AN eRHIC DETECTOR: DESIGN CONSIDERATION AND ITS REALIZATION BY MEANS OF DETECTOR R&D
Physics of strong color fields

- Establish the existence of saturation regime
- Explore non-linear QCD
- Measure momentum and space-time of glue

Spin physics with polarized $e+p$

- Precisely image sea-quarks and gluons for determining spin, flavor, and spatial structure of the nucleon

Determine quark and gluon contributions to the proton spin at last
Dedicated EIC Detector @ eRHIC

• Detector must be multi-purpose
  – One detector for inclusive (ep -> e’X), semi-inclusive (ep->e’hadron(s)X), exclusive (ep -> e’πp) reactions in ep/eA interactions
  – run at very different beam energies (and ep/A kinematics)
    \[ E_{p/A}/E_e \sim 1 - 65 \rightarrow \text{HERA: 17 – 34; lepton beam energy always 27GeV} \]

• Inclusive DIS:
  – with increasing center-of-mass energy lepton goes more and more in original beam direction
  – high Q^2 events go into central detector
  – low Q^2 events have small scattering angle and close to original beam energy
    need low forward electron tagger for low Q^2 events
    low-mass high resolution trackers over wide angular acceptance

• Semi-Inclusive DIS
  – hadrons go from very forward to central to even backward with lepton beam energy increasing
    good particle-ID over the entire detector

• Exclusive Reactions:
  – decay products from excl. \( \rho / \phi / J/\psi \) go from very forward to central to even backward with lepton beam energy increasing
Design Interaction Region

- 10 mrad crossing angle and crab-crossing
- High gradient (200 T/m) large aperture Nb$_3$Sn focusing magnets
- Arranged field-free region where electron pass through the hadron triplet magnets
- Integration with the detector: efficient separation and registration of low angle collision products
- Gentle bending of the electrons to avoid SR impact in the detector

eRHIC - Geometry high-lumi IR with $\beta^*=5$ cm, $I^*=4.5$ m and 10 mrad crossing angle → this is required for $10^{34}$ cm$^{-2}$ s$^{-1}$

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- High gradient (200 T/m) large aperture Nb$_3$Sn focusing magnets
- Arranged field-free region where electron pass through the hadron triplet magnets
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All optimized for dedicated detector

Have ±4.5m for main-detector

→ roman pots / ZDC

→ low Q²-tagger

need to be integrated in the IR design
Detector Concept
• Si-Vertex Detector
  – MAPS technology from IPHC concept as STAR-HFT, CBM, Alice, ...
    • Barrel:
      4 double sided layers @ 2.5 / 5.0 / 7.5 / 15.0 cm, 10 sectors in \( \Phi \)
      Rapidity coverage: at least \(|\eta| = 1\)
      Chip 20mm x 30mm \(\rightarrow\) 1cm 300 pixel pitch 33 \(\mu\)m
      Dual sided readout, one column 60 \(\mu\)s readout time
      Radiation length 5 % / layer (50\(\mu\)m Si)
      \(< 5\mu m \) Vertex resolution

• Forward Disks:
  At least 4 single sided disks spaced in \(z\) starting from 20cm
  Radial extension 3 (19 \(\mu\)m pixel) to 12 cm (75 \(\mu\)m pixel),
  Dual sided readout \(\rightarrow\) 300x200ns = readout time 60\(\mu\)s
  Need a 0.3\(\mu\)m region at each side of the wedge for readout
  Radiation length 3 % / layer
  Stitching technology
MIMOSA26 is a reticule size MAPS with binary output, 10 k images / s

- Pixel array: 1152 x 576, 18.4 μm pitch
- Architecture:
  - Pixel (Amp+CDS) array organised in // columns r.o. in the rolling shutter mode
  - 1152 ADC, a 1-bit ADC (discriminator) / column
  - Integrated zero suppression logic
  - Remote and programmable

Lab. and beam tests

- ENC ~ 13-14 e⁻
- Efficiency 99.5% for fake rate $10^{-4}$
- Single point resolution ~4 μm
Tracking - Barrel

Catho

End Plate

B = 1 T

Preliminary

\[ \sigma_x = \sqrt{\sigma_0^2 + \left( \frac{C_D}{N_{eff}} \right)^2} \]

fitting result

\[ \frac{C_D}{\sqrt{N_{eff}}} = 22.6 \pm 0.7 \, [\mu m/\sqrt{cm}] \]

\[ C_D = 101.6 \pm 0.4 \, [\mu m/\sqrt{cm}] \]

\[ \frac{C_D}{\sqrt{N_{eff}}} \approx 22.6 \pm 0.7 \, [\mu m/\sqrt{cm}] \]

\[ N_{eff} \sim 20 \pm 1 \]
• TPC readout with Micro Pattern Gas Detector (GEM, MicroMegas)
• Readout based on
  • Pads and analogue FE (ALTRO)
  • Pixel readout -> TimePix: can provide digital $dE/dx$ measurement
  • Combination of both
• Counting gas studies
  • Resolution (longitudinal/transverse diffusion)
  • Drift velocity
  • Ion back drift
  • Field distortions
• Low mass TPC
• Best track finding ($> 25$ space points) with $\sigma_r < 150 \, \mu m$, $\sigma_z \sim 300 \, \mu m$
Tracking - Forward

COMPASS GEM Tracker → GEM Forward Tracker in eRHIC

Honeycomb plates

GEM foils

3 mm DRIFT
2 mm TRANSFER 1
2 mm TRANSFER 2
2 mm INDUCTION

2-D Readout board

GDD, CERN

Pitch for each layer: 400 μm
GEMs are used in the TOTEM (tracking and triggering) and LHCb Muon (triggering) systems.

**TOTEM GEMs:**
- 2D readout (strips & pads)
- GEM modules
- Coincidence Chips
- 11th Card
- Horse Shoe Card
- HV cables
- Electronics cooling
- VFAT Hybrids

**LHCb Muon Trigger:**
- (12 double TGEM detectors)
- Rate - 5 kHz mm-2
- Time resolution 4.5 ns rms
- Radiation hard up to integrated charge of 20 mC mm-2 (15 LHCb years)

**S. Lami, 2009 IEEE NSS/MIC Conference Record.**

Particle Identification

Barrel
- TPC with dE/dx combined with Cherenkov detector (CD) with gaseous radiator (CF$_4$; $n_r = 1.0005$)
- DIRC
- ToF: “next generation” with ~10ps time resolution -> $t_0$ problem
- Aerogel as proximity focused CD plus ToF
- Proximity focused CD with liquid radiator ($C_6F_{14}$, $n_r = 1.27$)
- EmCal

Forward
- CD with gaseous radiator ($C_4F_{10}$ or $C_4F_8O$; $n_r = 1.0014$, CF$_4$) and CsI-GEM photo-detectors, plus tracking
- ToF
- EmCal

Very forward
- EmCal
• Liquid radiator (e.g. liquid C$_6$F$_{14}$) followed by expansion volume.

• HBD like readout (GEMs with CsI) -> smaller readout area

• $\pi$/K separation depends on:
  – Index of refraction
  – Expansion distance

• Other radiators required to fulfill the need of production / transparency to VUV photons (~100-200 nm for CsI readout)
DIRC: Detection of Internally Reflected Cherenkov light

- DIRC intrinsically 3-dim detector
- Radiator and light guide: Synthetic Fused Silica
- Internal reflections are responsible for conservation of Cherenkov angle
- Readout in “expansion region” -> compact device
- Cherenkov photons are measured
  - x, y, t “coordinates”
  - Define $\theta_c$, $\phi_c$, $t_{prop}$
• BABAR PID in 1-5 GeV range
• Efficiency drop about 2.5 GeV
• Getting worse for $p > 3.5$ GeV
  – Extend with higher granularity readout?
### Forward Particle Identification

#### Cherenkov UV radiators

<table>
<thead>
<tr>
<th>Material</th>
<th>n</th>
<th>$\pi_{\text{thr}}$ (GeV/c)</th>
<th>$K_{\text{thr}}$ (GeV/c)</th>
<th>$P_{\text{thr}}$ (GeV/c)</th>
<th>$\Theta_{\text{max}}$ (deg $\beta=1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fused silica</td>
<td>1.474</td>
<td>0.13</td>
<td>0.45</td>
<td>0.85</td>
<td>47.</td>
</tr>
<tr>
<td>C6F14</td>
<td>1.29</td>
<td>0.17</td>
<td>0.60</td>
<td>1.13</td>
<td>39.</td>
</tr>
<tr>
<td>AeroGel</td>
<td>1.05 – 1.01</td>
<td>0.4 – 1.</td>
<td>1.5 – 3.5</td>
<td>3. – 7.</td>
<td>18 – 8</td>
</tr>
<tr>
<td>C4F10</td>
<td>1.0014</td>
<td>2.6</td>
<td>9.</td>
<td>17.</td>
<td>3.</td>
</tr>
<tr>
<td>Isobutane</td>
<td>1.00127</td>
<td>3.</td>
<td>10.</td>
<td>18.</td>
<td>2.9</td>
</tr>
<tr>
<td>Argon</td>
<td>1.00059</td>
<td>4.</td>
<td>14.</td>
<td>27.</td>
<td>2.</td>
</tr>
<tr>
<td>CF4</td>
<td>1.00050</td>
<td>5.</td>
<td>16.</td>
<td>30.</td>
<td>1.8</td>
</tr>
<tr>
<td>Methane</td>
<td>1.00051</td>
<td>5.</td>
<td>16.</td>
<td>30.</td>
<td>1.8</td>
</tr>
</tbody>
</table>
EM Calorimetry

- **EMCal:**
  - **Backward/Barrel:**
    - PWO (PbWO₄) - crystal calorimeter -> good resolution, small Molière radius -> electron-ID: e/π
    - measure lepton via EMCal (important for DVCS)
  - **Forward:**
    - Less demanding: sampling calorimeter (scintillating fibers and tungsten powder)
- **Preshower**
  - Si-W technology as proposed for PHENIX MPC-EX
EM Calorimetry

PWO

- **Pros**: Inexpensive and easy production
- **Cons**: Low light yield output, resolution affected by electronic noise

Good resolution for high energy electrons, worse for low energy
Study needed for doped PWO to improve light yield output and electronic noise reduction.
EM Calorimetry

Jian Wu et al, NIMA 404 (1998) 311

CMS PWO: ~18 phe/MeV for $^{137}$Cs

About a factor of 2 achieved with new doped technique.

Doped PWO from SICCAS:
$^{60}$Co: 29.8 phe/MeV
$^{137}$Cs: 30.4 phe/MeV
✓ The Electron Ion Collider EIC will answer compelling questions for QCD
✓ eRHIC is one EIC option
  • eRHIC will be considering eSTAR, ePHENIX, and a dedicated eRHIC-detector
  • Dedicated eRHIC detector capable to cover EIC physics
✓ Ongoing studies for eRHIC sub detectors
✓ Detector R&D for
  ✓ Tracking -> VTX, Forward, Barrel
  ✓ PID
  ✓ Calorimetry
Future DIS experiment at an Electron Ion Collider: A high energy, high luminosity (polarized) $ep$ and $eA$ collider and a suitably designed detector

Measurements:

[1] $\rightarrow$ Inclusive


[1] and [2] and [3] $\rightarrow$ Exclusive

Inclusive $\rightarrow$ Exclusive

Low $\rightarrow$ High Luminosity

Demanding Detector capabilities
Physics Requirements

**Inclusive Reactions:**
- Momentum/energy and angular resolution of $e^\prime$ critical
- Very good electron id
- Moderate luminosity $>10^{32}$ cm$^{-1}$ s$^{-1}$
- Need low $x \sim 10^{-4} \rightarrow$ high $\sqrt{s}$ (Saturation and spin physics)

**Semi-inclusive Reactions:**
- Good particle ID: $\pi,K,p$ separation over a wide range in $\eta$
- Full $\Phi$-coverage around $\gamma^*$
- Good vertex resolution $\rightarrow$ Charm, bottom identification
- High luminosity $>10^{33}$ cm$^{-1}$ s$^{-1}$ (5d binning $(x,Q^2,z,p_t,\Phi)$)
- Need low $x \sim 10^{-4} \rightarrow$ high $\sqrt{s}$

**Exclusive Reactions:**
- Exclusivity $\rightarrow$ high rapidity coverage $\rightarrow$ rapidity gap events
- high resolution in $t \rightarrow$ Roman pots
- high luminosity $>10^{33}$ cm$^{-1}$ s$^{-1}$ (4d binning $(x,Q^2,t,\Phi)$)
All energies scale proportionally by adding SRF cavities to the injector.

All magnets would be installed from the day one and we would be cranking power supplies up as energy is increasing.

erHIC design has evolved to make optimal use of existing RHIC infrastructure, and to permit straightforward (multi-step) upgrades from Phase 1 to eventual full electron energy.

Technical design review
Aug. 1-3, 2011; aim for cost review Spring 2012
Detector Requirements

• Wide acceptance \(-5 < \eta < 5\) for both the scattered lepton and the produced hadron.
• The same coverage in electromagnetic calorimetry and tracking.
• High electron track finding / reconstruction efficiency, high precision for momentum (energy) reconstruction.
• Particle identification to separate electrons and hadrons as well as pions, kaons and protons over a momentum range of 0.5 GeV to 10 GeV for rapidities between \(|\eta| < 2\) and 0.5 GeV to 80 GeV for \(2 < |\eta| < 5\).
• Good vertex resolution.
• High acceptance for forward going protons and neutrons from exclusive reactions as well from the breakup of heavy ions.
# EM Calorimetry

## Small d, small sampling fraction (A)
SciFi calorimeters.

**Pros:**
- Good energy, position resolution.
- Fast, compact, hermetic.

**Cons:**
- Projectivity, high cost ($1/10^{th}$ of crystals).

**Example (H1)**

<table>
<thead>
<tr>
<th>$R_{\text{Moliere}}$</th>
<th>$X_0$</th>
<th>Energy resol.</th>
<th>Density</th>
<th>Number of fiber/tower</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8 cm</td>
<td>0.7 cm</td>
<td>$\sim 10% /\sqrt{E}$</td>
<td>$\sim 10$ g/cm$^3$</td>
<td>$\sim 600$ (0.3 mm diameter, 0.8 mm spacing)</td>
</tr>
</tbody>
</table>

## Small d, large sampling fraction (B)
“Shashlik” type.

**Pros:**
- Excellent energy resolution
- Reasonably fast
- Small dead areas

**Cons:**
- Low density, projectivity.
- Moderate cost

**Example (KOPIO/PANDA)**

<table>
<thead>
<tr>
<th>$R_{\text{Moliere}}$</th>
<th>$X_0$</th>
<th>Energy resol.</th>
<th>Density</th>
<th>Number of layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 cm</td>
<td>3.4 cm</td>
<td>$4% /\sqrt{E}$</td>
<td>2.5 g/cm$^3$</td>
<td>Pb/Sc $\times 400$</td>
</tr>
<tr>
<td>0.3 mm Pb/1.5 mm Sc</td>
<td>400 layers</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Large d, large sampling fraction (C)
Tile/Fiber type.

**Pros:**
- Energy resolution OK
- Reasonably fast
- Very cost effective

**Cons:**
- Moderate density, large dead areas.

**Example (STAR BEMC)**

<table>
<thead>
<tr>
<th>$R_{\text{Moliere}}$</th>
<th>$X_0$</th>
<th>Energy resol.</th>
<th>Density</th>
<th>Number of layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 cm</td>
<td>1.2 cm</td>
<td>$15% /\sqrt{E}$</td>
<td>6 g/cm$^3$</td>
<td>Pb/Sc $\times 20$</td>
</tr>
<tr>
<td>5 mm Pb/ 5 mm Sc</td>
<td>20 layers</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
EM Calorimetry

PWO @ CMS

Test-beam performance

The careful control of crystal properties shows that a very good resolution can be obtained

Crystal 2070
E = 280 GeV
σ/E = 0.40%

280 GeV electrons

1999 prototype
- 30 preprod. crystals
- Charge ADC

Resolution as a function of energy

$$\sigma \over E = 2.74\% \over \sqrt{E} \oplus 0.40\% \oplus {142\text{MeV}} \over E$$
Electromagnetic fiber calorimeter
Electromagnetic fiber calorimeter

Measured scintillation light from a 23cm long bundle of nine 1mm diam BCF10 scintillating fibers. Read out with a 3x3mm MPPC. Uncollimated Cs-137 source moved along length.

Challenge is to collect all this light onto a relatively small area (SiPM or APD)
Momentum/Theta resolution using parameterization inspired by ZEUS 20 GeV x 100 GeV and 5 GeV x 100 GeV
Roman Pots

Example: Roman Pot system @ TOTEM

- Vertical and horizontal pots
- Vacuum compensation system interconnected to machine vacuum
- Individual stepper motors
- Adjustable jacks for alignment

\[ \delta = 47 \, \mu m \text{ insensitive area} \]
\[ c = 200 \, \mu m \text{ distance to window} \]
\[ t = 150 \, \mu m \text{ window thickness} \]
\[ s(t) = < 50 \, \mu m \text{ flatness} \]

\[ f = \text{window displacement in case of vacuum loss} = 50 \, \mu m \text{ at 100 mbar}. \]
Roman Pots

Generated Quad aperture limited RP (at 20m) accepted
• Two horizontal RP stations at z=20m
  • Active area 10 cm x 7 cm each
• Two vertical RP stations at z=22m
• Each station implemented as
  • Four layers Si
  • One layer scintillator