LHC beam dump, injection system and other kickers

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Outline of talk

- Beam dumping
  - Existing LHC beam dumping system
  - Issues and challenges of LHC energy upgrades
    - Extraction, dilution, absorption, protection;
  - Possible beam dump upgrade paths
- Injection
  - Injecting at 1-1.3 TeV
    - Issues and challenges, possible upgrade paths
- Other kicker systems
- Conclusion

Present system - concept

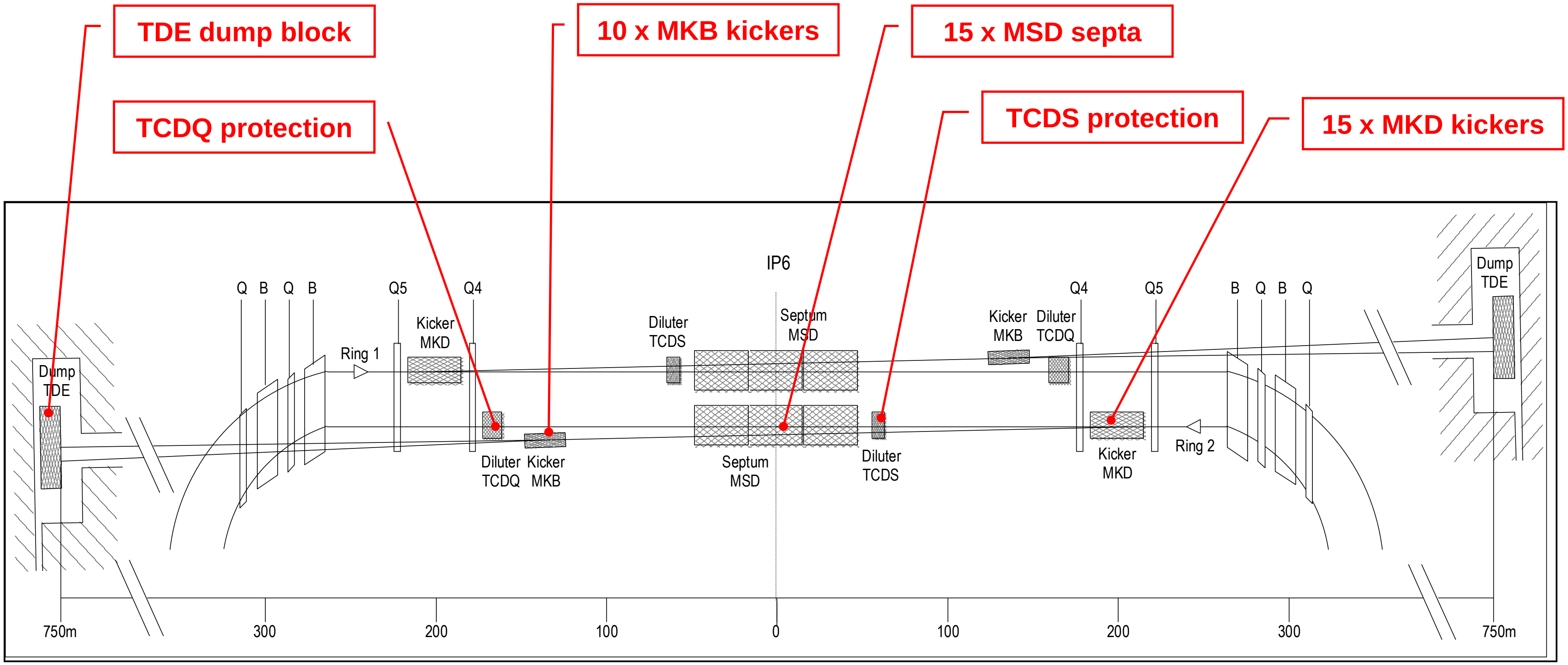
extract ⇒ dilute ⇒ absorb

- "Loss-free" fast extraction system
  - Laminated steel kickers (H)
  - DC Lambertson septum (V)
- Dilution system
  - Laminated steel kickers (H&V)
  - ~650 m drift length
- Vacuum windown
  - 15 mm thick CC, 0.2 mm thick steel backing foil
- Beam dump (absorber) block
  - 7.7 m long, 0.7 m Ø C cylinder, steel and concrete shielding
- Protection devices
  - Graphite/CC/composite dilutors for septum and LHC machine

Assumptions

- Reuse existing tunnel and caverns
  - Same (similar) extraction trajectories in H & V
    - Similar kicker and septum angles
  - Maximum ~300 mm dilution sweep radius
- Similar quadrupole layout and optics
  - 2 matching quads in LSS per side of IP (Q4, Q5)

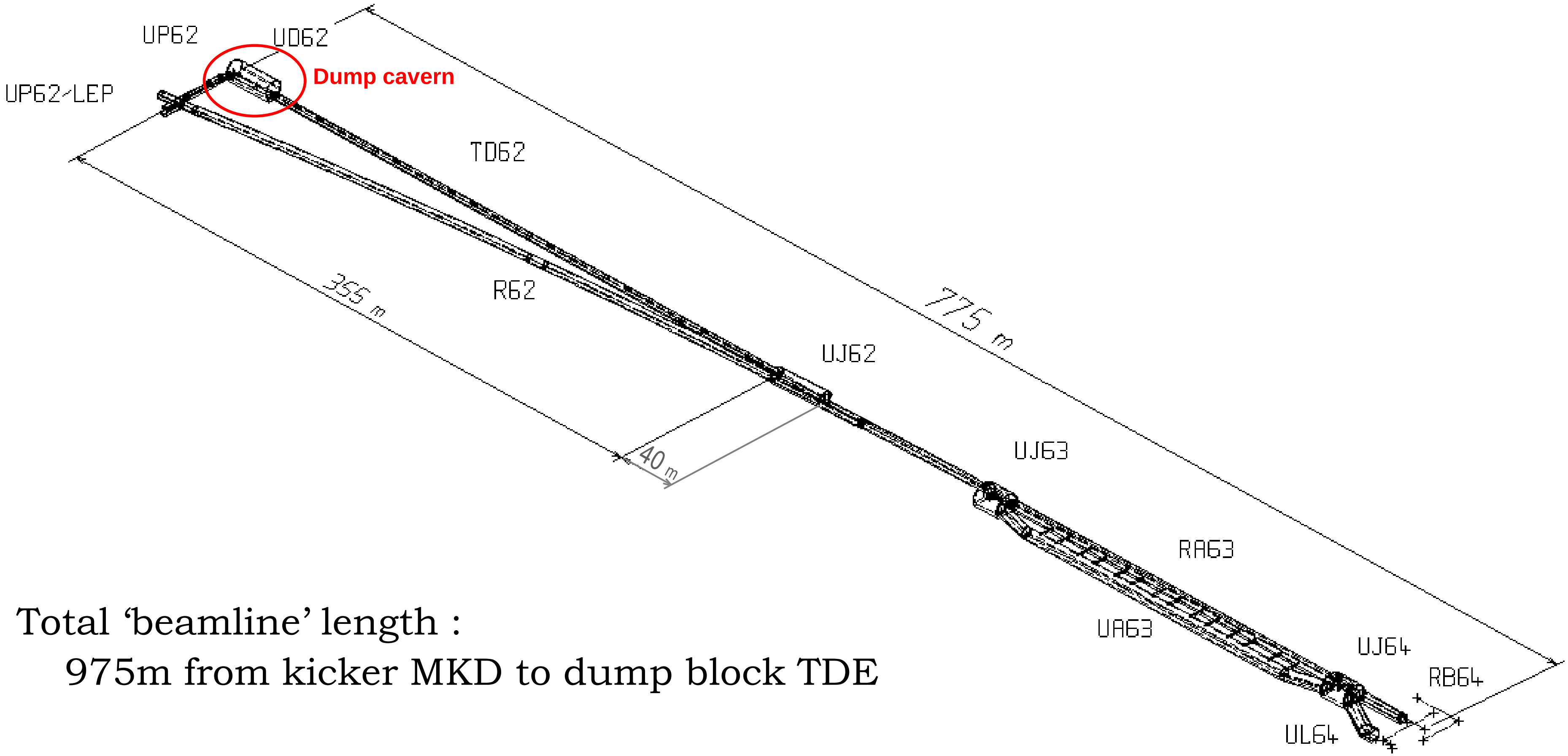
Present design - schematic layout



Total ‘beamline’ length :

975m from kicker MKD to dump TDE

Present design - tunnel layout



Total 'beamline' length :
975m from kicker MKD to dump block TDE

Extraction kickers – option I

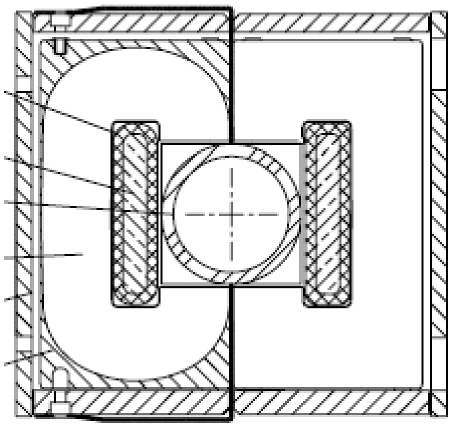
- Keeping existing kicker types and 3 us rise time
  - Can increase installed length or increase field

		LHC Nominal	HE longer	HE higher I
MKD V gap	mm	72	72	72
MKD rise time	us	3.00	3.00	3.00
MKD angle	mrad	0.27	0.27	0.27
MKD B.dl	Tm	6.3	14.9	14.9
MKD gap field	T	0.30	0.30	0.71
MKD peak field	T	0.41	0.41	0.95
MKD dI/dT	kA/us	6.17	6.23	14.53
MKD I	kA	18.5	18.7	43.6
MKD length	m	21.0	49.0	21.0
MKD Filling factor		0.761	0.761	0.761
MKD Required length	m	27.6	64.4	27.6
MKD magnets		15	35	15

- Increased length: 35 magnets/beam
  - System length more than doubled
  - 70 m spacing between Q4 and Q5 in LSS6
- Increased field
  - dI/dt more than doubled – 70 kV on switches.
  - Not OK for air-insulated system (oil gains~30% but complex)
  - 43 kA feedthrough very challenging

Extraction kickers – option II

- New design: reduce vertical opening and increase rise time
- Scaling kicker opening to √(450/1000): 62 → 42 mm
- Kicker magnetic gap 72 → 52 mm (vacuum chamber)



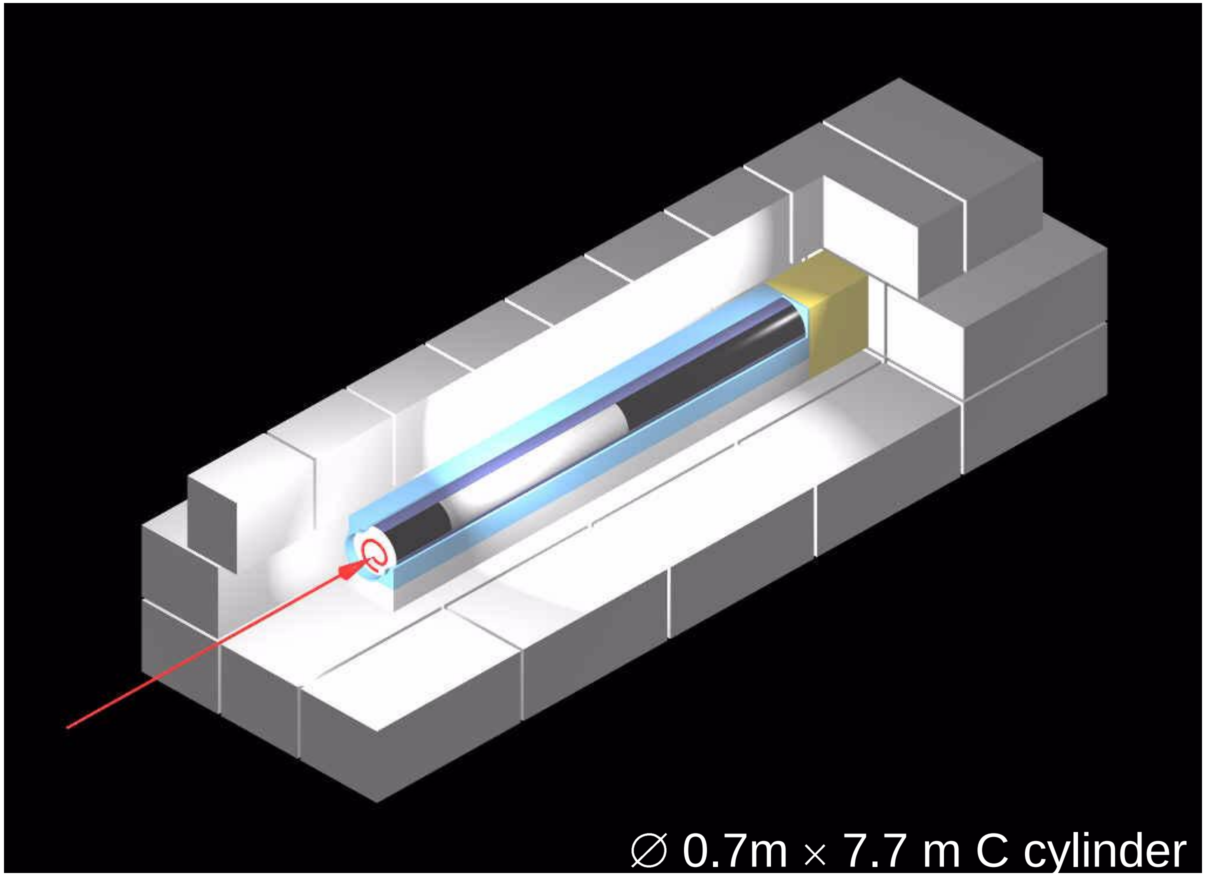
		LHC Nominal	HE Nominal
MKD V gap	mm	72	52
MKD rise time	us	3.00	5.10
MKD angle	mrad	0.27	0.27
MKD B.dl	Tm	6.3	14.9
MKD field	T	0.30	0.71
MKD peak field	T	0.41	0.95
MKD dI/dT	kA/us	6.17	6.17
MKD I	kA	18.5	31.5
MKD length	m	21.0	21.0
MKD Filling factor		0.761	0.761
MKD Required length	m	27.6	27.6
MKD magnets		15.0	15.0

- 15 magnets, 0.71 T and 31.5 kA: gives 5.1 us rise time
- R&D needed on high current switches and high current feedthroughs, but looks more feasible

Dilution kickers and dump

- For beam dump block, would need full study to analyse extra dilution required from MKB kicker system
- Peak p+ density factor ~2.4 times higher
- Shower maximum further into dump block
- Transverse shower extent at shower maximum assumed to scale as beam size (pessimistic)
- Total energy to dump ~500 MJ – as for LHC ultimate
- Assume sweep length should increase by a factor 2

Dump block - present TDE absorber



- Likely to require longer block with lower density, or at least different grading of carbon densities
- Longitudinal space exists in the UD caverns

Dilution kickers parameters

- Scaling sweep length required by energy and intensity means present 100 cm could be sufficient
  - Need to check explicitly with FLUKA – effect of smaller beam size may not be an issue at the shower maximum
- 7 to 16.5 TeV requires 2.3 times more $\int B.dl$
  - Already near saturation in iron → not possible to increase field per magnet
  - Apertures determined (to first order) by required sweep → not possible to reduce magnet gaps (maybe can optimise with two families per plane)
- Could keep same maximum strength but increase frequency
  - 14 to 32 kHz, but increases dI/dt and hence V

Dilution kicker option I

- Increase installed length keeping switch voltage at 30 kV

		LHC Nominal	HE Nominal
MKB frequency	kHz	14.0	14.0
MKB angle	mrad	0.27	0.27
MKB B.dl	Tm	6.3	14.9
MKB field	T	1.13	1.21
MKB peak field	T	1.52	1.63
MKB voltage	kV	22.30	23.89
MKB I	kA	25.0	26.8
MKB length (H+V)	m	11.2	24.6
MKB Filling factor		0.49	0.49
MKB Required length	m	22.9	50.3
MKB magnets		10	22

- Peak field increases to 1.63 T – just about OK
- Needs 22 magnets (presently 10)
- Installed length increases to 50.3 m

Dilution kicker option II

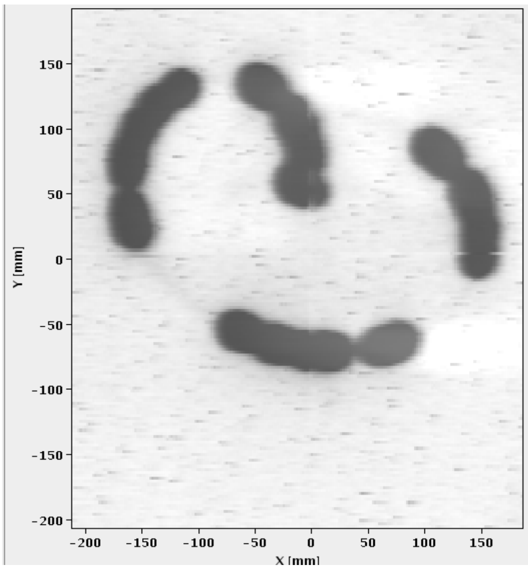
- Increase frequency, reducing kick angle

		LHC Nominal	HE Nominal
MKB frequency	kHz	14.0	28.0
MKB angle	mrad	0.27	0.135
MKB B.dl	Tm	6.3	7.4
MKB field	T	1.13	0.74
MKB peak field	T	1.52	0.99
MKB voltage	kV	22.30	29.20
MKB I	kA	25.0	16.4
MKB length (H+V)	m	11.2	20.2
MKB Filling factor		0.49	0.49
MKB Required length	m	22.9	41.1
MKB magnets		10	18

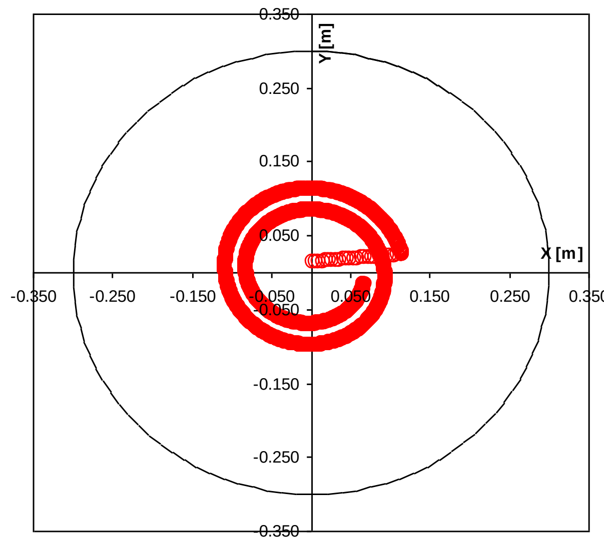
- Needs 18 magnets total (presently 10)
- Total installed length 40 m (presently 22.9)
  - Will have an impact on the aperture – probably needs few types
- As magnets not saturated, would gain with higher switch voltage

Dilution: Option II – increase frequency

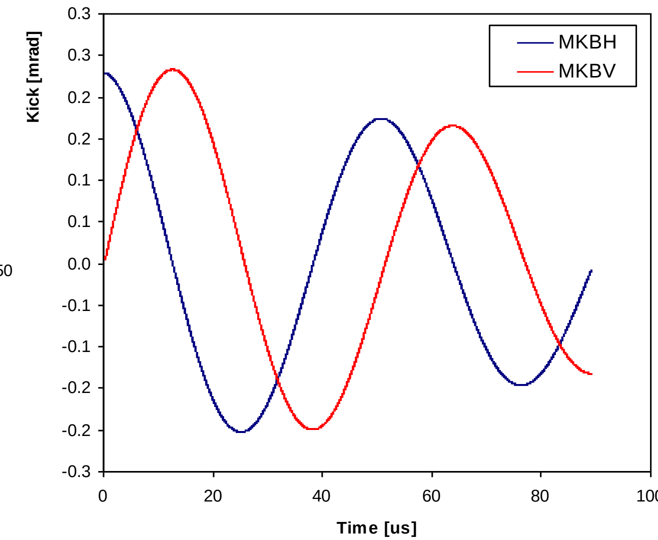
- Dilution kicker frequency increase x2 - sweep length 100 cm with spiral



108 cm sweep length 14 kHz



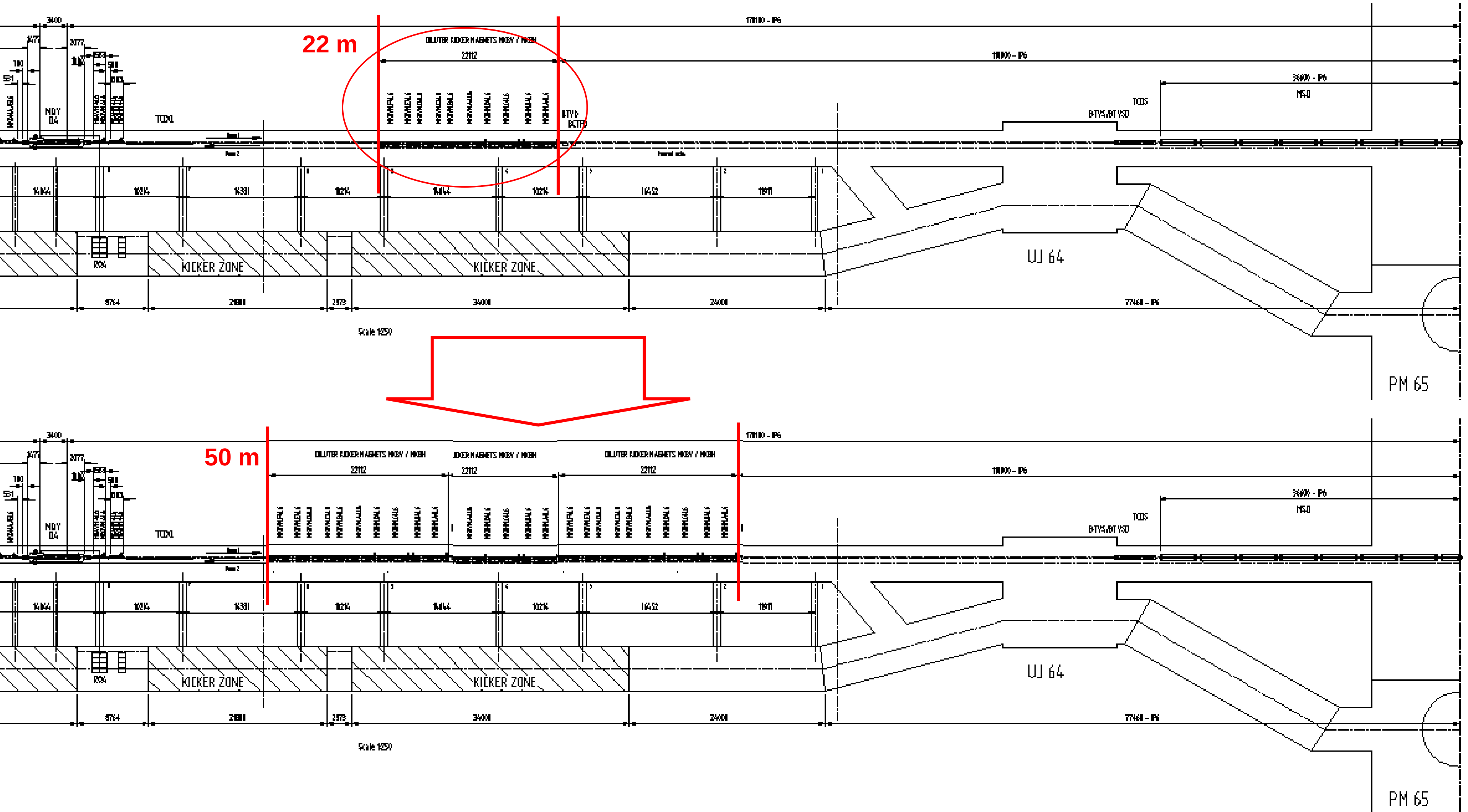
~100 cm sweep length 28 kHz



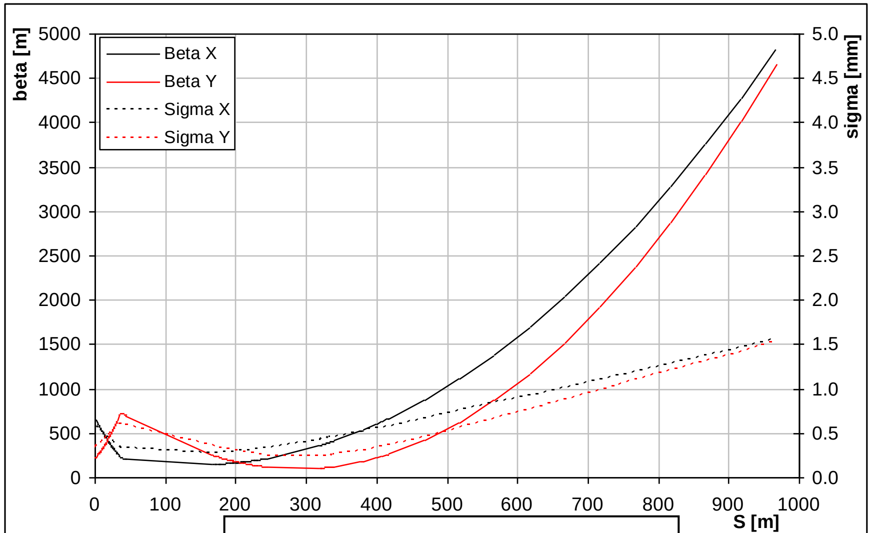
- Potential issues:
  - Can only realistically build damped sinusoidal field (can't spiral outwards) so need to cross inner turn with start of the sweep
  - Temperature profile and mechanical stresses in dump block to evaluate

Dilution system physical installation

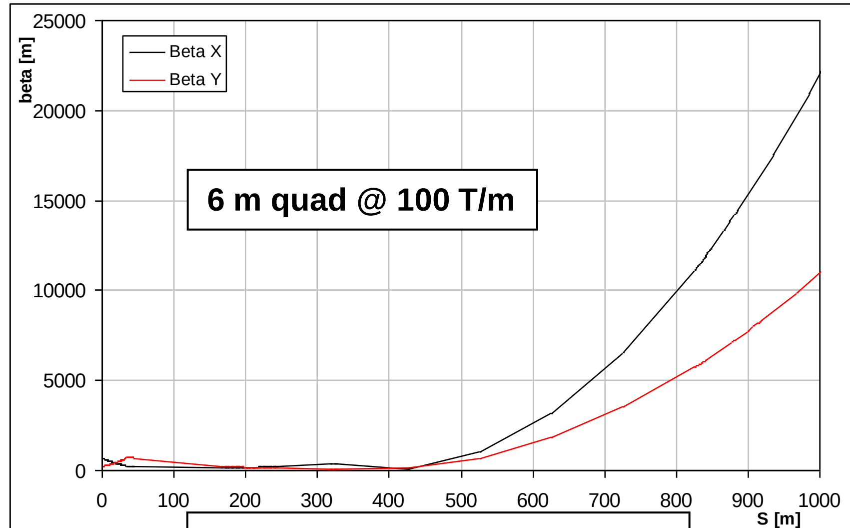
- 10 magnets presently on extracted beam line in long drift space between IP (extraction septa) and Q4



(Extra) dilution with SC quad in dump line?



Present optics β_{max} ~5km

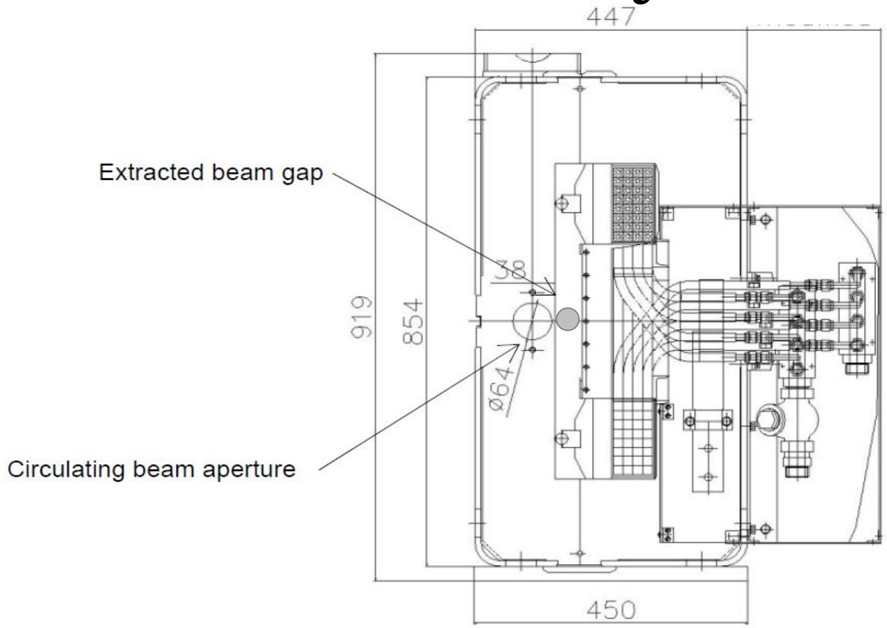


Dilution quad β_{max} ~10-20km

- Present betas: 4-5 km
- Add quadrupole to reach about 12 km beta, to get similar sigmas
  - Need 6 m @ 100 T/m, ~100 mm full aperture
- Orbit : 4 mm ⇒ 45 urad ⇒ ~30 mm at dump (650 m drift).
  - Maybe slightly larger absorber block size and dump line : ∅ ≈ 0.8 m
- Integration likely to be an issue upstream of diluter kickers

Extraction septa

- 15 magnets, 4.5 m long each, to provide total of 2.4 mrad vertically
- Lambertson design
  - 3 types, 0.8, 0.99 and 1.17 T (septum 6, 12, 18 mm)
- Need to increase $\int B.dl$ by factor 2.35



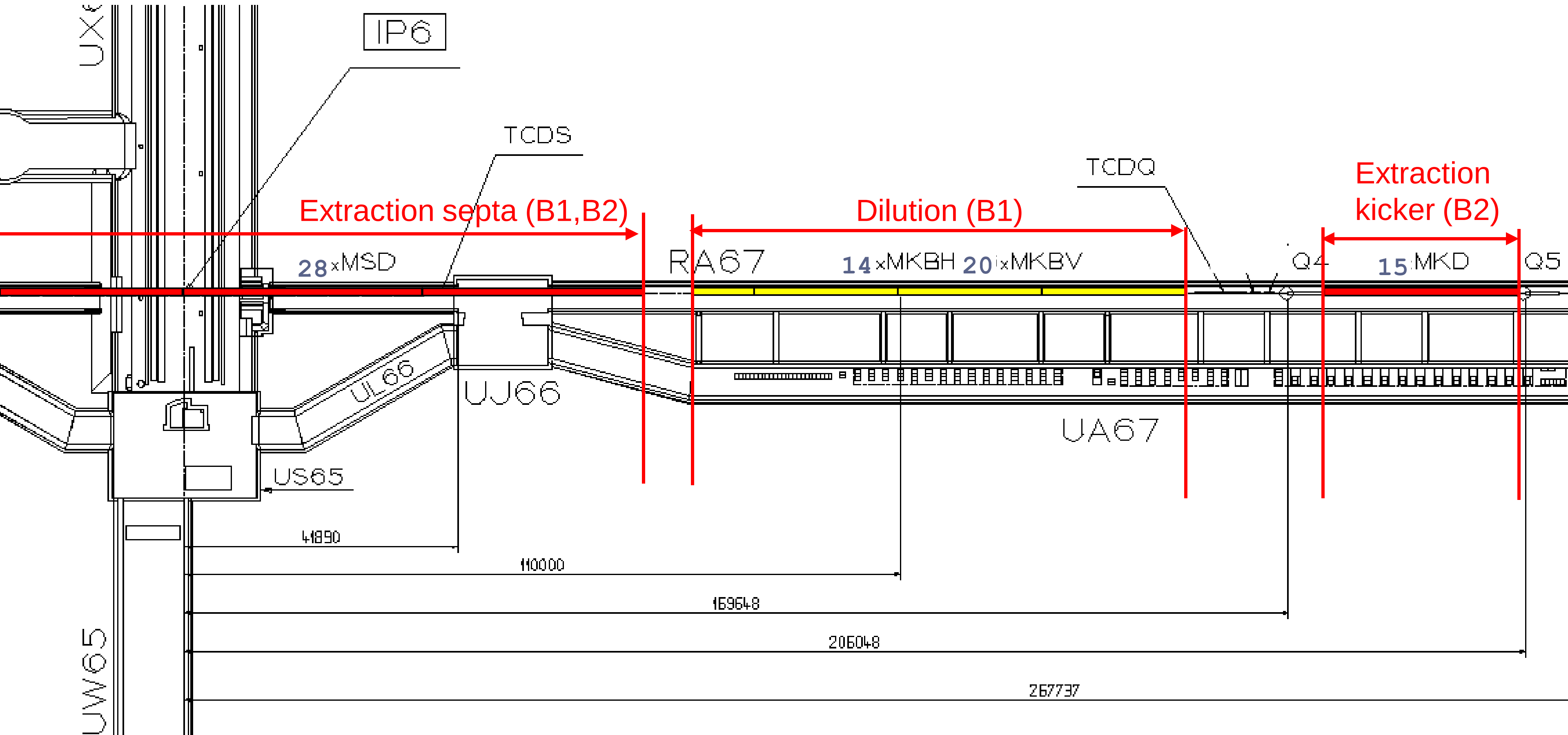
Extraction septa parameters

- Use only type B and type C
  - Thinnest septum anyway not needed behind TCDS
- Increase field to maximum possible

		LHC Nominal	HE Nominal
MSD angle	mrad	2.4	2.4
MSD B.dl	Tm	56.0	132.0
MSD field	T	0.84	1.06
MSD length	m	66.7	124.8
MSD Filling factor		0.916	0.916
MSD Required length	m	72.8	136.2
MSD magnets		15	28

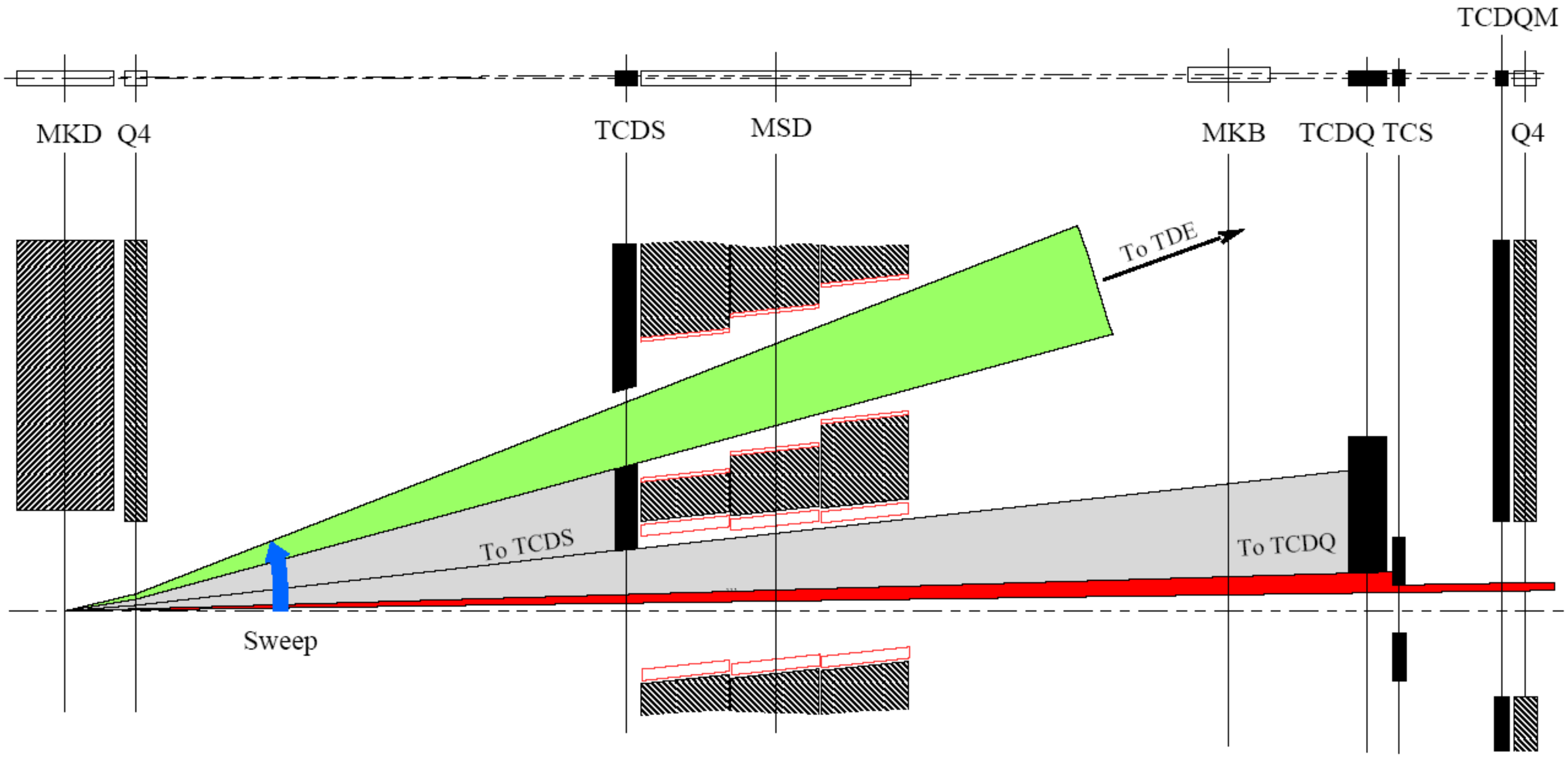
- Total magnets/beam needed : 28 (14 B + 14 C)
- Total installed length is ~136 m (present 73 m)
  - Assume 32 m extra each side of IP6

28 Extraction septa in layout (R6)



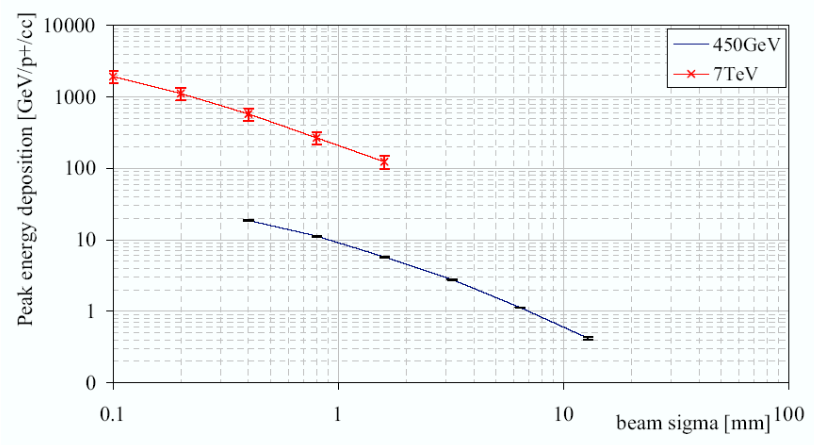
- Layout maybe just feasible – integration for protection devices and lattice quads?

Dump Protection devices



- Long (6 m), low density (C) absorbers intercept undiluted bunches
  - In front of septum (fixed) and in front of Q4 (mobile)
- Fixed 2.4 m steel mask in front of Q4

Dump protection – difficult with increasing E



Peak GeV/cc in Cu vs beam size at 450 GeV ad 7 TeV

- Low density to avoid material damage
- More total material required to dilute energy density
- Very long objects as a result…
- …reduces apertures for extracted beam
- Or use sacrificial absorbers – exchange after (hopefully rare) impacts with high intensity

- 10^7 dilution factor, need ~16 λ_r of C 1.8 g/cc, or ~6 m at 7 TeV
- For 10^7 at 16.5 TeV, need ~0.6 - 0.8 g/cc to avoid damage $\Rightarrow$ 14-16 m
- Some optimisation with graded density to get more λ_r

Injection at 1-1.3 TeV

- Assume reuse of same transfer line tunnels
- An issue is strength of the injection kicker
  - Will need similar deflection to present – 0.8 mrad
  - System already at technological limit (60 kV switch)
  - No extra space in present insertion layout
    - Complicated by combining injection and experiment!
  - Possible "solutions":
    - Increase installed length from 16.9 to around 34 – 40 m
      - 40 – 46 m between quadrupoles (presently 22 m)
      - Completely new insertion layout and optics
    - Double rise time: 1 us increases to around 2 us
      - Ferrite saturation should be OK below about 0. 2 T
      - Keep presently installed length of 16.9 m
      - Could increase PFN length by factor 2 and pulse length from 8 to 16 us, to reduce impact on LHC filling factor (but injector implications)
  - Need to watch out for issues like impedance, beam screen, heating, …

Injection kicker: option 1

- Keep about the same installed length
- Reduce magnet gap according to beam size
- Increase kick strength at expense of rise time…

		LHC Nominal	HE I TeV	HE 1.3 TeV
MKI H gap	mm	54	46	42
MKI rise time	us	1.00	1.90	2.20
MKI angle	mrad	0.8	0.8	0.8
MKI B.dl	Tm	1.2	2.7	3.5
MKI gap field	T	0.08	0.18	0.24
MKI peak field	T	0.09	0.20	0.26
MKI dI/dT	kA/us	5.40	5.37	5.51
MKI I	kA	5.4	10.2	12.1
MKI length	m	14.6	14.6	14.6
MKI Filling factor		0.864	0.864	0.864
MKI Required length	m	16.9	16.9	16.9
MKI magnets		4	4	4

- About 1.9 us for 1 TeV and 2.2 us for 1.3 TeV
  - Could increase pulse length to compensate
  - Ferrite saturation might be an issue for 1.3 TeV

Injection kicker: option 2

- Keep same rise time and increase number of magnets
- Reduce magnet gap according to beam size

		LHC Nominal	HE I TeV	HE 1.3 TeV
MKI H gap	mm	54	46	42
MKI rise time	us	1.00	1.00	1.00
MKI angle	mrad	0.8	0.8	0.8
MKI B.dl	Tm	1.2	2.7	3.5
MKI gap field	T	0.08	0.09	0.11
MKI peak field	T	0.09	0.10	0.12
MKI dI/dT	kA/us	5.40	5.10	5.39
MKI I	kA	5.4	10.2	12.1
MKI length	m	14.6	29.2	32.9
MKI Filling factor		0.864	0.864	0.864
MKI Required length	m	16.9	33.8	38.0
MKI magnets		4	8	9

- 34-38 m needed for injection kickers, so say 38-42 m between quadrupoles

Injection at 1-1.3 TeV – septum

- Injection septum design – like dump septum
- More units and more space
  - Add more units – need 43 – 55 m installed length (presently 21.8 m, with 22 m free drift) – need also to provide lever arm to get past cryostat, so should have maybe 50-60 m between quadrupoles around septum

Injection at 1-1.3 TeV - protection

- As for dump, injection protection device design increases in difficulty for 1-1.3 TeV
- Protection in transfer lines
- Protection against injection kicker failures
  - 8 MJ in 1.3 TeV injected beam, if 16 us long at 50 ns
  - Likely to need 6 - 8 m long objects

Other kickers (tune, aperture, AC dipole)

- Second order concerns
  - Weak devices – presently single magnets with combined functions
  - ‘Easy’ to add more kicker modules and separate functions – no space constraints

Summary

- 16.5 TeV dump system: does not look impossible in similar layout to present system
  - 5 μs kicker rise time feasible, x2.6 kicker length →optics issues
  - Increase septa ∫B.dl (x1.9 septa length, maybe gain by using more of MSDC type), seems feasible (integration?)
  - Increase dilution sweep length: higher f_0, needs more kickers OR SC dilution quadrupole plus kickers; integration issues
  - Upgrade dump block (longer, lower density), seems feasible
  - Upgrade protection devices for higher energy (longer, sacrificial elements), difficult
- 1-1.3 TeV injection system will need new layout
  - Longer kicker rise time 1.9 – 2.2 μs with longer pulse feasible, OR 1 μs with 8 – 9 magnets and 40 m quad spacing: optics?
  - Double number of septa but 60 m between quads: optics?
  - Injection protection devices need more space
  - Cohabitation with experiments in injection regions??