Injector considerations

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Acknowledgements to many others in the FCC study teams

Outline

- Requirements and beam parameters
- Choice of FCC-hh injection energy
- Assumed injector chain elements
- Options at CERN using existing tunnels
- Comparison of parameters and technologies
- Connecting LHC to FCC-hh collider
- Study status and directions

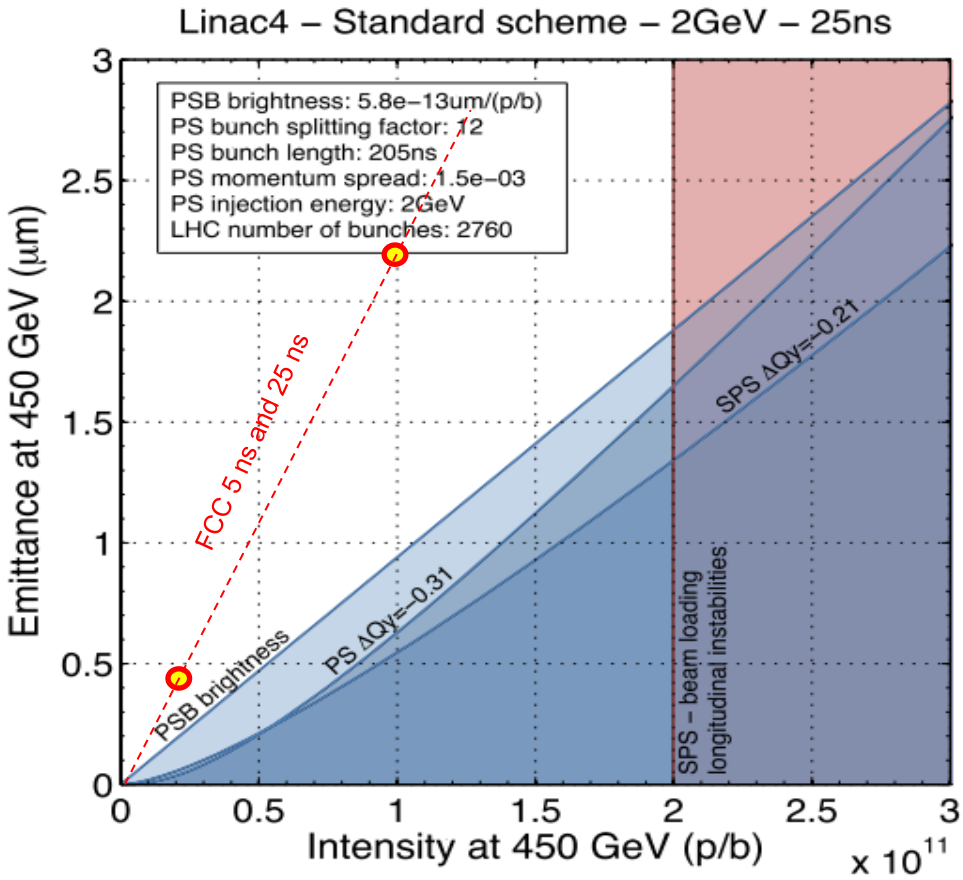
Requirements

- Injector chain for p+ and heavy ions
- Key parameters for 'scoping' of injectors: FCC-hh injection energy and required filling time
- Bunch intensity, emittance and filling pattern enter into machine protection considerations ➔ W.Bartmann, R.Schmidt

Parameter	Unit	Value (option)
Bunch spacing	ns	25 (5)
FCC-hh injection energy	TeV	3.3
Bunch intensity	e11 p+	1.0 (0.2)
Transverse emittance	mm.mrad	2.2 (0.44)
FCC-hh filling time	minutes	10-30

Injector parameters

- Take LHC Injectors Upgrade (LIU) targets as baseline performance from SPS
  - Will be used for HL-LHC
- 25 ns brightness and bunch intensity do not seem challenging
  - Already delivered from SPS
  - Questions could be:
    - HEB emittance preservation
    - Minimum emittance for 5 ns



FCC-hh injection energy

- 3.3 TeV is baseline energy
  - Defined by FCC-hh: chosen as same energy swing for LHC, but important for impedance and aperture
  - 1.8 TeV would be same field (T) as present LHC
- Clearly a critical “project level” parameter
  - For FCC-hh collider (magnet aperture and cost, injection field, dynamic effects, impedance, stability, …)
  - For injector chain (affects technology, machine length, cycling time, machine protection, …)
  - Scope for optimisation

FCC-hh filling time

- Minimum FCC filling time (on paper) should be in shadow of overall assumed turnaround time (4-5 hours)
  - 10-30 minutes is a reasonable target
  - To note: at present could fill both LHC rings in under 10 minutes – on paper. Reality is closer to 30 minutes
  - More detailed analysis with FCC-hh luminosity lifetime and optimum fill length may revise this number

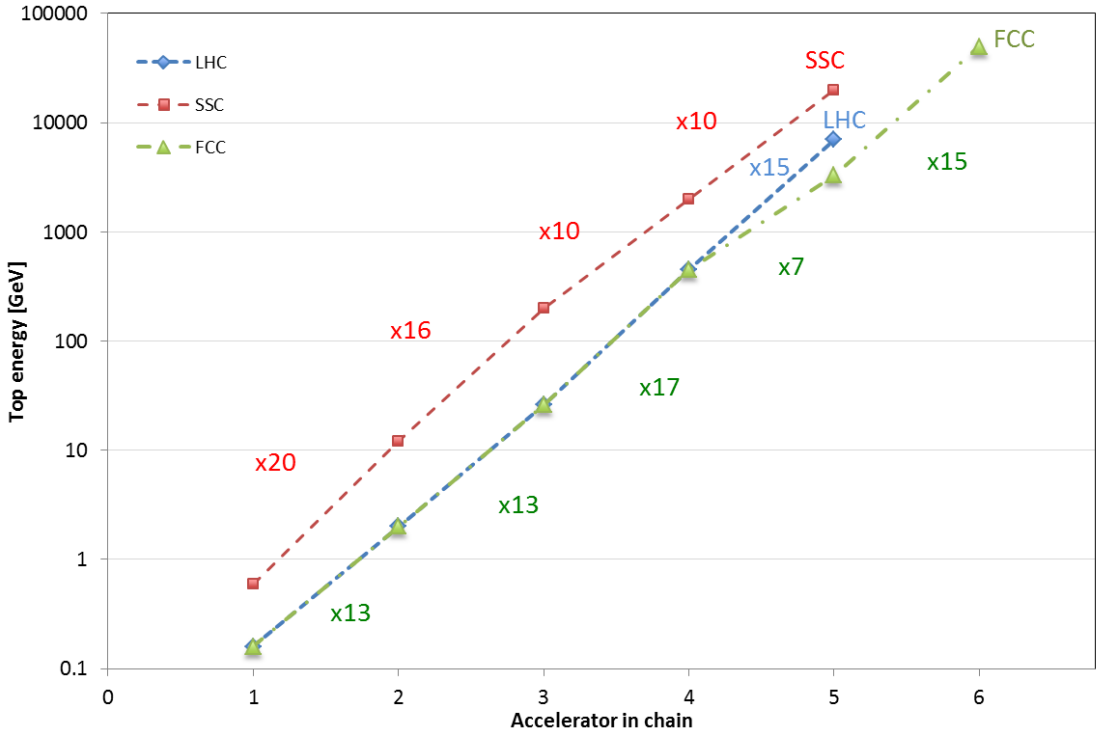
FCC-hh at CERN

- Maximise CERN facility reuse
  - Add High Energy Booster (HEB) to present LHC injectors
  - Not (yet) studying “SPL/PS2” option to rebuild full complex
- Take HL-LHC injector chain output for granted
  - 2.5e11 p+/bunch in 2 μm ε_{xy} at 25 ns is assumed
- FHC: 100 km collider length, 50 TeV/beam
  - 1e11 p+ per bunch, 25 ns spacing, need to fill ~11’000b
- Assumed HEB design with 2 rings or polarity reversal
- Filling times calculated assuming present injector complex cycle times (but increase PS batches in SPS from 4 to 8: same total intensity as HL-LHC beam)

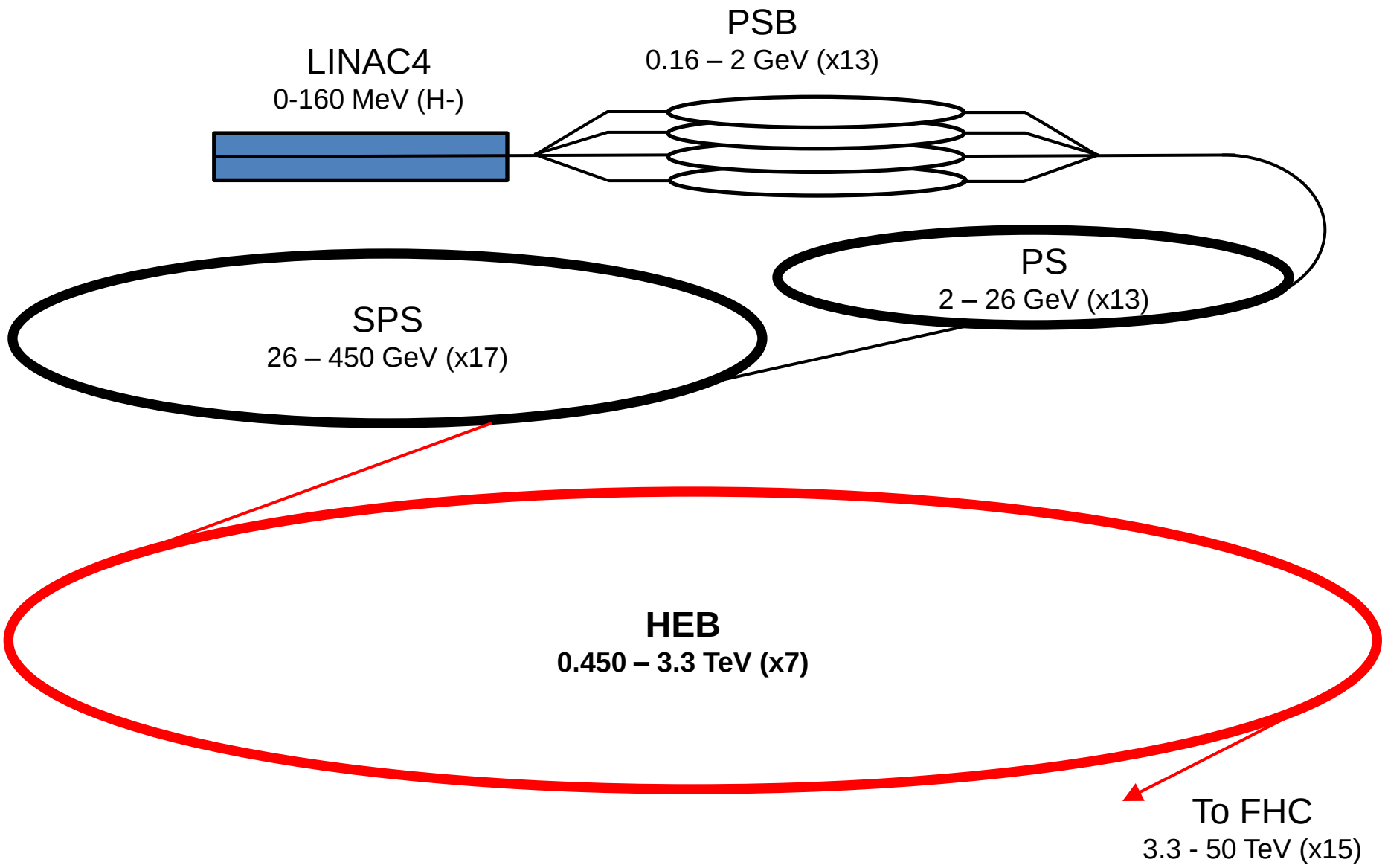
Assumed injector elements

- For 3.3 TeV, with existing CERN chain, 5 main accelerating steps in the injector chain
  - Linac4: 0-160 MeV
  - PS Booster: 160-2000 MeV
  - PS: 2 – 26 GeV
  - SPS: 26 – 450 GeV
  - HEB: 0.45 – 3.3 TeV

(SSC chain: 4 steps, starting at 600 MeV)



A CERN FHC-hh injector chain



Existing tunnels and lengths

Parameter	unit	SPS	LHC	FCC-hh
Circumference	km	6.9	26.7	100.0
Number dipoles		744	1232	
Number dipoles		744	1232	4400
dipole length (iron)	m	6.2	14.3	15
bend angle per dipole	mrad	8.445	5.100	1.428
beam rigidity	Tm	1503.17	23337.2	
Field at injection	T	0.117	0.534	1.024
Field at top energy	T	2.03	8.3	16
Magnetic length	m	6.253	14.34	15
Total dipole length	m	4612.8	17617.6	66000
Dipole filling factor		0.67	0.66	0.66
Ramp time	s	10.8	1100	
Ramp rate	T/s	0.1771	0.0071	

HEB options…

- Starting point for injectors at CERN assumes re-use of existing LHC chain, up to and including SPS
  - New HEB: reach 3.3 TeV, fill FHC in 10-30 minutes
- Initial HEB options for evaluation:
  - 7 km SC machine in SPS:
    - 15 T Nb_3Sn to reach 3.3 TeV
    - 9 T NbTi possible if FCC-hh injection at 2 TeV
  - 27 km existing LHC reuse ➔ W.Herr
    - Ramp rate to increase by as much as possible: x5 reasonable target
    - New 2-quadrant higher voltage powering, new QPS, remove low-β, …
    - Decommissioning of highly activated zones to study
  - 100 km NC/SF machine
    - 30-60 km of iron dipoles, ~1000 quads (or combined function?)

HEB@SPS

100 km FCC-hh version		SPS tunnel	
Parameter	**Unit**	**SC very high field**	**SC high field**
FHC collision energy	TeV	50	50
HEB extraction energy	TeV	3.3	2.0
Ring filling-factor		0.67	0.67
Number of beams accelerated		2	2
Extraction dipole field	**T**	**15.0**	**9.0**
Dipole ramp rate	**T/s**	**0.025**	**0.20**
Bunches per PS extraction		72	72
PS extractions to fill SPS		10	10
SPS extractions to fill HEB		2	2
Bunches in each HEB ring		720	720
HEB bunch train length	us	40.55	40.55
HEB extractions to fill FCC		15	15
FHC bunches		10800	10800
PS cycle length	s	3.6	3.6
SPS cycle length	s	43.2	43.2
Minimum HEB ramp up+down time	s	1036	69
Minimum FCC filling time (both rings)	min	272	38

- 3.3 TeV at 25 mT/s is > 4 h filling time
- 2.0 TeV at 0.2 T/s would be 38 minutes….is this dB/dT realistic?

HEB@LHC

100 km FCC-hh version		LHC tunnel		
Parameter	**Unit**	**Reuse existing LHC**	**LHC x5**	**SF**
FHC collision energy	TeV	50	50	50
HEB extraction energy	TeV	3.3	3.3	1.7
Ring filling-factor		0.67	0.67	0.67
Number of beams accelerated		2	2	1
Extraction dipole field	**T**	**3.9**	**3.9**	**2.0**
Dipole ramp rate	**T/s**	**0.007**	**0.035**	**0.05**
Bunches per PS extraction		72	72	72
PS extractions to fill SPS		9	9	9
SPS extractions to fill HEB		8	8	4
Bunches in each HEB ring		2592	2592	2592
HEB bunch train length	us	149.2	149.2	74.1
HEB extractions to fill FCC		4	4	8
FHC bunches		10368	10368	10368
PS cycle length	s	3.6	3.6	3.6
SPS cycle length	s	39.6	39.6	39.6
Minimum HEB ramp up+down time	s	959	192	58.9
Minimum FCC filling time (both rings)	min	77	32	28

- Present LHC ramp rate is too slow
- 2.0 T SF machine in LHC tunnel only reaches 1.7 TeV
- 5x faster linear LHC ramp (35 mT/s) allows 32 minutes

HEB@FCC

100 km FCC-hh version		FCC tunnel	
Parameter	**Unit**	**SF**	**NC**
FHC collision energy	TeV	50	50
HEB extraction energy	TeV	3.3	3.3
Ring filling-factor		0.35	0.35
Number of beams accelerated		1	1
Extraction dipole field	**T**	**2.0**	**2.0**
Dipole ramp rate	**T/s**	**0.05**	**4.00**
Bunches per PS extraction		72	72
PS extractions to fill SPS		10	10
SPS extractions to fill HEB		15	15
Bunches in each HEB ring		10800	10800
HEB bunch train length	us	310.625	310.625
HEB extractions to fill FCC		2	2
FHC bunches		10800	10800
PS cycle length	s	3.6	3.6
SPS cycle length	s	43.2	43.2
Minimum HEB ramp up+down time	s	68.2	0.9
Minimum FCC filling time (both rings)	min	23	22

- 2 T NC or SF has no limitation on energy or filling time

HEB options compared

Parameter	Unit	SPS tunnel	LHC (x5)	FCC tunnel
FCC-hh injection energy	TeV	3.3	3.3	3.3
Dipole field	T	15.0	3.9	2.0
Dipole technology		Nb_3Sn	NbTi	NC (SF)
Total dipole length	km	4.6	17.8	35.0
Dipole filling factor	%	67	67	35
Single dipole length	m	6.2	14.4	8.0
Number of dipoles		744	1232	4375
Ramp rate	T/s	0.025	0.035	0.05
HEB ramp up+down time	s	1036	192	140
Cycles to fill FCC-hh		15	4	2
FCC-hh filling time	min	272	32	22

- 15 T SPS: 4 h filling time comes from slow cycle, x15
- 4 T LHC: with 5x ramp rate acceptable, scope to reach 6.5 TeV
- 2 T 100 km HEB in FCC tunnel: limited by cycle time of pre-injectors. Filling factor only 35%, scope to reach ~6 - 8 TeV
- Filling times: ~20 minutes needed to get all bunches to 450 GeV

Improved filling time with LHC?

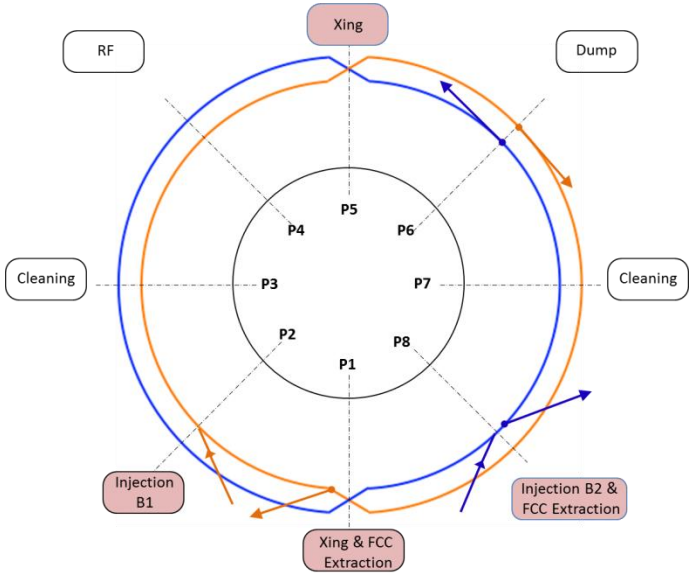
- 8x PS injections to fill SPS: 28.8 s
  - 3.6 s PS cycle time
- 8x SPS injections to fill both LHC rings: 316.8 s
  - 10.8 s SPS ramp up + ramp down time
- 4 LHC ramps to fill FCC-hh: 2359.2 s (39 minutes – "real" ramp)
  - 312 s LHC ramp-up + ramp down time (50 A/s in linear part)

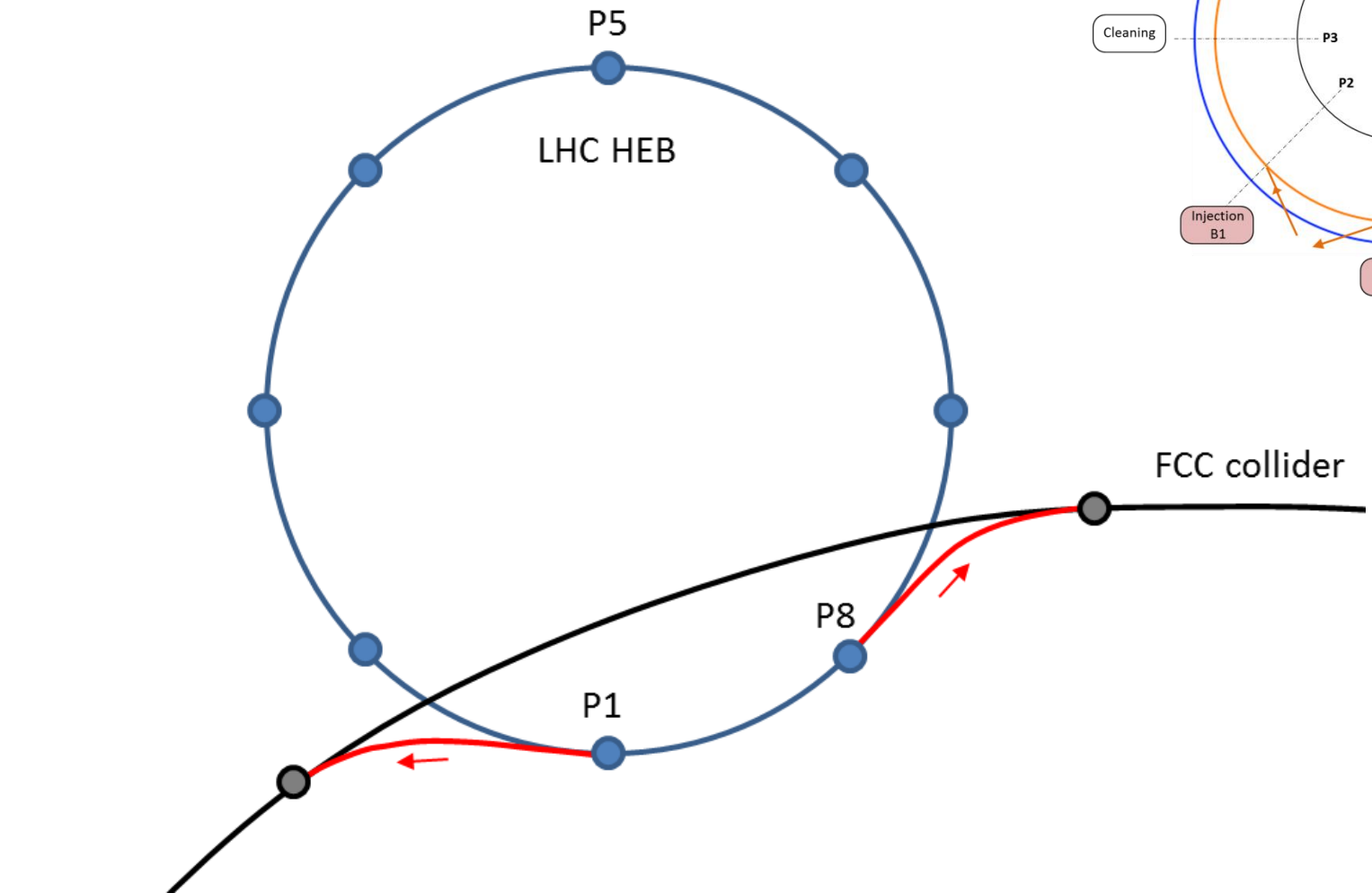
- Further gains? Need ~300 PS cycles to fill FCC, plus ramping
  + Speed up PSB cycle to 600 ms: 2205 s (37 minutes)
  + Speed up PS cycle to 2.4 s (single batch): 2052 s (35 minutes)
  + x2 faster LHC roundoffs (96 s of 156 s is 50 A/s ramp): 1842 s (31 minutes)

- Note: times are minimum filling time "on paper": from LHC experience need to multiply by 2-3
  - Realistically ~1 – 1.5 hour (for 4 LHC ramps……)

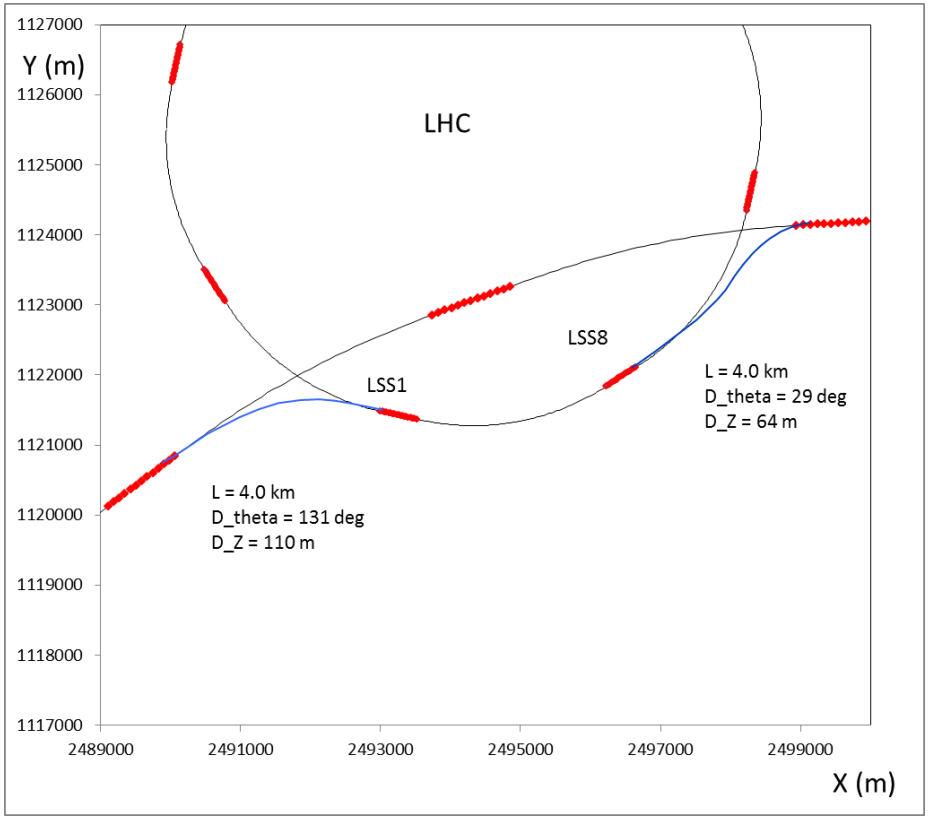
Connecting LHC to FCC-hh

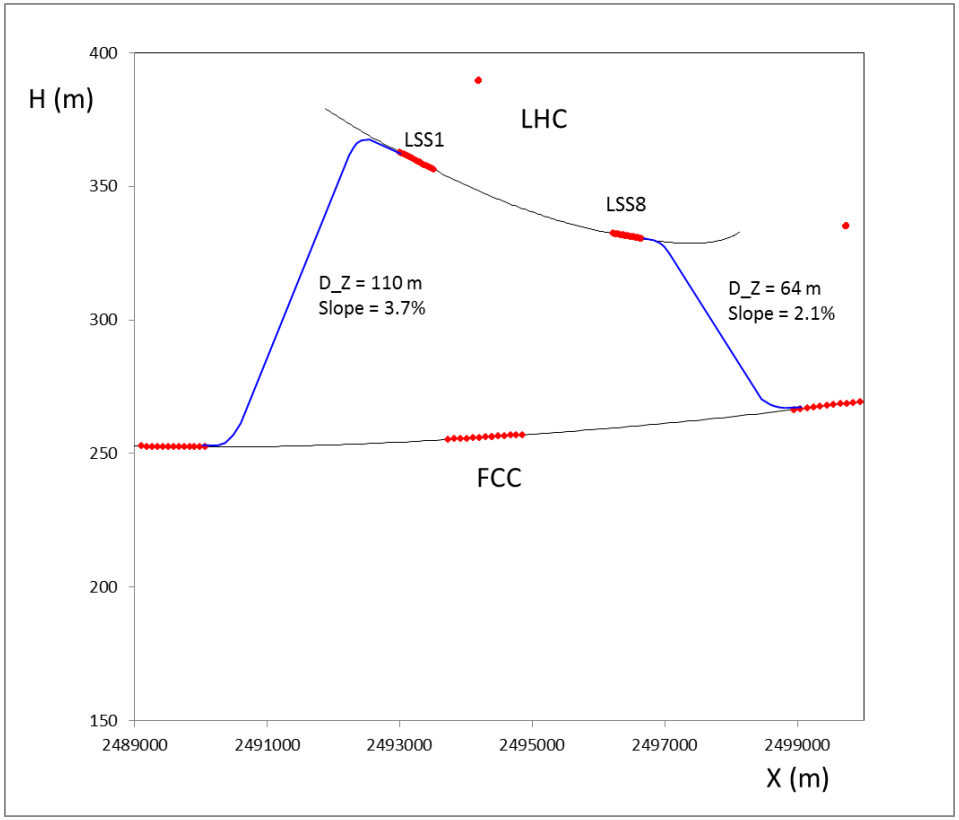
“Intersecting” layout (100 km)





“Intersecting” TLs

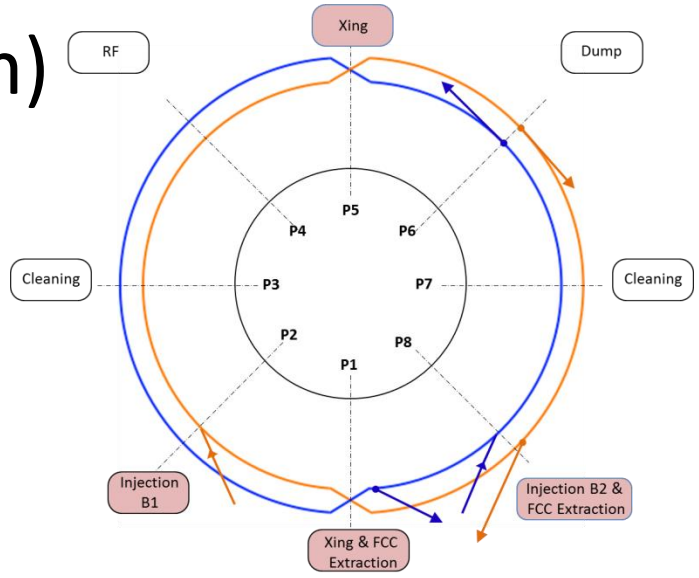


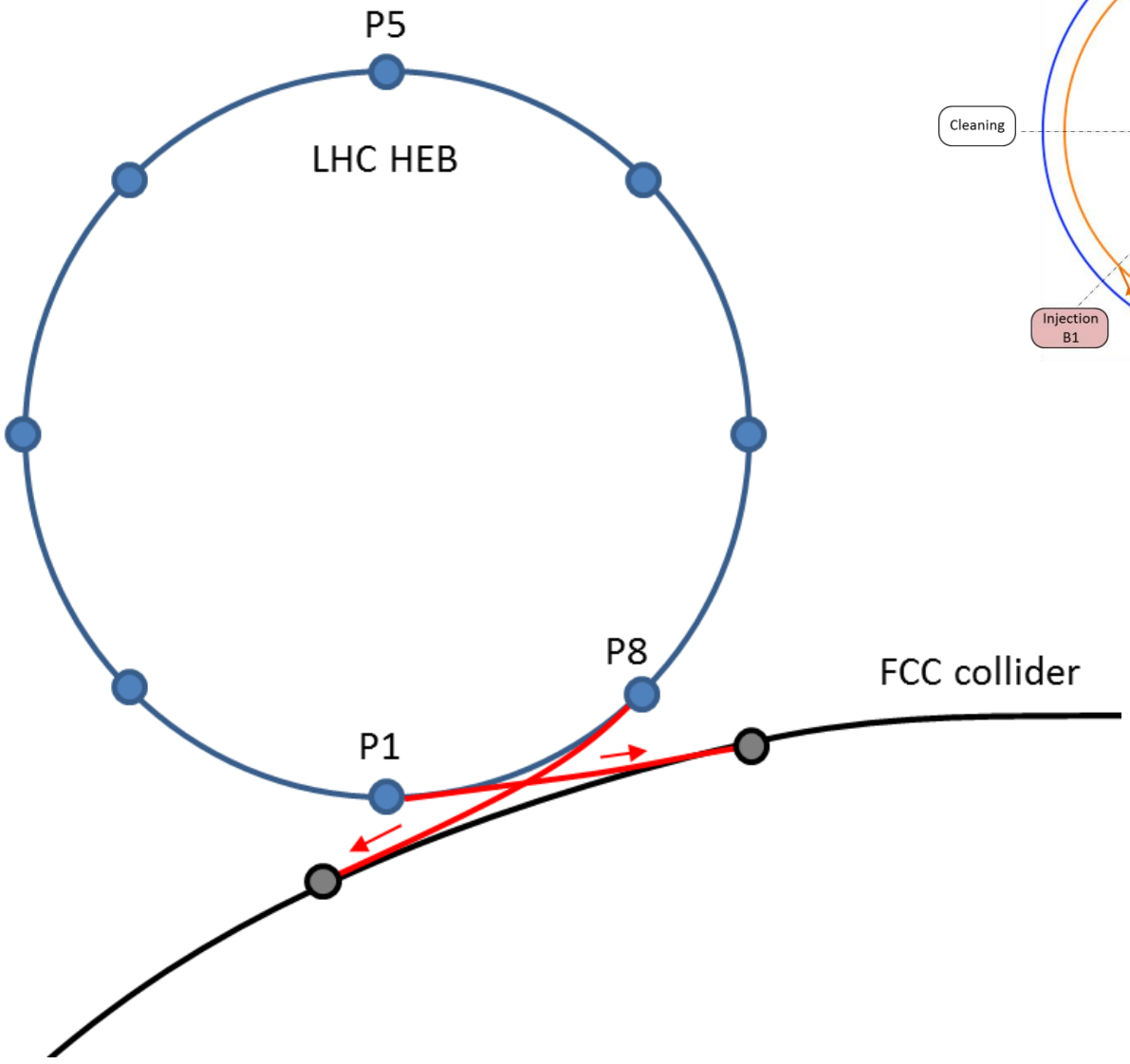


- Significant horizontal bending for both lines (160 deg total)

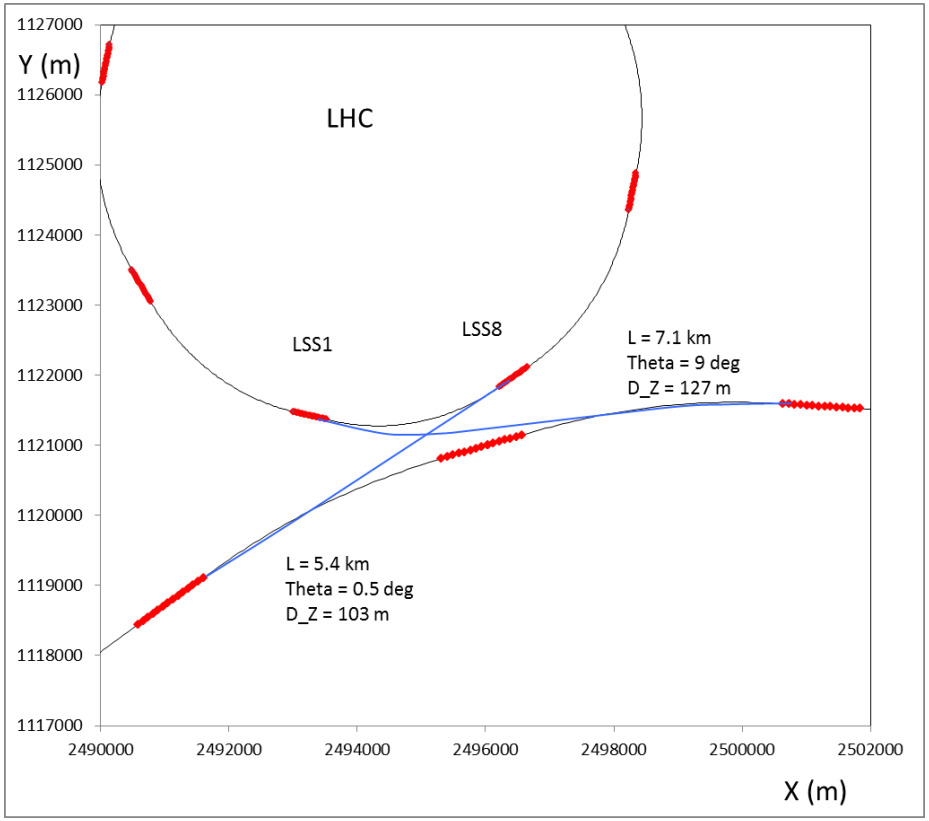
Connecting LHC to FCC-hh

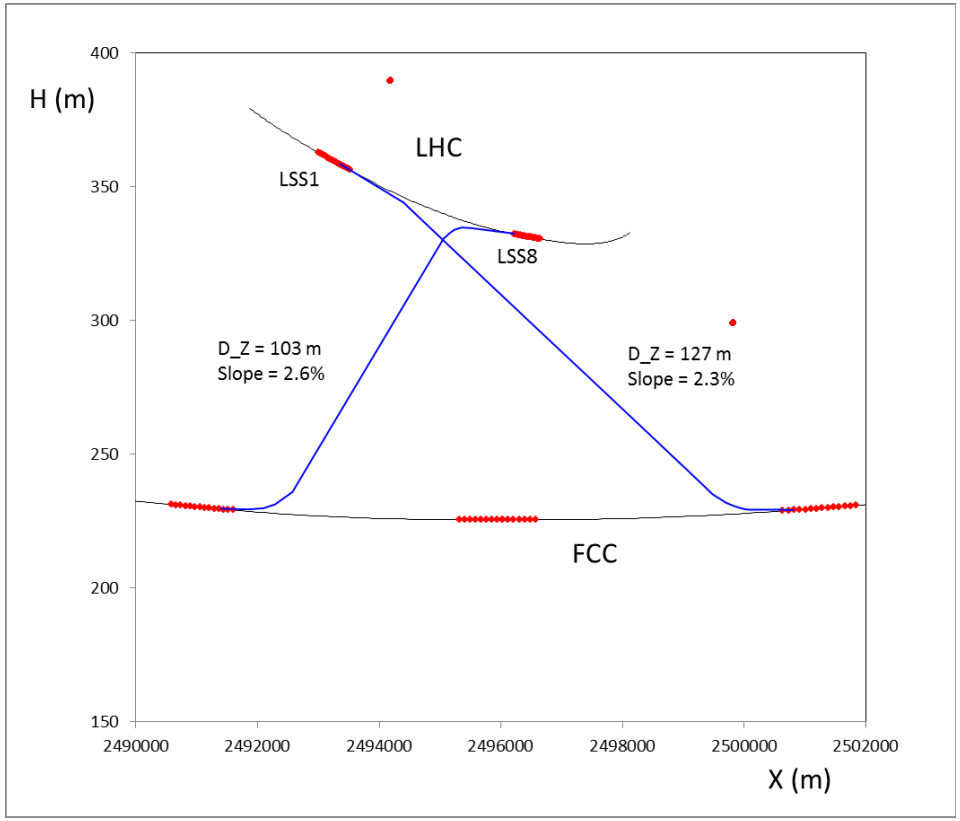
“Non-intersecting” layout (93 km)





“Non-intersecting” TLs





- Little horizontal bending for both lines (10 deg total)
- Would allow injection straight positions to be moved together…

TL comparison

		Non-intersecting (93 km FCC)	Intersecting (100 km FCC)
Length [km]	TL from LSS1	7.1	4.0
	TL from LSS8	5.4	4.0
Vertical offset [m]	TL from LSS1	127	110
	TL from LSS8	103	64
Maximum slope [%]	TL from LSS1	2.3	3.7
	TL from LSS8	2.6	2.1
Horizontal bend angle [deg]	TL from LSS1	9	131
	TL from LSS8	1	29

- Intersecting version has 4.5 km less tunnel but 150° more bend angle (at 3.3 TeV)
  - Costs about 40 m of dipole per degree bend (at 5 T): 6 km more dipole!
- TL slopes of up to 4%
  - more if FCC is deeper for other reasons – reaches 6.6%

Summary

- Proton beam parameters for 25 ns baseline are feasible
- Injector options for FCC-hh being studied by adding HEB to existing CERN complex
- HEB is assumed to fill collider at 3.3 TeV, around 11'000 bunches
  - Beam transfer and machine protection both get difficult…
- Tentative baseline for FCC study is upgraded LHC (x5 faster ramp, new layout, other mods). 4 ramps to fill collider: 30 minutes min.
- Other options are:
  - SPS (very high fields needed, long filling time for 3.3 TeV),
  - SF machine in the collider tunnel (long machine, cost evaluation needed),
  - Replacing LHC with new 5 T faster cycling machine (looks profligate).
- Present study status:
  - Reuse of LHC studied in some detail: connection to FCC-hh, ramping, lattice, modifications, beam transfer (talks this week from W.Herr, W.Bartmann)
  - SPS and FCC tunnel HEB options to be investigated (magnets A.Milanese)

Specific topics for studies

- Minimum injection energy in FCC-hh
  - Lower E opens more options for HEB...but E could equally increase
- Maximum allowed time for filling FCC-hh
  - Is ~30 minutes adequate? Feasibility of options to speed up complex?
- Feasibility of LHC reuse for HEB
  - Simplified lattice design, ramping at ~50 A/s, decommissioning
- Feasibility of HEB in SPS tunnel
  - Magnets, integration, ramp rate, 1 or 2 apertures…
- Feasibility of HEB in 100 km tunnel
  - Beam dynamics at 450 GeV (space charge, impedance, IBS, …)
- Delivery of polarised beam to FCC-hh?
- Delivery of Fixed-Target 3.3 TeV p+ (e.g. for test beams)?
- Preliminary cost scaling for main systems for all options

FCC Hadron Injectors study group: http://indico.cern.ch/category/5262/

FCC-hh Physics with Injectors: http://indico.cern.ch/category/6070/

156 s LHC ramp for FCC