

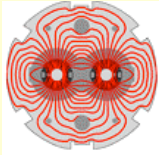


The Large Hadron Collider The Energy Frontier Machine

U. Wienands, SLAC

presently LARP Long Term Visitor @ CERN

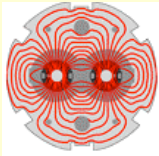
With acknowledgement to the many CERN colleagues making up the LHC commissioning team, led by Mike Lamont.



LARP

Outline

- Introduction: The LHC Complex
- LHC Performance in 2010
- LHC planned Running & Improvements
- LHC Upgrades: Where to go
- Conclusion



LARP

The CERN Accelerator Complex

Introduction

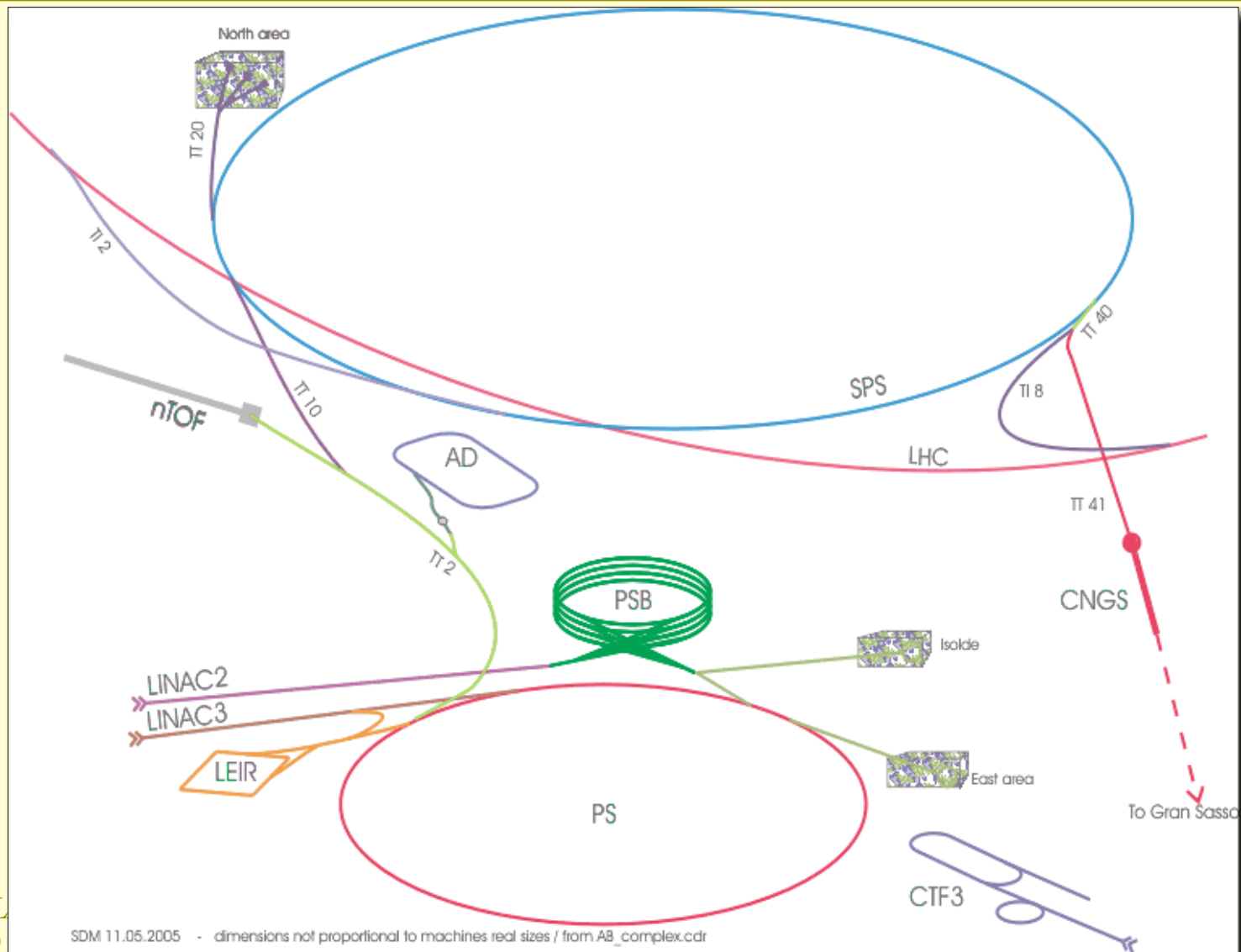
Performance

Accel.
Physics

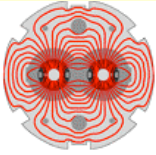
Plan

Upgrades

Conclusion



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Paris 17-Sep-10



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LHC Ring Layout

Introduction

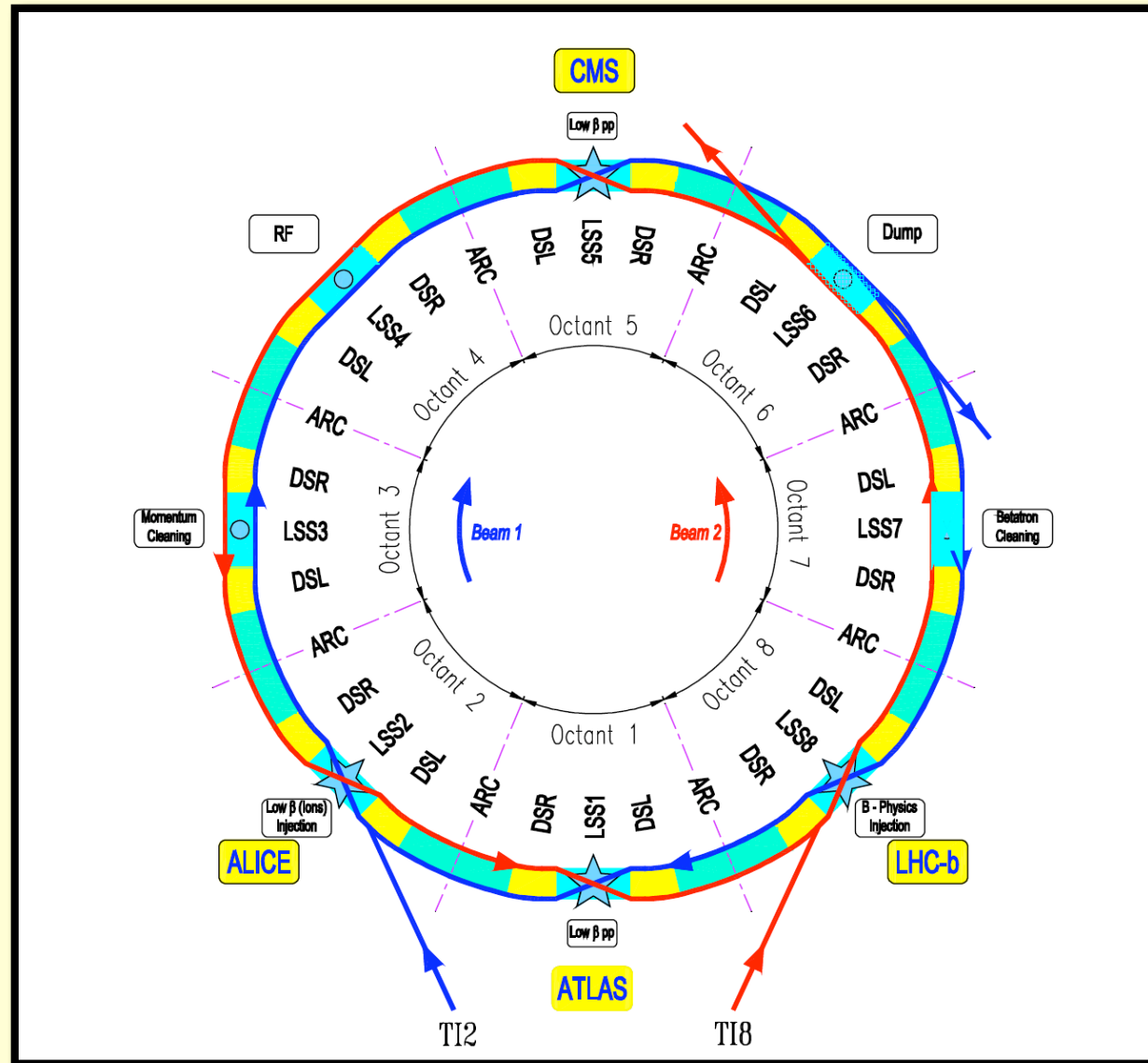
Performance

Accel.
Physics

Plan

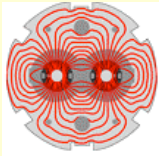
Upgrades

Conclusion



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The LHC Tunnel

Introduction

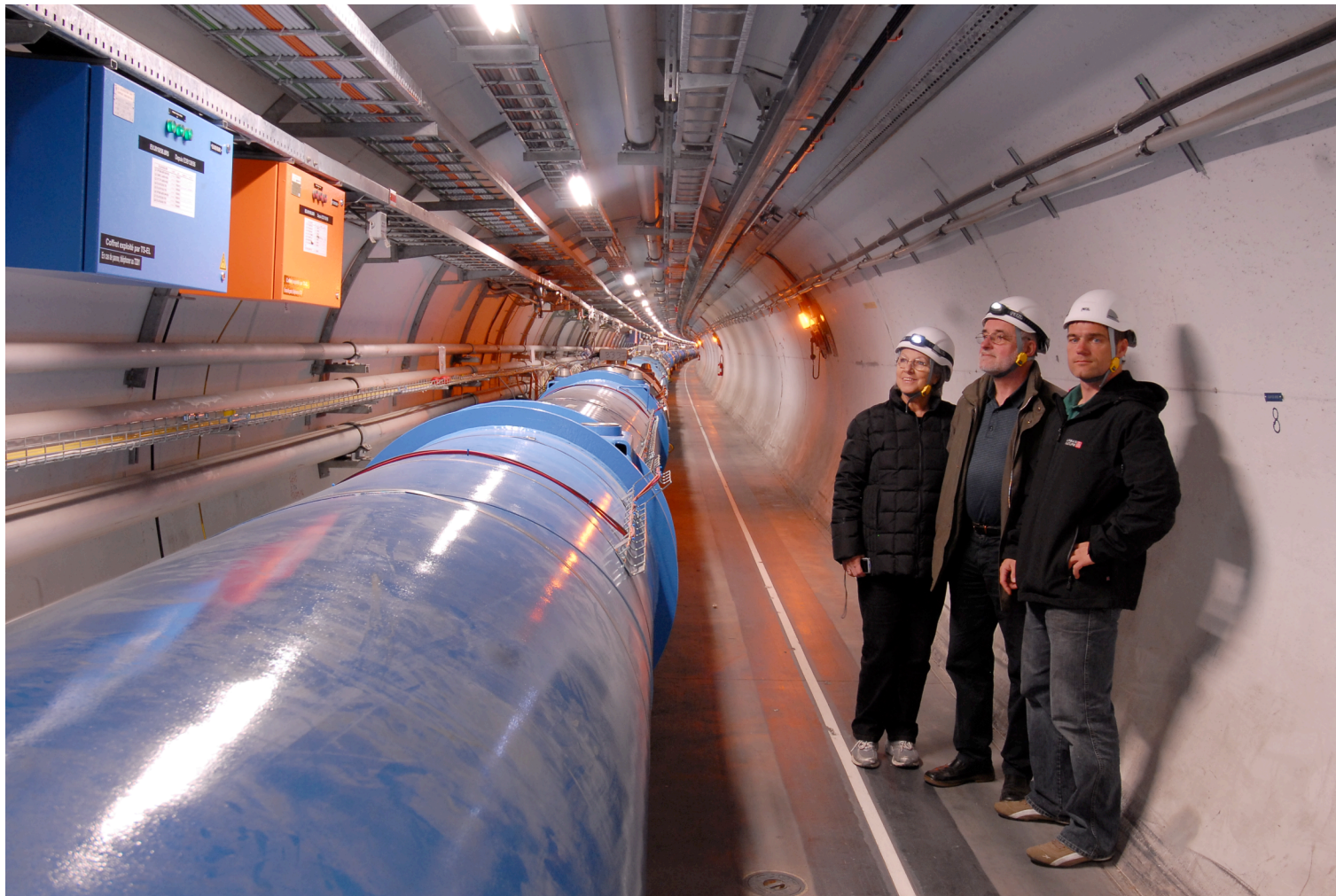
Performance

Accel.
Physics

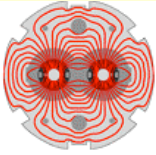
Plan

Upgrades

Conclusion



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Distribution Box

Introduction

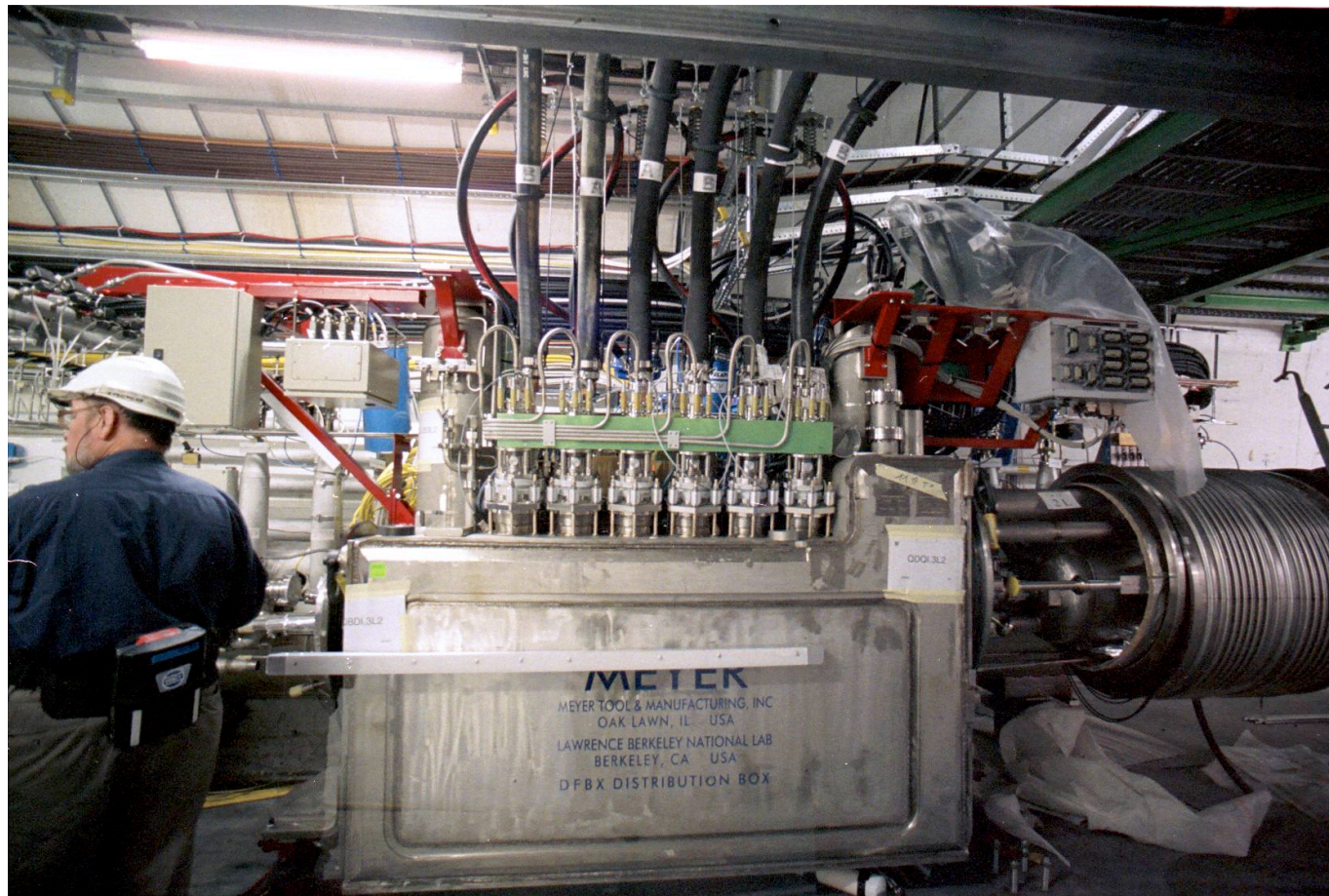
Performance

Accel.
Physics

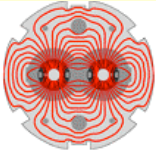
Plan

Upgrades

Conclusion



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Warm Section

Introduction

Performance

Accel.
Physics

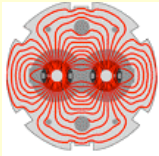
Plan

Upgrades

Conclusion



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Rf in Tunnel

Introduction

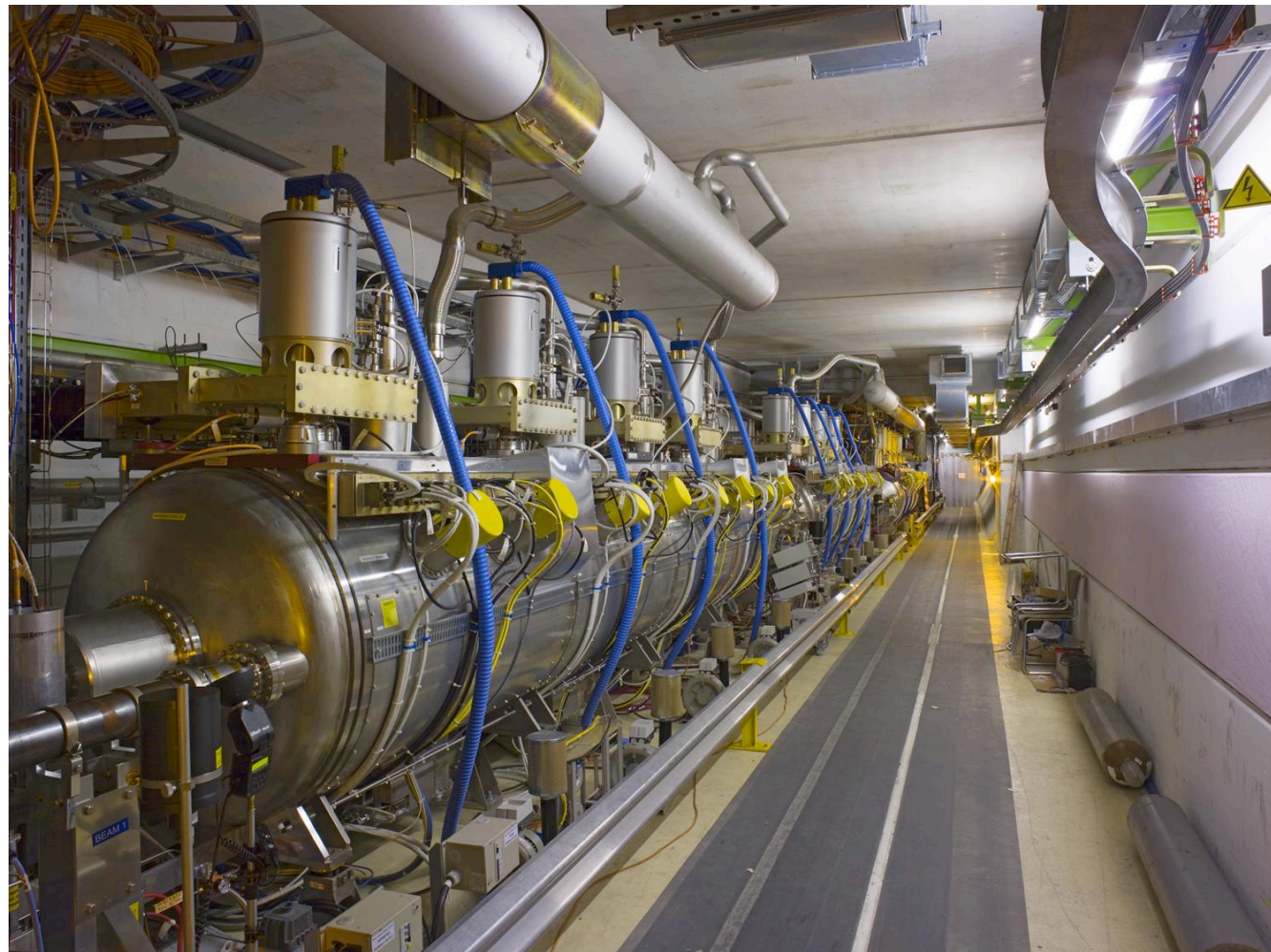
Performance

Accel.
Physics

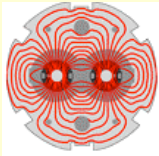
Plan

Upgrades

Conclusion



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LARP

What makes it unique

Introduction

Performance

Accel.
Physics

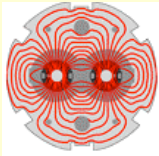
Plan

Upgrades

Conclusion

- **Sheer size:**
 - 26.7 km circumference
- **Beam energy:**
 - 7 on 7 TeV (spec.)
- **Luminosity**
 - $10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- **Magnetic field:**
 - 8.33 T at 7 TeV/beam
- **Synchrotron radiation**
 - 6.7 keV/ring; ≈ 3 kW, 26 h trans. damping time
- **Stored energy**
 - 11 GJ at 7 on 7 TeV, 350 MJ in each beam
- **Persistent currents**
 - significant chromaticity & tune changes

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Stored Energy:

Introduction

Performance

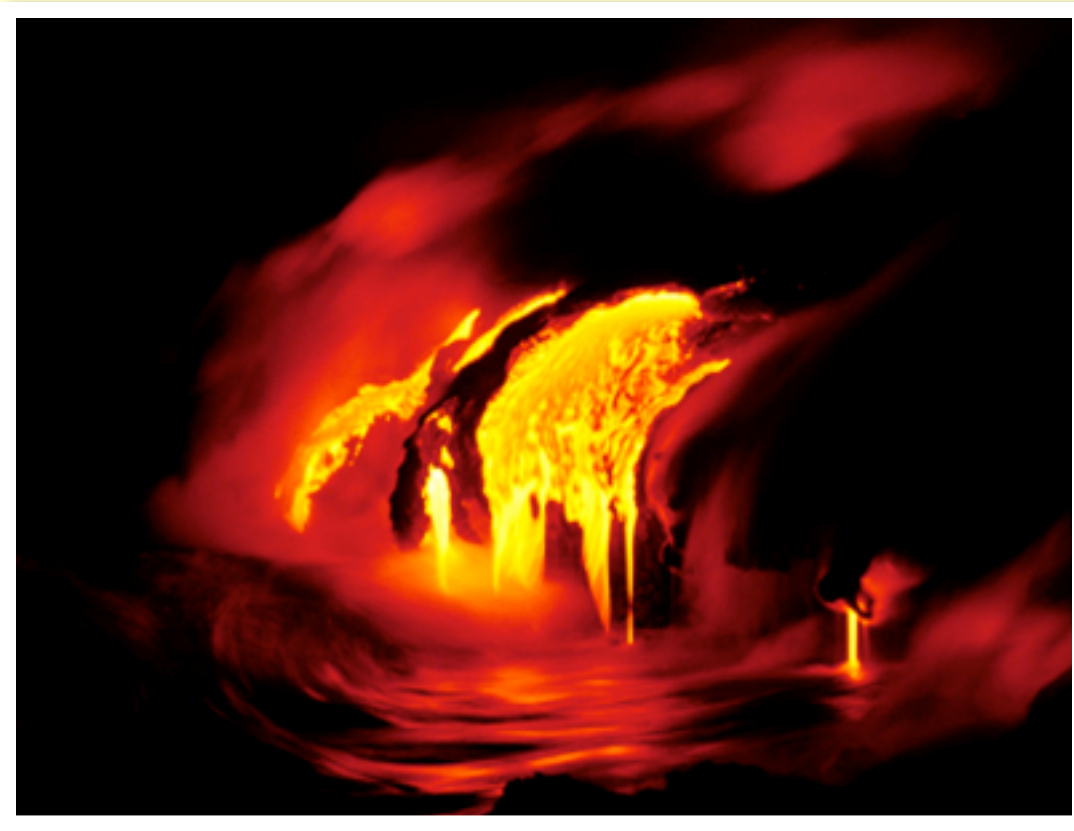
Accel.
Physics

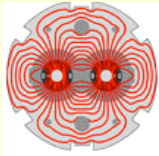
Plan

Upgrades

Conclusion

- 11 GJ: melt 15 T of Cu (1.3 m³)





LARP

Introduction

Performance

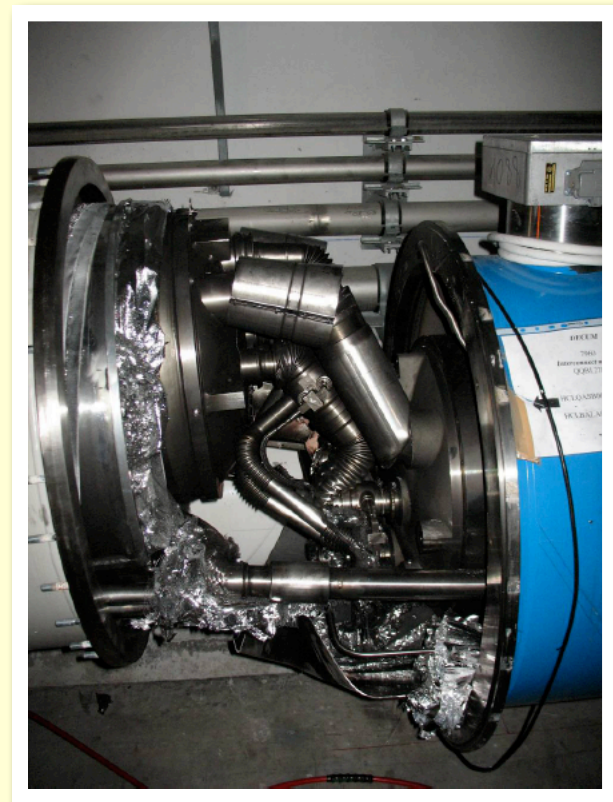
Accel.
Physics

Plan

Upgrades

Conclusion

- What happened at $\approx 5\text{GJ}$ stored energy (magnets):





Beam Commissioning Main Steps

Introduction

Performance

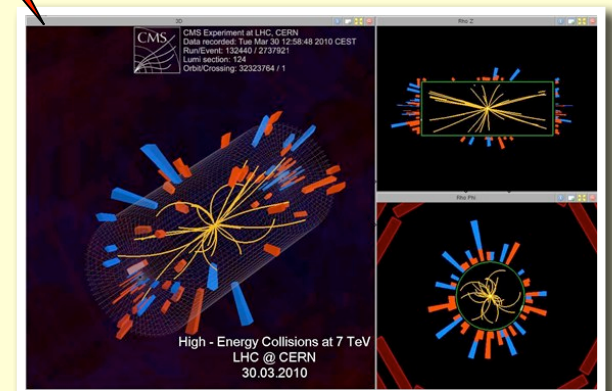
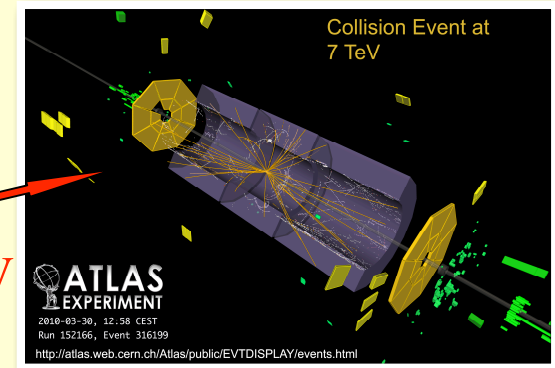
Accel.
Physics

Plan

Upgrades

Conclusion

- Low intensity
 - Establish clean injection
 - Measure & correct optics
 - **Establish Collisions @ 3.5 on 3.5 TeV**
 - Commission β squeeze at the IPs
 - commissioned to 2 m but for machine protection use 3.5 m for now
 - Establish beam-collimation setup
 - strict hierarchy of apertures
- Nominal bunch intensity ($\approx 1.1 \times 10^{11}$, 1 bunch)
 - assess beam stability
 - commission dampers
 - assess beam-beam effect
 - **Check collimation setup**
- Multibunch collisions
 - redo all of the above
 - **Check collimation setup**



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Paris 17-Sep-10*



Parameters Achieved to Date

Introduction


Performance

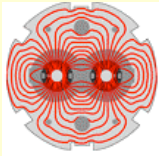
Accel.
Physics

Plan

Upgrades

Conclusion

- Energy: 3.5 on 3.5 TeV
- $\mathcal{L}_{peak} = 1E31$
- # bunches: 50 on 50
- E_{stored} : 2.8 MJ 
- β^* : 3.5 m operational, 2 m in dedicated runs
- Beam emittance (norm): $\approx 3.5 \times 10^{-6}$ m-r
 - growth of 2...3.5%/h seen
- Luminosity life time: ≈ 20 h
 - effect of beam size growth significant



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Luminosity

Introduction

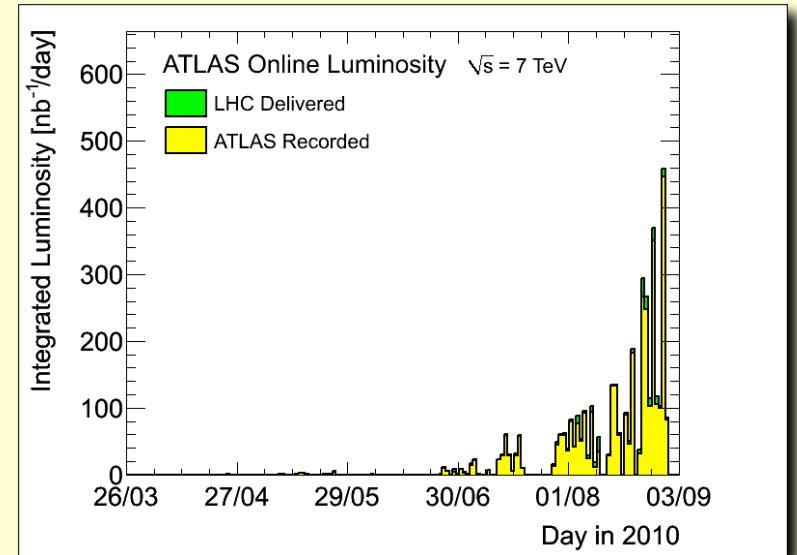
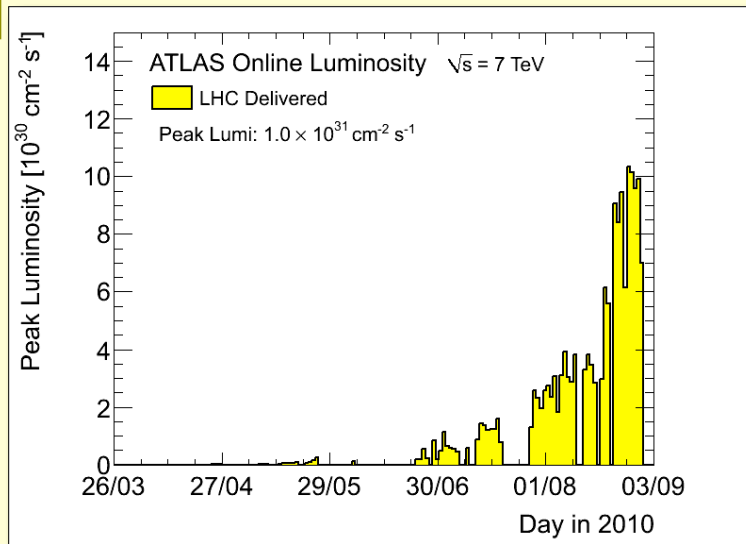
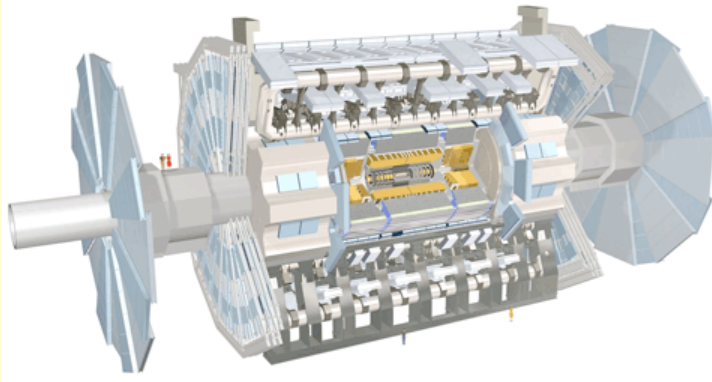
Performance

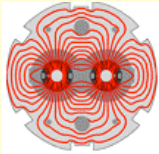
Accel.
Physics

Plan

Upgrades

Conclusion





LARP

$\int L dt$

Introduction

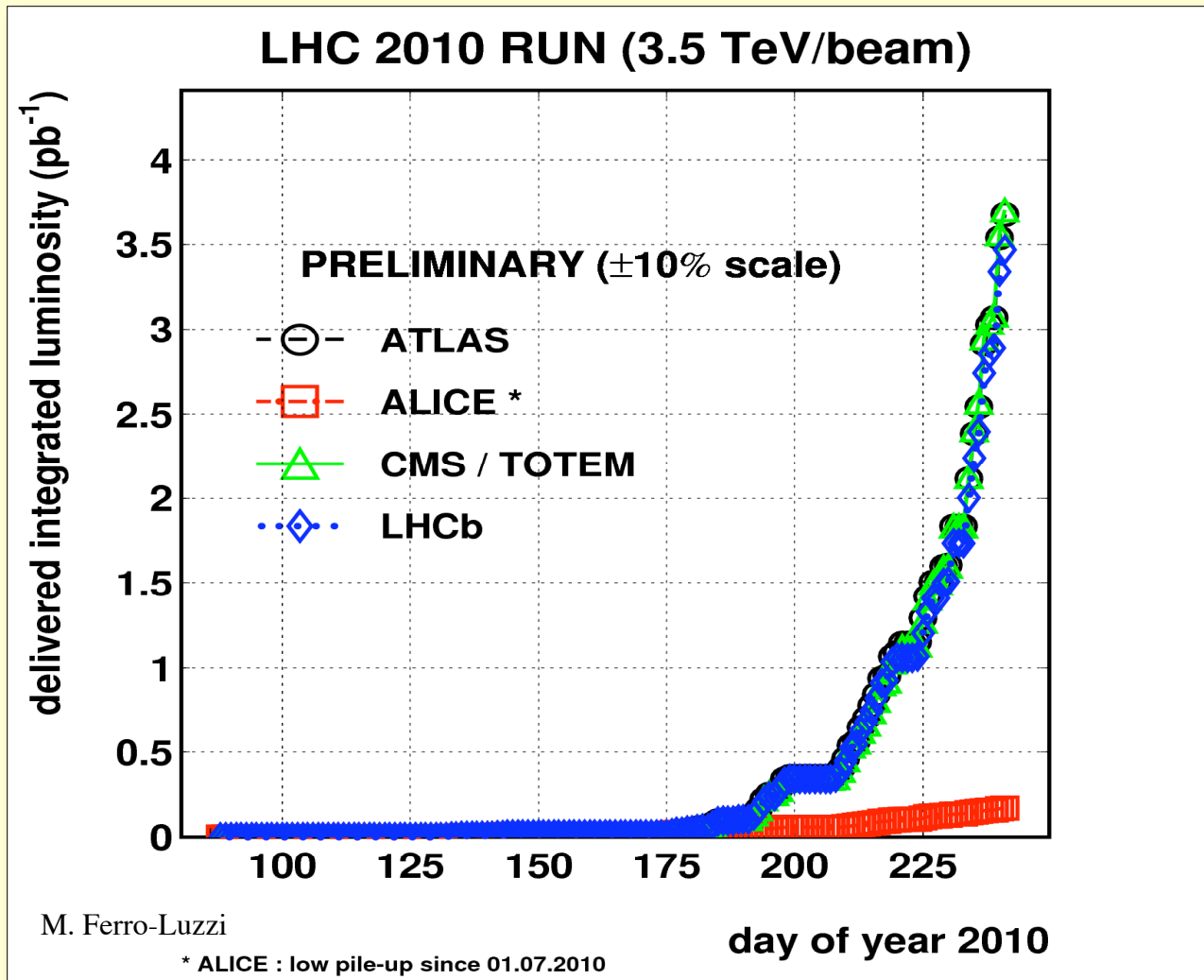
Performance

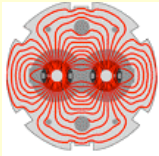
Accel.
Physics

Plan

Upgrades

Conclusion

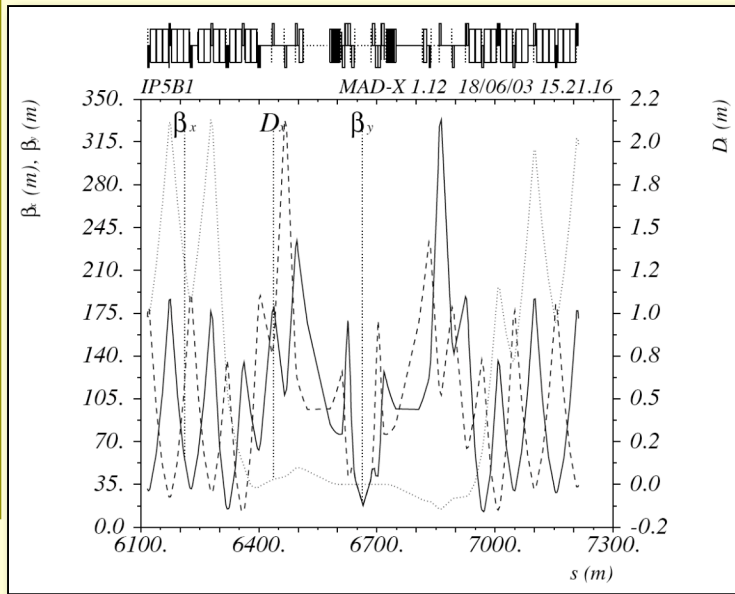




LARP

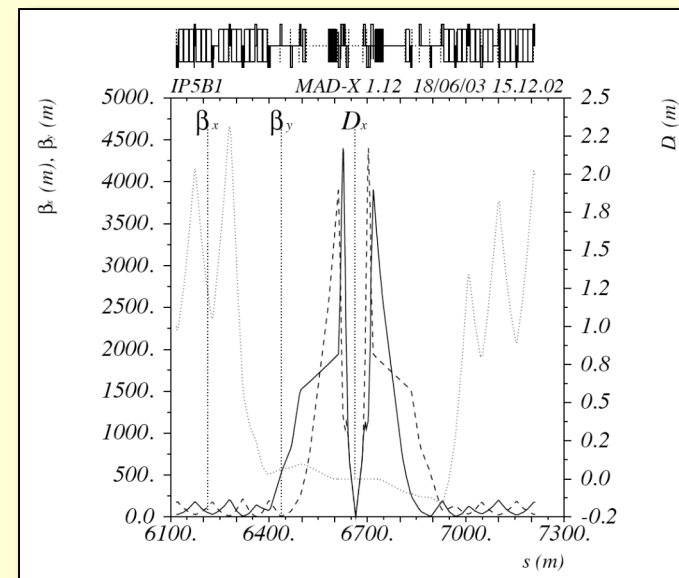
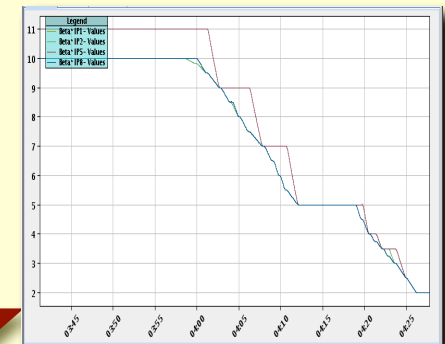
IR Lattice

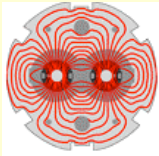
- Introduction
- Performance
- Accel. Physics
- Plan
- Upgrades
- Conclusion



Collision configuration
 $(\beta^*=0.55 \text{ m})$

Squeeze
 Injection configuration





LARP

Beam-Beam Scan

Introduction

Performance

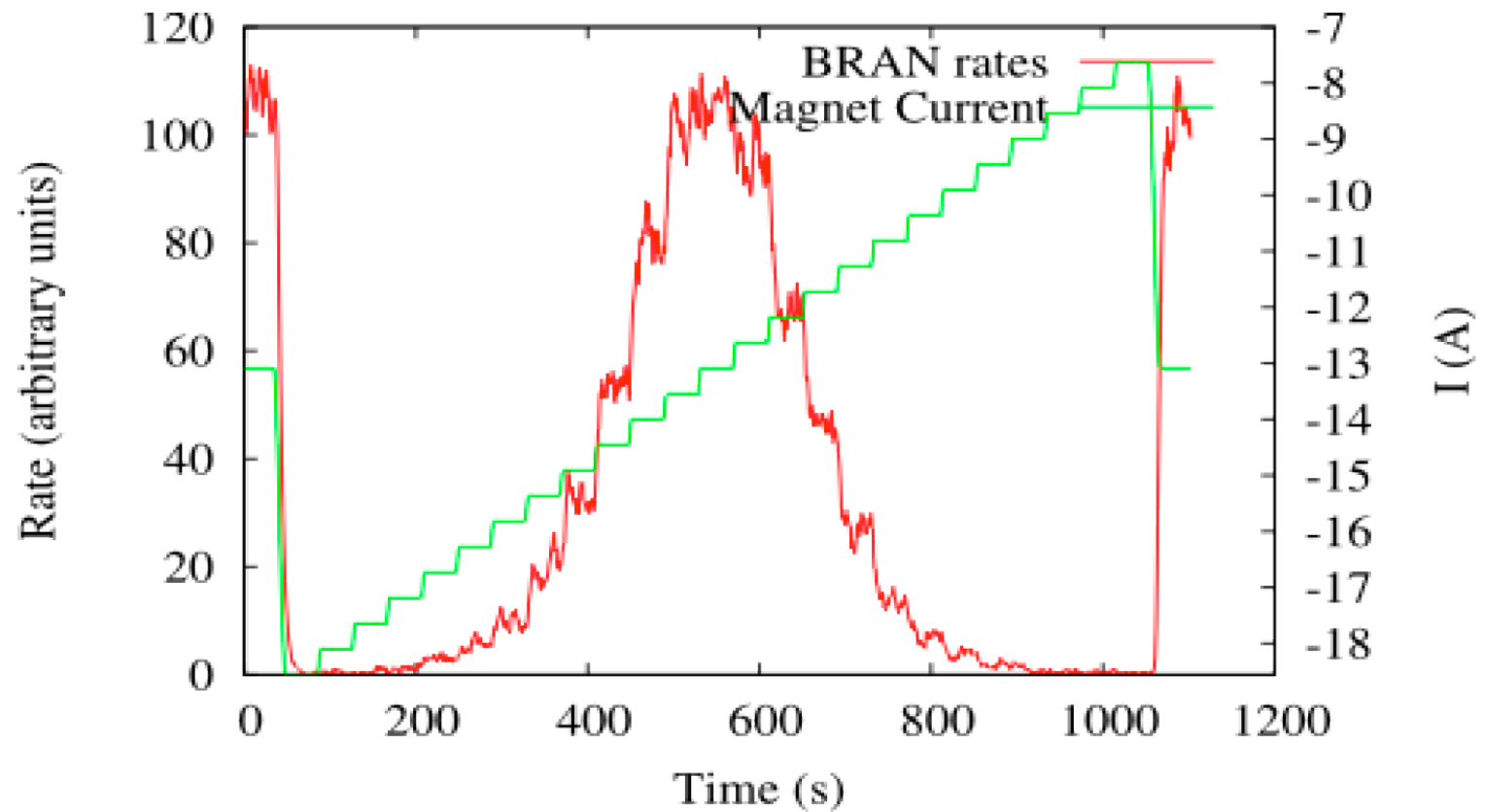
Accel.
Physics

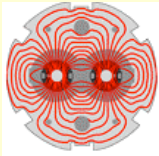
Plan

Upgrades

Conclusion

Time history plot of a scan done at IP5.

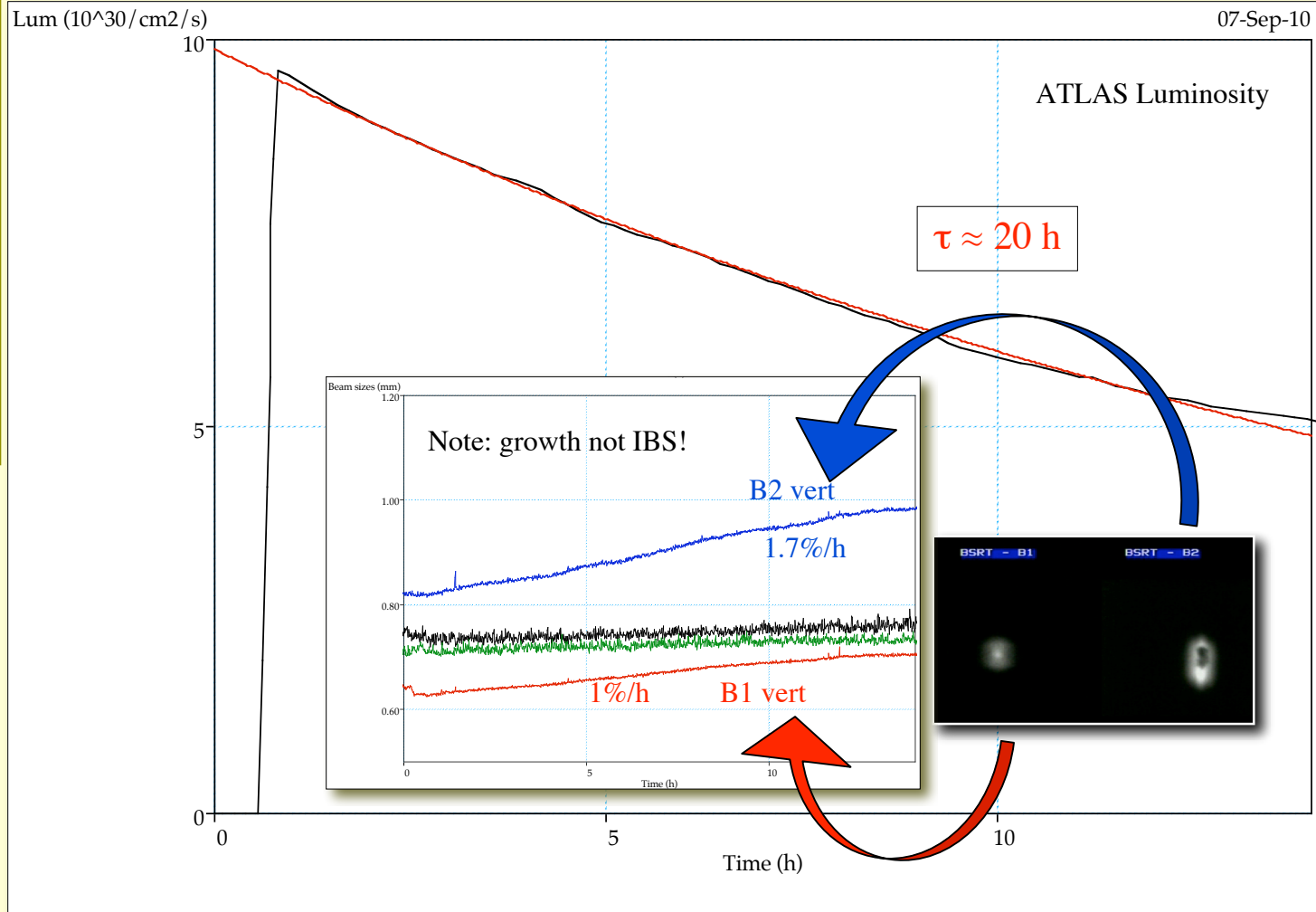


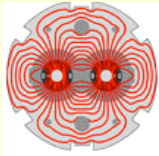


LARP

Luminosity Lifetime

- Introduction
- Performance
- Accel. Physics
- Plan
- Upgrades
- Conclusion

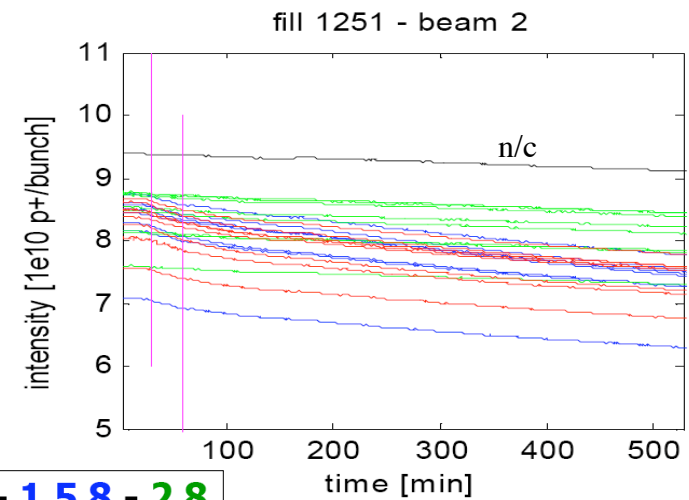
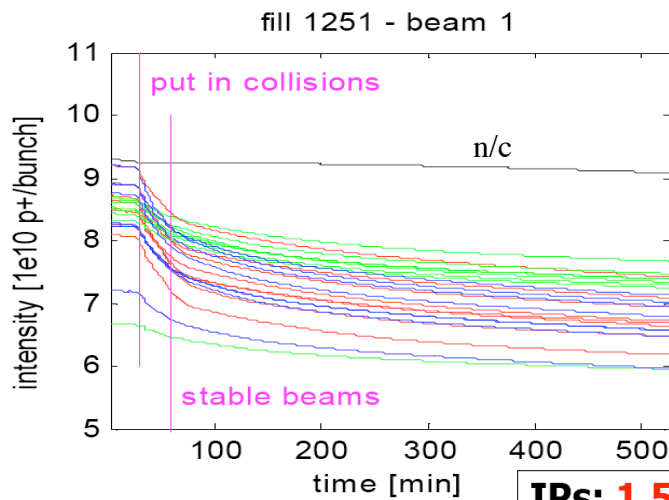




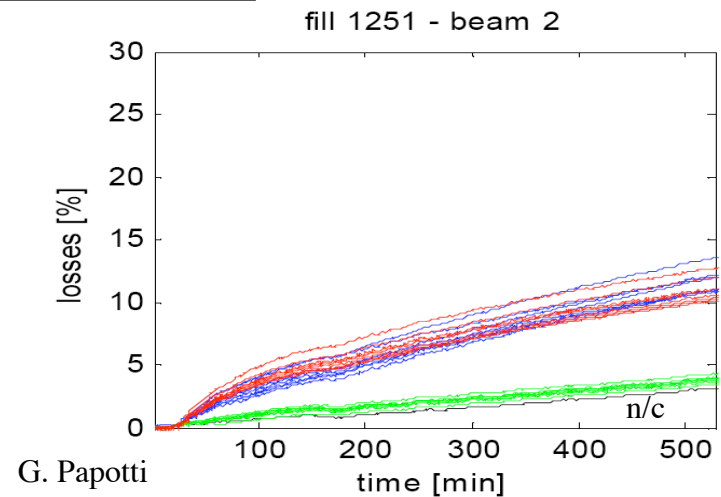
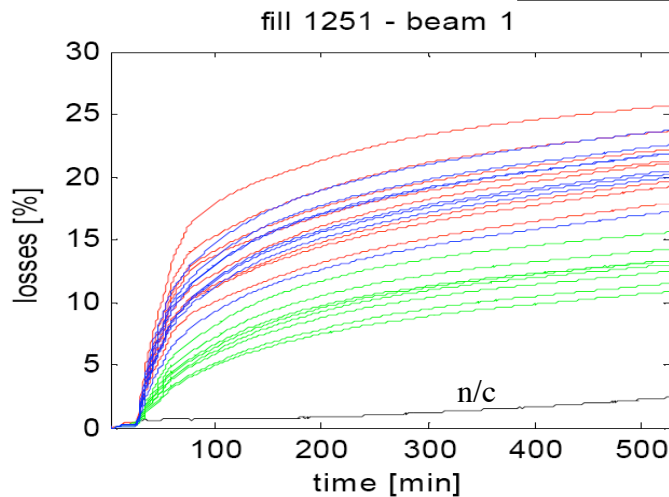
LARP

Beam-beam Effect

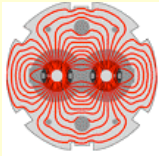
- Introduction
- Performance
- Accel. Physics
- Plan
- Upgrades
- Conclusion



IPs: 152 - 158 - 28



G. Papotti



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Beam-Beam...48-bunch fill

Introduction

Performance

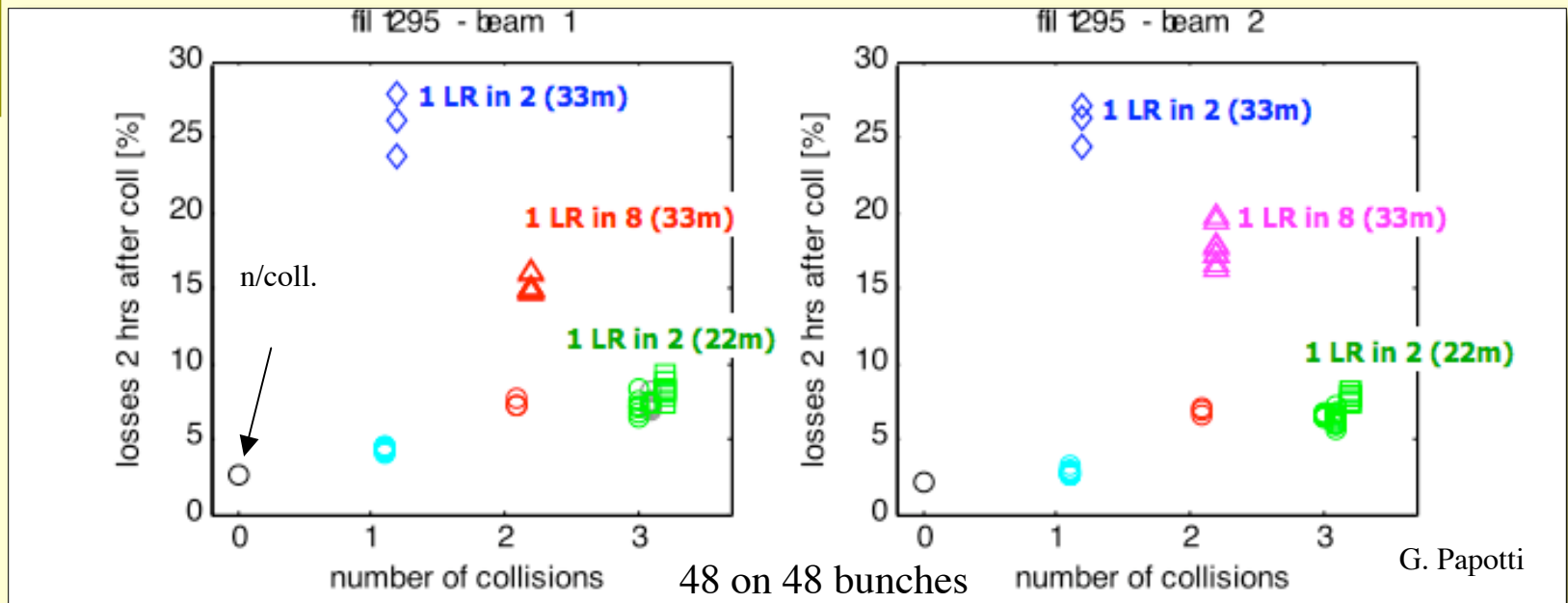
Accel.
Physics

Plan

Upgrades

Conclusion

- $\xi \approx 0.003$ at these parameters
 - little problem for head-on collisions
 - parasitics are a different issue, though...
 - need crossing angle for larger # of bunches





Optics: Envelope Functions

Introduction

Performance

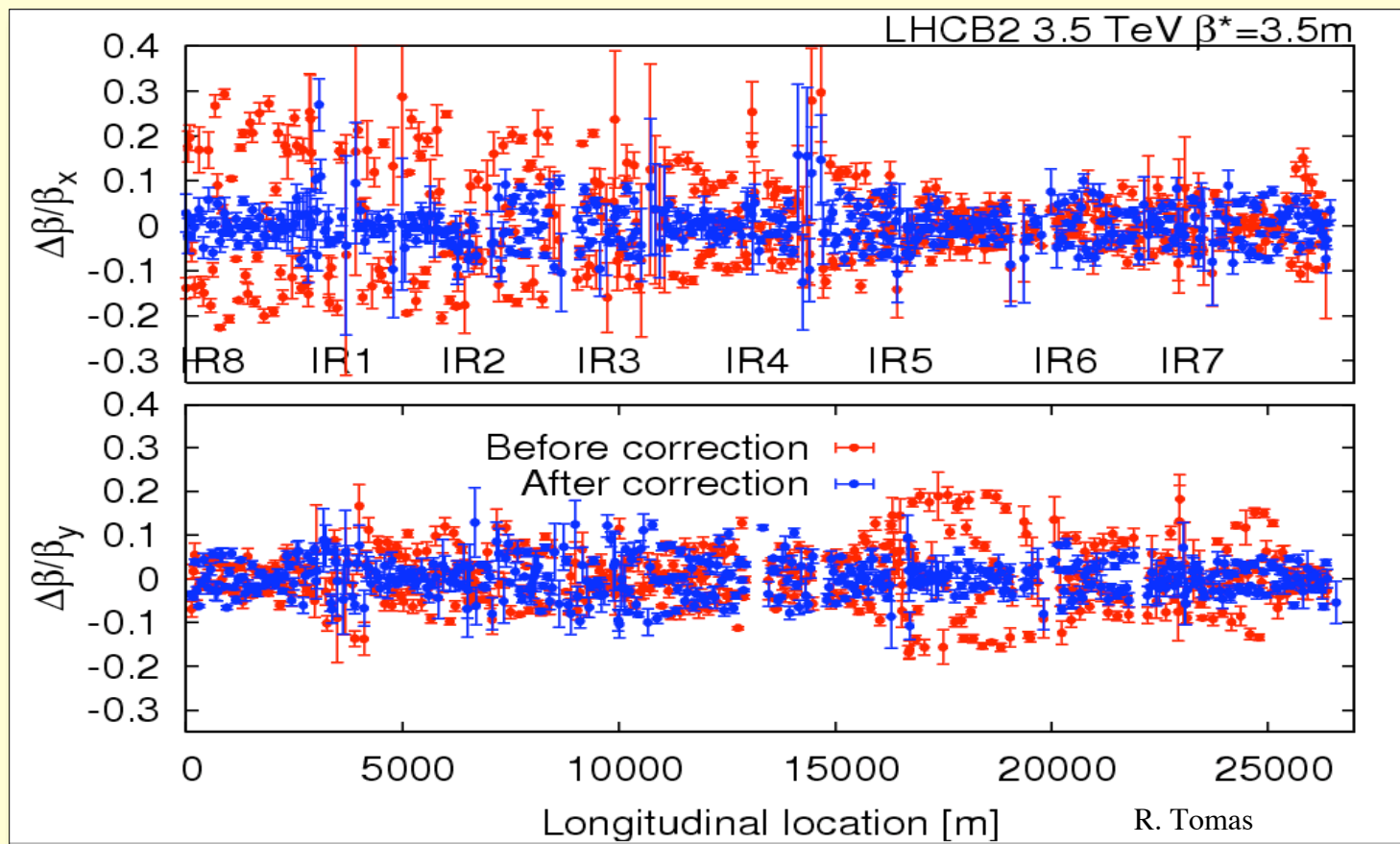
Accel.
Physics

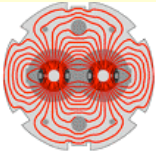
Plan

Upgrades

Conclusion

- $d\beta/\beta_{model} \leq 20\%$ (better than spec.)





LARP

W Function (β chromaticity)

Introduction

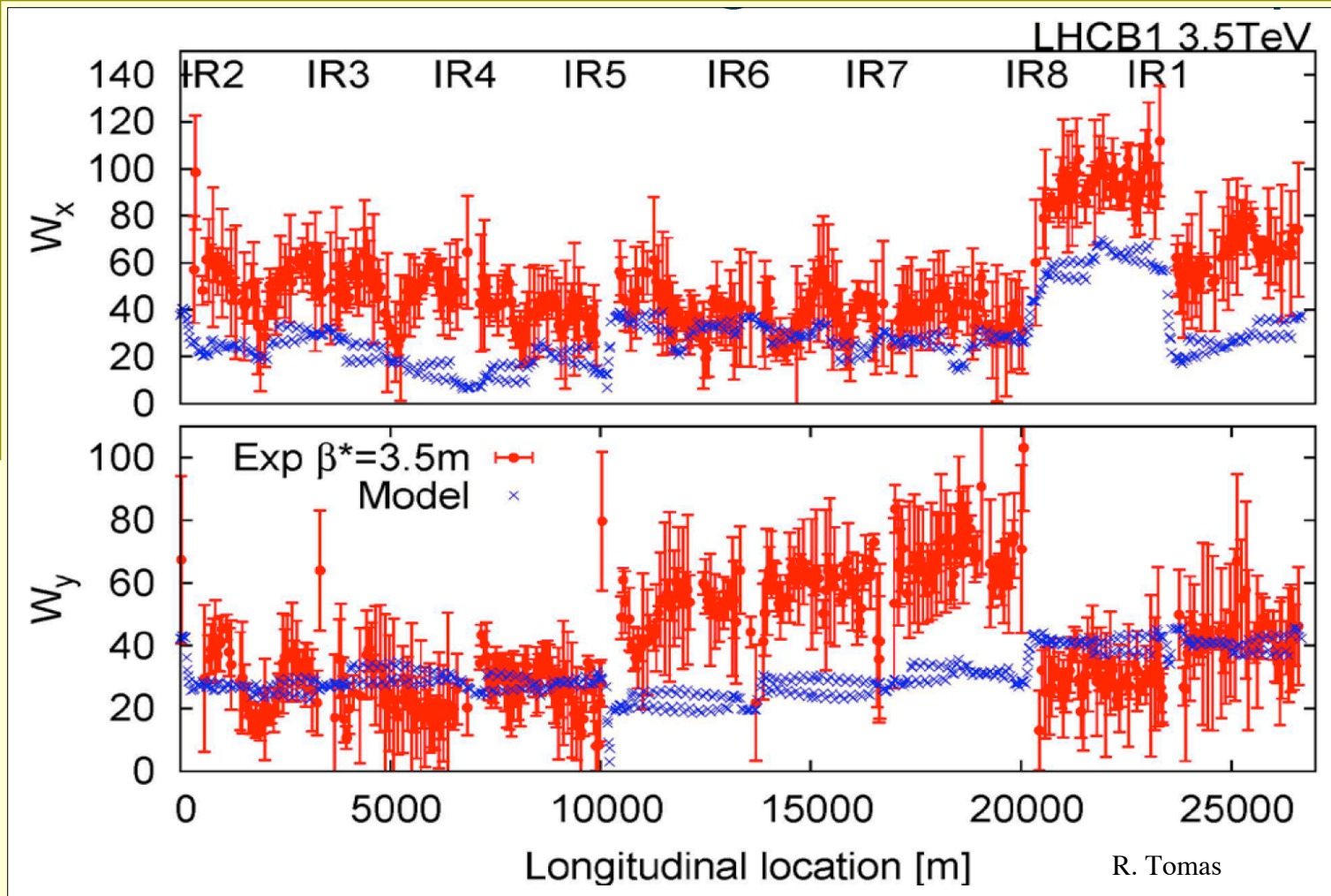
Performance

Accel.
Physics

Plan

Upgrades

Conclusion





Decoherence after a ping

Introduction

Performance

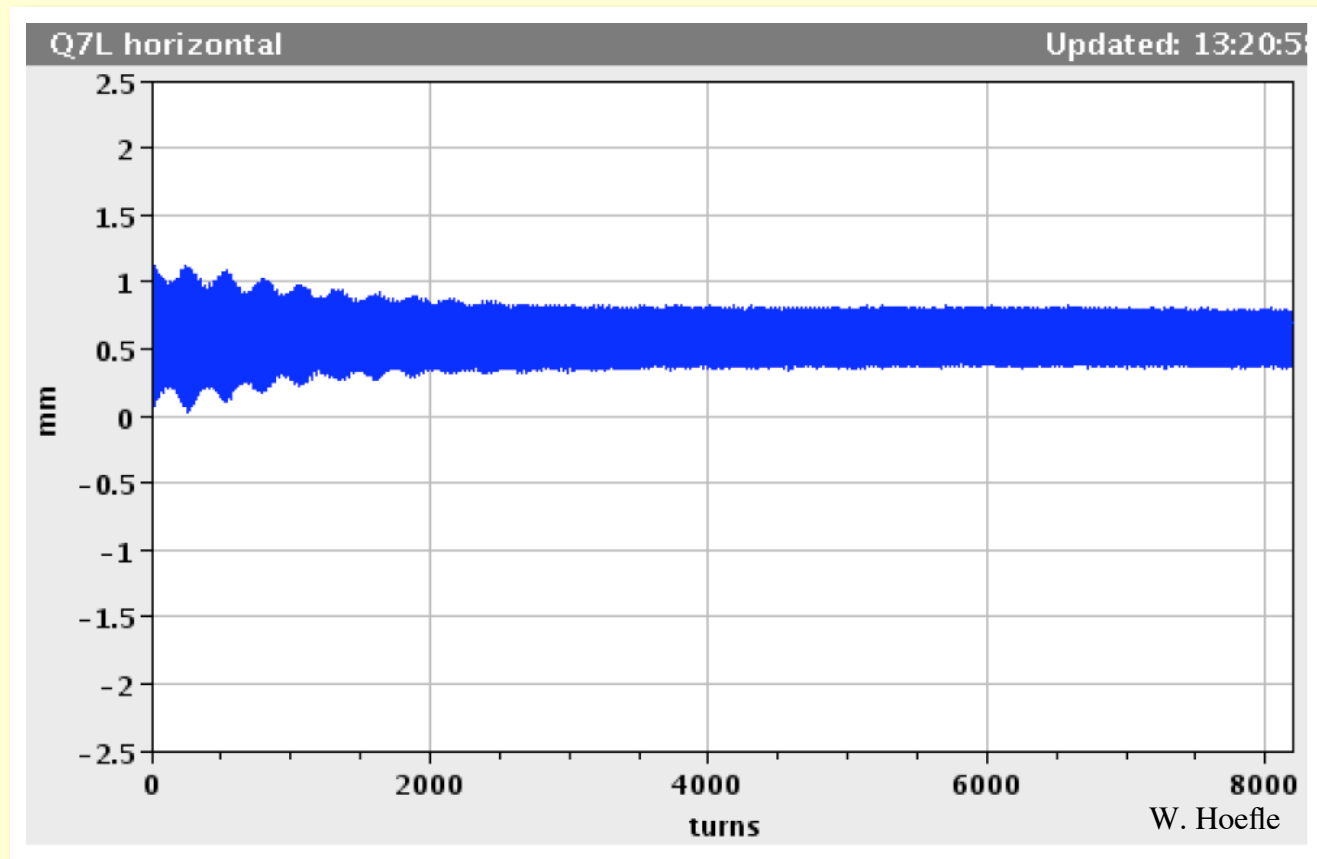
Accel.
Physics

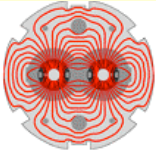
Plan

Upgrades

Conclusion

- Linear machine => long decoherence time

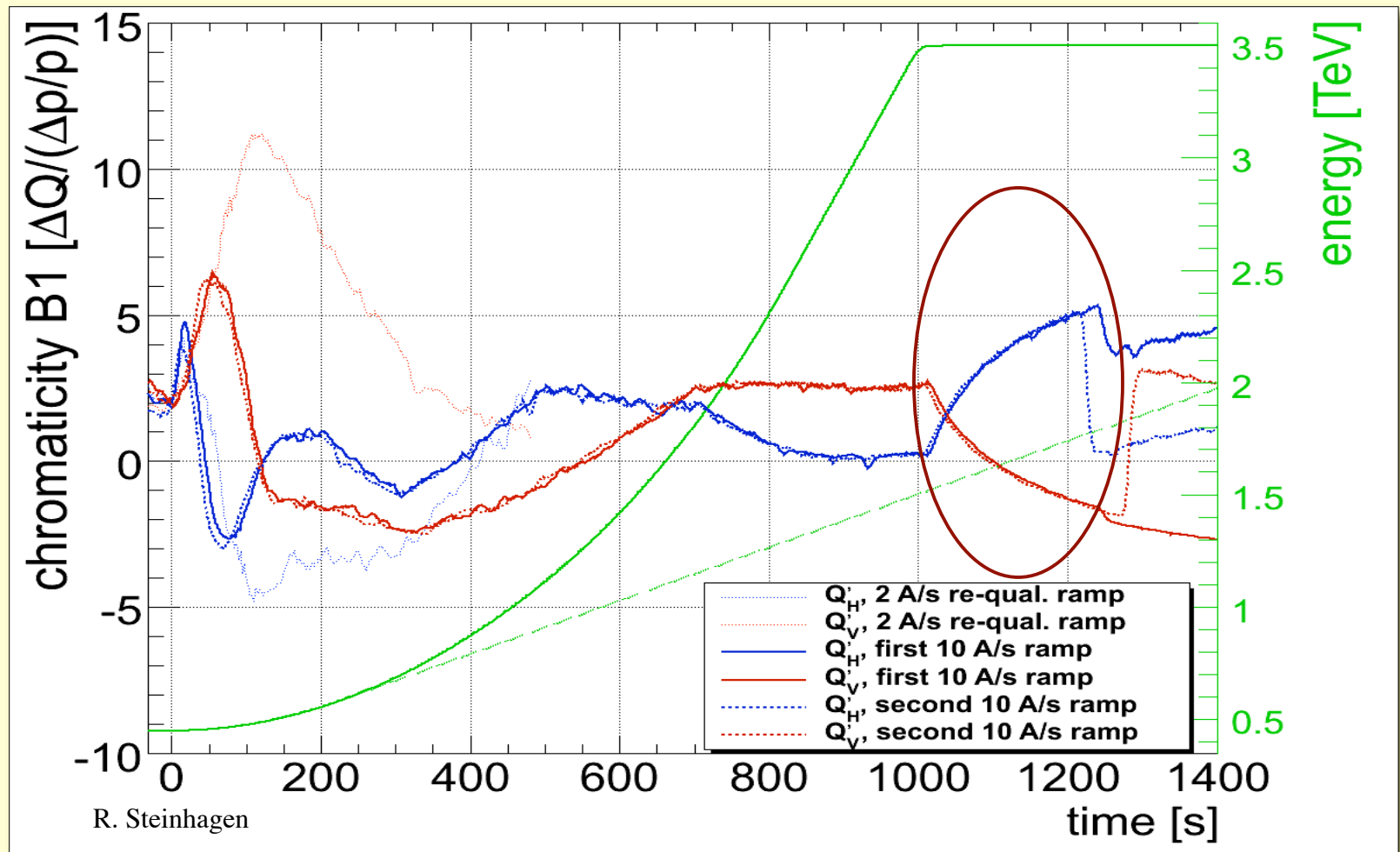


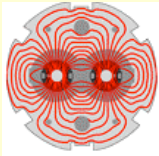


LARP

Chromaticity During Ramp

- Introduction
- Performance
- Accel. Physics
- Plan
- Upgrades
- Conclusion

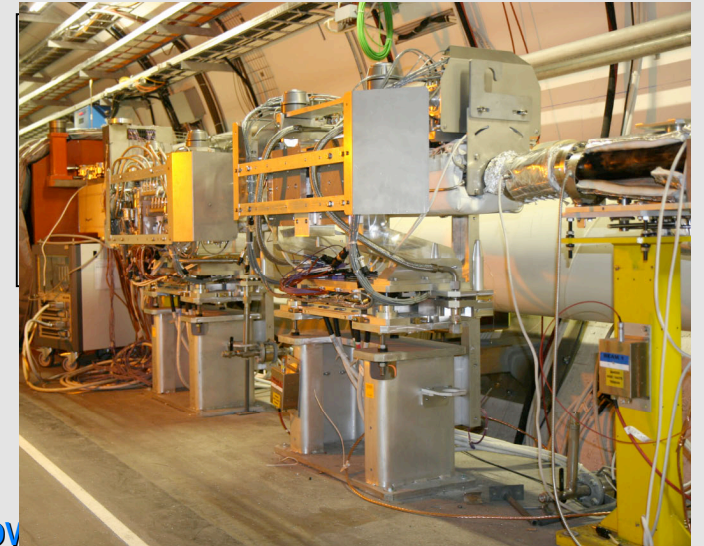
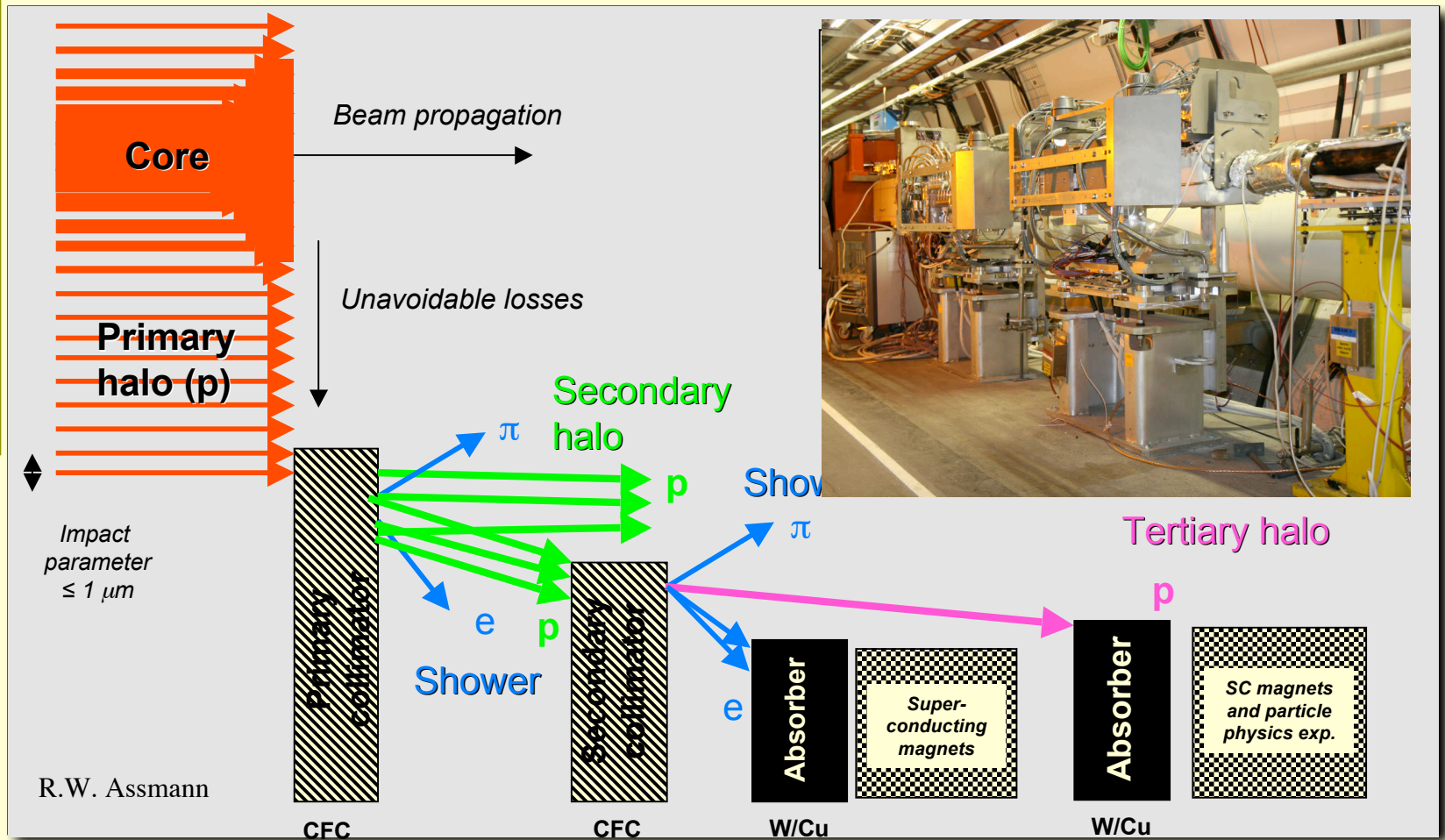


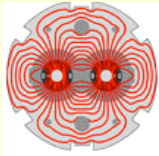


LARP

Beam Collimation

- Introduction
- Performance
- Accel. Physics
- Plan
- Upgrades
- Conclusion





LARP

Beam Loss Map in Collision

Introduction

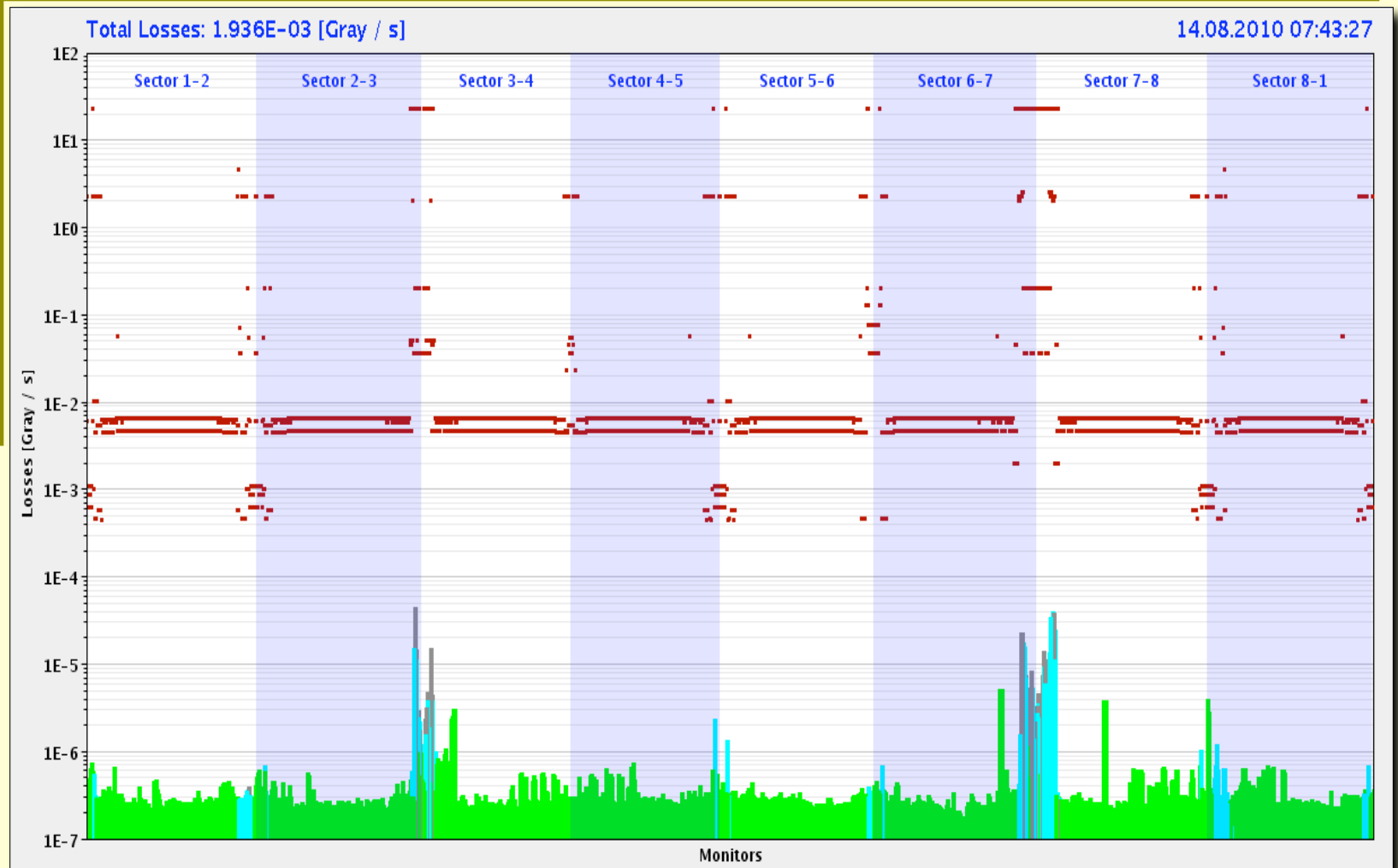
Performance

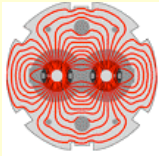
Accel.
Physics

Plan

Upgrades

Conclusion





LARP

Momentum-Space Beam Loss

Introduction

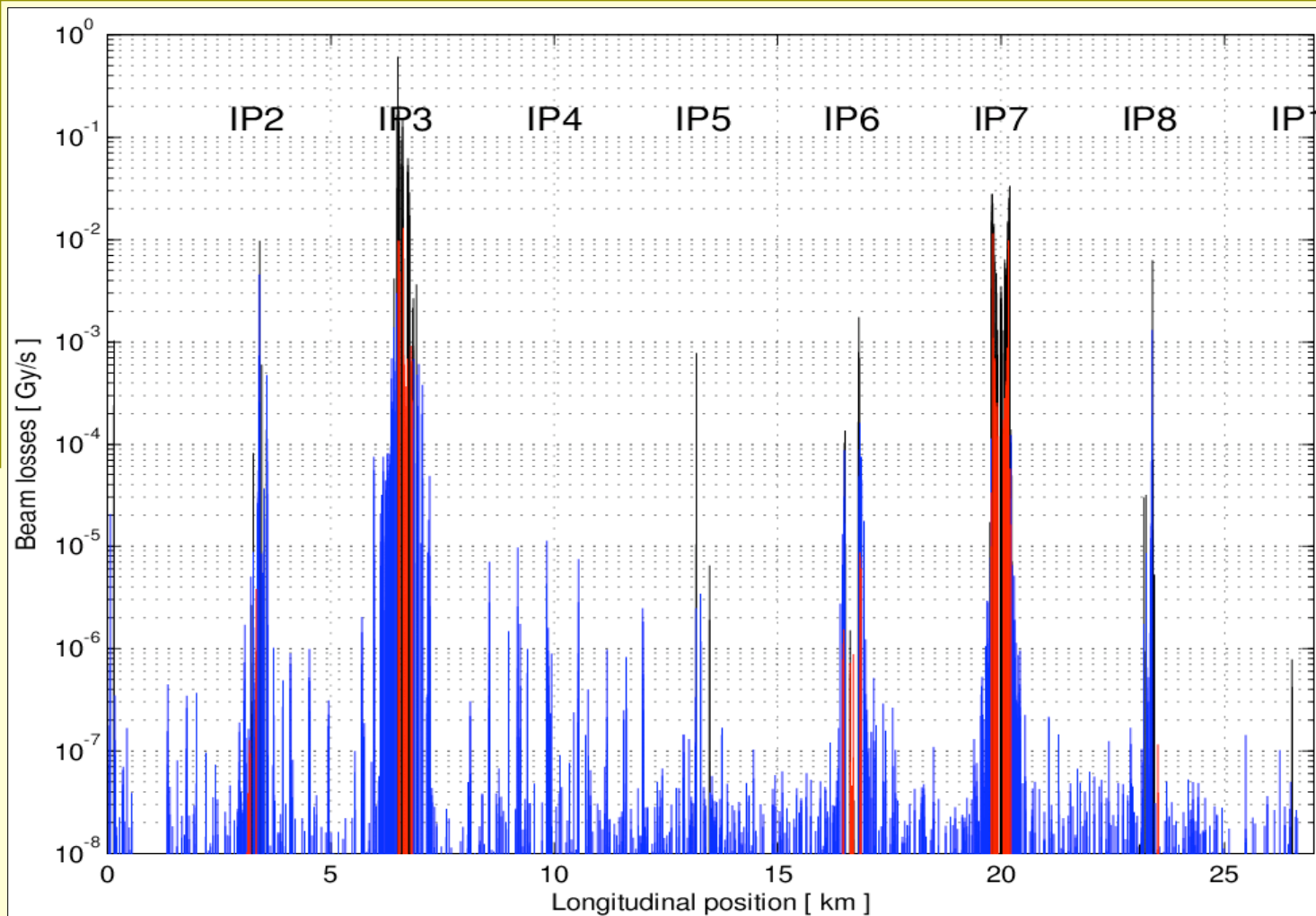
Performance

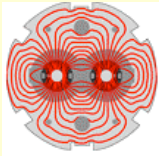
Accel.
Physics

Plan

Upgrades

Conclusion





LARP

Intensity-Related Effects

Introduction

Performance

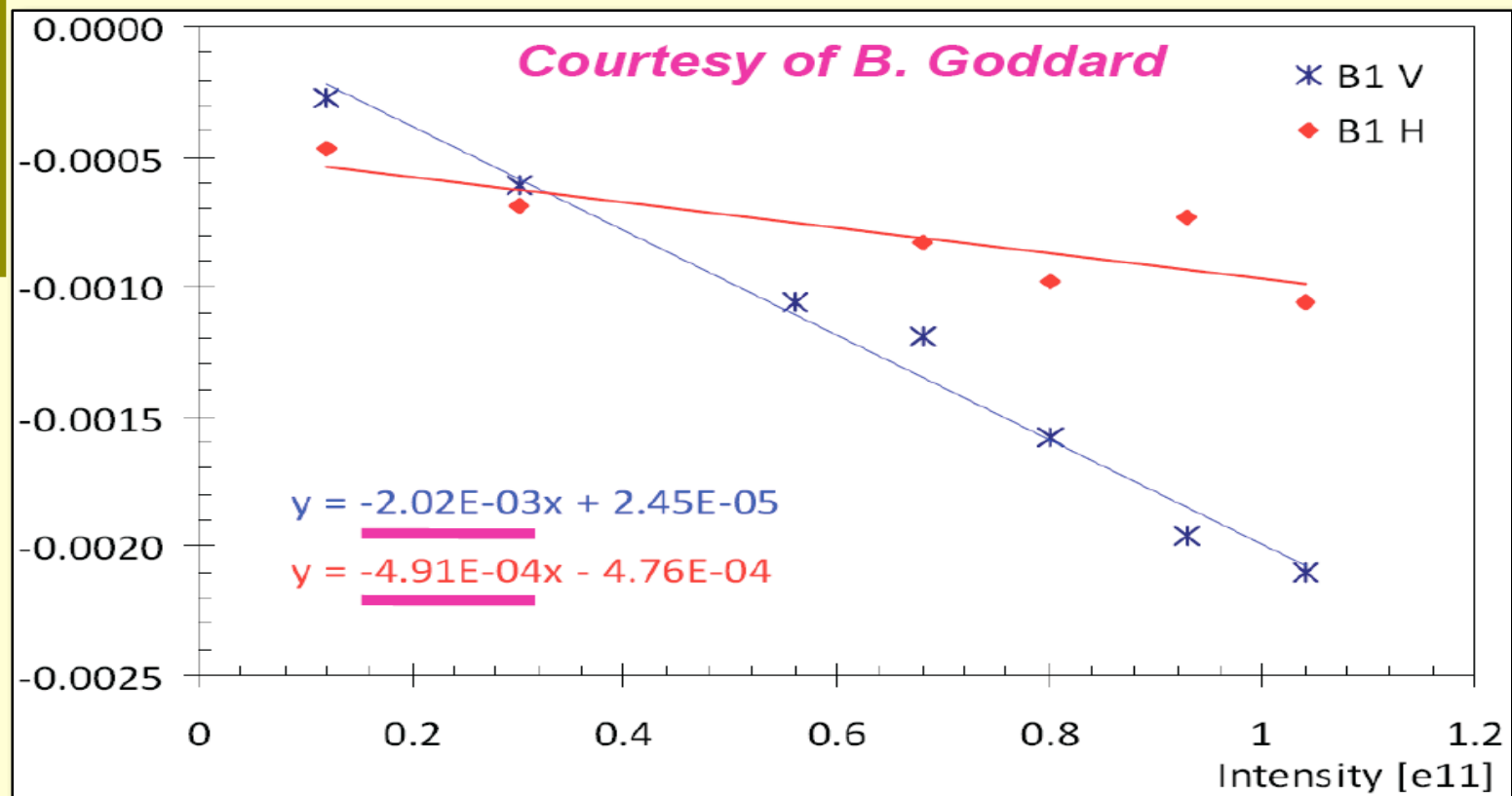
Accel.
Physics

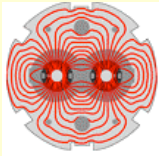
Plan

Upgrades

Conclusion

- Higher than expected tune shift with intensity
 - (high-frequency-) impedance... collimators?





LARP

Intensity-Related Effects

Introduction

Performance

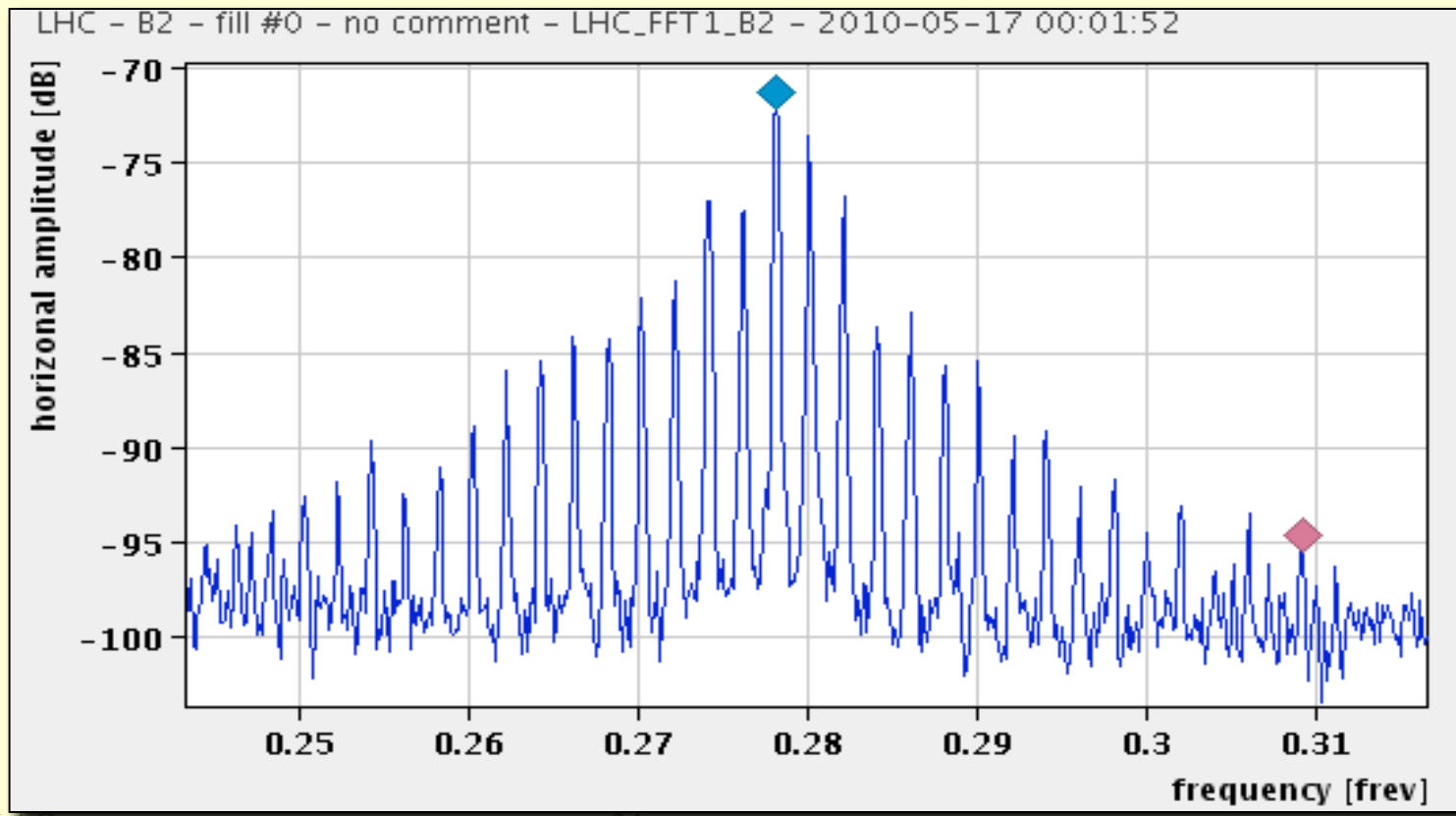
Accel.
Physics

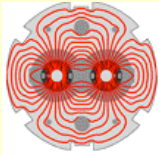
Plan

Upgrades

Conclusion

- Coherent signal seen with multibunch beam
 - then cured with octupoles, no issue with trans. damper





LARP

Intensity-Related Effects

Introduction

Performance

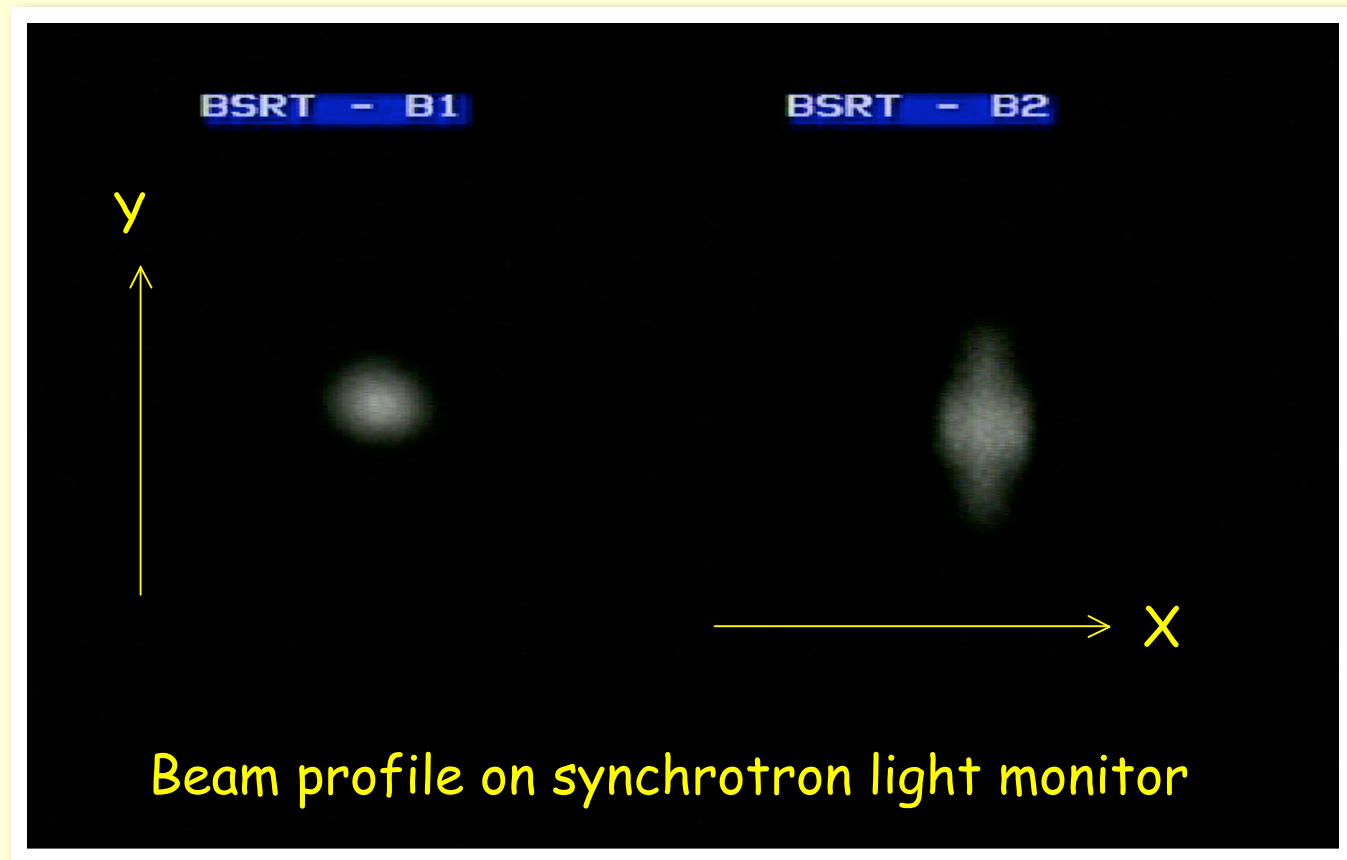
Accel.
Physics

Plan

Upgrades

Conclusion

- “Saturn” instability



Beam profile on synchrotron light monitor



Transverse Damper Performance

Introduction

Performance

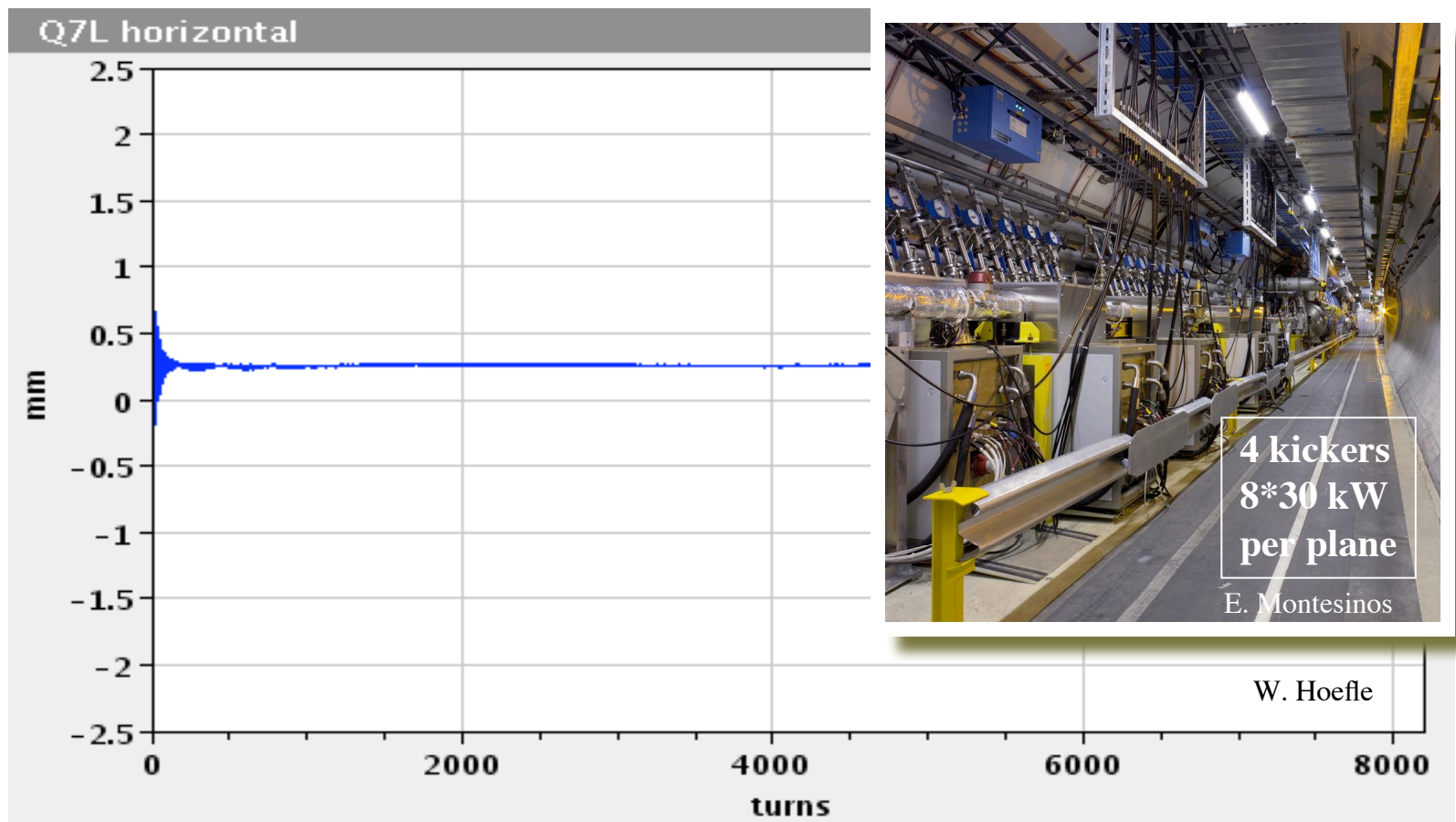
Accel.
Physics

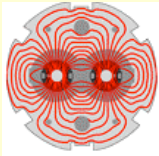
Plan

Upgrades

Conclusion

- Damps well... ≤ 20 turns damping time meas't





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Transverse Damper

Introduction

Performance

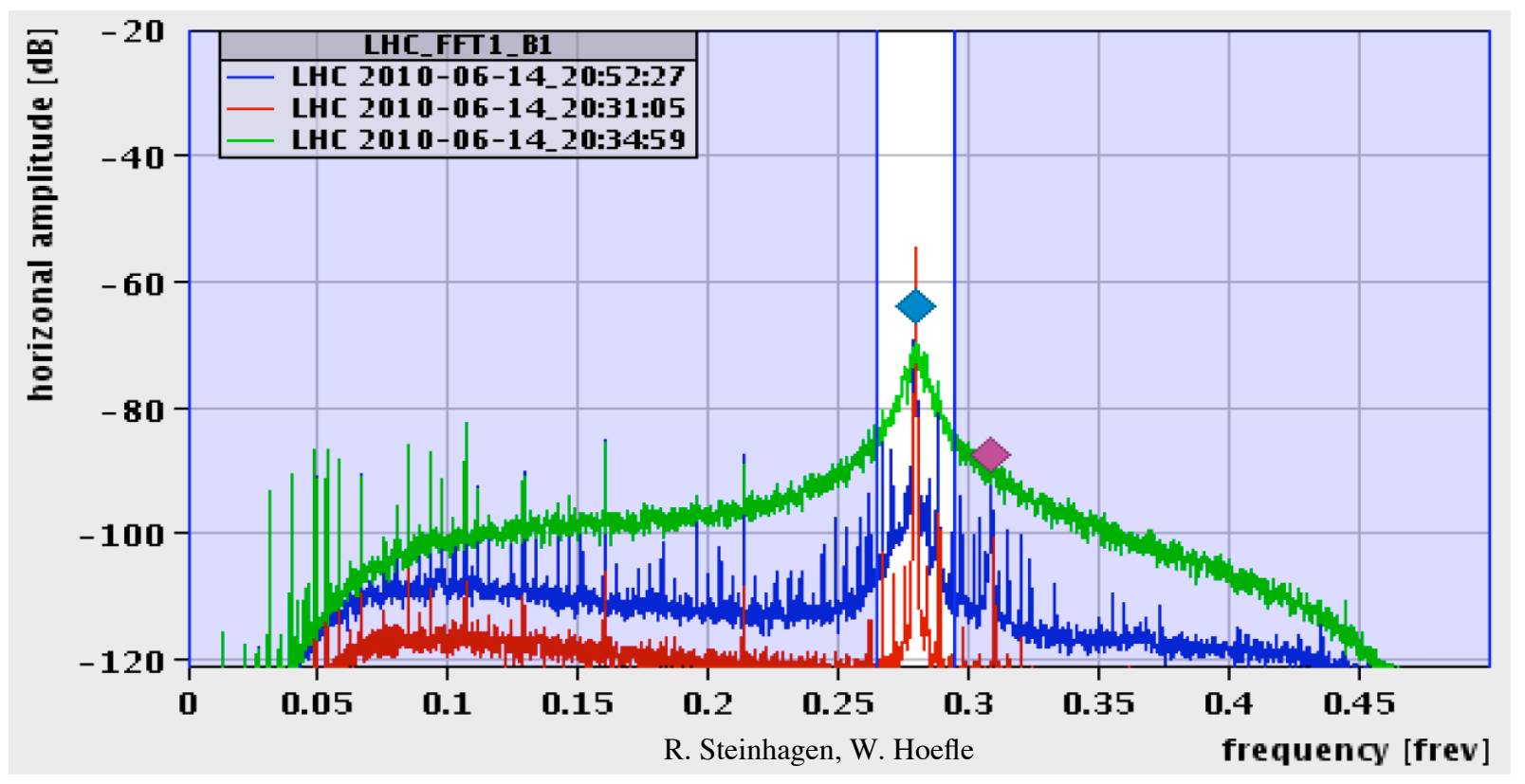
Accel.
Physics

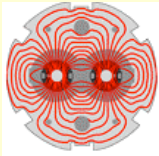
Plan

Upgrades

Conclusion

- ...but tune spectrum shows increased noise...





LARP

Spontaneous Beam Loss

Introduction

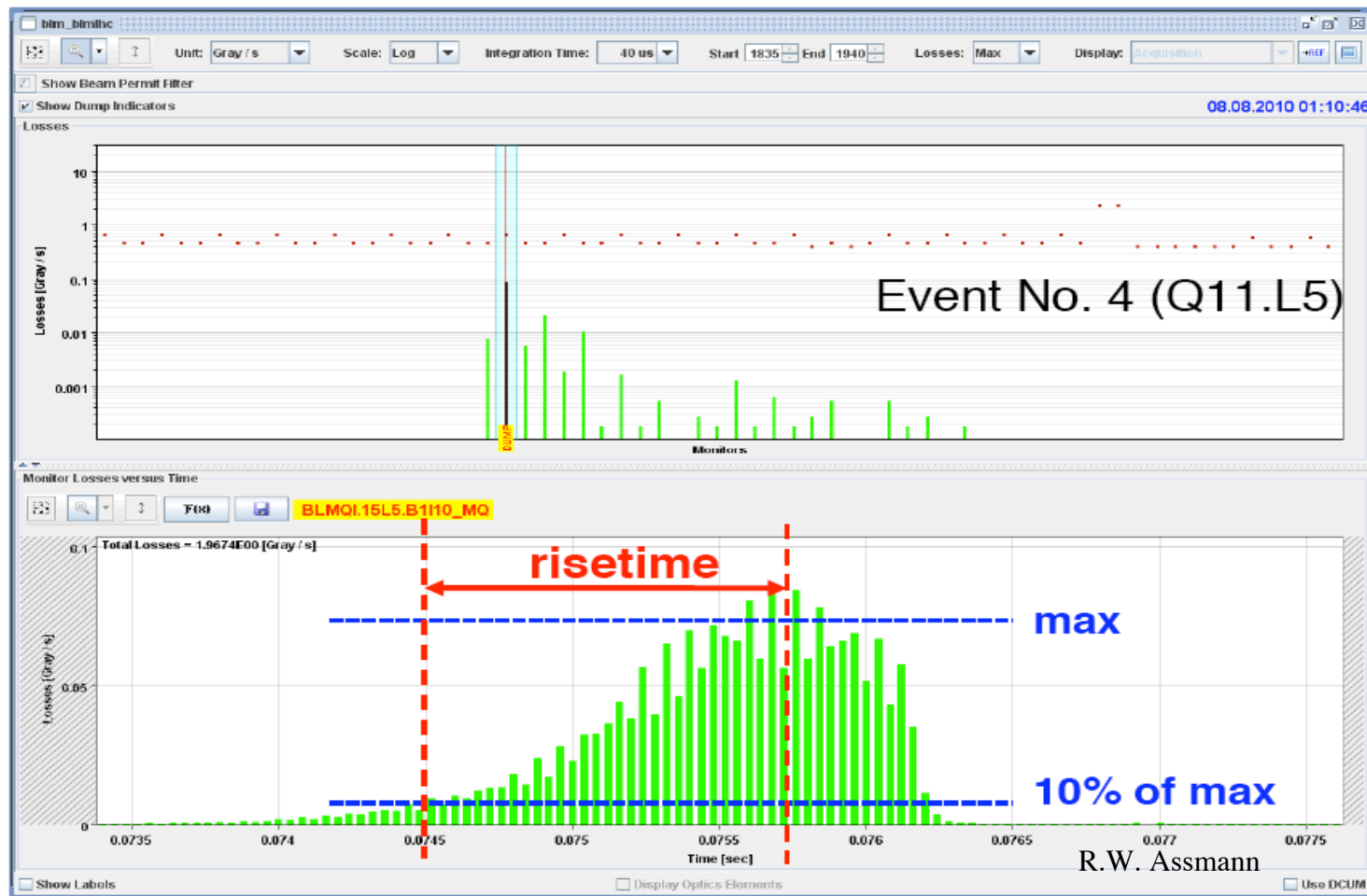
Performance

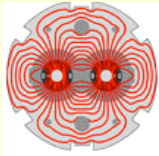
Accel.
Physics

Plan

Upgrades

Conclusion





LARP

??Dust Event??

Introduction

Performance

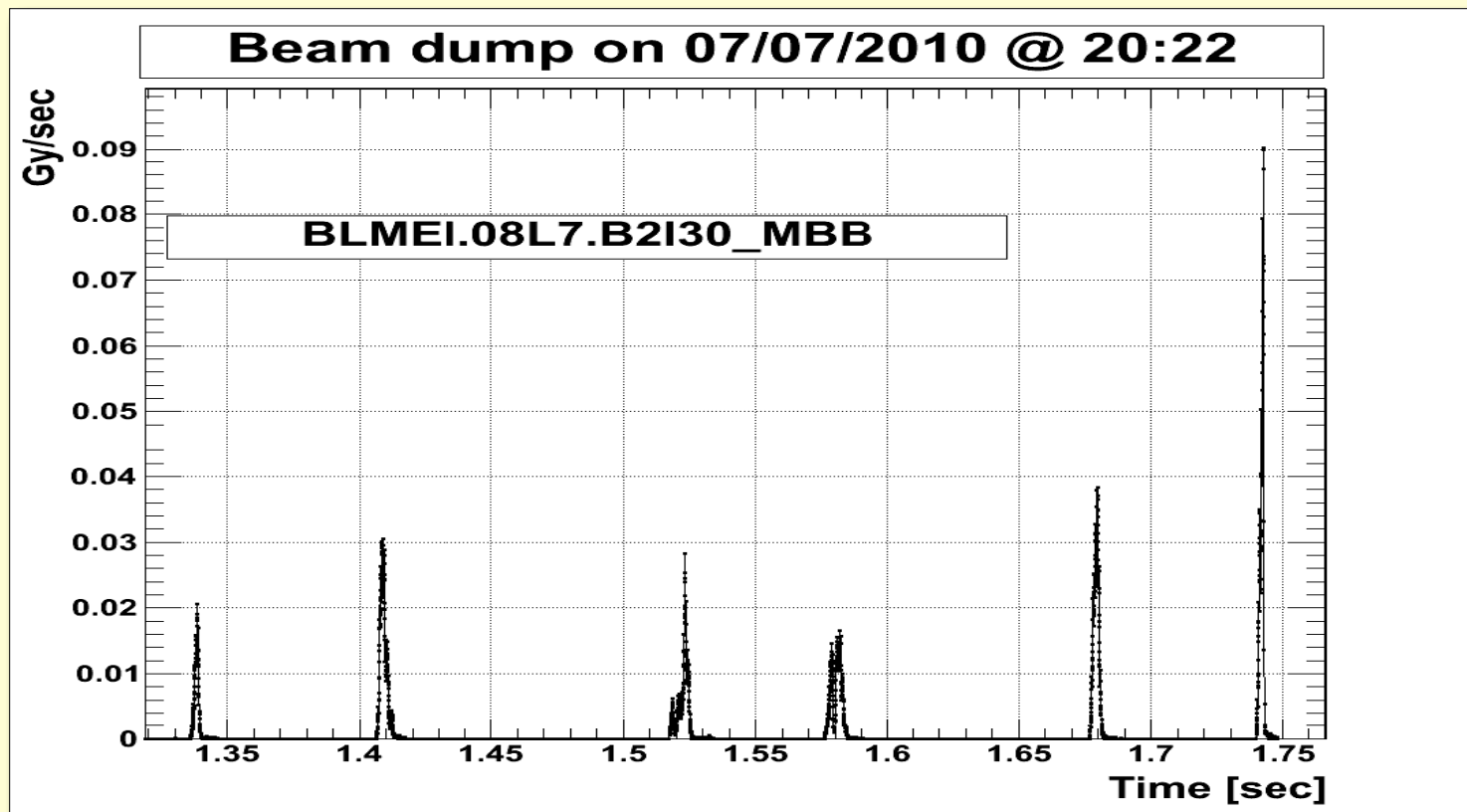
Accel.
Physics

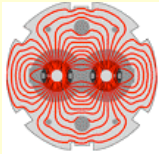
Plan

Upgrades

Conclusion

- Signature said to be consistent with dust particles ejected after ionization





LARP

Goals for 2010-2011

Introduction

Performance

Accel.
Physics

Plan

Upgrades

Conclusion

| | 2009 | | 2010 | | 2011 | |
|-------------|---------------------|-------------------------|-------------------------------------------------------------------------------------|------|--------------------------------------------------------------------|------|
| Performance | Repair of Sector 34 | 1.18 TeV nQPS 6kA | 3.5 TeV $I_{\text{safe}} < I < 0.2 I_{\text{nom}}$ $\beta^* \sim 2 \text{ m}$ | Ions | 3.5 TeV $\sim 0.2 I_{\text{nom}}$ $\beta^* \sim 2 \text{ m}$ | Ions |
| Plan | No Beam | B | Beam | | Beam | |

Goal for 2011: 1 fb⁻¹/exp at 3.5 TeV/beam.

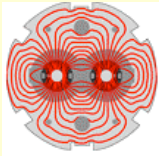
Large increase of L needed by the end of 2010

$$L \approx 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$$

~ Tevatron Luminosity

~700 bunches of 8×10^{10} p/bunch
stored energy of ~ 30 MJ - >10% of nominal

| Optics | $\beta^*_{\text{inj.}}$ | $\beta^*_{\text{coll.}}$ |
|------------------|-------------------------|--------------------------|
| IP1 / IP5 | 11 m | 2 m |
| IP2 ⁺ | 10 m | 3 m |
| IP8 ⁺ | 10 m | 2 m |
| IP5-TOTEM | 11 m | 90 m |



LARP

Plan to 2016

Introduction

Performance

Accel.
Physics

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Upgrades

Conclusion

- 2010: Commission crossing angle
 - 150 ns bunch spacing, 50 ns??
 - 400...500 bunches, $L \geq 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
 - ≈ 30 MJ stored beam
- 2011: 1 fb⁻¹ each to experiments
- 2012: down: splice consolidation
- 2013-2015:
 - $\rightarrow 6.5$ TeV, up to nominal intensity
- 2016: down
 - Upgrade injectors
 - some detector upgrades
 - 7 TeV



Luminosity Upgrades

Introduction

Performance

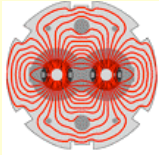
Accel.
Physics

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- **Limits:**
 - beam-beam parameter: 0.01 believed realistic (SPS exp.)
 - control with crossing angle
 - β^* : aperture of IR triplets, crossing angle
 - 0.25 or maybe 0.15 m possible?
 - cryo capability: 2.3E11 ppb (25 ns beam)
 - already need dedicated IR cryo plants.
 - @50 ns less e-cloud => higher limit (x2?)
 - data rate in detectors: ≤ 100 evts./crossing
- **Crab cavity to restore head-on collisions**
 - most straightforward lumi-levelling
- **Other factors**
 - particle burn-off, filling time, chromaticities, ...
- **HL-LHC Upgrade study initiated**
 - Upgrade to Ultimate Beam in 2016
 - Upgrade of Triplet in 2020/2021



LARP

LHC Upgrades

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- **Injector upgrades**
 - increase brightness to fully support LHC and its upgrades
 - New injector linac (L4)
 - Raise PS injection to 2 GeV
 - Raise SPS limit by remedial action against e-cloud Energy upgrades
 - implement during 2016 downtime
- **CERN is beginning to explore what a significant energy upgrade would entail**
 - 18 TeV/beam is being considered; $B \approx 20$ T
 - Long-range plan



Conclusion

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- The LHC is now the highest-energy operating collider in the world
- Initial beam commissioning has shown most systems to operate at or near design performance
 - no show-stoppers
- Highest stored beam energy (2.8 MJ)
 - need deliberation and due care
- delivered Luminosity has increased by an order of magnitude in the last 40 days.