Collimators and Cleaning, Could this Limit the LHC Performance ?

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Answer is easy:

You bet, collimation and cleaning can limit us!

The question we are considering:

How can we build a collimation system that will not limit LHC performance?

Work done in

Beam Cleaning Study Group / Collimation WG
(since 9/2001. Mandate: AP and OP issues of collimation)

LHC Collimation Project
(since 10/2002. Mandate: finalize design, build prototype, produce full system, supervise installation, commissioning)

Close collaboration with LHC Machine Protection Working Group.

Meetings:

Collimator Project Meetings and LHC Collimation Working Group

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

The Collimation Team:

- Project Management
- Engineering/Technical Support
- Material Simulations for Collimator Jaws
- Material Tests
- Theoretical Studies/System Design/System Simulations
- Operational Scenarios/Instrumentation/MD's
- Additional Link Persons

Many team members contribute only a small fraction of their time – expertise anyway crucial!

O. Aberle, R. Assmann (Project Leader), I. Baichev, M. Brugger, L. Bruno, P. Bryant, H. Burkhardt, E. Chiaveri, B. Dehning, A. Ferrari, J.B. Jeanneret, M. Jimenez, V. Kain, D. Kaltchev, M. Lamont, M. Mayer, H. Preis, T. Risselada, F. Ruggiero, F. Schmidt, R. Schmidt, P. Sievers, V. Vlachoudis, J. Wenninger, F. Zimmermann

+ colleagues in Collimation WG and Machine Protection WG

Link persons:

B. Goddard, G. Peon, R. Ostojic, W. Kalbreier, J. Uythoven, W. Weterings

Outline

1. The LHC Collimation System

2. Limitations for machine availability (collimation hardware)

3. Limitations on machine parameters (cleaning efficiency)

4. Outlook

The Collimation System

Design and build a collimation system …

… that absorbs the beam halo

… of the high power LHC beam

… such that the quenches are avoided

… and the equipment is protected

… in the tight LHC cold aperture

… ensuring collimator survival

… respecting AP, vacuum, radiation boundary conditions

… and compatibility with operation

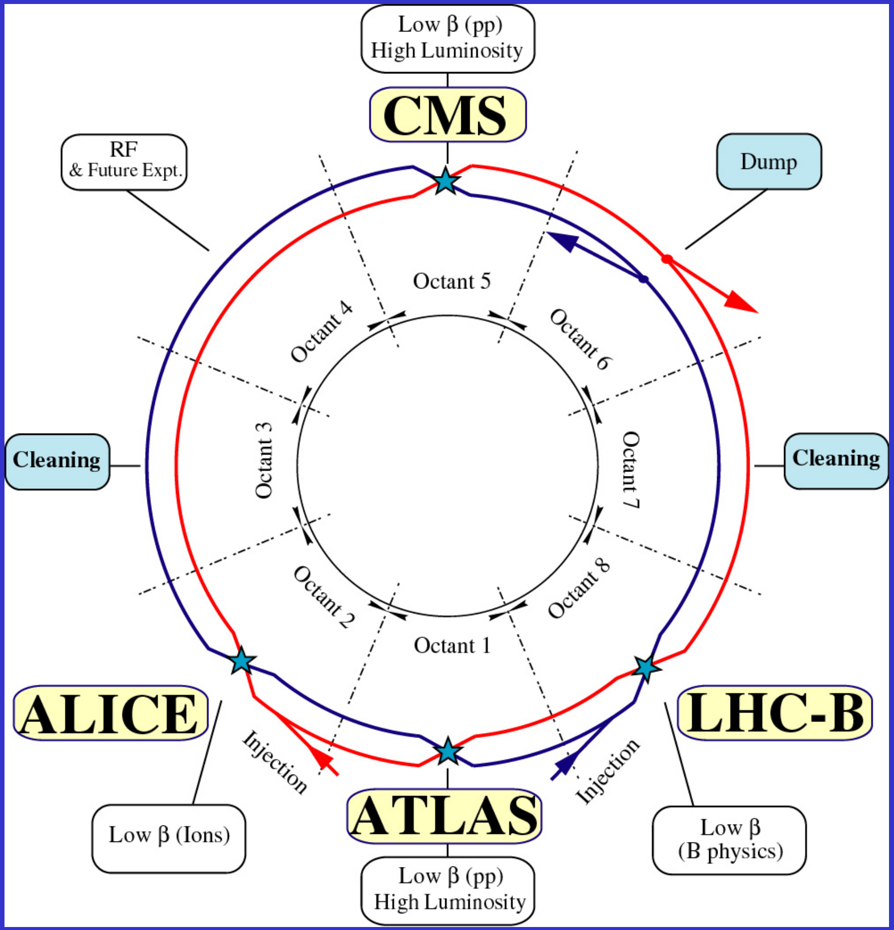
The LHC Cleaning Insertions

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*

Significant system: ~ 200 degrees of freedom!

Collimators & absorbers at 7 TeV:

Region	Type	Orientation	Materi al	Number	Length	Setting
IR1	TCL (Q5)	X	Cu	2	1.0 m	10.0 σ
	TAS	Round	Cu?	2	1.8 m	12.0 σ
	TCL (D2)	*X*	*Cu*	*2*	*1.0 m*	*10.0 σ*
IR3	TCP	X	Al	1	0.2 m	8.0 σ
	TCS	X, Y, XY	Cu	6	0.5 m	9.3 σ
IR5	TCL (Q5)	X	Cu	2	1.0 m	10.0 σ
	TAS	Round	Cu?	2	1.8 m	12.0 σ
	TCL (D2)	*X*	*Cu*	*2*	*1.0 m*	*10.0 σ*
IR6	TCDQ	X (1 side)	C	1	9.5 m	10.0 σ
IR7	**TCP**	**X, Y, XY**	**Al**	**4**	**0.2 m**	**6.0 σ**
	TCS	**X, Y, XY**	**Cu**	**16**	**0.5 m**	**7.0 σ**

- Numbers are for Al, Cu system. Length is given per collimator
- All collimators two-sided except noted.
- Number is per beam.
- TCL (D2) is an upgrade for LHC ultimate performance.
- Table is for 7 TeV.
- Settings are for nominal luminosity and nominal β^* (n_1 = 7 in the triplet).
- For injection add TDI, TCL (inj), and TCDS. All around 10 σ. IR1 and IR5 settings could be open for injection, others remain at similar settings.

Basic concept of collimation

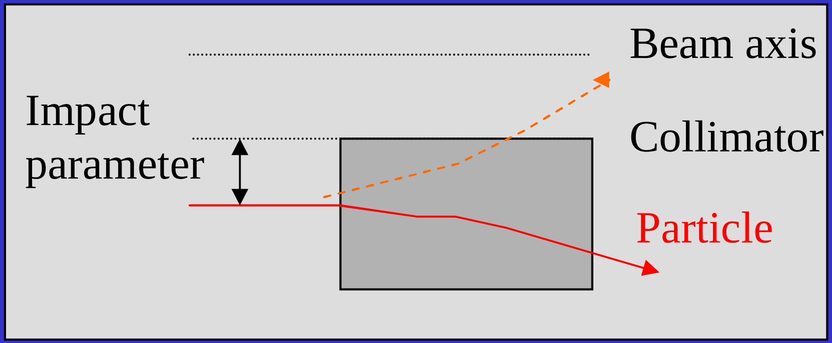
“Conventional” jaws (blocks of appropriate solid materials).

“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



Protection of aperture against halo and beam

Expected physical aperture limits (freely available, a is half aperture)

Energy	Location	a [m]	β [m]	a_{norm} [$m^{1/2}$]	$a_{norm}/\varepsilon^{1/2}$
450 GeV	Arc	0.012	180	8.8×10^{-4}	10
7 TeV	Triplet	0.015	4669	2.2×10^{-4}	10

Collimator setting (prim) required for triplet protection from 7 TeV secondary halo:

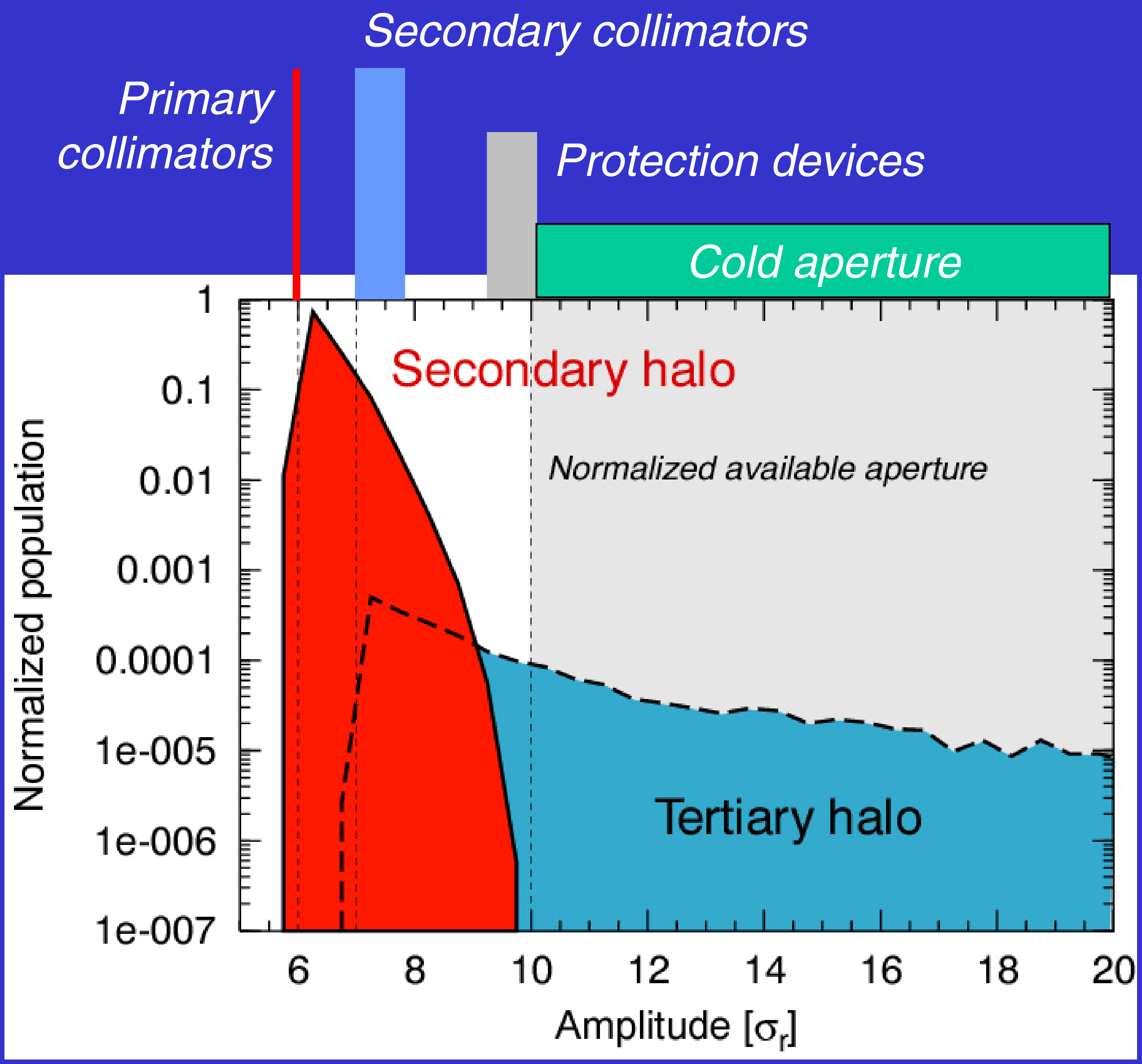
$$a_{coll} \leq a_{triplet} \cdot \overbrace{\sqrt{\frac{\beta_{coll}}{\beta_{triplet}}}}^{\sim 0.15} \cdot \overbrace{\left(\frac{A_{primary}^{max}}{A_{secondary}^{max}} \right)}^{\sim 0.6}$$

Collimator gap must be **10 times smaller** than available triplet aperture!

Collimator settings usually defined in sigma with nominal emittance!

Aperture allowances: 3-4 mm for closed orbit, 4 mm for momentum offset, 1-2 mm for mechanical tolerances.

Secondary and Tertiary Beam Halo (zero dispersion)



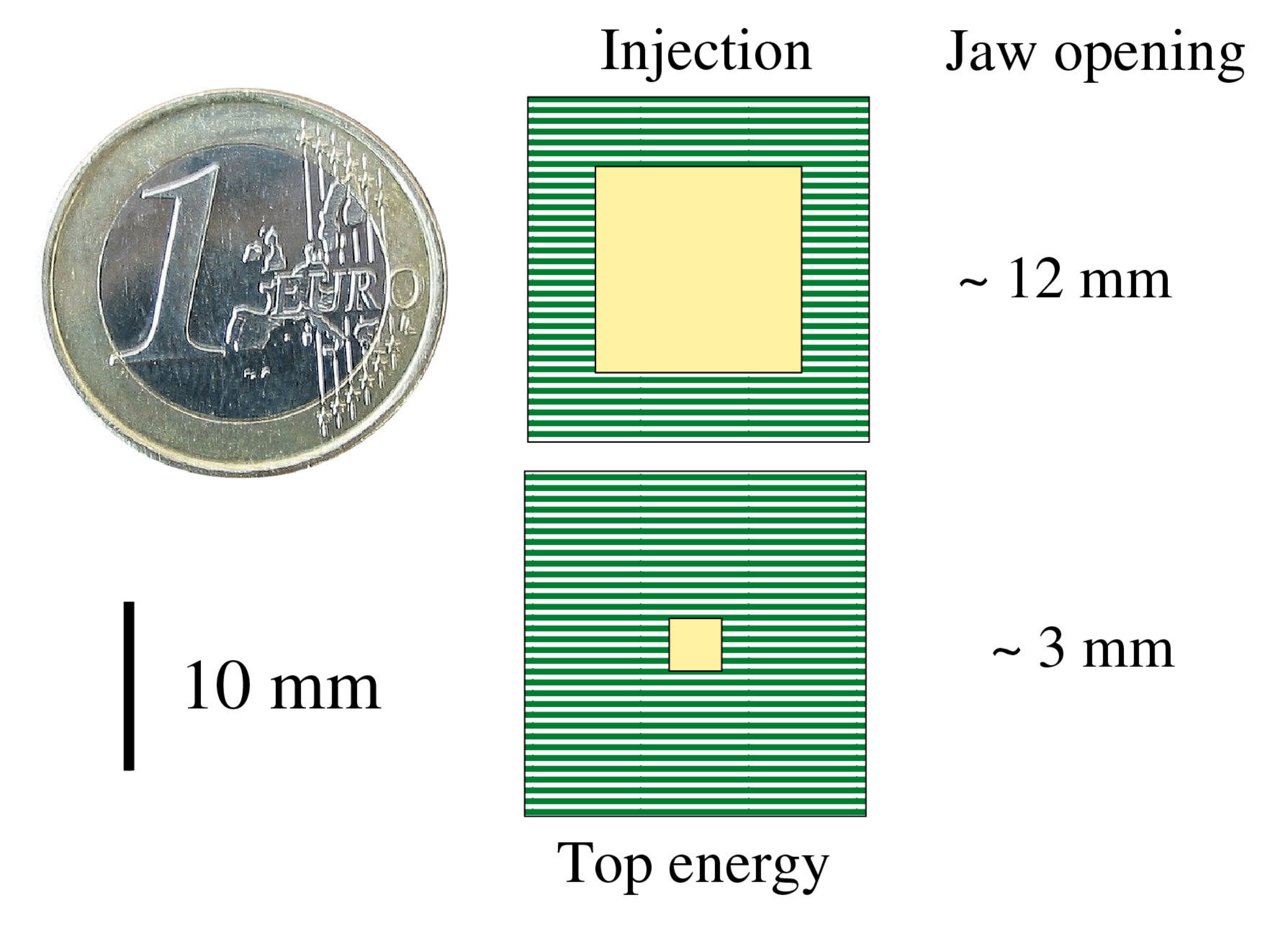
Strategy:

Primary collimators are closest.

Secondary collimators are next.

Absorbers for protection just outside secondary halo before cold aperture.

Relies on good knowledge and control of orbit around the ring!



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

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Limitations for Machine Availability

Physics Potential = Energy and Luminosity

High LHC luminosity translates into high transverse energy density:

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

d = demagnification (β_{coll}/β^*)
N_p = protons per bunch
f_{rev} = revolution freq.
E_b = beam energy

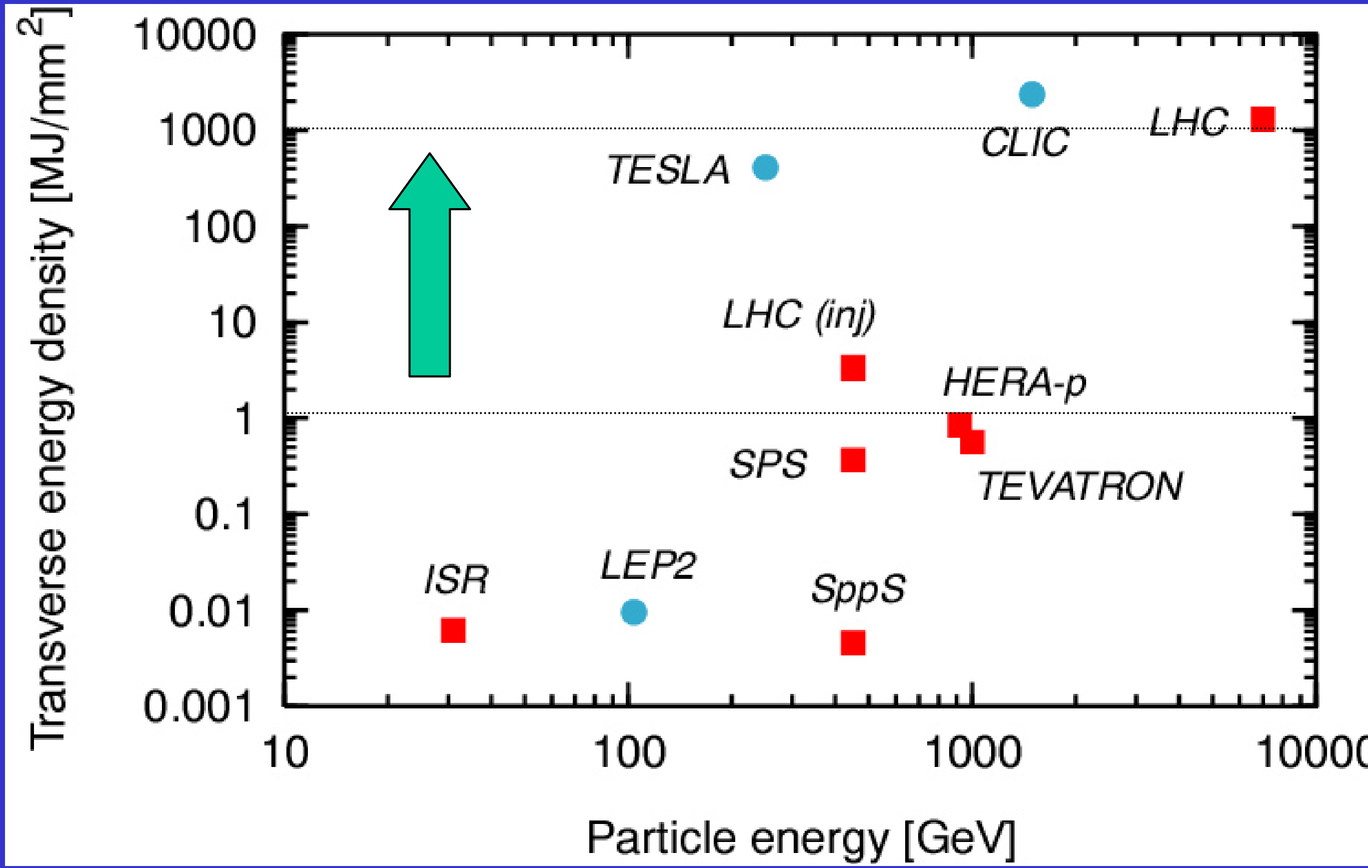
Fixed or limited

Increase luminosity via transverse energy density.

Parameter for material damage: ρ_e

LHC advancement: Factor 7 in beam energy
Factor 1000 in ρ_e

Compare…



LHC nominal Parameters:

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

At less than 1% of nominal intensity LHC enters new territory.

Collimators must survive expected beam loss…

Collimators will be highly activated!

Beam loss at the 10^{-5} level can damage components: (for Cu)

Failures that we consider for collimator design:

Fast cases (< 1 turn):	**Pre-fire of one dump kicker module**	(2.2 MJ)
	Asynchronous beam dump (miss dump gap)	(0.5 MJ)
	Impact from one full batch at injection	(2.3 MJ)
Slow case:	**Impact during low beam lifetime** (0.2 h to1 h)	(4.4 MJ in 10s)
Beam types:	Protons and ions	
Full stored beam power:	331 MJ (7 TeV) Energy to melt 1 kg Cu:	0.7 MJ

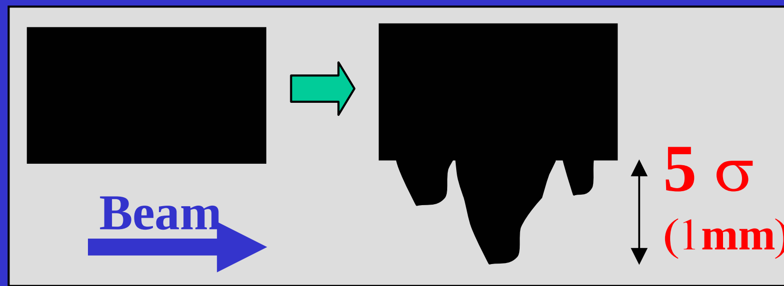
Observations:

- Losses on the **1% level** expected.
- Sufficient to **melt several kg Cu**.
- Al/Cu system (V6.4) would withstand on the < 0.01% level. **Factor 400 improvement** needed.

Note: Only one primary per plane.
Disturbed beam can bypass primary and hit secondary (1 turn).
Any collimator can be hit (don't constrain LHC tune).

Consequences of damage for LHC (non-catastrophic):

HERA experience:



1. Observe quenches (lower cleaning efficiency).
2. Try to identify damaged jaw(s) (damage can be on ~ 100 µm level).
   Many jaws close-by in phase advance.
3. Confirm hypothesis by hardware inspection.
4. Remove highly radioactive jaw/collimator tank.
5. Install new jaw/collimator tank.
6. Re-adjust collimator settings.

Can be a **lengthy procedure** (even if only a few times per year). Build **robust collimators** (no damage) or have **fully remote** procedure (revolver of jaws).

Further worry: 158 moving jaws (all coll/abs, 2 beams) with up to **316 motors** in a **highly radioactive environment**!

Basic strategy

Two possibilities:

1) A solution can be found that has sufficient robustness such that frequent damage is avoided (low Z jaws).

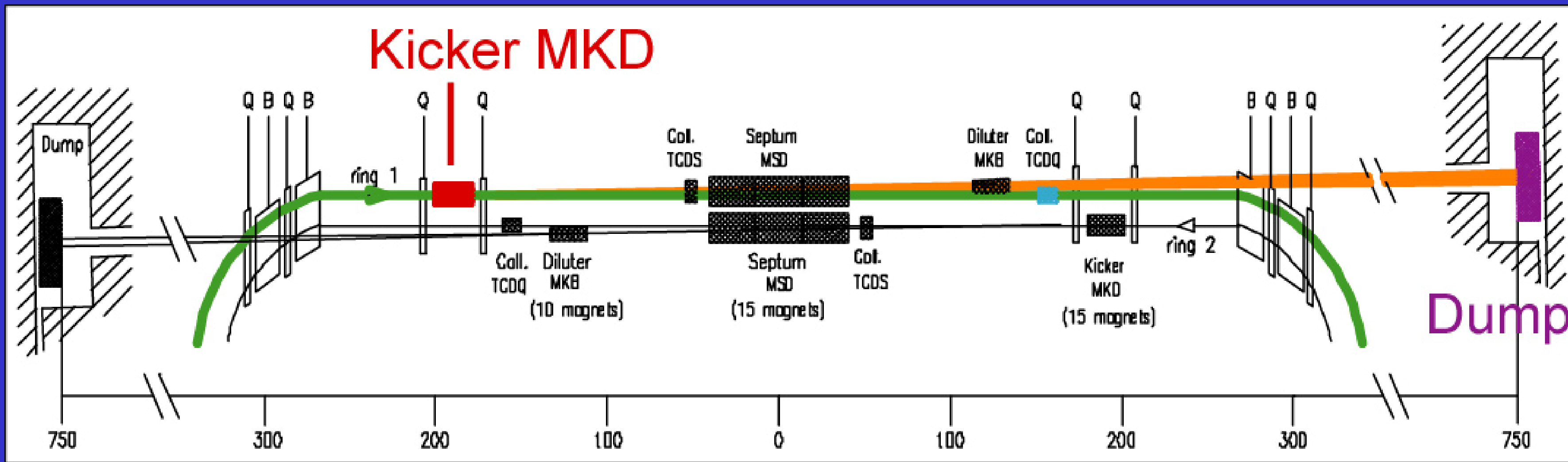
2) The jaws will be damaged regularly and we must foresee easy diagnostics and remote repair/exchange possibilities of the highly radioactive jaws (revolver of jaws).

Solution 1 is preferable and all effort concentrates on it for the moment!

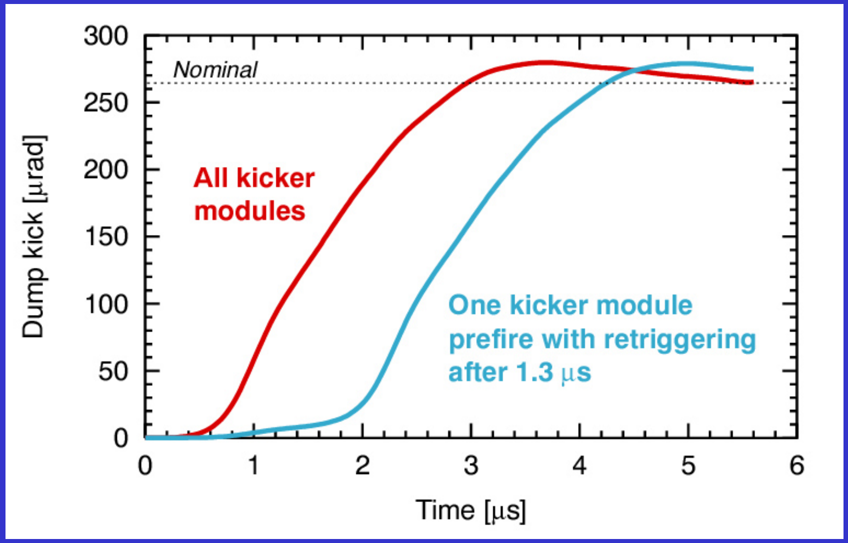
Talk by P. Sievers!

Advance the most simple solution that promises to be adequate. Keep more complicated/less convenient concepts in mind as backup solutions. Carbon!
(Beryllium, Diamond, multi-layer structures, crystal collimation, renewable high-Z collimators, repairable high-Z collimators, tertiary collimators at the triplets, primary collimators covering the phase space, anti-kicker at dump …)

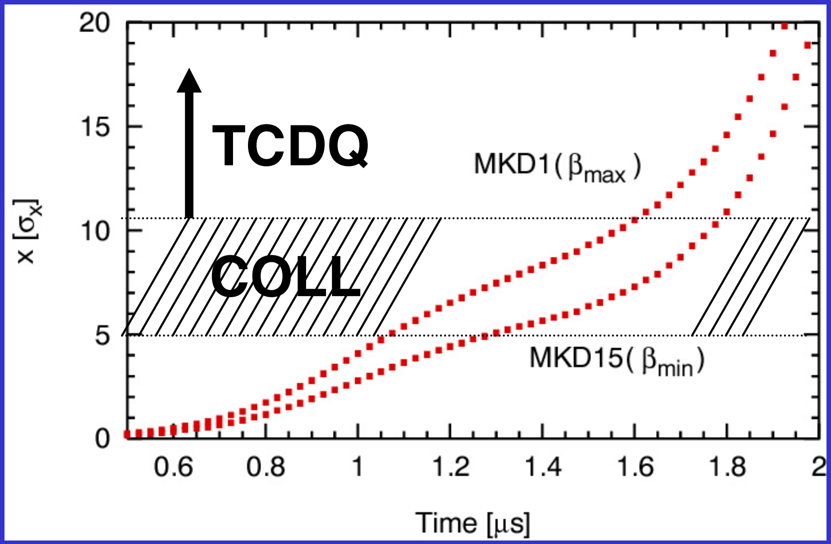
Abnormal dump actions



Kick [μrad]

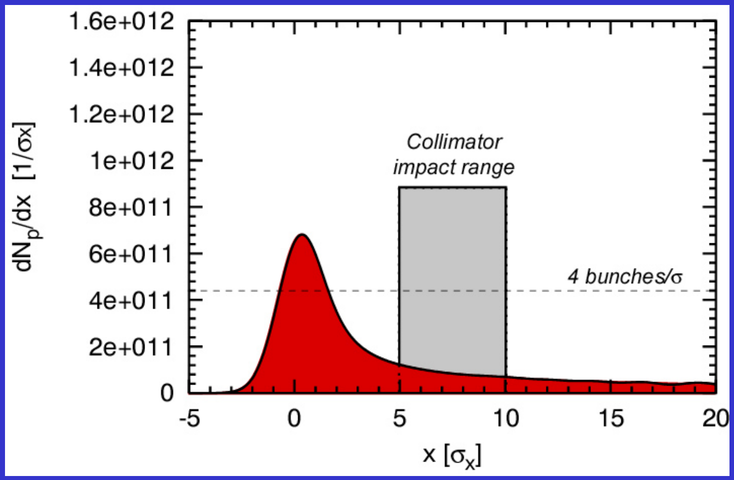


Downstream offset [σ]



One module pre-fire

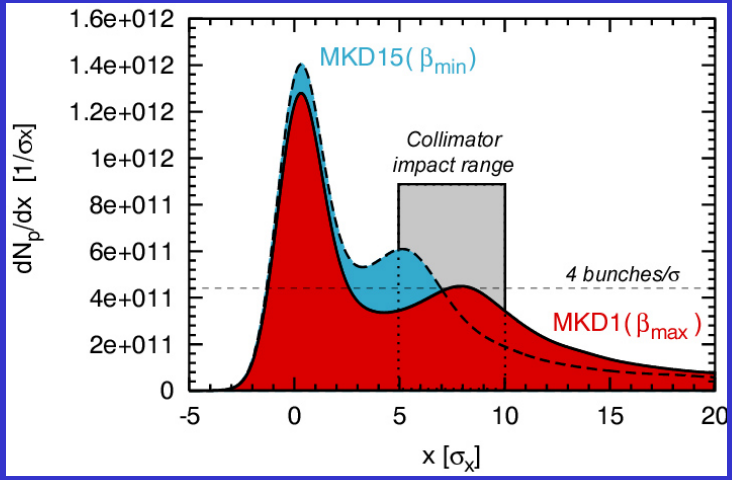
Abnormal dump actions as input for FLUKA



Beam abort asynchronous with abort gap:

Total: 6 bunches over 5 σ

Peak: **1.5 bunches in 1 σ**



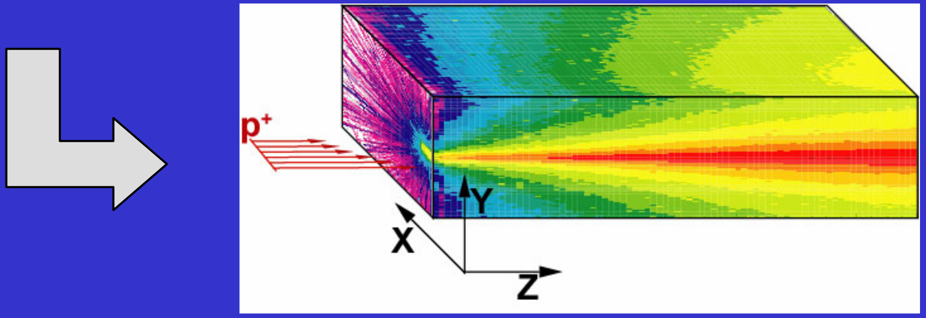
1 module pre-fire with re-triggering of 14 after 1.3μs:

Total: 20 bunches over 5 σ

Peak: **6 bunches in 1 σ**

R. Assmann, B. Goddard, E. Weisse, G. Vossenberg

Talk by P. Sievers!



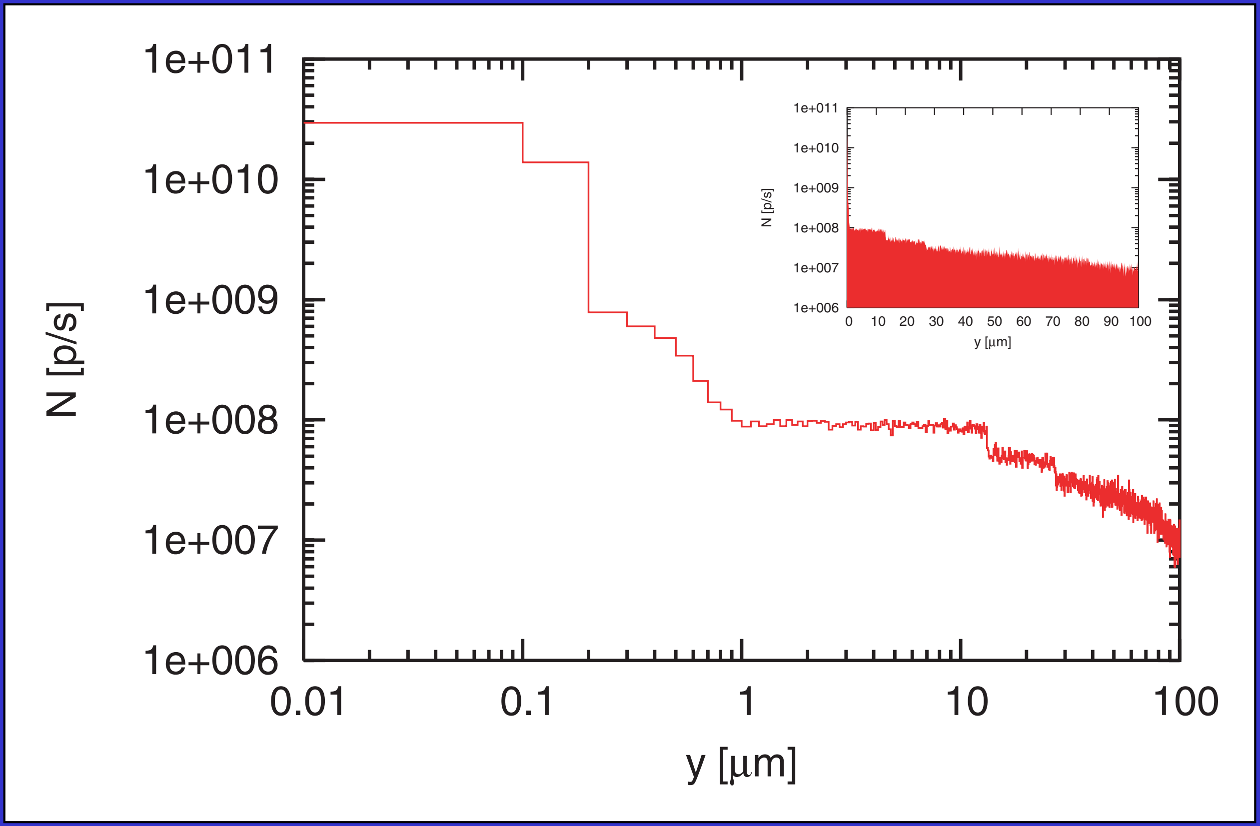
A. Ferrari, V. Vlachoudis

Further cases under preparation: Slow losses and ions

Slow loss:

Uniform “emittance” blow-up

Beam lifetime: **0.2 h**		Loss rate:	4.1e11	p/s
		Loss in 10 s:	4.1e12	p (**1.4 %**)
			(~ 40 bunches)	
Assume drift:	0.3	sig/s		
	5.3	**nm/turn**	(sigma = 200 micron)	



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

Transverse impact parameter

Almost all particles impact with

$y \leq 0.2\ \mu m$

Surface phenomenon!

R. Assmann

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A) Intensity at the quench limit

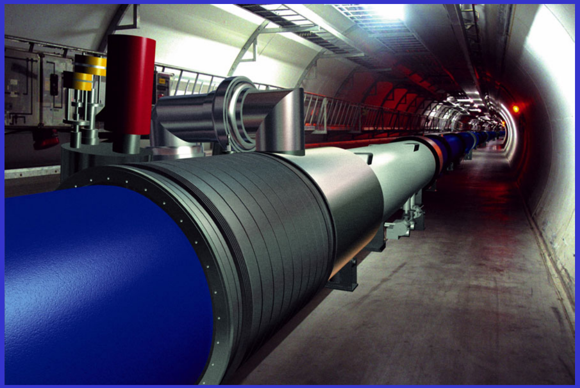


Illustration of LHC dipole in tunnel

Allowed intensity

Quench threshold
(7.6×10^6 p/m/s @ 7 TeV)

$$N_p^{\max} \approx \tau \cdot R_q \cdot L_{dil} / \eta_c$$

Beam lifetime
(e.g. 0.2 h minimum)

Dilution length
(50 m)

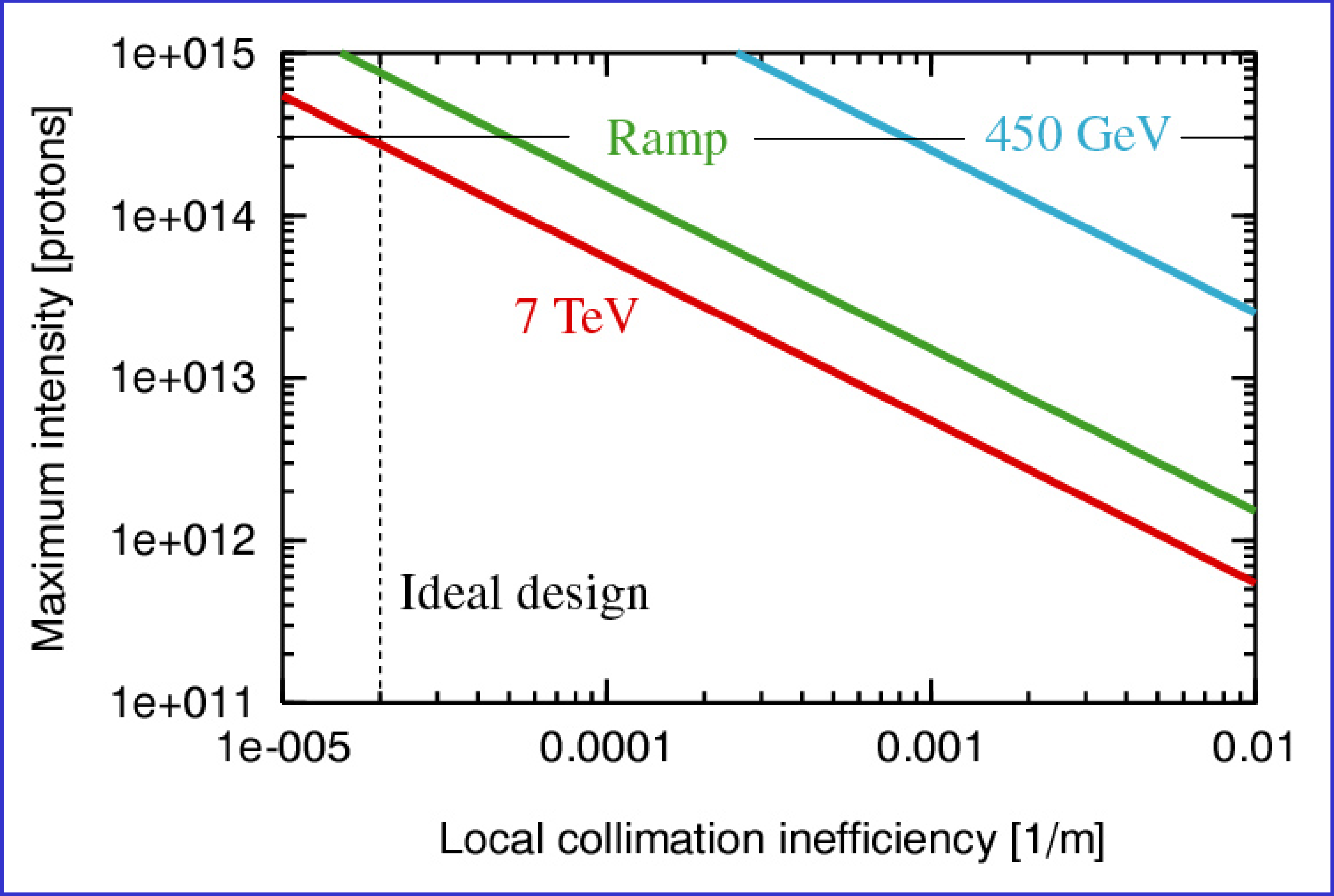
Cleaning inefficiency

=

$$\frac{\text{Number of escaping p } (>10\sigma)}{\text{Number of impacting p } (6\sigma)}$$

Collimation performance can limit the intensity and therefore LHC luminosity.

Allowed Intensity Versus Cleaning Efficiency



For a 0.2 h minimum beam lifetime during the cycle.

Trade-off for given quench limit between:

Inefficiency – Allowed intensity – Minimum allowable lifetime

B) Acceptable β^*

Tolerance for loosing less than 50% of efficiency:

$$n_{\text{prim}} \cdot \sqrt{\frac{\Delta\beta}{\beta_0}} \cdot \sigma_x + \Delta x_{\text{orbit}} \leq 0.6 \cdot \Delta x_{\text{retract}}$$

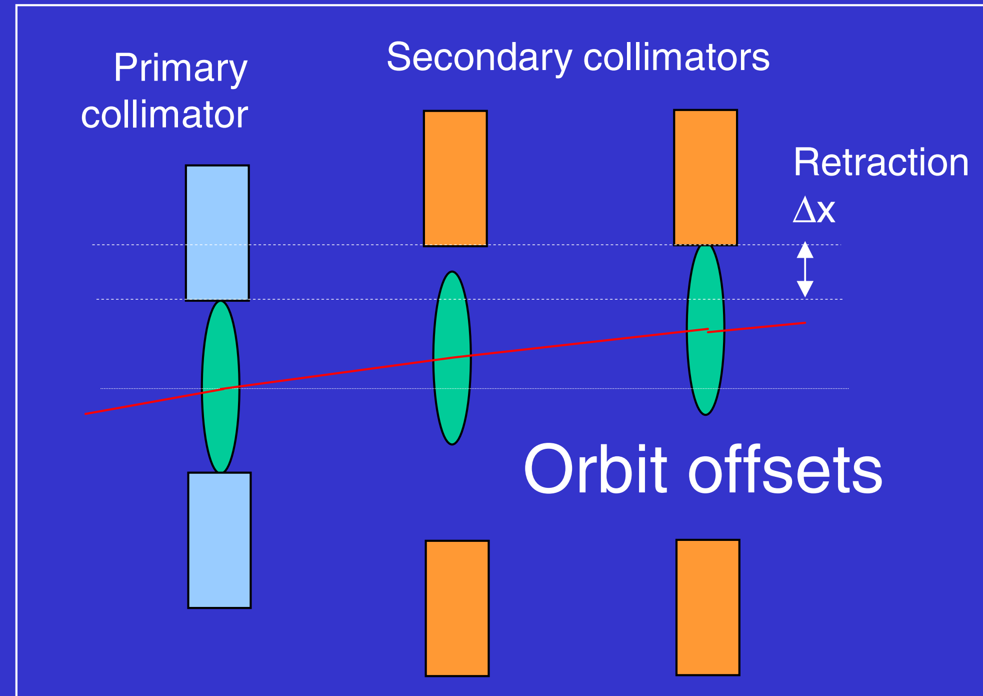
We find in simulations:

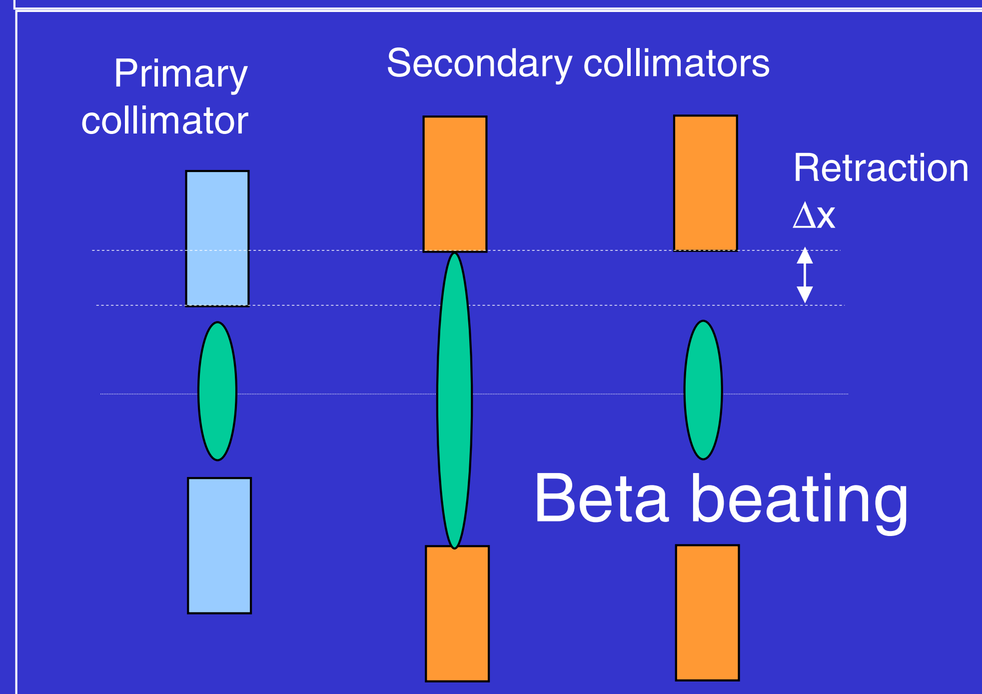
Beta beat: ≤ 8%
Orbit: ≤ 0.6 σ

(less if we combine both)

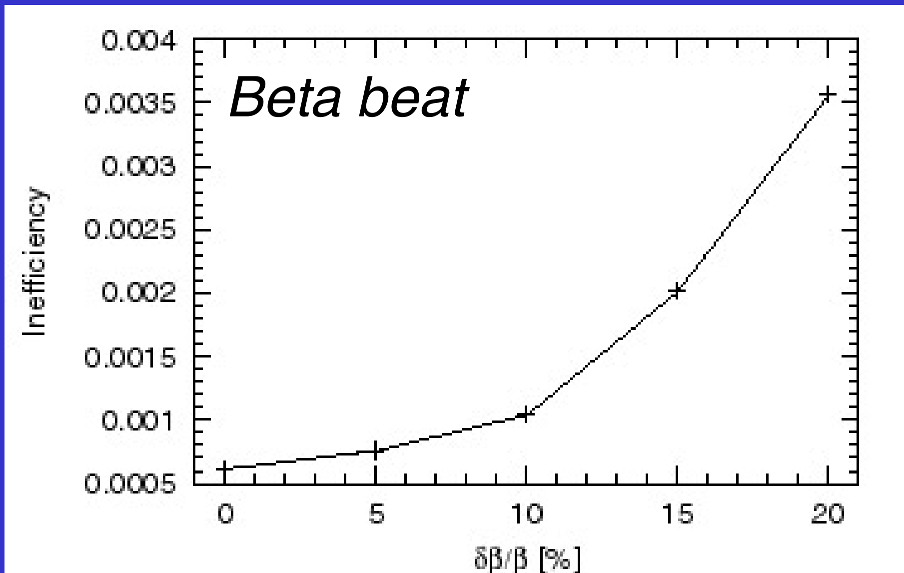
If tolerances are violated during squeeze, for example:

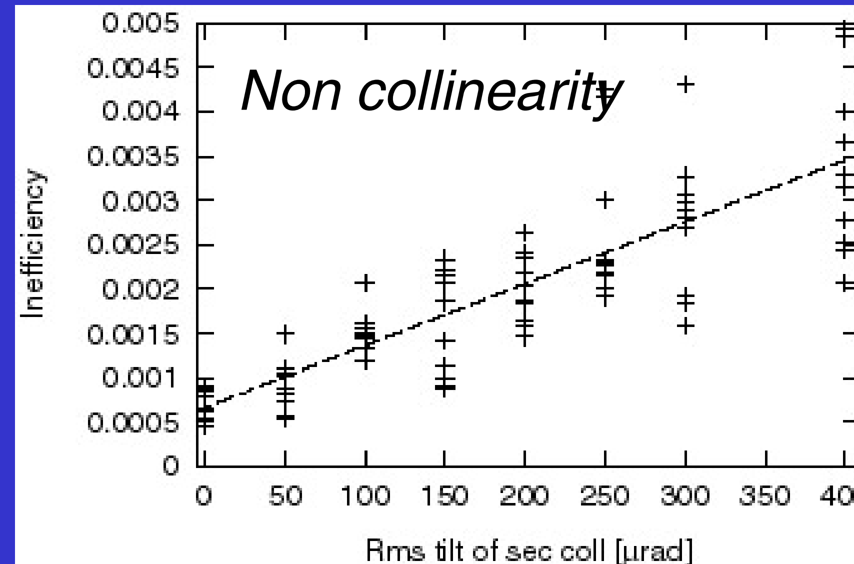
risk of quench!

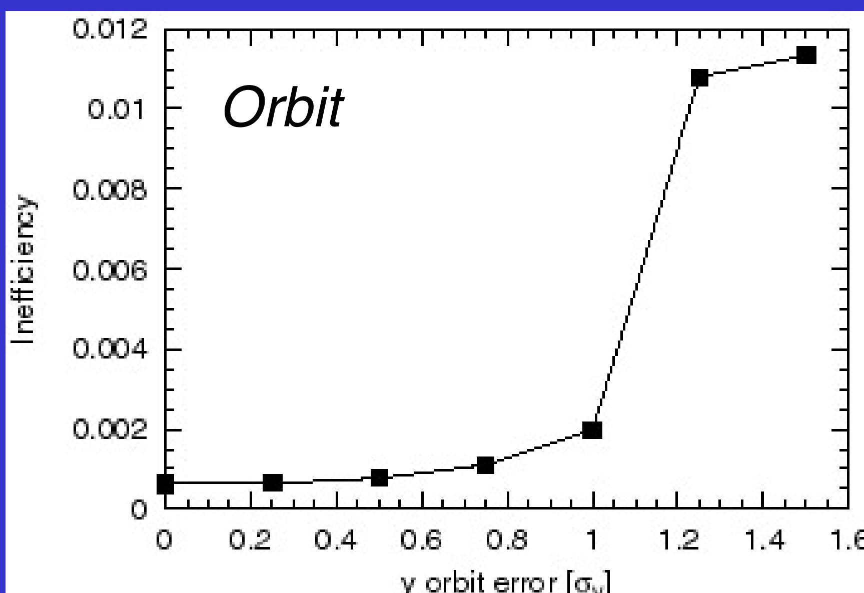


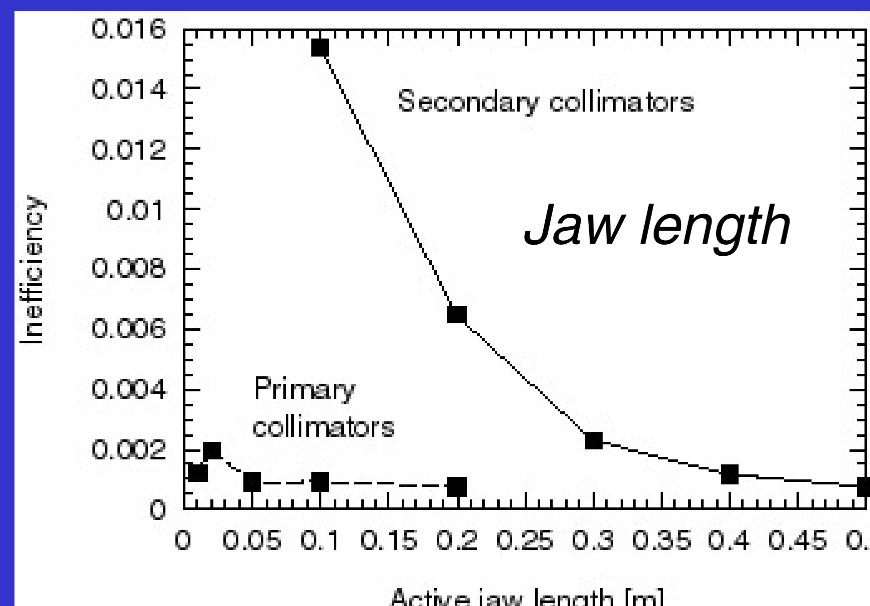


Inefficiency versus imperfections









If retraction is adjusted such to allow some maximum transient beta beat and orbit error, then **constraint of β^*:**

$$\beta^* \geq \frac{C}{a^2_{triplet} \cdot \beta_{coll}} \cdot \left(n_{\text{prim}} + \Delta A_{\text{max}} + 1.7 \cdot \left[n_{\text{prim}} \cdot \sqrt{\frac{\Delta\beta_{\text{max}}}{\beta_0}} + \frac{\Delta x^{\text{max}}_{\text{orbit}}}{\sigma_{\text{x}}} \right] \right)^2$$

Increase triplet aperture

Increase beta at collimators

Close primary

Sufficient number of secondaries at specific phases

Minimize any transient beta beat

Minimize transient orbit changes

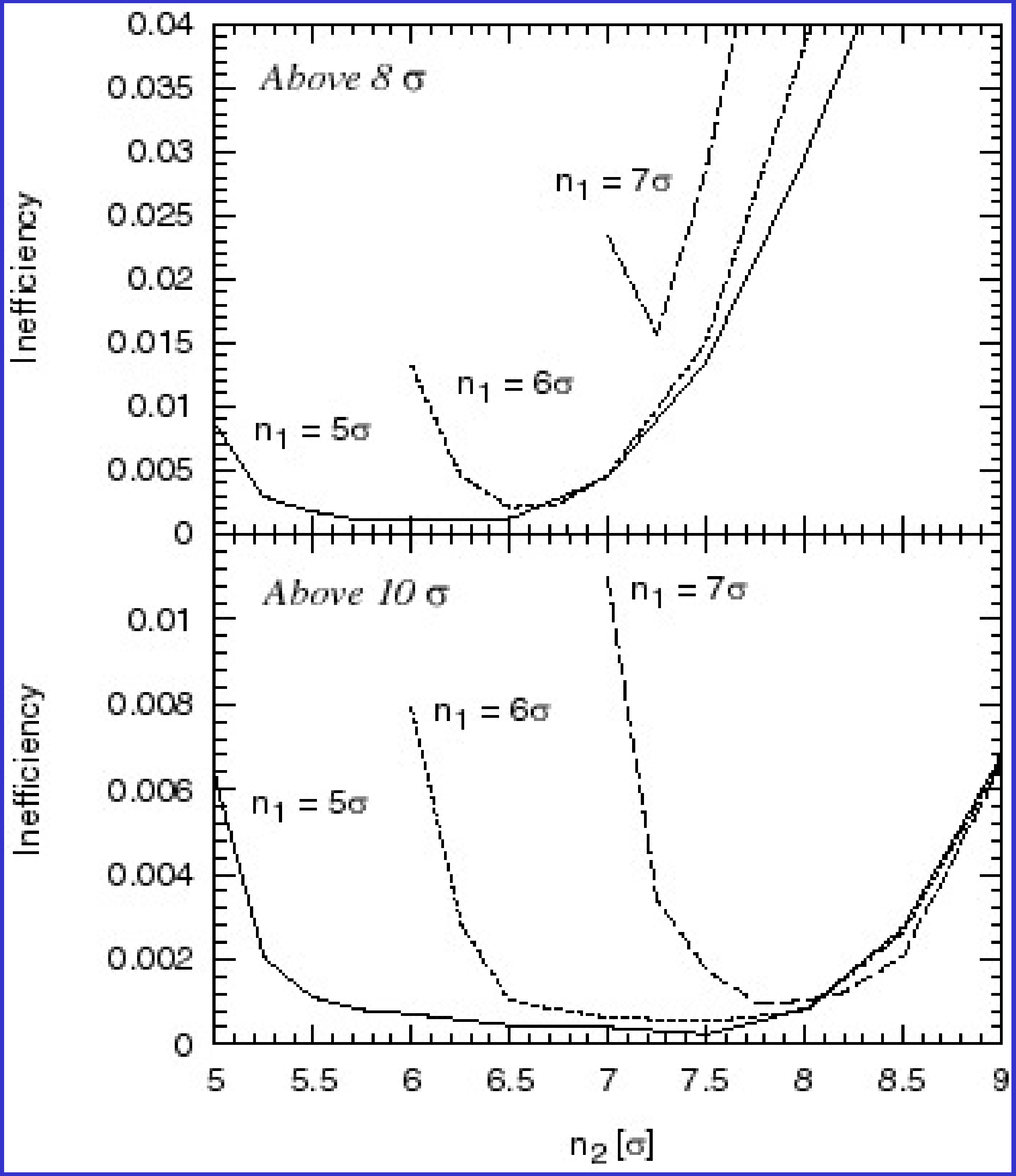
Larger β^* - A way to relax operational collimator tolerances!

(However, loose passive protection)

Inefficiency for different collimator settings:

n1 = setting of primary collimator

n2 = setting of secondary collimator



Aperture limited at 8 σ

Aperture limited at 10 σ

C) Impedance limit:

Third look at impedance in Feb 03 revealed a problem:

$$\frac{Z_\perp^{\rm coll}}{Z_\perp^{\rm arc}} \sim \frac{(L^{\rm coll}/L^{\rm arc}) \times \sqrt{\rho^{\rm coll}/\rho^{\rm arc}}}{(a^{\rm coll}/a^{\rm arc})^3} \sim$$
$$\sim \frac{(20\,{\rm m}/20\,{\rm km}) \times \sqrt{\rm RRR \sim 30}}{(1.8\,{\rm mm}/18\,{\rm mm})^3} \sim$$
$$\sim \frac{10^{-3} \times 5}{10^{-3}} \sim 5!$$

F. Ruggiero

- Required robustness at reach (factor ~3 missing)!
- Jaw lengths remain quite reasonable!
- Space is available and optics can be re-matched!
- Activation is reduced and remote handling requirements are relaxed!
- Vacuum group does not rule out C!
- Impedance was presented as uncritical!

1 INJECTION

D. Angal, L. Vos, *Coupled Bunch Instabilities in the LHC*, EPAC 2002 :

Budget transverse impedance resistive, *H*,*V*)

45	**57 MΩ/m**

Includes contribution single graphite collimator (estimated aperture and β) :

0.3	**1.1 MΩ/m**

Impedance of all graphite collimators with correct aperture and β (2003):

13.3	**16.8 MΩ/m**

New total

58	**73 MΩ/m**

Can be handled by transverse feedback

2 HIGH ENERGY

D. Angal, L. Vos, *Coupled Bunch Instabilities in the LHC*, EPAC 2002 :

Budget transverse impedance resistive, *H*,*V*)

84	**118 MΩ/m**

Includes contribution single graphite collimator (estimated aperture and β) :

2.2	**7.9 MΩ/m**

Impedance of all graphite collimators with correct aperture and β (2003):

841	**1017 MΩ/m**

New total

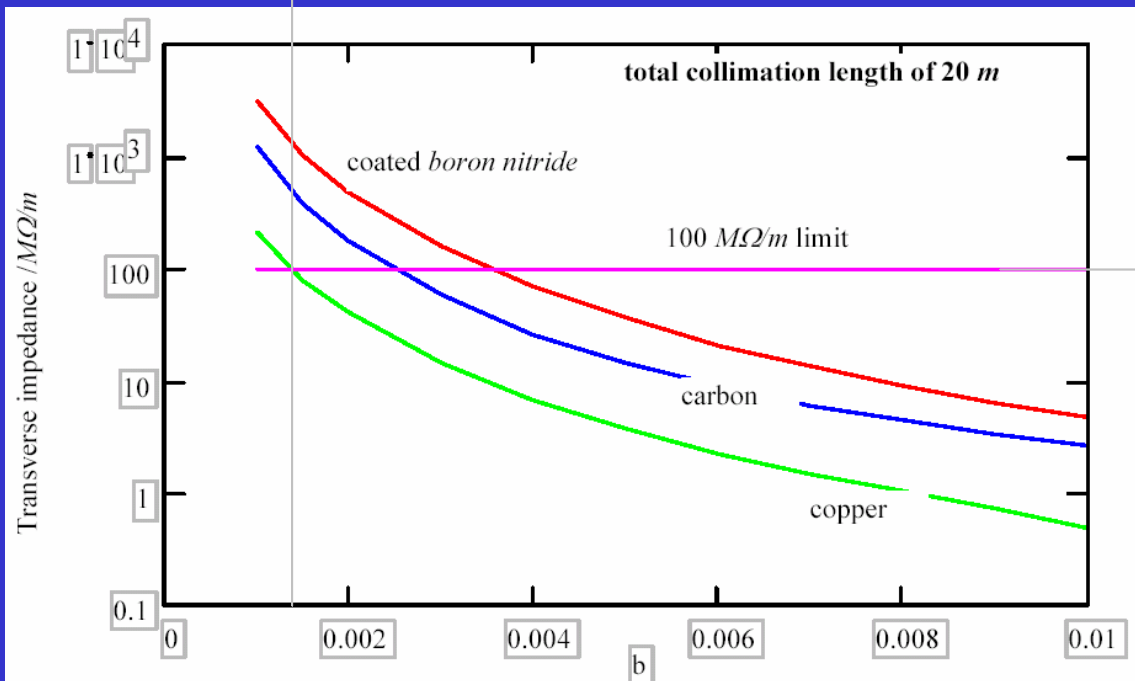
923	**1127 MΩ/m**

L. Vos

Main problem at 7 TeV: Al/Cu system doubles impedance budget!
C system increases impedance tenfold!

Impedance for different materials as a function of collimator half gap:

Typical collimator half gap



Half gap b [m]

F. Ruggiero, L. Vos

LHC impedance without collimators

How to counteract?

Factor 10 higher gain of transverse feedback (factor 3-4.5 margin) before collision.
Check thresholds for beam instabilities, stabilizing effect of long-range beam-beam.
Metallic plate or low-Z metal (Be?).
Copper doped graphite to reduce impedance?
Open collimators (hardly possible w/o additional collimators at triplets or increase of β^*).
Increase beta function at collimators (not possible and gain only with sqrt).
Increase triplet aperture (not possible, triplets have been built).

Too early to conclude! Studies are ongoing to address this problem!

Showering studies for BLM system (mock-up C collimation system)

Question: What do the BLM signals measure?
Can the BLM signals be used to tune the collimator settings?

Collimator (j)	Beam loss monitor (i)						
	1	2	3	4	5	6	7
TCP1	0.0178	0.4662	0.02684	0.04321	0.0079	0.00361	0.00123
TCS1	0.0	1.19	0.02911	0.03889	0.00361	0.00177	0.00069
TCS2	0.0	0.0	1.081	1.085	0.138	0.03858	0.00992
TCS3	0.0	0.0	0.00039	1.044	0.3245	0.1187	0.03493
TCS4	0.0	0.0	0.0	0.0	0.9891	0.513	0.16417
TCS5	0.0	0.0	0.0	0.0	0.0	0.9848	0.5093
TCS6	0.0	0.0	0.0	0.0	0.0	0.0	0.9445

I. Kouroutchikov (IHEP), B. Dehning, J.B. Jeanneret

Non-diagonal response matrix of the BLM system for the collimation system in IR7.

Good decoupling for the two beams.

Non-trivial tuning of collimator settings with BLM’s.

Further studies ongoing (response to settings, operational conditions, …).

4. Outlook

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

The collimation and cleaning can strongly limit the LHC performance (diagnostics and repair time, intensity limits, limit on β^*, impedance, tuning time, radiation exposure of personnel, …)

Detailed engineering design has started to avoid any LHC performance limits from collimation: appropriate materials (low Z), lengths, mechanics, cooling, damage and fatigue analysis, tolerances, …

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

Concentrating for now on a low-Z system based on Graphite (simplest solution, see Peter Sievers).

Operational considerations have been started. However, first decide the basic design: collimator material, length, insertion optics, …

We plan to have an appropriate system ready for the LHC start-up. However, it will be a large and difficult system, central for integrated luminosity (avoiding quenches).

System commissioning with relaxed requirements: Lower intensity + larger emittance + larger β^*.

When we push luminosity: Not unsimilar to the LEP2 RF system.

The set-up and schedule

Sep 2001	LHC Beam Cleaning Study Group
Jan 2002	Consensus to consider low Z material (impedance presented as non-critical)
Jun 2002	Consensus on detailed requirements First tolerances
Oct 2002	Project LHC Collimation, new ATB group
Jan 2003	Full simulation chain: *Beam – FLUKA – ANSYS* Cleaning efficiency and optics with low Z Review of impedance, other constraints
April 2004	Prototype collimator
2004/2005	Production
2006	Installation

$$\Delta x_{\text{retract}} \approx 1.7 \cdot \left[n_{\text{prim}} \cdot \sqrt{\frac{\Delta\beta_{\max}}{\beta_0}} \cdot \sigma_x + \Delta x_{\text{orbit}}^{\max} \right]$$

$$A_{\text{secondary}}^{\max} = n_{\text{prim}} + \frac{\Delta x_{\text{retract}}}{\sigma_{\text{x}}} + \Delta A_{\max}$$

Assuming that retraction is set to limits of beta and orbit errors

$$A_{\text{secondary}}^{\max} = n_{\text{prim}} + \Delta A_{\max} + 1.7 \cdot \left[n_{\text{prim}} \cdot \sqrt{\frac{\Delta\beta_{\max}}{\beta_0}} + \frac{\Delta x_{\text{orbit}}^{\max}}{\sigma_{\text{x}}} \right]$$

$$a_{coll} \propto a_{triplet} \cdot \sqrt{\beta^* \cdot \beta_{coll}} \cdot \left(\frac{n_{\text{prim}}}{A_{secondary}^{\max}} \right)$$