LHeC Accelerator Studies and Considerations

- Motivation -LHC Infrastructure
  -Accelerator innovation and development

-

On behalf of the LHeC Collaboration!

With input and contributions from many colleagues!

- Summary

LHeC: Motivation

- Physics: → presentations by M. D'Onofrio and G. Altarelli

  Plus Test Facility applications : → E. Jensen

  → Unique opportunity for realizing an ep and e-ion collider in the TeV center of mass region

- Infrastructure

  → Full exploitation of the existing LHC infrastructure

  → New installation with a potential user community beyond HEP and LHeC

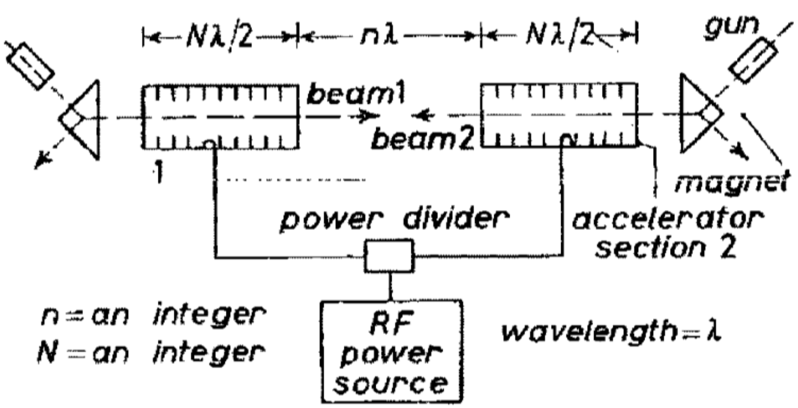
- Technology and Accelerator Physics

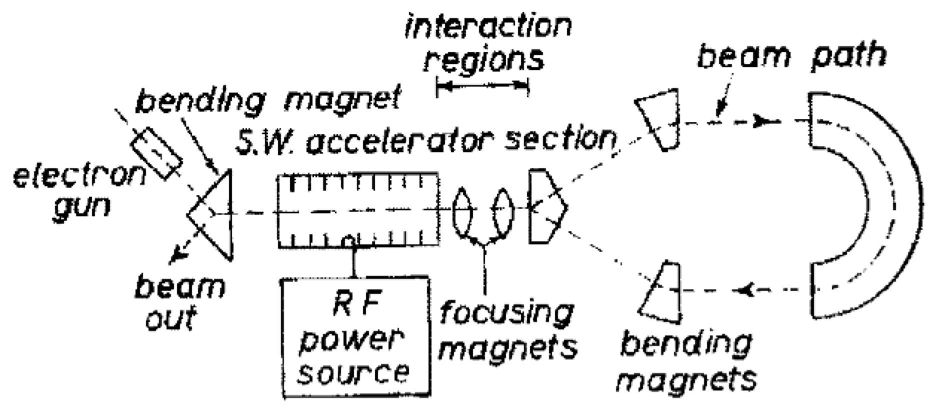
  → Unique opportunity for realizing a revolutionary new accelerator concept with a manifold of potential applications beyond HEP!

Motivation: Accelerator Technology Development

- Energy Recovery Linac concept: First proposal 50 years ago

  M. Tigner: "A Possible Apparatus for Electron Clashing-Beam Experiments", Il Nuovo Cimento Series 10, Vol. 37, issue 3, pp 1228-1231,1 Giugno 1965





- First Tests: Done at SCA @ Stanford in 1986

  Interesting concept for FELs and Compton photon light sources, and high current electron cooler concepts and **colliders → SRF!!!**

CDR Options for LHeC Infrastructure:

CDR Study assumptions:

-Assume parallel operation to HL-LHC

-TeV Scale collision energy

➔ 50-150 GeV Beam Energy

-Limit power consumption to 100 MW

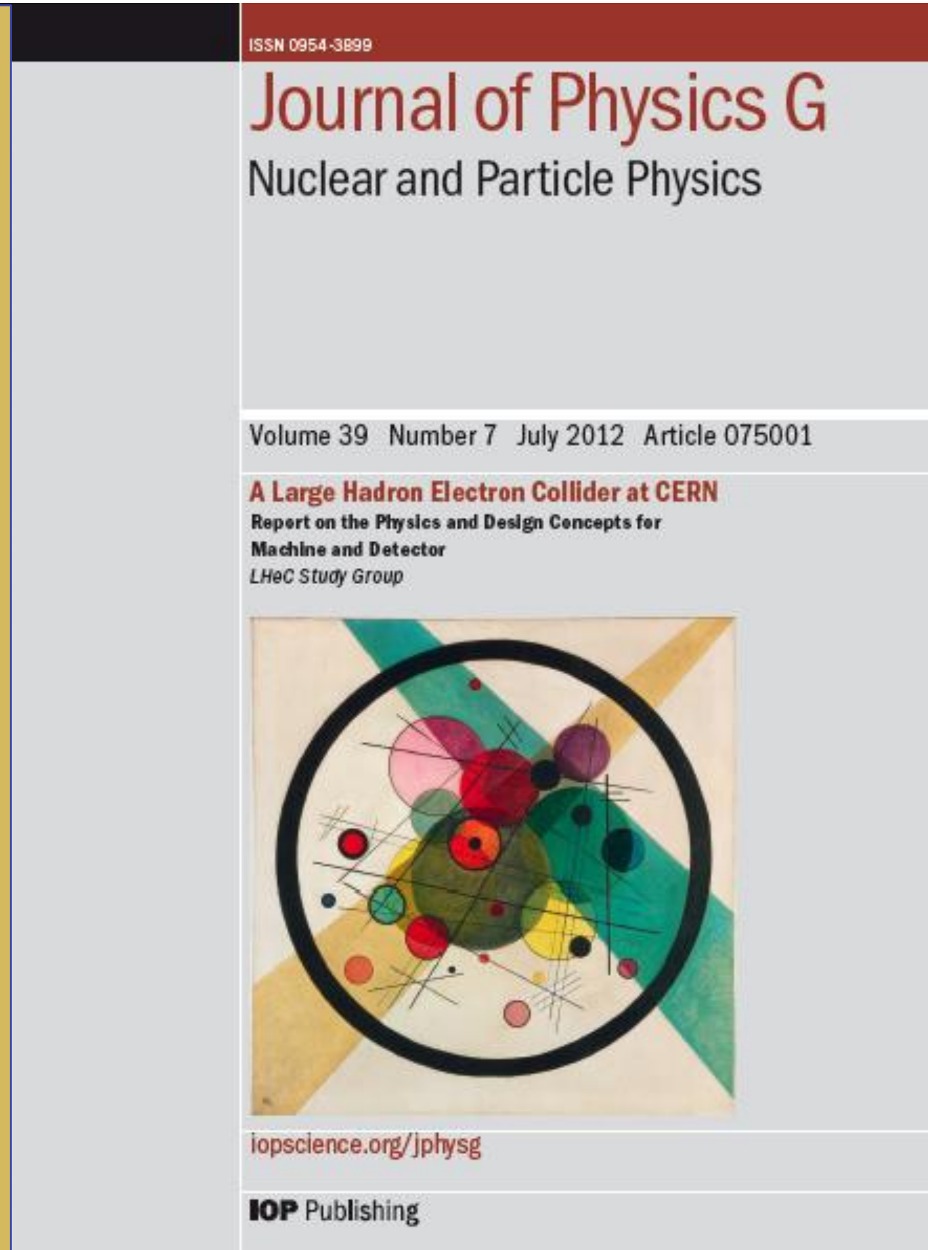
➔ (beam & SR power < 70 MW)

➔ 60 GeV beam energy

-Int. Luminosity > 100 * HERA

-Peak Luminosity > 10^{33} $cm^{-2}s^{-1}$

Higgs @ 125GeV➔ > 10^{34} $cm^{-2}s^{-1}$



CDR Choices:

Ring-Ring versus Linac-Ring:

Ring-Ring:

-Between LEPI and LEPII

➔ We know we can do it ✓

-Severe interference for installation with LHC operation:

- Detector bypass (≈ 1.5km) ✗
- LHC equipment in the LHC tunnel hampers installation ✗

-Luminosity reach (emittance, beam-beam and SR power) ✗

➔ Not chosen as baseline for the post CDR LHeC studies

CDR Choices:

Ring-Ring versus Linac-Ring:

Linac-Ring:

-Installation largely decoupled from LHC operation ✓

-can accept larger beam-beam → larger bunch current ✓

-energy efficiency and luminosity reach ✗

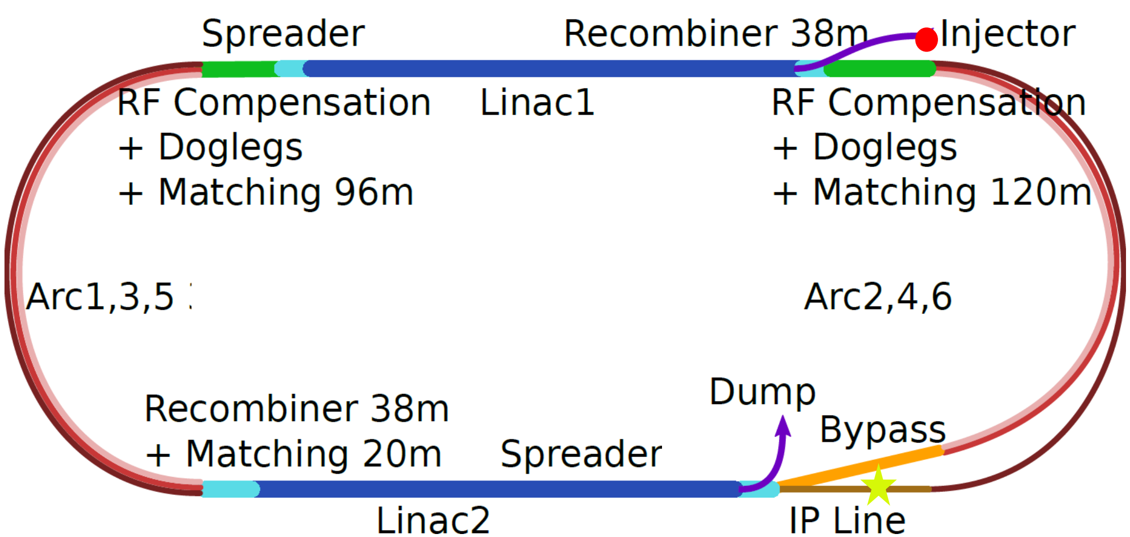
→ Recirculating Linac with Energy Recovery Mode (ERL) ✓

→ New accelerator concept & SRF technology (Q_0, HOM damping)

Recirculating Linac with Energy Recovery:

- 60 GeV acceleration with Recirculating Linacs:

Animation from A. Bogacz (JLab) @ ERL'15



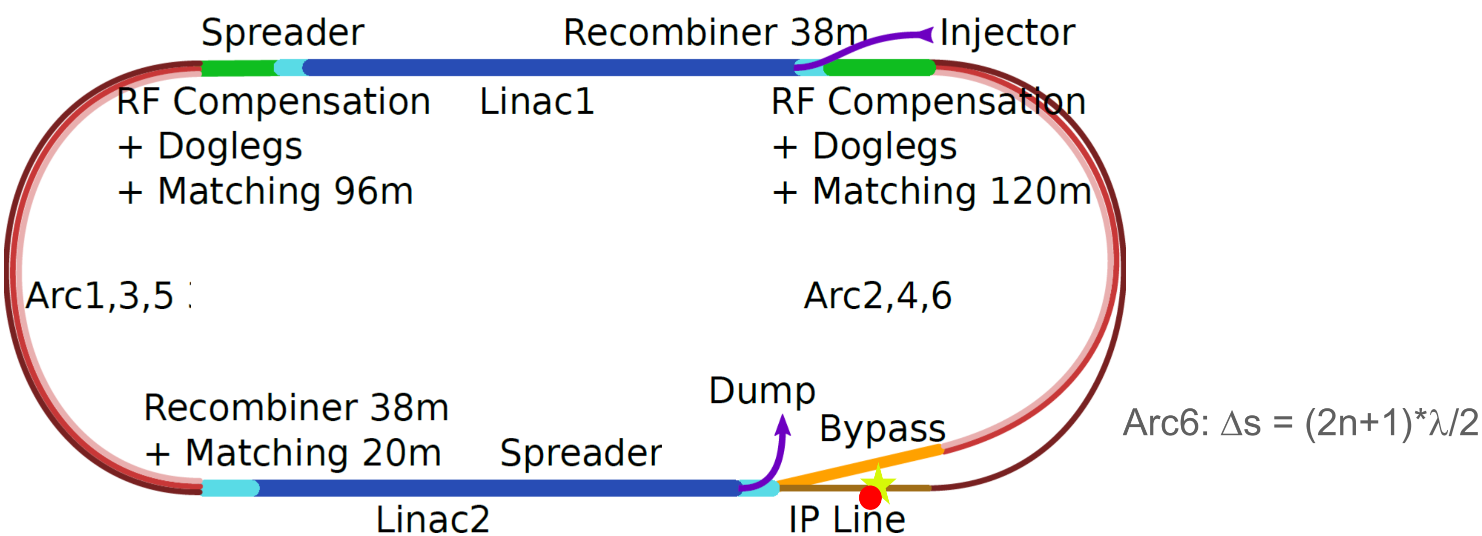
➔ Three accelerating passes through each of the two 10 GeV linacs (efficient use of LINAC installation!)

➔ 60 GeV beam energy

Recirculating Linac with Energy Recovery:

Collisions with one HL-LHC Beam:

Animation from A. Bogacz (JLab) @ ERL'15



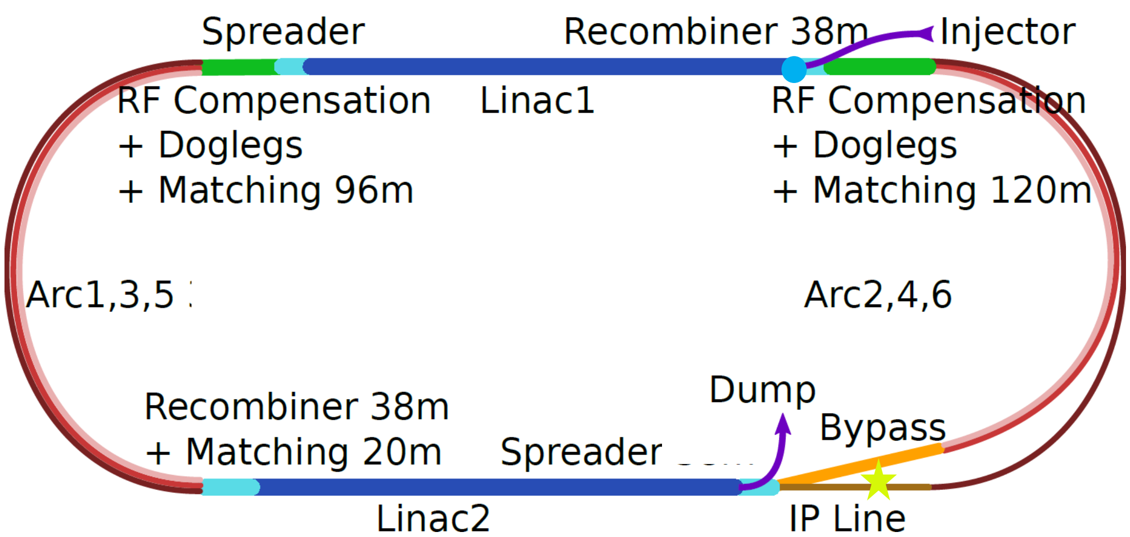
➔ Collisions with one of the LHC proton beams

➔ l/2 RF wave length shift on return arc following the collision

Recirculating Linac with Energy Recovery:

60 GeV deceleration with Recirculating Linacs:

Animation from A. Bogacz (JLab) @ ERL'15



- ➔ Three decelerating passes through each of the two 10 GeV linacs
- ➔ Beam dump at injection energy (e.g. 500 MeV)

CDR Choices: Technology & Design Comparison

LHeC

- RR Advantages and Challenges:
  - -efficient use of beam
  - -source: e^+ and e^-
  - -SR & maximum Energy reach
  - -beam size & beam-beam
- LR Advantages and Challenges:
  - -beam size and beam-beam
  - -energy reach
  - -source requirements!
  - -power consumption & cost
- ERL Advantages and Challenges:
  - -efficient use of beam with CW operation
  - -efficient use of LINACs ➔ energy reach and cost
  - -beam size and beam-beam
  - -source requirements e^+/e^- & Q_0 ⇐⇒ Cryogenic system
  - -multi-turn ERL operation ➔ high current in SRF (HOM&Z)
  - -SR in last return arc

LHeC: RL with ERL Operation as Baseline

Super Conducting Recirculating Linac with Energy Recovery

Choose ⅓ of LHC circumference ➔ Two 1 km long, 10 GeV SC LINACs with 3 accelerating and

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 @ IP[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

CDR Choices: Technology and Design

Optics:

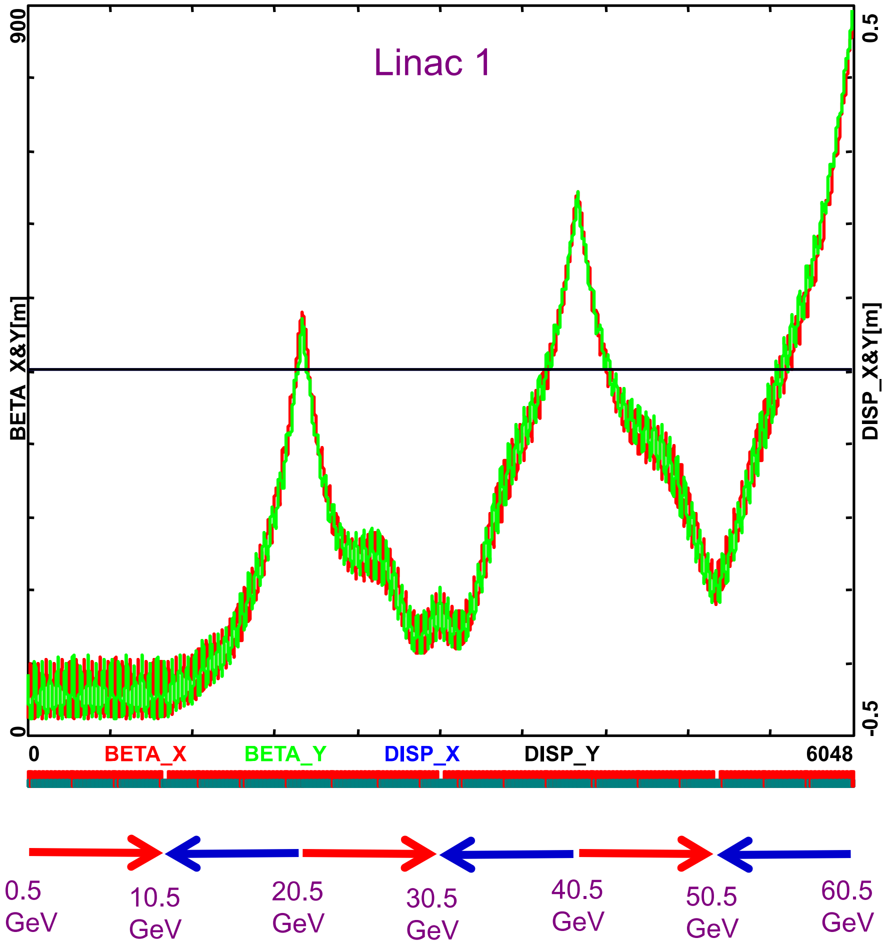
-SRF Linac with quadrupoles between the cryo modules

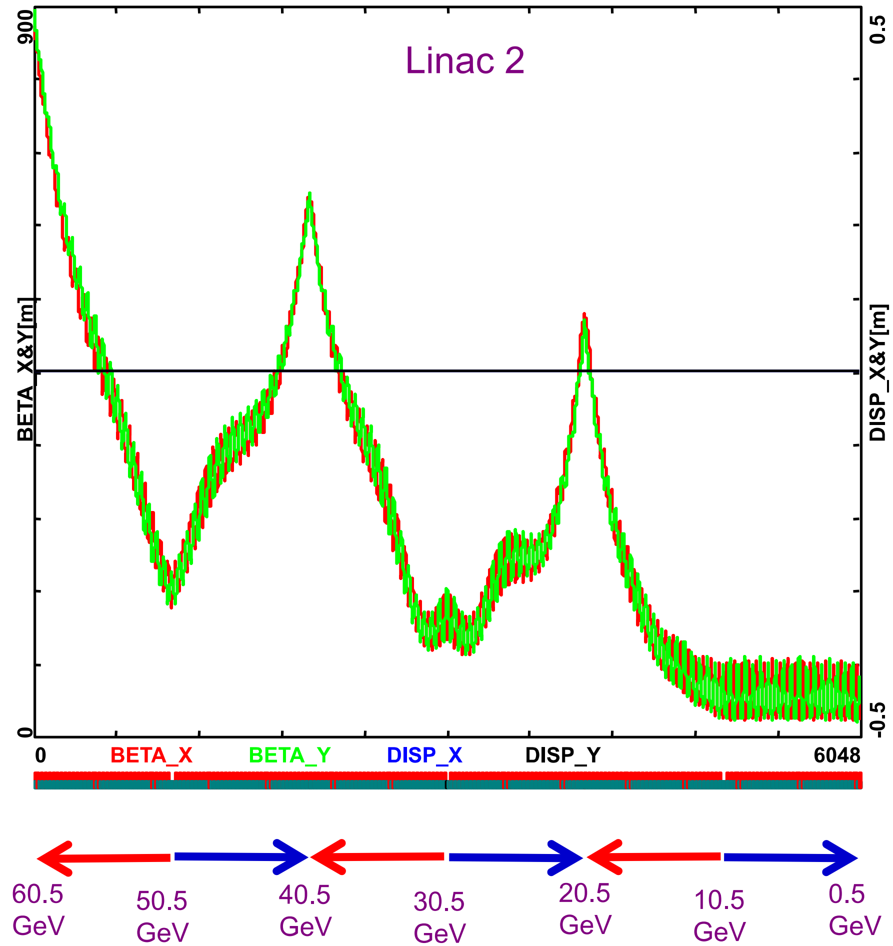
-Flexible Momentum Compaction [FMC] arc optics

Linac 1 and 2 – Multi-pass ER Optics

A. Bogacz (JLab) @ ERL2015, Stony Brook University, June 9, 2015

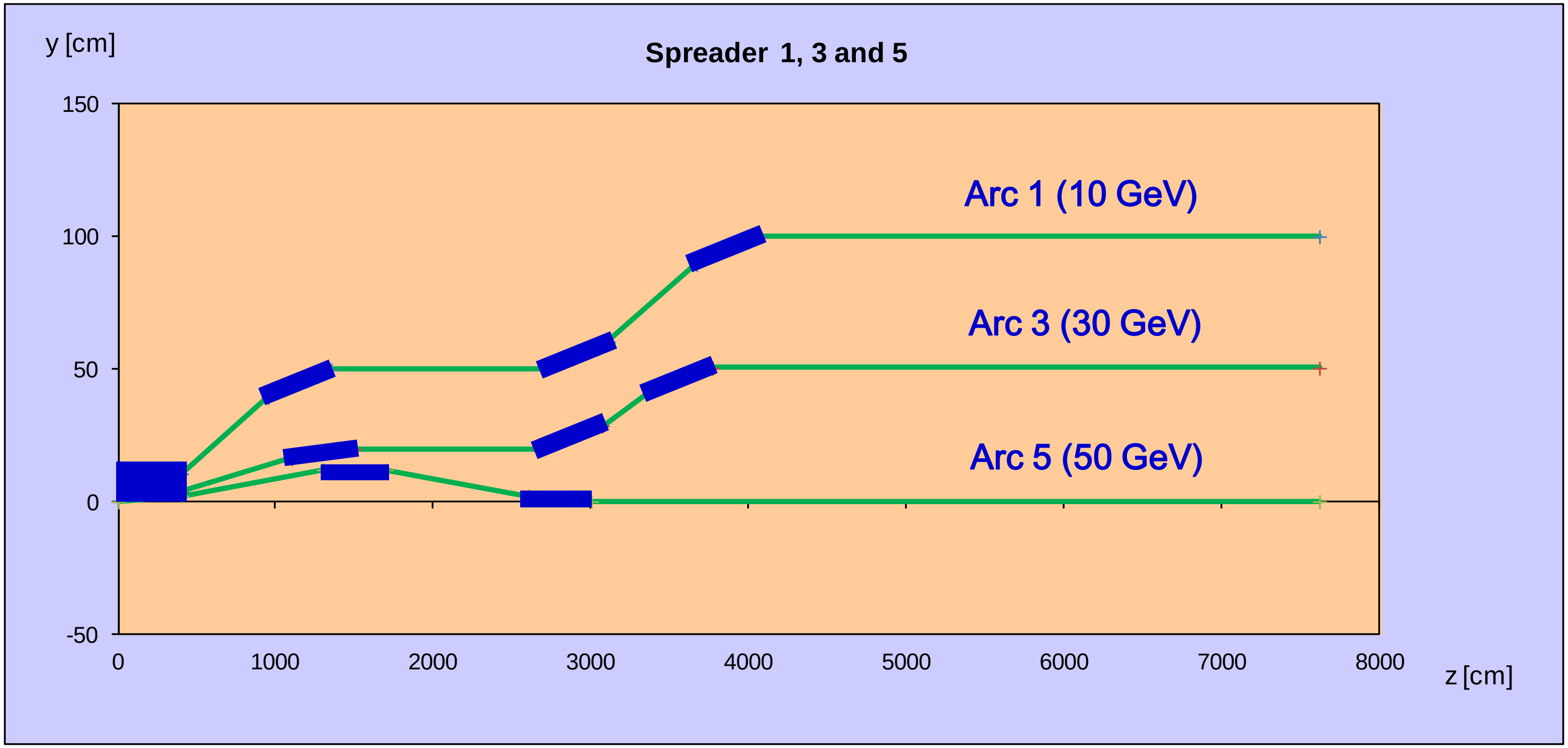
Acceleration/Deceleration





Vertical Separation of Arcs

A. Bogacz (JLab) @ ERL2015, Stony Brook University, June 9, 2015



Arc Optics: Emittance preserving FMC cells

[Flexible Momentum Compaction]

A. Bogacz (JLab) @ ERL2015, Stony Brook University, June 9, 2015

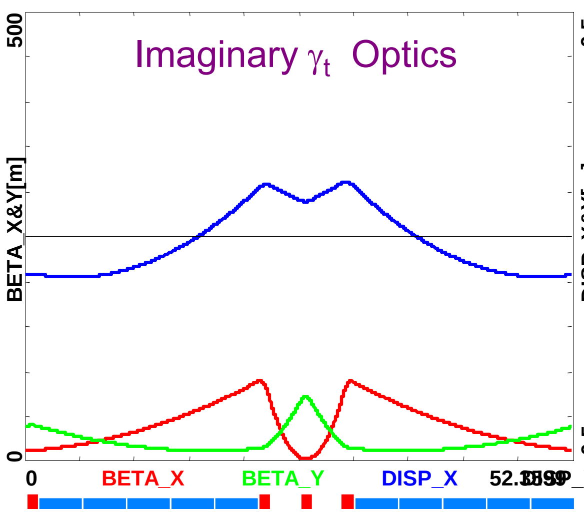
- Emittance dilution due to quantum excitations:

$$\Delta\epsilon^N = \frac{55\, r_0}{48\sqrt{3}} \frac{\hbar c}{mc^2} \gamma^6 I_5$$

$$I_5 = \int_0^L \frac{H}{|\rho|^3} ds = \frac{\theta \langle H \rangle}{\rho^2}$$

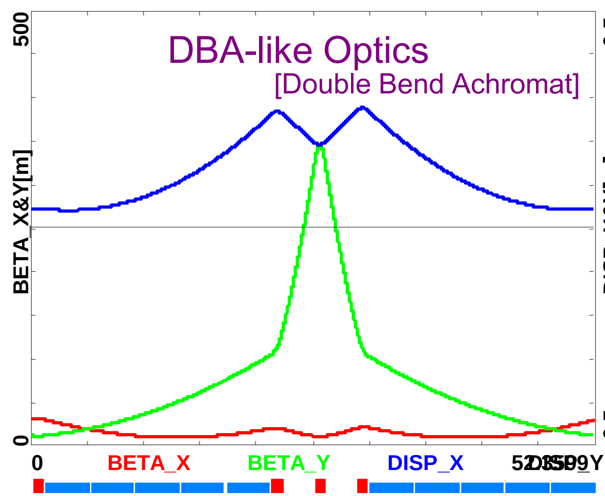
$$H = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

Arc 1 , Arc2



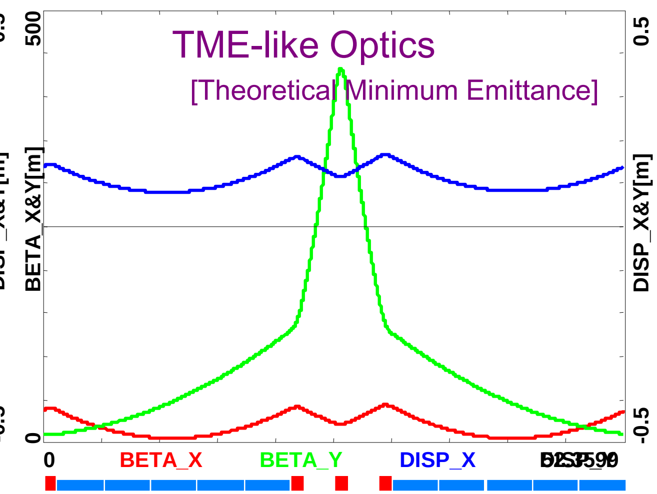
$$\langle H \rangle = 8.8 \times 10^{-3}\ m$$

Arc 3, Arc 4



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

Arc5, Arc 6



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

factor of 20 smaller than FODO

total emittance increase in Arc 1- 5: $\Delta\epsilon_x^N = 4.9\ \mu m$ rad

CDR Choices: Technology and Design

Magnets:

-Arc magnets (both for Linac-Ring and Ring-Ring):

➔ light and low cost normal conducting arc magnets

-IR design ➔ SC magnet magnet requirements

LHeC Ring-Ring dipole 400 mm long CERN m...

- interleaved ferromagnetic laminations
- air cooled
- two turns only, bolted bars
- 0.4 m models with different types of iron

...masini]

	...gth magnet
	70
	5.45
...s]	127-763
...gnets	3080
...perture [mm]	40
... width [mm]	150
Number of coils	2
Number of turns/coil	1
Current [A]	1500
Conductor section [mmxmm]	92x43
Conductor material	aluminum
Magnet Inductance [mH]	0.15
Magnet Resistance [mΩ]	0.2
Power per magnet [W]	450
Cooling	air
Weight [tons]	1.5

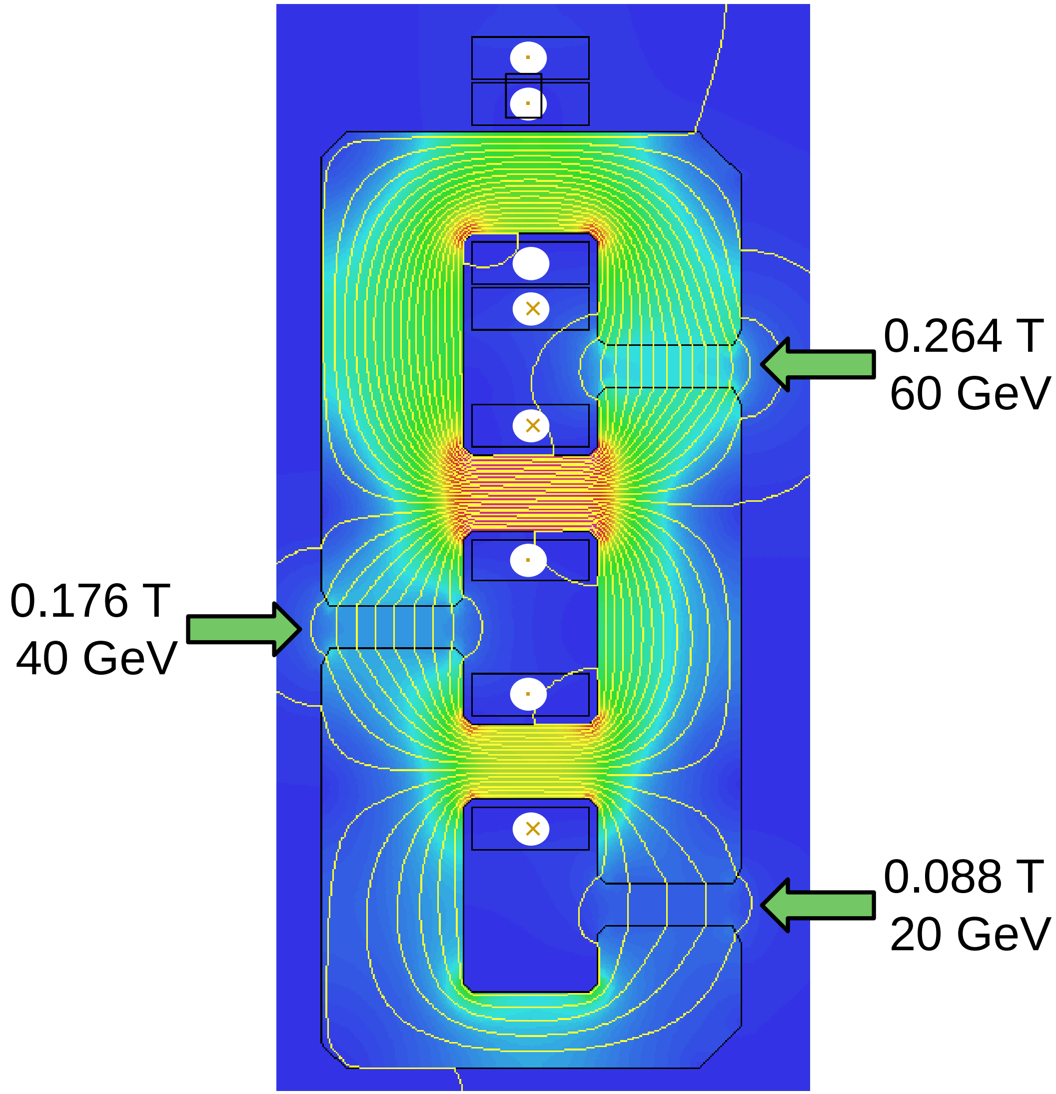
		$\cdot 10^{-5}$
		$6\cdot 10^{-5}$
	$3\cdot 10^{-5}$	$3\cdot 10^{-5}$
	$4\cdot 10^{-5}$	$5\cdot 10^{-5}$
...l)	$2\cdot 10^{-5}$	$4\cdot 10^{-5}$

Similar prototype development from Novosibirsk!

→ Long prototype with light magnet design shows that required field quality and reproducibility are feasible!

...ure & tests of 3 models

Post CDR: Return Arc Dipoles optimization

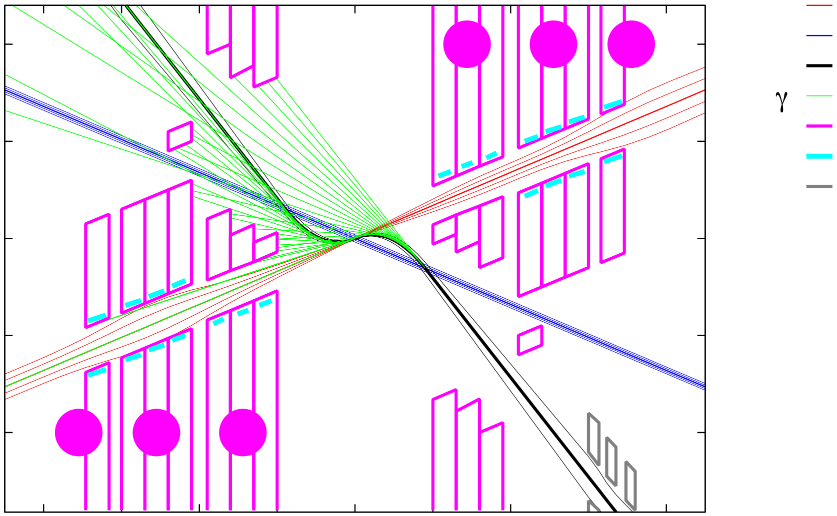


Attilio Milanese

Alternative coil arrangement

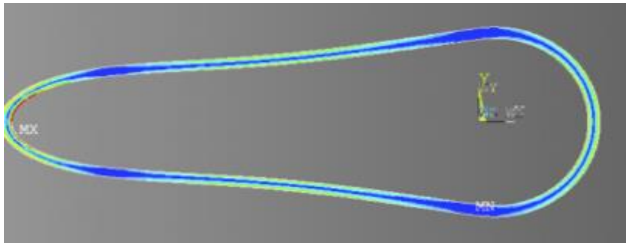
- keep the idea of recycling Ampere-turns
- stack the apertures vertically but offset them also transversally
- same vertical gap, 25 mm
- simple coils / bus-bars, same powering circuit
- as before, trim coils can be added for two of the apertures, to give some tuning

Asymmetric IR Design: example LHeC



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

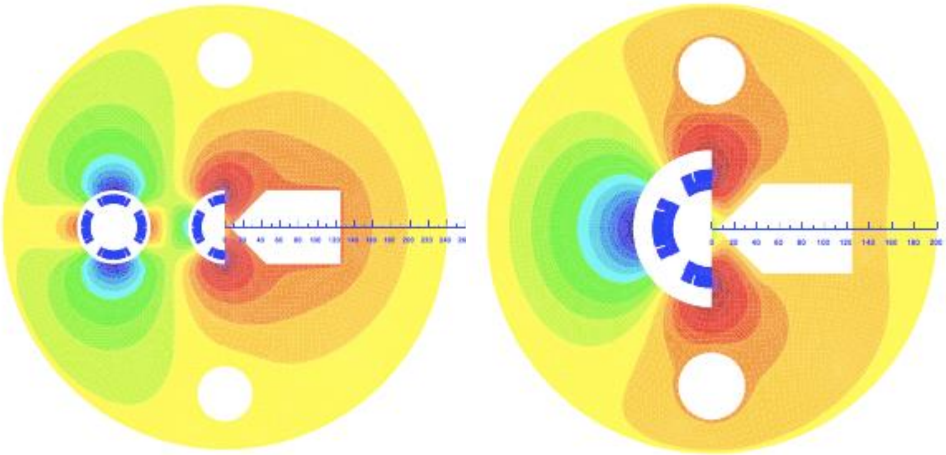
Composite material R+D, prototype, support..
→ Essential for tracking, acceptance and Higgs



S. Russenschuck

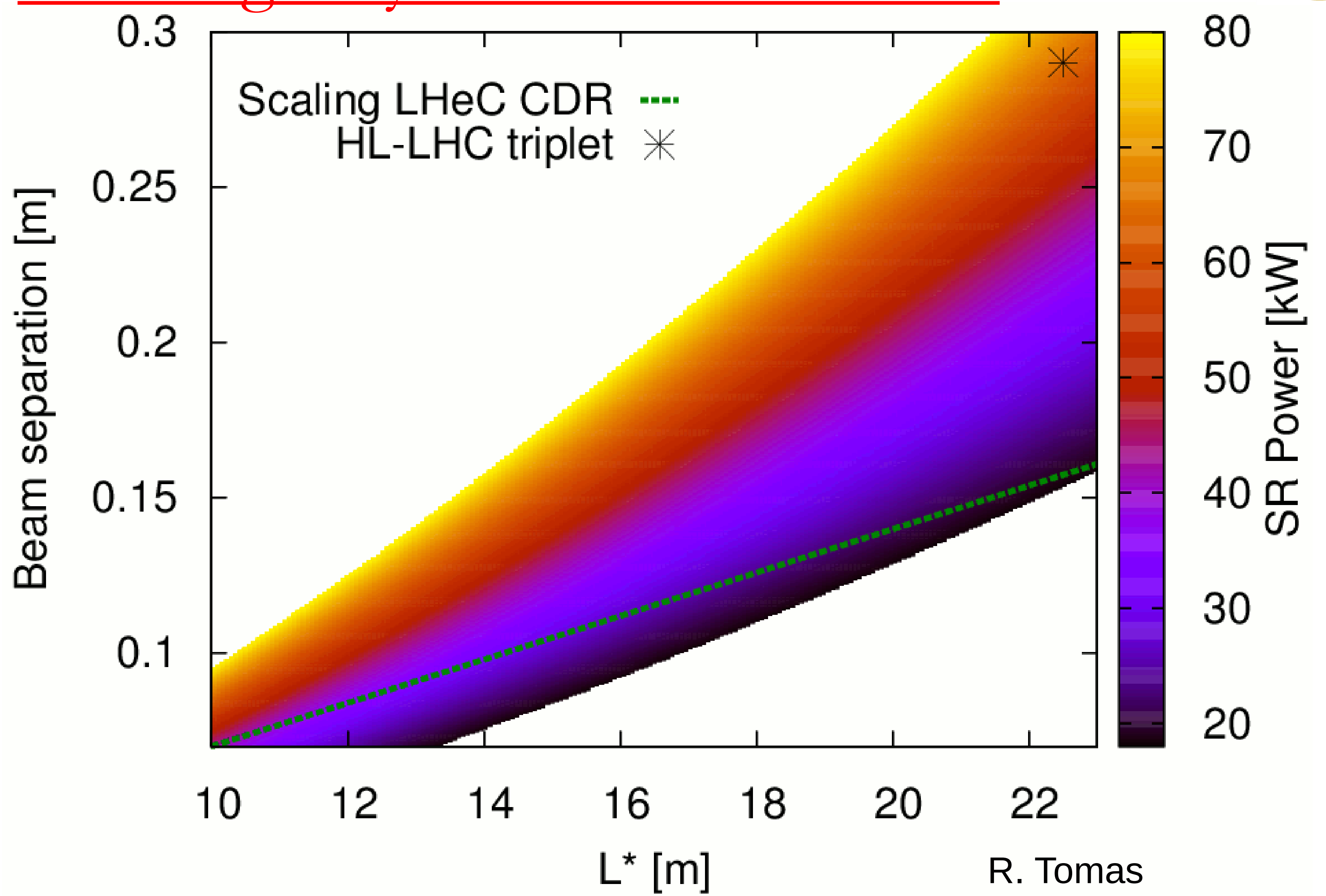
Have optics compatible with HL-LHC ATS optics and β*=0.1m
Head-on collisions mandatory →
High synchrotron radiation load, dipole in detector

Optimize 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

IR Design: Synchrotron Radiation



CDR Choices: Technology Choices and Design:

LHeC

Super Conducting RF:

-Requirements imposed by LHC beam structure (n * 40 MHz)

-Existing technologies world wide (e.g. ILC, ESS)

-Beam stability considerations

-RF Power considerations

-Synergies with other projects (e.g. FCC)

Post CDR Studies: RF Frequency

LHeC

Review of the SC RF frequency:

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

Frequency choice: *h* * 40.079 MHz

h=18: 721 MHz or h=33: 1.323GHz

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

Existing technologies do not quite match that requirement (20MHz)!

Post CDR Studies: ERL Beam Dynamics

LHeC

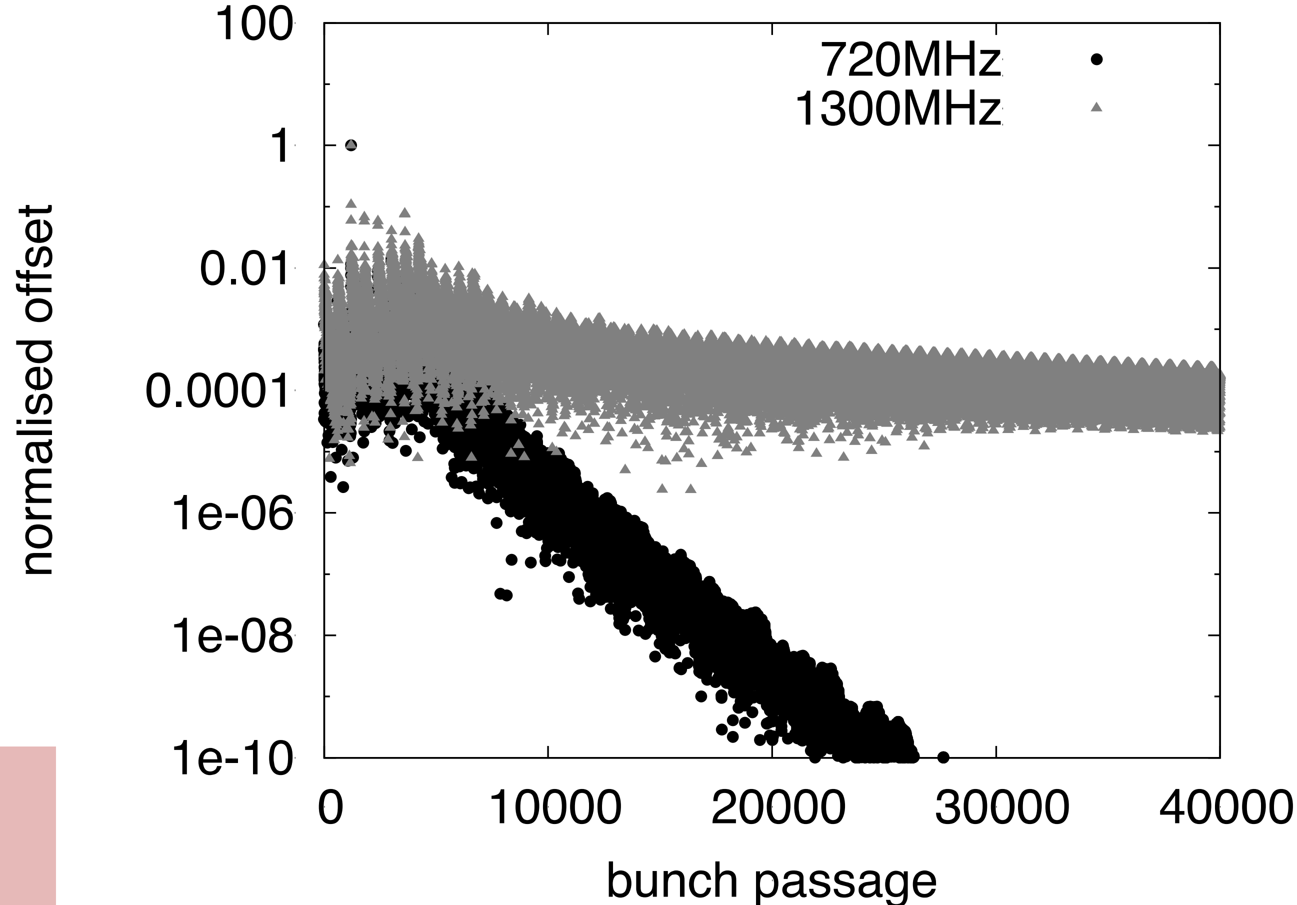
Beam-Beam effects:

Daniel Schulte @ LHeC Seminar 12. March 2013

$N=3\ 10^9$
Beam-beam effect included as linear kick

Result depends on seed for frequency spread
“worst” of ten seed shown

F_{rms}=1.135 for ILC cavity
F_{rms}=1.002 for SPL cavity



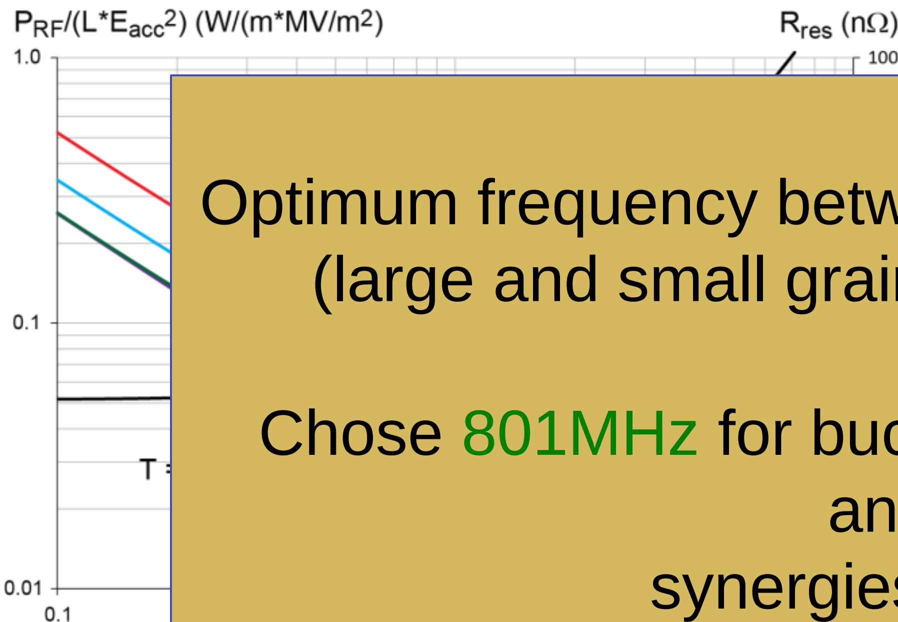
Beam is stable but very small margin with 1.3GHz cavity ➔ lower frequency

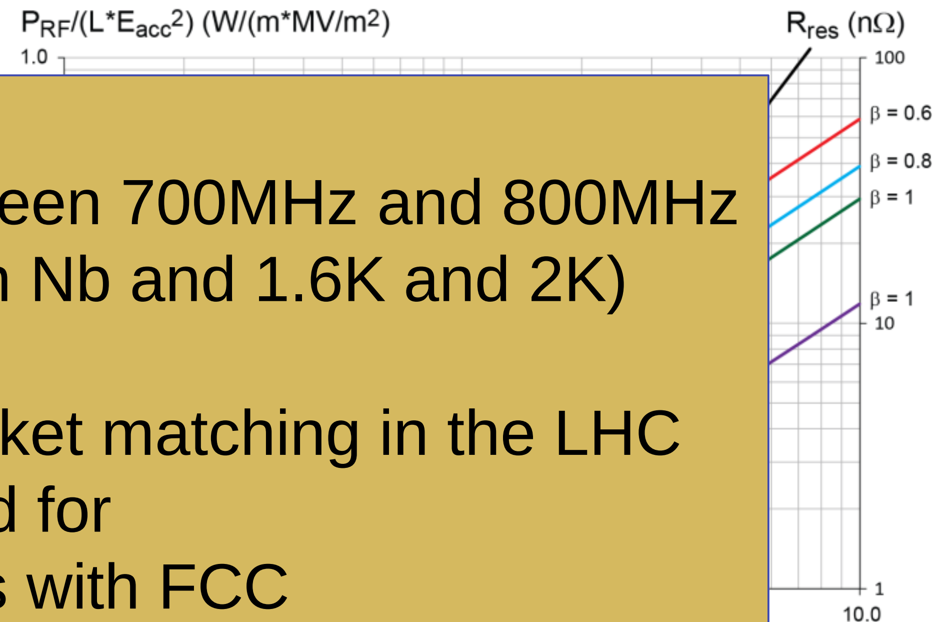
➔ Optimum choice for LHeC RF frequency

Optimum RF Frequency: Power Considerations

Results from F. Marhauser

Erk Jensen at Daresbury meeting 12 March 2013





Optimum frequency between 700MHz and 800MHz (large and small grain Nb and 1.6K and 2K)

Chose 801MHz for bucket matching in the LHC and for synergies with FCC

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

Site Considerations:

LHeC Interaction Region options:

-IR1 and IR5 house the LHC General Purpose detectors and parallel operation with HL-LHC excludes IR1 and IR5

-IR4 is excluded due to LHC RF installation

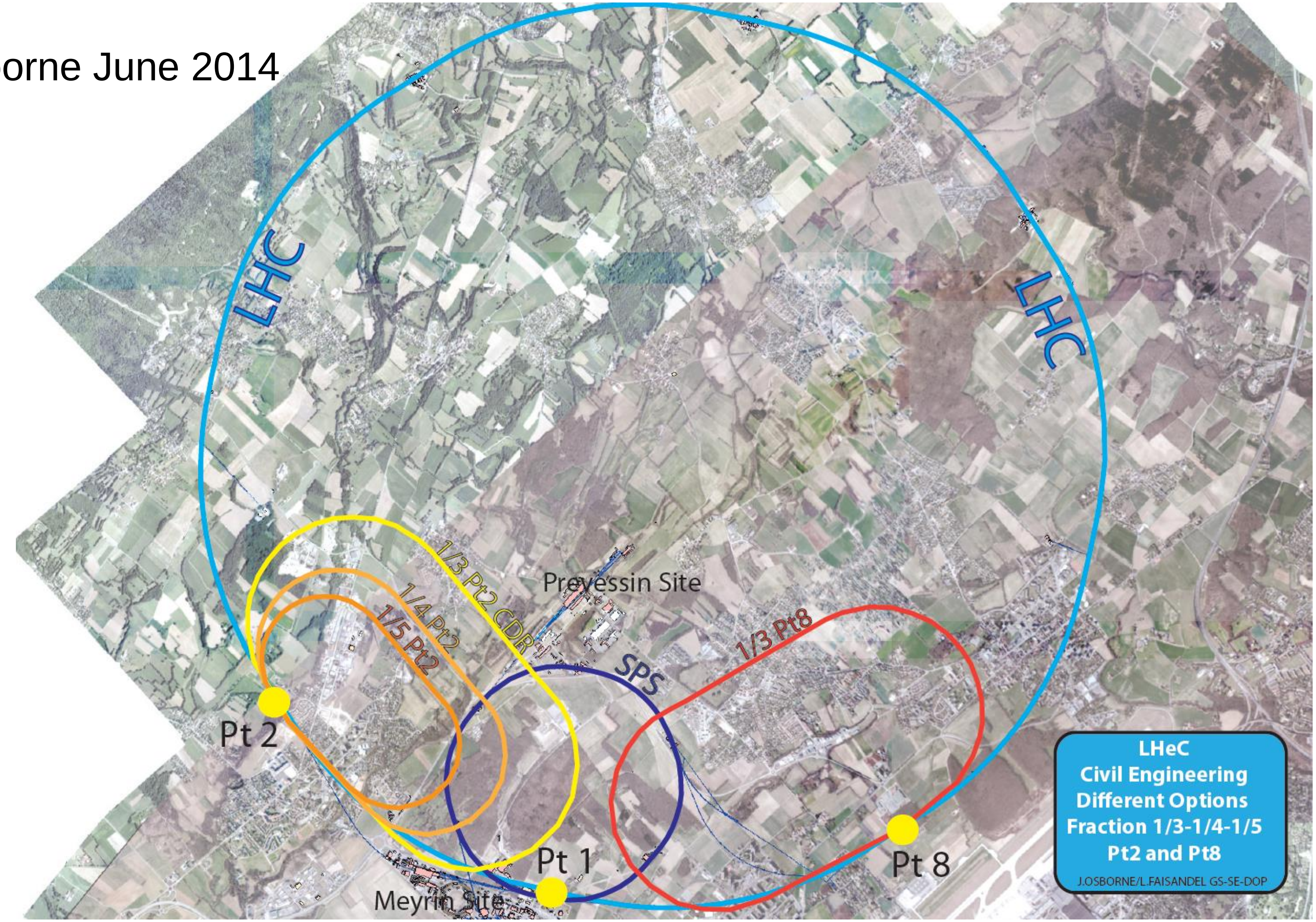
-IR3 and IR7 have no caverns and are excluded due to the LHC collimation system

-IR6 is excluded due to the installation of the LHC beam dumping system

➔ Leaves only IR2 and IR8 as options assuming that ALICE or LHCb Physics program has been finished

Site Considerations:

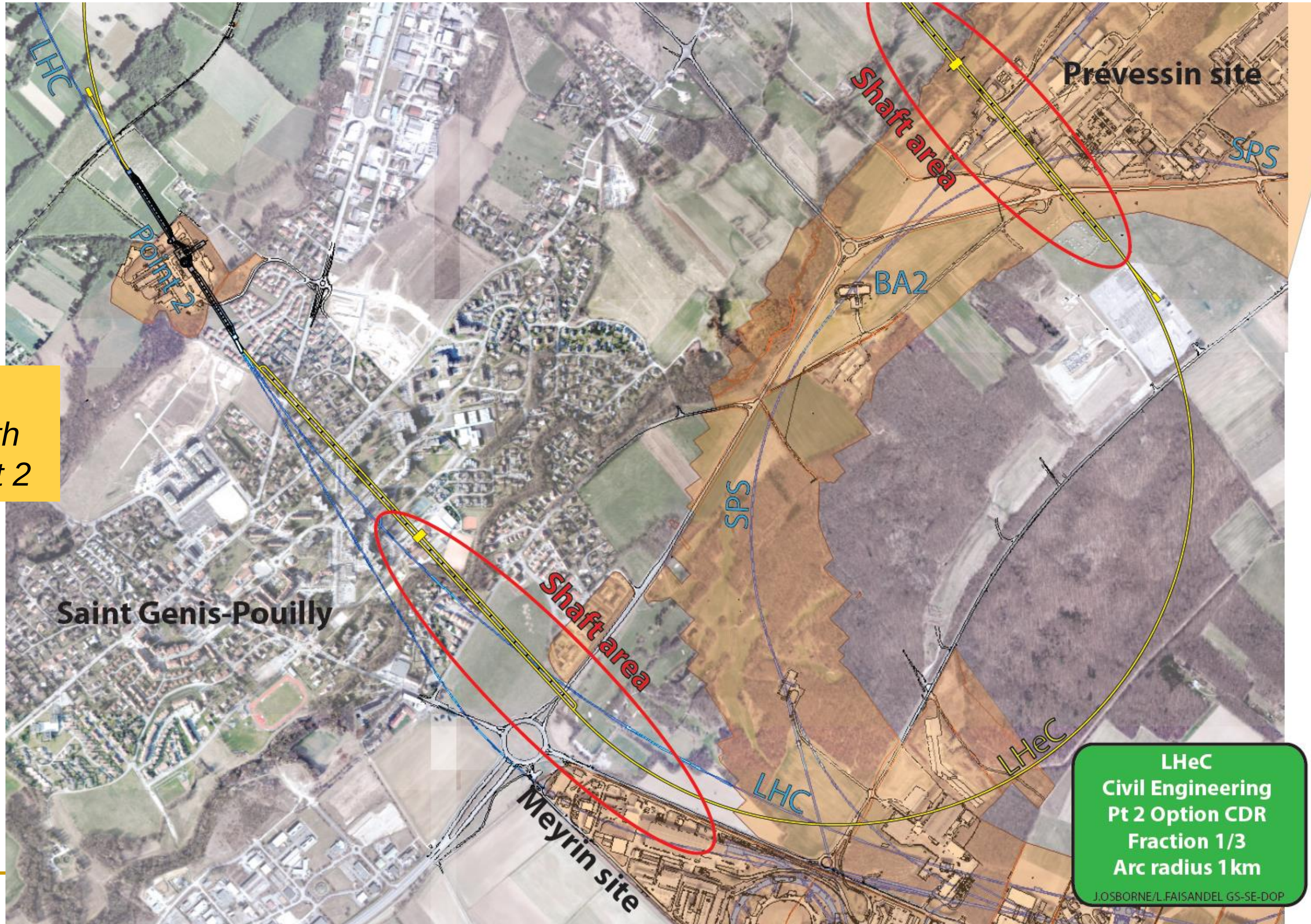
John Osborne June 2014



Site Considerations: IR2

John Osborne June 2014

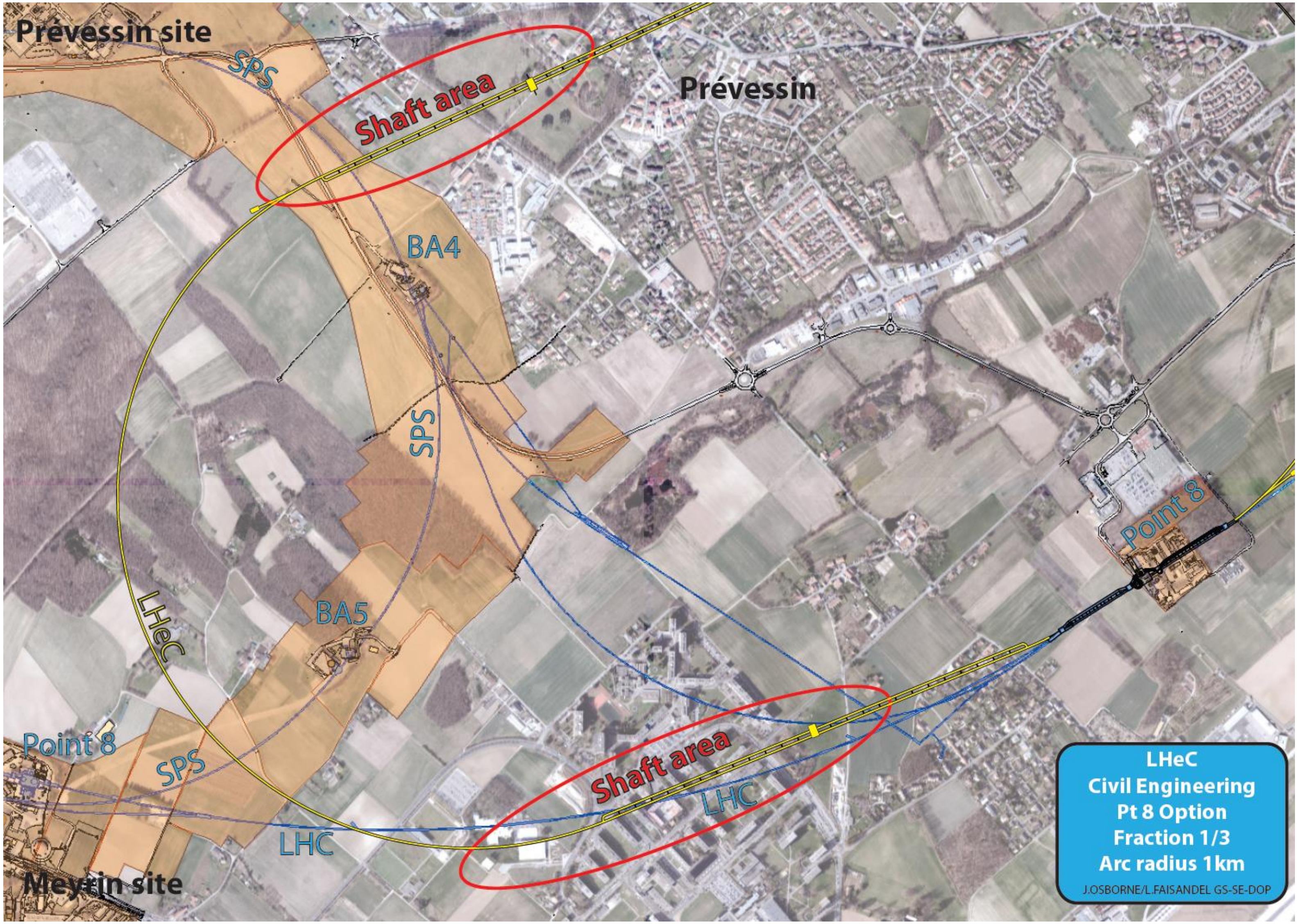
CDR-like 60GeV with IR at Point 2



Site Considerations: IR8

John Osborne June 2014

CDR-like 60GeV with IR at Point 8



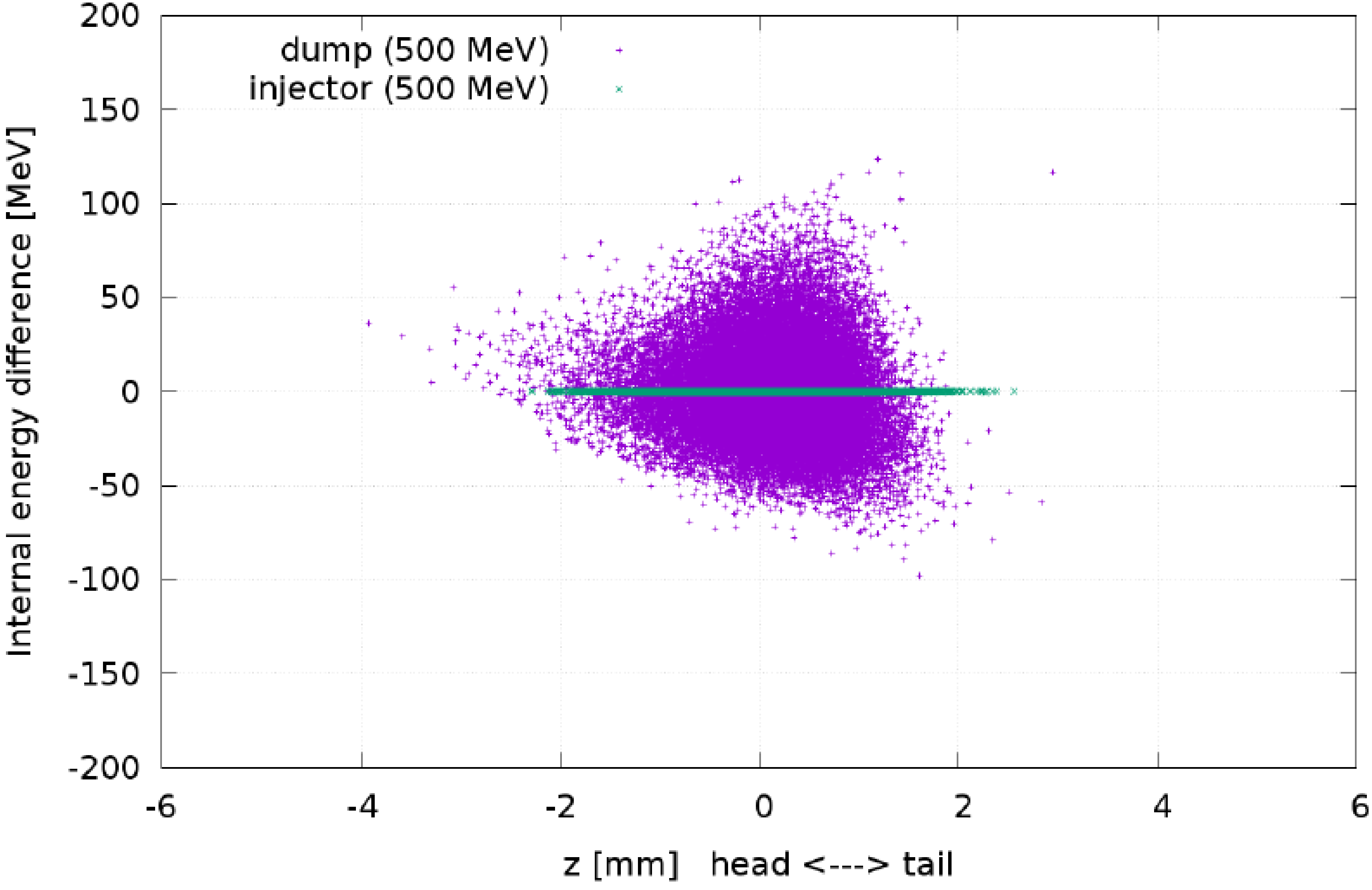
Beam Dynamics and ‘front-end’ Simulations:

- Key Studies (performed with PLACET2 code from CLIC):
  - ➔ Synchrotron radiation
    bunch shape and acceptance for deceleration and dump
  - ➔ Beam-beam interaction
    bunch shape and beam stability
  - ➔ RF Wakefields and HOM
    beam stability
  - ➔ Recombination patters
    beam stability (filling of the RF buckets can be controlled by tuning the arc lengths)
  - ➔ Cavity alignment requirements
    orbit and emittance control

Synchrotron Radiation

Evolution of the Longitudinal Phase Space

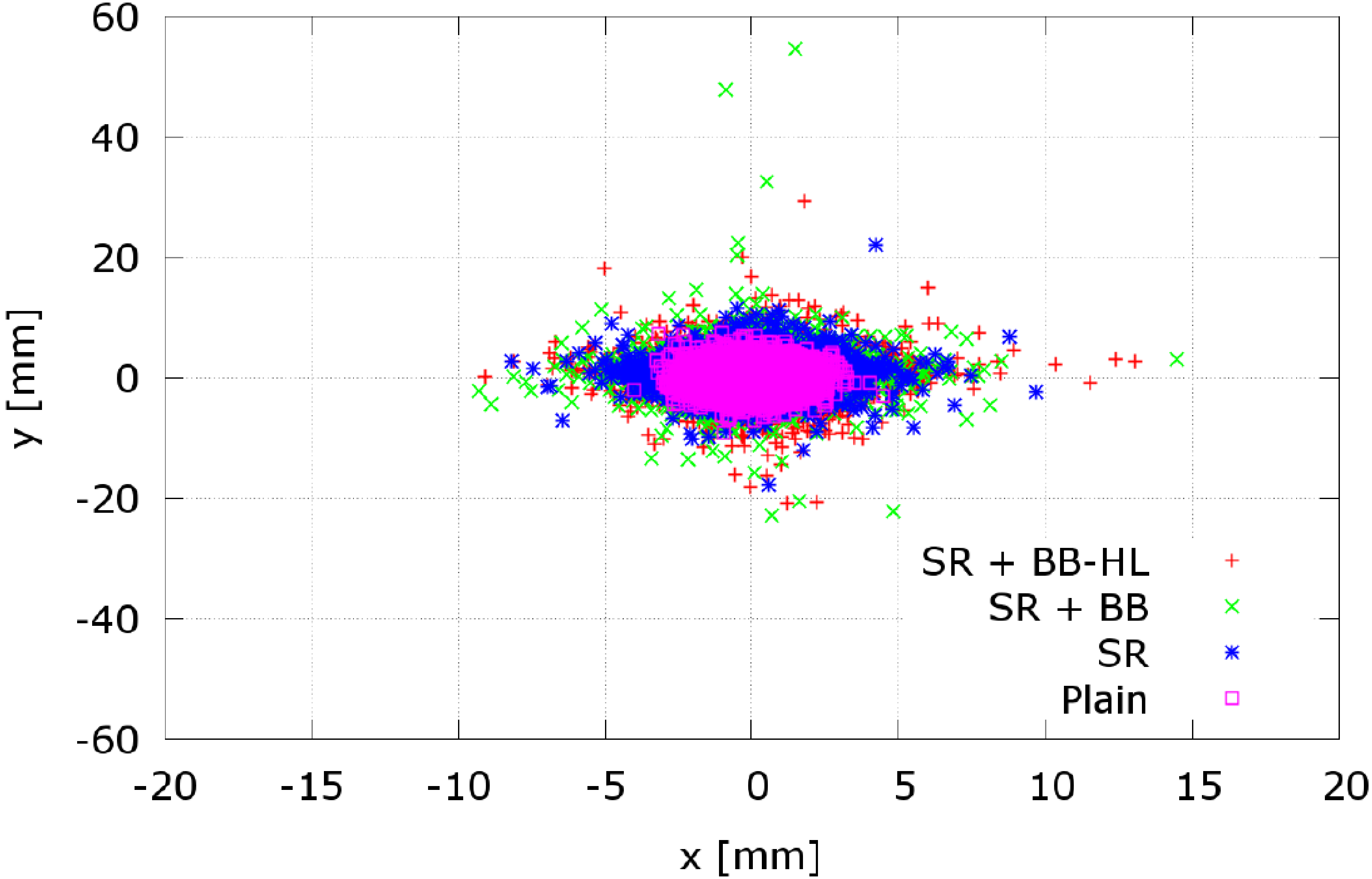
D. Pellegrini (EPFL/CERN) @ ERL'15



Synchrotron Radiation and Beam-Beam

Transverse Plane at Dump

D. Pellegrini (EPFL/CERN) @ ERL'15



Aperture radius of the SPL cavity is 40 mm.

Summary:

- LHeC ERL design is viable:
  physics program ➔ talks by M. D'Onofrio & G. Altarelli later

- LHeC offers a further exploitation of the LHC infrastructure

- LHeC is a unique application for the novel ERL concept
  ➔ Innovative accelerator concept with many applications
  ➔ New infrastructure for CERN with applications beyond LHeC

- The LHeC ERL design has also been adopted as baseline for FCC-eh and could operate as injector to FCC-ee
  ➔ synergy with FCC studies

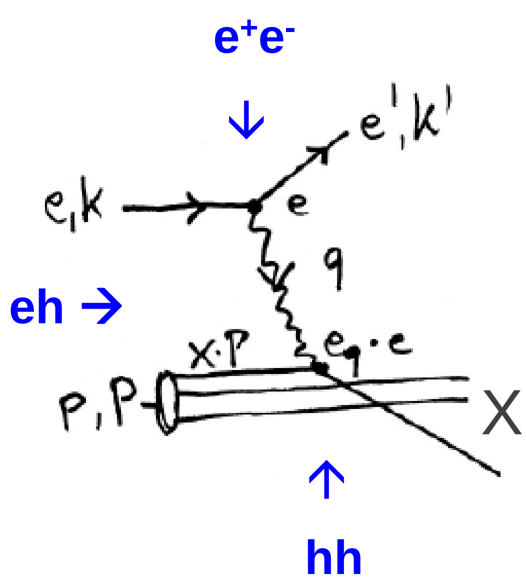
Reserve Transparencies

Electron-Ion Collider Project Overview

- HERA: the first and only Electron-Proton collider
- Future Accelerator projects for fixed target e-A experiments:
  - -CEBAF 12 GeV upgrade @ JLab (RCL design)
  - -MESA @ U Mainz, Germany (ERL operation)
- Electron-Ion collider @ Ion Accelerator Facilities:
  - -ENC @ FAIR, Germany
  - -CEIC @ HIAF, China
- Dedicated Electron-Ion collider projects for QCD exploration:
  - -eRHIC @ BNL, U.S.A. [Collider, polarization]
  - -MEIC @ JLab, U.S.A. [Collider, polarization]
- Energy Frontier:
  - -LHeC @ CERN using 7 TeV protons from LHC
  - -FCC-eh @ CERN using 50TeV protons

Motivation: EIC facilities as a microscope:

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

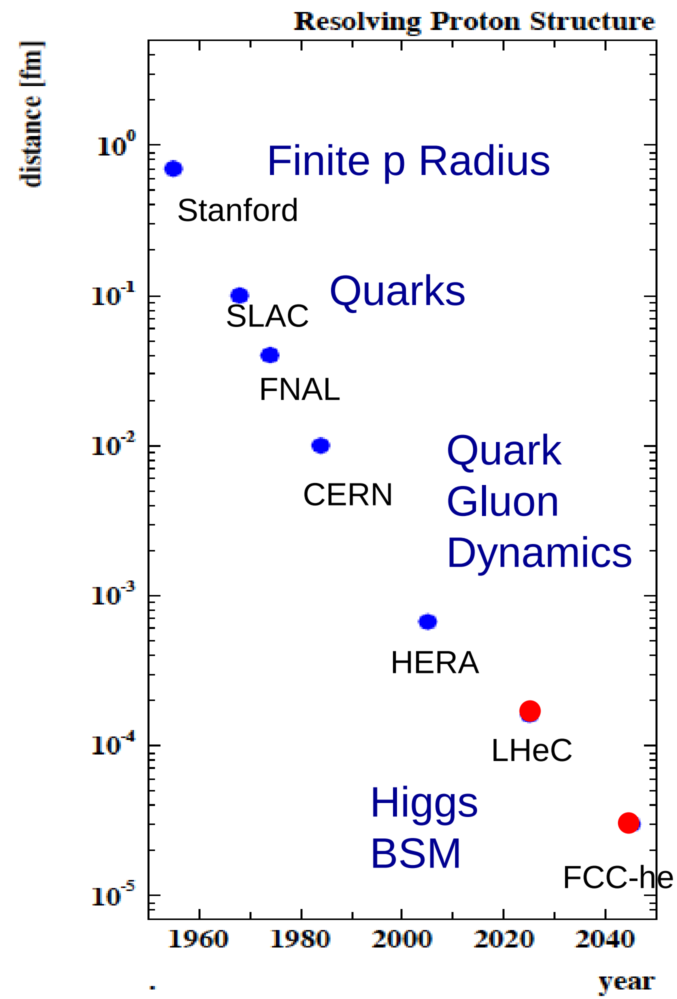


$$x = \frac{Q^2}{sy}$$

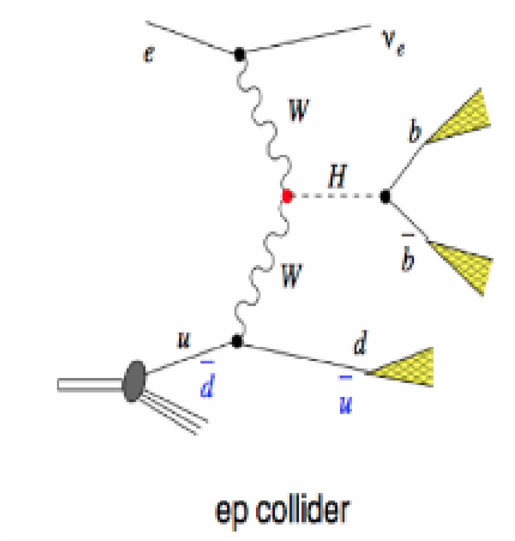
$$Q^2 = -(k - k')^2$$

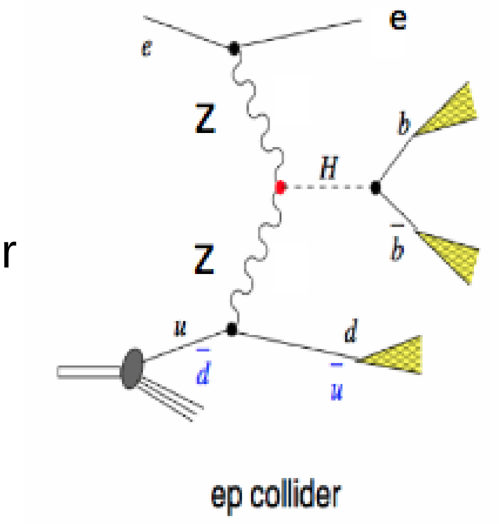
$$y_{lab} = 1 - \frac{E_e'}{E_e}$$

$$s = 4E_eE_p$$

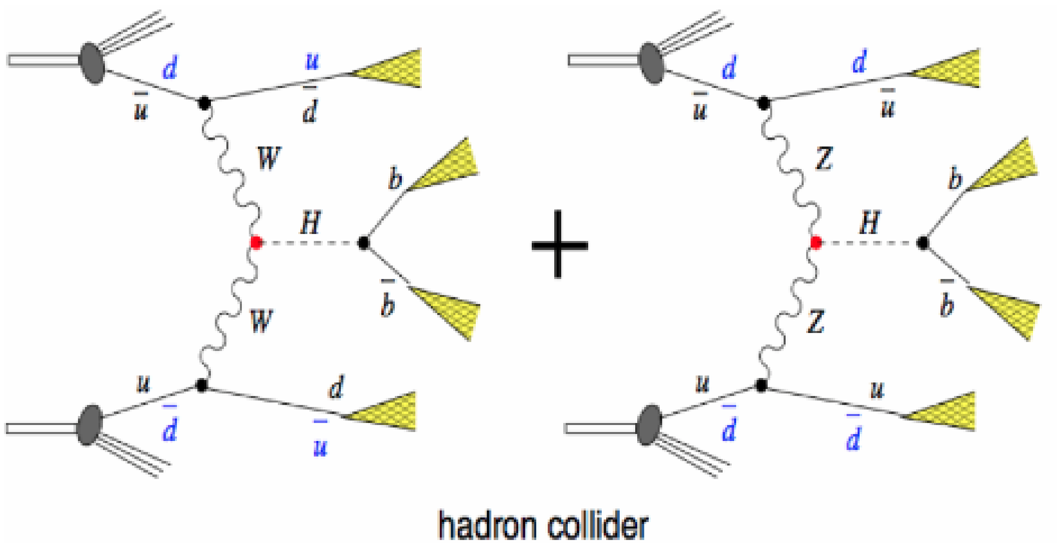


Motivation: LHeC as a Higgs Factory

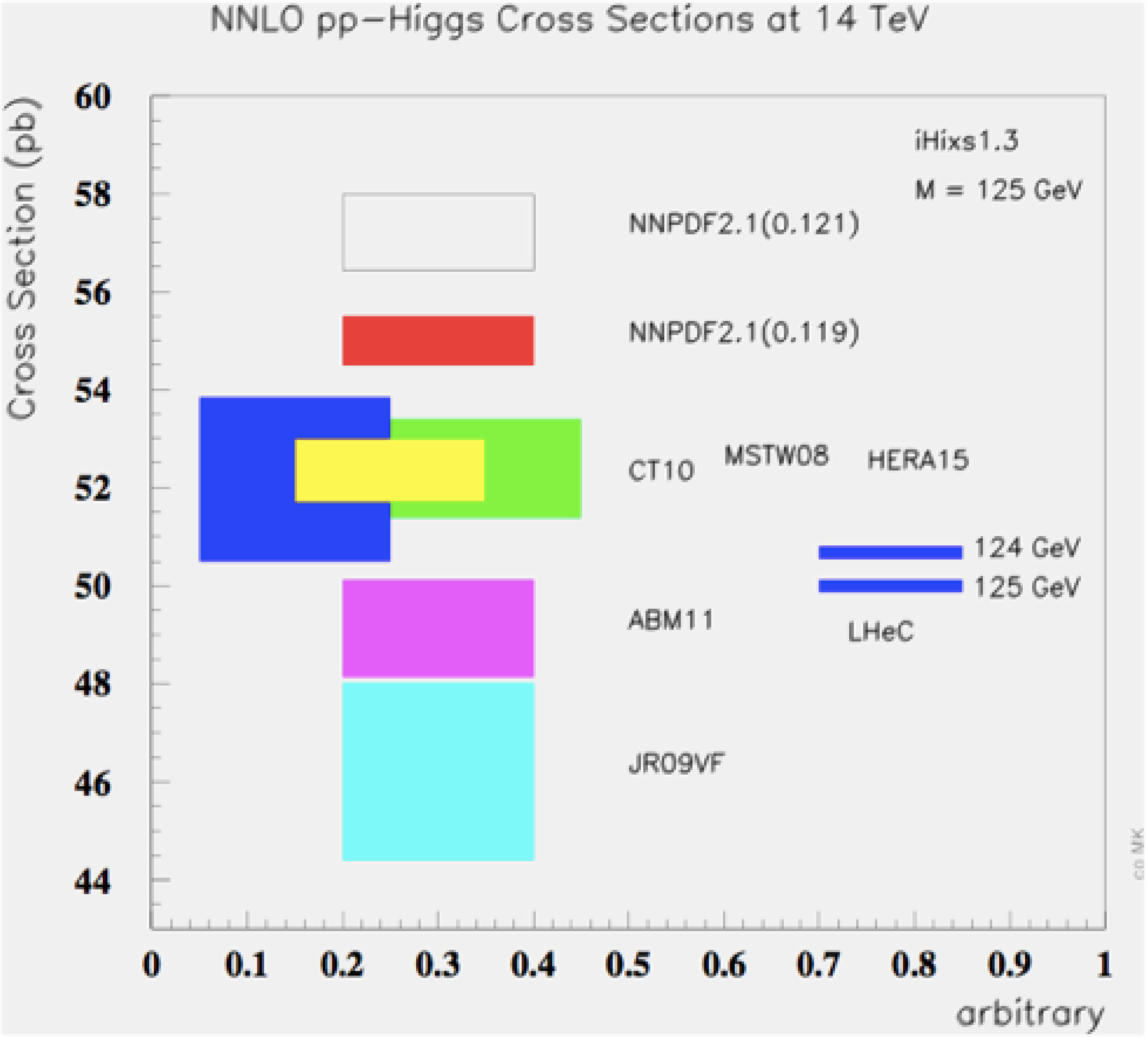




- -Cross section of 200fb @ LHeC
- -Clean bb final state (S/B ≈ 1)
- -e-h cross calibration ➔ precision
- -Pile-up in ep @ $10^{34}cm^{-2}s^{-1}$ is 0.1
- -pile-up in pp @ 5 $10^{34}cm^{-2}s^{-1}$ is 140



Motivation: Precision for Higgs @ LHC:



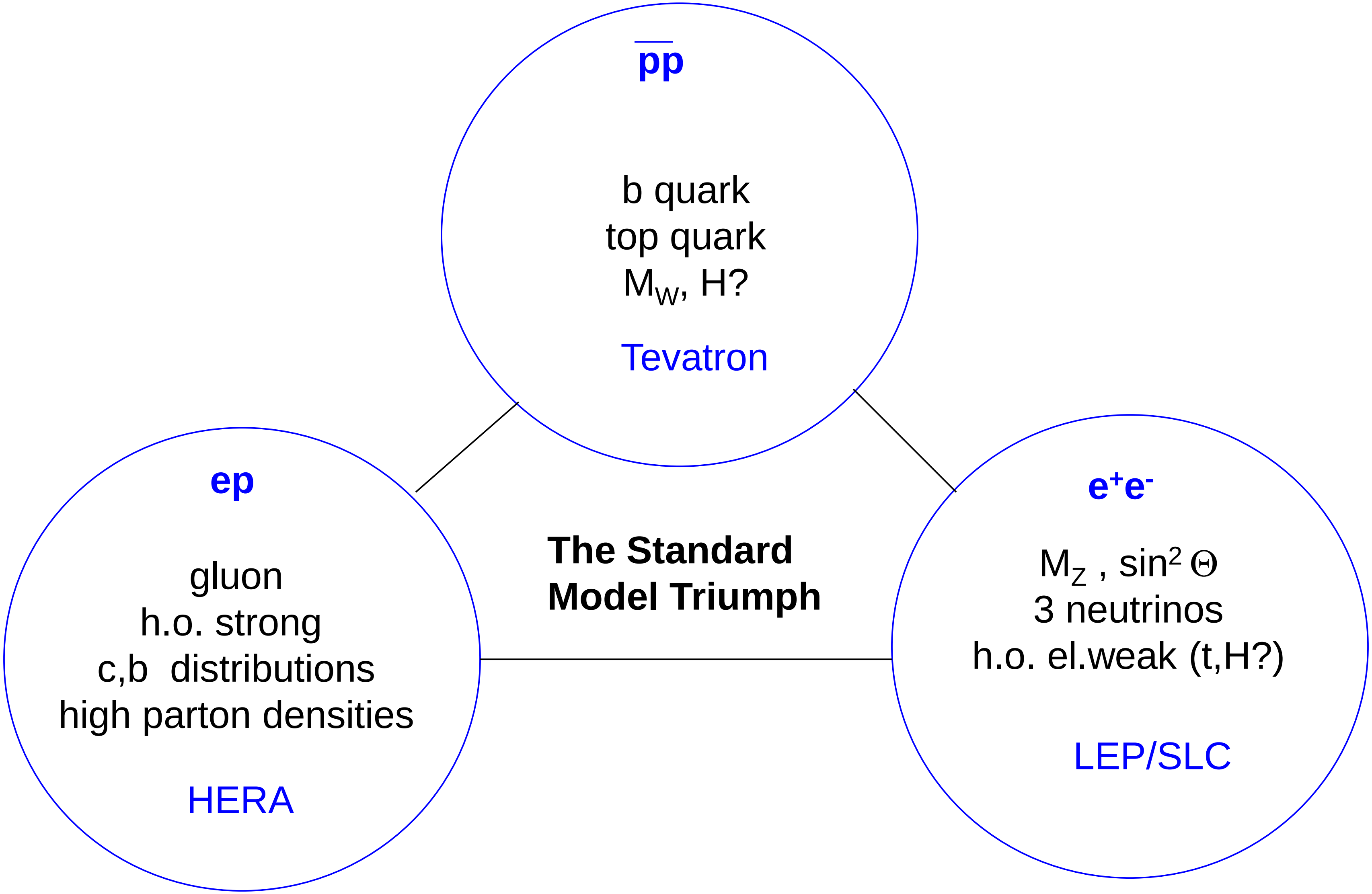
Experimental uncertainty H cross section becomes 0.25% (stat + uncertainty) with LHeC

Leads to mass sensitivity

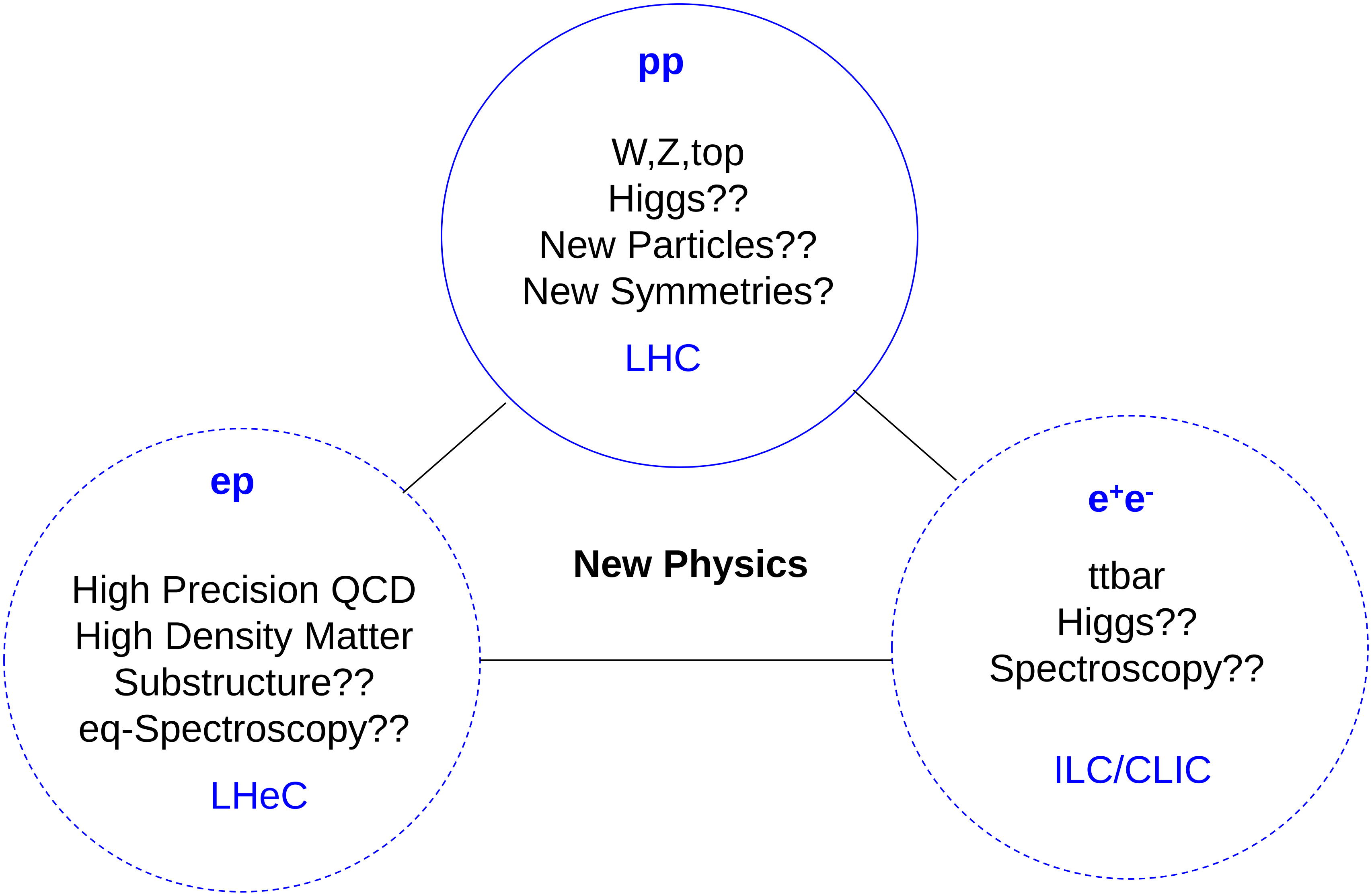
Needs N^3LO calculations

arXiv:1305.2090, MPLA 2013

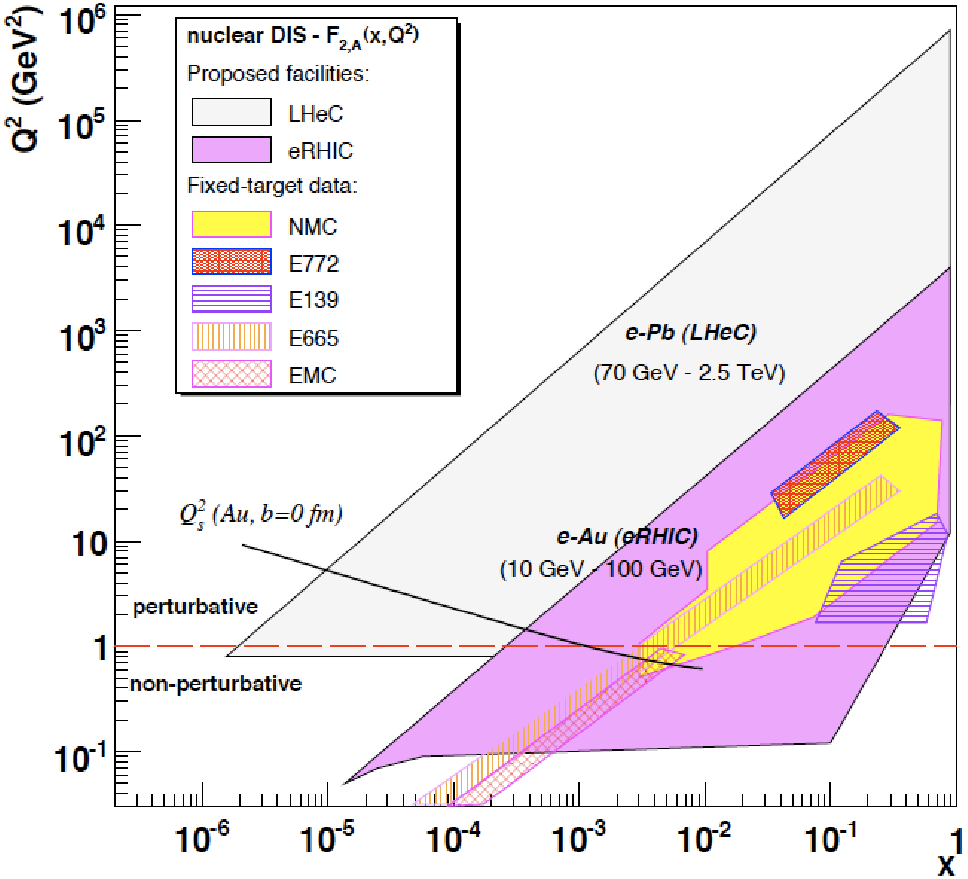
Motivation: The Fermi Scale [1985-2010]



Motivation: The TeV Scale [2010-2035..]



Motivation: 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)

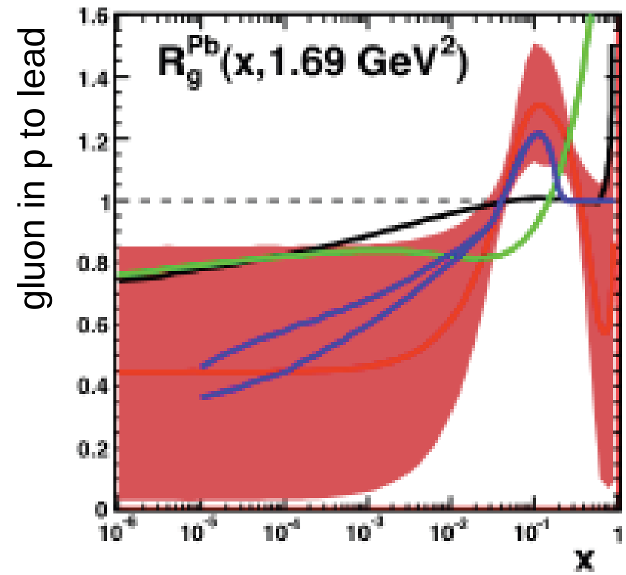
Qualitative change of behaviour

- Bb limit of F_2

- Saturation of cross sections
- amplified with $A^{1/3}$

- Rise of diffraction to 50%?

- partons in nuclei – widely unknown

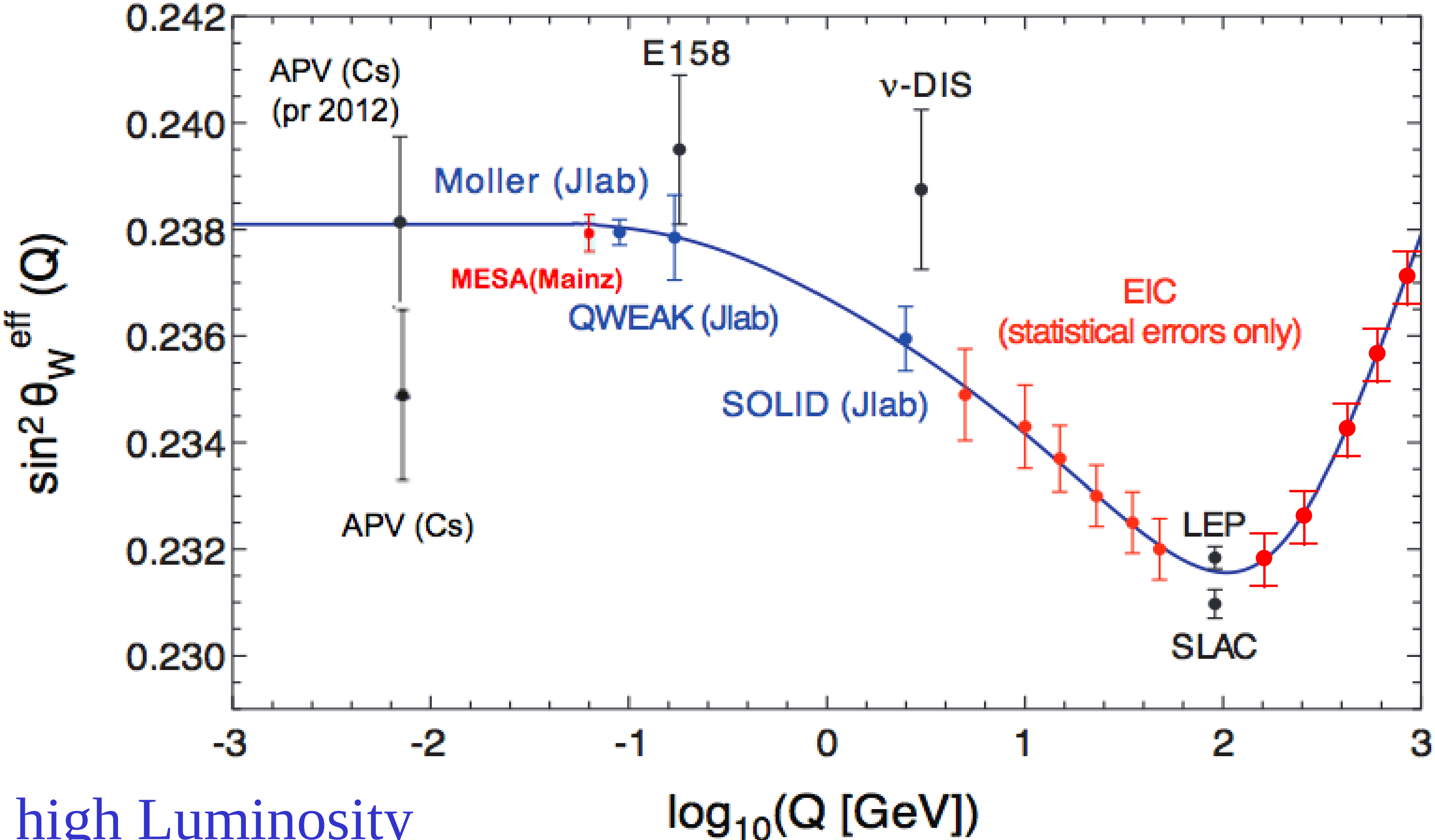


Motivation: Electron-Weak Precision Physics

LHeC

Precision Measurements: Running of weak interactions

Fills in the regions that have not yet been measured



➔ requires high Luminosity

FCC-eh (RR and LR EIC options at FCC)

- 80 inf ar
- *pp* de re
- e^+ po
- ***p-***
- int ho

~16
~20

Two Options:

Ring-Ring collider using FCC-hh and FCC-ee

Linac-Ring collider using LHeC and FCC-hh

Both options offer performance reach of

$$L = 10^{33} – 10^{34}\ cm^{-2}\ s^{-1}\ @\ ca.\ 4\ TeV\ CM$$

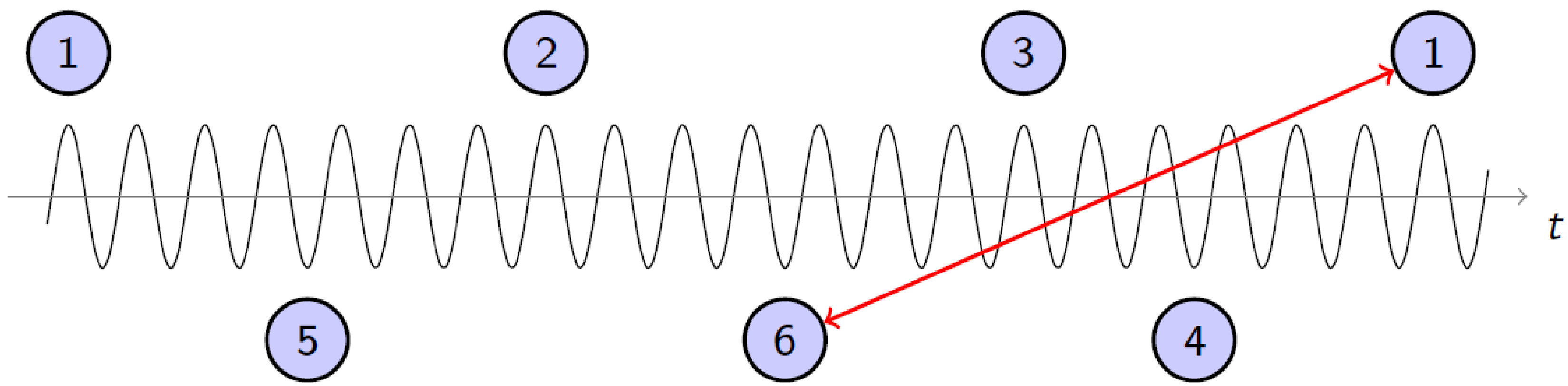
preliminary (!) parameters for *FCC-he-ERL w/o FCC-ee*

parameter [unit]		
species	***e-***	***p***
beam energy (/nucleon) [GeV]	**60**	**50000**
bunch spacing [ns]	25	25
bunch intensity (nucleon) [10^{10}]	**0.4**	**10**
beam current [mA]	**25.6**	**500**
normalized rms emittance [μm]	**20**	**2.0**
geometric rms emittance [nm]	**0.17**	**0.04**
IP beta function $\beta_{x,y}^*$ [m]	**0.10**	**0.4**
IP rms spot size [μm]	**4.0**	**4.0**
lepton *D* & hadron ξ	**32**	**0.0002**
hourglass reduction factor H_{hg}	**0.94**	
pinch enhancement factor H_D	1.35	

Recombination Pattern

D. Pellegrini (EPFL/CERN) @ ERL'15

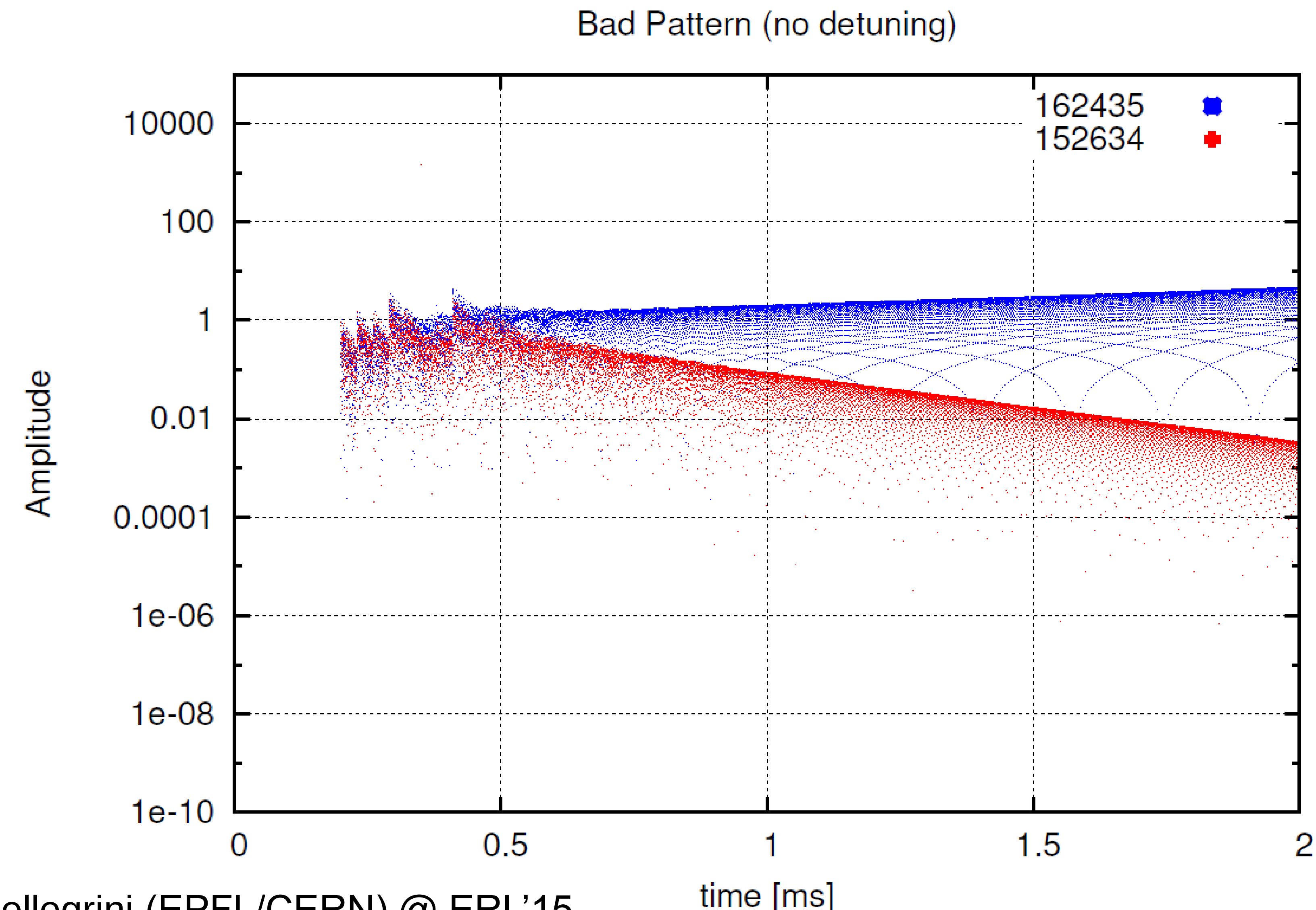
Multi-bunch effects are enhanced by the value of $\frac{\beta}{E}$ $\rightarrow$ low energy particles are more susceptible.
The filling of the RF buckets of the LHeC can be controlled tuning the lengths of the arcs $\rightarrow$ maximise the separation between the bunches at first and sixth turn.



- Pattern 162435 is bad!
- Pattern 152634 is better!

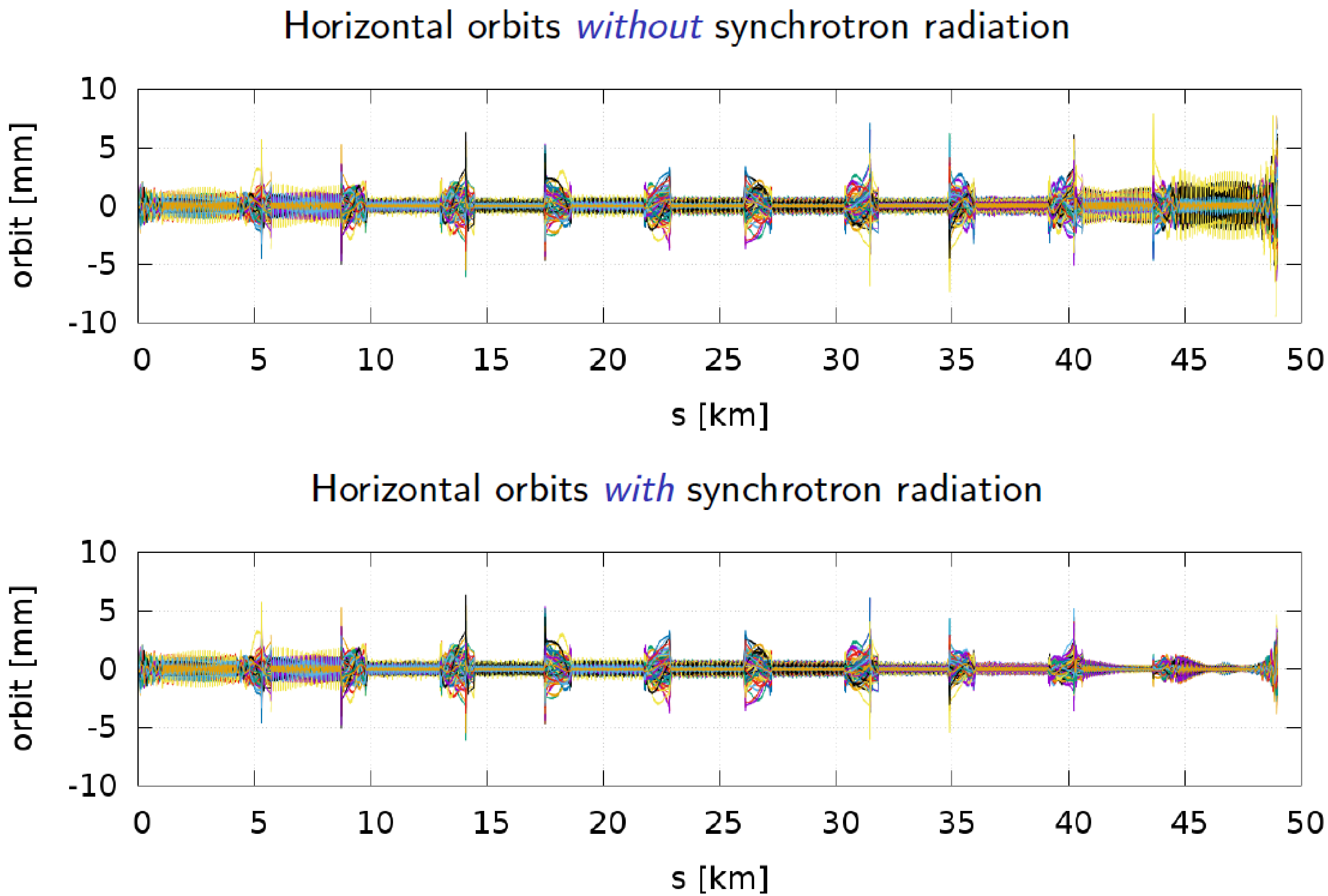
Pattern and Long Range Wakefields

The pattern has an influence on the threshold current



Cavity misalignments

100 uncorrected orbits obtained for 300 μm **misalignments and** 300 μrad **tilts.**



CDR Choices: Linac-Ring

- Colliding with one of the LHC beams:

-Requires the same bunch pattern as the LHC ➔ 25ns spacing

-Continuous collisions with all LHC bunches requires CW operation for the LINAC

-For a recirculating LINAC it requires that the

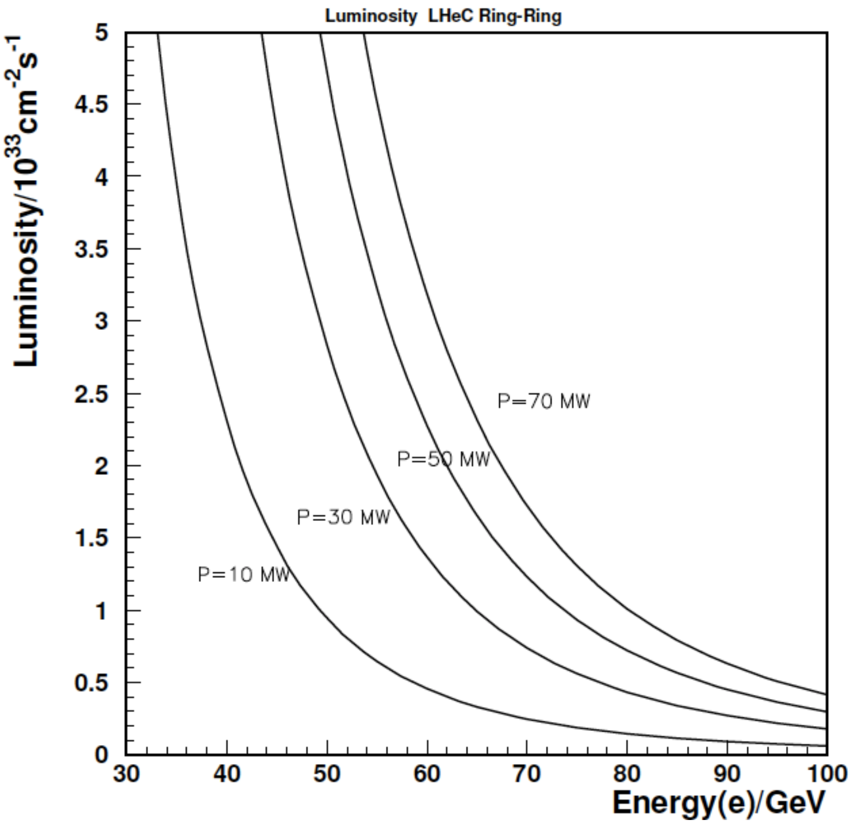
LHC Infrastructure: 7 TeV Proton beams

CM ep collision energy: $E^2_{CM} = 4\, E_e * E_{p,A}$ ➔ 50 to 150GeV provides TeV scale collisions

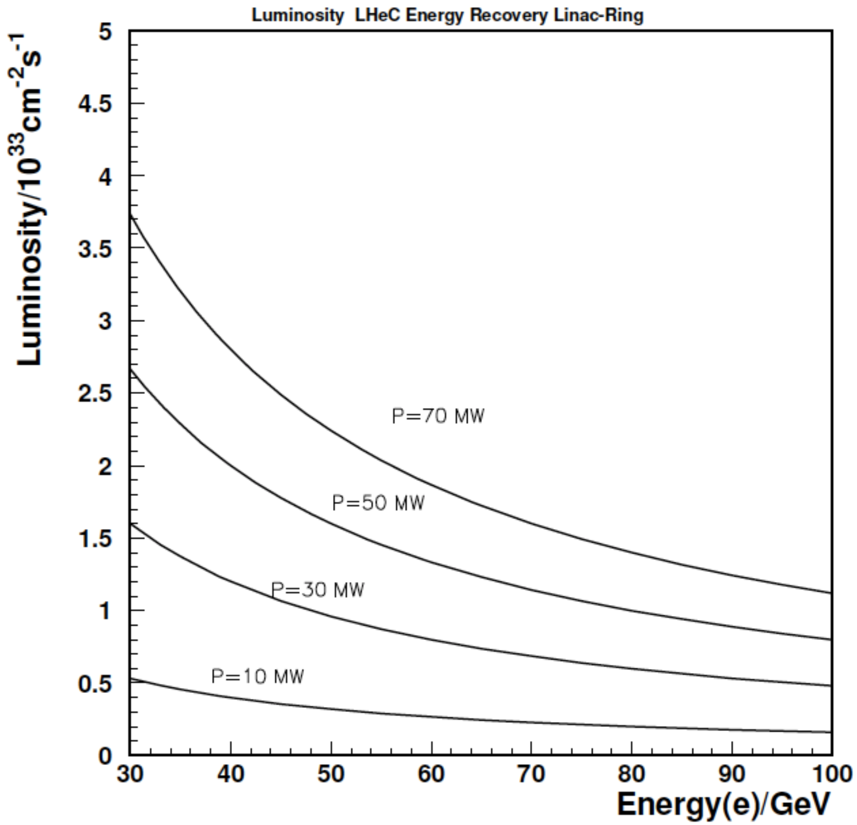
Integrated $e^{\pm}p$: O(100) fb^{-1} ≈ 100 * L(HERA) ➔ synchronous ep and pp operation

Luminosity O (10^{33}) $cm^{-2}s^{-1}$ with 100 MW power consumption ➔ Beam Power < 70 MW

e Ring in the LHC tunnel (Ring-Ring - RR)

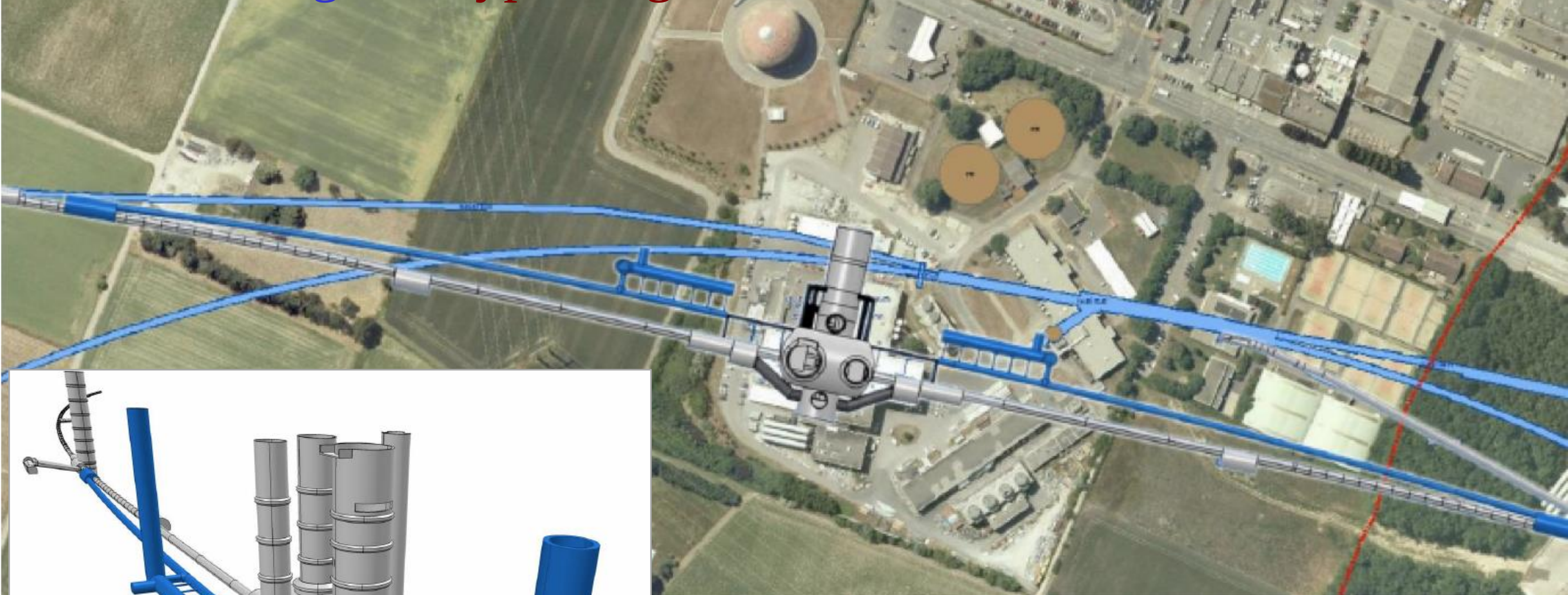


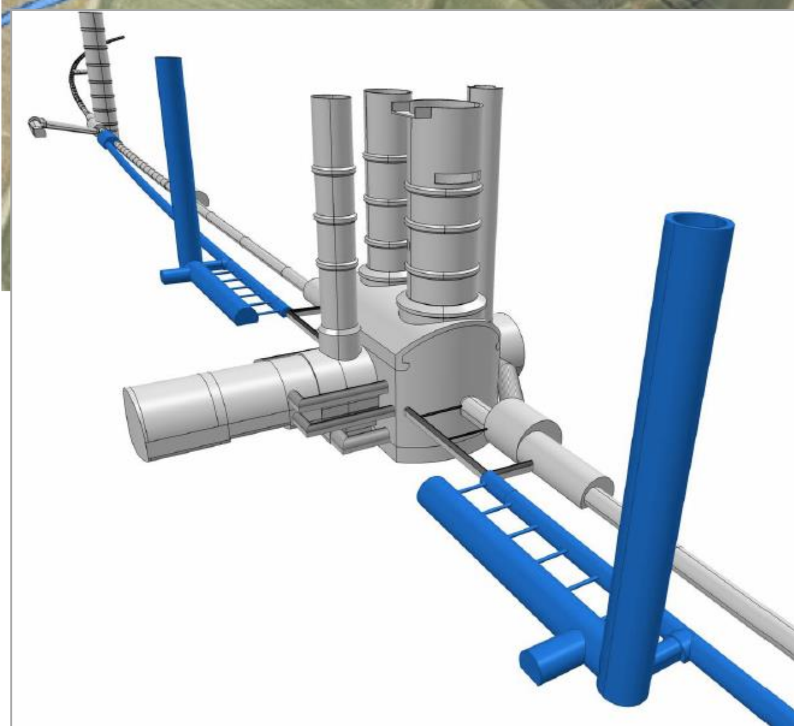
Superconducting ERL (Linac-Ring -LR)



CDR Choices: LHeC: Ring-Ring Option

Challenge 1: Bypassing the main LHC detectors





Without using the survey gallery the ATLAS bypass would need to be 100m away from the IP or on the inside of the tunnel!

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

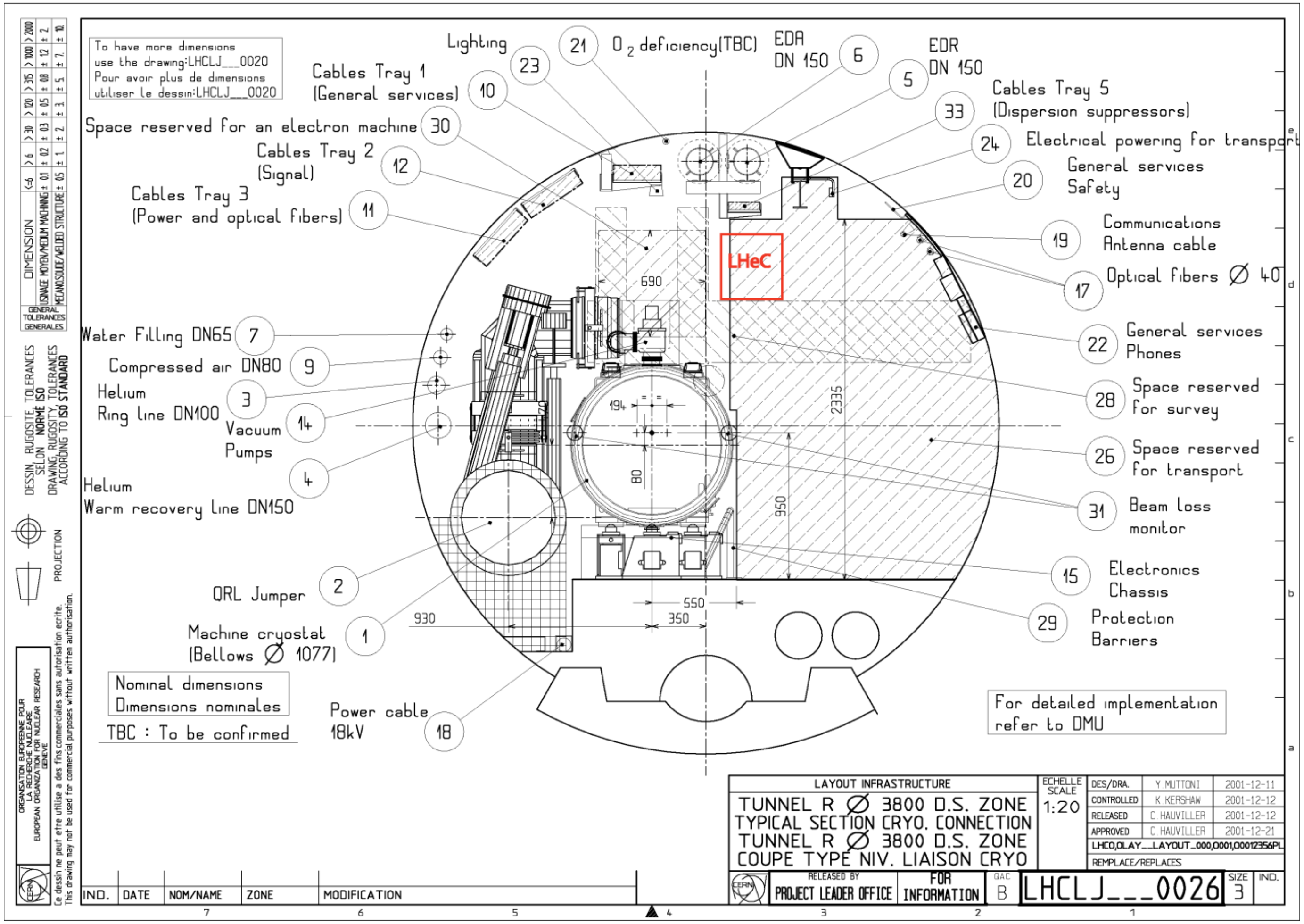
ca. 1.3 km long bypass

ca. 170m long dispersion free area for RF

CDR Choices: LHeC: Ring-Ring Option

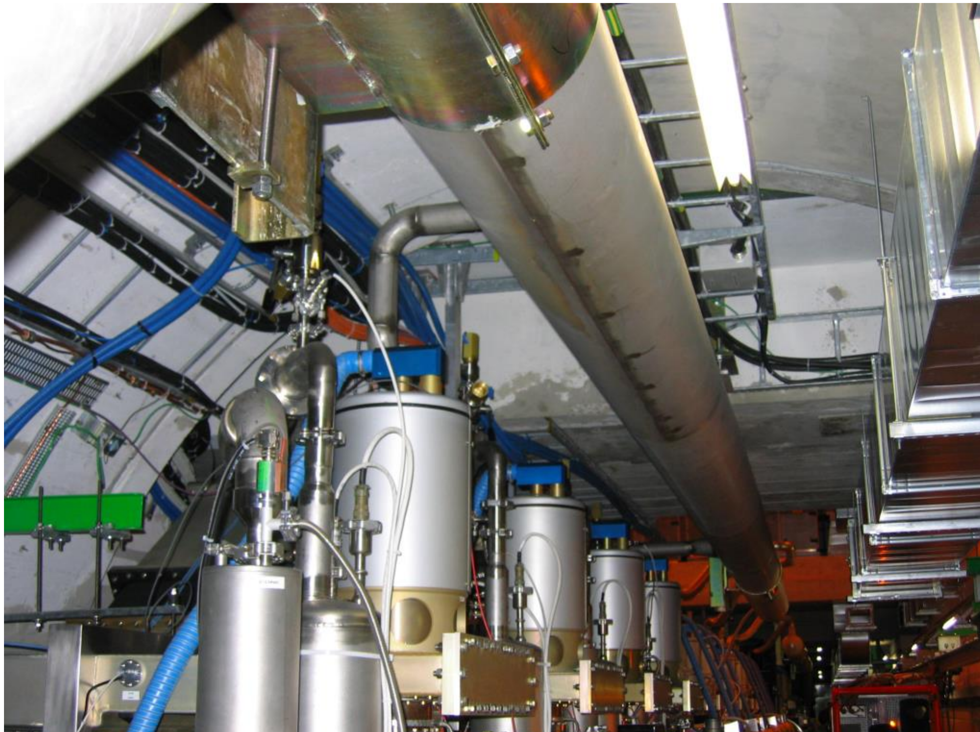
Challenge 3: Installation with LHC circumference:

requires: support structure with efficient montage and compact magnets

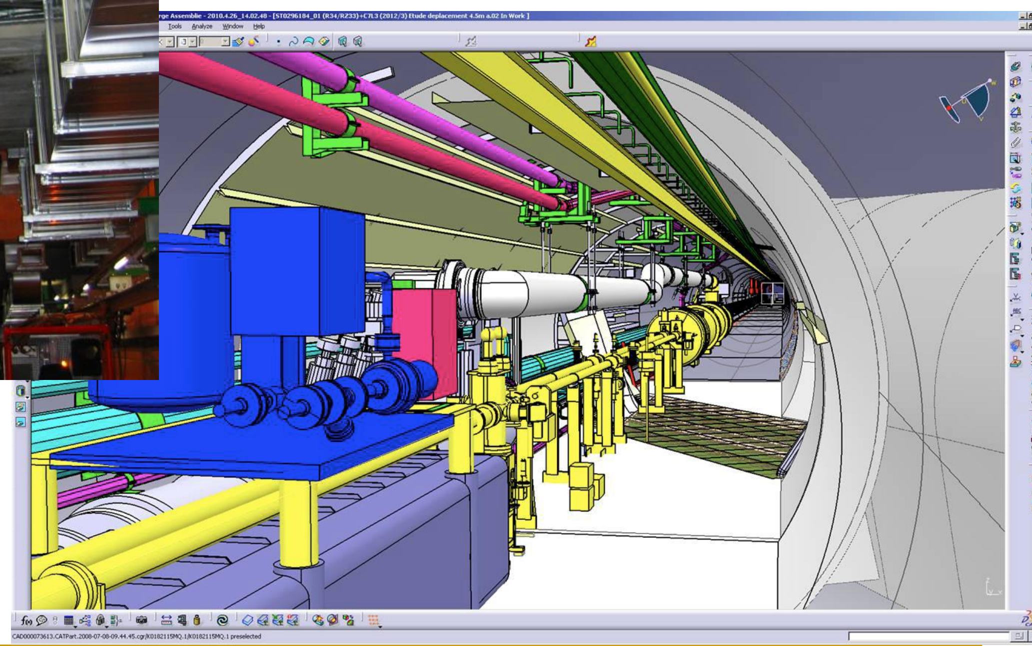


CDR Choices: LHeC: Ring-Ring Option

Challenge 2: Integration in the LHC tunnel

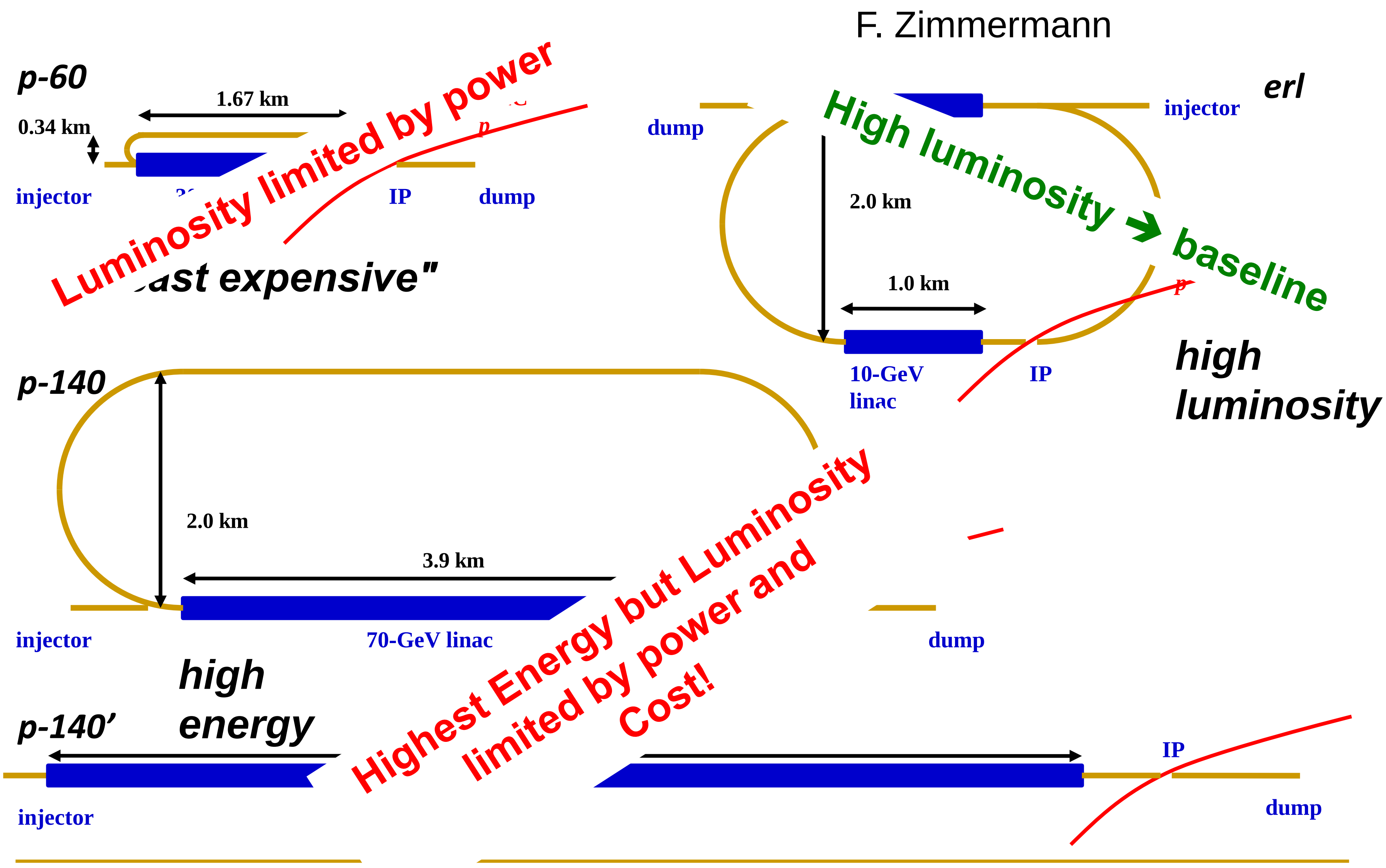


RF Installation in IR4



Cryo link in IR3

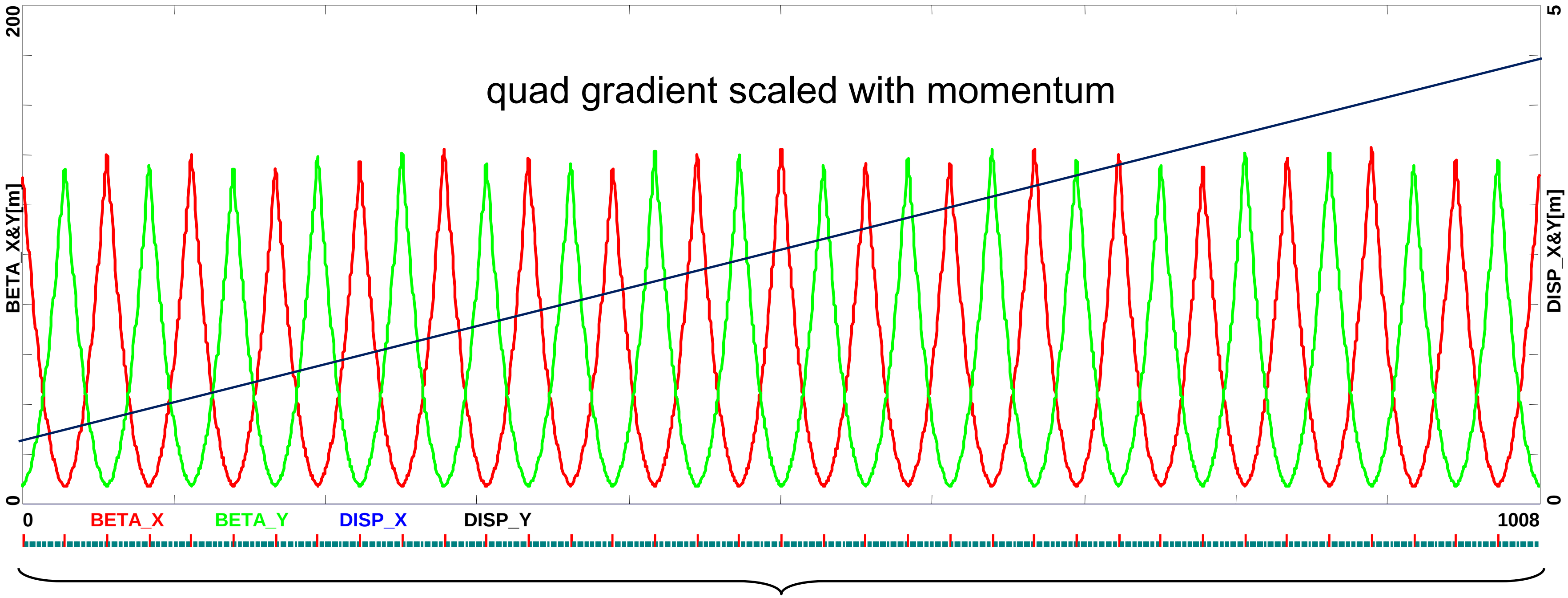
CDR Choices: various LR options



10 GeV Linac Optics - Focusing Profile

E = 0.5 – 10.5 GeV

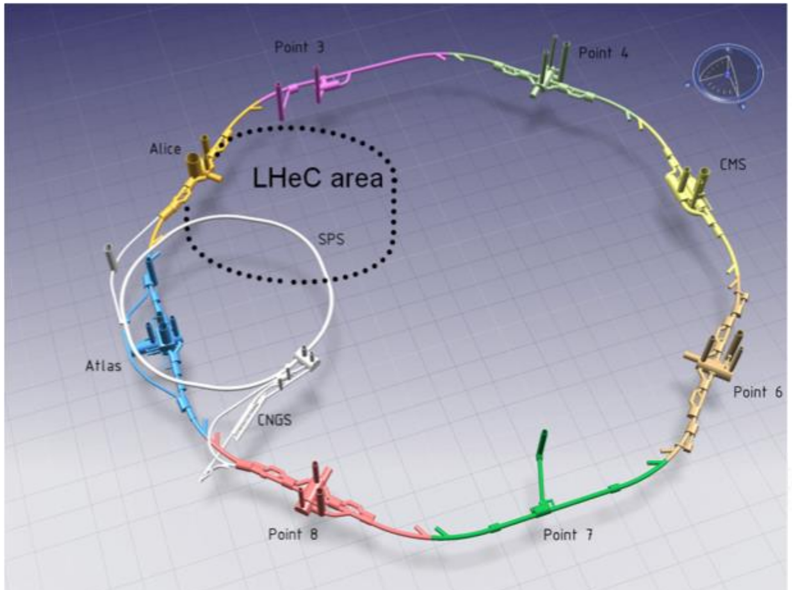
A. Bogaz (JLab) @ ERL2015, Stony Brook University, June 9, 2015

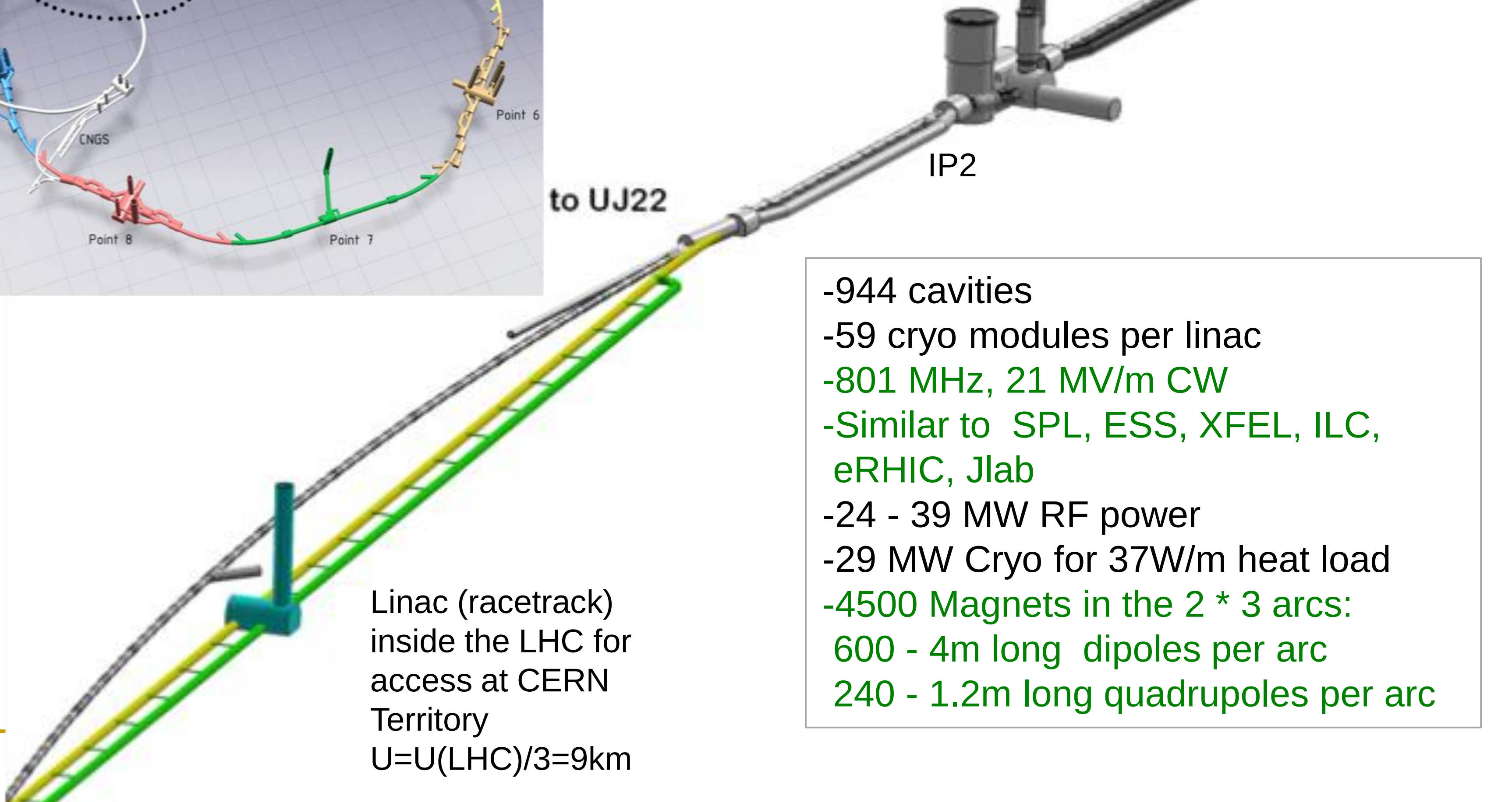


19 FODO cells (19 × 2 × 16 = 608 RF cavities)

$$\left\langle \frac{\beta}{E} \right\rangle = \left(\frac{1}{L} \int \frac{\beta}{E}\, ds \right)_{\min}$$

CDR Choices: ERL Footprint





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

- -944 cavities
- -59 cryo modules per linac
- -801 MHz, 21 MV/m CW
- -Similar to SPL, ESS, XFEL, ILC, eRHIC, Jlab
- -24 - 39 MW RF power
- -29 MW Cryo for 37W/m heat load
- -4500 Magnets in the 2 * 3 arcs:
  600 - 4m long dipoles per arc
  240 - 1.2m long quadrupoles per arc

LHeC: Motivation

- Physics:
  Details in presentations and by M. D'Onofrio and G. Altarelli
  LHeC: -Most powerful microscope
  -Electro-Weak High precision measurements
  -Higgs production with e-p collisions
  -Structure functions for precision physics with HL-LHC
  -Exploring the unknown @ the TeV scale
  -Unique possibility of an EIC @ the TeV scale
  Plus Test Facility applications : → E. Jensen
  - electron and photon physics with high precision
  (electromagnetic, weak, nuclear, BSM subjects)
  -SRF, SC magnets, Beam Instrumentation etc.

LHeC Motivation:

- Physics: -Most powerful microscope

  -Electroweak high precision measurements

  HL-LHC

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Technology Driver:

Unique opportunity for realizing a revolutionary accelerator concept with a manifold of potential applications!

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importance for energy efficient accelerators (ERL facility) and energy frontier (e.g. FCC eh) physics and new technical developments