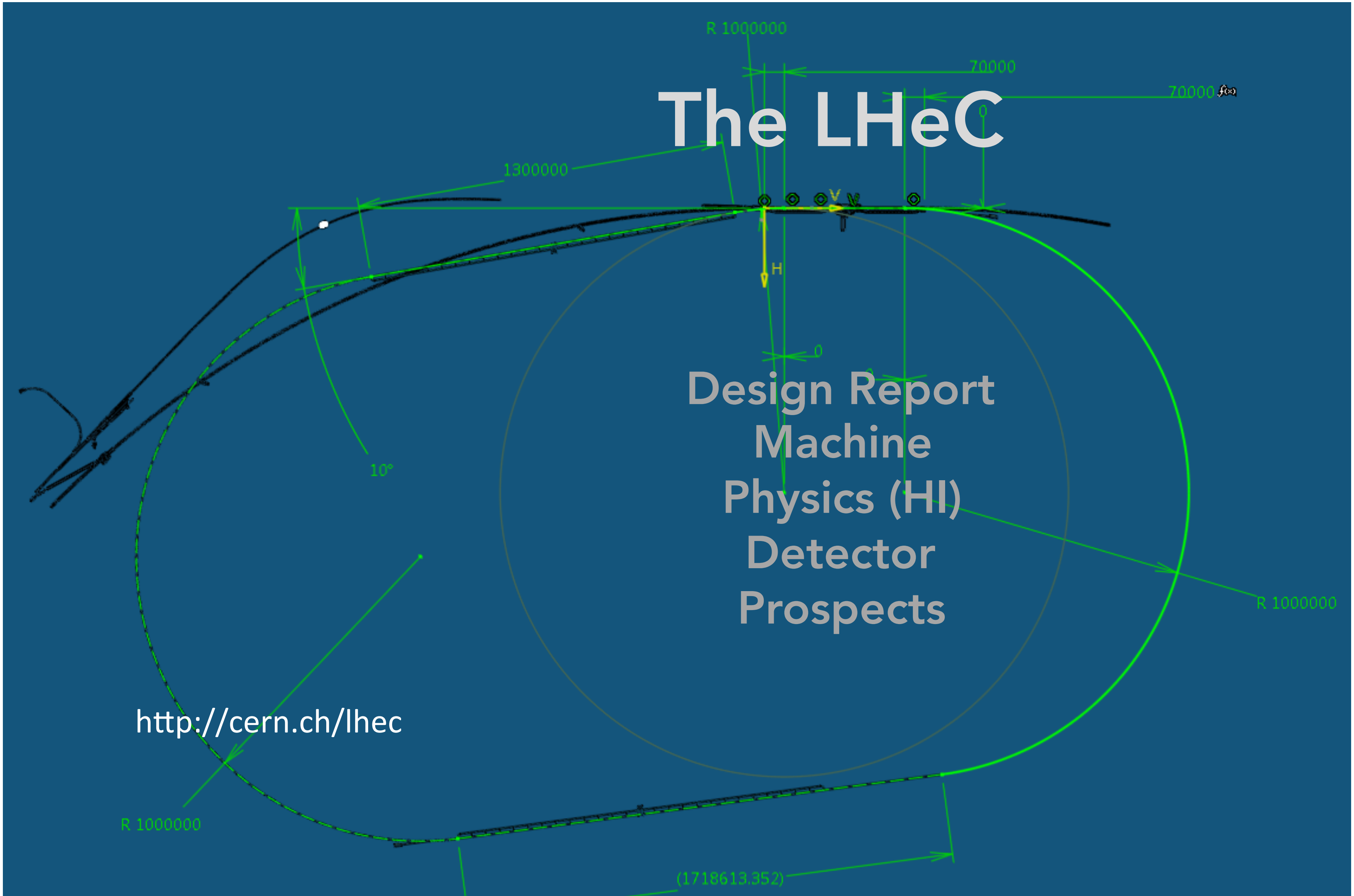
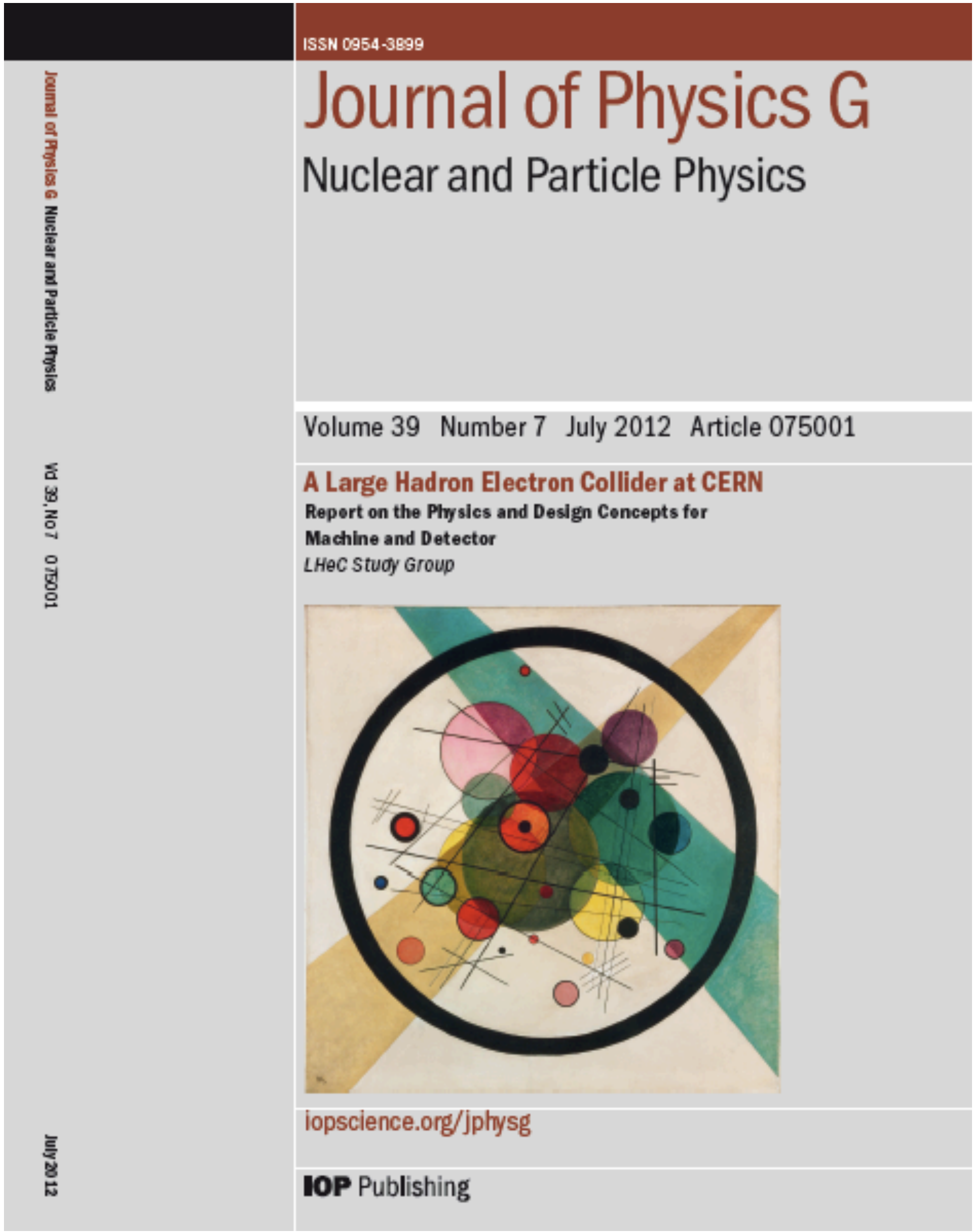


The LHeC

Design Report
Machine
Physics (HI)
Detector
Prospects

http://cern.ch/lhec

Max Klein, University of Liverpool + CERN - NuPECC Meeting at Sevilla, 6.10.2012



ISSN 0954-3899

Journal of Physics G

Nuclear and Particle Physics

Volume 39 Number 7 July 2012 Article 075001

A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group

iopscience.org/jphysg

IOP Publishing

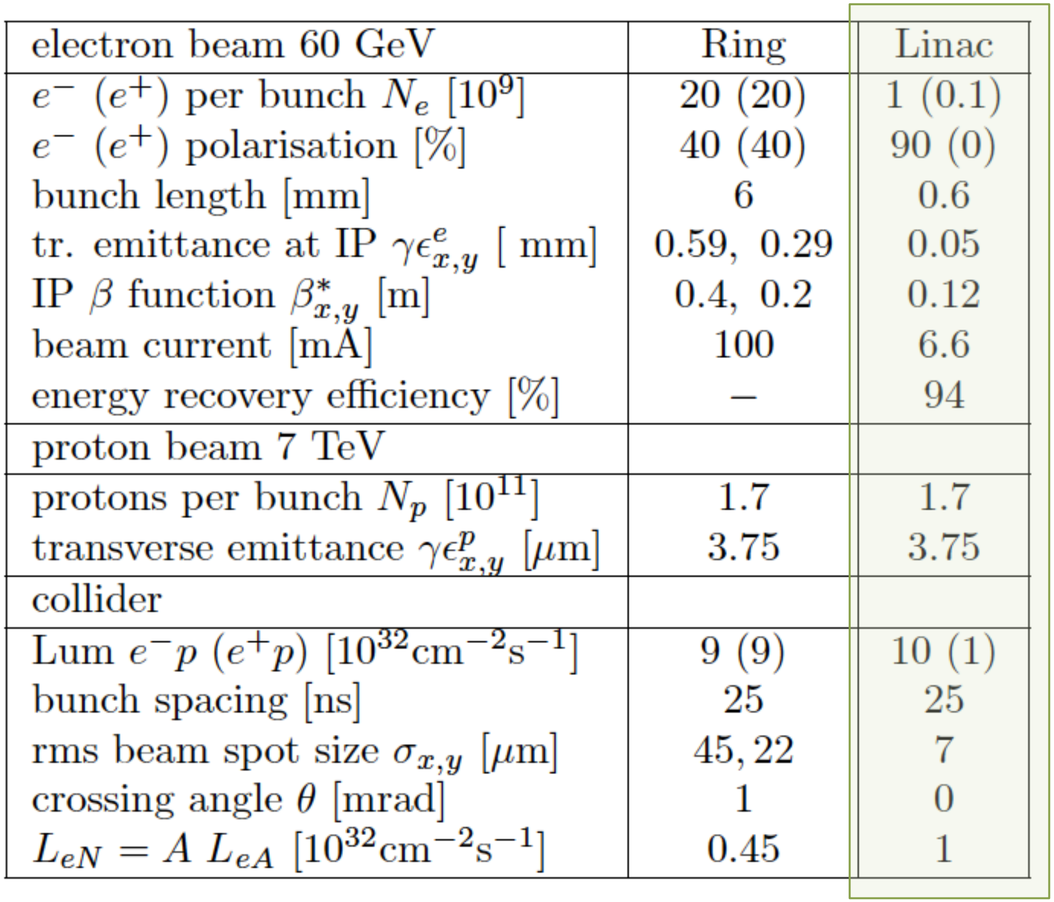
Journal of Physics G Nuclear and Particle Physics Vol 39, No 7 075001 July 2012

CERN Referees

Ring Ring Design
Kurt Huebner (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)
Linac Ring Design
Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)
Energy Recovery
Georg Hoffstaetter (Cornell)
Ilan Ben Zvi (BNL)
Magnets
Neil Marks (Cockcroft)
Martin Wilson (CERN)
Interaction Region
Daniel Pitzl (DESY)
Mike Sullivan (SLAC)
Detector Design
Philippe Bloch (CERN)
Roland Horisberger (PSI)
Installation and Infrastructure
Sylvain Weisz (CERN)
New Physics at Large Scales
Cristinel Diaconu (IN2P3 Marseille)
Gian Giudice (CERN)
Michelangelo Mangano (CERN)
Precision QCD and Electroweak
Guido Altarelli (Roma)
Vladimir Chekelian (MPI Munich)
Alan Martin (Durham)
Physics at High Parton Densities
Alfred Mueller (Columbia)
Raju Venugopalan (BNL)
Michele Arneodo (INFN Torino)

Published 600 pages conceptual design report (CDR) written by 200 authors from 60 Institutes and refereed by 24 world experts on physics, accelerator and detector, which CERN had invited.

LHeC Parameters

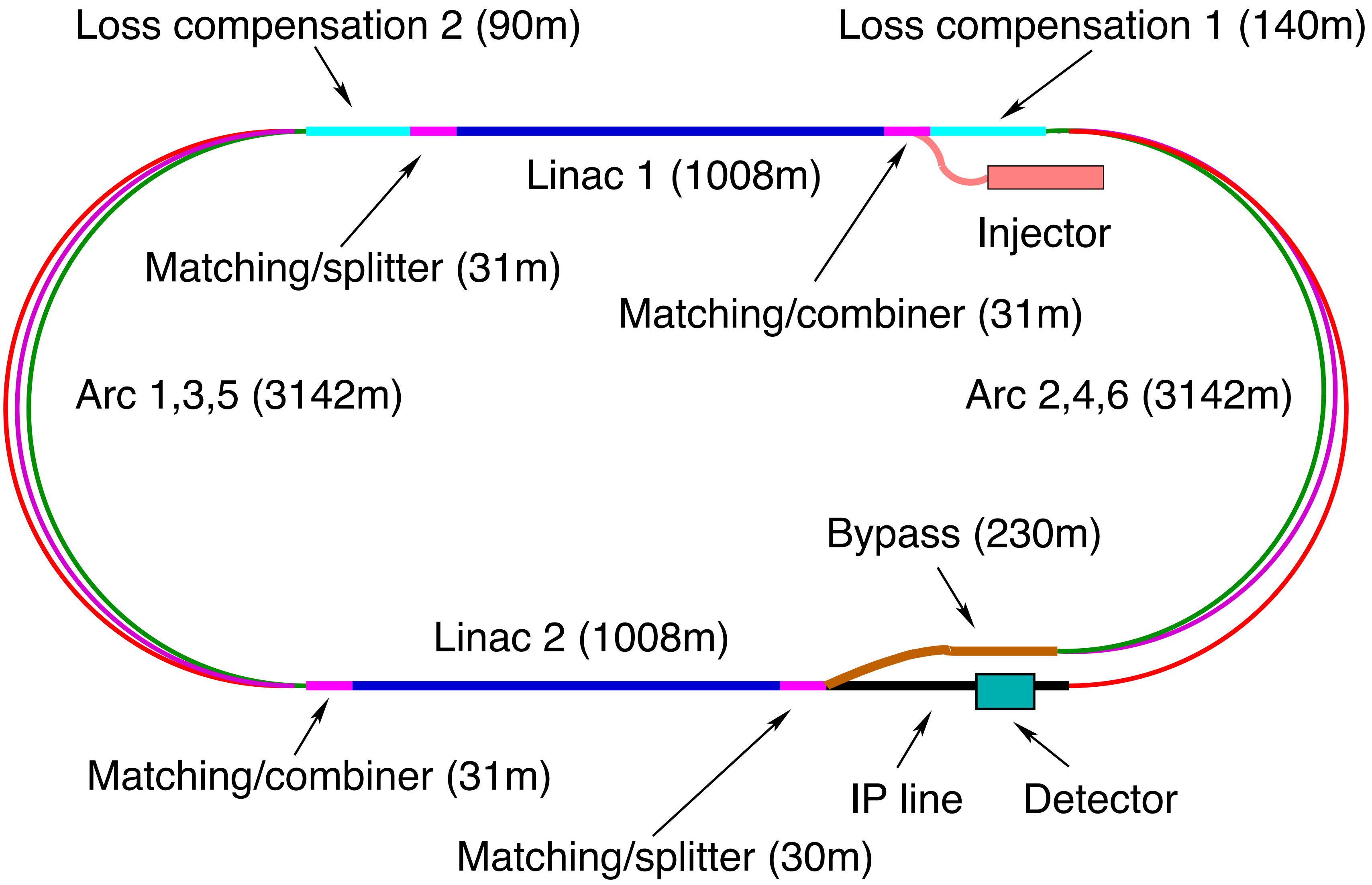


electron beam 60 GeV	Ring	Linac
e^- (e^+) per bunch N_e [10^9]	20 (20)	1 (0.1)
e^- (e^+) polarisation [%]	40 (40)	90 (0)
bunch length [mm]	6	0.6
tr. emittance at IP $\gamma\epsilon^e_{x,y}$ [mm]	0.59, 0.29	0.05
IP β function $\beta^*_{x,y}$ [m]	0.4, 0.2	0.12
beam current [mA]	100	6.6
energy recovery efficiency [%]	–	94
proton beam 7 TeV		
protons per bunch N_p [10^{11}]	1.7	1.7
transverse emittance $\gamma\epsilon^p_{x,y}$ [μm]	3.75	3.75
collider		
Lum e^-p (e^+p) [10^{32}cm^{-2}s^{-1}]	9 (9)	10 (1)
bunch spacing [ns]	25	25
rms beam spot size $\sigma_{x,y}$ [μm]	45, 22	7
crossing angle θ [mrad]	1	0
$L_{eN} = A\ L_{eA}$ [10^{32}cm^{-2}s^{-1}]	0.45	1

Linac Power Consumption

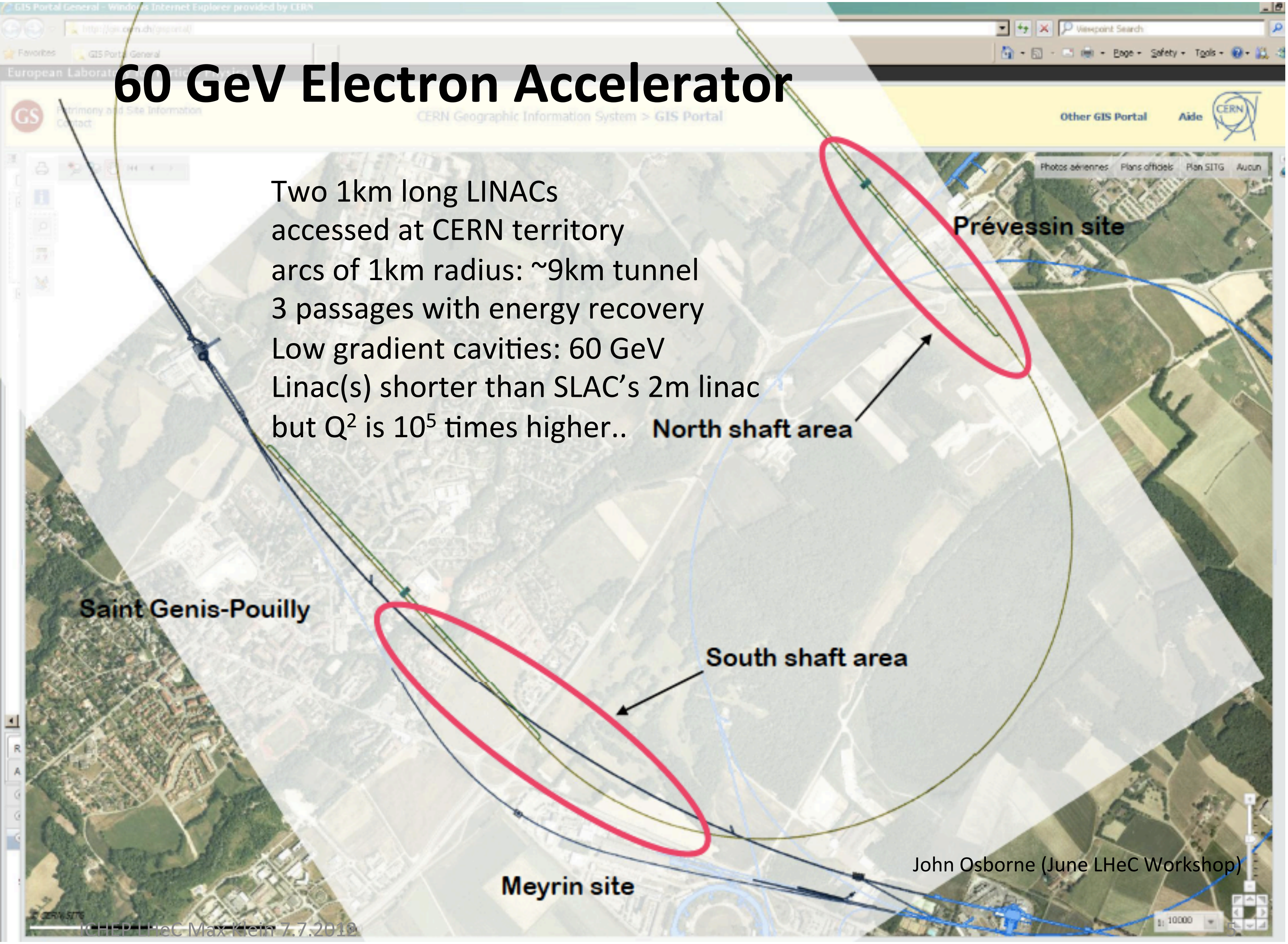
Source	Power [MW]
Cryogenics (linac)	21
Linac grid power	24
SR compensation	23
Extra RF cryopower	2
Injector	6
Arc magnets	3
Total	**78**

CDR: Two options for electron beam: Ring or (Racetrack) Linac with E-recovery for L > 10^{33}cm^{-2}s^{-1}
Synchronous operation of pp and ep in HL-LHC phase. e Ring required bypassing pp experiments
Subsequent workshop (6/12) decided to develop Linac as baseline, following CERN mandate



60 GeV electron beam energy, L= 10^{33} cm^{-2}s^{-1}, $\sqrt{s}$=1.3 TeV: Q^2_{max} 10^6 GeV^2, $10^{-6} < x < 1$
Recirculating linac (2 * 1km, 2*60 cavity cryo modules, 3 passes, P < 100 MW, ERL)

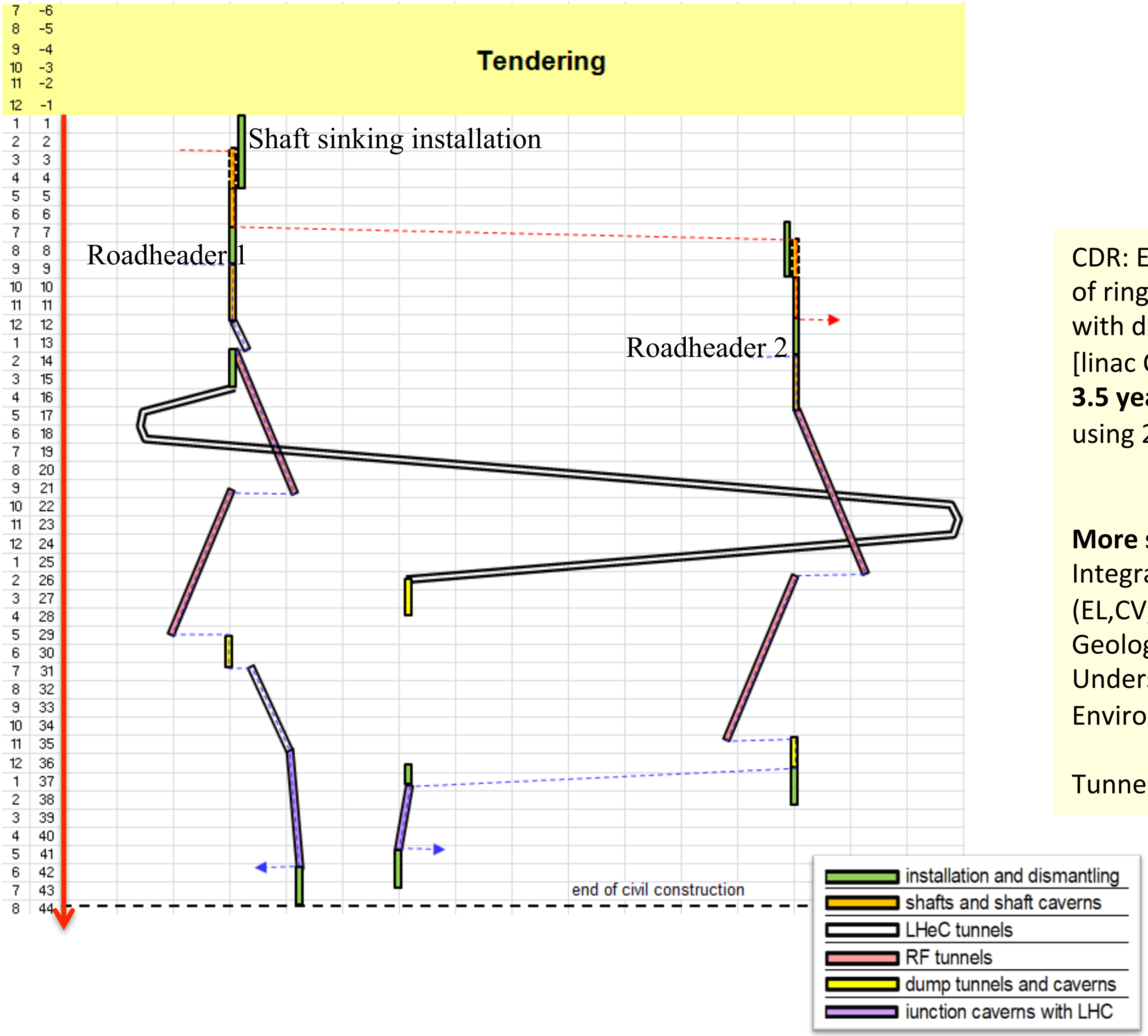
60 GeV Electron Accelerator



Two 1km long LINACs
accessed at CERN territory
arcs of 1km radius: ~9km tunnel
3 passages with energy recovery
Low gradient cavities: 60 GeV
Linac(s) shorter than SLAC's 2m linac
but Q^2 is 10^5 times higher..

John Osborne (June LHeC Workshop)

Civil Engineering



CDR: Evaluation of CE, analysis of ring and linac by Amber Zurich with detailed cost estimate [linac CE: 249,928 kSF..] and time: **3.5 years for underground works** using 2 roadheaders and 1 TBM

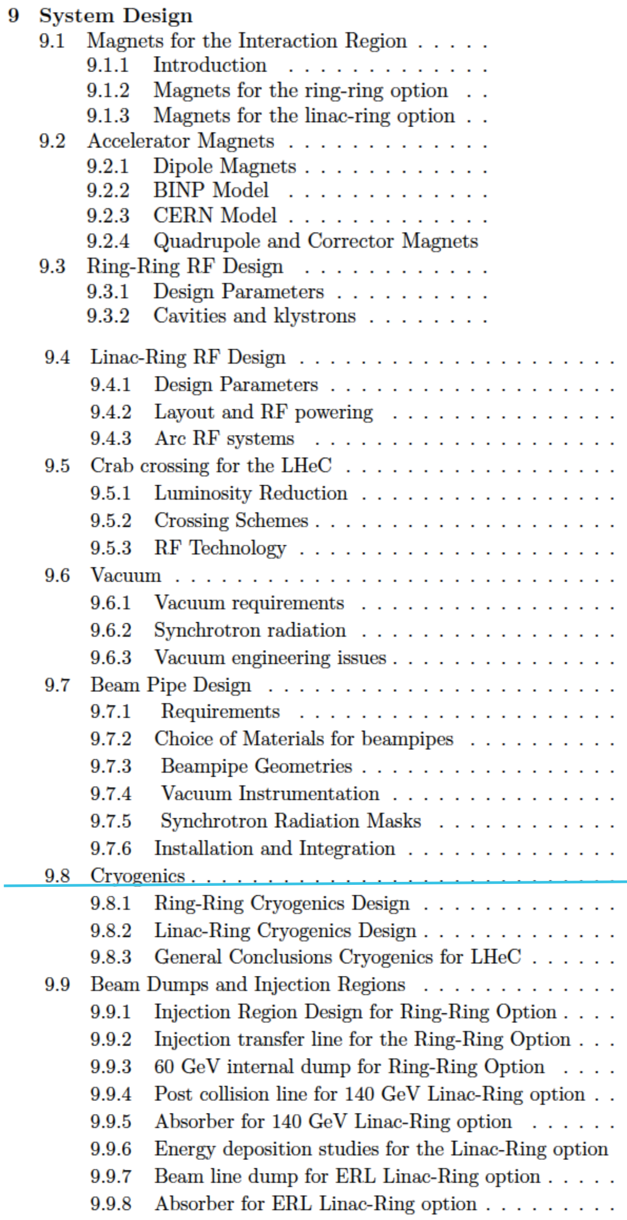
More studies needed for
Integration with all services (EL,CV, transport, survey etc).
Geology
Understanding vibration risks
Environmental impact assessment

Tunnel connection in IP2

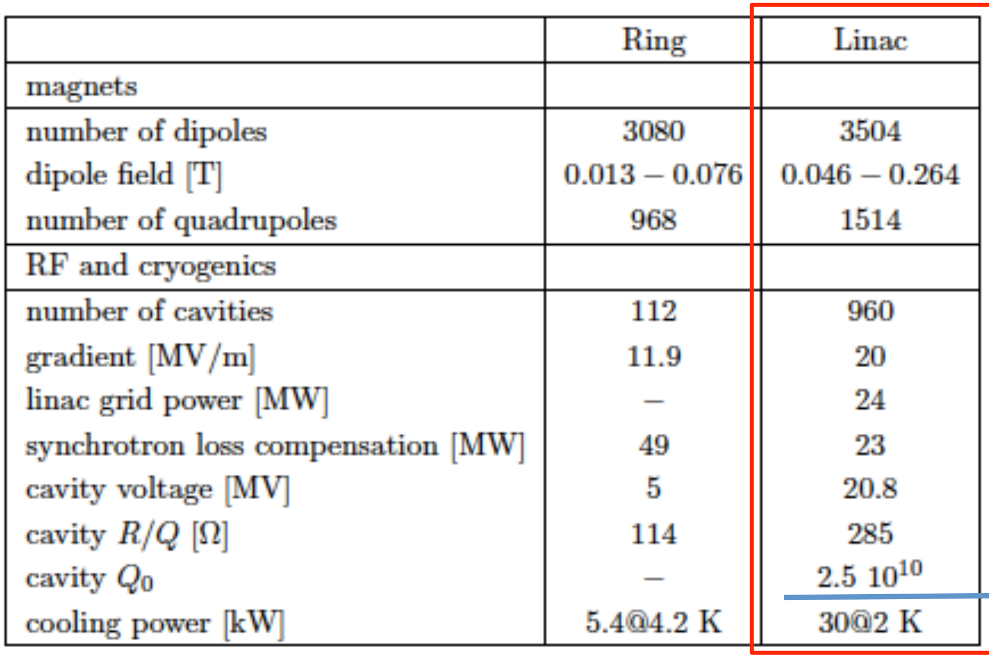
J.Osborne, Chavannes

Chapter 9 of CDR

Components and Cryogenics

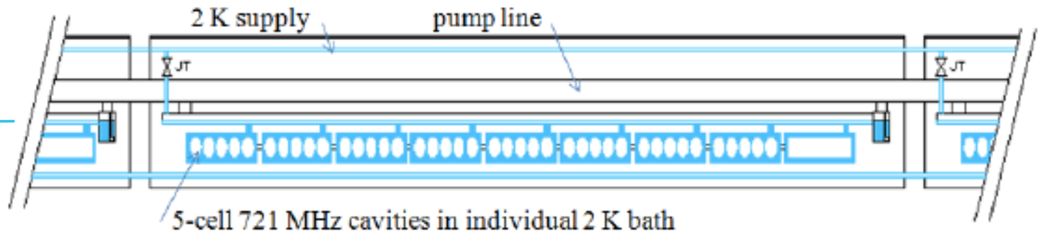


9 System Design



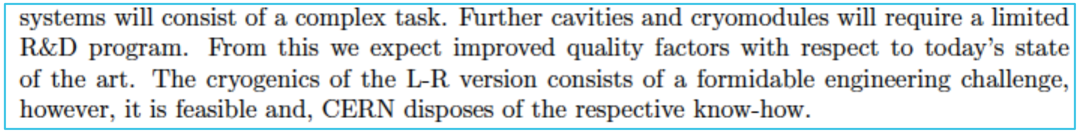
	Ring	Linac
magnets		
number of dipoles	3080	3504
dipole field [T]	0.013 – 0.076	0.046 – 0.264
number of quadrupoles	968	1514
RF and cryogenics		
number of cavities	112	960
gradient [MV/m]	11.9	20
linac grid power [MW]	–	24
synchrotron loss compensation [MW]	49	23
cavity voltage [MV]	5	20.8
cavity R/Q [Ω]	114	285
cavity Q_0	–	2.5 10^{10}
cooling power [kW]	5.4@4.2 K	30@2 K

Jlab:
4 10^{11}



5-cell 721 MHz cavities in individual 2 K bath

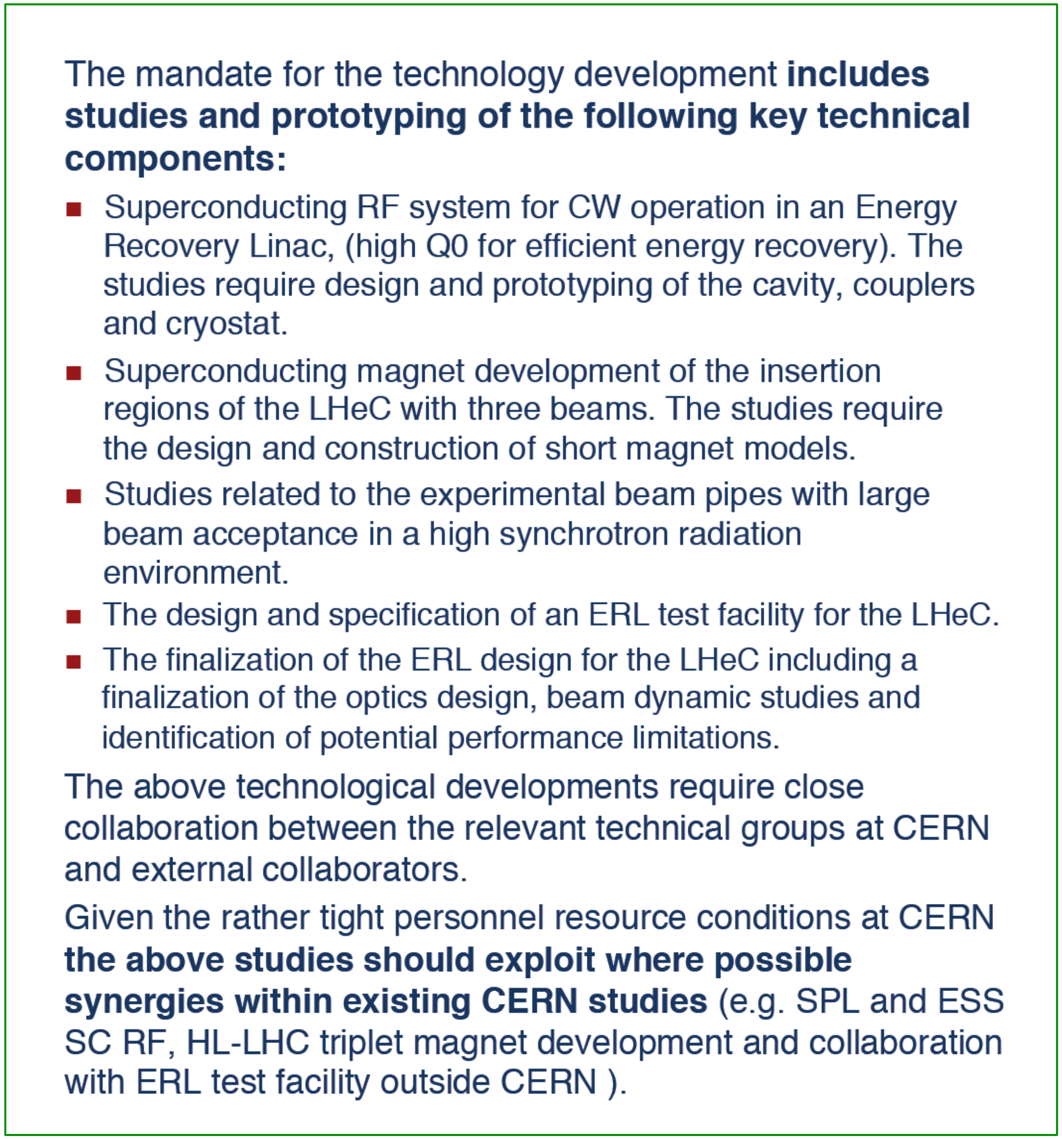
Need to develop LHeC cavity (cryo-module)



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

Preparations after CDR



The mandate for the technology development **includes studies and prototyping of the following key technical components:**

- Superconducting RF system for CW operation in an Energy Recovery Linac, (high Q0 for efficient energy recovery). The studies require design and prototyping of the cavity, couplers and cryostat.
- Superconducting magnet development of the insertion regions of the LHeC with three beams. The studies require the design and construction of short magnet models.
- Studies related to the experimental beam pipes with large beam acceptance in a high synchrotron radiation environment.
- The design and specification of an ERL test facility for the LHeC.
- The finalization of the ERL design for the LHeC including a finalization of the optics design, beam dynamic studies and identification of potential performance limitations.

The above technological developments require close collaboration between the relevant technical groups at CERN and external collaborators.

Given the rather tight personnel resource conditions at CERN **the above studies should exploit where possible synergies within existing CERN studies** (e.g. SPL and ESS SC RF, HL-LHC triplet magnet development and collaboration with ERL test facility outside CERN).

S.Bertolucci at Chavannes workshop 6/12 based on
CERN directorate's decision to include LHeC in the MTP

LHeC received mandate from CERN to prepare a TDR by ~2015

→ Corresponding first steps being taken

Preparation of MoUs by/with CERN

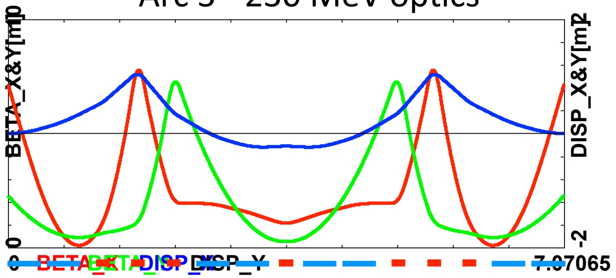
Much increased attention from international community:
LINAC12 BNL, Jlab, SLAC, ESS, BESSY, GSI, DESY, ..

At Cracow new expressions of interest in detector collaboration from several institutes in Italy, Sweden, Slovakia

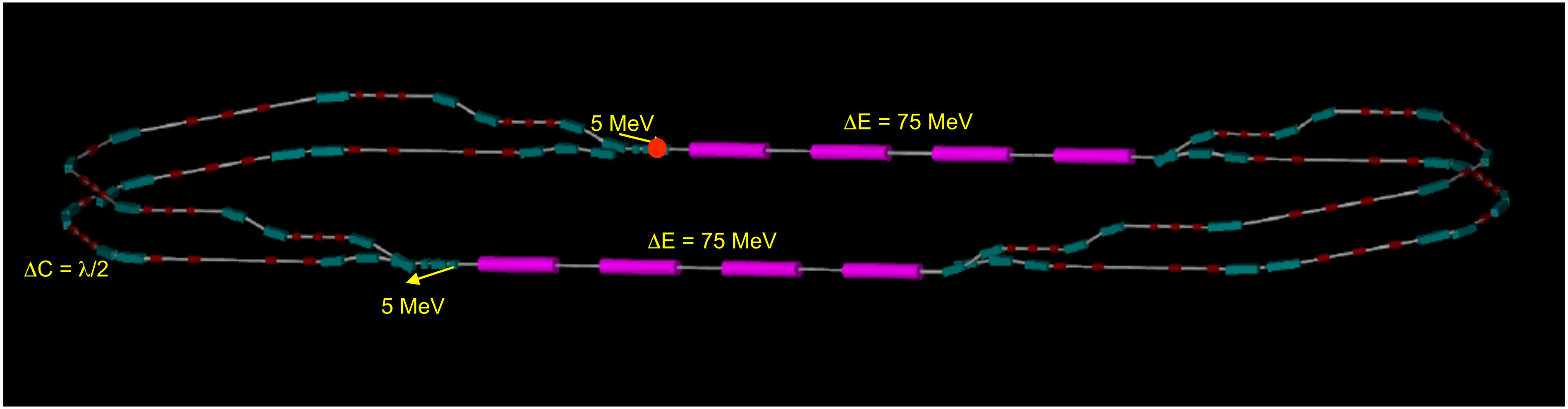
Visible support by the ESPP process will allow moving the LHeC development to the required next level of support.

LHeC – ERL - Testfacility at CERN

Tentative study of multipass optics and lattice



Arc 3 - 230 MeV optics

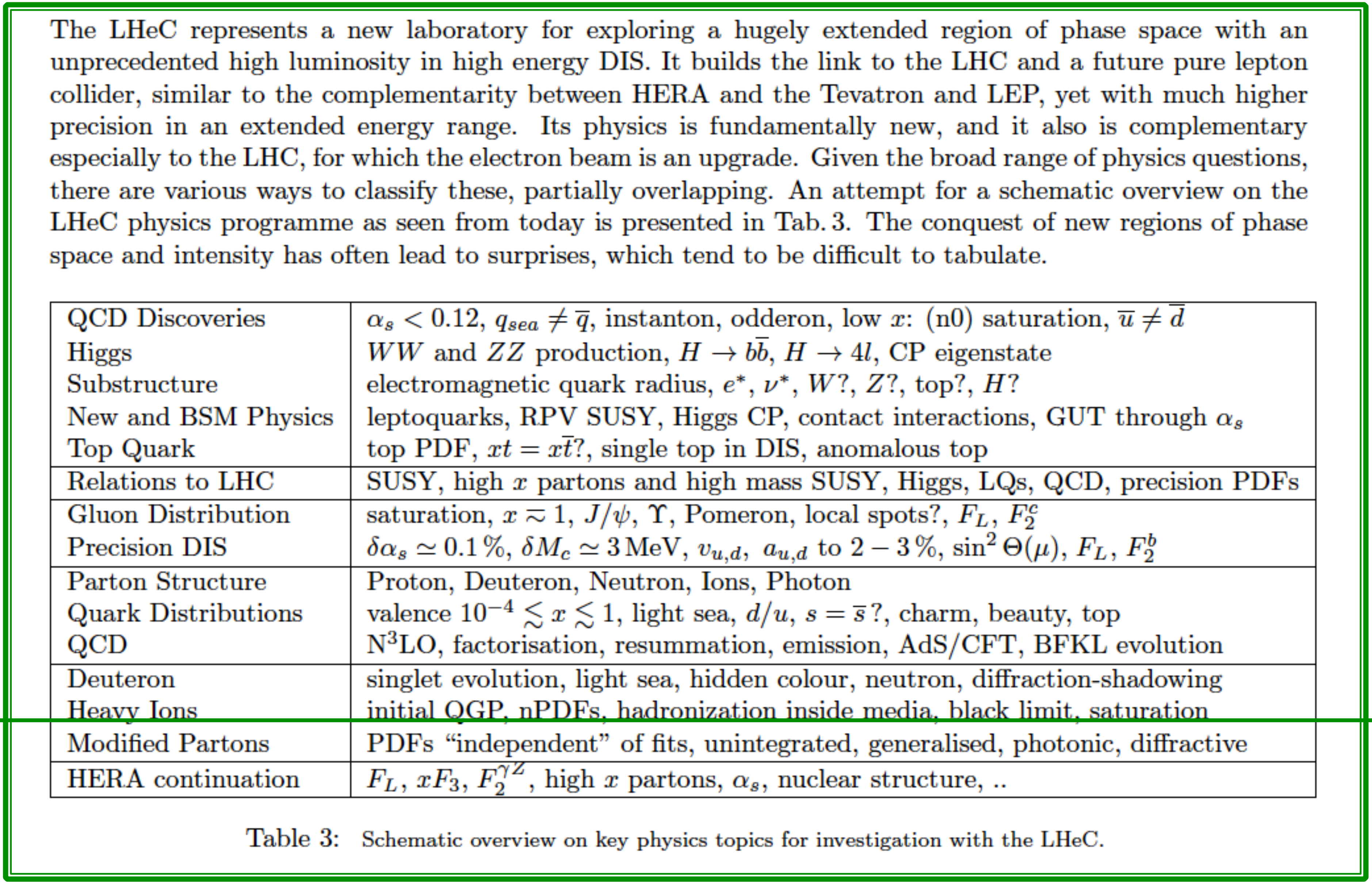


Alex Bogacz, JLab, August 21, 2012

Other key prototypes and preparations regard IR magnet, HL-LHC/e optics, beam pipe etc

LHeC (TF): Highest energy application of ER
Europe has ER plans and ALICE (at Daresbury)
Interest in sc rf development at CERN
Collaboration CERN, Jlab, Daresbury..

LHeC is a New Lab for PP+NP [Cracow paper 147]



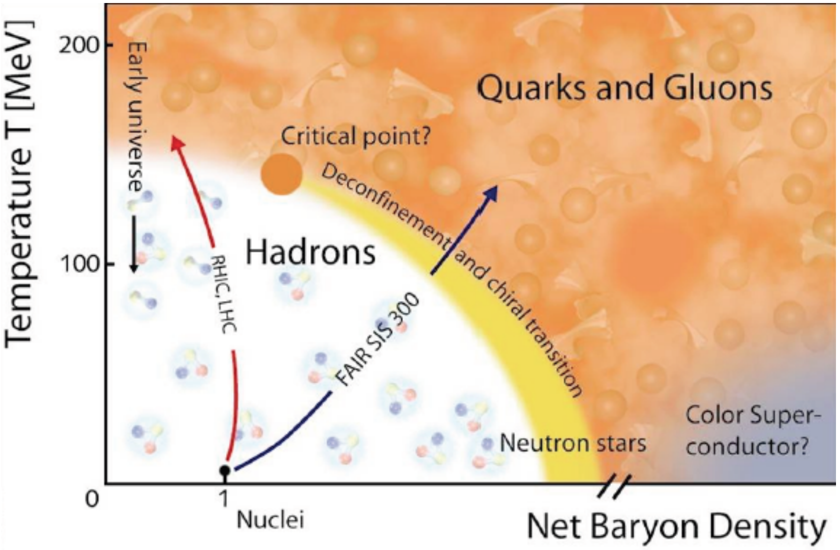
The LHeC represents a new laboratory for exploring a hugely extended region of phase space with an unprecedented high luminosity in high energy DIS. It builds the link to the LHC and a future pure lepton collider, similar to the complementarity between HERA and the Tevatron and LEP, yet with much higher precision in an extended energy range. Its physics is fundamentally new, and it also is complementary especially to the LHC, for which the electron beam is an upgrade. Given the broad range of physics questions, there are various ways to classify these, partially overlapping. An attempt for a schematic overview on the LHeC physics programme as seen from today is presented in Tab. 3. The conquest of new regions of phase space and intensity has often lead to surprises, which tend to be difficult to tabulate.

QCD Discoveries	$\alpha_s < 0.12$, $q_{sea} \neq \overline{q}$, instanton, odderon, low x: (n0) saturation, $\overline{u} \neq \overline{d}$
Higgs	WW and ZZ production, $H \to b\overline{b}$, $H \to 4l$, CP eigenstate
Substructure	electromagnetic quark radius, e^*, ν^*, W?, Z?, top?, H?
New and BSM Physics	leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through α_s
Top Quark	top PDF, $xt = x\overline{t}$?, single top in DIS, anomalous top
Relations to LHC	SUSY, high x partons and high mass SUSY, Higgs, LQs, QCD, precision PDFs
Gluon Distribution	saturation, $x \approx 1$, J/ψ, Υ, Pomeron, local spots?, F_L, F_2^c
Precision DIS	$\delta\alpha_s \simeq 0.1\,\%$, $\delta M_c \simeq 3\,\mathrm{MeV}$, $v_{u,d}$, $a_{u,d}$ to $2-3\,\%$, $\sin^2\Theta(\mu)$, F_L, F_2^b
Parton Structure	Proton, Deuteron, Neutron, Ions, Photon
Quark Distributions	valence $10^{-4} \lesssim x \lesssim 1$, light sea, d/u, $s = \overline{s}$?, charm, beauty, top
QCD	N^{3}LO, factorisation, resummation, emission, AdS/CFT, BFKL evolution
Deuteron	singlet evolution, light sea, hidden colour, neutron, diffraction-shadowing
Heavy Ions	initial QGP, nPDFs, hadronization inside media, black limit, saturation
Modified Partons	PDFs "independent" of fits, unintegrated, generalised, photonic, diffractive
HERA continuation	F_L, xF_3, $F_2^{\gamma Z}$, high x partons, α_s, nuclear structure, ..

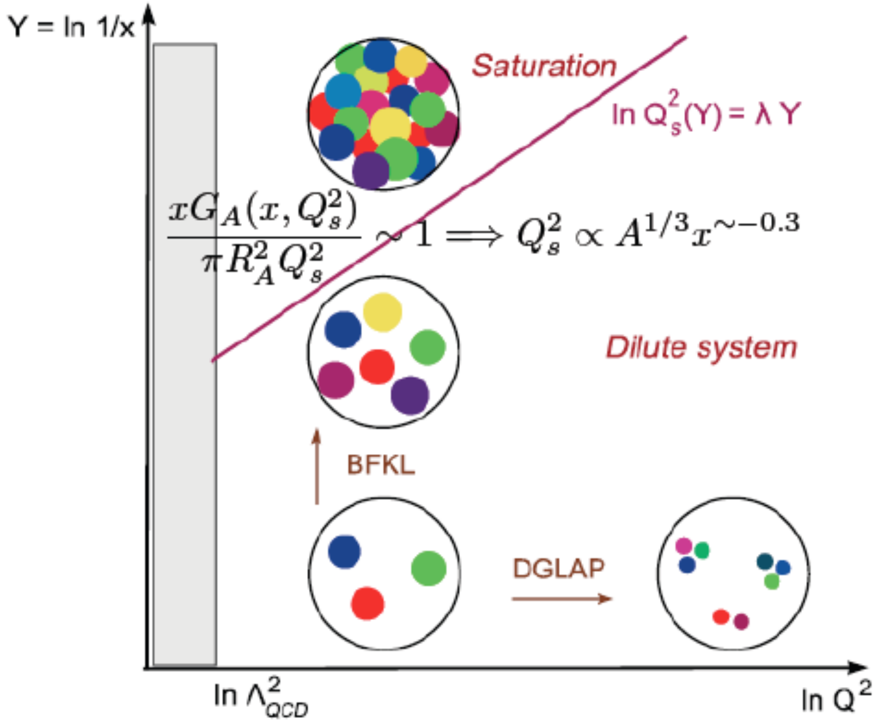
Table 3: Schematic overview on key physics topics for investigation with the LHeC.

Heavy Ion Physics

QCD Phase Diagram – eA most suited system with kinematics fixed by e. HERA never did heavy ions. LHeC has huge HI discovery potential



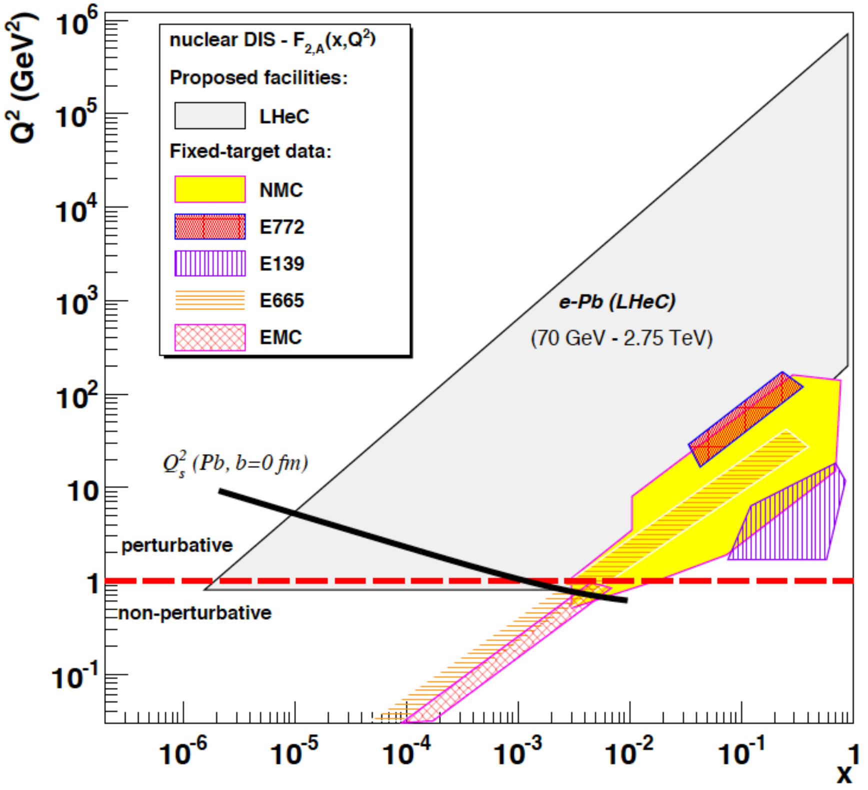
Deconfined parton system appears as strongly coupled liquid with small viscosity



Basic questions:

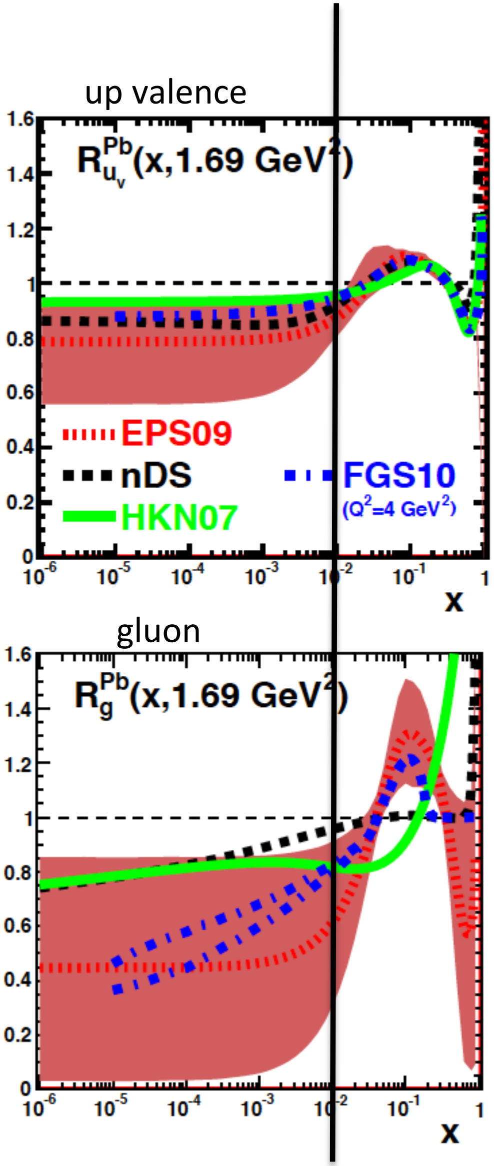
A new phase of matter – small coupling, high density – saturation in QFT ..?
Initial conditions of **Quark Gluon Plasma** and the mechanism of particle production ?
Intriguing theory background (AdS/CFT) in which gauge FT is linked to strings/gravity

Nuclear Parton Distributions



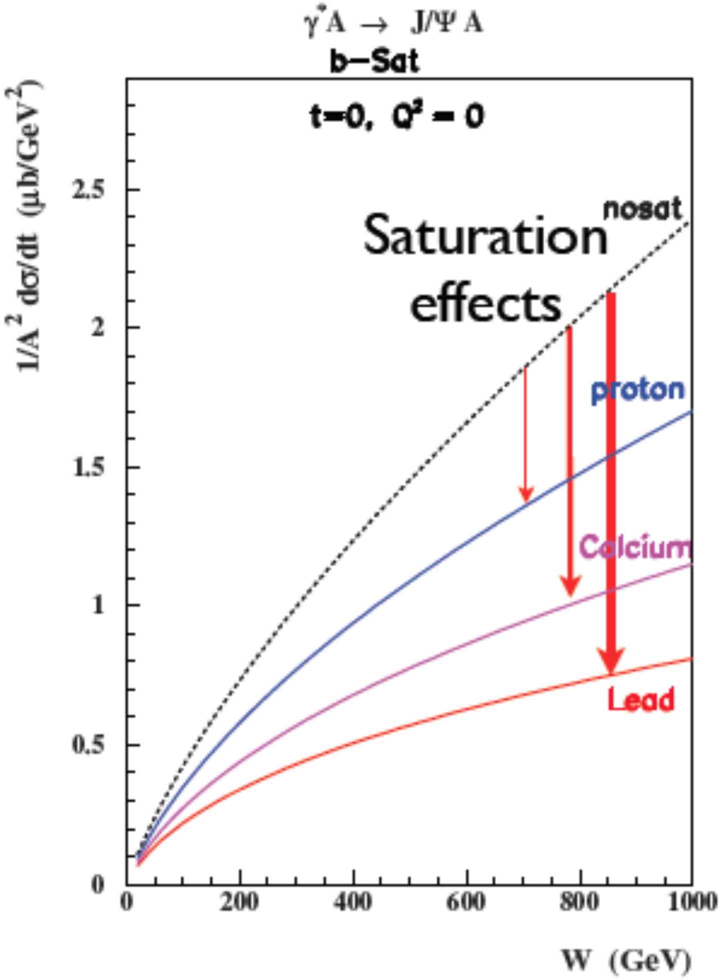
LHeC will put nPDFs on completely new ground:
Extend kinematics by 4 orders of magnitude,

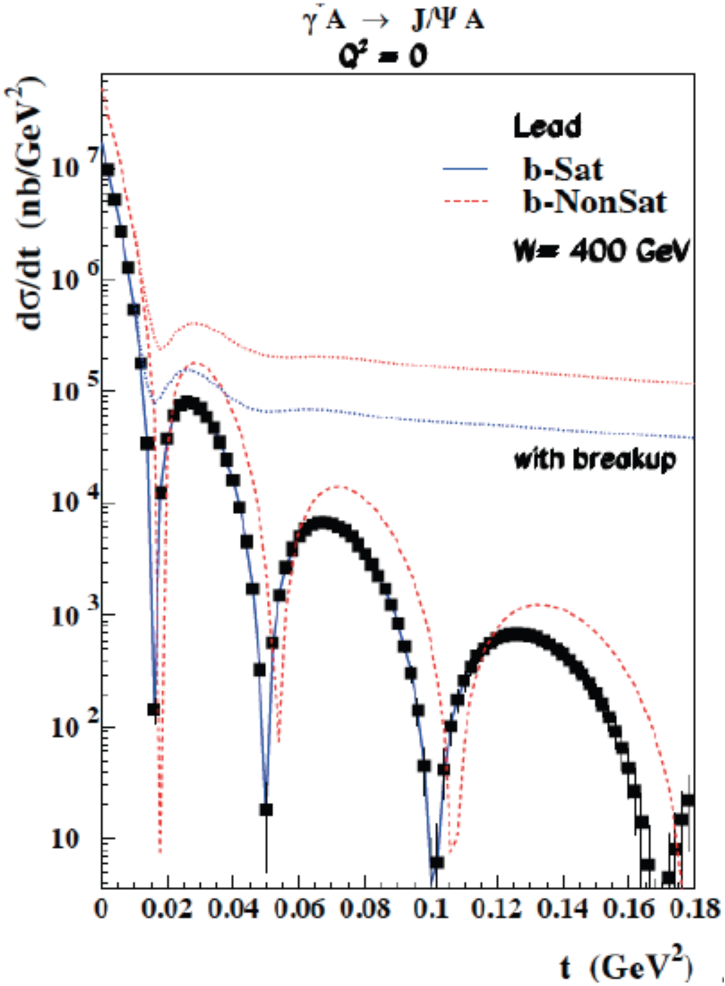
Resolve flavour composition of sea,
Mapping xg, - saturating – is there a unitarity bound?
Link shadowing to diffraction (Gribov)…



unmeasured | known?

J/ψ in eA





Huge saturation effects in coherent J/ψ production

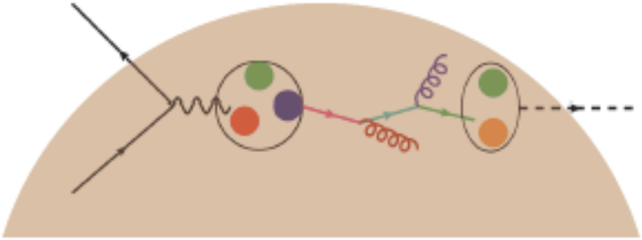
Transverse mapping of the nucleus (and p)

Radiation and Hadronization

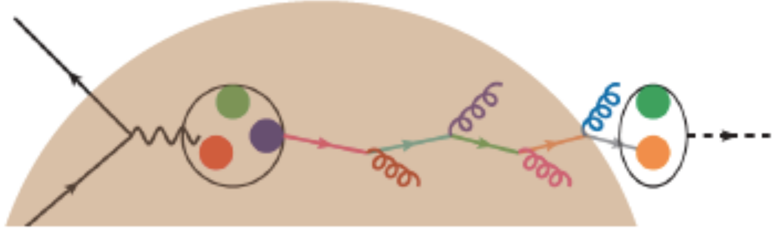
- LHeC: dynamics of QCD radiation and hadronization.
- Most relevant for particle production off nuclei and for QGP analysis in HIC.

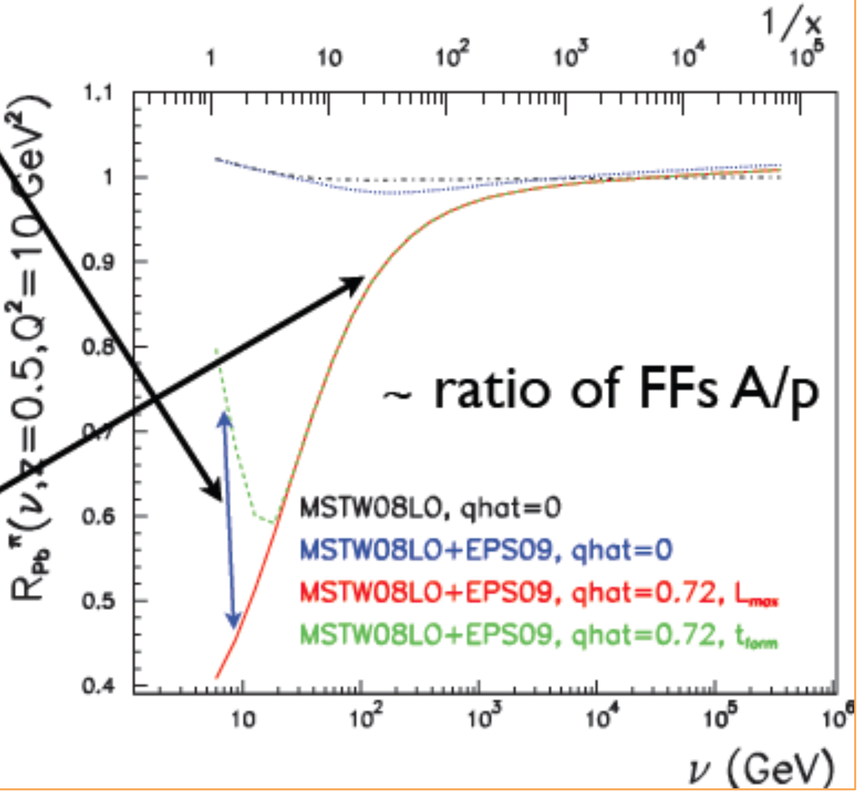
$$R_A^h(z,\nu) = \frac{1}{N_A^e}\frac{\mathrm{d}N_A^h(z,\nu)}{\mathrm{d}\nu\,\mathrm{d}z} \Bigg/ \frac{1}{N_D^e}\frac{\mathrm{d}N_D^h(z,\nu)}{\mathrm{d}\nu\,\mathrm{d}z}$$

- Low energy: hadronization inside → formation time, (pre-) hadronic absorption,...



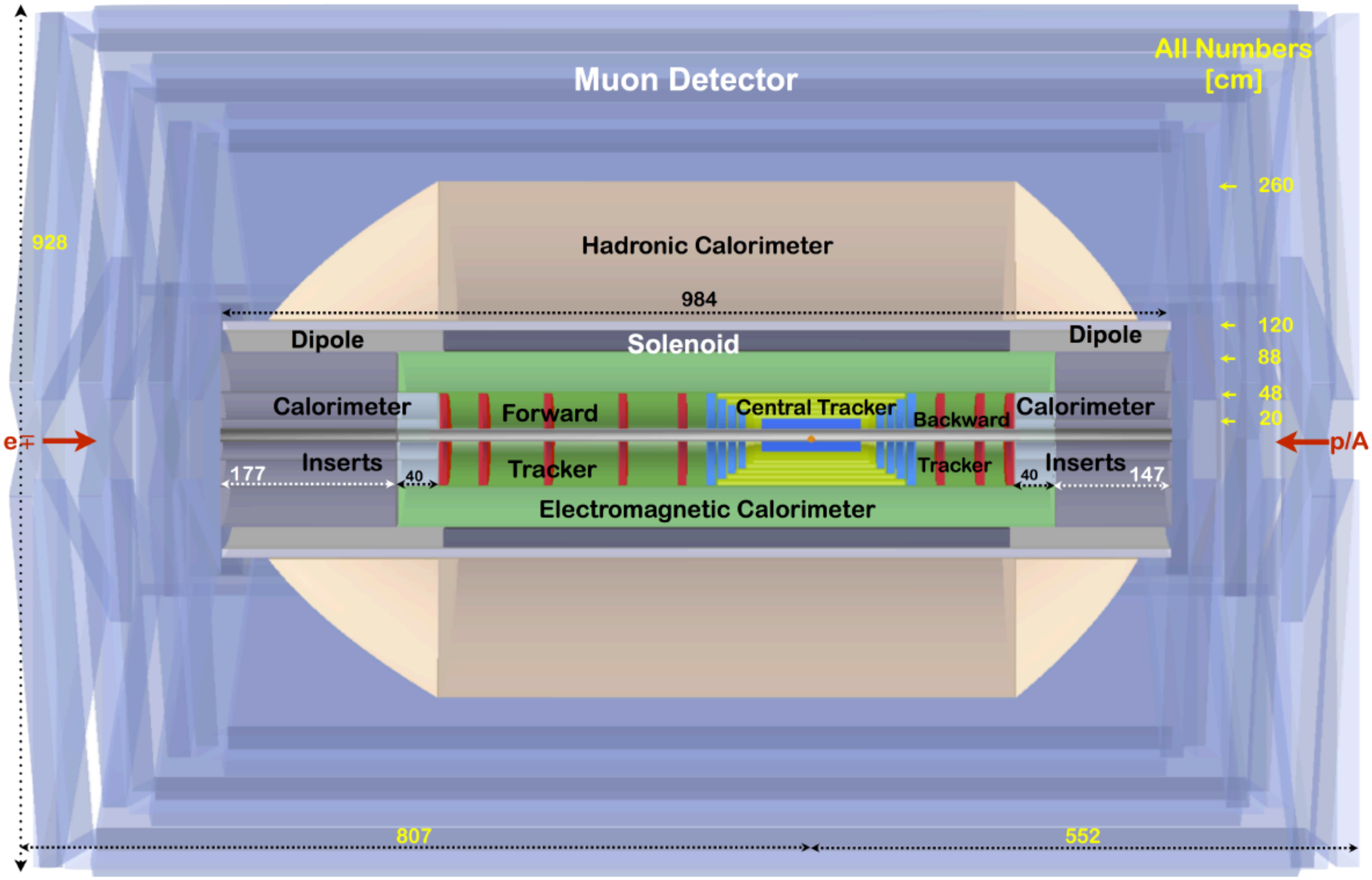
- High energy: partonic evolution altered in the nuclear medium.





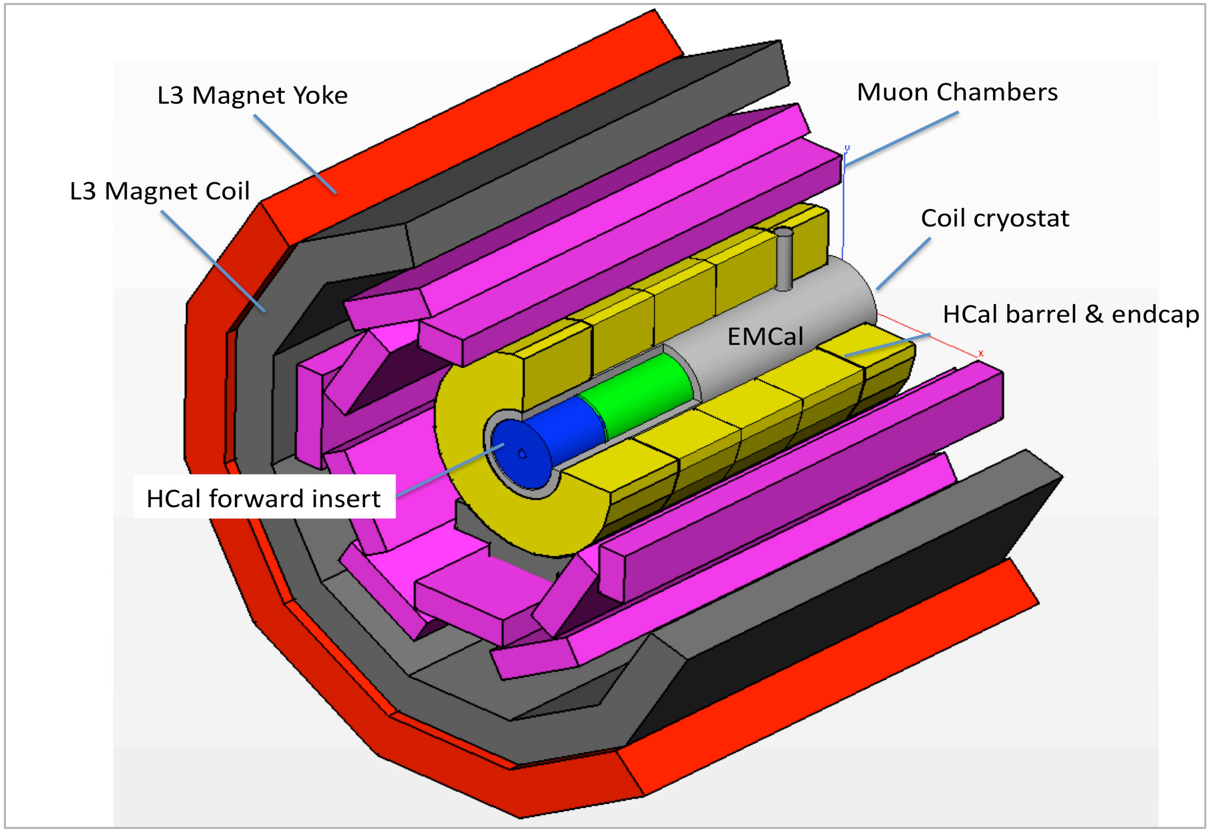
N.Armesto

Detector in CDR



High precision, large acceptance (1-179°), forward b tagging, backward electron,…
Technology choices based on proven technology, no time for R+D, no pile-up..

Detector Installation



First concepts presented in CDR (A.Ghaddi, A.Herve, H.tenKate..). Use L3 magnet structure as LHeC detector support. Requires 30 months for dismantling and installation of premounted detector. Only possible in 2-3 years shutdown, during which also the electron linac is connected to the LHC beam.

Prospects 1

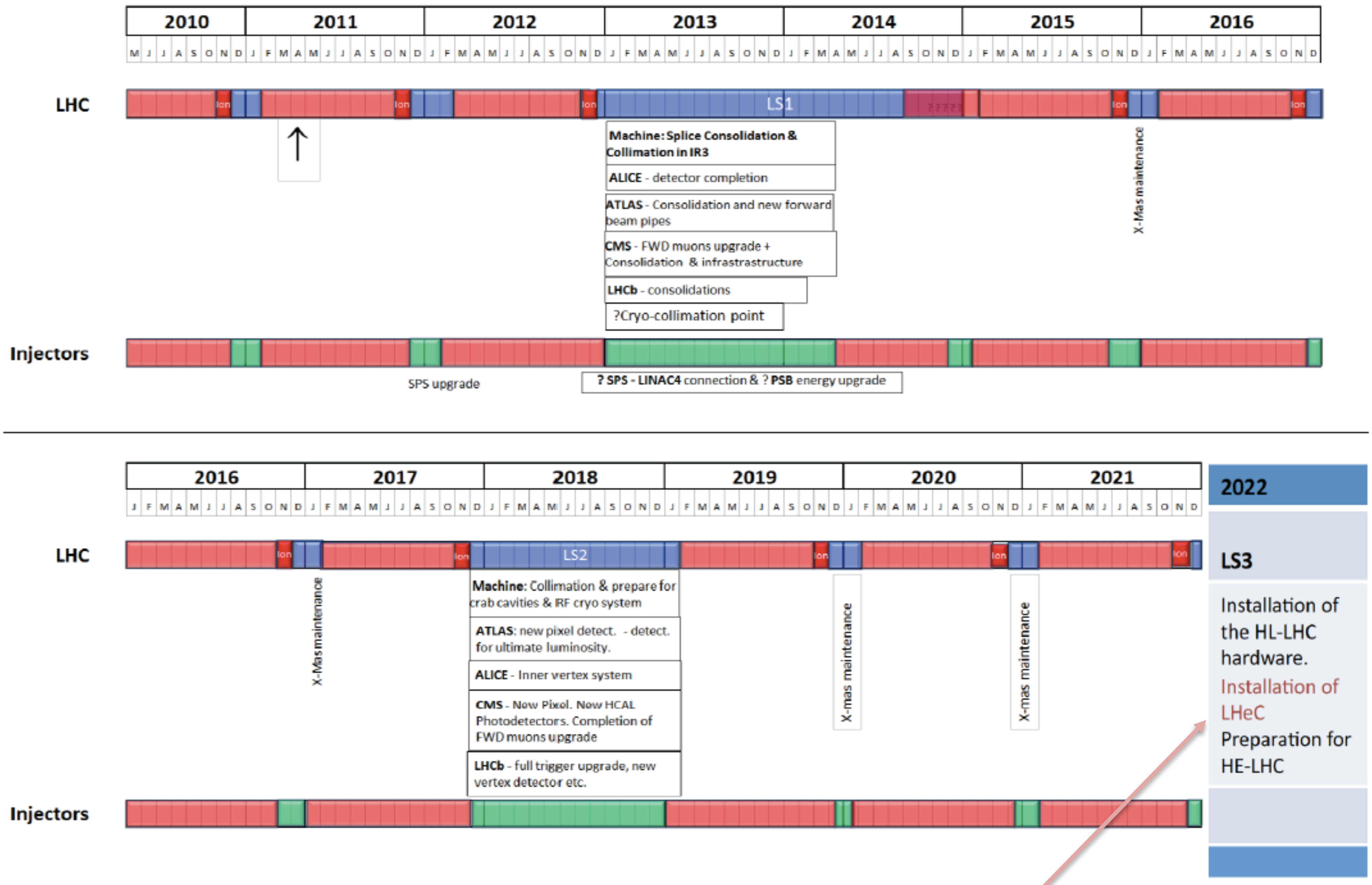
The LHeC has made major progress with its refereed CDR and the CERN mandate for the development of the LINAC. There is an increasing interest and international collaboration, both on the machine development and the detector.

The project in order to be meaningfully realised has to run synchronous to HL-LHC as otherwise there is not enough time to collect the luminosity as required for Higgs, top, high x and other physics, nor to vary the beam conditions (p,d,A,e^+, E).

The project is linked to ALICE via IP2 but more important via the HI physics.
It therefore has been discussed between the ALICE and LHeC Collaborations that it is desirable to work out a common understanding and plan for a joint collaboration, which allows the completion of the now (LHCC) endorsed ALICE operation for $10nb^{-1}$ after LS2, and as well the installation of the LHeC such that it has the time to deliver its physics and is not in contradiction with the LHC and ATLAS, CMS, possibly LHCb upgrades either.

That points to LS3, the currently foreseen transition to the HL-LHC phase, with a new injector, inner triplet, masks etc and e.g. a new ATLAS inner tracker.

LHC Schedule for the coming decade



Machine: Splice Consolidation & Collimation in IR3

ALICE - detector completion

ATLAS - Consolidation and new forward beam pipes

CMS - FWD muons upgrade + Consolidation & infrastrastructure

LHCb - consolidations

?Cryo-collimation point

? SPS - LINAC4 connection & ? **PSB** energy upgrade

Machine: Collimation & prepare for crab cavities & RF cryo system

ATLAS: new pixel detect. - detect. for ultimate luminosity.

ALICE - Inner vertex system

CMS - New Pixel, New HCAL Photodetectors. Completion of FWD muons upgrade

LHCb - full trigger upgrade, new vertex detector etc.

2022

LS3

Installation of the HL-LHC hardware.
Installation of LHeC
Preparation for HE-LHC

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

as shown by S. Myers at EPS 2011 Grenoble - Principal guidance of CDR

Prospects 2

While formally one may see a clash between the ALICE 10nb^{-1} run and the LHeC installation, there are various considerations which lead to the conclusion that an appropriate rescheduling of LS3 will enable BOTH projects to happen as desired, one after the other.

- The HL-LHC is not an approved phase yet and the LS3 therefore not seriously scheduled.
- From the LHC experience and current considerations (as the delayed and extended LS1 compared to still recent plans) it is most likely that LS3 moves in time by +1-2 years, while also the LHC operation time may lead into the 30ies. ALICE does not need LS3, LHeC as seen from today does.
- The nature of the AA operation, for 1 month/year, allows principally to contract n years into n months. A dedicated extended operation for AA before LS3, should it about happen as envisaged now, therefore will allow to collect extra luminosity and the machine to radiatively cool down before intervention.
- No one can exclude delays, at various places, to which one has to adapt.

Conclusion

From these considerations it is desirable that NuPECC restates its strong interest in both projects and expresses the expectation to CERN that support is provided and, in due time, measures are taken for an appropriate scheduling of the LHC interrupts. This provides a major perspective for HI physics for ~25 years.

Thanks to the LHeC Study Group, CERN, ECFA, thanks to you and to Paolo et al.

J.L.Abelleira Fernandez[16,23], C.Adolphsen[57], A.N.Akay[03], H.Aksakal[39], J.L.Albacete[52], S.Alekhin[17,54], P.Allport[24], V.Andreev[34],
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V.N.Litvinenko[37], A.Lombardi[16], J.Maeda[58], C.Marquet[16], B.Mellado[27], K.H.Mess[16], A.Milanese[16], S.Moch[17], I.I.Morozov[40],
Y.Muttoni[16], S.Myers[16], S.Nandi[55], Z.Nergiz[39], P.R.Newman[06], T.Omori[61], J.Osborne[16], E.Paoloni[49], Y.Papaphilippou[16],
C.Pascaud[42], H.Paukkunen[53], E.Perez[16], T.Pieloni[23], E.Pilicer[62], B.Pire[45], R.Placakyte[17], A.Polini[07], V.Ptitsyn[37], Y.Pupkov[40],
V.Radescu[17], S.Raychaudhuri[35], L.Rinolfi[16], E.Rizvi[71], R.Rohini[35], J.Rojo[16,31], S.Russenschuck[16], M.Sahin[03], C.A.Salgado[53,a],
K.Sampei[58], R.Sassot[09], E.Sauvan[04], U.Schneekloth[17], T.Schörner-Sadenius[17], D.Schulte[16], A.Senol[22], A.Seryi[44], P.Sievers[16],
A.N.Skrinsky[40], W.Smith[27], H.Spiesberger[29], A.M.Stasto[48,d], M.Strikman[48], M.Sullivan[57], S.Sultansoy[03,e], Y.P.Sun[57], B.Surrow[11],
L.Szymanowski[66,f], P.Taels[05], I.Tapan[62], T.Tasci[22], E.Tassi[10], H.Ten.Kate[16], J.Terron[28], H.Thiesen[16], L.Thompson[14,30],
P.Thompson[06], K.Tokushuku[61], R.Tomás García[16], D.Tommasini[16], D.Trbojevic[37], N.Tsoupas[37], J.Tuckmantel[16], S.Turkoz[01],
T.N.Trinh[47], K.Tywoniuk[26], G.Unel[20], J.Urakawa[61], P.VanMechelen[05], A.Variola[52], R.Veness[16], A.Vivoli[16], P.Vobly[40], J.Wagner[66],
R.Wallny[68], S.Wallon[43,46,f], G.Watt[16], C.Weiss[36], U.A.Wiedemann[16], U.Wienands[57], F.Willeke[37], B.-W.Xiao[48], V.Yakimenko[37],
A.F.Zarnecki[67], Z.Zhang[42], F.Zimmermann[16], R.Zlebcik[51], F.Zomer[42]

Conclusion

From these considerations it is desirable that NuPECC restates its strong interest in both projects and expresses the expectation to CERN that support is provided and, in due time, measures are taken for an appropriate scheduling of the LHC interrupts. This provides a major perspective for HI physics for ~25 years.

NO-MADEJA-DO

Sevilla hat mich nicht verlassen… (AlfonsX) NuPECC encouraged us to continue..

Thanks

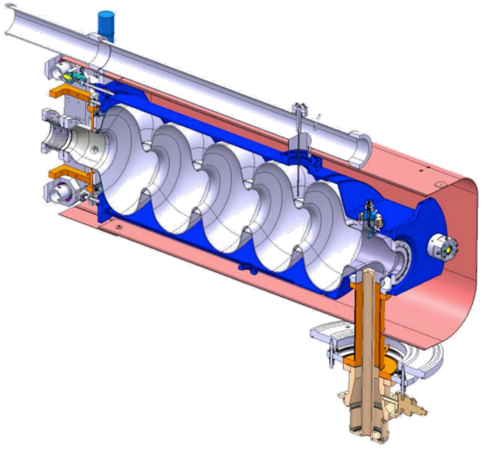
RF until 2015

Frequency choice: *n* * 120.237 MHz
N=6: 721 MHz, n=11: 1.3GHz (XFEL)

Detailed comparison (threshold current, cryo power, Rf power, size, cost, collaboration, synergy..)

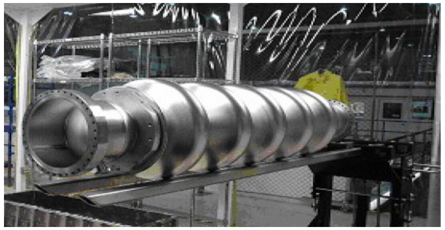
ALICE 1.3 GHz, not CW – only EU ERL facility operational
Daresbury develops cryomodule for ESS (700 MHz)
CERN: in house collaboration with SPL, and eRHIC/BNL

SPL cryomodule 704 MHz

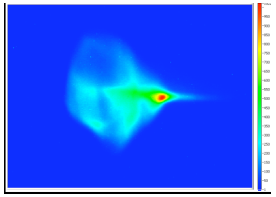


Accelerator physics motivation:
 ERL demonstration, FEL, γ-ray source, e-cooling demo!
 Ultra-short electron bunches
One of the 1st low-frequency, multi-pass SC-ERL
 synergy with SPL/ESS and BNL activities
High energies (200 … 400 MeV) & CW
Multi-cavity cryomodule layout – validation and gymnastics
Two-Linac layout (similar to LHeC)
MW class power coupler tests in non-ER mode
Complete HOM characterization and instability studies!
Cryogenics & instrumentation test bed … E.Jensen

BNL 704 MHz cavity (20 MV/m with high Q0 demonstrated)



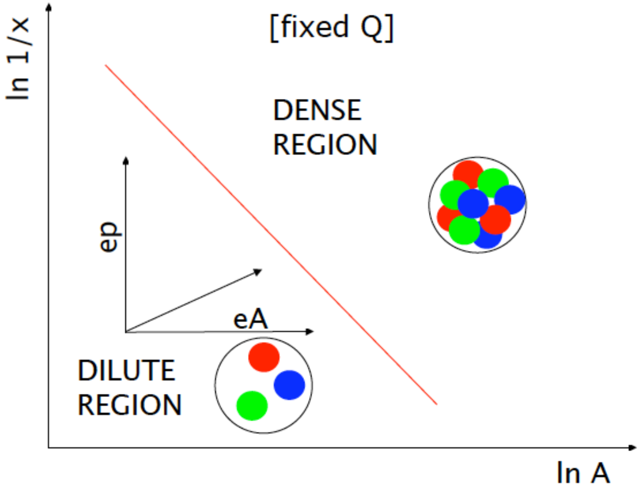
Steps: Design of LHeC ERL TF, cavity-cryo module (hi Q), lattice, optics, magnets, source, ….
Watch out for surprises as humming bird:
Building international collaboration
(CERN,Daresbury, Jlab, others?)

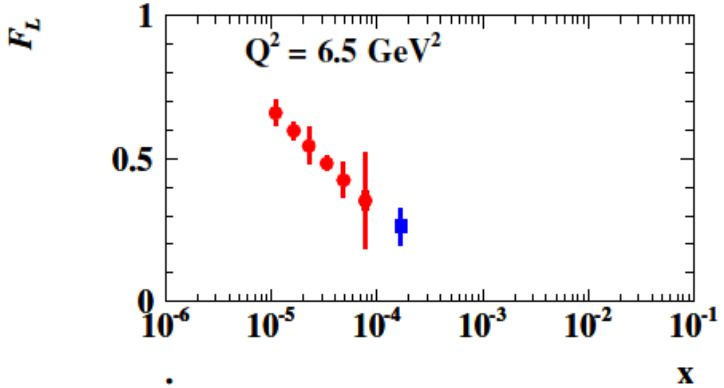


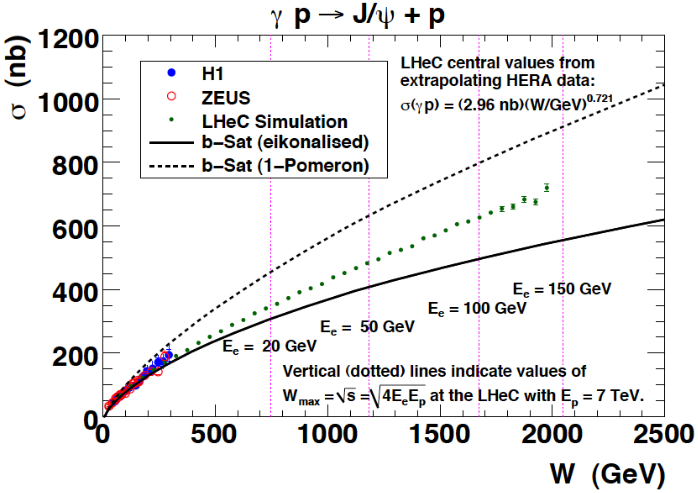
beam structure at ALICE with 230-kV DC gun voltage

Saturation [in ep and eA] – Low x

Precision Measurements of crucial observables (F_2, F_L, J/ψ..







New phase of matter: small coupling but non-linear parton-parton interactions:

- End of DGLAP ? BFKL?
- Access to 10 TeV scale SUSY via BFKL ("DP") arXiv:1205.6713 Kowalski, Lipatov, Ross
- Restauration of unitarity?
- Relevant for UHE neutrino scattering