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CpFM for UA9

Cherenkov detector for proton Flux Measurements

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on behalf of the UA9 Cherenkov detector team

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Cherenkov detector for proton Flux Measurements

- Introduction on the UA9 Experiment
- Description of the CpFM
- Choice of the detection chain components
- Simulation of the CpFM
- Beam tests of simplified prototypes
- Next steps
The UA9 mission
Investigate bent crystals as primary collimators in hadron colliders

Bent crystals work as a “smart defectors” on primary halo particles (W. Scandale 10.1103/PhysRevSTAB.11.063501)

If crystalline planes are correctly oriented, particles are subjected to a coherent interaction (channeling):

- small angular acceptance
- localization of the losses on a single absorber, thanks to large deflection angle
- reduced probability of diffractive events and ion fragmentation/dissociation.

- Need of a detector for counting the number of protons of the halo deflected by the crystal

in SPS since 2009

\[ \theta_{\text{ch}} \approx \alpha_{\text{bending}} \]

\[ \theta_{\text{optimal, } 7\text{ TeV}} \approx 40 \mu\text{rad} \]
our proposal: Cherenkov proton counting detector

Initial idea belongs to the PNPI group with a prototype tested in SPS

**Aim:** count the number of protons with a precision of about 5% in the LHC environment (mean value over several bunches)

**Constraints at the LHC:**

- inside the primary vacuum $\rightarrow$ no degassing materials
- very hostile radioactive environment $\rightarrow$ radiation hardness of the detection chain $\rightarrow$ readout electronics at 300 m
- small place available $\rightarrow$ compact radiator inside the beam pipe $\rightarrow$ small footprint of the photodetector + cables + .... inside the tunnel

**Our proposal:**

- Radiator: quartz
- Photodetector: SiPM PMT
- Readout electronics: WaveCatcher

CpFM
Cherenkov detector for proton flux measurements
The CpFM concept

1. interception of the channeled beam by a quartz radiator (retractable finger)
2. emission of Cherenkov light readout by a PMT placed 4 m from the beam pipe (light brought by optical fibers)
3. PMT amplified signal readout by the WaveCatcher module 200 – 300 m from this position
Radiation hardness of the CpFM components

Annual Radiation levels close to the pipe:
- γ dose = 10 Mrad
- thermal neutrons fluence = 10^{14} n/cm^2
- protons fluence = 10^{13} p/cm^2

Quartz radiation hardness

3 fused silica types (Corning 7980, Schott Lithosil Q0, Heraeus Suprasil 1) irradiated with 150 MeV proton beam with dose levels: 100krad, 1Mrad and 10Mrad

→ No significant radiation damage observed in any fused silica sample

γ Irradiation (^{60}Co) with a dose of 11 M Gy (1100 M rad): stability of the samples Heraeus Suprasil Standard & Infrasil, Spectrosil A and B (Saint-Gobain) and Corning 7940

Our choice: Corning 7980 & Heraeus Suprasil

(1 Gy = 100 rad)
Radiation hardness of optical fibers

Studies of radiation hardness of fibers (WLS, pure quartz, ...): upgrade of ATLAS HCAL, ATLAS LUCID, upgrade of CMS Hadronic Endcap

Irradiation with protons

transmitted light spectra from a 1.25m of qq fiber

« Best » results with fiber with quartz core and quartz clad

Good candidate: LEONI all silica fiber:

core 600 µm
attenuation @350nm <=0,06dB/m
operational in 200-1200 nm range

18 rad/s (0.3 rad/s LHC worst)

Irradiation with γ and neutrons

U. Akgun, CALOR 2008

P. Bruecken

FBP 600-660-710 spectra before and after irradiation: 17.6 MRad of n and 73.5 MRad of γ

Measurement after irradiation performed 10 weeks after it ....
HAMAMATSU and NDL developed new devices:

- 15 μm cell size MPPC (1 mm²)
- 10 μm cell size NDL (0.25 mm²) SiPM

which survived $10^{13}$ n/cm² 1 MeV equivalent neutron flux not enough for UA9.
Effects of radiation on Photodetectors: PMTs

- Protons / neutrons / γ-rays
  - Deterioration of the borosilicate window transmittance but not for a fused silica window
  - Increase of the dark current
  - No important change of the gain and quantum efficiency

Coloring of the glass

Glass scintillation

Protons / neutrons / γ-rays:
- γ: 60Co, E = 1.22 MeV
- Dose = 20±1 Mrad

No variation of the transmittance of quartz window

Our choices: Hamamatsu R762 & R7378A

HAMAMATSU R762

Gain curves for PMT/g before and after irradiation

Dark current of PMT/g before and after irradiation

A. Shrizzi LUCID in ATLAS

Our choices: Hamamatsu R762 & R7378A
The CpFM readout

The WaveCatcher board

- LAL/CEA IRFU development
- 16-channel, USB powered Waveform digitizer
- 500 MHz bandwidth, 3.2 GS/s sampling rate, 12 bits, <10-ps rms sampling time precision

The WaveCatcher electronics is not radiation hard, not even tolerant, because it is based on standard components, especially FPGAs. It thus has to be located in a low radiation area. For the LHC, the proposed location is in the TZ76 tunnel.

Need of long signal cables with very low attenuation coefficient
Quartz radiator geometries simulations

Straight configuration

~ 10 p.e

taking into account a PMT with Bialkali PC + CE

~ 22 p.e

Geant 4 simulations

V. Puill, IPRD13, Siena, October 2013
Quartz radiator geometries simulations

45° configuration

~ 13 p.e *

* taking into account a PMT with Bialkali Photocathode + Collection Efficiency

~ 42 p.e *

Geant 4 simulations
The light transportation

Too much radiation to place the PMT close to the beam pipe → need of a (long) fibers bundle

Not realistic connection between the viewport and the fiber bundle because of the acceptance aperture of the fiber we want to use.

Photons which would NOT be kept inside the fiber

Critical angle ~ 8° for NA = 0.22

Photons which would be kept inside the fiber

Need of a quartz adapter
Quartz + fiber bundle

Quartz radiator + viewport + fiber adapter = single piece

Fiber adapter to optimize the entrance of the photons inside the fibers

Taking into account a PMT with Bialkali PC + CE

≈ 420 photons/proton at the quartz piece output

Mechanical integration

Not enough space to bend the fiber bundle !!!!!

new geometry ...
« Hockey stick » configuration

straight connection to the bundle

When connected to a 10 m bundle composed of 223 fibers

angle distribution of the photons

Is it enough? → need to do tests

Geant4 simulations
Beam Tests @ BTF

- Beam is extracted from high current LINAC (injection system of DAFNE) and driven toward an experimental area.
  - Current of primary beam is too high for purpose of BTF (1-500 mA e-, 100 mA e+)
  - Attenuation system allows to tune BTF beam intensity and energy.

Characteristics of the e- beam @ BTF

- Particles number: 1 - 10^5 e-/pulse
- Energy: 25 – 500 MeV
- Frequency: 20 MHz
- Pulse duration: 10 ns
Optical readout by MA-PMT R5900U-L16 (quartz plate window)
10.1 x 20.1 x 105 mm³ quartz radiator coupled with MA-PMT through 25 quartz fibers 120mm long

Results:
Larger relative increase of light @45° (300-400%) than in MA-PMT direct coupled, this due to optic acceptance angle of fibers (numerical aperture)

Optical coupling quality efficiency ~10%
Next beam tests @BTF (14-18 October)

- Quartz 10 cm
- fiber bundle 0.3 m
- low attenuation cable 30 m
- PMT

Quartz type
Fibers
PMTs
Coaxial cable
Readout electronics

all the CpFM components chosen for the SPS and the LHC

- Optimization of the optical coupling
- Measurement of the signal attenuation in the cable
- Comparison of the measurements and the simulations

Proof of principle
Conclusion and next steps

Cherenkov Detector in the primary vacuum = Challenging detector development

- BTF tests will prove the feasibility of the CpFM principle
- Mechanical support design on going at CERN
- The CpFM prototype will be tested under irradiation (protons and $\gamma$)
- The CpFM will be calibrated at BTF and then installed
  1. inside the SPS beam pipe in June 2014
  2. inside the LHC beam pipe at the beginning of 2015
UA9 CpFM Backup slides
Particles are repeatedly deflected by Multiple Coulomb Scattering also producing hadronic showers that is the secondary halo.

Collimation efficiency in LHC \(\sim 99.98\% \) @ 3.5 TeV

- Probably not enough in view of a luminosity upgrade
- Basic limitation of the amorphous collimation system
  - need of a more efficient system
Prototype crystal collimation system installed in CERN-SPS (~ 5 days per year):

- **2010**: Comparative results on collimation of the SPS beam of protons and Pb ions with bent crystals (*Physics Letters B*, vol. 703, no. 5, pp. 547–551).
- **2011**: Direct measurement of a strong reduction of the off-momentum halo in crystal assisted collimation of the SPS beam (*Physics Letters B*, 714(2-5), 231–236).
- **2012**: Direct observation of the halo population reduction far from the crystal, SPS loss maps, optimized apertures for collimation system elements, ... (data taking still on-going)
UA9 at SPS, a prototype system for LHC

- 2006: First of a crystal-assisted collimation layout (Assmann, Redaelli, Scandale EPAC2006).
- 2008: Medipix in a Roman pot
- 2009: Cherencov quartz detector in the primary vacuum
- 2012: First goniometer industrially produced suited for the LHC requirements
Summary of the UA9 findings

- Test with extracted beams at CERN North Area (~ 3÷5 weeks per year):
  - Crystal – beam interactions
  - Measurement of crystal properties before installation in CERN-SPS

- Prototype crystal collimation system installed in CERN-SPS (~ 5 days per year):
  - 2009: First results on the SPS beam collimation with bent crystals  
  - 2010: Comparative results on collimation of the SPS beam of protons and Pb ions with bent crystals  
  - 2011: Direct measurement of a strong reduction of the off-momentum halo in crystal assisted 
    collimation of the SPS beam  
  - 2012: Direct observation of the halo population reduction far from the crystal, SPS loss maps, 
    optimized apertures for collimation system elements, … (data taking still on-going)

- Working for future installation of a prototype system in LHC
  - 2006: First of a crystal-assisted collimation layout (*Assmann, Redaelli, Scandale EPAC2006*).
  - 2008: Medipix in a Roman pot
  - 2009: Cherencov quartz detector in the primary vacuum
  - 2012: First goniometer industrially produced suited for the LHC requirements.
• In UA9 (PNPI) there is some experience with quartz in vacuum
  – Good correlation with beam losses but no precise counting so far

New UA9 PNPI thin quartz radiators recently installed in SPS

G.Cavoto and P.Valente, INFN Roma
UA9 instrumentation workshop May 2012
Roman pots

- Movable device housing detectors in secondary vacuum
  - Used to *acquire images of channeled beam*
    - Very important to confirm channeling online
  - Relevant to measure channeled beam direction (from centroid) and flux of proton of channeled beam

Vertical displacement

Horizontal displacement

Online picture with Medipix
Location of the counter for the deflected protons in LHC
Quartz radiation hardness (protons with $E_{\text{kin}} = 150$ MeV)

Reference:
Matthias Hoek, 6th International Workshop on Ring Imaging Cherenkov Counters (RICH2007), Trieste.

- Irradiation with protons $E_{\text{kin}} = 150$ MeV, 100krad, 1Mrad and 10Mrad
- Samples of quartz which has been studied:
  - **Corning 7980** → our default choice
  - Schott Lithosil Q0
  - Heraeus Suprasil 1

![Fused Silica – Corning 7980](image)

- 3 fused silica types irradiated with 150MeV proton beam
  - 3 established dose levels: 100krad, 1Mrad and 10Mrad
  - Irradiation spots clearly visible in crown glass and LiF
- Transmission behaviour between 200 and 800 nm monitored
  - No significant radiation damage observed in any fused silica sample
  - Sensitivity better than 1.0%
- No surface dilatation observed
Quartz radiation hardness (gammas and electrons Co$^{60}$)

Reference:

<table>
<thead>
<tr>
<th>Описание параметра</th>
<th>Марка кварцевого стекла</th>
<th>КУ-1</th>
<th>КС-4В</th>
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<tr>
<td>Радиационно-оптическая стабильность (к гамма-излучению)</td>
<td>стабилен</td>
<td>стабилен при дозах облучения Co$^{60}$ до 11МГр</td>
<td></td>
</tr>
</tbody>
</table>

Type of the quartz | KU-1 | KS-4V

Radiation – optical stability (for gamma irradiation) | Stable | Stable for doses (Co$^{60}$) which does not exceed 11 MGY (1100 Mrad)

Closest analogs of KU-1 are: Suprasil Standard (Heraeus), Spectrosil A and B (Saint-Gobain) and Corning 7940 (Corning), Dynasil1100 and 4100 (Dynasil).

FDIRC, FTOF Material: Fused silica corning HPFC 7980 standard grade.

Closest analogs of KS-4V is: Infrasil (Heraeus).
Angular acceptance of the fiber

Numerical aperture $\sqrt{n_{\text{Core}}^2 - n_{\text{Cladding}}^2}$

$\alpha_{\text{critical}}$ vs. $\lambda$, nm

- NA = 0.22
- NA = 0.37
- NA = 0.48
- NA = 1.08 (Air)

$\alpha_{\text{critical}}$ vs. $\theta_{\text{acceptance}}$

<table>
<thead>
<tr>
<th>NA</th>
<th>$\alpha_{\text{critical}}$</th>
<th>$\theta_{\text{acceptance}}$</th>
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</thead>
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<tr>
<td>0.22</td>
<td>81.5°</td>
<td>8.5°</td>
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<tr>
<td>0.37</td>
<td>75.6°</td>
<td>14.4°</td>
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<tr>
<td>0.48</td>
<td>71.0°</td>
<td>19.0°</td>
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<tr>
<td>1.08</td>
<td>42.5°</td>
<td>47.5°</td>
</tr>
</tbody>
</table>
Standard CERN cables (signal)

- Cables with low loss:
  COAXIAL CABLE 50 OHM - LOW LOSS - TYPE C-50-11-1
Calibration of the CpFM at the Beam Test Facility (DAPHNE) at Frascati

- e-/e+ @ 450 MeV produced by an upstream LINAC/target/dipole system
- variable intensity thanks to slits (from single particle up to $10^4$)
- bunched structure of beam
- variable beam spot size (slight spread in air)

$\beta(\text{e- 450 MeV}) = \beta(\text{p 7 TeV}) = 0.9999$
On-line monitoring of the CpFM

Need of monitoring the variation of the PMT response with time (because of the radiations effects)

\[ Q_{\text{PMT}} = \alpha \times N_{\text{photons}} \]

\[ \alpha = \text{Tr} \times Q_{\text{\varepsilon}} \times C_{E} \times G \]

Tr : light transmission factor

\[ Q_{\text{\varepsilon}} \] : PMT quantum efficiency

\[ C_{E} \] : PMT collection efficiency

\[ G \] : PMT gain

Injection of different light intensities \( \rightarrow \) measurement of the mean (M) of the spectrum its standard deviation (\( \sigma \))

\[ \sigma^{2} = \alpha (M - M_{0}) + \sigma_{0}^{2} \]

A. Baldini et al, NIMA545

The variation of \( \alpha \) is monitored

Bias voltage of the PMT can be adjusted