R&D for high resolution calorimetry at the future Electron-ion collider

Carlos Muñoz Camacho
(for the eRD1 calorimetry consortium)

Institut de Physique Nucléaire d’Orsay, CNRS/IN2P3 (France)
Electron-Ion Collider: physics highlights

3D structure of the nucleon is nontrivial
- Far more than the simple valence quark structure
- How proton properties arise from the elementary constituents?

How do gluons confine themselves into hadrons

Gluon dynamics plays a large role in proton spin
- Spin= intrinsic (parton spin) + motion (orbital angular momentum)

Dynamical balance between gluon radiation and recombination
Saturation of gluons?
Calorimetry for EIC

- Electron identification and triggering (e-EMC, barrel EMC)
- Electron kinematic measurements (e-EMC, barrel EMC), high resolution needed.
- Jet, DIS kinematics and triggering via hadron final states (barrel EMC/Hcal, h-EMC/Hcal)
- Photon ID for DVCS
- Diffractive ID via rapidity gap (h-HCal)
- High momentum track energy measurement (h-Hcal)

BeAST (Brookhaven eA Solenoidal Tracker)

Jlab EIC detector design

Babar-magnet based detector (RHIC)
Ongoing calorimetry R&D for EIC

Consortium created in 2012, funded by generic EIC detector R&D funds from US DOE

- Sci-fiber EM calorimeter (SPACAL)
  - Compact W-scifi calorimeter, developed at UCLA
  - Investigating high resolution version for e-going endcap
  - Investigating large scale production and projectivity, driven by sPHENIX project
- Crystal EMCal at small angle: high energy resolution and PID needed
  - Option for high resolution e-going endcap calorimeter
- Shashlyk EMCal
  - Option for h-going endcap calorimeter
- HCal
  - Prototype development in collaboration with STAR forward upgrade and sPHENIX
- Sensor
  - SiPM and APDs, radiation studies and support electronics
- Simulation
  - Full detector simulation and analysis frameworks
SPACAL: towards high energy resolution

- For e-going endcap ECal, high resolution is preferred:
  With the SPACAL technology, higher resolution could be achieved with high sampling frequency and fraction

- UCLA tested W(75%)/Sb(25%) - SciFi SPACAL with $d=0.67\text{mm}$ in 2015, but the light yield is low w.r.t. expectation.

- Study on high resolution SPACAL test beam last week!

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For e-going EMC, high resolution is preferred compared to h-going EMC. The plot shows the performance of various experiments with the goal of minimizing the energy resolution $\sigma/\sqrt{E}$, where $E$ is the energy and $\sigma$ is the resolution. The SPACAL technology is highlighted, aimed at achieving a lower energy resolution than current experiments like ZEUS (Pb), ZEUS (U), HELIOS, U2A, and others. The SPACAL technology is expected to improve the resolution significantly, as indicated by the lower values on the plot. A portion of the SPACAL technology tested in 2015 is shown in the image, indicating a promising future for high energy resolution in particle physics experiments.
SPACAL beam test at FermiLab (May 4-10, 2016)

Goals:
- Is production homogeneity of the block sufficient? (SF kept within +-0.2% from block to block during production)
- Is local density/composition variations are under control?
- (W/Sn composite absorber during packing)
- Is light yield is sufficient to think about compact readout with Si sensors in future?
- What is the effect of ‘dead’ area between superblocks.
- What are benefits of using square fibers?

Two prototypes:
  a) High Frequency.
  b) High Sampling Fraction

Results presented for the worst case scenario:
- Impact hits selected with sc. Hodoscope centered between four blocks
- Impact angle 10 deg (minimal angle for EIC)
- Energy scans taken with orientation of ‘wide’ central gap being vertical as shown and horizontal, i.e. for cases when narrow core of EM showers sample or integrate dead area.

O. Tsai
SPACAL beam test: results

Square fibers meet EIC design goals

\[ f(E) = \sqrt{\frac{p_0^2}{E} + p_1^2 + 0.01875^2} \]

ECal Resolution

Beam energy spread \( \sim 2\% \)

O. Tsai
SPACAL beam test: results

‘High Frequency’ prototype:
Combination of composite absorber and thin fibers leads to internal inhomogeneities, which increases constant term about factor of three (3%) compared to detector built from square fibers.

Effets of cracks in E resolution

W/Sn composite absorber and thin fibers

Constant term < 1%, when removing hits +/- 2.5 mm near the cracks.
SPACAL beam test: conclusions

- Is production homogeneity of the block sufficient?
  Yes, for Square Fiber EM Prototype.
- Is local density/composition variations are under control?
  Probably No, for composite absorber.
- Is light yield is sufficient to think about compact readout with Si sensors in future?
  Yes, 5000 p.e./GeV, Square fibers.
- What is the effect of 'dead' area between superblocks.
  Increased constant term, need to reduce 'vertical' crack in future.
- What are benefits of using square fibers?
  More light, shape may be more suitable for future compact readout.

Very promising results, already better than excellent H1 EMcal. Clear direction for future developments and improvements.
High resolution calorimetry for electron endcap

*PID requirements in the electron endcap primarily driven by semi-inclusive and exclusive processes, e.g., DVCS
Detection at very small angle is needed*

EM calorimetry has two main functions:

- **Particle identification**: important for discriminating single photons from, e.g., DVCS and two photons from p0 decay, and e/p.
- **Particle reconstruction**: driven by the need to accurately reconstruct the four-momentum of scattered electrons at small angles, where the angular information is provided by the tracker, but the momentum (or energy) can come from either the tracker or the EM calorimeter.

**Requirements:**

- Good resolution in angle to at least 1 degree to distinguish between clusters
- Energy resolution to a few %/sqrt(E) for measurements of cluster energy
- Ability to withstand radiation down to at least 1 degree with respect to the beam line

Collaboration: BNL, Caltech, CUA, IPN-Orsay
A key question of ongoing R&D is to determine whether the EIC could use more relaxed crystal specs, also in terms of parameter variation between crystals.
High resolution calorimetry based on PbWO₄ crystals

- PbWO₄ has been extensively used for high precision calorimetry (CMS, JLab, PANDA…) because its energy and time resolutions and its radiation hardness.
- BTCP (Russia) produced high quality crystals in the past using the Czochralsky growing method, but it’s now out of business.
- SICCAS (China) uses the Bridgeman method, but has problems maintaining good crystal quality.
- Need to develop an alternate supplier of PbWO₄ in order to ensure worldwide availability of high quality crystals (potential candidate: CRYTUR, Czech Republic).

\[
dk = \frac{\ln(T_{bef} / T_{aft})}{D}
\]

Light yield: large variations crystal to crystal

Radiation hardness of recent SICCAS crystals

PANDA requirements
\(dk<1.1\) after 30Gy
Setting up infrastructure for crystal testing

IPN-Orsay (France)

- Optical Transmittance (L/T)
  - Varian Cary 5000 spectrometer
  - Setup was commissioned with BTCP crystals on loan from Giessen
  - To accommodate crystals of lengths greater than 15 cm a more versatile configuration with a fiber-based spectrometer is being commissioned

- Crystal light yield and timing
  - A setup is currently being tested with cosmic rays

- Radiation Hardness
  - Panoramic irradiation facility available ($^{60}$Co sources):
    - 5000 Gy/h at 10 cm
    - 300 Gy/h at 35 cm
    - 6 Gy/h at 260 cm
  - At ~1m 30 Gy in ~30 min

  - ALTO at IPN-Orsay:
    - 50 MeV electrons up to 1uA
    - Proton beam (Tandem) also available
Test of recent CRYTUR crystals

- 3 new (2016) crystal with dimensions: 20x20x18.5 mm³
- Low light yield (12-13 pe at 18°), with tolerable non-uniformity (maybe due to high doping)
- Acceptable tranmittance. Longitudinal transmittance does not show absorption band in the luminescence range
- Crystal similar to CMS quality (shift of transmittance edge and low radiation induced coefficient)

First full size (2x2x20 cm³) crystal produced by CRYTUR (Oct 2015)

Grown in Ar atmosphere & doped with La+Y
Setting up infrastructure for crystal testing

CUA (USA)

Light yield:

Temperature dependence

Comparison with Giessen measurement at 18°:
- CUA: 19.4 +/- 0.7 pe/MeV
- Giessen: 19.2 pe/MeV

Warning: PMTs quantum efficiencies are similar, but probably different.
Lambda 750
UV/VIS/NIR

Transverse transmittance of individual crystal

T (360.0 nm) = 57.73 %
T (420.0 nm) = 64.99 %
T (620.0 nm) = 71.45 %
Edge at 342.0 nm

Stepper motor based setup

Variation of crystals' transverse transmittance in the lot
Other activities in progress

Radiation hardness

Lower energy range (1-160 keV)

Intermediate energy (1.17, 1.33 MeV)

X-ray machine

0.5 mCi - Co-60

Scintillating with x-rays

Light annealing (LED)

Thermal annealing (oven)
Calorimetry: simulations and radiation dose estimates

EIC neutron fluence (as BeAST in eRHIC) calibrated to STAR
Worst region in h-going calorimeter

1 year EIC run $\sim$ a few $10^{10}$ $n_{eq}/cm^2$ $\sim$ 1 RHIC run
Challenging but possible for SiPM, also considering APD options
e-going calorimeter and barrel calorimeter
$\sim$ two order magnitude lower n-flux
Safe for SiPM operation

eRD1 also plays major roles in maintaining simulation & analysis frameworks, that is open source for full EIC detector simulation

BeAST detector placed in STAR hall

Evaluated with EICRoot by A. Kiselev (BNL)
Crosschecked with sim STAR in RHIC

Neutron flux above 100 KeV per $10^6$ PYTHIA events
Summary and conclusions

eRD1 explores calorimeter technology for EIC in multiple fronts:

- **Scintillation fiber calorimeter**
  - Developed by UCLA group for EIC barrel and endcaps
  - Very promising results from recent test run at FermiLab
  - On-going R&D focus on higher energy resolution, mass-production capabilities and projectivities

- Potentially 2 vendors available for PWO crystals:
  - SIC show quality control instabilities
  - Crytur making very good progress towards mass production capabilities

- Infrastructure being developed at CUA and IPNO for crystal quality control
- Prototype being constructed for beam test
- **SiPM radiation tests**, neutron background ≤ RHIC
- Full detector **simulation** environment open to users