LHeC ERL: Beam Dynamics Challenges

ERL17, CERN

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for the LHeC Machine Study Group

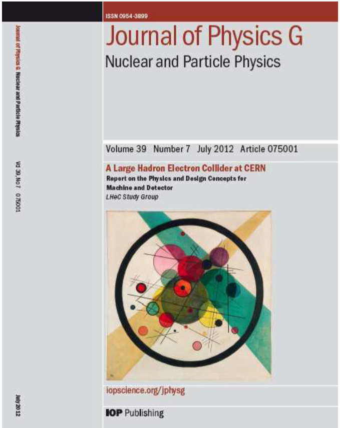
June 21st, 2017

Scope of the Talk

- Review the LHeC design and its main components.
- Stress various beam dynamics challenges including my personal view on the main pending aspects.

- Highlight the importance of PERLE: an high current, multi-turn ERL facility on a small scale.
- LHeC Workshop in September 11-13th: contributions are welcomed!

The Large Hadron Electron Collider



http://lhec.web.cern.ch

- ERL facility capable to provide electrons for collision with the beam in LHC,
- Entirely decoupled (except IR) from the LHC to minimise the impact on its plan.

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})

Machine Parameters

baseline → hi-lumi upgrade

	Protons	Electrons
Beam Energy [GeV]	7000	60
Luminosity [10^{33} cm^{-2}s^{-1}]	$1 \rightarrow 10$	
Normalised Emittance [μm]	$3.75 \rightarrow 2$	50 (...16?)
IP beta function $\beta^*_{x,y}$ [m]	$0.1 \rightarrow 0.05$	0.032 (...0.1?)
RMS IP beam size $\sigma^*_{x,y}$ [μm]	$7.2 \rightarrow 3.7$	$7.2 \rightarrow 3.7$
Bunch Spacing [ns]	25	25
Bunch Population	2.2×10^{11}	$1 \rightarrow 4.0 \times 10^{9}$
Effective crossing angle	0.0	

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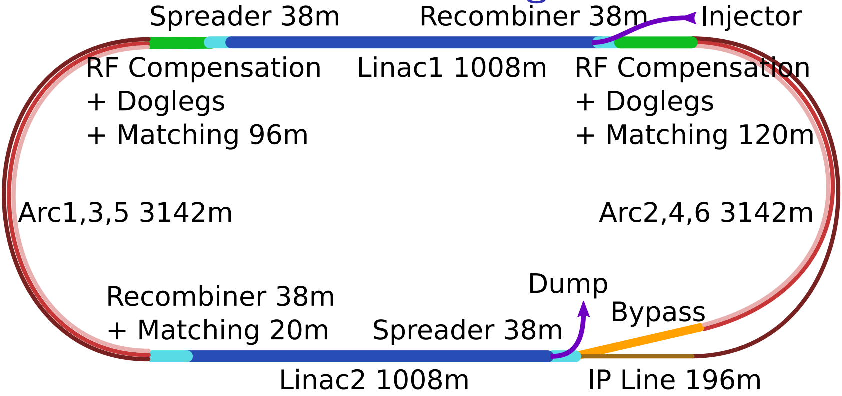
- HERA luminosity: 10^{31} (HERA I) upgraded to 4×10^{31} (HERA II) $\to 10^{33}$ is already a HUGE improvement,
- 10^{34} allows to collect ~ 1000 fb^{-1} necessary to study the Higgs in many channels in presence of kinematic cuts ($\sigma_{e+p\to H+X} \approx 200$ fb).

Baseline Design



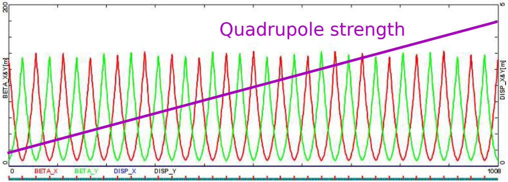
- CW operation: bunches are continuously injected and extracted from the racetrack.
- Bunches at different number of turns (accelerating and decelerating) are interleaved.
- Integer fraction of the LHC length (1/3) so that a gap for ion clearing does not shift with respect to the proton beam.

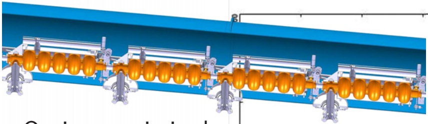
Overview of the Machine Sections

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

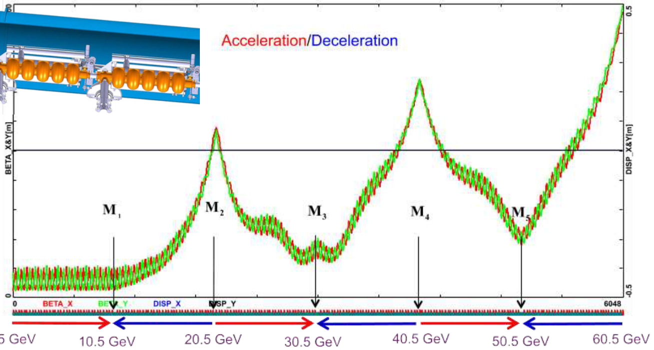




Optics optimised for:

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

to reduce the impact of wakefields.



RF frequency choice and Bunch Pattern

LHC bunch spacing requires bunch spacing with multiples of 25 ns (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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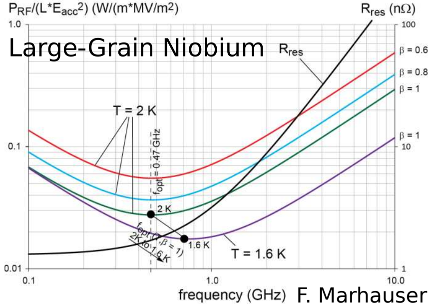

F. Marhauser

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

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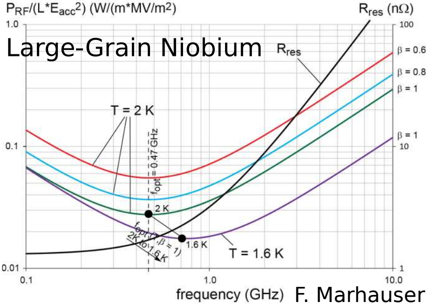

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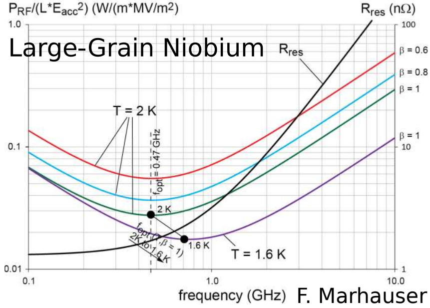

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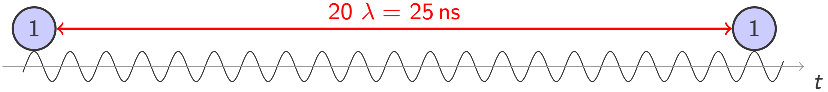

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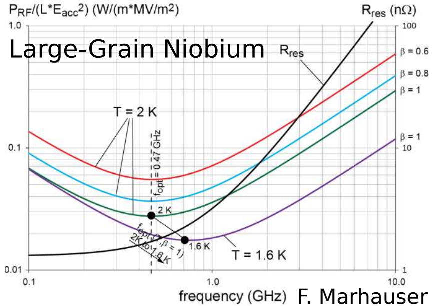

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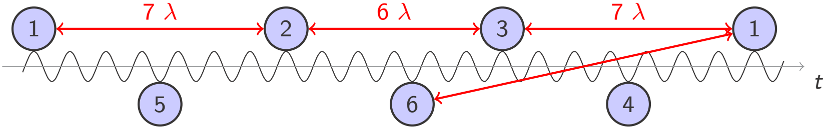
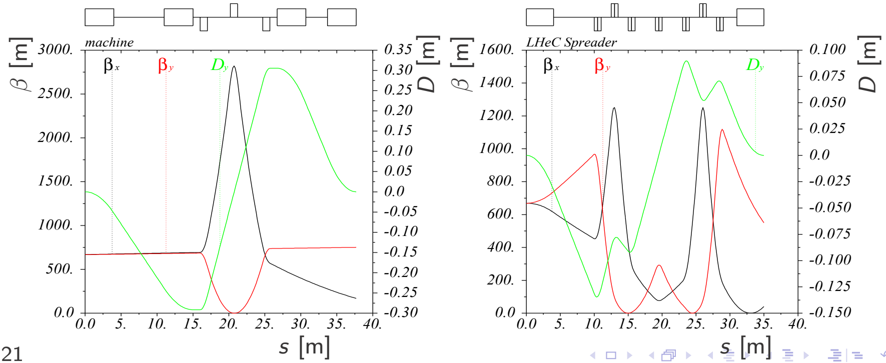


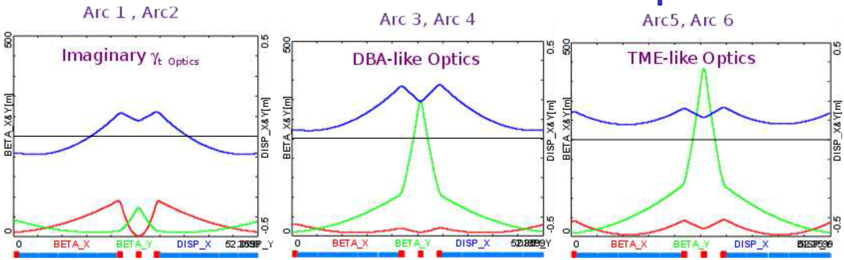
Max separation between the bunches at 1st and 6th turn to mitigate wakefields.

Vertical Spreading Sections

- Provide separation and match each beam from the linac to the arcs;
- Single step design developed to mitigate synchrotron radiation and limit the peak β, but needs superconducting quadrupoles.



Arcs - Flexible Momentum Compaction



- 1 km radius for all of them: can share the same tunnel being stacked vertically.
- 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.

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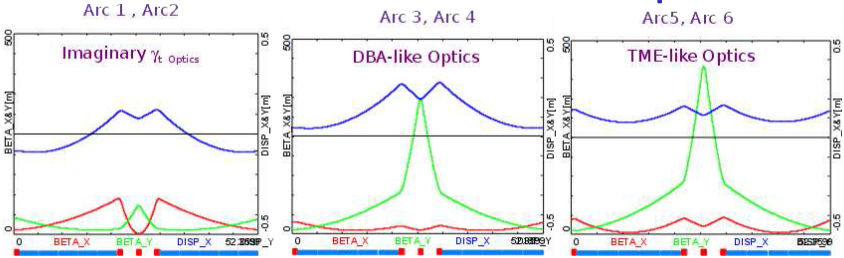

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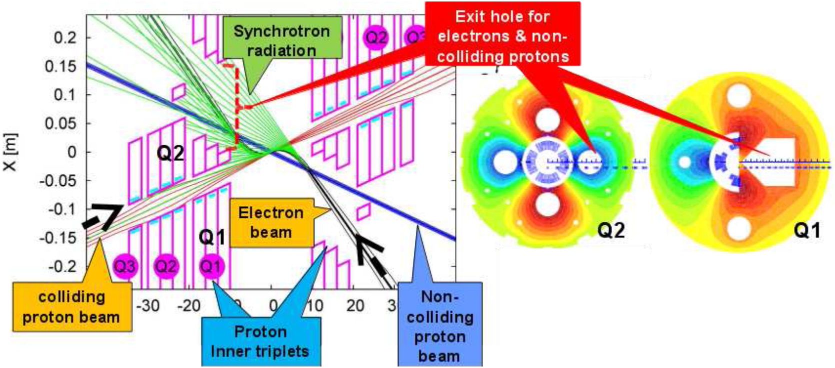
  - Lowest energy arcs are tuned to contain the beam size and compensate for the bunch lengthening.
- Possibility for FFAG arcs?
  - Tracking simulations with strong-focussing combined-function magnets performed for Arc 6 (on energy: uniform bending) looked ok.
  - Need for a full design and experimental validation.

Interaction Region



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

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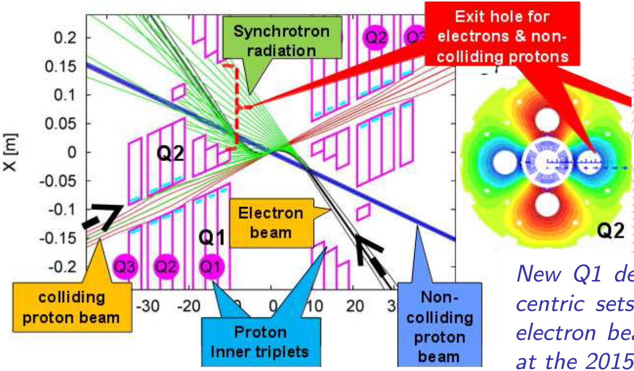

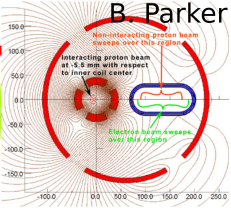

New Q1 design with two con-centric sets of coils and warm electron beam screen proposed at the 2015 LHeC workshop!

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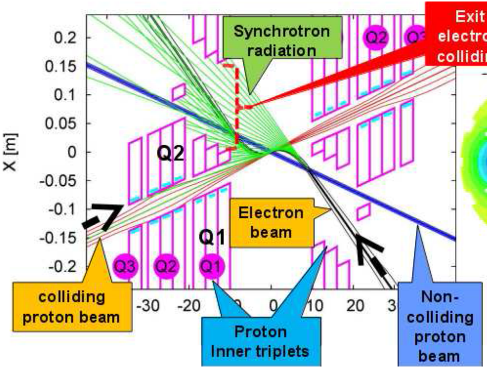

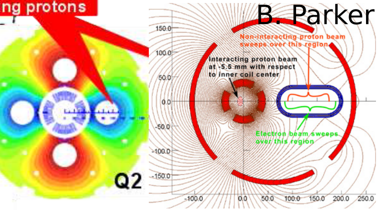

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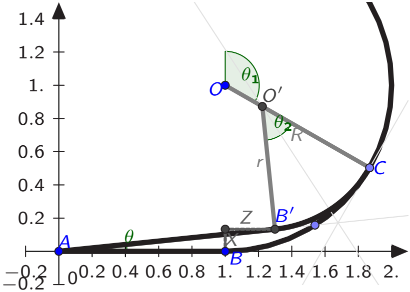
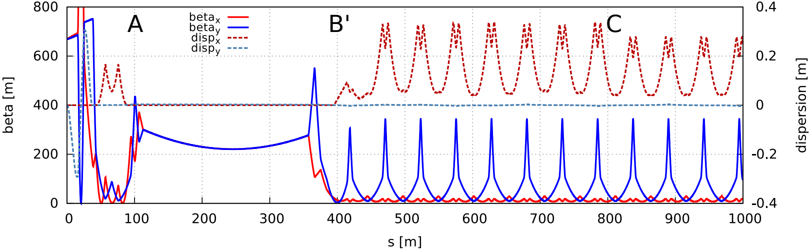
- The electron beam goes across the Q1 $\rightarrow$ delicate magnet design with a vanishing-field region and high radiation flux.
- Proton β^* smaller than in Atlas/CMS $\rightarrow$ can be achieved with the telescopic squeeze? (Extendended ATS optics, E. Cruz)

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

Detector Bypass

- Arc 2 and Arc 4 needs to be separated from the detector.
- Smooth connection to Arc 6 by seven cells with increased bending field.
- SR losses are contained.





Beam Physics and Dynamics

Beam dynamics overview

Single-particle/single-bunch effects:

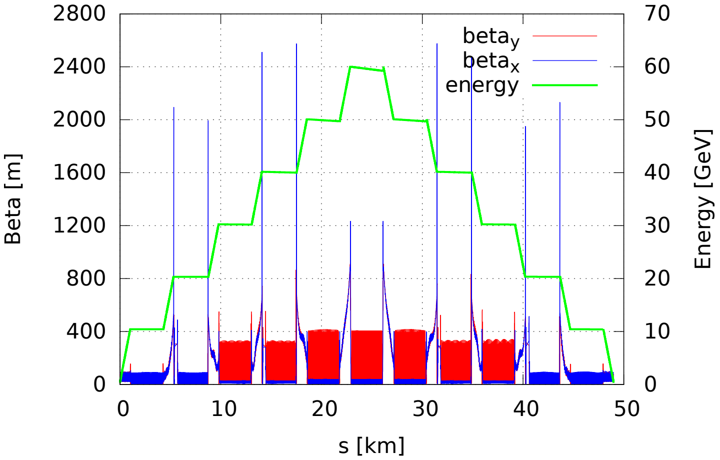
- *Synchrotron Radiation:*
    - Almost 2 GeV lost around the racetrack, 750 MeV in Arc 6.
    - Induced energy spread and emittance blowup limiting the deceleration.
- *Beam-Beam effect:*
    - Disruption of the electron beam (still need to be decelerated).
    - Stability of the proton beam (impact on the other LHC experiments).
- *Short range wakefields and impedances:*
    - energy spread and emittance growth.
- *Lattice imperfections:*
    - Misalignments and field errors, RF stability.

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).

End-to-end Optics

Computed with PLACET2, extracting the optics parameters from the particles distribution followed from the injector to the dump.



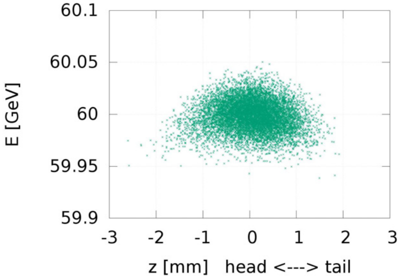
Notable: the energy loss due to synchrotron radiation in Arc 6, the different average β in the arcs, the recovery of the mismatch generated in the linacs.

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

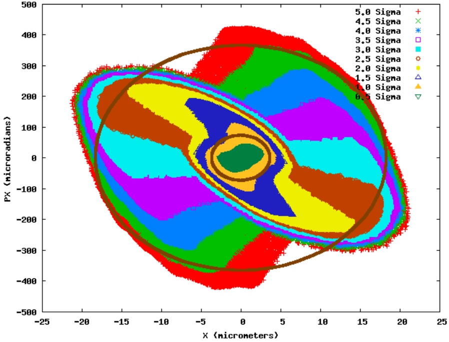


	initial/CDR	IP
ε_x [μm]	50	57.4
ε_y [μm]	50	50.8
δ	0.0020	0.0026
RMS x [μm]	7.20	7.66
RMS y [μm]	7.20	7.21
RMS z [mm]	0.600	0.601
RMS e [MeV]	-	15.4

- 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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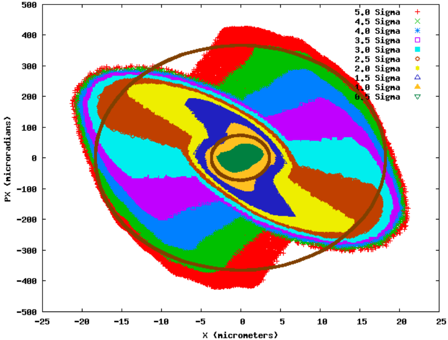

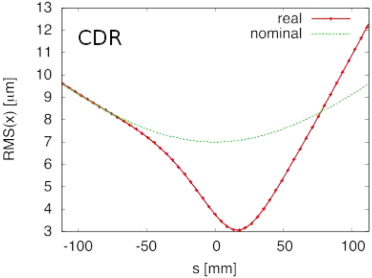

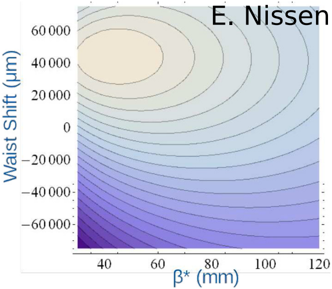

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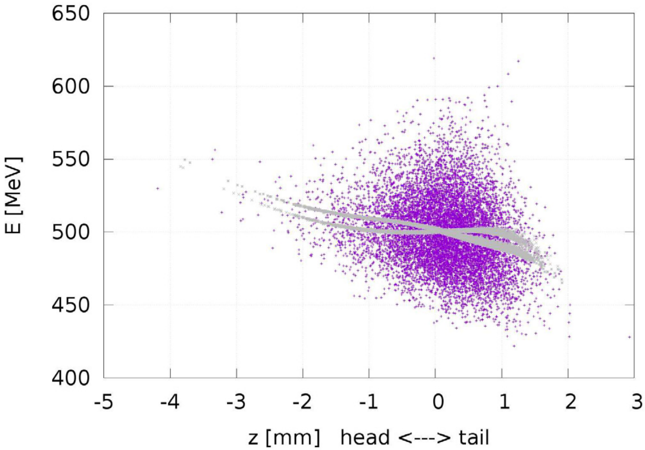
Beta [mm]	Waist [mm]	Luminosity [$10^{33}cm^{-2}s^{-1}$]
120	0	8.1
120	45	9.6
39	45	9.8

Longitudinal Phase Space at Dump

Short Range Wake Fields + Synchrotron Radiation:

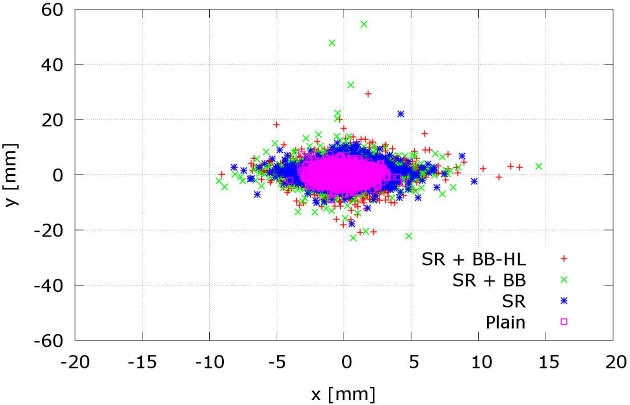


Big energy spread from quantum excitation, optics and sr wake effect masked!

Transverse Plane at Dump

The electron beam can be decelerated to the dump (500 MeV) in all the cases considered.

Losses are very limited for an iris radius of the cavity > 50 mm, but cannot decelerate much more.



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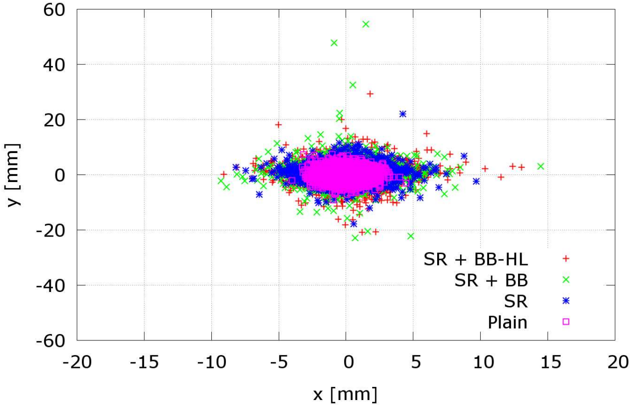
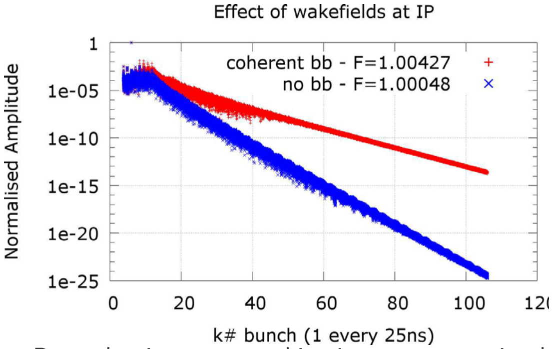


The *proton beam* is much less perturbed:

- 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
    - Feedback requirements investigated for both the beams.

Long Range Wakefields and Beam Break Up

- Bunches entering the RF 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.



- Fill the machine with perfectly centred bunches,
- Inject a bunch with some offset,
- Keep injecting perfect bunches,
- Monitor the slope of the tail and the sum of the normalised amplitudes (total crosstalk).

Dependencies on: recombination pattern, cavity detuning, phase advances, feed forward system + interplays with beam-beam, ion cloud, ...

Outstanding Issues (I)

Linacs:

- Tolerances on phase and voltage, establish the total external power required for RF stability.
- Alignment and orbit correction: six beams ideally on the same orbit, need to avoid wakefield excitation.

Arcs:

- Requirements for time-of-flight matching and tuning: chicanes are not effective at high energy, possibility of distributed orbit bumps?
- Finalisation of the magnet and vacuum chamber designs with High SR.

IR and MDI:

- Very crowded and challenging area at early stage of design.
- Detector integrated dipoles with potentially unacceptable SR and albedo background.
- Possibility of using Crab Cavities for one or both beams?

Injector:

- 20 mA at 500 MeV are 1 MW of beam power: a challenging machine on its own.

Outstanding Issues (II)

Second Harmonic RF cavities (1.6 GHz) for SR compensation:

- Crucial component installed in the arcs and allowing to reuse them for the deceleration.
- They need to replenish up to 50 MW of beam power lost by synchrotron radiation.

Beam dynamics aspects:

- Requirements for the gap for ion clearing: need for detailed simulations of ion effects and their coupling with wakefields.
- Sextupole-free arcs come with large natural chromaticity: can this lead to instabilities due to collective effects?
- More accurate estimations of the max current, feed-forward requirements.
- Response of the max current with alternative bunch spacings (for FCC-eh).

Operational aspects:

- Machine bootstrapping: slowly ramp up the bunch intensity?
- Not so much stored-beam energy: 12 kJ in Arc 6 filled with 20 mA, machine protection issues?
- Emergency dump system: one beam dump in each arc?

Conclusions

The LHeC is...

- a unique opportunity to realise ep and eA physics at the TeV energy scale with high luminosity: $1 \times 10^{34}\,\mathrm{Hz\,cm^{-2}}$ for ep and $\sim 1 \times 10^{33}\,\mathrm{Hz\,cm^{-2}}$ for eA,
- an innovative large-scale accelerator with massive return of technology,
- an occasion to complement and fully exploit the LHC infrastructure,
- a new installation with a potential user community beyond HEP and LHeC itself.

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

- Proof-of-concept design available:
  - excellent performances from simulations,
  - but still a complex machine with many open issues.

Need for a demonstrator: *PERLE@Orsay*

PERLE CDR: `https://arxiv.org/abs/1705.08783`

Thank you!

Acknowledgments:

A. Bogacz, O. Brüning, M. Klein, A. Latina, D. Schulte, F. Zimmerman

http://lhec.web.cern.ch

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),
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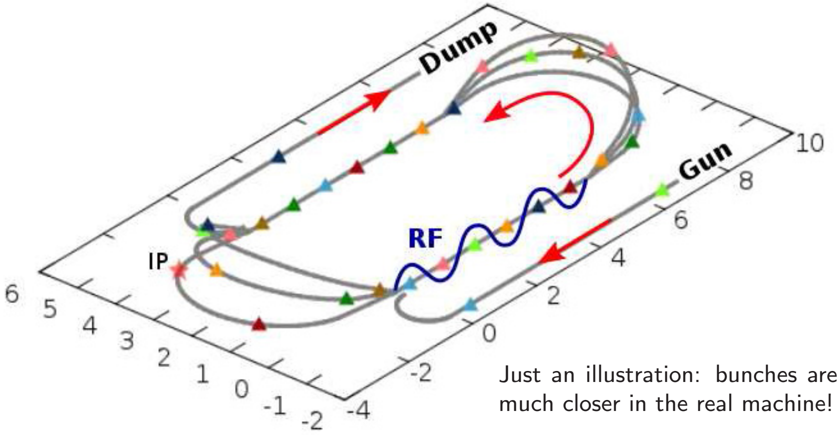
The Linac-Ring was selected as baseline.

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.

Simulation tool

Tracking particle beams in recirculating machines is hard!

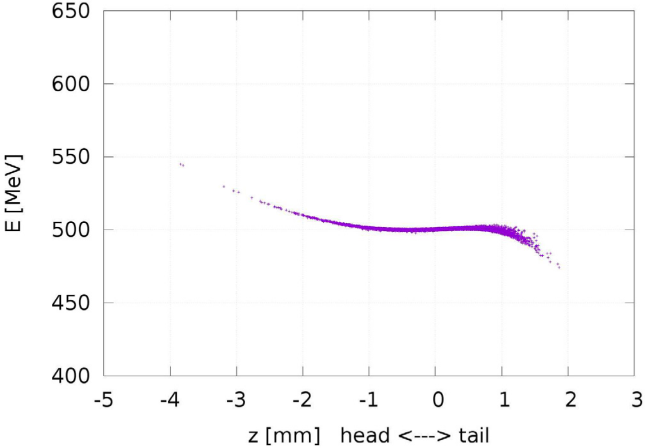
- Beam goes through the same elements a few times,
- At each turn new bunches are added and some removed,
- Neither ring nor linac codes are fully suited.

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.

Longitudinal Phase Space at Dump (I)

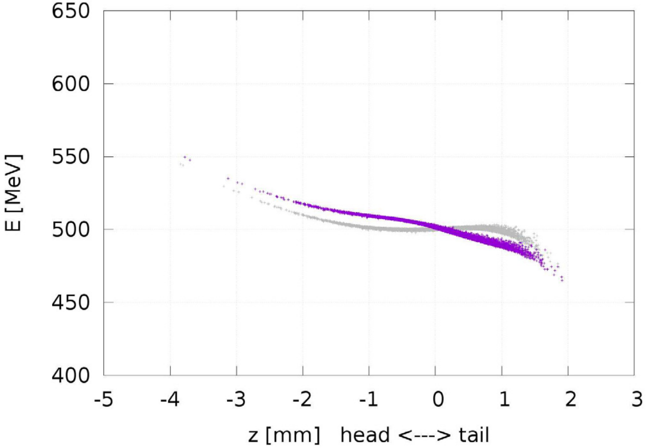
Optics only:



Non perfect isochronicity together with the RF curvature.

Longitudinal Phase Space at Dump (II)

Short Range Wake Fields:

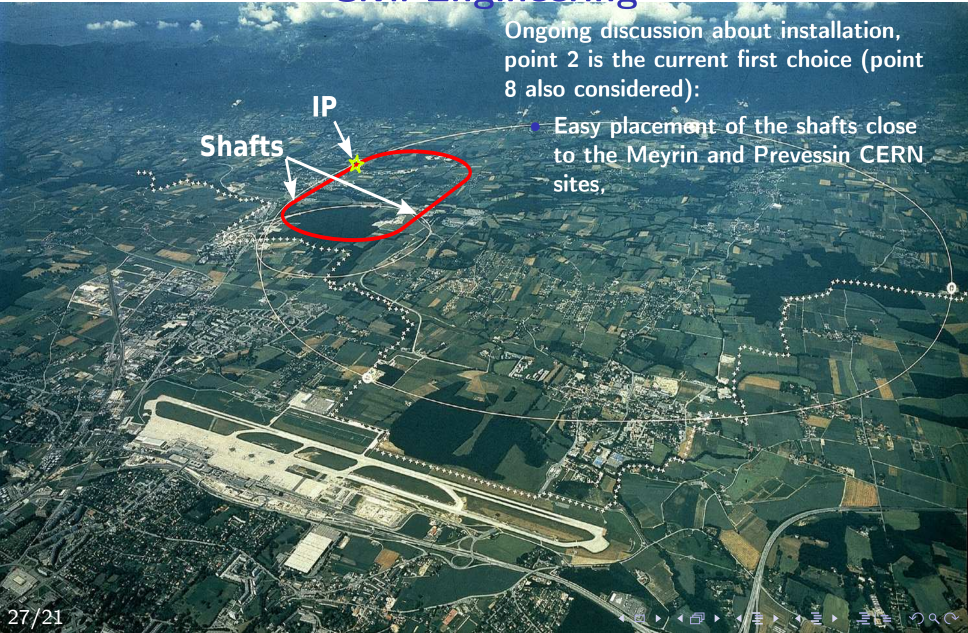


Second harmonic RF losses compensation (no RF curvature from it).

Civil Engineering

Ongoing discussion about installation, point 2 is the current first choice (point 8 also considered):

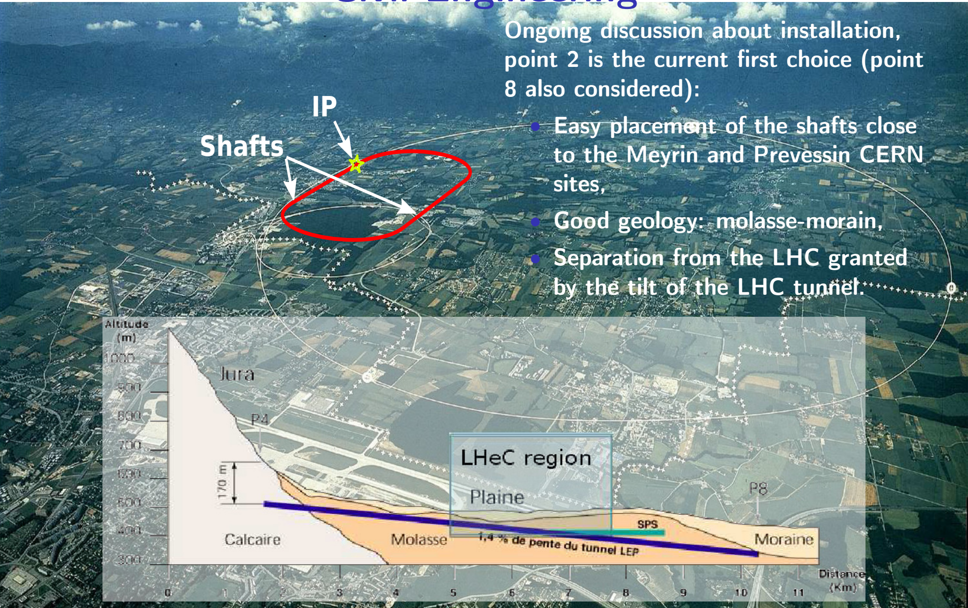
- Easy placement of the shafts close to the Meyrin and Prevessin CERN sites,



Civil Engineering

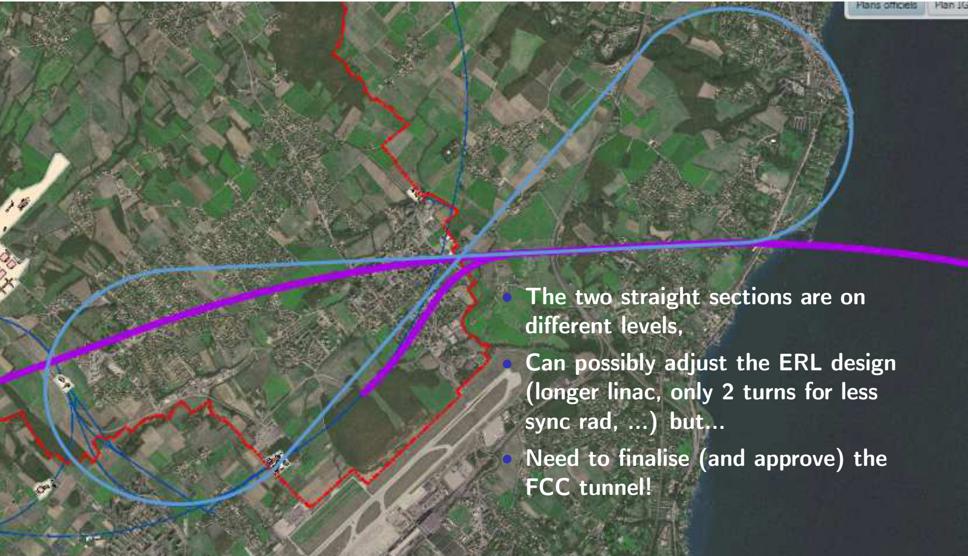
Ongoing discussion about installation, point 2 is the current first choice (point 8 also considered):

- Easy placement of the shafts close to the Meyrin and Prevessin CERN sites,
- Good geology: molasse-morain,
- Separation from the LHC granted by the tilt of the LHC tunnel.



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!