LHeC Accelerator Design

- Introduction and Motivation

- Two options: -Ring-Ring collider

  -Linac-Ring collider with Energy Recovery

- Technical Considerations and Developments

- Planning and timeline

- Next steps

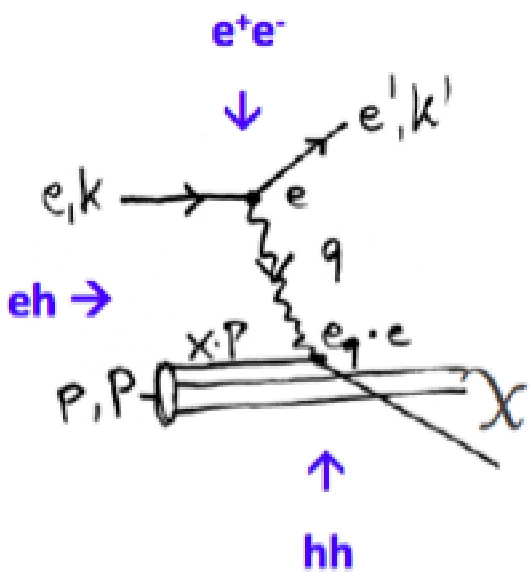
LHeC Accelerator Design

On behalf of the LHeC Collaboration!

- Introduction and Motivation
- Two options: -Ring-Ring collider
  -Linac-R… …er with Energy Recovery
- Technical Consid… …nd Developments
- Plann… …meline
- Next steps

LHeC offers a most powerful microscope:

- Finest microscope with resolution varying like $\sqrt{1/Q^2}$
- Parton momentum fixed by electron kinematics:

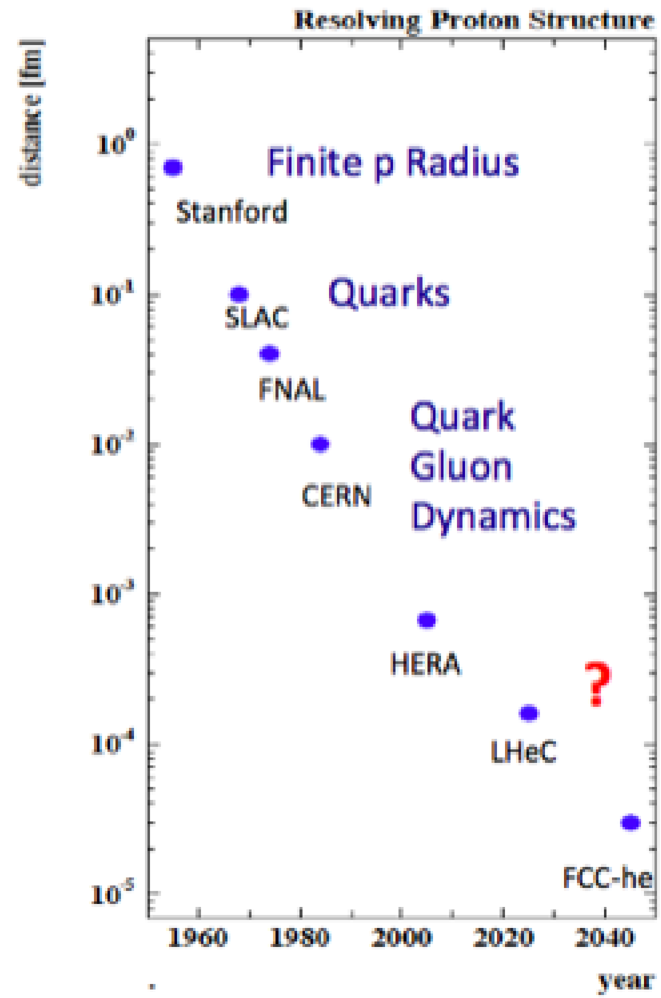


$$x = \frac{Q^2}{sy}$$

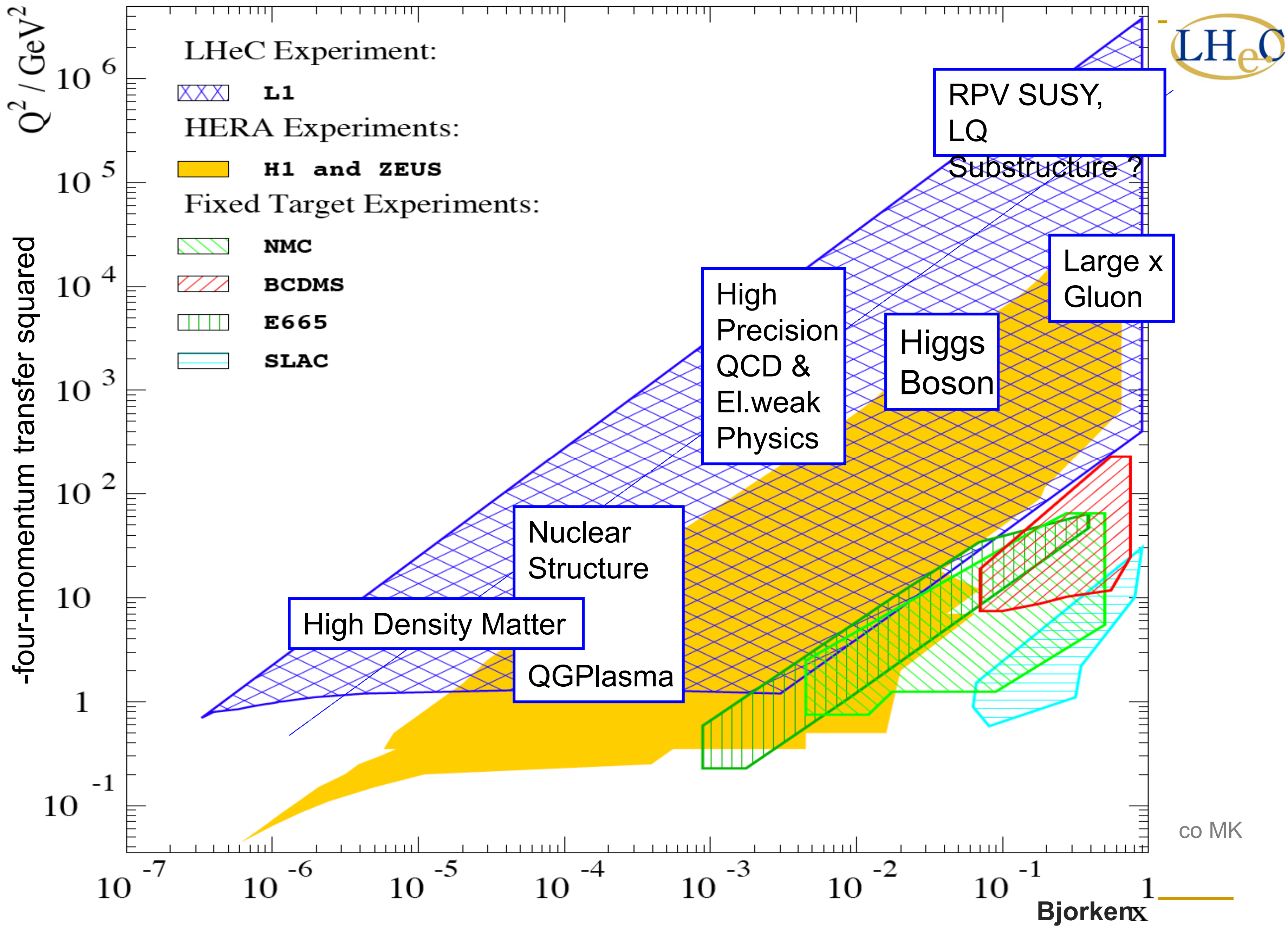
$$Q^2 = -(k - k')^2$$

$$y_{lab} = 1 - \frac{E_e'}{E_e}$$

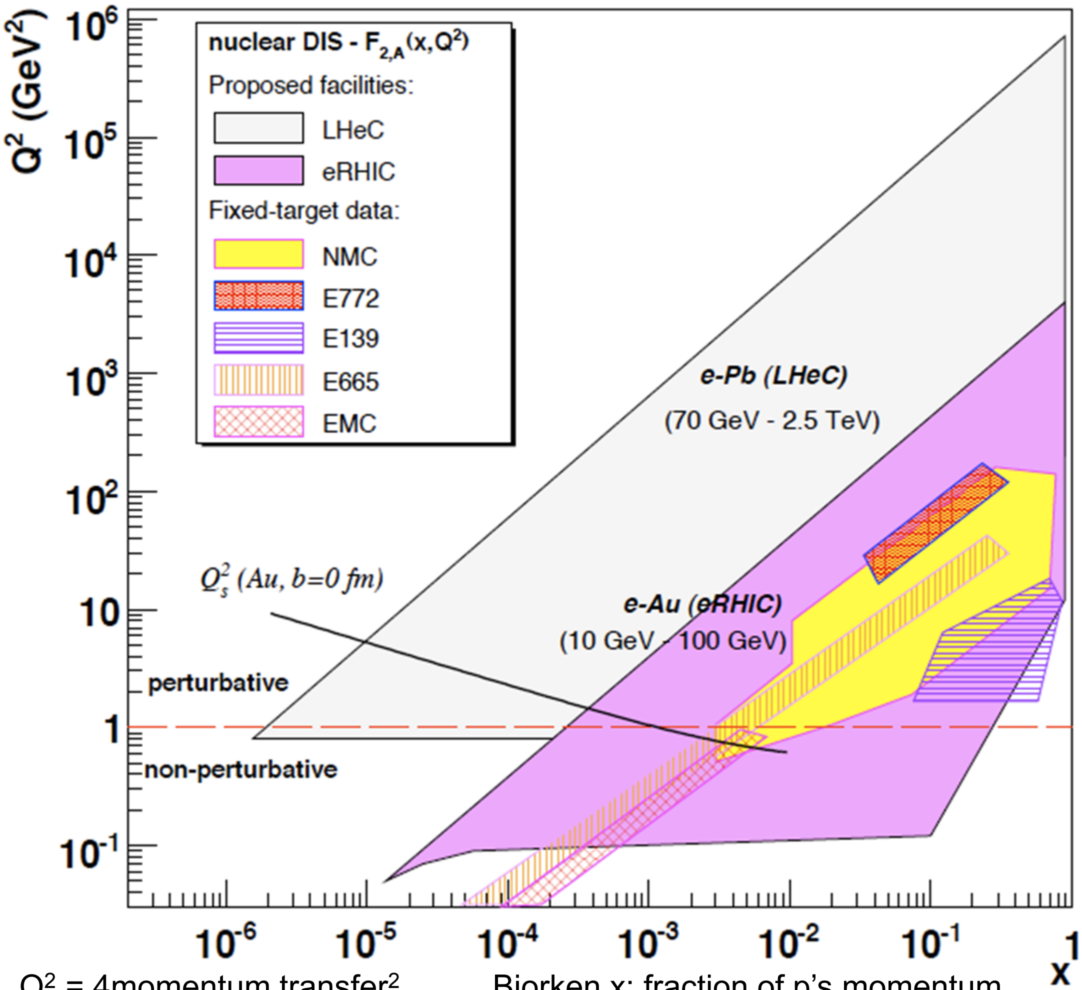
$$s = 4E_eE_p$$



Max Klein


LHeC
LHeC Experiment:
L1
HERA Experiments:
H1 and ZEUS
Fixed Target Experiments:
NMC
BCDMS
E665
SLAC
RPV SUSY, LQ Substructure ?
Large x Gluon
High Precision QCD & El.weak Physics
Higgs Boson
Nuclear Structure
High Density Matter
QGPlasma
Q^2 / GeV^2
-four-momentum transfer squared
Bjorken x
co MK

Electron-Ion Scattering: eA → eX

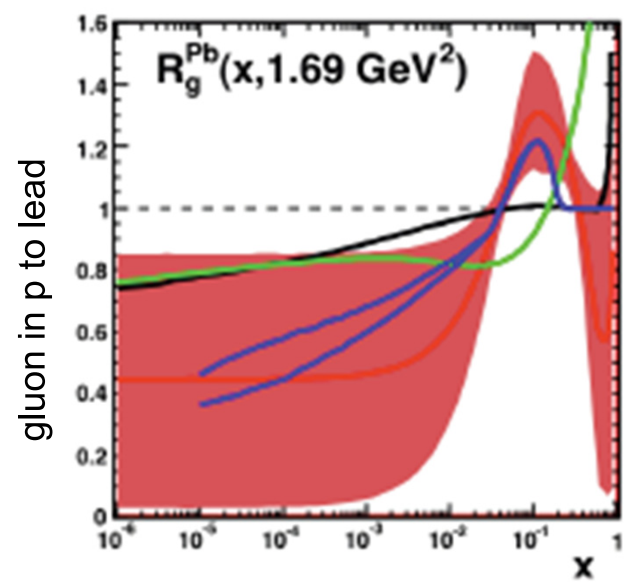


Q^2 = 4momentum transfer^2 Bjorken x: fraction of p's momentum

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



Next decades

Rolf Heuer at
Aix Les Bains
1. 10. 2013

Road beyond Standard Model

LHC results vital to guide the way at the energy frontier

At the energy frontier through synergy of

hadron - hadron colliders (LHC, (V)HE-LHC?)

lepton - hadron colliders (LHeC ??)

lepton - lepton colliders (LC (**ILC** or CLIC) ?)

LHeC CDR: Site specific boundary conditions

- Power consumption:

  -Limit LHeC power consumption to 100MW

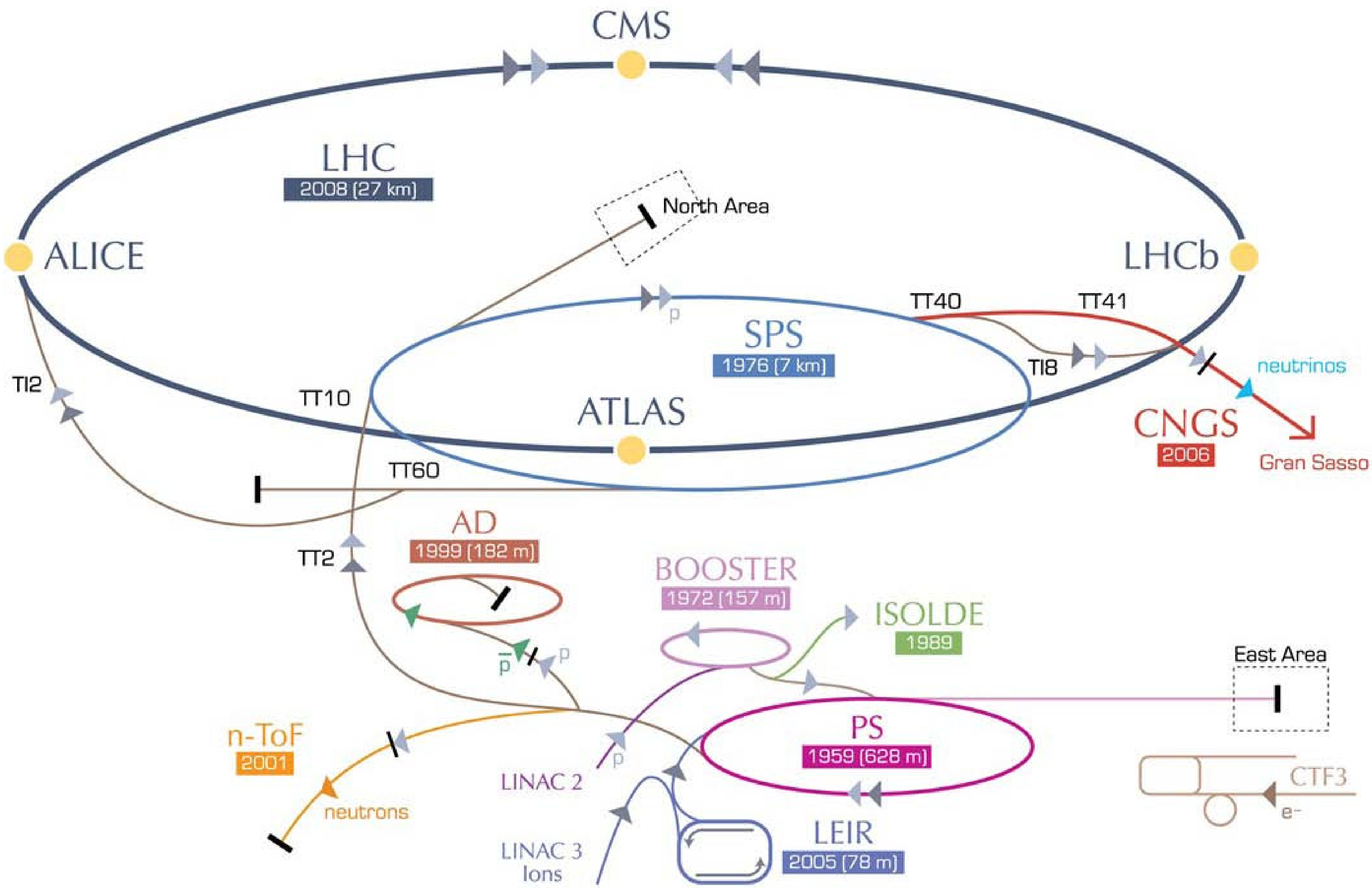
  (LHC has about 110MW [4 TeV] and the SPS about 70 MW and CERN site ca 200 MW peak power consumption)

- Maximize use of existing LHC infrastructure:

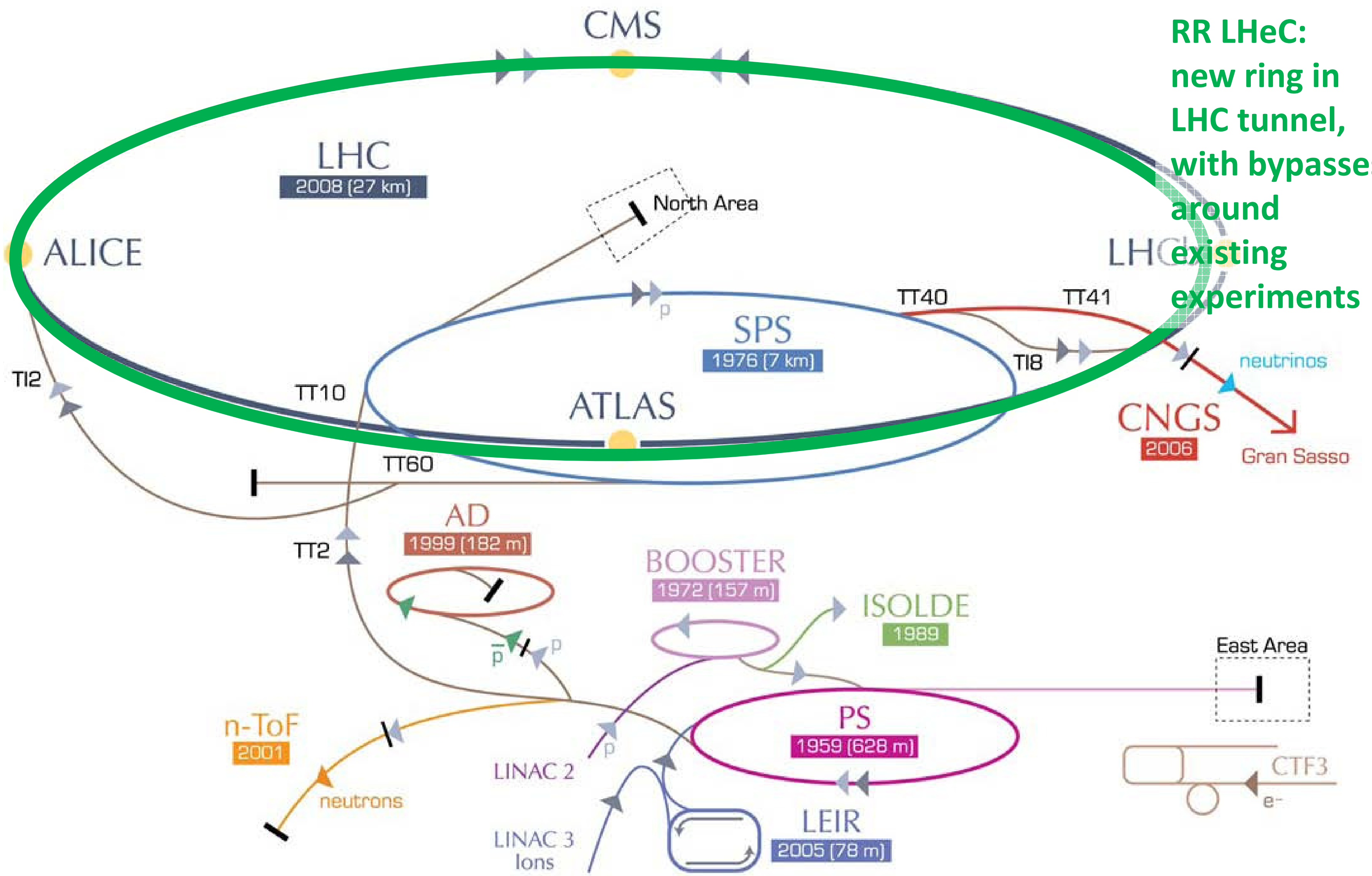
  -Parallel exploitation of LHeC to the HL-LHC operation

  -Be ready for LHeC operation shortly after HL-LHC startup

LHeC options: RR and LR

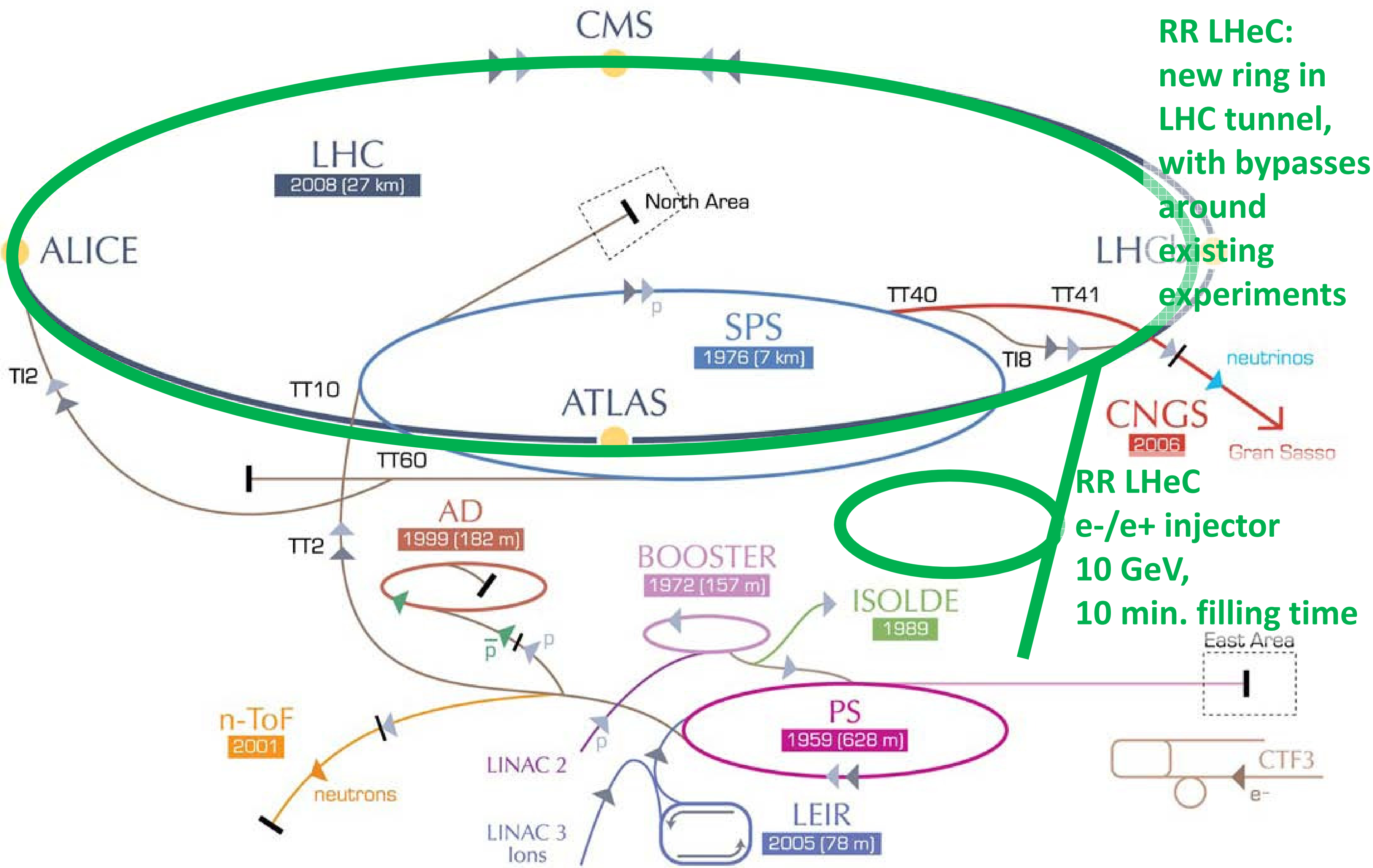


LHeC options: RR and LR

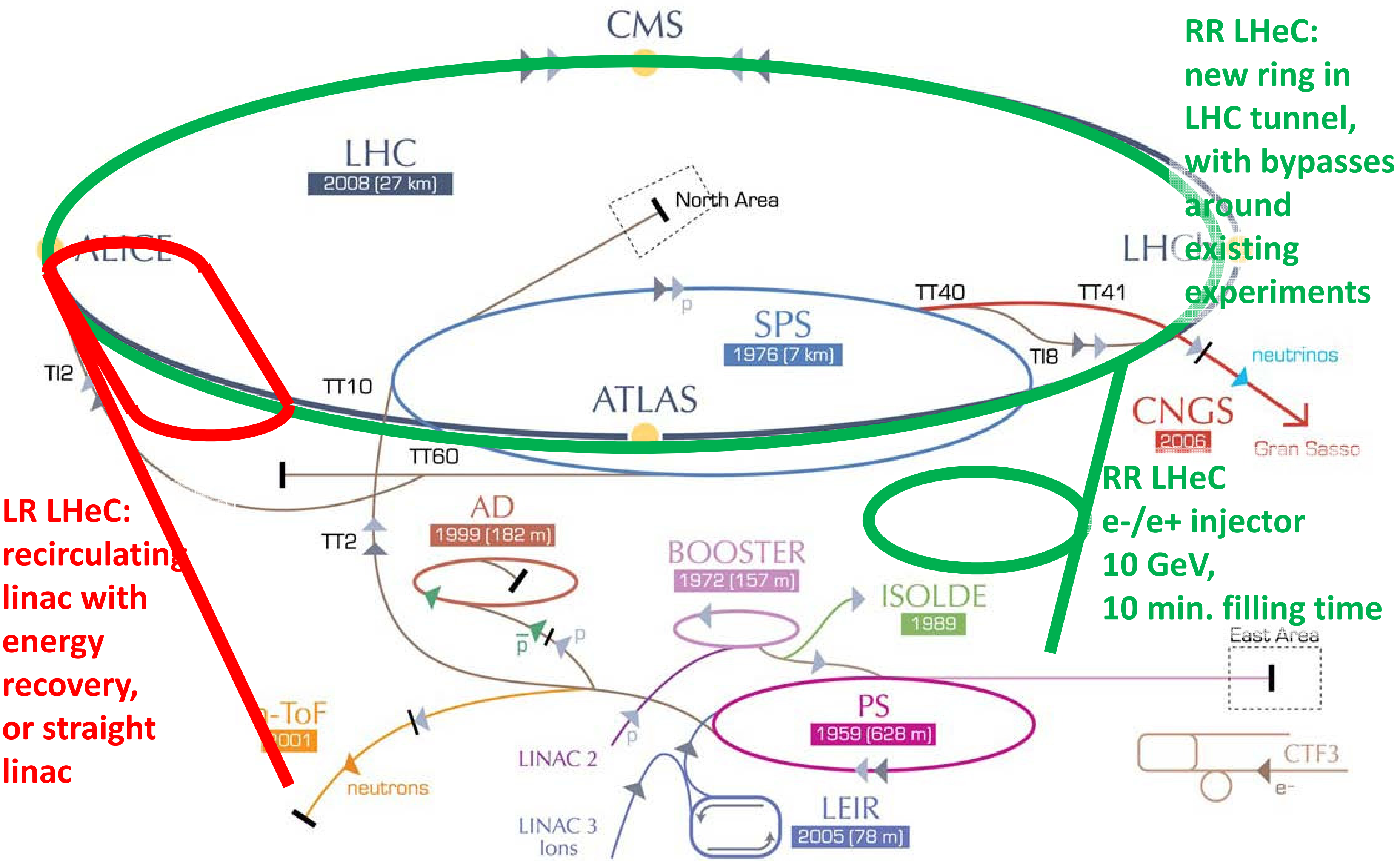


RR LHeC: new ring in LHC tunnel, with bypasses around existing experiments

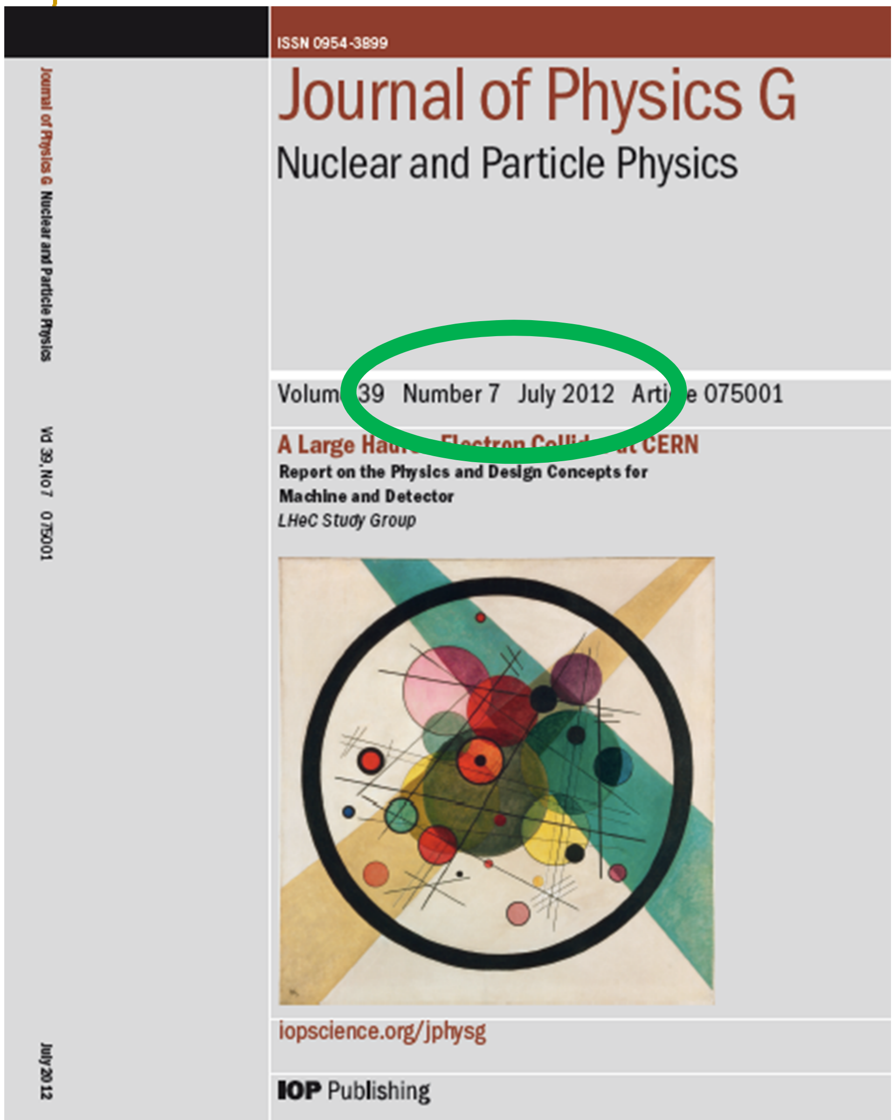
LHeC options: RR and LR



LHeC options: RR and LR



Both Options are described in the CDR



1. Design for synchronous ep and pp operation (including eA) → after LS3 which is about 2025 – no firm schedule exists for HL-LHC, but it may operate until ~2035

2. LHeC is a new collider: the cleanest microscope of the world, a complementary Higgs facility, a unique QCD machine with a striking discovery potential, with possible applications as γγ → H or
injector to FCC-ee or others
AND an exciting new accelerator project

3. CERN Mandate to develop key technologies for the LHeC for project decision after start of LHC Run II and in time for start parallel to HL LHC phase

LHeC CDR: Executive Summary

Ring-Ring option:

-We know we can do it: → LEP 1.5

-Challenge 1: integration in tunnel and co-existence with LHC HW

-Challenge 2: installation within LHC shutdown schedule

Linac-Ring option:

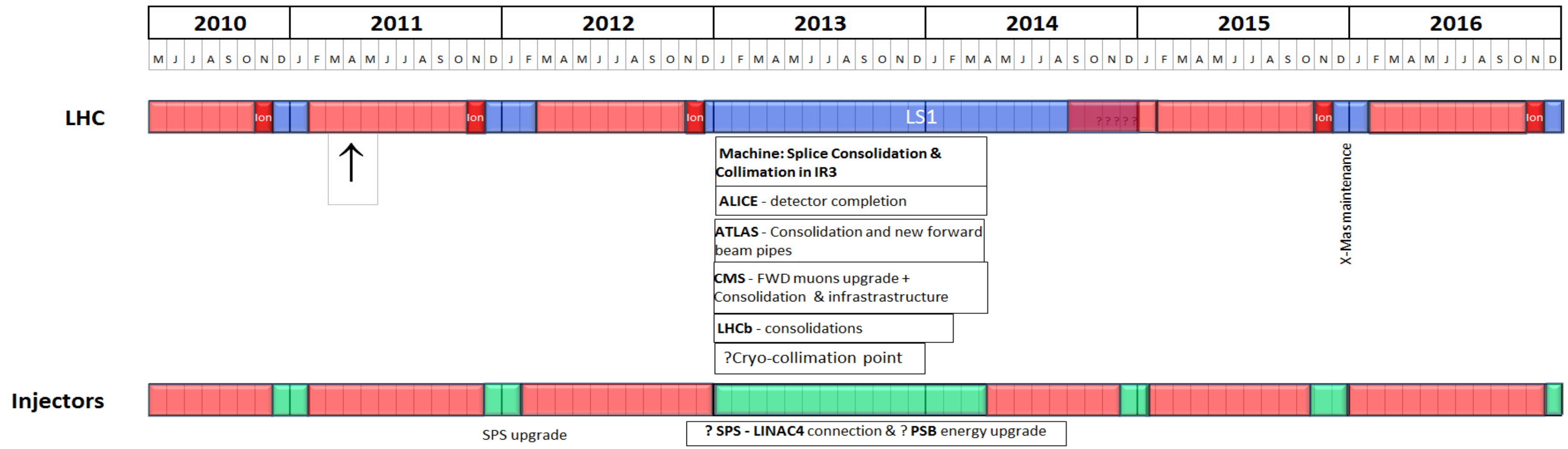
-Installation decoupled from LHC operation and shutdown planning

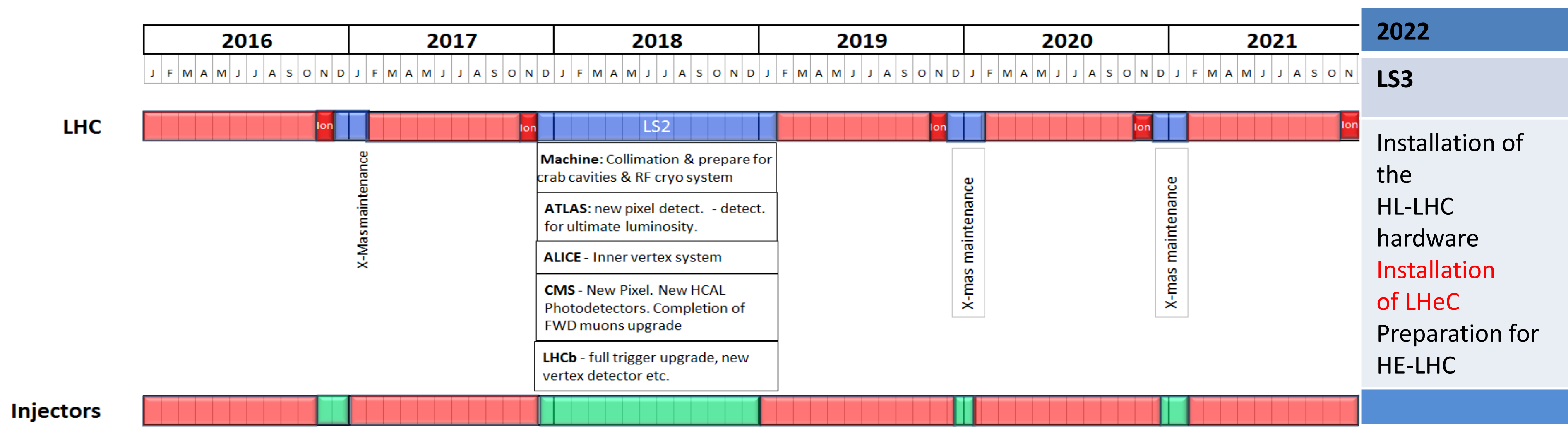
-Infrastructure investment with potential exploitation beyond LHeC

-Challenge 1: technology → high current, high energy SC ERL

-Challenge 2: Positron source

‘Old’ (pre 2014) 10 Year Plan for LHC Operation





‘Old’ (pre 2014) 10 Year Plan for LHC Operation

R-R Installation is very challenging within current schedule!

LS1 essentially finished and LS2 is too soon to be used for LHeC activities inside LHC tunnel!

Leaving essentially only one long shutdown for LHeC installation!

➔

Chavannes 2012 workshop: Decision to focus future activities on ERL option which allows construction and installation Independent of LHC schedule!

CERN LHeC Mandate 2012: 5 main points

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 Q_0 for efficient energy recovery) S
- 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 dynamics studies and identificationof 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 with existing CERN studies.**

S.Bertolucci at Chavannes workshop 6/12 based on

CERN directorate's decision to include LHeC in the MTP

‘New’ (as of 2014) LHC schedule beyond LS1

Only EYETS (19 weeks)   (no Linac4 connection during Run2)
LS2   starting in 2018 (July)   18 months + 3months BC (Beam Commissioning)
LS3   LHC: starting in 2023 =>   30 months + 3 BC
      injectors: in 2024   =>   13 months + 3 BC

‘New’ (as of 2014) LHC schedule beyond LS1

New CERN Schedule provides more time and more Shutdown options for LHeC installation!

Higgs Discovery and desire for high L:

- CDR Base Line aimed at $L = 10^{33}$ cm^{-2} s^{-1}

  ➔ ca. 100 times the HERA performance at high Q^2

- Light Higgs discovery @ LHC:

  -Various Higgs decays and CP Properties can be accessed in the LHeC in e-p collisions via WW and ZZ fusion.

  -LHeC has the potential of measuring H->bb with high precision in a clean environment

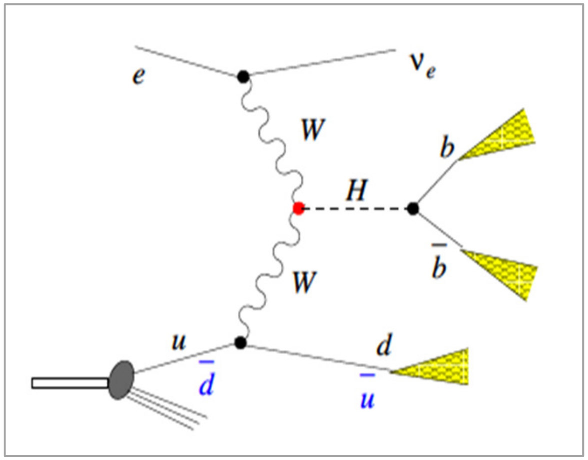
  -1 ab^{-1} integrated luminosity would open up a wide range of precision Higgs physics analysis

➔ Drive to stretch LHeC to $L = 10^{34}$ cm^{-2} s^{-1} performance reach!

Higgs with the LHeC:

LPCC LHeC Workshop at CERN– April12+ 13: indico: 244768 and 244990

ZZ → H
~10 times lower rate



Unique production mechanism (WW,ZZ)
Clean conditions: No pileup, simpler final state …

LHeC at 10^{34}cm^{-2}s^{-1} : arXiv:1211:5102
Nb: Cross section and luminosity as large as are projected for the ILC. Access to difficult channels (ττ, cc – under study)

With its unique Higgs measurements and precision N^{3}LO PDFs and $\delta\alpha_s$, **ep upgrade transforms the LHC facility into a precision Higgs factory.**
[cf arXiv:1211:5102 + OB, MK: arXiv:1305:2090]

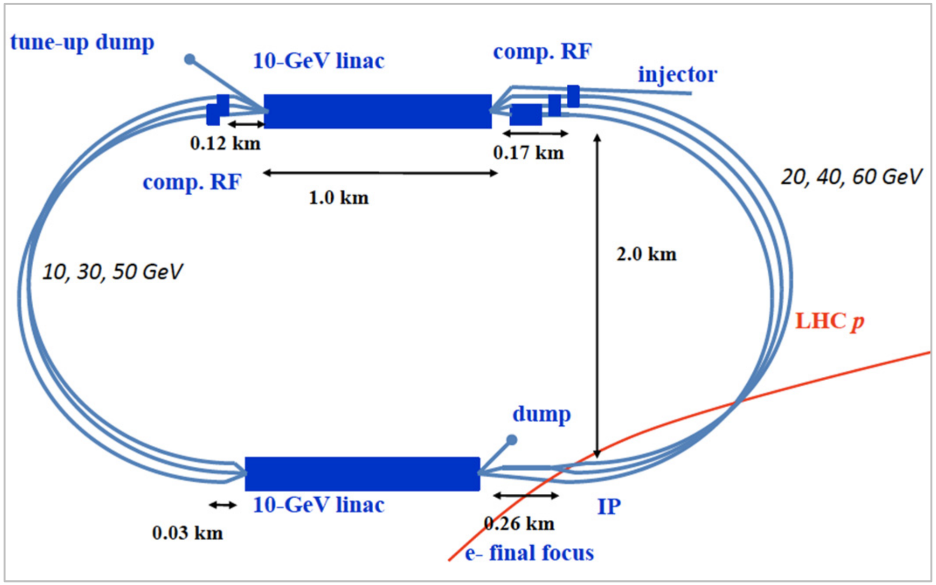
LHeC Higgs		CC (e^-p)
Polarisation		-0.8
Luminosity [ab^{-1}]		1
Cross Section [fb]		196
Decay	BrFraction	N^H_{CC} e^-p
$H \to b\bar{b}$	0.577	113 100
$H \to c\bar{c}$	0.029	5 700
$H \to \tau^+\tau^-$	0.063	12 350
$H \to \mu\mu$	0.00022	50
$H \to 4l$	0.00013	30
$H \to 2l2\nu$	0.0106	2 080
$H \to gg$	0.086	16 850
$H \to WW$	0.215	42 100
$H \to ZZ$	0.0264	5 200
$H \to \gamma\gamma$	0.00228	450
$H \to Z\gamma$	0.00154	300

Max Klein, Les Houches 12.6.13

Rates for E_e=60 GeV, proportional to E_e
Initial study for CDR:
H →bbar: selection efficiency: ~2.5%
which gives 5000 events with S/B=1.
corresponding to 0.7% coupling precision.
[cf: CDR, U.Klein ICHEP12, B.Mellado LPCC]

LHeC: Baseline Linac-Ring Option

- Super Conducting Linac with Energy Recovery & high current (> 6mA)



Two 1 km long SC linacs in CW operation ($Q > 10^{10}$)

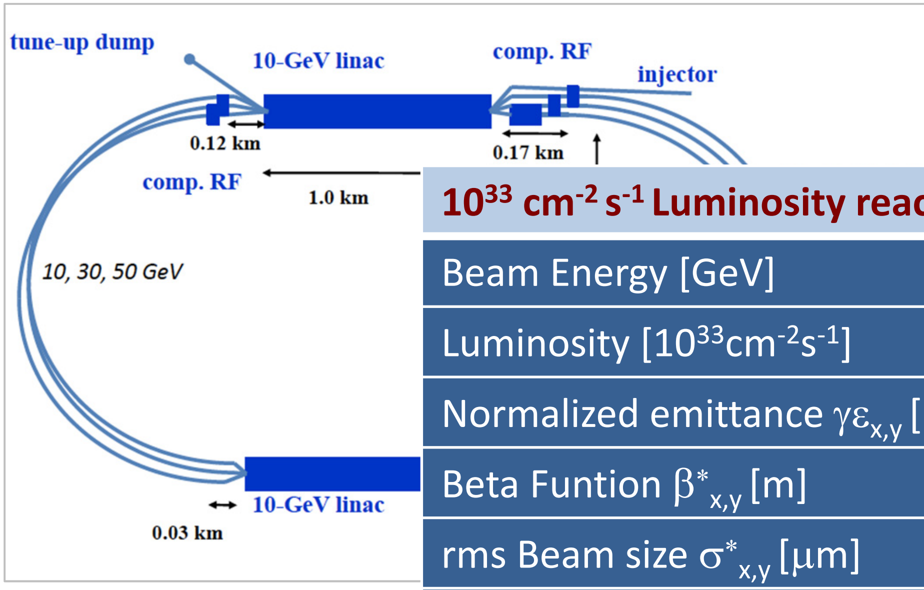
➔ requires Cryogenic system comparable to LHC system!

- Relatively large return arcs
  - ➔ ca. 9 km underground tunnel installation
  - ➔ total of 19 km bending arcs
  - ➔ same magnet design as for RR option: > 4500 magnets

LHeC: Baseline Linac-Ring Option

- Super Conducting Linac with Energy Recovery & high current (> 6mA)

Two 1 km long SC linacs in CW operation



10^{33} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [$10^{33} cm^{-2} s^{-1}$]	1	1
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	3.75	50
Beta Funtion $\beta^*_{x,y}$ [m]	0.1	0.12
rms Beam size $\sigma^*_{x,y}$ [μm]	7	7
rms Beam divergence $\sigma'^*_{x,y}$ [μrad]	70	58
Beam Current [mA]	430 (860)	6.6
Bunch Spacing [ns]	25 (50)	25 (50)
Bunch Population	$1.7*10^{11}$	$(1*10^9)$ $2*10^9$
Bunch charge [nC]	27	(0.16) 0.32

- Relatively large

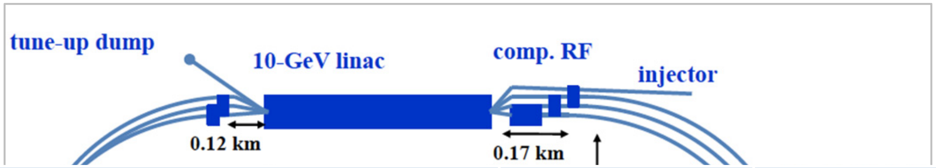
➔ ca. 9 km under

➔ total of 19 km

➔ same magnet c

LHeC: Baseline Linac-Ring Option

- Super Conducting Linac with Energy Recovery & high current (> 6mA)



Two 1 km long SC
linacs in CW operation

10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60	7000	60
Luminosity [$10^{33}cm^{-2}s^{-1}$]	16	16	1	1
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20	3.75	50
Beta Funtion $\beta^*_{x,y}$ [m]	0.05	0.10	0.1	0.12
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4	7	7
rms Beam divergence σ□$^*_{x,y}$ [μrad]	80	40	70	58
Beam Current [mA]	1112	25	430 (860)	6.6
Bunch Spacing [ns]	25	25	25 (50)	25 (50)
Bunch Population	$2.2*10^{11}$	$4*10^{9}$	$1.7*10^{11}$	$(1*10^{9})$ $2*10^{9}$
Bunch charge [nC]	35	0.64	27	(0.16) 0.32

Post CDR Studies: RF Frequency

Review of the SC RF frequency:

-HL-LHC bunch spacing requires bunch spacing with multiples of 25ns (40.079 MHz)

Frequency choice: *h* * n* 40.079 MHz

Symmetry in ERL: n=3 ➔ h * 120.237 MHz

h=6: 721 MHz or h=11: 1.323GHz

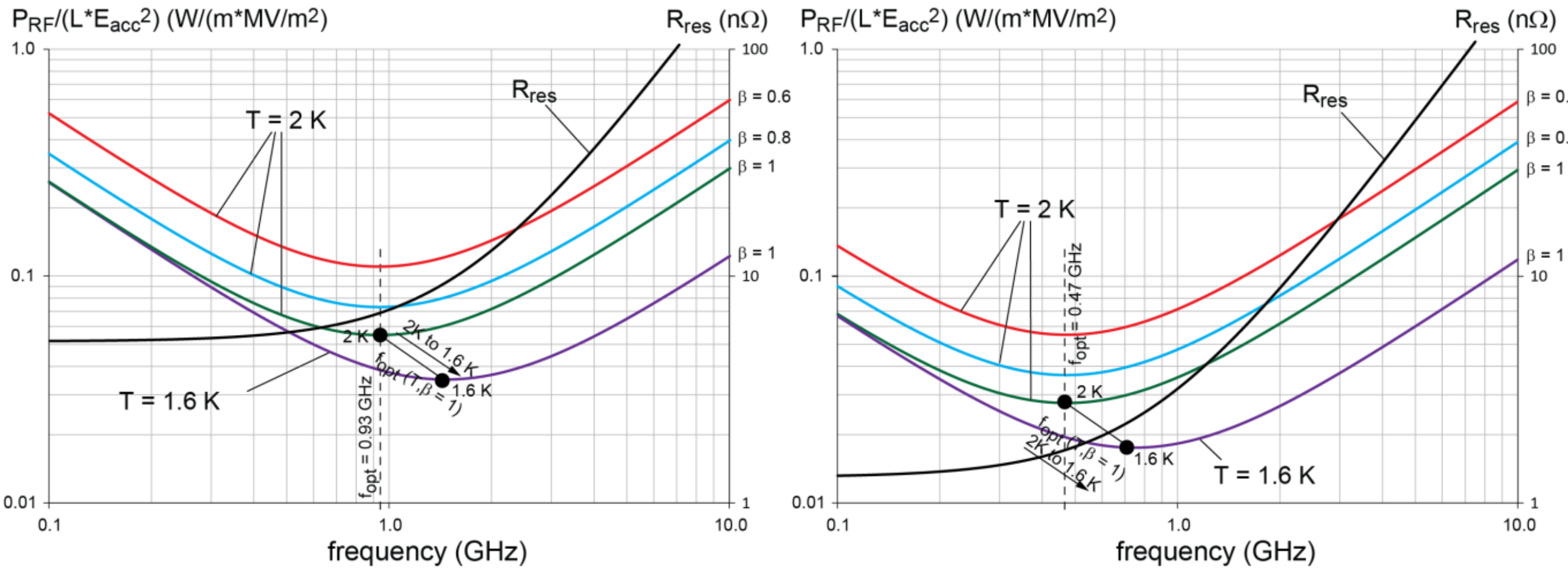
SPL & ESS: 704.42 MHz; ILC & XFEL: 1.3 GHz

Frequencies are different (20MHz) from existing technologies! Having a harmonic number which is not a multiple of the ERL symmetry could be explored ➔ asymmetric bunch patterns

RF Frequency: Power Considerations

Results from F. Marhauser

Erk Jensen at Daresbury meeting
12 March 2013



Small-grain (normal) Nb:
Optimum frequency at 2K between 700 MHz and 1050 MHz
Lower T shift optimum F upwards

Large-grain Nb:
Optimum frequency at 2K between 300 MHz and 800 MHz
Lower T shift optimum F upwards

RF Frequency: Power Considerations

Results from F. Marhauser

Erk Jensen at Daresbury meeting

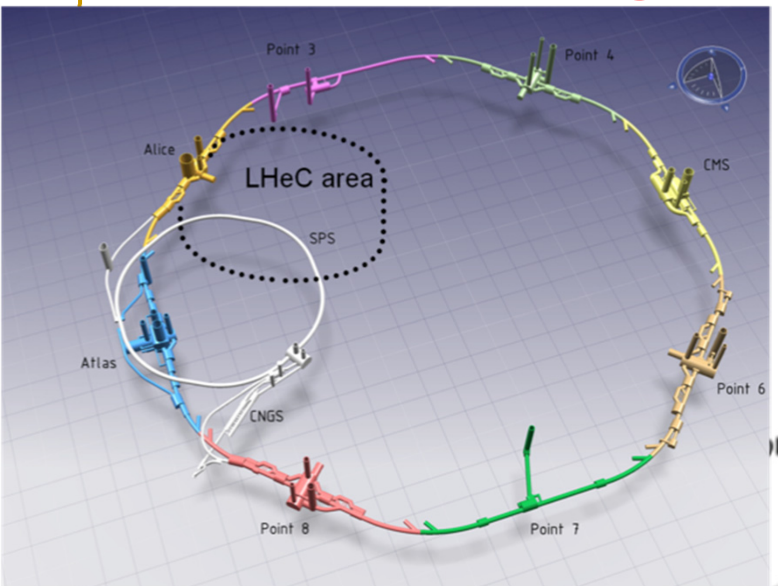
→ Ca. 800 MHz is in the optimum frequency range for both material options

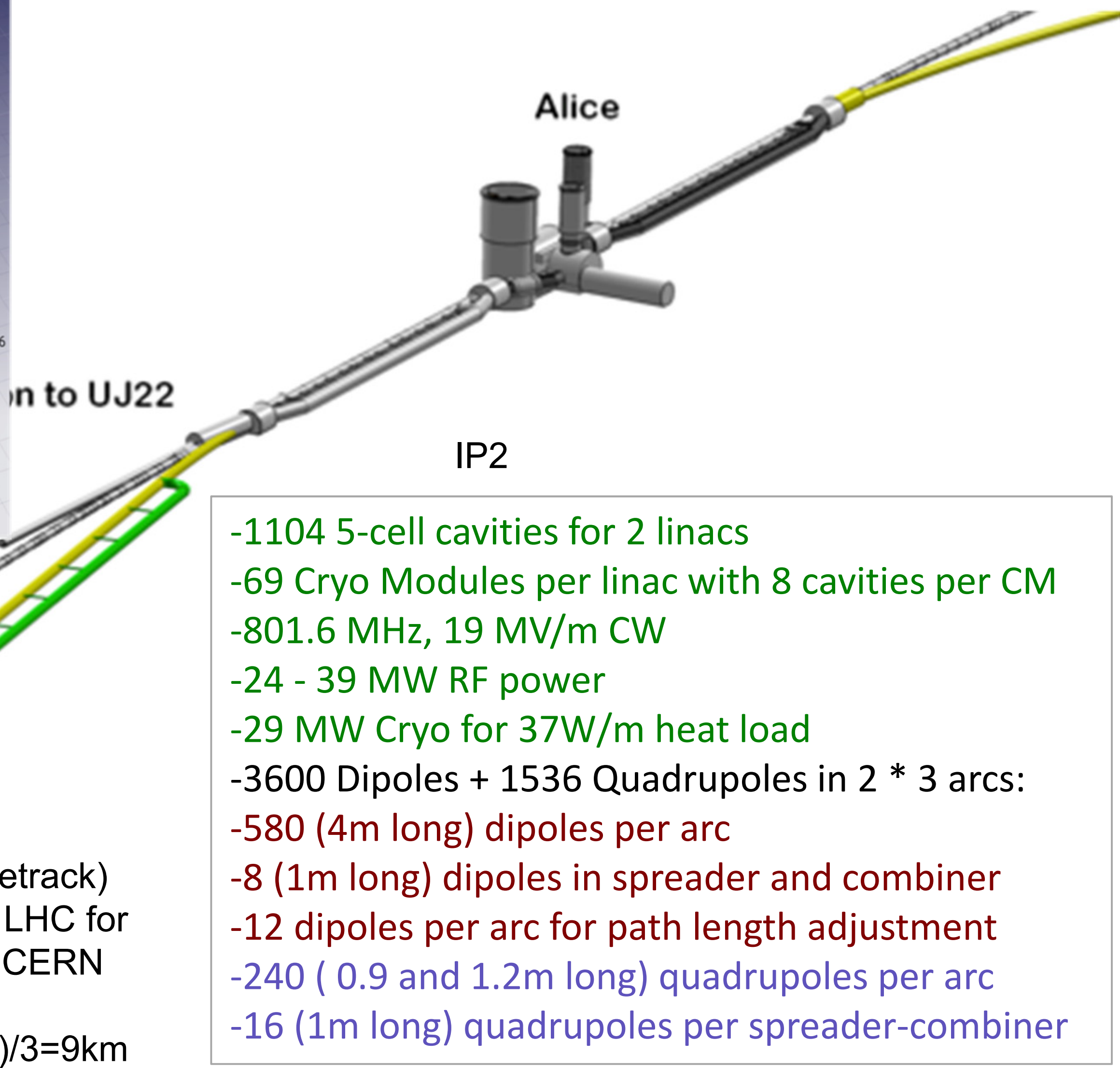
→ 801.58 MHz chosen in the end for the LHeC
→
Synergy with other projects (e.g. HL-LHC, and FCC ee and hh) and
→ international collaboration option (MESA)

Optimum frequency at 2K between
700 MHz and 1050 MHz
Lower T shift optimum F upwards

Optimum frequency at 2K between
300 MHz and 800 MHz
Lower T shift optimum F upwards

LINAC – Ring: connection to the LHC



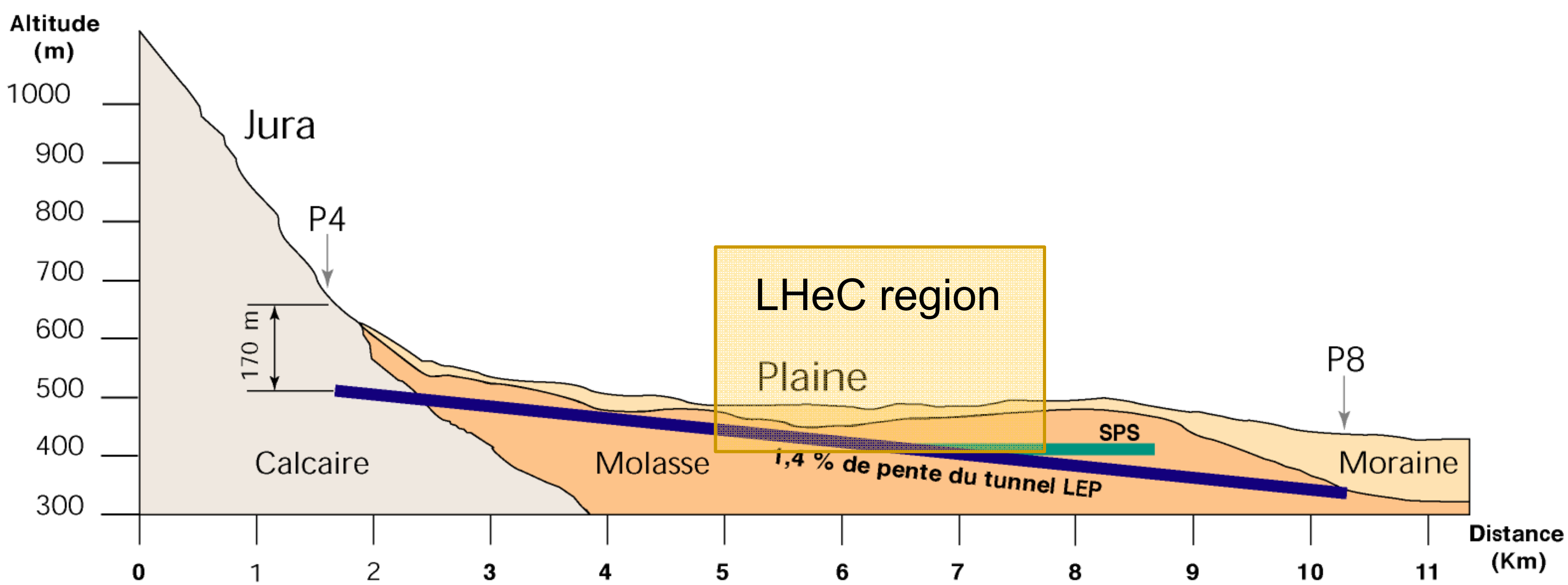


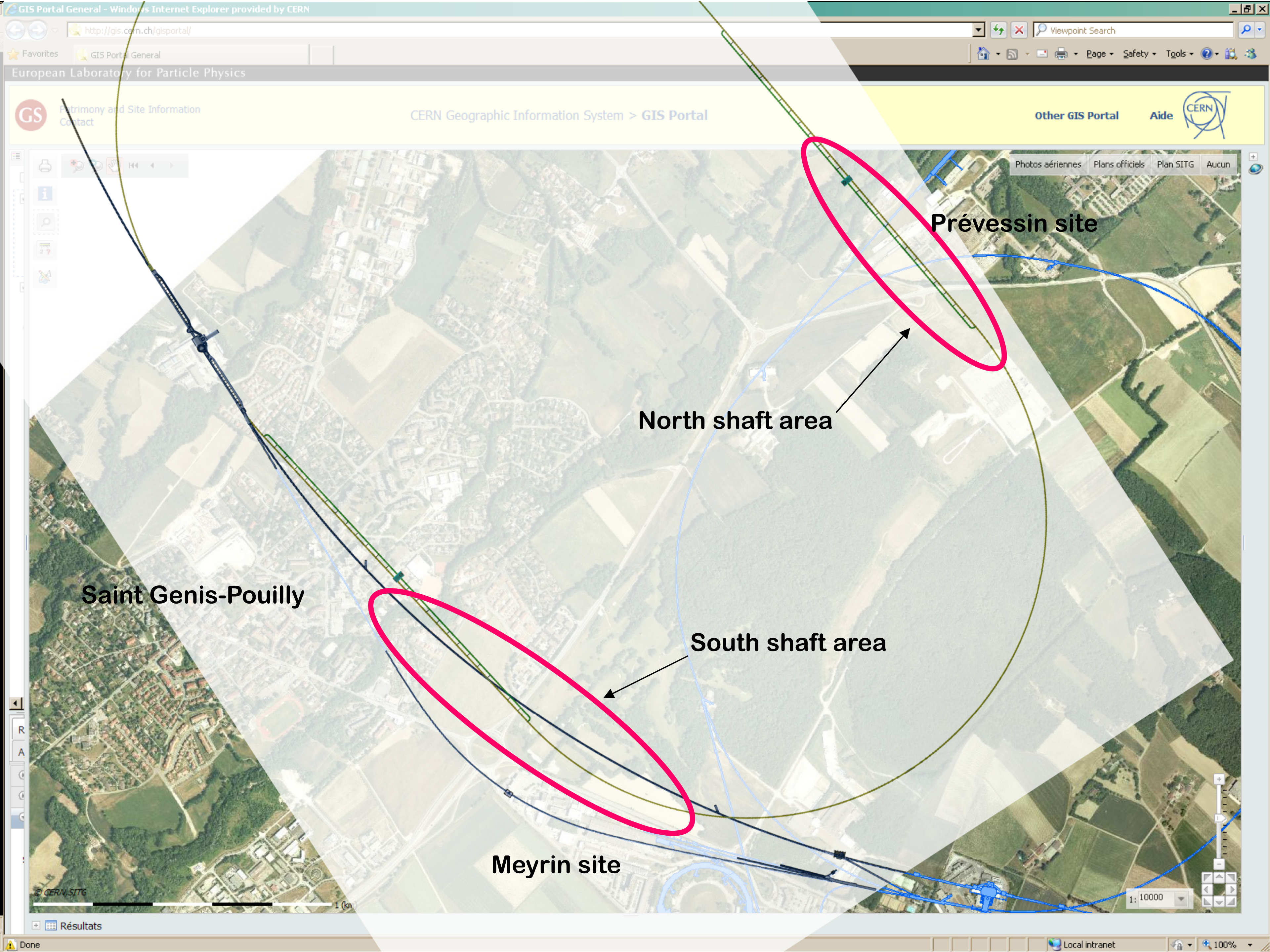
- -1104 5-cell cavities for 2 linacs
- -69 Cryo Modules per linac with 8 cavities per CM
- -801.6 MHz, 19 MV/m CW
- -24 - 39 MW RF power
- -29 MW Cryo for 37W/m heat load
- -3600 Dipoles + 1536 Quadrupoles in 2 * 3 arcs:
- -580 (4m long) dipoles per arc
- -8 (1m long) dipoles in spreader and combiner
- -12 dipoles per arc for path length adjustment
- -240 (0.9 and 1.2m long) quadrupoles per arc
- -16 (1m long) quadrupoles per spreader-combiner

Linac (racetrack) inside the LHC for access at CERN Territory
U=U(LHC)/3=9km

Site Features: Geology

- Geology: Jan 20th 2014 John Osborne
  - Molasse – Moraine
    - Profile LHeC region (showing also location of LHC and SPS)

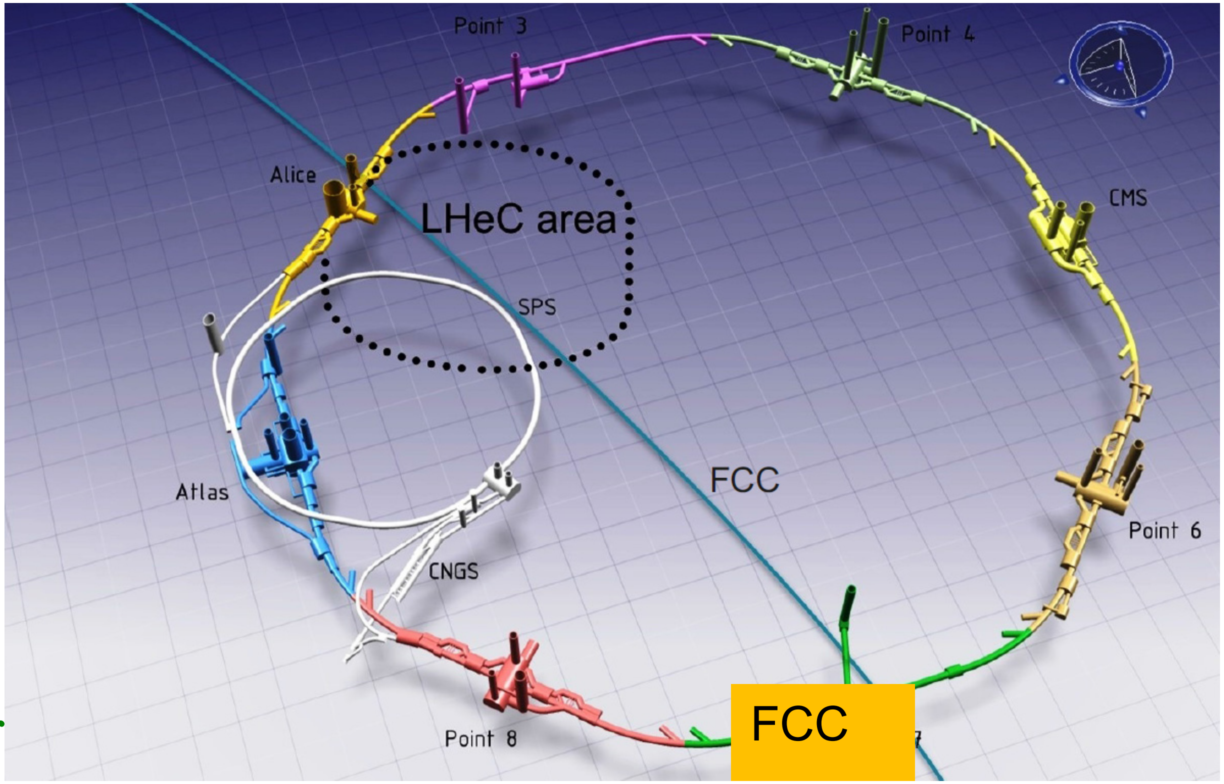



GIS Portal General - Windows Internet Explorer provided by CERN
http://gis.cern.ch/gisportal/
Viewpoint Search
Favorites
GIS Portal General
Page
Safety
Tools
European Laboratory for Particle Physics
Patrimony and Site Information
Contact
CERN Geographic Information System > GIS Portal
Other GIS Portal
Aide
CERN
Photos aériennes
Plans officiels
Plan SITG
Aucun
Prévessin site
North shaft area
Saint Genis-Pouilly
South shaft area
Meyrin site
© CERN, SITG
1 km
1: 10000
Résultats
Done
Local intranet
100%

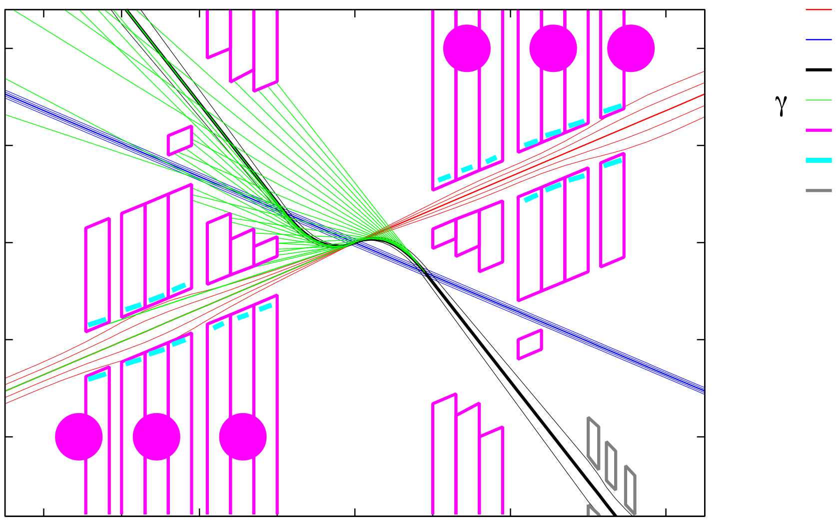
LHeC in the Context of FCC:

John Osborne @ FCC Kick-off meeting

- ERL applications:
  - ➔ LHeC could provide collisions with HL-LHC
  - ➔ LHeC could potentially provide collisions with FCC-hh
  - ➔ LHeC could operate as injector for FCC-ee

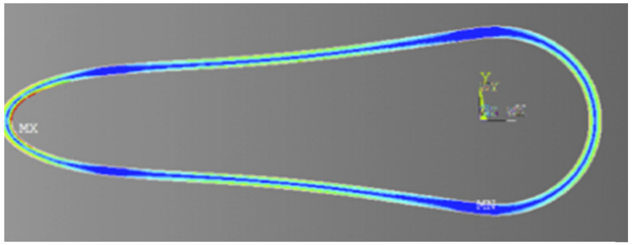


Next Steps: Interaction Region Optimization



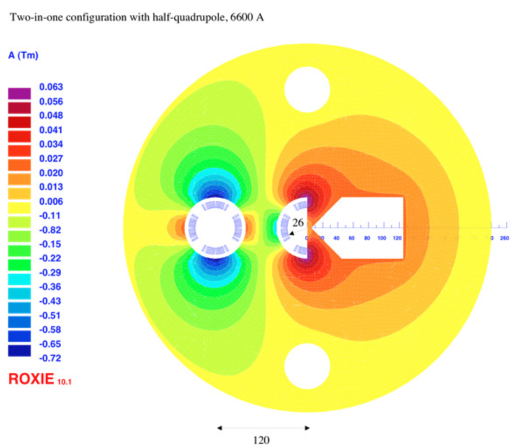
Beam pipe: in CDR 6m, Be, ANSYS calculations

Composite material R+D, prototype, support..
→ Essential for tracking, acceptance and Higgs



Have optics compatible with LHC ATS optics and β*=0.1m
Head-on collisions mandatory →
High synchrotron radiation load, dipole in detector

Adapt LHeC to LHC ATS optics
Specification of Q1 – NbTi prototype



Revisit SR (direct and backscattered),
Masks+collimators
Beam-beam dynamics and 3 beam operation studies

Next Steps: Interaction Region Optimization

First conceptual SC magnet designs exist

But: Still requires additional design work and R&D!

Synergies with HL-LHC triplet development!

→ CDR based on e-L* > p-L*

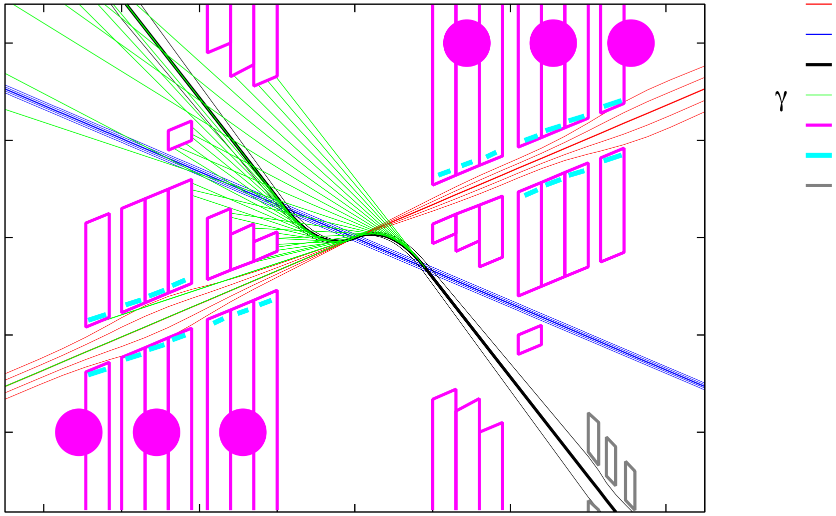
→ Post CDR studies also evaluate e-L* < p-L*

(driven by small β* for Luminosity reach)

Masks+collimators

Beam-beam dynamics and 3 beam operation studies

Proton IR Optics – Half-Quadrupole



Proton L*=10m

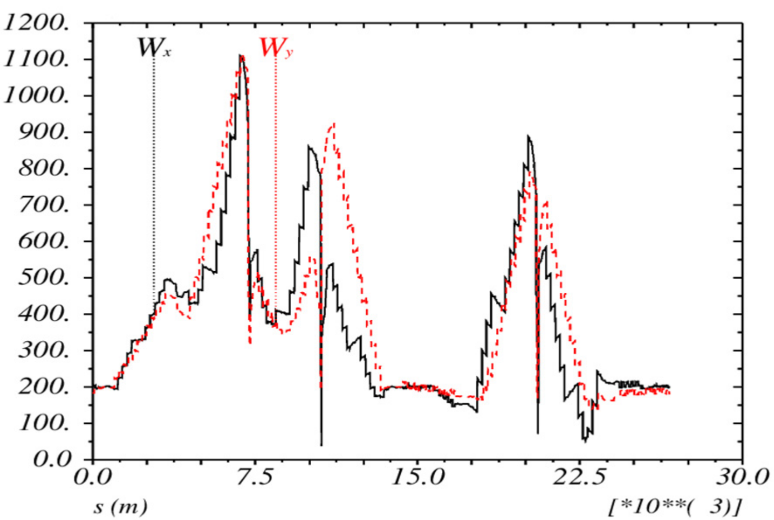
Electron L*=30m

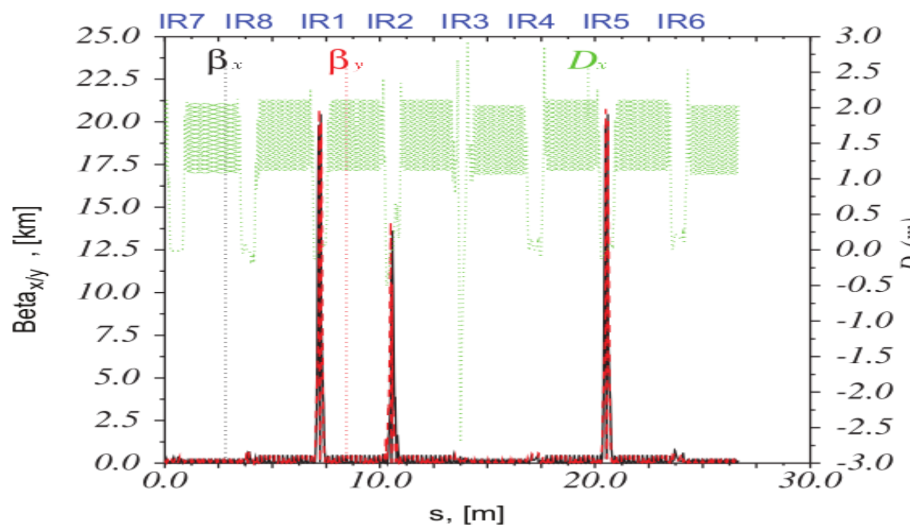
Proton β*=10cm in IP2

Proton β*=15cm in IP1 & IP5

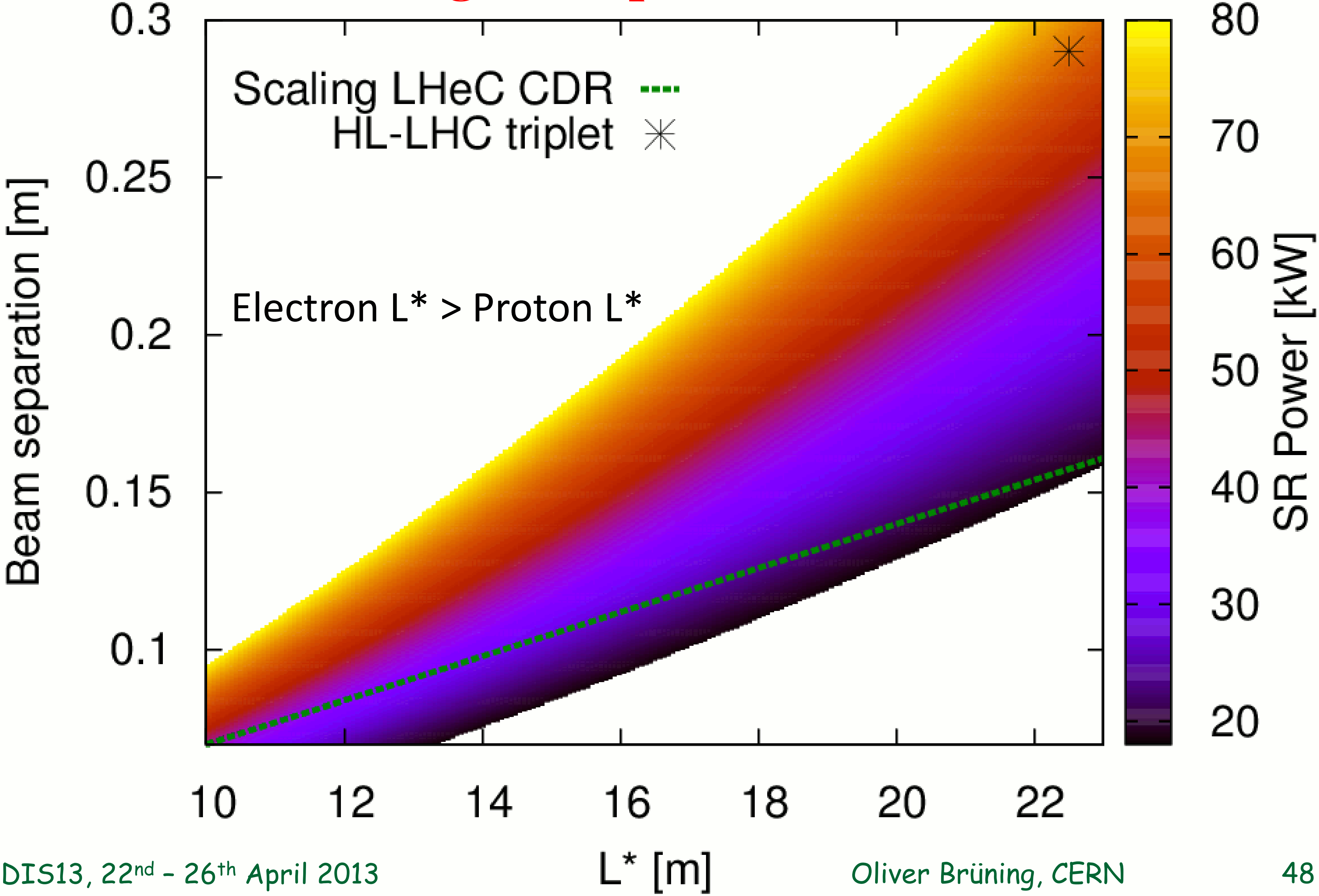
Electron β*=10cm in IP2

[Emilia Cruz]

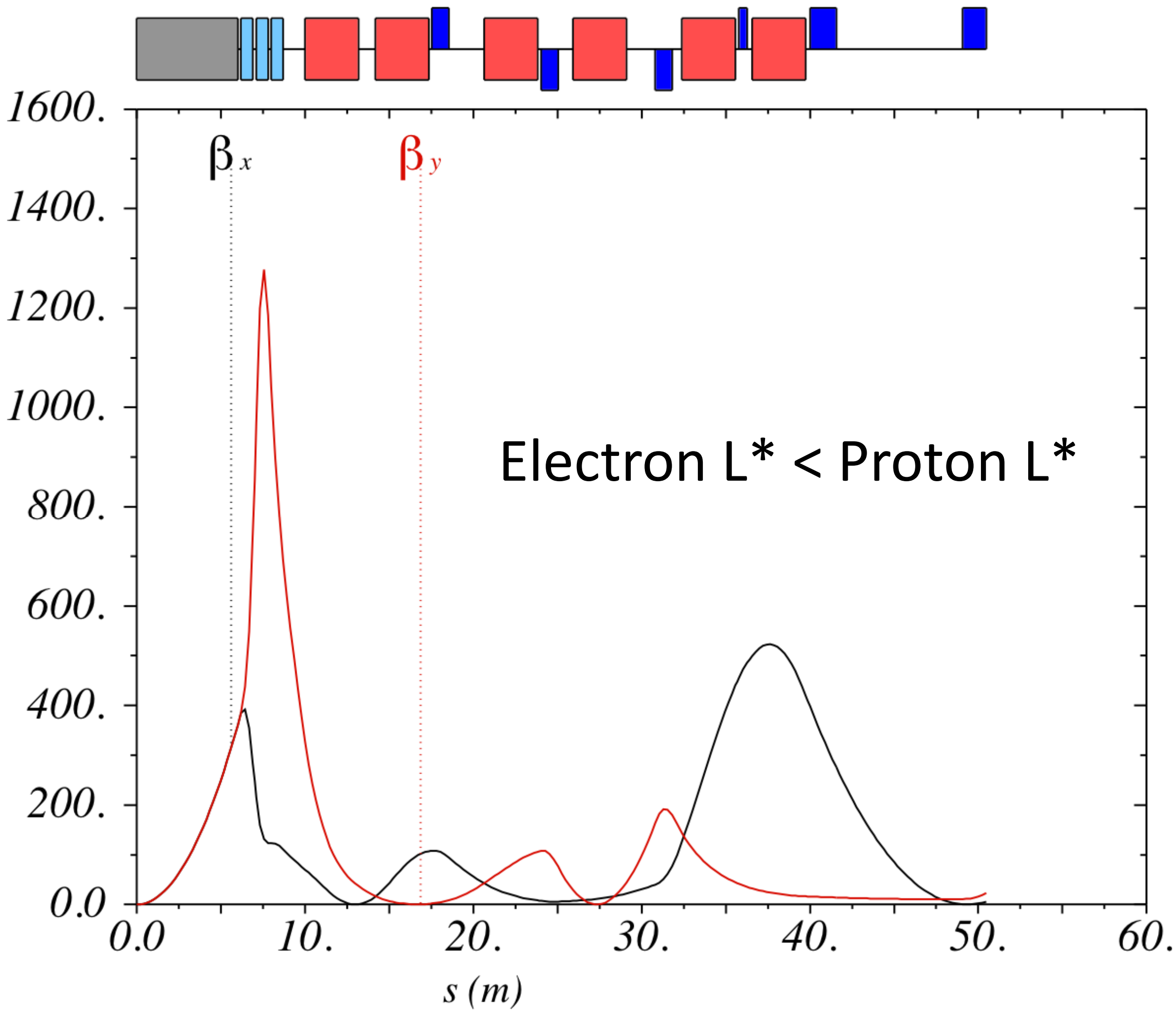




Interaction Region Optimization



Electron IR Optics – Half-Quadrupole



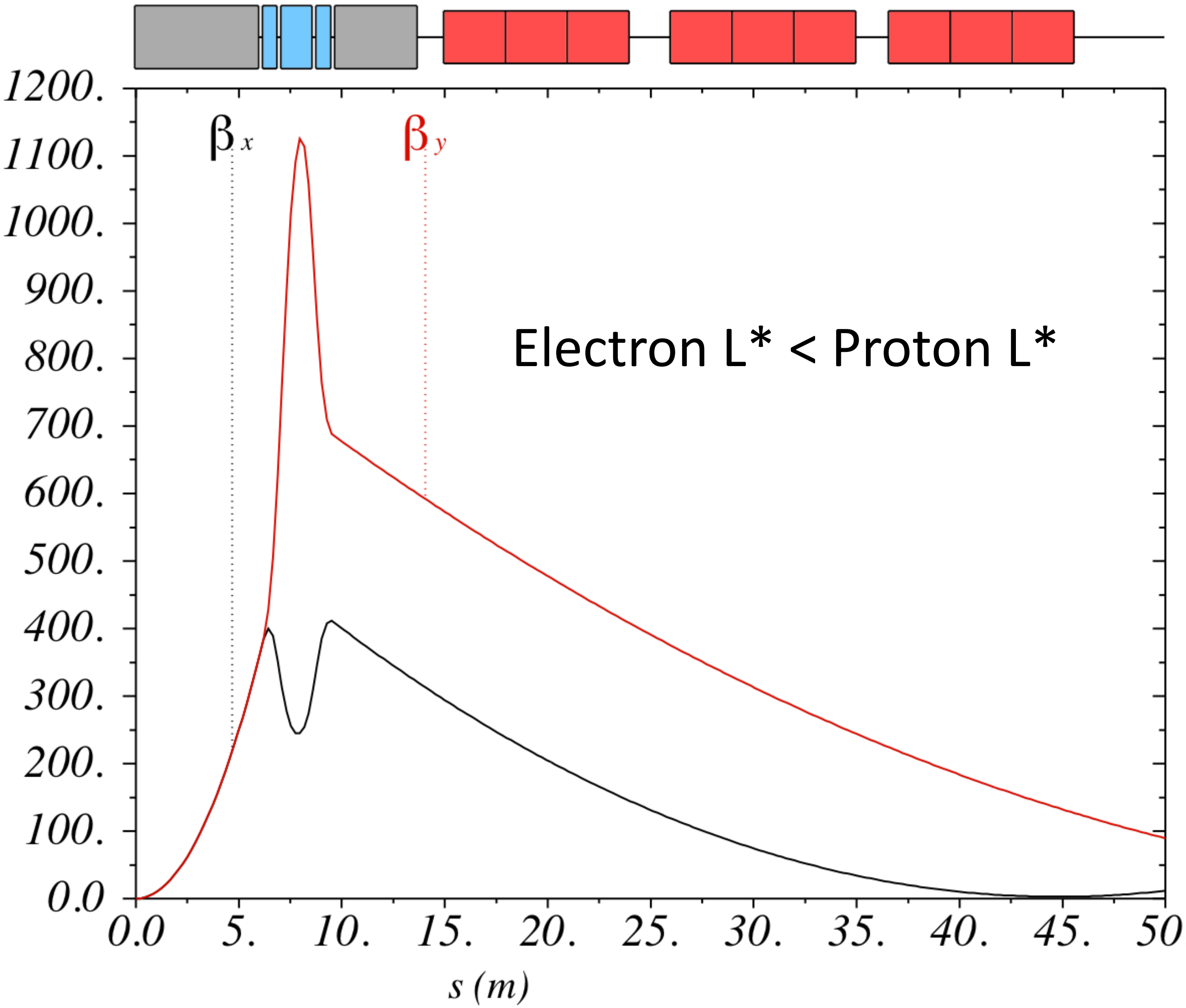
Luke Thompson

- Electron final triplet (offset)
- Electron matching
- Proton final triplet
- Electron dipoles

Proton L* = 10m
Electron L* = 6m
Proton β*in IP2 = 5cm

Electron IR Optics – No Half-Quadrupole

Luke Thompson



Electron final triplet (offset)

Proton final triplet

Electron dipoles

Proton L* = 15m
Electron L* = 6m
Proton β*in IP2=10cm

LHeC Workshop January 2013

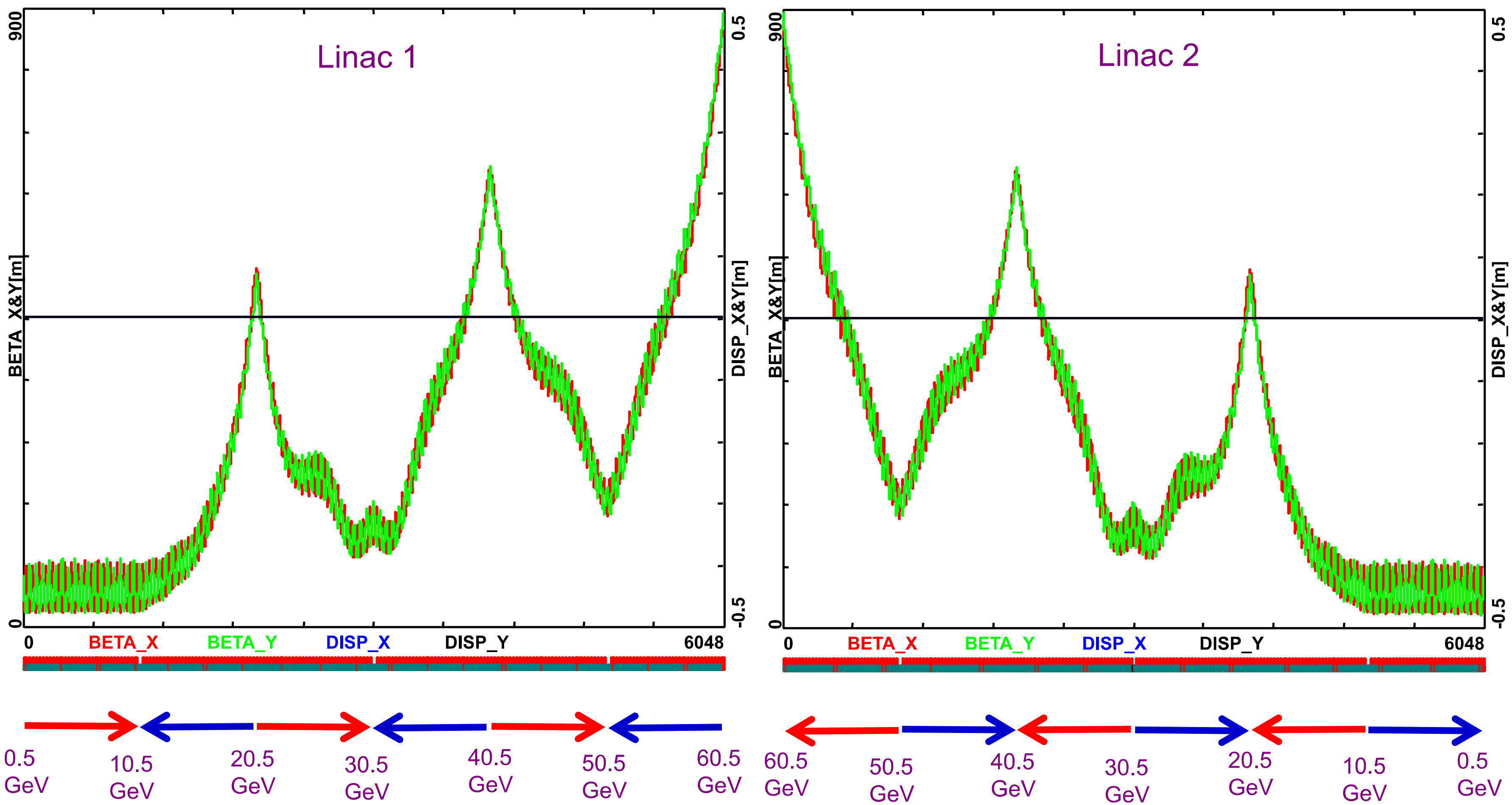
- We have a good optics baseline for ERL:

  ➔ Presentation by Alex Bogacz @ parallel session of Working Group 1 on Beam Physics

Linac 1 and 2: Multi-pass ER Optics

Alex Bogacz

Acceleration/Deceleration

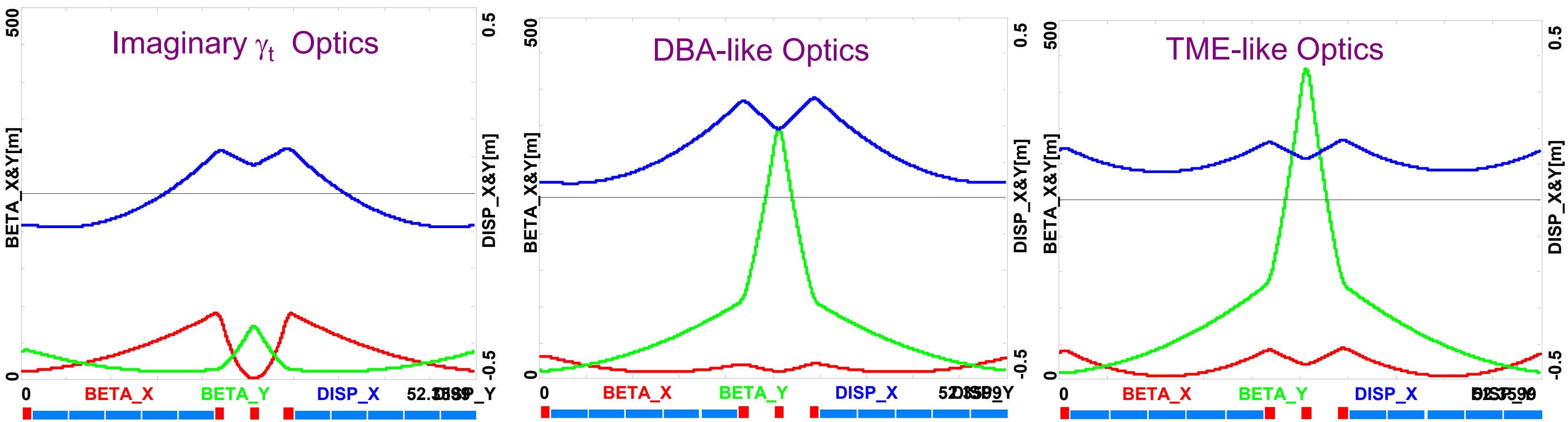


Arc Optics: Emittance preserving FMC cell

$$\Delta\varepsilon^N = \frac{55\, r_0}{48\sqrt{3}} \frac{\hbar c}{mc^2} \gamma^6 \langle H \rangle \frac{\theta}{\rho^2} \qquad H = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

Alex Bogacz

Arc 1 , Arc2 — Arc 3, Arc 4 — Arc5, Arc 6



$\langle H \rangle = 8.8 \times 10^{-3}\ m$ — $\langle H \rangle = 2.2 \times 10^{-3}\ m$ — $\langle H \rangle = 1.2 \times 10^{-3}\ m$

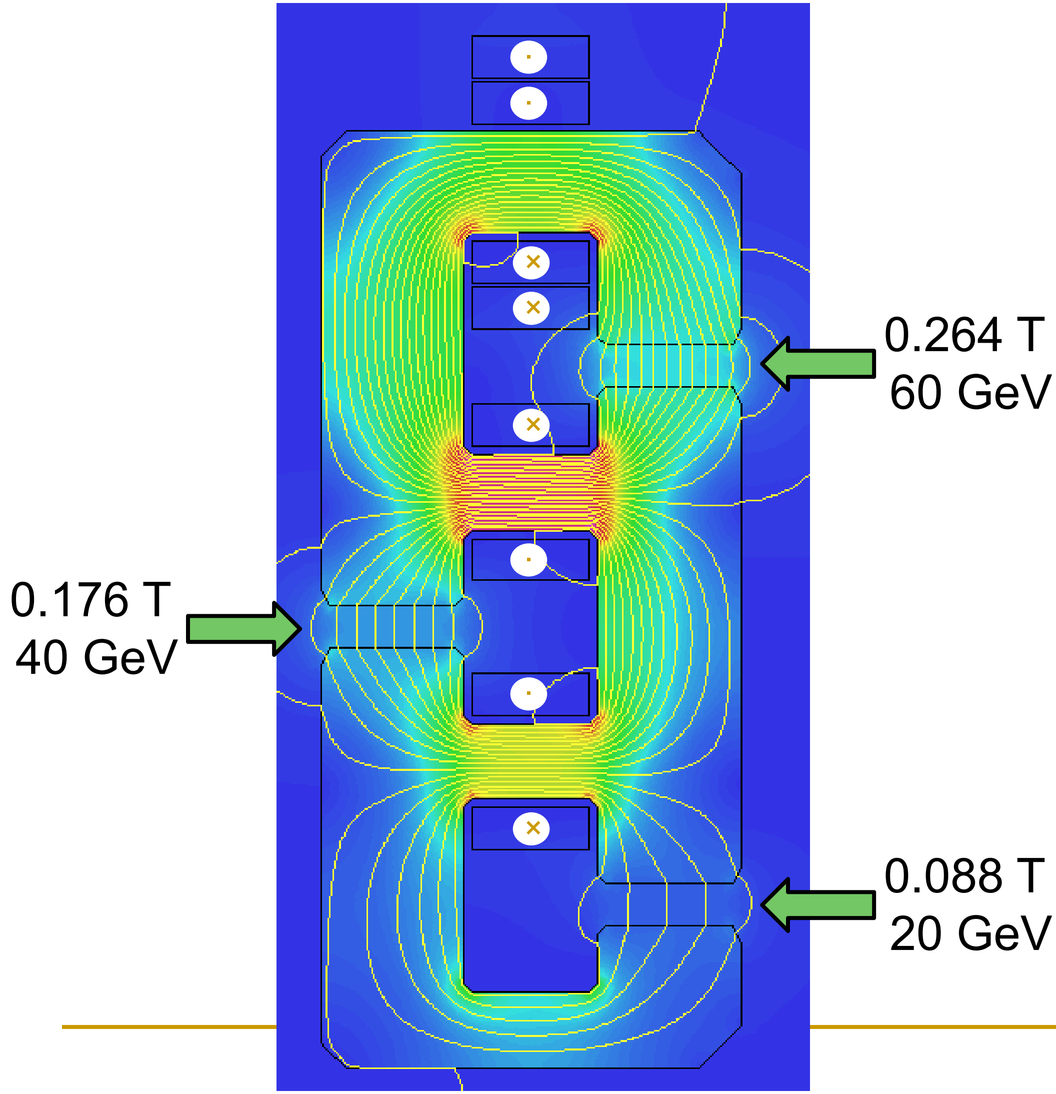
factor of 18 smaller than FODO

FMC = Flexible Momentum Compaction

total emittance increase in Arc 5: $\Delta\varepsilon_x^N = 4.268\ \mu m\ rad$

Return Arc Dipoles post-CdR

Attilio Milanese

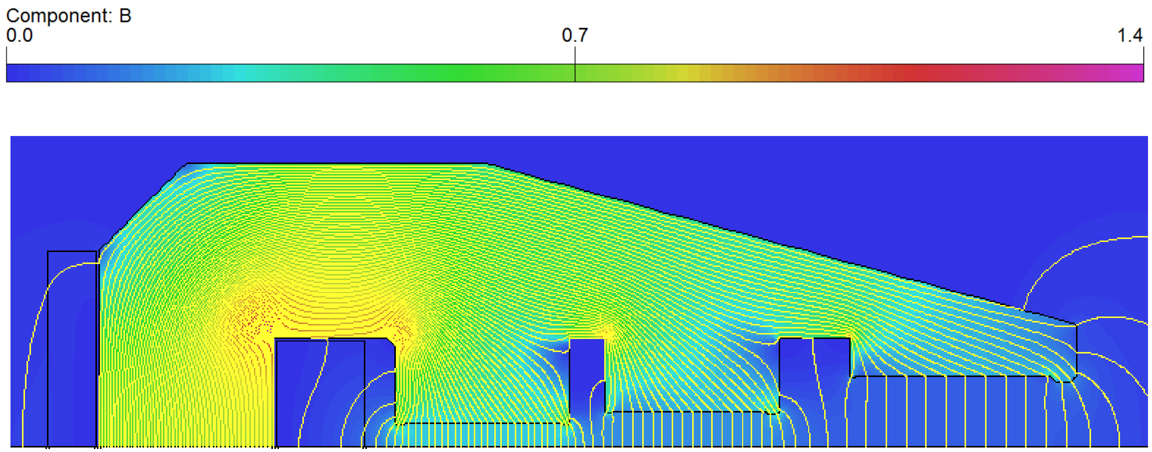


Alternative coil arrangement

- keep the idea of recycling Ampere-turns
- stack the apertures vertically but offset them also transversally
- same vertical gap, 25 mm
- simple coils / bus-bars, same powering circuit
- as before, trim coils can be added for two of the apertures, to give some tuning

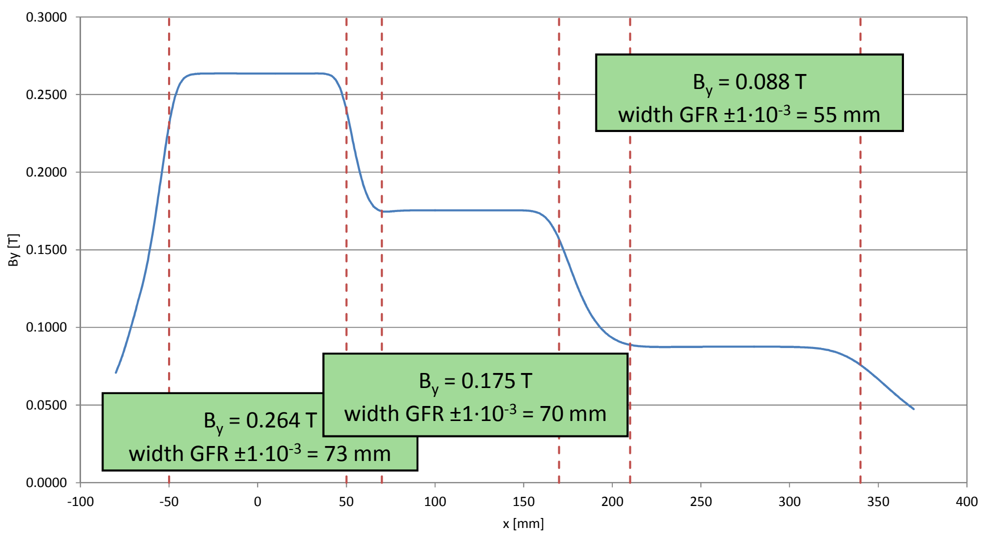
Return Arc Dipoles in post-CdR

Attilio Milanese



(1/2 of the dipole shown)

field across the three apertures

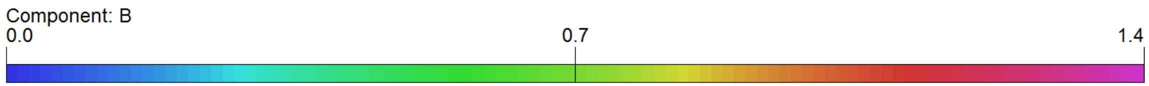


Side-by-side concept

- needs some spacing between the apertures to keep a flat enough field distribution
- the Ampere-turns are fully recycled for the three energies
- trim coils can be added for two of the apertures, to give some tuning

Return Arc Dipoles in post-CdR

Attilio Milanese



Side-by-side

Interesting area for Prototype Development!

en
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(1/2
dipole

LHeC Workshop in January also brought up the option of FFAG arcs for the LHeC ERL.

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➔ an interesting option that should be studies in more detail of the coming month!

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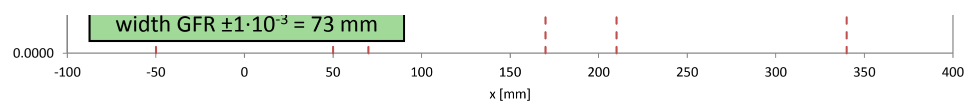

the apertures, to give some tuning

LHeC: Post CDR Developments

- Develop CDR for an ERL test facility @ CERN:
  - -Beam Dynamics for ERL operation → develop expertise at CERN
  - -Synergy with other research plans: SC RF and high field magnet developments for FCC related studies

- Mandate a Coordination Group and an International Advisory Committee:
  - -Mandate and formation by CERN directorate (IAC Chair: H. Schopper)
  - -First IAC meeting at January 2014 LHeC Workshop
  - -First Coordination Group meeting February 2014

LHeC: Post CDR Developments

- ➔ Presentations by Alessandra Valloni and Erk Jensen @ parallel session of Working Groups 1 and 3 on Beam Dynamics and RF

- Mandate a Coordination Group and an International Advisory Committee:

  -Mandate and formation by CERN directorate

  (IAC Chair: H. Schopper)

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LHeC: Post CDR Developments

➔ Presentations by Alessandra Valloni and Erk Jensen @ parallel session of Working Groups 1 and 3 on Beam Dynamics and RF

- Mandate a Coordination Group and an International Advisory Committee:

➔ Next IAC meeting planned for June 2014

-First Coordination Group meeting February 2014

LHeC Summary

- We have a first p-optics integration into HL-LHC [Rogelio Thomas, Maxim Korostelliev, Emilia Cruz]

- We have a first e-optics integration into HL-LHC IR [Rogelio Thomas, Luke Thompson]
  Two options, with and without SC Half Quadrupoles

- Ongoing optimization for Interaction Region:
  - -Performance need in light of Higgs & FCC integration
  - -optimization of L* (SRP, magnet design, luminosity)
    - ➔ ATS optics and Q' correction
    - ➔ synchrotron radiation issues for LHeC

LHeC Next Steps

- We have first developments for:

  ➔ 'Front-End' beam dynamic studies of the Electron Beam
  [Edward Niessen]

  ➔ Perturbations from beam-beam interactions
  [Dario Pellegrini]

- Studies in Preparation of an ERL Test Facility @ CERN
  - -site choice
  - -auxiliary applications (magnet test facility, physics etc)
  - -possible staging of the ERL TF installation

    ➔ see presentation by A. Valloni
  - -RF preparations

    ➔ see presentation by E. Jensen