Development of light-weight spherical mirrors for RICH detectors

RICH2007
6th International Workshop on Ring Imaging Cherenkov Counters
Stazione Marittima, Trieste, Italy
15 - 20 October 2007

Technological aspects of Cherenkov detectors
Friday 19 October 2007

Fabio Metlica
Bristol University-UK
On Behalf of the LHCb Collaboration
Light-weight mirrors are required in RICH detectors whenever the material budget must be minimized, to reduce particle interactions with the mirror material inside the detector acceptance.

Two promising light-weight mirror technologies were R&Ded for the spherical mirrors of the RICH1 detector in LHCb.

- glass-coated beryllium
- carbon-fiber (chosen for RICH1)

The mirrors must satisfy the following requirements:
- light-weight: radiation length $< 2\% \cdot X_0$; interaction length $< 1\% \cdot \lambda_i$;
- radiation hardness up to $\sim 10kGy$ (equivalent to 10 years in LHCb);
- compatibility with fluorocarbon radiator gas environment ($C_4F_{10}$);
- good mirror rigidity and optical quality.
Introduction: Mirror Optical Quality

Three important parameters define the mirror optical quality (measured at CERN):

- **Reflectivity**: requirement ~90% in 200-600nm range;
- **R radius of curvature**: RoC requirement $R \pm (1\% \cdot R)$;
- **Average geometrical quality $D_0$**: requirement $D_0 < 2.5\text{mm}$;

$D_0$ is the diameter of circle at the mirror center of curvature (CoC) which contains 95% of the reflected light intensity from a point source placed at the CoC.

$D_0$ and $R$ measurement:
- point source illuminates uniformly whole mirror;
- reflected image (spot) recorded by camera;
- sliding table moves in 1mm steps, range 40mm;
- smallest spot image $\Rightarrow D_0, R$;
- $\sigma(D_0) \sim 0.06\text{mm}$ and $\sigma(R) \sim 1\text{mm}$.

CERN lab setup to measure $D_0$ and $R$
Beryllium (Z=4) has unique properties ideal for lightweight applications:

- “transparency” to particles;
- radiation hard;
- fluorocarbon compatibility;
- non-magnetic;
- light-weight;
- good rigidity.

Principal disadvantages:

- high manufacturing costs;
- high toxicity, requires safety measures for manufacturing and handling.

Polished beryllium surfaces:

- ~50% reflectivity in visible and UV range;
- ~20-30 nm rms average surface roughness.

High mirror reflectivity ~90% in visible and UV achievable by:

- fusing a thin glass layer onto a beryllium substrate;
- polishing glass surface and applying an Al reflective coating film.

### Comparison of properties for typical mirror materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$X_0$ (g/cm²)</th>
<th>$\lambda_I$ (g/cm²)</th>
<th>$E$ (GPa)</th>
<th>$\alpha$ ($10^{-6}$/°C)</th>
<th>$\rho$ (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyrex (borosilicate glass)</td>
<td>28.1</td>
<td>≈ 97</td>
<td>64</td>
<td>3.2</td>
<td>2.23</td>
</tr>
<tr>
<td>Beryllium</td>
<td>65.19</td>
<td>75.2</td>
<td>255</td>
<td>11.5</td>
<td>1.848</td>
</tr>
<tr>
<td>Aluminum</td>
<td>24.01</td>
<td>106.4</td>
<td>69</td>
<td>23.9</td>
<td>2.70</td>
</tr>
<tr>
<td>Plexiglass (PMMA)</td>
<td>40.49</td>
<td>83.0</td>
<td>3.3</td>
<td>70</td>
<td>1.19</td>
</tr>
</tbody>
</table>

$X_0$: radiation length  
$\lambda_I$: interaction length  
$E$: Young’s Modulus  
$\alpha$: coefficient of thermal expansion  
$\rho$: density
Three small sized glass-coated beryllium prototypes manufactured in Russia and tested successfully at CERN.

Prototype 1: flat mirror, 10mm Be + 1mm glass coating, \( D_0 < 0.1 \text{mm}, 3.6\% \cdot X_0 \).

Prototype 2: spherical mirror with rib-like support, 5-20mm Be + 1mm glass coating, \( D_0 = 0.85 \text{mm}, R = 7926 \text{mm} \) (design 8000mm), 3.3\% \cdot X_0.

Prototype 3: spherical mirror rectangular shaped, 6mm Be + 0.3mm glass coating, \( D_0 = 0.41 \text{mm}, R = 1696 \text{mm} \) (design 1700mm), 1.9\% \cdot X_0.

Good \( D_0 \), and \( R \) close to the design value, <2\% \cdot X_0.
**Beryllium Full-Sized Prototype: Design**

Designed to be as thin as possible but rigid enough not to deform under its own weight.

- 3mm thick beryllium substrate + 0.3mm glass coating;
- rectangular shaped ~400mm x 660mm, size constrained by manufacturing limitations;
- 20mm thick beryllium rim at one edge to support mirror;
- R=2700mm (RICH1 specs).

**FEA** (finite element analysis) done for beryllium substrate to study mirror support mechanism:

- mirror stresses and distortions for different support schemes for mirror in RICH1, i.e. tilted ~12° w.r.t. vertical;
- natural vibration modes;
- calculate the effect on D₀ due to the gravity deflection of the mirror: ~0.3mm.

**Central single point** mirror support scheme chosen; best option based on FEA studies.
**Beryllium Full-Sized Prototype: Manufacture**

- **Beryllium blanks produced at Ulba in Kazakhstan:**
  Powder Metallurgy and Vacuum Hot Pressing: beryllium powder placed in die; apply pressure, heat, vibrations (to homogenize) and vacuum (to outgas).

- **Beryllium blank machined at Kompozit (Moscow-Russia)**
  Blank machined, grinded, annealed several times, and cut; ⇒ ~4mm thick beryllium substrate with RoC close to final value.

- **Glass dressing at Vavilov (St. Petersburg-Russia)**
  - glass type selected with coefficient of thermal expansion to match beryllium;
  - several thin glass sheets placed onto Be-substrate front face covering it;
  - placed in oven ~600°C to melt glass and then left to cool down;
  - glass polished with standard optical methods (~0.3-0.5mm thick);
  - fine tuning of RoC possible by glass polishing.

- **Mirror mount holes:** titanium inserts
  - glued (rad-hard) into holes of rim:
    - central insert bolted to support frame;
    - pins in side inserts as safety mechanism to prevent rotation.
Beryllium Full-Sized Prototype: Characterization

- \( D_0 = 3.3 \text{mm}, R=2675\text{mm} \):
  \( D_0 \) out of specs \((D_0 < 2.5\text{mm})\) but tolerable.

- Beryllium substrate \(~3.8\text{mm}\):
  high risk in breaking substrate during manufacture to reach 3mm.

- Glass coating \(~0.4\text{mm}\):
  thinnest at center \(~0.3\text{mm}\) up to \(~1\text{mm}\) at edges, done to correct RoC.

- Optical dead area due to air bubbles, holes and chamfer \(~0.5\%\)

- \(~1.6\% \cdot X_0, \sim 1\% \cdot \lambda_1\); weight 2.7 kg, size \(~400\text{mm} \times 660\text{mm}\)

**SUMMARY:**
- Overall optical quality good;
- Within the requirements (except \( D_0 \));
- First ever large sized beryllium-glass-coated mirror having a thin beryllium substrate and glass coating;
- Refinement of manufacturing technique \( \Rightarrow \) improved optical quality.
Carbon Fiber Mirror Technology (CFRP)

Carbon fiber reinforced polymer (CFRP) used to fabricate light-weight mirrors.

Mirrors fabricated at CMA (USA) and consist of:
- carbon fiber (~70%): reinforcement material
- resin (~30%): matrix material which binds fibers together (cyanate ester resin)

Advantages:
- light-weight: areal density ~6 kg/m² equivalent to ~1.4%·X₀, ~0.7%·λ₁;
- cheaper than beryllium;
- no safety implications.

Potential disadvantages: uncertainty over
- fluorocarbon compatibility;
- radiation hardness.

{ tested successfully at CERN }
CFRP: Prototype Testing

**Prototypes:**
- demonstration mirror: 600mm x 600mm, RoC=2200mm;
- two small mirrors: Ø 150mm, RoC=1890mm;
- two flat carbon-fiber samples for mechanical tests (~0.5mm thick).

**Testing:**
Expose to either radiation or C$_4$F$_{10}$ but not to both.

- **Radiation: 10 kGy**
  - in 3 steps with a total absorbed dose of 1 kGy, 4 kGy, 10 kGy;
  - 1 kGy equivalent to 1 year radiation in RICH1 environment;
  - gamma radiation; at Ionisos a Cobalt-60 facility near Lyon-France.

- **Fluorocarbons: ~1 year C$_4$F$_{10}$**
  - continuous exposure to C$_4$F$_{10}$ gas in tank at room temperature and pressure.
CFRP: Testing of Prototype Mirrors

No change in optical properties after 10kGy and ~1 year in $C_4F_{10}$.

- **Demo Mirror**: $D_0=1.0\pm0.15\text{ mm}; RoC=2205\pm3\text{ mm};$ exposed to $C_4F_{10}$, mirror too large to measure reflectivity.

- **Two small mirrors**:
  
  $D_0=0.8\pm0.15\text{ mm and } RoC=1890\pm3\text{ mm (for both mirrors)}$;

- Reflectivity (small mirrors):
  - coating: 70 nm Al + 70 nm SiO (CMA coating);
  - CMA coating gives low reflectivity in the UV range.

Reflectivity vs. wavelength for small mirror 1

Reflectivity vs. wavelength for small mirror 2

Small Mirror 1

$C_4F_{10}$ exposure

Small Mirror 2

radiation exposure

CoC spot of demo mirror
Two flat CFRP samples (sample-A → C₄F₁₀ exposure, sample-B → irradiated):

- mechanical properties: tensile (pulling) and flections (bending) tests;

  - tensile rigidity: ~8kN/mm
  - flexural rigidity: ~33N/mm

- average surface roughness (Ra):
  - sample A: ~1.8±0.15 μm
  - sample B: ~1.7±0.15 μm

- comparison of microscope photos of surface: no noticeable change.

No noticeable change in mechanical properties after 10kGy and ~1 year in C₄F₁₀.
CFRP: Production Mirrors Design

- 4 mirrors of size ~640mm x 835mm; RoC=2700mm.
- Honeycomb structure ⇒ 2 CFRP skin core cell reinforcement:
  - two “outer” edges reinforced with square cells;
  - rest reinforced with circular cells;
  - cells glued to back-face and front-face CFRP skins.
- Areal density: ~ 5.5 kg/m² (~1.3%X₀)
- 3-point mounting: points located at the periphery of mirror, outside the mirror acceptance
- CFRP support frame: two C-halves joined at the center
a) **Mandrel** (Pyrex glass):
final polishing done at CMA. Pyrex coefficient of thermal expansion matches CF.

b) **CFRP** pre-impregnated sheets and core cells are laid over the mandrel:
several CFRP layers (~few 100μm thick, single direction) are laid in fixed orientations (e.g. pi/3),
depending on shape and mechanical requirements, resulting in a quasi-isotropic material.

c) **Curing:** heat, pressure, vacuum applied:
CFRP material hardens and takes shape of the mandrel.

d) **Replica (CFRP)** separated from the mandrel:
Then vacuum coated with thin reflective film after cleaning surface.
• Ronchigram lines are reasonably straight ⇒ good spherical mirror surface (measured at CMA).

• D₀, R measurement: D₀~1.2mm, R~2710mm

<table>
<thead>
<tr>
<th>Mirror number</th>
<th>D₀(mm)</th>
<th>R(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>1.07</td>
<td>2710</td>
</tr>
<tr>
<td>#2</td>
<td>1.15</td>
<td>2710</td>
</tr>
<tr>
<td>#3</td>
<td>1.38</td>
<td>2709</td>
</tr>
<tr>
<td>#4</td>
<td>1.18</td>
<td>2710</td>
</tr>
</tbody>
</table>

Production mirrors are of good optical quality and well within specs.
CFRP Mirrors: Reflectivity Coating (SESO)

- Four production CMA mirrors coated at SESO (Aix-en-Provence, France) in Feb07.
- CMA standard coating is Al+SiO (visible range).
- Al(80nm)+MgF₂(160nm) coating chosen for good reflectivity in visible and UV range (SESO).
- SESO coated production mirrors:
  - average reflectivity ~90%;
  - reflectivity >85% in 200-600nm range.

Reflectivity curves of production CMA mirrors

average reflectivity ~90%
CFRP Production Mirrors in RICH1

CFRP mirror assembly on testing rig

CFRP mirrors installed in RICH1 in July 2007

CFRP support frame

4 CFRP mirrors

glass flat mirrors

beampipe
Summary

• Two technologies tested successfully for light-weight mirrors: glass-coated beryllium and carbon-fiber.

• Glass-coated beryllium:
  - first ever large sized (~400mm x 660mm) beryllium glass-coated mirror with a thin substrate (~4mm) ⇒ ~1.6%·X₀;
  - overall optical quality good: D₀=3.3mm; R=2675mm;
  - improvement in mirror quality to be expect with the refinement of the manufacturing technique.

• Carbon-fiber (CFRP):
  - four large production mirrors for RICH1: ~640mm x 835mm;
  - well within specs: D₀~1.2mm; R~2710mm; ~1.3%·X₀; reflectivity~90% (200-600nm);
  - testing:
    - fluorocarbons: ~1 year C₄F₁₀ exposure
    - radiation: ~10kGy (~equivalent to 10 years in RICH1)
  \} no change in opto-mechanical properties

• Both technologies highly suitable for light-weight mirror applications.

• Carbon-fiber (CFRP) chosen for RICH1 because very promising, but also on grounds of delivery time and costs.