The LHC Collimation System

R. Assmann, CERN-SL

for the people who are working / have worked on LHC Collimation:

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E. Chiaveri, B. Dehning, A. Ferrari, C. Fischer, B. Goddard,
E. Gschwendtner, M. Hayes, J.-B. Jeanneret, R. Jung, V. Kain,
M. Lamont, S. Marque, R. Schmidt, V. Vlachoudis, E. Vossenberg,
E. Weisse, J. Wenninger, CERN, Geneva;
I. Baishev, IHEP, Protvino, Moscow Region;
D. Kaltchev, TRIUMF/University of Victoria, Victoria

…and related activities (beam dump).

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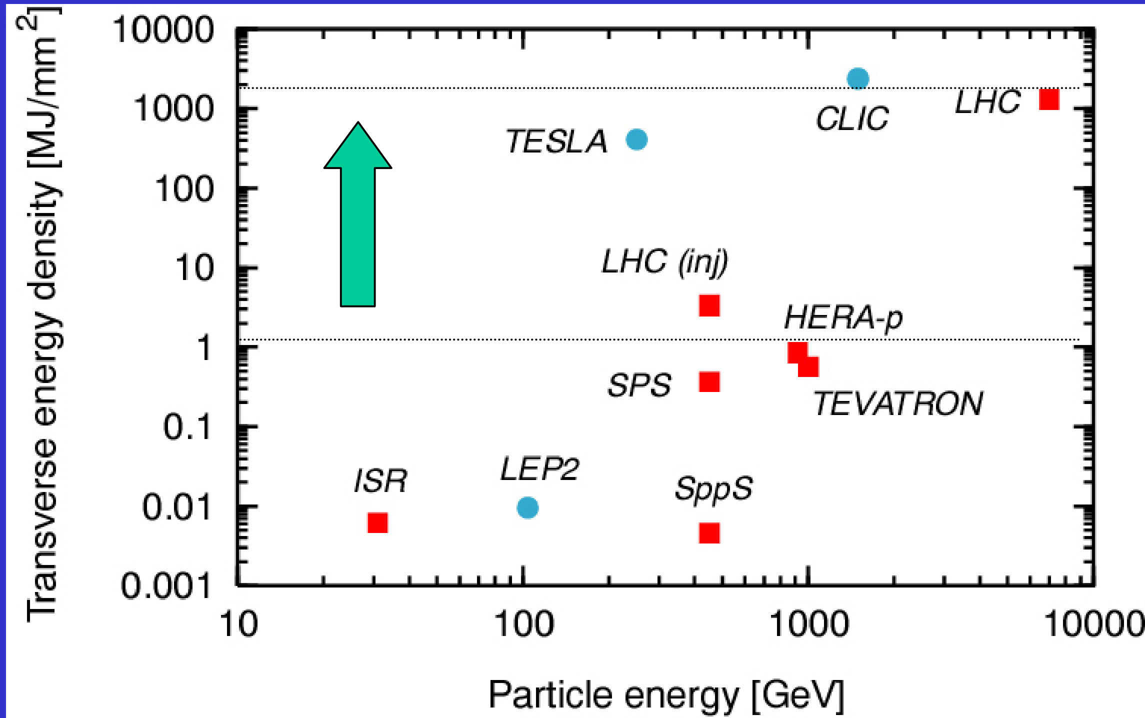
I. Overview on LHC Collimation

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:

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

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

Increase transverse energy density

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.

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).

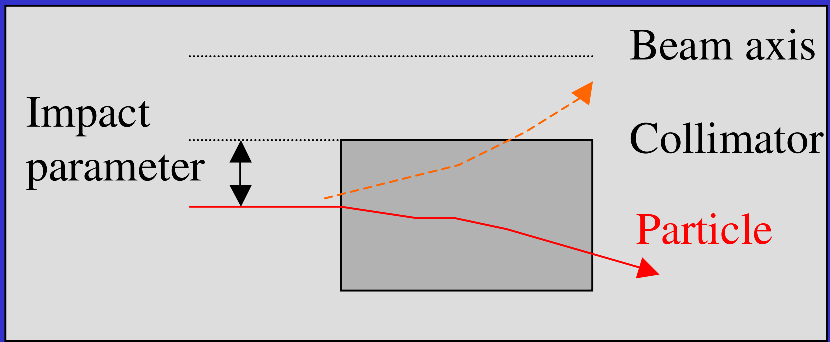
Two stage cleaning systems:

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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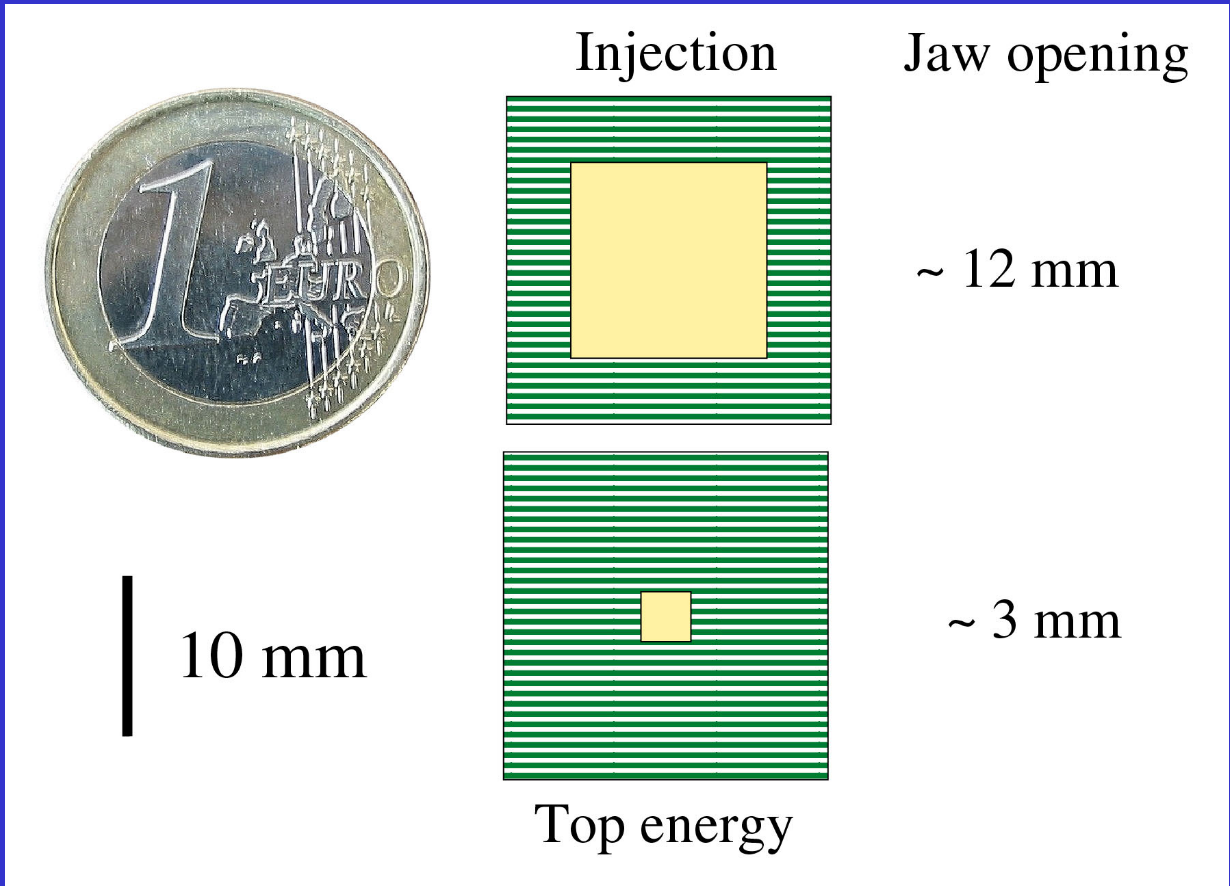


Collimator settings:

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

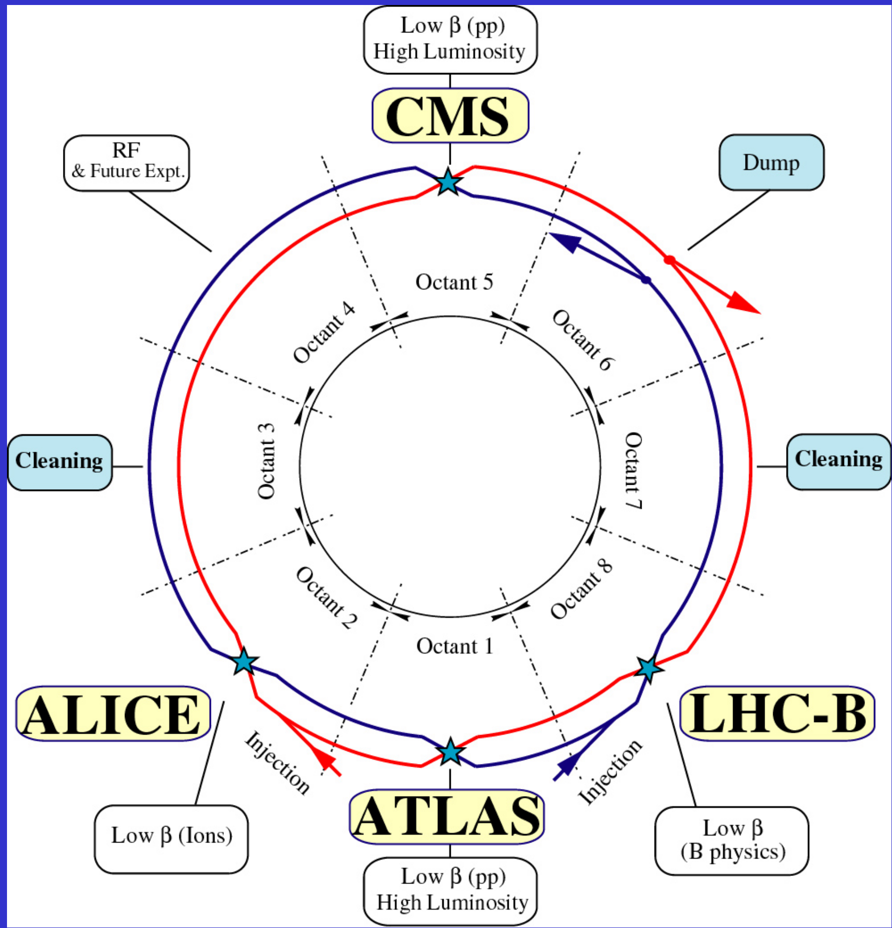
The LHC Cleaning Insertions

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.

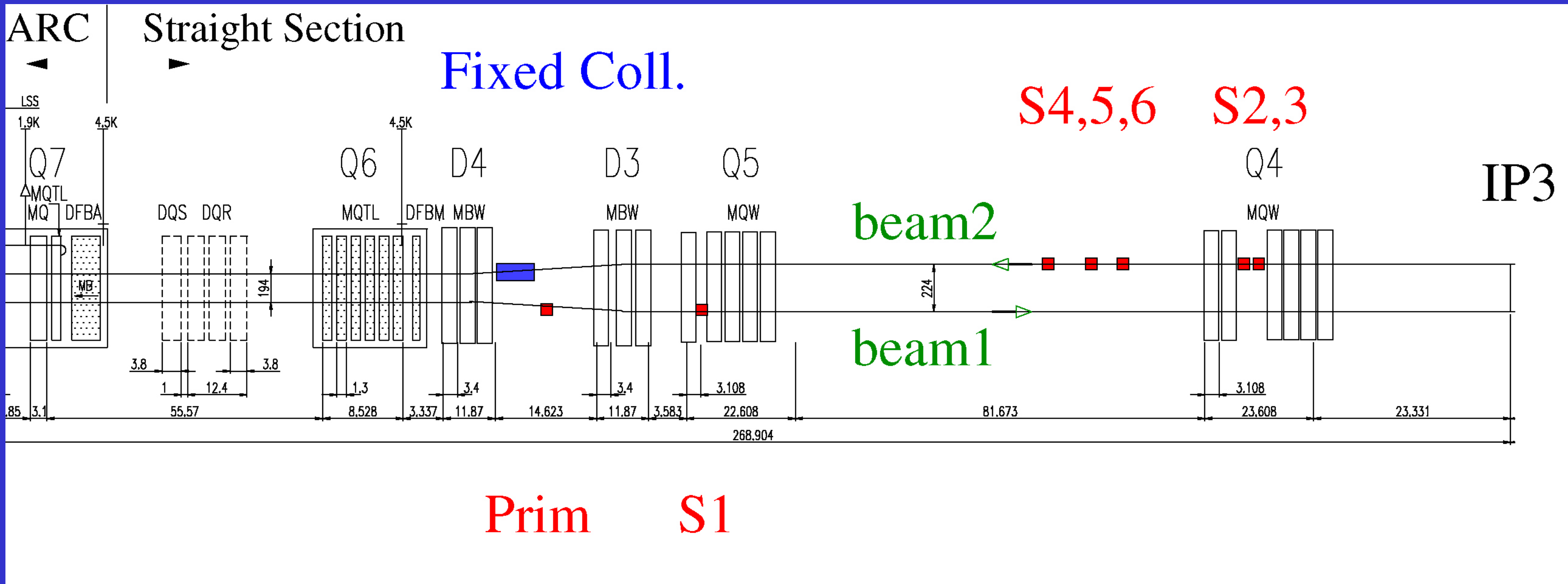


54 movable collimators for high efficiency cleaning, two jaws each *+ other absorbers for high amplitude protection*

Big system: 108-200 degrees of freedom!

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!

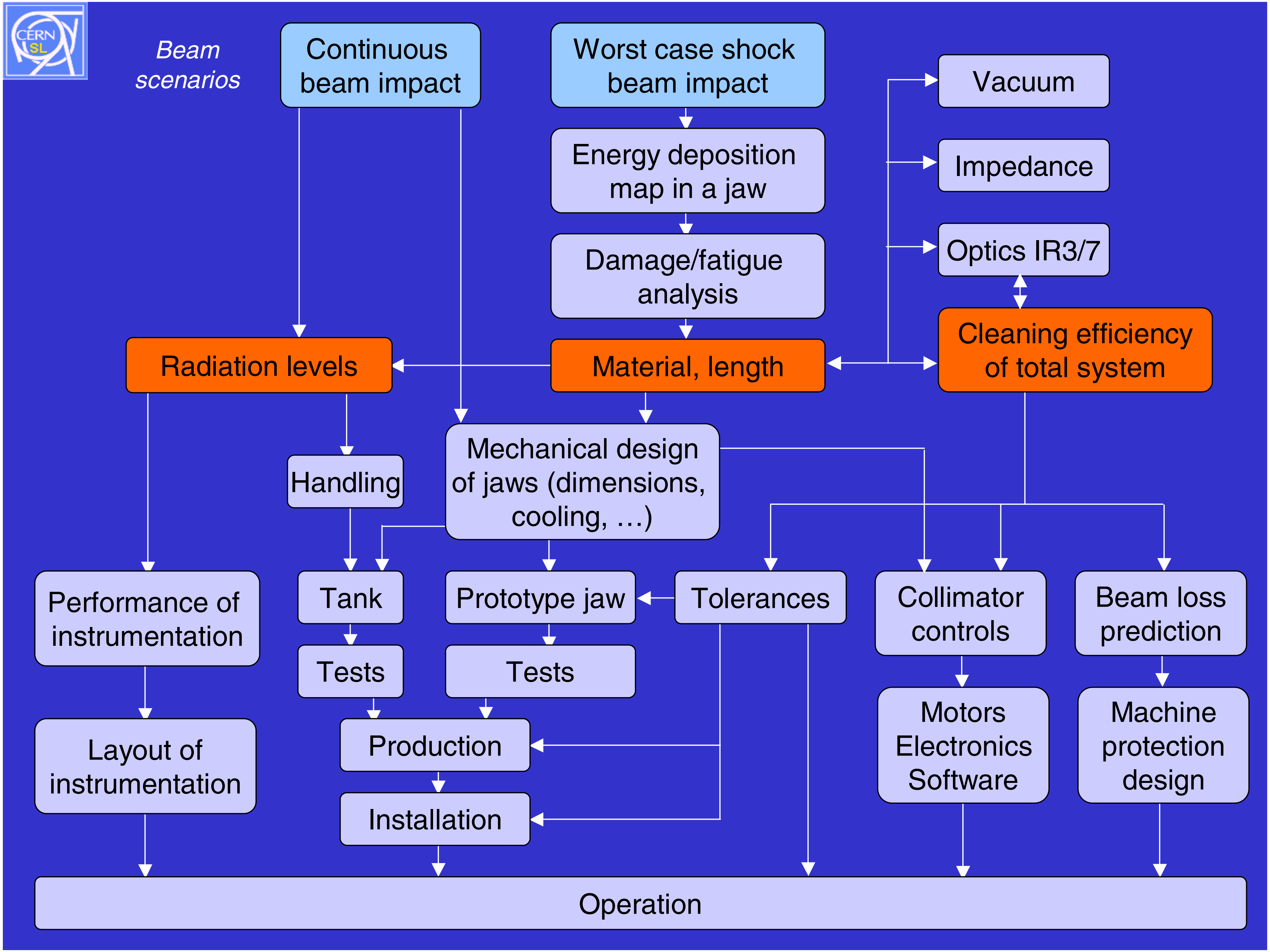
Concept and basic layout developed and verified over last 10 years.

II. Defining and building the final system

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)

3. **Put together a functional collimation system (~70 movable jaws/beam) that delivers high robustness and excellent cleaning efficiency.**
   (AP, operation, instrumentation, controls)



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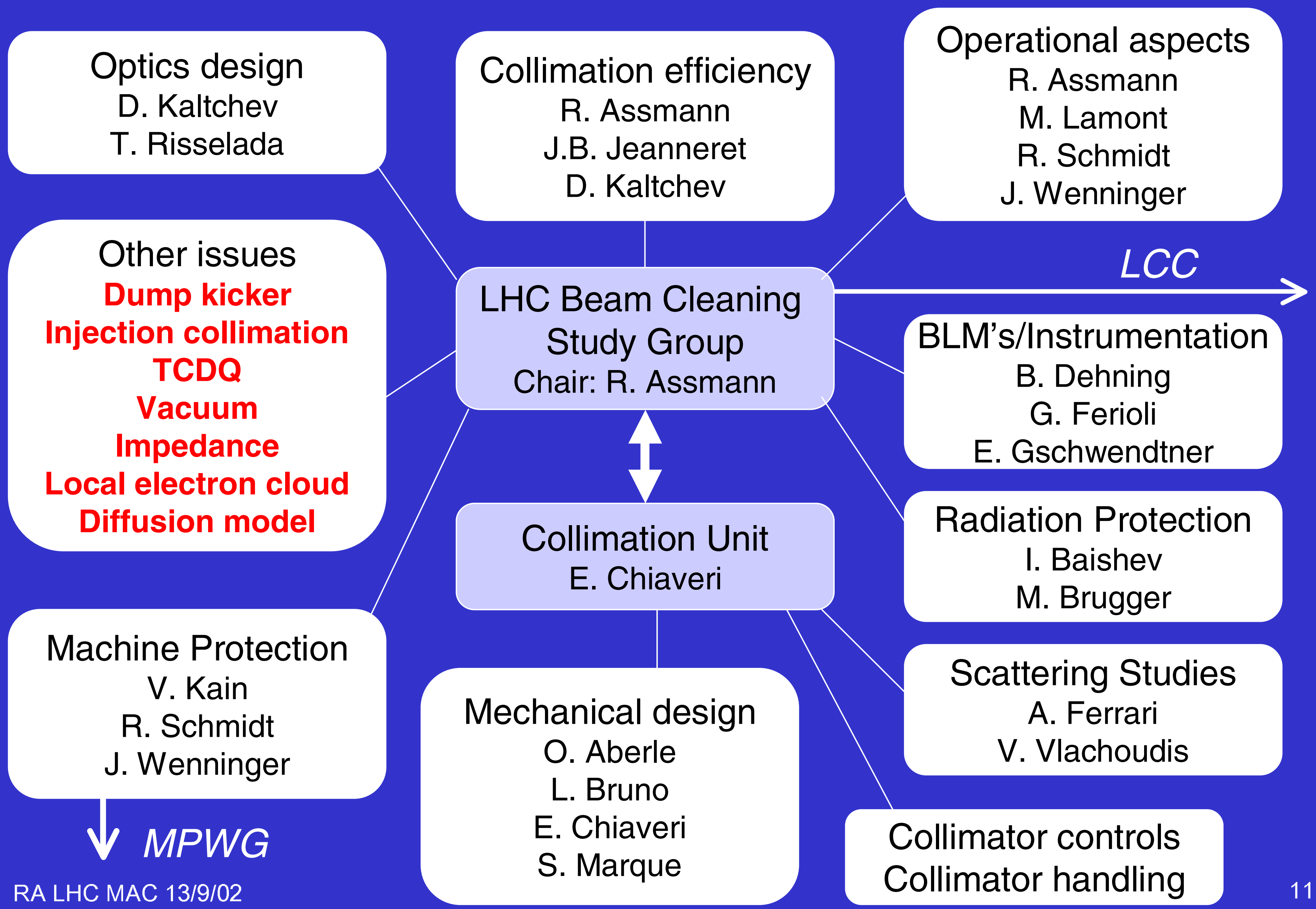
Who is doing the work? (resource allocation is ongoing)



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III. Status of work

Much work in LHC Beam Cleaning Study Group (since Sep 2001):
(Chairman R. Assmann)

Mandate: Study beam dynamics and operational issues for the LHC collimation system. Identify open questions, assign priorities, and show the overall feasibility of the LHC cleaning system.

Activities:

- *16 meetings*
- *LHC collimation web site*
- *7 LHC project notes and reports*
- *Organization CERN Meeting on Collimation (180 p minutes)*
- *Presentations/discussions at BI-Review, LCC, EPAC, …*

First priority: **Consensus about collimation requirements and design criteria.**

CERN-LHC-PROJECT-REPORT-599: REQUIREMENTS FOR THE LHC COLLIMATION SYSTEM.
By R.W. Assmann, I. Baishev, M. Brugger, L. Bruno, H. Burkhardt, G. Burtin, B. Dehning, C. Fischer, B. Goddard, E. Gschwendtner, M. Hayes, J.B. Jeanneret, R. Jung, V. Kain, D. Kaltchev, M. Lamont, R. Schmidt, E. Vossenberg, E. Weisse, J. Wenninger (CERN & Serpukhov, IHEP & TRIUMF).

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

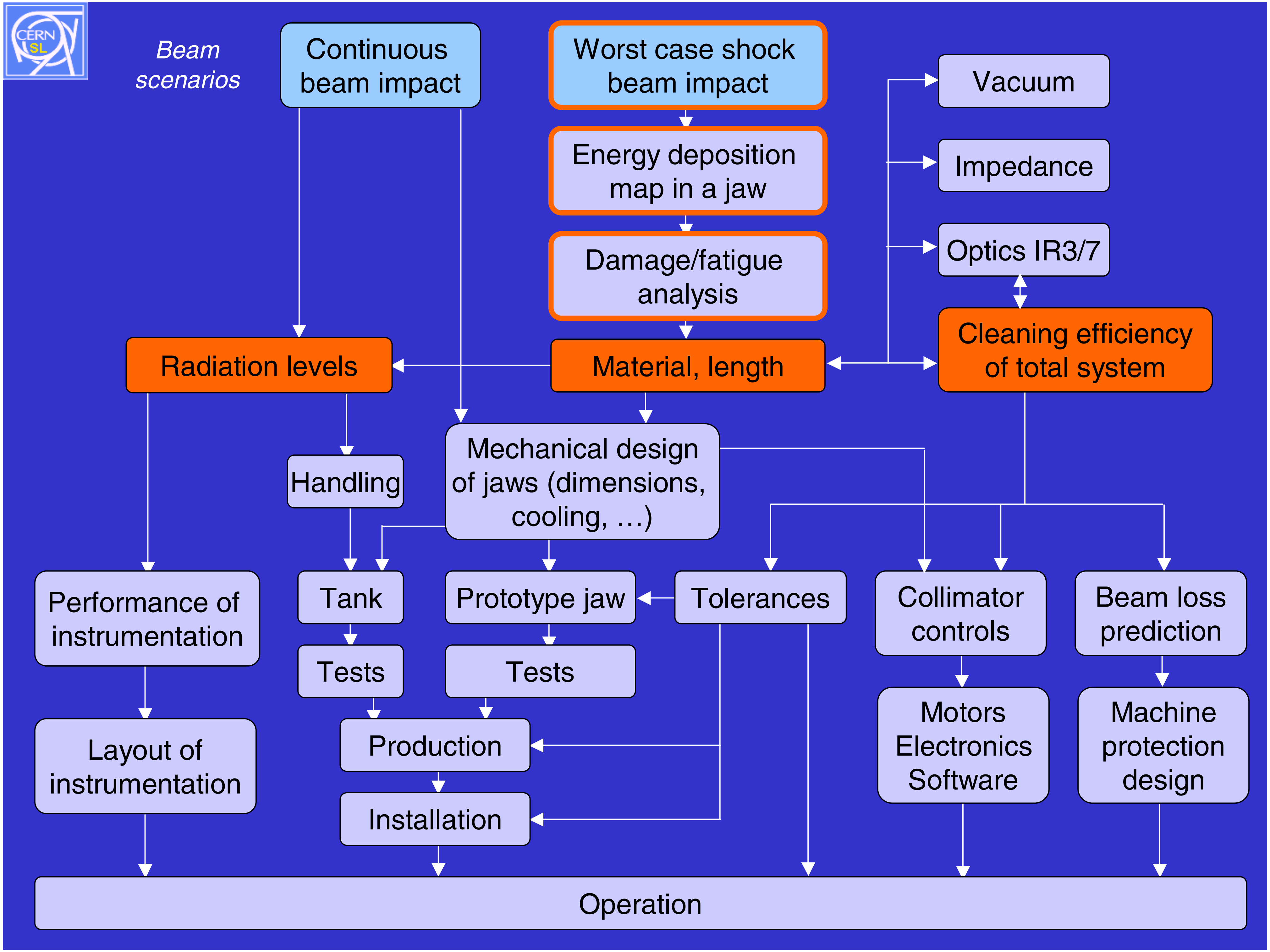
CERN-LHC-PROJECT-REPORT-592: EQUILIBRIUM BEAM DISTRIBUTION AND HALO IN THE LHC. By R. Assmann, F. Schmidt, F. Zimmermann, M.P. Zorzano (CERN & I.N.T.A.).

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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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).

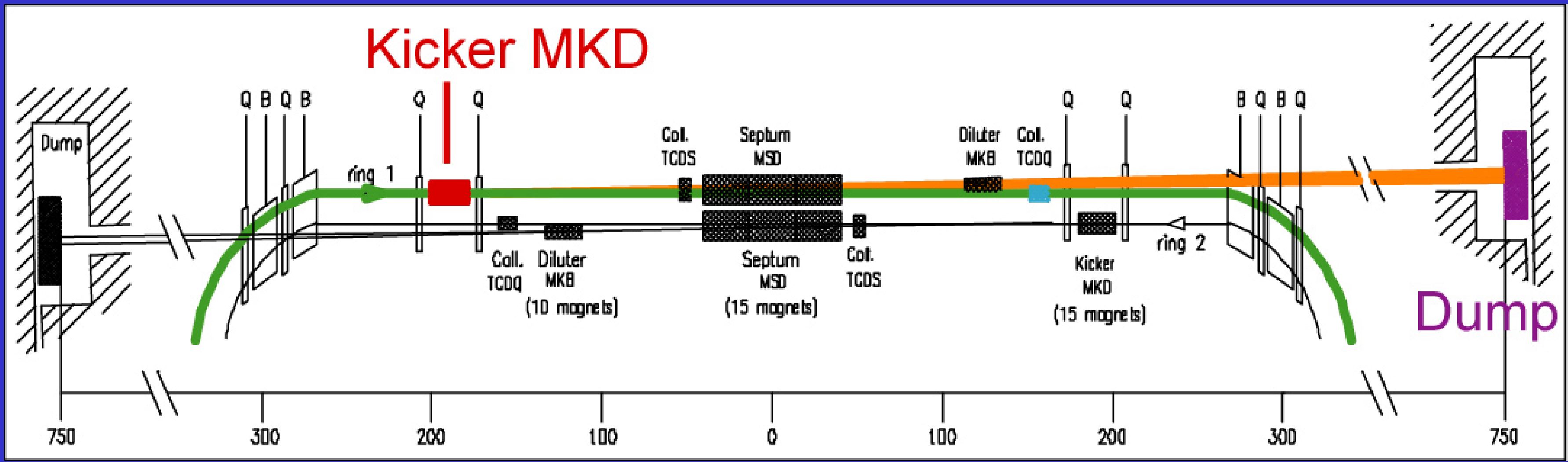
Failure modes:

- 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.

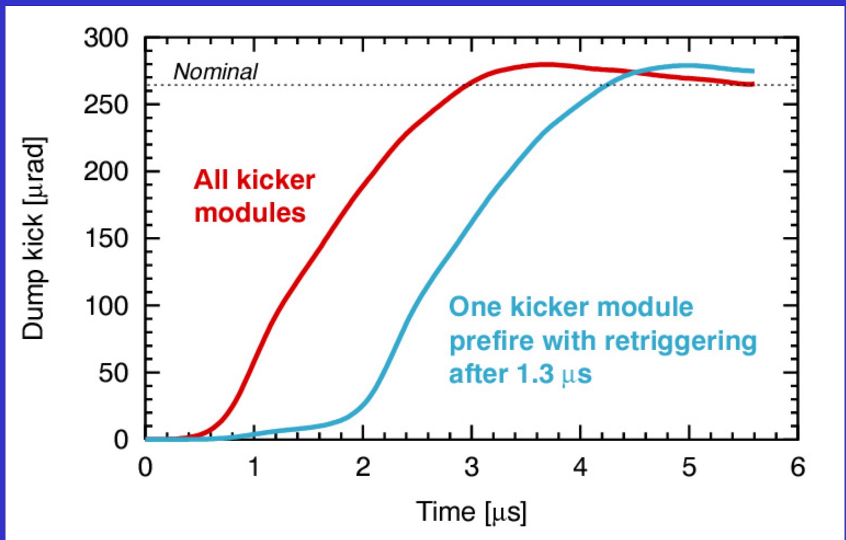
} Difficult to predict

Assume at least once per year!

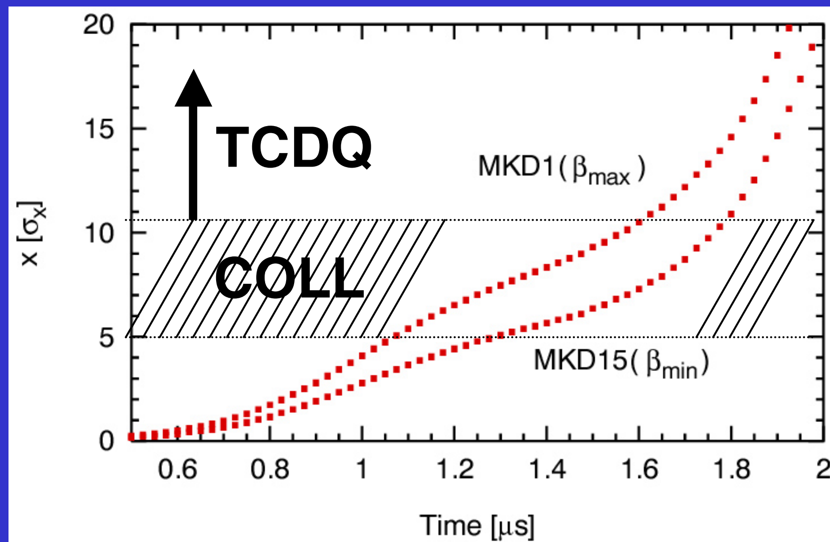
Abnormal dump actions



Kick [μrad]

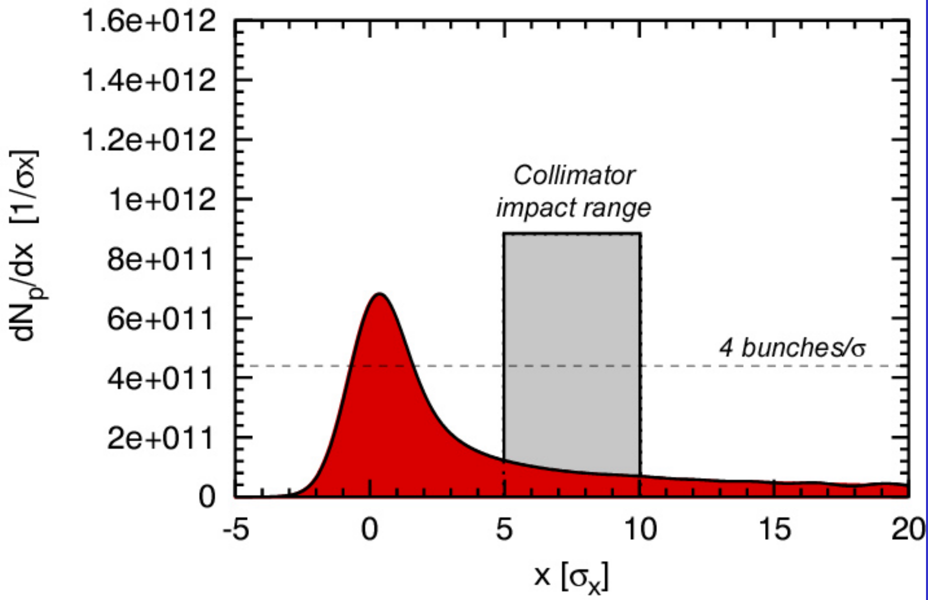


Downstream offset [σ]



One module pre-fire

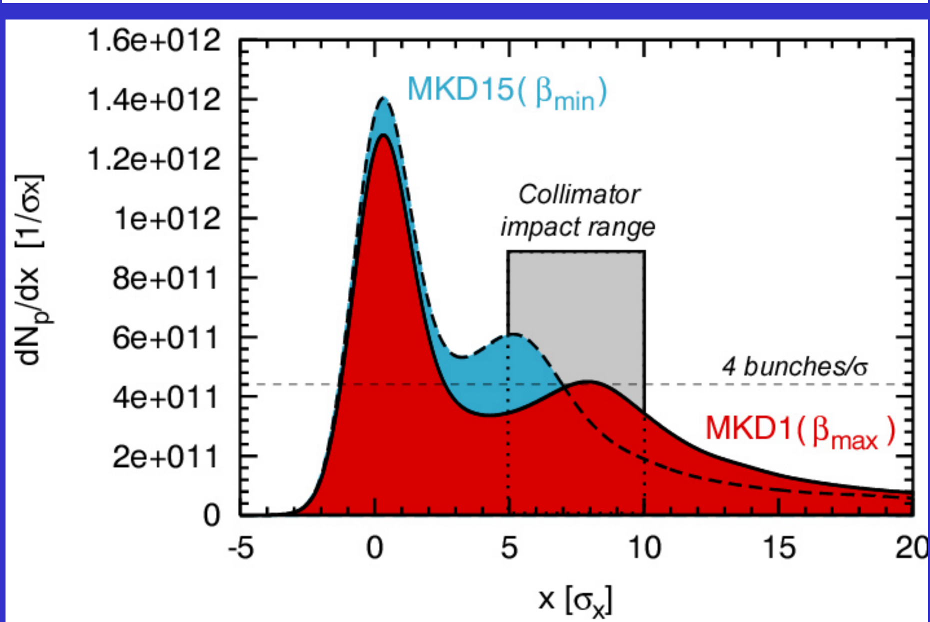
Abnormal dump actions



Beam abort asynchronous with abort gap:

Total: 6 bunches over 5 σ

Peak: **1.5 bunches in 1 σ**

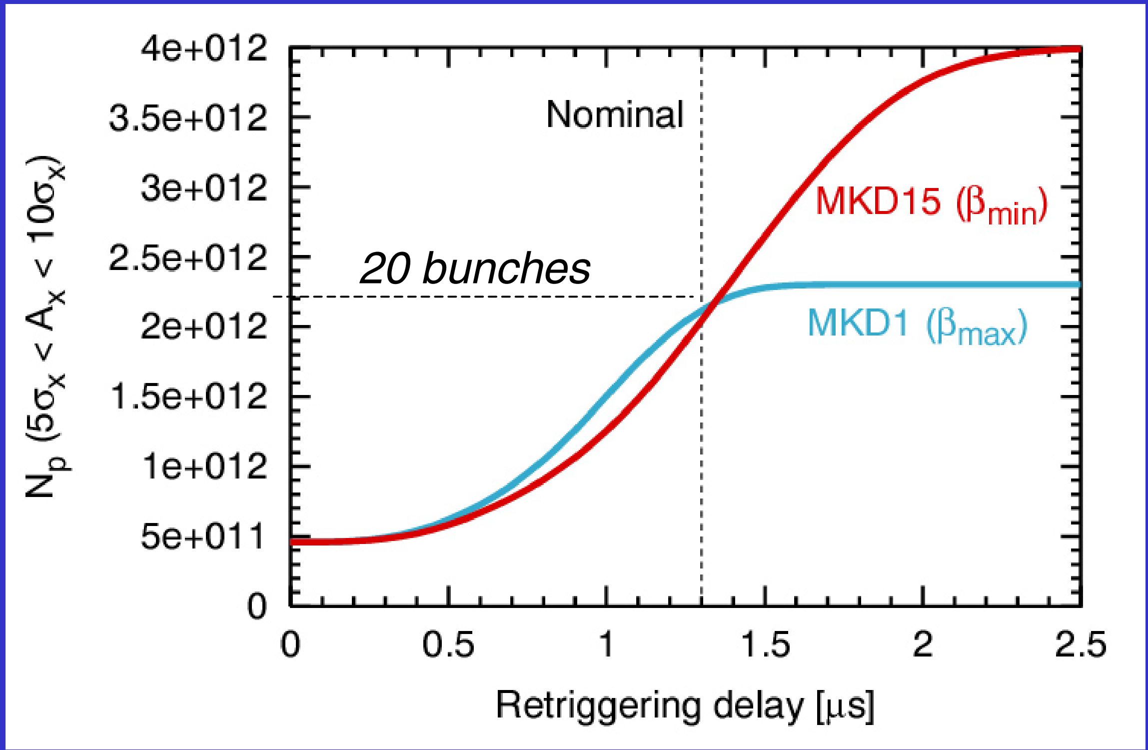


1 module pre-fire with re-triggering of 14 after 1.3μs:

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

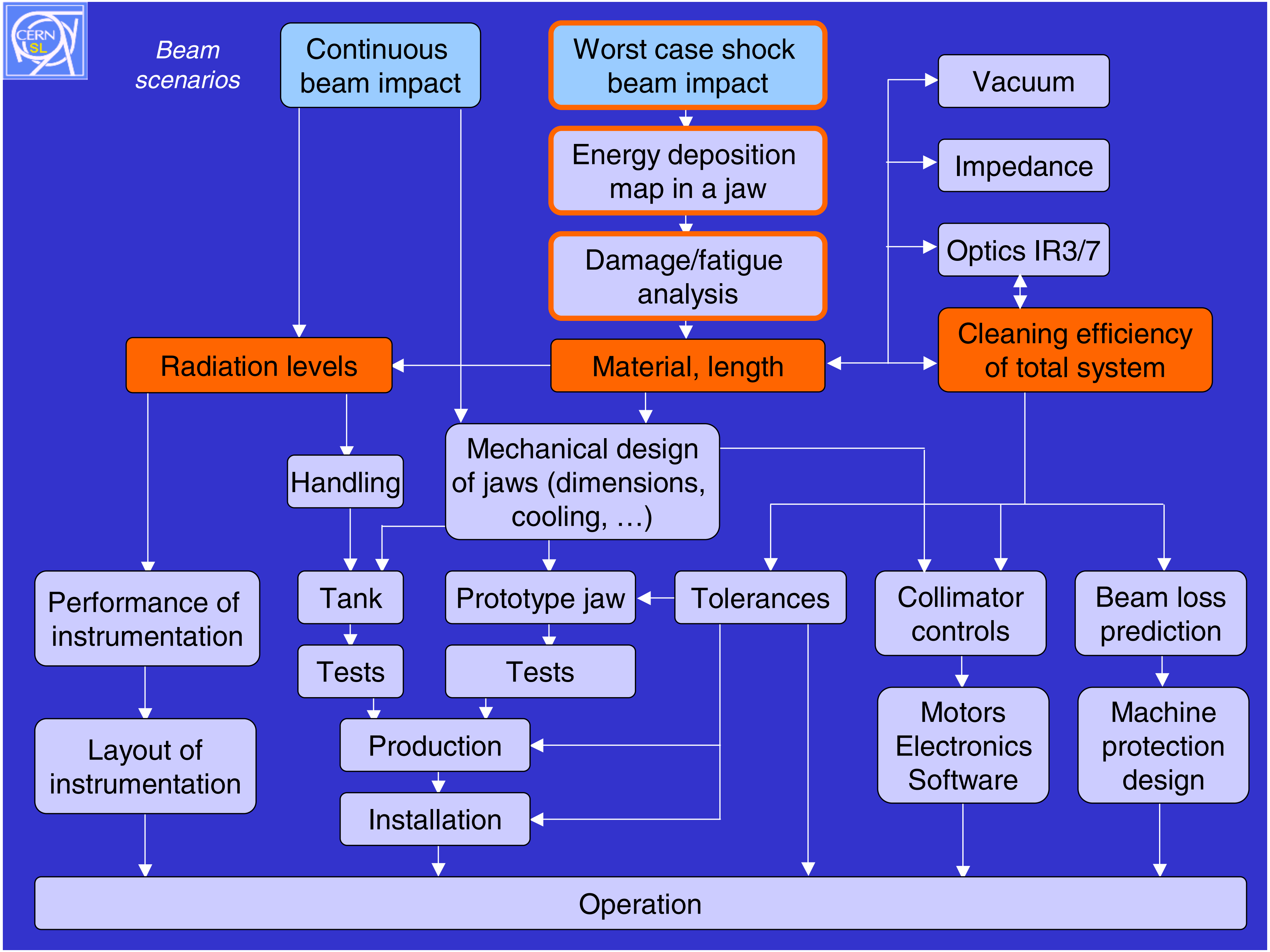
Detailed calculation with measured kicker waveform yields *higher beam impact* on collimators than assumed.

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).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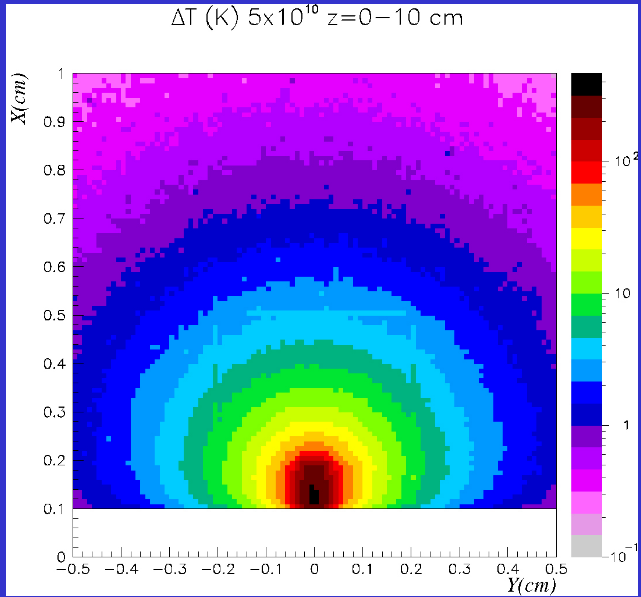
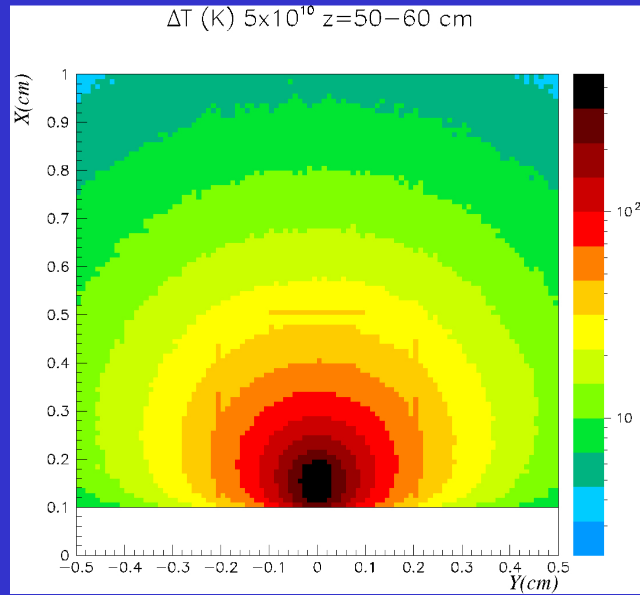
Energy deposition map in a jaw

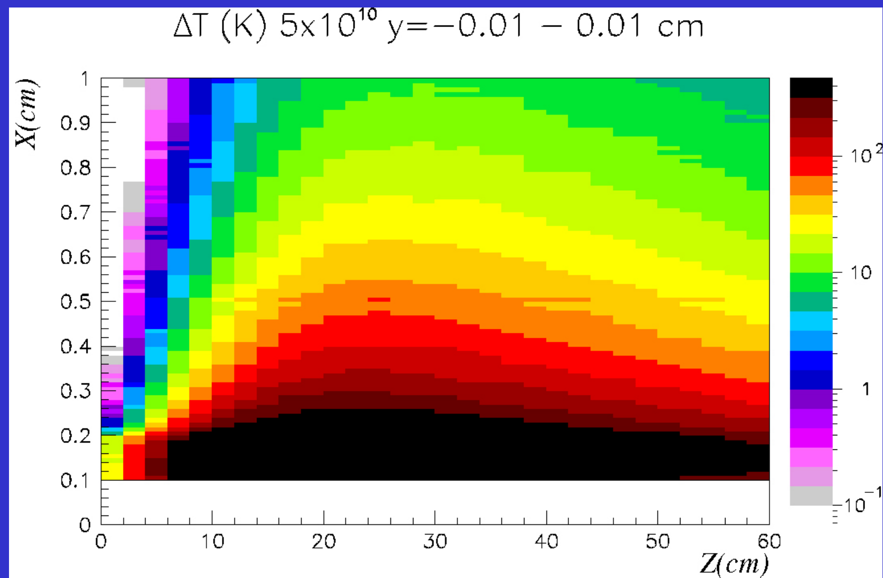




Half a nominal LHC bunch

Cu secondary coll.

A. Ferrari, V. Vlachoudis



Cu cannot take 20 bunches!

Radiation levels

Goal: Benchmark codes against measured activation for various materials

Measurements at CERF and NA60: M. Brugger, Y. Donjoux, A. Mitaroff, S. Roesler, M. Silari

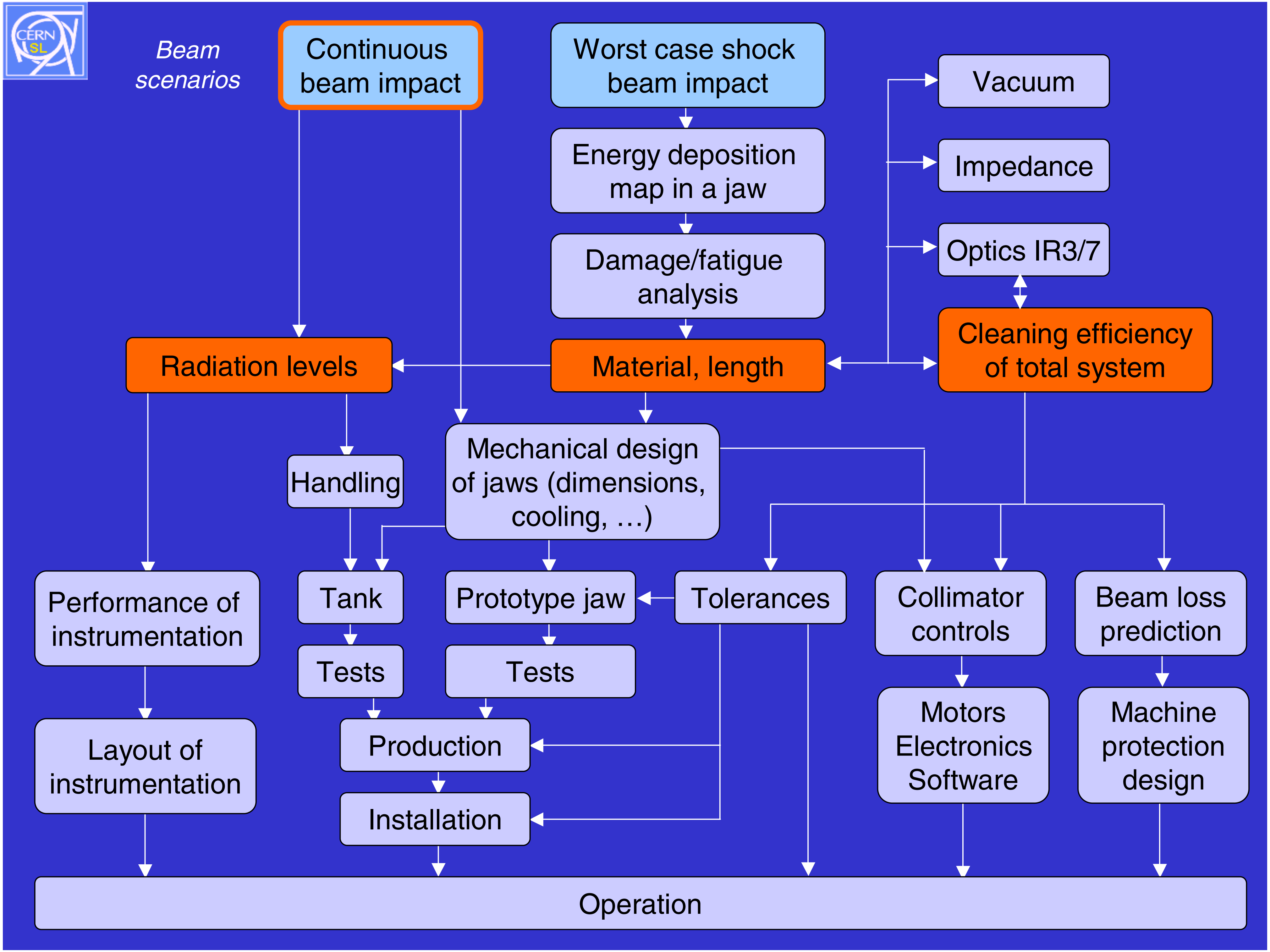
CERF:
120 GeV mix-beam (p, K, mesons)
2cm size
1.4e8

Materials:
Al, Cu, Fe, stainless steel, **BnNi, C composite**

NA60:
400 GeV mix-beam (p)
1mm size
1e7-1e9

Materials:
Be, In, Pb

Benchmark FLUKA. Once material is decided radiation levels will be predicted within factor 2 or better.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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)

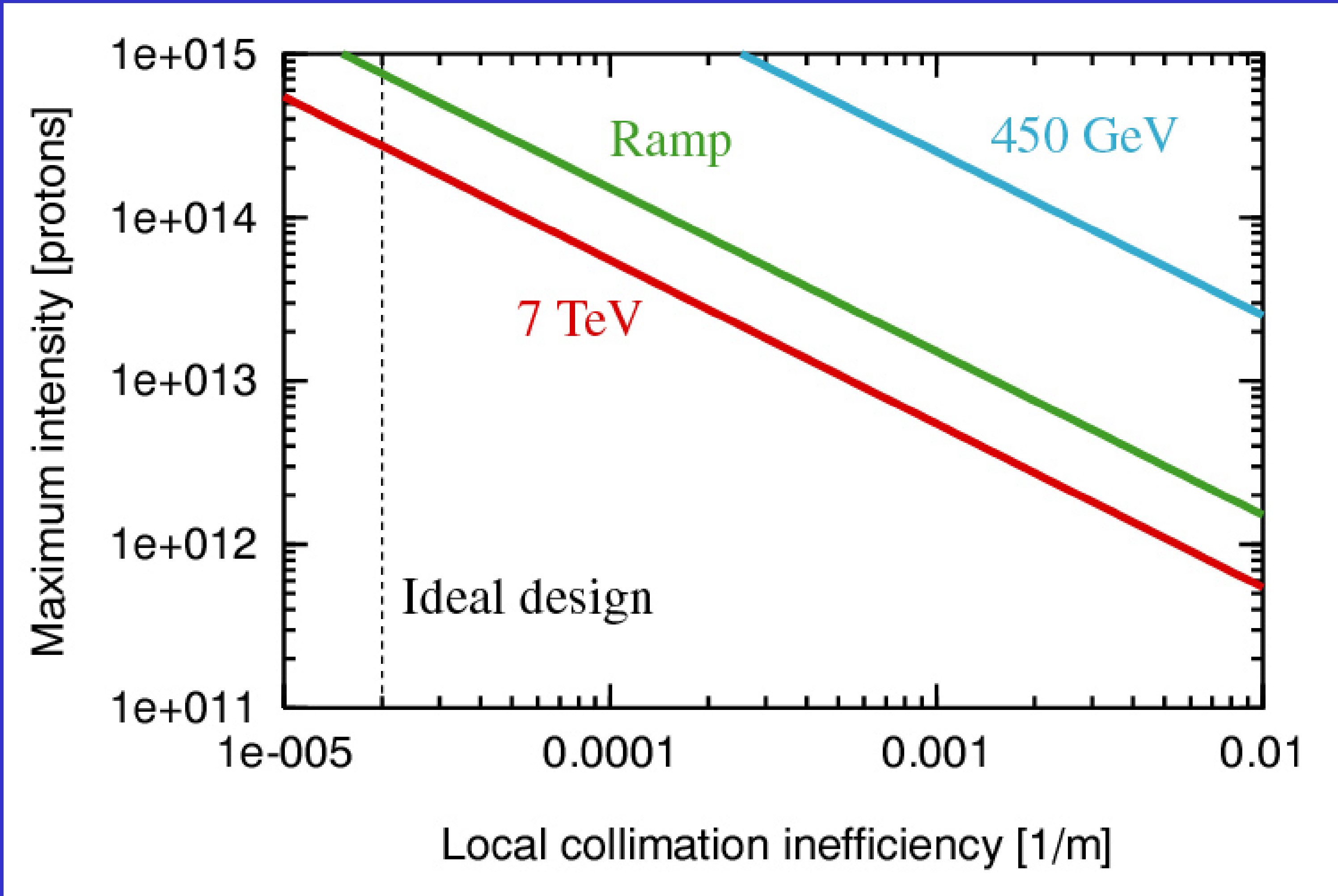
2) Accept low lifetimes during cycle

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!

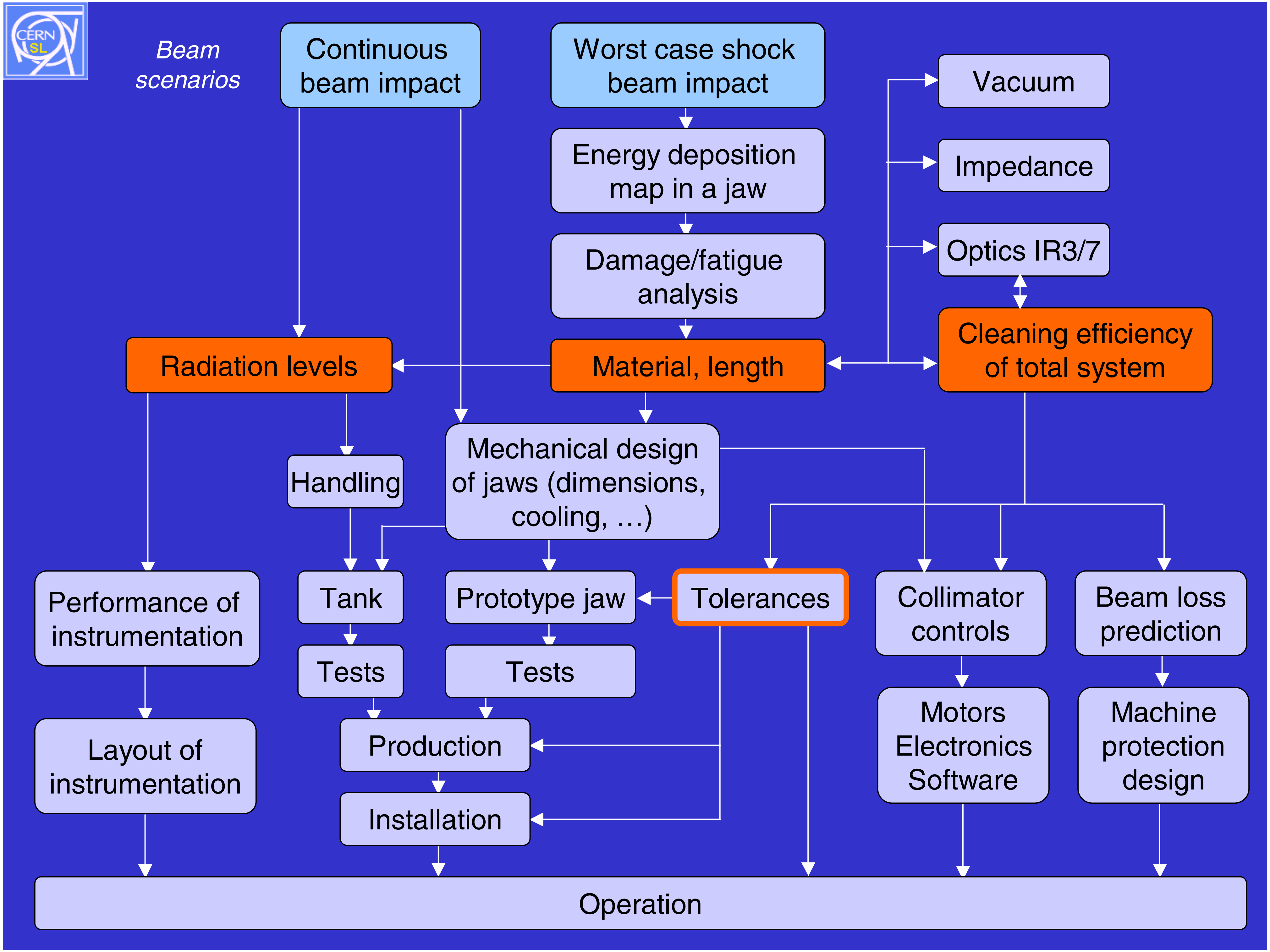
Material, length, cooling, …

Running at the quench limit for τ = 0.2 h



Trade-off for given quench limit between:

Inefficiency – Allowed intensity – Minimum allowable lifetime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System evaluation: Tolerances

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

Transient changes: Orbit, Beta beat

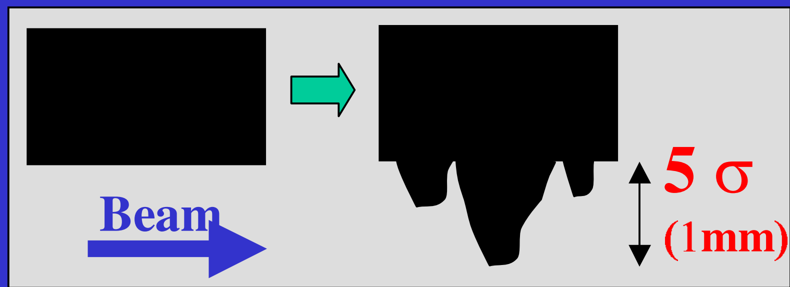
Error	Tolerance
Orbit	0.6 σ
Beta beat	8%
Longitudinal angle	50 μrad
$\Delta L/L$ (prim)	75%
Surface flatness (prim)	10 μm
$\Delta L/L$ (sec)	20%
Surface flatness (sec)	25 μm
Setting accuracy (prim)	-1.0/+0.5 σ
Setting accuracy (sec)	$\geq \pm 0.5\ \sigma$

Preliminary estimates:

Combined effect can make tolerances more severe!

Collimators need not only be robust, but also precise!

HERA experience:



Set-up of tools, thinking about operation started

Tools:
- SIXTRACK with collimators
- Comparison of scattering physics
- Interface of halo prediction to BLM studies

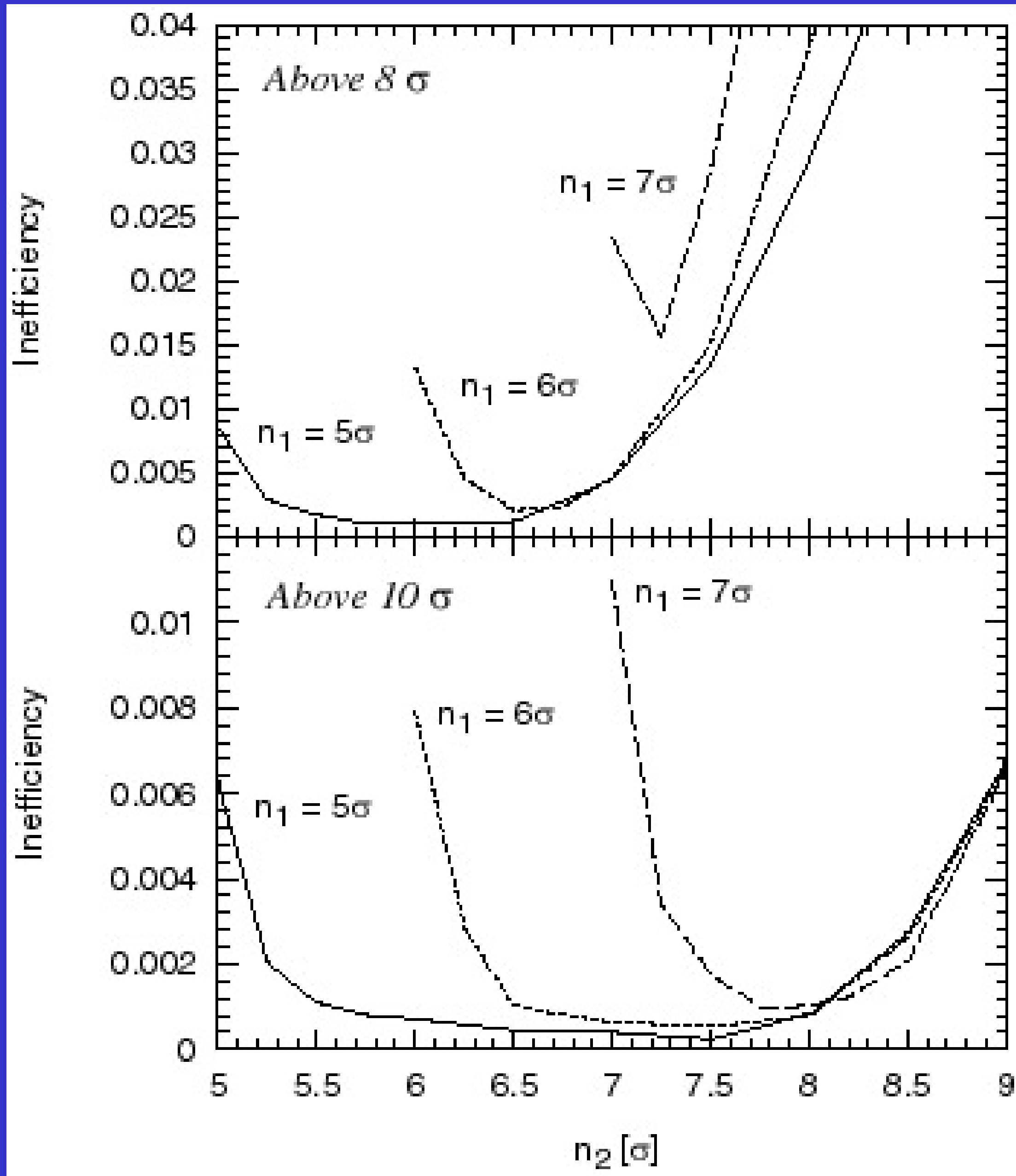
Operation:
- Operational strategies
- Orbit feedback
- Machine protection
- Required accuracy for beam diagnostics
- Allowed deterioration of beam parameters

All ongoing… (fast results when mechanical properties decided)

Inefficiency versus settings

n1 = setting of primary collimator

n2 = setting of secondary collimator



Aperture limited at 8 σ

Aperture limited at 10 σ

IV. Outlook

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.

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!

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!

Schedule

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

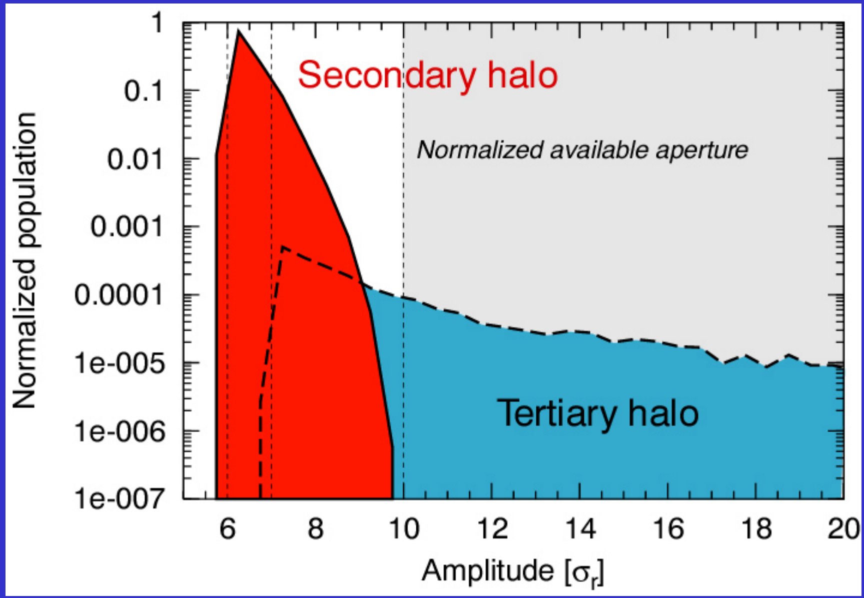
Required schedule:

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.

Additional slides

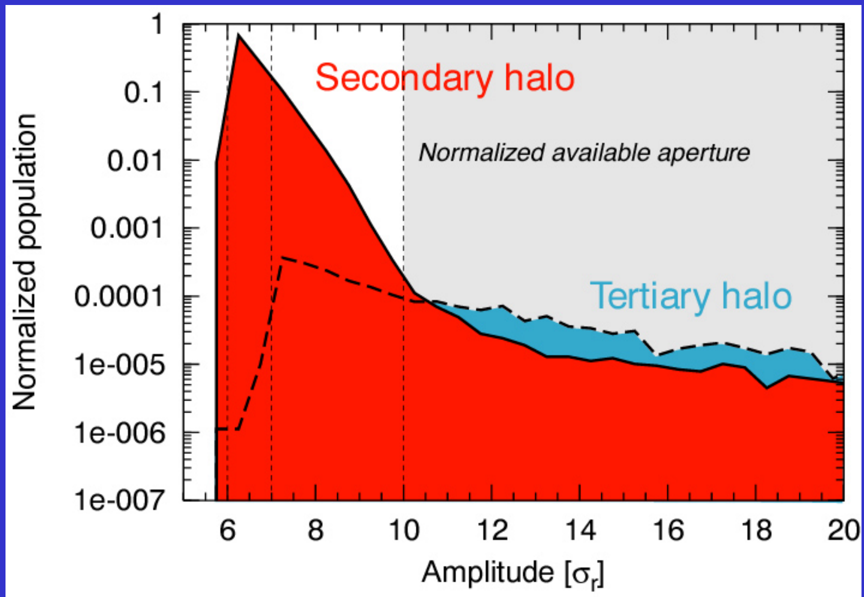
Secondary and tertiary beam halos



Scattering in collimator jaws (at 6/7 σ)

Transverse scattering angles + momentum loss

Halo at zero dispersion



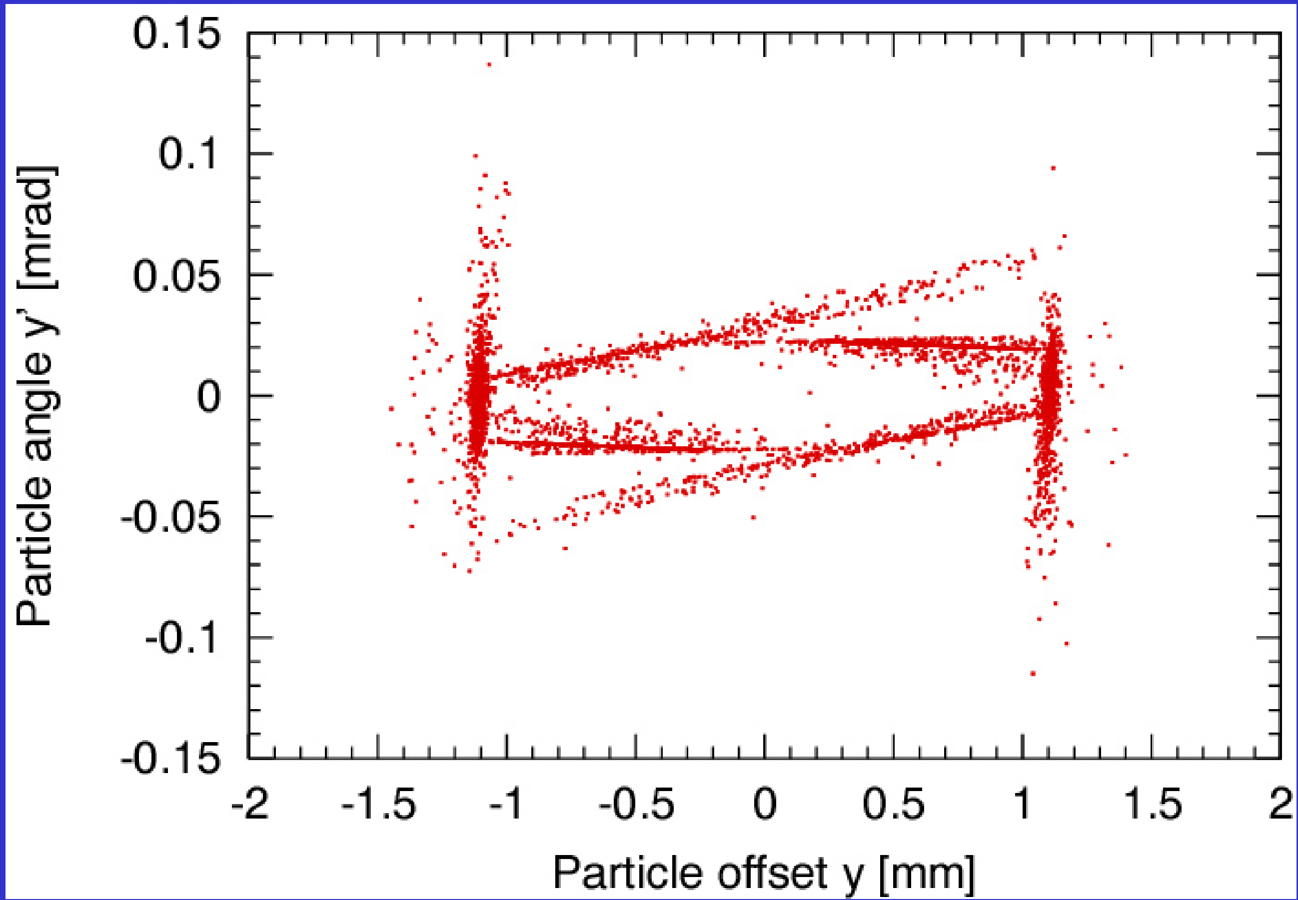
Halo at max dispersion

Local inefficiency [1/m]:

Integrate halos above 10σ

Divide by dilution length (50 m)

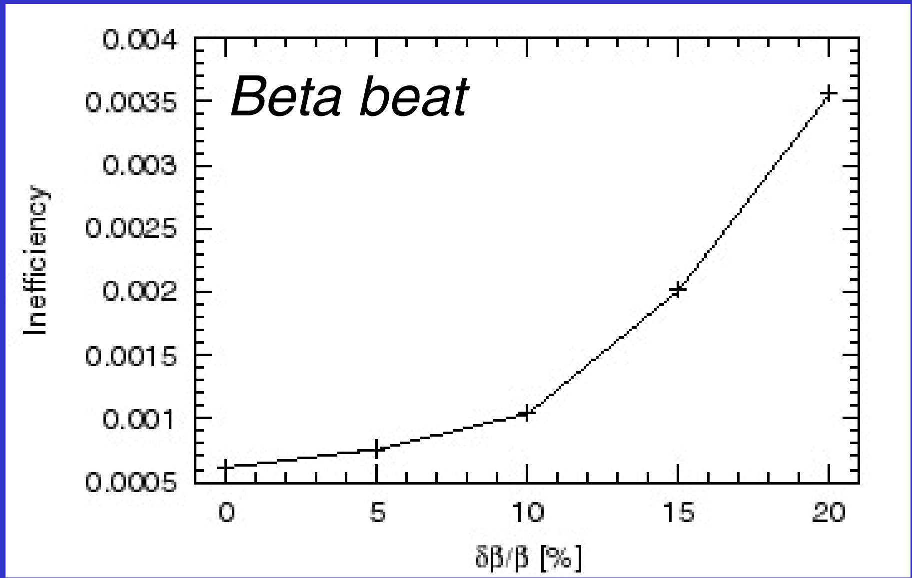
Tertiary halo in phase space

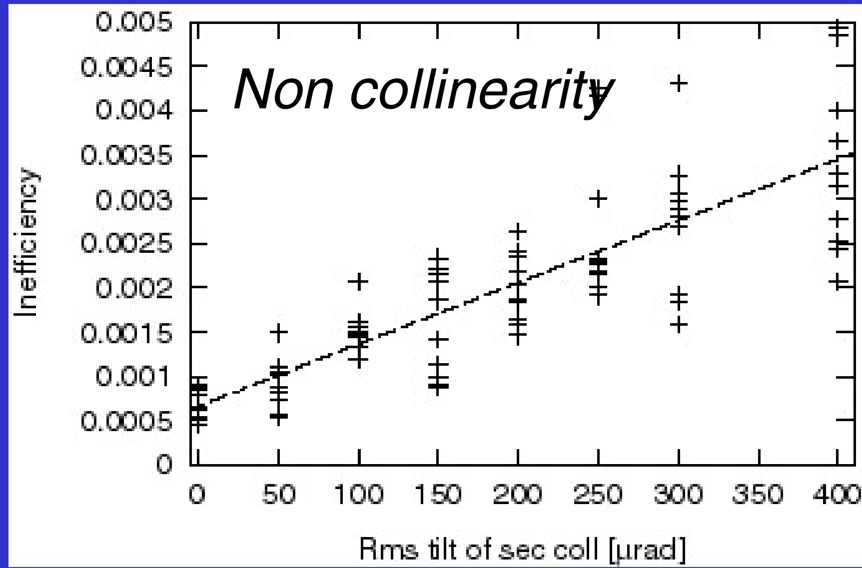


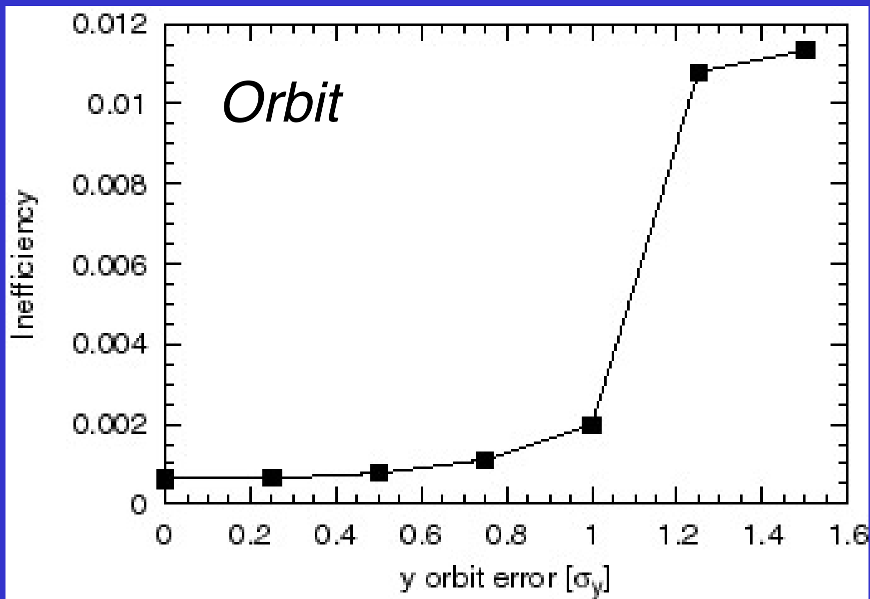
Halo generated at specific phase space locations!

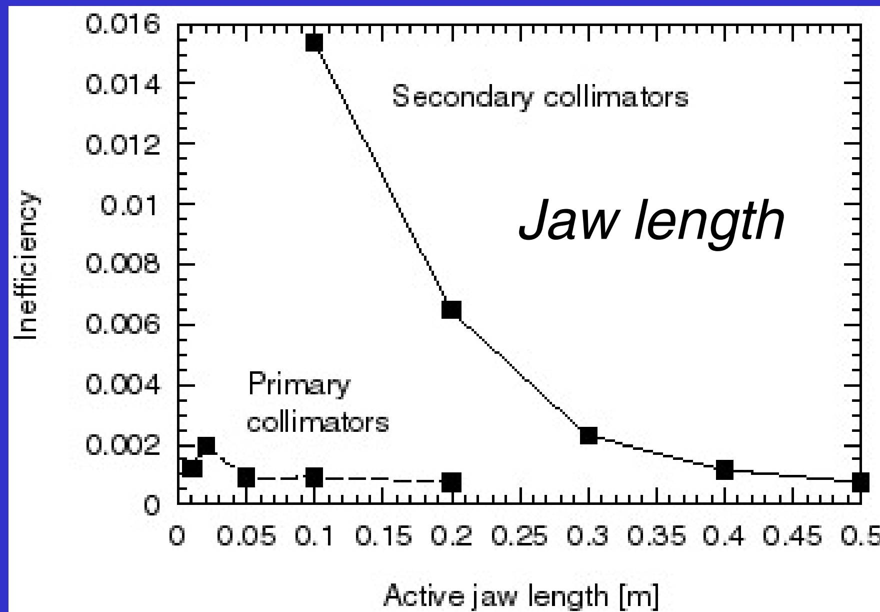
Input to studies of **local loss distribution** (dilution, expected signals of Beam Loss Monitors BLM).

Inefficiency versus imperfections

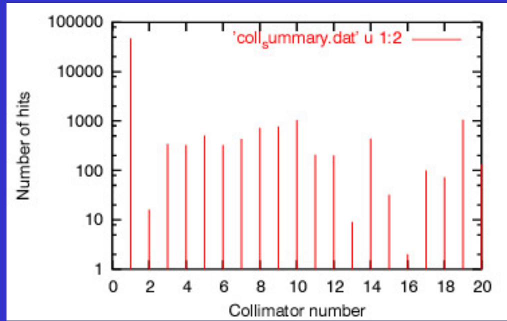


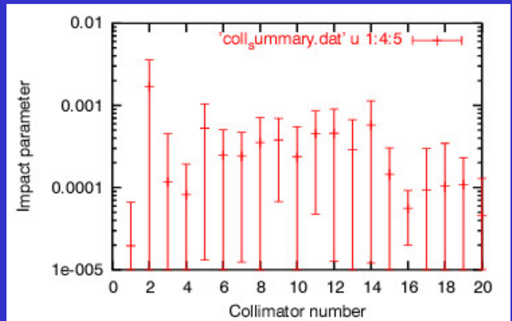


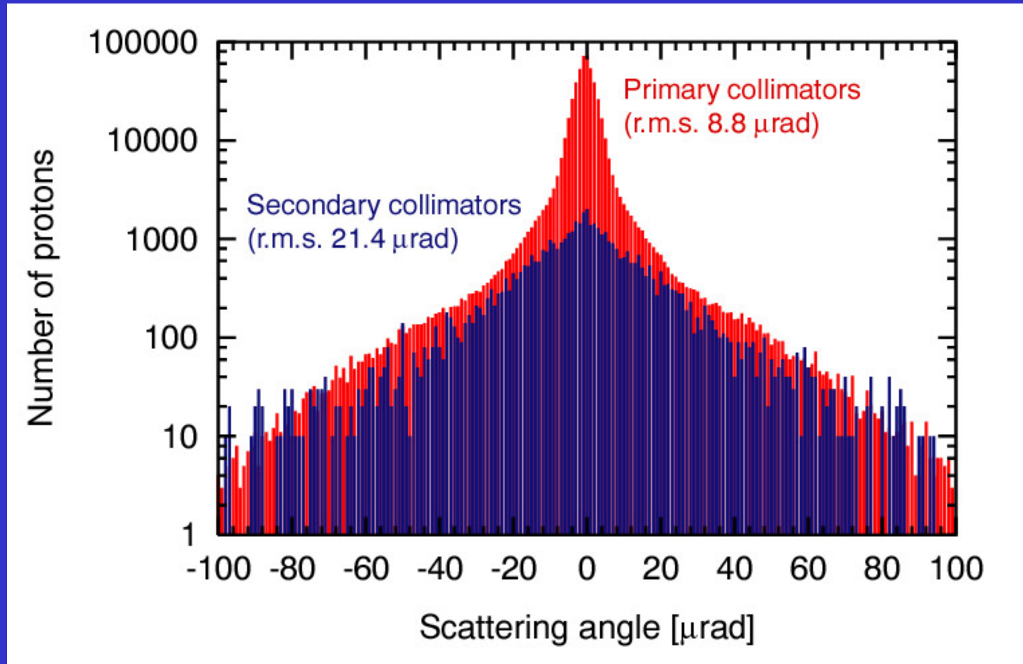


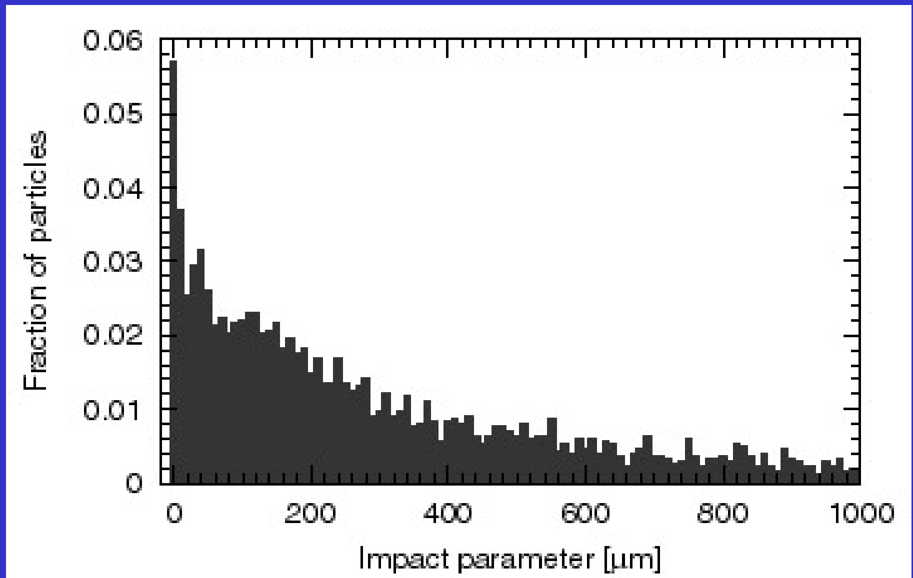


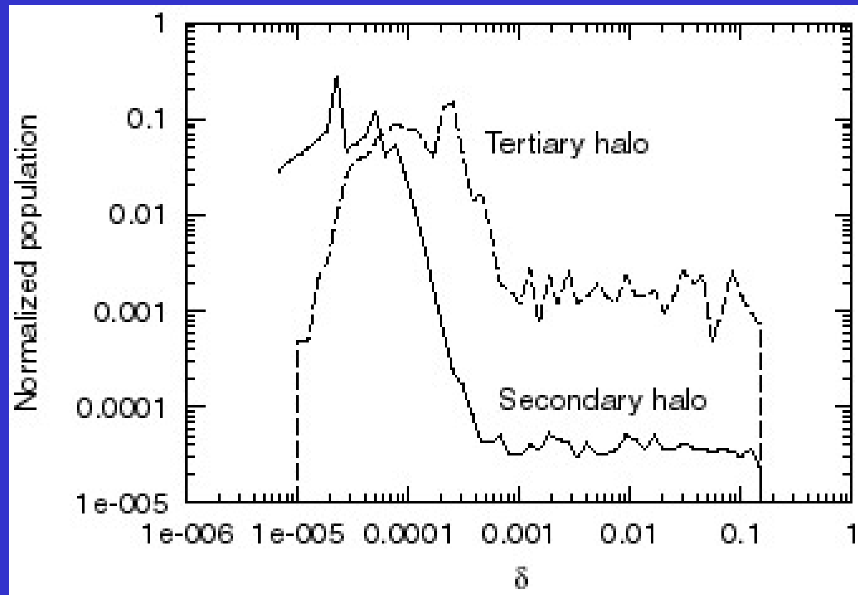
Scattering physics



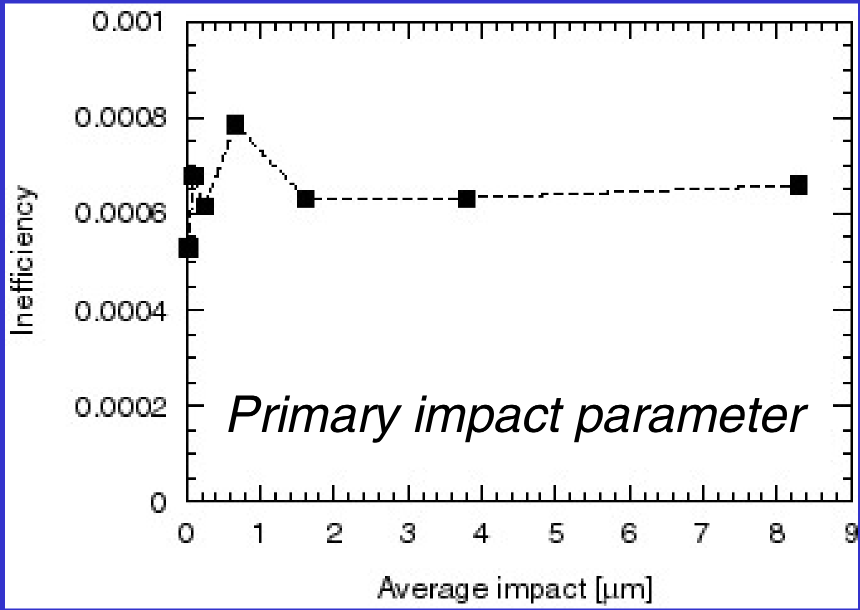


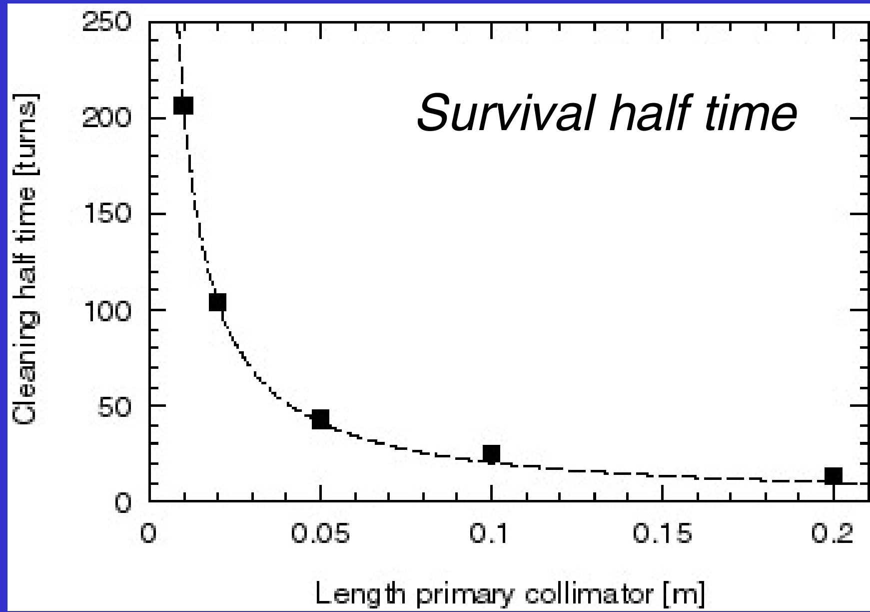


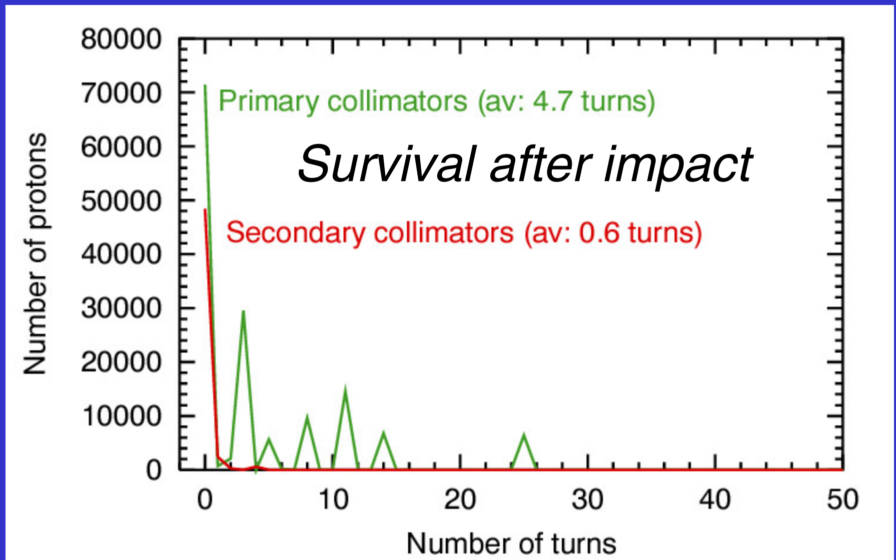


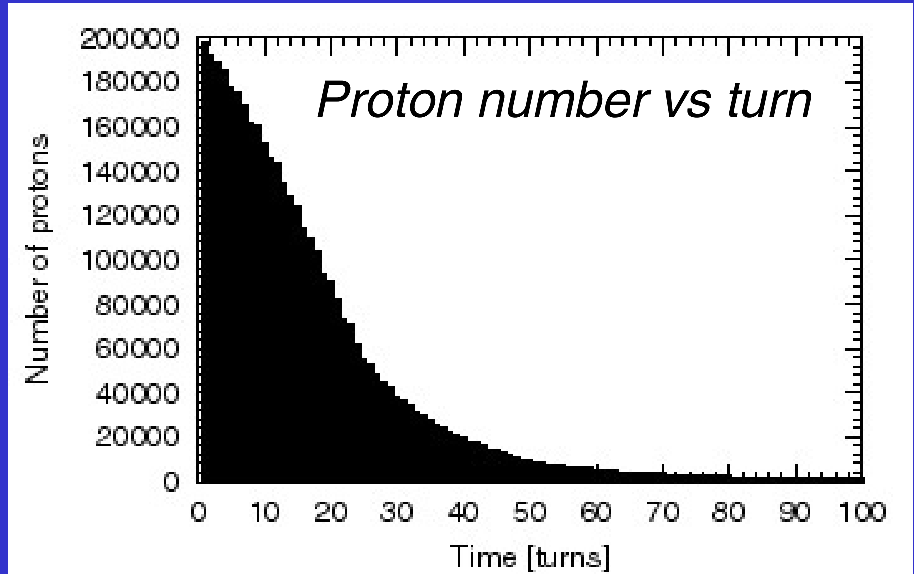


Multi-turn properties and impact parameter









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

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!

Super-Conducting Environment

Proton losses into cold aperture

⇩

Local heat deposition

⇩

Magnet can quench

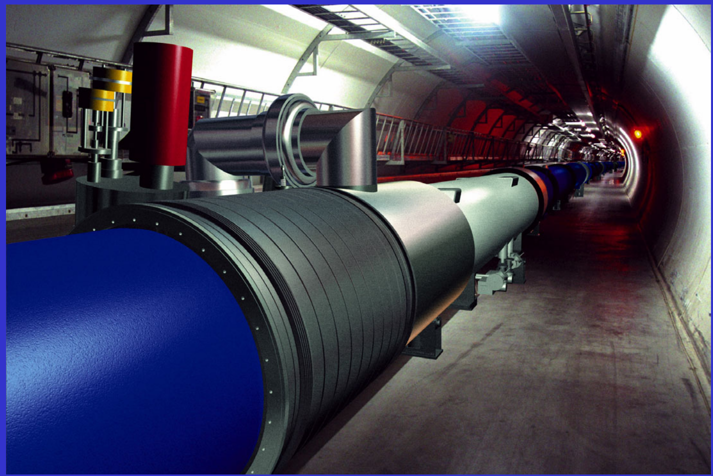


Illustration of LHC dipole in tunnel

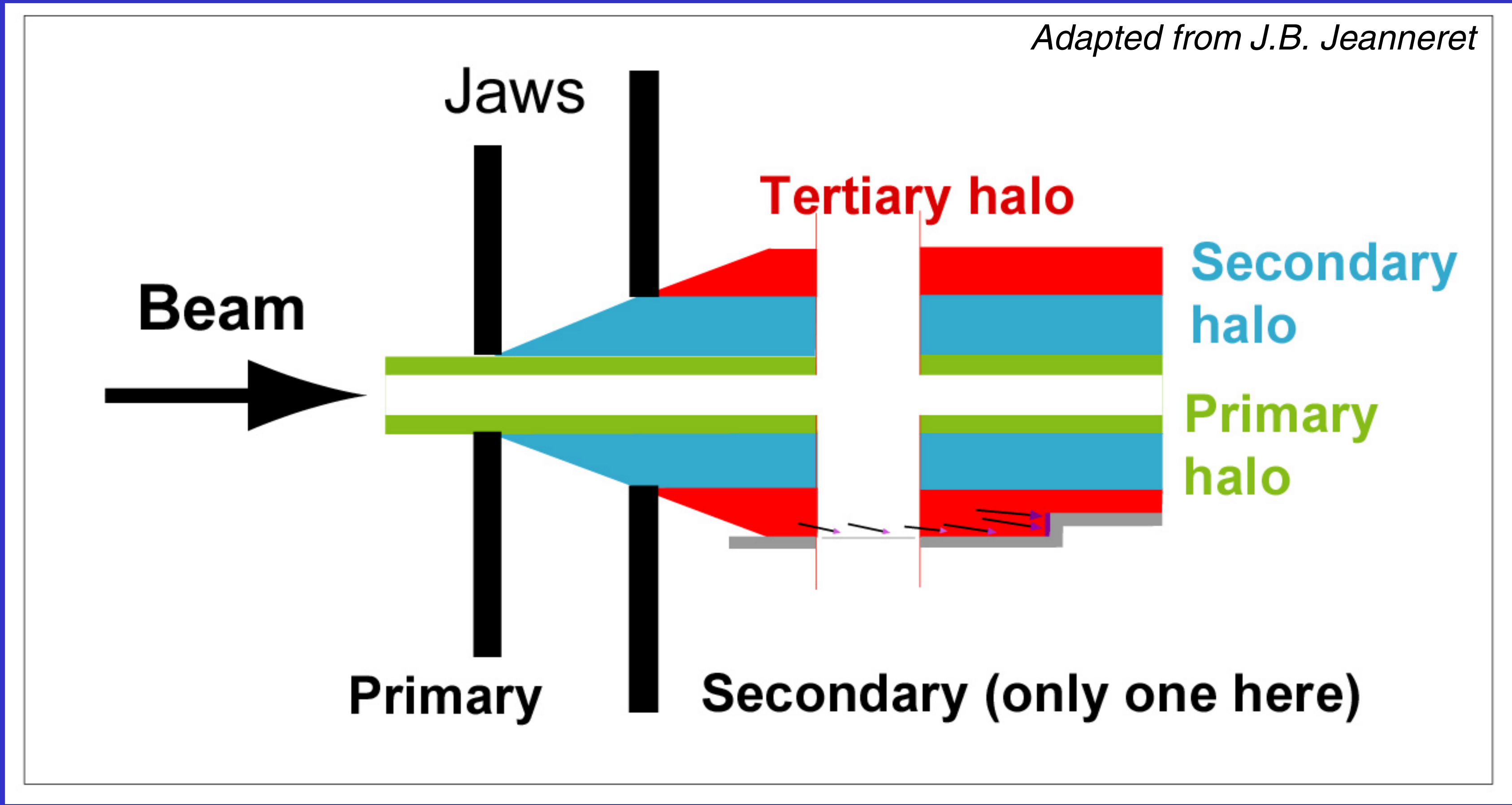
Energy [GeV]	Loss rate (10 h lifetime)	Quench limit [p/s/m] (**steady losses**)	Cleaning requirement
450	8.4e9 p/s	7.0e8 p/s/m	92.6 %
7000	**8.4e9 p/s**	**7.6e6 p/s/m**	**99.91 %**

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)*

Two stage collimation system



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