# Luminosity Considerations for eRHIC

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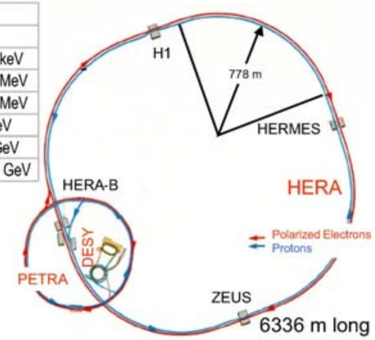
# Topics

- eRHIC luminosity goals and specials
- Limitations from ion beams & constraints from IR design
- The electron beam parameters
- Higher luminosity operation with ZDR design
- Summary

# eRHIC ring-ring collider design is based on existing $e^-e^+$, e-p and ion colliders

| | Protons | Electrons | |
|---|---|---|---|
| 20 keV | Source | Source | 150 keV |
| 750 keV | RFQ | Linac II | 450 MeV |
| 50 MeV | Linac III | Pia | 450 MeV |
| 8 GeV | DESY III | DESY II | 7 GeV |
| 40 GeV | PETRA | PETRA | 12 GeV |
| 920 GeV | HERA-p | HERA-e | 27.5 GeV |

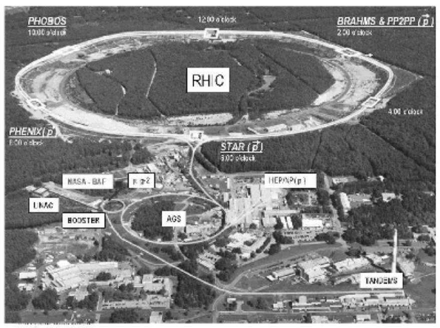



HERA e-p 27.5/920 GeV

$e^-e^+$

PEP II 9 GeV/3.1GeV

KEKB 8 GeV/3.5GeV




RHIC

Polarized p: 25-250GeV

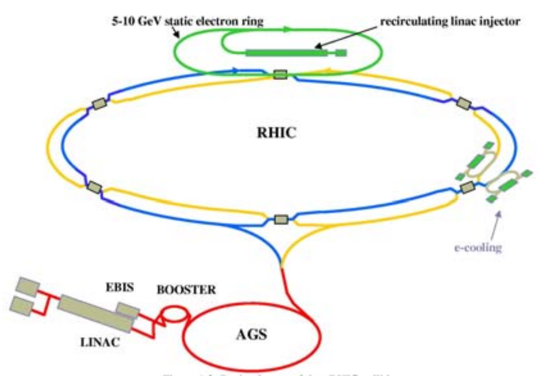
Au-Au: 100 GeV/u

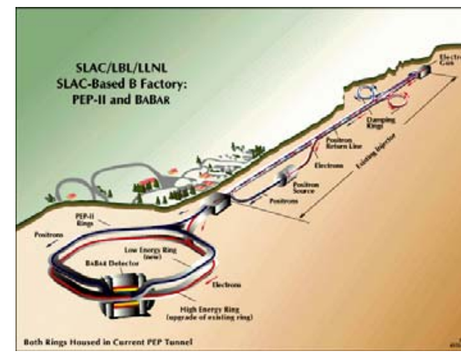
d-Au, …..

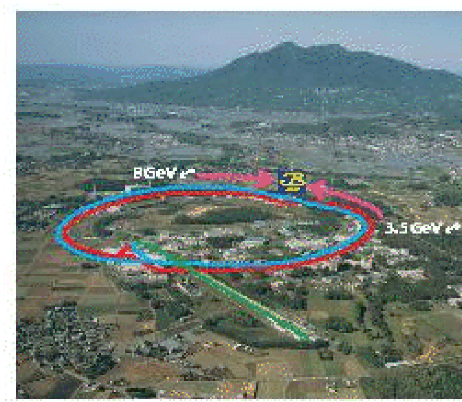
eRHIC e-p: 5-10GeV/50-250GeV

e-Au: 5-10GeV/50-250GeV

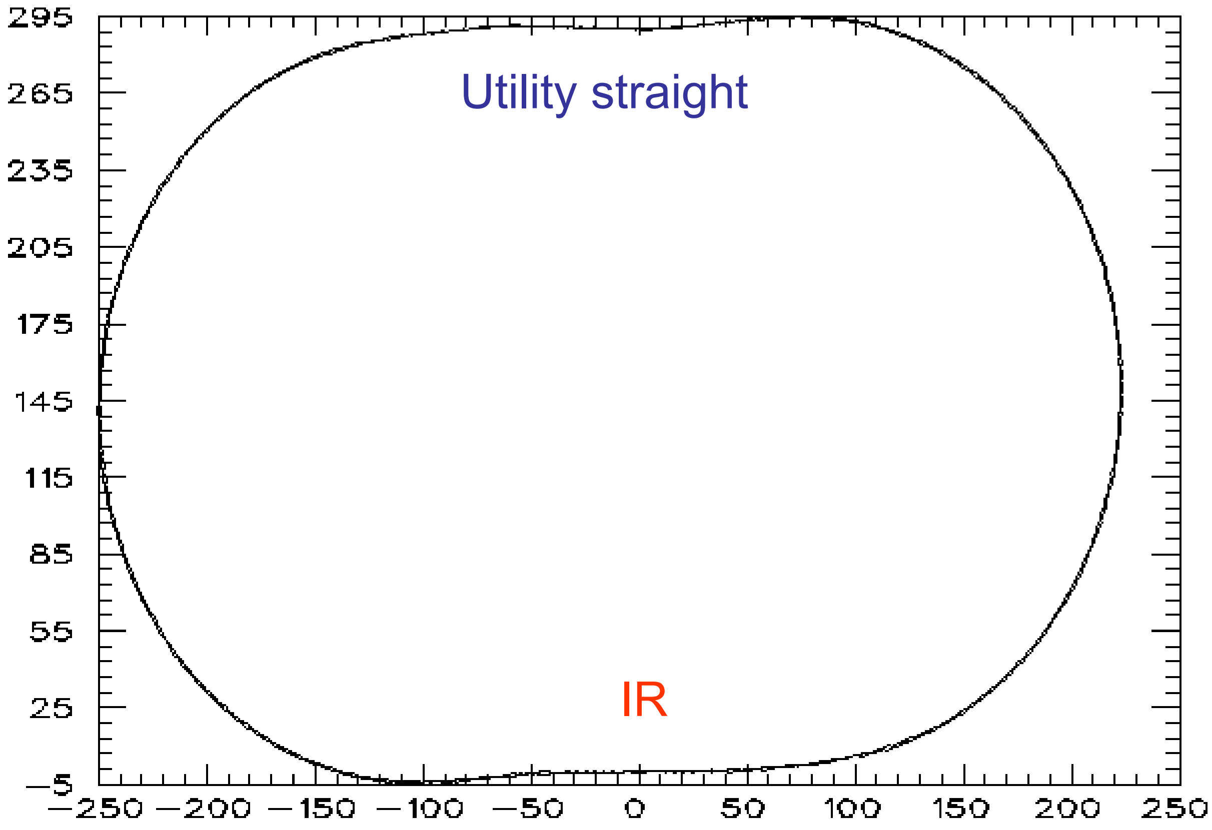
e+, …



# Scaled eRHIC e-ring layout



# HERA Luminosity Equation

HERA ep 27.5GeV/920GeV

G. Hoffstaetter

$$L = \frac{N_p I_e}{4\pi e \varepsilon^p \sqrt{\beta_x^p \beta_y^p}}$$

**Parameters**

| Parameter | up to 2000 | | after the upgrade | |
|---|---|---|---|---|
| | HERA-e | HERA-p | HERA-e | HERA-p |
| $E$(GeV) | 27.5 | 920 | 27.5 | 920 |
| $I$(mA) | 50 | 100 | 58 | 140 |
| $N_{ppb}(10^{10})$ | 3.5 | 7.3 | 4.0 | 10.3 |
| $n_{tot}/n_{col}$ | 189/174 | 180/174 | 189/174 | 180/174 |
| $\beta_x^\star/\beta_y^\star$(m) | 0.90/0.60 | 7.0/0.5 | 0.63/0.26 | 2.45/0.18 |
| $\epsilon_x$(nm) | 41 | $\frac{5000}{\beta\gamma}$ | 20 | $\frac{5000}{\beta\gamma}$ |
| $\epsilon_y/\epsilon_x$ | 10% | 1 | 17% | 1 |
| $\sigma_x/\sigma_y(\mu\mathrm{m})$ | 192/50 | 189/50 | 112/30 | 112/30 |
| $\sigma_z$(mm) | 11.2 | 191 | 10.3 | 191 |
| $2\Delta\nu_x$ | 0.024 | 0.0026 | 0.068 | 0.0031 |
| $2\Delta\nu_y$ | 0.061 | 0.0007 | 0.103 | 0.0009 |
| $\mathcal{L}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$ | $16.9\cdot10^{30}$ | | $75.7\cdot10^{30}$ | |
| $\mathcal{L}_s(\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{mA}^{-2})$ | $0.66\cdot10^{30}$ | | $1.82\cdot10^{30}$ | |

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Concerned: ($N_p/\varepsilon^p$) & p bunch length limits by IBS, $I_e$ limit.

Beam-beam limit is not reached for protons, and may be close for leptons.

Lepton: ~45mA, proton ~ 90 mA.

Minimum lepton beam energy: 26.5 GeV, set by the "mini-spin – rotator" work range. Routine polarization ~60%, $\varepsilon_y/\varepsilon_x$=10%.

# PEP II Luminosity Equation

*John T. Seeman*

*e+e- Super-B-Factory Workshop*
*Hawaii, USA.  January 19, 2004*

$\xi_y$ is the beam-beam parameter (~0.08 now)
$I_b$ is the bunch current (1 ma x 2 ma)
n is the number of bunches (~942)
$\beta_y^*$ is the IP vertical beta (~11 mm)
E is the beam energy (3.1 and 9 GeV)
$r_0$ is the classic electron radius
Luminosity is about 6.11 x $10^{33}$ $cm^{-2}$ $s^{-1}$

$$L = 2.17x10^{34}(1+r)\frac{n\xi_y E I_b}{\beta_y^*}$$

**r: y/x size aspect ratio🕔0.02**

$$\xi_y^+ = \frac{r_0 N_b^- \beta_y^{*+}}{2\pi\gamma^+ \sigma_y^{*-} \sigma_x^{*-}}(flatbeams)$$

# eRHIC Luminosity Equation

Head on collisions, size matched elliptical e & p beams,

$\sigma_y < \sigma_x$

$$L = \frac{\pi}{r_e r_i} f_c \gamma_e \gamma_i \xi_i \xi_e \sigma'_{i,x} \sigma'_{e,y} \frac{(1+k)^2}{k}$$

$$= \frac{\pi}{r_e r_i} f_c \gamma_e \gamma_i \xi_i \xi_e \sigma'_{i,x} \sqrt{\frac{\varepsilon_{e,x}}{\beta^*_{e,x}} k_e} \frac{(1+k)^2}{k^2}$$

$$\xi_{i,x} = \frac{r_i}{2\pi Z} \frac{N_e}{\gamma_i \varepsilon_i} \frac{1}{(1+k)}$$

$$\xi_{e,y} = \frac{r_e Z}{2\pi} \frac{N_i}{\gamma_e \varepsilon_{e,x}} \frac{1}{k_e(1+1/k)}$$

with $\sigma'_{e,y} \leq \sigma'_{e,x}$

$\xi_{i,e}$ : beam-beam tune shift limit for ion beam or electron beam.
$\beta^*$ : β-function at IP, ¤ 19 cm.
ε: ion or electron beam geometric emittance.
$k_e = \varepsilon_{e,y}/\varepsilon_{e,x}$ :electron beam emittance ratio, ~0.2.
$k=\sigma_y/\sigma_x$ :beam aspect ratio at IP, ~0.5.
$\sigma_{i,x}'$: ion beam angular amplitude. $\sigma'_{i,x}$ ◉93 urad is an aperture limit (IR design)
$\sigma_{e,y}'$: elecetron beam angular amplitude, not a real aperture limit.
$r_{i,e}$: classic ion or electron radius.
Z: ion atomic number

# eRHIC ZDR design  luminosity goals

| | e-p, $e^+$-p | e-p,$e^+$-p | e-Au, $e^+$-Au | e-Au, $e^+$-Au |
|---|---|---|---|---|
| Energy (GeV)<br>Lepton/hadron | 10/250 | 5/50 | 10/100 | 5/100 |
| Lonitudinal Polarization at IP | ≥70%<br>$e^\pm$ & p | ~60% for e<br>≥ 70% for p | ≥ 70% $e^\pm$ | ~60%  e |
| Luminosity<br>$\times 10^{32}$ $cm^{-2}s^{-1}$ | 4.4 | 1.5 | 0.044 | 0.02 |

# Limitations from ion beams (p/250 GeV, Au/100 GeV)

| Description | limits | Effect on luminosity | Causes & measures |
|---|---|---|---|
| Bunch length | 25->19 cm | Minimum $\beta^*$ | IBS<br>Suppression: e-cooling |
| Bunch number | 360(335) | Colliding frequency | Injection system, Injection pressure rise,electron cloud, cryogenic Load.<br>Bunch spacing requirement from Detector & IR design. |
| Bunch intensity (Related to total current) | p:$1\times10^{11}$<br>Au: $1\times10^{9}$ | Max. $\xi_{ey}$ | Cryogenic Load<br>Instability<br>Injection |
| Beam-beam tune shift | 0.007<br>per IP | Directly | Based on experiment and simulations. ? |
| Emittance (95% normalized) | p:~$15\pi\mu$m<br>Au:~ $6\pi\mu$m | IR design<br>High b-b limit with low e-bunch charge | Injection , IBS<br>e-cooling |

# Constrains from Interaction Region Design

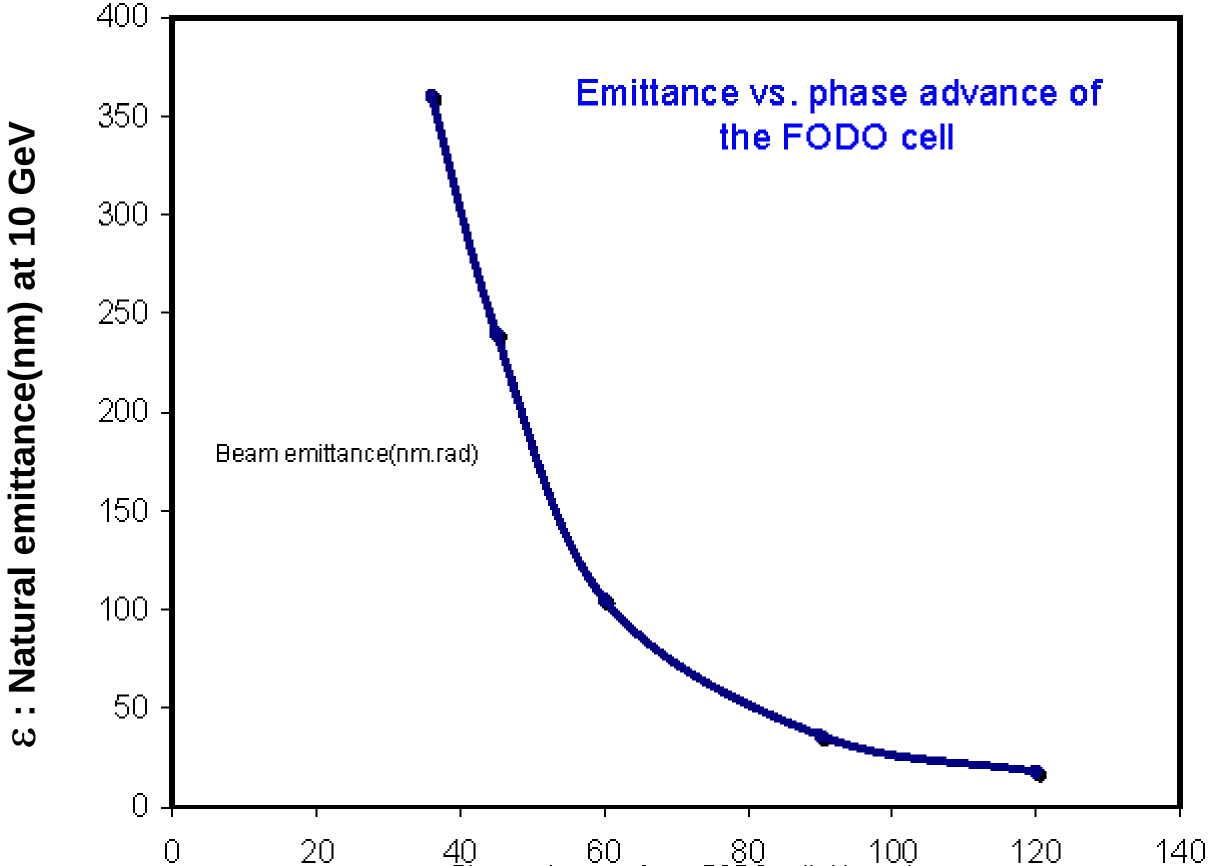
| | Restriction | Effects | Causes |
|---|---|---|---|
| Ion beam angular amplitude aperture | $\sigma'_{i,x} \odot 93\mu rad$ | Directly on luminosity | Beam separation at IR |
| Round beam collisions | No solution | Non equal b-b tune shifts | Same as above |
| Beam size aspect ratio | $\leq$ 0.5 | Same aspect ratio for e & p beam | Hadron beam optics |
| Crossing angle collisions | No | Head-on collisions only | Crab cavity )for hadron beam) RF voltage will be too high |

# The electron beam parameters

| | Requirement | Reason | Concerns & Measures |
|---|---|---|---|
| **Beam emittance (uncoupled x, nm)** | 40-60 (10 GeV)<br>50-90 (5GeV) | Match ion beam | Arc lattice<br>Wiggler \|\| superbend |
| **Beam y/x emittance ratio** | ~0.2 | High luminosity | 70% polarization ?<br>High $P_{eq}$ ~ high $K_e$, HERA update? study |
| **Damping decrement** | Damping time < ~25 ms at 5GeV? | Less beam-beam limit reduction at low E | Wiggler \|\| superbend<br>for low E operations |
| **Bunch intensity (120 bunches)** | $1 \times 10^{11}$<br>(0.45A) | High luminosity | Vacuum chamber (syn. radiation), RF, instability … |
| **Injection** | On energy, top-off or continues | Integrated luminosity.<br>High e b-b limits lead to short lifetime | On energy Injection, flexible bunch-bunch filling. |
| **Beam-beam tune shift limit** | $\xi_y$ ~ 0.08 | B-factory achieved | Working point near integer(spin), study |
| **Coherent b-b effect in Unequal-circumference collider** | | Increase instability region ? | Study |

# The natural beam emittance vs. horizontal betatron phase advance per FODO cell (ZDR design, 10 GeV)

D. Wang




Phase advance per FODO cell (degree)

**Watching momentum aperture for large ε operation.**

| | | |
|---|---|---|
| e/p (GeV) ZDR | 10/250 | 5/50 |
| $\varepsilon_{e,x}$(nm) | 56 | 85 |
| β phase/cell x/y degree | ~ 72/60 | ~38/38 |
| Moment. Compaction α | 0.0026 | 0.0091 |
| RF V(MV) | 25 | 5 |
| $\nu_s$ | 0.04 | 0.05 |

# Lepton beam emittacne y/x ratio vs. luminosity

e-p 10/250 GeV

ZDR IR design: k=0.5,$\xi_{i,x}$=0.0065, electron beam bunch density:1x$10^{11}$

| Ke= $\varepsilon_{e,y}/\varepsilon_{e,x}$ | $\varepsilon_{e,x}$ (nm.rad) | $\beta_{e,x}^*$ (m) | $\beta_{e,y}^*$ (m) | $\sigma'_{e,y}$ ($\mu$rad) | Protons $10^{11}$/bunch | $\xi_x$ | $\xi_y$ | $\mathcal{L}$ 1e32 ($cm^{-2}s^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| 0.1 | 54 | 0.19 | 0.47 | 339 | 0.57 | 0.016 | 0.08 | 2.5 |
| 0.15 | 54 | 0.19 | 0.31 | 417 | 0.85 | 0.024 | 0.08 | 3.8 |
| 0.18 | 54 | 0.19 | 0.26 | 456 | 1.0 | 0.029 | 0.08 | 4.5 |
| 0.20 | 54 | 0.19 | 0.23 | 485 | 1.13 | 0.032 | 0.08 | 5.0 |
| 0.25 | 54 | 0.19 | 0.19 | 533 | 1.41 | 0.04 | 0.08 | 6.3 |
| 0.30 | 45 | 0.23 | 0.19 | | 1.41 | 0.048 | 0.08 | 6.3 |
| 0.5 | 27 | 0.38 | 0.19 | | 1.41 | 0.08 | 0.08 | 6.3 |

The increase of $k_e$ is equivalent to increase $\sigma'_{e,y}$ (by reducing $\beta^*_{e,y}$). The luminosity increases proportionally to $k_e$, until $\beta^*_{e,y}$ reaches the low limit (here 0.19m).

## Low electron beam energy (5 GeV) operation:

Weak synchrotron damping, τ(x)🕓59 ms (compare to ~7 ms at 10 GeV)

Problems: Lower b-b tune shift limit, lower injection rate ~ 5 Hz and smaller emittance .

$$\xi_y^{\infty} = f[\lambda_d] = f[\frac{1}{f_{rev} \cdot \tau \cdot n_{IP}}]$$ beam – beam parmeter before blow up

$\xi_y^{\infty} \propto \lambda_d^{\sim 0.3-0.4}$. from exp. data(LEP,Petra). Reduction»50% from 10 GeV to 5GeV

•Damping wiggler: (CESR)

25m, field(peak)=2 Tesla. Prad.=(0.7+0.34)MW(0.5A), τ🕓 25 ms,

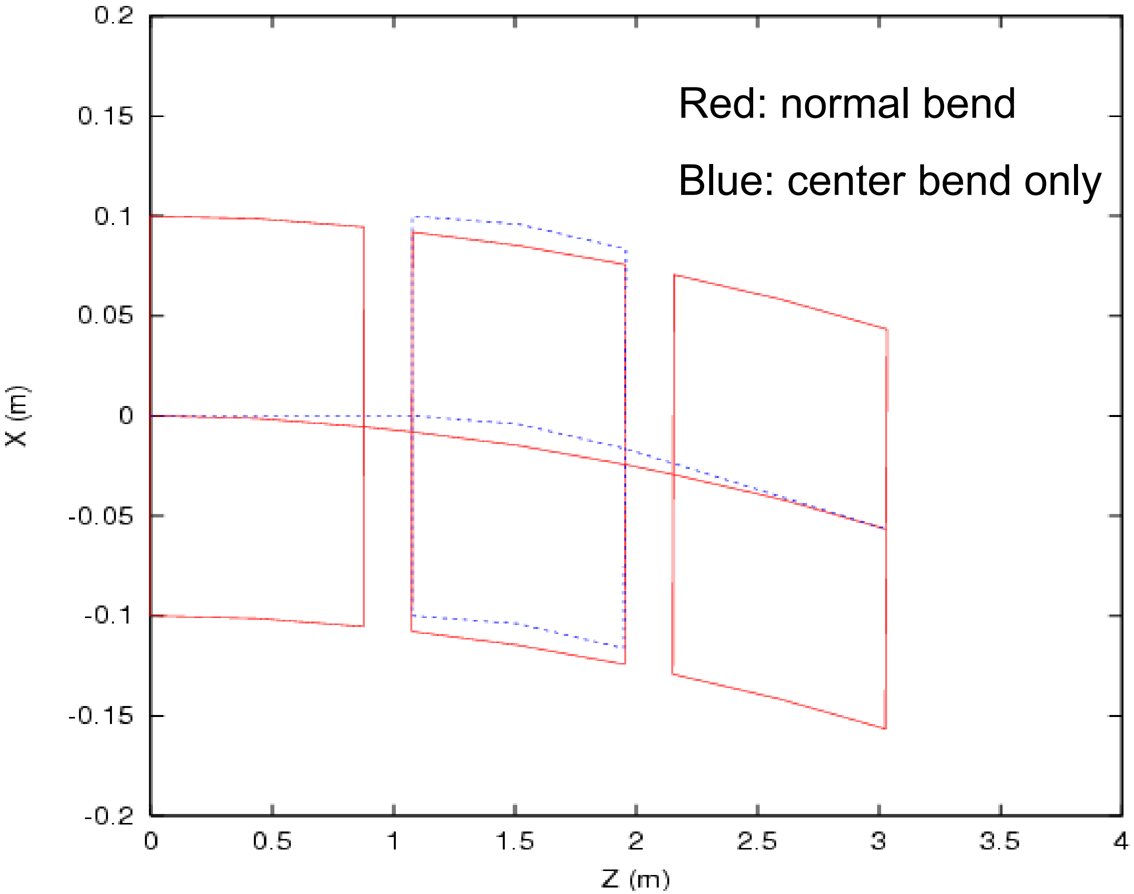
$\xi^{\infty}_y$ reduction ~30%, inj. Rate 13 Hz.

Concentrated rad. power, …? Impact on optics, beam dynamics?

•“Super-bend”: The 3m dipole => three sep. powered, ~0.9m dipoles. At 5 GeV only use the center one. Prad.=1MW.(0.45A).

Bmax≈7.1 KG. Arc magnet, vac. chamber complications.

# Scratch of a "super-bend" for radiation enhancement at 5 GeV




| | All bends on | Center bend on only |
|---|---|---|
| ρ (m) | 70.3m | 23.4 |
| P (MW) | ~0.35 | ~1.06 |
| $\tau_x$ (msec) | ~54.5 | ~18.1 |

$\xi^{\infty}_{y}$ reduction ~ 20%

(Compare to 10 GeV)

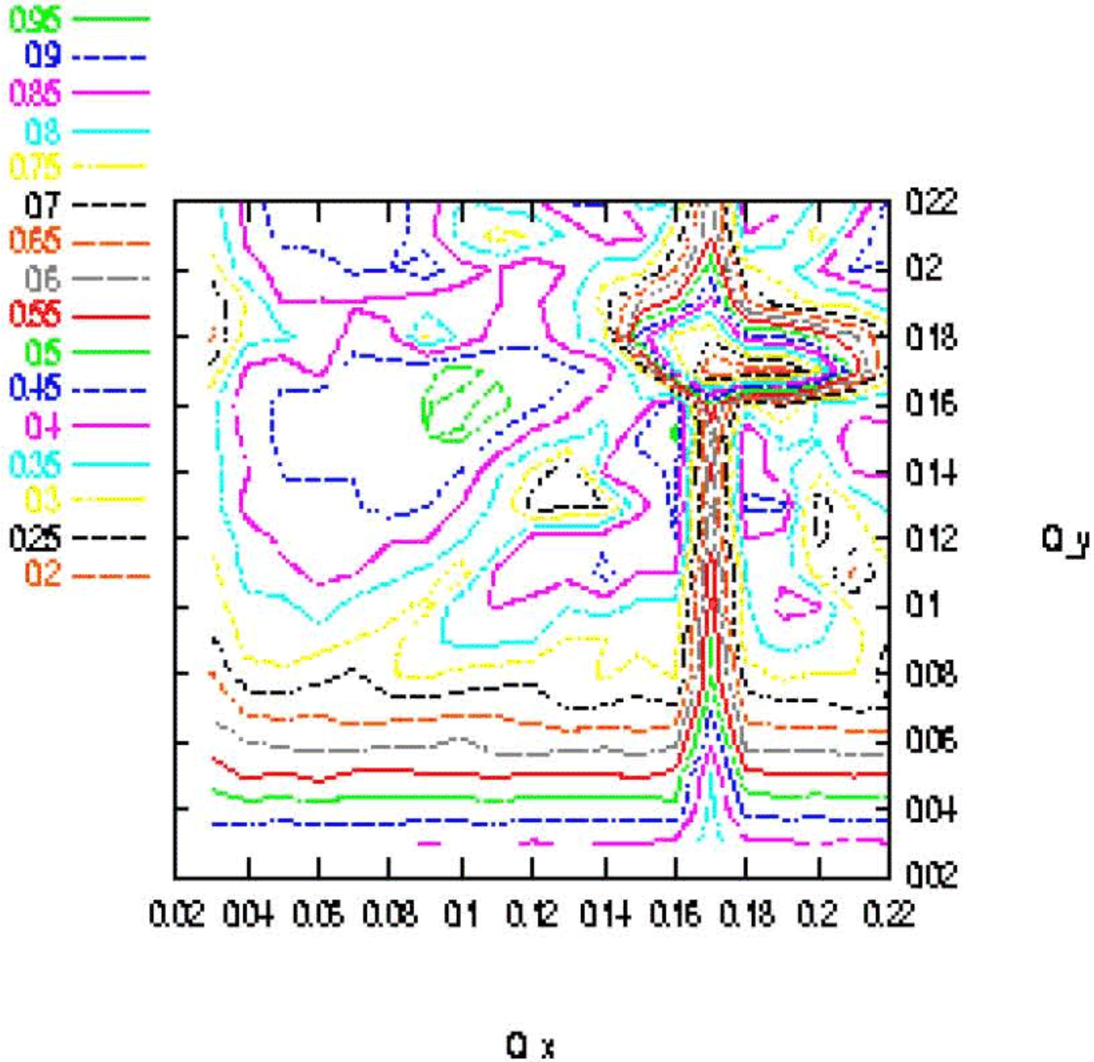
*Total path length increase: ~4.47cm.
* Linear rad. power at 10 GeV ~14kW/m

e-ring path length adj. requirement (with super-bends)

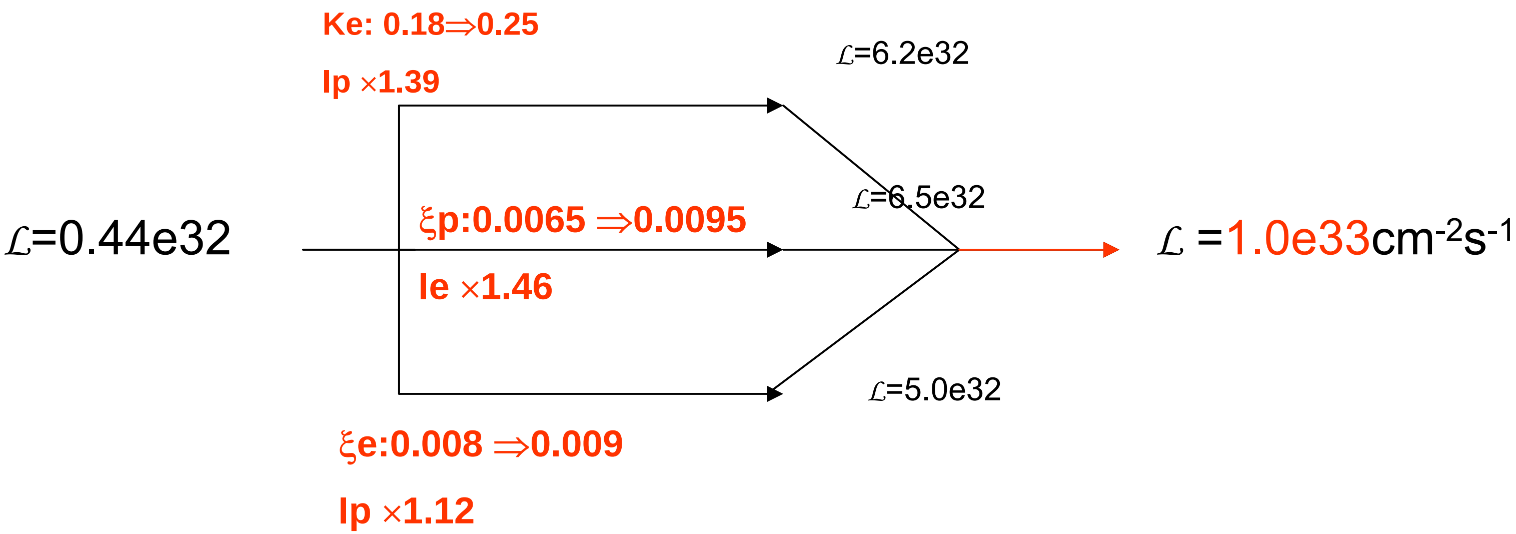
## Beam-beam Contour plot, $\xi_x$=0.025, $\xi_y$=0.08 for the ZDR design (Linear lattice)

C. Montag

$\mathcal{L}/\mathcal{L}_0$



# Higher luminosity option with ZDR design




- Possible higher beam-beam & e emittance aspect ratio.
- Present: $\xi_{p\text{-}p}$(3×IP) ~0.02.
- Higher (×1.5) lepton & hadron beam intensities.
- e-ring technical system: linear rad. power density ~ 20kW/m, (vacuum etc.) design

  (Super KEKB: 21.6kW/m ). RF system capacity.

# Higher luminosity operation

| | | ZDR Design | | | | Higher Luminosity Operation | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Electron | Proton | Electron | Au | Electron | Proton | Electron | Au |
| Energy E | [GeV] | 10 | 250 | 10 | 100 | 10 | 250 | 10 | 100 |
| k=εy/εx | | 0.18 | 1 | 0.14 | 1 | 0.23 | 1 | 0.18 | 1 |
| Kσ=σy/σx | | 0.50 | 0.50 | 0.50 | 0.50 | 0.48 | 0.48 | 0.43 | 0.43 |
| $\varepsilon_n$ (ion) | [π mm mrad] | | 15.0 | | 6.0 | | 15.0 | | 6.0 |
| Emittancs εx | [nm.rad] | 53.0 | 9.4 | 54.0 | 9.4 | 54.0 | 9.4 | 54.0 | 9.4 |
| Emittancs εy | [nm.rad] | 9.5 | 9.4 | 7.6 | 9.4 | 12.4 | 9.4 | 9.7 | 9.4 |
| βx* | [m] | 0.19 | 1.08 | 0.19 | 1.08 | 0.19 | 1.08 | 0.19 | 1.08 |
| βy* | [m] | 0.27 | 0.27 | 0.34 | 0.27 | 0.19 | 0.25 | 0.19 | 0.2 |
| ξx | | 0.029 | 0.0065 | 0.022 | 0.0065 | 0.043 | 0.0095 | 0.033 | 0.0095 |
| ξy | | 0.08 | 0.1000 | 0.08 | 0.0033 | 0.09 | 0.0046 | 0.08 | 0.0041 |
| Particles/Bunch | | 1.00E+11 | 9.98E+10 | 9.88E+10 | 1.00E+09 | 1.45E+11 | 1.50E+11 | 1.38E+11 | 1.43E+09 |
| Luminosity L | [$cm^{-2}s^{-1}$] | | 4.4E+32 | | 4.4E+30 | | 1.0E+33 | | 1.0E+31 |

# Bunch intensity comparison

| | PEP II HER | PEP II LER | KEKB HER | KEKB LER | eRHIC ering 0.44E33 | eRHIC ering 1.0E33 |
|---|---|---|---|---|---|---|
| Energy (GeV) | 9 | 3.1 | 8 | 3.5 | 10 | 10 |
| Circumference (m) | 2200 | 2200 | 3016.26 | 3016.26 | 1277.948 | 1277.948 |
| Bending Radius (m) | 165 | 13.751 | 104.46 | 16.31 | 81.02 | 81.02 |
| Beam Current (A) | 1.38 | 2.43 | 1.10 | 1.86 | 0.45 | 0.65 |
| Critical SR Energy (KeV) | 9.80 | 4.81 | 10.87 | 5.83 | 27.38 | 27.38 |
| ***Linear Power Density (kW/m)*** | ***4.7*** | ***3.7*** | ***5.8*** | ***14.8*** | ***9.7*** | ***13.9*** |
| RF Voltage (MV) | 14 | 3.2 | 13 | 8 | 25 | 25 |
| Energy Loss /turn (MeV) | 3.52 | 0.59 | 3.47 | 0.81 | 10.92 | 10.92 |
| ***Radiation Power (MW)*** | ***4.86*** | ***1.44*** | ***3.82*** | ***1.51*** | ***4.92*** | ***7.10*** |
| Bunch number | 1317 | 1317 | 1284 | 1284 | 120 | 120 |
| Bunch spacing (ns) | 4.2 | 4.2 | 7.9 | 7.9 | 35.5 | 35.5 |
| ***particles/bunch (*1E11)*** | ***0.5*** | ***0.8*** | ***0.5*** | ***0.9*** | ***1.0*** | ***1.4*** |
| Charge/bunch [nC] | 7.7 | 13.5 | 8.6 | 14.6 | 16.0 | 23.1 |

# Summary

- The ZDR luminosity goals are based on expected RHIC upgrade, realistic electron ring and IR design, mature technologies and without an extensive R &D program.

  e-p 10/250 GeV: $0.44 \times 10^{33}$ $cm^{-2}s^{-1}$, …
- Higher luminosity option: possible, under study.

  Goal (e-p 10/250 GeV): $10^{33}$ $cm^{-2}s^{-1}$,

  peak 86 $pb^{-1}$/day, ~25 $fb^{-1}$/year.
- Time scale:

  The eRHIC ring-ring collider can be ready in 7 to 8 years to run the proposed new experimental program at the earliest possible time. More ambitious collider designs for even higher luminosities may then become available for a next generation of physics experiments.