Requirements and Design Criteria for the LHC Collimation System

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for the LHC Beam Cleaning Study Group:

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…including colleagues from connected activities (beam dump).
Work started in September 2001.

Contents

What is collimation for the LHC?

Blocks of material that are put closest to the beam such that:

99.9 % of protons lost (e.g. with 1 h beam lifetime at 7 TeV) are captured in the collimators.

Less than 0.1 % of protons lost can escape and can impact in the SC magnets, which otherwise quench.

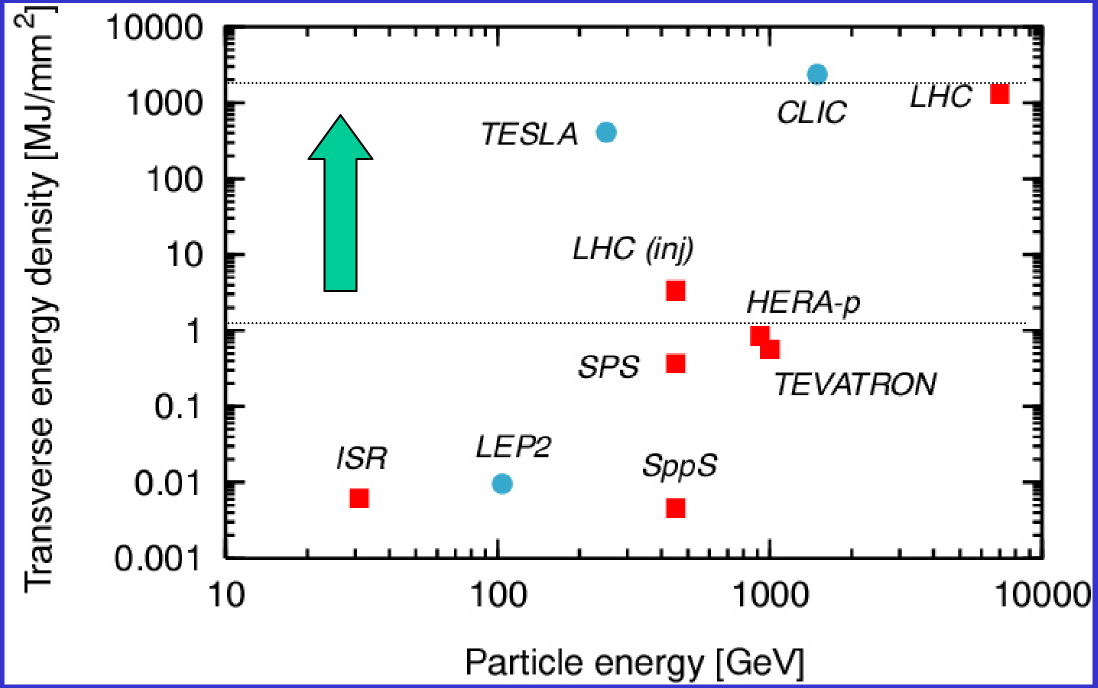
Less than 0.002 % of the stored beam intensity can be lost at any place in the ring other than the collimators, because otherwise magnets could be damaged.

Any beam loss is detected immediately at the collimators and the beam is dumped within 2-3 turns.

(top energy)

Challenge: High Stored Energy 1

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

Challenge: High Stored Energy 2

If you are interested in material damage:

Energy density (3 LHC bunches) = Energy density (full HERA-p beam)

If your are interested in heat load:

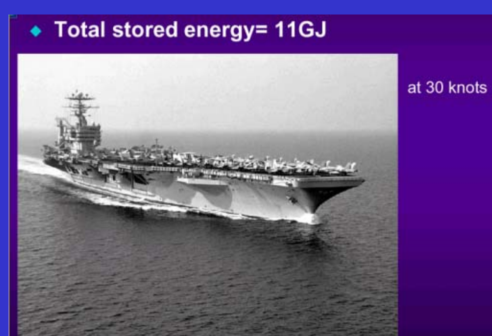
Energy (20 LHC bunches) = Energy (full HERA-p beam)

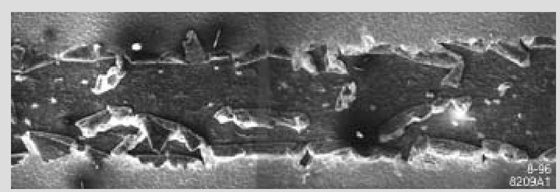
= Energy to melt 3 kg Copper

If you are interested in real things:

Energy (2 full LHC beams) = 7% of energy stored in an airplane carrier at 30 knots

K.H. Mess





Picture of damaged SLC collimator

Challenge: High Stored Energy 3

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

This made the reconsideration of present collimator jaw materials necessary!

5-12 nominal bunches at injection

0.05-0.4 nominal bunches at top energy

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

Challenge: Super-Conducting Environment

Proton losses into cold aperture

⇩

Local heat deposition

⇩

Magnet can quench

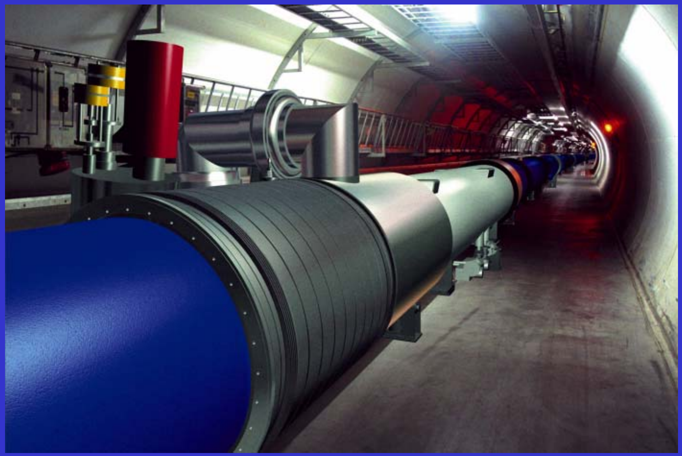


Illustration of LHC dipole in tunnel

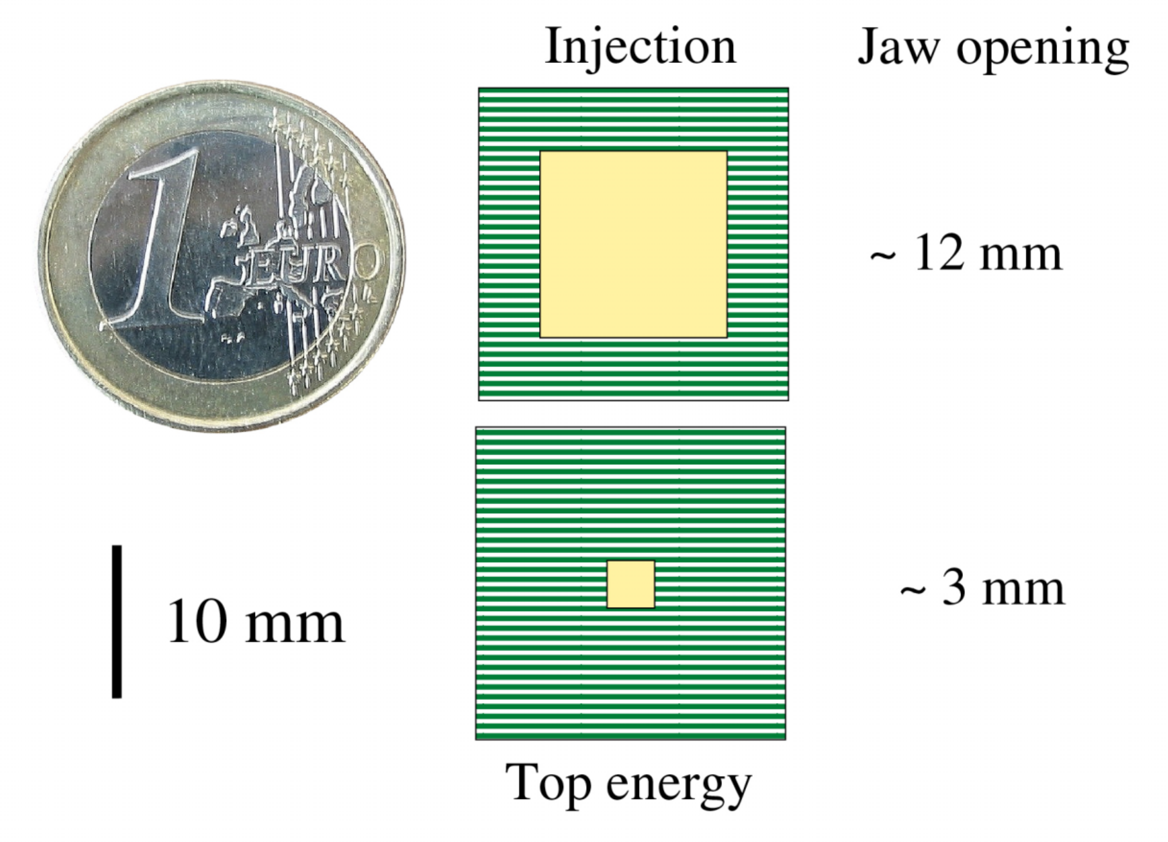
Energy [GeV]	Loss rate (10 h lifetime)	Quench limit [p/s/m] (**steady losses**)	Cleaning requirement
450	8.4e9 p/s	7.0e8 p/s/m	92.6 %
7000	**8.4e9 p/s**	**7.6e6 p/s/m**	**99.91 %**

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)*

Challenge: Tight and Efficient Collimation 1



Collimator settings:

5 - 6 σ (primary)
6 - 9 σ (secondary)

σ ~ 1 mm (injection)
σ ~ 0.2 mm (top)

Number of protons reaching 10σ:

10^{-4} of p at 6 σ

Reminder: Normalized available LHC aperture specified to be 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

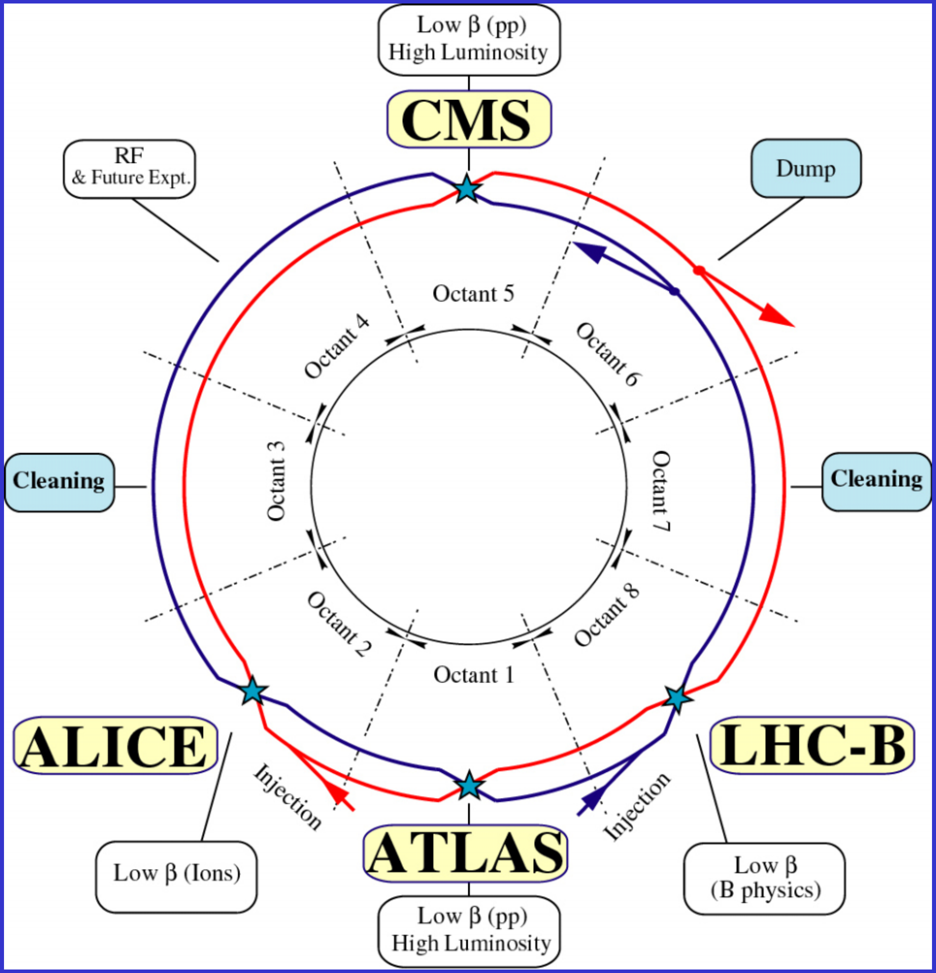
Challenge: Tight and Efficient Collimation 2

Two LHC insertions dedicated to cleaning:

IR3 Momentum cleaning
1 primary
4 secondary

IR7 Betatron cleaning
4 primary
16 secondary

Two-stage collimation system.



50 movable collimators for high efficiency cleaning
+ other absorbers for high amplitude protection

Contents

1) The challenge
   High stored energy and energy density
   Super-conducting environment
   Efficient and tight collimation

2) Irregular proton losses
   Dump failure modes
   Beam impact at collimators

3) Regular proton losses
   Running at the quench limit (intensity and beam lifetime)
   Heat load
   Efficiency and imperfections (halos)

4) Outlook

Irregular proton losses

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:

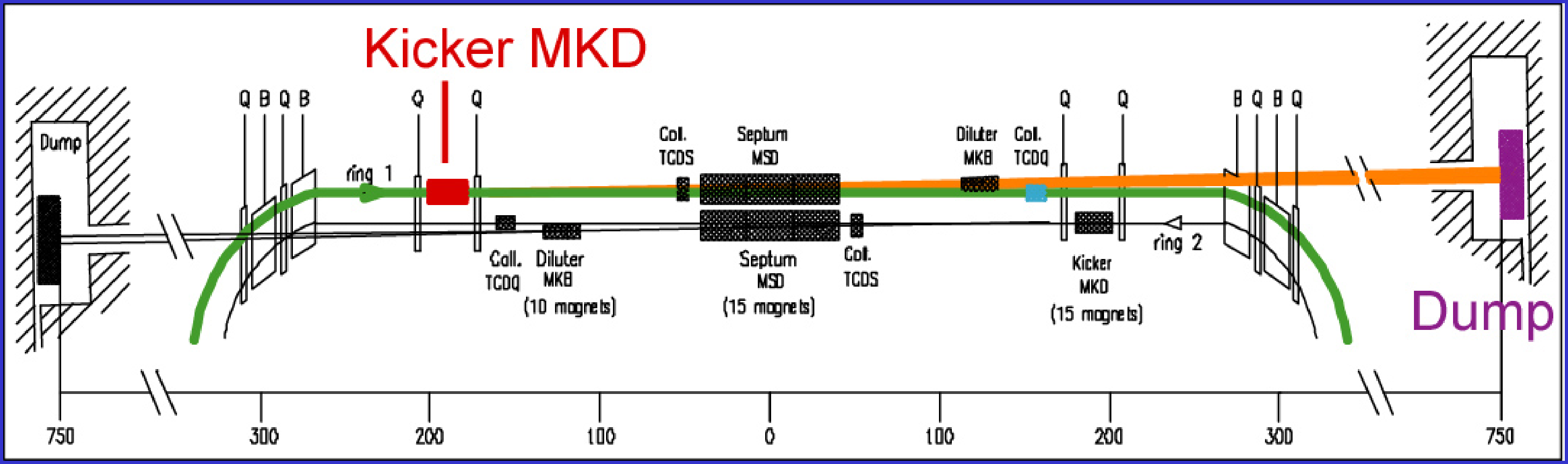
- Total failure of dump or dump trigger (> 100 years)
- Dump action non-synchronous with dump gap
- Dump action from 1 of 15 modules, others retriggering after 1.3 μs.

Difficult to predict

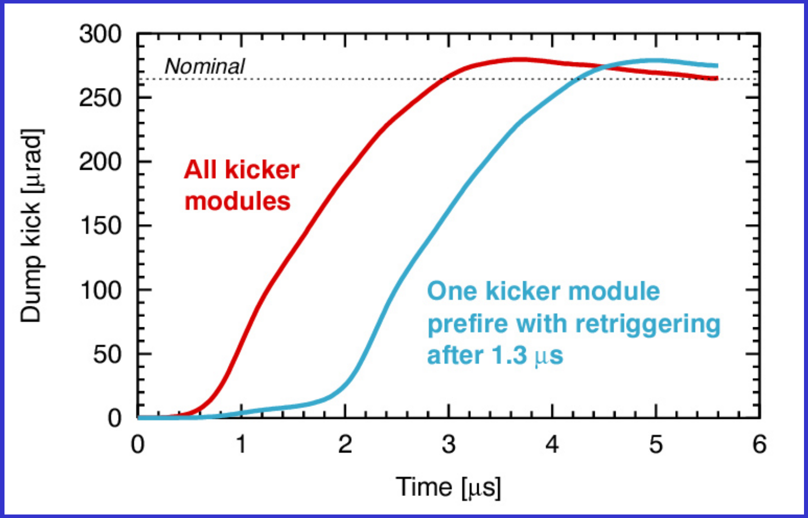
Assume at least once per year!

Magnet failures: V. Kain et al, MOPLE032

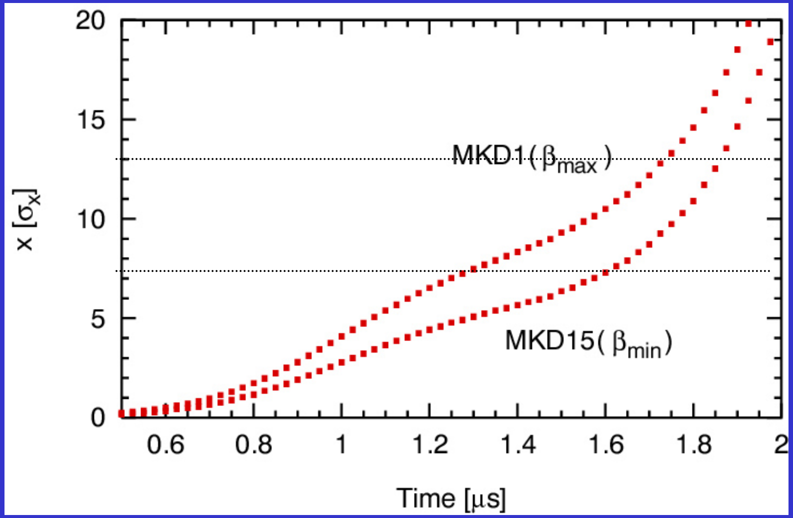
Abnormal dump actions



Kick [μrad]

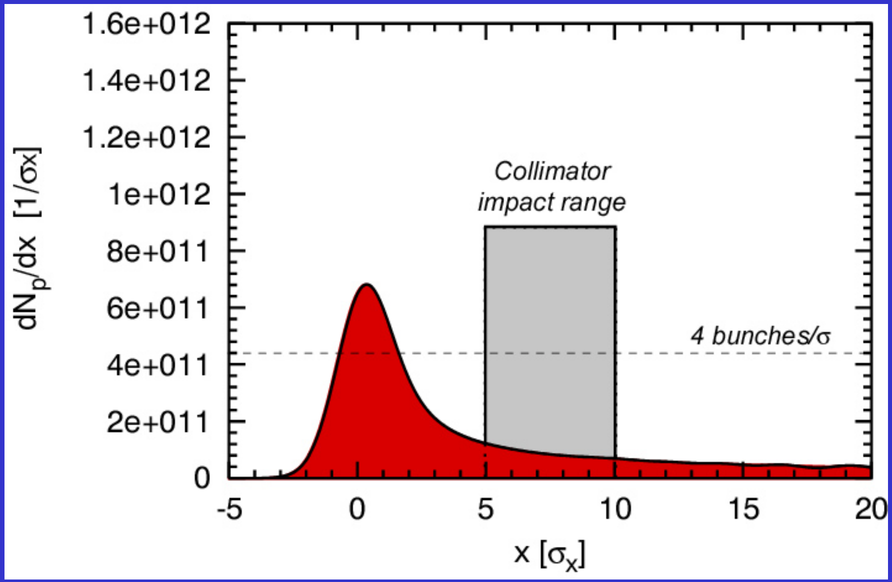


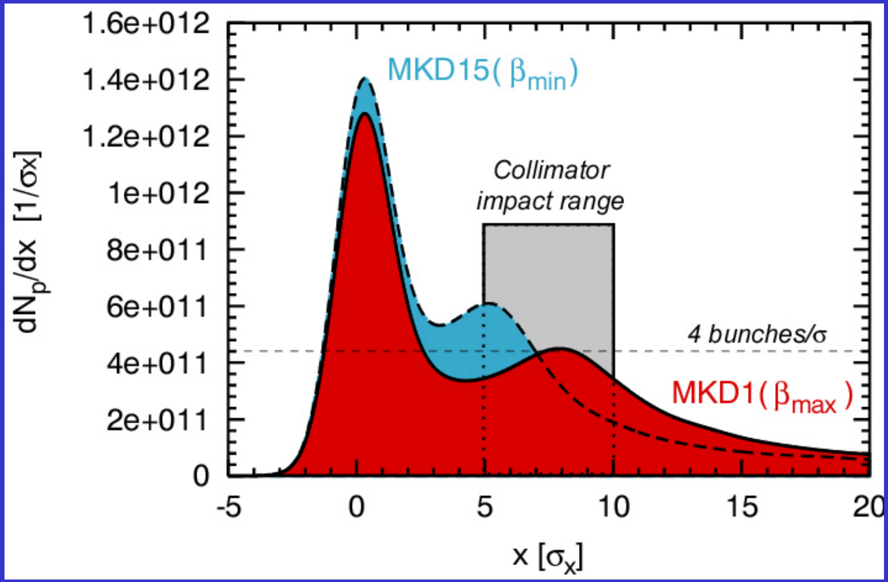
Downstream offset [σ]



One module pre-fire

Abnormal dump actions





Beam abort asynchronous with abort gap:

Total: 6 bunches over 5 σ

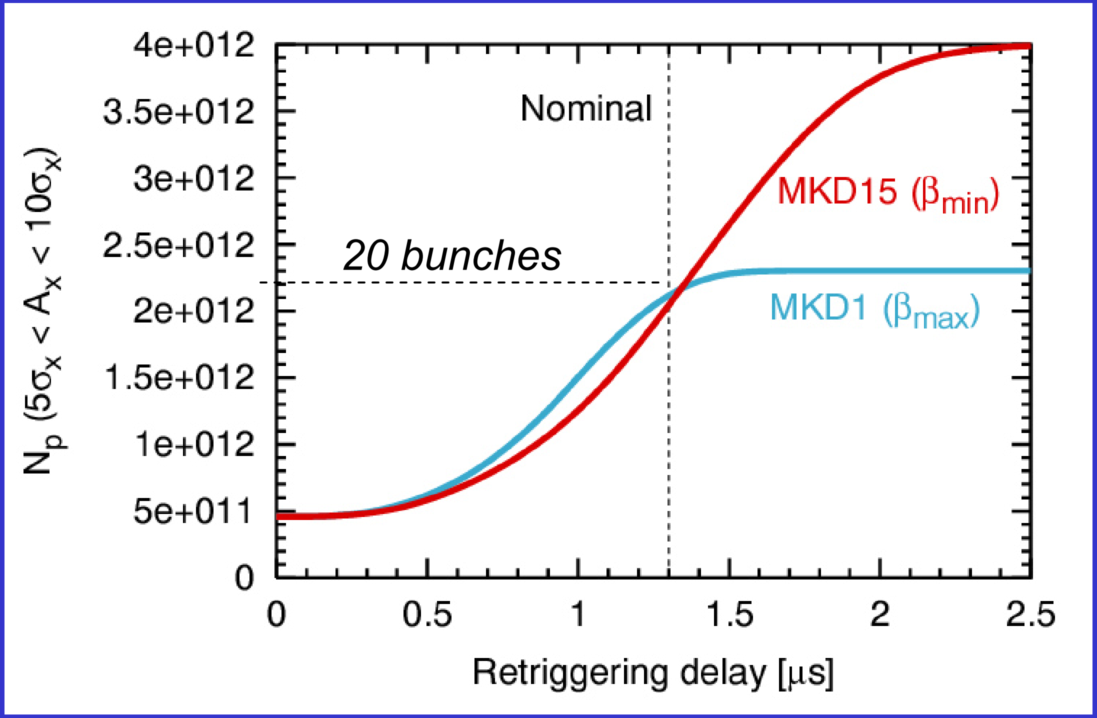
Peak: **1.5 bunches in 1 σ**

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

Total: 20 bunches over 5 σ

Peak: **6 bunches in 1 σ**

Abnormal dump actions



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, …

Low Z collimator material!

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Regular proton losses

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

Desirable:

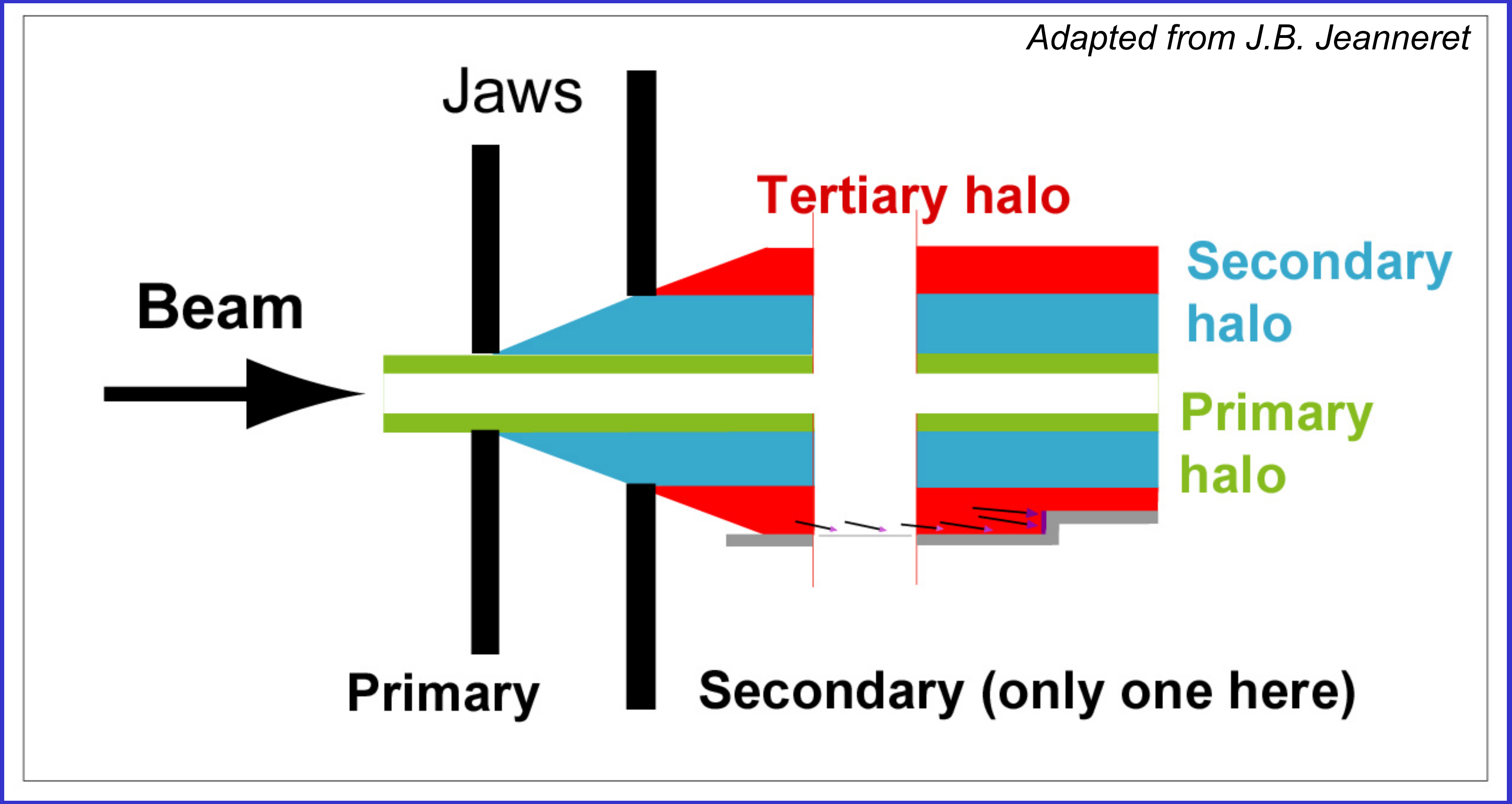
1) Possibility to run at quench limit (τ = 0.2 h for top energy)

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!

Two stage collimation system



Betatron cleaning: 4 primary and 16 secondary collimators
Optimize phase advance for minimal secondary halo

Improving our confidence in predictions

Two scattering routines used: K2 and STRUCT

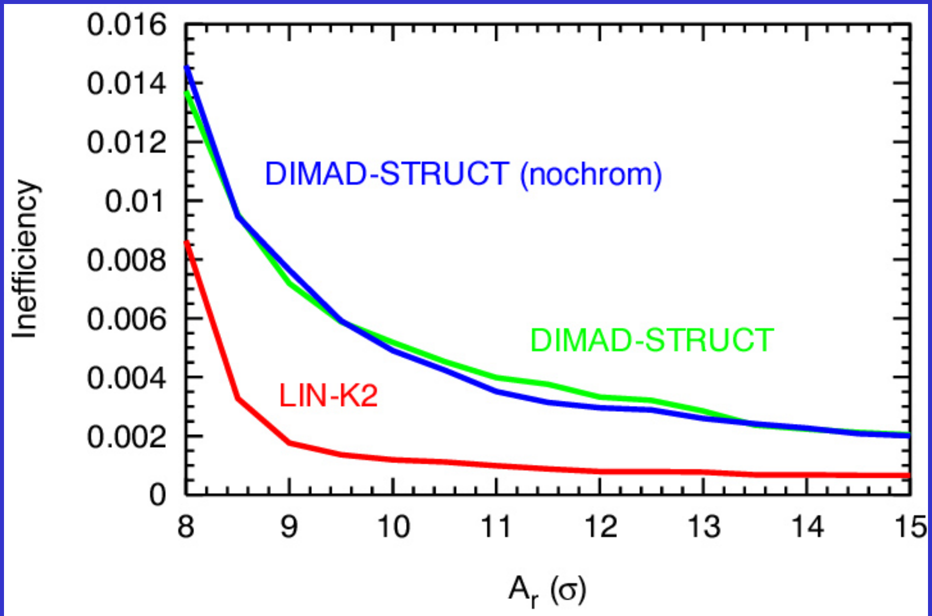
Tracking programs:

Linear transfer matrices
DIMAD
SIXTRACK

Effects being considered:

Scattering physics
Chromatic effects
Non-linear fields (diffusion)

M. Hayes et al, WEPLE044
F. Zimmermann et al, WEPLE048
R. Assmann et al, MOPLE030



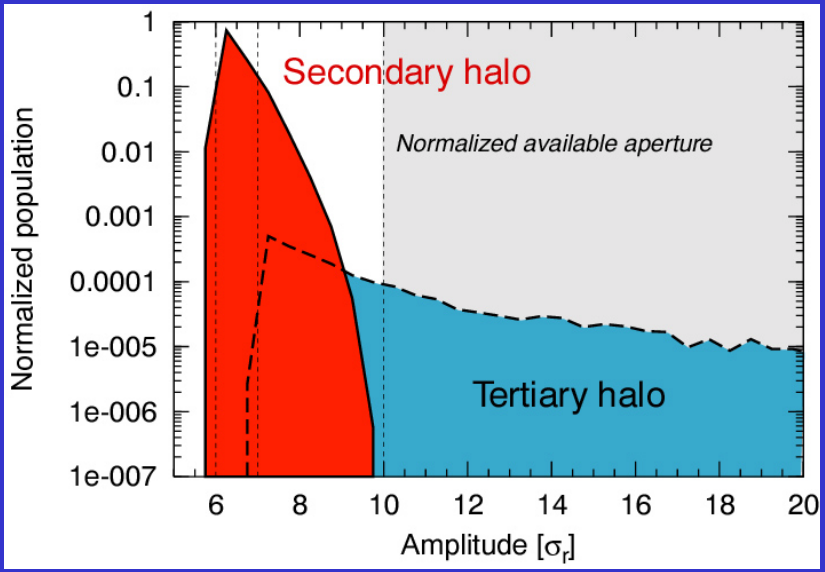
preliminary

Same order of magnitude results

Factor 5 disagreement to be understood.

System requires detailed understanding of 7 TeV proton interaction in matter.

Secondary and tertiary beam halos

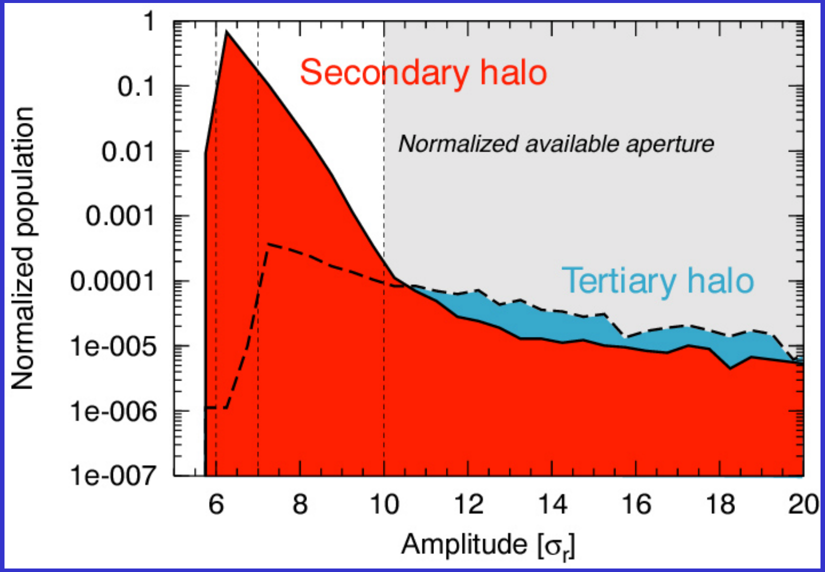


Scattering in colli-mator jaws (at 6/7 σ)

Transverse scattering angles + momentum loss

Halo at zero dispersion

Halo at max dispersion

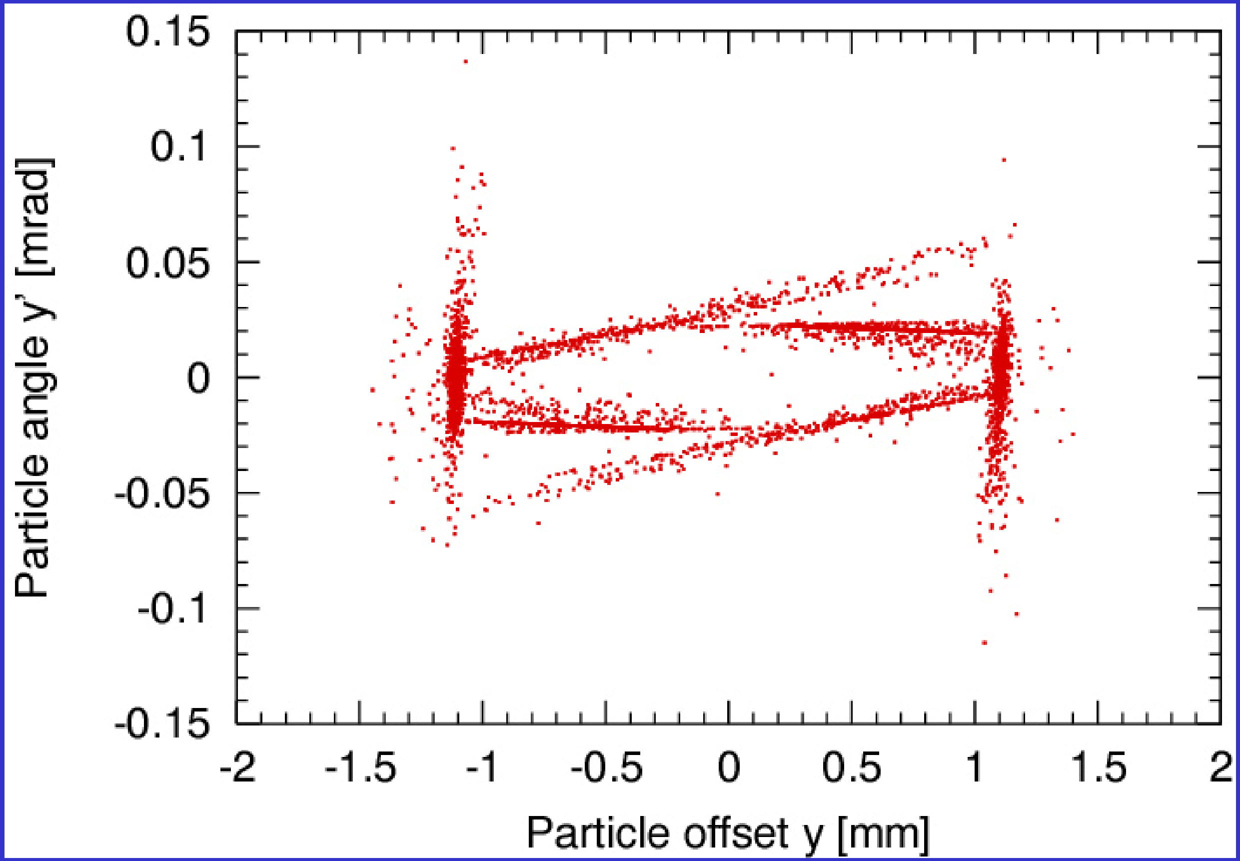


Local inefficiency [1/m]:

Integrate halos above 10σ

Divide by dilution length (50 m)

Tertiary halo in phase space

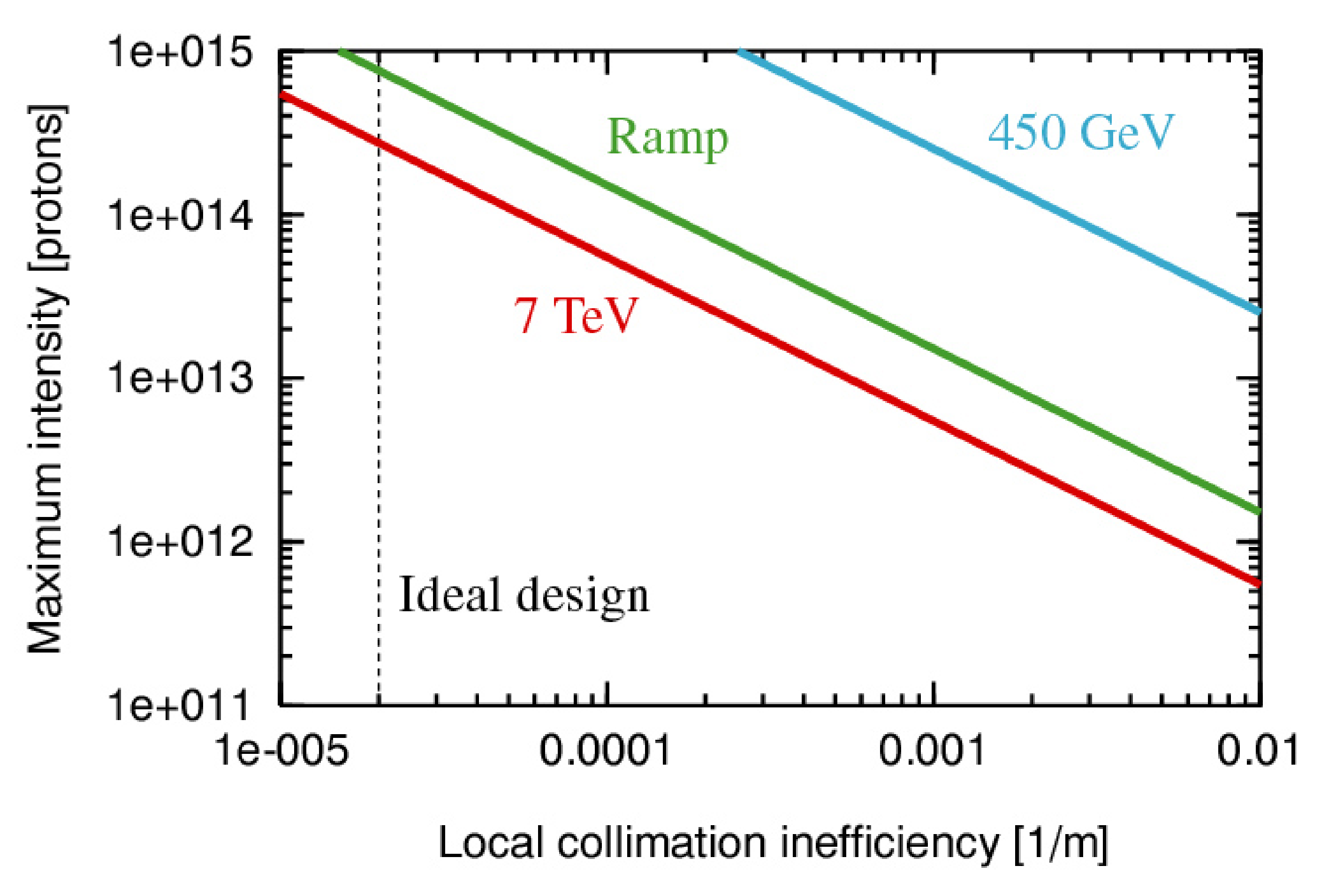


Halo generated at specific phase space locations!

Input to studies of **local loss distribution** (dilution, expected signals of Beam Loss Monitors BLM).

E. Gschwendtner et al, THPRI083

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



Trade-off for given quench limit between:

Inefficiency – Allowed intensity – Minimum allowable lifetime

Inefficiency with imperfections

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

R. Assmann et al, MOPLE030

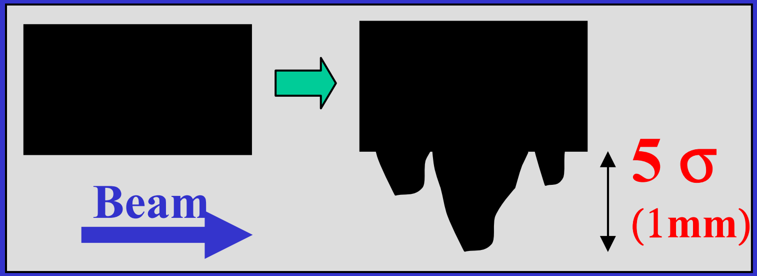
Error	Tolerance
Orbit	$0.6\ \sigma$
Beta beat	8%
Longitudinal angle	$50\ \mu$rad
$\Delta L/L$ (prim)	75%
Surface flatness (prim)	$10\ \mu$m
$\Delta L/L$ (sec)	20%
Surface flatness (sec)	$25\ \mu$m
Setting accuracy (prim)	$-1.0/+0.5\ \sigma$
Setting accuracy (sec)	$\geq \pm 0.5\ \sigma$

Transient changes (Orbit, Beta beat)

Preliminary estimates:

Combined effect can make tolerances more severe!

Collimators need not only be robust, but also precise!



Summary and Outlook 1

Beam impact requirements analyzed (failure modes and operational requirements) for a robust and efficient LHC collimation system!

Now engineering design starting: appropriate materials (low Z), lengths, mechanics, cooling, damage and fatigue analysis, tolerances, …

Additional concerns: Impedance, vacuum, local e-cloud, radiation impact.

Two cleaning insertions, each two-stage, defined since years for high efficiency cleaning.

Accelerator physics and operational analysis is ongoing:

Overall tolerance specifications (flatness, required adjustments, orbit and optics requirements, …). Operational optimization. Realistic diffusion and aperture models (BLM signals). Chromatic effects.
Cross-checks of different scattering and tracking tools.

Summary and Outlook 2

The performance of the collimation system can limit…

… **peak luminosity** due to maximum allowed intensity.

… **integrated luminosity** due to beam aborts and repair time.

This we want to prevent with the best possible design!

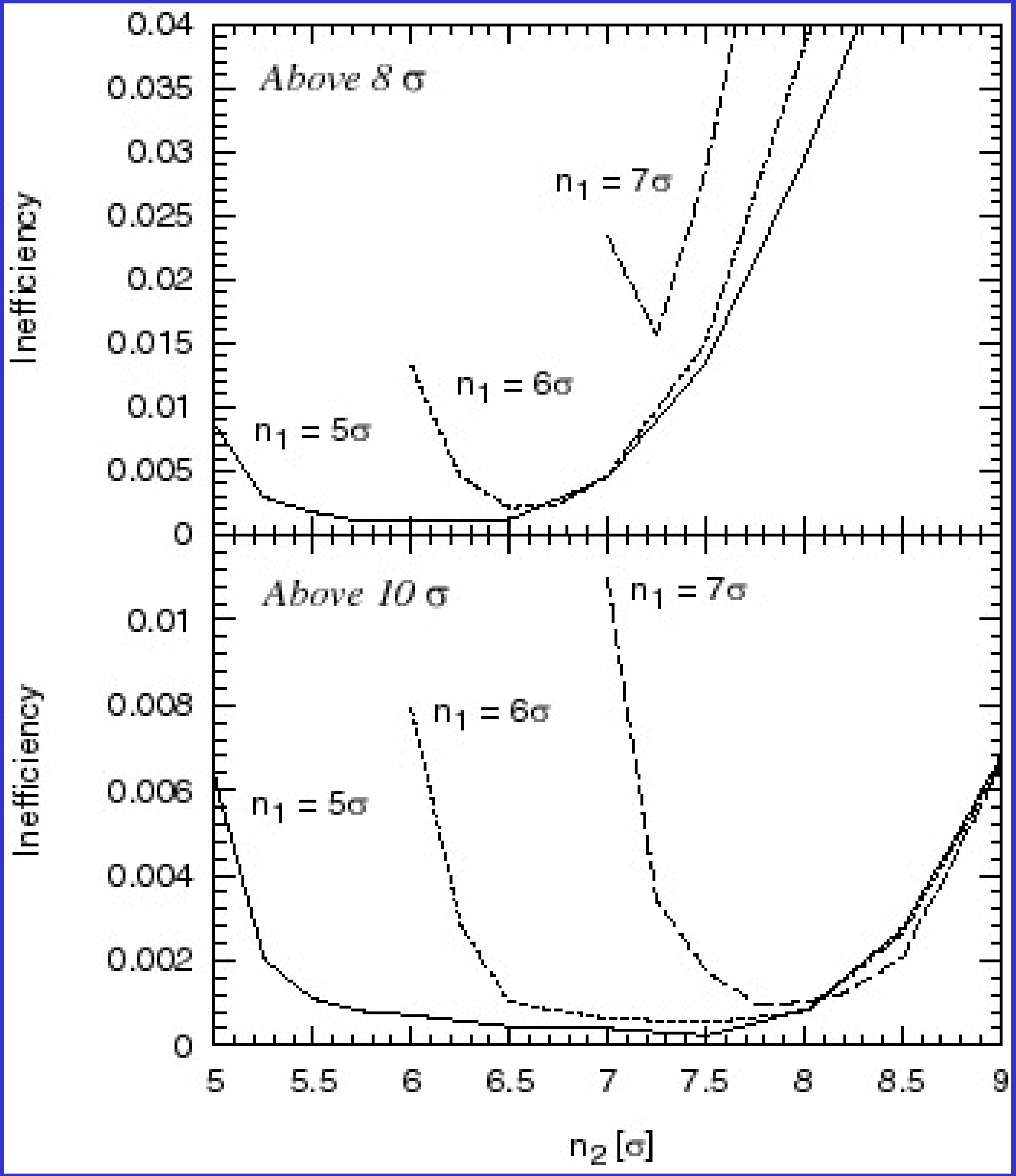
Collimation is a performance-critical topic

from day 1 of LHC physics!

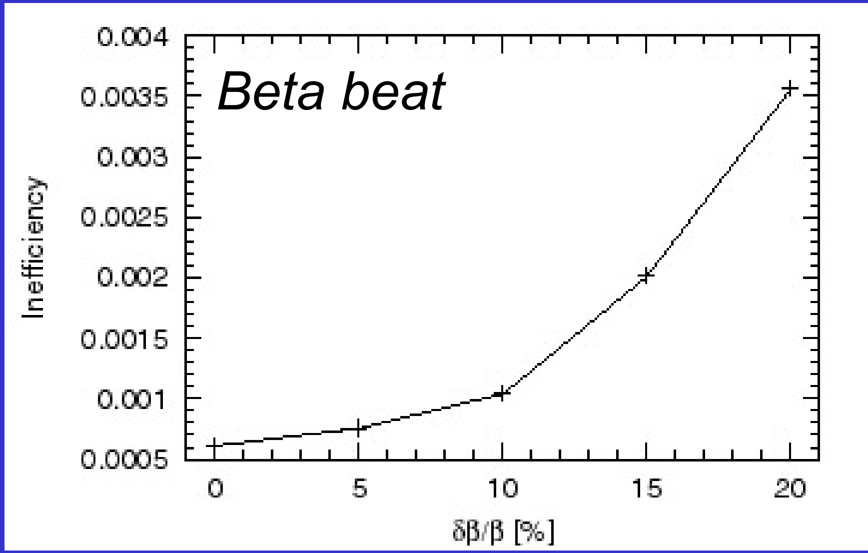
It pushes accelerator physics understanding of beam halo and material science to new frontiers!

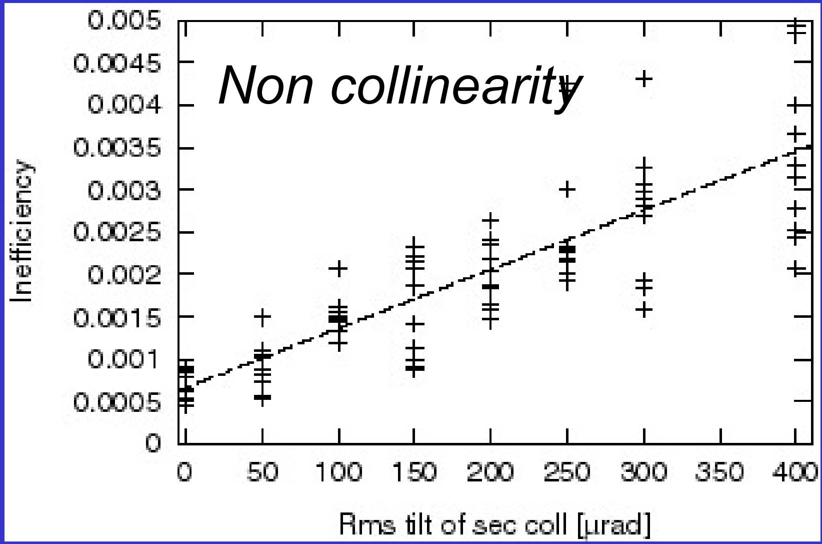
Additional slides

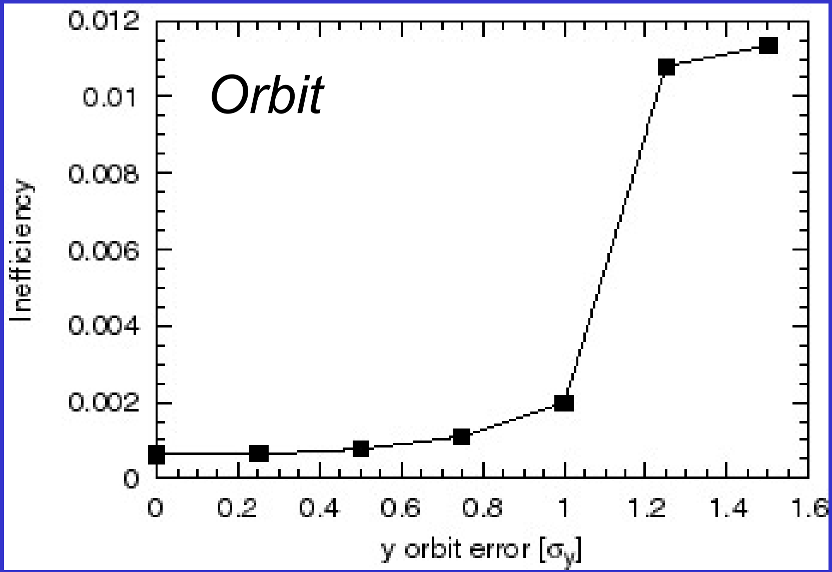
Inefficiency versus settings

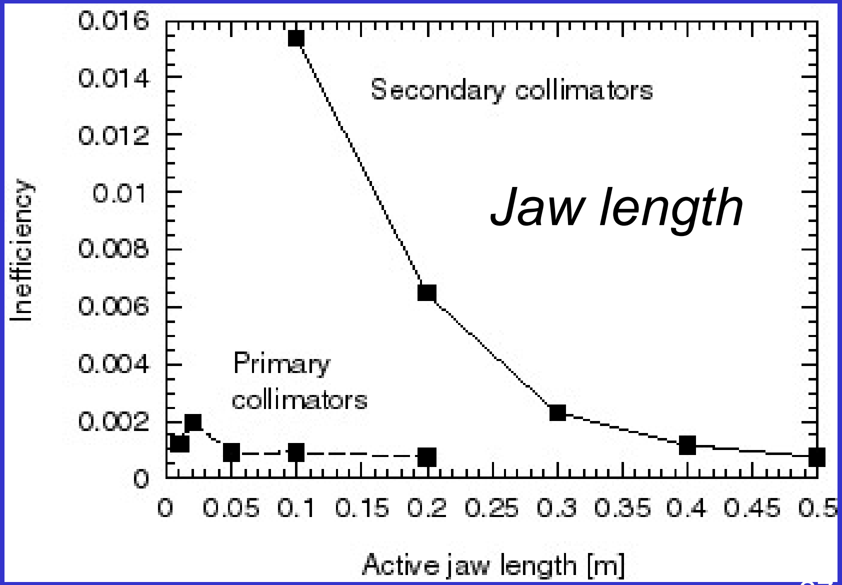


Inefficiency versus imperfections

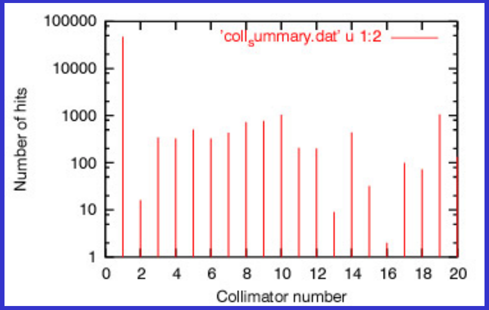


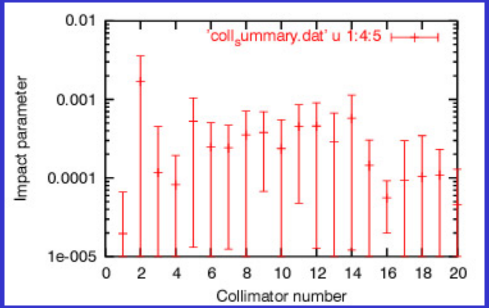


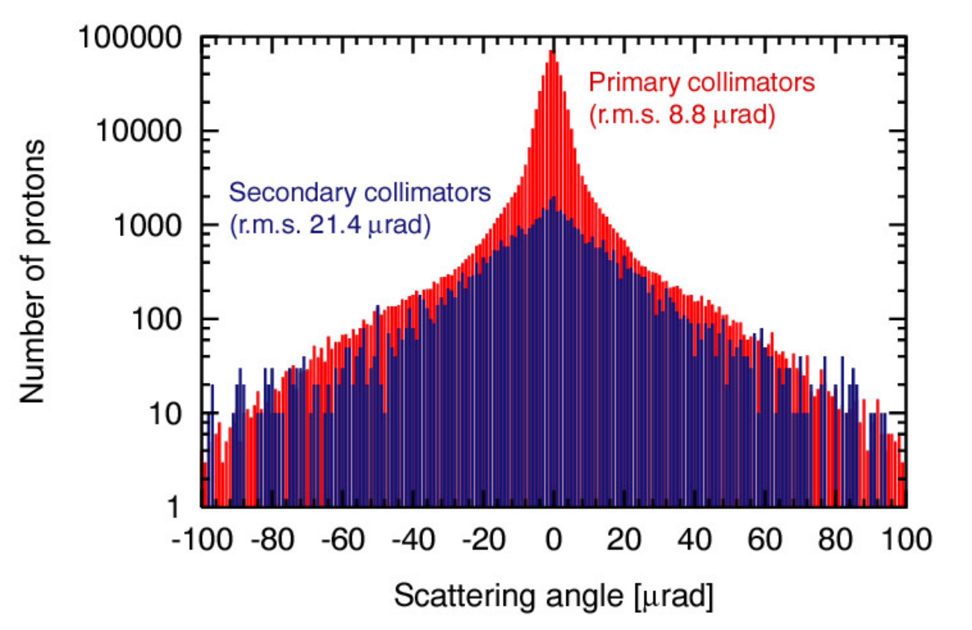


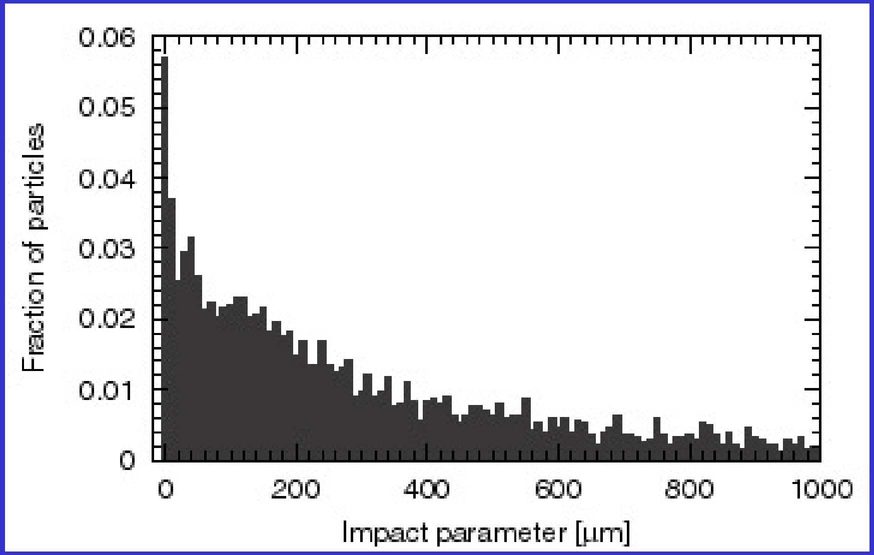


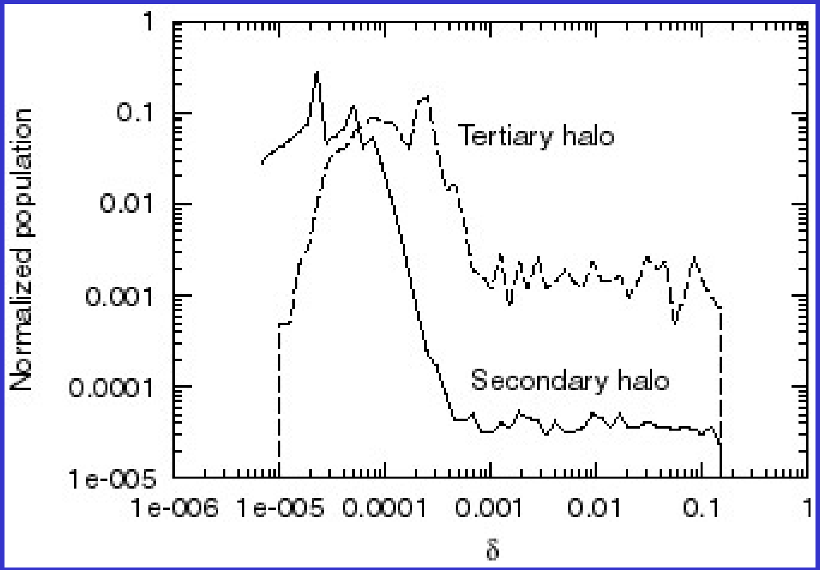
Scattering physics











Multi-turn properties and impact parameter