FCC week, 1 July 2021

ARC: a solution for particle identification at FCC-ee

Roger Forty (CERN)

Study performed in collaboration with *Corrado Gargiulo (CERN)*

Abstract (abridged)

A novel RICH detector concept is presented, a solution for the particle identification requirements of an experiment at FCC-ee (or other future collider)

It is focused on achieving a compact and low-mass detector with excellent resolution
Preliminary engineering considerations and predicted performance are shown
along with compelling lines of R&D that would help to realize the concept

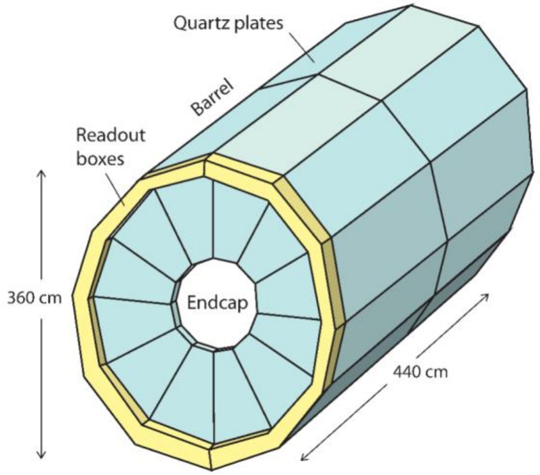
Background

- This study was inspired by preparation of ECFA **Detector R&D Roadmap**: Symposium held on Particle ID and Photon detectors (TF4, 6 May 2021)
- I reviewed Time-of-flight technologies there, including the CMS Barrel Timing Detector that will make extensive use of **SiPM** as photosensors — a technology that also featured strongly in other presentations

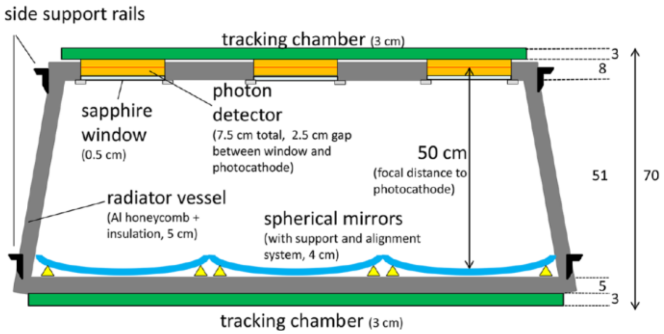
  Also discussed **TORCH** concept, adopted for the future upgrade of LHCb, + current ideas for future e^+e^- collider experiments: TORCH K-π separation up to 10 GeV over 10 m at LHCb, but at FCC-ee this would be a challenge…
- *Silvia Dalla Torre* proposed that pressurized RICH vessels should be studied as proposed in the **VHMPID** at ALICE, or for a forward RICH at the **EIC**
- *Carmelo D'Ambrosio* concluded his review of RICH technologies with the provocative title "Do RICH detectors have a bleak future?"
- Finally, *Alain Blondel* challenged those present at the end of the symposium to consider possible solutions for particle ID at **FCC-ee**

  → These elements all fed into the detector concept presented here

TORCH: conceptual layout for an FCC-ee experiment



VHMPID studied for ALICE

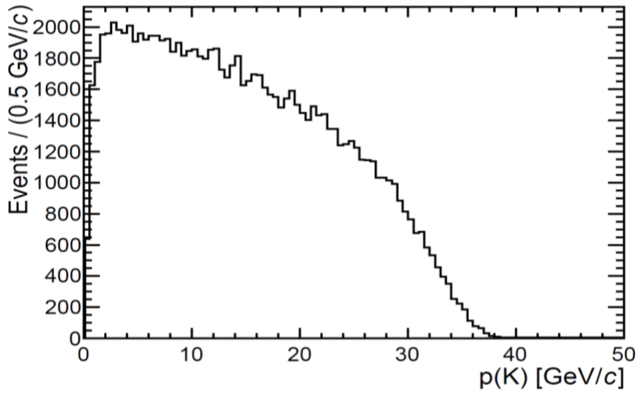


T. Acconcia et al, NIMA 767 (2014)

Motivation

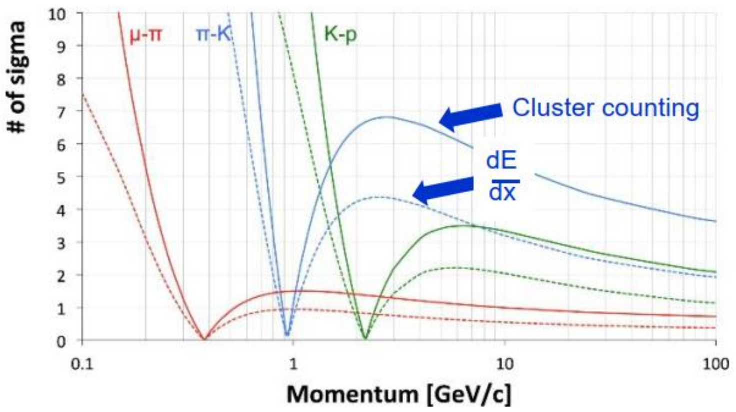
- FCC-ee will make available enormous statistics at the Z opening possibility of a world-class flavour physics programme, in addition to the Higgs and EW physics
- Flavour physics requires excellent **hadron particle identification** (separation of π, K, p) to resolve combinatorics + separate modes Will also be important for separating Higgs decays to cc, bb, etc.
- Physics motivation and possible detector technologies recently reviewed by *Guy Wilkinson* [IAS-HEP, 15/1/2021 → figures shown on this slide]
- Two-body Z decays give daughters with 46 GeV momentum Range for low multiplicity B decay products: 1–40 GeV
- Designs for e^+e^- collider experiments traditionally do not have dedicated particle ID detectors, focusing instead on leptons, jets, and particle flow, although *do* have *dE/dx* from tracker "for free"
- Time-of-flight may help fill the *dE/dx* hole at low momentum Cluster counting *dN/dx* holds promise of improved separation
[see previous talk, *Attilio Andreazza* on the IDEA tracking system]

$B_s \to D_sK$ simulation in Z events



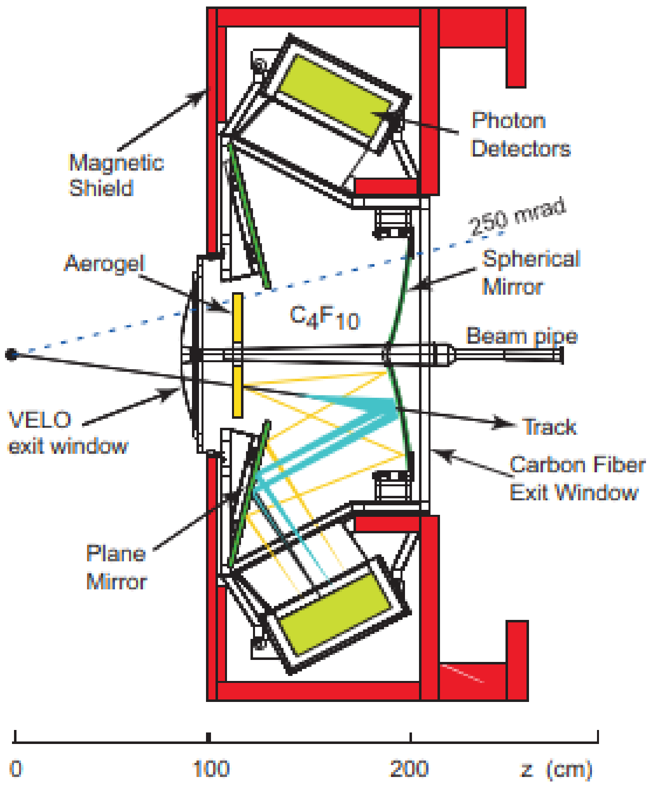
Guy: Long-standing efforts to demonstrate benefits of cluster counting – hard work!
Word of warning – not from a full simulation!
Based on analytic calc. assuming 80% efficiency

Particle Separation (dE/dx vs dN/dx)



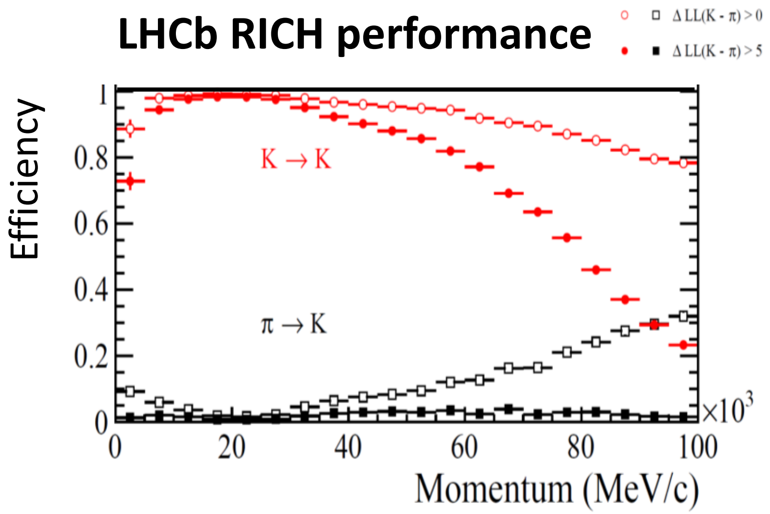
RICH detectors

- RICH detectors are gold standard for charged hadron ID at high momentum
- The challenge is to adapt such a detector to a collider (4π) layout
- Previous instances: DELPHI and SLD
  Highly challenging, delicate systems
  main issue was the space required
- Modern **photosensor** developments: compact, higher efficiency, insensitive to magnetic field → remove shielding
- Need to reduce gas radiator depth from 85 cm in LHCb → **pressurize**
- At 3.5 bar (absolute) same photon yield is achieved in 3.5x less depth (+ gain bit more with newer sensors)

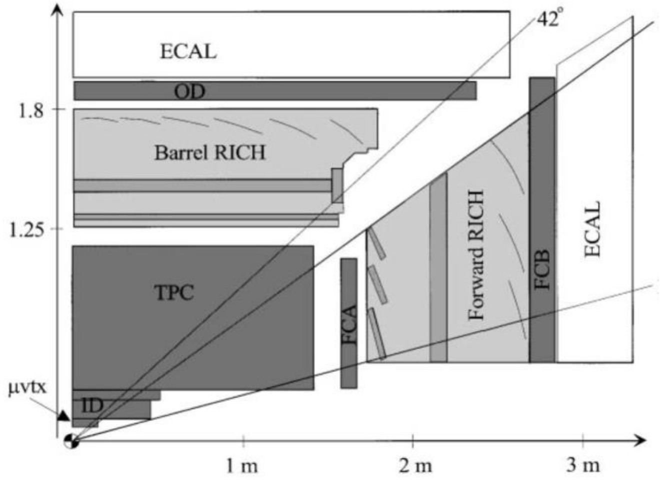


LHCb RICH1 dual radiator in its original design: aerogel + C_4F_{10} gas
Aerogel later removed, due to high track density at the LHC

LHCb RICH performance



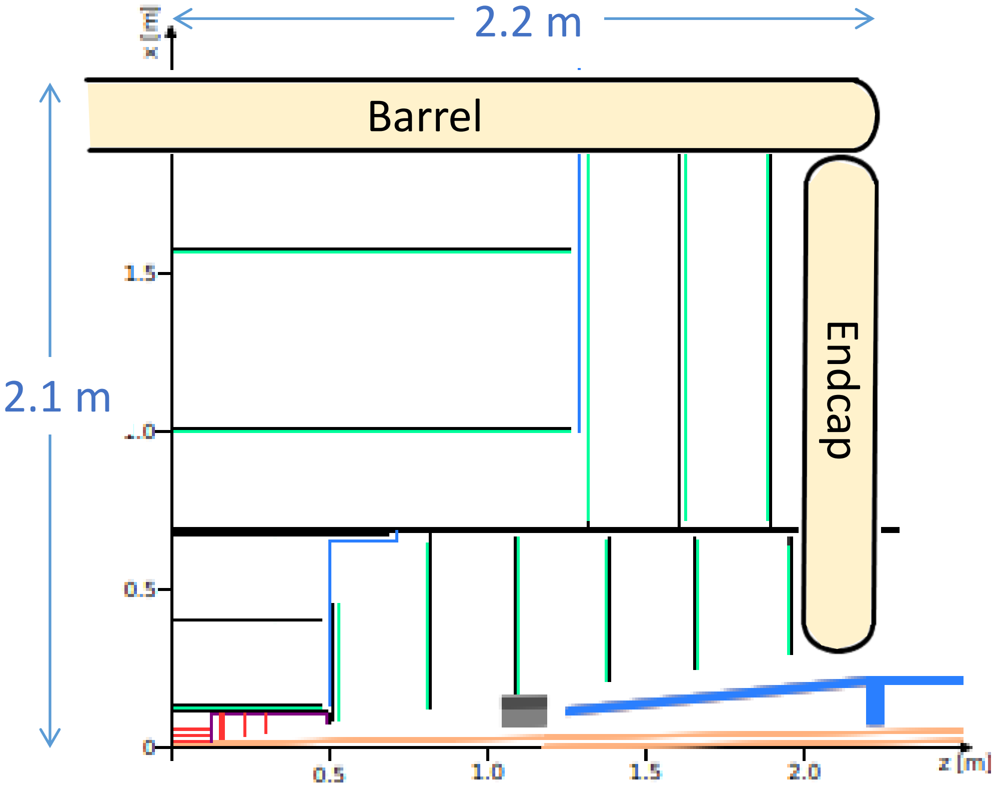
DELPHI RICH



Collider RICH layout

- To be concrete, based the design on the current **CLD** experiment concept for FCC-ee [N. Bacchetta et al., arXiv:1911.12230]
- Target a radial depth of 20 cm, and material budget of 10% X_0

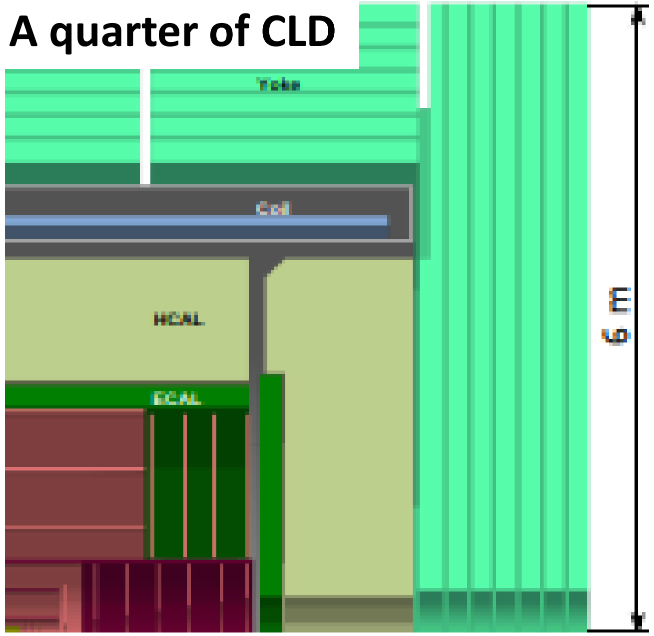
CLD tracker



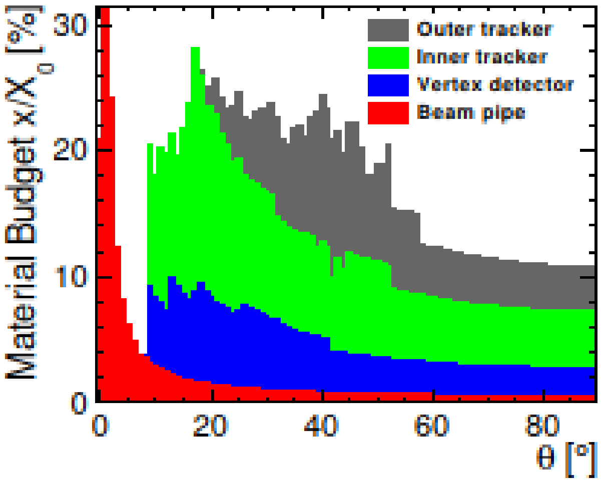
RICH pressure vessel
(Barrel + Endcaps)
= solids of revolution around the beam axis

Tracker would need to be re-optimized using 10% less radial space (already studied in Appendix B of CLD note: intended to make calorimeter smaller and save money…)

A quarter of CLD



CLD x/X_0



Pressure vessel

- Lightweight vessels for cryostats currently under intensive R&D, strong synergy with aerospace (e.g. for composite fuel tanks)

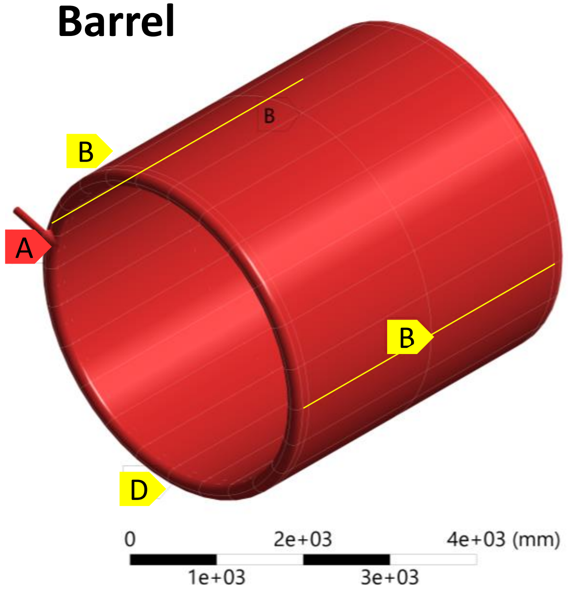
Corrado Gargiulo,
ECFA TF8, 31/3/2021

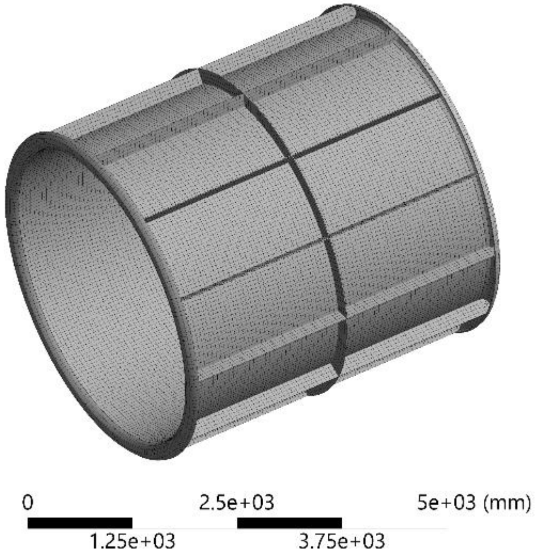
- Working group in CERN-EP future detector R&D programme led by Corrado Gargiulo who also convenes related Task Force on Integration for the ECFA R&D Roadmap

→ Corrado has developed a first design:

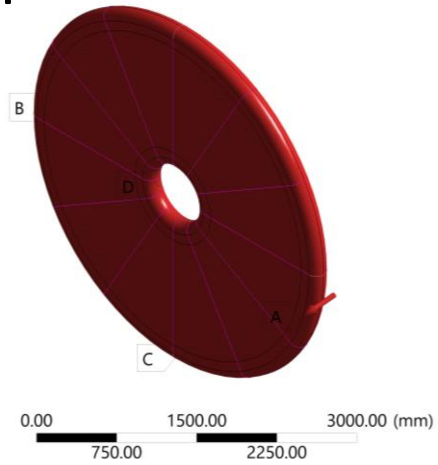
External wall hidden to show reinforcing ribs

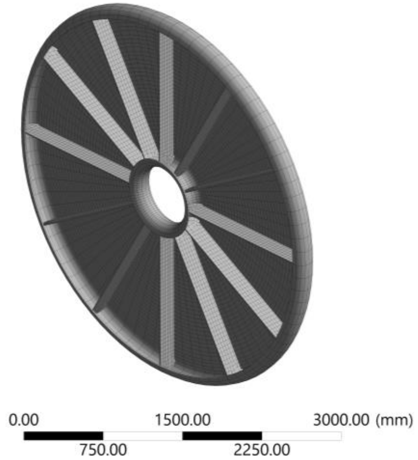
Barrel





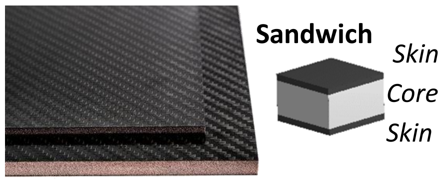
Endcap





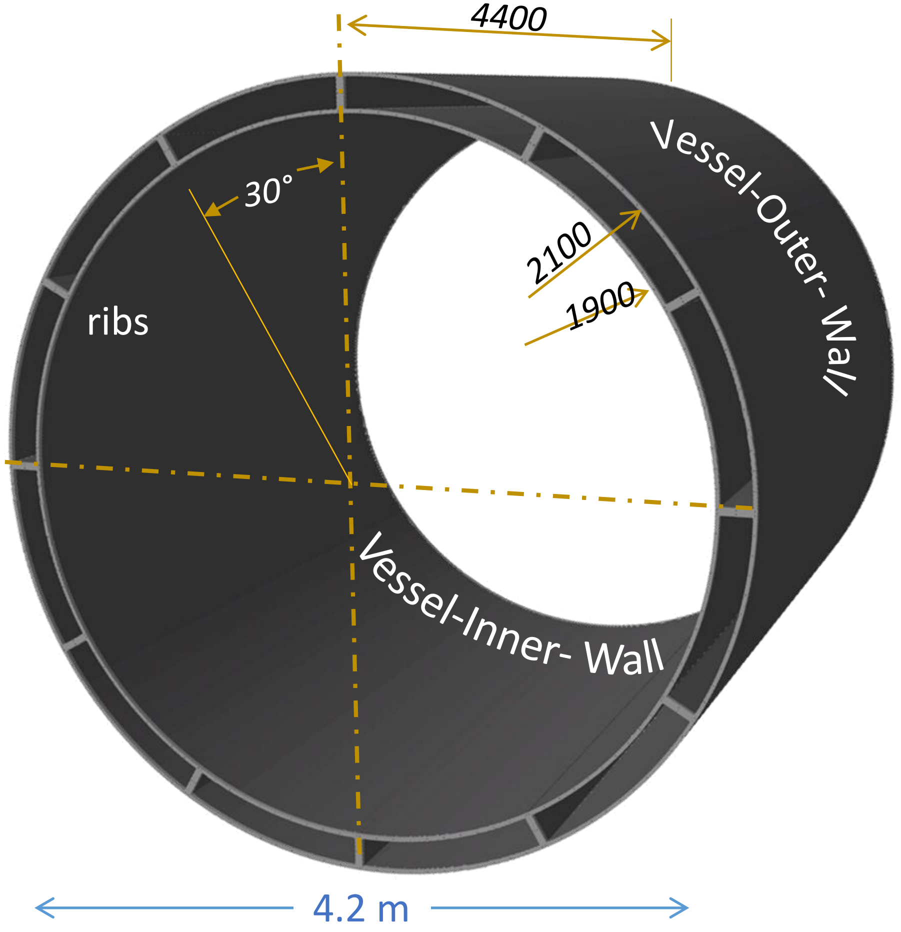
Construction

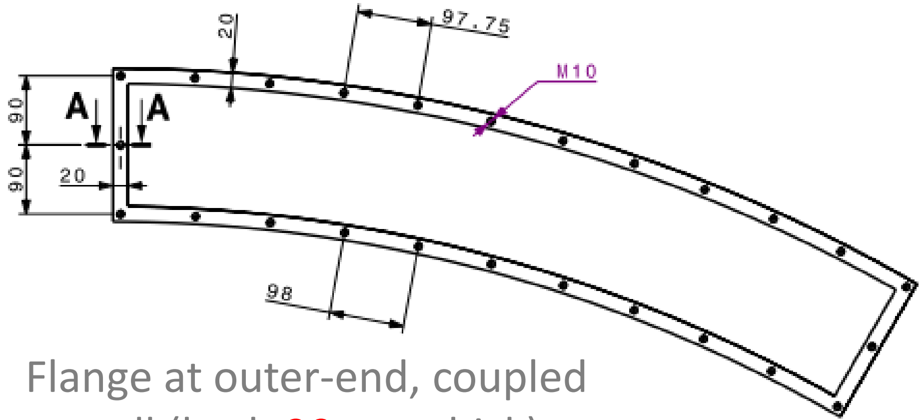
- Propose to use carbon-fibre composite sandwich with foam core: stiff + light



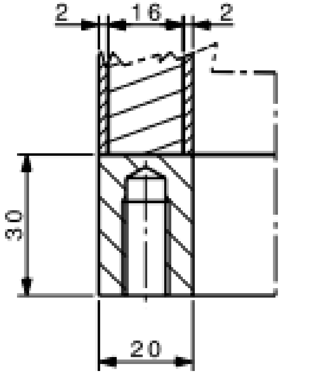
- 12-fold symmetry adopted for stiffening ribs → **sectors**
  Two options for construction, to be further analyzed:

  1. Vessel constructed as single unit, detector elements inserted from outer-end for each sector, on rails
  2. Sectors each constructed separately, then integrated to form overall vessel → smaller units to be constructed, but would expect slightly higher material budget for the walls



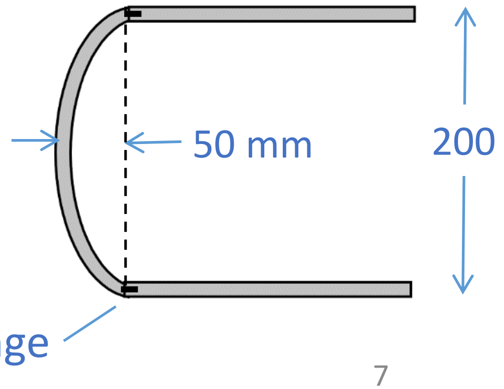


Flange at outer-end, coupled to wall (both 20 mm thick)



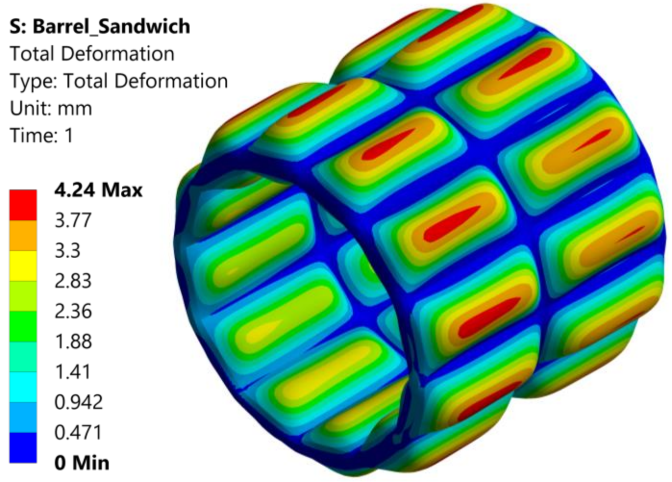
A-A

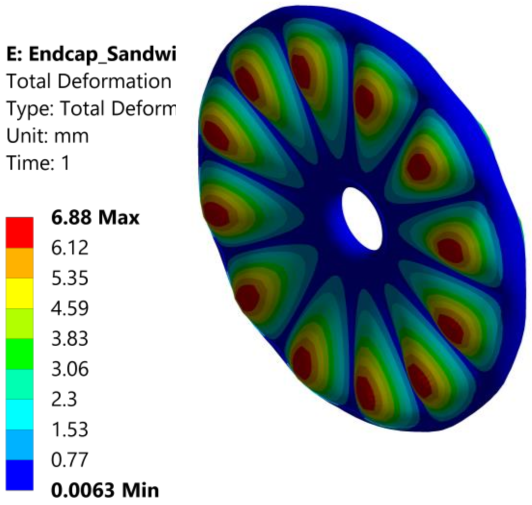
Side-view at end: removable semi-elliptical caps

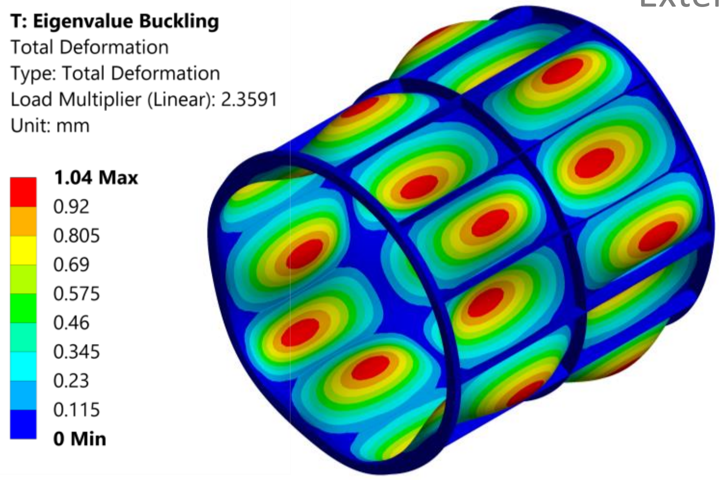


Finite-element analysis

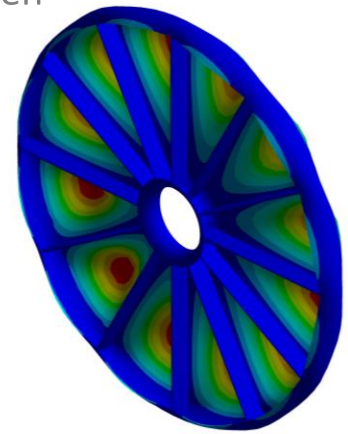
- Performed by Corrado using ANSYS, at 4 bar pressure, i.e. less than bicycle tyre but large volume:
  ~ 8.8 m^3 (Barrel), 1.7 m^3 (each Endcap)
- Maximum deflection of walls under pressure: 4 mm (Barrel), 7 mm (Endcap)
  Safety factor ≈ 2*, may need further checks to ensure compliance with pressure vessel safety regulations
- Achieved with 20 mm-thick walls, with remarkably low material budget: 2.7% X_0 (per wall); room for further optimization
  e.g. more aggressive material option available (UHM + honeycomb: 1.8% X_0)
- R&D needed to ensure leak tightness of CF walls (linerless), out-of-autoclave curing to avoid need of large autoclave, etc.







External wall hidden

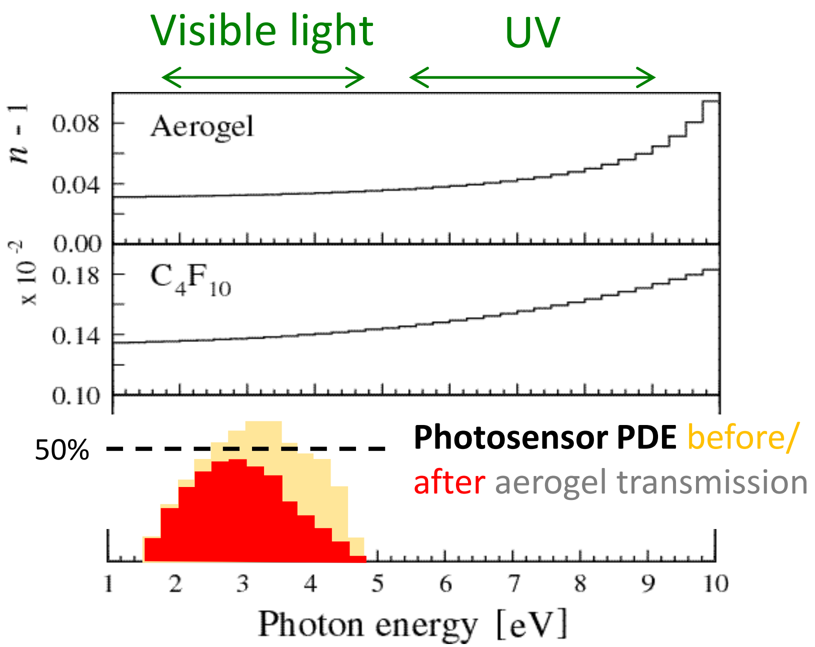


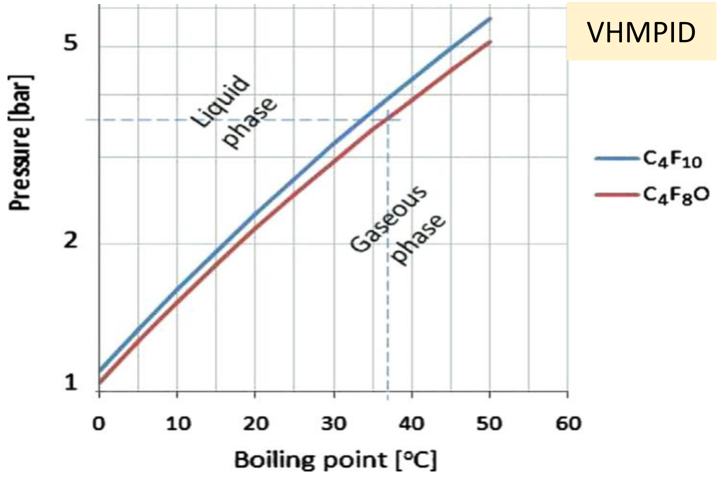
* Taking into account only pressure load: complete set of loads + boundary conditions must be considered for detailed analysis

Gaseous radiator

- **C_4F_{10}** is baseline assumption: well-known, used in LHCb RICH1
- Refractive index increases with pressure ($n - 1 \propto$ density)
  n = 1.0014 at room temp, n = 1.0049 at 3.5 bar → $\theta_C \approx$ 100 mrad
  Chromatic dispersion also increases, but still excellent
- This is why fluorocarbons used, despite being greenhouse gases (GWP ~ 8000); chromatic dispersion is even lower in the visible
- At 3.5 bar pressure, boiling point of C_4F_{10} increases to 33 °C
  → would need to maintain gas volume at ~40 °C
- **C_4F_8O** has similar properties, has been tested as a RICH radiator
  [M. Artuso et al, arXiv:0505110 (BTeV); T. Acconcia et al, NIMA 767 (2014) 50 (VHMPID)]
  and is more readily available, but slightly higher boiling point
- **C_3F_8** has been suggested for use in a pressurized RICH at EIC
  It is used for medical applications (eye surgery) and has lower boiling point, would allow detector at to be **room temperature**

  Would need slightly higher pressure (and is still a fluorocarbon)





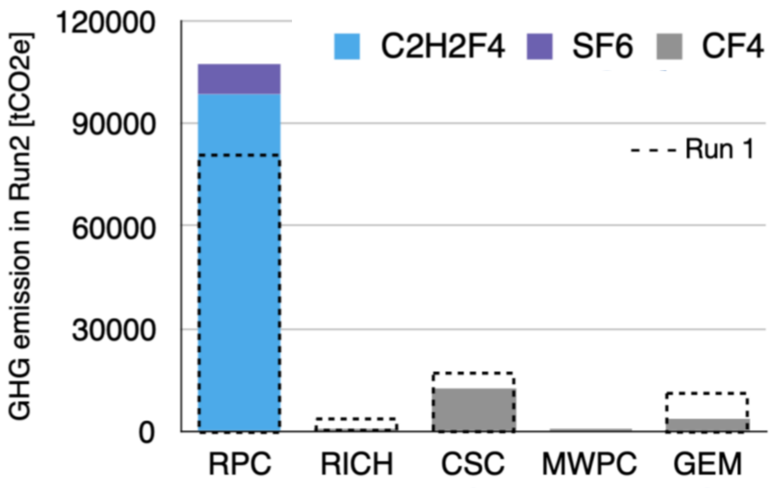
Environmental impact

- RICH detectors do not *use* gas: only closed loop circulation is needed to maintain purity → if engineered to avoid leaks they are environmentally friendly

  e.g. at CERN, LHCb RICH1 impact is dwarfed by RPCs
- Nevertheless, the supply of fluorocarbons may become difficult so it may be prudent to investigate alternatives
- **C_4H_{10}** has similar refractive index but flammable (butane)
- **Xenon** is not a greenhouse gas, and stays in gas phase at room temperature up to over 20 bar
  However, lower refractive index (n = 1.0007) so would need higher pressure than C_4F_{10}, and significantly worse dispersion
- For such new gas choices, R&D needed to ensure suitability
- A leak-free system using suitably pressurized C_3F_8 at room temperature looks the most attractive choice (to me)

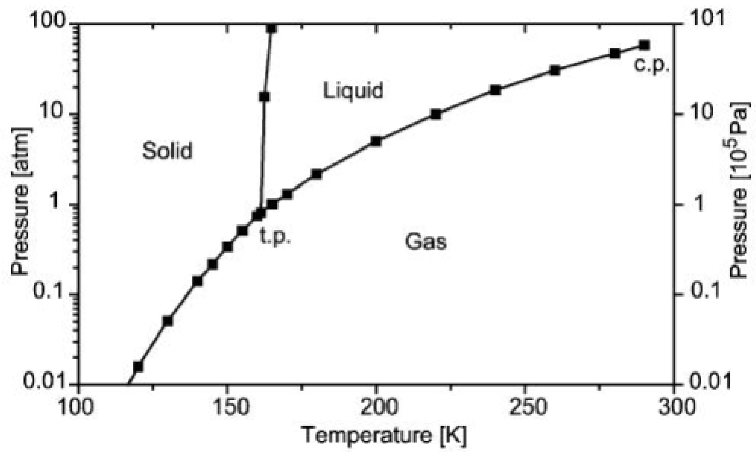
GHG at LHC Run 2

B. Mandelli, ECFA TF1



Phase diagram of xenon

Cherubini and Bifone, 2003

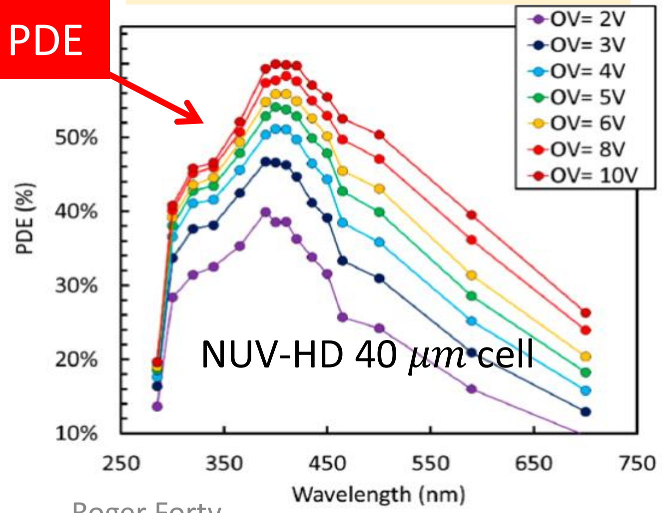


Photosensors

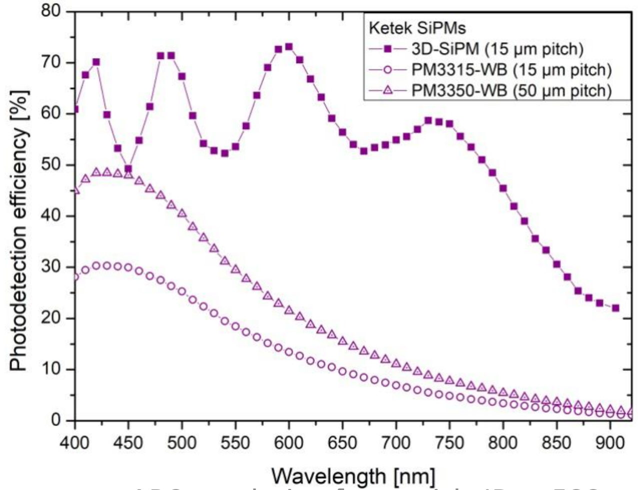
- Silicon PMs have come of age: widely adopted e.g. in MEG, DarkSide (30 m^2 area!), LHCb SciFi, CMS Barrel Timing Layer
- Excellent Photon Detection **Efficiency** > 50% possible, mostly in the visible: rapidly developing, e.g. in automotive industry
- Extremely **compact**, assume can fit the photosensor (and its readout electronics) in a few mm-thick layer
- Excellent **granularity** (sub-mm possible, e.g. 250 μm for SciFi) and fast timing resolution at ~ 10 ps level

Assume this PDE

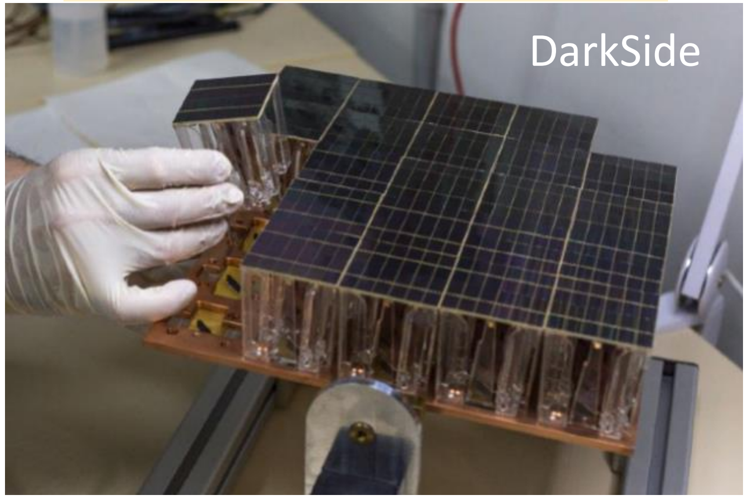
A. Gola et al, Sensors 19 (2019) 308

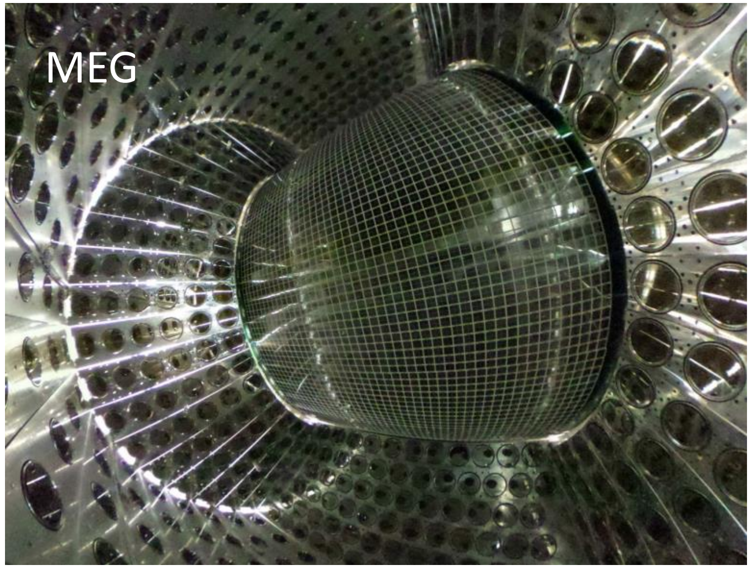


arXiv:2010.10183, K. Krüger, ECFA TF6



A. Kish, CERN Detector Seminar, 28/5/2021

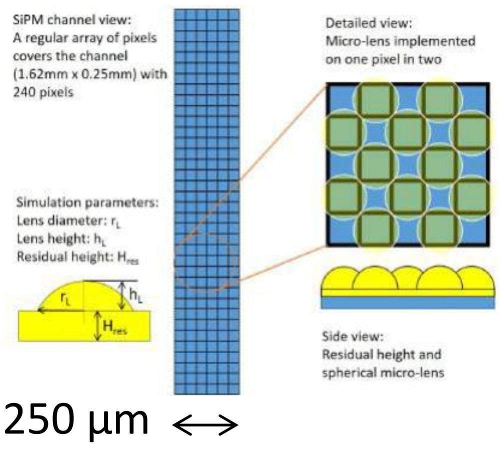




SiPM challenges

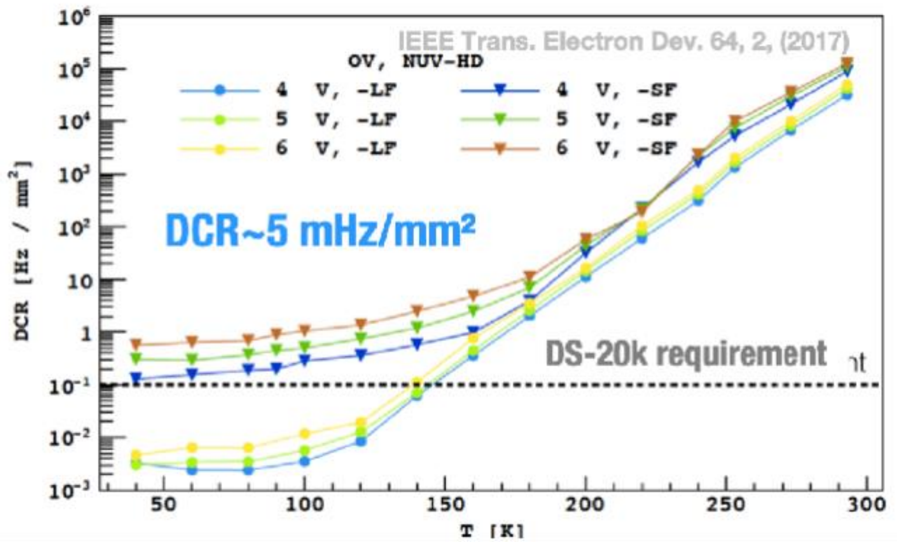
- The active area fraction of sensors can be limited, various approaches investigated to improve (e.g. microlenses)
- Their main issue is Dark Count Rate (**DCR**): high at room temperature but falls fast as temperature is reduced
- No problem for cryogenic detectors like DarkSide or MEG; CMS BTL will use CO_2 (-30 °C) or add thermoelectric (-45 °C)
- Major concern at LHC is increase of DCR with irradiation: *not an issue* at FCC-ee (ILC vertex detector: ~10^{11} n_{eq}/cm^2)
- Ring-imaging detectors are robust against random noise, and timing cuts can suppress it → acceptable level of DCR (and hence target temperature) needs to be established
- Nevertheless, assume cooling will be required → SiPMs + electronics mounted on cooling plate with CO_2 circulation
- Need to insulate from gas volume, while allowing Cherenkov light through: **aerogel** is an excellent thermal insulator!

SciFi microlens concept



A Kuonen, EPFL thesis 8842 (2018)

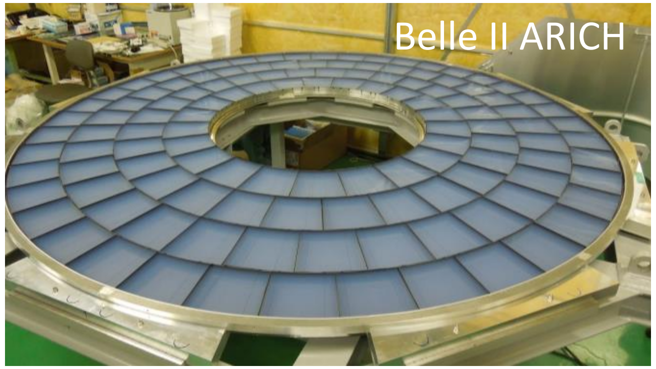
Wikipedia

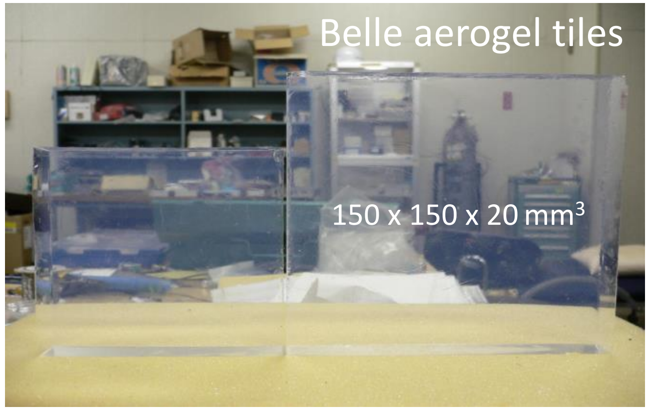


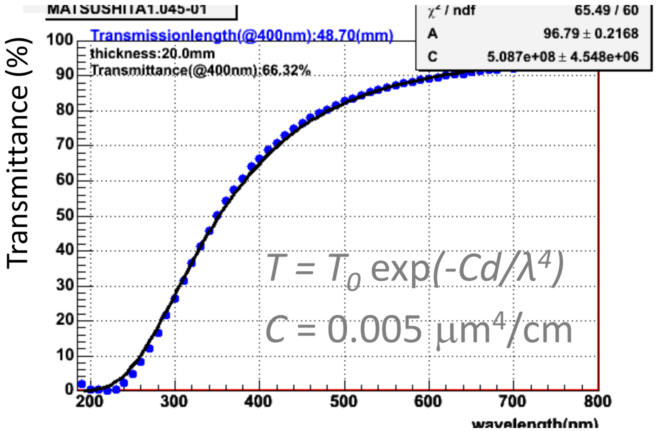
Aerogel radiator

- Silica aerogel is amazing stuff: the lightest solid, withstands pressure > 4000 bar [M. Gorgol et al, Acta Phys Polonica A 132 (2017) 1531], tunable refractive index n = 1.01–1.10, **thermal conductivity** is tiny: ~ 0.015 W/m·K
- For 2 cm thickness, assuming ΔT = 70 K, heat transmitted through a 20 x 20 cm^2 tile is only a few watts << heat that will anyway need to be extracted from the electronics
- Propose to use both as a secondary Cherenkov radiator (suitable for the low momentum tracks) *and* as thermal insulation around sensors
- *Drawback:* the photons from the gas radiator have to pass through aerogel → some loss from scattering, but also shifts towards visible
- High clarity, large area aerogel tiles developed by Belle for ARICH [I. Adachi, ECFA TF4, 6/5/2021] (other recipes also available): assume 2 cm thick tiles of clarity C = 0.005 μm^4/cm, n = 1.03 → $\theta_C \approx$ 240 mrad
- Aerogel photons focused by same mirror as those from gas onto same sensor plane → concentric rings if track above both thresholds

  Efficient use of same sensors for both radiators



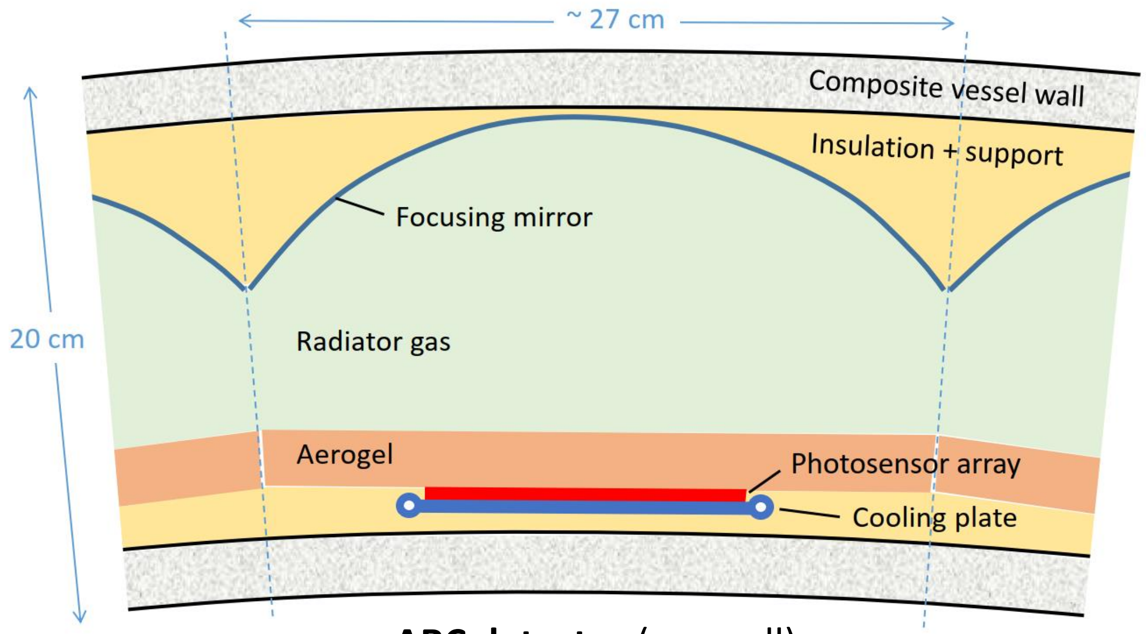




Detector cell

- Challenge to arrange optical elements so that Cherenkov light focused onto a single sensor plane, as the detector radial thickness is reduced
- Concept inspired by the compound-eye of an insect: tile the plane with many separate cells, each with its own mirror and sensor array
- Use spherical focusing mirrors: focal length = radius-of-curvature/2
  → select radius-of-curvature $R \approx 30$ cm for radiator thickness of 15 cm

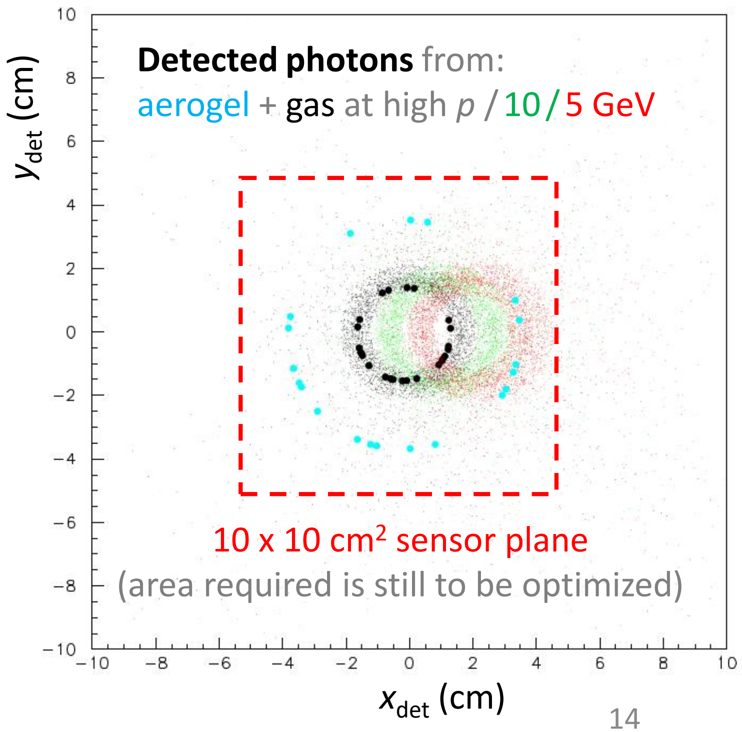
https://www.findlight.net/blog/2019/01/23/artificial-compound-eyes/



ARC detector (one cell)

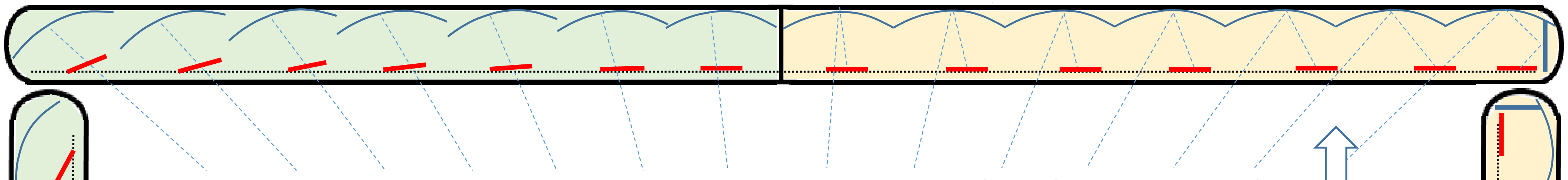
Simulate tracks from IP crossing detector uniformly over acceptance and ray trace Cherenkov photons to sensor plane: (here for $\theta \approx 90°$)

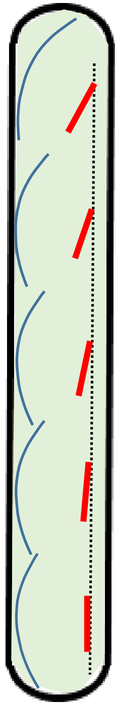
Ring radii = $R \cdot \theta_C / 2$ = 1.5 cm (3.6 cm) for gas (aerogel)



Optical layout

- As move away from normal incidence, i.e. θ = 90° (Barrel) or 0° (Endcap), need to adjust focusing
  Either mirrors kept parallel, radius-of-curvature adjusted (R-half); or tilted and/or parabolic mirrors (L)
  For first solution, add a plane mirror at the end, to keep ring images inside the detector volume

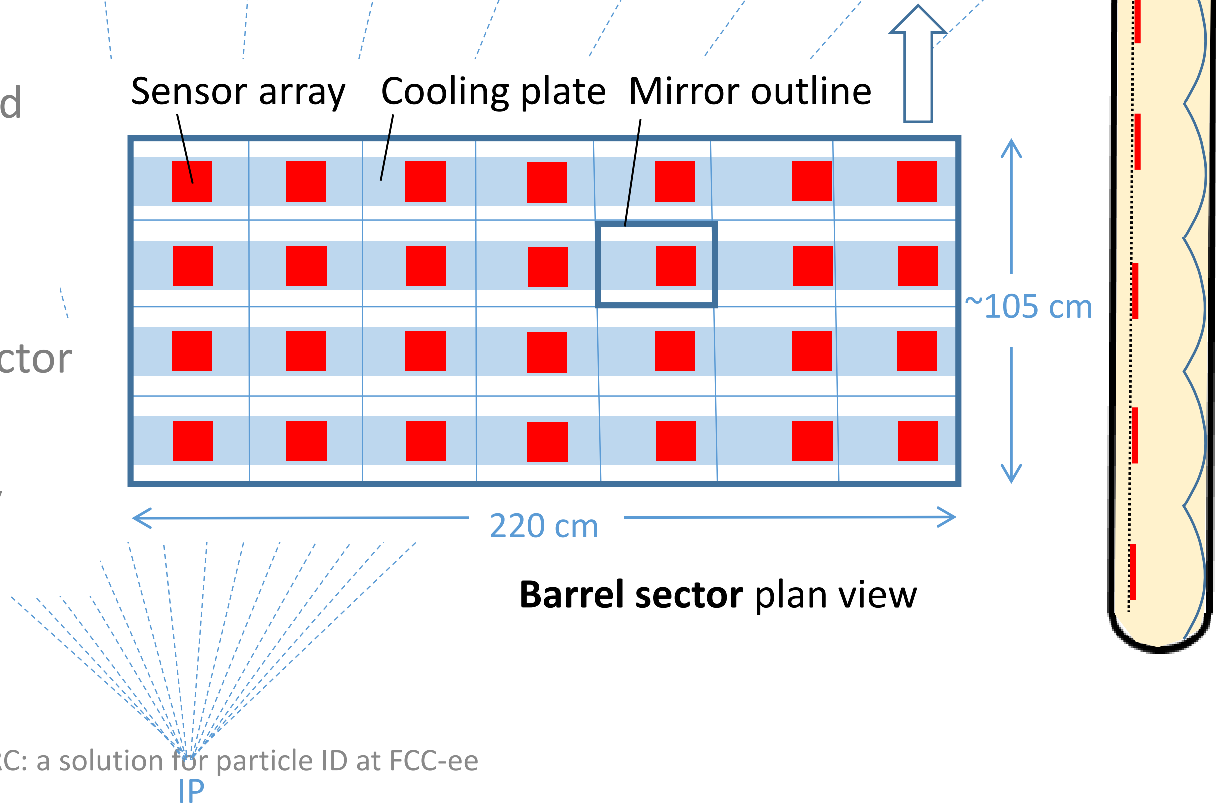




Easier to integrate cooling plate and aerogel if sensors lie on a plane
But focusing quality might oblige tilting — optimization in progress

28 (11) cells per Barrel (Endcap) sector
24 (24) sectors → 936 cells in total

If each has 10x10 cm^2 sensor array
→ ~ 10 m^2 total area to instrument



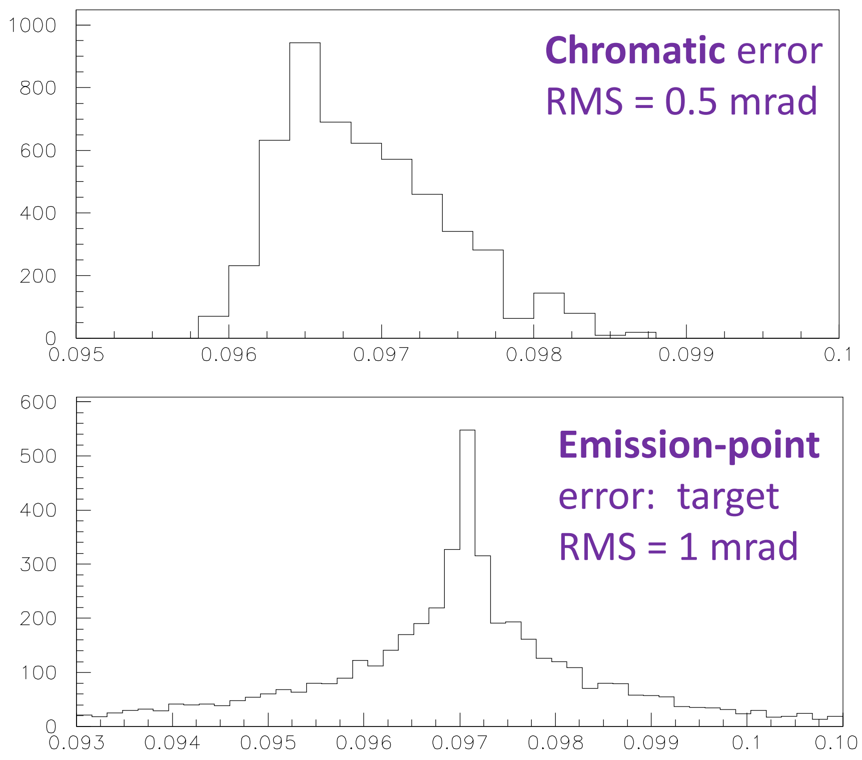
Barrel sector plan view

Expected resolution

- **Chromatic** dispersion in the radiator is the fundamental limit once the bandwidth of the photosensors has been chosen
  → 0.5 mrad (1.5 mrad) for gas (aerogel), per detected photon
  Remarkably low, due to targeting of visible light with SiPM
- **Emission-point** uncertainty: reflects quality of the focusing
  (i.e. how well photons emitted at different points along the track are brought to the same focus on the sensor)
  ~ 1 mrad achieved for gas image at high momentum, $\theta \approx 90°$
  Work in progress to ensure maintained across full acceptance
  Similar for aerogel: reduced thickness compensates larger rings
- **Pixel** size chosen to avoid limiting the angular resolution
  for d = 0.5x0.5 mm² (square pixels) → $2d/\sqrt{12}\,R \approx$ 1 mrad
  (factor √12 for the RMS of a top-hat distribution)
  → ~25,000 pixels per SiPM array, total channel count ~24 M*
- **Track** angular resolution error must be good enough not to limit RICH performance: requires $\sigma_{track} < \sigma_{photon} / \sqrt{N_{pe}} \approx$ 0.3 mrad
  (given 4-25 *billion* silicon channels in CLD tracker, should be OK)

* If cost is part of the optimization, probably use 1 mm pixels → reduce to 6 M channels

From ray-tracing simulation (gas)



Reconstructed Cherenkov angle (rad)

Overall resolution per photon:
$\sigma_{photon} = \sigma_{chromatic} \oplus \sigma_{emission} \oplus \sigma_{pixel}$
≈ 1.5 mrad (2.0 mrad) for gas (aerogel)

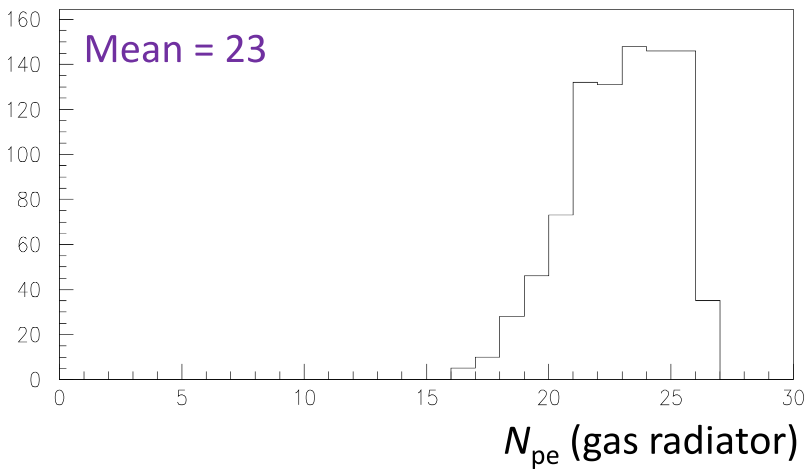
Predicted performance

- Number of detected photons $N_{pe} = A\,L \int \varepsilon \sin^2 \theta_C \, dE$
  where L is radiator length, $A = \alpha^2 / r_e m_e c^2 = 370\ \text{cm}^{-1}\ \text{eV}^{-1}$
- Efficiency ε = PDE · active area · mirror reflectivity · aerogel transmission, as a function of photon energy E
- Assume SiPM active area = 0.8, mirror reflectivity 0.9, other values as given earlier → $\langle N_{pe} \rangle$ = 23 (12) for gas (aerogel)
  Larger θ_C of aerogel compensates for lower radiator thickness
- Angular resolution per track from combining photons:
  $\sigma_\theta = \sigma_{photon} / \sqrt{N_{pe}} \oplus \sigma_{track} \approx$ 0.3 (0.6) mrad for gas (aerogel)
- Significance of K-π separation: $N_\sigma = \dfrac{|m_K^2 - m_\pi^2|}{2\,p^2\,\sigma_\theta \sqrt{n^2-1}}$
- Threshold for K, p to give light: 5, 10 (2, 4) GeV for gas (aerogel)

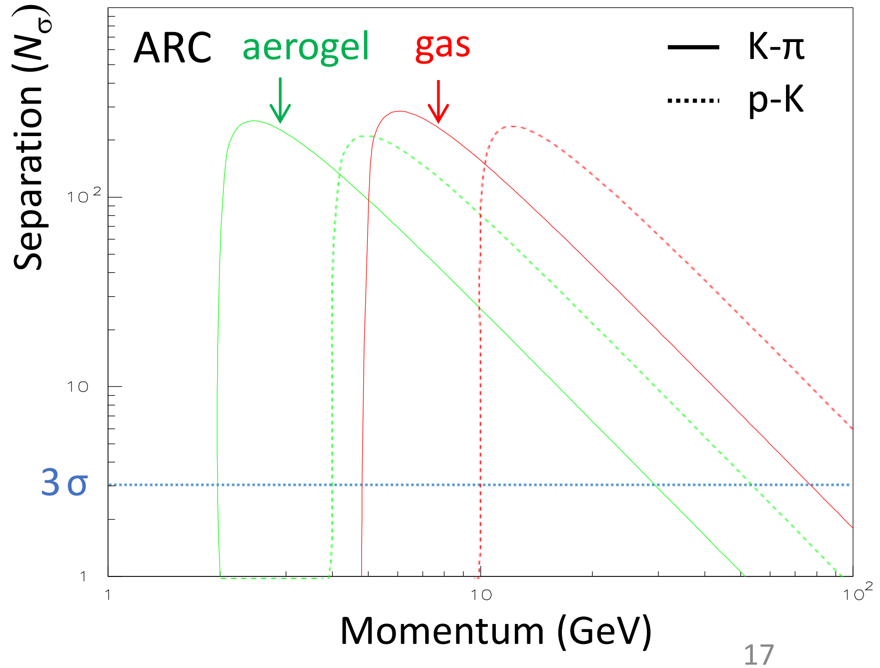
→ Excellent particle identification performance should be achieved over the full momentum range required

(Performance numbers are fresh, subject to confirmation: aerogel surprisingly good…)

From ray-tracing simulation (gas)



Preliminary! analytic calc., assumes focusing target achieved

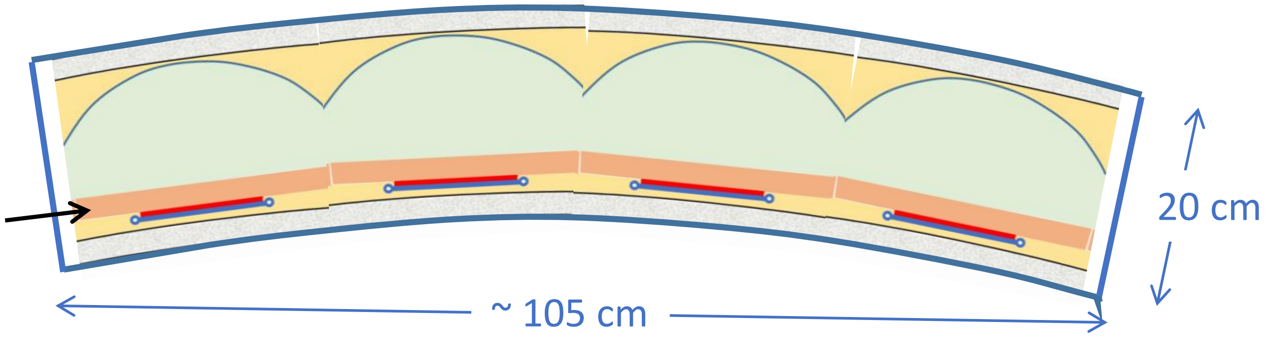


Alternative layouts

- Current proposal has been outlined assuming the use of aerogel is necessary for thermal insulation of photosensor + readout electronics from gas volume: named **ARC**, for **A**erogel **R**ICH **C**ellular detector

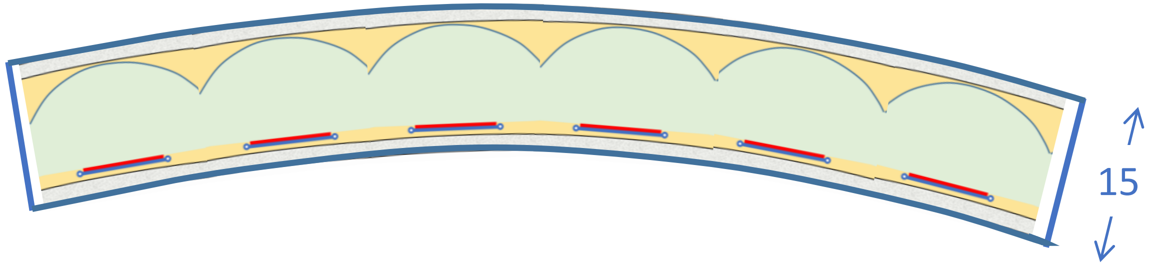
4 cells to a sector
(transverse view)

Aerogel tiles



- If (with further study) a photosensor is found which could operate at the same temperature as the gas, or e.g. if higher momentum range is targeted for the particle ID, then the aerogel might not be needed
→ the radial depth could be squeezed further using a similar “cellular pressurized RICH” design:

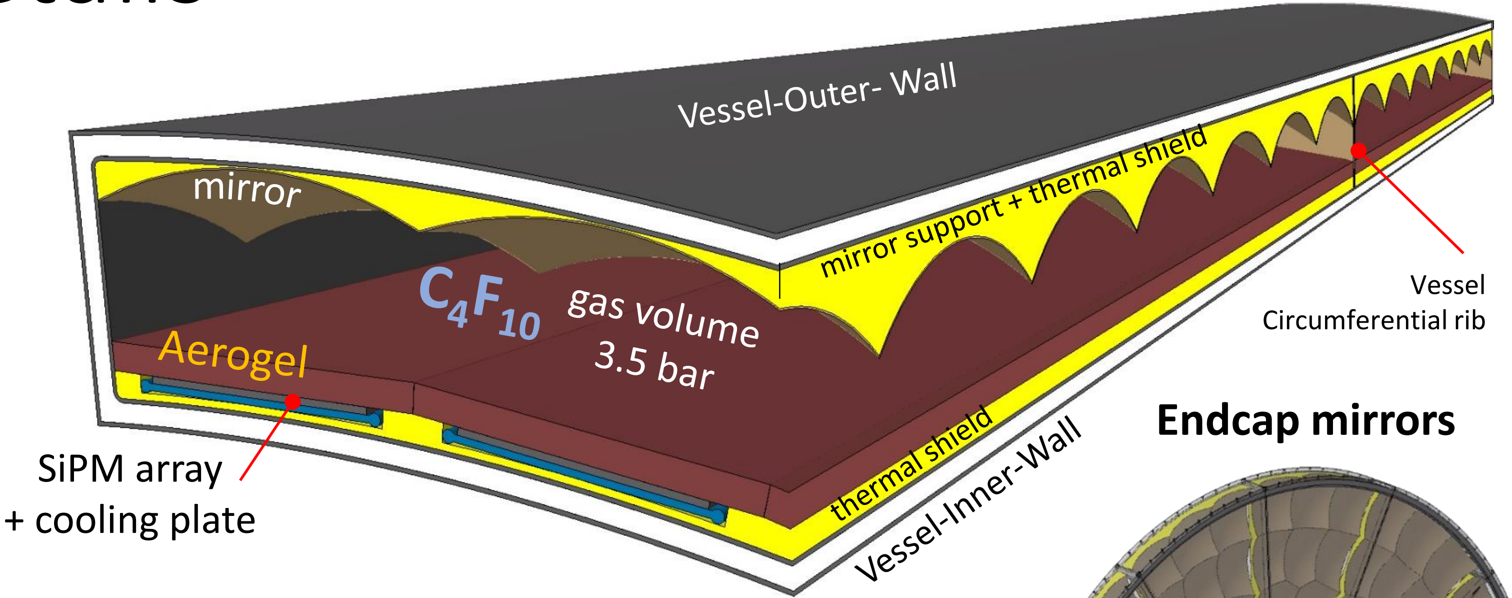
e.g. 6 cells to a sector



15 cm might then be possible?

ARC detector details

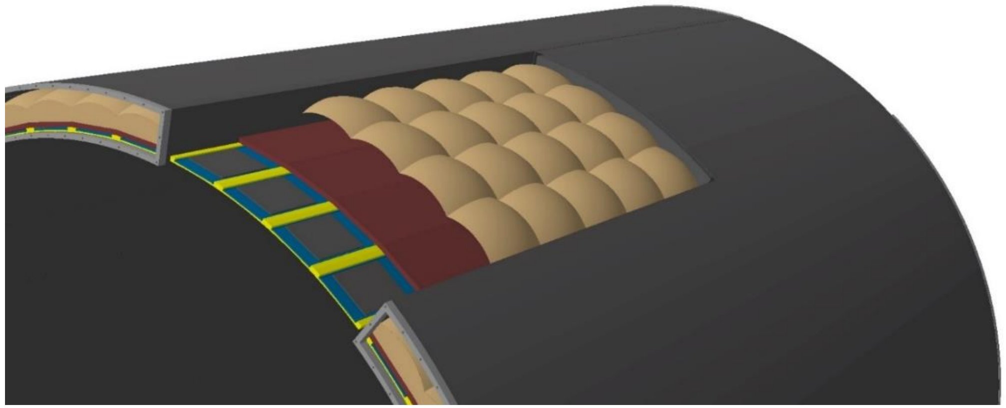
- Beautiful CAD views from Corrado
- Thermal insulation around the mirror and sensor array would be very low mass (MLI: the shiny stuff that satellites are wrapped in)



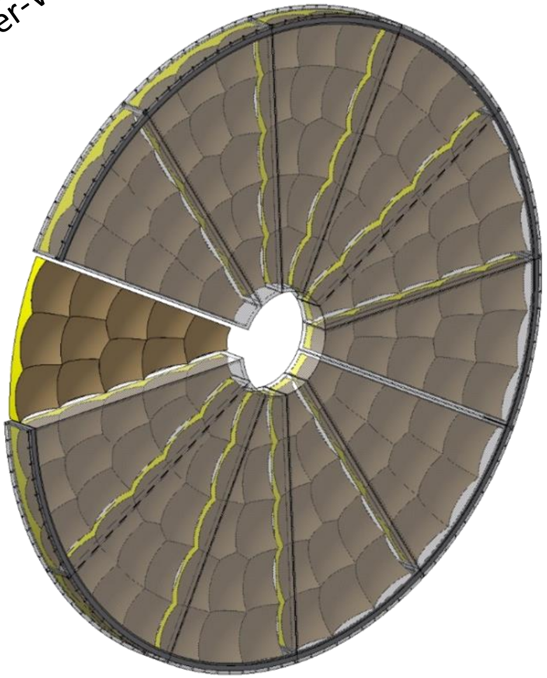
Material budget estimate

Detector component	X/X_0
2 x vessel wall	5 %
Photosensor array/electronics	1 %
Cooling plate (3 mm CF)	1 %
Aerogel (2 cm, n = 1.03)	1 %
C_4F_{10} gas (13 cm @ 3.5 bar)	1 %
Focusing mirror	1 %
Total	10 %

Barrel sector and integration



Endcap mirrors



Related R&D

- The detector concept is clearly only a conceptual design at this stage, but (while it pushes boundaries) I am convinced it *could* be built using currently available technology
- If it is supported, the next step would be detailed performance studies: implementing the detector in full simulation (Geant4), using common framework [Clément Helsens and Gerardo Ganis have made contact]
- Nevertheless, there are still some years to go before construction of the FCC-ee experiments, and there are compelling lines of related R&D which could further confirm or extend the performance: care should be taken to ensure they feature in the ECFA Detector R&D Roadmap
  - **Pressure vessel:** leak tightness, minimizing material budget, safety aspects, access for services, construction of separate sectors vs. inserting detector modules into an overall pressure vessel
  - **Gaseous radiator:** tuning choice of gas, operating temperature vs. pressure, chromatic resolution, use fluorocarbon with leak-free system vs. Xe (or other) due to environmental concerns
  - **Aerogel:** clarity, tuning choice of refractive index, developing large tiles, ensuring compatibility with the gaseous radiator, necessary to separate from gas with a thin glass window?
  - **Photosensor:** SiPM PDE vs. wavelength, active area (e.g. microlenses), DCR, cooling, insulation, what noise level can be tolerated while maintaining performance? prototyping, beam tests, etc.

Conclusions

- A pressurized RICH detector— **ARC** —is proposed to fit the geometry of a 4π collider experiment, with barrel and endcaps, suitable for integration in FCC-ee (or elsewhere)
- Such detectors have been discussed before (VHMPID, EIC, …) but three novel aspects of current concept should allow both the radial depth (~20 cm) and material budget (~10% X_0) to be minimized:
    1. **Aerogel** has dual use both as secondary radiator and as thermal screen for the sensors: if SiPM are used, can be cooled as required to limit noise, in a thermally isolated volume
    2. **RICH** pressure vessel is an innovative design of low-mass carbon-composite construction: few-mm wall displacement acceptable up to 4 bar absolute with safety factor of 2
       Gaseous radiator choice includes options that could be operated at room temperature
    3. **Cellular** RICH, a novel optical layout, is proposed to squeeze into a limited radial space
- Exquisite resolution looks achievable (to be checked) → excellent PID performance predicted
- Such a detector could evolve along with the physics programme of FCC-ee, replacing the radiators according to the momentum range required for particle identification (within the same vessel)
- A related R&D programme has been outlined — I hope that this concept will one day see the light!

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