# Status of LHeC Accelerator Design Studies

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DESY

ENC/EIC Workshop
GSI Darmstadt
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# All transparencies from B.Holzer, CERN  DIS2009 Madrid

## *LHeC Study Group: 3 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)**

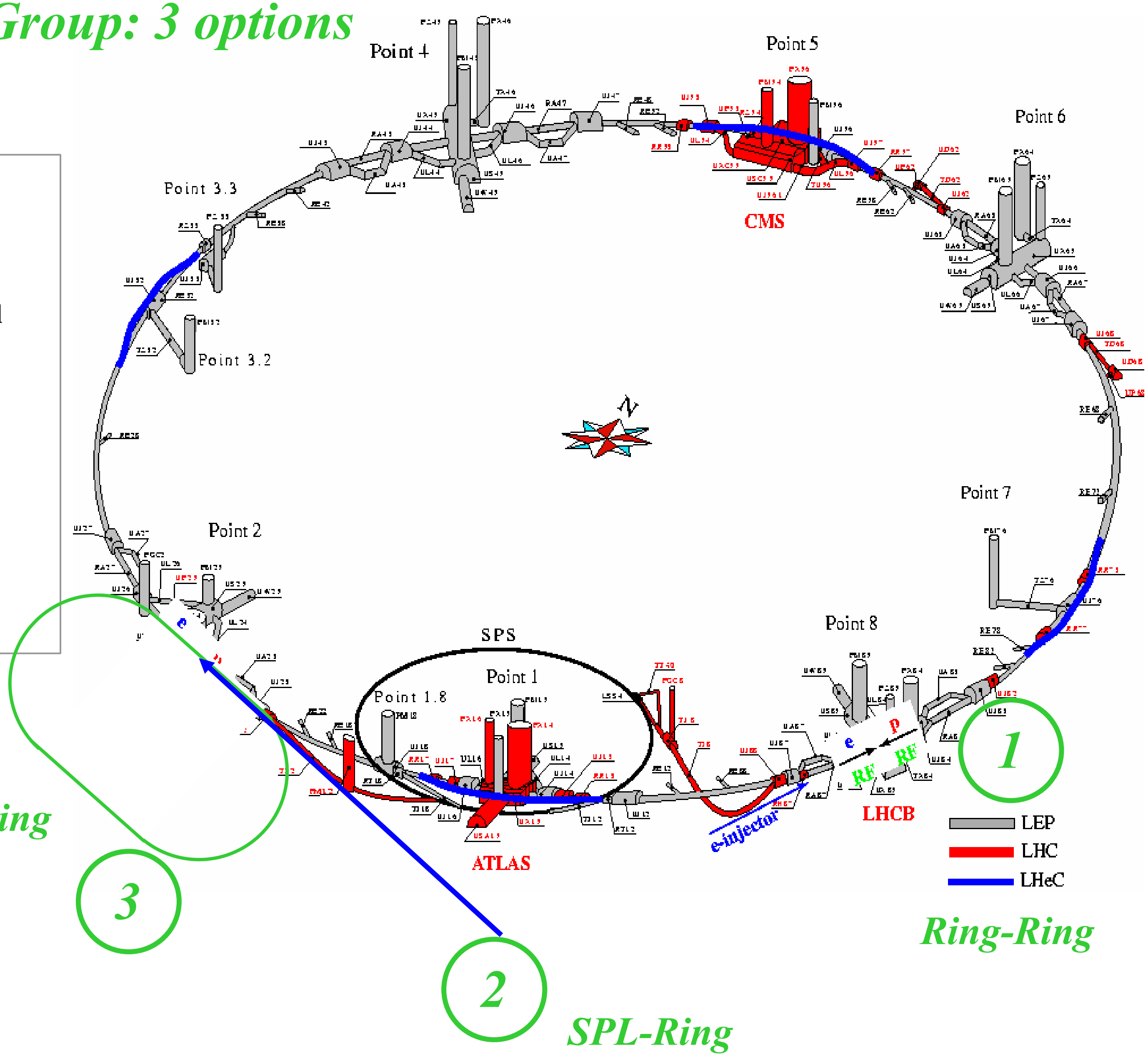
**Detector Design**

**Peter Kostka (DESY),**

**Rainer Wallny (UCLA),**

**Alessandro Polini (Bologna)**

... and many colleagues



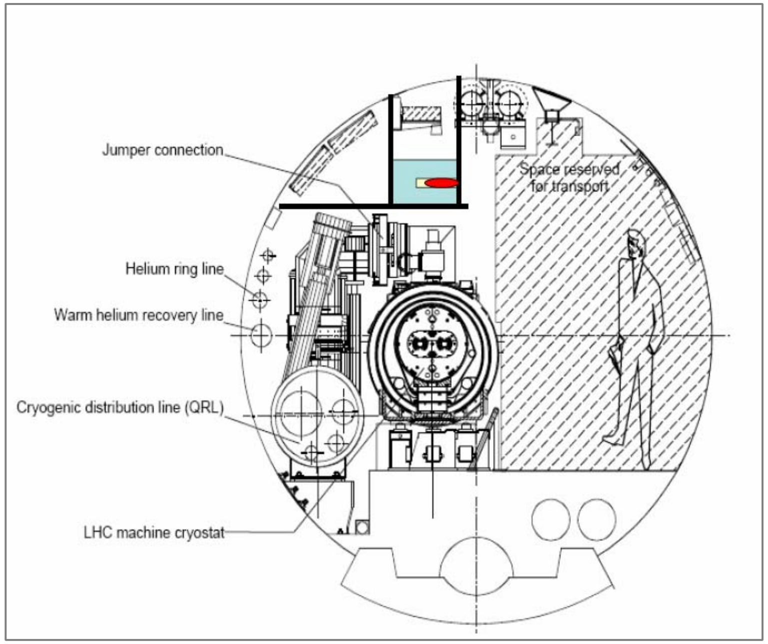
# Goal: Technical Design of the three Alternatives CDR within a Year

***General Statement: Whatever we do ... the fundamental layout of the LHC delivers an enormous potential for e/p Luminosity***

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

## *Example: LHeC Ring-Ring: basic parameters*

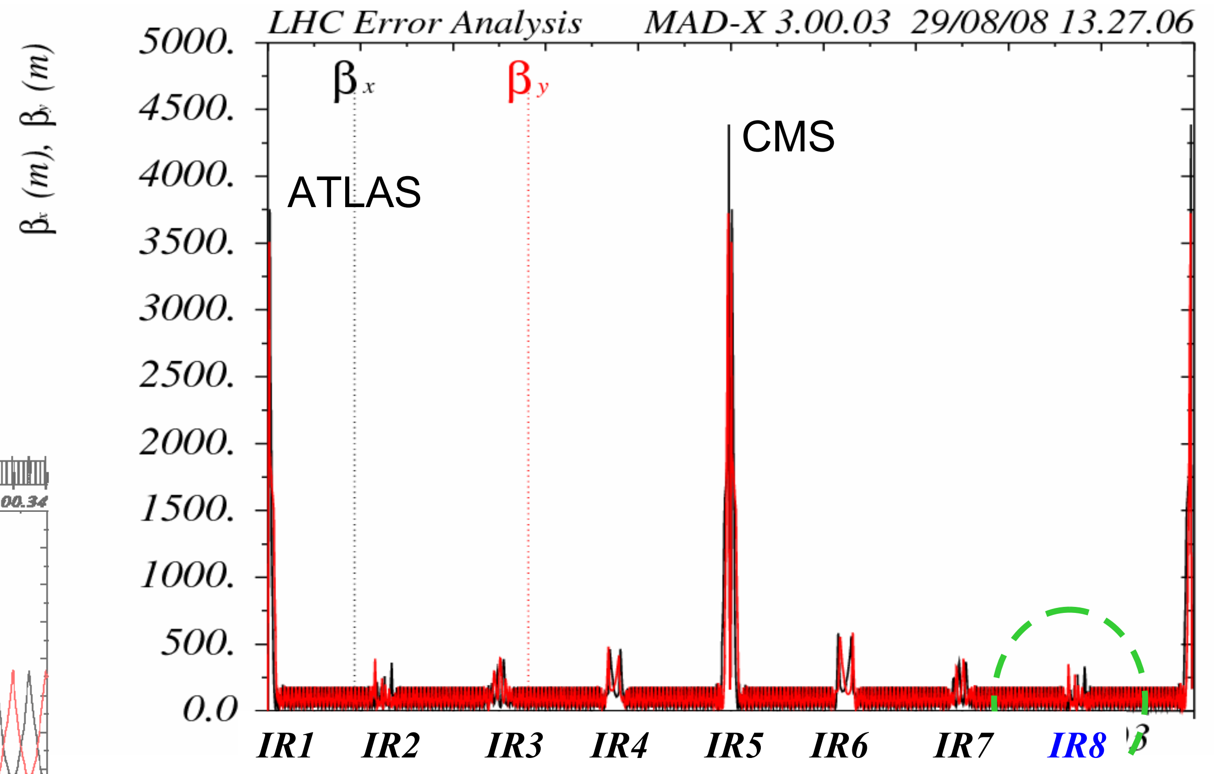
| | Protons | Electrons |
|---|---|---|
| Standard Parameters | $N_p=1.15*10^{11}$ | $N_e=1.4*10^{10}$ |
| | nb=2808 | nb=2808 |
| | Ip=582mA | Ie=71mA |
| Optics | $\beta_{xp}$=180cm | $\beta_{xe}$=12.7cm |
| | $\beta_{yp}$=50cm | $\beta_{ye}$=7.1cm |
| | $\varepsilon_{xp}$=0.5nm rad | $\varepsilon_{xe}$=7.6nm rad |
| | $\varepsilon_{yp}$=0.5nm rad | $\varepsilon_{ye}$=3.8nm 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 | $8.2*10^{32}\ cm^{-2}\ s^{-1}$ | |



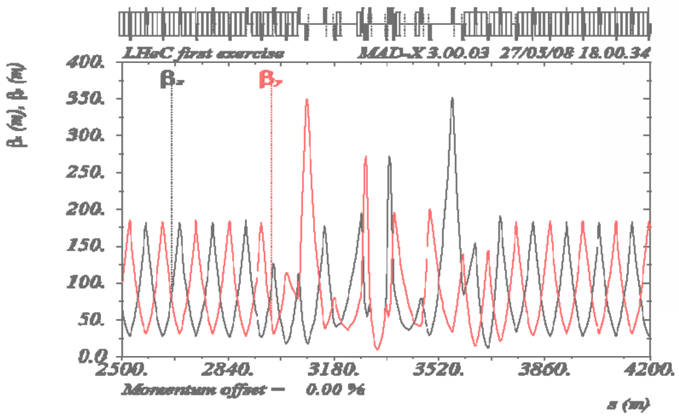

*e storage ring on top of LHC*

# Optics Design: Proton Ring

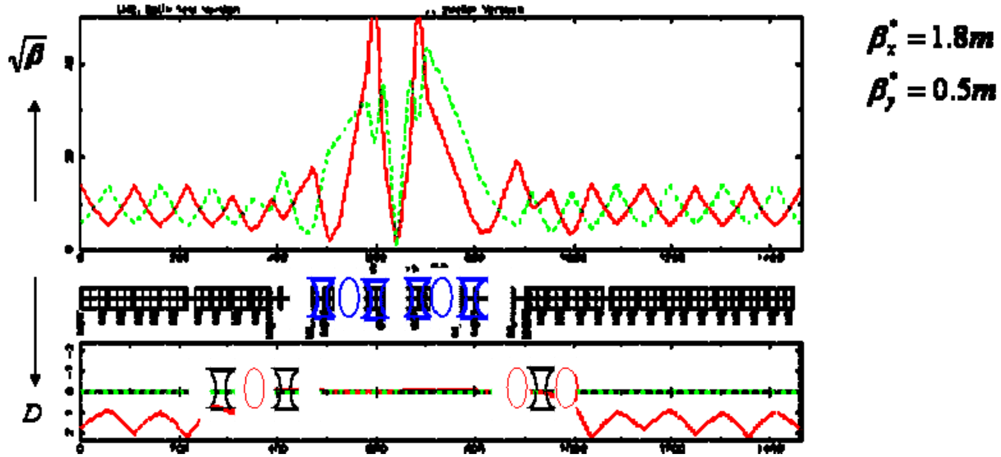
*LHC Standard Luminosity Optics*




... but an asymmetric one




*Standard LHC IR8 Optics*



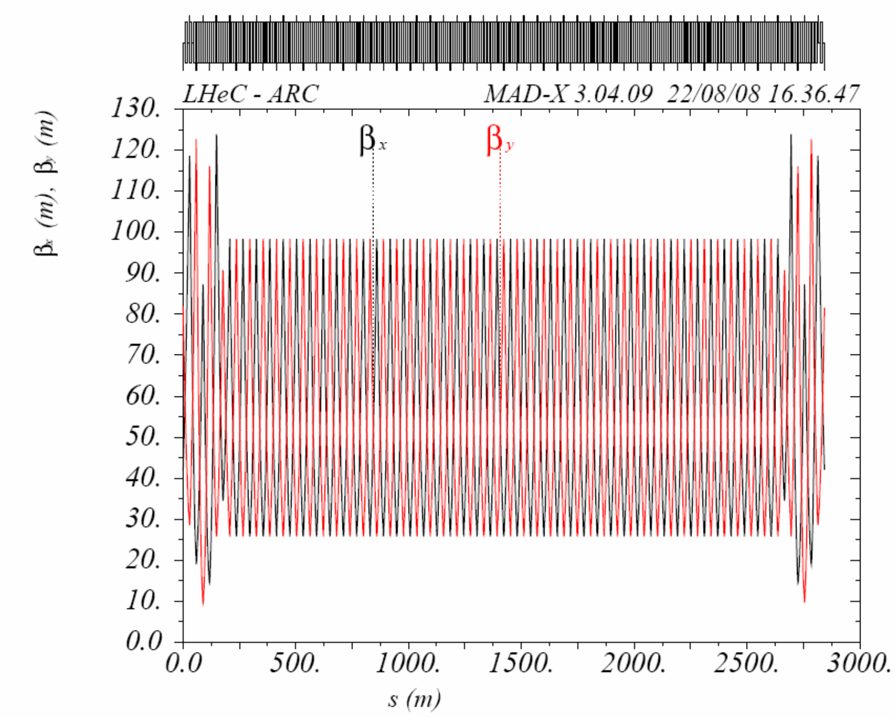

*new p Optics*
*including triplett for the e-beam*

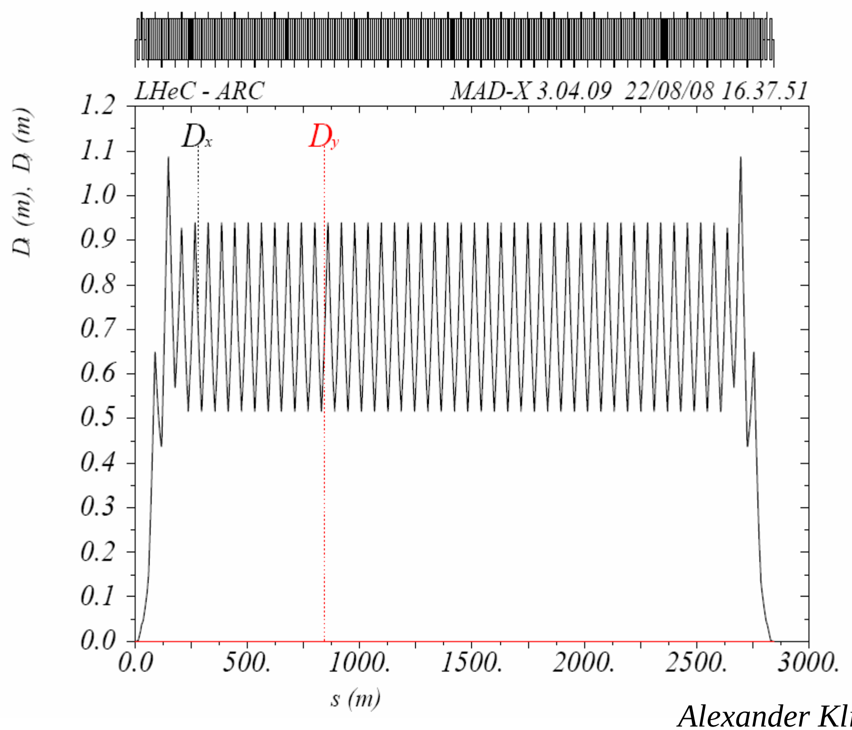
# Optics Design: Electron Ring

## 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

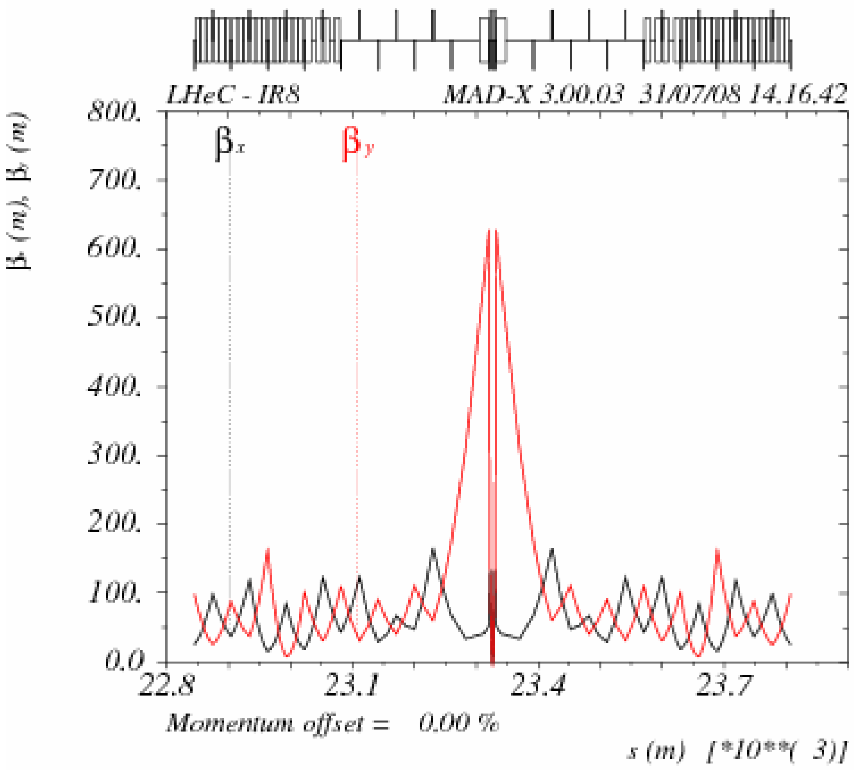
| | Lep | LHeC |
|---|---|---|
| cell length | 79m | 59.25m |
| phase advance | 60/90/108° | 72° |
| number of cells | 290 | 384 |

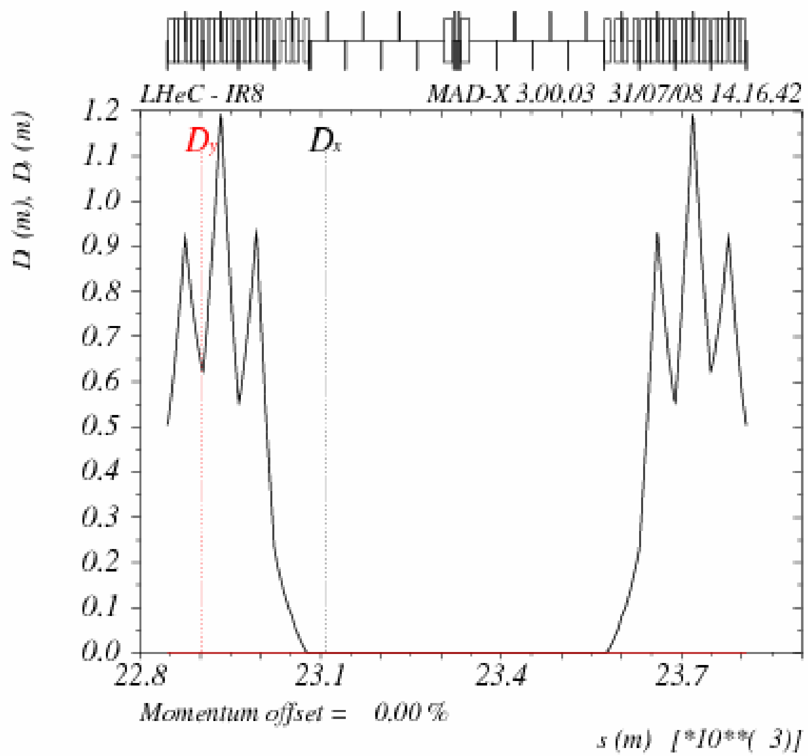



Alexander Kling

# *Electron Ring: Optical functions in IR 8*




*Alexander Kling*

## *Electron Ring*

## *Layout IR 8*

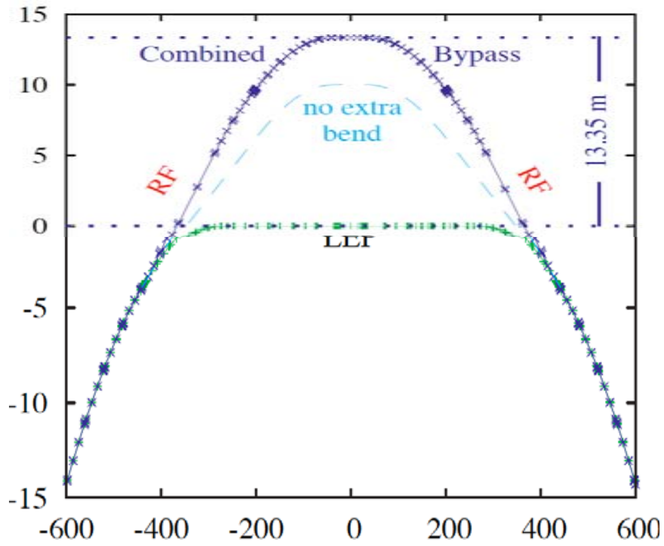
- *Use a triplet focusing*
- *Triplet is displaced to allow for a quick beam separation*
  *--> additional dispersion created close to IP*
- *Beam separation facilitated by crossing angle (1.5 mrad).*
  *15 m long soft separation dipole completes the separation before the focusing elements of the proton 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*
- *Layout is asymmetric*
  *asymmetry compensated by asymmetrically powered dispersion suppressors.*
- *Optical functions matched to the values at the IP:*

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

## *Layout IR 1 & 5*

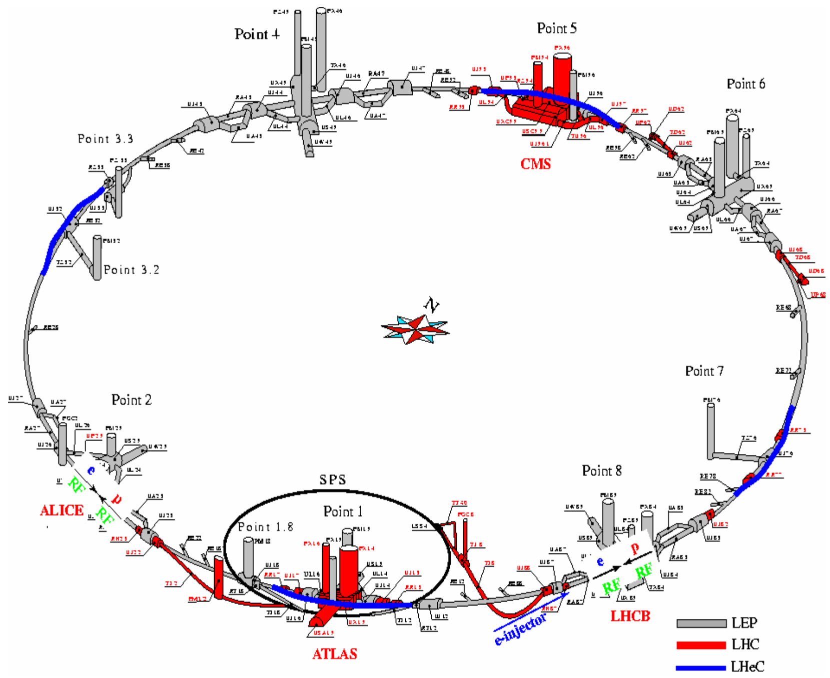
*Guide the electron beam in "Bypass Beam Lines" around Atlas & CMS*

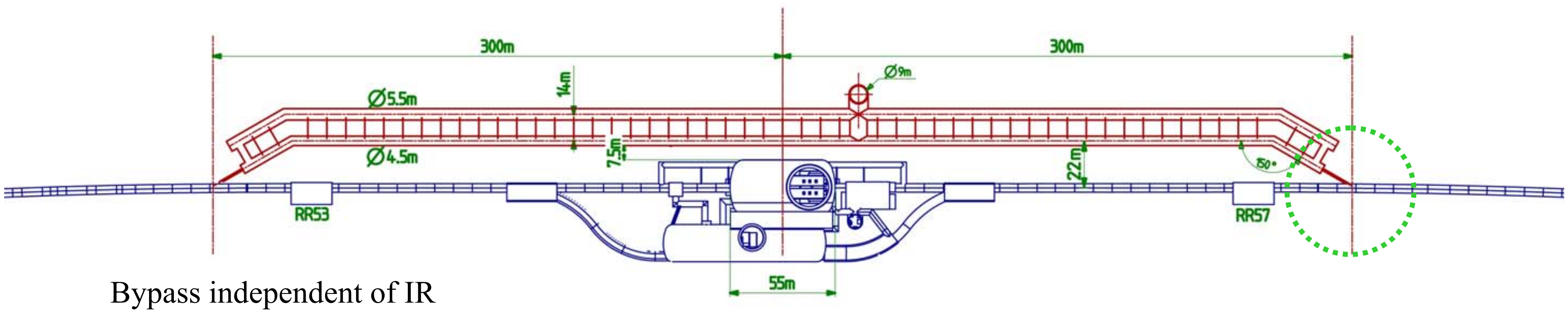
# *Electron Beam in IR 1 & 5*




***geometrical layout of the bypass sections***

*Helmut Burkhardt*



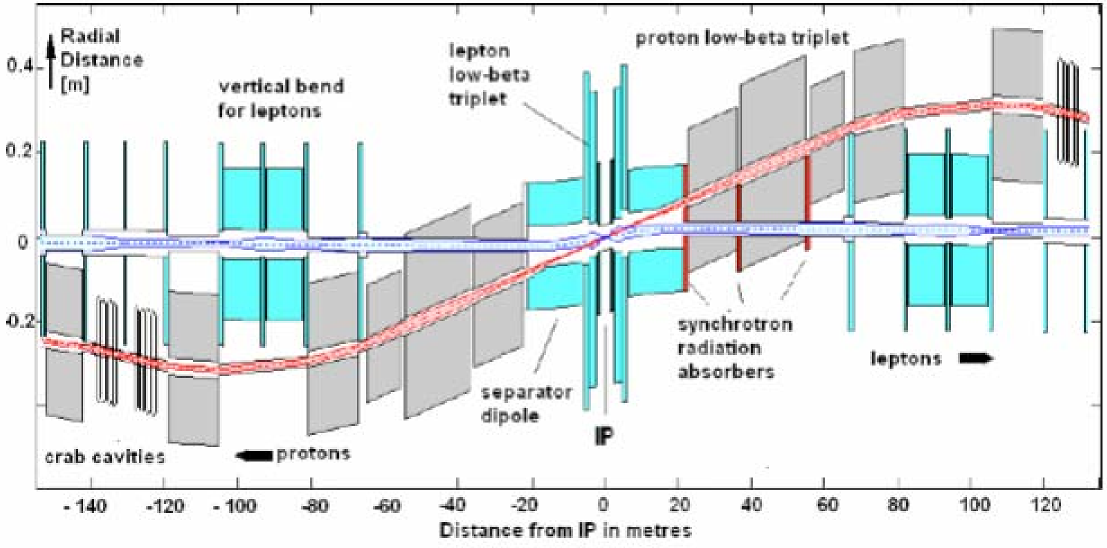

Bypass independent of IR
~30m distance, 1 shaft

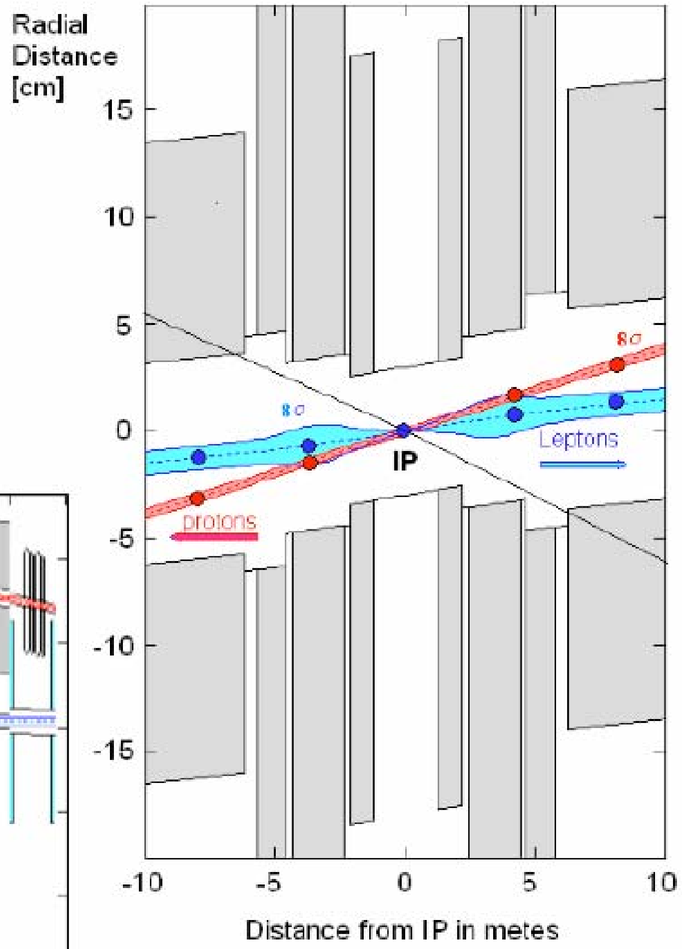
*S.Myers, J.Osborne*

# Interaction Region Design:

## A First Complete Design for 10 ^33

| | Protons | Electrons |
|---|---|---|
| Standard Parameters | $N_p=1.15*10^{11}$ | $N_e=1.4*10^{10}$ |
| | $n_b=2808$ | $n_b=2808$ |
| | $I_p=582mA$ | $I_e=71mA$ |
| Optics | $\beta_{xp}=180cm$ | $\beta_{xe}=12.7cm$ |
| | $\beta_{yp}=50cm$ | $\beta_{ye}=7.1cm$ |
| | $\varepsilon_{xp}=0.5nm\ rad$ | $\varepsilon_{xe}=7.6nm\ rad$ |
| | $\varepsilon_{yp}=0.5nm\ rad$ | $\varepsilon_{ye}=3.8nm\ rad$ |
| 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 | $8.2*10^{32}\ cm^{-2}\ s^{-1}$ | |



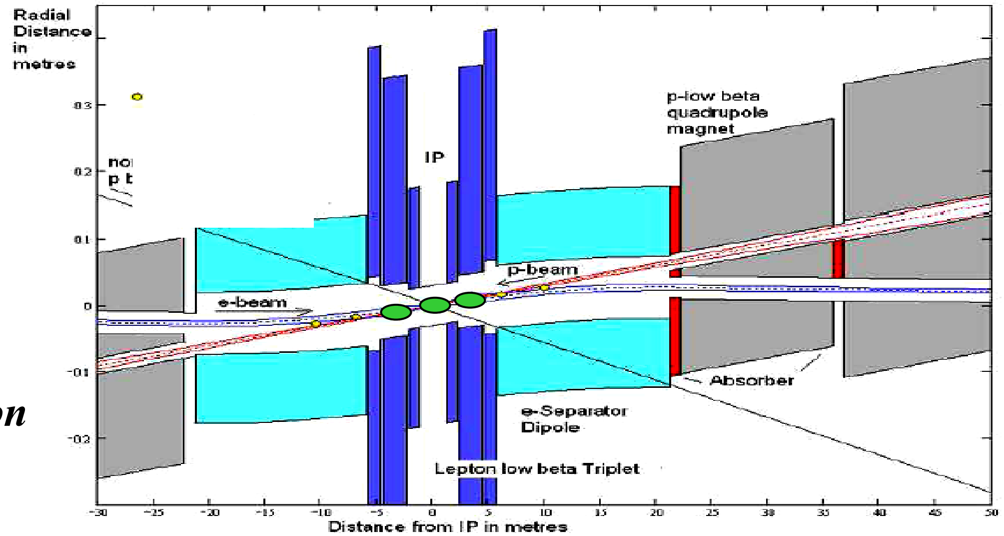
# *Interaction Region Design: Challenges*

*Advantage of LHC:* *large number of bunches* → ***high luminosity***
*Disadvantage:* ***fast beam separation needed***
***crossing angle to support early separation***

***LHC bunch distance:*** ***25 ns***
***1st parasitic crossing:*** ***3.75m***
***first e-quad positioned at*** ***1.2m***
***... too far for sufficient beam separation***

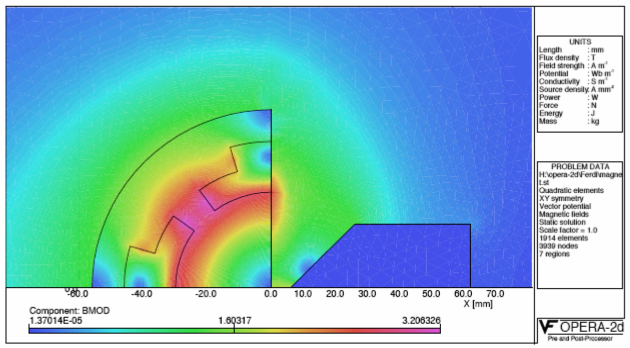
***separation has "to start at the IP"***

***--> support the off-centre-quadrupole separation scheme by crossing angle at the IP.***

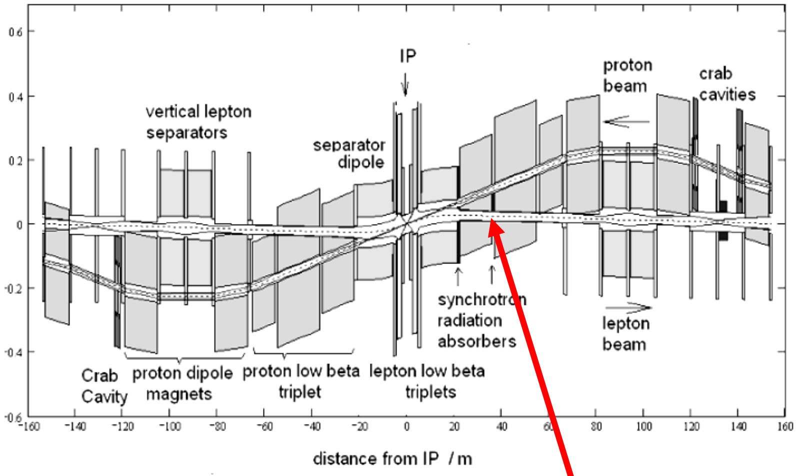


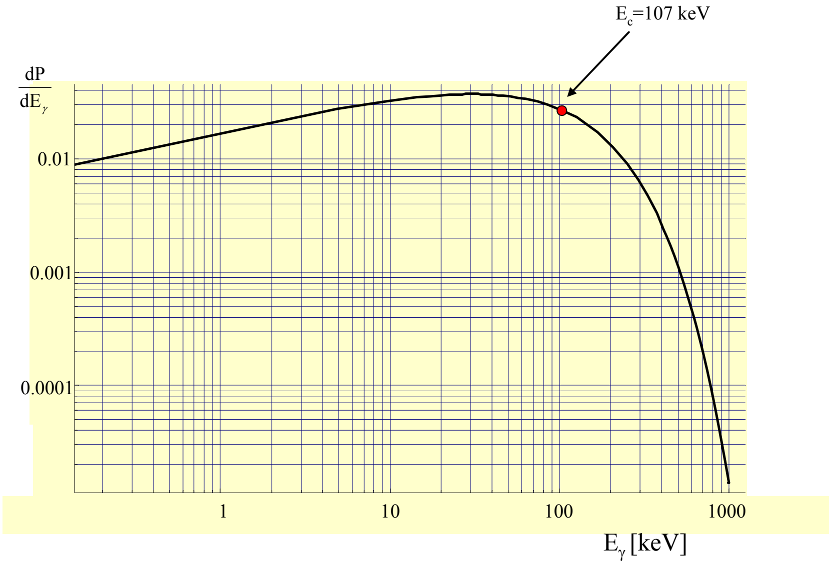

***technical challenges:***
***sc half quadrupoles,***
***e beam guided through p-quad cryostat***
***crab cavities needed to avoid loss of luminosity***

Present design does not accommodate luminosity monitor

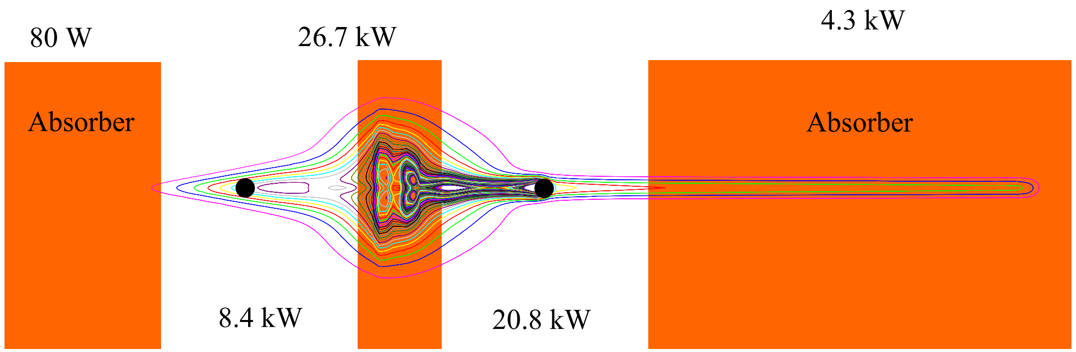


# *IR Design: Synchrotron Radiation*




***large contribution from quadrupole magnets***




*Boris Nagorny*

***overall radiation power in IR: 60 kW (HERA II: 30 kW)***
***geometry of detector beam pipe and synchrotron radiation masks ?***

# *Ring-Ring Parameters*

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

***LHC upgrade: $N_p$ increased.***
***Need to keep e tune shift low:***
*by increasing $\beta_p$, decreasing $\beta_e$*
*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:*

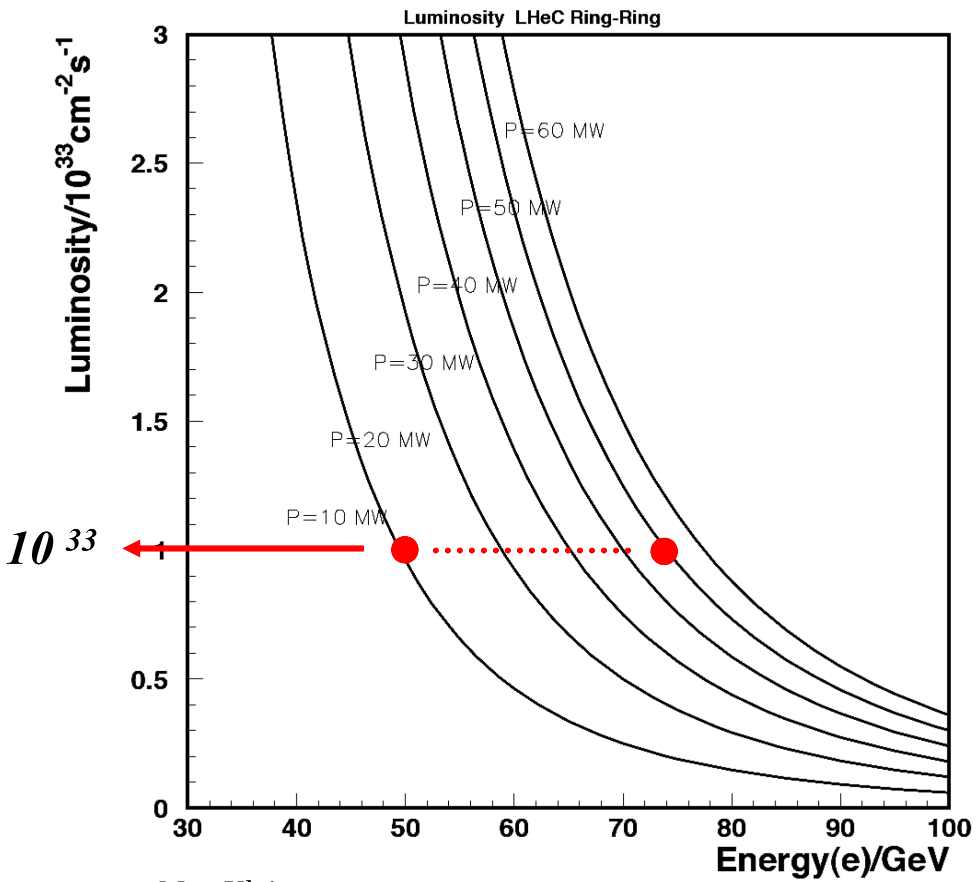
| | |
|---|---|
| ***LEP*** | ***$\Delta\nu_e = 0.048$*** |
| ***LHC-B*** | ***$\Delta\nu_p = 0.0037$*** |
| ***HERA*** | ***$\Delta\nu_e = 0.051$*** |
| | ***$\Delta\nu_p = 0.0016$*** |

| 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 | $L=8.2*10^{32}$ | | |
| | | | |
| 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 | $L=1.03*10^{33}$ | | |
| | | | |
| 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 | $L=1.44*10^{33}$ | | |

# *Luminosity Ring Ring & Performance Limit*

***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.***

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




*Max Klein*

## *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 ↔ $P_{syn}$ = 10MW***
***$E_e$ = 75 GeV ↔ $P_{syn}$ = 50MW * 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$^o$. Can be done with reduced luminosity.

=> Look into two different interaction region setups

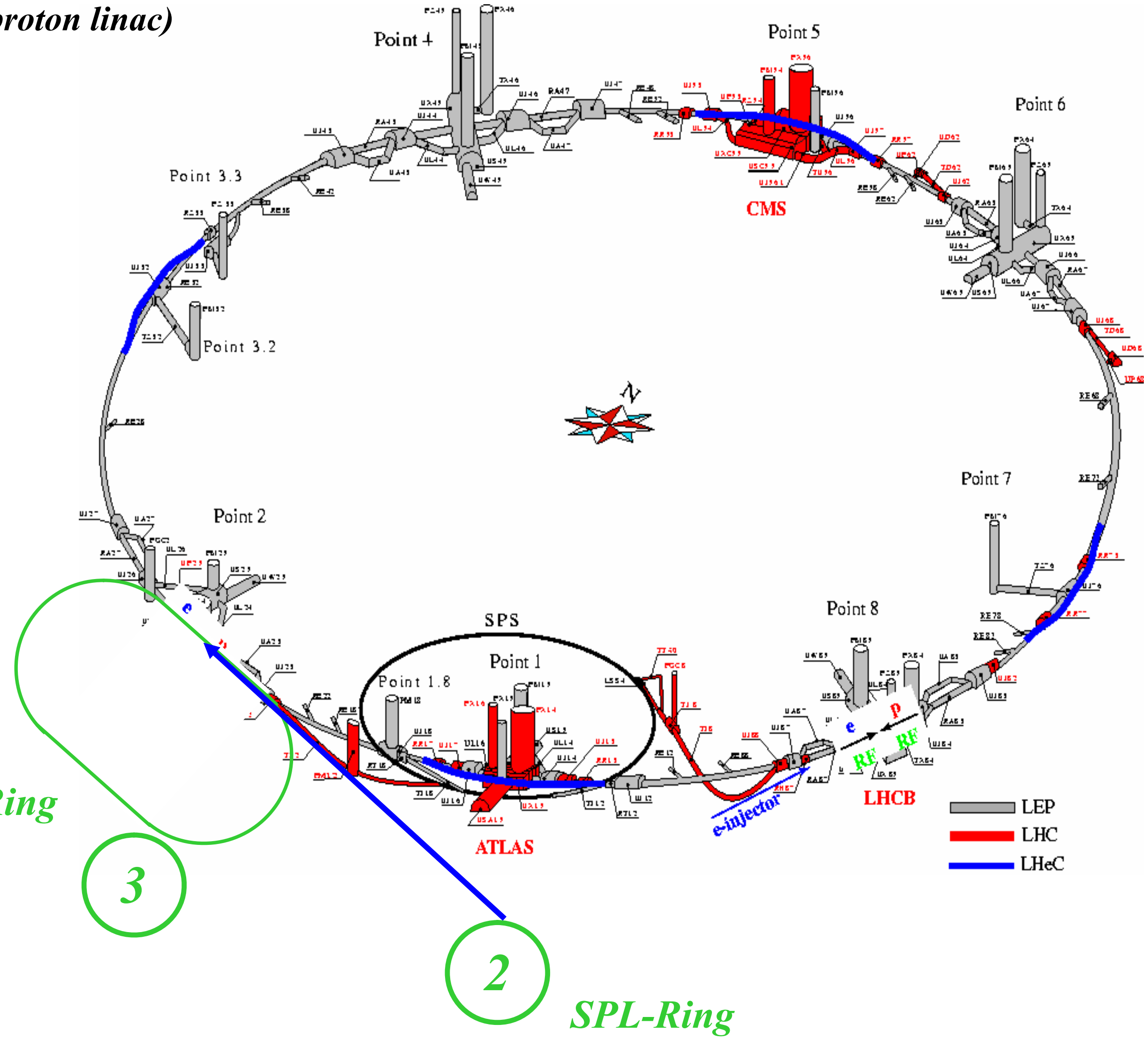
- $L = 10^{33}$ cm$^{-2}$ s$^{-1}$, $10^o < \theta < 170^o$ (prefer magnets not in front of calorimeter)
- $L = 10^{32}$ cm$^{-2}$ s$^{-1}$, $1^o < \theta < 179^o$

Example HERA I and HERA II IRs and Detectors

# *Linac Ring Options:*

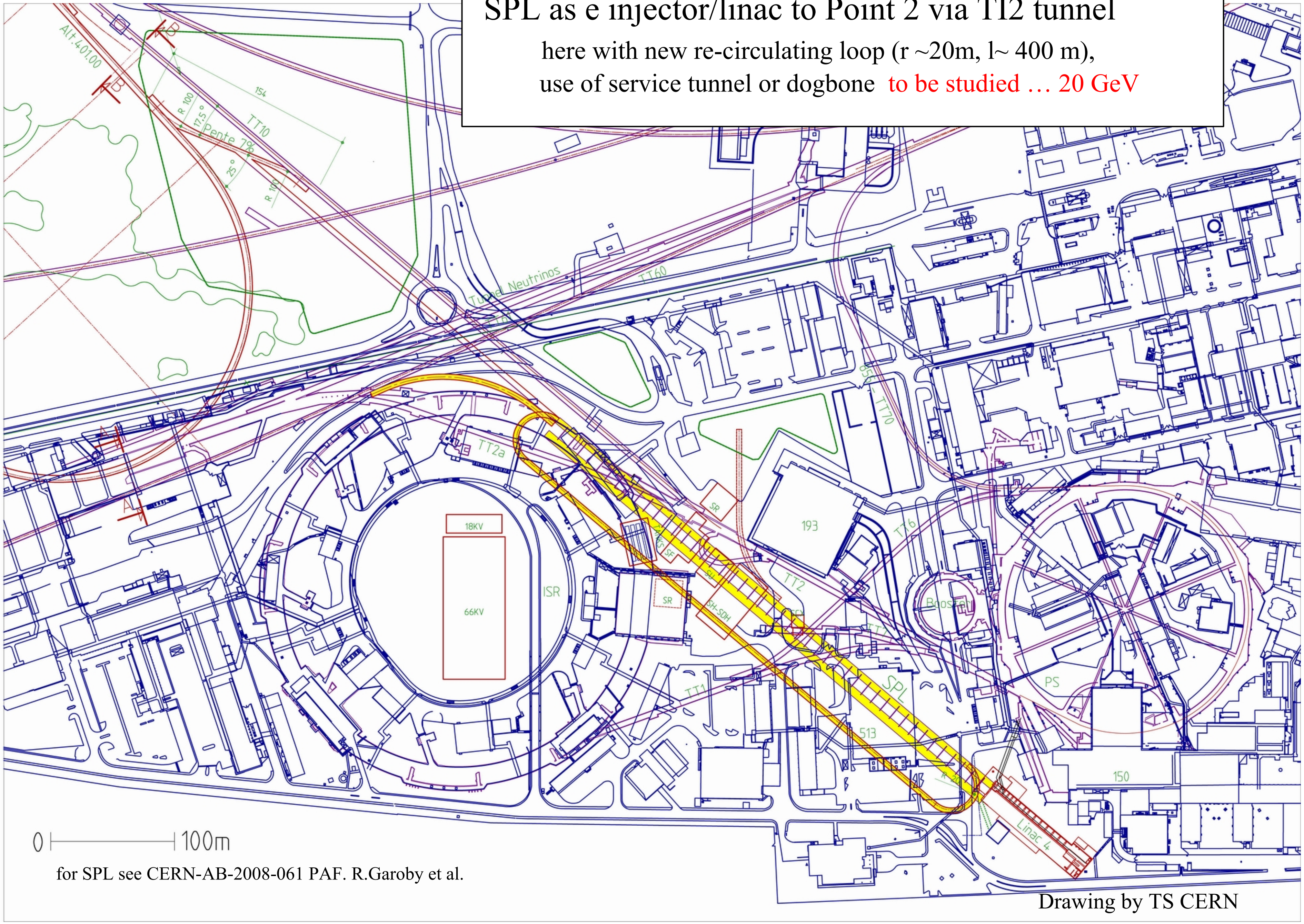
## *SPL ... or a recirculating Linac*

***(super conducting proton linac)***



# SPL as e injector/linac to Point 2 via TI2 tunnel

here with new re-circulating loop (r ~20m, l~ 400 m),
use of service tunnel or dogbone to be studied … 20 GeV




for SPL see CERN-AB-2008-061 PAF. R.Garoby et al.

Drawing by TS CERN

## *Linac Ring Options:*

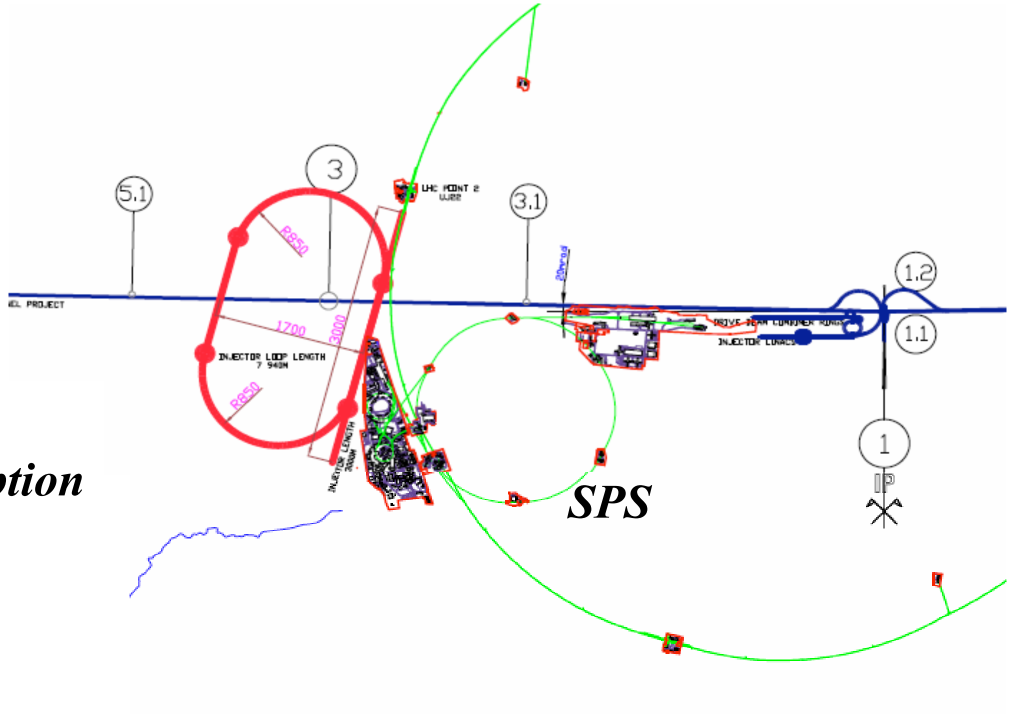
***SPL ... or a recirculating Linac***

| | | Pulsed | CW |
|---|---|---|---|
| e- energy [GeV] | 30 | 100 | 100 |
| comment | SPL* (20)+TI2 | LINAC | LINAC |
| #passes | 4+1 | 2 | 2 |
| wall plug power RF+Cryo | 100 (1 cr.) | 100 (3 cr.) | 100 (35 cr.) |
| bunch population [$10^9$] | 10 | 3.0 | 0.1 |
| duty factor [%] | 5 | 5 | 100 |
| average e- current [mA] | 1.6 | 0.5 | 0.3 |
| emittance $\gamma\varepsilon$ [µm] | 50 | 50 | 50 |
| RF gradient [MV/m] | 25 | 25 | 13.9 |
| total linac length $\beta$=1 [m] | 350+333 | 3300 | 6000 |
| minimum return arc radius [m] | 240 (final bends) | 1100 | 1100 |
| beam power at IP [MW] | 24 | 48 | 30 |
| e- IP beta function [m] | 0.06 | 0.2 | 0.2 |
| ep hourglass reduction factor | 0.62 | 0.86 | 0.86 |
| disruption parameter D | 56 | 17 | 17 |
| **luminosity [$10^{32}$ cm$^{-2}$ s$^{-1}$]** | **2.5** | **2.2** | **1.3** |

F.Zimmermann, S. Chattopadhyay

# *Linac Ring Options:*

*Interaction Region Design*
*... similar or scalable to Ring Ring option*



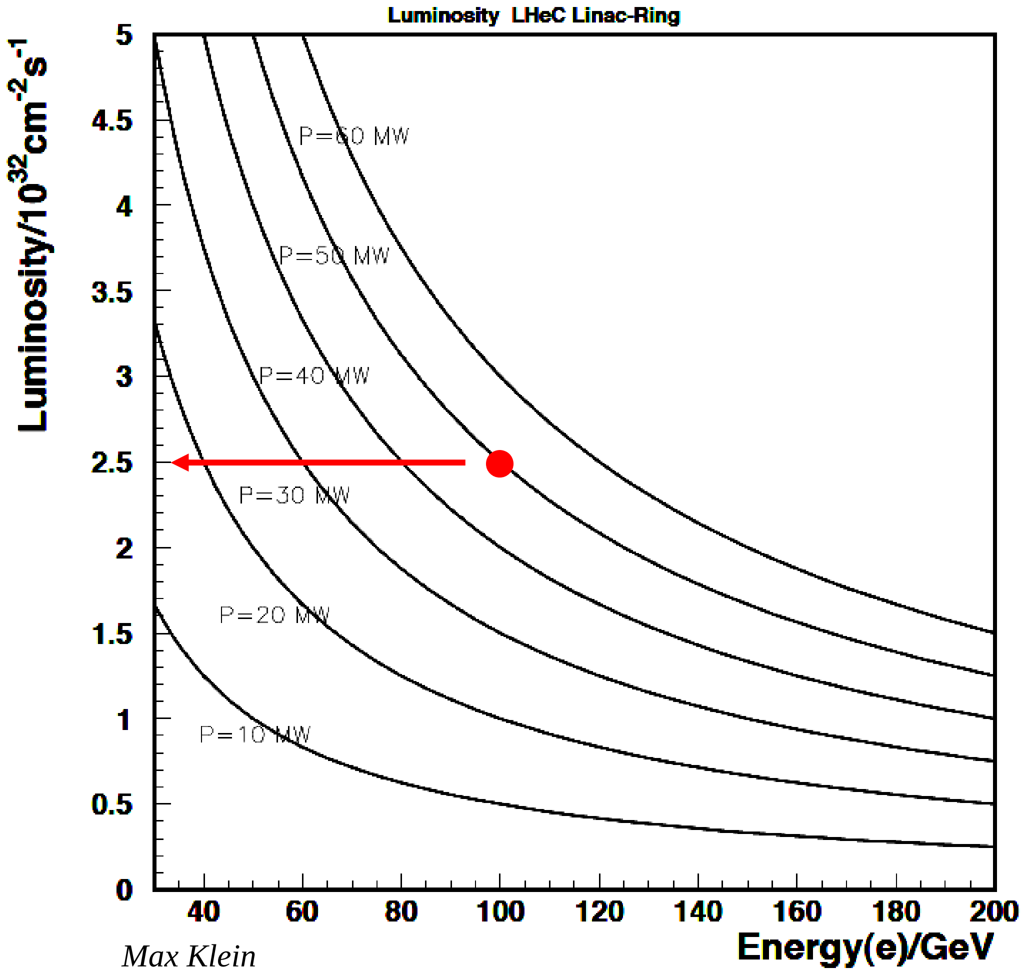

*SPL: perfect synergy*
*machine will be needed for LHC upgrade in any case*
*no new tunnel needed*
*cheap, easy, fast to build*
*energy limited to 20 GeV + 10 GeV ?*

*new e-Linac: 100 GeV seem to be feasible*
*recirculating*
*size ≈ SPS / HERA*

# *Luminosity Linac Ring:*

$$L = \frac{N_p \gamma}{4\pi\, \varepsilon_{pn} \beta^*} * \frac{P_{total}}{E_e}$$

*M.Tigner, B.Wiik, F.Willeke, Acc.Conf, SanFr.(1991) 2910*




*Max Klein*

***Luminosity Performance Limit: beam power***

***adequate for high beam energy***

# *Conclusion:*

** three options studied,*

*Ring-Ring*
*SPL - Ring* … *optimising still to be done*
*Linac Ring*

** Interaction Region & beam separation scheme do not differ too much,*
*have to be optimised according to the beam charateristics*

** Performance Limitations are quite different*
*given an overall power limit of 100MW*

| | | | | |
|---|---|---|---|---|
| *Ring Ring:* | *75 GeV /* | *7 TeV ,* | $L = 2.2*10^{33}$ | *limited in energy* |
| *SPL:* | *20-30 GeV / 7 TeV* | | *L = 2.5*10 32* | *fast, cheap, easy* |
| *Linac Ring:* | *100 GeV /* | *7 TeV ,* | $L = 2.2*10^{32}$ | *limited in luminosity* |
| | *140 GeV /* | *7 TeV ,* | $L = 1.0*10^{33}$ | *only if energy recovery works* |

# Electron-nucleus (e-A) collisions

- The LHC will operate as a nucleus-nucleus (initially Pb-Pb) collider
  - Physics programme is expected to include:
    - Pb-Pb at $\sqrt{s_{NN}} = 5.5\ \text{TeV}$
    - 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

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

    $k_b = 592$ bunches of $N_b = 7\times10^7\ {}^{208}\mathrm{Pb}^{82+}$ nuclei
- Assume lepton injectors can create matching train of $e^-$

    $k_b = 592$ bunches of $N_b = 1.4\times10^{10}\ e^-$
- Lepton-nucleus or lepton-nucleon luminosity in ring-ring option at 70 GeV

$$L = 1.09\times10^{29}\ \mathrm{cm^{-2}s^{-1}} \Leftrightarrow L_{en} = 2.2\times10^{31}\ \mathrm{cm^{-2}s^{-1}}$$

  - May be some scope to exploit additional power by increasing electron single-bunch intensity

# Very(!) tentative e-d luminosity

- Rough guess for beam via Linac3
  - Same beam size as protons, fewer bunches, as for Pb

$$k_b = 592 \text{ bunches of } N_b = 1.7 \times 10^9 \text{ deuterons}$$

- 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

$$L = 2 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1} \quad (\text{gives 11 MW radiated power})$$

  - Optimist might hope for maybe 10-50 times more if Linac4 and other systems work well.
  - A lot of further study required!!