LHeC and FCChe: performances, designs and challenges

Accelerators Revealing the QCD Secrets

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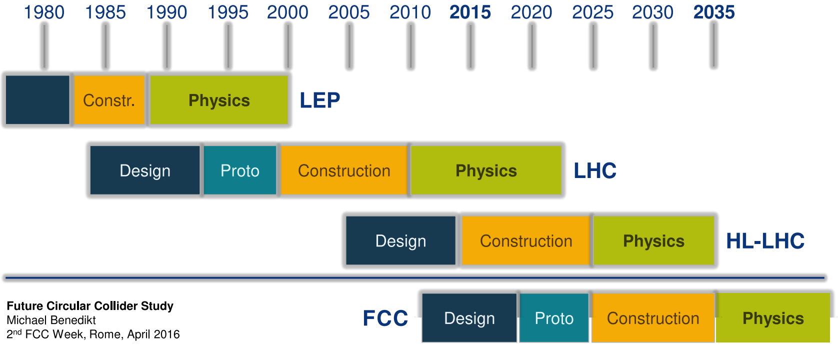
for the LHeC and FCC-he Study Groups

Sept 3-5, 2016

Lepton-hadron collisions at CERN?



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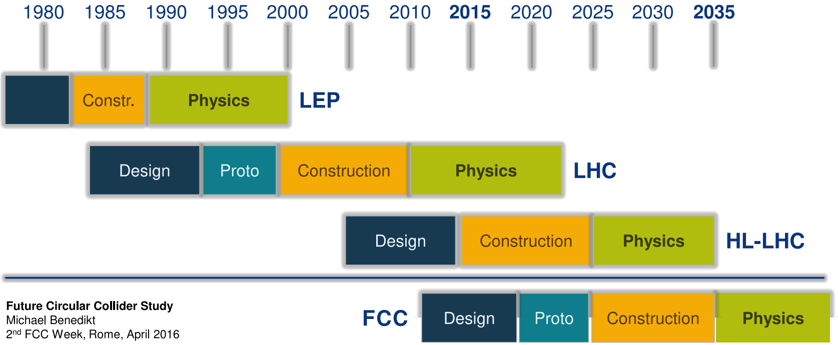

- Short term (<10y): focus on the HL-LHC → still can do development, prototyping, technology demonstrator.
- Mid term (10-20y): upgrade the HL-LHC with a lepton facility?
- Long term (>20y): which possibilities within the FCC context?

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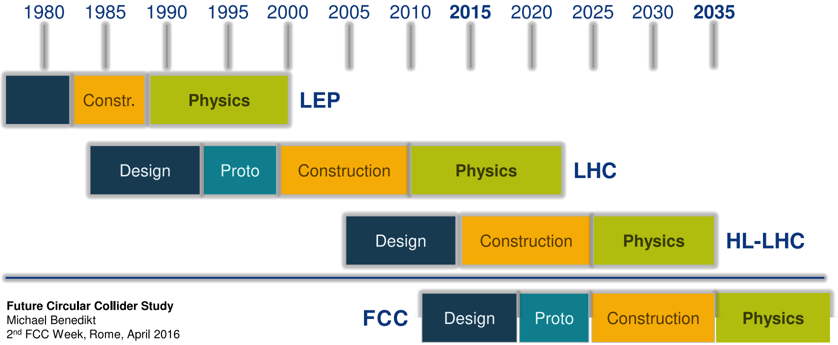

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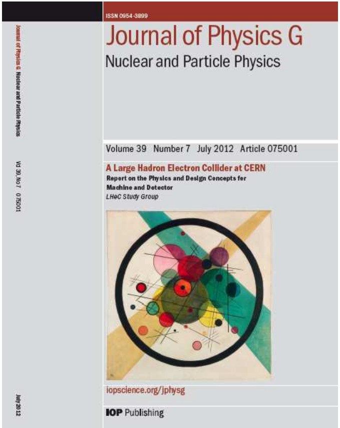
Which kind of design to maximise performance/cost while minimising interference?

LHeC

The Large Hadron Electron Collider



http://lhec.web.cern.ch

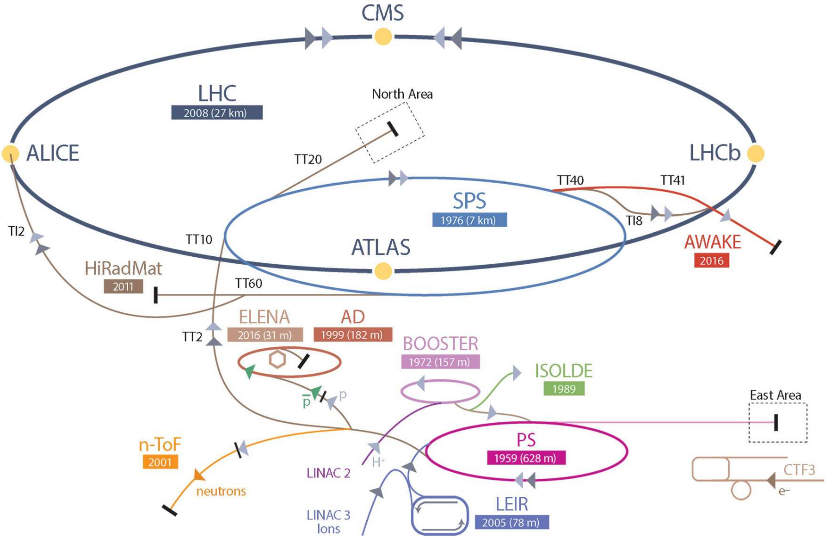
- Design a facility capable to provide electrons for collision with the beam in LHC,
- Minimize the impact on the LHC:
  - during construction (avoid long shutdown period),
  - during operation (minimal perturbation of the LHC beams).

Total grid power consumption < 100 MW

Trade off between energy and luminosity:

- 60 GeV as baseline energy
- Highest luminosity achievable ($> 10^{33}$ cm^{-2}s^{-1})

Ring-Ring or (Energy Recovery) Linac-Ring



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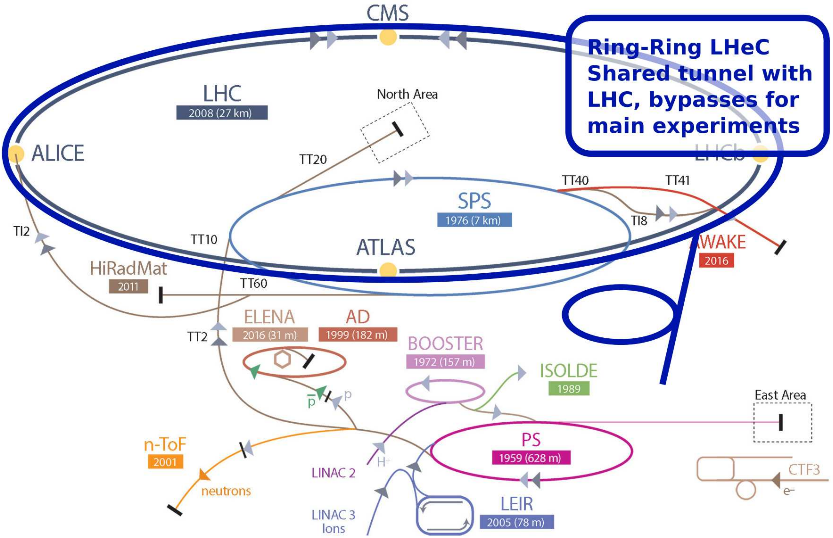
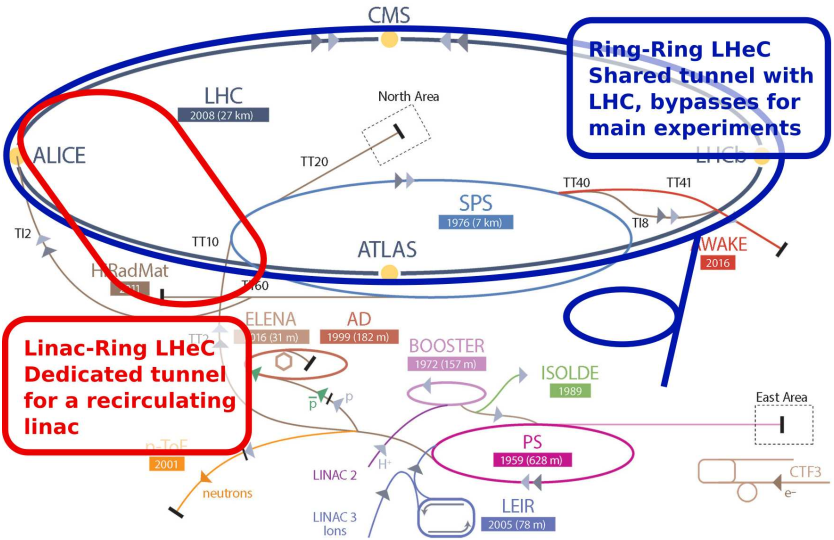


Ring-Ring LHeC Shared tunnel with LHC, bypasses for main experiments

Ring-Ring or (Energy Recovery) Linac-Ring



Ring-Ring | Linac-Ring

- ☺ Basically "LEP 1.5": we know that we can do it!
- ☺ Positrons can be easily provided for collisions,
- 😐 Maximum luminosity limited by synchrotron radiation (100 MW for $L = 5 \times 10^{33}$ cm^{-2} s^{-1} @ 60 GeV),
- ☹ Conflicts with LHC devices (Atlas, CMS, RF section, extraction kickers...),
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- ☺ More compact,
- ☺ Similar if not higher luminosity,
- 😐 Much less experience with construction and operation tolerances (exciting for scientists, worrisome for management),
- ☹ No adequate positron sources,
- ☹ Many superconductive components (need for cryo installation),

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The Linac-Ring was selected as baseline.

Machine Parameters

baseline → hi-lumi upgrade

	Protons	Electrons
Beam Energy [GeV]	7000	60
Luminosity [10^{33} cm^{-2}s^{-1}]	$1 \to 10$	
Normalised Emittance [μm]	$3.75 \to 2$	50 (...16?)
IP beta function $\beta^*_{x,y}$ [m]	$0.1 \to 0.05$	0.032 (...0.1?)
RMS IP beam size $\sigma^*_{x,y}$ [μm]	$7.2 \to 3.7$	$7.2 \to 3.7$
Bunch Spacing [ns]	25	25
Bunch Population	2.2×10^{11}	$1 \to 4.0 \times 10^{9}$
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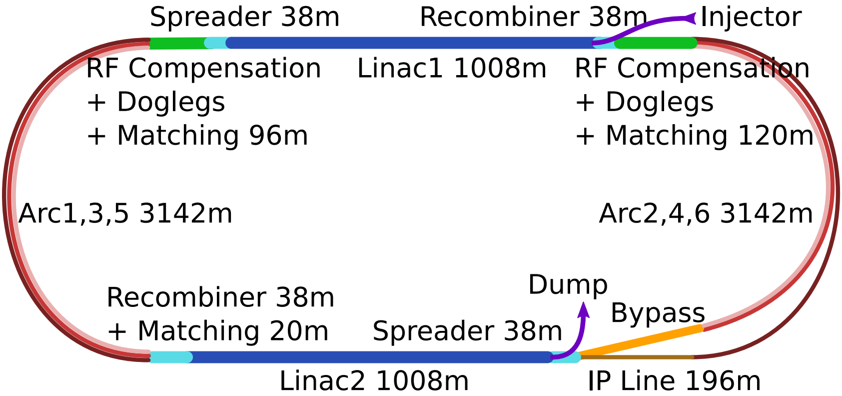
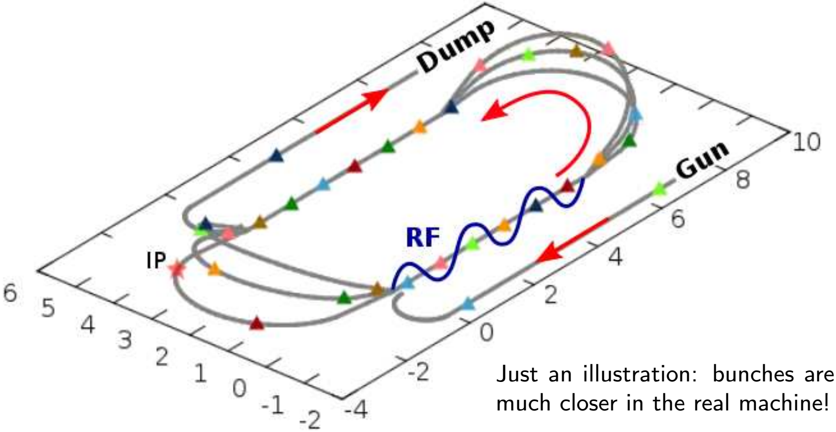
- HERA luminosity: 10^{31} (HERA I) upgraded to 4×10^{31} (HERA II) $\rightarrow 10^{33}$ is already a HUGE improvement,
- 10^{34} allows to collect ~ 1000 fb^{-1} necessary to study the Higgs in many channels in presence of kinematic cuts ($\sigma_{e+p \rightarrow H+X} \approx 200$ fb).

Baseline Design



Continuous Wave (CW) operation



Just an illustration: bunches are much closer in the real machine!

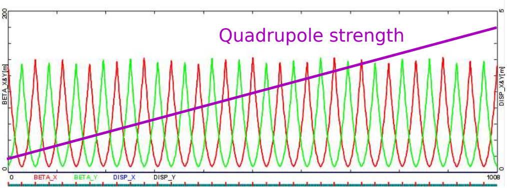
- New/spent bunches are continuously injected/dumped,
- In the linacs bunches at different turn numbers and energies are interleaved,
- Gap for ion cleaning requires an integer fraction of the LHC length (1/3) → protons bunches collide at every turn or never.

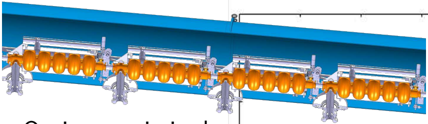
Overview of the Machine Sections

Two Superconducting Linacs

Each 1 km long, providing 10 GeV acceleration.

802 MHz RF, 5-cell cavity:	
λ	37.38 cm
L_c ($5\lambda/2$)	93.45 cm
Gradient	18 MeV/m

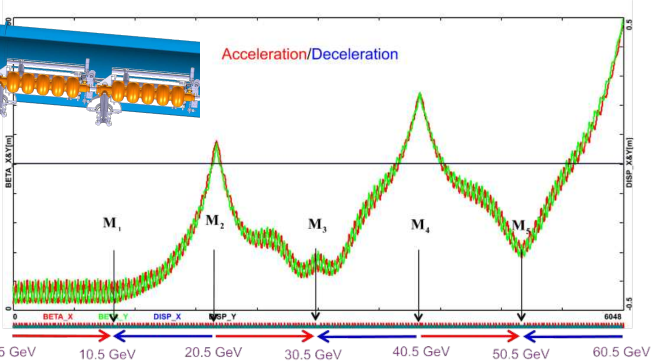




Optics optimised for:

$$\int \frac{\beta}{E} ds$$

to reduce the impact of wakefields.



RF frequency choice

LHC bunch spacing requires bunch spacing with multiples of 25ns (40.079 MHz). Available designs:

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

Both off by 20 MHz compared to LHC harmonics.

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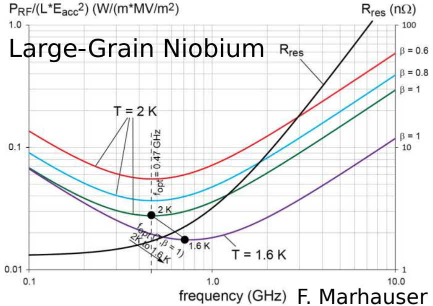

F. Marhauser

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

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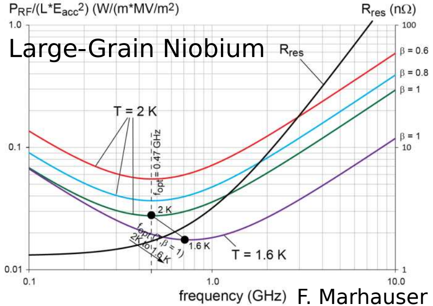

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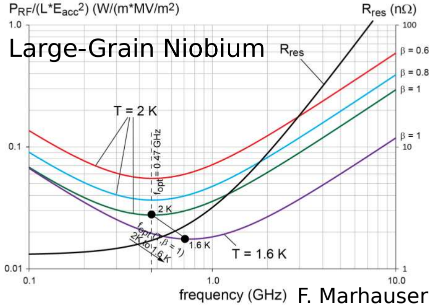

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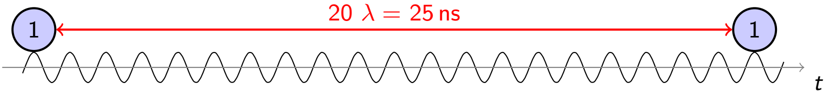

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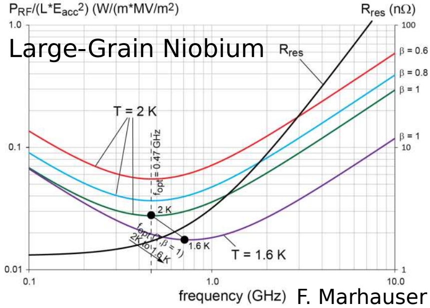

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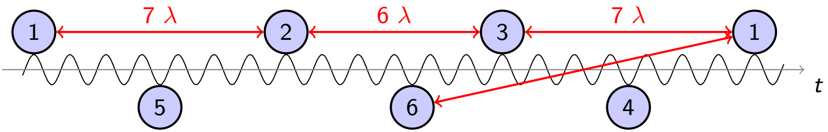
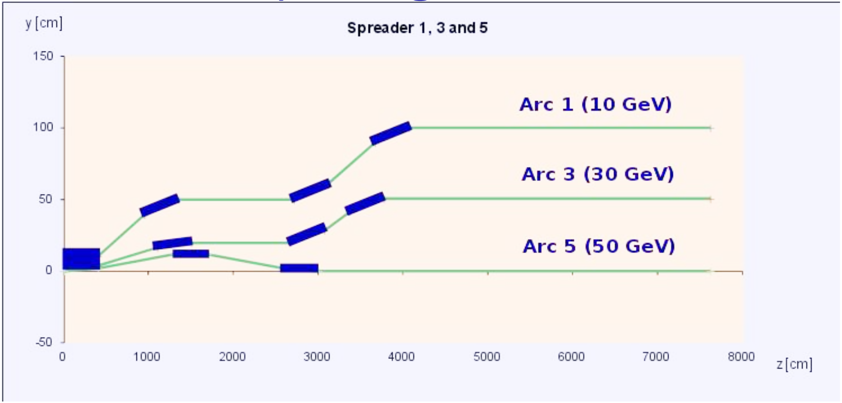


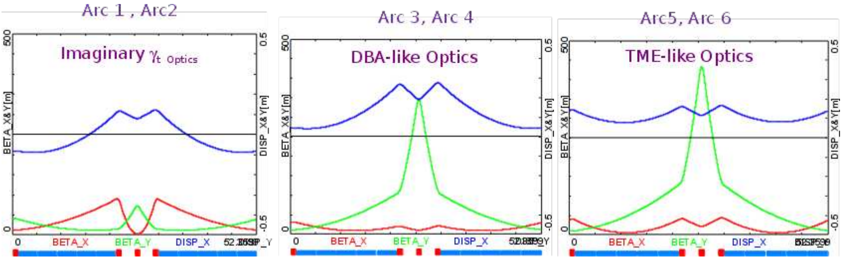
Max separation between the bunches at 1st and 6th turn to mitigate wakefields.

Spreading Sections



- Provide vertical separation while matching each beam from the linac to the right arc;
- Integrate chicanes for path length adjustment, and 1600 MHz RF compensating sections for synchrotron radiation losses;
- New single step design developed to mitigate synchrotron radiation and limit the peak β.

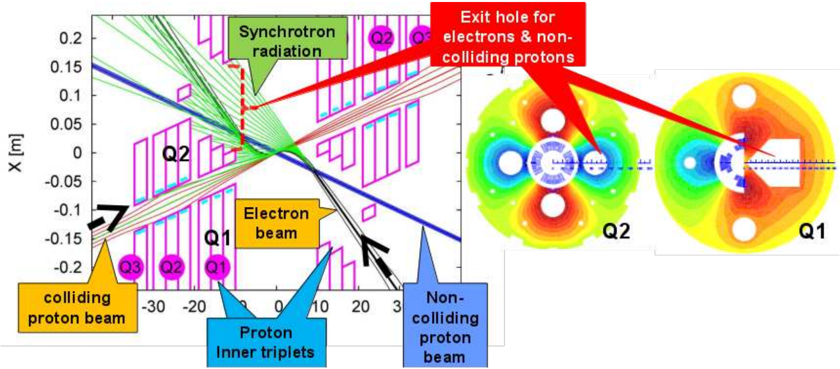
Arcs - Flexible Momentum Compaction



- 1 km radius for all of them,
- Same arrangement for each arc to simplify the installation in the tunnel,
- Tunable cells:
  - Highest energy arcs are tuned to minimize the energy spread induced by synchrotron radiation (quantum excitation),
  - Lowest energy arcs are tuned to contain the beam size and compensate for the bunch lengthening.

Very effective design verified with tracking simulations!

Interaction Region



- The electron beam goes across the Q1 → delicate magnet design with a vanishing-field region and high radiation flux.

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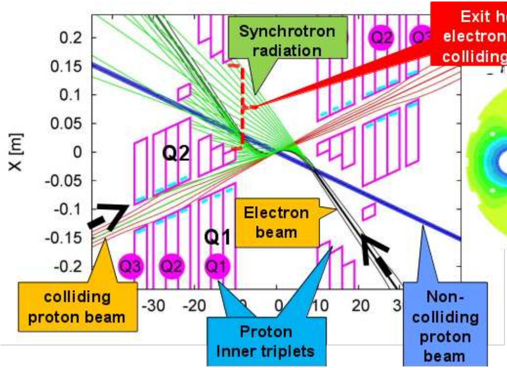

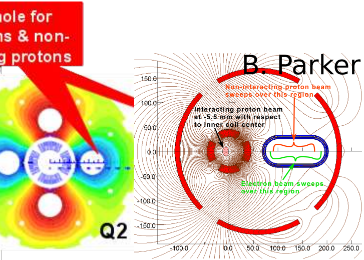

New Q1 design with two con-centric sets of coils and warm electron beam screen proposed at the 2015 LHeC workshop!

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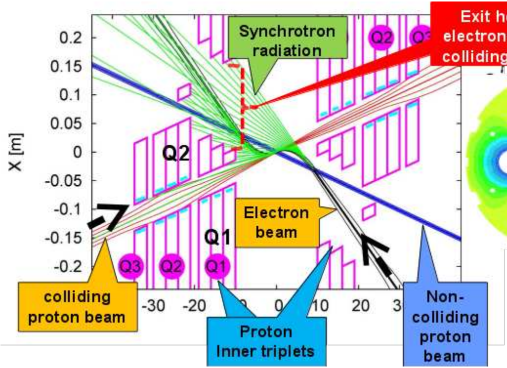
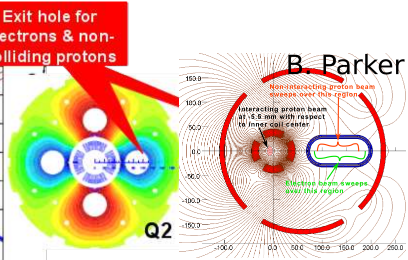


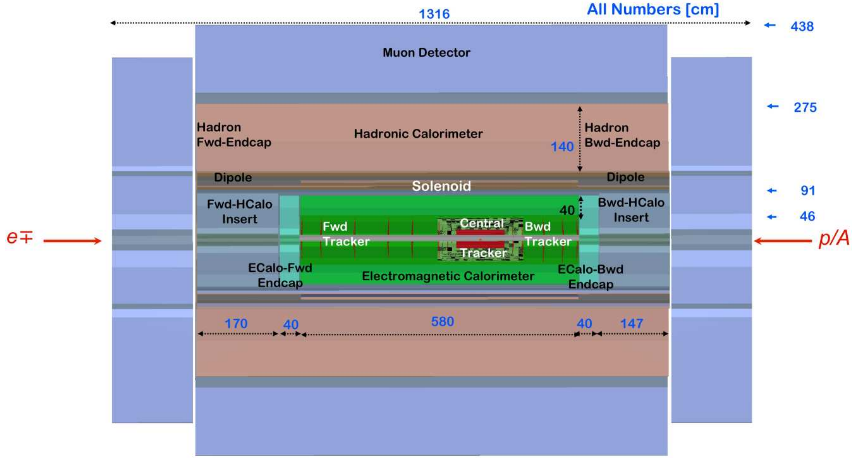


New Q1 design with two con-centric sets of coils and warm electron beam screen proposed at the 2015 LHeC workshop!

- The electron beam goes across the Q1 $\rightarrow$ delicate magnet design with a vanishing-field region and high radiation flux.
- β^* smaller than in Atlas/CMS $\rightarrow$ can be achieved with the telescopic squeeze?

Machine detector interface: many open issues and parameters to be defined.

Detector Studies



- Forward / backward asymmetry reflecting beam energies (870 mm offset)
- Dipole for head-on e-p collisions and central solenoid in common cryostat
- Present size fits inside 14 m x 9 m (fits inside the solenoid from the L3 LEP experiment)

Beam Physics and Dynamics

Beam dynamics overview

Assessed with extensive tracking simulation

Single particle/single bunch effects:

- *Synchrotron Radiation:*
  - 750 MeV are lost in arc 6,
  - induced energy spread (quantum excitation).
- *Beam-Beam effect:*
  - Disruption of the electron beam (still need to be decelerated),
  - Stability of the proton beam (impact on the other LHC experiments).
- *Short range wakefields and impedances:*
  - energy spread and emittance growth.

Multi bunch effects:

- *Long range wakefields* (excitation of higher order modes in the cavities),
- Ion cloud build up (preliminary estimations in the CDR, seems ok but needs to be reviewed)

Simulation tool

Tracking particle beams in recirculating machines is hard!

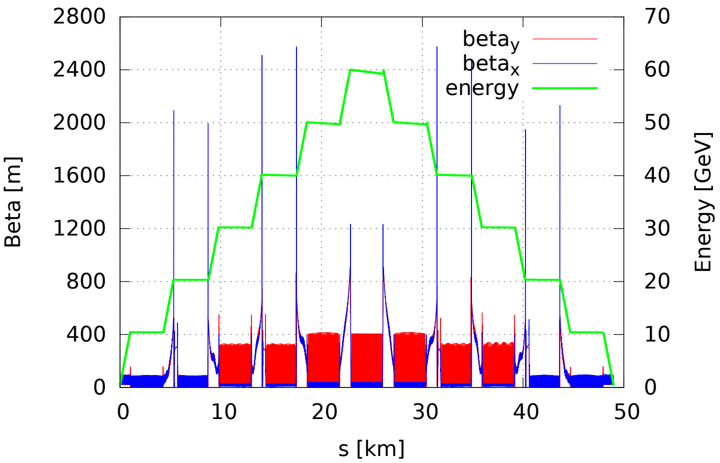
- Beam goes through the same elements a few times,
- At each turn new bunches are added and some removed,
- Neither ring nor linac codes are fully suited.

Multibunch tracking in the ERL performed with the recently developed PLACET2 tracking code, from CLIC.

- Determines path of the bunches based on flexible criteria,
- Can merge bunches into trains, preserving the time order in each part of the machine,
- Can handle time dependences all around the machine.

End-to-end Optics

PLACET2 extracts the optics parameters from the particles distribution. A test bunch is followed from the injector to the dump. Basic validation of the setup.



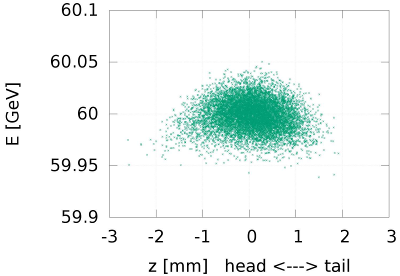
Notable: the energy loss due to synchrotron radiation in Arc 6, the different average β in the arcs, the recovery of the mismatch generated in the linacs.

Beam at the IP

Higgs Factory Parameters - $L = 10^{34}$ cm^{-2}s^{-1}

Injection/Dump Energy	500 MeV
Bunch Spacing	25 ns
Particles per bunch	$4 \times 10^9 = 640$ pC
Normalised RMS Emittance	50 μm
IP β function	0.032 m

Longitudinal phase space at IP

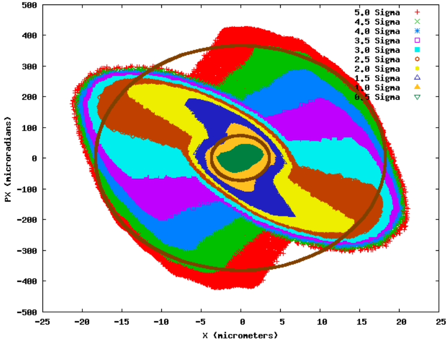


	initial/CDR	IP
ε_x [μm]	50	57.4
ε_y [μm]	50	50.8
δ	0.0020	0.0026
RMS x [μm]	7.20	7.66
RMS y [μm]	7.20	7.21
RMS z [mm]	0.600	0.601
RMS e [MeV]	-	15.4

- The beam at the IP maintains a very good quality, still need to verify imperfections and stability;
- The acceleration mitigates many effects, but the deceleration amplifies them...

Beam-Beam Effect

Effect of the proton beam on the electron beam with the high lumi parameters:



Tails are folded back, but the core is disrupted.

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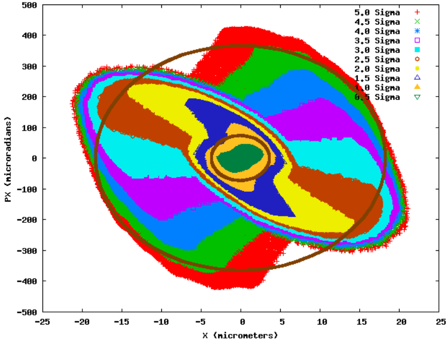

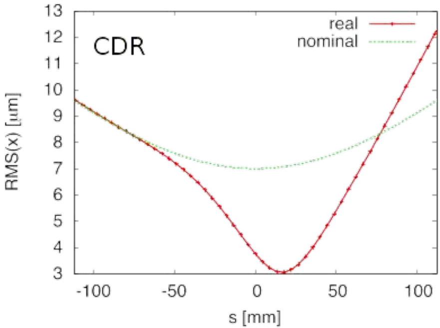

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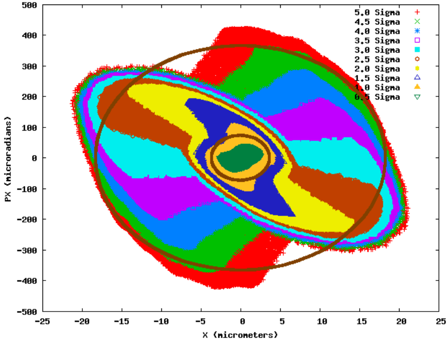

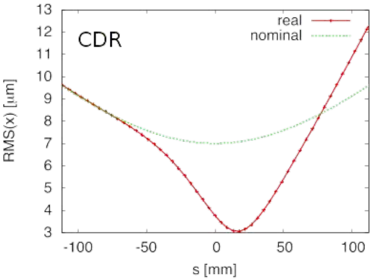

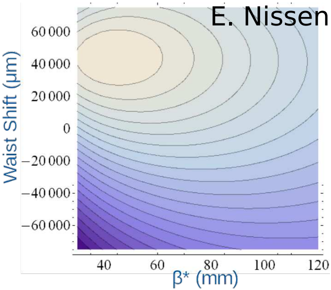

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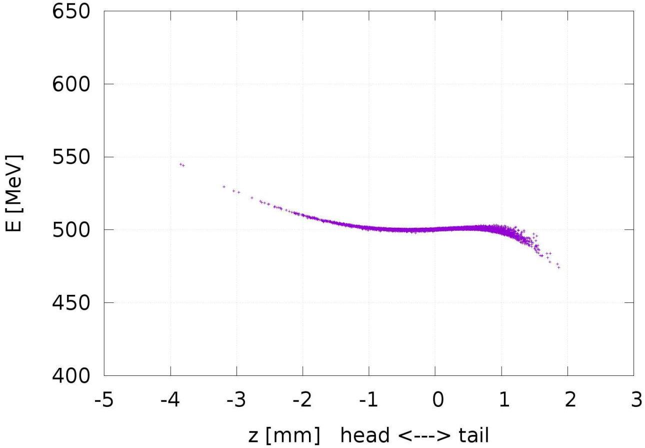
Beta [mm]	Waist [mm]	Luminosity [$10^{33} cm^{-2} s^{-1}$]
120	0	8.1
120	45	9.6
39	45	9.8

Longitudinal Phase Space at Dump (I)

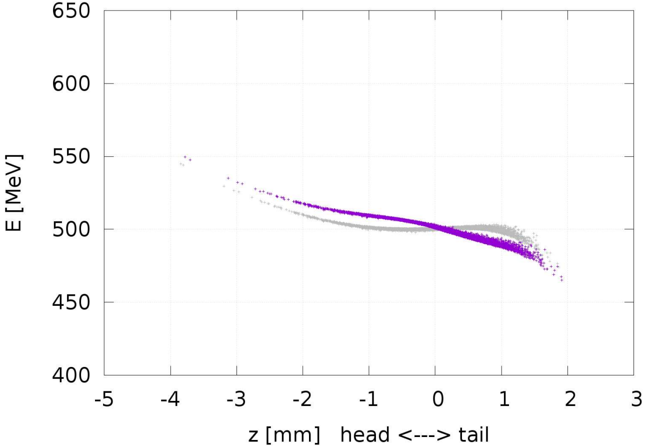
Optics only:



Non perfect isochronicity together with the RF curvature.

Longitudinal Phase Space at Dump (II)

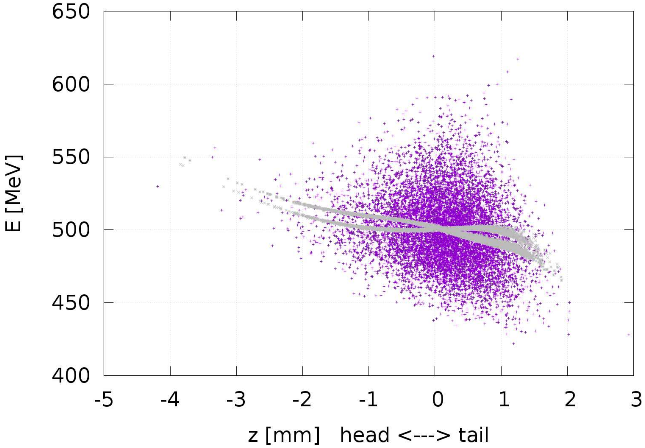
Short Range Wake Fields:



Second harmonic RF losses compensation (no RF curvature from it).

Longitudinal Phase Space at Dump (III)

Short Range Wake Fields + Synchrotron Radiation:

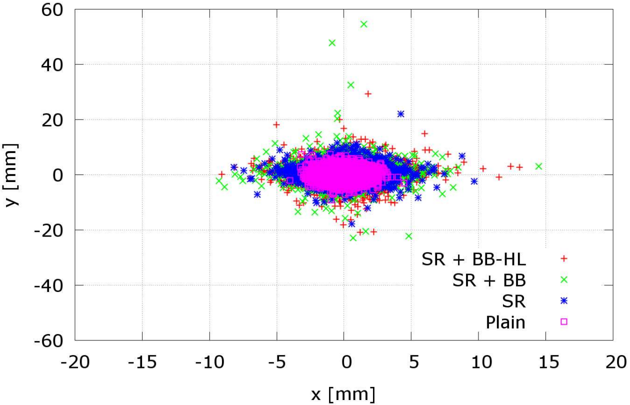


Big energy spread from quantum excitation, optics and sr wake effect masked!

Transverse Plane at Dump

The electron beam can be decelerated to the dump in all the cases considered.

Losses are very limited for an iris radius of the cavity > 50 mm.



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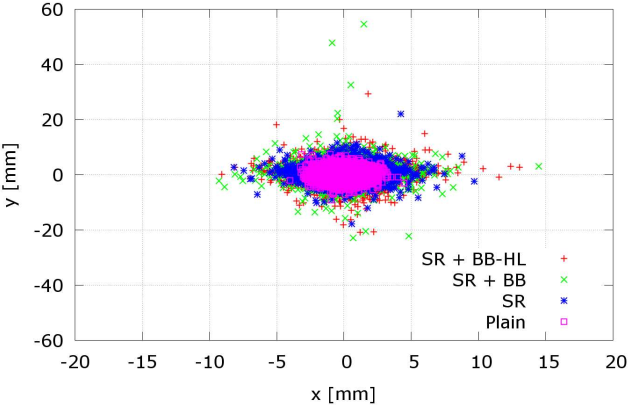

The *proton beam* is much less perturbed:

- Limited tune shift: 6×10^{-4},
- Emittance growth (target $< 10\%$/day), sensitive the offset between the two beams at collision $\rightarrow$ max jittering: 0.01σ
  - Feedbacks requirements investigated for both the beams.

Long Range Wakefields

- Bunches entering the radio frequency cavities excite higher order modes of oscillation of the field (HOMs intensity $\propto \omega^3$),
- Bunches coming later are kicked by the excited modes, exciting even more the ones in the next cavities,
- Dipolar modes are particularly strong and can amplify the beam jitter and, in the worst case, cause beam loss.

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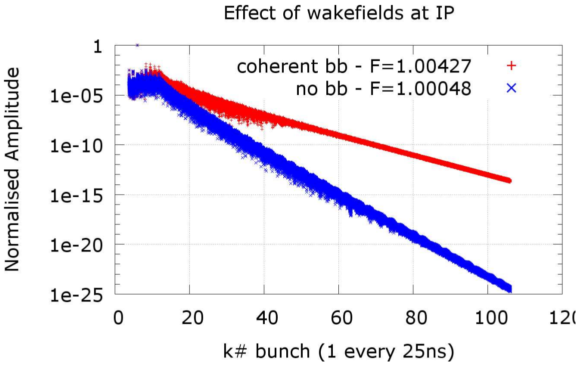

- Fill the machine with perfectly centred bunches,
- Inject a bunch with some offset,
- Keep injecting perfect bunches and see how they are perturbed.

Long Range Wakefields

- Bunches entering the radio frequency cavities excite higher order modes of oscillation of the field (HOMs intensity $\propto \omega^3$),
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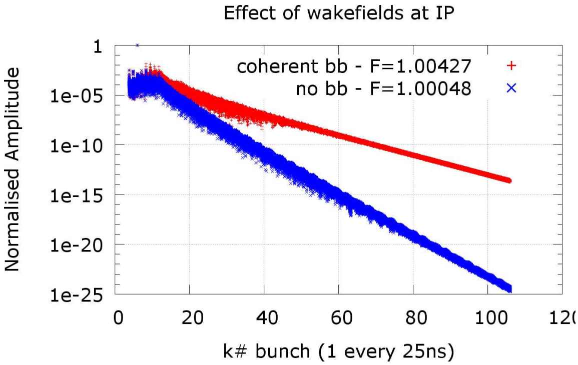
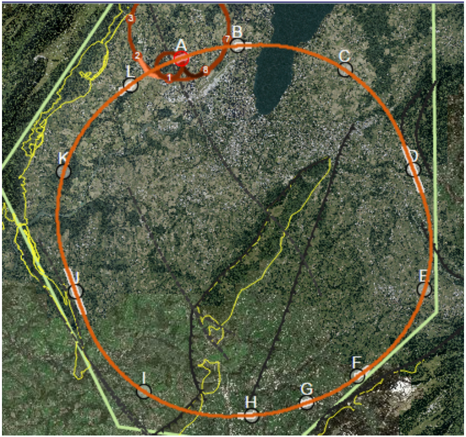


- Fill the machine with perfectly centred bunches,
- Inject a bunch with some offset,
- Keep injecting perfect bunches and see how they are perturbed.
- *No feedforward: the excitation from beam-beam is fed-back during the deceleration!*

FCC-he

(Im)possibilities within the FCC



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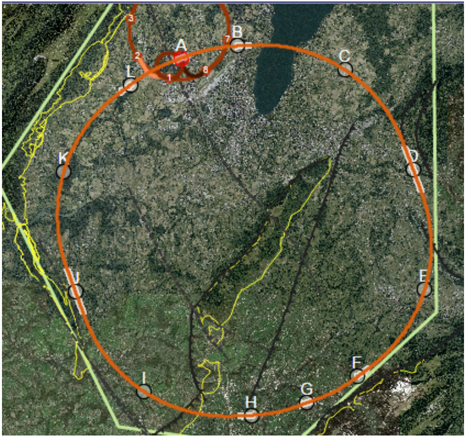

FAQ:

Collisions between protons in the LHC and electrons in the FCC-ee?

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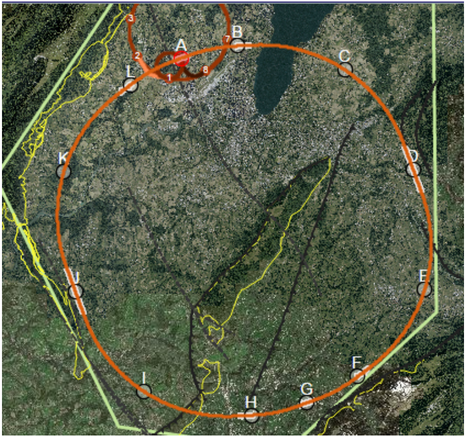

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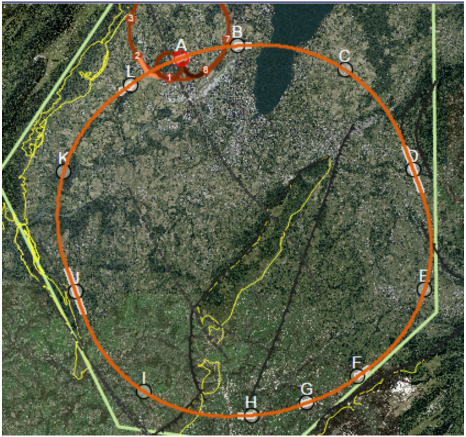
Collisions between protons in the LHC and electrons in the FCC-ee?

Not an option!

- Many additional constraints (none of the beams is easily bent).
- Vertical separation (FFC goes below lake Geneva).
- LHC will be at the end of its lifetime.

(Im)possibilities within the FCC



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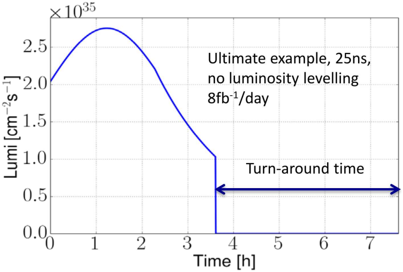
The FCC-he is for now envisioned as an ERL-based electron facility coupled to the FCC-hh $\rightarrow$ reuse the LHeC design profiting from the higher energy of the proton beam.

FCC-hh key parameters

	Baseline	Ultimate
CMS energy [TeV]	100	100
Luminosity [10^{34}cm^{-2}s^{-1}]	5	20
Bunch distance [ns]	25 (5)	
Background events/bx	170 (34)	680 (136)
Bunch charge [10^{11}]	1 (0.2)	
Norm. emitt. [μm]	2.2(0.44)	
RMS bunch length [cm]	8	
IP beta-function [m]	1.1	0.3
IP beam size [μm]	6.8 (3)	3.5 (1.6)
Max ξ for 2 IPs	0.01 (0.02)	0.03

- Two main and two additional experiments
- Use dipole magnets of up to 16 T → 80% dipole filling factor in arcs → 82km of arcs
- Current baseline: C=99.971 km (3.75 times the LHC)



- Need to review the length of the ERL → adjust to $C/11$.
- Some luminosity lost due to the FCC-hh filling pattern (80 % filled).

A Baseline for the FCC-he

Oliver Brüning[1] Max Klein[1,2], Daniel Schulte[1], Frank Zimmermann[1]
[1] CERN, [2] University of Liverpool
March 3rd, 2016

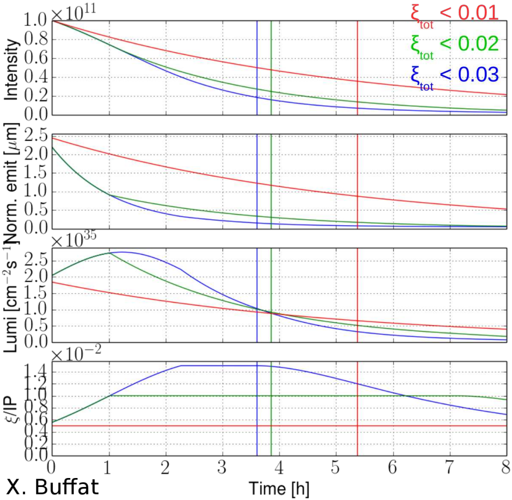
Table 1: Baseline parameters of future electron-proton collider configurations based on the ERL electron linac.

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	15	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.9	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.2	1
ϵ_p [μm]	3.7	2	2	2.2
electrons per bunch [10^9]	1	2.3	2.3	2.3
electron current [mA]	6.4	15	15	15
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor	0.9	0.9	0.9	0.9
pinch factor	1.3	1.3	1.3	1.3
luminosity [10^{33}cm^{-2}s^{-1}]	1.3	10.1	15.1	9.2

Up to 400 fb^{-1} in 5 years with 25 ns bunch spacing.

A deeper look into FCC-he

Tune shift flattening by controlled emittance blow-up:



X. Buffat

A deeper look into FCC-he

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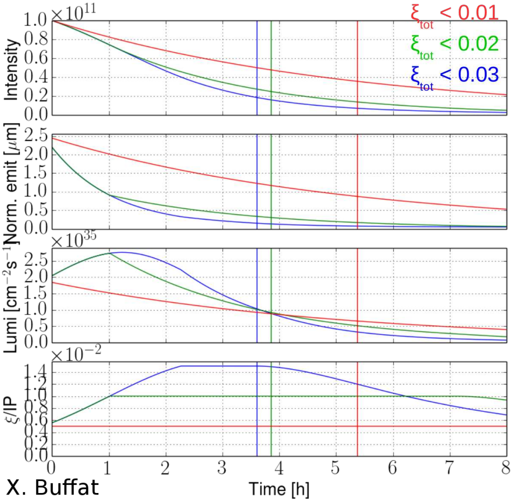

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FCC-he prefers the baseline proton parameters: slower proton burning $\rightarrow$ longer fills $\rightarrow$ more ep collision time.

Ultimate parameters foresee smaller emittance and β^* $\rightarrow$ shorter fills, impact on integrated luminosity, but mostly ok.

Bigger impact on lumi if FCC-hh goes to 25 $\rightarrow$ 5 ns spacing (bunch intensity 1 $\rightarrow$ 0.2×10^{11}) to reduce pileup.

Need to compute performances taking into account the pinch from beam-beam!

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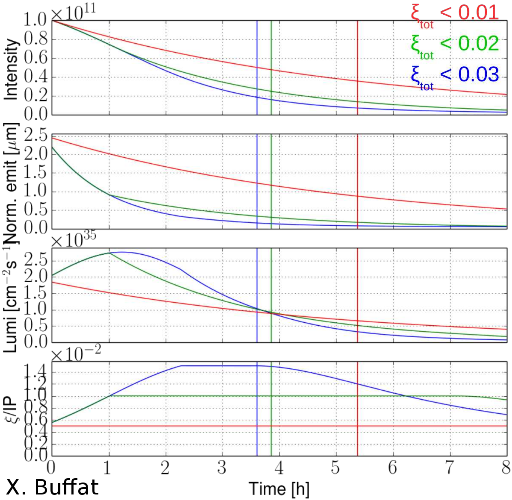

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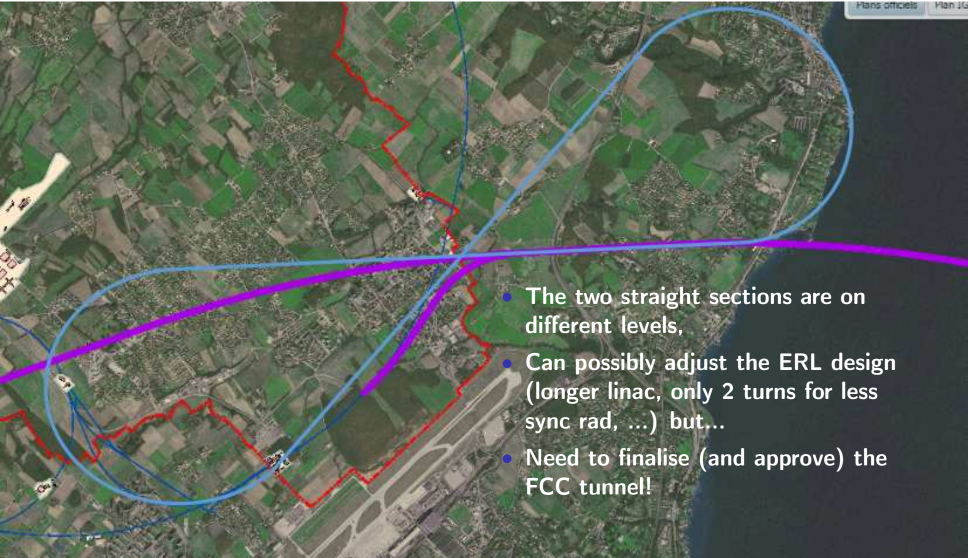
See FCC-he by D. Schulte, FCC Week, Rome, 2016.

Unifying LHeC, FCC-ee injector and FCC-he?

A single machine may do it all



- The two straight sections are on different levels,
- Can possibly adjust the ERL design (longer linac, only 2 turns for less sync rad, ...) but...
- Need to finalise (and approve) the FCC tunnel!

Conclusions

The LHeC is...

- a unique opportunity to realise ep and e-ion physics at the TeV energy scale,
- an innovative large-scale accelerator with massive return of technology,
- an occasion to fully exploit the LHC infrastructure,
- a new installation with a potential user community beyond HEP and LHeC.

- Can become the FCC-ee injector and later be coupled to FCC-hh for increased centre of mass energy.

- Basically complete ERL design available:
  - excellent performances from simulations,
  - but need to demonstrate the high current operation and find precise limits and tolerances,
  - challenging machine detector interface.

Outlook

Outstanding machine-related issues:

- IR layout finalization with SR power optimization,
- IR optics design with integration into HL-LHC ATS optics,
- SC IR magnet,
- SC RF development,
- ERL demonstration with high current ($> 10\,\mathrm{mA}$) & multi-turn (≥ 3).

Next step: ERL demonstrator!

- PERLE: CDR to be published soon,
- Studies for a minimum scale demonstrator...

Thank you!