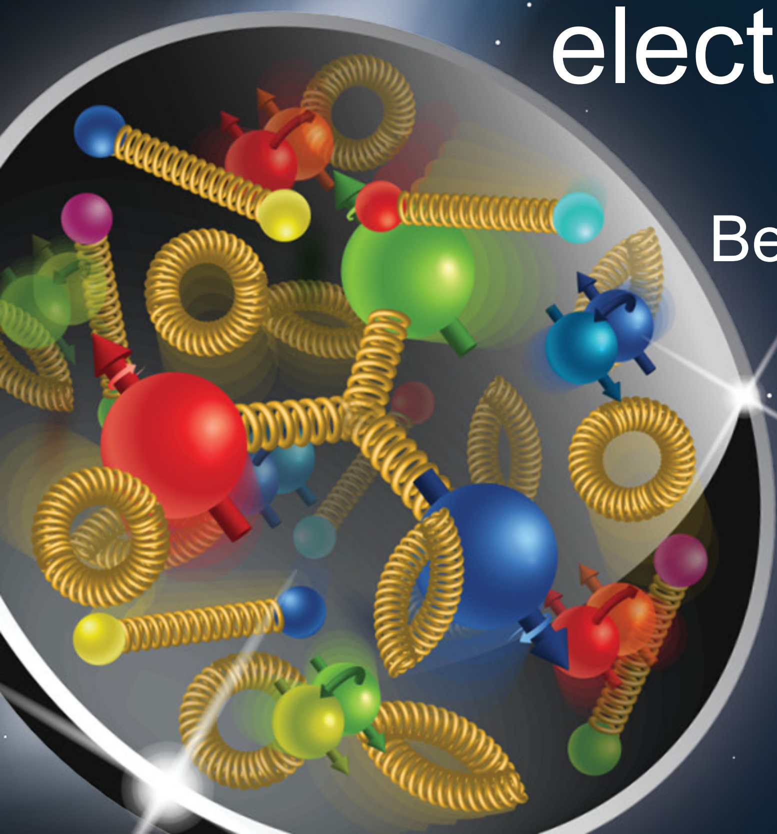
Proton beam emittance growth due to due strongly disrupted electron beam in eRHIC



Beam-Beam Effects in Circular Colliders
Berkeley, 5-7 February 2018

G. Bassi*, Y. Hao, A. He, Y. Luo,
C. Montag, V. Smaluk, F. Willeke

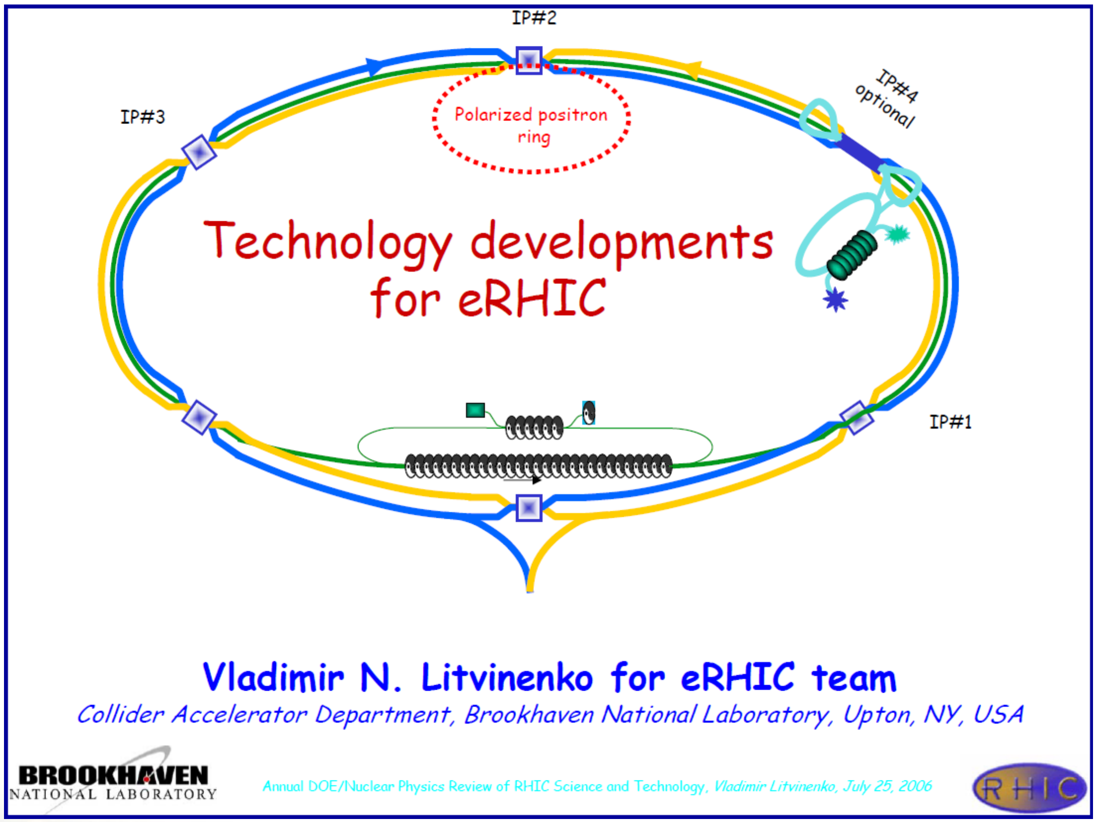
Electron Ion Collider – eRHIC

BROOKHAVEN NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- **Linac Ring eRHIC and beam-beam effects**
- **Strong-strong beam beam simulations with BBSS (K. Ohmi):**
  - **Electron beam disruption.**
  - **Proton beam emittance growth due to fluctuations of the electron bunch centroid at the interaction point (IP).**
- **Discussion/future studies**

Linac-Ring eRHIC



Appendix A of the eRHIC ZDR

Linac-Ring eRHIC.

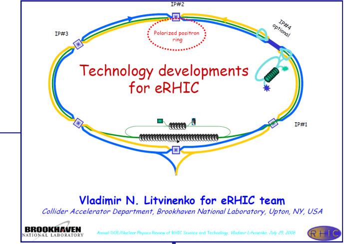
Daniel Anderson, Ilan Ben-Zvi[1], Rama Calaga[1], Xiangyun Chang[1], Manouchehr Farkhondeh[2], Alexei Fedotov[1], Jörg Kewisch[1], Vladimir Litvinenko[1], William Mackay[1], Christoph Montag[1], Thomas Roser[1], Vitaly Yakimenko[3]

[(1)] C-AD, BNL [(2)] Bates, MIT [(3)] Physics Department, BNL

Content — page

172

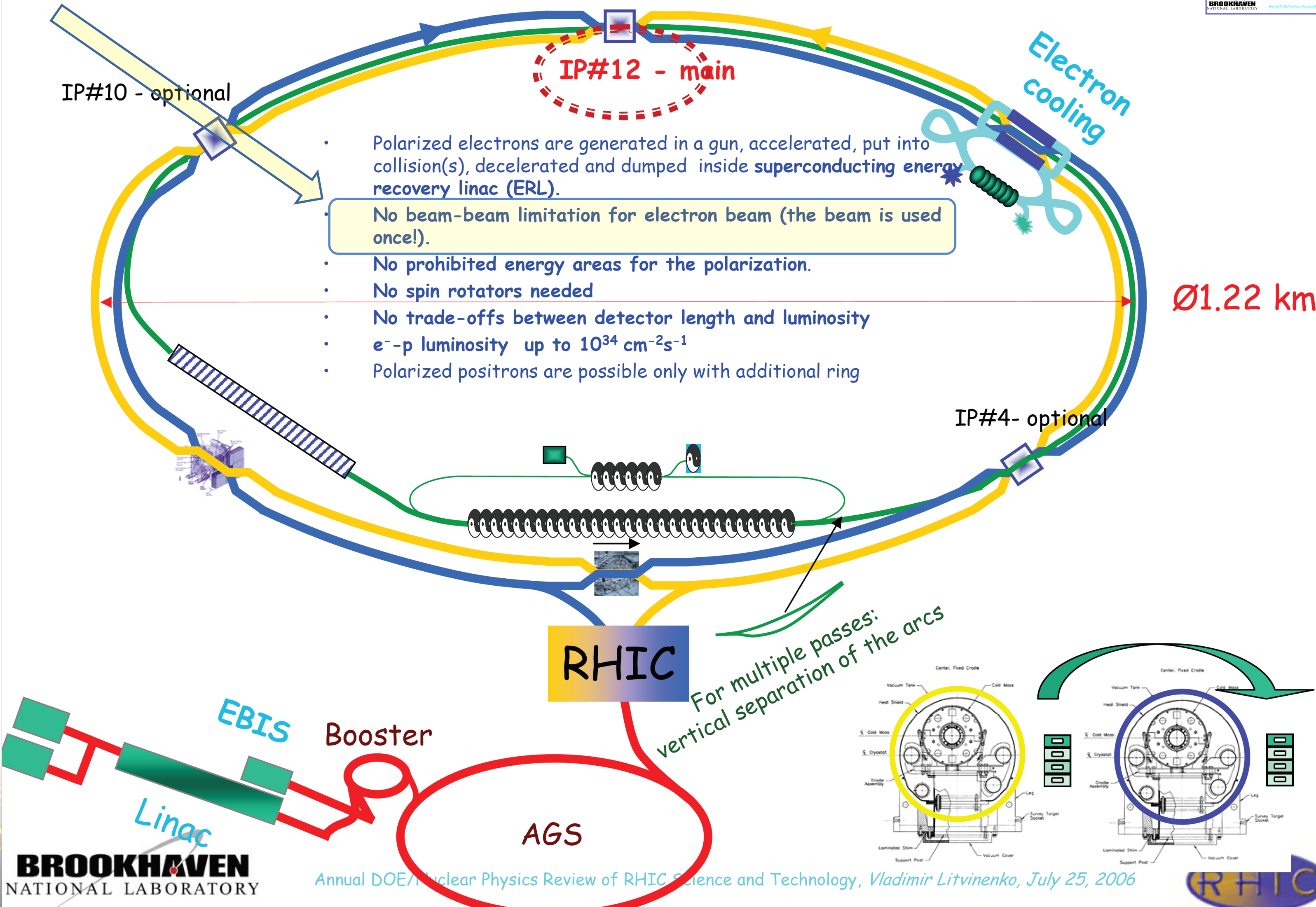
Linac-Ring eRHIC Design



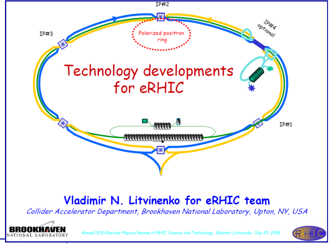
my highlight

Linac-Ring Design based on 5-20⁺ GeV ERL

- Polarized electrons are generated in a gun, accelerated, put into collision(s), decelerated and dumped inside **superconducting energy recovery linac (ERL).**
- No beam-beam limitation for electron beam (the beam is used once!).
- **No prohibited energy areas for the polarization.**
- **No spin rotators needed**
- **No trade-offs between detector length and luminosity**
- **e^--p luminosity up to 10^{34} $cm^{-2}s^{-1}$**
- Polarized positrons are possible only with additional ring



Linac-Ring eRHIC: Round Beams



In linac-ring eRHIC luminosity is determined by the hadron beam!

$$L = f_c \frac{N_e N_h}{4\pi \beta_h^* \varepsilon_h}$$

Round beams $\beta_e^* \varepsilon_e = \beta_h^* \varepsilon_h$

$$L = \gamma_h \cdot (f_c \cdot N_h) \cdot \frac{\xi_h \cdot Z_h}{\beta_h^* \cdot r_h}$$

In parallel with STAR and PHENIX

$$\xi_h = \frac{N_e}{\gamma_h} \frac{r_h}{4\pi Z \varepsilon_h} = 0.007$$

Luminosity 10^{33} cm^{-2}sec^{-1}	Protons 26 GeV	Protons 50 GeV	Protons 100 GeV	Protons 250 GeV
Electrons 5(2)-10(20) GeV	0.28	0.52	0.96	2.8

Luminosity (per nucleus) 10^{31} cm^{-2}sec^{-1}	Au 50 GeV/u	Au 100 GeV/u
Electrons 5(2)-10(20) GeV	1.4	2.8

Dedicated eRHIC mode with 250 GeV p or 100 GeV/u Au

$$\xi_h \to 0.02 \quad \Leftrightarrow \quad L_{p\ e} \to 1 \cdot 10^{34}$$

Electron Disruption

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **13**, 071003 (2010)

Effect of electron disruption in the energy recovery linac based electron ion collider

Y. Hao and V. Ptitsyn

Brookhaven National Laboratory, Upton, New York 11973, USA

(Received 2 February 2010; published 19 July 2010)

Beam-beam effects present one of the major factors limiting the luminosity of colliders. In the energy recovery linac (ERL) based eRHIC design, the electron beam, accelerated in a superconducting ERL, collides with the proton beam circulating in the RHIC ring. During such collisions the electron beam undergoes a very strong beam-beam interaction with the protons, which warrants careful examination. We evaluated transverse disruption and linear mismatch effects in the electron beam caused by collisions and considered several countermeasures to mitigate the emittance growth from these interactions. The minimum required aperture of transport lines is calculated that should allow the transport of the electron beam during the deceleration process.

TABLE I. ERL-based eRHIC beam parameters.

	High-energy setup		Low-energy setup	
	p	*e*	*p*	*e*
Energy (GeV)	250	10	50	3
Number of bunches	166		166	
Bunch intensity (10^{11})	2.0	1.2	2.0	1.2
Beam current (mA)	420	260	420	260
95% normalized emittance (π mm mrad)	6	115	6	115
rms emittance (nm rad)	3.8	1.0/(5.0)	19.0	3.3/(16.5)
β^* (cm)	26	100/(20)	26	150/(30)
Beam-beam parameter	0.015	2.3/(0.46)	0.015	2.3 (0.46)
Disruption parameter	0.005	5.8	0.01	3.8
rms bunch length (cm)	20	0.7	20	1.5
Polarization (%)	70	80	70	80
Peak luminosity (10^{33} cm^{-2} s^{-1})	2.6		0.53	

Beam-Beam Strong-Strong Code

BBSS

K.Ohmi, KEK

Particle In Cell

- Beam potential

$$G(x,y)=\frac{1}{2}\ln(x^2+y^2)$$

$$\phi(\boldsymbol{x})=-\frac{2Nr_e}{\gamma}\int d\boldsymbol{x}'G(\boldsymbol{x}-\boldsymbol{x}')\rho(\boldsymbol{x}')$$

- Inte $G(x_i,y_j)=\int_{y_j-\Delta y/2}^{y_j+\Delta y/2}\int_{x_i-\Delta x/2}^{x_i+\Delta x/2}G(x,y)dxdy$

$$g(x,y)\equiv\int\int\log(x^2+y^2)dxdy=-3xy+$$
$$x^2\tan^{-1}(y/x)+y^2\tan^{-1}(x/y)+xy\log(x^2+y^2)$$

Chromaticity

- Effective Hamiltonian/generating function at IP.

$$H_I(x,\bar{p},\bar{\delta})=\sum_{n=1}\frac{a_nx^2+2b_nx\bar{p}+c_n\bar{p}^2}{2}\bar{\delta}^n$$

Relations between a,b,c and chromaticity, ν',α',β'.

$$a_1=\frac{\sin^2\mu_0}{\beta_0^2}\left[-\beta_1(\cot\mu_0+\alpha_0)(1+\alpha_0^2)+\{-\alpha_1+\mu_1\csc^2\mu_0+2\alpha_1\alpha_0\cot\mu_0+(\alpha_1+\mu_1\csc^2\mu_0)\alpha_0^2\}\beta_0\right],$$

$$b_1=\frac{\sin^2\mu_0}{\beta_0}\left[-\beta_1(1+\alpha_0^2)+\{\alpha_1\cot\mu_0+(\alpha_1+\mu_1\csc^2\mu_0)\alpha_0\}\beta_0\right],$$

$$c_1=\left[\beta_1\cot\mu_0-\beta_1\alpha_0+(\alpha_1+\mu_1\csc^2\mu_0)\beta_0\right]\sin^2\mu_0$$

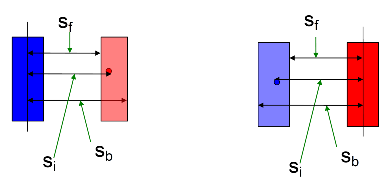
$$\mu=\mu_0+\mu_1\delta,\ \beta=\beta_0+\beta_1\delta\ \text{and}\ \alpha=\alpha_0+\alpha_1\delta$$

Transformation for chromaticity

$$\bar{x}=x+\frac{\partial H_I}{\partial\bar{p}}=x+\sum(b_nx+c_n\bar{p})\bar{\delta}^n,$$
$$p=\bar{p}+\frac{\partial H_I}{\partial x}=\bar{p}+\sum(a_nx+b_n\bar{p})\bar{\delta}^n,$$
$$\bar{z}=z+\frac{\partial H_I}{\partial\bar{\delta}}=z+\sum n(a_nx^2+2b_nx\bar{p}+c_n\bar{p}^2)\bar{\delta}^n$$

&HERING
chrmh=0.5,-48.,-17.7,1.5,81.5,-0.609

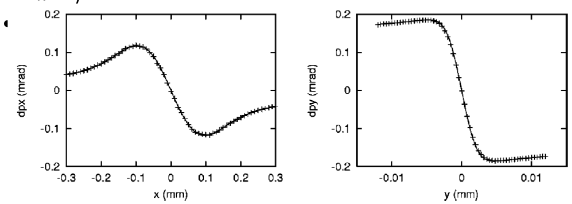
3D symplectic integrator for slice-by-slice collision



- Since the interaction depends on z, energy kick should be taken into account dϕ/dz.
- We repeat the same procedure exchanging particle and slice.

Beam-beam force for flat beam

- Integrated Green function is indispensable to reproduce correct beam-beam force for flat beam, $\sigma_x/\sigma_y>100$.



K. Yokoya had used Integrated Green function since 1980'.

Crossing angle, crab cavity

- Crossing angle is equivalent to collision of two beams with xz tilt.

$$\bar{x}=\tan\theta_{crs}z+\left(1+\frac{\bar{p}_x}{\bar{p}_s}\sin\theta_{crs}\right)x$$
$$\bar{y}=y+\sin\theta_{crs}\frac{\bar{p}_y}{\bar{p}_s}x$$
$$\bar{z}=\frac{z}{\cos\theta_{crs}}-\frac{\bar{H}}{\bar{p}_s}\sin\theta_{crs}x$$
$$\bar{p}_x=\frac{p_x-\tan\theta_{crs}H}{\cos\theta_{crs}}$$
$$\bar{p}_y=\frac{p_y}{\cos\theta_{crs}}$$
$$\bar{p}_z=p_z-\tan\theta_{crs}p_x+\tan^2\theta_{crs}]H,$$

$$H=(1+p_z)-\sqrt{(1+p_z)^2-p_x^2-p_y^2}$$

$$p_s=\sqrt{(1+p_z)^2-p_x^2-p_y^2}.$$

$$H=\pm\theta_{crs}p_xz\delta(s-s^*)$$

$$\bar{x}=x\pm\theta_{crs}z\qquad\bar{z}=z\pm\theta_{crs}$$

xz tilt can be controlled by crab cavity.

$$\frac{eV_{crab}\omega_{crab}}{cE_0}\sqrt{\beta_x^*\beta_{x,crab}}=\theta_{crs}$$

$$H=\frac{eV_{crab}}{E_0}x\sin\left(\frac{\omega_{crab}z}{c}\right)\delta(s-s_{crab})$$

$$H_{eff}^*=\frac{c\theta_{crb}}{\omega_{crb}}p_x\sin\left(\frac{\omega_{crb}z}{c}\right)\delta(s-s^*)$$

K.Ohmi, Phys. Rev E 62, 5 (2000)

Arc transformation

- Linear transfer matrix (6x6)

$$M_{2\times2\times2}=\begin{pmatrix}M_x&0&0\\0&M_y&0\\0&0&M_z\end{pmatrix}\qquad M_i(s)=\begin{pmatrix}\cos\mu_i+\alpha_i\sin\mu_i&\beta_i\sin\mu_i\\-\gamma_i\sin\mu_i&\cos\mu_i-\alpha_i\sin\mu_i\end{pmatrix}$$

- Take into account of dispersion and x-y coupling at IP

$$M_6=R_\eta M_{4\times2}R_\eta^{-1}\qquad R_\eta=\begin{pmatrix}\{1-\frac{|R_{\eta,x}|}{1+r_{\eta,0}}\}I_2&\frac{R_{\eta,x}S_2R_{\eta,y}^TS_2}{1+r_{\eta,0}}&R_{\eta,x}\\\frac{R_{\eta,y}S_2R_{\eta,x}^TS_2}{1+r_{\eta,0}}&\{1-\frac{|R_{\eta,y}|}{1+r_{\eta,0}}\}I_2&R_{\eta,y}\\S_2R_{\eta,x}^TS_2&S_2R_{\eta,y}^TS_2&r_{\eta,0}I_2\end{pmatrix}$$

- Crabbing and crossing angle, ζ

$$R_{\eta,i}=\begin{pmatrix}\zeta_i&\eta_i\\\zeta_i'&\eta_i'\end{pmatrix}\ i=x,y$$

$$M_4=RM_{2\times2}R^{-1}\qquad R=\begin{pmatrix}r_0I_2&-S_2R_2^TS_2\\-R_2&r_0I_2\end{pmatrix}\qquad R_2=\begin{pmatrix}r_1&r_2\\r_3&r_4\end{pmatrix}$$

- Important parameters

Flat beam β_x, α_y(waist) , β_y, ν_x, ν_y, η_y, η'_y, r_1-r_4, ζ_x(crab angle),

Round beam + η_x, η'_x, α_x

twissl=0., 2., 34.08, 0., 0.07, 31.09, 0., 8., 0.025,
0.0, 0.0, 0.0, 0.0,
0.,0.,0.,0.,0.,0.,0.,0.

3D beam-beam interaction

Strong-strong

- β_y=1mm, σ_z=2.3(LEP3)-1.7(TLEP-h)mm. For $\sigma_z>\beta_y$, the beam-beam force varies significantly along the bunch length.
- A bunch is divided into several slices which contain many macro-particles.
- Collision is calculated slice by slice.

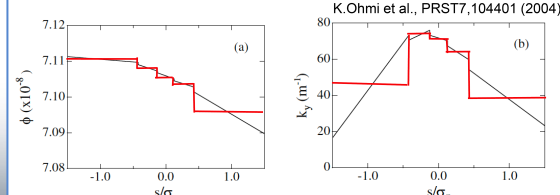
$$\prod_{i=1}^{N_{sl,-}}\exp\left[-:V_{0,+}^{-1}(s_{-,i})\phi_{-,i}(+,s_{-,i})V_{0,+}(s_{-,i})\Delta s:\right]$$
$$\prod_{i=1}^{N_{sl,+}}\exp\left[-:V_{0,-}^{-1}(s_{+,j})\phi_{+,j}(-,s_{+,j})V_{0,-}(s_{+,j})\Delta s:\right]$$

drift between slices

$$V_0(s)\equiv V_0(s,0)=S\exp\left[-:\int_0^sH_0ds:\right]=\prod_{i=\pm}\exp\left[-:\frac{p_{x,i}^2+p_{y,i}^2}{2}s:\right],$$

Potential and linear kick of he slice-by-slice collision

KEKB case
K.Ohmi et al., PRST7,104401 (2004)



$$k_y=\partial^2\phi(s)/\partial y^2=\Delta p_y/\Delta x$$

$$\phi_j(s)=\phi_j(s_b)+\frac{\phi_j(s_f)-\phi_j(s_b)}{s_f-s_b}(s-s_b)$$

$$\phi_j(s)=\phi_j(s_c)$$

- potential is interpolated.
- potential at center of slice, BAD method

eRHIC Beam-Beam Simulations with BBSS

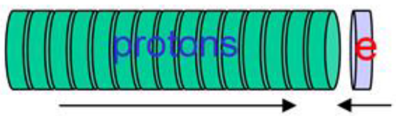
Machine and Beam Parameters Linac-Ring Option*

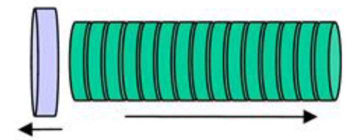
	Unit	protons	electrons
Circumference	m	3833.845	
Energy	GeV	250	10
Bunch population	10^{11}	1	1.2
Number of bunches		330	
Emittance	nm	3.8	5.0
Beta at IP	m	0.26	0.2
Bunch length	cm	20	0.7
Beam-beam parameter		0.015	0.23
Betatron tune		31.310/32.305	
Synchrotron tune		0.002	0.025
Radiation damping time	ms		25.5/51
Energy spread		0.0007	0.0005
Luminosity	10^{33} cm^{-2}s^{-1}	2.7	

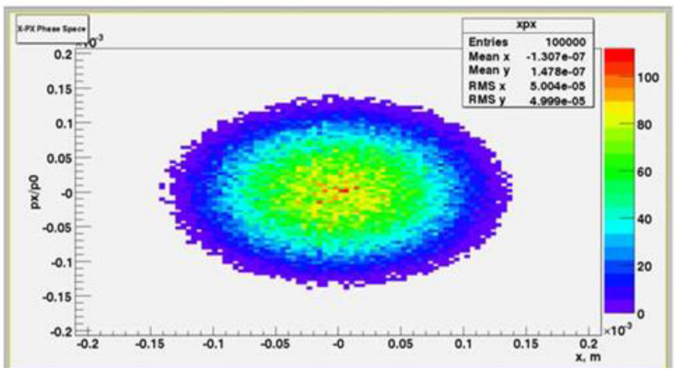
* Phys. Rev. ST Accel. Beams **13**, 071003 (2010)

Comparing Electron Disruption ($\beta_e^* = 1m, \ \varepsilon_e = 2.5nm$)

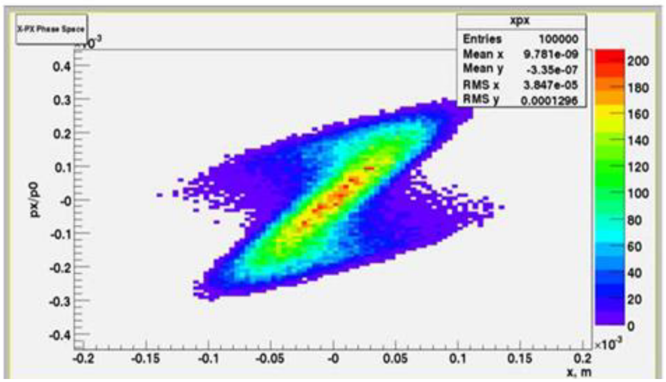
Beam Disruption -LINAC-RING (Y. Hao)

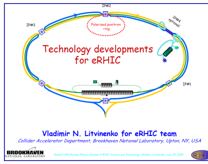


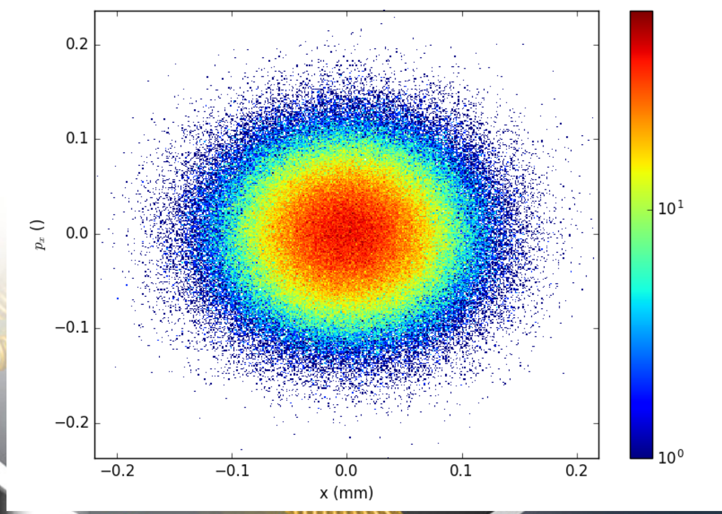


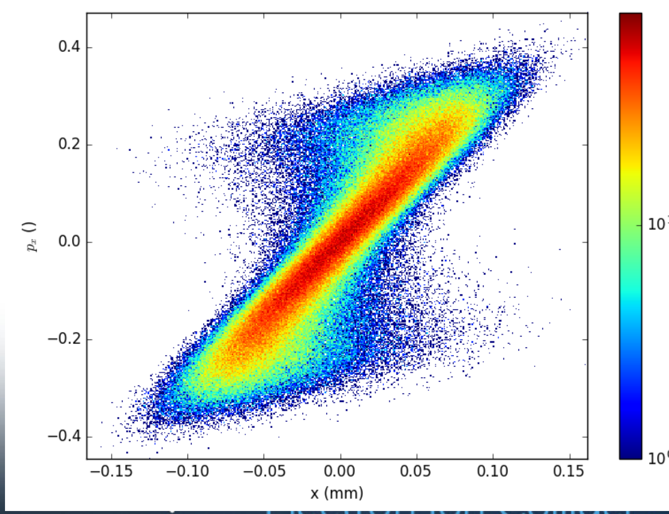


Interaction









BBSS

BBSS simulations with random offsets in e-beam

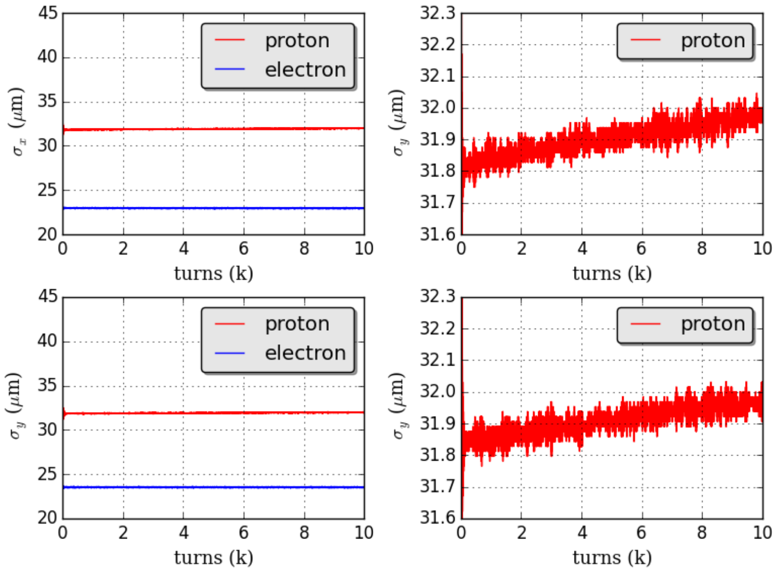
- **Centroid of freshly injected e-bunch perturbed by randomly generated offsets(x/y) at IP.**

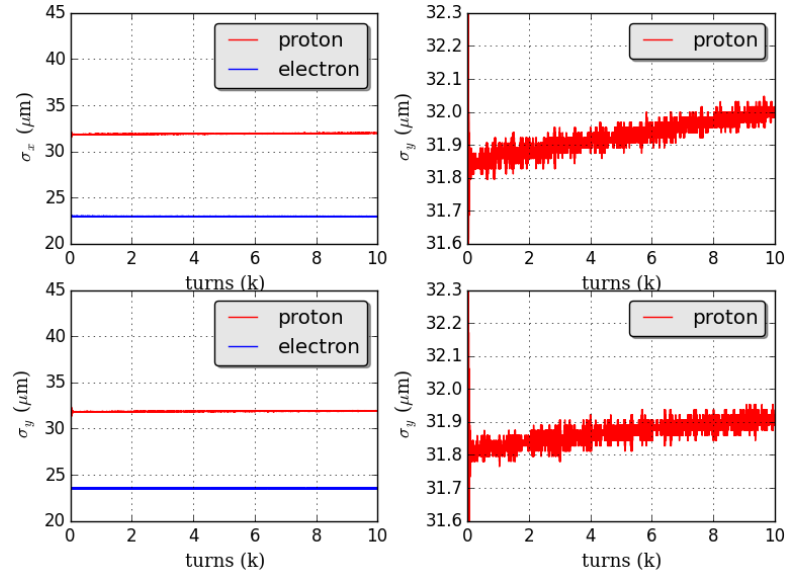
- **Offsets normally distributed with zero mean and standard deviation σ_{offs}.**

- **Effect of random offsets studied by calculating growth rates of proton bunch size.**

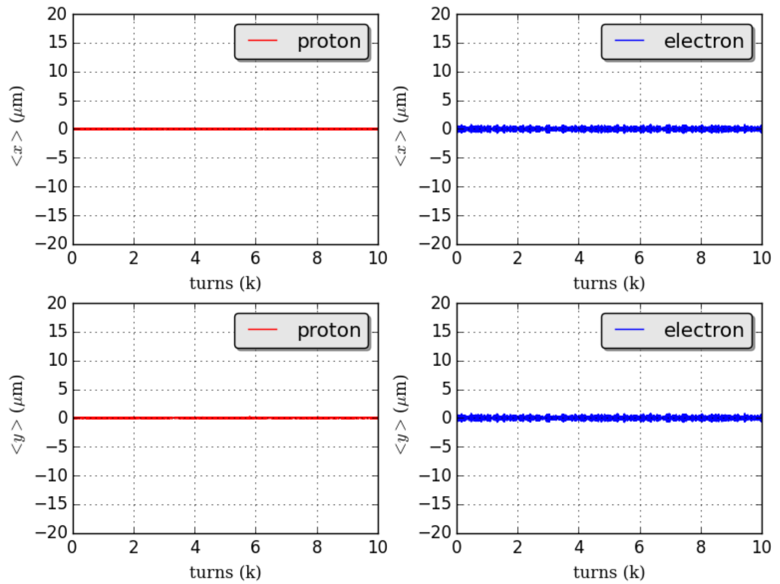
BBSS simulations without random offsets in e-beam

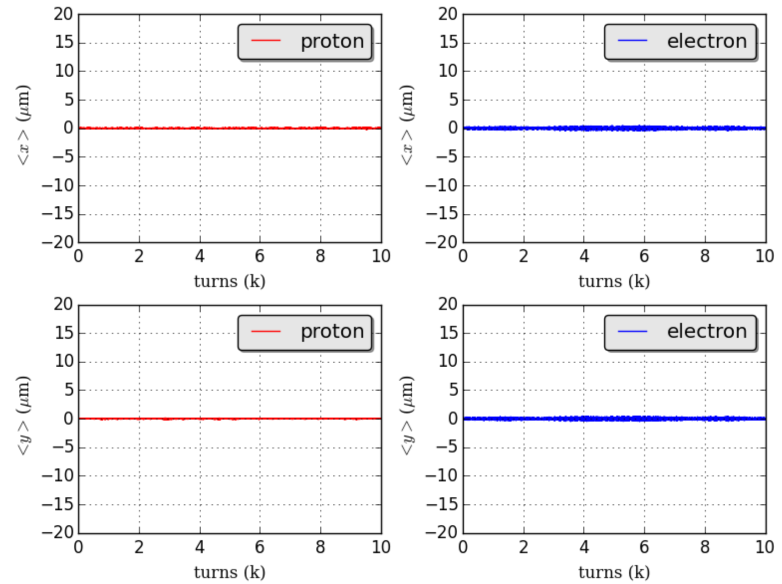
$M_p = M_e = 500k$ M # of macroparticles $M_p = N_e = 1M$





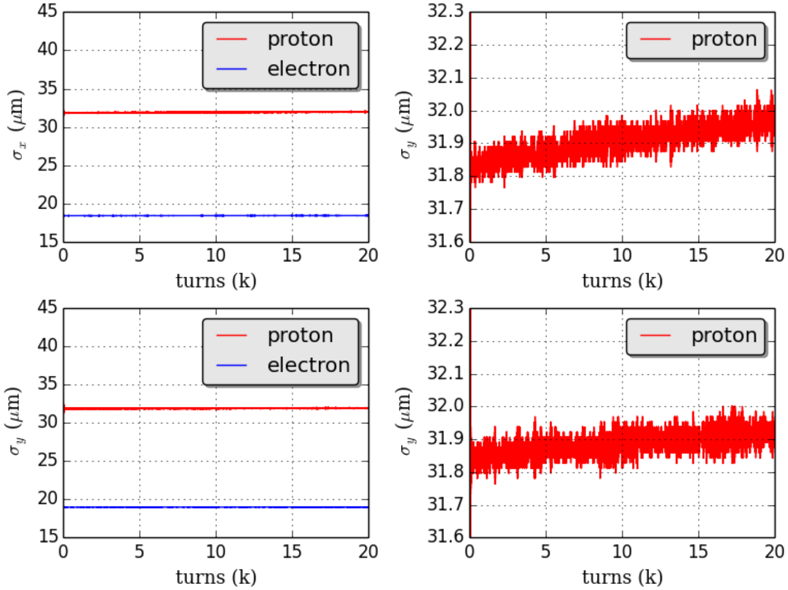
similar proton size growth rates: $g_{x,p} \approx 0.2$ μm/s, $g_{x,p} \approx 0.1$ μm/s



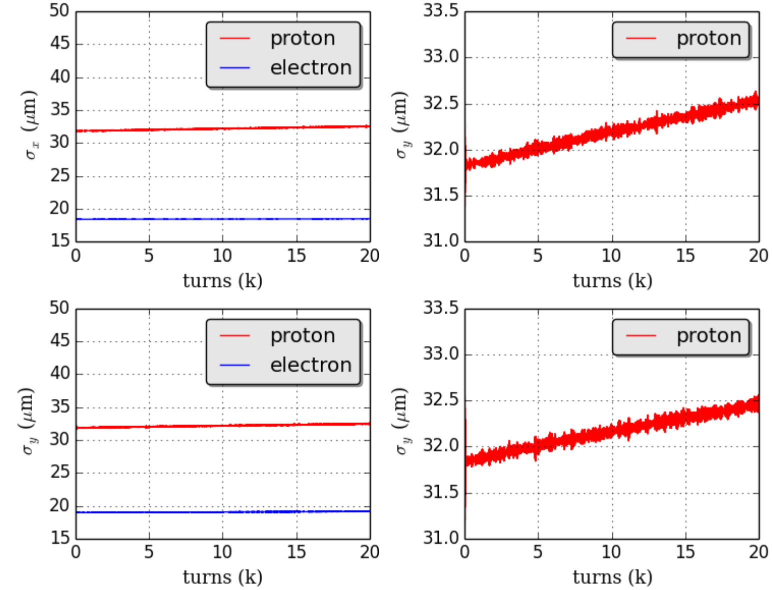


BBSS simulations with random offsets in e-beam

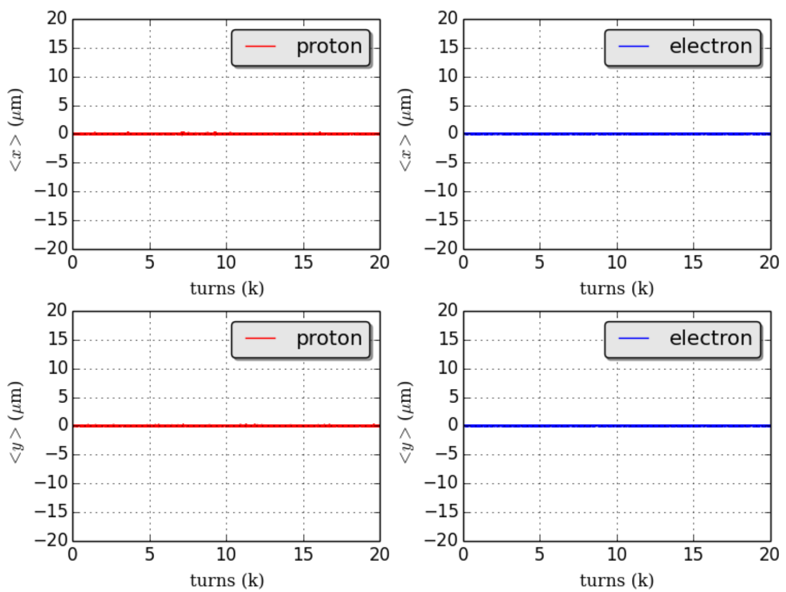
σ_{offs} = 0.03μm



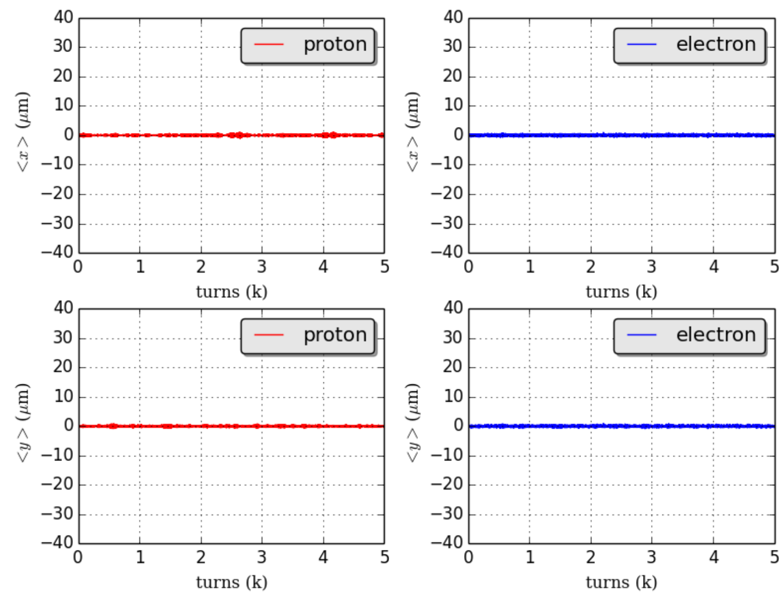
σ_{offs} = 0.5μm



$g_{x,p} \approx 0.2$ μm/s, $g_{x,p} \approx 0.1$ μm/s

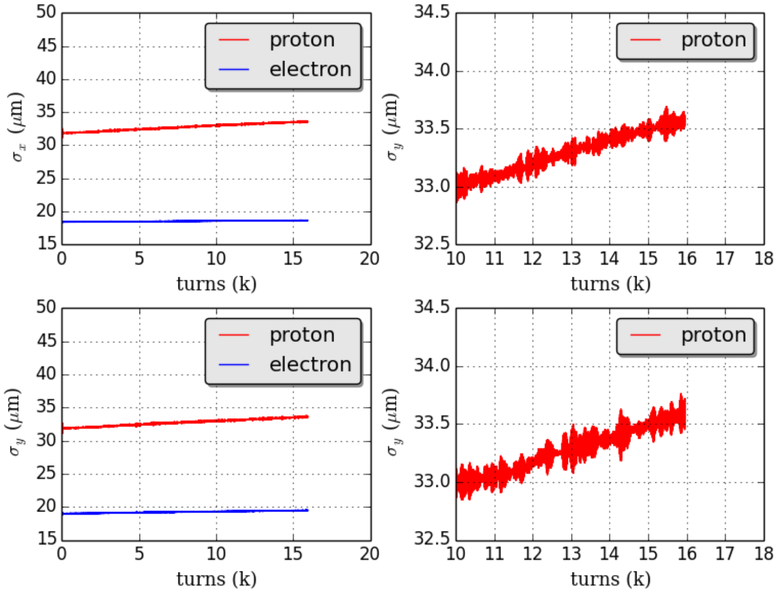


$g_{x,p} \approx 1.0$ μm/s, $g_{x,p} \approx 0.9$ μm/s

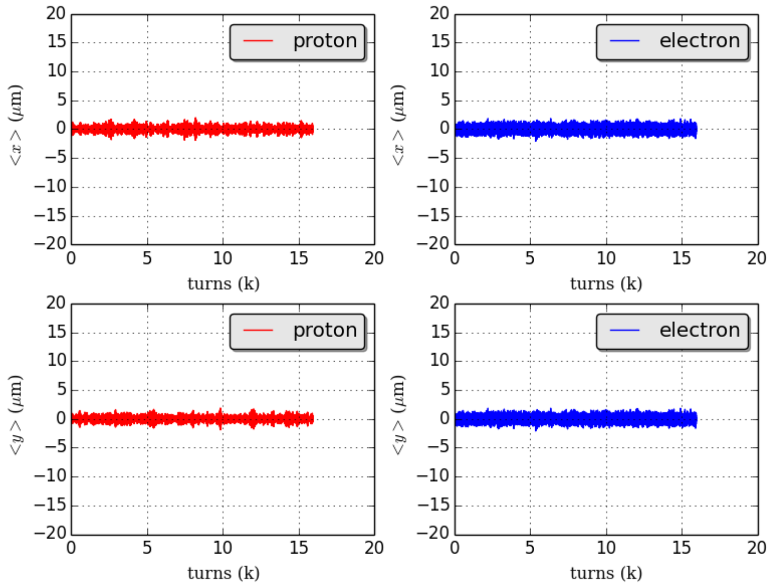


BBSS simulations with random offsets in e-beam

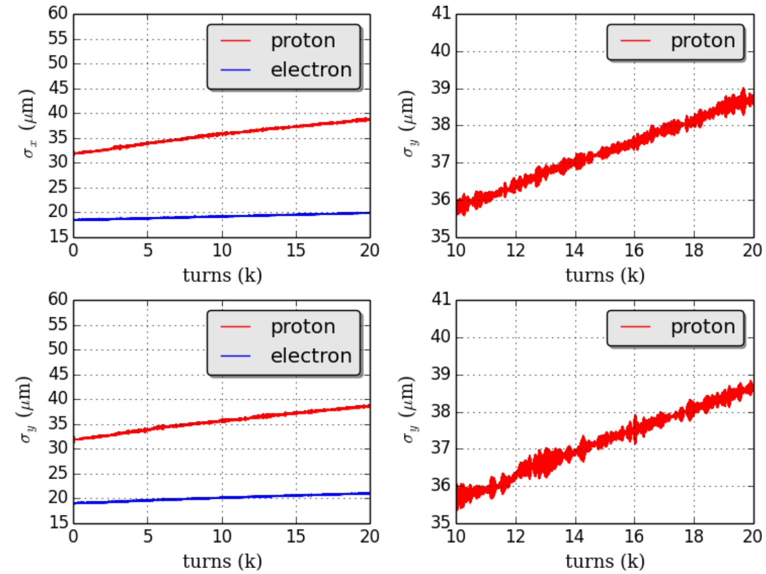
σ_{offs} = 1μm



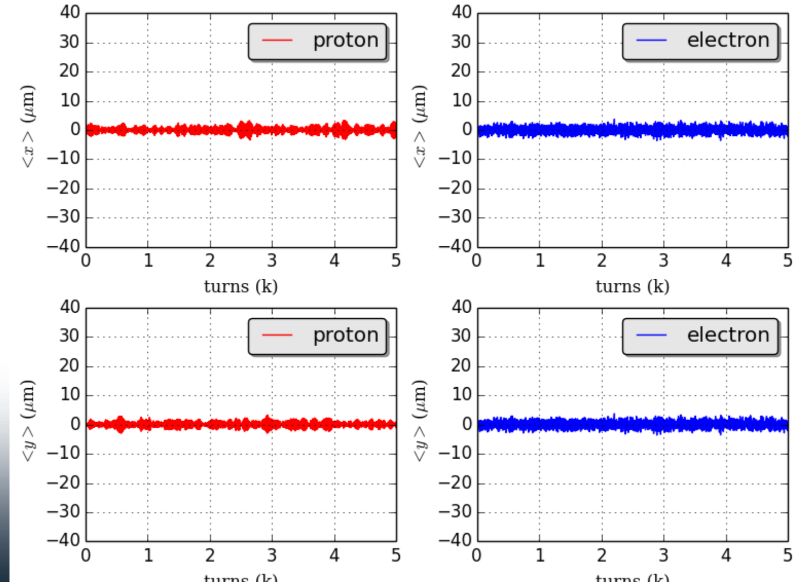
$g_{x,p} \approx 2.9$ μm/s, $g_{x,p} \approx 3.1$ μm/s



σ_{offs} = 2μm

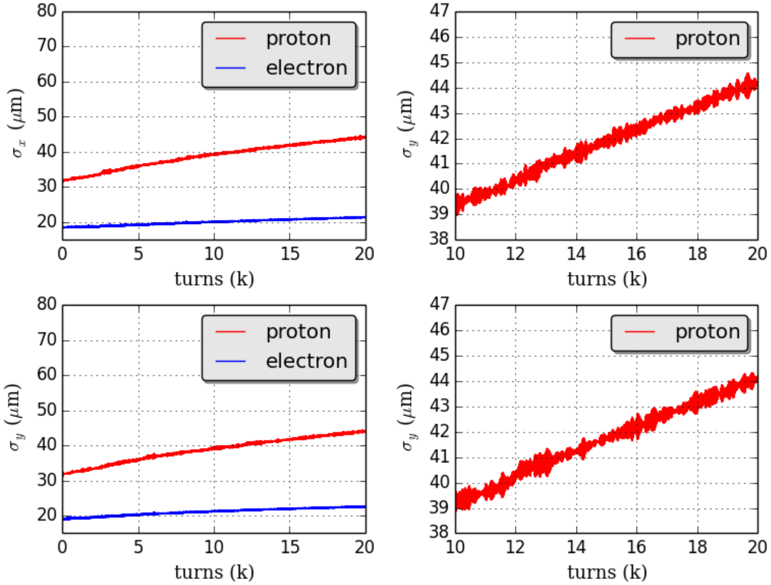


$g_{x,p} \approx 8.6$ μm/s, $g_{x,p} \approx 8.2$ μm/s

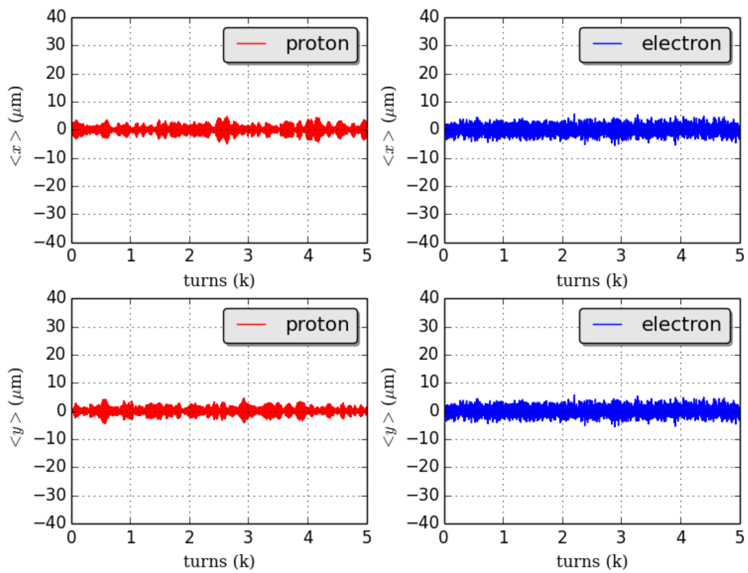


BBSS simulations with random offsets in e-beam

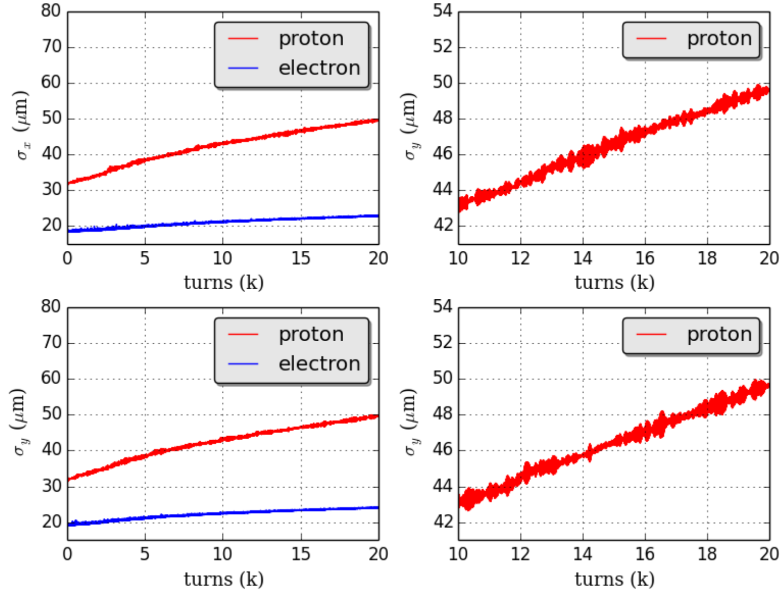
σ_{offs} = 3μm



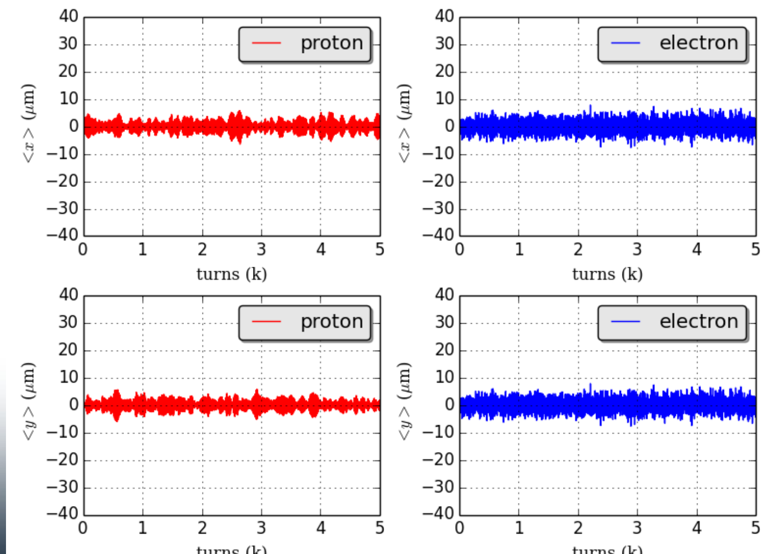
$g_{x,p} \approx 13.3$ μm/s, $g_{x,p} \approx 13.6$ μm/s



σ_{offs} = 4μm



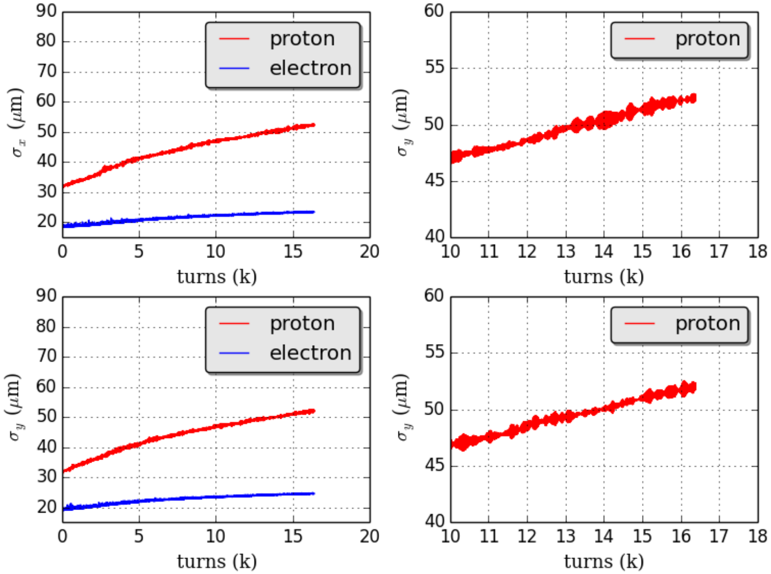
$g_{x,p} \approx 17.6$ μm/s, $g_{x,p} \approx 18.6$ μm/s

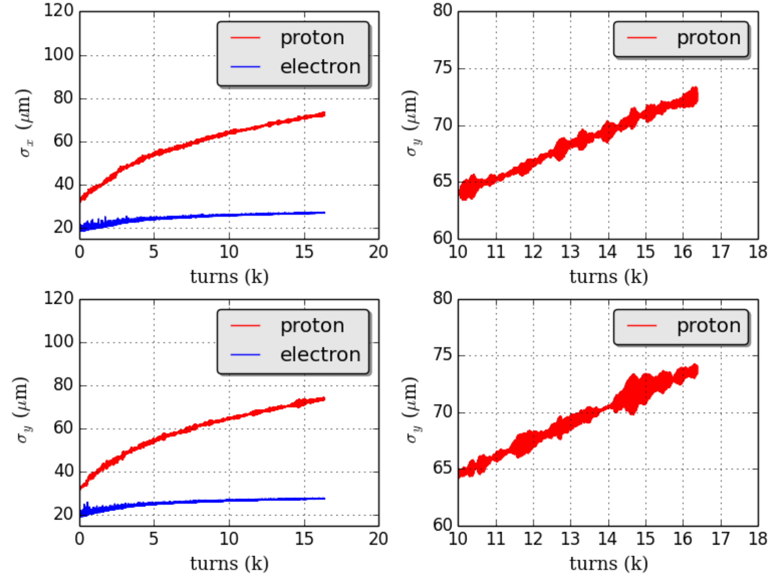


BBSS simulations with random offsets in e-beam

σ_{offs} = 5µm

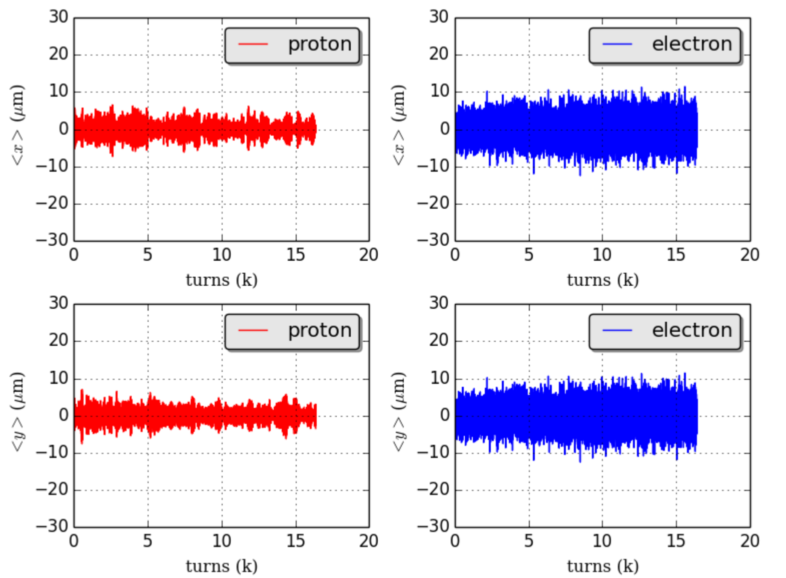
σ_{offs} = 10µm

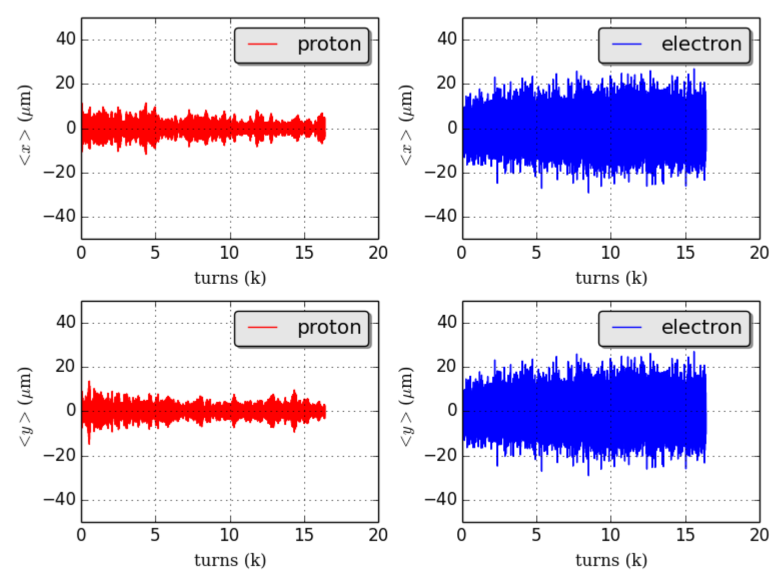




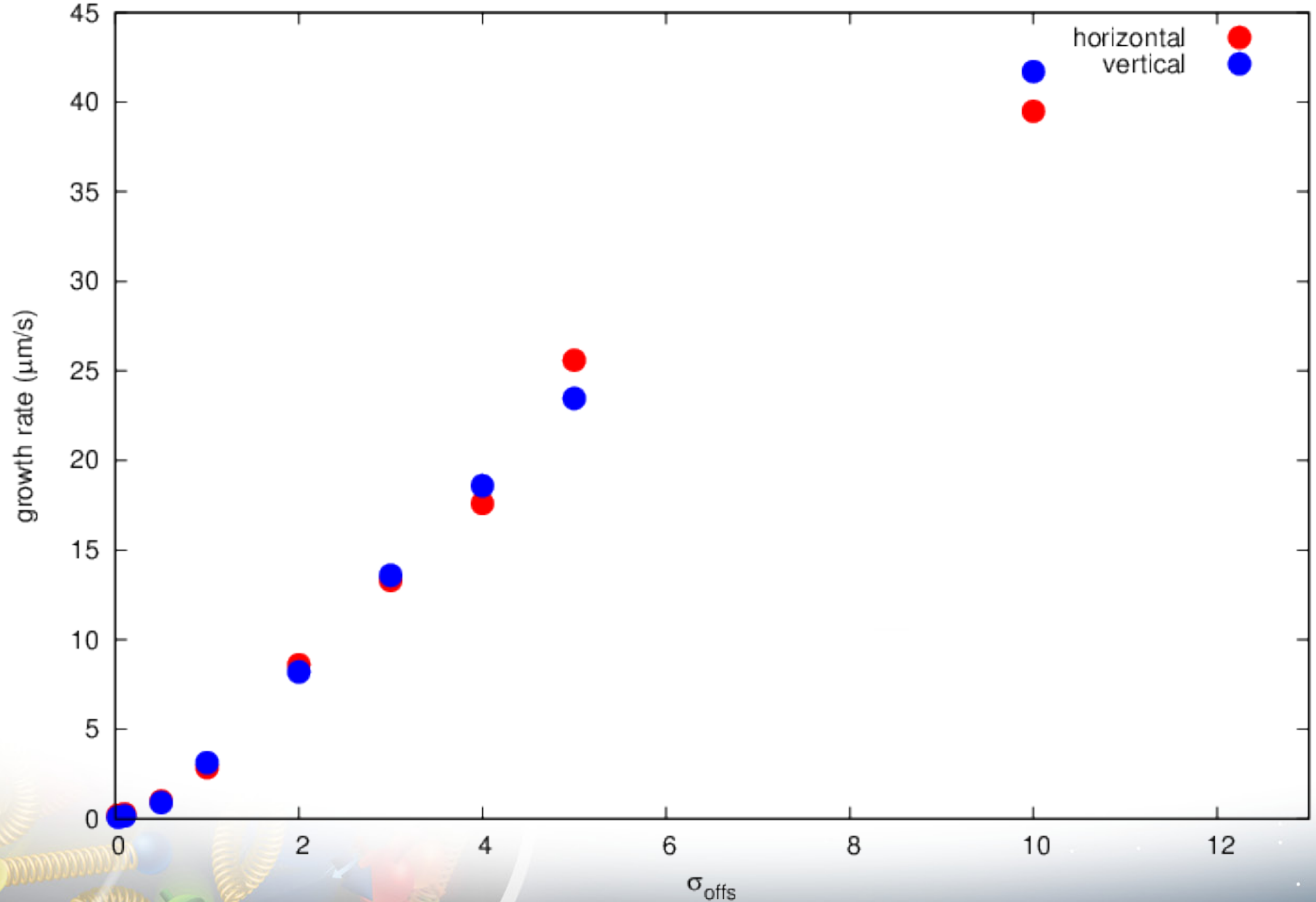
$g_{x,p}$ ≈ 25.6 µm/s, $g_{x,p}$ ≈ 23.5 µm/s

$g_{x,p}$ ≈ 39.5 µm/s, $g_{x,p}$ ≈ 41.7 µm/s





Proton Size Growth Rates

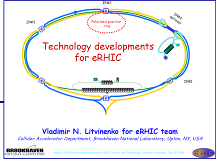


Discussion and Further Studies

- Random offsets in electron bunches at the interaction point induce large proton size for $\sigma_{offs} > 0.03\ \sigma_{x/y,p.}$
- Convergence/asymptotic studies are required to characterize the stability of the proton beam.
- Further studies will consider the impact of fluctuations in the electron bunch population on the stability of the proton beam.

Thank you for your attention!

Back Up Slides



Advantages & Disadvantages

Ring-Ring

- Proven technology (B-factory)
- Supports both electron and positron (!) beams options
- Requires significant (3-fold) increase to reach $L=0.8 \times 10^{33}$ cm^{-2} sec^{-1} but with very short (±1 m) detector
- Reasonable detector length (±3 m) reduces luminosity for present proton/ion intensities in RHIC below or about 10^{32} cm^{-2} sec^{-1}
- Polarization is not available in forbidden energy zones
- Single IP (period).
- Machine element inside detector
- Luminosity plummets at lower E_{cm}

Linac-Ring

- High luminosity up to 10^{34} cm^{-2} sec^{-1}
- Satisfy eRHIC physics goal with present proton/ion intensities in RHIC ($L>10^{33}$ cm^{-2} sec^{-1})
- Allows multiple IPs
- No machine elements inside detector(s)
- No significant limitation on the lengths of detectors
- Allows wider range of CM-energies with high luminosities
- Full spin transparency at all energies
- Energy of ERL is simply upgradeable
- Novel technology
- Need R&D on polarized gun
- Needs a dedicated ring positrons (if required)

Documentation on Linac-Ring eRHIC

Physics Requirements

- To provide electron-proton and electron-ion collisions
- Energy ranges:
  - 2-10 GeV polarized e^- or 10 GeV polarized e^+
  - 26-250 GeV polarized protons or 100 GeV/u Au
- Luminosities:
  - > 10^{33} $cm^{-2}s^{-1}$ region for e-p
  - > 10^{31} $cm^{-2}s^{-1}$ region for e-Au
- >70% polarization degree for both lepton and proton beams
- Longitudinal polarization in the collision point

eRHIC

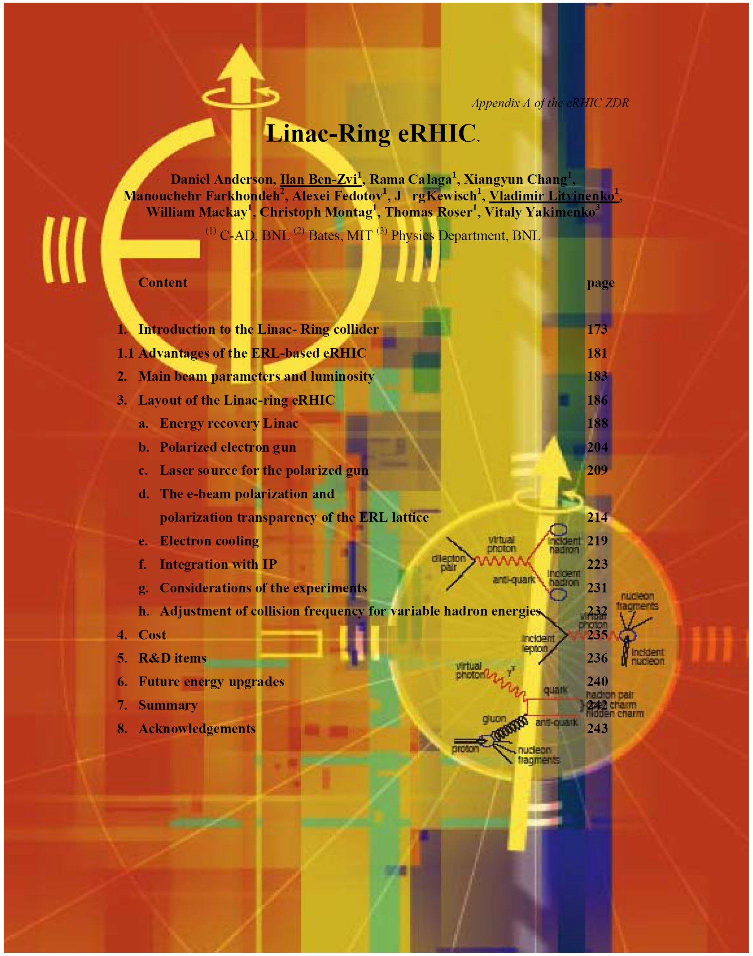
Zeroth-Order Design Report

BNL: L. Ahrens, D. Anderson, M. Bai, J. Beebe-Wang, I. Ben-Zvi, M. Blaskiewicz, J.M. Brennan, R. Calaga, X. Chang, E.D. Courant, A. Deshpande, A. Fedotov, W. Fischer, H. Hahn, J. Kewisch, V. Litvinenko, W.W. MacKay, C. Montag, S. Ozaki, B. Parker, S. Peggs, T. Roser, A. Ruggiero, B. Surrow, S. Tepikian, D. Trbojevic, V. Yakimenko, S.Y. Zhang
MIT-Bates: W. Franklin, W. Graves, R. Milner, C. Tschalaer, J. van der Laan, D. Wang, F. Wang, A. Zolfaghari and T. Zwart
BINP: A.V. Otboev, Yu.M. Shatunov
DESY: D.P. Barber

Editors: M. Farkhondeh (MIT-Bates) and V. Ptitsyn (BNL)

http://www.agsrhichome.bnl.gov/eRHIC/

Goals for eRHIC



Appendix A of the eRHIC ZDR

Linac-Ring eRHIC.

Daniel Anderson, Ilan Ben-Zvi[1], Rama Calaga[1], Xiangyun Chang[1], Manouchehr Farkhondeh[2], Alexei Fedotov[1], J rgKewisch[1], Vladimir Litvinenko[1], William Mackay[1], Christoph Montag[1], Thomas Roser[1], Vitaly Yakimenko[3]
(1) C-AD, BNL (2) Bates, MIT (3) Physics Department, BNL

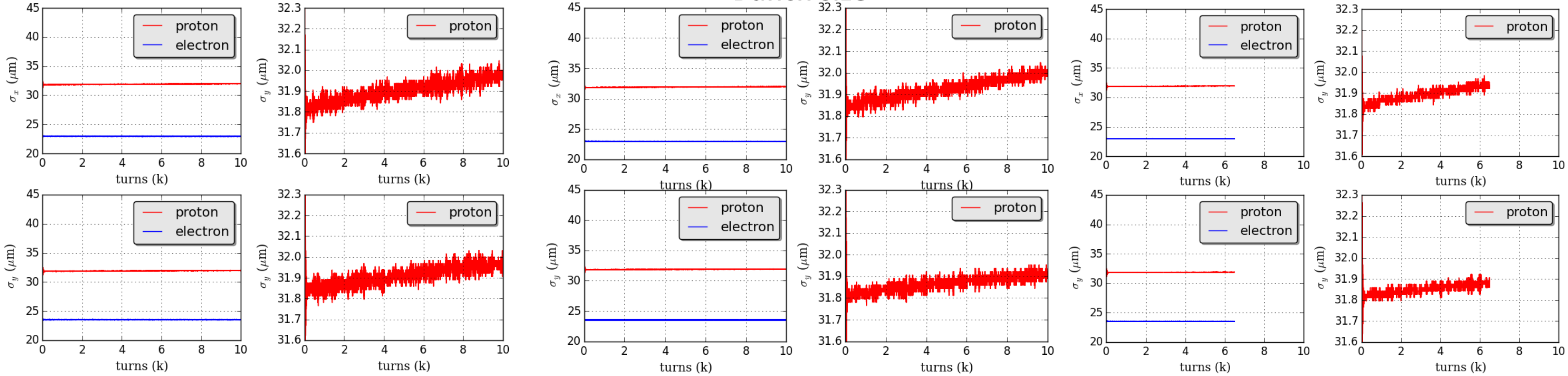
Content **page**

BBSS simulations with no random offsets in e-beam

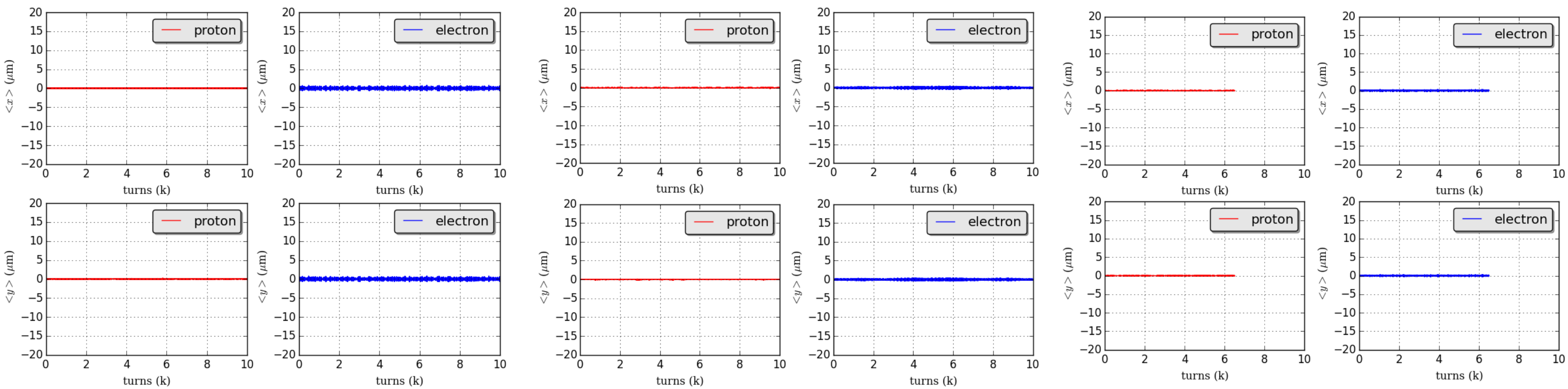
M # of macroparticles

$M_p = M_e = 500k$ | **$M_p = N_e = 1M$** | **$M_p = M_e = 2M$**

Bunch size

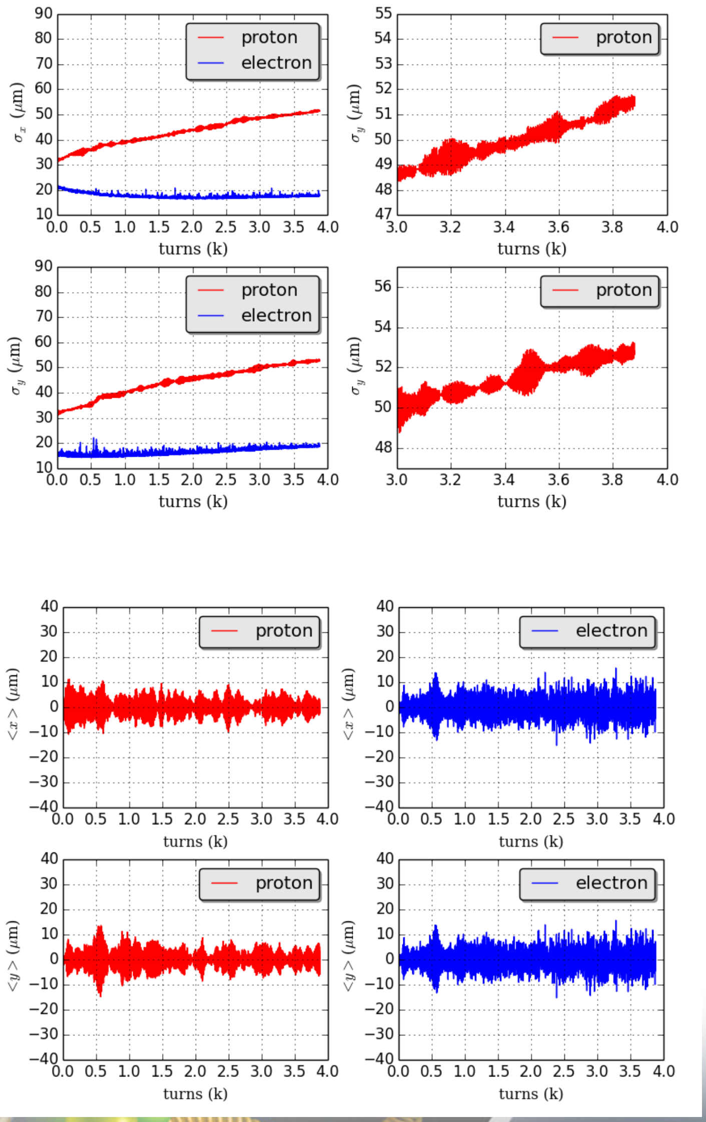


Bunch centroid



BBSS simulations with random offsets in e-beam

Rms offset 10 microm, Np =2



Rms offset 1 microm, Np =2