LHC AS FCC INJECTOR

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Outline

- FCC injector requirements
- LHC hardware modifications to reach 5 x faster ramping
- LSS modifications
- TLs to FCC
- LHC machine tests in view of FCC

FCC injector requirements

- Injection energy baseline: 3.3 TeV
  - Study range 0.45 TeV – 6.5 TeV
- Reuse as much as possible existing injector chain
  - Profit from LIU upgrades for Hilumi and knowledge of delivered/projected beam parameters
- FCC filling time around 40 min
- Focus on 25ns – started investigating only recently 5ns
- Keep non-LHC physics program (SPS North Area)
- Envisage future physics program also at LHC (P5)

Table 1: Parameters of Beams to Inject into FCC-hh

Parameter	**Unit**	**Value (option)**
Beam energy	TeV	3.3
Bunch spacing	ns	25 (5)
Bunch population		$1.0\ (0.2)\times10^{11}$
H/V emittance (norm.)	mm.mrad	2.2 (0.44)
RMS bunch length	cm	8.0
Bunches per transfer		50-100
Turnaround time	h	5.0

FCC filling time

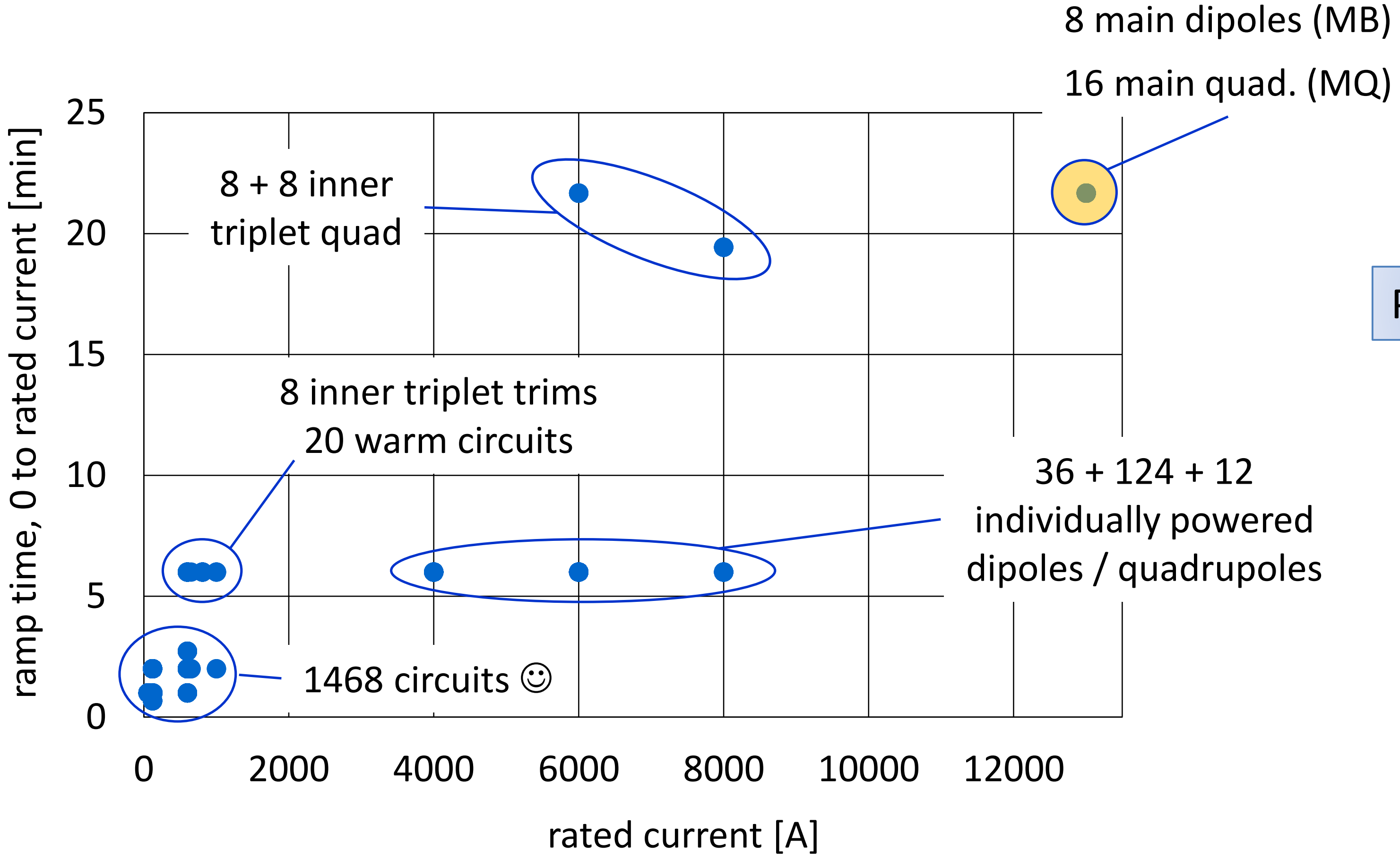
- FCC turnaround of 4-5 h
- FCC filling time should be ~40 min
- Present ramp rate would lead to 90 min filling → increase ramp rate by factor 5

Hardware constraints for faster ramp rate

- Protection diodes of main dipoles
  - 6 V turn-on voltage limits to 60 A/s
- Quench protection system:
  - After a quench, dipoles ramped down at 120 A/s
  - No issues expected for 100 A/s for QPS
- Cryogenic load
  - Ramp to full current in 1200 s → 480 J/m (hysteresis and eddy currents)
  - System designed for full current to zero in 80 s (3000 J/m)
- Voltage during ramp
  - Arc inductance 15.7 H: 160 V for 10 A/s → 800 V for 50 A/s
  - Dipoles are tested to 475 V
  - 50 A/s possible with new power converters/sectorisation
- No limitations expected from
  - Premature quenches – ok up to 100 A/s
  - Field quality – slow crossing in beginning for snap-back, small contribution from eddy currents
  - RF can cope already now with factor 5 faster ramp

10 A/s → 50 A/s

Faster ramping of LHC



Present LHC

The ramp rate limiting circuits are the 13 kA main dipoles and quadrupoles

Ramp function

- Now using Parabolic-Exponential-Linear-Parabolic (PELP) for smooth current derivatives
- Initial ramp critical for snapback and chromaticity
- Use knowledge of LHC magnet model to feedforward and speed up this part
- Ramp up time of 156 s → cycle time of 312 s, assume 10 s for flattop and faster ramp down
- To be tested with maximum ramp rate available now

PPLP scheme

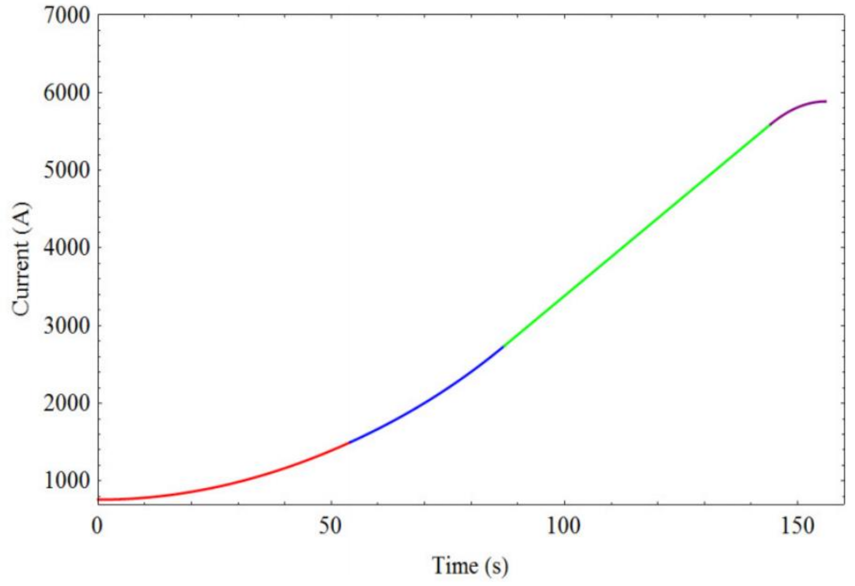
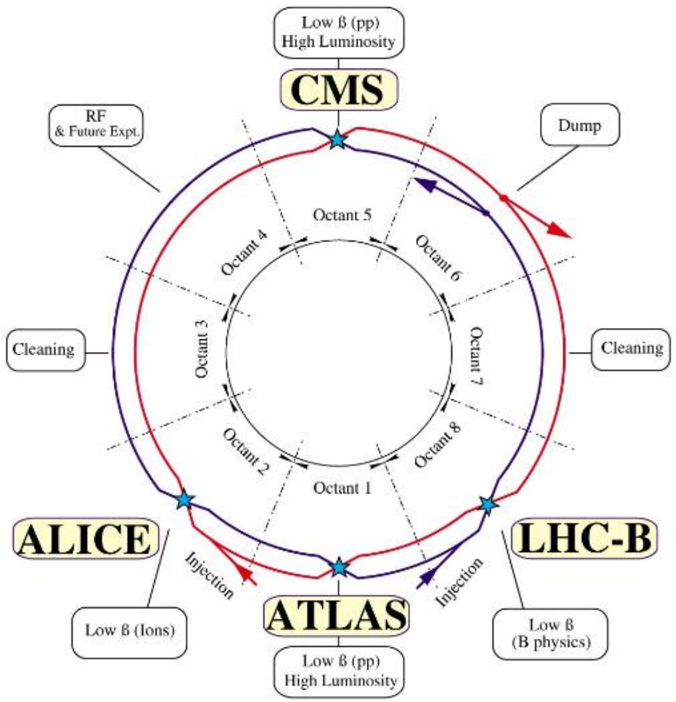


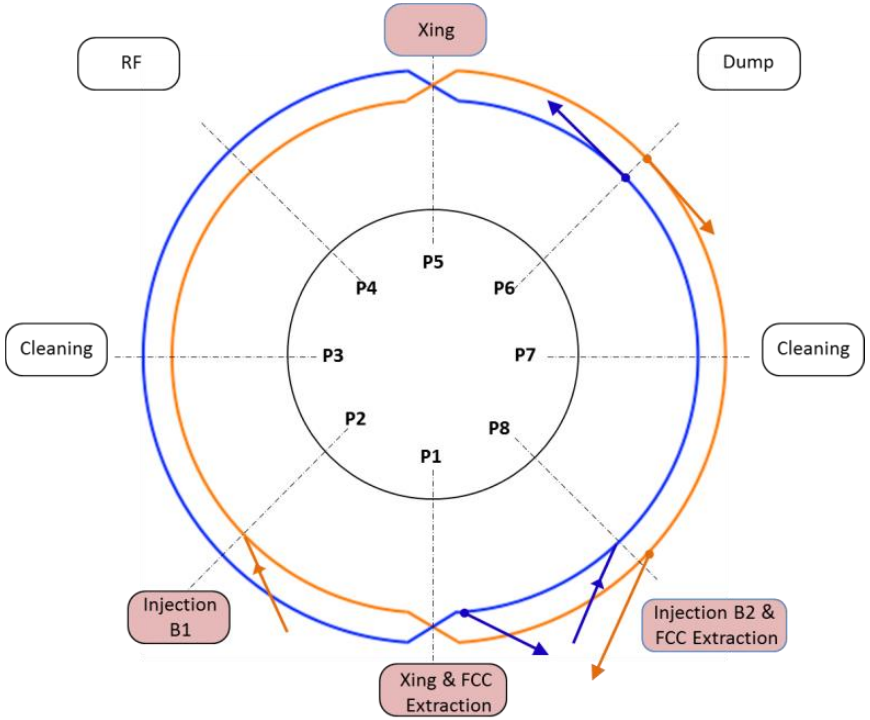
Figure 3: Main dipole current for 156 s LHC ramp-up with 50 A/s linear ramp rate (green).

Filling time

- Assuming to fill FCC with four LHC ramps
  - 300 PS cycles a 3.6 s
  - 32 SPS cycles a 10.8 s additional
  - 3.5 LHC cycles a 312 s additional
- **Total of 44 min to fill FCC**
  - 12.5 min for first cycle (Low and intermediate intensities injected for safety/injection validation)
  - 10.5 min for cycles 2-4
- Additional improvements
  - PSB basic period from 1.2 to 0.6 s
  - Single batch injection into PS
  - LHC ramp, speed up round and out, 60 s – 30 s
- Can reach ~8 min reduction of FCC filling time – at the expense of cost and performance

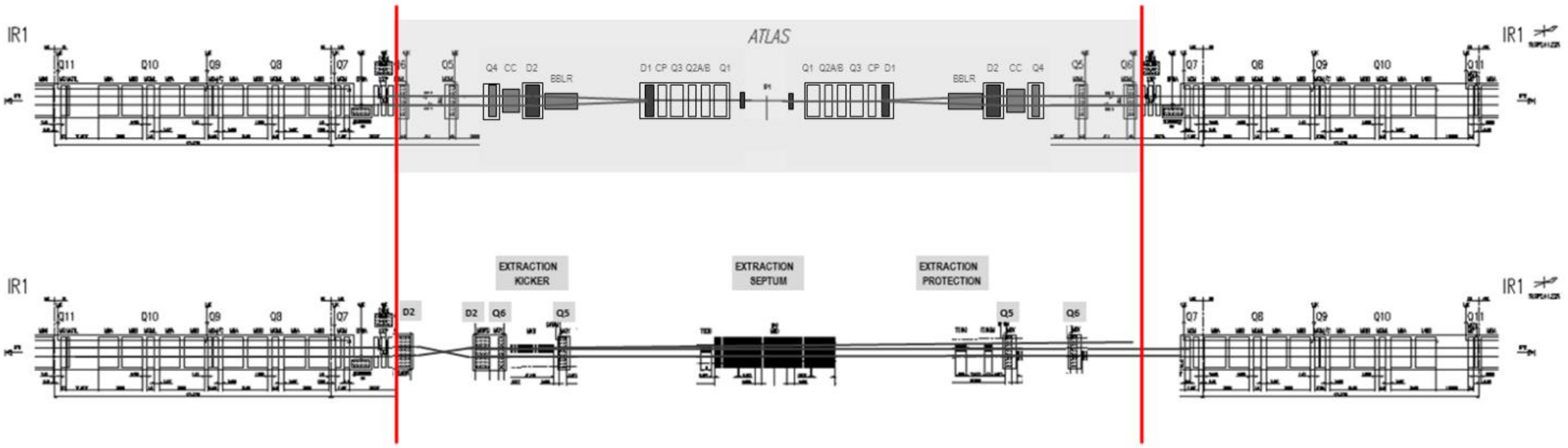
LSS modifications





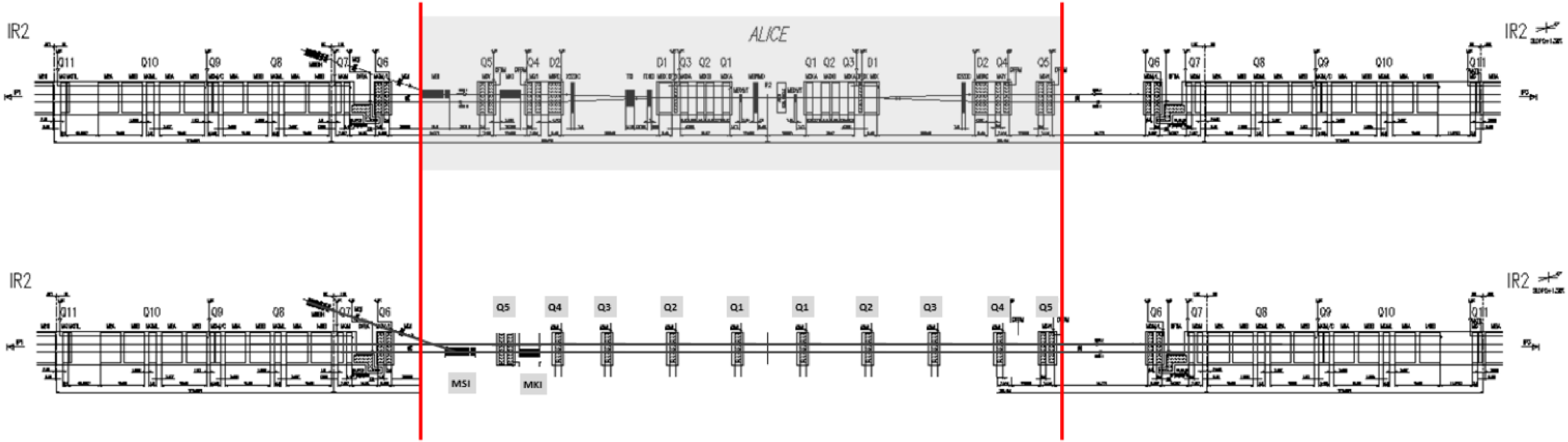
- Keep LSS3 (momentum collimation), LSS4 (RF), LSS6 (dump), LSS7 (betatron collimation)
- LSS modifications
  - LSS1 – Replace low beta insertion by anticlockwise extraction
  - LSS2 – Move injection to inner ring
  - LSS5 – Remove low beta insertion; can also envisage a new LHC experiment here
  - LSS8 – Move injection to inner ring, add clockwise extraction

LSS1



- Low beta insertion removed from Q6 inwards
- A new extraction channel combined with a new superconducting crossing
- Relatively long drift available

LSS2



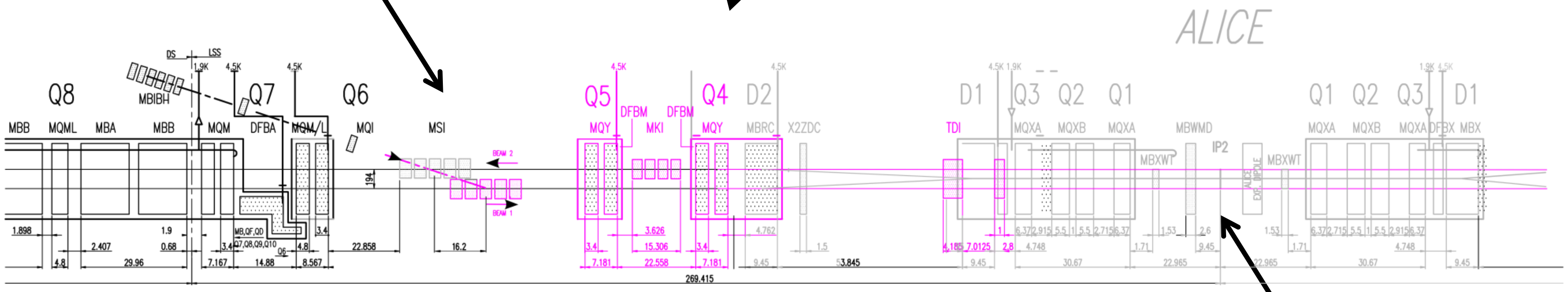
- Low beta insertion and crossing replaced from Q5 inwards by straightforward FODO
- Injection moved to inner ring and downstream

LSS2 Injection region modifications

Swap MSI onto inner beam and shift by 16.2 m

Shift Q5, MKI, Q4, (D2) by 16.2 m

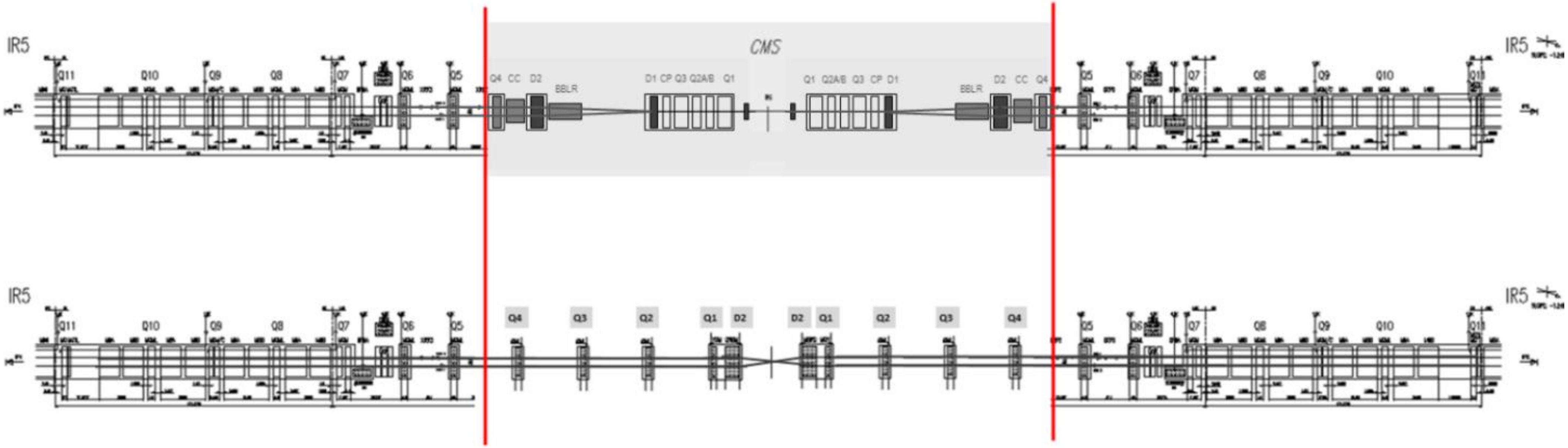
Replace elements between D2s (incl) with FODO



Swap TDI onto inner beam and shift (keep 90° phase advance wrt MKI)

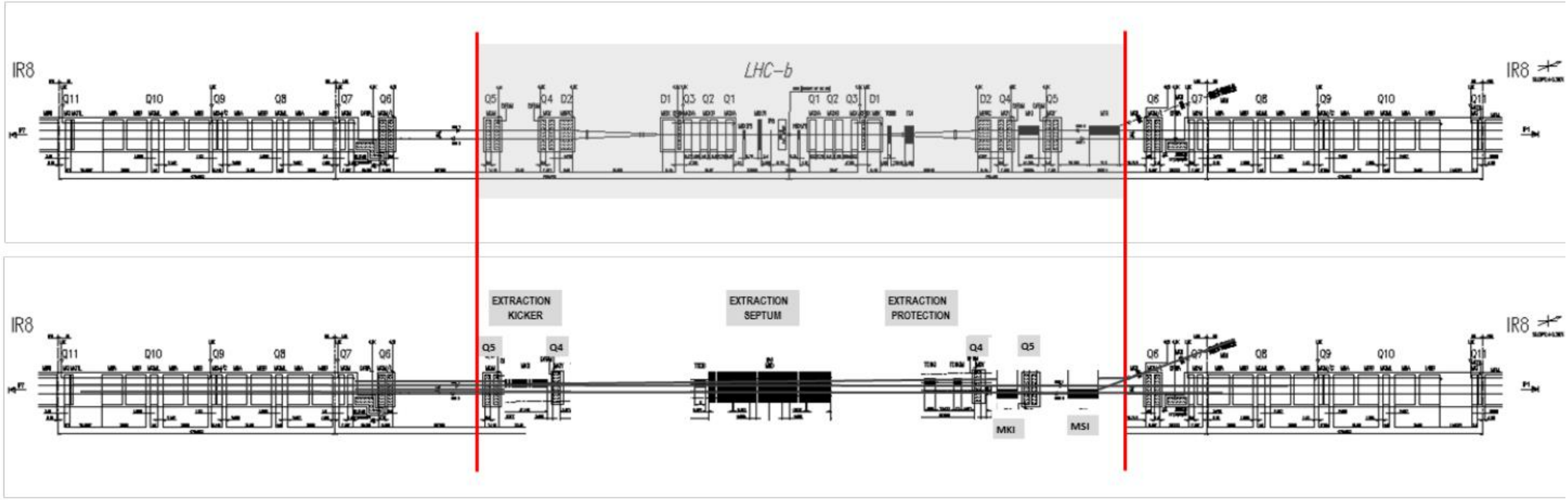
Common vacuum chamber replaced by separated one

LSS5



- Low beta insertion replaced from Q4 inwards by FODO
- Crossing scheme with superconducting crossing dipoles
- Possibility to design new experiment in this straight

LSS8

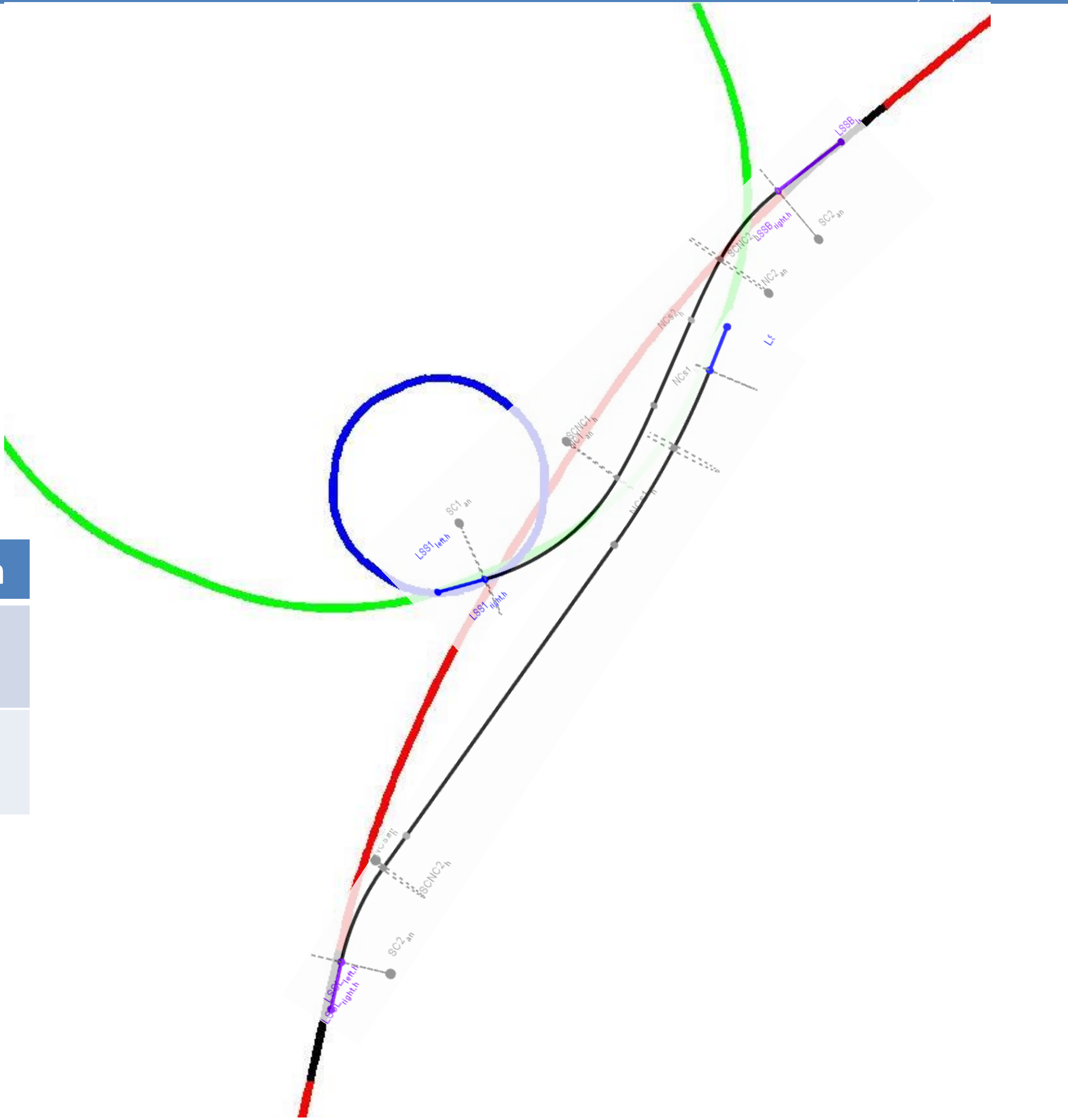


- Remove low beta insertion from Q5 inwards
- Move injection to inner ring as for LSS2 - shifts injection equipment 16.2 m further in direction present IP
- Extract beam from the outer ring
- Extraction can be squeezed next to injection assuming doubling of current through kicker switches c.f. present situation to reach 3.3 TeV
- Can reach up to 6.5 TeV assuming a factor 5 increase of current through switches

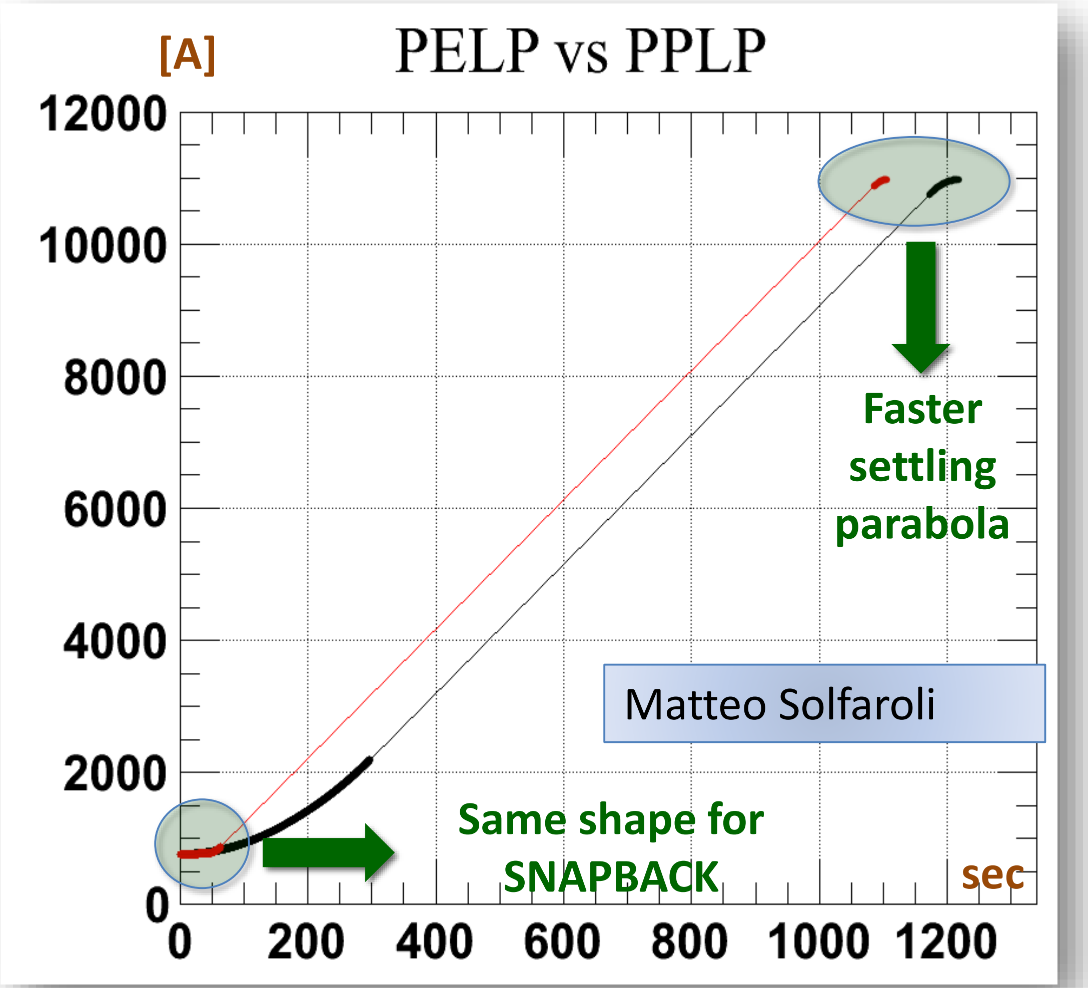
LHC to FCC transfer lines

- Extraction from P1 and P8 at 3.3 TeV

	SC (6T)	NC (2T)	Straight	Total length
LHC1 → B	2.4 km	1.4 km	0.9 km	4.7 km
LHC8 → L	1.1 km	2.4 km	3.6 km	7.1 km



LHC machine tests – faster ramp and 225 GeV injection



225 GeV injection:

- Crucial to understand the potential energy swing for the main bends and the control of chromaticity at low energy
- In particular for the scSPS as injector option with 1.3 TeV extraction energy limit
- All systems (magnets, PC, BI, RF,…) have been discussed and no showstopper identified
- Heavy impact on interlocking systems – might be scheduled at the end of a run

Conclusions

- Aim at 3.3 TeV extraction energy and 40 min filling time with 4 ramps - requires 5 x faster ramping
- Maximum ramp rate of 50 A/s dictated by main dipole diodes and induced voltage on the string; main 13 kA power converters require upgrades to follow the increase of inductive voltage
  - No limitations expected from RF, cryogenics, quenches and quench detection
- Decommission LHC experiments and low beta insertions
- Add two extraction systems in IR1 and IR8 to transfer to FCC
  - Requires new kicker systems for staggered transfer
- Keep RF, collimation and beam dumps as they are
- 11.8 km lines, of which 3.5 km superconducting
- LHC is demanding and expensive to operate and maintain in comparison to dedicated injector options