Performance reach of LHC beam dump

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Outline of talk

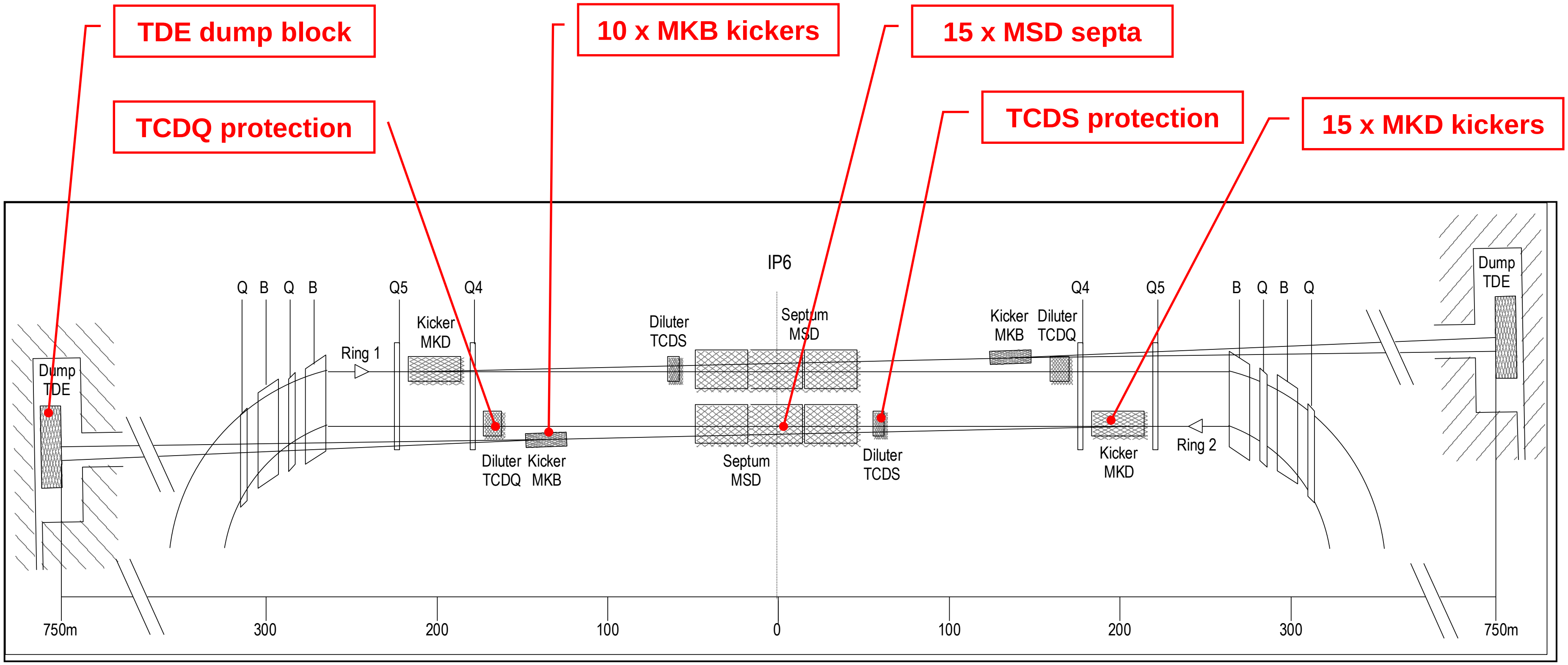
- Introduction
- Existing LHC beam dumping system
- 16.5 TeV beam dump in present LHC tunnel
- 50 TeV beam dump
- Summary

Present LHC dump system - concept

extract ⇒ dilute ⇒ absorb

- "Loss-free" fast extraction system
  - Laminated steel kickers (H deflection)
  - DC Lambertson septum (V deflection)
- Dilution system
  - Laminated steel 'sweep' kickers (H&V)
  - ~650 m drift length
- Beam dump (absorber) block
  - 7.7 m long, 0.7 m Ø C cylinder, steel and concrete shielding
- Protection devices (against asynchronous dump)
  - Graphite/CC/composite dilutors for septum and LHC machine

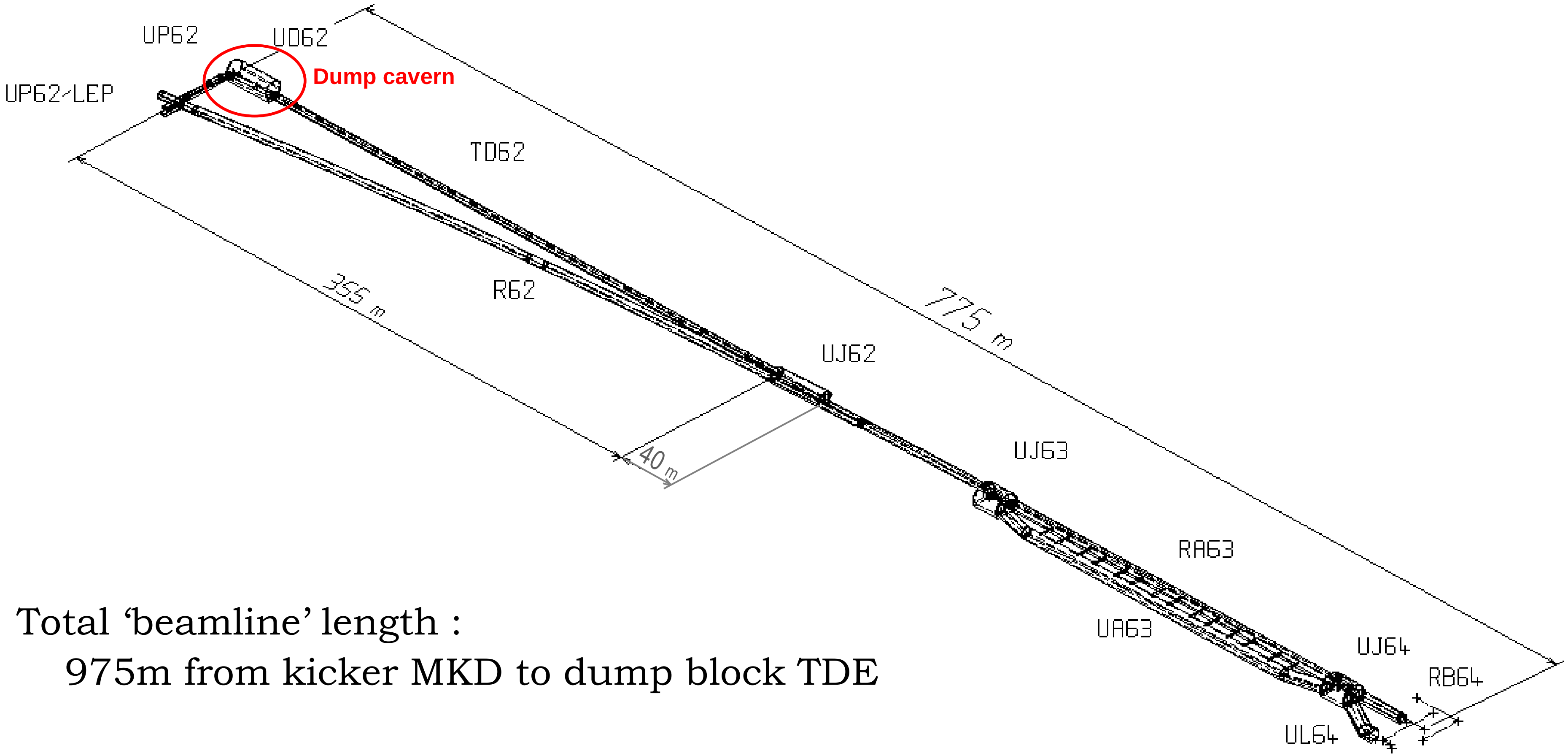
Present design - schematic layout



Total 'beamline' length :

975m from kicker MKD to dump TDE

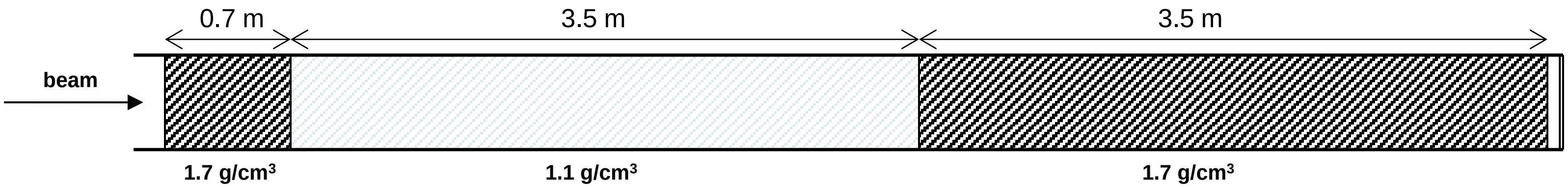
Present design - tunnel layout

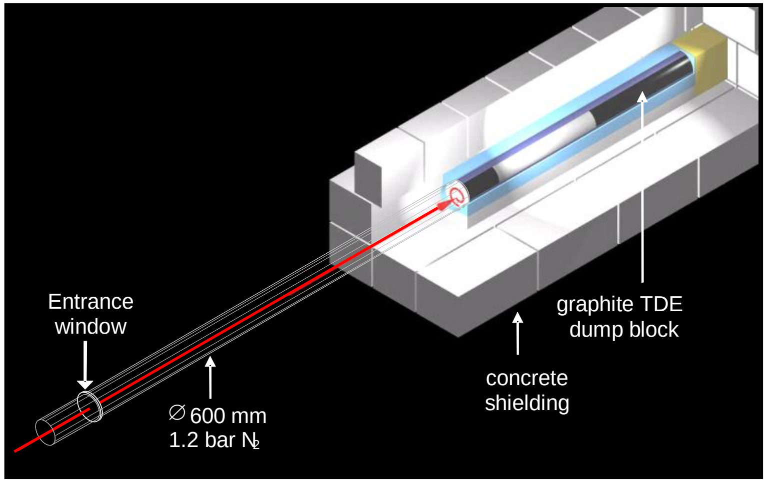


Total 'beamline' length :
975m from kicker MKD to dump block TDE

Beam dump block (TDE)

- 700 mm ∅ graphite core, with graded density of 1.1 g/cm^3 and 1.7 g/cm^3
- 12 mm wall, stainless-steel welded pressure vessel, at 1.2 bar of N_2
- Surrounded by ~1000 tonnes of concrete/steel radiation shielding blocks





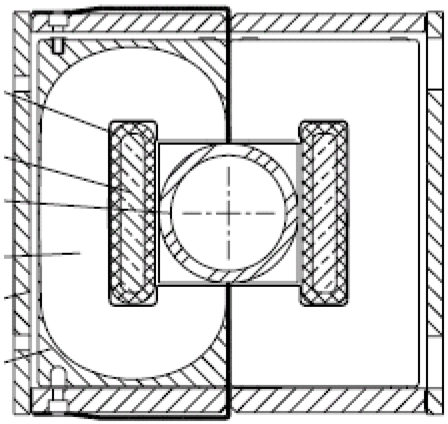
30 May 2006

Assumptions for 16.5 TeV HE-LHC

- 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)

Extraction kickers for 16.5 TeV HE-LHC

- 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
- Same installed kicker length
- R&D needed on high current switches and high current feedthroughs (19 -> 32 kA), but looks feasible

Dilution kickers and dump for 16.5 TeV

- Peak p+ density factor ~2.4 times higher
- Shower maximum further into dump block
- Total energy to dump ~500 MJ – as for LHC ultimate
- Assume sweep length of 100 cm still OK
  - Effect of smaller beam size may not be an issue at the shower maximum
  - For beam dump block, would need full FLUKA study to analyse if extra dilution required from MKB kicker system
- Likely to require longer block with lower density, or at least different grading of carbon densities
- Longitudinal space exists in the UD caverns

Dilution kicker parameters

- 7 to 16.5 TeV requires 2.3 times more ∫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 Bdlbut 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	26.70	28.60
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

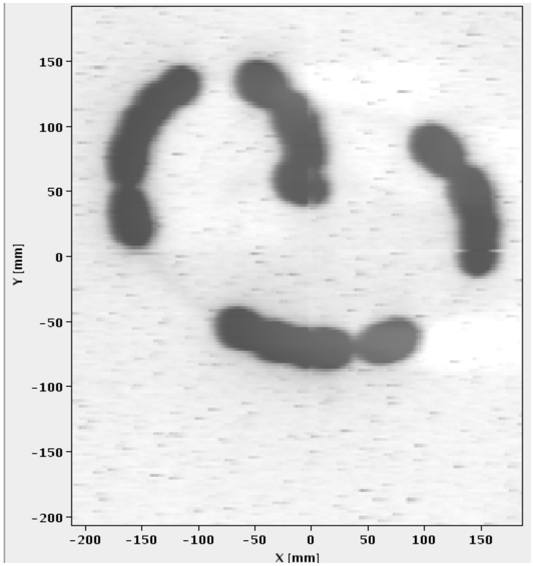
- Increase frequency, reducing kick angle

		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	26.70	34.96
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

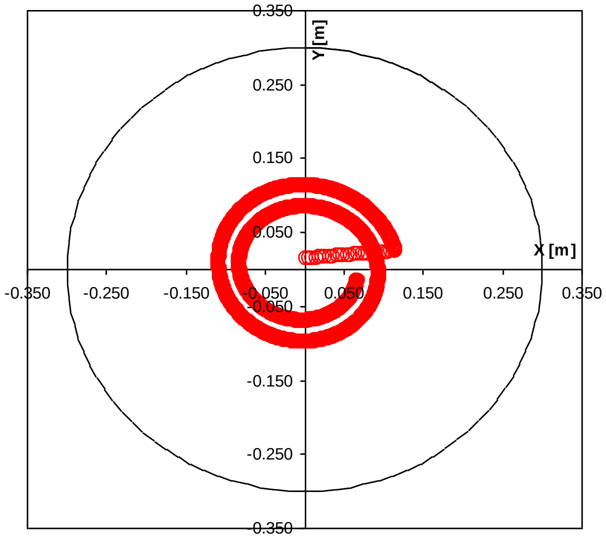
- Needs 18 magnets total (presently 10)
- Total installed length 40 m (presently 22.9)
  - Will have an impact on the aperture – probably needs few types
- As magnets not saturated, gain with higher switch voltage
- Need to reach 35 kV

Dilution: Option II – increase frequency

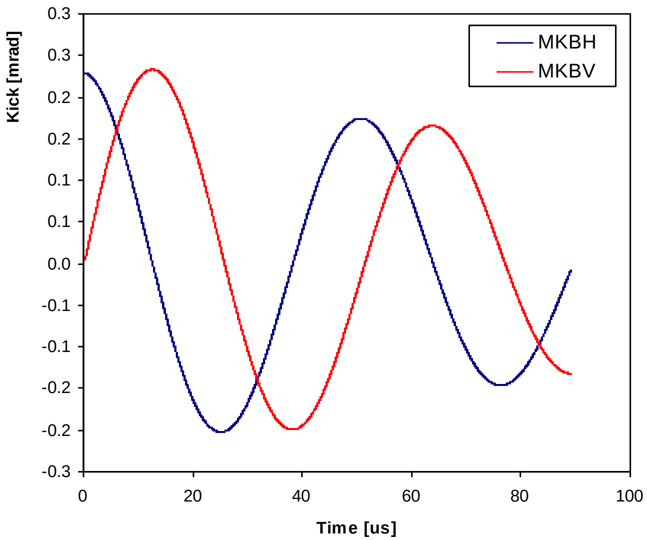
- Dilution kicker frequency increase x2 - sweep length 100 cm with spiral



108 cm sweep length 14 kHz



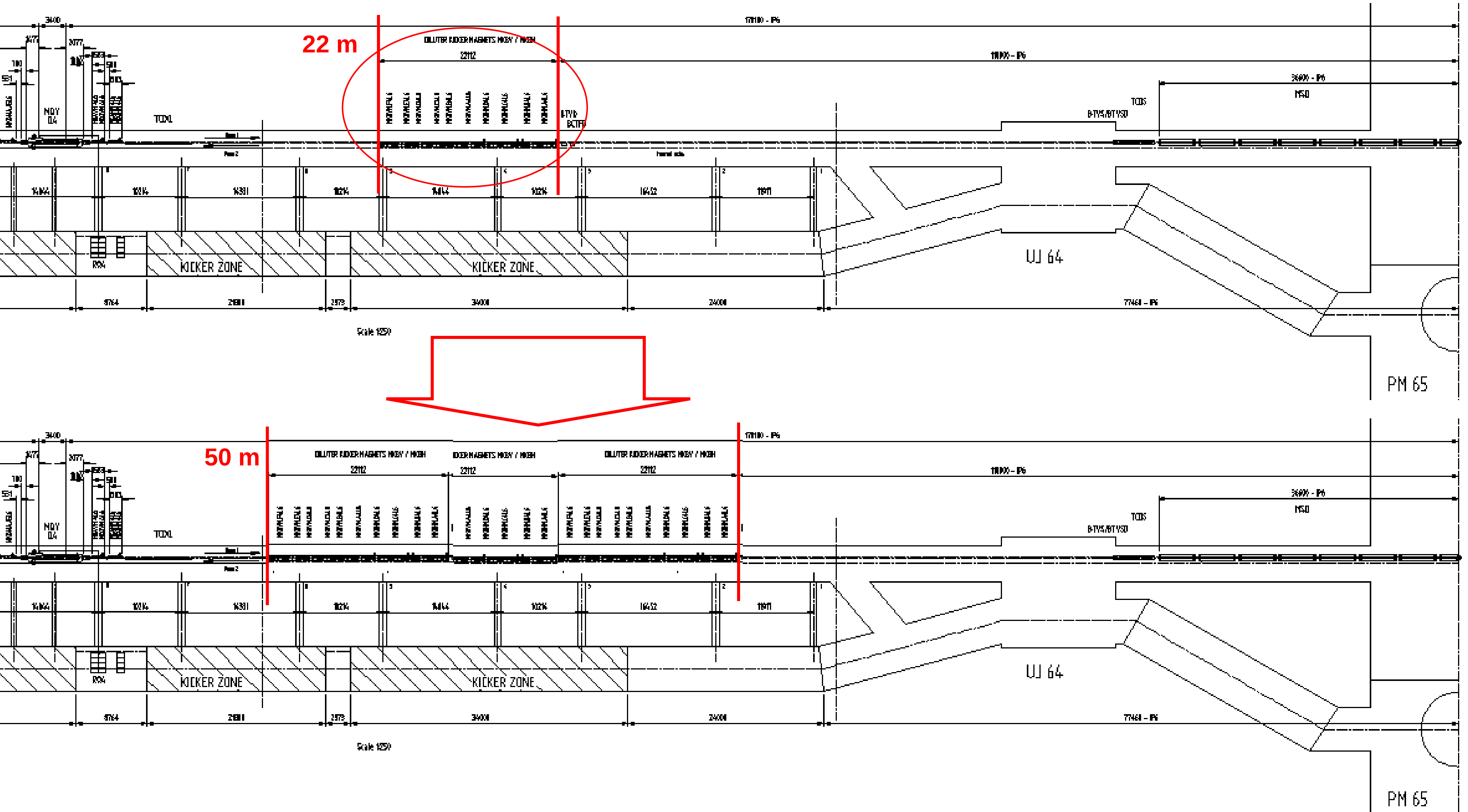
~100 cm sweep length 28 kHz



- 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

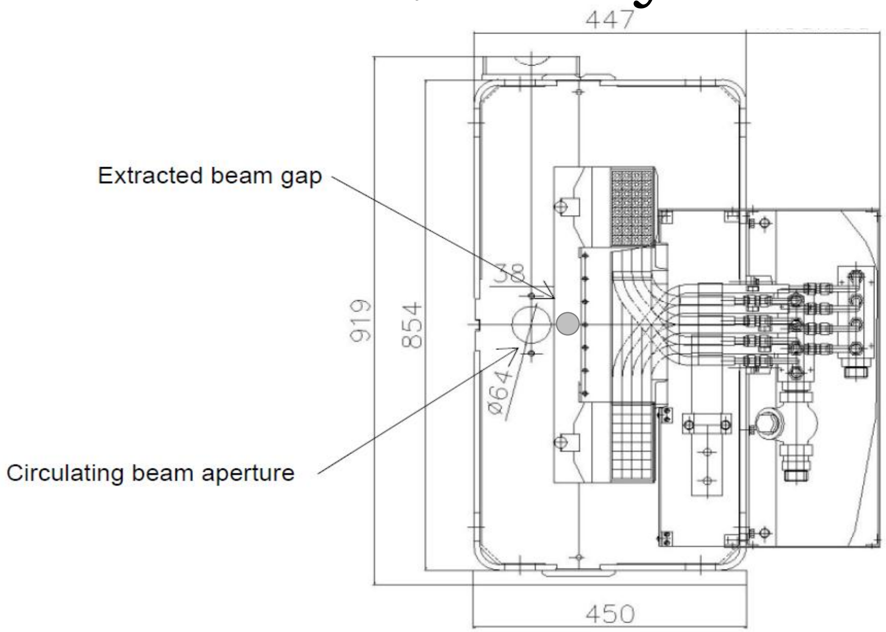
Dilution system physical installation

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



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



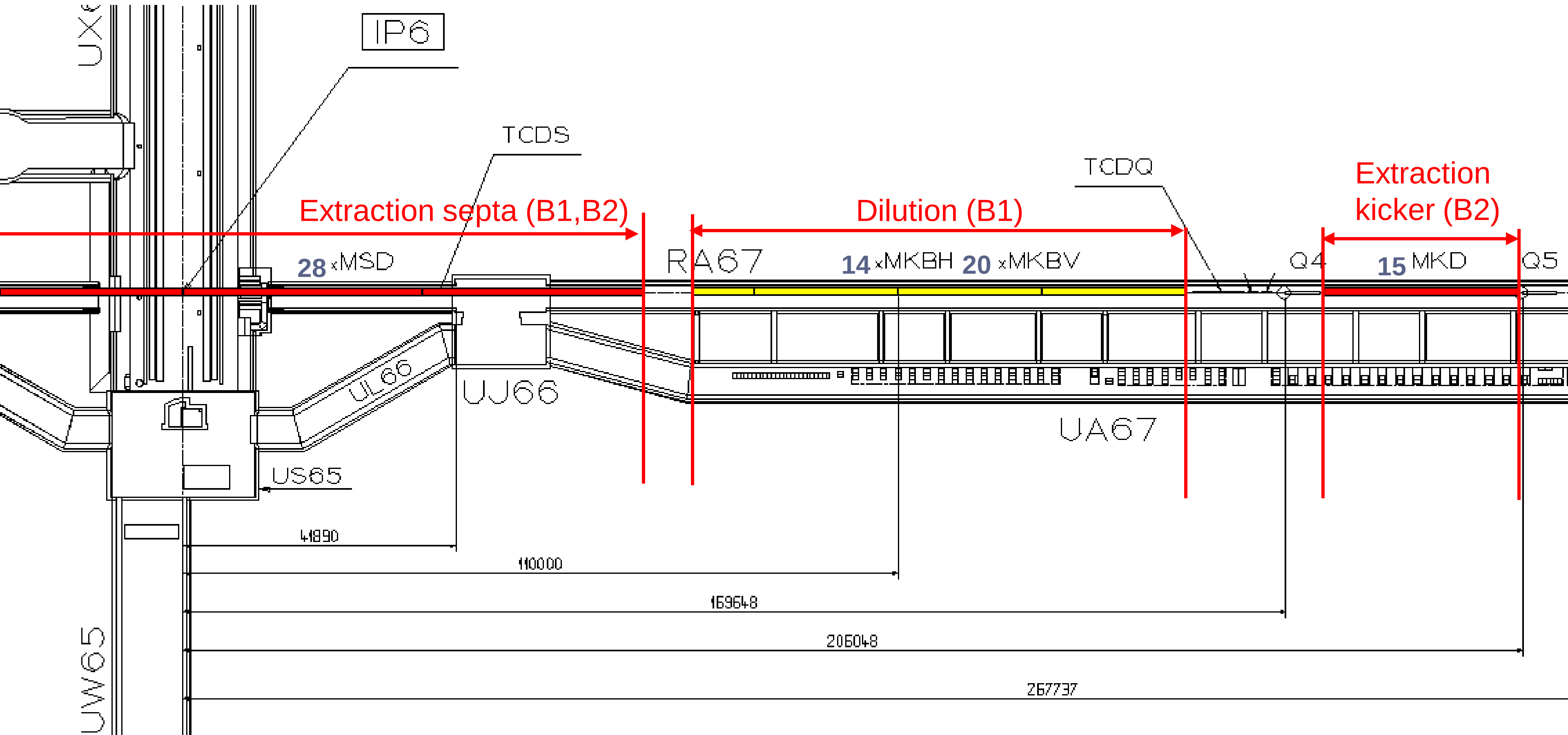
Extraction septa parameters

- 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

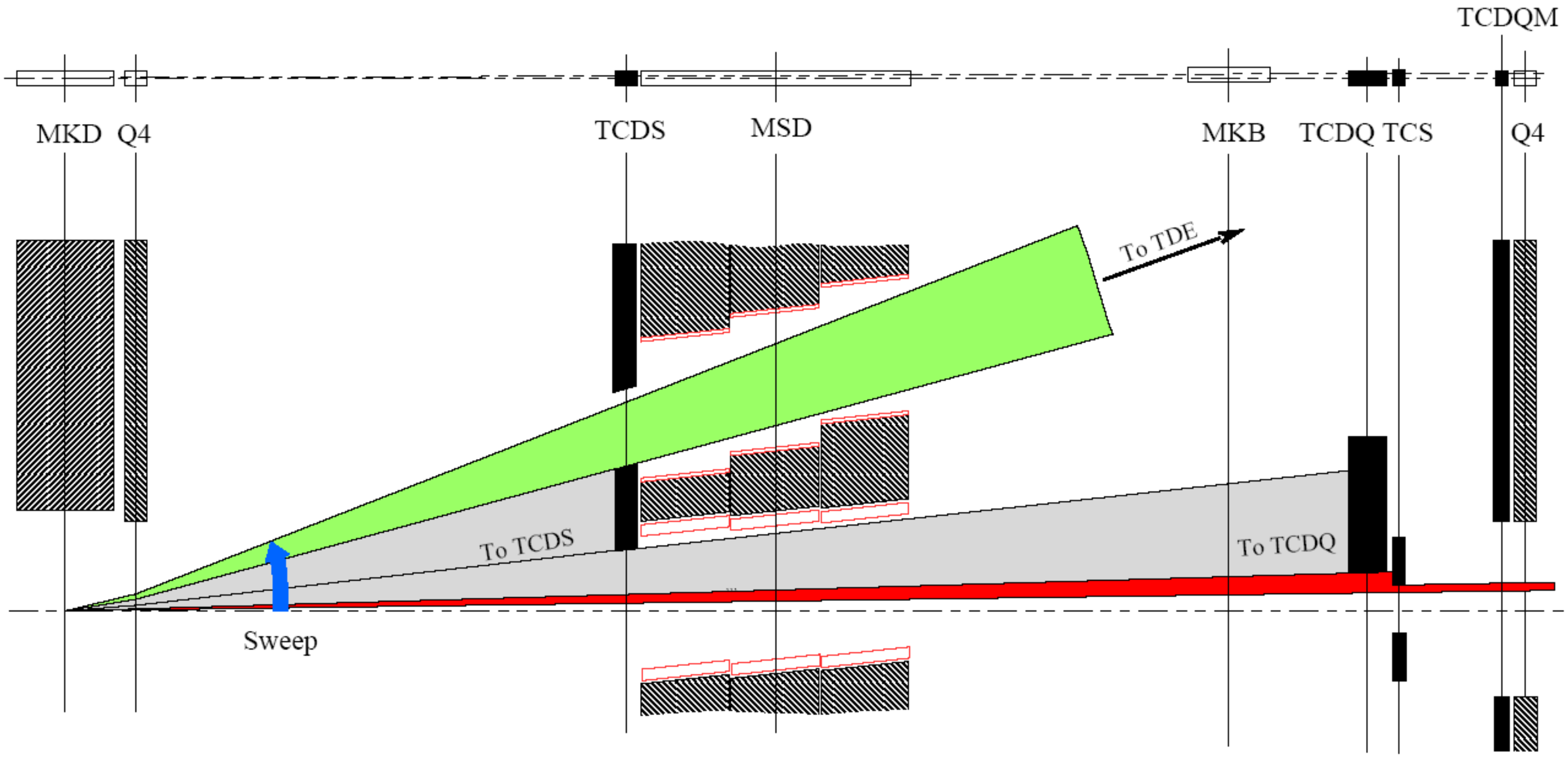
- Total magnets/beam needed : 28 (14 B + 14 C)
- Total installed length is ~136 m (present 73 m)
  - Assume 32 m extra each side of IP6

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
- Will be difficult for 16.5 TeV

16.5 T dump system outline

- 16.5 TeV dump system: does not look impossible in similar layout to present system
  - 5 μs kicker rise time (new magnet design with smaller gap) feasible
  - 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
  - Upgrade dump block (longer, lower density), seems feasible
  - Upgrade protection devices; difficult (sacrificial?)

50 TeV beam dump

- Key parameters:
  - 50 TeV energy (x7 wrt LHC ultimate)
  - 4.5 GJ stored energy (x8.5 wrt LHC ultimate)
  - 1.5 um transverse emittance
  - 264 us revolution period
  - 1.34e11 p+/bunch

50 TeV extraction kickers

- Beam rigidity: 167 T.km
- Vertical gap of ~40mm (shielded, ~30 mm for beam)
- Current of 32 kA (30 kV switches)
- Gap field of 0.92 T (peak 1.23 T)
- 230 urad deflection with 30 kicker modules
- Installed length ~55 m (x2 wrt present LHC system)
- Rise time 5.1 us
- Can foresee closed orbit bump system at dump septum
  - Reduce kicker strength requirements
  - Slow system so easy to interlock
  - Possibly 5-10 mm deflection at 50 TeV

Extraction kickers

- Extraction kicker parameters

		LHC Nominal	VHE-LHC
MKD V gap	mm	72	40
MKD rise time	us	3.00	5.10
MKD angle	mrad	0.27	0.23
MKD B.dl	Tm	6.3	38.4
MKD field	T	0.30	0.92
MKD peak field	T	0.41	1.24
MKD dI/dT	kA/us	6.17	6.17
MKD I	kA	18.5	31.5
MKD length	m	21.0	41.8
MKD Filling factor		0.761	0.761
MKD Required length	m	27.6	55.0
MKD magnets		15.0	30

50 TeV extraction kicker prefires

- Major concern for machine protection
- Seen once in LHC in 3.5 years of running – luckily with only one pilot bunch at injection
- ~8 sigma deflection per module for VHE-LHC
  - Very messy with full beam at this amplitude
- Two options for mitigation
  - 1) Retriggering with minimum delay (LHC-like)
    - Assume 1 us retriggering delay, produces ‘slow’ asynchronous dump sweeep
  - 2) add “antikicker” to trigger only by pre-trigger
    - Again with ~1 us turn-on delay
- Slowing down kicker rise time is advantage

50 TeV asynchronous dumps

- With some good design, pre-trigger of one module can be reduced to (almost) the same load case as an asynchronous dump
- Again, seen in LHC, but without beam
- ~10x energy density (per swept mm) c.f. LHC
- Will rely on passive protection
  - In front of extraction septum
  - In front of next lattice quadrupole
  - In front of experiments
  - At impacted collimators
- Excellent optics control may allow clever design of diluter/sacrificial absorber to protect machine
- Also rare event (kicker design and surveillance)
- Splitting kickers further could also help (x60??)

50 TeV extraction septa

- Around 2 mrad angle at 50 TeV needs 330 Tm!
  - Scaled-up present LHC system would work…although at least 350 m needed in lattice
- Options to explore would be:
  - Long sequence of normal conducting septa (thin, thick Lambertson, open C-core dipole). Cannot save much in length.
  - Superconducting septa (not really any issue if they quench with passage of dumped beam)?
  - Hybrid SC extraction lattice quadrupoles, with passage for extracted beam, ideally providing dipole field for additional deflection?
  - Make problem easier with “slim” lattice SC quads?

50 TeV dilution system

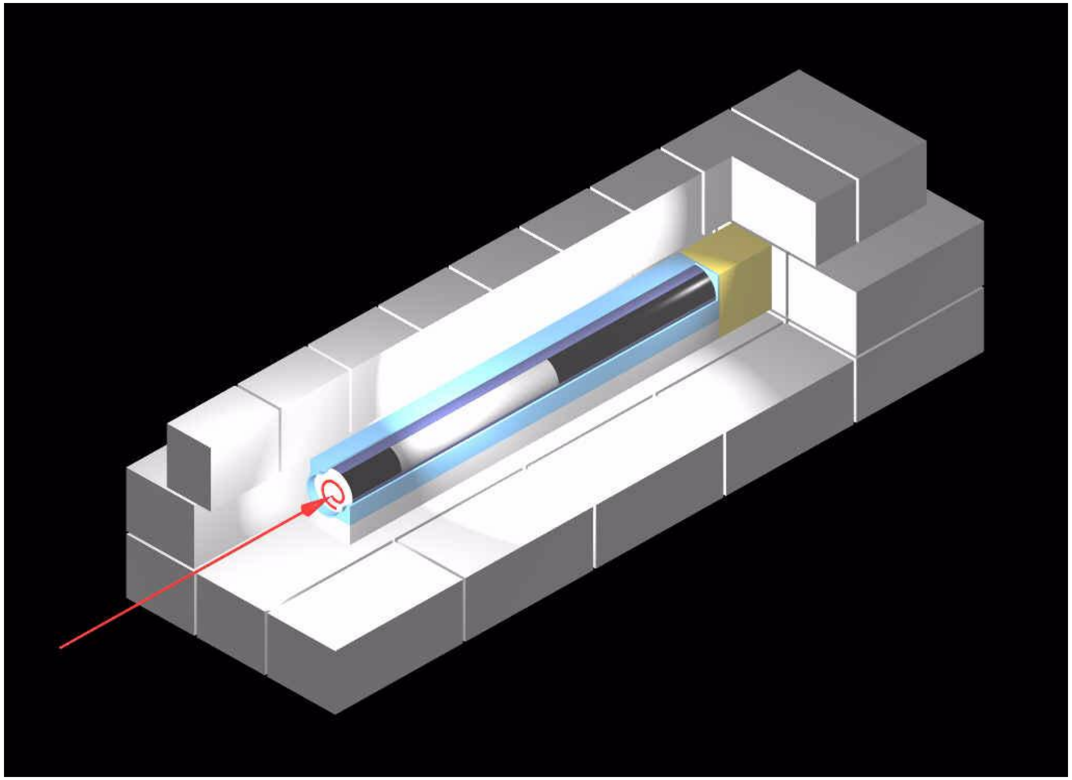
- 4.5 GJ in 264 us
- Need to increase dilution sweep length from present LHC ~100 cm to around 700 cm
  - for same peak energy density per swept linear mm
- 12 kHz frequency, sweep length becomes ~750 cm in 264 us, with 2 km drift
- Assume same nominal/peak field of 1.13/1.5 T
- Switch voltage then becomes 23 kV (from 27!)
  - Magnets already close to saturation – can't increase
- Installed length increased by x7, to ~160 m
  - No impact on lattice, as all are in dump line
- Sweep diameter ~110 cm (3 turn spiral)

Dilution

- Dilution kicker system parameters

		LHC Nominal	VHE-LHC
MKB frequency	kHz	14.0	12.0
MKB angle	mrad	0.27	0.27
MKB B.dl	Tm	6.3	45.1
MKB field	T	1.13	1.15
MKB peak field	T	1.52	1.55
MKB voltage	kV	26.70	23.40
MKB I	kA	25.0	25.6
MKB length (H+V)	m	11.2	78.4
MKB Filling factor		0.49	0.49
MKB Required length	m	22.9	160.0
MKB magnets		10	70

Dump block at 50 TeV

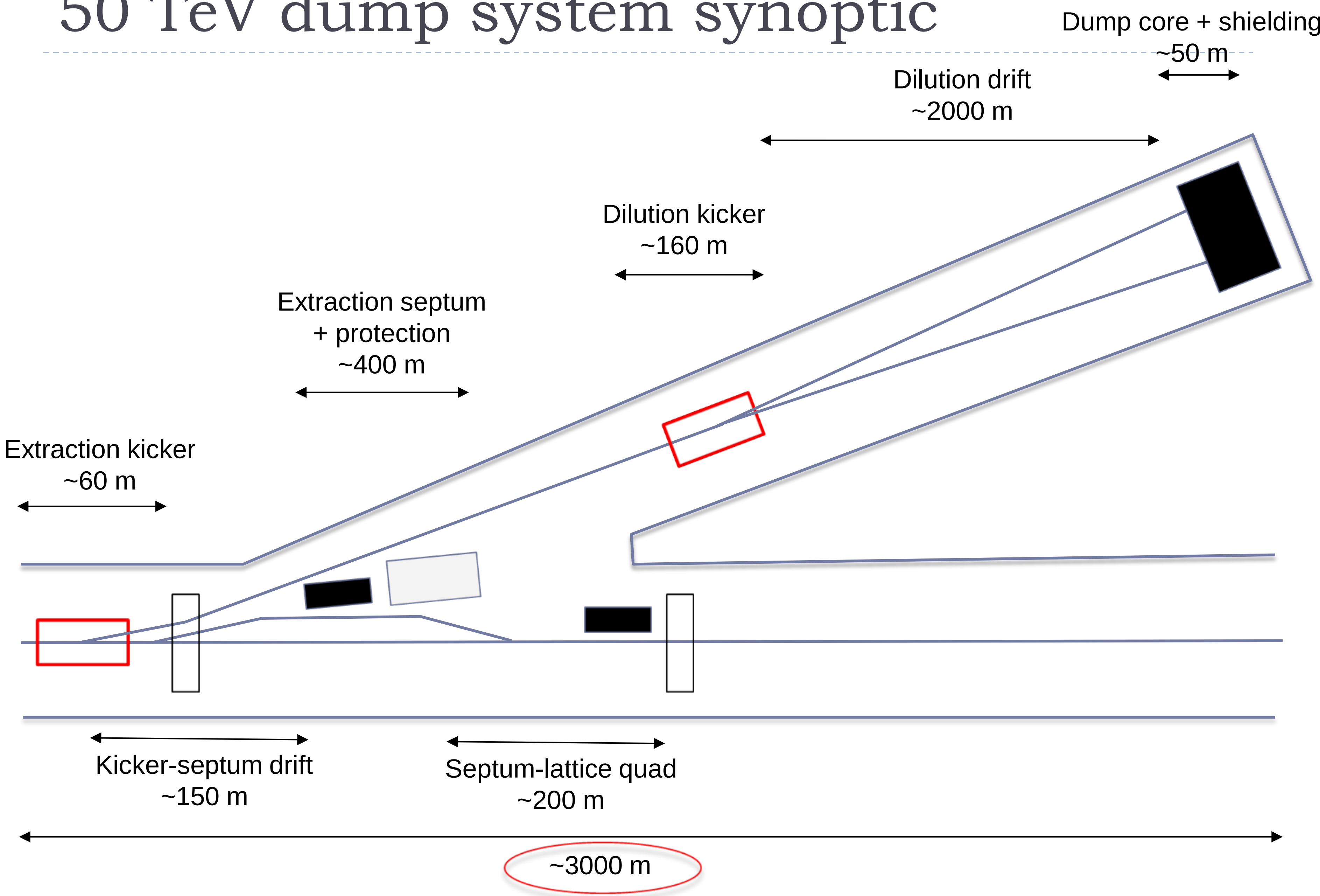


- Need ~2 km drift from dilution kickers to develop sweep
- Inner core ~1.5 m diameter, 10-15 m length?
- Thermal stresses need careful evaluation
- 4.5 GJ/8 h is about 150 kW average power….
- C? Or sthg more radical: pressurized water? ice?

50 TeV dump system outline

- ~60 m, 0.2 mrad extraction kicker (before QD)
- 5-10 mm closed orbit bump at septum
- 5-6 us abort gap (not much gain to make longer)
- Antikicker for pre-trigger mitigation?
- Passive/sacrificial septum protection
- Extraction septum could be area for studies
  - SC septum?
  - Combined lattice SC quadrupole/septum?
  - "Slim" SC lattice quadrupole?
  - ~350 m of warm septum???
- Dilution system: 33 kHz, 160 m of kickers
  - Investigate more elegant options (if we think of any!)
- 2 km drift to Ø1.5 m x 10 m CfC dump block?

50 TeV dump system synoptic



Summary

- 16.5 TeV dump system in present LHC tunnel
  - Extension of present system seems feasible
  - New extraction kickers, more septa, more diluters
  - Robustness of protection devices dumps likely to be an issue, but seen in LHC Run 1 to be ‘rare’ events.
- 50 TeV dump system for VHE-LHC
  - It will be a monster (~3 km long from kicker to dump?)
  - Think about best approach for septum – maybe SC?
  - However we design them, passive protection devices will likely be sacrificial, …
  - Dump block thermal loading to look at in detail

Potential R&D directions

- High-current switches and feedthroughs
  - >30 kA needed for VHE-LHC extraction kickers
- High voltage, high current, fast turn-on solid-state switches
- SC septa
- Combined SC quadrupole/septum
- “Slim” SC quadrupoles
- Sacrificial protection devices
- Alternative dilution methods
- Beam dump materials/concepts/energy deposition

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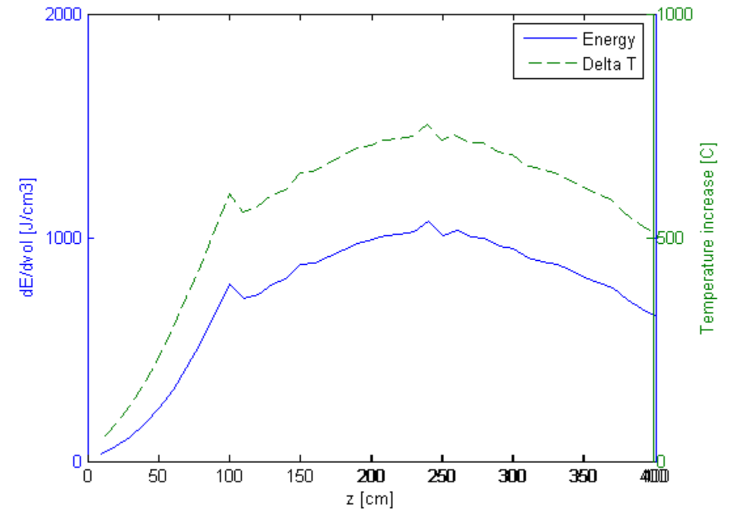
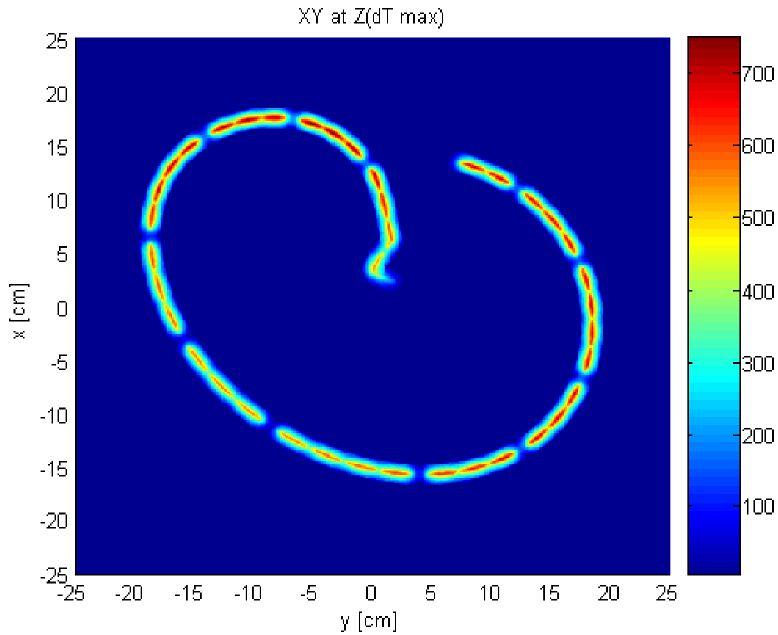
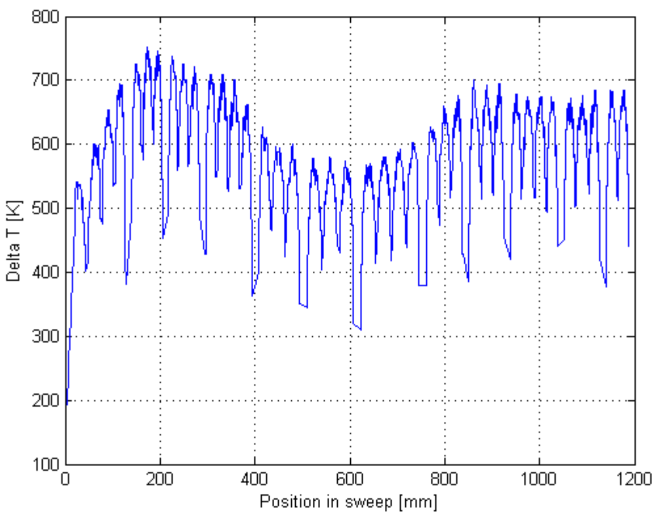
Temperature rise in dump block



Peak energy deposition along dump block length

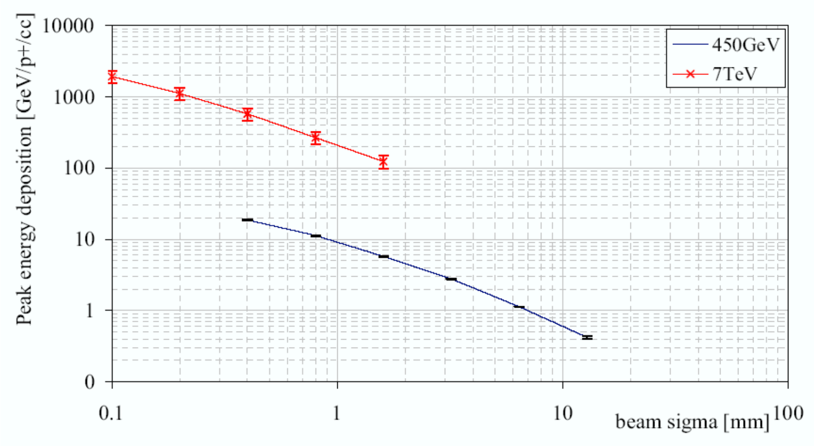


Temperature profile through dump block at Z=250 cm



Temperature profile along sweep path at Z=250 cm

Dump protection – difficult with increasing E

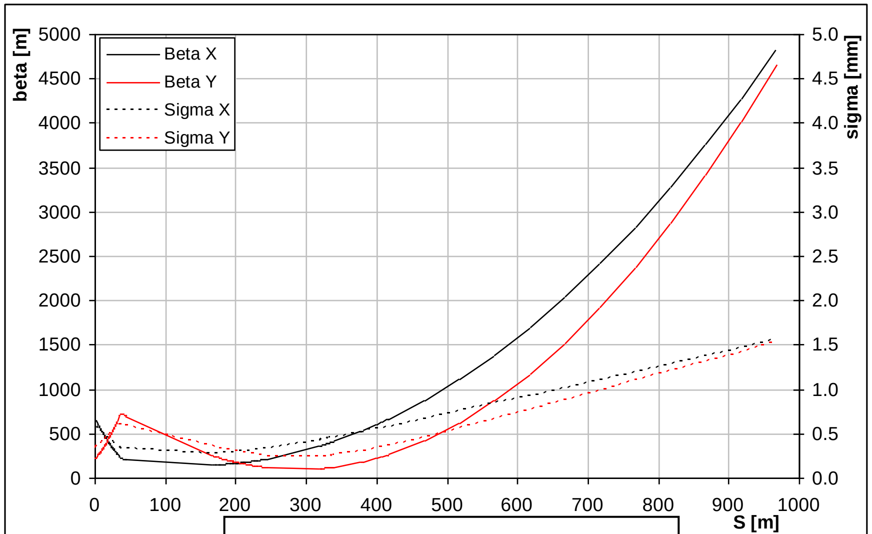


Peak GeV/cc in Cu vs beam size at 450 GeV ad 7 TeV

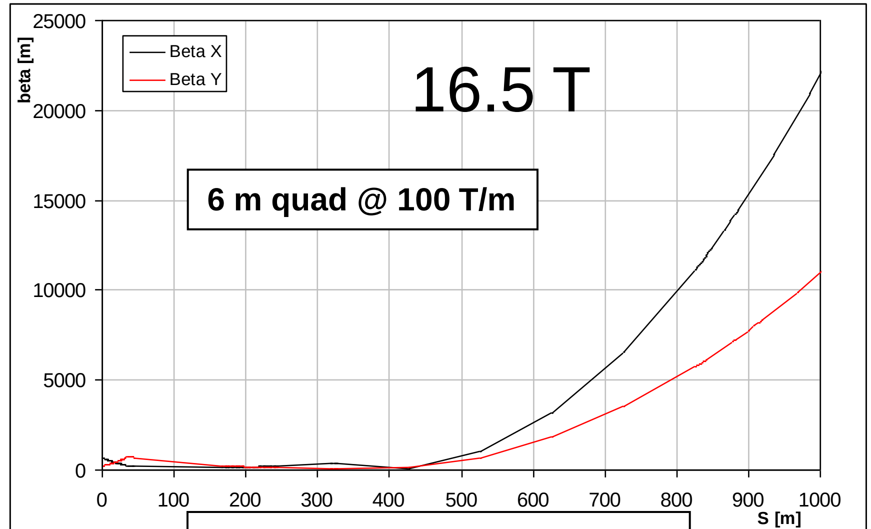
- Low density to avoid material damage
- More total material required to dilute energy density
- Very long objects as a result…
- …reduces apertures for extracted beam
- Or use sacrificial absorbers – exchange after (hopefully rare) impacts with high intensity

- 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

(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 : Ø ≈ 0.8 m
- Integration likely to be an issue upstream of diluter kickers