Machine Design Progress and Options at BNL: eRHIC and MeRHIC

Vladimir N. Litvinenko
Brookhaven National Laboratory, Upton, NY, USA
Stony Brook University, Stony Brook, NY, USA
Center for Accelerator Science and Education
Materials are from eRHIC R&D group and EIC task force

V.N. Litvinenko, EIC AC meeting, TJNAF, November 2-3, 2009
Collider beam physics laws assert that with any given beam and IR parameters, a linac-ring collider outperforms a ring-ring collider.

We developed detailed technical design and cost estimate for the first stage of eRHIC, called MeRHIC.

We developed a clear staged pass toward full energy high luminosity eRHIC, based on the experience from hadron and lepton-hadron colliders.

eRHIC R&D is focused on:

- (a) Single cathode and Gatling polarized electron guns
- (b) Compact SRF linacs with HOM damping
- (c) Multi-pass high average current ERLs
- (e) Small gap magnets and vacuum chambers
- (f) Coherent electron cooling
We prepared for tomorrow following topics on MeRHIC design

- MeRHIC design — Vadim Ptitsyn
- Beam dynamics — Yue Hao
- Engineering challenges and solutions — Andrew Burrill
Content

• What is eRHIC
• eRHIC staging
• MeRHIC design
• IP developments
• R&D program for eRHIC
• Costs
eRHIC Scope - QCD Factory

**Electron accelerator**

Unpolarized and polarized leptons
4-20 (30) GeV

70% beam polarization goal
Positrons at low intensities

**Center mass energy range: 15-200 GeV**

eA program for eRHIC needs as high as possible energies of electron beams even with a trade-off for the luminosity: 20 GeV is absolutely essential and 30 GeV is strongly desirable

**RHIC**

Polarized protons
25\textendash}50-250 (325) GeV

Light ions (d, Si, Cu)
Heavy ions (Au, U)
50-100 (130) GeV/u

Polarized light ions
(He\textsuperscript{3}) 215 GeV/u

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Choosing the focus: ERL or ring for electrons?

- Two main design options for eRHIC:
  - Ring-ring:
    - Electron storage ring
    \[ L = \left( \frac{4 \pi \gamma_h \gamma_e}{r_h r_e} \right) \left( \xi_h \xi_e \right) \left( \sigma_h \sigma_e \right) \]
    \[ \xi_e \sim 0.1 \]
  - Linac-ring:
    - Electron linear accelerator
    \[ L = \gamma_h f N_h \frac{\xi_h Z_h}{\beta^*_h r_h} \]
    \[ \xi_e > 1 \]

Natural staging strategy

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2008: Staging of eRHIC

- **MeRHIC**: Medium Energy eRHIC
  - Both Accelerator and Detector are located at IP2 of RHIC
  - $4 \text{ GeV } e^- \times 250 \text{ GeV } p$ (63 GeV c.m.), $L \sim 10^{32}-10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$
  - 90% of hardware will be used for HE eRHIC

- **eRHIC**, High energy and luminosity phase, inside RHIC tunnel
  - **Full energy, nominal luminosity**
  - Polarized $20 \text{ GeV } e^- \times 325 \text{ GeV } p$ (160 GeV c.m.), $L \sim 10^{33}-10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$
  - $30 \text{ GeV } e \times 120 \text{ GeV/n } Au$ (120 GeV c.m.), $\sim 1/5$ of full luminosity
  - and $20 \text{ GeV } e \times 120 \text{ GeV/n } Au$ (120 GeV c.m.), full luminosity

- **eRHIC up-grades - if needed**
  - Higher luminosity
  - Higher hadron energy
Staging of eRHIC: Re-use, Beams and Energetics

- **MeRHIC**: Medium Energy electron-Ion Collider
  - > 90% of ERL hardware will be use for full energy eRHIC
  - Possible use of the detector in eRHIC operation

- **eRHIC** - High energy and luminosity phase
  - Based on present RHIC beam intensities
  - With coherent electron cooling requirements on the electron beam current is 50 mA
  - 20 GeV, 50 mA electron beam losses 4 MW total for synchrotron radiation.
  - 30 GeV, 10 mA electron beam loses 4 MW for synchrotron radiation
  - Power density is <2 kW/meter and is well within B-factory limits (8 kW/m)

- eRHIC upgrade(s) if needed

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4 GeV $e \times 250$ GeV $p - 100$ GeV/u $Au$

**MeRHIC**

- 2 x 60 m SRF linac
- 3 passes, 1.3 GeV/pass

**Polarized $e$-gun**

**Beam dump**

**3 pass 4 GeV ERL**

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10 to 20 GeV e x 325 GeV p - 130 GeV/u Au eRHIC

- 2 x 200 m SRF linac
- 4 (5) GeV per pass
- 5 (4) passes

Possibility of 30 GeV low current operation

20 GeV e-beam
16 GeV e-beam
12 GeV e-beam
8 GeV e-beam

4 to 5 vertically separated recirculating passes

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Possible layout in RHIC IP of CeC driven by a single linac – to boost polarized pp- luminosity

Kicker for Yellow

FEL for Yellow

ERL dual-way electron linac 2 Standard MeRHIC modules

Beam dump 1

Modulator for Blue

Gun 2

Kicker for Blue

Modulator for Yellow

Gun 1

FEL for Blue

Beam dump 2

\[ \begin{array}{|c|c|c|}
\hline
E_p, \text{ GeV} & \gamma & E_e, \text{ MeV} \\
\hline
100 & 106.58 & 54.46 \\
250 & 266.45 & 136.15 \\
325 & 346.38 & 177.00 \\
\hline
\end{array} \]

V.N. Litvinenko, EIC AC meeting, TJNAF, November 2-3, 2009
MeRHIC with 4 GeV ERL at 2 o’clock IR of RHIC

Lattice and IR by D. Trbojevic, D. Kayran

4 GeV Arcs with the Flexible Momentum Compaction Lattice
Total length 11 m

Interaction Region
$\beta^* = 0.5$ m - total length 53 m

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© J.C. Brutus, J. Tuozzolo, D. Trbojevic, G. Mahler, B. Parker, W. Meng

MeRHIC in IR 2: 3D layout

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Myriad of beam dynamics issues were studied for MeRHIC
No show-stoppers!

Majority of these findings were reported at MAC meeting in March 2009
Main finding - we could operate main SRF linacs without 3rd harmonics
ERL spin transparency at all energies

Bargman, Mitchel, Telegdi equation

\[ \frac{d\hat{s}}{dt} = \frac{e}{mc} \left( \left[ \frac{g}{2} - \frac{1}{\gamma} \right] \hat{B} - \frac{\gamma}{\gamma + 1} \left( \frac{g}{2} - 1 \right) \hat{\beta} \cdot \hat{B} \right) \left( \frac{g}{2} - \frac{\gamma}{\gamma + 1} \right) \left[ \hat{\beta} \times \hat{E} \right] \]

\[ a = \frac{g}{2} - 1 = 1.1596521884 \cdot 10^{-3} \]

\[ \hat{\mu} = \frac{g}{2 m_o} \hat{s} = (1 + a) \frac{e}{m_o} \hat{s} \]

\[ \nu_{spin} = a \cdot \gamma = \frac{E_e}{0.44065[GeV]} \]

Total angle \( \Delta \phi = a \cdot \gamma \theta \)

Has solution for all energies:

\[ \begin{cases} \gamma_i + 2 \cdot (\Delta \gamma_1 + \Delta \gamma_2) = \gamma_f \\ a \cdot (\gamma_i (2n - 1) + n(\Delta \gamma_1 \cdot n + \Delta \gamma_2 (n - 1))) = N \end{cases} \]

\( \Delta \gamma_1, \Delta \gamma_2, \Delta E_1, \Delta E_2 \) for spin transparency

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Methods and solutions: asynchronous arcs

Dispersion function oscillates between ±1.8 m and the momentum compaction is adjustable:

\[
\alpha = \frac{1}{C_0} \int \frac{D}{\rho} \, ds \approx 0
\]

Goals:
- Have a good packing factor
- \( \alpha_c = 0 \) or \( M_{5.6} = 0 \)
- Small dispersion
- Small betatron functions
- Reduce cost of civil construction

Dejan Trbojevic: EPAC 1990, pp. 1536:
“Design Method for High energy Accelerators without Transition Energy.”

V.N. Litvinenko, EIC AC meeting, TJNAF, November 2-3, 2009
100 MeV Pre Accelerator ERL

**Injector Parameters**
- Polarized Gun (200kV)
- Cathode GaAs,
- Laser 780nm
- Emax = 10 MeV
- Iavr = 50 mA,
- Q per bunch = 5nC

**Pre-accelerator ERL:**
- One pass
- Energy gain 90 MeV
- Einj & Eextr = 10 MeV
- Emax = 100 MeV

**eBeam parameters:**
- E = 100 MeV
- Iavr = 50 mA
- Ipeak = 500 A
- Reprate = 9.8 MHz
- Emittance = 70 mm-mrad
- Banchlength = 3 mm
- dE/E = 1E-3

D. Kayran

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The multi cathode to reduce load on a single cathode can be used.
Polarized e-beam injector

Meeic electron injector design

Xiangyan Chang, Ian Ben-Zvi, Yue Hao, Jorg Koeleve, Vladimir Litvinenko,

Injector layout

Envelope vs. Z

Voltage: 200kV
Laser parameters: transverse uniform with $R_{MAX}=4\text{mm}$
longitudinal Gaussian with $\sigma_0=250\text{ps}$ (FWHM=500ps)
Bunch charge = 5nC/bunch
Chirping cavity & Booster linac frequency: 112MHz
Energy after booster linac: 10MeV
rms dE/E at exit: 1%

Emittance

Emittance-X: 60mm.mr
Emittance-Y: 54mm.mr
These emittances can be easily reduced to below 50mm.mr

Longitudinal phase space

1. Bunch length is 2.8nm including all the particles.
2. Dropping off small amount of the “bad” particles the bunch length will be even smaller. So do the transverse emittances.
MeRHIC Linac Design

- 703.75 MHz
- 1.6 m long
- Drift
- 1.5 m long
- 65 m total linac length
- All cold: no warm-to-cold transition

Based on BNL SRF cavity with fully suppressed HOMs
Critical for high current multi-pass ERL

I. Ben Zvi

Current breakdown of the linac
- N cavities = 6 (per module)
- N modules per linac = 6
- N linacs = 2
- L module = 9.6 m
- L period = 10.6 m
- $E_f = 18.0$ MeV/m
- $\langle dE/ds \rangle = 10.2$ MeV/m

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TBBU stability (©E. Pozdeyev)

- HOMs based on R. Calaga’s simulations/measurements
- 70 dipole HOM’s to 2.7 GHz in each cavity
- Polarization either 0 or 90°
- 6 different random seeds
- HOM Frequency spread 0-0.001

Excitation process of transverse HOM

\[
\begin{bmatrix}
  x \\
  x'
\end{bmatrix}_{\text{return}} =
\begin{bmatrix}
  m_{11} & m_{12} \\
  m_{21} & m_{22}
\end{bmatrix}
\begin{bmatrix}
  0 \\
  x'
\end{bmatrix}_{\text{comming}}
\]

Simulated BBU threshold (GBBU) vs. HOM frequency spread.

<table>
<thead>
<tr>
<th>F (GHz)</th>
<th>R/Q (Ω)</th>
<th>Q</th>
<th>(R/Q)Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8892</td>
<td>57.2</td>
<td>600</td>
<td>3.4e4</td>
</tr>
<tr>
<td>0.8916</td>
<td>57.2</td>
<td>750</td>
<td>4.3e4</td>
</tr>
<tr>
<td>1.7773</td>
<td>3.4</td>
<td>7084</td>
<td>2.4e4</td>
</tr>
<tr>
<td>1.7774</td>
<td>3.4</td>
<td>7167</td>
<td>2.4e4</td>
</tr>
<tr>
<td>1.7827</td>
<td>1.7</td>
<td>9899</td>
<td>1.7e4</td>
</tr>
<tr>
<td>1.7828</td>
<td>1.7</td>
<td>8967</td>
<td>1.5e4</td>
</tr>
<tr>
<td>1.7847</td>
<td>5.1</td>
<td>4200</td>
<td>2.1e4</td>
</tr>
<tr>
<td>1.7848</td>
<td>5.1</td>
<td>4200</td>
<td>2.1e4</td>
</tr>
</tbody>
</table>

Threshold significantly exceeds the beam current, especially for the scaled gradient solution.

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eRHIC IR developments

- eRHIC IR lattice is designed in direct communication with EIC task-force and with inputs from EIC collaboration.

- **Main boundary conditions on present IR designs** - **our main priority**
  - There should be no magnetic elements (except dipole magnets used for EIC physics!) of both electron and hadron accelerators.
  - One of the golden measurements (diffraction) required
    - A) very strong dipole next to the IP
    - B) very long element-free straight sections for excellent energy resolution
    - C) no – zilch! - hard X-rays in the detector
  - No - Zilch! - hard X-ray in the detector chamber

- This limits choice of $\beta^*$ to 40 cm without CeC and to 25 cm with CeC. We found solutions to all existing demands. Focusing is not a problem in all this scenario and excellent fits are found for all cases (Tepikian for RHIC, Trbojevic of ERL).

- Luminosity hungry experiments may require a dedicated IR, where accelerator elements are integrated into a detector (aka BarBar).

- CeC can compress hadron bunch lengths to few cm and $\beta^* \sim 5$ cm or even shorter are possible in such IR - few possible scenarios are under consideration. This IR can bring eRHIC luminosity well above $10^{34}$. V.N. Litvinenko, EIC AC meeting, TJNAF, November 2-3, 2009
Integrated IR design
MeRHIC 4 GeV e x 250 GeV p/100 GeV Au

Remove DXes - 40 m to detect particles scattered at small angles

To provide effective SR protection:
- soft bend (~0.05T) is used for final bending of electron beam

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© E. Aschenauer

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Beam Disruption

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Suppression of kink instability

Nonlinear force model with Hourglass effect
With rms proton energy spread $=1e^{-3}$

The optimum chromaticity is around $\xi = +4$

Recent studies proved our early assumption that using simple feed-back on electron beam suppress kink instability completely for all MeRHIC/eRHIC parameter ranges

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### eRHIC parameters

<table>
<thead>
<tr>
<th></th>
<th>MeRHIC</th>
<th>eRHIC with CeC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p /A</td>
<td>e</td>
</tr>
<tr>
<td>Energy, GeV</td>
<td>250/100</td>
<td>4</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>111</td>
<td>105 nsec</td>
</tr>
<tr>
<td>Bunch intensity (u), $10^{11}$</td>
<td>2.0</td>
<td>0.31</td>
</tr>
<tr>
<td>Bunch charge, nC</td>
<td>32</td>
<td>5</td>
</tr>
<tr>
<td>Beam current, mA</td>
<td>320</td>
<td>50</td>
</tr>
<tr>
<td>Normalized emittance, $1e-6$ m, 95% for p / rms for e</td>
<td>15</td>
<td>73</td>
</tr>
<tr>
<td>Polarization, %</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>rms bunch length, cm</td>
<td>20</td>
<td>0.2</td>
</tr>
<tr>
<td>$\beta^*$, cm</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Luminosity, x $10^{33}$, cm$^{-2}$s$^{-1}$</td>
<td>0.1 -&gt; 1 with CeC</td>
<td></td>
</tr>
</tbody>
</table>

< Luminosity for 30 GeV e-beam operation will be at 20% level>
Using only two of JLab assumptions for ELIC micro-beta*, traveling RF focusing, on a paper, brings eRHIC luminosity to $1.4 \times 10^{35}$ cm$^{-2}$ sec$^{-1}$.

$$L = f_c \frac{N h N e}{4 \pi \beta^* \varepsilon}$$

Reducing $\beta^*$ by a factor of 50 (from 25 cm to 0.5 cm) boost luminosity by a factor of fifty.
## Parameters

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<tr>
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<tr>
<td><strong>Energy, GeV</strong></td>
<td>325 / 130</td>
</tr>
<tr>
<td><strong>Number of bunches</strong></td>
<td>166</td>
</tr>
<tr>
<td><strong>Bunch intensity ((u), (10^{11})</strong></td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Bunch charge, nC</strong></td>
<td>32</td>
</tr>
<tr>
<td><strong>Beam current, mA</strong></td>
<td>420</td>
</tr>
<tr>
<td><strong>Normalized emittance, (1\cdot10^{-6}) m, 95% for p / rms for e</strong></td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Polarization, %</strong></td>
<td>70</td>
</tr>
<tr>
<td><strong>rms bunch length, cm</strong></td>
<td>4.9</td>
</tr>
<tr>
<td><strong>(\beta^*), cm</strong></td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Luminosity, (x;10^{35}), cm(^{-2})s(^{-1})</strong></td>
<td>1.4</td>
</tr>
</tbody>
</table>

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</tr>
<tr>
<td>rms bunch length, cm</td>
<td>4.9</td>
</tr>
<tr>
<td>(\beta^*), cm</td>
<td>25</td>
</tr>
<tr>
<td>Luminosity, (x 10^{35}), cm(^{-2})s(^{-1})</td>
<td>0.028</td>
</tr>
</tbody>
</table>

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eRHIC’s assumptions

are based on beam optics for HE hadron colliders such as RHIC, HERA, Tevatron, LHC

We have potential for future up-grades beyond capabilities of present day colliders:
increase intensities of electron and proton bunches about 2 fold, the rep-rate 2 fold and reduce beta* 5 fold – total up to 20 fold increase in luminosity.
Challenges and Advantages

- **Main Challenge** - 50 mA polarized gun for e-p program
- **Main advantage** - RHIC
  - Unique set of species from d to U
  - The only high energy polarized proton collider
  - Large size of RHIC tunnel (3.8 km)
- **Main limitation**
  - Ion cloud limits the hadron beam intensity

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Main technical challenge is 50 mA CW polarized gun: we are building it

Based on demonstrated current technology developed at JLab

Single cathode DC gun

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**Coherent Electron Cooling (CeC)**

At a half of plasma oscillation

\[
q_{\lambda_{FEL}} \approx \int_0^{\lambda_{FEL}} \rho(z) \cos(k_{FEL} z) dz
\]

\[
\rho_h = k q(\varphi_1); \quad n_h = \frac{\rho_h}{2 \pi \beta E}
\]

Dispersions section (for hadrons)

**Dispersions**

\[
c \Delta t = -D \cdot \gamma - \gamma_0; \quad D_{\text{free}} = \frac{L}{\gamma}; \quad D_{\text{chicane}} = l_{\text{chicane}} \cdot \Theta
\]

**Amplifier of the e-beam modulation in an FEL with gain**: 

\[
G_{FEL} \approx 10^2 \text{ to } 10^3
\]

**Electrons**

\[
\Delta E_h = -e \cdot E_o \cdot \gamma \cdot \sin \left( k_{FEL} \frac{D E - E_o}{E_o} \right)
\]

\[
\left( \frac{\sin \phi_2}{\phi_2} \right) \left( \frac{\sin \phi_1}{2} \right) \cdot Z \cdot X; \quad E_o = 2G_e e \gamma_0 / \beta \epsilon_{\text{in}}
\]

**Kicker**

\[
\lambda_{FEL} = 2 \pi \beta \epsilon_n / \gamma
\]

\[
k_{FEL} = 2 \pi / \lambda_{FEL}; \quad k_{cm} = k_{FEL} / \gamma
\]

\[
n_{\text{amp}} = G_0 \cdot n_h \cos(k_{cm} z)
\]

\[
\Delta \varphi = 4 \pi \epsilon n \Rightarrow \varphi = -\varphi_0 \cdot \cos(k_{cm} z)
\]

\[
E = -\nabla \varphi = -2E_o \cdot X \sin(k_{cm} z)
\]

\[
E_o = 2G_o e \gamma_0 / \beta \epsilon_{\text{in}}
\]

\[
X = q / e \approx Z(1 - \cos \varphi_1) / Z
\]

---

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**Possible layout for Coherent Electron Cooling proof-of-principle experiment in RHIC IR**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species in RHIC</td>
<td>Au ions, 40 GeV/u</td>
</tr>
<tr>
<td>Electron energy</td>
<td>21.8 MeV</td>
</tr>
<tr>
<td>Charge per bunch</td>
<td>1 nC</td>
</tr>
<tr>
<td>Train</td>
<td>5 bunches</td>
</tr>
<tr>
<td>Rep-rate</td>
<td>78.3 kHz</td>
</tr>
<tr>
<td>e-beam current</td>
<td>0.39 mA</td>
</tr>
<tr>
<td>e-beam power</td>
<td>8.5 kW</td>
</tr>
</tbody>
</table>

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eRHIC loop magnets: LDRD project

- Small gap provides for low current, low power consumption magnets
  - \( \rightarrow \) low cost eRHIC
  - Dipole prototype is under tests
  - Quad and vacuum chamber are in advanced stage

Gap 5 mm total
0.3 T for 30 GeV

©, G. Mahler, W. Meng, A. Jain, P. He, Y. Hao
Price will be in the precision not in the size
R&D ERL

Status of the R&D ERL

- The ERL is in an advanced stage of construction
- Beam will be generated next year
- Major systems are coming on

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A Prototype eRHIC Cavity

- ½ Cell SRF injector
  - Demountable cathode stalk
  - HTS Solenoid
- UHV load-lock cathode
- MW twin couplers

High-current SRF electron-gun

G5 Test:
First e-beam from gun through 5 cell cavity to beam dump quad

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eRHIC New Cavity Design

- Reduce peak magnetic field.
- Reduce stiffness.
- Apply new ideas in HOM damping.
- Reduce fundamental at HOM couplers
- Increase real-estate gradient
- Development / measurement program

Rich program of tests:
Gun, photocathode, emittance, halo, more...
To be followed up by full ERL
Conclusions

- Collider beam physics laws assert that with any given beam and IR parameters, a linac-ring collider outperforms a ring-ring collider.

- We developed detailed technical design and cost estimate for the first stage of eRHIC, called MeRHIC.

- We developed a clear staged pass toward full energy high luminosity eRHIC, based on the experience from hadron and lepton-hadron colliders.

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  - (b) Compact SRF linacs with HOM damping
  - (c) Multi-pass high average current ERLs
  - (e) Small gap magnets and vacuum chambers
  - (f) Coherent electron cooling
We prepared for tomorrow following topics on MeRHIC design

- MeRHIC design – Vadim Ptitsyn
- Beam dynamics – Yue Hao
- Engineering challenges and solutions – Andrew Burrill
Back-up
**eRHIC R&D** (more in T. Roser’s presentation)

- Polarized gun for e-p program
- Development of compact recirculating loop magnets
- R&D ERL
- Compact eRHIC SRF with HOM damping
- Coherent Electron Cooling including PoP
- Polarized $^3$He source

**Resources in FY 2009**

- Administrative - 1
- Scientists (include 2 PhD students) - 8
- Professionals - 3
- Technicians - 4
- Total - 16
eRHIC targeted LDRD-proposals

• Accelerator:
  – Proof of principle for a gatling gun polarized electron source
    PI: Ilan Ben-Zvi
  – laser development for polarized electron source
    PI: Treveni Rao
  – undulator development for coherent electron cooling
    PI: Vladimir Litvinenko
  – polarized $^3$He source development
    PI: Anatoli Zelenski
Progress with eRHIC

- **Continued:**
  - Development of R&D ERL
  - Small gap magnets
  - Understanding and suppression of kink instability
  - Simulation of electron beam disruption in the collision
  - Simulations of the beam-beam effects on hadron beam

- **New developments**
  - MeRHIC lattice and cost estimating
  - eRHIC staging and cost estimate
  - Coherent electron cooling for RHIC pp and eRHIC
  - Compact spreaders and combiner
  - Effects of wake-fields on beam energy loss and beam quality
  - Synchrotron radiation effects

- **Publications on eRHIC-related accelerator R&D**
  - About 25 papers in last year including one Phys. Rev. Lett.
Gains from coherent e-cooling:  
Coherent Electron Cooling vs. IBS

\[ X = \frac{\varepsilon}{\varepsilon_{x_0}}; \quad S = \left( \frac{\sigma_s}{\sigma_{s_0}} \right)^2 \left( \frac{\sigma_E}{\sigma_{E_0}} \right)^2; \]

\[ \frac{dX}{dt} = \frac{1}{\tau_{IBS \perp}} \frac{1}{X^{3/2}S^{1/2}} - \frac{\xi_{\perp}}{\tau_{CeC}} \frac{1}{S}; \]

\[ \frac{dS}{dt} = \frac{1}{\tau_{IBS \parallel}} \frac{1}{X^{3/2}Y} - \frac{1-2\xi_{\perp}}{\tau_{CeC}} \frac{1}{X^3}; \]

\[ X = \sqrt{\frac{\tau_{CeC}}{\tau_{IBS \parallel}}} \frac{1}{\sqrt{\tau_{IBS \perp}}} \cdot \frac{1}{\sqrt{\xi_{\perp} (1-2\xi_{\perp})}}; \quad S = \frac{\tau_{CeC}}{\tau_{IBS \parallel}} \cdot \frac{\tau_{IBS \perp}}{\sqrt{\tau_{IBS \parallel}}} \cdot \frac{\xi_{\perp}}{(1-2\xi_{\perp})^3}; \]

\[ \varepsilon_{x_0} = 2 \mu m; \quad \sigma_{s_0} = 13 \ cm; \quad \sigma_{\delta_0} = 4 \cdot 10^{-4} \]

\[ \tau_{IBS \perp} = 4.6 \ hours; \quad \tau_{IBS \parallel} = 1.6 \ hours; \]

\[ \varepsilon_{x_n} = 0.2 \mu m; \quad \sigma_s = 4.9 \ cm \]

Dynamics: 
Takes 12 mins to reach stationary point

This allows
a) keep the luminosity as it is
b) reduce polarized beam current down to 25 mA (5 mA for e-I)
c) increase electron beam energy to 20 GeV (30 GeV for e-I)
d) increase luminosity by reducing \( \beta^* \) from 25 cm down to 5 cm

IBS in RHIC for eRHIC, 250 GeV, \( N_p=2 \cdot 10^{11} \)
Beta-cool, ©A.Fedotov

V.N. Litvinenko, EIC AC meeting, TJNAF, November 2-3, 2009
4 GeV e x 250 GeV p - 100 GeV/u Au

MeRHIC

120m SRF linac
3 passes, 1.3 GeV/pass

Beam dump
Polarized e-gun

3 pass
4 GeV ERL

STAR

MeRHIC detector

V.N. Litvinenko, EIC AC meeting, TJNAF, November 2-3, 2009
10 to 20 GeV e x 325 GeV p - 130 GeV/u Au eRHIC

2 x 200 m SRF linac
4 (5) GeV per pass
5 (4) passes

Gap 5 mm total
0.3 T for 30 GeV

Possibility of 30 GeV low current operation

4 to 5 vertically separated recirculating passes

V.N. Litvinenko, EIC AC meeting, TJNAF, November 2-3, 2009
30 GeV $e \times 800$ GeV $p - 320$ GeV/u $U$

**Up-grade:**
- New LHC-class SC magnets in Blue ring

**eRHIC II**
- 3 x 200 m SRF linac
- 6 GeV per pass
- 5 passes

**Yellow ring serves as 200 GeV injector into upgraded Blue ring**

4 to 5 vertically separated recirculating passes

- 20 GeV e-beam
- 16 GeV e-beam
- 12 GeV e-beam
- 8 GeV e-beam

**Common vacuum chamber**

V.N. Litvinenko, EIC AC meeting, TJNAF, November 2-3, 2009
## eRHIC parameters

<table>
<thead>
<tr>
<th></th>
<th>MeRHIC</th>
<th>eRHIC with CeC</th>
<th>eRHIC II 8T RHIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p/A</td>
<td>e</td>
<td>p/A</td>
</tr>
<tr>
<td><strong>Energy, GeV</strong></td>
<td>250/100</td>
<td>4</td>
<td>325 / 125</td>
</tr>
<tr>
<td><strong>Number of bunches</strong></td>
<td>111</td>
<td>166</td>
<td>166</td>
</tr>
<tr>
<td><strong>Bunch intensity (u) , 10^{11}</strong></td>
<td>2.0</td>
<td>0.31</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Bunch charge, nC</strong></td>
<td>32</td>
<td>5</td>
<td>32</td>
</tr>
<tr>
<td><strong>Beam current, mA</strong></td>
<td>320</td>
<td>50</td>
<td>420</td>
</tr>
<tr>
<td><strong>Normalized emittance, 1e-6 m, 95% for p / rms for e</strong></td>
<td>15</td>
<td>73</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Polarization, %</strong></td>
<td>70</td>
<td>80</td>
<td>70</td>
</tr>
<tr>
<td><strong>rms bunch length, cm</strong></td>
<td>20</td>
<td>0.2</td>
<td>4.9</td>
</tr>
<tr>
<td><em><em>β</em>, cm</em>*</td>
<td>50</td>
<td>50</td>
<td>25 (5)</td>
</tr>
<tr>
<td><strong>Luminosity, x 10^{33}, cm^{-2}s^{-1}</strong></td>
<td>0.1 -&gt; 1 with CeC</td>
<td>2.8 (14)</td>
<td>17 (85)</td>
</tr>
</tbody>
</table>

< Luminosity for 30 GeV e-beam operation will be at 20% level>
MeRHIC parameters for e-p collisions

<table>
<thead>
<tr>
<th></th>
<th>not cooled</th>
<th>With cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy, GeV</strong></td>
<td>p: 250 e: 4</td>
<td>p: 250 e: 4</td>
</tr>
<tr>
<td><strong>Number of bunches</strong></td>
<td>111</td>
<td>111</td>
</tr>
<tr>
<td><strong>Bunch intensity, 10^{11}</strong></td>
<td>2.0 e: 0.31</td>
<td>2.0 e: 0.31</td>
</tr>
<tr>
<td><strong>Bunch charge/current, nC/mA</strong></td>
<td>32/320 e: 5/50</td>
<td>32/320 e: 5/50</td>
</tr>
<tr>
<td><strong>Normalized emittance, 1e-6 m, 95% for p / rms for e</strong></td>
<td>15 e: 73</td>
<td>1.5 e: 7.3</td>
</tr>
<tr>
<td><strong>rms emittance, nm</strong></td>
<td>9.4</td>
<td>9.4</td>
</tr>
<tr>
<td><em><em>beta</em>, cm</em>*</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td><strong>rms bunch length, cm</strong></td>
<td>20 e: 0.2</td>
<td>5 e: 0.2</td>
</tr>
<tr>
<td><strong>beam-beam for p /disruption for e</strong></td>
<td>1.5e-3 e: 3.1</td>
<td>0.015 e: 7.7</td>
</tr>
<tr>
<td><strong>Peak Luminosity, 1e32, cm^{-2}s^{-1}</strong></td>
<td>0.93</td>
<td>9.3</td>
</tr>
</tbody>
</table>

Luminosity for light and heavy ions is the same as for e-p if measured per nucleon!

V.N. Litvinenko, EIC AC meeting, TJNAF, November 2-3, 2009
• 40 cm $\beta^*$ and 40 m element free space
• Integrated 5.8 m long 4 T solenoid
• First indication that it is good layout for diffraction physics
• There is enough flexibility in the layout to accommodate main detector needs

V.N. Litvinenko, EIC AC meeting, TJNAF, November 2-3, 2009
RHIC lattice modification - Steven Tepikian

\[ \beta^* = 0.4 \text{ m} \]
Methods and solutions: construction of the asynchronous arcs:

Medium Energy electron Ion Collider (MEeIC)

Normalized Dispersion in the Arc Cell

- Doublet
- B2H
- B2
- FODO
Switchyard at the linac

V.N. Litvinenko, EIC AC meeting, TJNAF, November 2-3, 2009
Vertical splitters -
3.35 GeV, 2.05 GeV, and 0.75 GeV

© Nicholas Tsoupas
V.N. Litvinenko, EIC AC meeting, TJNAF, November 2-3, 2009
HV feedthrough
Caesium x 6
Laser
Laser mirrors
Electron Beams
Laser windows
Linac design with const. grad quads

- $E_{\text{inj}}/E_{\text{max}} = 100\text{MeV} / 4\text{GeV}$
- 3 acc./decel. passes
- $N$ cavities = 72 (total)
- $L$ module/period = 9.6 / 11.1m
- $E_f = 18.0 \text{MeV/m}$
- $\langle dE/ds \rangle = 10.2 \text{MeV/m}$
Scaled gradient solution

Scaling gradient with energy produces more focusing and increases BBU threshold

\[ G_{\text{min}} \approx 100 \text{ G/cm} \]
\[ G_{\text{max}} \approx 500 \text{ G/cm} \]

Matching scaled linac to arcs is in the works
BBU simulations

- HOMs based on R. Calaga’s simulations/measurements
- 70 dipole HOM’s to 2.7 GHz in each cavity
- Polarization either 0 or 90°
- 6 different random seeds
- HOM Frequency spread 0-0.001

### Simulated BBU threshold (GBBU) vs. HOM frequency spread.

Beam current 50 mA

<table>
<thead>
<tr>
<th>F (GHz)</th>
<th>R/Q (Ω)</th>
<th>Q</th>
<th>(R/Q)Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8892</td>
<td>57.2</td>
<td>600</td>
<td>3.4e4</td>
</tr>
<tr>
<td>0.8916</td>
<td>57.2</td>
<td>750</td>
<td>4.3e4</td>
</tr>
<tr>
<td>1.7773</td>
<td>3.4</td>
<td>7084</td>
<td>2.4e4</td>
</tr>
<tr>
<td>1.7774</td>
<td>3.4</td>
<td>7167</td>
<td>2.4e4</td>
</tr>
<tr>
<td>1.7827</td>
<td>1.7</td>
<td>9899</td>
<td>1.7e4</td>
</tr>
<tr>
<td>1.7828</td>
<td>1.7</td>
<td>8967</td>
<td>1.5e4</td>
</tr>
<tr>
<td>1.7847</td>
<td>5.1</td>
<td>4200</td>
<td>2.1e4</td>
</tr>
<tr>
<td>1.7848</td>
<td>5.1</td>
<td>4200</td>
<td>2.1e4</td>
</tr>
</tbody>
</table>

Threshold significantly exceeds the beam current, especially for the scaled gradient solution.
Energy loss and its compensation

- Energy loss
  - Linac cavities: 0.54 MeV/linac. (6.5 MeV total)
  - Synch. radiation: 8.8 MeV total
  - CSR: negligible
- Total power loss: 765 kW
- Energy difference in arcs (max)
  - Before compensation: 2%
  - After compensation: 0.06%

\[ \sigma_z = 2 \text{ mm} \]
\[ q_b = 5 \text{ nC} \]
Energy spread and its compensation

<table>
<thead>
<tr>
<th></th>
<th>$\delta E$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF</td>
<td>0.17%</td>
</tr>
<tr>
<td>Cavity Wakes</td>
<td>8.9</td>
</tr>
<tr>
<td>Synch. Rad. (4$rms$)</td>
<td>1.35</td>
</tr>
<tr>
<td>Resistive Wall</td>
<td>small</td>
</tr>
<tr>
<td>CSR</td>
<td>small</td>
</tr>
<tr>
<td>Total</td>
<td>10.25</td>
</tr>
</tbody>
</table>

Dog-leg with M56=15 cm, M566=125 cm²

Energy spread vs. Arc #

Energy spread compensation

10 MeV -> 1.6 MeV
Beam losses: Touschek

Total beam loss beyond given energy aperture

Not a large problem but not negligible
Beam losses: Collisions with residual gas

- Scattering
- Bremsstrahlung

Losses beyond aperture at 100 MeV
- Small, can be neglected

Losses beyond energy aperture
- Small, can be neglected
Energy spread compensation

\[ m_{56} = 15 \text{ cm} \]
\[ m_{566} = ? \]

Smal \( \delta \phi \), Large \( dE \)

Large \( \delta \phi \), fits the RF wave \(-\) small \( dE \)

\[
\frac{\delta E_f}{\delta E_i} = \frac{\delta \phi_i}{\delta \phi_f} = \frac{\delta \phi_i}{l_b} \lambda_{RF}
\]

10 MV \(-\) 1.6 MV