The Status and Prospects of the LHeC and FCC-he Developments

E. Cruz-Alaniz

on behalf of the LHeC Study Group

DIS 15
Dallas, USA

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LHeC Participating Institutes

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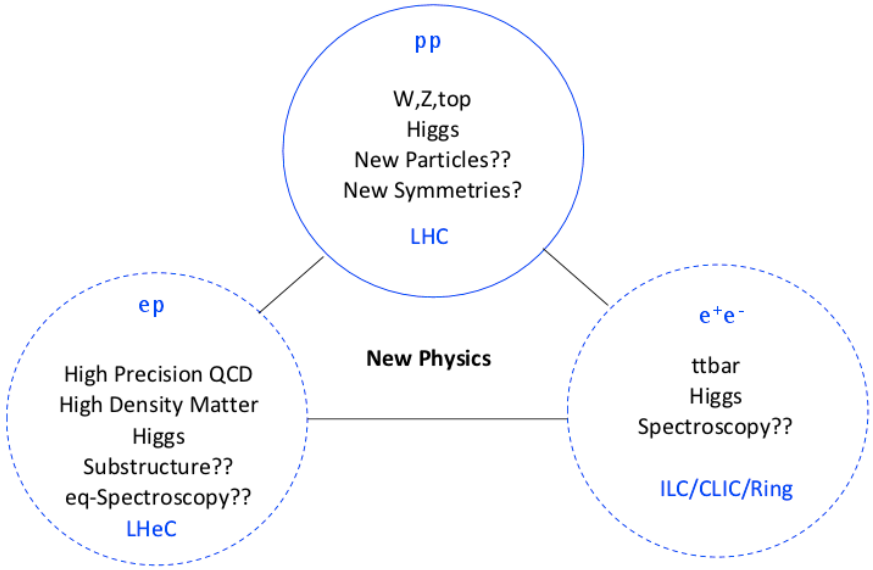
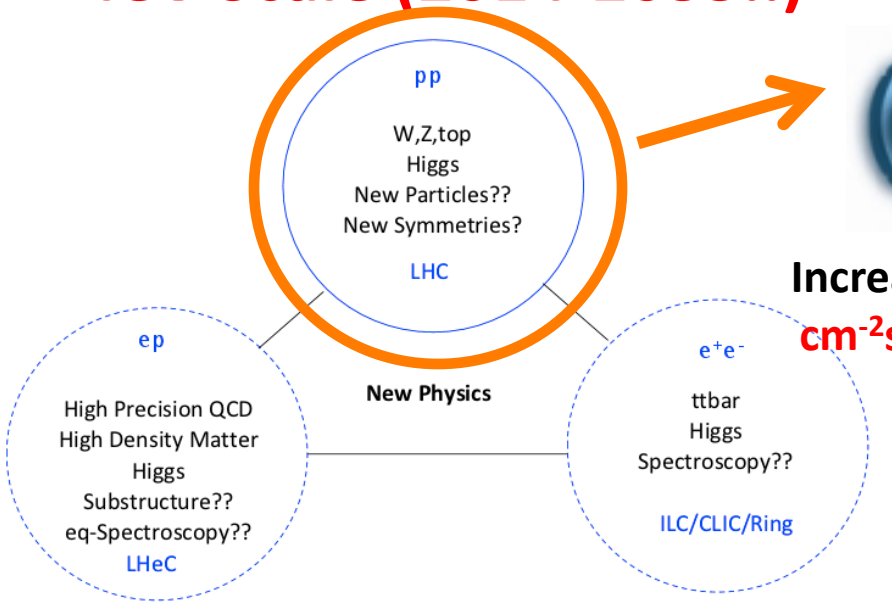
LHC Upgrade Program

TeV Scale (2009-2014..)



LHC Upgrade Program

TeV Scale (2014-2035..)

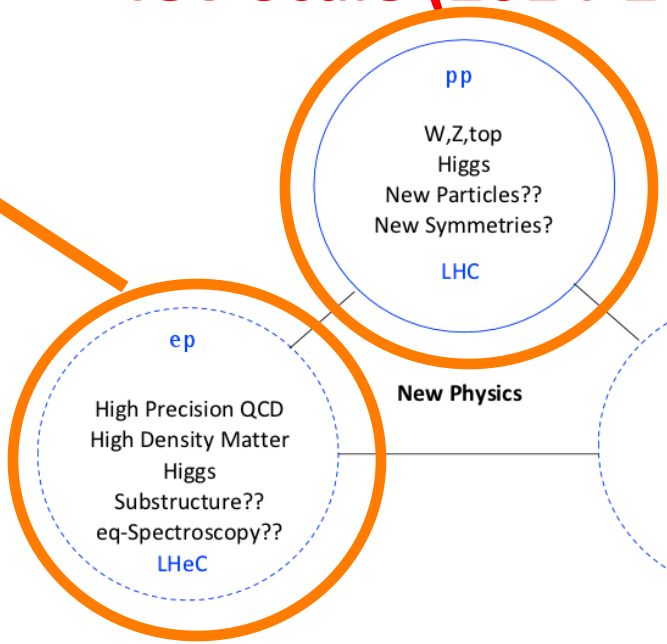


High Luminosity LHC

Increase Luminosity($5x10^{34}$ $cm^{-2}s^{-1}$) in IP1 (ATLAS) and IP5 (CMS)

LHC Upgrade Program

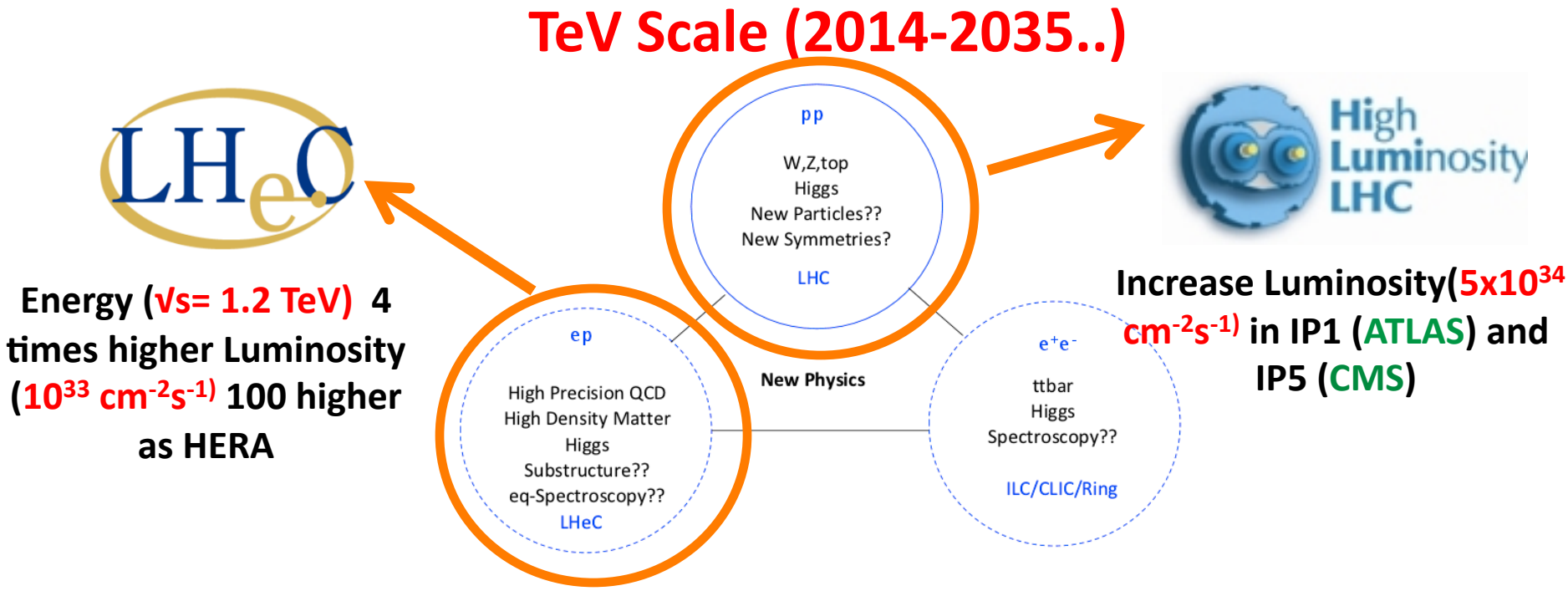
TeV Scale (2014-2035..)



Energy ($\sqrt{s}$= 1.2 TeV) 4 times higher Luminosity (10^{33} $cm^{-2}s^{-1}$) 100 higher as HERA

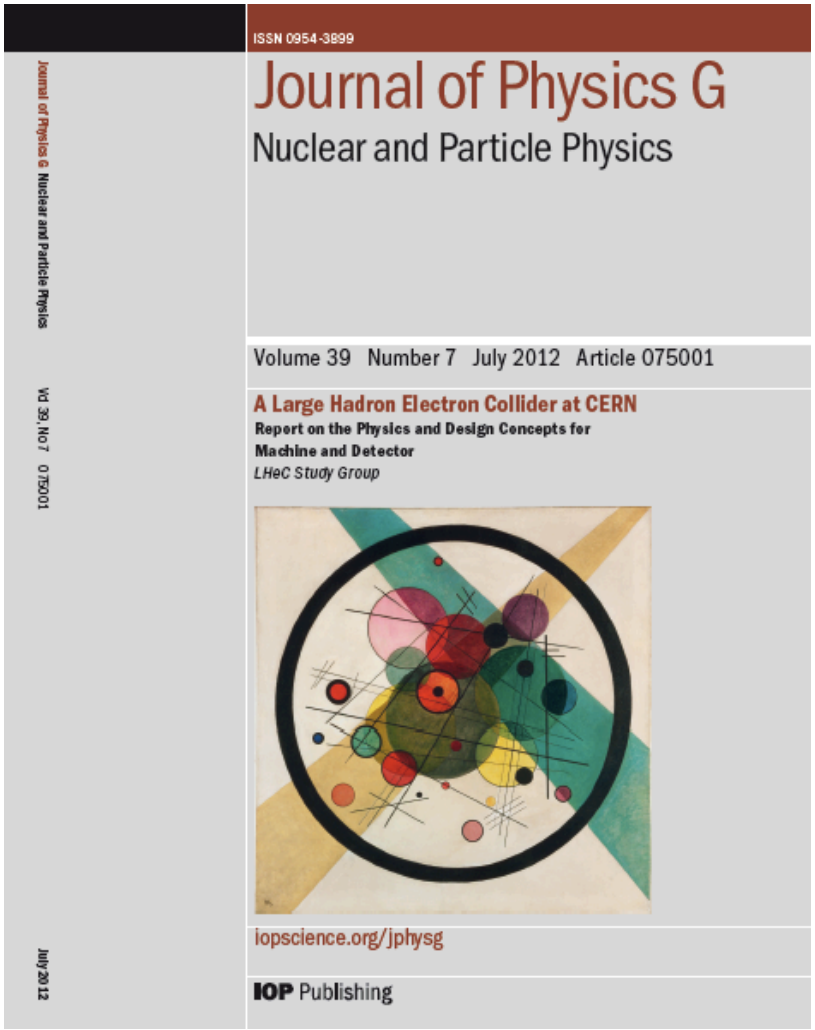
Increase Luminosity(5×10^{34} $cm^{-2}s^{-1}$) in IP1 (ATLAS) and IP5 (CMS)

LHeC Goals



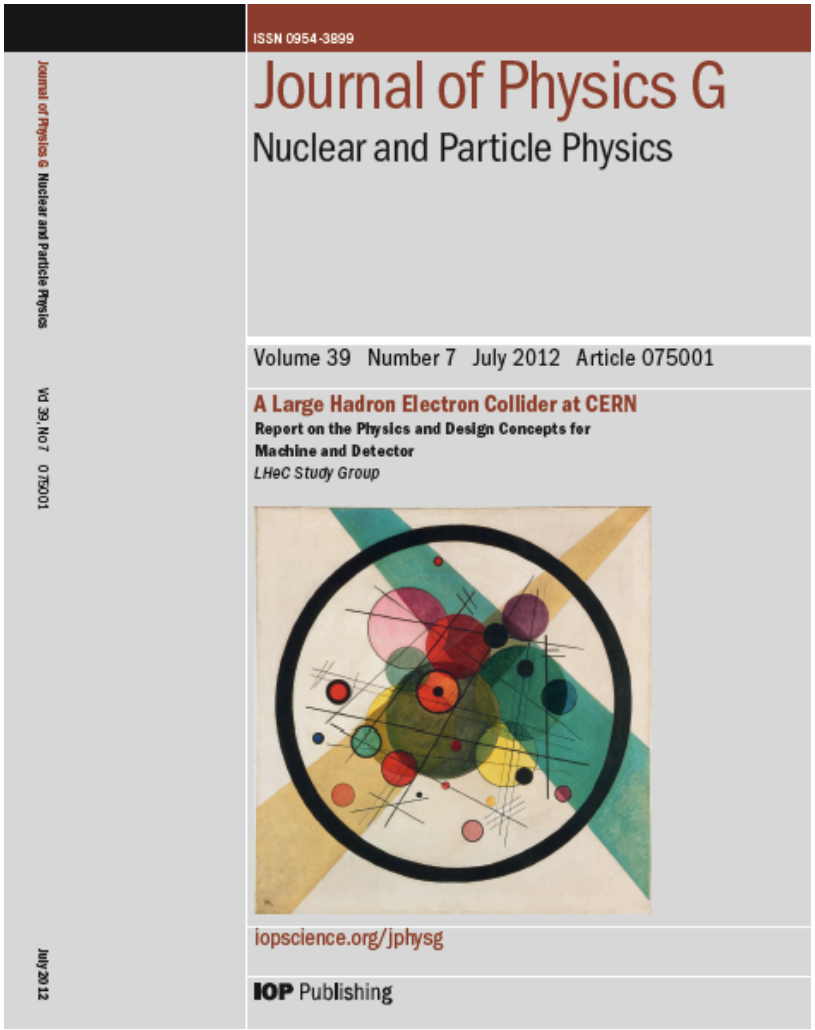
- Synchrotonous pp and ep operation at high Luminosity
- Power consumption for lepton complex ≤ 100 MW

Conceptual Design Report (CDR) July 2012



1. **INTRODUCTION**
2. **PHYSICS**
3. **ACCELERATOR**
4. **DETECTOR**
5. **CONCLUSIONS**

CDR



1. **INTRODUCTION**

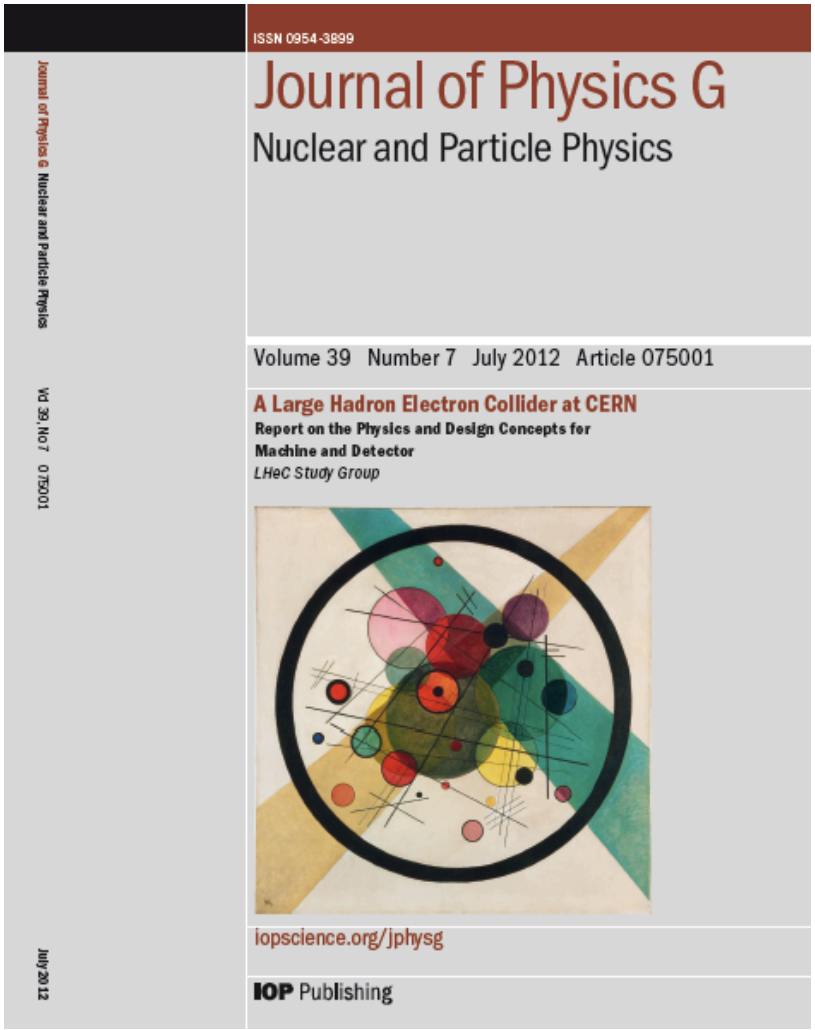
2. **PHYSICS**
   - Precision QCD and Electroweak Physics
   - Physics at High Parton Densities
   - New Physics at high energy

3. **ACCELERATOR**

4. **DETECTOR**
   - Detector Requirements
     - Central Detector
     - Forward and Backward Detector

5. **CONCLUSIONS**

CDR



1. **INTRODUCTION**

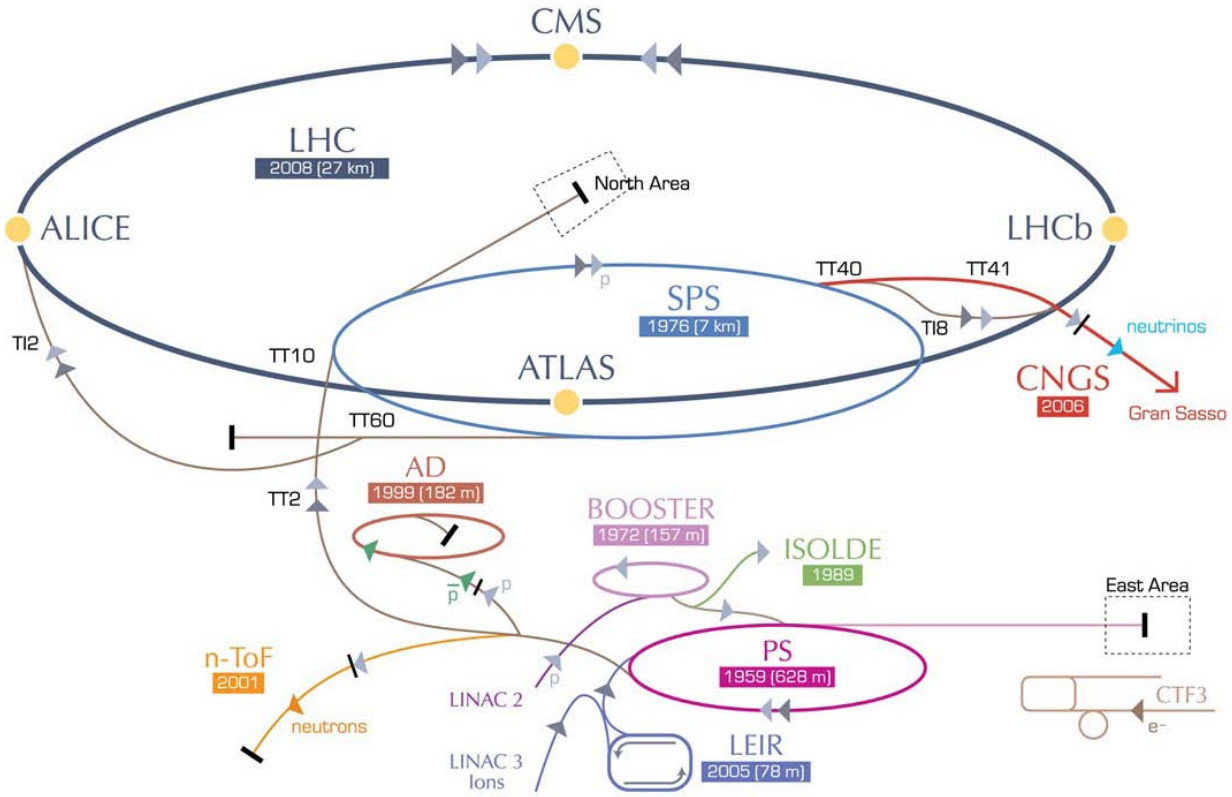
2. **PHYSICS**

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

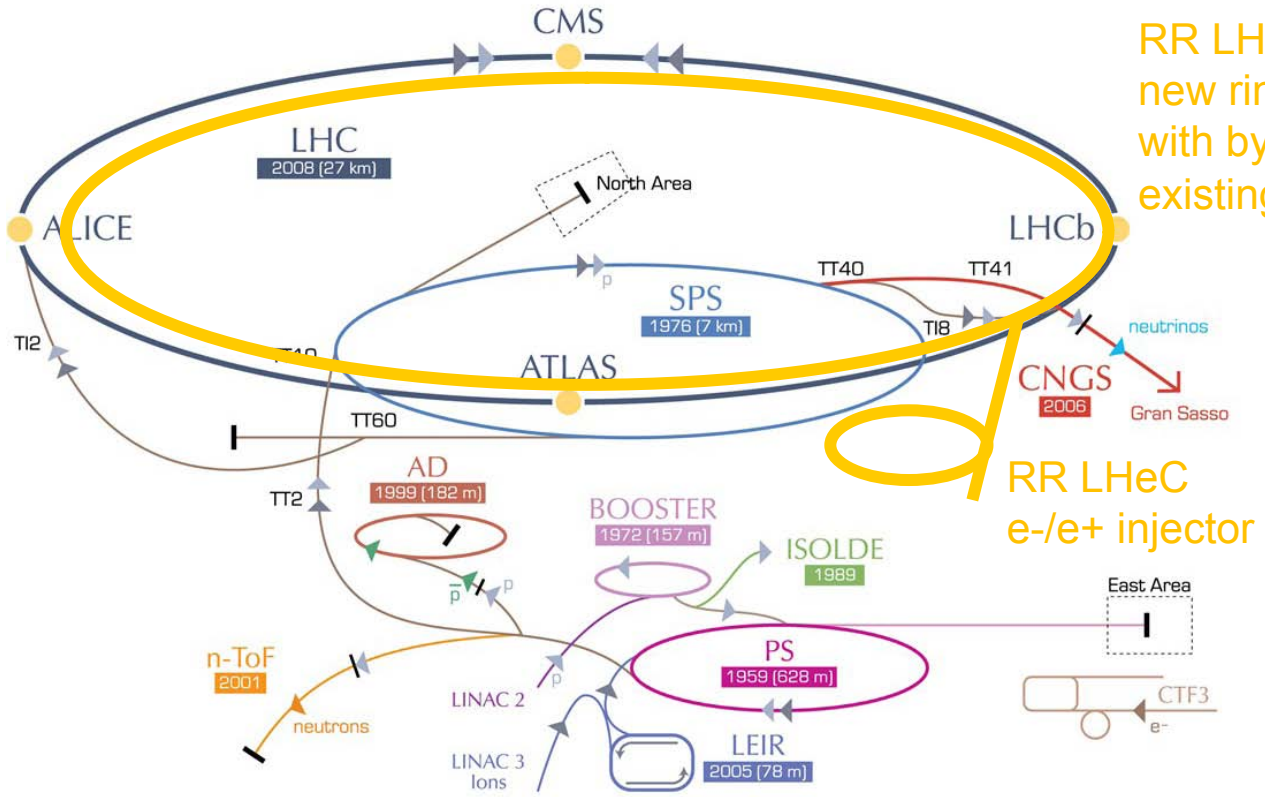
4. **DETECTOR**

5. **CONCLUSIONS**

CDR LHeC Options



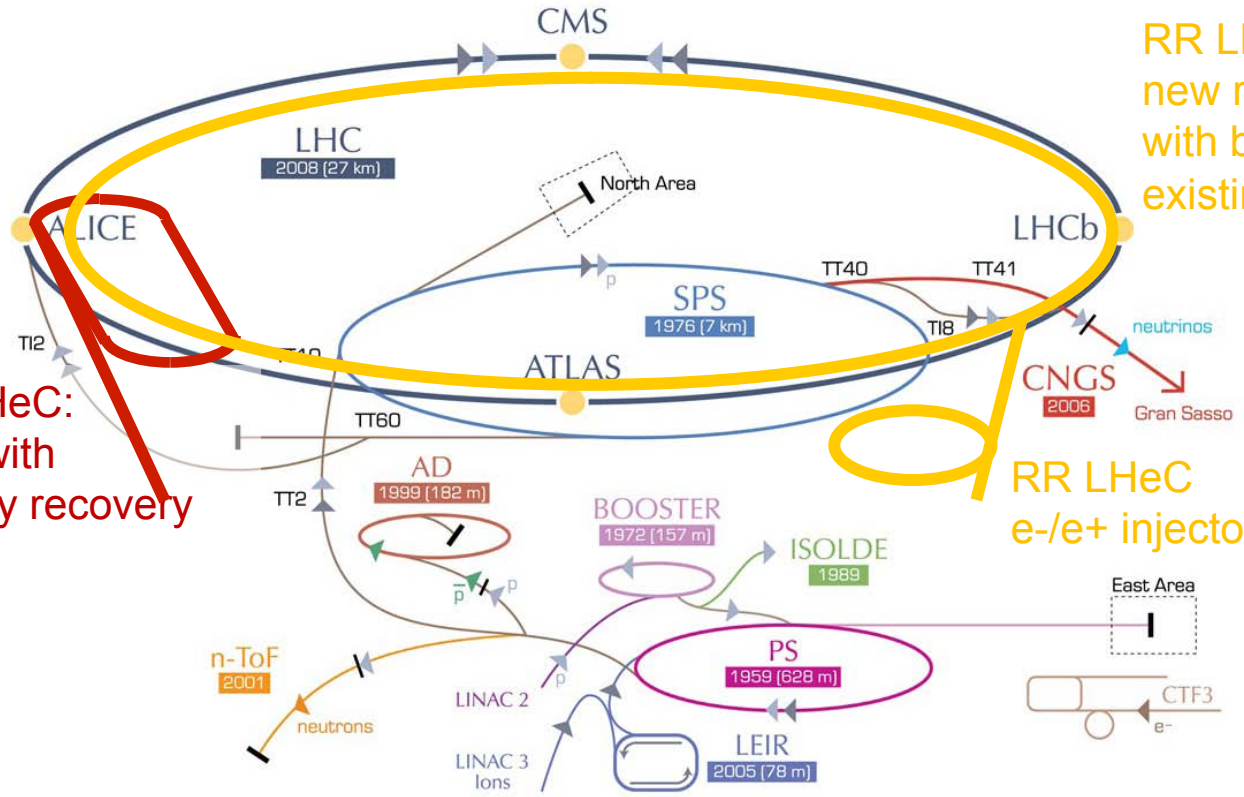
CDR LHeC Options



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

RR LHeC
e-/e+ injector

LHeC Options



RR LHeC:
new ring in LHC tunnel,
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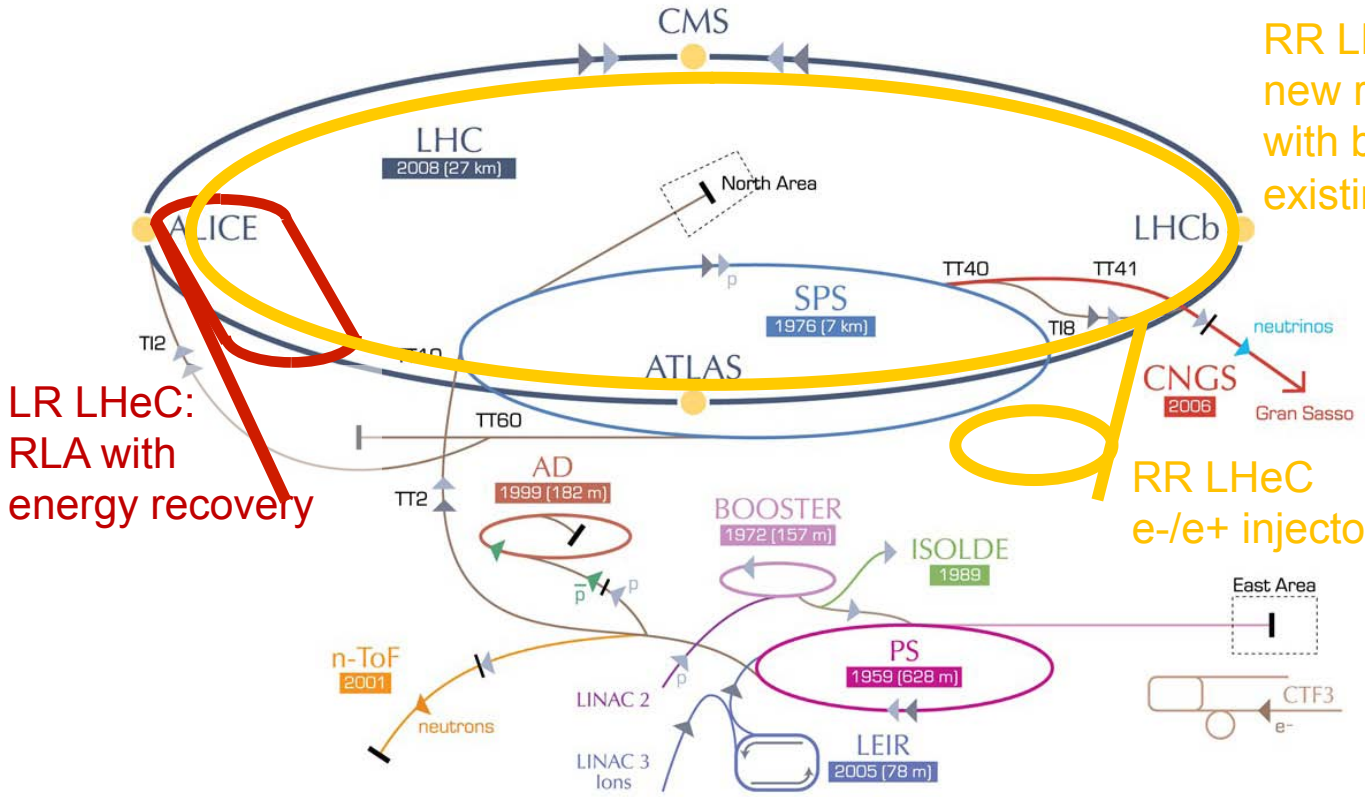
LR LHeC:
RLA with
energy recovery

RR LHeC
e-/e+ injector

LHeC Options



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

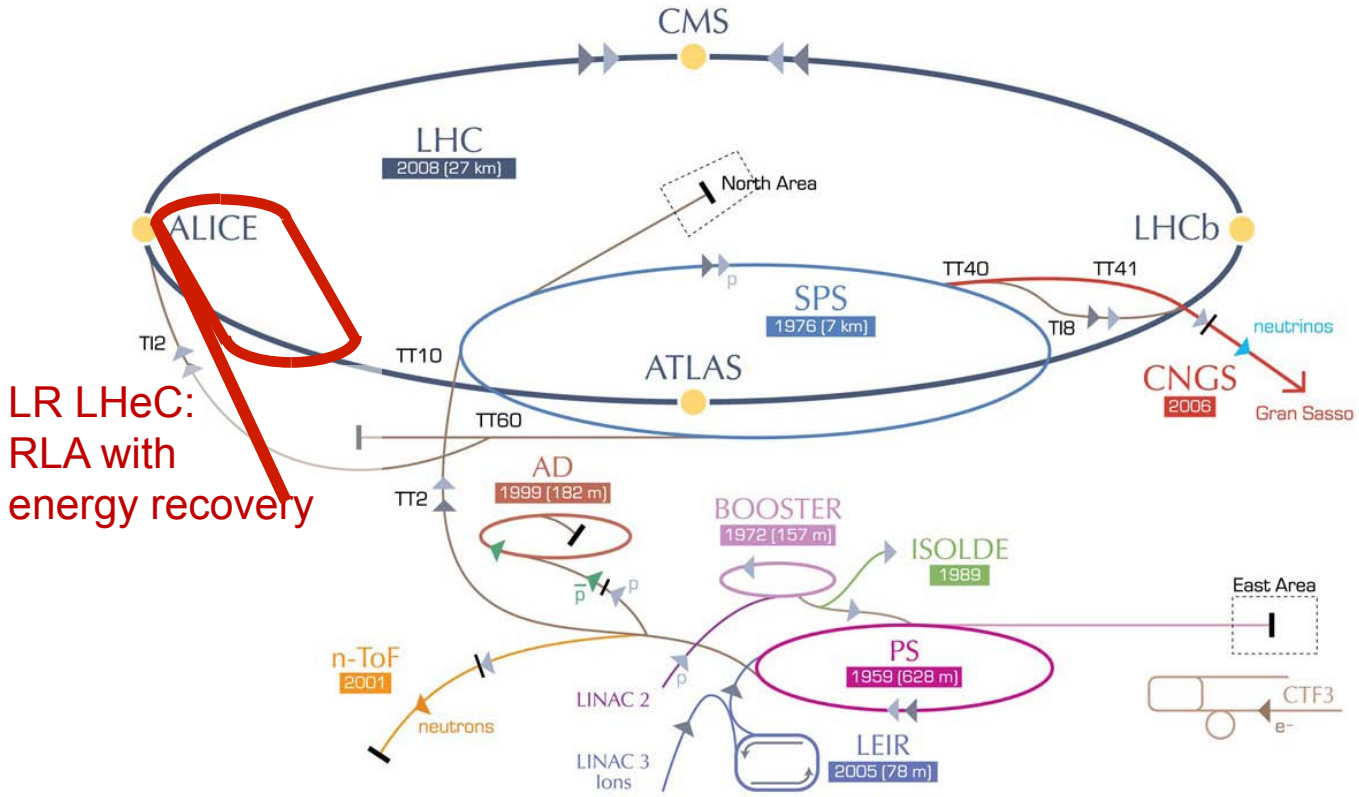
LR LHeC:
RLA with energy recovery

RR LHeC
e-/e+ injector

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

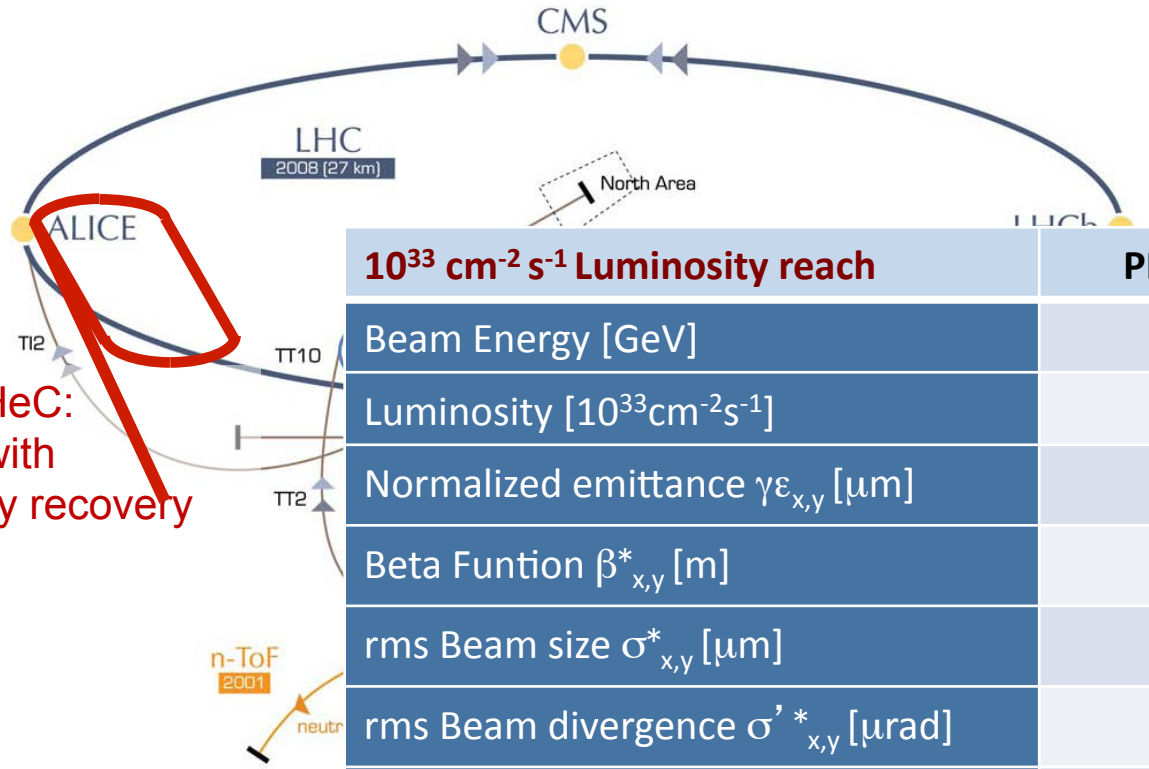
Linac-Ring option, the baseline solution exists, will now have to find the best solution

Linac-Ring LHeC



LR LHeC:
RLA with
energy recovery

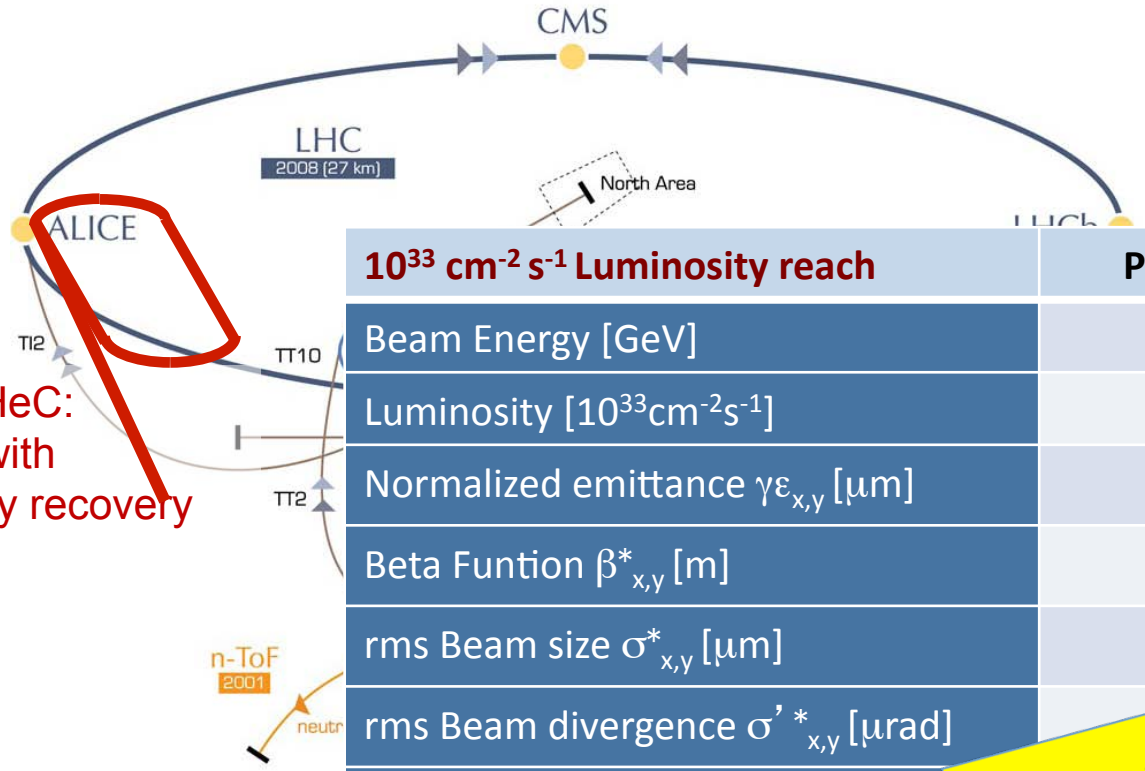
Linac-Ring LHeC



LR LHeC:
RLA with
energy recovery

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

Linac-Ring LHeC



LR LHeC:
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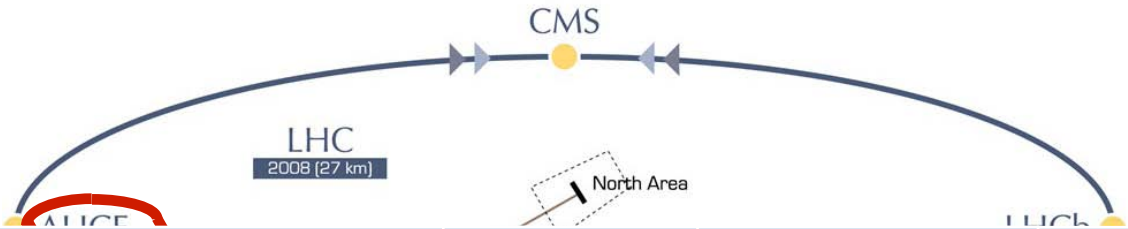
Bunch Spacing [ns]		
Bunch Population		
Bunch charge [nC]		(0.16) 0.32

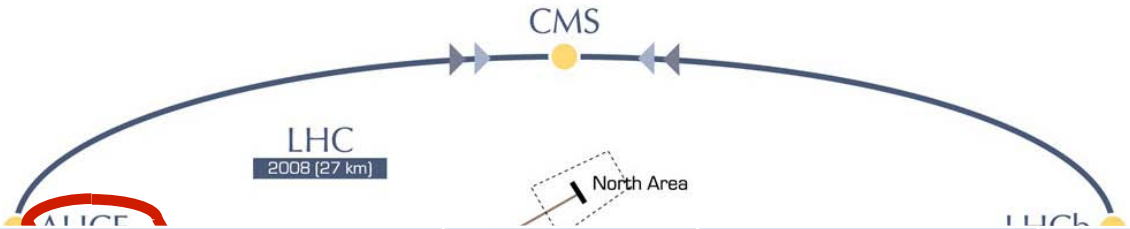
Energy 4 times
Luminosity
100 times larger
than HERA

Linac-Ring LHeC



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 $\sigma'^*_{x,y}$ [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

Linac-Ring LHeC



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Beam Current [mA]	1112			6
Bunch Spacing [ns]	25			
Bunch Population	2.2*10^{11}	4*1		
Bunch charge [nC]	35	0.6		16) 0.32

Luminosity 1000 times larger than HERA

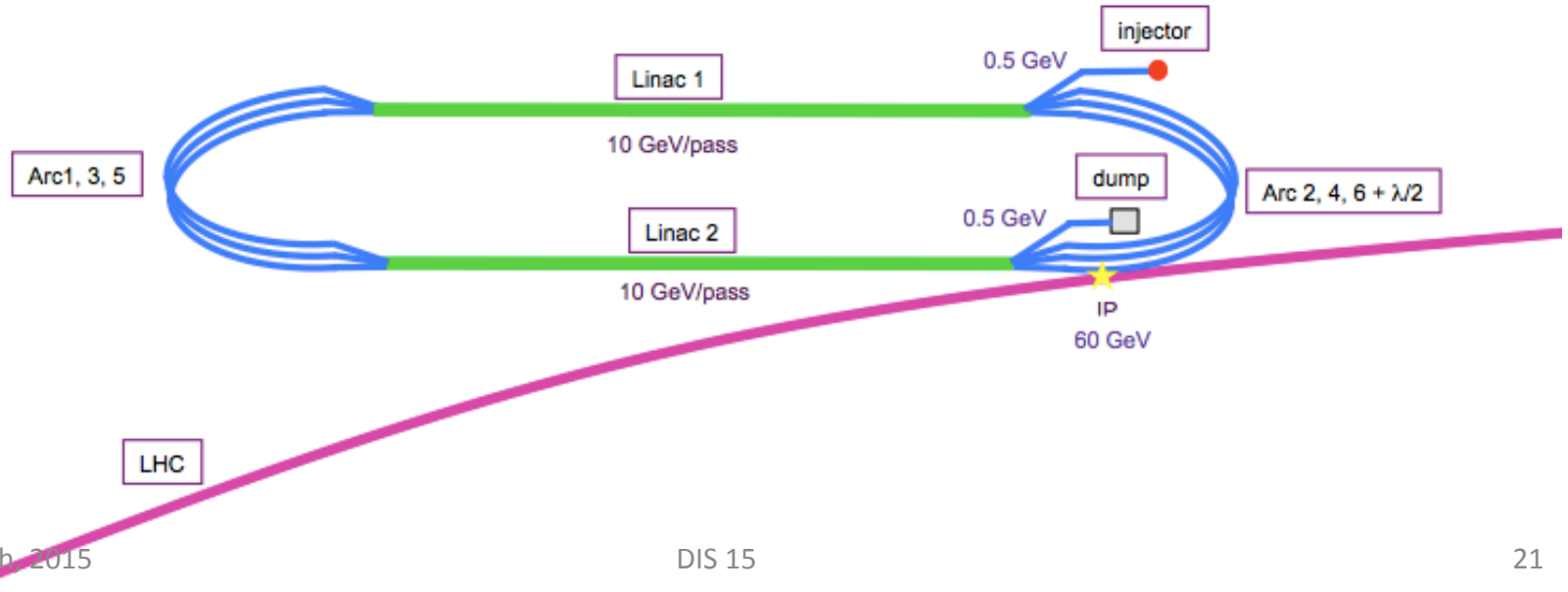
CERN Mandate 2012

- Superconducting RF System
- Superconducting magnet development
- Pipes with large beam acceptance
- The finalization of the ERL design for the LHeC (optics design, beam dynamics studies and identification of potential performance limitations)
- The design and specification of an Energy Recovery LINAC (ERL) test facility for the LHeC

Energy Recovery Linac

A conventional LINAC would never fit into the power constraints!
(> 100 MW for L = 10^{33} cm^2 s^1 @ 60 GeV!)

A multipass Energy Recovery LINAC is appealing:
1. Multipass: reach the desired energy with a more compact and cost-effective design
2. Energy recovery: minimize the power consumption using the energy of the spent beam to accelerate a fresh one.

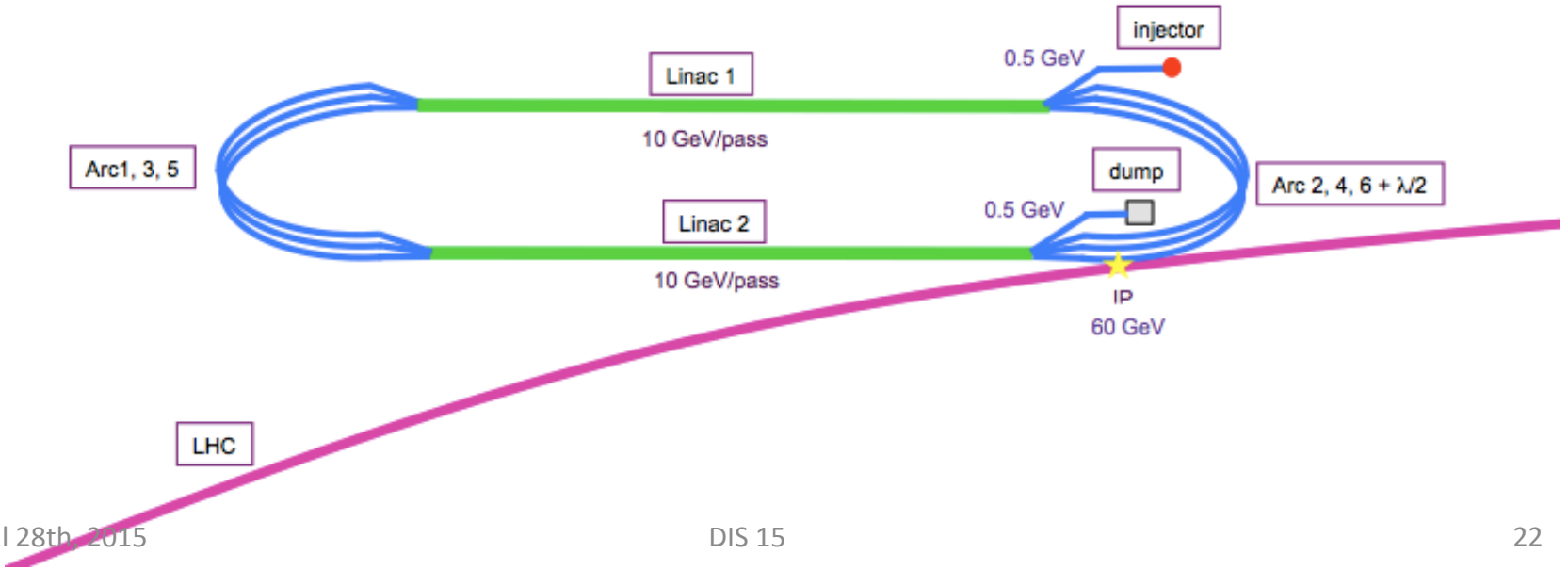


Energy Recovery Linac

RECIRCULATOR COMPLEX

1. 0.5 GeV injector
2. 2 linacs (10 GeV per pass)
3. Six 180°, 1 Km arcs
4. Final 60 GeV energy
5. Extraction dump at 0.5 GeV

A. Bogacz

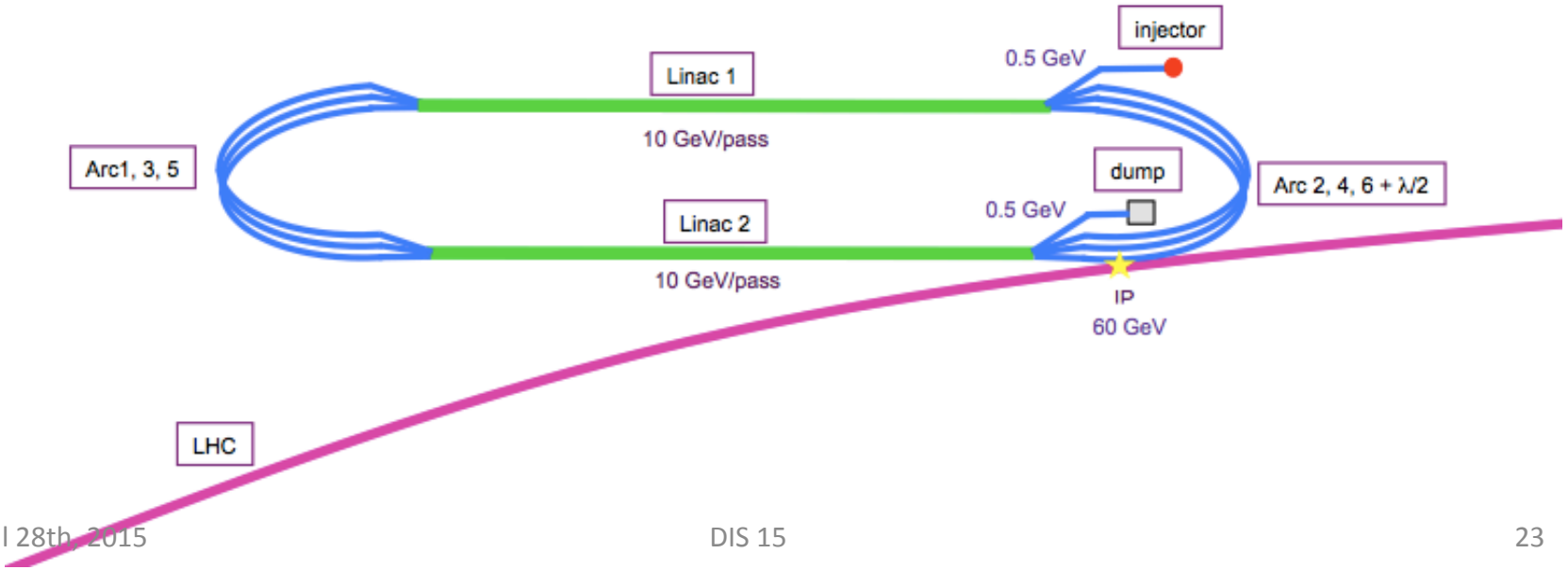


ERL-Post CDR

BEAM ISSUES-SYNCHROTRON RADIATION!

1. Energy loss
2. Emmitance Growth
3. Momentum spread

A. Bogacz



Synchrotron Radiation

Energy loss in the arcs due to the 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 beam power lost to SR = 12.2 MW
60% wall plug to beam efficiency= 20.3 MW

Compensated by additional LINACs

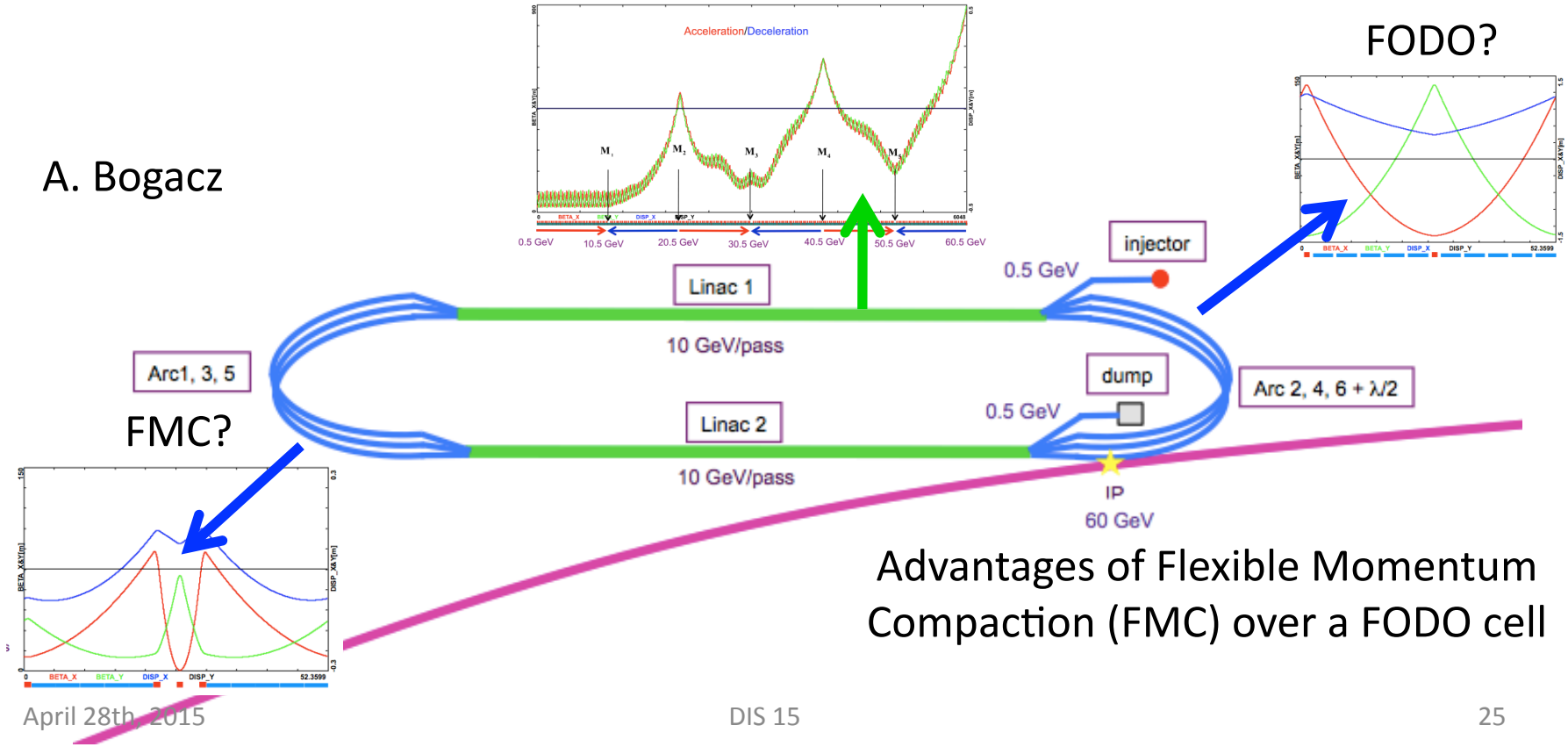
ERL-Post CDR

BEAM ISSUES-SYNCHRTOTRON RADIATION!

1. Energy loss
2. Emmitance Growth
3. Momentum compaction

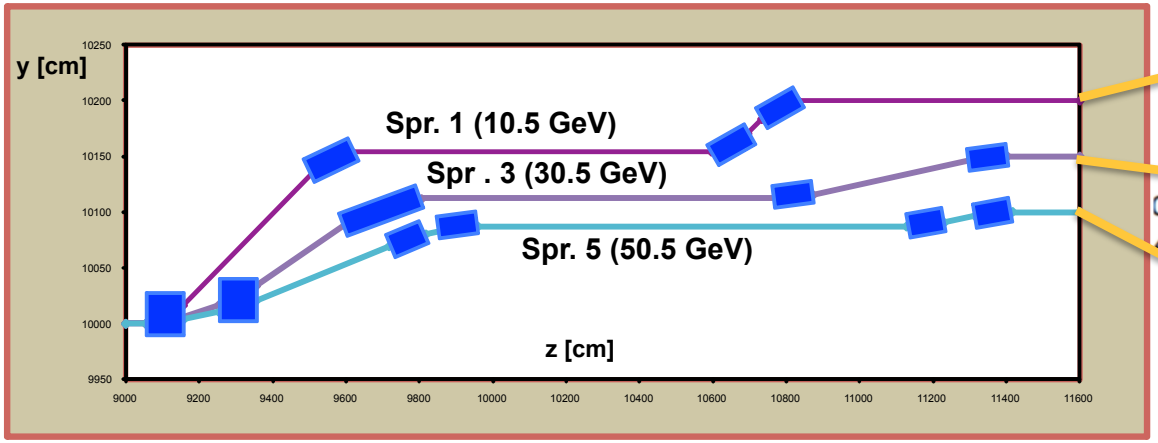
→ **PROPER LATTICE DESIGN**

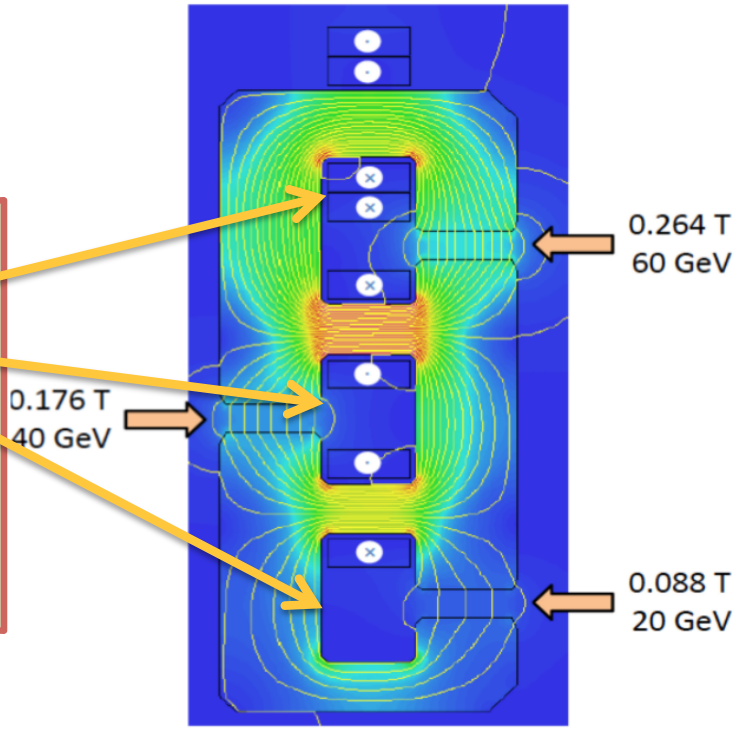
A. Bogacz



Advantages of Flexible Momentum Compaction (FMC) over a FODO cell

Post-CDR Magnets





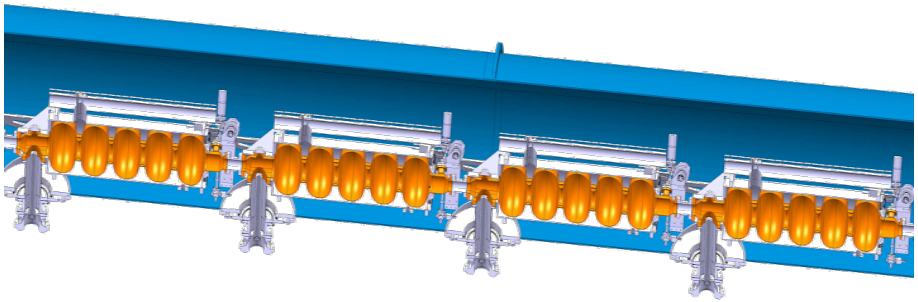
Optimized design:
Ampere turns are recycled, driving flux into different apertures.
1/3 of ampere turns can be saved

A.Milanese

RF Frequency

CDR

8 cavities per 14 m
Choice between **720 MHz** and **1.3 GHz**



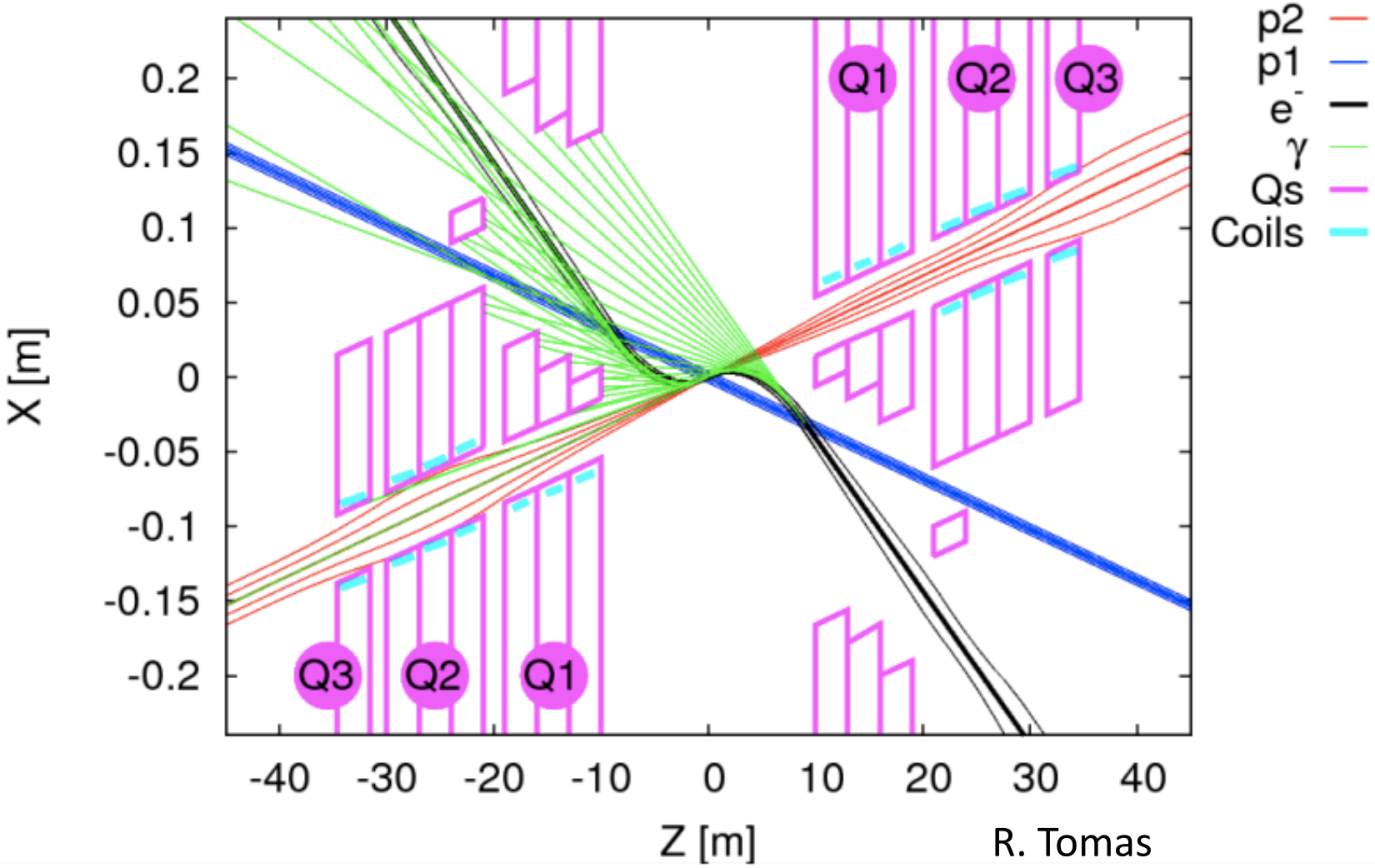
Daresbury Meeting 2013

POST-CDR

FINAL CHOICE: 801.58 MHz

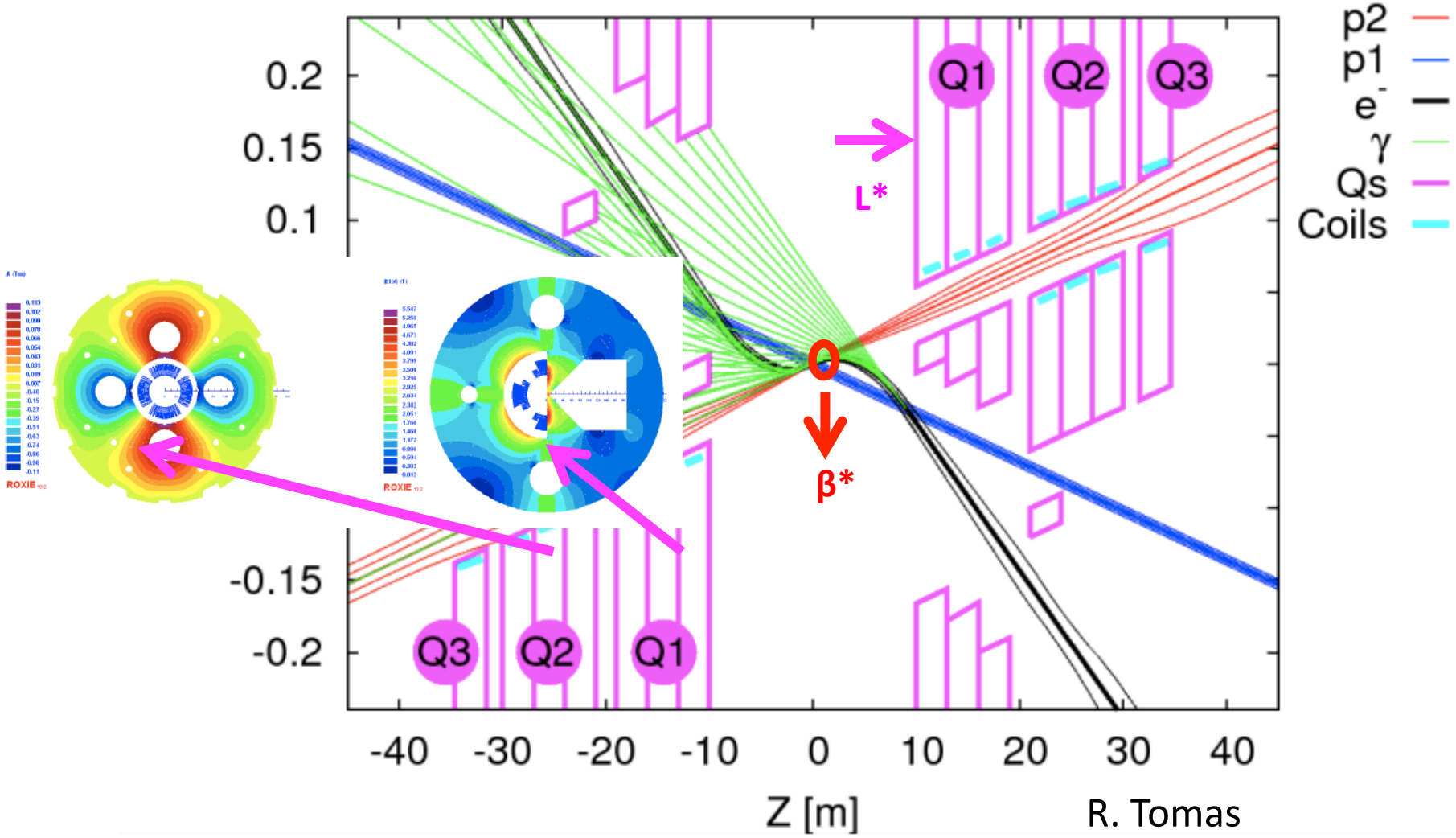
- Synergy with other projects (HL-LHC) and international collaboration option (MESA)
- Optimum frequency for both material options
- JLAB-CERN-Mainz 802MHz Cavity cryo module under design B.Rimmer, E.Jensen, K.Aulenbacher et al.

Interaction Region CDR



R. Tomas

Interaction Region CDR



IR Post-CDR

Towards Luminosity **≥10^{33} cm^{-2}s^{-1}**

$$L = \frac{1}{4\pi e}\frac{N_{b,p}}{\varepsilon_p}\frac{1}{\beta_p^*}I_e H_{hg} H_D$$

Minimize β* = More Luminosity!

$$\sigma_x = \sqrt{\epsilon\beta(s)}$$

IR Post-CDR

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Minimize β* = More Luminosity!

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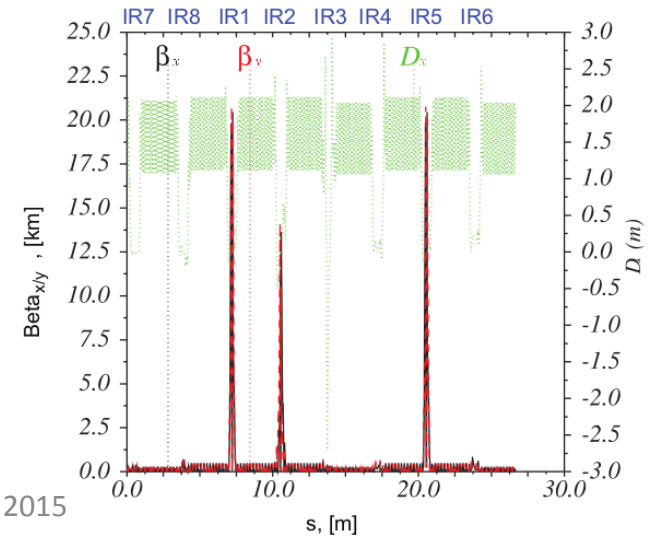
Achromatic Telescopic Squeezeing (ATS) Scheme



IR2 (LHeC)

β*=10 cm

IR1/IR5 (HL-LHC)

β*=15 cm

M. Korostelev

IR Post-CDR

- ✓ **Chromaticity correction** -> Use of sextupoles.
- ✓ Flexibility Parameters.

  Minimize β*. +More luminosity. L*=10-20 m.

  -More chromaticity.

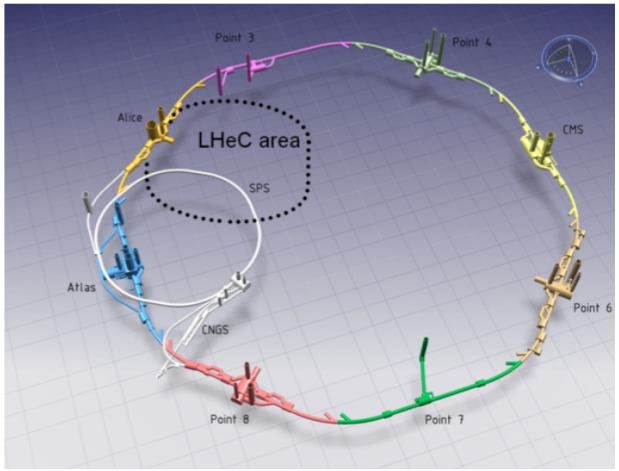
  Increase L*. + Less SR. β*=5-10 cm.

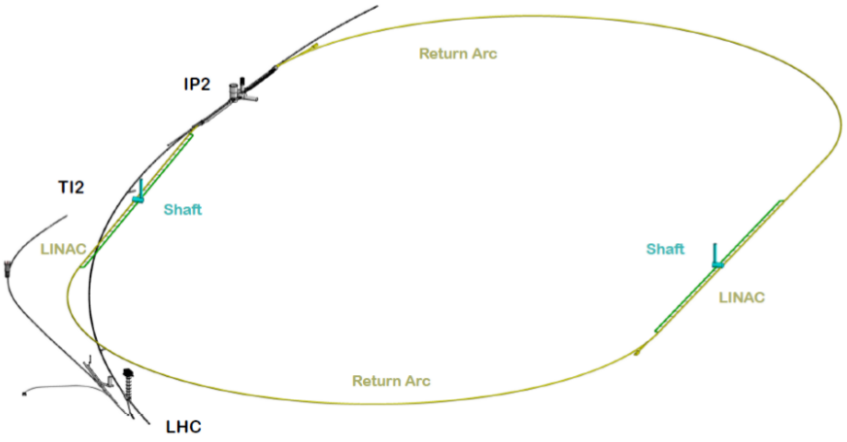
  -More chromaticity.
- ✓ Limits on the chromatic correction.
- ✓ Tracking studies

Civil Engineering

ERL placed tangential to the LHC and tangential to IP2

- Two 1 km LINACs
- Arcs 1 km long
- Whole racetrack 9 km long (1/3 LHC length)

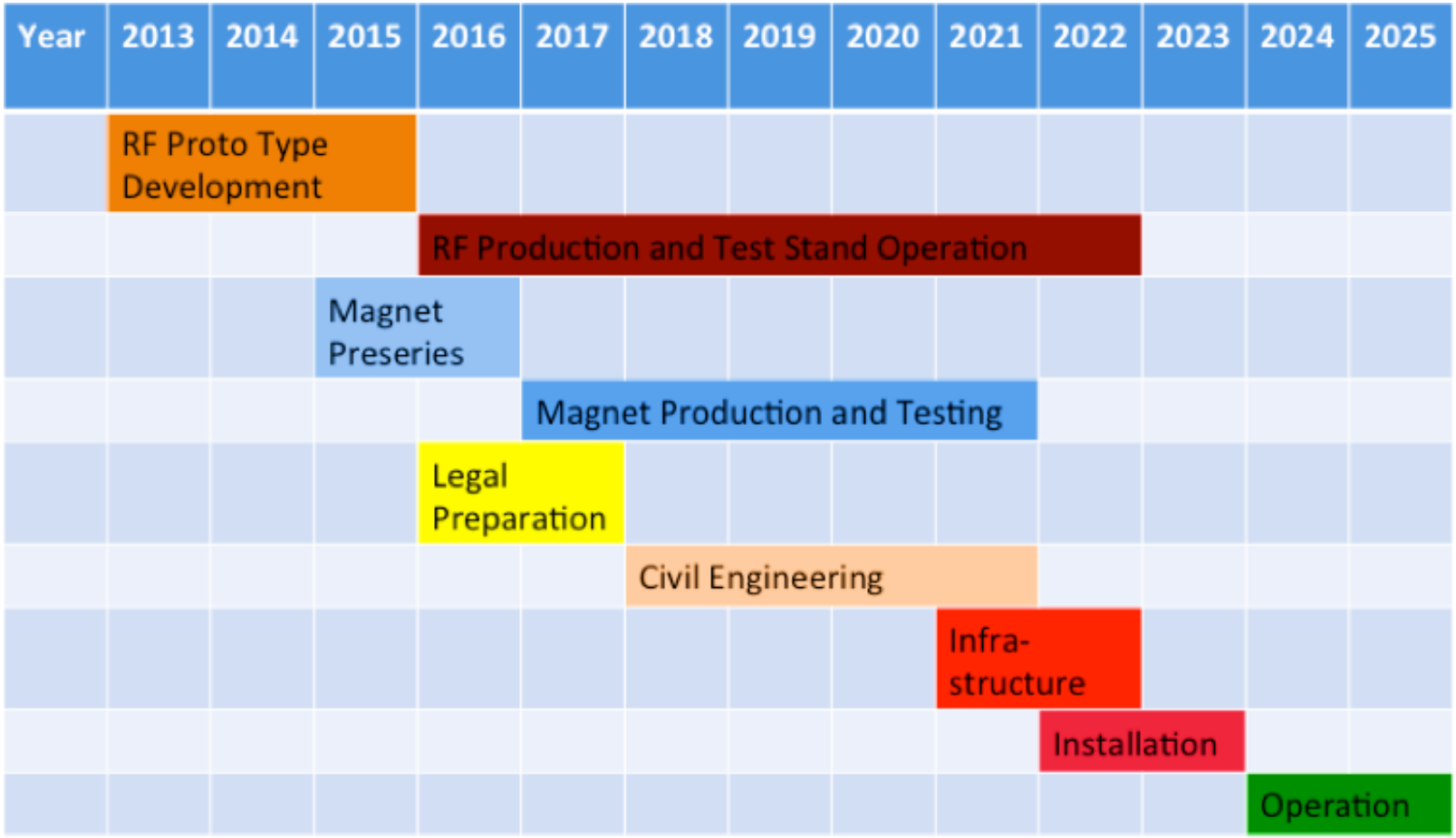




~ 960 cavities
~ 60 cryomodules per linac
~ 4500 magnets in the 2*3 arcs
~ 600 - 4 m long dipoles per arc
~ 240 - 1.2 m long quads per arc

LHeC Planning and Timeline

- Installation decoupled from LHC operation and shutdown planning



International Advisory Committee (IAC)

Guido Altarelli (Rome)
Sergio Bertolucci (CERN)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Oliver Brüning (CERN)
Hesheng Chen (IHEP Beijing)
Andrew Hutton (Jefferson Lab)
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Leandro Nisati (Rome)
Leonid Rivkin (Lausanne)
Herwig Schopper (CERN) – **Chair**
Jurgen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (STFC)

IAC Chair: H. Schopper

Meetings:

- January 2014
- June 2014

IAC Mandate (2014-2017)

Advice to the LHeC Coordination Group and the CERN directorate by following the development of options of an ep/eA collider at the LHC and at FCC, especially with:

- Provision of scientific and technical direction for the physics potential of the ep/eA collider both at LHC and at FCC, as a function of the machine parameters and of a realistic detector design, as well as for the design and possible approval of an ERL test facility at CERN

- Assistance in building the international case for the accelerator and detector developments as well as guidance to the resource, infrastructure and science policy aspects of the ep/eA collider.

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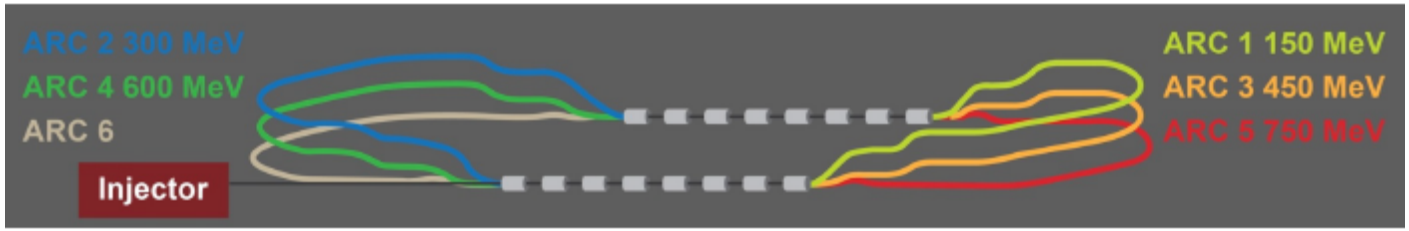
- Assistance in building the international case for the accelerator and detector developments as well as guidance to the resource, infrastructure and science policy aspects of the ep/eA collider.

ERL Facility

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

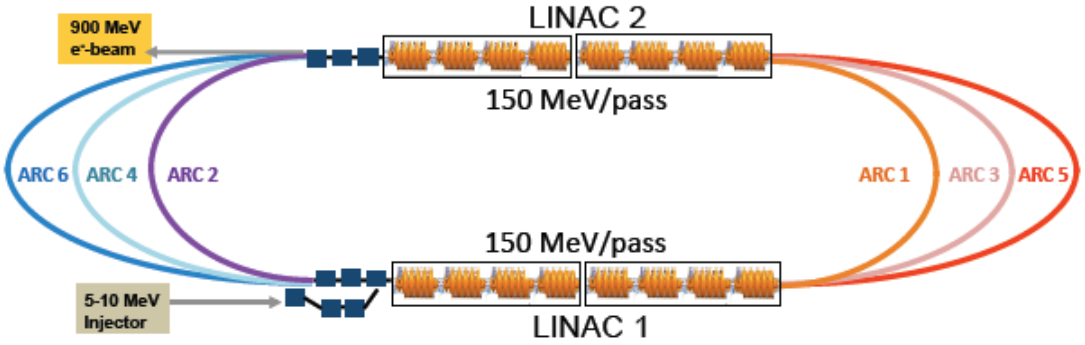
TARGET PARAMETER*	VALUE
Injection Energy [MeV]	5
Final Beam Energy [MeV]	900
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	50
Beam Current [mA]	10
Bunch Spacing [ns]	25 (50)
Passes	3



A. Valloni

Goals of the ERL Facility

- Test facility for SCRF cavities and modules
- Test facility for multi-pass multiple cavity ERL
- Injector studies: DC gun or SRF gun
- Study reliability issues, operational issues!
- Possible use for detector development, experiments and injector
- Could it be foreseen as the injector to LHeC ERL?



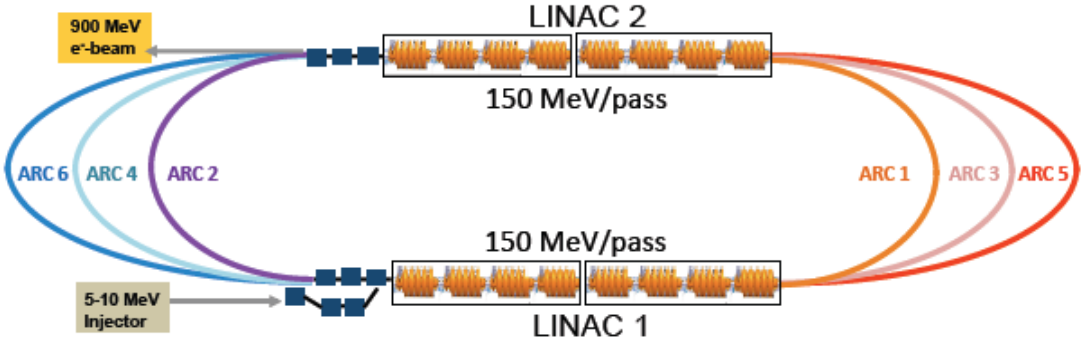
A. Valloni

ERL Facility Design

- Layout and Optics, LINACS and arcs
- Synchrotron Radiation studies
- Possible Site choices

- **Preparation of a Test Facility Proposal**

ARC	ENERGY
ARC 1	150 MeV
ARC 2	300 MeV
ARC 3	450 MeV
ARC 4	600 MeV
ARC 5	750 MeV
ARC 6	900 MeV

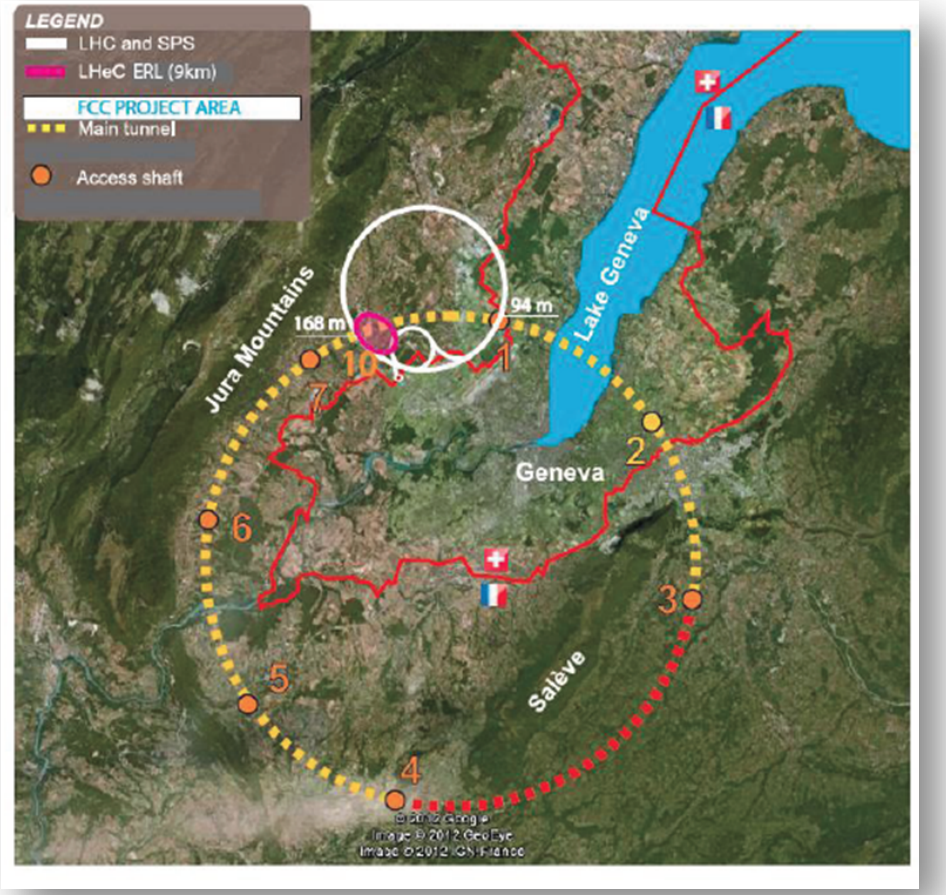


A. Valloni

Future Circular Collider

80-100 km tunnel infrastructure in Geneva area

- **FCC-hh**. Long term goal 100 TeV pp collisions in 80 or 100 km (20 T or 16 T magnets).
- **FCC-ee**. Potential intermediate step.
- **FCC-he**. Another potential intermediate step.



Meetings

FCC Kickoff 12-14 February, 2014

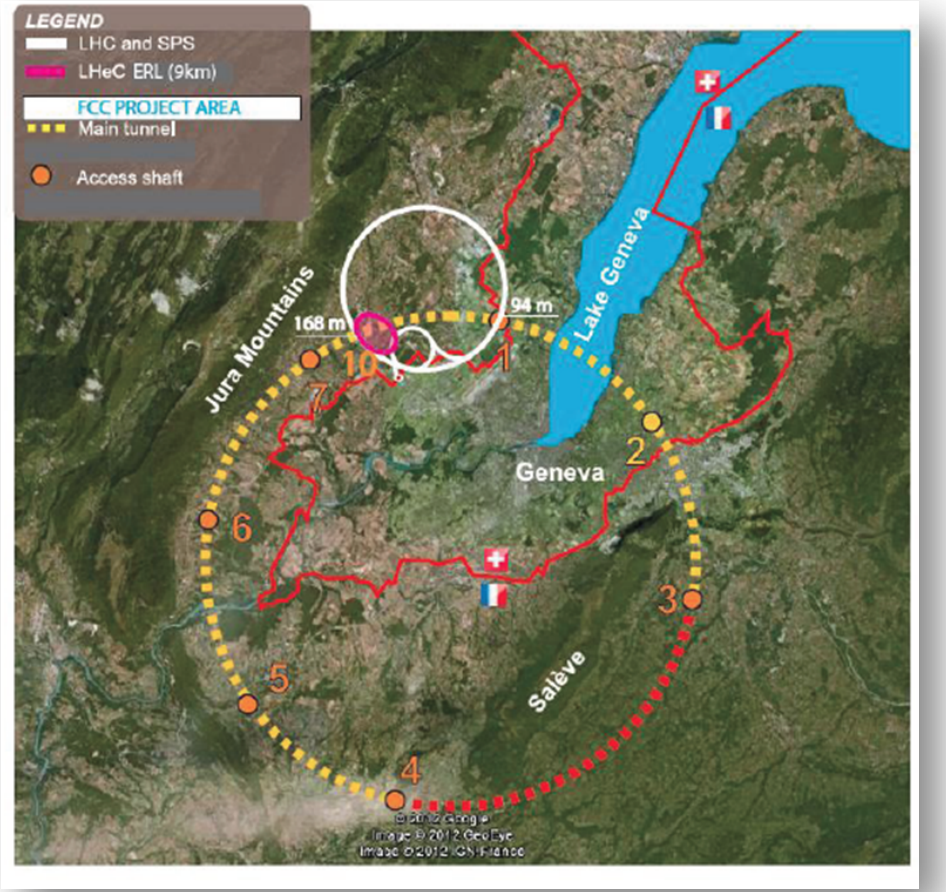
FCC Study Week, 23-27 March, 2015

https://fcc.web.cern.ch

FCC-he options

Two options for FCC-he

1. e^- from LHeC or other ERL
2. e^- from FCC-ee
   (if co-existing with FCC_hh)



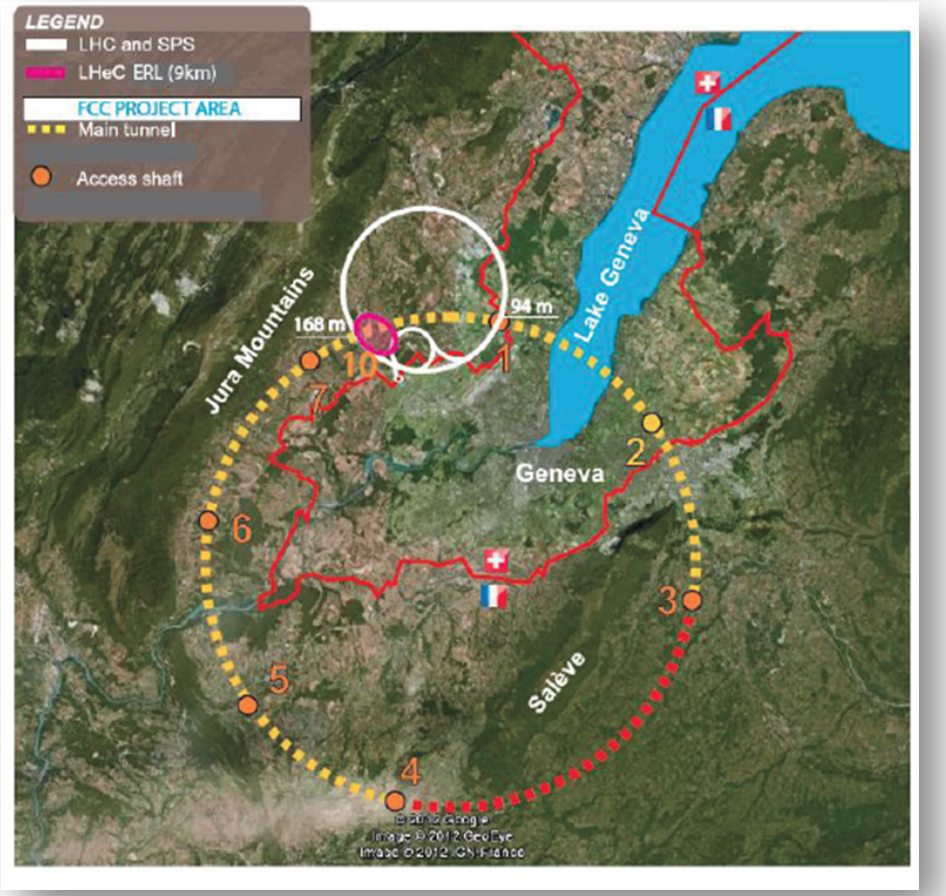
FCC-he options

Two options for FCC-he

1. **e^- from LHeC or other ERL**
2. e^- from FCC-ee
   (if co-existing with FCC_hh)

Collide **LHC proton** beam
with **LHeC electrons**
Ep = 7 TeV Ee= 60 GeV
$\sqrt{s}$ = 1.3 TeV

Collide **FCC proton** beam
with **LHeC electrons**
Ep = 50 TeV Ee= 60 GeV
$\sqrt{s}$ = 3.5 TeV



FCC he parameters

Collide **FCC proton** beam with **LHeC electrons**
Ep = 50 TeV Ee= 60 GeV
$\sqrt{s}$ = 3.5 TeV

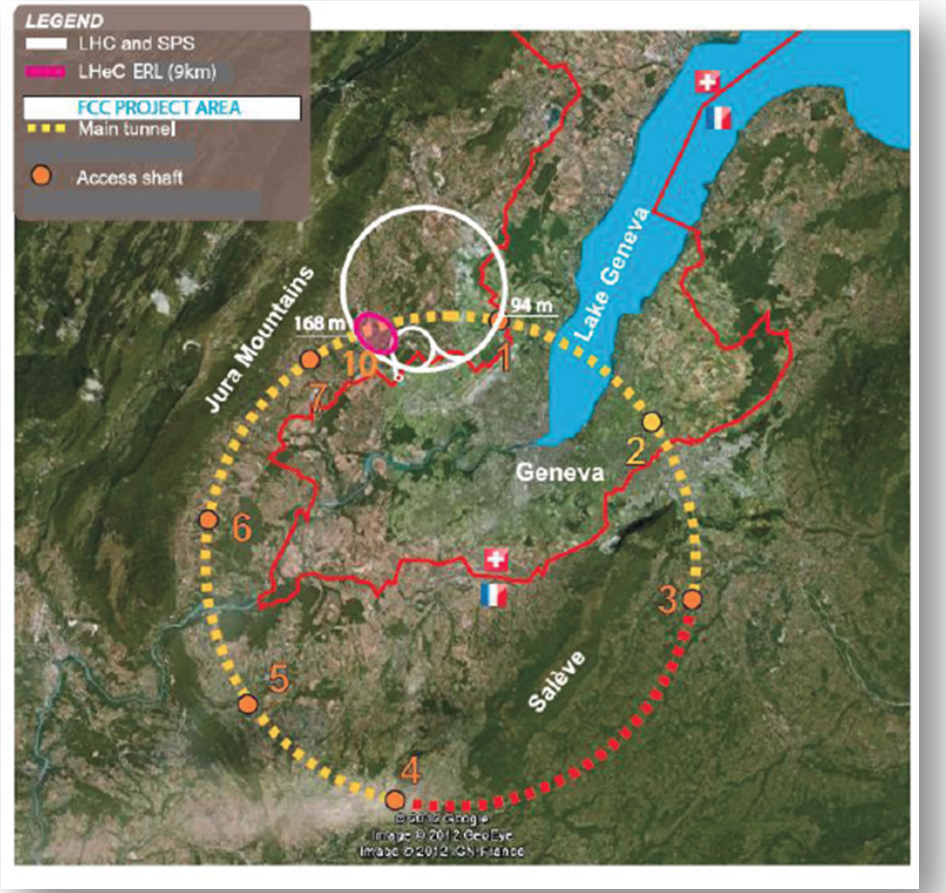
COLLIDER PARAMETERS	FCC PROTONS	LHeC ELECTRONS
Beam Energy [GeV]	50000	60
Luminosity [$10^{33}cm^{-2}s^{-1}$]	10	10
rms Emittance $\varepsilon n_{x,y}$ [μm]	2.2	20
IP Beta Function $\beta^*_{x,y}$ [m]	0.3	0.1
rms IP Spot size [μm]	3.5	3.5
Beam Current [mA]	500	25.6
Bunch Population	$1*10^{11}$	$0.04*10^{11}$

LHeC in the FCC context

Two options for FCC-he

1. **e^- from LHeC or other ERL**
2. e^- from FCC-ee
   (if co-existing with FCC_hh)

The LHeC could
- be realized in parallel with HL-LHC
- potentially provide collisions with FCC-hh
- operate as an injector for FCC-ee



Summary

- LHeC appears feasible and can be realized in parallel with HL-LHC
- Significant optimization has been done post-CDR:
  - Choice of RF Frequency
  - Lattice design arcs and linacs
  - Magnet design
  - IR/Detector Design
- Design of the ERL Test Facility

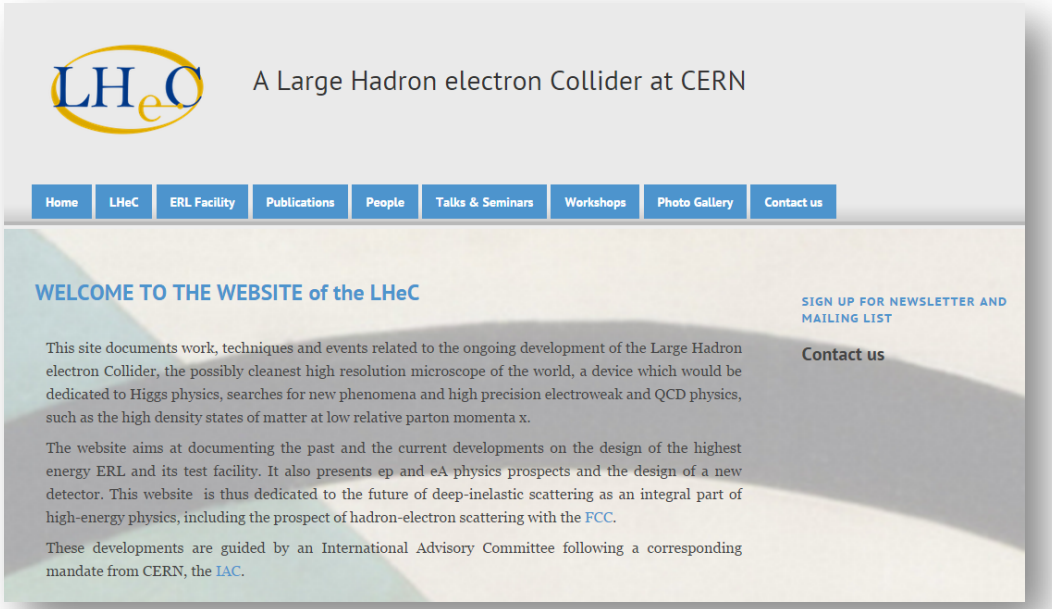
LHeC Next Steps

- **R &D** of individual components
- Ongoing parameter studies for **cost optimization** (slightly lower beam energy for significantly lower circumference)
- Some (potential) **international partners** have declared large interest (JLAB, Mainz, ASTeC and others).
- Completion of **Conceptual design study** of an **ERL-TF** at CERN by the end of 2015

References

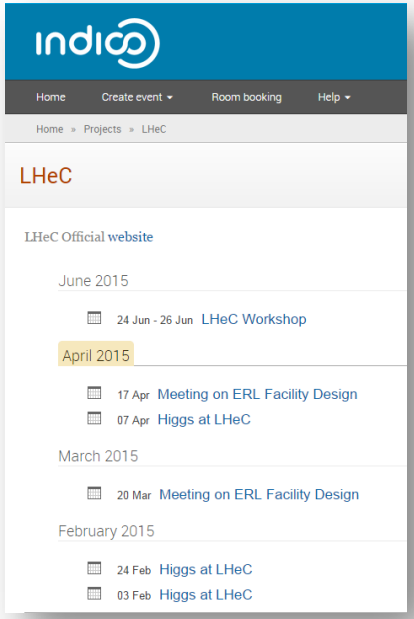
New web page http://lhec.web.cern.ch

Complete list of papers, conference proceedings, talks and seminars



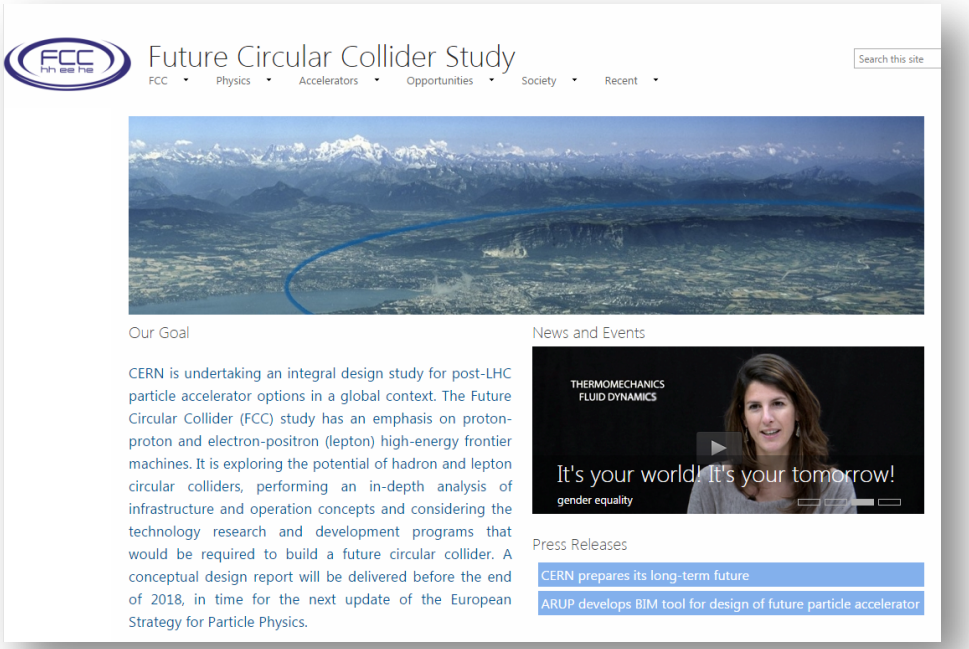
Indico page

https://indico.cern.ch/category/1874/



References

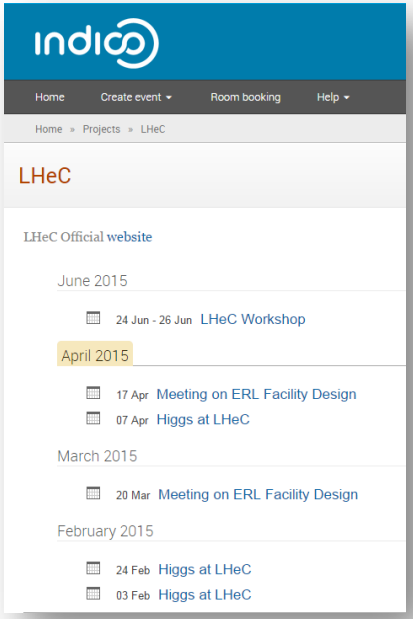
https://fcc.web.cern.ch



Indico page of FCC-he still on LHeC

https://indico.cern.ch/category/1874/

To be moved soon…



Thank you!

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