FCC-eh Accelerator Studies and Considerations

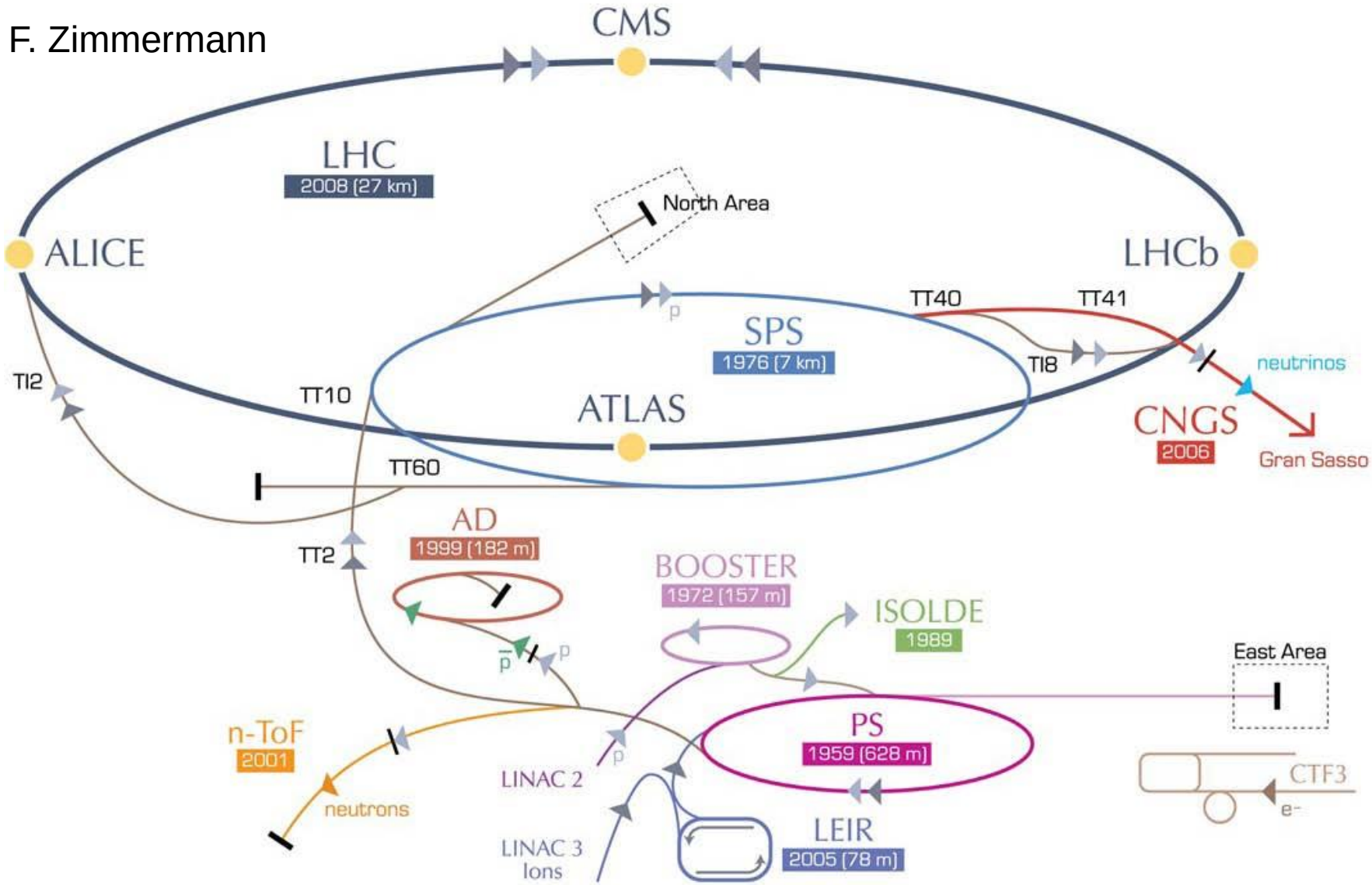
- Motivation -Physics: e-p and e-A physics program
  - -Full exploitation of LHC (and FCC) infrastructure
  - -Accelerator innovation and development (ERL)

- CDR Choices and Studies:
  - -Ring-Ring and Linac-Ring options ➔ ERL baseline
  - -Optics and layout: arc and IR
  - -Magnets: superconducting and normal conducting
  - -SRF Frequency choice
  - -Site options
  - -Simulations

- Summary

CDR Options for LHeC Infrastructure:

F. Zimmermann



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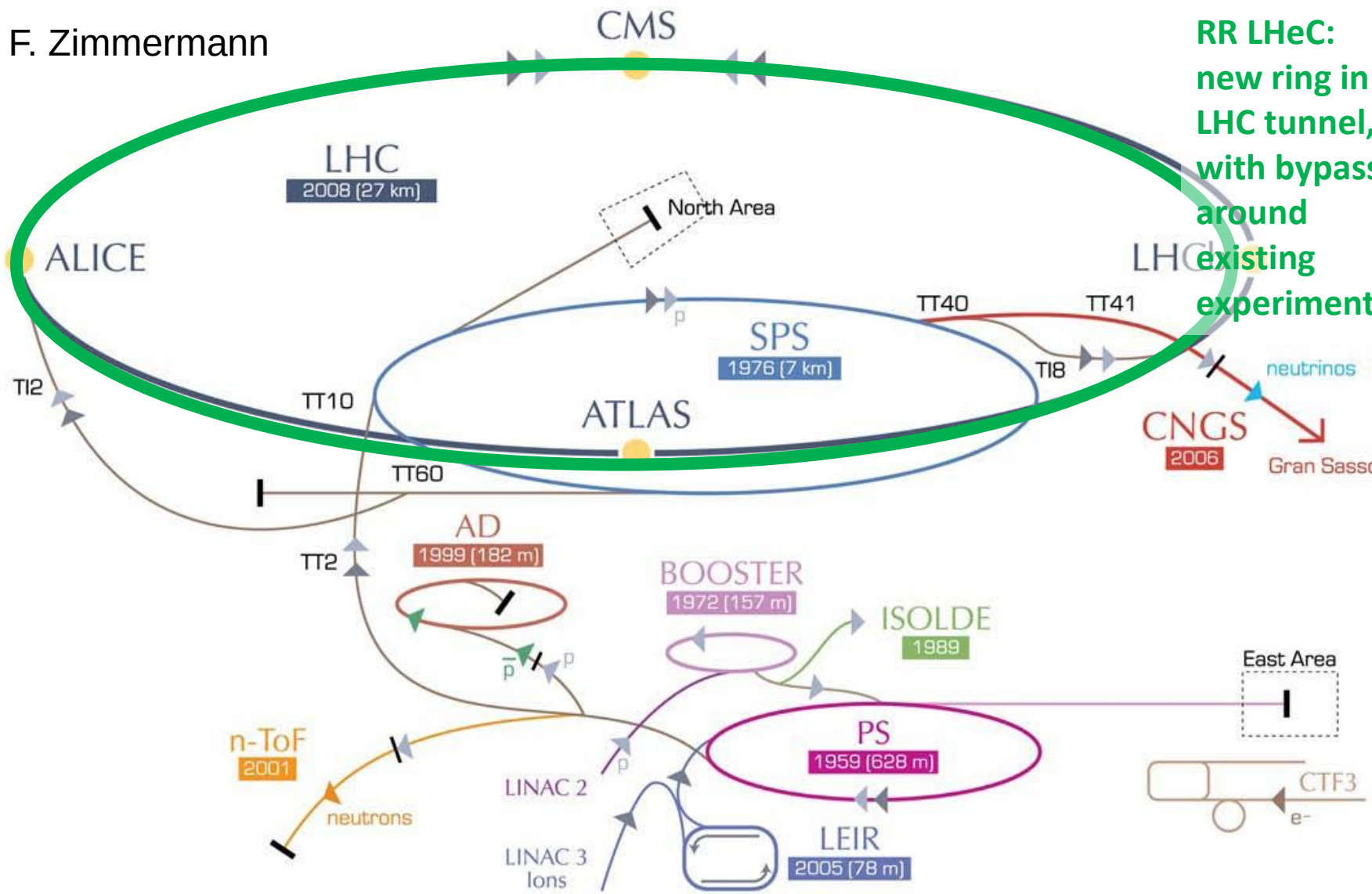
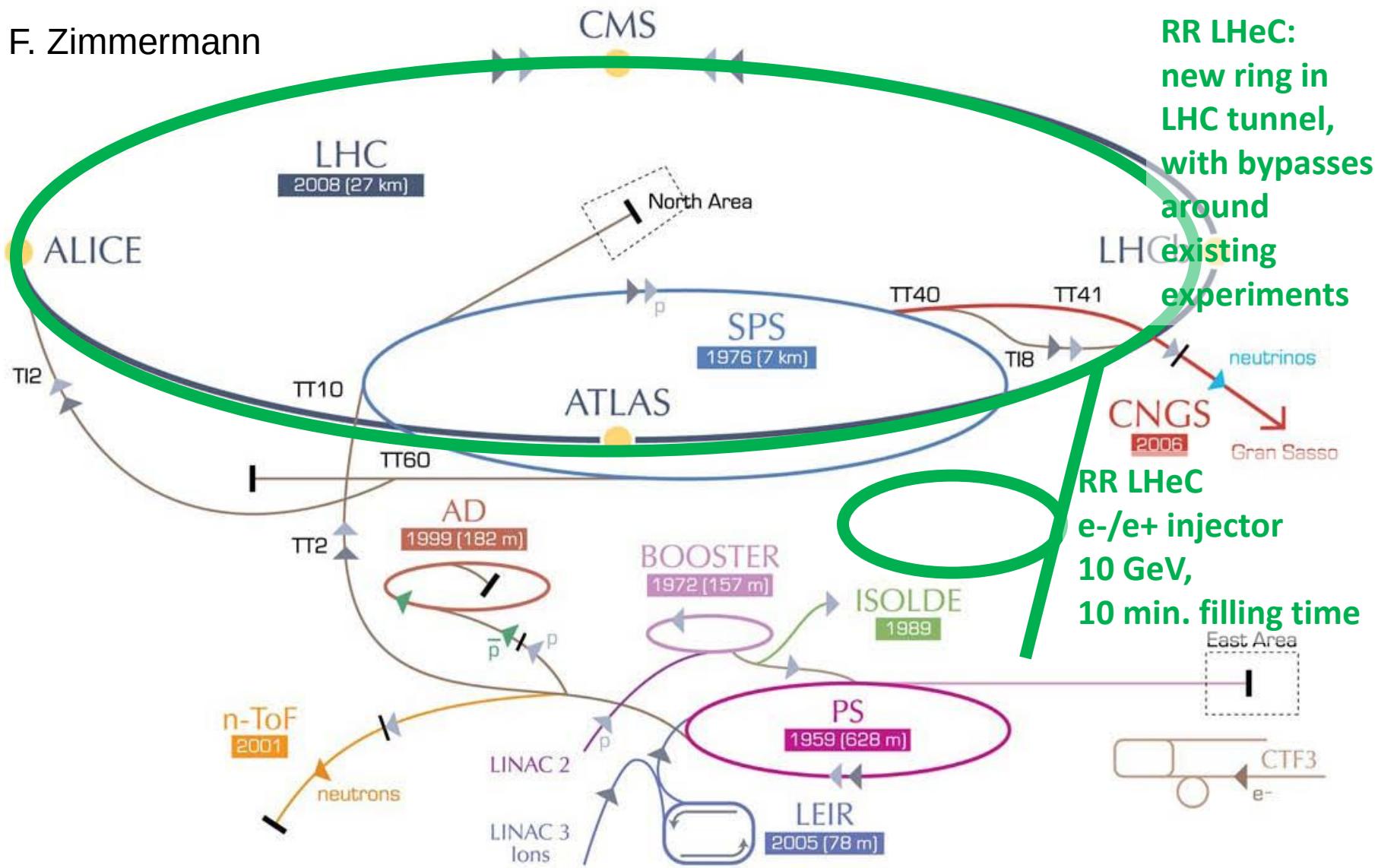


RR LHeC: new ring in LHC tunnel, with bypasses around existing experiments

CDR Options for LHeC Infrastructure:

F. Zimmermann



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RR LHeC e-/e+ injector 10 GeV, 10 min. filling time

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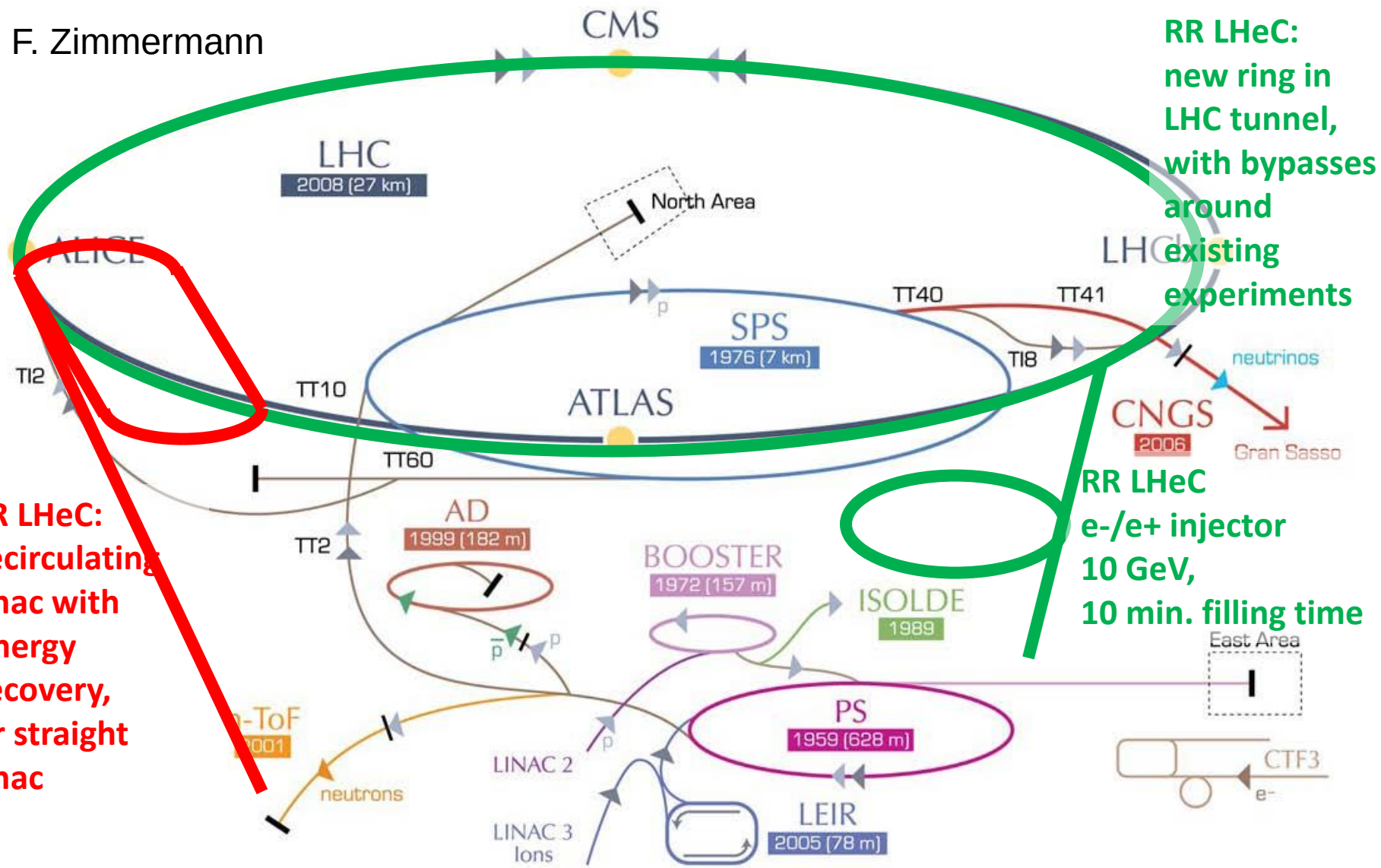


RR LHeC: new ring in LHC tunnel, with bypasses around existing experiments

RR LHeC e-/e+ injector 10 GeV, 10 min. filling time

LR LHeC: recirculating linac with energy recovery, or straight linac

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

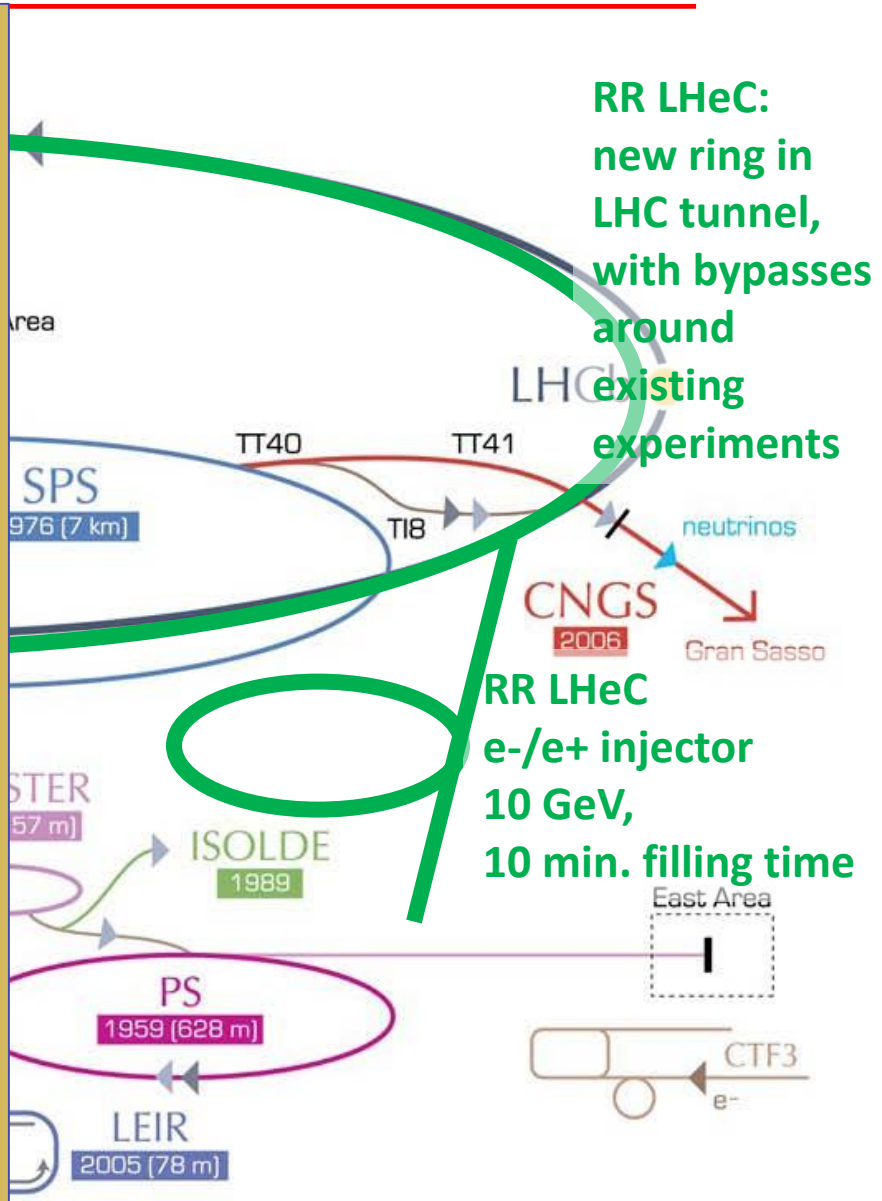
➔ (beam & SR power < 70 MW)

➔ 60 GeV beam energy

-Int. Luminosity > 100 * HERA

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

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



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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

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 ✕

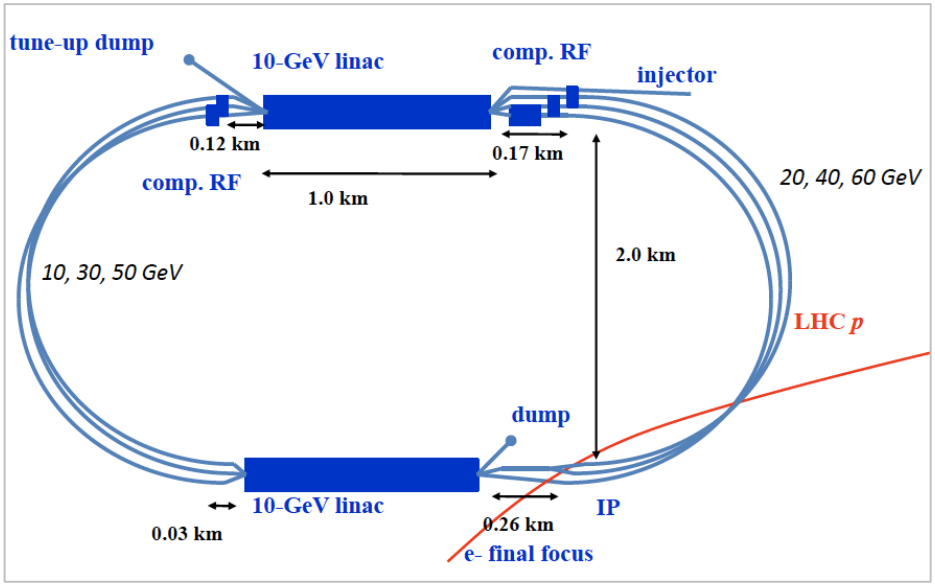
➔ Recirculating Linac with Energy Recovery Mode (ERL) ✓

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

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 3 decelerating passes in CW operation

➔ SRF sees 6*current at the IP (≈ 4ns spacing)

➔ $Q_0 = 10^{10}$ requires cryogenic system comparable to LHC system! $Q_0 > 10^{10}$

➔ 944 cavities; 59 cryo modules per linac

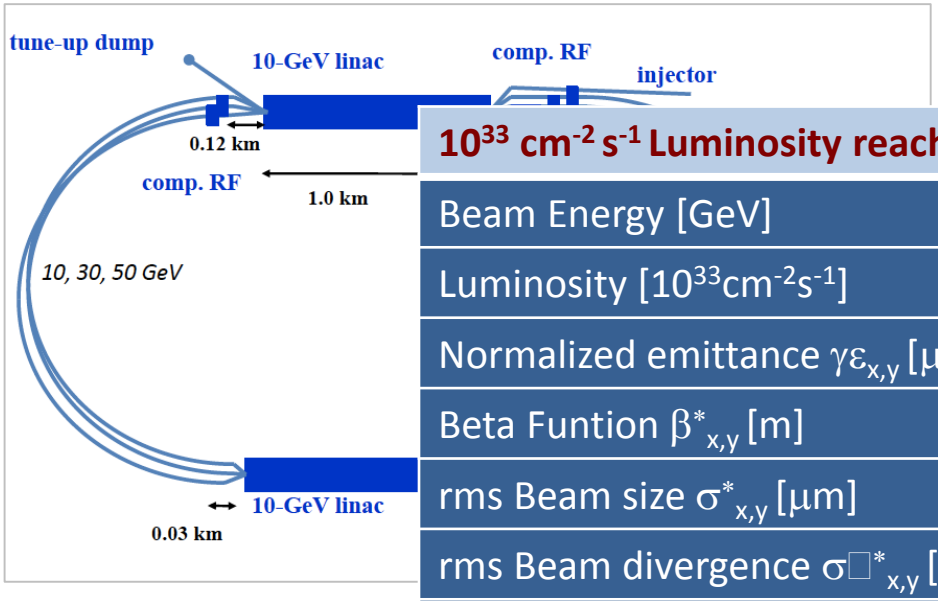
➔ ca. 9 km underground tunnel installation

➔ more than 4500 magnets (same magnet design as for RR option)

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^{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 $\sigma\square^*_{x,y}$ [μrad]	70	58
Beam Current @ IP [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

➔ 944 cavities; 59 cr

➔ ca. 9 km undergro

➔ more than 4500 m

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

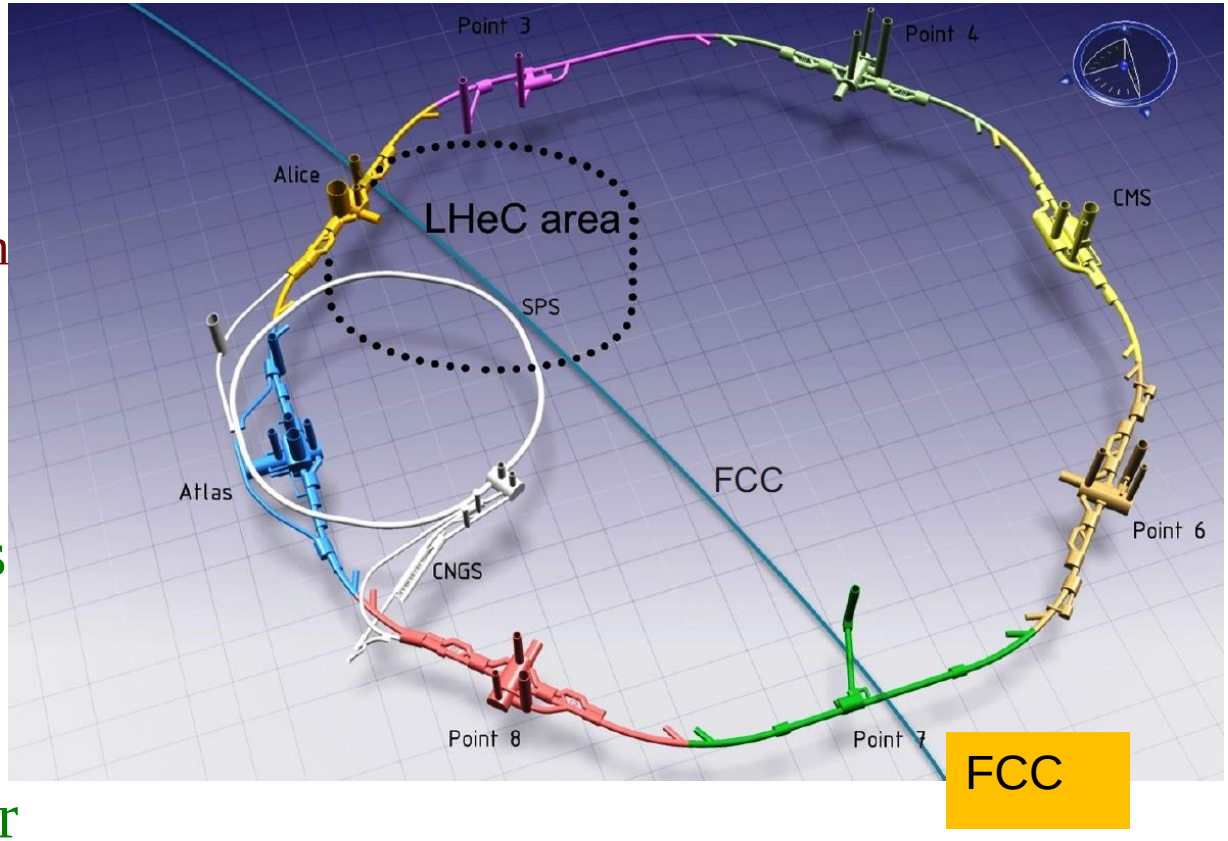
10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60	7000	60
Luminosity [10^{33}cm^{-2}s^{-1}]	16	16	1	1
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20	3.75	50
Beta Funtion $\beta^*_{x,y}$ [m]	0.05	0.10	0.1	0.12
rms Beam size $\sigma^*_{x,y}$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

LHeC in the Context of FCC:

- Various applications:

John Osborne @ 2014 FCC Kick-off meeting

- ➔ LHeC could operate parallel to HL-LHC
  - ➔ PDFs; preparation for FCC-hh
- ➔ ERL could potentially provide collisions with FCC-hh
- ➔ ERL could operate as injector for FCC-ee



CDR Choices: Technology and Design

Optics:

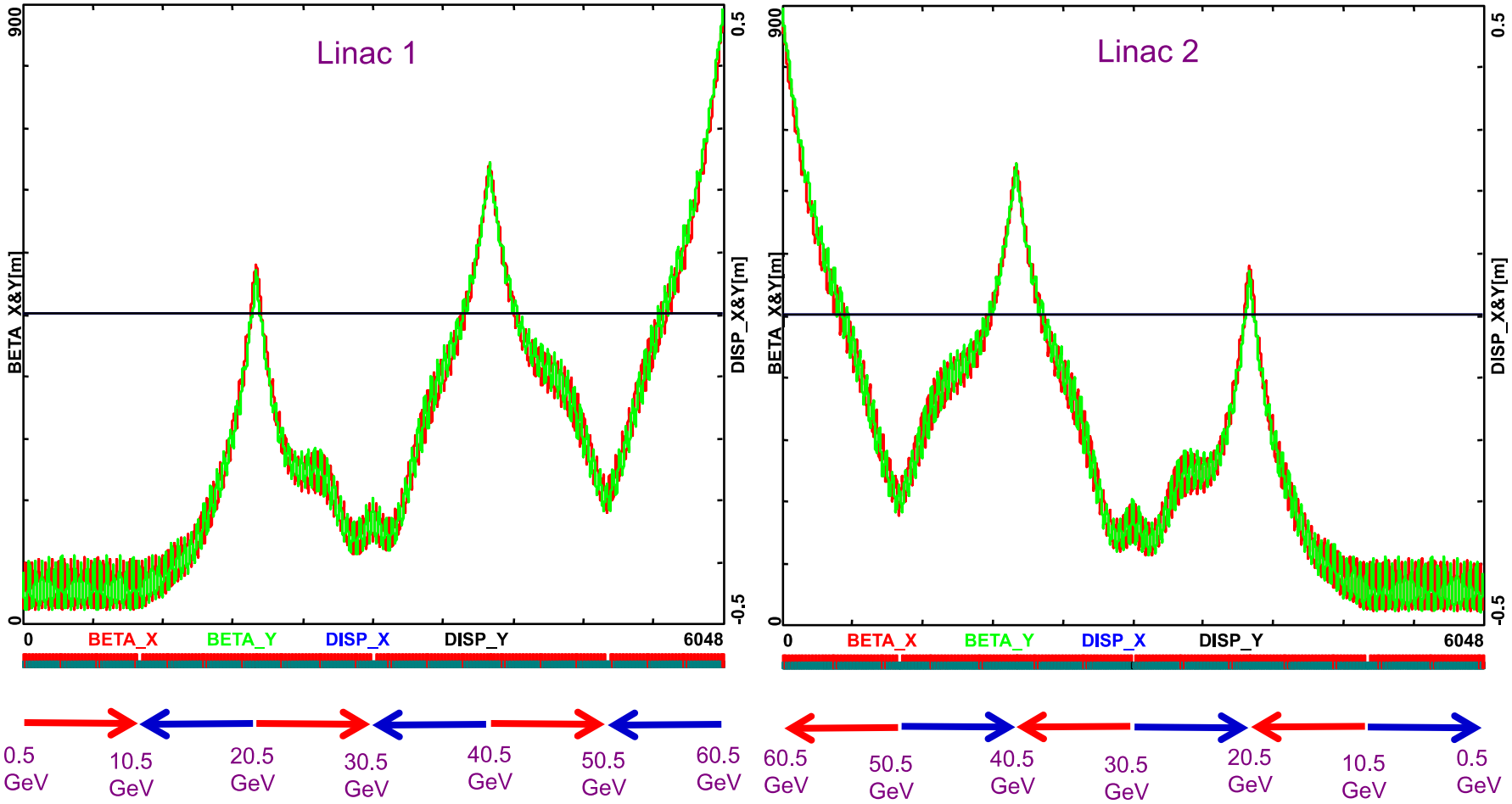
-SRF Linac with quadrupoles between the cryo modules

-Flexible Momentum Compaction [FMC] arc optics

Linac 1 and 2 – Multi-pass ER Optics

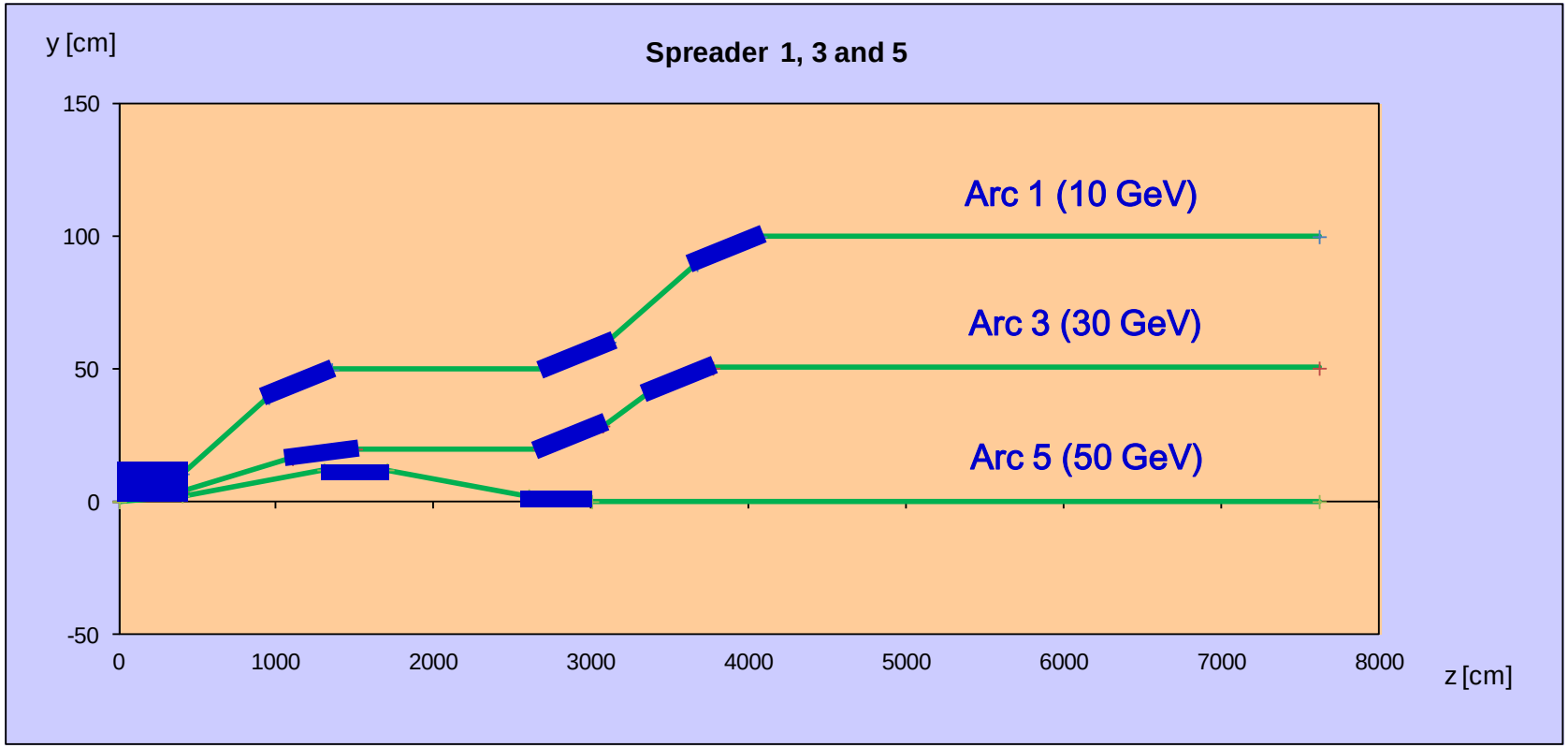
A. Bogacz (JLab) @ ERL2015, Stony Brook University, June 9, 2015

Acceleration/Deceleration



Vertical Separation of the Three 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

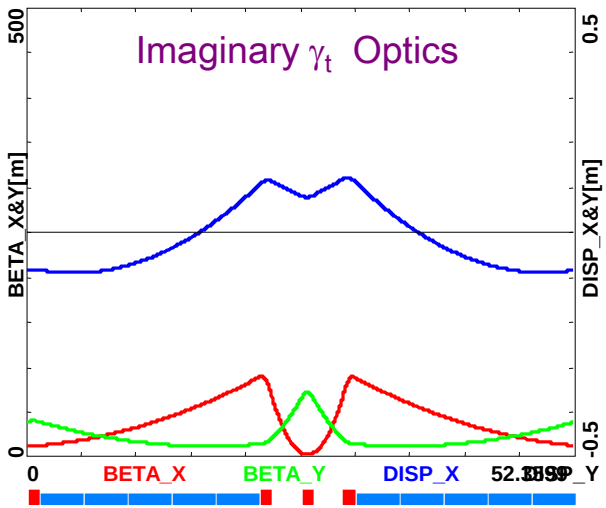
- Emittance dilution due to quantum excitations:

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

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

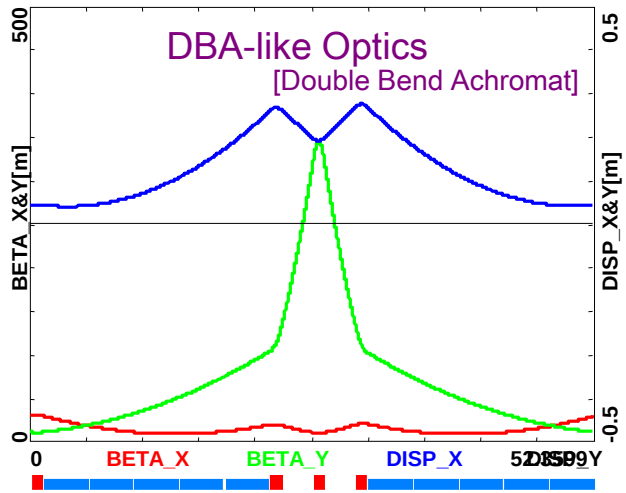
$$H = \gamma D^2 + 2\alpha DD' + \beta D'^2$$

Arc 1 , Arc2



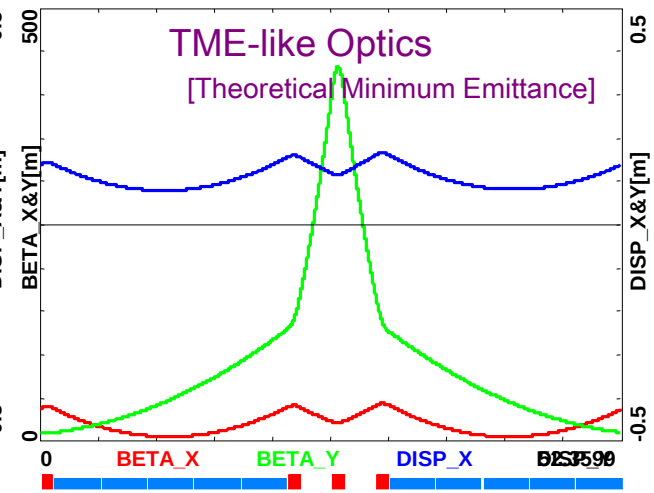
$$\langle H \rangle = 8.8 \times 10^{-3}\ m$$

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: $\Delta\varepsilon_x^N$ = 4.9 μm rad

CDR Choices: Technology and Design

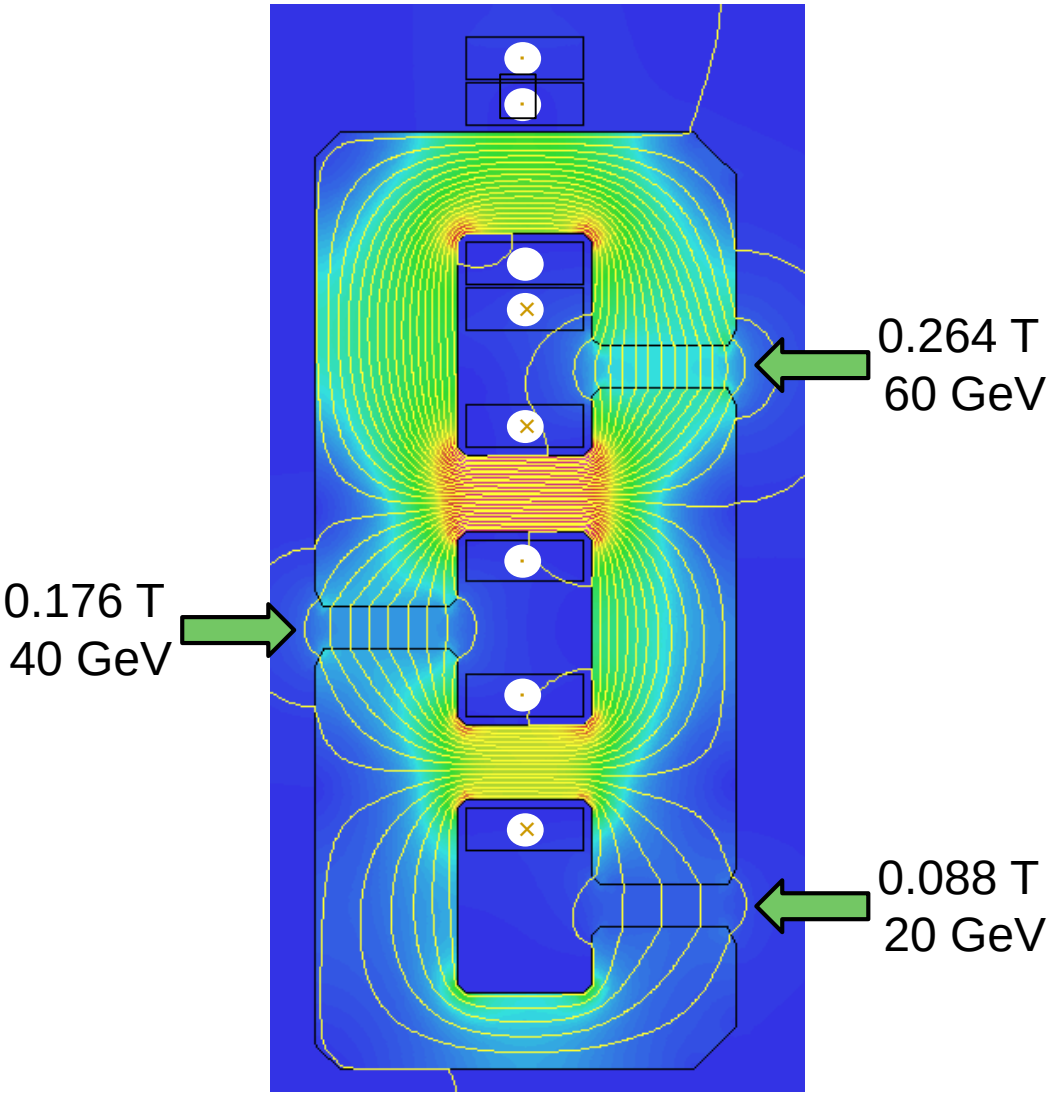
Magnets:

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

➔ light and low cost normal conducting arc magnets

-IR design ➔ SC magnet magnet requirements

Post CDR: Return Arc Dipoles optimization

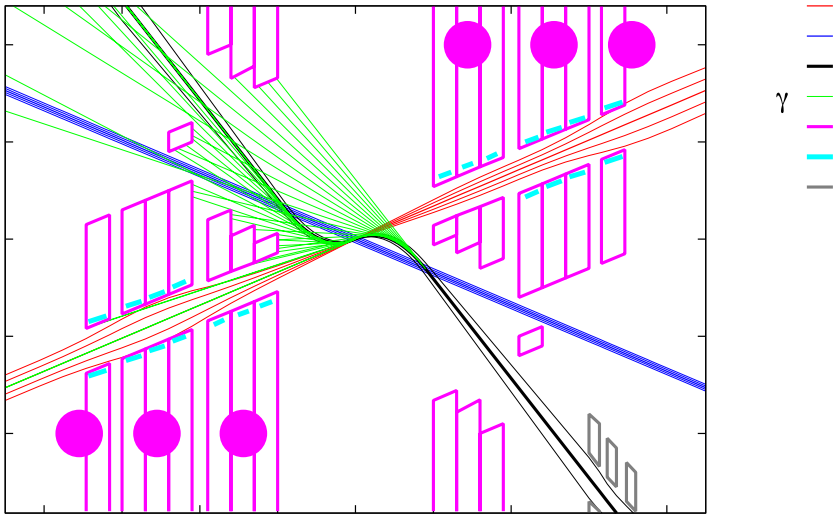


Attilio Milanese

Alternative coil arrangement

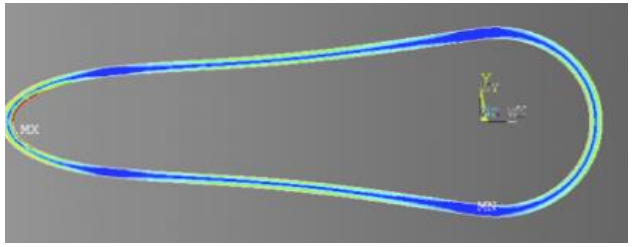
- keep the idea of recycling Ampere-turns
- stack the apertures vertically but offset them also transversally
- same vertical gap, 25 mm
- simple coils / bus-bars, same powering circuit
- as before, trim coils can be added for two of the apertures, to give some tuning

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

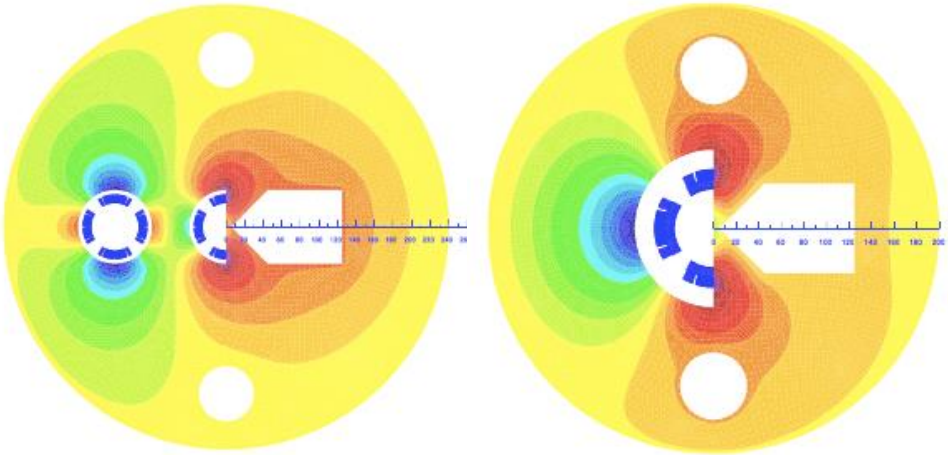


S. Russenschuck

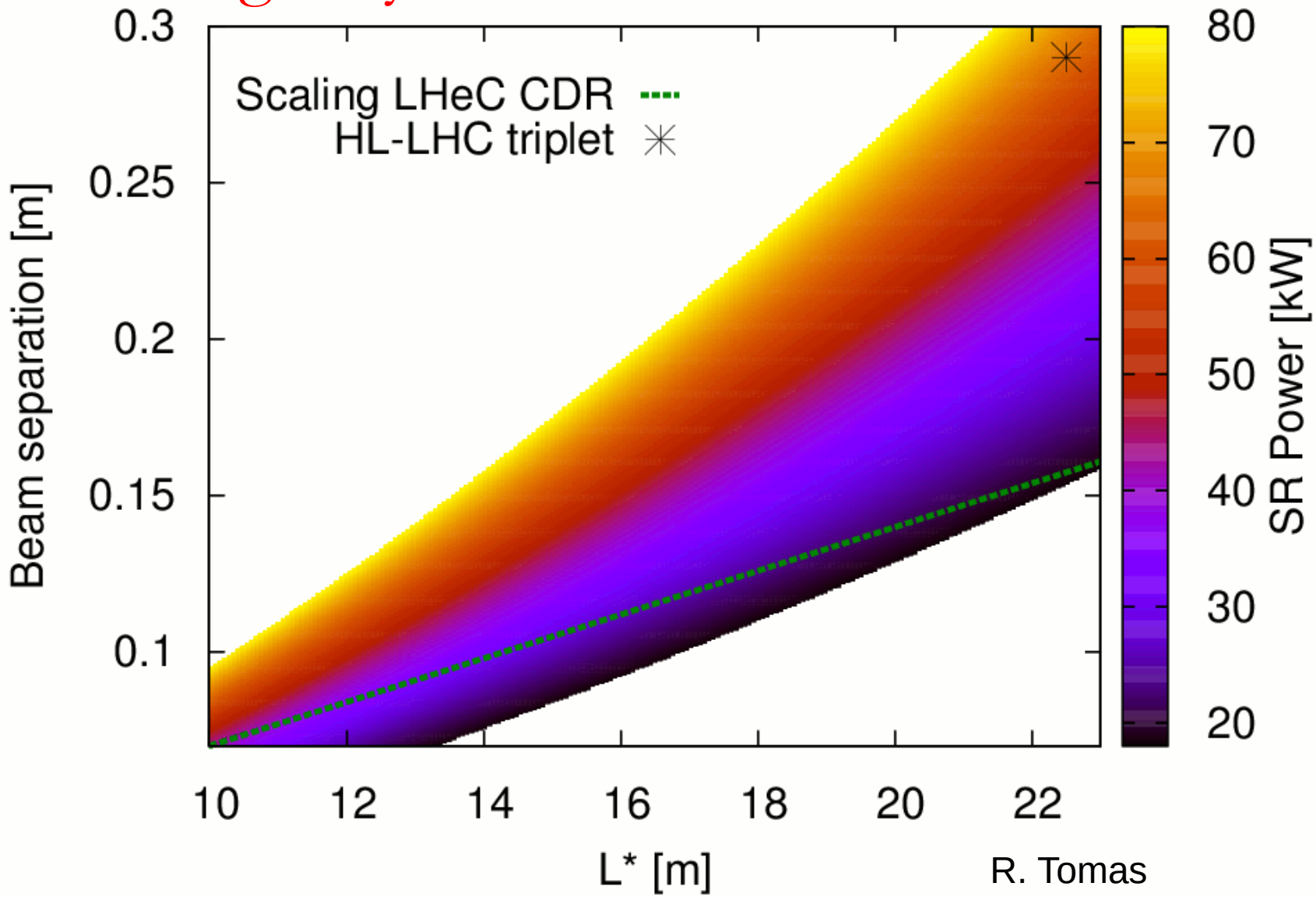
Have optics compatible with HL-LHC ATS optics and β*=0.1m
Head-on collisions mandatory →
High synchrotron radiation load, dipole in detector

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



R. Tomas

CDR Choices: Technology Choices and Design:

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

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

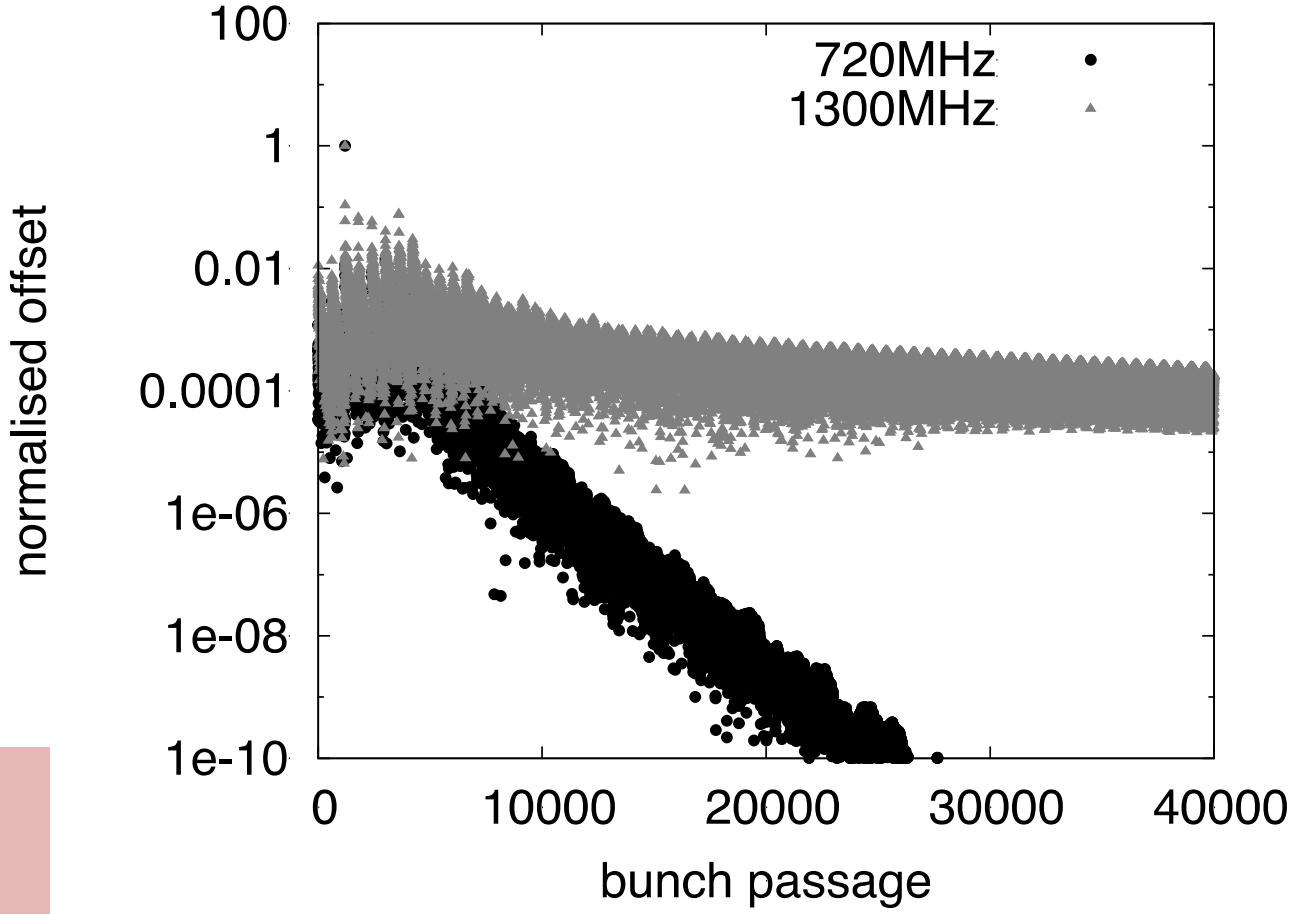
Beam-Beam effects:

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



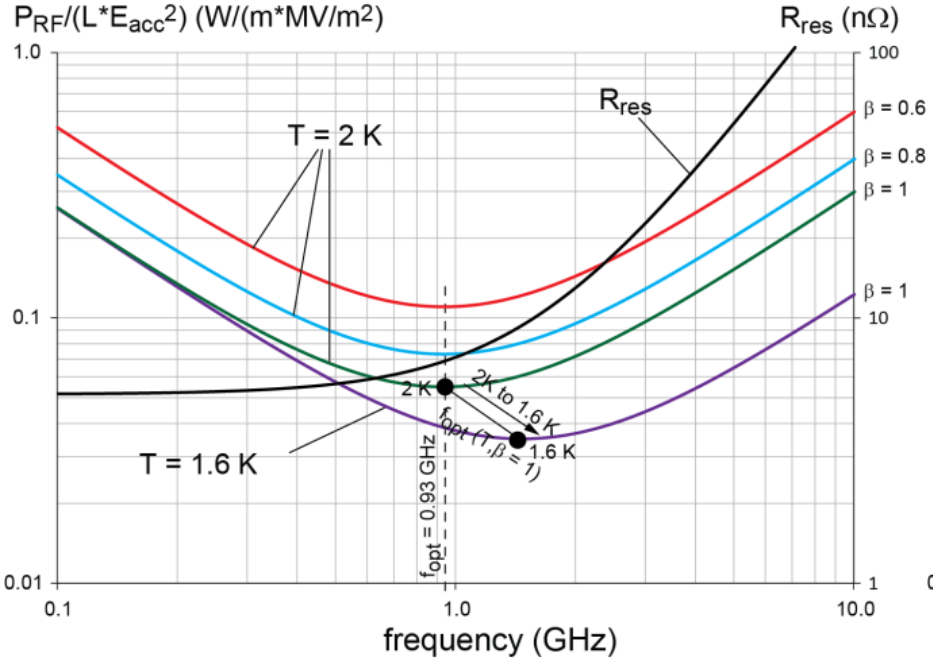
Beam is stable but very small margin with 1.3GHz cavity ➔ lower frequency

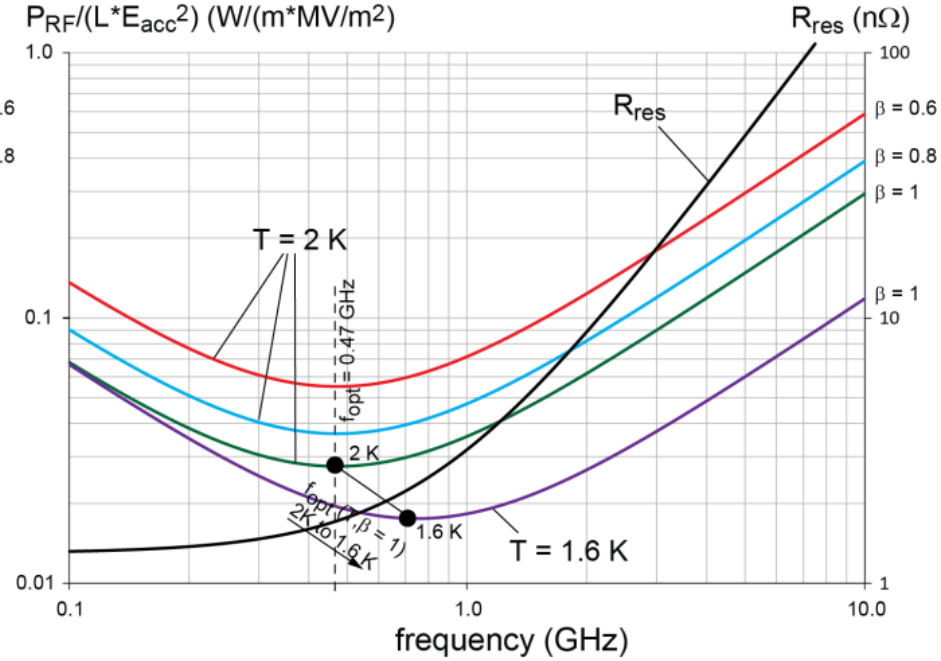
➔ Optimum choice for LHeC RF frequency?

Optimum RF Frequency: Power Considerations

Results from F. Marhauser

Erk Jensen at Daresbury meeting 12 March 2013





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

Optimum RF Frequency: Power Considerations

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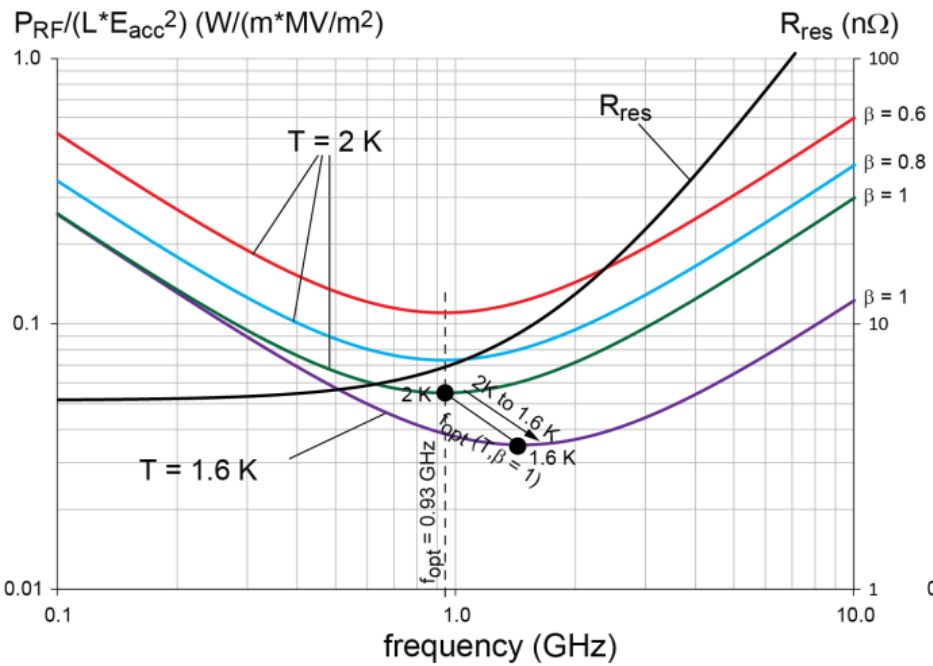

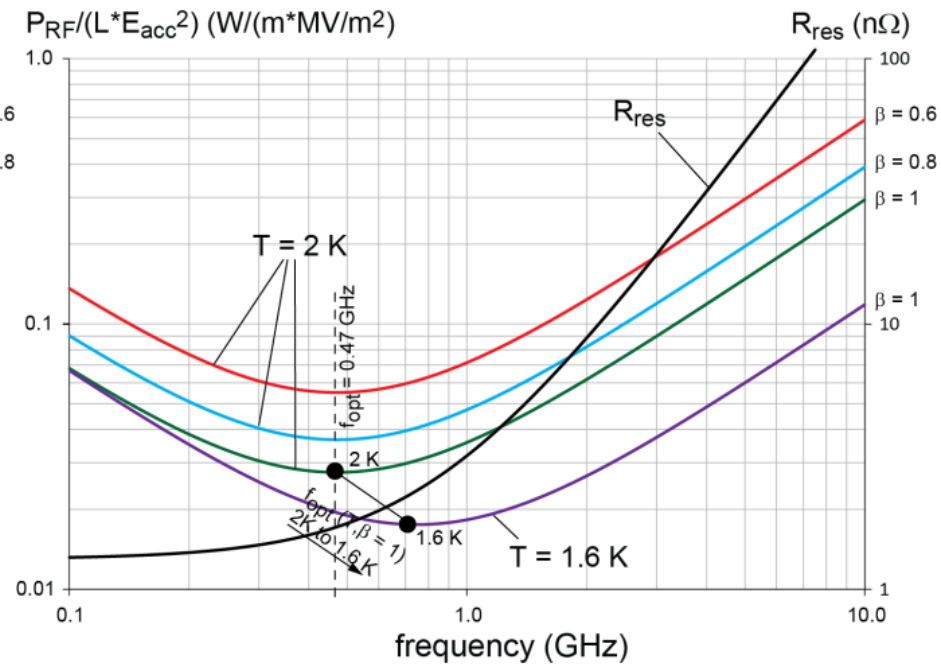

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Optimum RF Frequency: Power Considerations

Results from F. Marhauser

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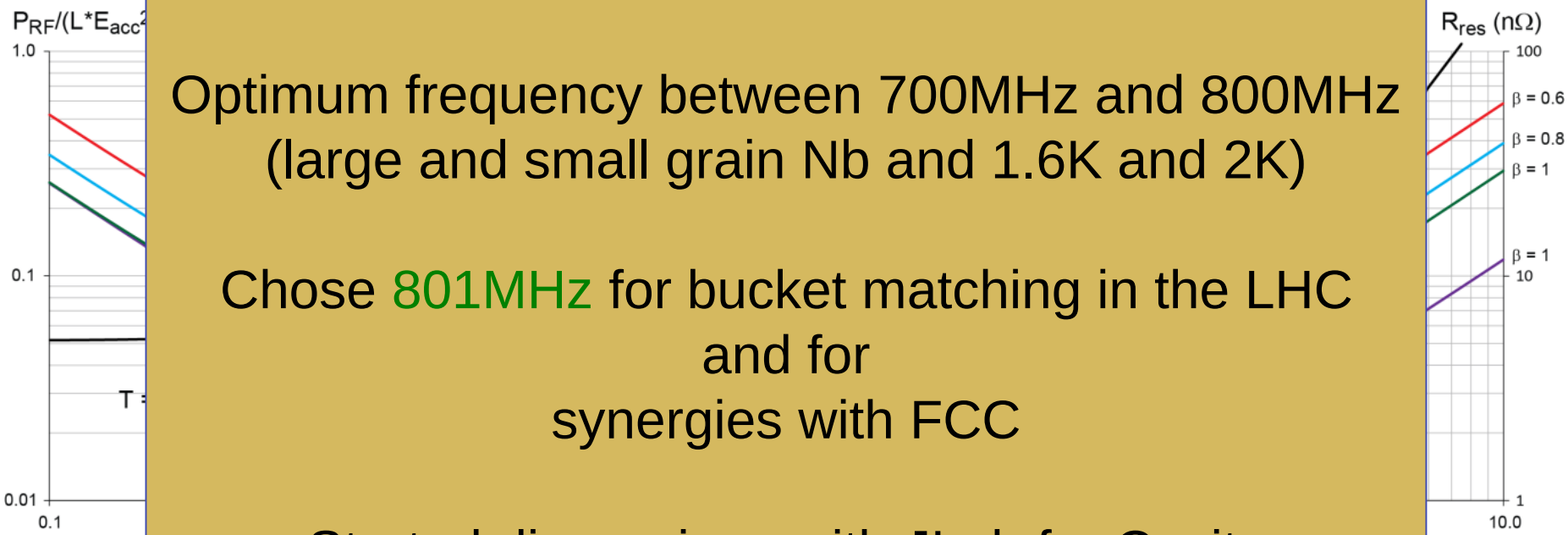

Optimum frequency between 700MHz and 800MHz (large and small grain Nb and 1.6K and 2K)

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

Started discussions with JLab for Cavity construction in Washington 2015 ➔ collaboration contract under signature under the FCC umbrella

Sma
Opti
700
Low
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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

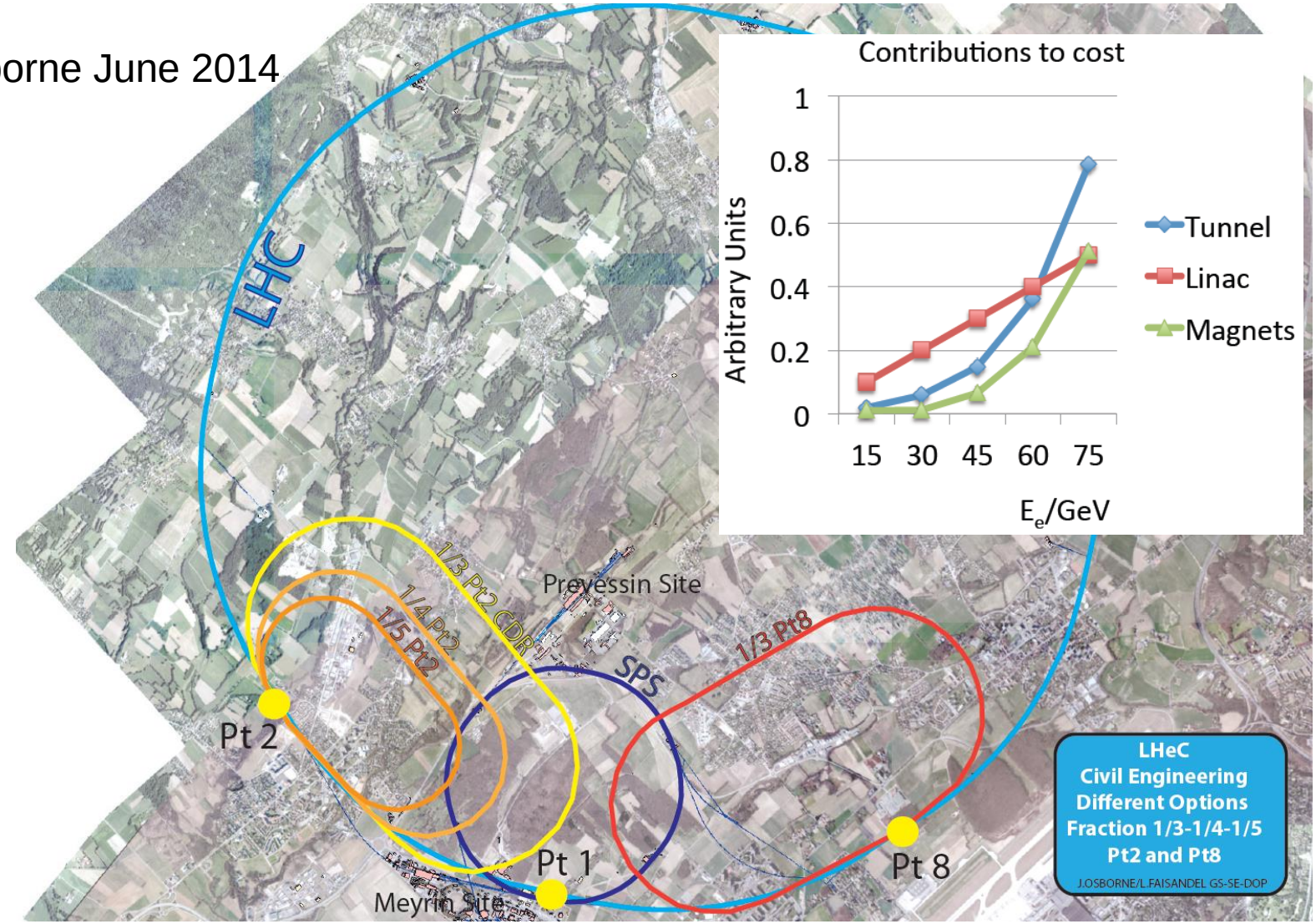
-IR3 and IR7 have no caverns and are excluded due to the LHC collimation system

-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 finished

Site Considerations:

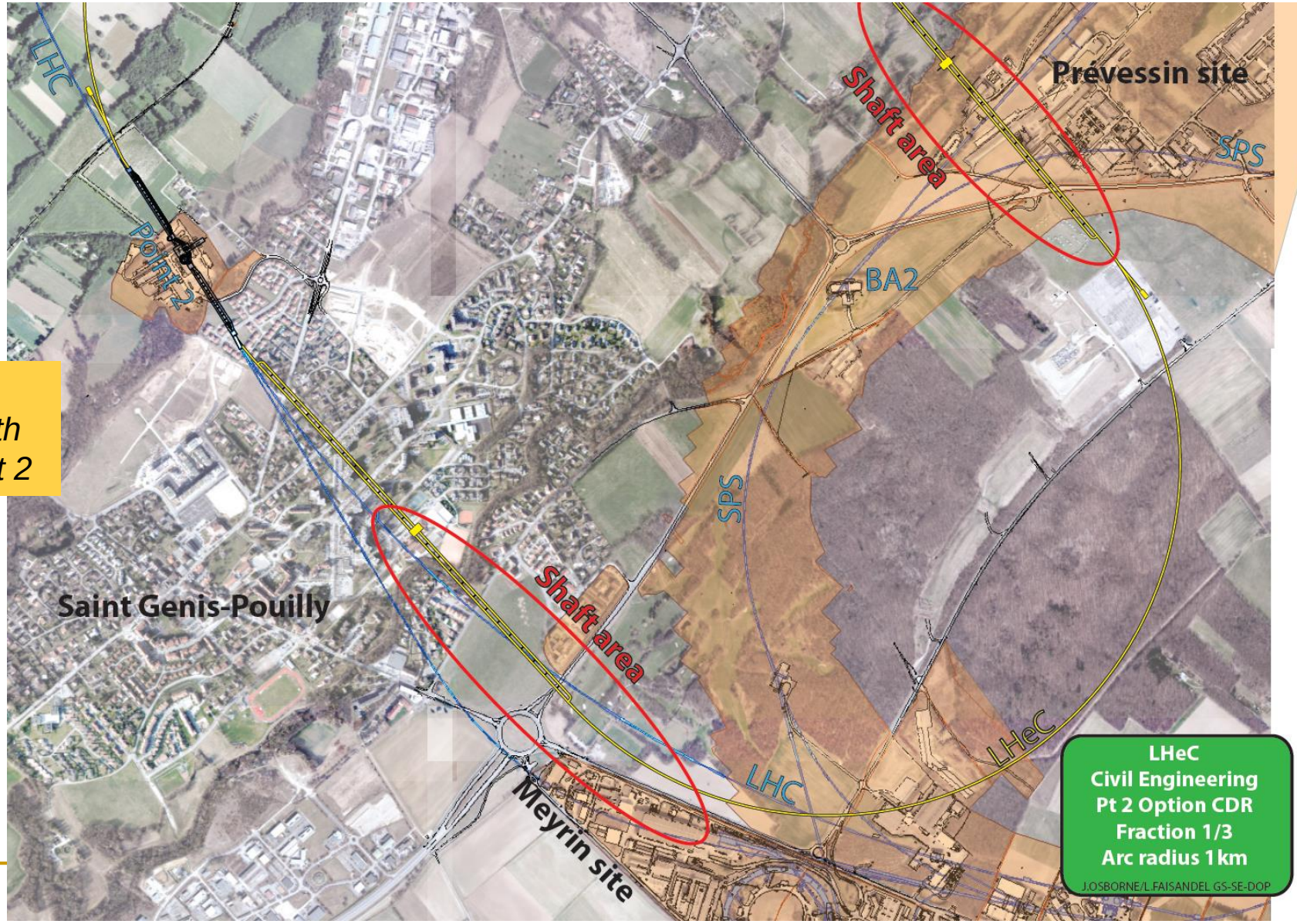
John Osborne June 2014



Site Considerations: IR2

John Osborne June 2014

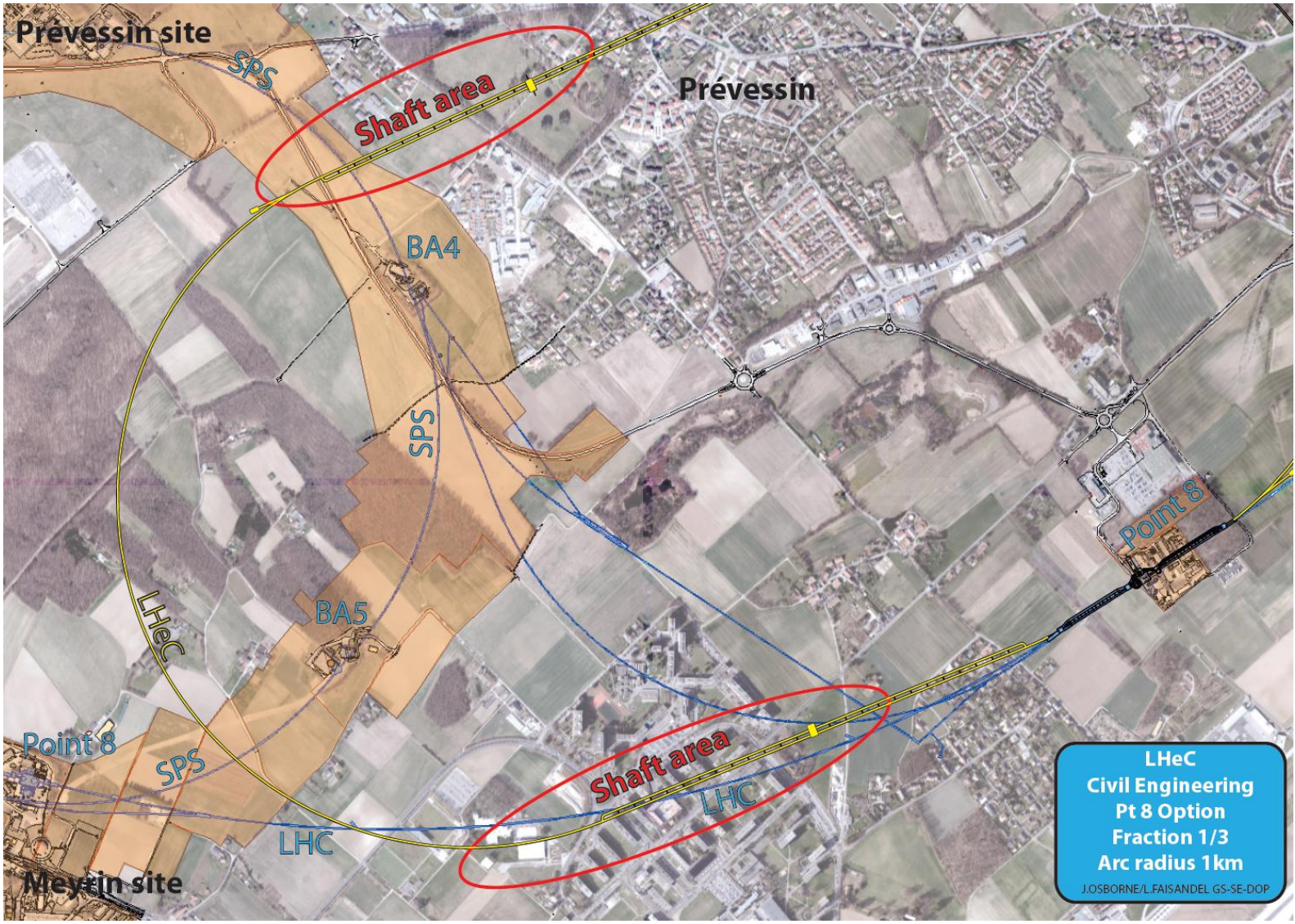
CDR-like 60GeV with IR at Point 2



Site Considerations: IR8

John Osborne June 2014

CDR-like 60GeV with IR at Point 8



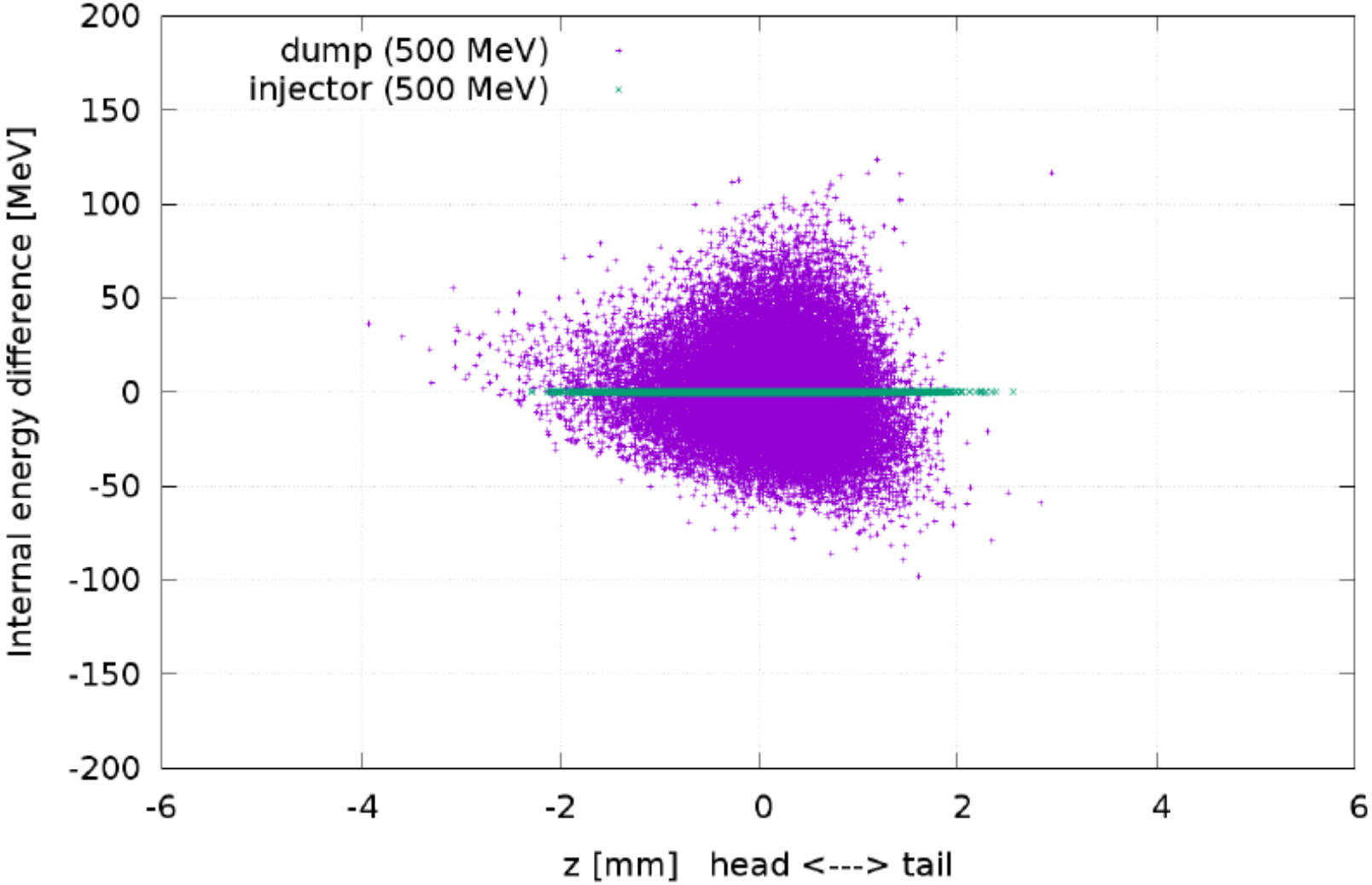
Beam Dynamics and 'front-end' Simulations:

- 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

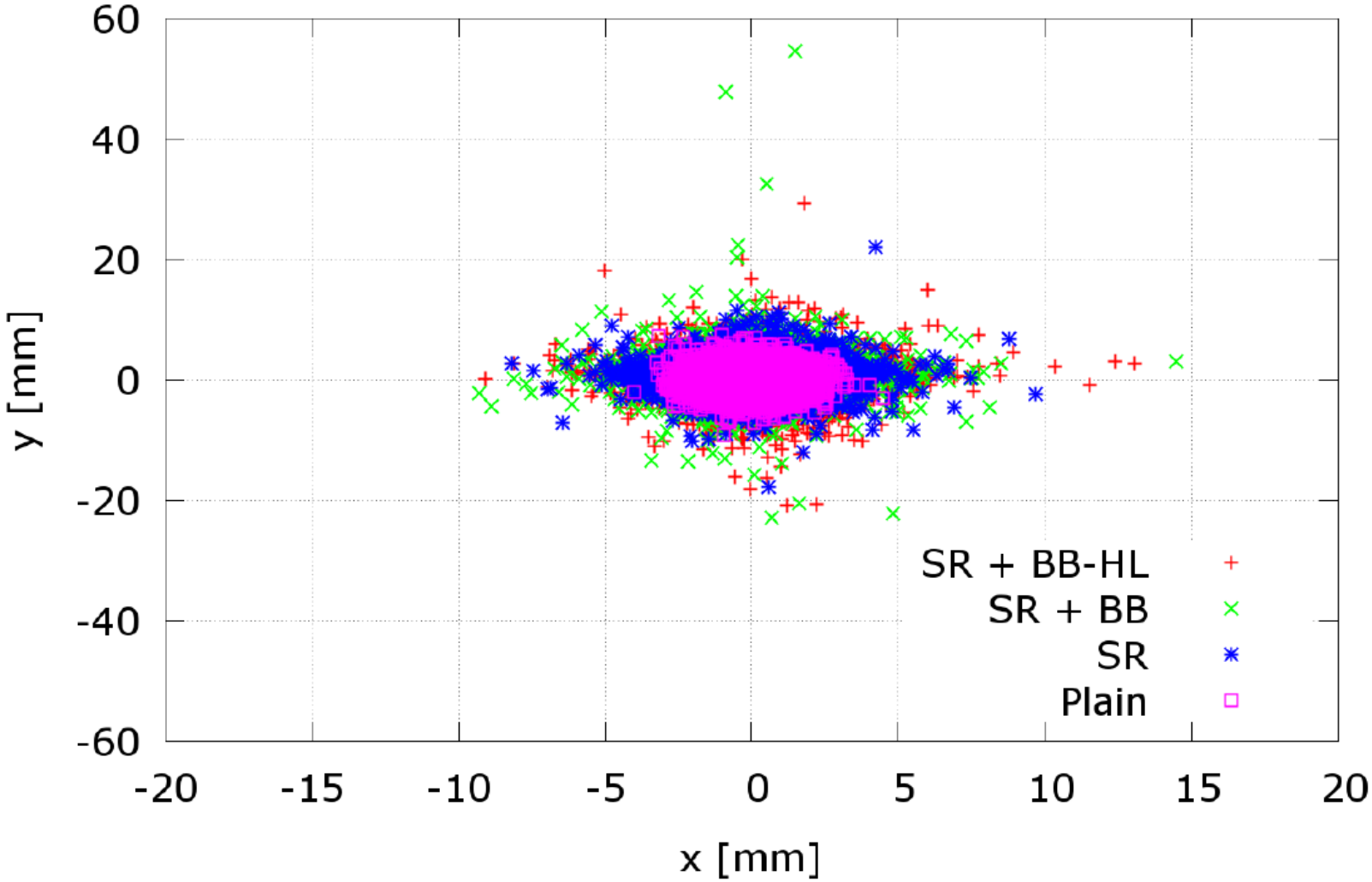
D. Pellegrini (EPFL/CERN) @ ERL'15



Synchrotron Radiation and Beam-Beam

Transverse Plane at Dump

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



Aperture radius of the SPL cavity is 40 mm.

ERL Demonstrator for LHeC:

Auxiliary applications:

-A test setup presents a unique infrastructure on its own

- ➔ Could eventually serve as injector for the LHeC
- ➔ Launched early on discussions with other potential clients

-Interesting auxiliary applications beyond LHeC:

- ➔ SC magnet and cable development: quench tests with beam
- ➔ Generic SC RF development: Cavity tests with beam
  - ➔ relevant for any SC RF development (CC in SPS)
- ➔ Test facility for Beam Diagnostics (after closure of CTF3)
- ➔ Detector component tests?
- ➔ Physics applications (electron and photon beam via Compton)

ERL Demonstrator for LHeC:

- Parameter choices for LHeC demonstration:

  -3 re-circulations

  -Beam current of at least 10mA

  -Use of LHeC proto-type SC RF Cryomodule

  -Beam energy of approximately 1 GeV (chosen for physics)

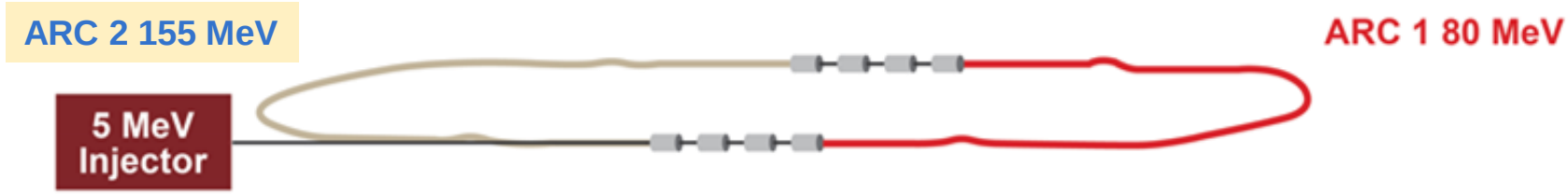
  -Sufficient space and infrastructure for SC magnet tests

  With a photo-injector the facility could test a range of RF frequencies [E. Jensen]

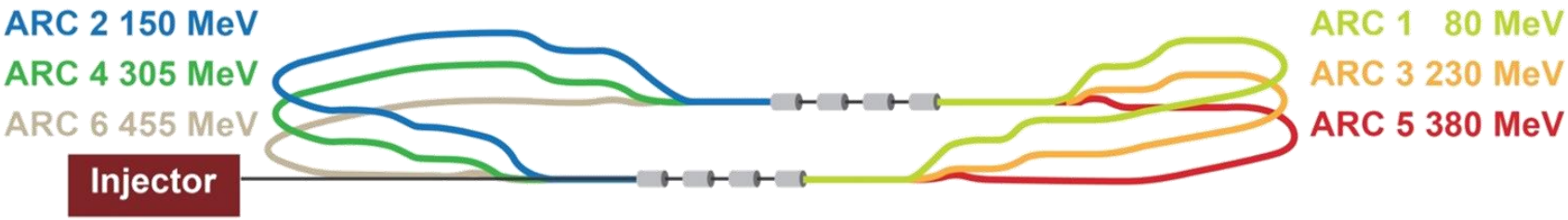
  -Staged implementation to build up expertize in steps and to tailor facility to different applications and tests

Staged Installation

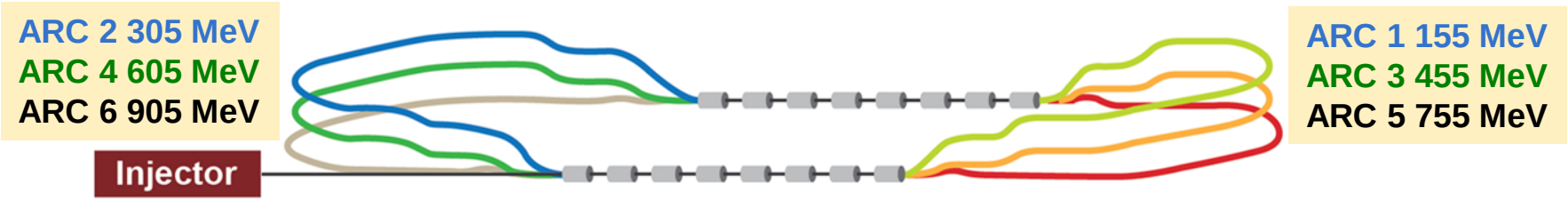
Stage 1 – 2 CMs, test installation – injector, cavities, beam dump.



Stage 2 – 2 CMs, set up for energy recovery, 2…3 passes



Stage 3 – 4 CMs, set up arcs for higher energies – reach up to 905 MeV

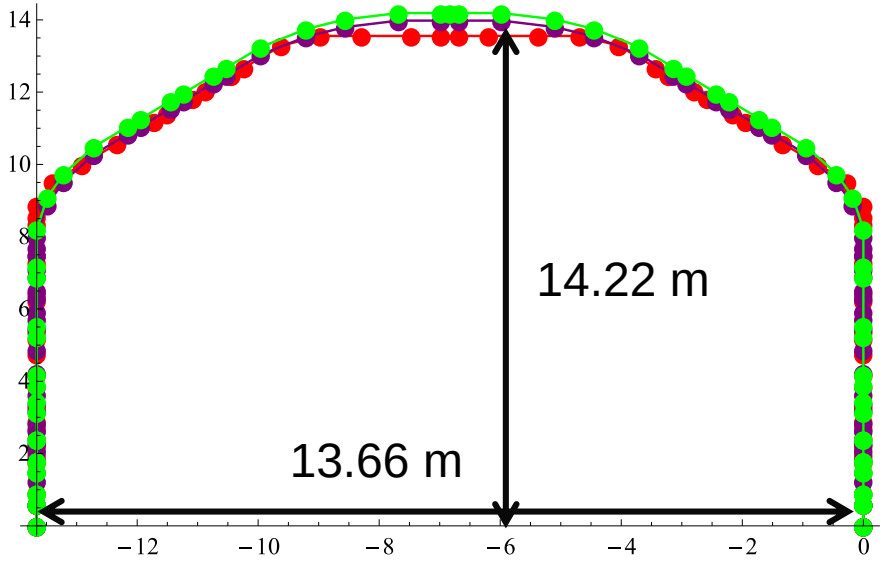


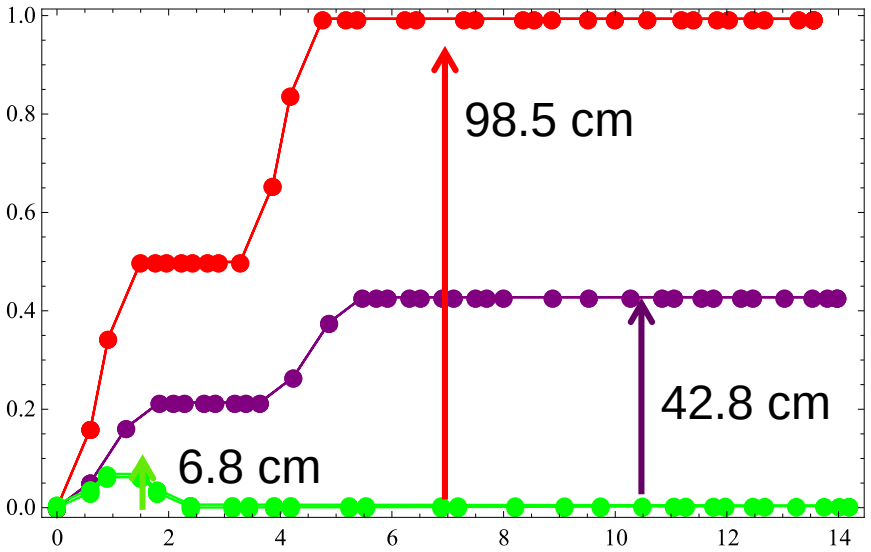
PERLE Parameters: CDR by 2016:

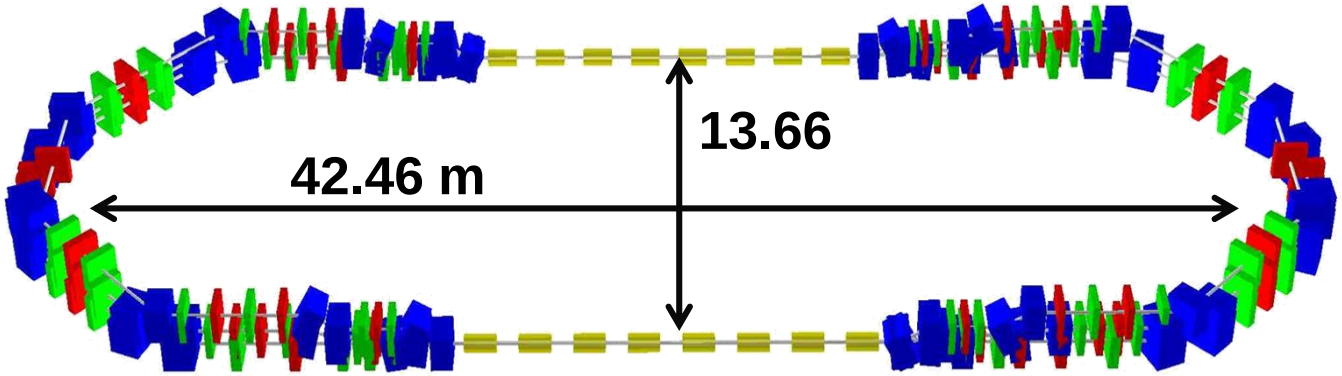
Parameter	Value	
injection energy	5MeV	
RF frequency	801MHz	
acc. voltage per cavity	20MV	
# cells per cavity	5	
, total cavity length		
# cavities per cryomodule	4	
RF power per cryomodule		
# cryomodules	2-4	
max. acceleration per module pass	80MV	
bunch repetition		
injected beam current	10-15mA	
nominal bunch charge		
number of passes	1	3
top energy	155Gev	905GeV
duty factor	CW	

PERLE Footprint:

A.Valloni 2/16







Remarks on the Project Status

LHeC: CERN Mandate in 2014 to continue the study:

Mandate to the International Advisory Committee 2014-2017

Chair: Herwig Schopper

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.

Next major goals:

Development of SRF (802 MHz) with Jlab. Design minimum Demonstrator (10mA, 3 turn, ERL)

Update of the CDR by 2018: LHC physics, 10^{34} lumi, detector and accelerator updates

FCC-eh: Utilize the LHeC design study to describe baseline ep/A option.

Emphasis: 3 TeV physics, IR and Detector: synchronous ep-pp operation.

Analyse other configurations and new physics developments (750..)

ERL Demonstrator for LHeC:

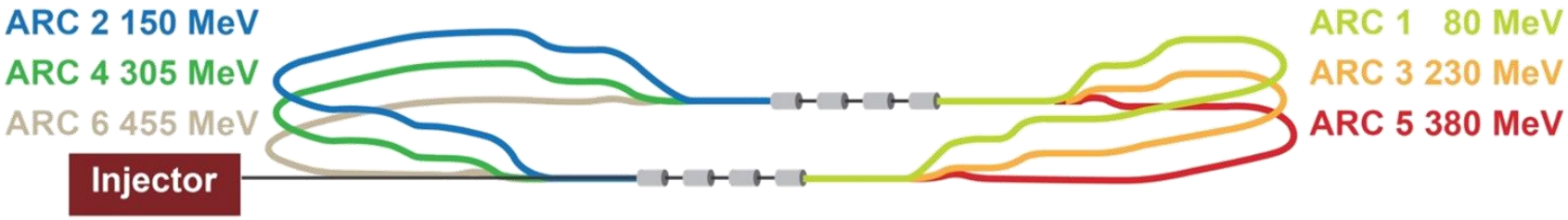
IAC outcome:

-Develop a Conceptual Design Report for a minimal test facility @ CERN

➔ Footprint, and required infrastructure

➔ Reduced version of PERLE Stage 2

Stage 2 – 2 CMs, set up for energy recovery, 2…3 passes

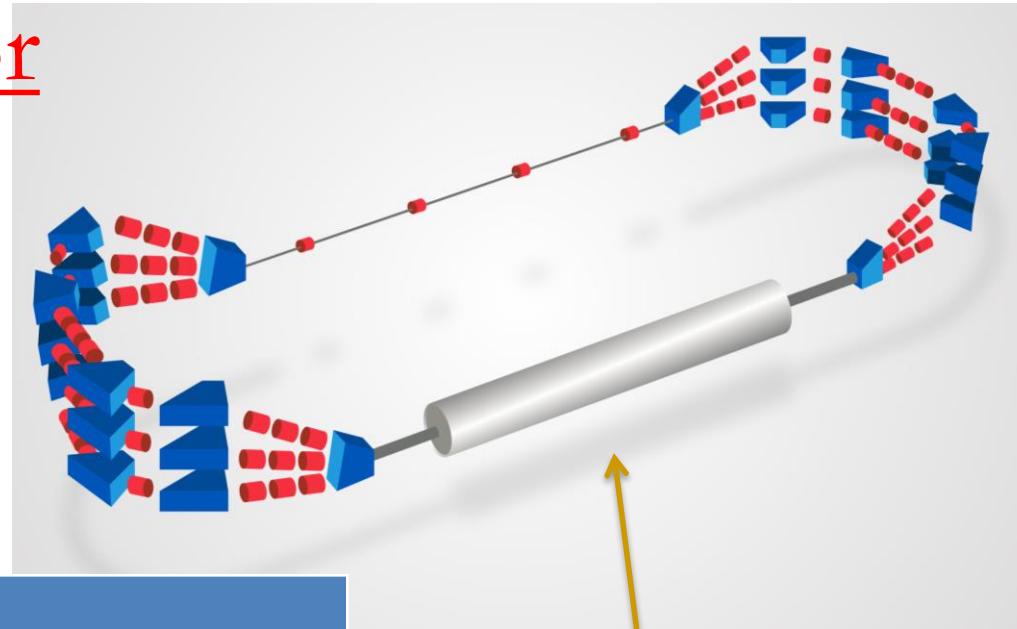


ERL Demonstrator

Demonstration of high current (10mA), multi(3)turn ERL

Test and development of 802MHz SCRF technology

E_e = 200 (400) MeV with 1(2) module



Parameter	Value
Dipoles per arc Dipole length Max B Field	3/4 50 cm 1.1 T
Quadrupoles per arc Quadrupoles in straight lines	5 4
Dipoles in Spreader/Combiner Quads in Spreader/Combiner	1-3 3
Dipoles for Injection-Extraction	6

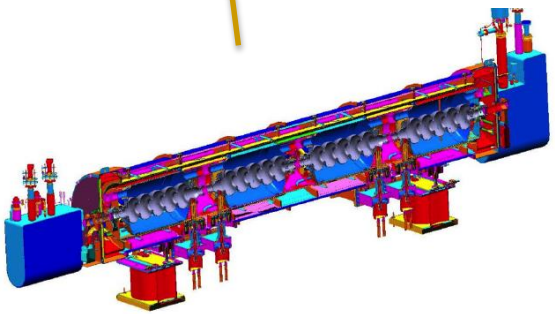


Figure 3.9: SNS high β module adapted to house β =1 5-cell cavities for LHeC.

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Summary:

- LHeC ERL design is viable:
  - ➔ But requires demonstration of multi-turn, high beam current!
- LHeC offers a further exploitation of the LHC infrastructure
  - ➔ Allowing parallel operation with HL-LHC
- 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

Outstanding Issues and Next Steps

Machine:

-IR layout finalization with SR power optimization

-IR optics design with integration into HL-LHC ATS optics

-SC IR magnet

-SC RF development

-Comparative study for different ERL sizes (1/3th; 1/4th; 1/5th)

-ERL demonstration with high current (>10mA) & multi-turn ($\geq$ 3)

Next Steps:

-ERL demonstrator

➔ Test Facility TDRs under preparation

(PERLE and minimum scale demonstrator)

Reserve Transparencies

2012 CERN Mandate: 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

Study Structure as of 2014: Coordination Group for DIS at CERN:

LCG (2014-2017) *)

Nestor Armesto
Oliver Brüning
Stefano Forte
Andrea Gaddi
Bruce Mellado
Paul Newman
Max Klein
Peter Kostka
Daniel Schulte
Frank Zimmermann

Directors (ex-officio)
Sergio Bertolucci, Frederick Bordry

*) LCG Composition early March 2014

The coordination group was invited end of December 2013 by the CERN directorate with the following mandate (2014-2017)

The group has the task to coordinate the study of the scientific potential and possible technical realization of an ep/eA collider and the associated detectors at CERN, with the LHC and the FCC, over the next four years.

It should also coordinate the design of an ERL test facility at CERN as part of the preparations for a larger energy electron accelerator employing ERL techniques.

The group will cooperate with CERN and an International Advisory Committee

International Advisory Committee:

The IAC was invited in December 2013 by the CERN DG

Guido Altarelli (Rome)
Sergio Bertolucci (CERN) *)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago)
Victor A Matveev (JINR Dubna)
Shin-Ichi Kurokawa (Tsukuba)
Leandro Nisati (Rome)
Leonid Rivkin (Lausanne)
Herwig Schopper (CERN) – **Chair**
Jurgen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersely (STFC)

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.

*) IAC Composition End of February 2014 + Oliver Brüning Max Klein ex officio

LHeC: Motivation

- Physics:
  - ➔ 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!

LHeC: Motivation

Physics:

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

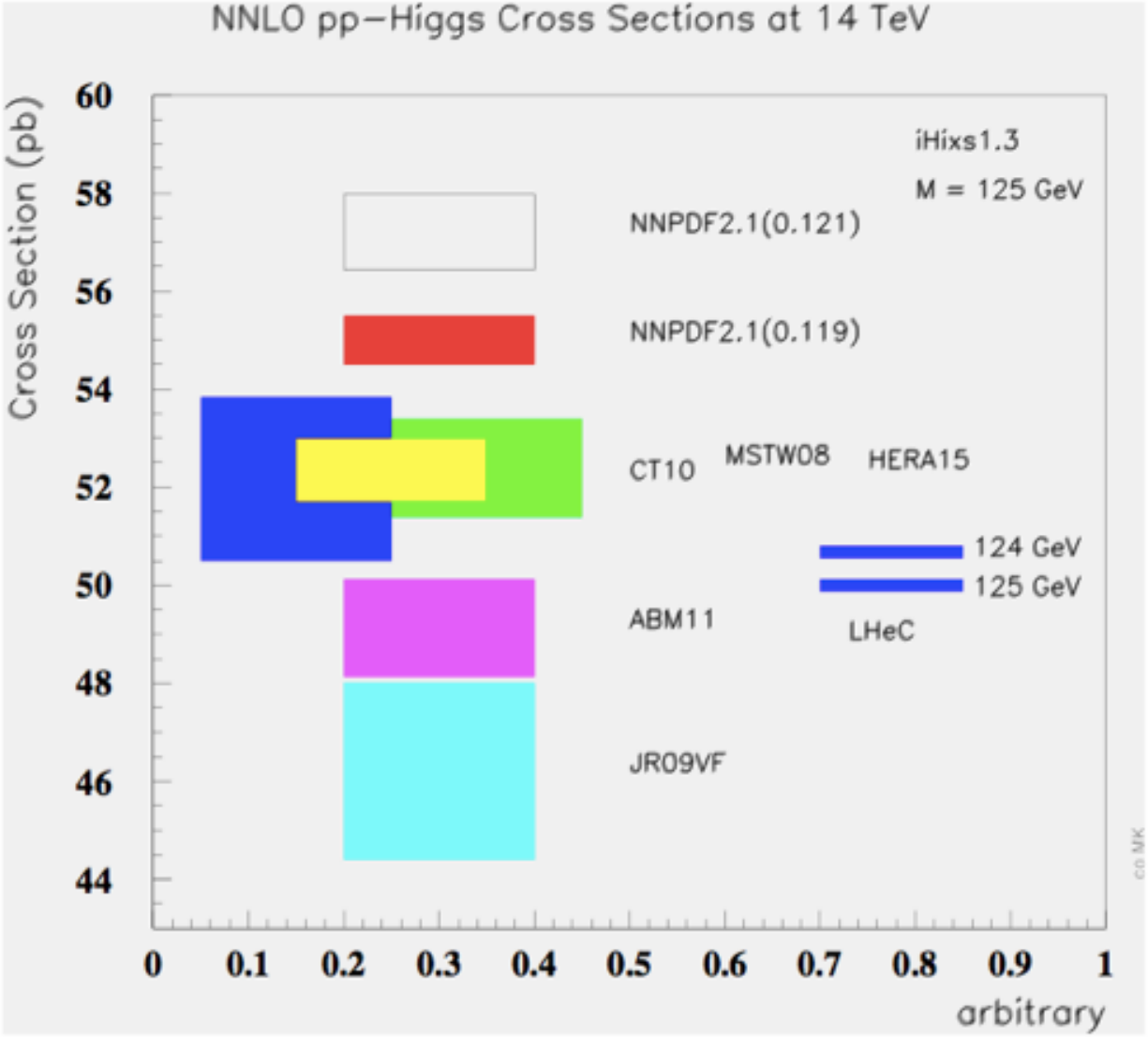
-Unique possibility of an EIC @ the TeV scale

Plus Test Facility applications :

- electron and photon physics with high precision (electromagnetic, weak, nuclear, BSM subjects)

-SRF, SC magnets, Beam Instrumentation etc.

Motivation: Precision for Higgs @ LHC:



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

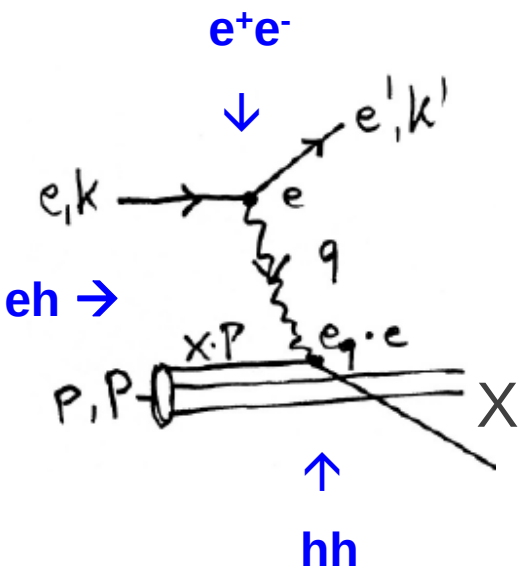
Leads to mass sensitivity

Needs N^3LO calculations

arXiv:1305.2090, MPLA 2013

Motivation: EIC facilities as a microscope:

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

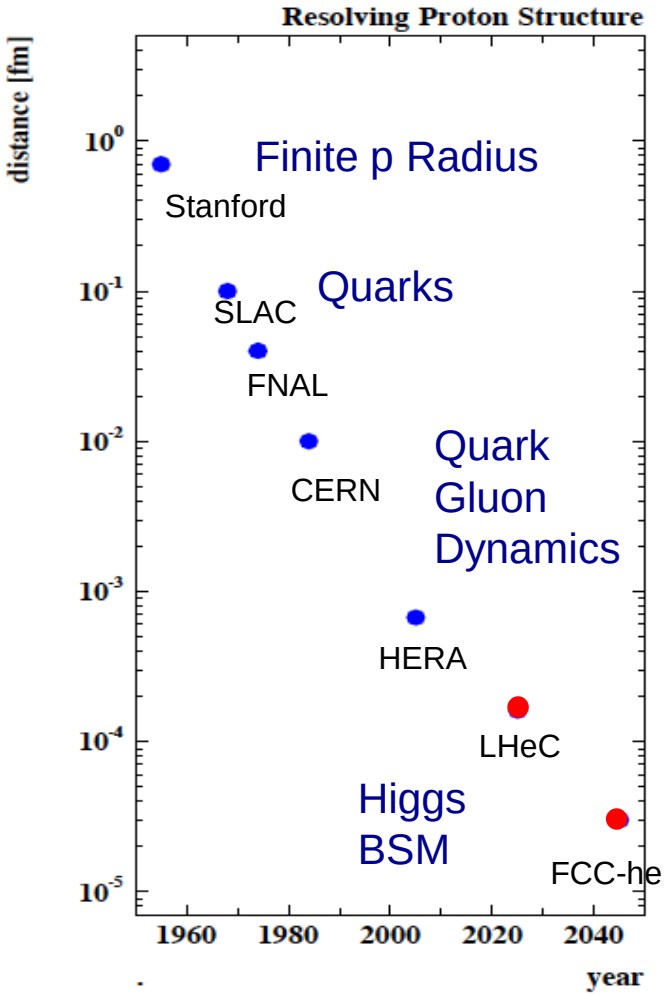


$$x = \frac{Q^2}{sy}$$

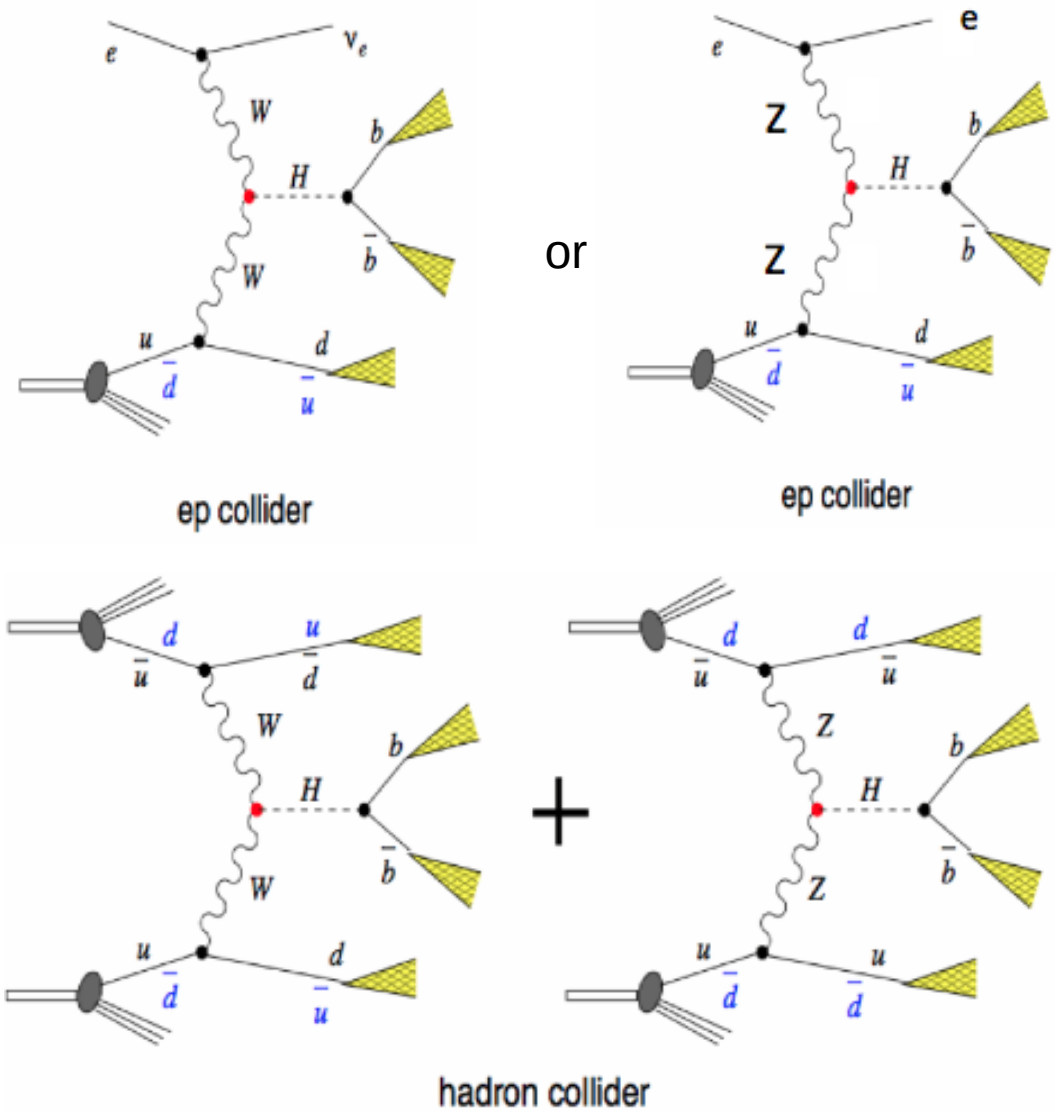
$$Q^2 = -(k - k')^2$$

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

$$s = 4E_eE_p$$



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