LHeC Recirculator with Energy Recovery – Beam Optics Choices

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in collaboration with

Frank Zimmermann and Daniel Schulte
LHeC Challenge

Add an \textit{electron} beam to the LHC

- Next generation $e^\pm p$ collider
- $e^\pm$ polarized beam
- $eA$ collider

Rich physics program: $e\bar{q}$ physics at TeV energies

- precision QCD & electroweak physics
- boosting precision and range of LHC physics results
- beyond the Standard Model
- high density matter: low $x$ and $eA$

\textbf{Tevatron/LEP/HERA (Fermiscale)} $\rightarrow$ \textbf{LHC/LC/LHeC (Terascale)}

100 fold increase in luminosity, in $Q^2$ and $1/x$ w.r.t. HERA
Kinematics & Motivation (60 GeV x 7 TeV ep)

- New physics, distance scales few $10^{-20}$ m
- Large x partons
- High precision partons in LHC plateau
- Nuclear Structure & Low x Parton Dynamics
- High Density Matter

- High mass ($M_{eq}, Q^2$) frontier
- EW & Higgs
- $Q^2$ lever-arm at smallest up to x near to 1 $\rightarrow$ PDFs
- Low x frontier [$x$ below $10^{-6}$ at $Q^2 \sim 1$ GeV$^2$]

$\sqrt{s} >> 1$ TeV

A. Polini
Linac-Ring Configurations

**Pulsed-60**
- 0.34 km
- 1.67 km
- Least effort: $\sim 10^{32}$

**Pulsed-140**
- 2.0 km
- 3.9 km
- High Energy, $0.5 \times 10^{32}$

**ERL**
- 1.0 km
- 2.0 km
- Luminosity $\sim 10^{33}$

**or linear**
- 7.8 km

A. Polini  
EIC Workshop, Washington, July 29th 2010
## Design Parameters

<table>
<thead>
<tr>
<th>electron beam</th>
<th>RR</th>
<th>LR</th>
<th>ERL</th>
<th>LR</th>
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<tbody>
<tr>
<td>e- energy at IP [GeV]</td>
<td>60</td>
<td>60</td>
<td>140</td>
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<tr>
<td>luminosity [10^{32} cm^{-2}s^{-1}]</td>
<td>17</td>
<td>10</td>
<td>0.44</td>
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<td>polarization [%]</td>
<td>5 - 40</td>
<td>90</td>
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<td>bunch population [10^9]</td>
<td>26</td>
<td>2.0</td>
<td>1.6</td>
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<tr>
<td>e- bunch length [mm]</td>
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<td>0.3</td>
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<td>bunch interval [ns]</td>
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<td>transv. emit. γε_{x,y} [mm]</td>
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<td>rms IP beam size σ_{x,y} [μm]</td>
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<td>e- IP beta funct. β_{x,y} [m]</td>
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<td>0.12</td>
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<td>full crossing angle [mrad]</td>
<td>0.93</td>
<td>0</td>
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<td>geometric reduction H_{ng}</td>
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<td>0.91</td>
<td>0.94</td>
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<td>repetition rate [Hz]</td>
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<td>beam pulse length [ms]</td>
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<td>ER efficiency</td>
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<td>N/A</td>
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<td>average current [mA]</td>
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<td>tot. wall plug power [MW]</td>
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<table>
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<th>proton beam</th>
<th>RR</th>
<th>LR</th>
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<tr>
<td>bunch pop. [10^{11}]</td>
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<td>tr. emit. γε_{x,y} [μm]</td>
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<td>spot size σ_{x,y} [μm]</td>
<td>30, 16</td>
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<tr>
<td>β_{x,y} [m]</td>
<td>1.8, 0.5</td>
<td>0.1$</td>
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<td>bunch spacing [ns]</td>
<td>25</td>
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</table>

$ smaller LR p-β* value than for nominal LHC (0.55 m):
- reduced l/ (23 → 10 m)
- only one p beam squeezed
- IR quads as for HL-LHC

In progress  last update  8.7.2010

RR = Ring – Ring
LR = Linac – Ring
ERL = Energy Recovery Linac
Linac-Ring Configuration

Baseline:
Energy Recovery Linac
60 GeV, Power 100MW

Also presented in CDR:
60 GeV pulsed $10^{32}\text{cm}^{-2}\text{s}^{-1}$
140 GeV pulsed $5 \times 10^{31}$

Note: CLIC x LHC $\sim 10^{30}$
due to different time structure (0.5 vs 50ns)

$10^{33} \text{cm}^{-2} \text{s}^{-1}$, $\int L = 100 \text{fb}^{-1}$, $E_e = 60\text{GeV}$
Energy Recovery Recirculating Linacs - Motivation

Future high energy (multi-tens of GeV), high current (tens of milli-Amperes) beams would require gigaWatt-class RF systems in conventional linacs – a prohibitively expensive proposition. However, invoking energy recovery alleviates extreme RF power demands; required RF power becomes nearly independent of beam current, which improves linac efficiency and increases cost effectiveness.

Energy recovering linacs promise efficiencies of storage rings, while maintaining beam quality of linacs: superior emittance and energy spread and short bunches (sub-pico sec.).

RLAs that use superconducting RF structures can provide exceptionally fast and economical acceleration to the extent that the focusing range of the RLA quadrupoles allows each particle to pass several times through each high-gradient cavity.

GeV scale energy recovery demonstration with high ratio of accelerated-to-recovered energies (50:1) was carried out on the CEBAF RLA (2003)
Overview - Design Choices

Examples of ER RLA’s
- CEBAF ER Exp & Jlab’s FEL

Multi-pass linac Optics in ER mode
- Choice of linac Optics - 130° FODO vs ‘No quad’ focusing
- Choice of quad gradient profile in the linacs
- Single pass wake-field effects
- Linear lattice: 3-pass ‘up’ + 3-pass ‘down’

Arc-to-Linac Synchronization - Momentum compaction
- Quasi-isochronous lattices
- Choice of Arc Optics -135° FODO vs FMC (Flexible Momentum Compaction)

Arc Optics Choice - Emittance preserving lattices
- Various flavors of FMC lattices in the second stability region (Im. $\gamma_t$, DBA, TEM)

Emittance dilution & momentum spread due to quantum excitations
- Magnet apertures
LHeC Recirculator with ER
Modifications include the installation of:

- $\lambda_{RF}/2$ path length delay chicane
- Dump and beamline with diagnostics
Transverse beam profiles

Beam viewer near the exit of the South Linac

~ 55 MeV Decelerating beam

~ 1 GeV Accelerating beam

3-wire scanner x 2 beams = 6 peaks
Gradient modulator drive signals *with* and *without* energy recovery in response to 250 μsec beam pulse entering an RF cavity.
JLAMP – RLA FEL with ER
Linac Optics – $130^0$ FODO Cell

$E = 0.5$ GeV

**Linac Quadrupoles**
Lq=100 cm  
GF= 0.103 Tesla/m  
GD= -0.161 Tesla/m

**700 MHz RF:**
Lc =100 cm  
5-cell cavity  
Grad = 17.361 MeV/m  
$\Delta E = 555.56$ MV

**Phase Adv/cell:** $\Delta\phi_{x,y} = 130^0$

2 8 cavities  
2 8 cavities
Linac 1 – Focusing profile

E = 0.5 – 10.5 GeV

18 FODO cells (18 \times 2 \times 16 = 576 RF cavities)
Linac 3 (Linac 1, pass 2) – Optics

\[
\langle \frac{\beta}{E} \rangle = \left( \frac{1}{L} \int \frac{\beta}{E} \, ds \right)_{\text{min}}
\]

E = 20.5 – 30.5 GeV

betatron phase advance
Linac 1 – multi-pass + ER Optics

\[ \langle \beta \rangle \]

- 0.5 GeV
- 10.5 GeV
- 20.5 GeV
- 30.5 GeV
- 40.5 GeV
- 50.5 GeV
- 60.5 GeV

- BETA_X
- BETA_Y
- DISP_X
- DISP_Y

Operated by JSA for the U.S. Department of Energy

Thomas Jefferson National Accelerator Facility

Accelerator Seminar, CERN/JLAB, Oct. 7/14, 2010
Linac 1 – Multi-pass ER Optics

\[ M = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \]
Linac 2 – Focusing profile

E = 10.5 – 0.5 GeV (ER)

quad gradient

18 FODO cells (18 2 16 = 576 RF cavities)

Linac 2 multi-pass optics with ER – mirror symmetric to Linac 1
Linac 1 and 2 – Multi-pass ER Optics

Linac 1

Linac 2

0.5 GeV

10.5 GeV

20.5 GeV

30.5 GeV

40.5 GeV

50.5 GeV

60.5 GeV

800

0

BETA_X & Y [m]

DISP_X & Y [m]

6048

BETA_X

BETA_Y

DISP_X

DISP_Y
Linac 1 – ‘NO quad’ focusing profile

E = 0.5 – 10.5 GeV

Zero quad gradient

18 FODO cells (18 2 16 = 576 RF cavities)
Linac 1 ‘NO quad’ – Multi-pass ER Optics

0.5 GeV  10.5 GeV  20.5 GeV  30.5 GeV  40.5 GeV  50.5 GeV  60.5 GeV
‘NO quad’ vs 130° FODO
E = 0.5 – 10.5 GeV

\[
\frac{\langle \beta \rangle}{E} = 12.9/12.7 \quad cm/MeV
\]

Zero quad gradient

130° FODO

\[
\frac{\langle \beta \rangle}{E} = 1.8/1.6 \quad cm/MeV
\]
Arc Optics - $135^0$ FODO Cell

50.5 GeV

Arc dipoles:
$L_b = 400$ cm
$B = 2.2$ kGauss
$\text{ang} = 0.3$ deg.
$rho = 764$ meter

Arc quadrupoles
$L_q = 100$ cm
$G = 1.2$ kG/cm

Phase adv/cell: $\Delta \phi_{x,y} = 135^0$
\[ H = \gamma D^2 + 2\alpha DD' + \beta D'^2 \]

\[ \langle H \rangle = 2.2 \times 10^{-2} m \]

\[ M_{56} = -\int \frac{D}{\rho} \, ds = -\theta_{bend} \langle D \rangle \]

\[ M_{56} = 3.19 \times 10^{-2} \, m \]
Momentum compaction

\[ M_{56} = - \int \frac{D}{\rho} \, ds = -\theta_{\text{bend}} \langle D \rangle \]

\[ \Delta C = -M_{56} \frac{\Delta p}{p} \]

\[ \Delta \phi_{RF} = \frac{360 \times \Delta C}{\lambda_{RF}} = -\frac{360}{\lambda_{RF}} N_{\text{cell}} M_{56}^\text{cell} \frac{\Delta p}{p} \]

\[ \frac{\Delta p}{p} = 3 \times 10^{-4} \]

\[ \lambda_{RF} = 0.428 \text{ m} \]

\[ N_{\text{cell}} = 60 \]

\[ M_{56}^{FODO} = 3.19 \times 10^{-2} \text{ m} \]

\[ \Delta \phi_{RF} = 0.5 \text{ deg} \]
Emittance growth due to quantum excitations

\[ \Delta \varepsilon^N = \frac{2}{3} C_q r_0 \gamma^6 \langle H \rangle \theta \rho^2 \]

\[ C_q = \frac{55}{32\sqrt{3}} \frac{\hbar c}{mc^2} = 3.8319 \times 10^{-13} \text{ m}, \]

\[ r_0 = 2.818 \times 10^{-15} \text{ m}, \]

\[ I_5 = \int_0^L \frac{H}{|\rho|^3} \, ds = \frac{\theta \langle H \rangle}{\rho^2}, \]

\[ H = \gamma D^2 + 2 \alpha DD' + \beta D'^2 \]

**total bend of the arc**: \[ \theta \in 0, 2\pi \]

**for 180° arc**: \[ \theta = \pi \]

\[ \langle H \rangle = 2.2 \times 10^{-2} \text{ m} \]

\[ \Delta \varepsilon^N = 82 \text{ micron rad} \]
Momentum spread due to quantum excitations

\[ \frac{\Delta \sigma_E^2}{E^2} = \frac{55\alpha}{48\sqrt{3}} \left( \frac{\hbar c}{mc^2} \right)^2 \gamma^5 \int_0^L \frac{1}{\rho^3} \, ds \]

\[ \int_0^L \frac{1}{\rho^3} \, ds = \frac{\theta}{\rho^2}, \]

total bend of the arc: \( \theta \in 0, 2\pi \)

\[ \frac{\Delta \sigma_E^2}{E^2} = \frac{55\alpha}{48\sqrt{3}} \left( \frac{\hbar c}{mc^2} \right)^2 \gamma^5 \frac{\theta}{\rho^2} \]

for 180° arc: \( \theta = \pi \)
Quasi-isochronous FMC Cell

\[ H = \gamma D^2 + 2\alpha DD' + \beta D'^2 \]

\[ \langle H \rangle = 8.8 \times 10^{-3} \text{ m} \]

factor of 2.5 smaller than FODO

\[ M_{56} = -\int \frac{D}{\rho} ds = -\theta_{\text{bend}} \langle D \rangle \]

\[ M_{56} = 1.16 \times 10^{-3} \text{ m} \]

factor of 27 smaller than FODO
Arc Optics – 135° FODO vs FMC Cell

135° FODO

\[ \langle H \rangle = 2.2 \times 10^{-2} \text{ m} \]

\[ M_{56} = 3.19 \times 10^{-2} \text{ m} \]

FMC Cell

\[ \langle H \rangle = 8.8 \times 10^{-3} \text{ m} \]

\[ M_{56} = 1.16 \times 10^{-3} \text{ m} \]
Quasi-isochronous condition – Arc into Linac

Momentum compaction

\[ M_{56} = - \int \frac{D}{\rho} \, ds = -\theta_{bend} \langle D \rangle \]

\[ \Delta C = -M_{56} \frac{\Delta p}{p} \]

\[ \Delta \phi_{RF} = \frac{360 \times \Delta C}{\lambda_{RF}} = -\frac{360}{\lambda_{RF}} N_{cell} M_{cell}^{56} \frac{\Delta p}{p} \]

\[ \frac{\Delta p}{p} = 3 \times 10^{-4} \]

\[ \lambda_{RF} = 0.428 \, \text{m} \]

\[ N_{cell} = 60 \]

\[ M_{56}^{FMC} = 1.16 \times 10^{-3} \, \text{m} \]

\[ \Delta \phi_{RF} = 0.018 \, \text{deg} \]

factor of 27 smaller than FODO

\[ M_{56}^{FODO} = 3.19 \times 10^{-2} \, \text{m} \]

\[ \Delta \phi_{RF} = 0.5 \, \text{deg} \]
FMC ‘Imaginary $\gamma_t$’ Cell

50.5 GeV

$\langle H \rangle = 8.8 \times 10^{-3} \, m$

$M_{56} = 1.16 \times 10^{-3} \, m$

**Arc dipoles:**
- $L_b=400 \, \text{cm}$
- $B=2.2 \, \text{kGauss}$
- $\text{ang}=0.3 \, \text{deg.}$
- $\rho = 764 \, \text{meter}$

**Arc quadrupoles**
- $G_0=-1.53 \, \text{kG/cm}$
- $G_1=5.06 \, \text{kG/cm}$
- $G_2=-5.32 \, \text{kG/cm}$
- $G_3=5.07 \, \text{kG/cm}$

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second stability region:

$\Delta \phi_{x,y} > 180^0$

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Accelerator Seminar, CERN/JLAB, Oct. 7/14, 2010
FMC ‘Double Bend Achromat’ Cell

50.5 GeV

Arc dipoles:
- $L_b = 400$ cm
- $B = 2.2$ kGauss
- $\theta = 0.3$ deg.
- $\rho = 764$ meter

Arc quadrupoles:
- $G_0 = 2.05$ kG/cm
- $G_1 = 2.90$ kG/cm
- $G_2 = -4.07$ kG/cm
- $G_3 = 2.97$ kG/cm

\[
\langle H \rangle = 2.2 \times 10^{-3} \ m
\]
\[
M_{56} = 5.6 \times 10^{-3} \ m
\]
Arc dipoles:
$Lb=400\text{ cm}
$B=2.2\text{ kGauss}
$\text{ang}=0.3\text{ deg.}
$\rho=764\text{ meter}

Arc quadrupoles
$G0=2.92\text{ kG/cm}
G1=2.89\text{ kG/cm}
G2=-4.08\text{ kG/cm}
G3=2.97\text{ kG/cm}

\[
\langle H \rangle = 1.2 \times 10^{-3}\text{ m}
\]
\[
M_{56} = 5.7 \times 10^{-3}\text{ m}
\]
Arc Optics – Cumulative emittance growth

\[
\Delta \varepsilon^N = \frac{2}{3} C_q r_0 \gamma^6 \langle H \rangle \frac{\pi}{\rho^2}, \quad H = \gamma D^2 + 2\alpha DD' + \beta D^2
\]

Arc 1, Arc2

Arc 3

Arc 4, Arc5, Arc 6

Imaginary $\gamma_t$ Optics

DBA-like Optics

TEM-like Optics

\[
\langle H \rangle = 8.8 \times 10^{-3} \ m
\]

\[
\langle H \rangle = 2.2 \times 10^{-3} \ m
\]

\[
\langle H \rangle = 1.2 \times 10^{-3} \ m
\]

factor of 18 smaller than FODO

total emittance increase (all 5 arcs):

\[
\Delta \varepsilon^N_x = 1.25 \times 4.5 \ \mu \text{m rad} = 5.6 \ \mu \text{m rad}
\]
Highest Arc Optics – Emittance growth

\[ \Delta \varepsilon^N = \frac{2}{3} C q r_0 \gamma^6 \langle H \rangle \frac{\pi}{\rho^2} \]

50.5 GeV, \( \gamma = 10^5 \)

\[ \frac{\Delta \sigma_E^2}{E^2} = \frac{55 \alpha}{48 \sqrt{3}} \left( \frac{\hbar c}{m c^2} \right)^2 \gamma^5 \frac{\theta}{\rho^2} \]

emittance increase (last arc): \( \Delta \varepsilon_x^N = 4.5 \) μm rad

RMS fluctuations of \( \Delta E/E_0 = 2.7 \times 10^{-4} \)

total emittance increase (all 6 arcs): \( \Delta \varepsilon_x^N = 1.25 \times 4.5 \) μm rad = 5.6 μm rad
Arc 5 – Beam envelopes, Magnet apertures

Last pass before IR, 50.5 GeV

$\varepsilon_x^N = 50 \, \mu\text{m rad}$

$\Delta p/p = 2.7 \times 10^{-4}$

$12 \times \sigma_{\text{RMS}} \text{ (beam stay clear)} \sim 48 \text{ mm}$
$\varepsilon_x^N = 200 \mu m$ rad
$\Delta p/p = 5 \times 10^{-4}$

**Arc 1 – Beam envelopes, Magnet apertures**

**ER lowest pass, 10.5 GeV**

$12 \times \sigma_{RMS}$ (beam stay clear) $\sim 96$ mm

Imaginary $\gamma_t$ FMC Optics

$\beta_x$ $\beta_y$ $\delta_x$ $\delta_y$
Conclusions

- Proof-of-existence ER RLAs: Jlab FEL, CEBAF-ER
- Solution for Multi-pass linac Optics in ER mode
  - Choice of linac Optics - 130° FODO
  - Linear lattice: 3-pass ‘up’ + 3-pass ‘down’
  - Optimized quad gradient profile in the linacs (single-pass wake-field effects)
- Arc-to-Linac Synchronization - Momentum compaction
  - Quasi-isochronous lattices
  - Choice of Arc Optics - Flexible Momentum Compaction
- Arc Optics Choice - Emittance preserving lattices
  - Arcs based on variations of FMC optics (Im. \(\gamma_t\), DBA, TEM)
- Acceptable level of emittance dilution & momentum spread
  - Magnet apertures