LHeC Accelerator Aspects

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DESY

ENC/EIC Collider Workshop
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Sept. 2009

Outline

- Motivation
- Overview
- Ring-Ring Option
- LINAC-Ring Option
- Conclusions

- Goal: conceptual design report end of 2010

Mainly reporting on status at the
2nd CERN-ECFA-NuPECC LHeC Workhop
1-3 Sept. 2009, Divonne
Using many slides from B. Holzer and
F. Zimmermann

Motivation for LHeC

M.Klein

Electron proton (nucleon) collisions in the LHC

- Unfolding completely the partonic structure of the proton (neutron and photon) and search for sub-substructure down to scales ten times below HERA limits
- Sensitive exploration of new symmetries and the grand unification of particle interactions with electroweak and strong interaction measurements of unprecedented precision
- Search for and exploration of new Tera scale physics, in particular for singly produced new states (LQ, RPV SUSY, excited fermions), complementary to the LHC pp program
- Exploration of high density matter (low x physics beyond the expected unitarity limit for the growth of the gluon density)
- Unfolding the substructure and parton dynamics inside nuclei and study of quark-gluon plasma matter, by an extension of the kinematic range of lepton-nucleus scattering by 4 orders of magnitude

Particle Physics Goals

- Lepton energies 50 to 150 GeV
- Maximum luminosity ≥ 10^{33} cm^{-2} s^{-1}
- Electron and positron beams
- Lepton polarization

- Rich physics program
  - High and low Q^2 physics

Talk by O. Behnke

LHeC Overview

Several options

Accelerator Design [RR and LR]

Oliver Bruening (CERN),

John Dainton (CI/Liverpool)

Interaction Region and Fwd/Bwd

Bernhard Holzer (CERN),

Uwe Schneeekloth (DESY),

Pierre van Mechelen (Antwerpen)

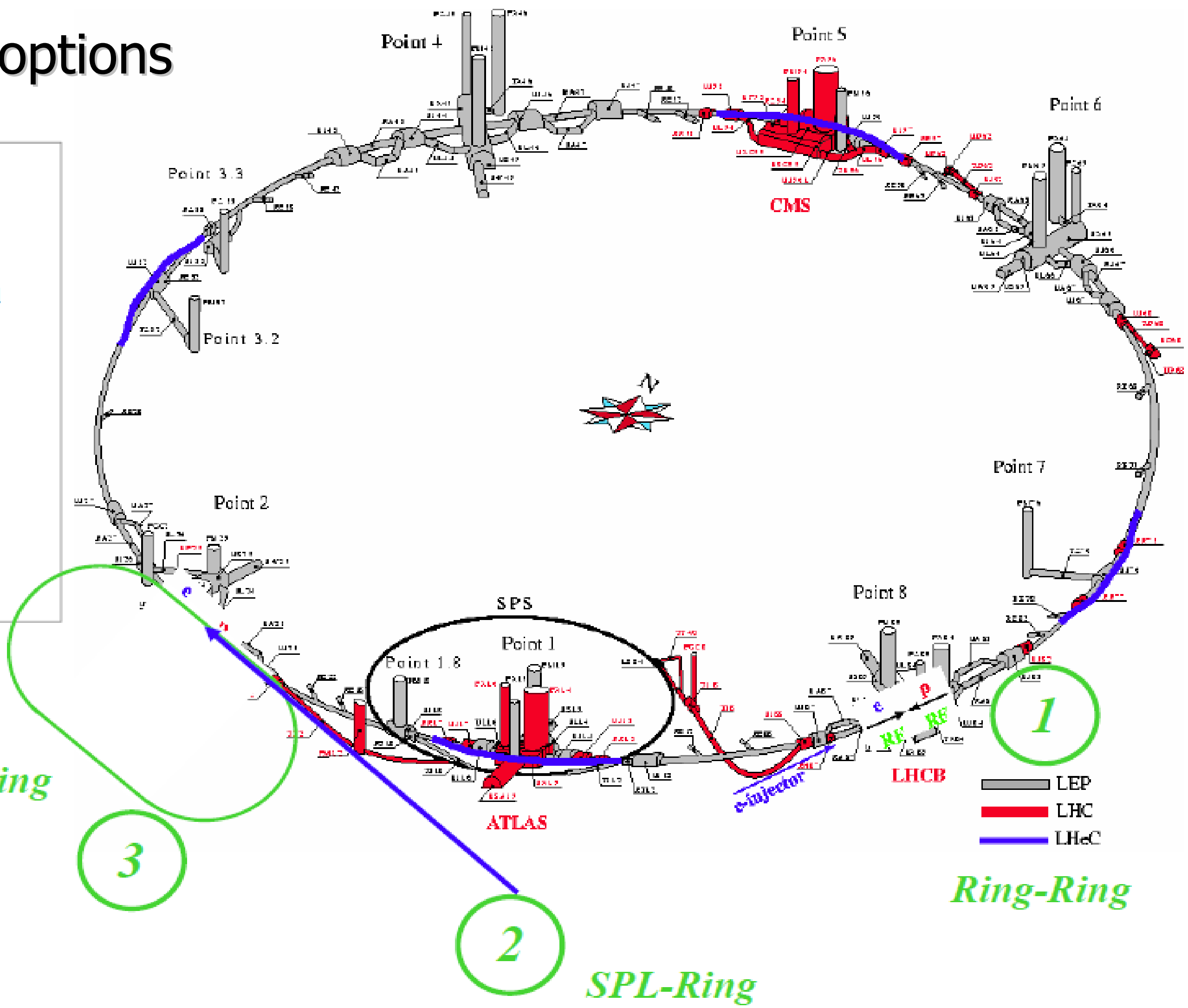
Detector Design

Peter Kostka (DESY),

Rainer Wallny (UCLA),

Alessandro Polini (Bologna)

... and many colleagues



LHeC Overview

General Statement

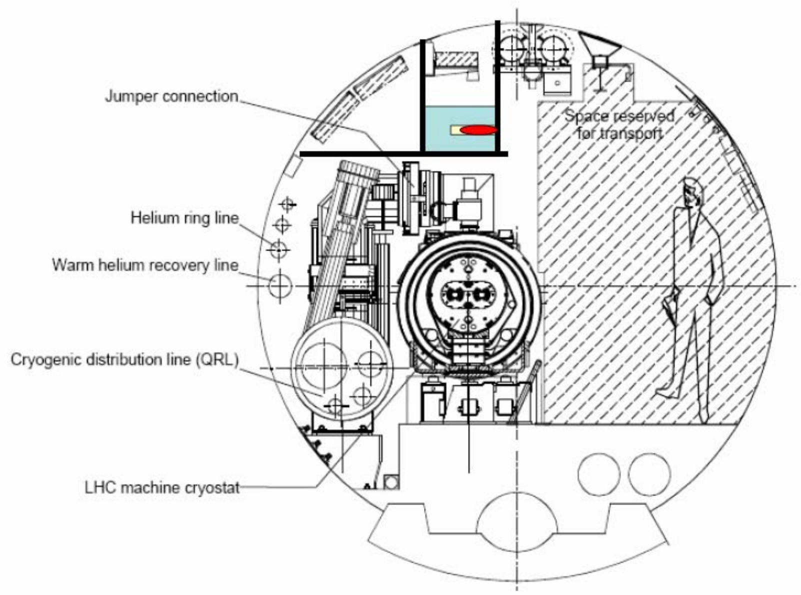
- Whatever we do ... the layout of the LHC delivers an enormous potential for e/p luminosity (B. Holzer)

  proton beam

  2808 bunches, 7 TeV → $\varepsilon_n = 3.75\ \mu m$

Example: LHeC Ring-Ring: basic parameters

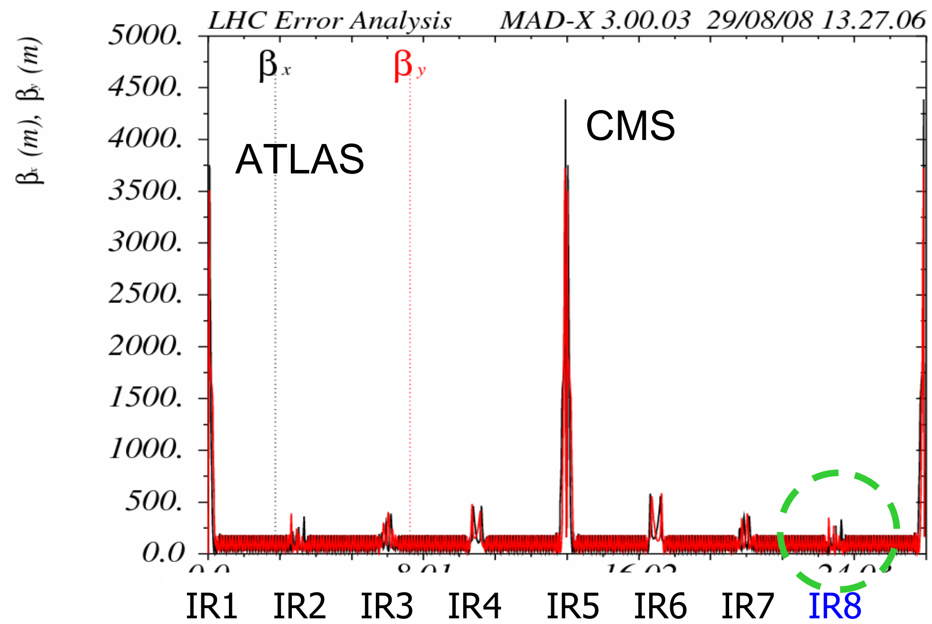
	Protons	Electrons
Standard Parameters	$N_p = 1.15 \cdot 10^{11}$	$N_e = 1.4 \cdot 10^{10}$
	$n_b = 2808$	$n_b = 2808$
	$I_p = 582\,mA$	$I_e = 71\,mA$
Optics	$\beta_{xp} = 180\,cm$	$\beta_{xe} = 12.7\,cm$
	$\beta_{yp} = 50\,cm$	$\beta_{ye} = 7.1\,cm$
	$\varepsilon_{xp} = 0.5\,nm\ rad$	$\varepsilon_{xe} = 7.6\,nm\ rad$
	$\varepsilon_{yp} = 0.5\,nm\ rad$	$\varepsilon_{ye} = 3.8\,nm\ rad$
Beam size	$\sigma_{xp} = 30\ \mu m$	$\sigma_{xe} = 30\,\mu m$
	$\sigma_{yp} = 15.8\ \mu m$	$\sigma_{ye} = 15.8\,\mu m$
Luminosity	$8.2 \cdot 10^{32}\ cm^{-2}\ s^{-1}$	



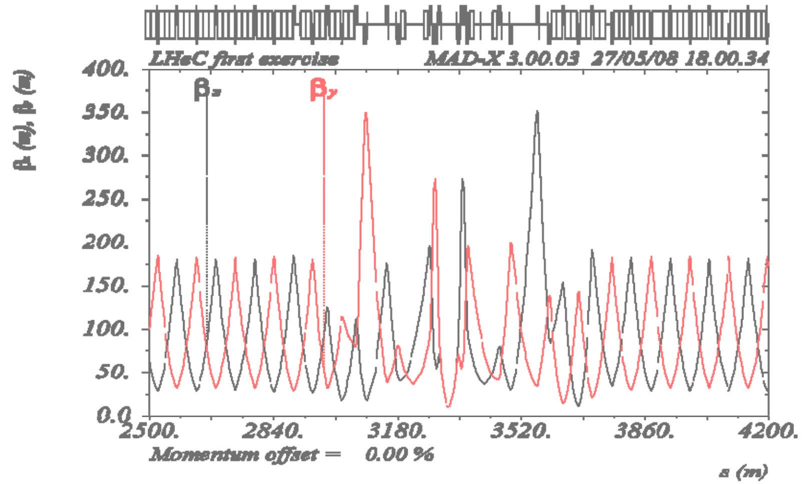
e storage ring on top of LHC

Proton Optics

LHC Standard Luminosity Optics

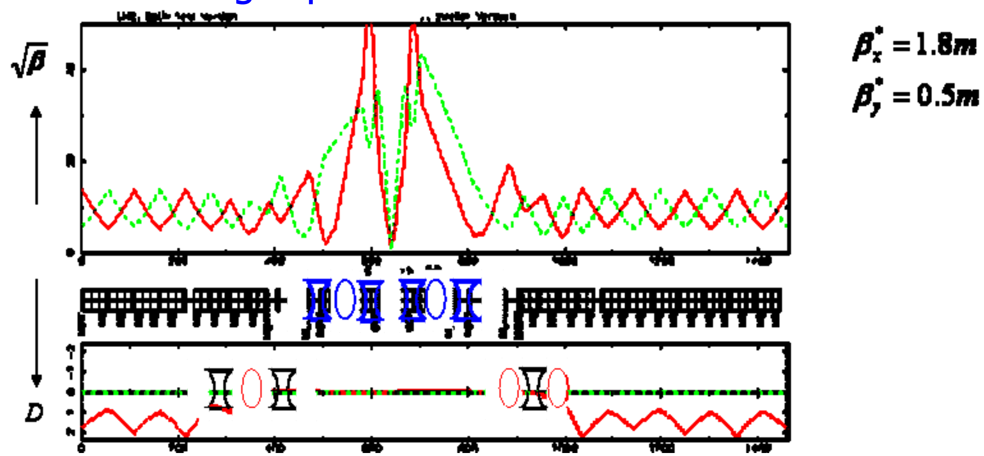


Standard LHC IR8 Optics



new p optics
including triplet for the e-beam

B. Holzer

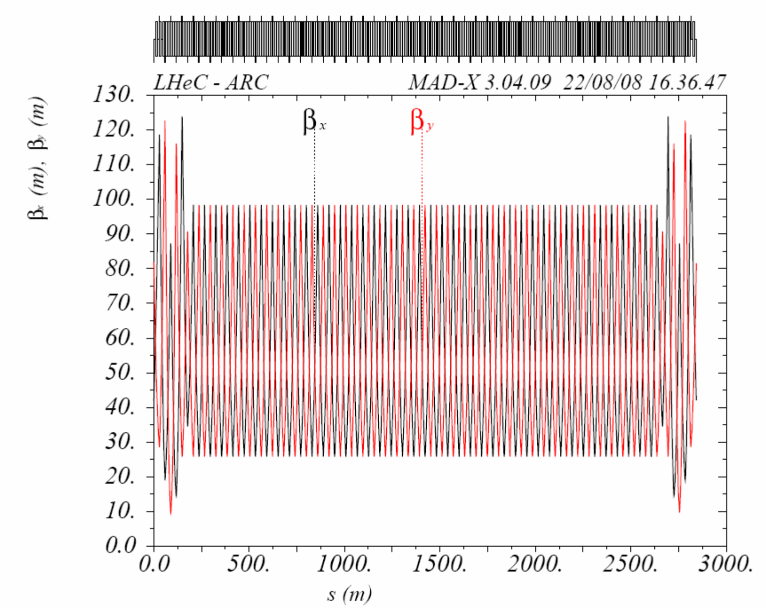


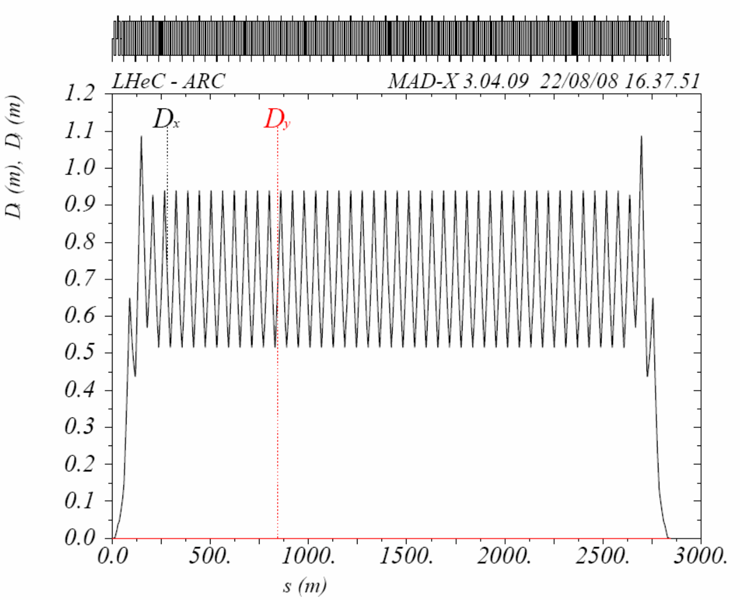
Electron Ring Optics

- Design constraints
  - Matched beam sizes at the IP required for stable operation.
  - Tolerable beam-beam tune shift parameters ... for both beams
  - Choose parameters close to LEP design and optimise the lattice for one ep interaction region

	LEP	*LHeC*
cell length	*79m*	*59.25m*
phase advance	*60/90/108°*	*72°*
number of cells	*290*	*384*

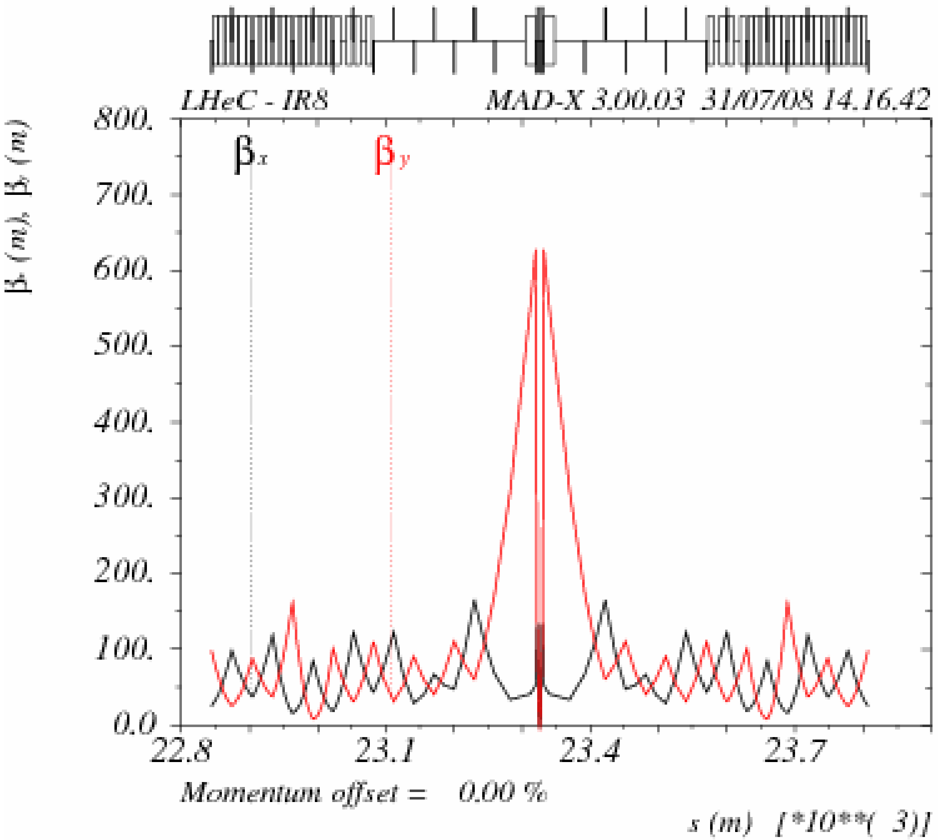
A. Kling

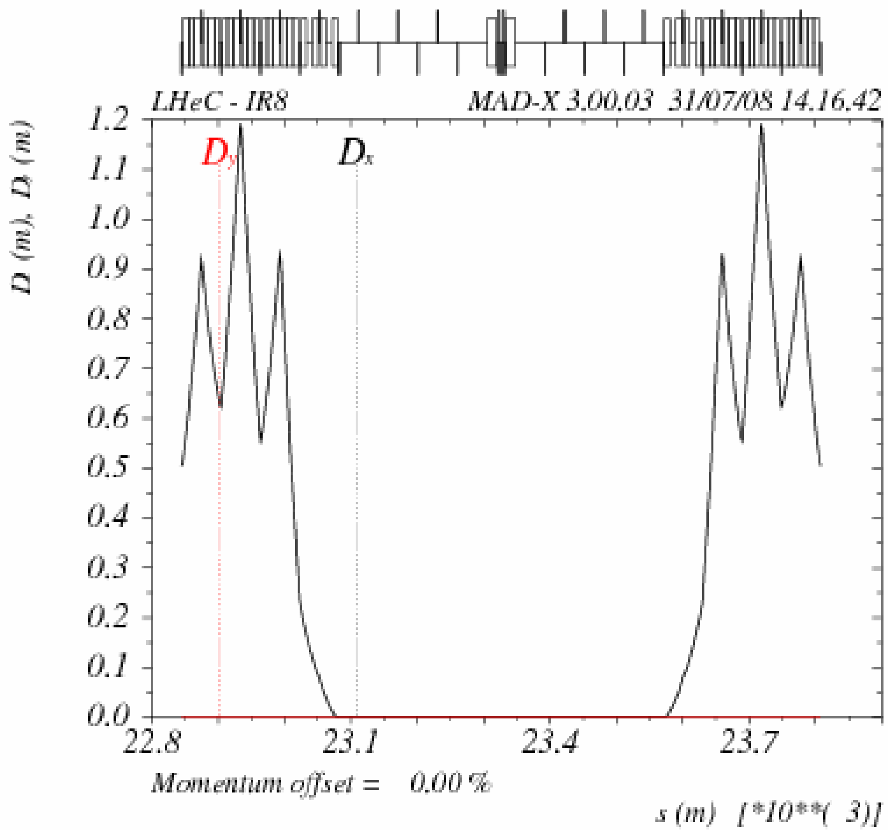




Electron Ring: IR 8 Optics

A. Kling





Electron Ring IR

Layout IR 8

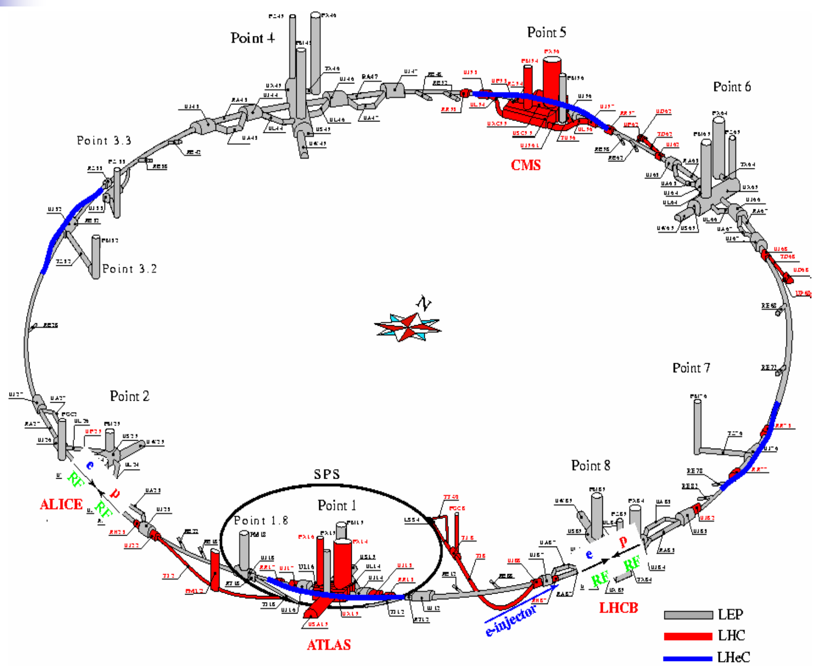
- Triplet focusing
- Triplet displaced to allow for a quick beam separation
  --> additional dispersion created close to IP
- Beam separation facilitated by crossing angle (1.5 mrad)
  15 m long soft separation dipole completes separation
  before the focusing elements of the proton beams.
- Interleaved magnet structure of the two rings: First matching quadrupole after the triplet: at 66.43 m to adjust optical functions --> try to avoid "large" β-functions
- Asymmetric layout (asymmetrically powered dispersion suppressors)
- Optical functions matched to the values at IP:

  $\beta x = 12.7cm$, $\beta y = 7.1$ cm

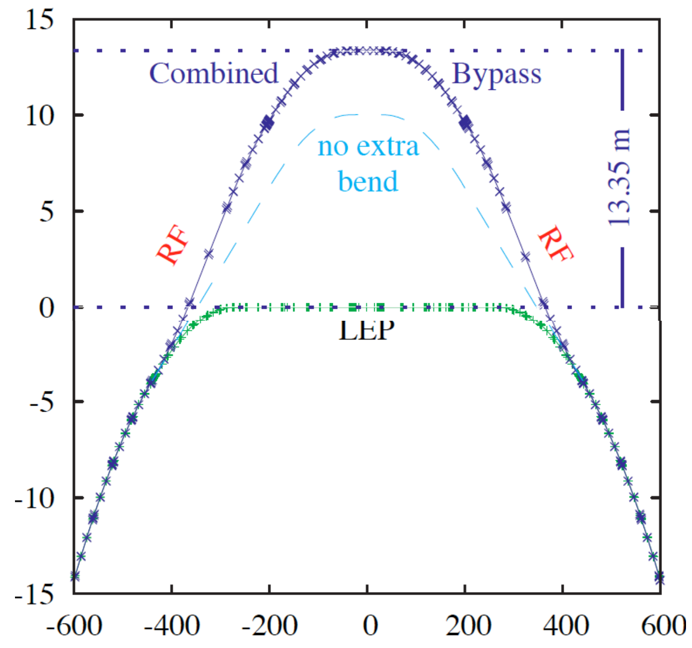
Layout IR 1 & 5

- Electron bypass at ATLAS and CMS

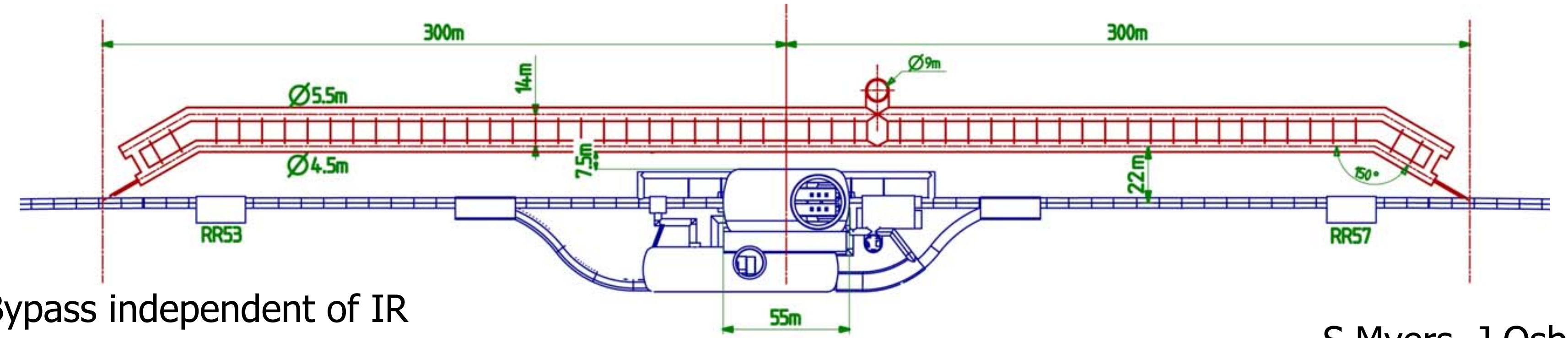
Electron Beam Bypass in IR 1 & 5



layout of bypass, H. Burkhardt



Top view



Bypass independent of IR
~30m distance, 1 shaft

S.Myers, J.Osborne

Ring-Ring IR Design

F. Willeke

	Protons	Electrons
Standard Parameters	$N_p=1.15*10^{11}$	$N_e=1.4*10^{10}$
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Beam size	$\sigma_{xp}=30\ \mu m$	$\sigma_{xe}=30\ \mu m$
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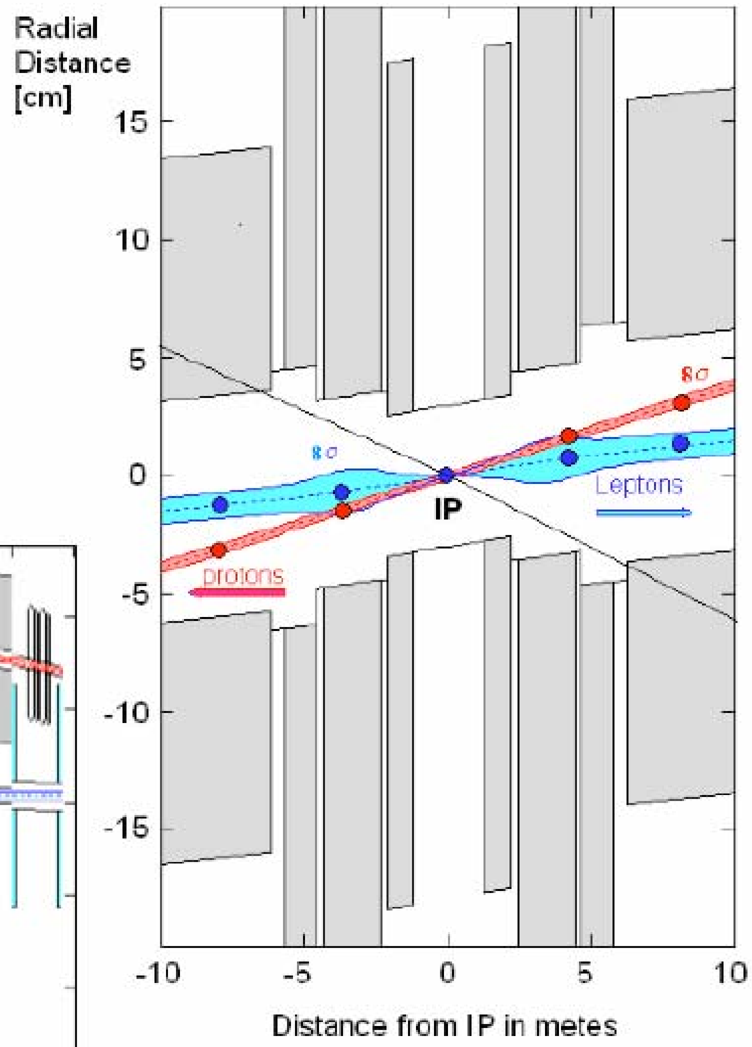
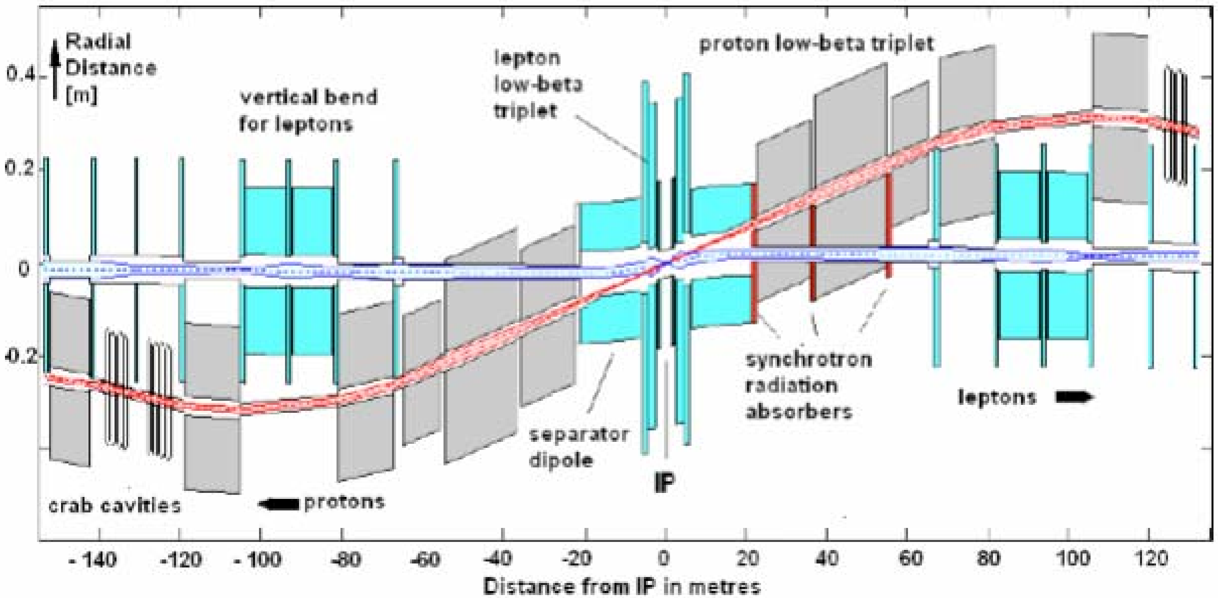
Luminosity	$8.2*10^{32}\ cm^{-2}\ s^{-1}$	



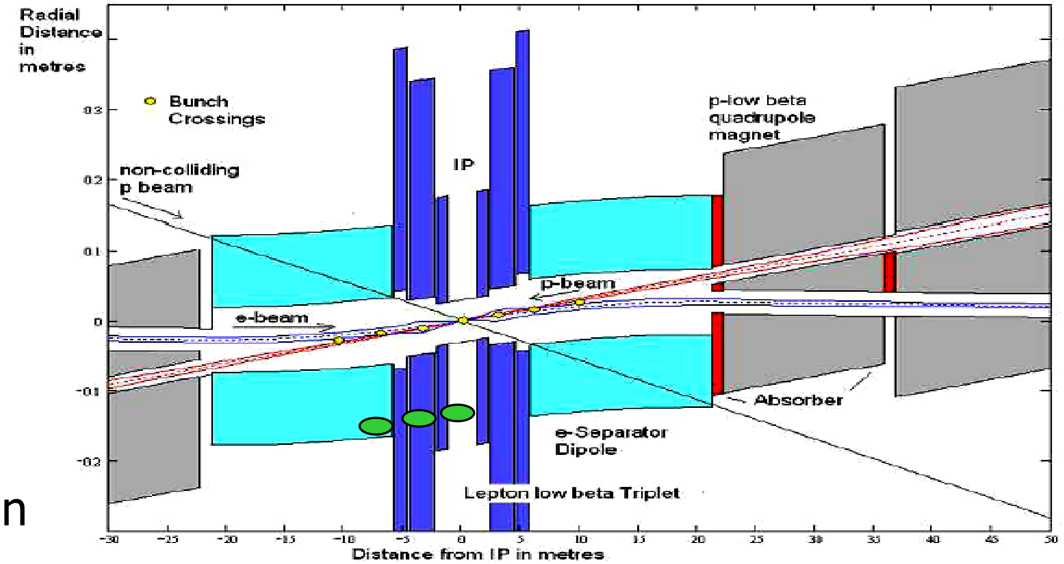


IR Design Challenges

F. Willeke

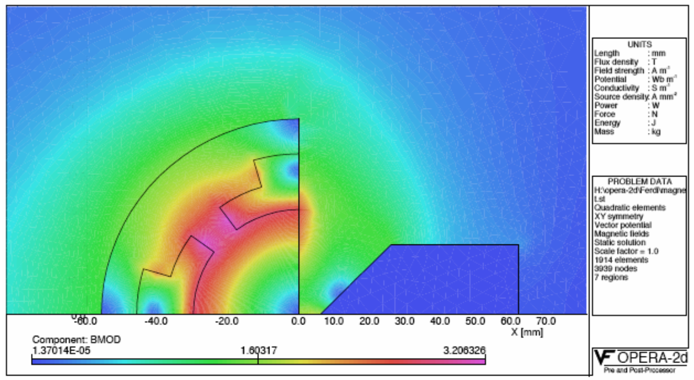
Advantage of LHC: Large number of bunches → high luminosity
Disadvantage: Need fast beam separation, crossing angle to support separation

LHC bunch distance: 25 ns
1st parasitic crossing: 3.75m
First e-quad positioned at 1.2m
... too far for sufficient beam separation
Separation has "to start at the IP"

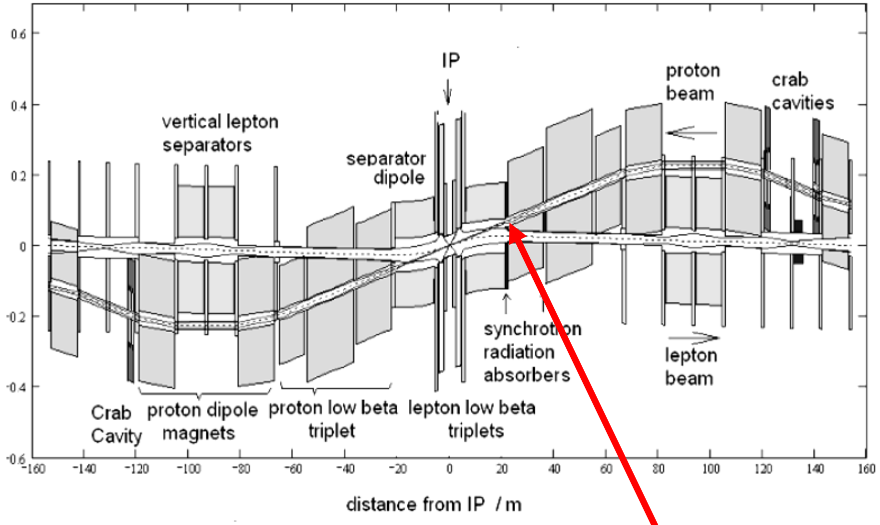


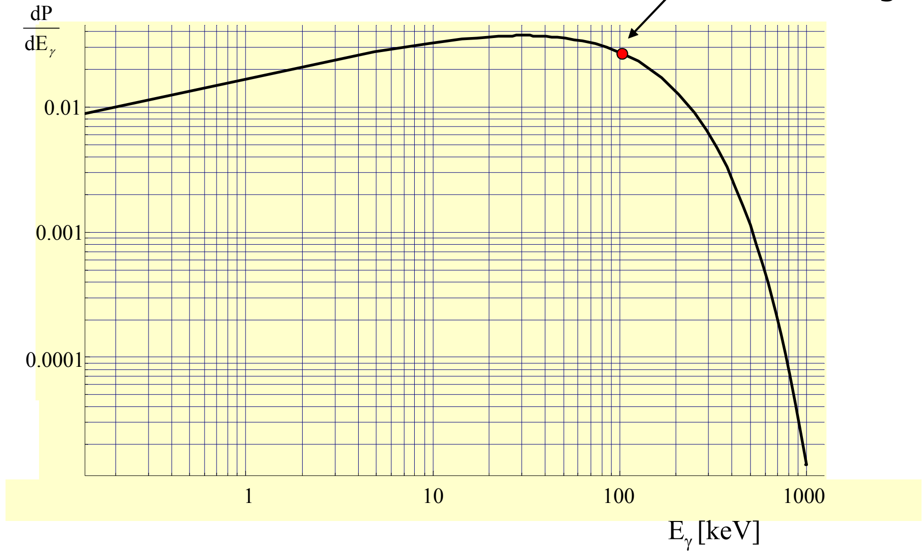
--> support off-center quadrupole separation scheme by crossing angle at the IP

Technical challenges:
- superconducting half quadrupoles
- e beam guided through p-quad cryostat
- crab cavities needed to avoid loss of luminosity



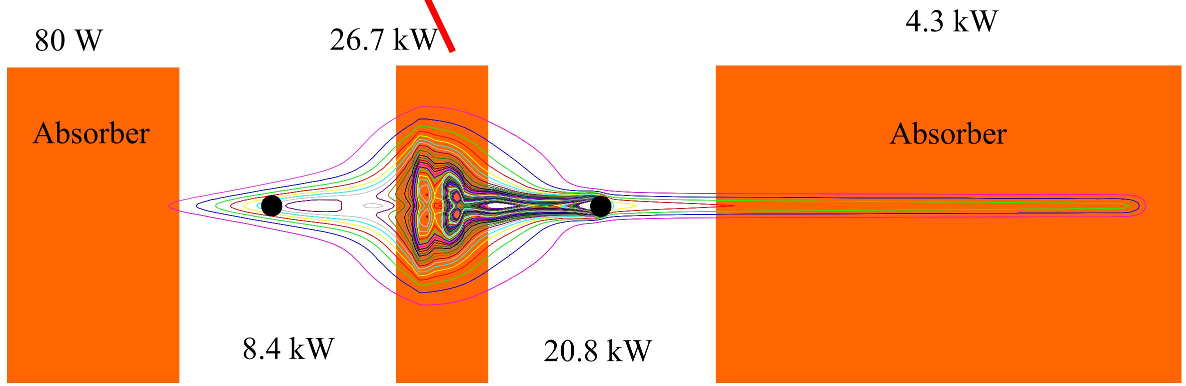
IR Design Synchrotron Radiation





B. Nagorny

large contribution from quadrupole magnets



Total synchrotron radiation power in IR 60 kW (HERA II 30 kW)
Have to study absorber, collimators, size of beam pipe

e-p Luminosity Limitations

$$L = \frac{N_e N_p n_b f_{rev} R(\sigma_p, \beta_{x,y,e,p})}{2\pi\sqrt{\varepsilon_{xp}\beta_{xp} + \varepsilon_{xe}\beta_{xe}}\sqrt{\varepsilon_{xp}\beta_{xp} + \varepsilon_{xe}\beta_{xe}}}$$

$$\sigma^e_{x,y} = \sigma^p_{x,y}$$

Lepton beam current:

RF power, LINAC technology and beam dynamics

$$L = \frac{\gamma_p}{2\pi e} \frac{N_p I_e R(\sigma, \beta)}{\cdot \varepsilon_N \sqrt{\beta^*_{yp} \cdot \beta^*_{xp}}}$$

Proton beam brightness:

injector chain, lepton bb effect, intra-beam scattering

IR design, chromatic correc-tions and hourglass factor

Ring-Ring Luminosity Prospects

Luminosity safely $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

LHC upgrade: N_p increased.
Need to keep e tune shift low:
by increasing β_p, decreasing β_e
but enlarging e emittance,
to keep e and p matched.

LHeC profits from LHC upgrade
but not proportional to N_p

Tuneshift limit:

$$\Delta\nu_{xe} = \frac{\beta_{xe} r_e}{2\pi\,\gamma_e} * \frac{N_p}{\sigma_{xp}(\sigma_{xp}+\sigma_{yp})}$$

Experience:

LEP	$\Delta\nu_e = 0.048$
LHC-B	$\Delta\nu_p = 0.0037$
HERA	$\Delta\nu_e = 0.051$
	$\Delta\nu_p = 0.0016$

Standard Parameter	Protonen	Elektronen	
	Np=1.15*10^11	Ne=1.4*10^10	nb=2808
	Ip=582 mA	Ie=71mA	
Optics	βxp=180 cm	βxe=12.7 cm	
	βyp= 50 cm	βye= 7.1 cm	
	εxp=0.5 nm rad	εxe=7.6 nm rad	
	εyp=0.5 nm rad	εye=3.8 nm rad	
Beamsize	σx=30 µm	σx=30 µm	
	σy=15.8 µm	σy=15.8 µm	
Tuneshift	Δνx=0.00055	Δνx=0.0484	
	Δνy=0.00029	Δνy=0.0510	
Luminosity	L=8.2*10^32		

nominal LHC — L = 8.2 10^{32}

Ultimate Parameter	Protonen	Elektronen	
	Np=1.7*10^11	Ne=1.4*10^10	nb=2808
	Ip=860mA	Ie=71mA	
Optics	βxp=230 cm	βxe=12.7 cm	
	βyp= 60 cm	βye= 7.1 cm	
	εxp=0.5 nm rad	εxe=9 nm rad	
	εyp=0.5 nm rad	εye=4 nm rad	
Beamsize	σx=34 µm		
	σy=17 µm		
Tuneshift	Δνx=0.00061	Δνx=0.056	
	Δνy=0.00032	Δνy=0.062	
Luminosity	L=1.03*10^33		

ultimate LHC — L = 1.0 10^{33}

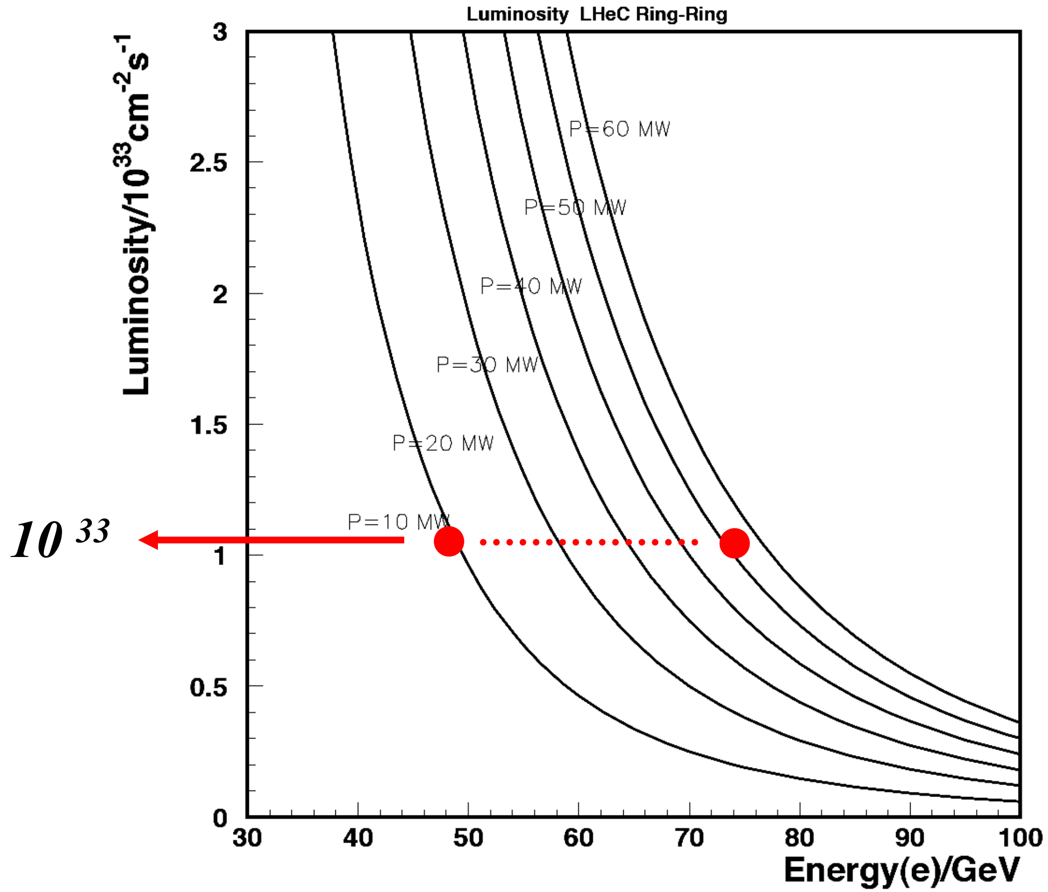
Upgrade Parameter	Protonen	Elektronen	
	Np=5*10^11	Ne=1.4*10^10	nb=1404
	Ip=1265mA	Ie=71mA	
Optik	βxp=400 cm	βxe= 8 cm	
	βyp=150 cm	βye= 5 cm	
	εxp=0.5 nm rad	εxe=25 nm rad	
	εyp=0.5 nm rad	εye=15 nm rad	
Strahlgröße	σx=44 µm		
	σy=27 µm		
Tuneshift	Δνx=0.0011	Δνx=0.057	
	Δνy=0.00069	Δνy=0.058	
Luminosität	L=1.44*10^33		

LHC upgrade (super LHC) — L = 1.4 10^{33}

Ring-Ring Luminosity vs. Energy

Design values are for 14 MW synrad loss (beam power) and 50 GeV on 7000 GeV. May have 50 MW and energies up to about 70 GeV.

$$L = \frac{\sum_{i=1}^{n_b} (I_{ei} * I_{pi})}{e^2 f_0 2\pi \sqrt{\sigma_{xp}^2 + \sigma_{xe}^2} * \sqrt{\sigma_{yp}^2 + \sigma_{ye}^2}}$$



Luminosity performance limit:
E_e ,I_e due to Synchrotron Radiation

$$P_\gamma = \frac{e^2 c}{6\pi\, \varepsilon_0} * \gamma^4 * r^2 * N_e$$

10^{33} can be reached in RR

$$E_e = 50\ GeV \leftrightarrow P_{syn} = 10MW$$
$$E_e = 75\ GeV \leftrightarrow P_{syn} = 50MW \quad *\,2$$

klystron efficiency 50%

Overall power consumption limited to 100MW

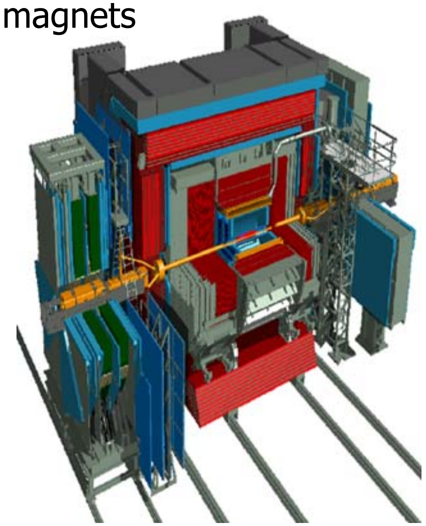
IR Design – Detector Acceptance

- So far high luminosity IR design with magnets 1.2m from IP
- Luminosity and acceptance very much depend on physics program
- Deep inelastic cross section ~1/Q^4 (momentum transfer)
  - High Q^2 physics (search for new physics, electron-weak studies) require high luminosity. Can be done with reduced acceptance
  - Low Q^2 physics (high parton densities, diffraction,…) requires good forward and rear coverage 1 – 179°. Can be done with reduced luminosity.

=> Look into two different interaction region setups

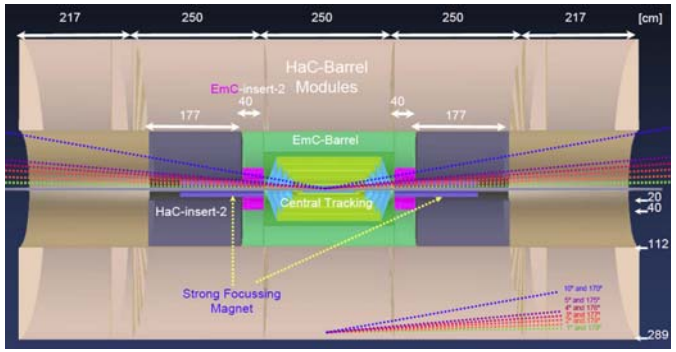
- $L = 10^{33}\ cm^{-2}\ s^{-1}$, $10^o < \theta < 170^o$ (prefer magnets not in front of CAL)
- $L = 10^{32}\ cm^{-2}\ s^{-1}$, $1^o < \theta < 179^o$

Example ZEUS with integrated HERA magnets

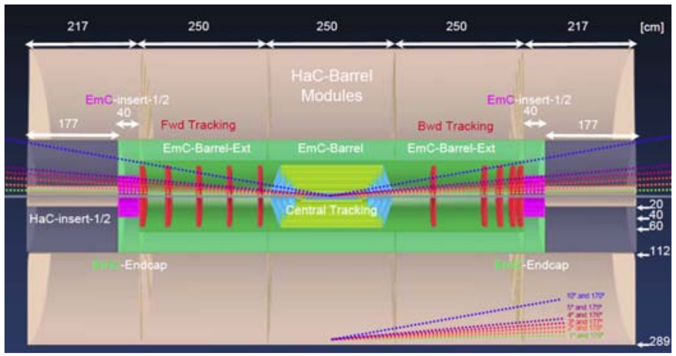


LHeC detector study (P. Kosta, A. Polini et al.)

high luminosity, high Q^2



low Q^2, full acceptance

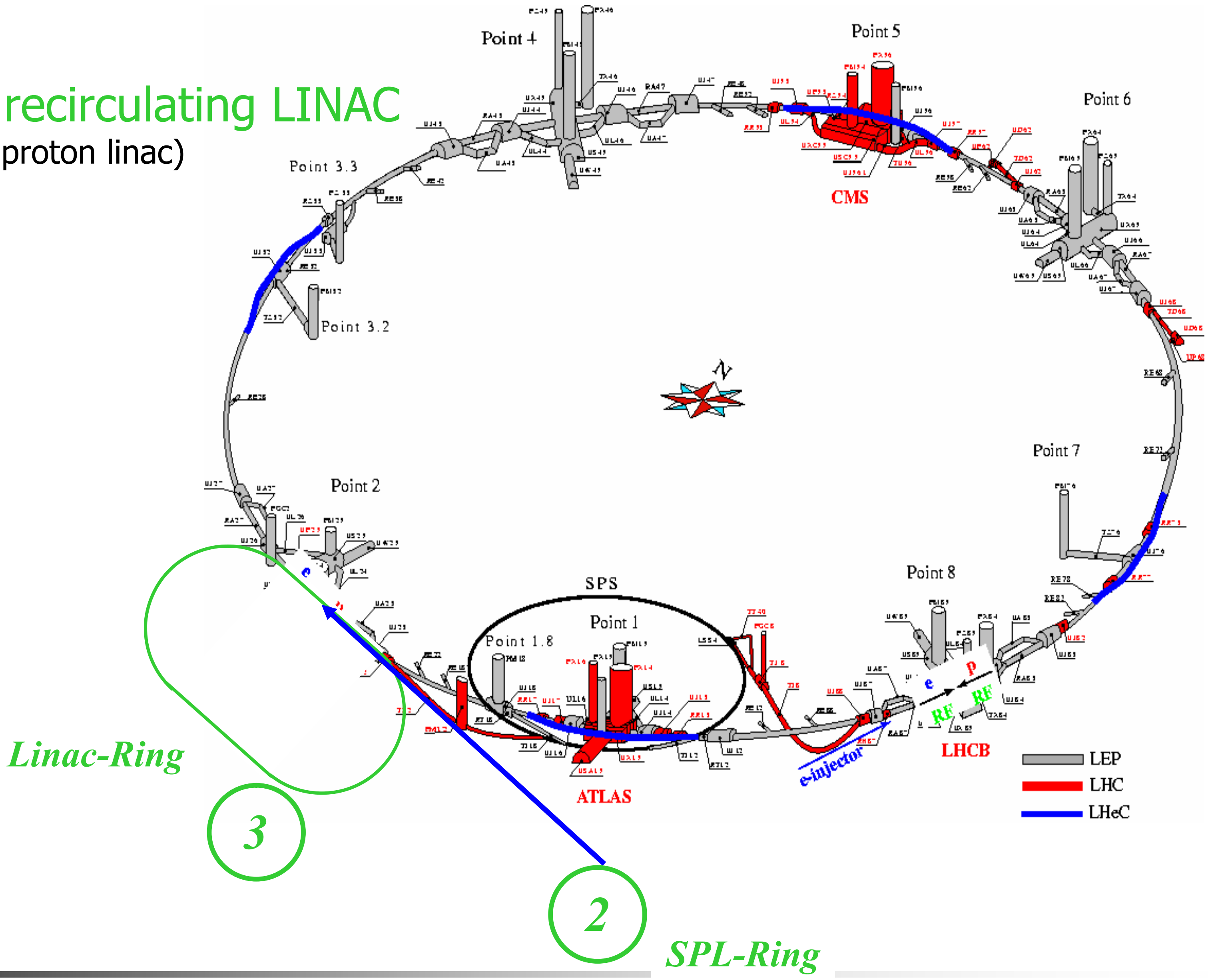


Ongoing Studies for Ring-Ring

- Beam-beam:
  - Large crossing angle might be acceptable without crab cavities
- Bypass design:
  - RF integration into the bypass tunnels
- Lattice design:
  - Lattice optimization for compact magnet design
  - e-ring magnet design
- Injector complex:
  - Design based on multy-pass SPL
- IR:
  - Optimize IR layout (so far only 10^{o} detector acceptance layout)
  - Synchrotron radiation absorbers and masks
  - Luminosity measurement options
  - Work on 1^{o} layout (full detector acceptance)

LHeC Ring-LINAC Options

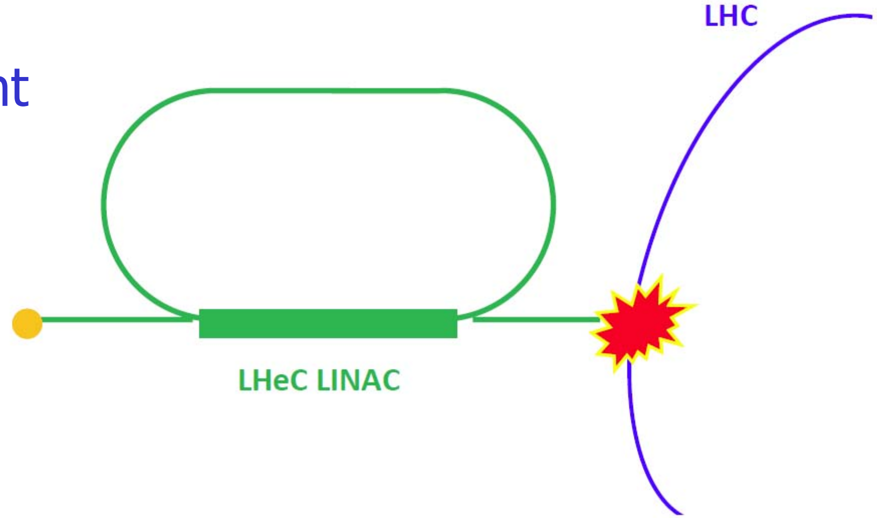
SPL ... or a recirculating LINAC
(super conducting proton linac)



Ring - LINAC Options

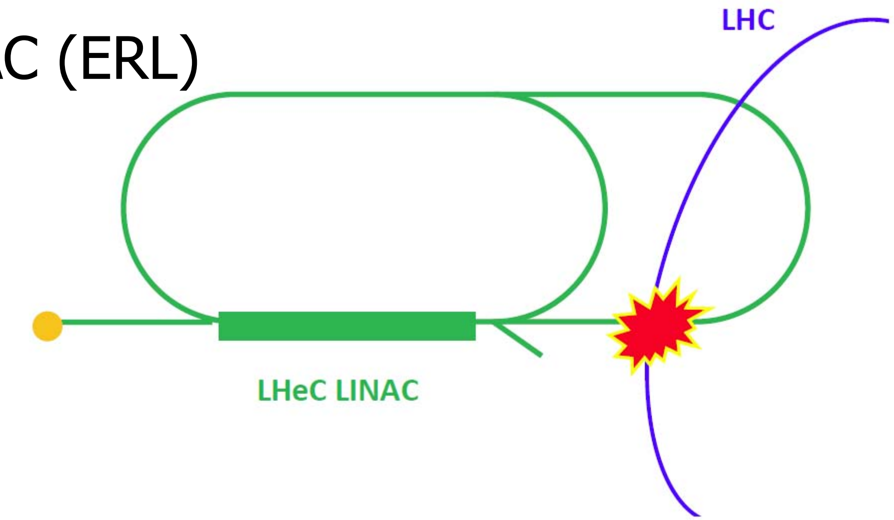
Two-pass recirculation LINAC

- 100-140 GeV, pulsed high gradient
- Cavity gradient 25 – 32 MV/m
- Total circumference 15 km, using 1.5 km arc radius (synchr. rad.)



Four-pass energy recovery LINAC (ERL)

- 60 GeV, cw lower gradient
- Cavity gradient 13 MV/m

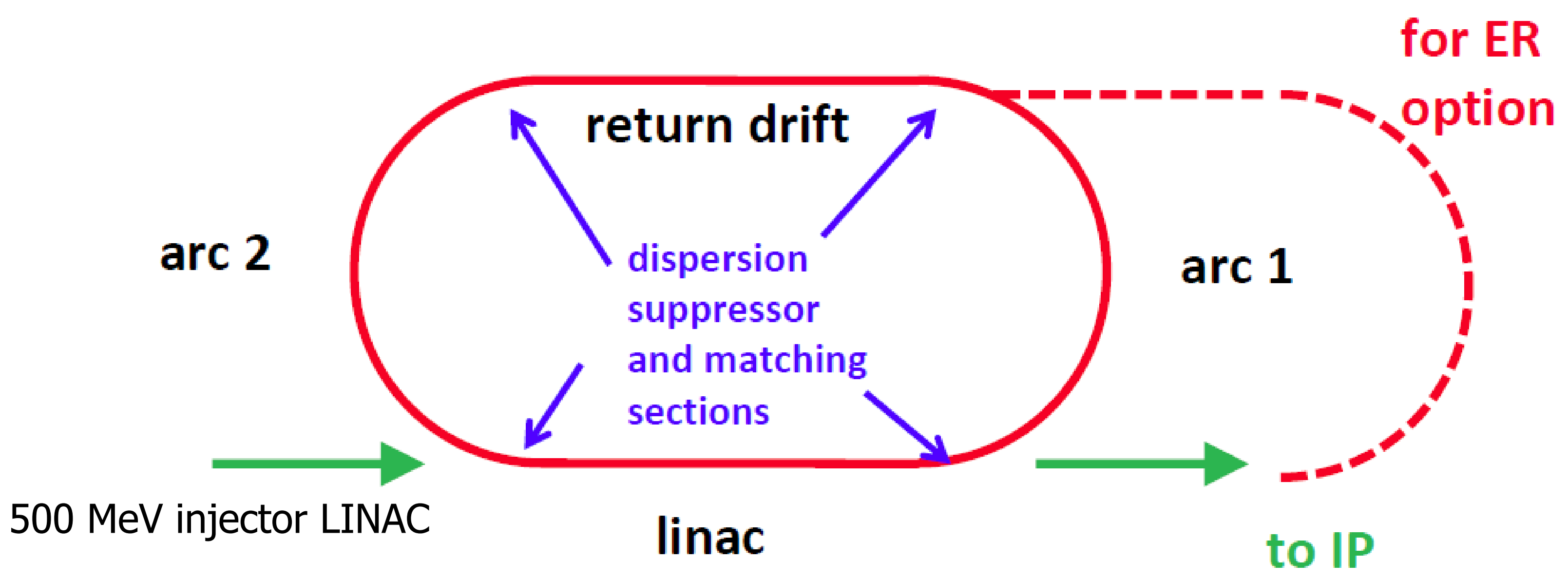


RLA Lattice

Basic cell and magnet parameters

- Standard FODO cell (length 24 m)
- Quadrupole length 470 mm
- Maximum quadrupole gradient 78 T/m (at end of 140 GeV linac)
- Separation between quadrupoles 11.53 m to accommodate rf cavities or dipoles, orbit correctors, BPMs, etc.
- Dipole length 9.8 m
- RF-cavity length 8.4 m
- Dipole bending radius of d in arcs 1.5 km
- 90º phase advance in the arcs and return drift

A. Eide, F. Zimmermann

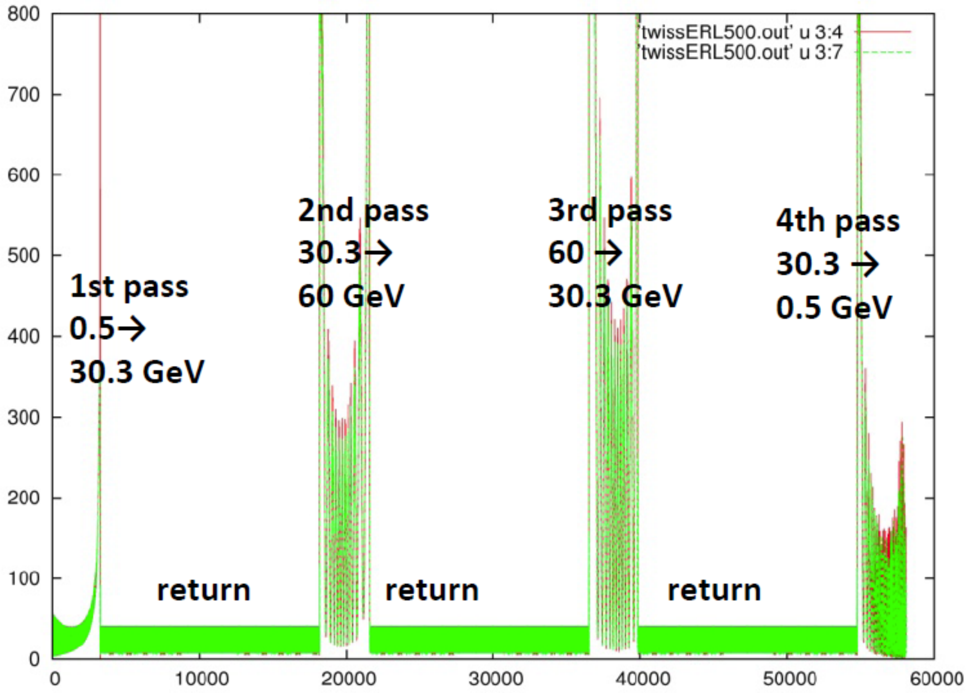


LINAC Optics

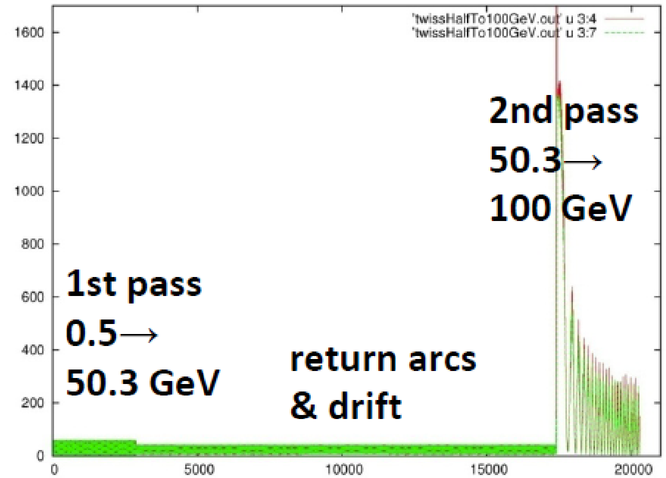
Complete optics worked out

A. Eide, F. Zimmermann

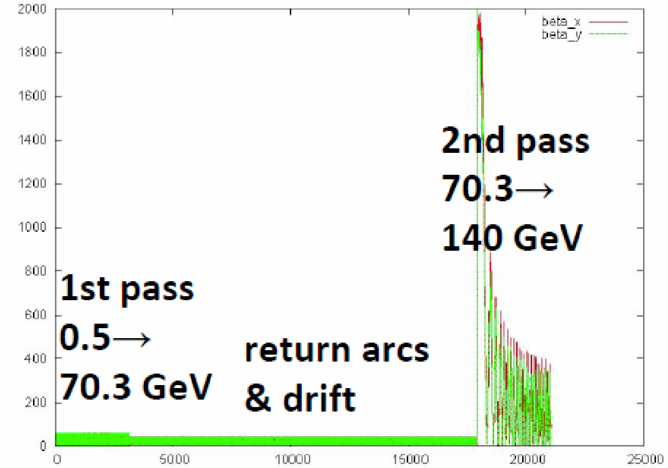
60 GeV ERL



100 GeV RLA



140 GeV RLA



Energy Recovery LINAC

- Energy recovery LINAC essential for achieving high beam current/luminosity for given wall pull power

- JLAB: recirculating linac
  - 99.5% of energy recovered at 150 MeV and 10 mA
  - ~98% recovery at 1 GeV and 100 μA with beam swung between 20 MeV and 1 GeV
  - plans for multi-GeV linacs with currents of ~100 mA

- Very nice, but not yet demonstrated at high energy and with large current
  - Assumed LHeC currents are relatively low compared to other ERL projects

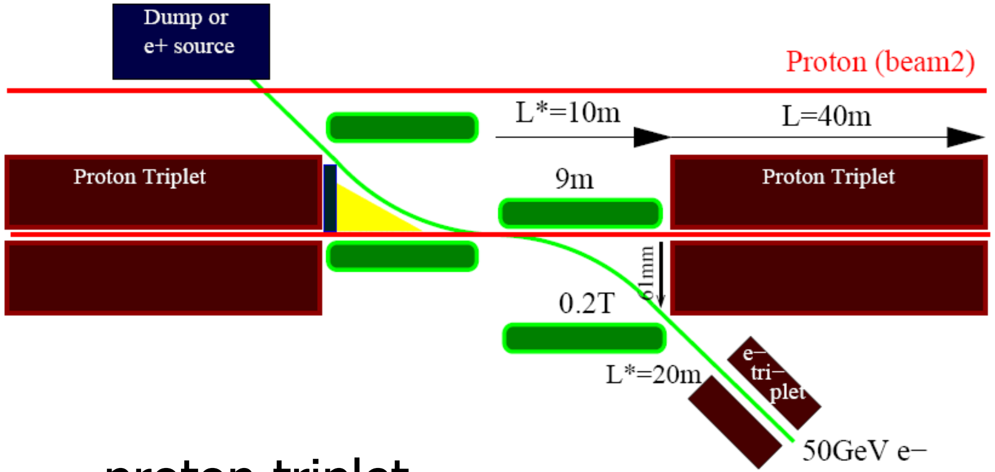
Positron Source for Ring-LINAC

- Challenge: 10 times more positrons than ILC design
- Large number of bunches, damping ring difficult
- Several options being considered (POSIPOL collaboration)
  - Spent electron beam on target
  - Crystal hybrid target
  - ERL Compton source for cw operation
  - Undulator source using spent electron beam
  - LINAC-Compton source for pulsed operation
  - Collimate beam to shrink emittance
  - Recycle positron beam

- Lepton Polarization
  - Electron beam: polarized dc gun, ~90% polarization, 10-100μm normalized emittance
  - Positron beam: up to ~60% polarization from undulator or Compton based source

Ring-LINAC IR Design 50GeV

R.Tomas



Distance of dipole to IP should be increased slightly or large radius (radially outside calorimeter)

proton triplet

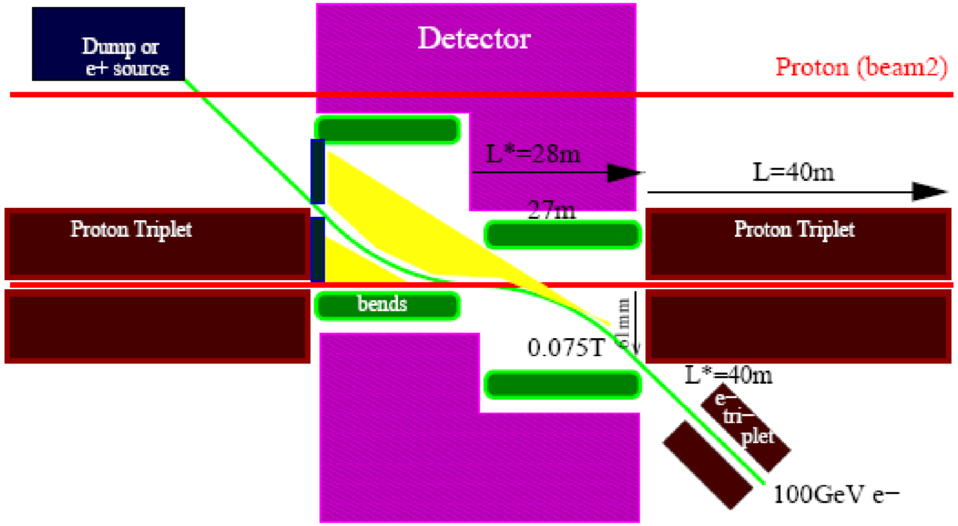
	Q_1			Q_2			
β^* [m]	Aper [mm]	Grad [T/m]	B_p [T]	Aper [mm]	Grad [T/m]	B_p [T]	ξ
0.25	23	176.7	4.0	32	115.0	3.7	635
0.18	23	264.5	6.0	32	180.0	5.7	660
0.10	26	318.6	8.4	36	250.0	9.1	1250

electron triplet

	Q_1			Q_2			
β^* [m]	Aper [mm]	Grad [T/m]	B_p [T]	Aper [mm]	Grad [T/m]	B_p [T]	ξ
0.10	21	13	0.26	23	15	0.3	1100

Ring-LINAC IR Design 100GeV

R.Tomas

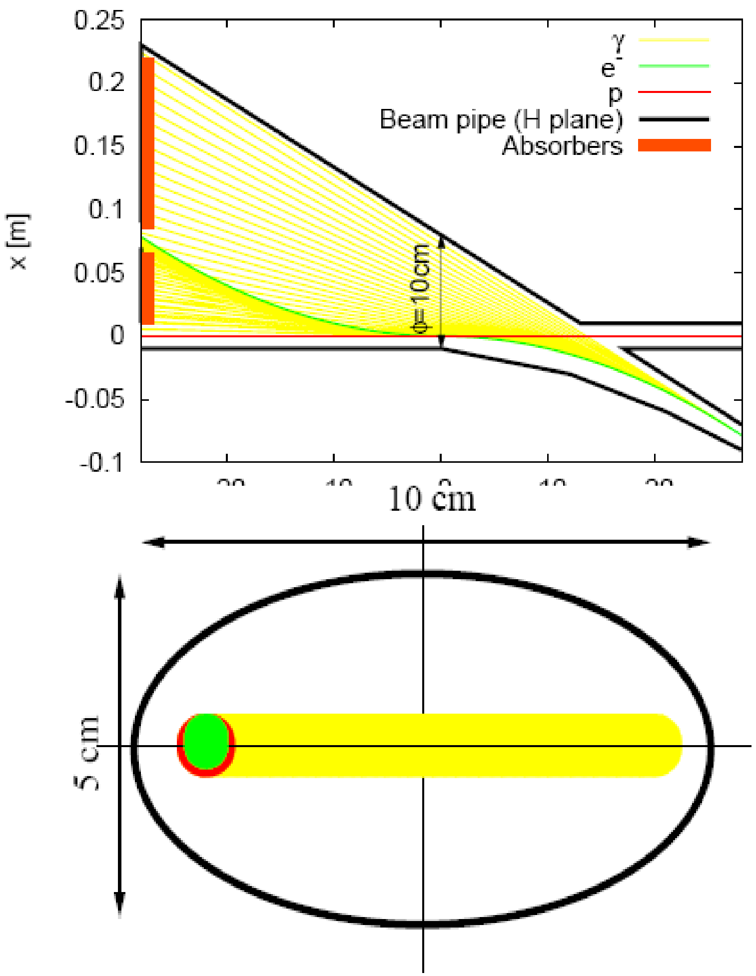


Distance of dipole to IP should be increased slightly or large radius (radially outside calorimeter)

proton triplet

	Q1			Q2			
β^*	Aper	Grad	B_p	Aper	Grad	B_p	ξ
[m]	[mm]	[T/m]	[T]	[mm]	[T/m]	[T]	
0.20	33	131.4	4.4	42	125.0	5.3	990

Synchrotron Radiation



100 GeV electron beam

Synchrotron radiation

- Power 4.2kW
- Critical energy 0.5MeV

Large horizontal spread at IP

Disadvantage of weak bent

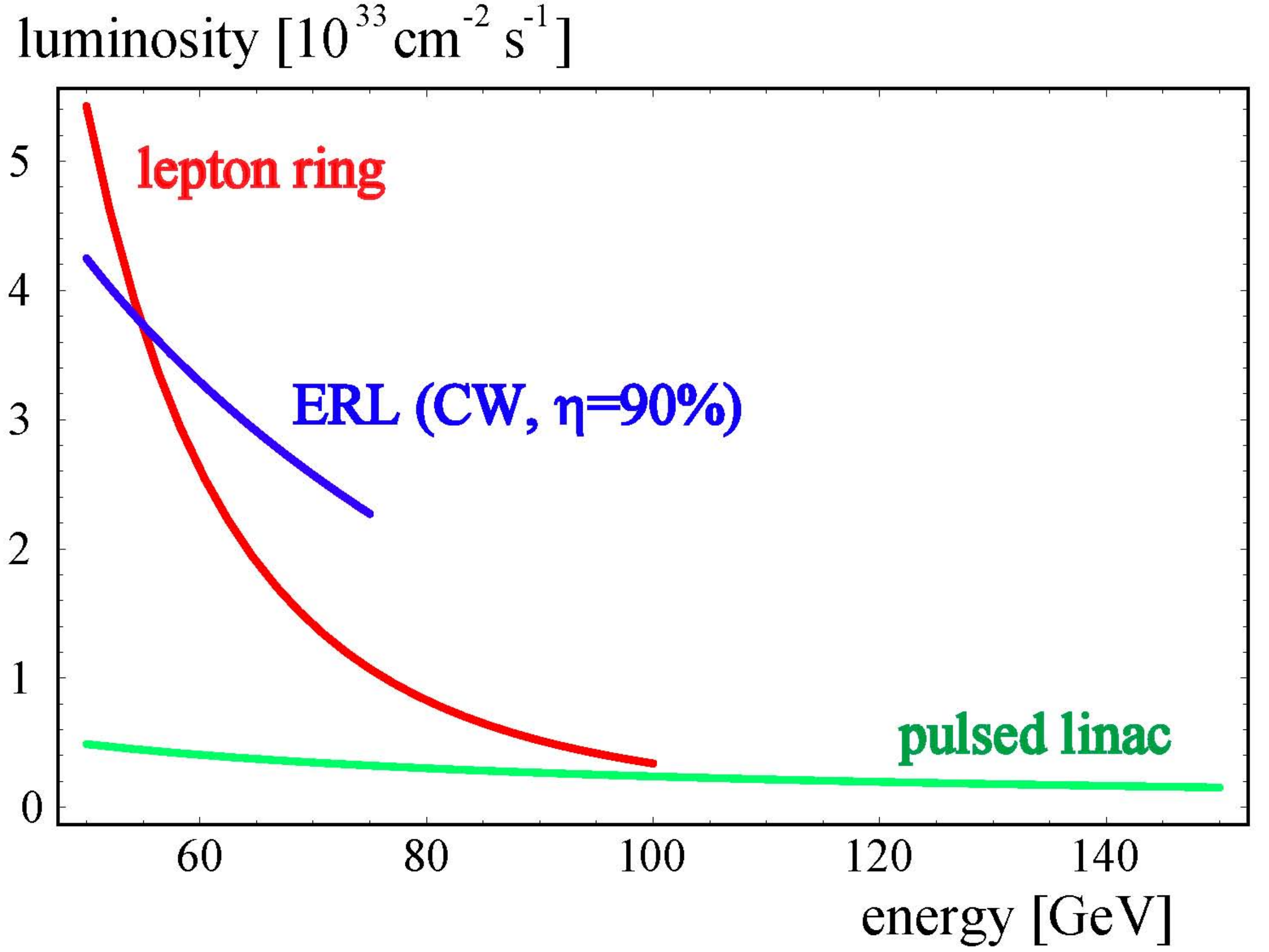
LHeC Parameters

Example LHeC Ring-ring and Ring-LINAC parameters

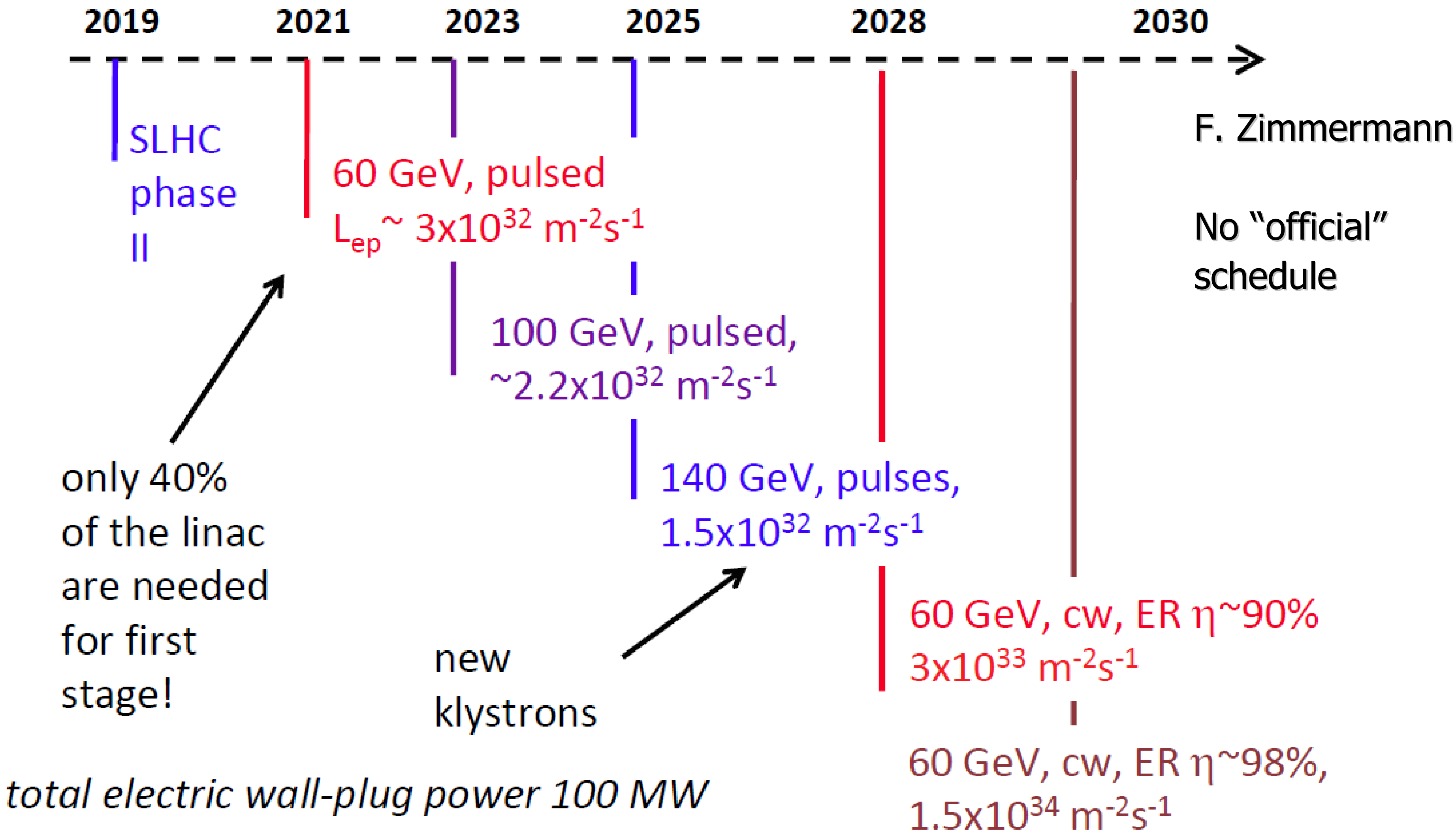
	LHeC-RR	LHeC-RL high lumi	LHeC-RL 100 GeV	LHeC-RL high energy	ILC	XFEL
e^- energy at IP [GeV]	60	60	100	140	(2×)250	20
luminosity [10^{32} cm^{-2}s^{-1}]	29	$29^{\dagger}$ ($2.9^{\ddagger}$)	2.2	1.5	200	N/A
bunch population [10^{10}]	5.6	$0.19^{\dagger}$ ($0.02^{\ddagger}$)	0.3 (1.5)	0.2 (1.0)	2	0.6
e^- bunch length [μm]	~10,000	300	300	300	300	24
bunch interval [ns]	50	50	50 (250)	50 (250)	369	200
norm. hor.&vert. emittance [μm]	4000, 2500	50	50	50	10, 0.04	1.4
average current [mA]	135	$7^{\dagger}$ ($0.7^{\ddagger}$)	0.5	0.5	0.04	0.03
rms IP beam size [μm]	44, 27	7	7	7	0.64, 0.006	N/A
repetition rate [Hz]	CW	CW	10 [5% d.f.]	10 [5% d.f.]	5	10
bunches/pulse	N/A	N/A	71430	14286	2625	3250
pulse current [mA]	N/A	N/A	10	10	9	25
beam pulse length [ms]	N/A	N/A	5	5	1	0.65
cryo power [MW]	0.5	20	4	6	34	3.6
total wall plug power [MW]	100	100	100	100	230	19

Using LHC upgrade parameters (50ns bunch spacing)
RR: assuming 14 MW beam power
† assume energy recovery η = 90%, ‡ η = 0

LHeC Luminosity



Possible Staged Schedule Ring-LINAC



Schedule driven by beam energy. Other option driven by luminosity.

Ongoing Studies for Ring-LINAC

- Re-circulating LINAC:
  - Optics studies for multi-pass in LINAC and return arcs
  - Study of β-beat and emittance low-up for multi-pass operation
- Energy recovery:
  - Cost & infrastructure estimates based on planned projects
  - Novel ERL options for high energy reach
- Source design:
  - Options for polarized and un-polarized sources

Electron-nucleus (e-A) collisions

J.M. Jowett

- The LHC will operate as a nucleus-nucleus (initially Pb-Pb) collider
  - Physics program is expected to include:
    - Pb-Pb at $\sqrt{s_{NN}} = 5.5\ \mathrm{TeV}$
    - p-Pb
    - A-A where A may be Ca, O, …
- Natural possibility of colliding electrons with $^{208}Pb^{82+}$ nuclei
  - Requires maintenance of LHC ion injector complex (source-LINAC3-LEIR) through to the time of operation of LHeC
  - Also requires inclusion of ion capability in new generation of injector synchrotrons (PS $\rightarrow$ PS2, SPS $\rightarrow$ SPS2 ??)
- Electron-deuteron e-d collisions would require a completely new source (at least!)
  - Present CERN complex does not foresee deuterons

e-Pb Collisions

J.M. Jowett

- Present nominal Pb beam for LHC
  - Same beam size as protons, fewer bunches

$$k_b = 592 \text{ bunches of } N_b = 7 \times 10^7 \ {}^{208}\text{Pb}^{82+} \text{ nuclei}$$

- Assume lepton injectors can create matching train of e⁻

$$k_b = 592 \text{ bunches of } N_b = 1.4 \times 10^{10} \ \text{e}^-$$

- Lepton-nucleus or lepton-nucleon luminosity in ring-ring option at 70 GeV

$$L = 1.09 \times 10^{29} \ \text{cm}^{-2}\text{s}^{-1} \quad \Leftrightarrow \quad L_{\text{en}} = 2.2 \times 10^{31} \ \text{cm}^{-2}\text{s}^{-1}$$

  - May be some scope to exploit additional power by increasing electron single-bunch intensity by factor 592/2808 = 4.7

- Ring-LINAC has potential for few times higher luminosity at Ring-Ring accessible energies

Conclusions

LHeC Ring-Ring and Ring-LINAC designs being studied

Ring-Ring Option

- Lots of experience: HERA, LEP and LHC
- Proven technology
- Electron energy about 70 GeV
- Luminosity 8.2 10^{32} to 1.4 10^{33} cm^{-2} s^{-1}
- Need few km (~ 2km) of new tunneling
- Electron ring installation needs long LHC shutdown (some anyway need needed for LHC and detector upgrades)
- Conceptual design quite advanced

Conclusions

Ring-LINAC option

- Most of civil construction and installation independent of LHC operation
- Need several km (~ 15km) of new tunneling
- Staged construction and exploitation possible
- High electron energy possible, increase in stages, w/o any fundamental limit
- Maximum luminosity 2-3 10^{32} cm^{-2} s^{-1} for 50 – 150 GeV
- In principle, energy recovery could boost luminosity above 10^{34}, but so far only demonstrated at low energies
- Large polarization possible (e^- 90%)
- Positron sources very challenging
- IR with better detector acceptance due to low emittance e beam
- Additional possibility of γ-p and γ-N collisions via laser Compton back-scattering
- Several design options and new ideas