DRAFT 1.0
Geneva, September 3, 2011
CERN report
ECFA report
NuPECC report
LHeC-Note-2011-003 GEN

A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

LHeC Study Group
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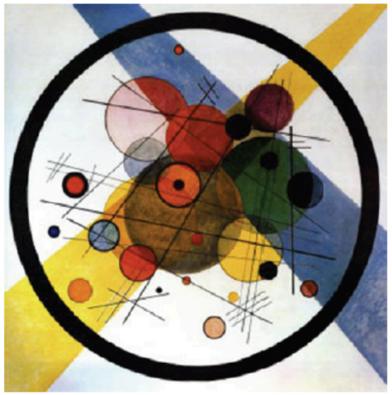


The LHeC Project at CERN

Design Concepts for the LHeC [WEODA03]

Max Klein (U.Liverpool+CERN)

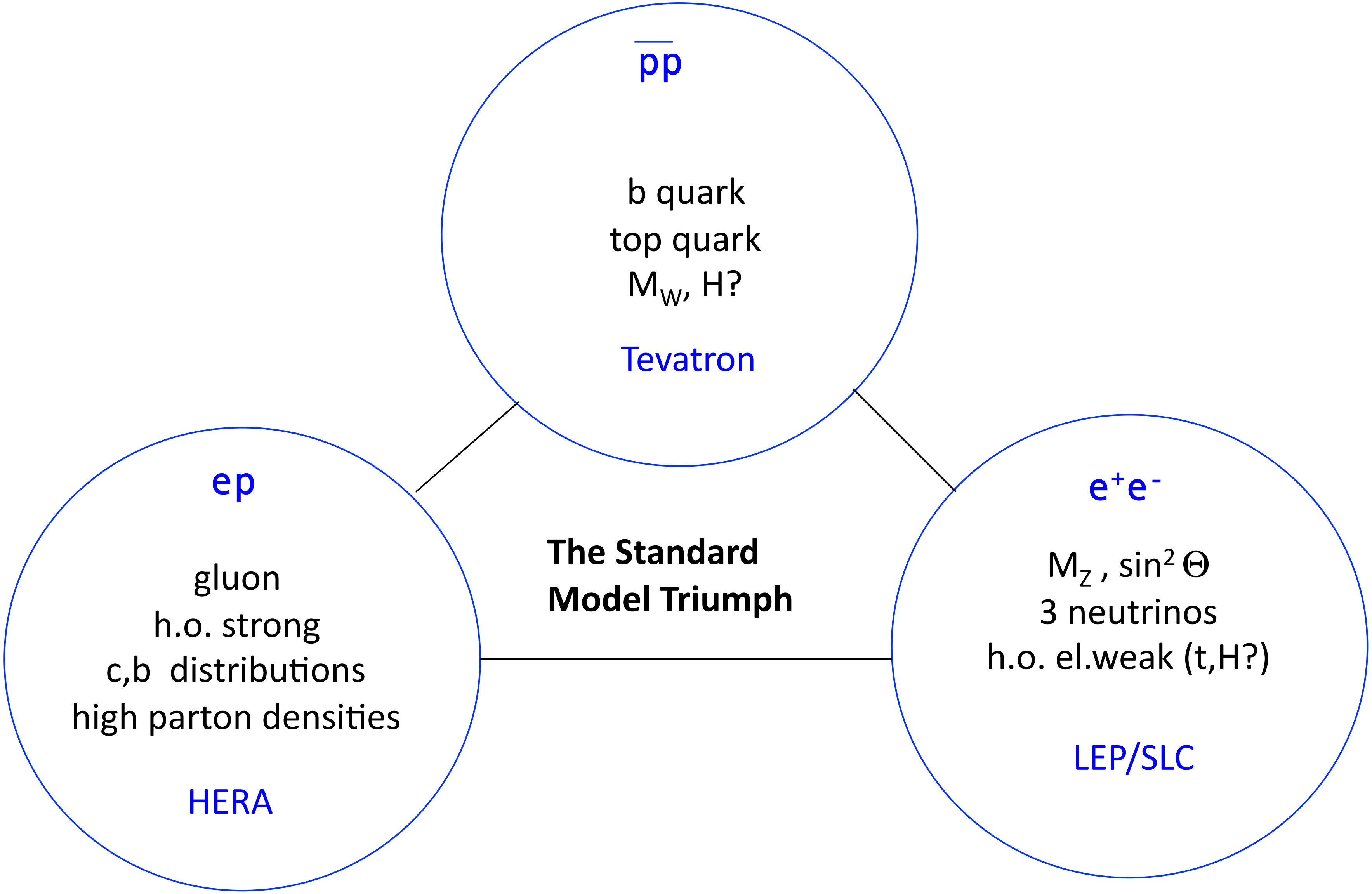
for the LHeC Study Group

Civil Engineering Studies for Major Projects after LHC

Considerations
Physics
Accelerator
Detector
Time Schedule

IPAC, San Sebastian, 7.9.11 - Dedicated to Gus Weber (1925-2011)

The Fermi Scale [1985-2010]



Two Options

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}}$$

$$N_p = 1.7 \cdot 10^{11}, \varepsilon_p = 3.8\mu m, \beta_{px(y)} = 1.8(0.5)m, \gamma = \frac{E_p}{M_p}$$

$$L = 8.2 \cdot 10^{32} cm^{-2} s^{-1} \cdot \frac{N_p 10^{-11}}{1.7} \cdot \frac{m}{\sqrt{\beta_{px}\beta_{py}}} \cdot \frac{I_e}{50mA}$$

$$I_e = 0.35mA \cdot P[MW] \cdot (100 / E_e[GeV])^4$$

Ring-Ring

Power Limit of 100 MW wall plug

"ultimate" LHC proton beam

60 GeV $e^{\pm}$ beam

→L = 2 10^{33} $cm^{-2}s^{-1}$ → O(100) fb^{-1}

LINAC Ring

Pulsed, **60 GeV**: ~10^{32}

High luminosity:

Energy recovery: $P=P_0/(1-\eta)$

β*=0.1m

[5 times smaller than LHC by reduced l*, only one p squeezed and IR quads as for HL-LHC]

L = 10^{33} $cm^{-2}s^{-1}$ → O(100) fb^{-1}

$$L = \frac{1}{4\pi} \cdot \frac{N_p}{\varepsilon_p} \cdot \frac{1}{\beta^*} \cdot \gamma \cdot \frac{I_e}{e}$$

$$N_p = 1.7 \cdot 10^{11}, \varepsilon_p = 3.8\mu m, \beta^* = 0.2m, \gamma = 7000/0.94$$

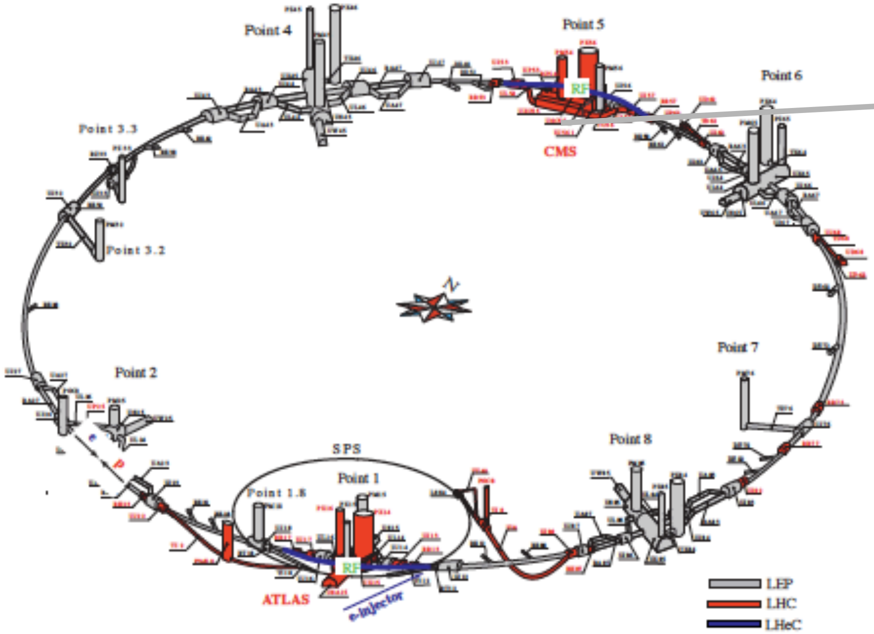
$$L = 8 \cdot 10^{31} cm^{-2} s^{-1} \cdot \frac{N_p 10^{-11}}{1.7} \cdot \frac{0.2}{\beta^*/m} \cdot \frac{I_e/mA}{1}$$

$$I_e = mA \frac{P/MW}{E_e/GeV}$$

Synchronous ep and pp operation (small ep tuneshifts)

The LHC p beams provide 100 times HERA's luminosity

e Ring- p/A Ring



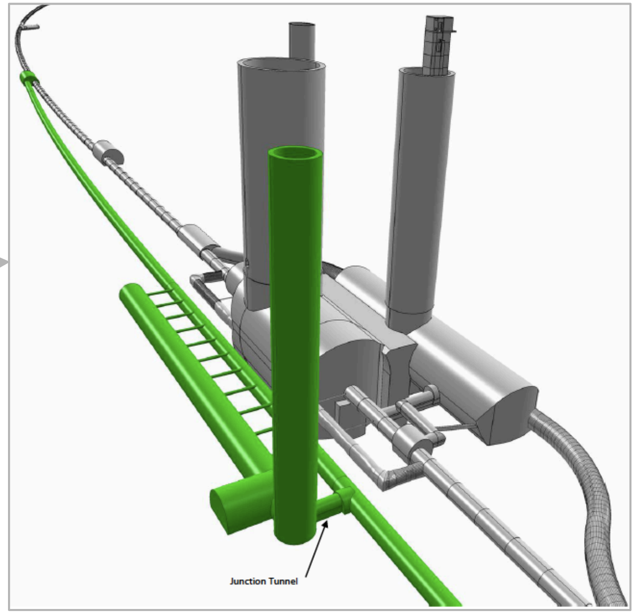
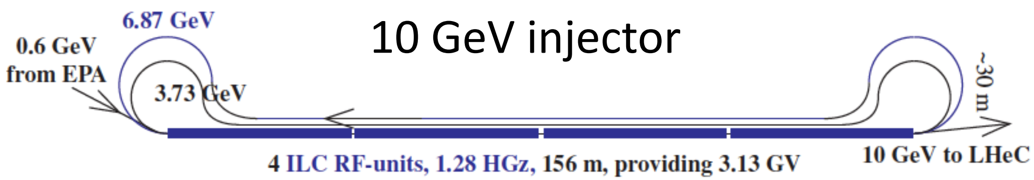
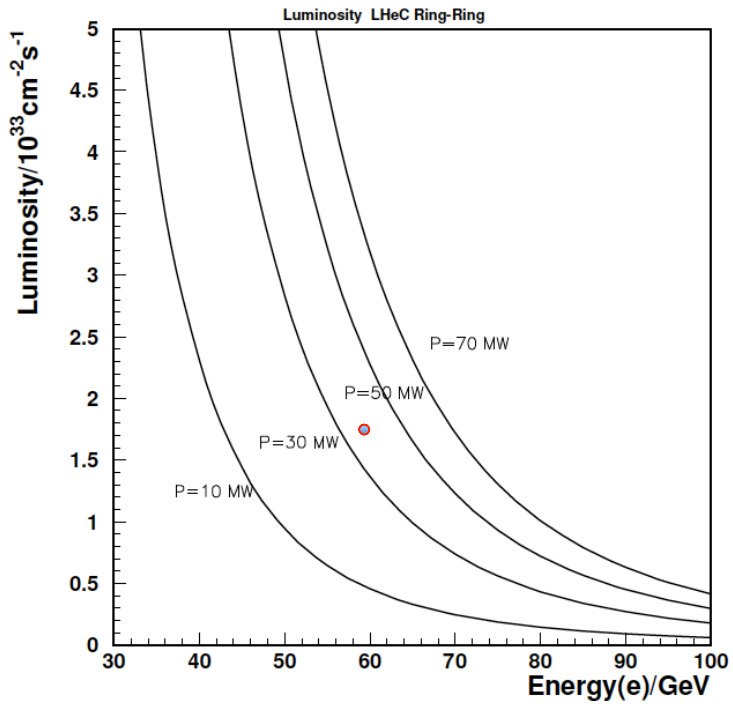


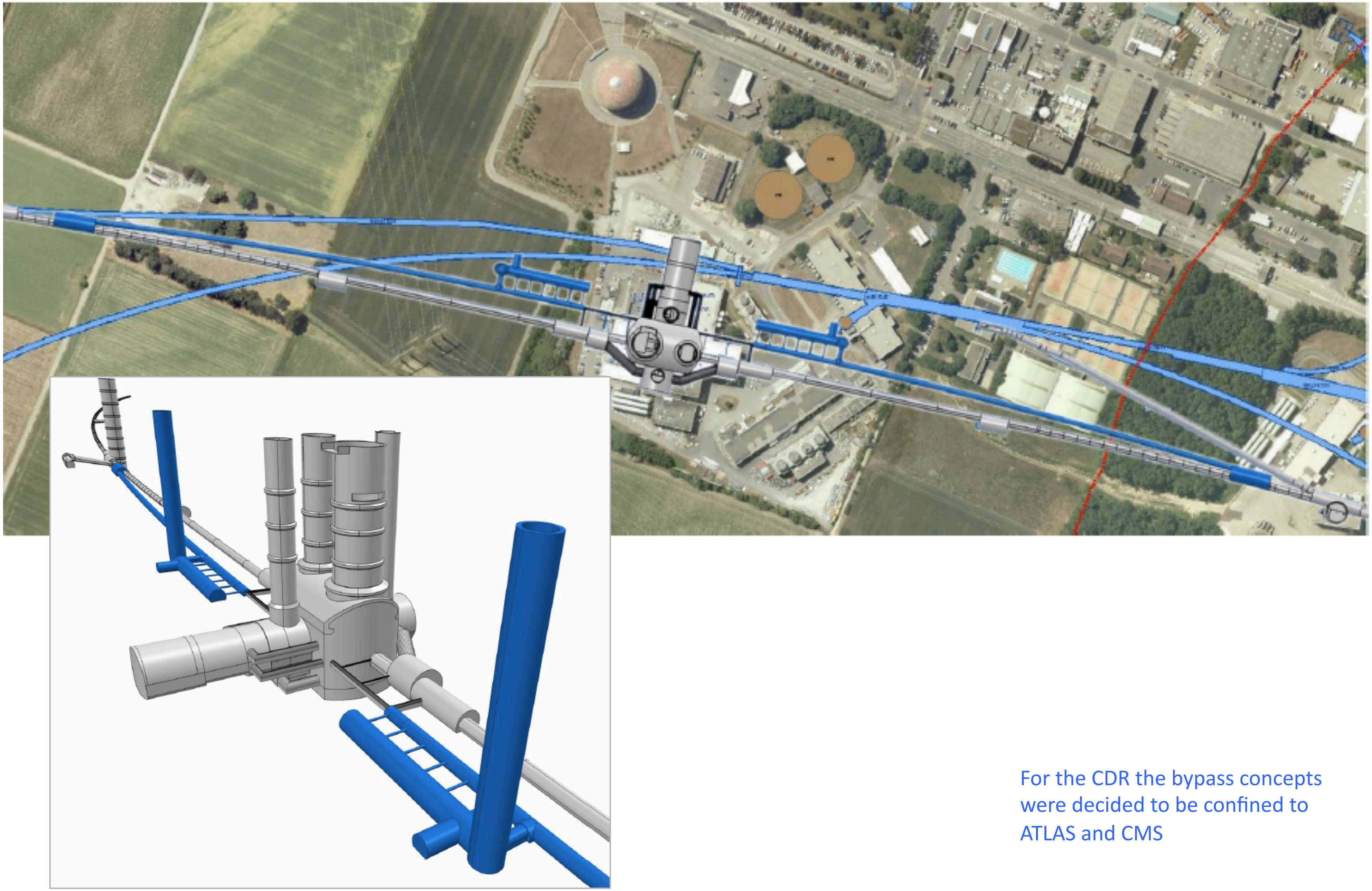
Figure 1: Schematic Layout of the LHC (grey/red) with the bypasses of CMS and ATLAS for the ring electron beam (blue) in the RR version. The e injector is a 10 GeV superconducting linac in triple racetrack configuration which is considered to reach the ring via the bypass around ATLAS.

10 GeV injector



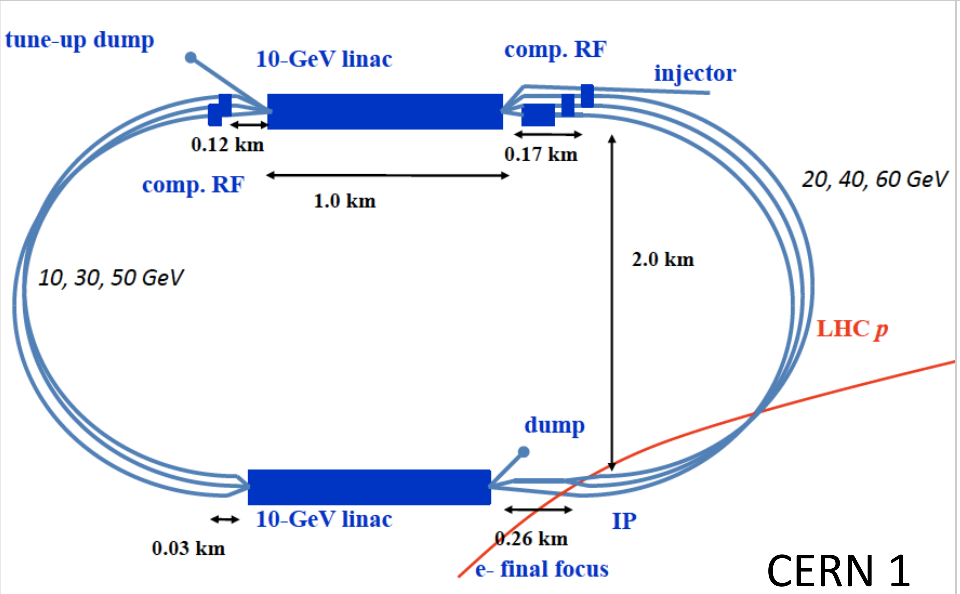


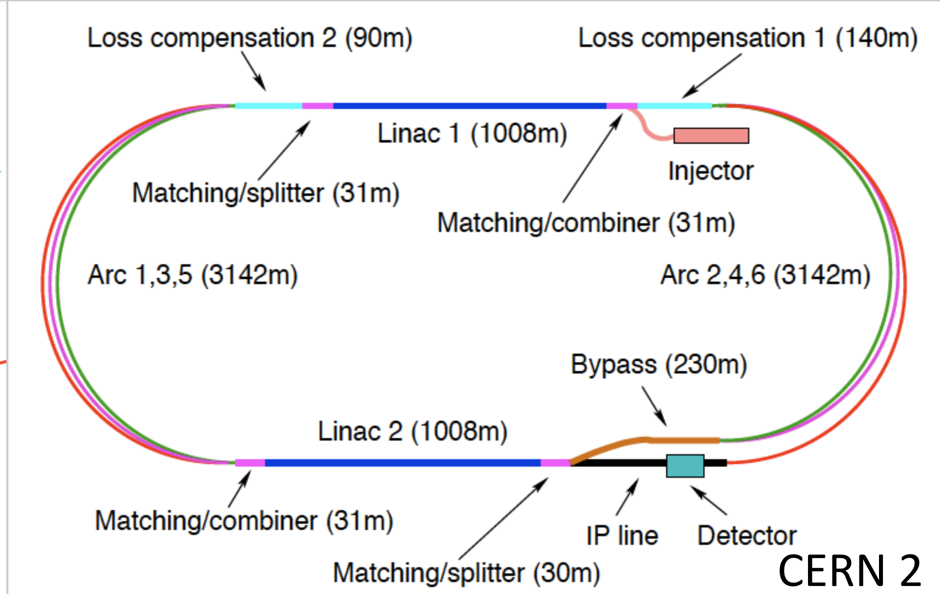
Bypassing ATLAS

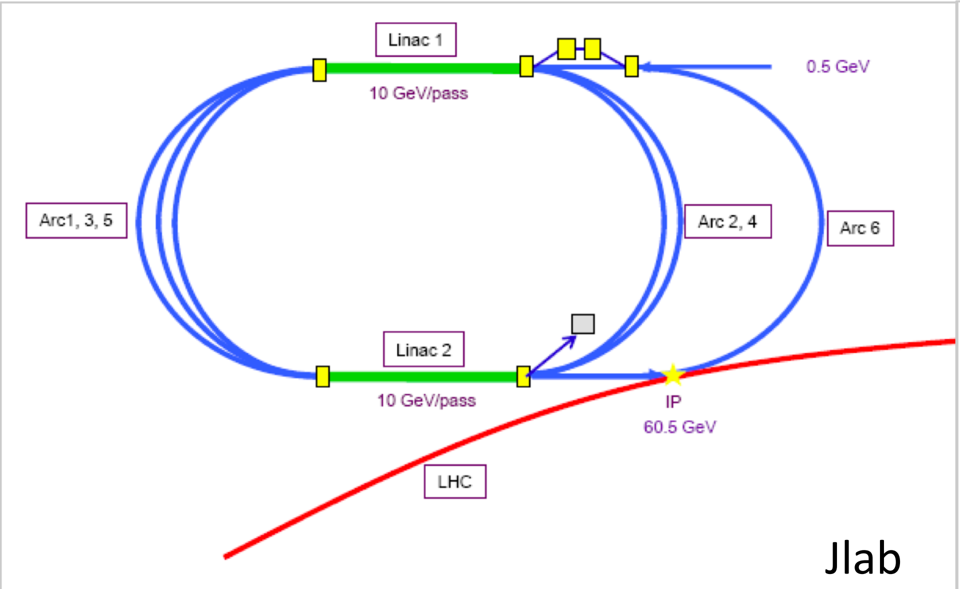


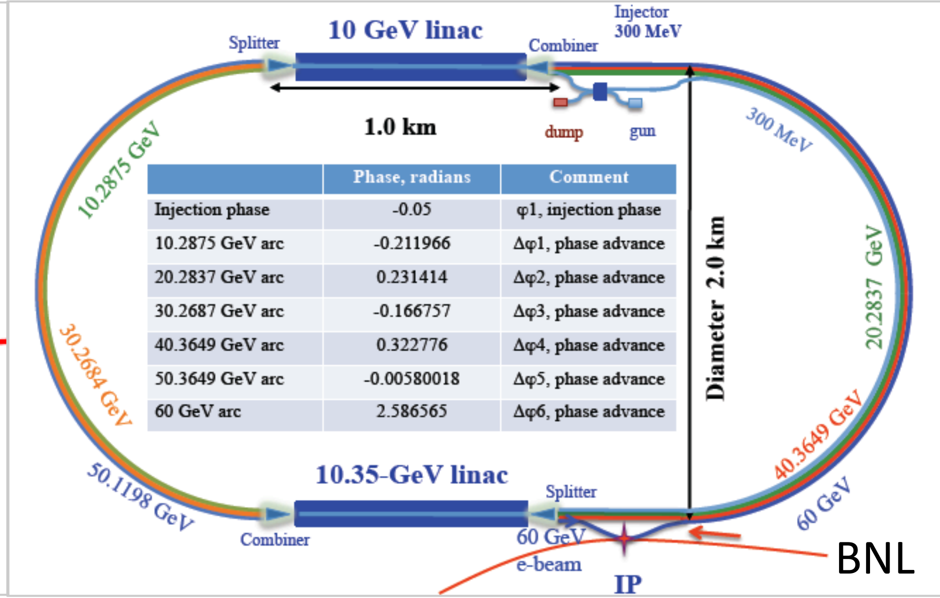
For the CDR the bypass concepts were decided to be confined to ATLAS and CMS

60 GeV Energy Recovery Linac





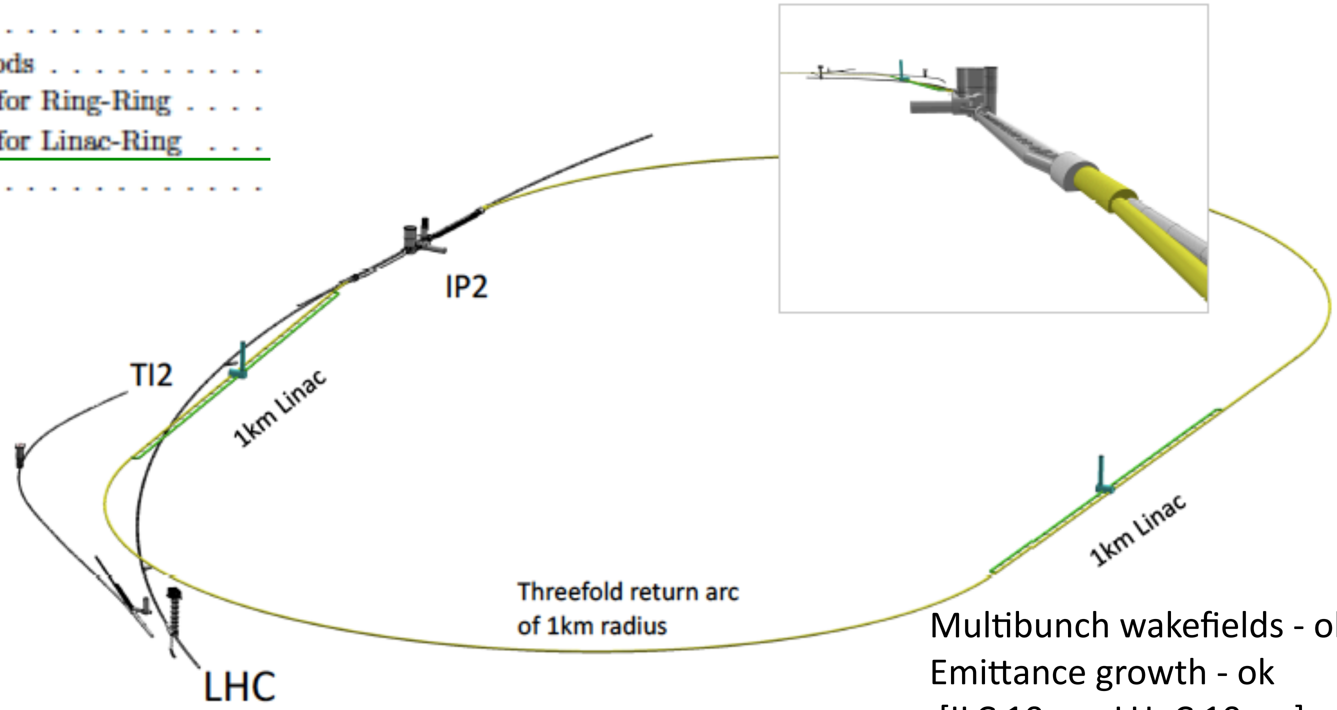




	Phase, radians	Comment
Injection phase	-0.05	φ1, injection phase
10.2875 GeV arc	-0.211966	Δφ1, phase advance
20.2837 GeV arc	0.231414	Δφ2, phase advance
30.2687 GeV arc	-0.166757	Δφ3, phase advance
40.3649 GeV arc	0.322776	Δφ4, phase advance
50.3649 GeV arc	-0.00580018	Δφ5, phase advance
60 GeV arc	2.586565	Δφ6, phase advance

Two 10 GeV energy recovery Linacs, 3 returns, 720 MHz cavities

$U_{LHeC}=U_{LHC}/3$: 1.5 x HERA

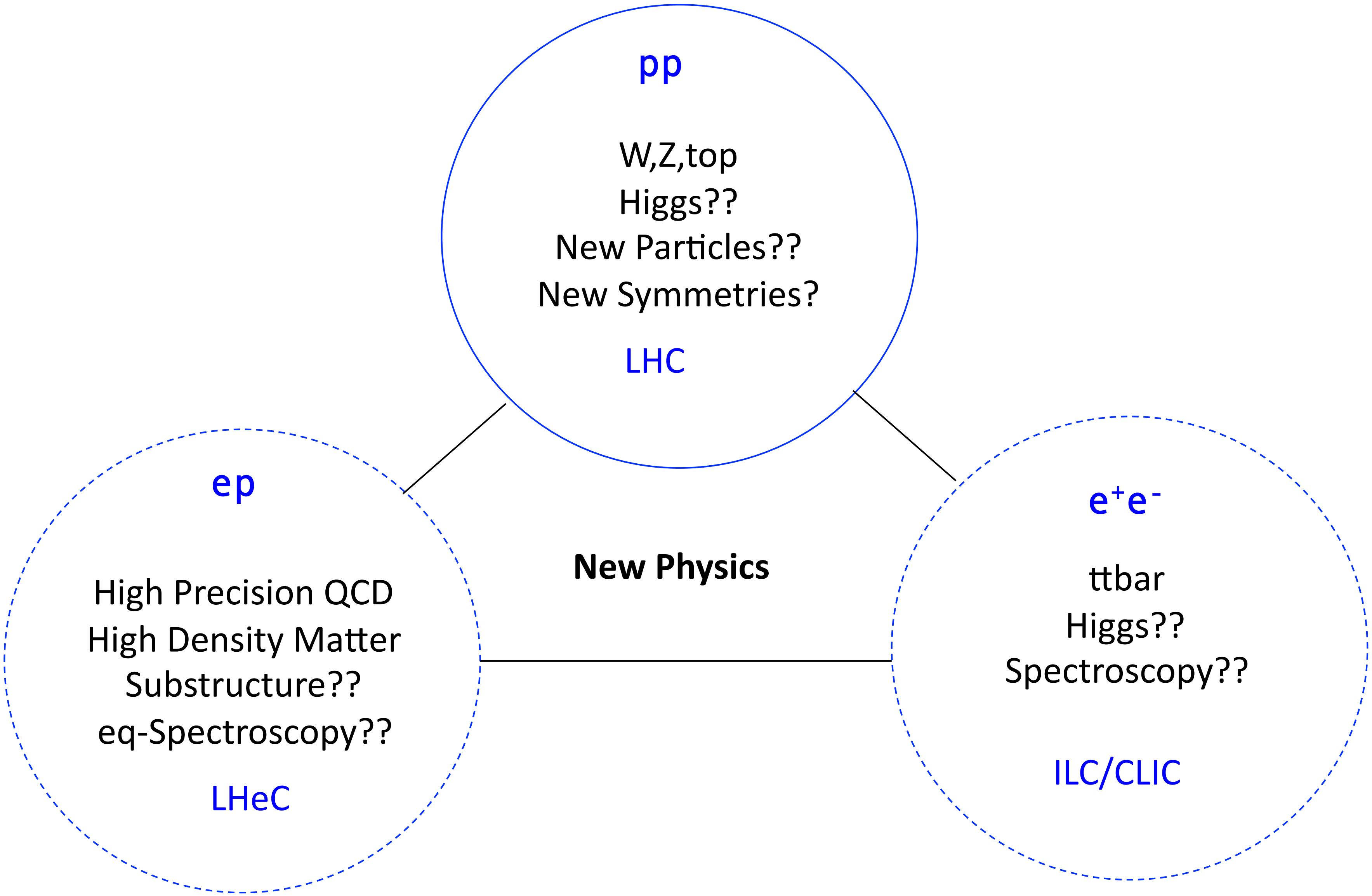


944 cavities
59 cryo modules per linac
721 MHz
20 MV/m CW

Multibunch wakefields - ok
Emittance growth - ok
[ILC 10nm, LHeC 10µm]
36σ separation at 3.5m - ok
Fast ion instability - probably ok
with clearing gap (1/3)

Figure 10.11: View on the ERL placed inside the LHC ring and tangential to IP2. TI2 is the injection line into the LHC. The insert shows the view towards IP2, which currently houses the ALICE experiment, from the direction of the protons colliding with the electron beam incoming from behind.

The TeV Scale [2010-2035..]



Why differ leptons from quarks? (Leptopartons)
Higgs? (production via gg (SM), bb(MSSM), quartic selfcoupling)
Mapping of the Gluon Field (next slide)
Non pQCD – 10 dim string theory (BFKL, odderon)
Ultimate precision of α_s and $\sin^2\Theta$ (0.1%, μ dependence)
Determination of ALL quark distributions
Confinement?? (Diffraction)
Generalised parton distributions (DVCS)
DGLAP → BFKL? (saturation of gluon density)
Structure of the neutron (no eD at HERA)
Partons in nuclei (4 orders of magnitude extended range)
New singly produced states (e^*)
Unfolding of Contact interaction effects (up to 50 TeV)

…

Default energy: E_e=60 GeV

So far LQ limits ~0.5 TeV

$Q^2 >> M_Z^2$

Gluon saturation at x ~10^{-5}
in the DIS region $Q^2 > M_p^2$

Synchrotron radiation ~ E_e^4

Cost and Luminosity:

L = 100 L_{HERA}, Q^2 and 1/x = 20 HERA

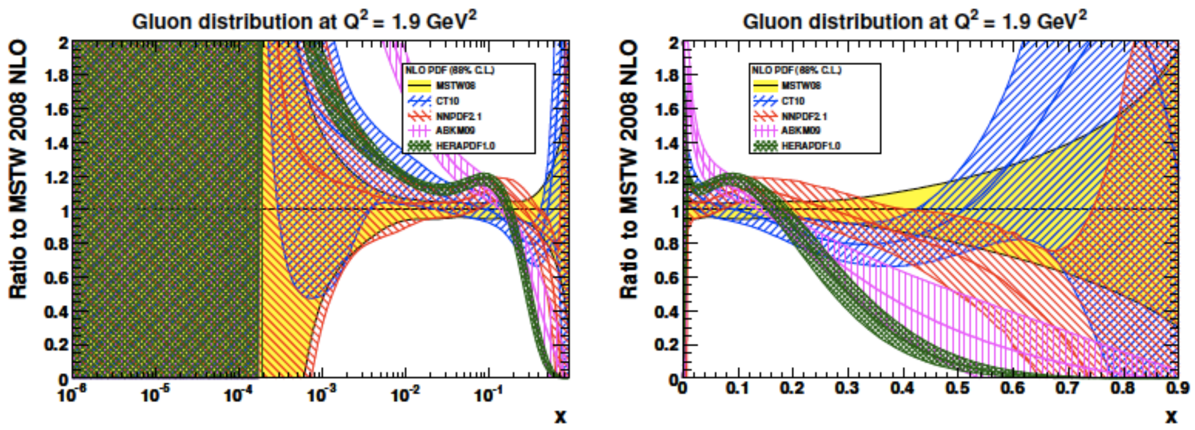
[LHC in 2014 may affect that choice.]

The LHeC has an outstanding, unique programme, which is complementary to the LHC. It requires:

High energy, high luminosity, polarised $e^\pm$, p, D, A.
The LHC provides all of that if complemented by an intense, high energy electron beam. This determines the schedule, and the site is no question.

II Physics

now



then

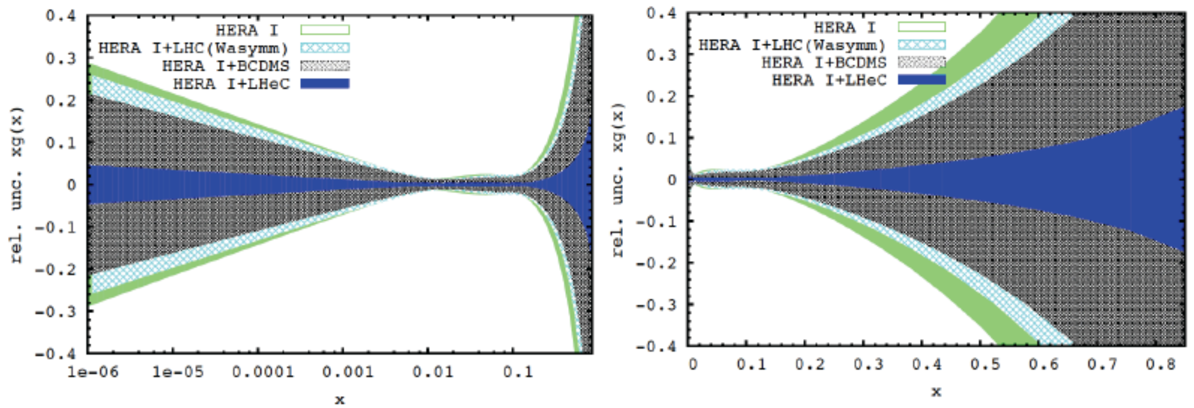
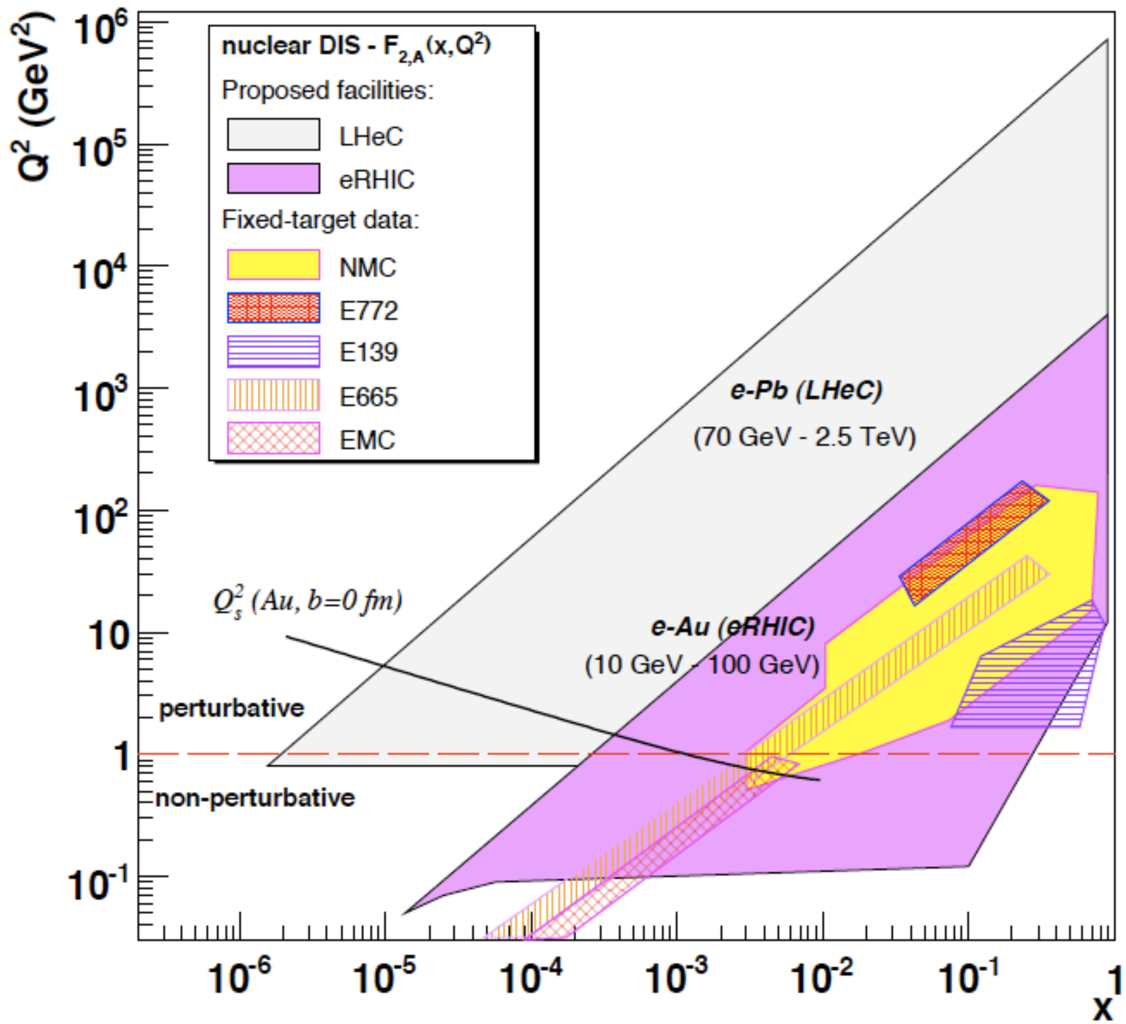


Figure 4.17: Relative uncertainty of the gluon distribution at $Q^2 = 1.9\,\mathrm{GeV}^2$, as resulting from an NLO QCD fit to HERA (I) alone (green, outer), HERA and BCDMS (crossed), HERA and LHC (light blue, crossed) and the LHeC added (blue, dark). Left: logarithmic x, right: linear x.

Precision measurement of gluon density to extreme x – α_s
Low x: saturation? radical change of understanding
High x: xg and valence quarks most crucial for new states
Gluon in Pomeron, odderon, photon, nuclei.. Local spots in p?
Heavy quarks intrinsic or only gluonic

Electron-Ion Scattering: eA → eX

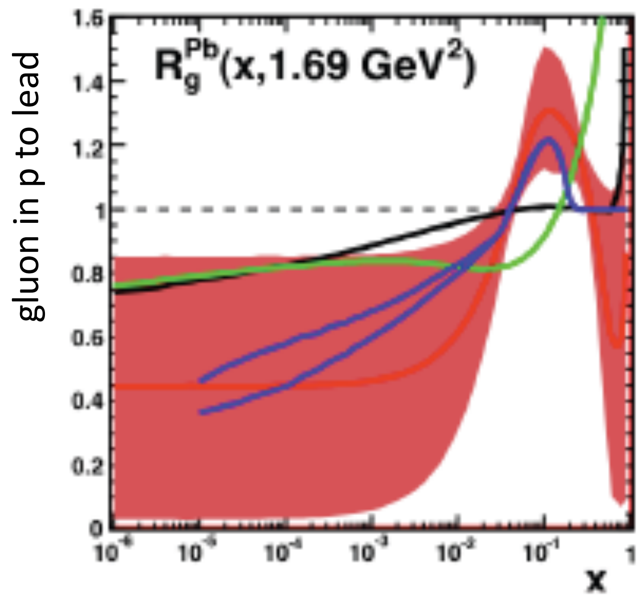


Q^2 = 4momentum transfer^2 Bjorken x: fraction of p's momentum

Extension of kinematic range by 3-4 orders of magnitude into saturation region (with p **and** with A)

Qualitative change of behaviour

- Bb limit of F_2
- Saturation of cross sections amplified with $A^{1/3}$
- Rise of diffraction to 50%?
- partons in nuclei – widely unknown



LHeC Accelerator Design: Participating Institutes

CERN

SLAC NATIONAL ACCELERATOR LABORATORY

NTNU
Norwegian University of Science and Technology

CLIC

The Cockcroft Institute of Accelerator Science and Technology

Jefferson Lab
Thomas Jefferson National Accelerator Facility

ANKARA ÜNİVERSİTESİ 1946

NİĞDE ÜNİVERSİTESİ 1992

ULUDAĞ ÜNİVERSİTESİ 1975

TOBB ETU

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

DESY

LAL Physique des accélérateurs

ECFA

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

UNIVERSITY OF LIVERPOOL

BROOKHAVEN NATIONAL LABORATORY

СИБИРСКОЕ ОТДЕЛЕНИЕ РАН
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им. Г.И.Будкера
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KEK

TUPC017 Civil Engineering Studies for Major Projects after LHC
John Andrew Osborne, Frederic Magnin, Eliseo Perez-Duenas

TUPC045 Recirculating Electron Linacs (REL) for LHeC and eRHIC
Dejan Trbojevic, Joanne Beebe-Wang, Yue Hao, Dmitry Kayran, Vladimir N. Litvinenko, Vadim Ptitsyn, Nicholaos Tsoupas

TUPC054 LHeC ERL Design and Beam-dynamics Issues
Alex Bogacz, Ilkyoung Shin, Daniel Schulte, Frank Zimmermann

WEODA03 Design Concepts for the Large Hadron Electron Collider
Max Klein for the LHeC Study Group

WEPZ013 Design Status of LHeC Linac-Ring Interaction Region
Rogelio Tomas, Jose Luis Abelleira, Stephan Hans Russenschuck, Frank Zimmermann, Nathan Rogers Bernard

THPZ014 LHeC Lattice Design
Miriam Fitterer, Oliver Sim Bruening, Helmut Burkhardt, Bernhard Johannes Holzer, John M. Jowett, Karl Hubert Mess, Thys Risselada, Anke-Susanne Mueller, Max Klein

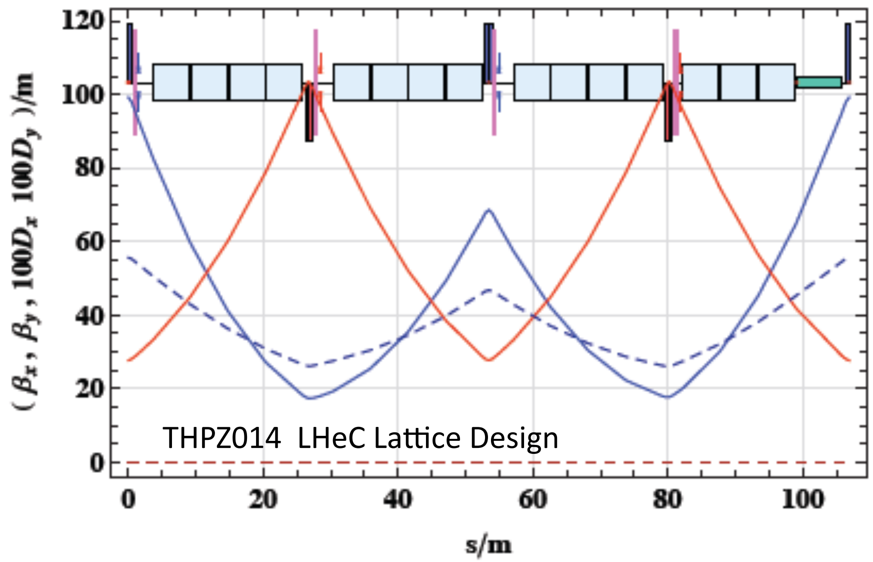
THPZ015 Synchrotron Radiation in the Interaction Region for a Ring-Ring and Linac-Ring LHeC
Nathan Rogers Bernard, Bernhard Johannes Holzer, Rogelio Tomas, Frank Zimmermann, Peter Kostka, Max Klein, Boris Nagorny, Uwe Schneekloth, Robert Appleby, Luke Thompson

THPZ016 Interaction Region Design for a Ring-Ring LHeC
Luke Thompson, Bernhard Johannes Holzer, Miriam Fitterer, Peter Kostka, Max Klein, Nathan Rogers Bernard, Robert Appleby

THPZ023 LHeC Spin Rotator
Mei Bai, Rogelio Tomas, Frank Zimmermann

Contributions to IPAC11

FODO (half LHC size, asy dipoles, 23 arc cells)



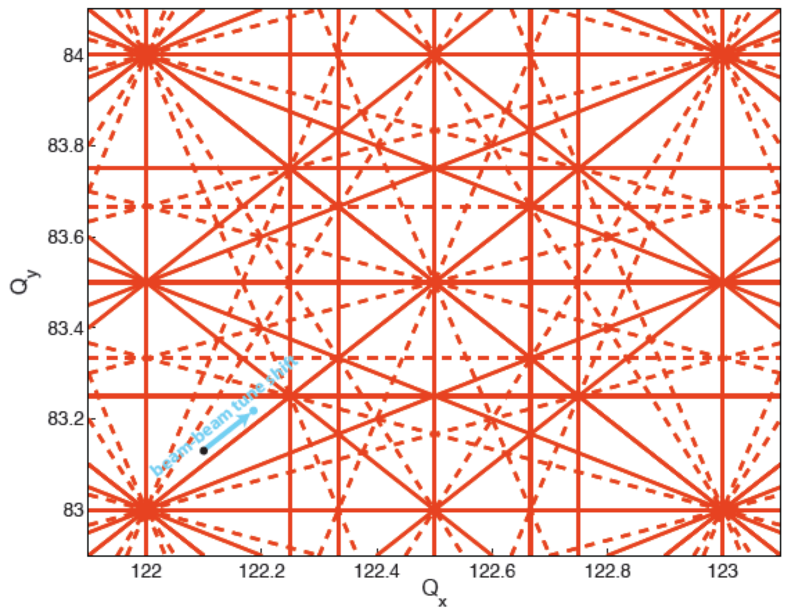


Figure 7.15: Working Point for the 1° optics. The dashed lines are the coupling resonances up to 4th order, the solid lines the constructive resonances up to 4th order. The black dot indicates the working point without beam-beam tune shift and the blue one with beam-beam tune shift.

Constraints:

Bypass existing LHC experiments

$U_p=U_e$ → shift of e ring to inside

100kg/m tunnel load limit: support from below (HERA)

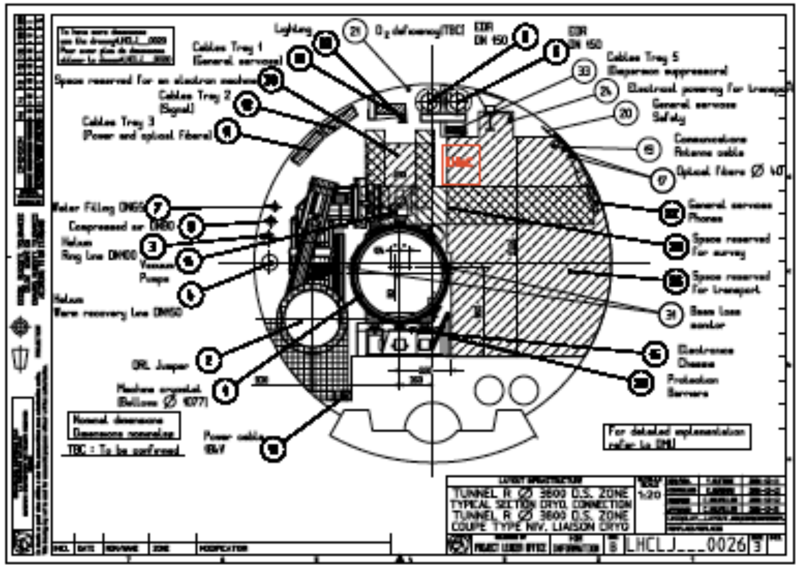


Figure 7.47: Cross-section of the LHC tunnel with the original space holder for the electron beam installation directly above the LHC cryostat and the shifted new required space due to the additional bypass in IR1 and IR5 and the need to keep the overall circumference of the electron ring identical to that of the proton beams.

Issues:

QRL service with jumper – asymmetric FODO

transport: magnets ok, cryo equipment full height

occurs during warmup – shift locally e beam?

dump area – reroute cables

proton rf -- e "just a pipe"

SEU's from e: shielding, LHC power converters then out

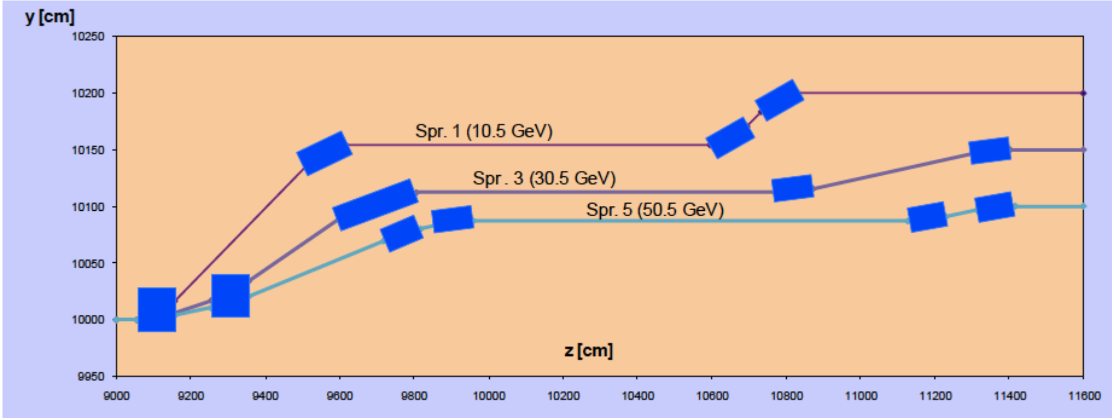
IP3, LSS7, p collimation …

no show stopper found but challenging and CAD needed next

ERL stores energy while ring stores electrons

Same RF for acc and deacc. → rf acc power independent of I

Switchyard: two-step spreaders and mirror symmetric recomb.



Multipass linear optics: sharing of arcs by acc/deacc. passes

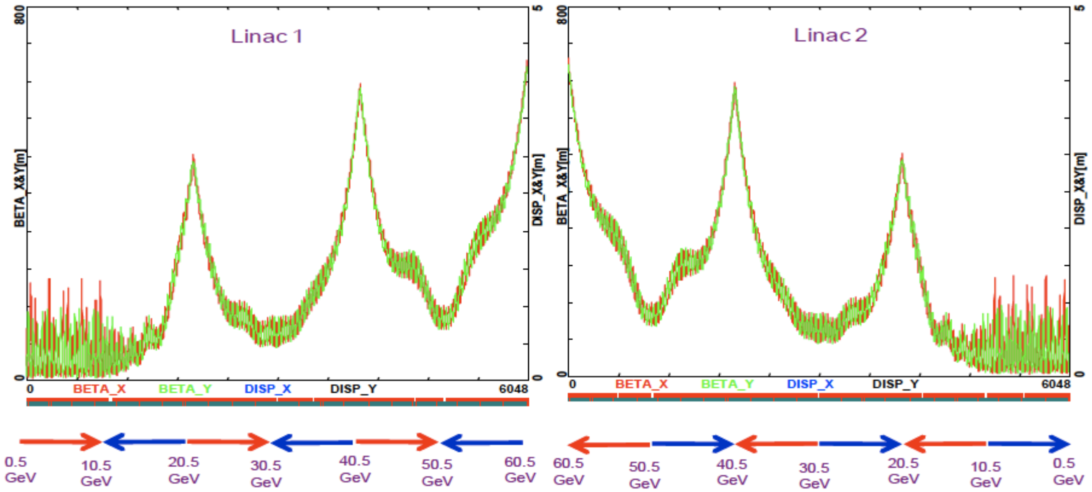


Figure 2: Multi-pass linac optics optimized for 3-pass ERL As a virtue of ER, Linac 1 and 2 are mirror reflections.

Cumulative transverse deflections from each cavity so far ok to 5mA

TUPC054
LHeC ERL Design and Beam-dynamics Issues

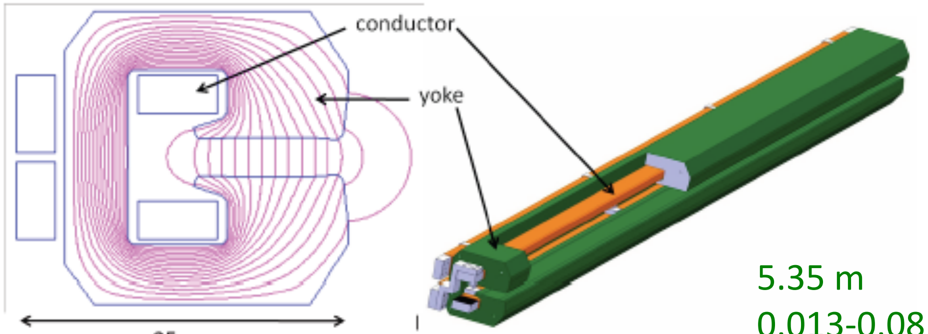
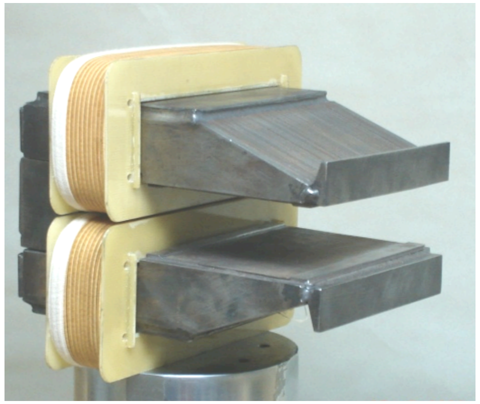


Fig. 2. Field lines and artistic view of a LHeC arc dipole.

5.35 m
0.013-0.08 T
~200kg/m



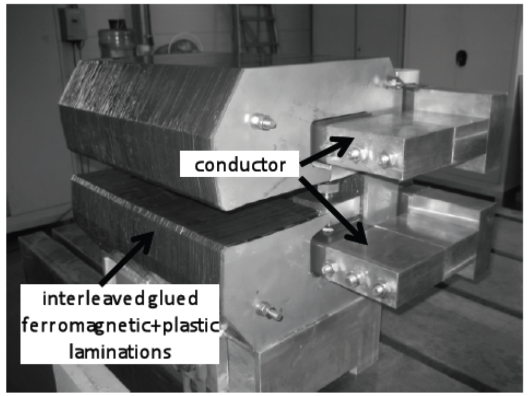


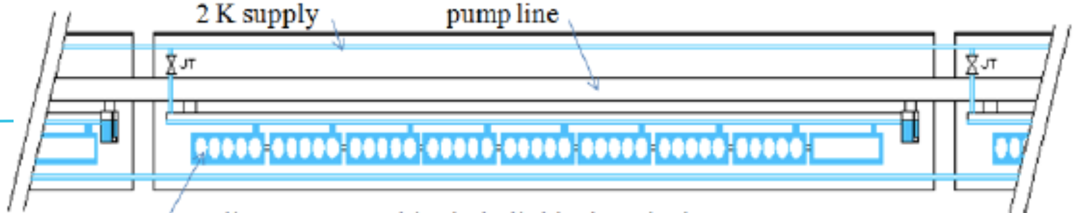
TABLE II REPRODUCIBILITY OF MAGNETIC FIELD OVER 8 CYCLES

Model	Low field	High fields
Maximum Relative Deviation from Average		
Model 1 (NiFe steel)	$5\cdot10^{-5}$	$4\cdot10^{-5}$
Model 2 (Low carbon steel)	$6\cdot10^{-5}$	$6\cdot10^{-5}$
Model 3 (Grain oriented 3.5% Si steel)	$4\cdot10^{-5}$	$6\cdot10^{-5}$
Standard Deviation from Average		
Model 1 (NiFe steel)	$3\cdot10^{-5}$	$3\cdot10^{-5}$
Model 2 (Low carbon steel)	$4\cdot10^{-5}$	$5\cdot10^{-5}$
Model 3 (Grain oriented 3.5% Si steel)	$2\cdot10^{-5}$	$4\cdot10^{-5}$

Prototypes from BINP and CERN: function to spec's

Table 2: Components of the Electron Accelerators

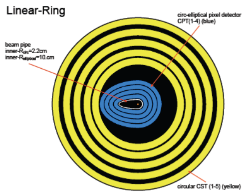
	Ring	Linac
magnets		
beam energy	60 GeV	
number of dipoles	3080	3600
dipole field [T]	0.013 – 0.076	0.046 – 0.264
total nr of quads	866	1588
RF and cryogenics		
number of cavities	112	944
gradient [MV/m]	11.9	20
RF power [MW]	49	39
cavity voltage [MV]	5	21.2
cavity R/Q [Ω]	114	285
cavity Q_0	–	$2.5\ 10^{10}$
cooling power [kW]	5.4@4.2 K	30@2 K



systems will consist of a complex task. Further cavities and cryomodules will require a limited R&D program. From this we expect improved quality factors with respect to today's state of the art. The cryogenics of the L-R version consists of a formidable engineering challenge, however, it is feasible and, CERN disposes of the respective know-how.

from CDR LHeC

IV Detector



Requirements High Precision (resolution, calibration, low noise, tagging of b,c)

Modular for 'fast' installation

State of the art technology - 'no' R+D (HERA,LHC upgrade)

1-179° acceptance for low Q^2, high x (beam pipe, synrad)

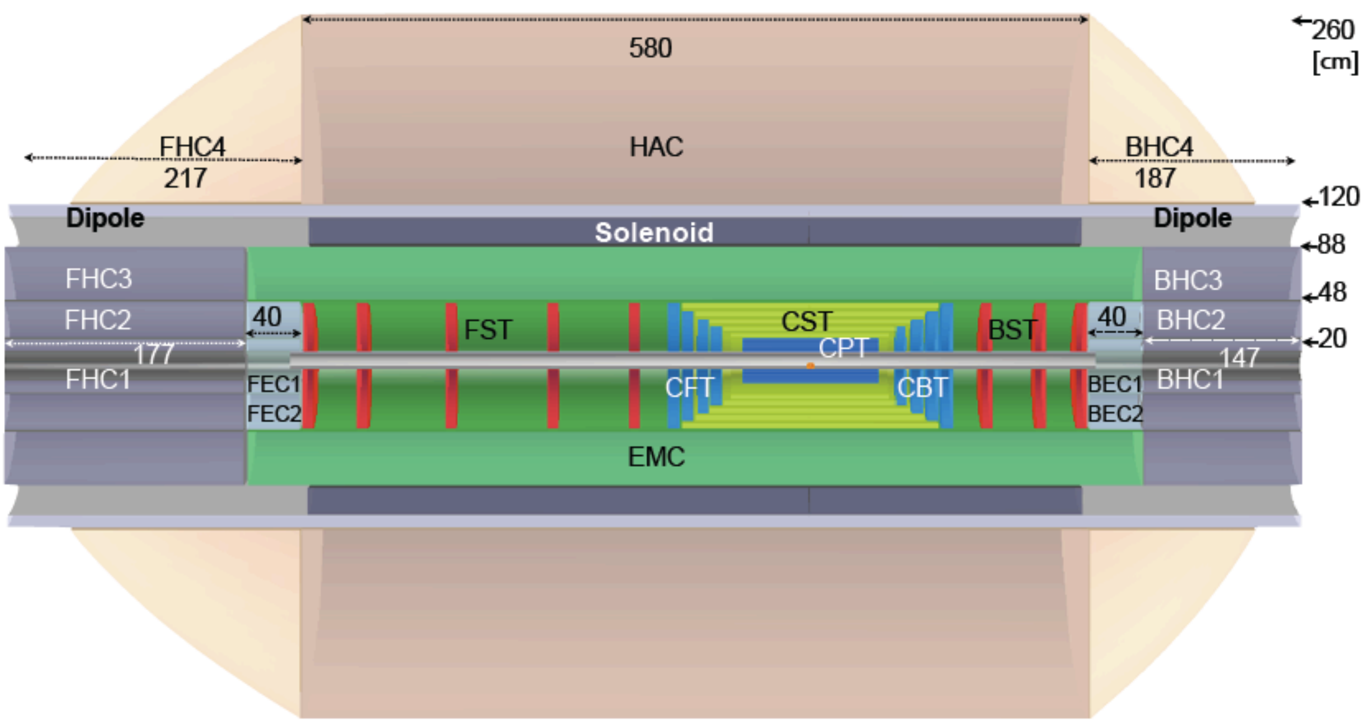


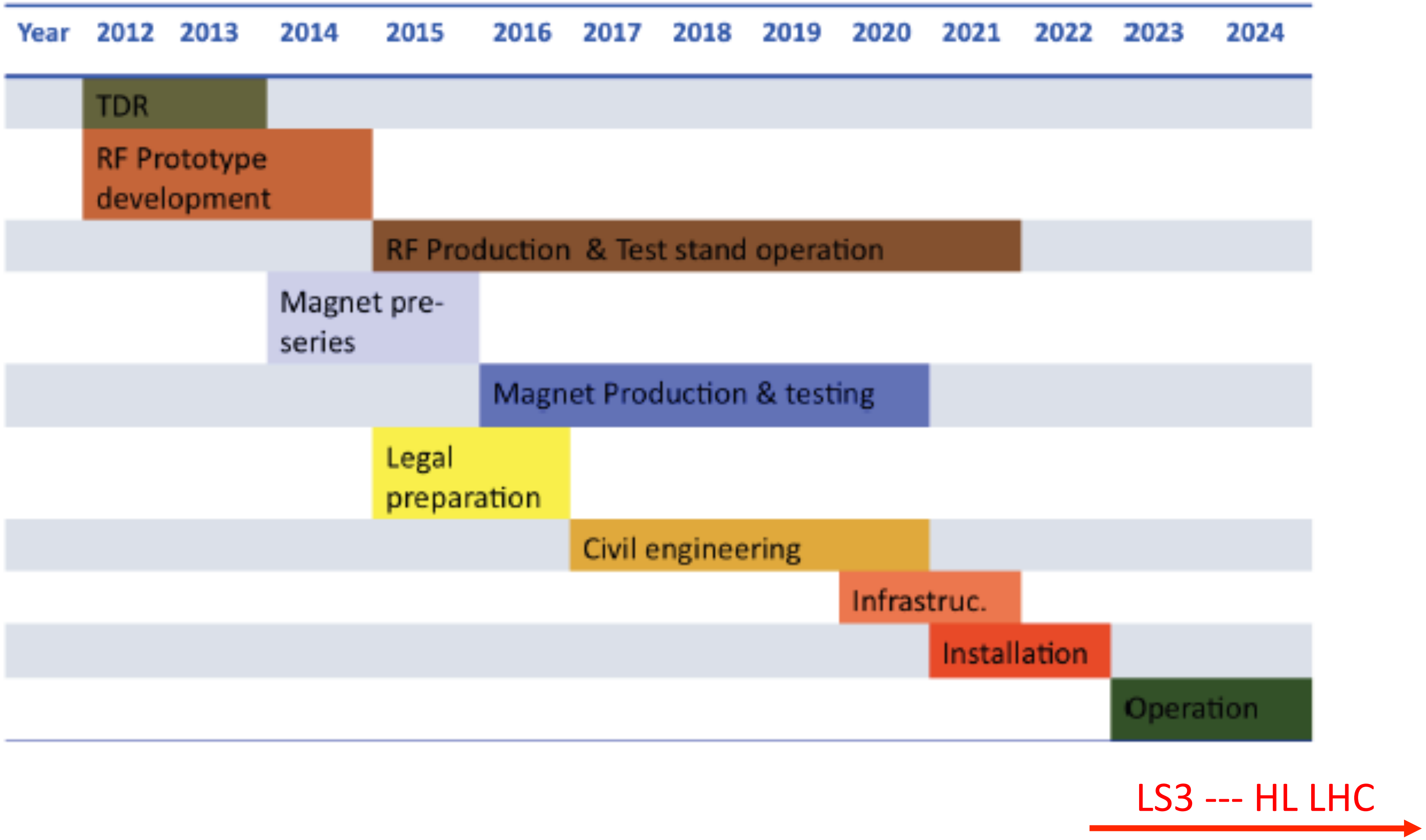
Figure 13.9: An *rz* cross section of the LHeC detector, in its baseline configuration (A). In

Si tracker, LAr elm cal, sc coil 3.5T, Tile hcal, Muon detector not shown

Present dimensions: LxD =14x9m² [CMS 21 x 15m², ATLAS 45 x 25 m²]

Taggers at -62m (e),100m (γ,LR), -22.4m (γ,RR), +100m (n), +420m (p)

LHeC Tentative Time Schedule



We base our estimates for the project time line on the experience of other projects, such as (LEP, LHC and LINAC4 at CERN and the European XFEL at DESY and the PSI XFEL)

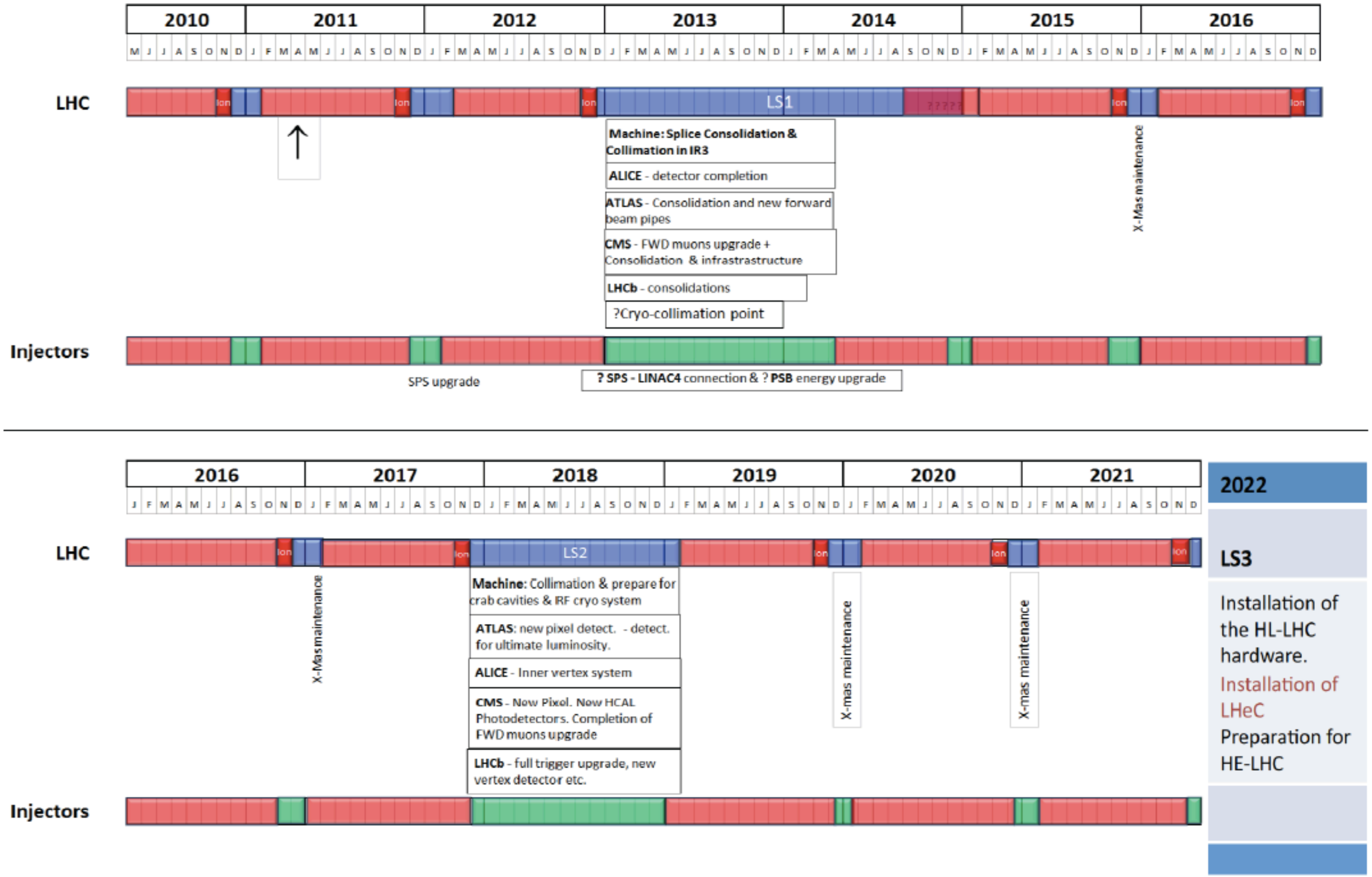


Figure 11.1: CERN medium term plan (MTP), draft as of July 2011

Table 1: Parameters of the RR and RL Configurations

	Ring	Linac
electron beam		
beam energy E_e	60 GeV	
e^- (e^+) per bunch N_e [10^9]	20 (20)	1 (0.1)
e^- (e^+) polarisation [%]	40 (40)	90 (0)
bunch length [mm]	10	0.6
tr. emittance at IP $\gamma\epsilon^e_{x,y}$ [mm]	0.58, 0.29	0.05
IP β function $\beta^*_{x,y}$ [m]	0.4, 0.2	0.12
beam current [mA]	131	6.6
energy recovery intensity gain	–	17
total wall plug power	100 MW	
syn rad power [kW]	51	49
critical energy [keV]	163	718
proton beam		
beam energy E_p	7 TeV	
protons per bunch N_p	$1.7 \cdot 10^{11}$	
transverse emittance $\gamma\epsilon^p_{x,y}$	3.75 μm	
collider		
Lum e^-p (e^+p) [10^{32}cm^{-2}s^{-1}]	9 (9)	10 (1)
bunch spacing	25 ns	
rms beam spot size $\sigma_{x,y}$ [μm]	30, 16	7
crossing angle θ [mrad]	1	0
$L_{eN} = A\, L_{eA}$ [10^{32}cm^{-2}s^{-1}]	0.3	1

Both the ring and the linac are feasible and both come very close to the desired performance. The pleasant challenge is to soon decide for one.

CERN-ECFA-NuPECC:
CDR Draft (530pages) being refereed
Publish early 2012

Steps towards TDR (tentative)

-Prototype IR magnet (3 beams)
-Prototype Dipole (1:1)
-Develop Cavity/Cryomodule
-Civil Engineering, …

Build international collaborations
for the accelerator and detector development. Strong links to ongoing accelerator and detector projects.

The LHC offers the unique perspective for a further TeV scale collider. The LINAC's are of about 2mile length, yet the Q^2 is 10^5 times larger than was achieved when SLAC discovered quarks. Particle physics needs pp, ll and ep.
Here is a realistic prospect to progress.

http://cern.ch/lhec

LHeC Study Group

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About 150 Experimentalists and Theorists from 50 Institutes

Tentative list

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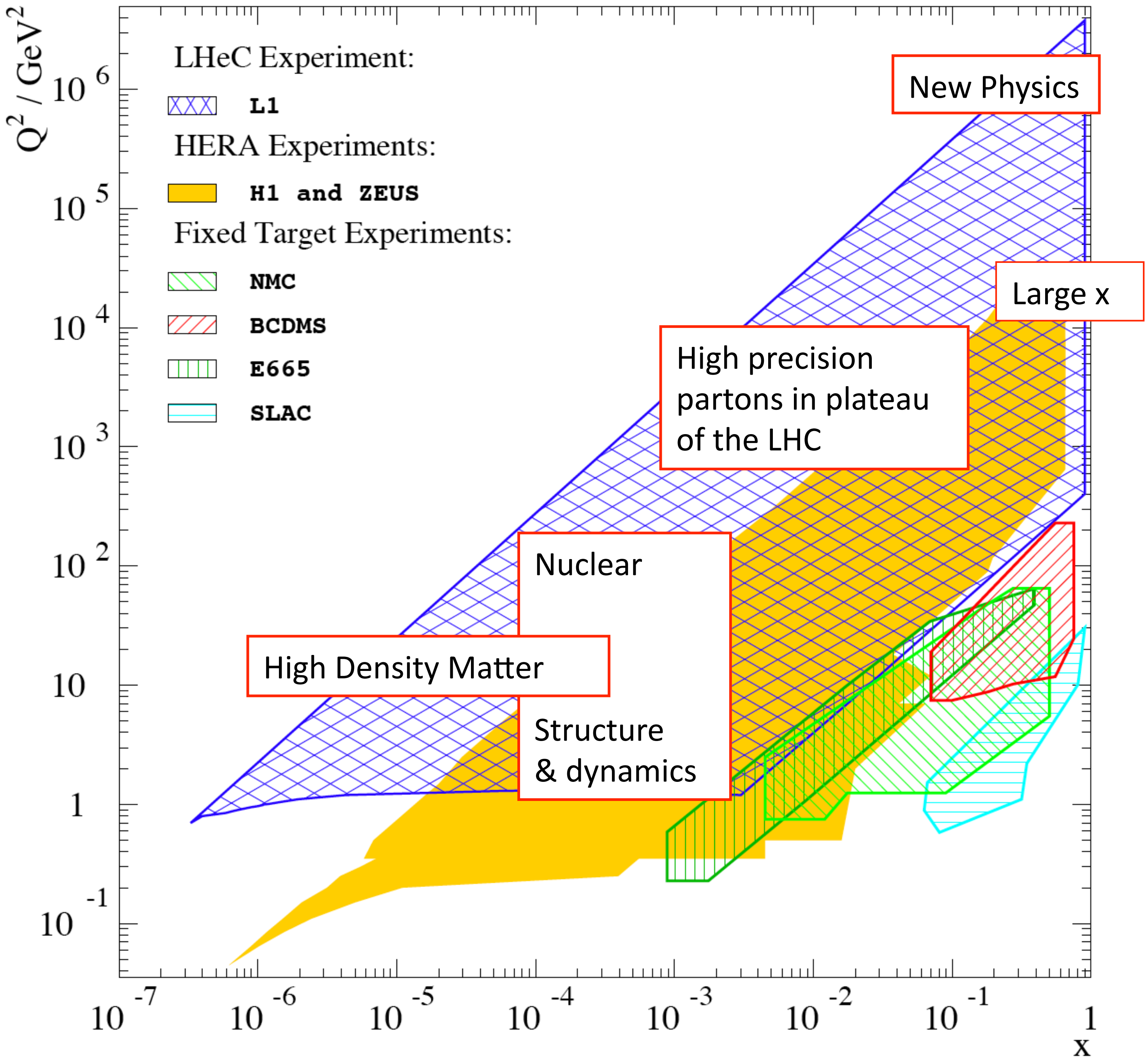
backup



Q^2 = 4momentum transfer^2

x = Bjorken x: fraction of p's momentum

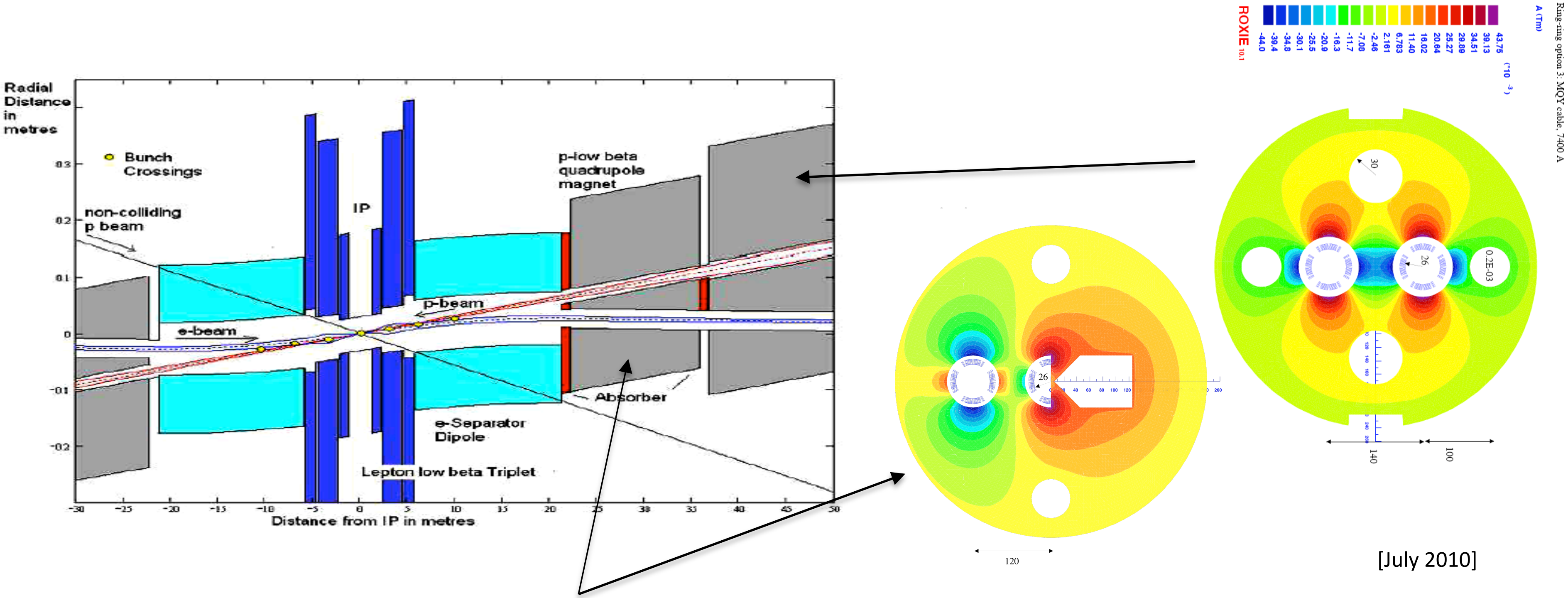
LHeC

Physics

eQ states
GUT ($\delta\alpha_s$=0.1%)
Excited fermions
Hot/cold spots
Single top
Higgs
PDFs
Multi-Jets
DVCS
Unintegrated partons
Saturation
Vector Mesons
IP - graviton
Odderons
NC couplings
$\sin^2\Theta$
Beauty
Charm
Partons in nuclei
Shadowing
....

Interaction Region(s)

RR -Small crossing angle ~1mrad (25ns) to avoid first parasitic crossing (L x 0.77)
LR – Head on collisions, dipole in detector to separate beams
Synchrotron radiation –direct and back, absorption simulated (GEANT4) ..



1st sc half quad (focus and deflect)
separation 5cm, g=127T/m, MQY cables, 4600 A

2nd quad: 3 beams in horizontal plane
separation 8.5cm, MQY cables, 7600 A