Design Status of the Large Hadron-Electron Collider

John Jowett (CERN)
for the LHeC Study Group

LHeC Machine Study Group

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UCLA: Rainer Wallny

EPFL: Leonid Rifkin

Forgotten someone ? … apologies!

Events in Machine Design

- Assuming familiarity with previous presentations
  - LHeC Web page: http://www.ep.ph.bham.ac.uk/exp/LHeC/
- **2008**
  - September: Divonne I workshop
  - November: **ECFA Plenary at CERN**
- **2009**
  - March Visit to SLAC [Linac]
  - April: **DIS09, Madrid**, talk by B. Holzer
  - April: PAC09 - Papers, Talks
  - May: Visit to BINP Novosibirsk (Ring Magnets)
  - September: **Divonne II (CERN-ECFA-NuPECC Workshop)**
    - Numerous talks on accelerator design aspects
- **2010**
  - Regular Machine Design meetings at CERN
  - Work packages for Conceptual Design Report, end 2010

Alternative Designs

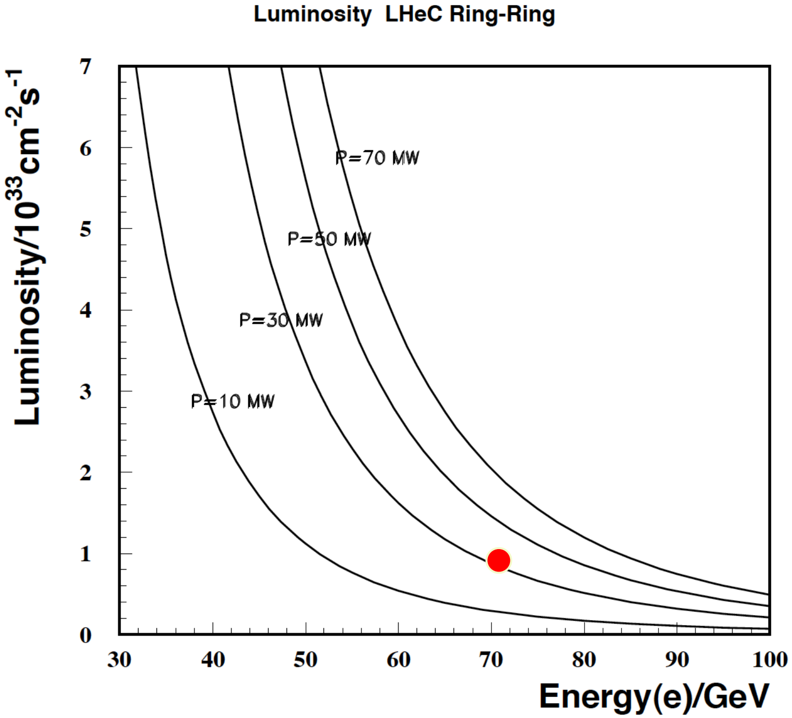
- Ring-ring
  - e-p and e-A (A=Pb, Ar, …) collisions, limited possibilities for polarized e
  - More "conventional" solution, like HERA, no difficulties of principle - at first sight - but constrained by existing LHC in tunnel
  - Steady progress with detailed design
- Linac-ring
  - e-p and e-A (A=Pb, Ar, …) collisions, polarized e from source, poorer Luminosity/Power
  - No previous collider like this (at present)
  - Comparisons of layouts
- SPL-ring
  - No longer an option

RING-RING DESIGN

Ring-Ring Design Criteria

- Compatibility with installed LHC and tunnel
  - Many details to study and take care of
  - LHC p-p will run in parallel
- Minimise length of installation shutdown
  - LHC p-p will be running for high integrated luminosity
- Design performance parameters
  - Achieve LHeC physics goals
- Bounds on power consumption

Baseline parameters



$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}} = 8.3 10^{32} \cdot \frac{I_e}{50mA} \frac{m}{\sqrt{\beta_{px}\beta_{pn}}} cm^{-2} s^{-1}$$

$$I_e = 0.35 mA \cdot \frac{P}{MW} \cdot \left(\frac{100 GeV}{E_e} \right)^4$$

Luminosity for $e^{\pm}p$ ~$10^{33} cm^{-2}s^{-1}$

Used "ultimate" LHC beam parameters

Energy limited by injection and syn.rad losses

Power limit set to 100 MW

Small p tuneshift: simultaneous pp and ep

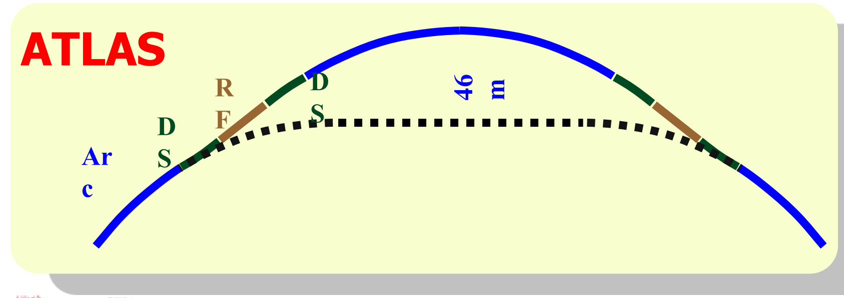
Ultimate Parameter	*Protons*	*Electrons*	
	$N_p = 1.7 \cdot 10^{11}$	*$N_e = 1.4 \cdot 10^{10}$*	*nb=2808*
	Ip=860mA	*Ie=71mA*	
Optics	*β_{xp}=230 cm*	*β_{xe}=12.7 cm*	
	β_{yp}= 60 cm	*β_{ye}= 7.1 cm*	
	ε_{xp}=0.5 nm rad	*ε_{xe}=9 nm rad*	
	ε_{yp}=0.5 nm rad	*ε_{ye}=4 nm rad*	
Beamsize	*σ_x=34 μm*		
	σ_y=17 μm		
Tuneshift	*$\Delta\nu_x$=0.00061*	*$\Delta\nu_x$=0.056*	
	$\Delta\nu_y$=0.00032	*$\Delta\nu_y$=0.062*	
Luminosity	*$L = 1.03 \cdot 10^{33}$*		

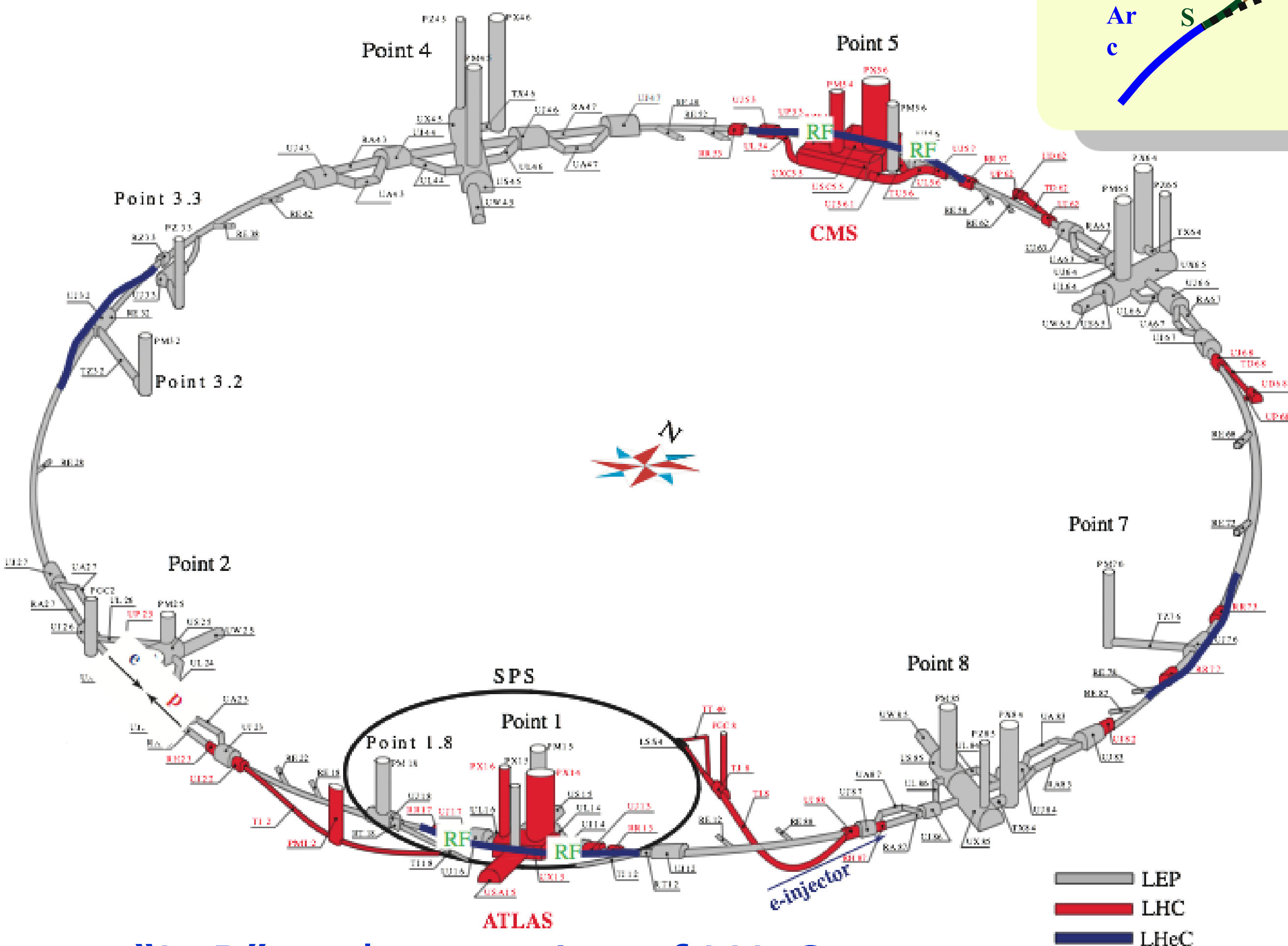
N.B. does not include significant reduction of luminosity from hour-glass, crossing angle (1.4 mrad). Crab-cavity may help.

May have E < 70 GeV.

Overall Layout and Bypasses

e-p/A experiment could be at IP2 (shown) or IP8





To be done:

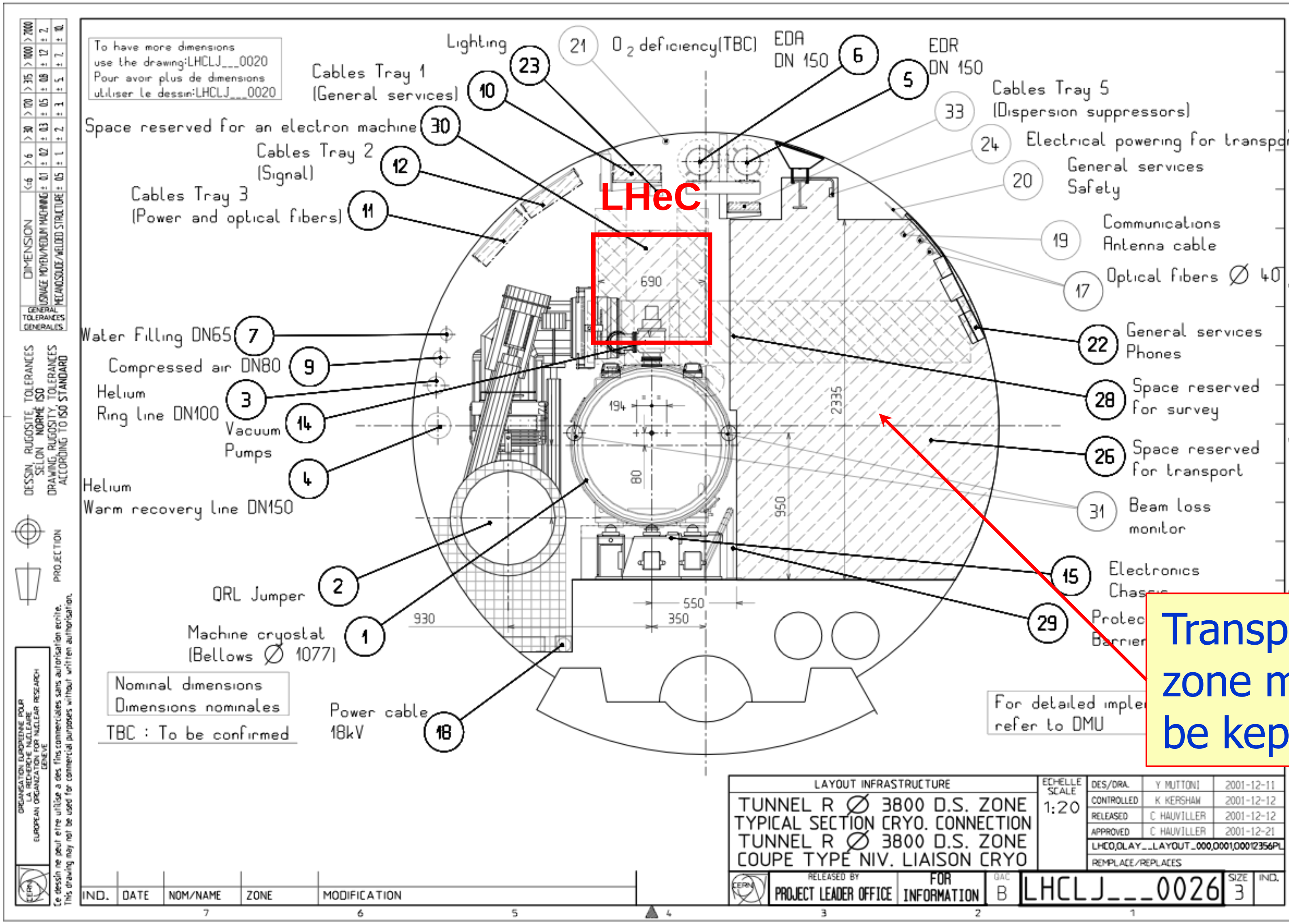
Detailed design of CMS and ATLAS bypasses and integration into optics

Bypass design:

- shutdown time
- cost for tunnel
- match LHC and LeR circumference ? Or leave ΔC ~ 1 m ?

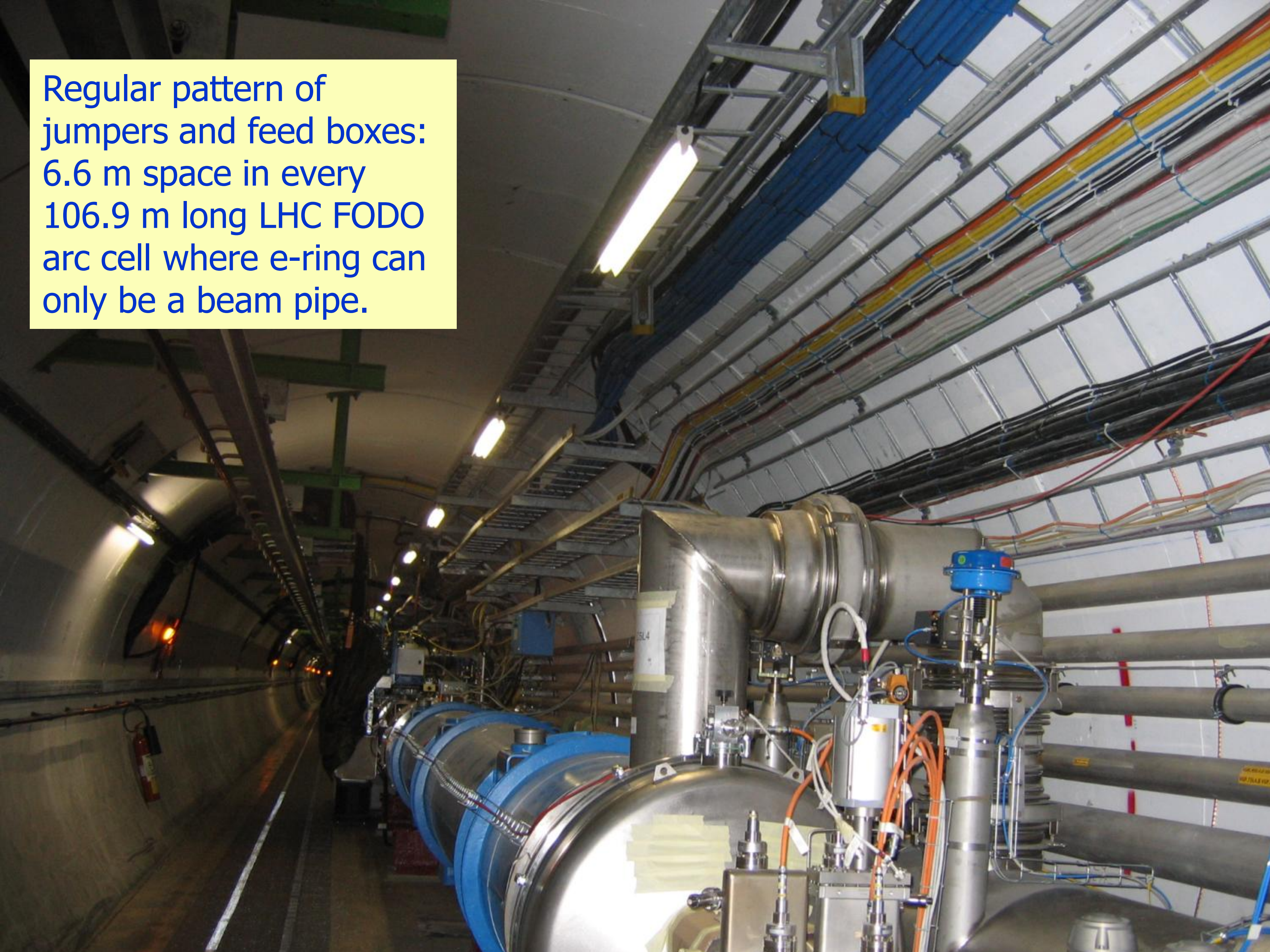
"LeR" = electron ring of LHeC

Fitting e-ring in tunnel



Transport zone must be kept free

Regular pattern of jumpers and feed boxes: 6.6 m space in every 106.9 m long LHC FODO arc cell where e-ring can only be a beam pipe.



Arc design and optics

- Natural to have simple relation between FODO arc cells of LeR and those of LHC

Choice of: $L_{\text{FODO,LeR}} = \frac{1}{2} L_{\text{FODO,LHC}}$

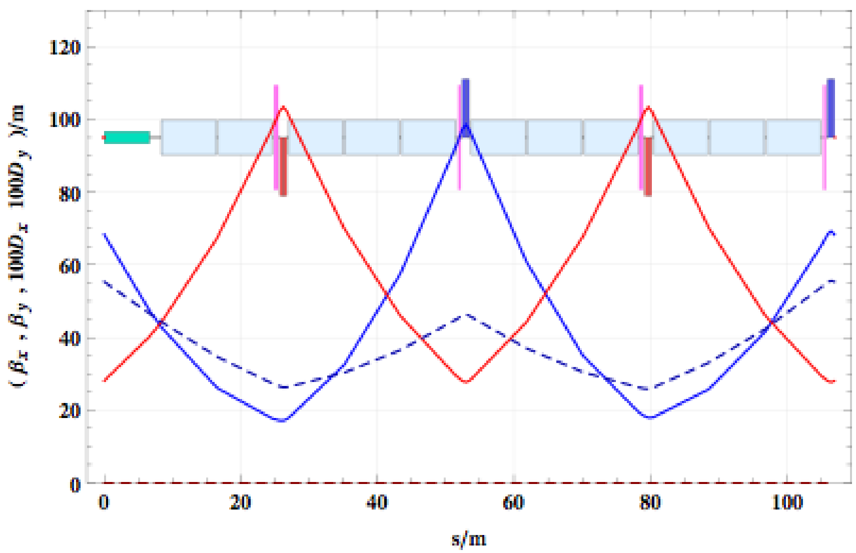
gives design emittance for LHeC at 70 GeV with reasonable betatron phase advances

(JMJ, Divonne 2008, 2009)

Excluded zone in each LHC cell

$\Rightarrow$ remove dipole magnet from every second cell

Arc Cell Design – double FODO



- No interference with LHC
- meets design parameters
- synchrotron radiation energy loss < 50 MW (maximum dipole filling)
- 2 quadrupoles families
- reasonable sextupole strength and length

Lcell → 106.903 Meter
phicell → 0.0303136
mux → 180 °
muy → 120 °
Ncell → 184
KQF → 0.0513516
KQD → -0.0419526
KSF → 0.315422
KSD → -0.283489
Lbend1 → 16 Meter
Lbend2 → 24 Meter
Lquad → 1.
Lsextf → 0.35
Lsextd → 0.6
Brho → 233.495 Meter Tesla
θBend1 → 0.00551157
θBend2 → 0.00826735
ρBend → 2902.99 Meter
Bbend → 0.0804327 Tesla
dBdxQF → $\frac{11.9903\ \text{Tesla}}{\text{Meter}}$
dBdxQD → $-\frac{9.79573\ \text{Tesla}}{\text{Meter}}$
I1 → 0.0108062 Meter
I2 → $\frac{0.0000104422}{\text{Meter}}$
I3 → $\frac{3.59706\times10^{-9}}{\text{Meter}^2}$
I4 → 0
I5 → $\frac{1.33064\times10^{-11}}{\text{Meter}}$
I8 → $\frac{0.00161315}{\text{Meter}}$

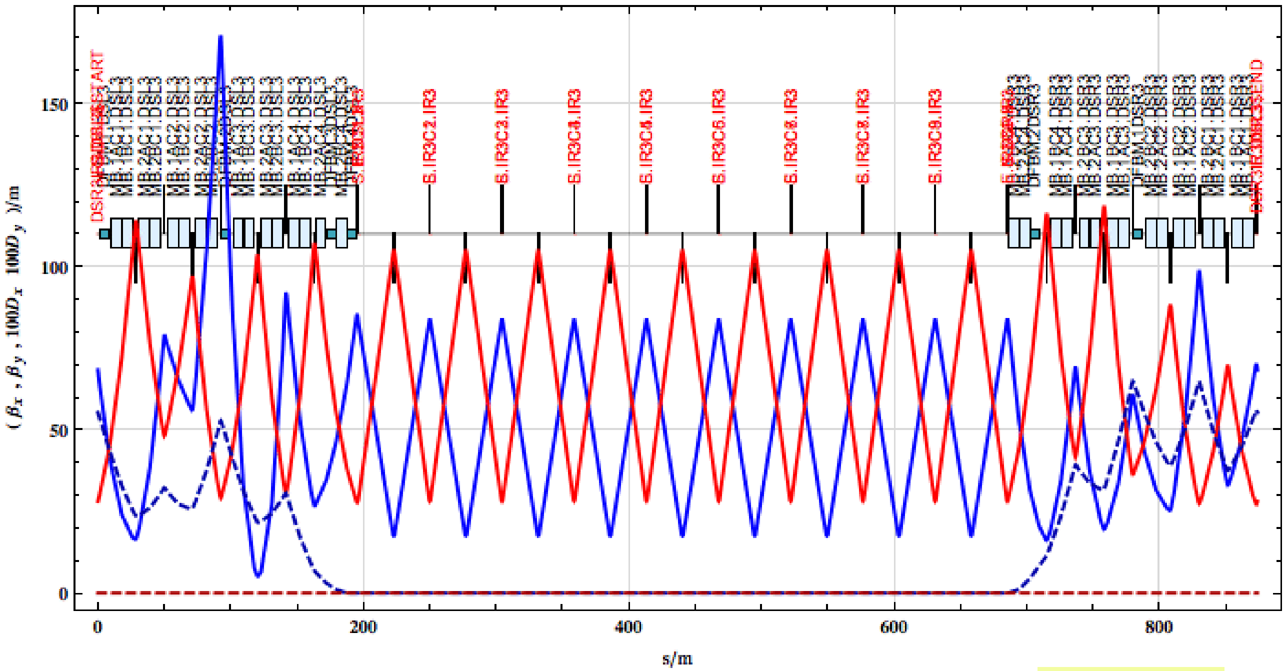
alphac → 0.0000745848
DQ1 → 0.00550352
DQ2 → 0.00543493
EGeV → 70.
kappa → 0.5
Je → 1.5
Jx → 1.5
Jy → 1
Jep → 308.968
U0 → 649.507 ElectronVolt Mega
Power → 46.0043 Mega Watt
taux → 0.0127783 Second
tauy → 0.0191675 Second
taue → 0.0127783 Second
Ex → 6.10876 Meter Nano
Exc → 4.58157 Meter Nano
Eyc → 2.29079 Meter Nano
Polarizationtime → 39.4071 Minute
sigE → 0.00128505
sigL → 4.1914 Meter Milli
sigxQF → 0.897582 Meter Milli
sigxQD → 0.439084 Meter Milli
sigyQF → 0.251985 Meter Milli
sigyQD → 0.486595 Meter Milli

	Protons	Electrons
N_{bunch}	2808	
E_{beam}	7 TeV	70 GeV
I_{beam}	860 mA	71 mA
$\varepsilon_{rms,x}$	0.50 nm rad	7.6 nm rad
$\varepsilon_{rms,y}$	0.50 nm rad	3.8 nm rad

M. Fitterer

Dispersion suppressors sections

- Built from similar magnets and cells to main arc
- Interrupted by similar feed boxes to arc
- Follow LHC DS (classical DS layouts do not fit geometry)
- 8 individually powered quadrupoles for matching
- Non-experimental straight sections filled with FODO cells for now

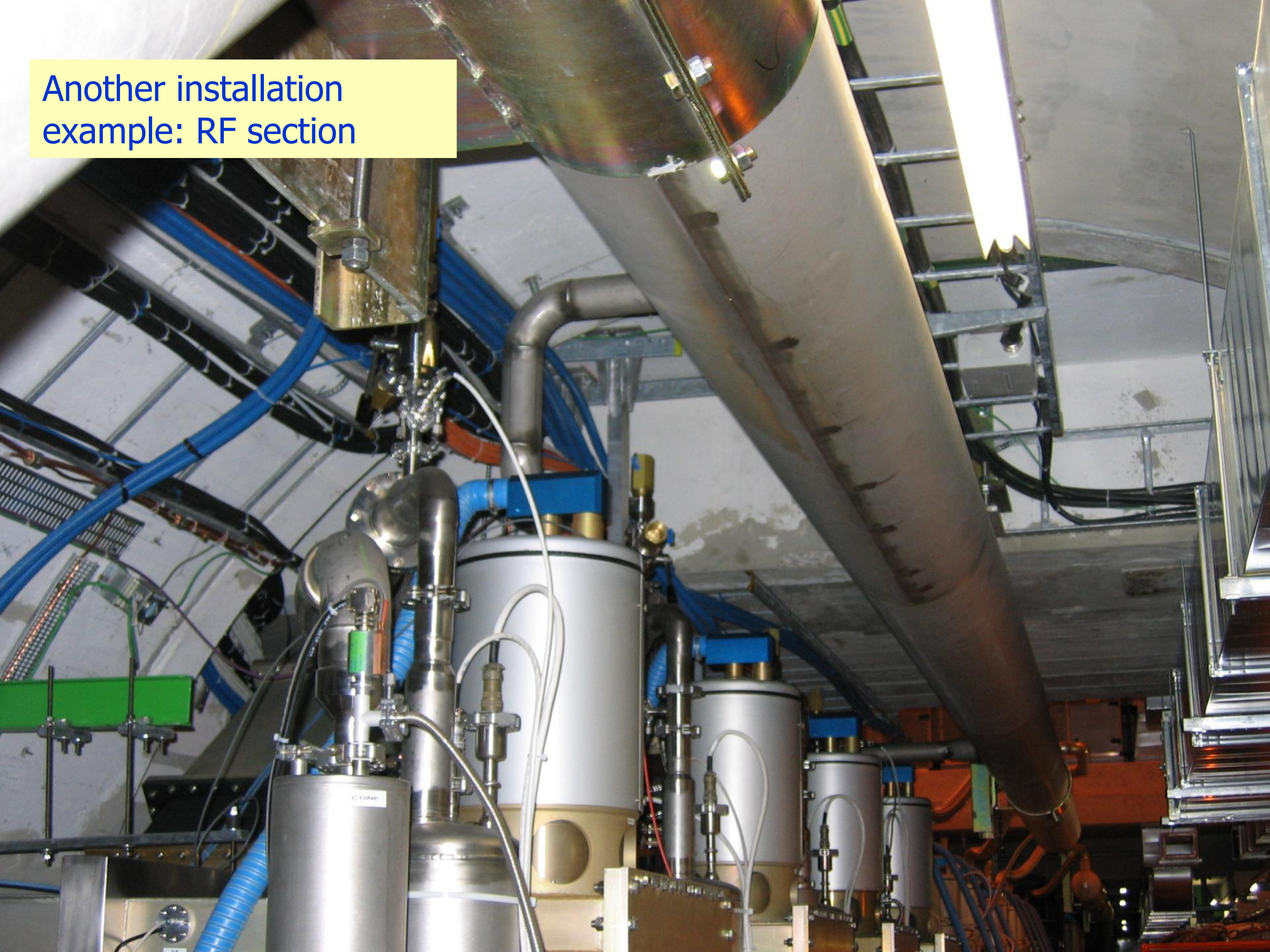


Detailed work continues to adapt these schemes to bypasses, LHC straight sections, LHeC IR.

Geometry very important.

M. Fitterer

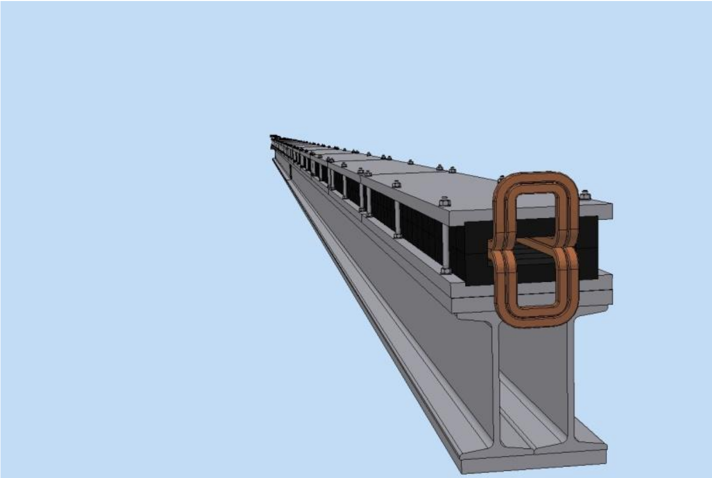
Another installation example: RF section



Other Ring-Ring Problems

- Circumference matching at 1 m level
  - Extra length of bypasses hard to compensate by radial displacement into transport zone
  - Unequal circumference (multiple of bunch spacing) could create complicated beam-beam problems
- Circumference matching at mm level
  - Unlike HERA, little freedom to move p or Pb beam radially – may modify damping partition for e beam, change emittance and luminosity (JMJ, Divonne 2009)

Arc dipole (bending)magnets



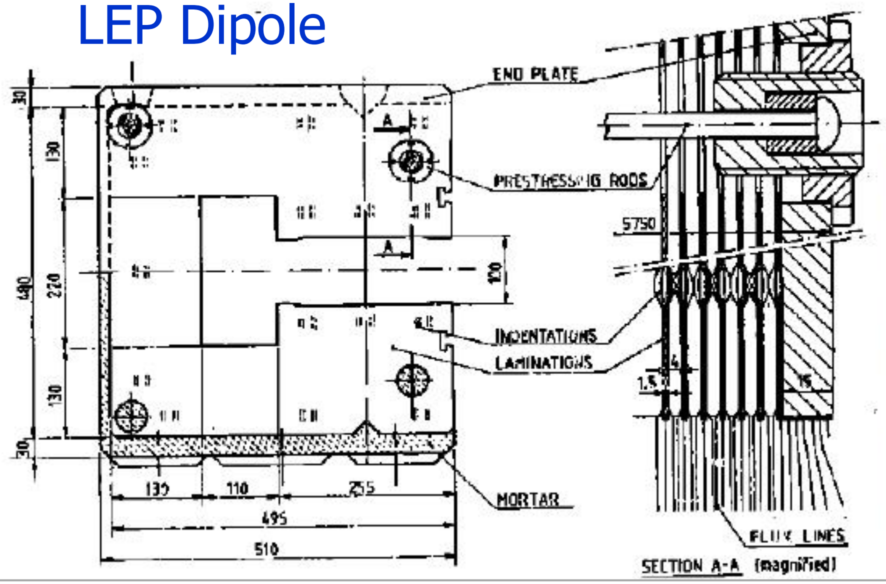
O-shaped magnet with ferrite core [BINP-CERN]

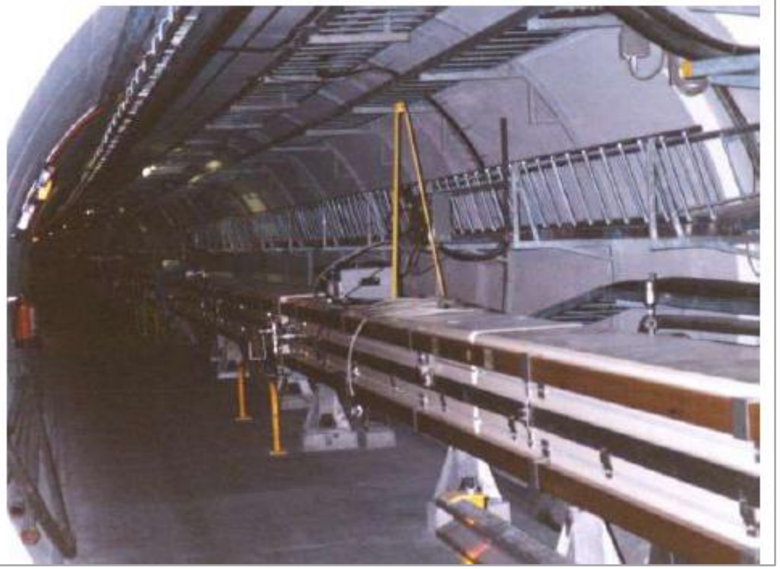
Accelerator	LEP	LHeC
Cross Section/ cm²	50 x 50	20 x 10
Magnetic field/ T	0.02-0.11	0.01-0.135
Energy Range/GeV	20-100	10-70
Good Field Area/cm²	5.9 x 5.9	6 x 3.8
FODO length/m	76	53
Magnet length/m	2 x 34.5	2 x 14.76
segmentation	6 cores	14
Number of magnets	736	488
Weight / kg/m	800	240

Field quality at injection?

Prototype design under way at Novosibirsk for May 2010

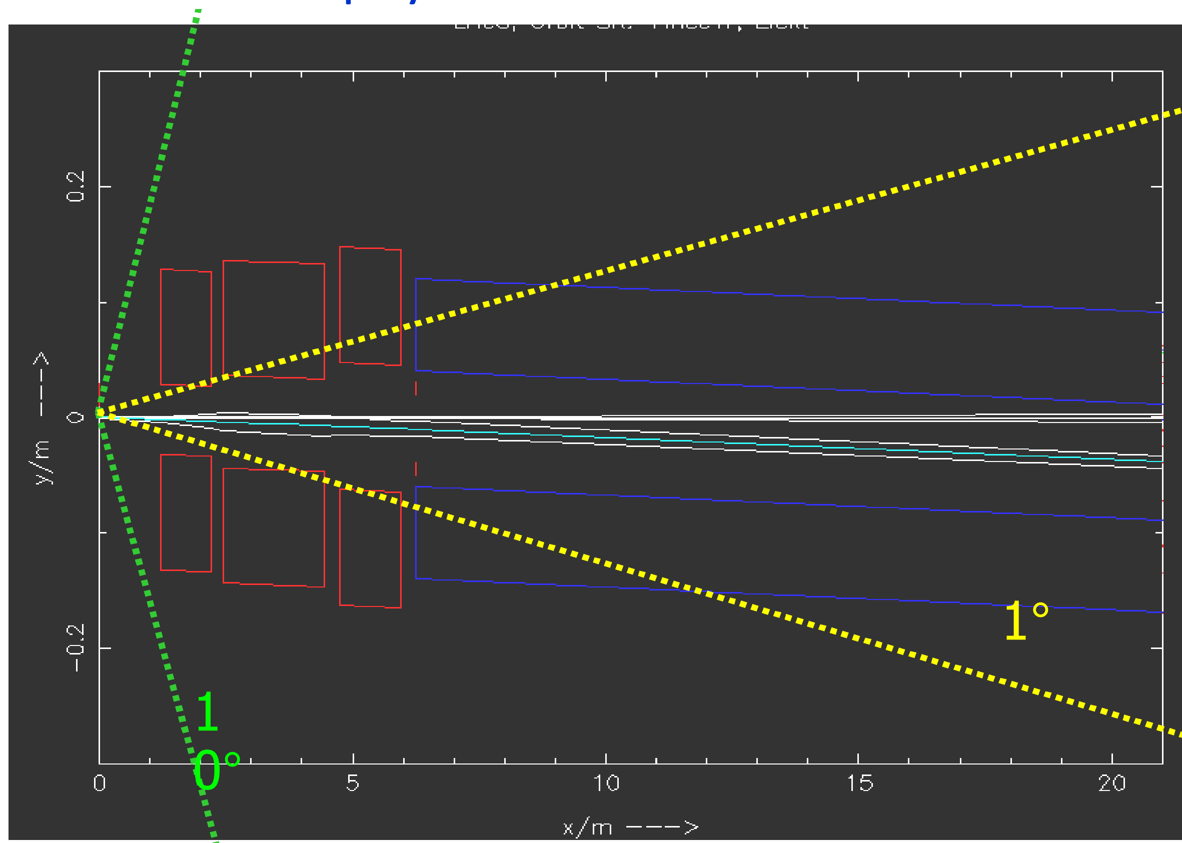
LEP Dipole





Ring-Ring IR Designs

- Higher acceptance allows lower Q^2 and x physics to be seen
- For high Q^2 and x, 10° opening angle
- For low Q^2 and x, 1° opening angle
- Luminosity:
    - 10°: $\sim 10^{33}$
    - 1°: $\sim 10^{32}$



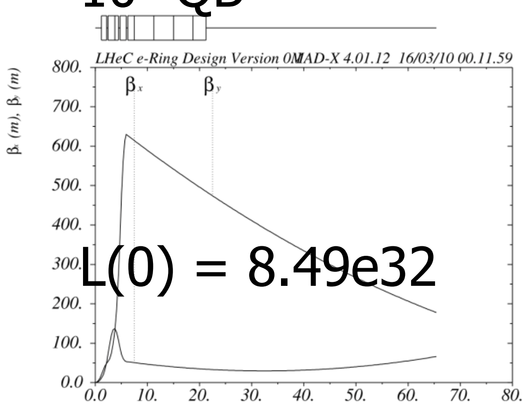
IR design driven by orbit/focusing coupling, and the production of synchrotron radiation

The first parasitic collision node is at 3.75 m….a crossing angle is unavoidable

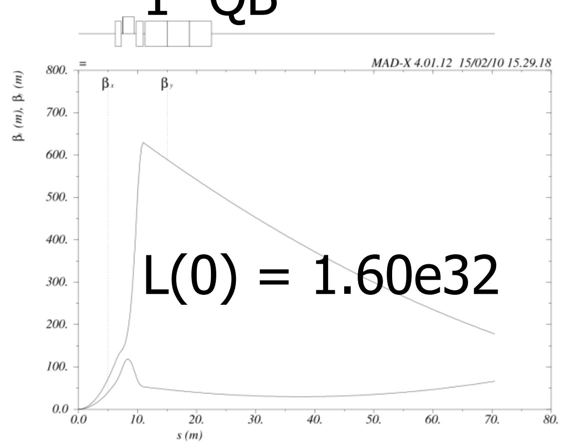
Appleby/Thomson/Holzer/Nagorny

Comparison of Designs

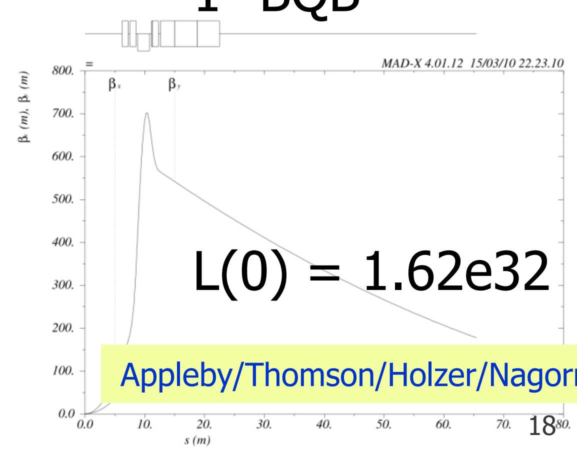
10° QB



1° QB

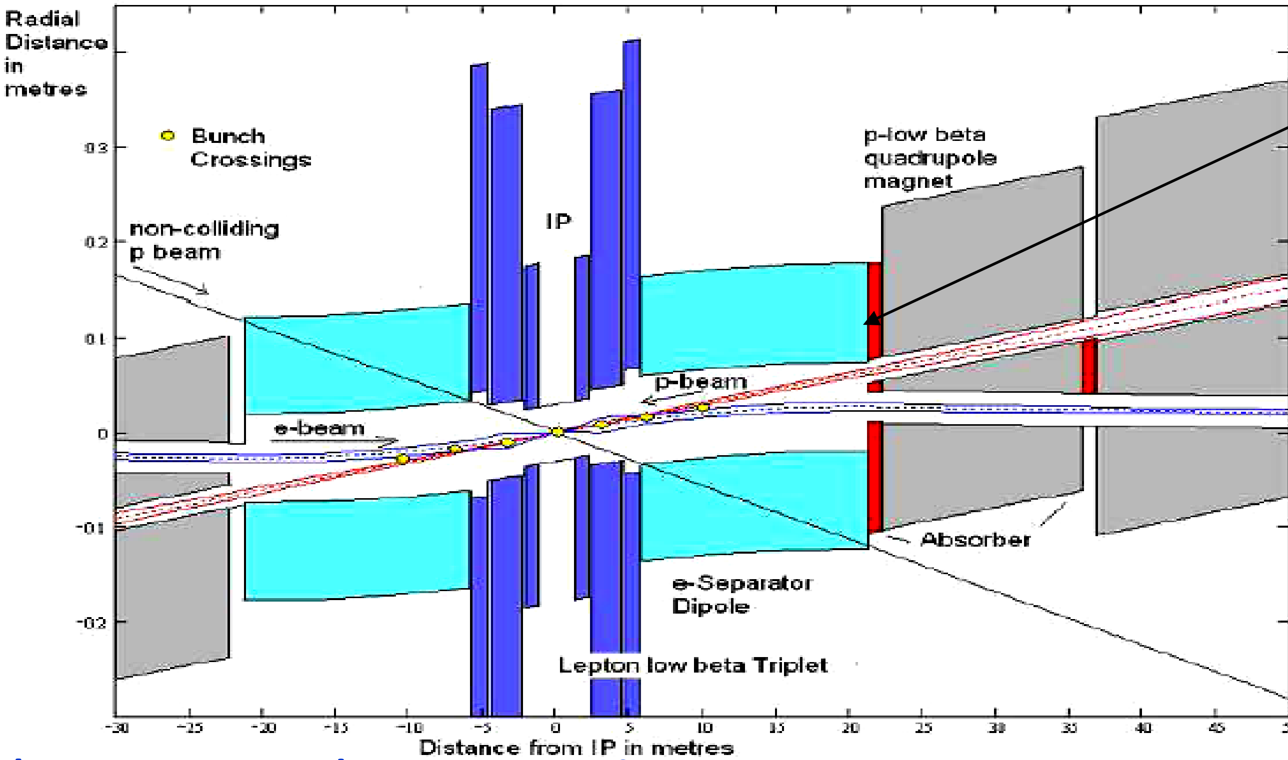


1° BQB



Appleby/Thomson/Holzer/Nagorny

Synchrotron Radiation – 10° QB



10° QB SR power ~60kW, E_c ~ 100KeV

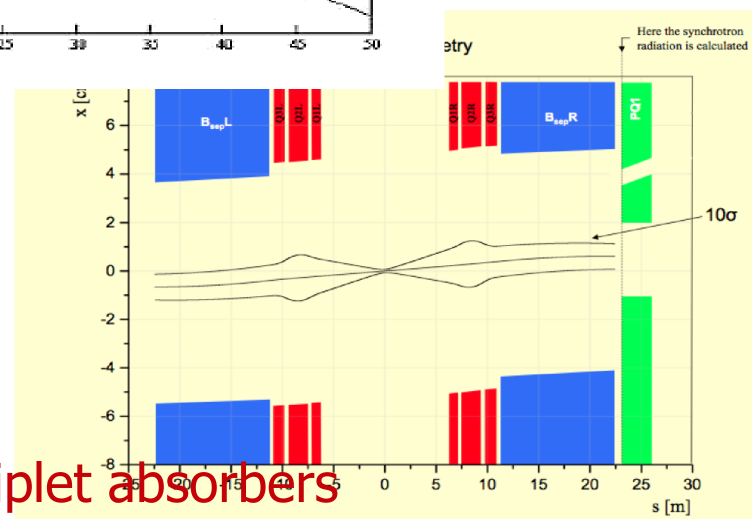
(E=70 GeV)

Synchrotron Radiation – 1° QB

1° QB SR power ~ 10kW,

(weaker bends)

(E=60 GeV)



Both designs: power concentrated on Final Triplet absorbers

Appleby/Thomson/Holzer/Nagorny

Current Status of IR Designs

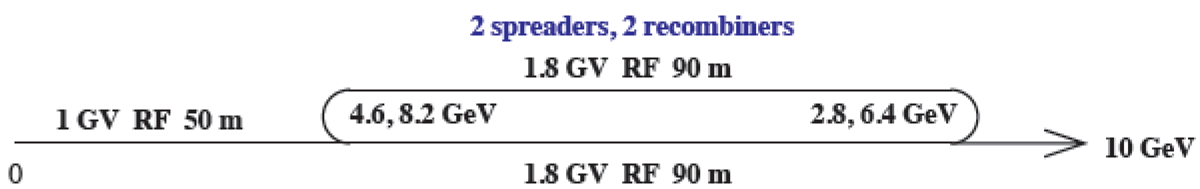
- Now have LHeC RR IR designs for high and low acceptance interaction regions
- p/e achieved with IR dipole, offset electron quads and crossing angle.
- SR production minimised by smooth, weak bends, and concentrated on dedicated SR masks on the proton triplet
  - 10° acceptance
    - Luminosity possible with crab cavities ~1.1×10^{33}
    - Separation/SR trade-off looks OK
    - SR power ~60kW
  - 1° acceptance
    - Luminosity achieved - ~1.5×10^{32}
    - Separation achieved with a crossing angle
    - SR generation sufficiently low
    - SR power ~10kW

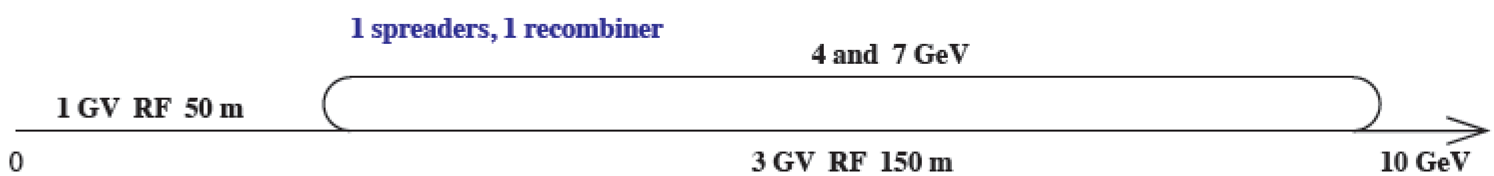
Appleby/Thomson/Holzer/Nagorny

Injector for Ring-Ring

- Consider 10 GeV electron injector
  - Not a major problem in comparison with rest of project but must be designed
  - Natural to use same SC cavities as LeR
  - Linac ~ 500 m,
  - Possibly with recirculation, like scaled-down former ELFE project
    - H. Burkhardt, LHeC Design Meeting, 2/3/2010

Injector options with recirculation





gaining a lot with just 2 re-circulation, 3 passages through the LINAC

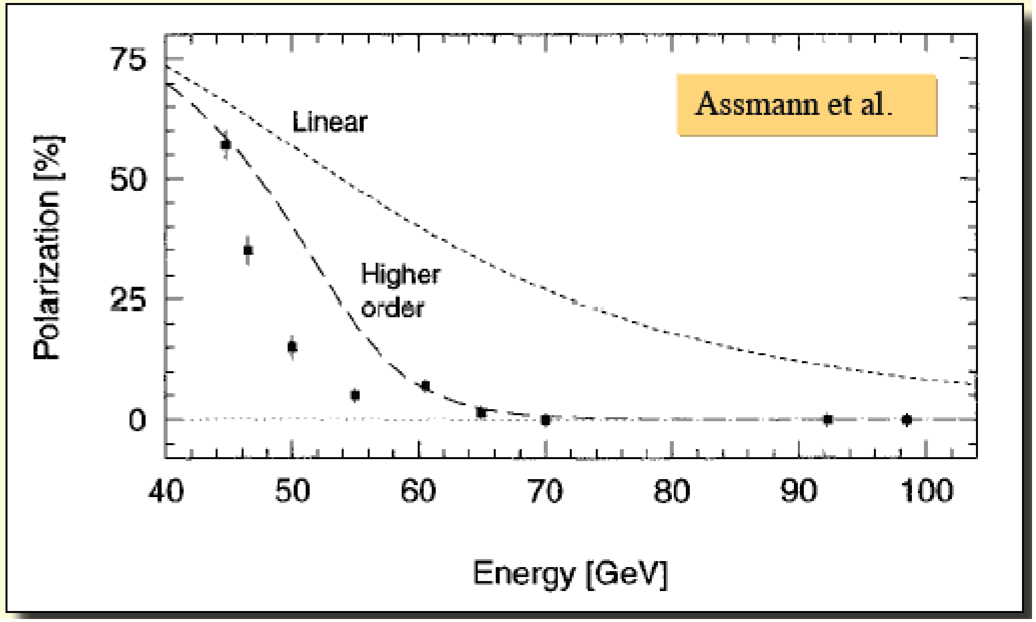
H. Burkhardt

Prospects for polarized electron beam

- Rely on self-polarization of e beam by Sokolov-Ternov mechanism
- Theoretical understanding of 1980s confirmed by empirical experience of LEP:

Depolarizing effects of energy spread: little polarization left above ~ 60 GeV

But reasonable levels attainable *with best design and techniques* below this energy.

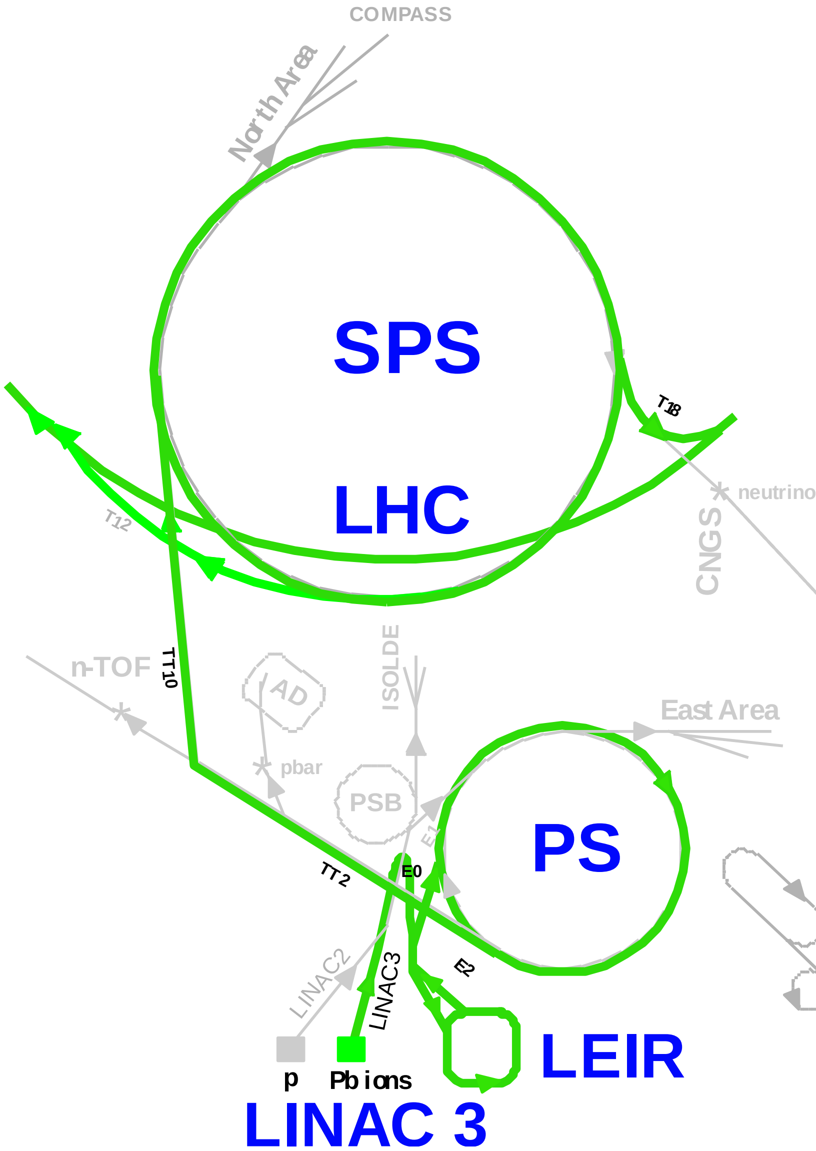


More exotic possibilities, e.g., snakes and asymmetric bends.

Recent simulations, models, D.P. Barber, U. Wienands

Present LHC Ion Injector Chain

- ECR ion source (2005)
  - Provide highest possible intensity of Pb^{29+}
- RFQ + Linac 3
  - Adapt to LEIR injection energy
  - strip to Pb^{54+}
- LEIR (2005)
  - Accumulate and cool Linac3 beam
  - Prepare bunch structure for PS
- PS (2006)
  - Define LHC bunch structure
  - Strip to Pb^{82+}
- SPS (2007)
  - Define filling scheme of LHC



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 at
    - A-A where A may be Ar, 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
- Electron-deuteron e-d collisions would require a completely new source (at least!)
  - Present CERN complex does not foresee deuterons

e-Pb collisions in Ring-Ring

- Assume present nominal Pb beam in LHC
  - Same beam size as protons, fewer bunches

$$k_b = 592 \text{ bunches of } N_b = 7\times10^7 \ {}^{208}\text{Pb}^{82+} \text{ nuclei}$$

- Assume lepton injectors can create matching train of e^-

$$k_b = 592 \text{ bunches of } N_b = 1.4\times10^{10} \ \text{e}^-$$

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

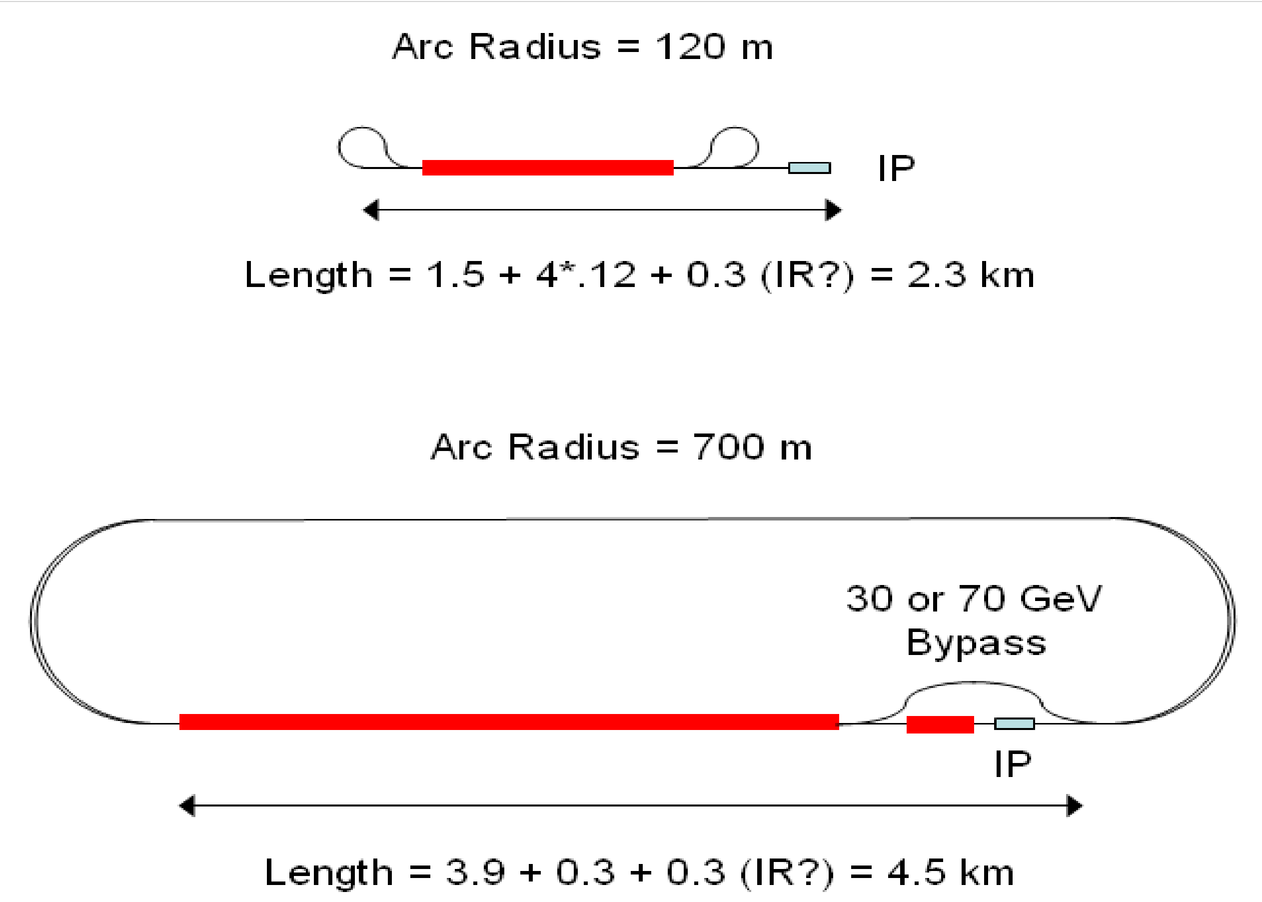
$$L = 1.09\times10^{29} \text{ cm}^{-2}\text{s}^{-1} \quad \Leftrightarrow \quad L_{\text{en}} = 2.2\times10^{31} \text{ cm}^{-2}\text{s}^{-1}$$

gives 11 MW radiated power

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

LINAC-RING DESIGN

Two LINAC Configurations [CERN-SLAC]



60 GeV

31 MV/m, pulsed

two passes

60 GeV

13 MV/m CW ERL

4 passes

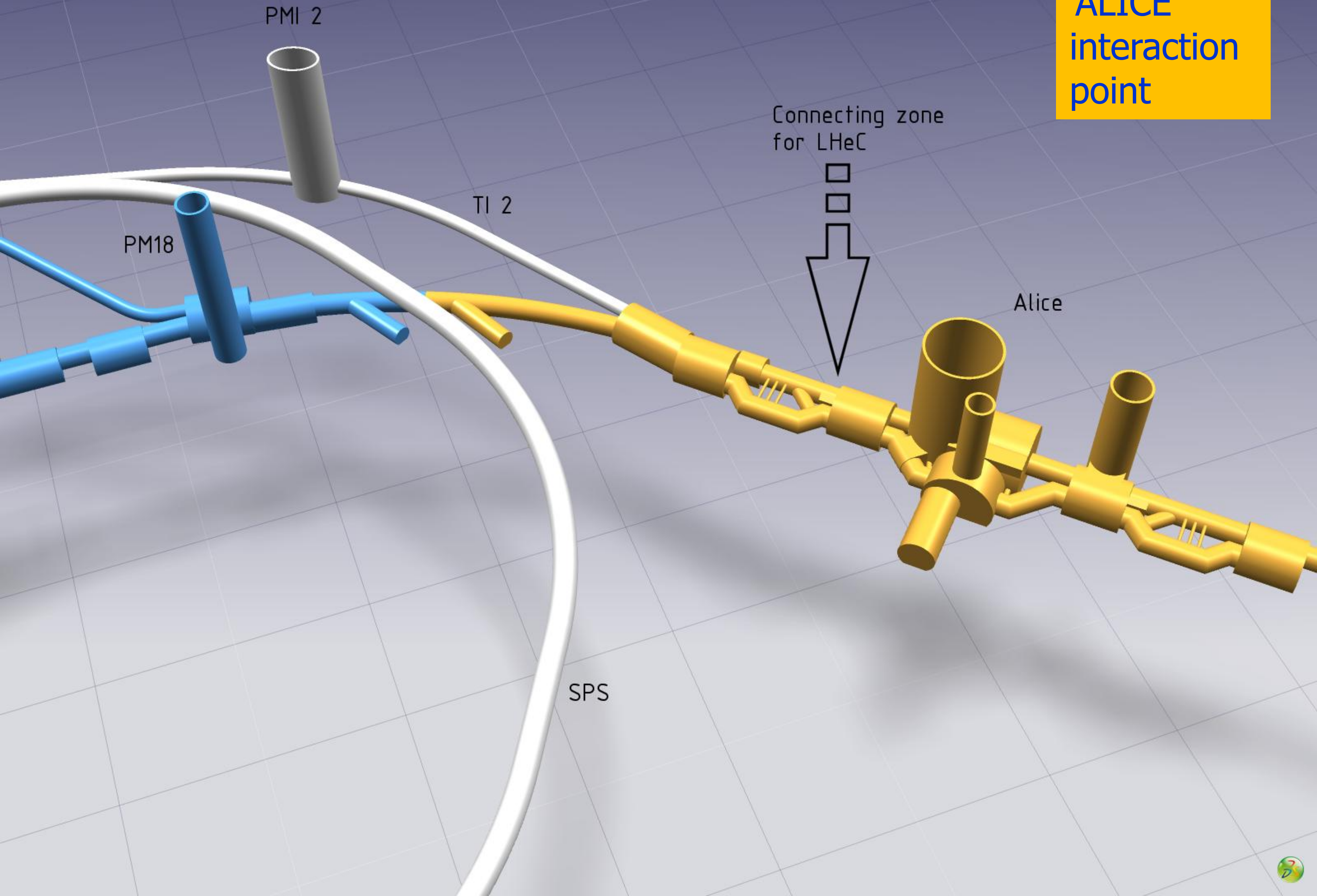
140 GeV

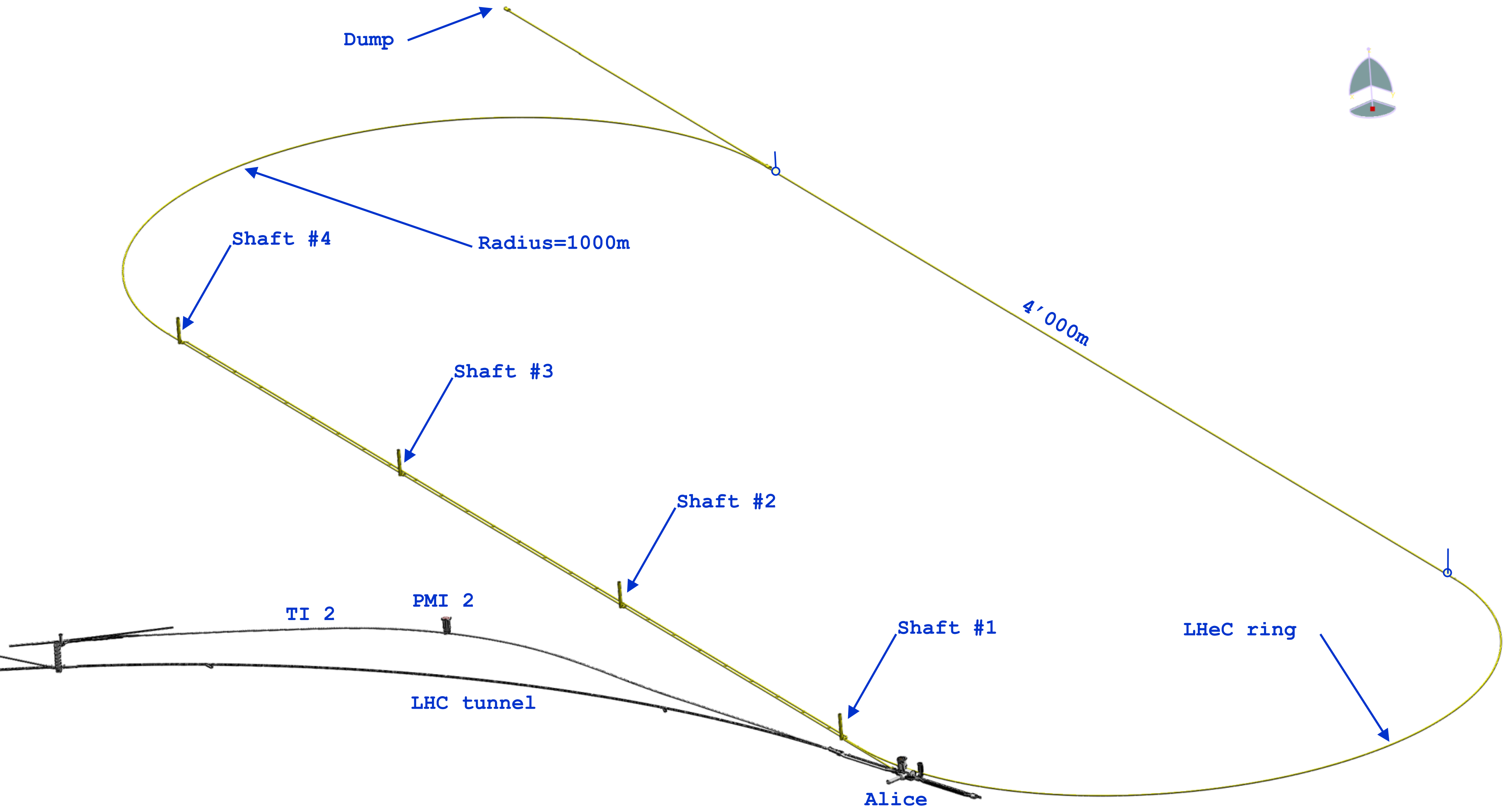
31 MV/m, pulsed

2 passes

Linac-Ring Civil Engineering

Assuming 'ALICE' interaction point



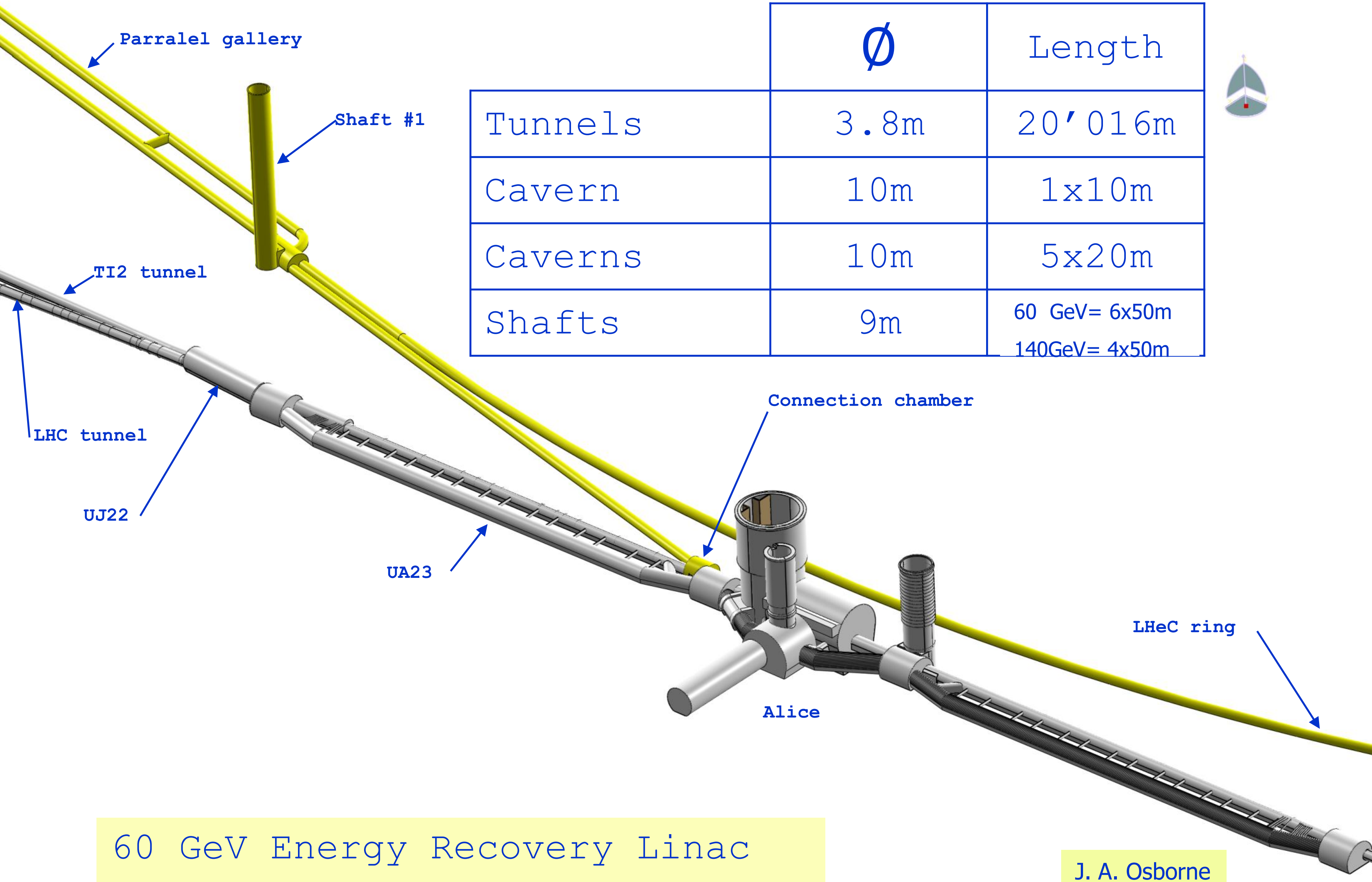


60 GeV Energy Recovery Linac = 2 shafts

Or 140 GeV pulsed Machine = 4 shafts

J. A. Osborne

	Ø	Length
Tunnels	3.8m	20’016m
Cavern	10m	1x10m
Caverns	10m	5x20m
Shafts	9m	60 GeV= 6x50m 140GeV= 4x50m



60 GeV Energy Recovery Linac

Or 140 GeV pulsed Machine

J. A. Osborne

LINAC-Ring Parameters

Configuration	60 GeV, pulsed	60 GeV CW ERL	140 GeV pulsed
N_e/bunch/ 10^9/50ns	4	1.9	2
gradient MV/m	32	13	32
normalised ε/ μm	50	50	100
cryo power/MW	3	20	6
effective beam power/MW	50	$40/(1-\eta_{ERL})$	50

Luminosity for ultimate beam

$$N_p = 1.7 \cdot 10^{11}, \varepsilon_p = 3.8 \mu m, \beta^* = 0.2 m, \gamma = 7000/0.94$$

$$L = 8 \cdot 10^{31} cm^{-2} s^{-1} \cdot \frac{N_p 10^{-11}}{1.7} \cdot \frac{0.2}{\beta^* / m} \cdot \frac{P / MW}{E_e / GeV}$$

An Electron-Proton Collider in the TeV Range

M. Tigner, Cornell Univ., Ithaca, NY
B. Wiik, F. Willeke, DESY, Hamburg, FRG

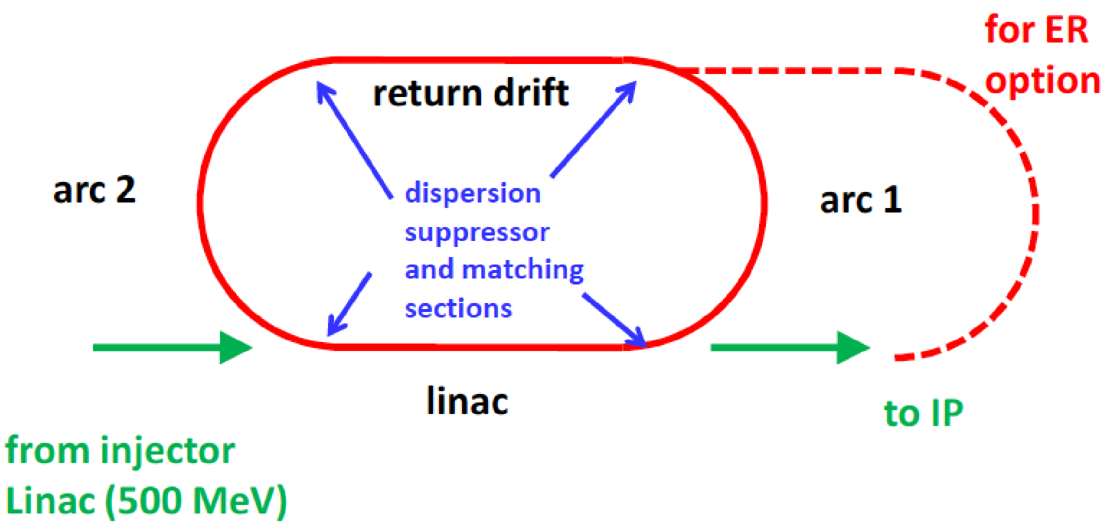
As the era of e-p colliders begins we need to begin a search for practical schemes for increasing the available center of mass energies. The use of an SC linac on SC proton ring approach may offer a practical possibility while maintaining a favorable electron to proton beam energy ratio.

The LR combination needs a better p beam and/or E_e recovery to reach luminosity beyond $10^{32} cm^{-2} s^{-1}$

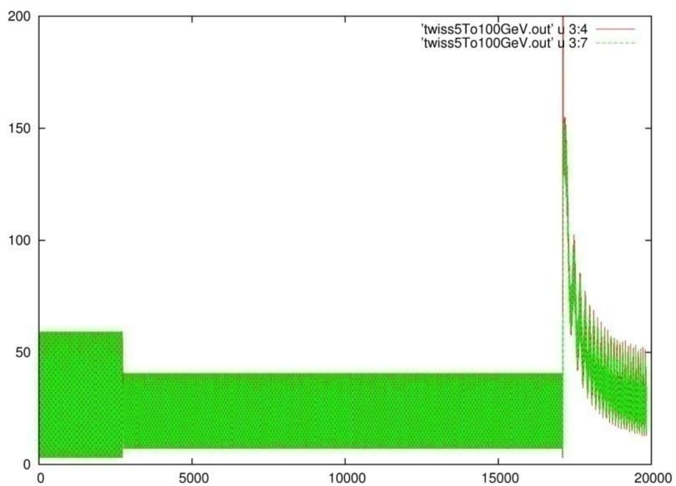
	Least Expensive	High Luminosity	High Energy
IP Energy (GeV)	60	60	140
Energy before IP Bypass (GeV)		58.3	138.3
Lum (10^32 cm^-2 sec^-1)	~ 2	~ 30	~ 2
Recover Beam Energy	No	Yes	No
Beam Duty	5% (1 ms, 50 Hz)	CW	5% (1 ms, 50 Hz)
Charge per bunch (10^10 e)	1.5	0.2	1.5
Bunch Spacing (ns)	250	50	250
Beam Current (mA)	9.6	6.4	9.6
Linac Gradient (MV/m)	31.5	13.0	31.5
Inj Energy	0.5	0.5	0.5
Dump Enregy	60	0.4	140
Pre-Bypass Energy Gain (GeV)	30.3	28.9	70.4
Post-Bypass Energy Gain (GeV)		1.7	1.7
Arc Layout	Dogbone	Half Circle	Half Circle
Max Arc Energy (GeV)	30.8	29.4	70.9
Arc Radius (m)	120	700	700
1st Pass Synch Loss (% Max E)	2.0	0.17	2.2
2nd Pass Synch Loss (% Max E)		2.72	
3rd Pass Synch Loss (% Max E)		0.17	
Total Synch Loss (% Max E)	2.0	3.1	2.2
Total Synch Loss (GeV)	0.0	1.8	3.0
Synch Emit Growth (microns)	50.6	0.02	3.5
Number of PreB RF Units (26 Cavities	38	86	86
RF Unit Length with Cold Boxes (m)	40	44	44
Number of ~4 MW Cryoplants	2	7	7
Linac Gap for Cryoplant (m)	12	12	12
Length of Pre-IP Linac (km)	1.5	3.9	3.9
Length of Post-IP Linac (km)		0.30	

Detailed parameters from Chris Adolphsen.

e Optics for LINAC

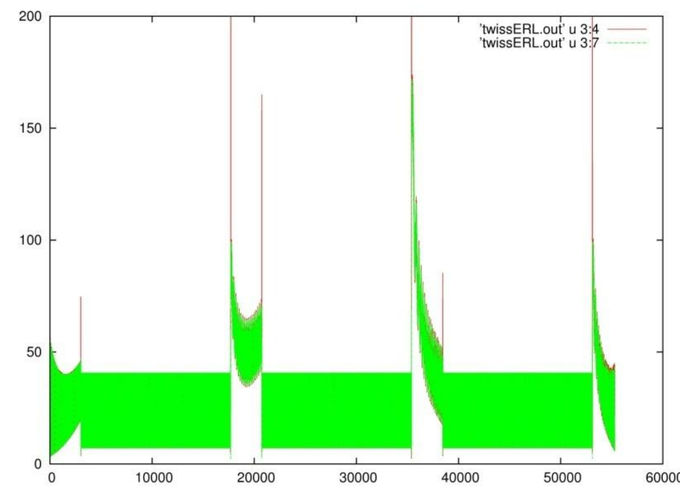


$\beta_{x,y}$



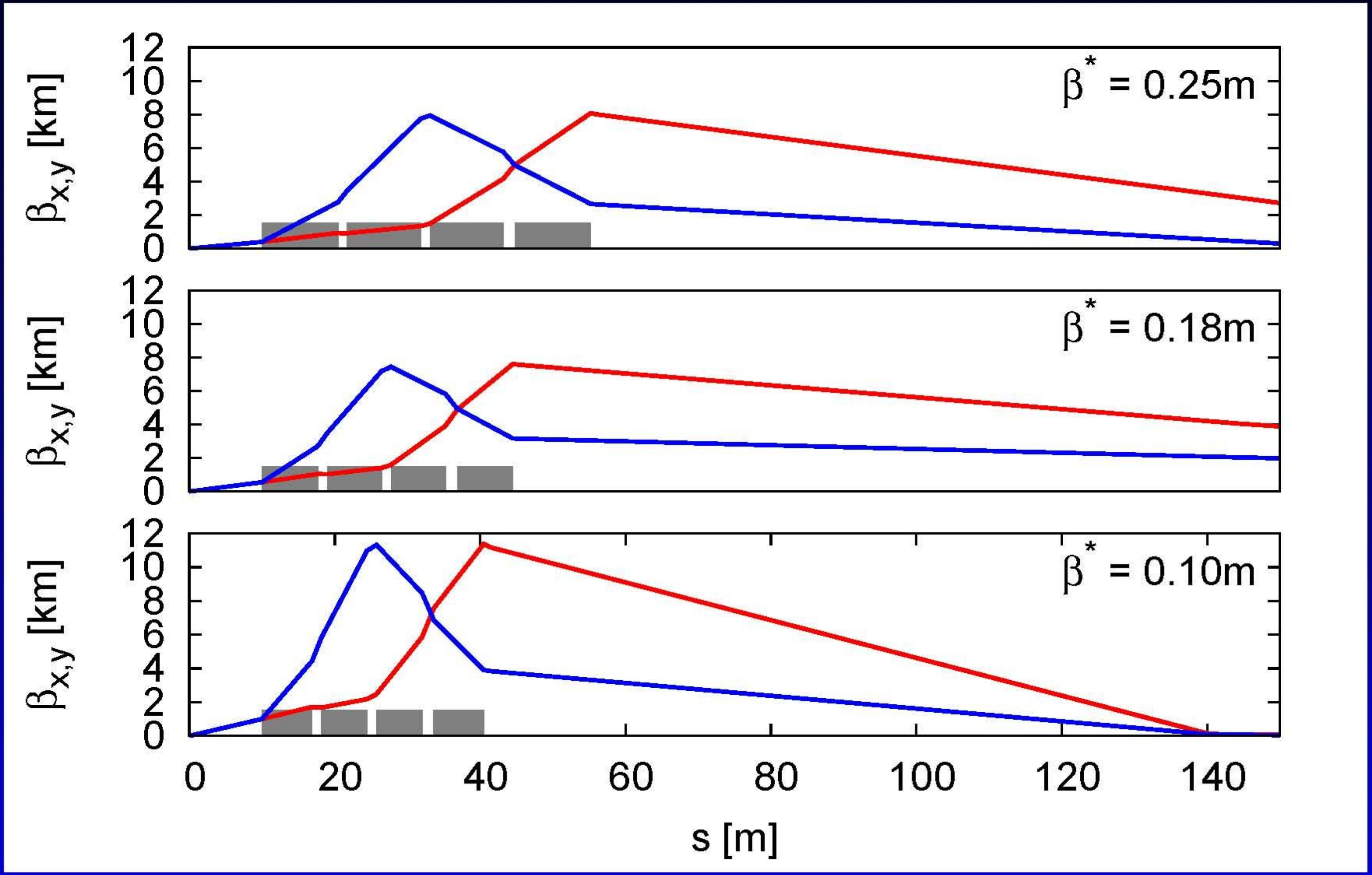
2 passes

$\beta_{x,y}$



4 passes - ERL

Proton triplet options (L*=10m) I



Rogelio Tomas, Divonne 2009

Proton triplet options (L^*=10m) II

	Q_1			Q_2			
β^*	Aper	Grad	B_p	Aper	Grad	B_p	ξ
[m]	[mm]	[T/m]	[T]	[mm]	[T/m]	[T]	
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

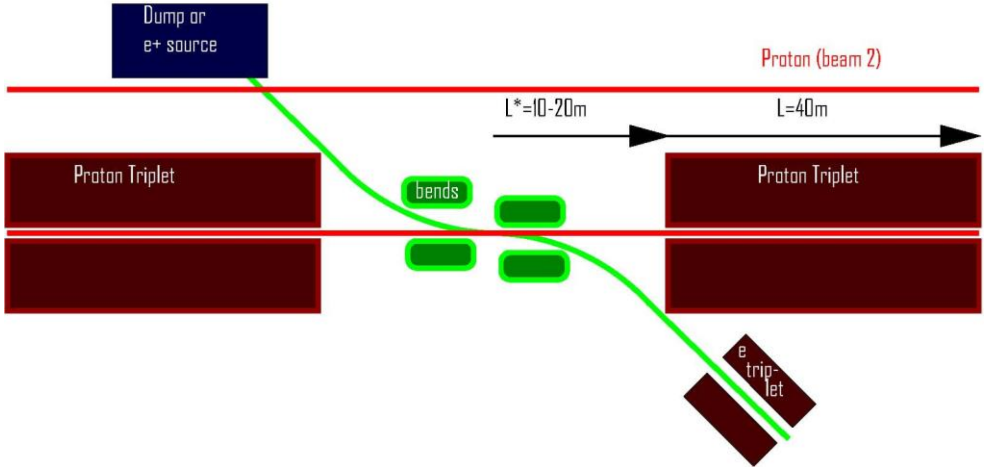
Aperture = 11σ + 10mm

$\beta^* = 0.18$m seems feasible today

$\beta^* = 0.1$m reachable with new technologies (Nb_3Sn, NbAl, ?) and some chromaticity correction scheme.

Rogelio Tomas, Divonne 2009

LINAC - Work in Progress



IR Options:

Head on → dipoles

Crossing → like RR IR

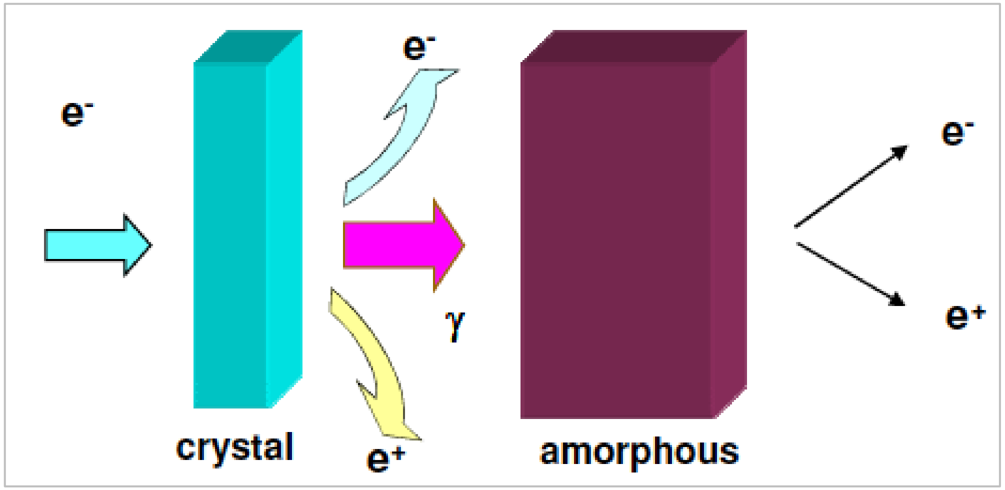
Positron source

Difficult to reach high intensity. Perhaps best suited: hybrid target

production of unpolarised

positrons. Several stations?

cf Divonne 2009



e-Pb collisions in Linac-Ring (1)

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

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

- Assume lepton injectors can create matching train of e^- - non-regular bunch spacing *with same average beam current and power*
  - Scale from F. Zimmermann in EPAC2009

The electron beam size is assumed to be matched to the size of the protons, $\sigma_p^* = \sigma_e^*$, as a smaller electron beam could have adverse effects on the proton beam lifetime. For round-beam collisions, the luminosity is

$$L = \frac{1}{4\pi e} \frac{N_{b,p}}{\epsilon_p} \frac{1}{\beta_p^*} I_e \, H_{\rm hg}, \qquad (1)$$

where e denotes the electron charge, and the subindices p or e refer to protons or electrons. The luminosity (1) depends only on the p beam brightness $(N_{b,p}/\epsilon_p)$ with $N_{b,p}$

e-Pb collisions in Linac-Ring (2)

	LHeC-RR	LHeC-RL high lumi
e^- energy at IP [GeV]	60	60
luminosity [10^{32} cm^{-2}s^{-1}]	29	$29^\dagger$ ($2.9^\ddagger$)
bunch population [10^{10}]	5.6	$0.19^\dagger$ ($0.02^\ddagger$)
e^- bunch length [μm]	~10,000	300
bunch interval [ns]	50	50
norm. hor.&vert. emittance [μm]	4000, 2500	50
average current [mA]	135	$7^\dagger$ ($0.7^\ddagger$)

$$L = 1.19\times10^{30}\ \text{cm}^{-2}\text{s}^{-1} \quad \Leftrightarrow \quad L_{en} = 2.5\times10^{32}\ \text{cm}^{-2}\text{s}^{-1}$$

which is about a factor 2 better than Ring-Ring with similar level of optimism about using available power (or a factor 10 if Ring-Ring is taken to be limited in bunch intensity).

Summary

- Thanks to the enthusiastic contributions of many people, an impressive amount of work has been done and the LHeC design concepts are being gradually fleshed out with a view to CDR in 2010.
- Ring-Ring and Linac-Ring options remain on table
  - Higher L but less E, P with RR
  - Maybe higher E, P, lower L with LR
- Substantial problems remain to be solved in both cases!