CERN

Alessandra Valloni on behalf of the LHeC collaboration

POETIC IV workshop

Overview of the LHeC Design Study at CERN

Jyväskylä, 2nd-5th September

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The LHeC participating institutes

LHeC

CERN

CLIC

KEK-JAPAN

The Cockcroft Institute
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EPFL
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

SLAC
NATIONAL ACCELERATOR LABORATORY

UNIVERSITY OF
LIVERPOOL

NTNU
Norwegian University of
Science and Technology

DESY

ECFA

Jefferson Lab

BROOKHAVEN
NATIONAL LABORATORY

ANKARA UNIVERSITY

TOBB
UNIVERSITY OF
ECONOMICS AND TECHNOLOGY

ULUDAĞ ÜNİVERSİTESİ 1975

NİĞDE ÜNİVERSİTESİ 1992

INFN
Istituto Nazionale
di Fisica Nucleare

LAL
LABORATOIRE
DE L'ACCÉLÉRATEUR
LINÉAIRE

CORNELL UNIVERSITY
FOUNDED A.D. 1865

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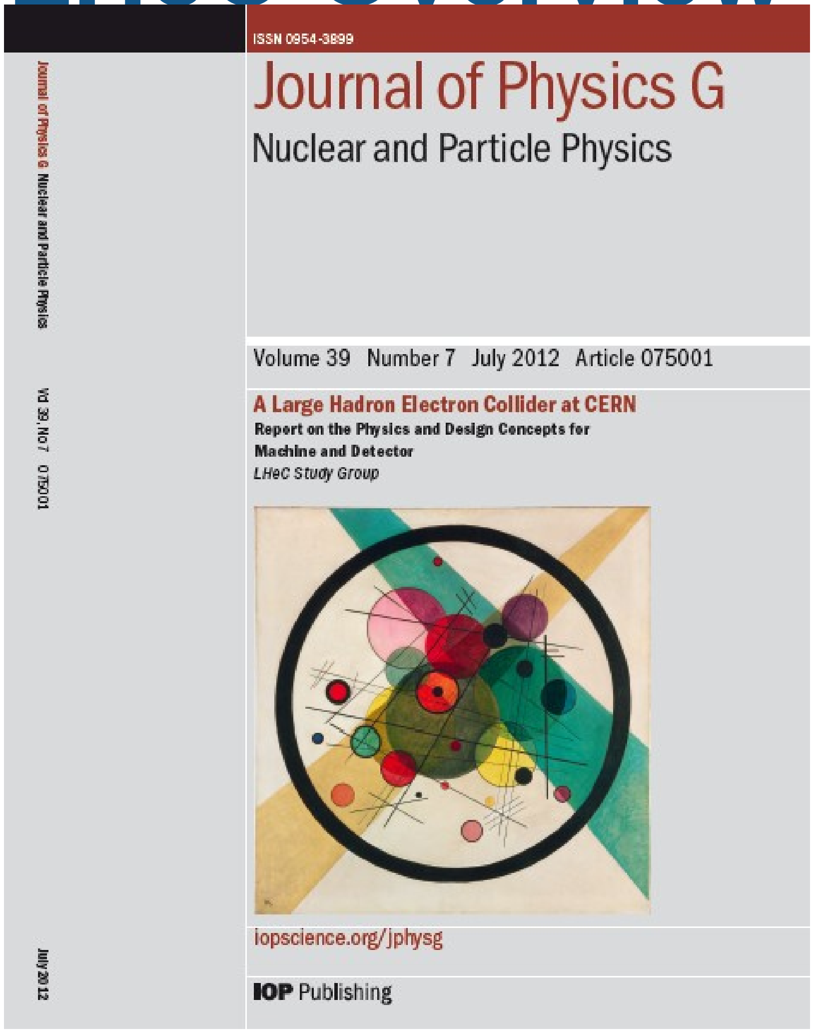
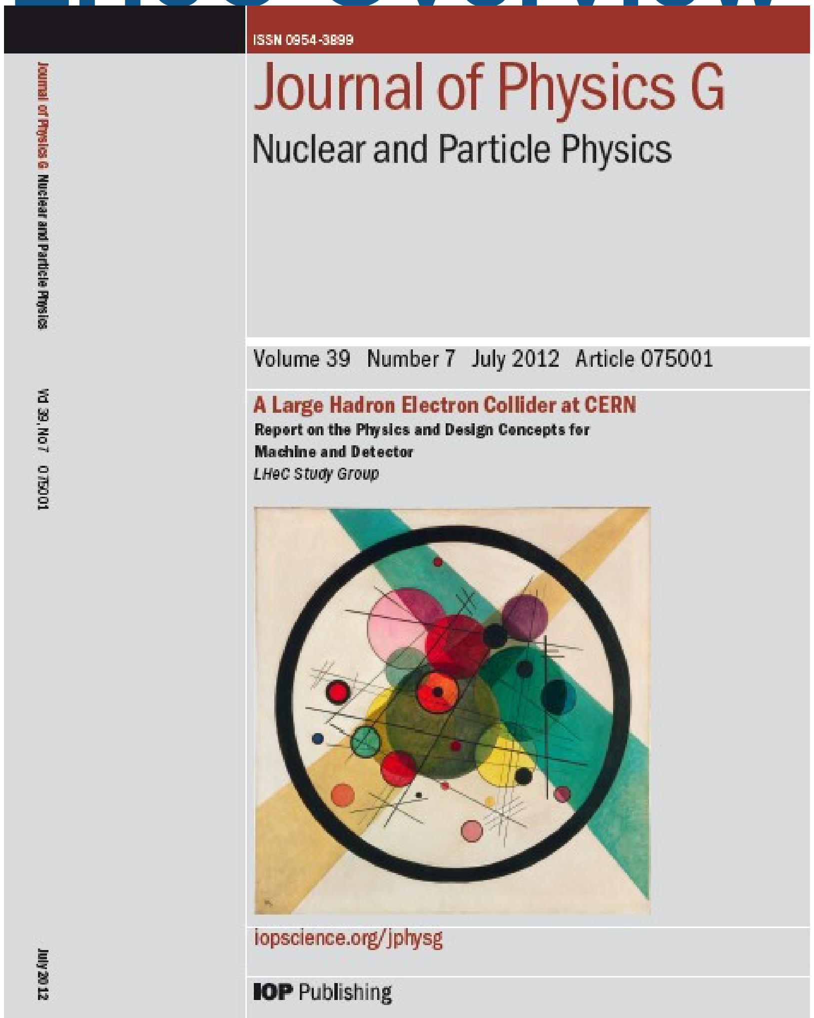
LHeC Overview



1. introduction
2. Physics
3. accelerator
4. Detector
5. Conclusions

LHeC Overview



1. **introduction**

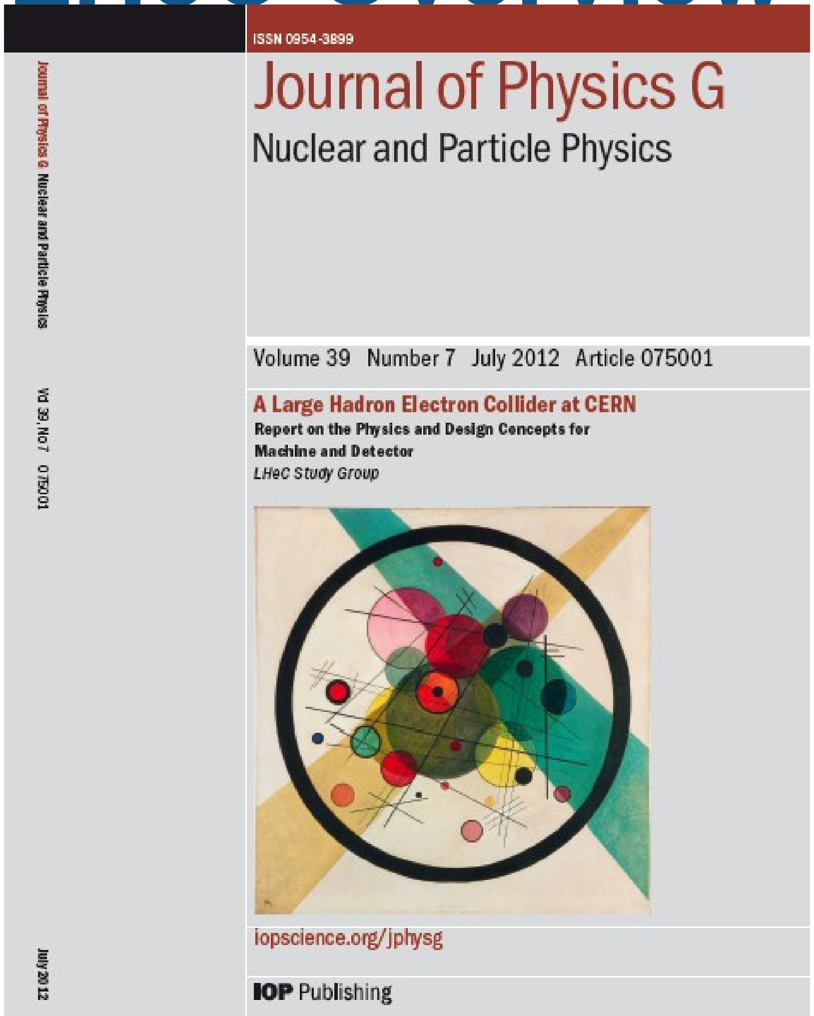
2. **Physics**
   - Precision QCD and Electroweak Physics
   - Physics at High Parton Densities
   - New Physics at high energy

3. **Accelerator**

4. **Detector**

5. **Conclusions**

LHeC Overview



1. **introduction**

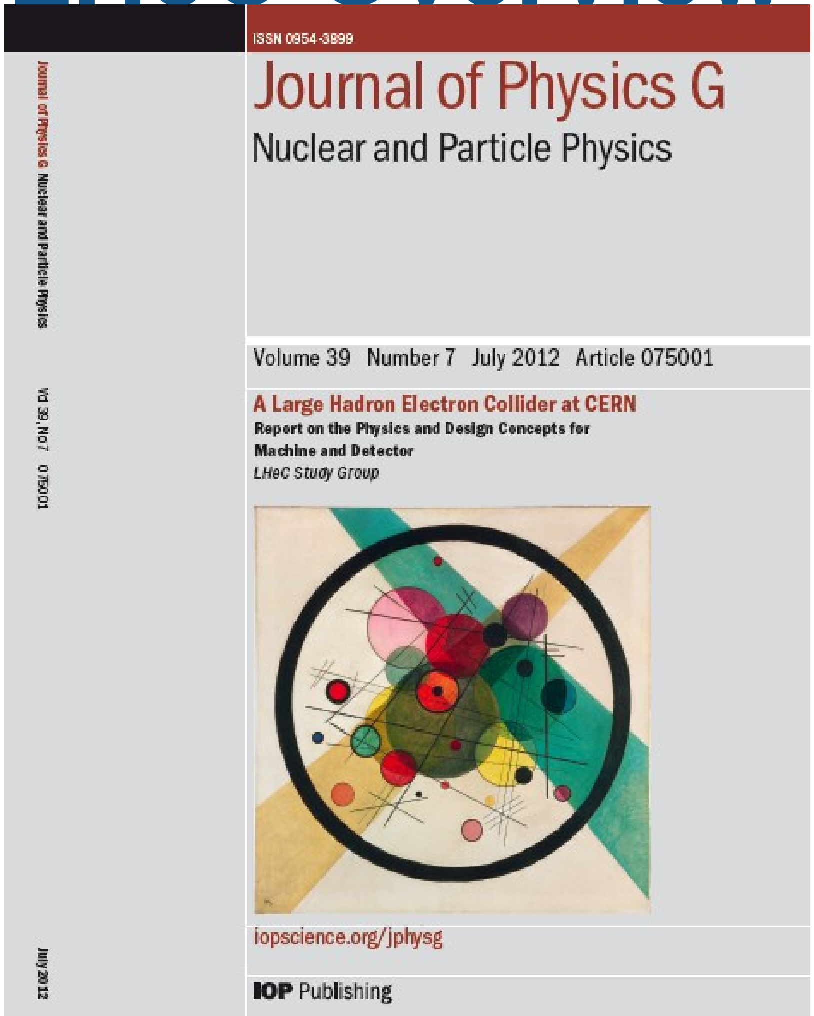
2. **Physics**

3. **Accelerator**
   - Ring-Ring Collider
   - Linac-Ring Collider
   - System Design
   - Civil Engineering and Services

4. **Detector**

5. **Conclusions**

LHeC Overview



1. **introduction**
2. **Physics**
3. **Accelerator**
4. **Detector**
   - Detector Requirements
   - Central detector
   - Forward and Backward Detectors
5. **Conclusions**

Outline

1. **Baseline parameters and configuration**
   - Goals
   - physics requirements

2. **General Design considerations**
   - LINAC-Ring collider

3. **Post cdr plans**
   - an ERL test facility

4. **Planning and timeline**

5. **Next steps and r&D activities**

Physics Programme

LHeC is a new collider: the cleanest microscope of the world

- Exploration of the energy frontier, complementing the LHC and its discovery potential for physics beyond the Standard Model with high precision deep inelastic scattering measurements

- Investigation of a variety of fundamental questions in strong and electroweak interactions

- Electron-deuteron and electron-ion scattering in a (Q2, 1/x) range extended by 4 orders of magnitude as compared to previous lepton-nucleus DIS experiments

- Novel investigations of neutron's and nuclear structure, the initial conditions of Quark-Gluon Plasma formation and further quantum chromodynamic phenomena

LHeC Goal

Collide LHC beam with electrons or positrons

- LHC hadron beams: Ep = 7 TeV
  CM collision energy: E2CM = 4 Ee* Ep,A
  Required lepton energy 50 GeV to 150 GeV

- Integrated e±p : O(100) fb-1 ≈ 100 * L(HERA)
  Synchronous ep and pp operation

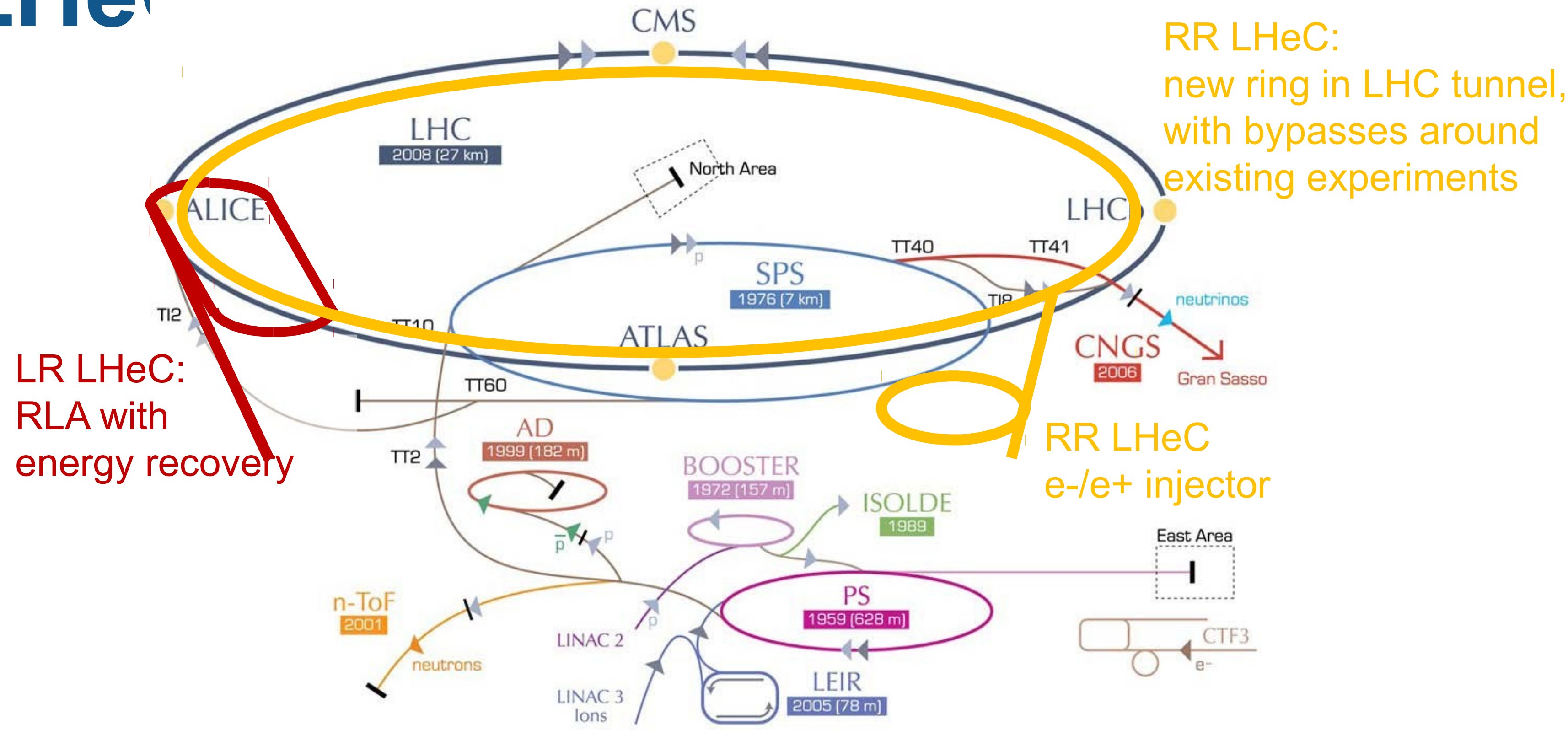
- Luminosity of ≈ 1033cm-2s-1 (proposal for 1034cm-2s-1 exists, but not verified)
  Power consumption for lepton complex ≤ 100 MW
  Beam Power < 70 MW

- Polarisation

- No interference with pp physics

- Start of LHeC operation together with HL-LHC in 2023

LHeC option: RR and LR



Study team provided CDR:

Ring-ring option, feasible but impact LHC operation during installation

Linac-ring option, the baseline

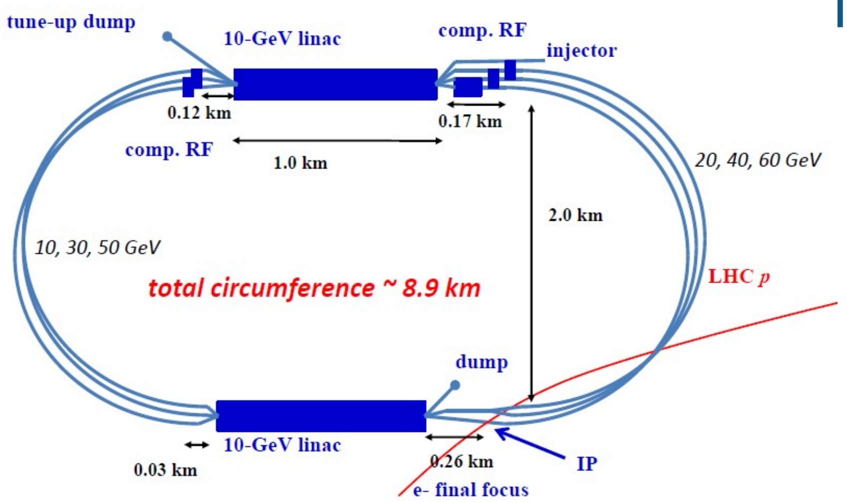
A solution exists, will now have to find the best solution

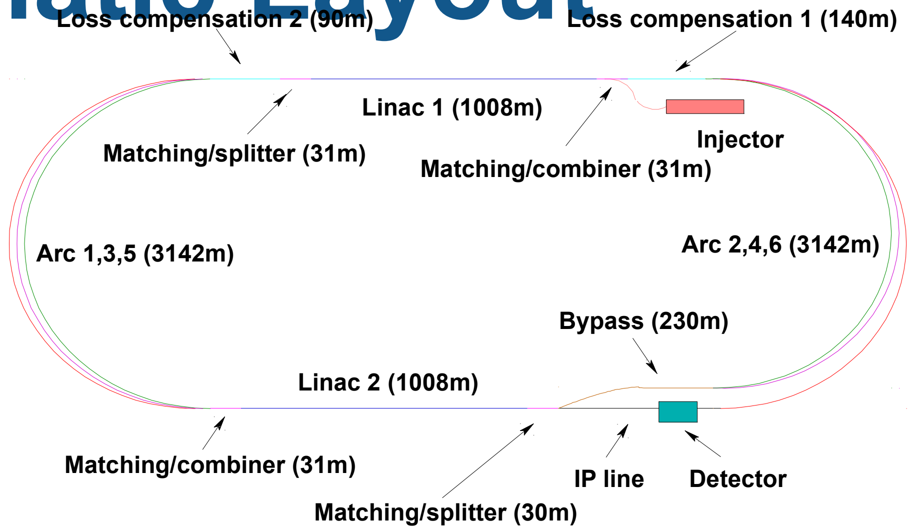
Already have a baseline and alternatives for some components

Linac-Ring layout: IP Parameters

	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [1033cm-2s-1]	1	1
Normalized emittance γεx,y [μm]	3.75	50
Beta Function β*x,y [m]	0.10	0.12
rms Beam size σ*x,y [μm]	7	7
rms Divergence σ'x,y [μrad]	70	58
Beam Current [mA]	(860) 430	6.6
Bunch Spacing [ns]	25 (50)	25 (50)
Bunch Population	1.7*1011	(1*109) 2*109

Recirculating Linear Accelerator Complex : Schematic Layout



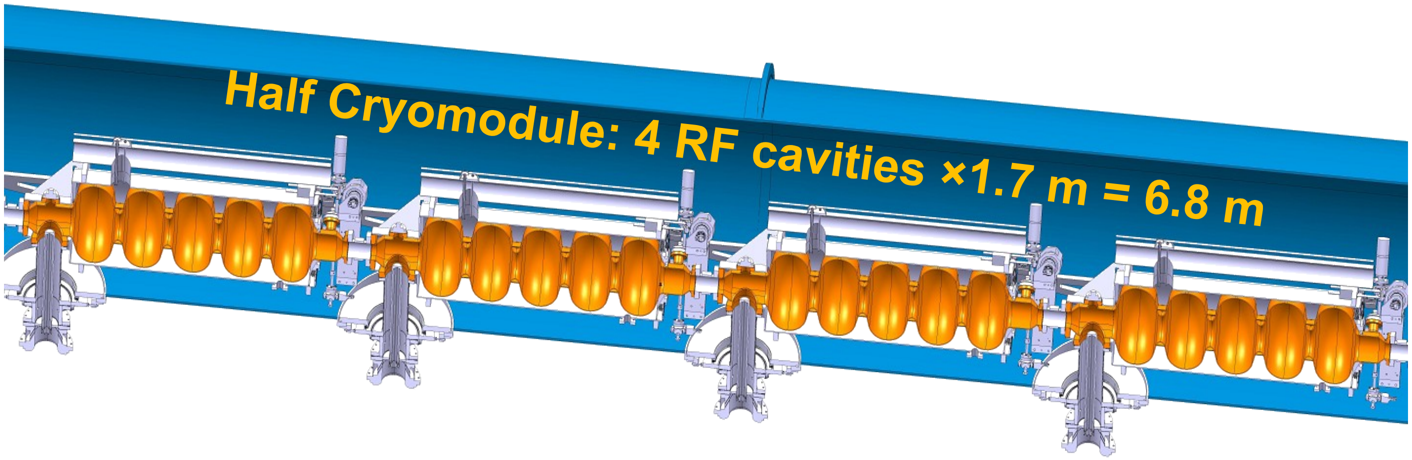


RECIRCULATOR COMPLEX

1. 0.5 Gev injector
2. A pair of SCRF linacs with energy gain 10 GeV per pass
3. Six 180° arcs, each arc 1 km radius
4. Re-accelerating stations to compensate energy lost by SR
5. Switching stations at the beginning and end of each linac
6. Matching optics
7. Extraction dump at 0.5 GeV

Linac Design

In **CDR**: 8 cavities per 14 m long module
Choice between O(720 MHz) and O(1.3 GHz) made this year
~ 720 MHz had been baseline for CDR



Half cryomodule, 4 RF Cavities
721.4 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 Cryomodule

- Q0=2.5*1010 assumed,
- R=1.43*1013 Ω (ILC: R=1.04*1013 Ω)
- 2 modules per quadrupole pack (2 m)
- ~ 60 modules per 1000 m long linac

Daniel Schulte

Post CDR frequency choice

LHeC Meeting at Daresbury Laboratory, January 2013

The Cockcroft Institute of Accelerator Science and Technology

CERN

Science & Technology Facilities Council ASTeC

Jefferson Lab

BROOKHAVEN NATIONAL LABORATORY

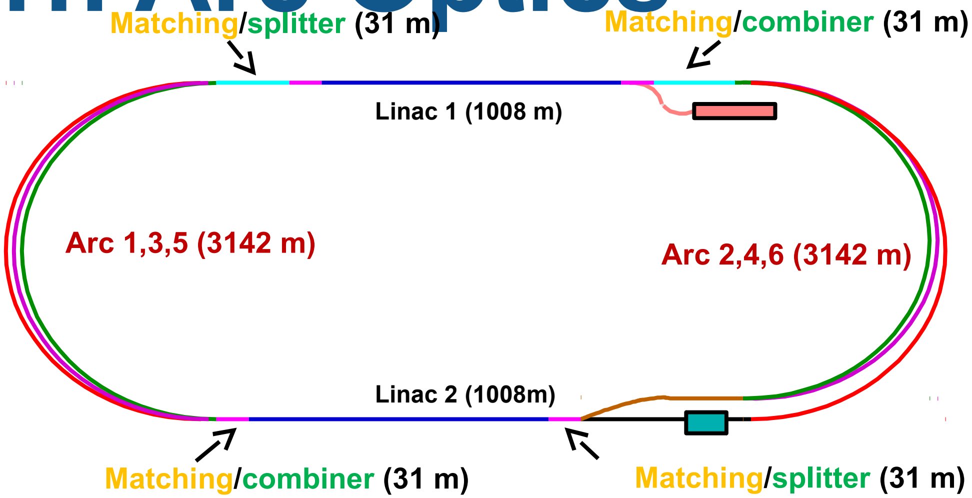
LOWER FREQUENCY	
ADVANTAGES	DISADVANTAGES
Reduced losses	Somewhat higher RF cost Might be offset by reduced cryo cost or improved performance
Less required cooling power	
Reduced wakefield	

Erk Jensen

FINAL CHOICE: 801.58 MHz

- Frequency of a future LHC harmonic system
- It is (to less than a few kHz) equal to the existing SPS Landau system

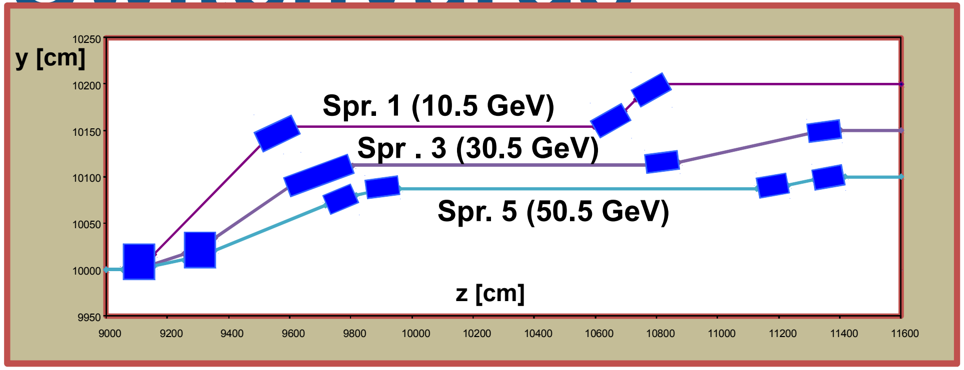
Return Arc Optics

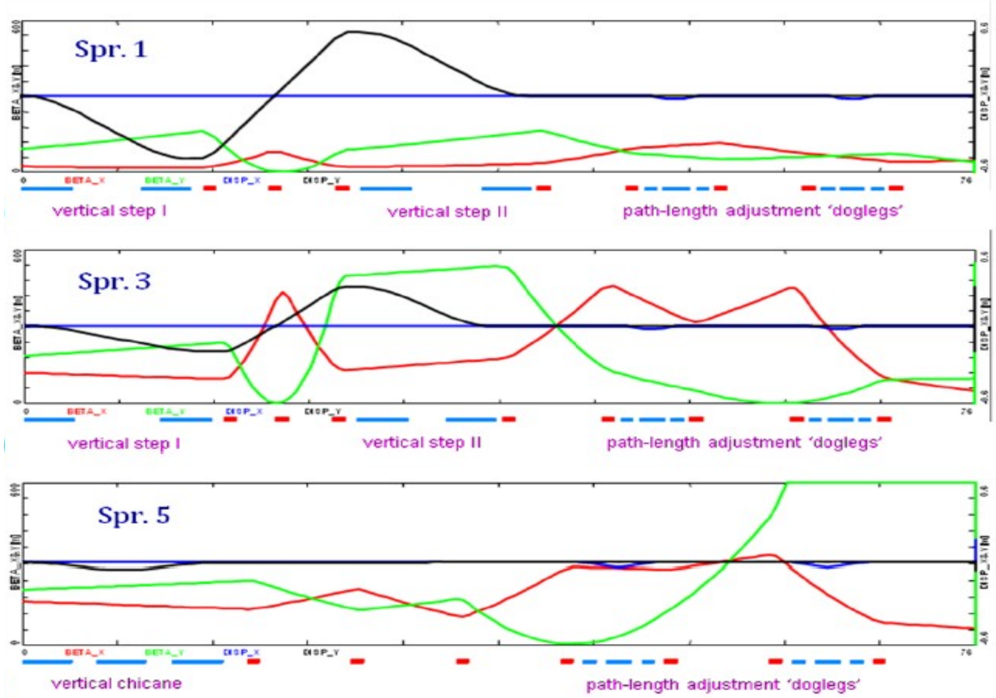


Switchyard
Matching sections
Arc lattices

- 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. γt, DBA, TEM)
- Acceptable level of emittance dilution and momentum spread
  Magnet apertures

Switchyards





- Two-step-achromat spreaders and mirror symmetric recombiners
- Arcs are separated into 1m high vertical stack
- Very compact switchyard system (~20 m long)
- Horizontal doglegs used for path-length adjustment

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Emittance Preserving Arc Optics

Proper lattice design in the arcs to address
the effect of SR on electron beam phase-space:
cumulative emittance and momentum growth due to quantum excitations

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

Various flavors of FMC Optics used

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Emittance not exceeding 50 μrad required for the LHeC luminosity

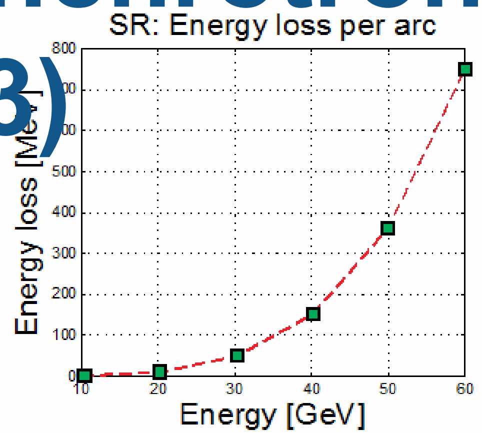
Synchrotron radiation in return arcs (1/3)

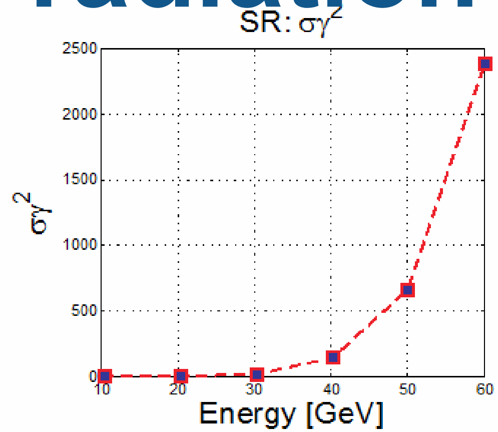
- Energy loss due to synchrotron radiation in the arcs
- Integrated energy spread induced by synchrotron radiation

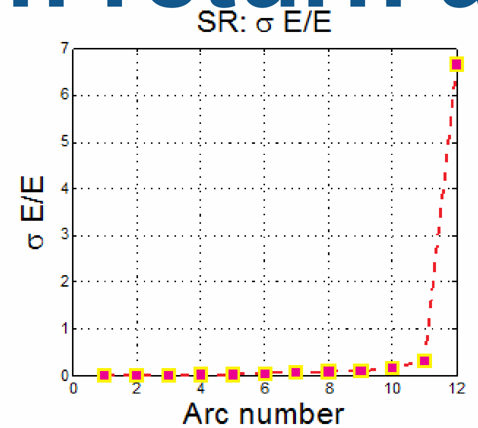
ARC	E [GeV]	ΔE [MeV]	σE/E [%]
1	10.4	0.678	0.00052
2	20.3	9.844	0.00278
3	30.3	48.86	0.00776
4	40.2	151.3	0.01636
5	50.1	362.3	0.02946
6	60	751.3	0.04829
7	50.1	362.3	0.06366
8	40.2	151.3	0.08065
9	30.3	48.86	0.10808
10	20.3	9.844	0.16205
11	10.4	0.678	0.31668
dump	0.500	0	6.66645

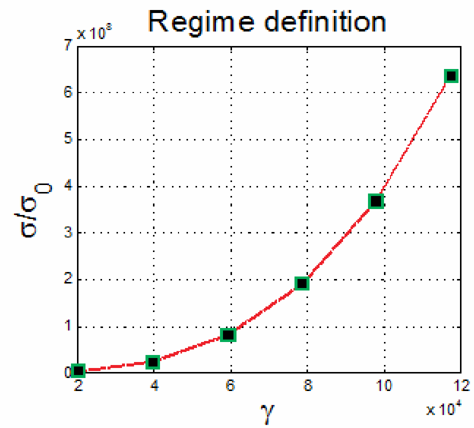
Total loss per particle about ~1.9 GeV → 12.2 MW beam power
Compensated by additional linacs
60% wall plug to beam efficiency → 20.3 MW

Synchrotron radiation in return arcs (2/3)









Bending Radius [m]=764
Particles per bunch =2000000000
Bunch length [m]=0.0003
Total Energy loss [GeV] (SR)=1.8974
Cumulative σE/E @ 60 GeV=0.00048294
Cumulative σE/E @ dump =0.066665
Pcsr[W]=57.7918
Pcsr/per particle [eV]=1443937.8404

Total loss per particle about ~1.9 GeV → 12.2 MW beam power
Compensated by additional linacs
60% wall plug to beam efficiency → 20.3 MW

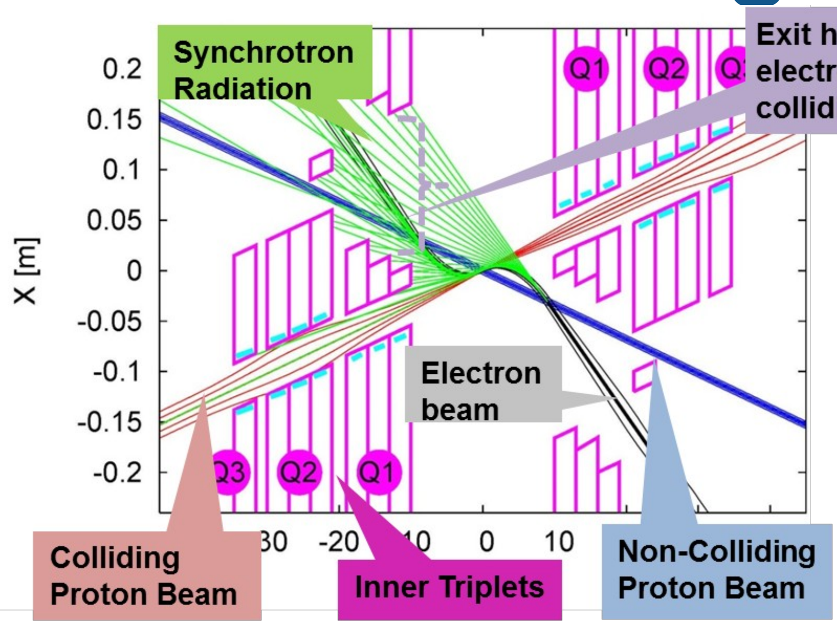
Synchrotron radiation in return arcs (3/3)

- Emittance growth in each individual arc*
- Integrated growth including all previous arcs

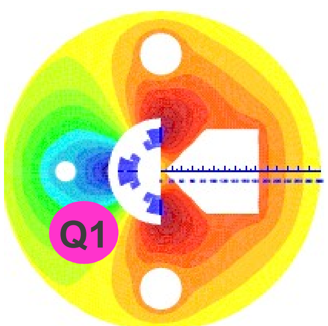
ARC	E [GeV]	ΔεARC [μm]	Δεt [μm]
1	10.4	0.0025	0.0025
2	20.3	0.140	0.143
3	30.3	0.380	0.522
4	40.2	2.082	2.604
5	50.1	4.268	6.872
6	60	12.618	19.490
5	50.1	4.268	23.758
4	40.2	2.082	25.840
3	30.3	0.380	26.220
2	20.3	0.140	26.360
1	10.4	0.0025	26.362

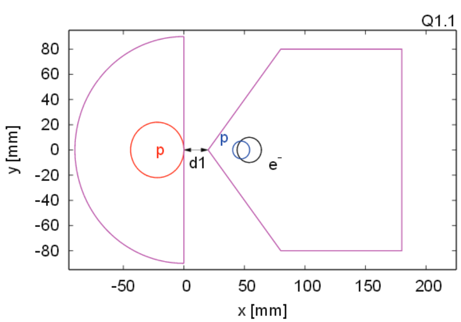
Before the IP a total growth of ~ 7 μm is accumulated
The final value is ~ 26 μm

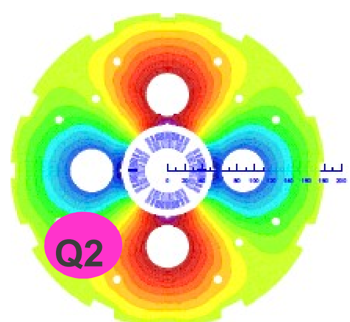
Interaction Region layout



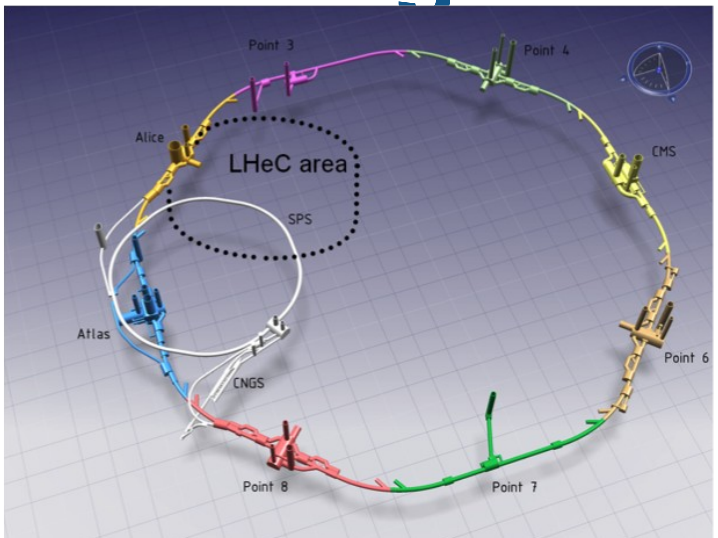
- β*of 0.1 m with proton triplets close to the IP to minimize chromaticity
- Head-on *p-e-* collisions achieved by dipoles around the IP
- 6 mrad crossing angle between the non-colliding *p* beams
- Only the p beam colliding with the *e-* is focused
- Mirror quadrupole design using Nb3Sn technology



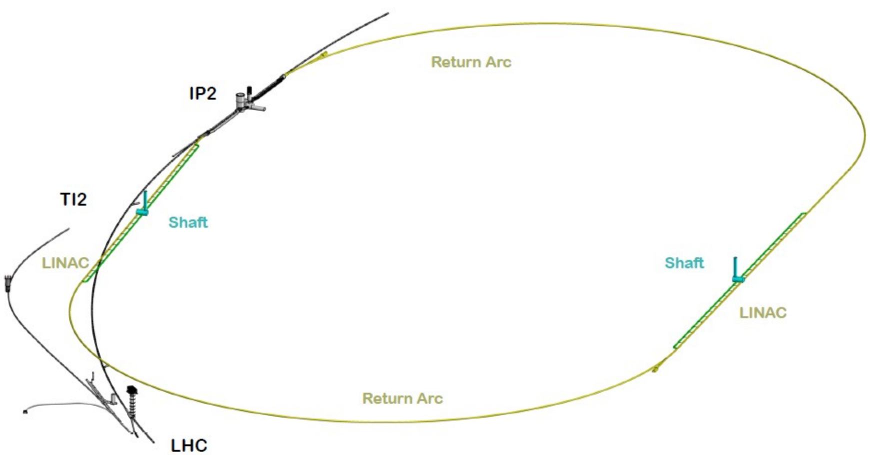




Civil Engineering Feasibility Studies



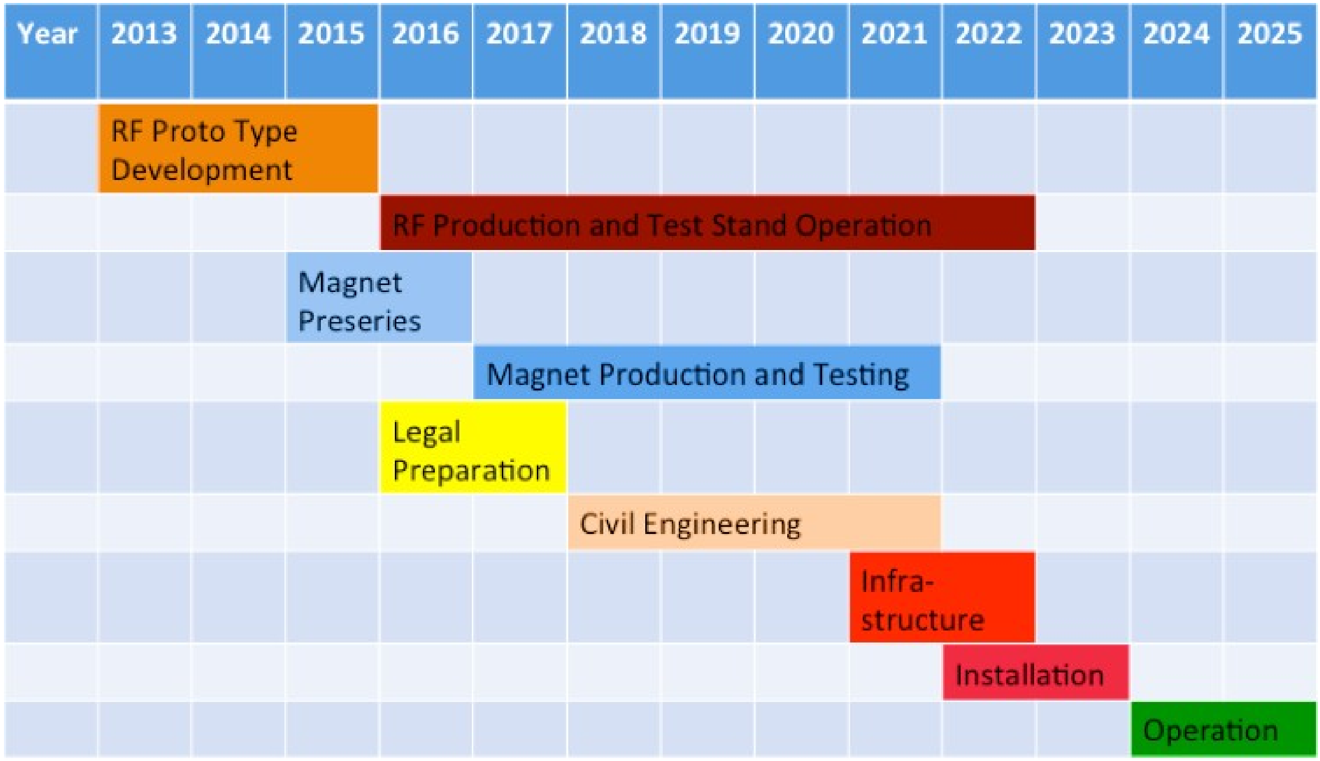
- ERL placed inside the LHC ring and tangential to IP2
- Two 1 km long LINACs; arcs have 1 km radius and are passed 3 times
- Whole racetrack ~9 km long (1/3 of the LHC length)



~ 960 cavities
~ 60 cryomodules per linac
~ 4500 magnets in the 2*3 arcs
~ 600 - 4 m long dipoles per arc
~ 240 - 1.2 m long quads per arc

LHeC Planning and Timeline

- Installation decoupled from LHC operation and shutdown planning
- Infrastructure investment with potential exploitation beyond LHeC



CERN Mandate

Studies and prototyping of the following key technical components:

- Superconducting RF system for CW operation in an ERL
- Superconducting magnet development of the insertion regions of the LHeC with three beams
- Studies related to the experimental beam pipes with large beam acceptance
- The design and specification of an ERL test facility for the LHeC
- The finalization of the ERL design for the LHeC (optics design, beam dynamics studies and identification of potential performance limitations)

LHeC test facility

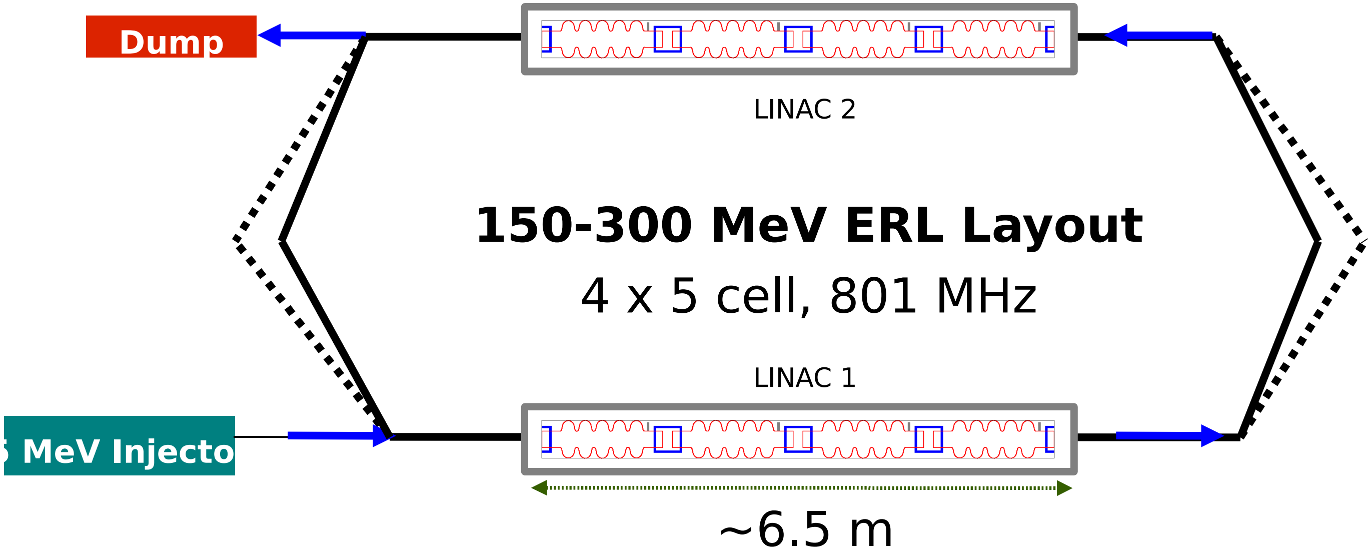
The next major step of the LHeC R&D is a demonstrator at CERN of an energy recovery linac

- **The test facility would consist of SC linacs, recirculation and energy recovery**

- **Among the purposes of this test facility are**
  1. Demonstrating the feasibility of the LHeC ERL design
     - Study behaviour of a high energy multi-pass multiple cavity ERL for LHeC
     - Optics, RF power, synchronization & delay issues …
     - HOMs and HOM couplers, cryogenics, instrumentation, controls, LLRF …
  2. Injector studies (DC or SRF gun)
  3. Study real SCRF cavities with beam
  4. Analyzing electron beam dynamics challenge
  5. Reliability issues, operational issues
  6. Beam facility for controlled SC magnet quench tests
  7. Beam facility for HEP detector R&D
  8. Demonstrator and study facility for e-cooling
  9. Could it be foreseen as the injector to LHeC ERL ?

LHeC test facility: Possible Schematics (1)

100-MeV scale energy recovery demonstration of a recirculating superconducting linear accelerator

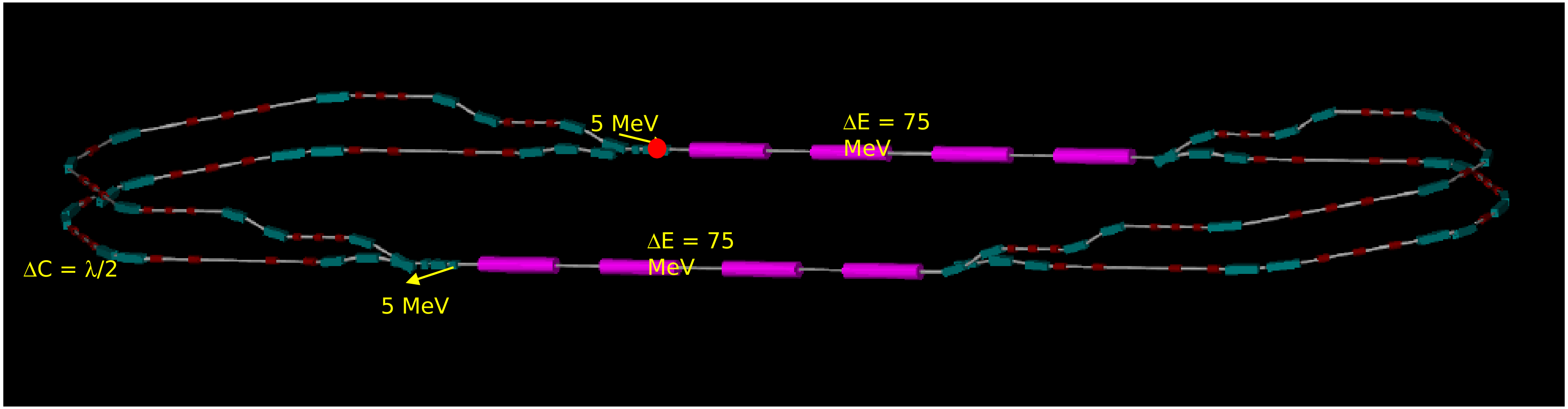


RECIRCULATOR COMPLEX

1. A 5 MeV in-line injector with an injection chicane
2. 2 SC linacs consisting of half cryomodule (4 RF cavities\ 5-cell per cavity)
3. Optics transport lines
4. Beam dump at 5 MeV

LHeC test facility: Possible Schematics (1)

Two passes 'up' + Two passes 'down'



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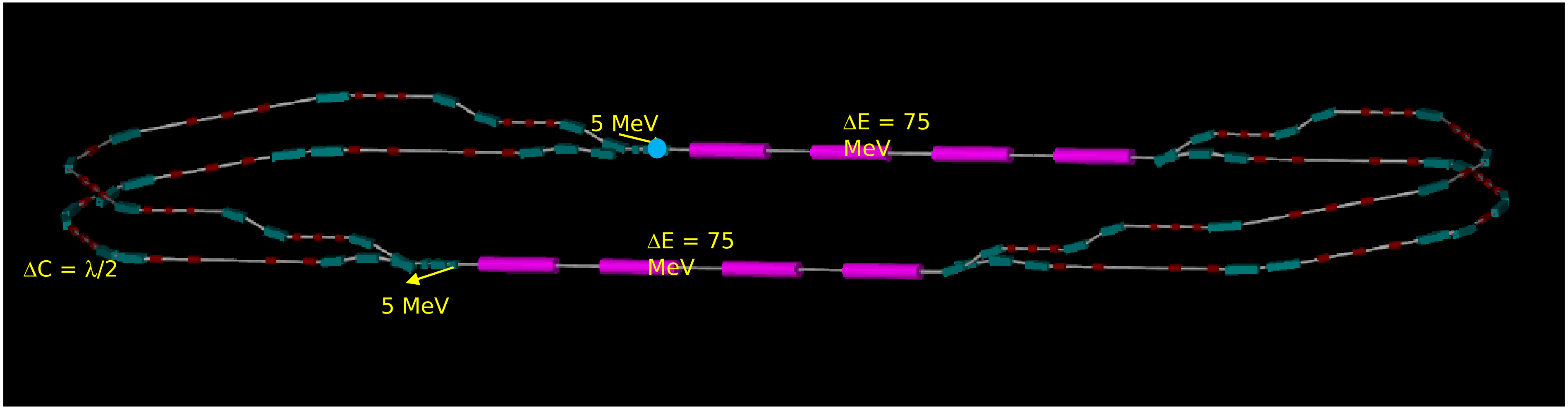
LHeC test facility: Possible Schematics (1)

Two passes ‘up’ + Two passes ‘down’



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Schematics 1: First Pass Lattice Design

LINAC :

Half Cryo Module ▭ 4 Cavities

801.58 MHz RF, 5 cell cavity:

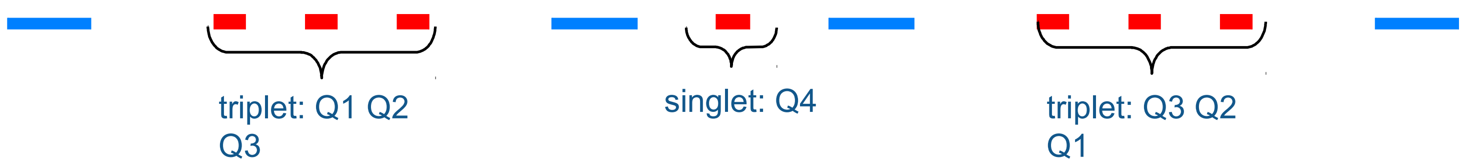
Grad = 18 MeV/m (18.7 MeV per cavity)

ΔE= 74.8 MV per Half Cryo Module

ARC 1 optics : (80 MeV)

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:

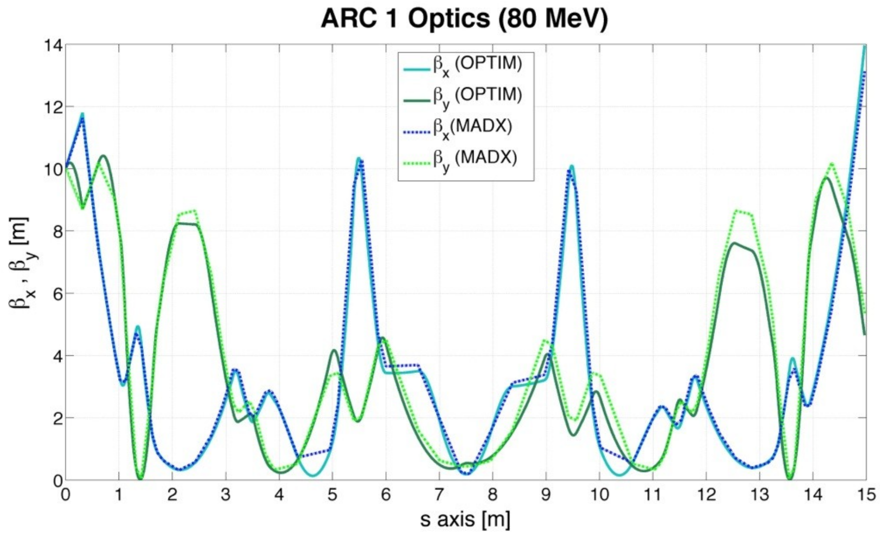
Spreader for Arc 1 @ 80 MeV

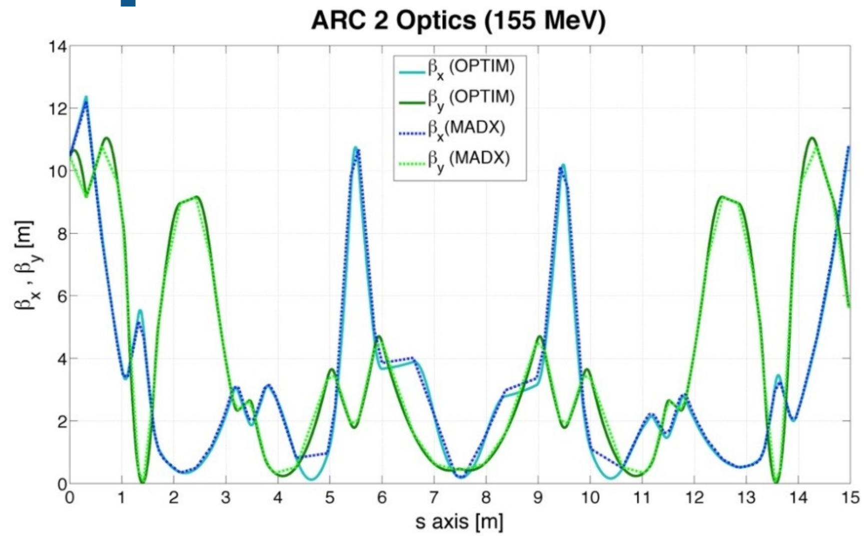
2 Vertical steps and quads triplet for hor. and vert. focusing

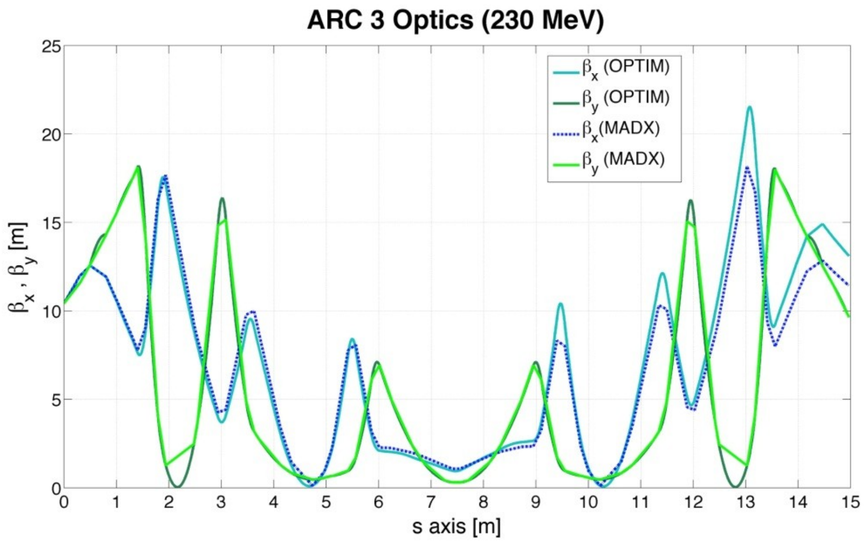
Spreader for Arc 3 @ 230 MeV

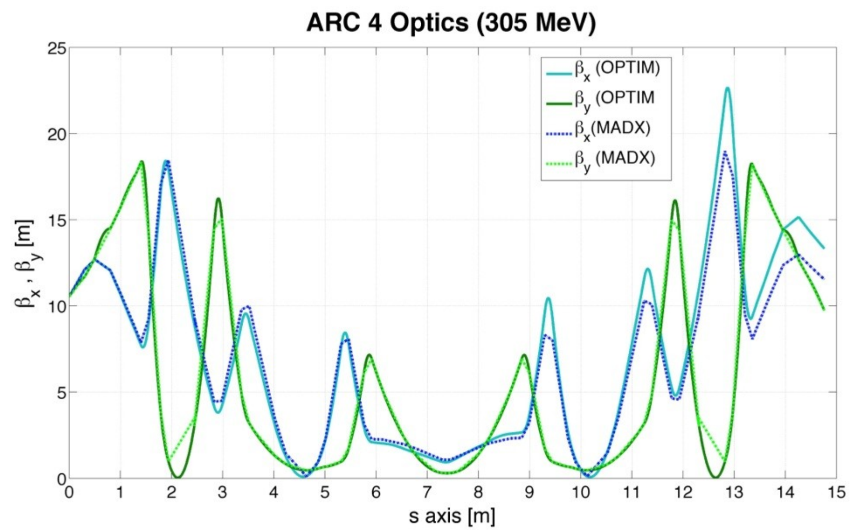
A vertical chicane plus 2 quads doublets

Schematics 1: Complete



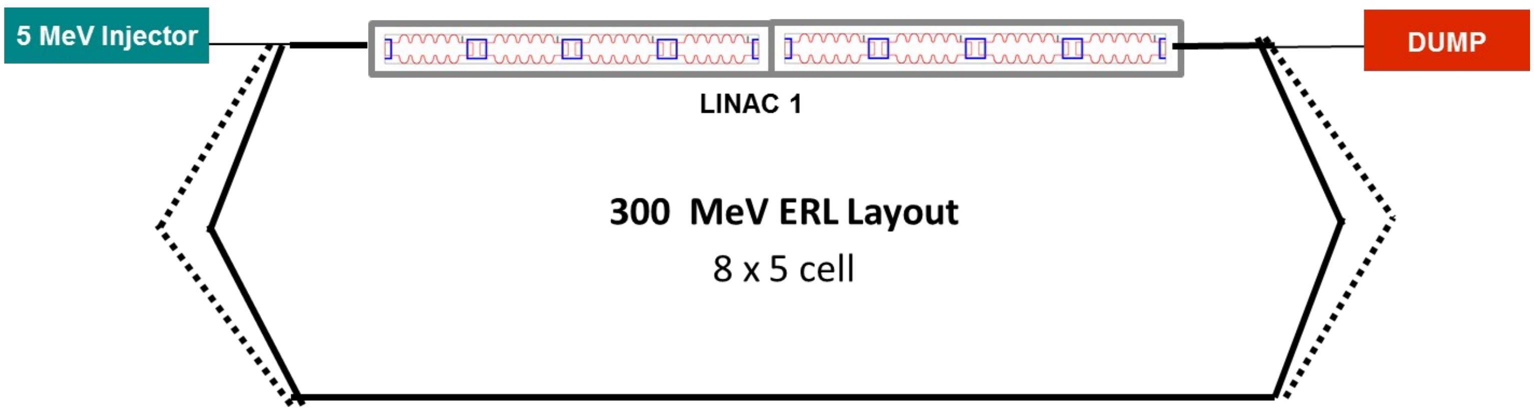






LHeC test facility: Alternative Schematics

100-MeV scale energy recovery demonstration of a recirculating superconducting linear accelerator



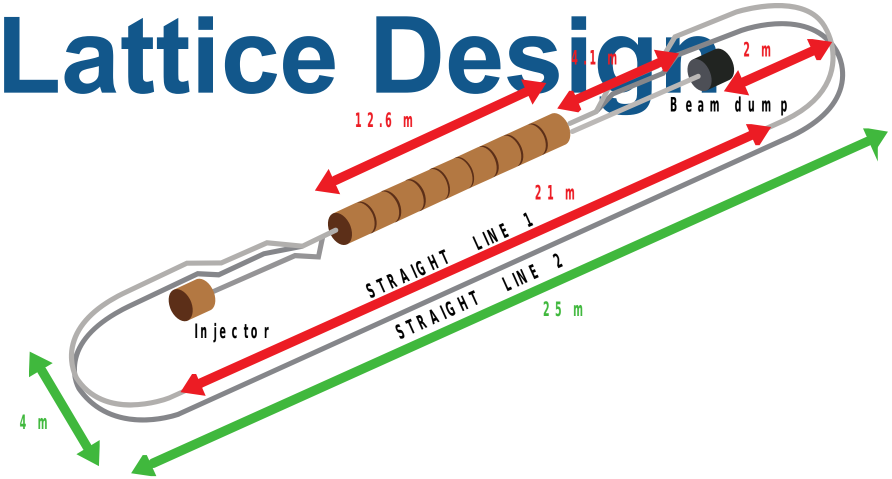
RECIRCULATOR COMPLEX

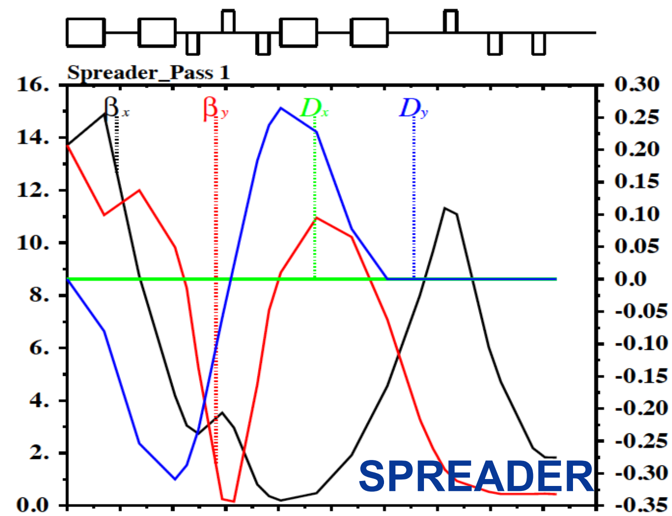
1. A 5 MeV in-line injector
2. 1 SC linac consisting of one CM
   (8 RF cavities\ 5-cell per cavity)
3. Optics transport lines
4. Beam dump at 5 MeV

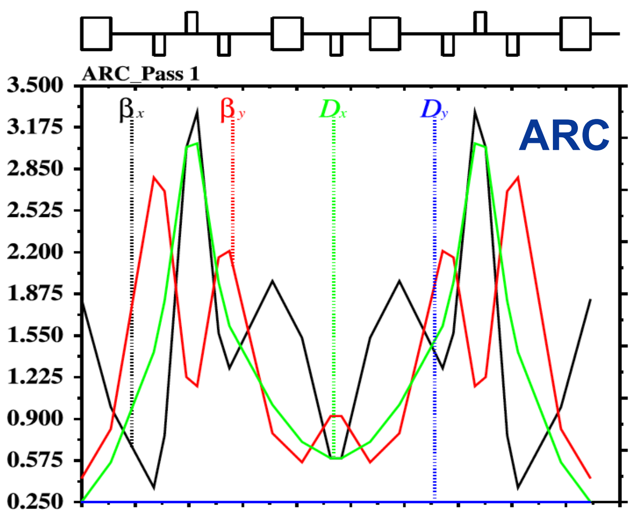
- Simpler
- Flexible

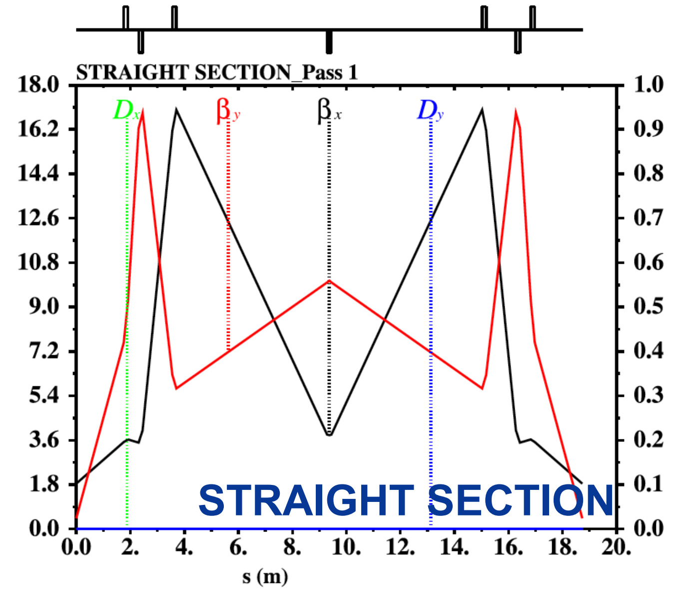
1. Available space for
   - implementation of feed-back,
   - phase-space manipulations,
   - beam diagnostic instrumentation…
2. Possible installation of an additional CM

Schematics 2: First Pass Lattice Design









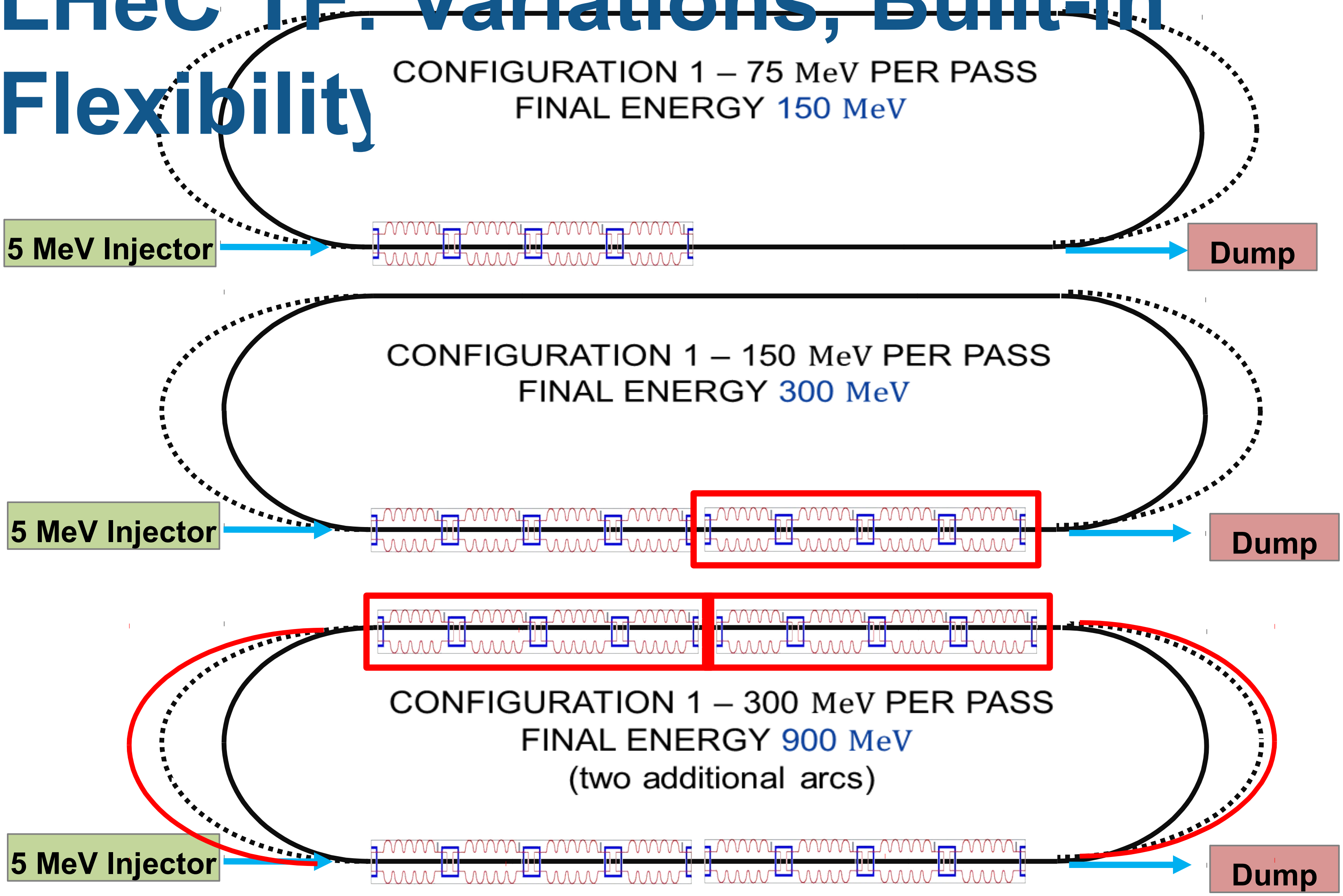
LHeC TF: Variations, Built-in Flexibility

100-MeV scale energy recovery demonstration of a recirculating superconducting linear accelerator

How much further can we go?

1-GeV scale energy recovery demonstration of a recirculating superconducting linear accelerator

LHeC TF: Variations, Built-in Flexibility



Summary and Outlook

LHeC appears feasible and can be realized in parallel with HL-LHC

- Significant room for optimization in design
  - Choice of RF frequency has now been done
  - Basic parameter choice should be reviewed for further improvements (higher luminosity?)

- Future plans
  - R&D on individual components
  - Preparation of a TEST FACILITY proposal

    Some (potential) international partners have declared large interest (JLAB, Mainz, ASTeC and others).
  - Beam dynamics studies

Thank you for your attention

Some References

1. *J. L. Abelleira Fernandez, et al.* [LHeC Study Group Collaboration], J. Phys. G 39 (2012) 075001 [arXiv:1206.2913 [physics.acc-ph]]
2. LHeC Collaboration, LHeC Meeting , Daresbury Laboratory, January 2013, https://eventbooking.stfc.ac.uk/newsevents/lhec-meeting
3. *S.A. Bogacz, et al.,* LHeC ERL Design and Beam-dynamics Issues , IPAC 2011, San Sebastian, Spain
4. M. Klein et al. , LHeC Design Report, J.Phys. G39 (2012) 075001 [arXiv:1206.2913]
5. *F. Zimmermann, et al.,* Design for a Linac-Ring LHeC, Proceedings of IPAC'10, Kyoto, Japan

Recent works presented at IPAC '13

1. Overview of the LHeC Design Study at CERN, *O.S. Brüning*, MOZB201
2. Civil Engineering Feasibility Studies for Future Ring Colliders at CERN, *J.A. Osborne et al.*, MOPWO036
3. LHeC IR Optics Design Integrated into the HL-LHC Lattice, *M. Korostelev et al.,* MOPWO063
4. The LHeC as a Higgs Boson Factory, *F. Zimmermann et al.*, MOPWO054
5. A Proposal for an ERL Test Facility at CERN, *R.Calaga et al.,* WEPWO049
6. Strawman Optics design for the LHeC ERL Test Facility, *A. Valloni et al.,* TUPME055

LHeC website: http://cern.ch/lhec

ACKNOWLEDGMENT

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