P. Antonioli – INFN Bologna

on behalf of the EIC Project Detector eRD110 - Photosensors
The eRD110 consortium

- Argonne National Laboratory (ANL)
- Brookhaven National Laboratory (BNL)
- Catholic University of America (CUA)
- Friedrich-Alexander-Universit¨at Erlangen-N¨urnberg (FAU)
- GSI Helmholtzzentrum f¨ur Schwerionenforschung (GSI)
- Istituto Nazionale di Fisica Nucleare (INFN) (Bologna, Ferrara, Genoa, Trieste, Turin)
- Mississippi State University (MSU)
- Stony Brook University (SBU)
- Thomas Jefferson National Accelerator Facility (Jlab)
- University of California Los Angeles (UCLA)
- University of South Carolina (USC)

Applied for FY22+ for SiPM, LAPPD and MCP-PMT (DIRC and RICHs)

Planned application since FY23 for calorimeters readout via SiPM
"The objective of the R&D effort presented here is to mitigate technical, cost, and schedule risk related to readout sensors of EIC Cherenkov detectors and Calorimeters. The call for this proposal requests that this R&D effort comes to a clear and well-informed decision for a baseline sensor solution for each PID detector in FY22. Our common consensus is that R&D effort beyond FY22 is absolutely necessary in order to be able to form a decision that capitalizes on all state-of-the-art technologies to mitigate all of the risks specified above".
## The table of requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>hpDIRC</th>
<th>dRICH – mRICH/pfRICH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>$\sim 10^6$</td>
<td>$\sim 10^6$</td>
</tr>
<tr>
<td>Timing resolution</td>
<td>$\leq 100 \text{ ps}$</td>
<td>$\leq 300 \text{ ps}$</td>
</tr>
<tr>
<td>Pixel size</td>
<td>2–3 mm</td>
<td>$\leq 3 \text{ mm}$</td>
</tr>
<tr>
<td>Dark noise</td>
<td>$\leq 1 \text{ kHz/cm}^2$</td>
<td>$\leq 1 \text{ MHz/cm}^2$</td>
</tr>
<tr>
<td>Radiation tolerance @ $10^{11}$ 1 MeV-neq</td>
<td>NEEDED</td>
<td>NEEDED</td>
</tr>
<tr>
<td><strong>Single-photon mode</strong></td>
<td>REQUIRED</td>
<td>REQUIRED</td>
</tr>
<tr>
<td>Magnetic field immunity</td>
<td>NEEDED (0.7-1.5 T)</td>
<td>NEEDED (0.7-1.5 T)</td>
</tr>
<tr>
<td>Photon Detection Efficiency</td>
<td>$\geq 20%$</td>
<td>$\geq 20%$</td>
</tr>
</tbody>
</table>
## The table of candidate photosensors

<table>
<thead>
<tr>
<th></th>
<th>MCP-PMT/Planacon</th>
<th>SiPM</th>
<th>LAPPD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Area</strong></td>
<td>5x5 cm²</td>
<td>Tiles available 5.76 cm²</td>
<td>20x20 cm²</td>
</tr>
<tr>
<td><strong>Pixel</strong></td>
<td>3x3 mm²</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Magnetic field</strong></td>
<td>Seen drop in collection efficiency at angle &gt; 10 deg</td>
<td>insensitive</td>
<td>0.7 T on 20 μm MC seems ok, depending orientation. Smaller MCP's for larger field</td>
</tr>
<tr>
<td><strong>Radiation</strong></td>
<td>insensitive</td>
<td>needs test + assess mitigation protocol (annealing)</td>
<td>No data, but reasonable to expect not a problem</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>In stock*</td>
<td>In stock*</td>
<td>&quot;In-stock&quot; for 20 μm</td>
</tr>
<tr>
<td><strong>Manufacturers</strong></td>
<td>Photonis/Photek</td>
<td>many (HPK, OnSemi, FBK/L-Foundry, Ketek/Boradcom)</td>
<td>Incom</td>
</tr>
<tr>
<td><strong>Price</strong></td>
<td>$15-20 k$ each (few units)</td>
<td>1 k$ / (8x8 tile 3x3 mm)</td>
<td>$25-50K each LAPPD (20x20 cm² or 10x10 cm² similar price)</td>
</tr>
<tr>
<td><strong>Unit price</strong></td>
<td>16 k$/25 cm² = 600 $/cm²</td>
<td>≈50-100 $/cm²</td>
<td>62.5-500 $/cm²</td>
</tr>
<tr>
<td><strong>Concerns</strong></td>
<td>cost</td>
<td>DCR increase with radiation</td>
<td>Cross talk, integration, availability</td>
</tr>
<tr>
<td><strong>Risks</strong></td>
<td>None</td>
<td>None if mitigation of DCR increase &quot;manageable&quot;</td>
<td>Achievable with risk, time schedule challenging</td>
</tr>
</tbody>
</table>
R&D program in a slide

MCP PMTs: Photonis xp85122-s-HiCE and Photek MAPMT253
   → check collection efficiency with B
   → evaluate Photek MAPMT253
   → full characterization
   → adapt NALU ASIC for custom readout

LAPPD/HRPPD: evaluation of Incom "Gen-II"
   → Gen-II == capacitively coupled → pixelation
   → 10 micron pore size/reduced stack height → improved tolerance to B
   → characterize sensors and test them on beam conditions

SiPM: evaluate radiation tolerance and mitigation procedures (annealing)
   → test large O(10-100) samples of commercial (HPK/OnSemi) and prototypes (FBK)
   → establish annealing protocol, evaluate DCR after repeated annealing cycles
   → characterize sensors and test them on beam conditions
   → realistic readout with ALCOR ASIC

Not funded by EIC project for FY22

USC – CUA – SBU - JLab

ANL – BNL – MSU – INFN TS/GE

INFN BO/FE/TO
LAPPD R&D highlights

capacitively coupled allow user flexibility for pixellation better spatial resolution expected timing resolution preserved

3x3 mm field

laser scan @ BNL

"from one photon – one hit to a multi-pixel cluster"

(see for more info the recent talk at 15th Pisa Meeting on Advanced Detectors May 22-28, 2022, La Biodola – Isola d’Elba (Italy)

8 June 2022

P. Antonioli - eRD110
Beam tests in 2021 (FNAL)

FTBF beam
120 GeV protons

Aspheric lens (not to scale)

LAPPD

"effective" photon source location

"imaginary" beam in the opposite direction

thick aspheric lens as controlled Cherenkov ring producer

accumulated pixel hits

Cherenkov ring radius resolution

single Cherenkov photon detection with sub-mm resolution!
Magnetic test @ ANL – 2022

Gain partially recovered at high B increasing MCP voltage

abstract submitted to IEEE NSS-MIC/2022

credits: Junqi X.
see also J. Xie et al., JINST 15 (2020) C0438
LAPPD – 2022 plans

- Rent state-of-the-art Gen II 20cm LAPPD and 10cm HRPPD tiles
  - 10 µm pore MCPs
  - 2 mm thin ceramic base plate and short ceramic walls
- Quantify expected reduction of the induced signal spread, spatial and timing resolution, gain uniformity and PDE
- Work on Gen I HRPPD readout interface

- Beam test at Fermilab June 13-26
  - Verify single photon and “TOF blob” timing resolution, as well as Cherenkov ring radius resolution
  - Provide a first direct π/K separation measurement, potentially using both Cherenkov imaging and time-of-flight technique
  - Configuration(s): mRICH mockup and / or pfRICH geometry

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8 June 2022 P. Antonioli - eRD110
SiPM R&D highlights @ INFN

Remember the 3 SiPM challenges
- high DCR \(O(100 \text{ kHz} - 1 \text{ MHz})\) at room temperature
- no radiation immune
- higher DCR after irradiation/annealing

- the cooling challenge
- the annealing challenge
- the data challenge

Front-end electronics & DAQ is part of the challenge (and of the solution)

- selection of SiPM candidates (HPK, FBK, OnSemi, Broadcom) + carrier boards for SiPM "matrix"
- readout electronics based on ALCOR chip (developed at INFN-TO)
- tests and characterization in climate chamber (mainly at INFN-BO)
- annealing at INFN BO/FE
- irradiation at Centro di Protonterapia in Trento (high intensity p beam 140 MeV)(10^8 \text{ – } 10^{11} \text{ 1-MeV neq/cm}^2 \text{ fluences})
HAMA1 new/after annealing

envelope represents variations over tested sensors (8 x column at given radiation level)

<table>
<thead>
<tr>
<th>Fluence (1 MeV-neq)</th>
<th>DCR (kHz)</th>
<th>DCR (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 µm</td>
<td>25 µm</td>
</tr>
<tr>
<td>new</td>
<td>1.1</td>
<td>2.4</td>
</tr>
<tr>
<td>~ $10^8$</td>
<td>4.4</td>
<td>7.0</td>
</tr>
<tr>
<td>$10^9$</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>$10^{10}$</td>
<td>100</td>
<td>95</td>
</tr>
<tr>
<td>$10^{11}$</td>
<td>730</td>
<td>770</td>
</tr>
</tbody>
</table>

SPAD cell size doesn't seem to make big difference, fill-factor might be other element to choose best SiPM sensor for RICH application.
SiPM 2022 plans

Improved setup for characterization in Bologna

Repeated irradiation-annealing cycles to prove the "mitigation strategy"

- $1 \times 10^9$ cm$^2$ 1 MeV-n$_{eq}$ → 4/6/2022
- $2 \times 10^9$ cm$^2$ 1 MeV-n$_{eq}$ → 16/7/2022
- $3 \times 10^9$ cm$^2$ 1 MeV-n$_{eq}$ → end of August
- $4 \times 10^9$ cm$^2$ 1 MeV-n$_{eq}$ → December

Five brand new SiPM carriers (134 sensors)
HAMA1, HAMA2, FBK (2), OnSemi
SiPM for calorimeters (I)

- very different context: no single-photon requirements
- very consolidated experience: SiPM made possible STAR Forward Calorimeter System (> $10^4$ SiPM from HPK) + sPHENIX (> $10^5$)
- operated with no cooling @STAR
- use of SiPM foreseen in EIC Detector 1 Calorimeters

2017 result!

Irradiation of a large sample of SiPM (152) showed different degradation at equal irradiation, traced then to heating (due to leakage current) in the avalanche region

→ fixed with current requirements on SiPM operated in the FCS

Note: for EIC applications need to move from 3x3 to 6x6 noise may reach 20 MeV (or cooling needed)

For calo eRD please check eRD105 and eRD106/7 presentations today

Use 2022 to develop FEE board for 6x6 (under eRD106) and apply to eRD110 in FY23 to buy SiPM
SiPM for calorimeters (II)

- SiPMs @sPHENIX will receive a dose $\sim 10^{11} \text{ n/cm}^2$ over the currently 3 yr lifetime.
- sPHENIX uses cooling system.

R&D Issues for SiPMs for EIC calorimeters:

- Need for large area ($\geq 6 \times 6 \text{ mm}^2$) SiPMs with small pixel size (10-15 $\mu\text{m}$) at low cost. Issue for manufacturers.
- Shashlik calorimeters will have high segmentation with an individual readout for each fiber. This will require low-cost small area ($\sim 2 \times 2 \text{ mm}^2$) SiPMs with small pixel size. However, due to high channel count, cost of readout electronics will be an issue.
- While radiation exposures at EIC are expected to be much less than at LHC or in RHIC HI running, devices with less susceptibility to radiation damage (particularly neutrons) would enhance long term stability and performance.
- SiPMs with less temperature dependence would also improve long term stability and performance.
- Lower noise would be extremely beneficial for RICH applications.

Credits: Craig W.
See his talk at SiPM meeting for more details.
Some recent meetings to get more info

https://indico.bnl.gov/event/14715/

Meeting on SiPM Use and Needs at EIC
Friday 4 Feb 2022, 08:00 → 10:00 US/Eastern
February meeting convened by Patrizia and Thomas

https://indico.bnl.gov/event/15059/

LAPPD Workshop
Monday 21 Mar 2022, 08:00 → 12:00 US/Eastern
March meeting convened by eRD110 -LAPPD

More info on SiPM calorimeter program in eRD110 (not covered too much in this talk)

Note talks from NALU, Incom and many other groups (behind EIC) + R&D at ANL (including magnetic field tests)
Summary and outlook

LAPPD:
• Proof of principle measurements confirming feasibility of Gen II LAPPD use for single photon detection in Cherenkov imaging applications → results presented at La Biodola workshop (May 2022)
• Readout board optimization on-going (spatial resolution performance, cross talk suppression and instrumented channel count optimization) → upcoming test beam @FNAL June 2022
• Magnetic field tests submitted to IEEE NSS-MIC

SiPM:
• Results of 2021 campaign to be presented at NDIP2022 in Troyes
• 2022 irradiation campaign will establish if annealing strategy/protocol holds → next step move to "cooling/heating" challenges + integrated dRICH tiles (256 SiPM with 4 8x8 tiles)
• for calorimeters: larger (6x6 mm²) SiPM with small cell (15 µm) one of the topics to be investigated in 2023
• summing up know-how and expertise from "RICH & CALO people" we can build a really nice SiPM-EIC team!

Many thanks to many eRD110 colleagues for material and input, including: Y. Ilieva, A. Kiselev, R. Preghenella, C. Woody, J. Xie.
Additional info
EIC and radiation levels

Having as target 100 fb\(^{-1}\) (several years at maximum luminosity) this brings \(10^{11} \text{n/cm}^2\) 1 MeV-neq as "maximum"

• 10 fb\(^{-1}\) in 30 weeks of operations at \(10^{34} \text{s}^{-1}\text{cm}^2\)
• 100 fb\(^{-1}\) in 10 years \(\rightarrow 1.5 \times 10^9 \text{n/cm}^2\)

Potential location of sensors in ATHENA design. To be revised in ECCE (180<z<280) but order of magnitude will not change.

\(\approx 1.5 \times 10^7 \text{n/cm}^2\) (100 keV \(\approx 1\) MeV-neq) every 1 fb\(^{-1}\)

Foreseen radiation levels allow one to consider solutions already available on the market + strategy to mitigate the radiation damages
ECCE radiation levels

Sources:
ECCE radiation levels: [https://indico.bnl.gov/event/14715/contributions/59782/attachments/39682/65822/SiPMs%20for%20EIC%202022.pdf](https://indico.bnl.gov/event/14715/contributions/59782/attachments/39682/65822/SiPMs%20for%20EIC%202022.pdf)
Detector positions: [https://physdiv.jlab.org/EIC/Menagerie/docs/DetectorParameterTable.pdf](https://physdiv.jlab.org/EIC/Menagerie/docs/DetectorParameterTable.pdf)
SiPM and radiation damages

Comprehensive (2018) review on radiation damages on SiPM from E. Garutti and Y. Musienko

NIM A 926 (2019) 69-84
https://doi.org/10.1016/j.nima.2018.10.191

M. Calvi et al., NIMA 922 (2019) 243–249
https://doi.org/10.1016/j.nima.2019.01.013

Hamamatsu S13360-1325CS (1.3x1.3 mm²)
Hamamatsu S13360-1350CS (1.3x13 mm²)

@ -40°C

After annealing

x 200
How often to do annealing?

**Credits:** Roberto P.  
see his talk at SiPM meeting for more details

**Key point:** we need to test the effect of iteration of radiation/annealing cycles
How a dRICH "tile" could look like (toward FY23)

- SiPM selection
- ASIC development
- annealing protocol
- cooling (& annealing *in situ*)

*a lot of R&D ahead of us!*

Cooling system from LCHb (SciFi tracker) for SiPM expected to work at -50 C
LHCb-PUB-2015-008
LAPPD readout details

Test setup

- Light-light enclosure
- Up to 320 DRS4 channels (V1742 digitizers)
- MCX to high-density Samtec adapter cards

Modular setup: it takes one only half an hour to exchange (or rotate) the readout board

Experimental setup (Fermilab Test Beam Facility)

- The same setup as in the lab, but instead of laser use a thick aspheric lens as a well controlled Cherenkov light source
  - Off-the-shelf component
  - (Almost) no stray photons
  - To first order no need in tracking
  - The used model (Edmund Optics #67-265, EFL 20.0mm) produces a crisp ~76mm diameter ring at the focal plane

 credits: Alexander K. see his talk at Elba meeting for more details