Beam absorbers for Machine Protection at LHC and SPS

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Based on the work of many colleagues, in particular:

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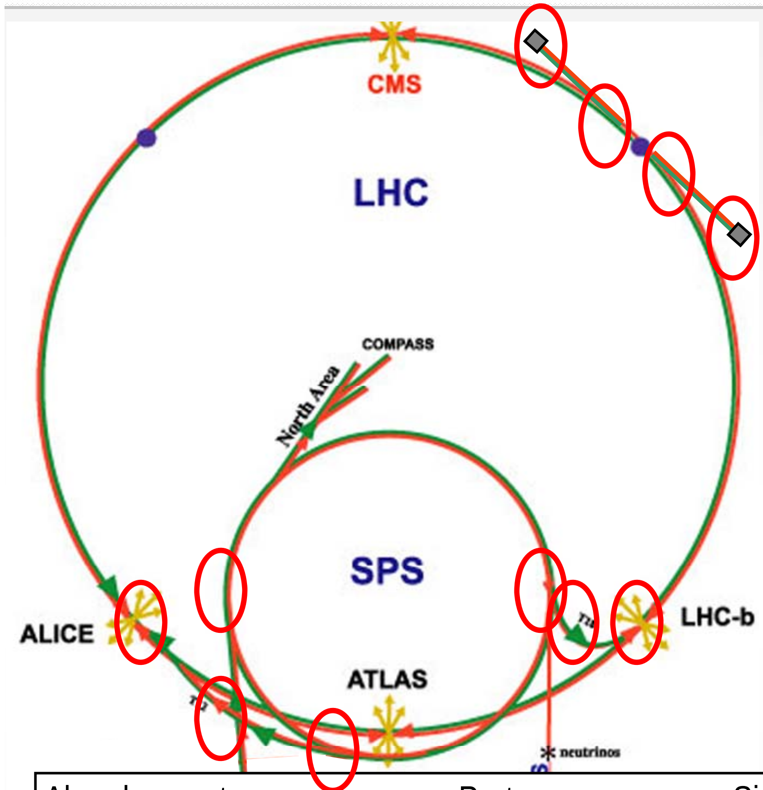
The LHC and SPS Machine Protection Absorber Zoo



Absorbers for machine protection –

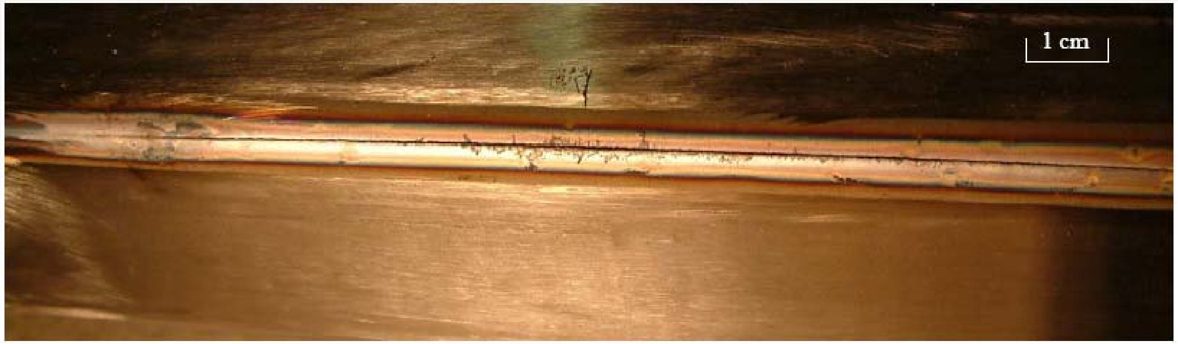
- **Dedicated beam intercepting devices to protect downstream elements against specific failures – in general those of fast pulse kicker magnets. Solicited for accident cases (hopefully rare)**
- **Beam dumps which need to be able to repeatedly absorb full beam, on a regular basis. For these beams are often deliberately swept or diluted to reduce the energy density**

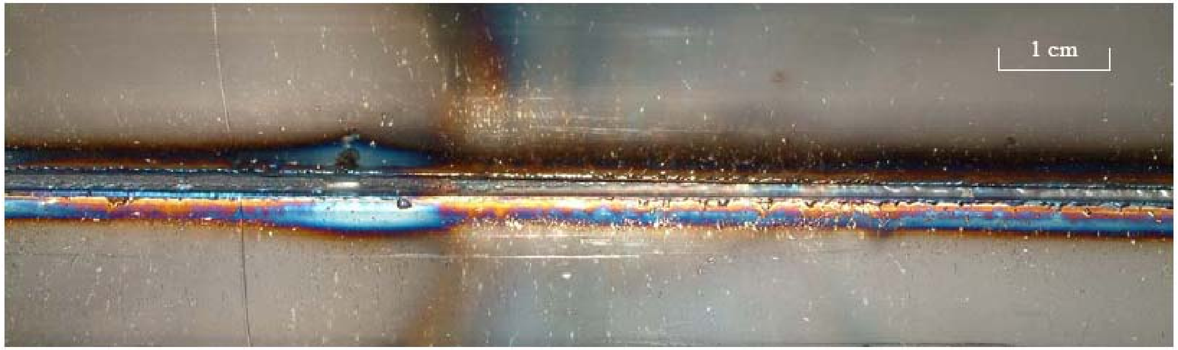
Absorber system	Proton energy GeV	Sigma H mm	Sigma V mm	Total Intensity p+	Intercepted Beam energy MJ	Sweep dilution factor	Energy density MJ/mm2
SPS internal beam dump	450	0.4	0.8	3E+13	2.4	50	0.02
SPS extraction protection	450	1.0	0.4	3E+13	2.4	1	0.83
SPS-LHC transfer protection	450	0.8	0.6	3E+13	2.4	1	0.79
LHC injection protection	450	0.9	0.6	3E+13	2.4	1	0.69
LHC extraction protection (I)	7000	0.28	0.34	6E+12	6.4	17	0.33
LHC extraction protction (II)	7000	0.48	0.28	4E+12	4.6	18	0.18
LHC beam dump	7000	1.59	1.36	3E+14	362	150	0.20

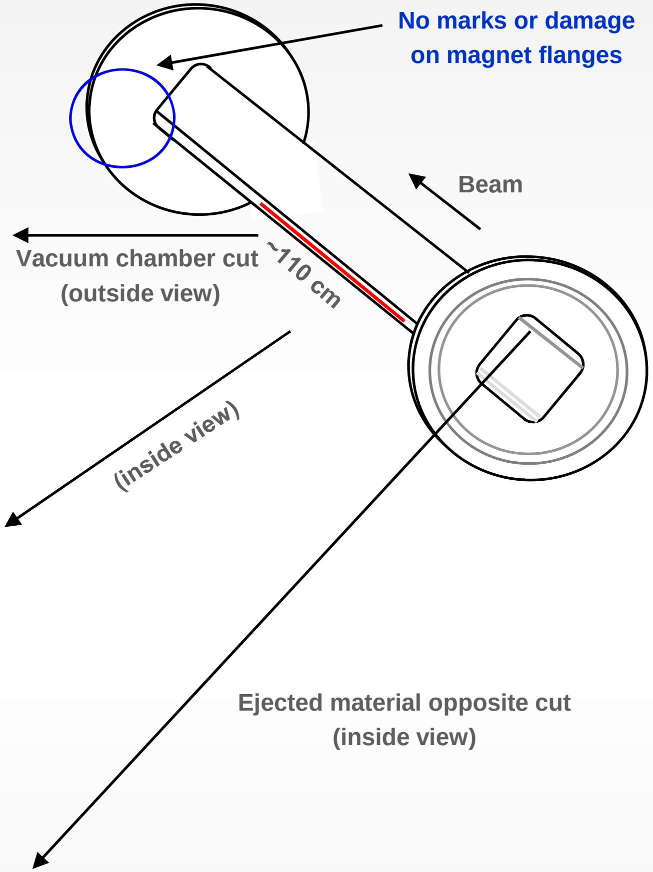
SPS beam characteristics

- **LHC beam extraction from the SPS**
  - 450 GeV/c, 288 bunches at 25 ns spacing
  - Transverse beam size ~0.7 mm (1 σ) with $\varepsilon_n \approx 3.5$ π.mm.mrad
  - 1.15 x 10^{11} p+ per bunch, for total intensity of 3.3 x 10^{13} p+
  - Total beam energy is 2.4 MJ
- **Well above damage limit**
  - Limit of about 2 x 10^{12} 450 GeV p+ (material at ~melting point)
  - FLUKA + benchmark studies
  - Normal incidence
- **Fast loss limit**
  - ~5 % of extracted beam

Beam damage during LHC beam extraction from SPS



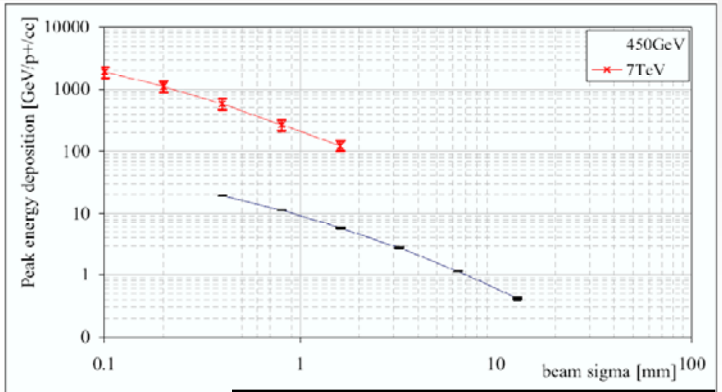




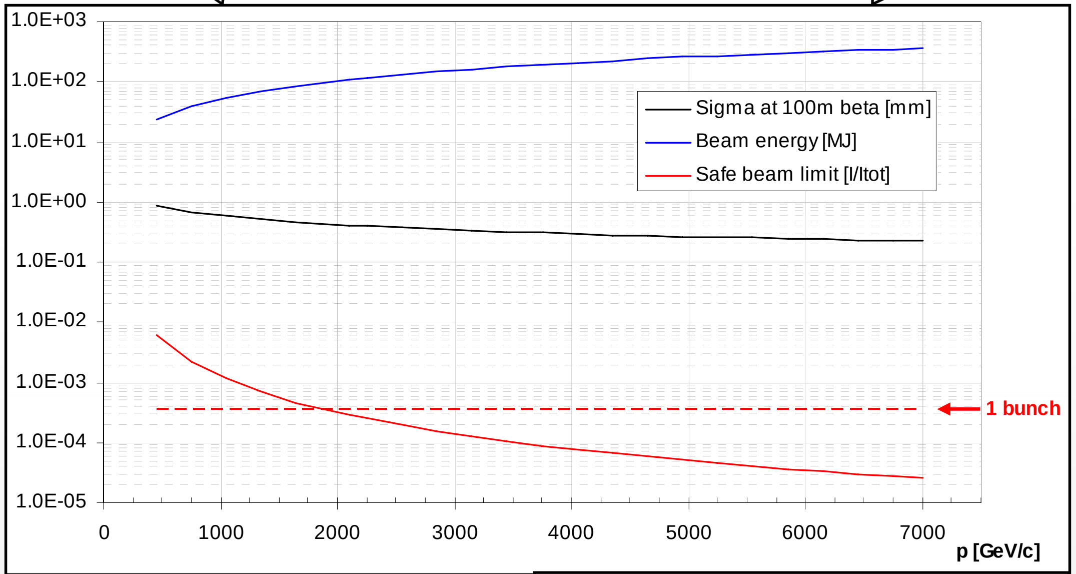
LHC beam characteristics

		Injection	Collision
Beam Data			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		1.15×10^{11}	
Number of bunches		2808	
Longitudinal emittance (4σ)	[eVs]	1.0	2.5[a]
Transverse normalized emittance	[μm rad]	3.5[b]	3.75
Circulating beam current	[A]	0.582	
Stored energy per beam	[MJ]	23.3	362

LHC beam characteristics



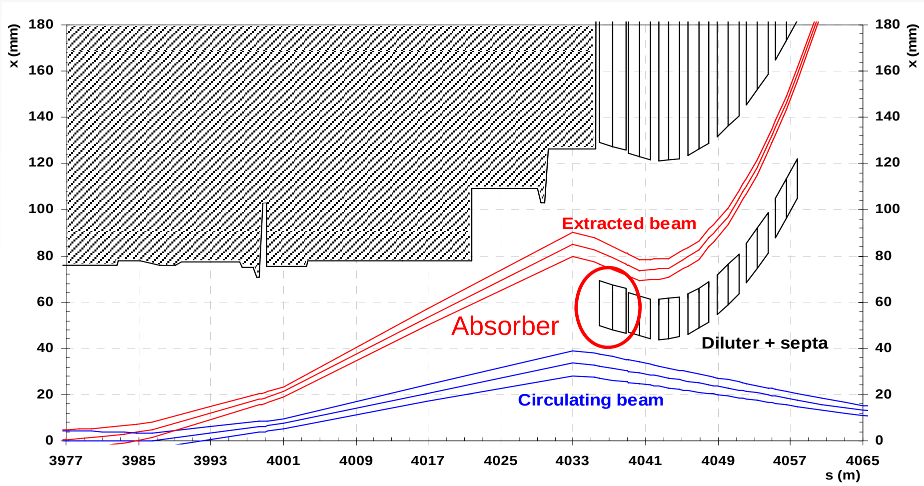
Peak energy deposition E_{dep} in Cu vs beam sigma, for 450 GeV/c and 7 TeV/c protons

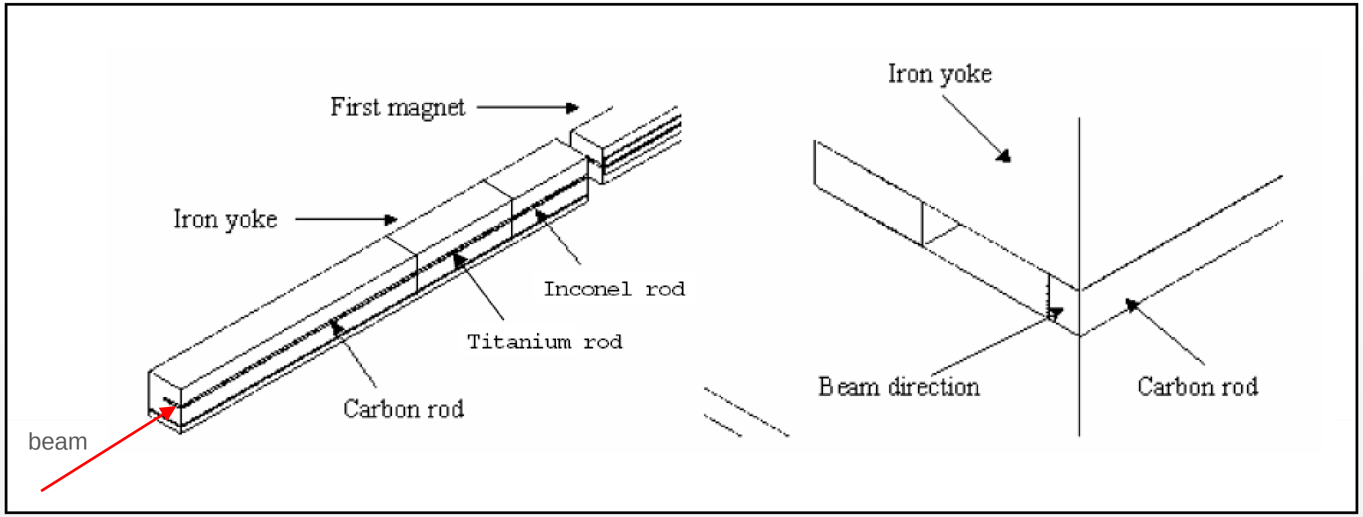


Variation of beam sigma, stored energy and safe fast loss limit from 450 GeV/c to 7 TeV/c

Absorbers for SPS extraction

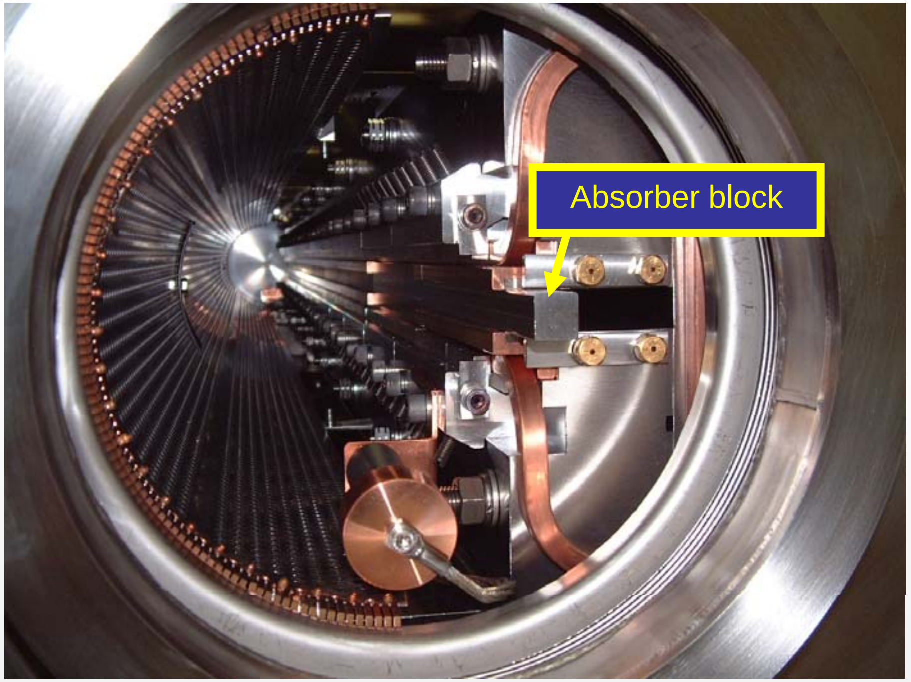
- **Fast extraction in H plane with orbit bump, fast kickers and DC septum**
- **Fixed absorber to protect extraction septum magnets (expensive, delicate, water-cooled and radioactive)**





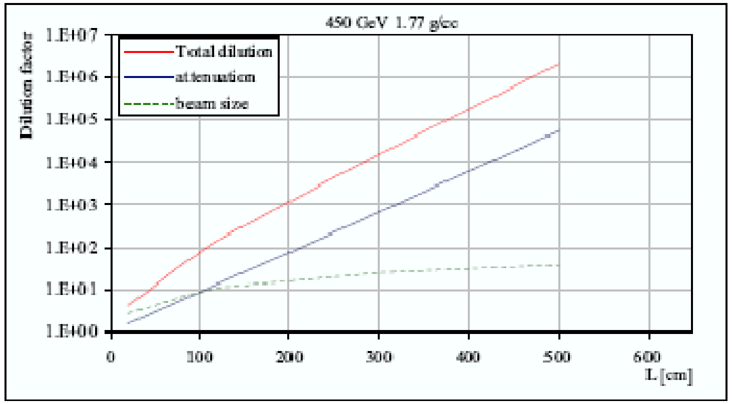
Absorbers for SPS extraction

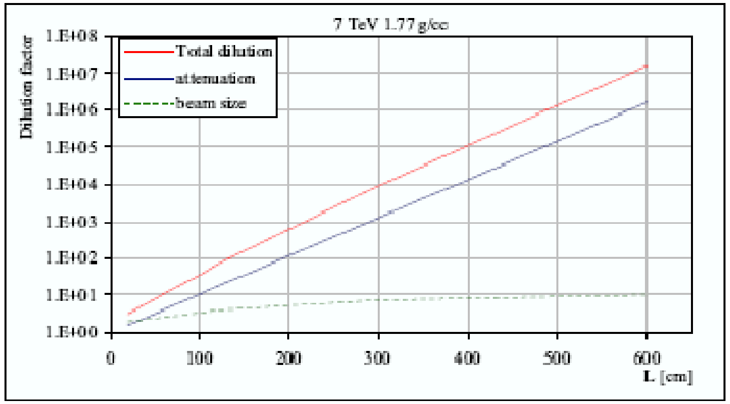
- Essentially a 'dummy septum" which must dilute the energy deposition to a safe level
- Dedicated device used to protect the local downstream element
- Stringent design criterion: septum water ΔT of 9º $\rightarrow$ 20 bar ΔP (more constraining that Cu damage limit)
- Space constraints: only ~3 m - septum is just downstream
- No room for more material
- No drift length between absorber and septum
- Difficult to get absorber AND septum to survive design impact
- Bad surprises with dynamic thermal stresses



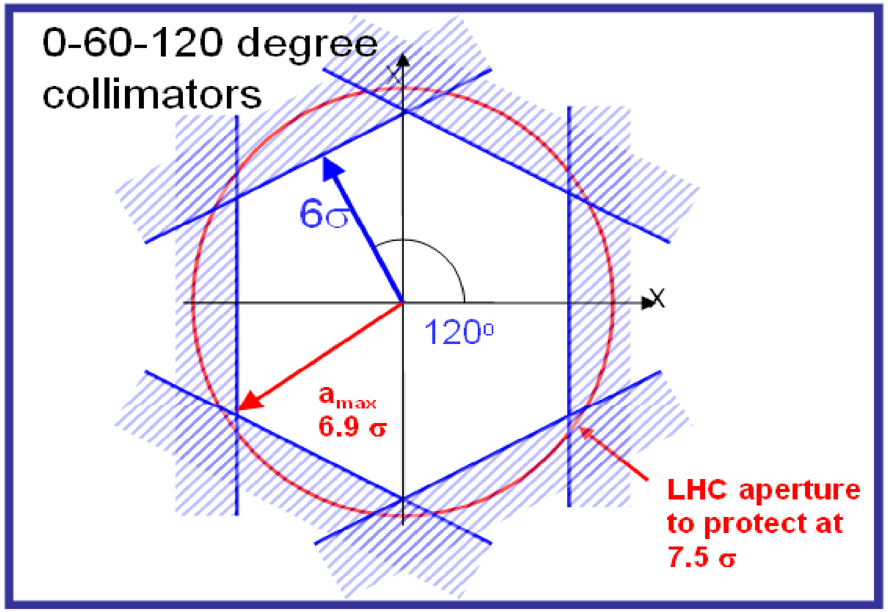
Absorbers for SPS-LHC transfer systems

- Generic protection against failures during beam transfer
- Multiple phase coverage (since source of error unknown)
- Short (~1 m) C devices provide very large <u>effective</u> dilution at lower energies by nuclear interaction AND emittance growth by scattering



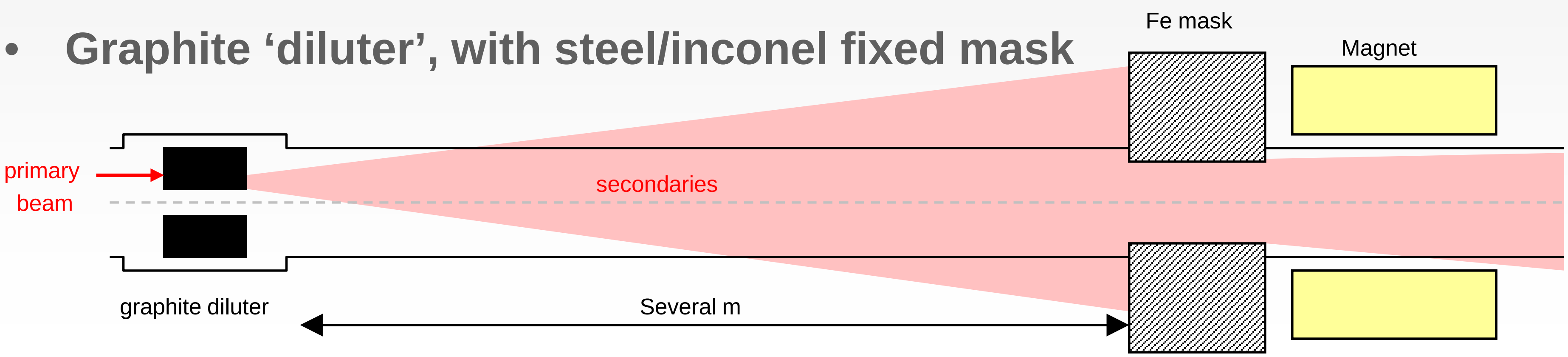


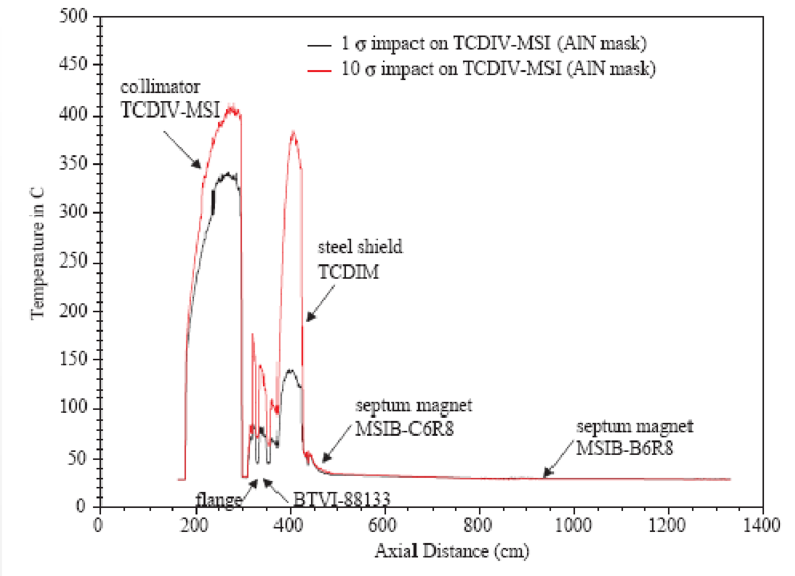
Dilution efficiency vs. length for p+ in 1.77 g/cm^3 C

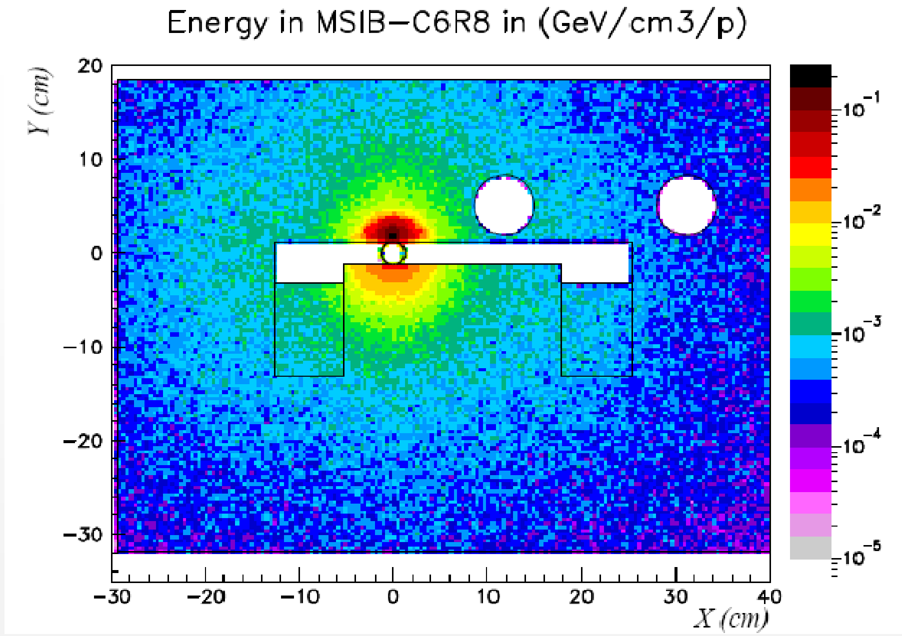


Absorber is a "diluter + mask" system

- Take advantage of 'long' drift lengths available
- Graphite 'diluter', with steel/inconel fixed mask

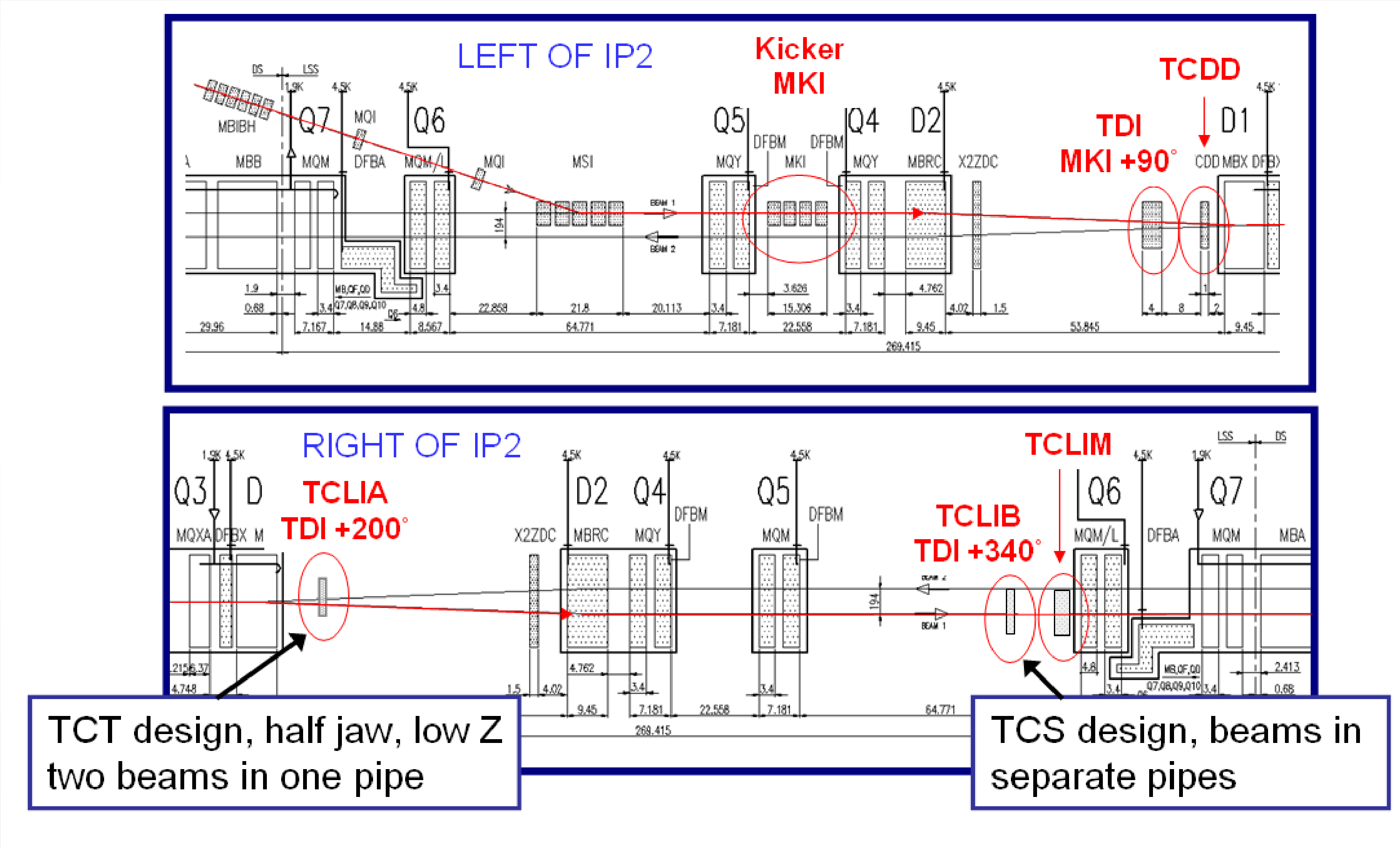






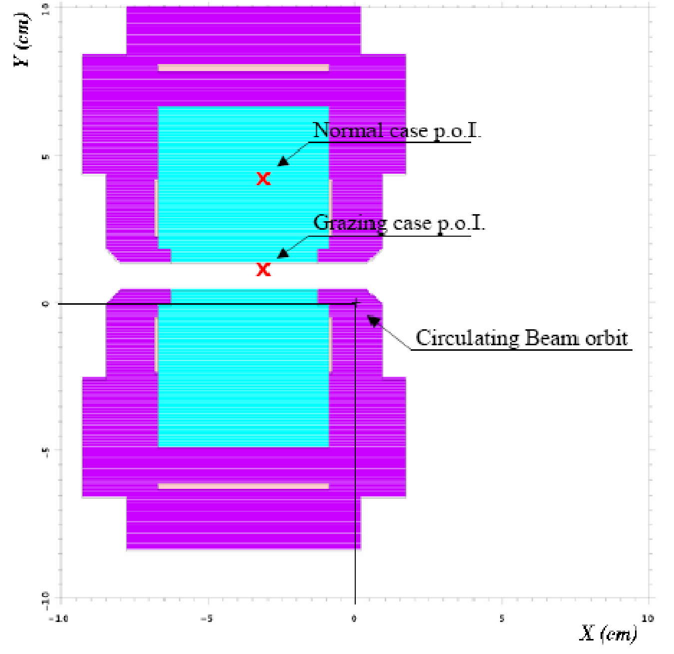
Absorbers for injection protection

- **Injection into LHC - in case of injection kicker failures have dedicated mobile absorbers and fixed secondary masks**

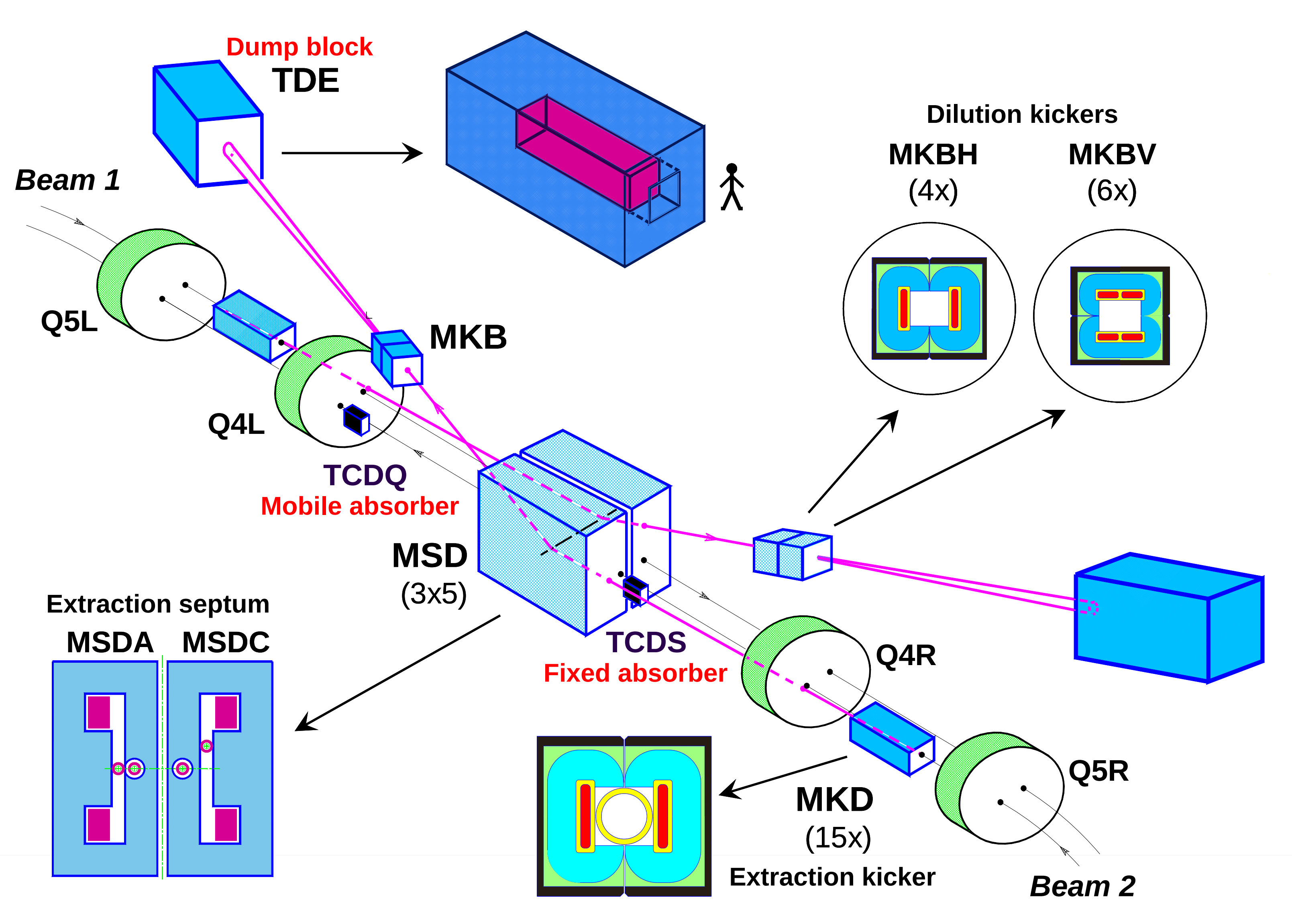


Absorbers for injection protection

- **Main absorber is designed to 'stop' the beam**
  - 4.2 m long, with 2.9 m hBN, 0.6 m Al and 0.7 m Cu.
- **Grazing incidence cases give a lot of energy escaping**
  - Downstream fixed 'mask' to protect the superconducting dipole coils

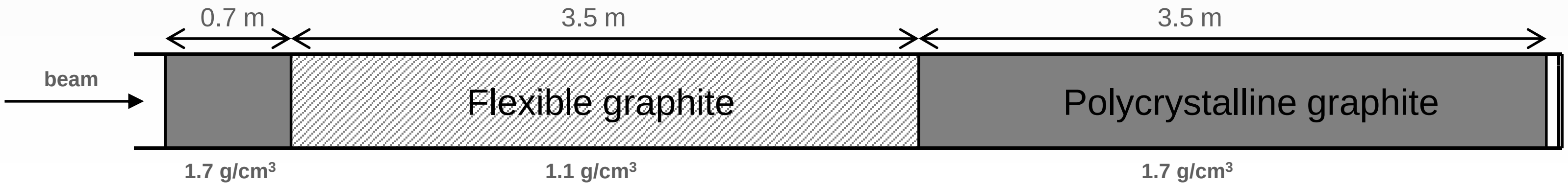


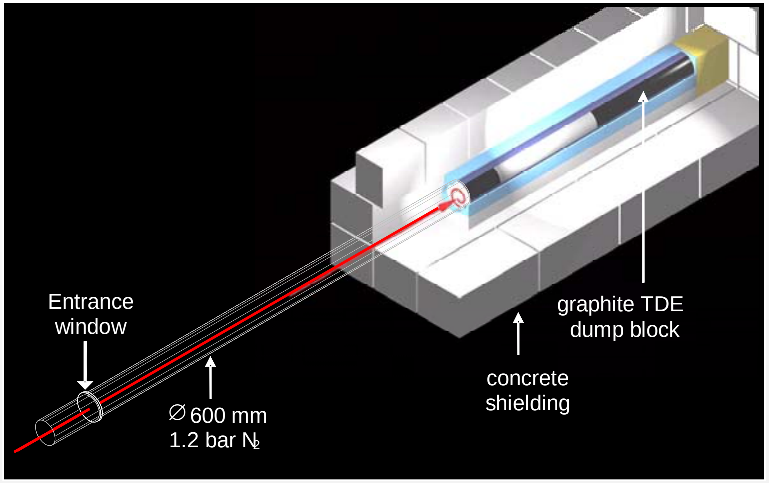
LHC beam dump system (and acronyms)



Beam dump block

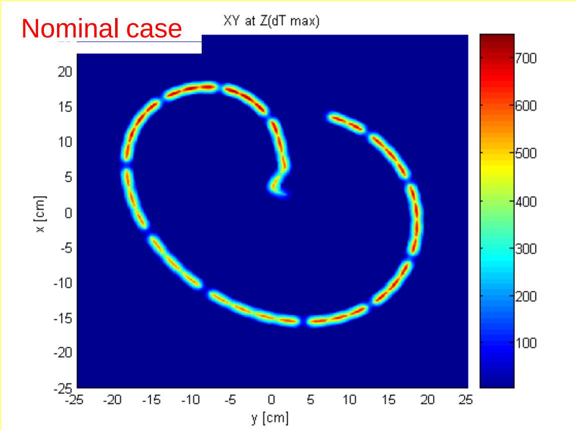
- 700 mm ∅ graphite core, with graded density of 1.1 g/cm^3 and 1.7 g/cm^3
- 12 mm wall, stainless-steel welded pressure vessel, at 1.2 bar of N_2
- Surrounded by ~1000 tonnes of concrete/steel radiation shielding blocks



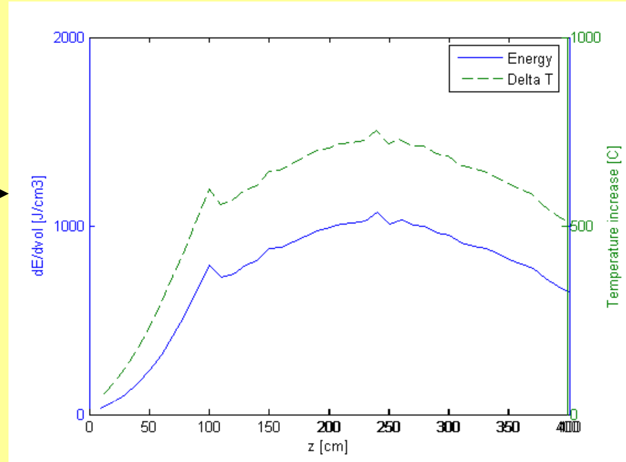


Temperature rise in dump block

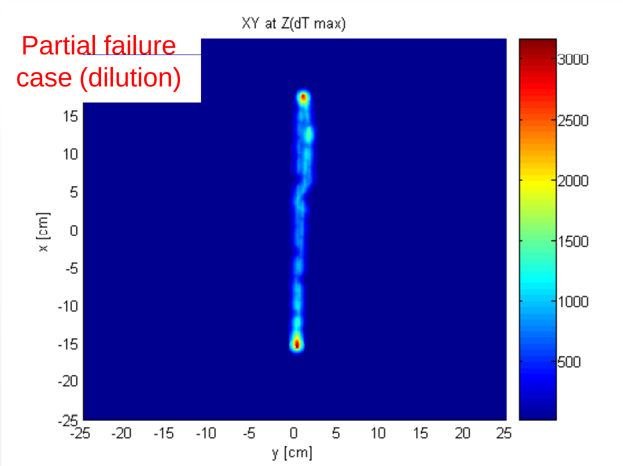
Beam drifts for ~500 m (gives large 1.5 mm σ) and swept ~100 cm by active dilution kickers



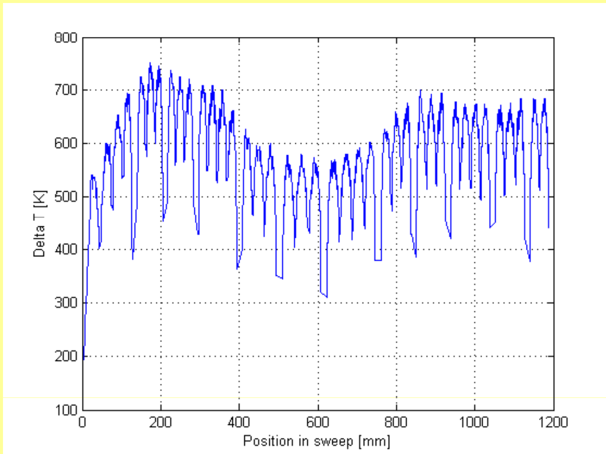
Temperature profile through dump block at Z=250 cm



Temperature profile along dump block length



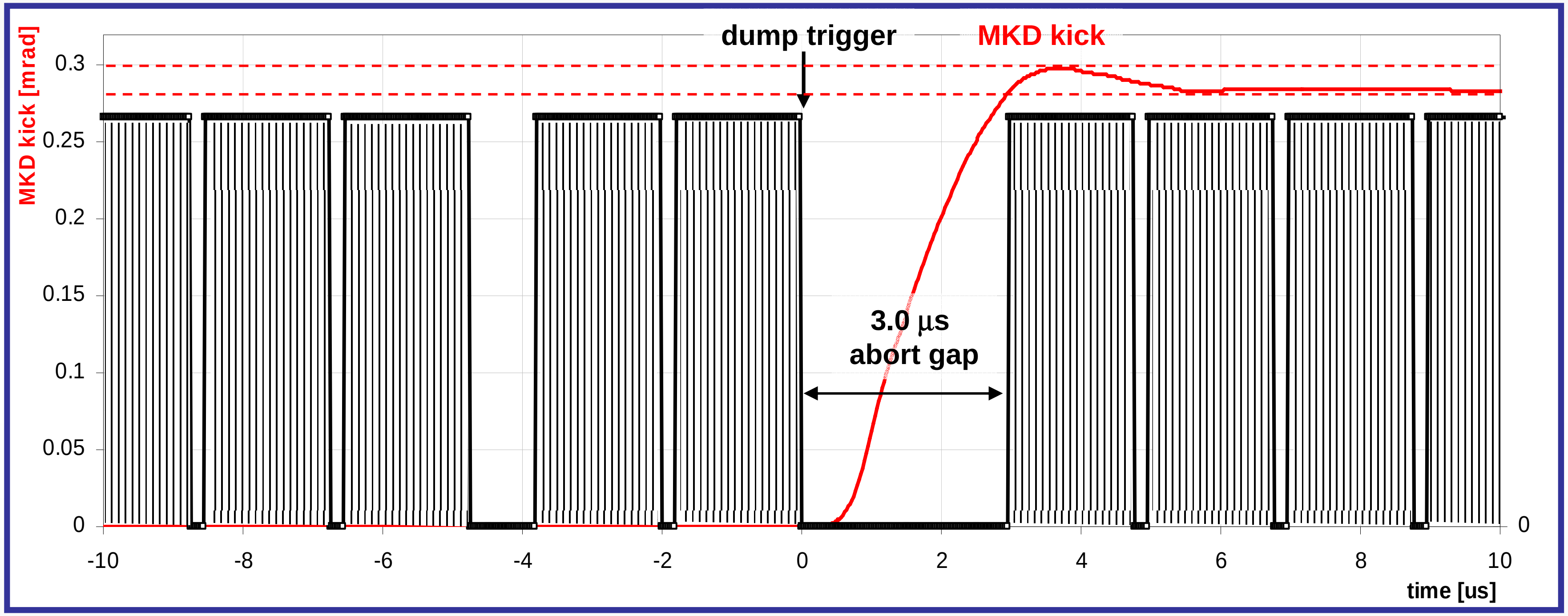
Horizontal dilution kicker failure



Temperature profile along sweep path at Z=250 cm

Dump failures

Synchronisation of dump with circulating beam



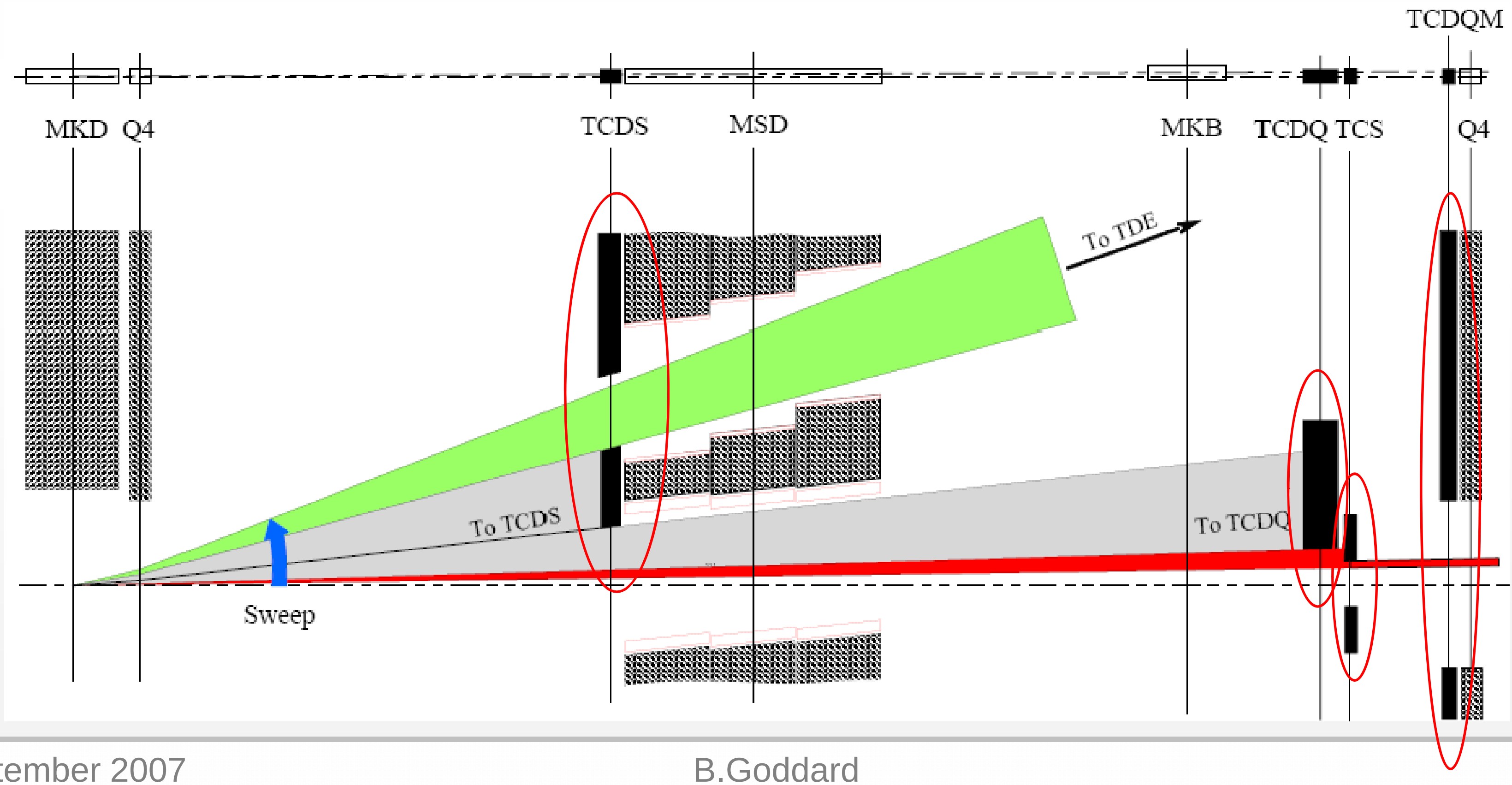
Beam losses will occur if:

- the dump trigger is not synchronised with the abort gap
- the abort gap contains spurious particles
- the extraction kicker field is not in tolerance
- the local orbit is out of tolerance

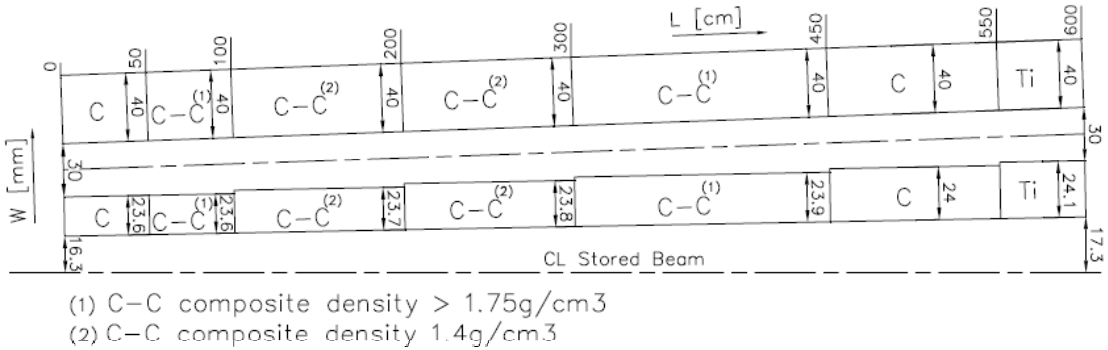
} absorbers

Local absorbers for dump failures

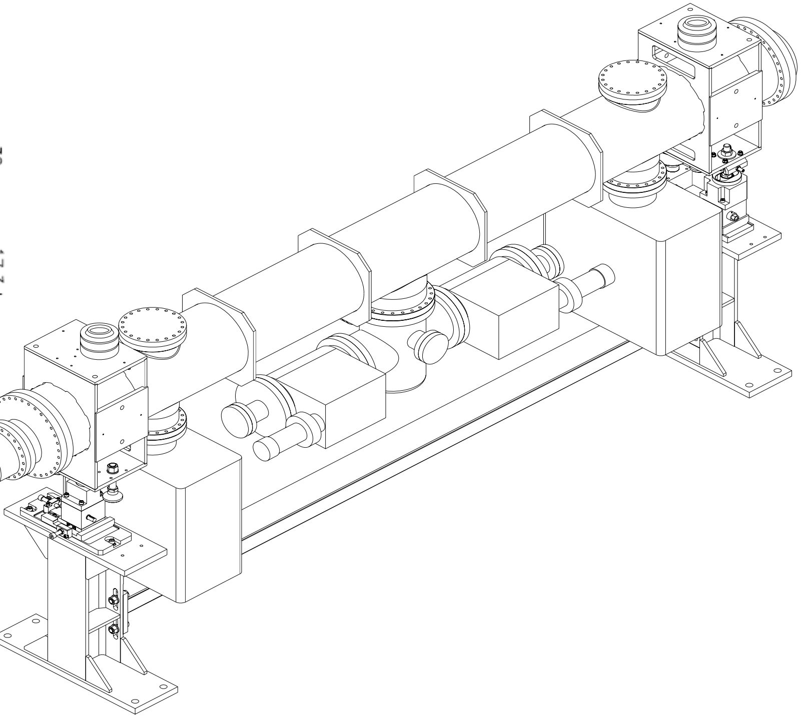
- **Dedicated "robust" absorbers in dump region**
  - Fixed 6 m long absorber to protect extraction septum
  - Mobile 6 m long single-sided absorber at ~7 σ from the beam
  - Mobile 2-sided absorber (LHC secondary collimator) for precise adjustment and positioning
  - Fixed 2 m long steel mask to protect quadrupole and downstream LHC elements
- **Also protection elements on each triplet (last resort) – Ralph's talk.**

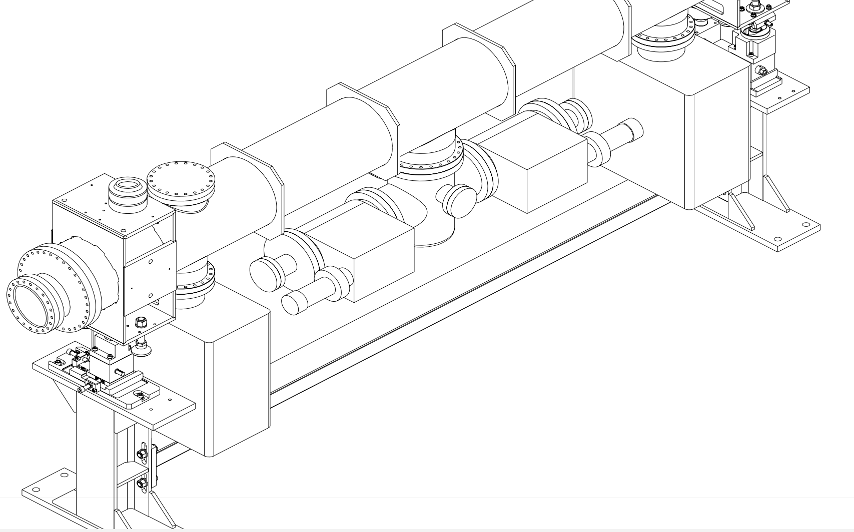


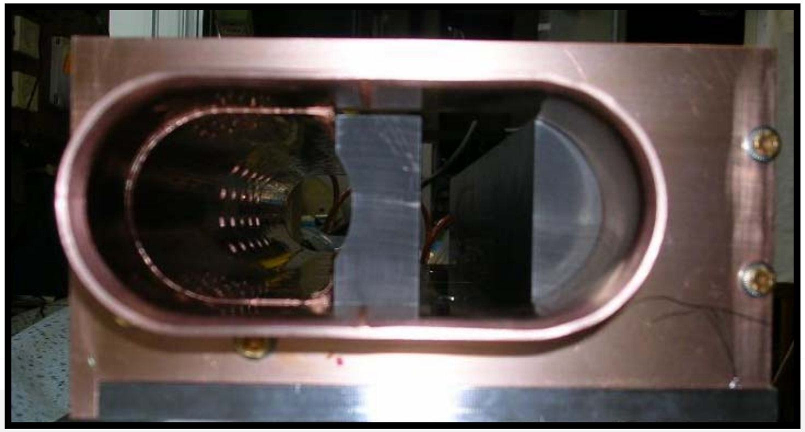
Fixed diluter to protect extraction septum



- 2 x 3 m absorbers in separate vacuum tanks
- CC and Ti 'sandwich'
- Must keep septum steel below 100 C



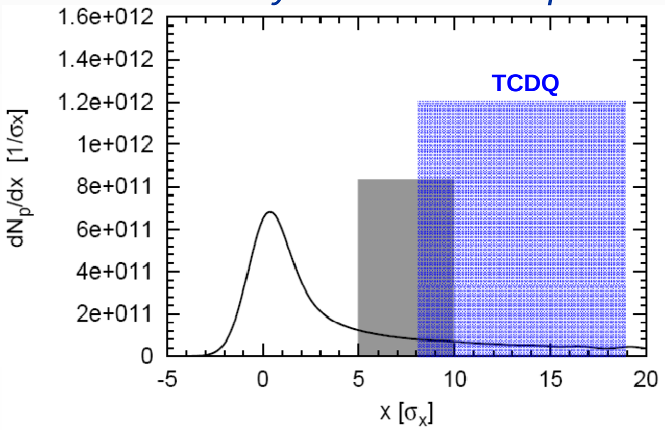


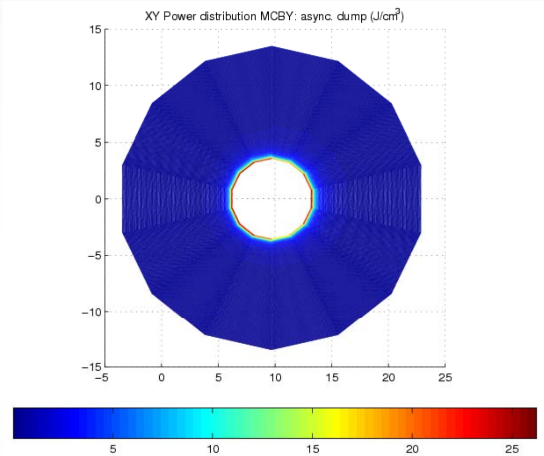


Mobile absorber to protect Q4 and LHC aperture

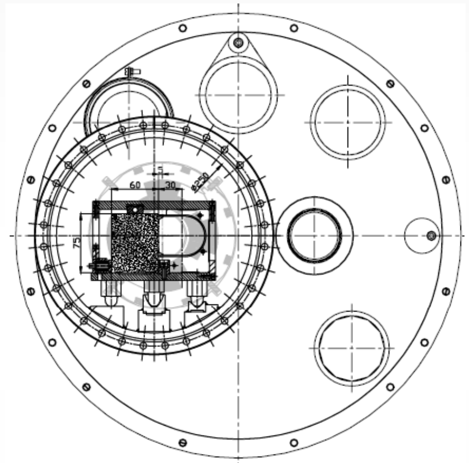
- Positioned close to beam (~7 σ) means large load for asynchronous dump
  - 6 m long single jaw graphite absorber, 1 m long 2-jaw collimator and 2 m fixed Fe mask
  - No damage, but quench of ~10-20 SC magnets expected after asynchronous dump
  - Problems with continuous beam load from halo and energy in SC Q4 coils

Asynchronous dump

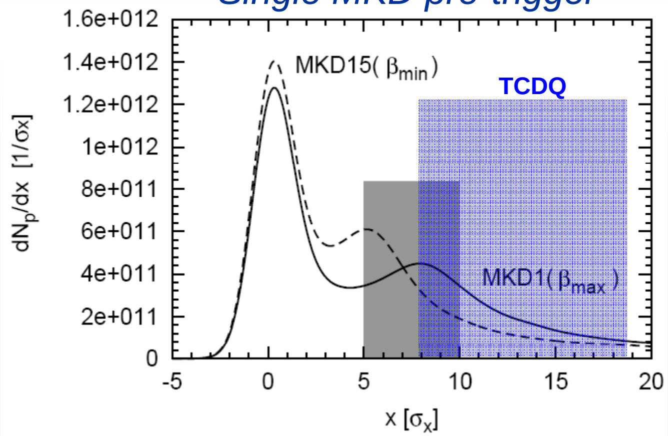


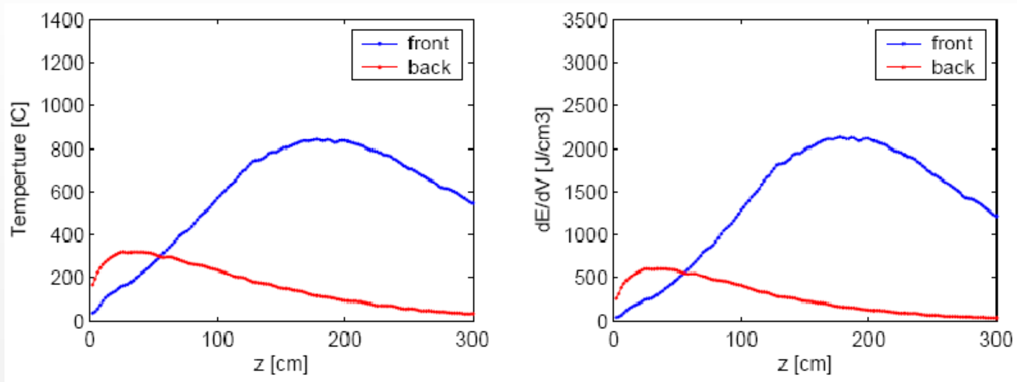


Energy deposited in SC Q4 coil



Single MKD pre-trigger





Temperature rise in TCDQ graphite

Different difficulties and solutions for each problem

- **Dumps in SPS and LHC –active dilution to reduce energy density**
  - Full beam can be stopped in single device
  - A lot of the "design challenge" is in the extraction and dilution system
- **Local protection of SPS and LHC extraction septa**
  - Generally space limited – need 'advanced' sandwich constructs
  - Some surprises from design constraints – e.g. low allowed water ΔT
  - Robustness of absorber material a major issue – especially higher Z parts
- **Generic protection of LHC using multi-phase absorbers**
  - Use 'diluter + drift + mask' to dilute primary beam and protect local elements
  - Difficulties arise with heating of local elements when drift insufficient
- **Specific protection devices for LHC injection kicker failures**
  - Low Z jaws need to be mobile, to close around the beam at injection
  - Fixed masks help safety margin and to avoid quenches
  - Mechanical tolerances important with large (~4 m long) absorbers
- **Dedicated system to protect against asynchronous beam dumps**
  - Mobile jaws and 6 m C length to dilute primaries – material robustness issues
  - Drift and secondary masks needed to protect local elements
  - Issues of interference with collimation

Future directions and limitations….?

- **Many potential different areas for research and development in future**
  - Increasing intensity and energy in SPS or LHC…existing devices and solutions already at limit in some cases!!
- **Some of the upgraded problems can be solved by addressing loading**
  - E.g. more blow-up or dilutions systems
  - Also “clever” system design – e.g. iron Lambertson septum elements….
- **Others will require improvements to materials to improve performance**
  - Rediscover in several devices ‘sandwich’ of CC-Ti-SS
  - Carbon composite seems to be ideal low-Z material
  - Main requirement would seem to be robust higher Z materials to obtain higher overall absorption – more radiation lengths in same space
  - Any industrially available magical materials on the horizon????
- **Other possibilities may also warrant R&D**
  - Single-use or disposable devices for ‘rare’ accident cases
  - Multiple-stage absorbers (as already beginning to be used)
  - Magnetized absorber materials, cryogenic absorbers, …
- **Or may just have to have more space…**
  - Already about 20 m in LHC layout per beam for mobile bump protection system