Outline

• Controls technology
  → the good old days
  → the intermediate period (the 1980’s…)
  → controls technology today

• What it needs before we can inject beams:
  A rapid walk through technical services

  • Controlling beam parameters…
    the central masterpiece of accelerator control

  • Additional circuits to improve/protect the accelerator… magnet protection, beam abort, power abort, real time feedbacks, insertion alignment feedback
Controls technology

• ...did barely exist in the « good old days ». Machines were small in size and all equipment control was routed via cables into a central control room.
• Switches, potentiometers and indicators (lampes, meters) were physically installed in the control room.
• Beam Diagnostcs was done with instruments locally in the control room.
The intermediate period...

- Onset of computer control…
- No widely accepted industry standards existed for front-end computers and for console computers; low educational level of technical staff on computer technology
- Complete lack of standards for real time operating systems and systems intercommunication.
- Networking only in its beginning
- Performance limits of computers were significant. Still many systems (beam instrumentation and RF) with direct high frequency cables to control room.

- In terms of controls: a total mess

The CERN Control Center
Workstation distribution

4 islands (TI, PS complex, SPS+EA, LHC) open towards each other
Access to each island without interfering with the other ones
Shared central area
Minimisation of acoustic interference while allowing visual contact

Workstation

3 fixed displays split between 2 workspaces
3 flat screens per workspace
1 keyboard
1 mouse
1 additional admin PC
Inside CCC

A typical Operator Console

- **Acoustic panel used as back door**
- **Screens with tunable distance and tilt**
- **PCs hidden but easily accessible**
- **Table height 72cm, American Oak look**
- **Task lighting**
Some keywords for LHC controls technology

- Base the HW architecture on available commercial standards and COTS:
  - VME64x standard for complex embedded I/O system with high performance demands
    (Commercial VME PPC processor boards, including O/S integration and support (LynxOS))
  - Commercial cPIC Intel based processor boards (Concurrent Technology for the time being)
  - Commercial serial controller boards, ADCs, ...
  - Commercial industrial PC platform for non-embedded systems (WorldFIP, PLC control)
  - HP Proliant servers for application servers and file servers
  - WorldFIP for applications requiring RT fieldbus features and radiation hardness
  - GPS for time stamping and overall accelerator synchronization

- Apply whenever possible vertical industrial control system solutions:
  - Siemens and Schneider PLCs for industry-like process control (Cryo, vacuum, electricity, RF power control, BT power control)
  - Supervisory Control and Data Acquisition Systems (SCADA) for commands, graphical user interfaces, alarms and logging

- Restrict home-made HW development to specific applications for which industrial solutions are not available:
  - VME boards for BIC, BST, Timing

- distributed system architecture, modular,
- data centric, data driven,
- n-tier software architecture,
- Java 2 Enterprise Edition (J2EE) applications, Java technology,
- XML technology,
- client/server model,
- Enterprise Java beans technology,
- generic components,
- code generation,
- Aspect oriented programming (AOP)

Architecture - 3-tier approach

- We wanted to deploy the system in 3 physical layers due to:
  - Central access to the database and to the hardware
  - Central security
  - Caching
  - Reduced network traffic
  - Reduced load on client consoles
  - Scalability
  - Ease of web development

- With a minimal cost of 3-tier architectures
  - Complexity of programming
  - Testing & debugging
  - Deployment

- Plus we needed support for standard services
  - Transactions, remote access,...
Architecture

- Modular
- Layered
- Distributed

Applications
LSA Client API
Spring RMI Remoting / Proxies

LSA Client API
LSA Client implementation
LSA CORE
(Settings, Trim, Trim History, Generation, Optics, Exploitation, Fidel)

JAPC
JAPC CMW/RDA
Spring JDBC

CORBA IIOP
JDBC

Business Tier (Web Container)

CORBA IIOP

Devices

Datastore

17/10/2007
LHC Software Architecture – ICALEPCS 2007 – Grzegorz Kruk

...and an uncountable number...
Technical Services

All we need even before thinking of injecting beam:

- Electrical supplies
- Uninterruptible Power Supplies (UPS), Arret Urgence Generale (AUG)
- Cooling & Ventilation
- Cryogenics systems
- Vacuum systems
- Access System (Personal Safety)
- Interlock Systems (Material Safety) i.e. powering interlocks, quench protection system
- General services (temperature monitoring, radiation monitoring)

The “look and feel” of all these systems example: vacuum system for LHC transfer line
A typical implementation

Finally: Beam Control

→ Transfer lines
→ Injection and Extraction (beam dumping system)
→ Beam optics controls
  i.e. all power converters
→ Beam instrumentation
→ RF
→ Beam interlocks
→ Collimation
→ Real Time feedbacks
→ Machine Protection
→ Timing Systems
→ Radiation monitors

Static and dynamic control,
We will discuss in detail the setting at injection and the ramping of the main dipole power converter

<table>
<thead>
<tr>
<th>Amps</th>
<th>Time (Seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>760.00</td>
<td>0</td>
</tr>
<tr>
<td>760.02</td>
<td>2</td>
</tr>
<tr>
<td>760.04</td>
<td>4</td>
</tr>
<tr>
<td>760.06</td>
<td>6</td>
</tr>
</tbody>
</table>

2 ppm = 14 MeV of full current

Im_{meas} vs I_{ref}
Requested Functionality:

- Modern Graphical User Interfaces
- Settings Generation available on 3 levels: ex: Tune
  a) Current in QF, QD: basic direct hardware level
  b) strength of QF, QD: independent of energy
  c) value of QH, QV: physics parameter; decomposition into QF, QD strength via optics model
- Function Generation for machine transitions (energy ramping, squeeze); viewing of functions; concept of breakpoints (stepping stones)
- Trimming of settings and functions
- Incorporation of trims into functions!
  Very important: different models (constant value, constant strength...)
- Feed Forward of any acquired knowledge into functions:
  Cycle history, Beam Measurements on previous cycle
- Trim and incorporation history, Rollbacks...

Tools for the control of beam parameters

Generic Equipment Control

CAS 2005 Hermann Schmickler (CERN - AB)
Generic Measurement

Measurement of power converters
Visualization of the settings

Trim
Trim history

Supporting Tools for Operation

- Beam Measurement – Inspection – Correction – Trim
  ex: Orbit Correction…The whole suite of beam diagnostics
- Sequencing
- Online Machine Models
- Archiving of measurements
- Automatic logging and data retrieval (correlation studies)
- Post Mortem Analysis Tools
- Fixed Displays (the 16 big screens in the CCC…)
- ELogBook
- Statistics
Logging & Monitoring

Statistics

Integrated luminosity per day in 2000

Data hauled from database automatically at end of fill
Retrieval of archived measurements

Browser & Viewer
With historical data on the database, reasonably easy to extract and analyze off-line.

Dedicated Video (FAST) Signals (LEP)

Data sampled at slower rate ➔ logging database.
Now we take a closer look:

Injection Setting generation for a main dipole string:

1) injection setting from requested beam momentum setting and calibration curve of Magnet
2) Magnetic history of dipoles handled via specific hysteresis cycles before injection (called: degaussing…)
3) Online Feedback to actual setting via reference magnet
4) Requested beam momentum refined by measuring extraction energy of preinjector
5) Other cycle history handled as trim and rollback utility (i.e. “cold machine after shutdown”, “warm machine after 1 day of permanent operation”)
   - in case of the LHC the main dipoles are superconducting
   the field model is more complicated than a simple look-up table

….next slides
Available data for LHC magnets

- warm measurements on the production:
  → all (superconducting) MB, MQ, MQM, MQY:
    • main field integral strength
    • higher order geometric harmonics
  → all (superconducting) MBX, MBRx, MQXx
  → warm measurement on MQTL so far at CERN
  → most (superconducting) lattice corrector and spool pieces
  → all (warm) MQW
  → a sample (5 to 10) of other warm insertion magnets (MBXW, … measured at the manufacturer before delivery)

- cold measurements on:
  → a high fraction of MB and MQ in standard conditions
  → special tests (injection decay and snap-back, effect of long storage) on 15…20 MB
  → a sample of MQM and MQY
  → ≈ 75 % of MBX, MBRx
  → 100 % of MQXx (Q1, Q2, Q3)
  → a limited sample of lattice correctors and spool pieces

Example of integral dipole field in an LHC dipole
The field model

- general decomposition in error sources, with given functional dependency on t, I, dl/dt, I(-t) geometric $C_{n}^{\text{geom}}$
  → DC magnetization from persistent currents $C_{n}^{\text{MDC}}$
  → iron saturation $C_{n}^{\text{saturation}}$
  → decay at injection $C_{n}^{\text{decay}}$
  → snap-back at acceleration $C_{n}^{\text{SB}}$
  → coil deformation at high field $C_{n}^{\text{def}}$
  → coupling currents $C_{n}^{\text{MAC}}$
  → residual magnetization $C_{n}^{\text{residual}}$

- linear composition of contributions:

$$C_{n} = C_{n}^{\text{geom}} + C_{n}^{\text{MDC}} + C_{n}^{\text{saturation}} + C_{n}^{\text{decay}} + C_{n}^{\text{SB}} + C_{n}^{\text{def}} + C_{n}^{\text{MAC}} + C_{n}^{\text{residual}}$$

Use of data

- The data will be used to:
  1. set injection values
  2. generate ramps
  3. forecast corrections (in practice only for MB’s or IR quads)

  on a magnet family basis

- Families are magnet groups powered in series, i.e. for which an integral transfer function (and, possibly, integral harmonics) information is needed. Example: the MB’s V1 line in a sector (154 magnets)
MB injection settings in sector 7/8

- From field model:

\[ TF = 10.117 \text{ (Tm/kA)} \]

- Required integrated field strength in sector 78 for an injection at 450 GeV from SPS: 1189.2 T m

\[ I = 763.2(5) \text{ A} \]

= this corresponds to the first step in the discussed sequence

The Control system receives and stores this setting and makes it available for trimming

...and now we have to ramp the whole lot

![Graph showing MB current vs. time with stages of operation]

<table>
<thead>
<tr>
<th>Stage</th>
<th>Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp down</td>
<td>~ 18 Mins</td>
</tr>
<tr>
<td>Pre-Injection Plateau</td>
<td>15 Mins</td>
</tr>
<tr>
<td>Injection</td>
<td>~ 15 Mins</td>
</tr>
<tr>
<td>Ramp</td>
<td>~ 28 Mins</td>
</tr>
<tr>
<td>Squeeze</td>
<td>&lt; 5 Mins</td>
</tr>
<tr>
<td>Prepare Physics</td>
<td>~ 10 Mins</td>
</tr>
<tr>
<td>Physics</td>
<td>10 - 20 Hrs</td>
</tr>
</tbody>
</table>
All routine operation based on a Semi-automatic sequencer

- Reproducibility
- Reduced scope for error

**PRE-INJECTION PLATEAU**
- Power converters
- Collimators
- Kickers, dump, RF
- Synchronization
- SPS/Transfer lines

**INJECTION PLATEAU BEFORE BEAM**
- Check everything
- Start correcting b1,b1,b3 drifts

**INJECT PILOT** [1x 5°]
- Measure & correct: tune, chromaticity, orbit, momentum
- Collimators, TDI

**INJECT INTERMEDIATE** [12 x 1°]
- Check time development of Q, Q', & p
- Fine positioning of collimators, orbit
- RF, LFB, TFB

**INJECT NOMINAL** [12 x 216/288 x 1.1°]
- Orbit feedback
- Beam loss, beam lifetime
- Q feedback
- Spot Q' measurements

**PREPARE RAMP**
- Produce prediction of snapback - incorporate into ramp
- Load all power converters with ramp function
- RF etc. etc.

**SNAPBACK**
- Feedback
- RF channel available

Accelerator Controls
CAS 2005 Hermann Schmickler (CERN - AB)
A very frightening problem…

Injection ~ 1200 s
Snapback ~ 70 s

| Parameter | Nominal tolerance | Limit on $b_3$ (MB) – Inj. | Approx. Decay | Parameter swing
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q'$</td>
<td>$Q' \approx 2$</td>
<td>$Q' \approx 1.7$</td>
<td>$Q' \approx 1.7$</td>
<td></td>
</tr>
</tbody>
</table>

CAS 2005 Hermann Schmickler (CERN - AB)
Accelerator Controls

Correction elements

Per aperture:
154 MCS sextupole spool pieces powered in series.
77 MCO & MCD spool pieces powered in series.
Therefore we’re working on the average per sector per aperture

CAS 2005 Hermann Schmickler (CERN - AB)
Accelerator Controls
Dynamic effects - correction

Per sector per aperture: magnitude of errors at \( t_0 \) and time evolution of \( b_n(t) \) during decay has been measured.

\[ b_n(t) \]

\[ I_{MB}(t) \]

\[ \Delta b_n \text{ applied as trim} \]

After time \( t_{inj} \) a prediction of the snapback is required. Download.

Based on this corrections applied as a function of time during the injection plateau.

Q’ - control

- Extract sextupole change in dipoles from slow Q’ measurements & \( b_3 \) corrections during injection to give \( \Delta b_3 \) and thus \( \Delta I \).
- Just before ramping:
  - Extract total \( b_3 \) correction
  - Invoke fit for snapback prediction
  - Convert to currents
  - Incorporate into ramp functions & download
- Functions invoked at ramp start by standard timing event
- Occasionally follow chromaticity over ramp by measurements and verify that the incorporation of the trims is still valid.
  - Extract from measurements deviation from constant chromaticity
  - Invert function and calculate corresponding correction function
  - Make this function available in the control system as additional trim (experts only)
…and if all this is not enough: real time feedbacks on beam parameters

- Time resolved measurements
  - LHC orbit: minimum 10 Hz
  - LHC betatron tunes: some Hz
  - LHC chromaticities: Hz

- Data centralization and computation of corrections (including error handling, dynamic change of twiss parameters…)

- Feedback of corrections to power converters

Nice Problem for the instrumentation group

LHC Feedback Success has a long Pedigree: Years of Collaboration, Development and leveraged Experience

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>Wide-Band-Time-Normaliser proposed for LHC BPM system</td>
</tr>
<tr>
<td></td>
<td>Radiation testing showed digital acq. needs to be out of tunnel</td>
</tr>
<tr>
<td></td>
<td>RT control specification, mostly decay-/snap-back and nominal performance (no MP yet)</td>
</tr>
<tr>
<td>2000</td>
<td>BPM design and capabilities &quot;inspired&quot; specs. Moving digital processing out of the tunnel</td>
</tr>
<tr>
<td></td>
<td>Recognition that collimation will rely on real-time Orbit-FBs</td>
</tr>
<tr>
<td>2002</td>
<td>Orbit-FB prototype tests at the SPS</td>
</tr>
<tr>
<td></td>
<td>iwBS'04: SLS, ALS, Diamond, Soleil and others → affirmed Orbit-FB strategy</td>
</tr>
<tr>
<td>2004</td>
<td>Orbit(-FB) and MP entanglement recognised FB: &quot;nice to have&quot; to &quot;necessary&quot;</td>
</tr>
<tr>
<td>2009</td>
<td>the year we established collisions: Q/Q'- &amp; Orbit FBs operational</td>
</tr>
</tbody>
</table>

BNL & CERN collaboration on Q/Q'(-FB)
initially BNL’s 200MHz resonant BPM

- Tune-FB included in original US-LARP
- TWC-based Schottky monitor proposed

- Direct-Diode-Detection → Base-Band-Tune (BBQ), prototyped at RHIC/SPS, robust Q-meas. & unprecedented sensitivity
- 1.7 GHz Schottky prototype at SPS

- FFT-based Q tracking op. deployed at SPS
- PLL-studies at RHIC
- FNAL-LARP involvement in Schottky design and front-end electronics

- Q & Coupling-FB demonstrated at RHIC
- PLL-Q and Q'(t) tracker demonstrated at SPS
- FNAL-design/CERN-built 4.8GHz TWC Schottky Tune Feedback Final Design Review (BNL)

Joint CARE workshop on Q/Q' diagnostics (BNL, FNAL, Desy, PSI, GSI, …)
→ affirmed Q/Q' strategy

2009 – the year we established collisions: Q/Q'- & Orbit FBs operational
To avoid inherent Cross-Talk between FBs...

... Cascading between individual Feedbacks

Orbit Feedback Performance

- Orbit feedback used routinely and mandatory for nominal beam

- Typical stability: 80 (20) µm rms. globally (arcs)

- Most perturbations due to Orbit-FB reference changes around experiments
Typical Q/Q'(t) Control Room View
2010 Statistics: Out of 191 Ramps...

... 155 ramps with > 99% transmission, 178 ramps with > 97% transmission
... only 12 ramps lost with beam (6 with Tune-FB during initial 3.5 TeV comm.)
... “if without FBs”: 83 crossings of 3rd, 4th or C- resonance, 157 exceeded |ΔQ|>0.01
Impressive performance for the first year of operation and low-ish intensities:

Available trim functions for Qh’
Summary

• Accelerator Controls is a vast activity
• Controls Hardware mainly based on commercially available products (COTS)
• Controls of beam parameters makes the link between:
  - accelerator physics
  - beam observation
  - equipment control
• …is fun to work on…