Status of the
LHC Collimation System

Towards a More Robust System

R. Assmann, CERN-AB

for the LHC Collimation Project Team

LHC Technical Board
26.2.2003

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

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+ colleagues in Collimation WG and Machine Protection WG

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II. The V6.4 Collimation System

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The Challenge…

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

Much more critical than in existing accelerators (background is a side issue)!

New territory without trivial solutions!

Major issues:

High beam power in the LHC and material damage

Cleaning efficiency and quench limit (possible intensity limit)

LHC aperture and collimator gaps (possible β^* limit)

High Beam Power in the LHC

Physics Potential = Energy and Luminosity

High LHC luminosity translates into high transverse energy density:

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

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

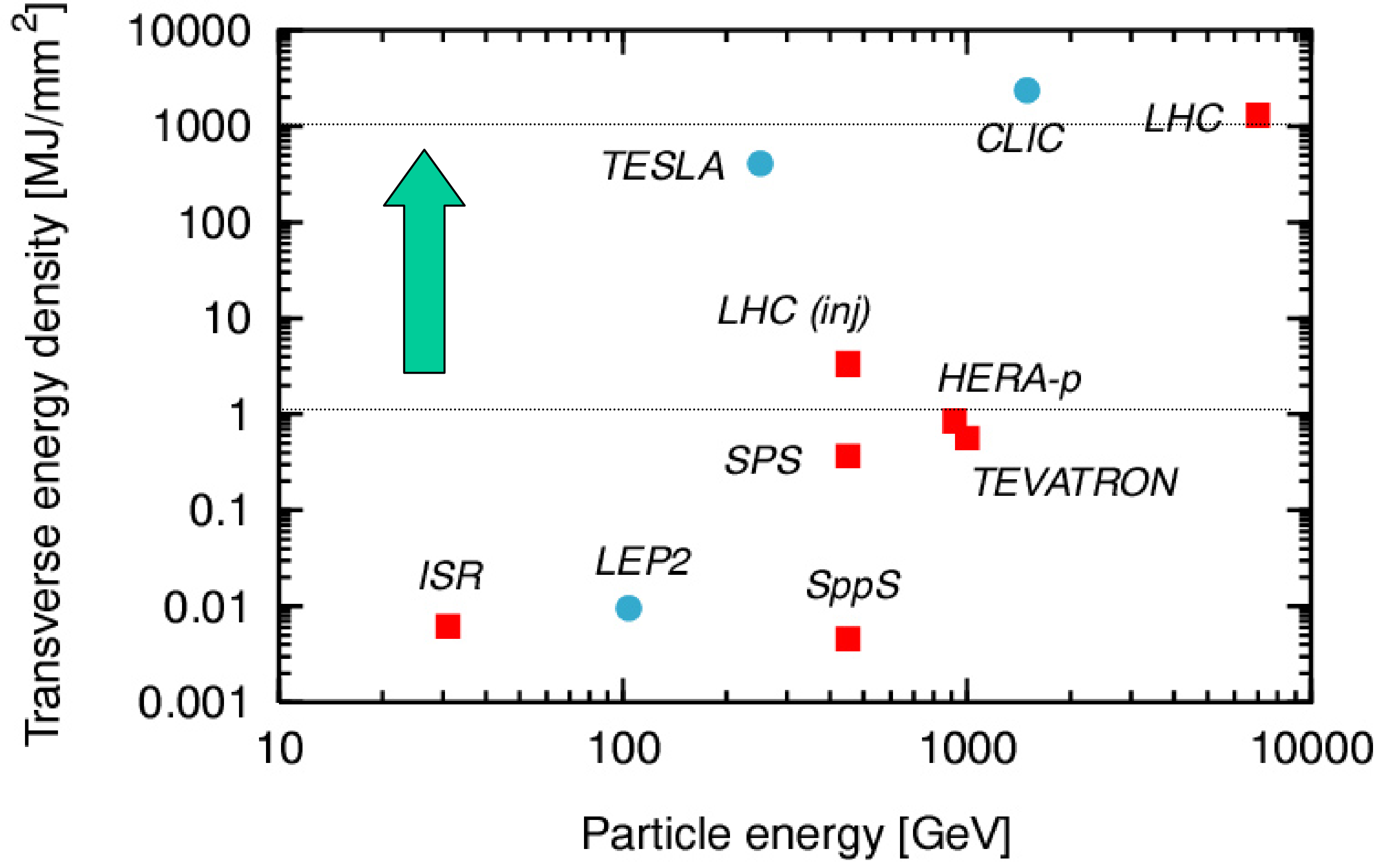
Fixed or limited

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!

Material Damage with LHC Beams

Destruction limits

Case	Destruction threshold [nominal intensity]	
	450 GeV	7 TeV
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!

Major issues:

High beam power in the LHC and material damage

Cleaning efficiency and quench limit (possible intensity limit)

LHC aperture and collimator gaps (possible β^* limit)

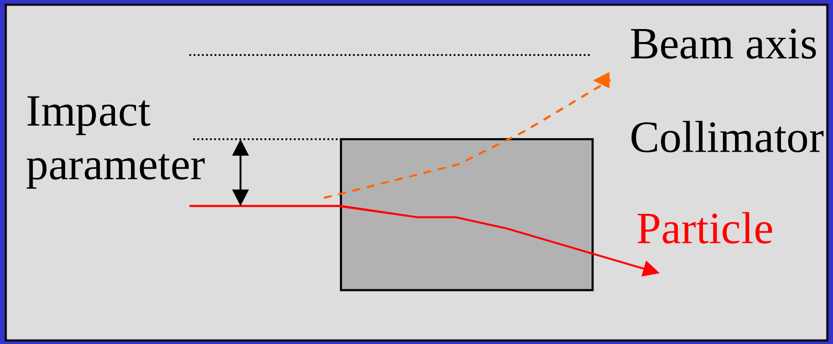
Basic concept of collimation

“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



Running at the quench limit

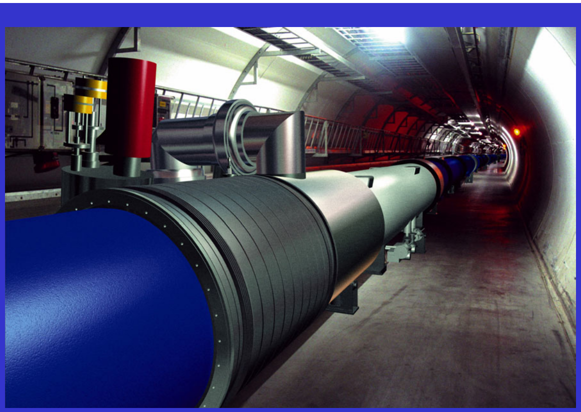


Illustration of LHC dipole in tunnel

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)

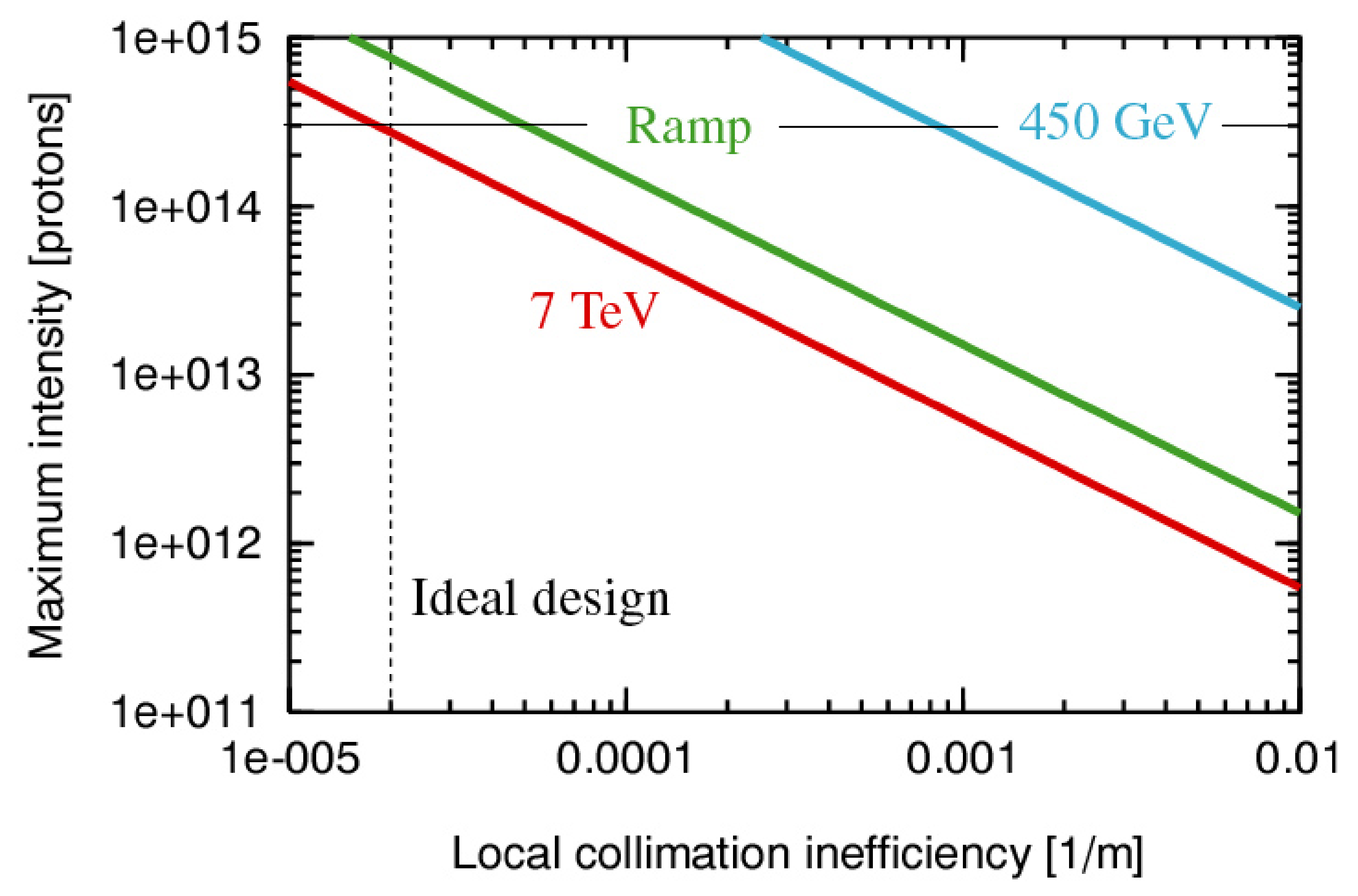
Cleaning inefficiency

=

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

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

Major issues:

High beam power in the LHC and material damage

Cleaning efficiency and quench limit (possible intensity limit)

LHC aperture and collimator gaps (possible β^* limit)

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:

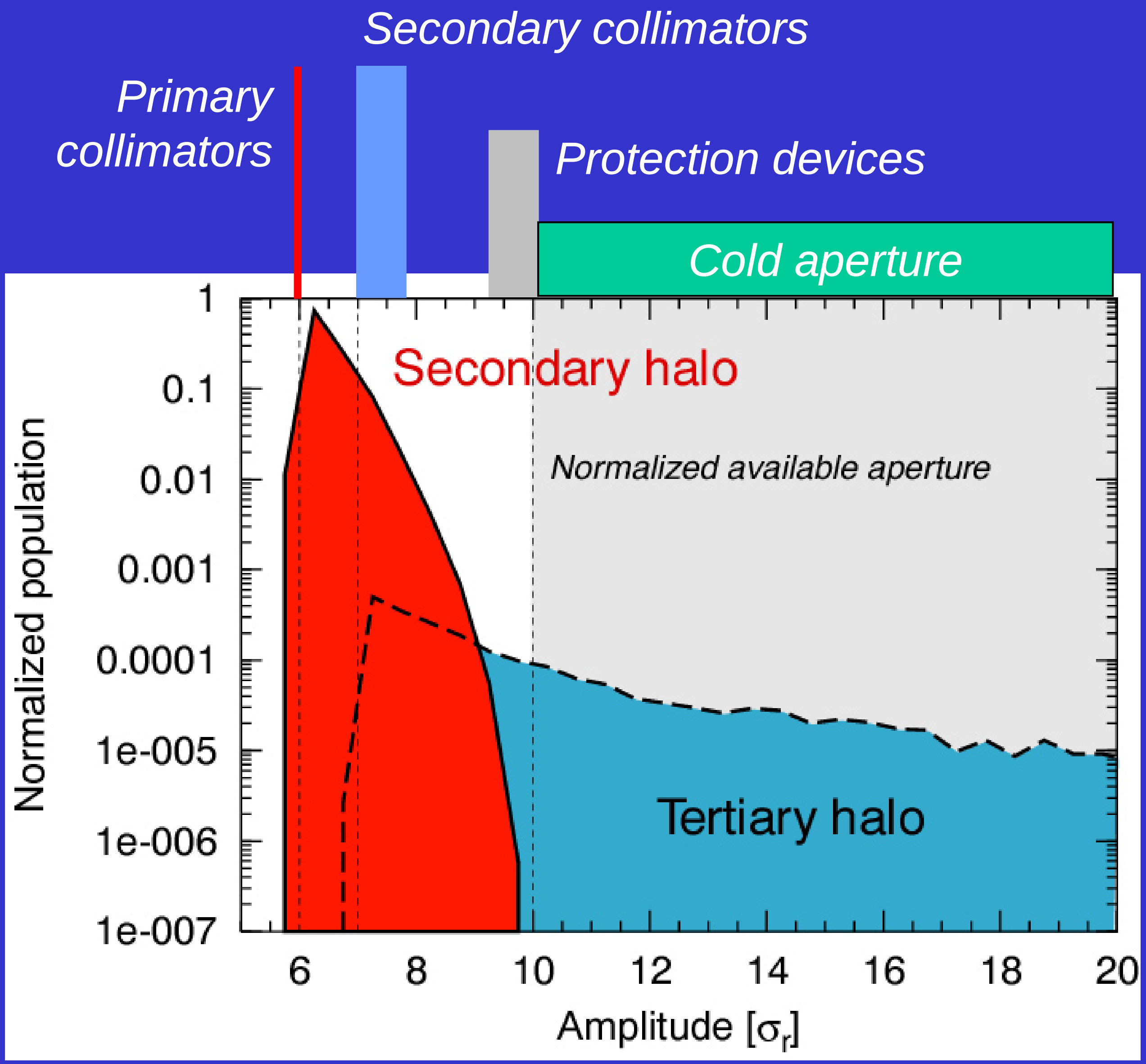
$$a_{coll} \le a_{triplet} \cdot \overset{\sim 0.15}{\sqrt{\frac{\beta_{coll}}{\beta_{triplet}}}} \cdot \overset{\sim 0.6}{\left(\frac{A^{max}_{primary}}{A^{max}_{secondary}} \right)}$$

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)



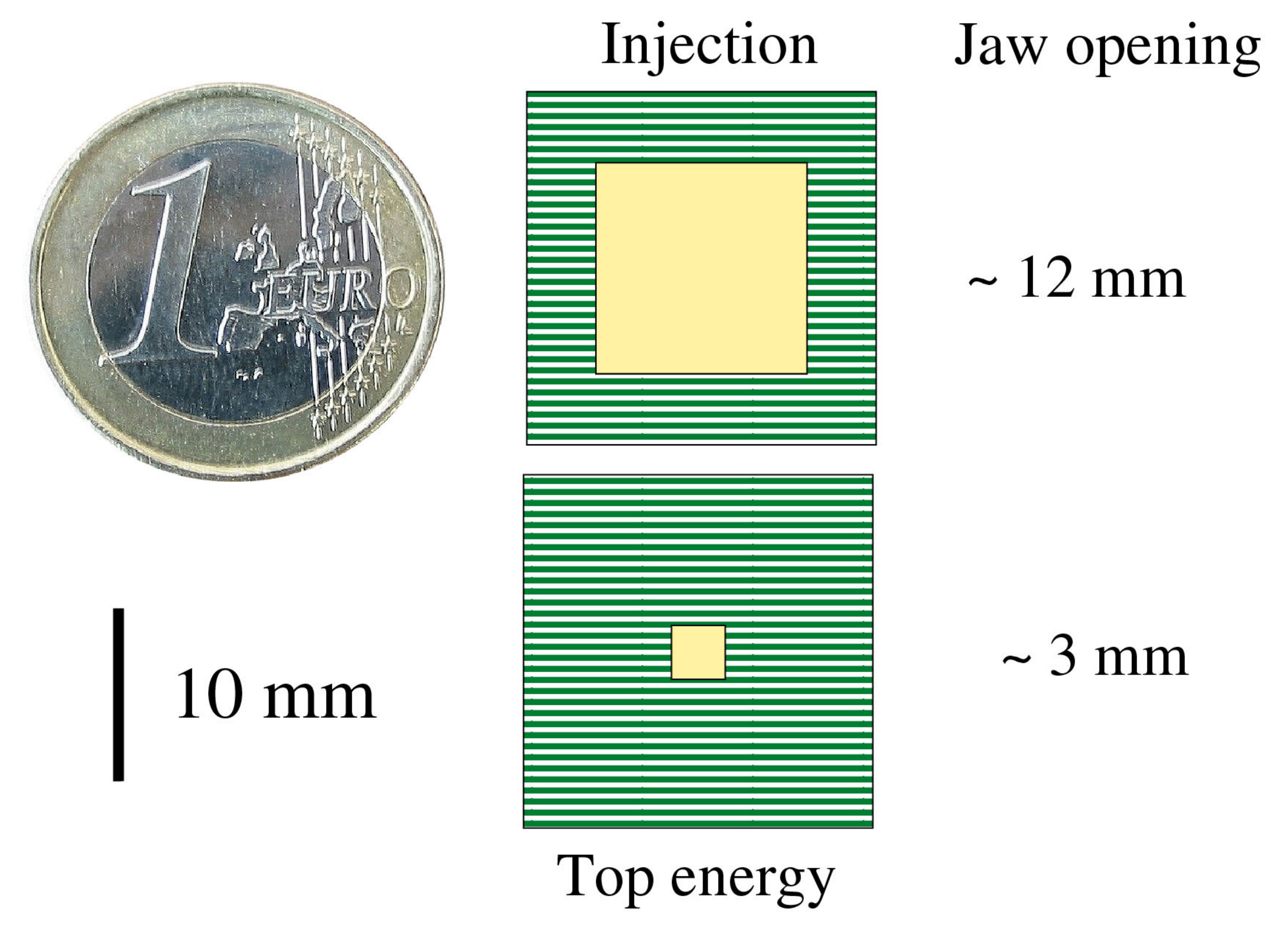
Strategy:

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:

$5 - 6\ \sigma$ (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 $6\ \sigma$

Possible limitation of β^*

If collimator gaps at 7 TeV must be increased due to

- inability to control relative orbit (0.5 σ, prim/sec)
- inability to control relative beta beat (8%, prim/sec)

secondary collimator should not become primary

- impedance constraints
- mechanical constraints

then

- decrease beta in the triplet
- increase of β^* (lower luminosity)
- loss of passive protection in case of failures

Care required to avoid any limitation of this kind!

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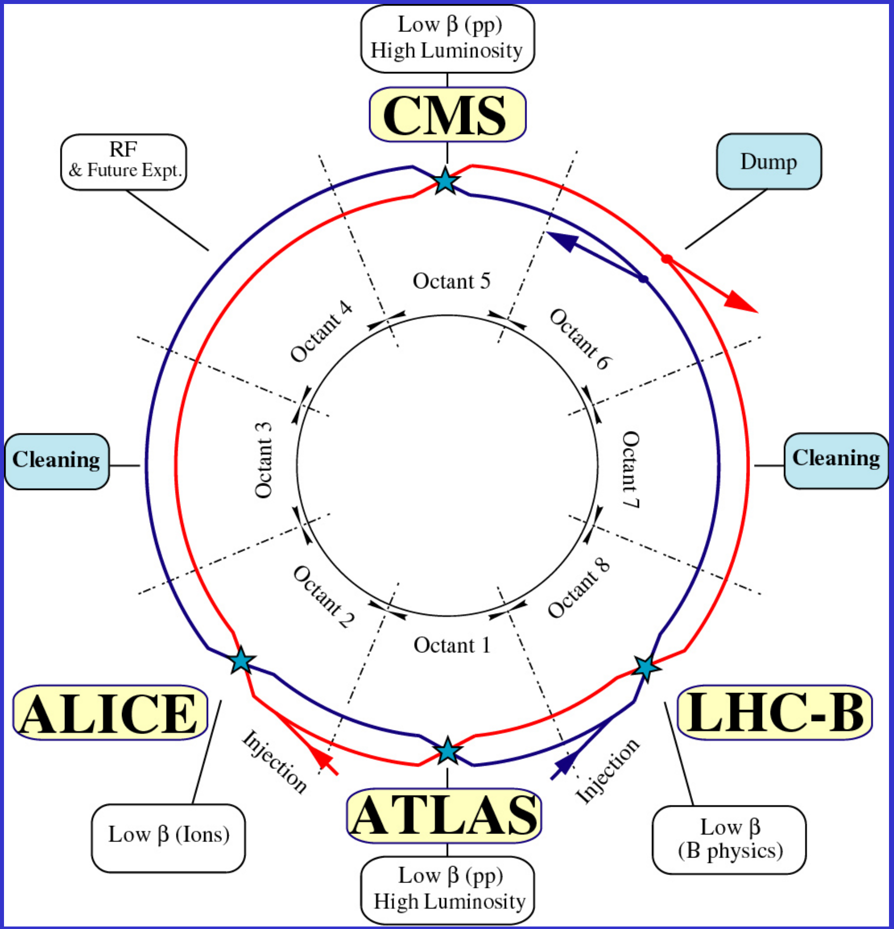
The LHC Cleaning Insertions

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!

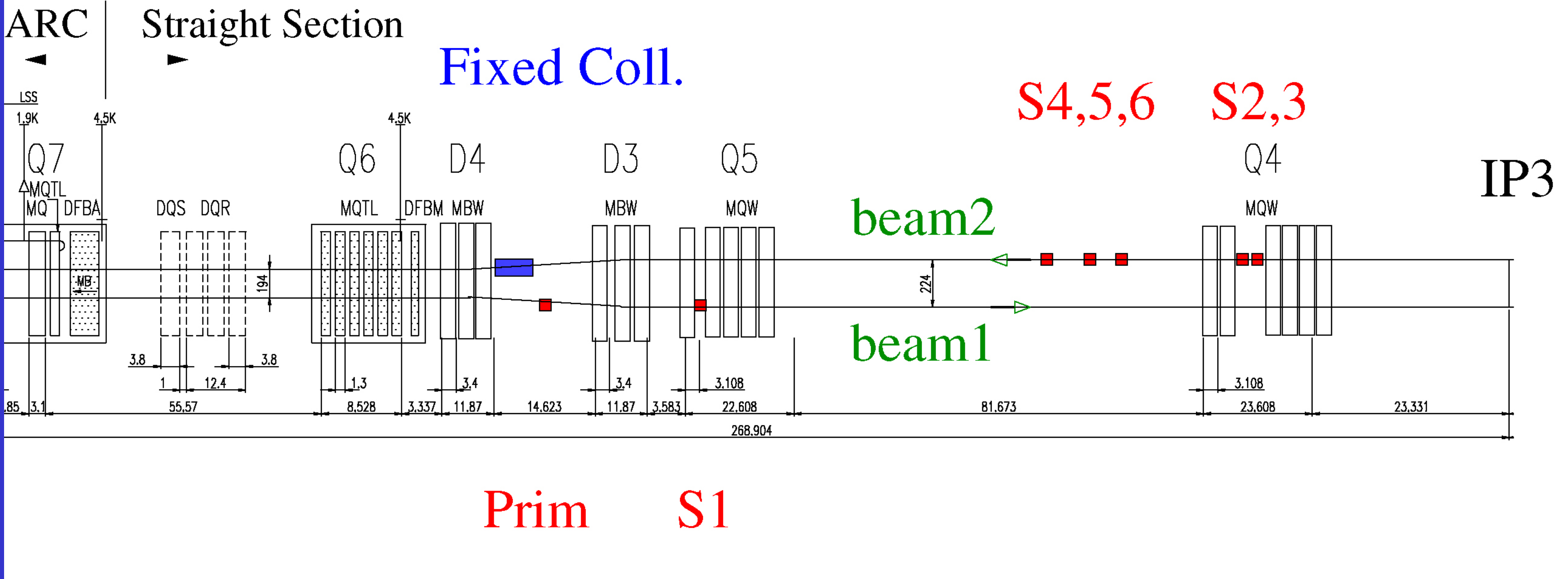
Collimators & absorbers at 7 TeV:

Region	Type	Orientation	Material	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.

Layout of Cleaning Insertion IR3

Present layout half IR3:



Special optics requirements (phase advance, dispersion)

Importance of LHC collimation reflected by the fact that two insertions are dedicated to it!

Concept and basic layout developed and verified over last 10 years.

V6.4 Solution: Achievements and problem.

Basic system design (two stage system, two cleaning insertions) works.

Required cleaning efficiency is provided.

LEP based material choices are not adequate:

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).

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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

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April 2004	Prototype collimator
2004/2005	Production
2006	Installation

Summary of requirements for LHC collimators:

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) × 0.2 mm (rms)
- 4 10^{12} p (4.5 MJ) in 10 s over area of 0.03 mm (rms) × 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 ~1.0 m 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)

Basic strategy

Collimators could be damaged from:

- Pre-fire of one dump kicker module
- Asynchronous beam dump (miss dump gap)
- Impact from one full batch at injection
- Impact during low beam lifetime (0.2 h to1 h)
- Protons and ions

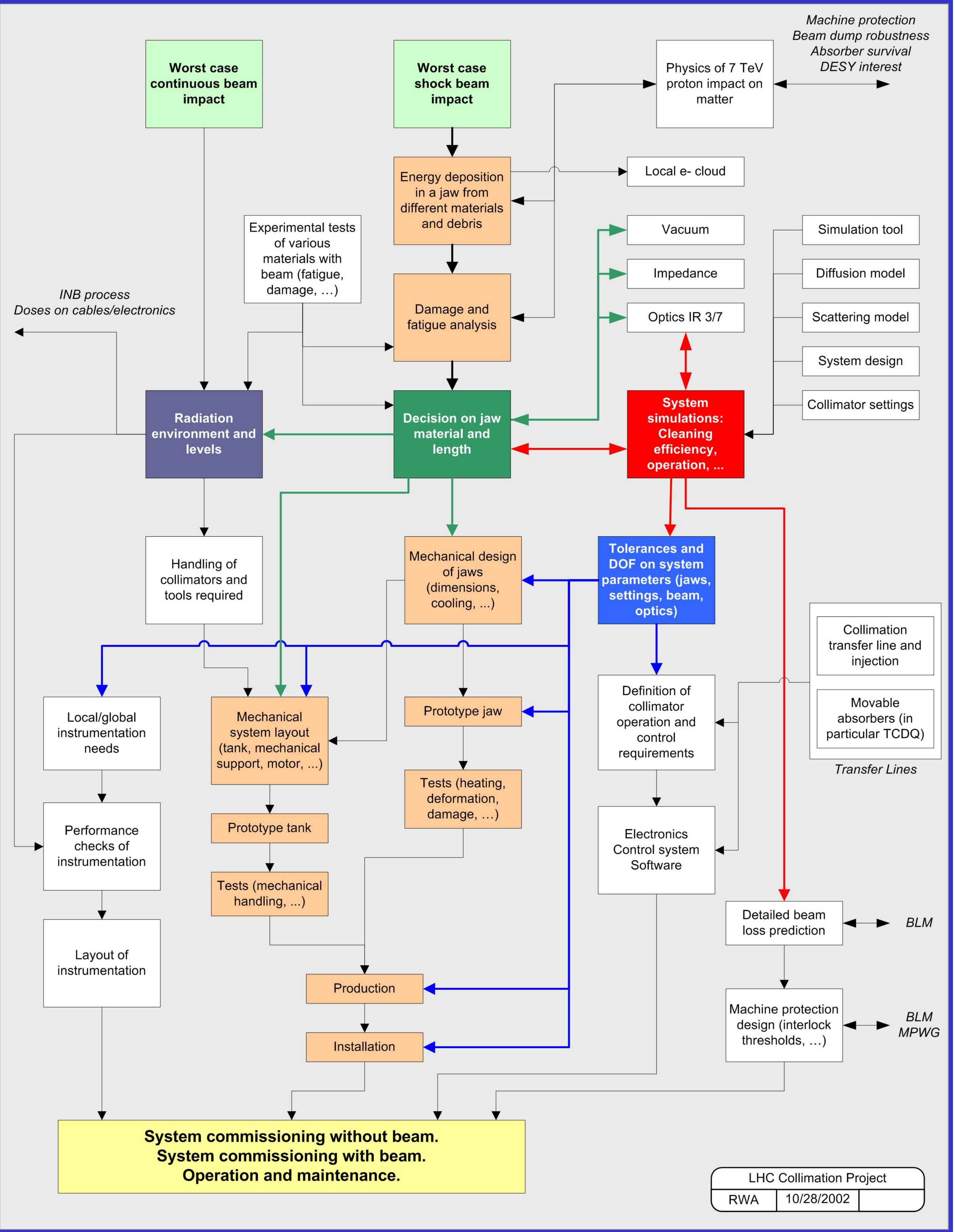
Two possibilities:

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!

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 …)


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

Scenario for worst case shock beam impact at 7 TeV

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).

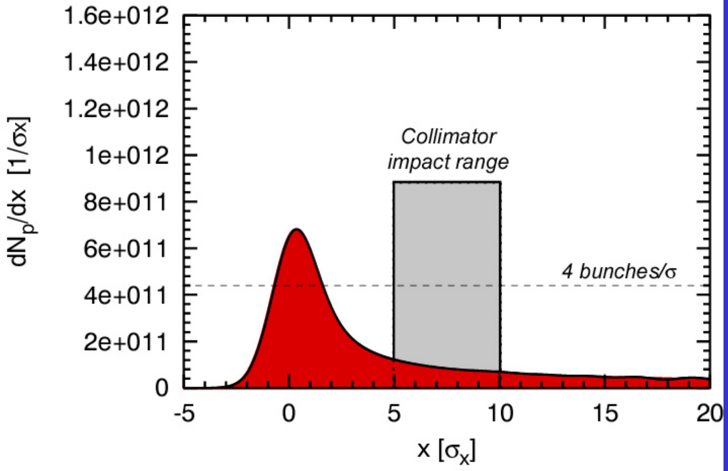
Failure modes:

- 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!

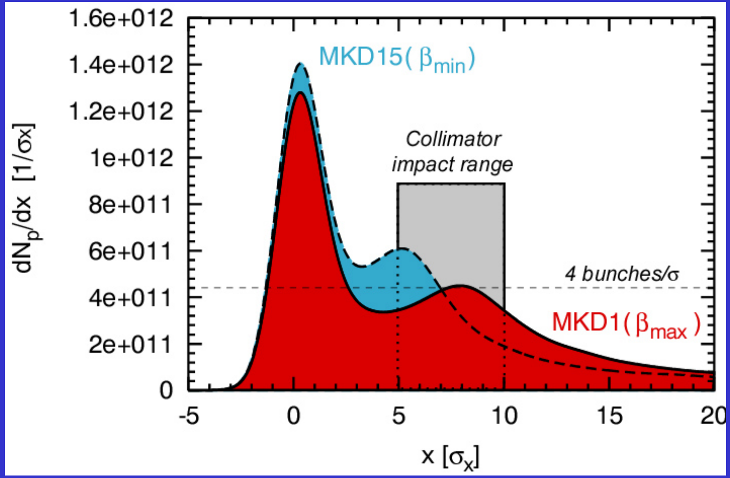
Abnormal dump actions as input for FLUKA



Beam abort asynchronous with abort gap:

Total: 6 bunches over 5 σ

Peak: **1.5 bunches in 1 σ**

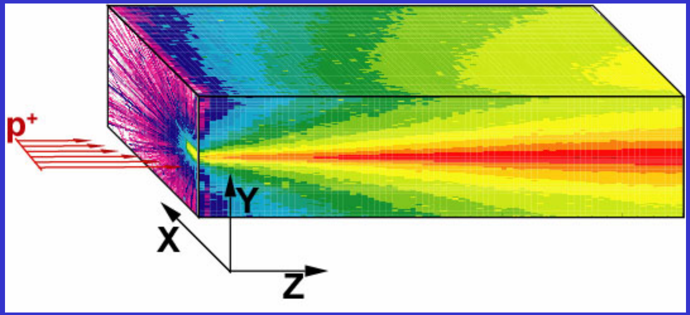


1 module pre-fire with re-triggering of 14 after 1.3µs:

Total: 20 bunches over 5 σ

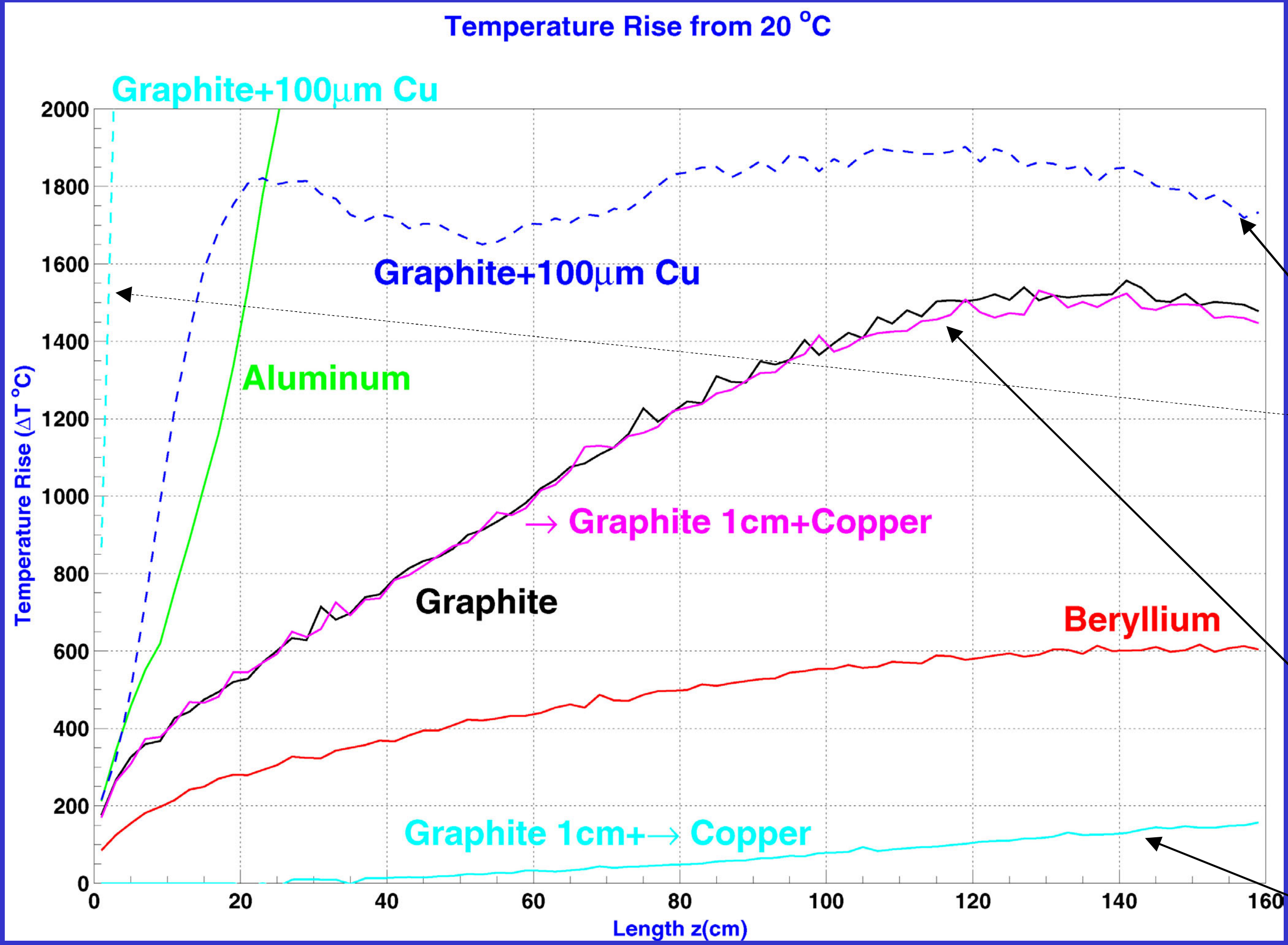
Peak: **6 bunches in 1 σ**

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



A. Ferrari,
V. Vlachoudis

Temperature rise in different materials for one module pre-trigger at 7 TeV



A. Ferrari, V. Vlachoudis

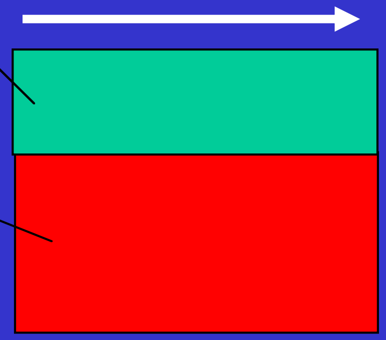
+ P. Sievers

Different cases:

1) Block of material

2) Graphite + 100µm coating of Copper

3) 1 cm Graphite plate on Copper



Length of low-Z jaw: ~ 1 m (discussed later)

Summary table

Material	**Density g/cm^3**	**Max Energy GeV/cm^3**	**Max Temp ºK approx.**	**Escaping %**	**EM %**
Aluminum	2.7	1.2×10^{14}	~6500	88.8	9
Beryllium	1.848	0.2×10^{14}	900	97	1
Copper	8.96	16×10^{14}	> 10000	34.4	52.4
Graphite	1.77	0.3×10^{14}	1900	96.4	1.8
Graphite + Cu 100µm	1.77+8.9	3.6×10^{14} on Cu	2200 on C	94.1	3.9
1cm Graphite + Copper	1.77+8.9	0.22×10^{14}	1900 C, 450 Cu	94.5	3.8
Titanium	4.54	4×10^{14}	> 4000	79.5	16.7

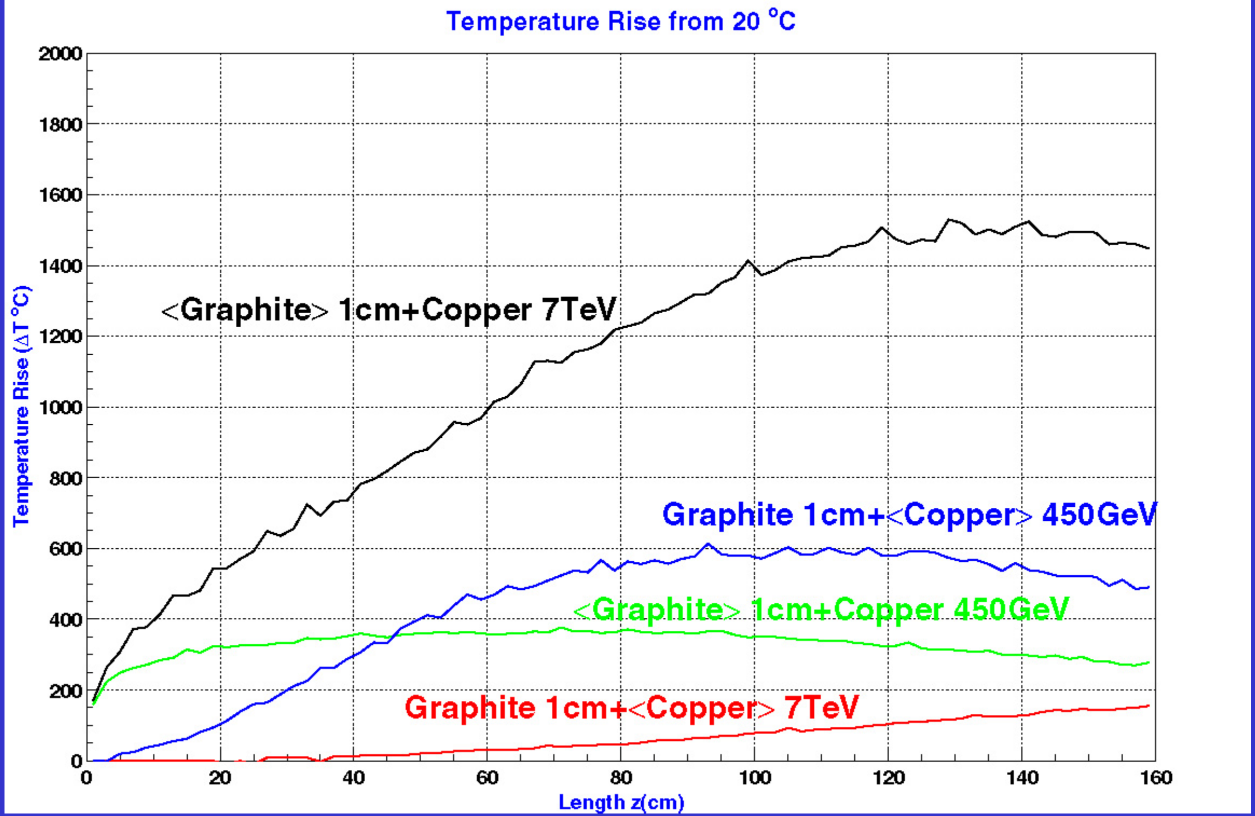
A. Ferrari, V. Vlachoudis

Note:

Almost all energy escapes the low Z jaw!
Lower jaw activation but more distributed!
What happens downstream?

Higher Z materials do not work (Ti)
100 µm Cu coating is not possible
Graphite is most promising!
Length of low-Z jaw: ~ 1 m (discussed later)

Temperature rises for Graphite plate on Copper: 7 TeV and 450 GeV



450 GeV case:

Impact of one full injected batch!

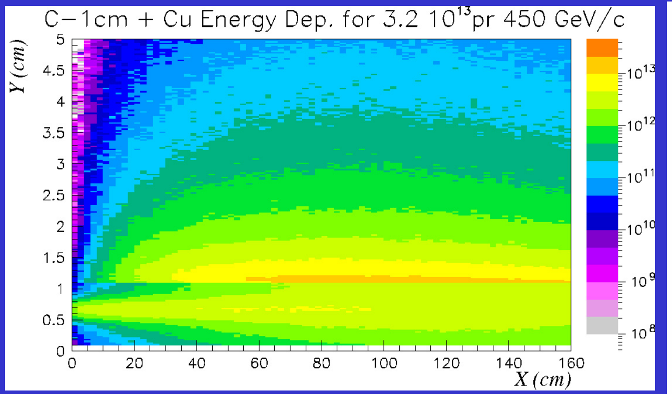
Observation:

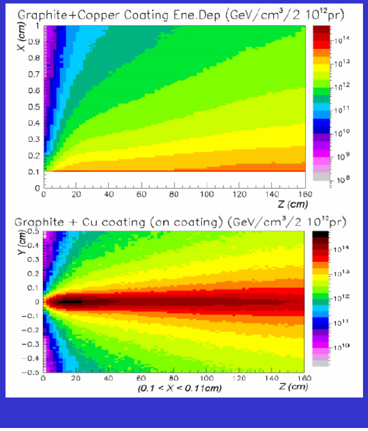
450 GeV less critical for Graphite plate

450 GeV more critical for Cu support (larger impact area due to beam size)

Graphite plate must have more than 1 cm!

A. Ferrari, V. Vlachoudis





Input to ANSYS

Damage and Fatigue Analysis

Further cases under preparation: Slow losses and ions

Slow loss:

Uniform "emittance" blow-up

Beam lifetime: **0.2 h**

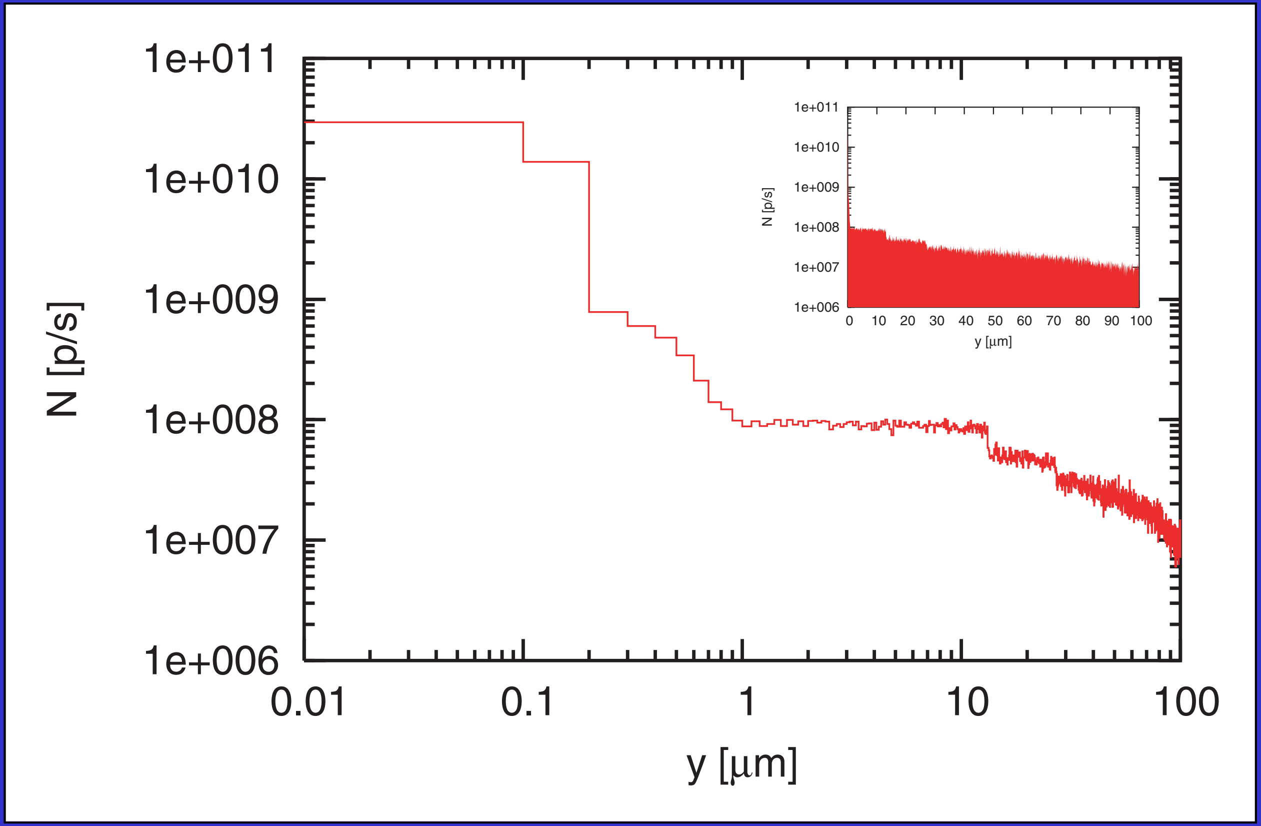
Loss rate: 4.1e11 p/s

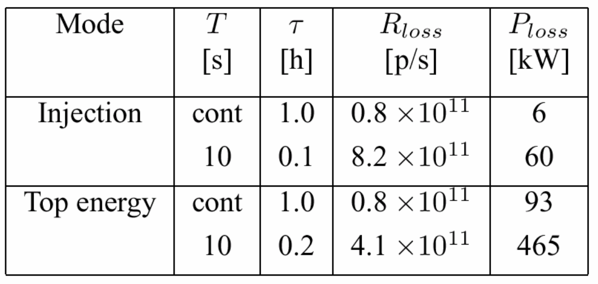
Loss in 10 s: 4.1e12 p (**1.4 %**)

(~ 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

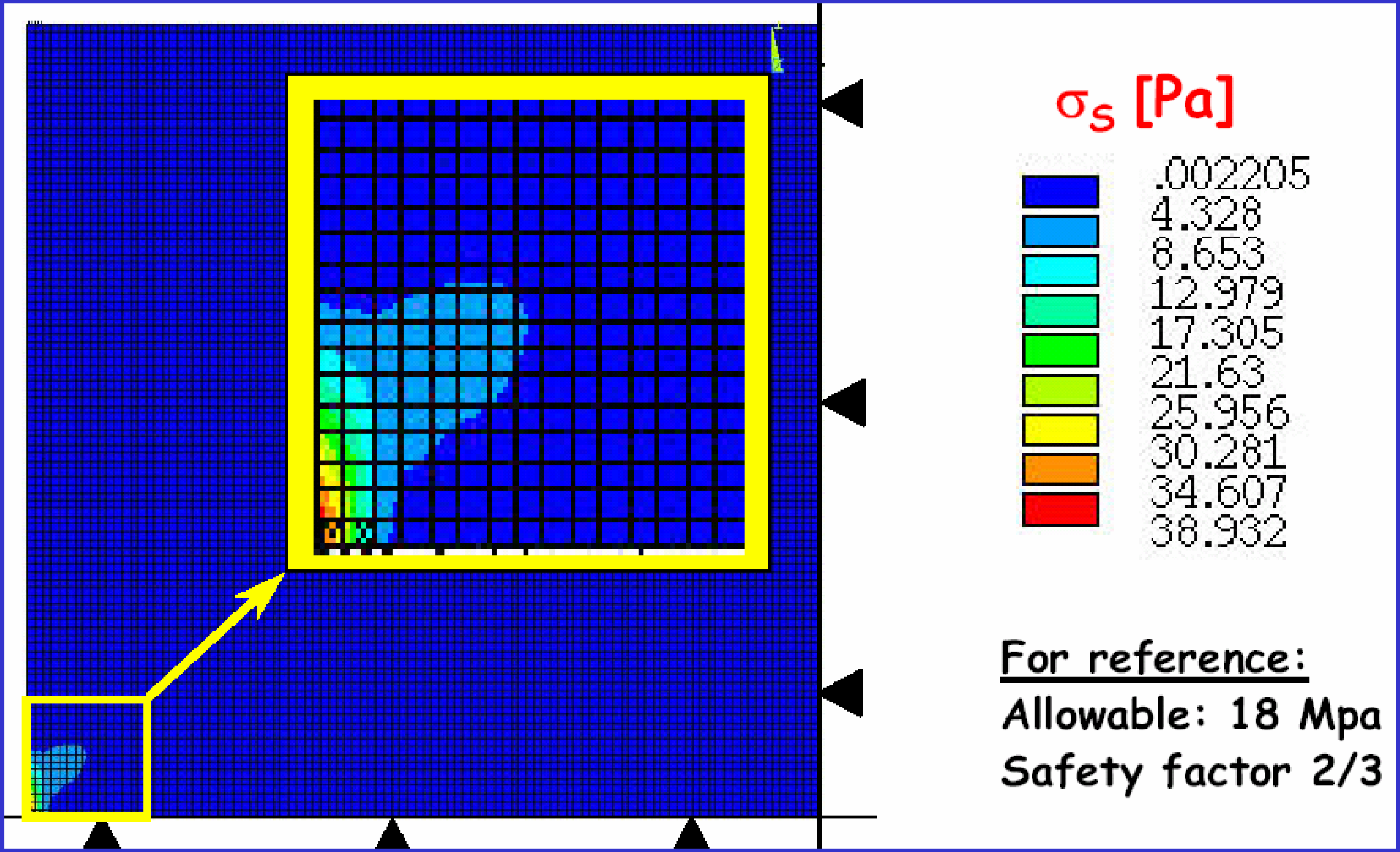
Almost all particles impact with

$y \lesssim 0.2$ µm

Surface phenomenon!

R. Assmann

Stress analysis for 7 TeV 1 module pre-trigger



For reference:

Allowable: 18 Mpa

Safety factor 2/3

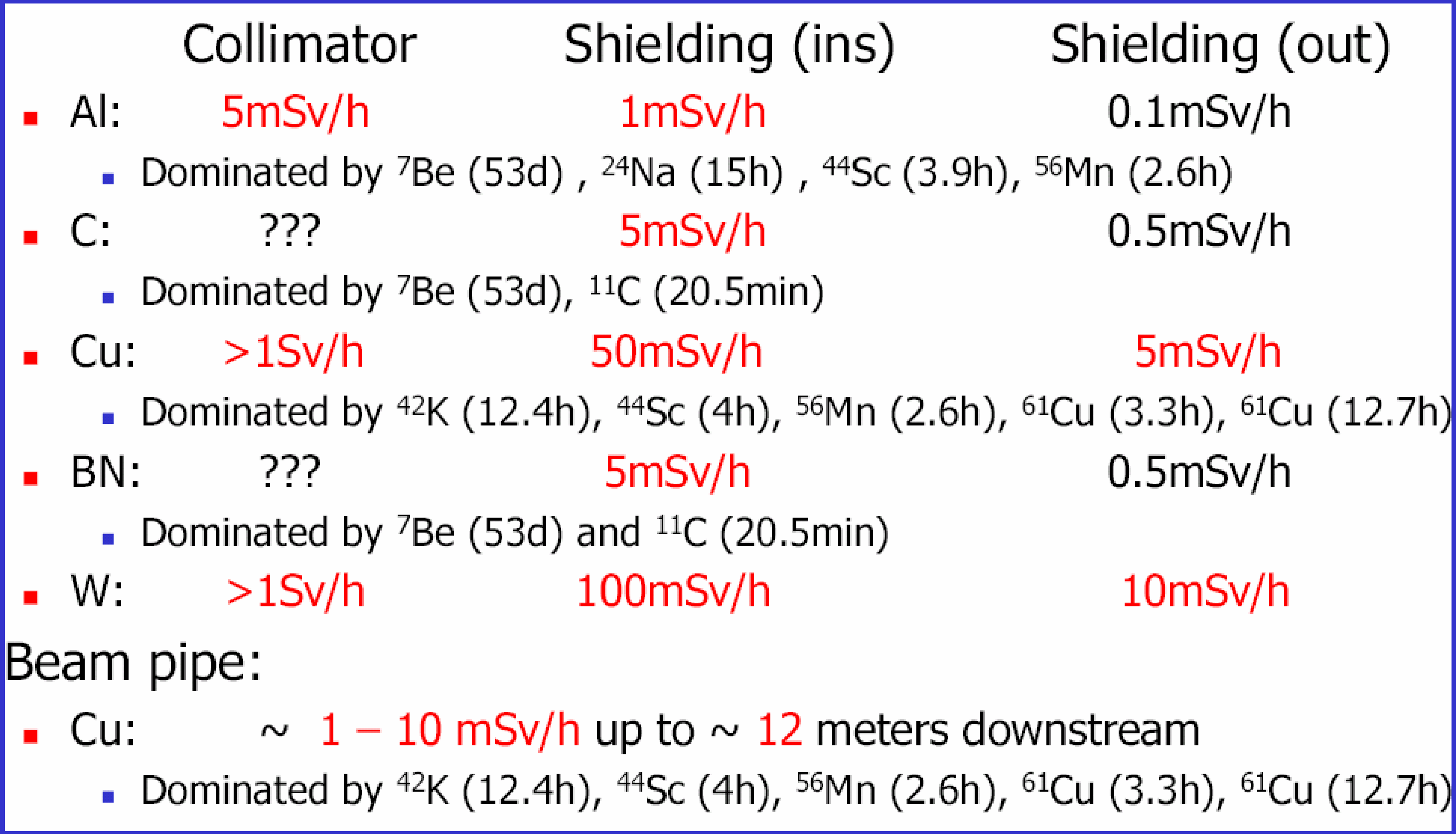
O. Aberle, L. Bruno

Calculated stress in simple Graphite about a **factor of 2 beyond** the allowable value!

This would be **sufficient for the first years** of LHC with 30-50% of nominal intensity.

Other forms of Carbon are expected to be more robust (**Carbon-Carbon**). To be studied.

Radiation studies for different materials (mock-up C collimation system)



	Collimator	Shielding (ins)	Shielding (out)
Al:	5mSv/h	1mSv/h	0.1mSv/h
Dominated by ^{7}Be (53d) , ^{24}Na (15h) , ^{44}Sc (3.9h), ^{56}Mn (2.6h)			
C:	???	5mSv/h	0.5mSv/h
Dominated by ^{7}Be (53d), ^{11}C (20.5min)			
Cu:	>1Sv/h	50mSv/h	5mSv/h
Dominated by ^{42}K (12.4h), ^{44}Sc (4h), ^{56}Mn (2.6h), ^{61}Cu (3.3h), ^{61}Cu (12.7h)			
BN:	???	5mSv/h	0.5mSv/h
Dominated by ^{7}Be (53d) and ^{11}C (20.5min)			
W:	>1Sv/h	100mSv/h	10mSv/h

Beam pipe:

- Cu: ~ 1 – 10 mSv/h up to ~ 12 meters downstream
  - Dominated by ^{42}K (12.4h), ^{44}Sc (4h), ^{56}Mn (2.6h), ^{61}Cu (3.3h), ^{61}Cu (12.7h)

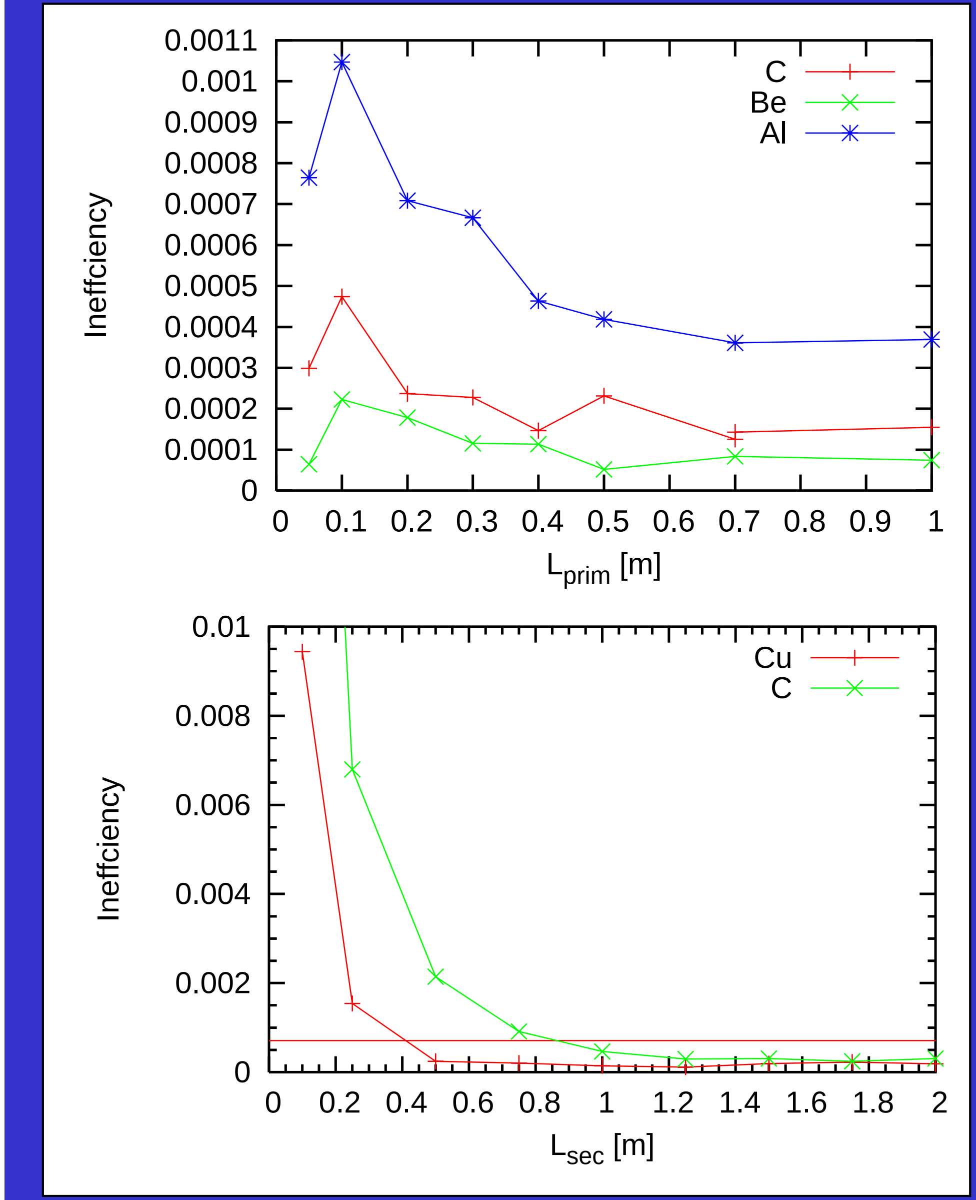
M. Brugger, S. Roesler

Low Z jaws are **less activated**.

Remote handling requirements are relaxed.

More activation downstream!

Required lengths of low Z jaws:



R. Assmann, J.B. Jeanneret

1) Keep secondaries (0.5 m Cu) and vary material and length of primary collimators!

Observations:
Win factor two for 0.2 m graphite (C)!
Stay with 0.2 m length for primary

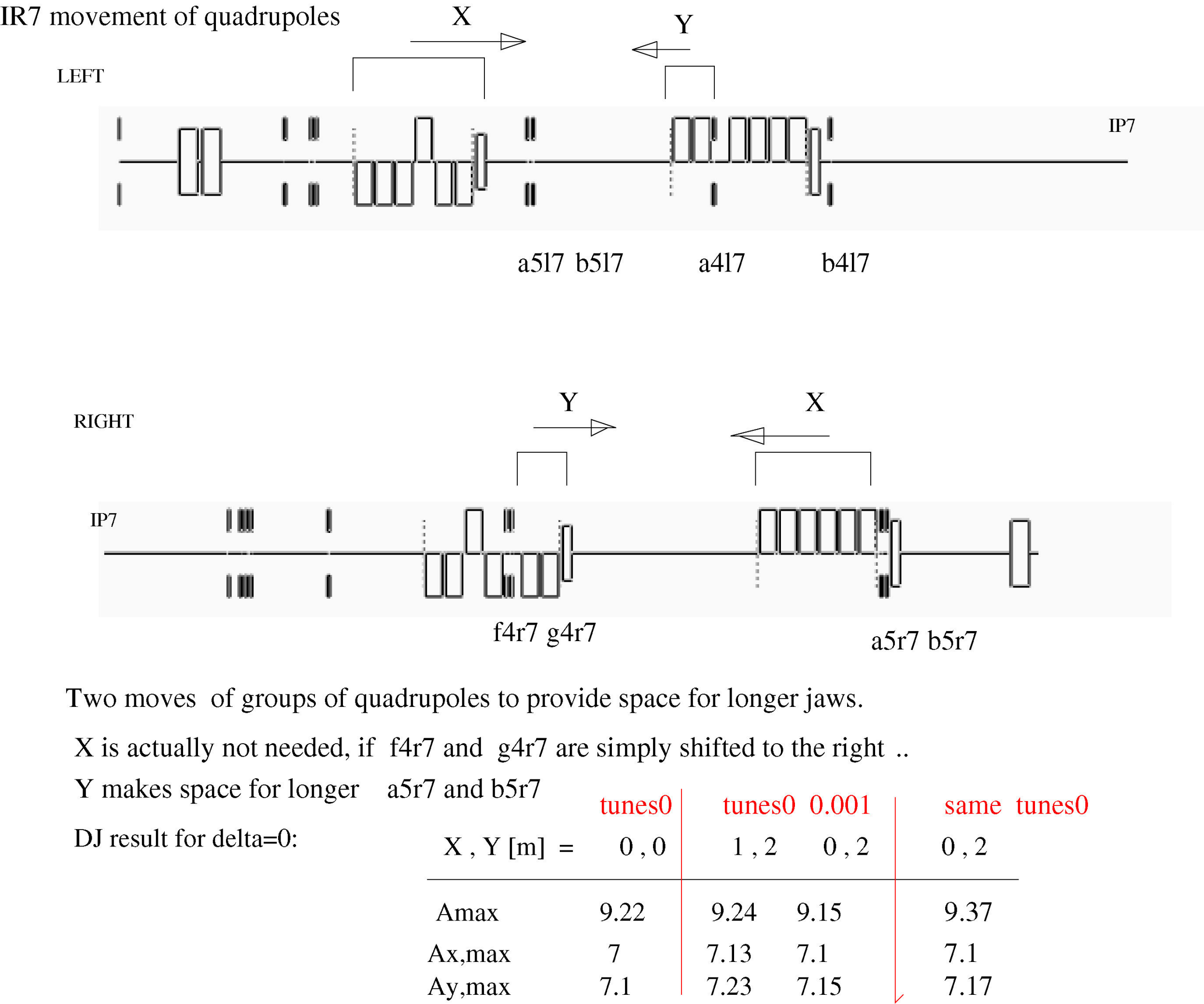
2) Choose 0.2 m C for primary collimators and vary material and length of secondary collimators!

Observations:
Secondary C collimators of 1 m length will restore the cleaning efficiency of the old system.

C system: 0.2 m and 1.0 m jaws!

Space for longer jaws in the cleaning insertions:

D. Kaltchev, TRIUMF



Two moves of groups of quadrupoles to provide space for longer jaws.

X is actually not needed, if f4r7 and g4r7 are simply shifted to the right ..

Y makes space for longer a5r7 and b5r7

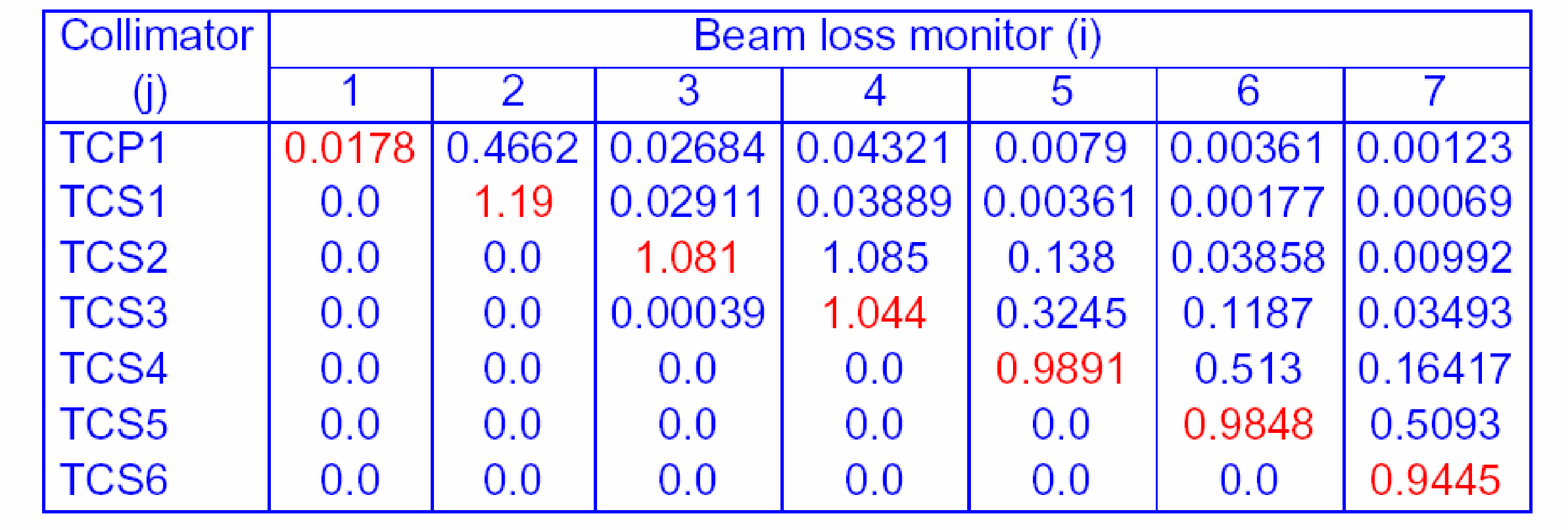
DJ result for delta=0:

	tunes0	tunes0	0.001	same tunes0
X , Y [m] =	0 , 0	1 , 2	0 , 2	0 , 2
Amax	9.22	9.24	9.15	9.37
Ax,max	7	7.13	7.1	7.1
Ay,max	7.1	7.23	7.15	7.17

Preliminary re-match done for up to 2 m quadrupole movements in IR7 (allowing for 1 m C jaws). Maximum escaping amplitude **almost maintained**.

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	Beam loss monitor (i)						
(j)	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.

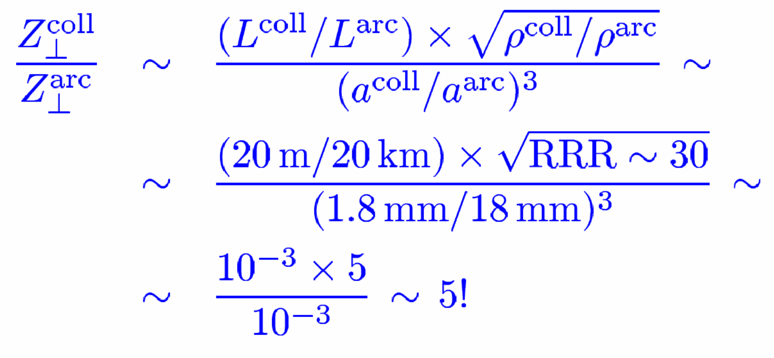
Non-trivial tuning of collimator settings with BLM’s.

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

Can we use a C-based system for the LHC?

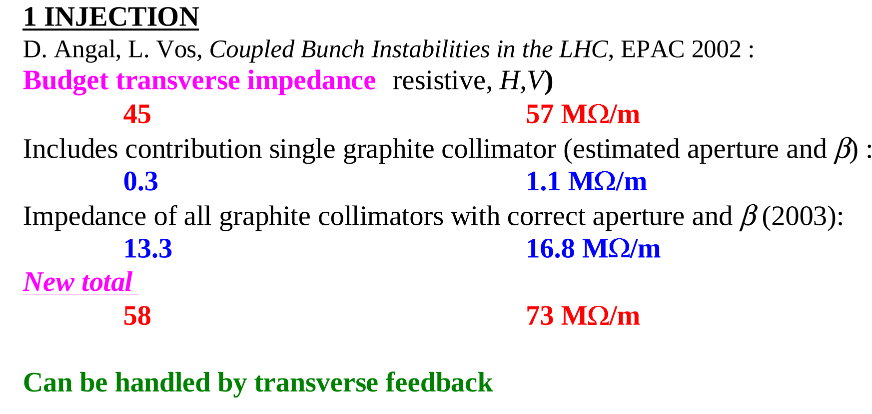
- Required robustness at reach (factor ~3 missing)!
- Jaw lengths remain quite reasonable!
- Space is available and optics can be re-matched!
- Activation is reduced and remote handling requirements are relaxed!
- Vacuum group does not rule out C!
- Impedance was presented as uncritical!

However, third look at impedance in Feb 03 revealed a problem:



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

F. Ruggiero



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

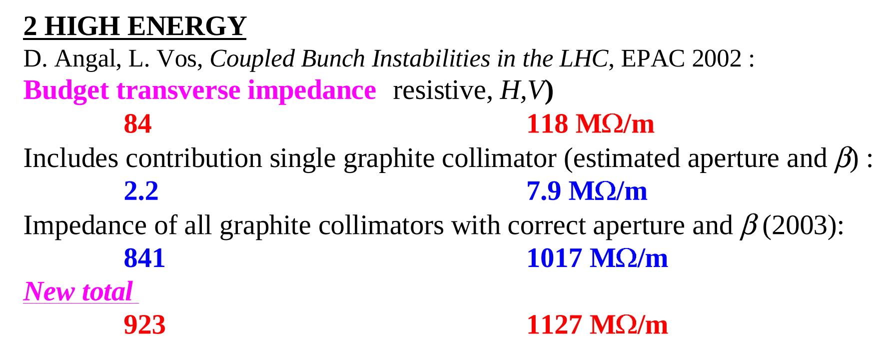
Impedance of all graphite collimators with correct aperture and β (2003):

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

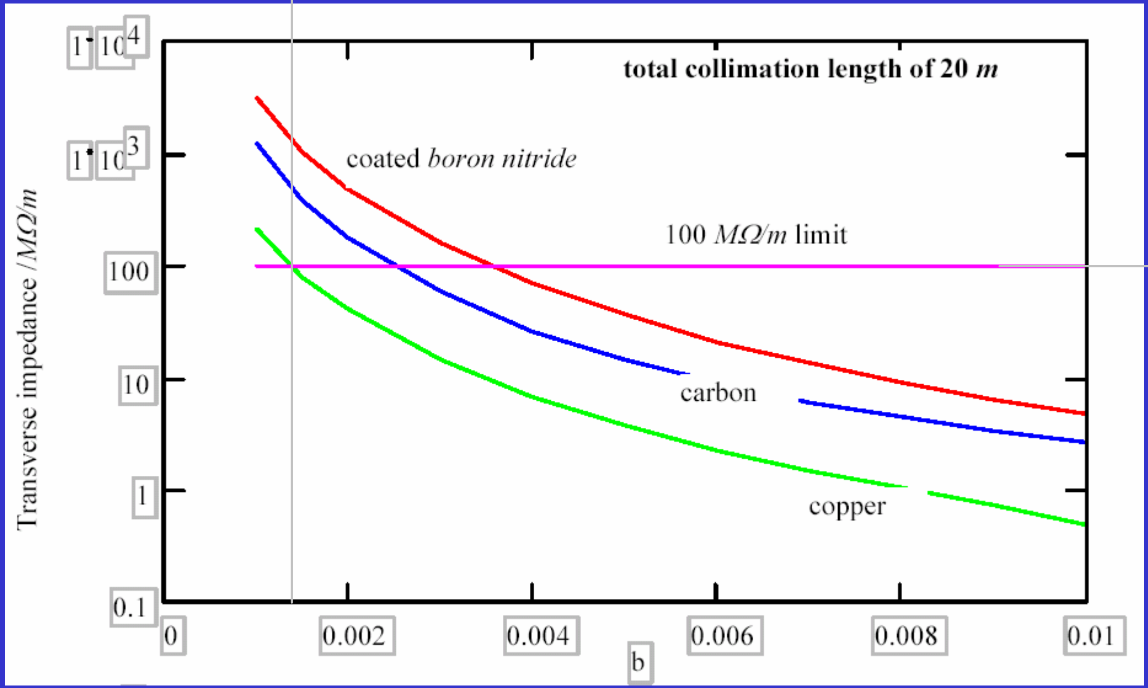
923	1127 MΩ/m

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?

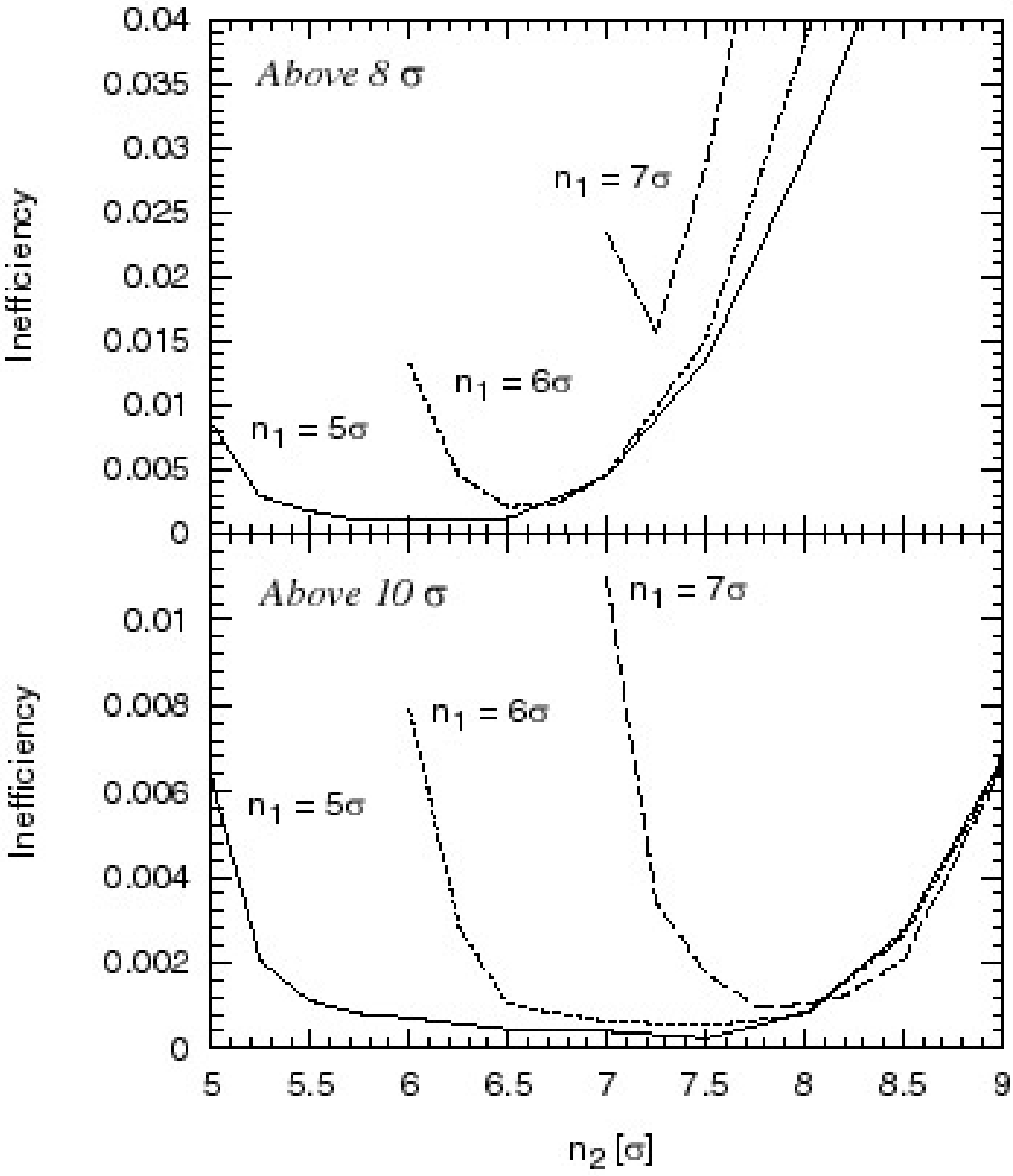
Factor 10 higher gain of transverse feedback (factor 3-4.5 margin) before collision.
Check thresholds for beam instabilities, stabilizing effect of long-range beam-beam.
Metallic plate or low-Z metal (Be?).
Copper doped graphite to reduce impedance?
Open collimators (hardly possible w/o additional collimators 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!

Inefficiency for different collimator settings:

n1 = setting of primary collimator

n2 = setting of secondary collimator

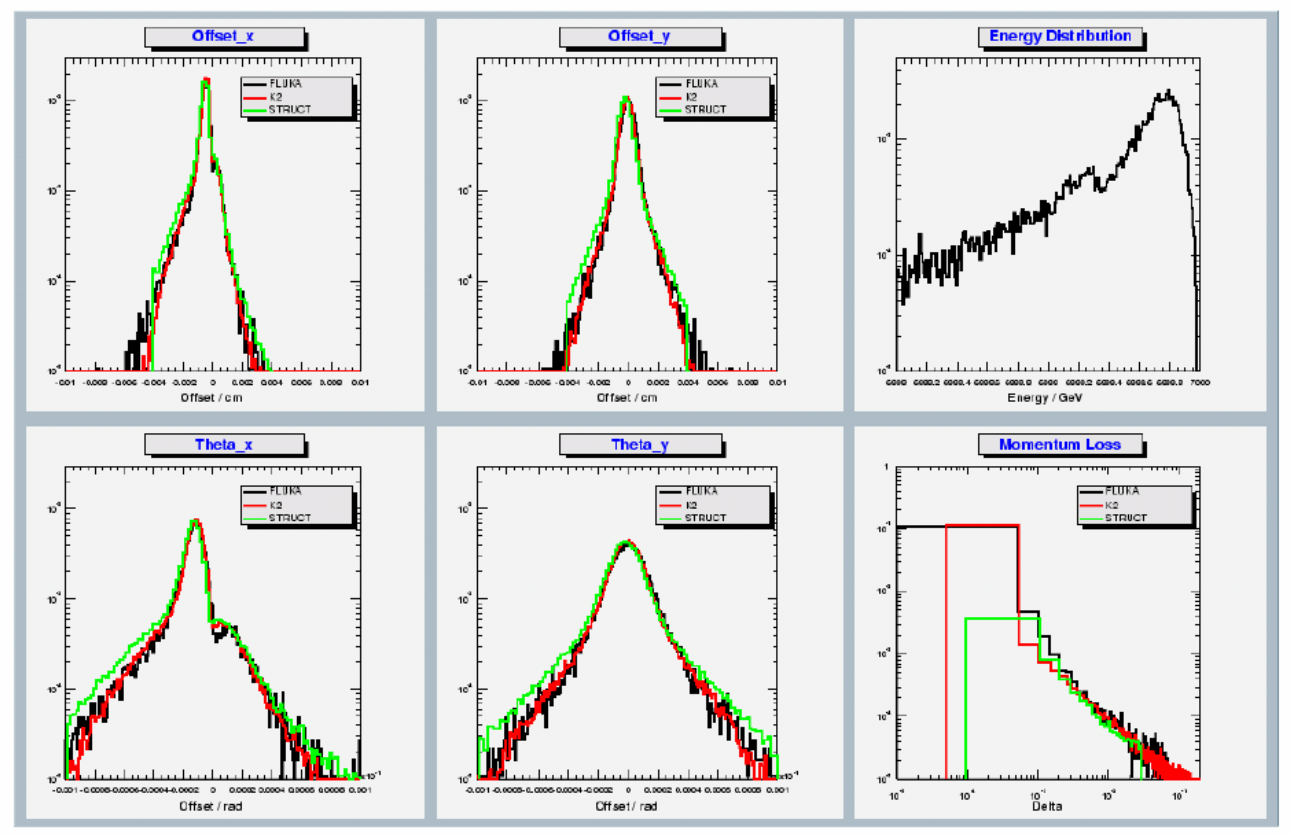


Aperture limited at 8 σ

Aperture limited at 10 σ

Other supporting activities:

Work on numerical tools. Establish systematic errors.



R. Assmann, I. Baishev,
M. Brugger, J.B. Jeanneret,
D. Kaltchev

Collimator scattering and tracking with collimators in SIXTRACK:

Fully chromatic, all errors possible, non-linearities, beam-beam, …

IV. Outlook

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

Detailed engineering design has started: 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):

- *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 collimator remote handling requirements are relaxed!*
- *Vacuum group does not rule out C!*
- *Resistive impedance is large, consequences are under study (feedback)!*

If this system is not feasible other solutions will be studied:

- *Low-Z system based on Beryllium.*
- *Tertiary collimators at triplets to allow opening secondary collimators.*
- *Short high-Z jaws with easy remote diagnostics and repair/exchange. They could be damaged frequently.*
- *…*