FCC – injectors ‘plan’

FCC WG on experiments with the CERN injectors 29/9/14

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Outline

- Initial assumptions
  - Requirements, pre-injector performance, constraints
- HEB tunnel options and features
  - SPS
  - LHC
  - FHC
- Injector complex baseline assumptions
- Comparison of idealised FT performance reach
- High luminosity IP in HEB performance reach
- Potential issues

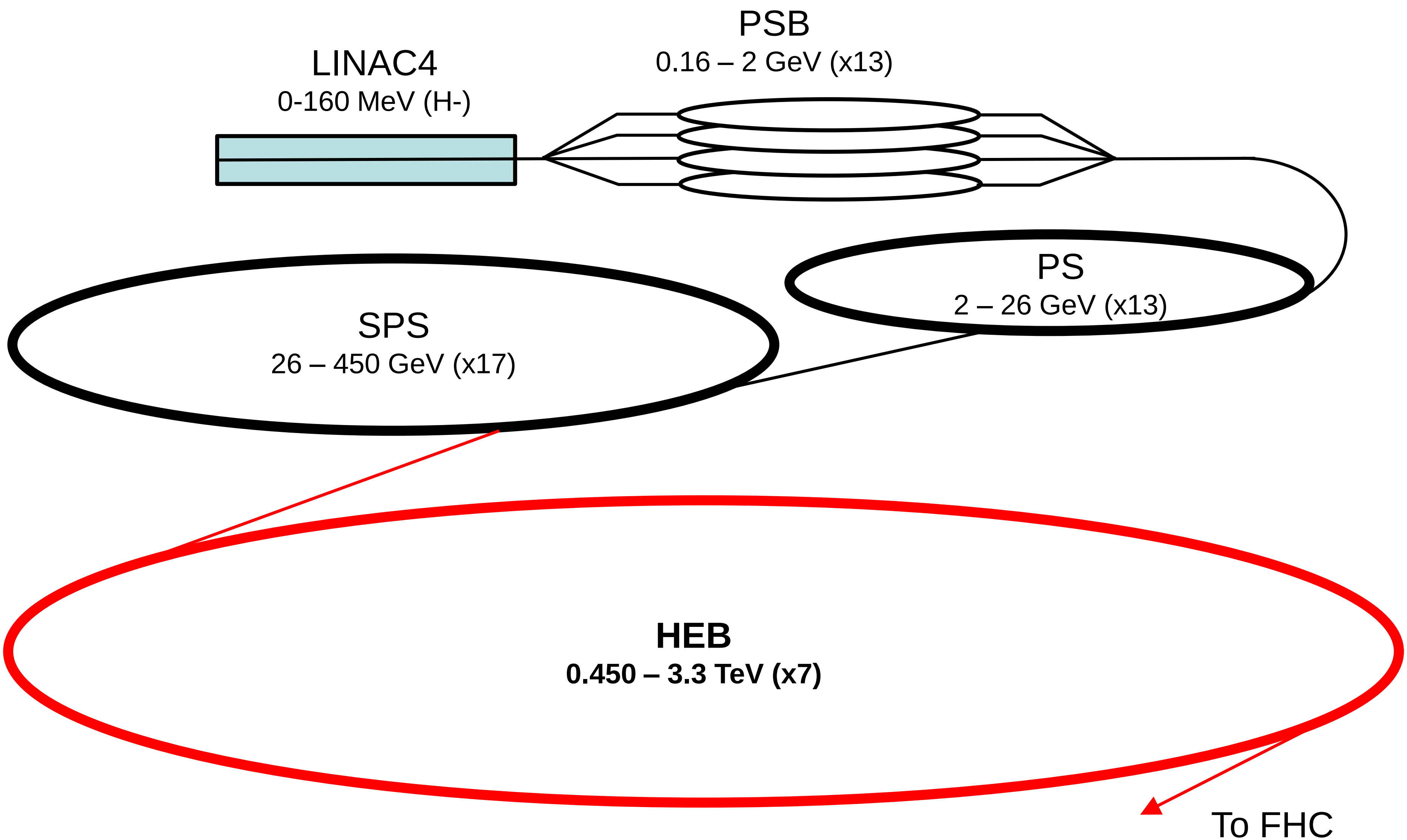
Basic assumptions for FCC injectors

- Maximise CERN facility reuse
  - Add High Energy Booster (HEB) to present LHC injector complex
  - Not considering an “SPL/PS2-like” option to rebuild full complex
  - No new ‘few MW proton driver’
- Take HL-LHC injector chain output for granted
  - 2e11 p+/bunch in 2 μm ε_{xy} at 25 ns
- FHC: 100 km collider length, 50 TeV/beam
  - 1e11 p+ per bunch, 25 ns spacing, need to fill ~11’000 bunches
- Evaluate HEB designs with 2-in-1 magnets
  - May not be realistic for all options
  - Only one ring assumed for FT beams!
- Collider filling times with present injector complex cycle times (but 4->8 PS batches in SPS)

FHC injection considerations

- Minimum FCC filling time (on paper) should be of order of 10 minutes
  - Aim to keep this ‘in the shadow’ of 50 TeV collider cycle time
  - To note: on paper present LHC could fill both rings in under 10 minutes
- Injection energy considered as 3.3 TeV
  - Gives same field ratio (collision/injection) as present LHC
  - Working hypothesis for injectors and collider studies
  - Lower may severely penalise FCC (magnet aperture, instabilities, …)
  - Possibility that this energy might increase, if found advantageous for 50 TeV collider design

An FHC injector chain



Energy swing in HEB is low: 5 TeV and x11 would fit better!

HEB magnet technology options

Type	Bmax (T)	Bdotmax (T/s)	Bmax/Bmin
NormCond	2.0	4	40
Superferric	2.5	2	40
SC (Nb-Ti) low field	5.0	1.4	15
SC (Nb-Ti) high field	9.0	0.2	15
SC (Nb3Sn)	16.0	0.025	15
SPS (NC)	2.0	1	28.6
LHC (Nb-Ti high field)	8.4	0.007	15.6

Existing tunnels and lengths

Parameter	unit	SPS	LHC	FHC
Circumference	m	6912	26659	100000
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	

CERN already has a good selection of ‘available’ tunnels, so the first HEB studies are based on these!

Options…

- Plenty of them….
- Starting point for injectors assumes re-use of existing LHC chain, up to and including SPS
  - New HEB: should reach ≥3.3 TeV and fill FHC in ~10 minutes
- Initial options for evaluation:
  - 7 km SC machine in SPS:
    - Very high field 18 T Nb3Sn (to reach ~4 TeV)
  - 27 km existing LHC reuse
    - Ramp rate to increase by as much as possible: x5 target
    - New 2-quadrant higher voltage powering, new QPS, remove low-β, …
    - Decommissioning of highly activated zones to study

    ...or replace LHC with new 'low-cost' machine….
  - 100 km NC/SF machine
    - 30-60 km of 2-in-1 iron dipole magnets, at least 1000 quadrupoles

Specific topics for FHI study

- Minimum injection energy in FHC
  - 1.8 TeV opens other options for HEB...but more likely to be >3.3 TeV
- Feasibility of HEB in SPS tunnel (if 2 TeV FCC injection possible)
  - Integration, ramp rate, 1 or 2 apertures…
- Feasibility of LHC reuse for HEB
  - Lattice design for simplified 3.3 TeV synchrotron
  - Key question of ramping dipole at ~50 A/s. Studies, tests??
  - Availability (how often were there 4 consecutive LHC ramps?)
  - Decommissioning feasibility
  - Civil engineering aspects
- Feasibility of HEB in 100 km tunnel
  - Beam dynamics at 450 GeV injection energy (space charge, impedance, IBS, …)
  - Basic lattice needed
- Preliminary cost scaling for key systems for all options
- Beam transfer, machine protection (both of these get difficult!)

HEB options – SPS tunnel

SPS tunnel: SC low-field can reach 1.1 TeV, but 3.3 TeV is tough

100 km FHC version		SPS tunnel		
Parameter	**Unit**	**SC very high field**	**SC high field**	**SC low field**
HEB injection energy	TeV	0.45	0.45	0.45
HEB extraction energy	TeV	3.3	2.0	1.1
FHC injection dipole field	T	1.06	0.64	0.35
Ring filling-factor		0.67	0.67	0.67
Circumference	m	6912	6912	6912
Brho at extraction	Tm	11031	6698	3698
Number of beams accelerated		2	2	2
Total magnetic dipole length	m	4610	4610	4610
HEB injection dipole field	T	2.09	2.09	2.09
HEB Extraction dipole field	**T**	**15.0**	**9.1**	**5.0**
Dipole technology		Nb3Sn	NbTi	NbTi
Dipole ramp rate	**T/s**	**0.025**	**0.20**	**1.40**
SPS extractions to fill HEB		1	1	1
Bunches in HEB		720	720	720
HEB extractions to fill FHC		14	14	14
FHC bunches		10080	10080	10080
HEB stored beam energy	MJ	38.0	23.0	12.7
HEB stored beam energy / LHC nominal		0.11	0.06	0.04
Minimum HEB ramp up+down time	s	1036	70	4
Minimum FHC filling time (both rings)	**min**	**248**	**23**	**8**

HEB options – LHC tunnel

LHC tunnel: wide range of possibilities – including reuse of LHC

100 km FHC version		LHC tunnel			
Parameter	**Unit**	**Existing LHC (SC high field)**	**SC low field**	**SF**	**NC**
HEB injection energy	TeV	0.45	0.45	0.45	0.45
HEB extraction energy	TeV	3.3	3.3	2.1	1.7
FHC injection dipole field	T	1.06	1.06	0.67	0.54
Ring filling-factor		0.67	0.67	0.67	0.67
Circumference	m	26659	26659	26659	26659
Brho at extraction	Tm	11031	11031	7031	5698
Number of beams accelerated		2	2	2	2
Total magnetic dipole length	m	17781	17781	17781	17781
HEB injection dipole field	T	0.54	0.54	0.54	0.54
HEB Extraction dipole field	**T**	**3.9**	**3.9**	**2.5**	**2.0**
Dipole technology		NbTi	NbTi	SF	NC
Dipole ramp rate	**T/s**	**0.007**	**1.40**	**2.00**	**4.00**
SPS extractions to fill HEB		4	4	4	4
Bunches in HEB		2560	2560	2560	2560
HEB extractions to fill FHC		4	4	4	4
FHC bunches		10240	10240	10240	10240
HEB stored beam energy	MJ	135.2	135.2	86.0	69.6
HEB stored beam energy / LHC nominal		0.38	0.38	0.24	0.19
Minimum HEB ramp up+down time	s	959	5	1.9	0.7
Minimum FHC filling time (both rings)	**min**	73	9	9	9

HEB options – FCC collider tunnel

FCC tunnel: 2.0/2.5 T NC/SF with 0.35/0.28 filling-factor

100 km FHC version		FHC tunnel	
Parameter	**Unit**	**SF**	**NC**
HEB injection energy	TeV	0.45	0.45
HEB extraction energy	TeV	3.3	3.3
FHC injection dipole field	T	1.06	1.06
Ring filling-factor		0.28	0.35
Circumference	m	100000	100000
Brho at extraction	Tm	11031	11031
Number of beams accelerated		2	2
Total magnetic dipole length	m	28000	35000
HEB injection dipole field	T	0.34	0.27
HEB Extraction dipole field	**T**	**2.5**	**2.0**
Dipole technology		SF	NC
Dipole ramp rate	**T/s**	**2.00**	**4.00**
SPS extractions to fill HEB		15	15
Bunches in HEB		10800	10800
HEB extractions to fill FHC		1	1
FHC bunches		10800	10800
HEB stored beam energy	MJ	570.2	570.2
HEB stored beam energy / LHC nominal		1.58	1.58
Minimum HEB ramp up+down time	s	2.1	0.9
Minimum FHC filling time (both rings)	**min**	10	10

Baseline option?

- Reuse of existing LHC machine has strong "naturalness" arguments in favour, if it is technically feasible and cost competitive

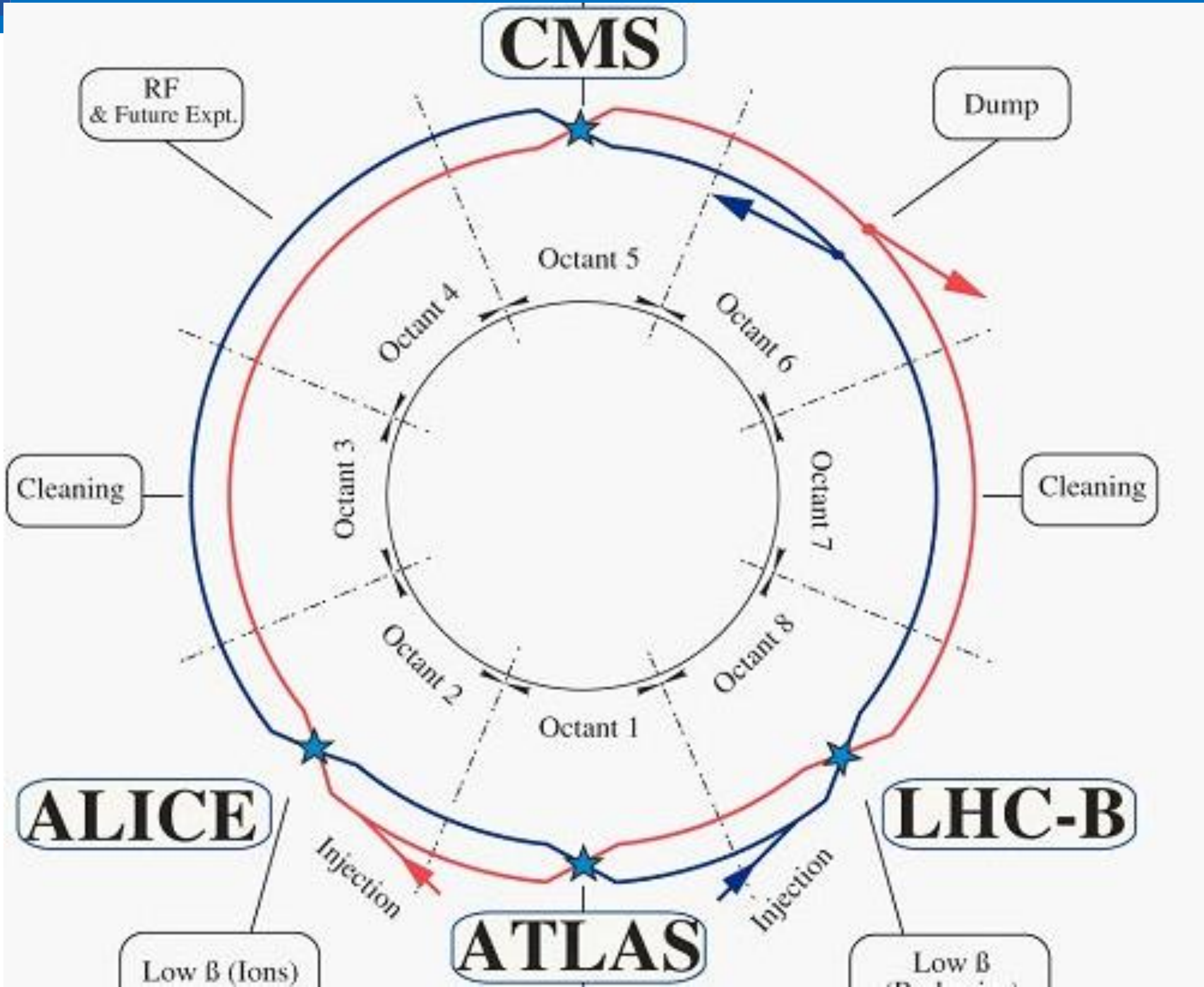
- So presently assumed to be baseline – other versions are options for study

….so, a digression on reuse of LHC….

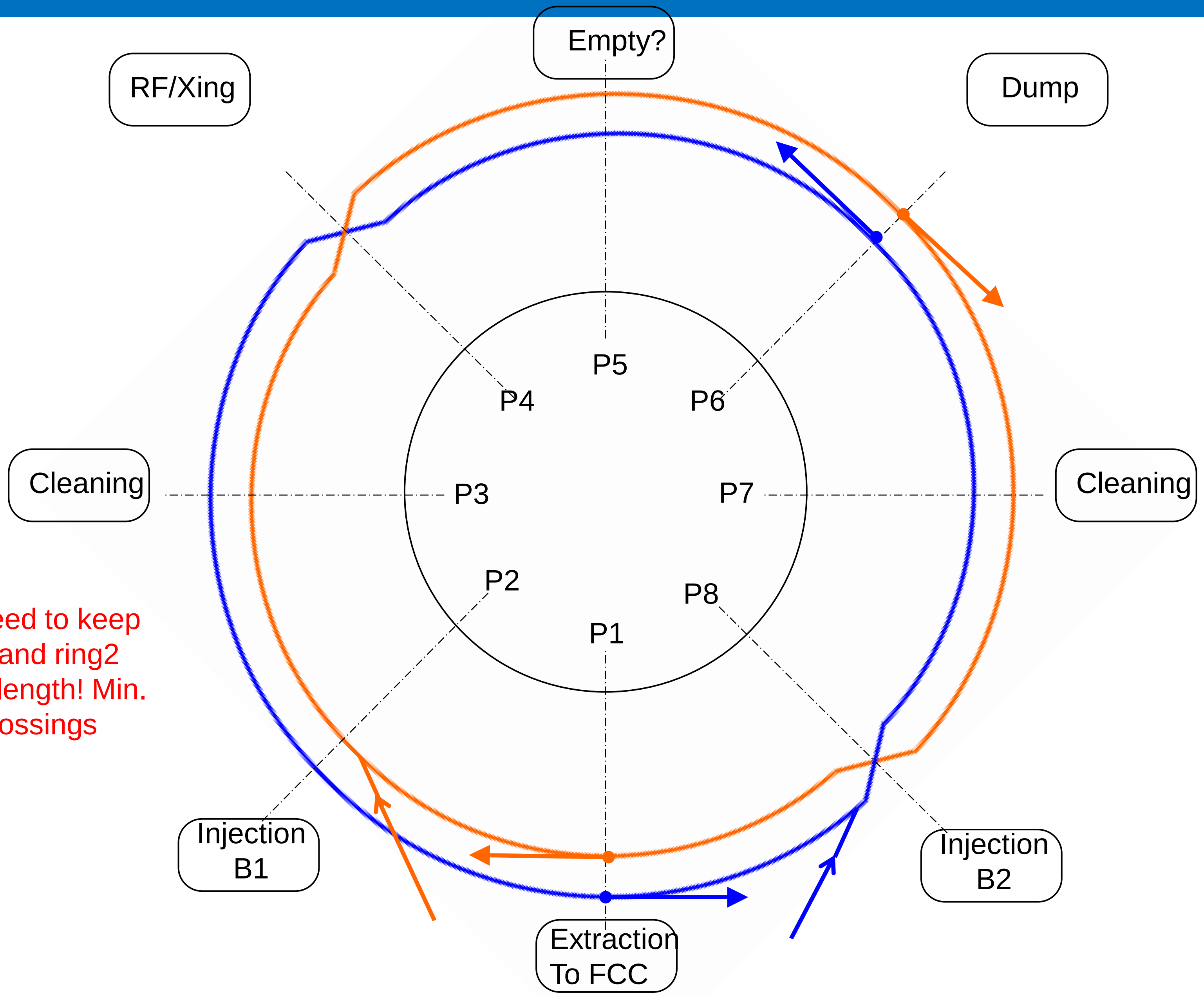
Constraints for LHC reuse

- For RF reasons, need to keep both rings the same length
  - Implies minimum of 2 crossings, at opposite IPs
- Should avoid decommissioning and repurposing IPs 3,6 and 7
  - Radiation
- Need to keep injections in IP2 and IP8
  - Otherwise major extra transfer lines to build
- Beam extraction to collider ideally in IP1 (IP5 also possible)
- No crossing in IP with beam extraction

Reusing LHC: From this…



To this…?



RF: need to keep ring 1 and ring2 same length! Min. of 2 crossings

Changes per IP (1-4)

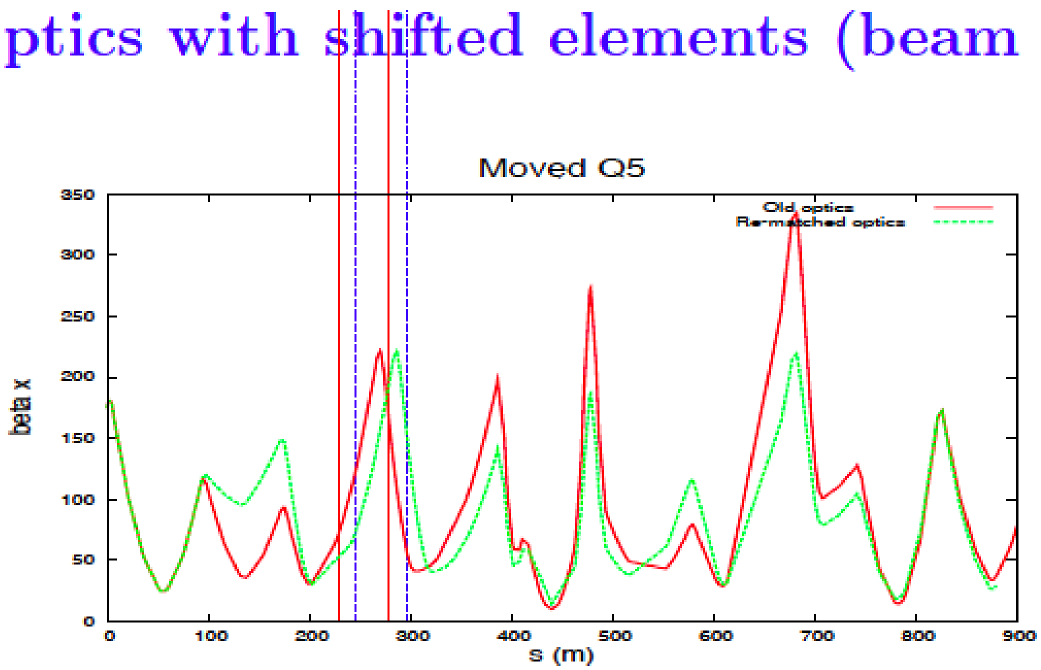
- IP1: extraction to collider:
  - removal of low-beta insertion and ATLAS, civil engineering for junctions to new TLs to collider, new extraction system
  - assume for now same optics and layout as present IP6
- IP2: injection of B1 (no crossing)
  - removal of low-beta and ALICE
  - modification of injection system to inject into INNER ring (presently to outer!)
- IP3: collimation – unchanged
- IP4: RF and new crossing
  - Addition of D2 magnets, plus required matching quadrupoles for crossing (not at IP…)

Changes per IR (5-8)

- IP5: FODO transport, no crossing
  - removal of low-beta and CMS, construction of floor through CMS cavern, installation of FODO quads
  - Possible location for FT extraction system
- IP6: beam dump – unchanged
- IP7: collimation – unchanged
- IP8: Injection beam 2 and crossing
  - removal/modification of low-beta and LHCb

Optics features in IP2

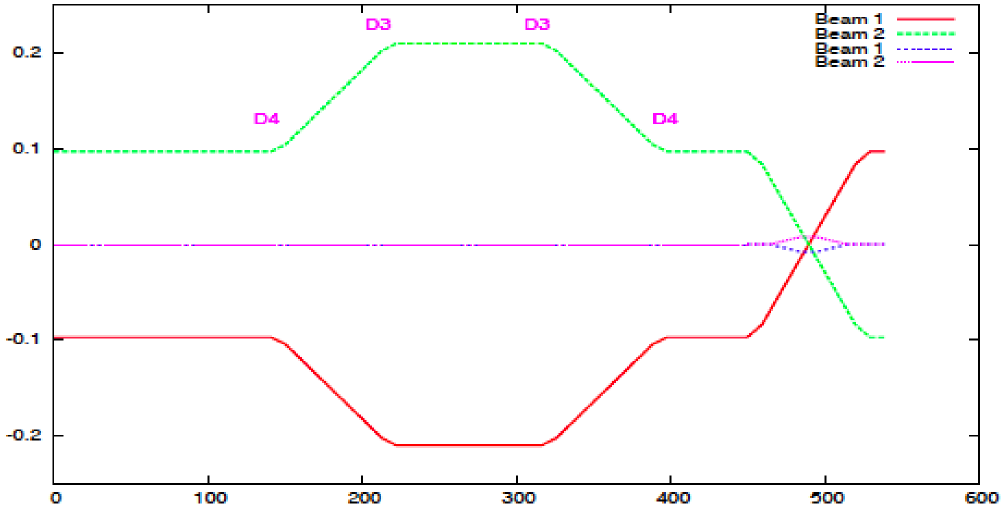
- Injection in IP2 to INSIDE ring
- Need to shift injection septa and kickers downstream by about 16 m, and Q5
- Optics implications seem manageable



Optics features in IP4

- Horizontal crossing needs pair of MBRB D4 magnets
- Vertical separation needs 2 MCBXV or MCBCV
- No major changes to optics at RF cavities
- Dispersion can be matched back down to a few cm for both beams

Proposed full crossing and separation scheme



FT extraction insertion in LHC

- Depends on where transfer to FCC takes place, but would be either P1 or P5
- Not yet looked at any details of extraction system requirements or possible layout
- Likely to be not particularly straightforward to design conceptually….
- Crystal extraction to be taken seriously as an option – discussing with W.Scandale and Collimation team about studies and SPS/LHC MD

FT PoT estimates

- Simple methodology to compare options….
- Limit peak power on targets to 2.0 MW
  - Maybe slightly pessimistic at this stage (or maybe not!)
- Stored energy in beam given by FCC filling constraints
- Adjust spill lengths to give 2.0 MW power
- Subtract FCC filling time
- 80% efficiency for FT physics
- Total cycle length and protons per spill then give maximum PoT per year (if no other limitations)
  - Reality will be worse

PoT from cycle length etc.

HEB@		SPS tunnel 16T	LHC reuse 5x faster	FCC Tunnel SF
Beam energy	TeV	3.3	3.3	3.3
Total intensity	p+	7.2E+13	2.6E+14	1.1E+15
Ramp up/down time	s	1290	239	3
Flat top time	s	23	82	345
HEB filling time	min	616	25	20
Fraction of time filling FCC (2 per day)		0.85	0.17	0.05
Operation days per year		250	250	250
FT efficiency		0.8	0.8	0.8
FT cycles per year		1908	10828	46994
FT PoT per year		1E+17	3E+18	2E+19
FT average power	MW	0.004	0.1	1.5
Peak power on target during spill	MW	2.0	2.0	2.0

so **e18 p+/year at 3.3 TeV** might be envisaged, from these considerations….
(note that 2e19 p+ for FCC tunnel option is limited by what SPS can produce!)

Extraction of FT beams from HEB

- Fast extraction works, but slow extraction is assumed essential…
  - For experiments (digesting ~e14 p+ in ~100 us…?)
  - For targets (20-700 MJ on target in ~100 us…?)
- Will be technologically "challenging" for a machine at 3.3 TeV!

Possible limitations - i

- Extraction system for 3.3 TeV
  - SPS works at 450 GeV
  - Space in lattice is ~100 m
  - Beam losses will be 10-20 kW in extraction region
    - Equipment performance, activation, radiation damage
  - Limiting elements are
    - Thin electrostatic septa (E field 100 kV/cm, 50 um diameter wires, 15 m active septum length)
    - Thin magnetic septa (5 mm thick, 7.5 kA current)

Possible limitations - ii

- Distributed beam losses in SC magnet system
  - For re-use of present LHC, would appear *very* challenging to incorporate an insertion with 1% beamloss, while maintaining sufficient cleaning efficiency elsewhere
  - For HEB@FCC tunnel, even if HEB is NC or SF, would be sharing a tunnel with 16-20T dipoles….
    - Maybe need separate parallel extraction straight for HEB for some 2-10 km, for extraction plus beam cleaning….cost, layout, …
  - For HEB@SPS, looks even more difficult to manage extraction losses, as the existing LSS are only 120 m long

Other challenges…

- 3.3 TeV beam transfer for slow-extracted beams
  - Losses may make SC magnets difficult, but huge bending radius with 2 T NC magnets!
- Targetry for 3.3 TeV, 2 MW beams
  - 3.3 TeV beam likely to pose different difficulties compared to typical ~GeV energy of spallation sources
- Shielding and experimental area design
- Secondary beamlines
- Very long spills…
  - Spill quality
  - Resonance and ripple control
  - POWER CONSUMPTION (HEB running most of time at top energy!)
  - Crystal extraction studies to look at

High luminosity IP in injector?

High luminosity options, IR8

$L_* = 23$ m:

$\beta^* = 0.25$m ➡ $\hat{\beta} = 2116$ m

$L_* = 12$ m:

$\beta^* = 0.20$m ➡ $\hat{\beta} = 720$ m

$\beta^* = 0.30$m ➡ $\hat{\beta} = 480$ m

$\beta^* = 0.40$m ➡ $\hat{\beta} = 360$ m

Smaller L_*, larger β^*, (much) smaller $\hat{\beta}$:

no issue for Q' correction

no issue for long range beam-beam

Performance?

- ~2800 colliding bunches
  - 2.2e11 p+/bunch
  - 2.5 um emittance
  - 3.3 TeV
  - Assume geometric reduction of 0.9 (with crab cavities)
- Aim for initial luminosity of 1e35 Hz/cm2
  - Needs beta* of ~15 cm
  - 230 events per crossing
- 200 days, H=0.25, 40% of time filling 50 TeV collider: <u>250 fb-1</u>
  - 7 TeV and 15 cm beta* would increase these numbers: L=2e35 Hz/cm2, 480 events/crossing, 520 fb-1/y

Possible limitations

- Where to start….?
- Probably a large perturbation from the 50 TeV collider operation (60% probably optimistic)
- Modifying LHC as HEB may limit energy reach to 3.3 TeV
- Faster ramping may require redesign/removal of many circuits needed for collider operation
- If ‘high intensity’ FT beams are needed, this is probably mutually exclusive, or at least will reduce integrated luminosity by ~x2
- Costs: operating, manpower, maintenance, …

Summary

- Injectors for FCC 'plan' on adding HEB to existing CERN complex
- HEB is assumed to fill collider at 3.3 TeV
- Baseline for FCC study is upgraded LHC (x5 faster ramp, new layout, other mods). 4 ramps to fill collider
- Other options are SPS (looks very unlikely), a NC machine in the collider tunnel (looks very long), or replacing LHC with new 5 T machine (looks very profligate).

Summary

- For 3300 FT beams, **O**e18 PoT/year at 3.3 TeV ‘could be envisaged’ from time-sharing arguments, depending on which HEB option
- Need to look seriously at feasibility of 3.3 TeV slow extraction from these HEB machines
  - Extraction concept, layout, technology
  - Losses, collimation, quenches, collider cross-talk
  - Spill quality and control
  - Targets, beam transport, experimental area
- For single high luminosity IP, 3.3 TeV could reach maybe 250 fb-1 per year, with 230 events per crossing at 25 ns
  - Serious concerns about compatibility with ‘injector’ operation
  - What experiments would be better at the HEB, instead of the FCC collider?

Input needed

- Is there a use for a single high luminosity IP in 3.3 TeV HEB?
  - If so, what would be:
    - Beam energy (default 3.3 TeV)
    - Integrated luminosity per year (probably <250 fb-1?)
    - Maximum pileup (around 230 events/crossing)
- Is there a use for 3.3 TeV FT beams for physics?
  - If so, what would be:
    - Beam energy (default 3.3 TeV)
    - PoT per year (maximum seems to be <3e18)
    - Spill length (few minutes?)
  - Same questions for test beams!

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