Plans for an ERL Test Facility at CERN

Frank Zimmermann

KEK WG meeting on ERL beam dynamics, Tsukuba, 7 November 2012

many thanks to A. Bogacz, JLAB; M. Klein, U. Liverpool; V. Litvinenko, BNL; O. Brüning, E. Jensen, D. Schulte, A. Valloni, CERN

work supported by the European Commission under the FP7 Research Infrastructures project EuCARD, grant agreement no. 227579
two proposals for ERL-ring lepton-hadron colliders:

• **LHeC based on the LHC at CERN**
  – 7 TeV $p$ or few TeV/nucleon heavy-ion beams
  – adding a 60-GeV ERL with 6.4 mA current

• **eRHIC based on RHIC at BNL**
  – 250 (325) GeV polarized $p$’s (& light ions) and 100 (130)-GeV unpolarized heavy ions
  – adding a 5-30 GeV ERL with 50-220 mA current
Large Hadron electron Collider (LHeC)

LHeC CDR published in

http://cern.ch/lhec

About 150 Experimentalists and Theorists from 50 Institutes

Thanks to all and to CERN, ECFA, NuPECC

~600 pages
Large Hadron electron Collider

RR LHeC: new ring in LHC tunnel, with bypasses around experiments

LR LHeC: recirculating linac with energy recovery

RR LHeC e-/e+ injector 10 GeV, 10 min. filling time
**L-R LHeC road map to \(10^{33} \text{ cm}^{-2}\text{s}^{-1}\)**

**luminosity of LR collider:**

\[
L = \frac{1}{4\pi \varepsilon p} \frac{N_{b,p}}{\beta_p^*} \frac{1}{\beta_p^*}
\]

- **highest proton beam brightness “permitted”** (ultimate LHC values)
  \(\gamma \varepsilon = 3.75 \mu\text{m}\)
  \(N_b = 1.7 \times 10^{11}\)
- **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 \(Nb_3Sn\)
- **\(\beta^*_p = 0.1 \text{ m}\)**
- **average \(e^-\) current limited by energy recovery efficiency** \(I_e = 6.4 \text{ mA}\)
- **maximize geometric overlap factor**
  - head-on collision
  - small \(e^-\) emittance
- **\(\theta_c = 0\)**
- **\(H_{hg} \geq 0.9\)**
- **\(H_D \sim 1.3\)**

D. Schulte
LHeC2010
### LHeC design parameters

#### Electron Beam

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RR</th>
<th>LR</th>
<th>LR*</th>
</tr>
</thead>
<tbody>
<tr>
<td>e- energy at IP[GeV]</td>
<td>60</td>
<td>60</td>
<td>140</td>
</tr>
<tr>
<td>ep luminosity $[10^{32} \text{ cm}^{-2}\text{s}^{-1}]$</td>
<td>8</td>
<td>10</td>
<td>0.4</td>
</tr>
<tr>
<td>eN luminosity $[10^{32} \text{ cm}^{-2}\text{s}^{-1}]$</td>
<td>0.45</td>
<td>1</td>
<td>0.04</td>
</tr>
<tr>
<td>polarization for e- (e+) [%]</td>
<td>40 (40)</td>
<td>90 (0)</td>
<td>90 (0)</td>
</tr>
<tr>
<td>bunch population $[10^9]$</td>
<td>20</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>e- bunch length [mm]</td>
<td>6</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>bunch interval [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>transv. emit. $\gamma \varepsilon_{x,y}$ [mm]</td>
<td>0.59, 0.29</td>
<td>0.05</td>
<td>0.1</td>
</tr>
<tr>
<td>rms IP beam size $\sigma_{x,y}$ [\mu m]</td>
<td>45, 22</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>e- IP beta funct. $\beta_{x,y}^*$ [m]</td>
<td>0.4, 0.2</td>
<td>0.12</td>
<td>0.14</td>
</tr>
<tr>
<td>full crossing angle [mrad]</td>
<td>0.93</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>geometric reduction $H_{hg}$</td>
<td>0.87</td>
<td>0.91</td>
<td>0.94</td>
</tr>
<tr>
<td>disruption enhancement</td>
<td>1.0</td>
<td>1.3</td>
<td>~1.0</td>
</tr>
<tr>
<td>repetition rate [Hz]</td>
<td>N/A</td>
<td>N/A</td>
<td>10</td>
</tr>
<tr>
<td>beam pulse length [ms]</td>
<td>N/A</td>
<td>N/A</td>
<td>5</td>
</tr>
<tr>
<td>ER efficiency</td>
<td>N/A</td>
<td>94%</td>
<td>N/A</td>
</tr>
<tr>
<td>average current [mA]</td>
<td>100</td>
<td>6.4</td>
<td>5.4</td>
</tr>
<tr>
<td>tot. wall plug power[MW]</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

#### Proton Beam

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RR</th>
<th>LR</th>
</tr>
</thead>
<tbody>
<tr>
<td>bunch pop. $[10^{11}]$</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>tr.emit. $\gamma \varepsilon_{x,y}$ [\mu m]</td>
<td>3.75</td>
<td>3.75</td>
</tr>
<tr>
<td>spot size $\sigma_{x,y}$ [\mu m]</td>
<td>30, 16</td>
<td>7</td>
</tr>
<tr>
<td>$\beta_{x,y}^*$ [m]</td>
<td>4.0, 1.0, 0.1</td>
<td></td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

50 ns & $N_b=1.7\times10^{11}$ probably conservative

### Notes

- RR = Ring – Ring
- LR = Linac – Ring

Higher-$L$ design exists

- $\beta^* \sim 0.025$ m possible in IP3 or 7 using ATS optics (S. Fartoukh);
- + also going to 2 \mu m emittance (H. Damerau, W. Herr),
- $\rightarrow L \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ within reach!

*) pulsed, but high energy ERL not impossible
LHeC  ERL layout

two 10-GeV SC linacs, 3-pass up, 3-pass down; 6.4 mA, 60 GeV e⁻'s collide w. LHC protons/ions

(C=1/3 LHC allows for ion clearing gaps)
R&D for LHeC SC linac in synergy with many future projects: ILC, ν factory, p-driven plasma acceleration, and Higgs factory γγ collider

**LHeC-ERL**

**SAPPHiRE**

*Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons*
<table>
<thead>
<tr>
<th>collider parameters</th>
<th>eRHIC (ult.)</th>
<th>LHeC (ult.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>species</td>
<td>$e^-$</td>
<td>$e^\pm$</td>
</tr>
<tr>
<td>b. energy(/nucleon) [GeV]</td>
<td>15 (30) 325, 130</td>
<td>60 7000, 2760</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>bunch intensity(nucl.)[10^9]</td>
<td>24 400, 600</td>
<td>1, 4 170, 25</td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.22 (.01) 3.3, 2.0</td>
<td>0.006 0.58, 0.006</td>
</tr>
<tr>
<td>rms bunch length [mm]</td>
<td>2</td>
<td>49</td>
</tr>
<tr>
<td>polarization [%]</td>
<td>80</td>
<td>70, 0</td>
</tr>
<tr>
<td>norm. rms emittance [μm]</td>
<td>5.8-57</td>
<td>0.2,0.2 CEC</td>
</tr>
<tr>
<td>$\beta_{x,y}$ *[m]</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>$\sigma_{x,y}$ *[μm]</td>
<td>6</td>
<td>6, 8</td>
</tr>
<tr>
<td>beam-beam parameter $\xi_h$</td>
<td>0.015</td>
<td>0.0001</td>
</tr>
<tr>
<td>lepton disruption $D$</td>
<td>52, 22</td>
<td>6</td>
</tr>
<tr>
<td>CM energy [TeV]</td>
<td>140 (197) 88 (125)</td>
<td>1300 810</td>
</tr>
<tr>
<td>lum./nucl.[10^{34}cm^{-2}s^{-1}]</td>
<td>14 (4), 8.2 (2.1)</td>
<td>0.1, 0.02</td>
</tr>
<tr>
<td>(recirculating) SC linac parameters</td>
<td>eRHIC (BNL)</td>
<td>LHeC</td>
</tr>
<tr>
<td>-----------------------------------------------------</td>
<td>-------------</td>
<td>---------------</td>
</tr>
<tr>
<td>#linacs</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>length/linac [km]</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>energy gain / linac [GeV]</td>
<td>2.45</td>
<td><strong>10.0</strong></td>
</tr>
<tr>
<td>#acceleration passes</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>maximum final energy [GeV]</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>real estate gradient [MV/m]</td>
<td>12.45</td>
<td>10.0</td>
</tr>
<tr>
<td>energy gain / cavity [MeV]</td>
<td>20.4</td>
<td><strong>20.8</strong></td>
</tr>
<tr>
<td>cells / cavity ; cavities / linac</td>
<td>5 ; 120</td>
<td>5 ; 480</td>
</tr>
<tr>
<td>RF frequency [MHz]</td>
<td>703.8</td>
<td><strong>721 (or 1300)</strong></td>
</tr>
<tr>
<td>cavity length [m]</td>
<td>1.065</td>
<td>1.04</td>
</tr>
<tr>
<td>R/Q [linac Ω]</td>
<td>506</td>
<td>570</td>
</tr>
<tr>
<td>Q₀ ([10^{10}])</td>
<td>4.0</td>
<td><strong>2.5</strong></td>
</tr>
<tr>
<td>power loss / cavity [W]</td>
<td>23.7</td>
<td>32</td>
</tr>
<tr>
<td>electrical cryopower per linac [MW]</td>
<td>2</td>
<td><strong>10</strong></td>
</tr>
</tbody>
</table>
linac features

LHeC linac 5x longer with 4x the energy gain
(cavity filling factor 0.50 vs 0.64)
eRHIC linac: no focusing

LHeC linac: ~100 quadrupoles
increase multi-pass BBU threshold

LHeC linac quadrupole options:
- electromagnets with indiv. powering
- clustered electromagnets
- permanent magnets

$Q_0$: a key parameter!
SPL/LHeC half cryo module - layout/specs

721.4 MHz RF, 5-cell cavity:
\( \lambda = 41.557 \, \text{cm} \)
\( L_c = \frac{5\lambda}{2} = 103.89 \, \text{cm} \)
grad = 20 MeV/m (20.8 MeV per cavity)
\( \Delta E = 80 \, \text{MV per Half Cryo Module} \)
### LHeC electrical power budget

<table>
<thead>
<tr>
<th>parameter</th>
<th>electrical power [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>total main linac cryopower</td>
<td>21</td>
</tr>
<tr>
<td>RF microphonics control</td>
<td>24</td>
</tr>
<tr>
<td>extra RF for SR losses</td>
<td>23</td>
</tr>
<tr>
<td>extra-RF cryopower</td>
<td>2</td>
</tr>
<tr>
<td>e⁻ injector</td>
<td>6</td>
</tr>
<tr>
<td>arc magnets</td>
<td>3</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>78</strong></td>
</tr>
</tbody>
</table>

**design constraint: total el. power <100 MW**
return arcs: energy loss from synchrotron radiation

$$\rho = 764 \text{ m } (E_{\text{max}} = 60 \text{ GeV}), \Delta E_{\text{tot}} = 2 \text{ GeV}$$

compensation with additional RF systems
750 MV at 60 GeV (721 MHz)
675 MV at lower energy (1.44 GHz)
LHeC: 3 passes, flexible momentum compaction arc lattice building block: 52 m long with 2 (10) dipoles & 4 quadrupoles

LHeC flexible momentum compaction cell; tuned for small beam size (low energy) or low $\Delta \varepsilon$ (high energy)

Limit chamber size (>12 $\sigma$ at 25 mm diameter)

Alex Bogacz
arc magnets

eRHIC dipole model

5 mm gap
max. field 0.43 T (30 GeV)

LHeC dipole model

25 mm gap
max. field 0.264 T (60 GeV)
ERL beam dynamics

• multi-pass beam break up
  – suppressed by cavity HOM damping & detuning
  – further suppression possible using correlated energy spread & arc chromaticity if needed (V. Litvinenko, PRST-AB 15, 074401 (2012))

• ion accumulation & ion instabilities
  – clearing gaps (circumference choice), excellent vacuum in warm ($10^{-9}$ hPa) and cold regions ($10^{-11}$ hPa)

• others: resistive wall, surface roughness, CSR, Touschek effect
beam stability requires both damping \( (Q \approx 10^5) \) & detuning \( (\Delta f/f_{\text{rms}} \approx 0.1\%) \), 720 MHz
scaling 700 MHz $\rightarrow$ 1400 MHz

$n$ cells – $n$ modes!

with $\frac{Z}{L} \propto f^2$ (at same offset!) plus the increased number of cells per cavity at higher $f$:

beam break-up threshold current decreases as $f^{-3}$!
dynamic wall losses

\[ R_s = R_{BCS} + R_{res} \]

for small \( R_{res} \), these clearly favour smaller \( f \)
one should aim for very large $Q_0$

ILC Cavities 1.3 GHz, BCP + EP (R. Geng SRF2009)

BNL 704 MHz test cavity, BCP only! (A. Burill, AP Note 376)

first cavities – large potential

Figure 2: (a) Surface resistance $R_s$ as a function of temperature before and after 1400 °C heat treatment. (b) $Q_0(B_p)$ measured at 2.0 K. The tests were limited by quench.

JLAB, 1.5 GHz, (Dhakal, Ciovati, Myneni 2012: http://arxiv.org/abs/1205.6736)
source $e^-$ beam parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>eRHIC</th>
<th>LHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^-$ / bunch $[10^9]$</td>
<td>5.6, 24</td>
<td>1.1</td>
</tr>
<tr>
<td>charge / bunch [nC]</td>
<td>0.9, 3.8</td>
<td>0.18</td>
</tr>
<tr>
<td>rms bunch length [mm]</td>
<td>2</td>
<td>3-30</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td>average current [mA]</td>
<td><strong>50, 220</strong></td>
<td>7</td>
</tr>
<tr>
<td>bunch peak current [A]</td>
<td>50, 200</td>
<td>7-70</td>
</tr>
<tr>
<td>polarization</td>
<td><strong>85-90%, none</strong></td>
<td>&gt;90%</td>
</tr>
</tbody>
</table>
eRHIC polarized electron gun - candidates

large-sized GaAs cathode gun

Gatling gun, combing beams from an array of 24 GaAs cathodes

Evgeni Tsentalovich

Vladimir Litvinenko
LHeC R&D items & possible time line

SC IR final “half quadrupole”; IR beam pipe;
RF cryostat including cavity & coupler;
dedicated LHeC ERL test facility; proto collaboration for detector

SR IR half quad model;
IR beam pipe prototype;
ERL TF design

2012

2014

final RF cryostat prototype

2016

TF construction

2018

TF beam measurements
decision to go ahead

LHeC construction

Start of operation

2022

2024

2026

2028

2030
ERL Test Facility at CERN

- ERL demonstrator, FEL, $\gamma$-ray source, e-cooling demo
- one of the 1$^{st}$ low-frequency multi-pass SC-ERLs
- e-cooling (@PS/SPS energies)
- ultra-short electron bunches
- strong synergy with SPL-ESS & BNL activities
- high energies & CW (100 – 400 MeV) & CW
- multi-cavity cryomodule layout - validation + gymnastics
- MW class power coupler tests in non-ER mode (vector feedback?)
- complete HOM characterization and instability studies
- cryogenics & instrumentation test bed
- a place to work, to practice and to train people
ERL-Test Facility (TF) at CERN

200-400 MeV ERL Layout
4 x 5 cell, 721 MHz

<table>
<thead>
<tr>
<th></th>
<th>units</th>
<th>1-CM</th>
<th>2-CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [MeV]</td>
<td></td>
<td>100</td>
<td>200-400</td>
</tr>
<tr>
<td>Frequency [MHz]</td>
<td></td>
<td>721</td>
<td>721</td>
</tr>
<tr>
<td>Charge [pC]</td>
<td></td>
<td>~500</td>
<td>~500</td>
</tr>
<tr>
<td>Rep. rate</td>
<td></td>
<td>CW</td>
<td>CW</td>
</tr>
</tbody>
</table>

~6.5 m

Rama Calaga
LINAC:
Half Cryo Module → 4 Cavities
721.44 MHz RF, 5-cell cavity:
λ = 41.557 cm
Lc = 5l/2 = 103.89 cm
Grad = 18 MeV/m (18.7 MeV per cavity)
ΔE= 74.8 MV per Half Cryo Module

ARC 1 OPTICS:
4 x 45° sector bends
Dipole + Quads triplet + Dipole + Quad singlet + Dipole + Quads triplet + Dipole
Dipole Length = 40 cm  B = 5.01 kG
Quadrupole Length = 10 cm
Q1 -> G[kG/cm] = -0.31  Q3 -> G[kG/cm] = -0.34
Q2 -> G[kG/cm] = 0.50  Q4 -> G[kG/cm] = -0.44

VERTICAL SPREADER OPTICS:
Spreader for Arc 1 @ 80 MeV
2 Vertical steps (dipoles with opposite polarity) and quads triplet
for hor. and vert. focusing
Spreader for Arc 3 @ 230 MeV
A vertical chicane plus and 2 quads doublets
ARC 1 + VERTICAL SPREADER AND COMBINER OPTICS

150-300 MeV ERL Layout
4 x 5 cell, 721 MHz

SCL1
5 MeV Injector

SCL2
Dump

~6.5 m

2-step vert. Spreader
Arc 1 optics
2-step vert. Recombiner

Alessandra Valloni
CERN oPAC fellow Alessandra Valloni – just started near-term work plan:

• getting comfortable with OptiM code (JLAB, FNAL)

• writing OptiM input files for ERL-TF in order to reproduce Alex Bogacz’s results for ERL-TF

• doing/understanding calculations on adverse effects in the arc optics design (cumulative emittance and momentum-spread growth due to synchrotron radiation, wake fields, ions, CSR, etc.)

• trying to understand all the beam dynamics challenges for the LHeC ERL in order to figure out parameters for the TF
ERL-TF (300 MeV) – Layout

Two passes ‘up’ + Two passes ‘down’
ERL-TF (300 MeV) – Layout

Two passes ‘up’ + Two passes ‘down’
Linac 1 – Multi-pass Optics

Arc 1

5 MeV

Arc 2

155 GeV

Arc 3

230 MeV
Linac 1 & 2 - Multi-pass ER Optics

Linac 1

Linac 2

Alex Bogacz  ERL-TF at CERN Mtg, Jefferson Lab, August 21, 2012
Arc 1 Optics – FMC Lattice

80 MeV

4×45° sector bends

$Q_{x,y} = 1.25$

triplet: Q1 Q2 Q3

singlet: Q4

triplet: Q3 Q2 Q1

**dipoles** (40 cm long)
B = 5.01 kGauss

**quadrupoles** (10 cm long)
Q1  G[kG/cm] = -0.31
Q2  G[kG/cm] = 0.50
Q3  G[kG/cm] = -0.34
Q4  G[kG/cm] = -0.44

Alex Bogacz  ERL-TF at CERN Mtg, Jefferson Lab, August 21, 2012
Arc 1 Optics – Isochronous Lattice

Synchronous acceleration in the linacs ⇒ Isochronous optics:

\[ M_{56} = I_1 = \int_0^L \frac{D}{\rho} ds \]

\[ I_1 = 0 \]
230 MeV

8×22.5° sector bends

\(Q_{x,y} = 1.25\)

dipoles (40 cm long)

\[B = 7.47 \text{ kGauss}\]

quadrupoles (15 cm long)

\begin{align*}
Q_1 & \quad G[\text{kG/cm}] = -0.47 \\
Q_2 & \quad G[\text{kG/cm}] = 1.43 \\
Q_3 & \quad G[\text{kG/cm}] = -1.14 \\
Q_4 & \quad G[\text{kG/cm}] = -0.34
\end{align*}
Switchyard - Vertical Separation of Arcs

Arc 1 (80 MeV)
Arc 3 (230 MeV)
Vertical Spreaders - Optics

Spr. 1

Spr. 3

vertical step I

vertical step II

vertical chicane

Alex Bogacz       ERL-TF at CERN Mtg, Jefferson Lab, August 21, 2012
Arc 1 Optics (80 MeV)

Isochronous Arc

2-step vert. Spreader

Spr. dipoles:
- 30° bends (1 rec. + 3 sec.)
- \( L_b = 30 \text{ cm} \)
- \( B = 5 \text{ kGauss} \)

Arc dipoles:
- 4×45° bends (sec.)
- \( L_b = 40 \text{ cm} \)
- \( B = 5 \text{ kGauss} \)

Rec. dipoles:
- 30° bends (3 sec. + 1 rec.)
- \( L_b = 30 \text{ cm} \)
- \( B = 5 \text{ kGauss} \)

quads:
- \( L_q = 10-15 \text{ cm} \)
- \( G \leq 0.6 \text{ kGauss/cm} \)

‘Arc 2’ = 2 × ‘Arc 1’

2-step vert. Recombiner

Alex Bogacz  ERL-TF at CERN Mtg, Jefferson Lab, August 21, 2012
Arc 3 Optics (230 MeV)

Spr. dipoles:
10° - 20° - 10° bends (rec.)
Lb = 30 cm
B = 5-10 kGauss

Arc dipoles:
8×22.5° bends (sec.)
Lb = 40 cm
B = 5 kGauss

Rec. dipoles:
10° - 20° - 10° bends (rec.)
Lb = 30 cm
B = 5-10 kGauss

quads: Lq = 10-15 cm        G ≤ 1.2 kGauss/cm

Alex Bogacz         ERL-TF at CERN Mtg, Jefferson Lab, August 21, 2012
ERL-TF Complete Lattice Design

Two passes ‘up’ + Two passes ‘down’
CERN ERL test facility design status

- ERL-TF at CERN
  - ‘Test bed’ for SRF cavities at high current

- Multi-pass linac Optics in ER mode
  - Choice of linac RF – 721 MHz SRF
  - Linear lattice: 2-pass ‘up’ + 2-pass ‘down’

- Arc Optics Choice
  - Synchronous acceleration → Isochronous arcs
  - Flexible Momentum Compaction Optics

- Complete Arc Architecture
  - Vertical switchyard
  - Matching sections: Linac-Switchyard-Arc

- ‘First cut’ Lattice design for ERL-TF
  - Two Linacs + Four Arcs
ERL-TF: HOM Measurements

Complete characterization of HOMs
Benchmark simulations
Improved damping schemes

Precision orbit measurement
Cavity & CM alignment

Erk Jensen
### ERL-TF: RF Power

→ **5 MeV injector** → $P_{\text{beam}} \sim 50$ kW (10 mA)
  
  higher power if we go to 100 mA

→ **Main LINAC**
  
  (0 beam loading)

<table>
<thead>
<tr>
<th>$Q$</th>
<th>$P_{\text{beam}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \times 10^6$</td>
<td>250 kW</td>
</tr>
<tr>
<td>$5 \times 10^6$</td>
<td>50 kW</td>
</tr>
<tr>
<td>$1 \times 10^7$</td>
<td>25 kW</td>
</tr>
</tbody>
</table>

![Peak detuning](image)

$P_g = \frac{V^2}{R/Q} \cdot \frac{\Delta f}{f}$  

$Q_{\text{opt}} = \frac{1}{2} \cdot \frac{f}{\Delta f}$

commercial television

IOT @700 MHz

reach steady state with increasing beam current

Erk Jensen
RF Power

use of IOTs ~ 50-100 kW at 700 MHz
high efficiency, low cost
amplitude and phase stability

50 kW TV Amplifier, BNL, at 700 MHz

Erk Jensen
we can use SPL like cryo distribution system

V. Parma, Design review of short cryomodule

Erk Jensen
RF Controls

development of digital LLRF system (Cornell type ?) ;
amplitude and phase stability at high $Q_0 \sim 1 \times 10^8$
reliable operation with high beam currents + piezo tuners ;
failure scenarios: cavity trips, arcs etc.

Rms amplitude stability

9-cell cavities at HoBiCaT, Liepe et al.

Erk Jensen
RF Failures

Slow failures (for example: power cut)

\[ Q_{\text{ext}} \text{ is very high } \rightarrow \text{ perhaps need to do nothing} \]

Fast failures (coupler arc)

If single cavity \rightarrow\text{ additional RF power may be ok}
Reduce beam currents or cavity gradients gradually

If entire LINAC \rightarrow\text{ lots of RF power}
Perhaps play with 2-LINAC configuration
for safe extraction of high energy beam

Erk Jensen
Timeline & Costs

If SPL R&D CM can be used,
then very fast turn-around (cheap option),
else 3-4 years of engineering & development
(SRF + beam line).
The costs should be directly derived from SPL CM
construction (< 5 MCHF ?)
Do we need high power couplers ?
R&D of HOM couplers needed for probing
high current & CW

*Key question:* where to place the ERL-TF to
have maximum flexibility ?
could the LHeC TF later become the LHeC ERL injector ERL?

Rama Calaga & Erk Jensen
it might be nice to also have some ERL collaboration with KEK
near term plan

CERN-CI-JLAB meeting at Daresbury end of January/early February 2013

topics:
• collaboration planning
• use of CI ALICE ERL for initial studies?
• choice of frequency 721 MHz or 1.3 GHz
thank you for your attention!

for more details:

- LHeC web site [http://cern.ch/lhec](http://cern.ch/lhec)
- eRHIC web site [http://www.bnl.gov/cad/eRhic](http://www.bnl.gov/cad/eRhic)
- ICFA Beam Dynamics Newsletter No. 58, special issue on future electron-hadron colliders, August 2012
back-up slides
OptiM

- Computer code for linear and non-linear optics calculations

- Code developed by V. Lebedev; used a JLAB and FNAL

- OptiM assists with linear optics design of particle accelerators (calculations are based on 6x6 transfer matrices), but it is also quite proficient with non-linear optics, tracking and with linear effects due to space charge

- It computes the dispersion and betatron functions (for both uncoupled and X-Y coupled particle motions), as well as the beam sizes, the betatron phase advances, etc. The values can be plotted or printed along machine circumference or computed at the end of lattice or at any element

- It can also fit parameters of accelerator elements to get required optics functions

- It offers a wide choice of elements that allows designing both circular and linear accelerators, along with recirculators

- It can perform computations not only at the reference orbit but also at a closed orbit excited by machine errors, correctors or energy offset. In this case the program first finds a new "reference" orbit then expands nonlinear terms for machine elements and then performs computations. One can then perform both linear optics computations and non-linear tracking relative to this new orbit