LHC: A New Frontier

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Fermilab

Google welcome screen from September 10, 2008

Acknowledgements

- Janet Conrad, for inviting me
- The authors of all of the talks I've plagiarized, particularly those presented the annual "LHC Performance Workshops", held in Chamonix, France
  - http://tinyurl.com/Chamonix2009
  - http://tinyurl.com/Chamonix2010
- PowerPoint, for letting me recycle stuff from my old talks
- Google, without which nothing would be possible
- You, for listening

Outline

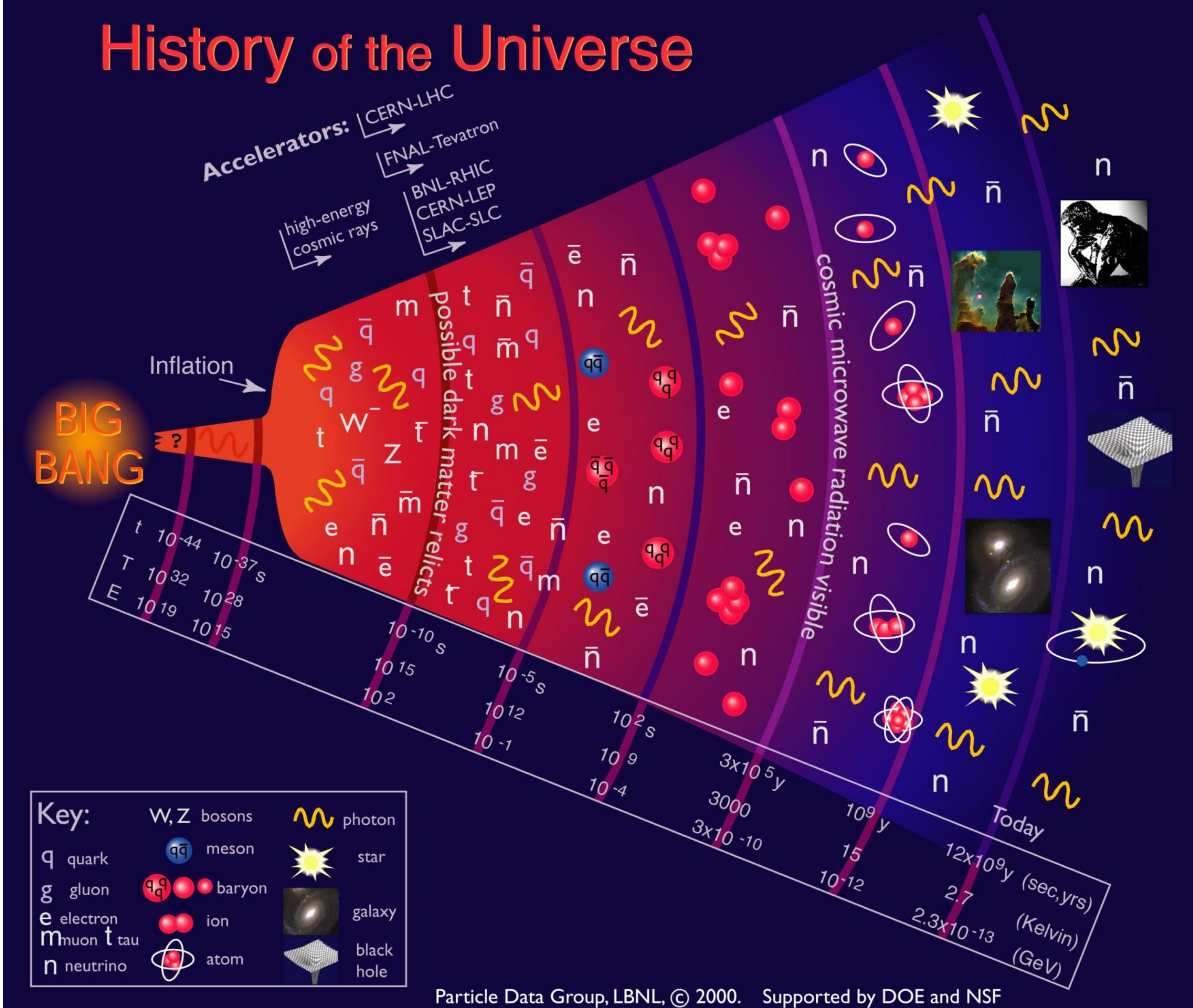
- The road to the LHC
- Fun facts about superconducting magnets
- LHC commissioning
- The "incident" of September 19th, 2008
- The repairs
- Current Status
- The future

It's all about energy and collision rate

- To probe smaller scales, we must go to higher energy

$$\lambda = \frac{h}{p} \approx \frac{(1.2\ \text{fm})}{p\ (\text{in GeV/c})}$$

- To discover new particles, we need enough energy available to create them
  - The Higgs particle, the last piece of the Standard Model probably has a mass of about 150 GeV, *just at the limit* of the Fermilab Tevatron
  - Many theories beyond the Standard Model, such as SuperSymmetry, predict a "zoo" of particles in the range of a few hundred GeV to a few TeV
  - Of course, we also hope for surprises.
- The rarer a process is, the more collisions (luminosity) we need to observe it.



Accelerators allow us to probe down to a few picoseconds after the Big Bang

The Case for Colliding Beams

- For a relativistic beam hitting a fixed target, the center of mass energy is:

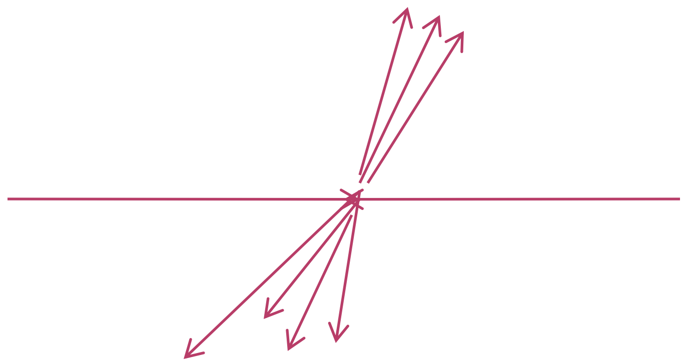
$$E_{\text{CM}} = \sqrt{2E_{\text{beam}} m_{\text{target}} c^2}$$

- On the other hand, for colliding beams (of equal mass and energy):

$$E_{\text{CM}} = 2E_{\text{beam}}$$

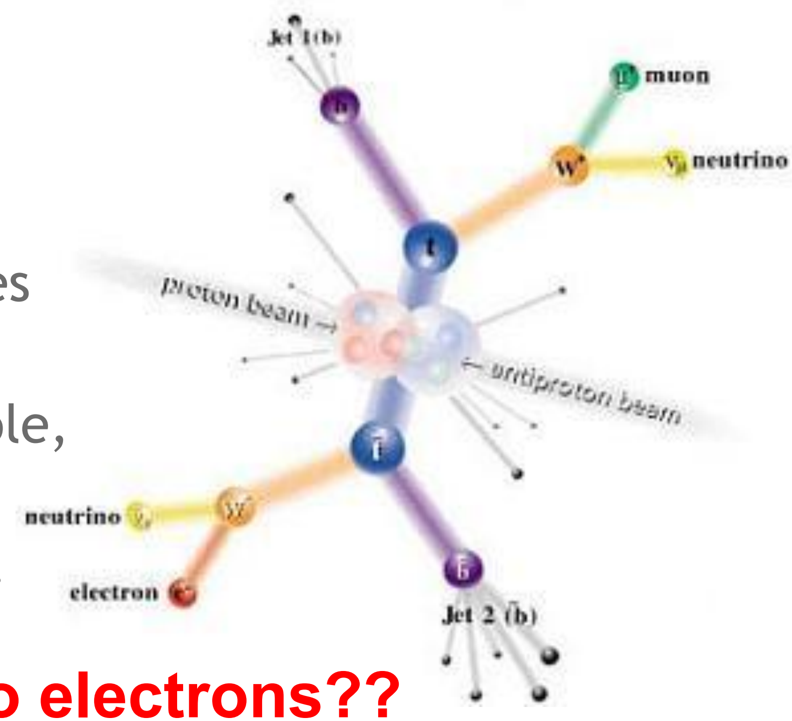
- To get the 14 TeV CM design energy of the LHC with a single beam on a fixed target would require that beam to have an energy of 100,000 TeV!
  - *Would require a ring 10 times the diameter of the Earth!!*

Electrons (leptons) vs. Protons (hadrons)



- Electrons are point-like
  - Well-defined initial state
  - Full energy available to interaction
  - Can calculate from first principles
  - Can use energy/momentum conservation to find "invisible" particles.

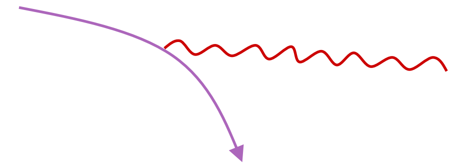
- Protons are made of quarks and gluons
  - Interaction take place between these consituents.
  - At high energies, virtual "sea" particles dominate
  - Only a small fraction of energy available, not well-defined.
  - Rest of particle fragments -> big mess!



So why don't we stick to electrons??

Synchrotron Radiation: a blessing and a curse

As the trajectory of a charged particle is deflected, it emits "synchrotron radiation"



Radius of curvature

$$P = \frac{1}{6\pi\varepsilon_0}\frac{e^2 c}{\rho^2}\left(\frac{E}{m}\right)^4$$

An electron will radiate about *10^{13} times more power* than a proton of the same energy!!!!

- **Protons:** Synchrotron radiation does not affect kinematics very much
- **Electrons:** Beyond a few MeV, synchrotron radiation becomes very important, and by a few GeV, it dominates kinematics
  - Good Effects:
    - Naturally "cools" beam in all dimensions
    - Basis for light sources, FEL's, etc.
  - Bad Effects:
    - Beam pipe heating
    - Exacerbates beam-beam effects
    - **Energy loss ultimately limits circular accelerators**

Practical consequences of synchrotron radiation

- Proton accelerators
  - Synchrotron radiation not an issue to first order
  - Energy limited by the maximum feasible size and magnetic field.
- Electron accelerators
  - Recall

$$P \propto \frac{1}{\rho^2}\left(\frac{E}{m}\right)^4 \propto \left(\frac{B}{E}\right)^2\left(\frac{E}{m}\right)^4$$

  - To keep power loss constant, radius must go up as the *square* of the energy ($B \propto 1/E \Rightarrow$ weak magnets, BIG rings):
    - The LHC tunnel was built for LEP, and e^+e^- collider which used the 27 km tunnel to contain 100 GeV beams (1/70th of the LHC energy!!)
    - Beyond LEP energy, circular synchrotrons have no advantage for e^+e^-
      - -> International Linear Collider (but that's another talk)
- What about muons?
  - Point-like, but heavier than electrons
  - That's another talk, too…

Proton-Proton vs. Proton-antiproton

- Beyond a few hundred GeV, most interactions take place between gluons and/or virtual "sea" quarks.
  - No real difference between proton-antiproton and proton-proton
- Because of the symmetry properties of the magnetic field, a particle going in one direction will behave exactly the same as an antiparticle going in the other direction
  - Can put protons and antiprotons in the same ring
    - That's how the SppS and the Tevatron work
- The problem is that antiprotons are hard to make
  - Can get ~2 positrons for every electron on a production target
  - Can only get about *1 antiproton for every 50,000 protons* on target!
  - Takes a day to make enough antiprotons for a "store" in the Fermilab Tevatron
  - Ultimately, the luminosity is limited by the antiproton current.
- Thus, the LHC was designed as a proton-proton collider.

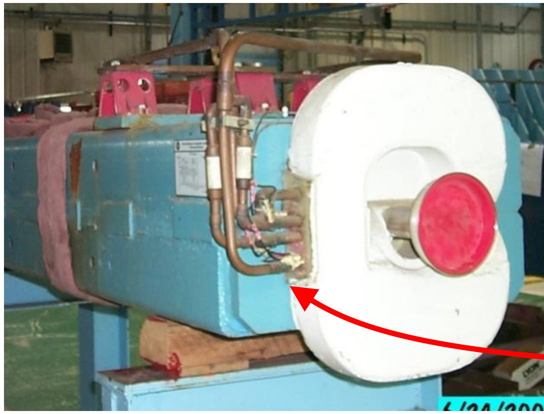
Superconducting magnets

- For a proton accelerator, we want the most powerful magnets we can get
- Conventional electromagnets are limited by the resistivity of the conductor (usually copper)

Power lost → $$P = I^2 R \propto B^2$$ ← Square of the field

- The field of high duty factor conventional magnets is limited to about 1 Tesla
  - An LHC made out of such magnets would be 40 miles in diameter – approximately the size of Rhode Island.
- The highest energy accelerators are only possible because of superconducting magnet technology.

Issues with superconducting magnets

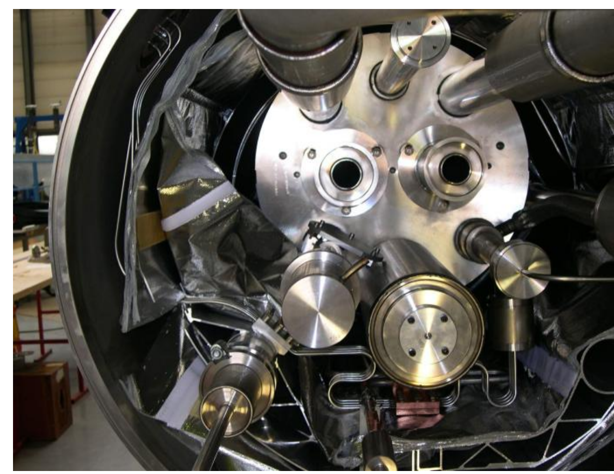


- Conventional magnets operate at room temperature. The cooling required to dissipate heat is usually provided by fairly simple low conductivity water (LCW) heat exchange systems.

- Superconducting magnets must be immersed in liquid (or superfluid) He, which requires complex infrastructure and cryostats
- Any magnet represents stored energy

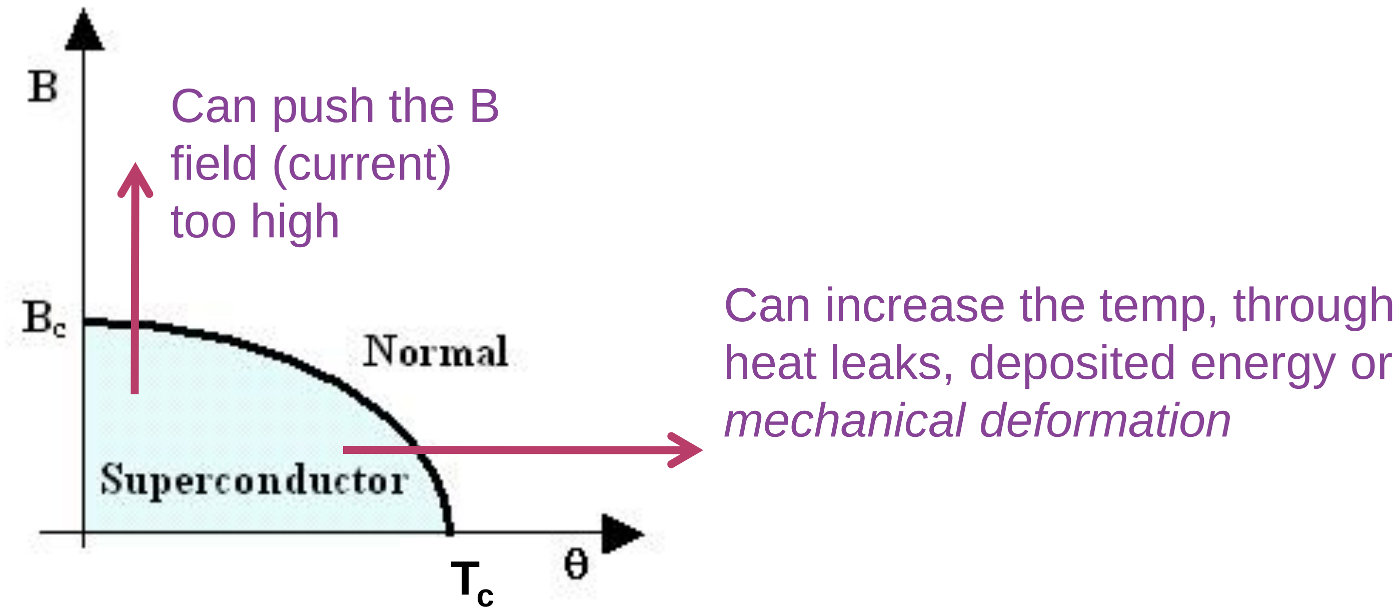
$$E = \frac{1}{2} L I^2 = \frac{1}{2\mu} \int B^2 dV$$

  - In a conventional magnet, this is dissipated during operation.
  - In a superconducting magnet, you have to worry about where it goes, *particularly when something goes wrong*.



When is a superconductor not a superconductor?

- Superconductor can change phase back to normal conductor by crossing the "critical surface"



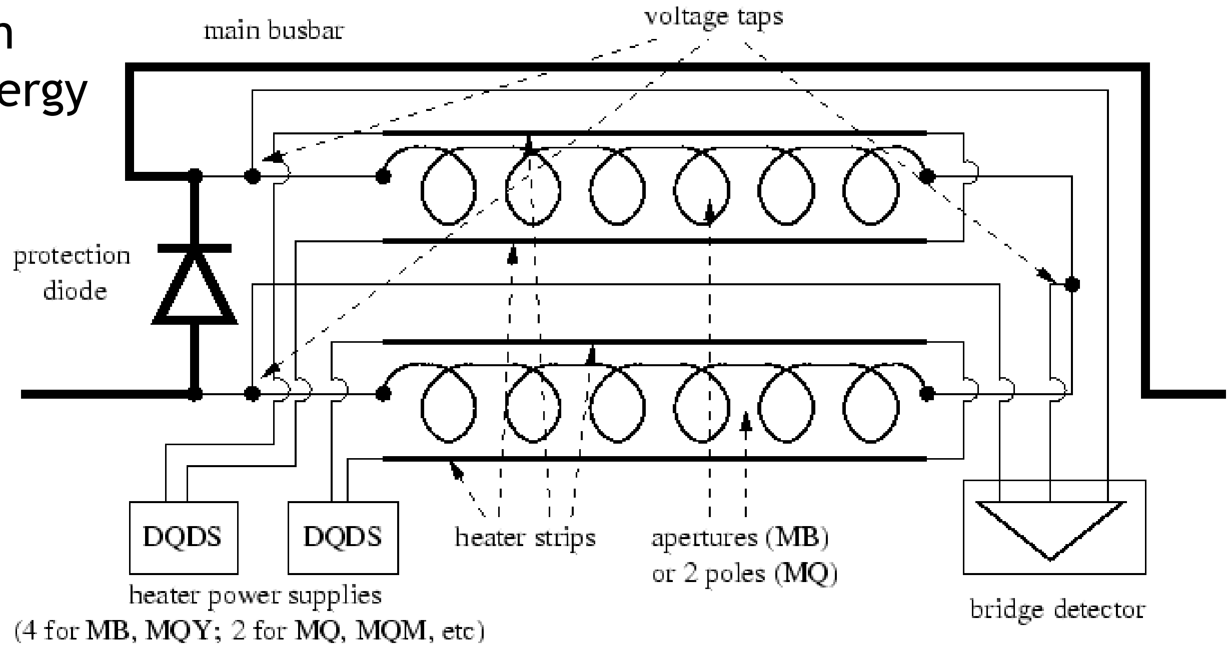
- When this happens, the conductor heats quickly, causing the surrounding conductor to go normal and dumping lots of heat into the liquid Helium
- This is known as a "quench".

Quench example: MRI magnet*

*pulled off the web. We recover our Helium.

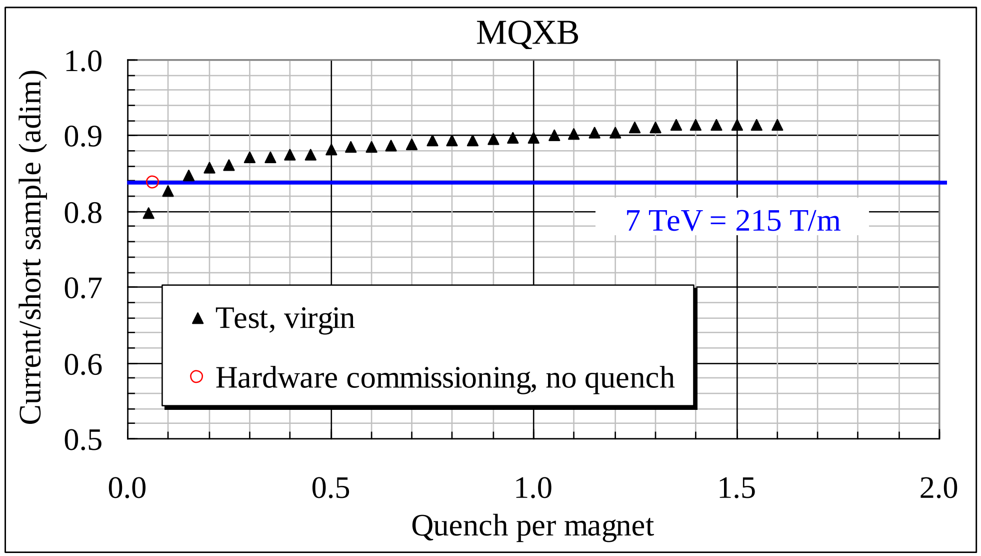
Quench protection

- Small magnets can be designed to absorb the energy of a quench without causing permanent damage, but building magnets this robust is very expensive on a large scale.
- Accelerator magnets are designed to detect a quench via a resistive voltage drop, and then fire *heaters* in the surrounding superconductor to drive it normally conducting and thereby distribute the energy loss.
- Additional circuits can be used to extract energy as the magnet goes normal:
- Quench protection is one of the most challenging parts of superconducting accelerator design.



Magnet "training"

- As new superconducting magnets are ramped, electromechanical forces on the conductors can cause small motions.
- The resulting frictional heating can result in a quench
- Generally, this "seats" the conductor better, and subsequent quenches occur at a higher current.
- This process is knows as "training"



- Some of the LHC magnets have "forgotten" some of their training, which will limit the initial operation of the LHC to 5 TeV rather than 7.

Milestones on the road to a superconducting collider

- 1911 – superconductivity discovered by Heike Kamerlingh Onnes
- 1957 – superconductivity explained by Bardeen, Cooper, and Schrieffer
  - 1972 Nobel Prize (the second for Bardeen!)
- 1962 – First commercially available superconducting wire
  - NbTi, the "industry standard" since
- 1978 – Construction began on ISABELLE, first superconducting collider (200 GeV+200 GeV) at Brookhaven.
  - 1983, project cancelled due to design problems, budget overruns, and competition from…
- 1978 – Work begins in earnest on the Fermilab Tevatron, a 1 TeV+1 TeV collider in the Fermilab Main Ring tunnel
  - Breaks energy record in 1983
  - First collisions in 1985
  - ~~Most powerful collider~~ in the world since then (980 GeV+980 GeV)

until now

Fermilab: Utopia on the prairie

History

- 1968 – Construction begins.
- 1972 – First 200 GeV beam in the Main Ring.
- 1983 – First (512 GeV) beam in the Tevatron ("Energy Doubler"). Old Main Ring serves as "injector".
- 1985 – First proton-antiproton collisions observed at CDF (1.6 TeV CoM). Most powerful accelerator in the world since them
- 1995 – Top quark discovery. End of Run I.
- 1999 – Main Injector complete.
- 2001 – Run II begins.
- 2009 – 5 pb^{-1}/experiment

The road to higher energy

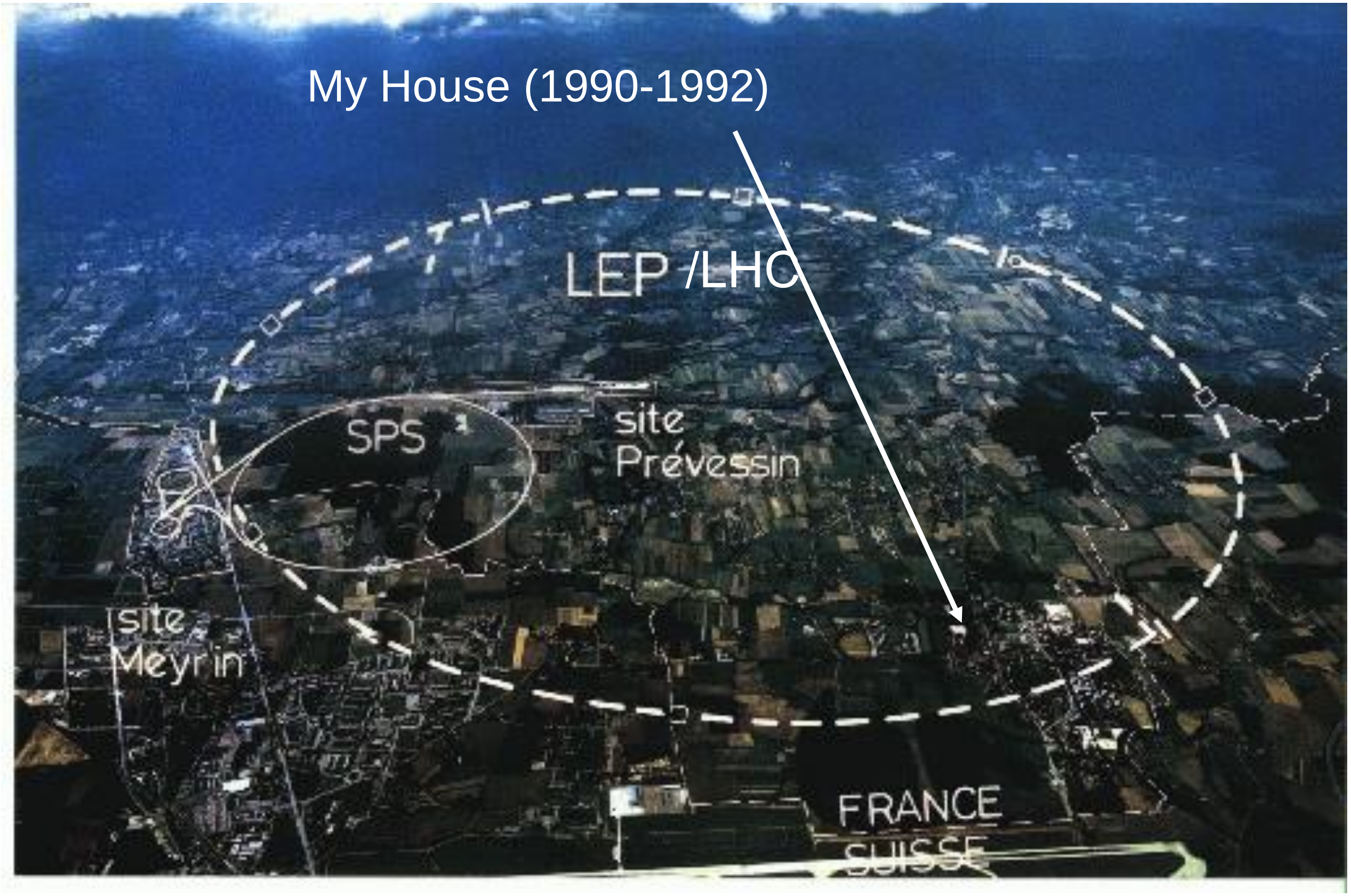
- 1980's - US begins planning in earnest for a 20 TeV+20 TeV "Superconducting Super Collider" or (SSC).
  - 87 km in circumference!
  - Considered superior to the "Large Hadron Collider" (LHC) then being proposed by CERN.
- 1987 – site chosen near Dallas, TX
- 1989 – construction begins
- 1993 – amidst cost overruns and the end of the Cold War, the SSC is cancelled after 17 shafts and 22.5 km of tunnel had been dug.

- 2001 – After the end of the LEP program at CERN, work begins on reusing the 27 km tunnel for the 7 TeV+ 7 TeV LHC

CERN: A brief history

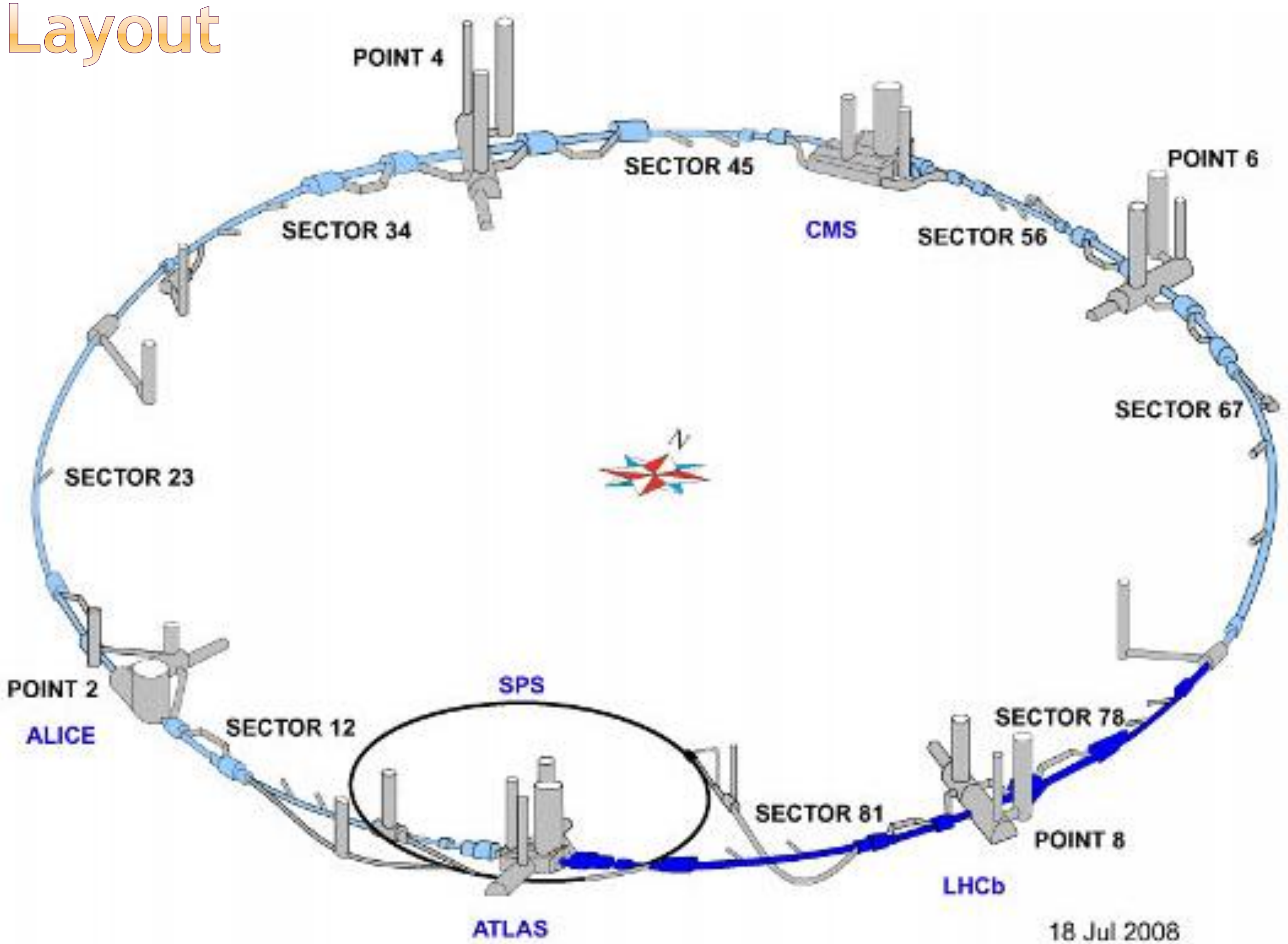
- 1951 – In a move to rebuild European science after WWII, the "Conseil Européen pour la Recherche Nucléaire" (CERN) established in a UNSESCO resolution proposed by I.I. Rabi to "establish a regional laboratory"
- 1952 – Geneva chosen as the site
- 1954 – "European Organization for Nuclear Research" officially formed of 12 member states – retains acronym "CERN"
- 1957 – first accelerator operation (600 MeV synchro-cyclotron)
- 1959 – 28 GeV proton synchrotron (PS) cements the tradition of extremely unimaginative acronyms
  - PS (and acronym policy) still in use today!
- 1971 – Intersecting Storage Rings (ISR) – first proton-proton collider
- 1983 – SppS becomes first proton-antiproton collider
  - Discovers W+Z particles: 1984 Nobel Prize for Rubbia and van der Meer
- 1989 – 27 km Large Electron Positron (LEP) collider begins operation at CM energy of 90 GeV (Z mass)
  - Unprecedented tests of Standard Model
- 1990 – Tim Berners-Lee invents the WWW
- 2000 – Dan Brown writes a very silly book

LHC: Location, location, location…



- Tunnel originally dug for LEP
  - Built in 1980's as an electron positron collider
  - Max 100 GeV/beam, but 27 km in circumference!!

LHC Layout



- 8 crossing interaction points (IP's)
- Accelerator sectors labeled by which points they go between
  - ie, sector 3-4 goes from point 3 to point 4

Nominal LHC parameters compared to Tevatron

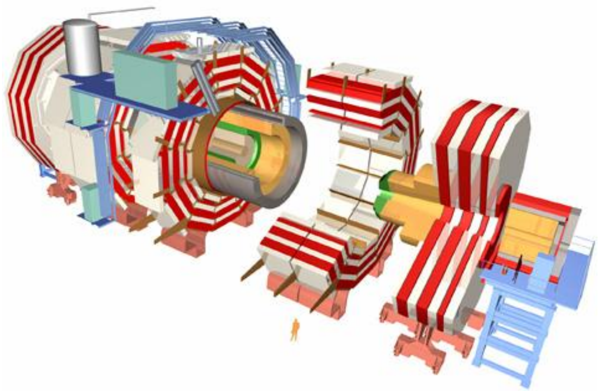
Parameter	Tevatron	“nominal” LHC
Circumference	6.28 km (2*PI)	27 km
Beam Energy	980 GeV	7 TeV
Number of bunches	36	2808
Protons/bunch	275×10^9	115×10^9
pBar/bunch	80×10^9	-
Stored beam energy	1.6 + .5 MJ	366+366 MJ*
Peak luminosity	3.3×10^{32} $cm^{-2}s^{-1}$	1.0×10^{34} $cm^{-2}s^{-1}$
Main Dipoles	780	1232
Bend Field	4.2 T	8.3 T
Main Quadrupoles	~200	~600
Operating temperature	4.2 K (liquid He)	1.9K (superfluid He)

$$1.0 \times 10^{34}\ cm^{-2}s^{-1} \sim 50\ fb^{-1}/yr$$

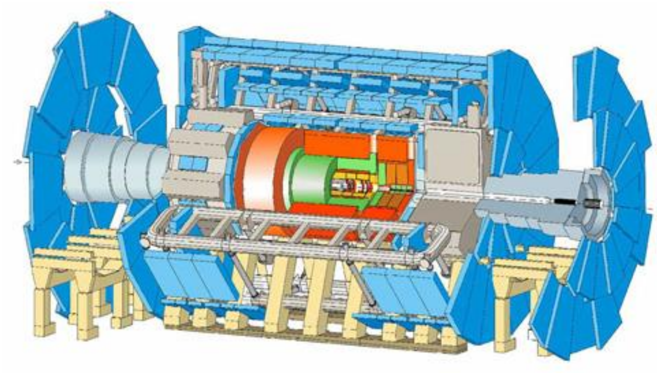
*2.1 MJ ≡ “stick of dynamite” ⇒ very scary numbers

CERN experiments

- Damn big, general purpose experiments:

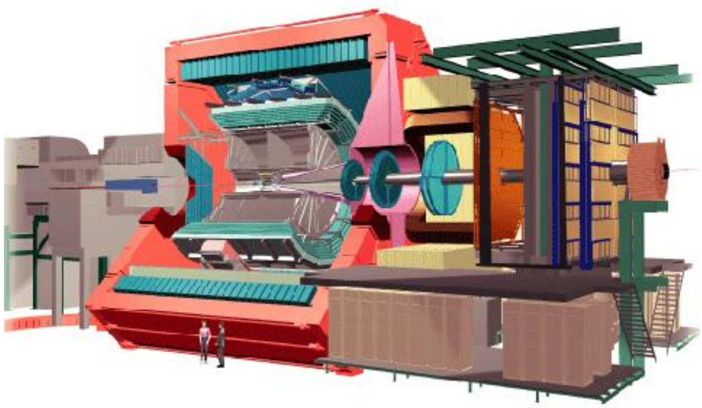


Compact Muon Solenoid (CMS)

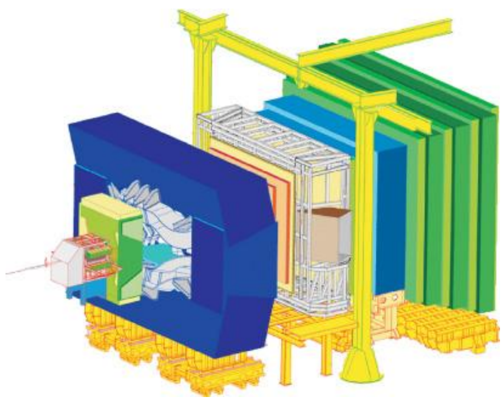


A Toroidal LHC ApparatuS (ATLAS)

- "Medium" special purpose experiments:

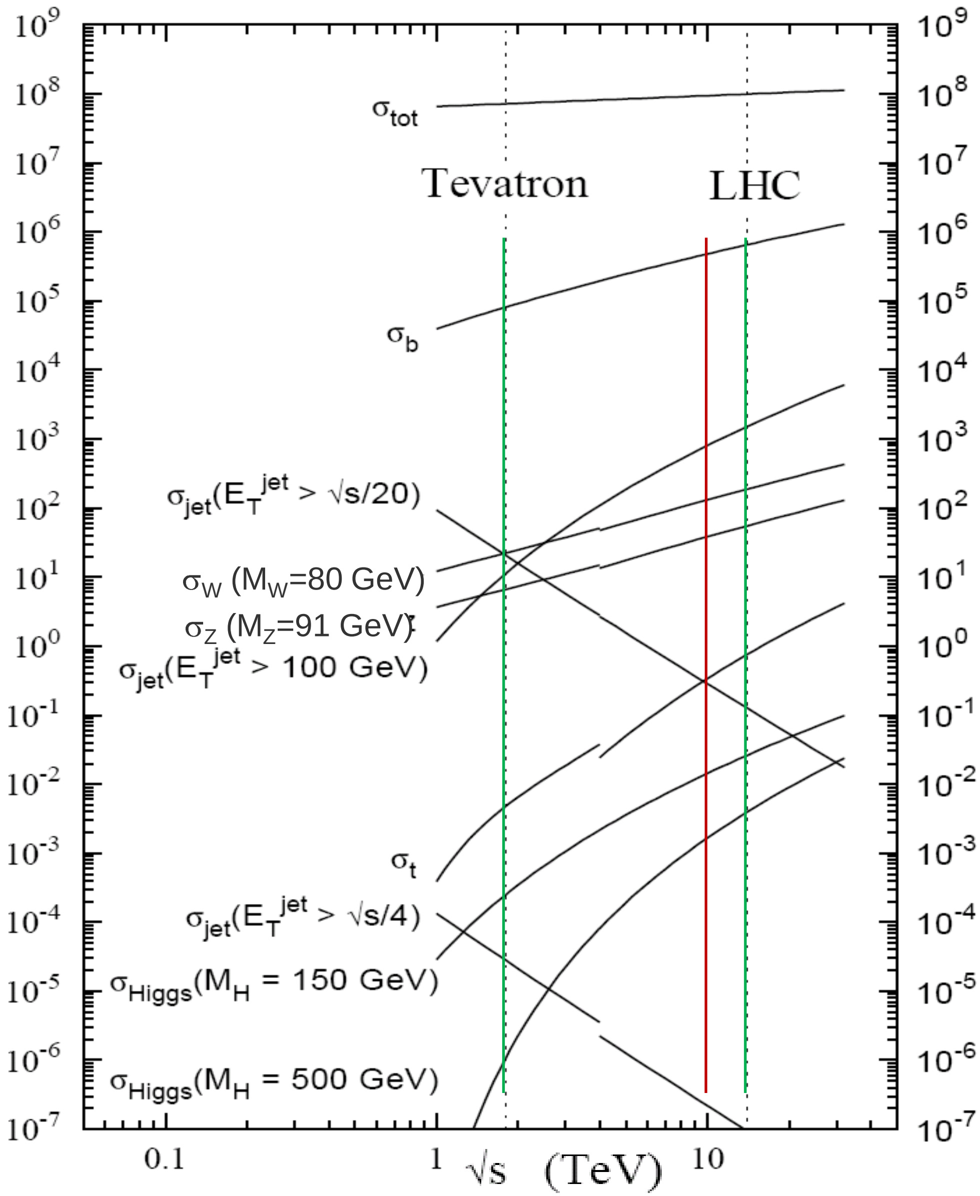


A Large Ion Collider Experiment (ALICE)



B physics at the LHC (LHCb)

Experimental reach of LHC vs. Tevatron



200 pb^{-1} at 5 TeV+5 TeV
~5 fb^{-1} at 1 TeV+ 1 TeV

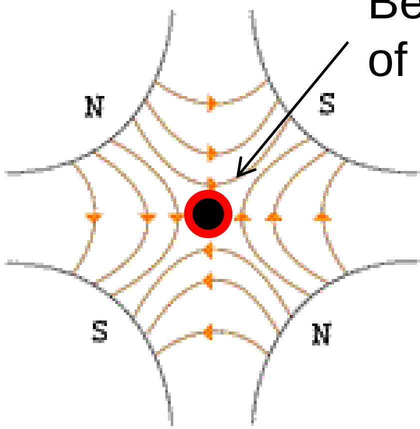
What is done during commissioning

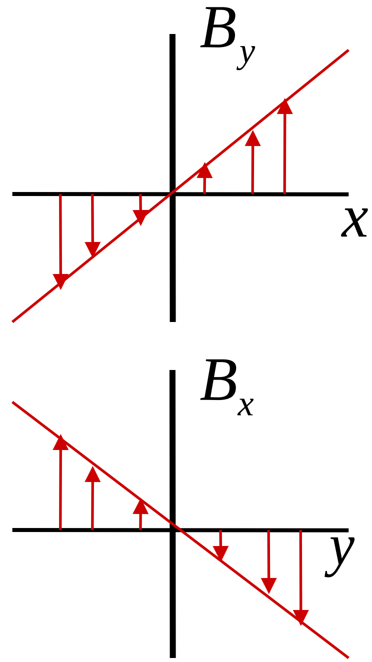
- The LHC would have no hope of ever working if there had not been a thorough quality control program in effect during all phases of construction and installation.
- However, it would be naïve to believe there are not still problems to solve, perhaps some of them significant, which will only be discovered when beam circulates.
- During beam commissioning
  - Exercise all systems, looking for mistakes and problems.
  - Methodically proceed with beam injection
    - Look for mistakes
    - Make corrections for inevitable imperfections

Nothing's perfect

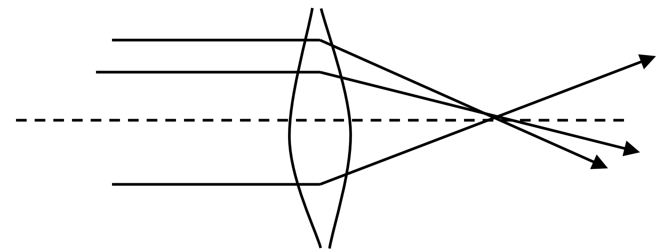
Recall : ideal quadrupole:

Beam (out of page)

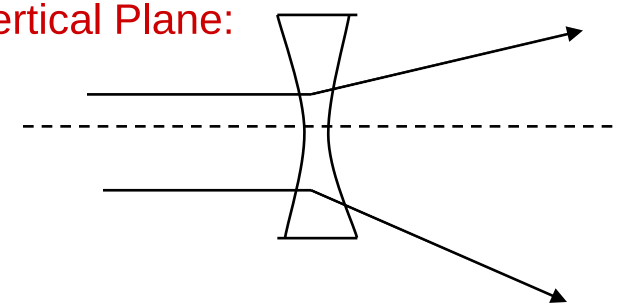




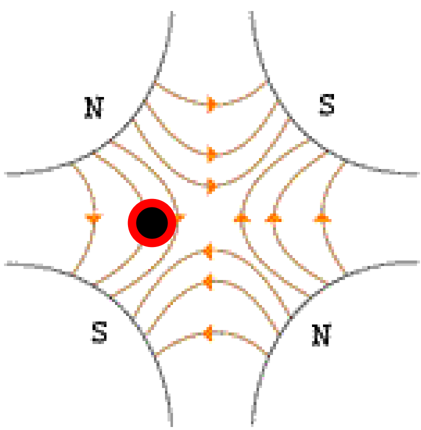
Horizontal Plane:



Vertical Plane:



But what if it's offset?



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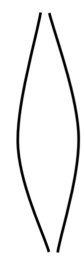
Focus



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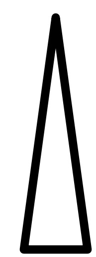
Bend

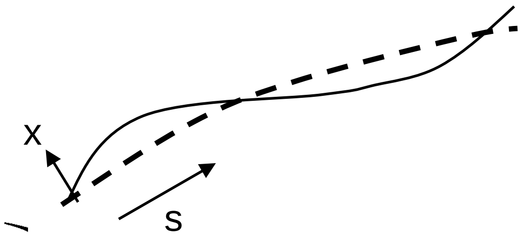


Big error? Move quad

Small error? Correct for problem

Betatron motion

For a particular particle, the deviation from an idea orbit will undergo "pseudo-harmonic" oscillation as a function of the path along the orbit:



Lateral deviation in one plane

$$x(s) = A\left[\beta(s)\right]^{1/2}\sin\left(\psi(s)+\delta\right)$$

Phase advance

$$\psi(s) = \int_0^s \frac{ds}{\beta(s)}$$

The "betatron function" $\beta(s)$ is effectively the local wavenumber and also defines the beam envelope.

A transverse "kick" (θ) (misaligned quad, miscalibrated dipole, etc) at one location in a beam will produce a lateral deviation at later points given by

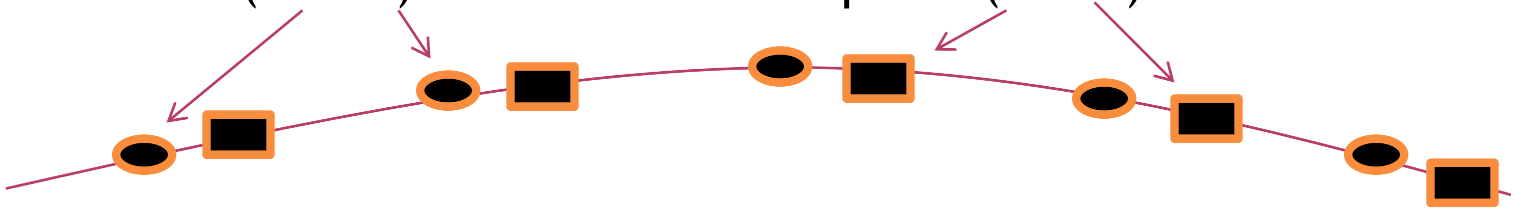
$$\Delta x(s) = \theta_0\sqrt{\beta_0\beta(s)}\sin\psi(s) = A(s)\theta_0$$

Linear relationship

In general, these can be canceled with a discrete set of intentional corrections

Orbit correction

- Generally, beam lines or synchrotrons will have beam position monitors (BPM’s) and correction dipoles (trims)



- We would like to use the trims to cancel out the effect of beamline imperfectins, ie

$$-\Delta x_i = \sum A_{ij}\theta_j$$

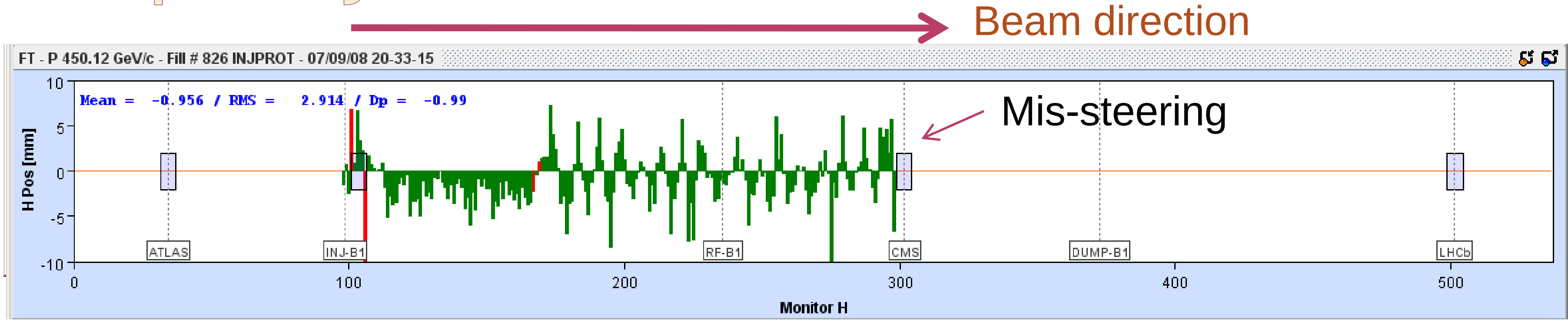
Cancel displacement at BPM *i* due to imperfections

Setting of trim *j*

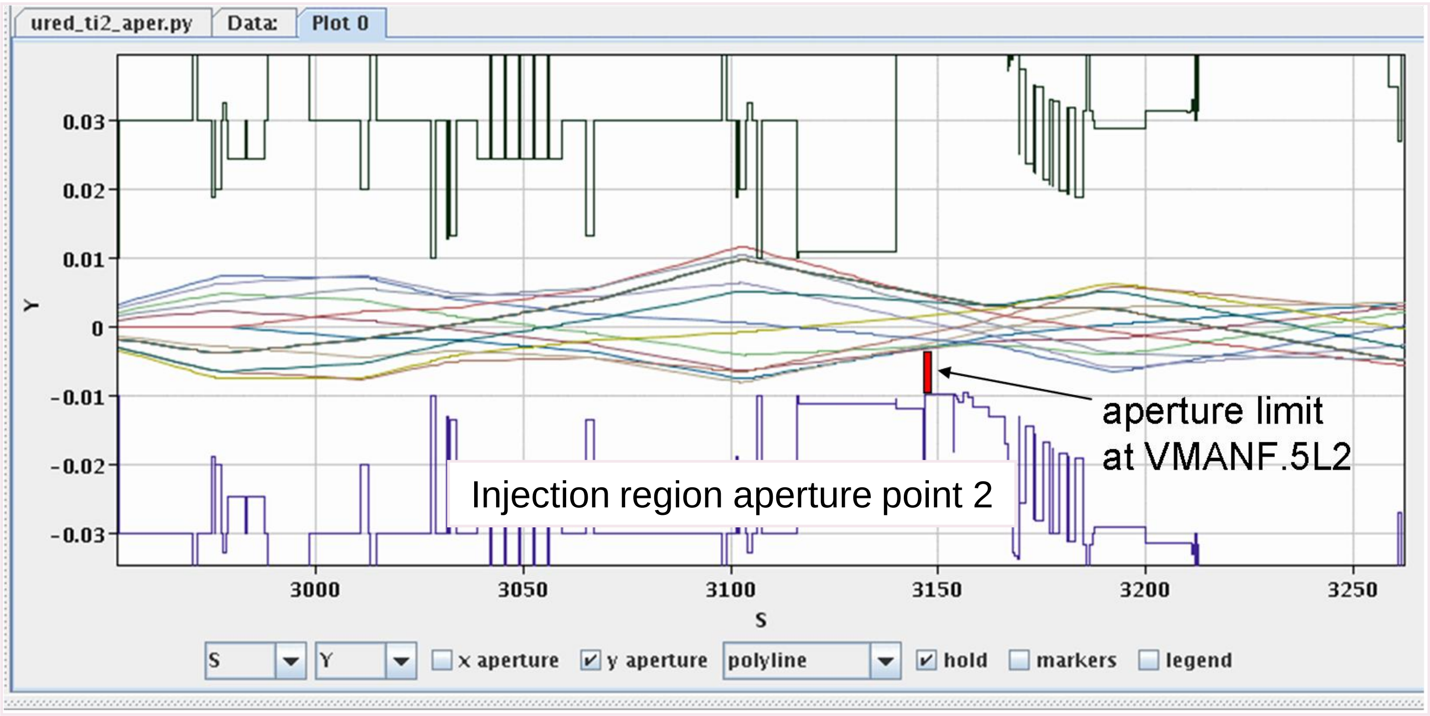
- Can express this as a matrix and invert to solve with standard techniques
  - If n=m, can just invert
  - If n>m, can minimize RMS

$$-\begin{pmatrix} \Delta x_0 \\ \Delta x_1 \\ \vdots \\ \Delta x_n \end{pmatrix} = \begin{pmatrix} A_{00} & A_{01} & \cdots & A_{0m} \\ A_{10} & A_{11} & \cdots & A_{1m} \\ \vdots & \vdots & \ddots & \\ A_{n0} & A_{n1} & & A_{nm} \end{pmatrix} \begin{pmatrix} \theta_0 \\ \theta_1 \\ \vdots \\ \theta_m \end{pmatrix}$$

Example: Injection test



- Aperture scan: move beam around until you hit something



Sept 10, 2008: The (first) big day

- 9:35 – First beam injected
- 9:58 – beam past CMS to point 6 dump
- 10:15 – beam to point 1 (ATLAS)
- 10:26 – First turn!
- …and there was much rejoicing
- Things were going great for 9 days until something *very bad* happened.

Nature abhors a (news) vacuum…

- Italian newspapers were very poetic (at least as translated by "Babel Fish"):

  "the black cloud of the bitterness still has not been dissolved on the small forest in which they are dipped the candid buildings of the CERN"

  "Lyn Evans, head of the plan, support that it was better to wait for before igniting the machine and making the verifications of the parts." *

- Or you could Google "What really happened at CERN":

Strange Incident at CERN

Did the LHC Create a Black Hole?

And if so, Where is it Now? **

by

George Paxinos

in conversation with

"An Iowan Idiot"

* "Big Bang, il test bloccato fino all primavera 2009", Corriere dela Sera, Sept. 24, 2008

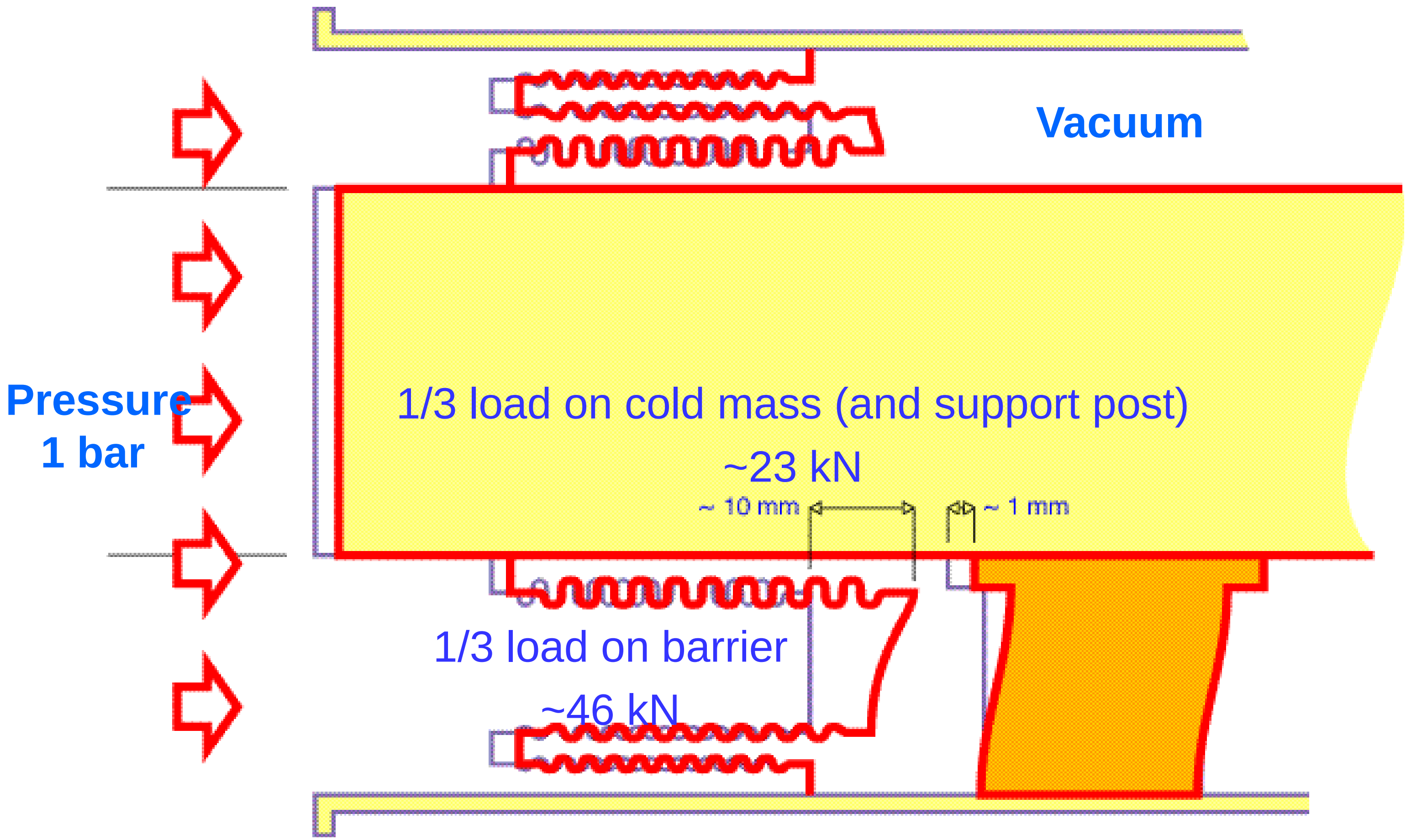
**http://www.rense.com/general83/IncidentatCERN.pdf

What (really) really happened on September 19th*

- Sector 3-4 was being ramped to 9.3 kA, the equivalent of 5.5 TeV
  - All other sectors had already been ramped to this level
  - Sector 3-4 had previously only been ramped to 7 kA (4.1 TeV)
- At 11:18AM, a quench developed in the splice between dipole C24 and quadrupole Q24
  - Not initially detected by quench protection circuit
  - Power supply tripped at .46 sec
  - Discharge switches activated at .86 sec
- Within the first second, an arc formed at the site of the quench
  - The heat of the arc caused Helium to boil.
  - The pressure rose beyond .13 MPa and ruptured into the insulation vacuum.
  - Vacuum also degraded in the beam pipe
- The pressure at the vacuum barrier reached ~10 bar (design value 1.5 bar). The force was transferred to the magnet stands, which broke.

*Official talk by Philippe LeBrun, Chamonix, Jan. 2009

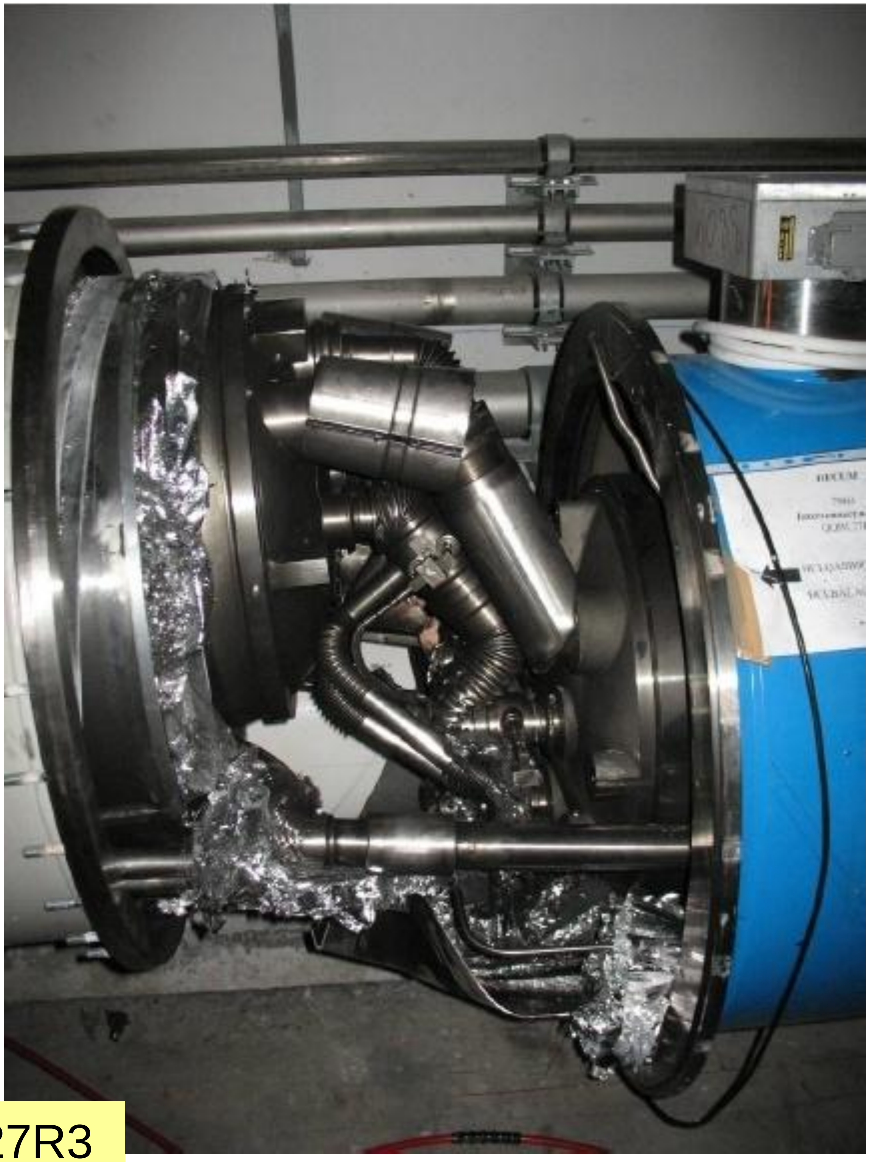
Pressure forces on SSS vacuum barrier



Total load on 1 jack ~70 kN

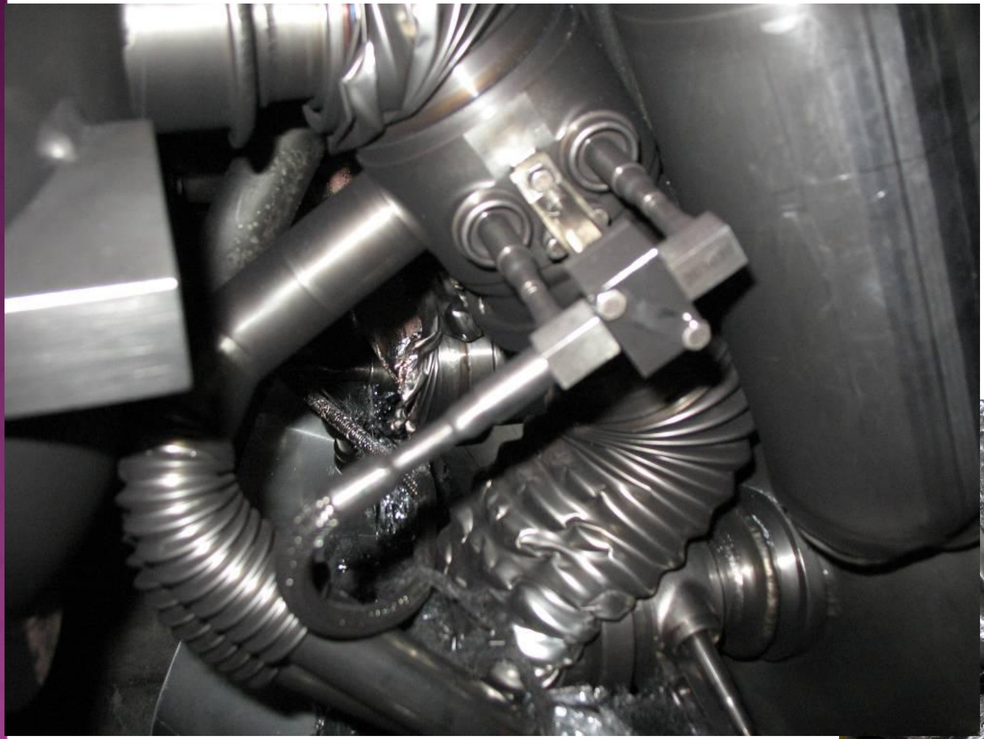
V. Parma

Collateral damage: magnet displacements

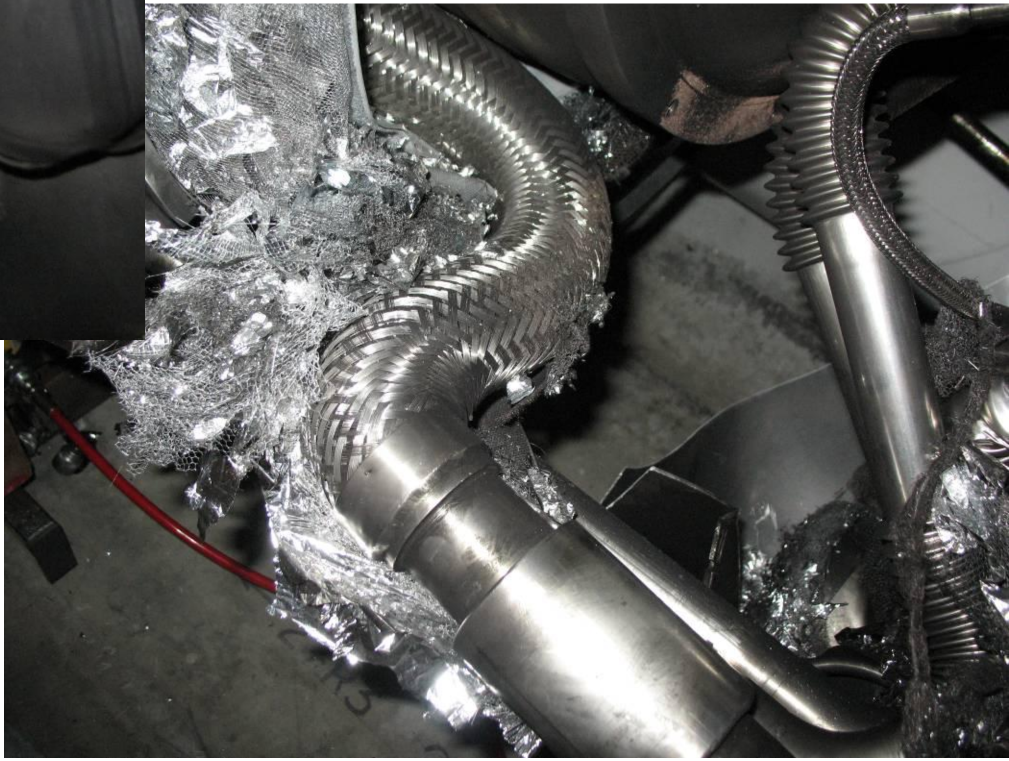


QQBI.27R3

Collateral damage: magnet displacements

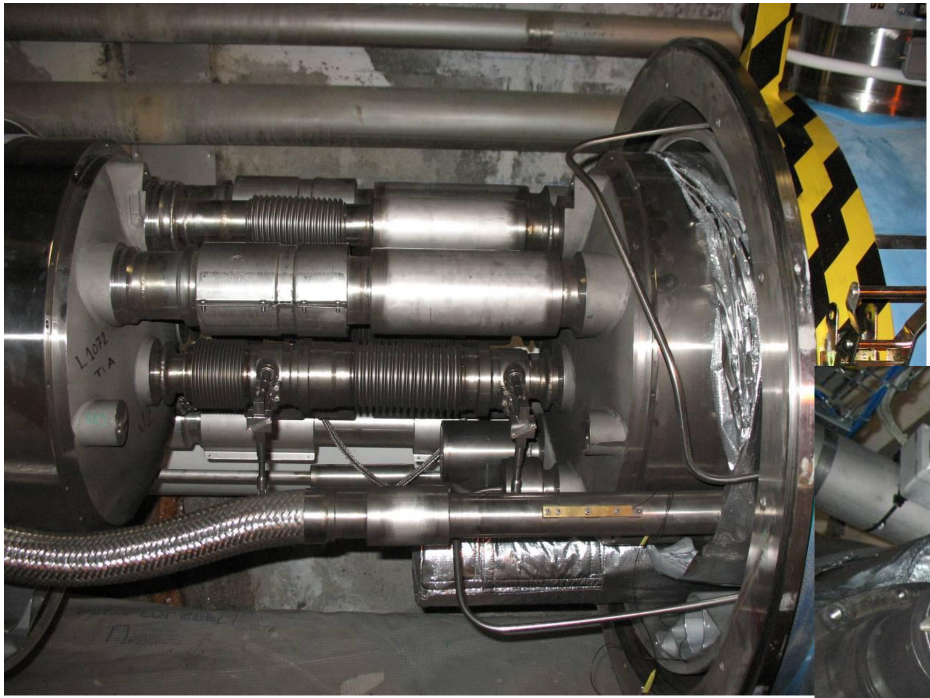


QQBI.27R3
V2 line



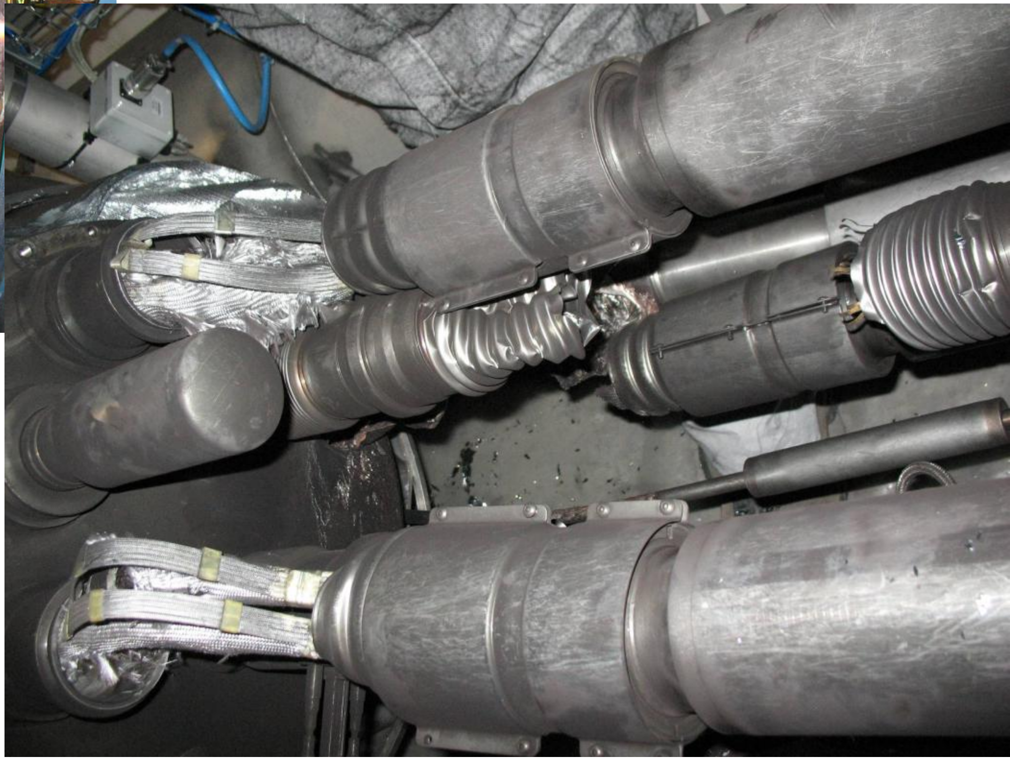
QQBI.27R3
N line

Collateral damage: magnet displacements

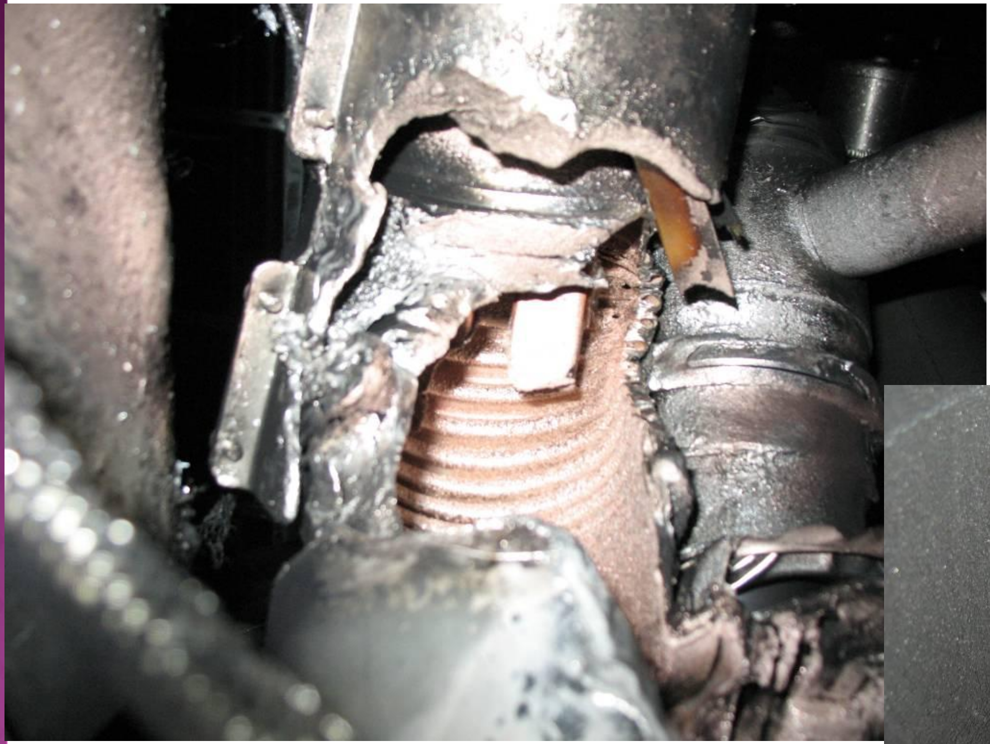


QBBI.B31R3
Extension by 73 mm

QBQI.27R3
Bellows torn open



Collateral damage: secondary arcs



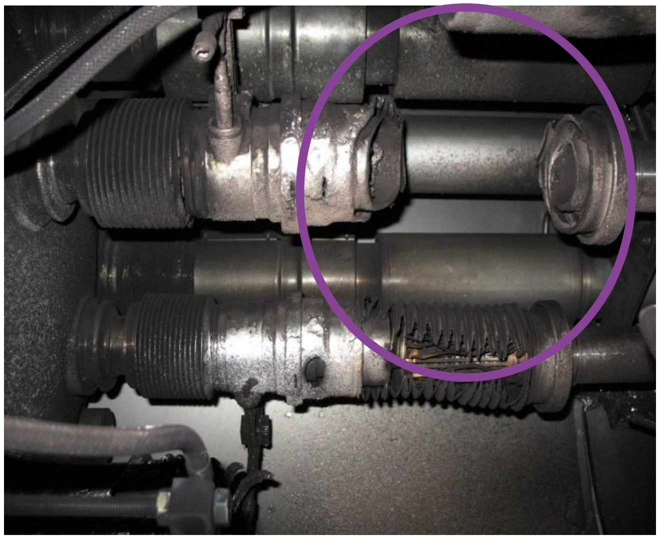
QQBI.27R3 M3 line

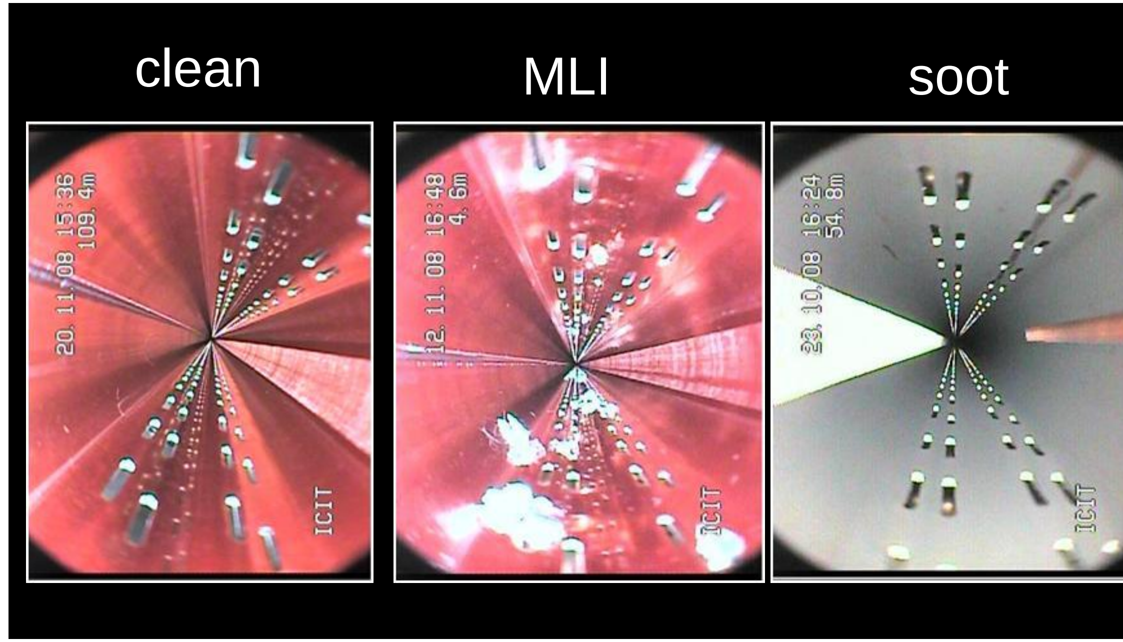
QBBI.B31R3 M3 line

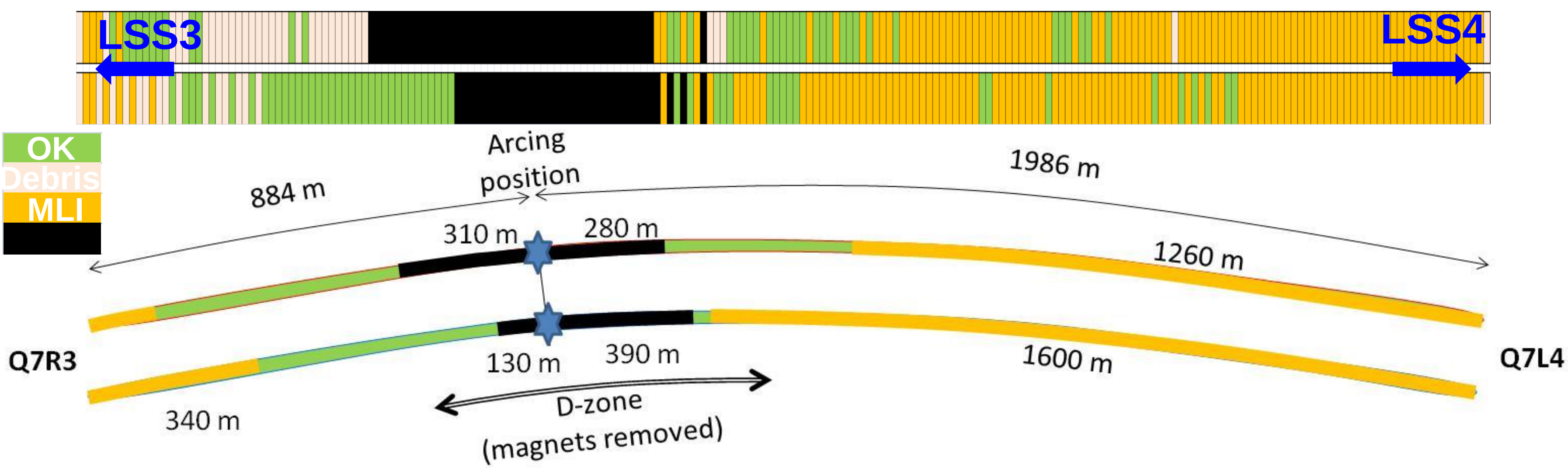
Collateral damage: ground supports

Collateral damage: Beam Vacuum

Arc burned through beam vacuum pipe







Replacement of magnets

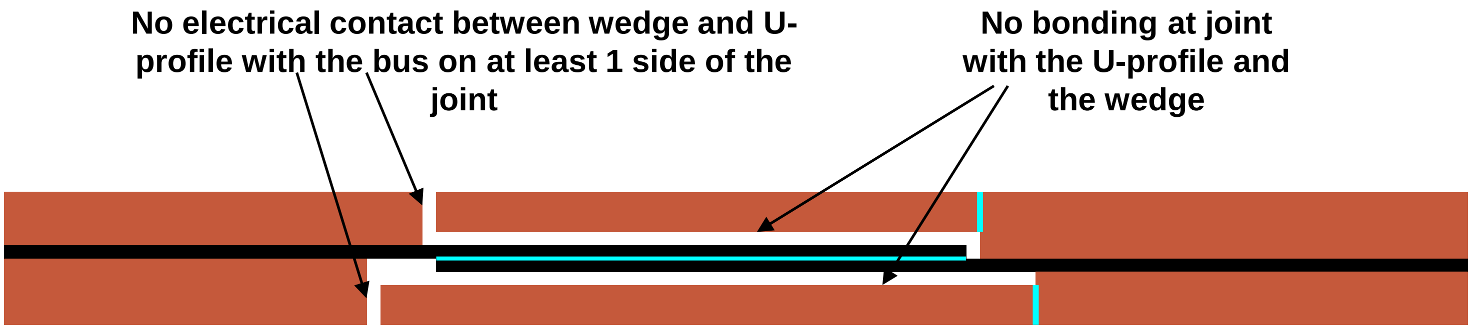
- 15 Quadrupoles (MQ)
  - 1 not removed (Q19)
  - 14 removed
    - 8 cold mass revamped (old CM, partial de-cryostating for cleaning and careful inspection of supports and other components)
    - 6 new cold masses
    - In this breakdown there is consideration about timing (quad cryostating tales long time; variants problems).
- 42 Dipoles (MBs)
  - 3 not removed (A209,B20,C20)
  - 39 removed
    - 9 Re-used (old cold mass, no decryostating –except one?)
    - 30 new cold masses
    - New cold masses are much faster to prepare than rescuing doubtful dipoles)

Important questions about Sept. 19

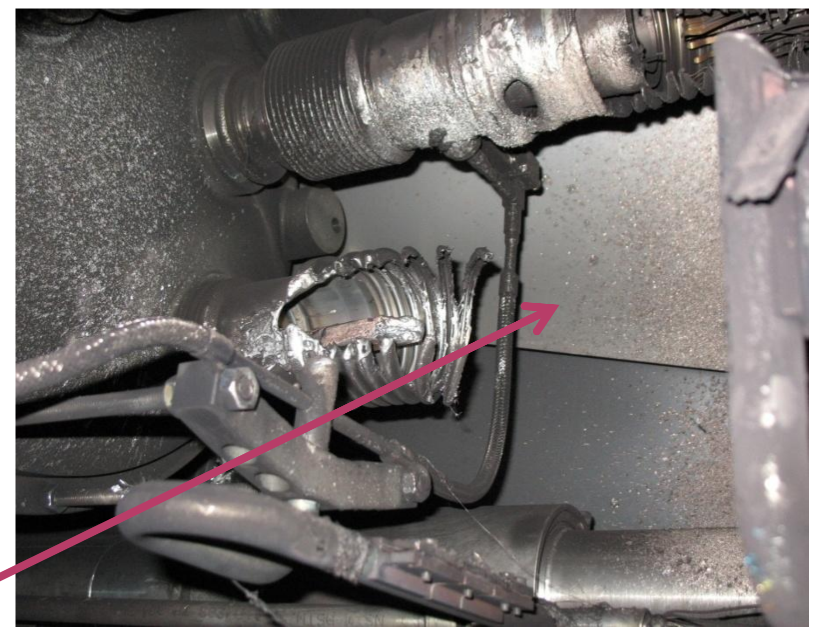
- Why did the joint fail?
  - Inherent problems with joint design
    - No clamps
    - Details of joint design
    - Solder used
  - Quality control problems
- Why wasn't it detected in time?
  - There was indirect (calorimetric) evidence of an ohmic heat loss, but these data were not routinely monitored
  - The bus quench protection circuit had a threshold of 1V, a factor of >1000 too high to detect the quench in time.
- Why did it do so much damage?
  - The pressure relief system was designed around an MCI Helium release of 2 kg/s, a *factor of ten* below what occurred.

What happened?

Theory: A resistive joint of about 220 nΩ with bad electrical and thermal contacts with the stabilizer



- Loss of clamping pressure on the joint, and between joint and stabilizer
- Degradation of transverse contact between superconducting cable and stabilizer
- Interruption of longitudinal electrical continuity in stabilizer



Problem: this is where the evidence used to be

A. Verweij

Improved quench protection*

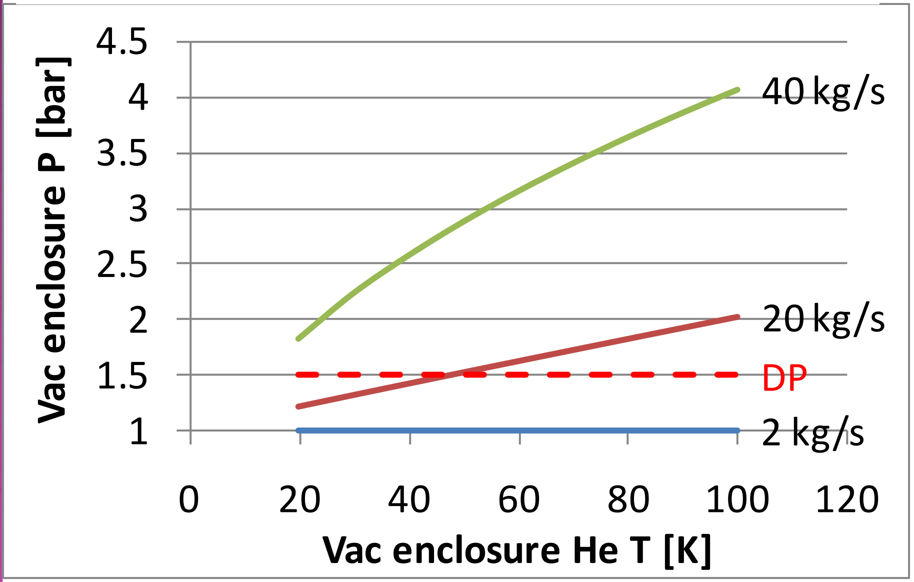
- Old quench protection circuit triggered at 1V on bus.
- New QPS triggers at .3 mV
  - Factor of 3000
  - Should be sensitive down to 25 nOhms (thermal runaway at 7 TeV)
  - Can measure resistances to <1 nOhm
- Concurrently installing improved quench protection for “symmetric quenches”
  - A problem found before September 19th
  - Worrisome at >4 TeV

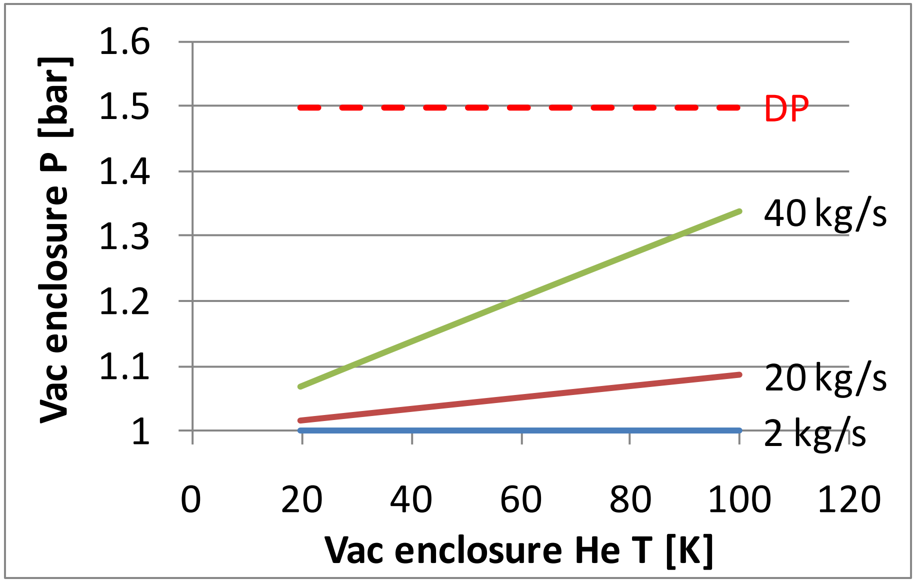
*See talks by Arjan Verveij and Reiner Denz, Chamonix 2009

Improved pressure relief*

New configuration on four cold sectors: Turn several existing flanges into pressure reliefs (while cold). Also reinforce stands to hold ~3 bar

New configuration on four warm sectors: new flanges (12 200mm relief flanges)





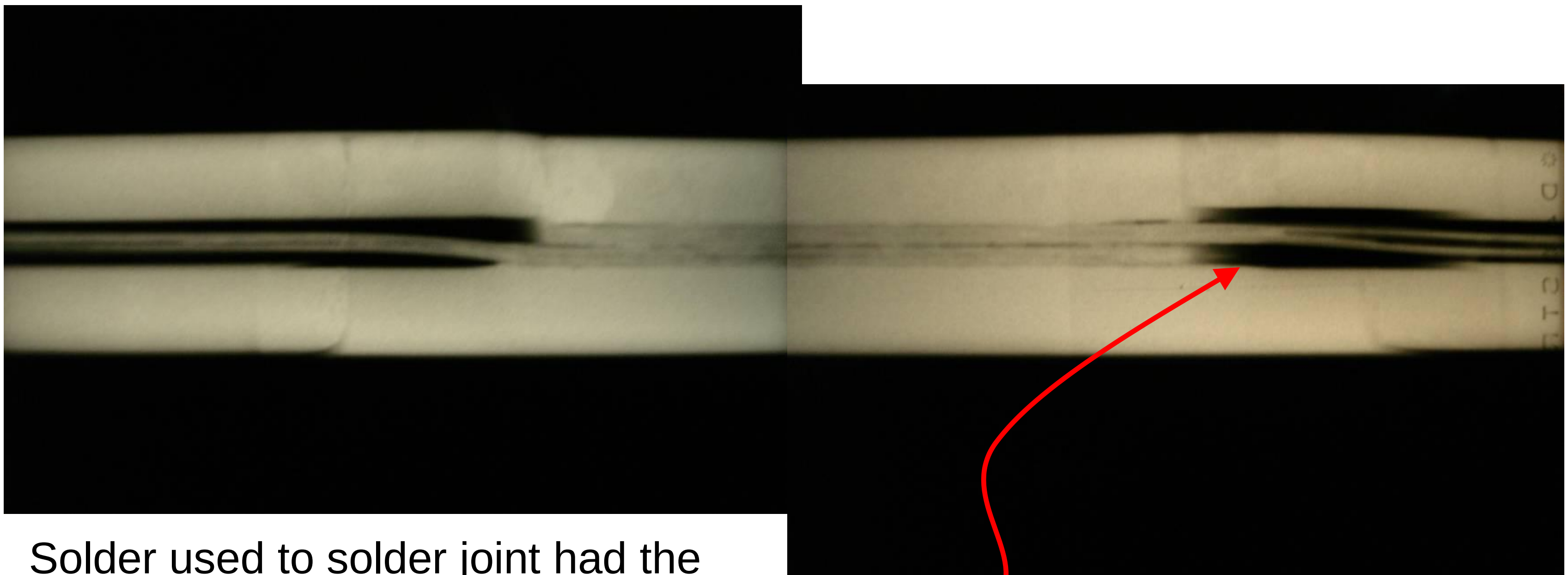
(DP: Design Pressure)

L. Tavian

*Vittorio Parma and Ofelia Capatina, Chamonix 2009

Bad surprise

- With new quench protection, it was determined that joints would only fail if they had bad thermal *and* bad electrical contact, and how likely is that?
  - Very, unfortunately ⇒ *must* verify copper joint



Solder used to solder joint had the same melting temperature as solder used to pot cable in stablizer
⇒**Solder wicked away from cable**

- Have to warm up to at least 80K to measure Copper integrity.

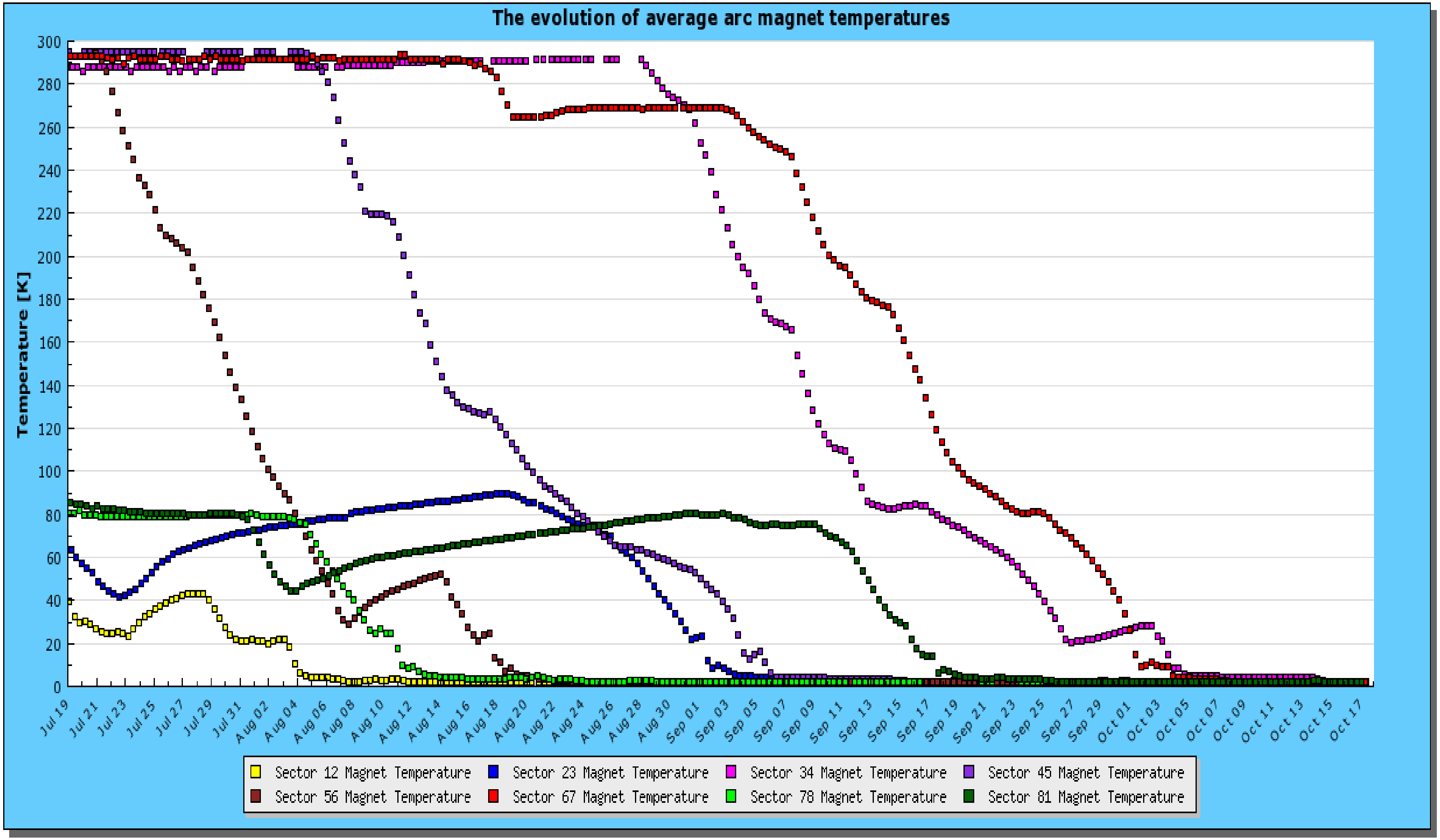
Machine wide activities Q4 2008 and 2009

Sector 34 repair | Restart

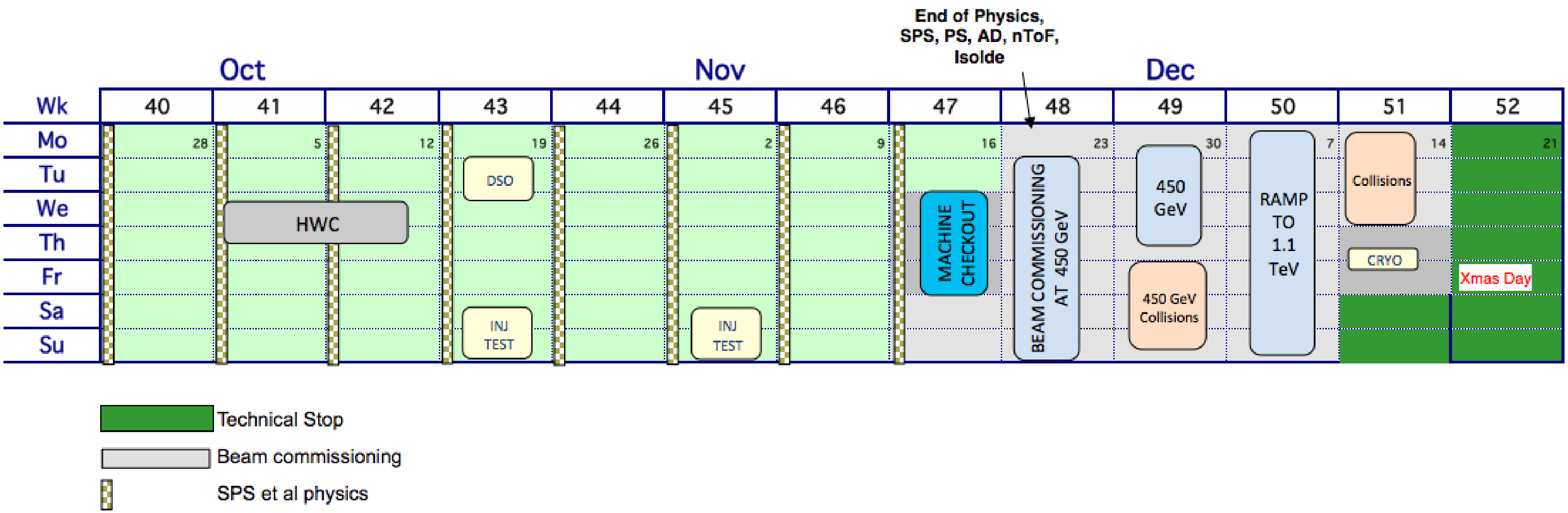
Sector	Q4 2008	Q1 2009	Q2 2009	Q3 2009	Q4 2009
12	Cold	Cold → Warm	Warm	Warm → Cold	Cold
23	< 100K	< 100K	< 100K → Cold	Cold → 80K → Cold	Cold
34	Warm	Warm	Warm	Warm → Cold	Cold
45	< 100K	< 100K	80K → Warm	Warm → Cold	Cold
56	Cold	Cold → Warm	Warm	Warm → Cold	Cold
67	Cold	Cold → Warm	Warm	Warm → Cold	Cold
78	Cold	< 100K	< 100K → 80K	80K → Cold	Cold
81	Cold	< 100K	< 100K → 80K	80K → Cold	Cold

- Did complete repairs in 4/8 sectors
- Warmed up one more to fix copper joints, but did not add enhanced pressure relief
- Three not warmed up

Cool down 2009



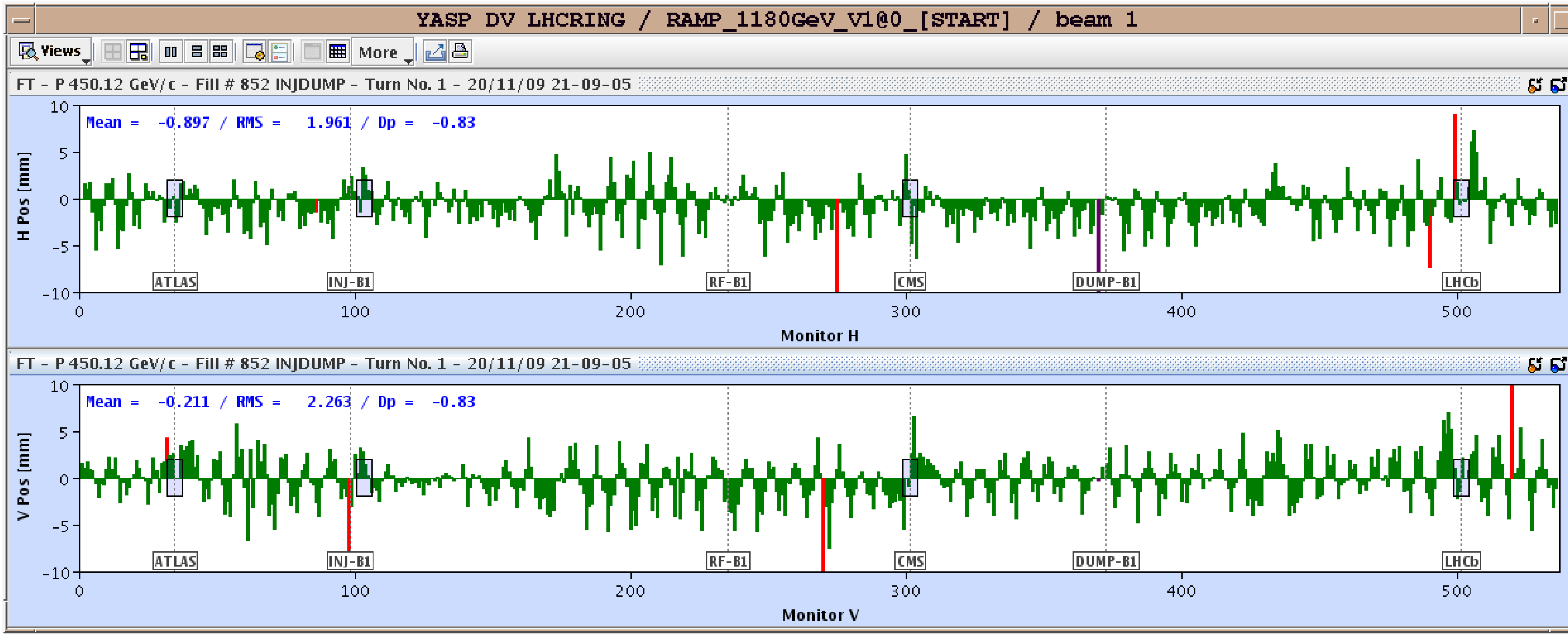
2009 Plans (as of November 1)*



- Decision to limit energy to 1.2 TeV based on need for final shakedown of new quench protection system.
- Somewhat ahead of this schedule

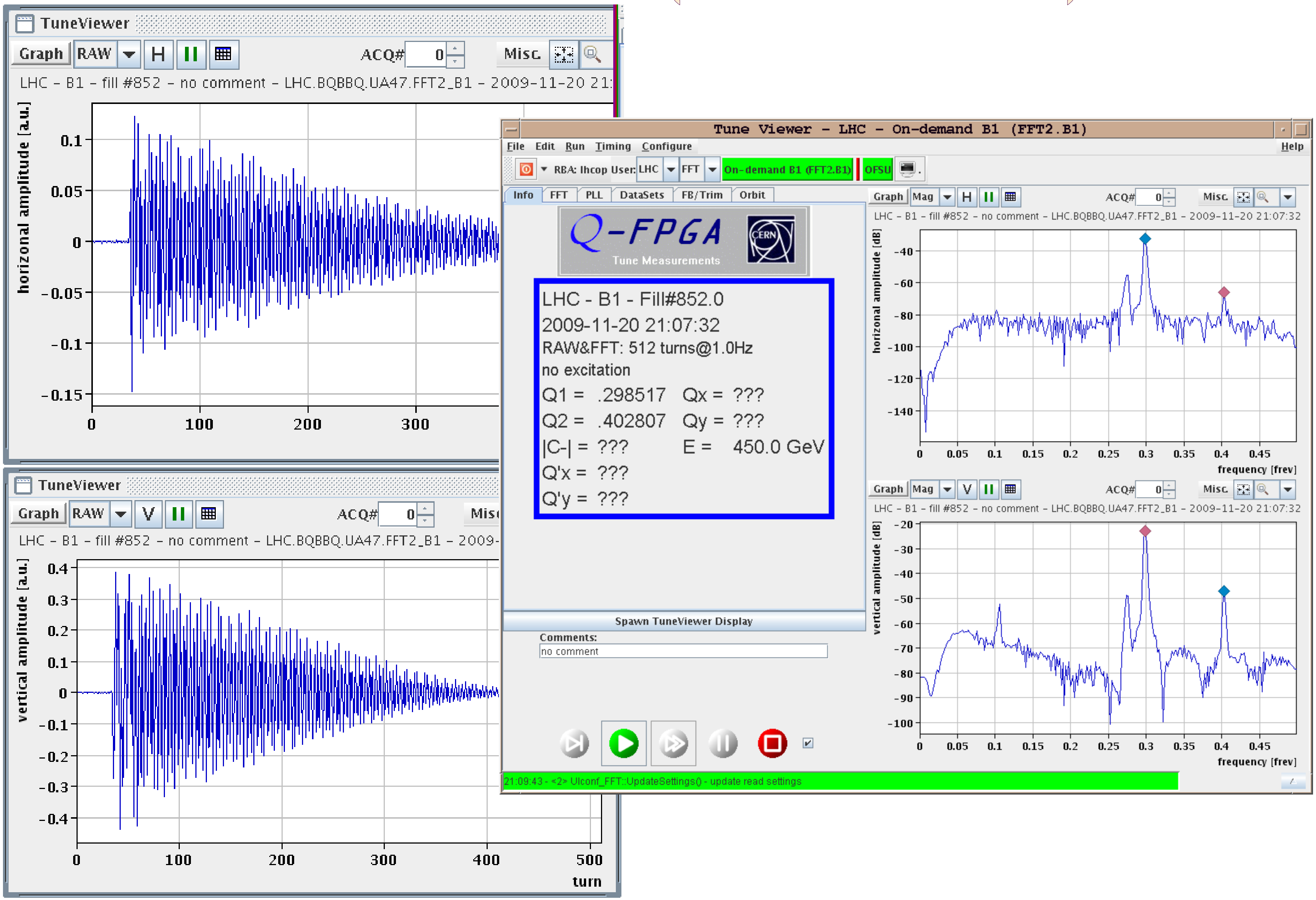
*Taken from slides by Roger Bailey, shown at LARP meeting

November 20, 2009: Going around…again

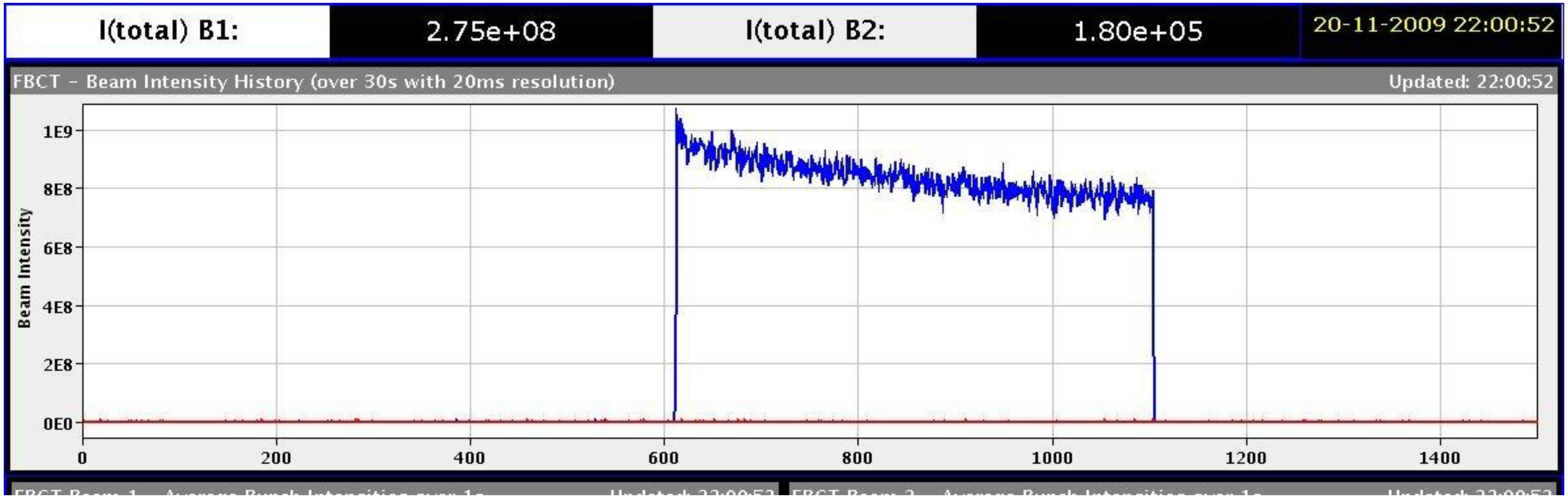


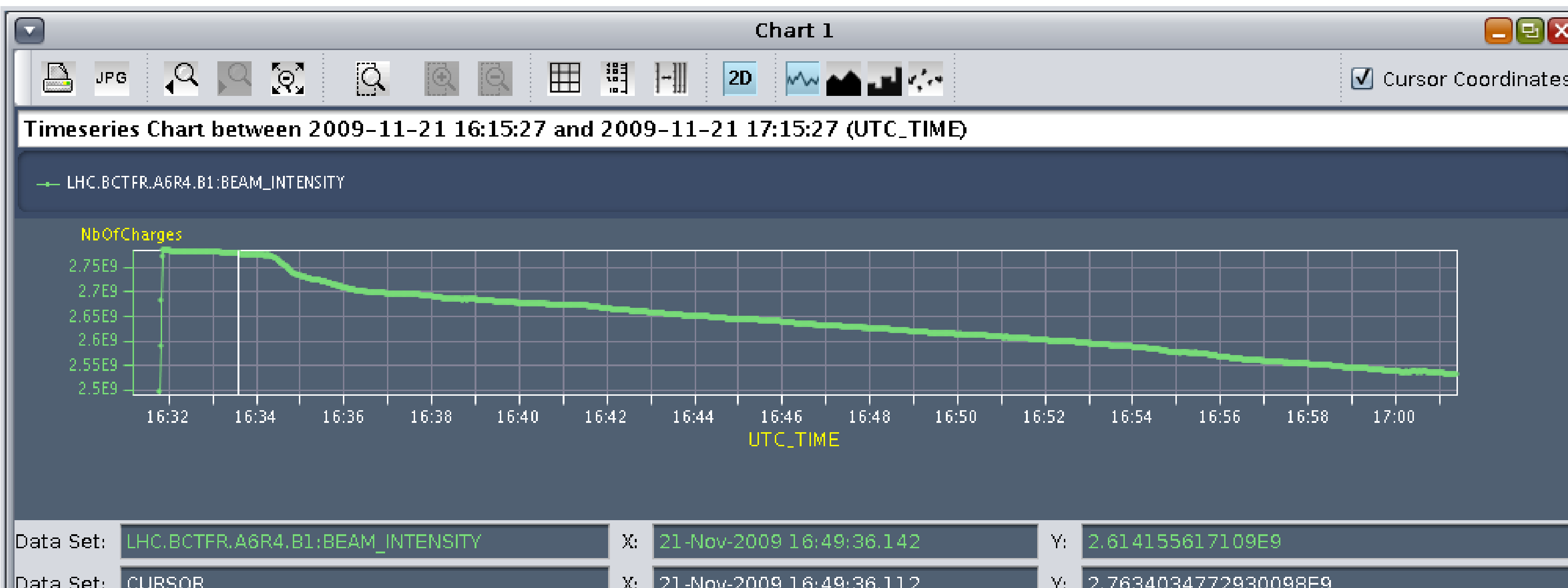
- Total time: 1:43
- Then things began to move with dizzying speed…

First Tune Measurement (within an hour)

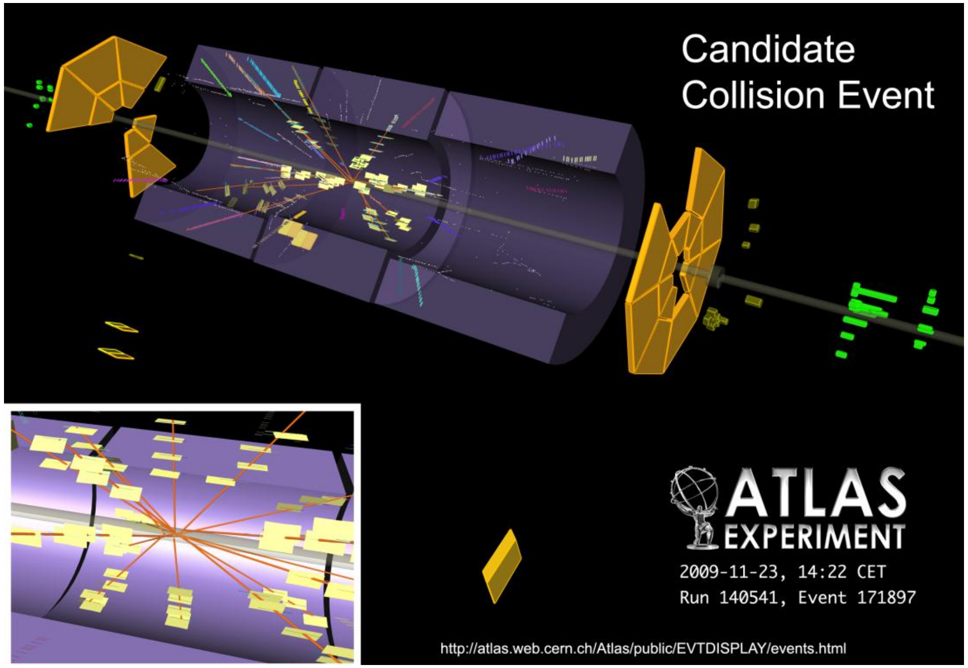


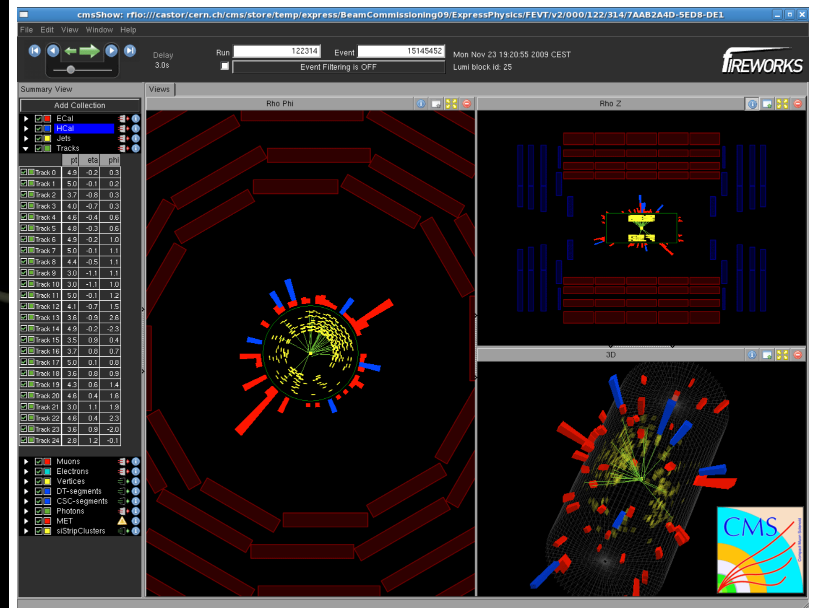
Beam 1 Captured about an hour after first turn!!

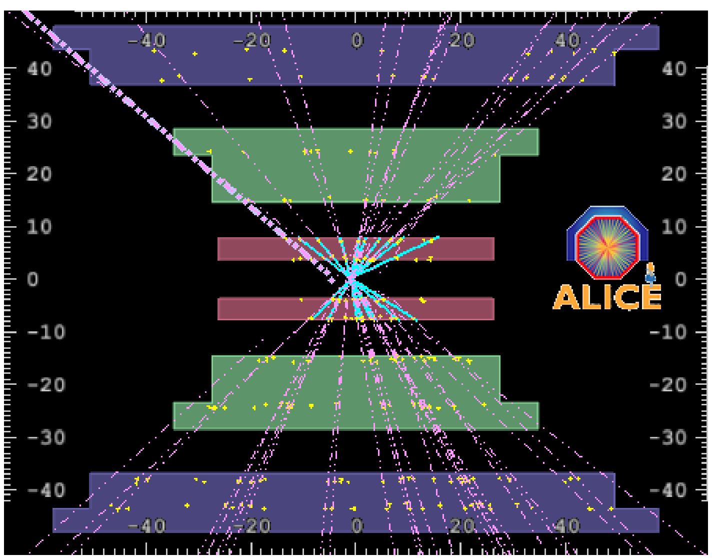




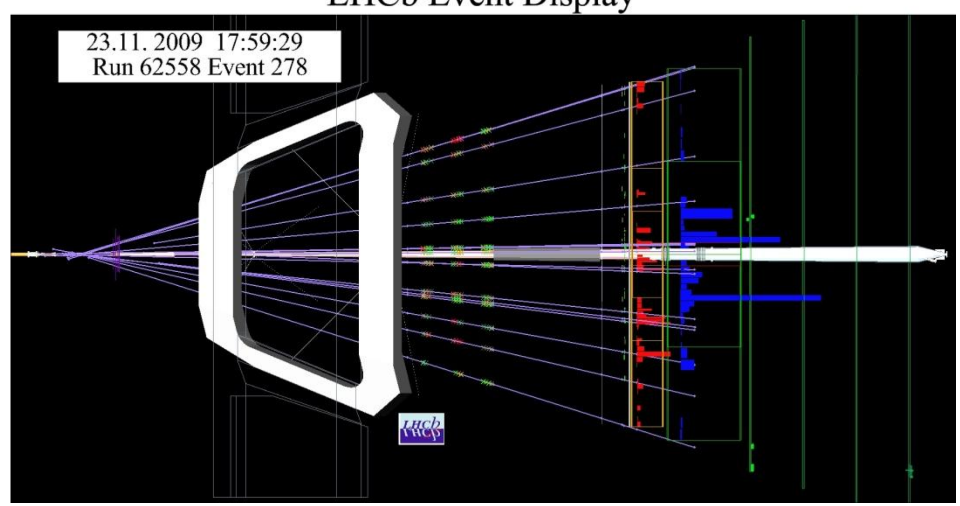
November 23rd: First Collisions!







LHCb Event Display



Progress since start up

- Sunday, November 29th
  - Both beams accelerated to 1.18 TeV simultaneously
- Sunday, December 6th
  - Stable 4x4 collisions at 450 GeV

LHC Highest energy accelerator

- Tuesday, December 8th
  - 2x2 accelerated to 1.18 TeV
  - First collisions seen in ATLAS before beam lost!
- Monday, December 14th
  - Stable 2x2 at 1.18 TeV
  - Collisions in all four experiments
  - 16x16 at 450 GeV

LHC Highest energy collider

- Wednesday, December 16th
  - 4x4 to 1.18 TeV
  - Squeeze to 7m
  - Collisions in all four experiments
  - 18:00 – 2009 run ended
    - >1 million events at 450x450 GeV
    - 50,000 events at 1.18x1.18 TeV
    - Merry Christmas – shutdown until Feb. 2010 to commission quench protection

Should be good to 3.5 TeV after restart

Decisions at Chamonix

- Case for caution
  - Don’t want to break machine again!
  - Already know there are things that still need to be done
    - Finish repairs on the sectors which were not warmed up
    - Improved joint design
- Case for increasing the energy as high as possible
  - Moving ahead with the science
  - Students and postdocs waiting for data
  - (although no one likes to talk about it) Need to find the other problems with the accelerator and the detectors
- Decisions at Chamonix
  - Existing joints NOT reliable above 3.5 TeV
  - Will run at 3.5+3.5TeV for fb-1, or until the end of 2011, whichever comes first
  - Then shut down for 12-18 months to rebuild *all 10,000 joints*!!
    - Clamps and or shunts

Understanding LHC Luminosity

Total beam current. Limited by:
- Uncontrolled beam loss!!
- E-cloud and other instabilities

Brightness, limited by
- Injector chain
- Max tune-shift

If n_b>156, must turn on crossing angle

$$L = \left(\frac{\gamma f_{rev}}{4\pi}\right)\frac{n_b N_b}{\beta^*}\left[\left(\frac{N_b}{\varepsilon_N}\right)R_\phi\right]$$

β*, limited by
- magnet technology
- chromatic effects

Geometric factor, related to crossing angle…

*see, eg, F. Zimmermann, "CERN Upgrade Plans", EPS-HEP 09, Krakow, for a thorough discussion of luminosity factors.

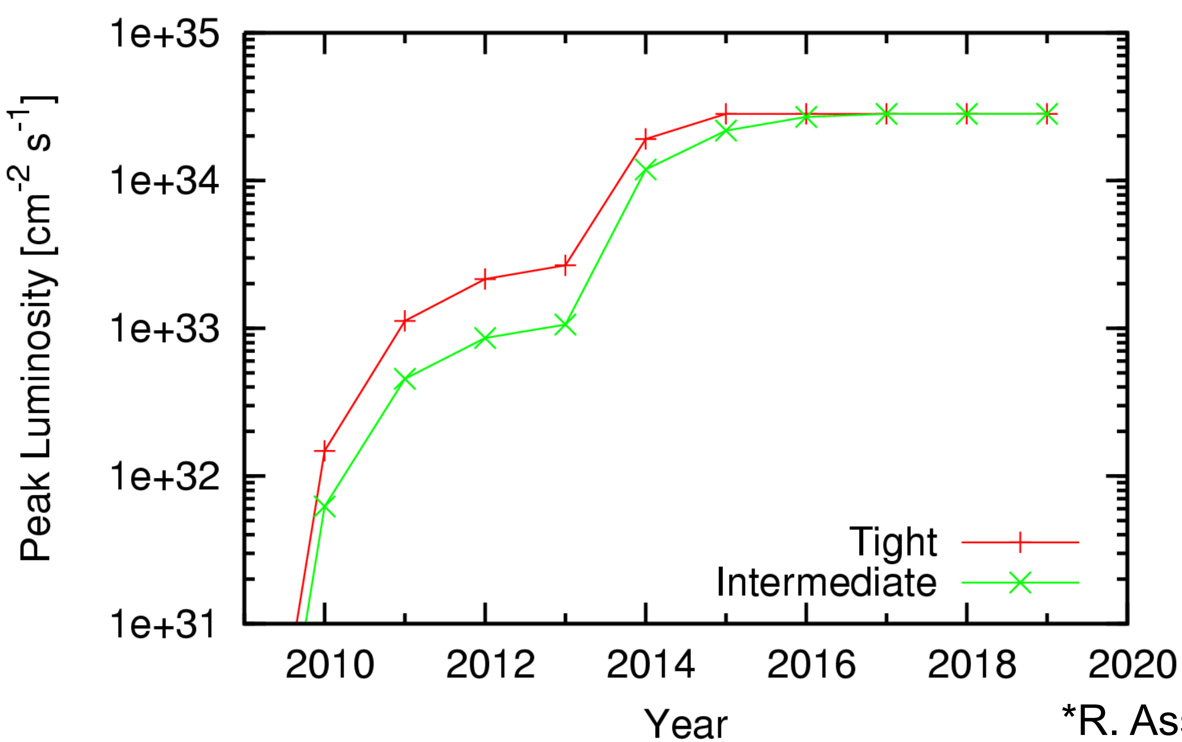
Target Performance in 2010

Comment	Energy (TeV)	Max Bunches	Protons/ bunch	% nom. Intensity	Min. β* (m)	Peak Lum. ($cm^{-2}s^{-1}$)	Int. Lum. (pb^{-1})
Pilot Physics, Partial Squeeze, Gentle increase in bunch int.	3.5	43	$3x10^{10}$		4	$8.6x10^{29}$	.1-.2
	3.5	43	$5x10^{10}$		4	$2.4x10^{30}$	~1
Max. bunches with no angle	3.5	156	$5x10^{10}$	2.5	2	$1.7x10^{31}$	~9
Push bunch intensity	3.5	156	$7x10^{10}$	3.4	2	$3.4x10^{31}$	~18
	3.5	156	$10x10^{10}$	4.8	2	$6.9x10^{31}$	~36
Introduce 50 ns bunch trains and crossing angle!	3.5	144	$7x10^{10}$	3.1	2	$4.4x10^{31}$	~23
Push n_b and N_b to limit of machine safety.	3.5	288	$7x10^{10}$	6.2	2	$8.8x10^{31}$	~46
	3.5	432	$7x10^{10}$	9.4	2	$1.3x10^{32}$	~69
	3.5	432	$9x10^{10}$	11.5*	2	$2.1x10^{32}$	~110

*limited by collimation system

Beyond 10^{32}

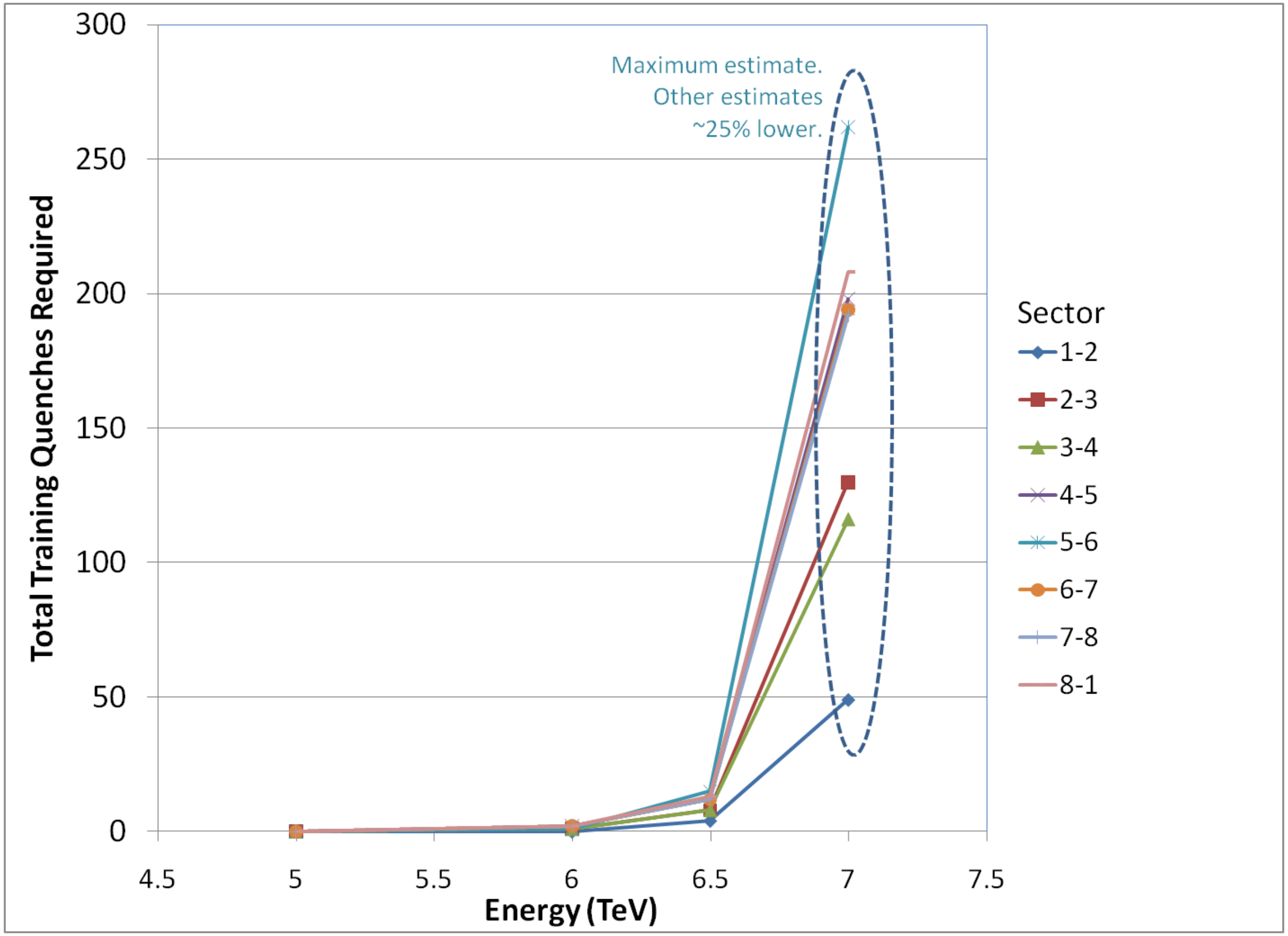
- Going beyond a few percent of the design luminosity depends on how far they are willing to push the existing collimation system.
  - Won’t really know about this until after significant running experience
- Getting anywhere near 10^{34} *requires* the Phase II collimation system
  - Details and schedule still being worked out
  - Expect some guidance from Chamonix



Projection assuming Phase II collimation and Phase I upgrade done in 2013/2014 shutdown*

*R. Assmann, “Cassandra Talk”

Getting to 7 TeV*



- Note, at high field, max 2-3 quenches/day/sector
  - Sectors can be done in parallel/day/sector (can be done in parallel)
- No decision yet, but it will be a while

*my summary of data from A. Verveij, talk at Chamonix, Jan. 2009

Closing remarks

- The LHC is the most complex scientific apparatus ever built – by a good margin
  - Only possible through the coordinated efforts of thousands of people

    “Nothing is particularly hard if you divide it into small jobs.” – Henry Ford

- After a spectacular start, an unfortunate event has delayed things somewhat, but there is no option by to learn from the incident and move forward as quickly and safely as possible, realizing that a project of this scale will always have an element of risk

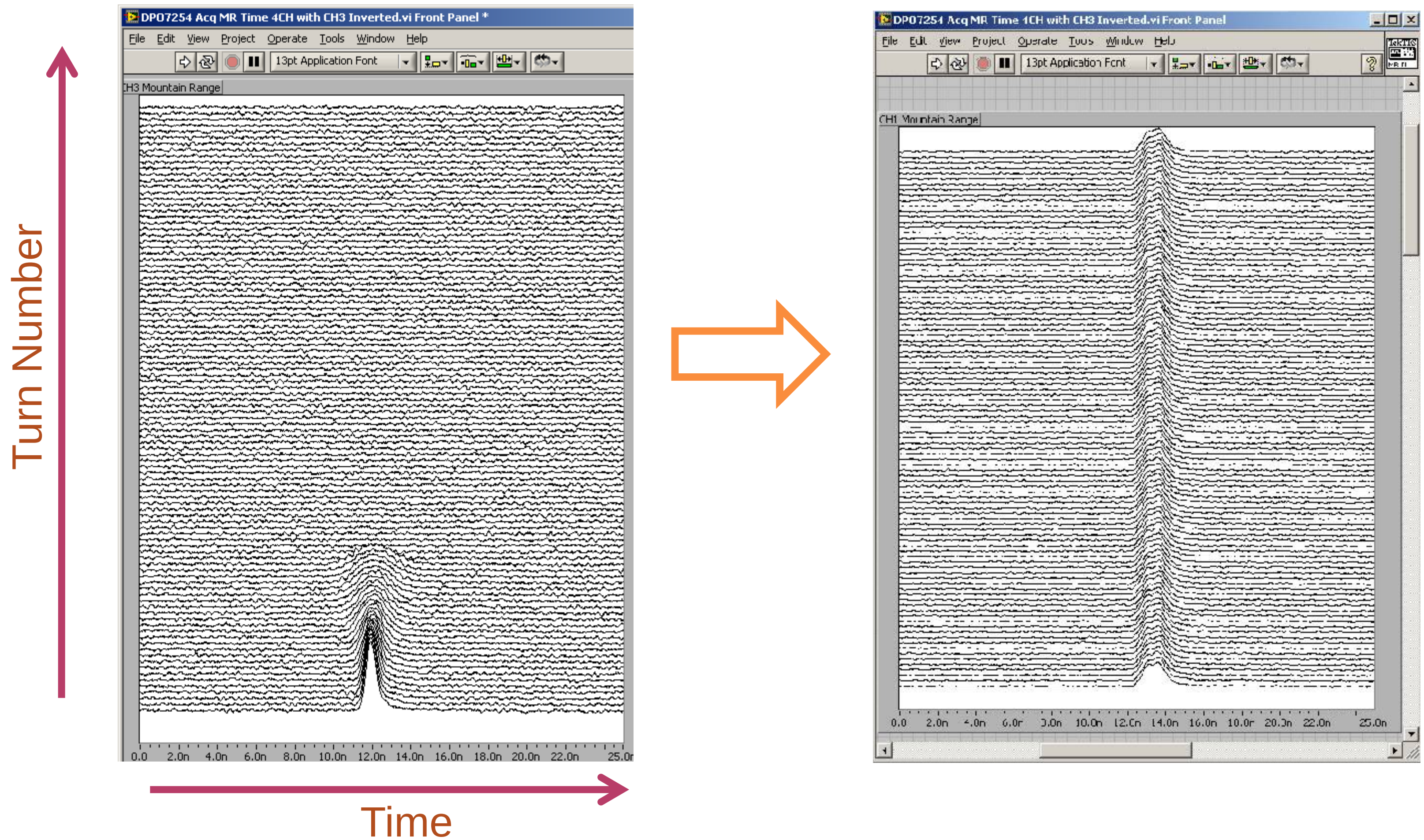
    “A ship in harbor is safe -- but that is not what ships are built for.” – John Shedd, as quoted by Steve Myers (CERN Associate Director for Accelerators)

Staying informed

- Lots and Lots of technical information
  - http://tinyurl.com/Chamonix2009
  - http://tinyurl.com/Chamonix2010
- Twitter feed (big news):
  - http://twitter.com/cern
- Commissioning log (more technical detail):
  - http://tinyurl.com/LHC-commissioning
- E-logbook (very technical, but good plots):
  - http://elogbook.cern.ch/eLogbook/eLogbook.jsp?lgbk=60
  - Only visible inside CERN network (if you have a CERN account, you can use remote desktop or VPN from US).

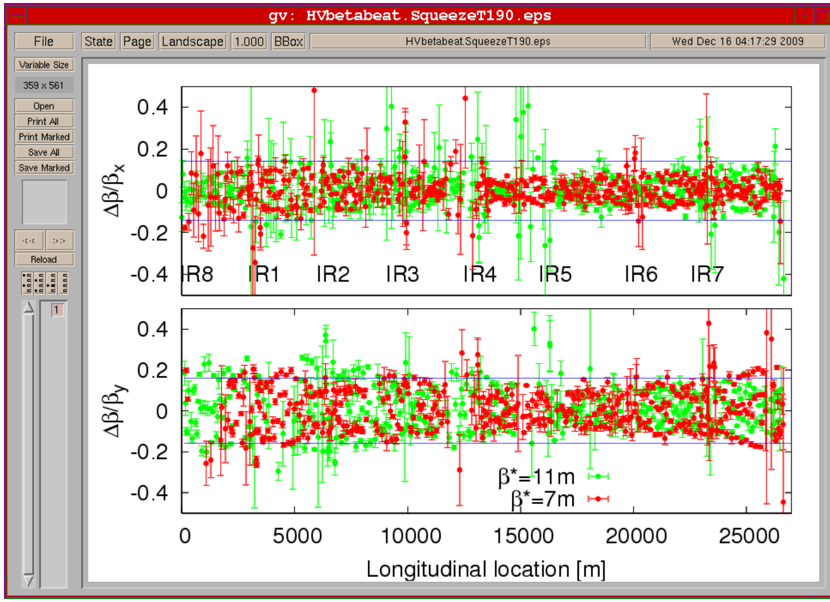
BACKUP SLIDES

After initial circulation: captured beam



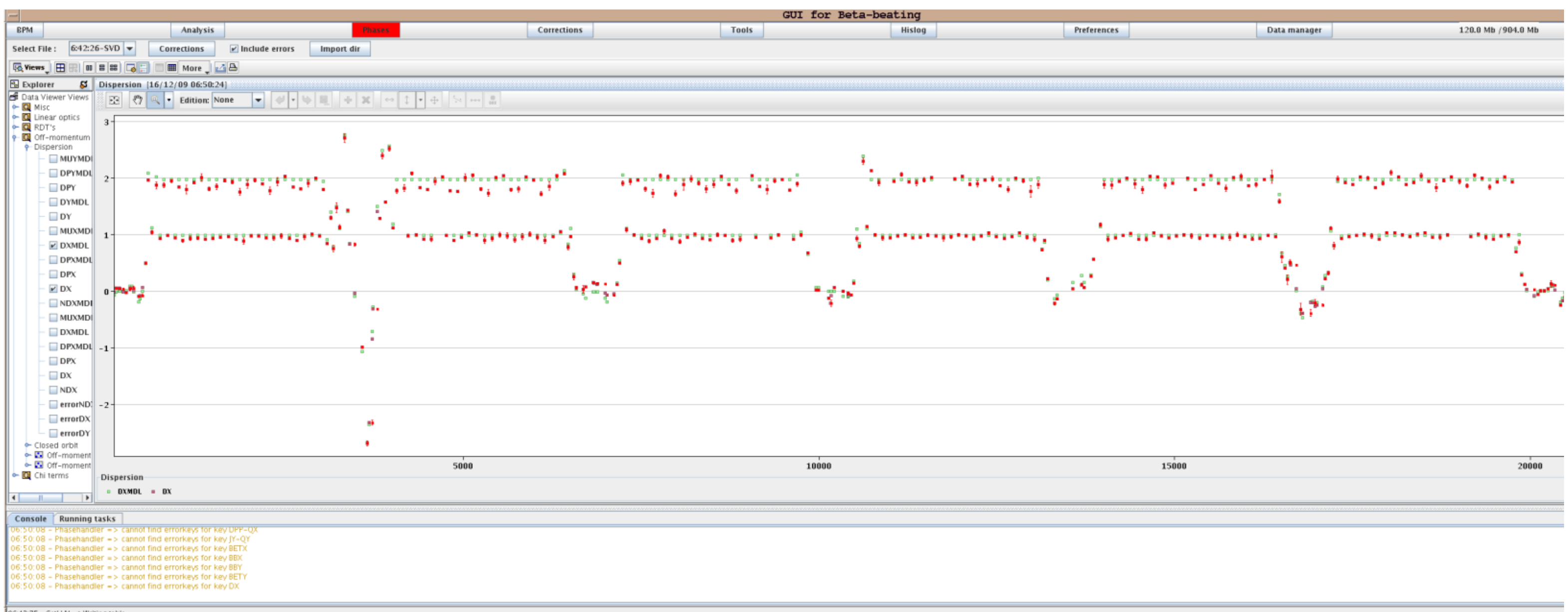
- Everything was going great until *something very bad happened* on September 19th
  - Initially, CERN kept a tight lid on news

Optics at 1.18 TeV



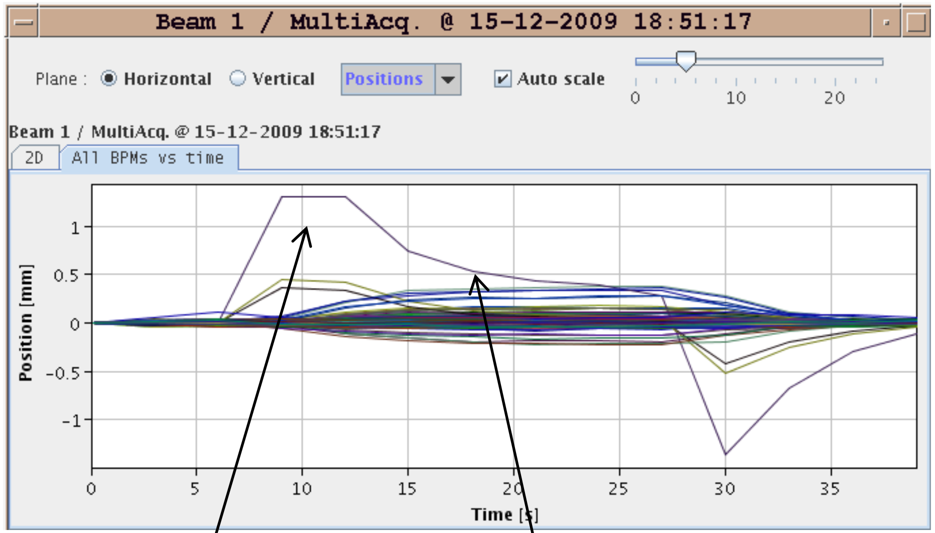
β functions

Dispersion



Beam Control at 1.18 TeV

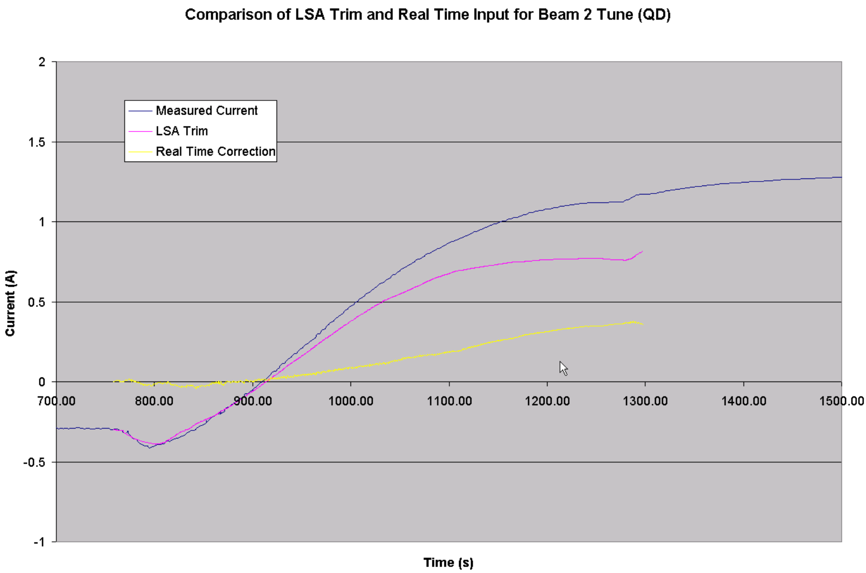
Position control



Bump introduced

Removed by feedback loop

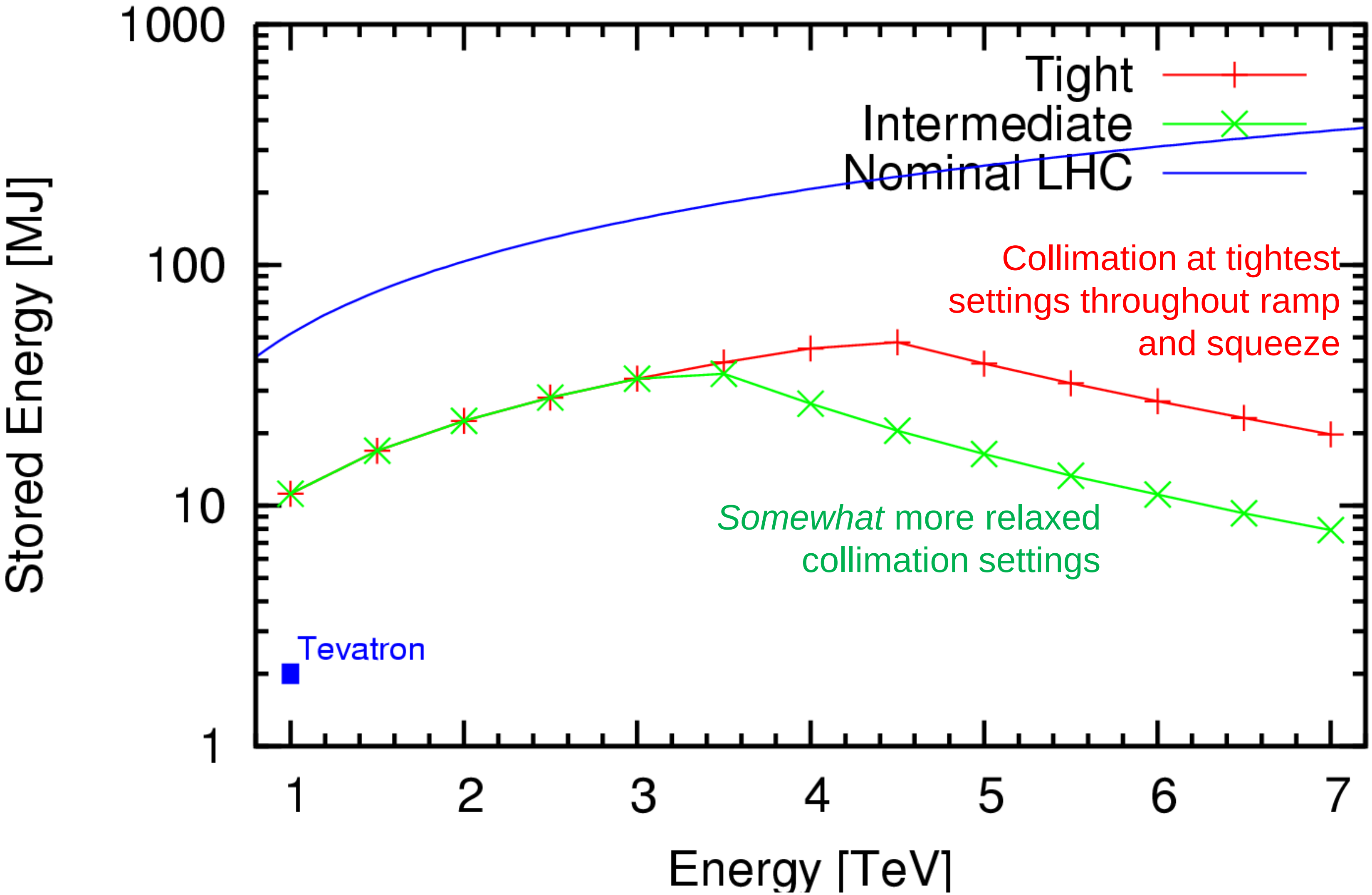
Tune feedback



Feel happy that yellow line and pink line add up to blue line

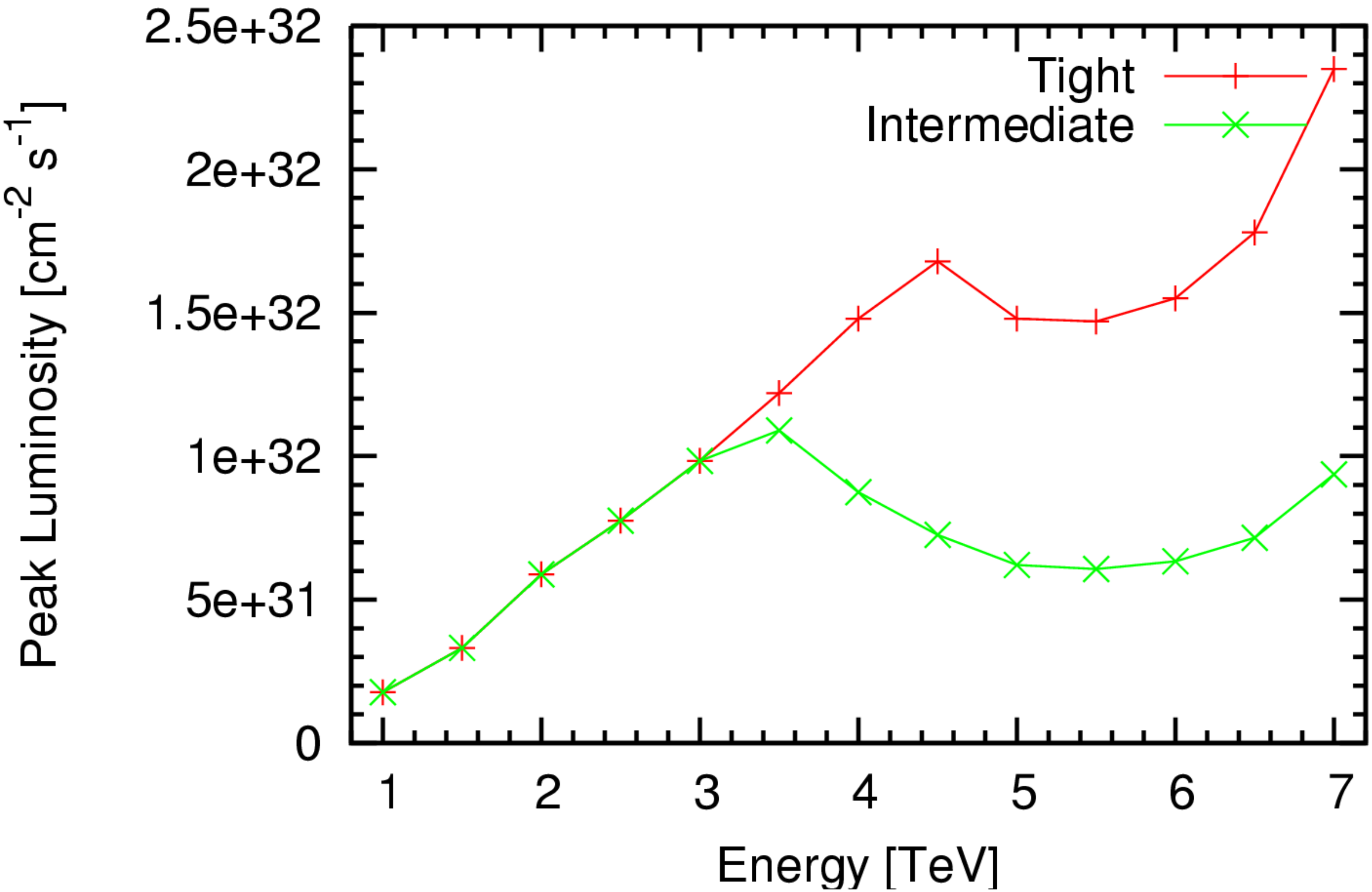
- Automated feedbacks seem to be working, but not quite yet standard operations.
- Bottom line: things look good!

Limits of Phase I Collimation System*

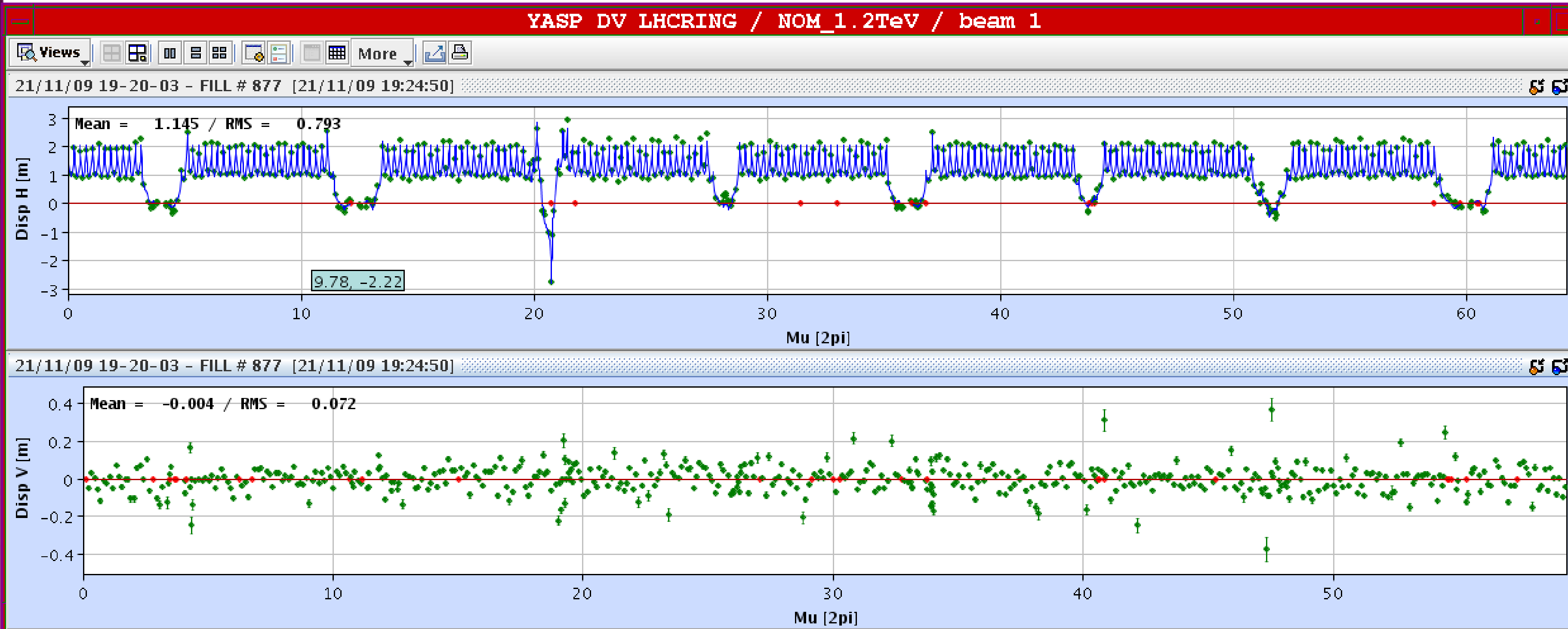


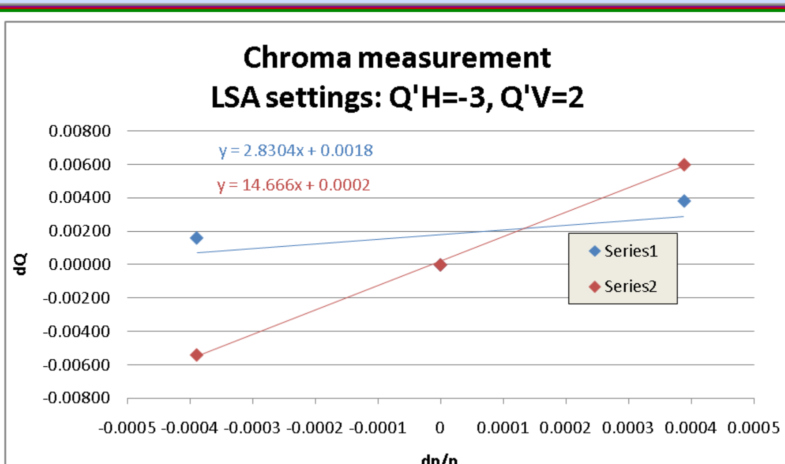
*Ralph Assmann, “Cassandra Talk”

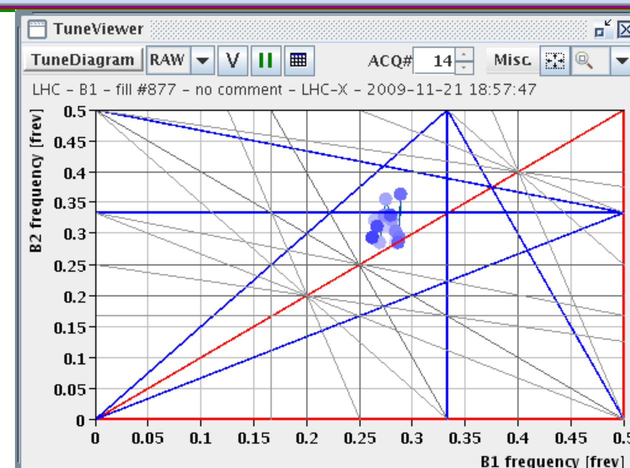
Collimation Limits to Luminosity



Optics Studies (examples)







(Main) physics run conditions