Linac-Ring LHeC – two options

- 60-GeV recirculating linac with energy recovery
- Straight linac
performance targets

e- energy $\geq 60$ GeV
luminosity $\sim 10^{33}$ cm$^{-2}$s$^{-1}$
total electrical power for e-: $\leq 100$ MW
e$^+$$p$ collisions with similar luminosity
simultaneous with LHC $pp$ physics
e$^-$/e$^+$ polarization
detector acceptance down to $1^\circ$

*getting all this at the same time is very challenging*
road map to $10^{33}$ cm$^{-2}$s$^{-1}$

**luminosity of LR collider:**

(round beams)

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

- highest proton beam brightness “permitted” (ultimate LHC values)
  - $\gamma\varepsilon=3.75$ $\mu$m
  - $N_b=1.7\times10^{11}$
  - bunch spacing 25 or 50 ns

- smallest conceivable proton $\beta^*$ function:
  - reduced $I^*$ ($23$ m $\rightarrow$ $10$ m)
  - squeeze only one $p$ beam
  - new magnet technology $Nb_3Sn$
  - $\beta^*=0.1$ m

- maximize geometric overlap factor
  - head-on collision
  - small e- emittance
  - $\theta_c=0$
  - $H_{hg}\geq0.9$

average e$^-$ current!
electron beam

e- emittances and $\beta^*$ not critical (protons are big, $\sim 7\mu m$!)

most important parameter: 
**average beam current**

in addition: bunch structure and polarization
CLIC main beam $\sim 0.01$ mA (factor 600 missing)

lowering voltage, raise bunch charge & rep rate $\rightarrow 0.06$ mA (NIMA 2007)

CLIC drive beam (30 mA, but 2.37 GeV)

ILC design current $\sim 0.05$ mA (factor $\sim 100$ missing)
SC linacs can provide higher average current, e.g. by increasing the duty factor 10-100 times, or even running cw, at lower energy & lower gradient

example design average currents:
CERN HP-SPL: \( \sim 2.5 \, \text{mA (50 Hz)} \)
Cornell ERL \( \sim 100 \, \text{mA (cw)} \)
eRHIC ERL \( \sim 50 \, \text{mA at 20 GeV (cw)} \)

*LHeC needs \( \sim 6 \, \text{mA at 60 GeV} \)
beam power

6.4 mA at 60 GeV
→ 384 MW beam power !
→ ~800 MW electrical power !!??

need for energy recovery!
power reduced by factor \((1-\eta_{ERL})\)

→ LHeC ERL high-luminosity baseline
choice of SC linac RF frequency:

1.3 GHz (ILC)?

~720 MHz?!

• requires less cryo-power (~2 times less from BCS theory); true difference ↔ residual resistance, [J. Tückmantel, E. Ciapala]

• better for high-power couplers? [O. Napoly]
  but the couplers might not be critical

• fewer cells better for trapped modes [J. Tückmantel]

• synergy with SPL, eRHIC and ESS
## linac RF parameters

<table>
<thead>
<tr>
<th></th>
<th>ERL 720 MHz</th>
<th>ERL 1.3 GHz</th>
<th>Pulsed</th>
</tr>
</thead>
<tbody>
<tr>
<td>duty factor</td>
<td>cw</td>
<td>cw</td>
<td>0.05</td>
</tr>
<tr>
<td>RF frequency [GHz]</td>
<td>0.72</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>cavity length [m]</td>
<td>1</td>
<td>~1</td>
<td>~1</td>
</tr>
<tr>
<td>energy gain / cavity [MeV]</td>
<td>18</td>
<td>18</td>
<td>31.5</td>
</tr>
<tr>
<td>$R/Q$ [100 $\Omega$]</td>
<td>400-500</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>$Q_0$ [$10^{10}$]</td>
<td>2.5-5.0</td>
<td>2 ?</td>
<td>1</td>
</tr>
<tr>
<td>power loss stat. [W/cav.]</td>
<td>5</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>power loss RF [W/cav.]</td>
<td>8-32</td>
<td>13-27</td>
<td>&lt;10</td>
</tr>
<tr>
<td>power loss total [W/cav.]</td>
<td>13-37 (!?)</td>
<td>13-27</td>
<td>11</td>
</tr>
<tr>
<td>“W per W” (1.8 k to RT)</td>
<td>700</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>power loss / GeV @RT [MW]</td>
<td>0.51-1.44</td>
<td>0.6-1.1</td>
<td>0.24</td>
</tr>
<tr>
<td>length / GeV [m] (filling=0.57)</td>
<td>97</td>
<td>97</td>
<td>56</td>
</tr>
</tbody>
</table>
ERL electrical site power

cryo power for two 10-GeV SC linacs: 28.9 MW
MV/m cavity gradient, 37 W/m heat at 1.8 K
700 “W per W” cryo efficiency

RF power to control microphonics: 22.2 MW
10 kW/m (eRHIC), 50% RF efficiency

RF for SR energy loss compensation: 24.1 MW
energy loss from SR 13.2 MW, 50% RF efficiency

cryo power for compensating RF: 2.1 MW
1.44 GeV linacs

microphonics control for compensating RF: 1.6 MW

injector RF: 6.4 MW
500 MeV, 6.4 mA, 50% RF efficiency

magnets: 3 MW

grand total = 88.3 MW
The eRHIC-type cryo-module containing six 5-cell SRF 703 MHz cavities.

Model of a new 5-cell HOM-damped SRF 703 MHz cavity.
measured Q vs. field for the 5-cell 704 MHz cavity built and tested (BNL -I)
predicted cryopower based on eRHIC

I. Ben-Zvi

The relevant parameters for BNL-I cavity and for new 5-cell cavity upon which we based our calculations (BNL-III) are:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value BNL-I</th>
<th>Value BNL-III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry factor</td>
<td>Ohms</td>
<td>225</td>
<td>283</td>
</tr>
<tr>
<td>R/Q per cell</td>
<td>Ohms</td>
<td>80.8</td>
<td>101.3</td>
</tr>
<tr>
<td>Bpeak/Eacc</td>
<td>mT/MV/m</td>
<td>5.78</td>
<td>4.26</td>
</tr>
</tbody>
</table>

**Calculation:**
Assume Q vs. E as measured for BNL-I. Assume 18 MV/m operation. Assume losses scale with surface magnetic field. For comparison with measured results, scale field by the magnetic field ratio of BNL-III to BNL-I, giving 13.3 MV/m. The measured Q for BNL-I at this field is 4E10. Assume losses scale down by the geometry factor, that leads to a Q of 5E10. With this Q at 18 MV/m the cryogenic load is 13 W/cavity at 1.8 K (instead of 37 W/cavity!)
Take SPL type cavity @18 MV/m  (similar to BNL design for eRHIC)

- 1.06 m/cavity => 19.1 MV/cav => 1056 cavities total (=132 x 8)
- Take 8 cavities in a 14 m cryomodule  (cf SPL) => 66 cryomodules/linac

Total length = 924 m/linac + margin ~10%

- Power loss in arcs = 14.35 MW, 13.6 kW/cavity, Take P_{rf} = 20 kW/cavity  with overhead for feedbacks, total installed RF 21 MW.
- No challenge for power couplers, power sources – could be solid state
- However, still need adjacent gallery to house RF equipment (high gradient = radiation !)  4-5 m diameter sufficient

- Synchrotron radiation losses in arcs: Energy difference accelerated and decelerated beam
- Can it be fully compensated by adjusting phases in the linacs, or do we need re-accelerating ‘mini’-linacs? – Needs further study
- Question  Could hardware prototyping be initiated, on SC cavities, - good synergy with SPL Proton driver study which is well underway,  test of ERL concept at CERN ?
ERL configuration

10-GeV linac

comp. RF

1.0 km

2.0 km

tune-up dump

injector

20, 40, 60 GeV

10, 30, 50 GeV

dump

IP

e- final focus

total circumference ~ 8.9 km
ERL component lengths

10-GeV linac length: 1008 m
cavity length 1 m, 56 m long FODO cell with 32 cavities,
#cavities/linac = 576, cavity filling factor = 57.1%
effective arc radius = 1000 m
bending radius = 764 m, dipole filling factor = 76.4% (A. Bogacz)

SRF compensation linac: maximum 84 m [at 60 GeV]
combiners & splitters: 20-30 m each
e- final focus: 200-230 m (R. Tomas)

total circumference = LHC circumference / 3 (D. Schulte)
underground layout / integration with LHC

LHeC area

Point 3

Point 4

CMS

Point 6

Point 7

Point 8

SPS

Atlas

Alice

CNGS
underground layout / integration with LHC
underground layout / integration with LHC
underground layout / integration with LHC

- use of existing Ti2 tunnel
- separate klystron gallery
## IP parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Protons</th>
<th>Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [GeV]</td>
<td>7000</td>
<td>60</td>
</tr>
<tr>
<td>Lorentz factor $\gamma$</td>
<td>7460</td>
<td>117400</td>
</tr>
<tr>
<td>Normalized emittance $\gamma \varepsilon_{x,y}$ [$\mu$m]</td>
<td>3.75</td>
<td>50</td>
</tr>
<tr>
<td>Geometric emittance $\varepsilon_{x,y}$ [nm]</td>
<td>0.50</td>
<td>0.43</td>
</tr>
<tr>
<td>IP beta function $\beta^*_{x,y}$ [m]</td>
<td>0.10</td>
<td>0.12</td>
</tr>
<tr>
<td>RMS IP beam size $\sigma^*_{x,y}$ [$\mu$m]</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>RMS IP divergence $\sigma'_{x,y}$ [$\mu$rad]</td>
<td>70</td>
<td>58</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>$\geq$430</td>
<td>6.6</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>25 or 50</td>
<td>50</td>
</tr>
<tr>
<td>Bunch population</td>
<td>$1.7 \times 10^{11}$</td>
<td>$2 \times 10^9$</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>0.0</td>
<td></td>
</tr>
</tbody>
</table>
beam-beam effects

protons
• head-on tune shift: $\Delta Q = 0.0001$ tiny
• long-range effect: none
  36 $\sigma_p$ separation at $s=3.75$ m
• emittance growth due to e-beam position jitter
  $\rho$ kick 10 nrad ($\sim 10^{-4}\sigma^*$) for $1\sigma$ offset,
  e- turn-to-turn random orbit jitter $\leq 0.04\sigma$
  [scaled from K. Ohmi, PAC’07;
   see also D. Schulte, F. Zimmermann, EPAC2004]

electrons
  can we achieve this stability?
• disruption
  $D_{x,y} \approx 6$, $\theta_0 \approx 600$ $\mu$rad ($\approx 10\sigma^*$) large
ε & optics change during collision

Emittance growth and potential growth from mismatch.

Emittance after collision is at the most 3x initial emittance; emittance growth can be reduced to 15% by rematching extraction optics to β∗~3 cm.
pulsed linac for 140 GeV

- linac could be ILC type (1.3 GHz) or 720 MHz
- cavity gradient: 31.5 MV/m, $Q=10^{10}$
- extendable to higher beam energies
- no energy recovery
- with 10 Hz, 5 ms pulse, $H_g=0.94$, $N_b=1.5\times10^9$:
  $\langle I_e \rangle=0.27$ mA $\rightarrow L\approx4\times10^{31}$ cm$^{-2}$s$^{-1}$
highest-energy LHeC ERL option

high energy e- beam is not bent; could be converted into LC?

High luminosity LHeC with nearly 100% energy efficient ERL. The main high-energy e- beam propagates from left to right. In the 1\textsuperscript{st} linac it gains \(\sim 150\ \text{GeV} \ (N=15)\), collides with the hadron beam and is then decelerated in the second linac. Such ERL could push LHeC luminosity to \(10^{35}\ \text{cm}^{-2}\text{s}^{-1}\) level.

\textit{this looks a lot like CLIC 2-beam technology}

V. Litvinenko,
2\textsuperscript{nd} LHeC workshop
Divonne 2009
summary

ERL (60 GeV):
$10^{33} \text{ cm}^{-2}\text{s}^{-1}$, <100 MW, < 9 km circumference, about 21 GV RF

pulsed linac (140 GeV)
$4 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$, <100 MW, < 9 km length, with $\gamma$-p option

high polarization possible, beam-beam beam benign, $e^+$ difficult
questions to RFTech experts

LHeC ERL: 721 MHz or 1.3 GHz?

Cryo power (heat load at 1.8 K in cw)?

Power to control microphonics?

Linac position jitter?
contributors

many thanks for your attention!