A route to LHeC with 10^{35} luminosity

Linac-ring design, including stability

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Content

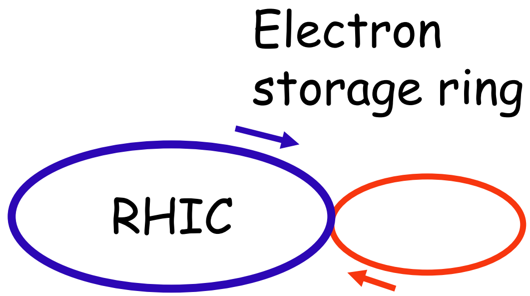
- High luminosity at low e-beam currents
  - ERL vs ring
- Beam stability
- Other option for high luminosity in LHeC

Electron-hadron colliders: ERL or ring for electrons?

- Two main design options

$$L = f_c \cdot (\gamma_e \cdot N_e) \cdot \frac{\xi_e}{\beta_e^* \cdot r_e}, \quad \xi_e \le 0.1$$

  - Ring-ring:

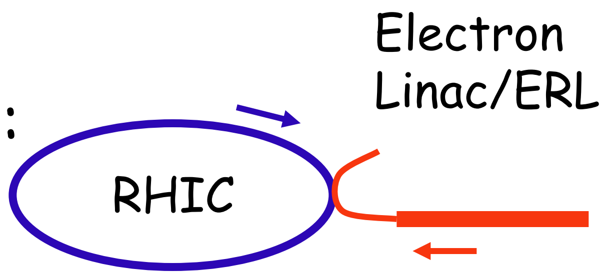


$in\ LHeC\ \xi_p <<< \xi_{p\max}$

$L_{ring-ring\max}\ e^- \sim 10^{33}\, cm^{-2} \sec^{-1}$

$@60\, GeV\ \&\ 30\, MeV\ SR\ power$

  - Linac-ring:



$$L = f_c \cdot (\gamma_p \cdot N_p) \cdot \frac{\xi_p \cdot Z_p}{\beta_h^* \cdot r_p}$$

$\xi_e \sim >10 \div 100$

$L_{ERL\max} \sim ???$

Limits at High e-beam energy

$$P_{SR}[W] @ 0.9 \times 10^5 \times \frac{E^4[GeV]}{R[m]} \times I[A]$$

$$I[mA] \pounds\, 0.01 \frac{P_{SR}[W]}{E^4[GeV]} R[m]$$

$$I[mA]_{@60\,GeV} \pounds\, 0.77 P_{SR}[MW] \times R[km]$$

$$L \sim I_e \sim \frac{P_{SR}}{E^4} R$$

$$L = \frac{1}{4\pi e} \frac{N_{b,p}}{\epsilon_p} \frac{1}{\beta_p^*} I_e H_{hg} H_D \ ,$$

60 GeV ERL -> 6.4 mA, L~10^33

Limits at High e-beam energy - ERL

$$\beta_e^*\varepsilon_e = \beta_p^*\varepsilon_p$$

$$\xi_p = \frac{N_e}{\gamma_p}\frac{r_p}{4\pi\varepsilon_p} = +0.0001$$

$$L = f_c \cdot (\gamma_p \cdot N_p) \cdot \frac{\xi_p \cdot Z_p}{\beta_h^* \cdot r_p} \sim I_e$$

Presently it is
about 1% of the LHC pp design tune shift

- Increasing e-beam current – already reached limit (except the linear ERL – see later)
- Reducing β* - already reached limit
- What is left is to increase ξ_p 100-fold to the beam-beam limit by cooling the hadron beam transversely. Operate LHeC in dedicated mode

60 GeV ERL, 6.4 mA, L->10^{35}

Evolution of beam in LHC at 7 TeV with IBS and CeC

(assuming nominal LHC bunch intensity 1.15e11 p/bunch and 40% of CeC cooling capability)

$$\frac{\sigma_\varepsilon^2}{\tau_{IBS\parallel}} = \frac{N r_c^2 c}{2^5 \pi \gamma^3 \varepsilon_x^{3/2} \sigma_s}\left\langle \frac{f(\chi_m)}{\beta_y \nu} \right\rangle; \quad \frac{\varepsilon_x}{\tau_{IBS\perp}} = \frac{N r_c^2 c}{2^5 \pi \gamma^3 \varepsilon_x^{3/2} \sigma_s}\left\langle \frac{H}{\beta_y^{1/2}} f(\chi_m) \right\rangle; k=1$$

$$f(\chi_m) = \int_{\chi_m}^{\infty} \frac{d\chi}{\chi} \ln\left(\frac{\chi}{\chi_m}\right) e^{-\chi}; \quad \chi_m = \frac{r_c m^2 c^4}{b_{max} \sigma_E^2}; b_{max} \cong n^{-1/3}; \quad r_c = \frac{e^2}{mc^2}; \quad (e- > Ze; m- > Am)$$

J.LeDuff, "Single and Multiple Touschek effects", Proceedings of CERN Accelerator School, Rhodes, Greece, 20 September - 1 October, 1993, Editor: S.Turner, CERN 95-06, 22 November 1995, Vol. II, p. 573

$$X = \frac{\varepsilon_x}{\varepsilon_{xo}}; \; S = \left(\frac{\sigma_s}{\sigma_{so}}\right)^2 = \left(\frac{\sigma_E}{\sigma_{sE}}\right)^2;$$

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

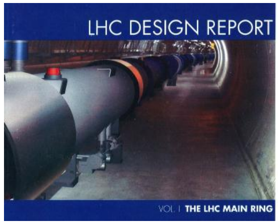
$$\frac{dS}{dt} = \frac{1}{\tau_{IBS\parallel}} \frac{1}{X^{3/2} S^{1/2}} - \frac{1-2\xi_\perp}{\tau_{CeC}} \frac{1}{X};$$

$$\varepsilon_{xn0} = 3.75\,\mu m; \; \sigma_{s0} = 7.55\,cm$$

$$\tau_{IBS\perp} = 80 \; hrs; \; \tau_{IBS\parallel} = 61 \; hrs$$

IBS rates in LHC from

Table 2.2

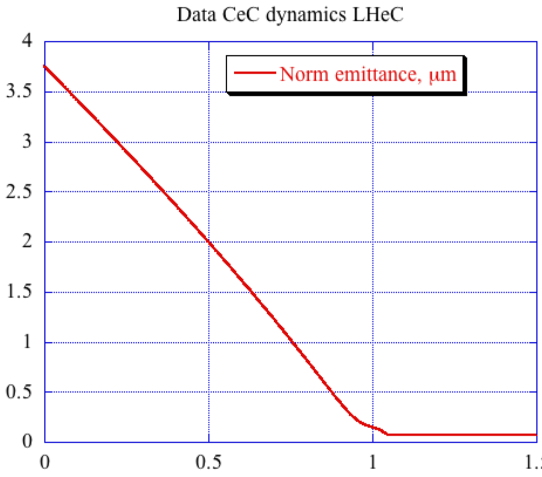


Stationary solution for τ_{CeC} = 0.8 hrs

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

$$\varepsilon_{xn} = 0.07\,\mu m$$

50-fold increase in LHeC luminosity



- High luminosity at low e-beam currents
  - ERL vs ring
- Beam stability in ERLs
- Other option for high luminosity in LHeC

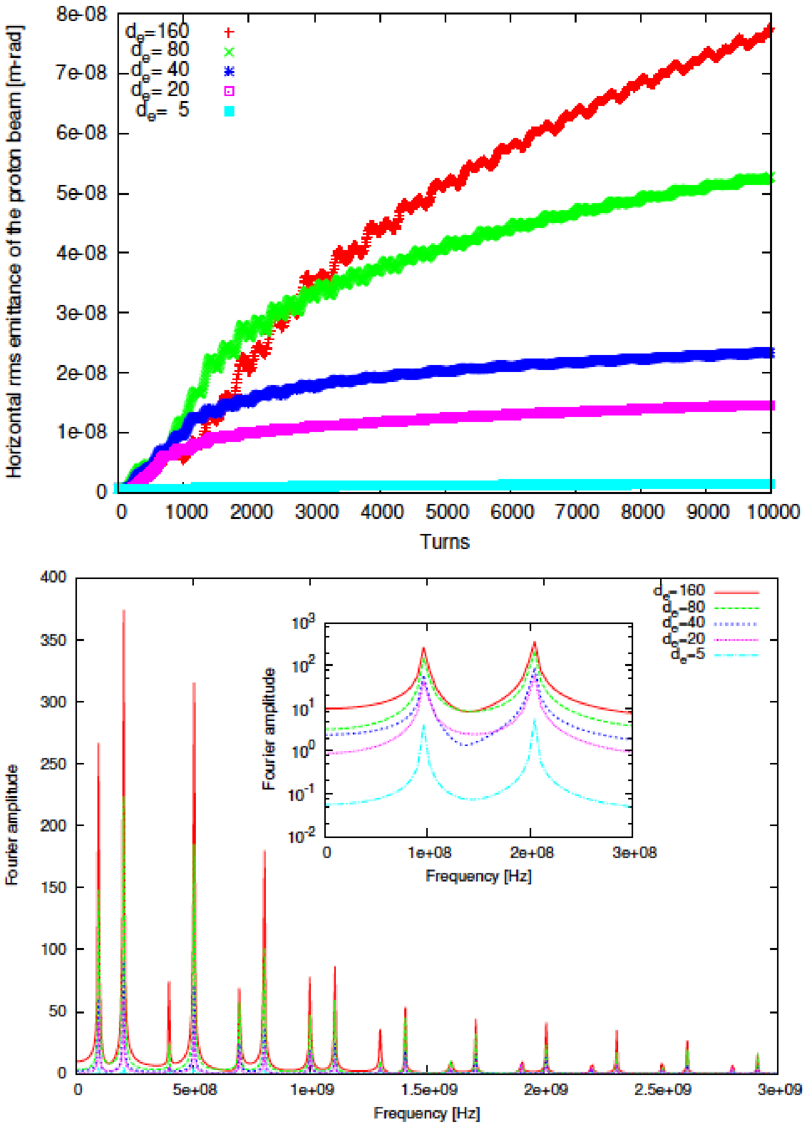


Figure 1: Top: The proton beam emittance growth due to kink instability at different disruption parameter. Bottom: The Fourier components of the turn by turn proton slice centroid data. The proton beam is cut to 100 longitudinal slices.

Table 2: Kink instability suppression in certain frequency ranges

Index	f_L (MHz)	f_H (MHz)	d_e range suppressed
1	50	300	5-25
2	300	600	5-30
3	600	900	5-50
4	900	1200	5, 25-80
5	1200	1500	50-90
6	1500	1800	80-90
7	1800	2100	None
8	2100	2400	None

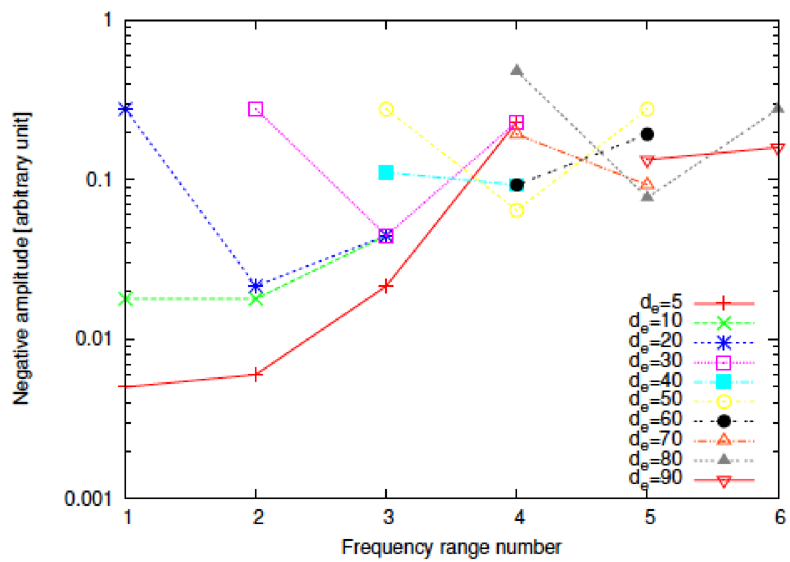
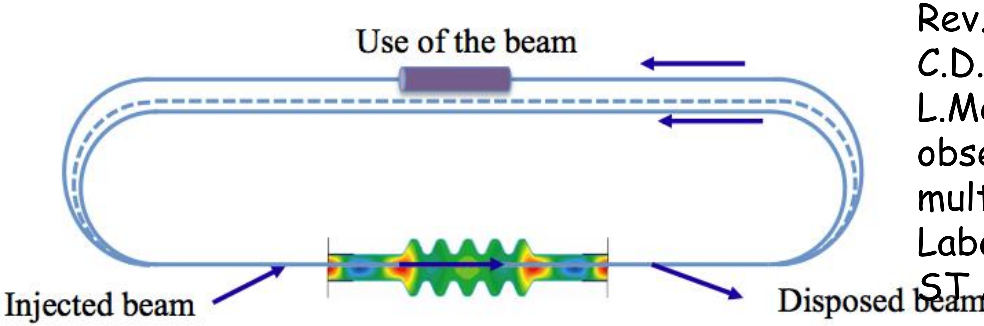


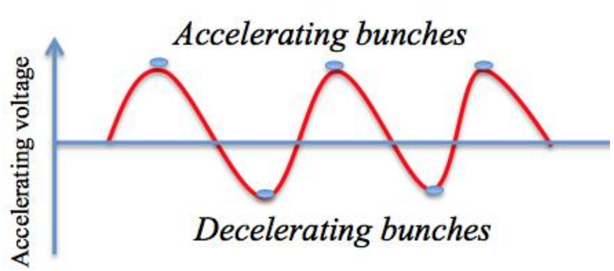
Figure 2: The minimum amplitude of the feedback system to suppress the kink instability for different frequency range index and disruption parameter.

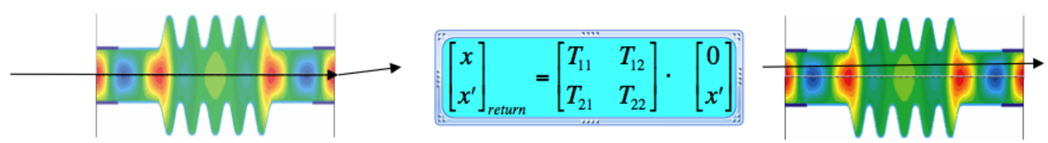
TBBU!
A killer of effective ERLs

It is believed that for a given Q*R/Q and spread of the HOM, the TBBU threshold is inverse proportional to number of ERL passes squared

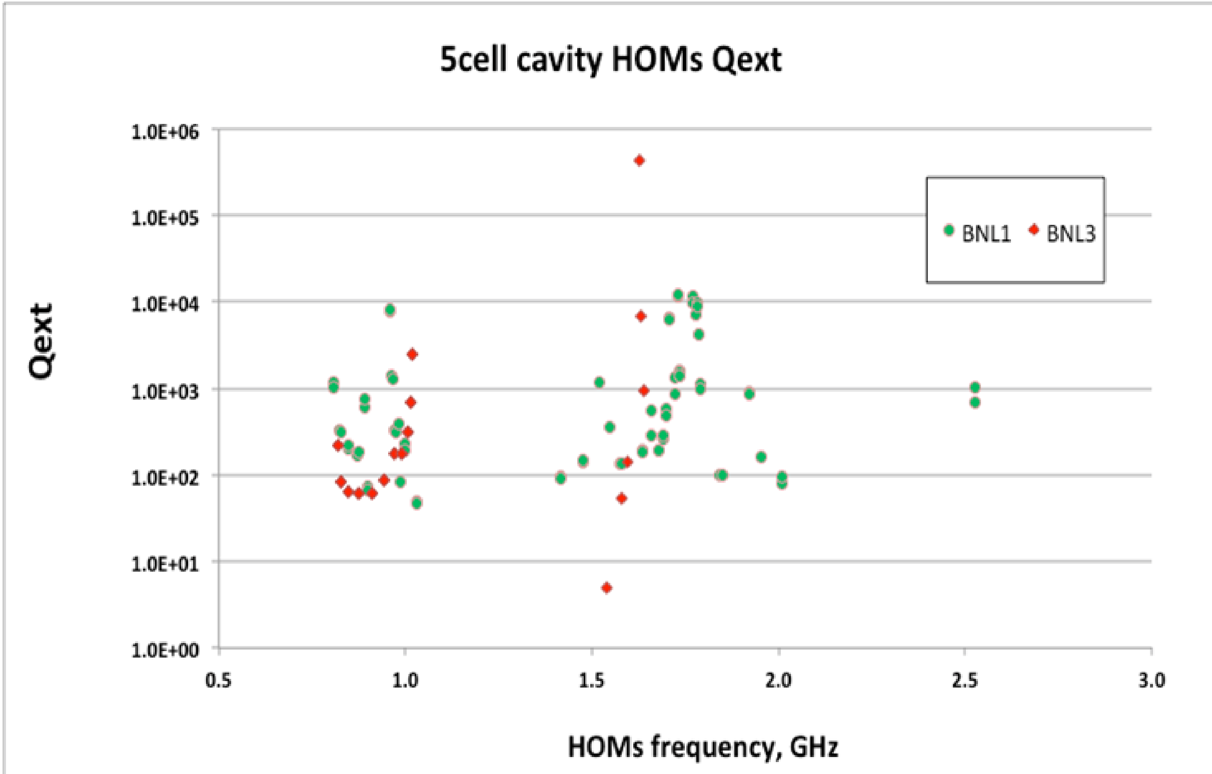
G.H. Hoffstaetter and I.V. Bazarov, "Beam-breakup instability theory for energy recovery linacs", Phys. Rev. ST AB 7, 054401 (2004)
C.D. Tennant, K.B. Beard, D.R. Kouglas, K.C. Jordan, L.Merminga, E.G. Pozdeyev, T.I. Smith "First observations and suppression of multipass, multibunch beam breakup in the Jefferson Laboratory free electron laser upgrade", Phys. Rev. ST AB 8, 074403 (2005)







HOMs used for BBU



Comparison of BNL1 and BNL3 dipole HOM's

14:00 Development of antenna-type HOM couplers at BNL - Sergey Belomestnykh (*BNL*)

BNL1

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

BNL3

F (GHz)	R/Q (Ω)	Q	(R/Q)Q
1.01E+09	30.6	313.0	9562.7
1.01E+09	30.5	313.0	9551.2
1.63E+09	1.0	6730.0	7030.9
1.02E+09	7.7	693.0	5328.8
1.02E+09	7.6	693.0	5301.0
9.11E+08	67.2	61.1	4108.1
9.11E+08	67.1	61.1	4101.6
9.90E+08	22.7	176.0	3991.7

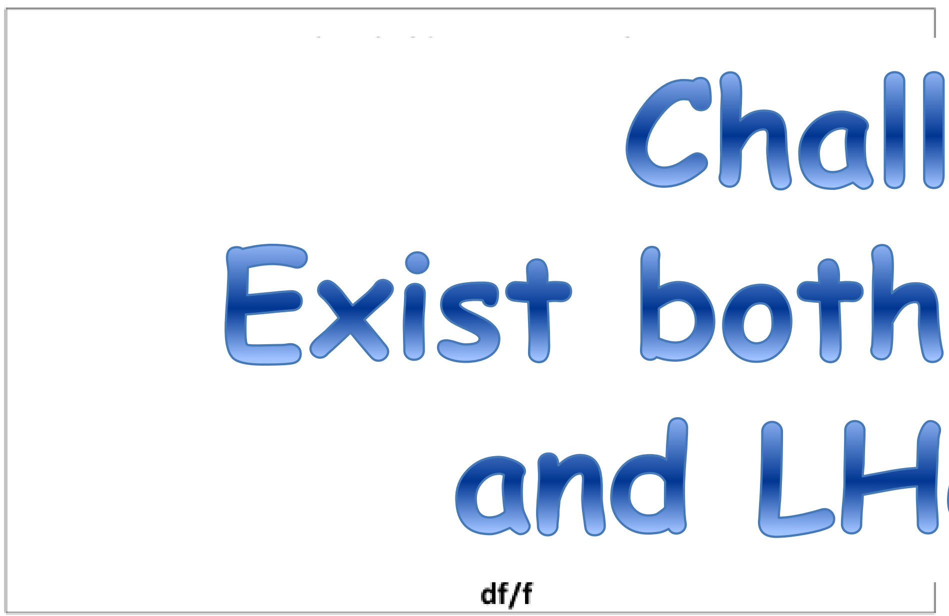
BBU simulation results

For simulation:

- 28 dipole HOMs are used for BNL3 and 70 HOMs for BNL1
- HOM Frequency spread 0-0.01
- Two different set of phase advances per each arc.

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

Challenges Exist both for eRHIC and LHeC ERLs



30 GeV top energy | **20 GeV top energy**

*) E.Pozdeyev, Phys.Rev. ST Accel. Beams Vol 8, 054401 (2005)

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Chromatic ERL Arcs

- ✓ The driver of the TBBU is the displacement of the beam in a RF cavity caused by a kick in another cavity, i.e. $T_{12}(s_1/s_2)$.
- ✓ Strong focusing ERL arcs (such as LHeC) have very large natural chromaticity ~ 100s
- ✓ It means that in combination with reasonable energy spread, there is exponential suppression of whole beam response

$$f(\delta) = \frac{1}{\sqrt{2\pi}\sigma_\delta}\exp\left(-\frac{\delta^2}{2\sigma_\delta^2}\right) \qquad \varphi = 2\pi C$$

$$\langle T_{12}\rangle = \frac{\langle x(s)\rangle}{x'} = \exp\left(-\frac{(\varphi\sigma_\delta)^2}{2}\right)\cdot \omega_{io}\omega_o\left(\cos(\psi_o - \pi/2) - \frac{u\varphi\sigma_\delta^2}{\omega_o}\sin(\psi_o - \pi/2)\right)$$

V.N. Litvinenko, Chromaticity and beam stability in energy recovery linacs, in press

Table 1. Suppression of the beam's response on a transverse kick by the chromaticity, C. In this table $X = \phi\sigma_\delta$; $Y = \upsilon\sigma_\delta$.

$f(\delta)$	Suppression factor $\langle T_{12}\rangle / w_{io} w_o$	Type
$\frac{1}{\sqrt{2\pi}\sigma_\delta}\exp\left(-\frac{\delta^2}{2\sigma_\delta^2}\right)$	$e^{-X^2/2}\cdot\left(\sin\psi + X\cdot Y\cos\psi\right)$	Gaussian
$\frac{1}{\pi\sigma_\delta}\left(1+\frac{\delta^2}{\sigma_\delta^2}\right)^{-1}$	$e^{-\lvert X\rvert}\cdot\left(\sin\psi + Y\cdot sign(X)\cos\psi\right)$	Lorentzian
$\frac{2}{\pi\sigma_\delta}\left(1+\frac{\delta^2}{\sigma_\delta^2}\right)^{-2}$	$e^{-\lvert X\rvert}\cdot\left((1+\lvert X\rvert)\sin\psi + X\cdot Y\cos\psi\right)$	$\kappa-2$
$\frac{1}{2\sigma_\delta}\begin{pmatrix}\theta(\delta-\sigma_\delta)- \\ \theta(\delta+\sigma_\delta)\end{pmatrix}$	$\frac{\sin X}{X}\sin\psi + Y\frac{\sin X - X\cos X}{X^2}\cos\psi$	Rectangular
$\frac{\lvert 1-\delta/\sigma_\delta\rvert}{\sigma_\delta}, \lvert\delta\rvert \le \sigma_\delta$	$2\left(\frac{\cos X\ -1}{X^2}\sin\psi + Y\cdot\frac{2(\cos X-1)+X\sin X}{X^3}\cos\psi\right)$	Triangular

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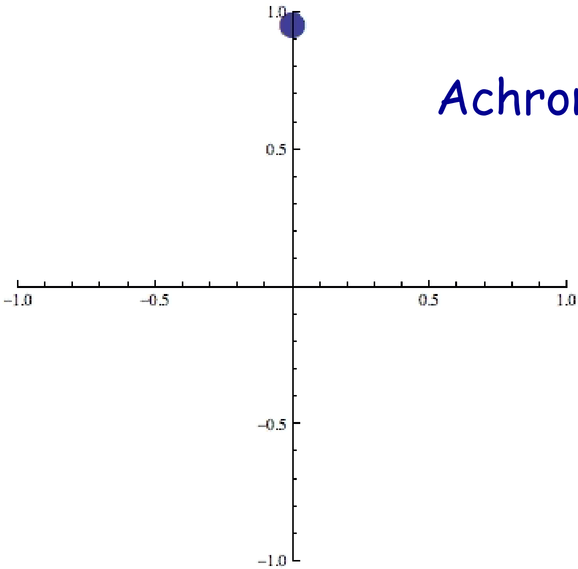
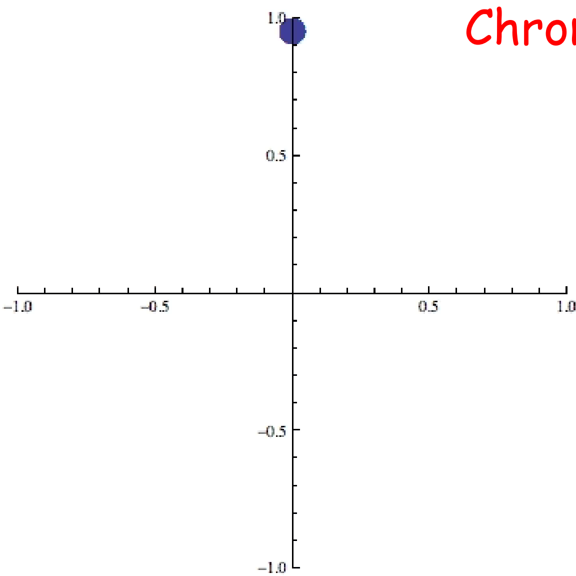
How it works

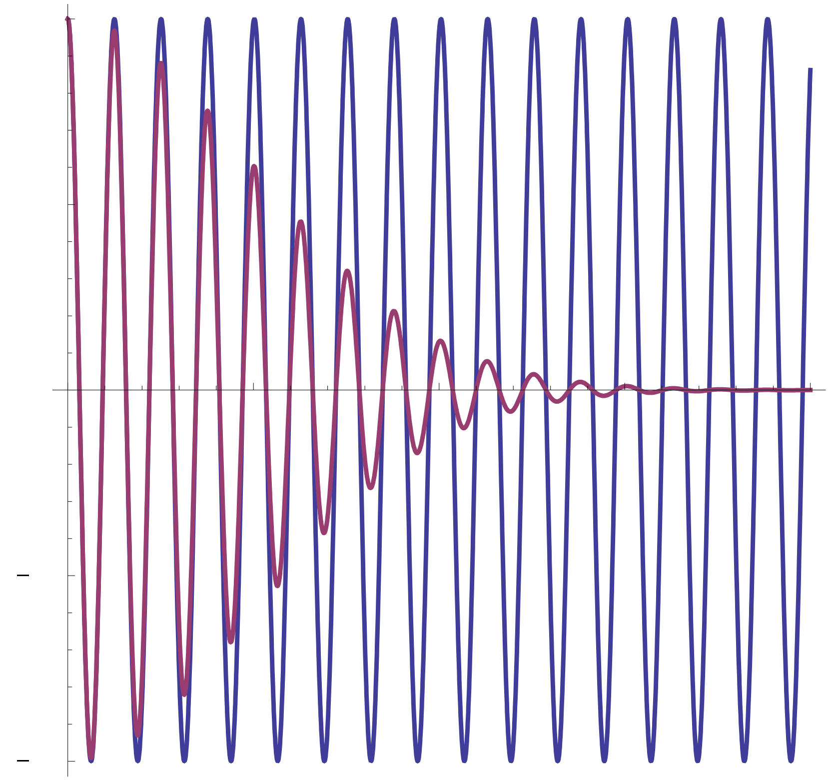


Achromatic lattice



Chromatic lattice

$\langle T_{12}\rangle / \sqrt{\beta\beta_o}\, x'_o$



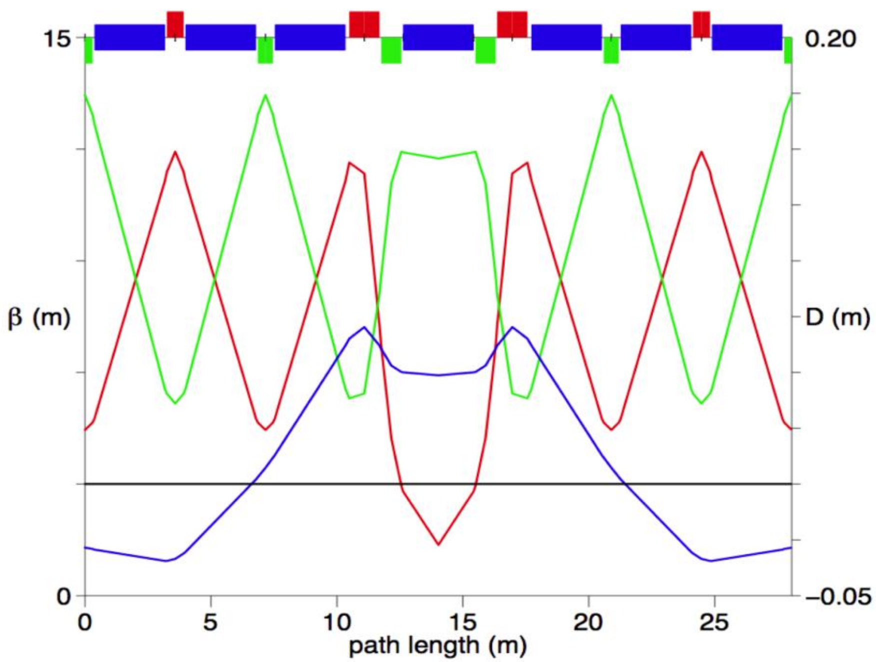
$$\langle T_{12}\rangle \propto \exp\left(-\frac{(\phi\sigma_\delta)^2}{2}\right)\cdot T_{12}(\max)$$

$$I_{th}(chromatic) \propto \exp\left(\frac{(\phi\sigma_\delta)^2}{2}\right)\cdot I_{th}(achromatic)$$

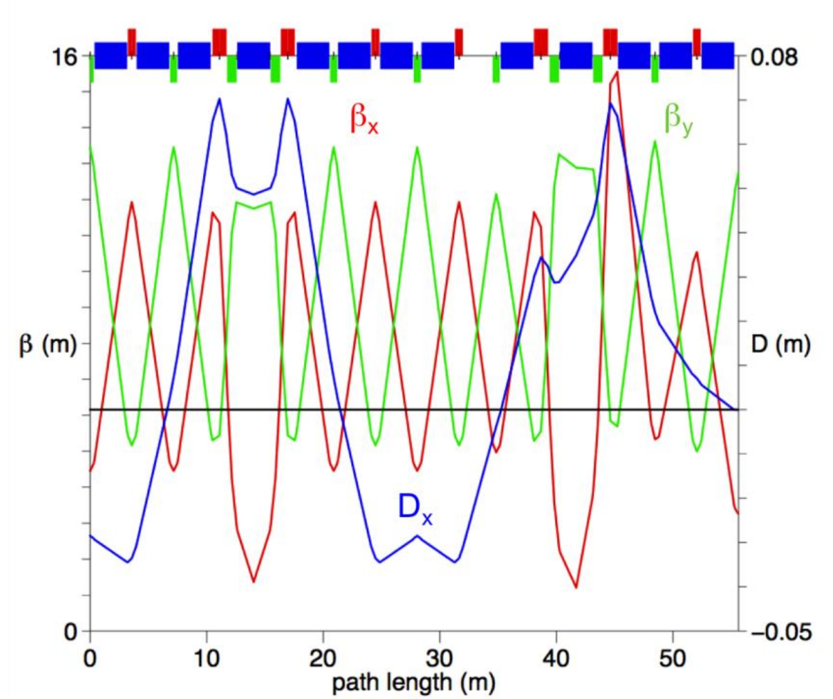
Arc's lattice

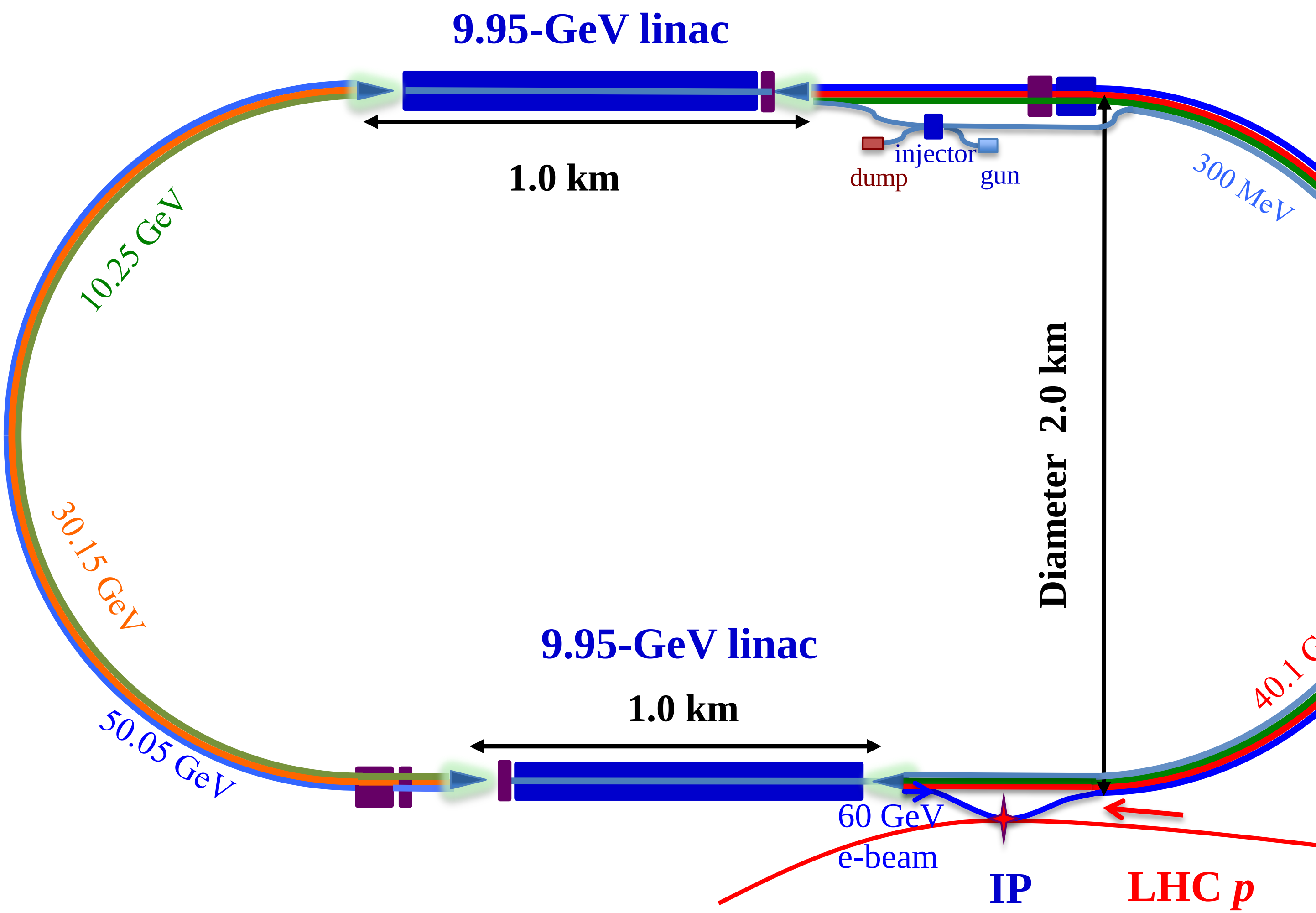
© D.Trbojevic

- Regular isochronous lattice of ERL's arcs. Length of cell is 27.8017 m. Red line – horizontal β-function, green - vertical β-function, blue – dispersion.



- The regular and the end of the arc cell lattice.





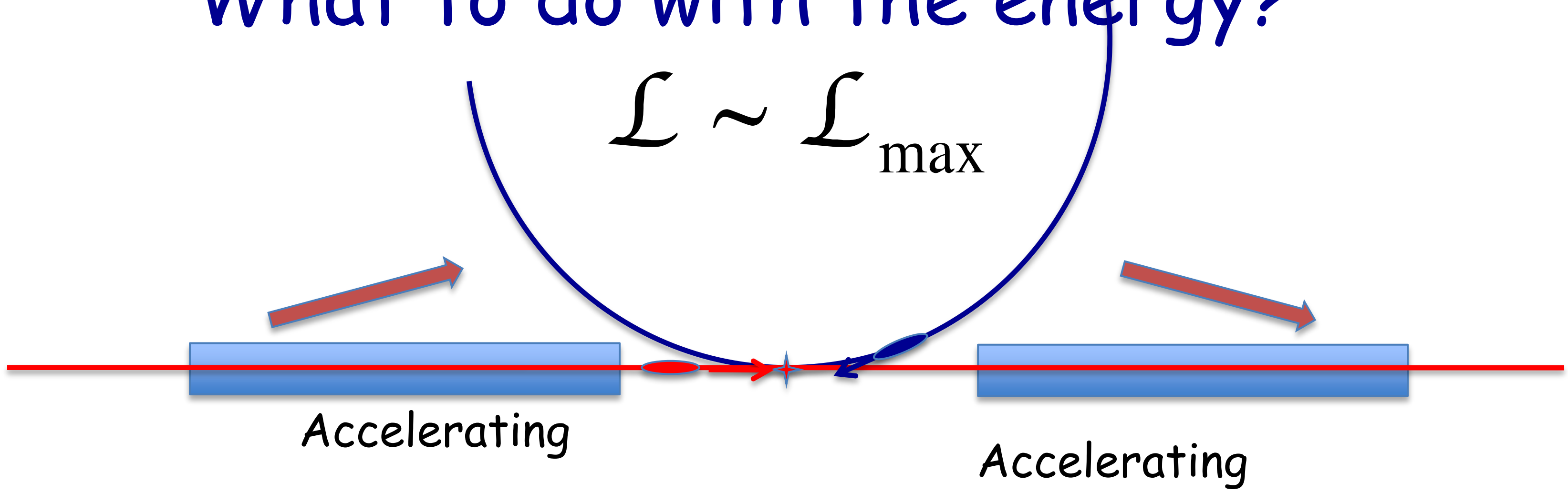
In LHeC's 60 GeV ERL requires only 0.13% RMS energy reduces **<T_{21}> 1,000-fold in each arc**. The round trip in such ERLs with modest energy spread (~10^{-4} of the top energy) completely washes up the transverse memory, i.e. the injection/ejection energy can be as low as desired.

- High luminosity at low e-beam currents
  - ERL vs ring
- Beam stability in ERLs
- Other option for high luminosity in LHeC

Linear ERL

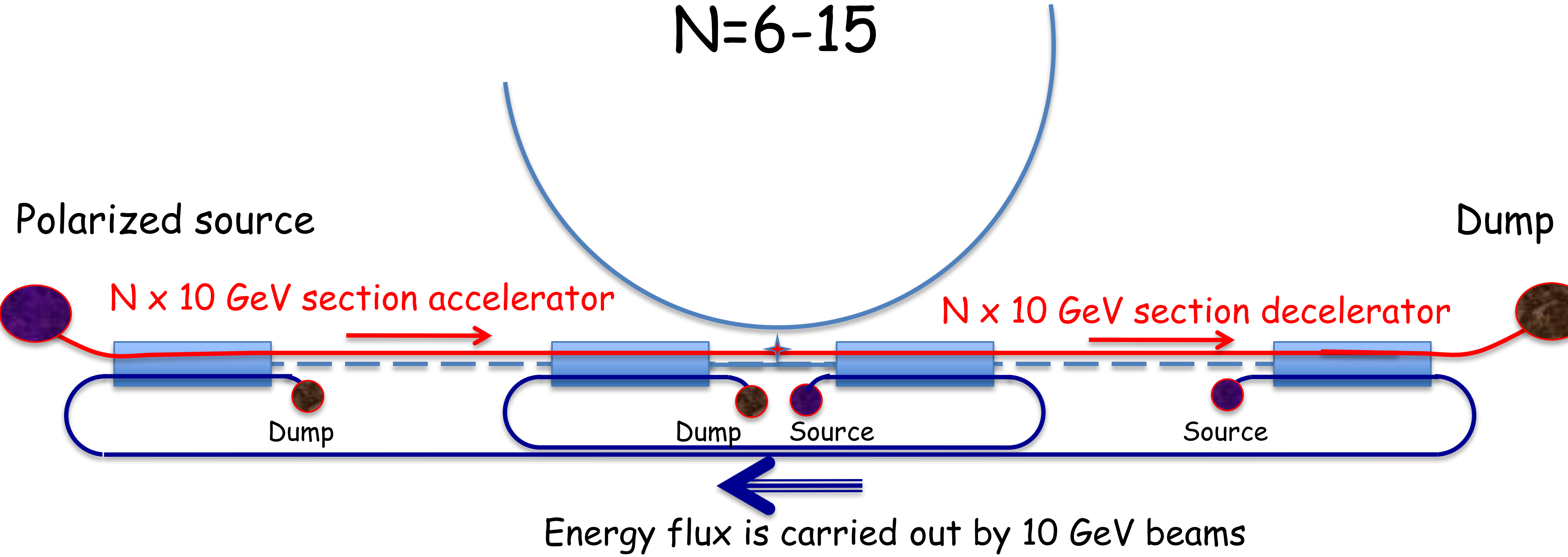
with 100% Energy recovery - needs 2 linacs
What to do with the energy?

$$\mathcal{L} \sim \mathcal{L}_{\max}$$



No severe limitations on e-beam current
Since SR is not a limit

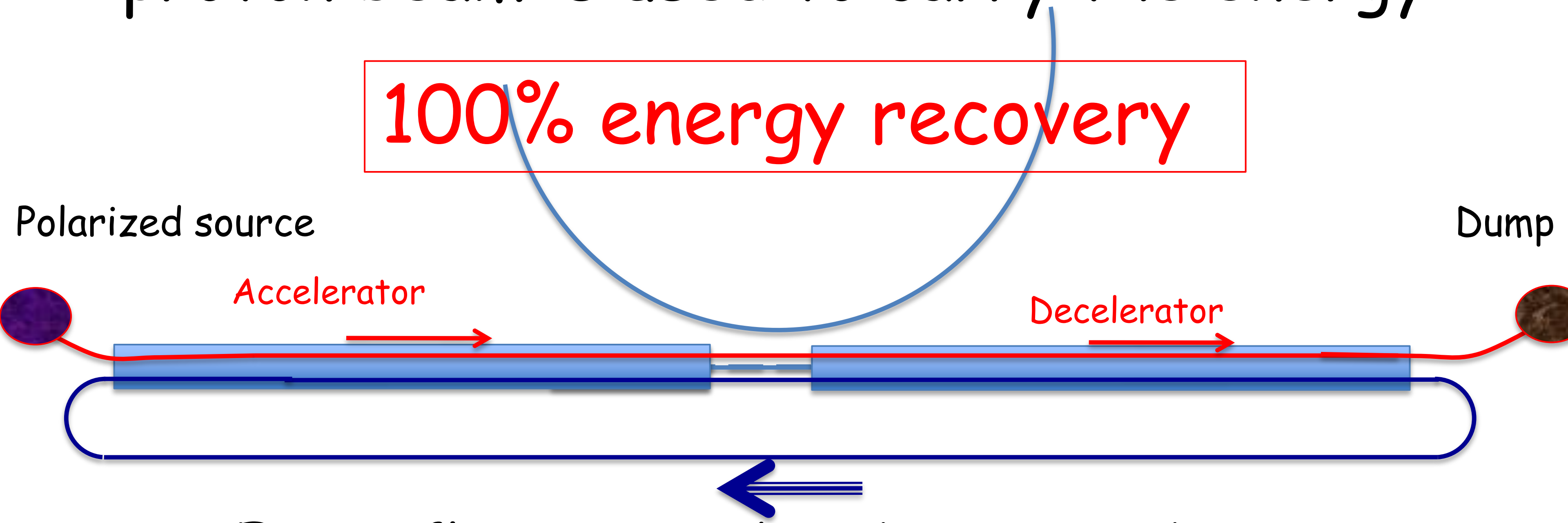
Nearly 100% energy recovery
LHeC II - E_e = 60-150... GeV
N=6-15



Synchrotron radiation a determined by energy of the returning beams. Losses grow linearly with the energy of the HE beam

Should work both for LHeC II and NLC

Other option of high energy high current ERL: proton beam is used to carry the energy



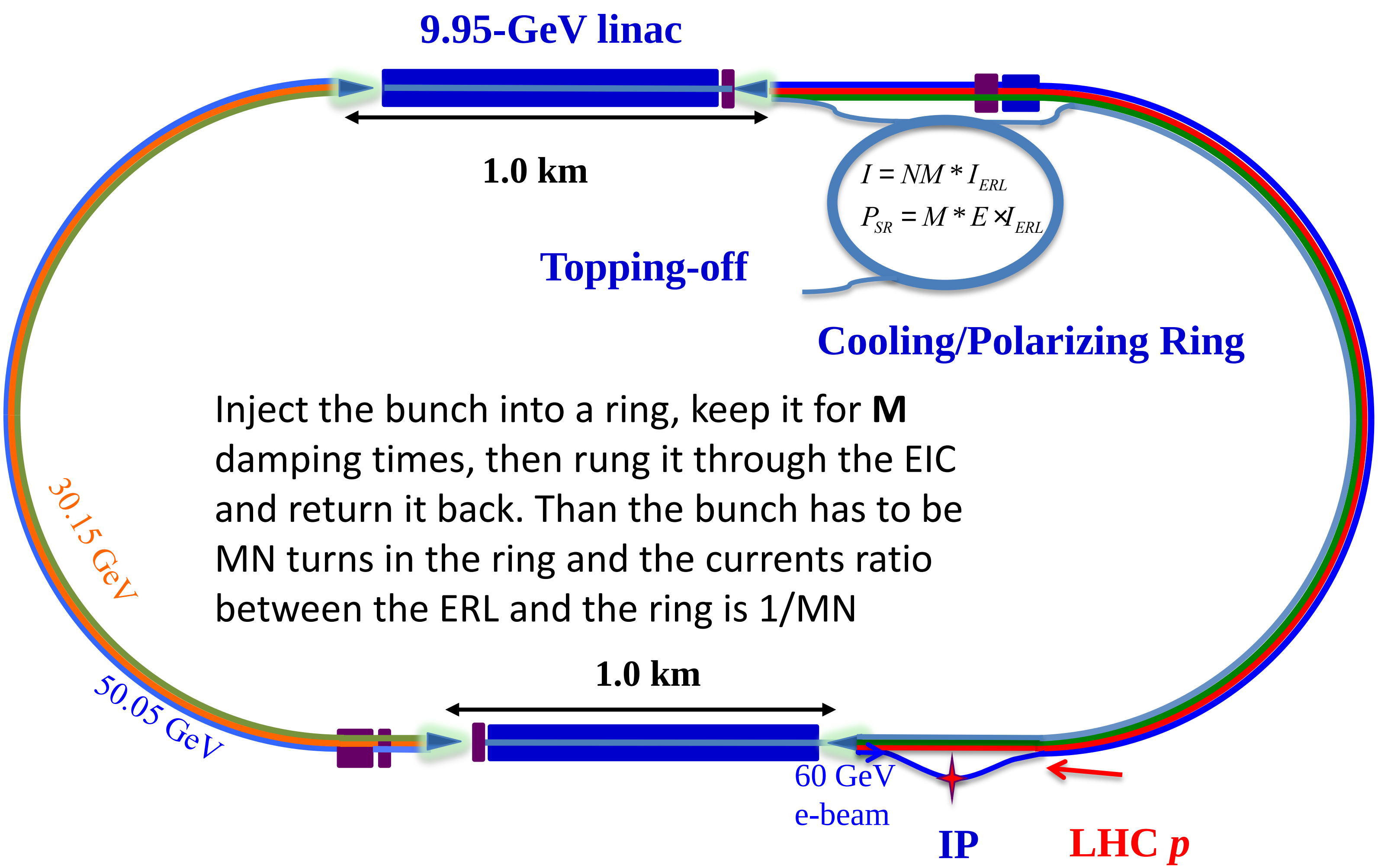
Energy flux is carried out by a proton beam

Synchrotron radiation is eliminated

Should work both for LHeC II and NLC

While very attractive, it is clearly more expensive scheme!

How about positrons?



Inject the bunch into a ring, keep it for **M** damping times, then rung it through the EIC and return it back. Than the bunch has to be MN turns in the ring and the currents ratio between the ERL and the ring is 1/MN

M=1, E=2 GeV, B=5T, I=11.28 A (Super-B type), PSR =12 MW
ERL positron beam current 3 mA, L ~ 10^{33}->$5*10^{34}$

Polarized current injectors for a scheme with a cooler ring

- 10-20 MW of synchrotron radiation provide a possibility to cool and even polarize e^+ e^- lepton beams to use in ERL driven EHC
- This scheme is applicable to both electrons and positions.
- Lifetime of the lepton beams in such scheme can be many hours and the injector need to provide only a nA of the average current

Conclusions

- High luminosity ERL-based LHeC looks feasible
- In a regular ERL scheme the e-beam current is limited and cooling the the hadron beam is needed to significantly increase LHeC luminosity. Cooling alone can bring LHeC luminosity close to 10^{35}
- CeC cooler will require additional 3.5 GeV ERL
- Instabilities originating from beam-beam effects can be handled with a feed-back system
- The TBBU threshold should be further increased 3-4 fold using natural chromaticity of ERL arcs
- Using linear ERL would allow both higher energies in ERL as well as significantly high currents
- Combination of linear ERL with cooling of hadron beam offers potential of a multi-order luminosity increase beyond current design
- Using recycling cooler ring can allow accumulating and recycling positrons with
- Only if needed, the LHeC with 10^{35} luminosity is feasible, but very non-trivial!
- Cooler/polarizer ring at few GeV in combination with ERL can be a reasonable approach to have a high luminosity positron-hadron collider

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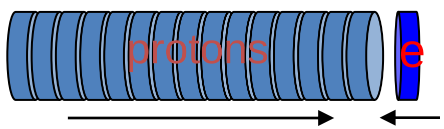
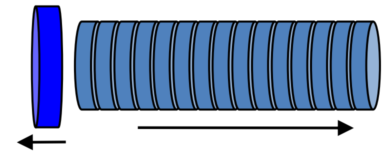
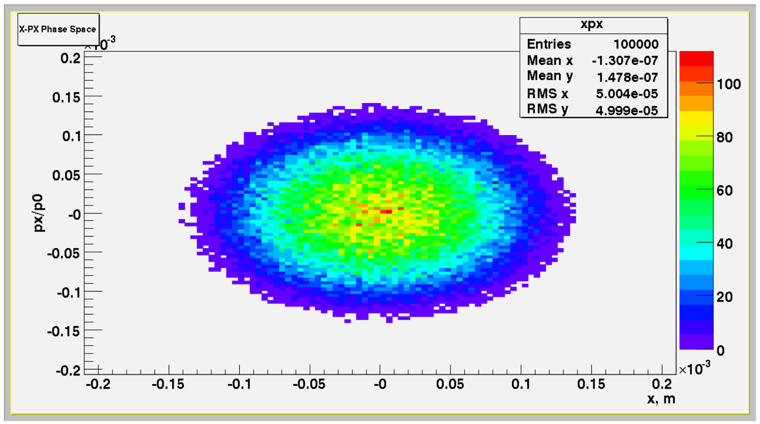
Back up

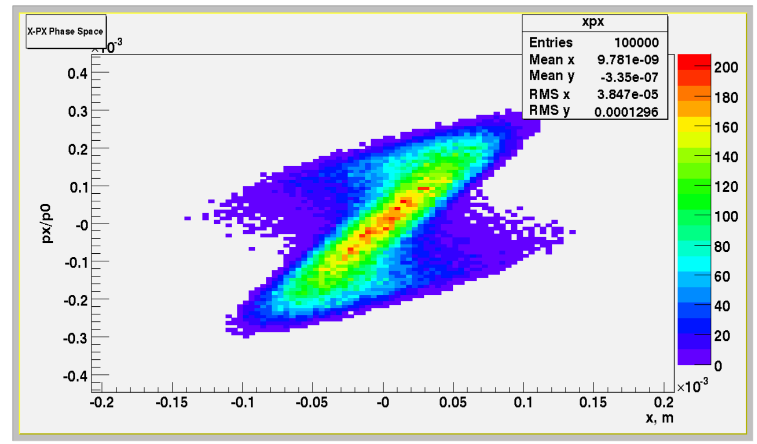
Beam Disruption



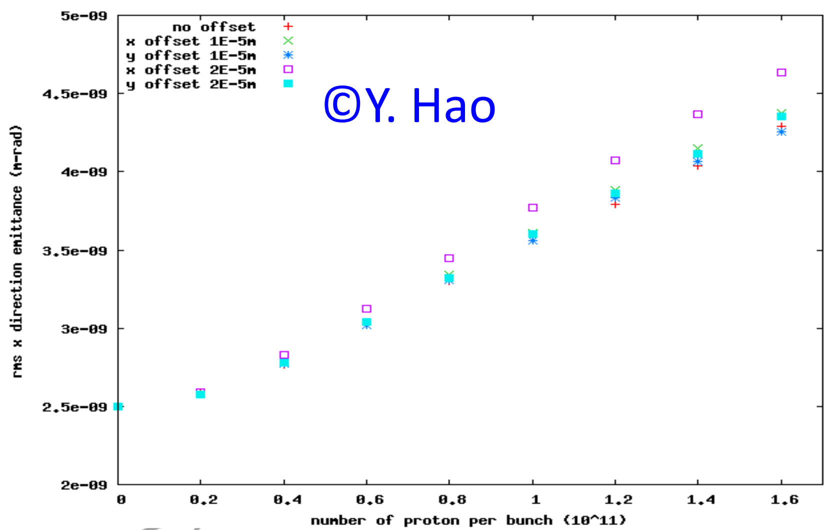


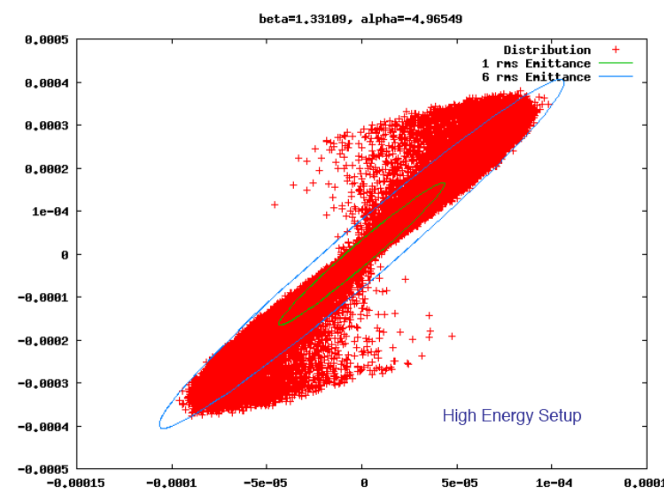


Interaction



Optimized





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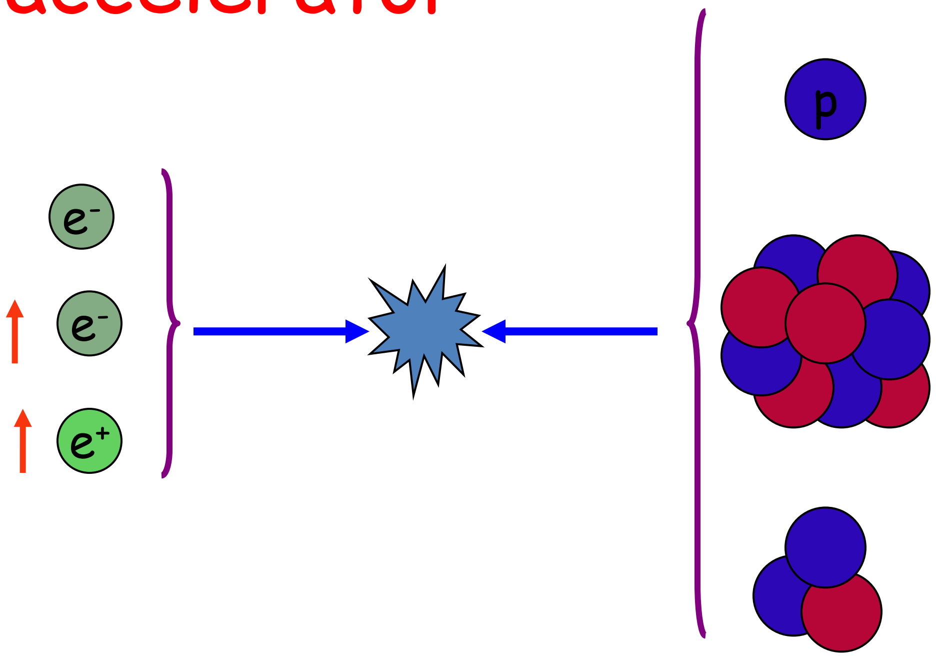
LHeC Scope

Electron accelerator

LHC

Unpolarized and
polarized leptons
60-140 GeV



Protons up to 7 TeV

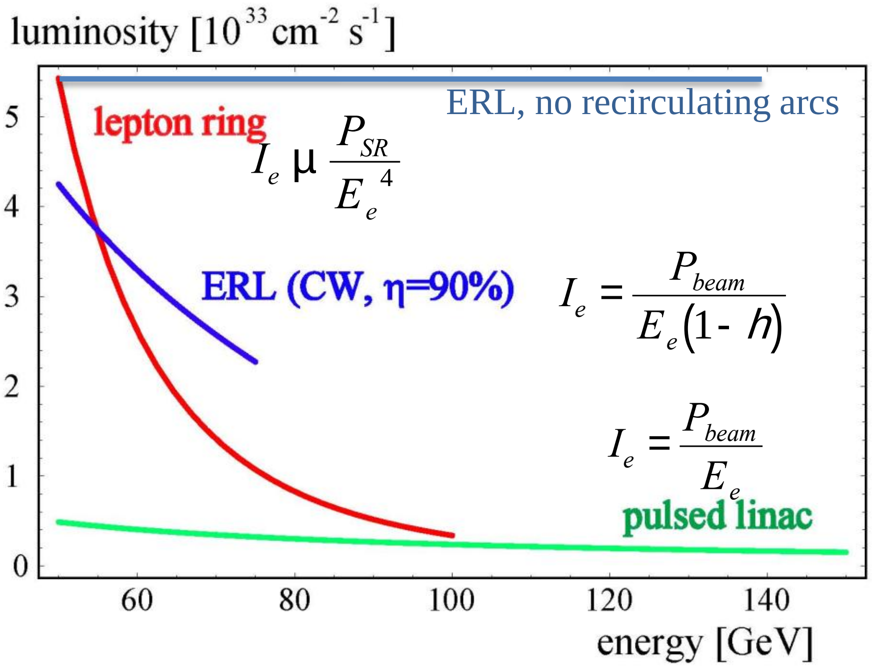
Heavy ions
3 TeV/u

Other ions?

Center mass energy range: 0.5- 2 TeV

Luminosity vs e-beam energy

for AC-plug power consumption set at 100 MW



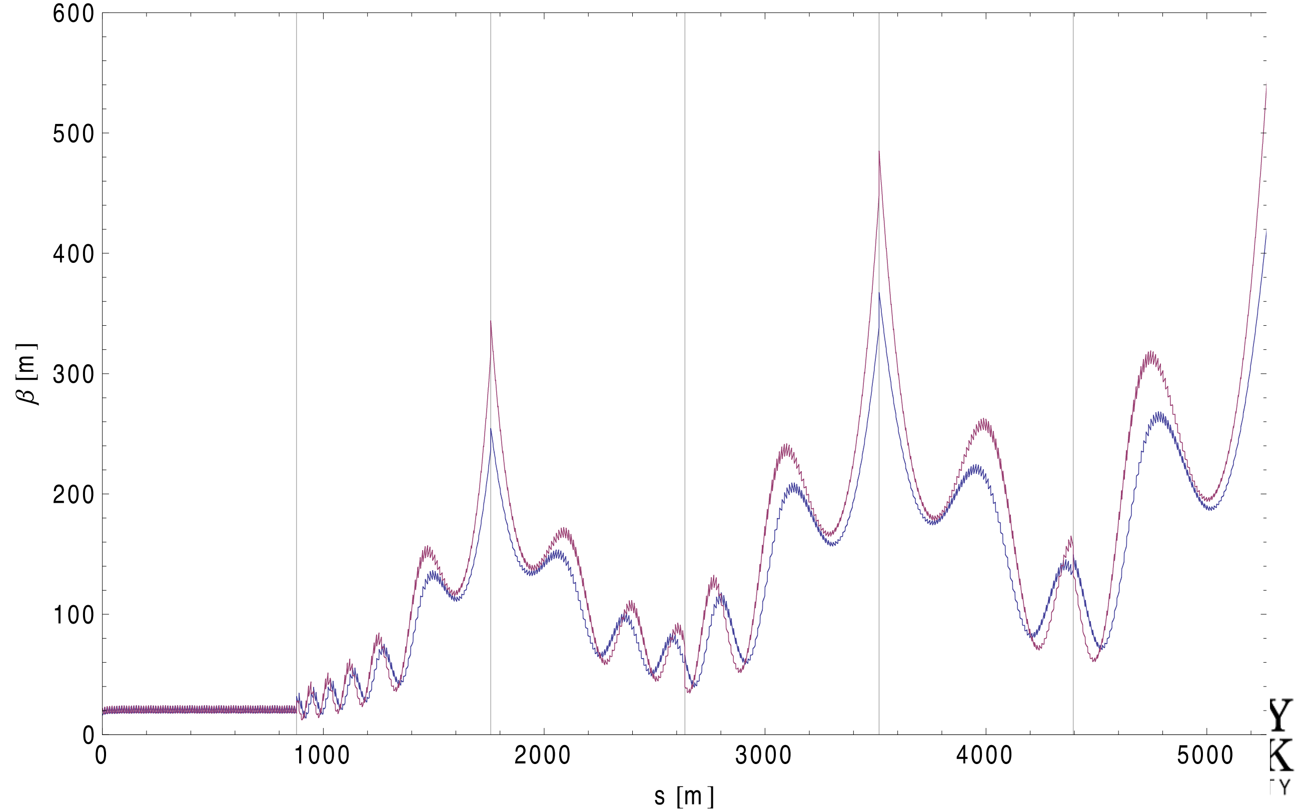
Linac without and with quads

# of pass in linac	β (entr.)	α (entr.)	β (exit)	α (exit)
1	294.6	-1.14	769.3	-1.18
2	898.1	1.89	905.3	-1.53
3	915.4	1.84	916.7	-1.61
4	919.7	1.81	920.0	-1.65
5	921.4	1.79	921.6	-1.67
6	922.3	1.78	922.2	-1.68

- On the way down the exit value becomes entrance and vice versa
- No quadrupoles inside linac

$$\frac{dx}{dt} = \approx \frac{p_x}{mc(\gamma_o + \gamma' z)};$$

For high energy, the average beta function is beta*+L^2/3/beta* (L is the half length of linac), therefore the best case is beta*=L/1.



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Arc cell

EMAX (GeV)	PC (GeV/c)	BRHO (Tm)
60.000000000	59.999999998	200.138457112

DIPOLES:

ANG	BL (m)	N_{DIP}	R_{DIP} (m)
0.004017382	2.80	1564	696.971326788

GF0 = 84.975 T/m QLF = 0.665 m

GD0 = -88.97 T/m QLD = 0.60 m

GF3 = 107.75 T/m QLF3 = 1.20 m

GD3 = -103.89 T/m QLD3 = 0.80 m

OFFW = 0.15272264 m

O1 = 0.065049881 m

O2 = 0.071114479 m

GF3S = 107.22407 T/m QLF3 = 1.20 m

GD3S = - 101.09491 T/m QLD3 = 0.80 m

ERL-based LHeC with achromatic arcs

Up to the collision point			
	$\delta\varepsilon_{norm}$	8.59	mm mrad
	σ_γ	31.27	
	σ_E	15.98	MeV
Accumulted			
	$\delta\varepsilon_{norm}$	36.53	mm mrad
	σ_γ	68.96	
	σ_E	35.24	MeV

Formulae can be derived from equations (5.16) and (5.6) in Kolomensky/Lebedev book

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$$\epsilon_n = \epsilon_{no} + \frac{55}{24\sqrt{3}} \Lambda_c r_e \int \gamma^6(s) K^3(s) H(s) ds$$

$$\langle \delta\gamma^2 \rangle = \langle \delta\gamma^2 \rangle_o + \frac{55}{24\sqrt{3}} \Lambda_c r_e \int \gamma^7(s) K^3(s) ds$$

Normalized emittance growth **per 180° arc!**

Arc	E, GeV	γ	δE, SR, GeV	δεn, m rad	$\delta\gamma^2$	*total*	*σγ/γ*
1	10.25	2.01E+04	6.93E-04	4.811615E-10	1.19E-02	*1.19E-02*	*5.44E-06*
2	20.2	3.95E+04	1.04E-02	2.818746E-08	1.37E+00	*1.38E+00*	*2.98E-05*
3	30.15	5.90E+04	5.18E-02	3.116532E-07	2.27E+01	*2.40E+01*	*8.31E-05*
4	40.1	7.85E+04	1.62E-01	1.725099E-06	1.67E+02	*1.91E+02*	*1.76E-04*
5	50.05	9.79E+04	3.94E-01	6.521871E-06	7.87E+02	*9.78E+02*	*3.19E-04*
6	60	1.17E+05	8.13E-01	1.935776E-05	2.80E+03	*3.78E+03*	*5.23E-04*
5	50.05	9.79E+04	3.94E-01	6.521871E-06	7.87E+02	*4.56E+03*	*6.90E-04*
4	40.1	7.85E+04	1.62E-01	1.725099E-06	1.67E+02	*4.73E+03*	*8.77E-04*
3	30.15	5.90E+04	5.18E-02	3.116532E-07	2.27E+01	*4.75E+03*	*1.17E-03*
2	20.2	3.95E+04	1.04E-02	2.818746E-08	1.37E+00	*4.76E+03*	*1.74E-03*
1	10.25	2.01E+04	6.93E-04	4.811615E-10	1.19E-02	*4.76E+03*	*3.44E-03*
Total			**2.05E+00**	**3.65E-05**	**4.76E+03**		

The bottom line – the quality of the beam is not spoiled neither in the collision point nor on the way back to the injection energy

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Classical radius of electron	r_e	cm	2.817938E-13	m	2.81794E-15
Compton wavelength of electron	Λ_e	cm	3.861591E-11	m	3.86159E-13

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- 13.54 MW of the SR losses radiated power with 6.6 mA CW current
- Max power density ~ 2 kW/m, which is well within the demonstrated 8kW/m in B-factories

Other losses

Bunch length	0.3mm
Number of electrons per bunch	2 10^9
Average arc radius	1000 m
Bending radius	697 m

- HOM loss
- CSR power loss
- **Resistive wall losses**
- …….

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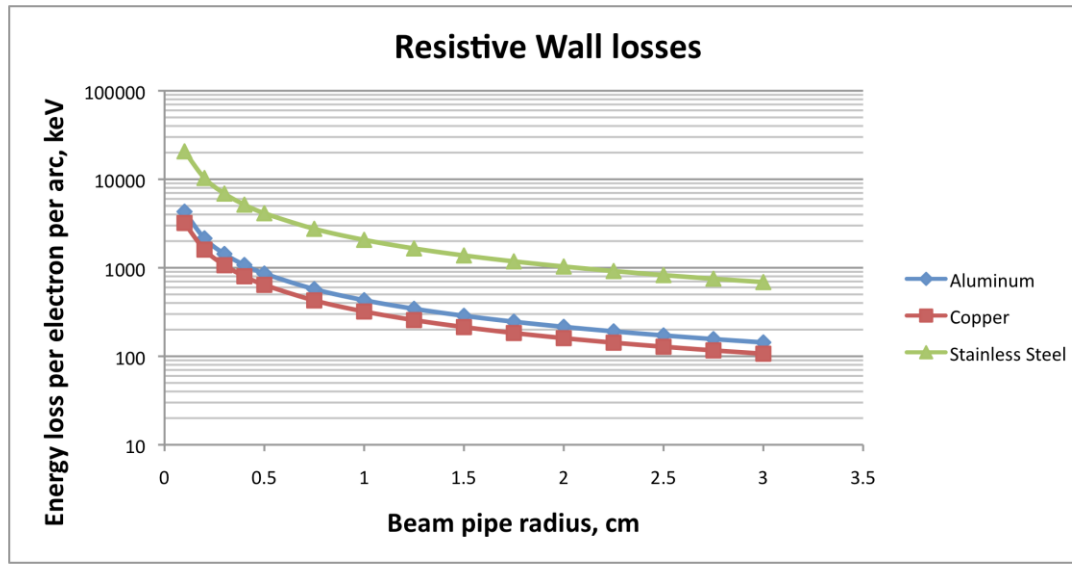


With the effective Al pipe radius ~ 2 mm there will be additional 24 MeV energy loss and similar level of the energy spread due to the resistive wall. While 24 MeV energy loss is very small compared with 2.05 GeV SR loss, the induced correlated energy spread is comparable with the 35 MeV RMS uncorrelated spread induced by SR

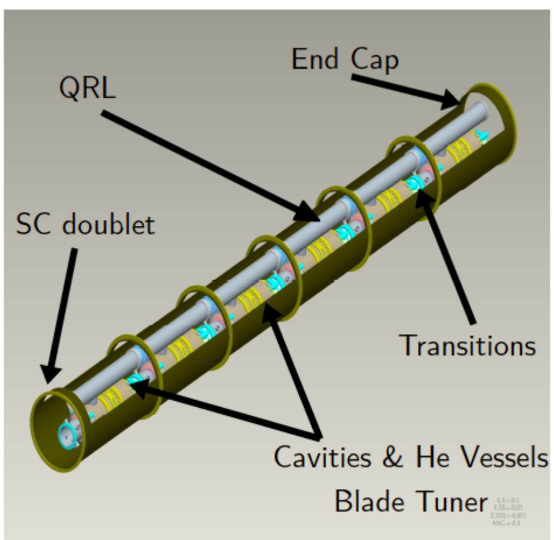
Linac: case #1

injection energy - 0.3GeV , top energy - 60GeV, energy gain per linac - 9.95GeV.
Each linac contains 80 eRHIC Cryomodules, each with 6 Cavities and 0.2m overhead length. Length of the linac is 800m with 20.73 MeV per cavity. More realistic is 83 modules (830 m) with 20 MeV per cavity.
Additional 1.4 GeV (90 m) of RF linacs at 700 MHz and 1.4 GHz to compensate for SRF

Linac: case #2

injection energy - 0.3GeV , top energy - 60GeV, max energy gain:
linac1 – 10 GeV, 84 modules, 840 m, 19.84 MeV per linac
linac2 – 10.35 GeV, 87 modules, 870 m, 19.83 MeV per linac

Preliminary Cryomodule

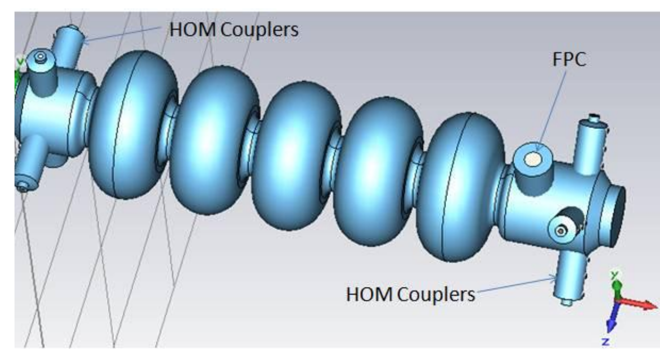


String assembly of multiple cavities. Heat shielding and top covers removed for clarity.

Breakdown of the eRHIC Cryomodule

- N cavities = 6 (but can 4-8)
- Module length = 9.6 m
- L period = 10.6 m
- E_{acc} = 18.0 MV/m
- dE/ds = 10.2 MeV/m

New design of 704 MHz cavity (BNL III):
-reduced peak surface magnet field
-reduced cryogenic load



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CSR power loss

Bunch length	0.3mm
Number of electrons per bunch	2 10^9
Average arc radius	1000 m
Bending radius	697 m

Without shielding, the beam will loose 1.4 MeV per arc due to Coherent Synchrotron Radiation (CSR). Again, it is dwarfed by the incoherent SR losses. The total induced correlated energy spread will be about 12 MeV. In any case, the CSR will be strongly suppressed by the walls of the vacuum chamber

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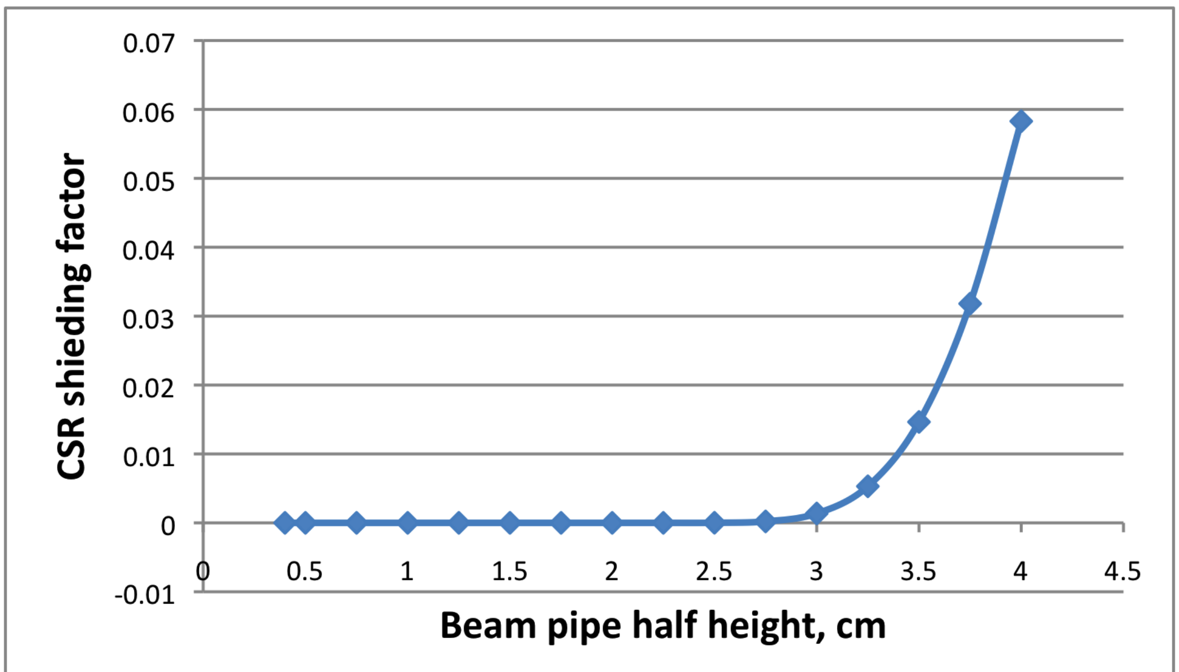

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Do not use sextupoles in ERL and enjoy extra stability and multi-pass economy

$$\langle T_{12}\rangle \propto \exp\left(-\frac{(\phi\sigma_d)^2}{2}\right)\cdot T_{12}(\max)$$

$$I_{th}(chromatic) \propto \exp\left(\frac{(\phi\sigma_d)^2}{2}\right)\cdot I_{th}(achromatic)$$

Assuming a strong focusing lattice for return loops, similar to that designed for eRHIC electron-hadron colliders the loop's chromaticity can be $C(s) \sim ''300$ and $''(s) \sim 2\#10^{3}$. Then for a beam with RMS energy spread of 0.2% the response $\langle T_{12}\rangle$ will be suppressed 3,000 fold, and according to formula (2) the threshold for TBBU instability will increase about 3,000 fold.

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