An Energy Recovery Electron Accelerator for DIS at the LHC

D. Schulte for the LHeC team

EPS, Stockholm, July 2013

LHeC Goal

- Collide LHC beam with electrons or positrons
  - Required lepton energy is ≥60GeV
  - Luminosity of $\approx 10^{33}cm^{-2}s^{-1}$ (proposal for $10^{34}cm^{-2}s^{-1}$ exists, but not verified)
  - Polarisation
  - No interference with pp physics
  - Detector acceptance down to 1°
  - Power consumption for lepton complex ≤100MW

- Study team provided CDR
  - Ring-ring option, feasible but impact LHC operation during installation
  - Linac-ring option, the baseline
  - Show that a solution exists, will now have to find the best solution
    - Already have a baseline and alternatives for some components
  - See http://www.cern.ch/hec

- CDR has been published as J. Phys. G: Nucl. Part. Phys. **39** (2012) 075001
  - Some design modification have been made since

Participating Institutes

CERN
LHeC

CERN
SLAC
NATIONAL ACCELERATOR LABORATORY
NTNU
Norwegian University of Science and Technology
The Cockcroft Institute
of Accelerator Science and Technology
Jefferson Lab
Thomas Jefferson National Accelerator Facility
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ANKARA ÜNİVERSİTESİ
NİĞDE ÜNİVERSİTESİ 1992
ULUDAĞ ÜNİVERSİTESİ 1975
TOBB ETU

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Laboratori Nazionali di Legnaro
DESY
Physique des accélérateurs
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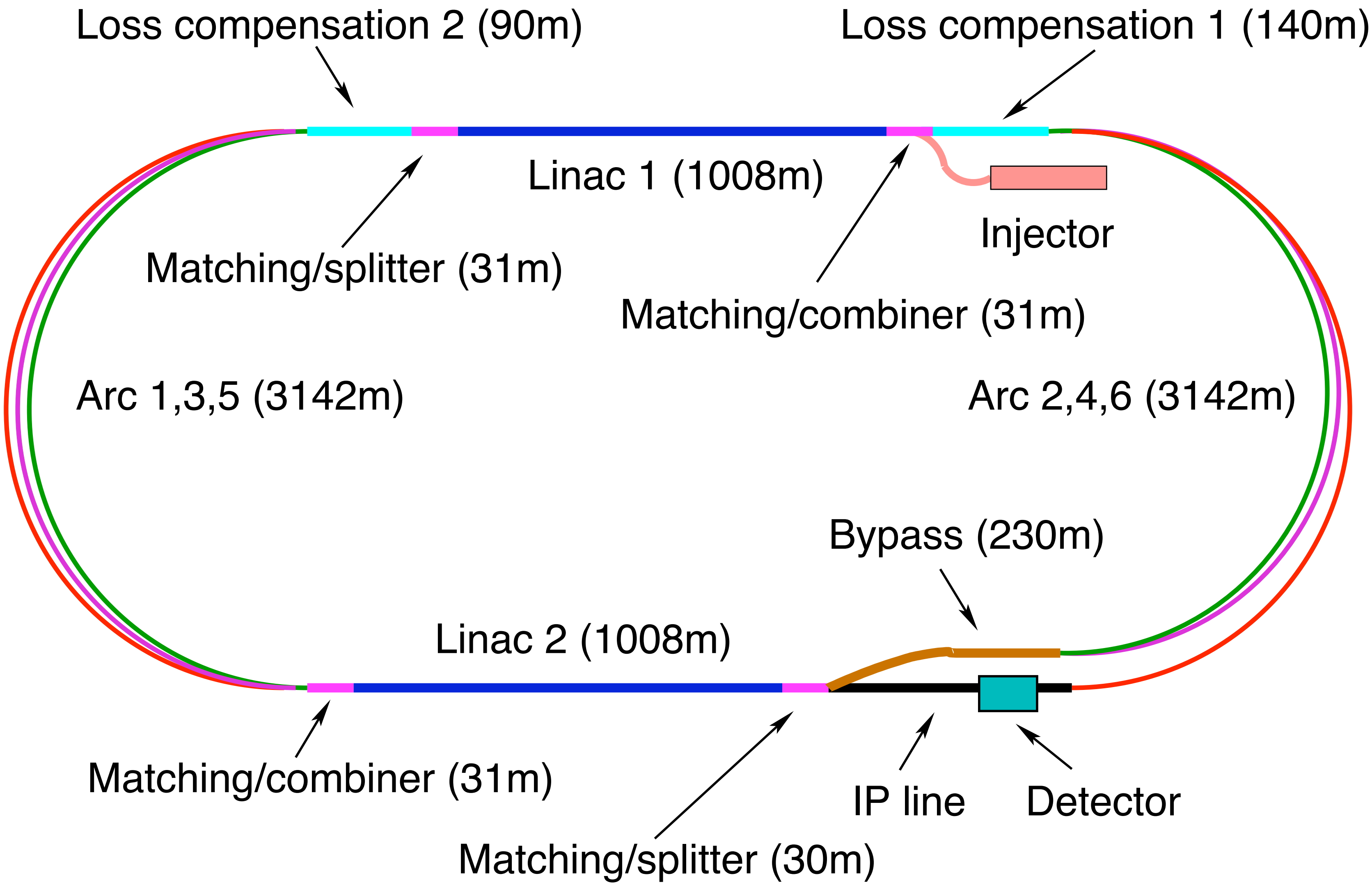
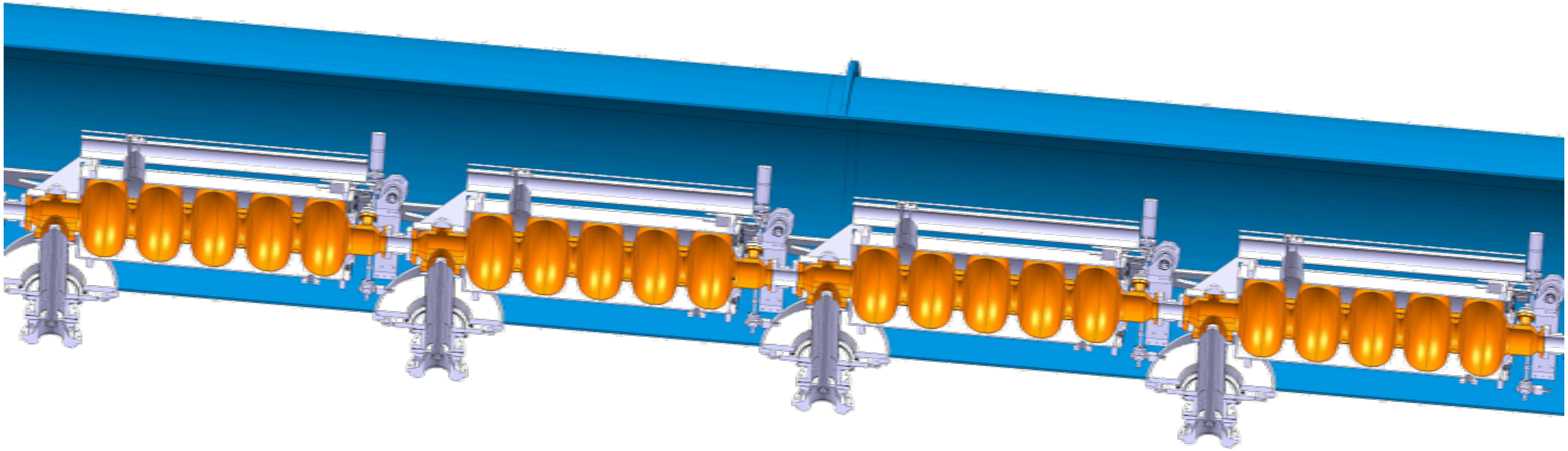
Baseline Linac-ring Layout

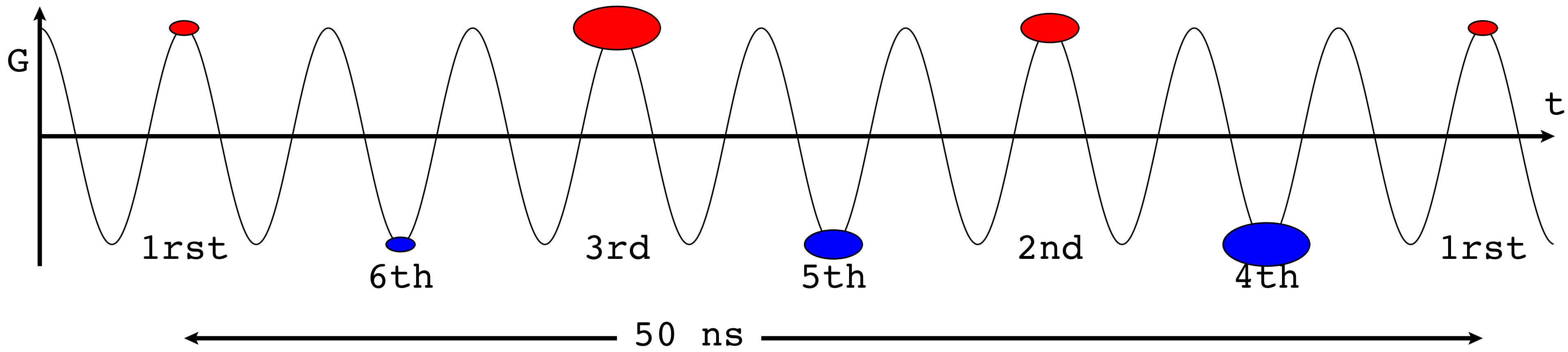


Linac Design



- In CDR: 8 cavities per 14m long module
  - 721.42MHz, 1.06m, 570Ω (linac convention), 20MV/m, (now 800MHz)
  - Will go to 801.6MHz (because will be used in LHC)
  - Q_0=2.5 10^{10} assumed, R=1.43 10^{13}Ω (ILC: R=1.04 10^{13}Ω)
- 2 modules per quadrupole pack (2m)
- ~60 modules per 1000m long linac
- Beam physicists assumed slightly different parameters (and only 18MV/m)

Beam Structure in Linac

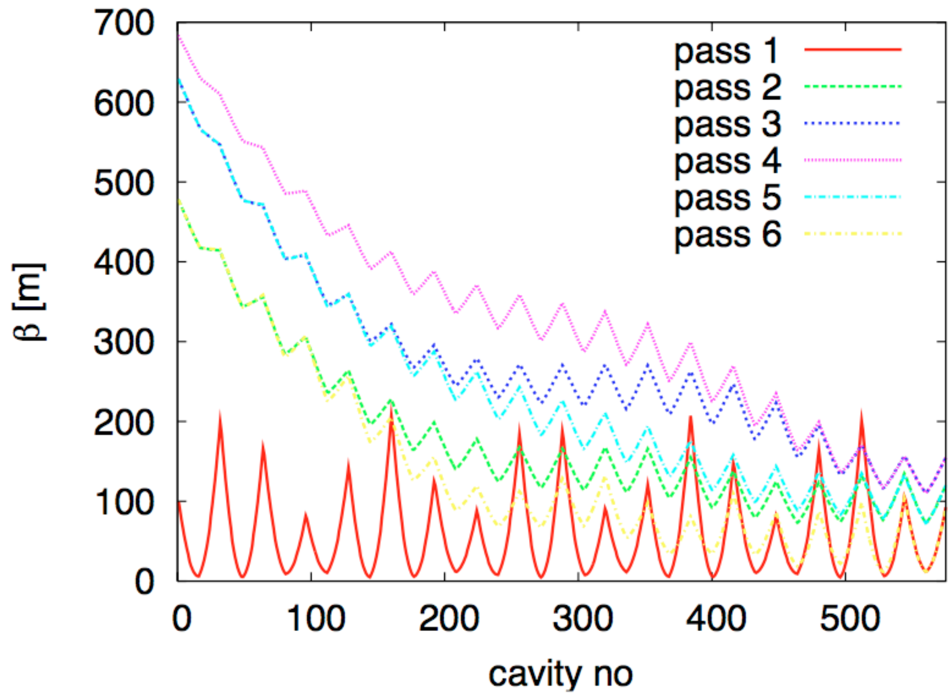


Bunches of different turns are interleaved

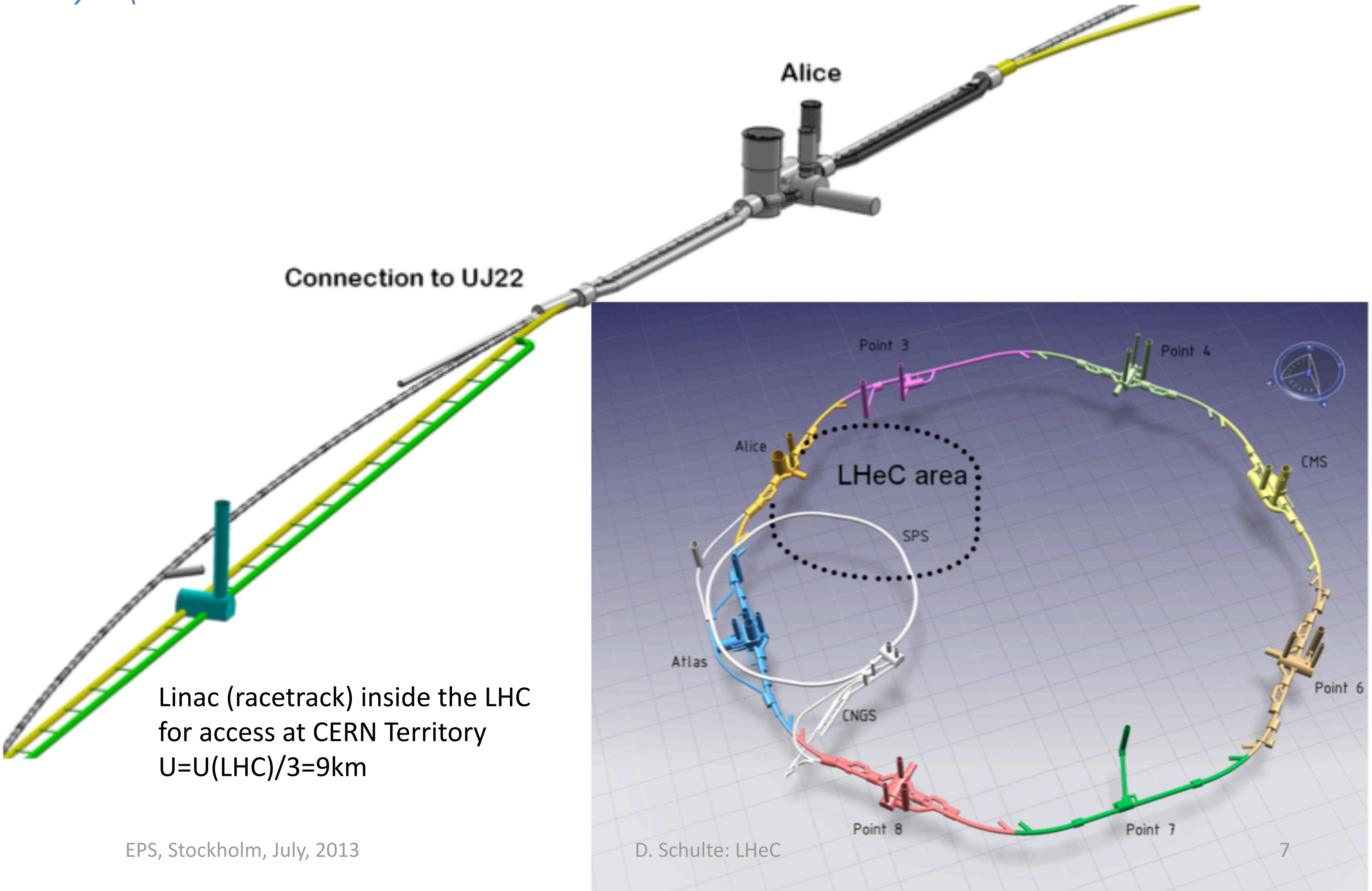
Interesting challenge for optics design and collective effects

- different energies
- wakefields
- fast beam-ion instability

We optimised the lattice to minimise multi-bunch wakefield effects

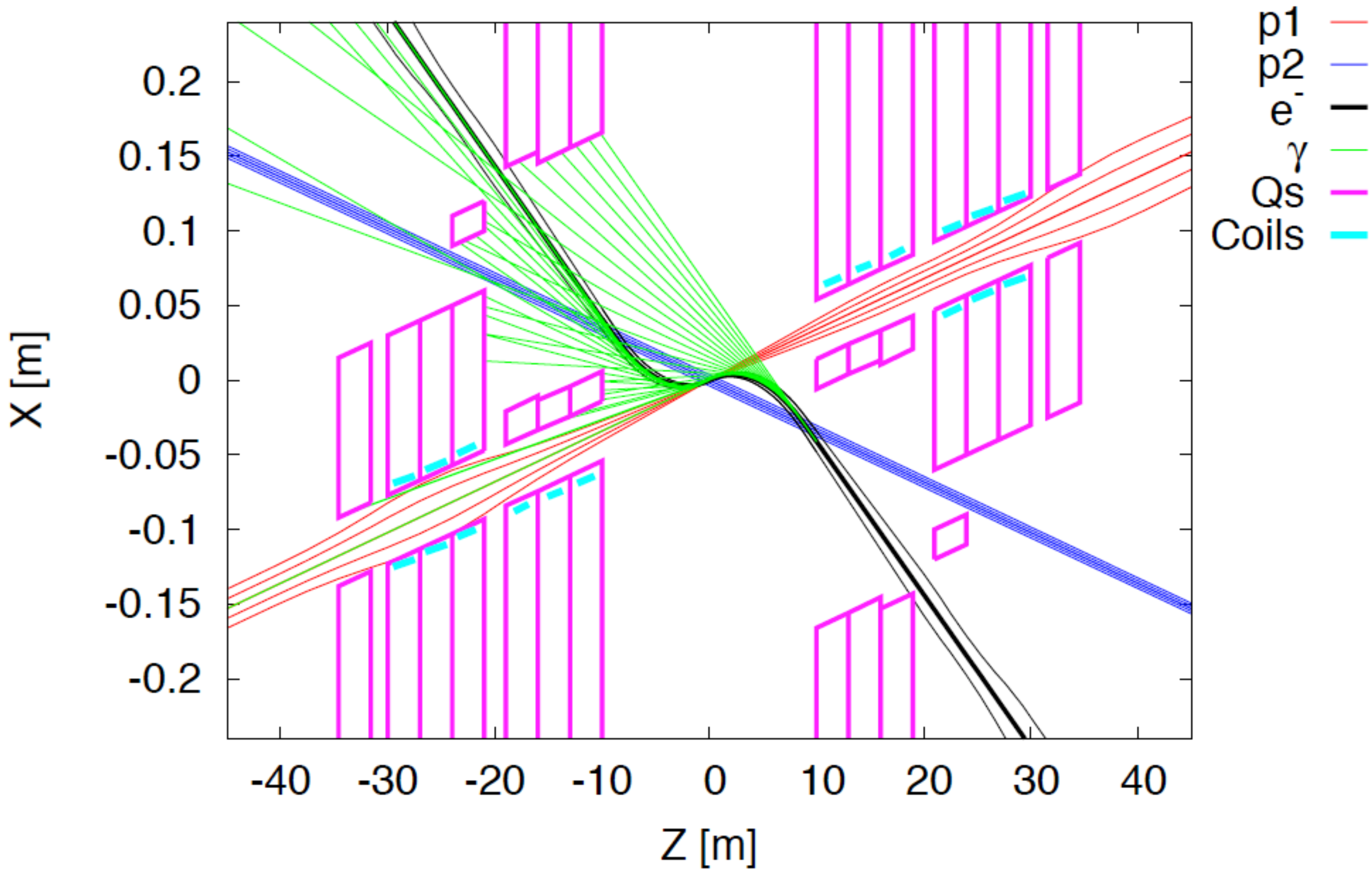


Integration with LHC



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

Interaction Region



0.3T dipole field to allow head-on collision

IP Parameters

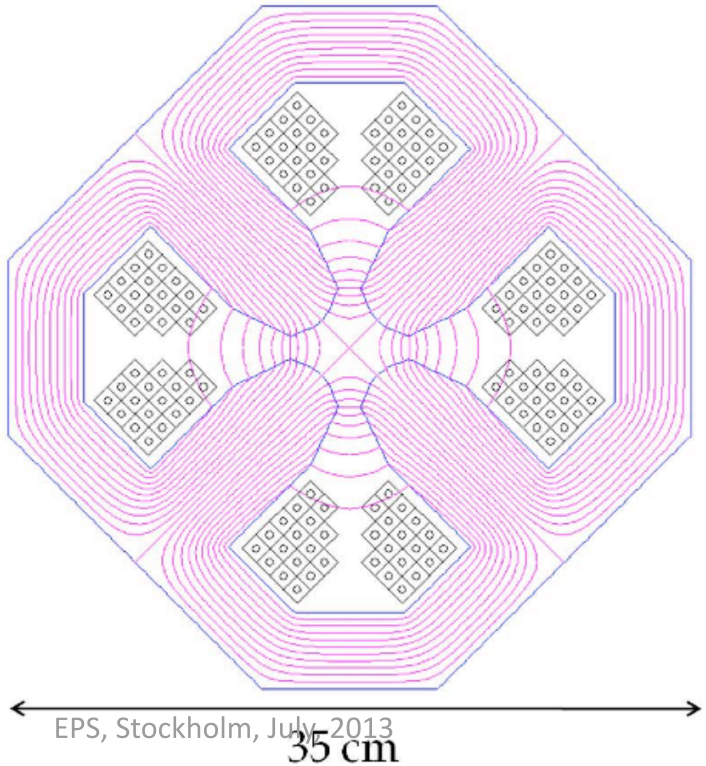
	protons	electrons
beam energy [GeV]	7000	60
Luminosity [$10^{33}cm^{-2}s^{-1}$]	1	
normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	3.75	50
IP beta function $\beta^*_{x,y}$ [m]	0.10	0.12
rms IP beam size $\sigma^*_{x,y}$ [μm]	7	7
rms IP divergence $\sigma'_{x,y}$ [μrad]	70	58
beam current [mA]	(860) 430	6.6
bunch spacing [ns]	(25) 50	(25) 50
bunch population	1.7×10^{11}	(1×10^9) 2×10^9
Effective crossing angle	0.0	

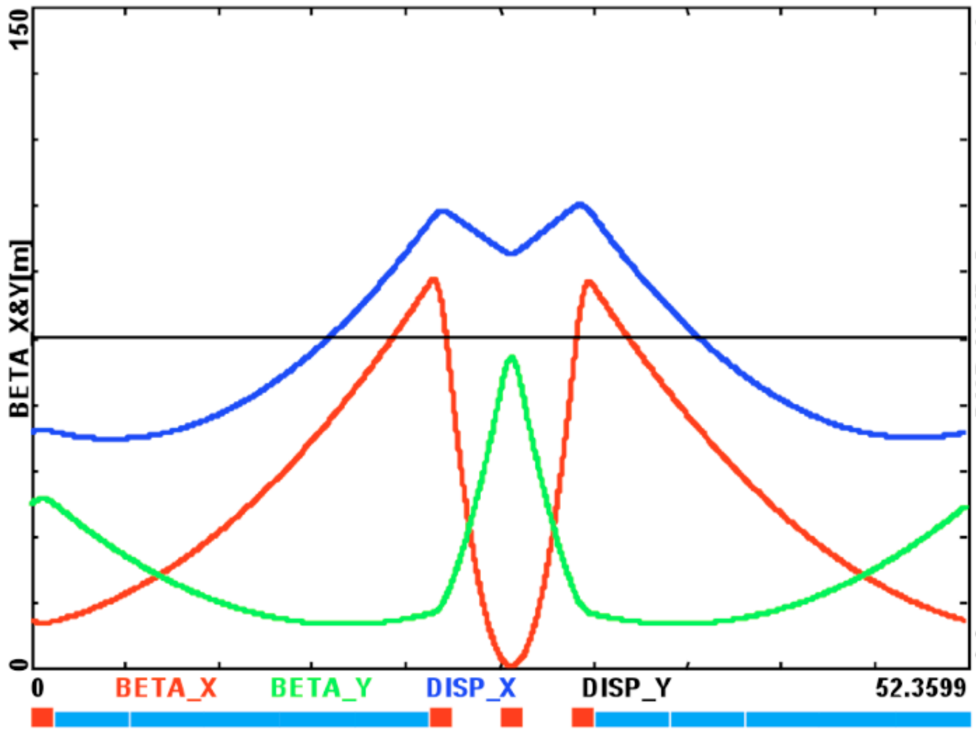
Arc Design

Lattice exist for all 6 arcs

- alternatives exist

Synchrotron radiation is OK for emittance (Δε ≤ 7μm, before collision)





A. Bogacz

Total of 1440 quadrupoles

3600 4m-long bends

Magnet designs exists

Power Consumption

- Luminosity is limited by allowed power consumption (100MW)

- Synchrotron radiation loss compensation RF
  - 20 MW
  - Can be calculated reliably
  - Include cryogenics etc for this part of the linacs

- Cryo power of linacs
  - 21 MW
  - Depends on cavity (Q_0) and gradient

- RF power to control linacs
  - 24 MW
  - Q_L due to microphonics, phase stability, …

- Injector and other consumers are less important
  - Depends on injection energy, hence wakefields etc.

Energy Loss

Energy loss due to synchrotron radiation in arcs (ρ=764m)

Total loss per particle about 1.9GeV

i.e. 12.2MW beam power

Compensated by additional linacs
60% wall plug to beam efficiency
-> 20.3MW

turn no	E GeV	ΔE [MeV]	$\sigma_E/E[\%]$
1	10.42	0.7	0.00036
2	20.33	9.8	0.0019
3	30.25	48.2	0.0053
4	40.17	150	0.011
5	50.08	362	0.020
6	60.0	746	0.033
7	50.08	362	0.044
8	40.17	150	0.056
9	30.25	48.2	0.074
10	20.33	9.8	0.11
11	10.42	0.7	0.216
dump	0.5	0.0	4.53

Linac Cooling

- Load from accelerating RF (720MHz, similar at 800MHz)
  - R/Q = 570 Ω (linac convention)
  - Gradient 20MV/m
  - $Q_0=2.5\ 10^{10}$
  - 31.5W/cavity
  - 944 cavities
  - Cooling inefficiency factor 700
  - Yields 21 MW expected cooling (dynamic heat load)

- Need to evaluate other cryo-loads
  - Beam induced HOM 0.1W in ILC RDR
  - Static heat load relatively less important

- Improvement of cavity (Q_0) will reduce cryo needs

Linac RF Power

Ideally only losses into the wall need to be replaced (Q_0=2.5 10^{10}, P_{loss}≈30W/cavity)
But need to control RF phase (small frequency errors due to mechanical vibrations, beam Phase errors etc.)

Need to couple cavity to the outside (Q_{ext}, Q_L)
This leads to power leaking from the cavity

Made relatively conservative assumption (Beam takes/leaves 420kW/cavity, we use 4% to control)

If we can establish more aggressive stability of RF in cavity, we could reduce the power

Assumed loaded Q_L	4.7 10^7
Compensating RF power required per cavity	16.8kW
Transmission losses	7%
RF power needed per cavity	17.9kW
Total RF power	17MW
Wall plug to RF power efficiency	70%
Total power	24MW

Note: Frequency Choice

- Choice between O(720MHz) and O(1.3GHz) made this year
  - 720MHz had been baseline for CDR

- Advantages of lower frequency
  - Reduced losses and less required cooling power
    - At 2K optimum f_{RF}=930MHz for fine-grain niobium (F. Marhauser)
    - f_{RF}=470MHz for large-grain niobium
  - Reduced wakefields
  - By choosing 800MHz, synergy with LHC

- Disadvantages
  - Somewhat higher RF cost
    - Might be offset by reduced cryo cost or improved performance

- Unclear
  - RF to control the cavity
    - Higher stored energy
    - More power to control same frequency spread due to microphonics
      - But cavity could be stiffer

Polarisation

- In linac-ring option polarisation should be reasonably straightforward for linac ring option
  - Expect O(80-90%)
  - Two options
    - Spin rotation before collision
    - Single collision and few turns allow to properly turn spin at injection
      - Some depolarisation expected but probably at the few percent level
  - Detail studies remain to be done
    - Depolarisation in arcs
    - Effective depolarisation in beam-beam collision
    - But expect positive outcome
- In ring-ring option polarisation would be quite difficult
  - Spin rotators required, sensitive to imperfections, most optimistic number is 25-40%

Positrons

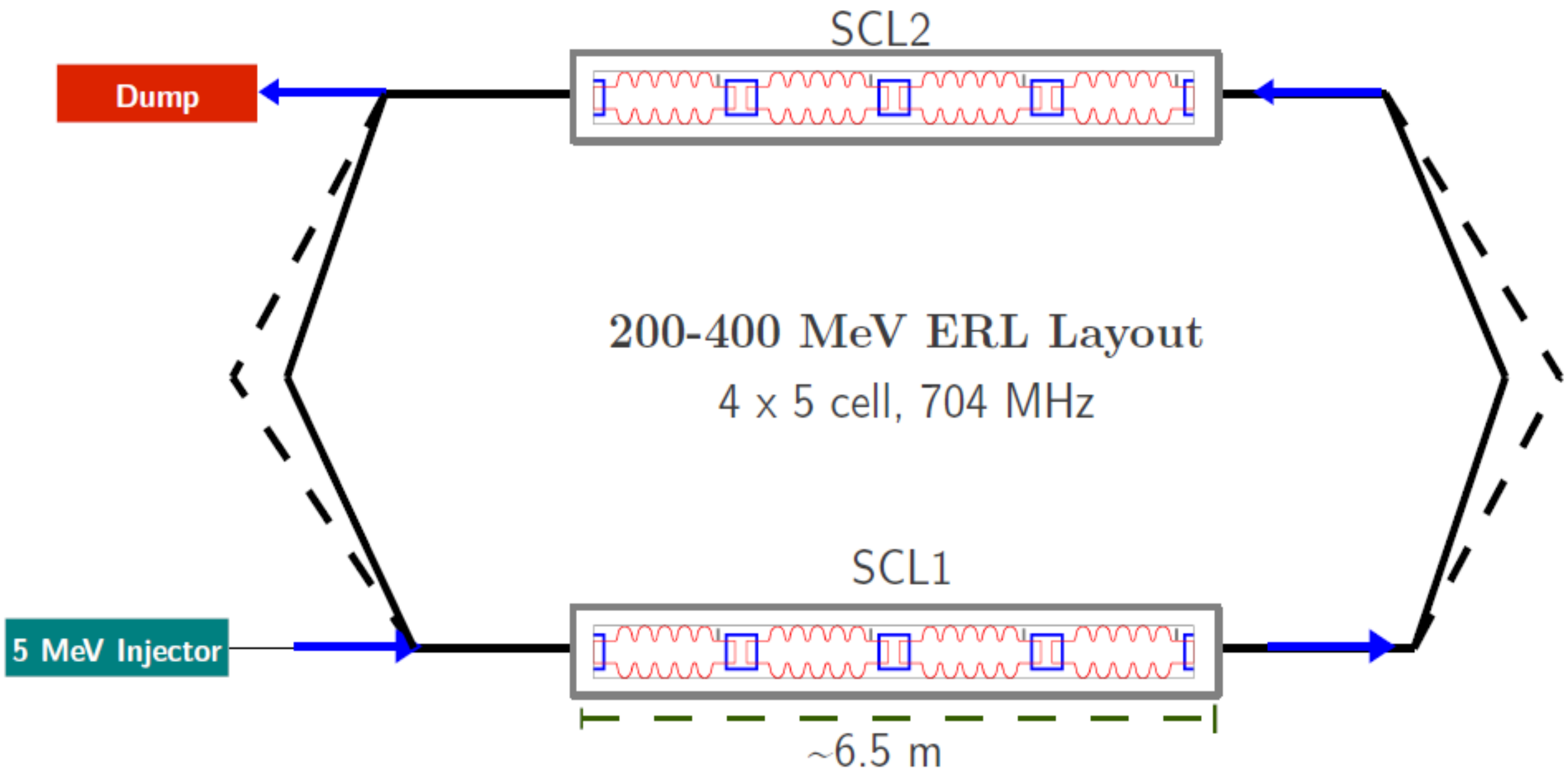
- Difficult for the linac-ring option
  - Total positron current is huge (about 100 times more than in ILC)
  - The ILC positron source does not work for LHeC (beam energy is too small)
  - A number of options have been suggested
    - but are all very challenging
    - Do not forget: the energy per produced positron has to remain below some GeV to be able to have same current and similar power consumption
  - Positrons on protons generate anti-pinch
    - Leads to luminosity reduction
  - Will most likely have to accept very much reduced luminosity with positrons (orders of magnitude)

- No significant problem for the ring-ring option
  - Need a positron source, but current is not large, since particles are used more often

ERL Test Facility at CERN

Potential layout
Other options exist

Test of power consumption (Q_0, Q_{ext}, Q_L)
And beam control
Will allow to adjust design beam parameters



Beam Dynamics Issues

- Emittance growth from arc design is OK
- Single bunch stability in linacs has been verified
- ILC-type alignment is sufficient for linacs

- Multi-bunch transverse beam-break-up is OK
  - Damping and cavity-to-cavity detuning needed
  - Including amplification due to beam-beam effect
  - Would be slightly marginal for 1.3GHz
- Fast beam-ion instability has been estimated
  - Should be OK with gap and 10^{-11}hPa partial pressure
  - Phase advance error due to ions is also OK
  - Full simulation missing

- Beam-beam effects are rough for electrons
  - But should be OK for spent beam
  - Impact on LHC beam appears acceptable but requires some more study
  - May require use of feedback and feed-forward

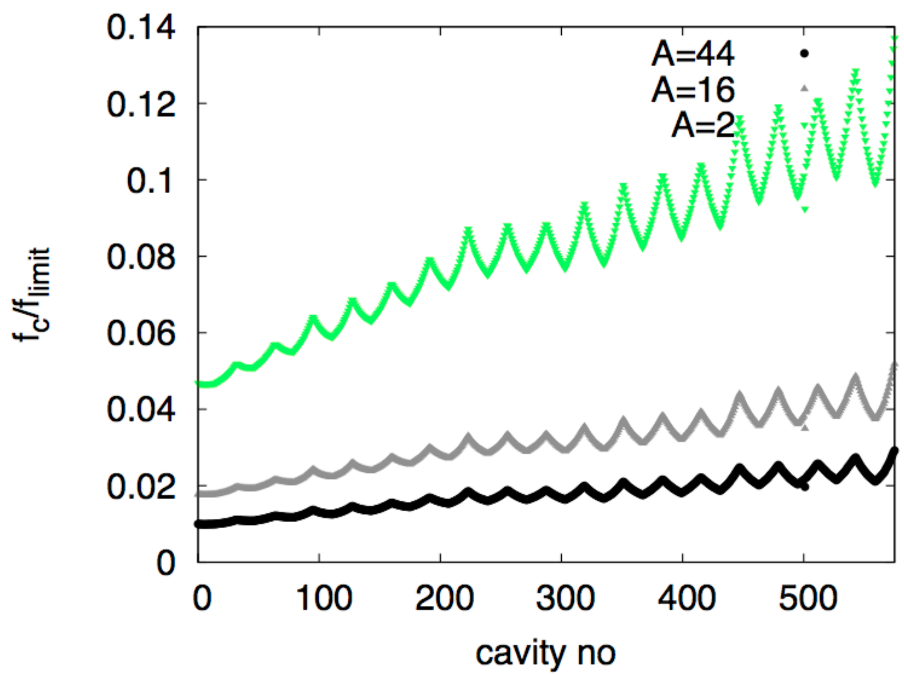
- More detailed studies would be desirable

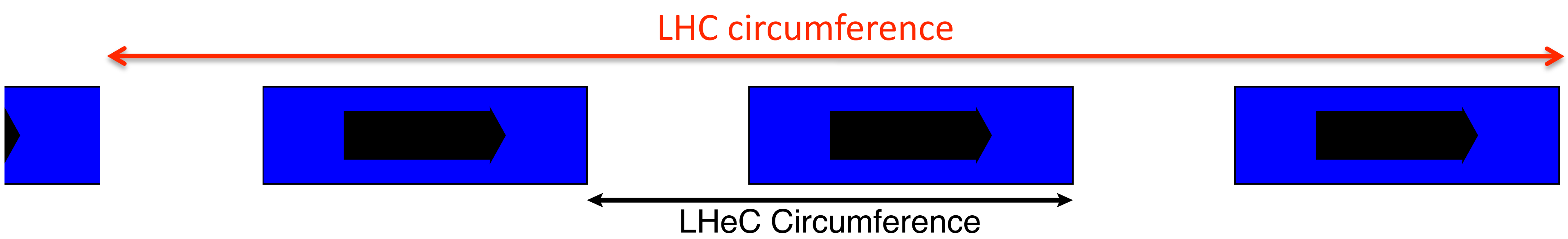
Potential Beam Pulse and Fast Beam-ion Instability

- Fast beam-ion instability may require a long gap
  - All ions are trapped in continuous beam ($f_c < f_{limit}$)
  - Beam will become unstable before neutralisation is reached

- Gaps of different turns need to overlap
  - Fix LHeC circumference to be 1/n of LHC
  - Each LHC bunch always or never collides with electron bunches

- Would increase bunch charge by 50% to 3×10^9
  - Needs to be reviewed



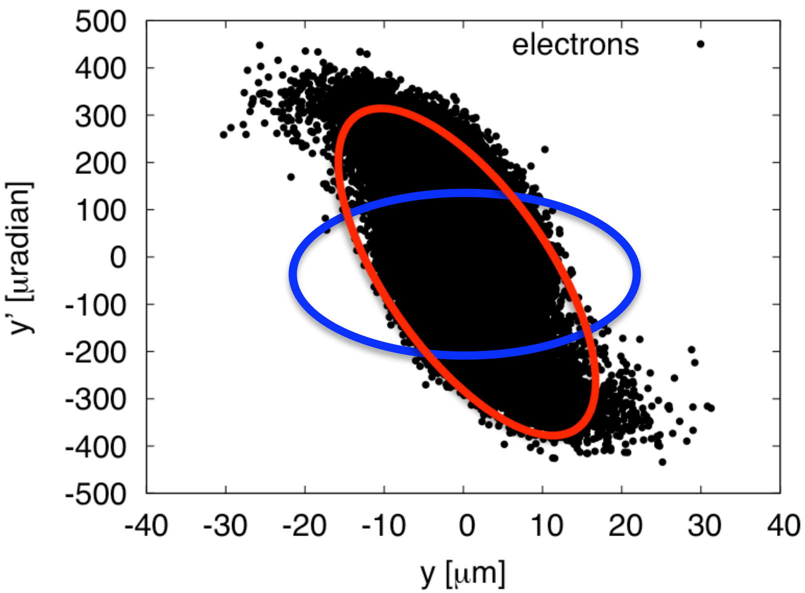


Beam-beam Effects

The main impact of LHeC on the proton beam

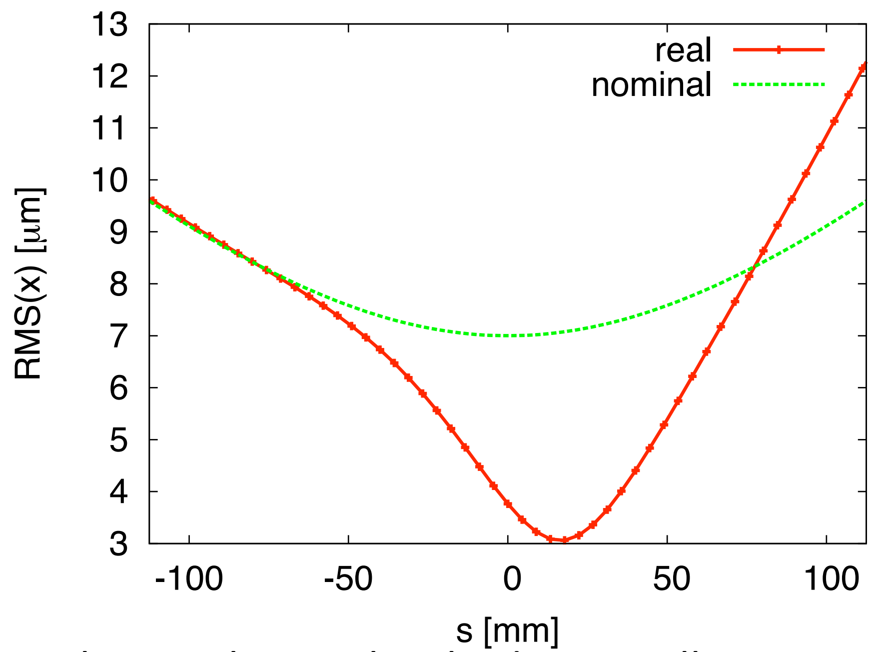
Disruption parameter is 6.2 for electrons
Ratio of focal length to bunch length

$$D_y = \frac{\sigma_z}{f_y} = \frac{2Nr_e\sigma_z}{(E/m_e)\sigma_y(\sigma_x+\sigma_y)}$$



Spent electron beam shown

Need special optics to catch electron beam



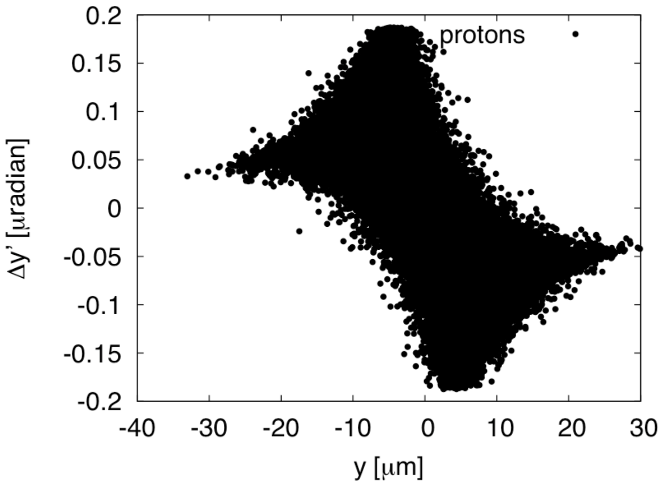
Electron beam shrinks during collision
Increases beam-beam tune shift for protons

Beam-beam Effects II

Nominal beam-beam tune shift 1.2×10^{-4} for protons

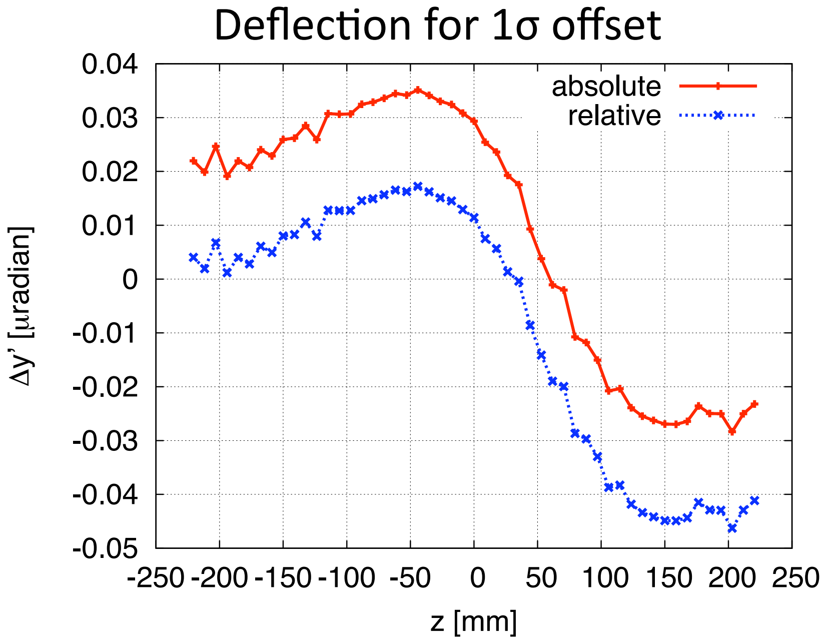
$$\xi_y = \frac{N r_e \beta_y}{2\pi (E/m_e)\sigma_y(\sigma_x + \sigma_y)}$$

Proton deflection as function of initial offset:



Real beam-beam tune shift is 6×10^{-4} for Protons due to electron beam disruption

Disruption also modifies collision with offsets



Beam-beam offset leads to emittance growth in proton beam

Conservative estimate:

$$\frac{\Delta\varepsilon}{\varepsilon} = O\left(10^{-7}\right)\frac{\sigma_{jitter}^2}{\sigma^2}$$

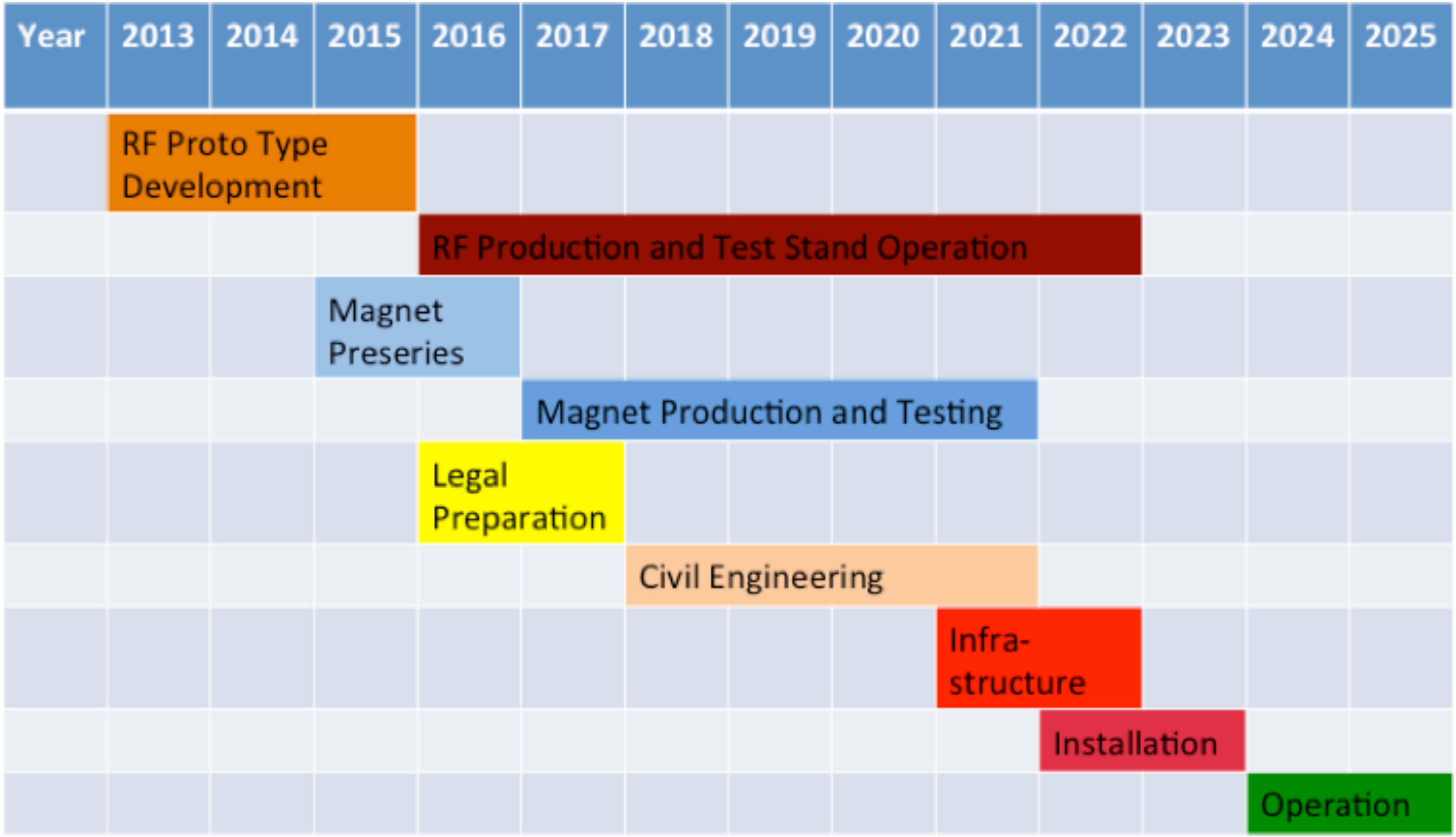
Cured by limiting beam-beam jitter to O(1%σ)

High Luminosity Proposal

	protons	electrons
beam energy [GeV]	7000	60
Luminosity [10^{33}]	1 -> 10	
normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	3.75 -> 2	50
IP beta function $\beta^*_{x,y}$ [m]	0.1 -> 0.05	0.12 -> 0.032
rms IP beam size $\sigma^*_{x,y}$ [μm]	7.2 -> 3.7	7.2 -> 3.7
beam current [mA]	860	6.4 -> 12.8
bunch spacing [ns]	25	25
bunch population	1.7×10^{11} -> 2.2×10^{11}	1×10^{9} -> 2×10^{9}
Effective crossing angle	0.0	

Oliver Brüning, Max Klein

LHeC Tentative Time Schedule



O. Brüning

Summary and Outlook

- LHeC appears feasible

- Significant room for optimisation in design
  - Choice of RF frequency has now been done
  - Basic parameter choice should be reviewed for further improvements (higher luminosity?)
  - In particular better understanding of possibility to improve Q_0, Q_L

- Future plans
  - Formation of a collaboration
  - R&D on individual components
  - Preparation of a test facility proposal
  - Some beam dynamics studies

- Resources situation is somewhat unclear