The Project on LHC Collimation

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http://www.cern.ch/lhc-collimation

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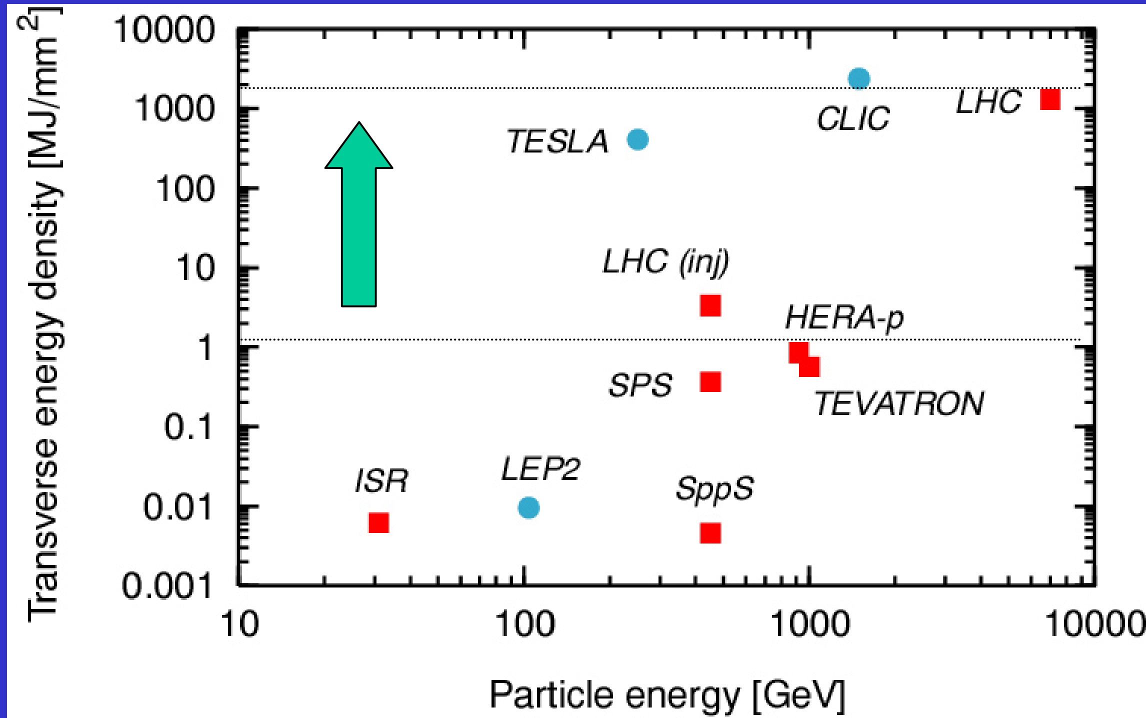
The High Power LHC Beam

Number of bunches:	**2808**
Bunch population:	**1.1e11**
Bunch spacing:	25 ns
Top energy:	
Proton energy:	**7 TeV**
Transv. beam size:	**0.2 mm**
Bunch length:	8.4 cm
Stored beam energy:	**350 MJ**
Injection:	
Proton energy:	450 GeV
Transv. Beam size:	1 mm
Bunch length:	18.6 cm



Factor 1000 in transverse energy density!

Physics Potential =
Energy and Luminosity:

$$L = \rho_e \frac{f_{rev} N_p}{4 E_b} \sqrt{d_x d_y}$$

Increase transverse energy density

d = demagnification
N_p = protons per bunch
f_{rev} = revolution freq.
E_b = beam energy

Handling of High-Intensity Beams: LHC Collimation System

1) Protect sensitive cold aperture against beam loss…

i. … from beam losses during regular operation
(99.9 % of protons lost, e.g. with 1 h beam lifetime at 7 TeV, are captured in the collimators)

ii. … from beam losses during failures (without being destroyed)
(Less than 0.002 % of the stored beam intensity can be lost at any place in the ring other than the collimators, because otherwise magnets could be damaged)

2) Detect any abnormal beam loss at collimators and initiate beam abort (basic machine protection philosophy)

Beam Loss Detectors monitor beam loss rate at collimators. → Compare signals with a threshold. → Trigger the beam dump to protect the machine

3) Important: Background minimization is only a side aspect

Beam much above pilot bunch cannot be put without working collimation system.

Material Damage

Destruction limits

Case	Destruction threshold [nominal intensity]	
Copper	1.9e-3	**1.8e-5**
Beam screen	**1.6e-3**	7.0e-5
S.C. coil	4.2e-3	14.0e-5

5-12 nominal bunches at injection

0.05-0.4 nominal bunches at top energy

This made the reconsideration of present collimator jaw materials necessary!

No safe operating point for LHC (top) without protection!

Super-Conducting Environment

Proton losses into cold aperture

⇩

Local heat deposition

⇩

Magnet can quench

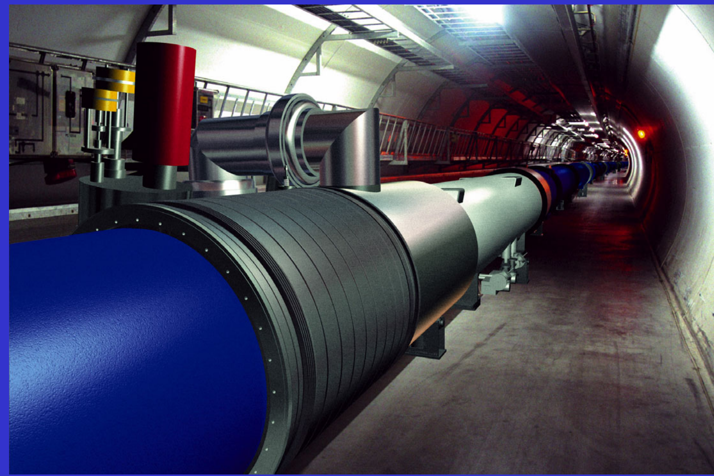


Illustration of LHC dipole in tunnel

Energy [GeV]	Loss rate (10 h lifetime)	Quench limit [p/s/m] (**steady losses**)	Cleaning requirement
450	8.4e9 p/s	7.0e8 p/s/m	92.6 %
7000	**8.4e9 p/s**	**7.6e6 p/s/m**	**99.91 %**

Control **transient losses (10 turns)** to ~1e-9 of nominal intensity (top)!

Capture (clean) lost protons before they reach cold aperture!

Required efficiency: **~ 99.9 %** *(assuming losses distribute over 50 m)*

Concept of LHC Collimation

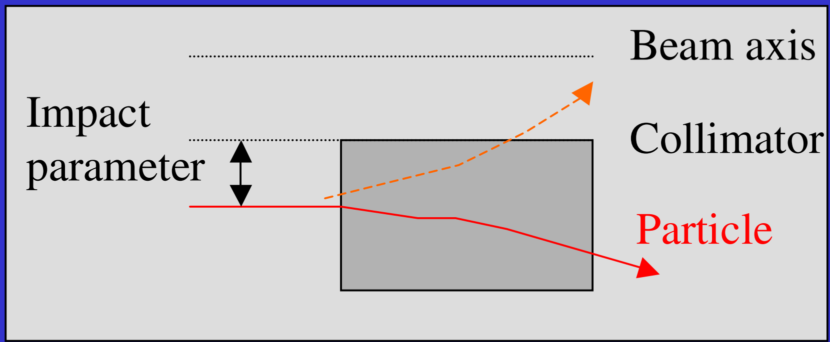
"Conventional" jaws (blocks of appropriate solid materials).

"Exotic" schemes (e.g. crystal collimation) not foreseen in baseline solution.
Unusual mechanical solutions can be envisaged ("consumable" jaws, connected jaws).

Two stage cleaning systems:

1) Primary collimators:
- Intercept primary halo
- **Impact parameter: ~ 1 μm**
- Scatter protons of primary halo
- Convert primary halo to secondary off-momentum halo

2) Secondary collimators:
- Intercept secondary halo
- **Impact parameter: ~ 200 μm**
- Absorb most protons
- Leak a small tertiary halo



Requirements for Collimator Settings

Reminder: Normalized available LHC aperture specified to be about 10σ at injection (arcs) and top energy (triplets).

+ 3-4 mm for closed orbit, 4 mm for momentum offset, 1-2 mm for mechanical tolerances

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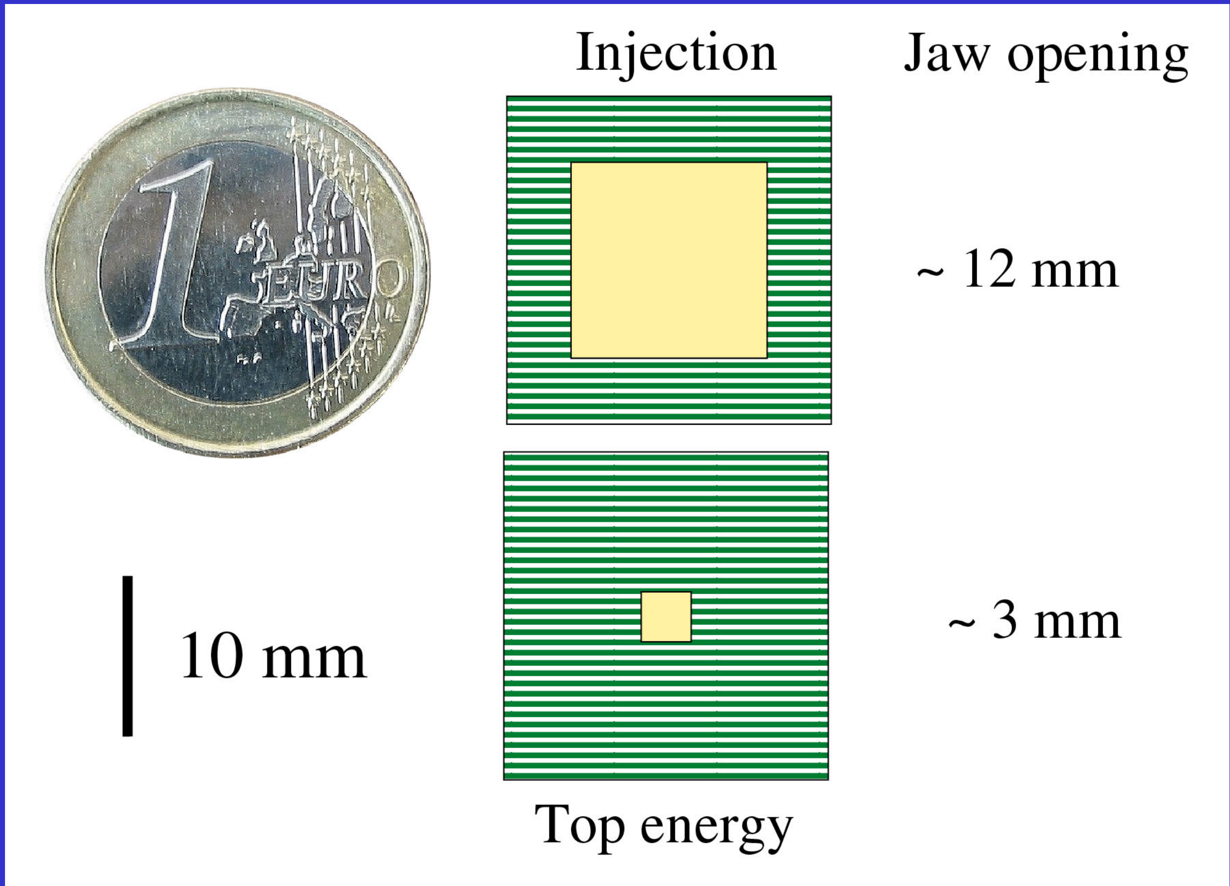


Collimator settings:

$5 - 6\ \sigma$ (primary)
$6 - 9\ \sigma$ (secondary)

$\sigma \sim 1$ mm (injection)
$\sigma \sim 0.2$ mm (top)

Number of protons reaching 10σ:

10^{-4} of p at $6\ \sigma$

LHC collimators must be robust and precise!

Survival of jaws with 7 TeV proton impact (no melting, cracks, dust formation, …).

- $2\ 10^{12}$ p (2.2 MJ) in 0.5 μs over area of 1 mm (full width) $\times$ 0.2 mm (rms)
- $4\ 10^{12}$ p (4.5 MJ) in 10 s over area of 0.03 mm (rms) $\times$ 0.2 mm (rms)

0.7 MJ to melt one kg Cu

Excellent cleaning inefficiency.

- Local losses ~10^{-5} of primary beam halo.
- Deformations of ~1.5m long jaws < 25 μm.
- Control/maintain beam-jaw position/angle to ~0.1 mm, ~60 μrad.
- …

… and available from day 1 of LHC operation (10% intensity still far beyond handled so far)

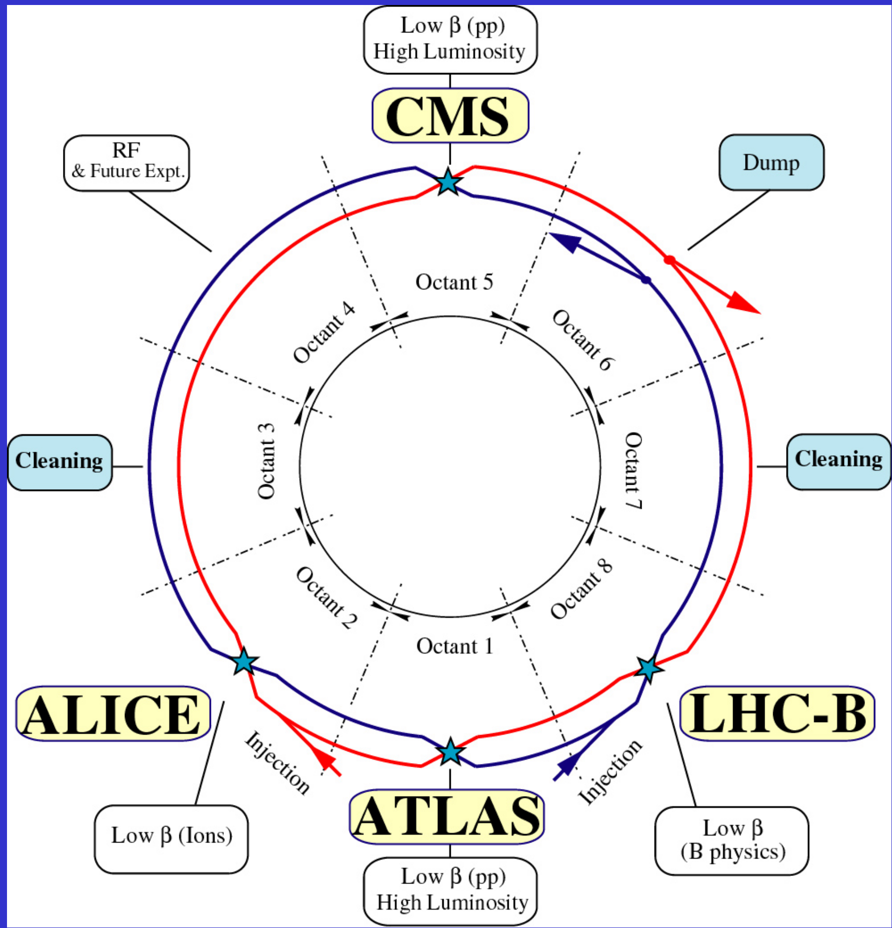
Two Dedicated LHC Insertions

Two warm LHC insertions dedicated to cleaning:

IR3 Momentum cleaning
1 primary
6 secondary

IR7 Betatron cleaning
4 primary
16 secondary

Two-stage collimation system.



54 movable collimators for high efficiency cleaning, two jaws each *+ other absorbers for high amplitude protection*

Full system: 66 collimator tanks + 12 spares

Our Tasks

1. **Understand the driving requirements and define detailed specifications.**
   (AP, operation, machine protection, radiation protection, vacuum)

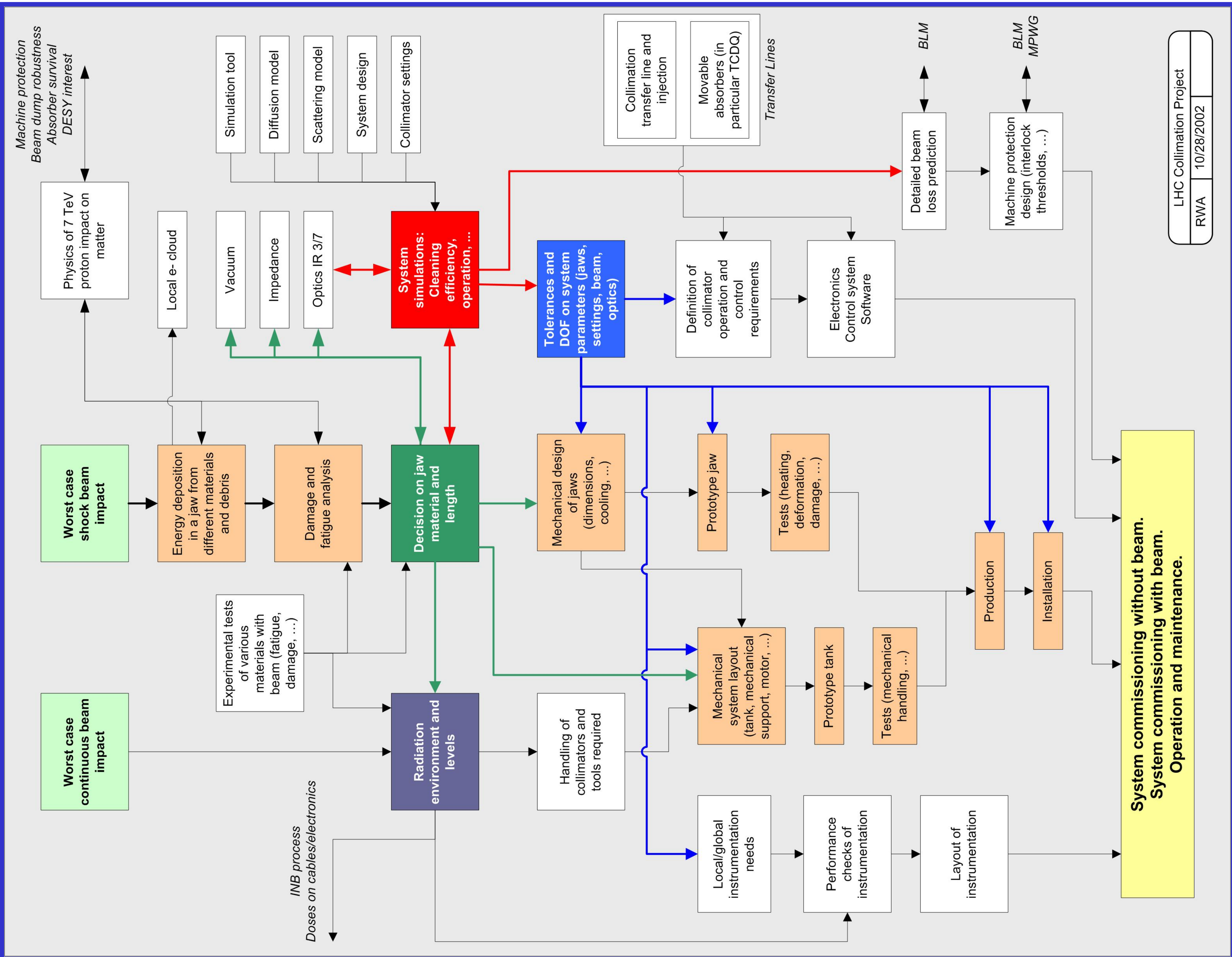
2. **Design, build prototype collimator jaws with the required properties, as robustness against beam loss, scattering properties, absorption quality.**
   (material science, mechanical engineering, AP, operation)

3. **Put together a functional collimation system** **(> 200 DOF for settings)** **that delivers high robustness and excellent cleaning efficiency.**
   (AP, operation, instrumentation, controls)

Demanding schedule:

(and budget)

end 2003	prototypes
2004/05	production
2006	installation
2007	commissioning



Machine protection
Beam dump robustness
Absorber survival
DESY interest
Physics of 7 TeV proton impact on matter
Local e- cloud
Simulation tool
Diffusion model
Scattering model
System design
Collimator settings
Vacuum
Impedance
Optics IR 3/7
System simulations: Cleaning efficiency, operation, ...
Collimation transfer line and injection
Movable absorbers (in particular TCDQ)
Transfer Lines
Tolerances and DOF on system parameters (jaws, settings, beam, optics)
Definition of collimator operation and control requirements
Electronics Control system Software
BLM
Detailed beam loss prediction
BLM
MPWG
Machine protection design (interlock thresholds, ...)
LHC Collimation Project
RWA
10/28/2002
Worst case shock beam impact
Energy deposition in a jaw from different materials and debris
Damage and fatigue analysis
Decision on jaw material and length
Mechanical design of jaws (dimensions, cooling, ...)
Prototype jaw
Tests (heating, deformation, damage, ...)
Production
Installation
System commissioning without beam.
System commissioning with beam.
Operation and maintenance.
Experimental tests of various materials with beam (fatigue, damage, ...)
Mechanical system layout (tank, mechanical support, motor, ...)
Prototype tank
Tests (mechanical handling, ...)
Worst case continuous beam impact
Radiation environment and levels
Handling of collimators and tools required
INB process
Doses on cables/electronics
Local/global instrumentation needs
Performance checks of instrumentation
Layout of instrumentation

Demanding goals require to put together best available CERN expertise in many different areas: Project LHC Collimation

Presently being set up. Snap-shot:

AB/ABP and TRIUMF	System design (efficiency, optics) Commissioning and operational scenarios Impedance Input to scattering/radiation studies Material tests
AB/ATB	Scattering calculations Damage/fatigue analysis Material choice (e.g. C, Be, C with Ti coating, BN, …) Vacuum link Supervision production/installation Maintenance and service Material tests
AB/BDI or AB/BT ?	Motorization, cables, electronics, and control Local instrumentation
TIS/RP and IHEP	Study of radiation, environmental impact Remote handling requirements

AB/OP	Commissioning and operational scenarios Controls and software Routine operation
AB/CO	Controls and software Interlock system, machine protection

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Help needed:

Selection of material…

Mechanical engineering…

Design…

Proto-typing…

Tests…	… of materials	(surface/vacuum properties, e-cloud, …)
	coatings	(technology, robustness, impedance, …)
	cooling	
	jaw support	
	vacuum tank	

Present Status

Beam scenarios defined: Requirements for LHC collimators specified in detail (published).

Studies of energy deposition started. Material pre-selection: C, Be, C with Ti coating, BN, Cu, …

Damage/fatigue analysis will start very soon.

Milestone 1: Selection of material and length.

Milestone 2: Final system design (layout, efficiency, optics).

Milestone 3: Detailed mechanical design.

Milestone 4: Prototype and tests (end 2003?!).

References

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CERN-LHC-PROJECT-REPORT-598: EFFICIENCY FOR THE IMPERFECT LHC COLLIMATION SYSTEM.
By R.W. Assmann, J.B. Jeanneret, D. Kaltchev (CERN & TRIUMF).

CERN-LHC-PROJECT-REPORT-592: EQUILIBRIUM BEAM DISTRIBUTION AND HALO IN THE LHC. By R. Assmann, F. Schmidt, F. Zimmermann, M.P. Zorzano (CERN & I.N.T.A.).

CERN-LHC-PROJECT-REPORT-589: TIME DEPENDENT SUPERCONDUCTING MAGNETIC ERRORS AND THEIR EFFECT ON THE BEAM DYNAMICS AT THE LHC. By R. Assmann, S. Fartoukh, M. Hayes, J. Wenninger (CERN).

LHC-PROJECT-NOTE-293: The consequences of abnormal beam dump actions on the LHC collimation system *by:* Assmann, R ; Goddard, B ; Vossemberg, E ; Weisse, E ; (2002)

LHC-PROJECT-NOTE-282: Summary of the CERN Meeting on Absorbers and Collimators for the LHC *by:* Assmann, R ; Fischer, C ; Jeanneret, J B ; Schmidt, R ; (2002)

LHC-PROJECT-NOTE-277: Preliminary Beam-based specifications for the LHC collimators *by:* Assmann, R ; (2002)

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Detailed beam scenarios for collimator requirements

RA; Meeting EST-SM
15/11/02

I) Scenario for worst case shock beam impact

Equipment failures
Equipment errors
Operational errors

→

Danger of damage to accelerator components.

In particular: Collimators close to beam!

Beam dump: Designed to extract beam within 2 turns.
Pulse rise time of 3 μs (dump gap).

Failure modes:

- Total failure of dump or dump trigger (> 100 years)

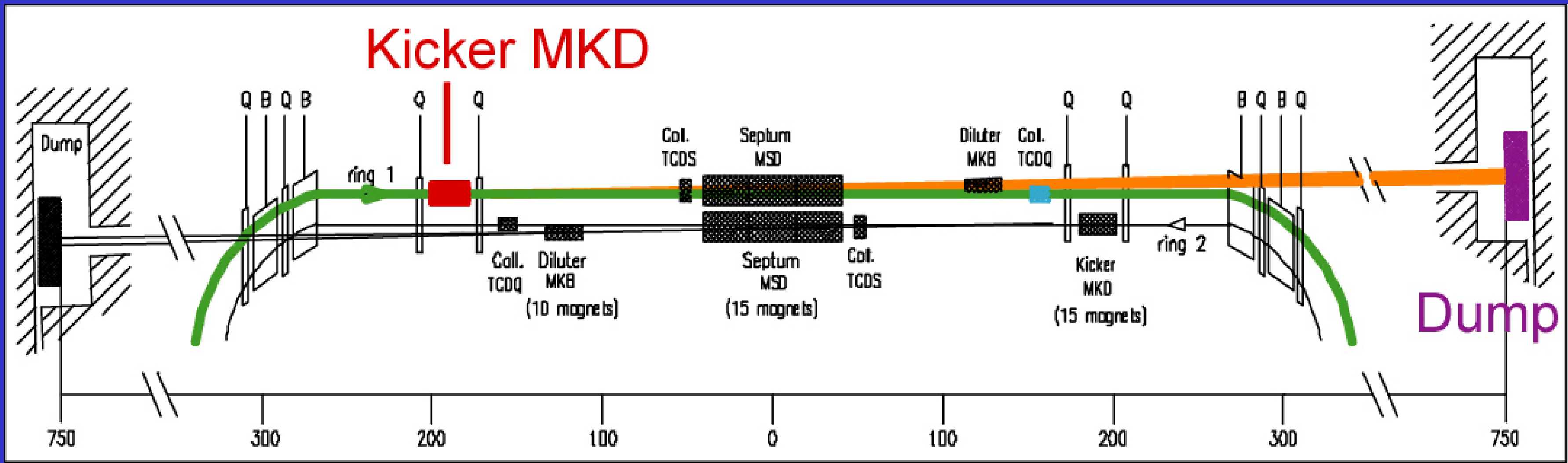
- Dump action non-synchronous with dump gap

- Dump action from 1 of 15 modules, others retriggering after 1.3 μs.

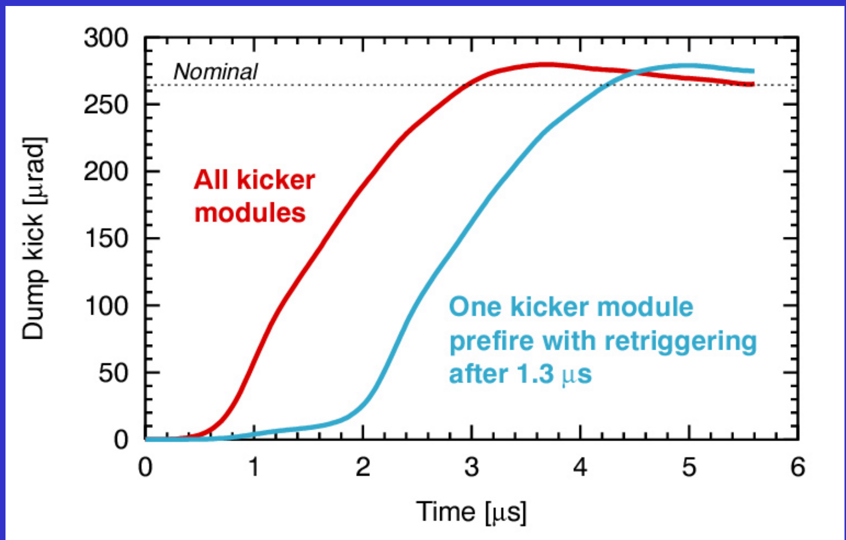
} Difficult to predict

Assume at least once per year!

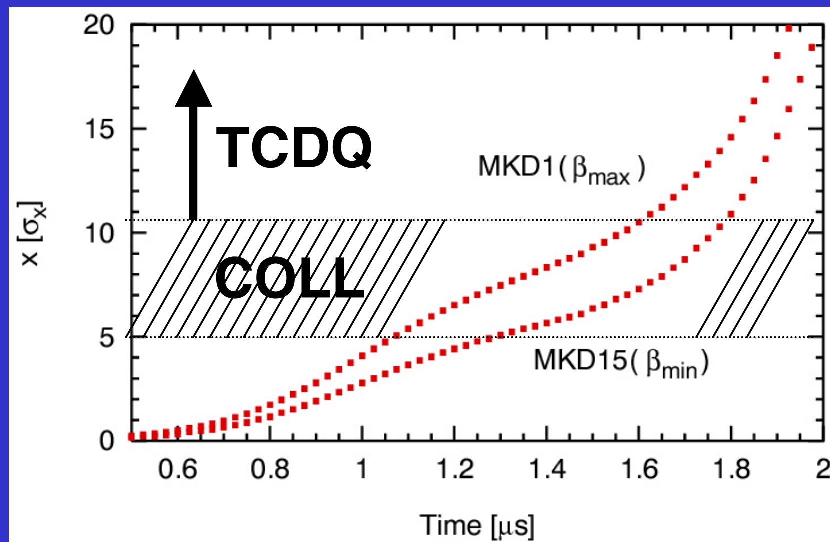
Abnormal dump actions



Kick [μrad]

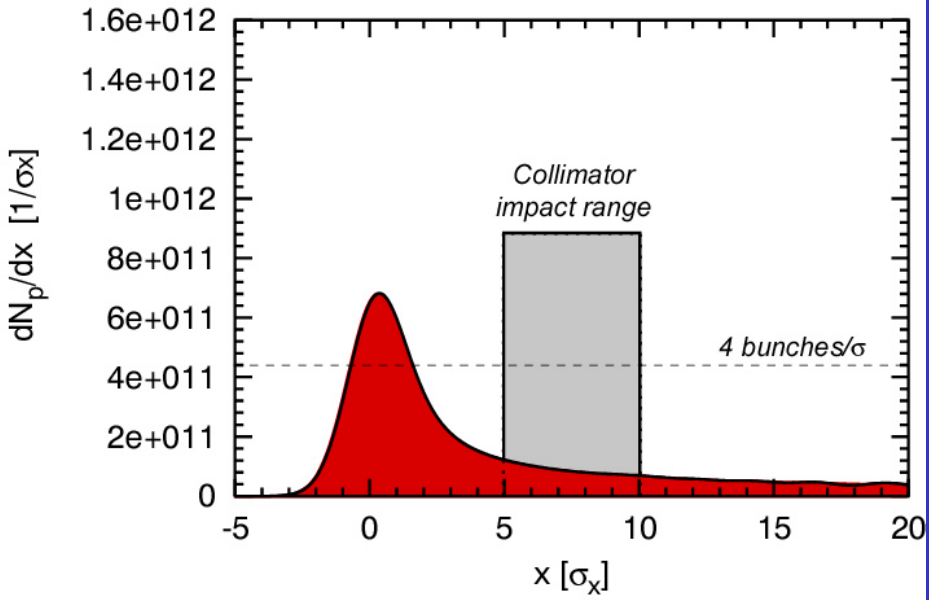


Downstream offset [σ]



One module pre-fire

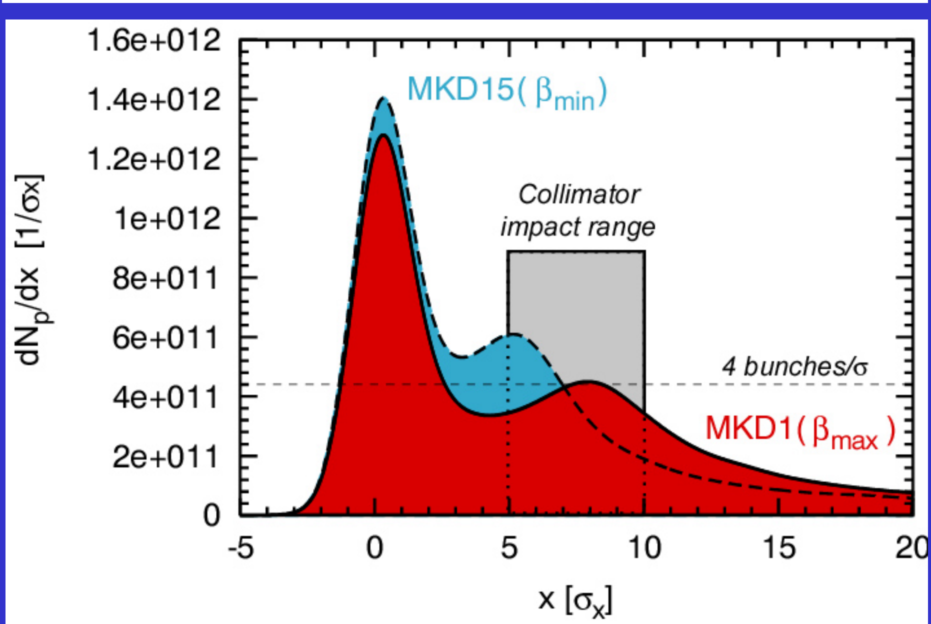
Abnormal dump actions



Beam abort asynchronous with abort gap:

Total: 6 bunches over 5 σ

Peak: **1.5 bunches in 1 σ**

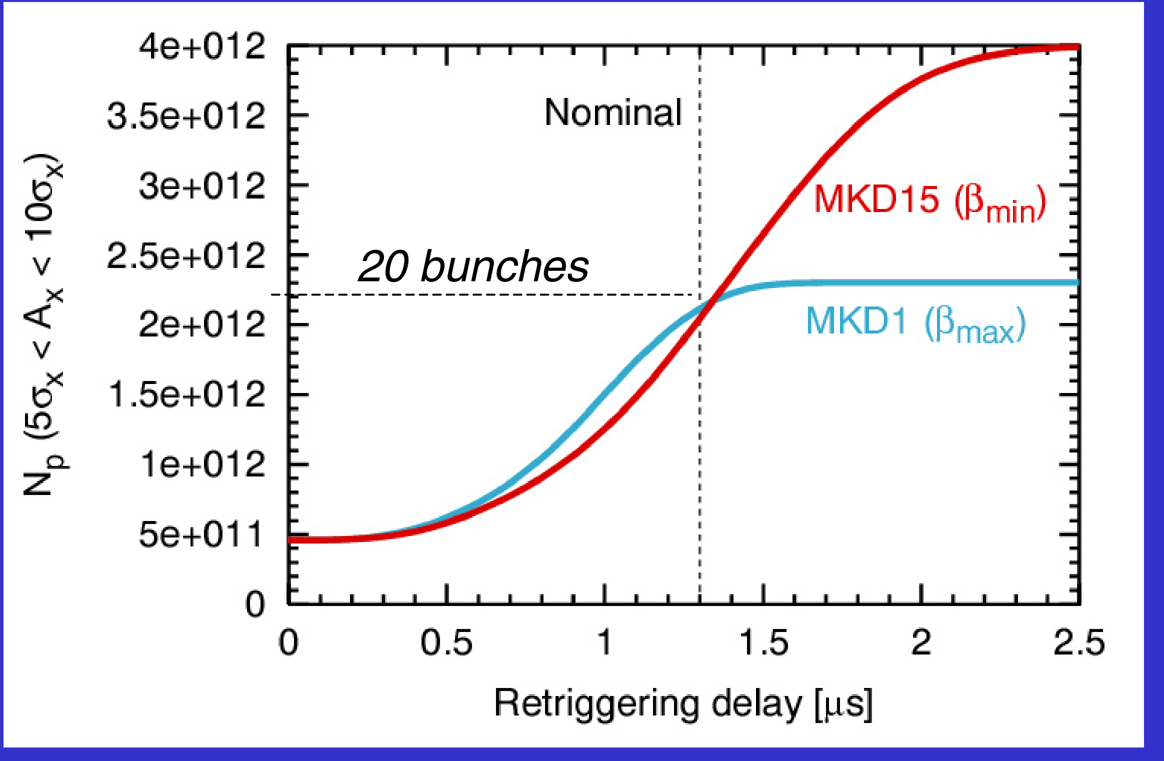


1 module pre-fire with re-triggering of 14 after 1.3μs:

Total: 20 bunches over 5 σ

Peak: **6 bunches in 1 σ**

Ease requirements from dump system?



One module pre-fire depends on details of dump kicker design (pulse form, number of magnets, re-trigger design)!

Possible remedies are being studied (require modifications to dump system).

Collimators should withstand this impact without damage!

Consequences for choice of material, jaw length, operation, exchange facilities, setting of TCDQ (10σ), distribution of radioactivity, …

Important consequences

Detailed calculation with measured kicker waveform yields *higher beam impact* on collimators than assumed.

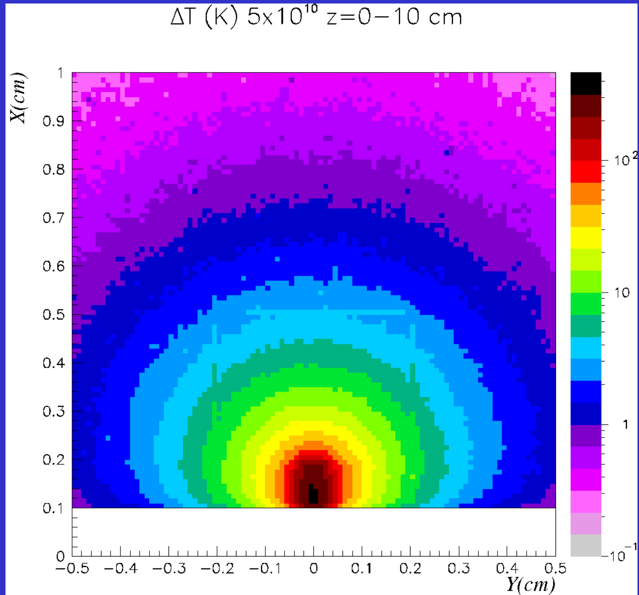
Frequency of abnormal beam dumps (several times per year) much higher than previously assumed (1/20y).

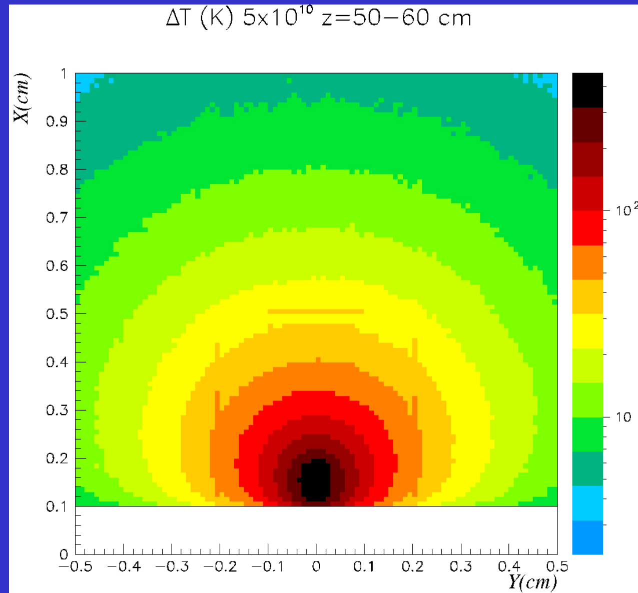
LEP technical solution (Cu, Al) cannot be used:

Damage threshold 0.05 bunches. We look for 20 bunches or we might need to replace collimators a few times per year!

New technical solutions are being pursued (low Z material, CERN meeting on collimators and absorbers).

Energy deposition map in a jaw

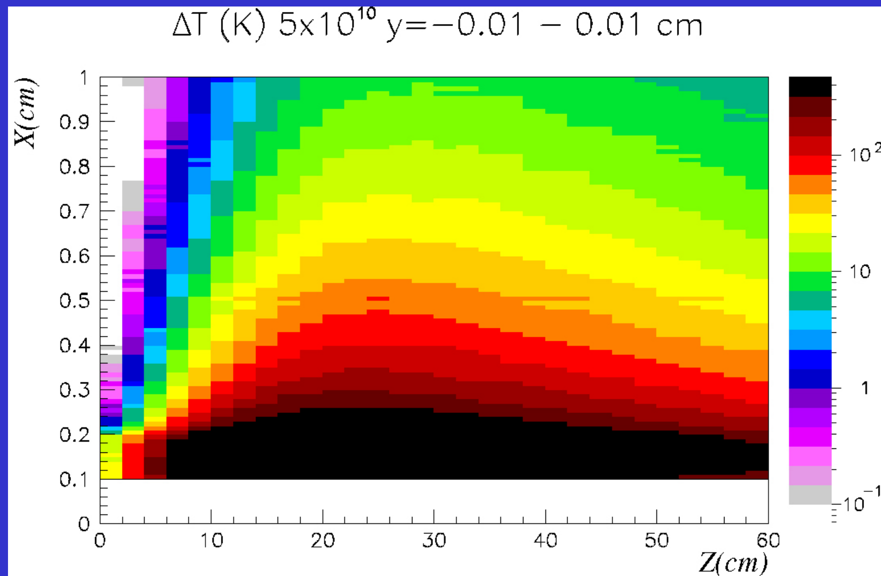




Half a nominal LHC bunch

Cu secondary coll.

A. Ferrari, V. Vlachoudis



Cu cannot take 20 bunches!

II) Scenario continuous beam impact

Proton losses observed in routine operation (include operational variation of beam lifetime)! *Studies for system with Al/Cu jaws.*

Desirable:

1) Possibility to run at quench limit (τ = 0.2 h for top energy)

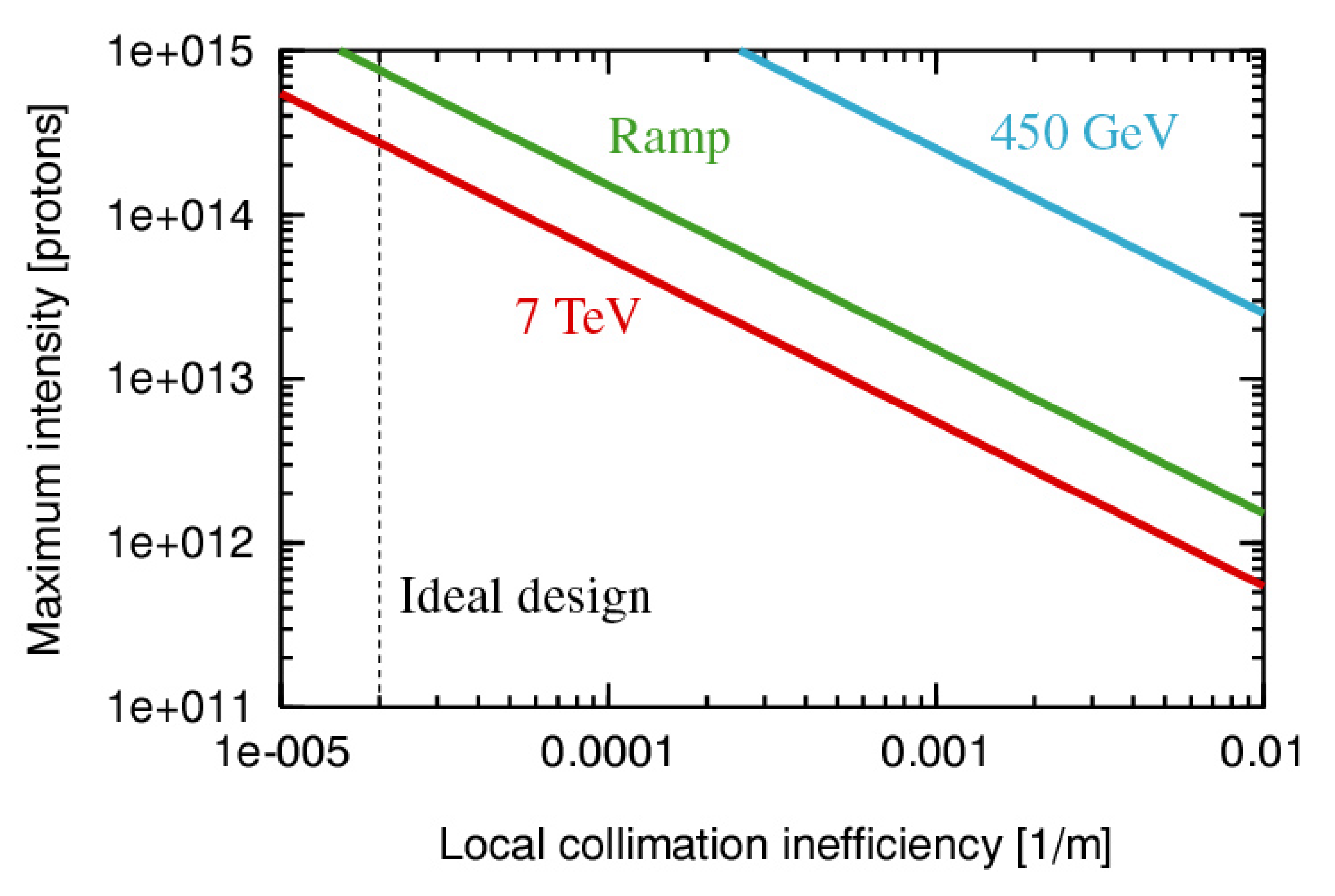
2) Accept low lifetimes during cycle

Mode	T [s]	τ [h]	R_{loss} [p/s]	P_{loss} [kW]
Injection	cont	1.0	0.8×10^{11}	6
	10	0.1	8.2×10^{11}	60
Top energy	cont	1.0	0.8×10^{11}	93
	10	0.2	4.1×10^{11}	465

Additional requirements for collimator hardware!

Material, length, cooling, …

Running at the quench limit for $\tau = 0.2$ h



Trade-off for given quench limit between:

Inefficiency – Allowed intensity – Minimum allowable lifetime

System evaluation: Tolerances

Value of imperfections for 50% increase (each) in inefficiency:

Transient changes: Orbit, Beta beat

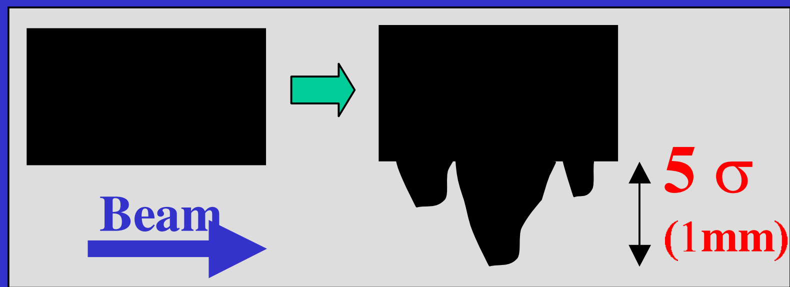
Error	Tolerance
Orbit	$0.6\ \sigma$
Beta beat	8%
Longitudinal angle	$50\ \mu$rad
$\Delta L/L$ (prim)	75%
Surface flatness (prim)	$10\ \mu$m
$\Delta L/L$ (sec)	20%
Surface flatness (sec)	$25\ \mu$m
Setting accuracy (prim)	$-1.0/+0.5\ \sigma$
Setting accuracy (sec)	$\geq \pm 0.5\ \sigma$

Preliminary estimates:

Combined effect can make tolerances more severe!

Collimators need not only be robust, but also precise!

HERA experience:



Schedule

Sep 2001	LHC Beam Cleaning Study Group started
June 2002	Consensus on worst case beam impact Core team of competence established

Required schedule:

July 02 – Dec 02	Showering, damage studies
Dec 02	Propose material, length, basic design
Mar 03	Verify system performance, specify tolerances, verify optics, iterate on length
Dec 03	First prototypes
2004/05	Production
2006	Installation

Resource allocation ongoing to assure that this schedule can be met.