Dec 2008, NPP ALD S. Vigdor: suggested to work on a simpler system than the deuteron

Protons at their magic momentum: All-electric storage ring experiment, eliminate all magnetic fields; much smaller R&D effort needed

BNL could provide the required beam today!
The current status

- Have developed R&D plans for 1) BPM magnetometers, 2) SCT at COSY and software, 3) E-field development, and 4) Polarimeter

- We had two successful technical reviews: Dec 2009, and March 2011.

- Exp. Method and R&D plan blessed by both review committees. We have greatly benefited from their recommendations

- Preparing a proposal to DOE for CD0 for a proton EDM experiment at BNL: end June 2011
EDMs of hadronic systems are mainly sensitive to

- Theta-QCD (part of the SM)
- CP-violating sources beyond the SM

Alternative simple systems are needed to be able to differentiate the CP-violating source (e.g. neutron, proton, deuteron,…).

At $10^{-29}$ e\cdot cm is at least an order of magnitude more sensitive than the best current nEDM plans.
A charged particle between Electric Field plates would be lost right away...
...but can be kept in a storage ring for a long time. The radial E-field is balanced by the centrifugal force.
The sensitivity to EDM is optimum when the spin vector is kept aligned to the momentum vector.

At the magic momentum

\[ p = \frac{m}{\sqrt{a}} \]

the spin and momentum vectors precess at same rate in a E-field.
The spin precession relative to momentum in the plane is kept near zero. A vert. spin precession vs. time is an indication of an EDM ($d$) signal.

\[ \vec{\omega}_a = 0 \]

\[ \frac{d\vec{s}}{dt} = \vec{d} \times \vec{E} \]
When $P = P_{\text{magic}}$ the spin follows the momentum.

No matter what the E-field value is, the spin follows the momentum vector, creating an ideal Dirac-like particle ($g = 2$).

1. Eliminates (to first order) geometrical phase effect
2. Equalizes the beta-functions of counter-rotating (CR) beams
3. Closed orbits of the CR beams are the same
High intensity charged particle beams can be stored for a long time

Statistics:
- High intensity ($4 \times 10^{10}$), highly polarized beams (>80%)
- Keep spin along the momentum, radial E-field (10MV/m) acts on proton EDM
- Long (~$10^3$s) spin coherence time (SCT) is shown
- High efficiency (0.5%), with large analyzing power (50%)

Systematics:
- Magnetic field shielding + feedback to keep vertical spin <0.3mrad/storage
- Store counter-rotating beams + BPMs to probe $<B_r>$
- Longitudinal impedance: <10KΩ
- Forward/backward bunch polarizations (polarimeter)

Software development:
- Benchmarking at COSY with stored beams
- At least two different approaches, speed, accuracy
Review of Dec 2009

• Great Physics; complementary to LHC
• Recommendation: Use all E-field focusing (all-electric ring)

• Critical items:
• 1) SCT (benchmark software with polarized beams at COSY)
• 2) BPMs (test with beams at RHIC)
Since Dec 2009 Review

1. Adopted the E-field focusing option in spring 2010 after studying issues

2. Started a test program at COSY on SCT; longer SCT w/ cooling; software benchmarking

3. Developed significant understanding of the E-field issues for beam dynamics tracking

4. Studied BPM systematics, developed BPM magnetometer based on low $T_c$ SQUIDS
The proton EDM ring

As shown at the March 2011 review with limited straight-section length

Weak vertical focusing to optimize SCT and BPM operation

B: quadrupoles
Since the March 2011 review

- The straight section length can be much longer than previously thought (>50m if needed!)

S. Haciomeroglu
Istanbul T.U., PhD student:

Studying SCT of an all-electric storage ring as a function of straight section length.

SCT is found to be independent of straight section length!
# Experimental needs

<table>
<thead>
<tr>
<th>C.R. proton beams</th>
<th>0.7 GeV/c</th>
<th>$\geq 80%$ polariz.; $\uparrow$</th>
<th>$\sim 4 \times 10^{10}$ protons/store</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 10^2$ m base length</td>
<td>Repetition period: $10^3$s</td>
<td>Beam energy: $\sim 1$J</td>
<td>Average beam power: $\sim 1$ mW</td>
</tr>
<tr>
<td>Beam emittance: 95%, norm.</td>
<td>Horizontal: 2 mm-mrad</td>
<td>Vertical: 6 mm-mrad</td>
<td>$(dp/p)_{rms} \sim 2 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

- CW & CCW injections: Average emittance parameters: same to $\sim 10\%$ at injection.

C-AD can provide a beam with these parameters even today!
The grand issues in the proton EDM experiment

1. BPM magnetometers (need to demonstrate in an accelerator environment)

2. Spin Coherence Time (SCT); Software development for an all-electric ring: SCT and systematic error studies

3. Electric field development for large surface area plates

4. Polarimeter development: high efficiency, small systematic errors
1. Beam Position Monitor

- Technology of choice: Low $T_c$ SQUIDS, signal at $10^1$-$10^4$Hz (10% vertical tune modulation)
- Test sequence:
  1. Operate SQUIDS in a magnetically shielded area-reproduce current state of art
  2. Operate in RHIC ring (evaluate noise in an accelerator environment)
  3. Operate in E-field string test
BPMs: CR beams split if $B_r \neq 0$

- The splitting depends on the vertical tune $Q_y$
- Modulating $Q_y$ would create a frequency dependent separation and a B-field at the same frequency.

$$\langle \delta y \rangle = 2 \frac{\beta c R_0 B_{r0}}{E_r \left( Q_y^2 - N^2 \right)} \sim 2 \text{pm}$$

Vertical position vs. time
Fourier transforms of the horizontal beam position and betatron tune as measured in the blue ring (RHIC)

Choose a quiet part of the spectrum for tune modulation
Schematic of a SQUID BPM system

Designed by D. Kawall, UMASS, based on existing technology

- Tristan Technology LSQ/20 SQUID
- 64 mm long, 12.7 mm diameter
- $\leq 1 \text{ fT}/\sqrt{\text{Hz}}$

- Beam’s eye view schematic of a SQUID BPM system
- Sense coils, leads, SQUIDs at 4.2K; leads and SQUIDs in superconducting shields
- Ferrite and $\mu$-metal at room temp.
- More magnetic shielding outside Al vacuum chamber
BPM magnetometers

- Need to be shielded from the beam high frequency EM noise (to avoid SQUID saturation)
- Need to observe the low frequency B-field coming from the beam

2. SCT Development

• We have a SCT working solution (analytically and with precision tracking). Plenty of straight section length.

• Planning tests with polarized deuterons and protons at COSY to benchmark software

• First tests at COSY (January 2011) are very encouraging.
Spin Coherence Time: need $>10^2$ s

- Not all particles have same deviation from magic momentum, or same horizontal and vertical divergence (all second order effects)

- They Cause a spread in the $g$-2 frequencies:

$$d\omega_a = a \mathcal{G}_x^2 + b \mathcal{G}_y^2 + c \left(\frac{dP}{P}\right)^2$$

- Correct small effects (as needed) using sextupoles (current plan) and/or cooling (mixing) during storage (under evaluation).
Polarization with cooling holds for a long time

Why is this important? Possibility to get statistics below $10^{-29}$ e-cm. Upgrade...

Uncooled, and cooled beam profiles

quick drop in oscillation amplitude, then slow decline with oscillation center close to zero

long-lived oscillation pattern, later seen with small decline ($1/e$ time = 520 s)
Our running schedule at COSY/Jülich

<table>
<thead>
<tr>
<th>Week</th>
<th>January 2012</th>
<th>February</th>
<th>March</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>02/01/12</td>
<td>09/01/12</td>
<td>16/01/12</td>
</tr>
<tr>
<td></td>
<td>23/01/12</td>
<td>30/01/12</td>
<td>06/02/12</td>
</tr>
<tr>
<td></td>
<td>13/02/12</td>
<td>20/02/12</td>
<td>27/02/12</td>
</tr>
<tr>
<td></td>
<td>05/03/12</td>
<td>12/03/12</td>
<td>19/03/12</td>
</tr>
<tr>
<td></td>
<td>26/03/12</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>FAIR</td>
<td>MD</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>20</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>28</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>31</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>34</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>37</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>39</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>41</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>44</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>47</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>49</td>
<td>50</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>52</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**April**

<table>
<thead>
<tr>
<th>Week</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
<th>25</th>
<th>26</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>02/04/12</td>
<td>09/04/12</td>
<td>16/04/12</td>
<td>23/04/12</td>
<td>30/04/12</td>
<td>07/05/12</td>
<td>14/05/12</td>
<td>21/05/12</td>
<td>28/05/12</td>
<td>04/06/12</td>
<td>11/06/12</td>
<td>18/06/12</td>
<td>25/06/12</td>
</tr>
<tr>
<td></td>
<td>MD</td>
<td>WASA (210), 3.4 - 3.7 GeV/c</td>
<td>Maintenance</td>
<td>Maintenance</td>
<td>MD</td>
<td>EDM (176.5) 0.97 GeV/c</td>
<td>PAC</td>
<td>ANKE (201.1) GeV/c</td>
<td>1.219</td>
<td>FAIR</td>
<td>EDM Tests</td>
<td>Maintenance</td>
<td>Maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>polarized deuterons</td>
<td></td>
<td></td>
<td></td>
<td>polarized deuterons</td>
<td></td>
<td>unpolarized protons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**May**

<table>
<thead>
<tr>
<th>Week</th>
<th>27</th>
<th>28</th>
<th>29</th>
<th>30</th>
<th>31</th>
<th>32</th>
<th>33</th>
<th>34</th>
<th>35</th>
<th>36</th>
<th>37</th>
<th>38</th>
<th>39</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>02/07/12</td>
<td>09/07/12</td>
<td>16/07/12</td>
<td>23/07/12</td>
<td>30/07/12</td>
<td>06/08/12</td>
<td>13/08/12</td>
<td>20/08/12</td>
<td>27/08/12</td>
<td>03/09/12</td>
<td>10/09/12</td>
<td>17/09/12</td>
<td>24/09/12</td>
</tr>
<tr>
<td></td>
<td>Maintenance</td>
<td>Maintenance</td>
<td>Maintenance</td>
<td>MD</td>
<td>TOF (193.2) &gt;3.15 GeV/c</td>
<td>Maintenance</td>
<td>MD</td>
<td>TOF (193.2) 2.95 GeV/c</td>
<td>EDM Tests</td>
<td>FAIR</td>
<td>Maintenance</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>polarized protons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**June**

<table>
<thead>
<tr>
<th>Week</th>
<th>40</th>
<th>41</th>
<th>42</th>
<th>43</th>
<th>44</th>
<th>45</th>
<th>46</th>
<th>47</th>
<th>48</th>
<th>49</th>
<th>50</th>
<th>51</th>
<th>52</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>01/10/12</td>
<td>08/10/12</td>
<td>15/10/12</td>
<td>22/10/12</td>
<td>29/10/12</td>
<td>05/11/12</td>
<td>12/11/12</td>
<td>19/11/12</td>
<td>26/11/12</td>
<td>03/12/12</td>
<td>10/12/12</td>
<td>17/12/12</td>
<td>24/12/12</td>
</tr>
<tr>
<td></td>
<td>Maintenance</td>
<td>EDM Tests</td>
<td>FAIR</td>
<td>MD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EDM Tests</td>
<td>FAIR</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Software Development (precise 2\textsuperscript{nd} order description needed)

Describe beam/spin dynamics in electric rings

1. Slow and accurate using 4\textsuperscript{th} order Runge-Kutta integration. At production stage. Already producing results

2. Fast and accurate integrating analytically: Advanced stage.

3. Accurate description of COSY ring near production
3. Electric Field Development

• Reproduce Cornell results with stainless steel plates treated with high pressure water rinsing

• Determine:
  1. E-field vs. plate distance
  2. Develop spark recovery method

• Develop and test a large area E-field prototype plate module.
E-field plate module: Similar to the (26) FNAL Tevatron ES-separators
E-field plate module: Similar to the (26) FNAL Tevatron ES-separators
## Large Scale Electrodes, New: pEDM electrodes with HPWR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tevatron pbar-p Separators</th>
<th>BNL K-pi Separators</th>
<th>pEDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>2.6m</td>
<td>4.5m</td>
<td>3m</td>
</tr>
<tr>
<td>Gap</td>
<td>5cm</td>
<td>10cm</td>
<td>3cm</td>
</tr>
<tr>
<td>Height</td>
<td>0.2m</td>
<td>0.4m</td>
<td>0.2m</td>
</tr>
<tr>
<td>Number</td>
<td>24</td>
<td>2</td>
<td>84</td>
</tr>
<tr>
<td>Max. HV</td>
<td>±180KV</td>
<td>±200KV</td>
<td>±150KV</td>
</tr>
</tbody>
</table>
How to Scale HPWR to 3cm gap?
4. Polarimeter Development

- Polarimeter tests with runs at KVI and COSY demonstrated << 1ppm level systematic errors (long paper has just been submitted)

- Technologies under investigation:
  1. Micro-Megas/Greece: high rate, pointing capabilities, most development part of R&D for ATLAS upgrade
  2. MRPC/Italy: high energy resolution, high rate capability, part of ALICE development
Proton EDM R&D cost: $2M

- BPM development & testing over two years: $0.6M
- E-field prototype development & testing: 1.8 years: $0.4M
- SCT tests at COSY, 2 years: $0.4M
- Polarimeter prototype, 2 years: $0.6M
Technically driven pEDM timeline

- Two years R&D
- One year final ring design
- Two years ring/beamline construction
- Two years installation
- One year “string test”
The bottom line

• The proton EDM in its magic momentum proposal is at an advanced stage: ready for prime time

• Two technical reviews (Dec 2009 and March 2011) were very successful encouraging the collaboration to proceed to the proposal stage

• BPM magnetometer concept is based on proven techniques. We need to prove it in an accelerator environment.

• Other issues are low/medium risk
A proposed proton EDM ring location at BNL. It would be the largest diameter all-electric ring in the world.
## Total cost: exp + ring + beamline for two different ring locations

<table>
<thead>
<tr>
<th>System</th>
<th>Experiment w/ indirects</th>
<th>Conventional plus beamline w/ indirects</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>pEDM at ATR</td>
<td>$25.6M</td>
<td>$20M</td>
<td>$45.6M</td>
</tr>
<tr>
<td>pEDM at SEB</td>
<td>$25.6M</td>
<td>$14M</td>
<td>$39.6M</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System</th>
<th>Experiment w/ 55% contingency</th>
<th>Conv. &amp; Beamline w/ contingency</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>pEDM at ATR</td>
<td>$39.5M</td>
<td>$29.2M</td>
<td>$68.7M</td>
</tr>
<tr>
<td>pEDM at SEB</td>
<td>$39.5M</td>
<td>$22.6M</td>
<td>$62.1M</td>
</tr>
</tbody>
</table>
Conclusion

1. Measurements of $d_n$ & $d_p$ with similar sensitivity essential to unfold underlying physics. Explain Baryogenesis

2. $d_p$ has potential to do (10x) better than $d_n$

3. $d_p$ at $10^{-29}\text{e-cm}$ **must do** experiment
   - Explores physics up to scales $O(3000\text{TeV})$ for $\phi^{\text{NP}}\sim O(1)$ i.e. beyond LHC or $\phi^{\text{NP}}\sim 10^{-7}$ at LHC discovery scales!

4. Sets stage for $d_D=d_n+d_p+d(2\text{ body}), d(3\text{He})\ldots$
Summary

✓ Proton EDM physics is a must do, an order of magnitude improvement over the neutron EDM
✓ Can leap-frog the competition; complementary
✓ E-field issues well understood
✓ Working EDM lattice with long SCT and large enough acceptance \(1.3 \times 10^{-29} \text{e}\cdot\text{cm/year}\)
  - Planning BPM-prototype demonstration including tests at RHIC
  - Proposal to DOE: by end of June 2011
  - Support it…
Extra slides
Revolution time vs. gamma

Radial oscillations change the particle energy $\rightarrow$ a symmetric pattern cancelling non-linearity

S. Haciomeroglu
Istanbul T.U., PhD student:

The straight sections do not contribute to SCT.
Radial oscillations vs. time

Lstr = 28m

Lstr = 49m

Lstr = 14cm

Lstr = 14m
Physics reach of magic pEDM (Marciano)

- Currently: $\bar{\theta} \leq 10^{-10}$, Sensitivity with pEDM: $\bar{\theta} < 0.3 \times 10^{-13}$

- Sensitivity to new contact interaction: 3000 TeV

- Sensitivity to SUSY-type new Physics:

$$pEDM \approx 10^{-24} \text{e} \cdot \text{cm} \times \sin \delta \times \left( \frac{1 \text{TeV}}{M_{\text{SUSY}}} \right)^2$$

The proton EDM at $10^{-29}\text{e} \cdot \text{cm}$ has a reach of $>300\text{TeV}$ or, if new physics exists at the LHC scale, $\delta < 10^{-7} - 10^{-6}\text{ rad}$ CP-violating phase; an unprecedented sensitivity level.

The deuteron EDM sensitivity is similar.
<table>
<thead>
<tr>
<th>System</th>
<th>Cost</th>
<th>W/ Indirects</th>
<th>Contingency</th>
<th>Total</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical</td>
<td>$4.3M</td>
<td>$6.45M</td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>V.C. + plates + Vacuum</td>
<td>$5.7M</td>
<td>$7M</td>
<td>10-50%</td>
<td></td>
<td>C-AD, S. Nayak</td>
</tr>
<tr>
<td>Magnetic shielding</td>
<td>$5.6M</td>
<td>$8.56M</td>
<td>50%</td>
<td></td>
<td>Amuneal company</td>
</tr>
<tr>
<td>Installation of M.S.</td>
<td>$0.860M</td>
<td>$1.45M</td>
<td>50%</td>
<td></td>
<td>Amuneal company</td>
</tr>
<tr>
<td>Polarimeter</td>
<td>$0.6M</td>
<td>$1.06M</td>
<td>50%</td>
<td></td>
<td>pEDM</td>
</tr>
<tr>
<td>Active magn. feed.</td>
<td>$732K</td>
<td>$1.46M</td>
<td>100%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Controls</td>
<td>$876.5K</td>
<td>$1.75M</td>
<td>100%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Control room</td>
<td>$250K</td>
<td>$0.5M</td>
<td>100%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Installation</td>
<td>$3.7M</td>
<td>$7.4M</td>
<td>100%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>SQUID-BPM</td>
<td>$2.5M</td>
<td>$3.91M</td>
<td>50%</td>
<td></td>
<td>pEDM</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>$39.54M</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Conventional, ring at ATR

<table>
<thead>
<tr>
<th>System</th>
<th>Cost</th>
<th>W/ Indirects</th>
<th>Contingency</th>
<th>Total</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Utilities</td>
<td>$165.9K</td>
<td>45%</td>
<td></td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>pEDM Ring &amp; services</td>
<td>$7,282.9K</td>
<td>45%</td>
<td></td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Service Buildings &amp; Utilities</td>
<td>$671.3K</td>
<td>45%</td>
<td></td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Beam Transport, Service buildings &amp; Utilities</td>
<td>$810.7K</td>
<td>45%</td>
<td></td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Architectural, Engineering &amp; Construction Services</td>
<td>$2,014.5K</td>
<td>45%</td>
<td></td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>12,587.1K</td>
<td>$5,664.2K</td>
<td></td>
<td><strong>$18,251.3K</strong></td>
<td></td>
</tr>
</tbody>
</table>
# beamline at ATR

<table>
<thead>
<tr>
<th>System</th>
<th>Cost w/small project ind. (SPI)</th>
<th>W/ large project Indirects (LPI)</th>
<th>Contingency</th>
<th>Total</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical distribution &amp; tray runs</td>
<td>$502.8K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Magnets</td>
<td>$2,215.4K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Power supplies</td>
<td>$1,362.5K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Vacuum System</td>
<td>$744K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Access controls</td>
<td>$152.6K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Instr. &amp; controls</td>
<td>$1,594.3K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Water cooling</td>
<td>$302.3K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Installation labor</td>
<td>$1,103.4K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7,302.5K</strong></td>
<td><strong>$3,651.2K</strong></td>
<td></td>
<td><strong>$10,953.7K</strong></td>
<td></td>
</tr>
</tbody>
</table>
## Conventional, ring at SEB

<table>
<thead>
<tr>
<th>System</th>
<th>Cost w/ SPI</th>
<th>W/ LPI</th>
<th>Contingency</th>
<th>Total</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removals</td>
<td>$5,543.3K</td>
<td>$4,773.8K</td>
<td>65%</td>
<td>$7,876.8K</td>
<td>C-AD</td>
</tr>
<tr>
<td>Utilities</td>
<td>$776.83K</td>
<td></td>
<td>65%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Ring shielding &amp; Installation</td>
<td>$2,641.9K</td>
<td></td>
<td>65%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Misc.</td>
<td>$1,366.7K</td>
<td></td>
<td>65%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>8,894.9K</strong></td>
<td><strong>$5,781.7K</strong></td>
<td></td>
<td><strong>$14,676.6K</strong></td>
<td></td>
</tr>
<tr>
<td>System</td>
<td>Cost w/ SPI</td>
<td>W/ LPI</td>
<td>Contingency</td>
<td>Total</td>
<td>Comments</td>
</tr>
<tr>
<td>----------------------</td>
<td>-------------</td>
<td>--------</td>
<td>-------------</td>
<td>---------</td>
<td>----------</td>
</tr>
<tr>
<td>Extraction</td>
<td>$430.16K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Magnets</td>
<td>$748.12K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Power supplies</td>
<td>$564.86K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Vacuum System</td>
<td>$685.97K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Access controls</td>
<td>$800.13K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Instr. &amp; controls</td>
<td>$779.76K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Water cooling</td>
<td>$295.25K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Installation labor</td>
<td>$1,249.9K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>AC power</td>
<td>$232.33K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td>Removels</td>
<td>$460.55K</td>
<td></td>
<td>50%</td>
<td></td>
<td>C-AD</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$5,267.9K</strong></td>
<td><strong>$5,267.9K</strong></td>
<td><strong>$2,634.0K</strong></td>
<td><strong>$7,901.9K</strong></td>
<td><strong>C-AD</strong></td>
</tr>
</tbody>
</table>
SCT data from the January 2011 run at COSY

- Beam polarization data with RF and cooling turned-on show a SCT > 500s; more than adequate for the experiment.

Figure 1: Measurements of the oscillation pattern with both electron cooling and the RF solenoid on as a function of time in the store in seconds. The data is a combination of the vector asymmetry from all four polarization states after subtraction of the unpolarized asymmetry and a normalization to one before the RF solenoid is actuated. The curve is a least squares fit of a sine function whose period is $0.658 \pm 0.002$ s.
Our running schedule at COSY/Jülich

<table>
<thead>
<tr>
<th>Week</th>
<th>January 2011</th>
<th>February</th>
<th>March</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>03/01/11</td>
<td>10/01/11</td>
<td>17/01/11</td>
</tr>
<tr>
<td>2</td>
<td>24/01/11</td>
<td>31/01/11</td>
<td>07/02/11</td>
</tr>
<tr>
<td>3</td>
<td>14/02/11</td>
<td>21/02/11</td>
<td>28/02/11</td>
</tr>
<tr>
<td>4</td>
<td>07/03/11</td>
<td>14/03/11</td>
<td>21/03/11</td>
</tr>
<tr>
<td>5</td>
<td>28/03/11</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Monday**
- **January 2011:**
  - **1:** Maintenance
  - **2:** FAIR (rights for WTH Aachen)
  - **3:** EDM 176.4

**Tuesday**
- **January 2011:**
  - **2:** FAIR

**Wednesday**
- **January 2011:**
  - **3:** WASA, 208, pd \( \Rightarrow \) He3 X

**Thursday**
- **January 2011:**
  - **4:** FAIR (CBM-ToF)

**Friday**
- **January 2011:**
  - **4:** ANKE 203, pn \( \Rightarrow \) K+ n A

**Saturday**
- **January 2011:**
  - **5:** Pol. Deuterons
  - **6:** Unpolarized Protons

**Sunday**
- **January 2011:**
  - **5:** 970 MeV/c

- **February:**
  - **8:** 2196 MeV/c

- **March:**
  - **12:** 2425, 2546, 2600 MeV/c

---

<table>
<thead>
<tr>
<th>Week</th>
<th>April</th>
<th>May</th>
<th>June</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>04/04/11</td>
<td>11/04/11</td>
<td>18/04/11</td>
</tr>
<tr>
<td>15</td>
<td>25/04/11</td>
<td>02/05/11</td>
<td>09/05/11</td>
</tr>
<tr>
<td>16</td>
<td>19/05/11</td>
<td>16/05/11</td>
<td>23/05/11</td>
</tr>
<tr>
<td>17</td>
<td>20/05/11</td>
<td>27/05/11</td>
<td>06/06/11</td>
</tr>
<tr>
<td>18</td>
<td>23/05/11</td>
<td>30/05/11</td>
<td>13/06/11</td>
</tr>
<tr>
<td>19</td>
<td>06/06/11</td>
<td>13/06/11</td>
<td>20/06/11</td>
</tr>
<tr>
<td>20</td>
<td>13/06/11</td>
<td>20/06/11</td>
<td>27/06/11</td>
</tr>
</tbody>
</table>

**Monday**
- **April:**
  - **14:** ANKE 203, pn \( \Rightarrow \) K+ n A

**Tuesday**
- **April:**
  - **15:** WASA, 209, \( \omega \)-decay in pp

**Wednesday**
- **April:**
  - **16:** Karfreitag

**Thursday**
- **April:**
  - **17:** WASA, 184.1, \( \eta \) in pp

**Friday**
- **April:**
  - **17:** Maintenance

**Saturday**
- **April:**
  - **18:** 1. Mai

**Sunday**
- **April:**
  - **19:** Unpolarized Protons

---

<table>
<thead>
<tr>
<th>Week</th>
<th>July</th>
<th>August</th>
<th>September</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>04/07/11</td>
<td>11/07/11</td>
<td>18/07/11</td>
</tr>
<tr>
<td>28</td>
<td>12/07/11</td>
<td>19/07/11</td>
<td>05/08/11</td>
</tr>
<tr>
<td>29</td>
<td>26/07/11</td>
<td>02/08/11</td>
<td>12/08/11</td>
</tr>
<tr>
<td>30</td>
<td>01/08/11</td>
<td>08/08/11</td>
<td>19/08/11</td>
</tr>
<tr>
<td>31</td>
<td>15/08/11</td>
<td>22/08/11</td>
<td>26/08/11</td>
</tr>
<tr>
<td>32</td>
<td>29/08/11</td>
<td>05/09/11</td>
<td>13/09/11</td>
</tr>
<tr>
<td>33</td>
<td>05/09/11</td>
<td>12/09/11</td>
<td>20/09/11</td>
</tr>
</tbody>
</table>

**Monday**
- **July:**
  - **27:** ANKE, 205

**Tuesday**
- **July:**
  - **28:** Maintenance

**Wednesday**
- **July:**
  - **29:** E-Cooler preparations and PAX

**Thursday**
- **July:**
  - **29:** FAIR

**Friday**
- **July:**
  - **30:** MD

**Saturday**
- **July:**
  - **31:** PAX Filterexperiment

**Sunday**
- **July:**
  - **31:** PAX

---

<table>
<thead>
<tr>
<th>Week</th>
<th>October</th>
<th>November</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>03/10/11</td>
<td>10/10/11</td>
<td>17/10/11</td>
</tr>
<tr>
<td>41</td>
<td>24/10/11</td>
<td>31/10/11</td>
<td>07/11/11</td>
</tr>
<tr>
<td>42</td>
<td>14/11/11</td>
<td>21/11/11</td>
<td>28/11/11</td>
</tr>
<tr>
<td>43</td>
<td>28/11/11</td>
<td>05/12/11</td>
<td>12/12/11</td>
</tr>
<tr>
<td>44</td>
<td>19/12/11</td>
<td>26/12/11</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>47</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>49</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>52</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Monday**
- **October:**
  - **40:** Feiertag

**Tuesday**
- **October:**
  - **41:** MD

**Wednesday**
- **October:**
  - **42:** MD

**Thursday**
- **October:**
  - **43:** Aller-heiligen

**Friday**
- **October:**
  - **44:** TOF (193.2), 2.7 GeV/c

**Saturday**
- **October:**
  - **45:** FAIR

**Sunday**
- **October:**
  - **46:** Maintenance

---

<table>
<thead>
<tr>
<th>Week</th>
<th>November</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>14/11/11</td>
<td>21/11/11</td>
</tr>
<tr>
<td>48</td>
<td>28/11/11</td>
<td>05/12/11</td>
</tr>
<tr>
<td>49</td>
<td>12/12/11</td>
<td>19/12/11</td>
</tr>
<tr>
<td>50</td>
<td>26/12/11</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>52</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Monday**
- **November:**
  - **47:** Feiertag

**Tuesday**
- **November:**
  - **48:** MD

**Wednesday**
- **November:**
  - **49:** FAIR

**Thursday**
- **November:**
  - **50:** Maintenance

**Friday**
- **November:**
  - **51:** E-Cooler Einbau

**Saturday**
- **November:**
  - **52:** Weihnachten

---

<table>
<thead>
<tr>
<th>Week</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
<td></td>
</tr>
</tbody>
</table>

**Monday**
- **December:**
  - **52:** Feiertag

**Tuesday**
- **December:**
  - **52:** MD

**Wednesday**
- **December:**
  - **52:** FAIR

**Thursday**
- **December:**
  - **52:** Maintenance

**Friday**
- **December:**
  - **52:** E-Cooler Einbau

**Saturday**
- **December:**
  - **52:** Maintenance

**Sunday**
- **December:**
  - **52:** Weihnachten
Recent Progress from ILC/ERL R&D (~5mm gap tests) Cornell/JLab

Fig. 4. Field emission current as a function of applied gradient for a 150-mm-diameter stainless steel electrodes: (squares) a typical untreated sample, (circles) first measurement of GCIB treated sample, (triangles) re-measurement of GCIB treated sample after high-voltage conditioning [14].
SCT tests at COSY, January 2011

Uncooled and cooled beam profiles

Vertical (left) and horizontal (right) beam profiles for the uncooled beam and Gaussian fits.

Vertical (left) and horizontal (right) beam profiles for 30 sec cooling and 30 sec cooling off and Gaussian fits.

Vertical (left) and horizontal (right) beam profiles for 60 sec cooling.
Storage Ring EDM Collaboration

- Aristotle University of Thessaloniki, Thessaloniki/Greece
- Research Inst. for Nuclear Problems, Belarusian State University, Minsk/Belarus
- Brookhaven National Laboratory, Upton, NY/USA
- Budker Institute for Nuclear Physics, Novosibirsk/Russia
- Royal Holloway, University of London, Egham, Surrey, UK
- Cornell University, Ithaca, NY/USA
- Institut für Kernphysik and Jülich Centre for Hadron Physics Forschungszentrum Jülich, Jülich/Germany
- Institute of Nuclear Physics Demokritos, Athens/Greece
- University and INFN Ferrara, Ferrara/Italy
- Laboratori Nazionali di Frascati dell’INFN, Frascati/Italy
- Joint Institute for Nuclear Research, Dubna/Russia
- Indiana University, Indiana/USA
- Istanbul Technical University, Istanbul/Turkey
- University of Massachusetts, Amherst, Massachusetts/USA
- Michigan State University, East Lansing, Minnesota/USA
- Dipartimento di Fisica, Università “Tor Vergata” and Sezione INFN, Rome/Italy
- University of Patras, Patras/Greece
- CEA, Saclay, Paris/France
- KEK, High Energy Accel. Res. Organization, Tsukuba, Ibaraki 305-0801, Japan
- University of Virginia, Virginia/USA

>20 Institutions
>80 Collaborators

http://www.bnl.gov/edm
## Risk factors

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin coherence time</td>
<td>High</td>
<td>Low-Medium</td>
</tr>
<tr>
<td>Beam position monitors</td>
<td>High</td>
<td>High (test in accelerator environment is required)</td>
</tr>
<tr>
<td>Polarimeter</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>E-field strength</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>E-field plates shape</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Software development</td>
<td>Medium</td>
<td>Low</td>
</tr>
</tbody>
</table>
Two different labs to host the S.R. EDM experiments

- BNL, USA: proton “magic” ring
- COSY/IKP, Jülich/Germany deuteron ring: JEDI
From Hans Stroeher’s presentation at the March 2011 review

**International srEDM Network**

- Institutional (MoU) and Personal (Spokespersons …) Cooperation

**srEDM Collaboration (BNL)**

**Common R & D**
- RHIC
  - Beam Position Monitors (...)
- EDM-at-COSY
  - Polarimetry
  - Spin Coherence Time Cooling (...)
- Spin Tracking

**Study Group**
- DOE-Proposal
- CD0, 1, ...
- Precursor; Ring Design
- HGF Application(s)

**pEDM Ring at BNL**

**JESS**
EDDA detector

32 bars measure azimuthal angle

rings measure scattering angle

Operate as stopping detector for deuterons, sets beam momentum to be $p = 0.97 \text{ GeV/c}$

Thick carbon target used for continuous extraction and high efficiency
COSY ring:

Use EDDA detector

EDDA detector:

Rings and bars to determine angles.

Azimuthal angles yield two asymmetries:

\[ \varepsilon_{EDM} = \frac{L - R}{L + R} \]

\[ \varepsilon_{g-2} = \frac{D - U}{D + U} \]
Detector systems: alternatives to scintillators

A. Multi-resistive plate chambers (Italy)
   - Pickup electrodes (green) also shown in photograph
   - The 20cm x 50cm prototype

B. Micro-megas avalanche detection system (Greece)

C. Gas electron multiplier (GEM) system
   - In-beam tests are needed (COSY) to provide sample data sets.
Sensitivity to Rule on Several New Models

Gray: Neutron
Red: Electron

e current
n current
e target
n target
p, d target
e target

Why COSY?

Scale like EDM ring
Polarized P/D beams
Electron cooling
Outside user program
Available equipment

History

Proposal in 2007
Visit SPIN@COSY run
Three polarimeter runs:
  June 2008 – initial tests
  September 2008 – trial data
  June 2009 – final long run
  (paper in preparation)
Polarization lifetime runs:
  January 2011 – initial tests

Prior work at KVI, Groningen
\( d=C \) data, 2004 + 2005
Systematic errors, 2007
In conclusion

BPMs:

• A combination of passive and active magnetic shielding

• Using proven techniques (Romalis et al.)

• Risk factor: high (even though using existing technology, it needs to be proven in accelerator environment)
SCT:

- Lattice: to 1st order SCT is ~10s. Use sextupoles to achieve ~200-500s.
- Tracking studies underway to fine tune the specs
- SCT January run 2011 at COSY a great success. Mixing w/ cooling eliminates the issue. Observed SCT w/ cooling >500s!
- Studying stochastic cooling for the experiment
- Risk factor: low/medium
Software development:

- Accurate beam and spin dynamics tracking based on 4\textsuperscript{th} order RK integration.
- It’s slow: 10 h CPU for 10 ms tracking
- It confirmed estimation of tunes, radial B-field effect, tune modulation, etc.
- Studying SCT dependence on lattice parameters, E-field plate shape, etc.
- Fast UAL+SPINK is used for SCT @ COSY
- Plus UAL+ETEAPOT for all-electric; more…
- Risk factor: low
E-field strength:

- ~10MV/m for 3 cm plate separation. Stainless steel and high pressure water rinsing (HPWR) is below expected E-field limit

- Challenge: QA is critical for large area plates

- Risk factor: low
cont’d

**Polarimeter:**

- Polarimeter data have been analyzed, long paper to be submitted
- Expected systematic error $\ll 1\text{ppm}$
- Risk factor: low
Deuteron case

Near 230 MeV, the forward cross section and analyzing power are favorable.

Proton case

Similarity to deuteron case means results apply to both.

We can expect:
- efficiency $\sim 1.1\%$ (over $2\pi$)
- analyzing power $\sim 0.6$

with some selection on elastics
Proton Statistical Error (230MeV):

\[ \sigma_d = \frac{2 \hbar}{E_R PA \sqrt{N_c f \tau_p T_{tot}}} \]

- \( \tau_p \): 10\(^3\)s  
  Polarization Lifetime (Spin Coherence Time)
- \( A \): 0.6  
  Left/right asymmetry observed by the polarimeter
- \( P \): 0.8  
  Beam polarization
- \( N_c \): 4\( \times \)10\(^{10}\)p/cycle  
  Total number of stored particles per cycle
- \( T_{tot} \): 10\(^7\)s  
  Total running time per year
- \( f \): 0.5\%  
  Useful event rate fraction (efficiency for EDM)
- \( E_R \): 10.5 MV/m  
  Radial electric field strength (95\% azim. cov.)

\[ \sigma_d = 1.6 \times 10^{-29} \text{e} \cdot \text{cm/year} \] for uniform counting rate and
\[ \sigma_d = 1.1 \times 10^{-29} \text{e} \cdot \text{cm/year} \] for variable counting rate
## Physics strength comparison

<table>
<thead>
<tr>
<th>System</th>
<th>Current limit [e⋅cm]</th>
<th>Future goal</th>
<th>Neutron equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron</td>
<td>&lt;1.6×10^{-26}</td>
<td>~10^{-28}</td>
<td>10^{-28}</td>
</tr>
<tr>
<td>$^{199}$Hg atom</td>
<td>&lt;3×10^{-29}</td>
<td>&lt;10^{-29}</td>
<td>10^{-25}-10^{-26}</td>
</tr>
<tr>
<td>$^{129}$Xe atom</td>
<td>&lt;6×10^{-27}</td>
<td>~10^{-29}-10^{-31}</td>
<td>10^{-25}-10^{-27}</td>
</tr>
<tr>
<td>Deuteron nucleus</td>
<td></td>
<td>~10^{-29}</td>
<td>3×10^{-29}-5×10^{-31}</td>
</tr>
<tr>
<td>Proton nucleus</td>
<td>&lt;7×10^{-25}</td>
<td>~10^{-29}</td>
<td>10^{-29}</td>
</tr>
</tbody>
</table>
Is the polarimeter analyzing power good at $P_{\text{magic}}$? **YES!**

Analyzing power can be further optimized.

---

Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only.

Fig. 4. The angle averaged effective analyzing power as a function of the proton kinetic energy. The magic momentum of 0.7GeV/c corresponds to 232MeV.
Main Systematic Error: particles have non-zero magnetic moments!

\[
\frac{\vec{d}s}{dt} = \vec{\mu} \times \vec{B} + \vec{\phi} \times \vec{E}
\]

• For the nEDM experiments a co-magnetometer or SQUIDS are used to monitor the B-field: cancellation level needed for \(10^{-28}\) e-cm is of order 3pG.
EDMs of different systems

Theta_QCD:

\[ d_n = -d_p \approx 3 \times 10^{-16} \bar{\theta} \, \text{e} \cdot \text{cm} \]

\[ d_D(\bar{\theta}) / d_N(\bar{\theta}) \approx 1/3 \]

Super-Symmetry (SUSY) model predictions:

\[ d_n \approx 1.4(d_d - 0.25d_u) + 0.83e(d_u^c + d_d^c) - 0.27e(d_u^c - d_d^c) \]

\[ d_p \approx 1.4(d_d - 0.25d_u) + 0.83e(d_u^c + d_d^c) + 0.27e(d_u^c - d_d^c) \]

\[ d_D \approx (d_u + d_d) - 0.2e(d_u^c + d_d^c) - 6e(d_u^c - d_d^c) \]

\[ d_N^{I-1} = 0.87(d_u - d_d) + 0.27e(d_u^c - d_d^c) \]

\[ d_N^{I-0} = 0.5(d_u + d_d) + 0.83e(d_u^c + d_d^c) \]

\[ d_N^{I-1} = (d_p - d_n) / 2 \]

\[ d_N^{I-0} = (d_p + d_n) / 2 \]
Polarimeter rates:

- Beam intensity with $2 \times 10^{10}$ pol. protons/$\sim 10^3$ s and a detection efficiency of 1% $\rightarrow$ 200KHz for $\sim 3000\text{cm}^2$ area, or $\sim 100\text{Hz/cm}^2$ on average but much higher at small radius. Design: $\sim 1\text{KHz/pad.}$
The Electric Dipole Moment precesses in an Electric field

The EDM vector $d$ is along the particle spin direction

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$
Software development

- Two competing requirements: accuracy, speed
- Total storage ~$10^9$ revolutions, ~1.5μs/rev.
- E-field complication: Kinetic energy changes with radial oscillations $\rightarrow$ horizontal focusing

**Velocity/c vs. radial motion [m]**
Software development

- 4th order R.K. integrator (accurate but slow)

Three different E-field dependences:

- $1/R$
- Constant
- $R^{0.2}$

Consistent with analytical estimations:

<table>
<thead>
<tr>
<th>E-field radial dep.</th>
<th>Horizontal tune</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1/R$</td>
<td>1.275</td>
</tr>
<tr>
<td>Constant</td>
<td>1.625</td>
</tr>
<tr>
<td>$R^{0.2}$</td>
<td>1.680</td>
</tr>
</tbody>
</table>

Radial motion [m] vs. time [s]
Software development

- 4th order R.K. integrator (accurate but slow, $10^4$ revolutions in ~10 hours CPU)

- Analytic integration with UAL+ ETEAPOT; UAL + SPINK: Fast enough,…
BPMs (high risk item/ must prove before construction approval)

- A radial B-field would cause an EDM-like spin precession AND would split the vertical position of the counter-rotating beams

- The splitting depends on the vertical tune $Q_y$

$$\langle \delta y \rangle = 2 \frac{\beta c R_0 B_{r0}}{E_r Q_y^2} \sim 2 \text{ pm}$$
BPMs

- The splitting depends on the vertical tune $Q_y$
- Modulating $Q_y$ would create a frequency dependent separation and a B-field at the same frequency.

Vertical position vs. time

$\langle \delta y \rangle = 2 \frac{\beta c R_0 B_{r0}}{E_r Q_y^2} \sim 2 \text{ pm}$

CW beam

CCW beam
BPMs

- Developed and installed a resonant BPM in IP10 of RHIC; resonance ~100MHz
- Statistics adequate for S/N=1 per day
- Estimated systematics large (BPM alignment, bunch parameters,…). Will still take data for diagnostics…

- We took a conservative approach instead: use near-DC effect → B-field generated by the beam itself (position modulated only when \( <B_{r0}> \neq 0 \)).
Low $T_c$ SQUIDS as BPMs

- Place them behind a shield (protect from the high frequency beam noise)
- Look at the vertical tune modulation frequency
- Minimize B-field noise from shields (important)
- Direction sensitive

- Commercially available SQUIDS have enough sensitivity. Expect $S/N > 6$, for $10^{-29} \text{e}\cdot\text{cm}$
- Plan to develop it and install it in RHIC ($0.6M$)
So what are the BPM issues?

• B-field noise: addressed by shielding + feedback

• Vibrations: Commercial SQUID system with vibration damping has noise figure plenty good enough
What are NOT BPM issues?

• Electronics rack temperature stability. NSLS II: two BPMs sense the absolute position of beam. They require 0.1°C stability for 200nm resolution.

• EDM ring: One BPM senses the difference between two C.R. beams at the modulation frequency. (Kurt Vettel responsible for NSLS II BPMs just joined the collaboration.)

• Ring temperature stability: just as any other accelerator.
Magnetic shielding
(active + passive: $3 \times 10^8$)

4 layers of 0.062" thick Amumetal with 3" spacing between layers: SF 133K:1 OD 35"

Quotation from Amuneal to produce 4 layers of clam shells (legos) ready to be installed.
**Magnetic shielding options**

(active + passive: $3 \times 10^8$)

- 4 layers of 0.062" thick Amumetal with 3" spacing between layers: SF 133K:1 OD 35"

<table>
<thead>
<tr>
<th>Item</th>
<th>Part</th>
<th>Rev</th>
<th>Description</th>
<th>Lead Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>17014-03</td>
<td>A</td>
<td>SRDEM Magnetic Shielding - 4 Layers of .062&quot; Thick Amumetal</td>
<td></td>
</tr>
</tbody>
</table>

1. This is a budgetary quote for a three layer clamshell magnetic shield to shield an approx 277 foot diameter ring.

2. Shield to be fabricated using .062" thick Amumetal, which conforms to MIL-N-14411C, Comp. 1 and ASTM A753-02, Alloy Type 4.

3. 3.00" spacing between shield layers.

4. Shields will be supplied as half cylinders with a 2.00" overlap in 60.00 long segments (two 30" segments assembled with joiner band).

5. Quoting spacers between layers to be fabricated from High Density Polyethylene (HDPE) plastic.

6. Price includes a one time engineering/programming charge, plus commercial truck freight to Brookhaven National Laboratory, Upton, NY 11973.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit Price</th>
<th>Extended Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>$5,560,858.00</td>
<td>$5,560,858.00</td>
</tr>
</tbody>
</table>
Table 2. The table of parameters for the proton EDM ring is shown here. The lattice has been estimated using the exact electric field and not an effective dipole magnetic field.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton Momentum</td>
<td>0.7007405 GeV/c</td>
<td>Kinetic energy: 232.8 MeV, $\beta = 0.59838$, $\gamma = 1.2481$</td>
</tr>
<tr>
<td>Ring bending radius</td>
<td>40 m</td>
<td>If more straight section length is needed the ring bending radius has to increase proportionally.</td>
</tr>
<tr>
<td>Total length of straight sections</td>
<td>11.6 m</td>
<td>For plate separation of 3 cm the voltage on the plates is about ±160 KV.</td>
</tr>
<tr>
<td>Radial E-field strength</td>
<td>10.5 MV/m</td>
<td>The E-field plates within a section are ~16m long each. They can be segmented into 5 pieces, 3.14 m long each.</td>
</tr>
<tr>
<td>Number of sections</td>
<td>16</td>
<td>The E-field is slightly increased at larger radius.</td>
</tr>
<tr>
<td>Radial E-field dependence at $y=0$</td>
<td>$\mathcal{R}^{0.2}$</td>
<td></td>
</tr>
<tr>
<td>Total length of orbit</td>
<td>263 m</td>
<td></td>
</tr>
<tr>
<td>Horizontal tune</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Vertical tune</td>
<td>0.2-0.1</td>
<td>To be modulated by ~10% around 0.1</td>
</tr>
<tr>
<td>$\beta_{x,\text{max}}$</td>
<td>28 m</td>
<td>Horizontal aperture: 3 cm</td>
</tr>
<tr>
<td>$\beta_{y,\text{max}}$</td>
<td>240 m</td>
<td>Vertical aperture: 8 cm</td>
</tr>
<tr>
<td>Cyclotron frequency</td>
<td>0.6839 MHz</td>
<td></td>
</tr>
<tr>
<td>$f_{\gamma} = 135 \times 0.6839$ MHz</td>
<td>90 MHz</td>
<td>Total RF voltage: 5 KV for synchrotron tune of 0.01</td>
</tr>
<tr>
<td>Slip factor</td>
<td>0.45</td>
<td>Sign is − (TBC)</td>
</tr>
</tbody>
</table>
Why does the world need a Storage Ring EDM experiment at the $10^{-29}$ e-cm level?

1. The proton, deuteron and neutron combined can pin-down the CP-violating source should a non-zero EDM value is discovered. Critical: they can differentiate between a theta-QCD source and beyond the SM.

2. The proton and deuteron provide a path to the next order of sensitivity.

Yannis Semertzidis, BNL
Magnetic field shielding issues

• Reduce the $N=0$ Fourier component of the radial magnetic field around the ring to below $0.02\text{nG}$ level, when its frequency dependence is below mHz. Higher frequency ($f_2$) B-fields need to be below $(f_2/f_1) \times 0.02\text{nG}$ level.

• For $N>0$, the field needs to be reduced below $(N/0.1)^2 \times (f_2/f_1) \times 0.02\text{nG}$ level

• A combination of a passive shield ($10^4$-$10^5$) and an active feedback ($\sim 10^4$) will be used.
Radial $B$ field splits CW and CCW beam in vertical direction

- Lorentz force from $B_r$ of opposite sign for CW and CCW beams $\Rightarrow$ they split vertically
- Expanding $B_r$ in multipoles, write the equation of motion in vertical $y$ :

$$\frac{d^2 y}{d\theta^2} + Q_y^2 y = \frac{\beta c R_0}{E_r} \sum_{N=0}^{\infty} B_{rN} \cos(N\theta + \phi_N)$$

- This has solutions :

$$\delta y(\theta) = \pm \sum_{N=0}^{\infty} \frac{\beta c R_0 B_{rN}}{E_r} \left[ \frac{1}{Q_y^2 - N^2} \right] \cos(N\theta + \phi_N) + y_0 \cos(Q_y \theta + \phi_Q),$$

- $Q_y$ is vertical betatron tune, last term is vertical betatron oscillation
- Distortion of equilibrium orbit of opposite sign for the CW and CCW beams
- Only $N=0$ term, $B_{r0}$, leads to $\langle \delta y_{CW} - \delta y_{CCW} \rangle \neq 0$
- With vertical tune $Q_y \approx 0.1$, average vertical displacement of each beam :

$$\delta y = \pm \frac{\beta c R_0 B_r}{E_r Q_y^2} = \pm \frac{0.6 \times 3 \times 10^8 \text{ m/s} \times 40 \text{ m} \times 2.2 \times 10^{-17} \text{ T}}{10.5 \times 10^6 \text{ V/m} \times 0.1^2} = \pm 1.5 \times 10^{-12} \text{ m.}$$

$\Rightarrow$ Net radial magnetic field $B_r$ of $2.2 \times 10^{-17}$ T splits the CW and CCW beams vertically by $\approx 3.0$ pm
High sensitivity magnetometry of small magnetic fields

- At least two approaches have demonstrated ability to detect such fields

    - Have demonstrated sensitivity of \( \approx 1 \, \text{fT}/\sqrt{\text{Hz}} \) at \( \omega \approx 2\pi \times 50 \, \text{Hz} \)

  - (ii) Commercially available low temperature superconductor DC SQUIDs (LTS dc SQUIDs)
    - Systems from Tristan Technologies have demonstrated \( \delta B \leq 1 \, \text{fT}/\sqrt{\text{Hz}} \)
    - http://www.tristantech.com
    - Many examples in literature of non-commercial devices with similar sensitivity
      (0.7 fT/\sqrt{Hz} by W. Vodel and K. Mäkiniemi, Meas. Sci. Technol. 3, 1155 (1992))
    - Systems primarily developed for study of heart and brain biomagnetic fields

- Will focus on solution using SQUIDs
  - Commercially available
  - Implementation and operation might be simpler than SERF magnetometers

⇒ System performance often limited by magnetic field noise - not the magnetometer
⇒ Need to reduce magnetic field noise at \( \omega_m \) below sensitivity of magnetometer
• $B$ field sensitivity depends on input current noise of SQUID and coil inductance

• For maximum sensitivity, need to match inductance of sense coil to input coil of SQUID

• For LSQ/20 LTS dc SQUID of Tristan Tech., input coil inductance $L \approx 1.8 \mu$H

• A 4 turn coil, 4 cm long $\times$ 1.5 cm high (area of 6 cm$^2$) has $L \approx 1.6 \mu$H

• LSQ/20 + flux locked loop and iMAG SQUID controller has $\delta I_{\text{noise}} \leq 0.7 \text{ pA}/\sqrt{\text{Hz}}$

• Magnetic field sensitivity extracted from flux sensitivity:

$$\delta \Phi_{\text{noise}} = NA\delta B_{\text{noise}} = \delta I_{\text{noise}} \times (L_{\text{input}} + L_{\text{sense}}) = (0.7 \times 10^{-12} \text{ A}/\sqrt{\text{Hz}}) \times (3.54 \times 10^{-6} \text{ H}) \times (4 \text{ turns}) \times (6 \times 10^{-4} \text{ m}^2/\text{turn}) = 1.0 \text{ fT}/\sqrt{\text{Hz}}.$$

⇒ If ambient field noise at $\omega_m$ is $\leq 1 \text{ fT}/\sqrt{\text{Hz}}$, combined noise $\leq 2 \text{ fT}/\sqrt{\text{Hz}}$

⇒ A single system is sensitive enough to measure $B_r$ to the required level

• Of course, would never rely on a single system

• Also want to improve $S/N \gg 1$
Summary and Conclusions

- Net radial magnetic field of 0.22 pG would cause precession equivalent to pEDM of $d_p = 10^{-29} \text{ e}\cdot\text{cm}$
- This field would split the CW and CCW beams by 3 pm
- Magnetic field from beams split in vertical has radial component
- By modulating vertical tune, can look for this field using SQUIDs and lock-in amplifier
- Require sensitivity $\leq 1 \text{ fT}/\sqrt{\text{Hz}}$ at $\omega_m$
- A single SQUID magnetometer has this sensitivity
- Magnetic shielding with noise $< 1 \text{ fT}/\sqrt{\text{Hz}}$ above 35 Hz has been demonstrated

- Large effort required:
  - Design cold finger/cryostat, integrate with other elements of experiment
  - Integration of SQUID controller output with lock in, DAQ, many parameters to be determined

⇒ Demonstrating that this works in storage ring environment will be necessary
⇒ Systematics: thermal, dimensional stability, ground motion, slow changes in $B$, ...
⇒ Great challenge and a great opportunity
The field emission without and with high pressure water rinsing (HPR) for 0.5cm plate separation.

Recent developments in achieving high E-field strengths with HPR treatment (from Cornell ILC R&D)
High Pressure Water Rinsing

![Graph showing the relationship between electric field (E) and current (I) for C.U. 5mm and C.U. B4 hpwr.]
Why Storage Ring EDMs?

- Storage rings offer a unique setting for a sensitive electric dipole moment (EDM) probe of charged particles. A number of simple systems can be probed with high accuracy: p, d, $^3$He,…
- The mechanical (centrifugal) force balances the strong radial E-fields.
- Pencil-like, high intensity/high polarization beams of protons and deuterons have been around for decades.
- Ready for prime time.
The spin precession relative to momentum in the plane is kept near zero. A vert. spin precession vs. time is an indication of an EDM ($d$) signal.

$$\vec{\omega}_a = 0$$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$
**pEDM polarimeter principle (placed in a straight section in the ring): probing the proton spin components as a function of storage time**

Extraction: lowering the vertical focusing

- "defining aperture" polarimeter target
- Micro-Megas TPC detector and/or MRPC

\[ \varepsilon_H = \frac{L - R}{L + R} \]

\[ \varepsilon_V = \frac{D - U}{D + U} \]

- Carries EDM signal increases slowly with time
- Carries in-plane (g-2) precession signal
The EDM signal: early to late change

- Comparing the \((\text{left-right})/(\text{left}+\text{right})\) counts vs. time we monitor the vertical component of spin.
Freezing the horizontal spin precession

\[ \vec{\omega}_a = \frac{e}{m} \left( a - \left( \frac{m}{p} \right)^2 \right) \vec{\beta} \times \vec{E} \]

- The spin precession is zero at “magic” momentum (0.7 GeV/c for protons, 3.1 GeV/c for muons,…)

- The “magic” momentum concept was first used in the last muon g-2 experiment at CERN and BNL.
- Side view schematic of a SQUID BPM system
- Sense coils, leads, SQUIDs at 4.2K; leads and SQUIDs in superconducting shields
- Ferrite and μ-metal at room temp, more magnetic shielding outside vacuum chamber
MINOS Tidal Data
Difference in two sensors 90 meters apart

Date

J T Volk Fermilab Dec 2008
Expected stability of B-field

- $10\mu \text{G}$ at 1Hz (mainly due to solar activity)
- $0.1\mu \text{G/m}$ gradient (earth’s dipole field)
- Human heart: $0.1\mu \text{G}$ (near chest wall)
- Shield factors of $10^4-10^5$ for large systems are achieved with commercially available systems

Measured by applying $1\mu \text{T}$ oscillating field in the Berlin shielded room: 7 mu-metal layers and one thick Al-RF shield.

We would need a shielding factor of $10^4-10^5$ at 10-100Hz for the modulation method to work.