Using Tevatron Magnets for HE-LHC
or
New Ring in LHC Tunnel ?

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Mini-Workshop on a “High-Energy LHC”, Villa Bighi, Malta
October 14-16, 2010

Outline

1. Expected qualities of injector accelerator to He-LHC
2. S-SPS and LER injector options for 33 TeV HE-LHC
3. Main arc magnet option for the S-SPS accelerator
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5. S-SPS to HE-LHC beam transfer magnets
6. LER to HE-LHC beam transfer options
7. Injection energy and the quality of HE-LHC beam
8. Using injector accelerator to increase luminosity at HE-LHC
9. HE-LHC stacking time with S-SPS and LER injectors
10. Cost considerations for S-SPS and LER injectors
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Expected qualities of injector accelerator to HE-LHC

- High quality of injected beam to minimize losses at injection and to secure optimal operation of HE-LHC
- Robust beam injection and stacking operations to minimize HE-LHC turnaround time
- Ability to pre-condition injected beams to facilitate high luminosity of HE-LHC
- Cost of construction and operation of the injector to be only a fraction of the HE-LHC design

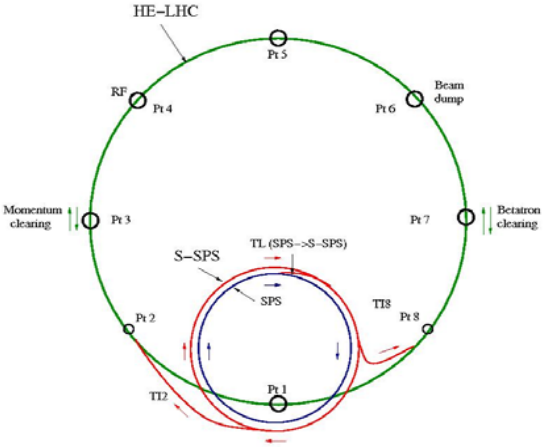
S-SPS and LER injector options for 33 TeV HE-LHC

Option 1: Super-SPS (S-SPS) accelerator in SPS tunnel –> single, 1 TeV beam

Option 2: LER (Low-Energy-Ring) in LHC tunnel –> dual, 1.65 TeV beam

S-SPS OPTION

SPS (150 GeV) -> S-SPS (1 TeV) -> HE-LHC (16.5 TeV)
24 S-SPS injections to fill HE-LHC

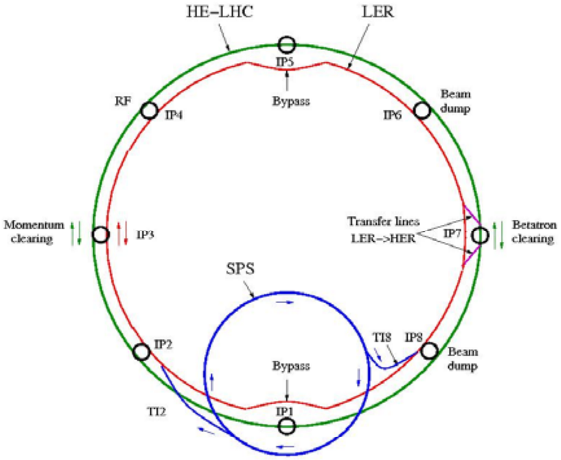


New beam lines: 12560 m

S-SPS: 6900 m (main ring) + 2 x 2800 m
(S-SPS->HE-LHC transfer lines)

LER OPTIONS

SPS (450 GeV) -> LER (1.65 TeV) -> HE-LHC (16.5 TeV)
Single LER transfer to HE-LHC

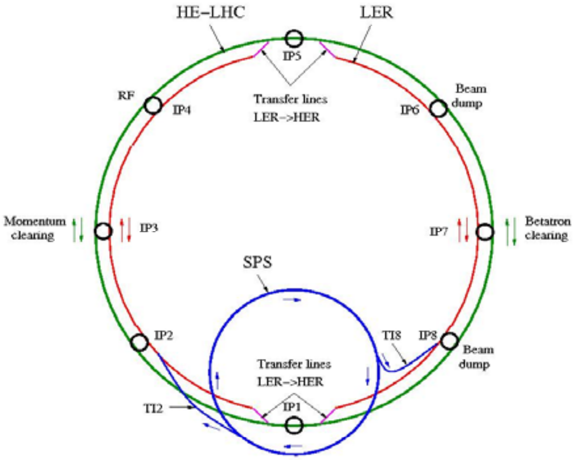


Option 1
Bypassing detectors & transferring beams at IP7

New beam lines: 26700 m

LER: 24240 m (main ring) + 2 x 1000 m (bypass)
+ 2 x 104 m (LER-> HE-LHC transfer lines)

Bypass lines require ~ 2000 m of new tunnel



Option 2
Transferring beams at IP1 & IP5

New beam lines: 26320 m

LER => 25904 m (main ring) + 4 x
104 m (LER-> HE-LHC transfer lines)

Main arc magnet options for S-SPS accelerator

S-SPS (1 TeV) [1]: B peak = 4.5 T, dB/dt = 1.3 T/s
S-SPS (1.3 TeV) [2]: B peak = 5.9 T, dB/dt = 1.7 T/s

S-SPS magnet power losses based on SIS200 magnet [3]

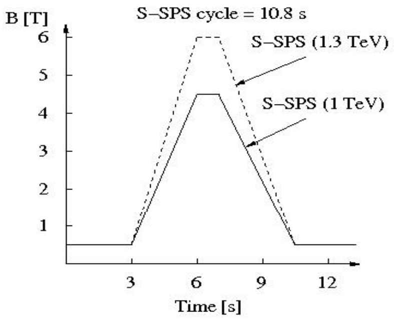
Power loss S-SPS (1 TeV) = 90 J / m _ 6 s = 15 W/m
Power loss S-SPS (1.3 TeV) = 175 J / m_6 s = 30 W/m
Cryogenic power S-SPS 1(1.3) TeV = 6.9 km x 0.8 x 15 (30) W/m = 83 (166) kW
Electric cryo-power = CF (70) x CFE (3.6) x OC (1.3) x 83 (166) = 27 (54) MW
Ramping power for SIS300 (6 T, 1 T/s, 0.4 km ring) = 4.5 MVA [4]
Electric ramping power = (6.9 km/ 0.4 km) x 5.9 (1.3 T/s) = 102 MVA
Electric ramping power = (6.9 km/ 0.4 km) x 7.7 (1.7 T/s) = 133 MVA
Total electric power => 129 MW (1 TeV), 187 MW (1.3 TeV)

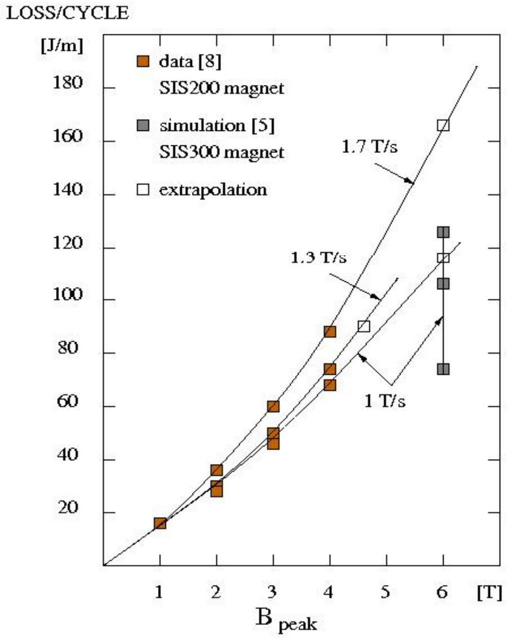
SIS-300 dipole stability [5]: 6 T, 1 T/s, LHe 40 g/s

Critical temperature: 5.3 K
Operating temperature: 4.8 K
Temperature margin: 0.5 K

Temp. margin (2.7 m, 6 T, 1.7 T/s) => < 0.5 K
Temp. margin (6.1 m, 5.9 T, 1.7 T/s) ???

[1] W. Scandale, “LHC upgrade based on high intensity, high energy injector chain”, LHC-LUMI-05, 2005, [2] F. Zimmerman, “LHC Beyond 2020“, KEK Seminar, 2010
[4] I. Bogdanov et al., “Study of the Quench Process in Fast-Cycling Dipole for SIS300 Ring, EPAC 2004
[5] V. Zubko et al., “Stability of Fast-Cycling Dipole for the SIS300 Ring”, EPAC 2004

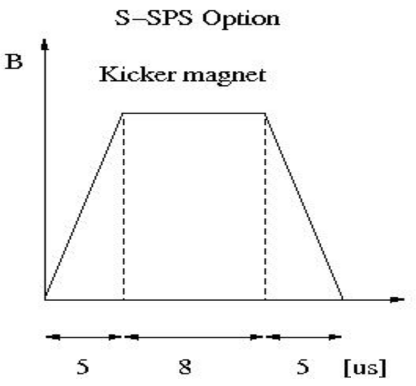




[3] M.N. Wilson et al., “Measured & calculated losses in a dipole for GSI’s Heavy Ion Synchrotron”, IEEE Appl. Superconductivity,**14**, 2004

S-SPS to HE-LHC beam transfer magnets

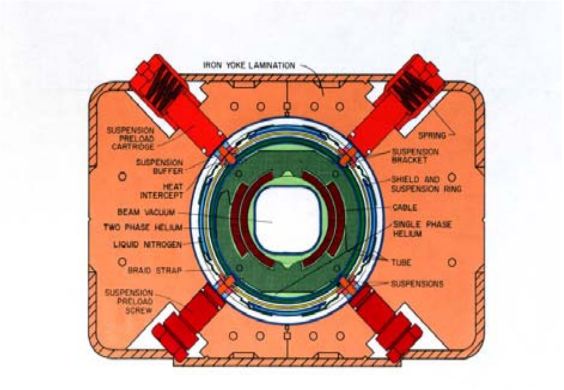
Kicker strings for S-SPS -> HE-LHC beam transfer



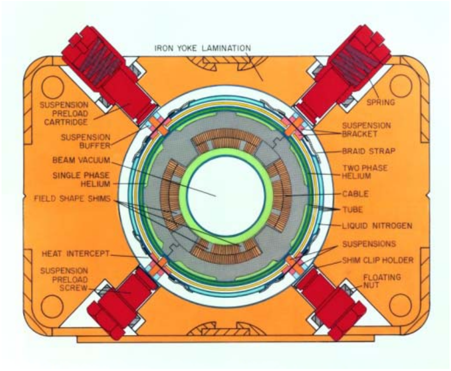
At SPS magnet string composed of 9 kickers & 6 septa injects beams in sequence to TI2 and TI8 transfer lines to LHC. At 450 GeV the combined kicker ∫Bdl = 1.44 Tm @ 52 kV, and for the septa ∫Bdl = 20.2 Tm. Kicker string length is ~ 33 m.

For 1 (1.3) TeV extracted beam to HE-LHC there will be 20 (26) kickers & 13 (17) septa making magnetic length of 74 (95)m.

Magnets for TI2 & TI8 S-SPS -> HE-LHC beam transfer lines



Tevatron dipole



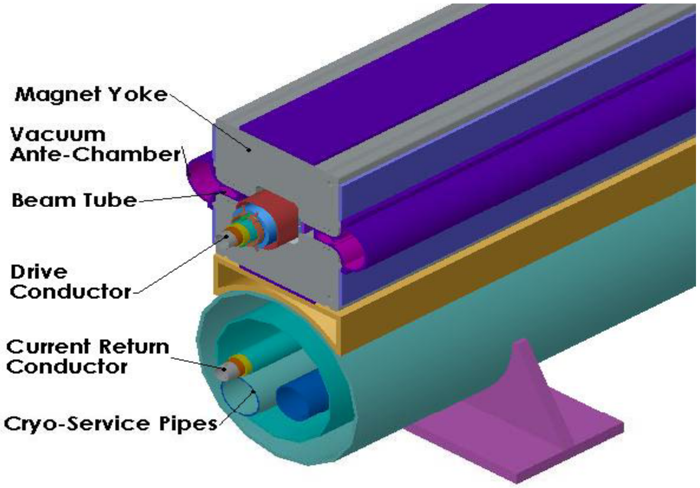
Tevatron quadrupole

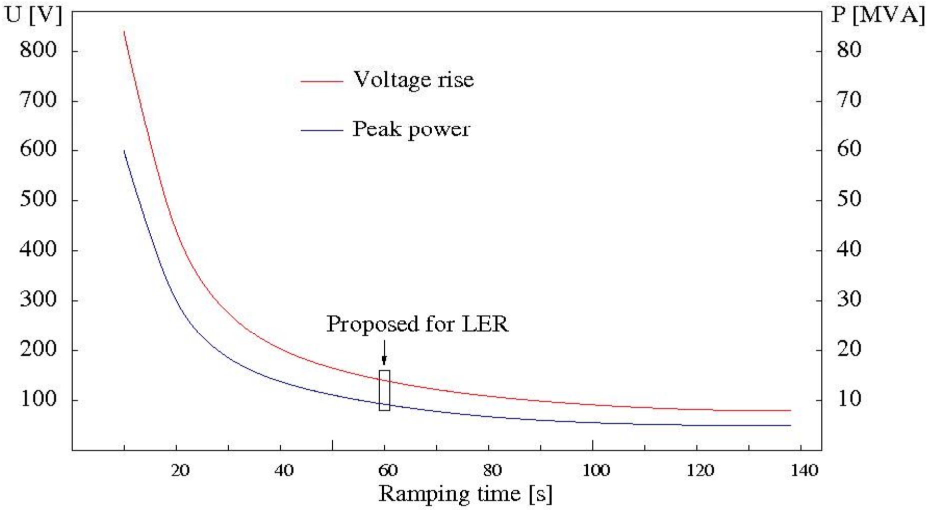
Tevatron ring: 6.28 km, SC dipole B max = 3.9 T.
Magnetic length = 6.1 m, radial aperture = 38 mm
Cryogenic power: 24 kW, Electric power: 7.9 MW

For 1 (1.3) TeV the TI2/TI8 SC dipole B = 4 (5.2) T with beam pipe 25 mm x 70 mm. Tevatron-style magnet B-field and beam gap must be scaled-up and so the cryogenic power will exceed 24 kW.

Main arc magnet for LER accelerator (1)

LER magnet scaled-down from VLHC-1 [6] dipole [7,8]
B peak = 1.76 T, B inj = 0.5 T, dBy/dt = 6.5 T/m
Beam pipe: 30 mm (v) x 40 mm (h)
Transmission-line cable (NbTi), I top = 83 kA, I inj = 13 kA
Inductance: 4.5 µH/m, L LER ≈ 120 mH
Ramping time: 60 s (0.022 T/s, 1.17 kA/s)
U rise =150 V, P peak = 10 MVA (1/12 of Main Injector)





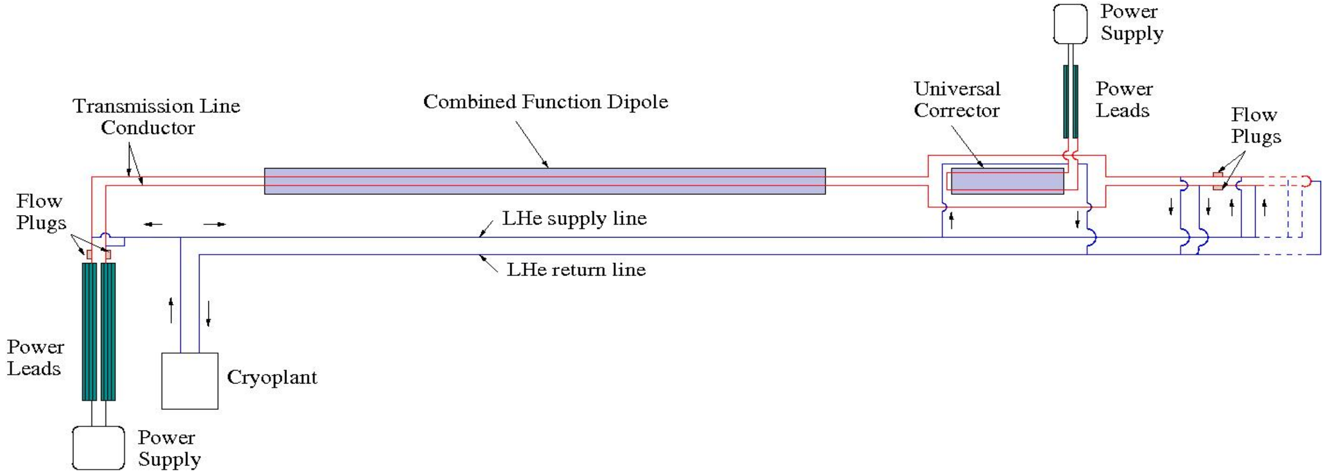
Critical temperature: 7 K
Av. operating temperature: 4.3 K @ 40 g/s
Temperature margin: 2.7 K

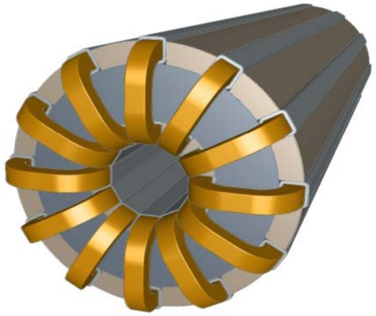
LER arc magnet static heat load: 4.4 kW
Ramping heat load @ 0.022 T/s: 0.6 kW
Temperature rise during ramp: 0.03 K
Electric power = 1.7 MW

LER total electric power 12 MW !!

[6] VLHC Design Study, Fermilab-TM-2149, 2001
[7] H. Piekarz et al., A Test of a 2 T Supercond. Transmission Line Magnet System, IEEE Trans. Appl. Supercond. 16 (2006) 342.
[8] G. Velev et al., Field Quality Measurements of a 2 T Transm. Line Magnet, IEEE Trans. Appl. Supercond. 16 (2006) 11840.

Main arc magnet for LER accelerator (2)





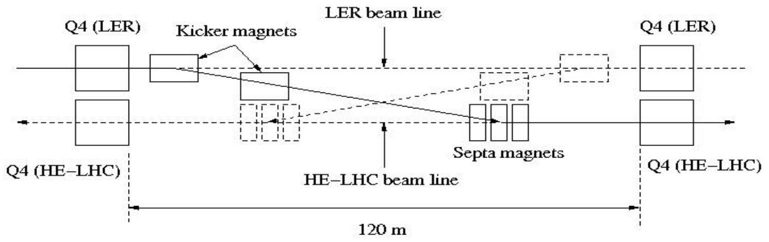
Transmission-line magnets can be individually cooled from the main LHe supply line. Pressure drop and temperature rise along 14 m magnet conductor length (equal to LHC magnet length) are negligible ensuring proper performance of the whole LER accelerator.

LER can use a universal corrector consisting of 12 coils over a hollow cylindrical magnetic core. Corrector can be normal or superconducting. With 5 power supplies per corrector there will be vertical (or horizontal) dipole, quadrupole, skew-quadrupole and sextupole, all in one unit.

LER to HE-LHC beam transfer options (part 1)

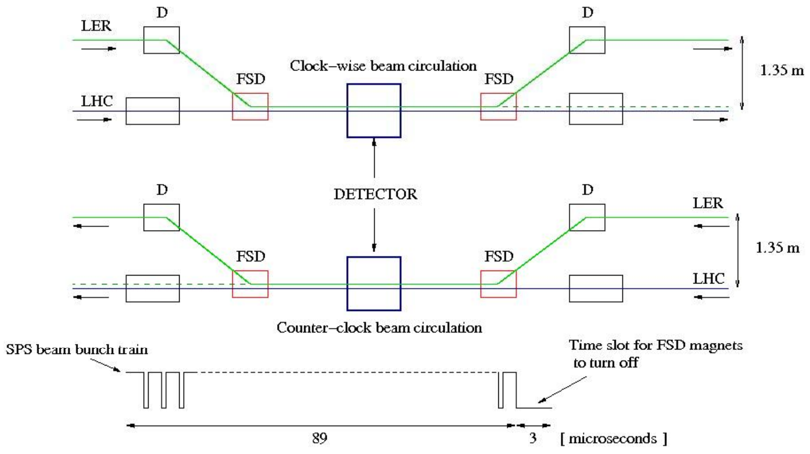
Option 1

LER->HE-LHC beam transfer at IP7



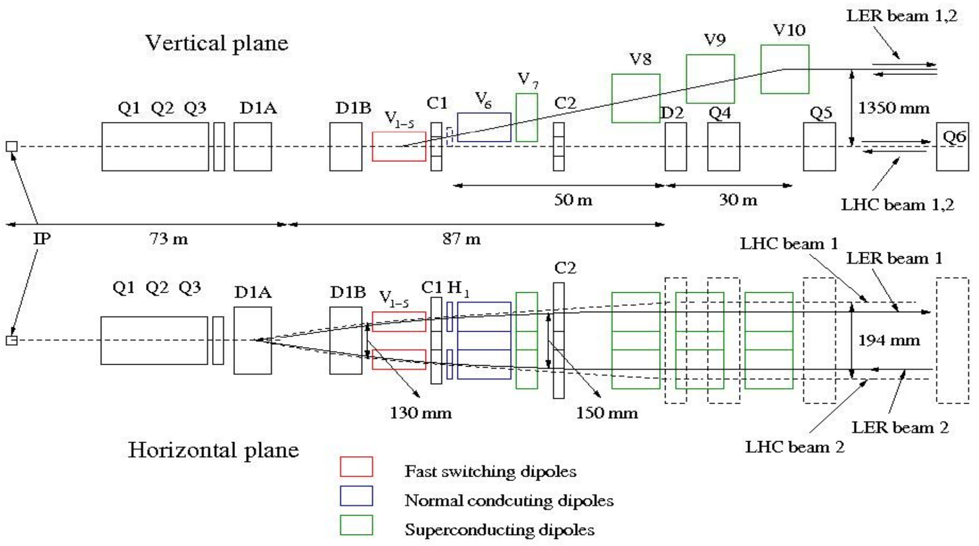
Option 2 (concept)

LER->HE-LHC beam transfer at IP1 & IP5



Option 2 (magnet arrangement)

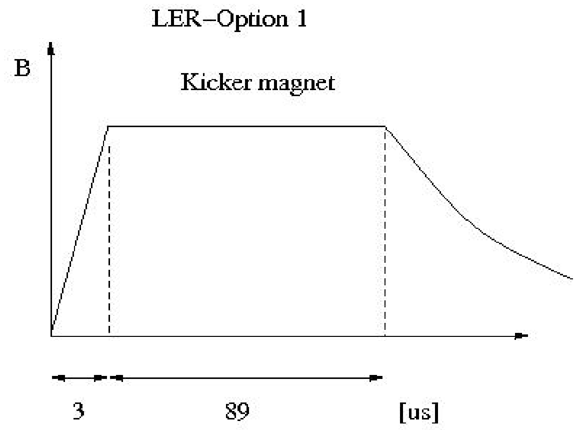
Magnet system for LER to LHC beam transfer [8]



Q1-3,D1a, D1b LHC dipoles are part of the LER during beam stacking. Turning off the fast switching dipoles enforces beams circulation in the LHC rings only.

[9] G. Ambrosio et al., “*LER-LHC Injector Workshop Summary*”, Proceedings LUMI-06 Workshop, Valencia, 2006

LER to HE-LHC beam transfer options (part 2)

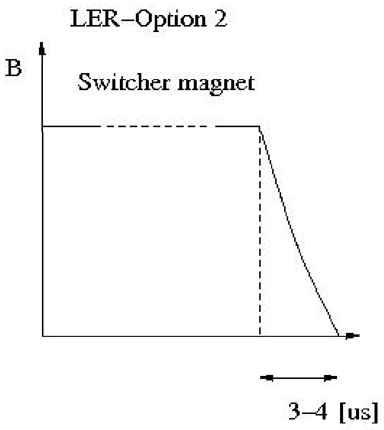


LER Option 1

Fast-pulsed magnets + Septa:

2-beam transfer to HE-LHC ==> possibly low beam losses & good quality of HE-LHC beam.

One can consider MKD kicker magnet technology but strong R&D is required in order to suppress the overshoots at injection and at flat-top, both necessary to secure high-quality of HE-LHC beam.



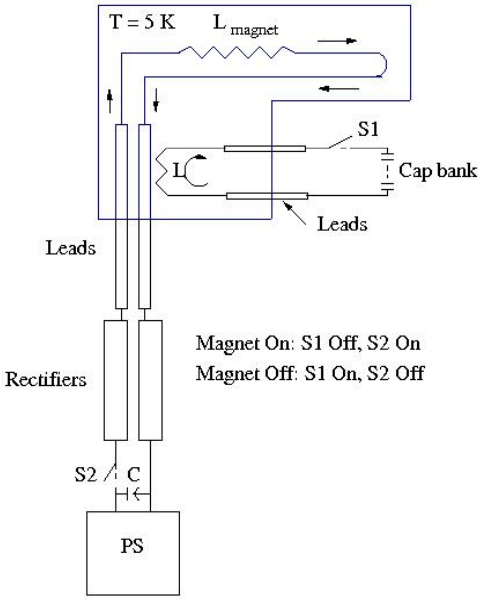
LER Option 2

Fast-switched magnets:

2-beam transfer to HE-LHC ==> possibly low beam losses & good quality of HE-LHC beam.

Significant R&D is required for a technology of a switcher magnet using currents in 70 kA range.

Concept of switcher magnet using commutation inductor (**courtesy of Steven Hays**)



Principle: cap bank injects opposite sign current into magnet power cable through commutation inductor L bringing magnet current to zero.

Magnet, inductor and ½ leads operate at 5 K. Capacitor bank operates at room temperature.

Injection energy and HE-LHC beam quality

Courtesy of Tanaji Sen :

- ❖Dynamic aperture – (1) beam size decreases with increased energy
  (2) B-field quality improves with increasing energy
- ❖Persistent currents and snapback – decrease at higher energies (higher B-field)
- ❖Instabilities (space charge, image current, electron cloud, etc.) – most (but not all) decrease with beam energy
- ❖Synchrotron radiation – increases but is well below photo-electron work function at 1.65 TeV
- ❖Rest gas scattering – emittance growth rate falls with increased energy

Higher injection energy will :

1. Improve properties of HE-LHC beams
2. Minimize beam losses
3. Reduce store setup time

All leading to the increased integrated luminosity !

Using injector accelerator to increase HE-LHC luminosity (part 1)

Two batches are slipped-stacked and coalesced in the injector accelerator doubling the bunch intensity (N_b) and possibly increasing HE-LHC luminosity up to factor of 4, $L \approx (N_b)^2$

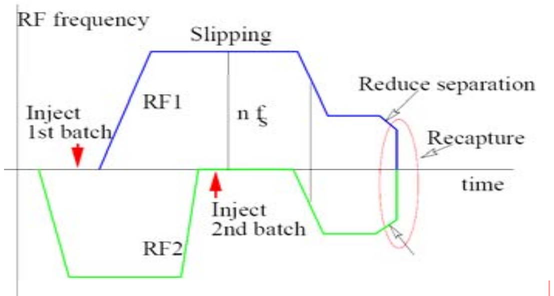
Procedure for the LER [8,9]:

SPS 450 GeV, batch length $\Delta t \approx 7\ \mu s$
Two beams use different Rf systems (RF $_{init}$ 2.7 MV)

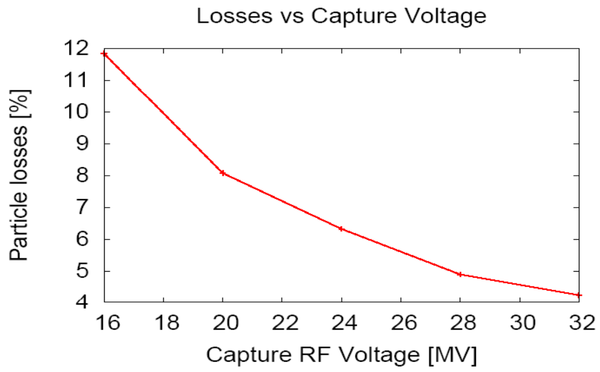
Inject 1st batch, accelerate by ΔE
Inject 2nd batch, decelerate by ΔE
2nd batch catches 1st batch at $t_{slip} = \Delta t / (\eta\ \Delta E/E)$

With LER $\Delta E = 0.8$ GeV => $t_{slip} = 11$ s
Re-capture RF voltage @ 5% beam loss = 28 MV

[9] G. Ambrosio et al., “LER-LHC Injector Workshop Summary”, CARE-HHH-APD, LHC-LUMI Workshop, 2006
[10] T. Sen, *“Intensity Increase in the LER”*, presentation at LER Workshop, CERN, Oct. 11, 2006



LER frequency curve - schematic



Using injector accelerator to increase HE-LHC luminosity (part 2)

Increased proton intensity => higher radiation levels => heating power cable
Injector magnets must operate within wide temperature margin !

There are 2 ways to deal with the radiation induced heat:

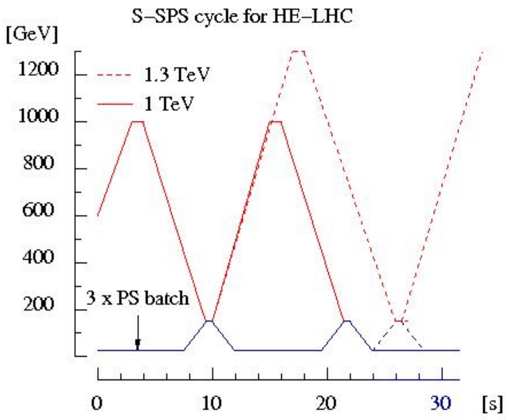
- Increase magnet gap cross-section area (expensive proposition)
- Use power cable able to operate in a wide temperature margin

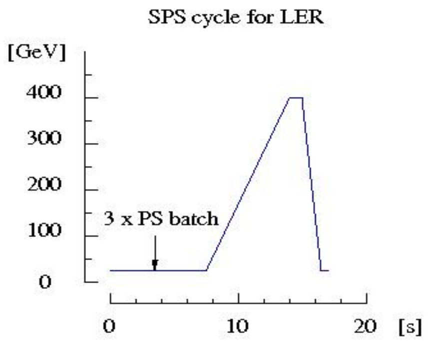
LER uses power cable of wide operational temperature margin =>
suitable for batch slip-stacking and bunch coalescing operations

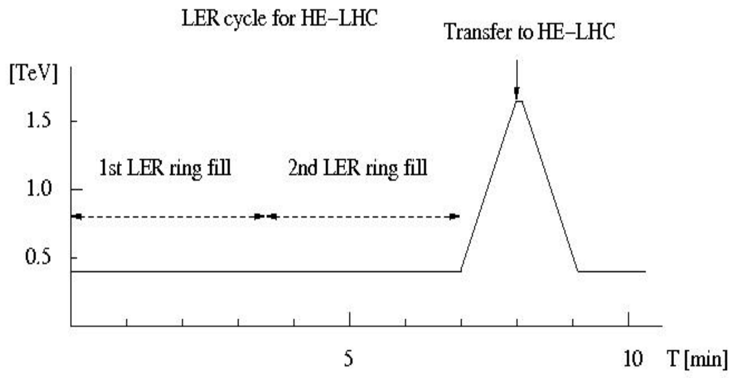
S-SPS uses power cable of very narrow operational temperature margin =>
batch slip-stacking and bunch coalescing operations not permissible

Ultimately, however, the allowed injector proton intensities will be determined by the level of proton intensities acceptable for HE-LHC !

HE-LHC stacking times with S-SPS and LER injectors







S-SPS cycle:
3 PS batches + ramp to 1 TEV @ 0.75 T/s= 10.8 s
3 PS batches + ramp to 1.3 TeV@ 0.75 T/s = 16.8 s

HE-LHC fill (1 TeV) = 24 x S-SPS cycle = 4.4’
HE-LHC fill (1.3 TeV) = 24 x S-SPS cycle = 6.8 ’

S-SPS cycle for HE-LHC = > (4.5-6.8)’
Add 2’ (24 x 5 s) if slip-stacking in S-SPS

S-SPS cycle for HE-LHC = > 6.5’ (1 TeV), 8.8’ (1.3 TeV)

SPS cycle: 3 PS batches + ramp to 0.4TeV = 18 s

LER 2-ring fill = 24 x SPS super-cycle = 7.2’
LER: 1.65 TeV (B = 1.8 T), 0.4 TeV (B = 0.45 T)
LER ramping rate = 0.022 T/s
LER ramping time = 1.35 T / 0.022 T/s = 1’

LER cycle for HE-LHC => 8.2’
Add 13 s if slip-stacking performed in LER
LER cycle for HE-LHC => 8.4’

HE-LHC ramping time (B 20 T, 0.0065 T/s) 52’ >> S-SPS or LER stacking time

Construction cost considerations for S-SPS and LER

S-SPS Option

Accelerator magnet system	1500 M€
TI2 & TI8 Transfer lines	300 M€
Total	**1800 M€**

S-SPS cost estimated based on "*FAIR Baseline Technical Report* " 2007, and C. Muehle, *"Fast-Pulsed Superconducting Magnets"*, HB2006, Tsukuba, 2006

LER option 1

Accelerator magnet system	180 M€
Kicker & septa transfer lines	40 M€
Detector bypass lines (including tunnels 50 M€)	150 M€
Total	**370 M€**

LER option 2

Accelerator magnet system	180 M€
Fast-switching transfer lines (including FSD R&D 10 M€)	90 M€
Total	**270 M€**

LER cost estimated using VLHC Design Study [6](2001) and material cost increased by a factor of 3.5 for copper (Camden Copper Prices 2000-2010), and by a factor of 2.5 for steel (GE Commercial Finance: Future of Steel, 2000-2007)

Summary

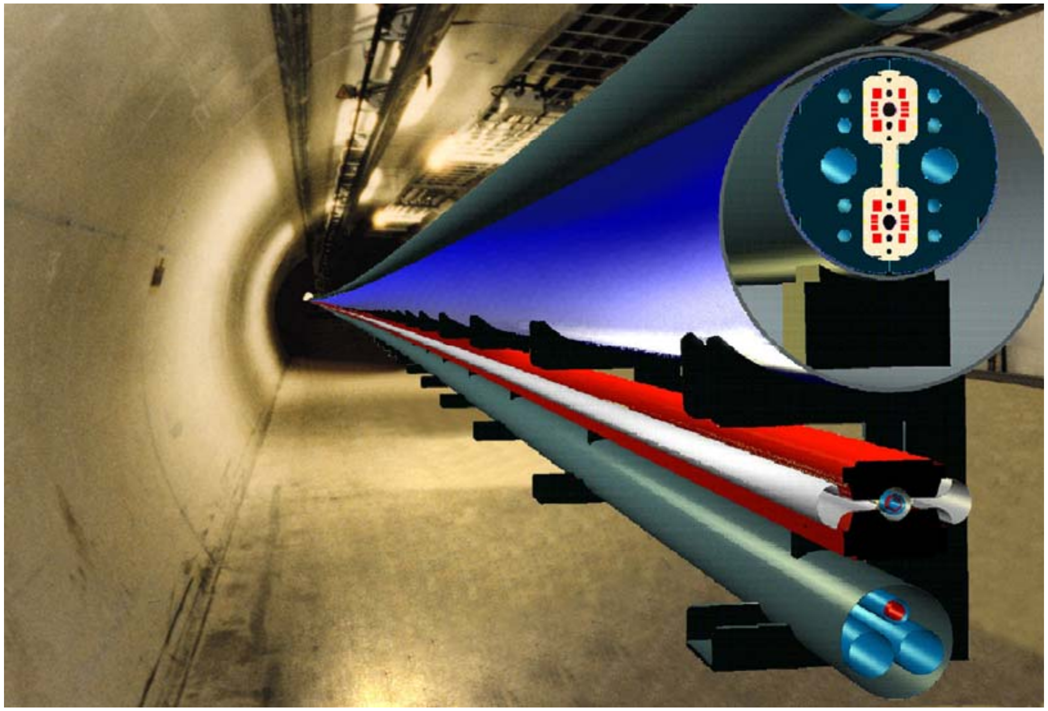
Injector properties	S-SPS	LER
Injection energy [TeV]	1 (1.3)	1.65
Doubling bunch intensity	NO	YES
Injection to HE-LHC	24	1
HE-LHC filling cycle [min]	4.5 (6.8)	8.2
Temperature margin [K]	0.5 (<0.5)	2.7
Quench probability	HIGH	LOW
Operation complexity	HIGH	LOW
Construction complexity	HIGH	MEDIUM
Construction cost (est.) [M€]	1800	370 (260)
Electric power use (est.)[MW]	129 (187)	26 (12)

S-SPS injector qualities are likely to be incompatible with HE-LHC

LER is well qualified as injector to HE-LHC

Conclusion

LER injector can strongly enhance HE-LHC performance with only modest construction & operation complexity and cost



Possible arrangement of LER and HE-LHC accelerators in LHC tunnel

Courtesy of VLHC, 2G 2B 4G !!!