SPS to LHC Transfer Line Collimation

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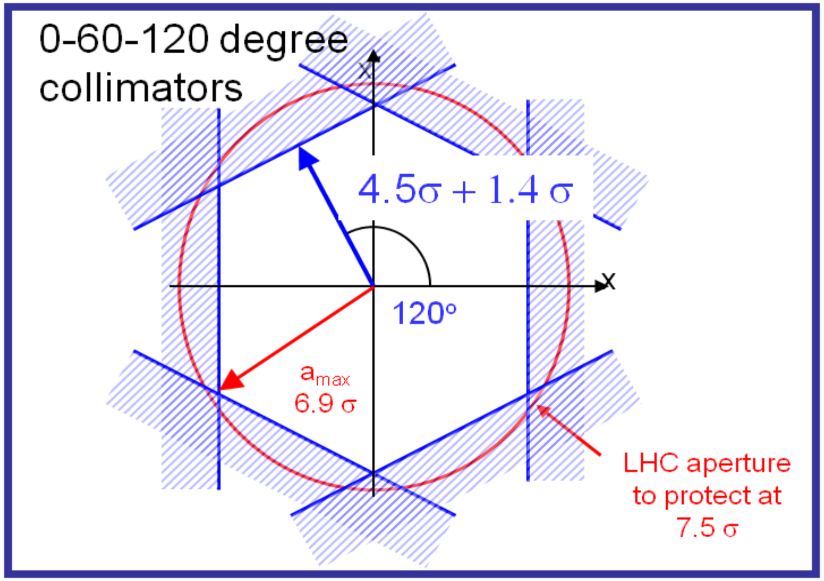
LHC Injection Protection Concept

- Injection with **intermediate intensity first**
  - Verification of line with low intensity
- Many circuits with small time constants: **Active Protection**
  - MSE septum moves trajectory by 40σ in 1 ms
  - Verification of power converter currents before extraction
  - Reaction time ms scale;
  - For fast circuits additional protection with FMCM (Fast Magnet Current Change Monitor): reaction time ~ 50 μs
  - Ultra-fast failures cannot be protected against with interlocks
    - Failures of kickers
- **Passive Protection with Transfer Line Collimators**
  - Last resort
  - Generic passive protection system to protect against ANY failure from SPS extraction or transfer
  - First priority: protect LHC ➔ as close as possible to LHC
    - And aperture bottleneck at the end of the line at injection septum

The Transfer Line Collimator Design

- Design for ultimate LHC intensity: 1.7×10^{11} ppb, 3.5 μm, 288 bunches
  - Attenuate intensity to safe level: ~ 2×10^{12}
  - Robust enough to survive beam impact

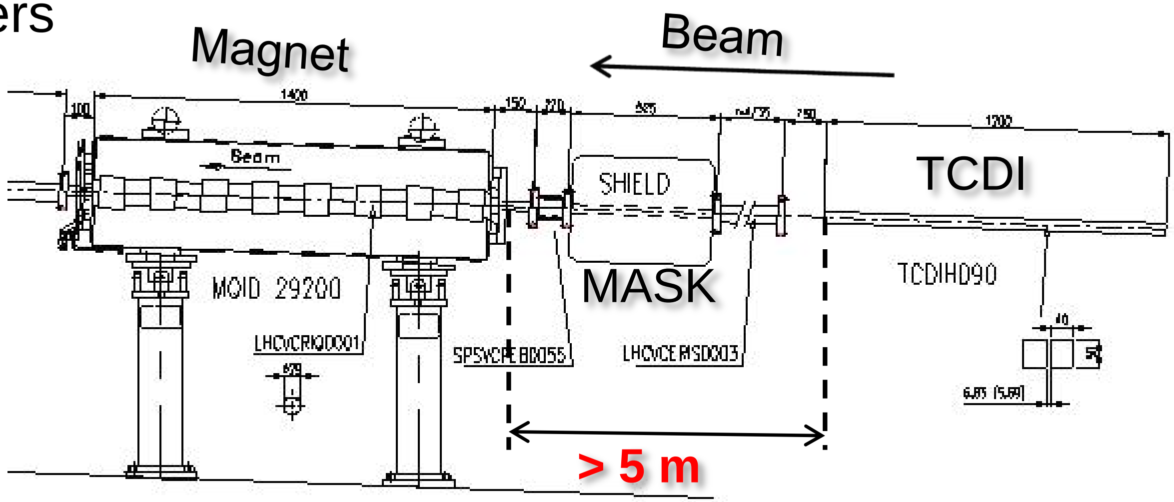
- Full phase space coverage in H and V
  - 3 collimators per plane, 60° phase-advance between
  - Transverse setting defined by LHC aperture and required tolerances



Current TCDI Transfer Line Collimator System

- Jaws of low-Z material for robustness reasons
  - **Graphite R4550**, density = 1.83 g/cc

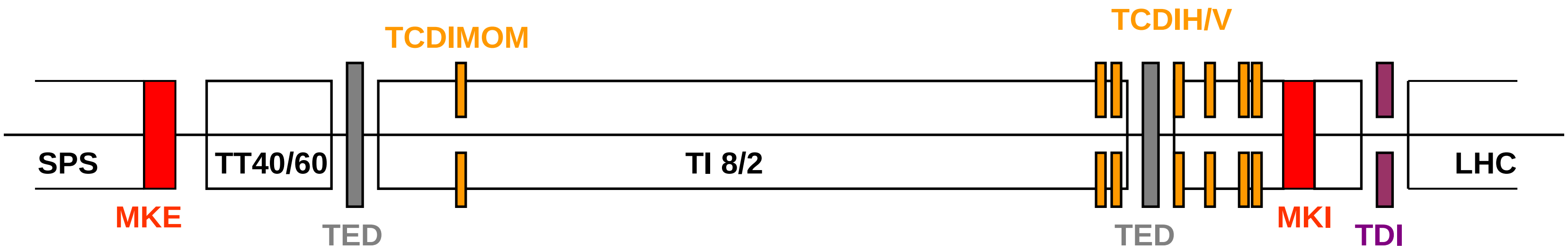
- Attenuation requirement defined length
  - Reduce impacting ultimate intensity to ~ 2×10^{12}: factor 20 reduction
  - Required length with graphite: **1.2 m** ➔ LHC secondary collimator design without taper
- Local protection: **mask** to protect downstream elements from secondary showers



Generic Layout of Transfer Line Collimation System

- Transfer Line Collimators are at the end of the lines
  - In the matching section where optics is matched to the LHC

- For any optics change at the collimators, phase advance constraint between TCDIs and matching to the LHC has to be fulfilled.
  - Virtually impossible to change optics at TCDIs significantly



LIU Beam Parameters – Attenuation Requirements

- LIU beams will be much brighter than LHC nominal or ultimate beams

	Bunch intensity	Normalized emittance	Number of bunches
standard LIU	2.3×10^{11}	2.1 μm	288
BCMS	2×10^{11}	1.3 μm	288

- What counts for damage is not only intensity, but number of protons per mm^2:
  - Intensity goes up and emittance goes down
  - Required attenuation therefore factor 70

$$\frac{N_{afterTCDI}}{\varepsilon_{afterTCDI}} = \frac{1}{20} \times \frac{N_{ultimate}}{\varepsilon_{ultimate}} = \frac{1}{70} \times \frac{N_{LIU\_BCMS}}{\varepsilon_{LIU\_BCMS}}$$

Most stringent: BCMS beam

2 Problems with LIU Beams

- Collimators will have to be become significantly longer
  - Graphite: 1.9 m instead of 1.2 m

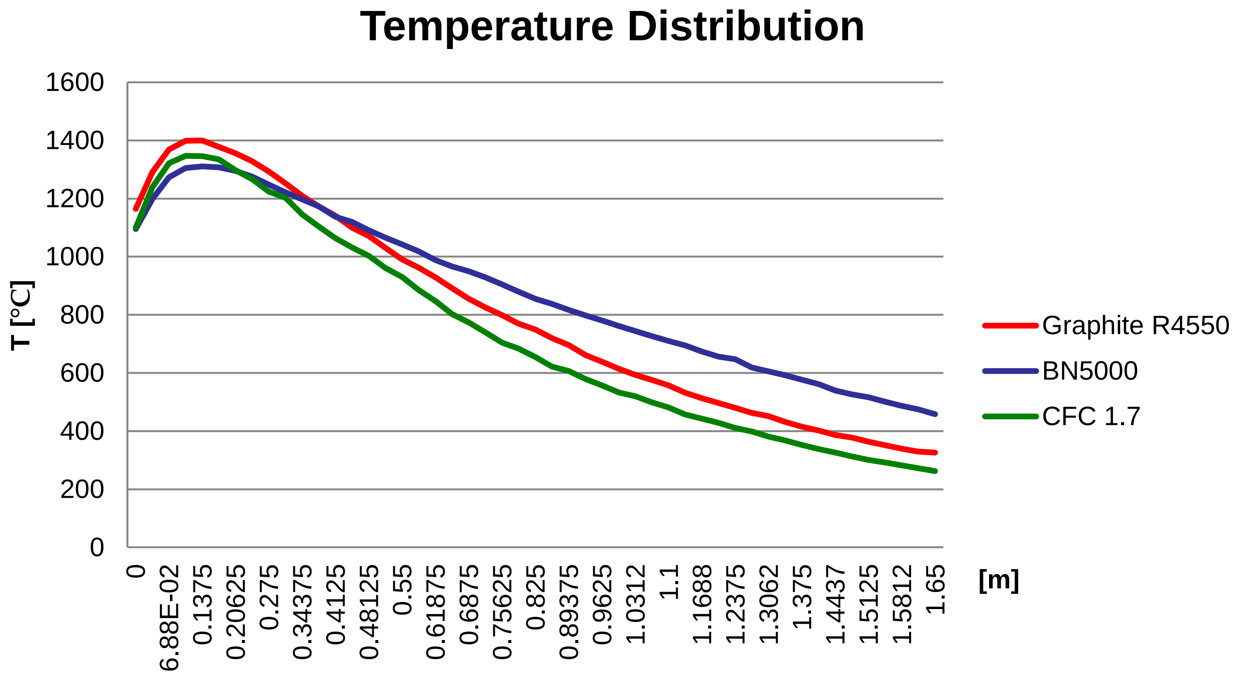
- Collimators at locations with current beta functions will not survive beam impact for LIU beams
  - Reach the limit of the tensile strength of material
  - Depends strongly on beam size at collimator

Started campaign in autumn 2013 to increase $\beta_x \times \beta_y$ at collimators and search for new materials

New optics for the transfer lines

- Defined new criterion for optics matching in addition to phase advance constraint

- $\beta_x \times \beta_y \geq 3500\ m^2$ … e.g. $\beta_x = \beta_y \approx 60$ m
- Temperature increase reduced below 1500° C



Summary of Material Investigation – quasi-static

- Stress resistance criterion for graphite: Mohr-Coulomb $F_s > 1$

$$F_s = \left[\frac{\sigma_1}{\sigma_{Tensile\ limit}} + \frac{\sigma_3}{\sigma_{compressive\ limit}}\right]^{-1},$$

New optics criterion, **BCMS beam**

Material	Density [g/cm³]	Mohr-Coulomb S.F.	Max T [°C]	Tensile strength /Max Tensile Stress [MPa]	Compressive strength /Max Compressive Stress [MPa]
BN5000	1.9	**0.46**	1311	**3/11**	**104/59**
Graphite R4550	1.8	**0.9**	1400	**29/32**	**118/81**
CFC	1.7	_	1370	**12.8/20**	**132/38**

- Graphite is the best compromise in terms of manufacturing issues and ratio between tensile strength and maximum tensile stress.

Result for Standard LIU 25 ns

- 2.3 × 10^{11} ppb, 2.1 μm emittance

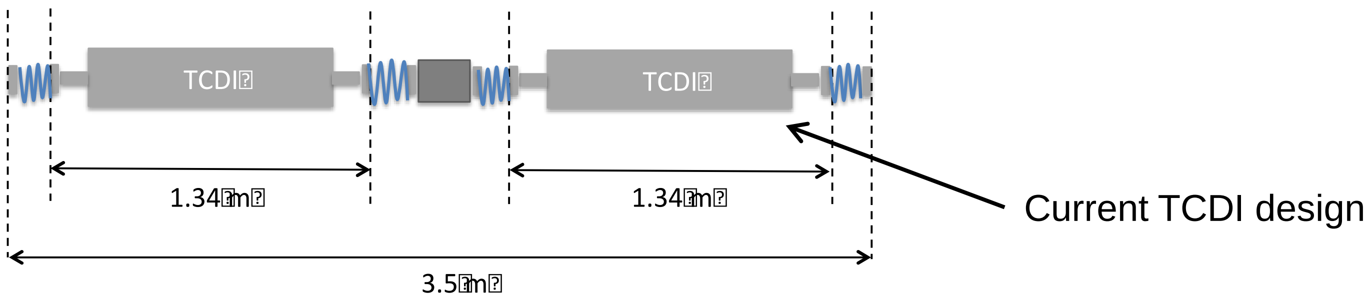
Material	Density [g/cm³]	Mohr-Coulomb S.F.	Max T [°C]	Tensile strength /Max Tensile Stress [MPa]	Compressive strength /Max Compressive Stress [MPa]
Graphite R4550	1.8	**1.4**	**1200**	**29/21**	**118/67**

- Graphite collimators would survive in case of new optics and standard LIU 25 ns
  - Caveat: without shock waves taken into account

- For completeness:
  - In order for collimators to survive with BCMS beams the $\beta_x \times \beta_y >= 6300\ m^2$
  - Too big an optics change

First Proposal from TCDI Review

- Long graphite collimators (requirement 1.9 m)
  - Possible solution feasible until LS2: twin TCDI collimators – 3.5 m



- TI 2 current locations fulfill all requirements (enough space, optics OK). Integration still to be fully verified

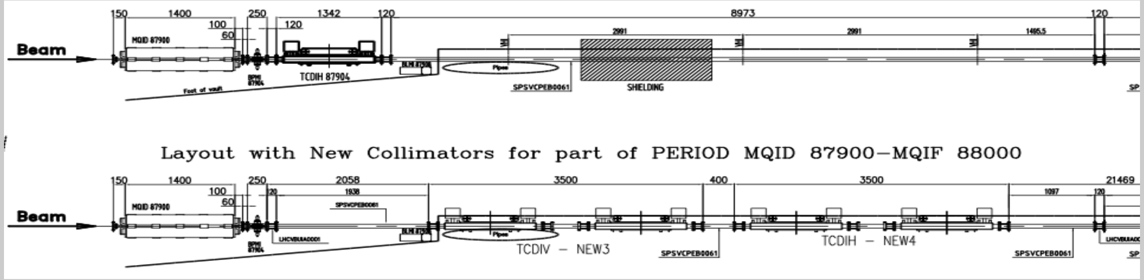
- TI 8 difficult. Solution found, but expensive.
  - 11 more individually powered quadrupoles, shift 1 quadrupole + mask + BPM + corrector
  - Integration details to be finalized. Could be tricky

Integration of new long collimators

- Work has only started

Example of potential conflict

TI8 TCDIV.NEW3 and TCDIH.NEW4 foreseen location



Synthesis: First proposal

+ Will adequately protect downstream and locally with masks

−/+ TCDIs slightly above maximum allowed stress for beam impact and will therefore probably break – sacrificial TCDIs

- Should test in HiRadMat
- For LIU standard beam (not BCMS) quasi-static analysis: enough safety factor
- Results from shock wave simulation still outstanding

− 11 new power supplies for TI 8 and many new TCDIs to be installed with tight space constraints

Some statistics from LHC run I

Before coming to the second proposal from TCDI Review – experience from LHC run I:

- Initial setting at 4.5 σ. Was increased to 5 σ later (2011)
  - Reason: more aperture available at injection in the LHC (> 10 σ).
  - σ with nominal emittance

- Routinely injected 50 ns full batches
  - 144 bunches, 1.8 $\times 10^{11}$ ppb, 1.5 μm emittance

- Injections in 2012:
  - 72 bunches: 3181
  - 144 bunches: 6015
  - 288 bunches: 370

- NEVER lost beam above 1 nominal bunch on a transfer line collimator during LHC run I.

Second Proposal from TCDI Review

Original locations, optics and length: **sacrificial higher Z jaws**

+ Will adequately protect downstream and locally with masks

− TCDIs will break
  - Sandwich structure
  - Will need quick plug-in
  - Have no proven solution: do not want material to break in catastrophic way

+ No new power supplies

Summary – Preliminary Recommendations from Review

The current Transfer Line Collimators would not adequately protect the LHC or the transfer lines and would break in case of LIU beam impact.

Main Recommendations from Review:

- Retain long graphite collimators as baseline
  - Can we produce one long TCDI ~ 2 m?
  - Continue optimization of optics/locations/integration
  - Evaluate effect of dynamic stresses
  - Prepare HiRadMat Test
- Keep higher Z jaws as back-up solution
- Check with HL-LHC whether BCMS is really needed
- Come up with conceptual design by end of 2014