The Conceptual Solution for LHC Collimation Phase II

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2/4/2009

for the Collimation Project

Conceptual Review Phase II
CERN

Conceptual Review Phase II Collimation

- Despite tight resources we found the time to work out a **conceptual solution for reaching nominal and ultimate intensities in the LHC**. Big step: **Factor 15-90**! Many thanks to all who helped.
- Now: **Have solution reviewed and start technical design work, if our proposals are supported.**
- What this review is: Collect and present solutions for all known problems (p, ions, experiments). Present a conceptual solution and readiness for starting technical design work.
- What this review is not: Detailed decision on technical choices e.g. for jaw material of phase II secondary jaws. No presentation of detailed technical designs, costs, assessment of resulting work for the super-conducting ring.
- Following along our **project plan**, as discussed in AB and the LHC project and as sent to the DG in 2007.

1) Reminder: The LHC Challenge

The Large Hadron Collider:

Circular particle physics collider with 27 km circumference.

Two colliding 7 TeV beams with each 3×10^{14} protons.

Super-conducting magnets for bending and focusing.

Particle physics reach defined from:

1) Center of mass energy **14 TeV**

➔ super-conducting dipoles

2) Luminosity **10^{34} cm^{-2} s^{-1}**

LHC nominal parameters

Number of bunches:	**2808**
Bunch population:	**1.15e11**
Bunch spacing:	25 ns
Top energy:	
Proton energy:	**7 TeV**
Transv. beam size:	~ **0.2 mm**
Bunch length:	8.4 cm
Stored beam energy:	**360 MJ**
Injection:	
Proton energy:	450 GeV
Transv. Beam size:	~ 1 mm
Bunch length:	18.6 cm

LHC Luminosity

- Luminosity can be expressed as a function of transverse energy density ρ_e in the beams at the collimators:

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

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

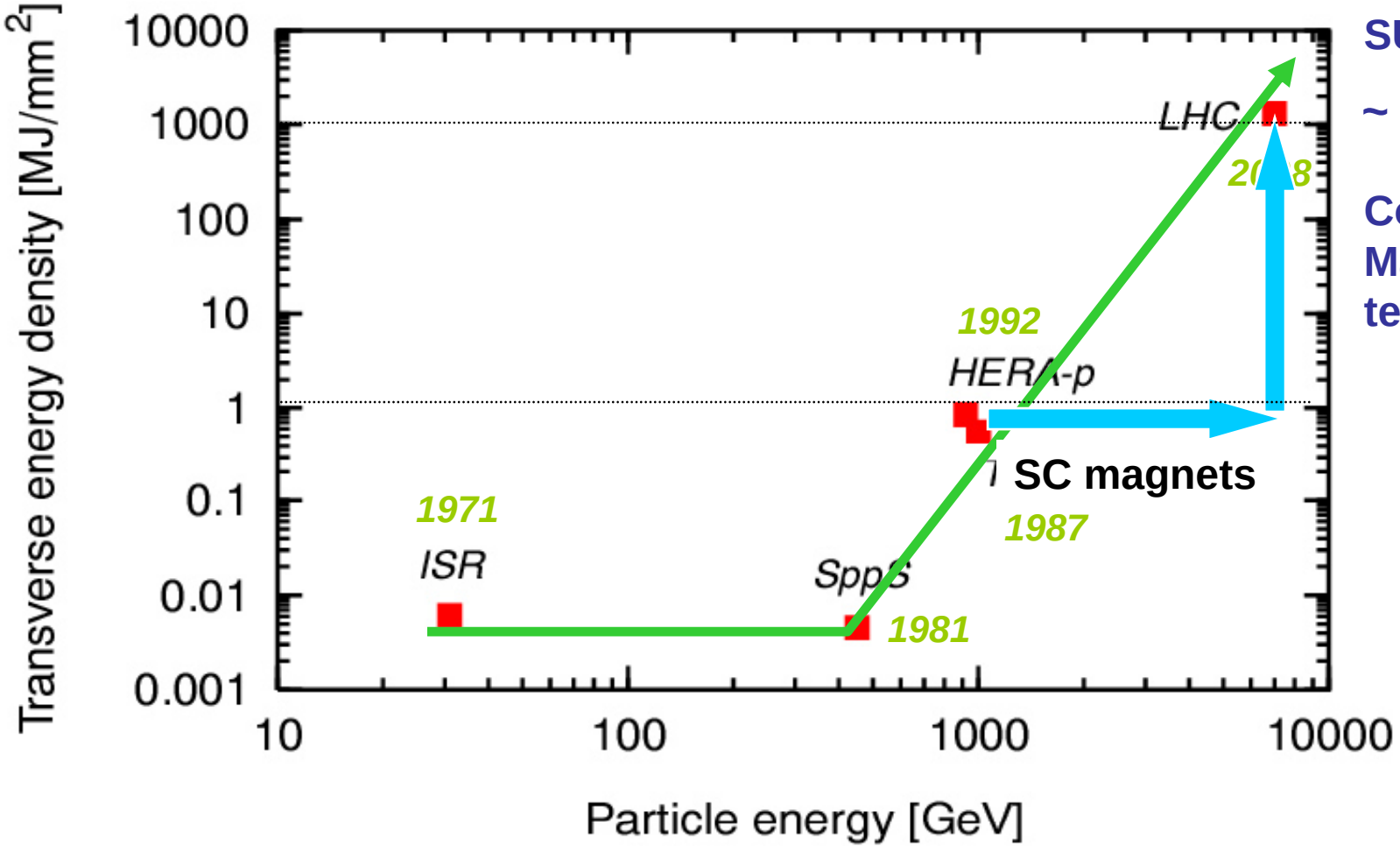
- Various parameters fixed by design, for example:
  - Tunnel fixes revolution frequency.
  - Beam-beam limit fixes max. bunch intensity
  - Machine layout and magnets fix demagnifica
  - Physics goal fixes beam energy.
- **Luminosity is increased via transverse energy density!**

LHC needs ~20 times more stored energy for the same luminosity (β^*=2m) as Tevatron which has higher f_{rev} and lower E_b!

At the same time, LHC quench limits are more severe (less losses tolerated)!

➔ Criticality of beam loss control and collimation!

pp, ep, and ppbar collider history



Higgs + SUSY + ???

~ 80 kg TNT

Collimation Machine Protection

The "new Livingston plot" of proton colliders: Advancing in unknown territory!

A **lot of beam** comes with a **lot of garbage** (up to 1 MW halo loss, tails, backgrd, ...)

➔ Collimation. Machine Protection. See talk J. Wenninger.

2) Collimation Design Parameters

- Most important collimation design parameters:
  - **Cleaning efficiency**
  - **Peak loss rate of stored beam**
  - **LHC quench limit (taken from design)**
  - **BLM threshold with respect to quench limit (taken from design)**
- Performance and requirements depend on design parameters and assumptions.
- Without beam experience we cannot be sure about our assumptions.
- LHC collimation design is based as much as possible on the experience from present and past colliders and on beam tests!

Required Cleaning Efficiency

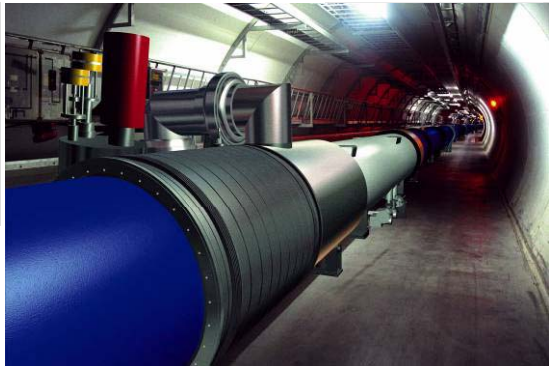


Illustration of LHC dipole in tunnel

Allowed intensity

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

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

Beam lifetime
(e.g. 0.2 h minimum)

BLM threshold
(e.g. 30%)

Loss length

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.

Specifying Peak Loss of Stored Beam

Mode	Energy [TeV]	Duration [s]	Min. lifetime [h]	Power [kW]
Injection	0.45	cont	1.0	6
		10	0.1	60
Ramp	0.45-7.0	10	0.1-0.2	60-465
	0.45	≈ 1	0.006	1000
Top energy	7.0	cont	1.0	93
		10	0.2	465

Table for nominal intensity.
LHC Design Report.

Peak fractional loss of 0.1 % per second.

LHC design value: **10^{-3} /s**

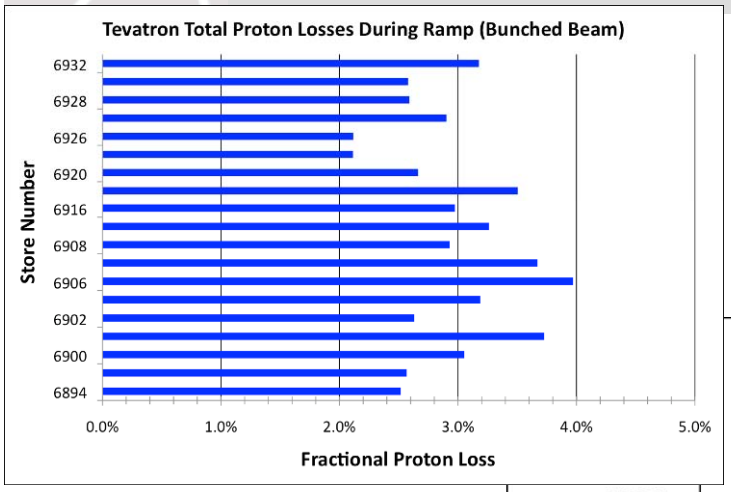
Tevatron 2009: **> 6 × 10^{-3} /s**

Reviewed by external review of LHC collimation project in June 2004.

Supported by HERA, RHIC, Tevatron experts.

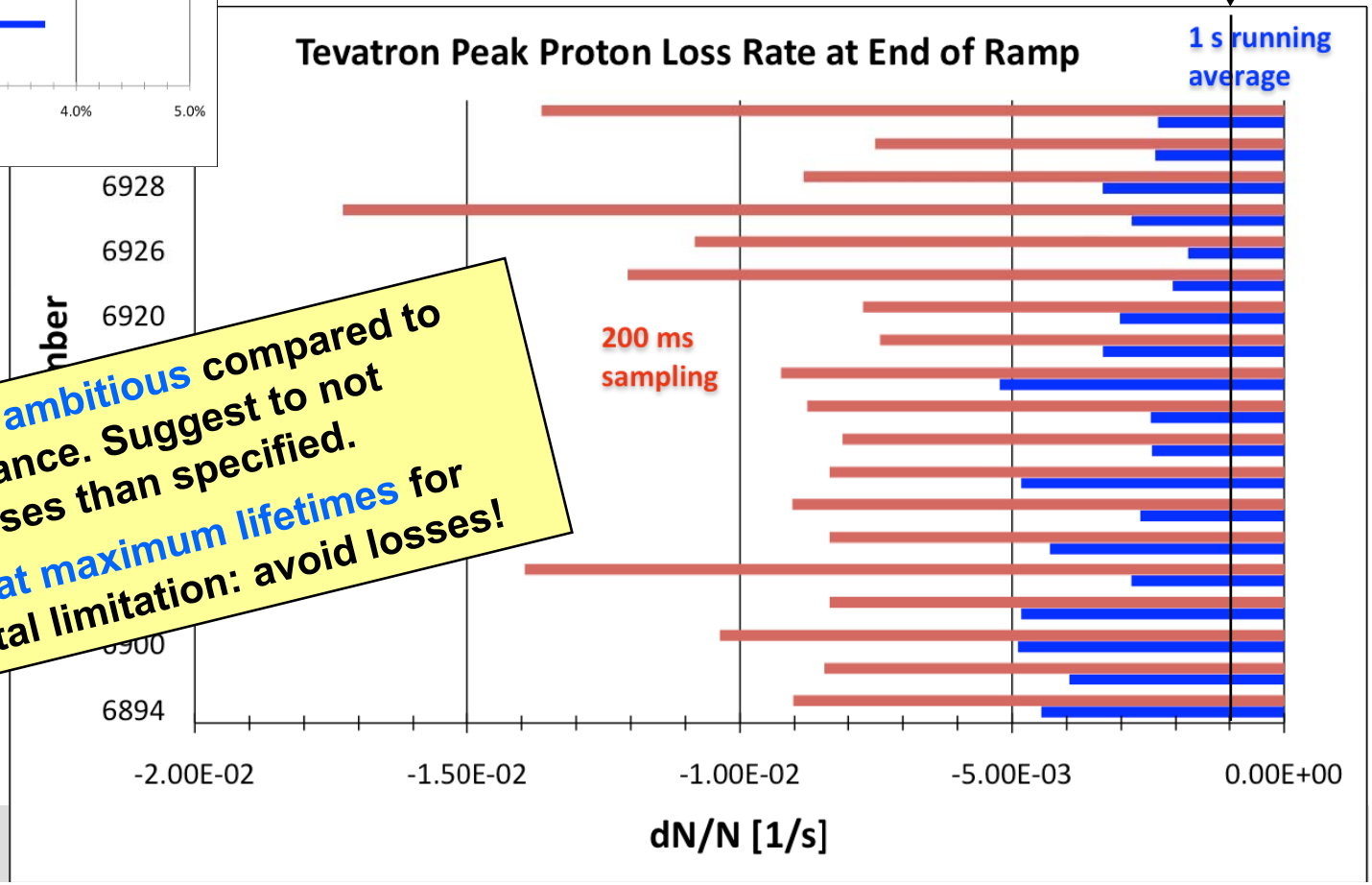
Tevatron 2009: End of Ramp Losses

(State of the Art)



Analysis of 19 physics fills
(two weeks in March 2009)
R. Assmann, D. Still, N. Mokhov

LHC assumption



Integrated losses during ramp are very good:

2 - 4 %

LHC design loss rate is ambitious compared to 2009 Tevatron performance. Suggest to not assume lower LHC losses than specified.

It is important to aim at maximum lifetimes for LHC! If no fundamental limitation: avoid losses!

The Phased LHC Collimation Solution

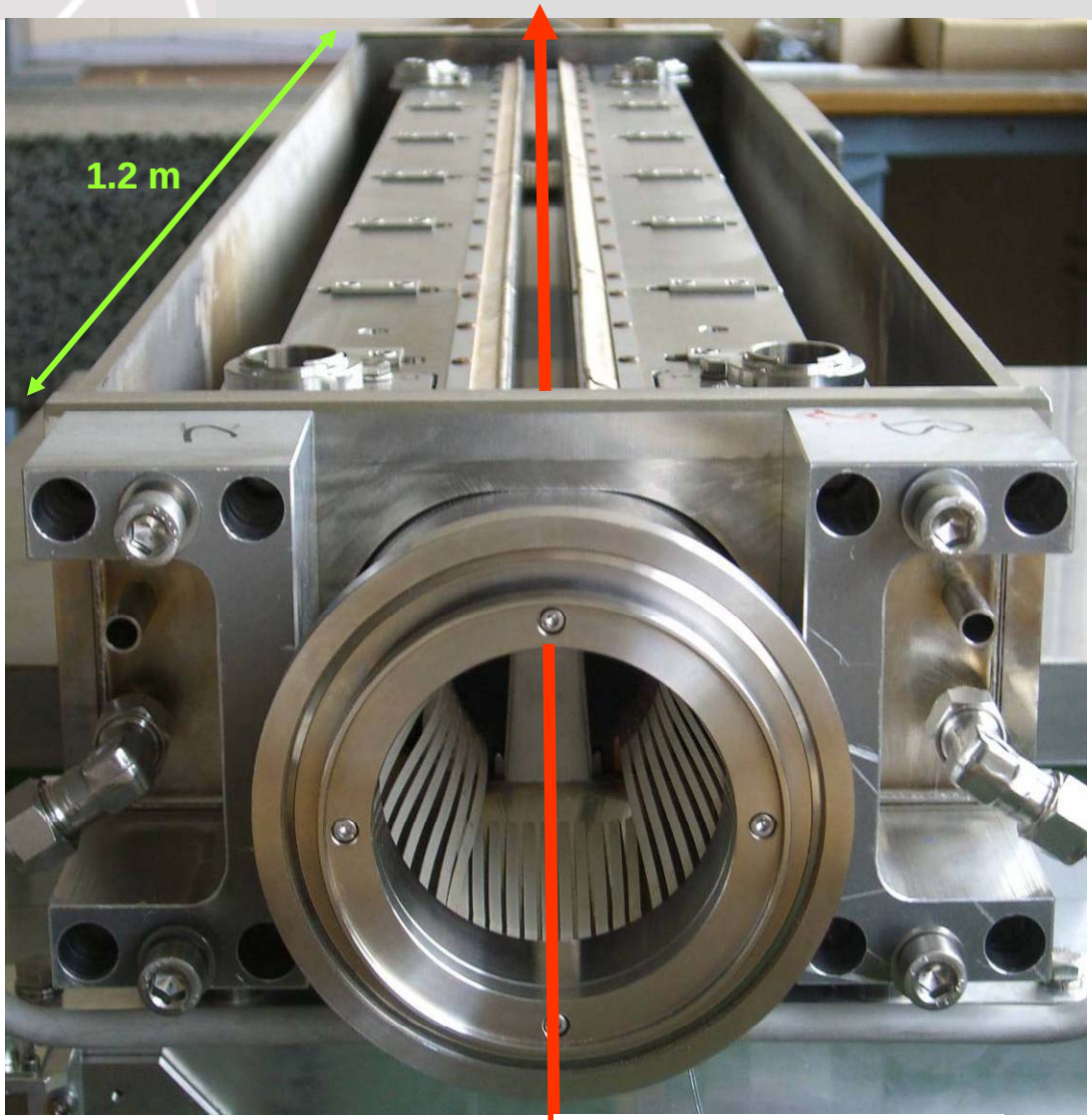
Different for LHC triplets and IR's:
➔ Phase 0 installed, phase 1 is upgrade!

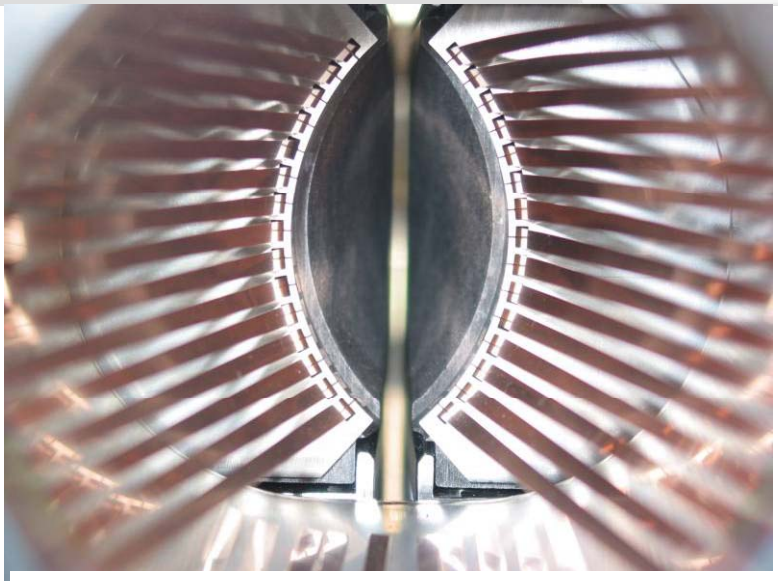
- Phase I (initial installation):
  - Relying on very **robust collimators** with advanced but conservative design.
  - Perceived to be **used initially** (commissioning) and **always in more unstable parts of LHC operation** (injection, energy ramp and squeeze).
  - Provides **excellent robustness** and survival capabilities.
  - **OK for ultimate intensities in experimental insertions** (triplet protection, physics debris), except some signal acceptance. ➔ See talk D. Macina.
  - L**imitations in efficiency (betatron & momentum) and impedance.**
  - Demanding R&D, testing, production and installation schedule over **6 years**.
- Phase II (upgrade for nominal/ultimate intensities):
  - **Upgrade for higher LHC intensities, complementing phase I.**
  - To be **used in stable parts of operation** like physics (robustness can be compromised).
  - **Fixes limitations in efficiency, impedance and other issues.**

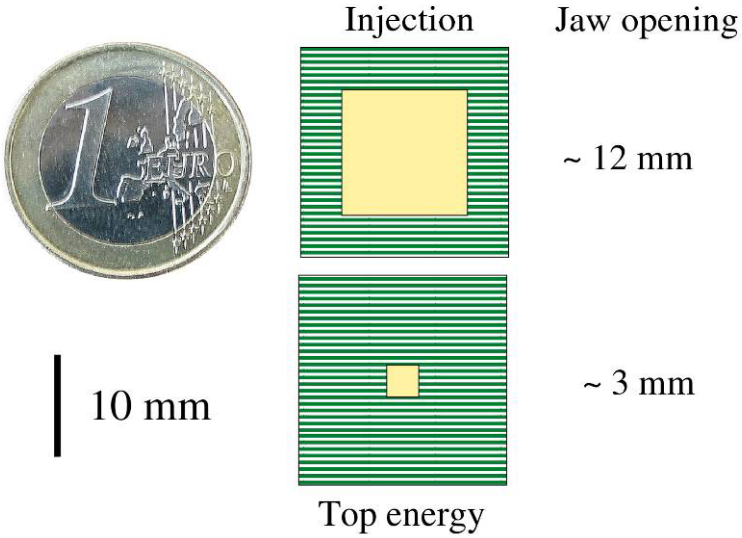
3) The Phase I System

- Includes **112 collimators in the LHC ring** and the transfer lines from the SPS to the LHC. In addition **19 spare collimators**.
- **38 tunnel locations** equipped with cables, water connections, vacuum pumping, instrumentation and replacement chambers (**preparation phase II**).
- We use 10 types of collimators in phase I, **robust collimators close to beam (survives injection and dump failures) and non-robust collimators further retracted**:
  - Robust **primary cleaning collimators TCP** (fiber-reinforced carbon jaws).
  - Robust **secondary cleaning collimators TCSG** (fiber-reinforced carbon jaws).
  - Non robust **cleaning absorbers TCLA** (copper-tungsten jaws).
  - Non robust **tertiary collimators TCT** (copper-tungsten jaws): cleaning, triplet protection.
  - Non robust **experimental absorbers TCLP** (copper jaws): catching physics debris.
  - Several **special type collimators**, robust and not robust.
- Essentially **fully installed by now** (except where conflict with Roman Pots).

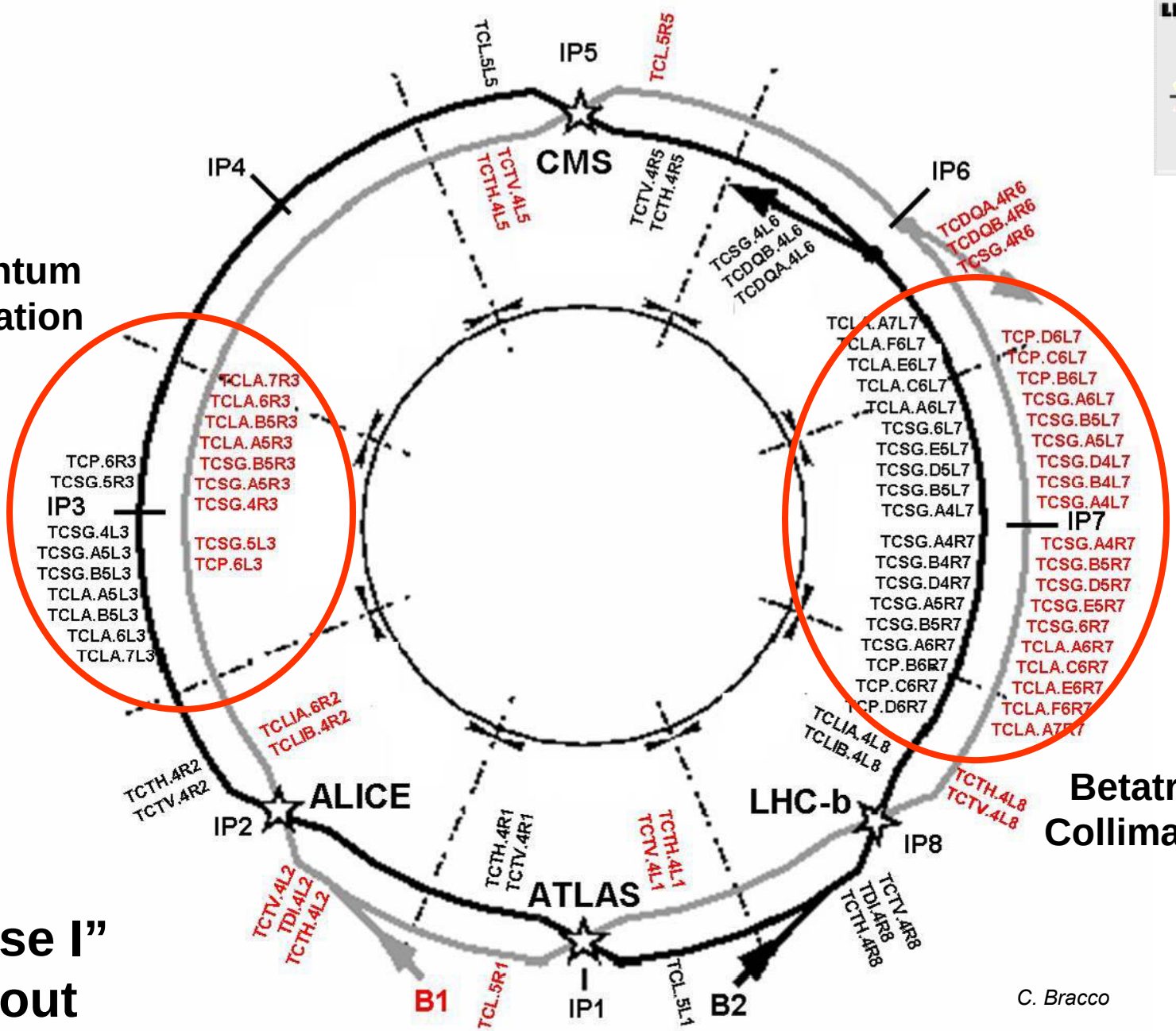
The Phase I Collimator







Momentum Collimation

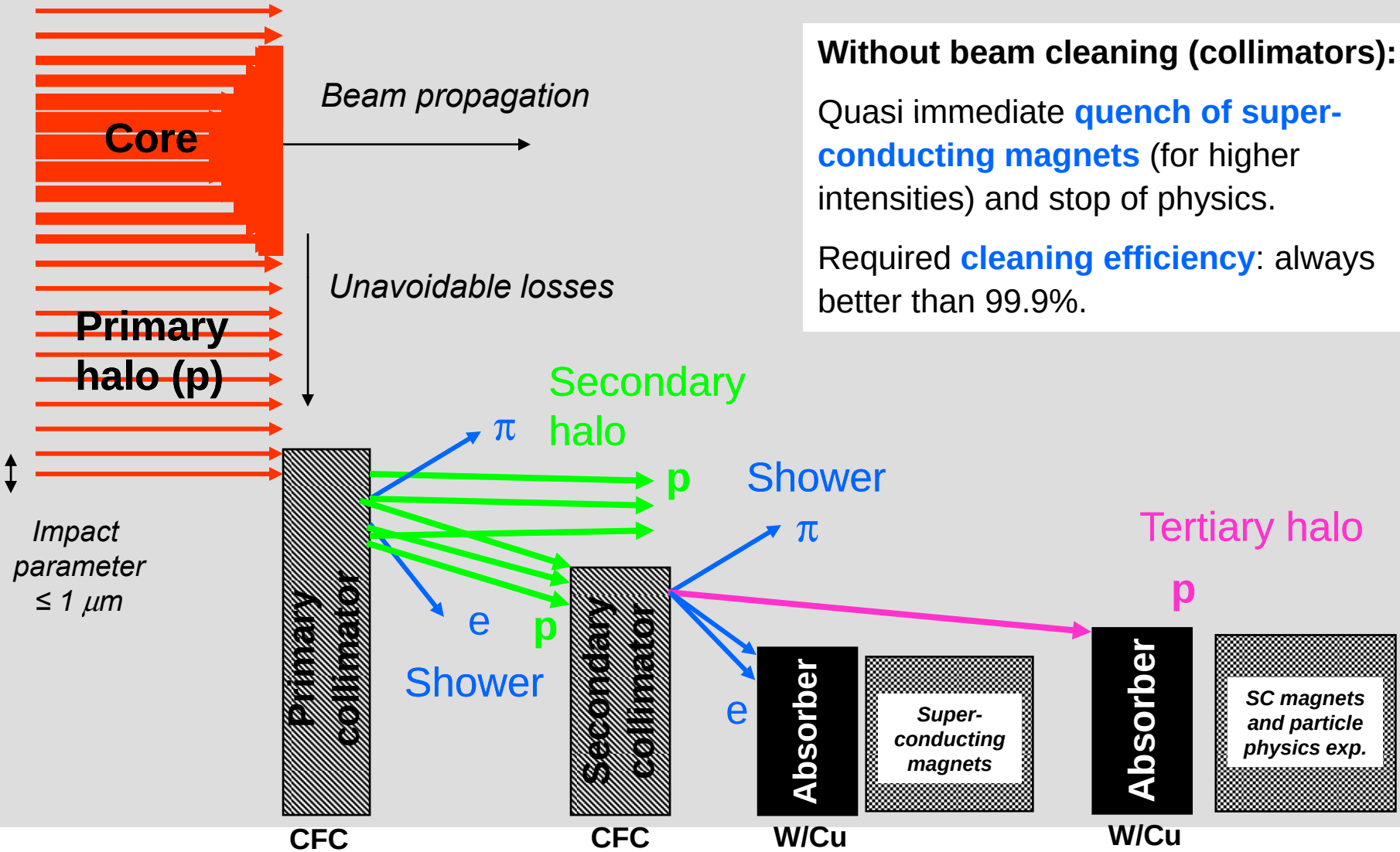


Betatron Collimation

C. Bracco

"Phase I" Layout

Multi-Stage Cleaning & Protection

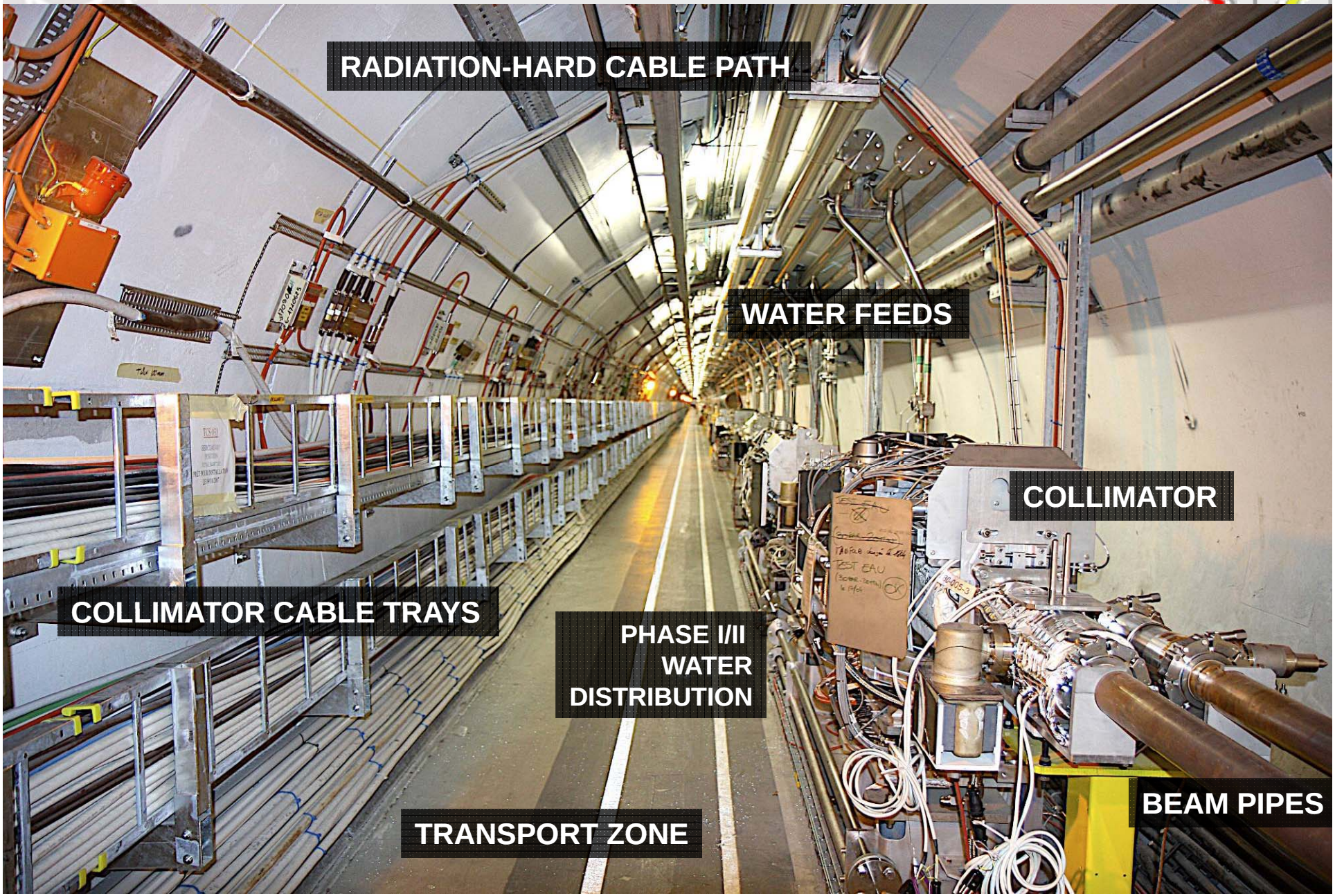


Without beam cleaning (collimators):

Quasi immediate **quench of super-conducting magnets** (for higher intensities) and stop of physics.

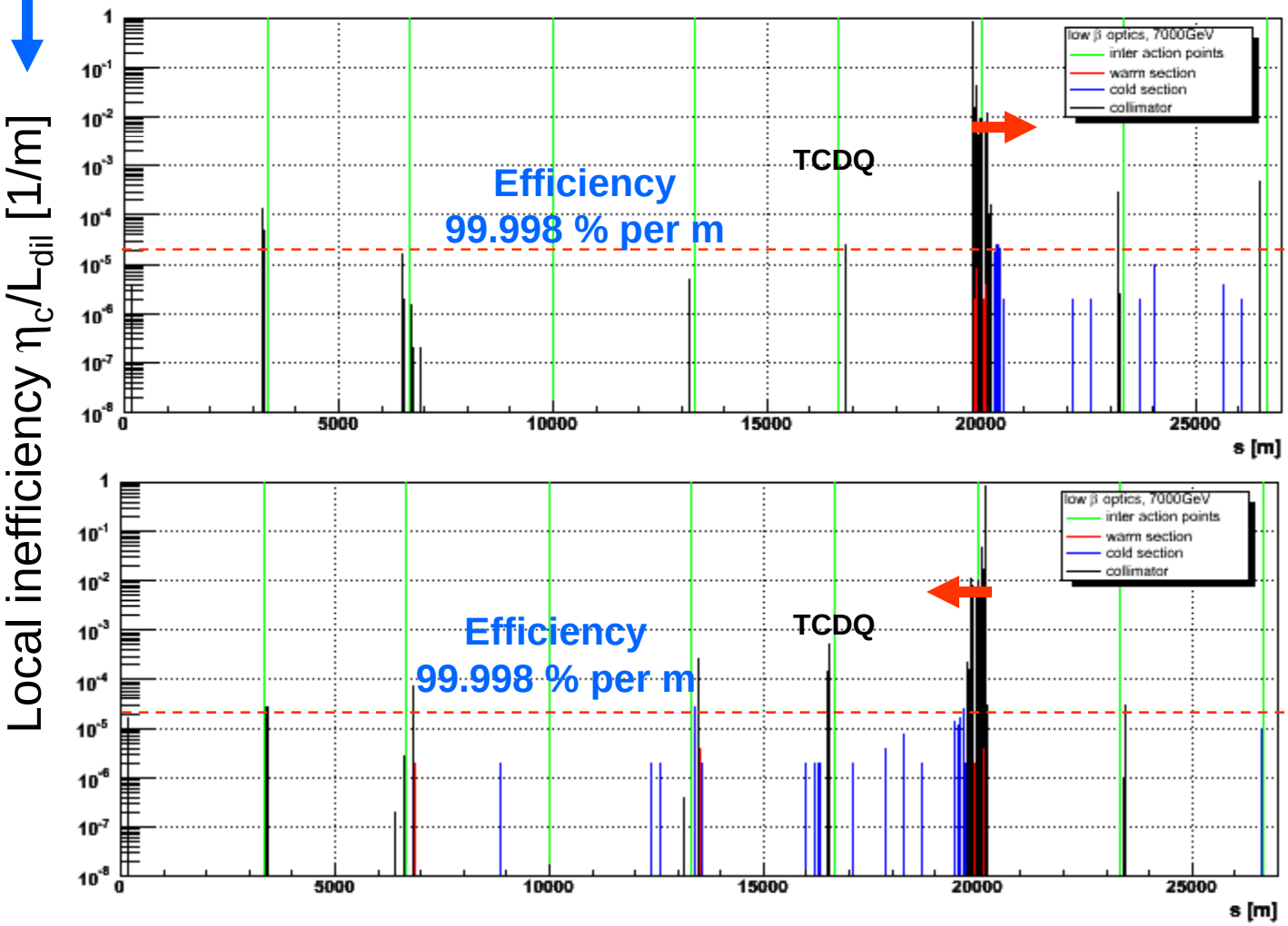
Required **cleaning efficiency**: always better than 99.9%.

Phase I in Tunnel (Radiation-Optimized)



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

Performance Limits with Phase I



Beam1, 7 TeV
Betatron cleaning
Ideal performance

Quench limit
(nominal I, τ=0.2h)

Beam2, 7 TeV
Betatron cleaning
Ideal performance

Quench limit
(nominal I, τ=0.2h)

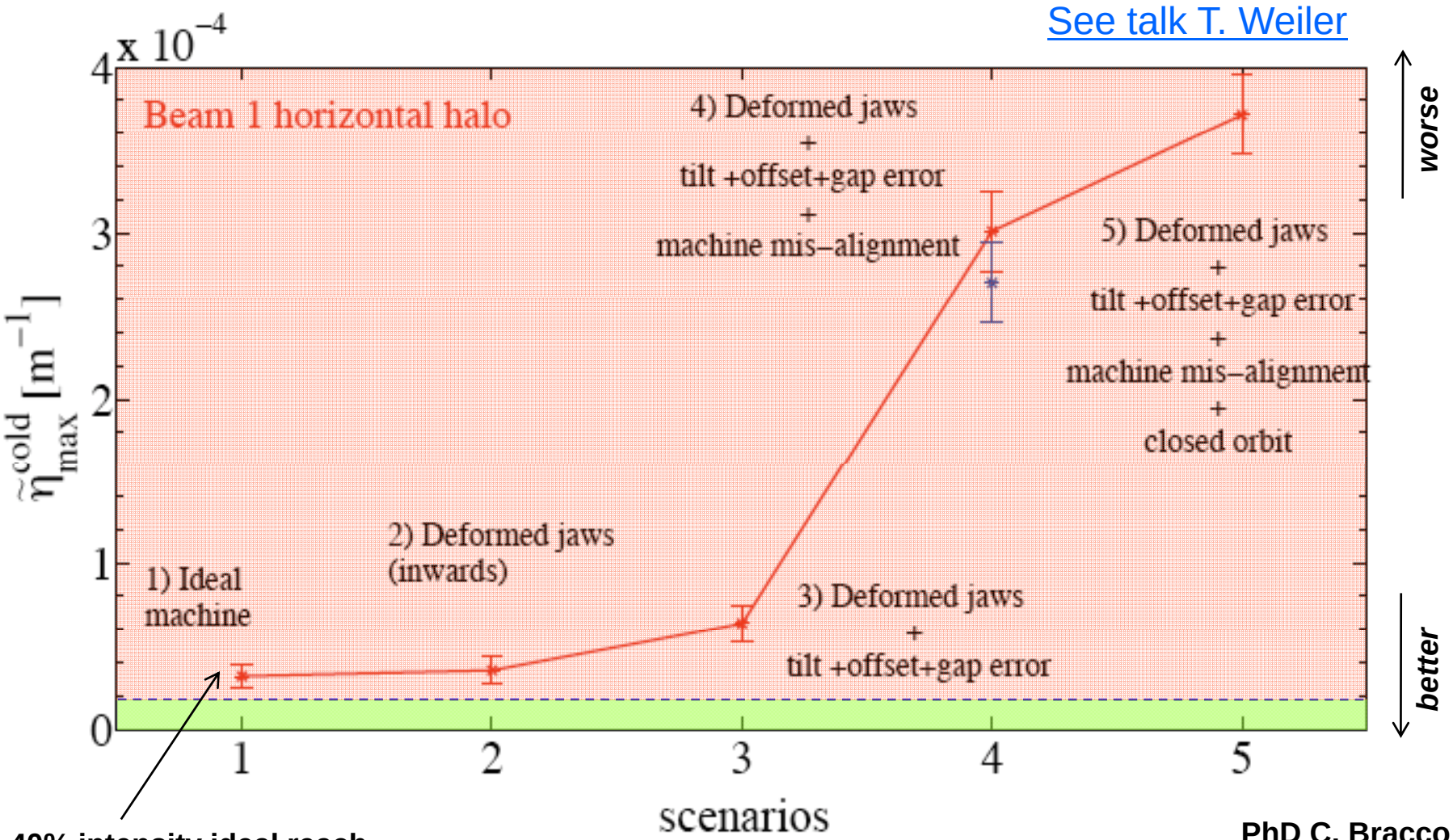
99.998 % needed

99.995 % predicted

Local inefficiency: #p lost in 1 m over total #p lost = leakage rate

Impact of Imperfections on Inefficiency (Leakage Rate) – 7 TeV

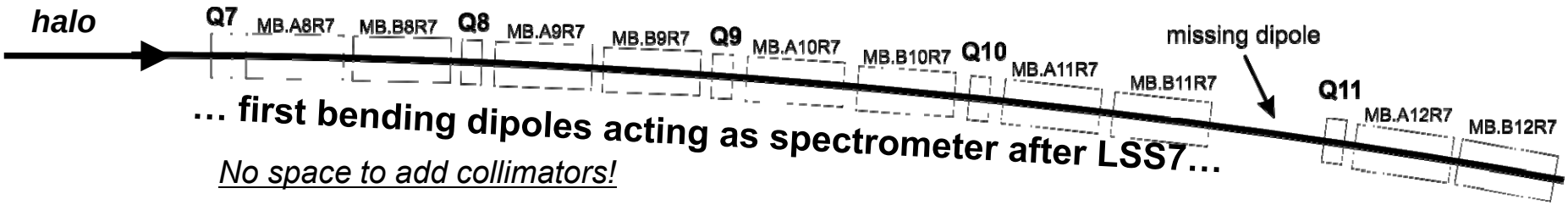
See talk T. Weiler

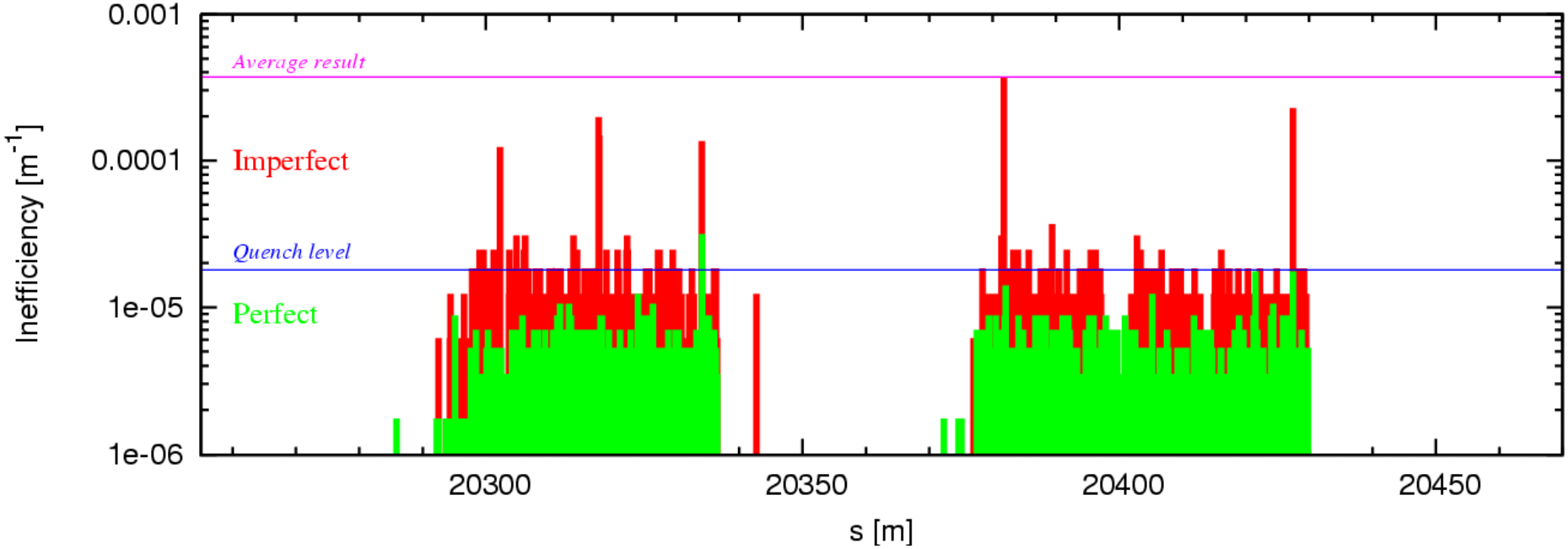


40% intensity ideal reach

PhD C. Bracco

Proton Losses in Dispersion Suppressor Downstream IR7 Cleaning Insertion





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

Why Do We Believe Strongly in Limitation?

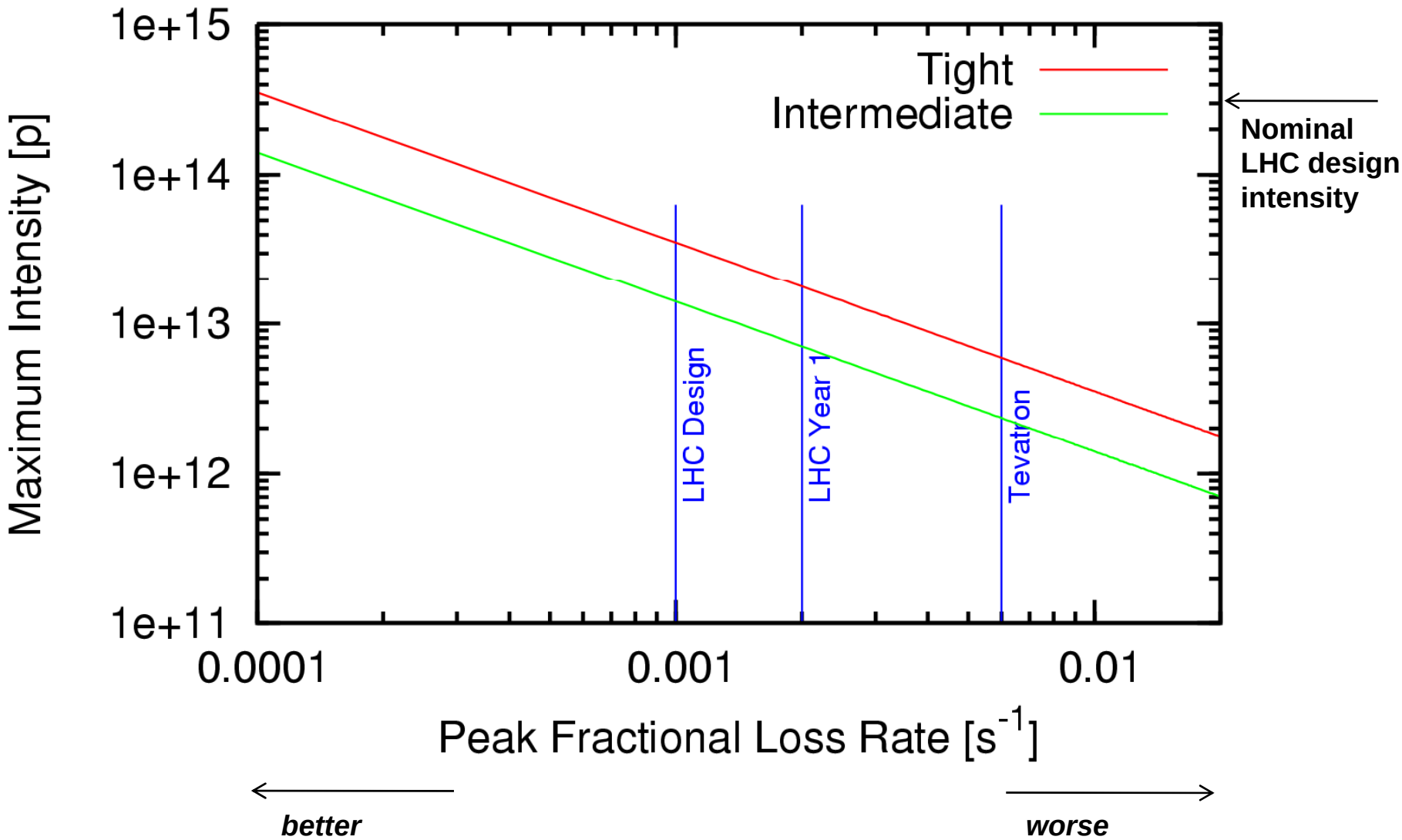
- Because it is **related to clear and well-known physics processes**:
  - Primary collimators intercept protons and ions, as they should.
  - **Small fraction of protons receive energy loss but small transverse kick (single-diffractive scattering), ions dissociate, …**
  - Subsequent collimators in the straight insertion (no strong dipoles) cannot intercept these off-momentum particles (would require strong dipoles).
  - Affected **particles are swept out by first dipoles after the LSS**. Main bends act as spectrometer and off-momentum halo dump ➔ quench.
- **Off-momentum particles generated by collimators MUST get lost at the dispersion suppressor** (if we believe in physics and LHC optics).
- No hope that this is not real (e.g. LEP2 was protected against this – not included for the LHC design and too late to be added when I got involved).
- Predicted for p, ions of different species (with different programs).

Summary Limits of LHC Collimation Phase I

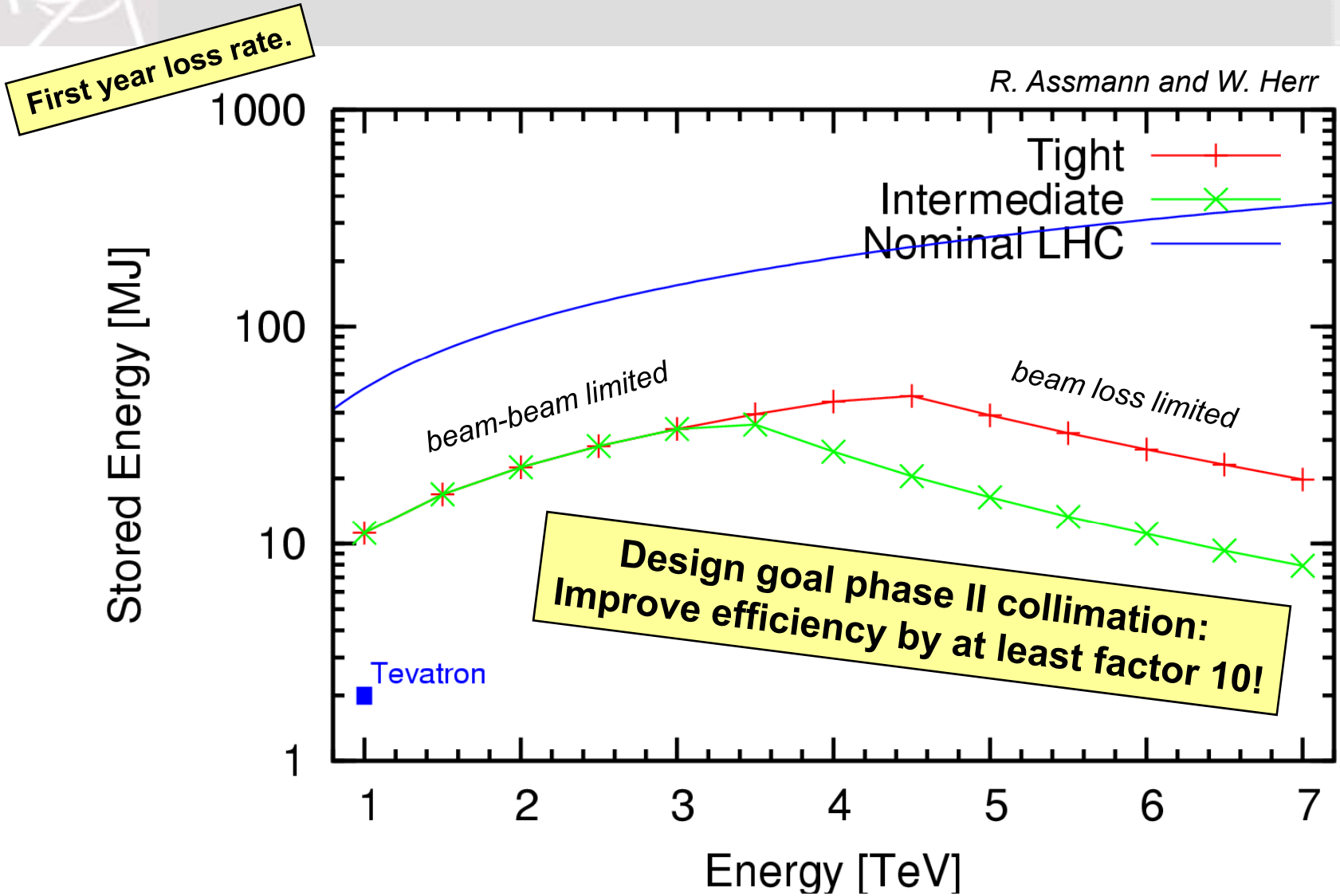
- **Cleaning efficiency (require > 99.995%/m):**
  - Ideal performance reach: **40%** of nominal LHC intensity
    (factor 100 better cleaning than Tevatron/HERA)
  - With imperfections: **loose up to factor 11** in performance
    (factor 10 better cleaning than Tevatron/HERA)
  - Imperfectionsand losses must be minimized.
  - Upgrade of collimation required ➔ **phase II**.
  - See talks T. Weiler and G. Bellodi.
- **Impedance:**
  - Beam stability limit: **40%** of nominal beam intensity. See talk E. Metral.
- Other possible limitations:
  - Collimator lifetime with radiation damage

Phase I Intensity Limit vs Loss Rate 7 TeV

Settings primary/secondary collimators:
Tight: 6/7 σ. Intermediate: 6/10 σ

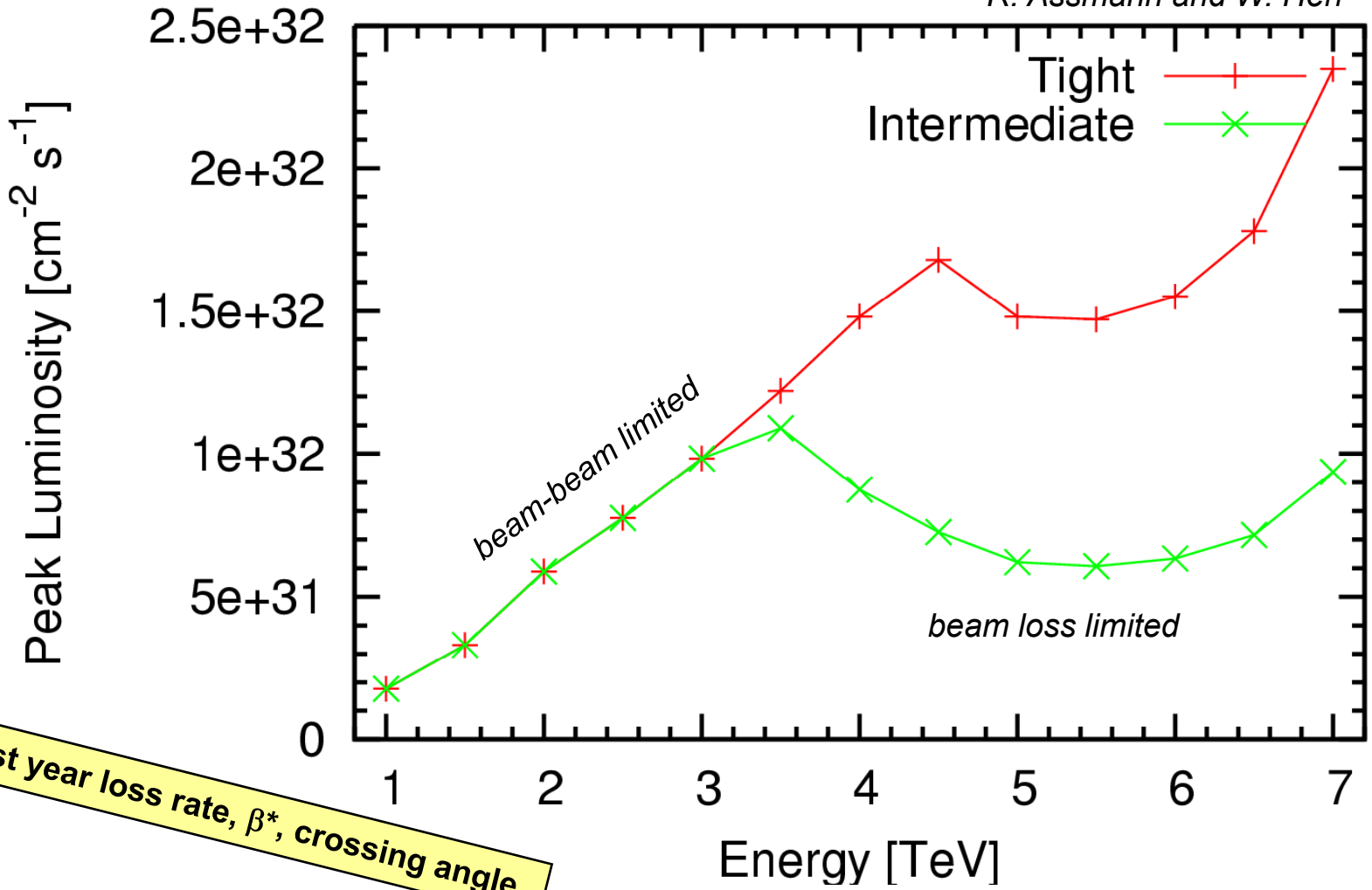


Limit Stored Energy vs Beam Energy



Limit Peak Instantaneous Luminosity

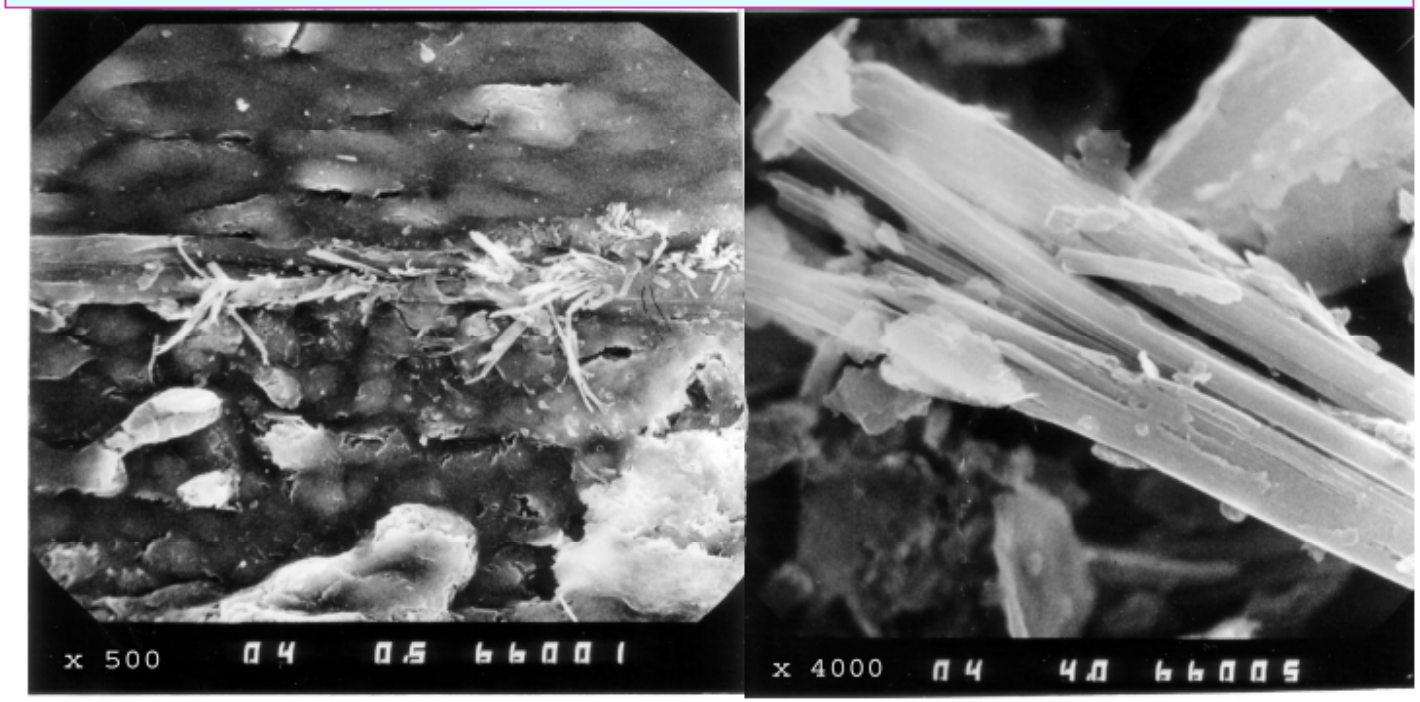
R. Assmann and W. Herr



First year loss rate, β^*, crossing angle.

Other Limit: Radiation Damage (p & ion)

Analysis of Radiation Induced Erosion in Graphite Composite Material AC Irradiated by Carbon Ions with the Energy 5 MeV at Irradiation Dose: 1x10 E17 p/см 2



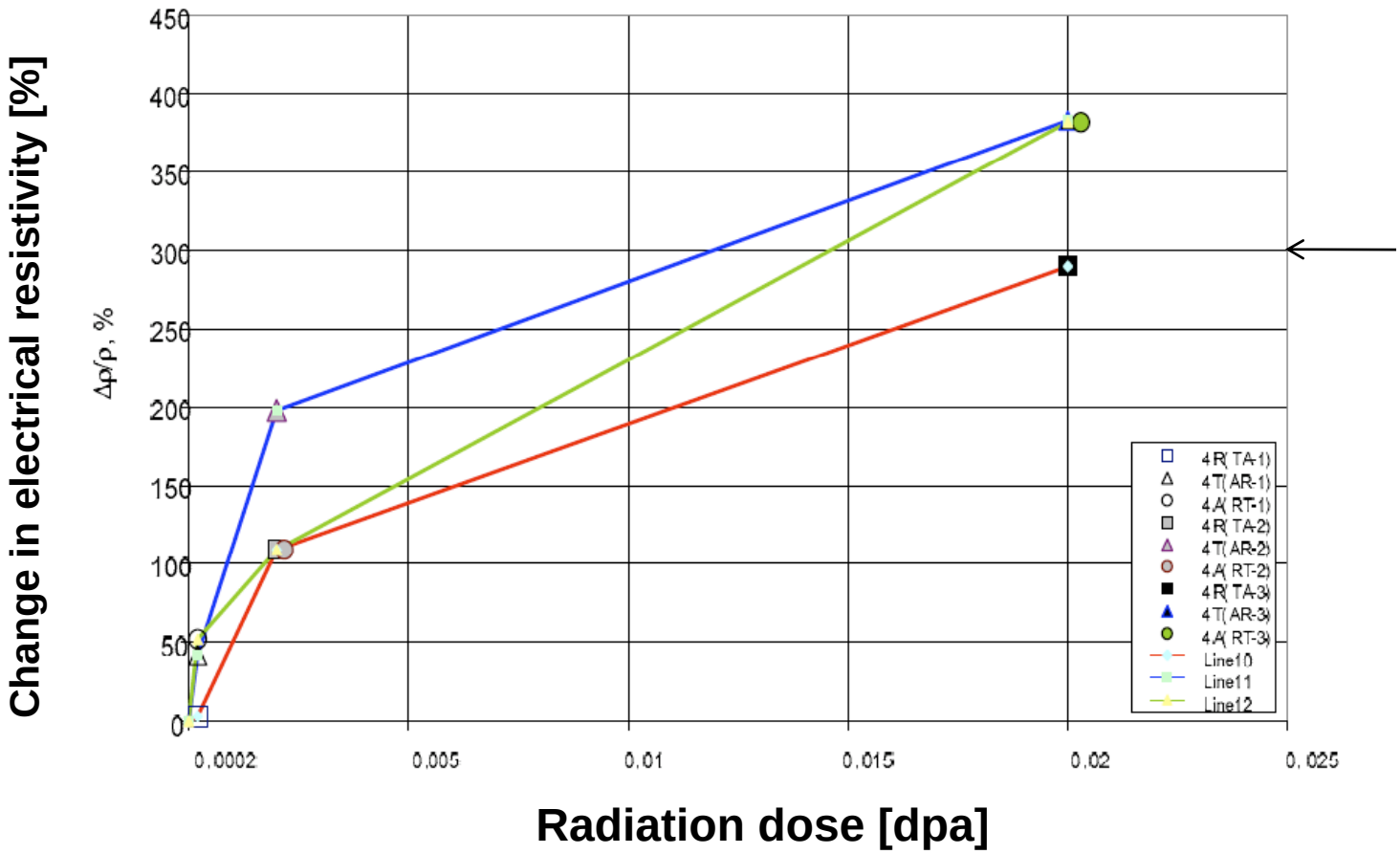
A. Ryazanov

➔ **Working on understanding radiation damage to LHC collimators from 10^{16} impacting protons of 7 TeV per year. Also with BNL/LARP…**

… in addition shock wave models…

Radiation Effect on Electrical Resistivity

(measured at Kurchatov Institute in Russia)



Four times electrical resisitivity:

higher impedance!

A. Ryazanov

Collimator properties will change with time ➔ many properties checked.

Beneficial to distribute radiation over phase I and phase II collimators!

4) The Phase II Solution

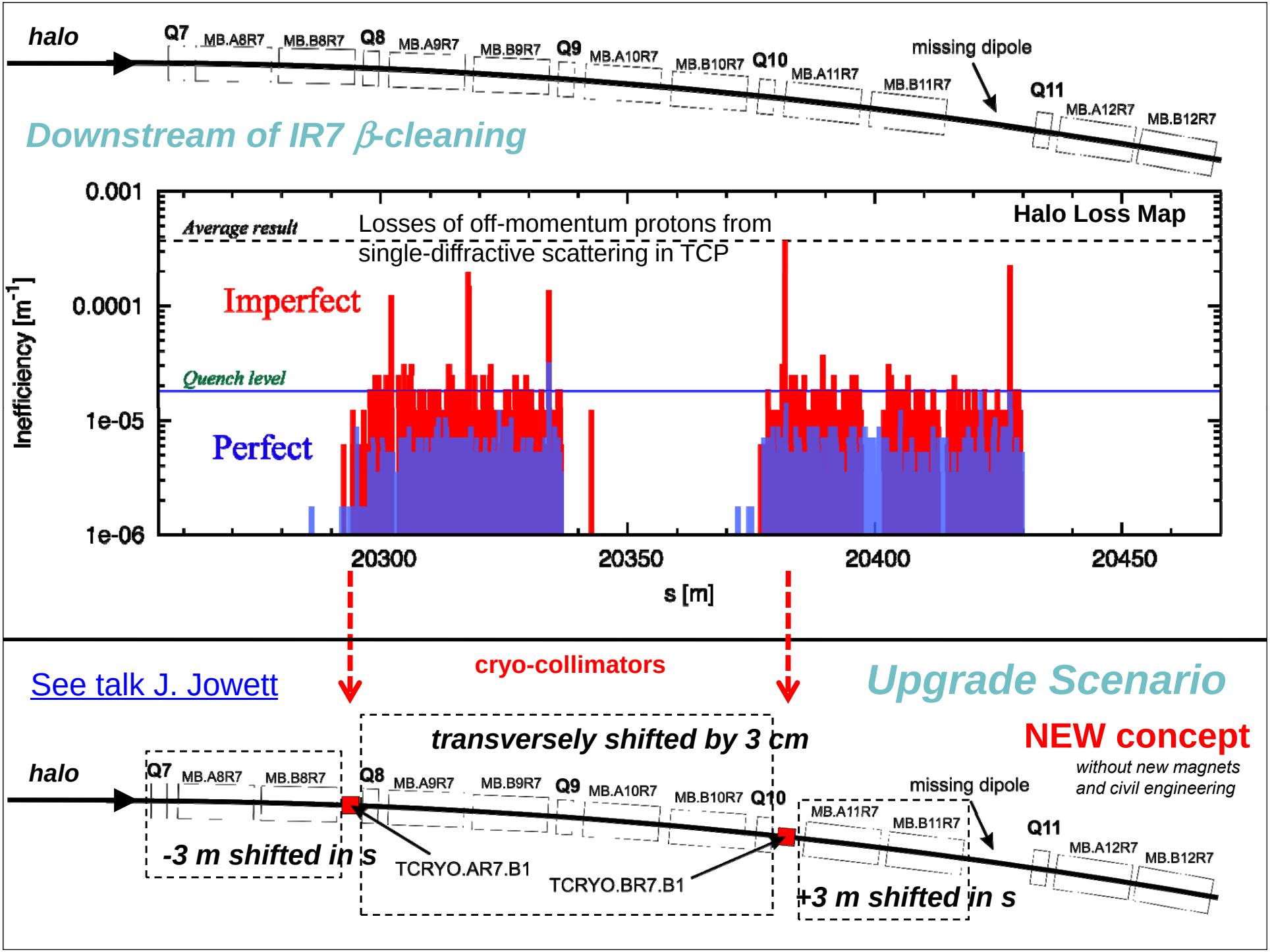
- Phase 2 collimation project on R&D has been included into the CERN white paper, new initiatives (LCI-COLL):
  - We set up **project structure** in January 2008. Key persons in place. Some work packages agreed.
  - Two lines: (1) Upgrade of collimation and improved hardware. (2) Preparation of beam test stand for test of advanced collimators.
  - After this review take first decisions.
- US effort (LARP, SLAC) is ongoing. First basic prototype results shown at EPAC08. See talk T. Markiewicz.
- FP7 funded program EUCARD with collimation work package "ColMat":
  - Makes **available additional resources** (enhancing white paper money).
  - Remember: Advanced collimation resources through FP7 (**cryogenic collimators with GSI, crystal collimation, e-beam scraper,** …). See talks W. Scandale and J. Smith.

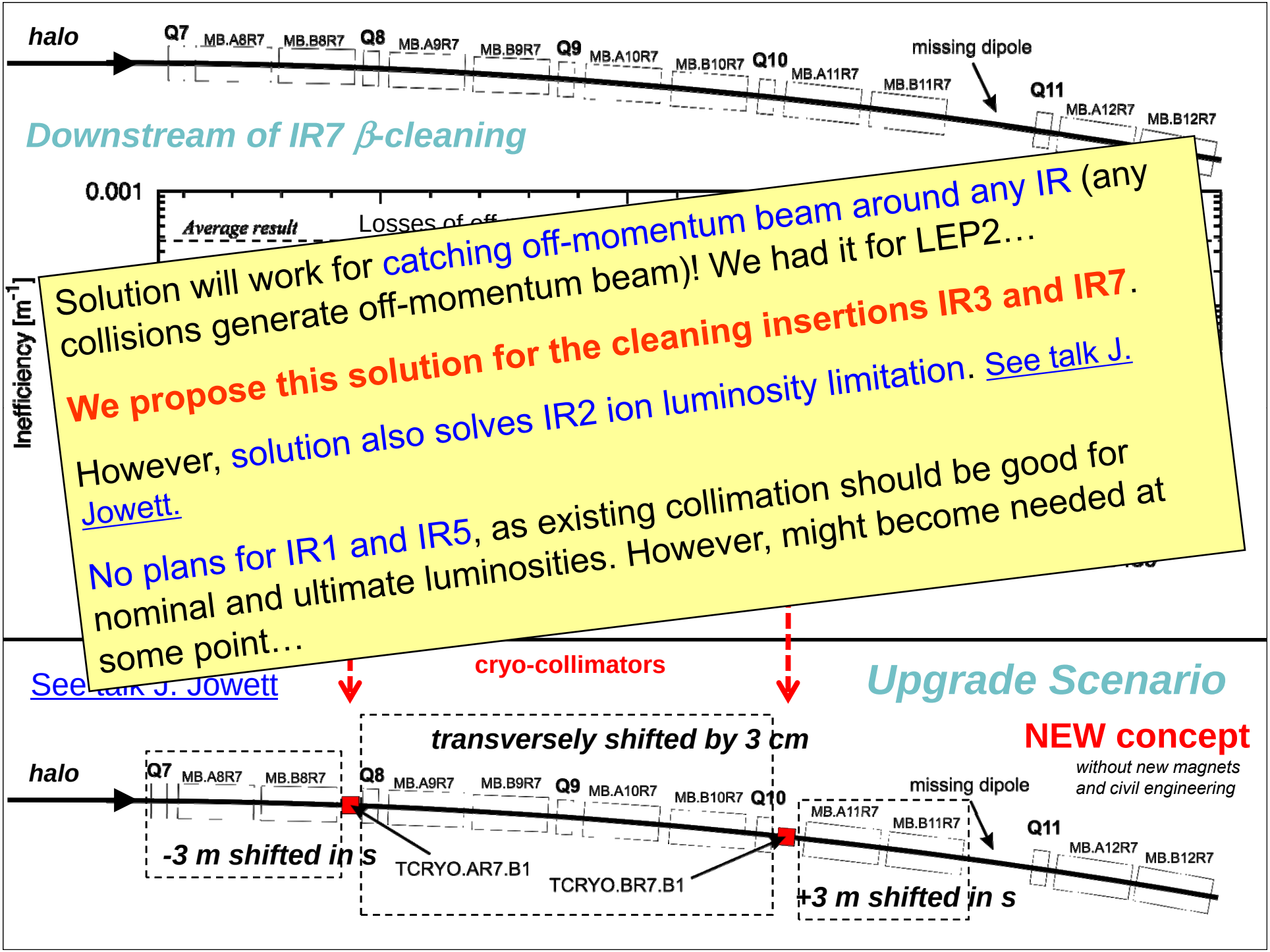
Phase II: Part 1

Modification of SC dispersion suppressors to accommodate additional collimators (“cryo-collimators”)

The 2008 Breakthrough

- The limitation (single-diffractive p scattering, ion fragmentation and dissociation) was understood early on in 2003/4 but it was too late to change cold areas.
- Possible solutions were discussed:
  - New, shorter and stronger dipole magnets to place collimators into SC area.
  - Enlarged tunnel in cleaning insertions to place stronger dogleg dipole magnets and put dispersive chicanes.
  - Other drastic measures…
  - All was **very heavy and not really realistic**.
- Breakthrough in 2008: We realized that we can use missing dipole space and rearrange magnets to create proper space for additional collimators.
- **Efficiency gain:** **Factor 15** for perfect machine simulated
  Factor 90 for imperfect machine predicted


halo
Q7
MB.A8R7
MB.B8R7
Q8
MB.A9R7
MB.B9R7
Q9
MB.A10R7
MB.B10R7
Q10
MB.A11R7
MB.B11R7
missing dipole
Q11
MB.A12R7
MB.B12R7
Downstream of IR7 β-cleaning
Halo Loss Map
Average result
Losses of off-momentum protons from
single-diffractive scattering in TCP
Imperfect
Quench level
Perfect
Inefficiency [m-1]
0.001
0.0001
1e-05
1e-06
20300
20350
20400
20450
s [m]
cryo-collimators
See talk J. Jowett
Upgrade Scenario
NEW concept
without new magnets
and civil engineering
transversely shifted by 3 cm
-3 m shifted in s
TCRYO.AR7.B1
TCRYO.BR7.B1
+3 m shifted in s



Solution will work for catching off-momentum beam around any IR (any collisions generate off-momentum beam)! We had it for LEP2…

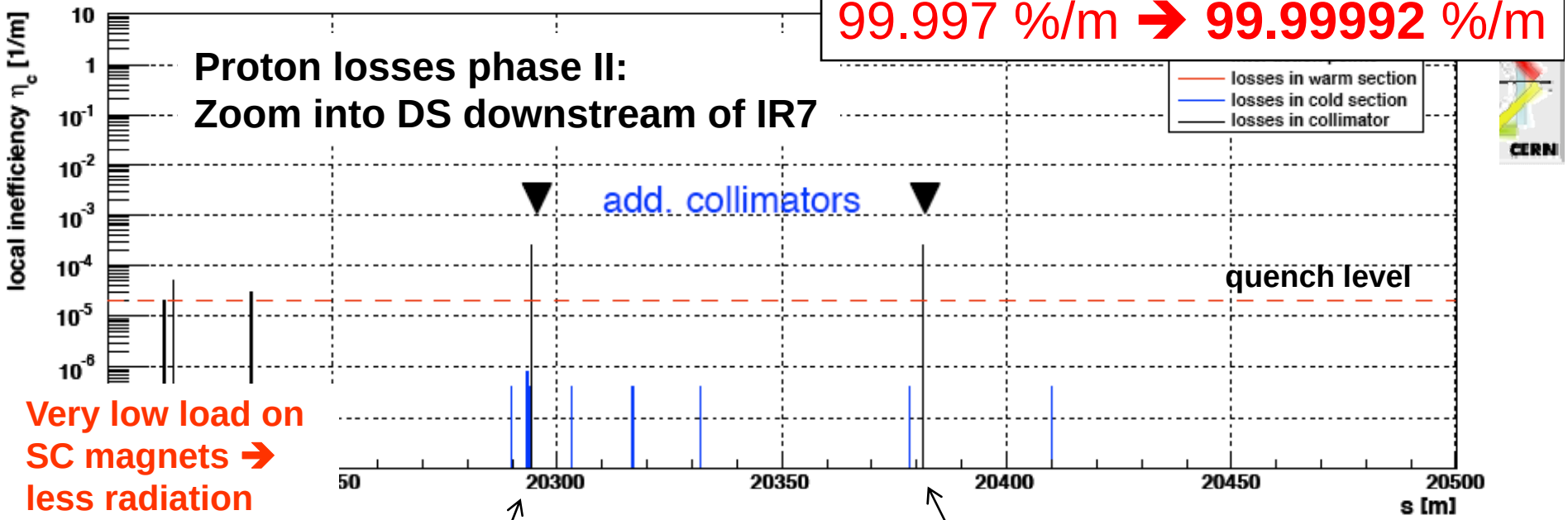
We propose this solution for the cleaning insertions IR3 and IR7.

However, solution also solves IR2 ion luminosity limitation. See talk J. Jowett.

No plans for IR1 and IR5, as existing collimation should be good for nominal and ultimate luminosities. However, might become needed at some point…

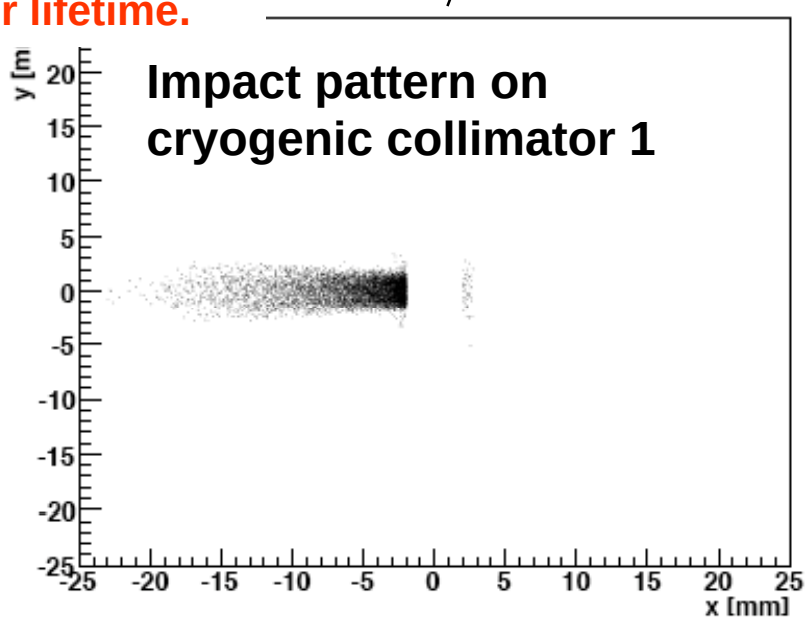
See talk J. Jowett

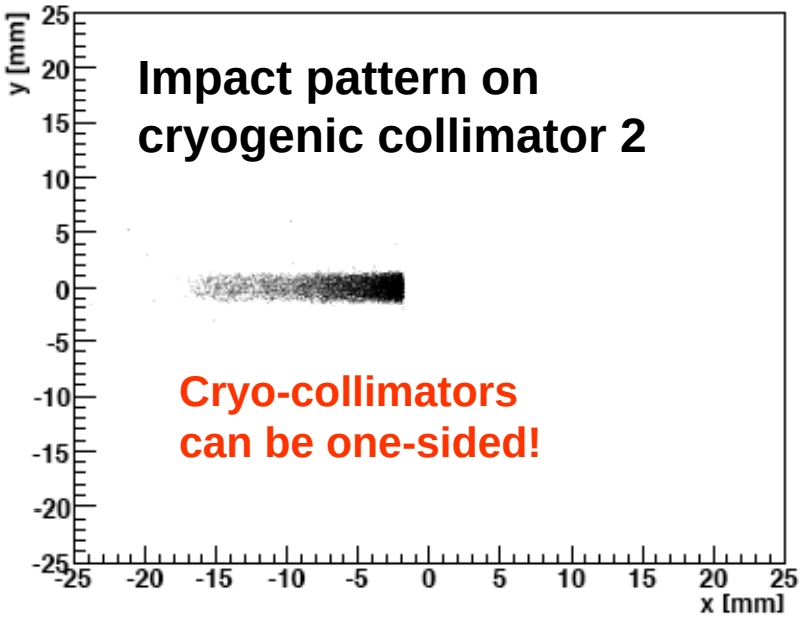
99.997 %/m ➔ **99.99992** %/m



Very low load on SC magnets ➔ less radiation damage, much longer lifetime.

T. Weiler





See talk T. Weiler

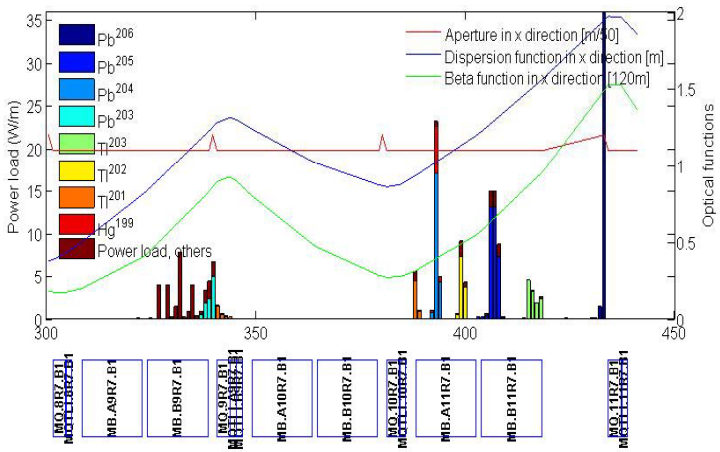
FLUKA Results

- Proton and ion tracking do not take into account showers.
- FLUKA provides more realistic estimates of energy deposition in SC magnets.
- Results for p:

Case	Peak Energy Deposition
Phase I	**5.0 mW/cm^3**
Phase II, 1 m Cu	**1.0 mW/cm^3**
Phase II, 1 m W	**0.3 mW/cm^3**

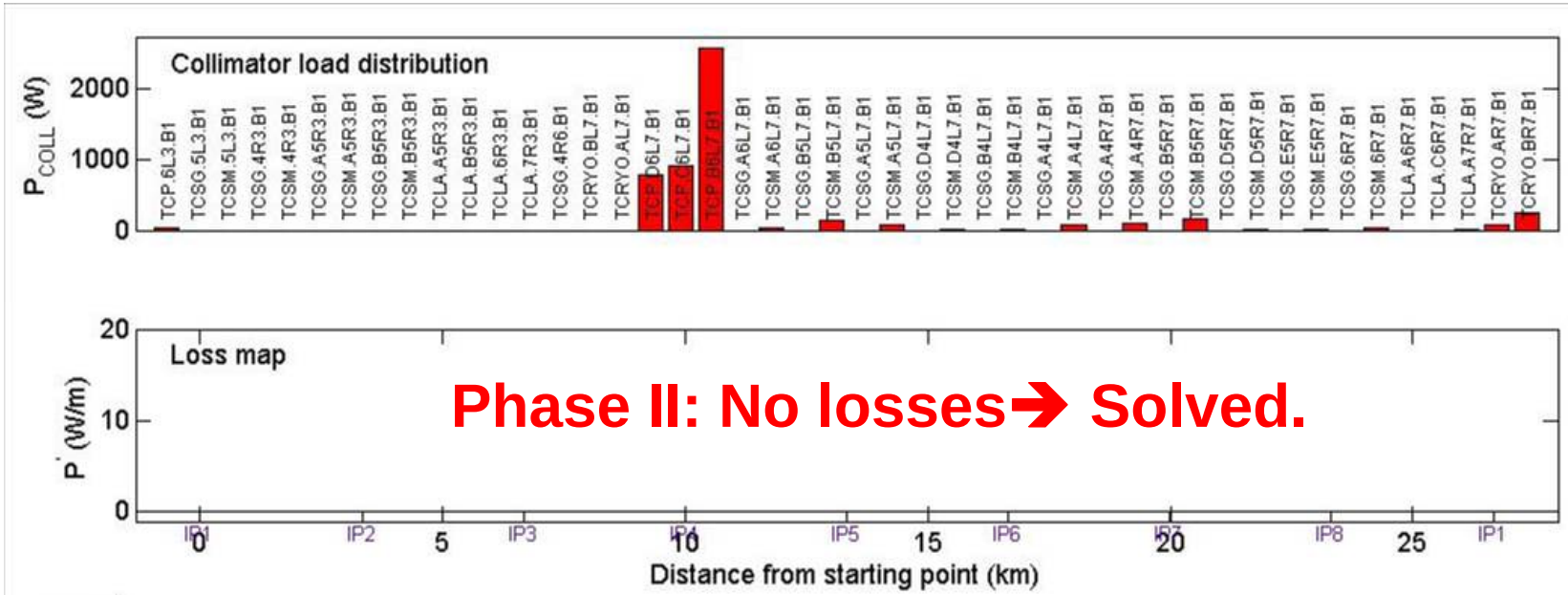
- **Factor 15** predicted from FLUKA simulations for p. Similar gains for ions.
- See talk F. Cerutti.
- Additional gain expected with imperfections (aperture steps from misalignments shadowed with collimators). See talk S. Redaelli.
- **Total efficiency gain will be between factor 15 to 90!**

Ion Efficiency with Cryo-Collimators



Phase I: Many losses. Limited to ~50% of nominal ion intensity.

See talk G. Bellodi.

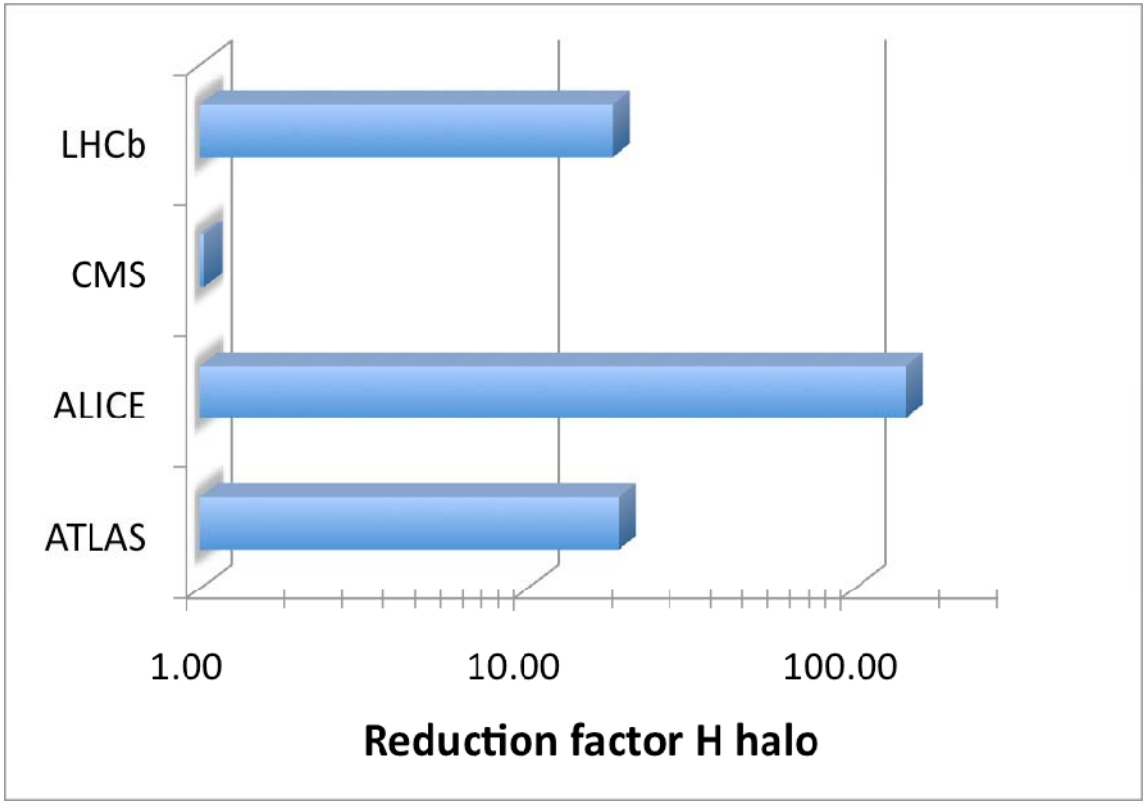


Phase II: No losses➔ Solved.

Remarks Cryo-Collimators

- Strictly speaking we mean collimators in the cryogenic region just after the long straight sections.
- These cryo-collimators can be warm elements (requiring cold-warm transitions) or cryogenic elements.
- Term comes from GSI, as designed for the FAIR project. They use collimators at about 50 K.
- Technical choice must be outcome of detailed technical design work.
- FLUKA studies ongoing to define best length and material.
- For our studies: **Cryo-collimator = 1 m long Cu or W block**
- Very low temperature is not important.
- Radiation studies show that both materials are feasible. Installation constraints from radiation must be taken into account. See talk H. Vincke.

Load Experimental Collimators (Beam 1)

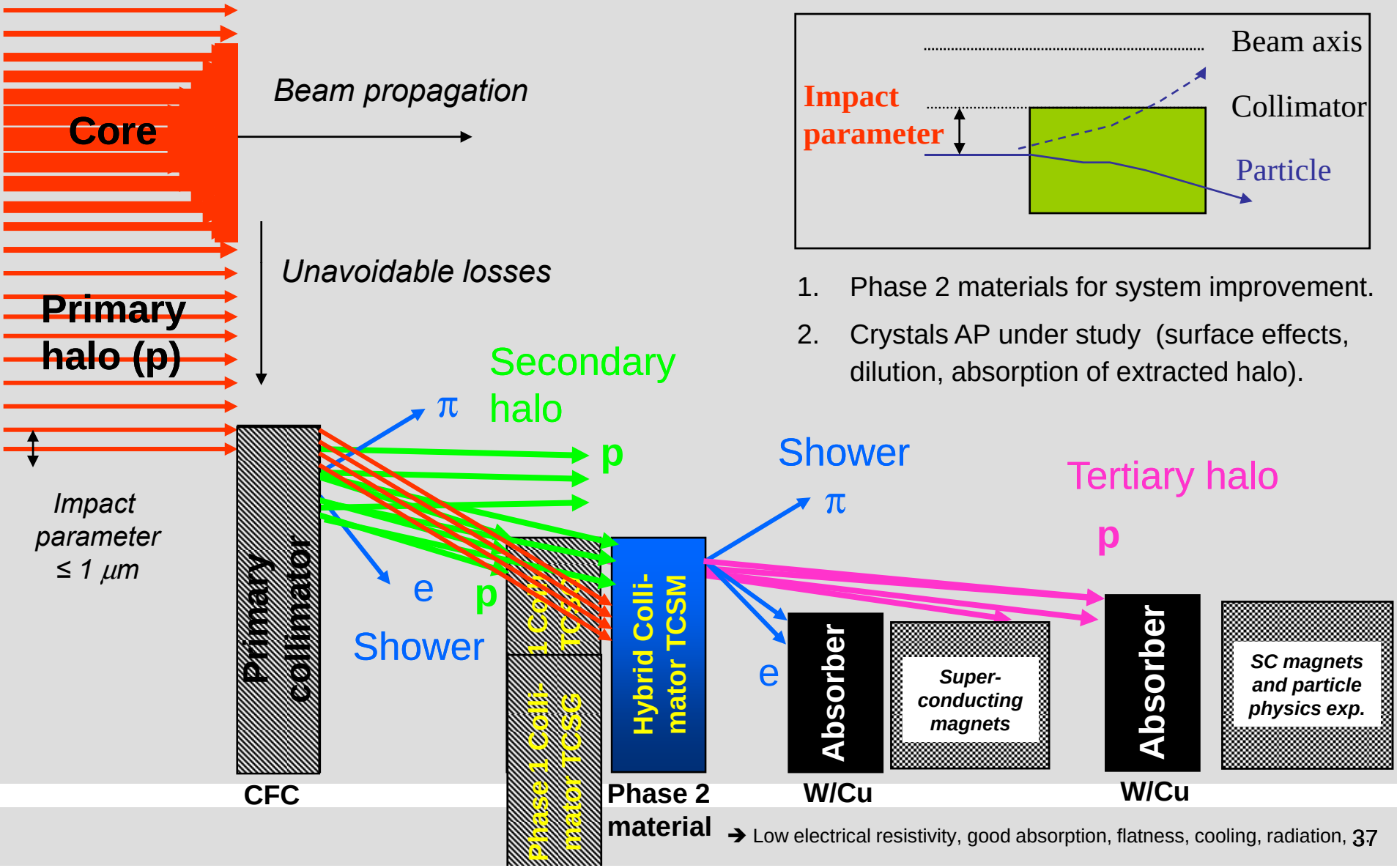


See talks T. Weiler and G. Bellodi.

- Figure shows average reduction in loss at horizontal tertiary collimators in the various insertions (collimation halo load). CMS is not improved as cryo-collimators were not yet included in IR3.
- Phase II collimation upgrade reduces losses in IR's by a factor up to 100!

Advanced Secondary Collimators for Pre-Equipped Phase II Slots

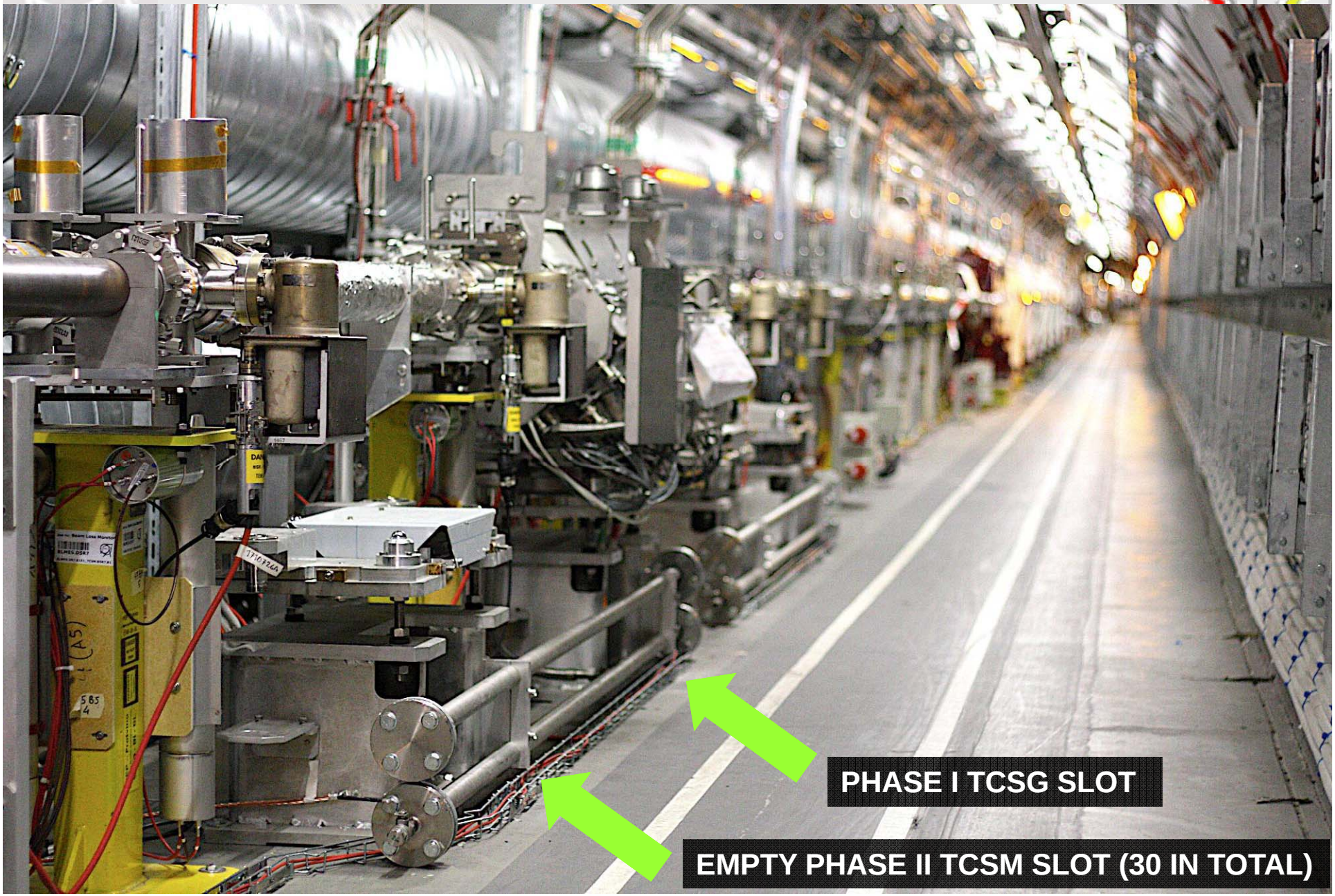
LHC Phase II Cleaning & Protection



1. Phase 2 materials for system improvement.
2. Crystals AP under study (surface effects, dilution, absorption of extracted halo).

➔ Low electrical resistivity, good absorption, flatness, cooling, radiation,

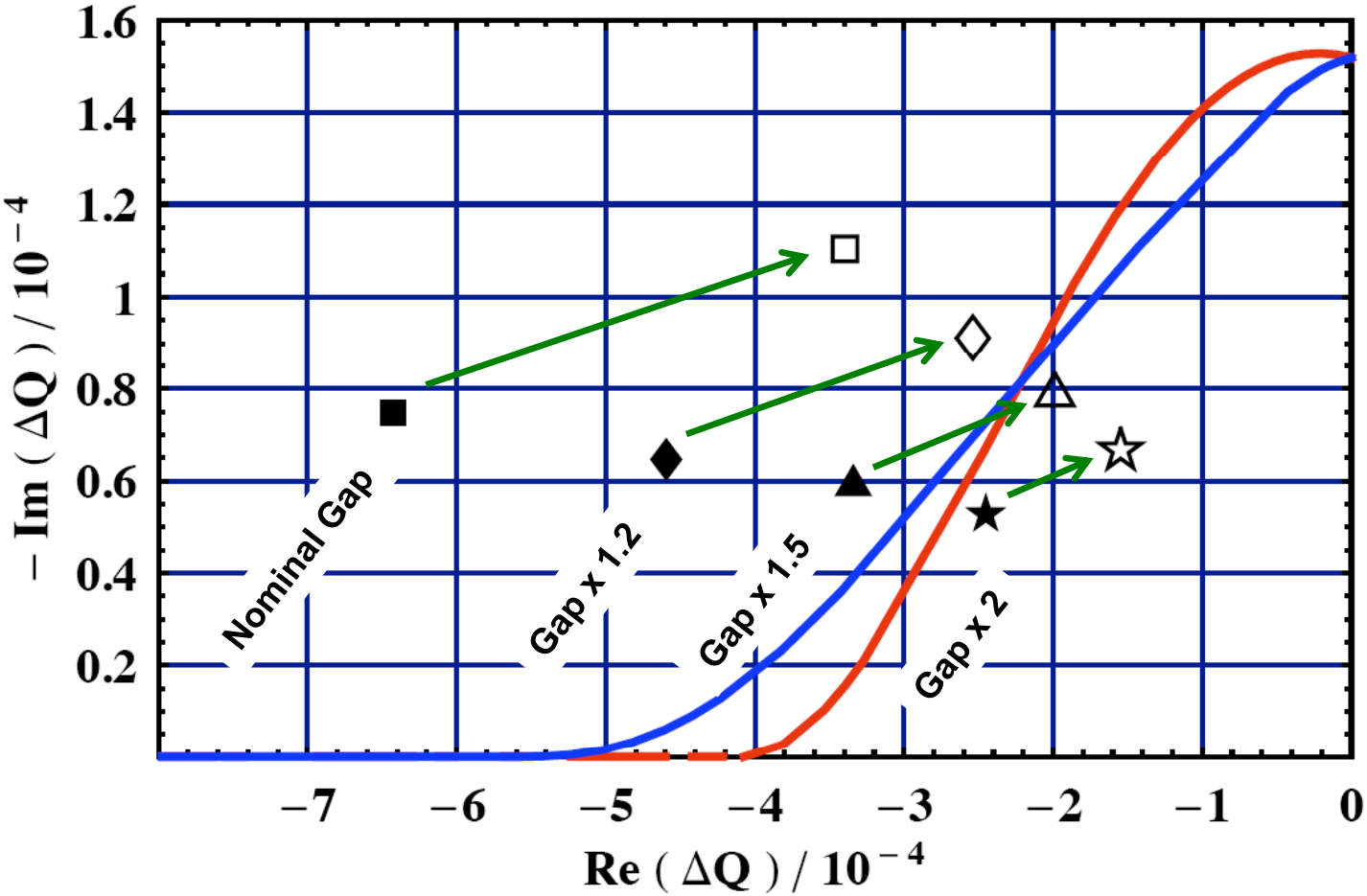
Phase II Secondary Collimator Slots



Phase II Advanced Secondary Collimators

- Will not very much improve the cleaning efficiency.
- However, will implement other important improvements:
  - Reduction in **impedance** (see talk E. Metral).
  - Non-invasive and fast collimator setup with **BPM buttons in jaw** (see talks A. Bertarelli and S. Redaelli).
  - Improvement of **lifetime for warm magnets** in cleaning insertion by factor ~3 (see talk F. Cerutti).
  - Improvement of **lifetime for phase I collimators** as radiation load is spread over phase I and phase II collimators.
- Design and prototyping has started. Material will be decided based on LHC beam experience: either Cu or ceramics/advanced composites. See talks E. Metral, A. Bertarelli, T. Markiewicz.
- Will not ensure collimator robustness but may include rotatable solution for handling many damages in-situ. See talk T. Markiewicz.

Impedance with SLAC Design and Cryo-Collimators



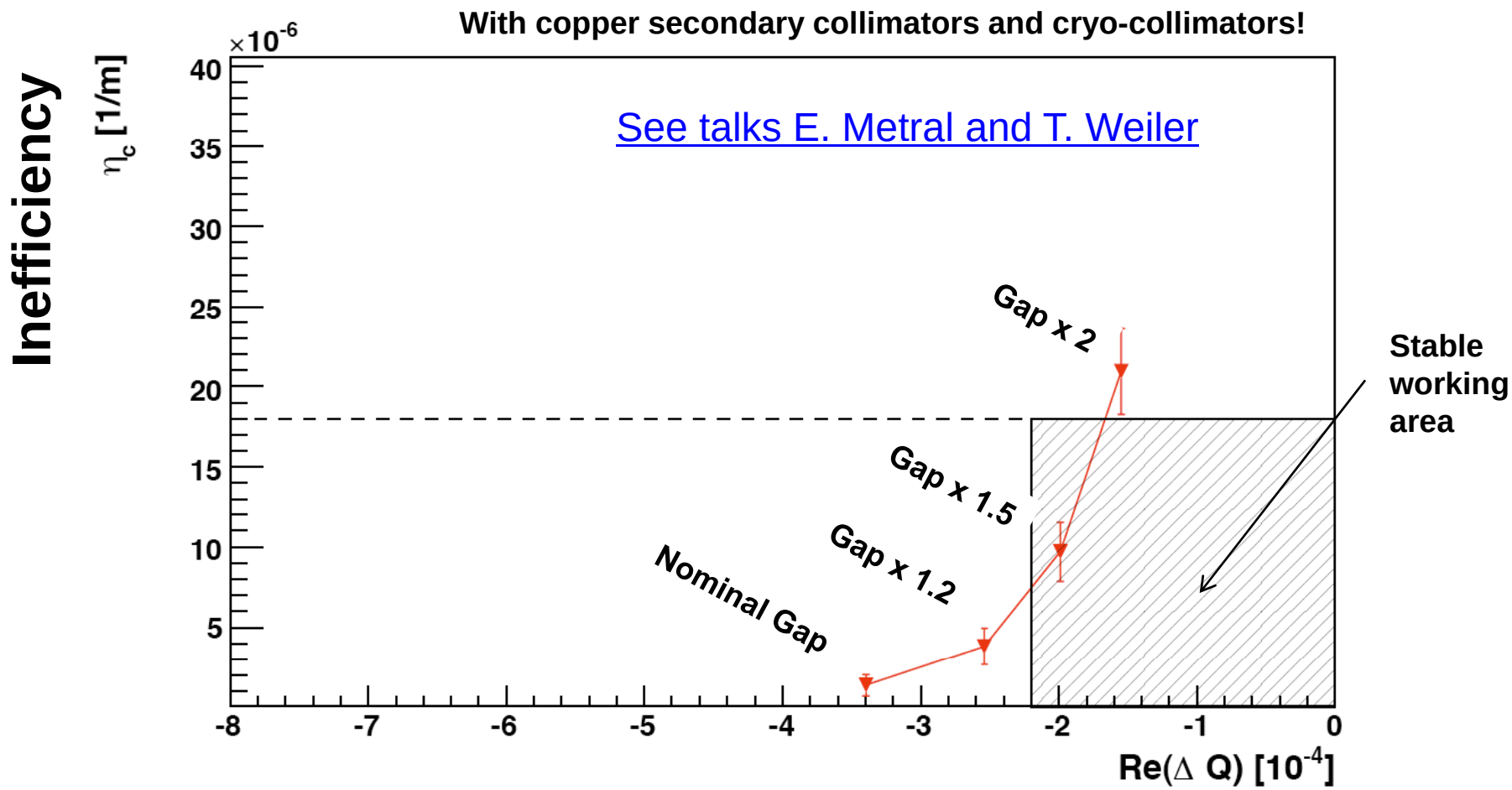
Baseline:

Stabilize with transverse feedback!

See talk E. Metral.

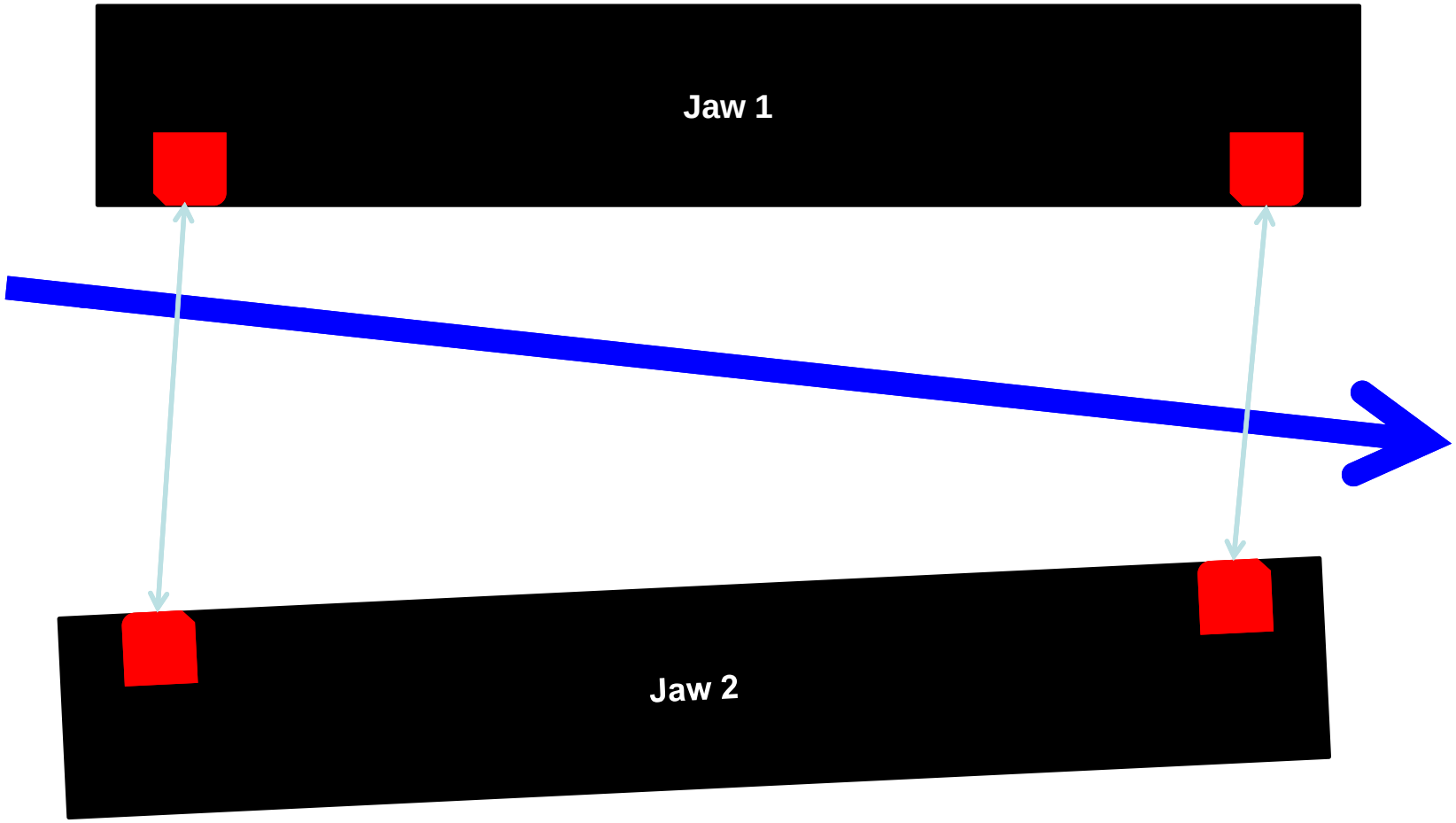
Metallic Cu secondary collimators (phase II) require less gap opening for stability ➔ illustrates lower impedance compared to phase I!

Phase II: Tradeoff p Inefficiency – Impedance (if transverse feedback cannot stabilize)



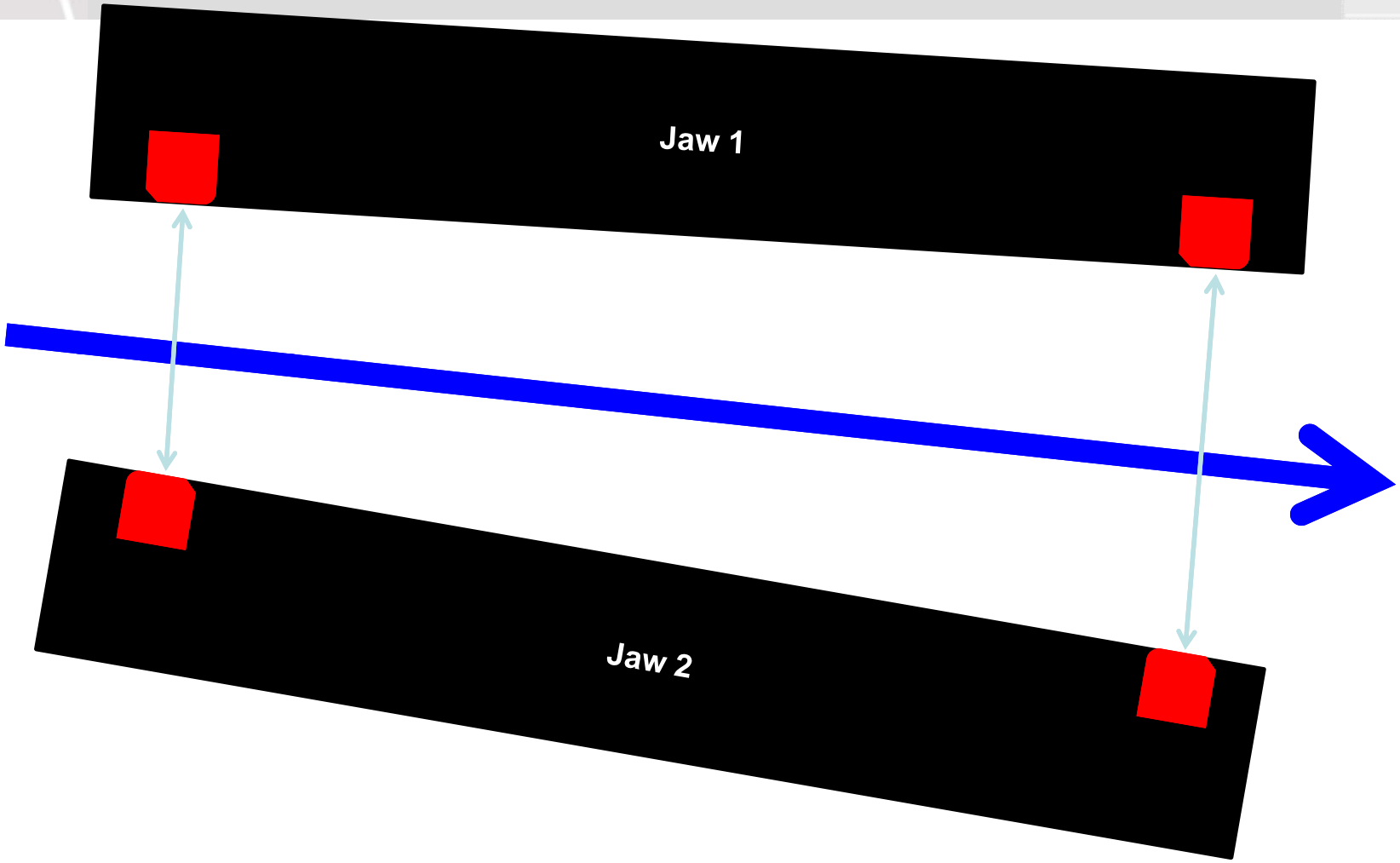
Phase II allows stable working point by opening gaps! Requires larger β*…

Non-Invasive Set-up with BPM Buttons



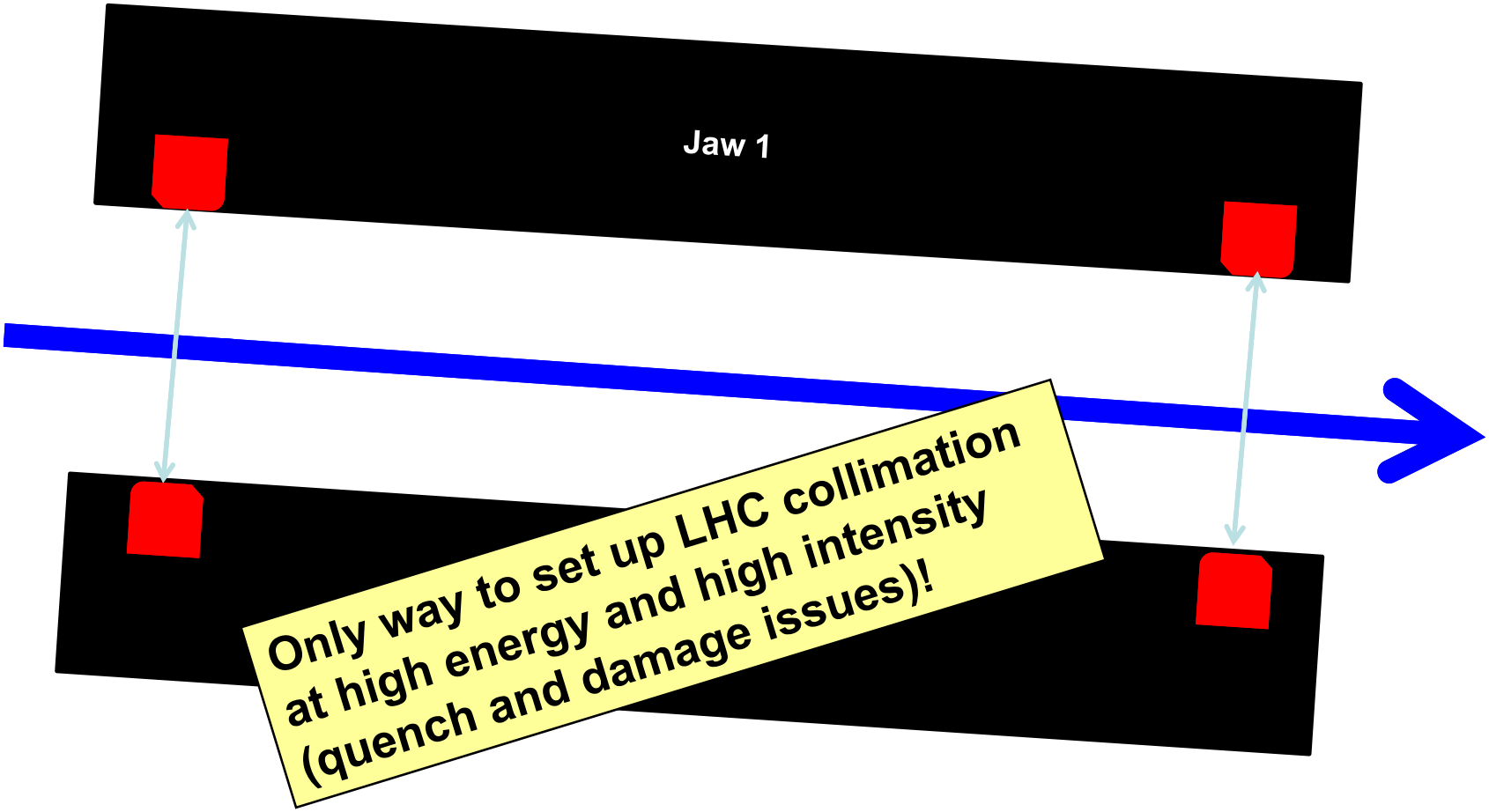
See talks A. Bertarelli and S. Redaelli.

Non-Invasive Set-up with BPM Buttons



1) Center jaw ends around beam by zeroing difference signal from pair of pickups.

Non-Invasive Set-up with BPM Buttons



2) Put the same gap at both ends as measured from jaw position (phase 1 feature).

Test Needs: HiRadMat

- Phase I was putting robustness first for near-beam collimators.
- Phase II considers using less robust collimators in stable physics.
- Assumptions:
  - **Rare damaging events.**
  - **Benign damage in case of hit.**
- Risk of non-benign risk must be assessed before installation of such collimators. Any LHC damage is much too expensive!
- Requires beam test area **HiRadMat**. 2 MJ pulsed beam at ~450 GeV from SPS for accident scenario test.
- Several collimator types will be tested, however, test facility also required for testing machine protection elements (absorbers, masks, dump, …).
- External interest for other applications (GSI, SLAC, universities, …).
- See talk I. Efthymiopoulos.

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

Abstract

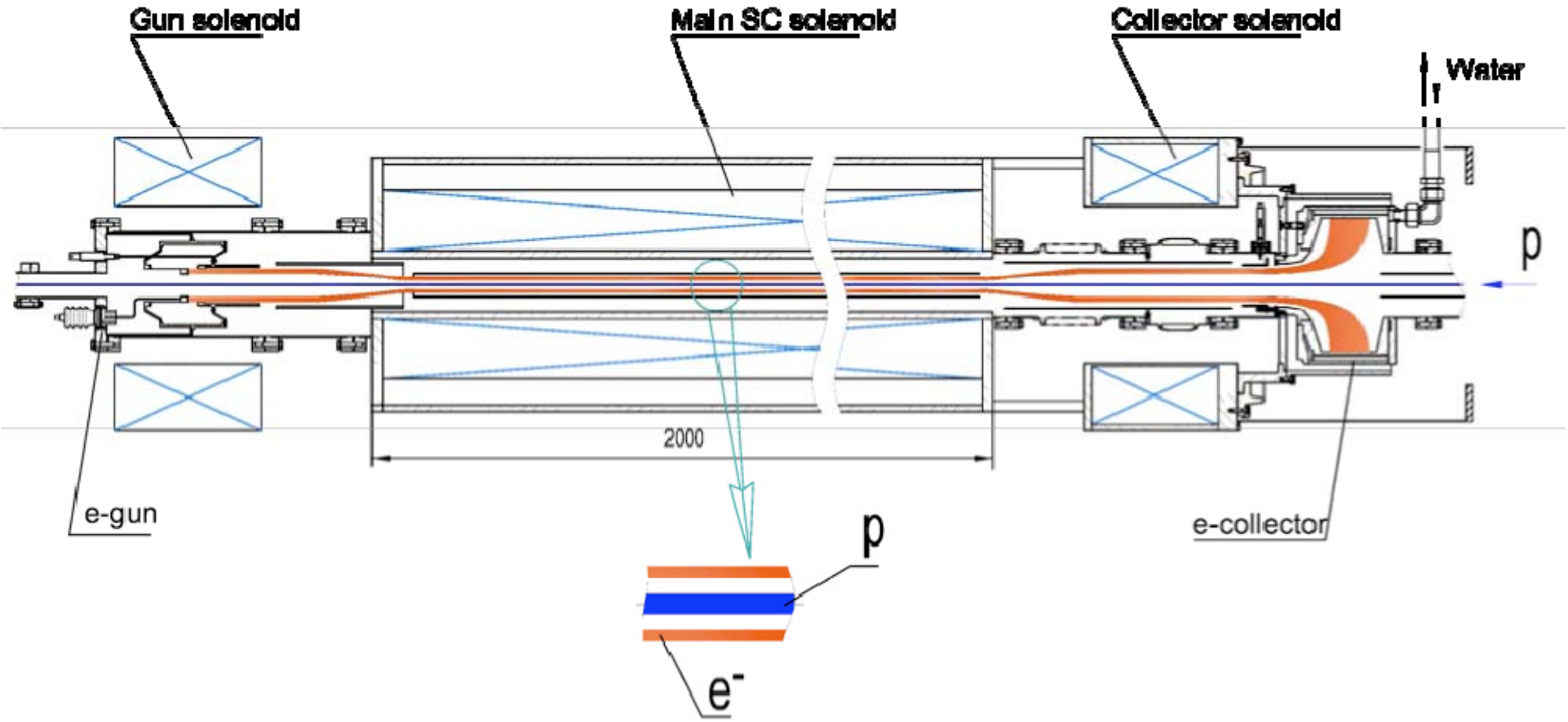
The characteristics of the LHC beam mean that the energy deposited in the event of interaction with accelerator components can be much above the damage thresholds of materials. This report specifies a test facility with high intensity LHC-type beam, as included in the framework of the "phase 2 LHC collimation project" and the "EUCARD proposal to FP7". The specified facility is required to test accelerator components and materials for sufficient robustness with beam shock impact, prior to installation into the LHC or its injectors. A 7 μs long pulse can be extracted about every 30 seconds and delivered into a small transverse area (controllable around 1 mm^2), carrying an energy of up to 2 MJ. The corresponding pulsed peak power is 340 GW for protons and 2.3 GW for lead ions. The facility will also provide opportunity for reproducing and analyzing any possible primary and secondary effects from beam-induced damage encountered during LHC operation.

Hollow e-Beam Lens for Scraping and for Limiting Peak Loss Rates

Loss Rates and Scraping

- Beam tails develop during operation and extend up to the boundary defined by the primary collimator walls.
- Any small "shaking" of the beam will induce a small beam loss, often modulated by the synchrotron tune (no smooth loss rate as assumed for the LHC). Often significant losses when bringing beams into collision.
- **Spiky behavior of beam loss and background worsens situation for beam cleaning**.
- Standard technique: Scraping (removal) of beam tails after/during the energy ramp and squeeze to avoid this effect (Tevatron, RHIC).
- Impossible for the LHC due to high power beams (no scraping below 5 sigma). No scrapers have been built. See talk F. Cerutti.
- Solution: **Use e-beam lens, used routinely as scraper in Tevatron. Adapt to provide hollow lens!** See talk J. Smith.

The Tevatron e-Beam Lens



See talk J. Smith.

Beyond Phase II

- The LHC foresees two upgrades of the insertions: Phase I triplet upgrade and a phase II insertion upgrade.
- Parameters for the second upgrade are ambitious and require further increased intensity.
- An R&D program on advanced collimation techniques is ongoing with a present focus on crystal collimation. Beam tests at SPS and Tevatron.
- See talk W. Scandale.
- This technology is not yet ready for implementation into an operational machine. Also, it would require major changes in the cleaning insertions (installation of MW class halo dump).
- Advanced collimation pursued as a long term upgrade to LHC collimation.

… wrapping it up …

Proposed Technical Work Plan

Fastest Possible Readiness for Nominal Intensity

- Technical design for **modified dispersion suppressors** in IR3/7. Design & build new cryostat for missing dipole. ➔ CERN.
- Start R&D on "**cryo-collimators**" for modified dispersion suppressors.

WP's A
No need for major testing, beam experience.

- Continue R&D on **advanced, low impedance materials** for LHC collimators. ➔ CERN, FP7.
- Continue R&D, prototyping and testing of **phase II secondary collimators**, in-jaw pick-ups and various jaw materials. Construct 30 plus spares. ➔ CERN/FP7, SLAC/LARP.
- Install **HiRadMat facility** for beam verification of advanced designs, following conceptual design ➔ CERN, SLAC.

WP's B
Continue to be ready for 2013/14. Needs major testing and beam experience.

- Start R&D, prototyping and testing on **hollow e-beam lens** for LHC scraping. ➔ FNAL, CERN.

WP's C
R&D and beam testing required.

- Minor modifications of **collimation in experimental insertions**.

WP's D

Schedule for Discussion

(ambitious and result-oriented "wish" schedule)

Year	Milestone
2009	Conceptual solution presented. Start/continuation of serious technical design work on all work packages (delays will shift all future milestones).
2010	Review of lessons with LHC beam. Technical design review.
2011	HiRadMat test facility completed and operational.
2012	Cryogenic collimation installed and operational ➔ nominal intensity in reach. Production decision for phase II secondary collimators.
2013	Hollow e-beam lens operational for LHC scraping.
2014	Phase II completed with installation of advanced secondary collimators ➔ Ready for nominal & ultimate intensities.

Looking Ahead

- We look forward to comments from the review committee and the report.
- Thanks a lot to all the experts on the committee for their valuable time and the effort spend to help us with advice and a fresh view on LHC collimation.
- We plan to produce a short conceptual design report, summarizing the solution you will be presented today.
- Our goal is to use this review of our conceptual solution as a basis for defining detailed technical work packages in the CERN departments and groups concerned.
- It will require resources in technical groups to define the technical designs, budget needs, manpower and a detailed project schedule.
- Once this work is done, we will organize a technical design review, including detailed schedule, budget and resources.