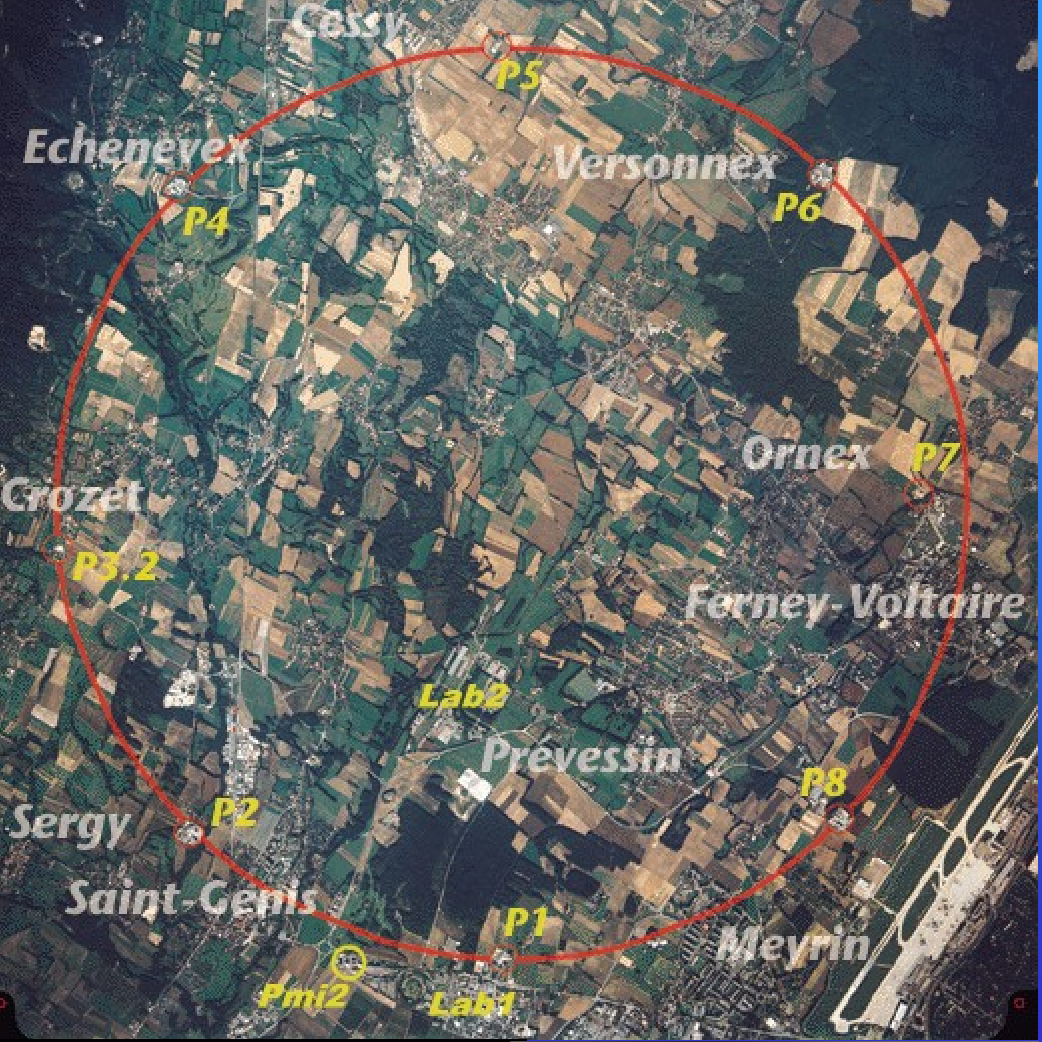


The LHC Experiment-Machine Interface

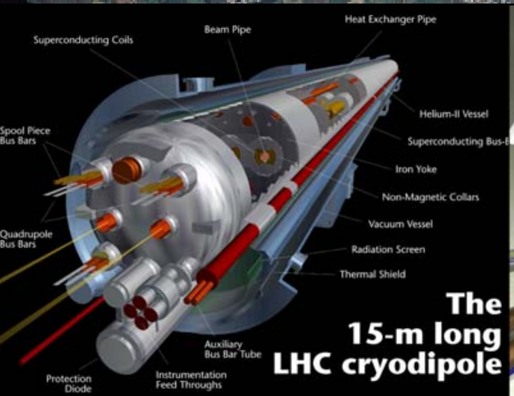
Lecture 3:

The LHC Accelerator

R.W. Aßmann, AB department
20.04.2005

Acknowledgements to input & material from

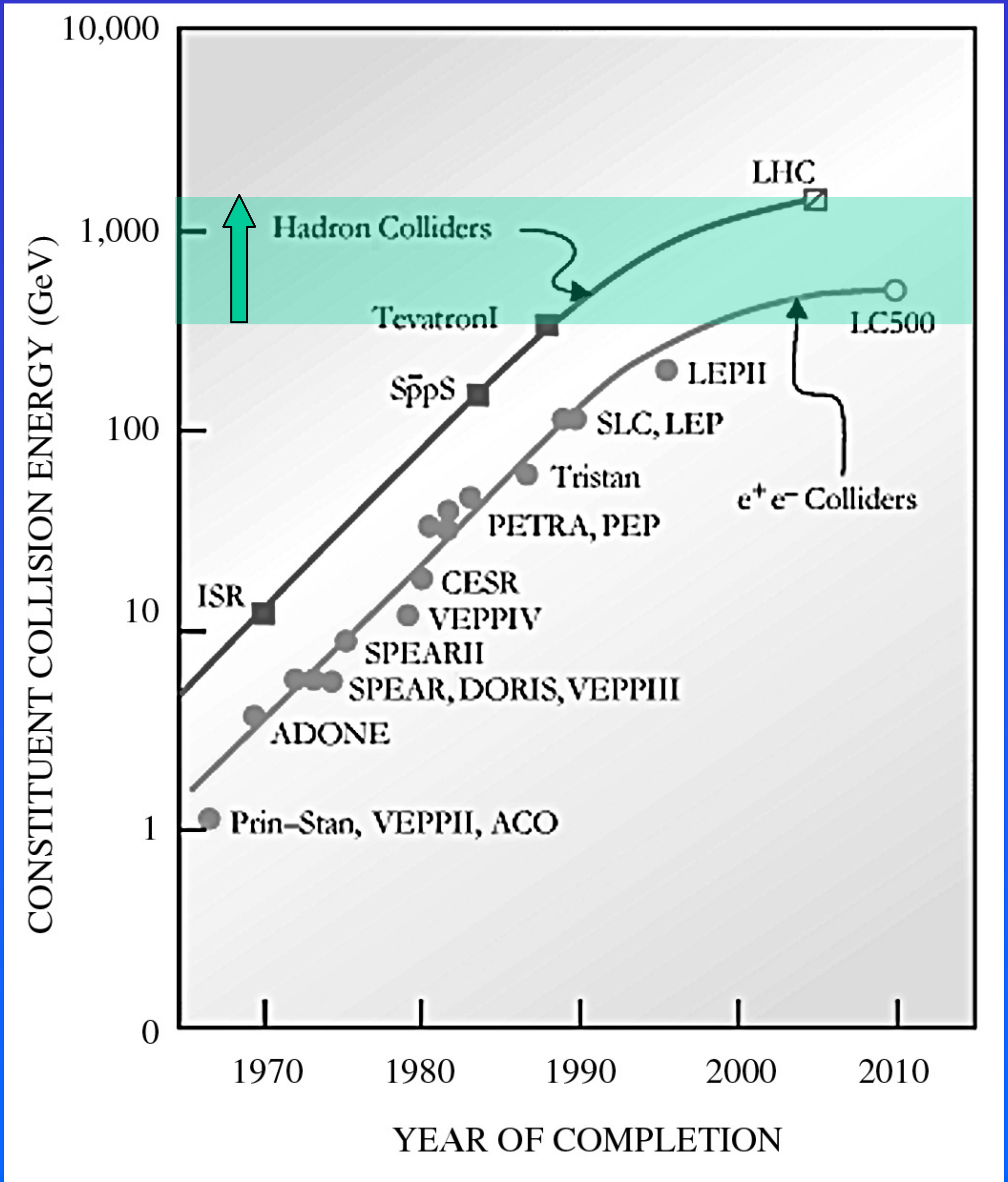
R. Bailey, O. Brüning, W. Herr, M. Lamont,
N. Mokhov, S. Redaelli, G. Robert-Demolaize,
F. Ruggiero, R. Schmidt, J. Wenninger



Contents

- Introduction to the LHC
- Accelerator Physics and Operational Challenges
  - Optics Control and Magnets
  - Beam-Beam Interactions and Working point
  - Collimation (Beam loss control)
  - Vacuum and Electron Cloud
  - Instrumentation
  - Machine Configurations (→ Different Optics)
  - Expected Input from Experiments
- Machine Commissioning
  - General Approach
  - Stages of Commissioning: From Pilot Run to Nominal
  - Physics Time per Year
- Conclusion

LHC Deliverables



The LHC will open new territory for particle physics:

The discovery potential depends on achieving the major accelerator deliverables!

These deliverables are:

- ➔ Energy
- ➔ Luminosity
- ➔ Efficiency
- ➔ Background

Feedback from experiments

(M. Tigner)

Instantaneous Luminosity

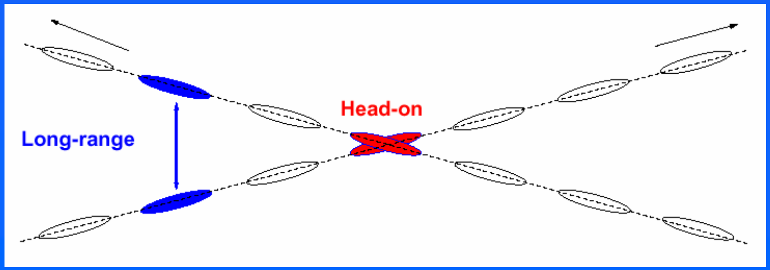
The instantaneous luminosity describes is a measure of the event rate at the IP's:

$$L = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} \cdot F \qquad F = 1 \Big/ \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sqrt{\varepsilon_n \beta^*}} \right)^2}$$

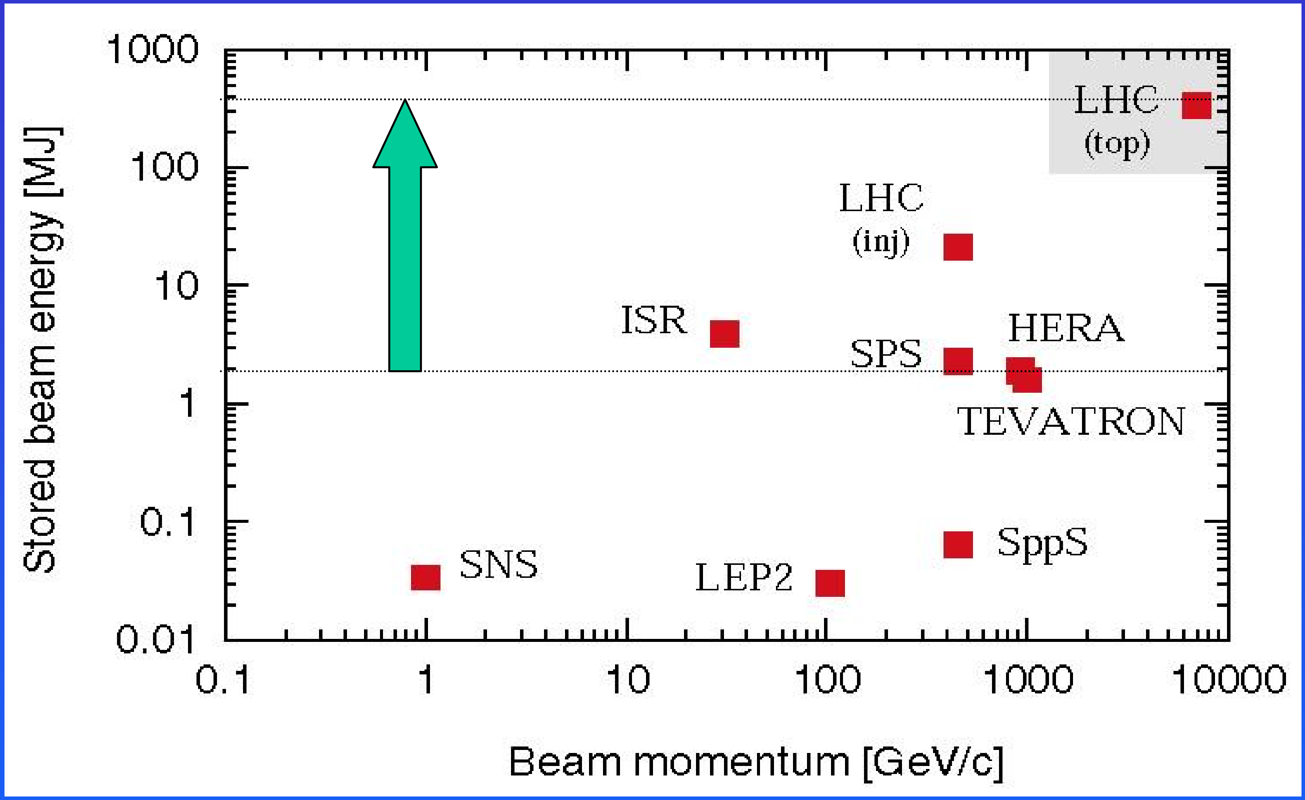
- N: Number of protons per bunch
- k_b: Number of bunches
- γ: Relativistic Lorentz factor
- θ_c: Full crossing angle
- σ_z: Bunch length
- ε_n: Normalized emittance
- β^*: Beta function at the IP

LHC nominal luminosity:

10^{34} cm^{-2} s^{-1}



The Energy Stored in the LHC beams

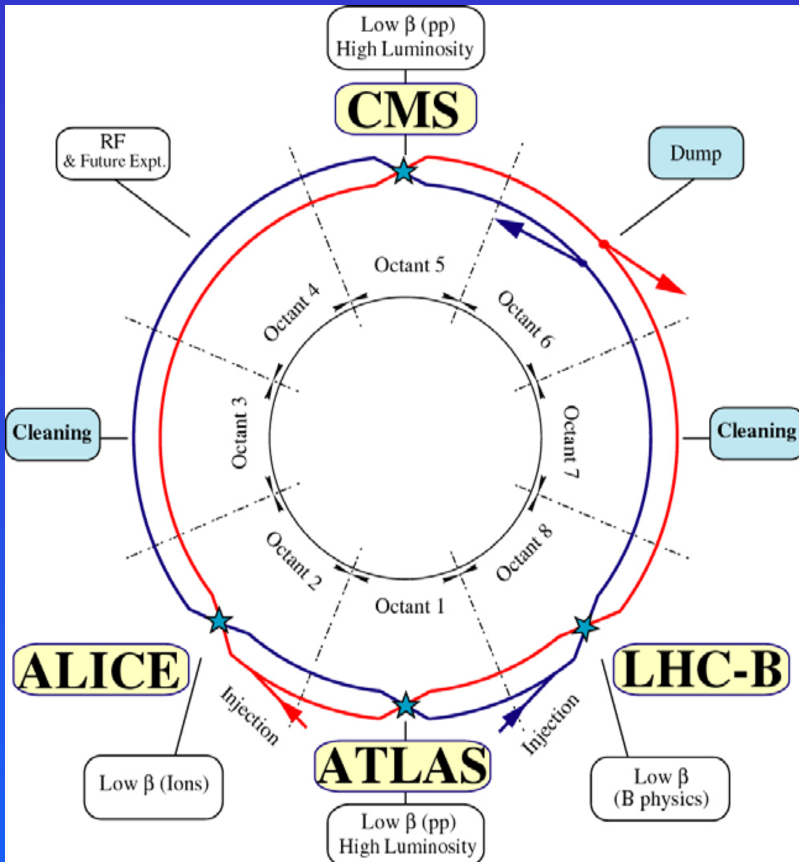


At less than 1% of nominal intensity LHC enters new territory. Stored beam energy equivalent to 120 kg TNT!

Why this challenge?

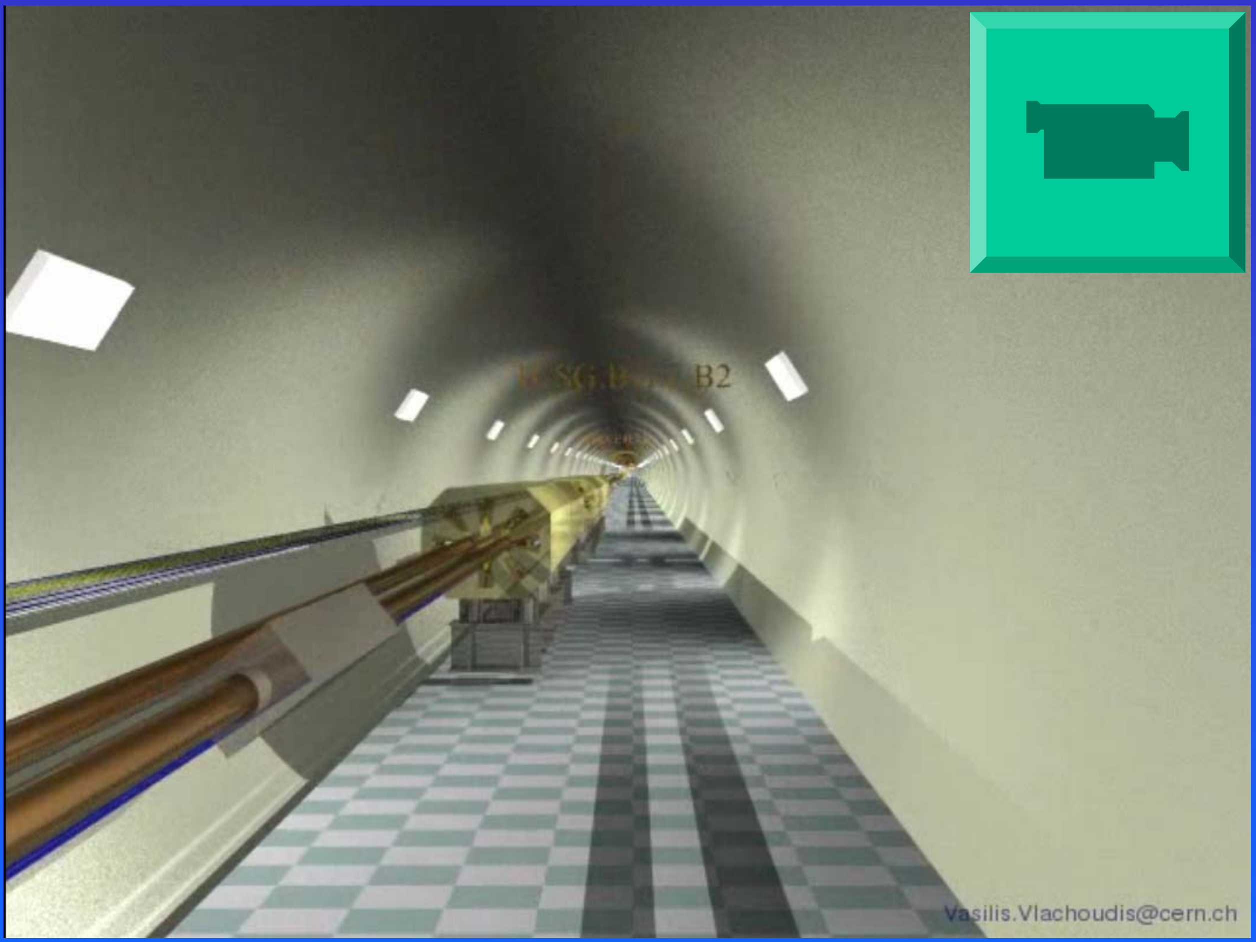
Luminosity ~ Stored beam energy

The Large Hadron Collider



- The LHC insertions are valuable machine space and used for particle physics experiments (4 IP's) and special machine purposes.
  - IR1 are IR5 high luminosity insertions. IR1: ATLAS. IR5: CMS and TOTEM.
  - IR2 houses ALICE experiment (ions) and injection for beam 1. Flexible optics for controlling luminosity.
  - IR3 and IR7 are dedicated to momentum and betatron collimation.
  - IR4 houses the RF system for beam acceleration and special beam instrumentation.
  - IR6 is dedicated to the beam dump for both of beam 1 and beam 2.
  - IR8 houses LHCb experiment (low luminosity) and injection for beam 2. Off center collisions.
- Each insertion has a unique design, optimized for its particular purpose.

Example of a Machine Insertion: IR7 (Collimation)



Betatron Cleaning:

Detailed FLUKA model with all magnets, magnetic fields, collimators (correct openings and angles), tunnel dimensions, RR's and UJ. Automatic tracking/FLUKA interface.

RR's:

Space for electronics in the tunnel (enlargements)

UJ:

Space for electronics in cavern.

Shielding:

For protecting electronics against radiation.

Contents

- Introduction to the LHC
- Accelerator Physics and Operational Challenges
  - Optics Control and Magnets
  - Beam-Beam Interactions and Working point
  - Collimation (Beam loss control)
  - Vacuum and Electron Cloud
  - Instrumentation
  - Machine Configurations (➔ Different Optics)
  - Expected Input from Experiments
- Machine Commissioning
  - General Approach
  - Stages of Commissioning: From Pilot Run to Nominal
  - Physics Time per Year
- Conclusion

Accelerator Physics and Operational Challenges

- LHC significantly advances the state of the art in accelerators!
- It is by no means an easy machine…
- Many challenging aspects…
- Look at a few challenges in the following slides.

Beam energy:	**7 TeV**
→ limited by maximum dipole field	
→ **extension by factor 7 beyond TEVATRON**	
Bunch intensity:	**1.15×10^{11} p**
→ limited by beam-beam effects	
Normalized emittance:	**3.75 μm**
→ limited by injectors and main dipole aperture (keep smaller or equal)	
Beam size at IP ($\beta^* = 0.5$ m):	**16 μm**
→ limited by triplet magnet aperture	
Crossing angle:	**300 μrad**
→ limited by triplet magnet aperture	
Number of bunches:	**2808**
→ limited by stored beam energy	
→ **extension in stored energy by factor ~200**	
Nominal luminosity:	**10^{34} cm^{-2}s^{-1}**
→ **extension by factor 100 beyond TEVATRON**	

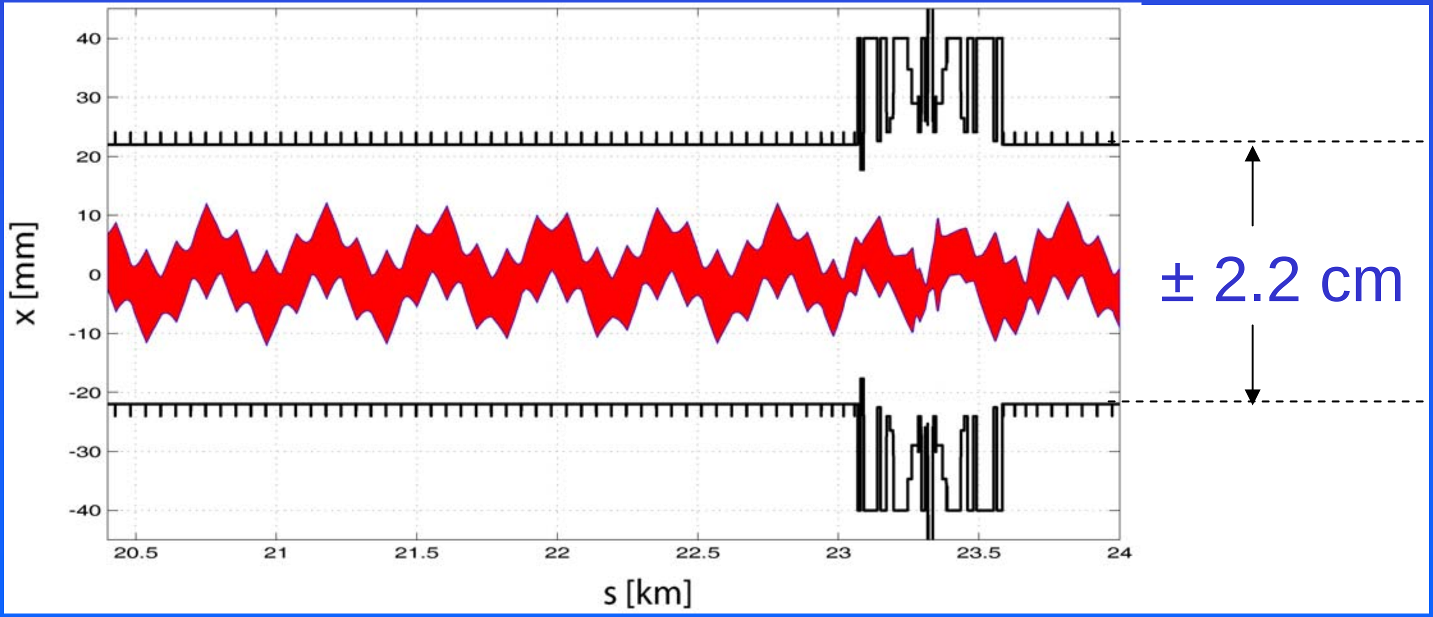
Orbit and Optics Control

Establish correct beta funstions (adjust guiding magnetic fields)

The n·σ beam envelope at a location s is given by:

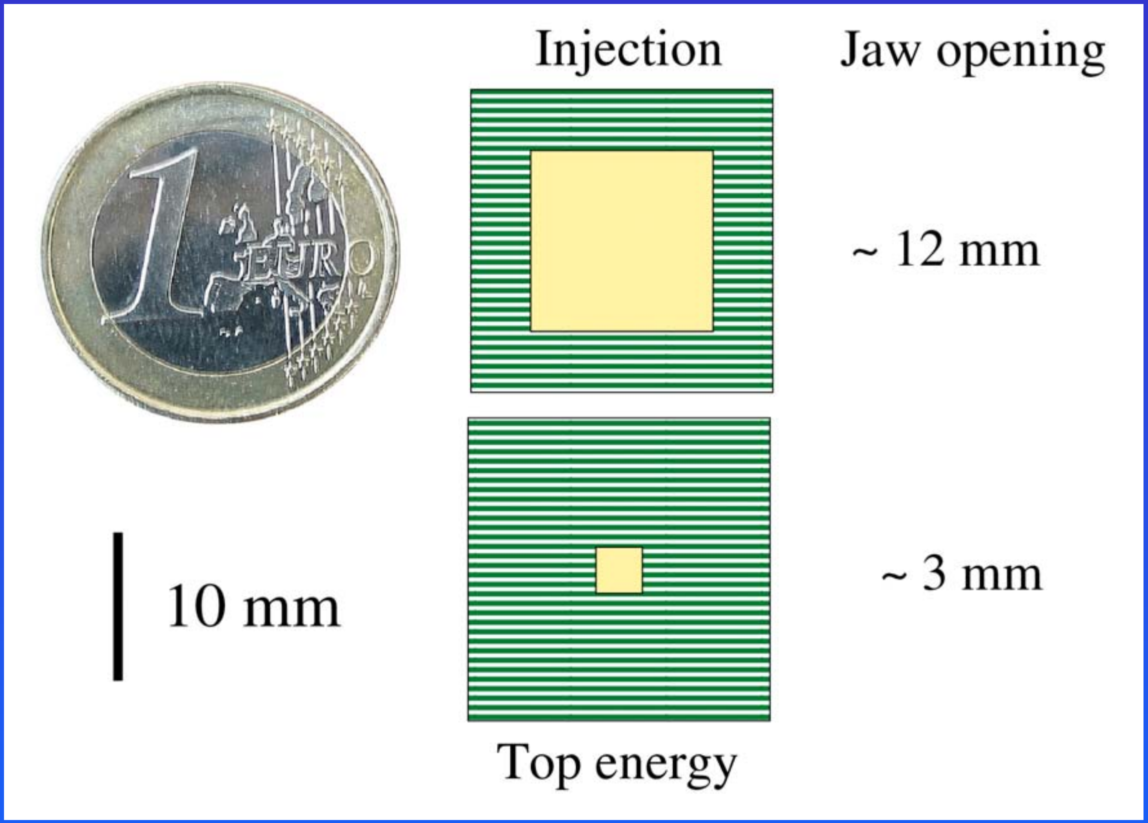
$$\mathrm{Envelope}(s,n) = \Delta x_{orbit}(s) \pm n \cdot \sqrt{\varepsilon \cdot \beta_0(s) \cdot \left(1 + \frac{\Delta\beta(s)}{\beta_0(s)}\right)}$$

Center the beam in the beam pipe aperture!



Demanding tolerances: $\Delta x_{max} \leq 4$ mm and $\Delta\beta/\beta \leq 20\%$!

LHC Aperture (Required Collimator Gap)



The smallest LHC physical and normalized aperture is at the collimators!

A small hole at 7 TeV and nominal collision optics for the high intensity beam!

R. Assmann

Operational Optics Challenges

- Inject the beam reasonably centered into the tight aperture (adjust kicker magnets).
- Match to injection optics and energy (adjust dipole and quadrupole magnets).
- Steer the beam through the center of the beam pipe all around the ring (use dipole corrector magnets).
- Adjust the machine tune (by adjusting quadrupole magnets).
- Establish design magnetic fields for bending and focusing (dipoles and quadrupoles).
- Measure and correct non-linearities in magnetic fields, as higher-order harmonics are design constraint for magnet construction from dynamic aperture (use sextupoles and higher order correctors).

➔ Beam physicists and operators will initially change lots of magnet parameters to achieve stored beam!

TI8 Transfer Line Test During 2004

- Beam down – first shot.
- Full set of measurements
  - optics, aperture etc.

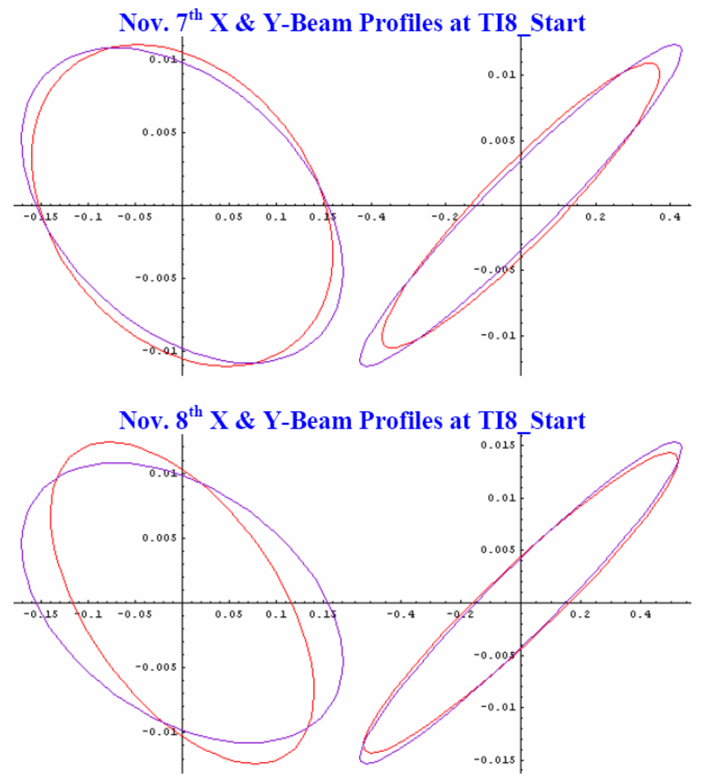
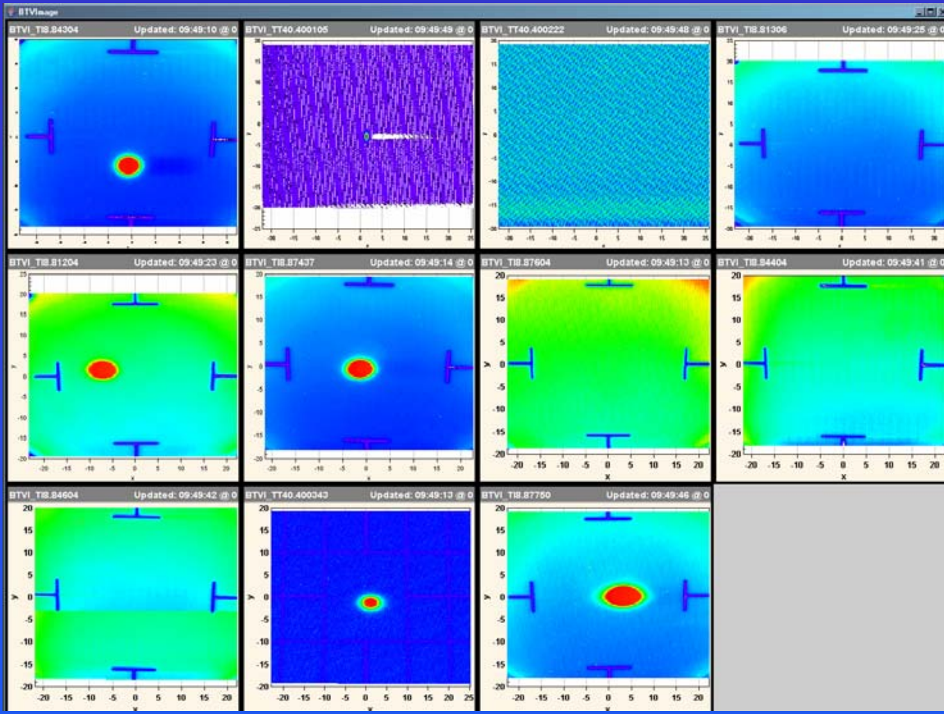


Figure 2. Comparison between Design & Measured Beam Profiles of 07/11 (top) and 08/11 (bottom); Actual beam size; units: mm & mrad (red: measured, blue: design)

Yu-Chiu Chao



Lionel Mestre

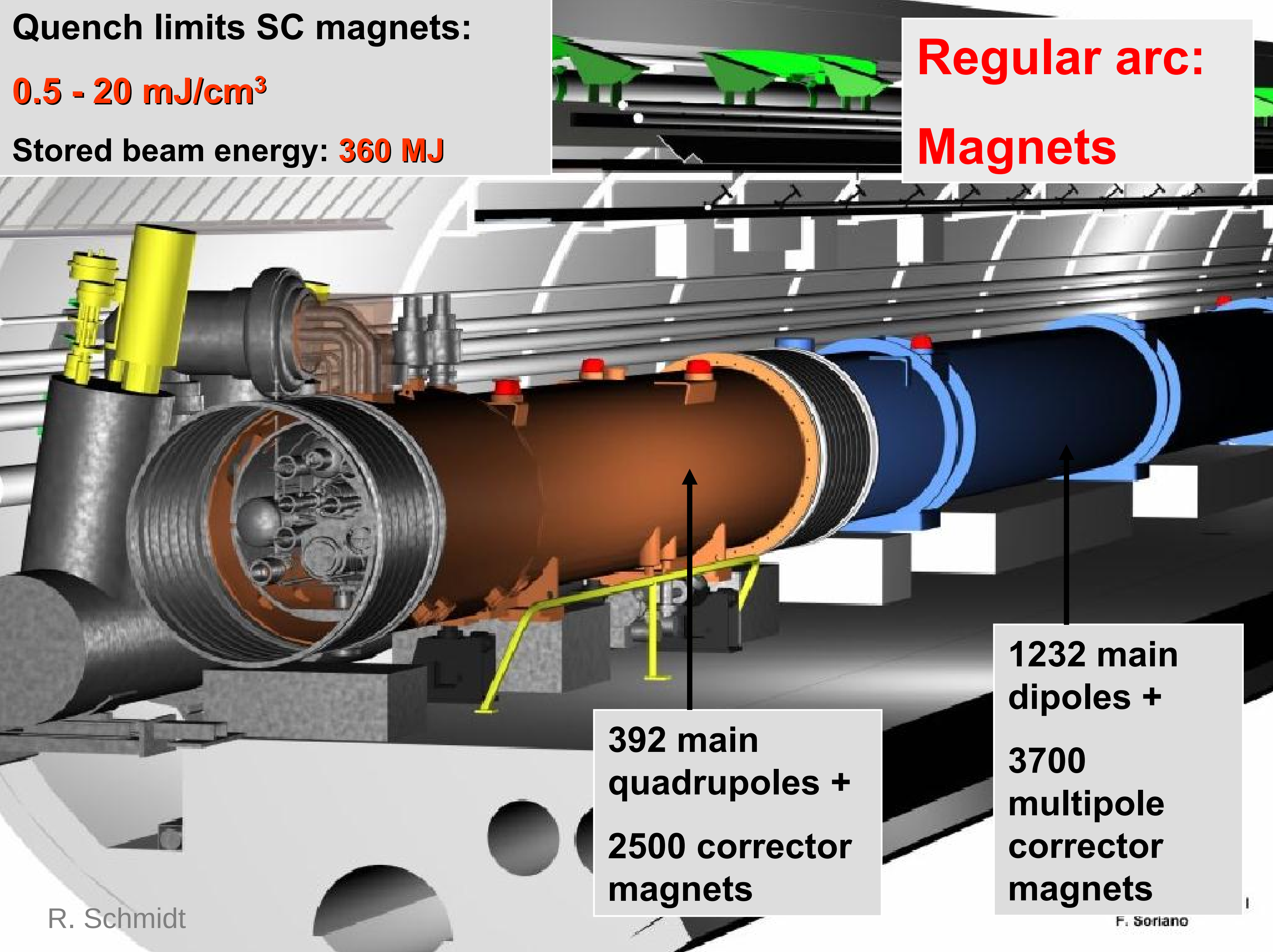
TI8 was excellent success!

Quench limits SC magnets:

0.5 - 20 mJ/cm^3

Stored beam energy: 360 MJ

Regular arc: Magnets

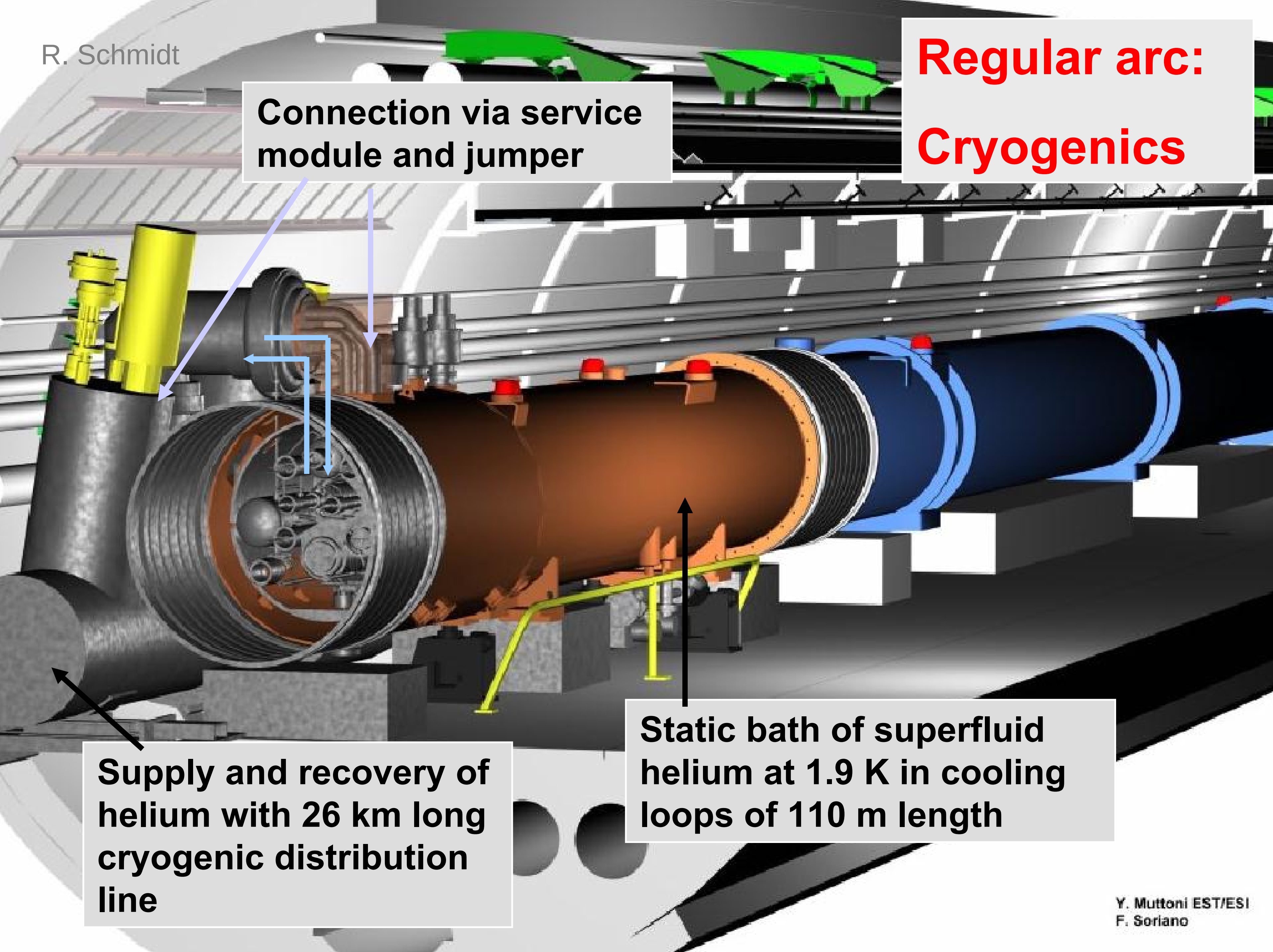


392 main quadrupoles +

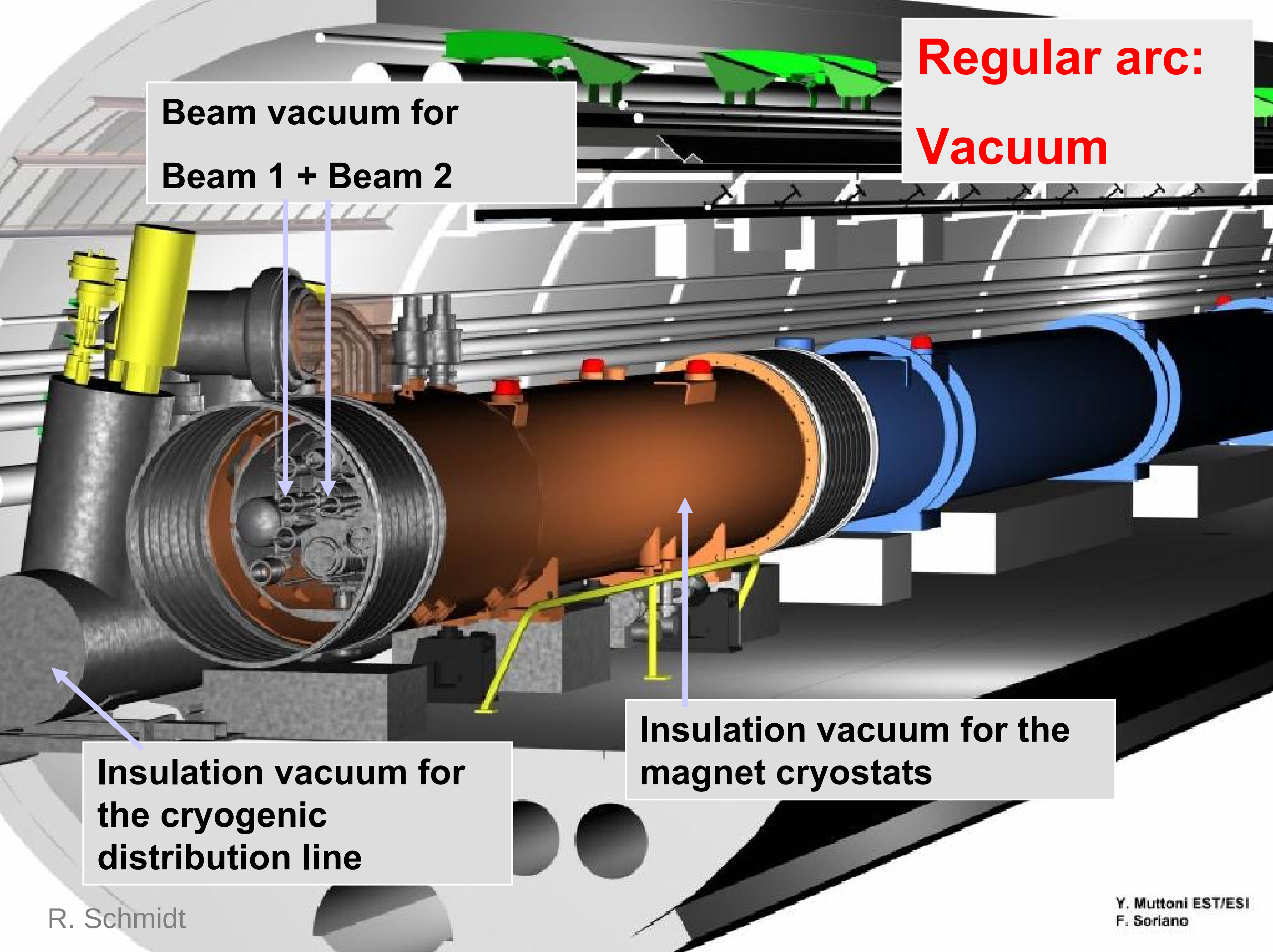
2500 corrector magnets

1232 main dipoles +

3700 multipole corrector magnets


R. Schmidt
Regular arc: Cryogenics
Connection via service module and jumper
Supply and recovery of helium with 26 km long cryogenic distribution line
Static bath of superfluid helium at 1.9 K in cooling loops of 110 m length
Y. Muttoni EST/ESI
F. Soriano

Regular arc: Vacuum



The LHC Dipoles

Parameters:

Double bore
Field quality

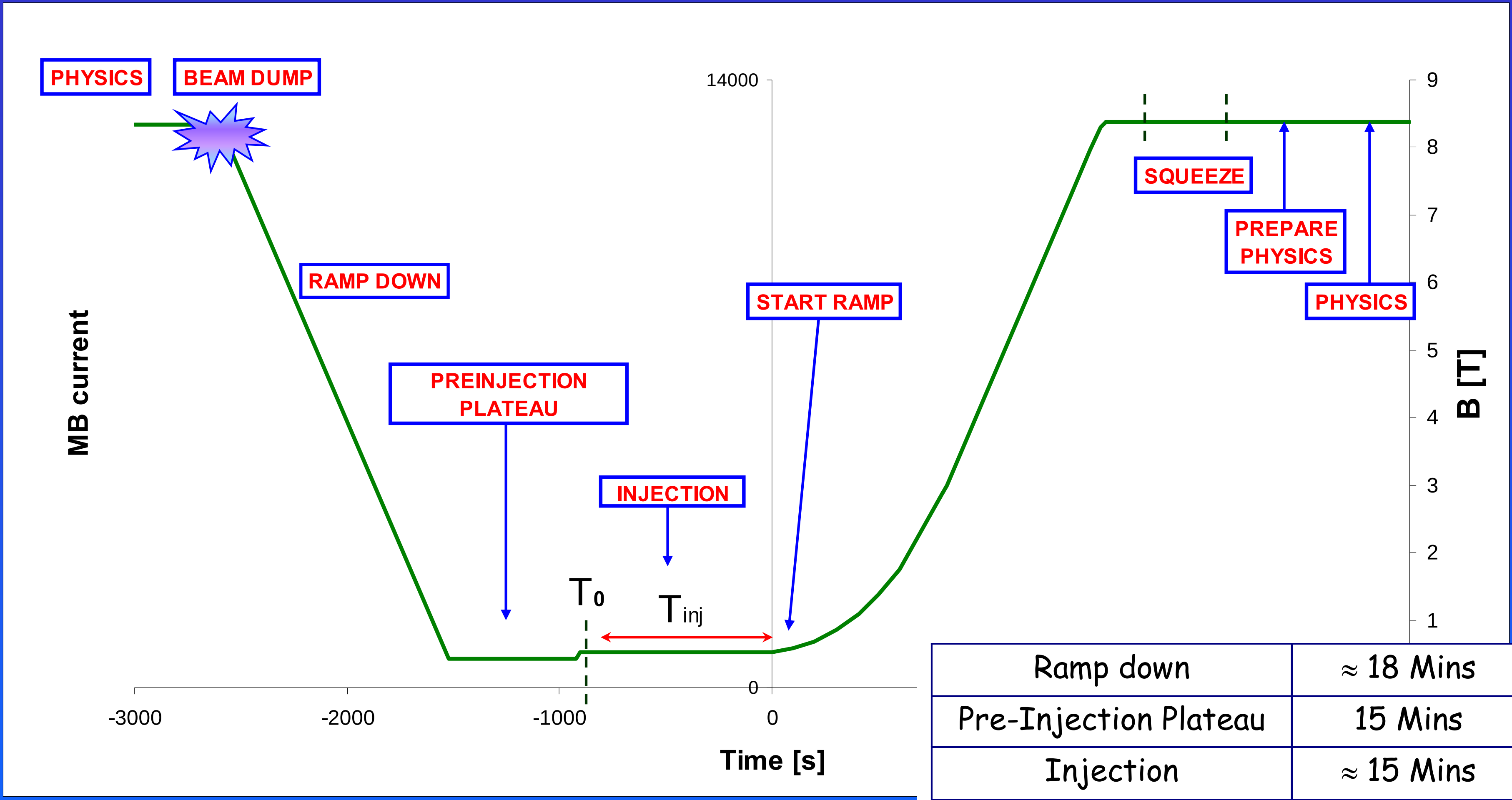
I = 11700 A
T = 1.9 K
B = 8.3 T
L = 15 m

Cooling:

Super-fluid He

30 kt cold mass
90 t He

Going to 7 TeV: LHC Operational Cycle



Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	< 5 Mins
Prepare Physics	≈ 10 Mins
Physics	10 - 20 Hrs

LHCOP: http://www.cern.ch/lhc-commissioning

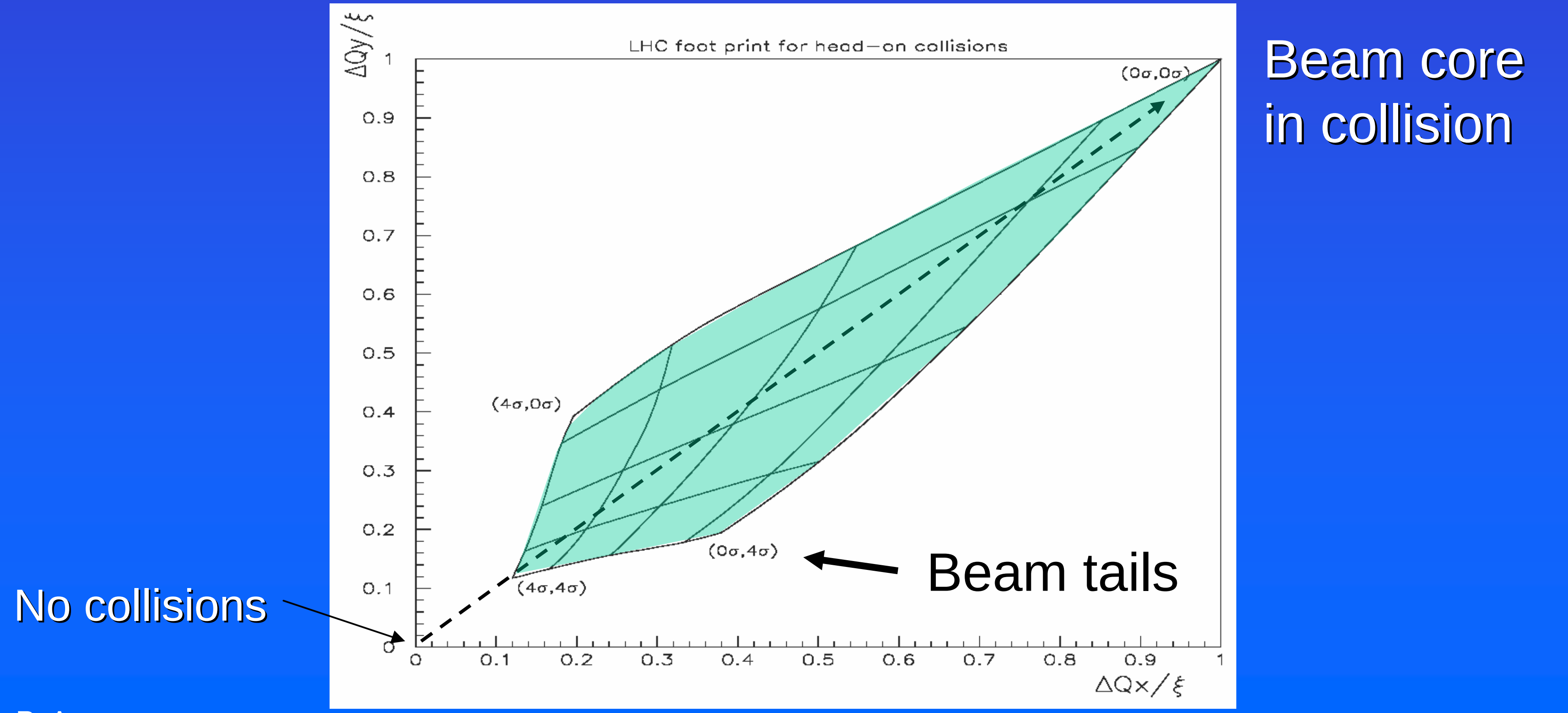
R. Assmann

Contents

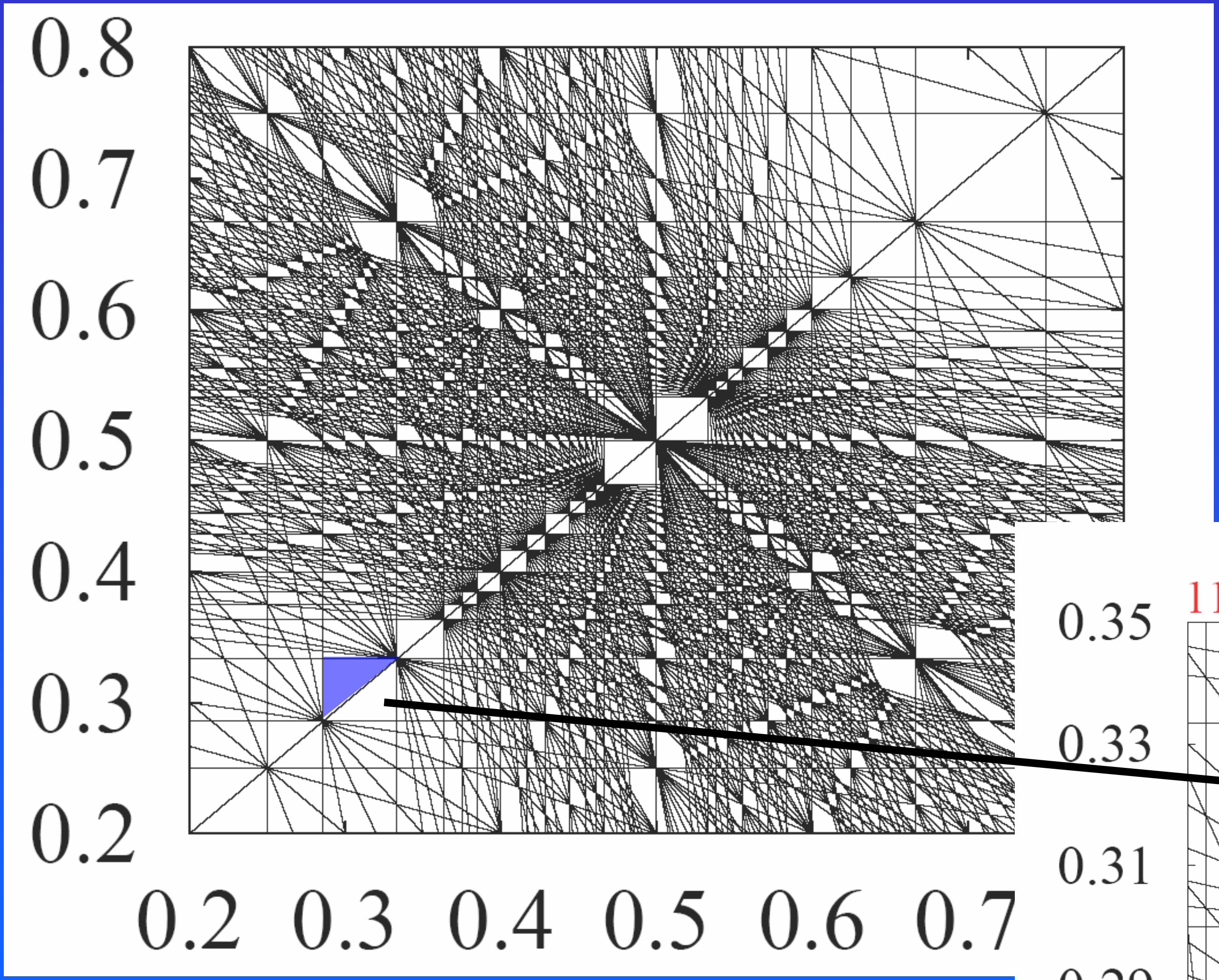
- Introduction to the LHC
- Accelerator Physics and Operational Challenges
  - Optics Control and Magnets
  - Beam-Beam Interactions and Working point
  - Collimation (Beam loss control)
  - Vacuum and Electron Cloud
  - Instrumentation
  - Machine Configurations (➔ Different Optics)
  - Expected Input from Experiments
- Machine Commissioning
  - General Approach
  - Stages of Commissioning: From Pilot Run to Nominal
  - Physics Time per Year
- Conclusion

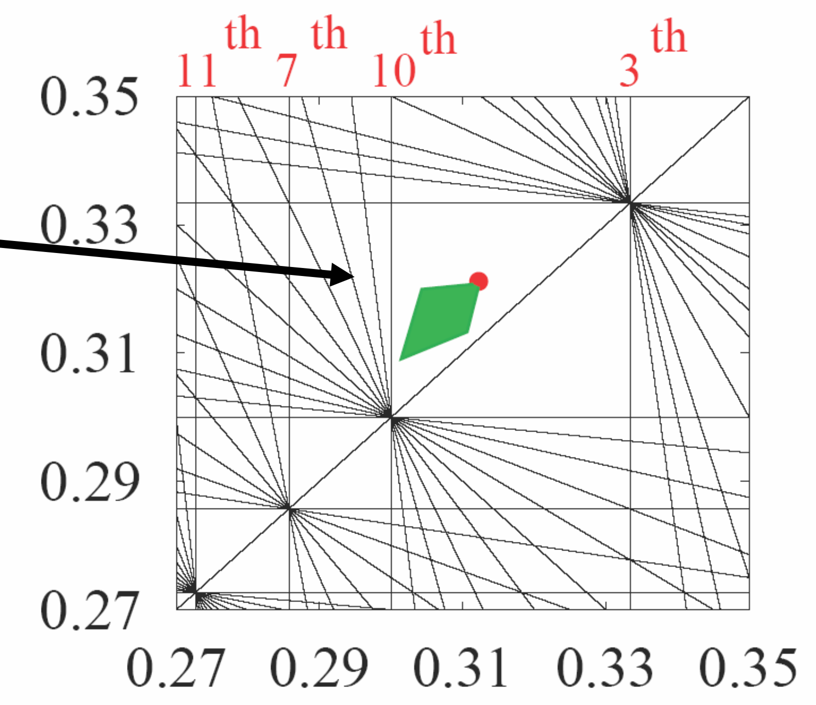
Beam-beam Interactions and Working Point

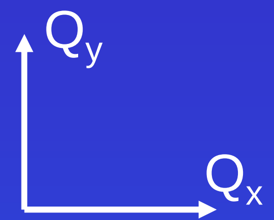
- Deliver luminosity: Collide the proton bunches of the two beams!
- The electro-magnetic fields of colliding bunches of particles induce perturbations on the circulating particles:
  - Can be described as a quadrupole effect!
  - Kicks induce beam-beam tune shift ξ and tune spread:



Tune Resonances Must be Avoided







$n + m < 12$

Allowable total tune shift:
~ 0.015

Fit Tune Footprint into free space!
The higher the luminosity, the harder!

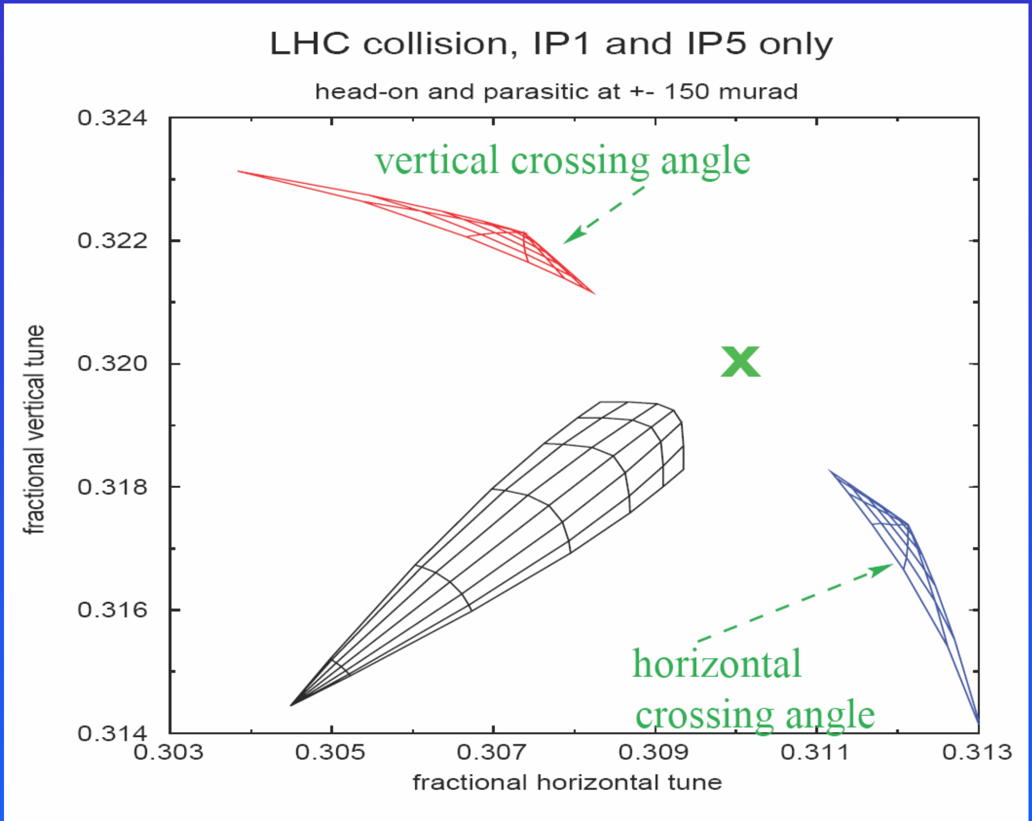
R. Assmann

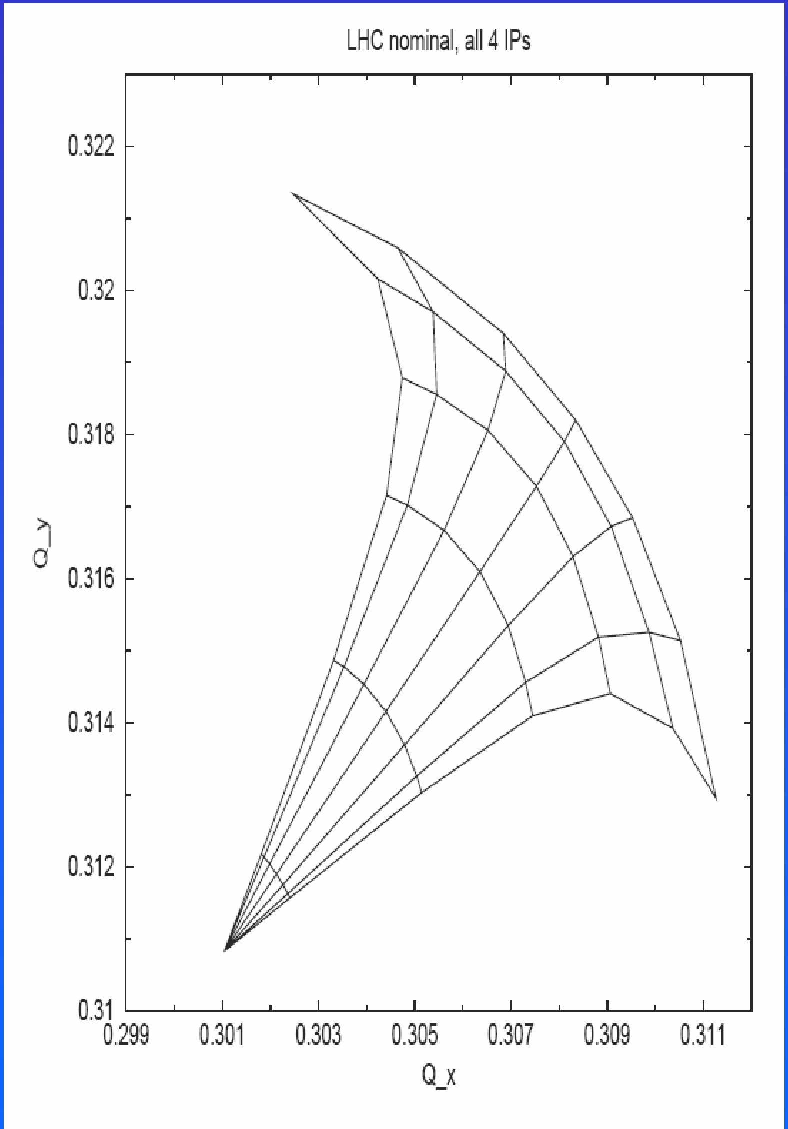
Single Bunch Current Limit and Consequences

- Total limit on beam-beam tune shift of 0.015. This leaves 0.005 per p-p experiment.
- With nominal normalized emittance of 3.75 μm a maximum bunch current of 1.1-1.7 × 10^{11} p is obtained.
- With nominal β^* of 0.5 m the following bunch luminosity is obtained:
  4.3×10^{30} cm^{-2} s^{-1}
  This corresponds to ~20 events per bunch crossing!
- In order to achieve 1×10^{34} cm^{-2} s^{-1} multi-bunch operation is required: 2808 bunches

➔ Crossing angles in the insertions!

Beam-Beam Tune Spread with Crossing Angle





All 4 IP's with nominal parameters

R. Assmann

Integrated Luminosity and Efficiency

- High peak luminosity requires high beam-beam tune shift (see before).
- High integrated luminosity requires good efficiency (maximum time in physics).
- Often a trade-off between peak performance and integrated luminosity:

  → Beam **losses can quench a SC magnet**. For 1% of beam lost in 10s: **~4 MJ** lost.

  → Losses are much above **quench limits** (**0.5 – 10 mJ/cm^3**). Cleaning not perfect.

  → Each quench disrupts operation and luminosity (beam dumped). **Several hours lost**!

  → Beam losses propagate around the ring and can induce **backgrounds**!

High intensity increases instantaneous luminosity (~360 MJ)	⟷	Low intensity lowers stored energy and leaves more quench margin.

- Crucial for high integrated luminosity: Choice of beam parameters compatible with **maximum time in collision mode and decent luminosity**!

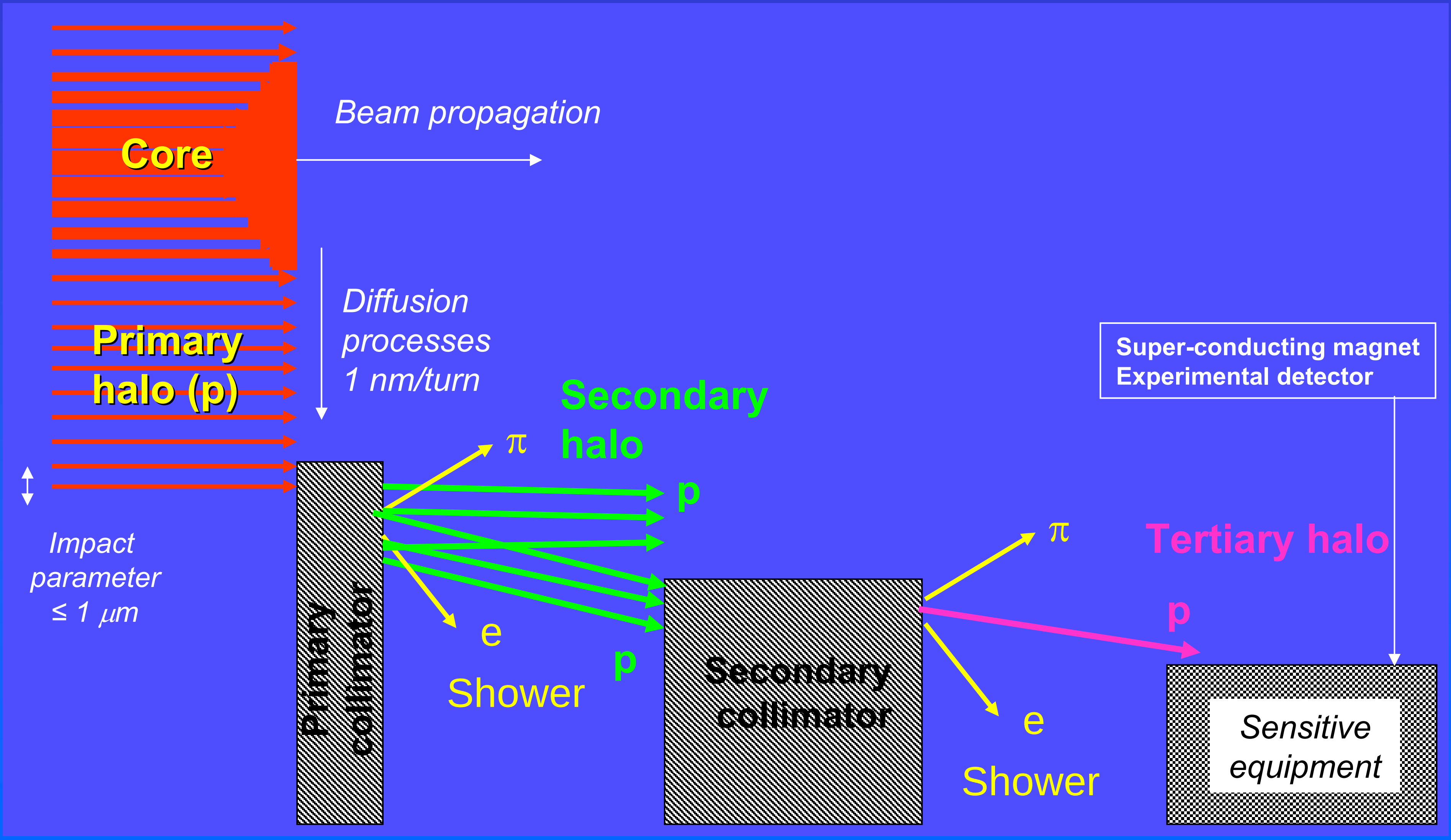
Contents

- Introduction to the LHC
- Accelerator Physics and Operational Challenges
  - Optics Control and Magnets
  - Beam-Beam Interactions and Working point
  - Collimation (Beam loss control)
  - Vacuum and Electron Cloud
  - Instrumentation
  - Machine Configurations (→ Different Optics)
  - Expected Input from Experiments
- Machine Commissioning
  - General Approach
  - Stages of Commissioning: From Pilot Run to Nominal
  - Physics Time per Year
- Conclusion

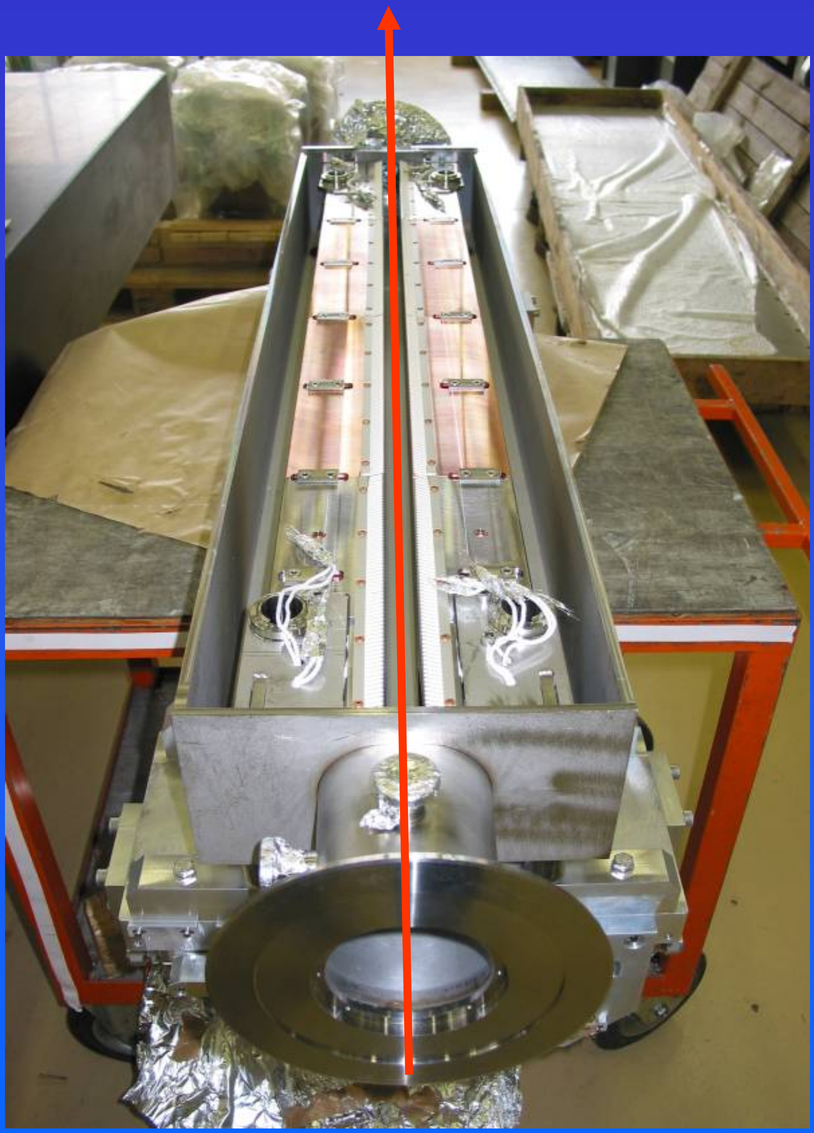
Two-Stage Cleaning in the LHC

Betatron: IR7
Momentum: IR3

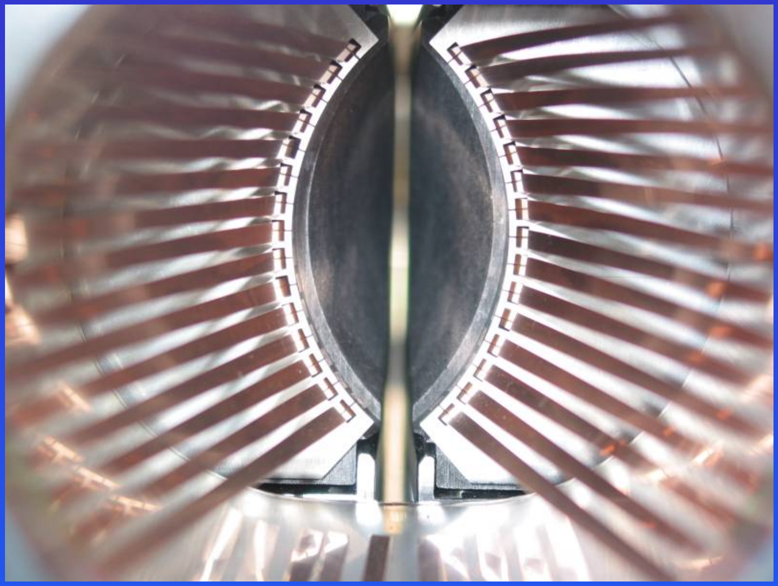
Note: *LHC collimation system optimized for preventing quenches, not for background!*



The LHC Phase 1 collimator



Vacuum tank with two jaws installed



Beam passage for small collimator gap with RF contacts for guiding image currents

Designed for maximum robustness:

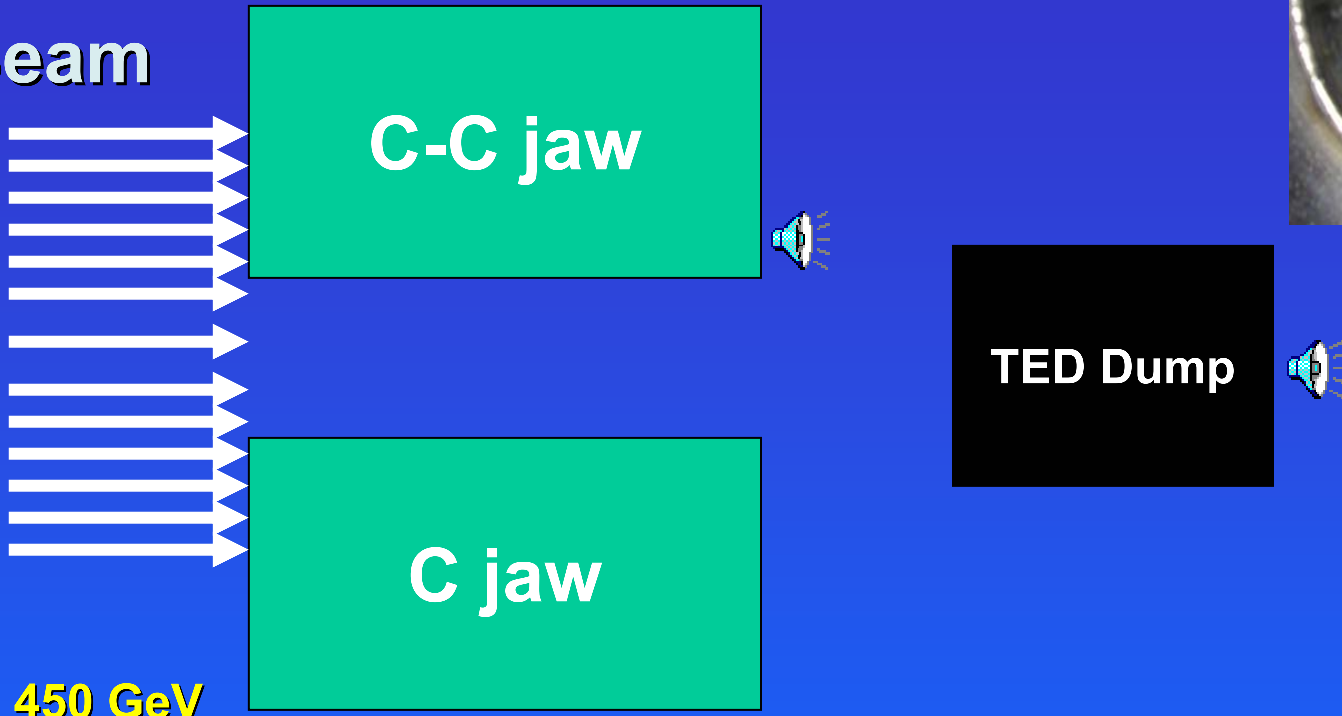
Advanced CC jaws with water cooling!

R. Assmann

Robustness Test

Microphone

Beam

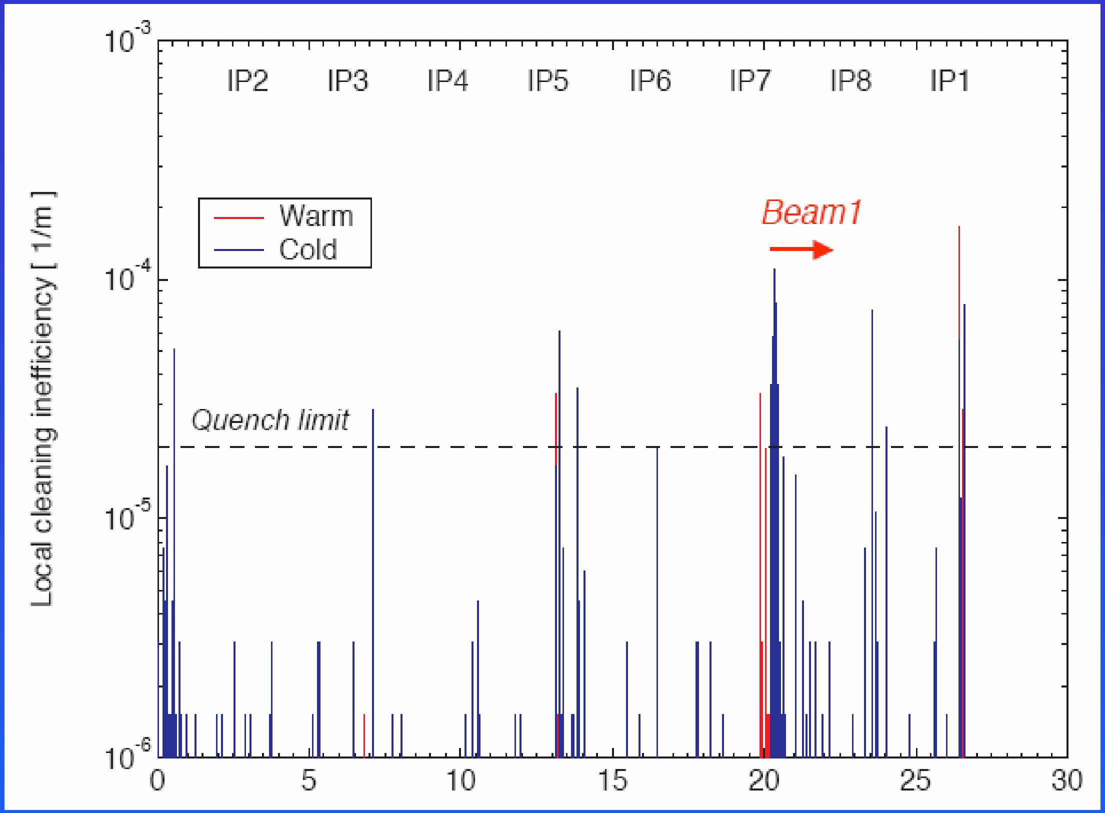


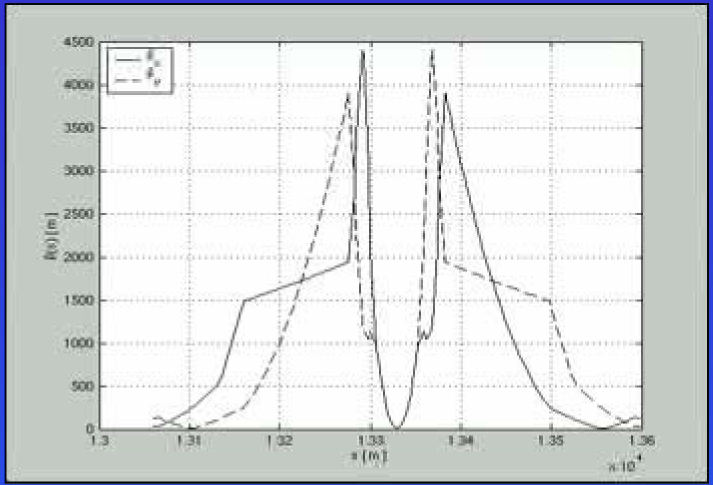
450 GeV
3 10^{13} p
2 MJ
0.7 x 1.2 mm²

~ Tevatron beam
~ ½ kg TNT

- **Jaw impact could be measured during all expected hits: no change in jaw dimensions (nothing fell off)**
- **Closure of two jaws to 1mm gap after test.**
- **Took out collimator and inspected (two months cooldown).**
- **Microscopic analysis to be done.**

Proton Loss Maps Around the LHC Ring





β*: 0.55 m ➔ 17 m (IR1)

Triplets at the LHC experiments become **aperture bottlenecks** at 7 TeV with squeezed optics (increase of β* at the triplets)!

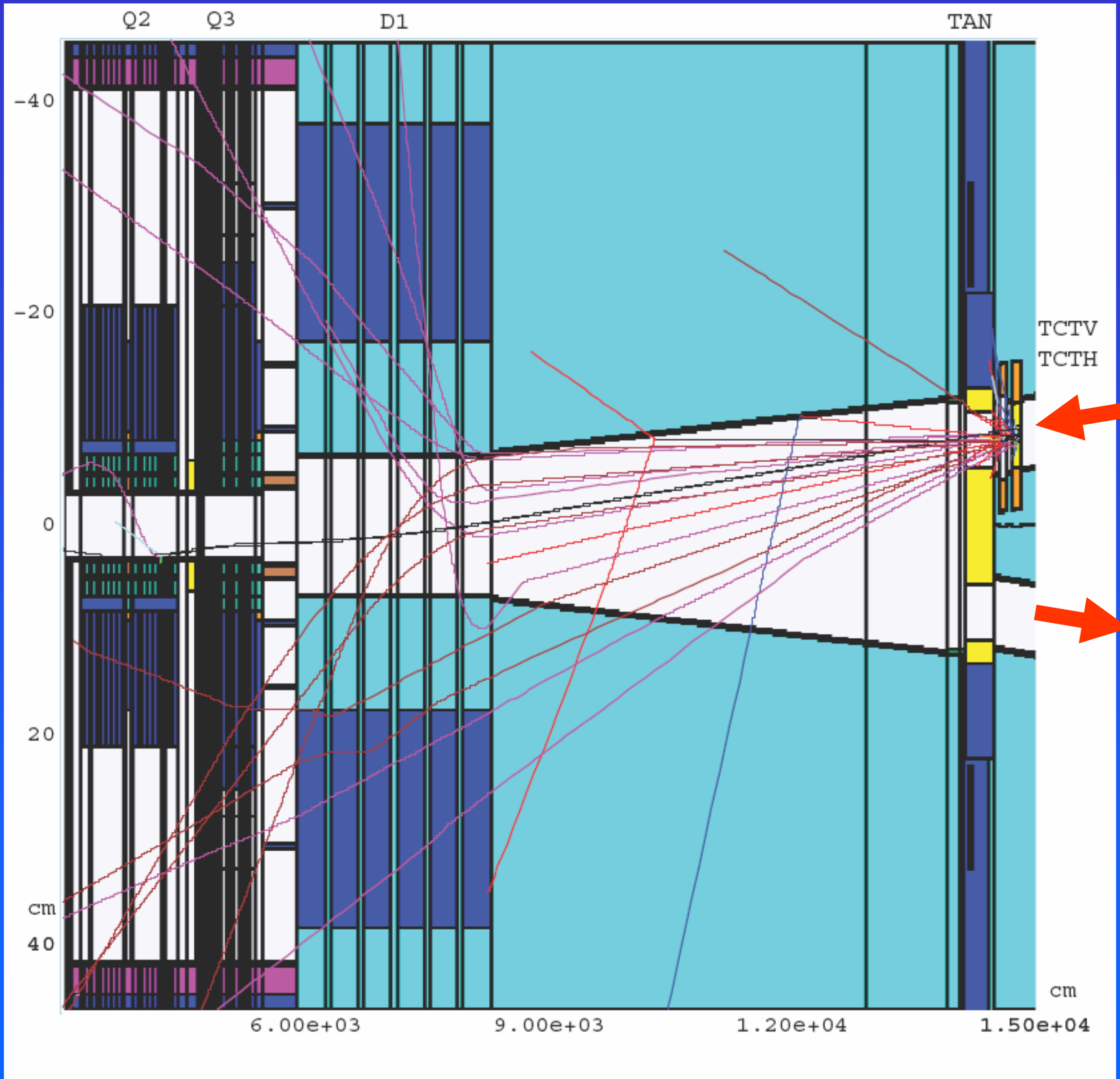
Triplets not protected against incoming beam (**cleaning and machine protection**)!

Add **local protection** (tertiary collimators) to complement cleaning and TCDQ protection!!

R. Assmann

Tertiary Collimators in Experimental Insertions

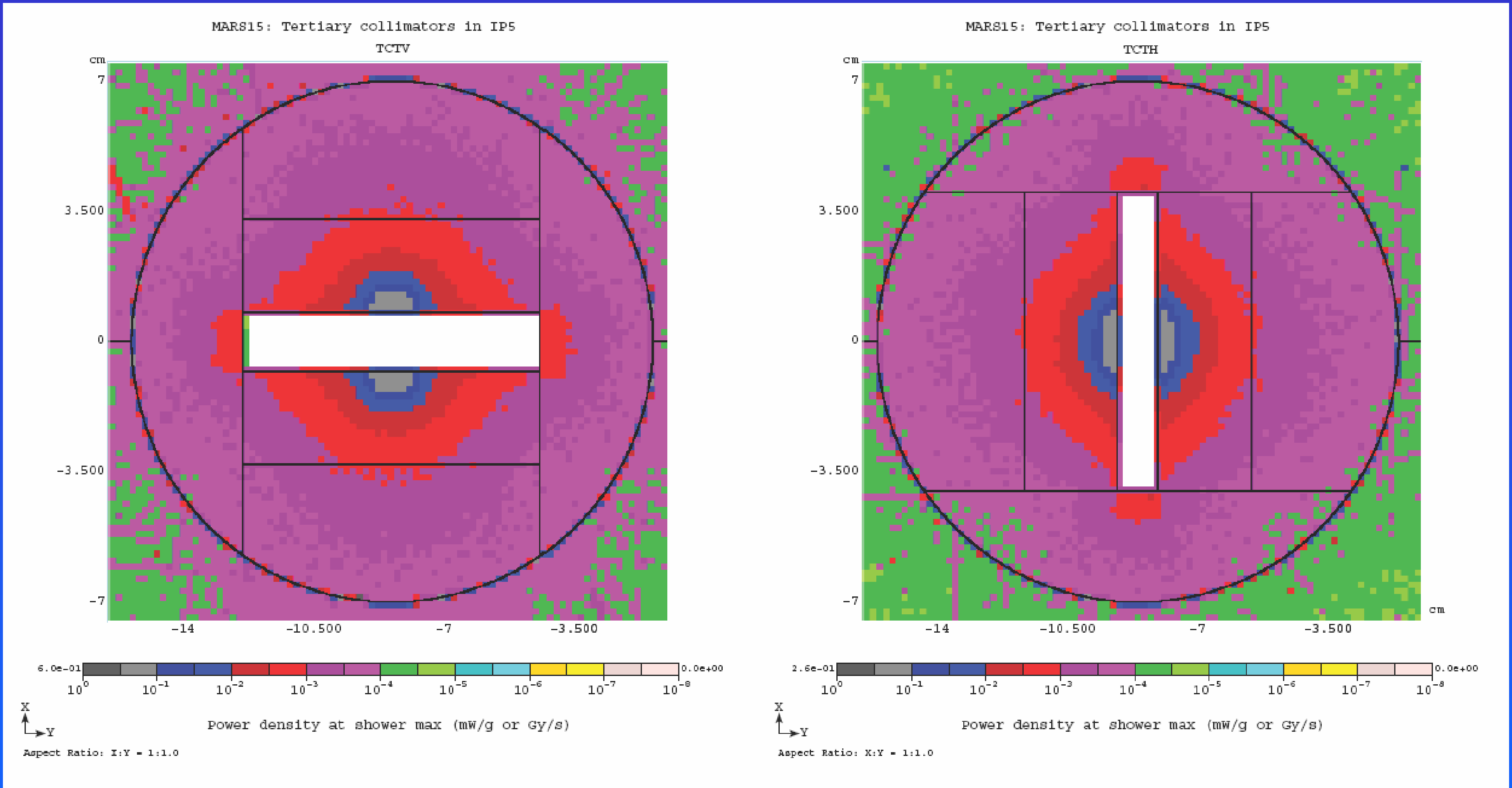
- Recently tertiary collimators have been added to prevent quenches of SC triplets (aperture bottlenecks at 7 TeV)!
- 2 collimators (H+V) per incoming beam!
- Studies done in framework of US contribution to the LHC (LARP) and the LHC Collimation project.
- Work done by N. Mokhov at FNAL with MARS.
- All results very preliminary!
- Use for discussion and not for conclusion!
- N. Mokhov will present final results.



Particle tracks E>10 GeV for a few 7-TeV protons on TCTs

N. Mokhov - Preliminary

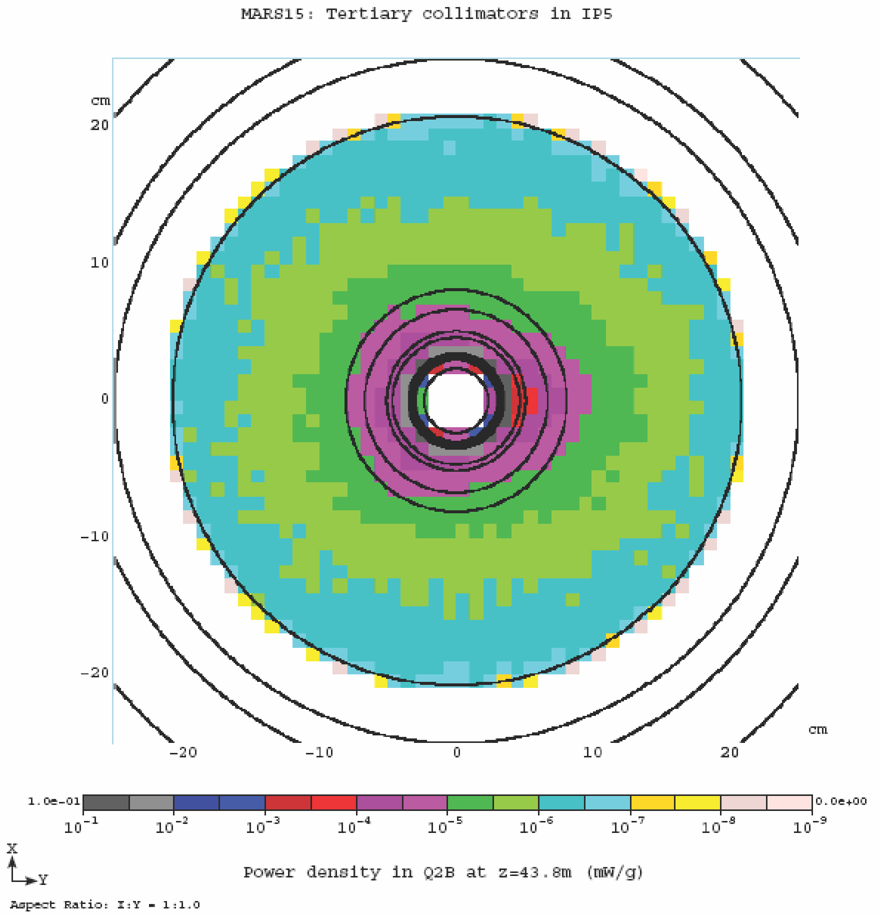
Power Density in Tertiary Collimators

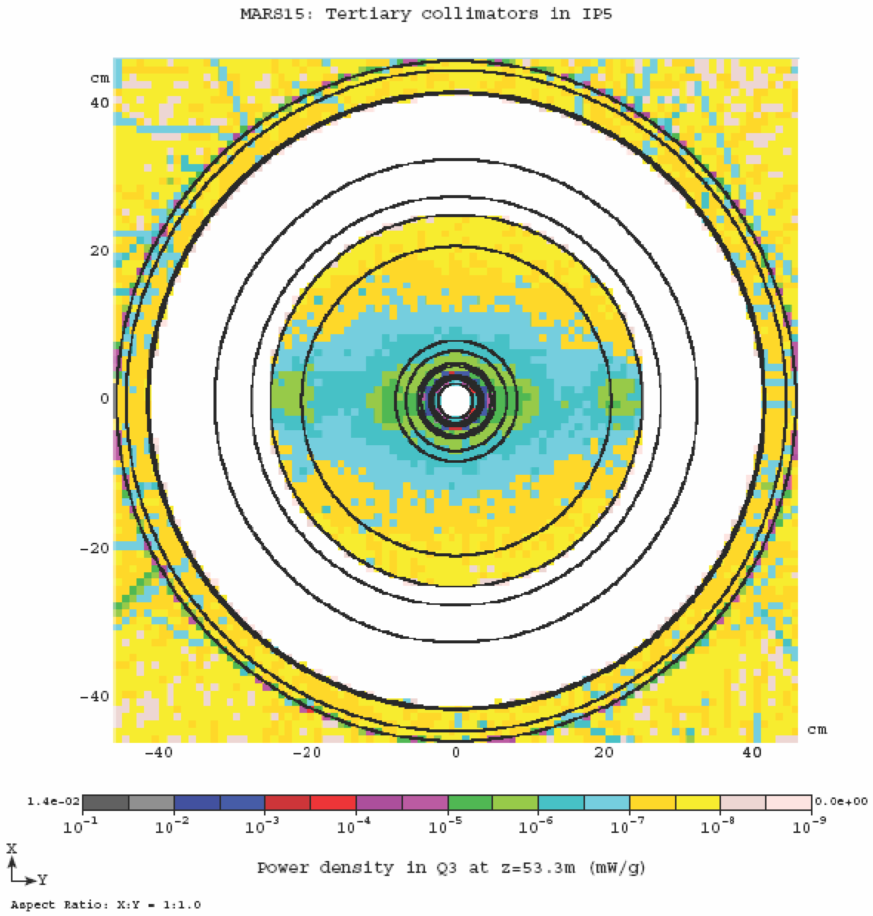


N. Mokhov - Preliminary

Results will be used to decide material for tertiary collimators:
Copper or Tungsten?

Power Density in Triplet Quadrupoles IP5



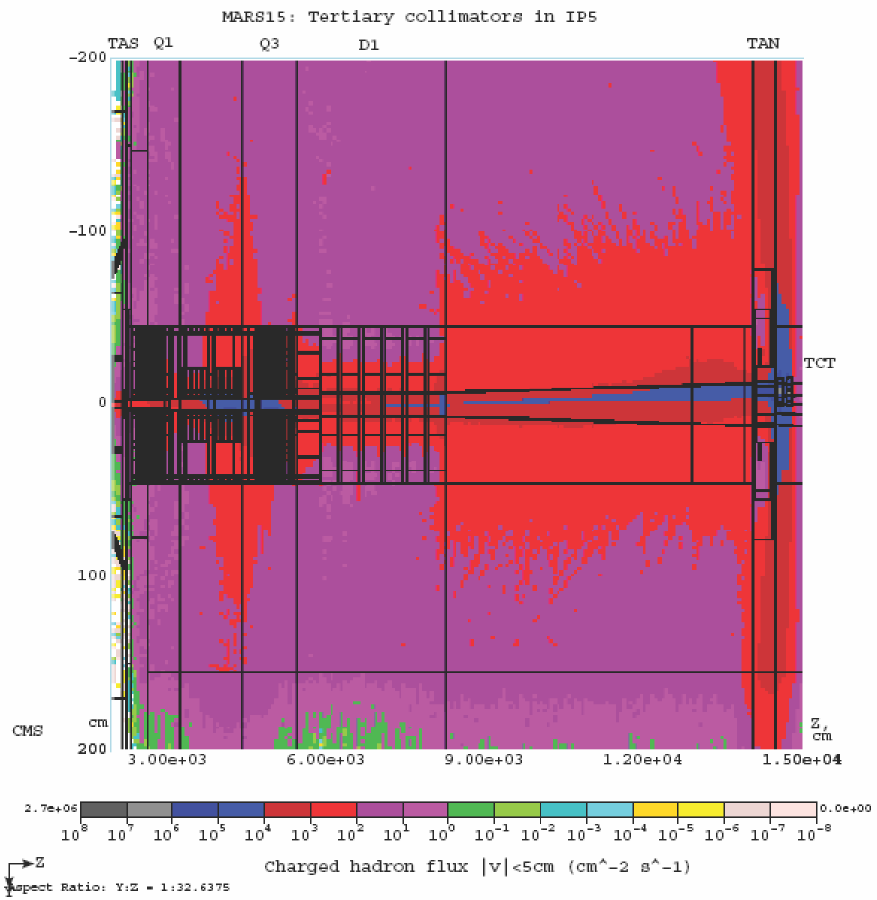


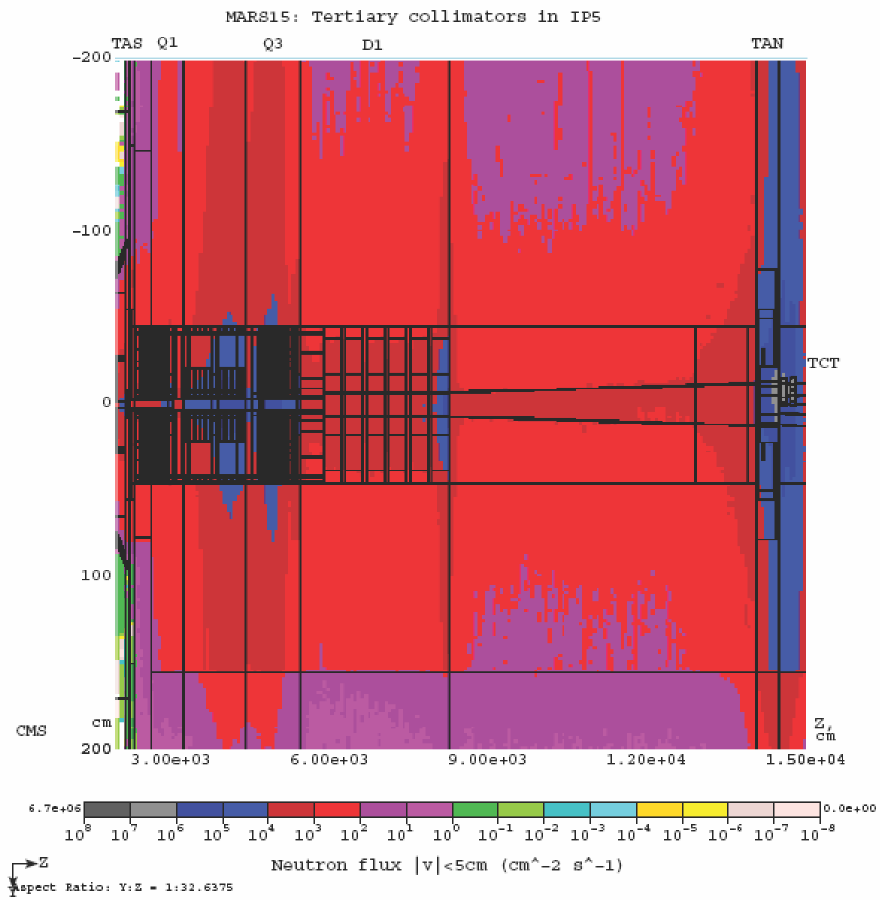
N. Mokhov - Preliminary

Goal: Demonstrate that triplets will not quench during spike in beam loss (loose 1% of beam in 10s)!

Convert quench into background spike!

TCT Induced Particle Fluxes in IP5





N. Mokhov - Preliminary

Particle fluxes can be used to estimate machine background!

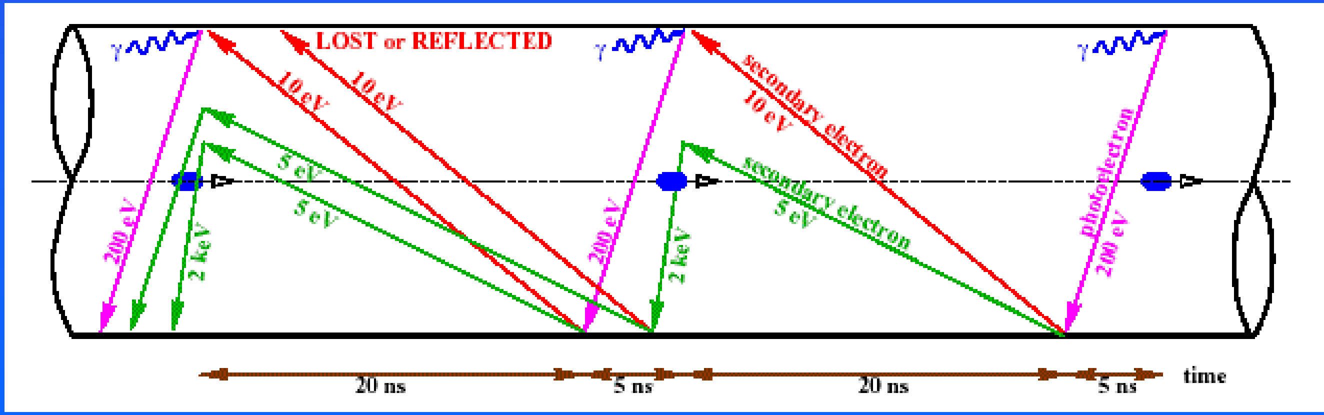
Generic study so far: Realistic if coupled with detailed loss maps!

Contents

- Introduction to the LHC
- Accelerator Physics and Operational Challenges
  - Optics Control and Magnets
  - Beam-Beam Interactions and Working point
  - Collimation (Beam loss control)
  - Vacuum and Electron Cloud
  - Instrumentation
  - Machine Configurations (➔ Different Optics)
  - Expected Input from Experiments
- Machine Commissioning
  - General Approach
  - Stages of Commissioning: From Pilot Run to Nominal
  - Physics Time per Year
- Conclusion

Vacuum and Electron Cloud

- The LHC accelerator features a ultra-high vacuum (< 10^{-8} Torr).
- This vacuum must be established at the start of the LHC to prevent gas scattering and various instabilities, for example electron cloud.
- Vacuum performance will improve with time (heating and "scrubbing") and gas pressures will reduce. Lower experimental backgrounds with time.
- Electron cloud limitation:
  Limit around 35% of nominal bunch intensity for 25ns bunch spacing?
  Dedicated scrubbing runs to reduce secondary electron emission yield of surfaces!



Instrumentation

- Successful setting up of the LHC will depend on beam instrumentation: beam position, tune, beam loss, luminosity, emittance, ... and related beam feedbacks!
- Lots of work to specify the various instruments for the LHC. For example, specification for the machine luminometer:

Luminosity sub-range	particle	Resolution		integration time
		Beam structure	Luminosity	
$1.0 \times 10^{26} \rightarrow 1.0 \times 10^{28}$	p-p	beam	± 10%	~ 1 mn
$1.0 \times 10^{28} \rightarrow 3.0 \times 10^{34}$	p-p	beam	± 1% (0.25%)	~ 1 s
$1.0 \times 10^{33} \rightarrow 3.0 \times 10^{34}$	p-p	bunch	~ ± 1%	~ 10s
$2.0 \times 10^{23} \rightarrow 5.0 \times 10^{25}$	Pb-Pb	beam	± 10%	~ 1 mn
$5.0 \times 10^{25} \rightarrow 1.0 \times 10^{27}$	Pb-Pb	beam	± 1% (0.25%)	~ 1 s

- Experiments will be additional eyes for the machine: offsets at IP, luminosity, background, ...

Contents

- Introduction to the LHC
- Accelerator Physics and Operational Challenges
  - Optics Control and Magnets
  - Beam-Beam Interactions and Working point
  - Collimation (Beam loss control)
  - Vacuum and Electron Cloud
  - Instrumentation
  - Machine Configurations (➔ Different Optics)
  - Expected Input from Experiments
- Machine Commissioning
  - General Approach
  - Stages of Commissioning: From Pilot Run to Nominal
  - Physics Time per Year
- Conclusion

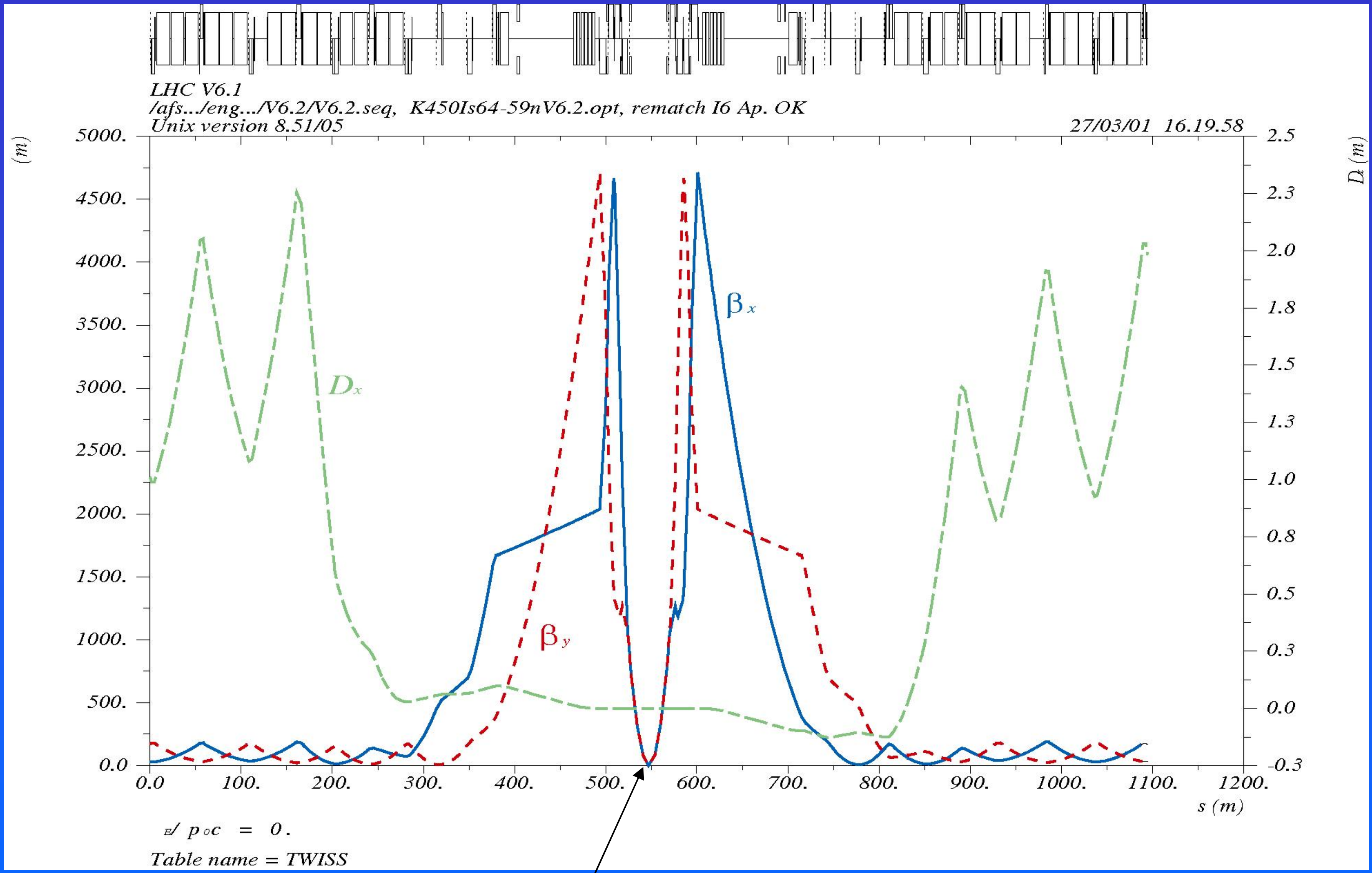
Machine Configurations

- The experimental insertions of the LHC can be configured for different conditions:
  - Different optics.
  - Different crossing angles.
  - Different beam-beam offsets (required for LHC-b).
  - Different separation bumps.

  → Design optimization.
- The machine can operate with different parameters:
  - Different collision energies (7 TeV is baseline)
  - Different particle types.
  - Different bunch intensities and number of bunches.
  - Different tunes.
  - Different collimation parameters (single to multi-stage cleaning).

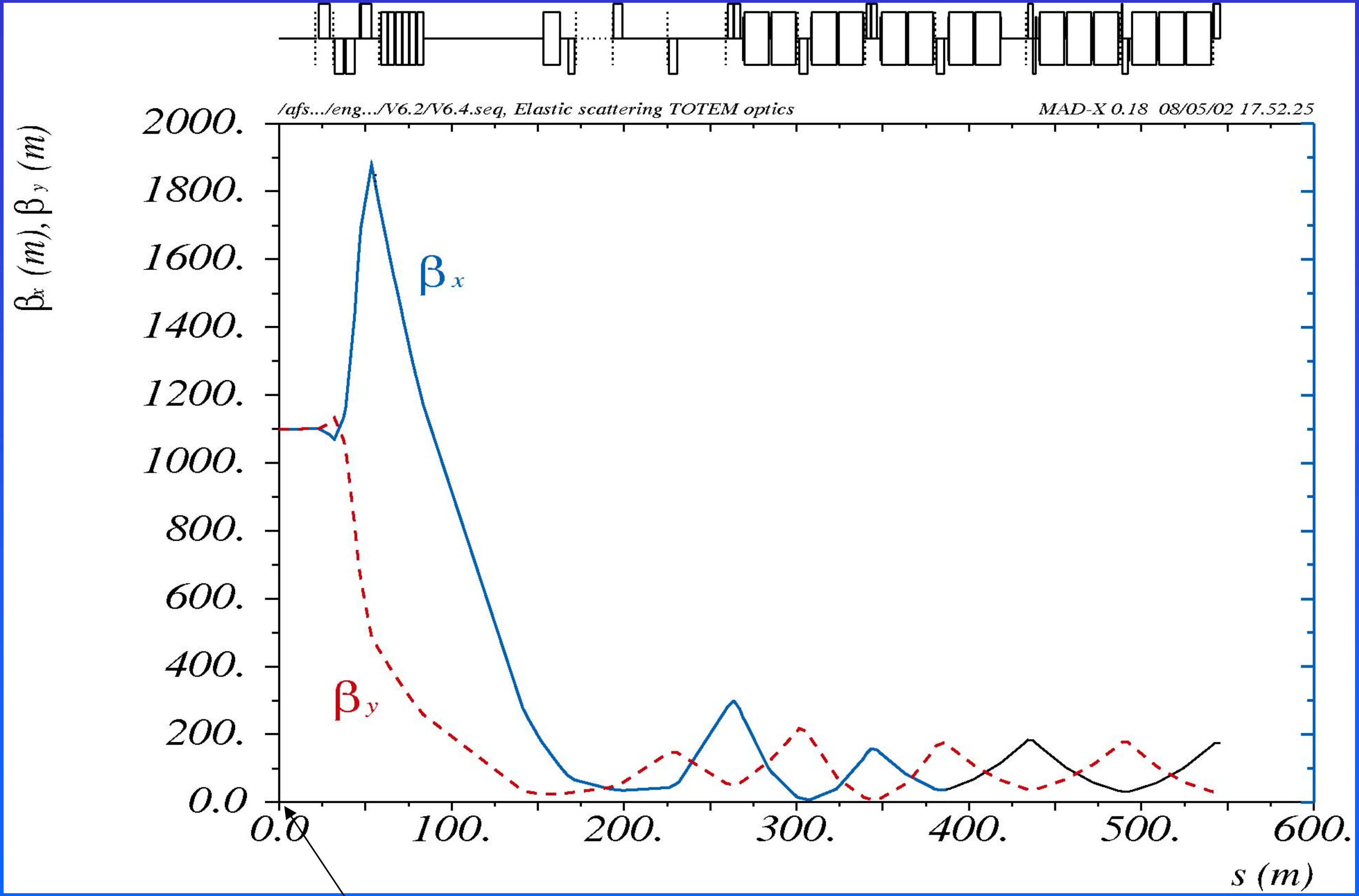
  → Operational optimization.

Low β Optics for IR1 and IR5



Collisions at IP with small spot size

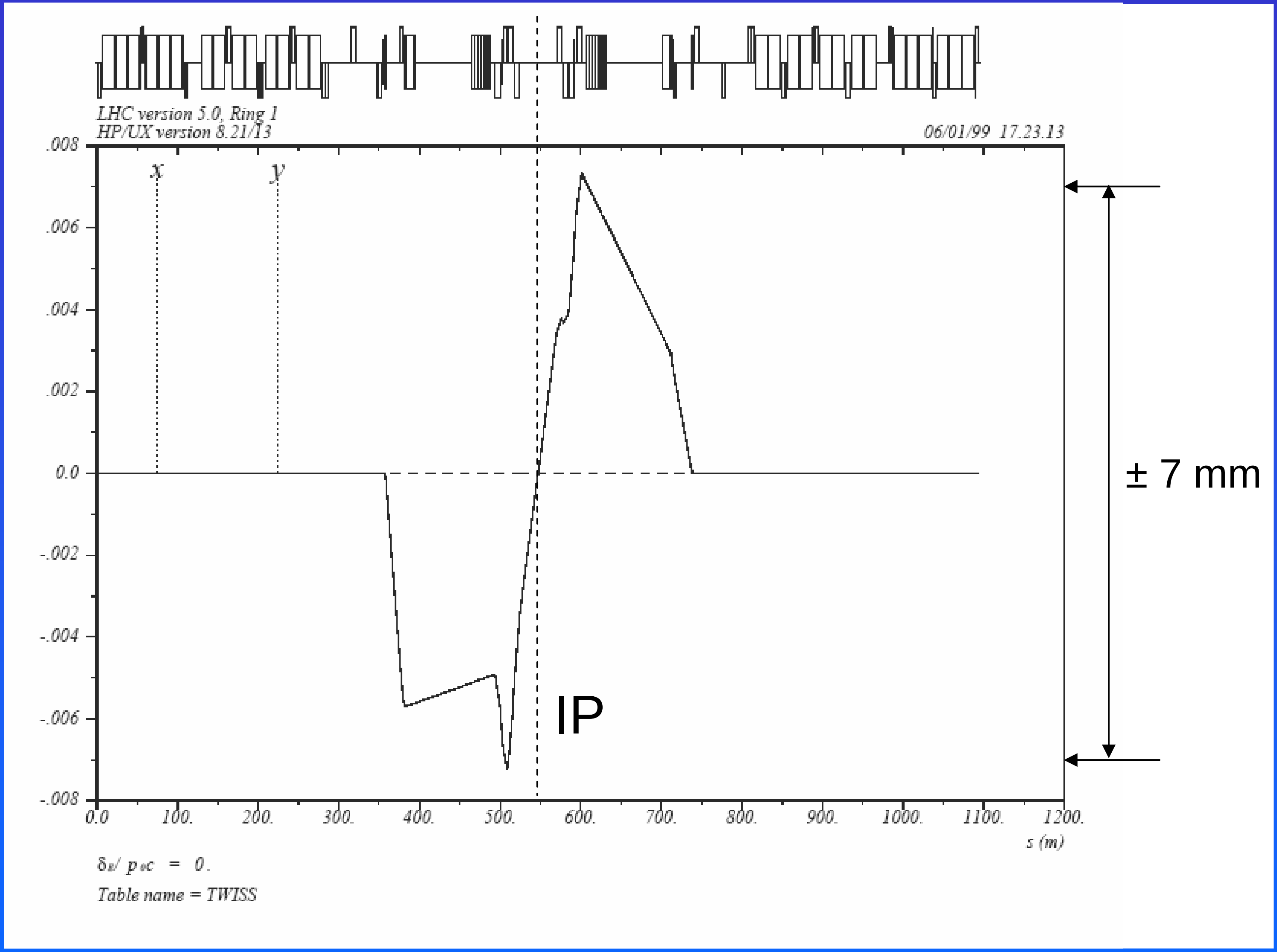
High Beta Optics (TOTEM)



Collisions at IP with large spot size (parallel beam)

R. Assmann

Crossing Angle IR5: 285 μrad



Different experiments have different crossing planes and different magnitudes! Depends on intensity and β^*!

R. Assmann

Input from Experiments

- General machine conditions: experiments, particle types, maximum event rate per crossing, energy.
- Note: Minimize number of machine configurations. Progress only with stable machine configuration. Each change costs time!
- Feedback on IP parameters: Transverse and longitudinal vertex positions with respect to detector, luminous region.
- Feedback on luminosity values: absolute values, imbalances between experiments.
- Feedback on backgrounds: Spatial and temporal properties of background. Acceptable (go to physics) or unacceptable (continue tuning of machine and collimation).
- Bunch by bunch information on luminosity and backgrounds? Indications for “bad bunches”?

Contents

- Introduction to the LHC
- Accelerator Physics and Operational Challenges
  - Optics Control and Magnets
  - Beam-Beam Interactions and Working point
  - Collimation (Beam loss control)
  - Vacuum and Electron Cloud
  - Instrumentation
  - Machine Configurations (➔ Different Optics)
  - Expected Input from Experiments
- Machine Commissioning
  - General Approach
  - Stages of Commissioning: From Pilot Run to Nominal
  - Physics Time per Year
- Conclusion

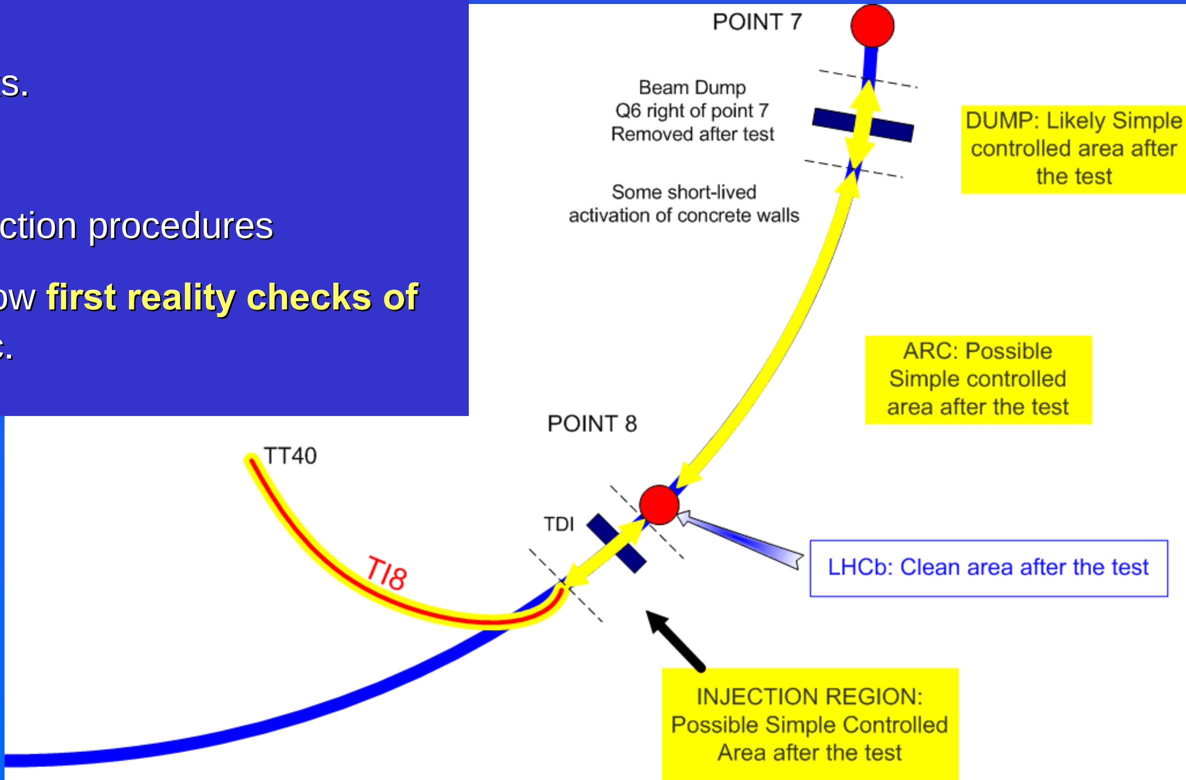
Machine Commissioning

- LHC: Some risky extrapolations beyond present state of the art (2-3 orders of magnitude).
- Enough stored energy to destroy significant parts of the accelerator!
- No short-cuts allowable in commissioning: make sure each machine protection system works as required (beam dump, interlock system, collimation, beam loss monitoring, ...).
- **Initial goals for commissioning:**
  - Establish colliding beams as quickly as possible.
  - Safely.
  - Without compromising further progress.
  - Achieve this by taking two moderate intensity multi-bunch beams to high energy and collide them.
- Gain experience (machine and experiments) and then push further!

LHCOP: http://www.cern.ch/lhc-commissioning

First Step: Sector Test in 2006

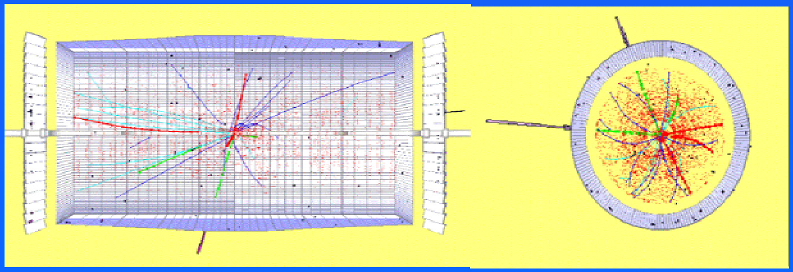
- Rigorous **check of ongoing installation and hardware commissioning**
- Pre-commission **essential acquisition and correction procedures**.
  - Commission injection system:
  - Commission Beam Loss Monitor system
  - Commission trajectory acquisition and correction.
  - Linear optics checks:
  - Mechanical aperture checks.
  - Field quality checks.
  - Test the controls and correction procedures
- Hardware exposure to beam will allow **first reality checks of assumptions of quench limits** etc.



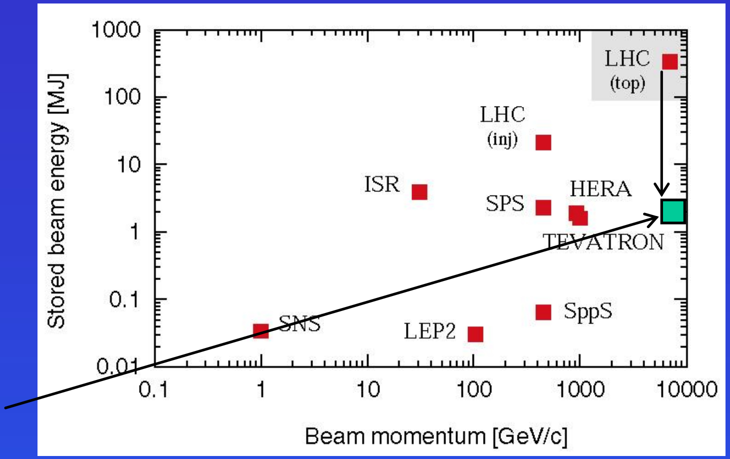
R. Assmann

So How to Get to Nominal Performance ?

- Avoid quenches (and damage)
  - Reduce total current to reduce stored beam energy
    - Lower i_b
    - Fewer bunches (we have 25ns 50ns 75ns spacing available)
  - Higher β^* to avoid problems in the (later part of) the squeeze
  - Reduce energy to get more margin
    - Against transient beam losses
    - Against magnet operating close to training limit
- Both machine and experiments will have to learn how to stand running at nominal intensities
- An early aim is to find a balance between robust operation and satisfying the experiments
  - Maximize integrated luminosity
  - Minimize event pile-up (to event + 2)



Proposal for Early Proton Running



Phase I collimators and partial beam dump

1. Pilot physics run with few bunches
   - No parasitic bunch crossings
   - Machine de-bugging no crossing angle
   - 43 bunches, unsqueezed, low intensity
   - Push performance (156 bunches, partial squeeze, higher intensity)
2. 75ns operation
   - Establish multi-bunch operation
   - Relaxed machine parameters (squeeze and crossing angle)
   - Push squeeze and crossing angle
3. 25ns operation with Phase I collimators + partial beam dump
   - Needs scrubbing for higher intensities ($i_b > 3\ 10^{10}$)

Phase II collimators and full beam dump

25ns operation

- Push towards nominal performance

Philosophy of Pilot Run

43 on 43 with 3 to 4 x 10^{10} ppb to 7 TeV

- No parasitic encounters
  - No crossing angle
  - No long range beam
  - Larger aperture
- Instrumentation
- Good beam for RF, Vacuum…
- Lower energy densities
  - Reduced demands on beam dump system
  - Collimation
  - Machine protection
- Luminosity
  - 10^{30} $cm^{-2}s^{-1}$ at 18 m
  - 2 x 10^{31} $cm^{-2}s^{-1}$ at 1 m

Stage 1 – pilot run luminosities

$$L = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F$$

- No squeeze to start
- 43 bunches per beam (some displaced in one beam for LHCb)
- Around 10^{10} per bunch
- Push one or all of
  - 156 bunches per beam (some displaced in one beam for LHCb)
  - Partial optics squeeze
  - Increase bunch intensity

Beam energy (TeV)	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0
Number of bunches per beam	43	43	156
β^* in IP 1, 2, 5, 8 (m)	18,10,18,10	2,10,2,10	2,10,2,10
Crossing Angle (μrad)	0	0	0
Transverse emittance (μm rad)	3.75	3.75	3.75
Bunch spacing (μs)	2.025	2.025	0.525
Bunch Intensity	$1\ 10^{10}$	$4\ 10^{10}$	$4\ 10^{10}$
Luminosity IP 1 & 5 ($cm^{-2}\ s^{-1}$)	$\sim 3\ 10^{28}$	$\sim 5\ 10^{30}$	$\sim 2\ 10^{31}$
Luminosity IP 2 ($cm^{-2}\ s^{-1}$)	$\sim 6\ 10^{28}$	$\sim 1\ 10^{30}$	$\sim 4\ 10^{30}$

LHCOP: http://www.cern.ch/lhc-commissioning

How long?

	Phase	R1/2	Time [days]	
	Injection	2	1	2
1	First turn	2	3	6
2	Circulating beam	2	3	6
3	450 GeV: initial commissioning	2	4	8
4	450 GeV: detailed measurements	2	4	8
5	450 GeV: 2 beams	1	2	2
6	Nominal cycle	1	5	5
7	Snapback – single beam	2	3	6
8	Ramp – single beam	2	4	8
9	Single beam to physics energy	2	2	4
10	Two beams to physics energy	1	3	3
11	Physics	1	2	2
12	Commission squeeze	2	4	4
13	Physics partially squeezed	1		
	TOTAL TIME (WITH BEAM)			*60*

Stage 2 – 75ns luminosities

$$L = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F$$

- Partial squeeze and smaller crossing angle to start
- Luminosity tuning, limited by event pileup
- Establish routine operation in this mode
- Move to nominal squeeze and crossing angle
- Increase bunch intensity ?
- Tune IP2 and IP8 to meet experimental needs

Beam energy (TeV)	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0
Number of bunches per beam	936	936	936
β^* in IP 1, 2, 5, 8 (m)	2,10,2,10	0.55,10,0.55,10	0.55,10,0.55,10
Crossing Angle (μrad)	250	285	285
Transverse emittance (μm rad)	3.75	3.75	3.75
Bunch Intensity	$4\ 10^{10}$	$4\ 10^{10}$	$9\ 10^{10}$
Luminosity IP 1 & 5 ($cm^{-2}\ s^{-1}$)	$\sim 1\ 10^{32}$	$\sim 4\ 10^{32}$	$\sim 2\ 10^{33}$
Luminosity IP 2 & 8 ($cm^{-2}\ s^{-1}$)	$\sim 2\ 10^{31}$	$\sim 2\ 10^{31}$	$\sim 1\ 10^{32}$

LHCOP: http://www.cern.ch/lhc-commissioning

Stage 3 – 25ns luminosities

$$L = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F$$

- Production physics running
- Start with bunch intensities below electron cloud threshold
  - ➢ Scrubbing run (1-2 weeks)
- Increase bunch intensities to beam dump & collimator limit
  - ➢ Install beam dump kickers
  - ➢ Install phase II collimators
- Increase bunch intensities towards nominal
- Tune IP2 and IP8 to meet experimental needs

Long shutdown (6months)

Beam energy (TeV)	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0	7.0
Number of bunches per beam	2808	2808	2808
β^* in IP 1, 2, 5, 8 (m)	0.55,10,0.55,10	0.55,10,0.55,10	0.55,10,0.55,10
Crossing Angle (μrad)	285	285	285
Transverse emittance (μm rad)	3.75	3.75	3.75
Bunch Intensity	$3\ 10^{10}$	$5\ 10^{10}$	$1.15\ 10^{11}$
Luminosity IP 1 & 5 ($cm^{-2}\ s^{-1}$)	$\sim 7\ 10^{32}$	$\sim 2\ 10^{33}$	10^{34}
Luminosity IP 2 & 8 ($cm^{-2}\ s^{-1}$)	$\sim 4\ 10^{31}$	$\sim 1\ 10^{32}$	$\sim 5\ 10^{32}$

TOTEM luminosities

$$L = \frac{N^2 k_b f\gamma}{4\pi\varepsilon_n \beta^*} F$$

- Total Cross Section and Elastic scattering
- Diffraction and minimum bias
- Characterized by
  - Several 1 day runs per year (starting early)
  - Some single beam runs
  - 43 and 156 bunches per beam
  - IP5 β^* = 1540m
  - IP5 β^* = 18m

Beam energy (TeV)	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0
Number of bunches per beam	43	156	2808
β^* in IP 5 (m)	1540	1540	18
Crossing Angle (μrad)	0	0	285
Transverse emittance (μm rad)	3.75	3.75	3.75
Bunch spacing (μs)	2.025	0.525	0.025
Bunch Intensity	$3\ 10^{10}$	$6\ 10^{10}$	$1.15\ 10^{11}$
Luminosity IP 5 ($cm^{-2}\ s^{-1}$)	$\sim 4\ 10^{27}$	$\sim 6\ 10^{28}$	$\sim 3\ 10^{32}$

ION luminosities

$$L = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F$$

- ALICE request short run “after the first long shutdown”
- First runs with “early ion scheme”
- Move to nominal when possible

	Early	Nominal
Beam energy / nucleon (TeV)	2.76	2.76
Number of bunches (per beam)	62	592
β^* in IP 2 (m)	1	0.5
Crossing Angle (μrad)	0	0
Transverse emittance (μm rad)	1.5	1.5
Bunch spacing (μs)	0.099	1.350
Bunch Intensity	$7\ 10^7$	$7\ 10^7$
Luminosity in IP2 ($cm^{-2}\ s^{-1}$)	~ $5\ 10^{25}$	10^{27}

LHCOP: http://www.cern.ch/lhc-commissioning

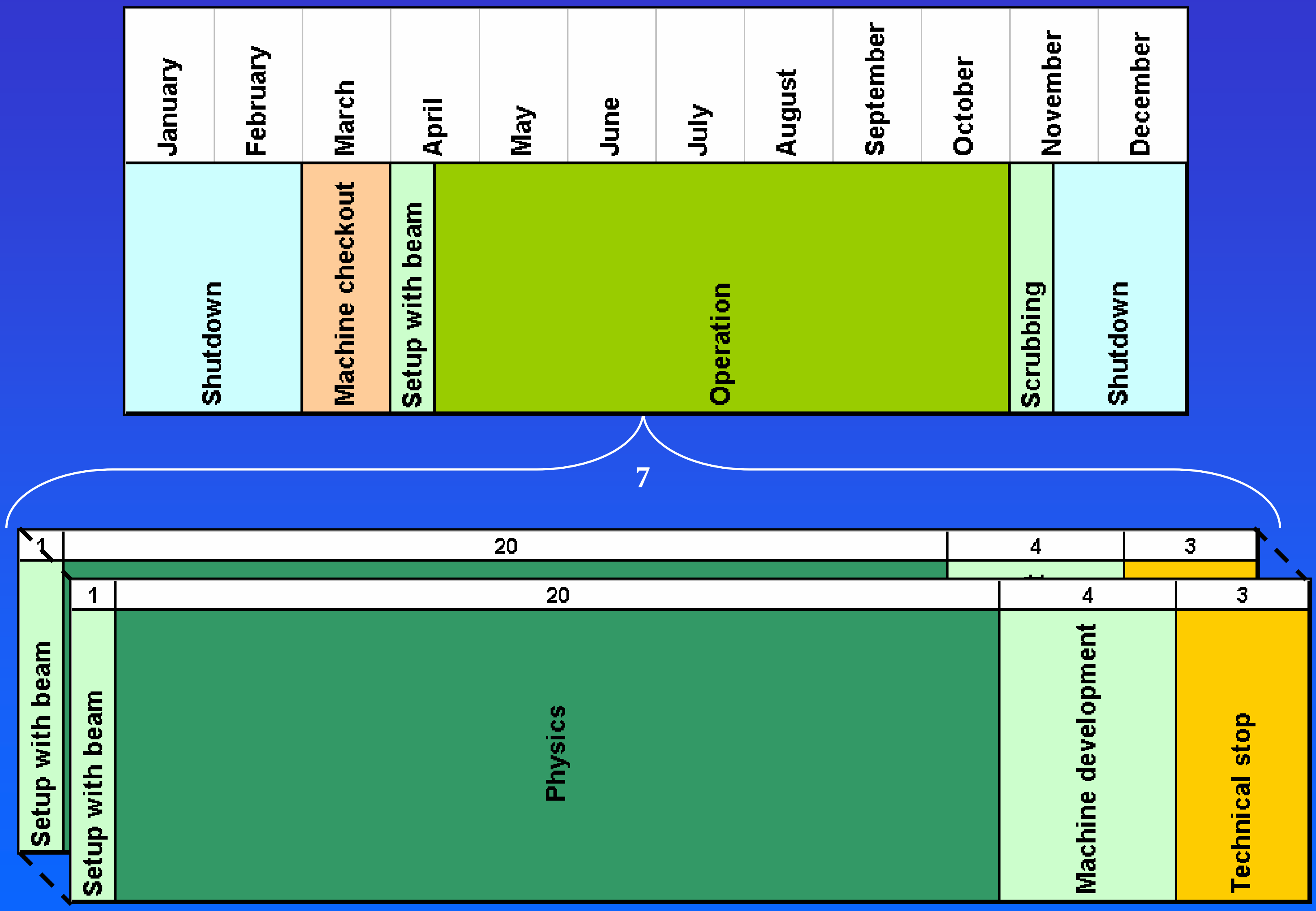
Guess on First Years' Running

Hardware commissioning	April	
	May	
	June	
Machine checkout	July	
	August	1
Beam commissioning	September	
	October	
Pilot proton run	November	
	December	
Shutdown	January	
	February	
Machine checkout	March	
75ns commissioning	April	
First ION run	May	
75ns run	June	2
	July	
	August	
Low intensity 25ns run	September	
	October	
	November	
Shutdown	December	
	January	
	February	
Machine checkout	March	
Startup and scrubbing	April	
	May	
Half intensity 25ns run	June	3
	July	
	August	
	September	
	October	
	November	
Shutdown	December	

	January	
	February	
Machine checkout	March	
Startup and scrubbing	April	
	May	
	June	4
	July	
Push to nominal 25ns	August	
	September	
	October	
	November	
	December	
Shutdown	January	
	February	
Machine checkout	March	
Startup and scrubbing	April	
	May	
	June	5
	July	
Nominal 25ns	August	
	September	
	October	
	November	
	December	

LHCOP: http://www.cern.ch/lhc-commissioning

Breakdown of an LHC Year



R. Assmann

Conclusion

- The LHC is a demanding machine. Not only does its physics reach enter into new territory, but also the machine challenges advance the state-of-the-art in some respects by 2-3 orders of magnitude.
- Many interfaces between the machine and experiment interests: energy, luminosity, beam background, ...
- The LHC machine is designed to master all the known accelerator physics and operational challenges.
- We must proceed carefully in order not to hinder further progress (damage to the accelerator or the experiments).
- A plan has been laid out for commissioning of the LHC: 2 months until colliding beams and 5 years to nominal performance (like LEP).
- We have exciting times ahead of us...

Upcoming Lectures

Two more lectures Thursday and Friday:

Lecture 4 - E. Tsesmelis: The Experimental Areas

Lecture 5 - D. Macina: The Experiment-Machine Interface