Scenarios and Technological Challenges for a LHC Luminosity Upgrade: Main Accelerator Science Challenges

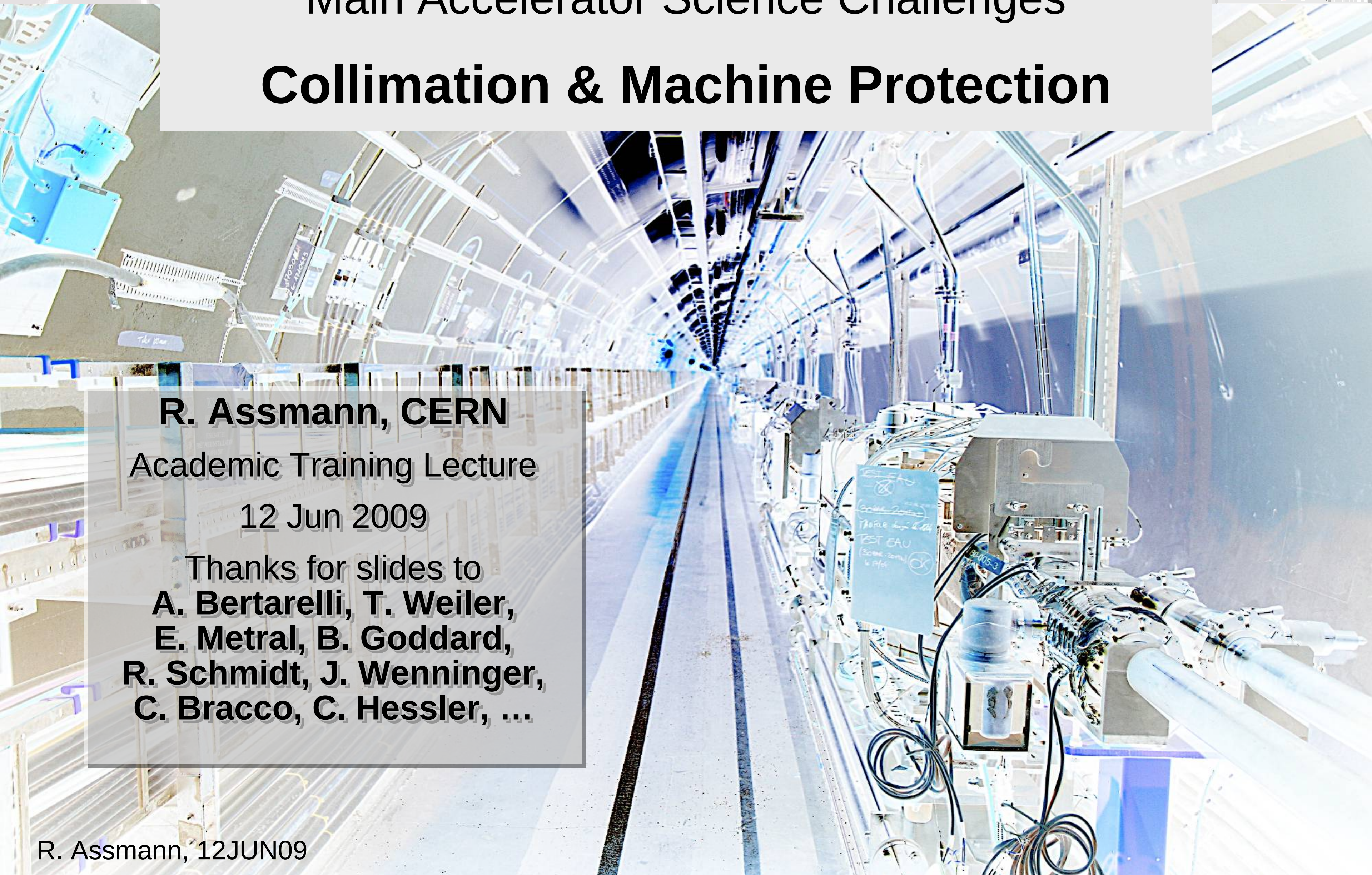
Collimation & Machine Protection

R. Assmann, CERN

Academic Training Lecture

12 Jun 2009

Thanks for slides to
A. Bertarelli, T. Weiler, E. Metral, B. Goddard, R. Schmidt, J. Wenninger, C. Bracco, C. Hessler, ...



Beam Energy and Stored Energy

- Let's assume we store N_b bunches (e.g. 2808, fitting the buckets of the accelerating RF voltage) which each contain N_p protons (e.g. 1.15 × 10^{11}). In total we have then $N_p \times N_b$ protons stored.
- Each proton is accelerated to the beam energy E_b (e.g. 7 TeV).
- The **proton beam then stores the following energy**:

$$E_{stored} = N_p \cdot N_b \cdot \frac{E_b}{(\mathrm{GeV})} \cdot 1.6022 \times 10^{-10}\,\mathrm{J}$$

- **For nominal LHC parameters this gives 362 MJ, the same energy as contained in 80 kg of TNT explosive.**

Why has LHC VERY High Stored Energy?
It is the Luminosity…

- Luminosity can be expressed as a **function of transverse energy** E_{stored} that is stored in each beam (*for round beams at IP*):

$$L = \frac{1}{4\pi \cdot m_0 c^2} \cdot \frac{f_{rev} \cdot N_p \cdot F}{\beta^* \cdot \varepsilon_n} \cdot E_{stored}$$

constant → $\frac{1}{4\pi \cdot m_0 c^2}$

tunnel length → f_{rev}

beam-beam limits → $N_p \cdot F$

IR optics limits → β^*

Injectors limits
Robustness limits → ε_n

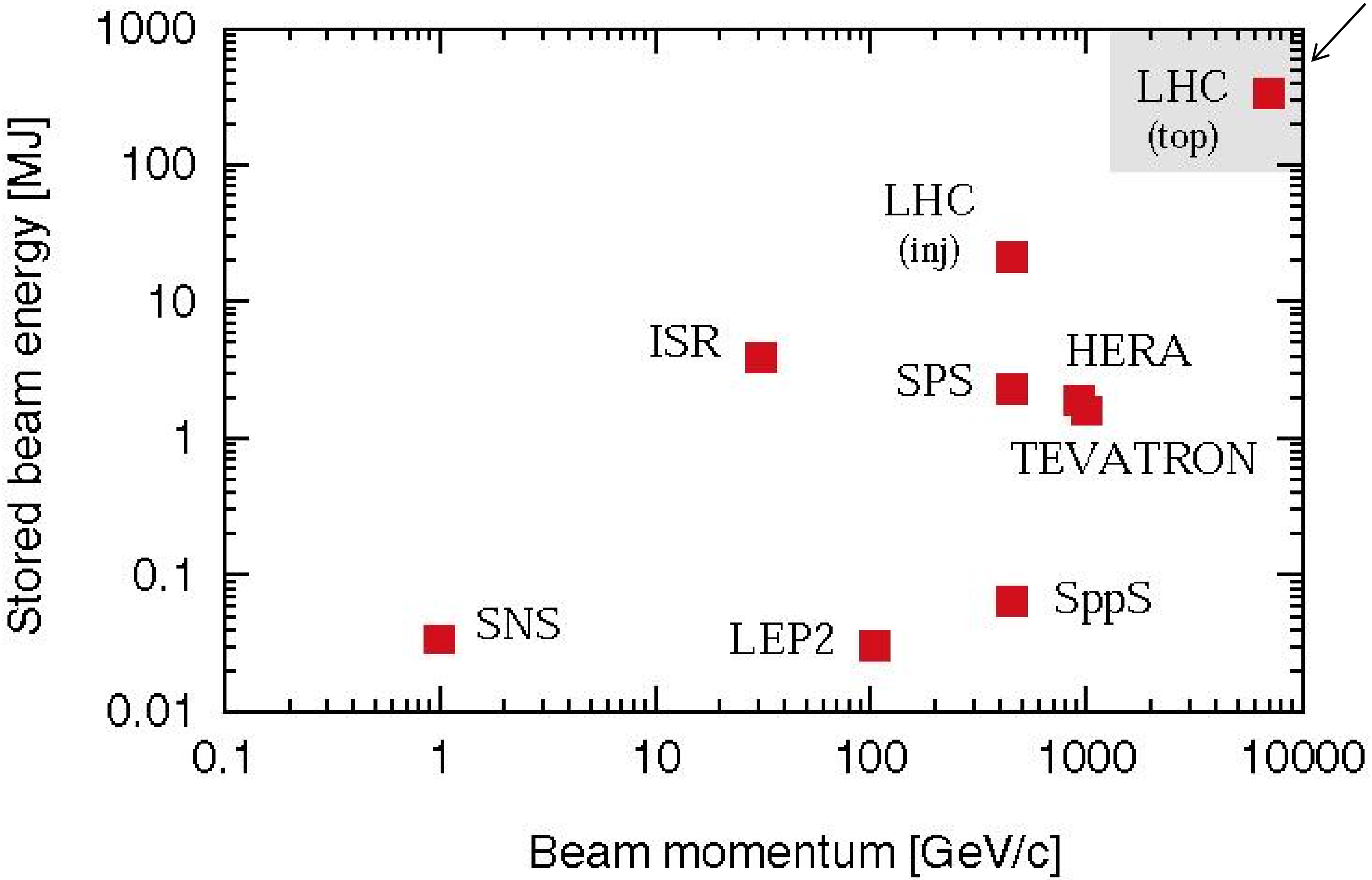
LHC luminosity is increased via stored energy! → E_{stored}

β^* = *IP beta function* (β_x=β_y)
ε_n = *norm. transv. emittance*
N_p = *protons per bunch*
f_{rev} = *revolution frequency*
F = *geometrical correction*
m_0 = *rest mass, e.g. of proton*
c = *velocity of light*

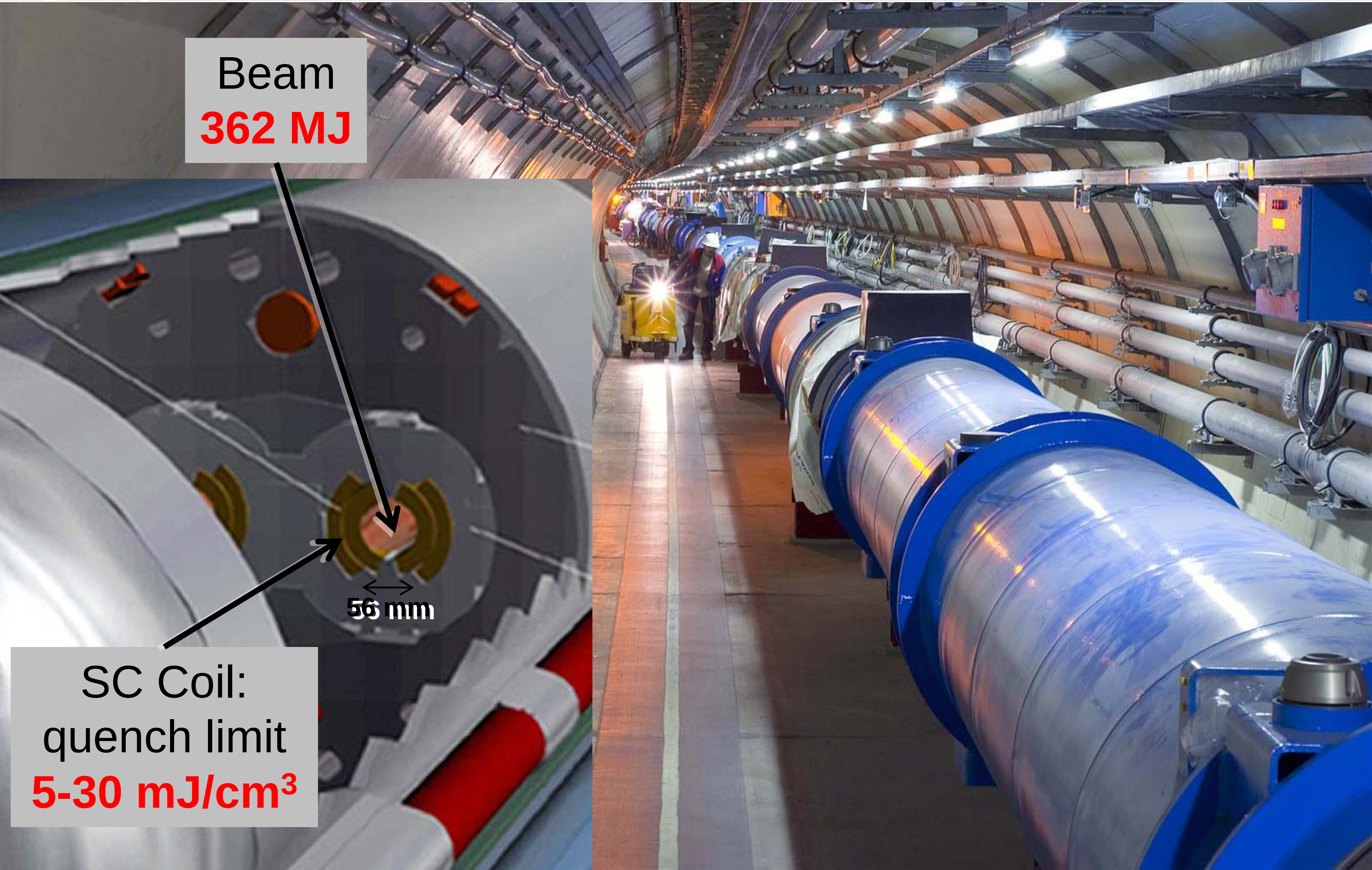
- What limits stored energy? No hard limit!
- **LHC was pushed to very high stored energy!**

Nominal LHC Stored Energy is Factor 200 Above World Record in SC Colliders

80 kg TNT



Quench Limit of LHC Super-Conducting Magnets



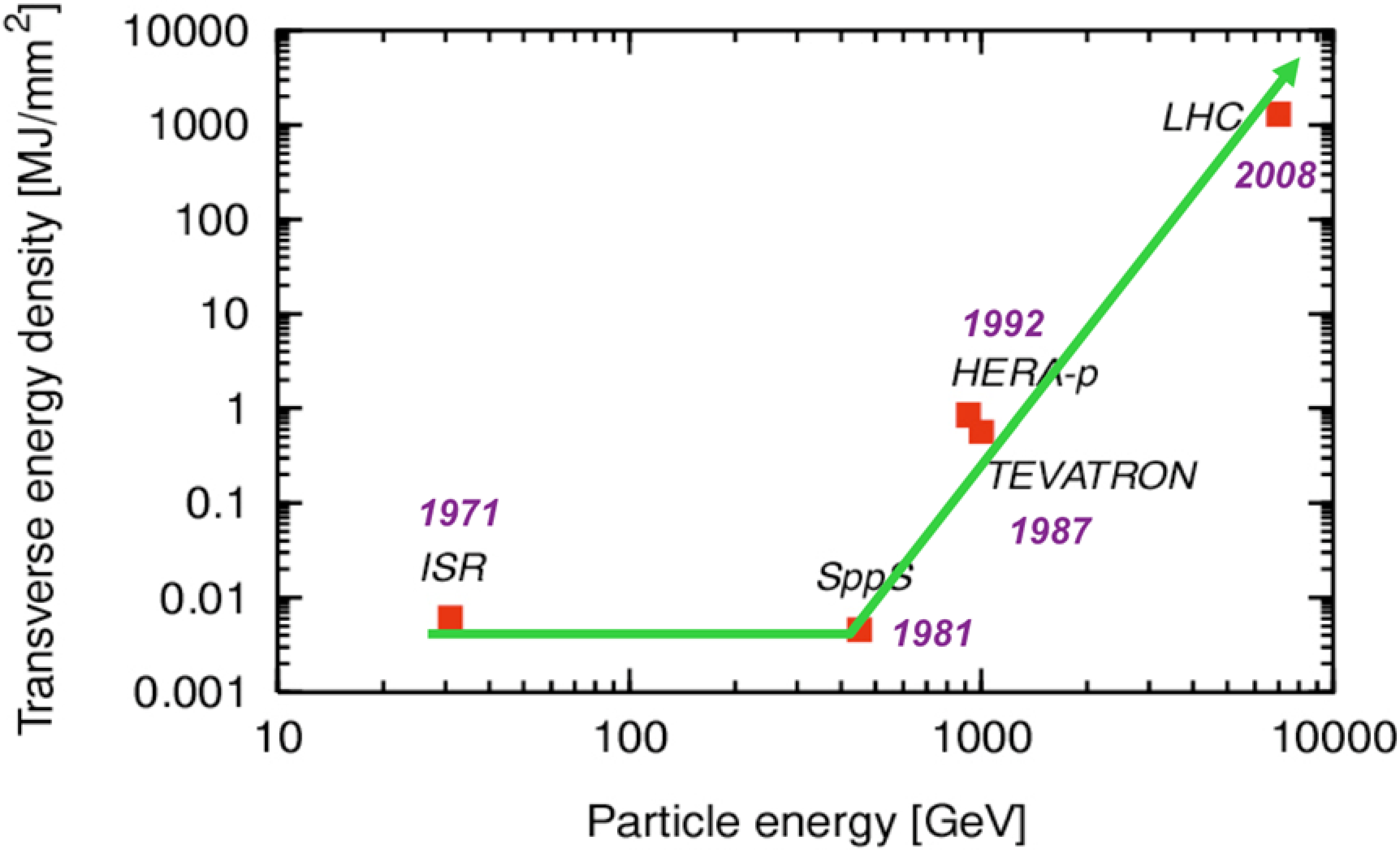
Stored Energy Density

- If a beam impacts on material, what matters is the stored energy density.
- With the horizontal and vertical beam sizes σ_x and σ_y we get **the stored energy density:**

$$\rho_E = \frac{E_{stored}}{\pi \cdot \sigma_x \cdot \sigma_y}$$

- Material damage is avoided if either the stored energy is low or diluted over a large area (big beam size).
- LHC beam sizes are very small. Typical values at 7 TeV: **~ 200 μm**
- **As a consequence the LHC beam can be extremely destructive if material is hit.**

Evolution Transverse Energy Density

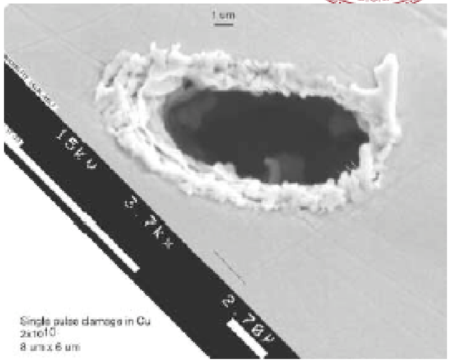


Examples of Beam-Induced Damage

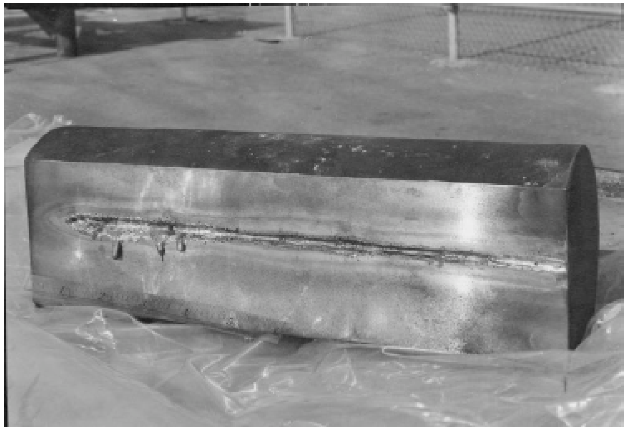
LARP

Exact Nature & Extent of Damaged Region still not really known well. We need beam tests with prototype.

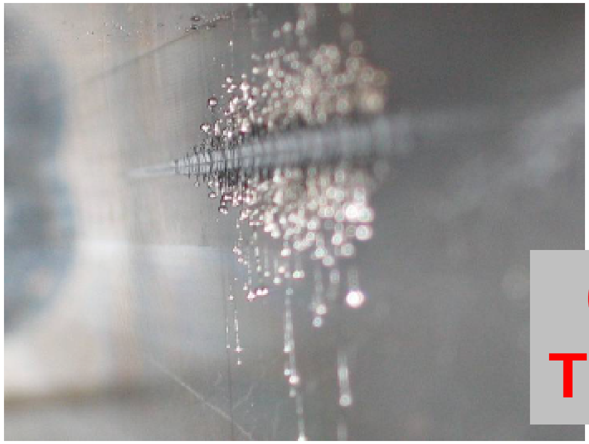
Thin Cu sample in FFTB electron beam at SLAC
Hole = Beam Size



2000um 500 kW 20 GeV e- beam hitting a 30cm Cu block a few mm from edge for 1.3 sec (0.65 MJ)



FNAL Collimator with .5 MJ



0.5 MJ Tevatron

Summary LHC Challenge

	Energy density ρ_E at collimators	Stored energy E_{stored}
State-of-the art (Tevatron, HERA)	1 MJ/mm^2	2 MJ
Nominal LHC	1 GJ/mm^2	360 MJ
LHC upgrade scenarios	**2 GJ/mm^2**	**800 MJ**
Limit (avoid copper damage/quench)	**50 kJ/mm^2**	**5-30 mJ/cm^3**

Perfect and Real World

- No problem in **the perfect world**: Beam is stored and no losses or only losses of very few protons appear (except some local losses at special locations).
- However, **reality is different**:
  - **Failures** (trips of power supplies, power cut, short circuits, …) lead to beam perturbations and loss of the full beam ➔ **machine protection for early interception of problems and safe beam dump before damage occurs.**
  - **Formation of beam halo and loss of small fractions of beam** from many different effects (beam resonances, shaking of magnets with distant earth quakes, dynamic aperture, chaotic islands, beam-beam effects, residual beam-gas scattering, fall of dust particle through the beam, …) ➔ **cleaning/collimation for safe interception and absorption of beam losses without magnet quenches**.

Part 1: Machine Protection

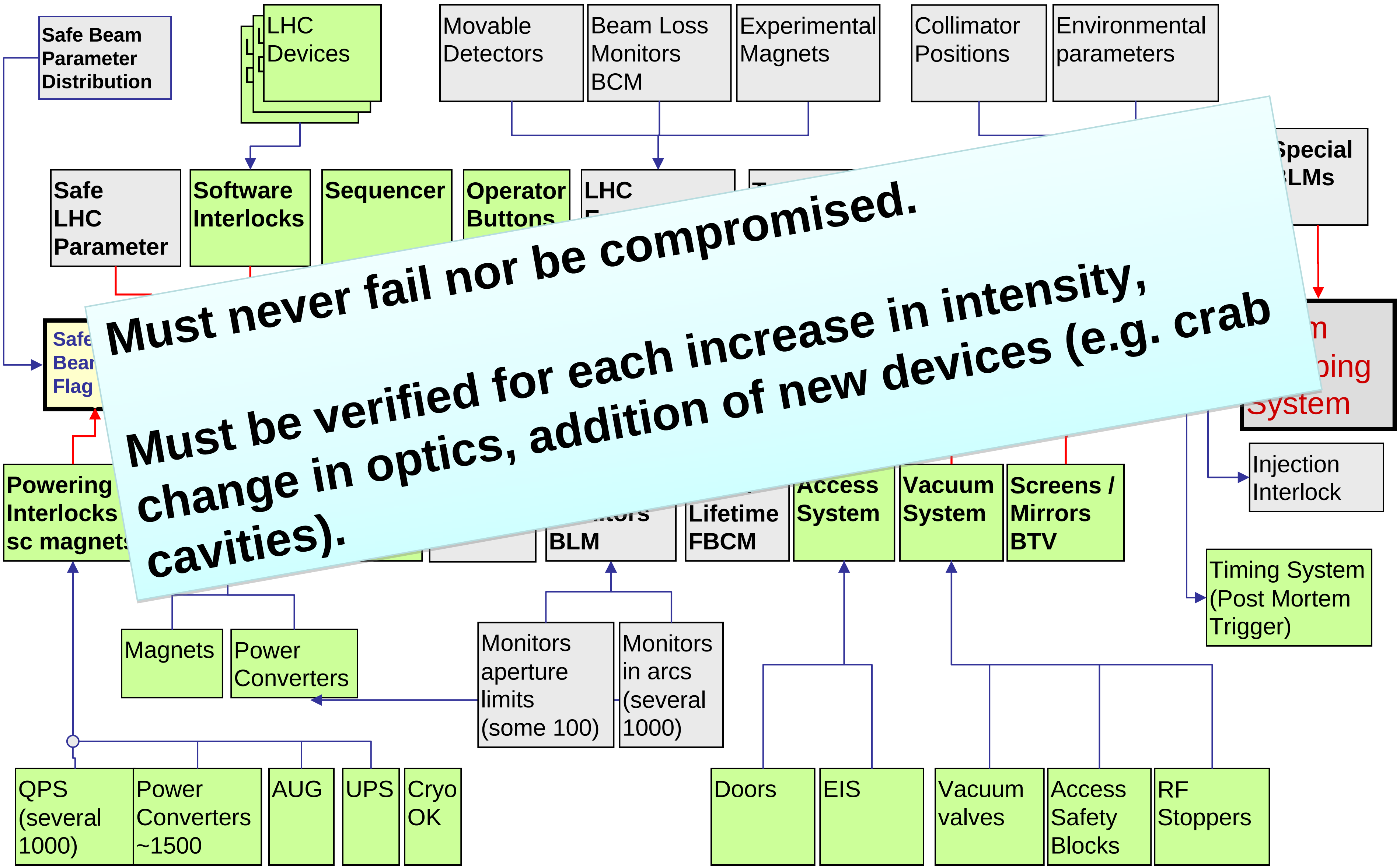
- LHC **machine protection relies on multiple sub-systems** for fulfilling its duty.
- Consequences are severe if it fails: System designed to rely on **multiple, redundant channels**.
- The systems are **OK for up to ultimate intensity**, except collimation.
- LHC machine protection **must be reviewed and re-qualified for upgrades beyond the LHC baseline design** with ultimate intensity:
  - New machine elements, e.g. new D1 in phase 1 triplet upgrade or crab cavities.
  - New optics.
  - Intensity above ultimate intensity. Requires hardware changes.
- Several places involved: **LHC Machine Committee, Machine Protection Panel, Beam Dump & Injection WG, Collimation WG**

LHC: Strategy for machine protection

• Definition of aperture by collimators.	**Beam Cleaning System**
• Early detection of failures for equipment acting on beams generates dump request, possibly before the beam is affected.	**Powering Interlocks** **Fast Magnet Current change Monitor**
• Active monitoring of the beams detects abnormal beam conditions and generates beam dump requests down to a single machine turn.	**Beam Loss Monitors** Other Beam Monitors
• Reliable transmission of beam dump requests to beam dumping system. Active signal required for operation, absence of signal is considered as beam dump request and injection inhibit.	**Beam Interlock System**
• Reliable operation of beam dumping system for dump requests or internal faults, safely extract the beams onto the external dump blocks.	**Beam Dumping System**
• Passive protection by beam absorbers and collimators for specific failure cases.	**Beam Absorbers**

Systems detecting failures and LHC Beam Interlocks

R. Schmidt, J. Wenninger

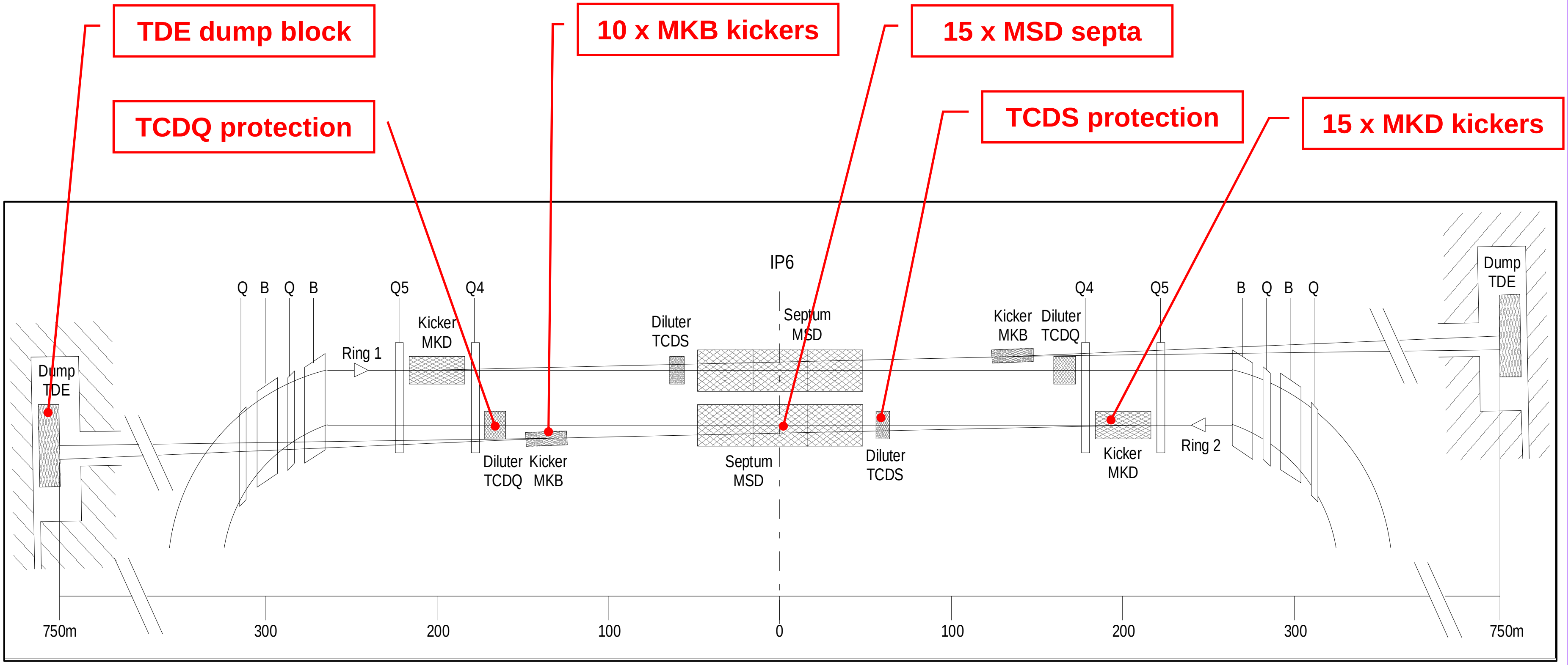


Must never fail nor be compromised.

Must be verified for each increase in intensity, change in optics, addition of new devices (e.g. crab cavities).

Beam dump design - schematic layout

Central MP System must ALWAYS work safely and survive the dumped beam – big challenge

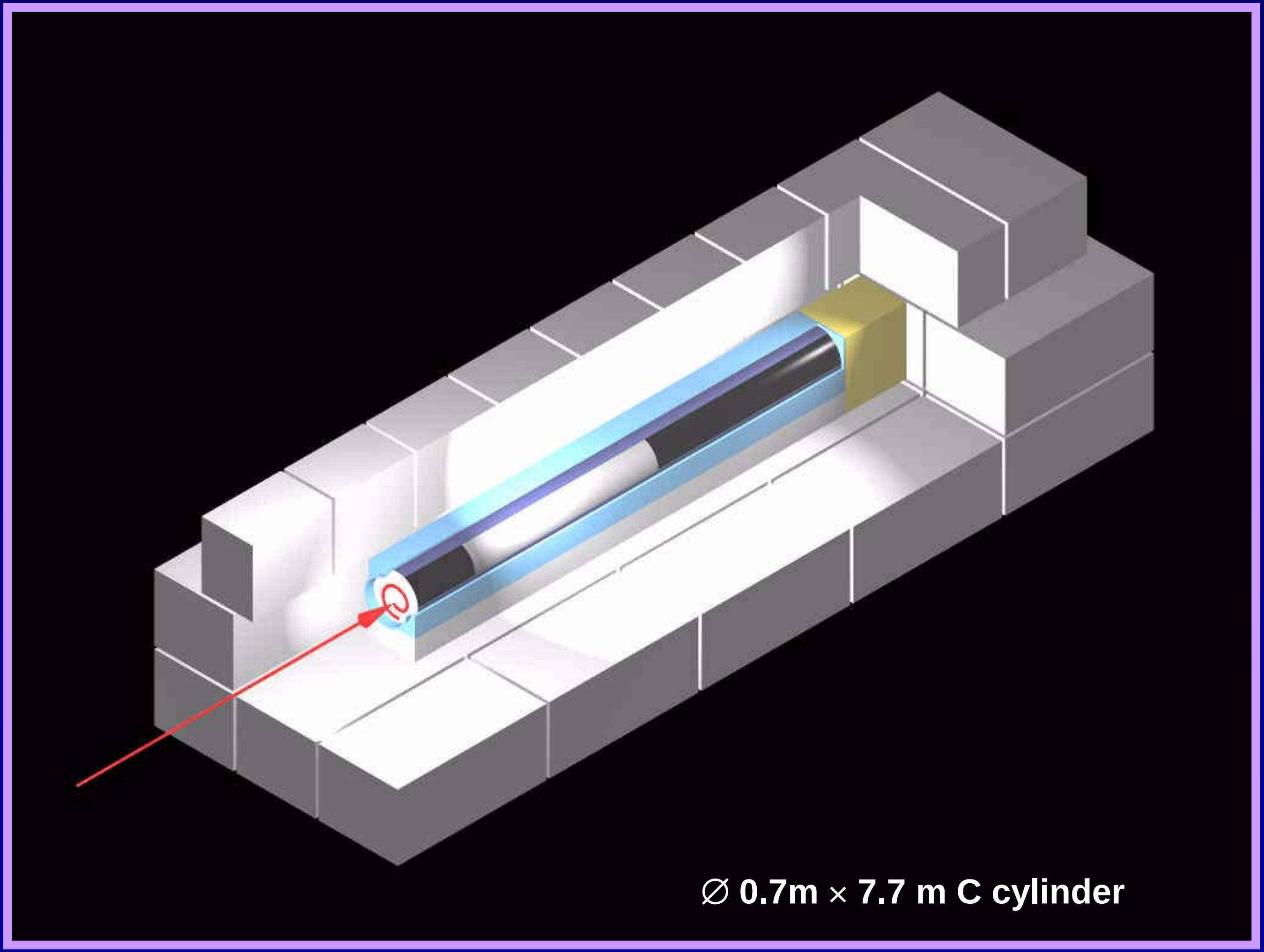


Total 'beamline' length :

975m from kicker MKD to dump TDE

B. Goddard

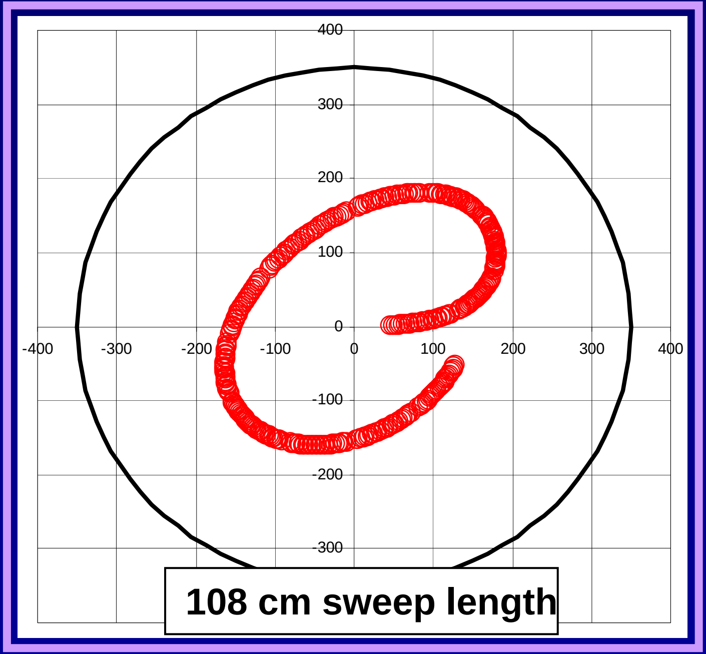
Present system – TDE absorber

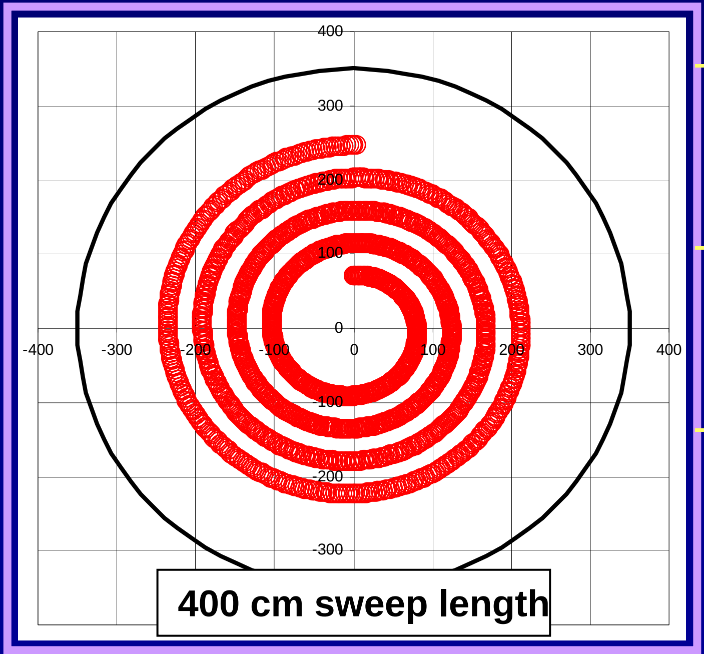


B. Goddard

Dilution with spiral sweep

- **Dilution kicker frequency increased – x4 sweep length**
  - **14 to 56 kHz… would require ~4 times more kicker length**





- Increase sweep length (higher $f_0 \Rightarrow$ more kickers)
- Upgrade dump block (longer, lower density C);
- Upgrade protection devices (longer, lower density C, more λ_r).

- **At 7 TeV would allow currents of ~4 A in distributed bunches**
- **At 14 TeV would allow ~1 A in distributed bunches**

B. Goddard

Part 2: Beam Cleaning / Collimation

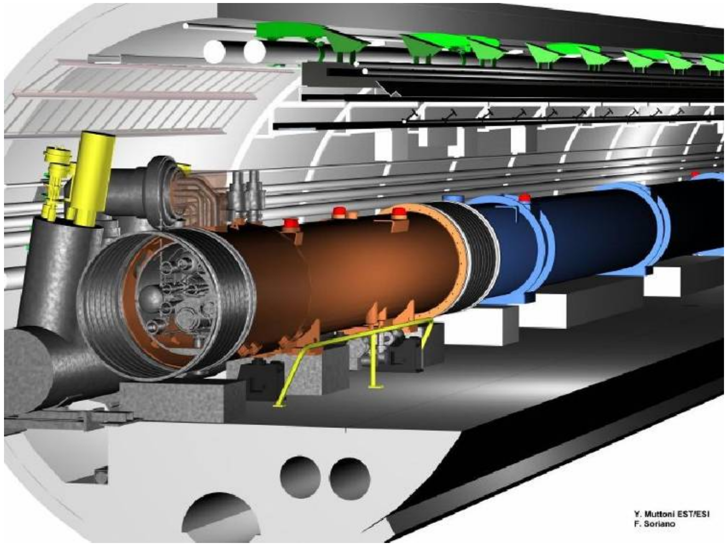
- Shock beam impact: **2 MJ/mm² in 200 ns (0.5 kg TNT)**

- Maximum **beam loss at 7 TeV**: 0.1% of beam (360 MJ) per second *(assumed 6-10 times better than Tevatron/HERA)*

360 kW → proportional to stored energy

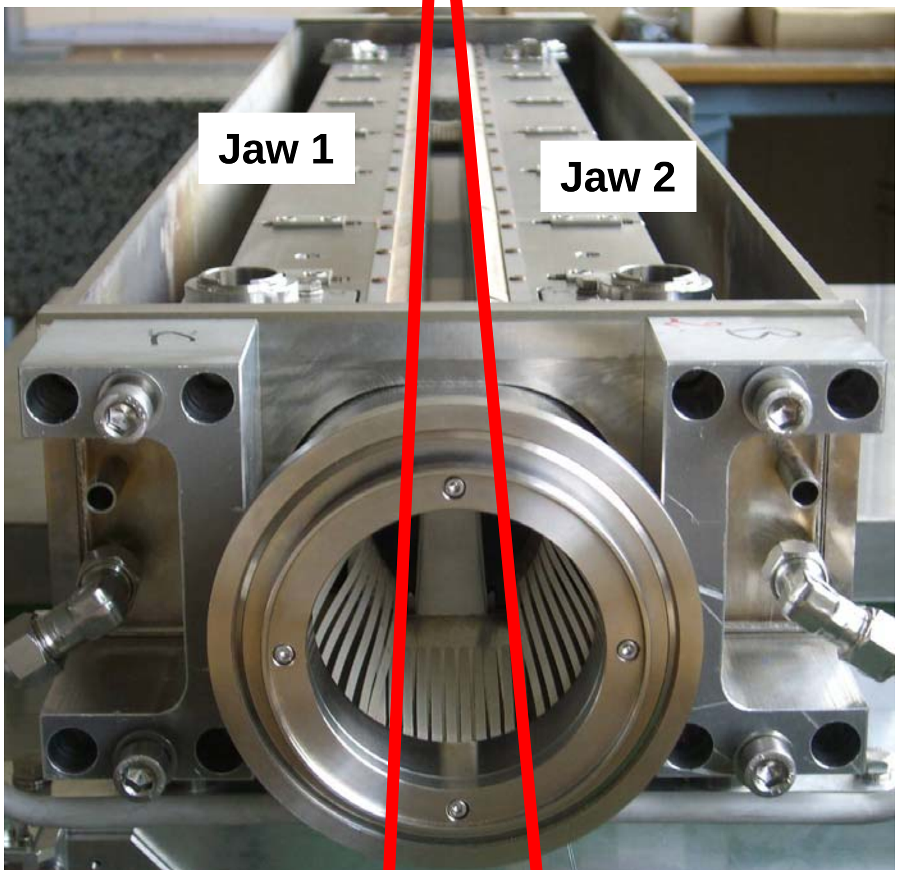
- **Quench limit** of SC LHC magnet:

~ 5 mW/cm³



LHC Collimators: Dilute and Stop

Quench limit: **~ 5 mJ/mm²** (any SC magnet)



Required "filter" factor:

1×10^{-10} = Leakage / Dilution

Leakage factor (inefficiency): **10^{-4}**

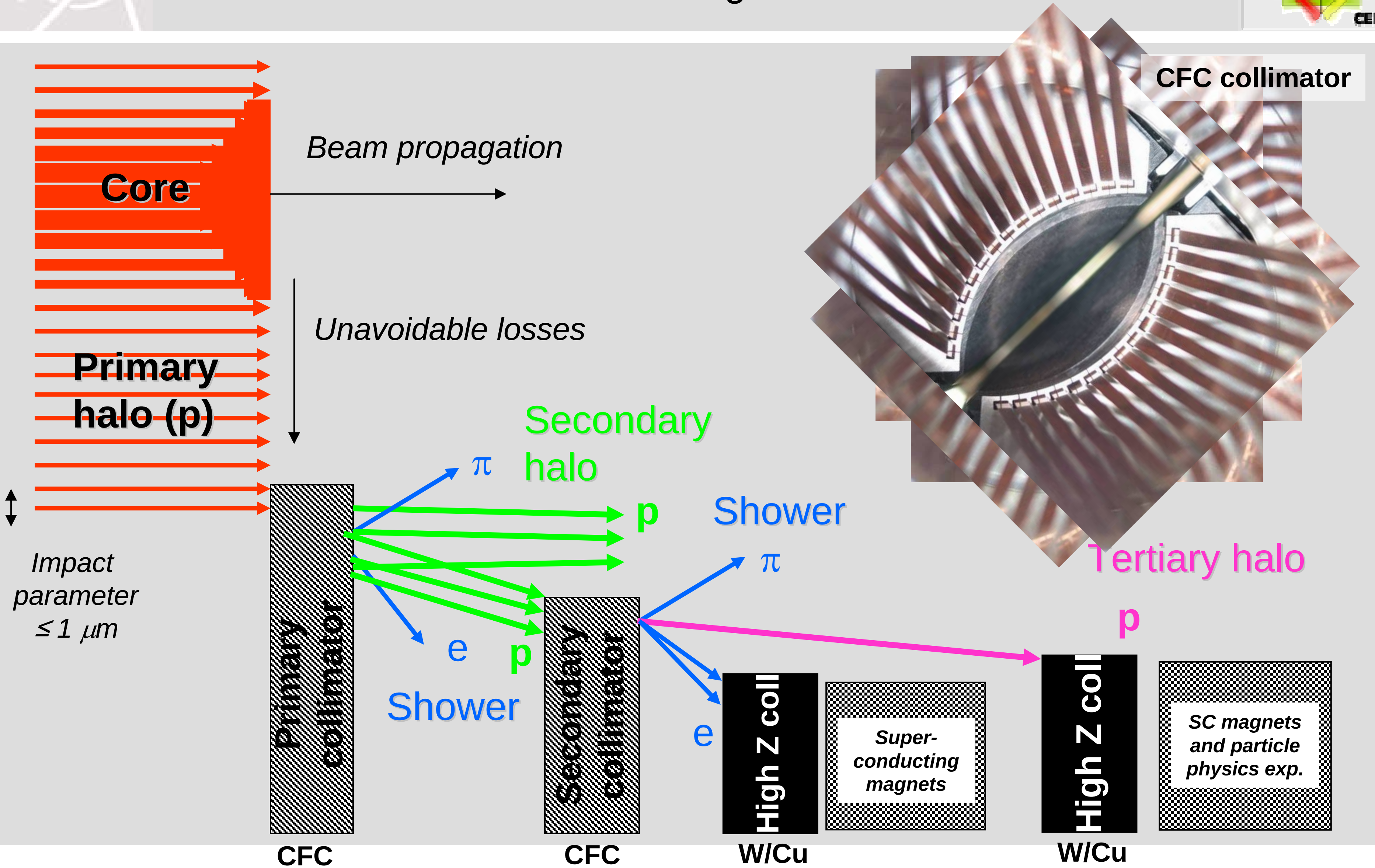
Dilution factor: **10^{6}**

Cannot be achieved with single collimator ➔ therefore multi-stage collimation for betatron cleaning (x, y, skew) and momentum cleaning.

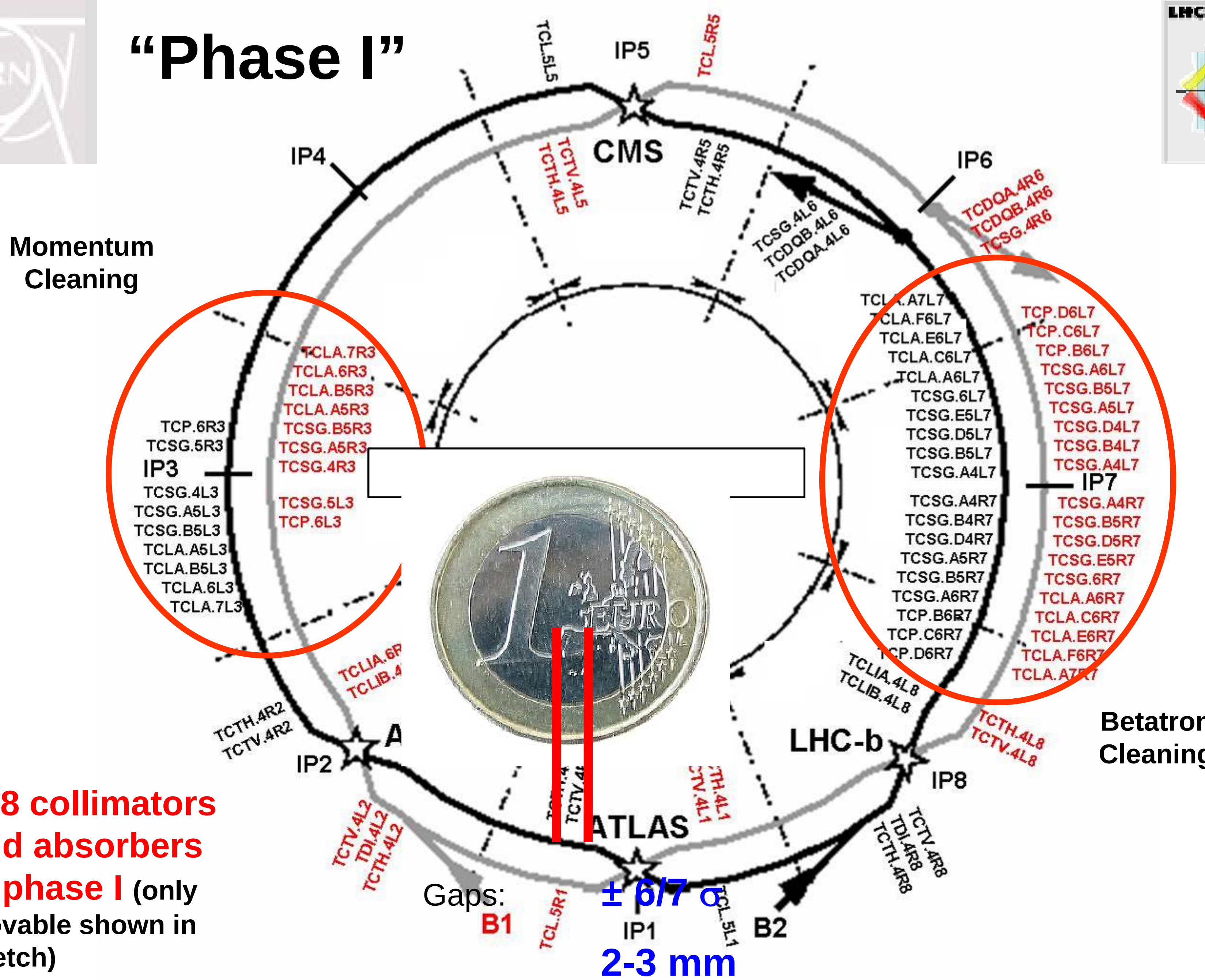
Incoming: up to **~ 50 MJ/mm²** (primary collimator)

Multi-Stage Cleaning & Protection

3-4 Stages



"Phase I"

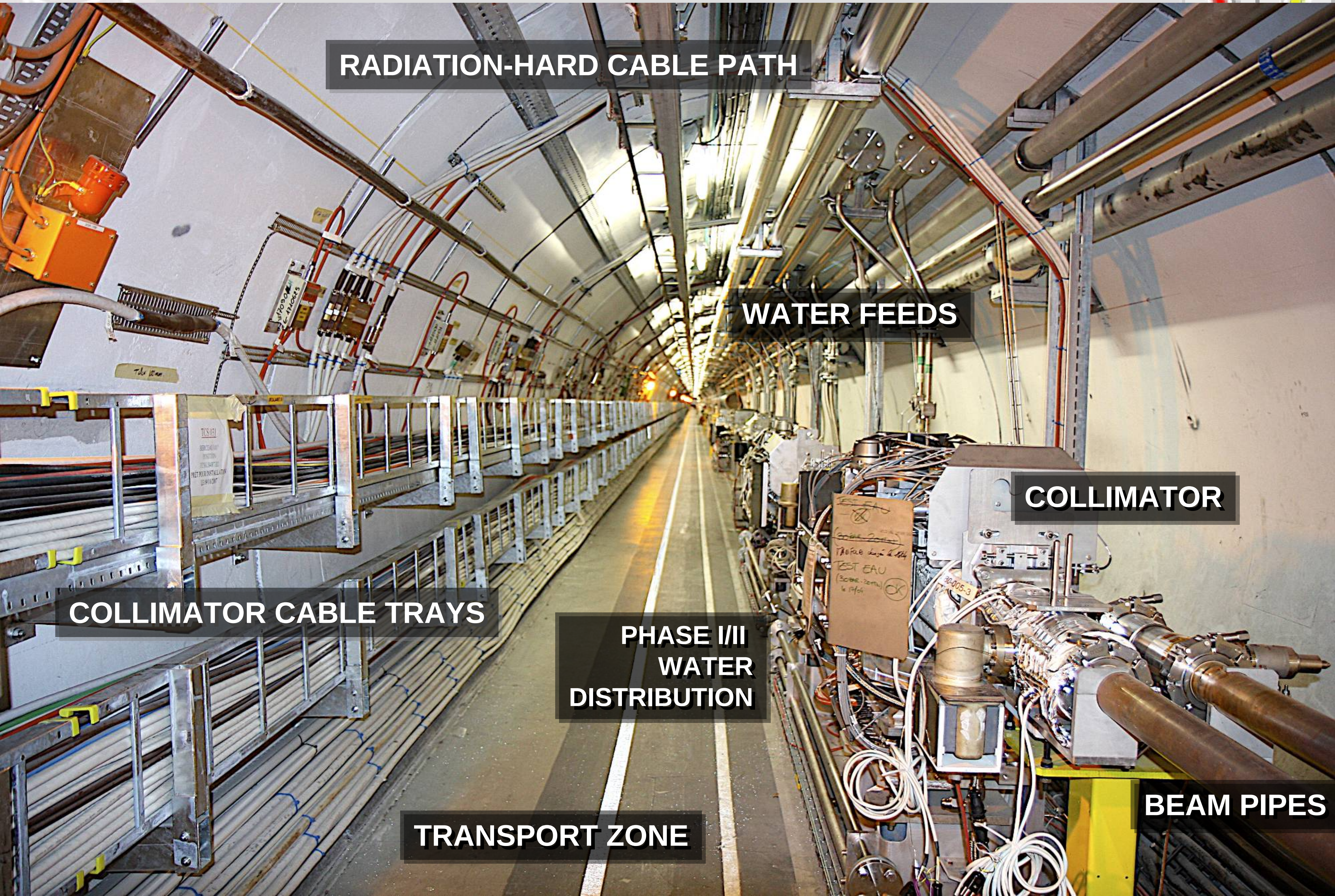


108 collimators and absorbers in phase I (only movable shown in sketch)

The LHC Collimation System

- The **by far largest and most precise system of its kind** that has been built to this date:
  - 130 phase I collimators and absorbers produced with specifications and control at 10 μm level (including spares).
  - **Phase I:** In total **108 devices** installed (~210 m length occupied). 97 movable collimators with a total of 194 jaws and > 450 degrees of freedom for positioning. **All ready for LHC startup.**
  - **Phase II:** In total **158 devices** installed (~ 310 m length occupied). 147 movable collimators. Majority approved and infrastructure installed.
  - **Maximum possible:** In total **168 devices** installed (~ 330 m length occupied). Only space reservations at this time.

Tunnel: Cleaning Insertion IR7



Cleaning/Collimation Limited Intensity Reach Model

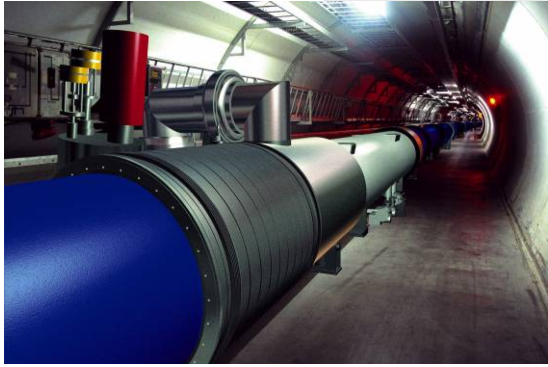


Illustration of LHC dipole in tunnel

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

- Allowed intensity → $N_p^{\max}$
- Quench threshold (7.6 ×10[6] p/m/s @ 7 TeV) → R_q
- Beam lifetime (e.g. 0.2 h minimum) → τ
- BLM threshold (e.g. 30%) → F_{BLM}
- Loss length → L_{dil}
- Cleaning inefficiency → η_c

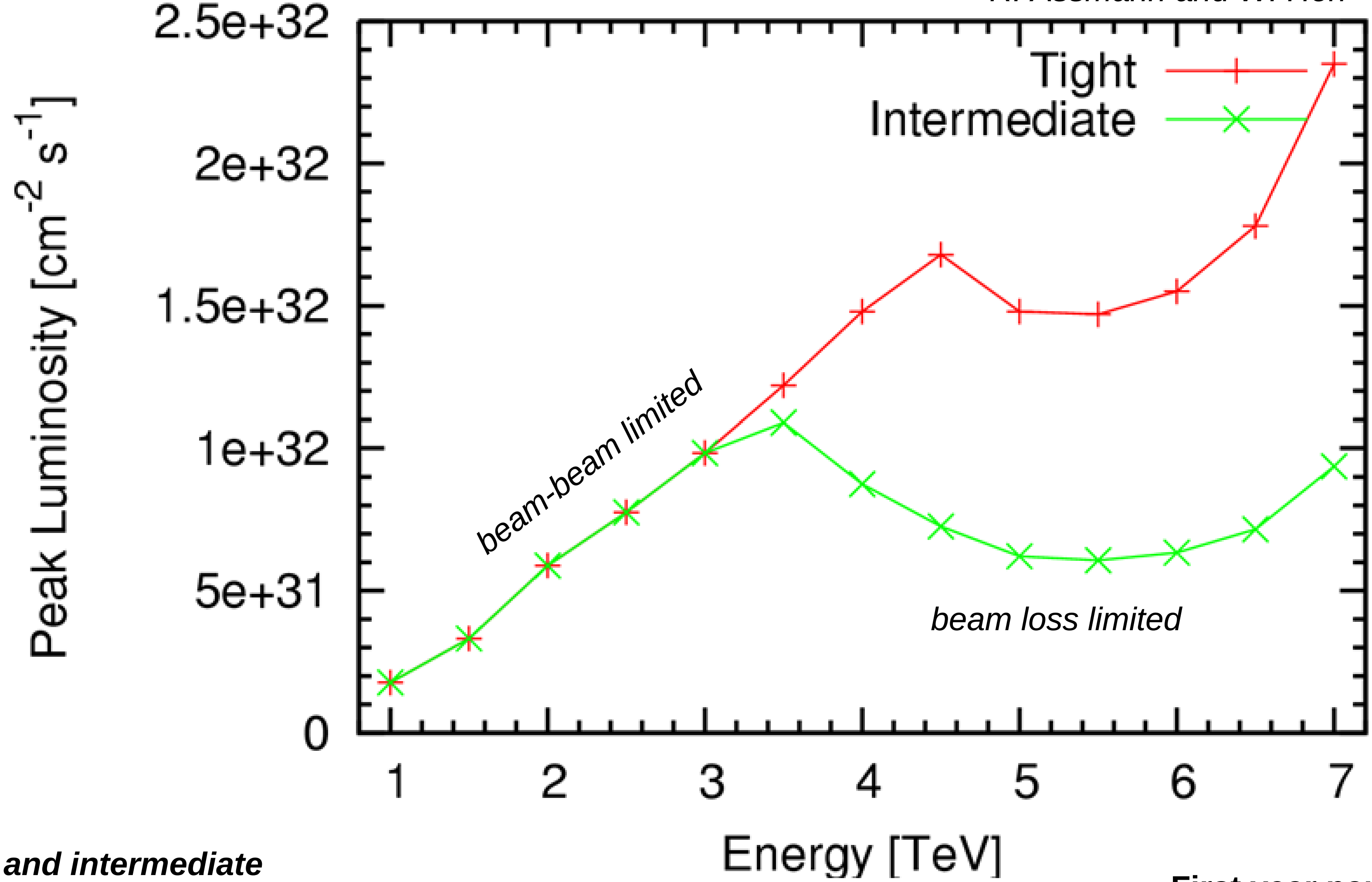
Cleaning inefficiency = $\dfrac{\text{Number of escaping p } (>10\sigma)}{\text{Number of impacting p } (6\sigma)}$

Collimation performance can limit the intensity and therefore LHC luminosity.

Simulations performed on the Grid (CPU limited)

Phase I Peak Instantaneous Luminosity

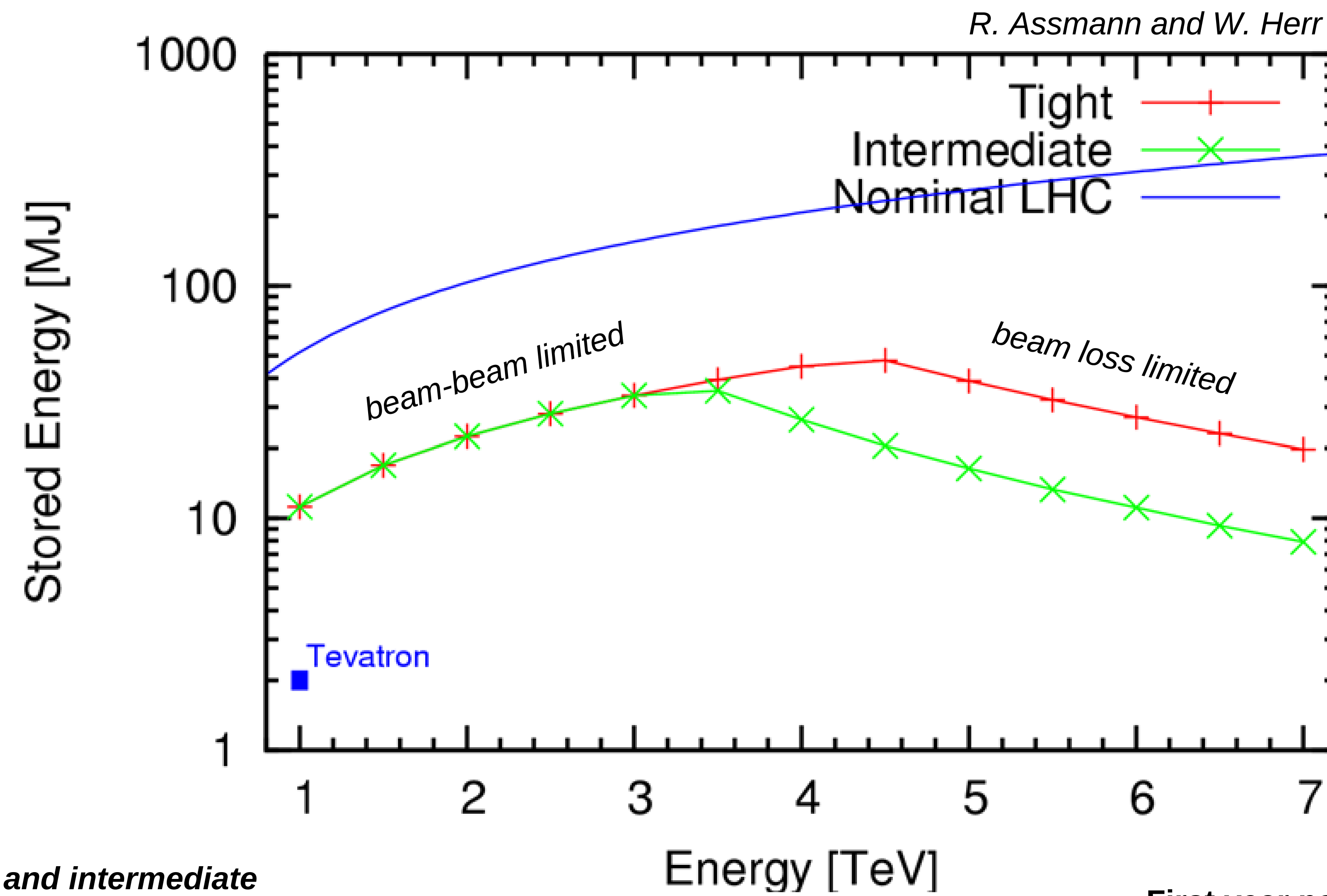
R. Assmann and W. Herr



Tight and intermediate collimation settings

First year parameters

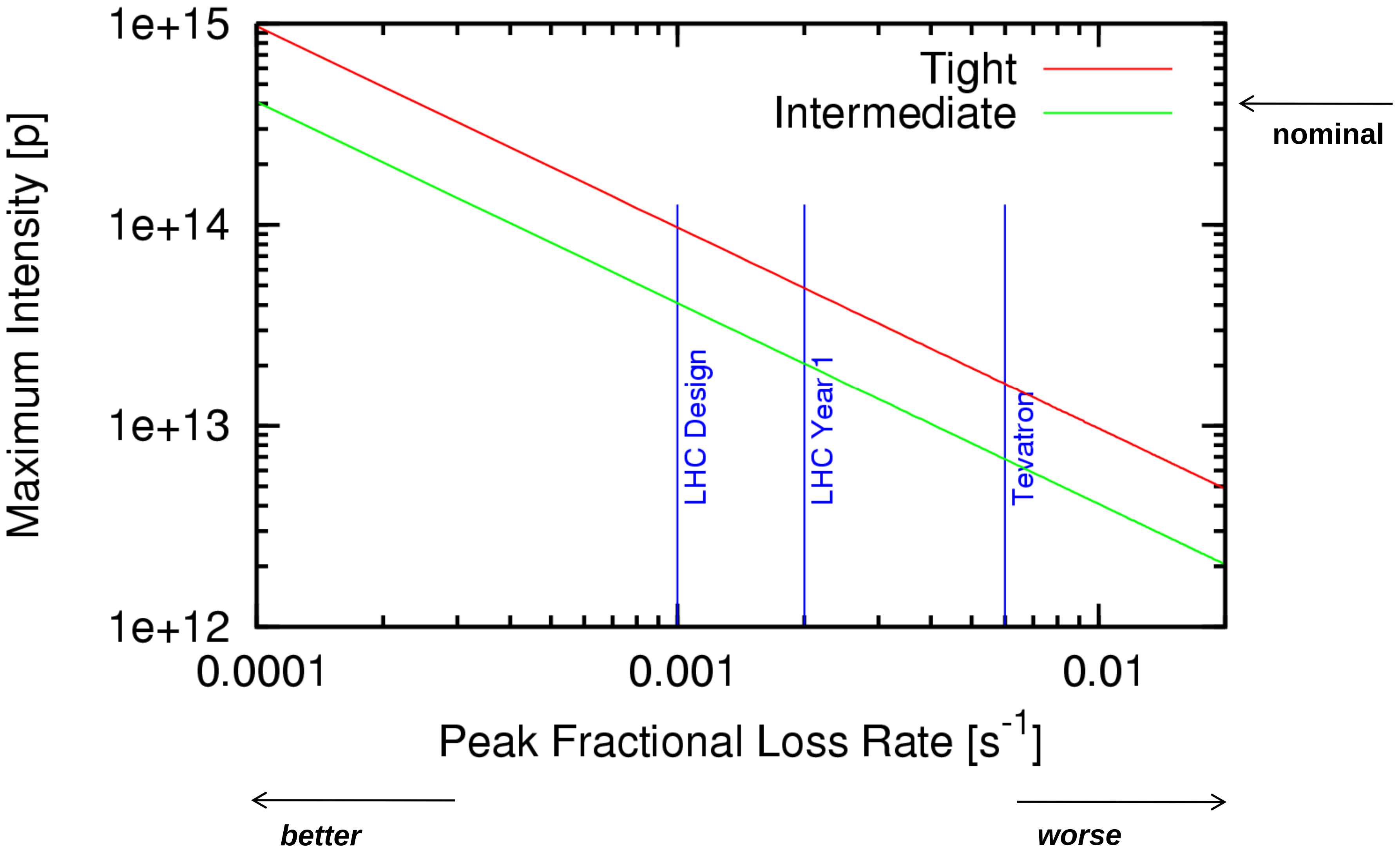
Phase I Collimation Limit for Stored Energy vs Beam Energy



Tight and intermediate collimation settings

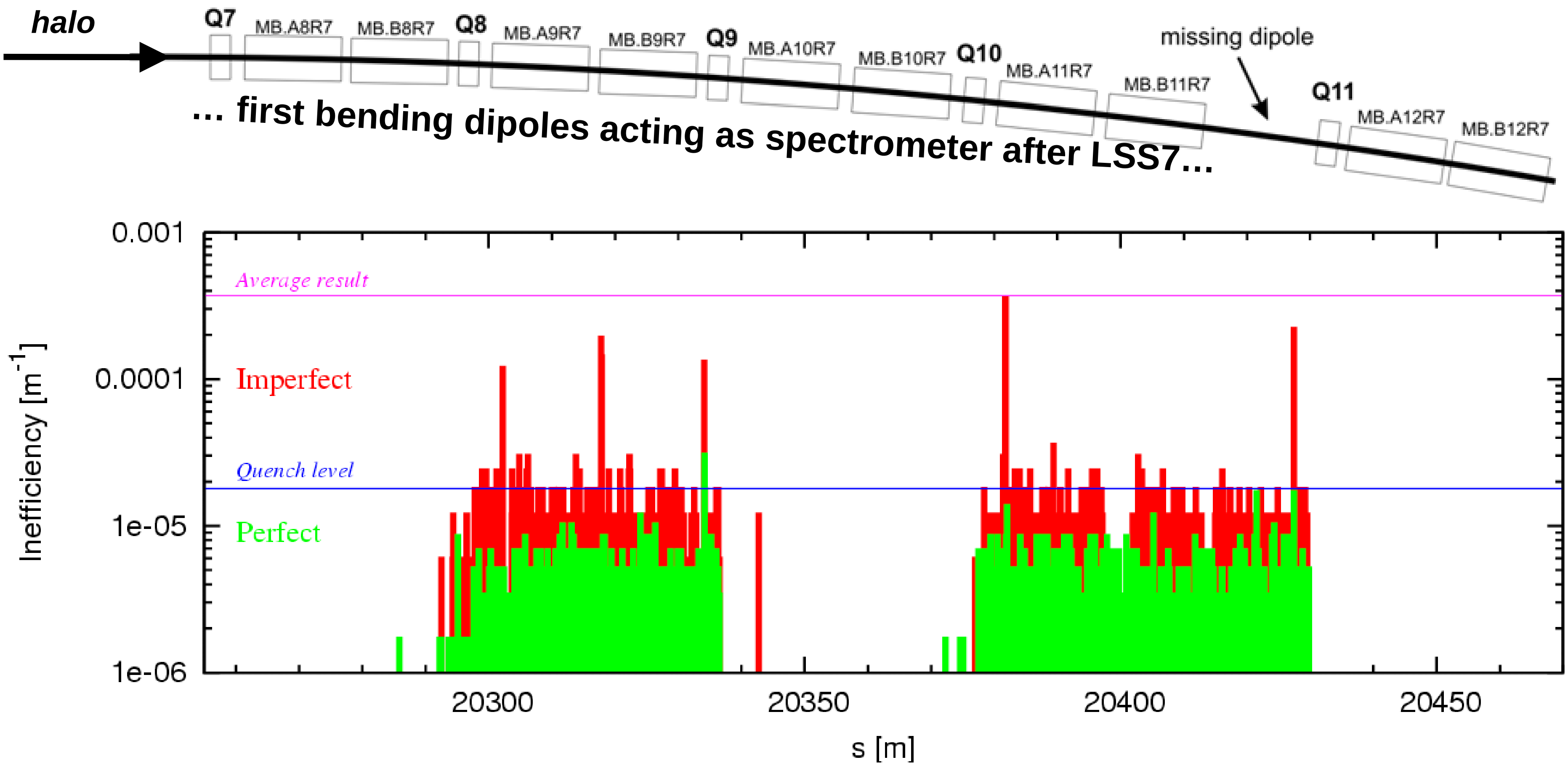
First year parameters

All Depends on Maximum Loss Rate Here for 5 TeV…

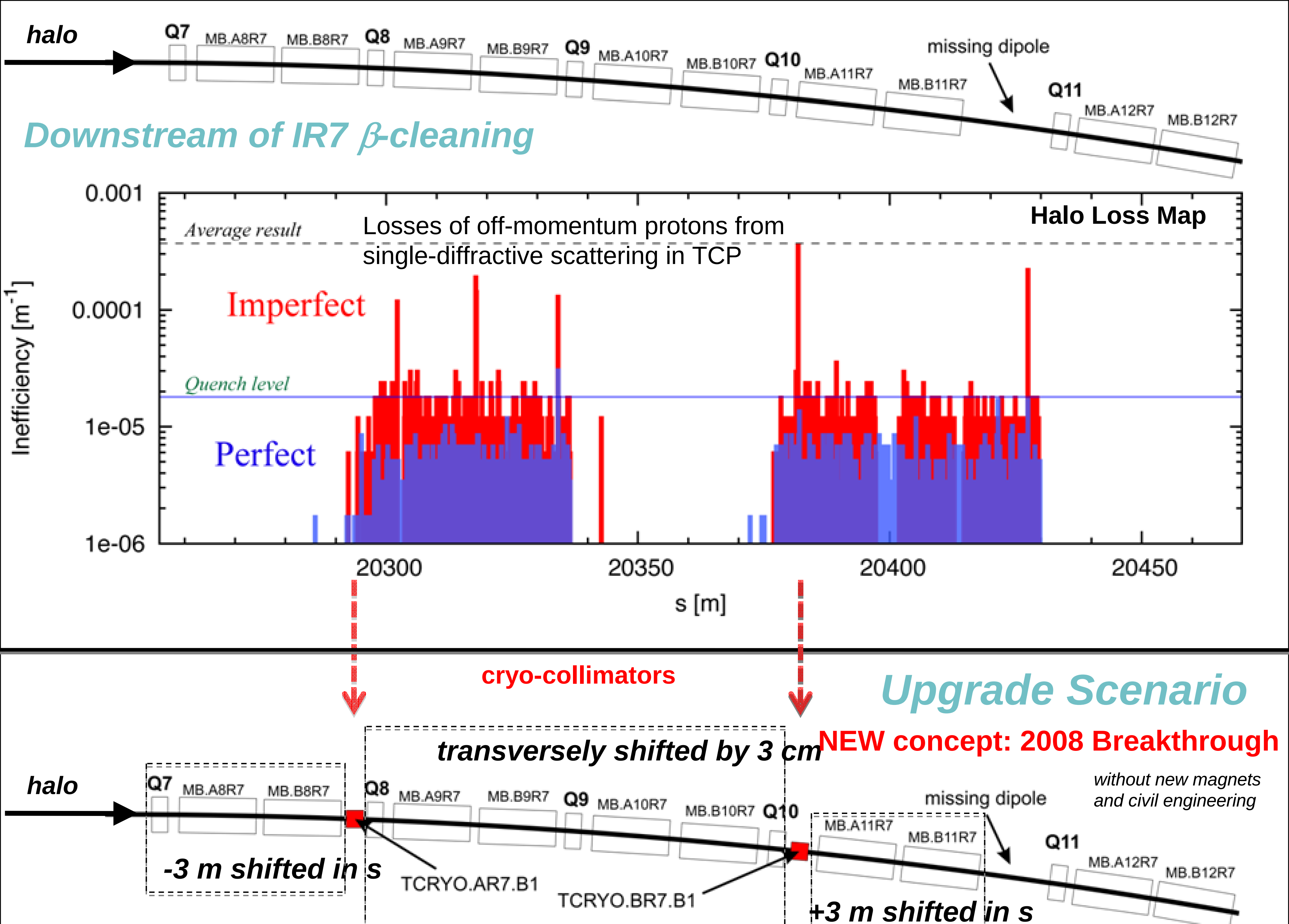


Tight and intermediate collimation settings

Limit: Proton/Ion Losses in Dispersion Suppressor Downstream IR7

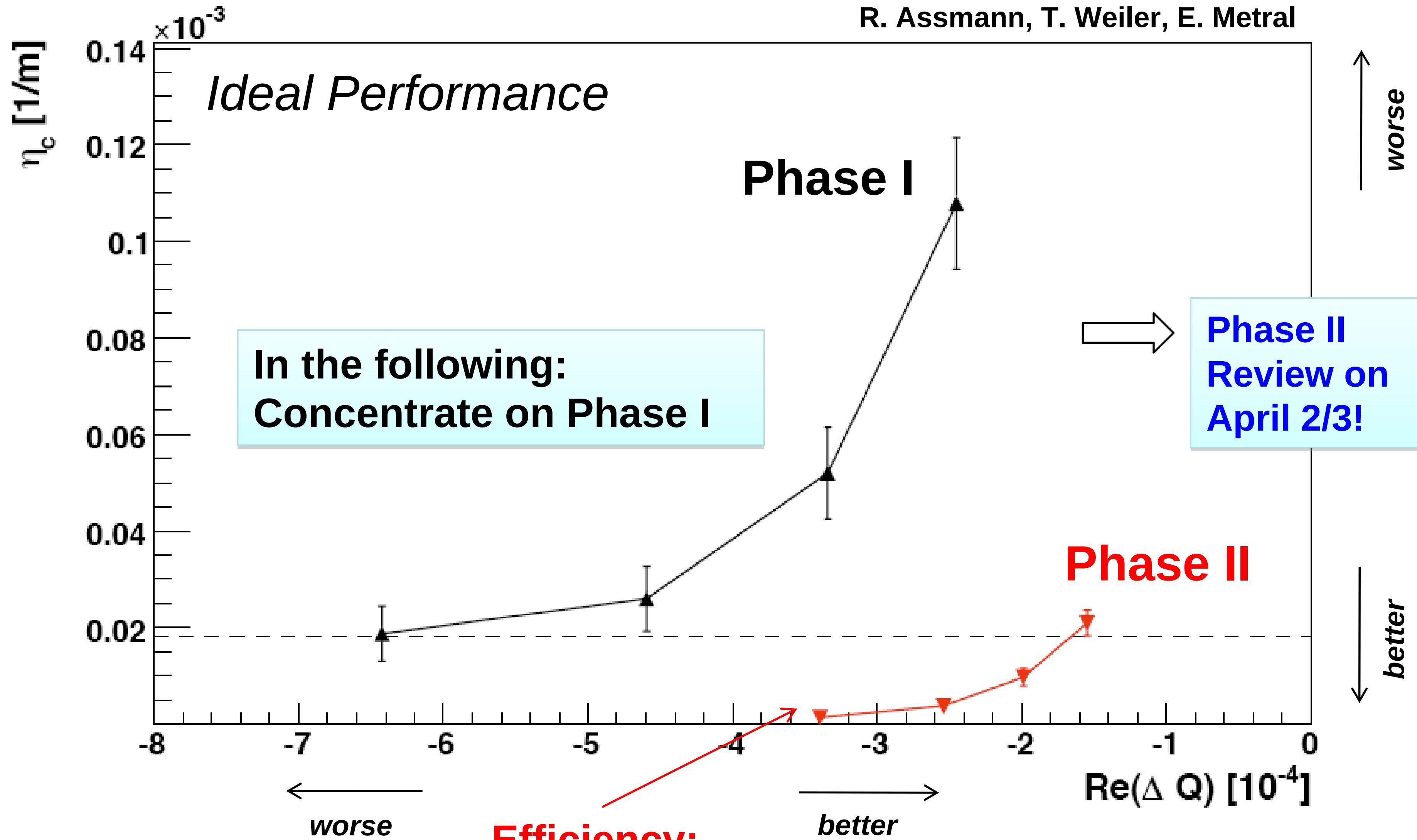


Collisions p on carbon generate off-momentum protons (mostly single-diffractive scattering). Are kicked out by the first bending dipoles (classical spectrometer).



R. Assmann, 12JUN09

Inefficiency versus "Impedance" for Various Coll. Settings (Phase I ➔ Phase II)



Efficiency: 99.99992 %

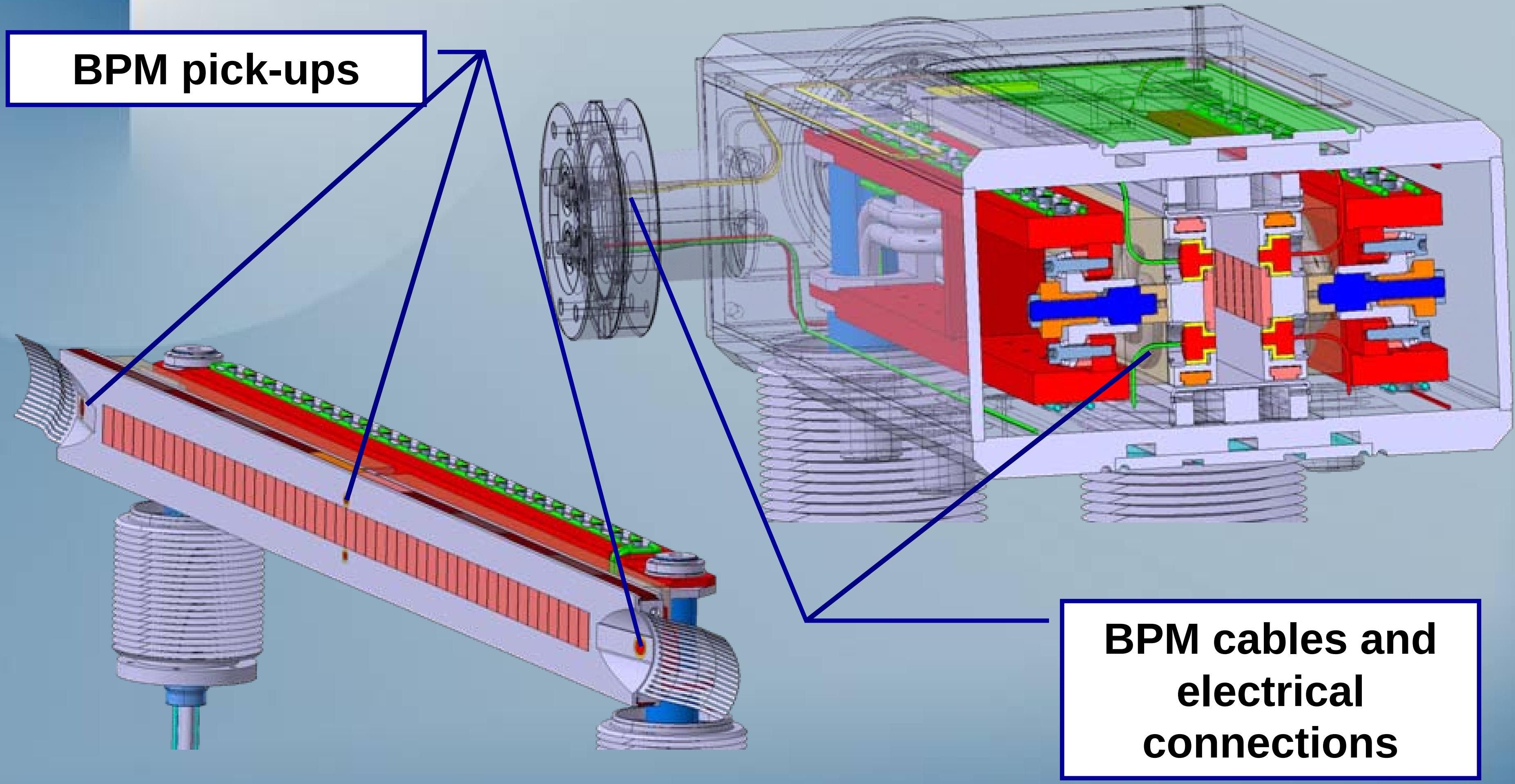
Simulations performed on the Grid (CPU limited)

Phase II Collimation Work Plan

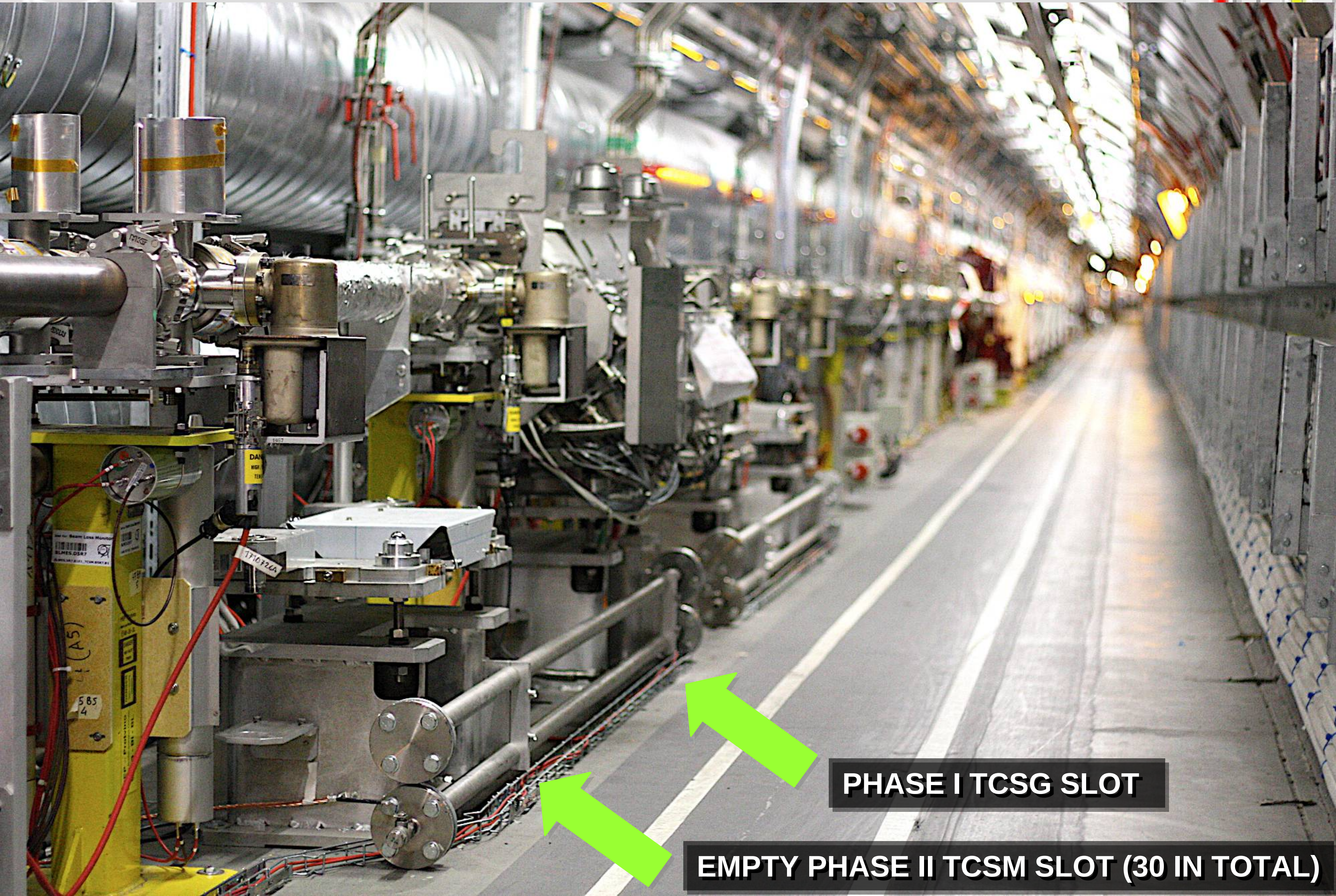
- R&D on advanced, low impedance materials for LHC collimators.
- Design, prototyping and testing of phase II secondary collimators, implementing in-jaw pick-ups (improved operation) and various jaw materials (lower impedance). Construct 30 plus spares.
- Install HiRadMat beam test facility for beam verification of advanced collimator designs.
- Start R&D, prototyping and testing on hollow e-beam lens for LHC scraping: FNAL and CERN.
- Work out technical design for modified dispersion suppressors in IR3/7. Design and build new cryostat for missing dipole. R&D on "cryo-collimators" for modified dispersion suppressors and construction.
- Support R&D on new concepts (crystal collimation, crab cavities, …).
- Collaboration with 12 institutes in Europe, funded by EU (FP7). Collaboration with 3 institutes in U.S., funded by DOE (LARP).

BPM integration

Integration of BPMs into the jaw assembly gives a clear advantage for set-up time ➔ Prototyping started at CERN

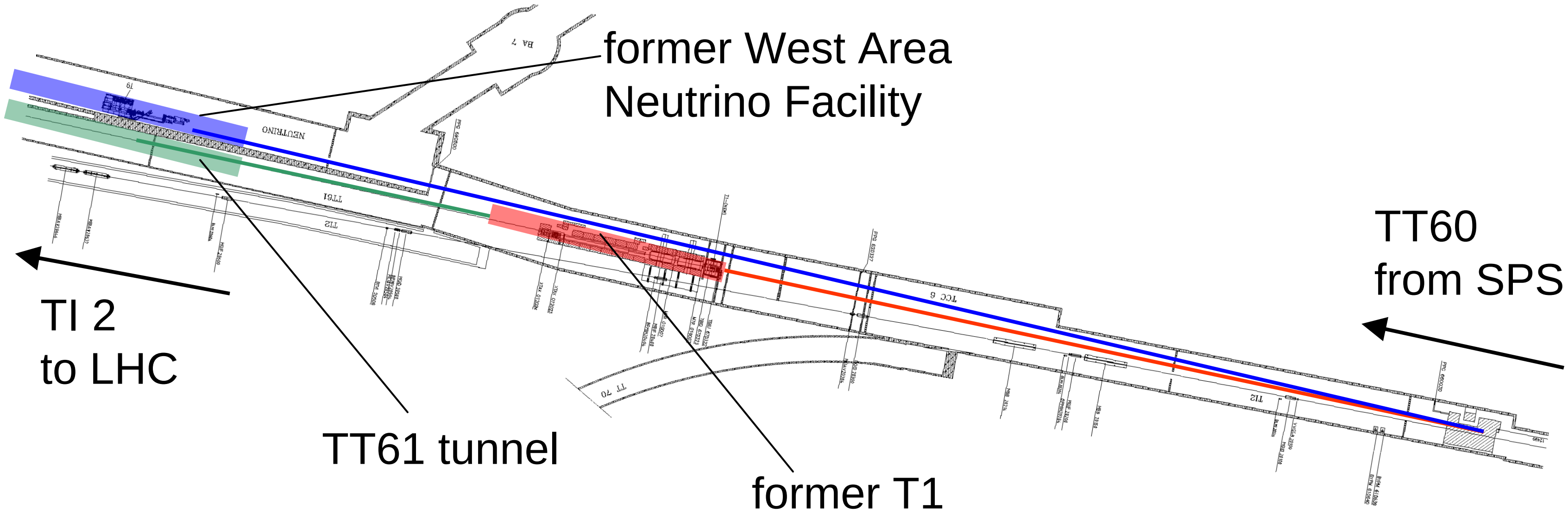


Tunnel: Phase II Collimator Slots



Location of HiRadMat: Testing BEFORE the LHC

3 possible locations of HiRadMat:



Specification for a Test Facility with High Power LHC Type Beam

R. Assmann, A. Bertarelli, I. Efthymiopoulos, B. Goddard, C. Hessler, T. Markiewicz[1], M. Meddahi, R. Schmidt, J. Sheppard[1], H. Vincke

C. Hessler

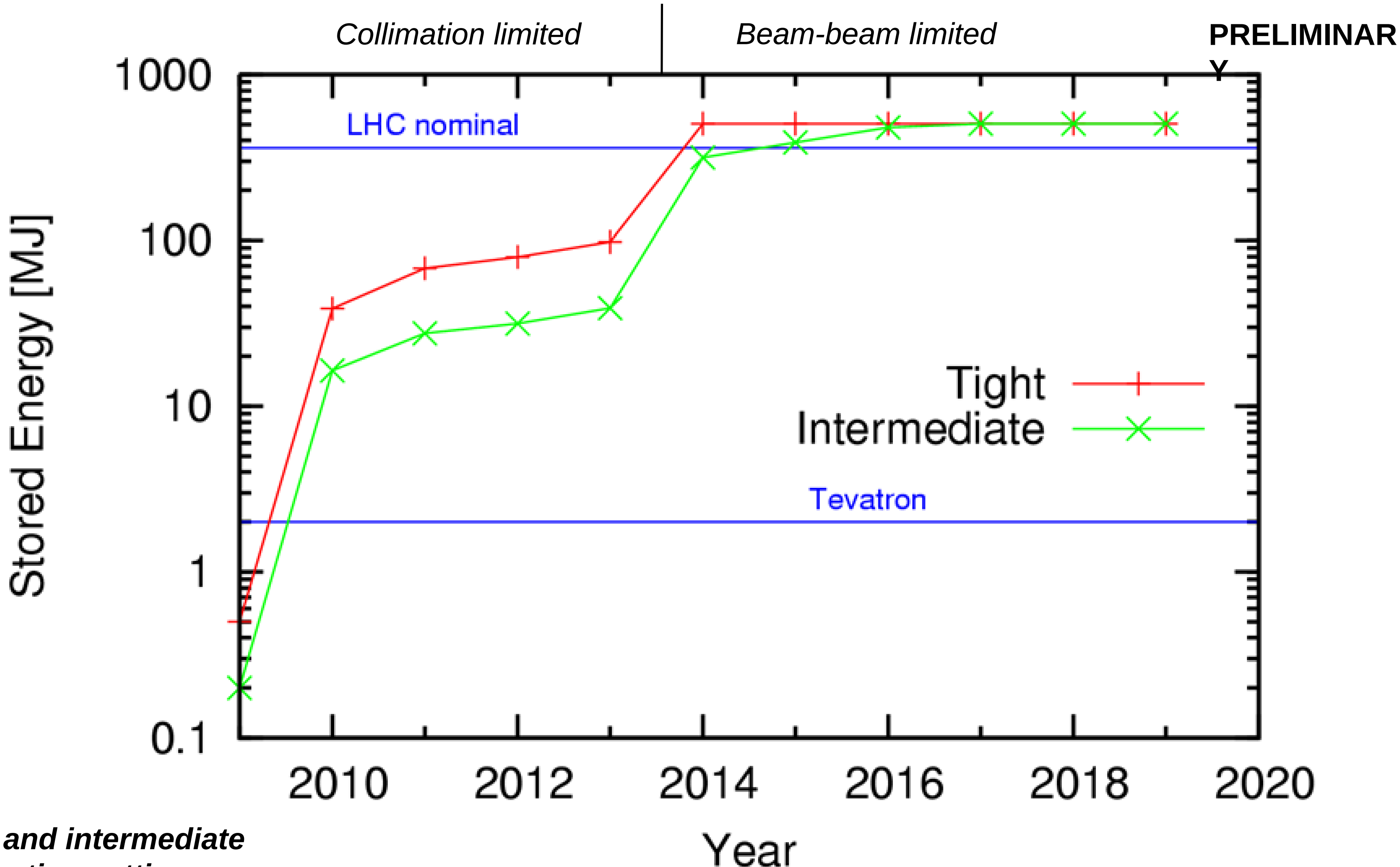
Scenarios for Collimation Upgrade

- **Conceptual solution** for collimation upgrade has been worked out, performance estimated and work plan proposed.
- Presented to international review beginning of April. See for presentations and supporting committee report:

  http://indico.cern.ch/conferenceDisplay.py?confId=55195

- Timeline for collimation upgrade will depend on available resources and priority put.
- Two scenarios analyzed:
  - Case 1: Upgrade **2013/14**.
  - Case 2: First step installed **2010/11**.
- Performance predictions for the two scenarios.

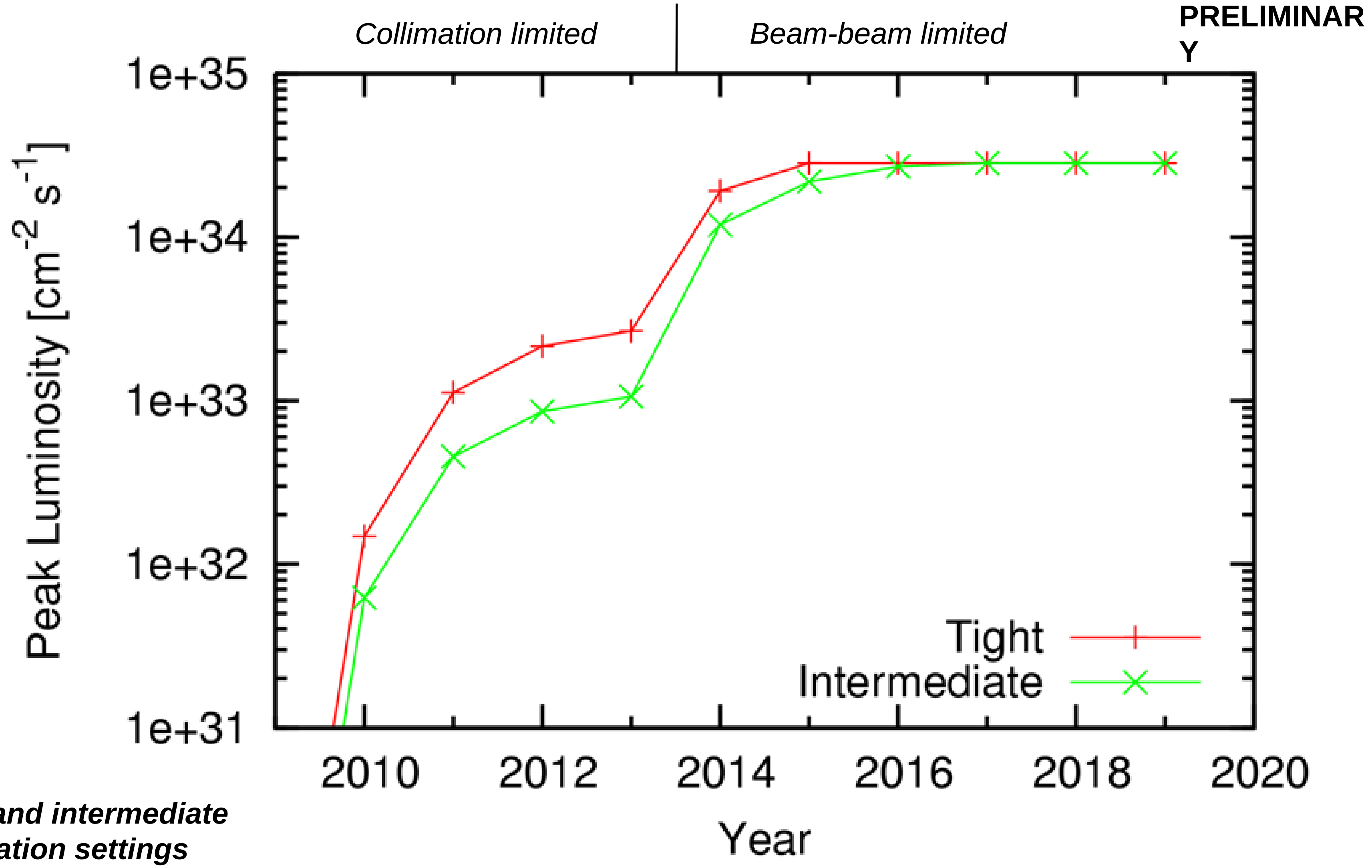
Case 1: Stored Energy versus Time
(without phase II IR upgrade)



Tight and intermediate collimation settings

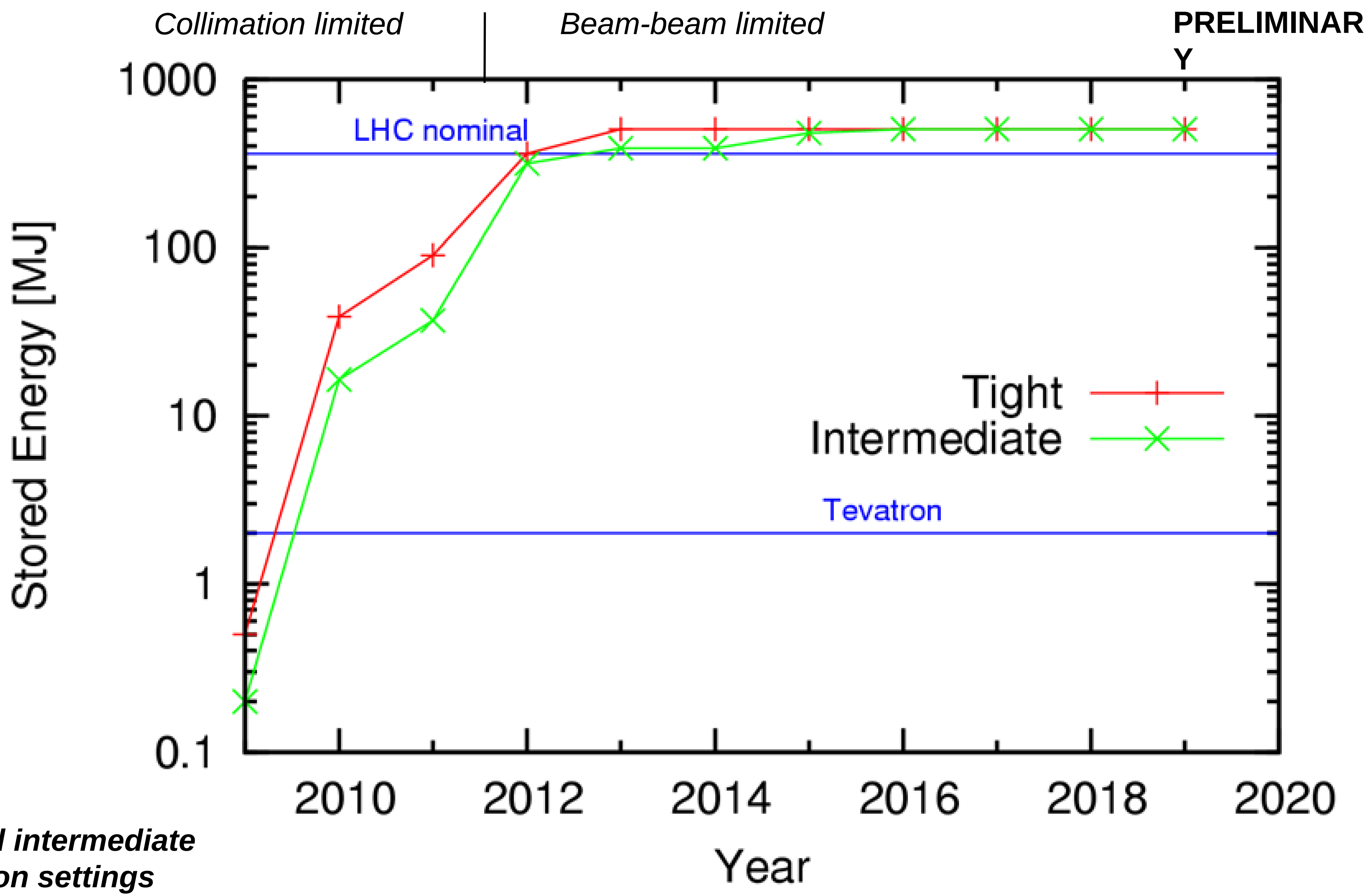
Case 1: Peak Luminosity versus Time

(without phase II IR upgrade)



Tight and intermediate collimation settings

Case 2: Stored Energy versus Time
(without phase II IR upgrade)

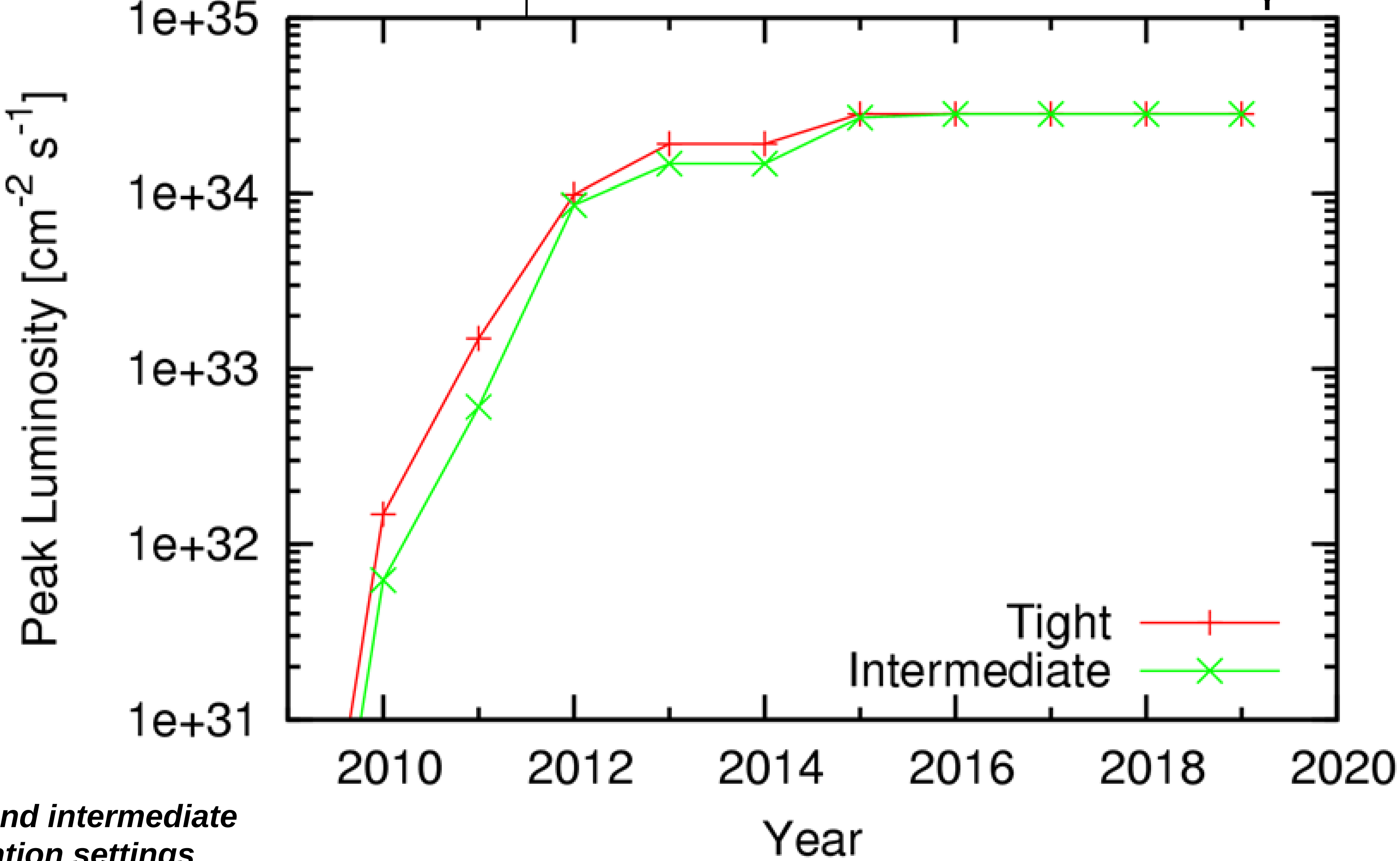


Tight and intermediate collimation settings

Case 2: Peak Luminosity versus Time
(without phase II IR upgrade)

Collimation limited | *Beam-beam limited*

PRELIMINARY



Tight and intermediate collimation settings

Conclusion

- LHC is designed to extend the intensity frontier by more than 2 orders of magnitude.
- **Machine protection OK up to ultimate intensity.** Revalidation for new devices, optics, configuration. New hardware above ultimate intensity.
- Cleaning/collimation (10 orders of magnitude dilution & absorption) will not be easy: staged approach.
- **Phase I collimation is completed and already is the largest such system built to date.** Expect to reach around 20 MJ (10 times world record) with phase I collimation, but below nominal design.
- **Phase II collimation** has been worked out and will be implemented in steps until 2014 to upgrade performance. It will allow nominal and higher intensities (hopefully before 2014, depending on support).
- Work is performed in international collaboration, supported by EU and DOE/LARP. Thanks to all who help us in this challenge!

Collimation Collaboration
(EuCARD, LARP, Germany)

EuCARD

ColMat

INFN

CERN

GSI

EPFL
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L-Università ta' Malta

Funded by German Ministry for Science

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

TECHNISCHE UNIVERSITÄT DARMSTADT

Funded by US DOE (LARP program)

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