LHC Phase II Collimation

R. Assmann, CERN/AB

25/11/2008

for the Collimation Project

HHH 08

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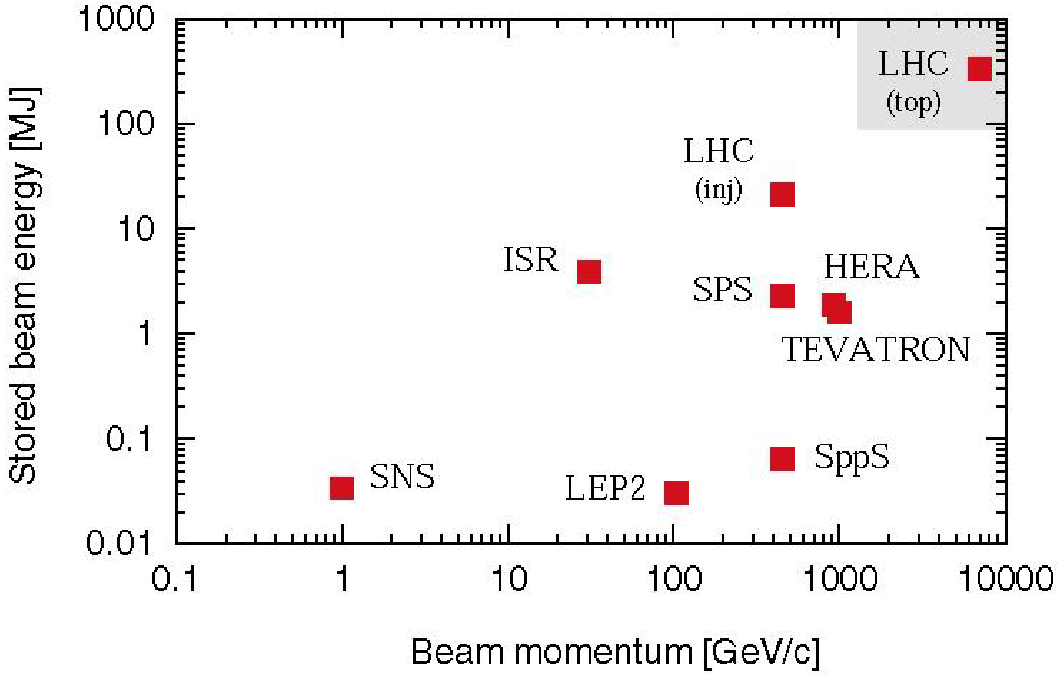
Weiler, AB/BDI, SLAC, …

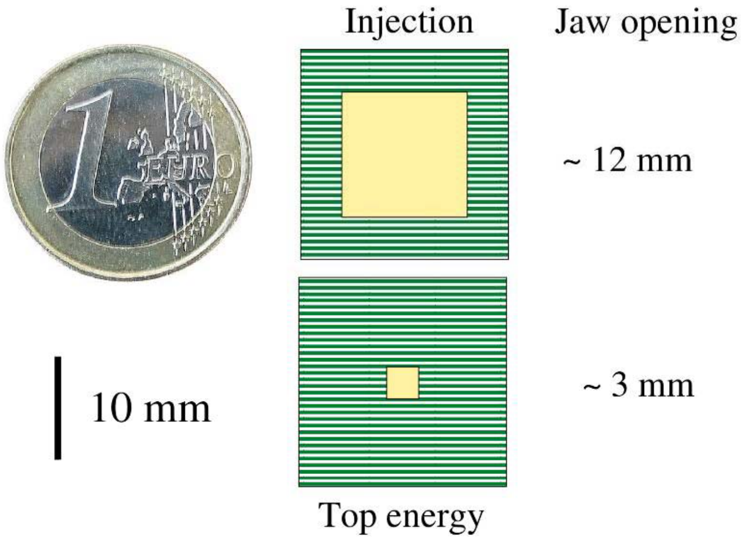
Reminder: The LHC Collimation Challenge

- Many papers discuss requirements and design criteria for the LHC Collimation System. Short reminder:

High stored energy and stored energy density!



Small collimation gaps!



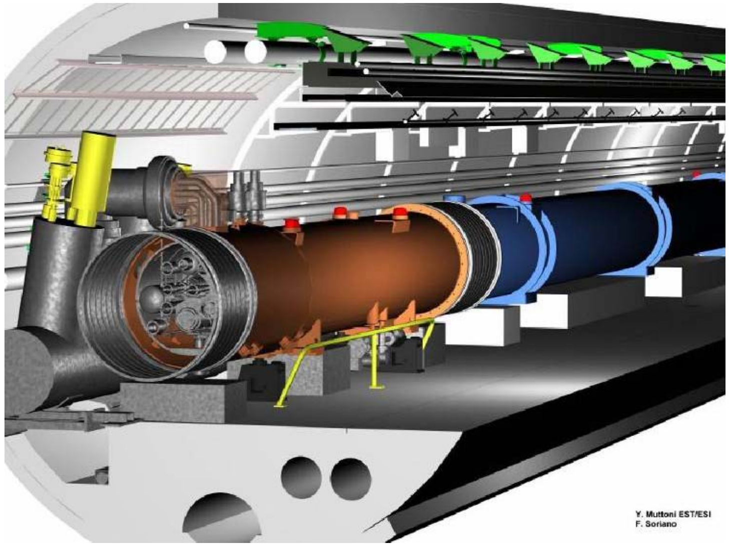
Major Function: Preventing Quenches

- Shock beam impact: **2 MJ/mm^2 in 200 ns   (0.5 kg TNT)**
- Maximum **beam loss at 7 TeV**: 1% of beam over 10 s

500 kW

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

8.5 W/m



Y. Muttoni EST/ESI
F. Soriano

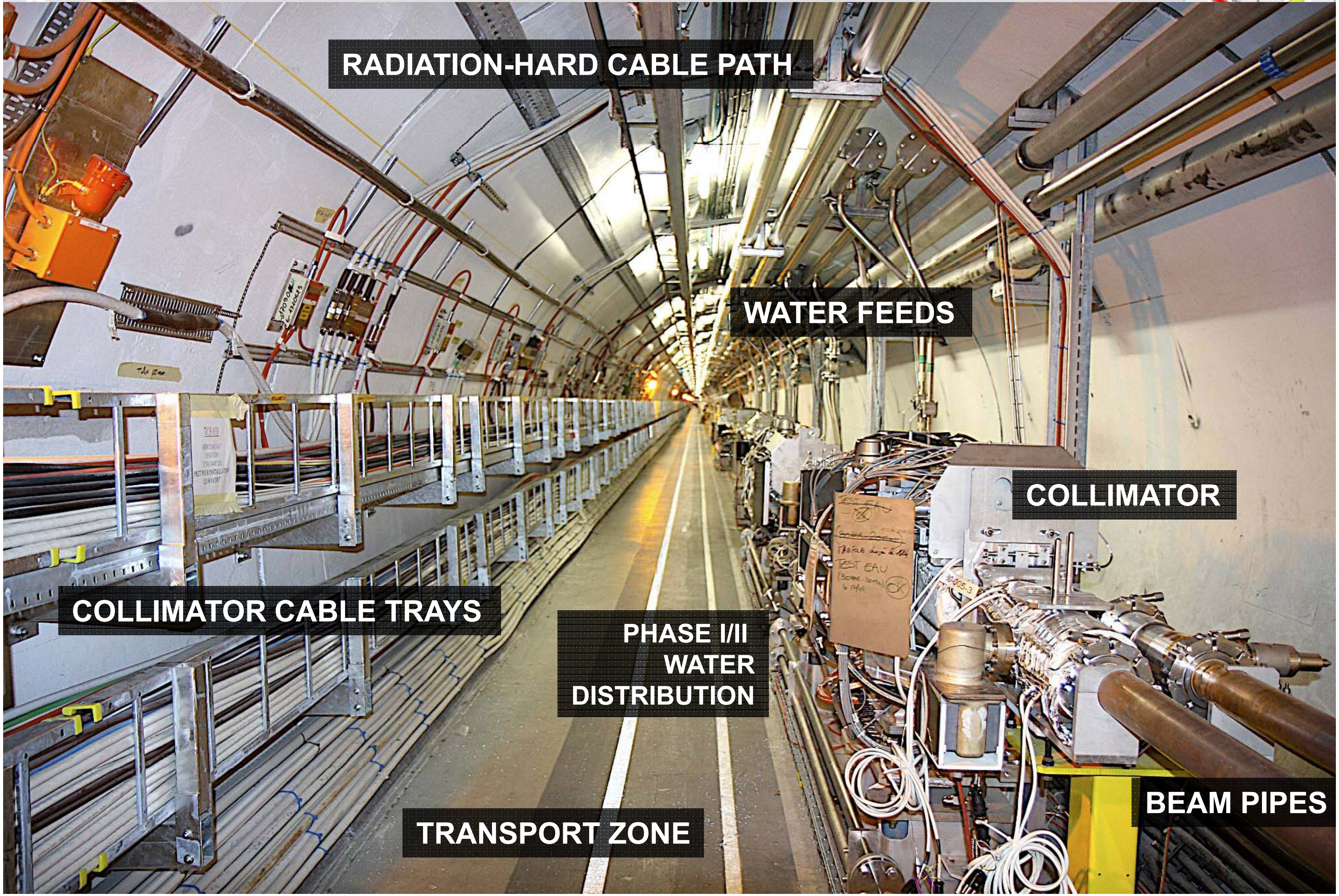
The Phased LHC Collimation System

- Huge LHC extrapolation in stored energy and predicted limitations in phase I system:

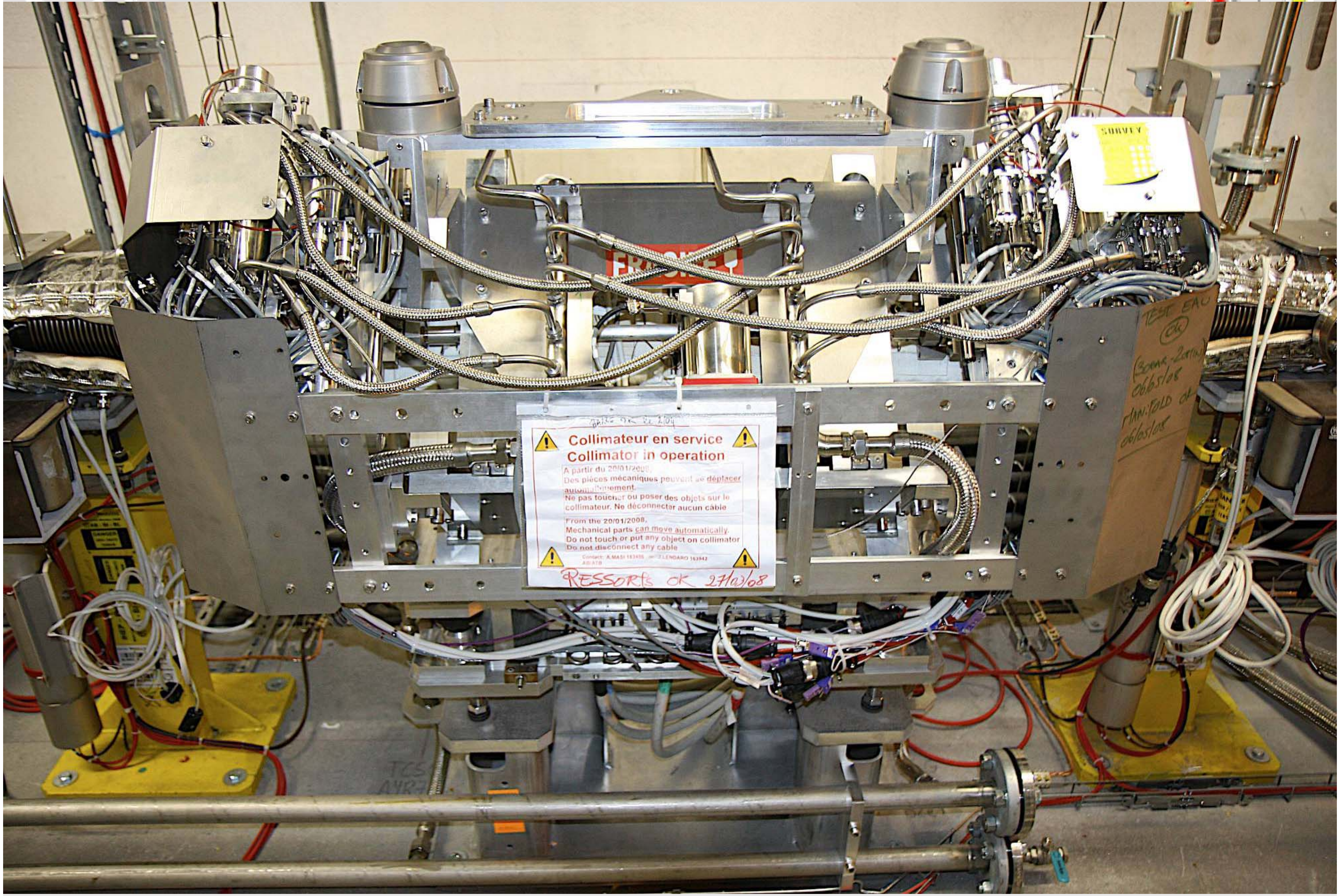
  > *The LHC collimation system was conceived and approved during its redesign in 2002/3 always as a staged system.*

- Phase I collimators will stay in the machine and will be complemented by additional phase II collimators.
- Significant resources were invested to prepare the phase 2 system upgrade to the maximum extent.
- Phase II slots in the LHC layout:
  - Secondary collimators: Empty slot after each secondary collimator of phase I, fully equipped with cables, water, base supports. 30 in total.
  - Scrapers: In total 8 empty slots for beam scrapers, fully equipped with cables and water.

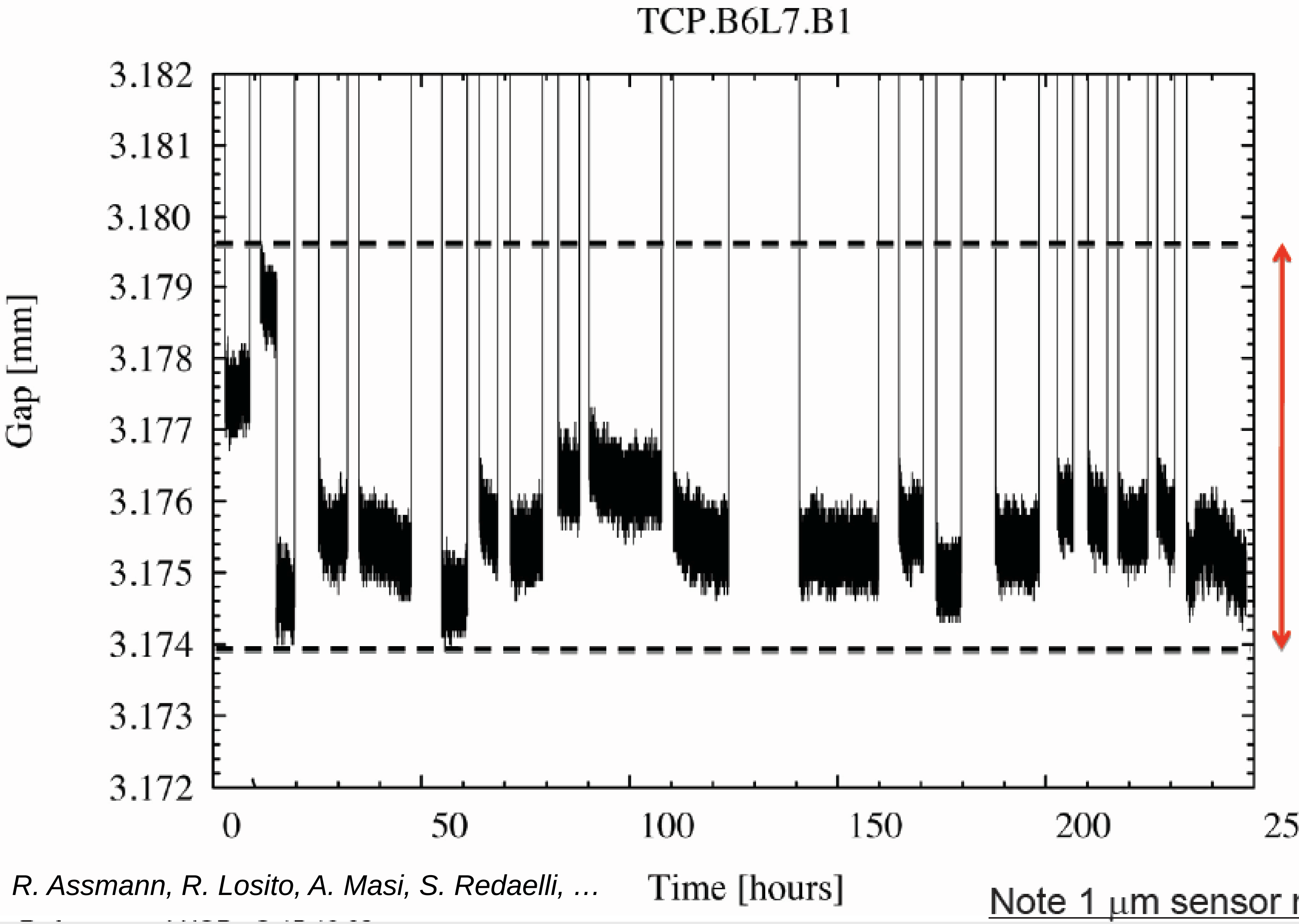
Cleaning Insertion IR7



Side View Phase I Collimator



Zoom into Collision Gaps

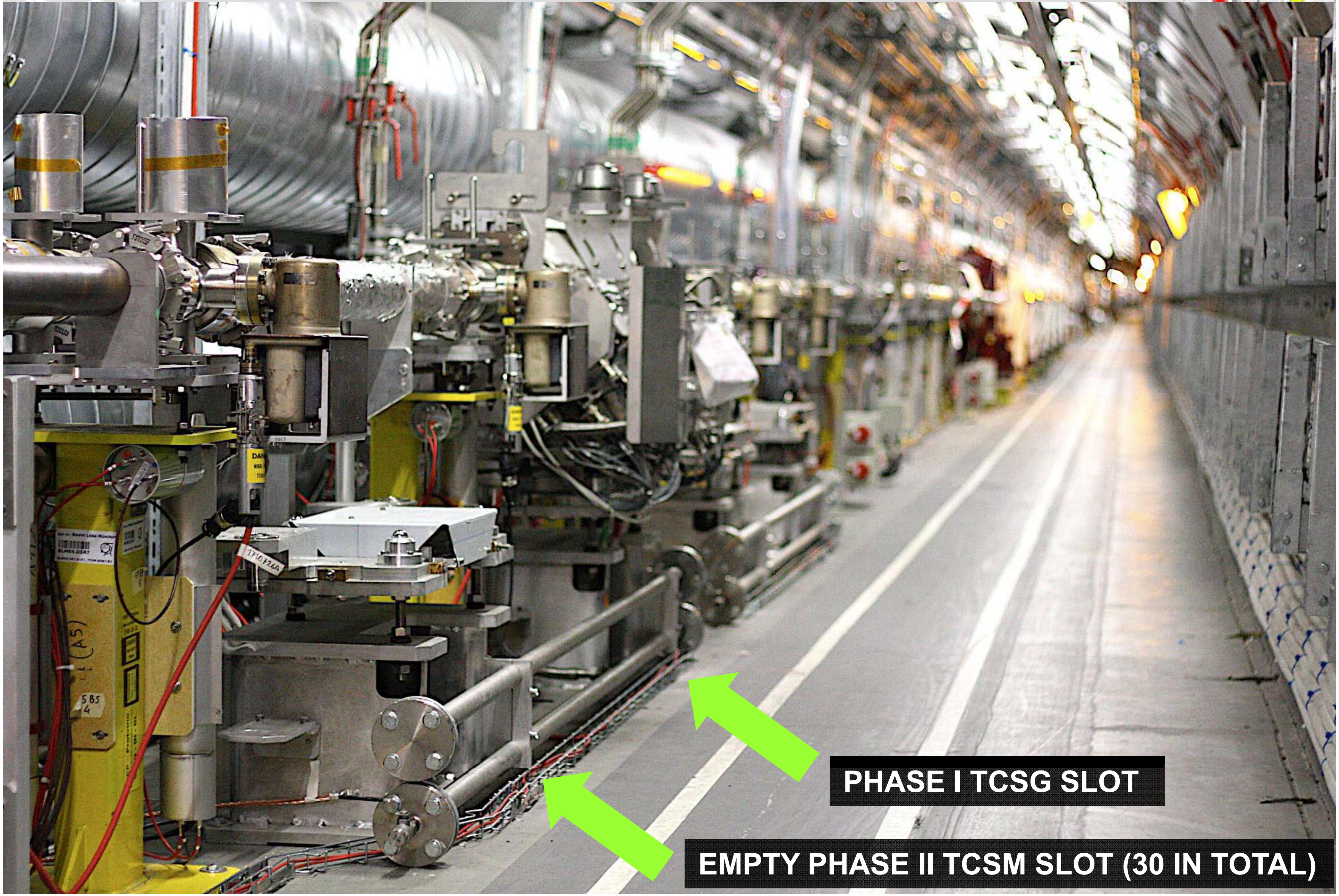


5.7 μm over 10 days

R. Assmann, R. Losito, A. Masi, S. Redaelli, …

Note 1 μm sensor noise.

Phase II Secondary Collimator Slots

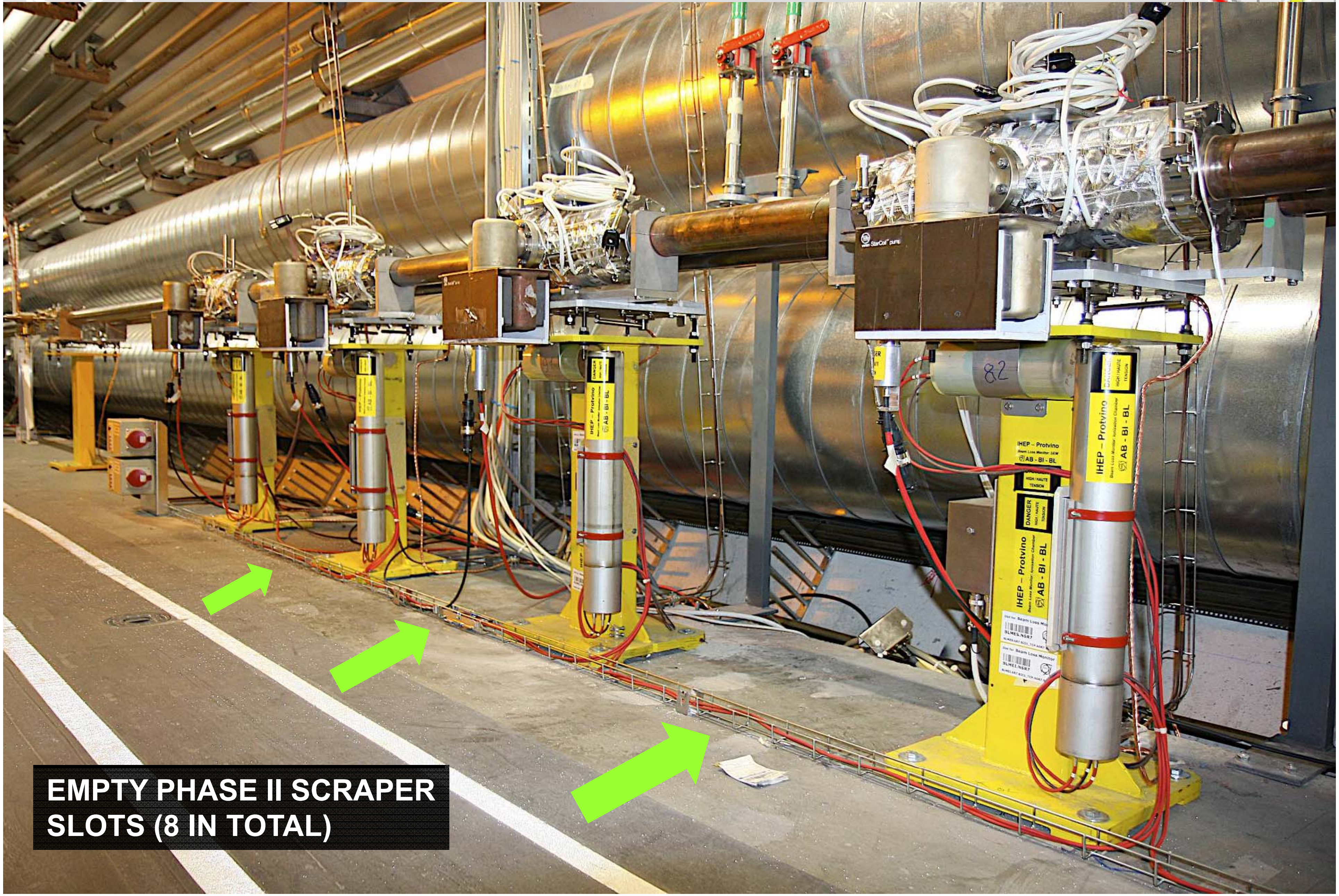


PHASE I TCSG SLOT

EMPTY PHASE II TCSM SLOT (30 IN TOTAL)

LHC Collimation Project

Phase II Beam Scraper Slots



EMPTY PHASE II SCRAPER SLOTS (8 IN TOTAL)

The Staged Collimation Path

	Energy density at collimators (nominal 7 TeV conditions)	**Stored energy**
State-of-the-art in SC colliders (TEVATRON, HERA, …)	**1 MJ/mm^2**	**2 MJ**
	↓	↓
Phase I LHC Collimation *(up to 40% of nominal)*	**≤ 400 MJ/mm^2**	**≤ 150 MJ**
	↓	↓
Nominal LHC	**1 GJ/mm^2**	**360 MJ**
	↓	↓
Ultimate & upgrade scenarios	**~4 GJ/mm^2**	**~1.5 GJ**
Limit (avoid damage/quench)	**~50 kJ/mm^2**	**~10-30 mJ/cm^3**

Constraints Collimation Phase I

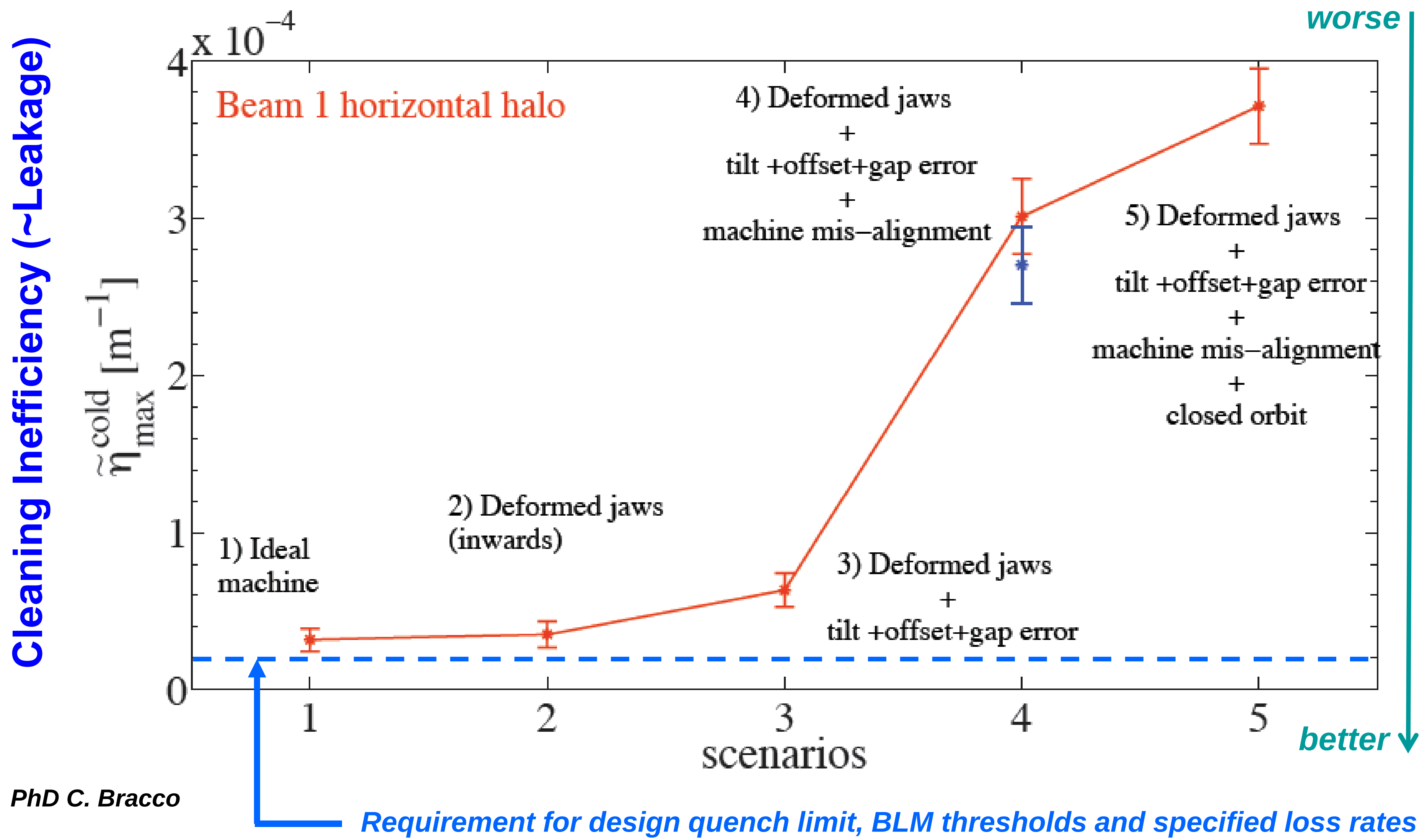
- Strict constraints imposed in 2003 for phase 1 system:
  - Availability of working collimation system for LHC beam start-up
  - Robustness against LHC beam (avoid catastrophic problems)
  - Radiation handling (access for later improvements)
  - No modifications to SC areas (due to short time and problems with QRL)
- Compromises accepted:
  - Limited advanced features (e.g. no pick-ups in jaws).
  - Risk due to radiation damage for fiber-reinforced graphite (electical + thermal conductivity changes, dust, swelling, …). Kurchatov data shows factor 4-5 changes with irradiation in various important parameters.
  - Steep increase in machine impedance due to collimators.
  - Excellent cleaning efficiency, however, insufficient for nominal intensity.

Phase I Performance Reach

- Predicted LHC limitations from collimation depend on magnet quench limits, BLM thresholds and maximum beam loss rates. Unavoidable uncertainties in predictions (if zero losses no collimation required).
- Phase I performance **analyzed and optimized over the last 6 years**:
  - Overall beam loss assumptions defined and discussed in external review.
  - Prediction of local losses from massive parallel simulations (now move to Grid).
  - Optimization of the collimation cleaning efficiency to protect SC magnets against quenches (including triplets ➔ background).
  - Placement and design of collimators to protect all equipment against damage.
  - Analysis and optimization of collimation-related radiation impact (dose to personnel, environmental impact, radiation to electronics, …).
- **Gained an overall factor ~200 in performance reach** (collimator robustness, efficiency, impedance, absorption of cleaning-induced showers, losses in SC triplets, air activation, …).
- Still predicted limitations after all optimization work…

Phase I Performance Reach

- Cleaning Inefficiency 7 TeV -

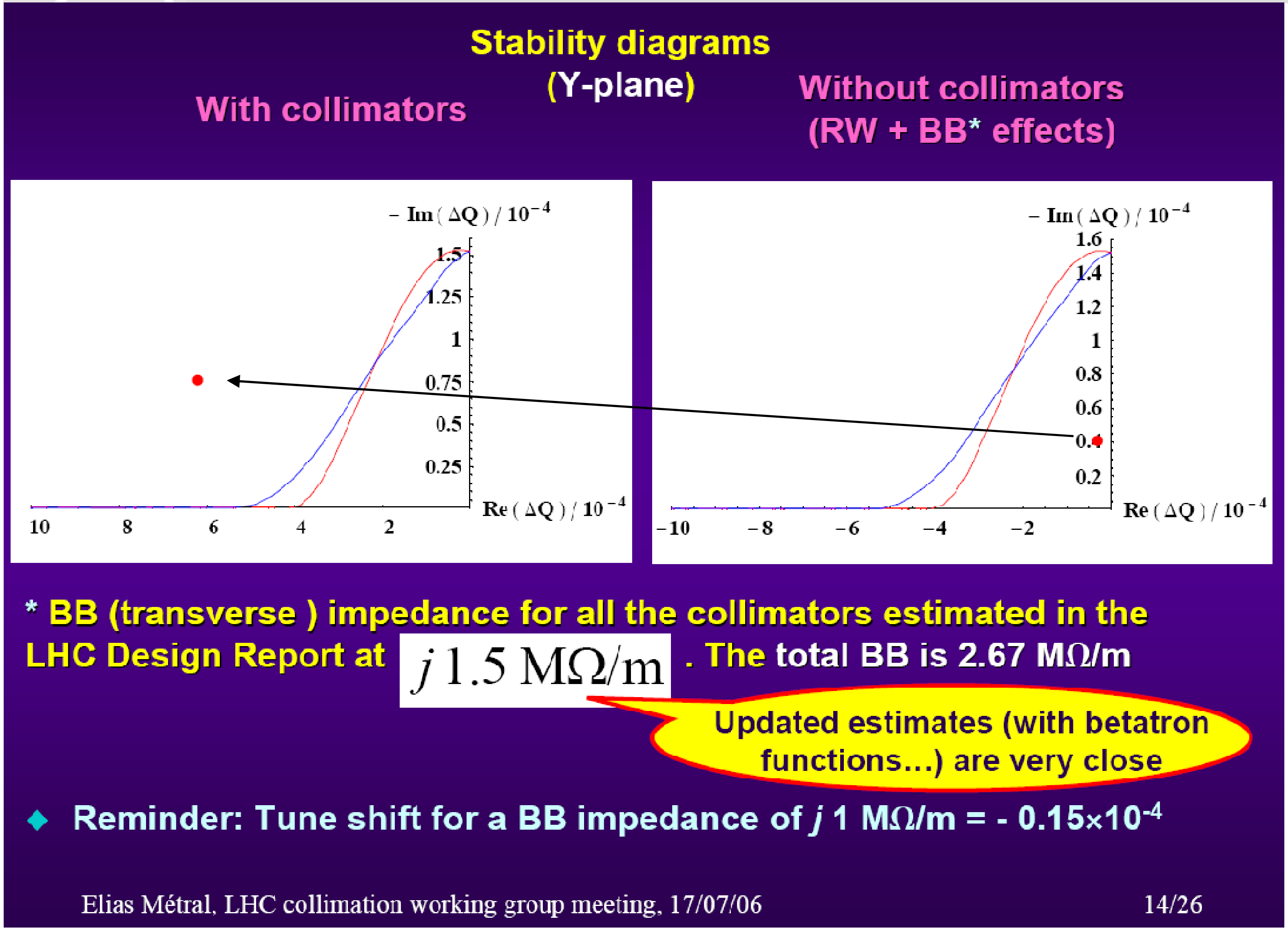


PhD C. Bracco

Requirement for design quench limit, BLM thresholds and specified loss rates

Phase I Performance Reach

- Impedance -



Stability diagrams (Y-plane)

With collimators

Without collimators (RW + BB* effects)

*** BB (transverse) impedance for all the collimators estimated in the LHC Design Report at $j\,1.5\ \mathrm{M\Omega/m}$. The total BB is 2.67 MΩ/m**

Updated estimates (with betatron functions…) are very close

- **Reminder: Tune shift for a BB impedance of j 1 MΩ/m = - 0.15×10^{-4}**

Elias Métral, LHC collimation working group meeting, 17/07/06

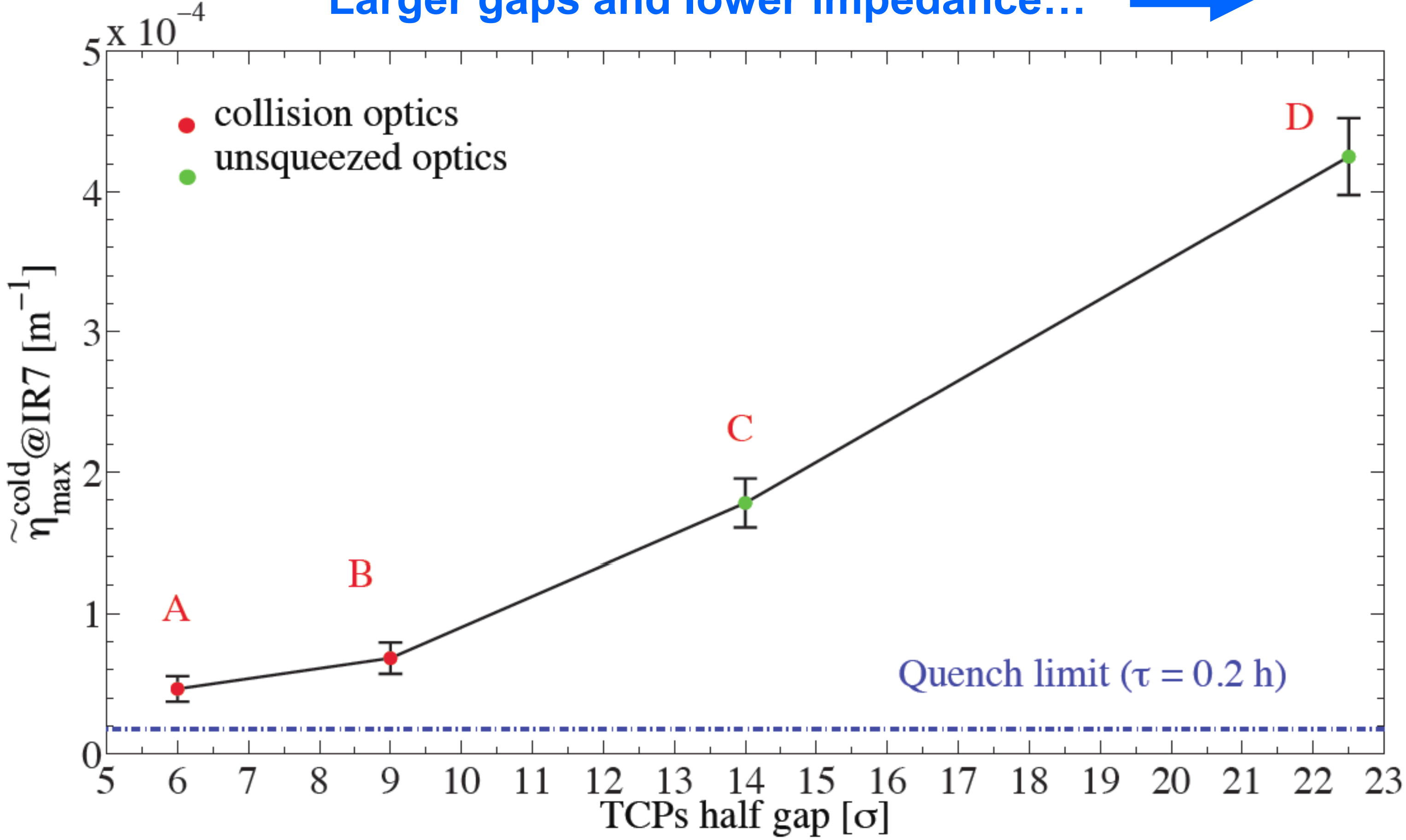
➔ Limitation at about **40% of nominal intensity**… (nominal β*, full octupoles)

E. Metral et al

Phase I Performance Reach

- Tradeoff Impedance vs. Efficiency -

Larger gaps and lower impedance… →



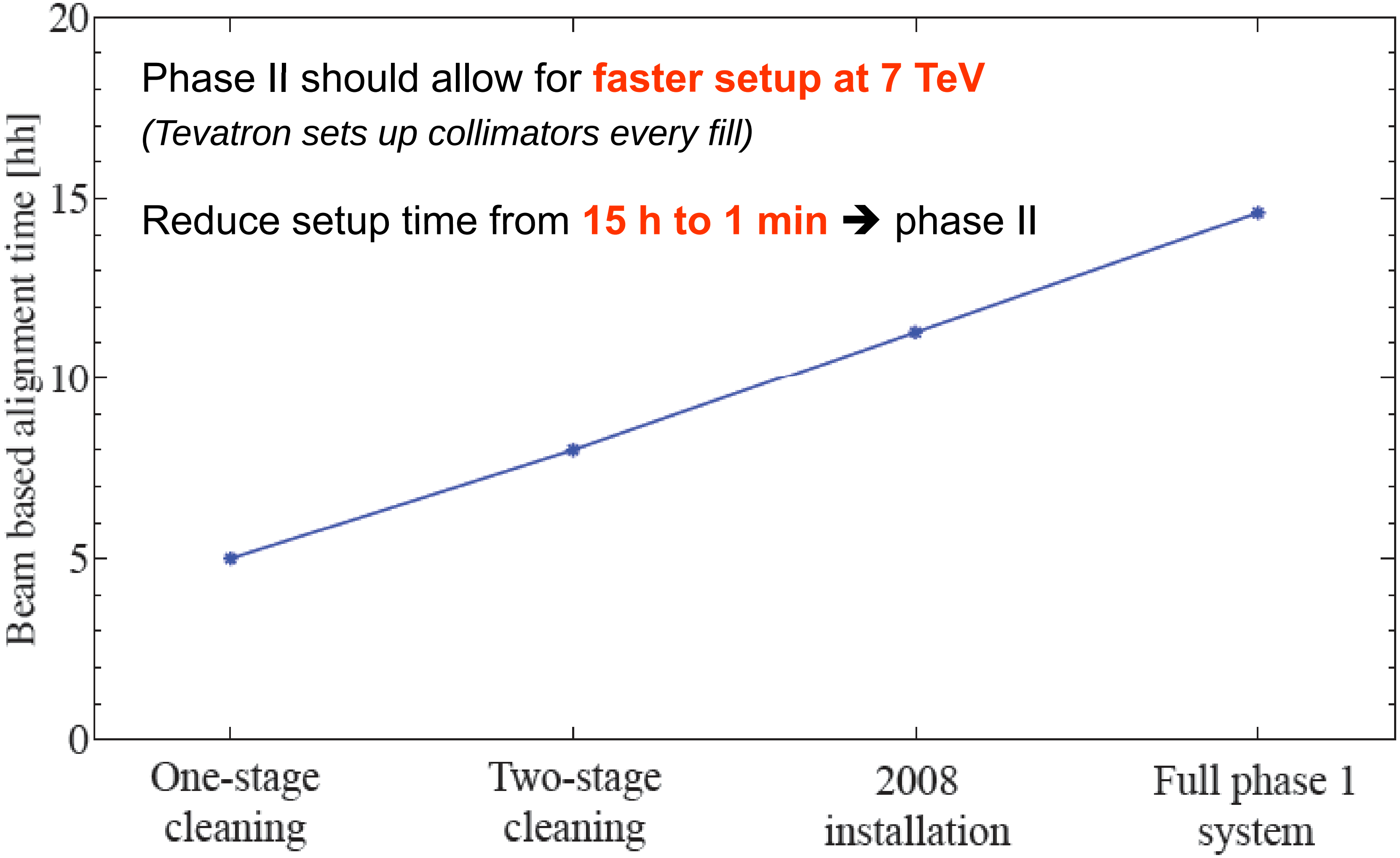
↑ Higher inefficiency, less cleaning performance

PhD C. Bracco

➔ **Phase I upgrade of the insertions will not improve predicted intensity limit from phase I collimation!**
Additional room from triplet aperture can only be used after collimation upgrade (our phase II)!

Phase I Performance Reach

- Operational Efficiency -



Phase II should allow for **faster setup at 7 TeV**

(Tevatron sets up collimators every fill)

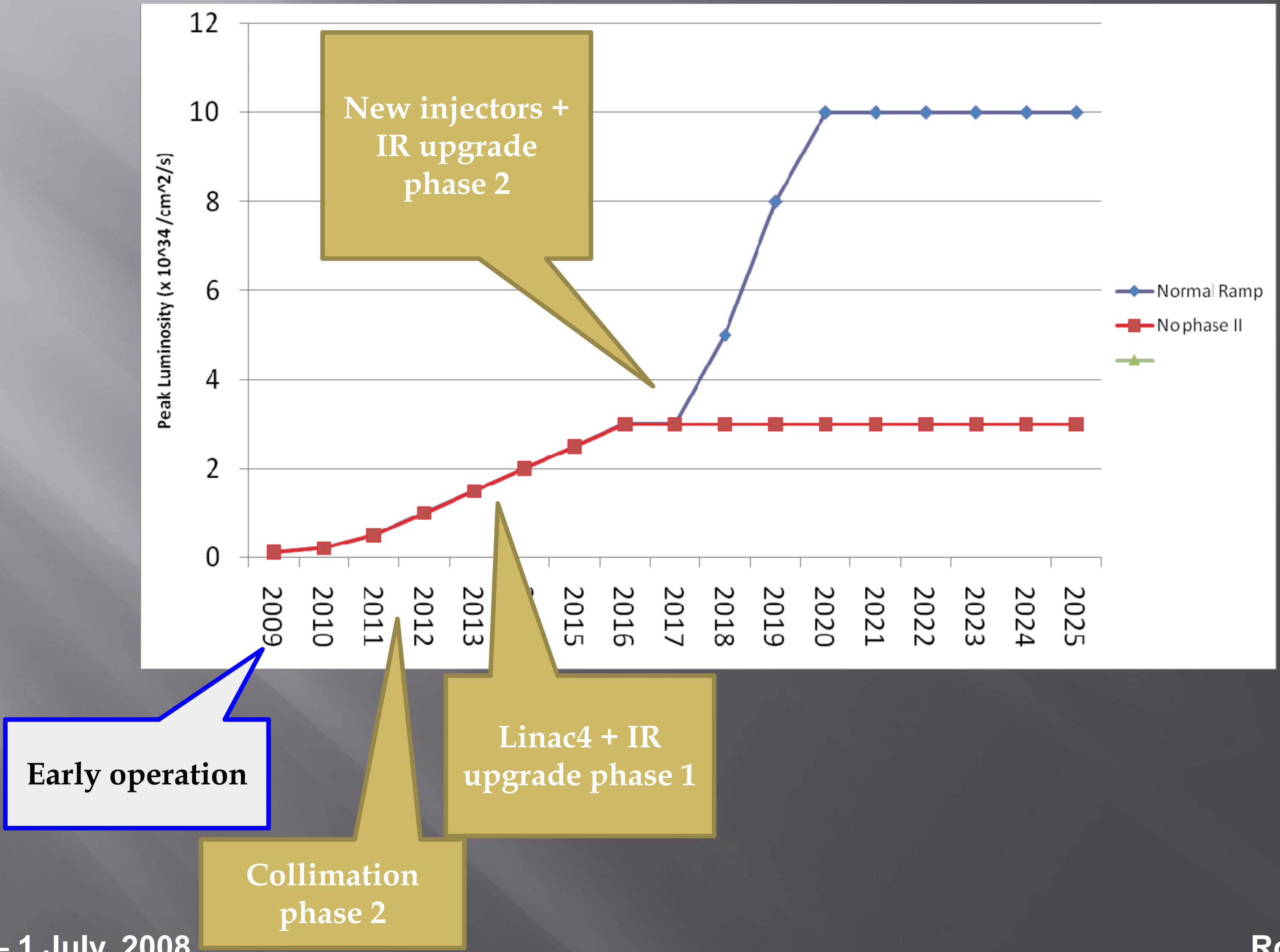
Reduce setup time from **15 h to 1 min** ➔ phase II

15 h

5 h

PhD C. Bracco

Peak luminosity…



New injectors + IR upgrade phase 2

Early operation

Collimation phase 2

Linac4 + IR upgrade phase 1

Constraints: Phase II

- Strict constraints in 2003 for phase 1 system:
  - ~~Availability of working collimation system for beam start-up (2007 originally)~~
  - ~~Robustness against LHC beam (avoid catastrophic problems)~~
  - ~~Radiation handling (access for later improvements)~~
  - ~~No modifications to SC areas (due to short time and problems with QRL)~~
- Phase 2 constraints:
  - Gain factor ≥10 in cleaning efficiency.
  - Gain factor ≥10 in impedance.
  - Gain factor ≥10 in set-up time (and accuracy?).
  - Radiation handling.
  - Sufficient robustness, also against radiation damage.

Phase II Collimation Project

- Phase 2 collimation project on R&D has been included into the white paper:
  - We set up project structure in January 2008. Key persons in place. Work packages agreed.
  - Two lines: **(1) Upgrade of collimation and improved hardware.** **(2) Preparation of beam test stand for tests of advanced collimators.**
  - Review in February 2008 to take first decisions.
- US effort (LARP, SLAC) is ongoing and we are well connectet. First basic prototype results shown at EPAC08 ➔ Tom et al.
- FP7 request EUCARD with collimation work package:
  - Makes available significant additional resources (enhancing white paper money).
  - Remember: Advanced collimation resources through FP7 (cryogenic collimators, crystal collimation, e-beam scraper, …).

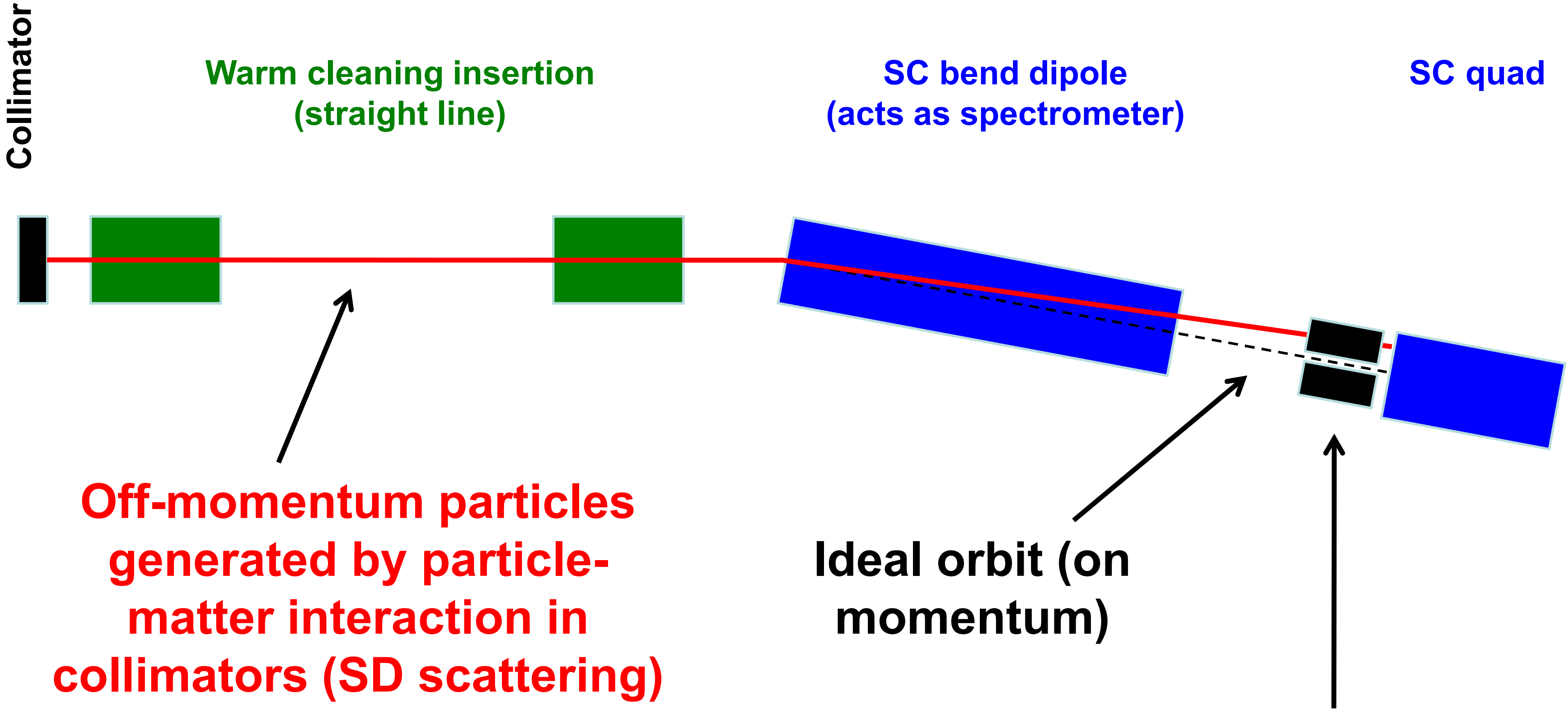
Concept to Realize Improvement on Phase II Timescale

- Factor 10 efficiency for protons and ions (work Thomas Weiler/Ralph Assmann):
  - Place metallic, advanced phase II collimators (efficiency study by Chiara Bracco). 2-3 complementary development paths in CERN and US (SLAC rotatable design).
  - Place cryogenic collimators into SC dispersion suppressor (use missing dipole space).
  - Different material for primary collimators (to be evaluated).
- Factor 10 in set-up time (and accuracy?):
  - Integration of pick-ups into collimator jaws for deterministic centering of jaws around circulating beam. Support from BI group (R. Jones et al).
  - Gain accuracy due to possibility to redo for every fill (avoid reproducibility errors fill to fill).
- Factor 10 in impedance:
  - No magic material yet (factor 2 seems possible). Pursue further the various advanced ideas! Work by Elias Metral and Fritz Caspers. Tests ongoing.
  - Rely to some extent on beam-based feedback. Work by Wolfgang Hoefle.
  - Open collimators or use less collimators with improved efficiency (see above) and increased triplet aperture (phase 1 triplet upgrade), if feedback cannot stabilize beam.

A) Concept for Improving Efficiency

- Fundamental problem:
  - Particle-matter interactions produce off-momentum particles in straight cleaning insertions (both p and ions). These are produced by different basic physical processes that we cannot avoid (single-diffractive scattering, dissociation, fragmentation).
  - No dispersive chicane after collimation insertion: Off-momentum particles get lost in SC magnets after first bend magnets downstream of straight insertion.
- Conceptual solution (no decisions taken – under study):
  - Reduce number of off-momentum particles produced (phase II primary and secondary collimators).
  - Install collimators into SC area, just before loss locations to catch off-momentum particles before they get lost in SC magnets.
  - Might be beneficial to install around all IR's, for sure in IR3 and IR7.
  - Elegant use for space left by missing dipoles!

Schematic Solution Efficiency



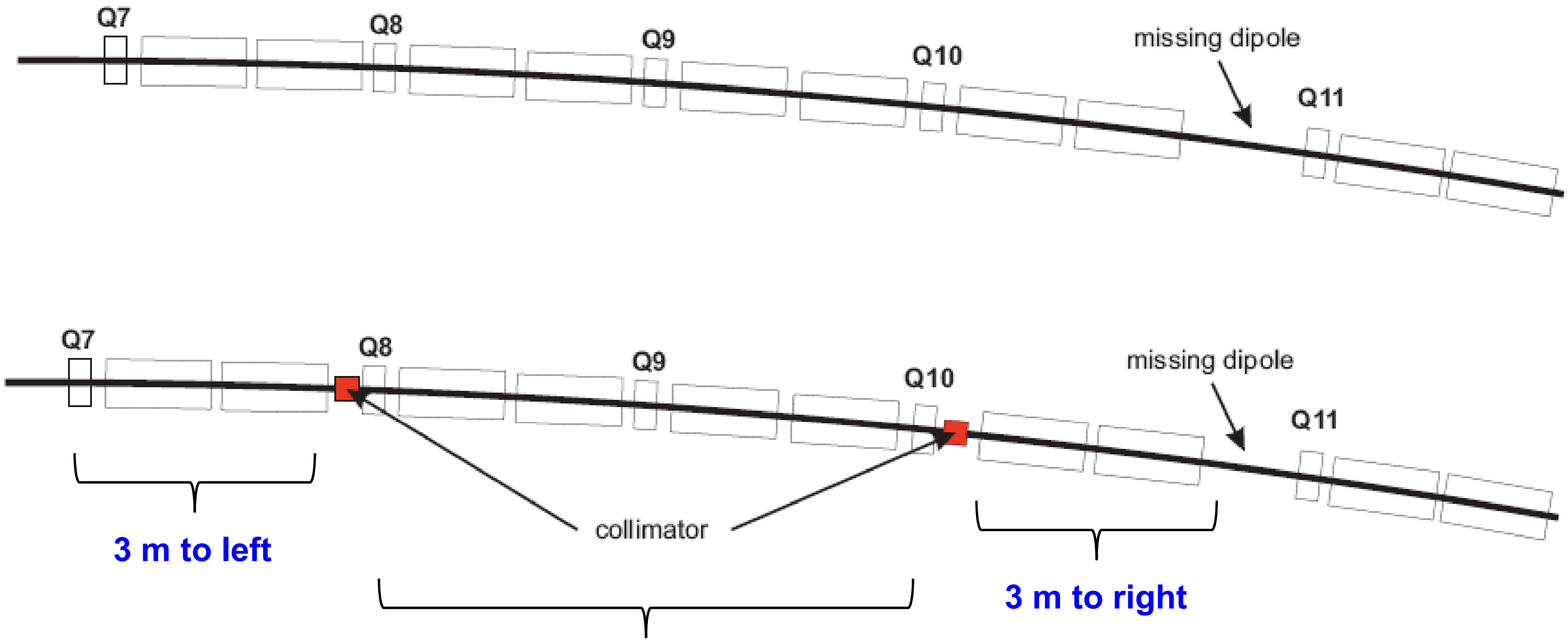
Off-momentum particles generated by particle-matter interaction in collimators (SD scattering)

Ideal orbit (on momentum)

Add cryogenic collimator, using space left by missing dipole (moving magnets)

+ metallic phase 2 collimators in IR3 and IR7

Change in Layout of DS



3 m to left

3 m to right

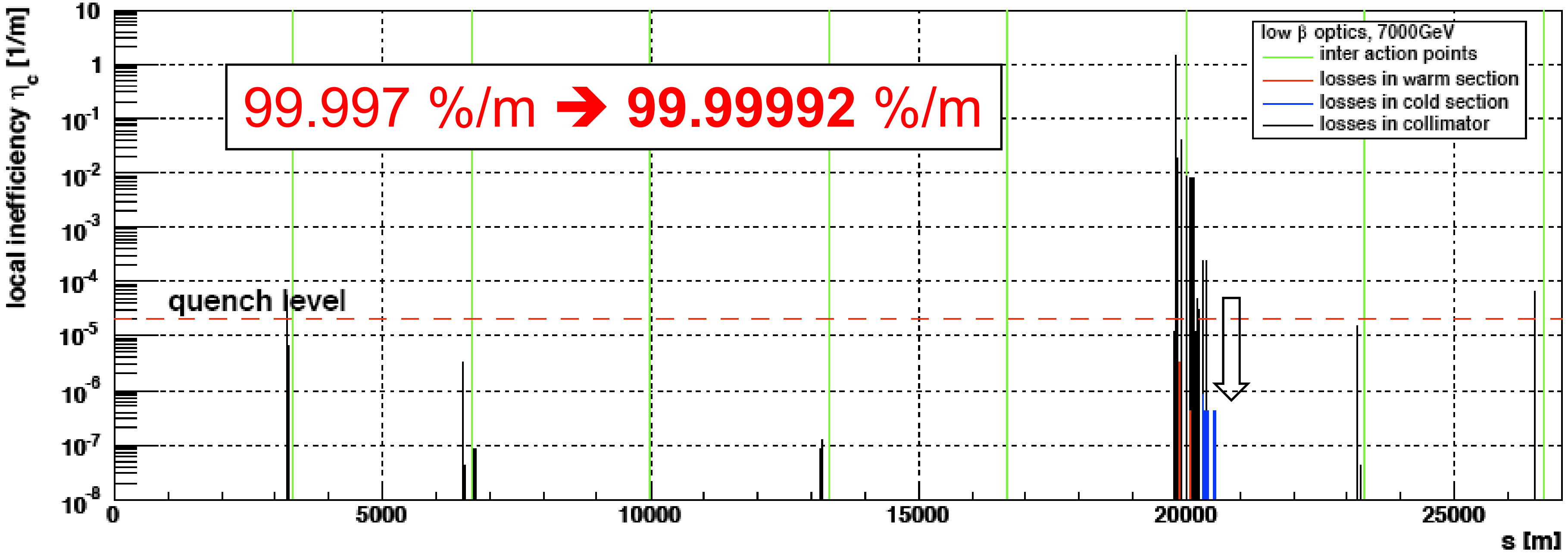
No longitudinal displacement.
Moves inwards by 3 cm.

T. Weiler & R. Assmann & J. Jowett

Layout and optics checked with MADX. No problem for the optics and survey seen. Optics change (move of Q7) small even without optics rematch. More careful work is required. Note, that impact on infrastructure was not checked yet!

Proton Collimation Efficiency with Phase II Cu Collimators and Cryogenic Collimators

T. Weiler & R. Assmann

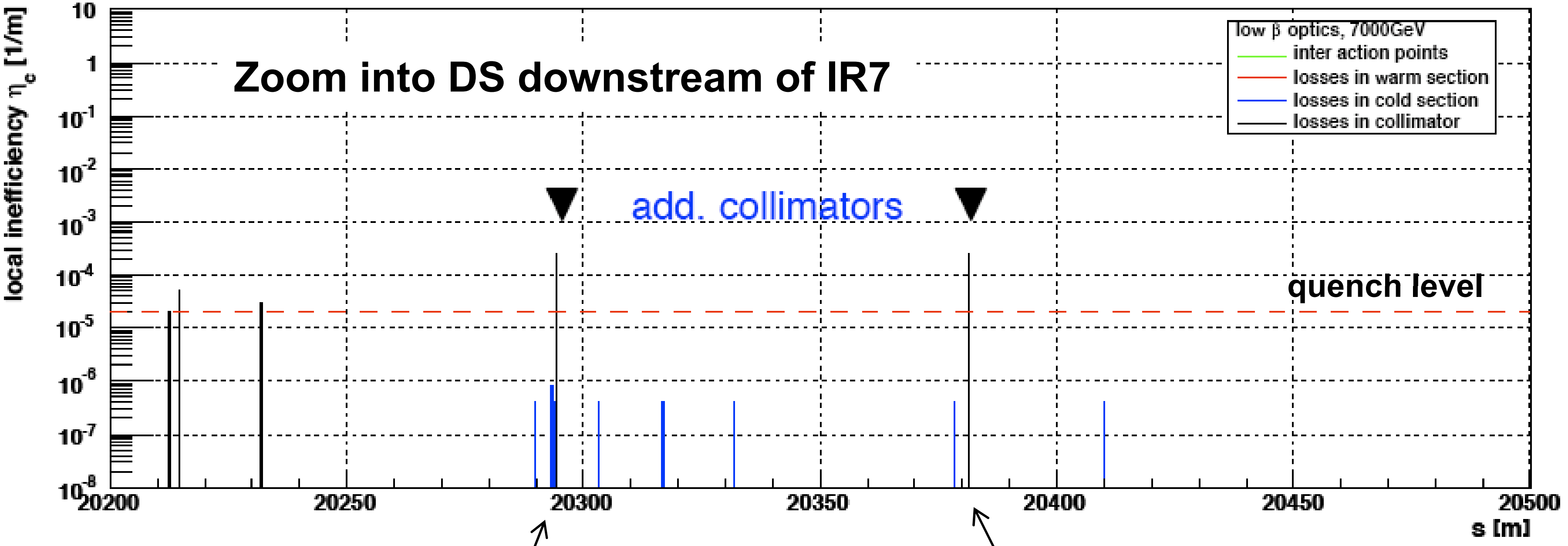

99.997 %/m ➔ **99.99992 %/m**

Inefficiency reduces by factor 30 (good for nominal intensity). Lower losses in the experimental collimators (background). Should also work for ions.

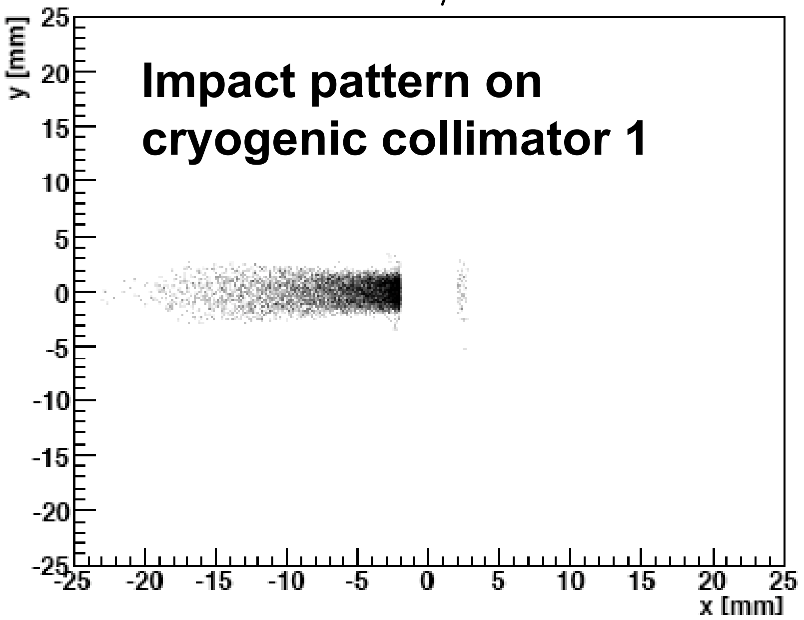
Caution: Further studies must show real feasibility of this proposal (energy deposition, heat load, integration, cryogenics, beam2, …). Just a concept at this point.

Cryogenic collimators will be studied as part of FP7 with GSI in Germany (➔ FAIR).

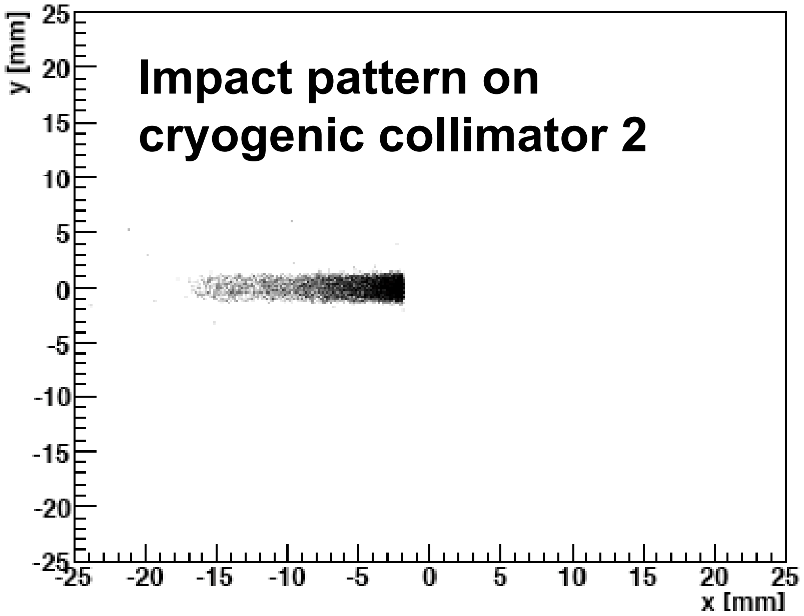
Zoom into DS downstream of IR7



T. Weiler



Impact pattern on cryogenic collimator 1



Impact pattern on cryogenic collimator 2

➔ FLUKA studies ongoing to define energy deposition!

Prediction Beam 1 Halo (H) Losses in Experimental Insertions

preliminary

IR	Phase I (perfect)	Phase I (imperfect)	Phase II (perfect)
IR1	**4.9×10^{-4}**	1.0×10^{-3}	**7.7×10^{-6}**
IR2	**1.3×10^{-4}**	2.1×10^{-4}	**2.2×10^{-6}**
IR5	**6.5×10^{-6}**	5.7×10^{-5}	**2.9×10^{-6}**
IR8	**3.0×10^{-4}**	7.5×10^{-4}	**5.6×10^{-5}**

- Numbers show fraction of overall loss that is intercepted at horizontal tertiary collimators in the various insertions (collimation halo load).
- Phase 2 collimation upgrade reduces losses in IR's by a factor up to 60!
- Beam 2 has opposite direction ➔ more losses in IR5 and less in IR1!

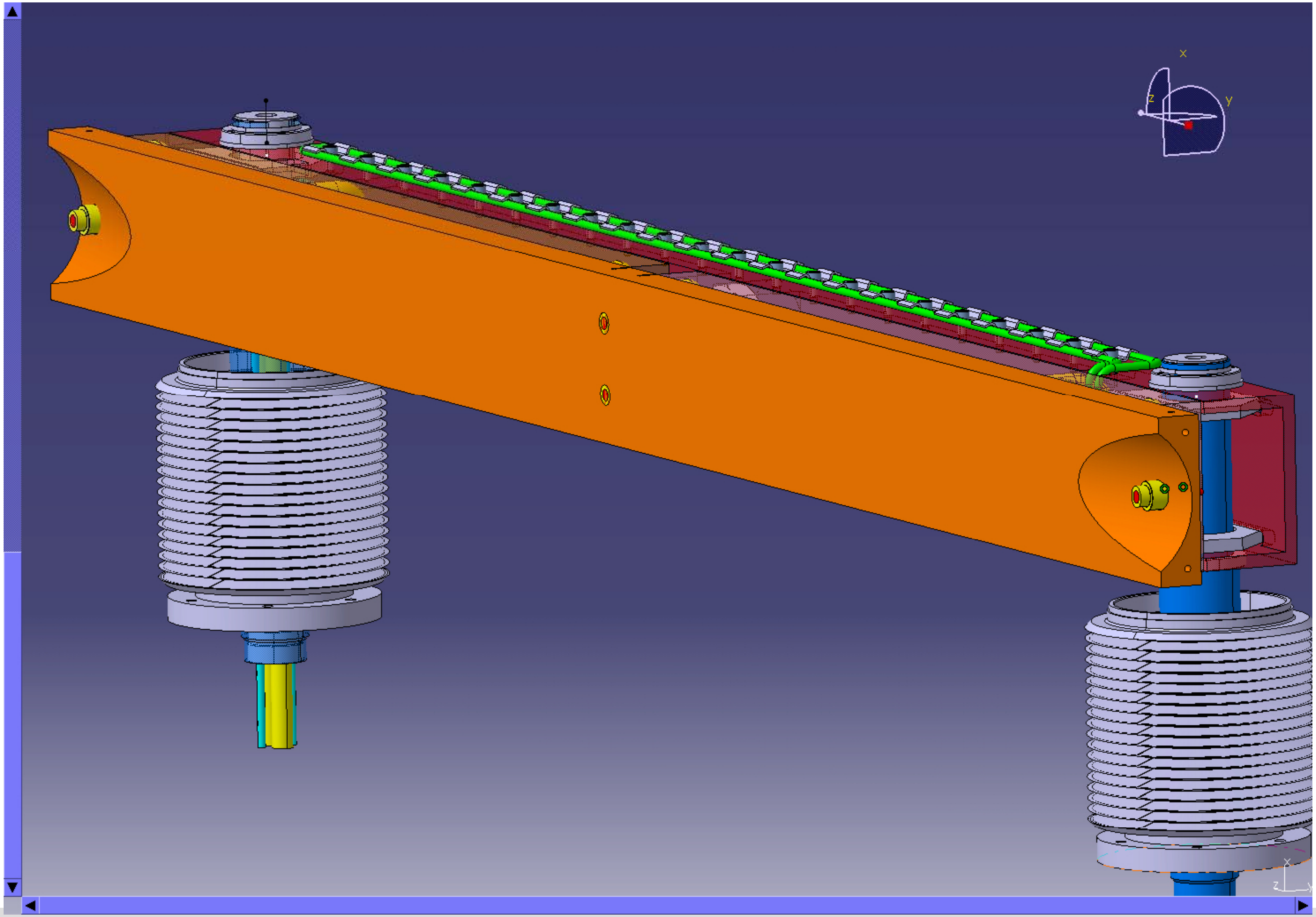
B) Concept for Improving Set-Up

- Standard method relies on centering collimator jaws by creating beam loss (touching primary beam halo with all jaws).
- Procedure is lengthy (48h per ring?) and can only be performed with special low intensity fills for the LHC (few nominal bunches).
- Big worries about risks, reproducibility, systematic effects and time lost for physics (integrated luminosity).
- Tevatron and RHIC must rely on collimator calibration and optimization performed at the start of each physics run.
- LHC can only do better if **non-invasive methods** are used (no touching of primary beam halo and no losses generated):
  - **integration of pick-ups and loss measurements into jaws.**

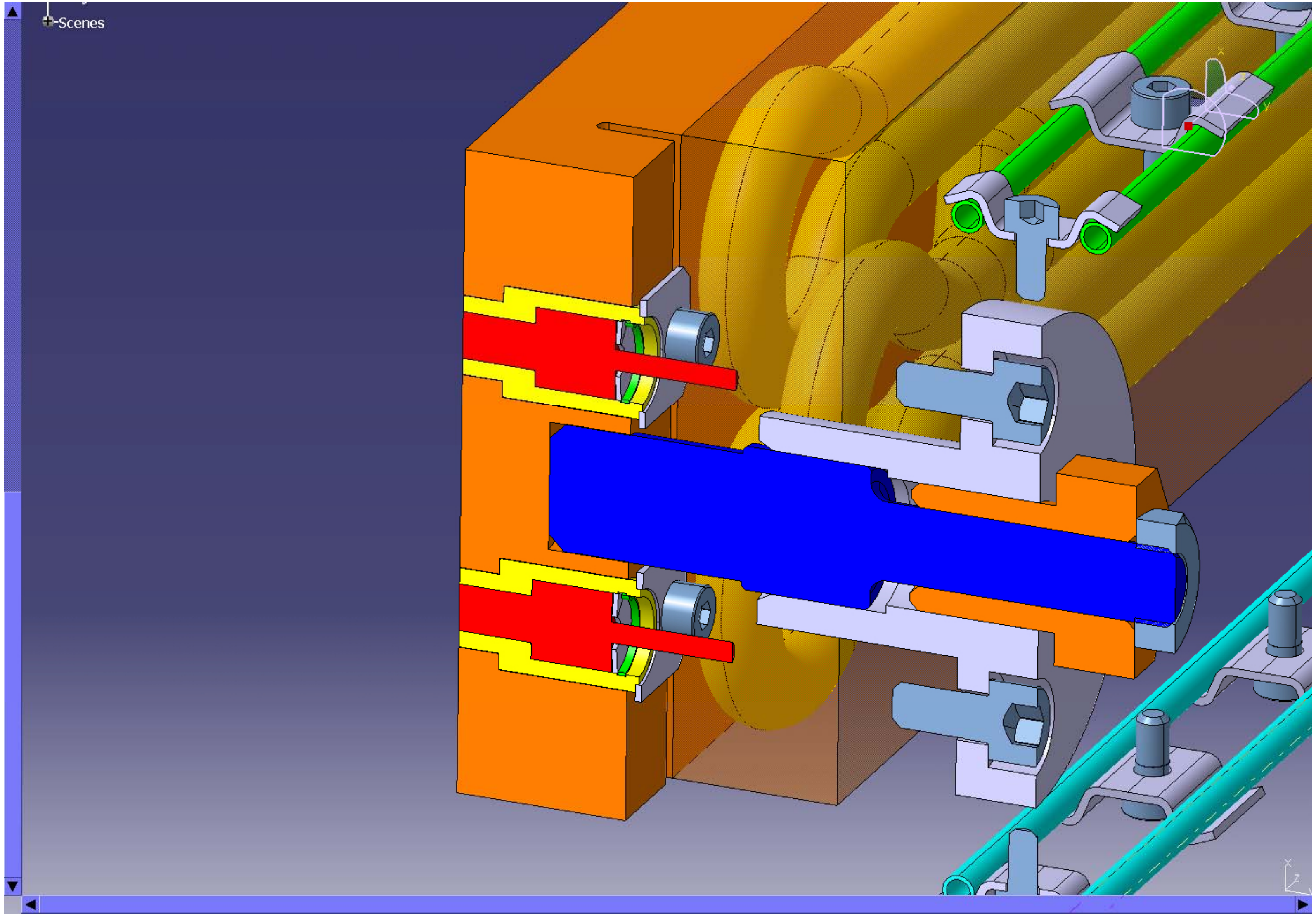
Collimator - BPM Study

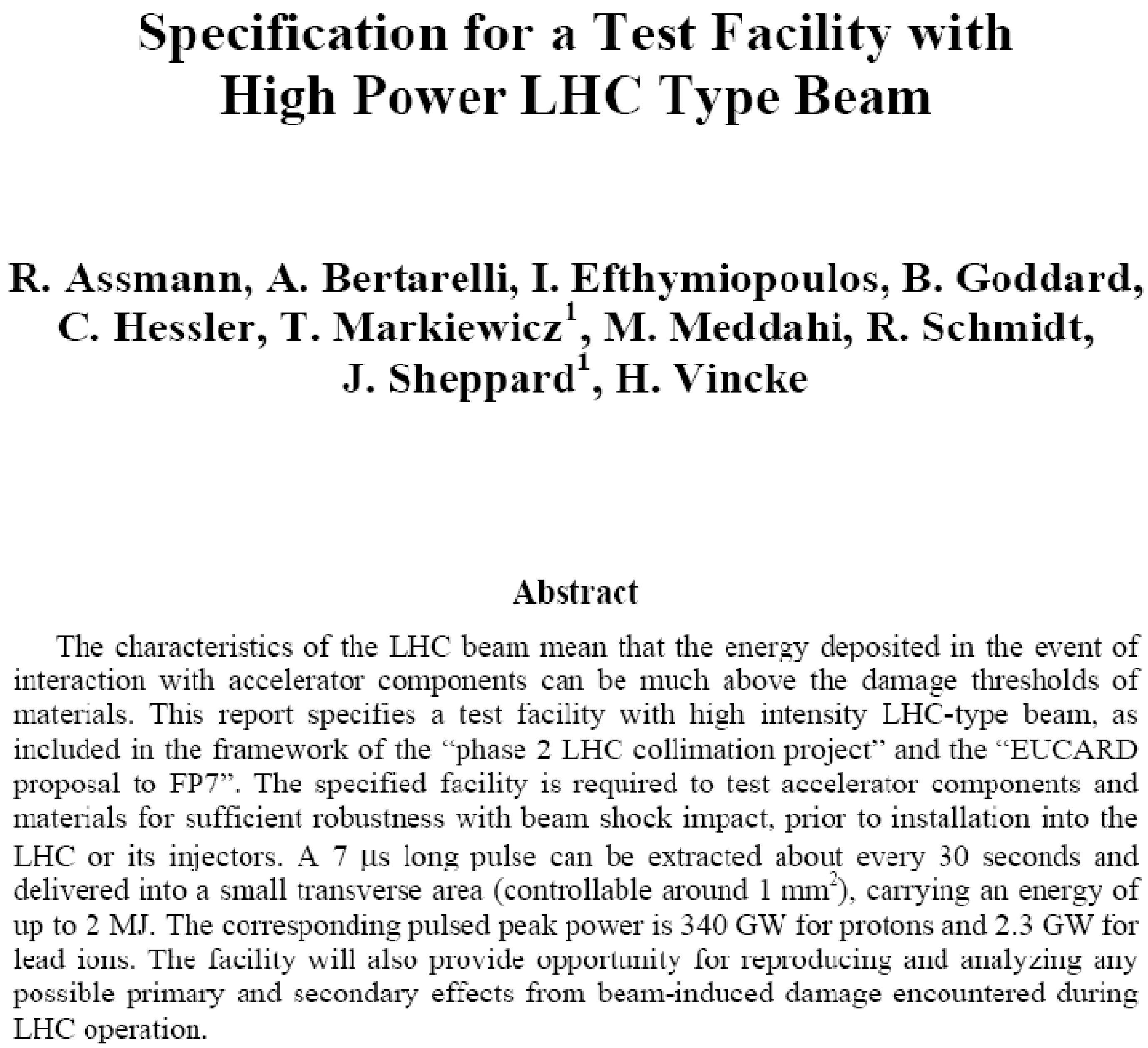
- No time for detailed studies and simulations this year. Will start next year.
- In the meanwhile implement “best guess” electrodes into mechanical design.
- Crucial help from BI group (R. Jones et al). Engineering design driven by TS in phase 2 collimation project.
- Ansatz: Implement some reasonable buttons, build a prototype and test with beam how well it works (improve then with second generation design).
- Needed for high intensity: Should not be too difficult to reach much better accuracy than with collimator beam-based alignment method.
- Will still require knowledge of local beta function. Can in principle be evaluated with movable BPM buttons. However, chance to measure with global methods regularly (1000 turn small kicks).

Engineering Design for Prototype



Electrode Design





Specification for a Test Facility with High Power LHC Type Beam

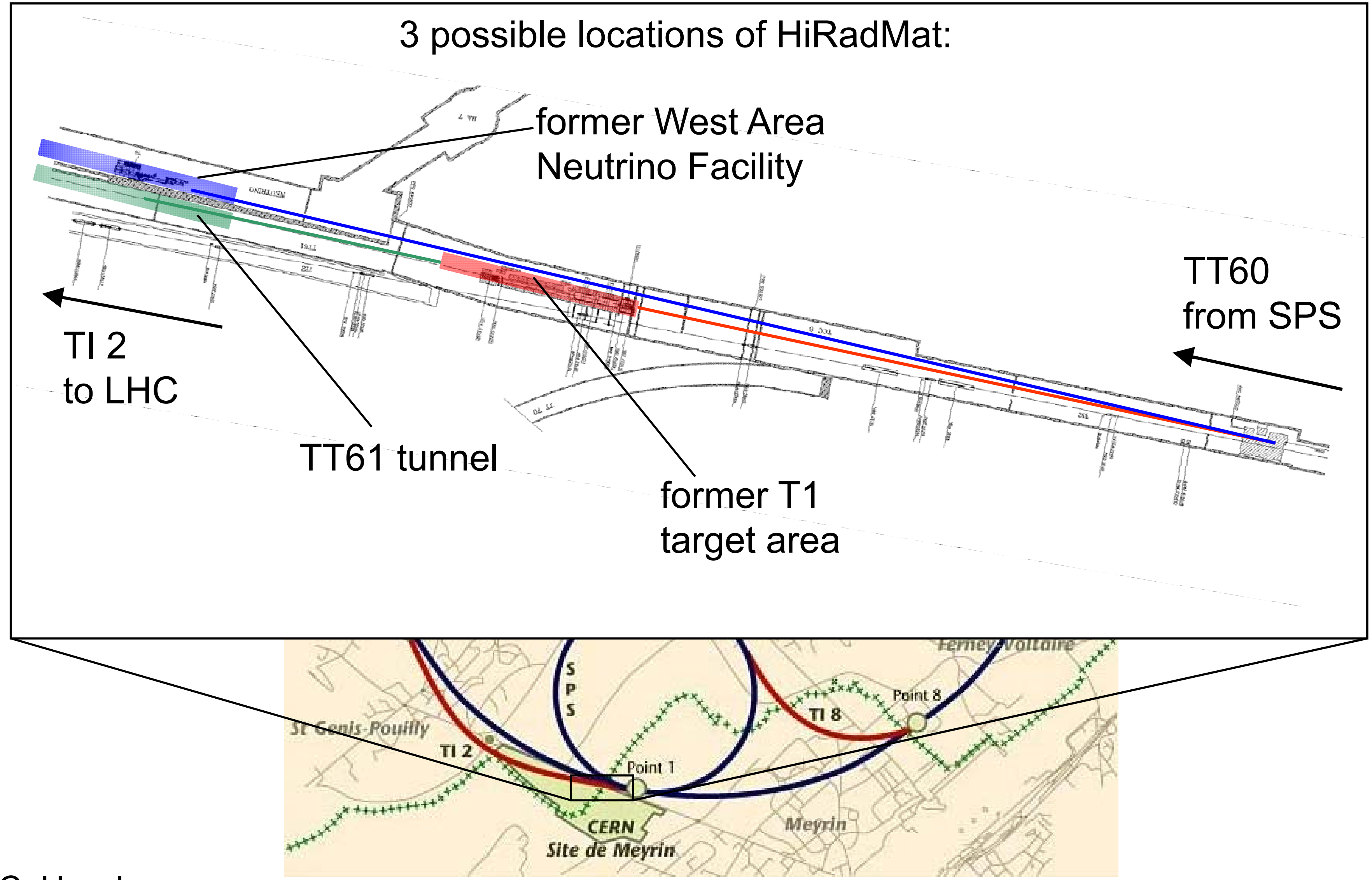
R. Assmann, A. Bertarelli, I. Efthymiopoulos, B. Goddard,
C. Hessler, T. Markiewicz[1], M. Meddahi, R. Schmidt,
J. Sheppard[1], H. Vincke

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.

Location of HiRadMat

3 possible locations of HiRadMat:



former West Area Neutrino Facility

TT60 from SPS

TI 2 to LHC

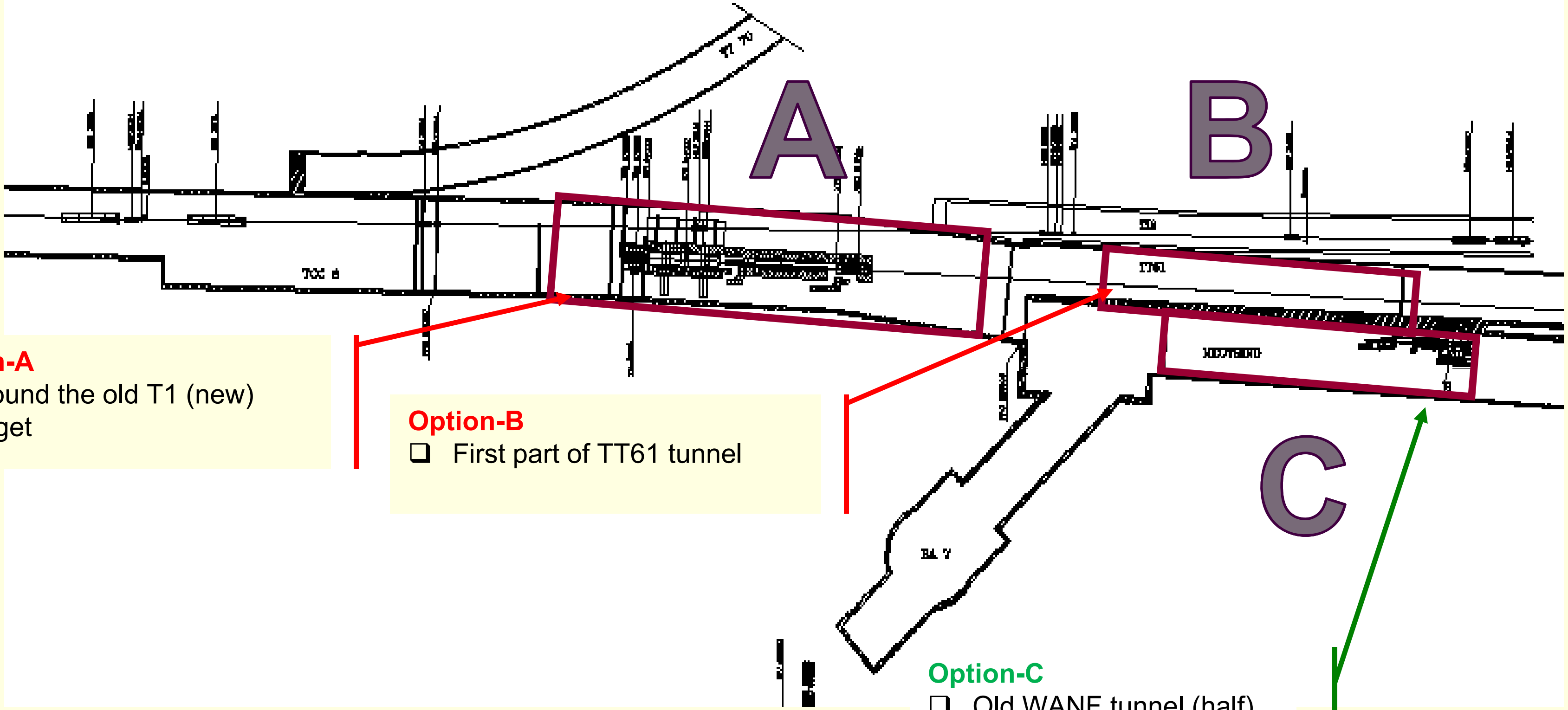
TT61 tunnel

former T1 target area

C. Hessler

I. Efthymiopoulos

TCC6 area layout



Option-A
- ❑ Around the old T1 (new) target

Option-B
- ❑ First part of TT61 tunnel

Option-C
- ❑ Old WANF tunnel (half)

LHC Collimation Timeline

- Present view, to be refined in February 2009 review:
  - **February 2009**: First phase II project decisions. Design work on phase II TCSM ongoing at LARP and CERN. Work on beam test stand at CERN.
  - **April 2009**: Start of FP7 project on collimation ➔ Start of development for cryogenic collimator and (lower priority) LHC crystal collimator.
  - **2009-2010**: Laboratory tests on TCSM and cryo collimator prototypes.
  - **Mid 2010:** Beam test stand available for robustness tests. Safe beam tests with TCSM and cryogenic collimators (catastrophic failure possible).
  - **2011**: LHC beam tests of TCSM and cryogenic collimators.
  - **2011-2012**: Production and installation of phase II collimation upgrade.
  - **Mid 2012**: Readiness for nominal and higher intensities from collimation side.
- Challenging time scale. The beam experience will accelerate or decelerate this effort. Strongly coupled to resources!

Conclusion

- The phased LHC collimation approach proceeds:
  - Phase I installed in tunnel, 100% complete after shutdown. Collimators perform as specified (reproducibility, …). Efficiency and impedance to be verified with beam.
  - Phase II preparations (cables, water, supports) in tunnel 100% complete (fast upgrade).
  - Collimation studies further improved (imperfections, Grid CPU resources). All available studies predict LHC intensity limitations with phase I collimation.
- The phase II effort has started in 2008 and made major progress:
  - AP study provided **upgrade concept to win more than factor 10 in efficiency** (FLUKA studies ongoing). Also addresses ion and impedance problems (tradeoff).
  - Solution would reduce load on experimental insertions significantly (factor 60?).
  - Phase II collimator design started at CERN. Complementary design at SLAC going well.
  - Need to **change superconducting dispersion suppressors in IR3/7** (project review 2009) and place special (cryogenic?) collimators (work with GSI/FAIR).
  - Implementation of required beam test stand is being defined for beam start in mid 2010.
  - More advanced concepts evaluated for the LHC: too early to rely on this for the LHC!

Reserve Slides

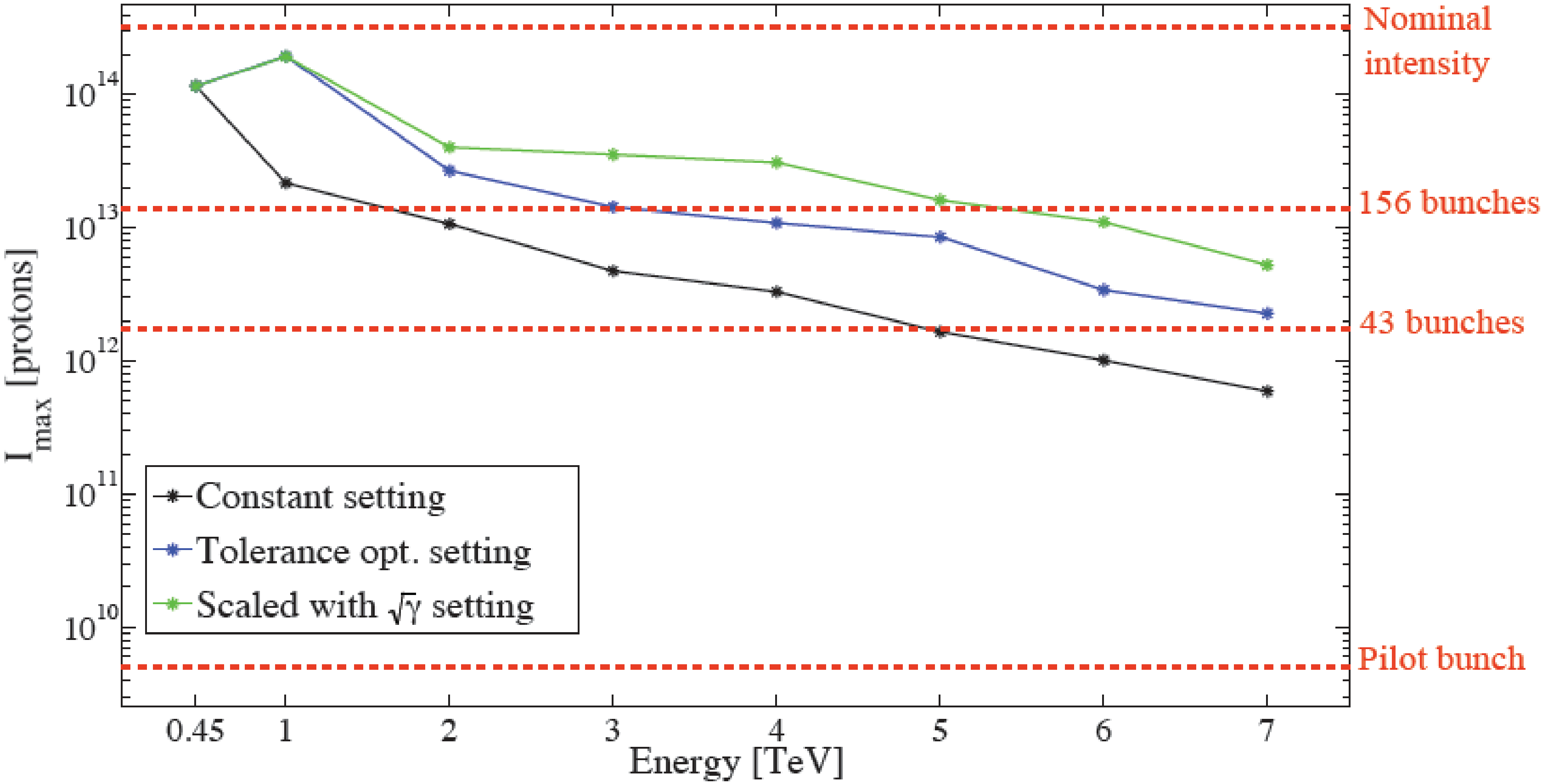
Uncertainties I

- There are **significant uncertainties** in our predictions.
- **Loss rates in normal operation:**
  - We allow for up to 0.1% of beam lost per second for up to 10 seconds (0.2 h beam lifetime).
  - Expect these losses during β squeeze, while bringing beams into collision, beam tuning (tune), …
  - Parameter strongly supported by international experts in external collimation review in 2004 (experience from HERA, TEVATRON, RHIC, SSC design, SNS design).
  - Can be better or worse. Judgement depends on the person looking at this.
- **Abnormal losses:**
  - We allow for up 0.3 % of 7 TeV beam lost on a collimator (single-turn) without damage (nominal dump error: single-module pre-fire).
  - Frequency of these errors unknown (assume at least once per year in LHC).
  - Population of beam halo close to collimators unknown: 1% of beam in the halo corresponds to twice the full TEVATRON beam!
  - General uncertainties from limited knowledge of halo beam dynamics.

Uncertainties II

- **Quench limits:**
  - Uncertainties in the quench level of SC magnets can reach a factor 2 easily.
- **Nuclear physics:**
  - The nuclear physics processes in the CFC collimator jaws can have up to a factor 2 uncertainties at 7 TeV.
  - Modeling of energy deposition can be affected by the limitations in the modeled geometry by up to a factor 2.
- **Impedance:**
  - LHC resistive wall impedance will be dominated by the collimator-induced impedance contributions.
  - Only tolerable with the predicted "inductive bypass" at low frequencies, which gains up to factor 100 compared to the classical thick wall theory. Never proven experimentally.
- **Collimator lifetime with strong radiation:**
  - High dose rates in the collimator jaws and other collimator parts (10-100 MGy/year).
  - Designed for robustness against radiation damage. However, lifetime unknown.

Intensity Reach versus Beam Energy for Phase I Collimation with Imperfections



➔ All simulations predict need for phase II collimation upgrade!

➔ Phase 2 collimation project put in place (white paper, new initiative).

Collimation: LHC Intensity Limitations I

Issue for protons	**Prediction**	**Consequences**
Collimator impedance	LHC impedance determined by collimators	≤ 40% of nominal intensity
Dispersion suppressors IR7	Losses of off-momentum p (single-diffractive scattering)	≤ 30-40% of nominal intensity for ideal cleaning
Unavoidable imperfections	Efficiency reduced to less than ideal	Set up time versus reduced efficiency
Efficient BLM thresholds	Factor 3-10 uncertainty from BLM reading on knowledge of beam loss	Thresholds at least factor 3 below intensity limit for quench
Radiation dose IR7 magnets (MBW, MQW)	2-3 MGy per year	Limited lifetime of magnets (specified for 50 MGy)
SC link in IR3	Risk of quench for losses of uncaptured beam	≤ 3.5% of nominal intensity in uncaptured beam
Dose on personnel	High remanent radiation	Limited access for modifications and upgrades in cleaning insertions
Environmental impact	OK for ultimate intensity	Review needed for any upgrade above ultimate ➔ bypass galleries

Collimation: LHC Intensity Limitations II

Issue for protons	Prediction	Consequences
Vacuum equipment (chambers, heating jackets)	Up to 8.5 MGy per year and up 500 W/m heating	Limited lifetime
Collimator robustness against failures	OK for accident cases with nominal intensity (450 GeV and 7 TeV), including water circuit in vacuum (up to 2 MJ)	Review for any upgrade in intensity, beam brightness, bunch structure, …
Collimator jaw damage	Under preparation	Limited lifetime of LHC collimators
Radiation to electronics close to cleaning insertions	OK for nominal intensity (0.5 Gy/y)	Review needed for any upgrade
Quench downstream of local dump protection (TCDQ)	MQY at 60% of quench limit for nominal intensity (beam 2).	Upgrade of TCDQ should be envisaged.

Issue for ions	Prediction	Consequences
Fragmentation and dissociation in primary collimator	Two-stage cleaning does not work.	Intensity limited to ~ 30% of nominal.