And some things that should not have been forgotten were lost. History became legend, legend became myth.

Lessons Learnt from LEP/LHC

ML
22-2-18

LESSONS LEARNT?

An experience, example, or observation that imparts new knowledge or understanding

- A: Project management/strategic
- B: Should have been obvious but…
- C: Exploitation: beam physics/applied physics/system engineering
- D: Unexpected stuff

LEP TIMELINE

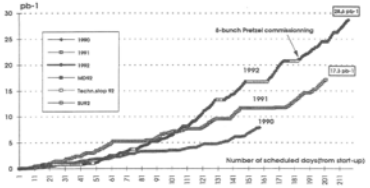
September 13, 1983
Civil engineering started

February 8, 1988
LEP tunnel finished

July 12, 1988
Injection test

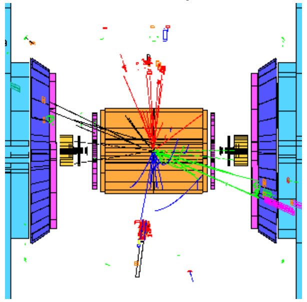
July 14, 1989
First injection

August 13, 1989
First collisions



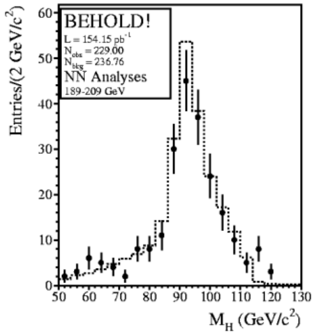
1995
LEP1.5
65, 68, 70 GeV

03:13 9th July 1996



1996
First Ws
80.5 to 86 GeV

1998
94.5 GeV
10^{32} cm^{-2}s^{-1}



2000
102 – 104.4 GeV
Discovery mode

1983	≈	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000

LEP challenges

- 27 km of equipment and instrumentation to keep running
  - 700 or so power converters,
  - 1000s of magnets: 8 of which superconducting
  - 20 or so electrostatic separators
  - Huge RF system
  - Lots of Collimators
  - Kickers, beam dumps
  - 250 BPMs, BCTs, Q-meter, BST, profile measurements, beam loss monitors etc
  - A few interlocks
  - Communication with the experiments

All held together with a rudimentary control system

LEP challenges

- Multi-cycle injection
  - Stability of lines, steering
  - Accumulation: resonances, coherent tune shifts, wigglers, radiation in experiments, etc. etc.
- Ramp between 22 GeV and 104 GeV
  - Tune, chromaticity and orbit control (particularly the start), resonances, bunch length, wigglers
- Squeeze between β^* = 20 cm and β^* = 5 cm.
  - Tune, chromaticity and orbit control
- Physics
  - Beam-beam, control of tune, chromaticity, orbit, beam crossings, coupling, lifetimes
  - Background optimization - collimation
  - Continual optimization to maximize delivered luminosity.

1989 - commissioning

- 14th July: first beam
- 23rd July: circulating beam
- 4th August: 45 GeV
- 13th August: colliding beams

These people are to blame for what followed

1990 - let's get operational

- Luminosity: 2 - 3 10^{30} cm^{-2} s^{-1}
- Beam current around 3 mA
- Pretzel test
- Lots of waist scans
- BIG beam sizes…

8.6 pb^{-1}

Conclusion from Chamonix 91

- a 70/76 team has been set up
- a dispersion team has been set up
- a dynamic aperture team has been set up
- a closed obit team has been set up
- an intensity limitation team has been set up
- a longitudinal oscillation team has been set up
- a crash pretzel team has been set up
- a beam-beam team already exists!

First Chamonix 1991

LEP – difficult teething

- Fractured high level control system
- It was slow (even in 2000 it took 15 s to acquire a closed orbit)
- Poor measurement facilities
  - Beam instrumentation lived in a world of its own. Very little integration.
  - Essential signals not available e.g. no beam lifetime, for example
  - Poor data management
  - Inflexible communication with experiments
  - No easy way of closing the measure/correct loop
- Poor and unreliable, incoherent data acquisition systems

- *After commissioning and 2 years of operations we were faced with just wanting to get the beam up the ramp occasionally. Operations a real struggle (turn around was around 7 hours back then)*

1992

28.6 pb-1

The sloppy start-up from hell. The super optics (94/100)
Combined ramp & squeeze

I can't believe they let us do this

"After another night trying to optimize the ramp & squeeze we came to the conclusion, supported by computer simulations that the 94/100 optics was intrinsically stable."

Pretzel commissioned

1996 - a transitional year

24.7pb^{-1}

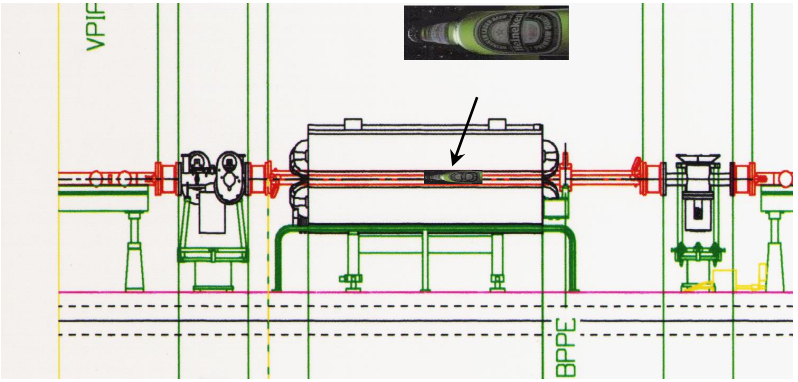
- The bloody bottle
- ramp squeeze ramp - getting confident now
- started with 108/60
  - lot of fun with coupling
  - aperture searches, err..
- back to 90/60
- 80.5 GeV - the first Ws
- Pagano and the L3 girder servo

Aims of the year

- Establish RF system
- Deliver some luminosity
- Come up with a new optics

2 out 3 ain't bad

Refreshing the particles that other beers cannot reach



x2

"Unsociable sabotage: both bottles were empty!!"

1998

Almost seemed as if we knew what we were doing...

- Tune feedback forced into operations at last
- 94.5 GeV
- Antennae cables and the bunch length in the ramp
- a Morpurgo of golden orbits

199.7 pb^{-1}

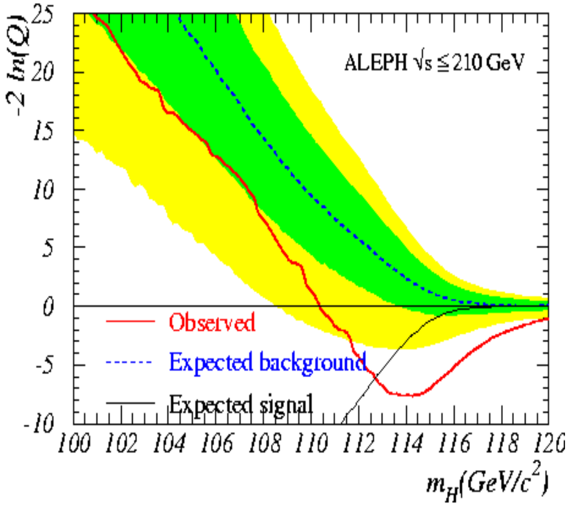
Cracked it:

- $10^{32}\ cm^{-2}s^{-1}$
- 3.6 pb^{-1} in 24 hours
- $\xi_y \sim 0.075$

2000 - the end

- Total integrated luminosity of 233.05 pb^{-1} of which
  - 4.42 pb^{-1} at 45 GeV
  - 228.63 pb^{-1} over 100 GeV
  - 131.73 pb^{-1} between 103.0 and 103.5 GeV
  - 10.74 pb^{-1} at 104 GeV or above

} Rather good



Dispatches

- Tried in vain
  - Transverse feedback, 1 mA per bunch, 4 x 4 x 4, 108^0 phase advance
- Lived without:
  - Vector sum feedback, Streak camera, tune feedback for a long time, wire scanners
- Lived with:
  - The bloody access system
  - β* knobs and 5 cm
  - Opal – thanks for the beer!!!
  - RF not ramping
  - storms, the control system, vacuum valves, L3, L3's girder, sparks, timing, magnet interlock system, experiments' beam dumps, SPS, PS, transfer line software

Systems - end of term report

Vacuum	A few holes in an overall excellent performance
BI	Late starter, always a bit slow on the uptake.
Accelerator physics	Interesting bunch, very excitable.
RF	Not bad
Magnets	Tendency to confuse North and South a distinct disadvantage.
Power converters	Very good but RM8QS15 will not be forgotten
Separators	Quite brilliant.
Controls	A jolly good spanking required
Cryogenics	A very cool performance

14:30

WE HAVE LOST <u>3 HOURS</u> TRYANG TO SET UP THE POLARIMETER [illegible] CAUSED BY THE RF TRIGGER CABLE FOUND DISCONNECTED !!!

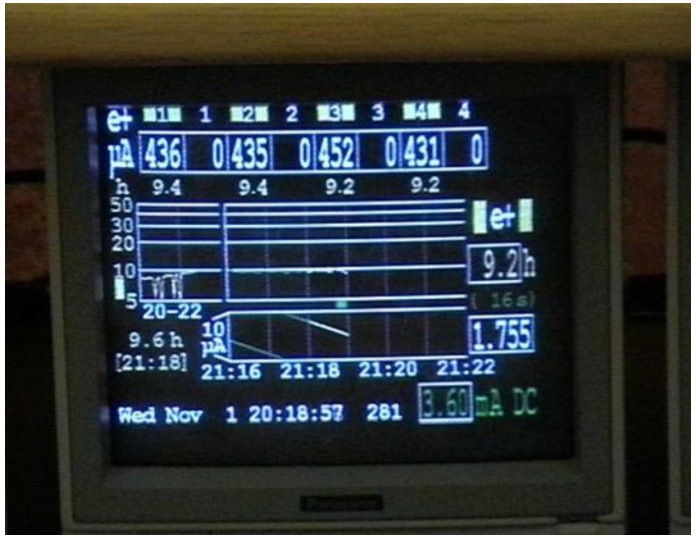
⇒ (3rd TIME IN STREAK CAMERA – POL. HISTORY!)

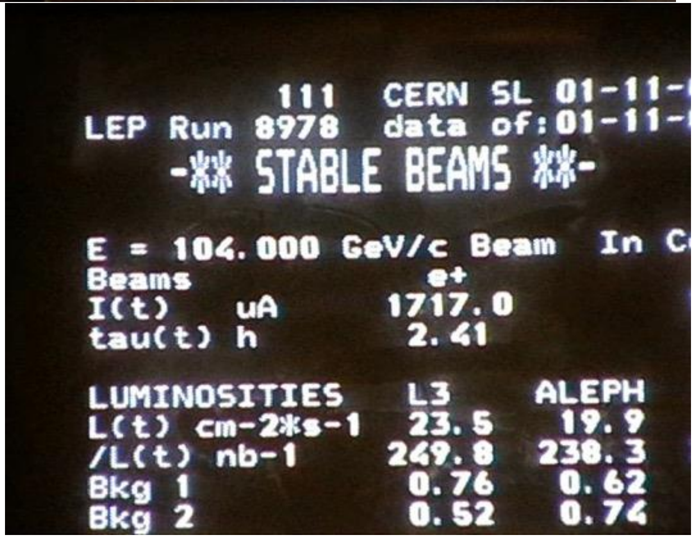
— M. Placidi

This is what they get the Faraday Cup for!

And other neat stuff

103.3 GeV → Mini-ramp → **104.0 GeV**



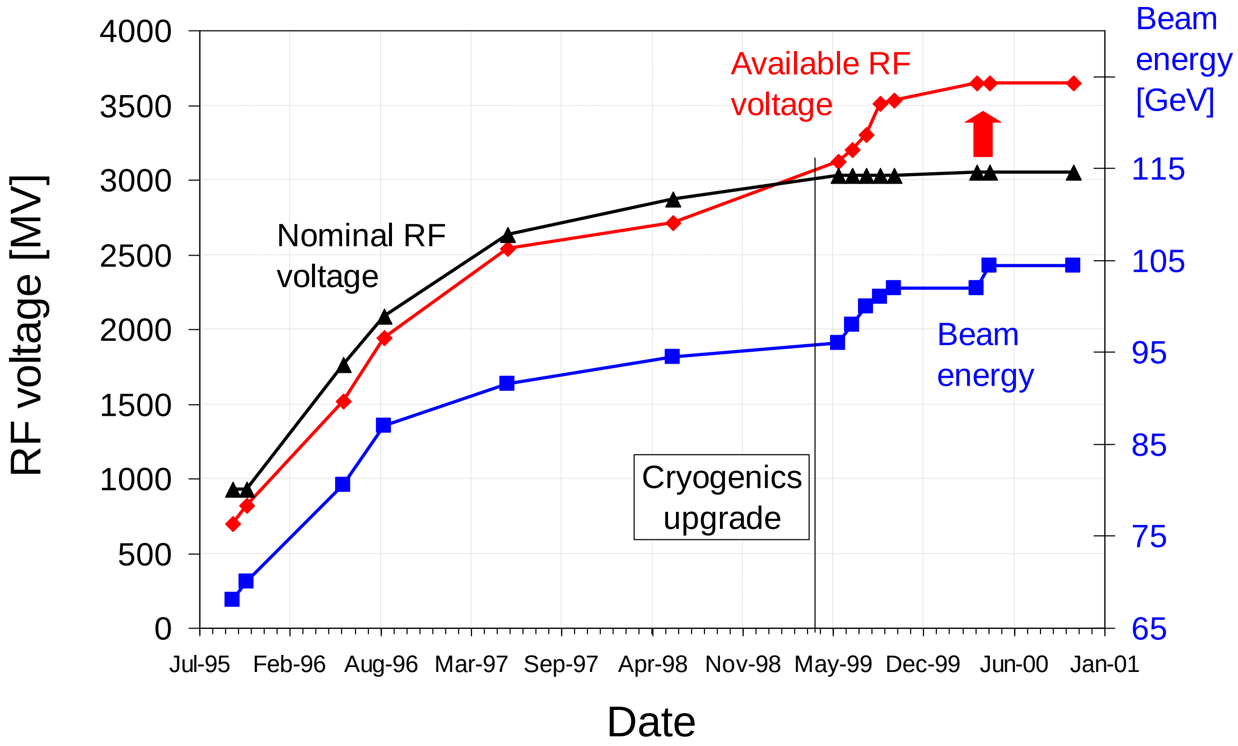


Beam lifetime:

9 hours → **3 hours**

quantum lifetime

“The … RF system is now almost nearly fully operational”



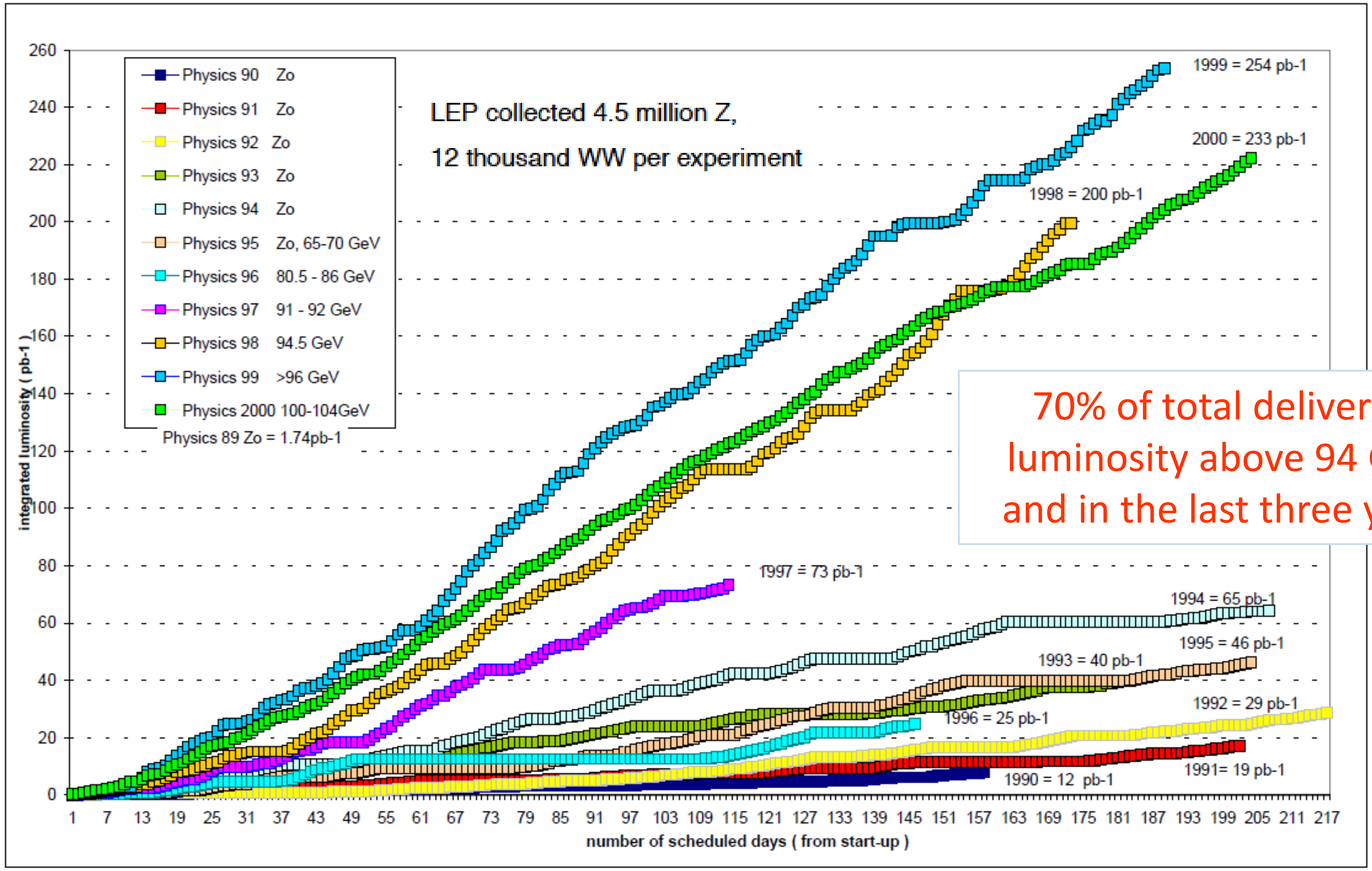
- In the **final year of operation** LEP had 288 SC cavities (272 niobium sputtered on copper; 16 solid niobium) and 56 copper cavities.
- Average accelerating field was 7.5 MV/m (design: 6 MV/m)
- Some operational tricks helped gain another ~2.3 GeV.
- **Industrial production & numerous technical problems overcome – a lot learnt**

1) LEP 200 was

– a major, very challenging, high-tech project

– a triumphant success

Chris Llewellyn Smith



70% of total delivered luminosity above 94 GeV and in the last three years

18 million Zs
96,000 Ws

The legacy of LEP

The physics data (luminosity, energy, energy calibration)

"It should be stressed that the whole body of knowledge accumulated by the study of LEP and SLD data is simply enormous"

The experience in running large accelerators.

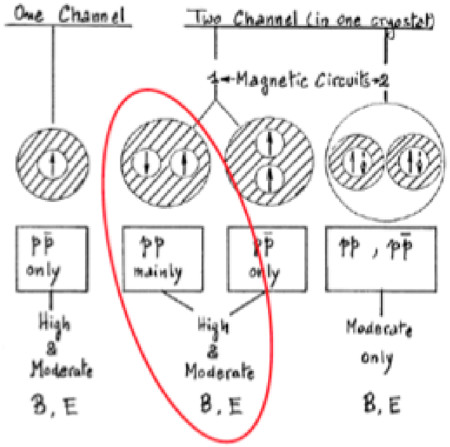
- Technical infrastructure
- Operational control (Orbit, tunes, ramp, squeeze…)
- Alignment, ground motion in deep tunnels
- Designing and running a large SC RF system.
- Impedance and beam dynamics in big machines
- Optics designs from 60/60 to 102/90 and 102/45

Operation in unique regime of ultra-strong damping:

- Vertical emittance with small solenoid effects (dispersion-dominated).
- Beam-beam limit with strong damping.
- First confirmation of theory of transverse spin polarization.

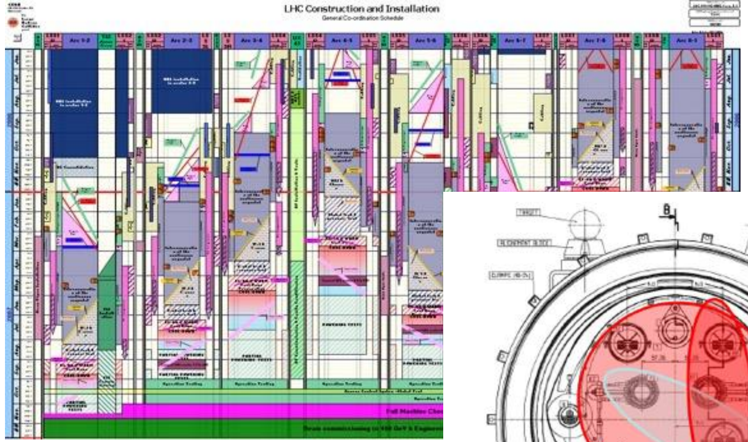
LEP COULD BE OPERATED BY ONE MAN!

Conception

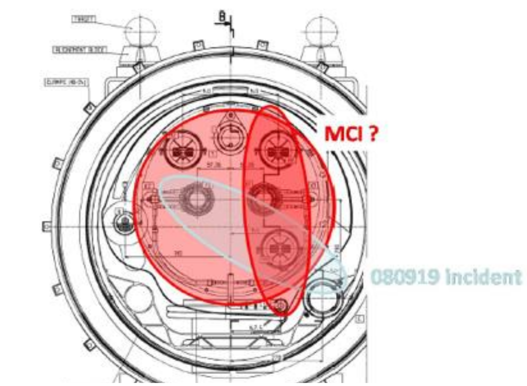


Initiation

LHC approved
by the Elders



Birth – overdue



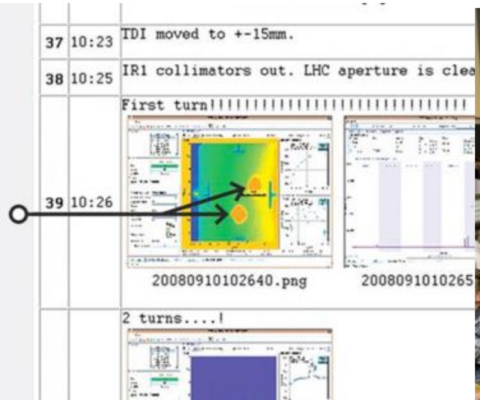
Withdrawal from community for mediation and preparation

Rival stumbles

SSC cancelled

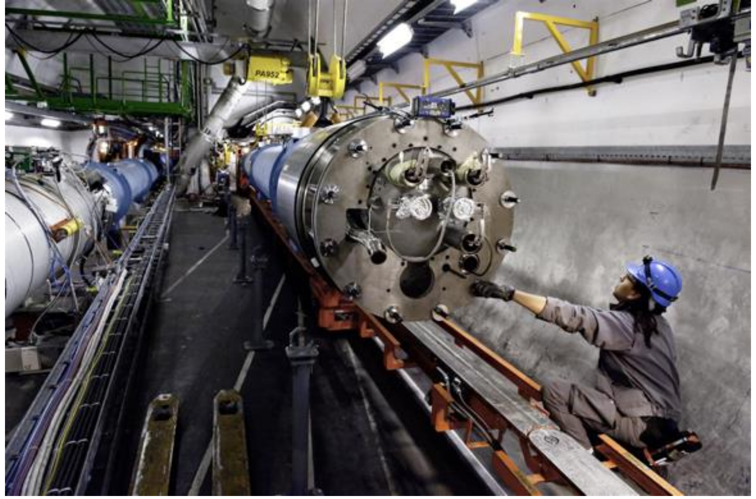
1984	//	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10

Hubris (?) September 10, 2008



Nemesis September 19, 2008

LHC

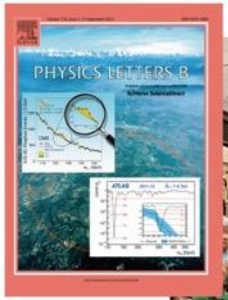


Trial/descent in the underworld

November 29, 2009

Resurrection and rebirth

Apotheosis and atonement

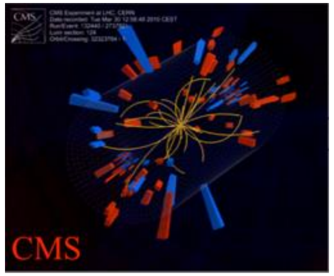


4 July, 2012

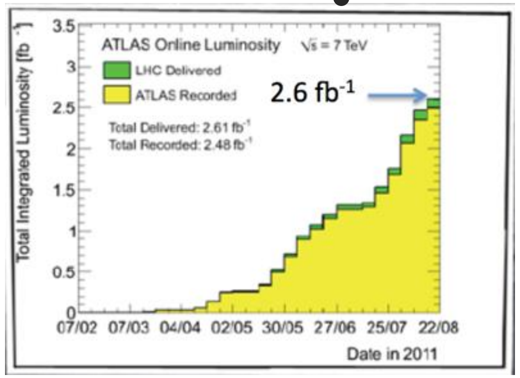
2009	2010	2011	2012	2013

March 30, 2010

First collisions at 3.5 TeV



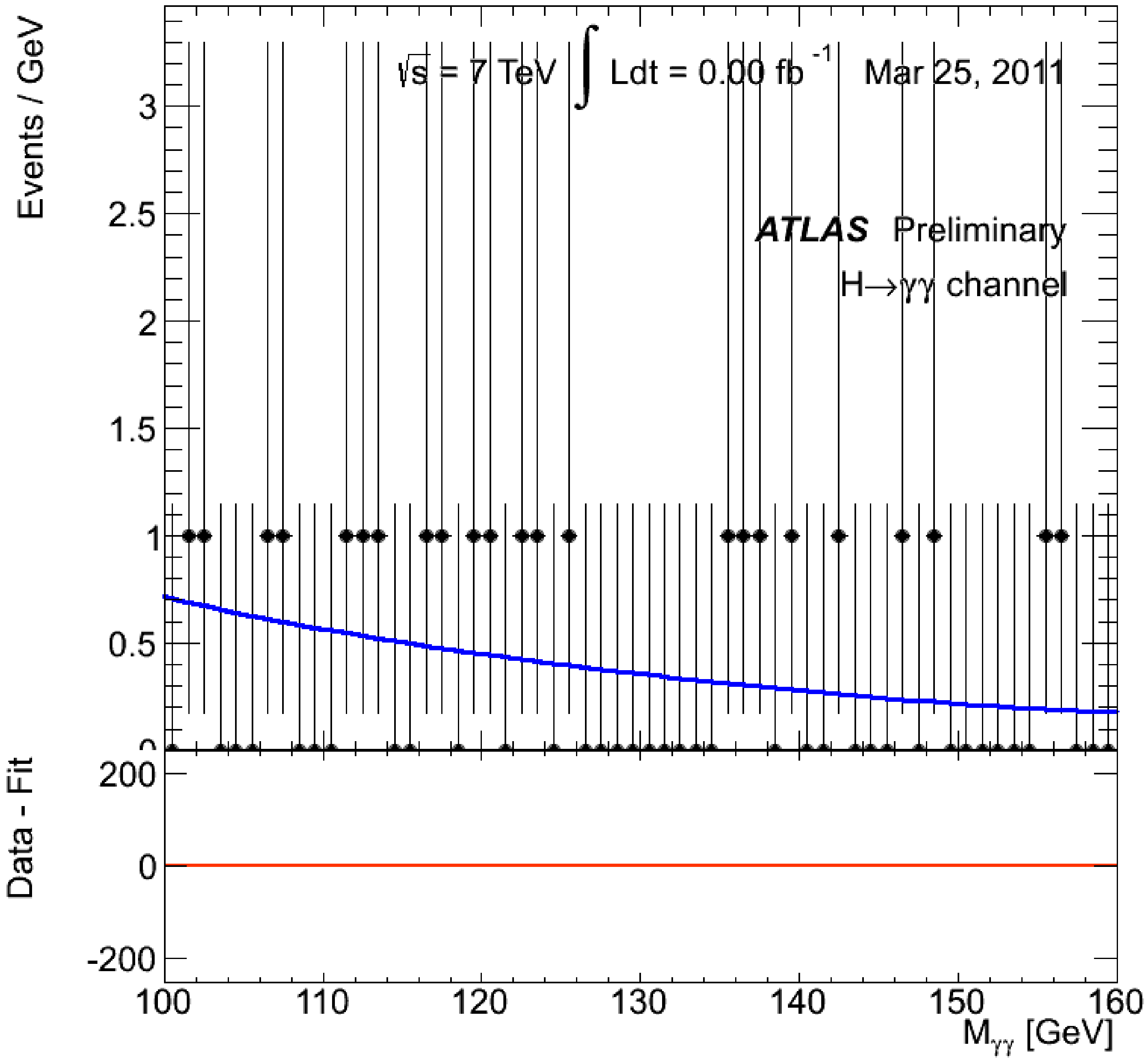
Ascension



Heroic subplot

And let us not forget Fortuna

- Late
- Over budget
- Blew it up after 9 days
- Costly, lengthy repair
- Rival coming up fast on the outside
- Had to run at half energy
- And yet…



√s = 7 TeV ∫ Ldt = 0.00 fb^-1 Mar 25, 2011
ATLAS Preliminary
H→γγ channel
Events / GeV
Data - Fit
M_γγ [GeV]

Superconducting magnets – long development, industrialization, **quality control**

Vacuum, cryogenics…

Accelerator physics: beam-beam, dynamic aperture, beam stability…

GET THE FOUNDATIONS RIGHT

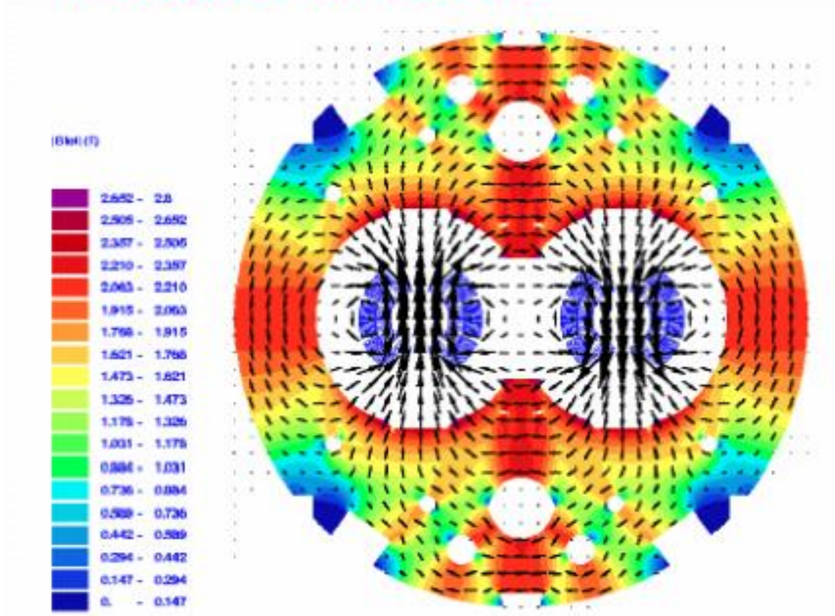
LHC twin-aperture dipole magnets

Concept perfected (design), demonstrated (models and prototypes) and realized on a **large industrial scale**

R. Perin

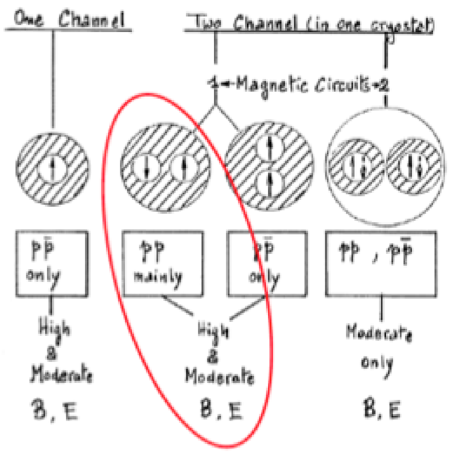
C. Wyss

L. Rossi



Courtesy Luca Bottura

ECFA-CERN workshop



June 1994
first full scale prototype dipole

1994 project approved by council (1-in-2)

SSC cancelled

June 2007 First sector cold

April 2008
Last dipole down

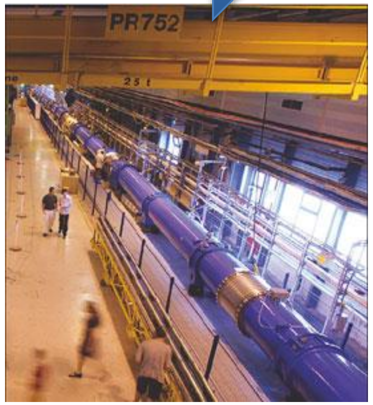
Main cor
cts signed

198 4 | 90 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10

Some of us practiced on a 27 km warm version

First set of twin 1 m prototypes
Over 9 T

2002 String 2



November 2006
1232 delivered

September 19, 2008

Magnets++

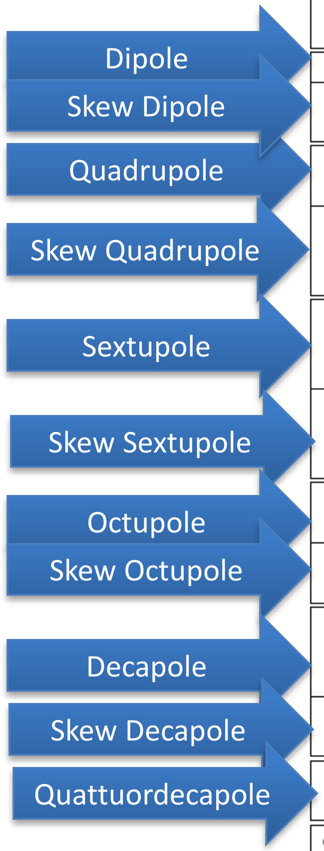
- **Field quality tracking and adjustment**
  - Field quality vitally important for beam stability - good after adjustments and faithful to the tight specifications
- **Sorting:** not all magnets are created equal
  - geometry - aperture
  - b3 - dynamic aperture/resonance driving terms
  - b1 – closed orbit perturbations
  - a2 – coupling, vertical dispersion
- **Magnetic measurement and modelling**
  - Characterize the important dynamic effects in anticipation of correction
  - All important magnetic strength versus current calibration

Field Quality Specification for the LHC Main Dipole Magnets

Stéphane Fartoukh and Oliver Brüning

Abstract

Based on criteria of different nature such as the control of the mechanical aperture or the preservation of the dynamic aperture, hard limits are given for the normal and skew harmonics a_n and b_n, $1 \leq n \leq 5$, and for the systematic b_7 component of the LHC main dipole magnets.

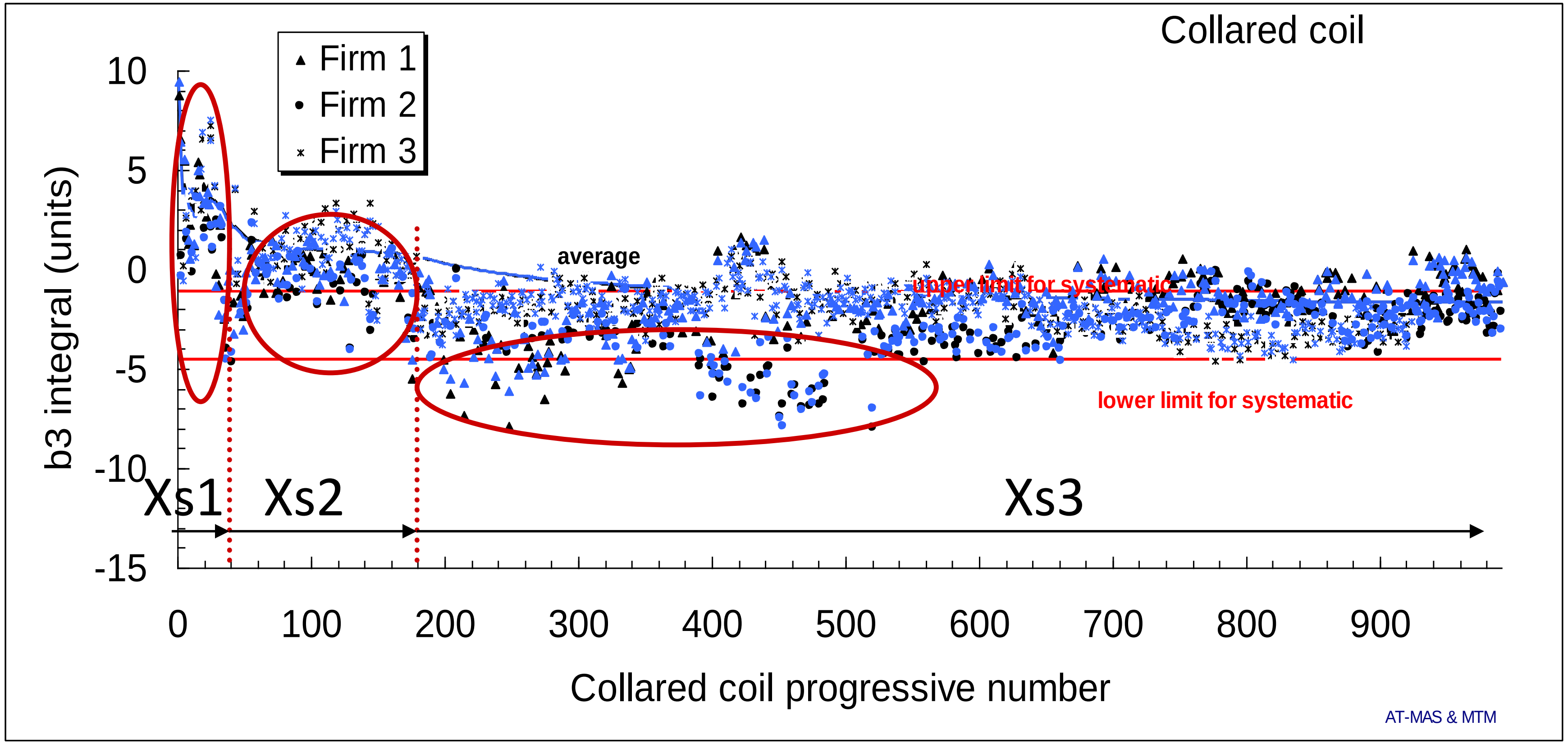


Harmonics a_n & b_n	Injection optics (450 GeV)	Injection optics (end of ramp)	Collision optics (7 TeV)	Systematic (max. value)	Uncertainty (max. value)	Random (r.m.s)	Criteria used
b_1	×	×	×	None	6.5	8.0	Closed orbit and MCB strength at 7 TeV
a_1 (including dipole roll)	×	×	×	6.5 (averaged per arc cell)		8.0	
b_2	×		×	1.4	0.8	0.7 0.8	β-beating and IP phasing
a_2	×	×	×		0.9	1.9 2.3 1.6	Vertical dispersion, linear coupling and MQS strength at 7 TeV
b_3	×		×	10.7 3.0	(including the bias due to uncertainty)	1.4 1.8	b_2 feed-down at injection, off-momentum β-beating, MCS strength at 7 TeV
a_3	×		×		1.5	0.7	Chromatic coupling inducing Q'' and MSS strength at 7 TeV
b_4	×		×	±0.2 (from Table 9901)	0.4	0.5	DA and Q'' at injection, MCO strength at 7 TeV
a_4	×				0.2	0.5 (from Table 9901)	DA at injection
b_5	×		×	1.1 0.8	(including the bias due to uncertainty)	0.5 0.4	DA and Q''' at injection, MCD strength at 7 TeV
a_5	×				0.4	0.4 (from Table 9901)	Off-momentum DA at injection
b_7	×			$-0.3 < \langle b_7 \rangle < 0.1$		0.2 (from Table 9901)	DA at injection
a_6, b_6, a_7 and higher order multipoles	×			OK with the Error Table 9901			DA at injection

Table 15: *Specifications for the dipole field quality at injection, end of ramp and in collision (a_n and b_n given in units of 10^{-4} relative field error at a reference radius $R_{ref} = 17$ mm).*

STEERING FIELD QUALITY IN THE MAIN DIPOLE MAGNETS OF THE LARGE HADRON COLLIDER

E. Todesco, B. Bellesia, L. Bottura, A. Devred, V. Remondino, S. Pauletta, S. Sanfilippo, W. Scandale, C. Vollinger, E. Wildner

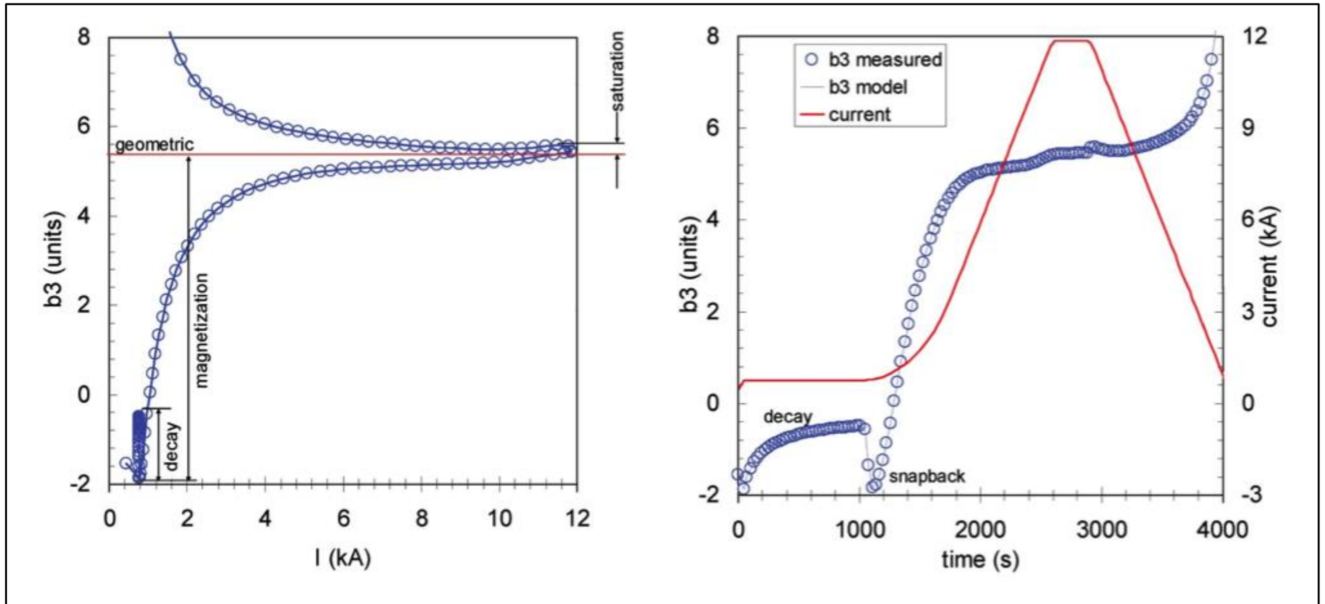


Plus: main field, magnetic length, quadrupole, octupole, decapole, skew quadupole, skew sextupole, skew octupole!

Courtesy Ezio Todesco et al

Magnet measurements and modeling

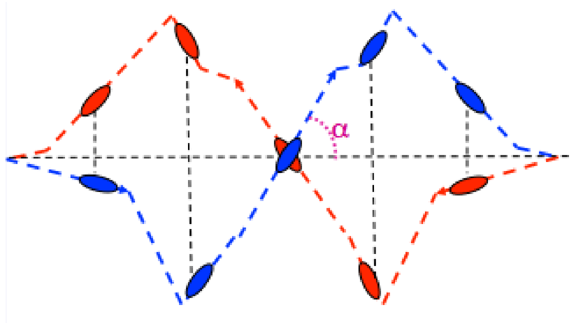
- … 10 years of measurements, dedicated instrumentation R&D, 4.5 million coil rotations, 50 GB of magnetic field data, 3 Ph.D.s and a few Masters Theses on the subject, 2 years of data pruning and modeling , collaborations and participation in runs in Tevatron and RHIC…
- **… today we have the most complex and comprehensive forecast system ever implemented in a superconducting accelerator**



Luca Bottura 2008 for the FIDEL team

Foreseen limitations circa 1995

- At low energy the main limitation for the beam lifetime comes from the machine non-linearities, i.e. the magnetic field errors
- At collision energy the limiting effects are caused by the beam-beam interaction
  - **Head-on** – conservative approach based on previous experience
  - **Long range** interactions - limiting factor for performance.
- Electron cloud
  - only identified as a problem for the LHC in the late 90ies
  - Pioneering work by Francesco Ruggiero & Frank Zimmermann



Optics and beam dynamics

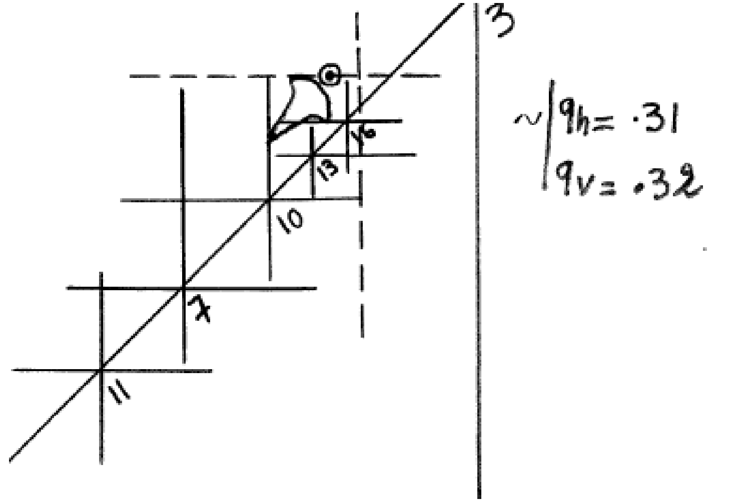
- **Major effort to optimize the optics**:
  - Which crossing scheme is preferred?
  - What is the effect of triplet errors?
  - Which is the preferred working point?
  - What are the best integer tunes?
- **Major simulation effort to study**:
  - Particle stability (dynamic aperture), beam instabilites
  - Effect of triplet errors, head-on beam-beam, long-range beam-beam
  - development of simulation tools (MAD and SIXTRACK) and the build up of computing resources (Frank Schmidt and Eric McIntosh)
- **Specification of corrector circuits and strategy**
  - Jean-Pierre Koutchouck et al

Beam-beam related effects for the LHC

(Relevant for LHC performance)

Jacques Gareyte

- Long range and head-on interactions
- Beam-beam induced synchrobetatron resonances
- Coherent beam-beam effects
- Beam-beam induced orbit effects

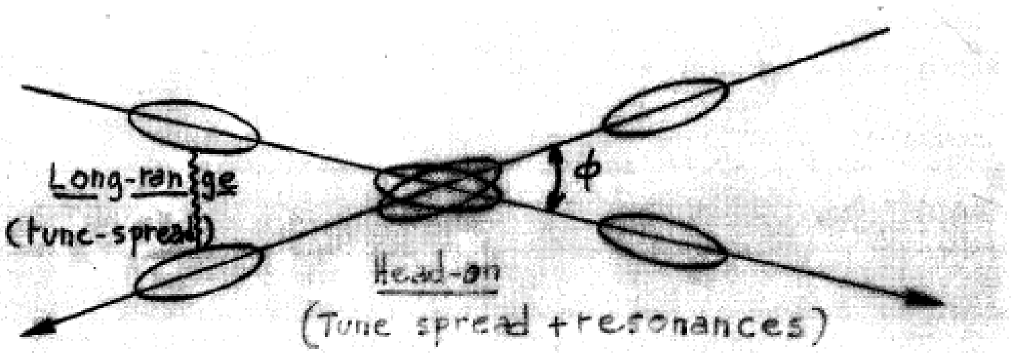


Quiet space to accomodate b.b. tune footprint

- Influence of triplet errors
- Long-range interactions

→ specify Xing angle ☐
triplet quality ☐

1) Avoid resonances $N \leq 12$

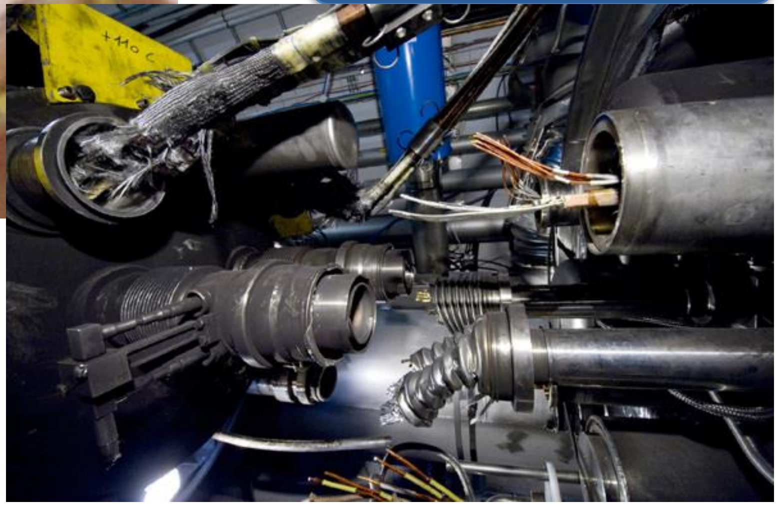


Foundations: Quality Control

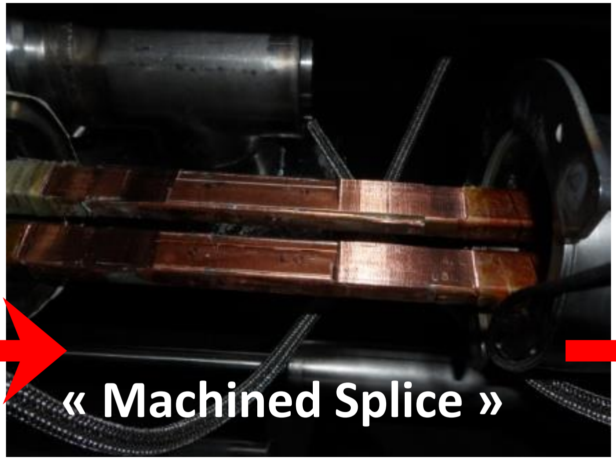
Cryogenic supply line

Plug In Modules

The incident

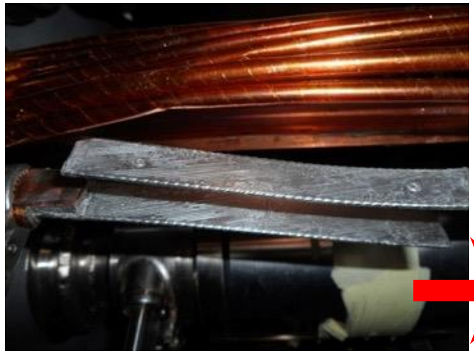


« Old Splice »

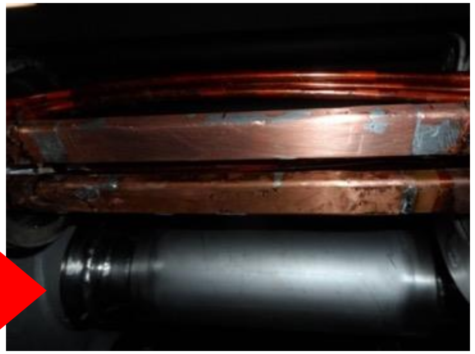


« Machined Splice »

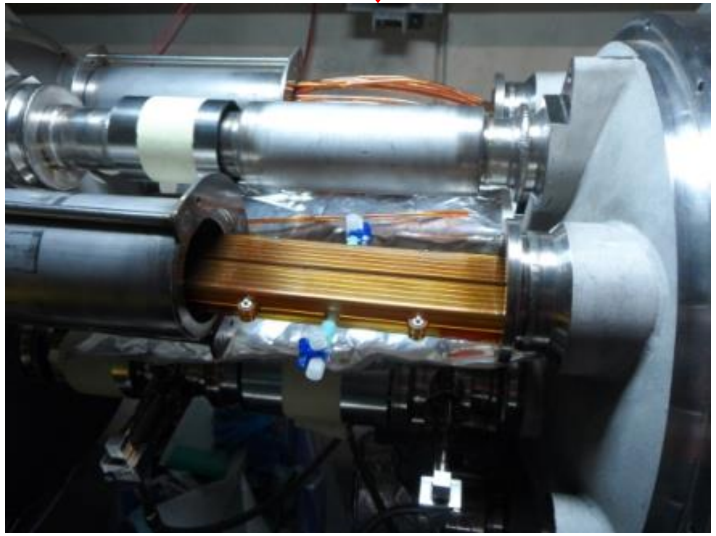
« Consolidated Splice »



« Cables »



« New Splice »



« Insulation box »

- Total interconnects in the LHC:
  - 1,695 (10,170 high current splices)
- Number of splices redone: ~3,000 (~ 30%)
- Number of shunts applied: > 27,000

INTERMEZZO 2001 - 2008

- LEP: building a machine is one thing, operating it is another

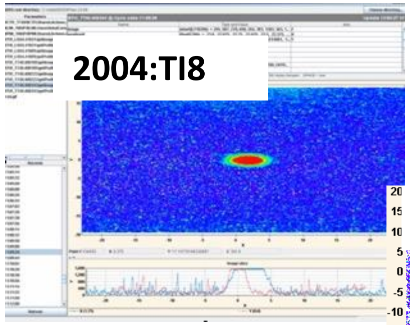
- While LHC construction and installation was ongoing the ex-LEP team started tackling:
  - How are we going to operate this machine?
    - Machine protection
    - Controls/Software
    - Instrumentation
    - Etc. etc.

- In “reasonable” shape by the start of commissioning in 2008

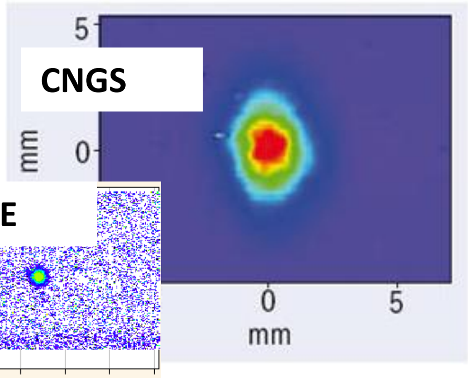
Preparation: beam tests through the years

2003:TT40

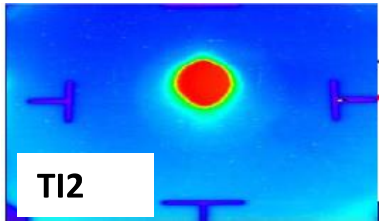
2004:TI8



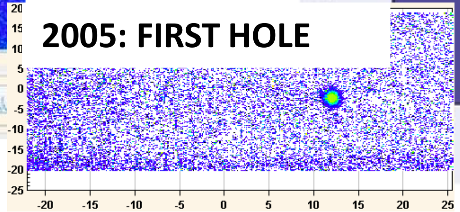
CNGS



TI2

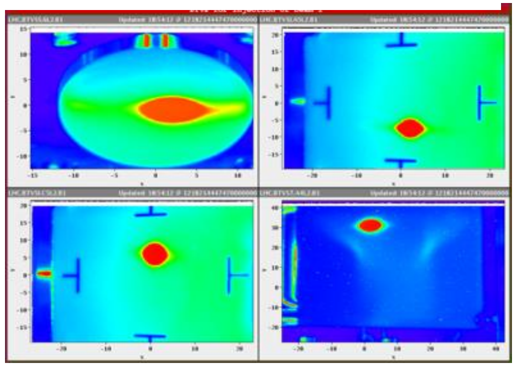


2005: FIRST HOLE

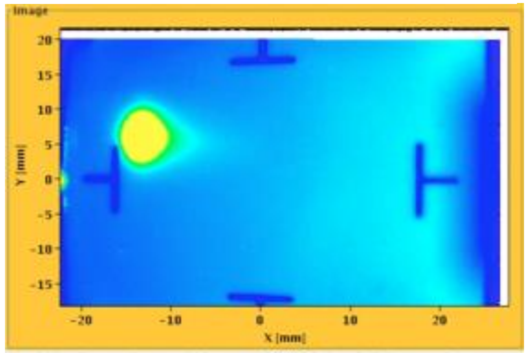


2008: SEPT 10

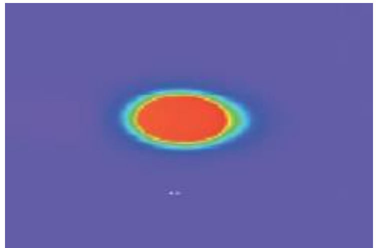
2008: FIRST BEAM TO LHC



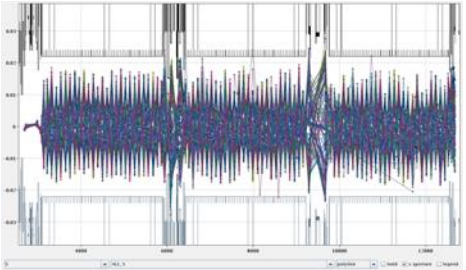
2008: FIRST BEAM TO IR3



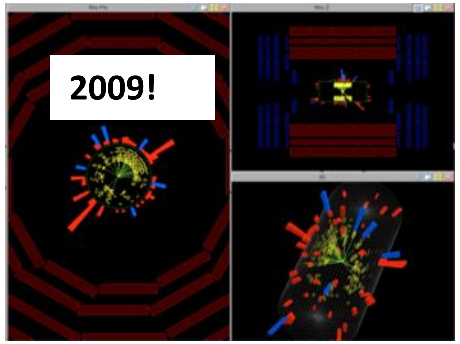
2009: FIRST IONS TO LHC



2009: Sector test

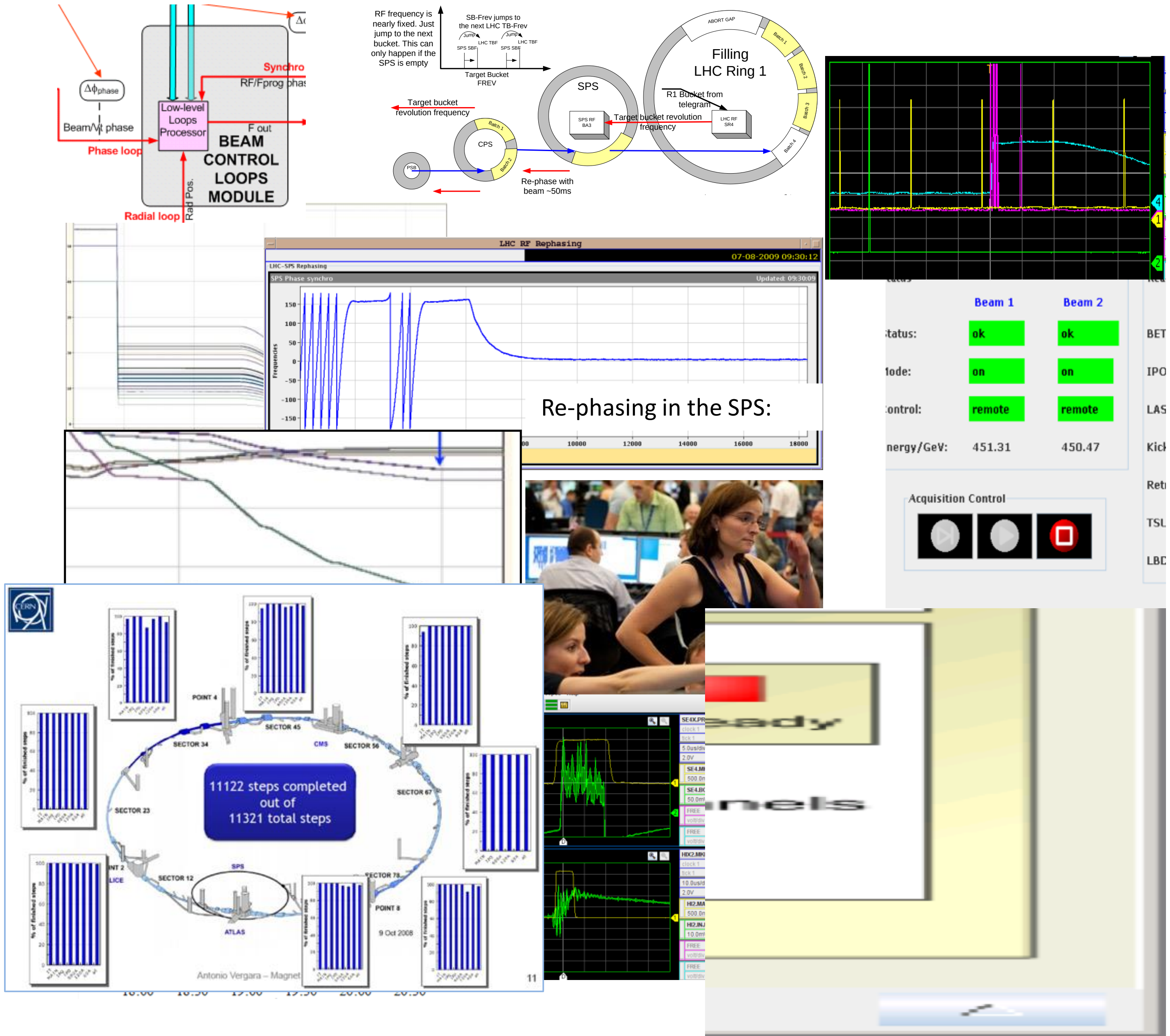


2009!



Preparation:
HWC and machine checkout

- MAGNET CIRCUIT TESTS++
- Transfer lines
- Injection, Extraction
- RF, injection sequence
- Timing System
- Beam Interlock System
- Collimators
- Vacuum
- Interlocks, SIS
- BLMs, BPMs
- BTV, BCT
- Beam dump
- Powering Groups of Circuits
- Magnet model
- Sequencer, alarms
- Controls, logging, DBs
- LSA, optics model, YASP



Design, manufacture and installation

Controls and software

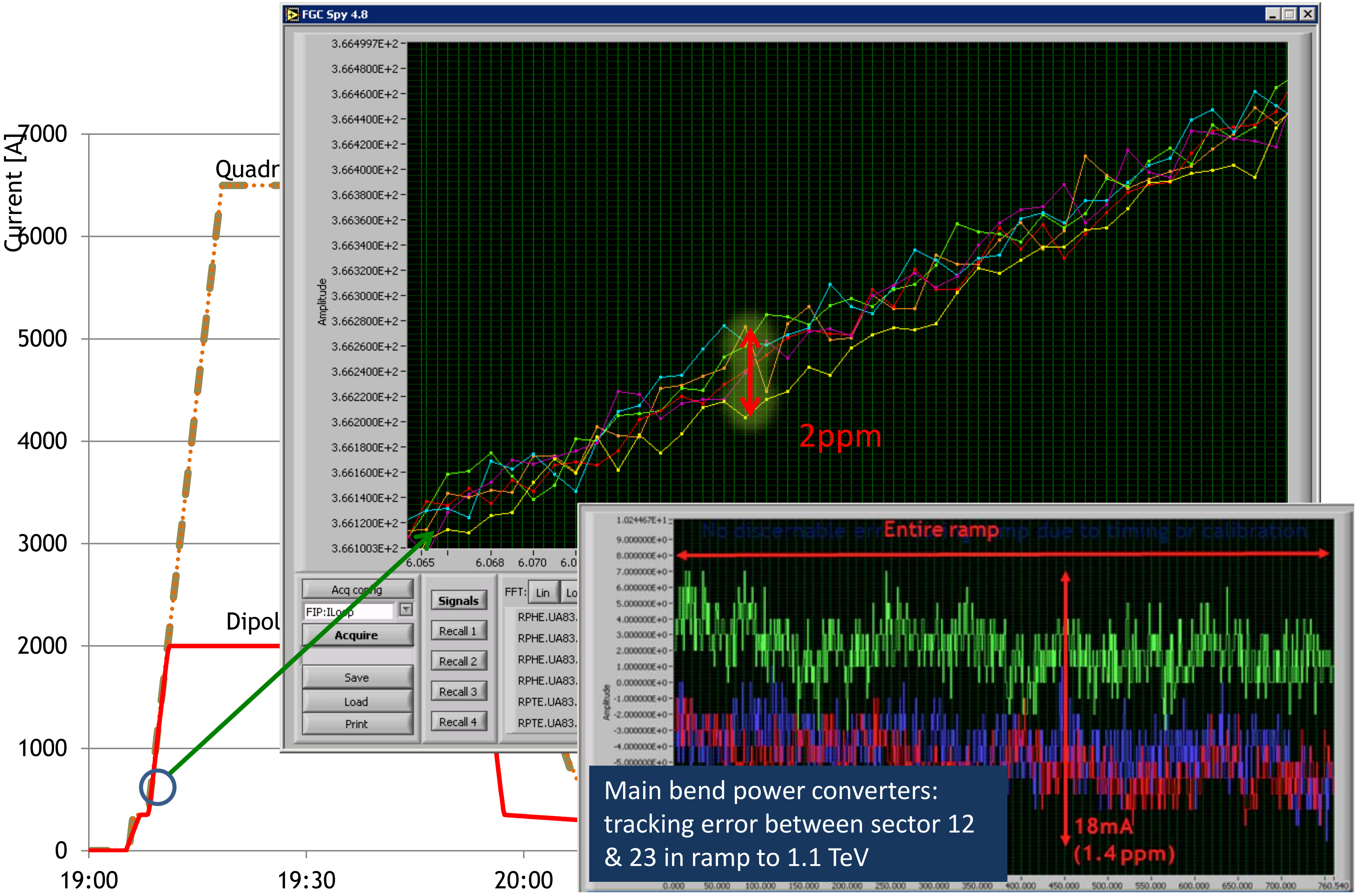
Exploitation

SYSTEMS – A SELECTION

RF, BI, transverse feedback, injection, beam dumps, collimation, powering, **protection…**

Performance can be seriously compromised by a weakness in any one of these.

Tracking between the three main circuits of sector 78



Phenomenal performance from the power converters

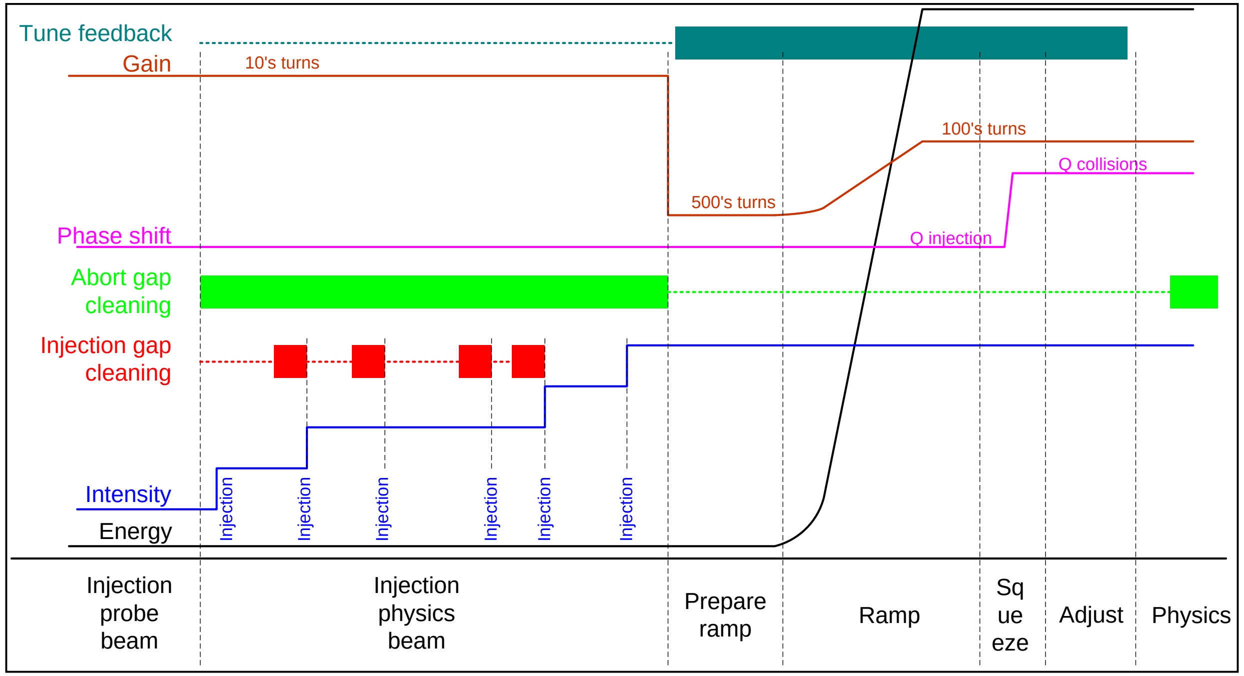
Courtesy Freddy Bordry & Dave Nisbet

Beam dump system – point 6

Video 2’10”

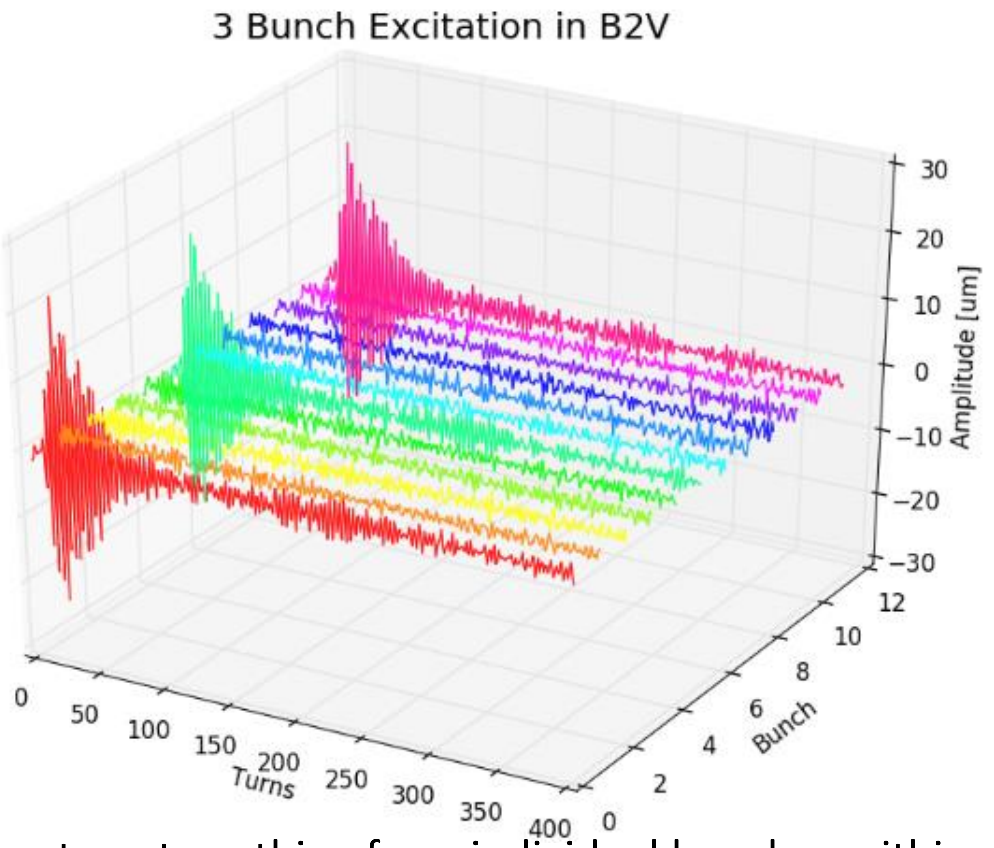
Transverse damper system (ADT)

Vital throughout the cycle



ADTObsBox A very powerful system capable of recording data from the ADT LLRF system gigabit links

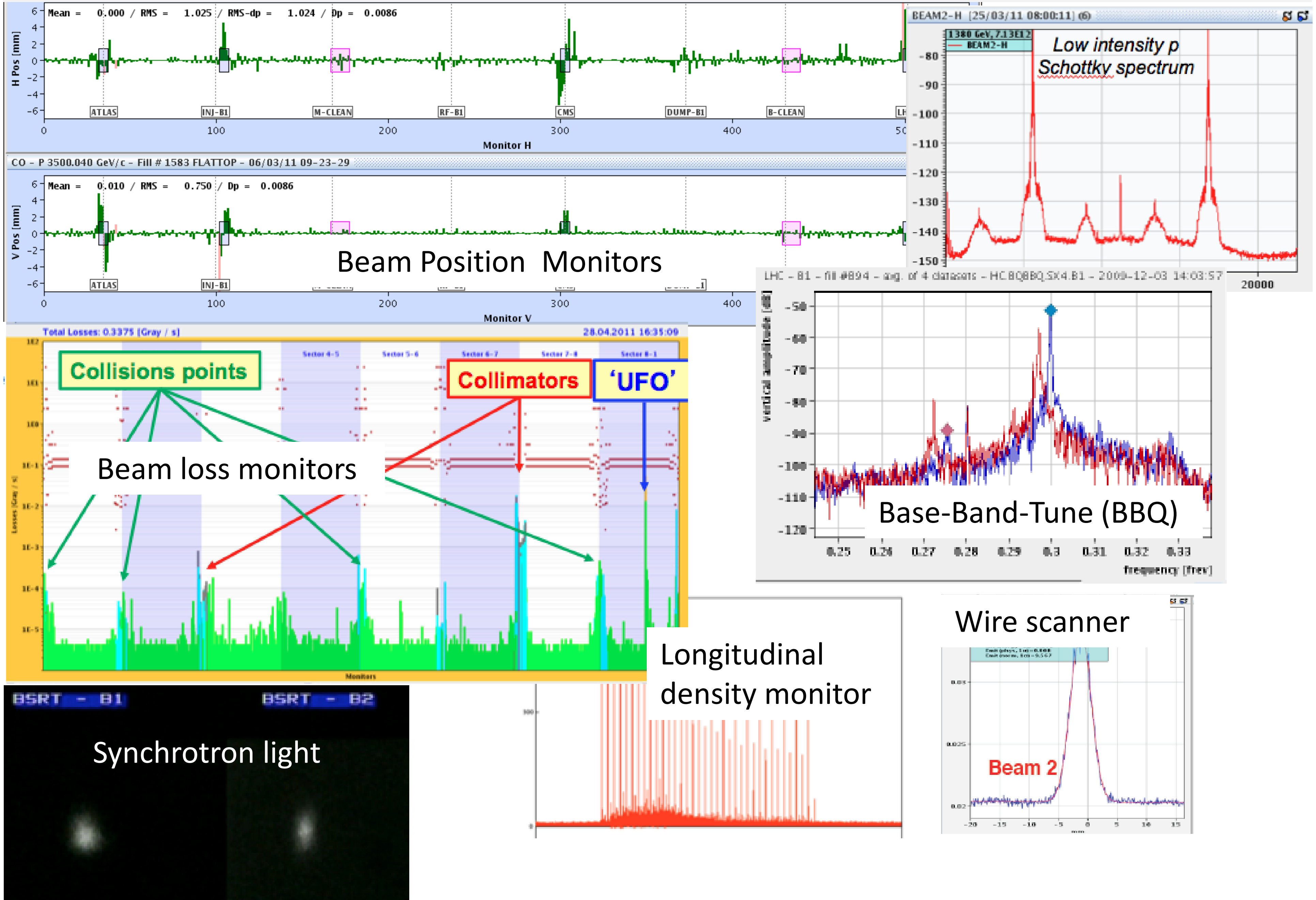
Access to the b-b-b position, all pickups, planes, beams



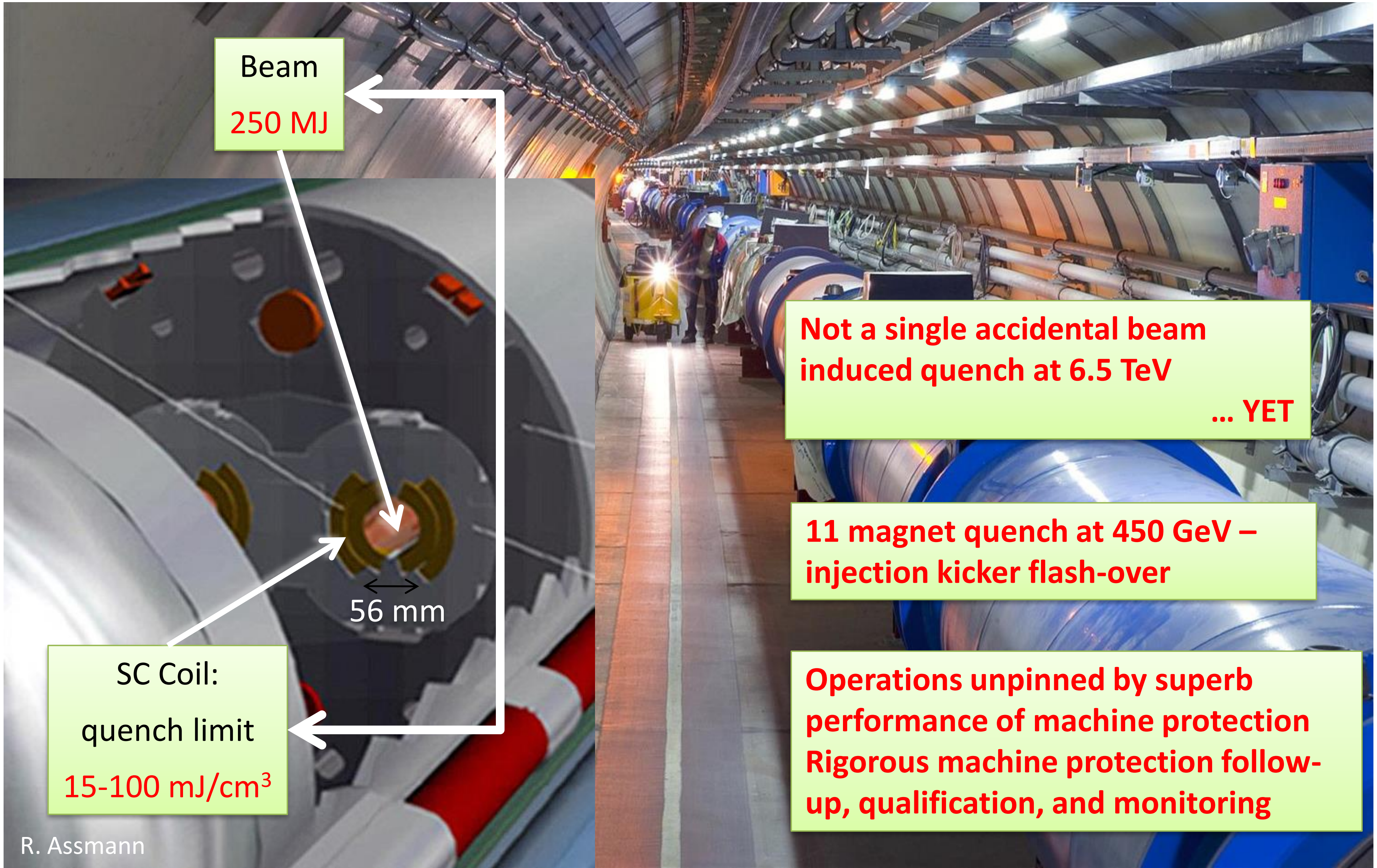
Can target anything from individual bunches within a train to a full beam

Courtesy Wolfgang Hofle & Daniel Valuch

Beam Instrumentation: brilliant – the enabler

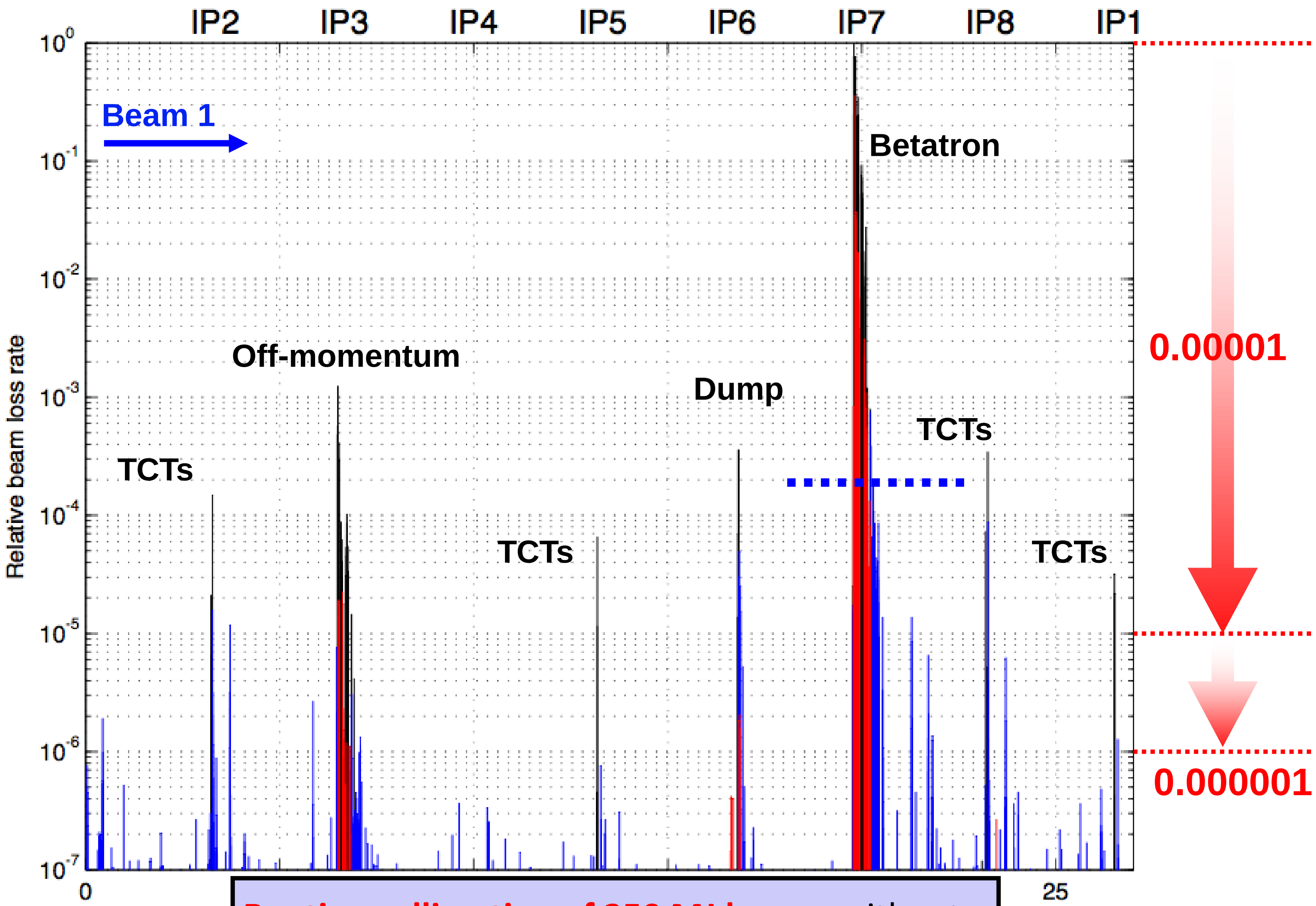


Machine protection



Collimation

Generate higher loss rates: excite beam with transverse dampers



Legend:
Collimators
Cold losses
Warm losses

Routine collimation of 250 MJ beams without a single quench from stored beam

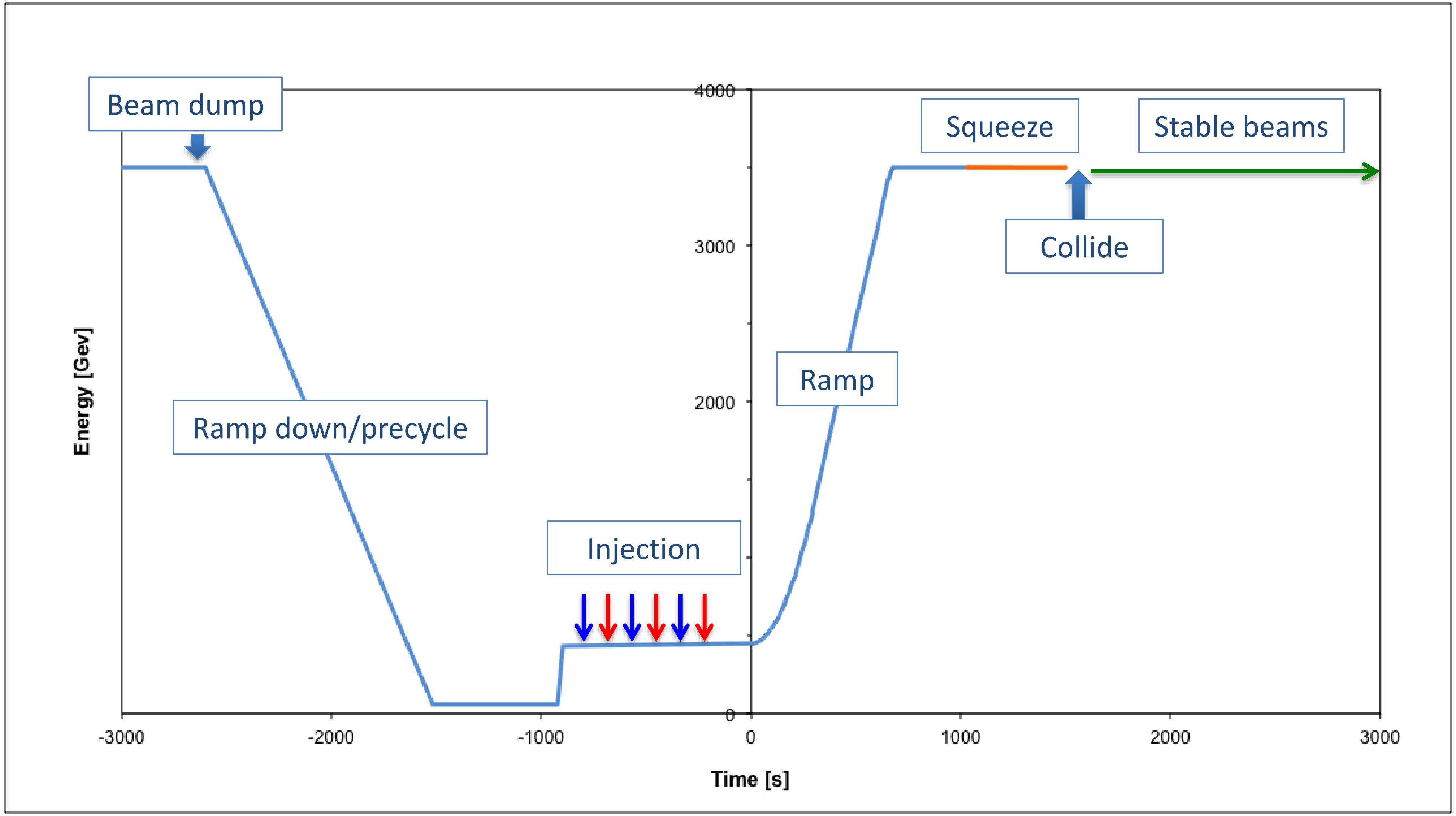
QPS

Make it so they have to give us access to do a reset…

Collimation team ->

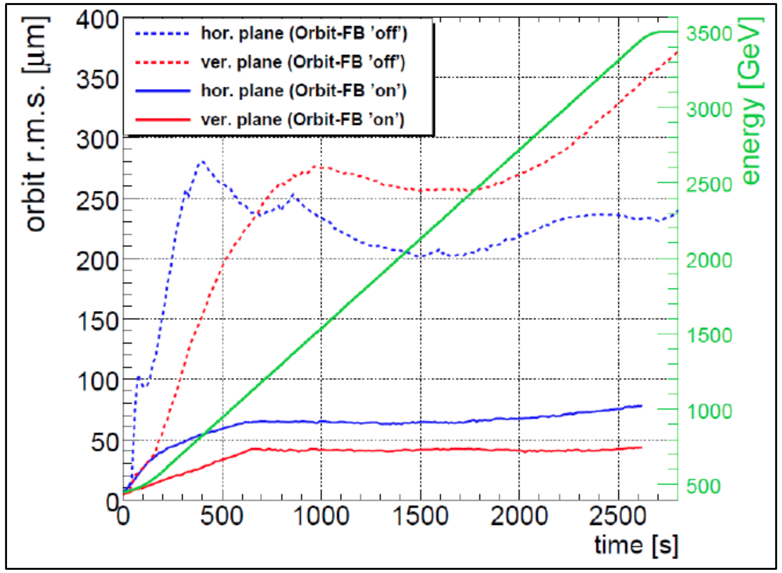
EXPLOITATION - COME TOGETHER

Nail the basics

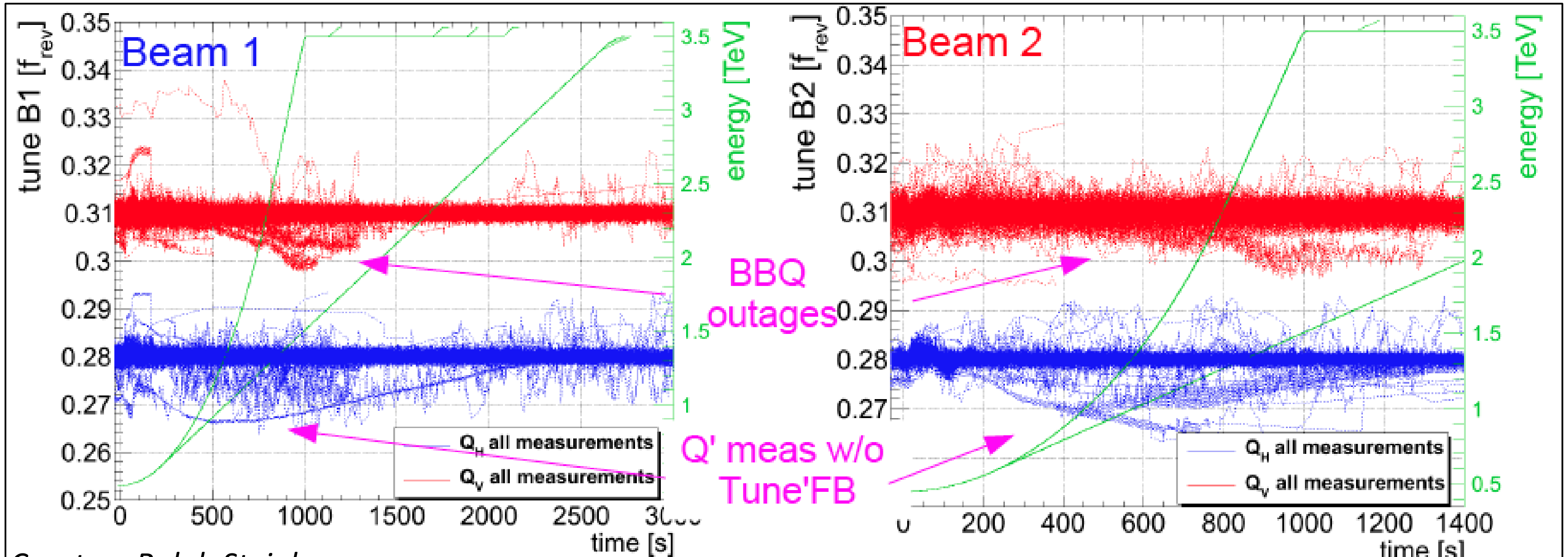


But stay flexible!

Tune and orbit feedback



Mandatory in ramp and squeeze

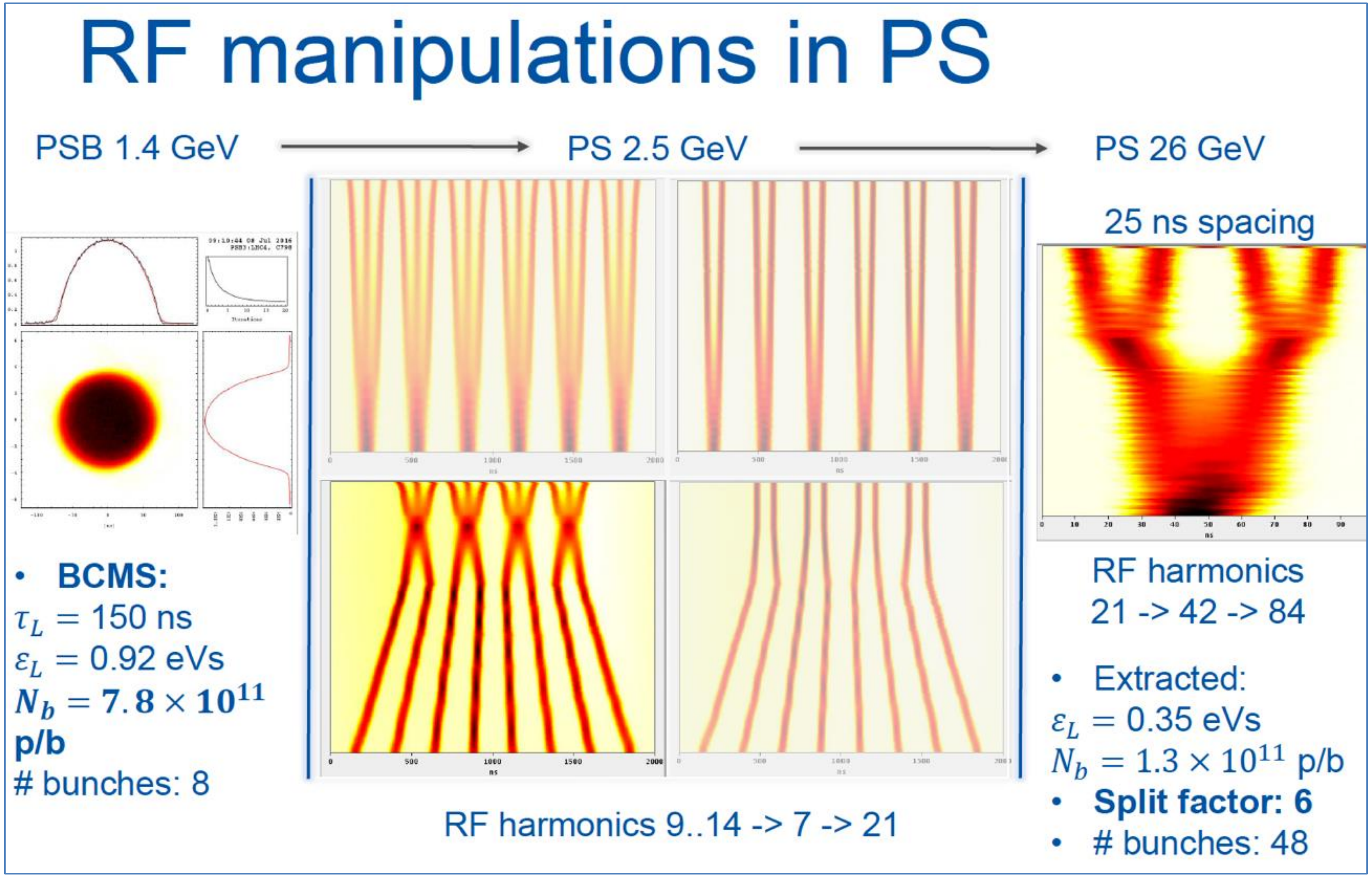


Courtesy Ralph Steinhagen

Get some smart people in to sort the beam out in the injectors

Beam from the injectors

Has been an absolute lifesaver

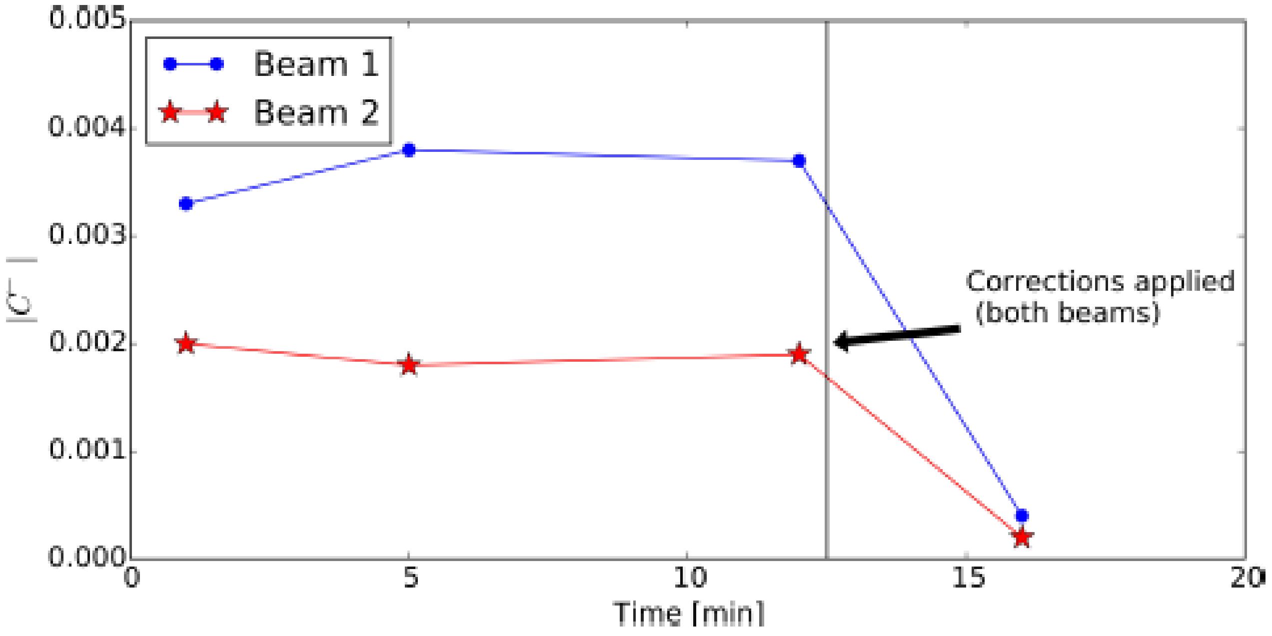


Commissioning was tough this year...

ADT can now drive forced oscillations of individual bunches

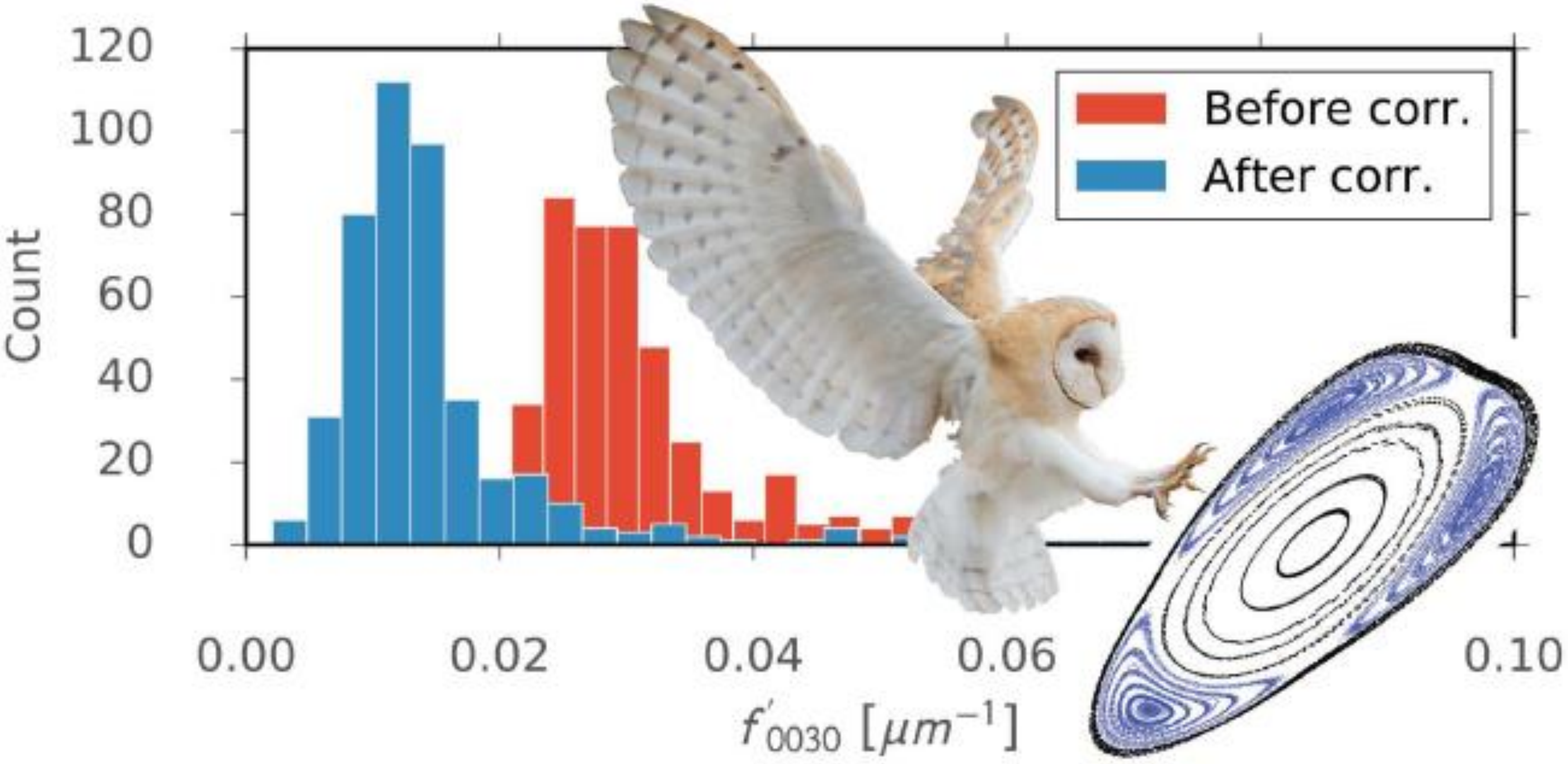
$\longrightarrow$ ADT-AC dipole!

- Used in regular operation $\rightarrow$ **overcome limit of regular AC-dipole**
- Obtain spectral data all around ring $\rightarrow$ **overcome limit of BBQ**
- **Automated OMC methods used to provide online correction for $\Re$e and $\Im$m parts of coupling**

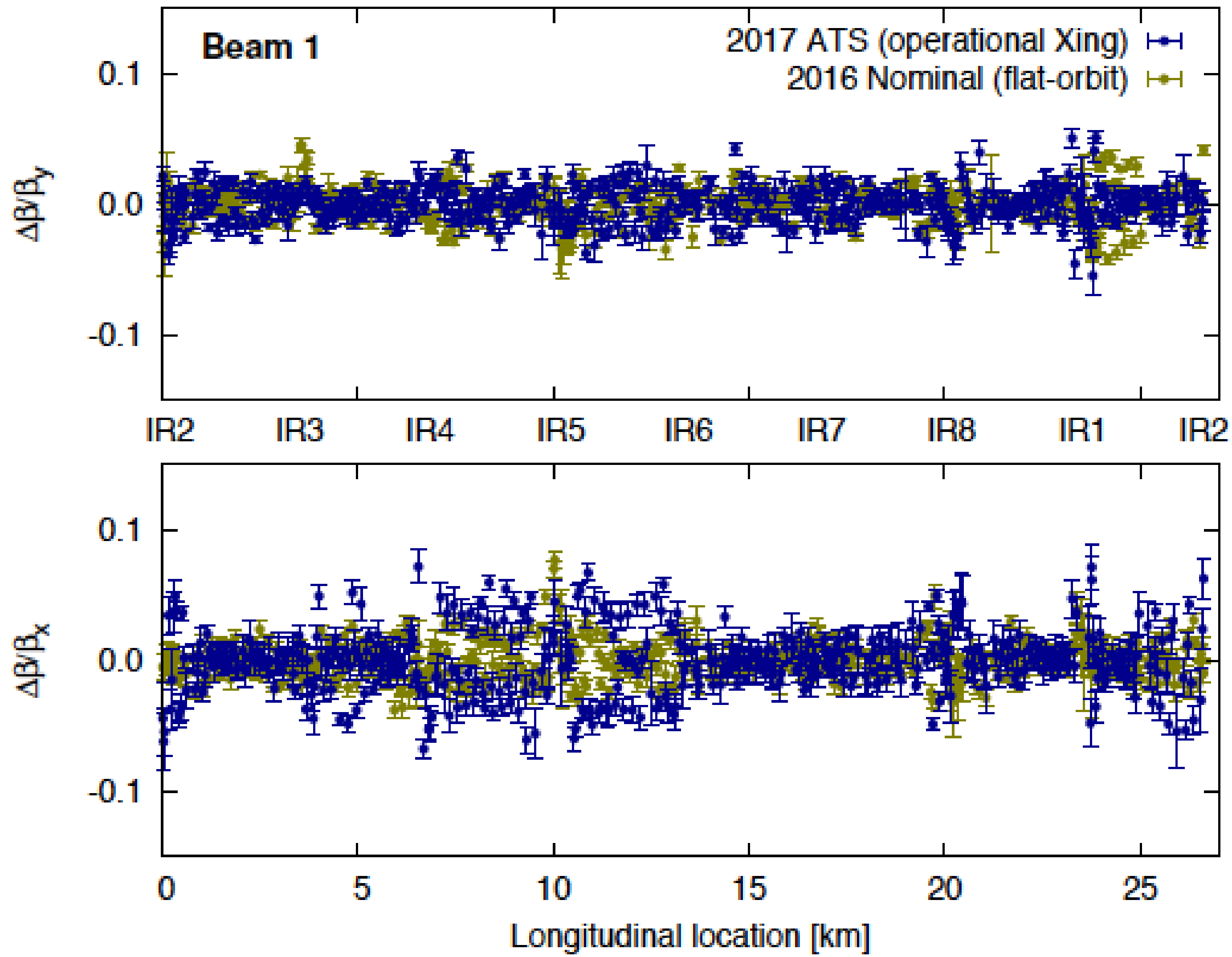


Corrected feed-down to tune in IR1 and IR5

→ **reduced strength of $3Q_y$ resonance**

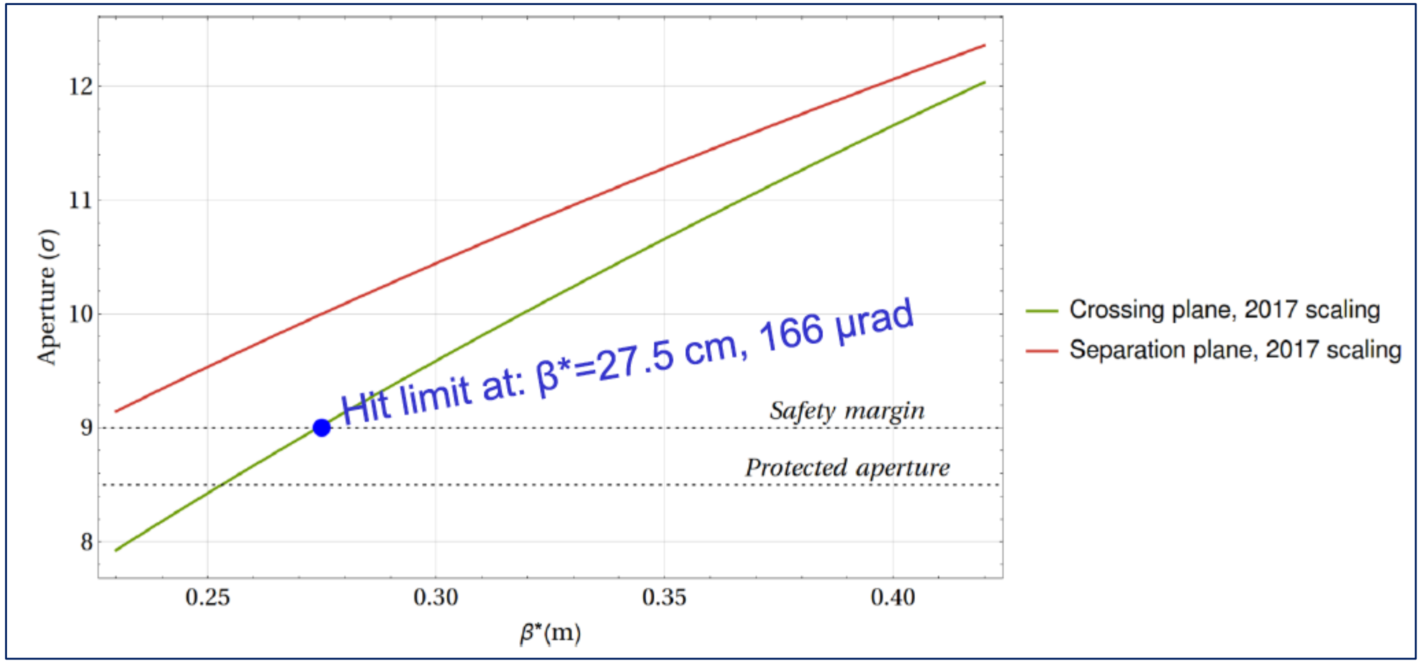


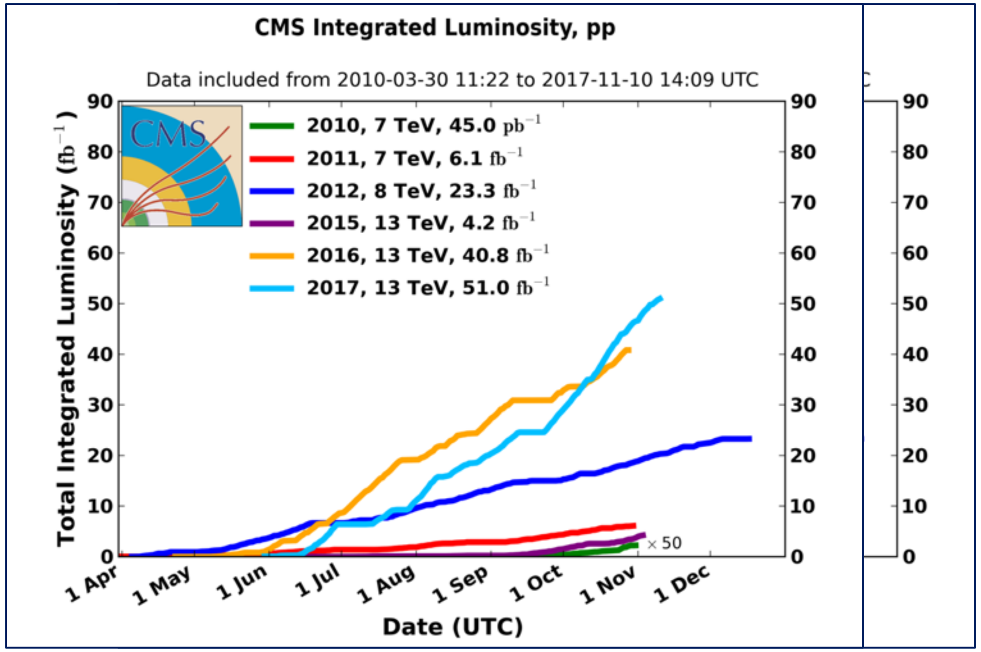
Global correction for nonlinear sources at operation crossing scheme restores comparable optics quality to flat-orbit



Beta* Use Case

- Characterization of collimation system hierarchy, cleaning efficiency, beam loss distribution etc.
- Semi-automatic collimator set-up
- Accurate aperture measurements
- New optics commissioning
  - beating measurement and correction, validation via loss maps etc.

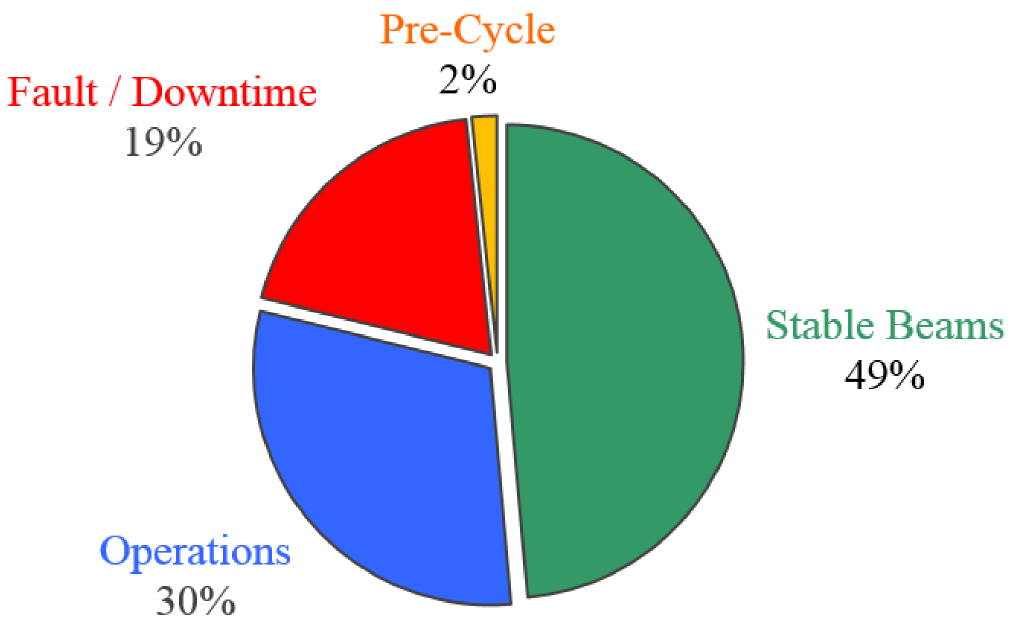




Availability

2017: 140½ days physics ≈ 3362.1 hours

	Duration [h]
Stable Beams	1633.9
Operations	1018.1
Fault/Downtime	652.9
Pre-Cycle	57.2
	= 3362.1



Evident that availability is important -> accurate fault tracking, target weaknesses…

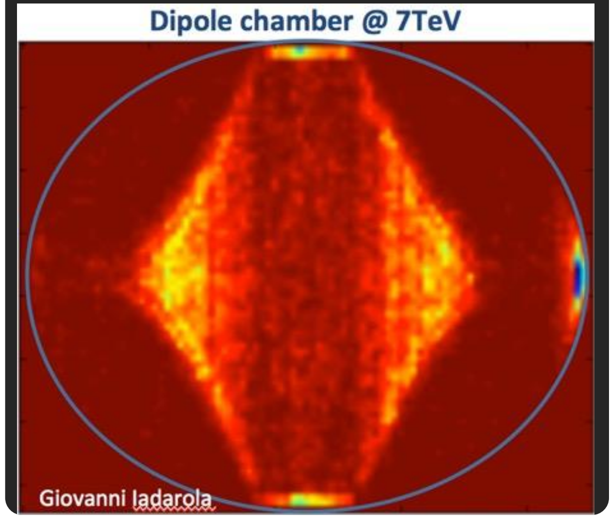
It’s not what happens – it how you react.

STUFF HAPPENS

2015: re-commissioning after LS1

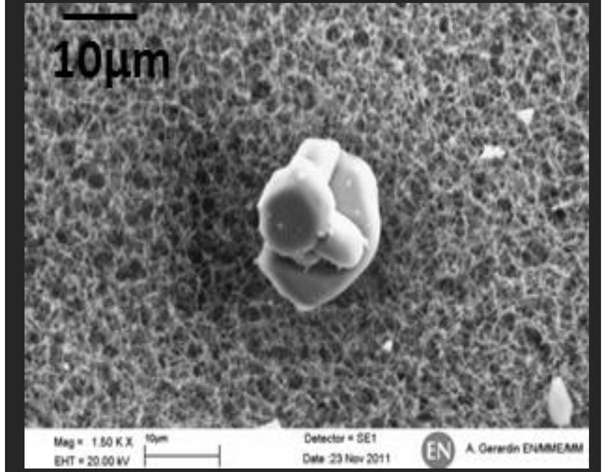
Electron cloud

- Anticipated
- Significant head load to cryogenics
- Very slow reduction despite significant dose



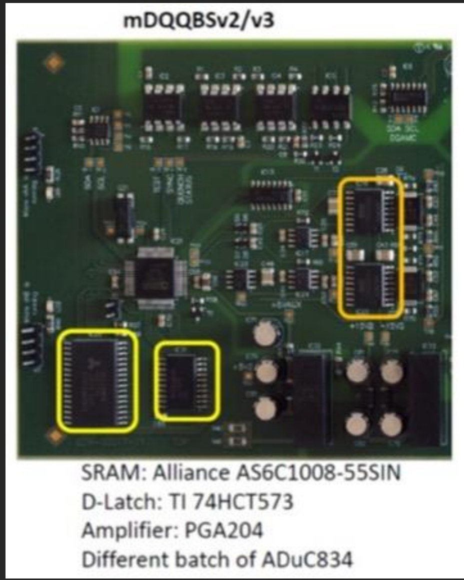
UFOs

- 8 UFO dumps within 2 weeks (Sep 20 to Oct 5)
- Conditioning observed



Radiation to electronics

- Mitigation measures (shielding, relocation…)
- Non-rad hard components used in LS1 upgrade



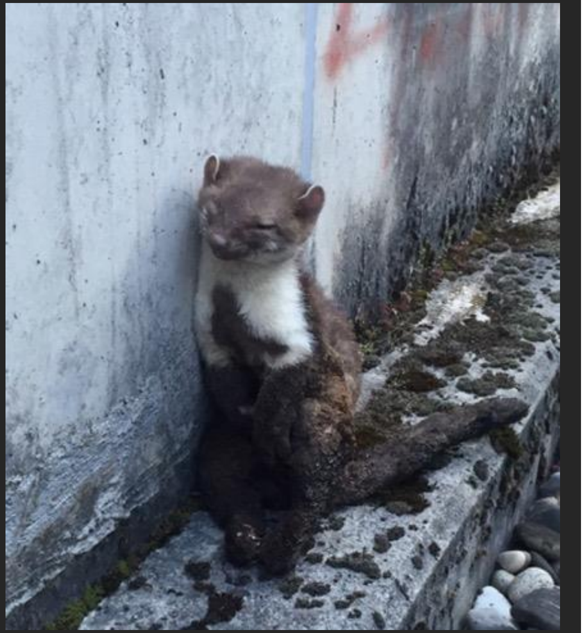
Unidentified lying objects

E-cloud…

1. **Preparation**: tools, monitoring, simulations, understanding, beams (vacuum, cryogenics, RF, injectors, ABP, OP)
2. **Scrubbing** - execution
3. **Exploitation** given the limits (heat-load, instabilities…)

Problems, problems, problems…

WEASELS



PS MAIN POWER SUPPLY

SPS BEAM DUMP

- Limited to 96 bunches per injection
- 2220 bunches per beam cf. 2750

Heaven and high water is moved in response

CONCLUDING REMARKS

Foundations

- Excellent foundations (key components, systems)
  - Underpin everything that follows
  - Lacunae in quality control rapidly exposed…
  - Testing CERN's impressive ability to tackle problems

- Coupled with system expertise and experience
  - Continuity, compartmentalization (but groups cover the complex)
  - Experience from LEP/Injectors stretching back generations

System performance

- RF, power converters, collimators, beam dumps, injection, magnets, vacuum, transverse feedback, machine protection
- Magnets, magnet protection & associated systems
- Beam instrumentation and beam based feedbacks
- Controls, databases, high level software
- Cryogenics, survey, technical infrastructure, access, radiation protection

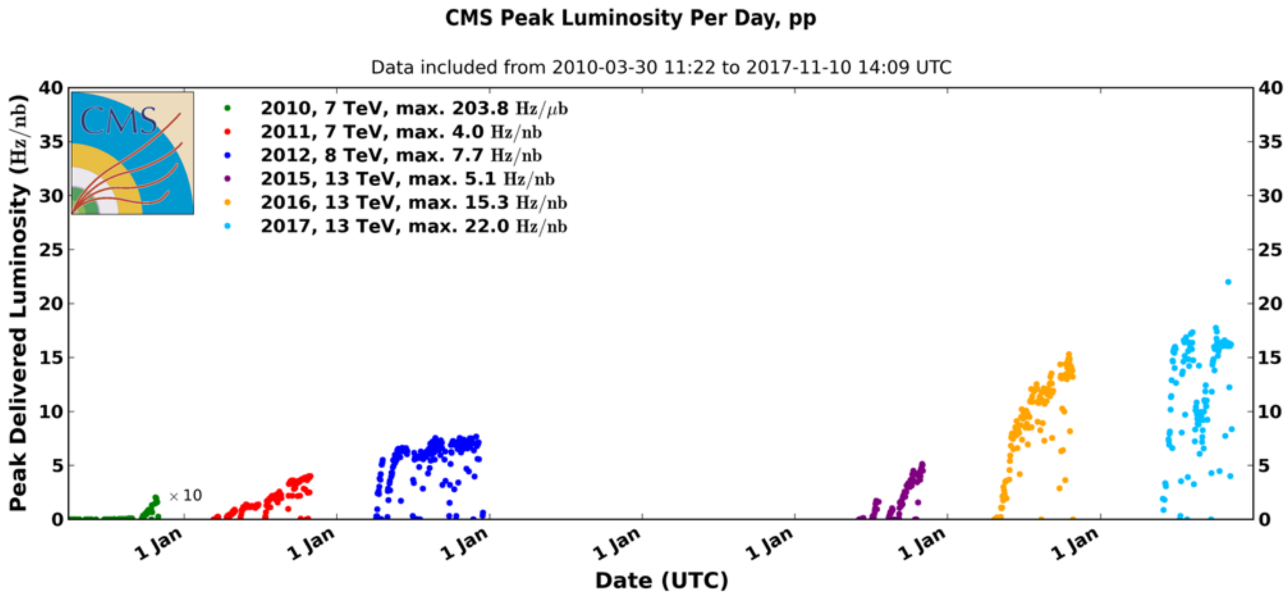
Impossible to do justice to the commitment and effort that's gone in to getting, and keeping, the complex operational

Exploitation 1/2

- Controls/software & instrumentation!
- Deep preparation, staged deployment, milestones
- Nail the operational basics
- Develop, and keep developing, understanding & tools
- Reproducibility
- Availability

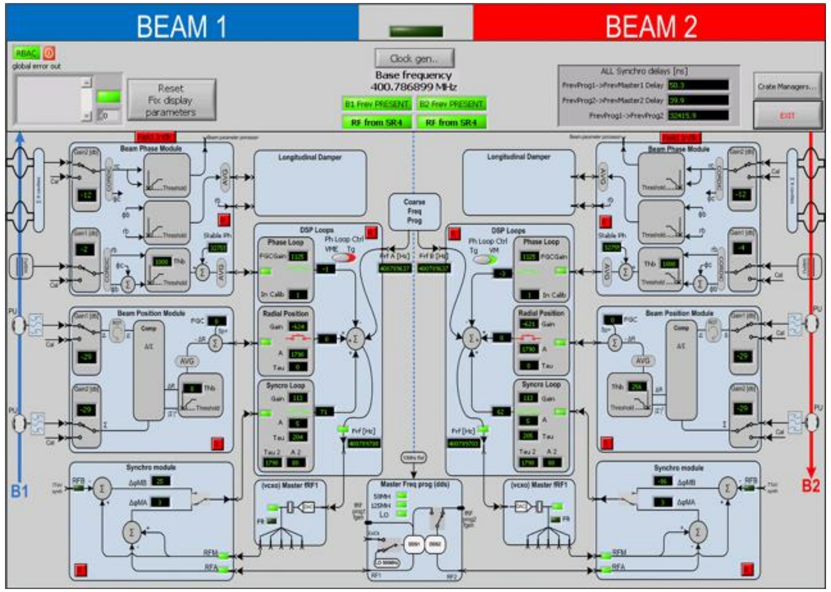
Exploitation 2/2

- Huge body of accelerator physics knowledge has been built up
  - instabilities, beam-beam, DA, non-linear, optics, longitudinal…
  - Electron cloud, UFOs, air leak into beam vacuum (16L2)…
- And applied to performance…
  - beta*, levelling, bunch configuration, beam stability, optics…

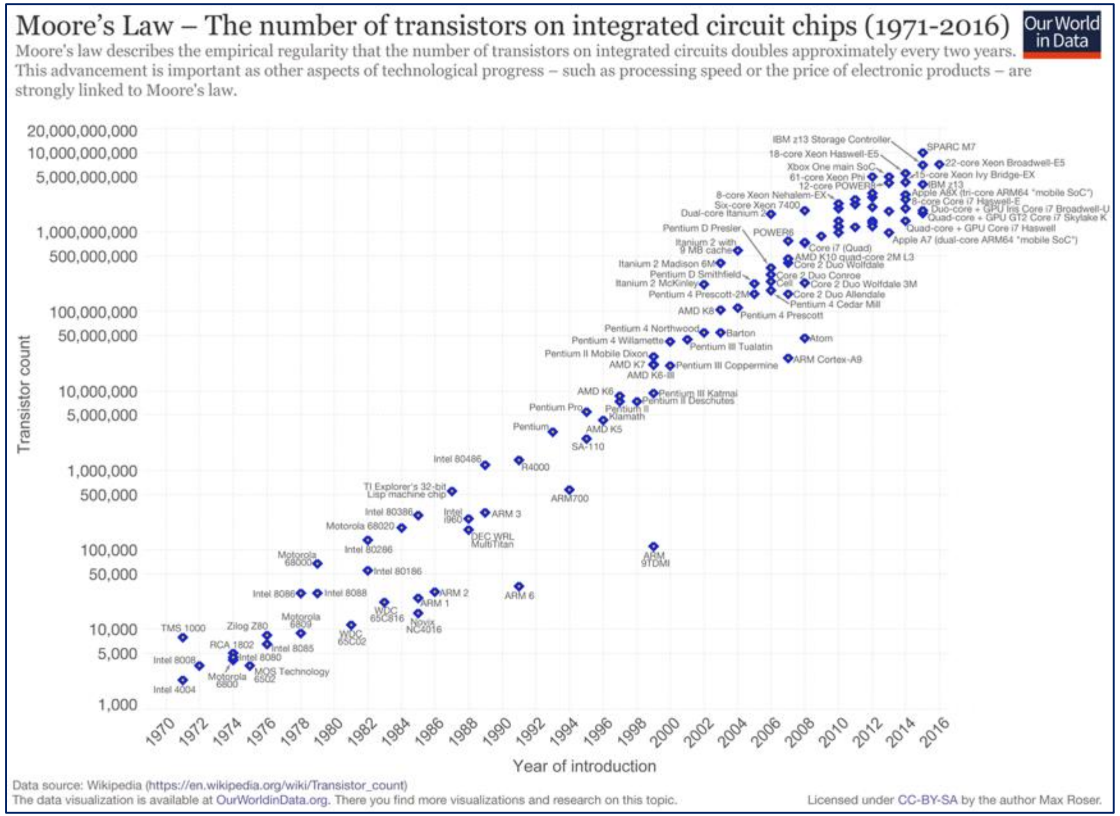


Technology

- **In a very different place now – and it's just as well**
- Profound impact on the functionality that is offered
- Embrace it, get in people who know what they doing
- Don't rely on the old guard!



- FPGAs, DSP…
- Processing power
- Network capacity and speed
- Data storage
- Language, tools, methods



Inclusive Culture

How do you help ensure that sort of commitment?

- Projects/teams setup as required – responsibility given, initiative seized
- Daily morning meetings – open to all
- Open committees, low on ceremony
- Chamonix/Evian workshops
- Cut loose smart young motivated people and give them support
- Vigorous machine development program
- **Resources (fortunately)**
- A sense of humour appears to help

PERSONAL COMPETANCIES

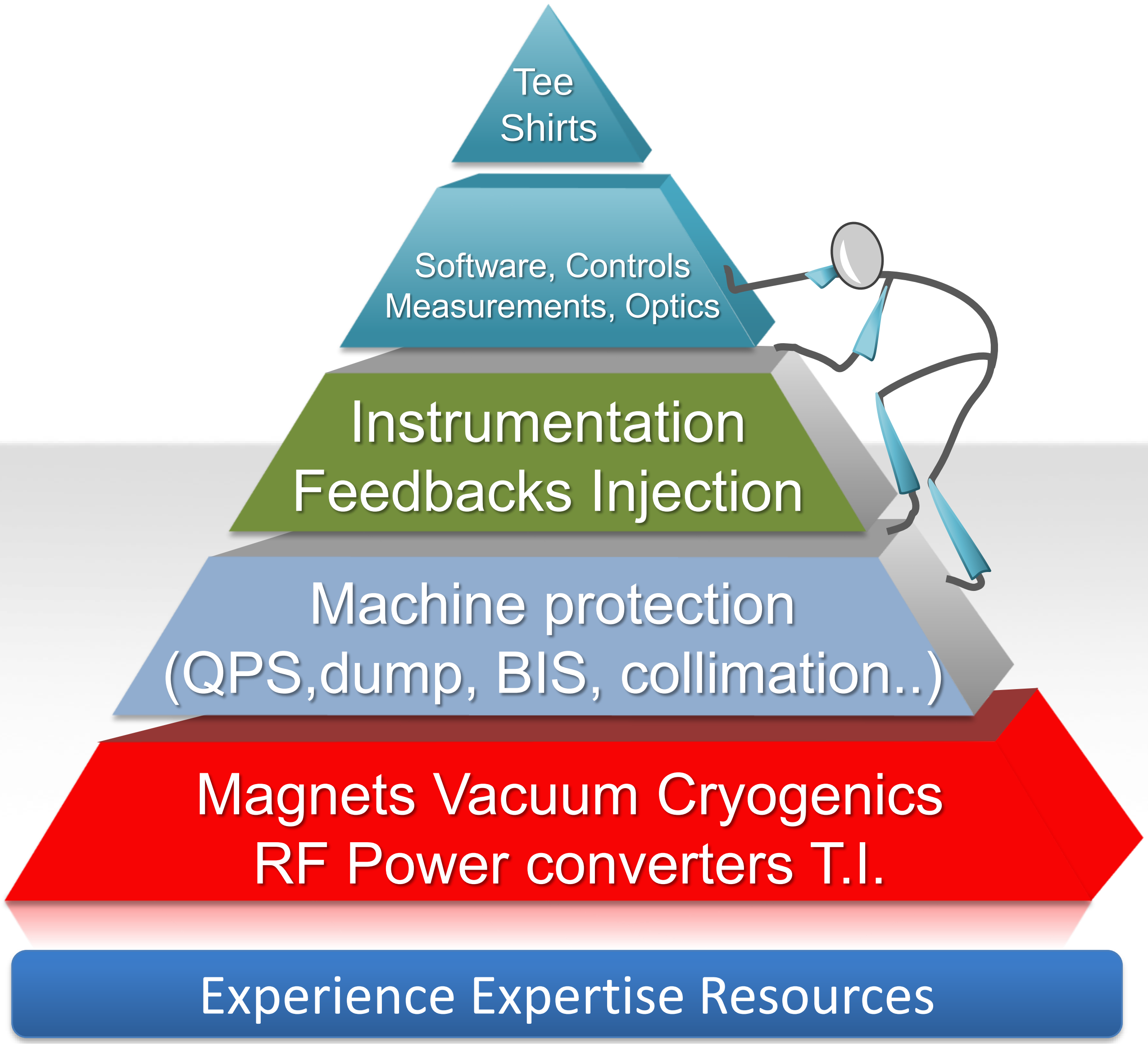
Leadership

Ability to relax

Teamwork

”One of the ways of differentiating a good-enough organization from one that is pathological is through its ability to exclude narcissistic characters from key posts."

Maslow's Hierarchy of Needs



We delivered 5.6 fb^{-1} to Atlas in 2011 and all we got was a blooming tee shirt

Last slide

- Occasionally I go into the LHC tunnel
- and ask myself how do we manage to get this to work…?
- You tell me!

To the entire LHC team

Congratulations and all our thanks for this splendid achievement !

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