FiDeL sees first beam - What did we learn ?

Presented by L. Bottura

Thanks to L. Deniau, P. Hagen, N. Sammut, M. Strzelczyk

E. Todesco, W. Venturini-Delsolaro, R. Wolf

and the FiDeL Team (please **do** see later for the *long list*)

Chamonix @ Chamonix 2009, Session 7, February 5th, 2009

Outline

- What is FiDeL
- What we knew before August 2008
- A midsummer night dream
  - Momentum, tune, chromaticity
  - Observations on cycling
- Practical aspects and other lessons learned
- A bit of self-celebration
- The plan

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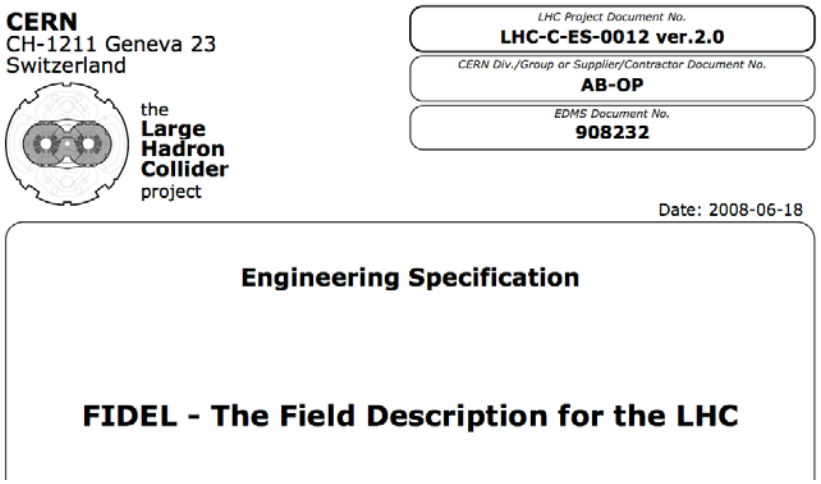
Magnetic model, FiDeL, etc. etc.

- The magnetic model of the LHC (aka Field Description of the LHC - **FiDeL**) is a **set of semi-*empirical* equations**, that are **fitted to**:
  - **Measured single magnet data**, if available, or
  - **Extrapolated single magnet data**, usually available, or
  - **Average data** for a given magnet family, always available
- The semi-empirical equations are *simple* mathematical formulae, based on a decomposition of the magnetic field in various (7) physical contributions of static and dynamic nature


CERN
CH-1211 Geneva 23
Switzerland

the Large Hadron Collider project

LHC Project Document No.
LHC-C-ES-0012 ver.2.0

CERN Div./Group or Supplier/Contractor Document No.
AB-OP

EDMS Document No.
908232

Date: 2008-06-18

Engineering Specification

FIDEL - The Field Description for the LHC

e.g., contribution of the persistent current to the transfer function

$$TF = \mu_m \frac{1}{I}\left(\frac{I_{inj}}{I}\right)^{1-p}\left(\frac{I_c - I}{I_c - I_{inj}}\right)^{q}\left(\frac{T_{c0}^{1.7} - T^{1.7}}{T_{c0}^{1.7} - T_{meas}^{1.7}}\right)^{m}$$

Similar formulae for all other harmonics and physical origins

What does FiDeL do in the LHC ?

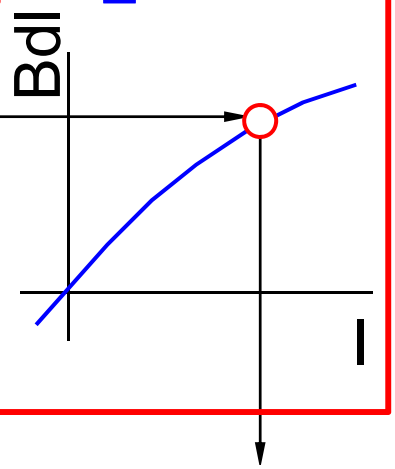
- **Today (Feb. 2009), it provides:**
  - Full-blown TF model for main magnets (optical elements)
  - Simplified TF model for correctors (linear + saturation)
  - Full-blown b3, b5 errors for the MB's (static + dynamic)
  - **On a circuit-by-circuit basis**
- **It does not provide:**
  - Accurate persistent current description for models operated at currents much below nominal
  - Hysteresis crossing of transfer functions (or harmonics)
  - Data on a magnet-by-magnet basis (or finer granularity) unless a magnet is a circuit

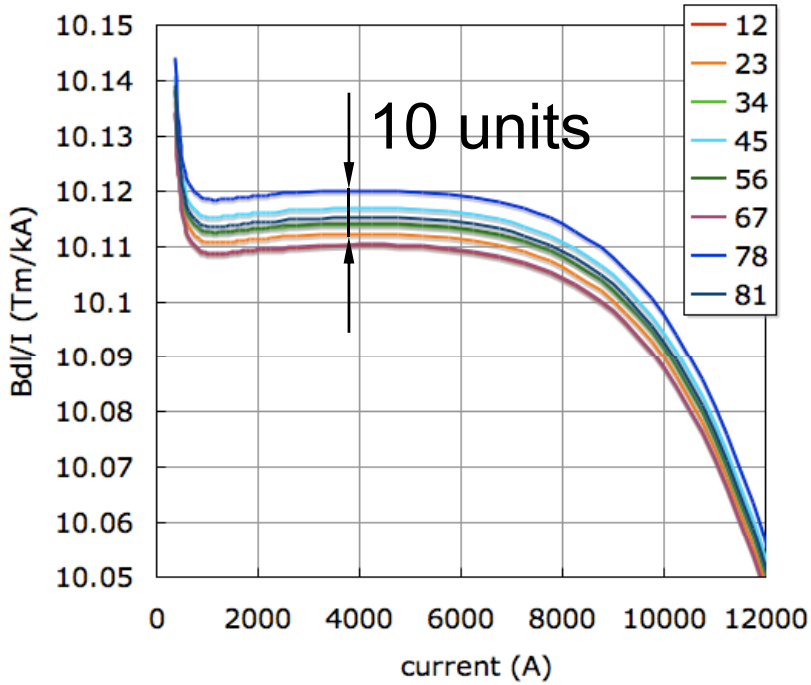
FiDeL is an integral part of the LHC controls (LSA)

The role of FiDeL

Specified optics strengths K → Field integral BdL in a magnet string → **FiDeL** → Current I(t) in the circuit

BdI_{MB} = 7.655278 Tm



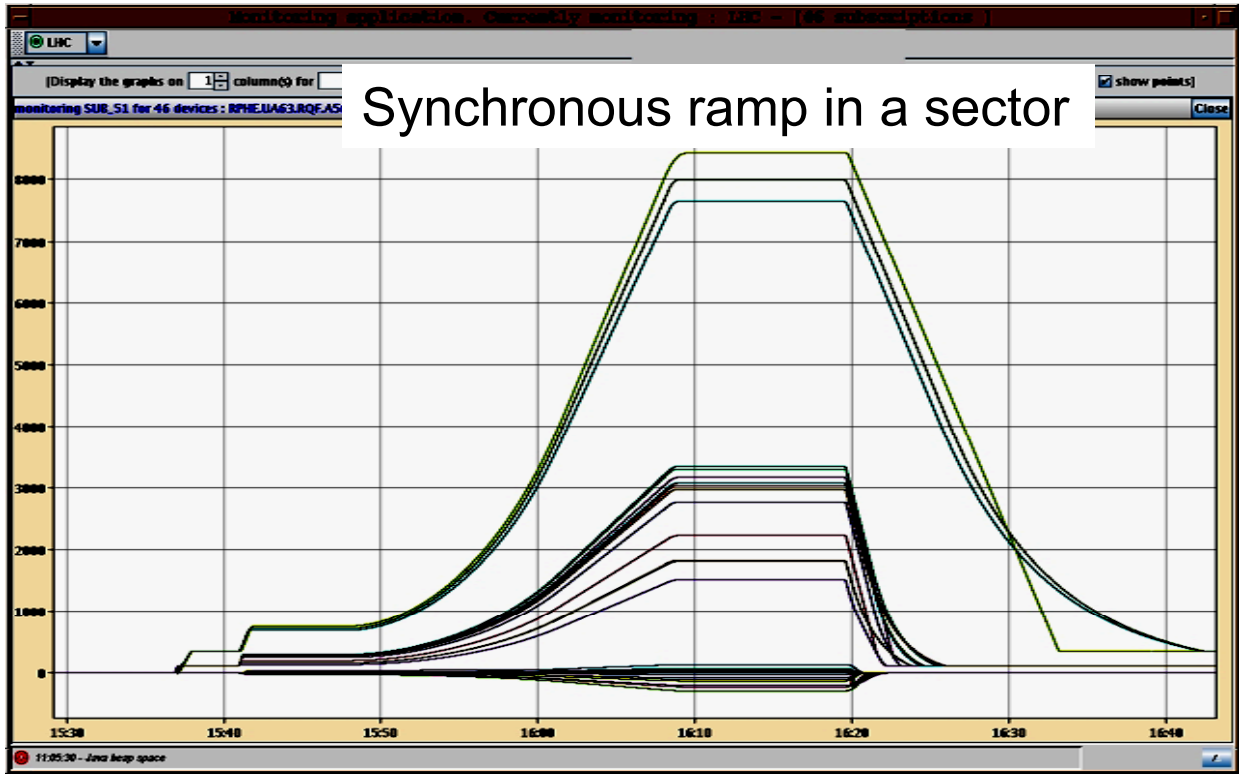


sector	IRB
12	757.206
23	757.052
34	756.924
45	756.704
56	756.907
67	757.190
78	756.471
81	756.830

NOTE: FiDeL is also used to predict field errors as a function of current, time and pre-cycle, and thus derive corrections of either static or dynamic nature. The mechanism is the same as above, only a bit more complex

Generated settings for the LHC

The **complete LHC optics** was converted in currents, dispatched to the power supplies, and played out synchronously



To the best of our knowledge this is the **most advanced model of the magnetic field in an accelerator magnet**, based on most recent advances in the physical understanding and the largest measurement database ever available

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Expected FiDeL Performance

Estimated uncertainty for commissioning (pure forecast mode) quoted in units of the main field @ R_{ref} of 17 mm

The RMS concept,
RMS international review,
CERN, July 27th, 2004

Magnetic Measurement Techniques for the LHC,
MT-19, Genova,
September 20th, 2005

		Error sources					
		sampling and W/C extrapolation	measurement error	magnet stability	powering cycle	modelling	**Estimated uncertainty**
MB							
	B1	**4.2**	**6.8**	**2.8**	**0.6**	**0.6**	**8.5**
	b2	0.26	0.11	0.05			0.3
	a2	0.46	0.12	0.25			0.5
	b3	**0.61**	**0.31**	**0.27**	**0.21**	**< 0.05**	**0.8**
	b5	0.16	0.06	0.04	0.07	< 0.01	0.2
MQ							
	B2	**10**	**17**			**1.1**	**19.8**

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Measurements and analysis by courtesy of J. Wenninger

LHC momentum - 1/2

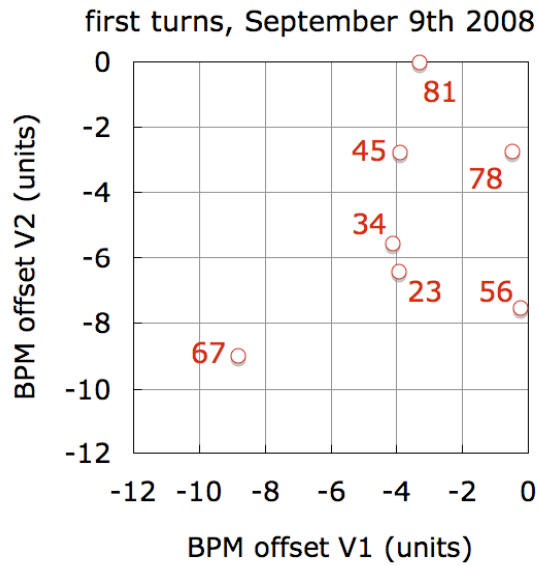
- Injection test August 8th-11th (S23)
  - LHC energy = 450.5 ± 0.2 GeV
  - **b_1 setting error = +11 ± 4 units**
- First turns September 10th
  - **b_1 setting error = +4.5 ± ??? units**
  - **Δb_1 between rings ≈ 1.5 units**
  - **Δb_1 among sectors ≈ 3 units**

Why did it change ?

Excellent !!!

First turn, September 9th, 2008

Beam 1 sector	Beam 1 offset (units)	Beam 2 sector	Beam 2 offset (units)
12		12	-3.9
23	-3.9	23	-6.5
34	-4.1	34	-5.6
45	-3.9	45	-2.8
56	-7.6	56	-0.2
67	-9.0	67	-8.8
78	-2.8	78	-0.5
81	-3.3	81	0.0



V1 and V2 are well de-correlated

Measurements and analysis by courtesy of J. Wenninger

LHC momentum - 2/2

- Captured beam 2, September 11th
  - **b_1 setting error = +7 units**
  - **Δb_1 among sectors = 2.7 units**
- Captured beam 2, September 12th
  - **b_1 setting error = +9.4 units**
  - **Δb_1 among sectors = 1.5 units**

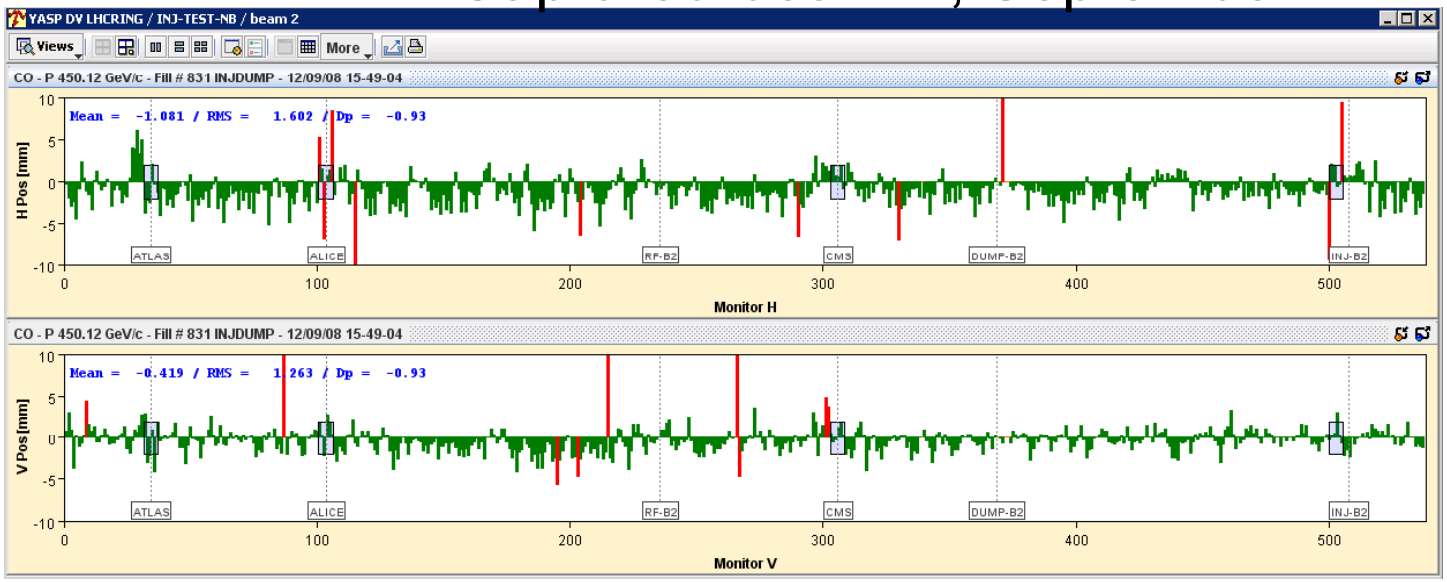
Why did it change ?

Stable !

Captured beam 2, September 12th

H offset

V offset



Summary on LHC momentum

- **The error on the energy setting of the LHC is +10 units, vs. ± 8.5 units expected uncertainty**
- The difference of energy between **beam 1 and beam 2** is of the order of **1…2 units**
- The difference of energy **between sectors** is of the order of **3 units r.m.s.**, with high de-correlation of apertures (i.e. unlikely to be an error of magnetic setting, but we need more analysis…)
- The **orbit is highly reproducible** (**≈ 1 units**) in steady conditions(inject/dump…inject/dump…), which allowed accurate corrections well below tolerances

- **??? - Energy errors from day to day varied by ≈ 5 units**

Measurements and analysis by courtesy of R. Steinhagen

LHC tune - 1/2

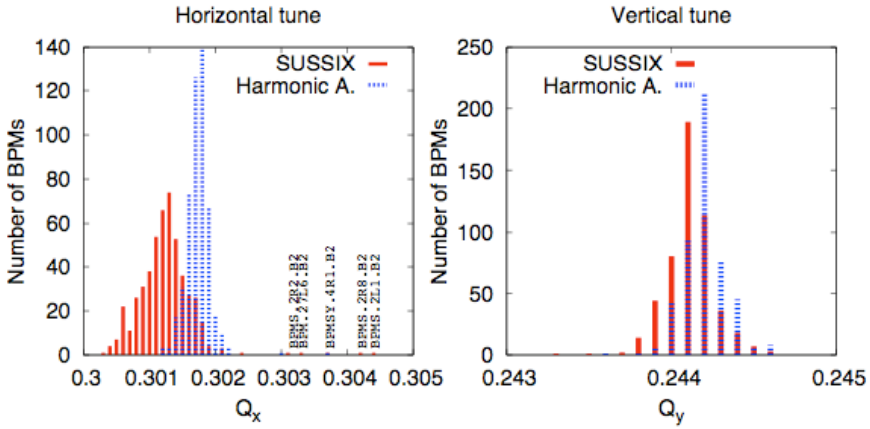
- Data available only on beam 2, but indications are that situation for beam 1 is comparable.
- Nominal tunes $Q_H = 0.28$, $Q_V = 0.31$
- First data on September 10th:
  - Initial tunes: $Q_H \approx 0.5$, $Q_V \approx 0.2 \ldots 0.25$
  - Trim study: $\delta Q_H \approx -0.1 \ldots 0.22$, $\delta Q_V \approx -0.1 \ldots -0.2$
  - Tunes at 21:33:16:
    - $Q_H - \delta Q_H = 0.3084 + 0.05 = 0.3584$
    - $Q_V - \delta Q_H = 0.2338 + 0.2 = 0.4338$

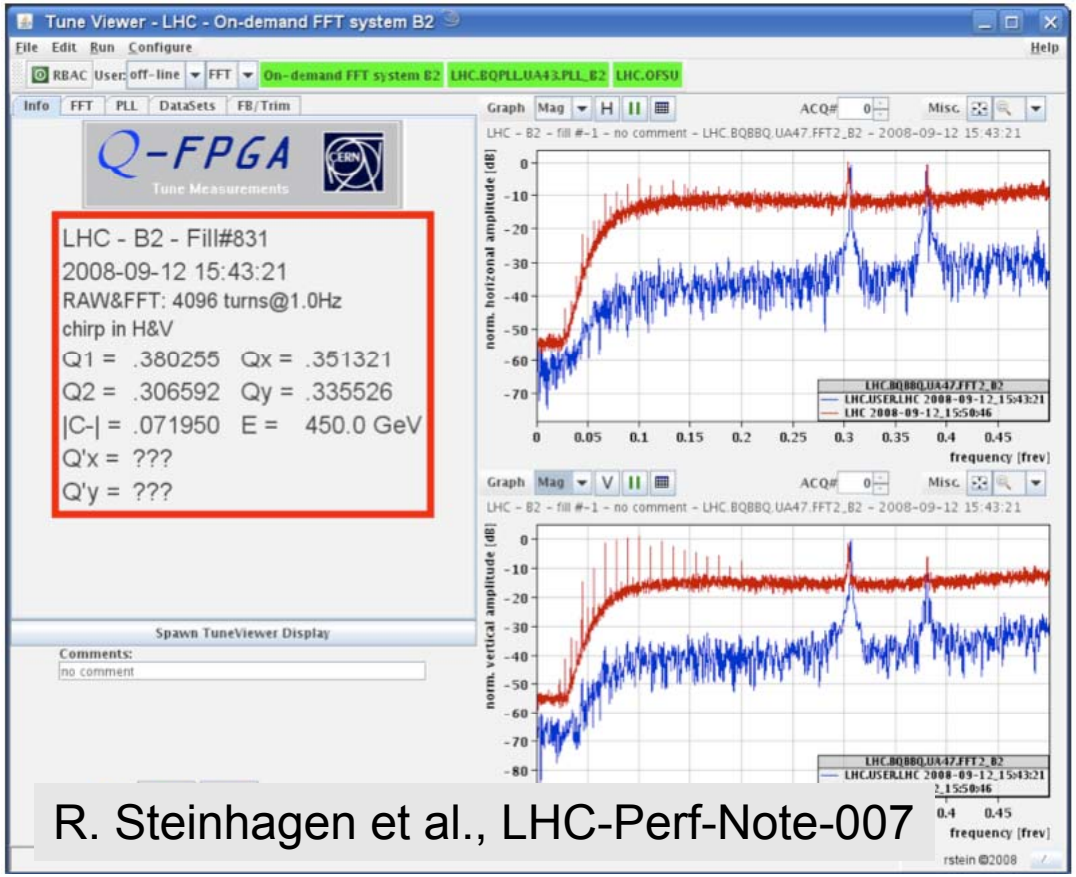
Both tunes appeared to be ≈ 0.1 from specs

LHC tune - 2/2

- Circulating beam 2 on September 12th, trims:
  - $\delta Q_H = 0.0$
  - $\delta Q_V = 0.1$
- Measured tunes:
  - R. Steinhagen et al. (LHC-Perf-Note-007):
    - $Q_H = 0.3803$
    - $Q_V = 0.3066$
  - R. Tomás et al., (LHC-Perf-Note-008):
    - $Q_H = 0.3015$
    - $Q_V = 0.2441$

R. Tomás et al., LHC-Perf-Note-008



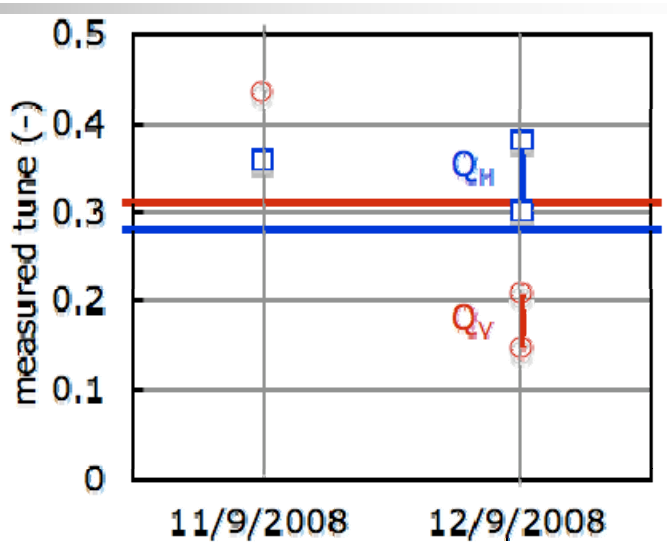


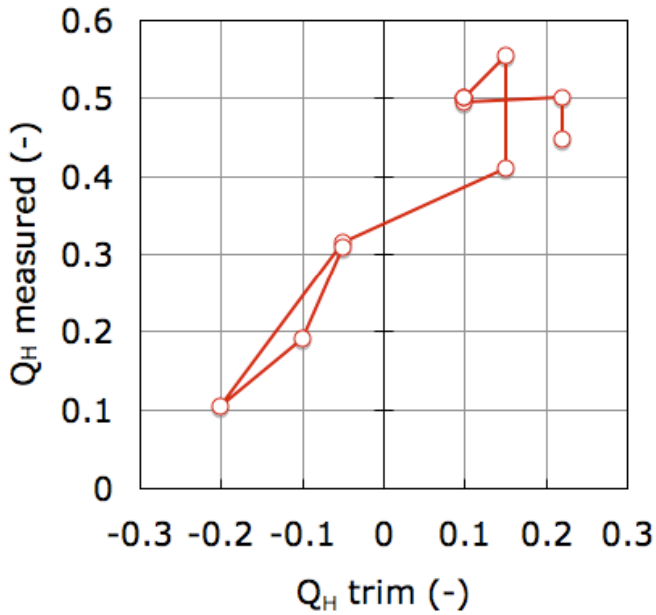
R. Steinhagen et al., LHC-Perf-Note-007

Measurements and analysis by courtesy of R. Steinhagen

Summary on LHC tunes

- **Measured tunes are within 0.15 (0.1) of the nominal ones, i.e. to ± 25 (16) units quadrupole setting error, vs. an expected uncertainty of ± 20 units**
- **??? - Vertical tune errors varied from day to day by 0.2 units**
- **??? - The tune trim appears to have a significant hysteresis, 0.05 to 0.1 units of tune**





Measurements and analysis by courtesy of R. Steinhagen and R. Tomás

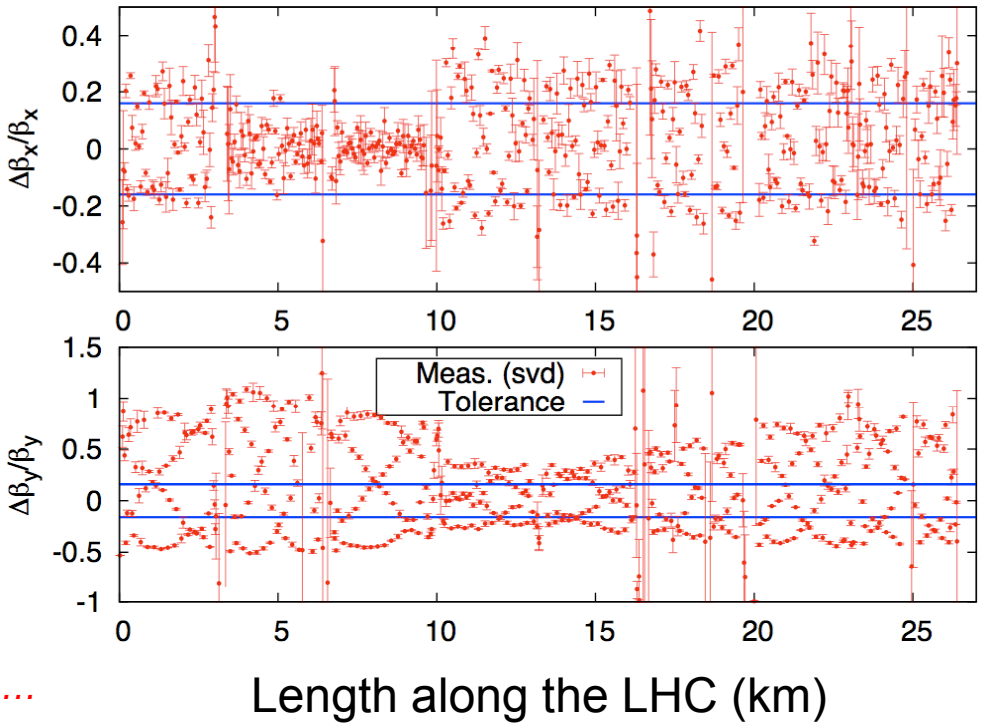
LHC coupling and beta-beating

- Coupling (not corrected) was measured on beam 2 in the range of 0.07 (R. Steinhagen et al., LHC-Perf-Note-007), compatible with the expected value of 0.04 (S. Fartoukh and O. Bruening, LHC Proj-Note-501).
- Measured beta-beating:
  - $\Delta\beta_x/\beta_x \approx 20\ldots30$ %
  - $\Delta\beta_y/\beta_y \approx 100$ %
- Expected values from simulations based on field and alignment errors (P. Hagen, et al, EPAC08):
  - $\Delta\beta/\beta \approx 15$ %

How about it, Steve ?!?

*Well, OK, something **is** fishy in the vertical plane…*

R. Tomás et al., LHC-Perf-Note-008



Measurements and analysis by courtesy of R. Steinhagen

Chromaticity

- Circulating beam September 11th
  - Q'_{trims} = +2, +5, +10, +20, -20, -30 (P. Collier and W. Venturini-Delsolaro). Stable beam at Q'_{trims} = 30 units
- Captured beam September 12th
  - $Q'_{measured}$ = 32 ± 2 units
- **Beam 2 has a chromaticity of ≈ 30 units, corresponding to 0.7 units of sextupole in the MB's, vs. ± 0.8 units expected uncertainty**
- **NOTE: the b3 decay correction (≈ 0.2 units) was deliberately ignored (not applied to the injection settings) to simplify operation procedure**

Summary of beam measurements

Expected vs. measured field errors (in units)

	Expected uncertainty	Setting error	Setting reproducibility	Trim error
B_1	8.5	10	**5**	1
B_2	19.8	20	**30**	15
b_3	0.8	0.5	**0.7**	

Measured values broadly confirm expectations for the machine setting. However, reproducibility and tune trim errors are relatively large - **why ???**

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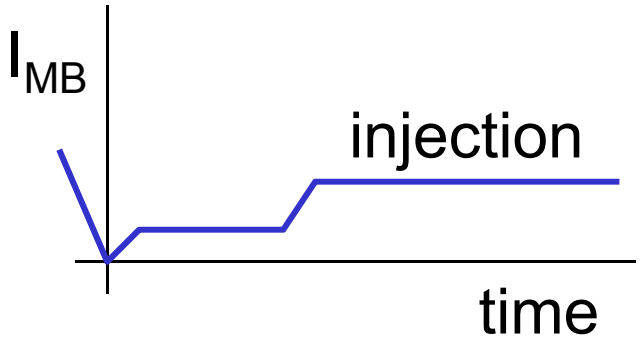
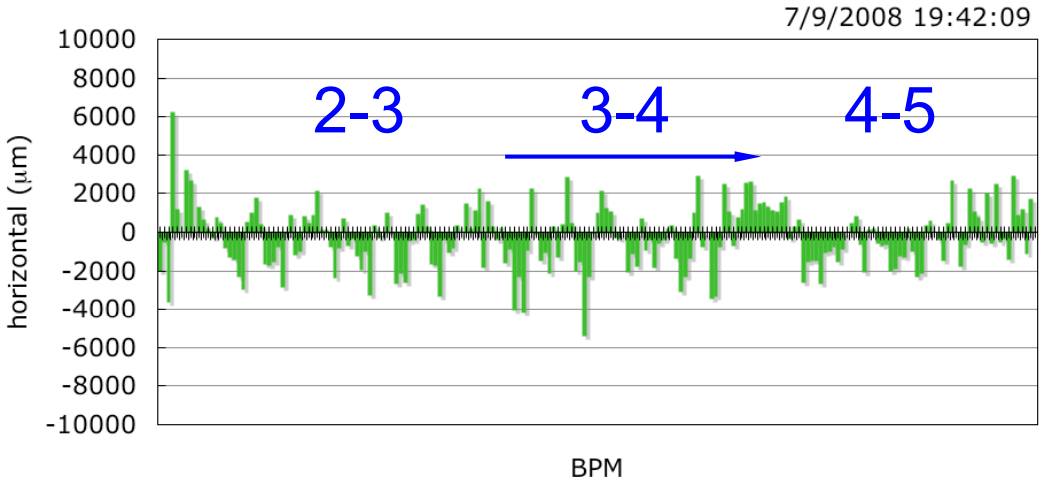
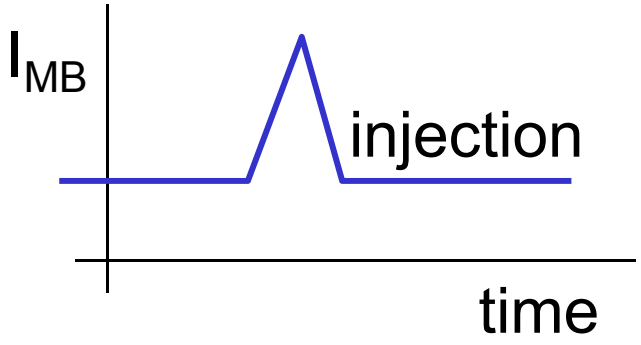
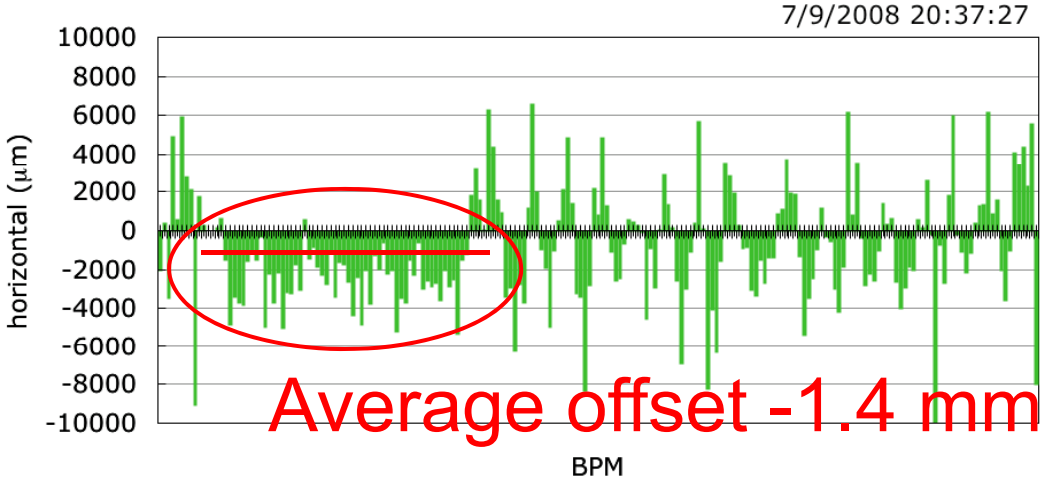
B_1 changes vs. cycling



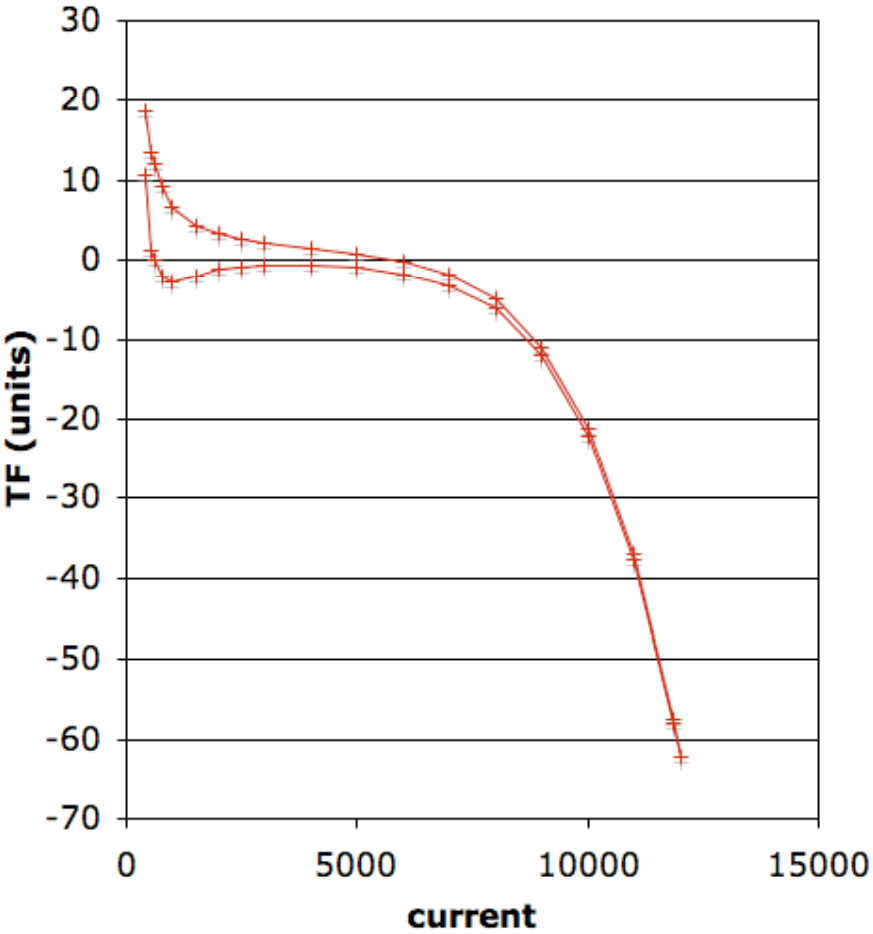
Measurements of 7/9/2008

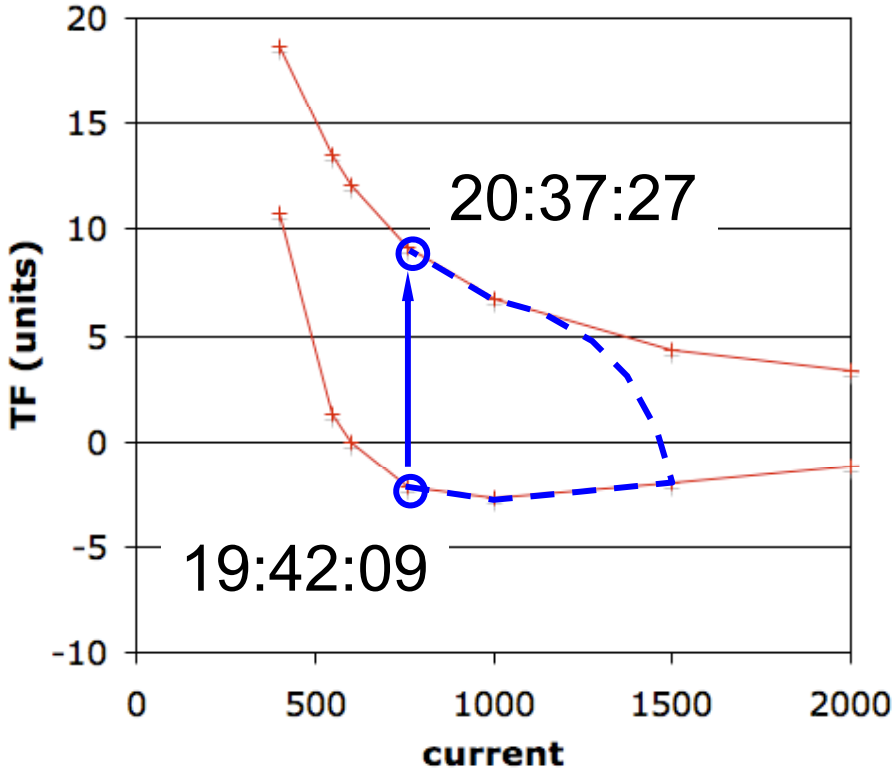






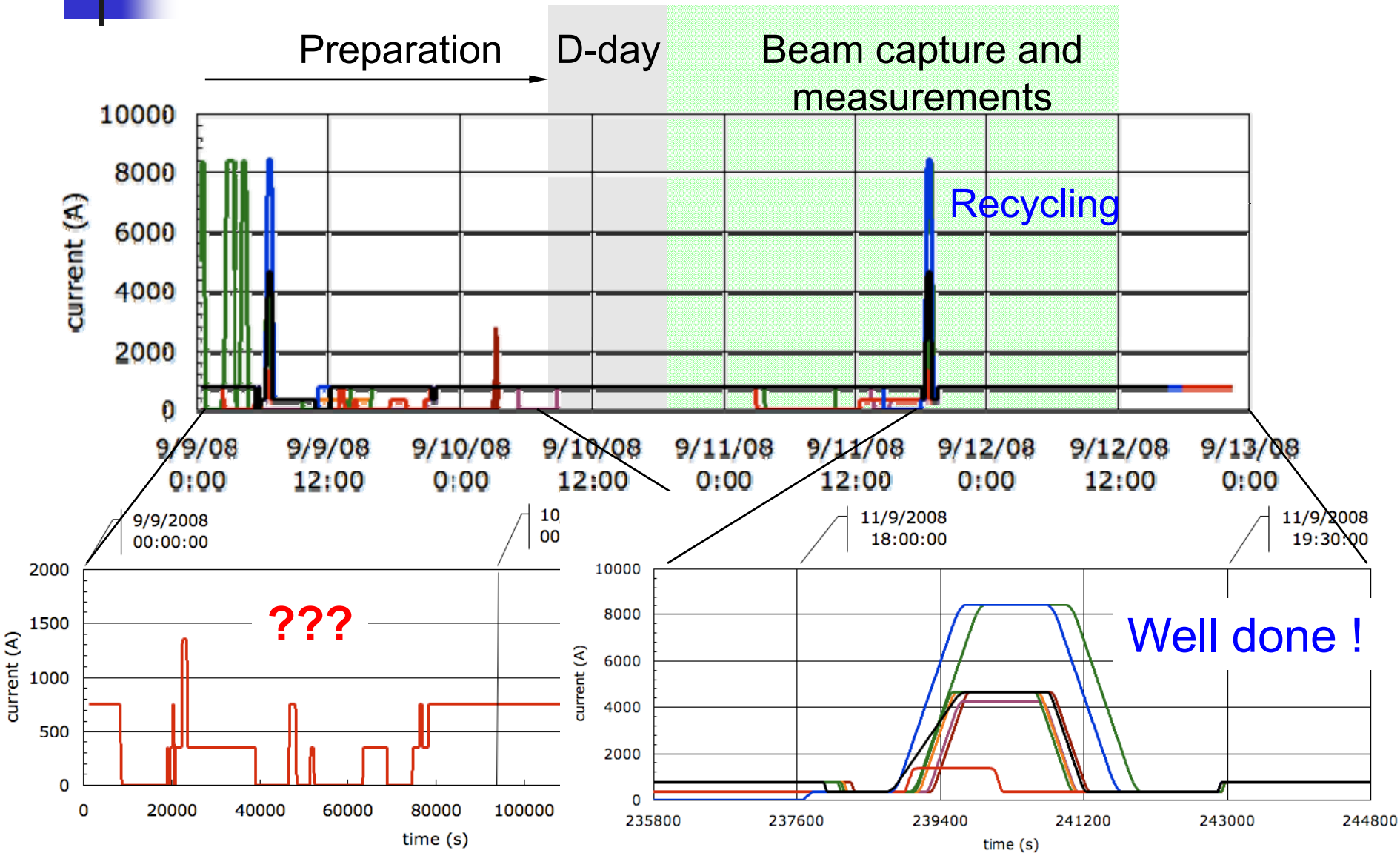
Details of B_1 changes





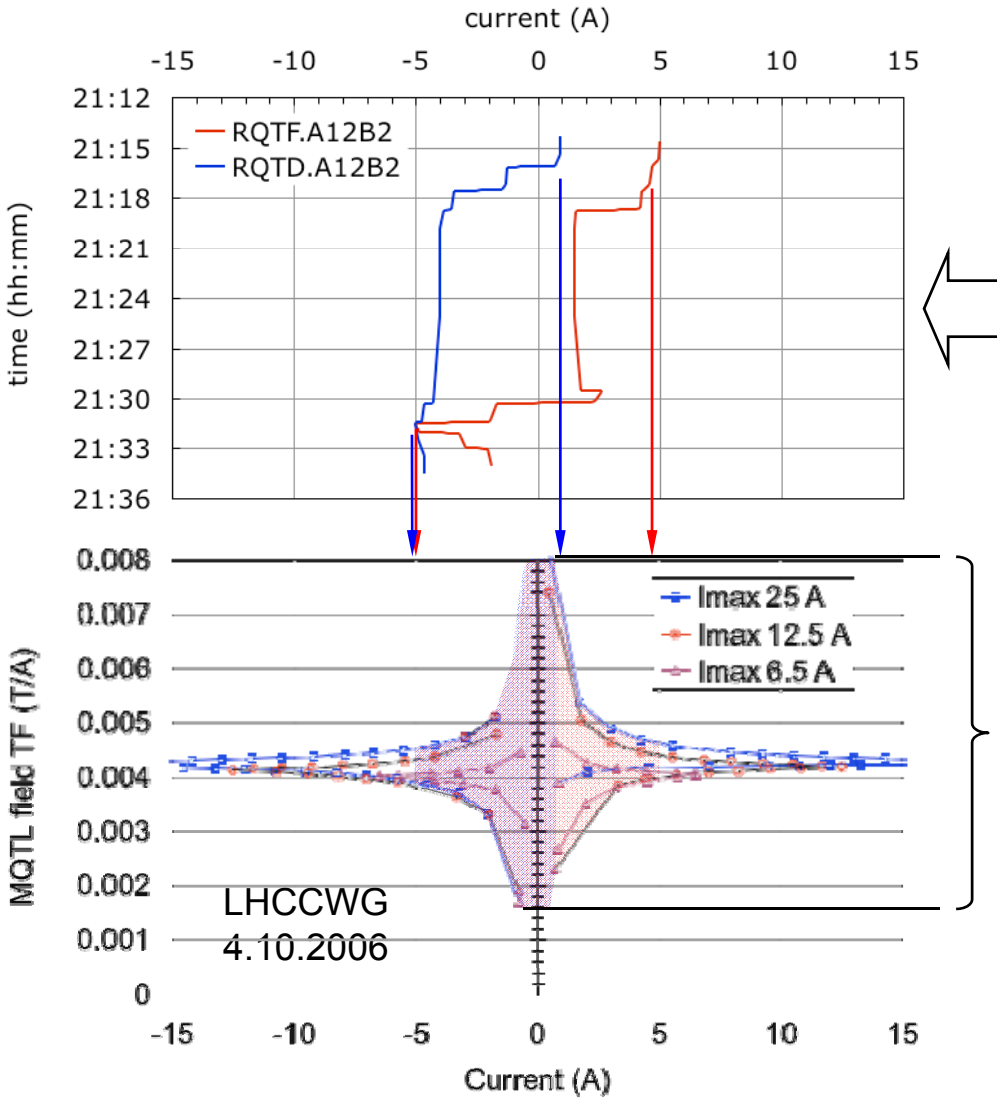
Expected change +11 units
Measured change +16 units

Machine cycles for first beam



Measured MQTL data by courtesy of W. Venturini-Delsolaro

Tune trims



xterm

```
LSA.cern.ch> dumpLSA -v QT_trim
ENTER> starting time
9/10/08 21:15:00
ENTER> end time
9/10/08 21:35:00
Time (local)            QH trim     QV trim
9/10/08 9:17 PM         0.22        -0.1
9/10/08 9:18 PM         0.22        -0.2
9/10/08 9:22 PM         0.1         -0.2
9/10/08 9:22 PM         0.1         -0.2
9/10/08 9:23 PM         0.1         -0.2
9/10/08 9:25 PM         0.1         -0.2
9/10/08 9:29 PM         0.15        -0.2
9/10/08 9:30 PM         0.15        -0.2
9/10/08 9:31 PM         -0.05       -0.2
9/10/08 9:31 PM         -0.2        -0.2
9/10/08 9:32 PM         -0.1        -0.2
9/10/08 9:33 PM         -0.05       -0.2

LSA.cern.ch> _
```

Requested trims

(assuming MQT ≈ MQTL, L_{mag} = 0.32 m)

$u(B_2\ dl)$ (1 A) ≈ 2 mT m @ 17 mm

$u(Q) \approx 0.06$

in the range observed

Abominable working points

- Several circuits set to < 1 % of nominal (of the order of 1 A and smaller) for the injection optics:
  - RCBH, RCBV (orbit correction) - this should be OK
  - RCO (MB b_4 compensation) (I_{min}=1.14 A, I_{nom}=100 A)
  - Cold arc RQT (MQT, I_{min}=48 mA, I_{nom}=550 A)
  - Warm RQT (MQWB, I_{min}=0.9 A, I_{nom}=600 A)
  - RQTL (I_{min} = 37 mA, I_{nom}=550 A)
- Requires ***tiding up* the optics** to attain a range of current suitable for precise control:
  - Shift working point, introducing an injection offset
  - Eliminate magnets from the optics if not needed
  - Other solutions will surely be found thanks to the unlimited ingenuity of our ABP colleagues

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Lessons learned - 1/2

- **We are in the right ball park for all settings !** This confirms the work so far, and gives clear indications on priority work for the next 6 months (see later for “The Plan”)
- **Non-nominal cycles are most likely the reason for the reproducibility issues observed.** A corollary is some confusion in the measurements (day-by-day variations). Objectively, it was simply impossible to do otherwise, and we are just happy it worked. We need to be more rigorous for the next runs

Lessons learned - 2/2

- **It was vital to be on the spot**, under a formally defined role (*system commissioner*) because we could:
  - Check the settings and give immediate feed-back
  - Be aware of the progress, single out issues and participate to the debugging
  - Get feed-back on the quality of our work
  - *Play* with the LHC (e.g. anomalous cycle in S23)
- We should have planned for **more time** (to prepare and verify settings) and for **better tools** (to query and evaluate settings in CCC)

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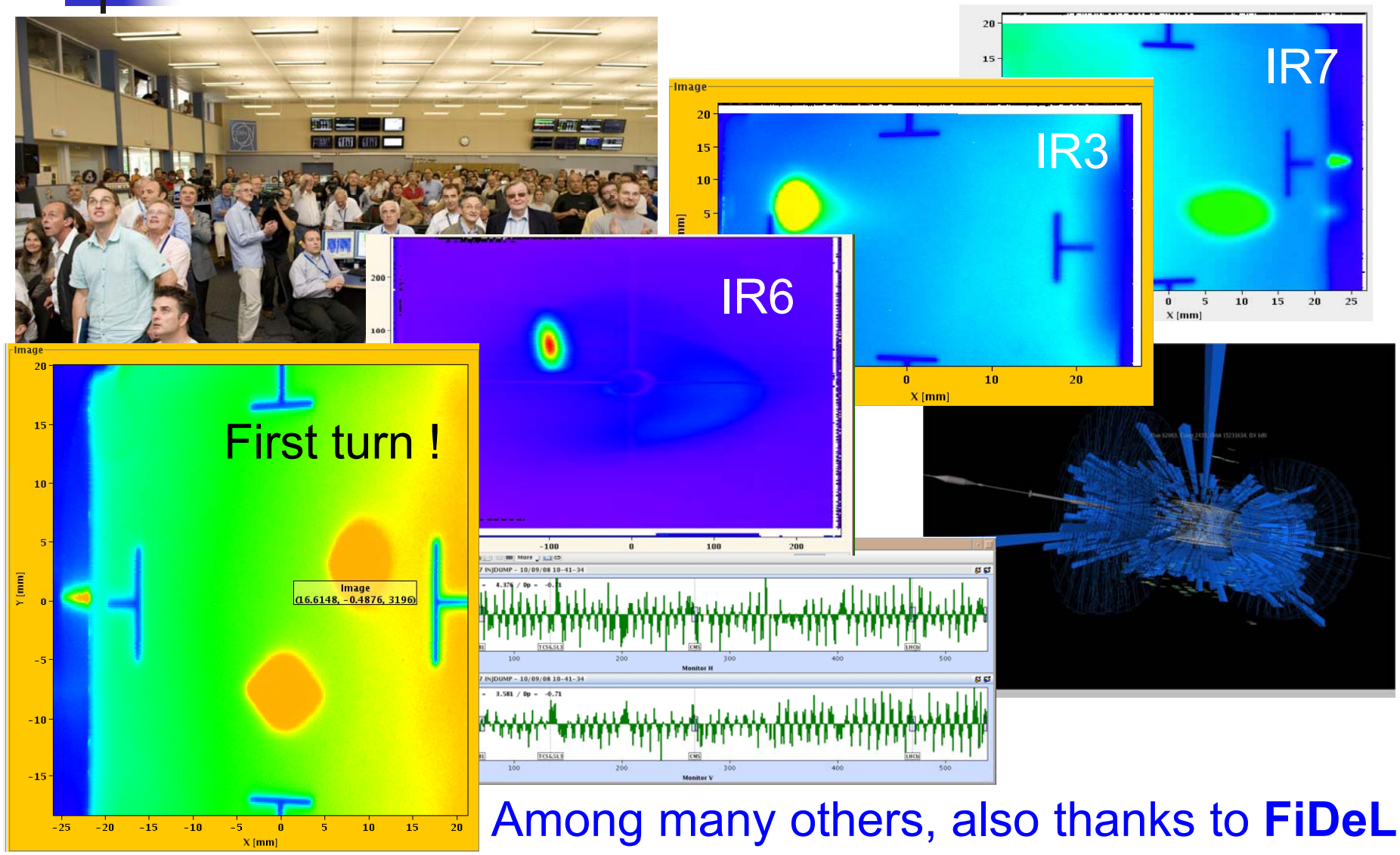
We have come a long way…

- First idea of a magnetic model presented at the DEWG in 1996, led:
  - first to the decision to displace reference magnets on the surface (1997, saving of 20 MCHF work in the tunnel),
  - then to the decision of eliminating reference magnets altogether (2004, saving of 5 MCHF in SM-18) …
- … 10 years of measurements, dedicated instrumentation R&D, 4.5 millions of 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 to runs in Tevatron and RHIC …
- **… today, we have the most complex and comprehensive field forecast system ever implemented in a superconducting accelerator**

… and it was BRILLIANT !!!



Among many others, also thanks to **FiDeL**

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The Plan (for the next 6 months)

- Complete this review of the results (**beam vs. expected**)
- Create a **database of reference data** and model parameters. Document. *Tidy-up and check, check, check…*
- **The ramp !!!** Verify settings, check tracking, try on dry-runs
- Tidy-up optics, revise settings and iterate on model, especially for **insertion quadrupoles** (MQM, MQY), and **trims** (MQT, MQWB)
- Complete **cycling prescriptions**, *indoctrinate operators*
- New data (**measurements**) of magnets where we expect issues such as MQM, MQY, MQT, MQW, simulate trim and squeeze
- Consolidate the **FiDeL support team**, by maintaining a *sensitivity to values of the order of 1 unit*

The long list

- It is a pleasure to acknowledge the work of many colleagues over the many years, and especially:
  - Reyes Alemany Fernandez, Gilles Berard, Marco Buzio, Nuria Catalan Lasheras, Laurent Deniau (secretary for the team), Mario Di Castro, Massimo Giovannozzi, Per Hagen, Jean-Pierre Koutchouk, Mike Lamont, John Miles, Vittorio Remondino, Nicholas Sammut, Stephane Sanfilippo, Frank Schmidt, David Sernelius, Marek Strzelczyk, **Ezio Todesco**, Walter Venturini-Delsolaro, Louis Walckiers, Rob Wolf, Panagiota Xidi

NOTE: in blue those presently *active* in the FiDeL team

Backup material

Accuracy by magnet family (WIP)

Modeling error indicators on integral transfer function

Circuit type	ε_{rms}	ε_{max}	$\varepsilon_{injection}$	$\varepsilon_{flat\text{-}top}$	$\sigma_{magnets}$
MB	0.2	0.6	0.1	0.1	≈ 5
MBX (D1)	4.2	8.8	1.4	4.8	
MBRC (D2)	0.7	1.2	1.0	0.5	
MBRS (D3)	3.6	6.4	0.6	5.3	
MBRB (D4)	0.6	0.9	0.7	0.6	
MQ	0.5	1.1	0.1	0.4	≈ 10
MQM	1.1	5.7	0.5	1.0	
MQY	1.3	9.5	1.2	1.1	
MQXA	5…6	10	3	5	
MQXB (modeling in progress)	EZIO				
MQWA	8.6	28	1.2	12	
MQWB	7.6	29	0.5	5.6	
Q6 (6 x MQTL) (TBD)	ROB				
Correctors	≈ 5				≈ 50

Caveats on expected accuracy

- MBX (D1) have only scarce cold database, at 4.5 K, and operate at 1.9 K (W/C correlations and temperature scaling applied)
- MQM and MQY (Q4…Q11) have a relatively large modeling error (o(10 u)) in the range of injection currents (*partial penetration* regime)
- MQXA and MQXB (Q1…Q3) have limited *cold* database, modeling based on various interpolations and extrapolations
- MQWA and MQWB (Q1…Q3) lack data at injection setting
- corrector hysteresis is not taken into account in the estimates, generally small but for MQT in the nominal range of trim

This is what we already knew,

and compensated for by *experienced guesses*

FiDeL and related work (MARIC, March 1st, 2006)

Phase I

- Short term (*2006 to sector test/commissioning*)
  - Define and validate the model
  - Create a common data structure
  - **Collect, prune, and complement data for all magnet types**
  - **Generate the configuration sets from the circuit and machine layout**

Phase II

- Medium term (*2007-2008*)
  - Participate in the implementation and test of the LHC configuration and control system
  - Prepare for commissioning through studies of the effect of magnetic uncertainties (within the scope of FQWG)
  - **Adapt the parameters sets and create parameters trims tables during sector test/commissioning**
  - **Define, perform and analyse measurements on off-line benches in SM-18**

Phase III

- Long term (> *2008*)
  - Maintain data structures, tools and settings
  - **Participate/motivate MD and dedicated field measurements to optimise LHC operation**

time

NOTE: dates intentionally left unchanged from those announced at MARIC of March 1st, 2006

Summary of work done

Task	*completed*	*Estimated manpower (men-months)*	*Required manpower (men-months)*
Model Specification	Jan 2008	1	≈ 2
Create FiDeL data structures	Apr 2007	3	≈ 3
Implement FiDeL Engine	Apr 2008	4	2(1)
Normalization cycles	May 2008	2	≈ 2
Magnetic data consolidation	-	20	≈ 40(2)
Data modeling (circuits TF)	-	-	18(2)
MB/MQ/correctors powering and tracking test	Dec 2007	6	10
Sector powering test	-	-	-
Adapt WISE interface to FiDeL	Jun 2008	2	2
Total		**38**	**≈ 79**

NOTES:

(1) Evaluation of parameters from REFPARM files

(2) Work in progress, approaching completion