Ring-Ring layout and bypass design

- Introduction - baseline assumptions
- **Bypass schemes and layout**
- Power considerations
- Injectors

based on

original plans : E. Keil, "LHC ep option," LHC-Project-Report-093 March 1997
more recently : J. B. Dainton, M.Klein, P. Newman, E.Perez, and F. Willeke, hep-ex/0603016
here mostly : discussions and material from CERN / DESY colleagues and in particular Oliver Brüning, John Jowett, Kurt Hübner, John Andrew Osborne, Brennan Goddard, Volker Mertens, Trevor Linnecar, Hans Braun, Werner Herr ; Bernhard Holzer
updating and extending on EPAC'08 papers ; my DIS2008 talk and recent written version
web references collected on http://hbu.home.cern.ch/hbu/LHeC.html

Introduction

LHeC : existing LHC 7 TeV Proton and Ion Ring

+ new ~ 50 - 70 GeV Electron Ring or Linac as presented by F.Z. et al.

for ~ TeV collisions in c.m.s

Ring-Ring : as starting point and baseline

Original plan : electron storage ring - could become an energy recovery ring

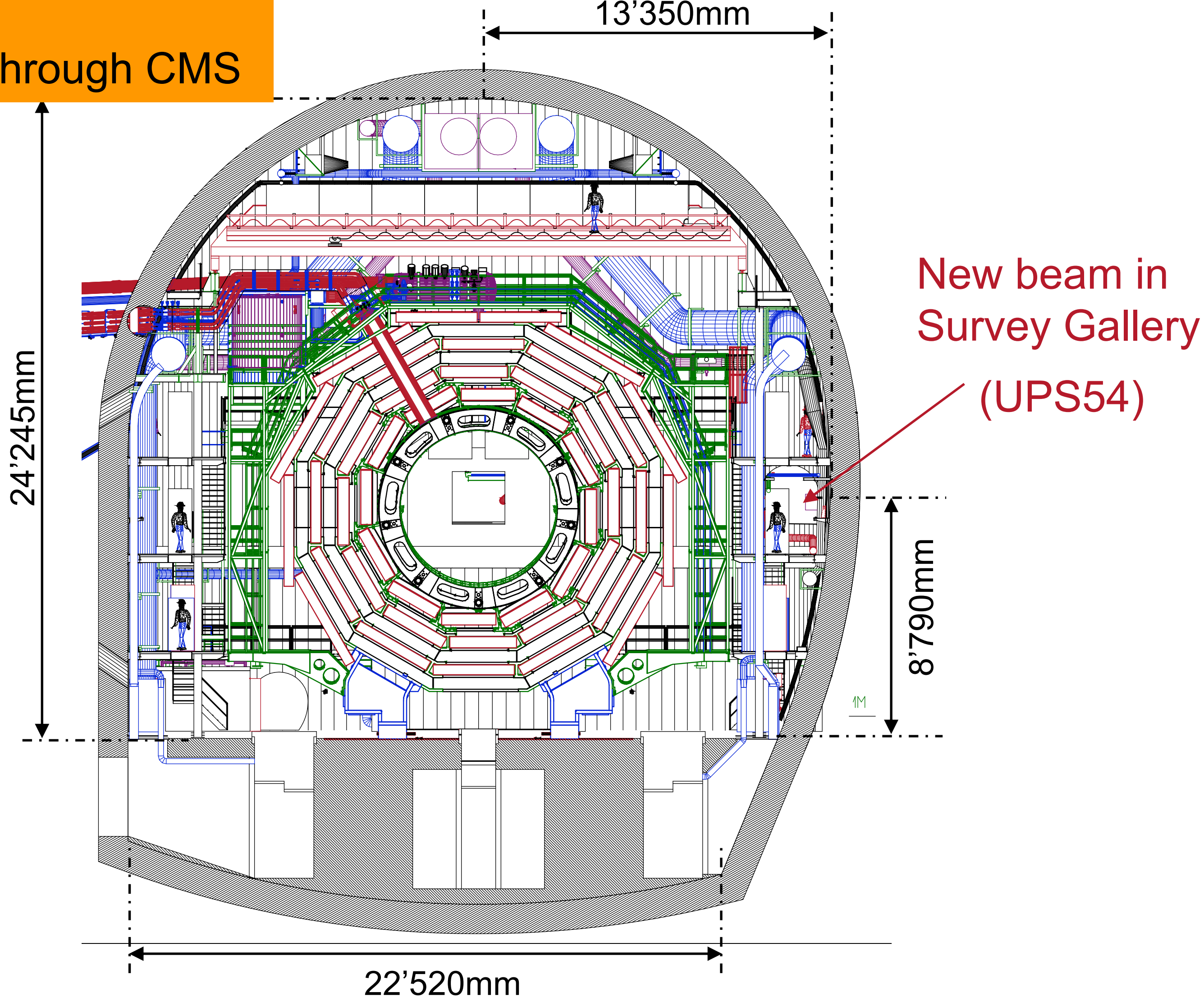
Here mostly : looking at layout, integration, estimates and scaling of largest bypasses around ATLAS / CMS

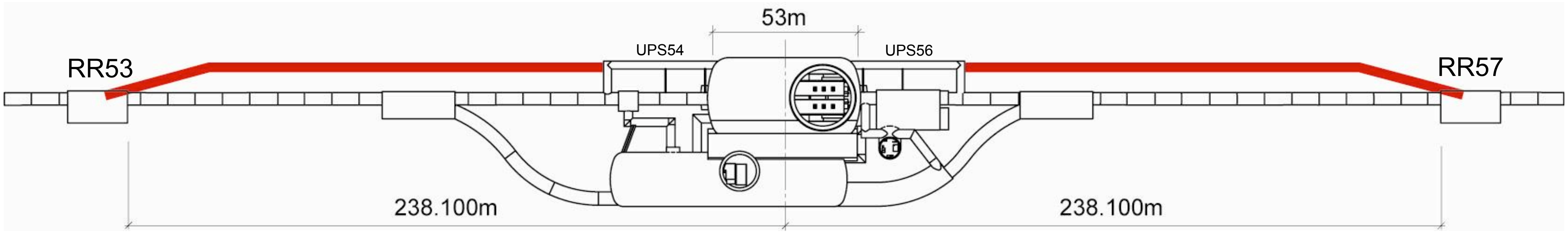
idea : allow to run the LHC and LHeC as much as possible in parallel

install LHeC without need for very long LHC shutdown

tunneling speed about 10 m / week : 250 m tunnel pieces in 1/2 y shutdown

LHeC
Typical Cross Section through CMS





from J.A. Osborne CERN/TS

LHeC
UPS 54 Survey Gallery

from J.A. Osborne CERN/TS

LHeC
View from UPS54 Survey Gallery into CMS Cavern on Walkways

from J.A. Osborne CERN/TS

Ring Layout and Optics Considerations

Well known starting point :

LEP with its FODO lattice, matching the tunnel and LHC layout.

basic LEP numbers :

73 % of circumference in arcs, 88 % of arcs with dipoles

79 m long cells ; bending angle of half cell 11.30640 mrad

from 3 × 11.55 m long dipoles

dipole bending radius ϱ = 3096.175 m

31 cells per octant; in total 8 × 31 = 244 cells

The bypass can be treated as local insertion device with nearly negligible effect on emittance and total power ; can be matched to different optics, i.e. as considered by John Jowett in the previous talk.

LHeC Electrons ; Intensity / Power considerations

f_{rev} = 11245. 5 Hz given by LHC circumference #bun = 2800

high collision frequency f = #bun × frev = 31.5 MHz and high beam current

beam current I = n e f $e = 1.60218 \times 10^{-19}$ As

Ring : loss in SynRad $U_0 = C_\gamma E^4/\rho$ ρ = 2997 m LEP had ρ_{eff} = 3026.42 m

LINAC : beam power P = V I

machine	N / bun	#bun	Ntot / beam	I beam	V [GV]	P_{acc}= V I [MW]	U_0 [GeV]	Psyn [MW]	
LEP 2	4.16E+11	4	1.67E+12	4×0.75 mA	100	300	2.923	8.77	
LHeC, ring-e	1.40E+10	2800	3.92E+13	70.63 mA	70	4944	0.7087	50.05	*ultimate*
					50	3531	0.184	13.0	LHeC 1

power needed in case of direct Linac, several GigaWatt

Equal Circumference of p and e Rings ?

Needed ?

- **Maybe** : for abort or rather ion-instability cleaning gap

- same C allows synchronisation with p-abort gap and fixed bunch pairing for collisions

- otherwise : packman bunch effects, mixed pairing with increased heating of p-beam. Principles : Hirata & Keil 1990, more quantitative study would probably require major beam-beam simulations

Possible ?

- **Yes** : a bypass adds little in circumference

the 13.35 m bypass shown later adds only $\Delta = 0.42$ m in C, can be compensated

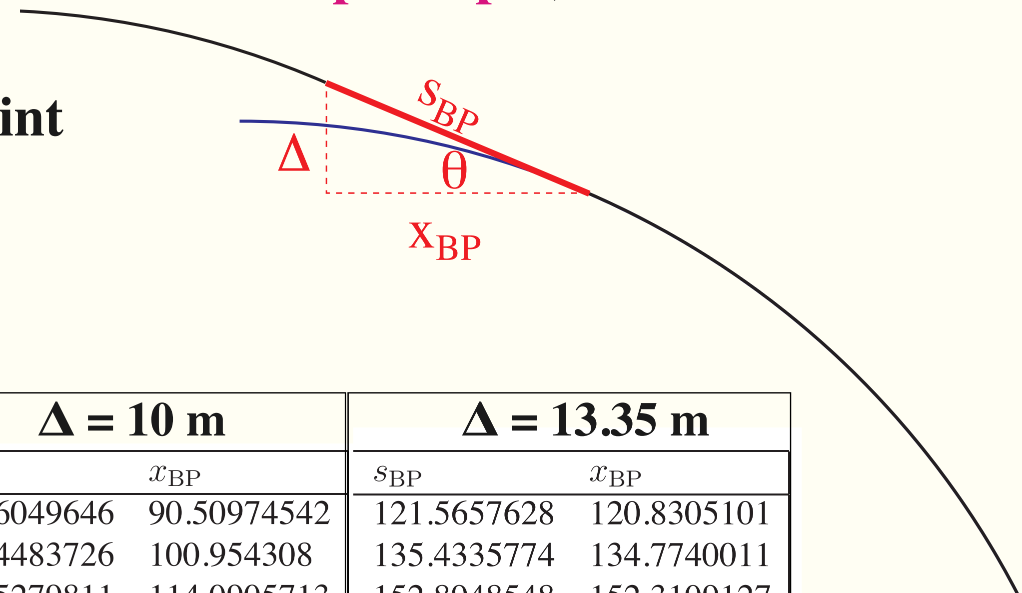
by decrease in e-ring radius of $\Delta/2\pi = 6.6$ cm

Prelim. conclusion : **use equal circumference**

Bypass Layout study. Type 1 : no extra bends

Start from LEP lattice with straight sections of length of ± 260 m

principle, one side



Insert straight piece of length s_{BP} at a point with angle θ.

Separation $\Delta = s_{BP} \sin\theta$

Straight part reduced by $x_{BP} = s_{BP} \cos\theta$

Point	θ	$\Delta\theta$	Δs IP5, m	Δ = 10 m s_{BP}	Δ = 10 m x_{BP}	Δ = 13.35 m s_{BP}	Δ = 13.35 m x_{BP}
QD24.L5	0.1100390391	0.0113064017	677.879431	91.06049646	90.50974542	121.5657628	120.8305101
QF23.L5	0.09873263743	0.0113064017	638.379431	101.4483726	100.954308	135.4335774	134.7740011
QD22.L5	0.08742623577	0.0113064017	598.879431	114.5279811	114.0905713	152.8948548	152.3109127
QF21.L5	0.07611983411	0.0113064017	559.379431	131.4987572	131.1179741	152.8948548	152.3109127
QD20.L5	0.06481343245	0.0113064017	519.879431	154.3970803	154.0728996	206.1201022	205.687321
QF19.L5	0.0535070308	0.0113064017	480.379431	186.9805354	186.7129364	249.6190147	249.2617701
QL18.L5	0.04220062914	0.0113064017	440.479431	237.0336409	236.8226064	316.4399106	316.1581796
QL17.L5	0.03843462774	0.0037660014	408.049431	260.2461126	260.0539158	347.4285603	347.1719776
QL16.L5	0.03089842621	0.0075362015	380.979431	323.6925822	323.5380778	432.1295972	431.9233338
QL15.L5	0.02336222468	0.0075362015	353.909431	428.0803669	427.9635505	571.4872899	571.3313399
QL14.L5	0.01582602315	0.0075362015	326.839431	631.8970568	631.817925	843.5825708	843.4769299
QL13.L5	0.008289821623	0.0075362015	299.769431	1206.31239	1206.270941	1610.427041	1610.371706
QL12.L5	0.0007536200942	0.0075362015	272.699431	13269.28651	13269.28274	17714.49749	17714.49246

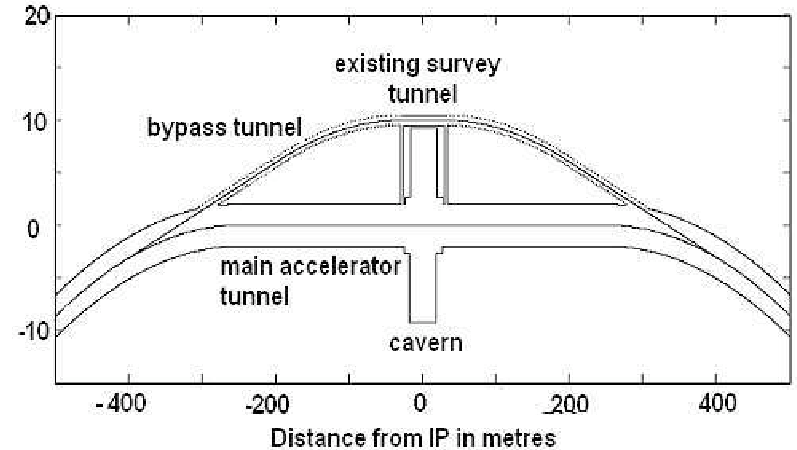
Allowing for at least 20 m remaining straight:

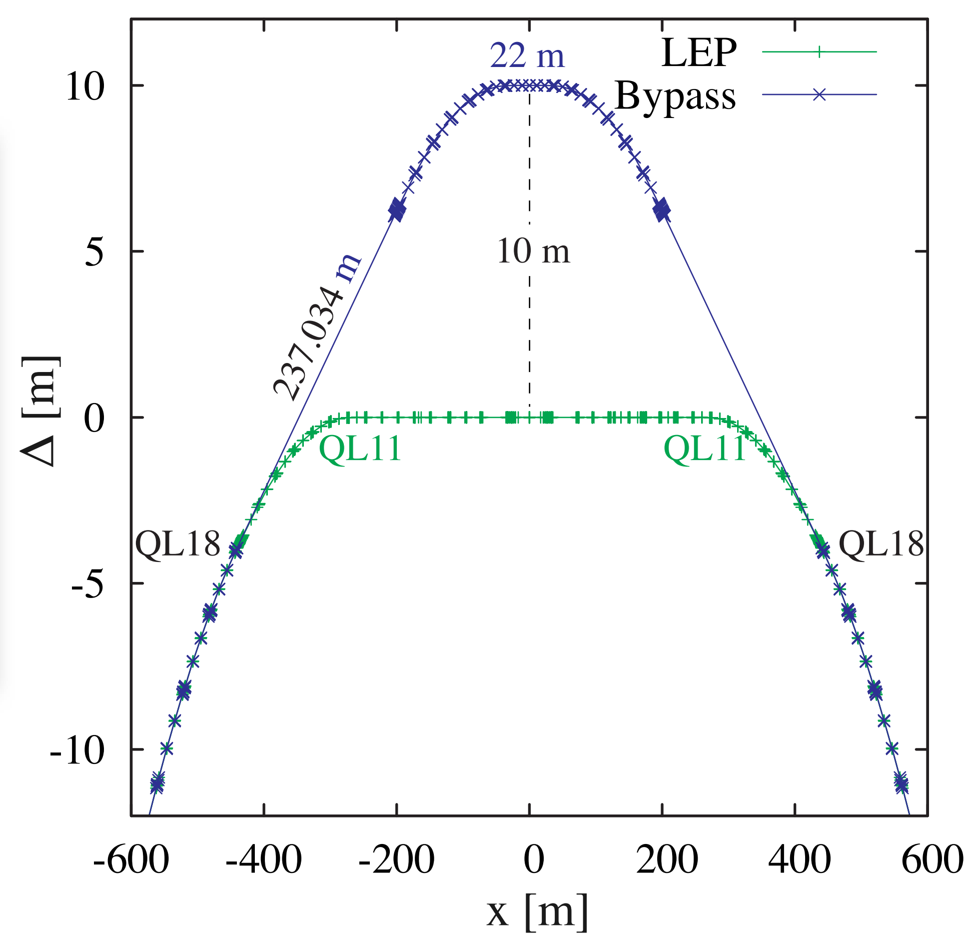
Δ = 10 m bypass. Start at QL18.L5, insert 237 m straights, total BP length 880 m

Δ = 13.35 m bypass. Start at QD20.L5, insert 206 m straights, total BP length 1040 m

Type 1 bypass, no extra bends; Layout

schematic layout
Dainton / Willeke et al.





A bit more realistic :

0-th iteration MAD-X lattice layout :

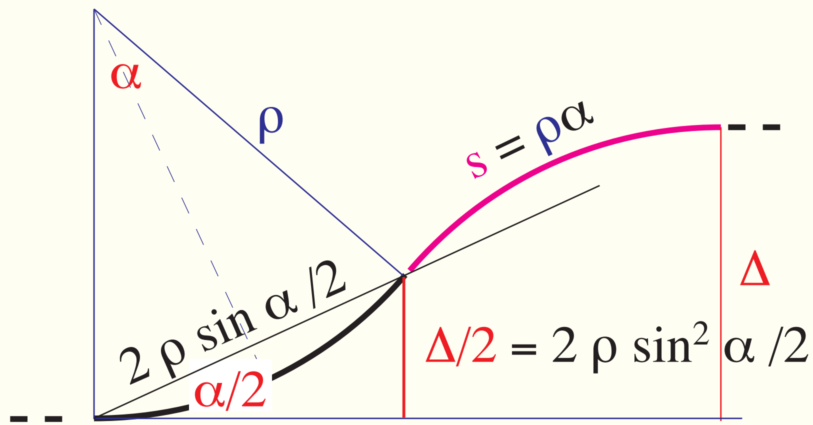
Δ = 10 m bypass. As previously shown at DIS2008 and EPAC 2008

Advantage : no extra power / radiation,

but rather long, about a 1 km !

Bypass Layout study. Type 2 : local bypass in straight

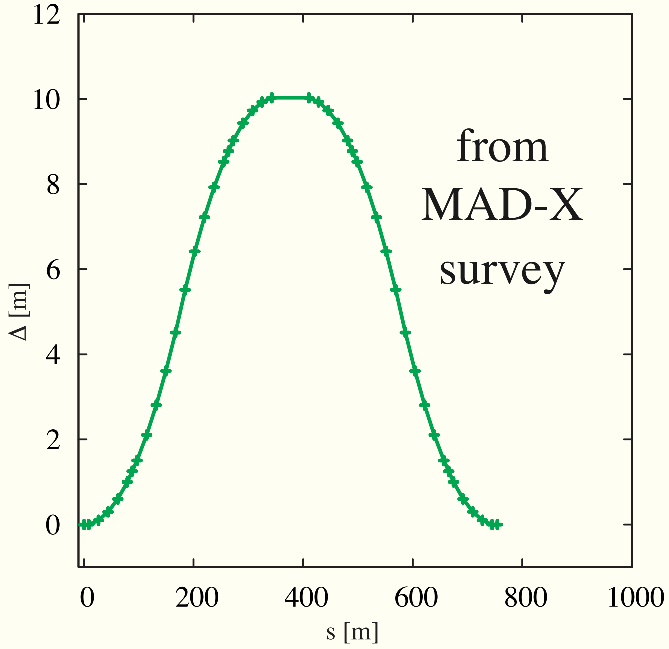
principle, one side



lateral separation $\Delta = 4\,\rho\,\sin^2\frac{\alpha}{2}$

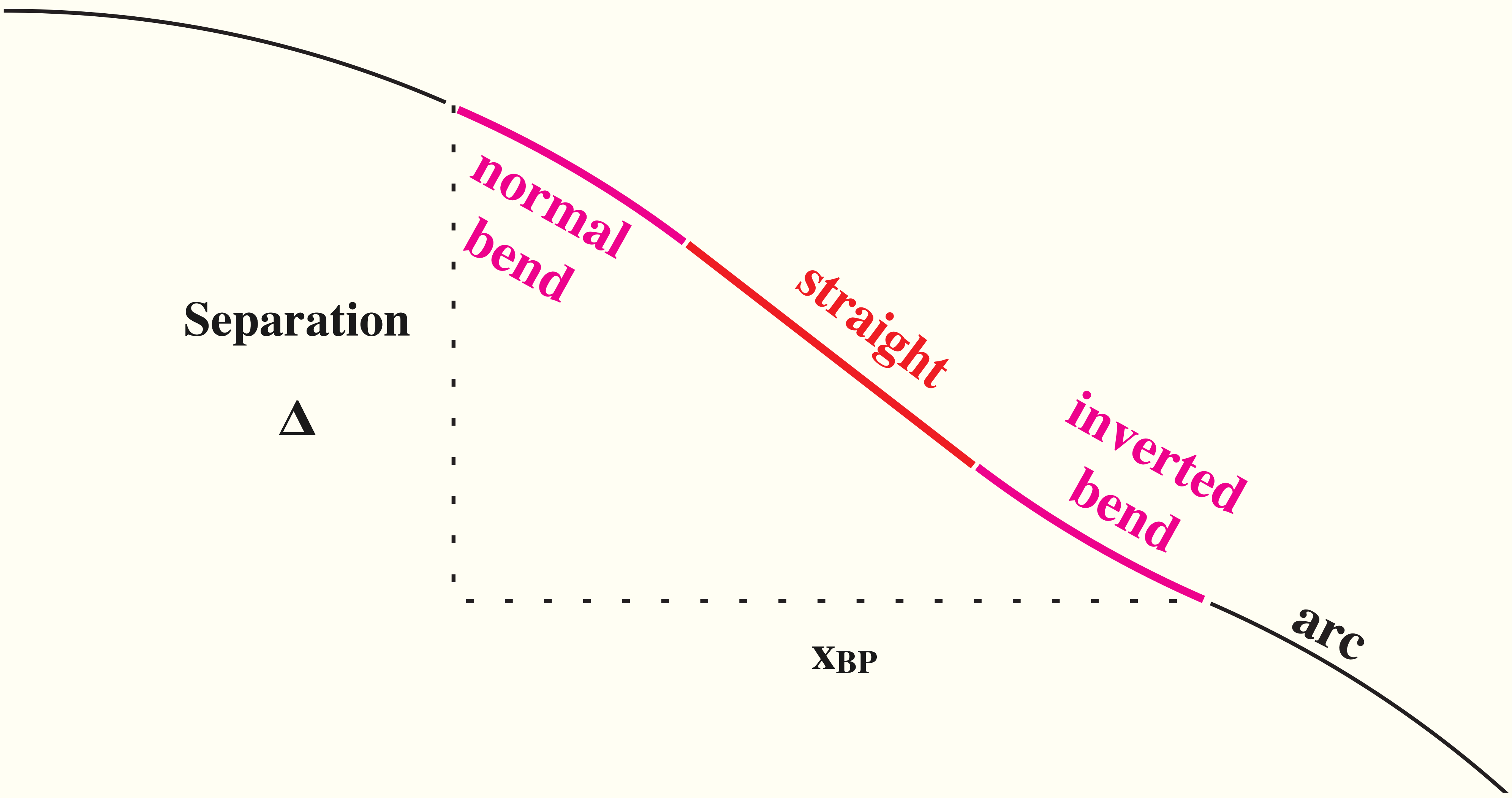
total length in bends in bypass $s = 4\,\rho\,\alpha$

tested by defining a local bypass sequence for MAD-X



using standard LEP bends, ρ = 3026 m, we would need α = 57 mrad to get Δ = 10 m separation by 4 x 176 = **704 m** just from the bends. This would add 3.6% in the total energy loss. In absolute, the loss in such a bypass is 1.8 MW at 70 GeV for 70 mA beam current. With 2x stronger bends in bypass : 4 x 124.5 = **500 m long bends**, adding 5.1% in power. With extra magnets and straights **not much shorter and disadvantage of extra power and hard radiation**. Now try to combine both types.

Bypass study : Combined bypass - straight + bends



Combined bypass layout for Δ = 13.35 m

1 inverted LEP cell (79 m) **+ straight + 1 normal bend cell**

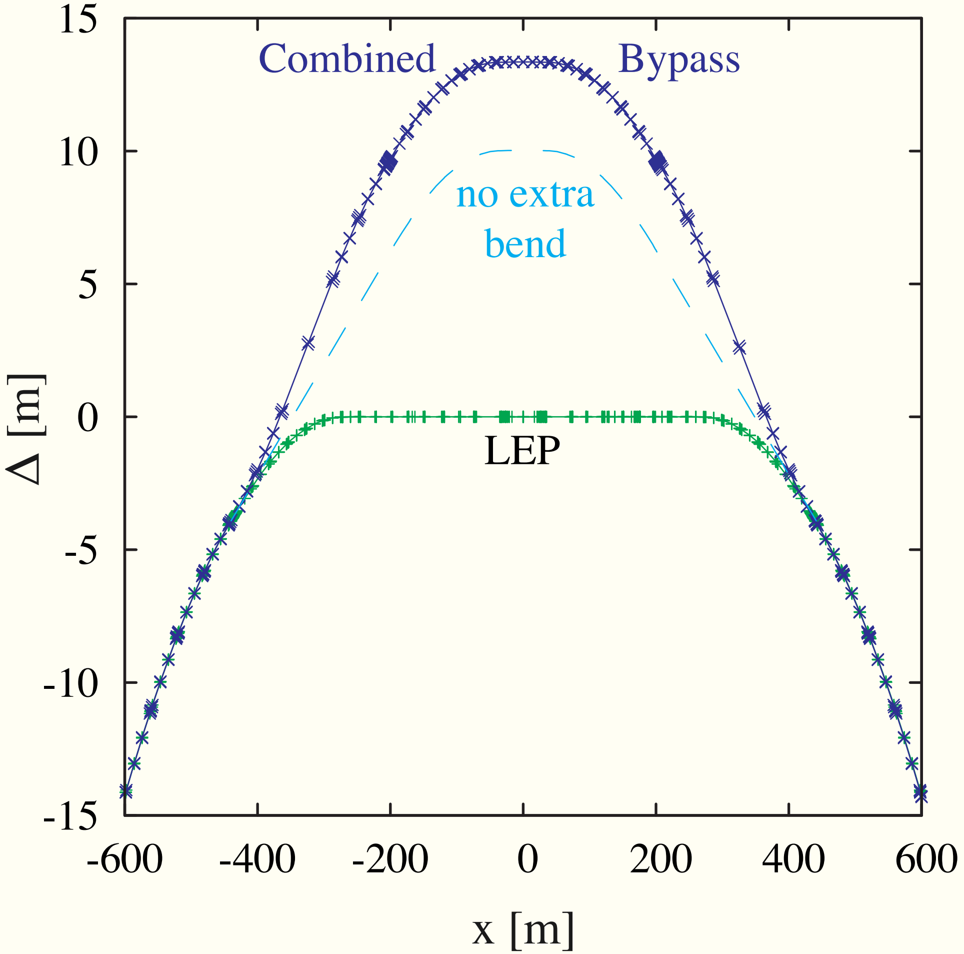
Per bypass 4 extra LEP cells.

Modest 4/244 = 1.6% increase in cells and energy loss.

Starting bypass with QL18.L5
Total bypass length 880 m.
Full 13.35 m separation
29.5 m straight part at IP5.

β-functions well behaved with extra quad in inserted straights

Potential to further optimise - using full bends instead of 10 % bends at the arc ends.
Then full match including dispersion.



LEP injectors

what we had, with electron energy range   and what is left

- LIL 600 MeV ; gone ; replaced by CLIC
- PS 0.6 - 3.5 GeV ; nothing left for e-acceleration - old machine - not very reasonable to re-upgrade for leptons
- SPS 3.5 - 22 GeV ; 8 MV 200 MHz TW cavities not ok for leptons ; had extra cavities for leptons, removed for impedance reduction ; Impedance issue - no increase wanted ! rather needs further reduction for LHC ultimate

LEP injectors were all removed.

Rebuilding them is not really an option.

Parts and components could be re-used in new injectors

(kickers, parts and components of transfer lines)

new LHeC injectors

higher injection energy, 20 GeV or more could make it interesting to directly collide from the injector with the protons -- consider under linac - ring option.

basic parameters for injector for ring-ring :

about 20 GeV injection energy (absolute minimum 10 GeV ?)

be able to fill reasonably fast - say within 10 min

low intensity 1.4×10^{10} / bunch – could do without accumulation

many (2800) bunches, 25 ns spacing, total intensity 3.92×10^{13} electrons

injection scheduling :

analog to protons (3 - 4 batches of nominally 72 bunches)

e+ and e– : no principle problem - needs extra e+ source and possibility to change polarities

options for direct injection @ about 20 GeV

- low energy Linac, e- and e+ conversion (@ 0.2 - 0.5 GeV), EPA like e+ acc. ring accelerate with synchrotron ; same principle as we had of LEP

- what about 20 GeV Linac based on CLIC ? clictable2007.html

  high gradient 100 MV/m in 85% of LINAC ; L = 235 m to reach 20 GeV

  N = 3.72e9 / bun; k = 312 bun/train ; Linac repetition rate of 50 Hz : 5.83e13 Elec/sec. Significant overhead for drive beam generation - probably not very economic for a relatively short LINAC

- 20 GeV SC Linac, inspired by ILC

  gradient 31.5 MV/m (ILC BCD) in 85% of LINAC : L = 747 m

  N = 2e10 / bun, k = 2820 bun /train ; repetition rate of 5 Hz : 2.82e14 Elec/secs

  modify to match LHC batch structure

- or →

ELFE @ CERN

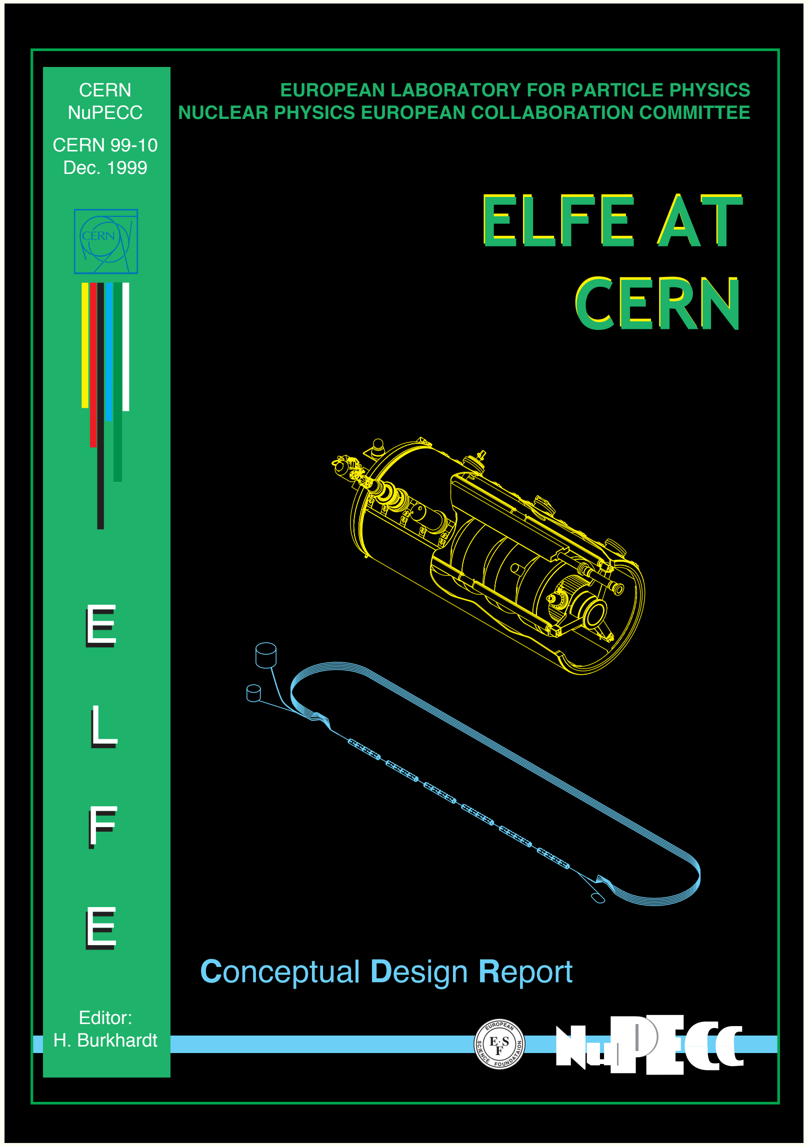


Table 1: ELFE performance parameters.

Top energy	25 GeV
Beam current on target	100 μA
Beam power on target	2.5 MW
Injection energy	0.8 GeV
Number of passes	7
Energy gain per pass	3.5 GeV
Relative r.m.s. momentum spread at top energy	$\leq 10^{-3}$
Emittance at top energy	$\leq$ 30 nm
Bunch repetition time on target	2.8 ns

Table 2: Estimated capital expenditure for the construction of ELFE at CERN.

System	MCHF	MCHF	MCHF
Injection	20.400		
RF system	10.868		
Cryogenics	63.000		
Magnets	55.209		
Vacuum	19.410		
Beam diagnostics	9.400		
Power converters	11.165		
Control system	10.000		
Accelerator components		199.452	
Electrical power distribution	29.031		
Civil engineering	109.700		
Experimental hall(s)	31.200		
Cooling, ventilation, etc.	25.773		
Access control, etc.	2.050		
Conventional construction		197.414	
Total			397.206

with LEP RF for free

modified ELFE as LHeC injector

ELFE@CERN

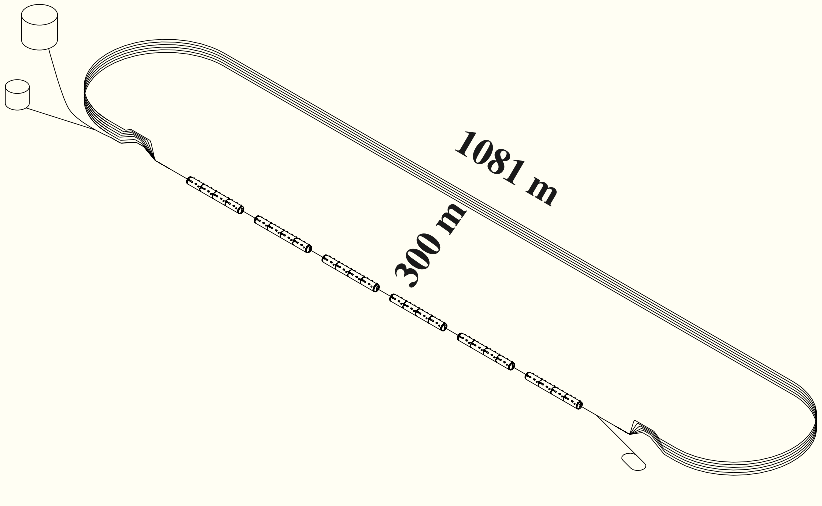
f_{rf} = 352 MHz, gradient 8 MV / m

V_{rf} = 3.5 GV, 72 rf-modules

7 passes (last at 21.5 GeV)

L = 3924 m of which Linac 1081 m

ϱ = 56.9 m



LHeC injector

$f_{rf} \sim 1$ GHz, gradient 31.5 MV/m

Linac L = 150 m 7× shorter

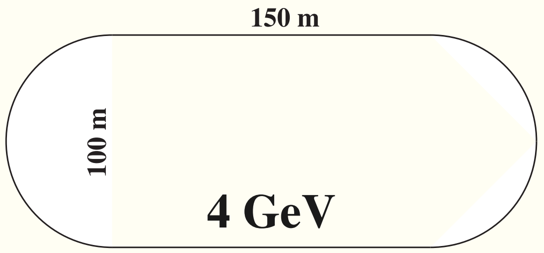
V_{rf} = 4 GV, 5 passes ; last 16 GeV

$\varrho = (16/21.5)^4 \times 56.9$ m = 17.5 m

or 3.3× shorter

significantly downscaled L ≈ 600 m

and simplified (5 passes) version of ELFE@CERN



recirculating LINAC

more cost effective (?) than single LINAC

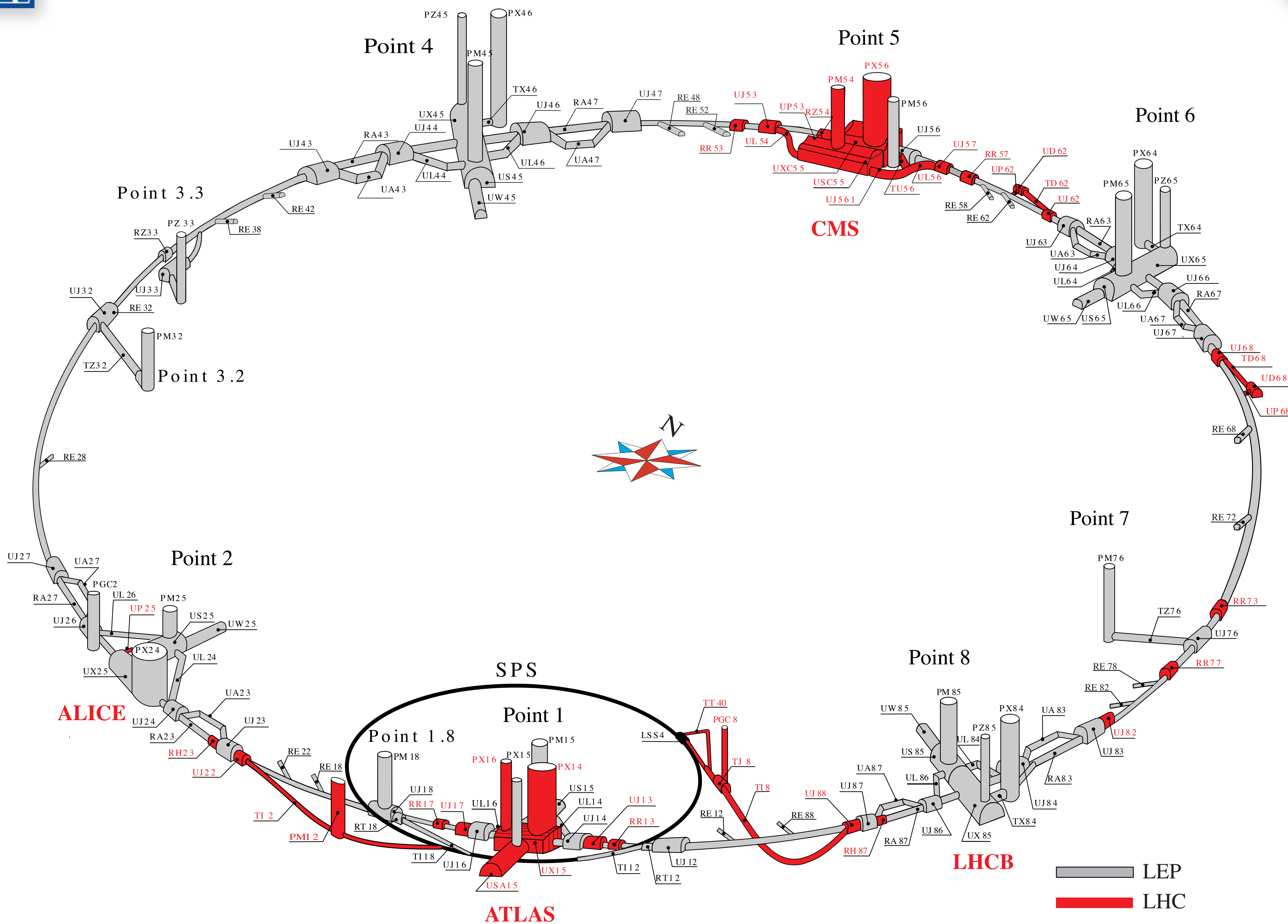
+ extra phys. potential

LHeC Ring-Ring : Summary Table for Extra Tunnels

	Point 1 ATLAS	Point 5 CMS	Point 2 and/or 8 RF	Point 3 Collimators	Point 7 Collimators	total
Type	Bypass Experiment	Bypass Experiment	Bypass ; allow for space for e - ring RF	Bypass Collimation	Bypass Collimation	
Approximate Tunnel length	900 m	900 m	500 m	500 m	500 m	about 3 km
Diameter	4.40 m	3.80 m	5.50 m	4.20 m	3.80 m	
Distance to p-Ring axis	10 - 14 m	13.4 m				

Based on layout and integration considerations, very prelim.
Hope to learn more from this workshop - in particular on needs for 2/8, 3/7

Layout LHC



Point 1
Point 1.8
Point 2
Point 3.2
Point 3.3
Point 4
Point 5
Point 6
Point 7
Point 8
SPS
ATLAS
ALICE
CMS
LHCB
N
LEP
LHC
PX45
PZ45
PX46
PM45
TX46
UX45
UJ44
UJ46
RA47
UJ47
RE 48
RE 52
UJ53
UP53
RZ54
PM54
PX56
PM56
UJ56
UL46
UA47
US45
UW45
UL44
UA43
RA43
UJ43
RE 42
RE 38
PZ 33
RZ33
UJ33
UJ32
RE 32
PM32
TZ32
RE 28
UJ27
UA27
PGC2
RA27
UL 26
UP 25
PM25
US25
UW25
UJ26
PX24
UL 24
UX25
UA23
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UJ 23
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RH23
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RE 22
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TI 2
PMI 2
RT 18
PM 18
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RR17
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UL16
PX16
PX15
PM15
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UJ13
RR13
TI18
UJ16
USA15
UX15
TI12
RT12
UJ 12
LSS4
TT 40
PGC 8
TJ 8
TI 8
RE 12
RE 88
UJ 88
UJ87
UA87
UL 86
US 85
UW85
PM 85
PX84
PZ85
UL 84
UA 83
UJ83
RA83
UJ84
TX84
UX 85
UJ 86
RA 87
RH 87
UJ82
RE 82
RE 78
RR77
UJ76
TZ76
PM76
RR73
RE 72
RE 68
UP 68
UD68
TD68
UJ68
UJ67
UA67
RA67
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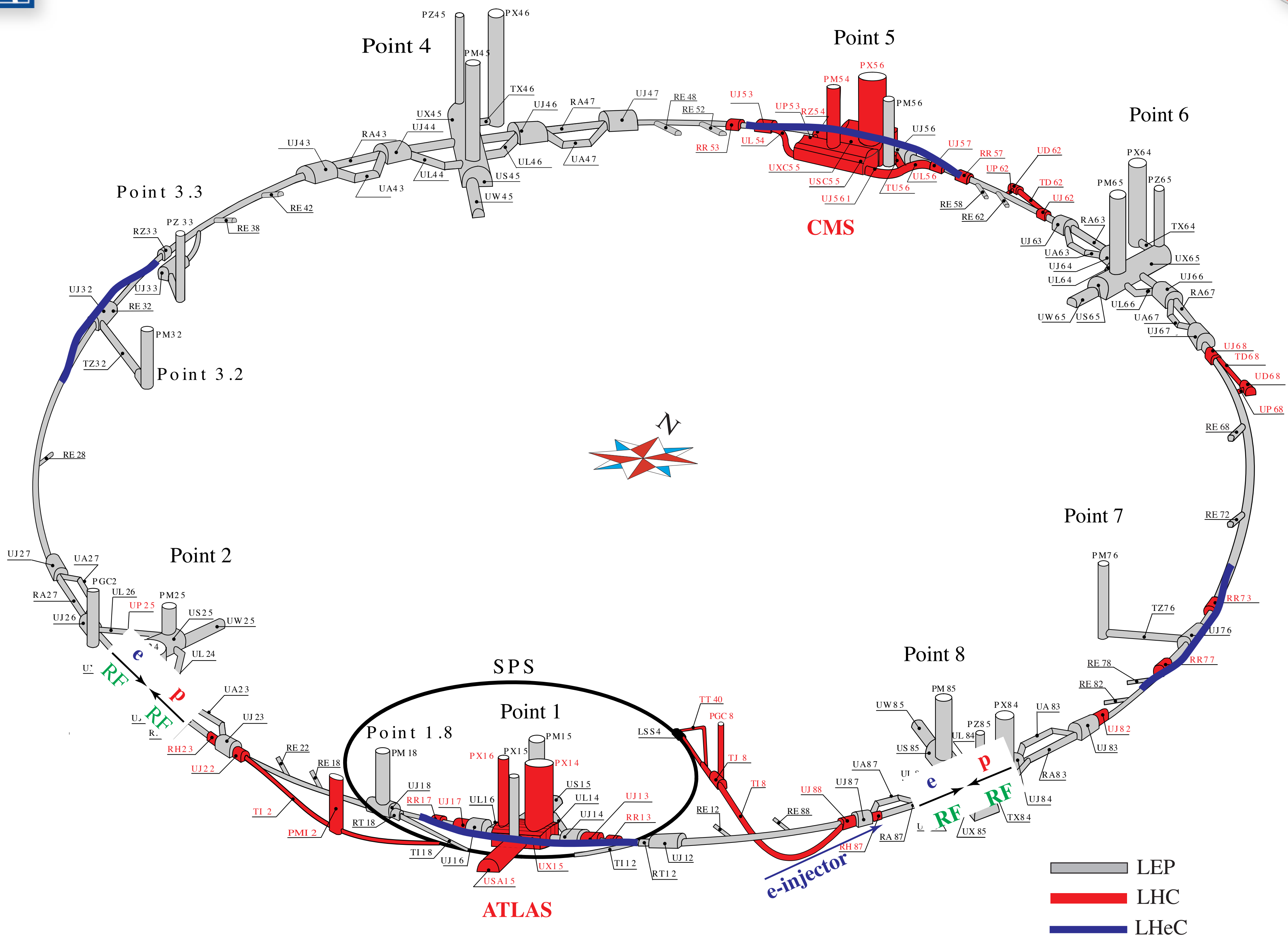
US65
UW65
UL64
UJ64
UA63
UJ 63
RA63
TX64
UX65
PM65
PX64
PZ65
UJ 62
TD 62
UP 62
UD 62
RR 57
UJ57
RE 58
RE 62
UL56
TU56
UJ561
USC55
UXC55
RR 53
UL 54

Layout LHeC, as shown in DIS2008 and EPAC2008



(my) conclusion

- p-Ring - e-Ring (both storage rings) as baseline option using proven technology : good starting point and reference. Should allow realiable performance predictions and cost estimates, no fundamental problems expected.
- **potential for synergies with LHC consolidation and upgrades** i.e. bypass and low radiation zones

Challenges :

- Large crossing angle - crab crossing
- RF, power and injectors
- Cost and time effective bypass design

Potential for R&D, extra physics options and extensions, brainstorming ideas ..

- e Ion collisions, e - polarisation, e+ or e–, e+e–
- synergy with energy recovery rings, ... e – cooling of ions, p ? ....