Abstract:
The future Electron Ion Collider (EIC) LHeC, FCCeh and eRHIC will be able to collide electrons with protons/ions. Electron acceleration is based on a concept of Energy Recovery Linacs (ERL) with maximum energies of 60 GeV for LHeC, 905 MeV for PERLE (Powerful Energy Recovery Linac for Experiments), and of 18 GeV for eRHIC. The electron energy will be almost completely recovered during deceleration.

We are presenting a single loop arc design for PERLE with two options: one is very similar to the CBETA (Cornell BNL ERL test accelerator) with spreaders and combiners, and one is without the spreaders and combiners. We present two examples of the LHeC design with double reduction in size of the linacs and thus reducing the overall cost of the machine. The previously proposed two 10 GeV linacs design is reduced to the two 5 GeV linacs (or two 4.425 GeV linacs) using a smaller loop with the maximum energy of $E_{\text{max}}=5$ GeV and an additional loop with the fixed field magnets assuming a radius of $R_0=1000$ m. This solution would reduce the previous three large beam lines to a single one with additional 5 (or 4.275) GeV smaller loop. The larger luminosity comes from the larger electron current for the same amount of 15 MW of the synchrotron radiation (previously set limit), as the maximum energy in the arcs is $E_{\text{max}}=55$ GeV instead of the previous $E_{\text{max}}=60$ GeV. For the LHeC fixed field magnet solution with 2x5 (or 4.275) GeV linacs the total synchrotron radiation loss for 25 mA is 11.1 MW.
OUTLINES

Introduction: large momentum acceptance fixed field beam lines

A new concept: fixed field beam line adiabatically matched with the linac

From CBETA to PERLE, LHeC and eRHIC

SUMMARY: The present design of the LHeC linacs size is reduced to a half and the six beam lines are replaced by a single beam line producing larger luminosity.
Introduction

A concept of Fixed Field Large Energy Acceptance Lattice

- Orbits in fixed field cells
- Tunes vs. energy
- Path Length vs. energy

Why are we confident of success:
- 3D OPERA fields tracking
- ATF experiment
- High quality Halbach magnets

Adiabatic matching to the ERL Linac
To minimize the dispersion function $H$ the BENDING MAGNET (DEFOCUSING) should be in the centered in the cell with a minimum of $\beta_{\text{xmin}} = L_d/2\sqrt{15}$ and $D_{\text{xmin}} = \theta*L_d/24$ @center.

“Fixed Field Alternating Gradient Lattice Without Opposite Bends”
Dejan Trbojevic*, Ernest D. Courant* and Al Garren
Presented in September 1999
CP530, “Colliders and Collider Physics at the Highest Energies: HEMC'99 Workshop”, edited by B. J. King

Dejan Trbojevic, LHeC/FCCeH and PERLE Workshop, June 27-29, 2018, LAL-Orsay
EMMA: the first linear fixed field accelerator with a large energy range

Electron Model for Many Applications

Daresbury Laboratory

LEARNING FROM PREVIOUS EXPERIENCE FROM First working Linear Large Momentum Acceptance Fixed Field Accelerator "EMMA"

ELECTRON ENERGY RANGE IN EMMA WAS BUILT TO SIMULATE MUON ACCELERATION 10–20 GeV

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Novelties in CBETA

From: Stephen Books
Properties of the linear fixed field large energy acceptance lattice for the CBETA project
Adiabatic transition from the arc to the straight with expanding the transition cell lengths
The Proton Gantry Design is based on few other examples

Merging of the orbits at the CBETA project
Revisiting the S4 splitter line

The momentum compaction $\alpha$

$$\alpha = \frac{1}{C_0} \int \frac{D(s)}{\rho(s)} ds$$
Start-to-End tracking

100 pC bunch calculated from GPT with space charge

\[ \beta_y \times 1000 \]
\[ \beta_x \times 1000 \]
\[ x(\text{mm}) \]
\[ y(\text{mm}) \]
\[ \text{Arrival time (ps)} \]

...spliced into Bmad 4-pass model

\[ \alpha, \sigma_y (\mu\text{m}) \]

Bunch sizes x (mm)

\[ s(\text{m}) \]

GPT - S.B. van der Geer
GENERAL PARTICLE TRACER: A 3D CODE FOR ACCELERATOR AND BEAM LINE DESIGN

Bmad – David Sagan
Chris Mayes results

http://www.lepp.cornell.edu/~dcs/bmad
Orbits in the CBETA Arc Cell (5 degrees)
CBETA measured tunes dependence on energy in the partial arc test May 2018

The graph shows the tunes $\nu_x$ and $\nu_y$ as a function of energy $E$ (in MeV) for CBETA. The data points represent measured values, with error bars indicating the uncertainty. The solid lines are fits to the data using the BMAD model.
Path length and time of flight in the CBETA arc cell as a function of energy.
Arc Cells Obtained from the 3D OPERA fields

Francois Meot’s results by using the ZGOUBI program with the OPERA 3D fields makes the doublet cell and presents the vertical magnetic field dependence on ‘s’.

Two effects: The field non-linearities intrinsic to the OPERA model and kinematic non-linearities which are present to high order due to the stepwise ray-tracing method.
NEW WAY TO MAKE COMBINED FUNCTION MAGNET

From:

STEPHEN BROOKS
Production of the Halbach magnets
First CBETA Girder with 4 Cells
Quality of the Halbach magnets

Table 1.9.9.3: Field harmonics from ERHIC-PMQ_0303_0002_001 at \( R=10 \text{mm} \). The nominal magnet length is 61.8597 mm and the average field corresponds to \(-19.1007 \text{ T/m}\).

<table>
<thead>
<tr>
<th>Field harmonic</th>
<th>Normal units</th>
<th>Skew units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>-19726.36</td>
<td>0.00</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>10000.00</td>
<td>-0.00</td>
</tr>
<tr>
<td>Sextupole</td>
<td>-1.62</td>
<td>1.35</td>
</tr>
<tr>
<td>Octupole</td>
<td>-2.50</td>
<td>0.85</td>
</tr>
<tr>
<td>Decapole</td>
<td>1.13</td>
<td>-0.56</td>
</tr>
<tr>
<td>Dodecapole</td>
<td>-0.05</td>
<td>0.22</td>
</tr>
<tr>
<td>14-pole</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>16-pole</td>
<td>0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>18-pole</td>
<td>-0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>20-pole</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>22-pole</td>
<td>0.00</td>
<td>-0.01</td>
</tr>
<tr>
<td>24-pole</td>
<td>-0.00</td>
<td>-0.00</td>
</tr>
<tr>
<td>26-pole</td>
<td>-0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>28-pole</td>
<td>0.00</td>
<td>-0.00</td>
</tr>
<tr>
<td>30-pole</td>
<td>-0.00</td>
<td>-0.00</td>
</tr>
</tbody>
</table>
The Fixed Field Alternating Gradient Experiment with bending 40° already tested at BNL

Electron energies in the experiment: 18, 24, 36, 54, and 72 MeV

Electron $p_{\text{max}} = 18 \text{ MeV} / c\quad \frac{p}{p} = 60\%$

Electron $p_{\text{cent}} = 45 \text{ MeV} / c$

Electron $p_{\text{min}} = 72 \text{ MeV} / c\quad \frac{p}{p} = +60\%$
The ATF experiment with 12 CBETA Halbach magnet
We are presenting for the first time an example of a novel approach in using the Fixed Field single beam line with large energy acceptance connected by an adiabatic transition to the ERL linac:

• This allows additional passes through the linac, this reduces the size of the linac
• Eliminates spreaders and combiners
• Simplifies the operation
• Significantly reduces the overall cost of the whole project
An example of the linear fixed field arcs adiabatically matched to the linac.
Lattice properties of the few arc cells

3.6 GeV
2.7 GeV
1.8 GeV
0.9 GeV

Triplet cells
Lattice properties of the single arc cell
Adiabatic transition of the Fixed Field racetrack

[Graph showing orbit, beta, and eta as functions of s (m)]

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Details of the adiabatic transition

Transition Cells

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The adiabatic transition towards the straight section
Details of the matched straight section
A detail part of the straight section
Few examples of the Fixed Field racetrack with linac
Few examples of the NS-Fixed Field racetrack with linac

Straight Section combined with the linac
(small Halbach Magnets with shielding iron around)

A report from RADIABEAM [WEPE077 IPAC 10 Kyoto Japan]

..“Praseodymium - Halbach magnets can operate at lower temperature than Nd-magnets and exhibit greater radiation hardness... Praseodymium cooled to 30 K exhibits a remnant field of 1.7 T and coercivity of 72 kOe.
Advantages of the Fixed Field Large momentum lattice:

• For multiturn ERL’s there is no other option but to use the fixed field magnets as with the present technologies it is impossible to change the magnetic field in a very short time (ns)

• With the exception of CBETA all ERL’s use multiple beam lines with the fixed magnetic field to bring the beam back to linacs.

• The **fixed field large momentum acceptance beam lines** show multiple advantages in the multiple pass ERL’s:
  – Multiple beam lines are replaced with a single one
  – Electron beam polarization is preserved
  – Operation is simplified
An Energy Recovery Linac (ERL) named as “Powerful Energy Recovery Linac for Experiments (PERLE) with a maximum energy of 905 MeV using two 150 MeV superconducting linacs is designed for Orsay.

The present ERL - PERLE design is a race track with two linacs on the opposite sides, connected by the three beam lines in each arc. Total of six passes through two linacs occur, three during acceleration and three in energy recovery, respectively.

We present an alternative ERL – PERLE design where the three separate arc beam lines (total of six arcs) are replace with a single large energy acceptance Fixed Field arcs.
“PERLE” Present Design

Figure 10. The facility is designed in a modular way. This picture shows a Step 1 layout of two parallel cryomodules to achieve $\sim 75$ MeV acceleration per linac and a final beam energy of 155 MeV (or half of it with just one initial cryomodule).

Figure 11. A second phase with recirculation could feature three-pass operation to reach 455 MeV.

Table 2. Basic Parameters of PERLE.

<table>
<thead>
<tr>
<th>Target parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection energy (MeV)</td>
<td>5–10</td>
</tr>
<tr>
<td>Maximum energy (GeV)</td>
<td>1</td>
</tr>
<tr>
<td>Normalised emittance $\gamma\varepsilon_{x,y}$ (mm mrad)</td>
<td>6</td>
</tr>
<tr>
<td>Average beam current (mA)</td>
<td>15</td>
</tr>
<tr>
<td>Bunch spacing (ns)</td>
<td>25</td>
</tr>
<tr>
<td>Bunch length (rms) (mm)</td>
<td>3</td>
</tr>
<tr>
<td>RF frequency (MHz)</td>
<td>801.58</td>
</tr>
<tr>
<td>Duty factor</td>
<td>CW</td>
</tr>
</tbody>
</table>
Figure 30. Cavity design (single-die, iris ID = tube ID) 801.58 MHz (top); axial field on axis (bottom).
Figure 35. Cavity, coupler and end can detail view.
Fixed Field Arc for PERLE – similar to CBETA

Linac 150 MeV

NS-FF #1
155 MeV
455 MeV
755 MeV

NS-FF #2
305 MeV
605 MeV
905 MeV

5 MeV Injector

16.00

44.6 m

8.0 8.0 12.6 m 8.0 8.0
Fixed Field Arc for PERLE – A solution similar to CBETA
A single right side arc covering the energy range between 155-755 MeV with the betatron and dispersion functions for all three energies.

Orbit Offsets and Lattice functions for the single right side arc cell.
Fixed Field Arc for PERLE 305-905 MeV—similar to CBETA

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Fixed Field single arcs for PERLE – new proposal as previously described with the triplet magnets between the 5 RF cell units
From Oliver Brüning

Layout of the LHeC-LHC-SPS
The baseline 60 GeV ERL option proposed can give an e-p luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$ (extensions to $10^{34}$ cm$^{-2}$s$^{-1}$ and beyond are being considered)
High Energy eRHIC NS-FF Cell

Synchrotron Radiation:
for 10 mA 20 GeV 3.32 MW
for 10 mA 15 GeV 1.62 MW
for 10 mA 16.67 GeV 1.95 MW

\[
B_{D} = B_{D0} + G_{D} \cdot x
\]
\[
\rho_{D} = 300.01 \text{ m}
\]
\[
\theta_{D} = 3.366 \text{ mrad}
\]

\[
B_{F} = B_{F0} + G_{F} \cdot x
\]
\[
\rho_{F} = 302.3 \text{ m}
\]
\[
\theta_{F} = 3.927 \text{ mrad}
\]

\[x_{\text{Doffset}} = +5.26 \text{ mm}\]
\[x_{\text{Foffset}} = -5.26 \text{ mm}\]

20 cm
\[
B_{D\text{max, min}} = [0.443, 0.046] \text{ T}
\]
\[
B_{D\text{max, min}} = [0.446, -0.225] \text{ T}
\]

20 cm
\[
E_{\text{cen}} = 16.198 \text{ GeV}
\]

1.3

12.96

11.8

6.54

-5.26

6.6

5.26

20 cm

20 cm

L = 2.797 m

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Built and successfully tested Halbach type of magnet with a horizontal gap for the eRHIC ERL type of solution
Fixed Field LHeC Recirculator with ER

Acceleration:
15 GeV
25
35
45
55

Recovery:
55 GeV
45
35
25
15

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NS-FF LHeC/FCCeh Recirculator with ER

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NS-FF LHeC Recirculator with ER

LHC

Linac 1
4.275 GeV

IP
60 GeV

Linac 2
4.275 GeV

Injector 150 MeV

8.7 GeV

Dump 200 MeV

4.425 GeV

Acceleration
12.975 GeV
21.525
30.075
38.625
47.175
55.725

Recovery
56.25 GeV
48.75
41.25
33.75
26.25
18.75
11.25

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### Synchrotron Radiation in LHeC with 2 x 5 GeV linacs

Maximum Collision Energy 60 GeV

<table>
<thead>
<tr>
<th>E(GeV)</th>
<th>Total Power (MW) 8.87 mA</th>
<th>Total Power (MW) 6.6 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>7.5779</td>
<td>5.6383</td>
</tr>
<tr>
<td>40</td>
<td>4.2080</td>
<td>3.1310</td>
</tr>
<tr>
<td>30</td>
<td>1.3902</td>
<td>1.0344</td>
</tr>
<tr>
<td>20</td>
<td>1.2881</td>
<td>0.9584</td>
</tr>
<tr>
<td>10</td>
<td>0.5359</td>
<td>0.3987</td>
</tr>
<tr>
<td>TOTAL</td>
<td><strong>15.000</strong></td>
<td><strong>11.1608</strong></td>
</tr>
</tbody>
</table>
The eRHIC ERL previous solution

Major Technical Components:

1. Funneling Gun
2. ERL mergers
3. Superconducting Linac - ERL
4. Spreaders and Combiners
5. NS-FF arcs
6. Merging arcs to straight section
7. Straight section
8. Extracted high energy beam
9. Detector By Passes

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Merging Fixed Field linear arcs to the straight section in eRHIC
eRHIC Fixed Field Orbits Magnified x1000

© Stephen Brooks
Linac 1.0 GeV
#1  5 GeV
#2  6 GeV
#3  7 GeV
#4  8 GeV
#5  9 GeV
#6  10 GeV
#7  11 GeV
#8  12 GeV
#9  13 GeV
#10 14 GeV
#11 15 GeV
#12 16 GeV
#13 17 GeV
#14 18 GeV

**eRHIC Layout**

5 – 18 GeV

**1 GeV LINAC**

18 passes through the Linac

X 3.7

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CONCLUSION

- Two lattice solutions are proposed for the PERLE design with a single arc line.

- A new LHeC proposal replaces the 2 x 10 GeV linacs and three arcs, with 2 x 5 GeV linacs and two fixed field 3.7 times energy acceptance arcs. This is a cost-effective solution. It reduces the synchrotron radiation in arcs, hence provides 35% larger luminosity for the same limit on the value of 15 MW for the total loss from synchrotron radiation.
Back up slides
Time of flight adjustments
Time of flight adjustments
Time of flight adjustments
Time of flight adjustments

maxorder = 5
Error seed = 0

5 MeV
\( t = 1.275161086 \times 10^{-05} \)
\( n = 1.579 \)
\( \text{calctime} = 0.00130846 \)
\( \text{Qx} = 0.34472196 \)

8.45 MeV
\( t = 1.275161086 \times 10^{-05} \)
\( n = 1.579 \)
\( \text{calctime} = 0.00130846 \)
\( \text{Qx} = 0.34472196 \)

10.9 MeV
\( t = 1.275161086 \times 10^{-05} \)
\( n = 1.579 \)
\( \text{calctime} = 0.00130846 \)
\( \text{Qx} = 0.34472196 \)

11.75 MeV
\( t = 1.275161086 \times 10^{-05} \)
\( n = 1.579 \)
\( \text{calctime} = 0.00130846 \)
\( \text{Qx} = 0.34472196 \)

15 MeV
\( t = 1.275161086 \times 10^{-05} \)
\( n = 1.579 \)
\( \text{calctime} = 0.00130846 \)
\( \text{Qx} = 0.34472196 \)

16.95 MeV
\( t = 1.275161086 \times 10^{-05} \)
\( n = 1.579 \)
\( \text{calctime} = 0.00130846 \)
\( \text{Qx} = 0.34472196 \)

18.55 MeV
\( t = 1.275161086 \times 10^{-05} \)
\( n = 1.579 \)
\( \text{calctime} = 0.00130846 \)
\( \text{Qx} = 0.34472196 \)

20 MeV
\( t = 1.275161086 \times 10^{-05} \)
\( n = 1.579 \)
\( \text{calctime} = 0.00130846 \)
\( \text{Qx} = 0.34472196 \)
Electrons with energies of 42, 78, 114, and 150 MeV arrive from the linac through the common dipole and are split to the four splitter beam lines. They are merged from the splitter to the Non-Scaling Fixed Field Alternating Gradient arc cells. The major splitters' roles are:

- To optically match the linac beam to the transfer line and to the fixed field arc cells.
- To provide accurate time of flight so the electron beam returns to the linac at a correct time during acceleration and for the 150 MeV beam to arrive with $l/2$ to the negative RF voltage to start the energy recovery process.
- It is very important to adjust the $M_{56}$ matrix element for the longitudinal deviations as $-d_s = M_{56} * (-d_s)^2$ or $-d_L/d_p = M_{56}$.

**CBETA SPLITTERS' OPTICS**

The Chicane: to provide the path length adjustment as well as the $M_{56}$ path length and time of flight in the arc cell as a function of energy.