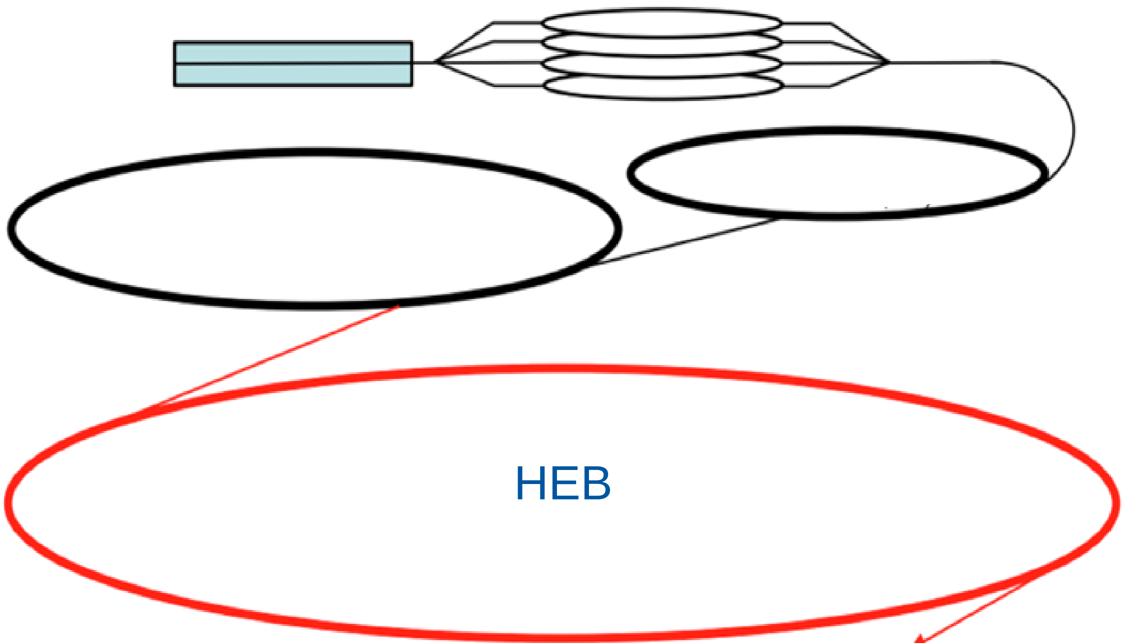
CERN

FCC-hh injector design



Jan Borburgh
CERN TE/ABT

On behalf of W. Bartmann, B. Goddard

Overview

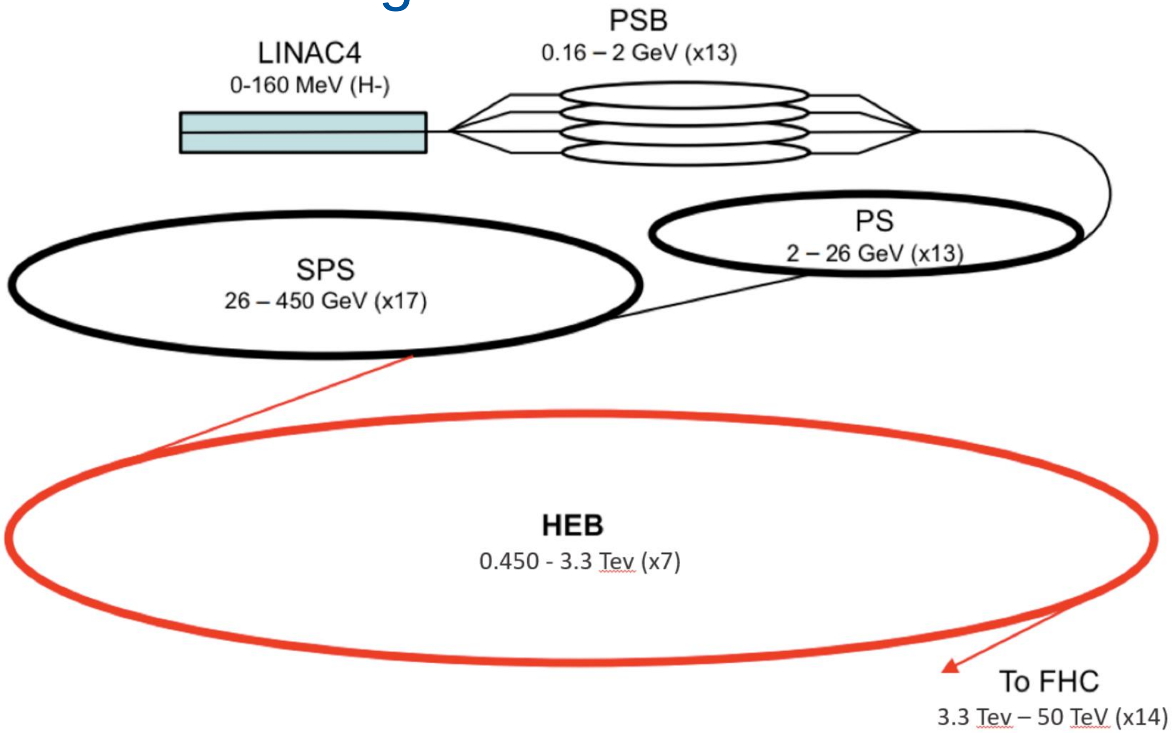
- Requirements and constraints
- HEB options
  - Reuse of LHC for 3.3 TeV HEB
  - Alternative 3.3 TeV options
  - 1.3 TeV s.c. SPS alternative
  - Performance comparison summary
- How to proceed
- Summary and outlook

High Energy Booster (HEB) requirements

- Inject at 3.3 TeV,
  - 1.3 TeV has been studied as low-energy option, but presently excluded by FCC-hh collider.
- Deliver required beam parameters:
  - Intensity, emittance, spacing.
- Fill FCC-hh as quickly as possible,
  - Target 30 minutes (LHC experience shows that this is reasonable).

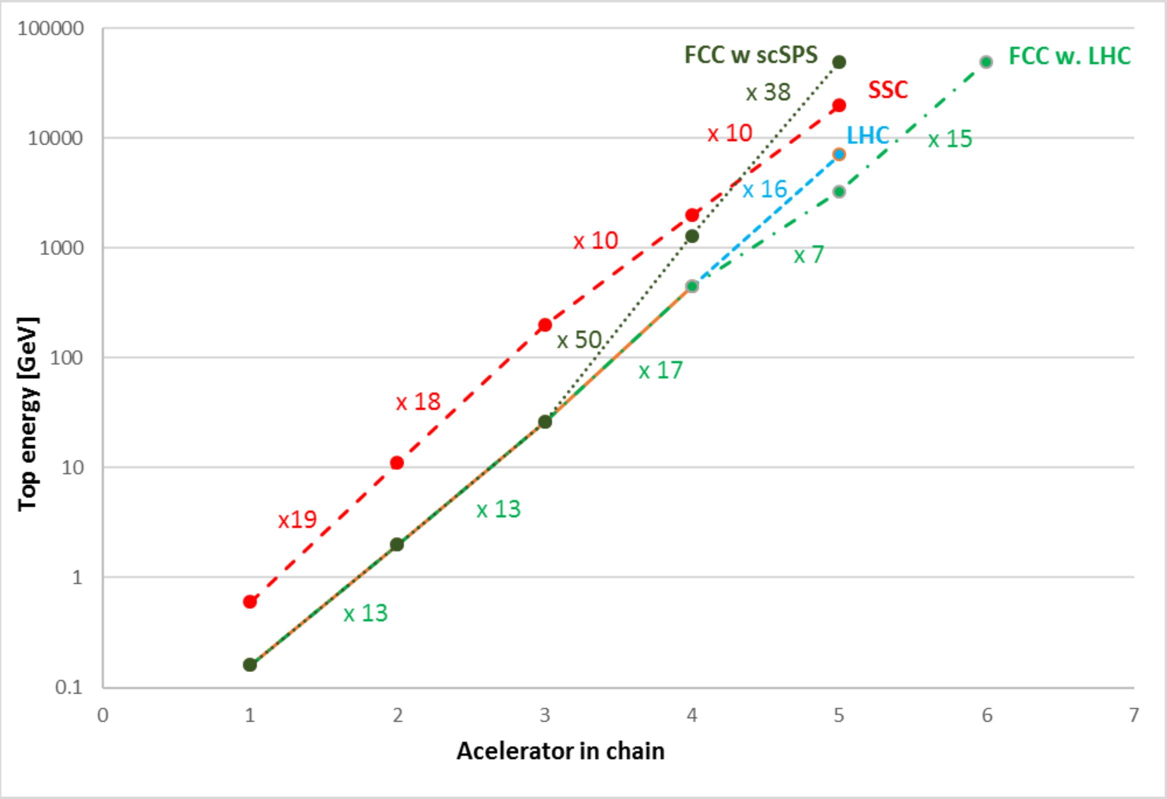
Constraints and options considered

- Re-use existing CERN proton complex as far as possible:
  - Assume post HL-LHC performance,
  - Keep the main project effort focused on the 100 km collider(s).
- Options studied based on existing tunnels:
  - SPS: 6.9 km
  - LHC: 26.7 km
  - FCC: 100 km



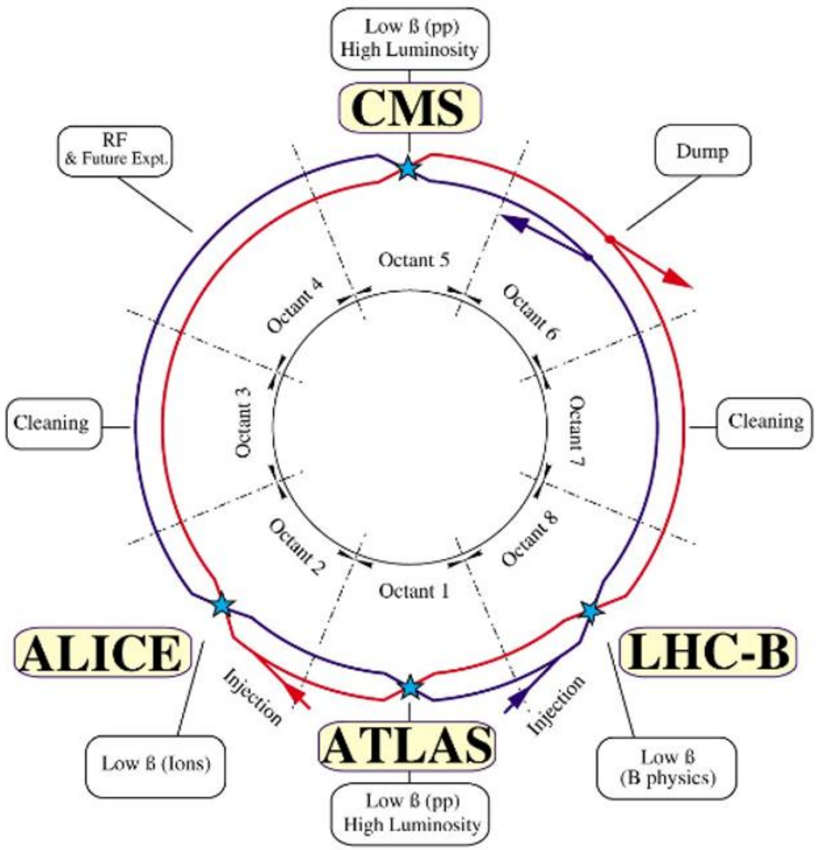
Injector chain in context

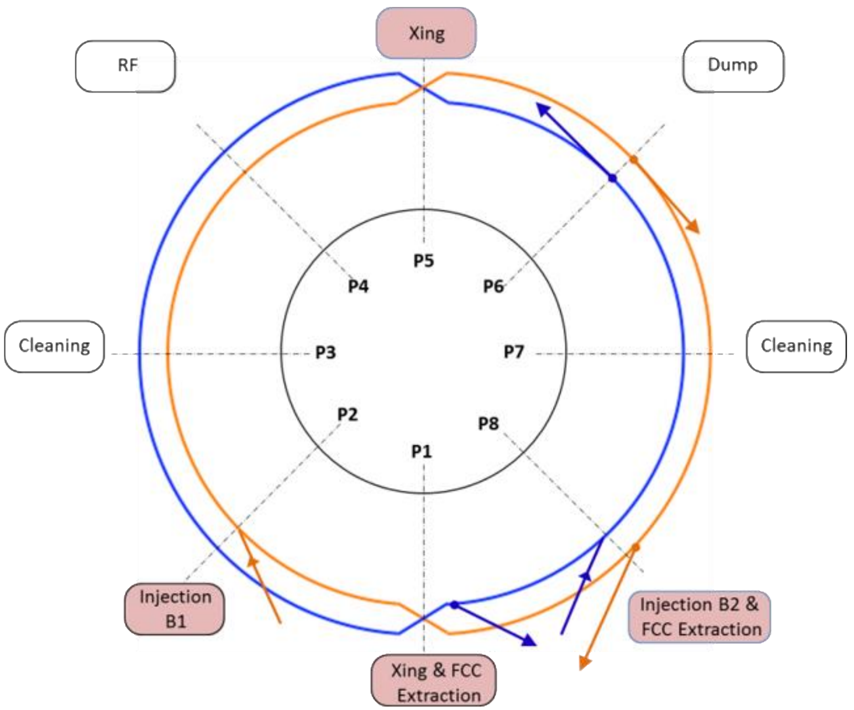
- Regular progression in energy gain per step (~x15) in existing accelerator complex.
- New HEB only modest energy gain (~x7).
- If s.c. SPS is used, energy gains would become large for HEB and FCC.



Baseline: reuse of LHC as 3.3 TeV HEB

Reuse of LHC: general layout changes

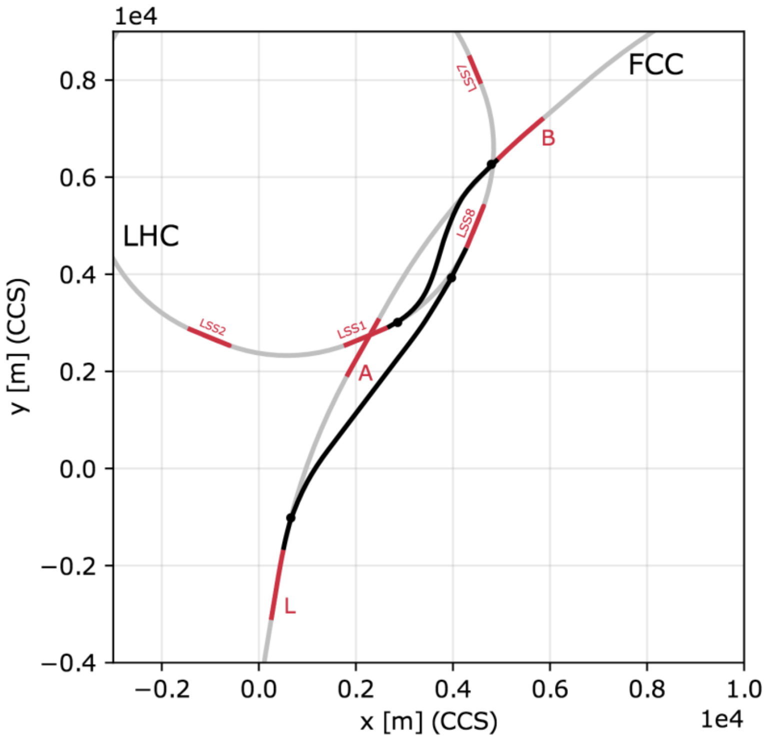




Reuse of LHC as 3.3 TeV HEB

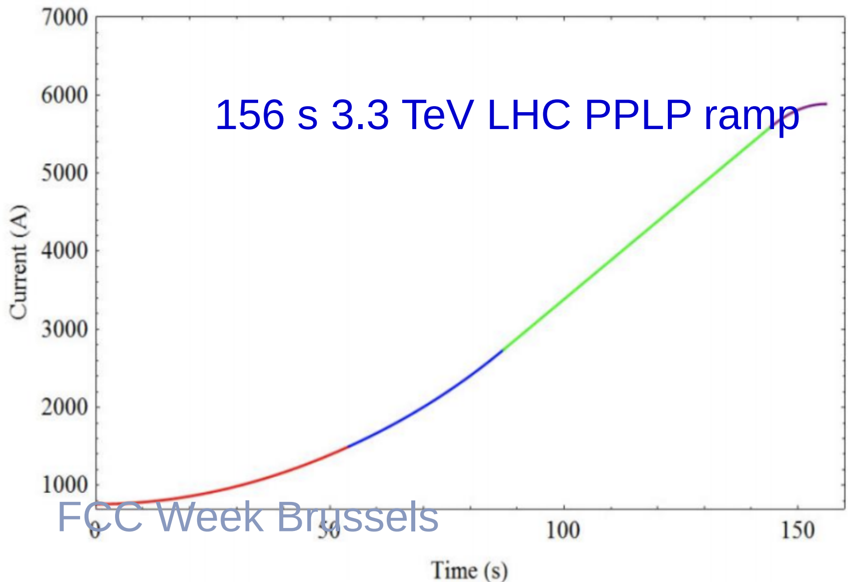
- LHC Straight sections:
  - IR1: **new extraction** system and **beam crossing,** plus **decommissioning** af ATLAS
  - IR2: **injection to inside ring** plus **decommissioning** of ALICE and crossing
  - IR3: **no changes** to momentum collimation
  - IR4: **no changes** to RF system
  - IR5: **decommissioning** of CMS, plus **beam crossing**
  - IR6: **no changes** to beam dump
  - IR7: **no changes** to betatron collimation
  - IR8: **injection to inside ring** plus **new extraction** plus **decommissioning** of LHCb and crossing

- Transfer from LHC P1 and P8 (11.7 km with 7 T dipoles)



3.3 TeV LHC performance: faster ramping

- Present LHC ramp up to 3.3 TeV would take 8′30″, total FCC filling time >1.5 hours.
- With dipole/quadrupole power converter upgrades and a ramp at 50 A/s, 3.3 TeV ramp takes 156 sec.
- PPLP scheme instead of PELP essential to fully profit from increased ramp rate (tested in 2017, used in LHC in 2018).
- Time to ramp down from 3.3 TeV driven by one-quadrant main quadrupole power converters. With upgrade, ramp down time shortened to 100 s.
- Overall FCC filling time (on paper) is then 46 minutes, for 4 LHC fills and ramps.



Alternative 3.3 TeV HEB options

100 km superferric HEB

- 3.3 TeV superferric 100 km HEB in FCC-hh tunnel

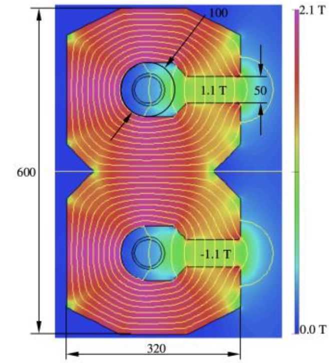
Features

- 1.1 T dipoles (for 70% filling factor)
- Single aperture + polarity reversal, or simple twin aperture →
- Impedance and stability at injection energy → could require magnet vertical gap ~80 mm
- Needs to be superferric: 50 kA SC cable (100 MW peak power if resistive)
- Ramp-up time 120 s (limited by RF)
- FCC filling in 32 minutes (injectors)

Critical points

- By-pass tunnels around 4 experiments - ∫15 km (FCC-ee)
- Very high stored energy of 670 MJ
- Issue of beam loss du to cross-talk between HEB and FCC-hh? (collimation, slow extraction)
- Integration into FCC tunnel still to demonstrate

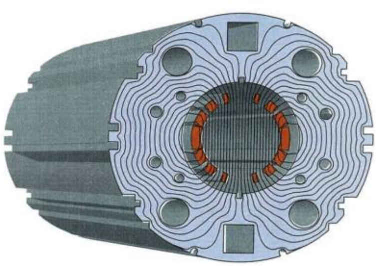
Vertical full gap [mm]	2 × 50
Good field region on midplane [mm]	±20
Pole width [mm]	100
Inter-beam distance [mm]	300
Outer diameter of cable cryostat [mm]	100
Overall dimensions [mm]	320 × 600
Iron weight per unit length [t/m]	1.2
Injection energy [TeV]	0.450
Injection field [T]	0.14
Current at injection energy [kA]	6.5
Extraction energy [TeV]	3.4
Extraction field [T]	1.1
Current at extraction energy [kA]	50



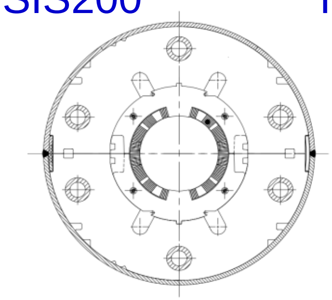
27 km, 4 T, s.c. LHC replacement

- 3.3 TeV superconducting 26.7 km HEB in LHC tunnel
  - Dedicated HEB: more suitable than re-purposed LHC.
  - More robust, less complex magnets will be used:
    - 4 T dipoles (4 K cos θ – RHIC, Tevatron, FAIR SIS200/300)
    - Single aperture needs polarity reversal, to avoid very long transfer lines, otherwise twin aperture (cost/complexity…)
  - Simplified LHC lattice, with insertions as per reused-LHC
  - Ramp-up time about 50 s (limited by RF system)
  - FCC filling time about 39 minutes (injectors)

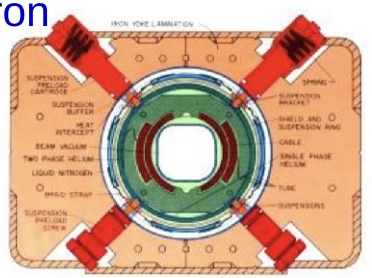
RHIC



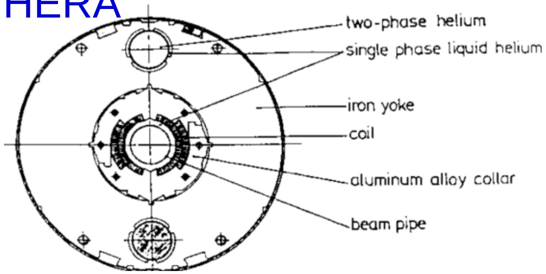
SIS200



Tevatron



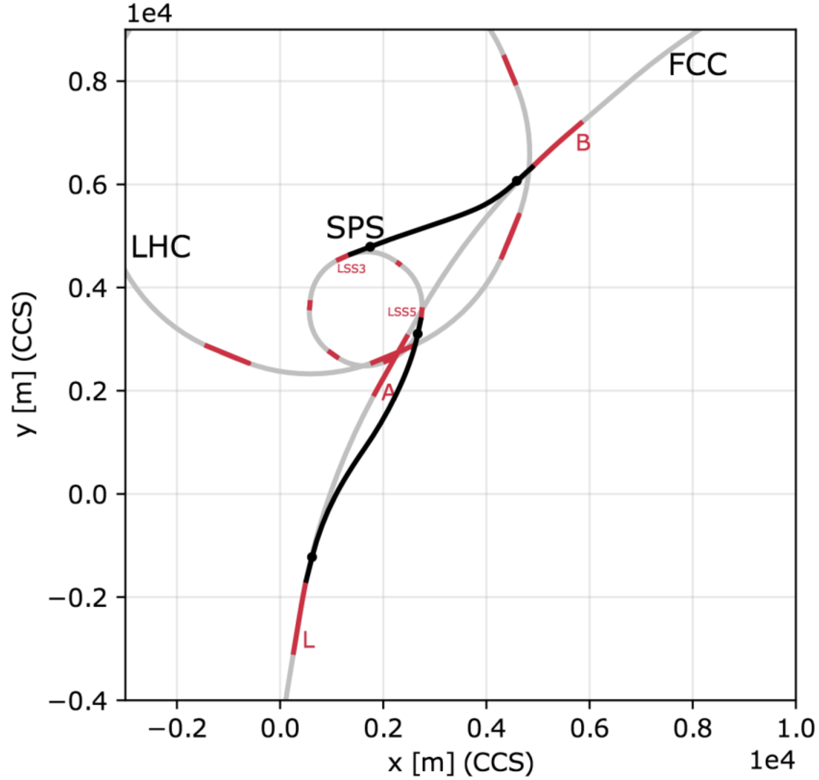
HERA



1.3 TeV scSPS alternative

1.3 TeV s.c. SPS as HEB

- Transfer from SPS P3 and P5 (10 km @ 1.8 T)
- s.c. SPS Straight sections:
  - LSS1: injection system
  - LSS2: slow extraction system to North Area
  - LSS3: fast extraction to FCC
  - LSS4: RF system
  - LSS5: fast extraction to FCC
  - LSS6: beam dump and collimation systems



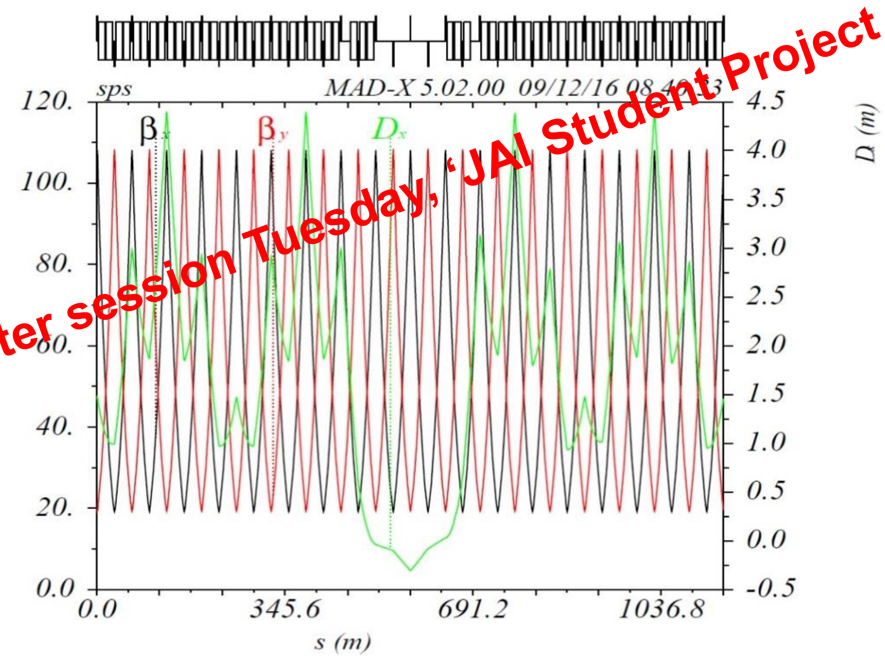
Florian Burkart et al.

1.3 TeV scSPS optics

Linear optics design based on present SPS concept

- 64 m cell length, missing magnet Dispersion Surpressor, 12 m, 6 T dipoles

Parameter	Unit	Value
Injection energy	GeV	26
Extraction energy	GeV	1300
Maximum dipole field	T	6
Dipole field at injection	T	0.12
Dipole magnet length	m	12.12
Cold bore inner diameter	mm	80
Number of dipoles		372
Number of quadrupoles		216
Ramp rate	T/s	0.35 - 0.5
Cycle length	min	1
Number of bunches per cycle		640
Number of injections into scSPS		8 (80b)
Number of protons per bunches		$\leq 2.5 \times 10^{11}$
Number of extraction per cycle		2 (2x320 b)
Number of cycles per FCC filling		34
FCC filling time	min	34 - 40
Max stored beam energy	MJ	33



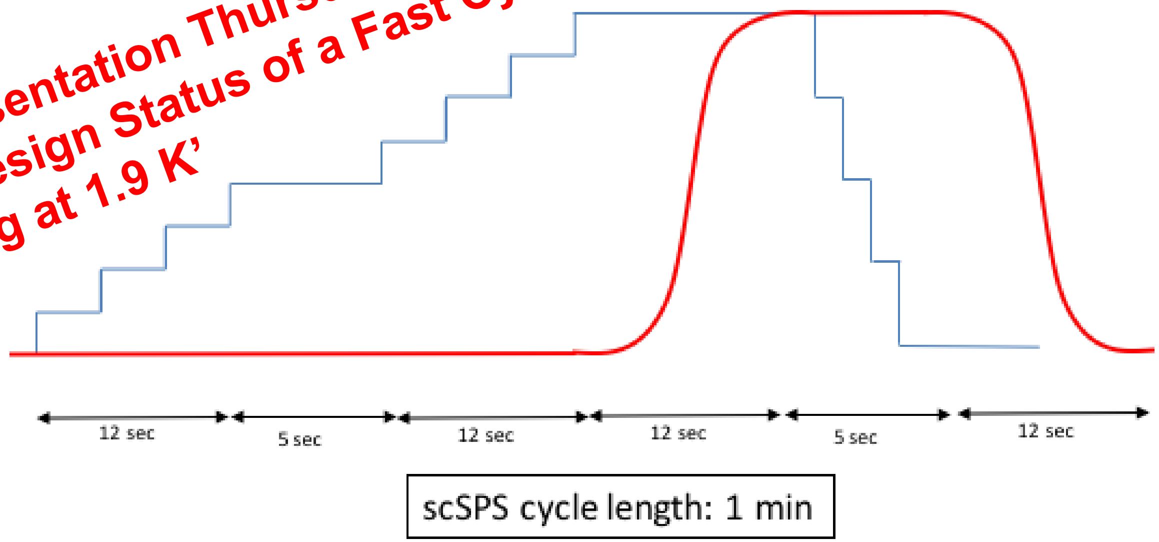
Please see Poster session Tuesday, 'JAI Student Project on scSPS)'

1.3 TeV s.c. SPS performance

- Dipole ramp rate ~0.5 T/s, 12 s ramp
  - 37 minutes on paper to fill FCC, with 34 cycles of the scSPS
  - Aperture dimensioned for slow extracted fixed-target beam
  - x 50 energy swing to validate

Please see Presentation Thursday 16:42 hrs, by Alexander Kovalenko, 'Design Status of a Fast Cycled Low Loss 6 T Model Dipole Cooling at 1.9 K'

Parameter	Unit	Value
Max. beta $\beta_{x,z}$	m	107
Max. dispersion D_x	m	4.3
Orbit + alignment tolerance [illegible]	mm	2.5
Injection oscillation	mm	1.5
Emittance $E_{x,y}$ (1 σ, norm)	m	2.2E-6
$\delta p/p$		5E-4
A_x / A_y	mm	76 / 69
Coldbore inner diameter	mm	80



Overall performance comparison

Parameter	Unit	6 T scSPS	reuse LHC	new 4 T LHC	1 T 100 km
Circumference	km	6.9	26.7	26.7	100
Apertures		1	2	1	2
Injection energy	GeV	26	450	450	450
Extraction energy	TeV	1.3	3.3	3.3	3.3
Injection field	T	0.12	0.6	0.6	0.14
Maximum field	T	6	4	4	1.1
Energy/field swing factor		50	7	7	7
Individual dipole length	m	12	14.3	14.3	8
Overall dipole filling factor		0.65	0.66	0.66	0.63
Number of dipoles		372	1232	1232	7856
Number of quads		216	480	480	1250
Total HEB bunches		640	2600	2'600	11'000
Stored HEB energy per beam	MJ	15	167	167	670
HEB filling time	min	0.5	7.5	3.8	30.1
HEB ramp rate	T/s	0.4	0.026	0.08*	0.011*
Total HEB cycle length	minutes	1.1	12	4.9	32
HEB cycles per FCC fill		34	4	8	2
FCC filling time (25 ns)	minutes	37	46	39	32

How to proceed

- A consensus needs to be found how to proceed over the next ~5 years, aiming for a HEB TDR.
  - Assume s.c. SPS and 100 km variant not further pursued.
  - Study in further details repurposing LHC or 4T 27 km HEB.
- Topics to be worked out:
  - Decision point: which variant to be retained (LHC vs. 4T HEB).
  - Power converters, quench protection, magnet design and other all hardware.
  - Beam transfer, transfer lines and civil engineering.
- Resource needs over 5 year period:
  - 1 fte Fellow with electrical engineering background,
  - 1-2 fte Fellows with physics background.

Summary and outlook

- Reuse of existing LHC with 5x faster ramp remains FCC-hh baseline.
  - Can deliver 3.3 TeV beam, albeit with longer filling time than desired.
  - To take into consideration:
    - high operating cost and complexity,
    - availability concerns.
- 4 T, 27 km, purposed built single aperture HEB alternative would have advantages:
  - Less complex machine.
  - Slightly faster filling time (39 minutes).
- To reach decision point on how to proceed → Costing is needed for real comparison of both options.
- scSPS option only valid if 1.3 TeV FCC injection is possible:
  - Presently excluded by FCC –hh collider because of dynamic aperture and the large energy swing may be an issue.
  - Still of interest for HE-LHC.

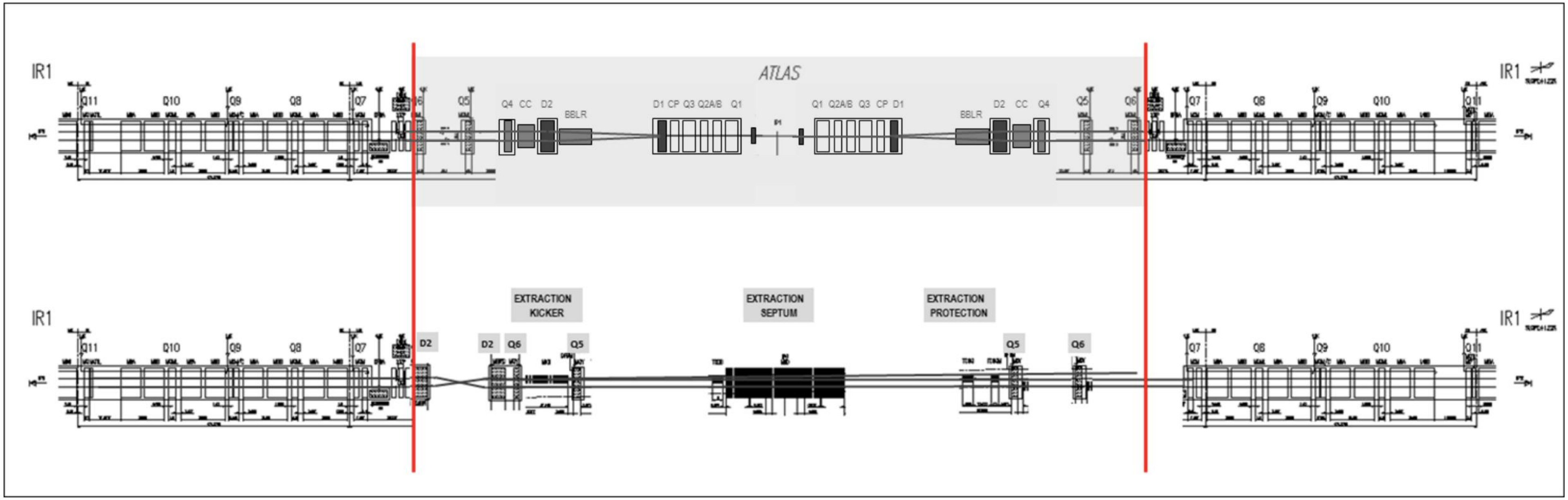
Bibliography

1) *FCC-hh injectors: scenarios, B. Goddard, FCC week 2018*
2) *Faster ramping of LHC in 2017 and prospects for lower energy injection into LHC in 2018, A. Milanese, FCC week 2018*
3) *The superconducting Super Proton Synchrotron, ed. L. Dyks et al, FCC note being published*
4) *High Energy Booster options for a Future Circular Collider at CERN*, L.Stoel et al., IPAC2016-MOPOY007
5) *Possible reuse of the LHC as a 3.3 TeV High Energy Booster for hadron injection into the FCC-hh*, B.Goddard et al., IPAC2015-THPF094
6) *Beam transfer to the FCC-hh collider from a 3.3 TeV Booster in the LHC tunnel*, W.Bartmann et al., IPAC2015-THPF089
7) *Faster ramp of LHC for use as an FCC High Energy hadron Booster*, A.Milanese et al., CERN-ACC-2015-0133
8) *Main changes to LHC layout for reuse as FCC-hh High Energy Booster*, B.Goddard et al., CERN-ACC-2015-0030
9) *Physics opportunities with the FCC-hh Injectors*, B.Goddard et al., arXiv:1706.07667-2017
10) *Concept of a hybrid (normal and superconducting) bending magnet based on iron magnetization for 80-100 km lepton/hadron colliders*, A.Milanese, IPAC2014-TUOCB01

Back up slides

LHC straight section layouts

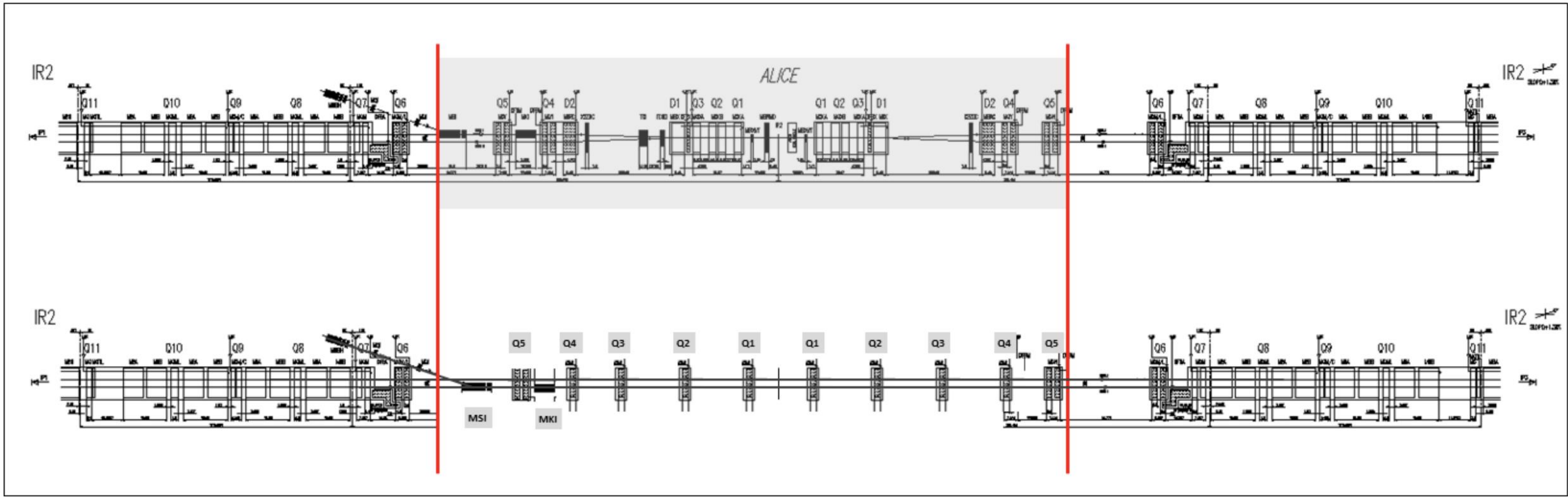
- Layouts of modified LHC straight sections: **IR1**



- Low beta insertion removed from Q6; new extraction channel combined with a new superconducting crossing

LHC straight section layouts

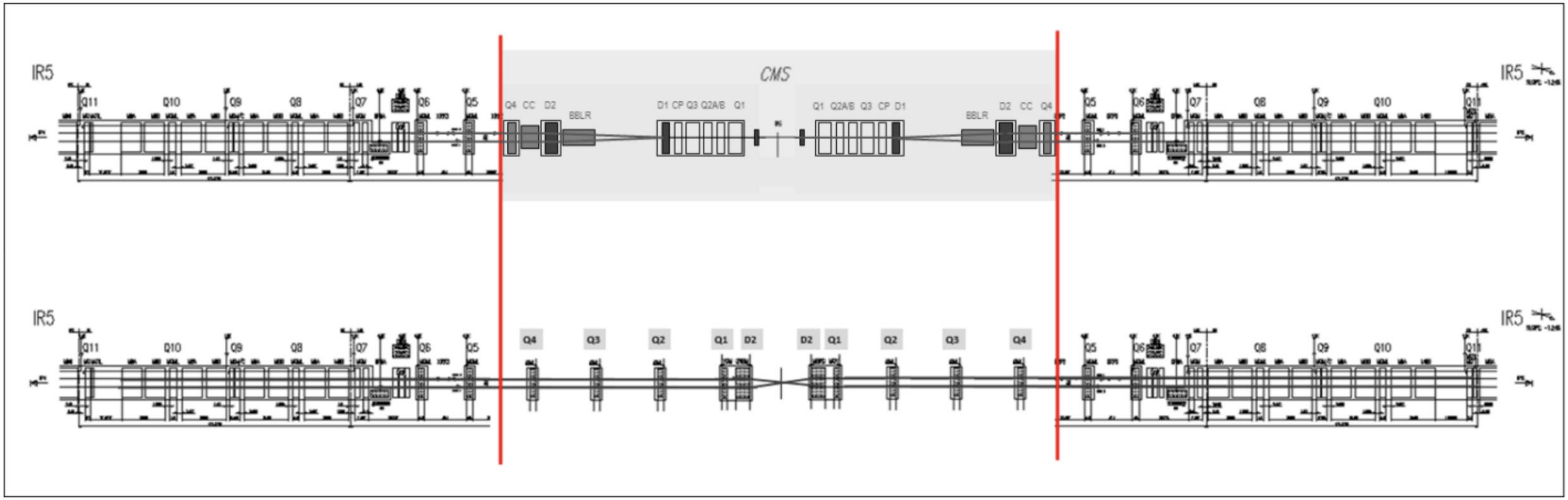
- Layouts of modified LHC straight sections: **IR2**



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

LHC straight section layouts

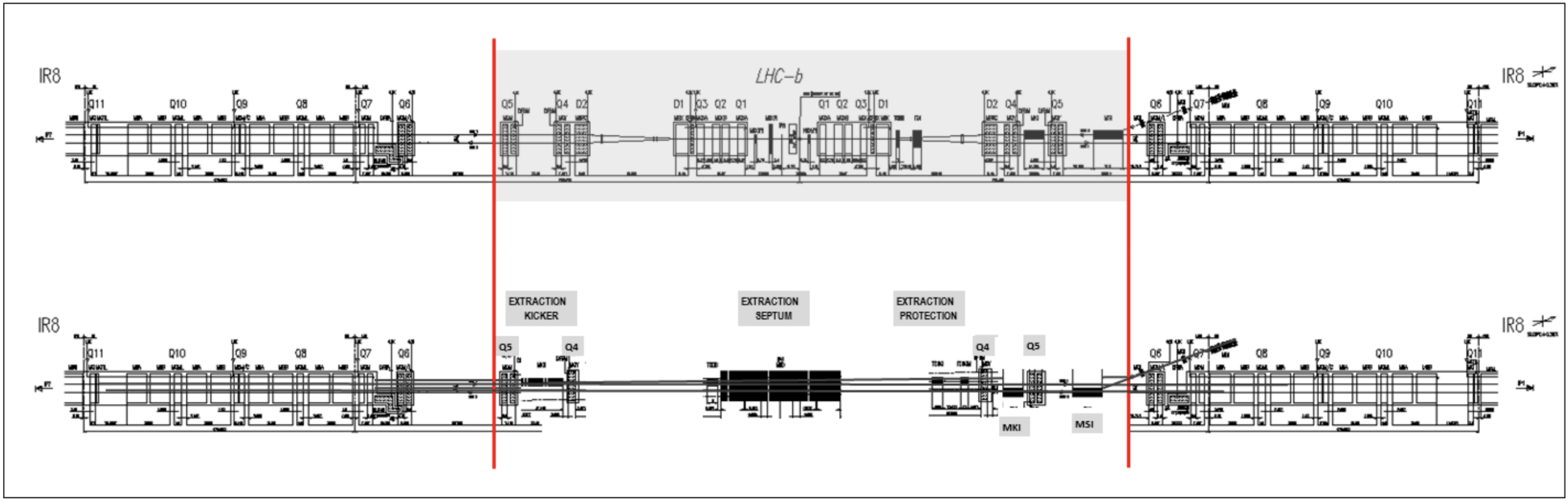
- Layouts of modified LHC straight sections: **IR5**



- Low beta insertion replaced from Q4 inwards by FODO; crossing with superconducting dipoles; possibility for (collider) experiment

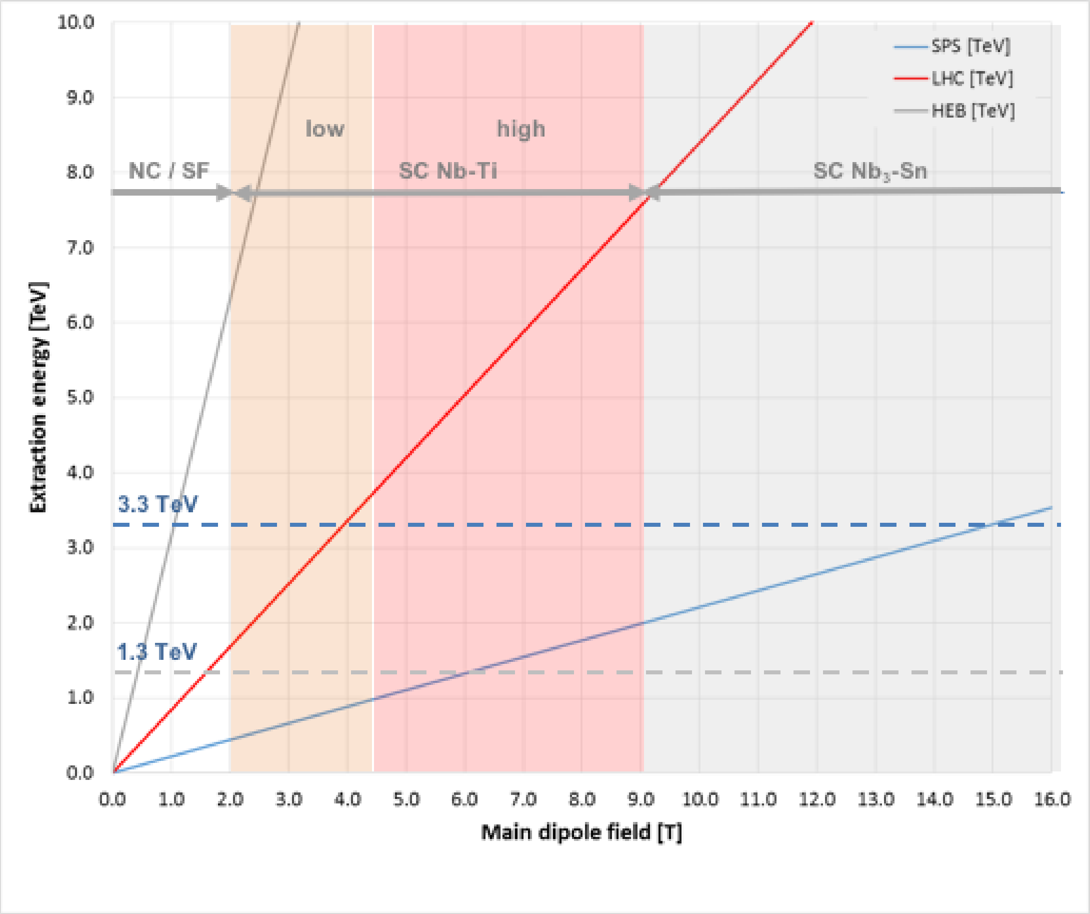
LHC straight section layouts

- Layouts of modified LHC straight sections: **IR8**

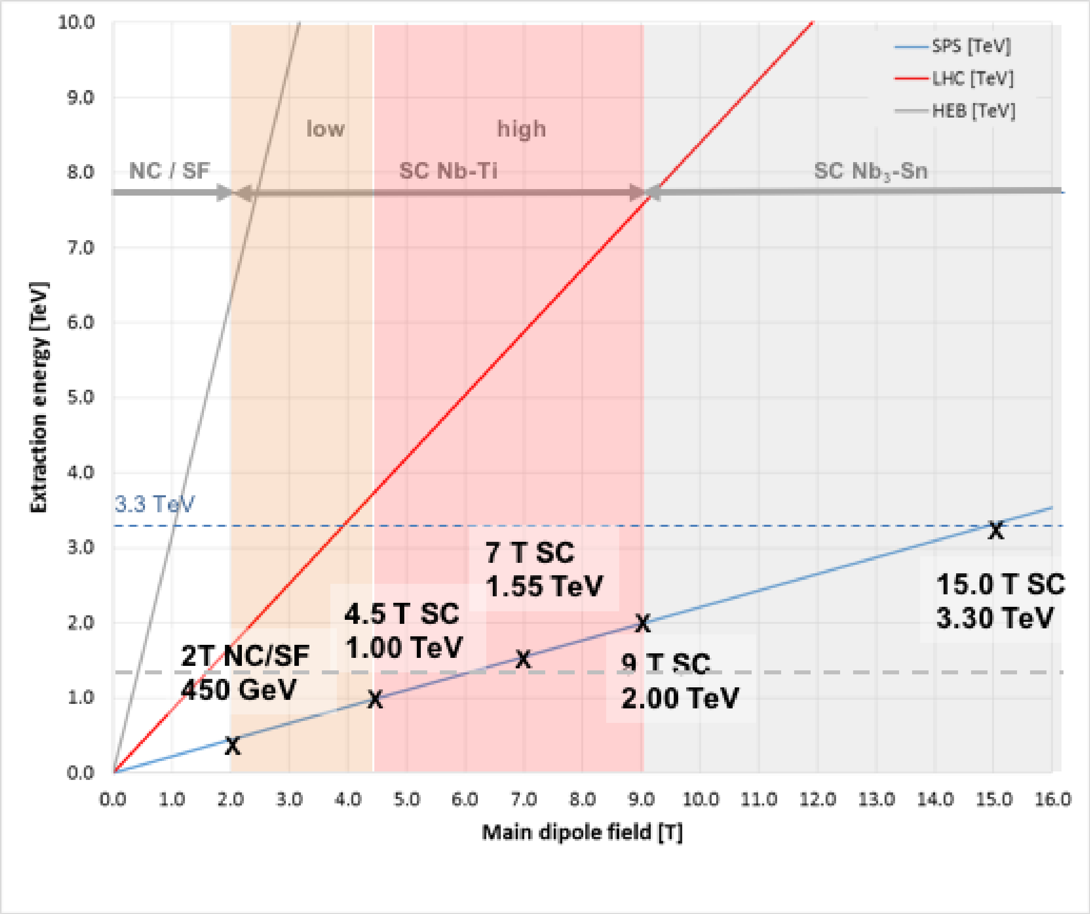


- Remove low beta insertion from Q5 inwards; move injection to inner ring; extract beam from outer ring

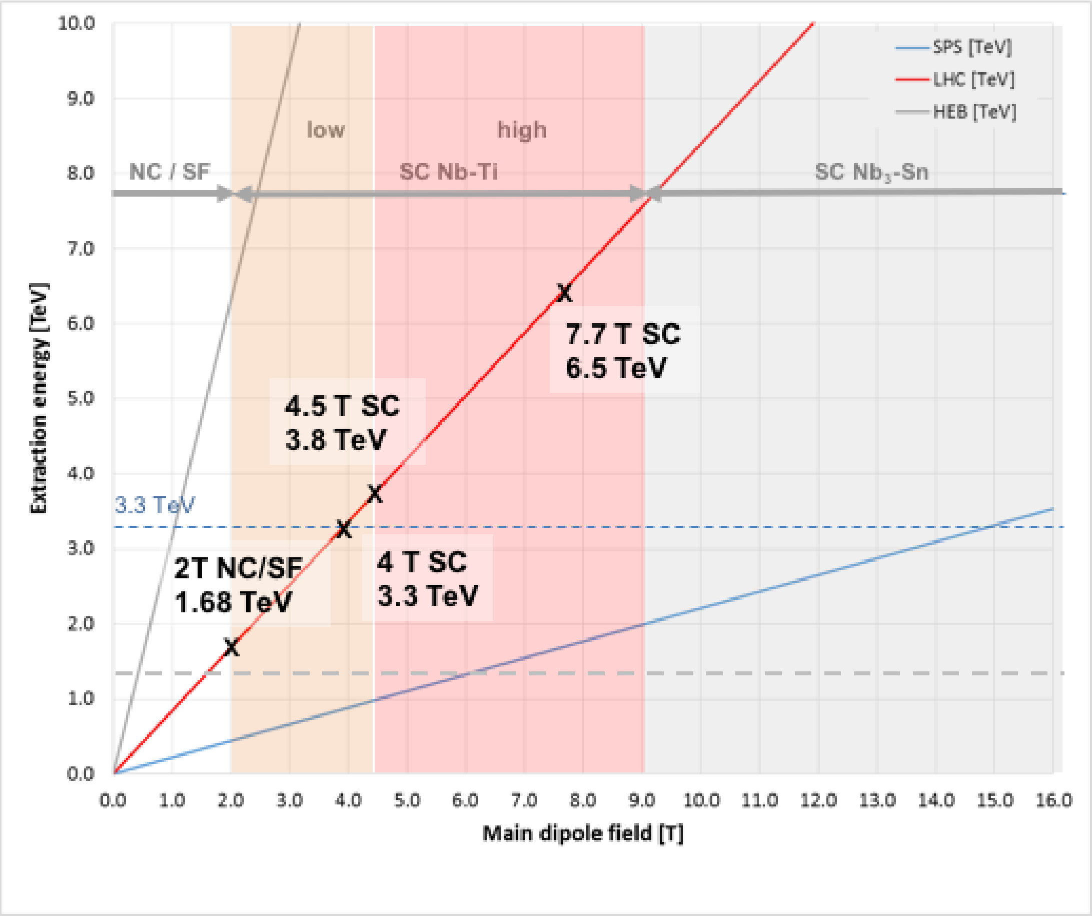
HEB options at CERN: energy vs field



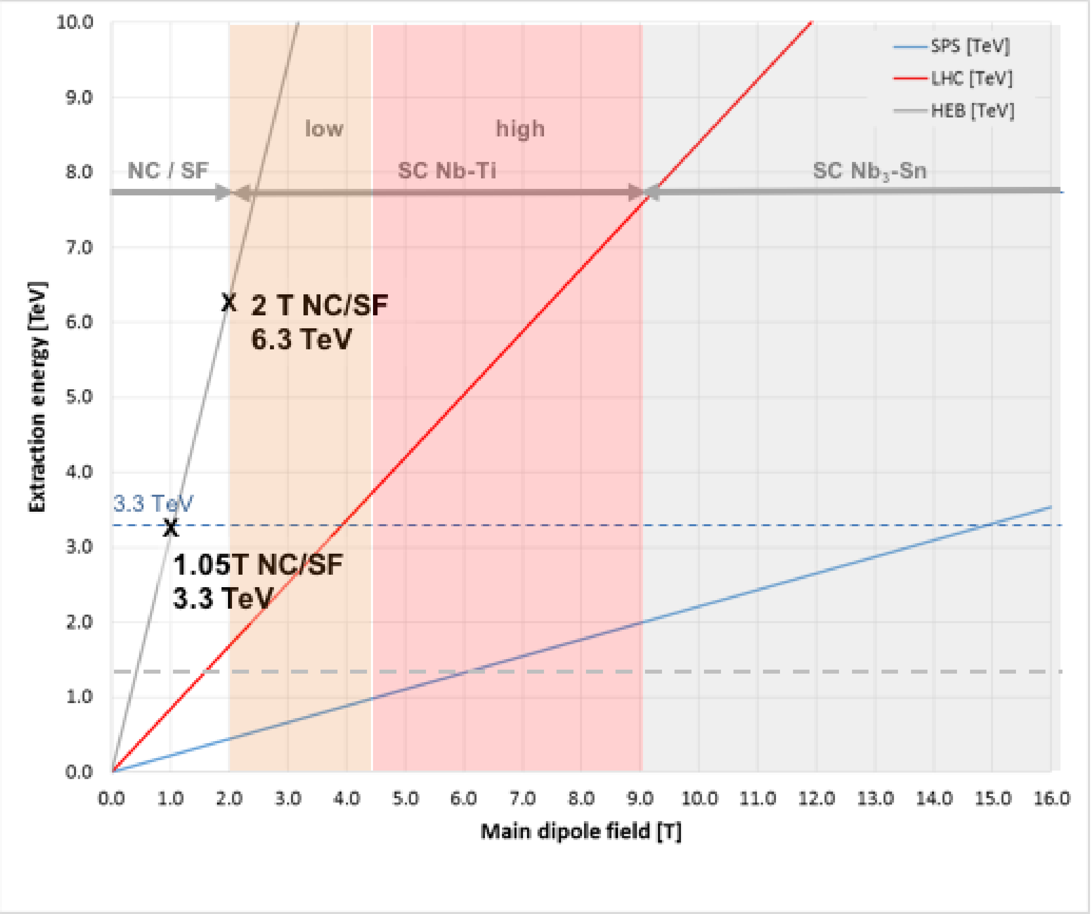
HEB options at CERN: SPS tunnel



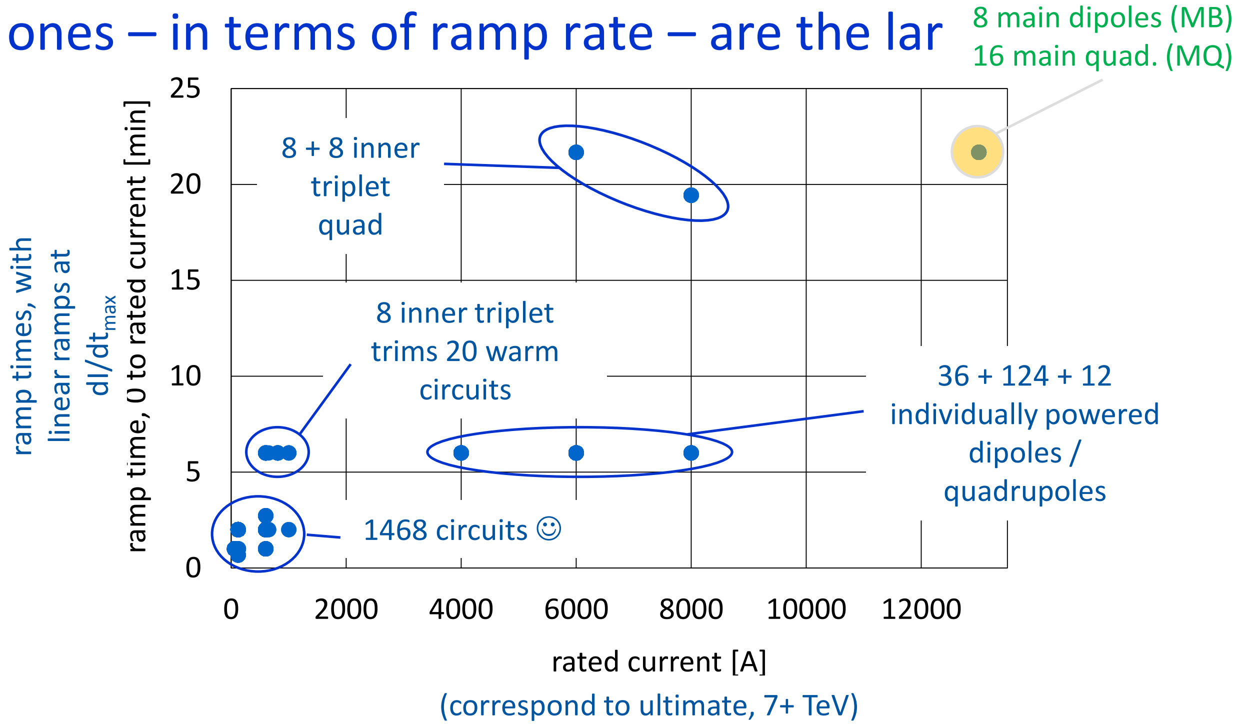
HEB options at CERN: LHC tunnel



HEB options: FCC collider tunnel



A ramp in the LHC involves 1700+ electrical circuits: the limiting ones – in terms of ramp rate – are the lar



data from electrical layout database