга толщиной $h_{foil}^{Al} = 50$ мкм ($X_0^{Al} = 8.89$ см)

2 Внешняя обечайка

Внешняя обечайка представляет собой цилиндр. Параметры цилиндра:
$R_{in} = 297.$ мм
$R_{ou} = 300.$ мм
Длина цилиндра $L_{ou} = 440$ мм, $h_{ou} = 3.0$ мм.
Материал цилиндра: углепластик.
На внешнею сторону цилиндра приклеена алюминиевая фольга толщиной $h_{foil}^{Al} = 50$ мкм.

Необходимость наличия алюминиевой фольги на обечайках будет понятна после испытания с прототипом, либо после изготовления собственно внутренней обечайки.

CMD3 drift chamber project

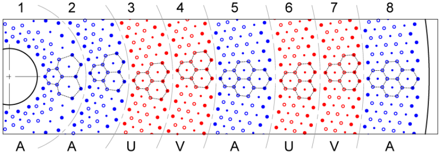
SUPERLAYER NUMBER	NUMBER OF LAYERS	NUMBER OF CELLS IN LAYER	NUMBER OF CELLS IN SUPERLAYER	STEREO ANGLE, mrad	CELL SIZE r ± Δr, mm		RADIUS OF ANODE WIRE LAYER, mm
1	2	19	38	0	6.000 8.642	0.175 0.038	31.543 43.185
2	2	37	74	0	6.279 7.516	0.094 0.019	64.106 74.762
3	2	53	106	+45	6.529 7.391	0.068 0.014	95.422 106.078
4	2	69	138	-48	6.667 7.330	0.054 0.011	126.848 137.512
5	3	87	261	0	6.562 7.072 7.534	0.042 0.008 0.001	157.404 167.757 178.827
6	2	109	218	+99	6.683 7.093	0.034 0.007	200.831 211.266
7	2	125	250	-101	6.750 7.109	0.030 0.006	232.613 243.097
8	3	141	423	0	6.772 7.091 7.370	0.027 0.005 0.001	263.236 273.713 284.629
TOTAL	18		1508				

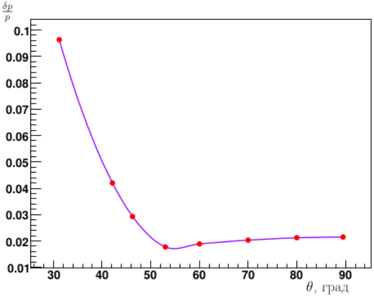
The CMD new drift chamber geometry

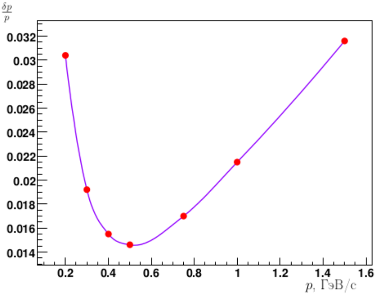
INNER DIAMETER, mm	40
OUTER DIAMETER, mm	600
WIRE LENGTH, mm	440
ENDPLATE THICKNESS, mm	7
NUMBER OF WIRES:	5 804
● SIGNAL 25 um	1 508
⬤ FIELD 100 um	1 920
○ FIELD 125 um	2 376
TOTAL TENSION LOAD, kg	882
ENDPLATE FLEXURE (MAX)*, mm	3.1

*ENDPLATE MATERIAL:
NIIKAM M55J quasi-isotropic carbon fiber with Young's modulus E = 168 GPa

A – axial
U, V – stereo

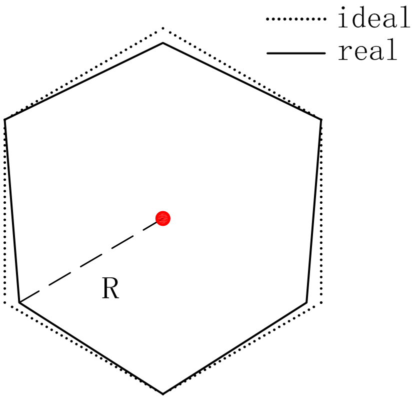






Optimization of the DC wire structure

- Due to the non-ideality of the hexagonal cell structure ⇒ distortion of the electric field from cylindrical symmetry occurs
- Solution ⇒ optimization of the wire structure to obtain a more isotropic field distribution in space

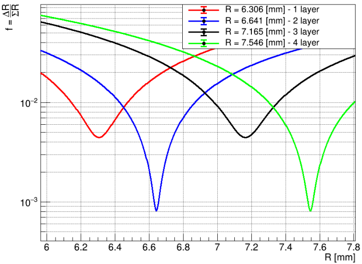


Distortion of the hexagonal structure due to the cylindrical geometry of the chamber

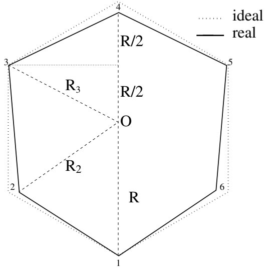
Optimization of the DC wire structure

- The wire structure was optimized sequentially layer by layer by minimizing the function f:

$$f = \frac{\sqrt{(R-R_2)^2+(R-R_3)^2+(R_2-R_3)^2}}{R+R_2+R_3}$$



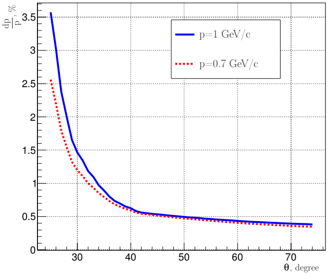
Dependence of function f on R for the entire first super layer



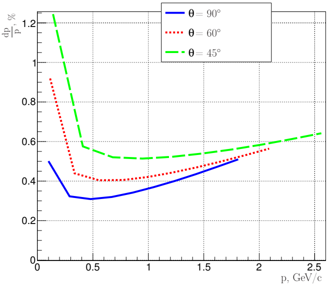
Definition of R, R_2, R_3

Momentum and dE/dx resolution

To find the momentum resolution, MC simulation of pions passing through the DC was performed:



Momentum resolution as a function of polar angle

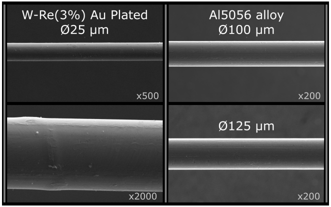


Momentum resolution as a function of total momentum

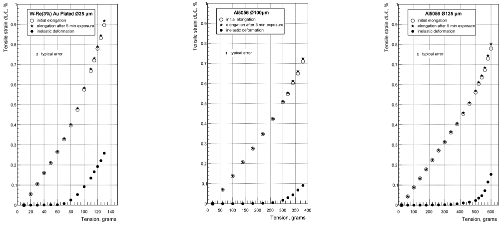
The dE/dx resolution was estimated from CLEO-III results $\sigma_{dE/dx} \sim 7\%$ and is comparable to Belle (6.9%) and BaBar (7.5%)

Wires

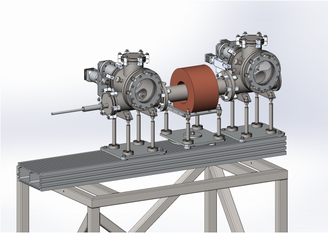
- Anode wire - 25 μm in diameter, W-Re(3%), coated with Au (tension $\sim$ 60 g)
- Two types of cathode wires made of Al - 125 μm (tension $\sim$ 220 g) and 100 μm (tension $\sim$ 140 g)
- Anode wires are made by LUMA (Sweden)
- Cathode wires are made by Danyang Litong Cable Technology Co. (China)



Wires

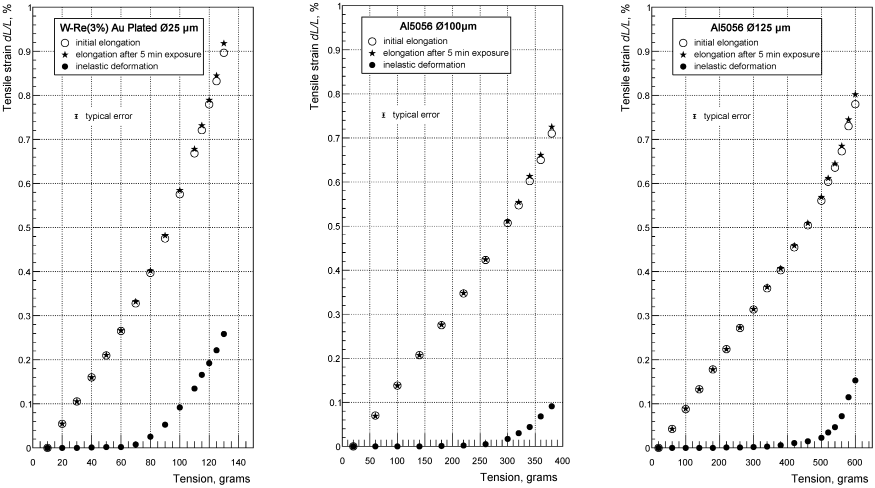


Mechanical tensile tests of wires



Magnetron sputtering system project

Mechanical were tests



Mechanical tensile tests of wires

Mechanical properties of wires

	W-Re(3%) Au Plated 25 µm in dia.	Al5056 alloy 100 µm in dia.	Al5056 alloy 125 µm in dia.
Manufacture Date	2019-04-03	2019-06	2019-06
Wire Type	861/67	-	-
Diameter (rating)	25 microns	100 microns	125 microns
Diameter Tolerance (±)	2%	2 microns	2 microns
Straightness grade	1	-	-
Ovality	2%	-	-
Measured Properties*:			
Diameter, microns	25.0 ± 0.2	102 ± 1	126 ± 1
Linear Density**, mg/m	9.4	21.6	32.9
Yield Strength, g	65 ± 5	240 ± 20	360 ± 20
Young's Modulus, GPa	381 ± 1	70 ± 2	70 ± 2
Tensile Strength, g	140 ± 5	400 ± 20	600 ± 20
Elongation (before breaking), %	> 0.92	> 0.72	> 0.8

*Based on samples taken from the first 10 meters of wire length on the spool.

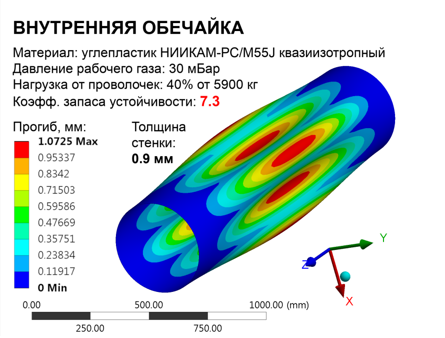
**Calculated mean value using the material density from the specification.

Characteristics of similar drift chambers

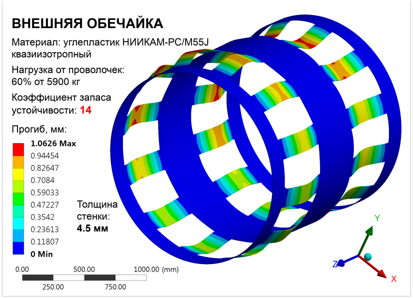
Characteristics	Detector				
	CLEOIII	BaBar	BESIII	BelleII	SCTF
B,T	1.5	1.5	1.0	1.5	1.5
N_{cells}	9796	7104	6796	14336	10903
Shape	Rect.	Hex.	Rect.	Rect.	Hex.
Anode wire d, μm	W(Au) 20	W(Au) 20	W(Au) 25	W(Au) 30	W(Au) 25
Field wire d, μm	Al(Au) 110	Al(Au) 120	Al(Au) 110	Al 126	Al 100, 125
Size mm $\times$ mm	14×14	18×12	12×12 16×16	7×7 10×10	$\sim 13 \times 13$
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}, V	1900	1930	2200	2300	~ 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	-	~ 0.35
$\sigma_{dE/dx}$, %	5.7	7.5	6.0	~ 6	~ 6.9
σ, μm	110	120	120	~ 100	~ 100

The paper on the DC for the Super C-Tau Factory was published:
https://doi.org/10.1016/j.nima.2021.165490

Inner/Outer cylinders



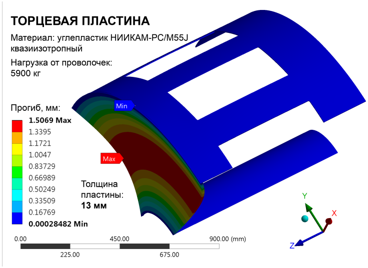
Inner cylinder simulation in ANSYS



Outer cylinder simulation in ANSYS

- To facilitate the wire stringing process, the outer cylinder contains 24 service windows
- The DC has a cylindrical geometry (material: carbon fiber)
- Wall thickness - 0.9 mm/4.5 mm $(X/X_0 = 0.46\%/2.1\%)$
- Load due to wire tension - 2.36 t/3.54 t (maximum transverse deformation 20 μm/80 μm)
- Stability safety factor is 7.3/14

End plates



End plates simulation in ANSYS

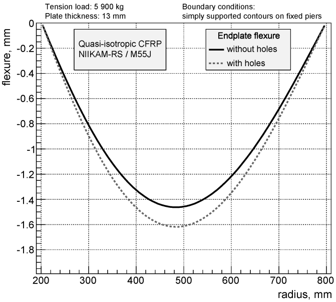


Plate deformation as a function of radius

- End plates are flat
- Holes drilled in the plates increase bending by 10%
- Wall thickness - 13 mm (material: carbon fiber, $X/X_0 = 5.9\%$)
- Total load is 5.9 t (maximum deformation 1.6 mm)

Stereo angles

SCTF		BELLE II		BaBar		BES III	
R mm	α_{stereo} mrad	R mm	α_{stereo} mrad	R mm	α_{stereo} mrad	R mm	α_{stereo} mrad
280.154	$+33.8$	257.0	$+45.4$	–	–	327.5	-30.68
290.136	-34.2	348.0	$+45.8$	318.5	$+44.9$	334.1	-31.31
405.941	$+48.9$	–	–	370.5	-52.3	402.1	$+31.41$
416.040	-49.3	476.9	-55.3	480.8	$+55.6$	415.5	$+32.46$
533.350	$+63.1$	566.9	-64.3	533.2	-62.8	531.7	-42.06
584.801	-63.4	–	–	–	–	583.0	$+40.37$
689.948	$+64.7$	695.3	$+63.1$	643.0	$+65.0$	676.3	-41.62
730.775	-65.0	785.3	$+70.0$	695.2	-72.1	–	–

Gas mixtures

Gas mixture	Proportions	X_0, m	N_p, $\frac{clusters}{\text{cm}}$	V_{dr}, $\frac{\text{cm}}{\mu\text{s}}$	D_l, $\frac{\mu\text{m}}{\sqrt{\text{cm}}}$	Experiment
He/iC_4H_{10}	80/20	807	21.2	2.79	141	BaBar
He/iC_4H_{10}	90/10	1313	12.7	2.31	162	Kloe
He/C_3H_8	60/40	569	31	3.06	133	CLEOIII BESIII
He/C_2H_6	50/50	686	22.9	3.52	142	Belle BelleII
He/CH_4	80/20	3087	7	2.54	172	Kloe
Ar/C_2H_6	50/50	178	34	5.27	143	CLEOII
He/DME	70/30	678	21	1.12	123	-

Characteristics of various gas mixtures in the absence of a magnetic field and at 1 kV/cm electric field