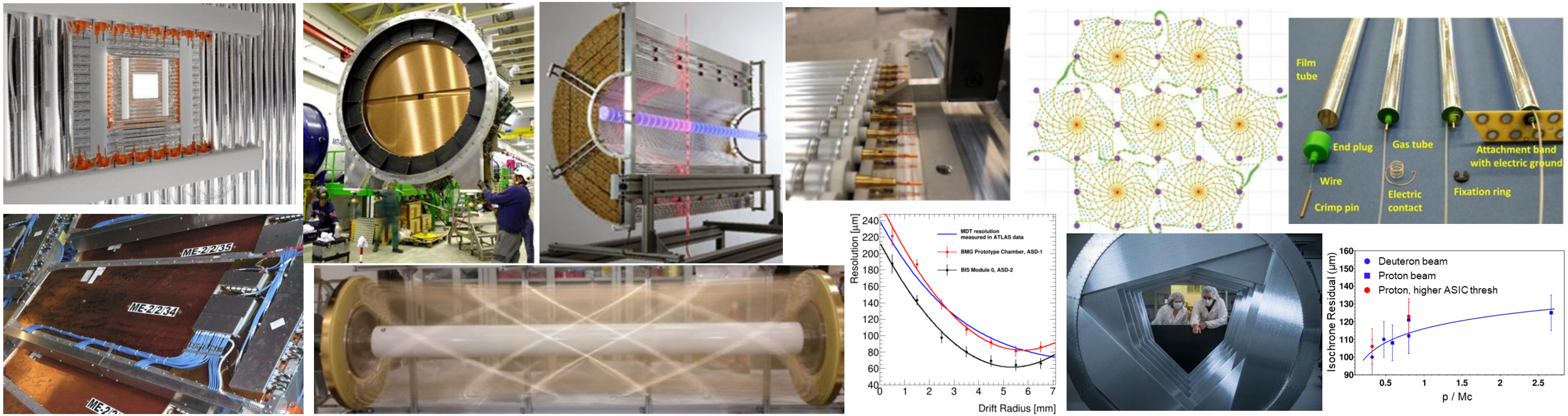


Straw Tubes, TGC, CSC and Other Wire Chambers

Overview, Limitations, Perspectives

Peter Wintz (IKP, FZ Jülich, Germany)

JÜLICH Forschungszentrum

Outline

- Technologies
- Applications
- R&D Topics
- DRD1 Aspects

Straw Tubes

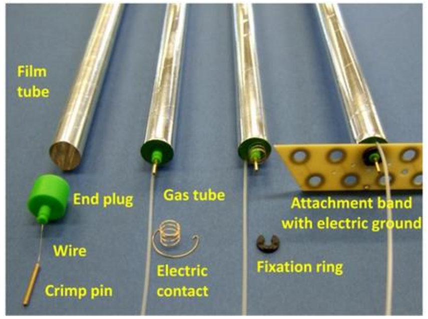
Overview

Straws = metallized tube as cathode, anode wire in center, gas filled

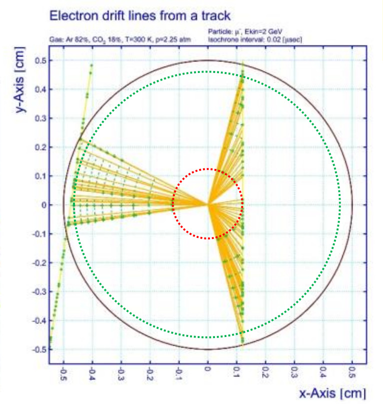
- Ionization (MIP): *⟨dE/dx⟩ ~ 2.5 keV/cm ~ 94 I.P./cm* in Argon (ntp)
- Ioniz. avalanche at thin wire, gas gain: ~ 10^4-10^5 (∅ ~ 20-30µm, HV ~ 2kV, $E \propto 1/r$)
- Electron drift time (LE-time) → isochrone radius r(t)
- Charge signal for dE/dx (sampling or time-over-thresh.)
- **Robust electrostatic configuration: shielded cell around wire**
- **Robust mechanical shape if thin-wall tube is pressurized**

Specifications:	***standard***	***perspective***
Diameter, wall	~ 10 mm / 30 µm	~ 5 mm / 15 µm
Typical X/X0	~ 0.04 %	~ 0.02 %
Spatial resolution	**100-150 µm**	same
Drifttime range	**~ 100-200 ns**	**< 80 ns**
Gas gain	**~ 5 × 10^4**	**~ 1 × 10^4**
Rate limit	**~ few 10 kHz/cm**	**~ few 100 kHz/cm**
Aging resistance:	> 1 C/cm	same

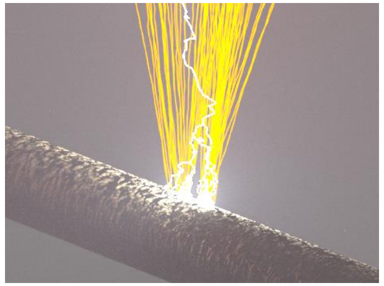
- **Staggered multi-layers** to resolve ambiguities in 2D-tracking
- **Stereo-layers** for 3D-tracking, alternative: propagation time difference, but ~ cm resol.



Straw tube components (for PANDA-STT [1])

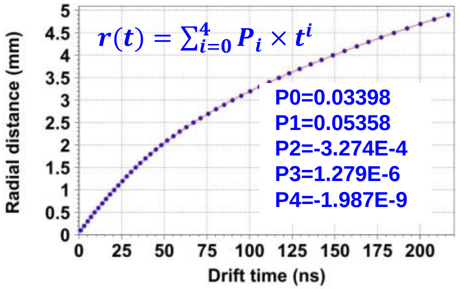


Ionisation and electron drift lines (simulation, Garfield)

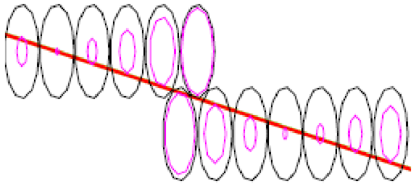

Avalanche simulation: drift electron (white), pos. ions (orange). Photo from [2].

Element	Material	X [mm]	X_0 [cm]	X/X_0
Film Tube	Mylar, 27µm	0.085	28.7	3.0×10^{-4}
Coating	Al, 2×100nm	6×10^{-4}	8.9	7.0×10^{-6}
Gas (2bar)	Ar/CO_2 (10%)	7.85	6131	1.3×10^{-4}
Wire	W/Re, 20µm	3×10^{-5}	0.35	8.6×10^{-6}
			Σ_{Straw}	4.5×10^{-4}

Material budget for PANDA straw tube [1]



r(t) relation for Ar/CO2(20%), p=2 bar (simulation)


Track fit tangent to isochrones (red circles) in staggered straw layers determines track point

Straw Tubes

Developments

Thinner film walls for low material budget X/X0

- Film 30µm → 15µm (8µm); tube winding helical or longitudinal / adhesion technique
- Materials: metallized Mylar (Al, Cu/Au, Al/Au) as cathode; sense wire: Au-plated W(/Re3)

Smaller diameter for faster timing and less occupancy

- “Standard“ diameter 10mm, reduce to 5mm (< 80ns drift time), trailing edge timing
- Items: wire centering, tube length, endplug design, electronic readout

Minimised frame by self-supporting straw layers

- Usual: tube stretching from straw ends by frame *(e.g. NA62)*
- Novel: gas over-pressure for (homog.) tube stretching & wire tension (50 gw)
- Reduce sag by close-packed, pressurized and glued straws module

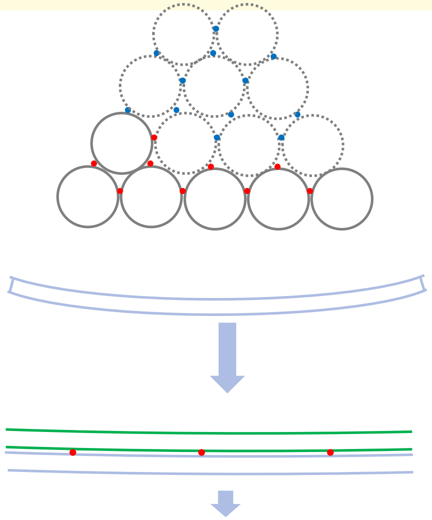
Charge readout for PID

- dE/dx $\propto 1/\beta^2$ for particle momenta <1 GeV/c (application: π,K,p separation)

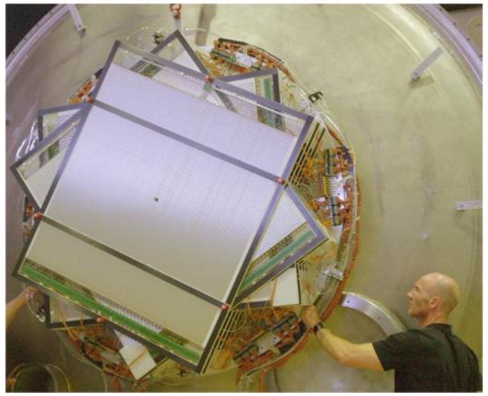
“Unique“ application: thin-wall straw chambers in vacuum

- *E.g. experiments: NA62 [3], COSY-TOF [5], Mu2e, CoMET, SHiP, HIKE*
- Stable at over-pressure (=1 bar abs.), under-pressure critical
- “Flag“-SHiP experiment: large straw area detector in vacuum (50m^2, 5m long tubes)

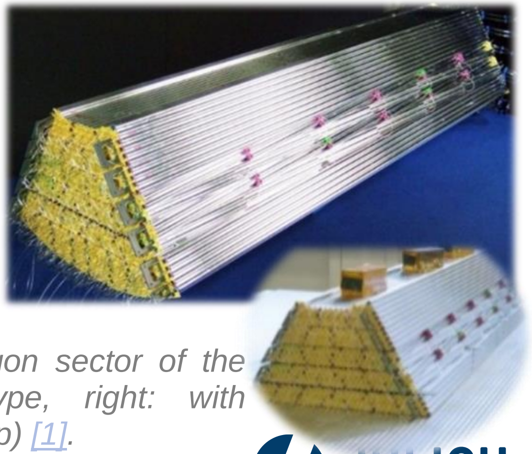
NA62 Straw station [3].



Close-packed dot-glued straw layers sustain wire tension and reduce bending.



COSY-TOF Straw tracker [4]



Self-supporting hexagon sector of the PANDA-STT (prototype, right: with 3×3kg Pb bricks on top) [1].

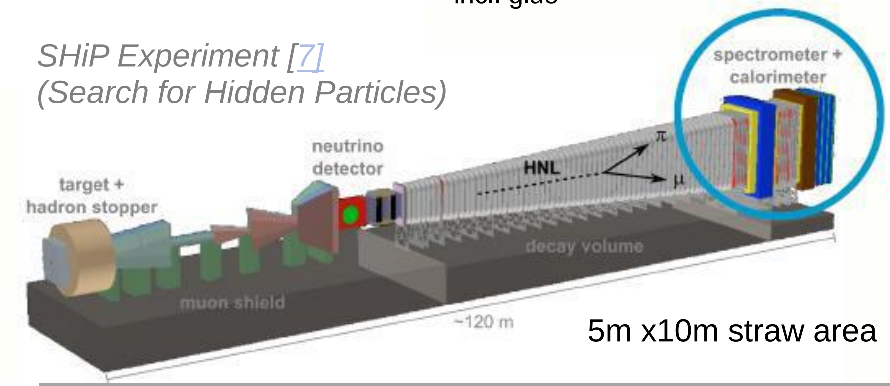
Straw Tubes

Experiments and Developments

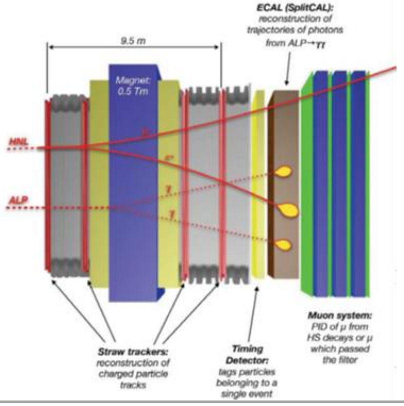
	TOF-STT [5] (COSY)	PANDA [8] STT/FT (FAIR)	NA62 [3] (CERN-SPS)	COMET [6] (J-PARC)	COMET+	SHiP [7] (CERN-SPS)	HIKE [18] (CERN-SPS)	Mu2e-I,II [17] (Fermilab)	SAND (DUNE)
Mylar film wall	32 µm*	27 µm*	36 µm	20 µm	12 µm	36 µm	19 (12) µm	15 µm	15 µm
Winding	helical, 2 strips glued		longitudinal ultrasonic welding					helical, 2 strips	Ultrasonic weld
Manufacturer	Commercial (LAMINA, UK)		JINR, Dubna					LAMINA, UK	
Tube diameter	10.0 mm	10.0 mm	9.8 mm	9.8 mm	5.0 mm	20 mm	4.8 mm	5.0 mm	5.0 mm
Cathode	Al (30 nm)	Al (100 nm)	Cu/Au (50/20nm)	Al (70nm)	Al (70nm)	Cu/Au (50/20nm)	Al/Au	Al/Au (50/20nm)	
Sense wire (diam.)	20 µm W/Re (-Au)		30µm W (-Au)	25 µm W/Re (-Au)			20µm W (-Au)	25µm W (-Au)	
Tube length	1050 mm	1400 mm	2100 mm	600 -1100 mm		5000 mm	2100 mm	1300 mm	3100 mm
Straw no.	2704	4224 / 12224	7168			16000		23040	231834
In vacuum	yes	no	yes	yes	yes	yes	yes	yes	no
Status	Completed	Prod. ongoing	Exp. ongoing	Prod. completd	Planned	Planned	Planned	2025+	Planned
Specific R&D	Vacuum tracker	Low X/X0 solenoid tracker	Vacuum tracker	Thinnest wall vacuum tracker		Long straws in vacuum, sag ctrl	Vacuum, low X/X_0	Vacuum, low X/X_0	Neutrino flux monitor

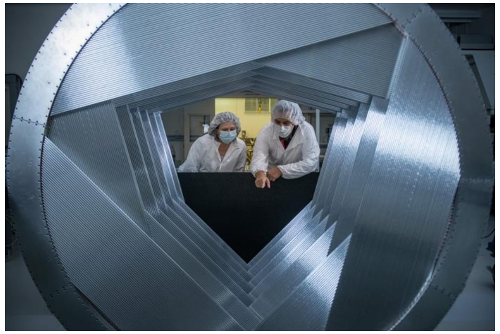
*incl. glue

SHiP Experiment [7]
(Search for Hidden Particles)

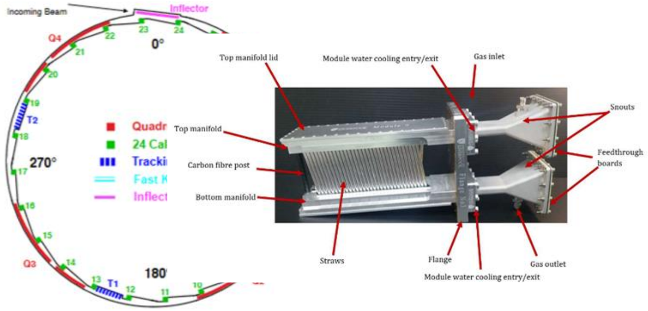


5m x10m straw area





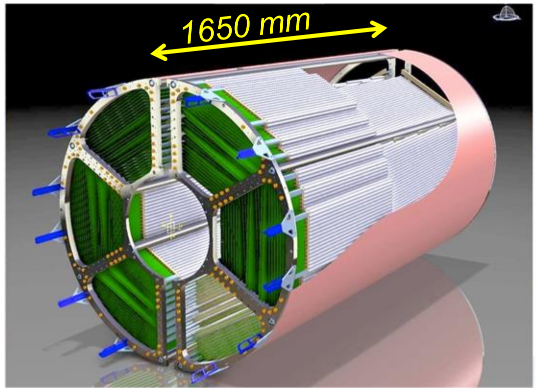
Mu2e: ~100 MeV/c electron tracker



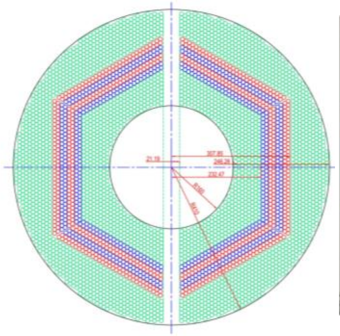
Muon g-2, beam monitor tracker [19]

Straw Tubes in PANDA Experiment

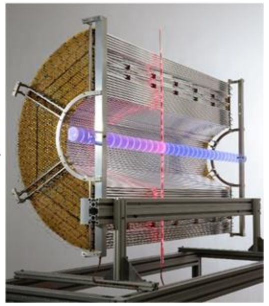
Anti-Proton Beam (1.5-15 GeV/c) on p(A) Target [8]



PANDA-STT (3D-view)



Straw layout, stereo layers in red/blue (cross-view).



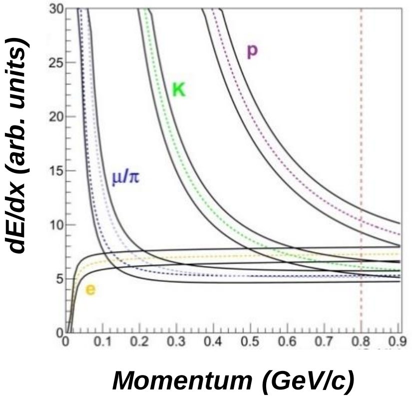
STT-protoype

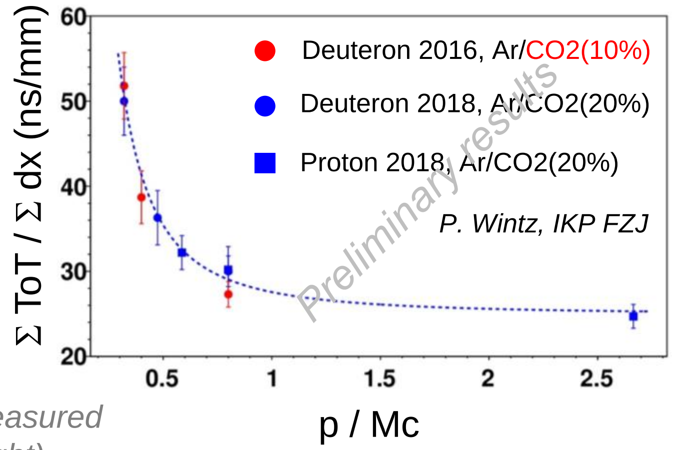
STT central tracker [1] in solenoid B-field

- **4224 straws**, ∅=10mm, 27µm Al-mylar film
- Ar/CO2 (2 bar abs.)
- **6 sectors** with **19 axial + 8 stereo-layers** (±3°)
- R = 150 - 420 mm, straw length = 1400 mm
- **Drift time and charge readout for PID** (PASTTREC-ASIC)
- **σ(r) < 150µm**, **σ(z) ~ 2-3mm**, **π/K/p-sep. < 1GeV/c**
- **X/X_0 ~ 1.3%, Δp/p ~ 1-2 %** (**2T B-field**, with MVD)
- Rates: < 10 kHz/cm², < 1 MHz/straw

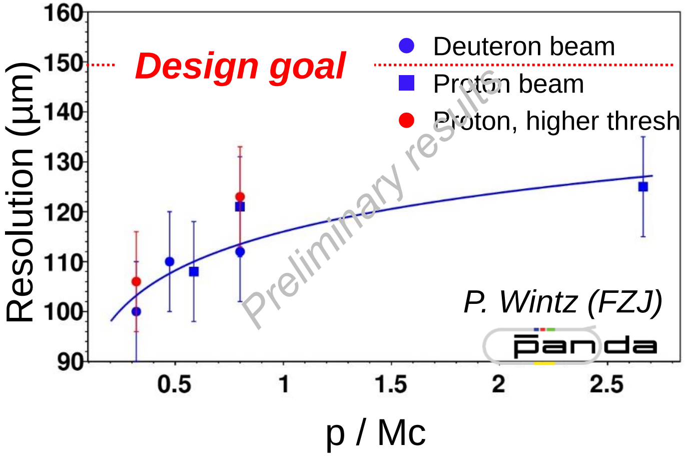
FT planar forward tracker [9]

- **12224 straws,** ∅=10mm, 27µm Al-Mylar
- Ar/CO2 (2 bar abs.)
- **FT1-6**, 4x double-layers per station (x,u,v,x)
- 640-1480mm straw length
- **X/X_0 ~ 2%**
- **Rates: < 25 kHz/cm²**
- **Δp/p ~ 1.5% (dipole magnetic field)**



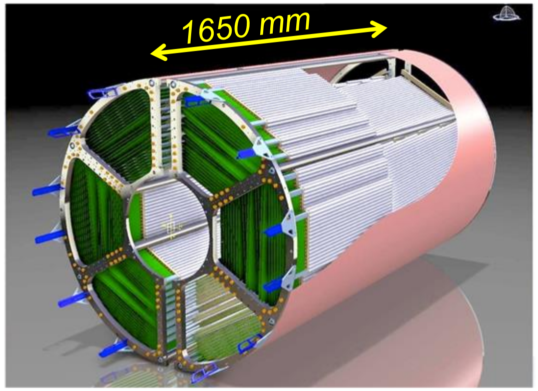


PID by dE/dx simulation (left) and measured separation by time-over-threshold (right).

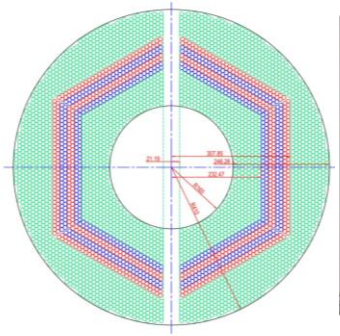


Straw Tubes in PANDA Experiment

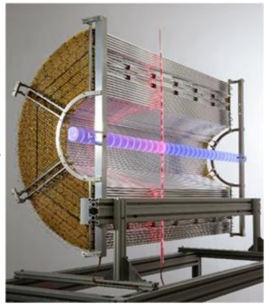
Anti-proton beam (1.5-15 GeV/c) on p(A) target [8]



PANDA-STT (3D-view)



Straw layout, stereo layers in red/blue (cross-view).



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- 640-1480mm straw length
- **X/X_0 ~ 2%**
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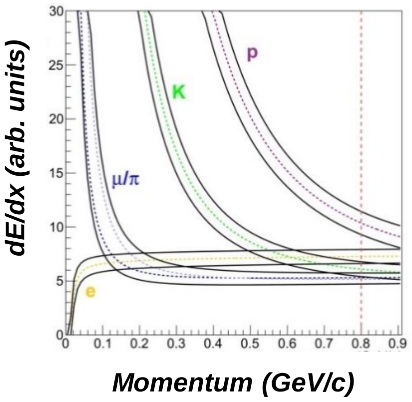
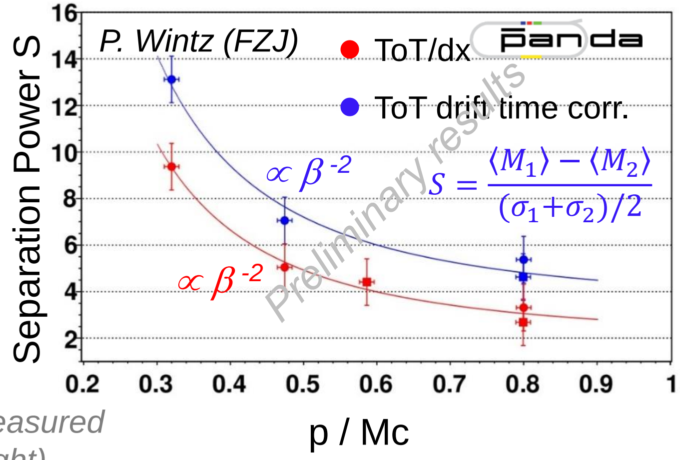
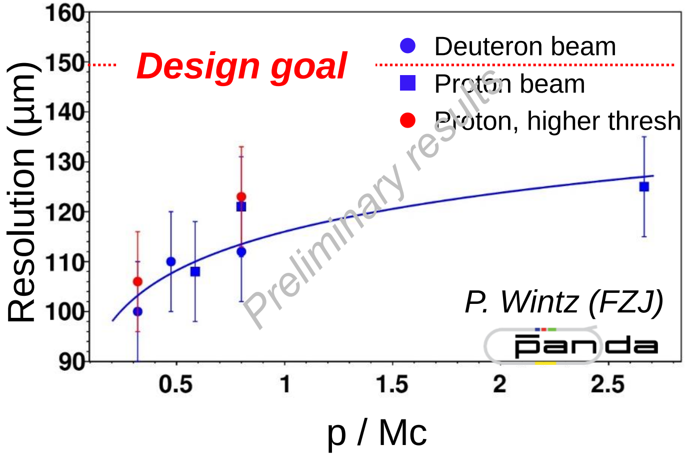






PID by dE/dx simulation (left) and measured separation by time-over-threshold (right).

Straw Tubes

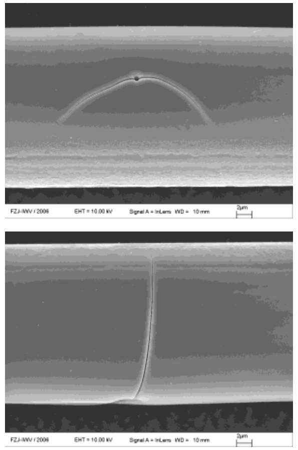
Charge Load and Ageing

- **Ageing effect: gas gain drop** (local or spreaded) or self-sustaining currents caused by **deposits on wire or cathode**

- **Ar/CO2 considered as “aging-free”** gas mixture (no polymerization)
  - But CO2 with limited quenching; CO2 decomposition may occur
  - Avoid limited streamer mode (e.g. A >5x10^{4}) causing accelerated ageing

- **Avoid hydro-carbon** (quencher), poss. polymerization (whiskers)
- **Avoid gas contamination** on ppm level (e.g. SiO2)
- **Experience** and curing recipes exist (e.g. O2 admixture)

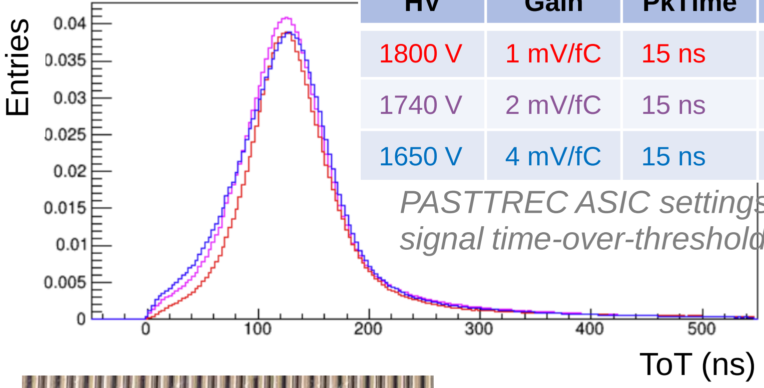
- **Au-plated W/(Re3) wire quality**
  - **Au-plated wire** considered inert, but plating porosity occurs (figure)
  - Wire oxidation through **imperfections** → wire swelling → gain drop



SEM picture of Au-plated wire with defects (no radiation exposure)

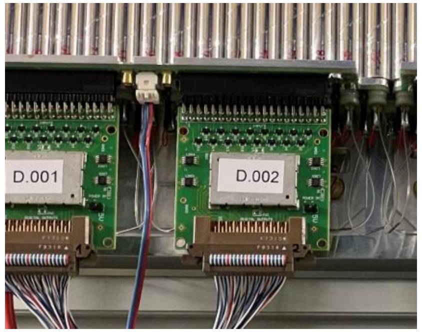
- **Gas gain is main parameter** and multiplier for possible aging
- **Low gas gain preferable**, requires low NL, low threshold (electr. readout)
  - e.g. PANDA-STT: factor 5 reduction: $5\times10^{4} \rightarrow 1\text{-}2\times10^{4}$ by higher electr. gain 1→ 4mV/fC

- **Charge loads > 1 C/cm in Ar/CO2** without gas gain drop tested

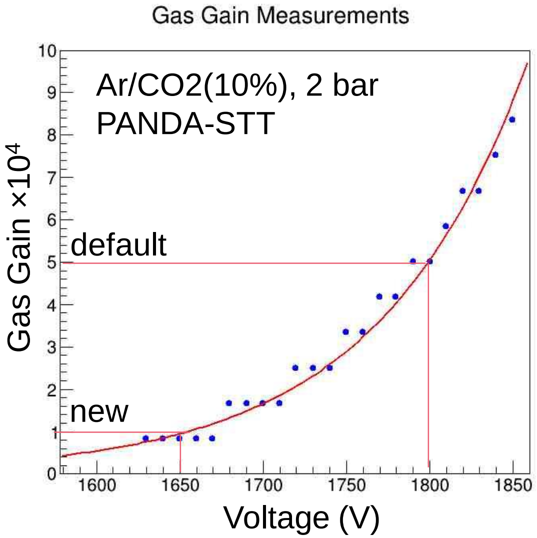


HV	Gain	PkTime	<ToT>	Set
1800 V	1 mV/fC	15 ns	126 ns	rc1
1740 V	2 mV/fC	15 ns	126 ns	rc3
1650 V	4 mV/fC	15 ns	129 ns	rc5

PASTTREC ASIC settings and measured signal time-over-threshold.



Front-end readout board with PASTTREC ASIC (AGH Krakow [20]) at PANDA-FT.



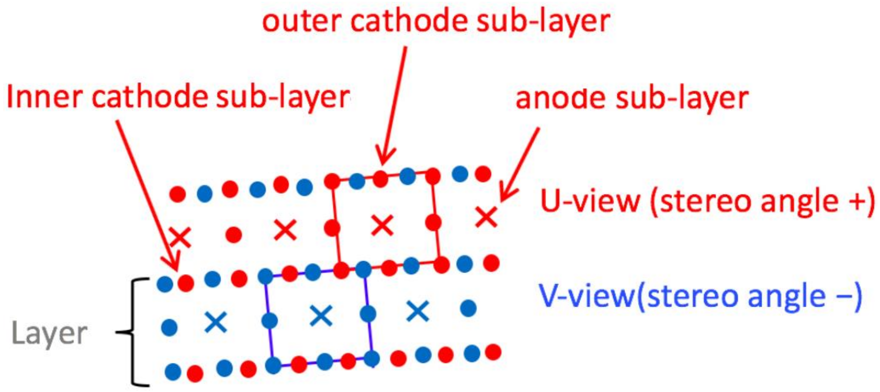
Drift Chambers

Overview

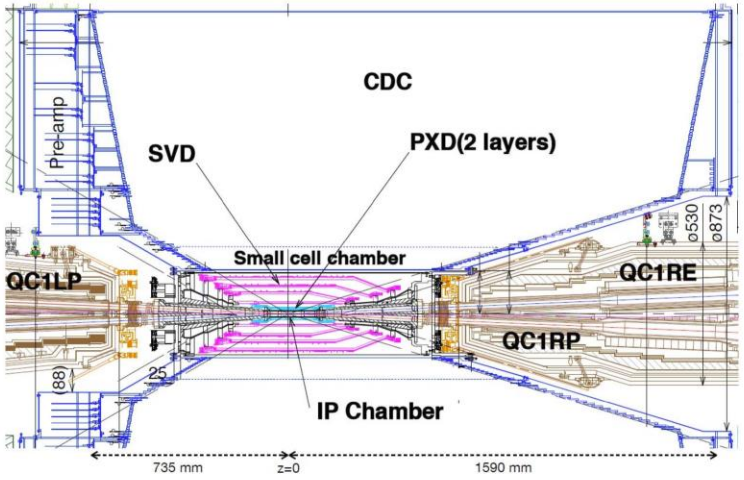
Feature: highest transv. momentum resolution tracking in solenoid B-field

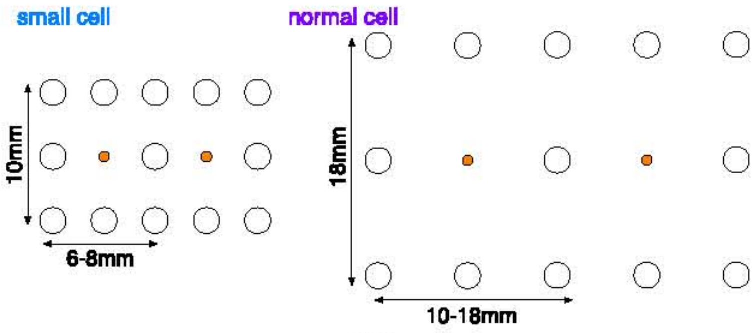
- Large gas volume and long lever arm (L ~ 1m)
- High transparency (X/X0 ~ 10^{-3}) for low MS, favours He-based gas
- **Helium requires high gas gain ~5×10^{5}** *(8 I.P./cm, ntp)*

- Small drift cells for short drift times (few 100ns), cathode wires surround anode
- Stereo drift cells for 3D-tracking, full stereo layout possible (MEG-II DCH)
- dE/dx or ion cluster counting (dN/dx) for PID

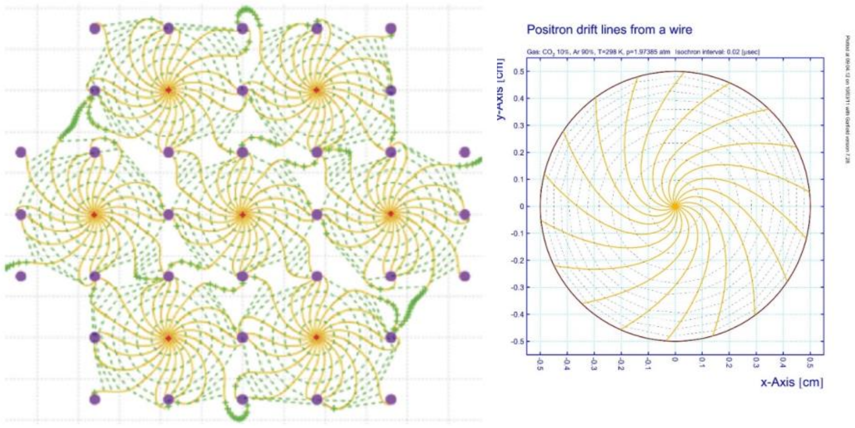


Full stereo drift cell layout with high field homogeneity in MEG-II drift chamber [11].





Belle drift chamber CDC (left). Smaller cells in inner region [10].



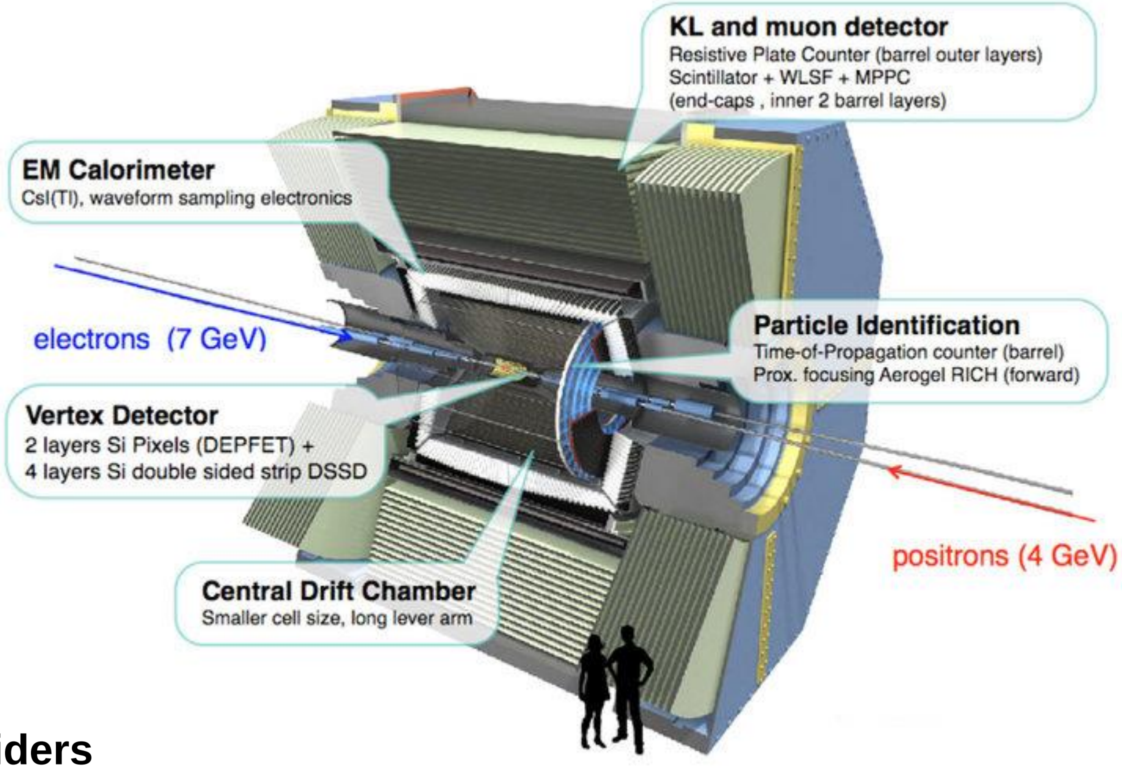
Electron drift lines for drift cells (left) and straw tube (right) in solenoid B-field (Garfield simulation).

Drift Chambers

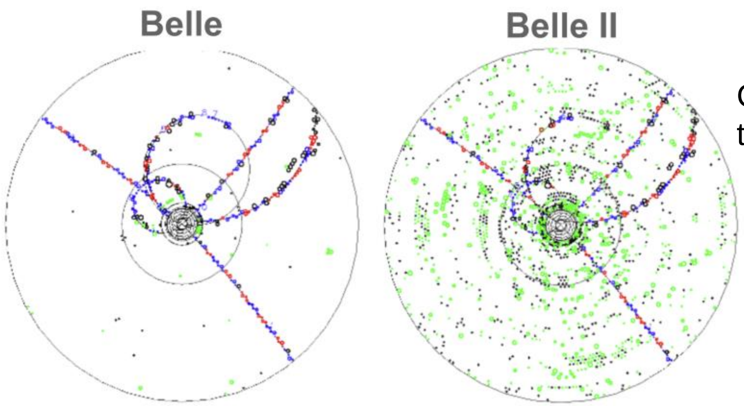
Example: Belle II CDC at SuperKEKB

Drift chamber at “extreme“ luminosity L= 8×10^{35} cm^{-2} s^{-1} [11]

- e-e+ collider, $\sqrt{s} \approx 10.6$ GeV
- CDC in 1.5 T solenoid B-field
  - **R = 160 - 1130 mm, 2300 mm length**
  - **14k anode wires** (30µm W(Au), 129µm Al cathode wires
  - **56 axial and stereo layers**
  - Drift gas He(50%) + C2H6
  - **σ(pt) / pt ~ 0.1 %**
  - High occupancy: 11 tracks with ~ 100 hits, ~ 10^4 background hits
  - Particle momentum up to ~ 7 GeV/c, π/K separation (~ 90%)

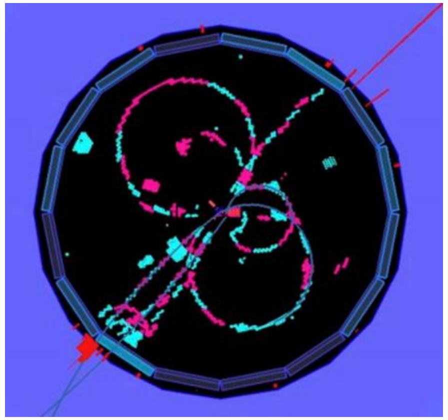


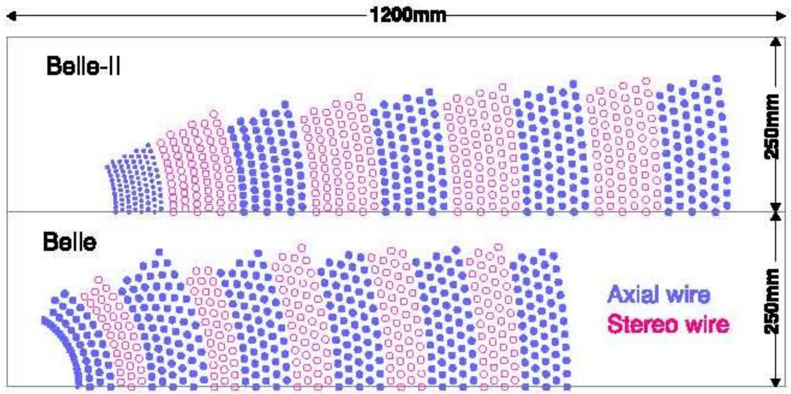
TPC concept study for “Belle“-like spectrometer at future colliders



Challenge: low momentum tracks $\rightarrow$ MS, curling tracks

First e+e- event in Belle II [11].





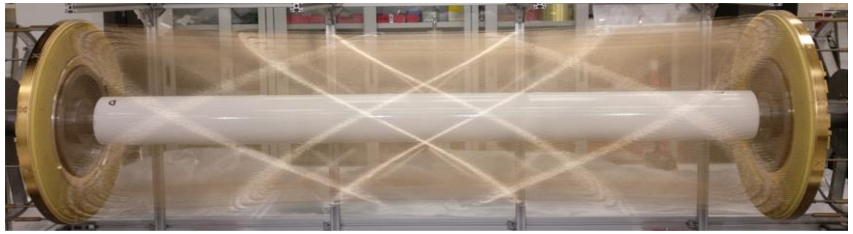
Drift Chamber

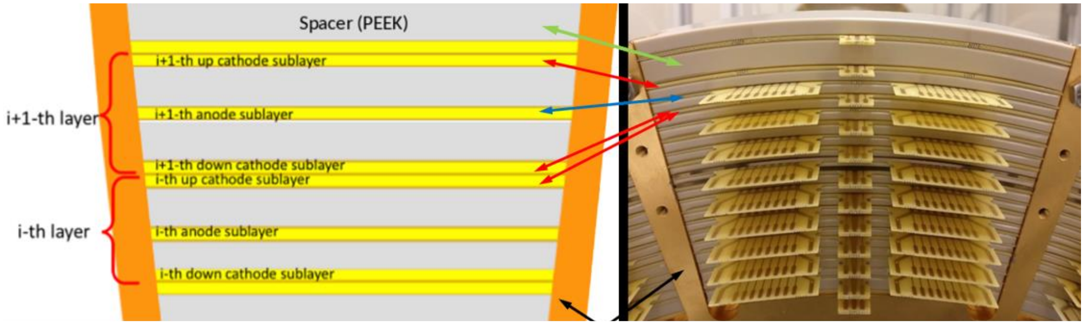
IDEA at FCC-ee

IDEA: full stereo, high resolution, ultra-light drift chamber [12], [13]

- **4000 mm length**, **350-2000 mm radius in ~ 2T solenoid B-field**
- **14 SL × 8 layers**, 24 φ-sectors
- **56k sense wires**, 20 µm diameter W(-Au)
- ~290k field and guard wires, 40/50 µm diameter Al(-Ag)
- He(90%) + i-C4H10
- X/X0 ~ 0.1 % (end plate incl. FEE with X/X0 ~ few %)
- Spatial resolution: σ ~ 100µm, mom. resolution: σ(pt)/pt < 0.3 %

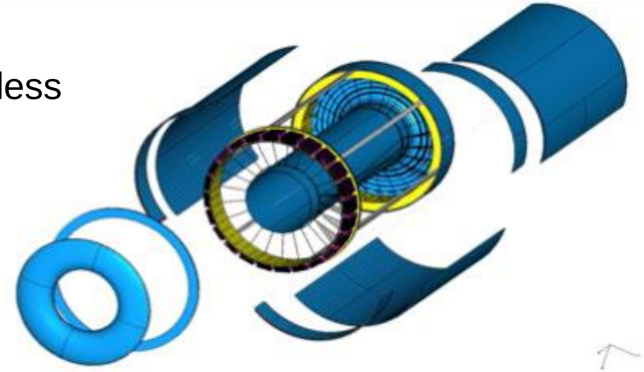
MEG-II drift chamber ($\mu \rightarrow e\gamma$ at PSI [11]).



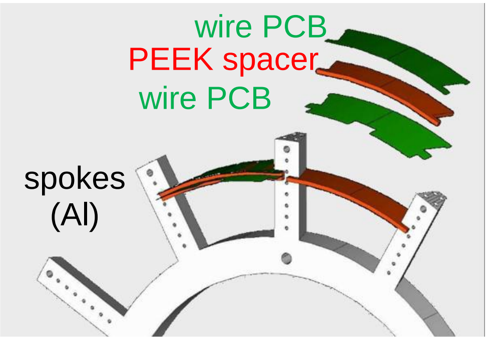


Mechanics design

- construction featuring high granularity and high transparency
- novel wiring method (MEG-II wiring robot technique), feedthrough-less
- wire support mech. structure separated from gas volume envelop



IDEA design based on MEG-II



Cathode Strip Chambers

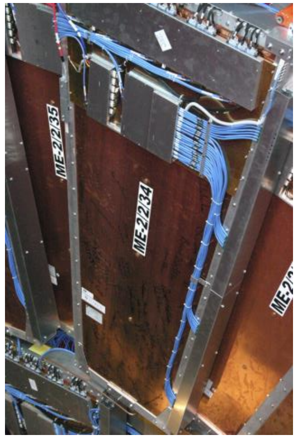
At CMS / ATLAS

CSC: grid of anode wires and cathode strips [14]

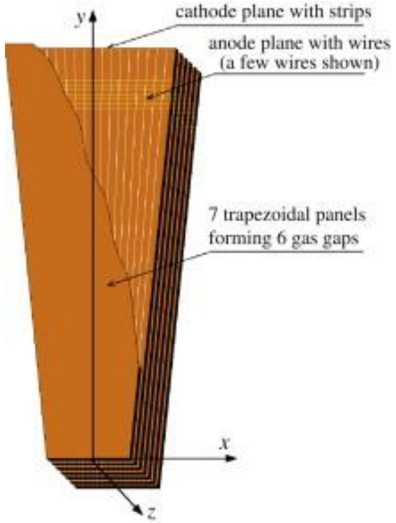
- Upgrade muon system in end caps for HL-LHC: $L=5x10^{34}\ cm^{-2}s^{-1}$
- CSC for **precise muon tracking and triggering**
- CMS: all endcap muon precision chambers are CSC
- ATLAS: CSC in low-angle region, Monitored DT (MDT) else
- HL-upgrades: readout with high speed optical links, trigger

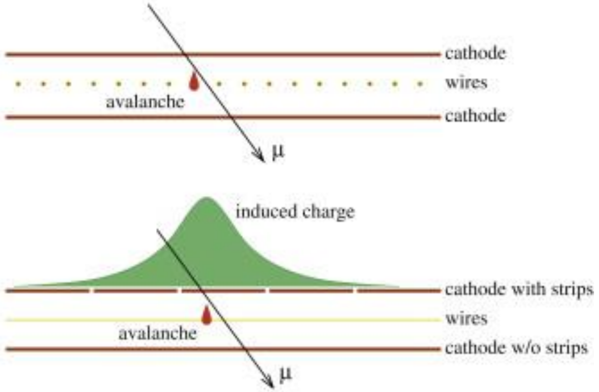
Specifications:

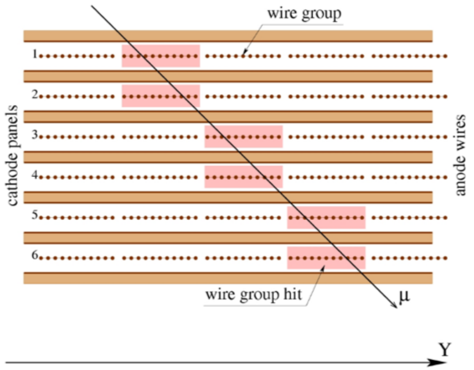
CSC size:	3.3 x 1.5 / 0.8 m^2 (trapezoidal)
Number of layers	6 layers per chamber
Anode wire:	50µm W/Au-plated
Anode-cathode gap:	**4.75 mm**
Wire spacing:	**3.12 mm**
Number wire groups:	210´816, 5 to 16 wires per group
Cathode strip width:	**8-16 mm (trapez.)**
Number cathode strips:	266´112
Gas:	Ar(40%)+CO2(50%)+CF4(10%)
Maximum drift time:	**60ns**

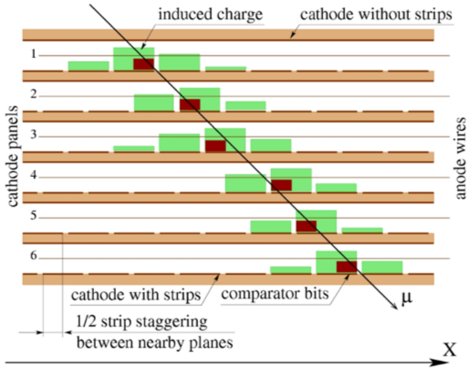


CSC with upgraded readout



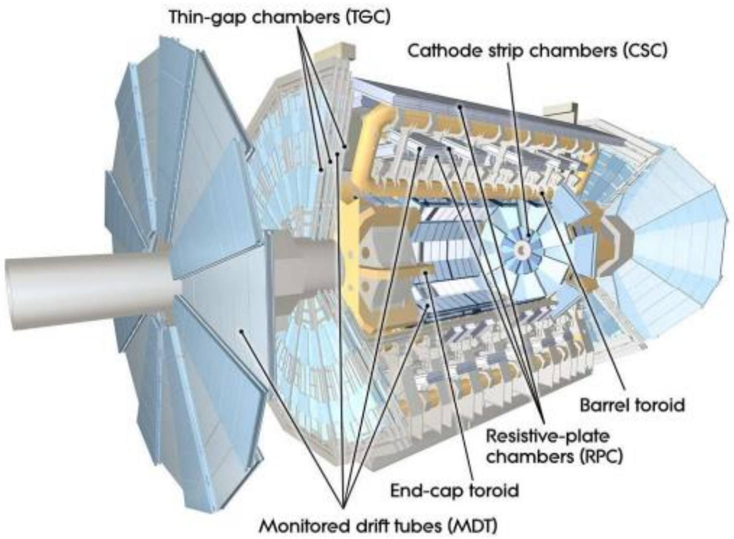






Thin Gap Chamber

ATLAS NSW Upgrade for HL-LHC



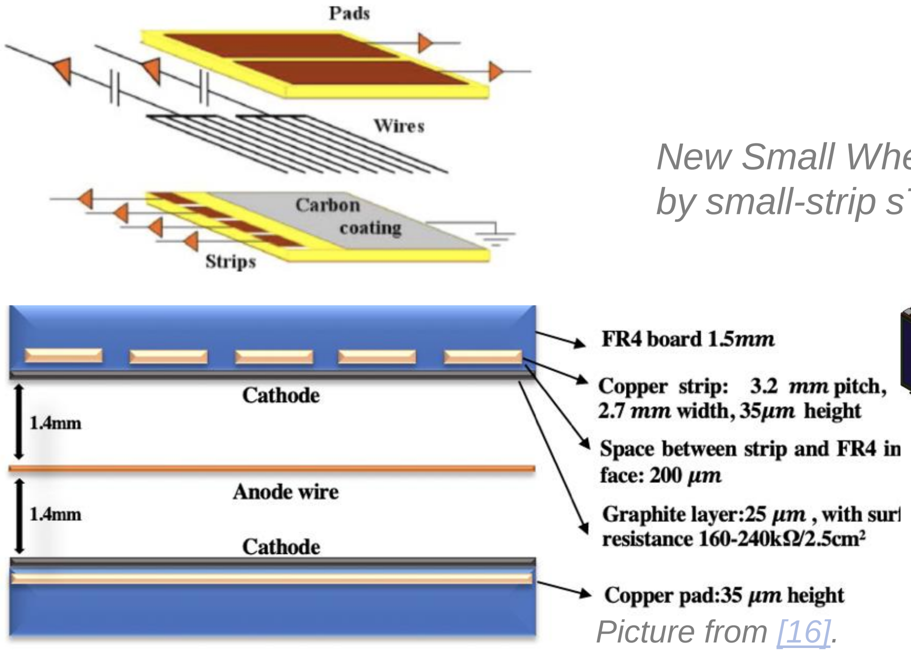
Thin Gap Chamber (TGC): smallest wire to cathode gap [15,16]

- Small-strip Thin Gap Chambers (sTGC) upgrade the ATLAS muon endcap
- New Small Wheel upgrade: fast trigger (<25 ns) and high precision tracking
  - 1mrad angular online resolution reduces fake muon trigger, 100µm spatial resolution (offline)
- Small gap issue: **gain uniformity**, **high chamber flatness required**

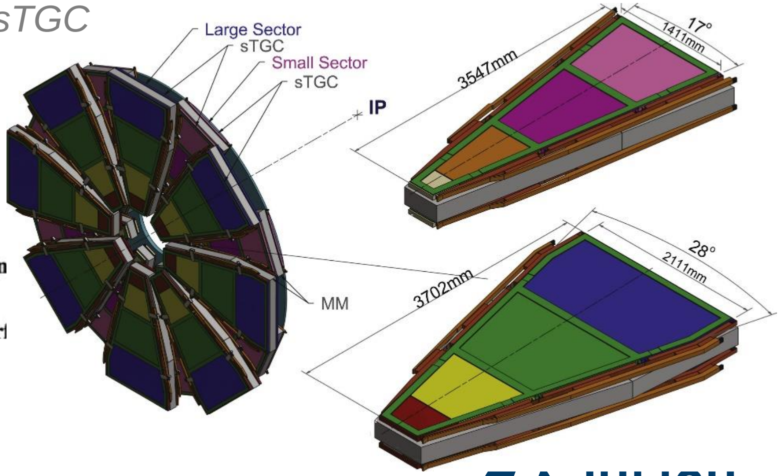
sTGC with smaller cathode strip width, readout upgrade, ..

Specifications:

sTGC trapez. size:	**3.7 x 2.1 / 0.5 m^2**
HV:	2.8 kV
Gas mixture:	CO_2(55%)+n-Pentane
Wire pitch:	**1.8 mm**
Wire to cathode gap:	**1.4 mm**
Wire, diameter:	50 µm W(-Au)



New Small Wheel upgrade by small-strip sTGC

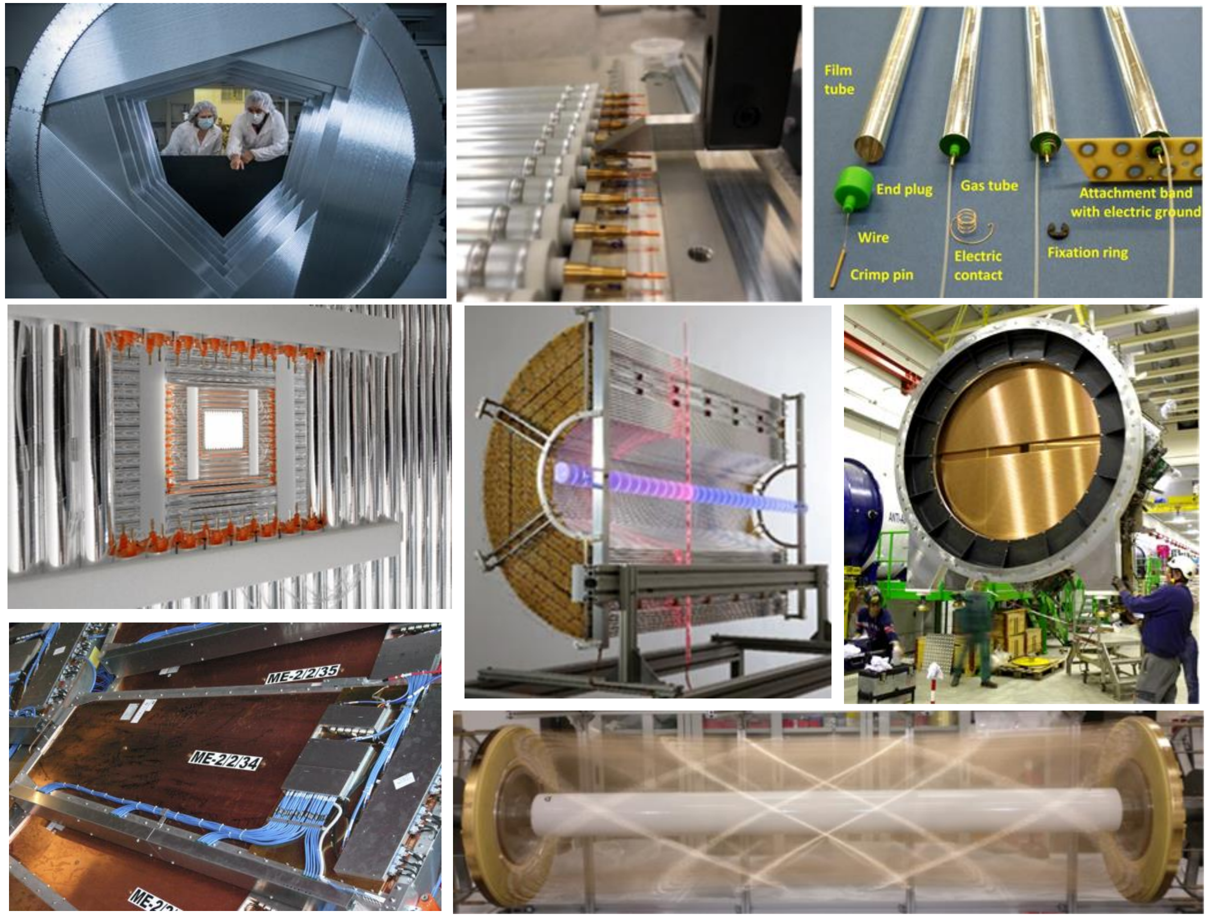


Picture from [16].

DRD1 – Wires

(Technology R&D Topics from Survey)

- **Fast timing** (< 80ns) and **less occupancy**
  - **Smaller straw diameter**: from “standard“ 10mm down to **5mm**
  - Items: wire centering, **high-resolution time readout**, trailing edge timing
  - Smaller diameter sMDT, sTGC with smaller cathode strip widths
- **Low material budget,** e.g. X/X0 ~ 0.02% per straw
  - **Thinner straw film walls**: from “standard“ 30µm down to **15µm**
  - Items: film tube winding, gluing or ultrasonic welding, cathode coating
  - **Operation in vacuum** and leakage control
- **Long straw film tubes**: up to 5m length
  - Items: Wire centering, sag control, long-term material relaxation
  - Large straw area detector designs (50m^2) and in vacuum
- **New wire materials**, new alloys, metallized carbon wire, ..
  - Items: wire corrosion, coating quality, .. thinner field wires for low X/X0
- **PID by dE/dx:** with time readout and time-over-threshold
- **4D-measurement**: 3D-space and track time (t0), trailing edge timing



DRD1 – Wires

(Transversal Technology R&D)

- **Gas system** design with high purity
- **Global Warming**: replace gas admixtures with high GW potential

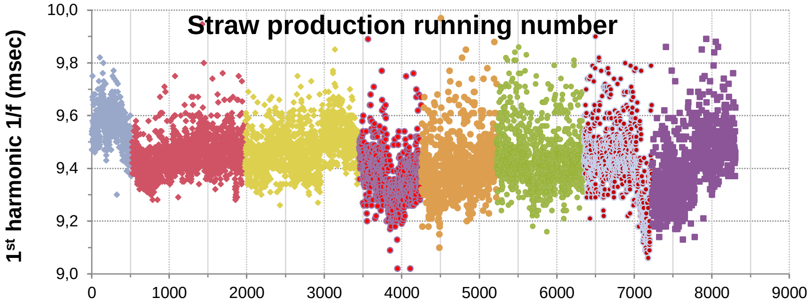
- **Ageing prevention**
  - “Aging-free“ gas mixtures, materials and components
  - Ageing curing recipes for wires and cathodes

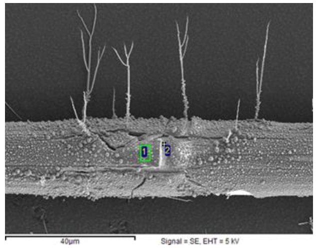
- **Detector designs** incl. front-end
  - Low X/X0 materials and frame structures, foils and coating
  - Detector alignment techniques and measures
  - Cooling scheme and system, detector control system

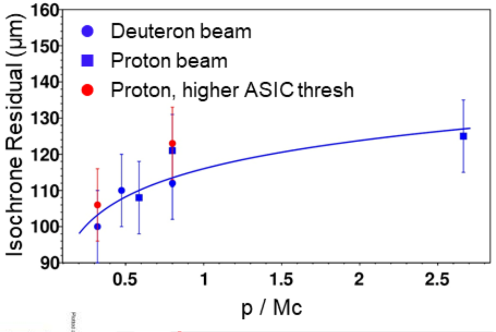
- **Assembly techniques**
  - Wiring robot, precise positioning; series production and QA

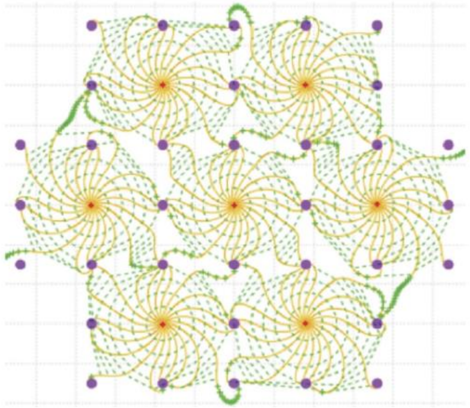
- **Electronic readout**
  - Time resolution, EMI shielding & grounding, low noise, low threshold

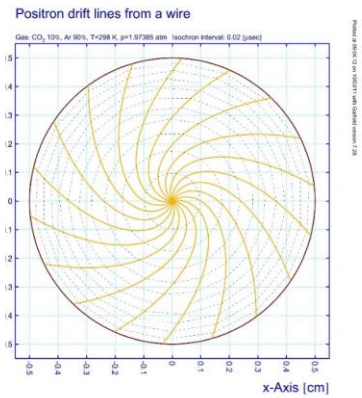
- **Detector calibration**, simulation and calibration SW and methods

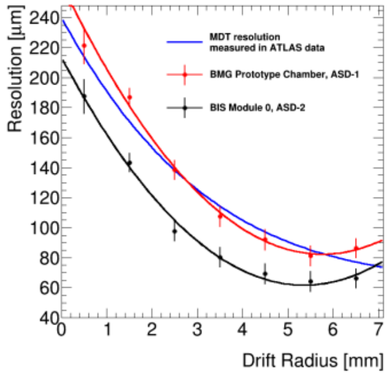












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Wide Reach of DRD1 – Wires Technology

From 100 MeV electron tracking with sub-MeV resolution to

GeV/c Hadron trackers and up to

TeV HL-LHC Muon systems

From Rare decay experiments, Neutrino physics to

Kaon and Hadron physics experiments and

High energy physics

And Dark sector experiment with 50m^2 straw area detector and

30µm thin film walls and in vacuum

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Thank you

for

your attention

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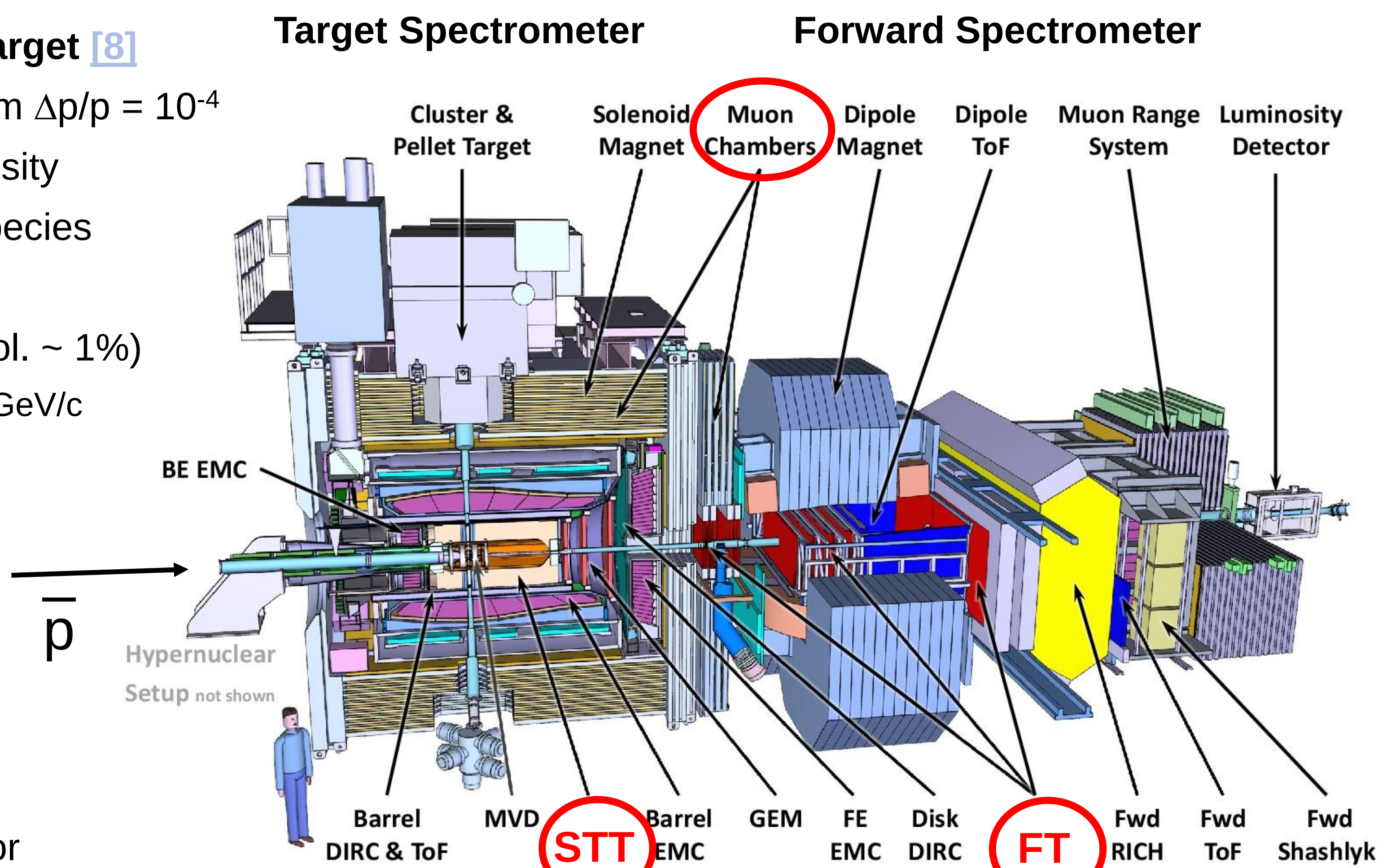
Backup

Straw Tubes

Example: PANDA-Spectrometer at HESR/FAIR

Anti-proton beam (1.5-15 GeV/c) on p(A) target [8]

- $\sqrt{s} \approx 2.2 - 5.5$ GeV, $L=2\times10^{32}$ $cm^{-2}s^{-1}$, beam $\Delta p/p = 10^{-4}$
- $2\text{x}10^7$ s^{-1} anti-p p interactions at full luminosity
- ~ 4π coverage and detecting all particle species
- 2T solenoid (TS) and 2Tm dipole (FS)
- Good charged particle tracking (mom. resol. ~ 1%)
  - broad momentum range: ~ 100 MeV/c to 8 GeV/c
  - delayed vertices (up to ~ 10 cm)
- Particle identification (γ, e, μ, π, K, p), calorimetry and muon detection



Straws tubes:

- **STT**: central tracker and PID around IP
- **FT:** six forward tracker stations
- Modules were installed in HADES@GSI for FAIR phase-0 experiment (Feb. 2021, in-beam commiss.)