Injection and extraction systems

B.Goddard

Acknowledgements to W.Bartmann, M.Benedikt, A.Koschik, M.Giovannozzi, M.Gyr, M.Barnes, A.Fowler, J.Borburgh,

PS2 study team, BT group

and many others

Injection and extraction systems

- Introduction
  - Required injection and extraction systems
- Specifics of individual systems
  - Fast injection
  - H- injection
    - Details of some issues and concerns
  - Fast extraction
  - 1/3rd integer extraction
  - Multi-turn extraction
- Fitting together in injection/extraction straight
- Key system parameters and issues
- Conclusion

Injection and extraction requirements

- Fast injection (1.3 GeV Pb^{54+} ions and 4 GeV p^+) from LEIR and PS
- H^- charge exchange injection (4 GeV H^-) from SPL
- Fast extraction (20 – 50 GeV p^+ / Pb^{54+}) for LHC beam to SPS and for PS2 EAs
- 5-turn low-loss island extraction (20 – 50 GeV p^+) for CNGS-type beam to SPS
- Slow (1/3rd integer) extraction (20 – 50 GeV p^+ / Pb^{54+}) for PS2 EAs

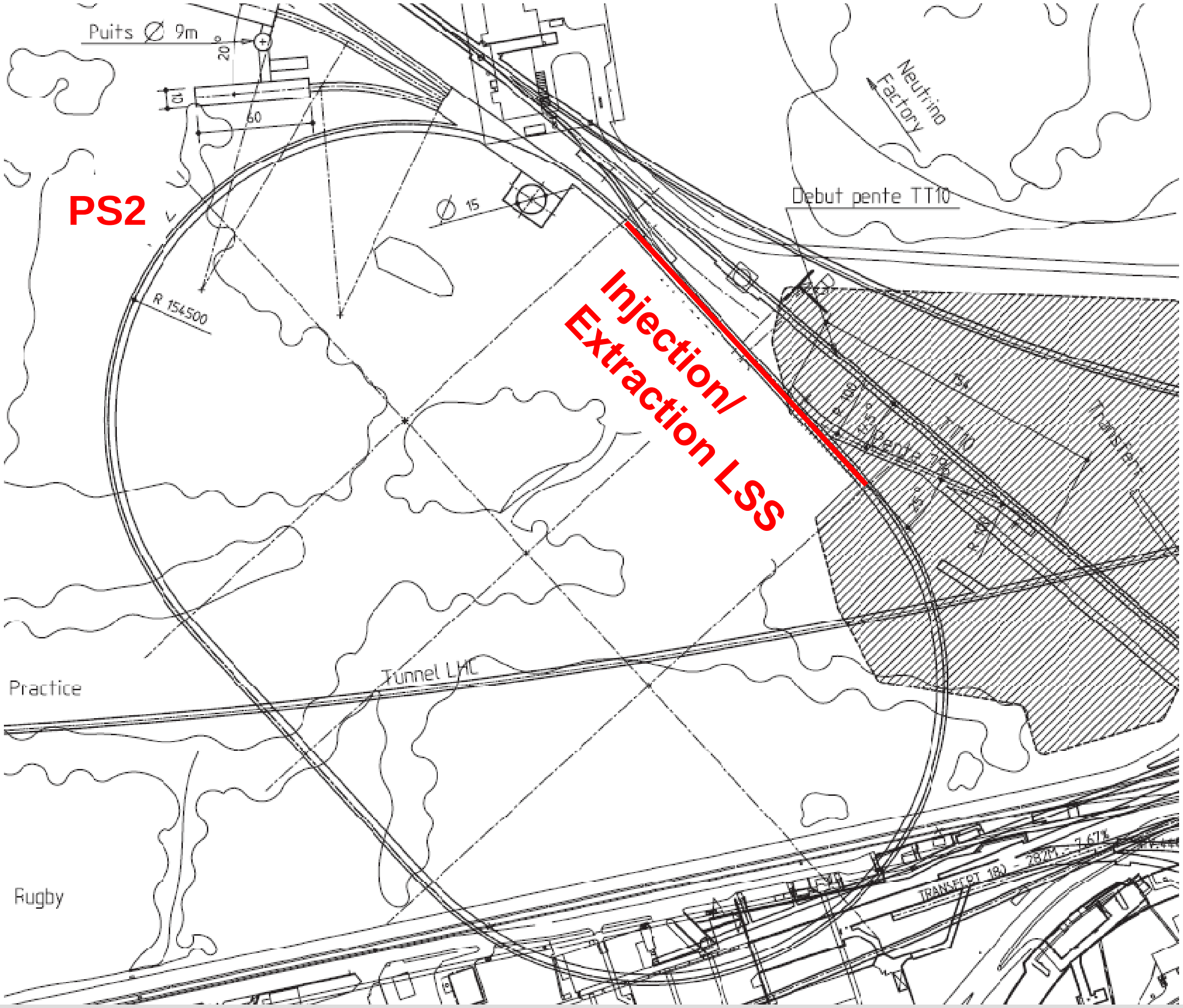
System	Energy [GeV]	Bρ [Tm]	Pulse/spill length	Rise/fall time [us]
Fast injection	1.3 – 4.0	6.8 – 16.2	2 us	0.10
H- injection	4.0	16.2	600 – 1200 us	2000 - 5000
Fast extraction	20 – 50	69.7 – 169.8	4.5 us	0.15
1/3rd integer extraction	20 – 50	69.7 – 169.8	1.2 s	-
MTE extraction	20 – 50	69.7 – 169.8	22.5 us	0.15

Assumptions

- Regular (FODO) lattice in the injection/extraction regions, with ~90º horizontal phase advance and 23 m cell length.
- 10 m free drift per half-cell available to accommodate beam transfer elements
- Dispersion function matched to ~zero in these regions (< 0.2 m).
- Enlarged quadrupoles with 85 mm good field region (regular quads 50 mm)
- Extraction trajectories via enlarged quadrupole coil windows, *a la* SPS
- Kicker and septa outside aperture of 50 mm at 33 m β (~ 300 π.mm.mrad acceptance).
- Injection energy 135 MeV/u (1.3 GeV p+) for Pb^{54+}, 4.0 GeV for H^- and p^+
- extraction energy 20 - 50 GeV.
- H/V beam emittances 15/8 π.mm.mrad (CNGS-type beam).
- From SPL, H- beam emittance assumed at 0.5 - 1 π.mm.mrad.
- Standard lattice quadrupole yokes are 700 x 700 mm, 1.75 m long
- Enlarged quadrupole yokes 900 x 900mm, 2.2 m long.

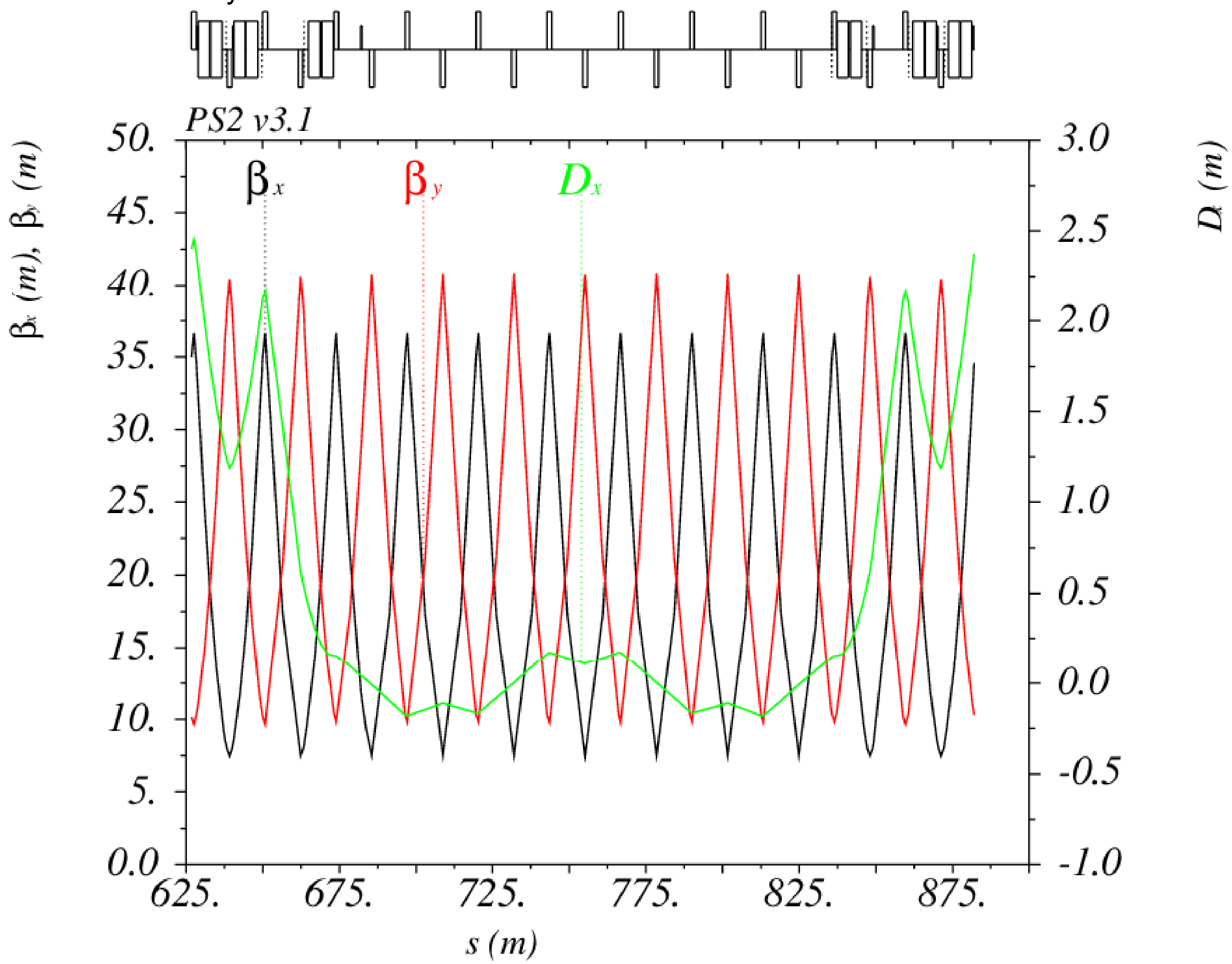
Injection/extraction straight

- PS2 with racetrack geometry
- Assume all injection and extraction systems in one long straight section



FODO Lattice – optics in the LSS

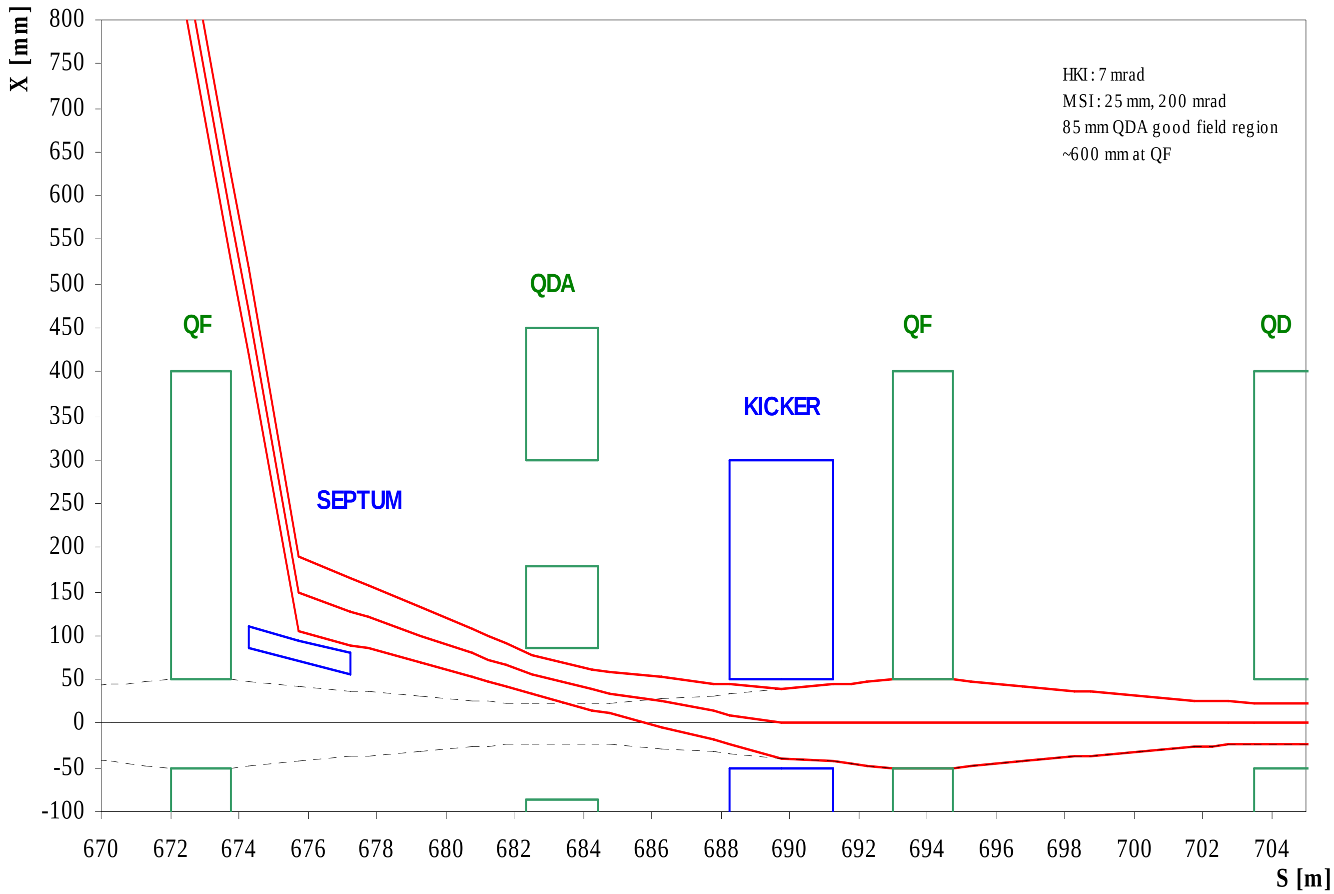
- $|D_x| < 0.2$ m, 89º H phase advance, 70º deg vertical (check exact numbes), β_x 7 – 37 m, β_y 9 – 41 m



Fast Injection

- A classical single-turn injection (septum, fast kicker) with variable kick length should cover the energy range from 1.3 GeV to 4.0 GeV, i.e. a maximum magnetic rigidity of $B\rho$ = 16.2 Tm.
- For the fast kicker the required pulse length is up to 2.5 μs, with rise and fall time of ≤100 ns.
- This single-turn injection system will always be needed for ion operation, and so it seems reasonable to design it for 4 GeV p+.

Injection: fast p+/ions, 1.3 – 4.0 GeV



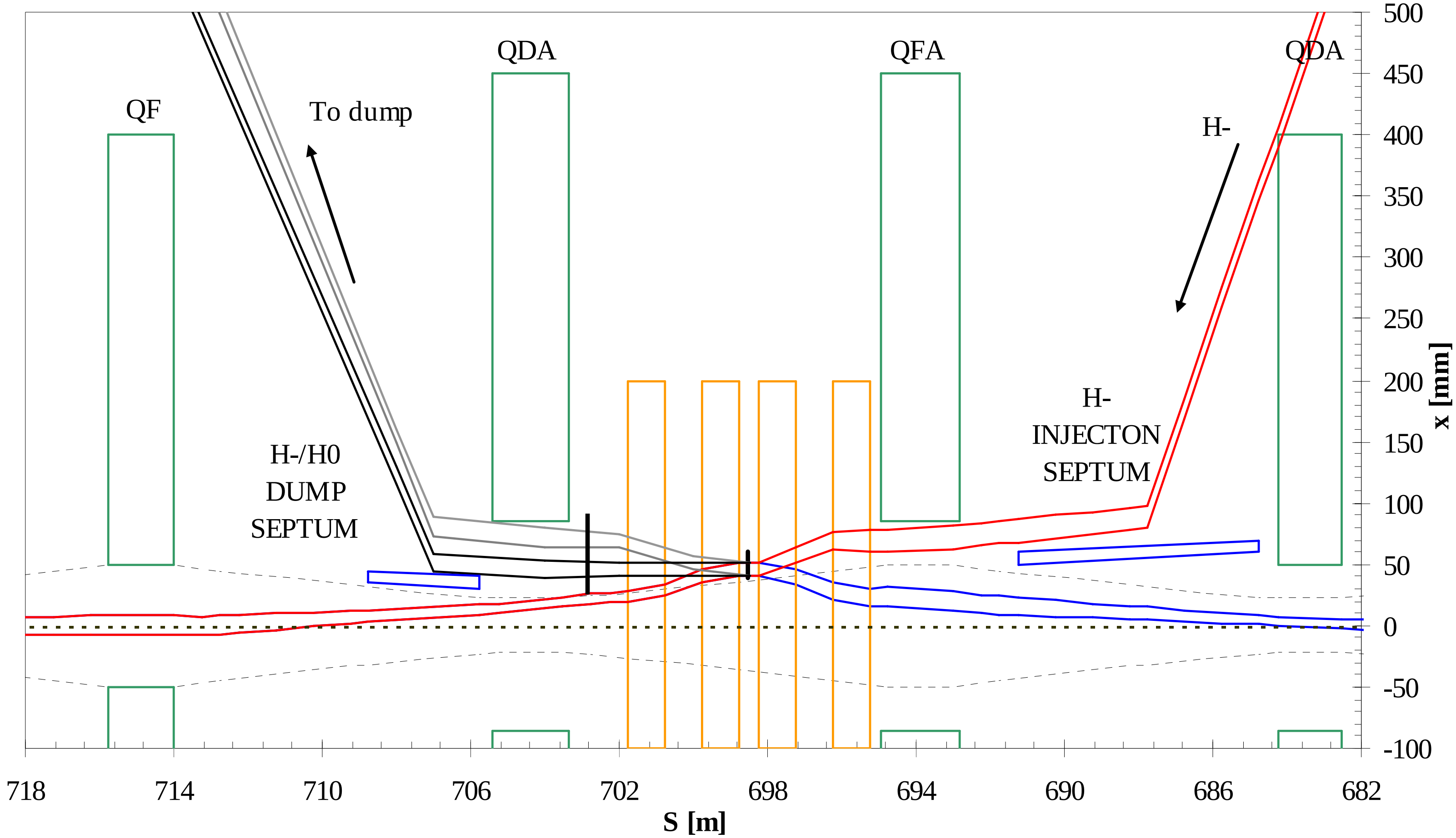
7 mrad, 100 ns kicker, 200 mrad, 25 mm septum

Requires 2 half-cells for fast injection system

Injection: H- multi-turn, 4.0 GeV

- H- injection for beam from SPL
  - Injection septum and injection chicane dipoles housing the stripping foil.
  - Fast orbit bumps (horizontal and vertical) will be needed to allow for phase space painting during injection process (≤300 turns i.e. ~1 ms).
  - Septa, beamline and dumps for the partially or unstripped H0 and H- beams are needed.
  - Low dispersion (<20 cm) to decouple longitudinal and transverse effects
- This is a difficult system at 4 GeV!
  - Limit on maximum dipole field H- beam can traverse, to avoid magnetic stripping and beam loss
  - 2 – 5 % of unstripped H- needs dedicated extraction septum and dump
  - Foil physics and beamloss control…
  - Dumping of stripped electrons….
  - For comparison: SNS H- injection at 1 GeV (!) takes up one of four straights, total of 32 m (two quadrupole doublets, two 6 m straights, one 12 m straight for injection chicane).

Injection: H- multi-turn, 4.0 GeV



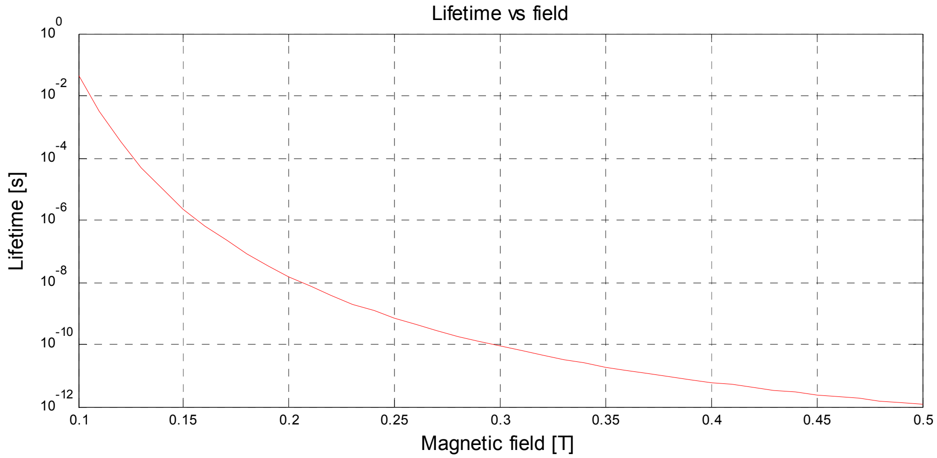
7 mrad injection chicane dipole, 72 mrad injection septum, 200 mrad H-/H0 dump septum (both 25 mrad)

~100 - 300 turns injection (500 - 1500 µs)

Requires 2.5 - 3 half-cells for h- injection system

H⁻-Inj: Lorentz Stripping – total losses

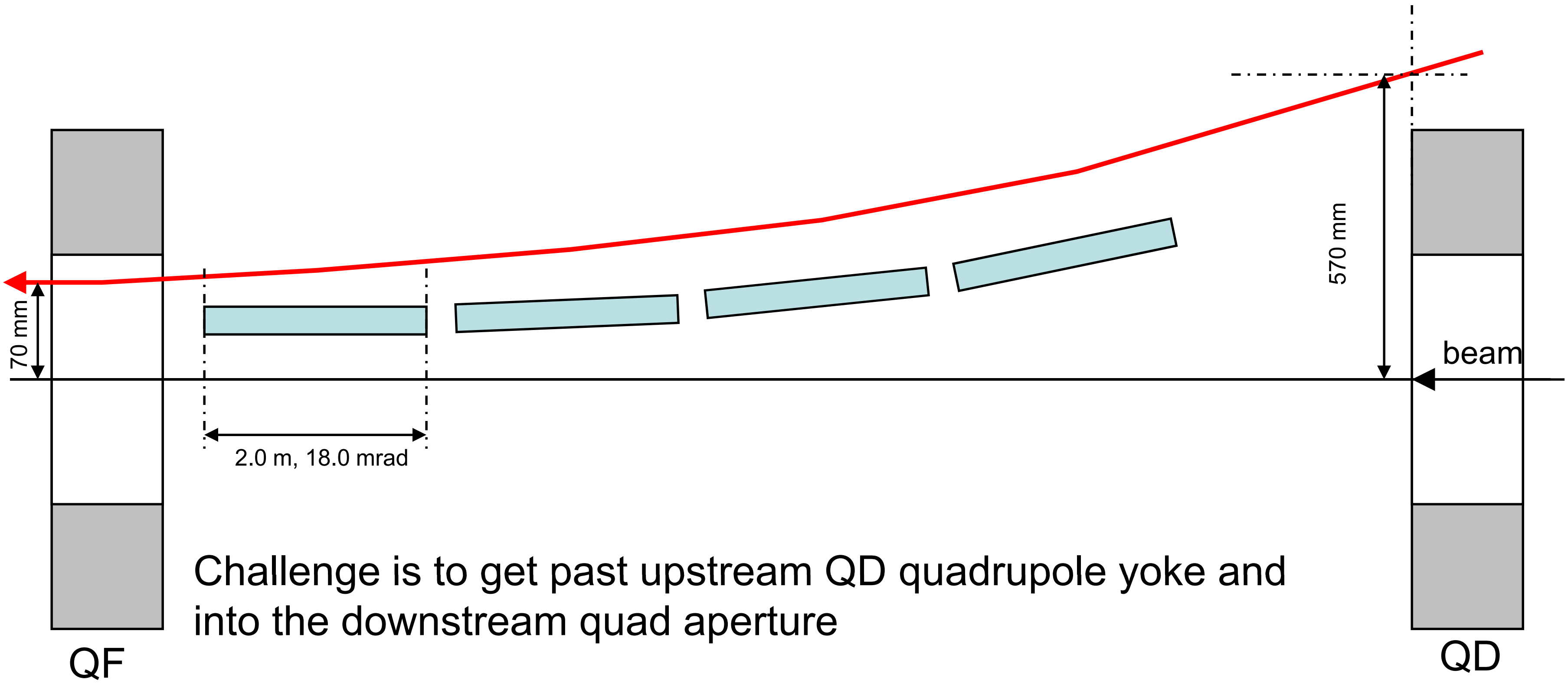
- Lifetime depends exponentially on field



- For PS2 injection at 4.0 GeV should keep fields below 0.13 - 0.15 T (corresponds to about 10^{-4} - 10^{-3} loss per m of dipole)
- Need to aim for $<10^{-3}$ total loss
  - Few 10^{-4} per element/system
  - Maximum bend about 9 mrad/m (4.0 GeV) – 125 m bending radius
- In one FODO ½ cell have ~ 10 m free drift
  - Assume 8 m magnetic length for septum
  - Maximum deflection is then ~ 70 mrad

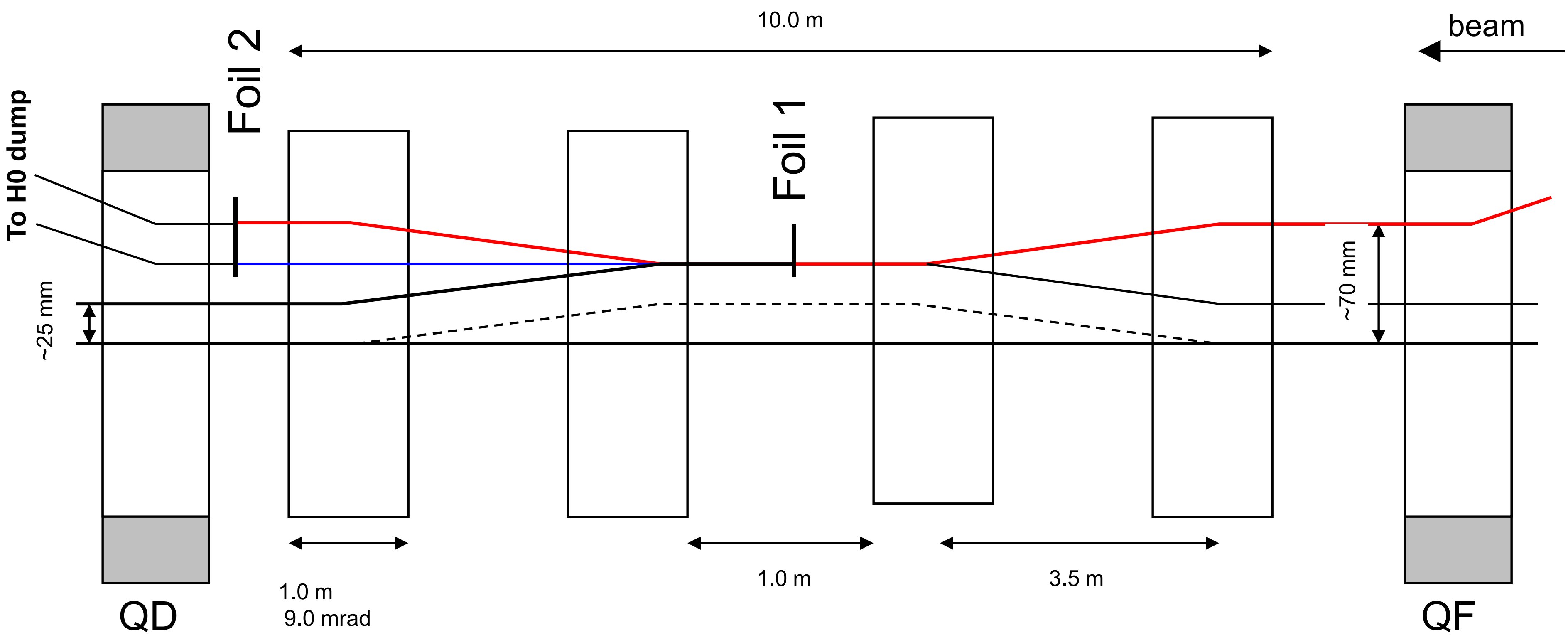
Injection septum ½ cell geometry

- A difficult item
  - ½ cell full of septum - at limit (8 m magnetic in ~10 m drift for 72 mrad)
  - Preferable to not rely on injecting through a quad coil window (aperture, extra fields, constraints, quad design)



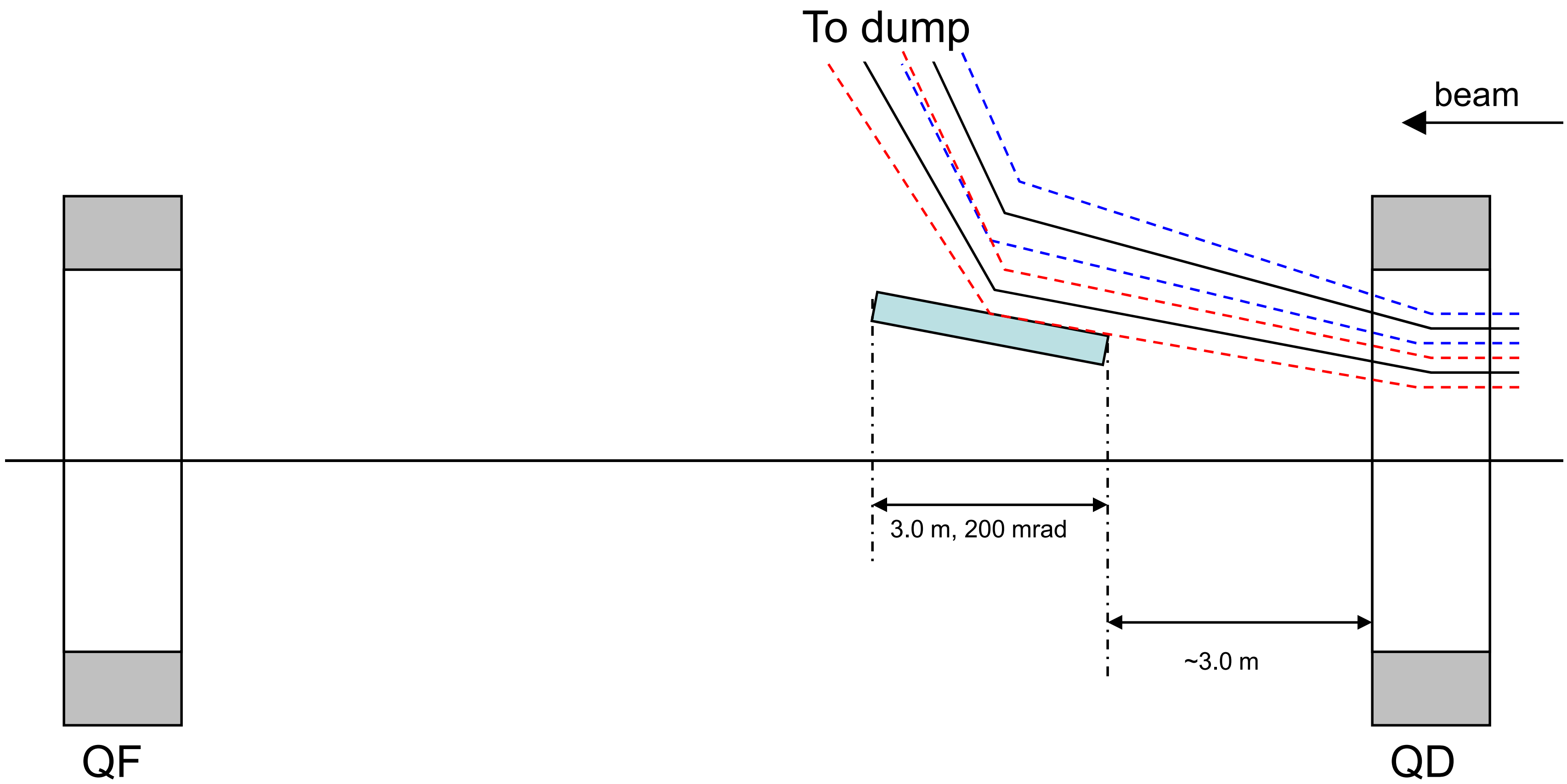
Challenge is to get past upstream QD quadrupole yoke and into the downstream quad aperture

Injection chicane ½ cell geometry



- ~25 mm chicane bump, ~25 mm painting bump (4 other magnets….)
- 1 m long chicane magnets with 3.5 m centres give ~7 mrad
- Foil edge at about 40 mm – just outside 'aperture' (50 mm x β/β_{max})

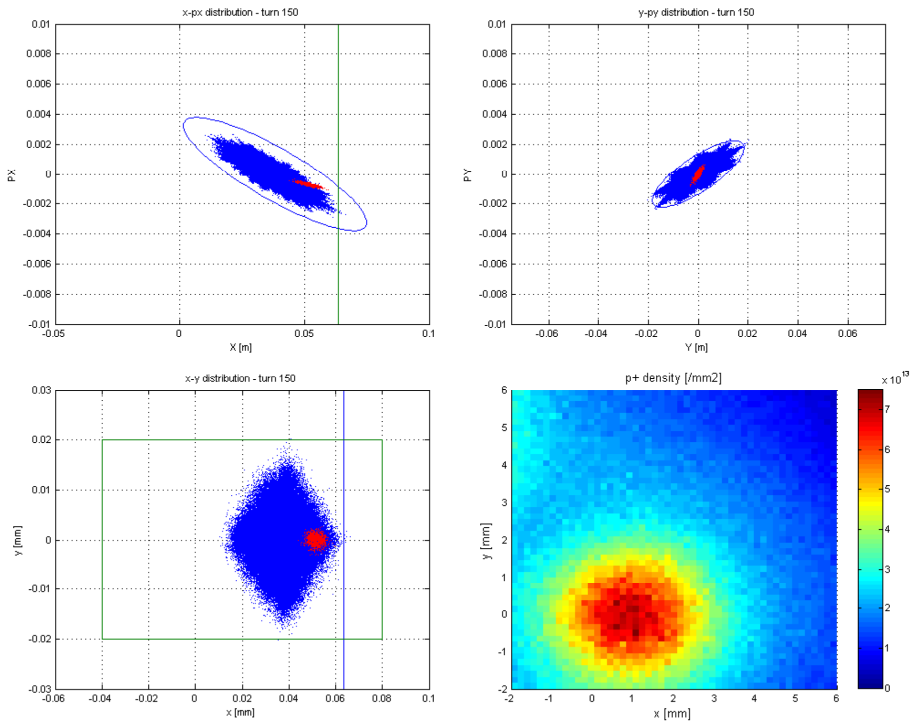
H^-/H^0 dump ½ cell geometry



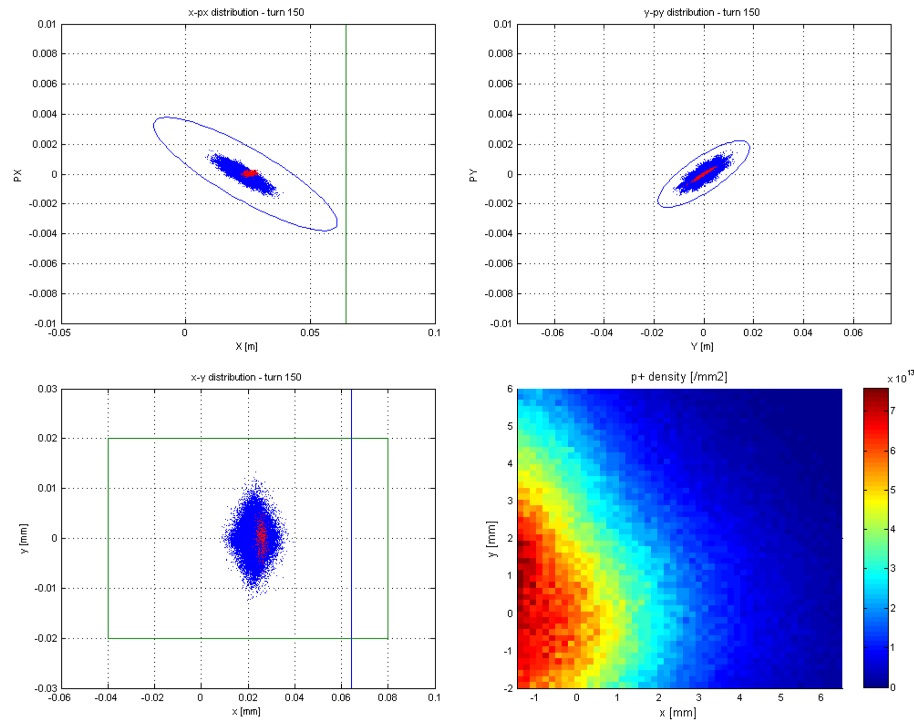
- Can use 'real' septum (>1.0 T); easy to get beam out (3 m → 200 mrad)
- ~5 kW of protons – need large acceptance TL….or internal dump (TK…)
- Dump line design proved difficult at SNS – large beam losses seen – redesigning

Painting and foils

- Assume phase space painting in H and V planes
- Example for linear painting functions with anti-correlated H/V
- Expect foil temperatures of ~1500 K



CNGS-type beam, ~300 turns



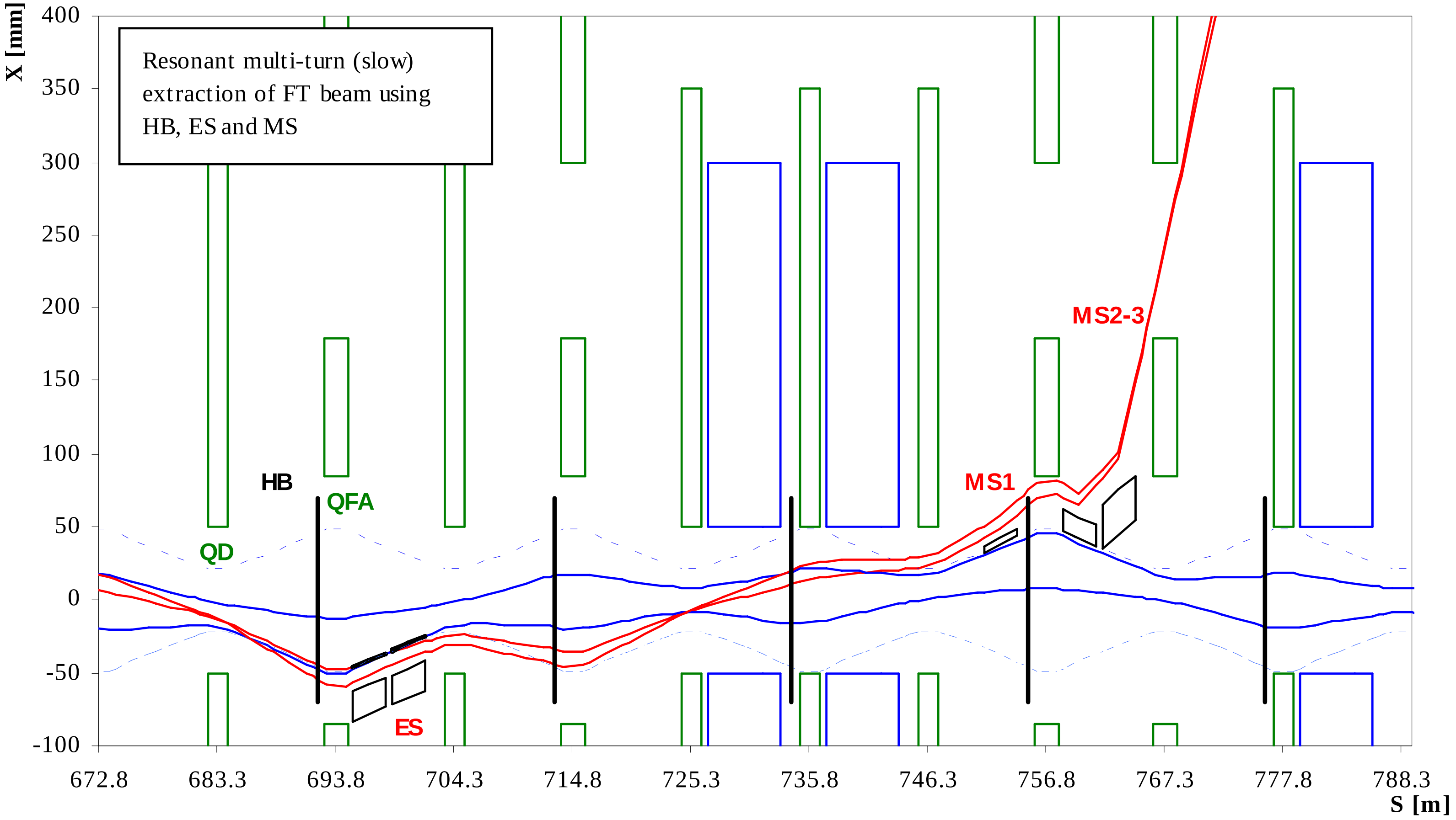
LHC beam, ~100 turns

Slow extraction

- Classical 1/3 integer scheme
  - Extraction angle ~40 mrad, to reach coil window gap at downstream QD
  - Thin electrostatic septum to minimise losses (about 1.2 mrad)
  - Thin, medium and extraction septum magnets (‘DC’) for the 40 mrad.
  - Horizontal orbit bumpers, providing ~1.2 mrad.
  - Special sextupole magnets in the lattice at suitable phases.
  - Some passive shielding of elements downstream of ES
- ES is located about 270º in phase upstream of the MS, to allow space for extraction kicker elements in the intervening half-cells.

Slow extraction

- Extraction using electrostatic septa (ES) and magnetic septa (MS)
- ES 270 degrees phase advance upstream of MS



1.1 mrad, 0.1 mm electrostatic septum

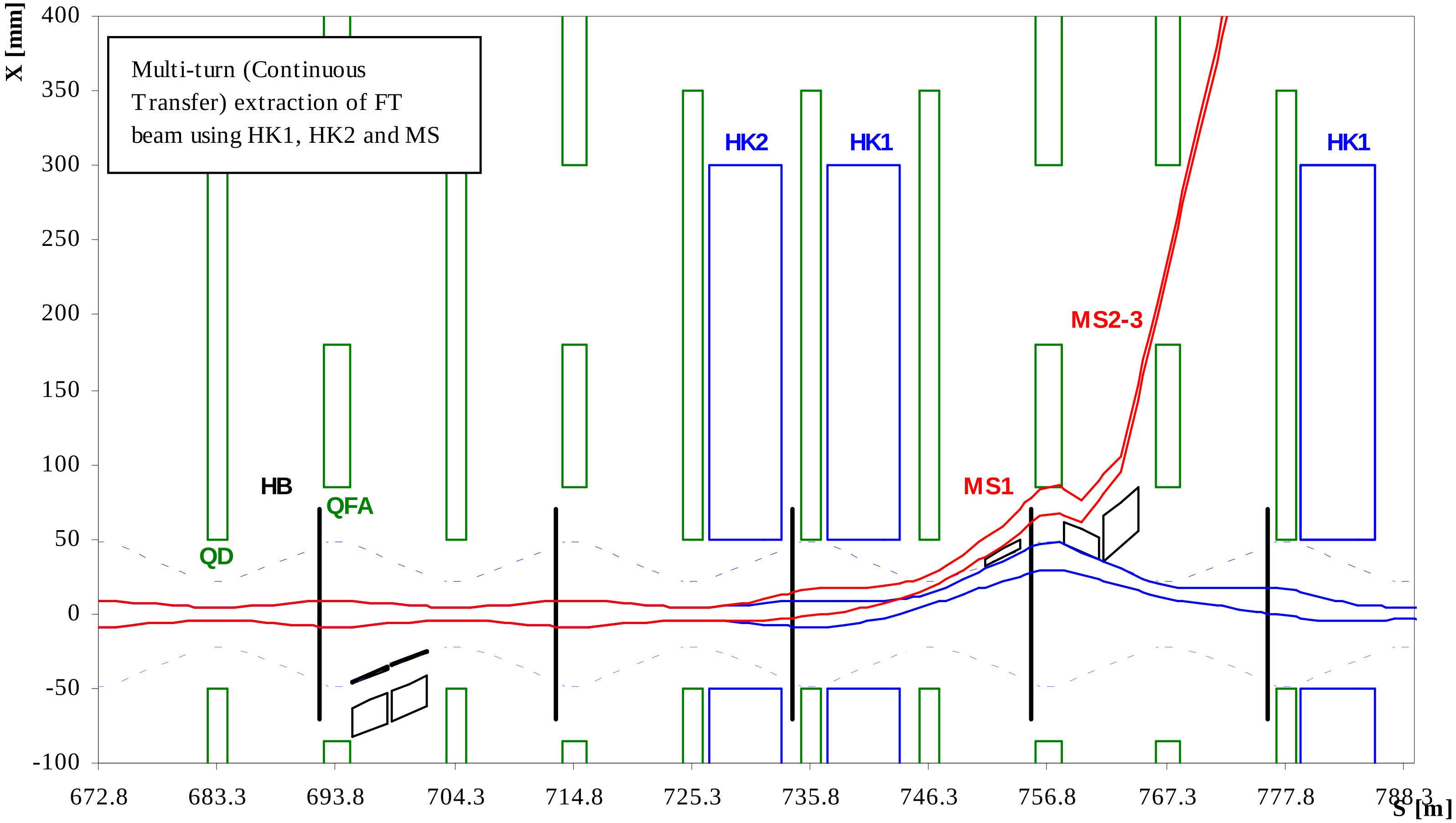
2.5/12/25 mrad, 5/15/25 mm DC magnetic septa

CT-MTE extraction

- Beam captured in stable islands to produce separation at extraction septum.
- Extraction at quarter-integer tune.
- Assume (for now) that extraction in horizontal plane
  - Use same magnetic septa as for slow extraction
  - Fast kicker systems (1 - 5 turns – 21 us) rise time of 150 ns, 1.6 mrad
  - Special multipole magnets (sextupoles and octupoles).
  - closed orbit bump to move beam close to septum
    - Short dipoles at QFs – 0.3 m, 1.2 mrad
- Two main systems of HK kicker/bumper magnets.
  - One system 90^{o} up- and downstream of MS -> closed bump over first 4 turns of the extraction, during which beam in islands are extracted.
  - Second system pulsed for 5^{th} turn only, to extract beam in central island.
  - Will probably also need small 3^{rd} system to close 1^{st} bump

CT-MTE extraction

- Extraction using fast kickers (HK1 and HK2) and magnetic septa (MS)
- Short HK unit to adjust the HK1 π bump closure is not shown



1.6 mrad, 150 ns kickers (2 systems)

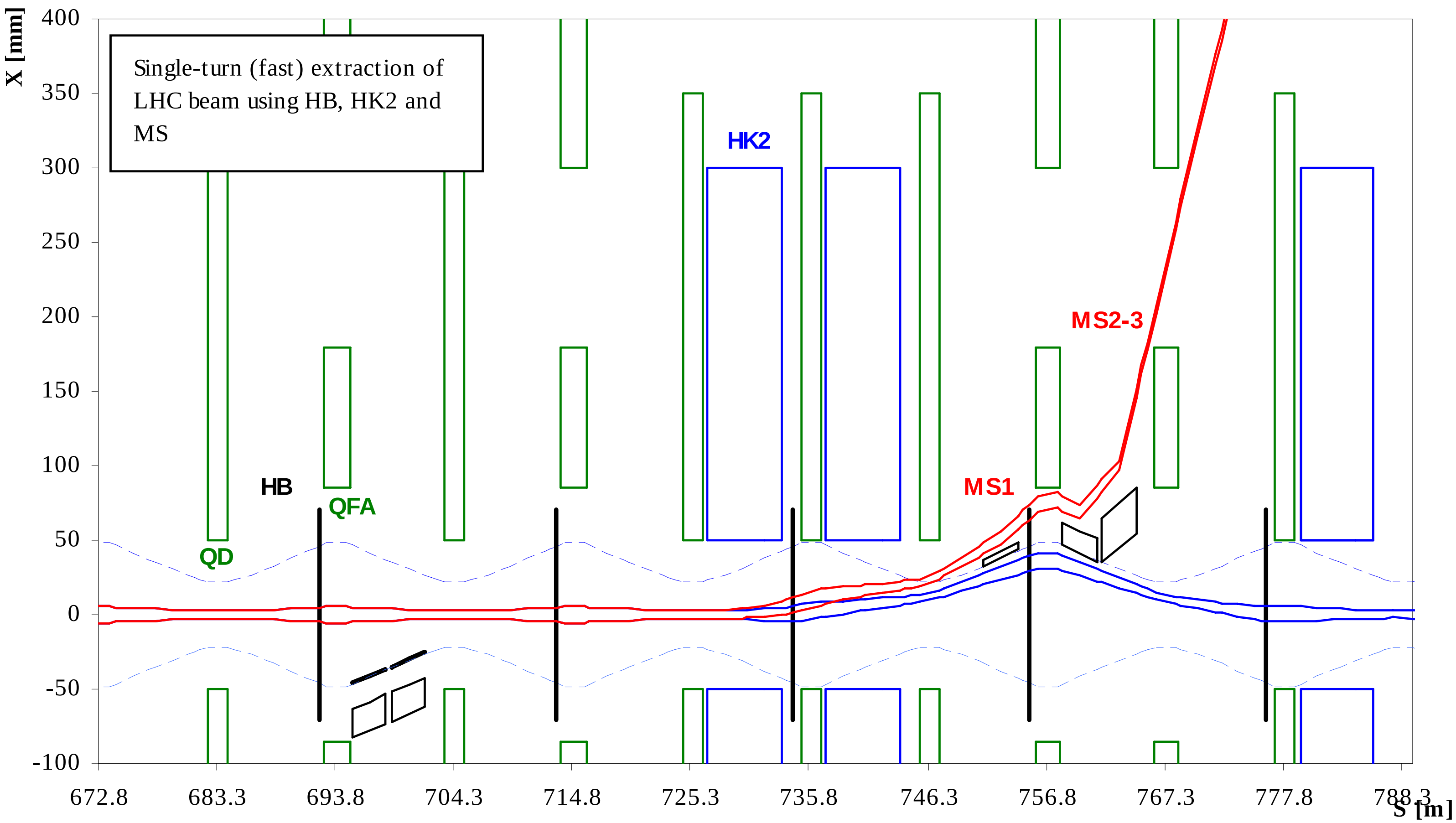
2.5/12/25 mrad, 5/15/25 mm magnetic septa

Fast extraction

- Fast single turn extraction
- Reuse kickers, septa and closed orbit bumpers
  - closed orbit bump to move beam close to septum
    - Need ~1.2 mrad from short bumpers at QFs
  - one of the HK systems to extract the beam.
    - HK2 (used for extraction of last turn in CT process):
    - 1 turn – 4.2 us, rise time of 150 ns, 1.6 mrad
  - all 3 magnetic septum systems

Fast extraction

- Extraction using bumpers, fast kicker (HK2) and magnetic septa (MS)



1.4 mrad, 150 ns kicker

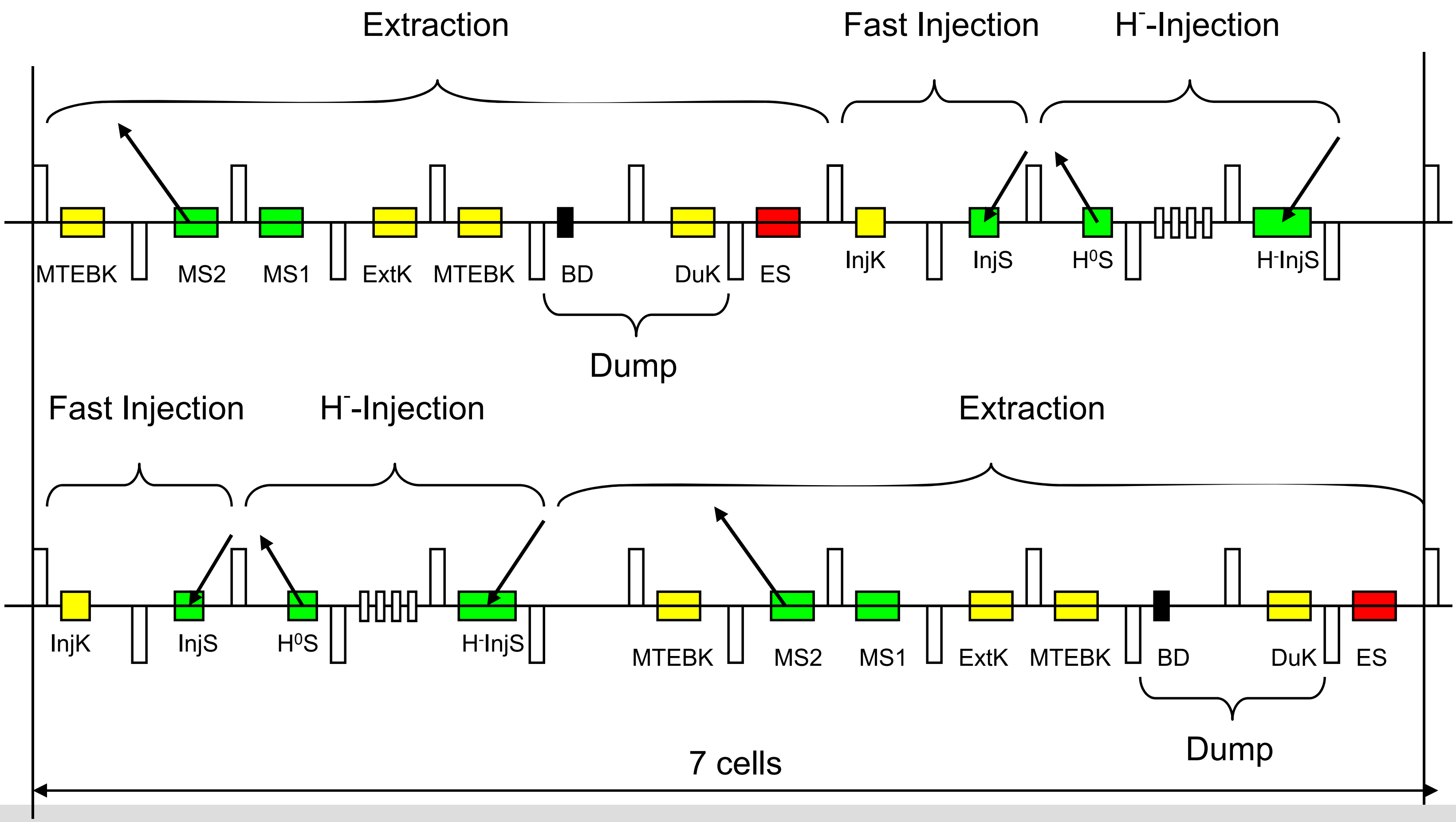
2.5/12/25 mrad, 5/15/25 mm magnetic septa

Overall space requirements

- Require 5 half-cells for injection systems
- Require 8 or 9 half-cells for extraction systems
  - 3 of these are ~empty, and could possibly accommodate a beam dump
- Total requirement is for 7 cells in the LSS
  - Seems possible to accommodate in DOFO or FODO in LSS, by changing the pairing of the kickers for the MTE/fast extraction

Injection/extraction straight

- Injection presently assume before extraction
  - could be reversed to gain space for a longer transfer line to SPS, but would give more complicated beamline layouts
  - beam loss control and collimation to be considered



Key system parameters

System	Bρ [Tm]	Angle [mrad]	B [T]	L_{mag} [m]	Aperture H/V [mm]	t_{rise} [μs]
Fast injection: kicker	6.7 – 16.2	7	0.03	4.1	120 / 90	0.10
Fast injection: septum	6.7 – 16.2	200	0.93	3.5	120 / 80	-
H- injection: chicane dipoles	16.2	7	0.11	1.0	150 / 100	5000
H- injection: injection septum	16.2	72	0.15	8.0	120 / 80	-
H- injection: dump septum	16.2	200	0.93	3.5	120 / 80	-
Fast/MTE extraction: kicker	70 – 170	1.6	0.05	6.0	120 / 90	0.15
Magnetic extraction septum #1	70 – 170	2.5	0.14	3.0	60 / 30	-
Magnetic extraction septum #2	70 – 170	12	0.68	3.0	60 / 30	-
Magnetic extraction septum #3	70 – 170	25	1.42	3.0	60 / 30	-
Electrostatic extraction septum	70 – 170	1.1	104 (kV/cm)	6.0	-	-

Extraction kicker limitations

- System is close to strength limit for 50 GeV….bulky and costly system.
- The issue of extraction kicker strength is not easy to overcome.
- Requirements on the very fast rise time (150 ns) impose low system inductance and therefore a relatively high characteristic impendence. This reduces the strength (current) of the magnet for a given applied voltage. Possible improvements could be obtained by:
  - Reducing the characteristic impedance to 8.3 or 7.1 Ω - gives 7.2 m magnetic or 5.4 m magnetic (but t_{rise} would increase to 190 or 250 ns).
  - Reducing the vertical gap AND horizontal gap proportionately, since this keeps the inductance of the system and hence the rise time for a given current, while increasing the field. But aperture likely to be a limit.
  - Reducing the required subsystem deflection – larger beta at kicker/septa
- Relax rise-time and help losses by chopping extraction gaps into FT beam for SPS?

Enlarged quads with coil windows

Quadrupole design

- Enlarged quadrupoles (assumed to be designed with coil window passages where only linear fields are present) will be required in the extraction regions, to accommodate the large excursions associated with the injected and extracted beams.

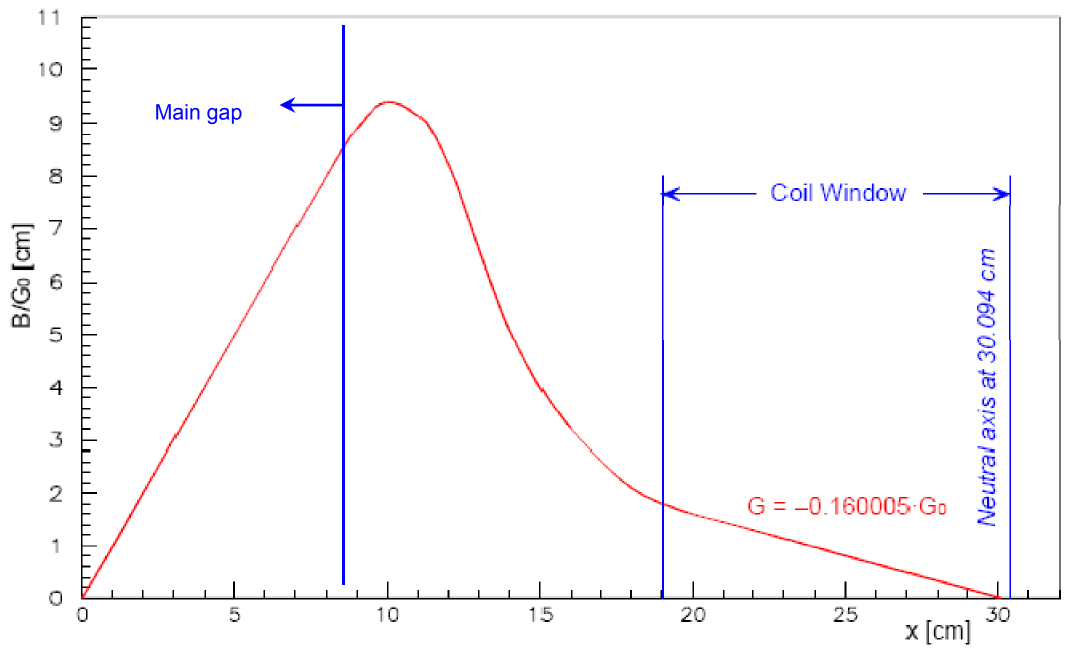


Figure 6: Field in Coil Window of Quadrupole QDA5171

SPS QDA

Conclusion

- Single injection extraction straight
- 2 injection systems, 3 extraction systems
- Challenging 4 GeV H- injection
  - Geometry constrained by Lorentz stripping
  - Beam losses and unstripped beam dumping
  - Foil physics
- Constraints on optics
  - low dispersion for H- injection and extractions
  - ~90 deg phase advance for extraction element strengths
- Constraints on other systems
  - Insertion quadrupoles – enlarged versions to study
- Challenges for kicker performance
  - Trade-offs with machine parameters, especially rise time/filling scheme?