1st EICAC Meeting Questions/Comments on ELIC Design

JLab ELIC Machine Design Team

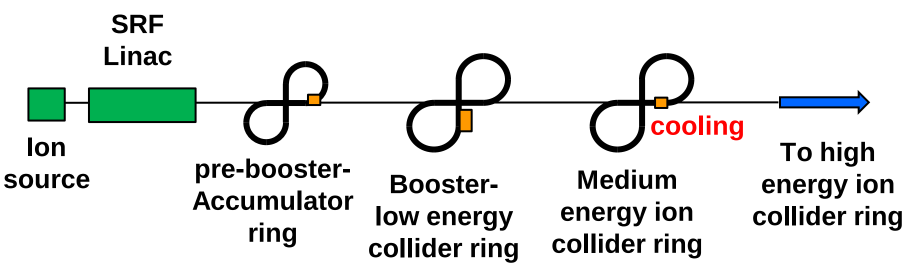
Nov. 3, 2009

ELIC Design Issues

- Ultra short bunch ion beam
  - Formation of high intensity beam: electron cooling and intra-beam scattering (Slava Derbenev, Yuhong Zhang)
  - Beam instability and life time (Byung Yunn)
  - Beamstrahlung (Slava Derbenev)
  - CSR effect (Rui Li)

- ELIC ring and interaction region (IR) design
  - Choice of figure-8 ring design (Slava Derbenev)
  - Asymmetric final focusing at interaction region (Alex Bogacz)
  - Lattice design with sufficient dynamical aperture (Alex Bogacz and Yves Roblin)

Forming of High Intensity High Bunch Repetition Ion Beams w/ Electron Cooling



- Ultra short (5 mm) ion bunch achieved with very small bunch charge, ~ 7×10^9/bunch
- Staged electron cooling (at injection, final and steady state) is essential.
- We have a working concept, next level design work is underway.

	Length (m)	Max. Energy (GeV/c)	Cooling Scheme	Process
SRF linac		0.2		Full stripping
Accumulator -Cooler Ring (Pre-booster)	~100	3	DC electron	Stacking/ accumulating Energy boosting
Low energy ring (booster)	~630	12	Electron (ERL)	Fill ring Energy boosting
Medium energy collider ring	~630	60	Electron (ERL)	Energy boosting SRF bunching

		Initial Cooling	after bunching & boost	Steady state Mode
Momentum	GeV/MeV	12 / 6.55	60 / 32.7	60 / 32.7
Beam current	A		0.6 / 3	
Particles/Bunch	10^{10}		0.74 / 3.75	
Bunch length	mm	200/200	10 / 30	5 / 15
Momentum spread	10^{-4}	5 / 1	5 / 1	3 / 1
Horizontal emittance, norm.	µm	4	1	0.56
Vert. emitt., norm.	µm	4	1	0.11
Laslett's tune shift	proton	0.002	0.006	0.1
Cooling length /circumference	m/m		15 / 640	
Cooling time	s	92	162	0.2
IBS growth time (longitudinal)	s			0.9

Ion Beam Stability

- **Single bunch instability (10^{10}/bunch)**

  Safe from longitudinal microwave instability and transverse mode coupling instability

  - longitudinal impedance less than 9 Ω
  - transverse impedance less than 200 MΩ/m

- **Multi-bunch instability**

  Active feedbacks necessary to control longitudinal and transverse coupled bunch instabilities

- **Intra-beam scattering**

  Beam cooling necessary to counteract growths

- **Beam life time**

  Touschek life time ~17 hrs

Beamstrahlung of Electron

Proton beam parameters at 60 GeV

- Energy loss relative to radiation in arcs :
  0.05% per IP

- Energy diffusion due to quantum beamstrahlung:
  0.5% per IP

- Impact on emittance (due to *dispersion-prime*):
  may require *zero dispersion* before the final focus quads
  – Needs further work

CSR Estimation for the MEIC Ion Ring

- Parameters

$$E_p = 60\,\text{GeV}, \quad N_p = 0.74\times10^{10}, \quad \sigma_z = 5\,\text{mm}, \quad R = 30\,\text{m}$$

assume aperture $\text{b} = 0.02\,\text{m}$

- CSR is shielded for the ion ring

CSR is shielded when $\lambda > \lambda_{th} = 0.3\,\text{mm}$

No coherent radiation at $\lambda \approx \sigma_z = 5\,\text{mm}$

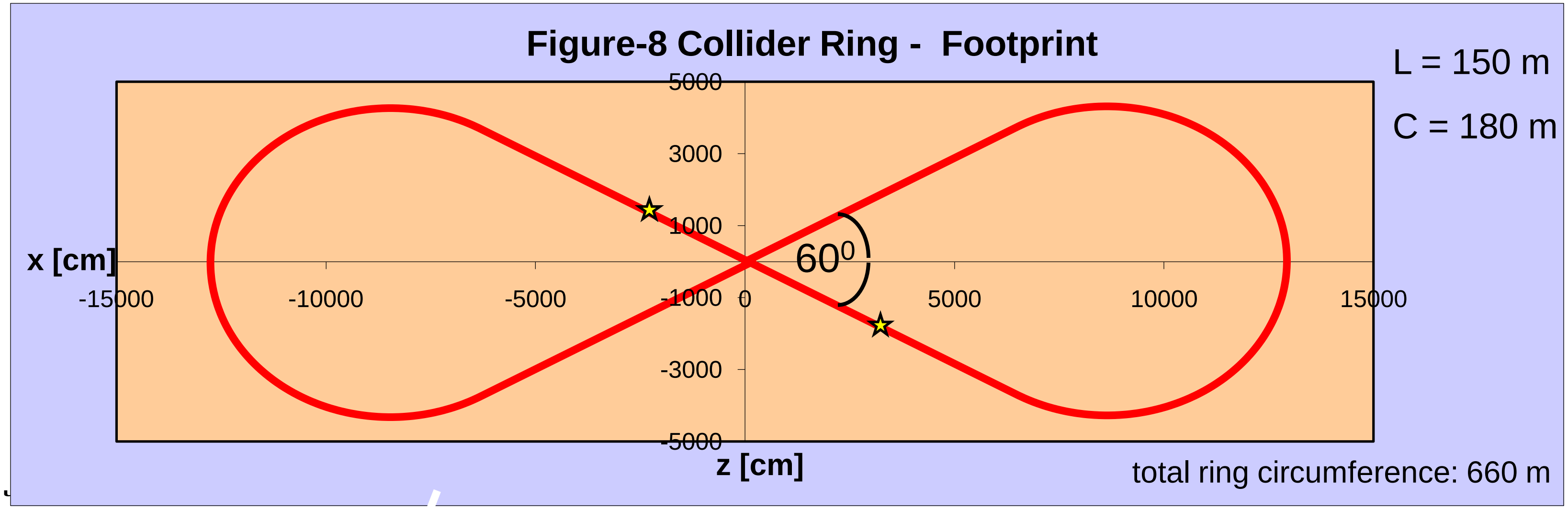
- No microbunching instability can be developed

Landau damping allows instability to develop only for $\lambda > 0.9\,\text{m}$, which is bigger than bunch length

Choice of Figure-8 Ion Rings

- Figure-8 optimum for polarized ion beams
  - Simple solution to preserve full ion polarization by avoiding spin resonances during acceleration
  - Energy independence of spin tune
  - g-2 is small for deuterons; Figure-8 ring is the only *practical* way to arrange longitudinal spin polarization at interaction point.
  - Allows multiple interactions in a same straight – can help with chromatic correction
- Only disadvantage is small cost increase
  - There are no technical disadvantages

Figure-8 Collider Ring – Optics



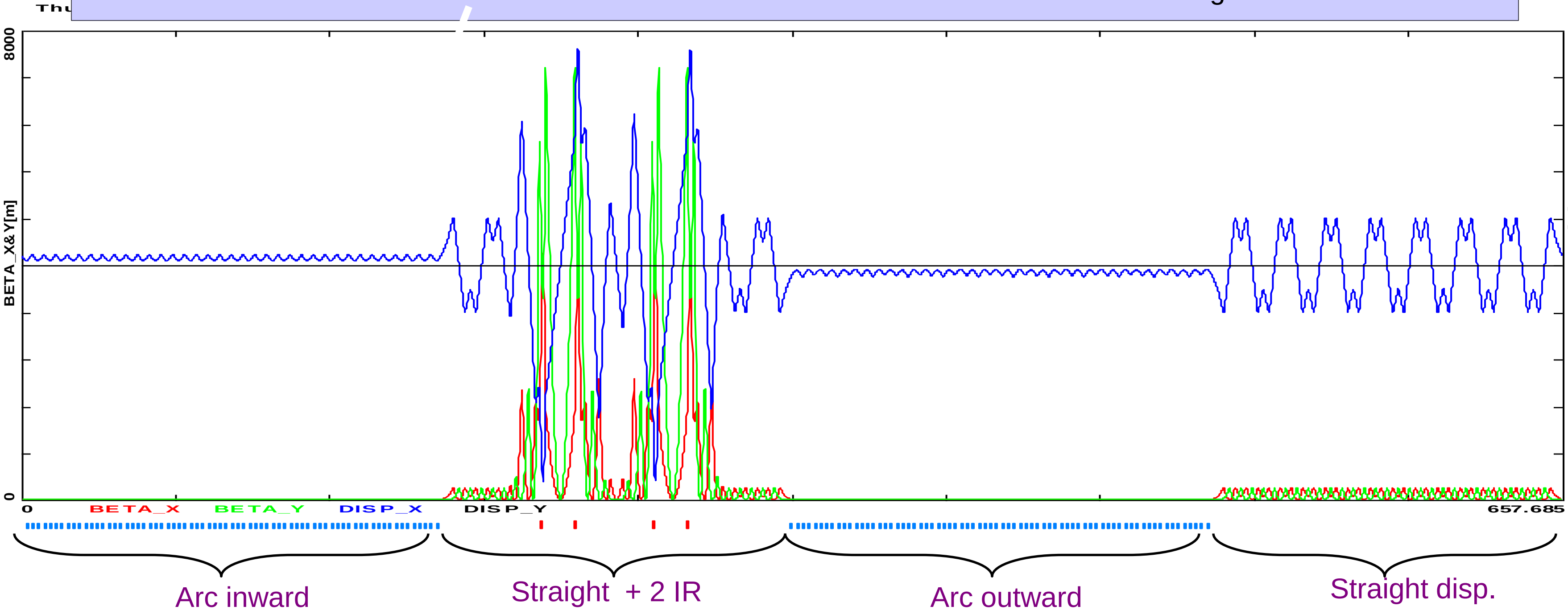
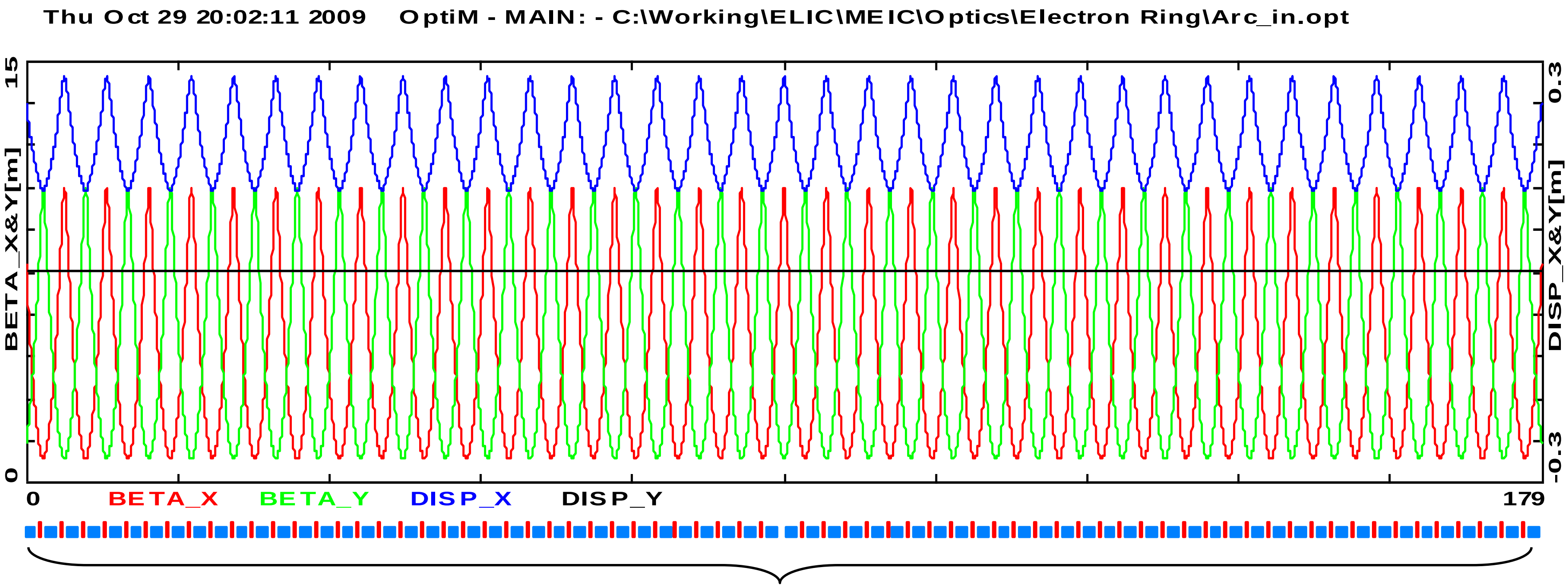


Figure-8 Collider Ring – Arc Optics



11 GeV

36 FODO cells, B, total arc length: 179 m

phase adv./cell ($\Delta\phi_{x,y}= 120^0$)

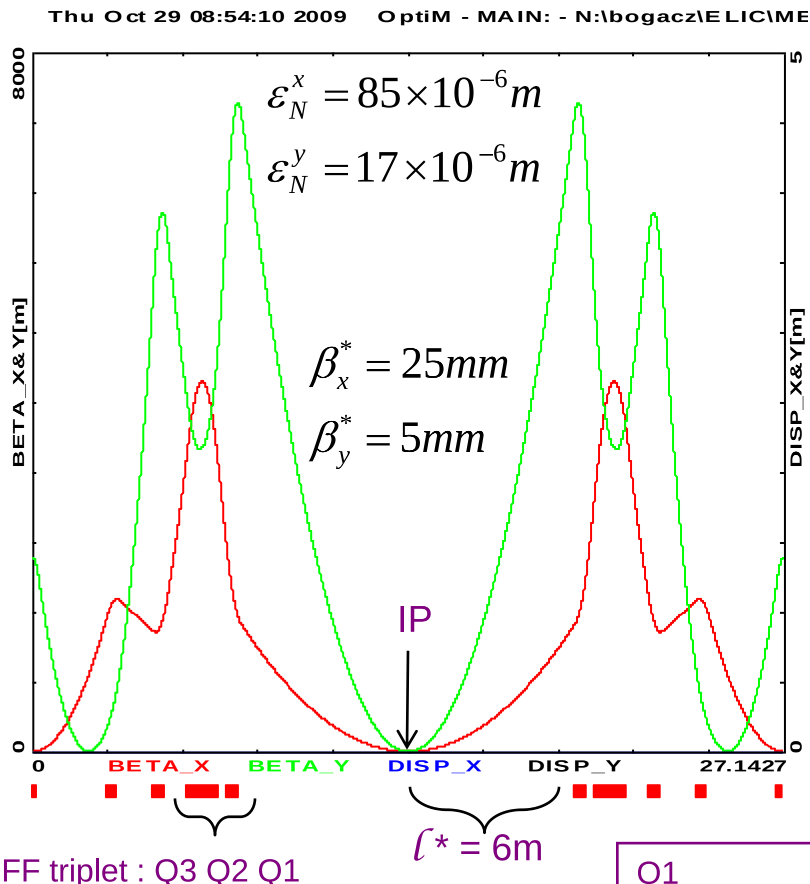
- Minimized emittance dilution due to quantum excitations
- Quasi isochronous arc to alleviate bunch lengthening (α~10^{-5})
- Dispersion pattern optimized for chromaticity compensation with sextupoles

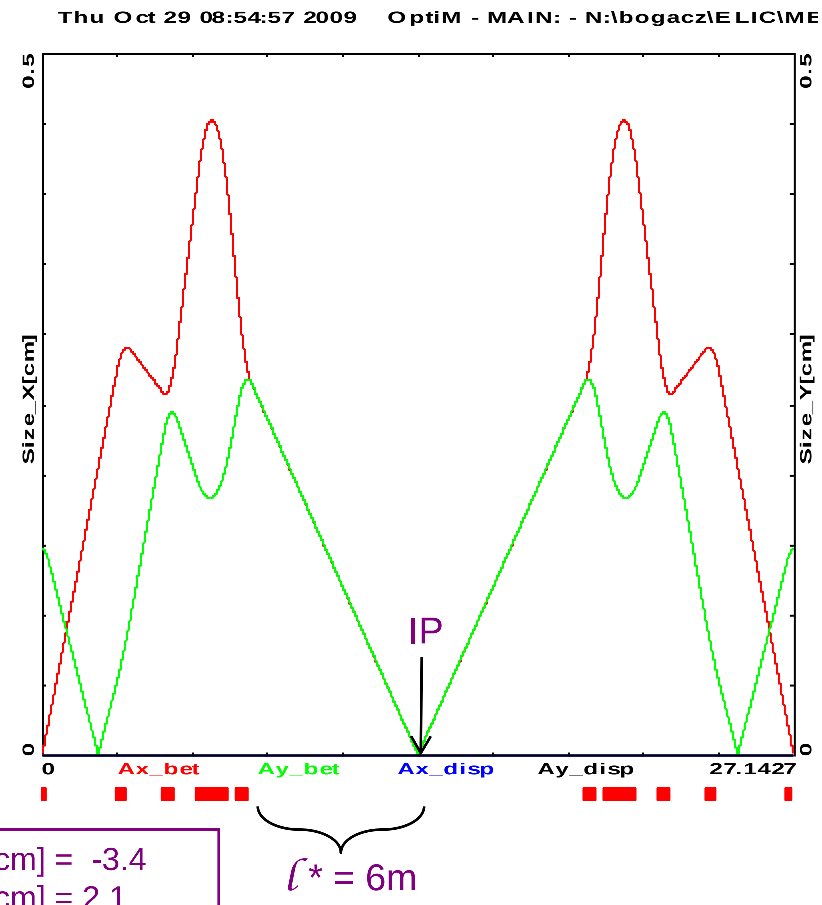
Dipoles
$Lb=150 cm
$B=**11.6** kG.

Quadrupoles
$Lq=50 cm
$G= ±**4.5** kG/cm

Interaction Region Optics

vertical focusing first

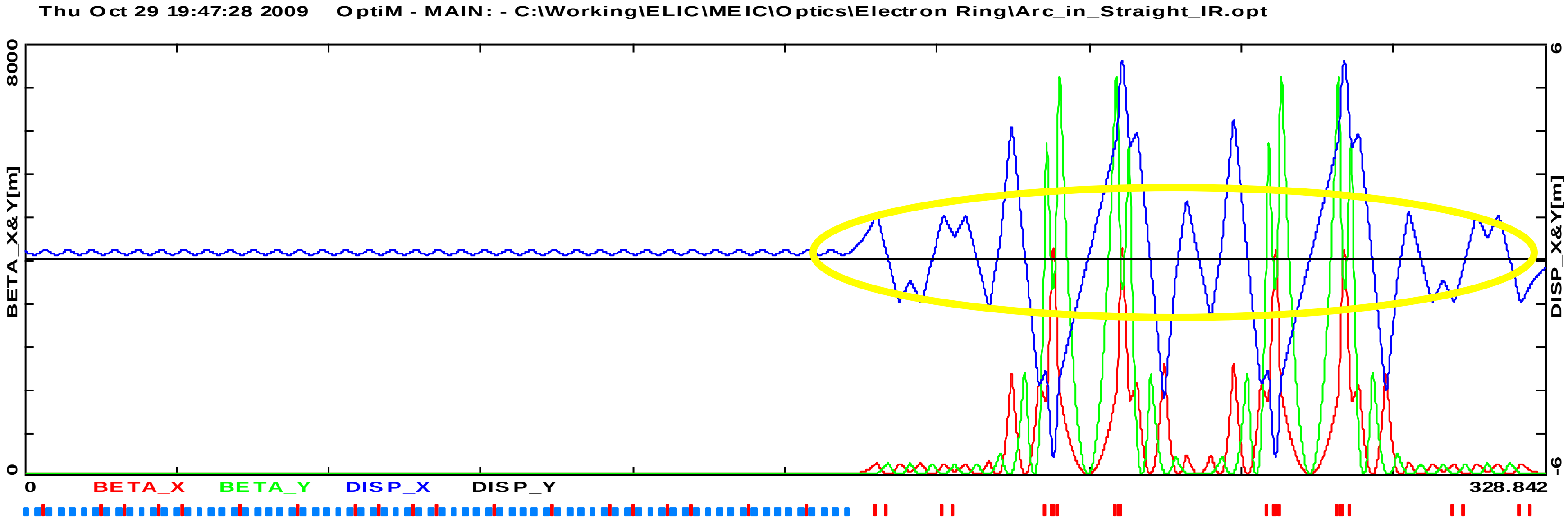


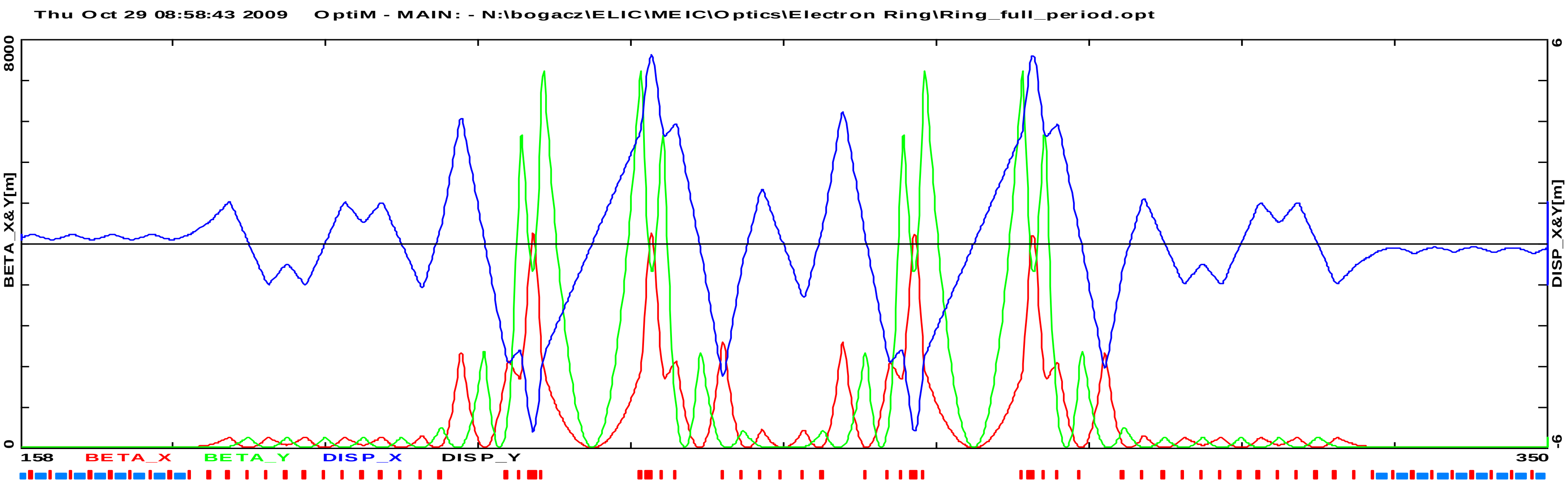


Q1	G[kG/cm] = -3.4
Q2	G[kG/cm] = 2.1
Q3	G[kG/cm] = -4.1

Natural Chromaticity: ζ_x=-305 ζ_y=-425

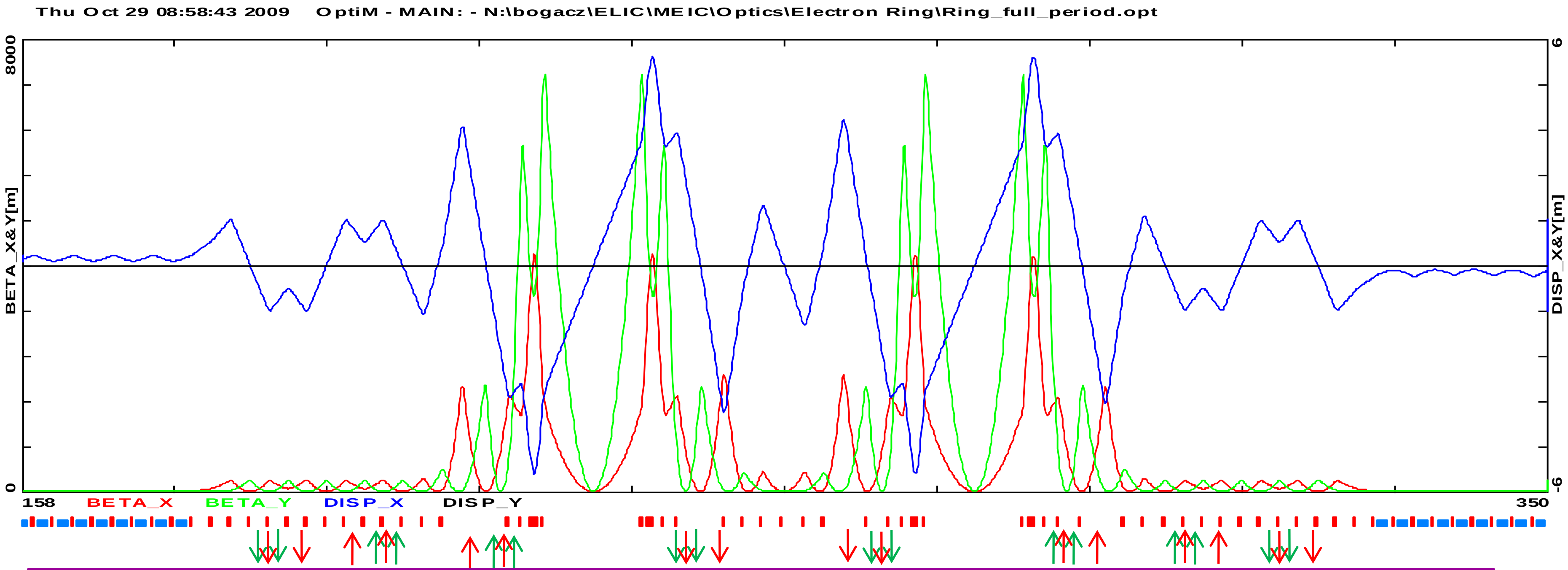
Collider Ring – a pair of IRs Optics





IR – Chromaticity Compensation

Uncompensated dispersion pattern coming out of the Arc



$$\zeta_{x,y}^{IR} \cong -\frac{1}{4\pi}\sum_i \beta_{x,y}^i \int g_0^i ds = -\frac{1}{4\pi}\sum_i \beta_{x,y}^i k_1^i \qquad k_1 = \frac{1}{B\rho}\int \frac{\partial B_y}{\partial x} dl = \frac{e}{pc}\int \frac{\partial B_y}{\partial x} dl \, [m^{-1}]$$

Natural Chromaticity: $\zeta_x = -650$ $\zeta_y = -990$

$$\zeta_{sext} = \frac{1}{4\pi}\sum_{sext} \beta \, \eta_0 g_1^{sext}$$

Compensating sextupole strength: $g_1 = 0.15$ m^{-2}

Issues and Status

Question	Assessment	Status
Ultra short ion bunch	• Forming ultra-short ion bunch • Beam dynamics and instability	Have a workable concept Checked cooling & IBS rates
Ion beam lifetime	General question (also beam instabilities)	Checked leading causes (Byung Yunn)
Figure-8 ion ring choice		Closed
Luminosity lifetime reduction due to beamstrahlung at IP		Checked (Slava Derbenev)
5 mm β^* in x and y	Good observation	β^* in x changed to 25 mm Electron linear optics complete Ion ring will be similar
Lattice design with sufficient dynamical aperture	Needs linear lattices, chromatic correction, and tracking studies	In progress. Tracking studies will start (Alex Bogacz, Yves Roblin)
CSR effect for unusually short ion bunch		Effects are small. Closed (Rui Li)

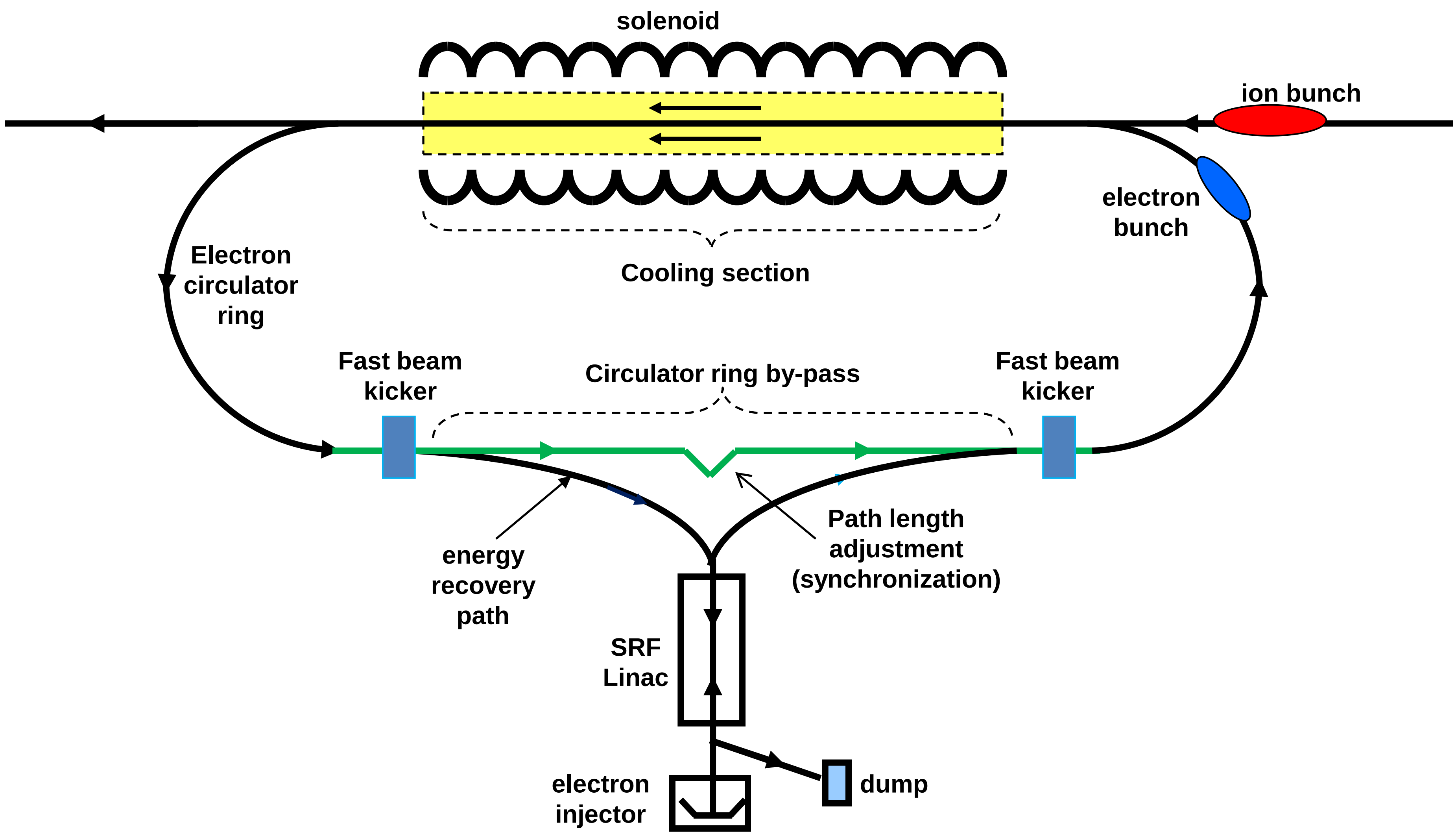
Backup Slides

Accelerator Design Related Comments

- "Of the two alternatives presented, the JLAB concept is in essence a new facility even though built around the existent CEBAF. As such, **a lot of (basic) accelerator design work has to be done. The ion ring has a number of challenging beam parameters (e.g. the ultra-short ion bunches, beam lifetimes, figure-8 rings etc.).** This is not to ignore the challenges for eRHIC. The common R&D effort should focus on the technologies needed for both approaches: cooling, MDI, beam-beam investigations, the various crabbing schemes. Beyond this, an R&D plan involving both labs for the eventual unified proposal will need to be developed. It would be good to see a detailed common plan addressing these issues at the next meeting, with deliverables and resources needed to get to a buildable design for the NSAC Long Range Plan in 2012. "

- "It would appear that it would be better to have a detailed review of the designs of the accelerator(s) by more accelerator experts if possible. A few specific comments are listed in the following; in my opinion, any one of them may have a possibility to be a show stopper and thus needs to be carefully considered.
  For eRHIC: For the ring-ring scheme, the Hirata-Keil effect should be looked at carefully as the density of the resonance lines increases three-fold. The very high disruption assumed for the ring-ERL scheme needs verification, as the electron bunch becomes unstable during a single collision which should affect the proton or ion beam to cause dilution of the emittance.
  For ELIC: **The luminosity lifetime will be much shorter than 24 hours due to the beam loss from Bremsstrahlung at the interaction point (IP). If so, much more frequent injection of electrons will be needed but such injections may heat up the protons or ions. The very tight focusing at the IP, 5 mm beta* in x and y, does not look feasible with the proposed length (7 m) between the IP and the first quadrupole, due to associated chromaticity and nonlinear effects to reduce the dynamic aperture. A consistent lattice should be shown with sufficient dynamic aperture. As the bunch length of the proton beam is unusually short, effects unfamiliar to a proton beam such as coherent synchrotron radiation may happen."**

ERL Based Circulator Electron Cooler



ELIC e-Cooler Design Parameters

- Number of turns in circulator cooler ring is determined by degradation of electron beam quality caused by inter/intra beam heating up and space charge effect.
- Space charge effect could be a leading issue when electron beam energy is low.
- It is estimated that beam quality (as well as cooling efficiency) is still good enough after 100 to 300 turns in circulator ring.
- This leads directly to a 100 to 300 times saving of electron currents from the source/injector and ERL.

Max/min energy of e-beam	**MeV**	**33/8**
Electrons/bunch	**10^{10}**	**3.75**
bunch revolutions in CCR		**~300**
Current in CCR/ERL	**A**	**3/0.01**
Bunch repetition in CCR/ERL	**MHz**	**500/1.67**
CCR circumference	**m**	**80**
Cooling section length	**m**	**15**
Circulation duration	**μs**	**27**
Bunch length	**cm**	**1-3**
Energy spread	**10^{-4}**	**1-3**
Solenoid field in cooling section	**T**	**2**
Beam radius in solenoid	**mm**	**~1**
Beta-function	**m**	**0.5**
Thermal cyclotron radius	**μm**	**2**
Beam radius at cathode	**mm**	**3**
Solenoid field at cathode	**KG**	**2**
Laslett's tune shift @60 MeV		**0.07**
Longitudinal inter/intra beam heating	**μs**	**200**

Ion Beam Instability

Note: Ion ring parameters are E = 60GeV, C = 630m, h = 3150, η = 0.01, V = 43 MV,

$\nu_s = 0.06 \quad \sigma_\delta = 3\times10^{-4} \quad \sigma_l = 5mm$ momentum aperture = 0.38 %

Potentially dangerous instabilities for ion ring are longitudinal microwave instability, transverse mode coupling instability, longitudinal and transverse coupled bunch instabilities. Design current $I_b = 0.75mA$ $(N_p = 10^{10})$ leads to following limits on impedances

Longitudinal Microwave Instability:

$$I_b^{threshold} = \frac{100hV}{\left|\frac{Z_L}{n}\right|_{eff}}\left(\frac{\sigma_l}{C}\right)^3 \rightarrow \left|\frac{Z_L}{n}\right|_{eff} \le 9\Omega$$

Transverse Microwave Instability:

$$I_b = \frac{4\left(\frac{E}{e}\right)\nu_s b}{\left|Z_T\right|_{eff}\beta_{av}R} \rightarrow \left|Z_T\right|_{eff}\frac{\beta_{av}}{b} \le 190G\Omega$$

Transverse Mode Coupling Instability:

$$I_b^{threshold} = \frac{16\pi\left(\frac{E}{e}\right)\nu_s}{\mathrm{Im}(Z_T)_{eff}\,\beta_{av}}\frac{\sigma_l}{C} \rightarrow \mathrm{Im}(Z_T)_{eff}\,\beta_{av} \le 1.9G\Omega$$

Ion Beam Instability (cont.)

Longitudinal Coupled Bunch Instability:

$$I_b^{threshold} = \frac{48\pi^2 h^3 V}{\mathrm{Im}(\frac{Z}{n})_{eff}} \left(\frac{\sigma_l}{C}\right)^5 \rightarrow \qquad \mathrm{Im}(\frac{Z}{n})_{eff} \leq 30 m\Omega$$

Intrabeam Scattering Growth Rates (log$_c$ = 10 is assumed):

$$\tau_s^{-1} = \frac{e^4 N_p \log_c}{8 m_p^2 c^3 \beta^3 \gamma^3 \sigma_z \varepsilon_x^{3/2} \sigma_\delta^2} \sqrt{\frac{\nu_x}{R}} \rightarrow \quad \tau_s = 1.8 s$$

,

$$\tau_x^{-1} = \frac{e^4 N_p \log_c}{16 m_p^2 c^3 \beta^3 \gamma^3 \sigma_z \varepsilon_x^{5/2}} \sqrt{\frac{R}{\nu_x}} \left(\frac{2}{\nu_x^2} - \frac{1}{\gamma^2}\right) \rightarrow \quad \tau_x = 1.7 s$$

Touschek Lifetime:

$$\tau_{Touschek}^{-1} = \frac{\sqrt{\pi} r_p^2 c N_p}{\gamma^5 \sigma_{x'}^3 \varepsilon_A^2 V_B} \left(\ln \frac{0.5618}{\varepsilon_A} - 1.5\right) \qquad \varepsilon_A = \frac{1}{\gamma \sigma_{x'}} \left(\frac{\Delta p}{p}\right)_{aperture}$$

$$\rightarrow \quad \tau_{Touschek} \approx 17 hrs$$