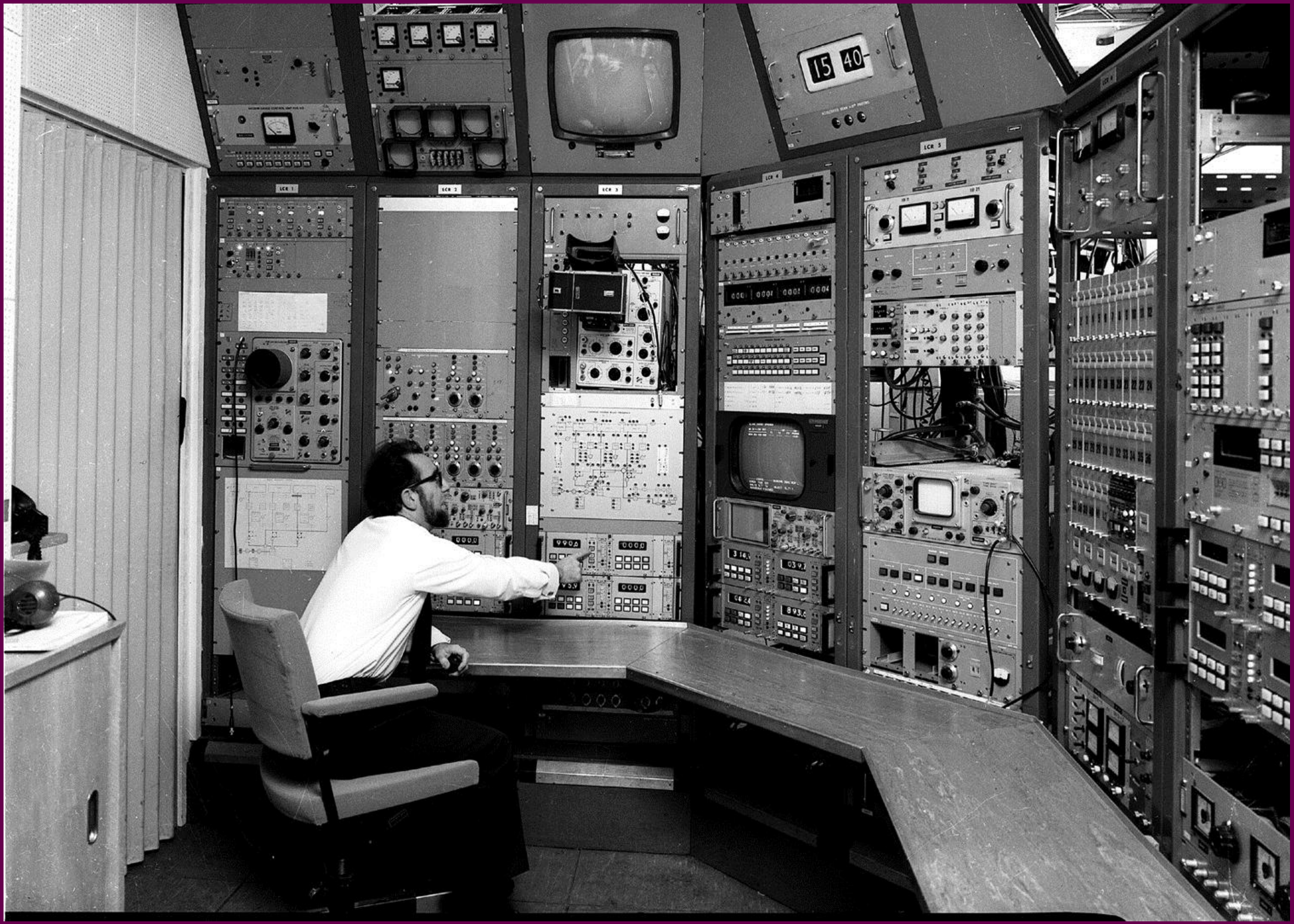
Accelerator Controls



Hermann Schmickler - CERN

Outline

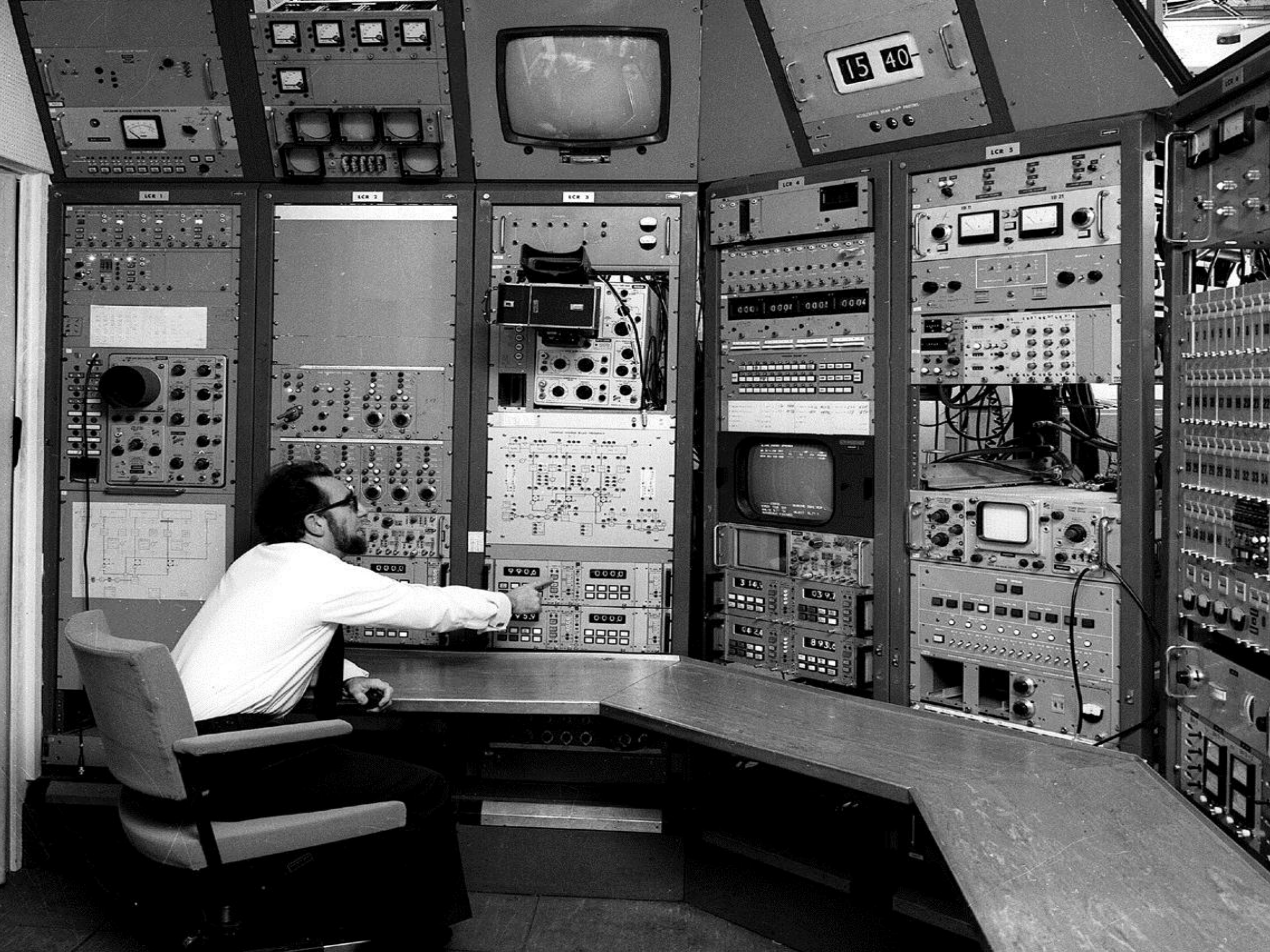
- Controls technology

→ 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
- Controling 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 Diagnstics was done with instruments locally in the control room.


15 40
LCR 1
LCR 2
LCR 3
LCR 4
LCR 5

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

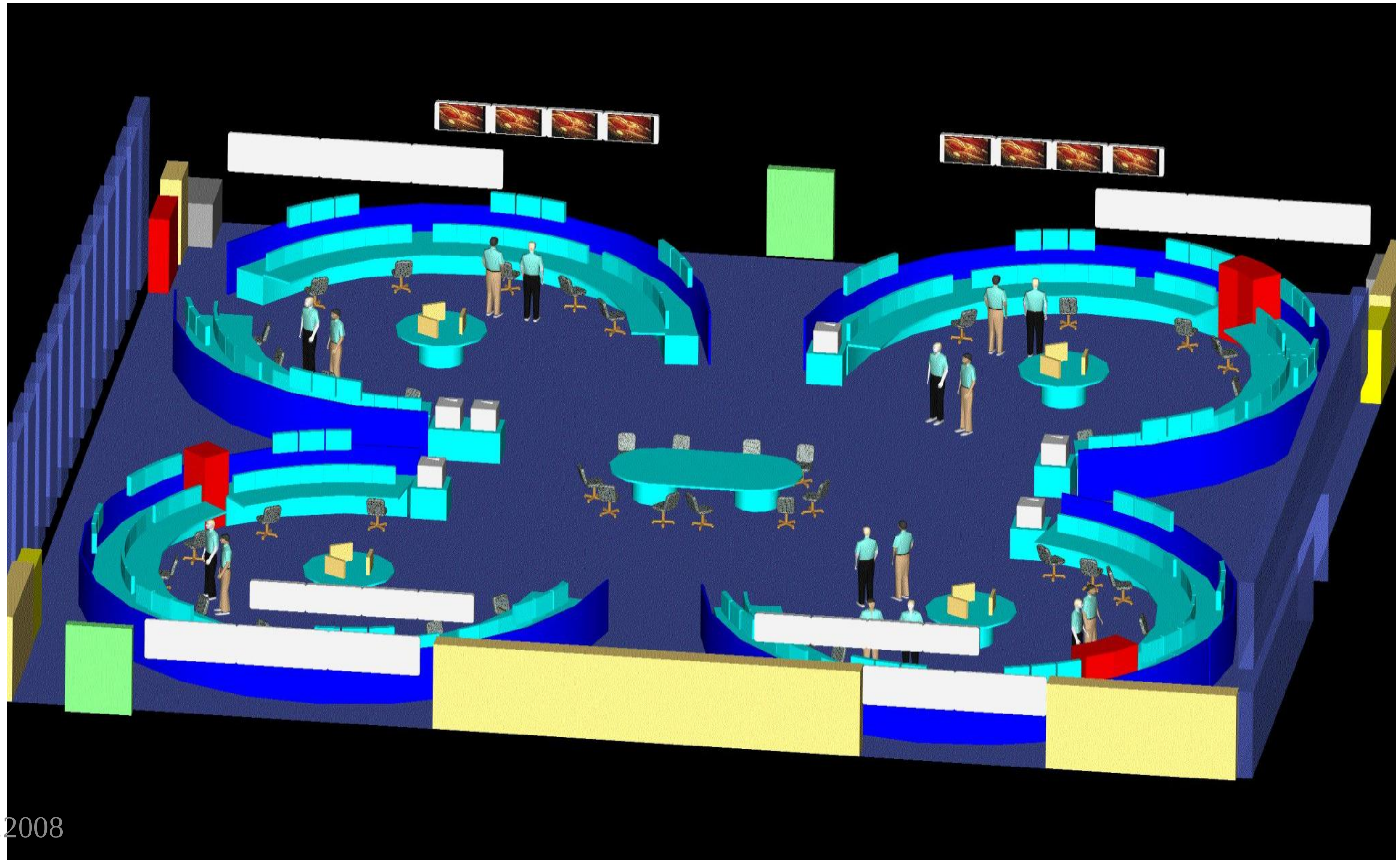
Workstation distribution

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

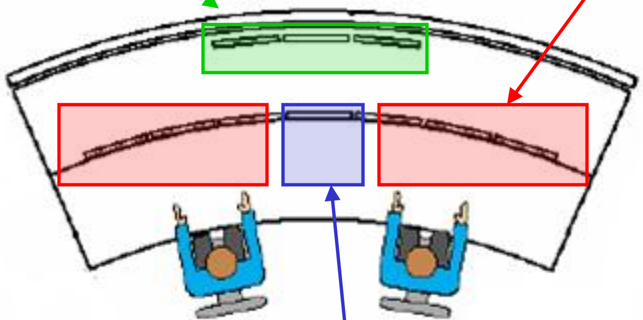


Workstation

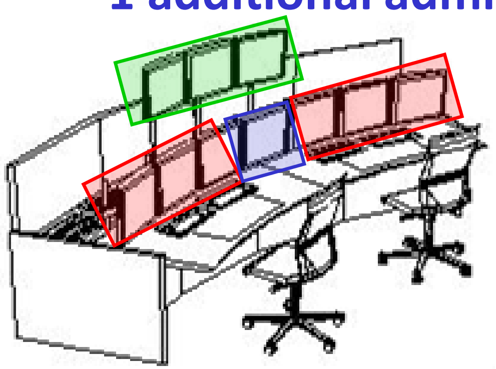
3 fixed displays split between 2 workspaces

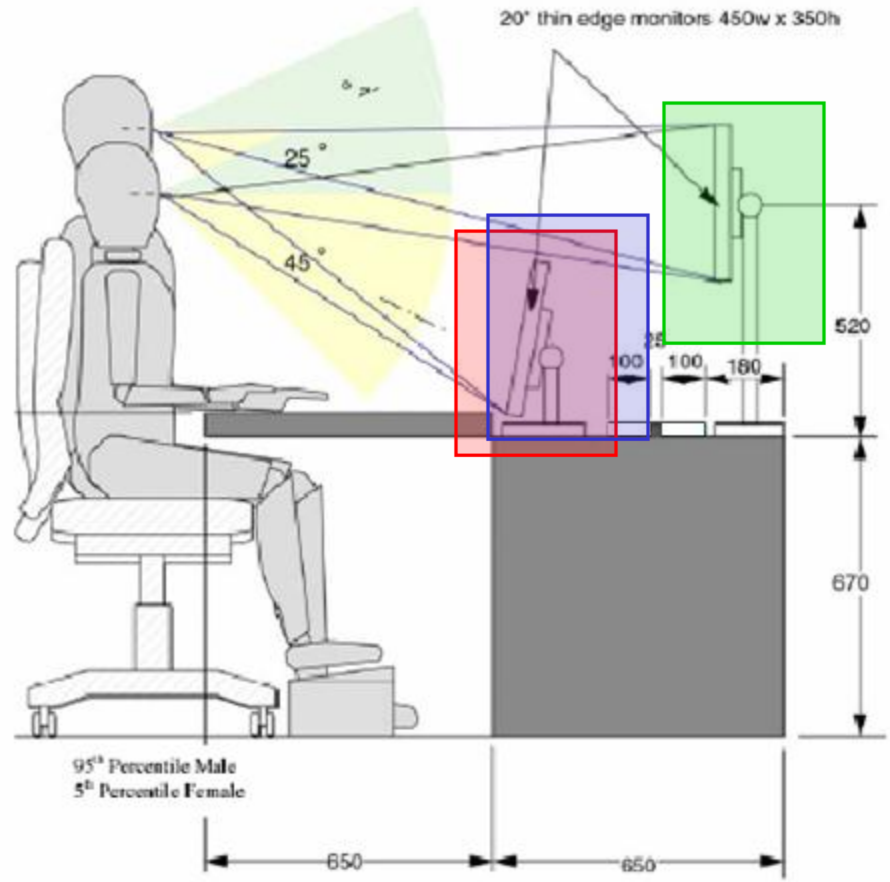
3 flat screens per workspace

1 keyboard 1 mouse



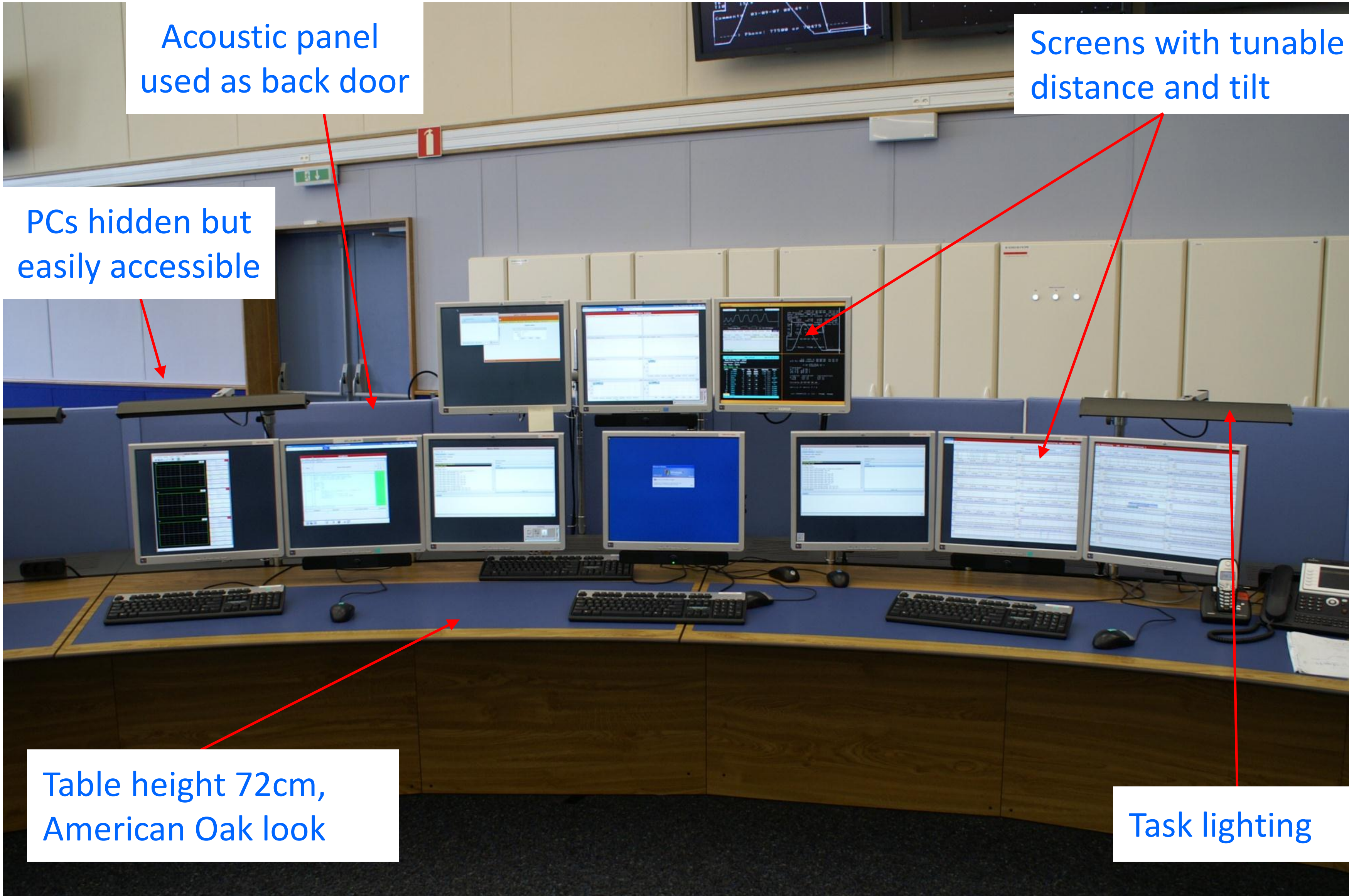
1 additional admin PC





Inside CCC

A typical Operator Console



Some keywords for LHC controls technology

- Base the HW architecture on available commercial standards and COTS:
  - → VME64x standard pour complex embedded I/O system with high performance demands commercial VME PPC processor boards(CES), including O/S integration and support (LynxOS)
  - → commercial cPIC Intel based processor boards (Concurrent Technology for the time being) and digital scopes
  - → 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 Schnieder PLCs for industry-like process control (Cryo, vacuum, electrivity, RF power control, BT power control)
  - → Supervisory Control and Data Acquisition Systems (SCADA) for commands, graphical user interfcaes, 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

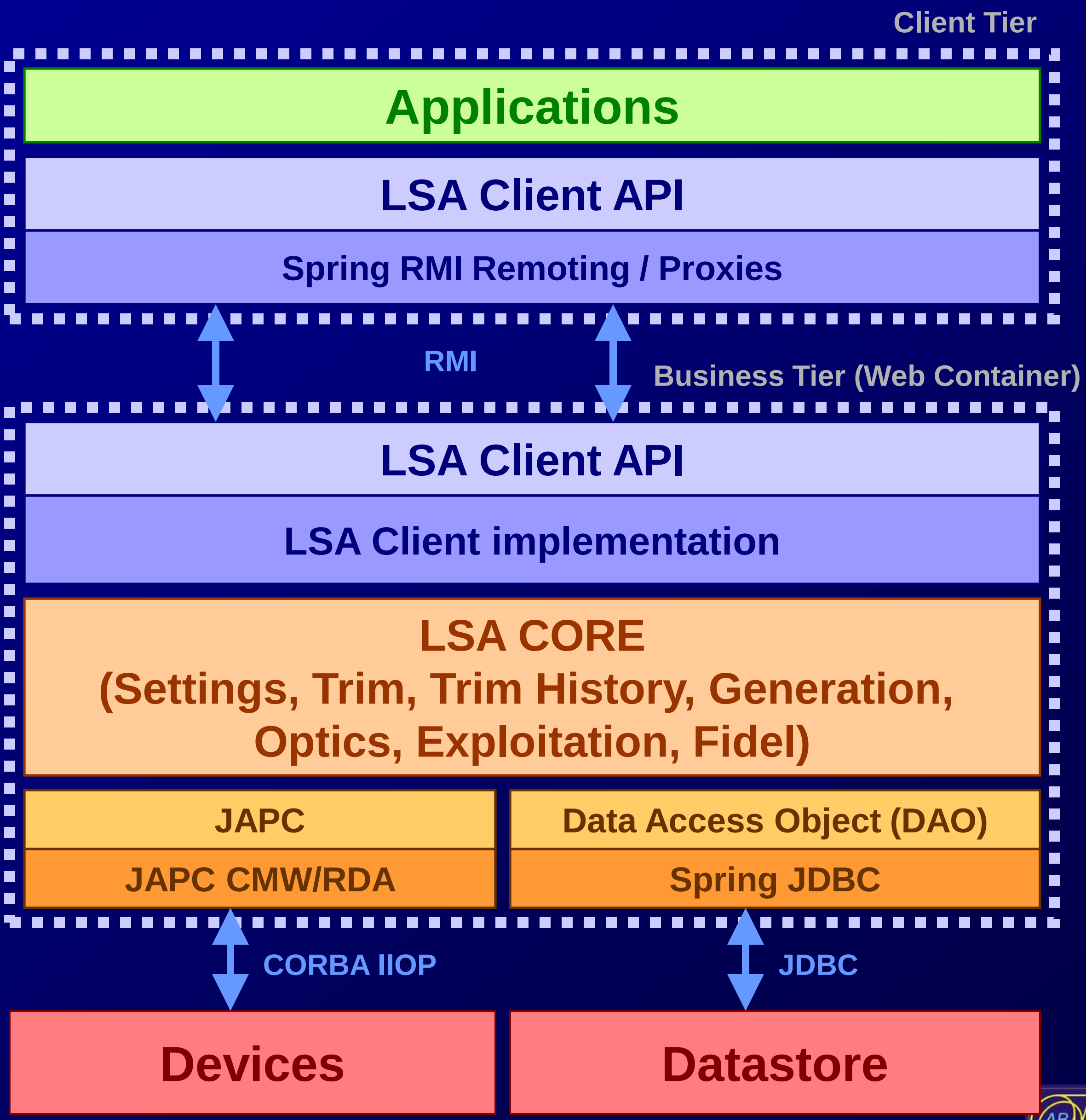
- With a minimal cost of 3-tier architectures
  - Complexity of programming
  - Testing & debugging
  - Deployment

tier, tire or tyre ??

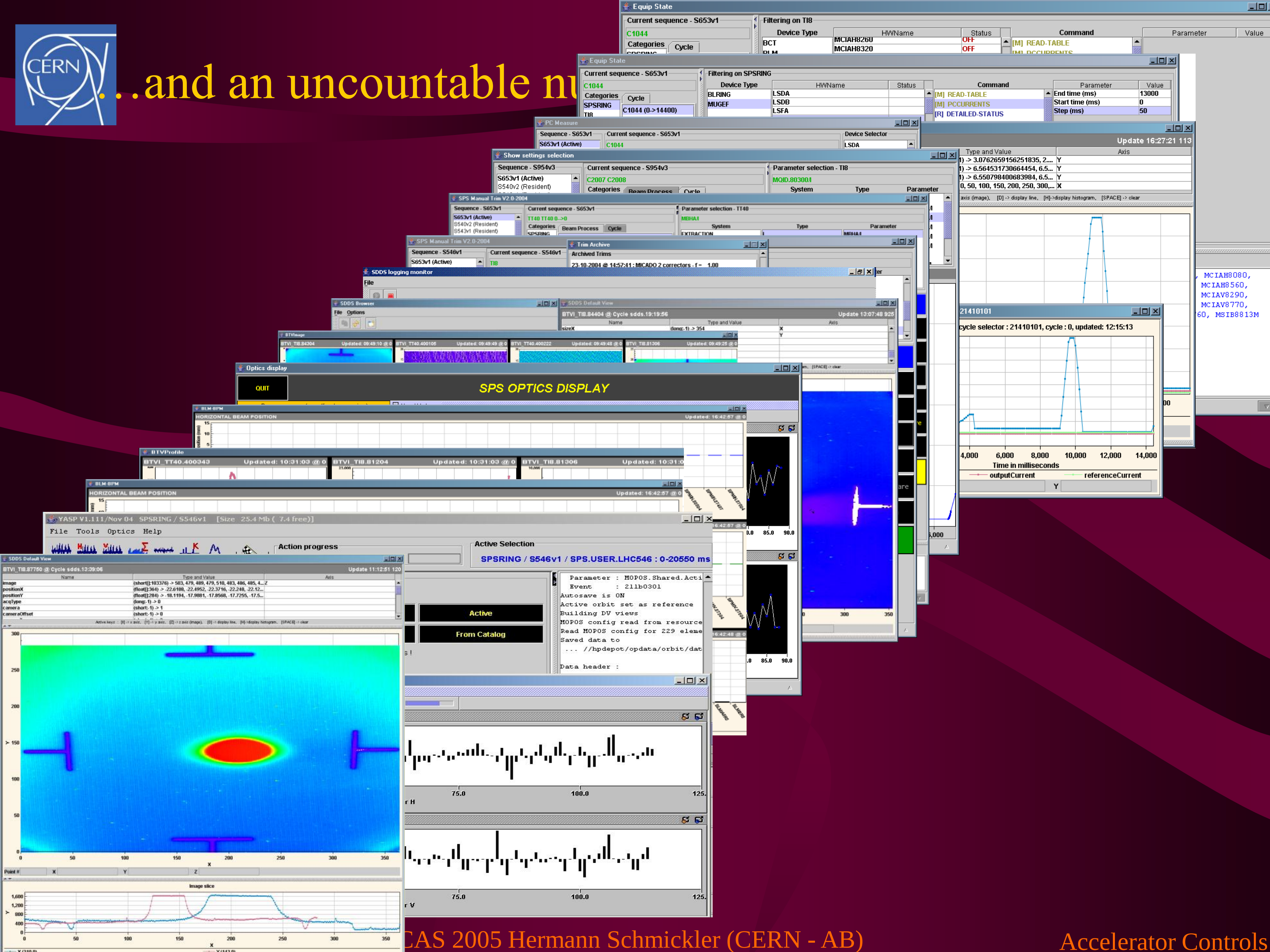
- Plus we needed support for standard services
  - Transactions, remote access,…

Architecture

- Modular
- Layered
- Distributed



…and an uncountable nu



Technical Services

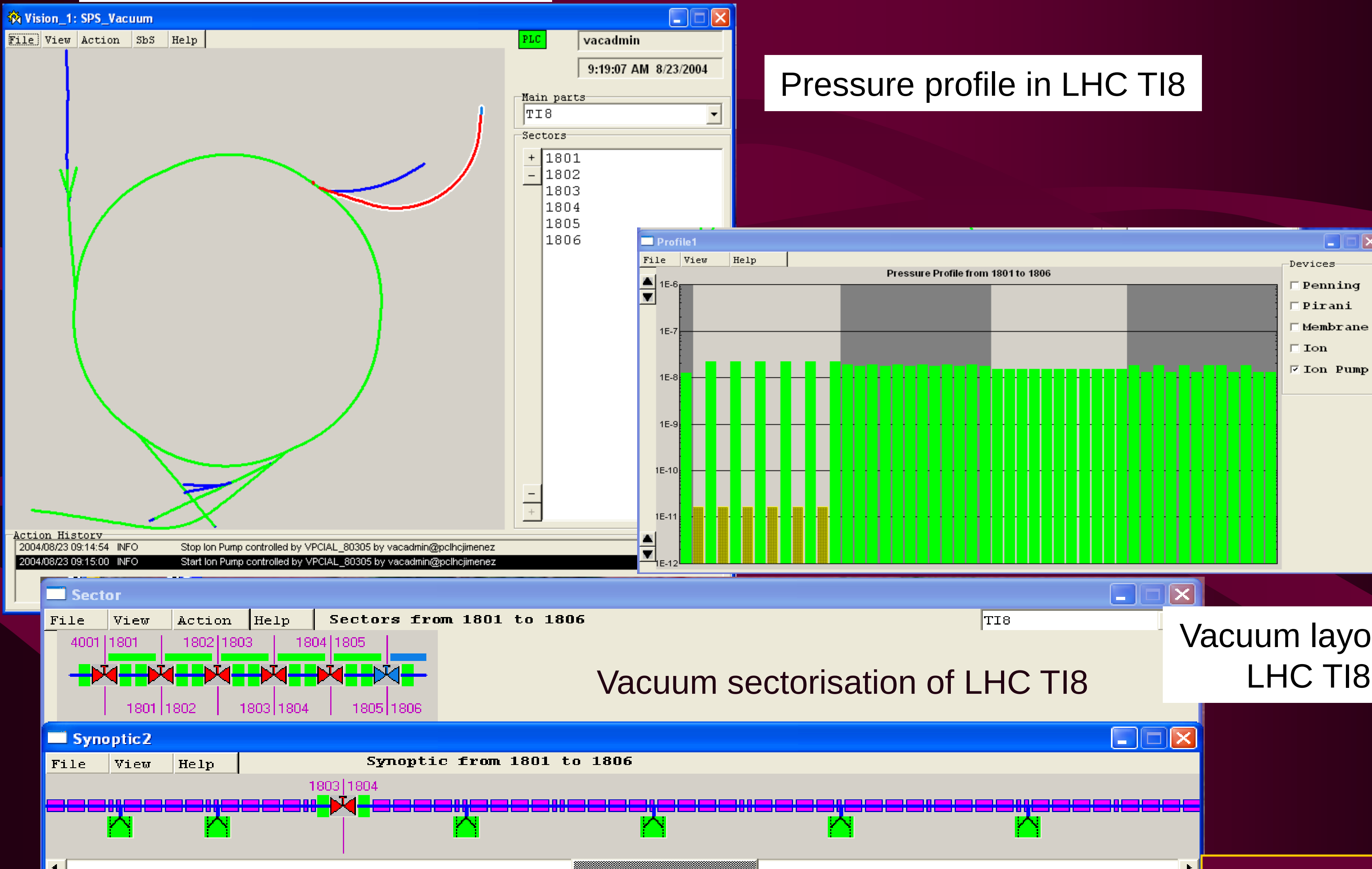
All we need even before thinking of injecting beam:

- 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

Synoptic of the SPS Complex

Pressure profile in LHC TI8

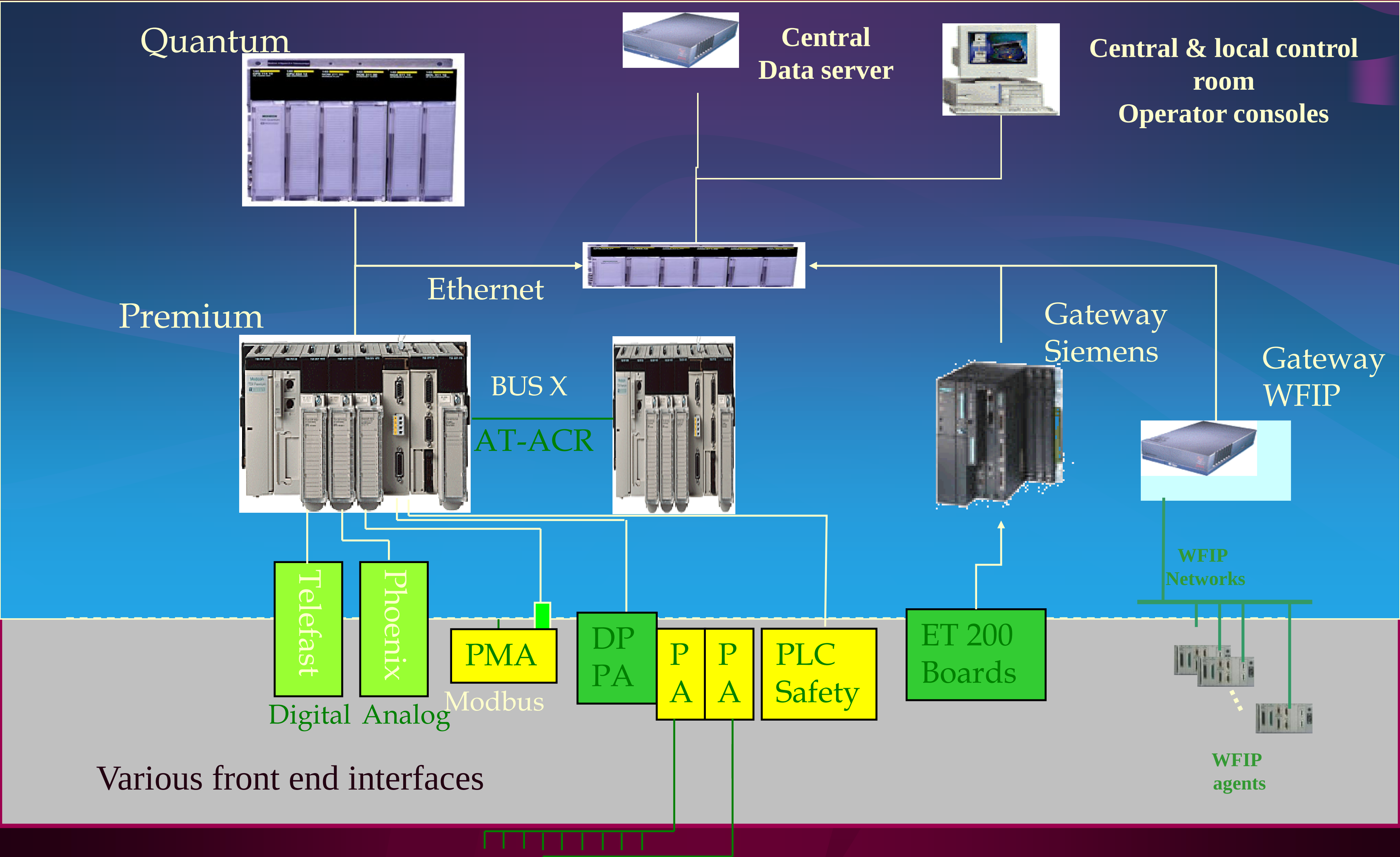


Vacuum sectorisation of LHC TI8

Vacuum layout of LHC TI8

I.Laugier AT-VAC

A typical implementation

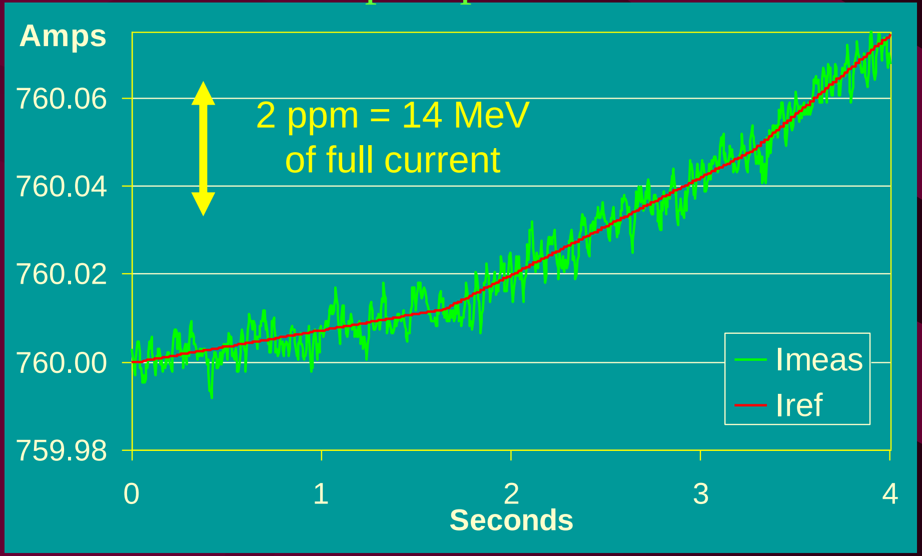


Finally: Beam Control

- →**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

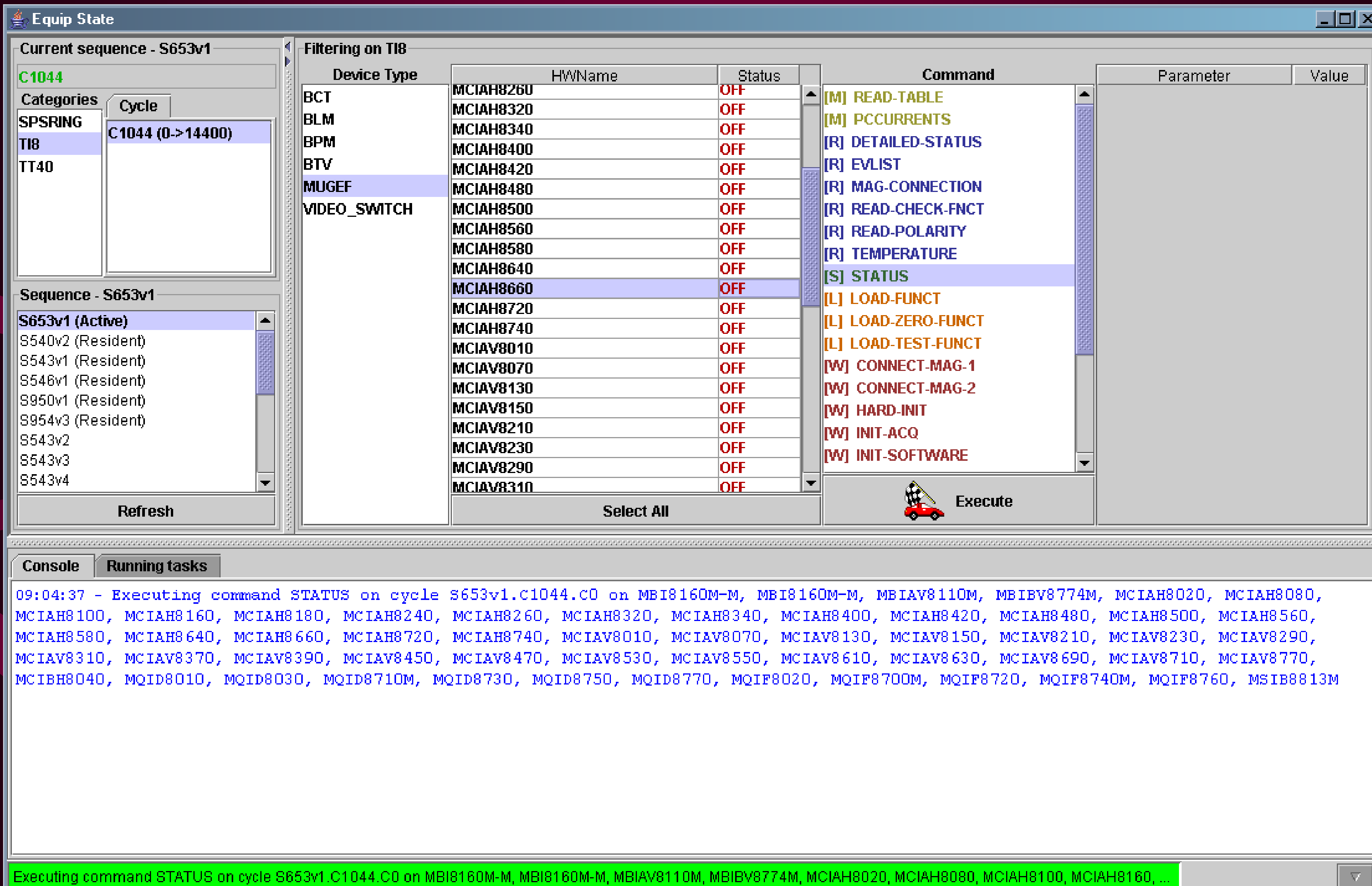


Tools for the control of beam parameters

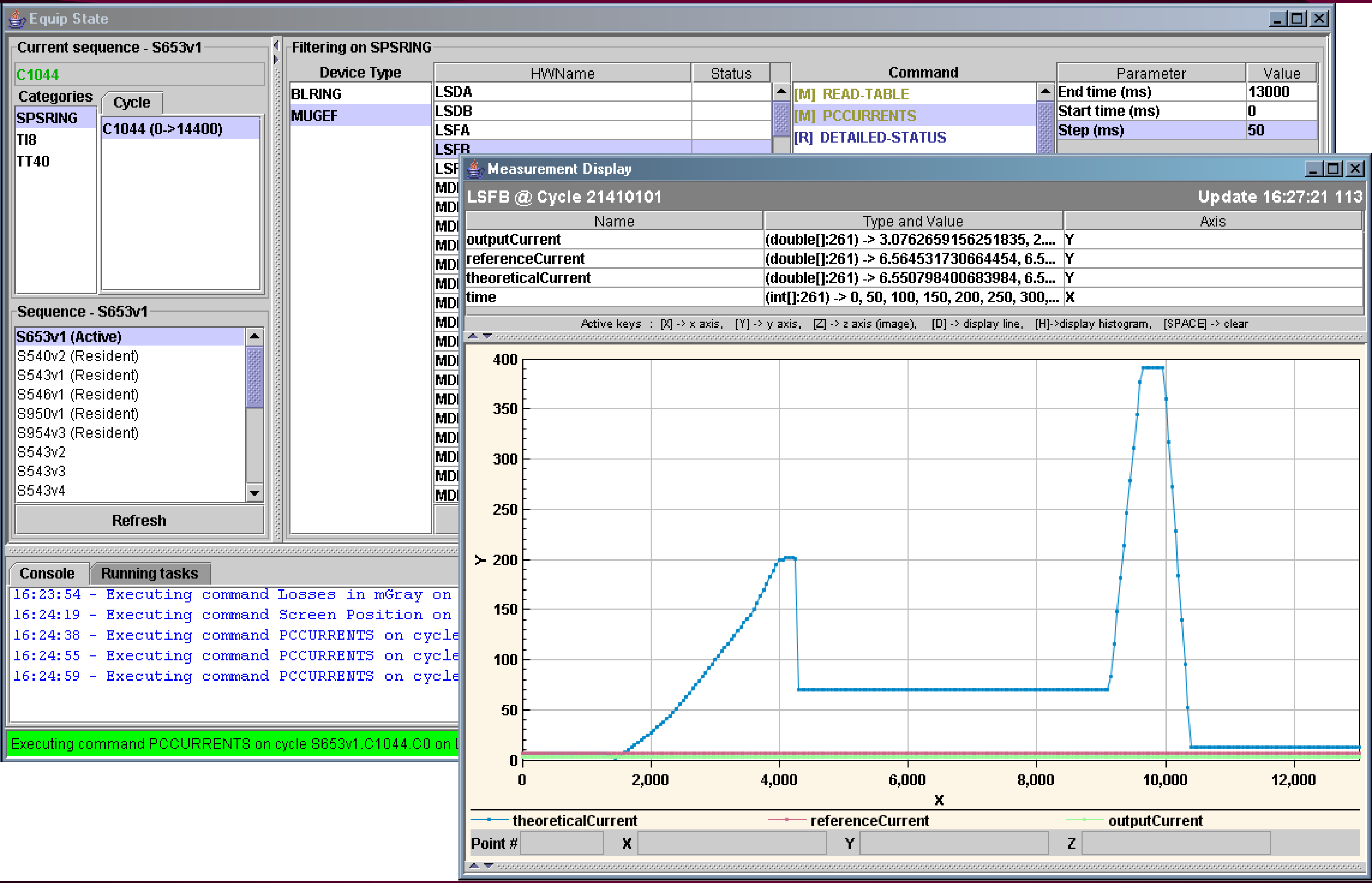
Requested Functionality:

- 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…

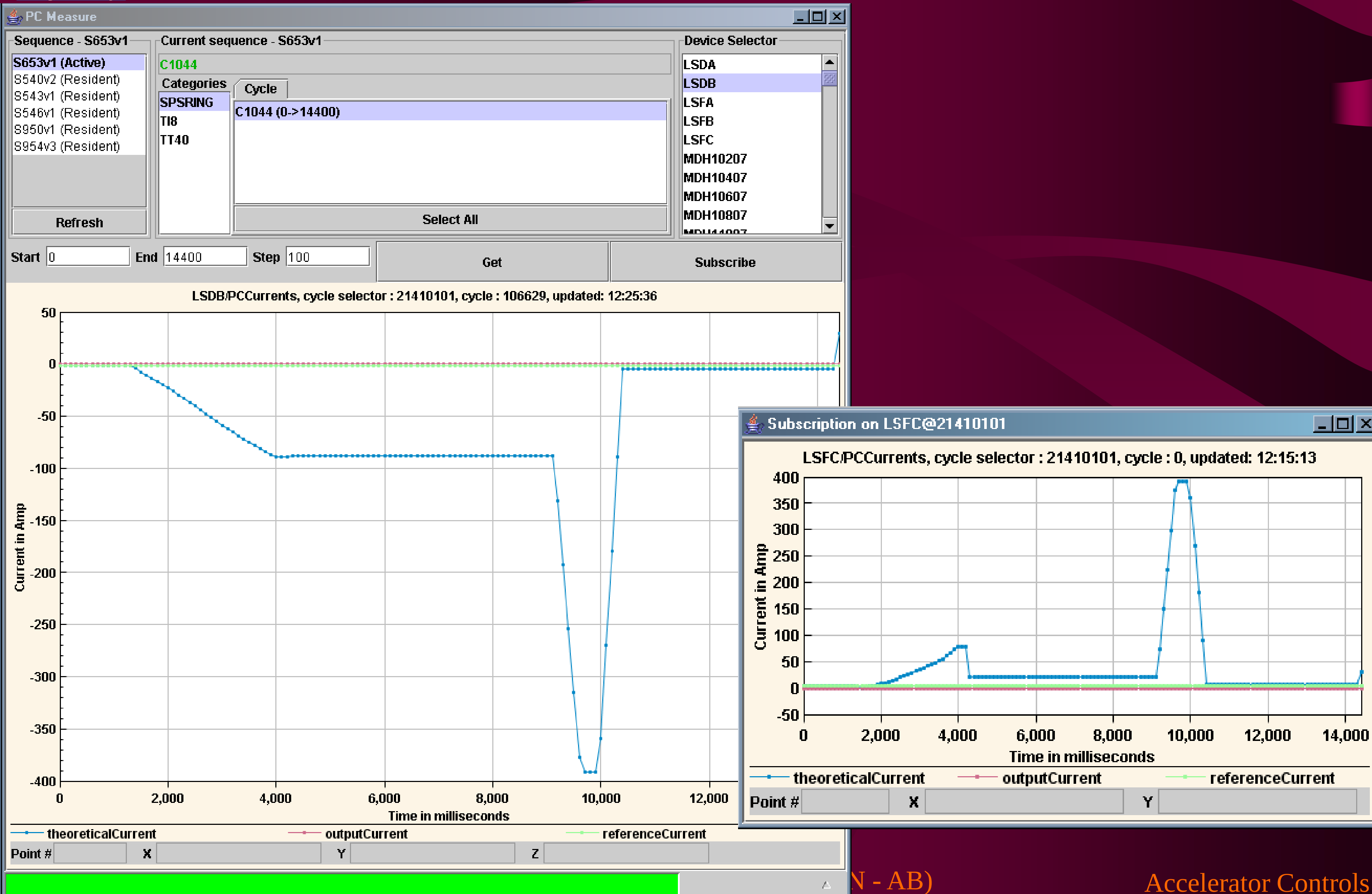
Generic Equipment Control



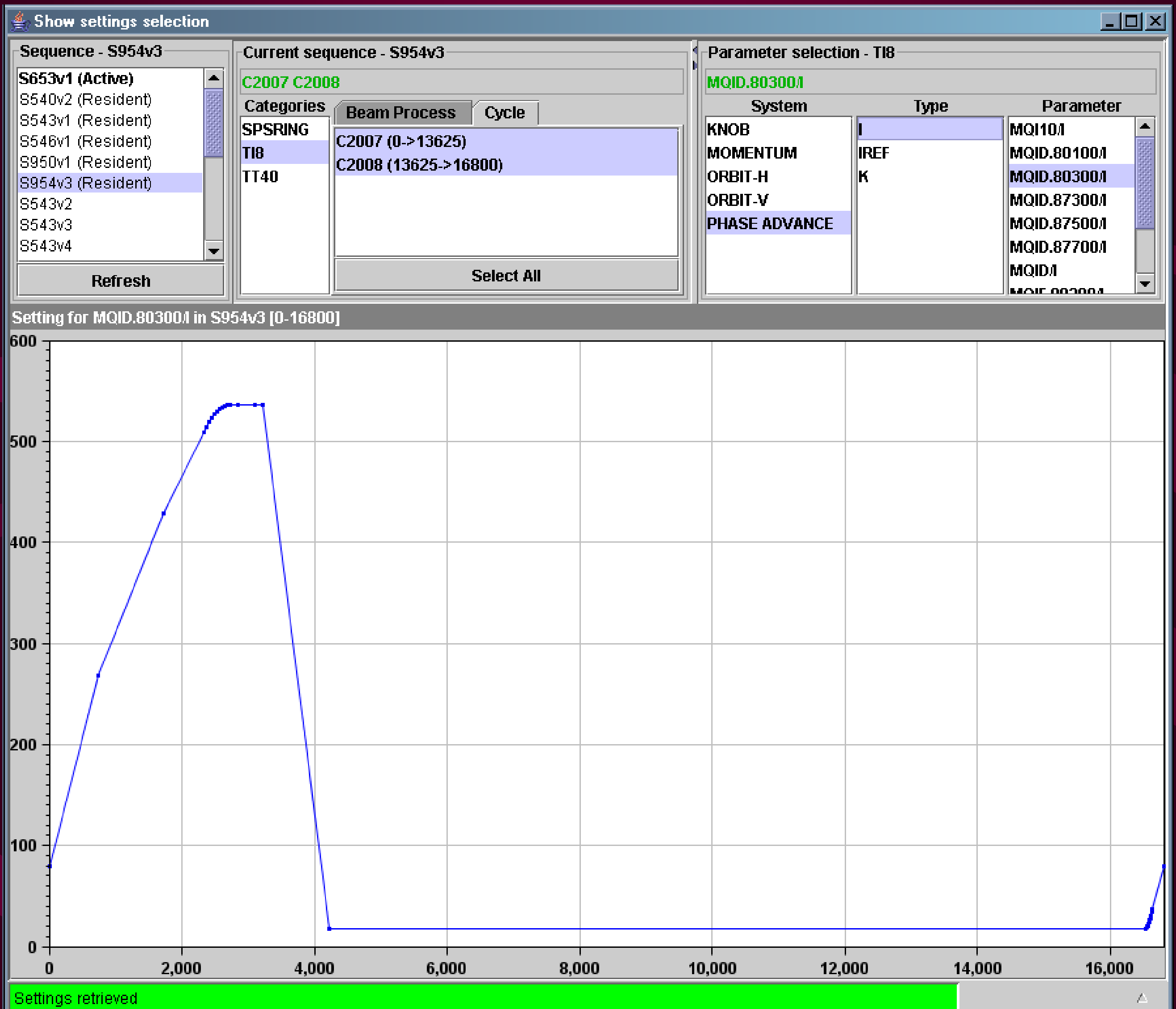
Generic Measurement



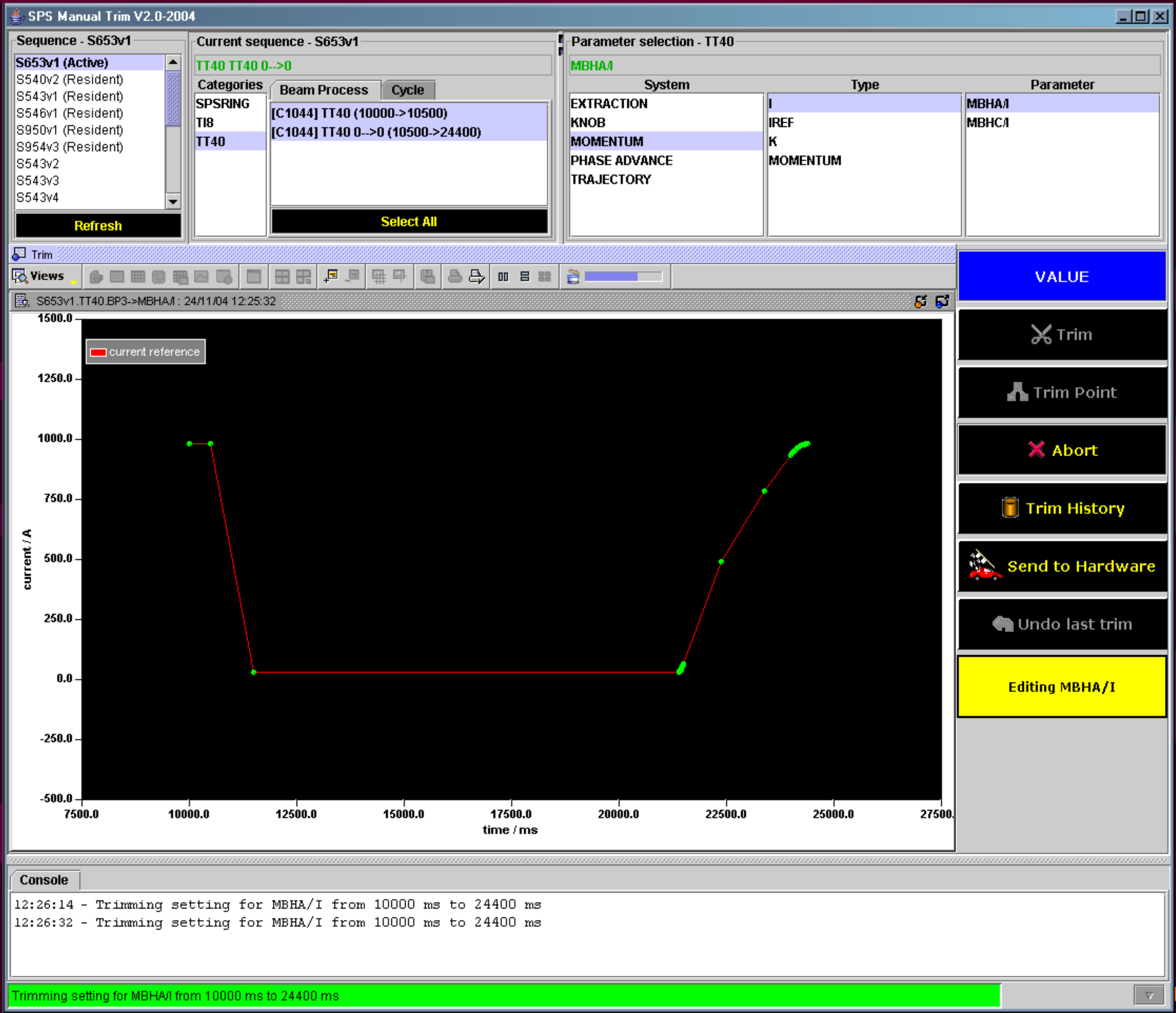
Measurement of power converters



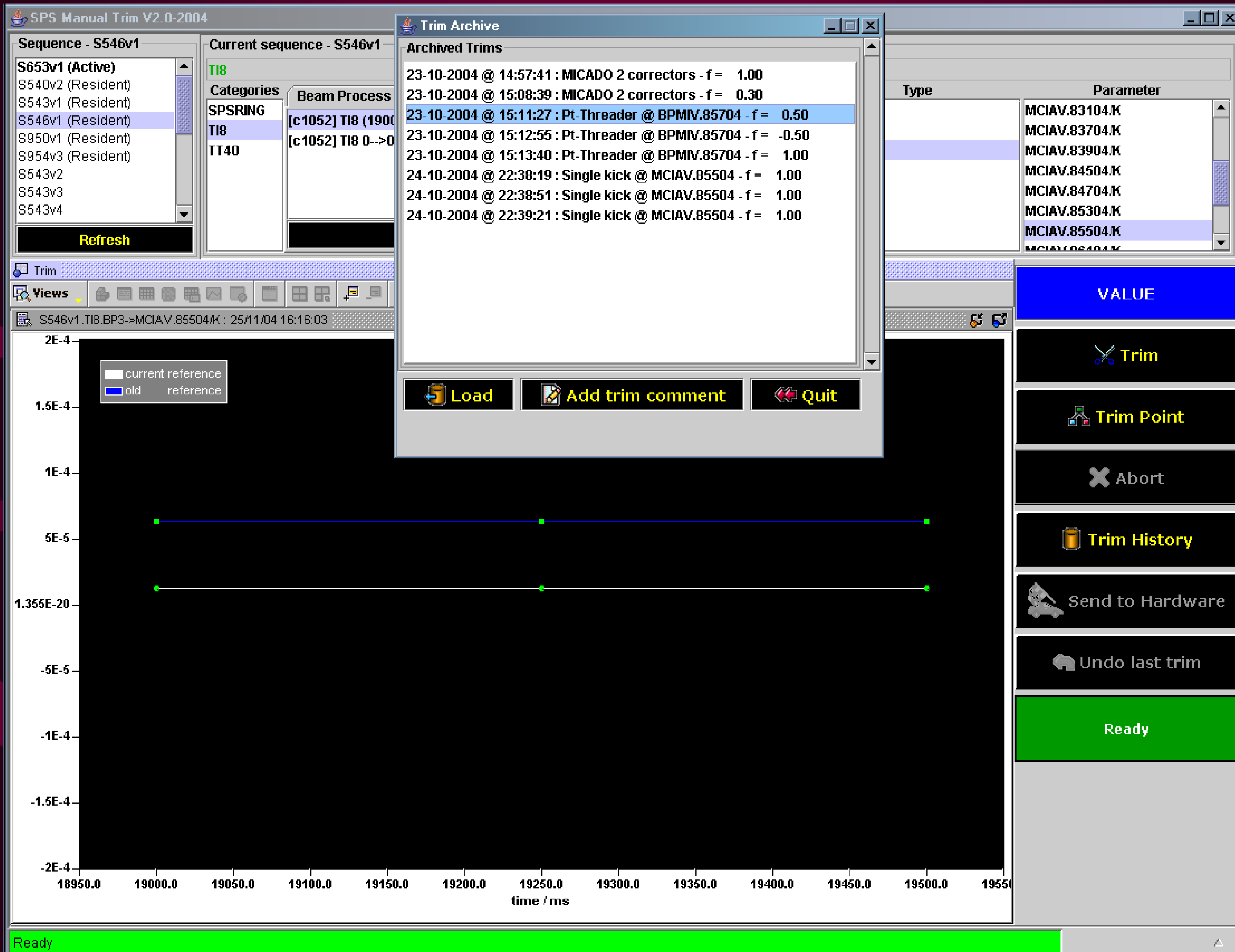
Visualization of the settings



Trim


SPS Manual Trim V2.0-2004
Sequence - S653v1
S653v1 (Active)
S540v2 (Resident)
S543v1 (Resident)
S546v1 (Resident)
S950v1 (Resident)
S954v3 (Resident)
S543v2
S543v3
S543v4
Refresh
Current sequence - S653v1
TT40 TT40 0-->0
Categories
Beam Process
Cycle
SPSRING
TI8
TT40
[C1044] TT40 (10000->10500)
[C1044] TT40 0-->0 (10500->24400)
Select All
Parameter selection - TT40
MBHA/I
System
Type
Parameter
EXTRACTION
KNOB
MOMENTUM
PHASE ADVANCE
TRAJECTORY
I
IREF
K
MOMENTUM
MBHA/I
MBHC/I
Trim
Views
S653v1.TT40.BP3->MBHA/I : 24/11/04 12:25:32
current reference
current / A
time / ms
VALUE
Trim
Trim Point
Abort
Trim History
Send to Hardware
Undo last trim
Editing MBHA/I
Console
12:26:14 - Trimming setting for MBHA/I from 10000 ms to 24400 ms
12:26:32 - Trimming setting for MBHA/I from 10000 ms to 24400 ms
Trimming setting for MBHA/I from 10000 ms to 24400 ms

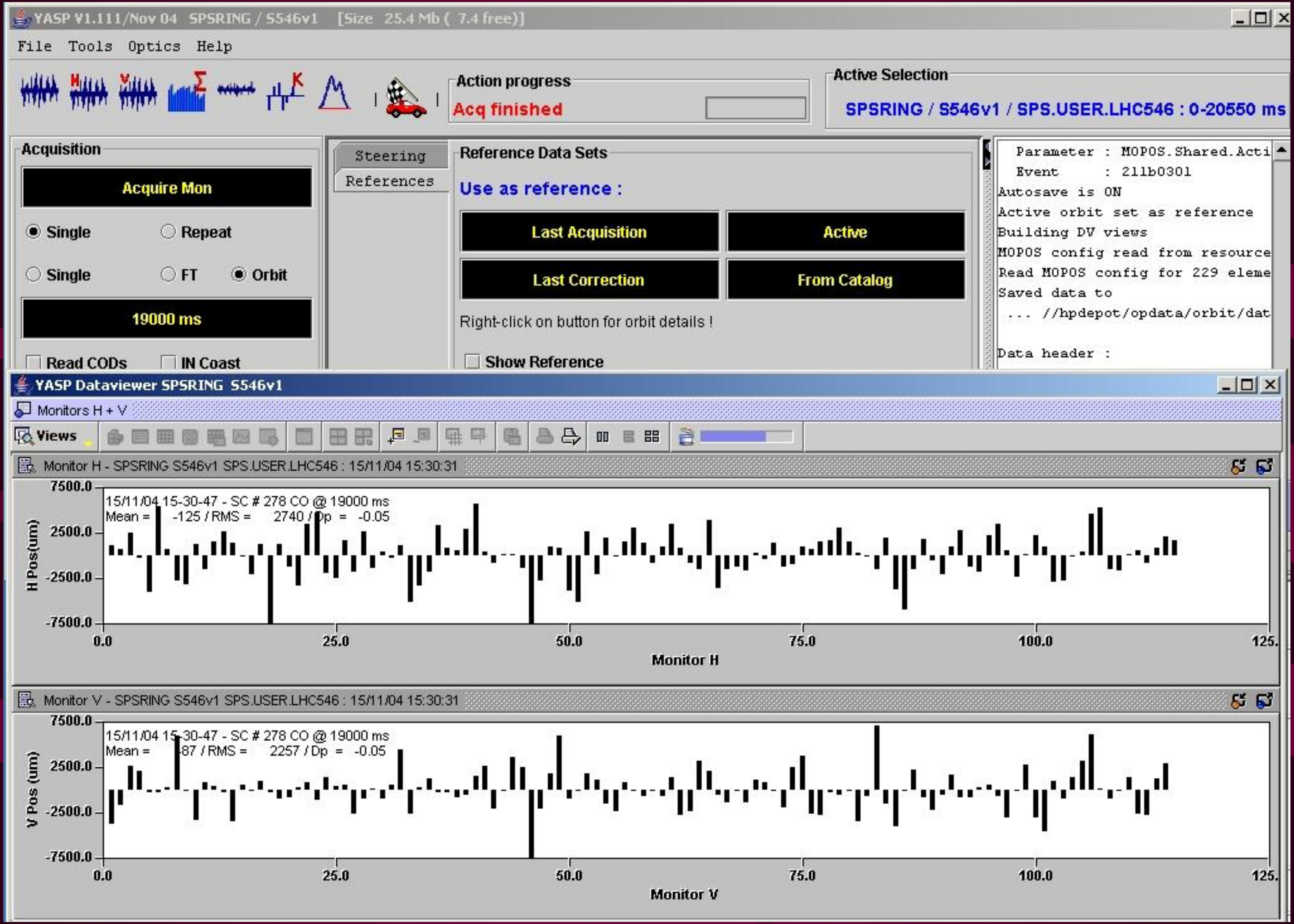
Trim history



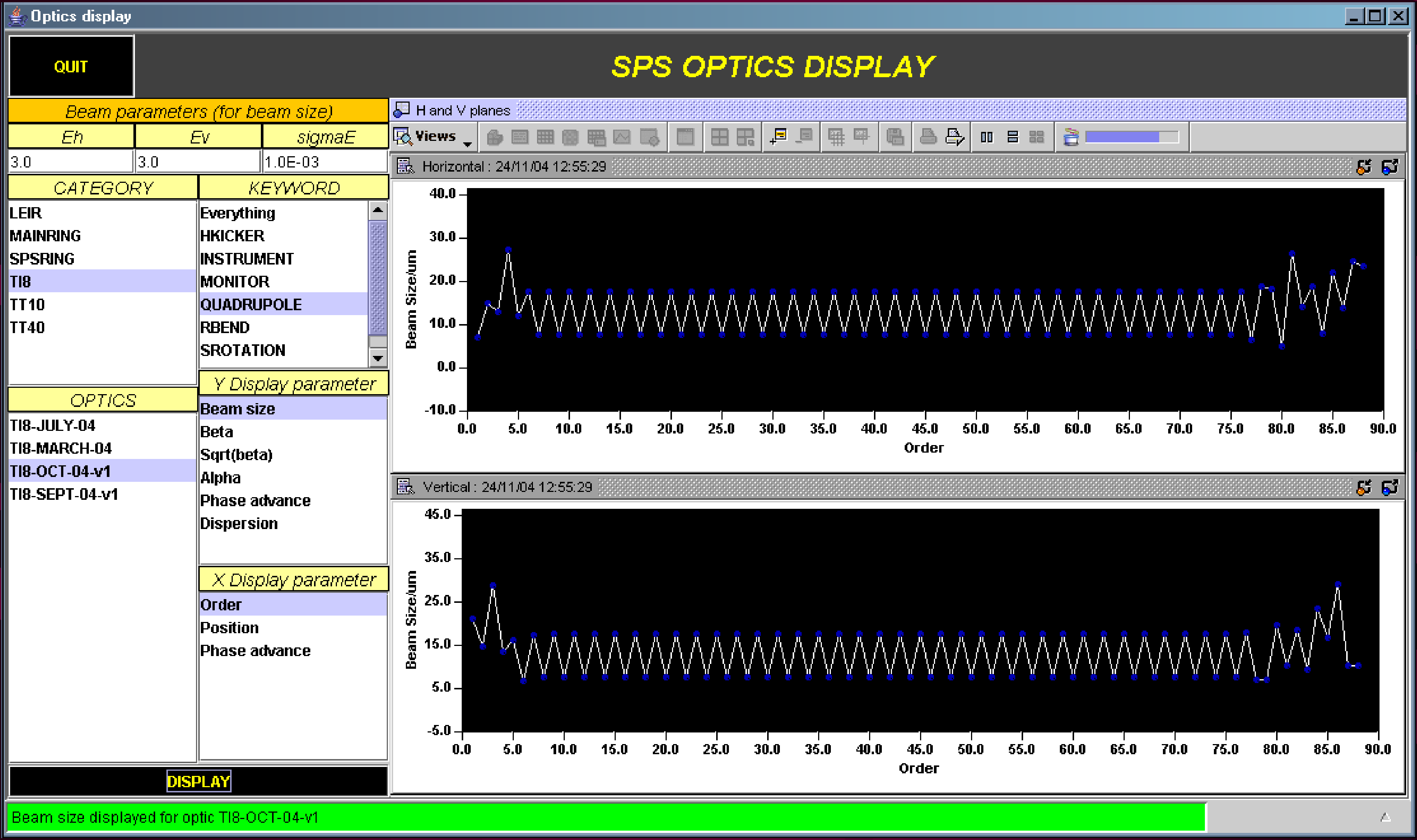
Supporting Tools for Operation

- 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

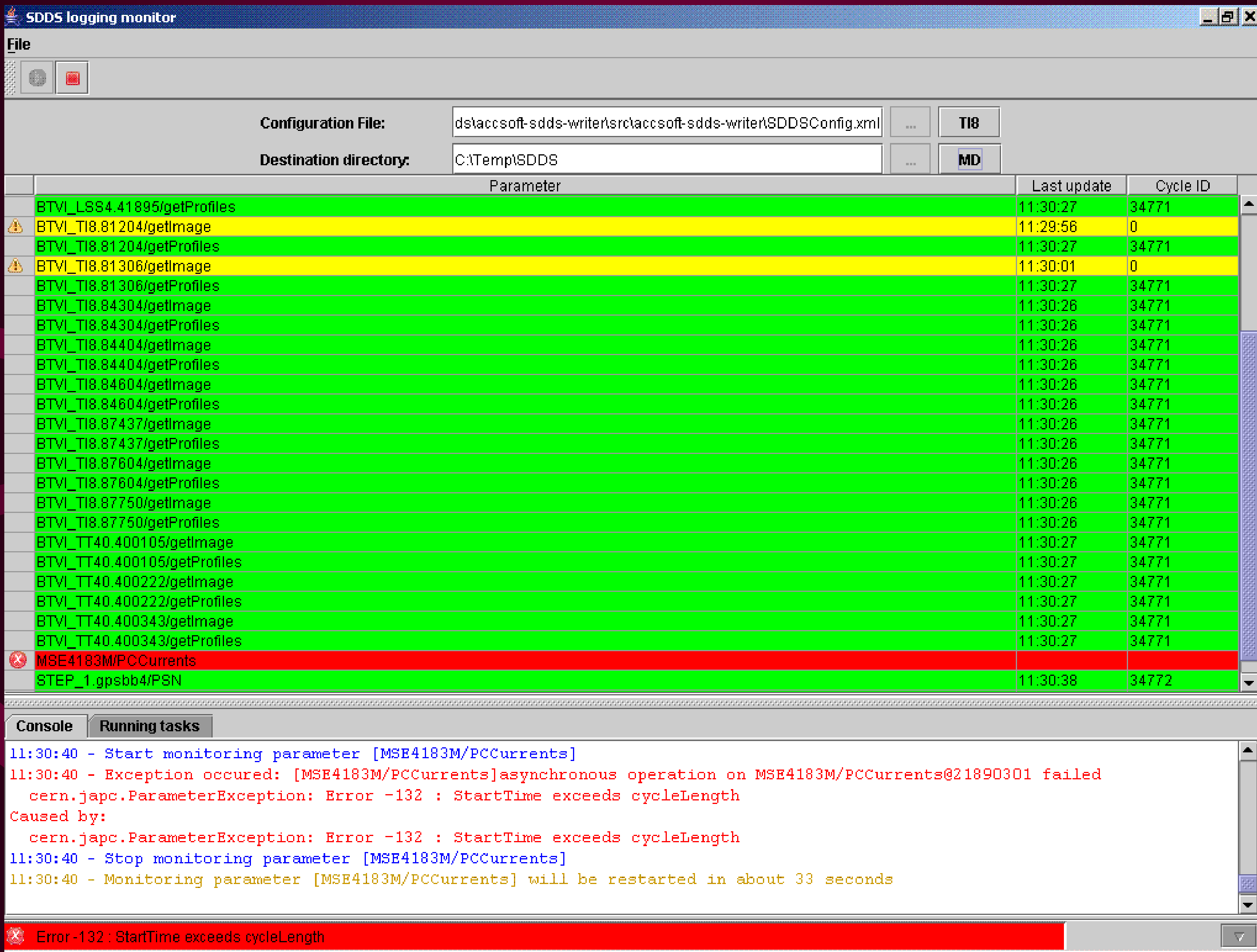
Orbit Steering



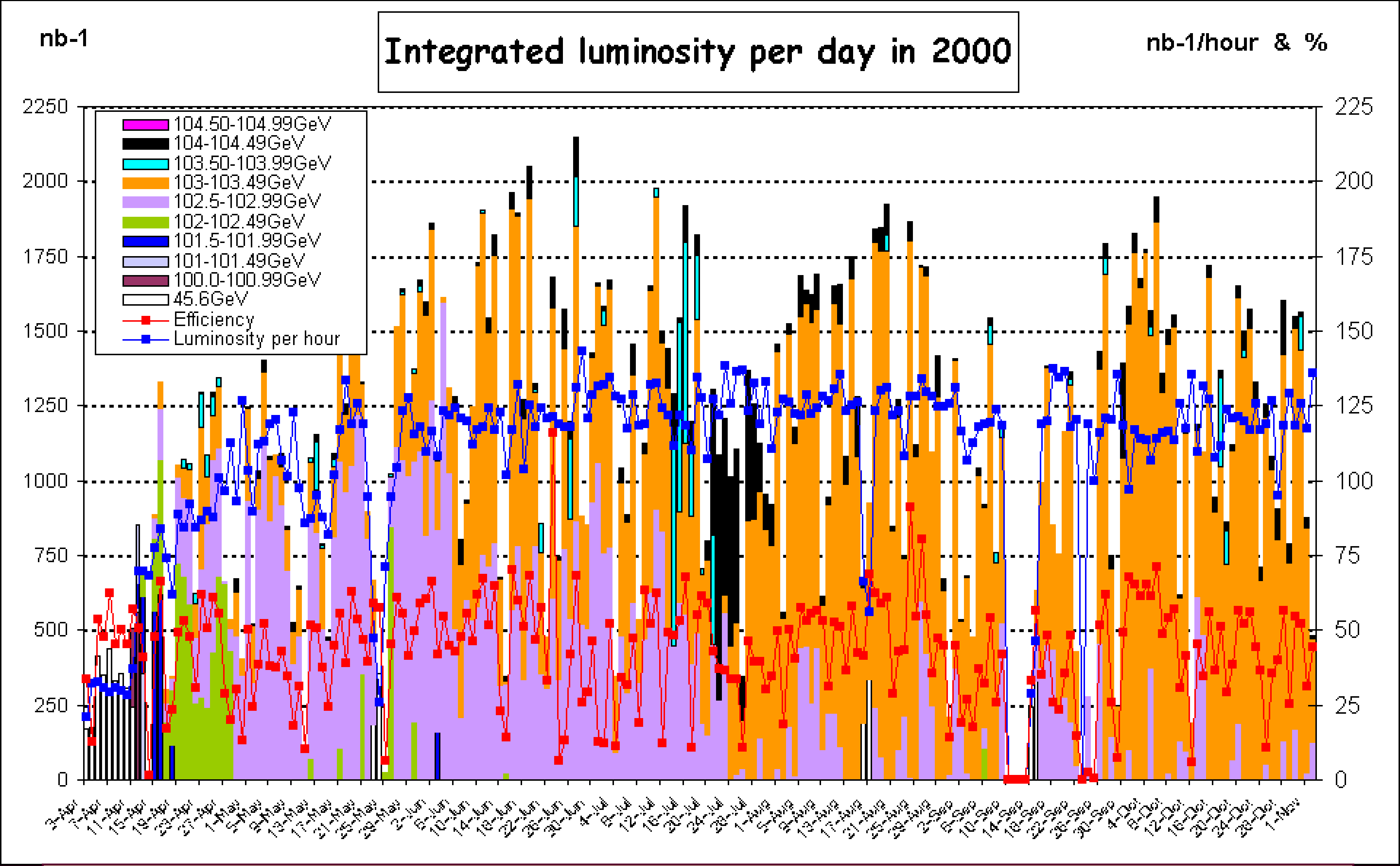
Optics Display



Logging & Monitoring

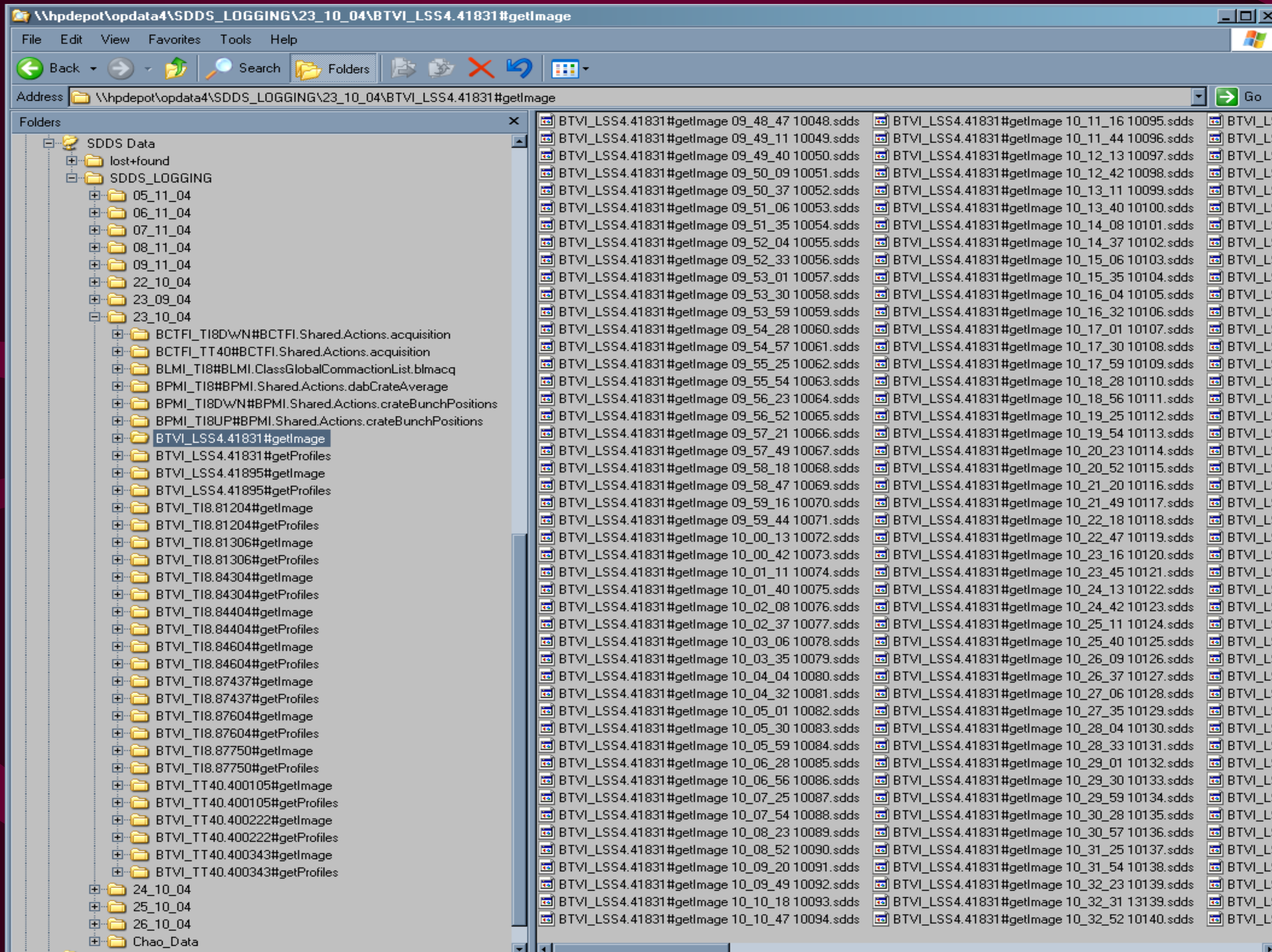


Statistics

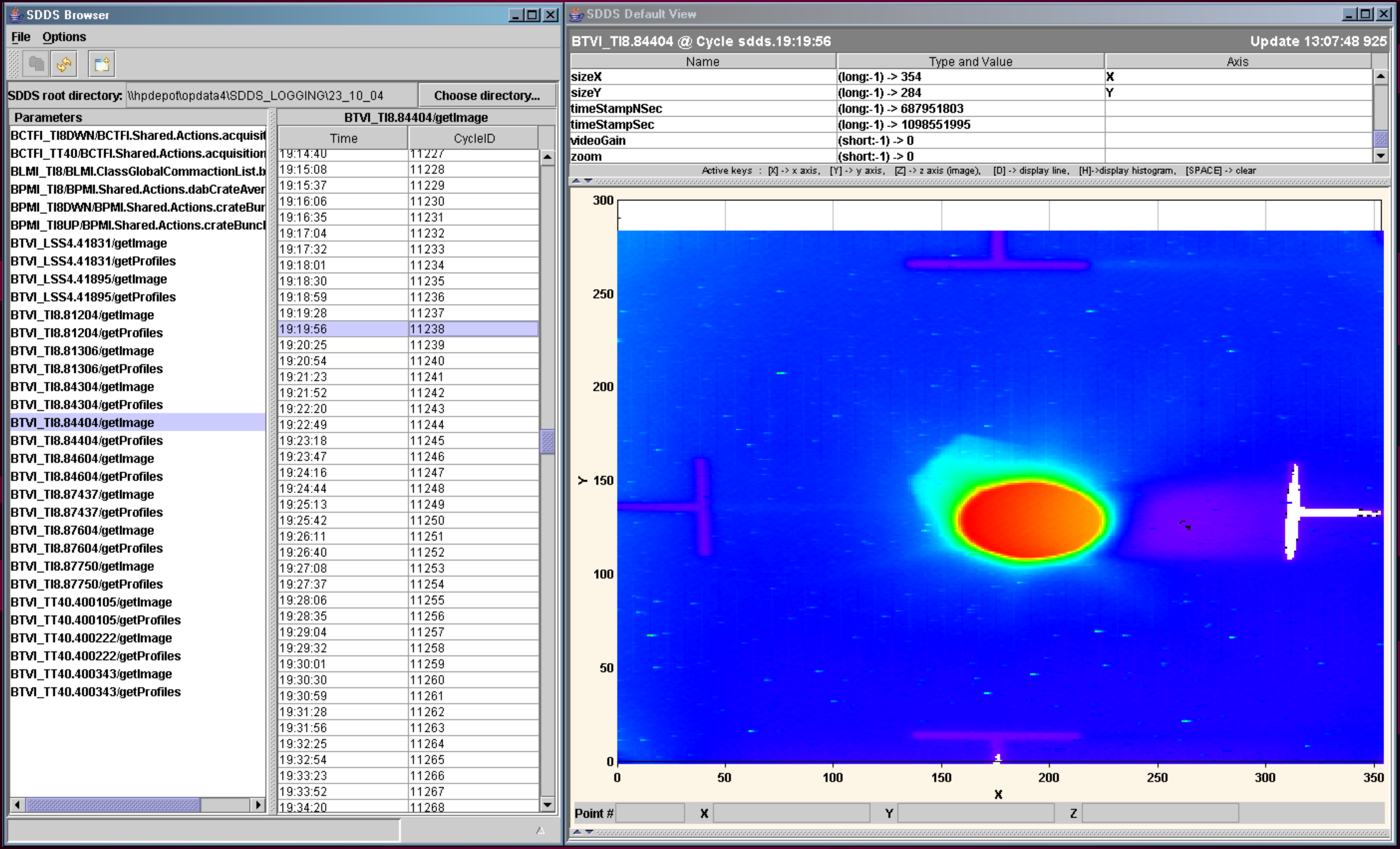


Data hauled from database automatically at end of fill

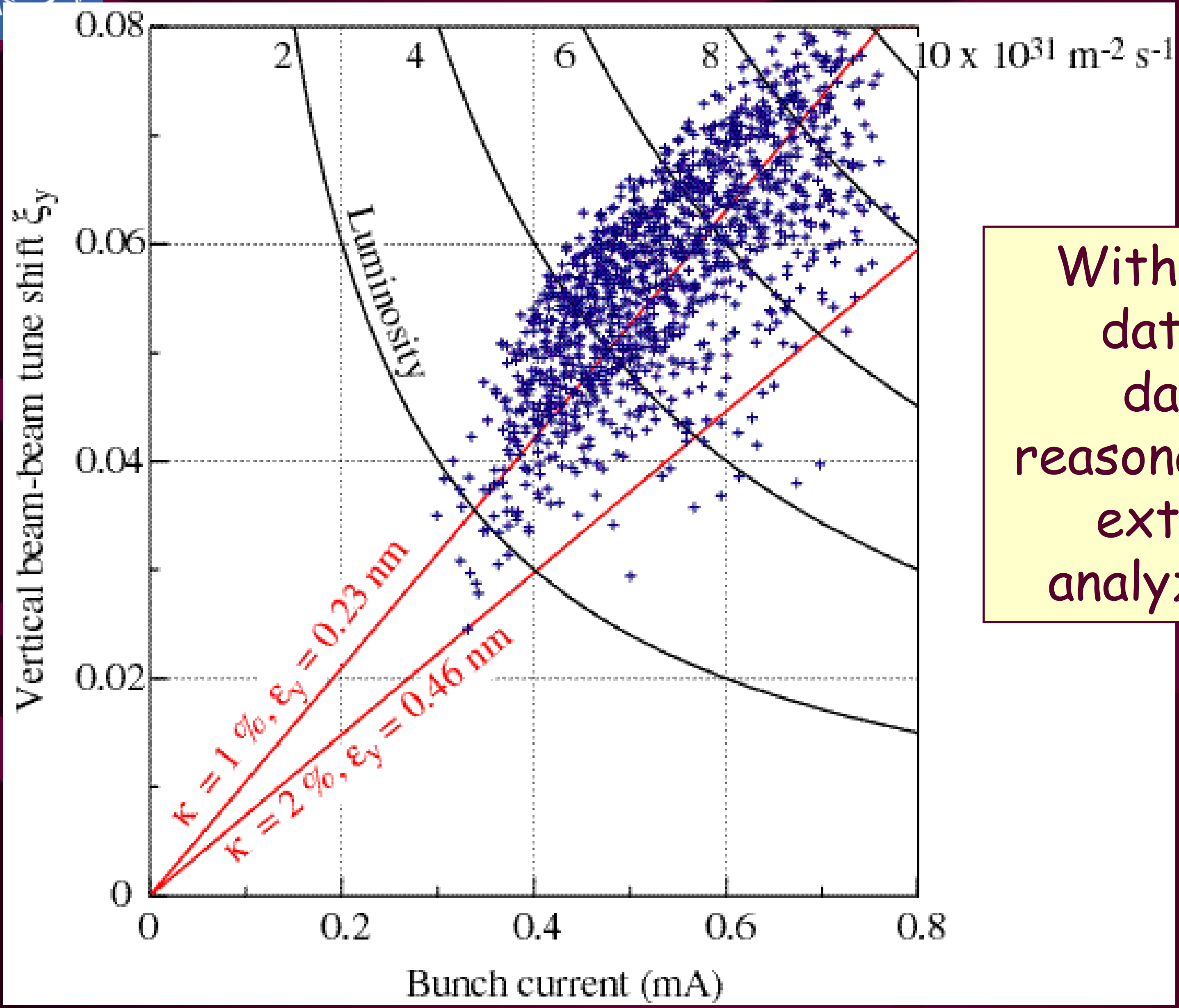
Retrieval of archived measurements



Browser & Viewer

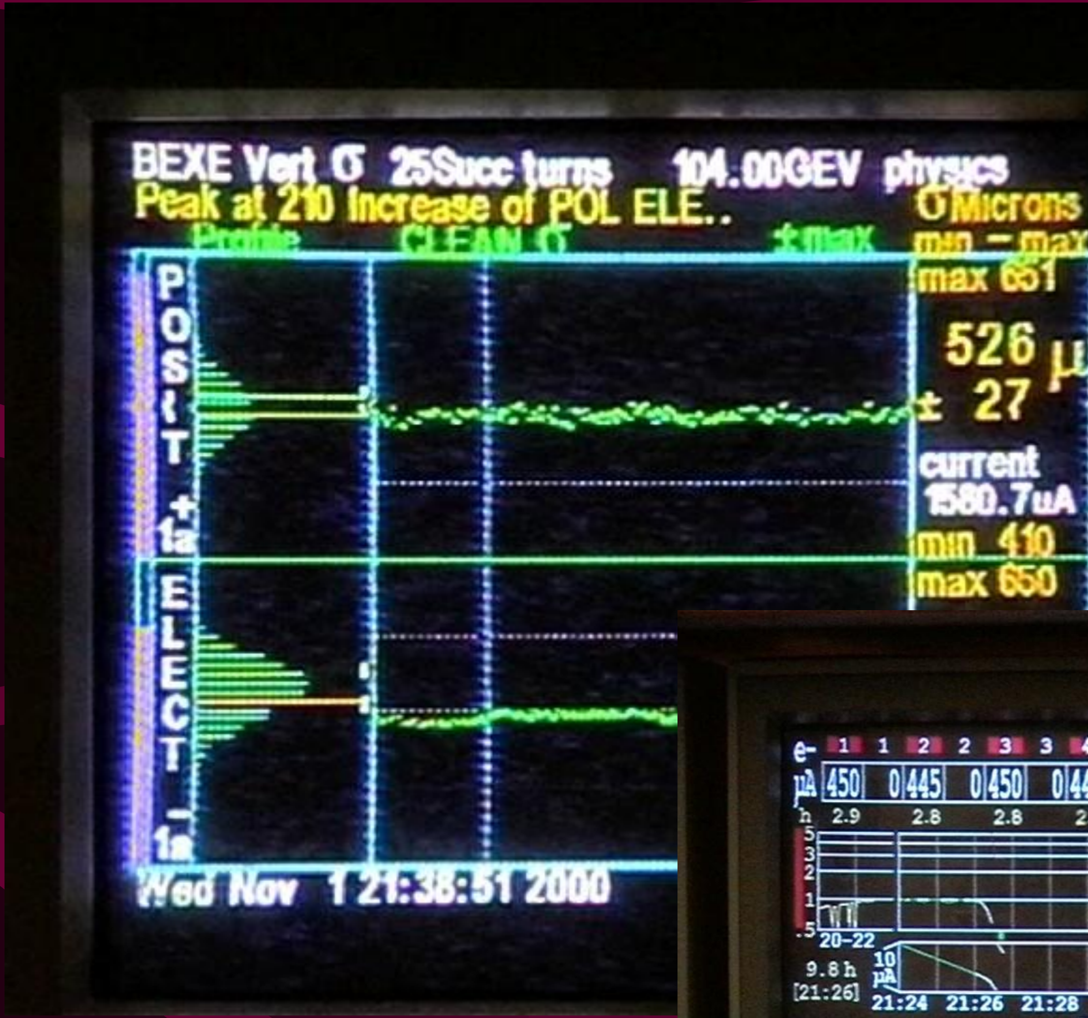


DATA EXTRACTION → POST RUN ANALYSIS



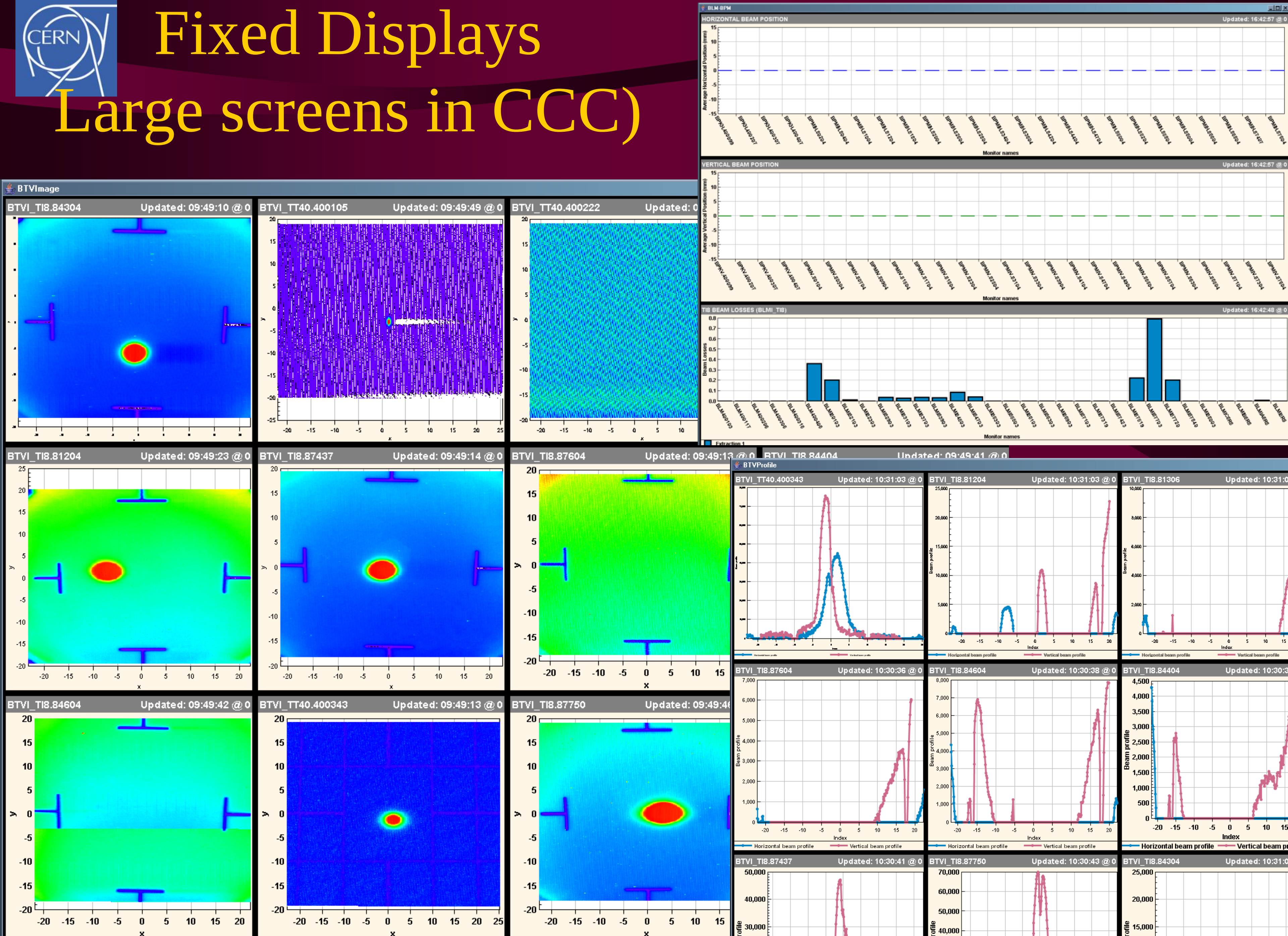
With historical data on the database, reasonably easy to extract and analyze off-line

Dedicated Video (FAST) Signals (LEP)



Data sampled at slower rate → logging database

Fixed Displays Large screens in CCC)



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”

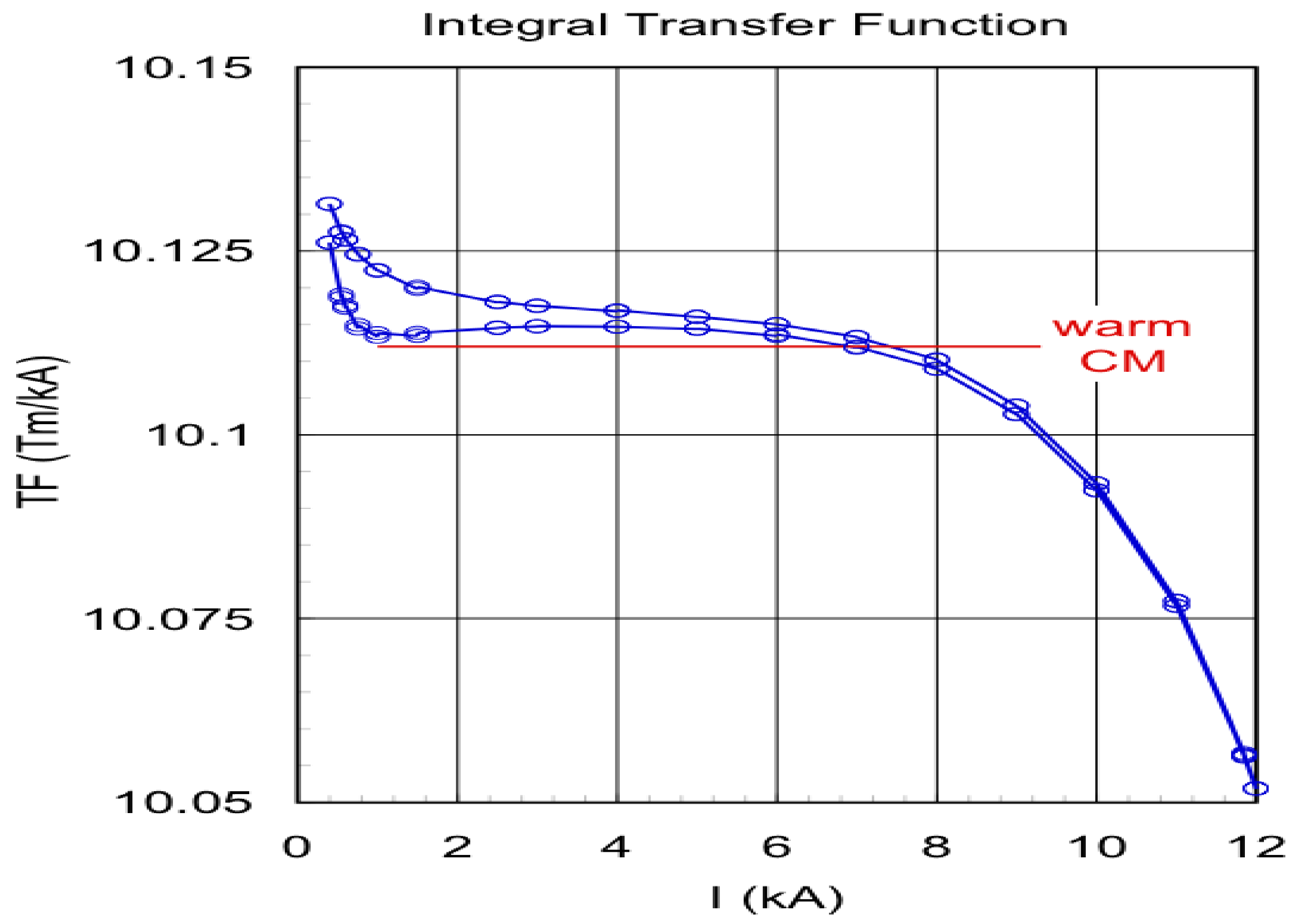
- in case of the LHC the main dipoles are superconducting→ the field model is more complicated then a simple look-up table ….next slides

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, dI/dt, I(-t) geometric C_n^{geom}
  - → DC magnetization from persistent currents C_n^{MDC}
  - → iron saturation $C_n^{saturation}$
  - → decay at injection C_n^{decay}
  - → snap-back at acceleration C_n^{SB}
  - → coil deformation at high field C_n^{def}
  - → coupling currents C_n^{MAC}
  - → residual magnetization $C_n^{residual}$

higher values
higher variability
higher uncertainty

↑

smaller values
smaller variability
smaller uncertainty

- linear composition of contributions:

$$\mathbf{C}_n = \mathbf{C}_n^{geom} + \mathbf{C}_n^{MDC} + \mathbf{C}_n^{saturation} + \mathbf{C}_n^{decay} + \mathbf{C}_n^{SB} + \mathbf{C}_n^{def} + \mathbf{C}_n^{MAC} + \mathbf{C}_n^{residual}$$

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 (Tm/kA)

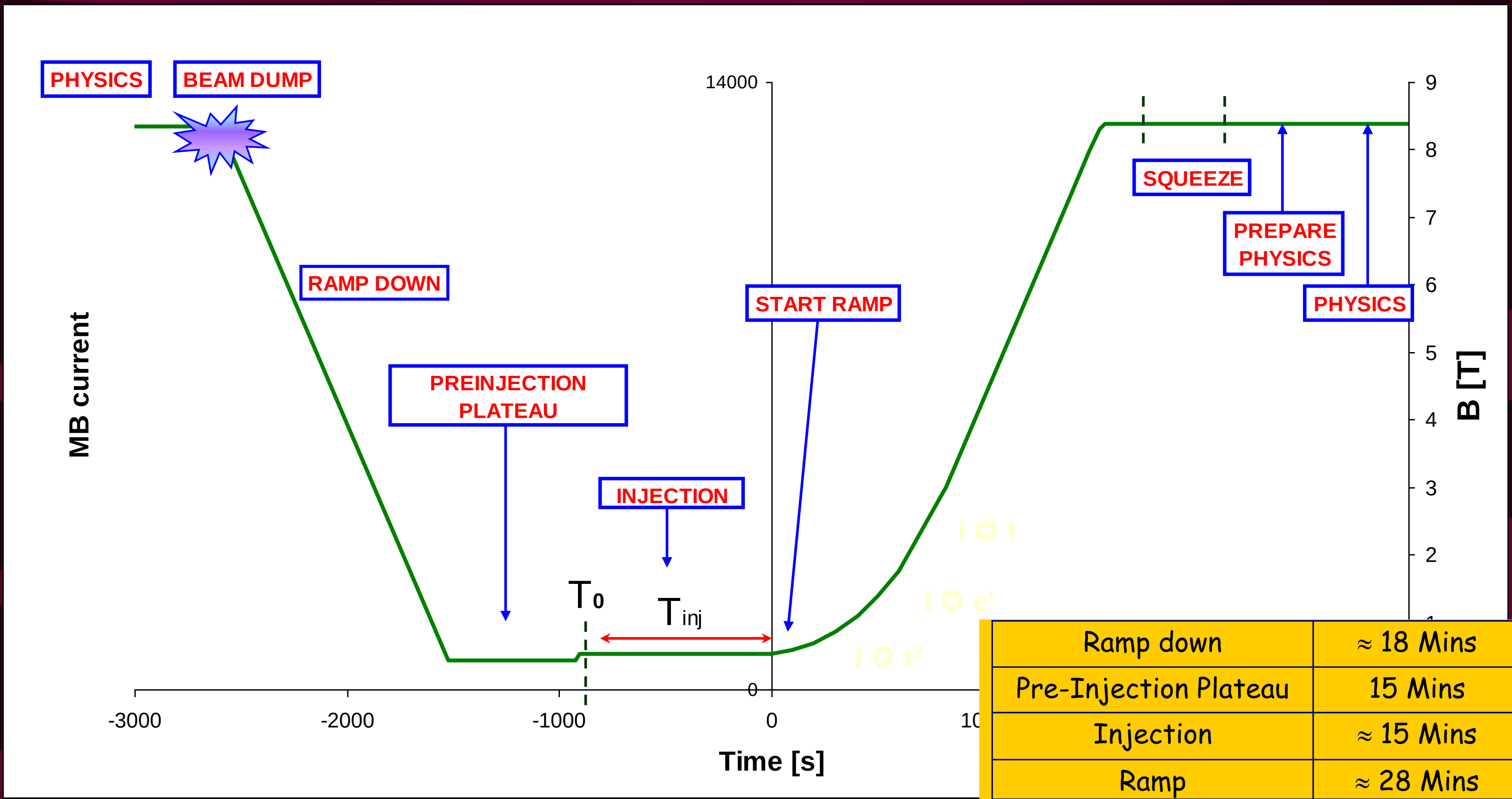
- Required integrated field strehngth in sector 78 for an injection at 450 GeV from SPS : 1189.2 T m

→ I = 763.2(5) 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

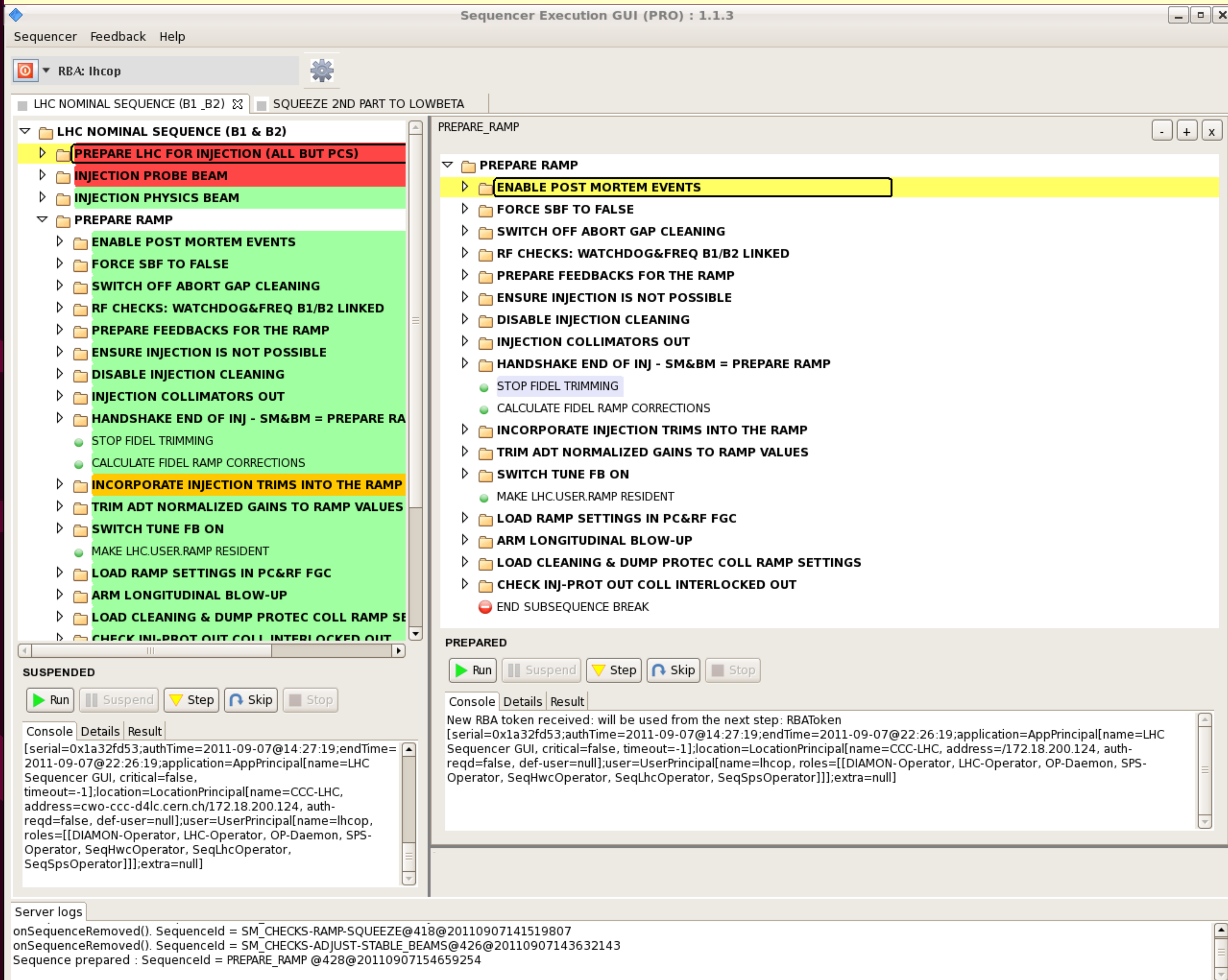
…and now we have to ramp the whole lot

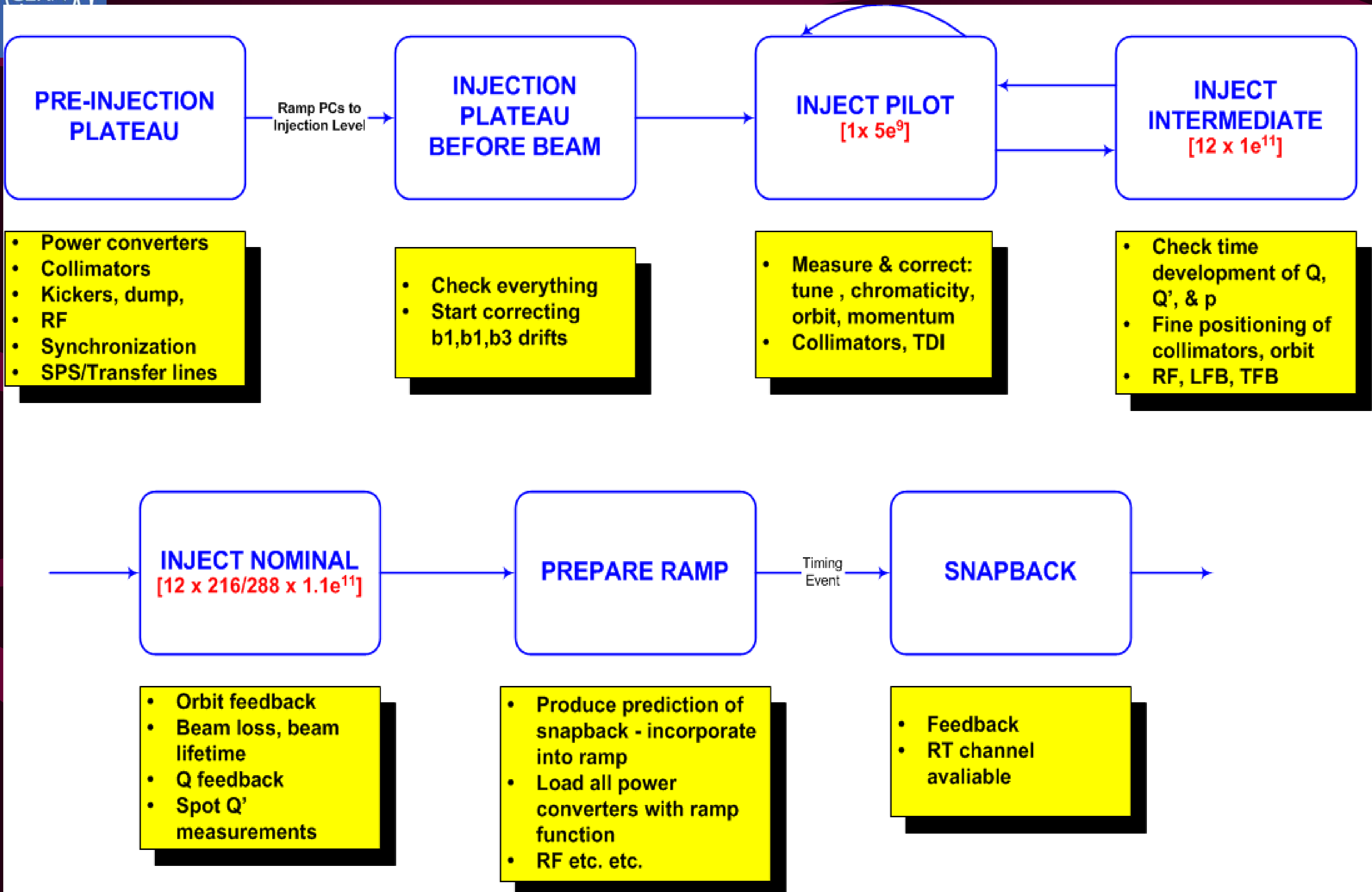


Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	< 5 Mins
Prepare Physics	≈ 10 Mins
Physics	10 - 20 Hrs

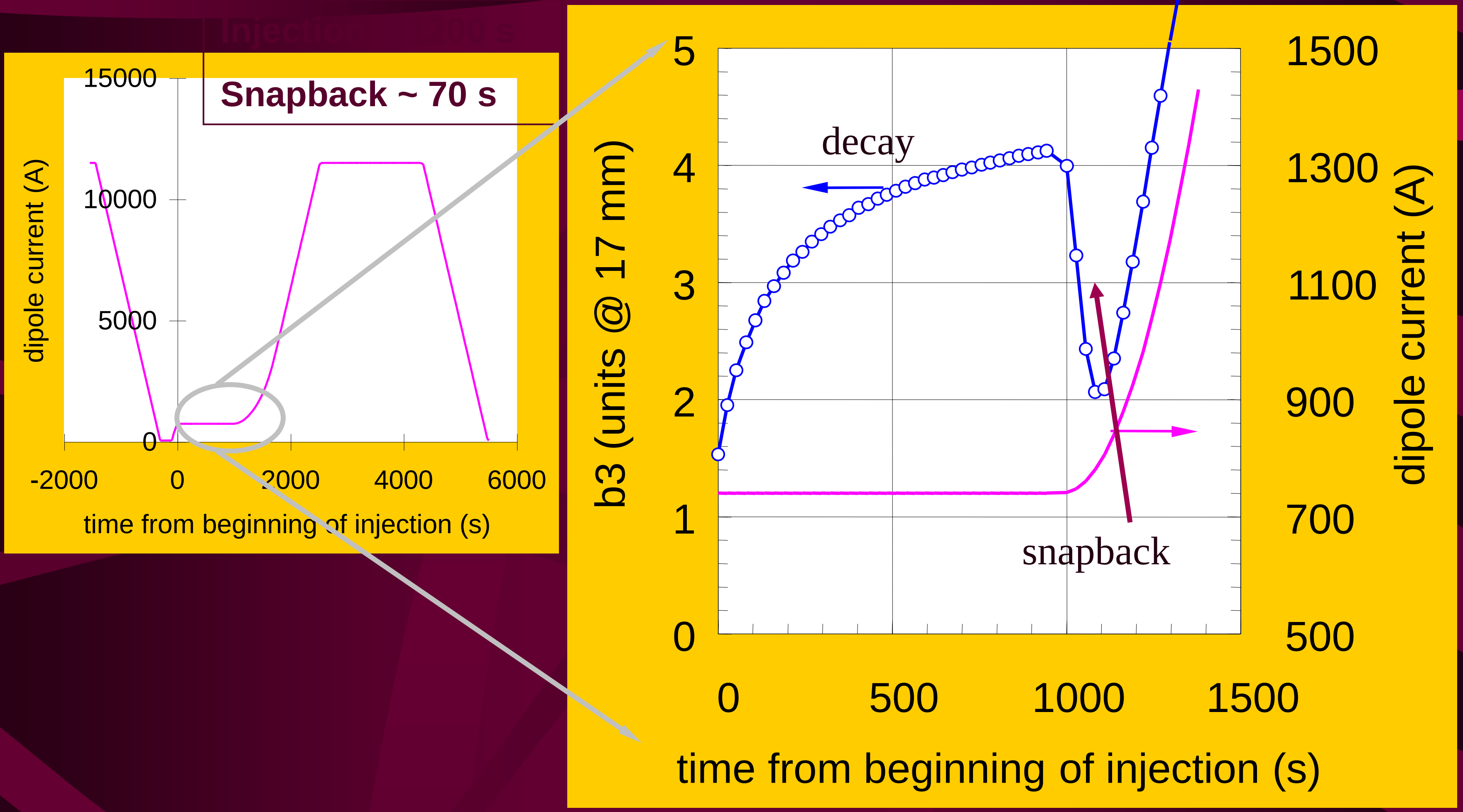
All routine operation based on a Semi-automatic sequencer

- Reproducibility
- Reduced scope for error



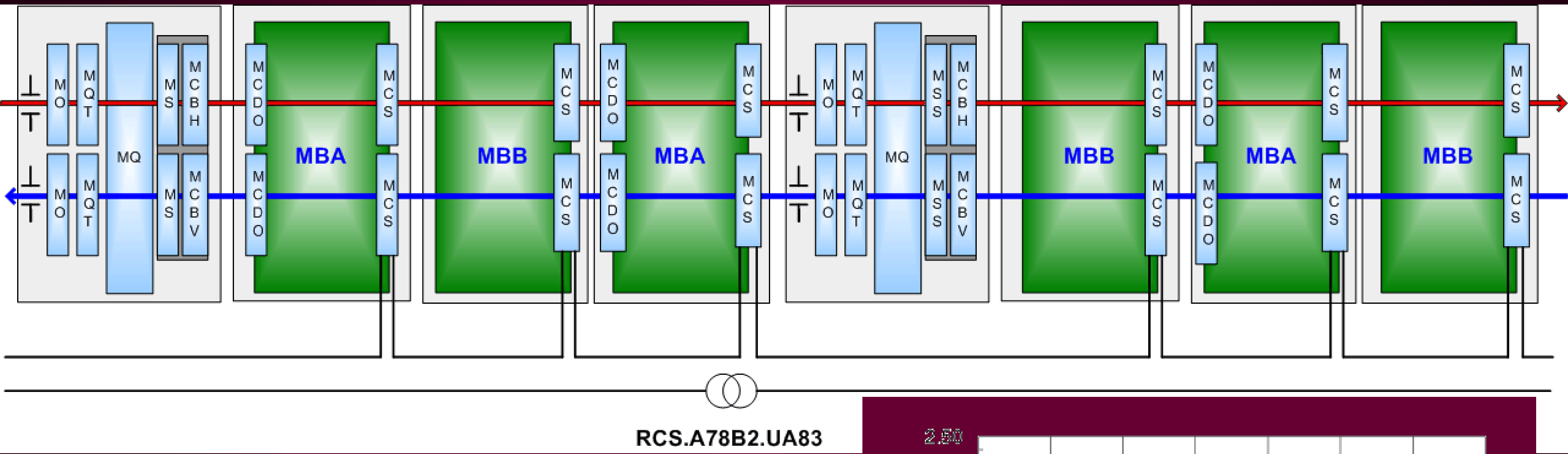

PRE-INJECTION PLATEAU
Ramp PCs to Injection Level
INJECTION PLATEAU BEFORE BEAM
INJECT PILOT
[1x 5e^{9}]
INJECT INTERMEDIATE
[12 x 1e^{11}]
• Power converters
• Collimators
• Kickers, dump,
• RF
• Synchronization
• SPS/Transfer lines
• Check everything
• Start correcting b1,b1,b3 drifts
• Measure & correct: tune , chromaticity, orbit, momentum
• Collimators, TDI
• Check time development of Q, Q', & p
• Fine positioning of collimators, orbit
• RF, LFB, TFB
INJECT NOMINAL
[12 x 216/288 x 1.1e^{11}]
PREPARE RAMP
Timing Event
SNAPBACK
• Orbit feedback
• Beam loss, beam lifetime
• Q feedback
• Spot Q' measurements
• Produce prediction of snapback - incorporate into ramp
• Load all power converters with ramp function
• RF etc. etc.
• Feedback
• RT channel avaliable

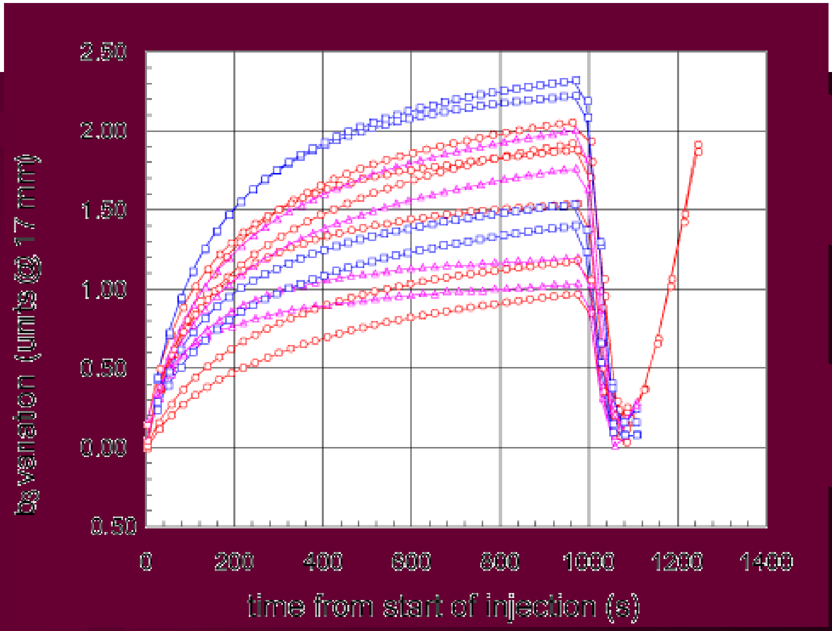
A very frightening problem…



Parameter	Nominal tolerance	Limit on b_n(MB) – Inj.	Approx. Decay	Parameter swing
Q’	Q’≈2 ΔQ’≈± 1	± 0.02	1.7	ΔQ’≈+71/-64

Correction elements





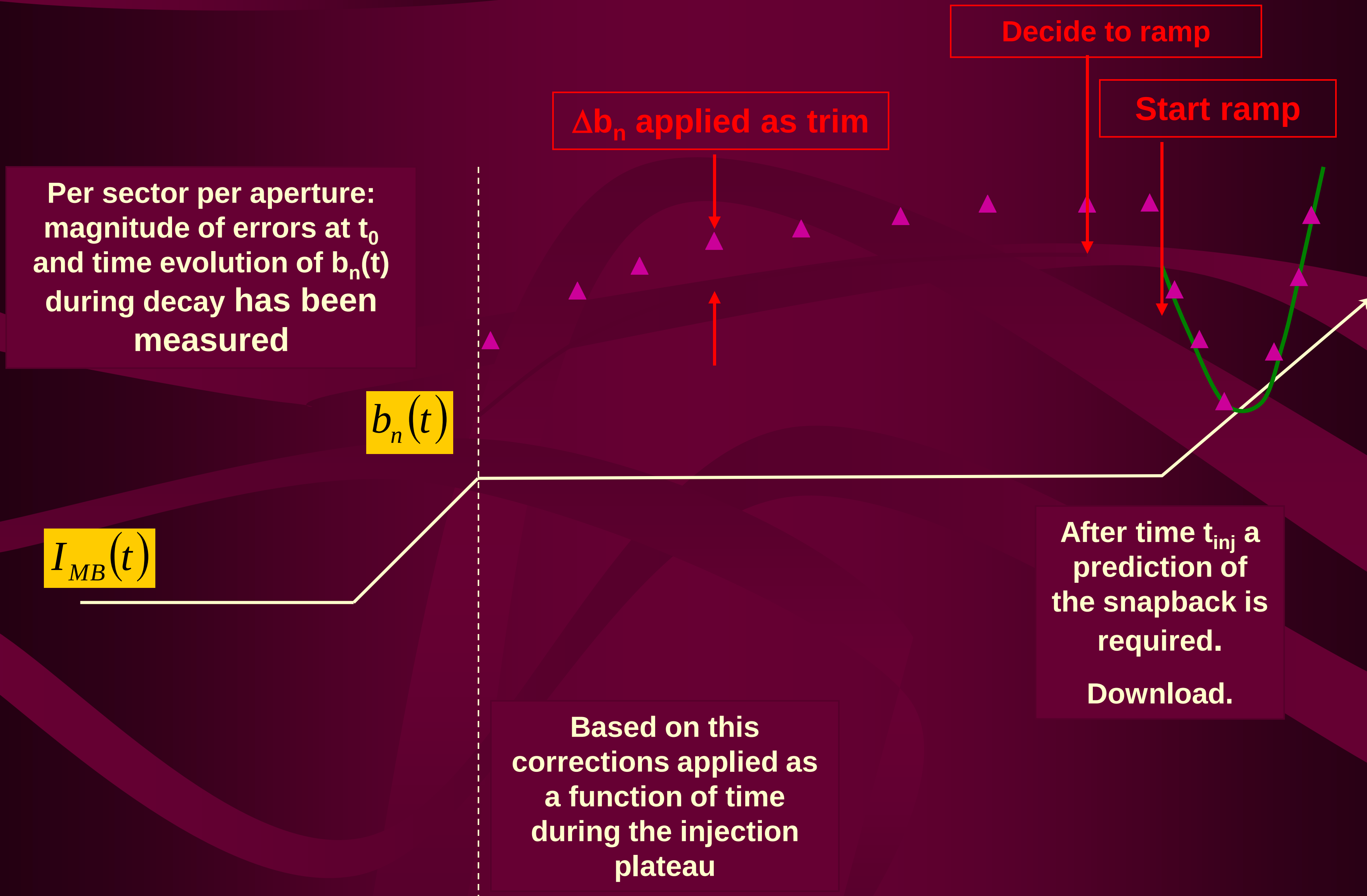
Per aperture:

154 MCS sextupole spool pieces powered in series.

77 MCO & MCD spool pieces powered in series.

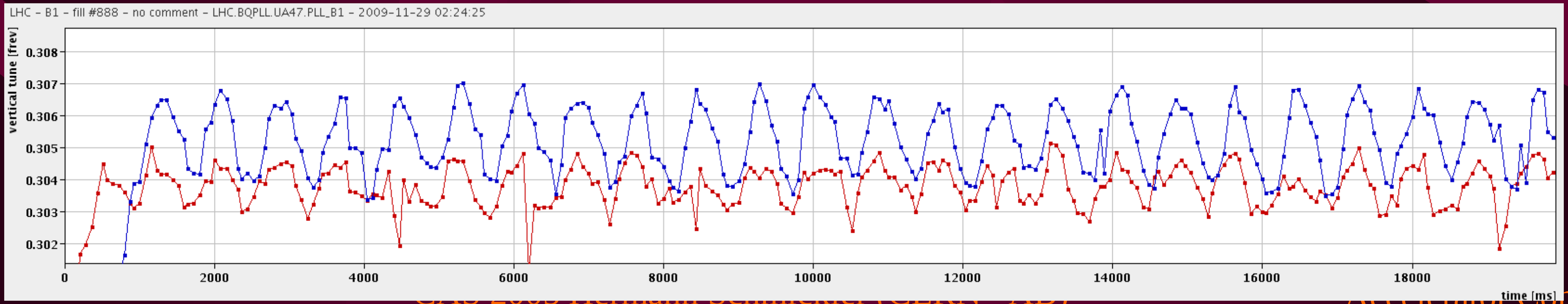
Therefore we're working on the average per sector per aperture

Dynamic effects - correction



Q' - control

- Extract sextupole change in dipoles from slow Q' measurements & b_3 corrections during injection to give Δb_3 and thus ΔI.
- 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 chromaticties: Hz

  } Nice Problem for the instrumentation group
- Data centralization and computation of corrections (including error handling, dynamic change of twiss parameters…
- Feedback of corrections to power converters

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

1996

Wide-Band-Time-Normaliser proposed for LHC BPM system

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

1999

Radiation testing showed digital acq. needs to be out of tunnel

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

2000

RT control specification, mostly decay-/snap-back and nominal performance (no MP yet)

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

2001

BPM design and capabilities "inspired" specs.
Moving digital processing out of the tunnel

2002

Recognition that collimation will rely on real-time Orbit-FBs

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

2003

Orbit-FB prototype tests at the SPS

2004

IWBS'04: SLS, ALS, Diamond, Soleil and others → affirmed Orbit-FB strategy

2005

Orbit(-FB) and MP entanglement recognised
→ FB: "nice to have" to "necessary"

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

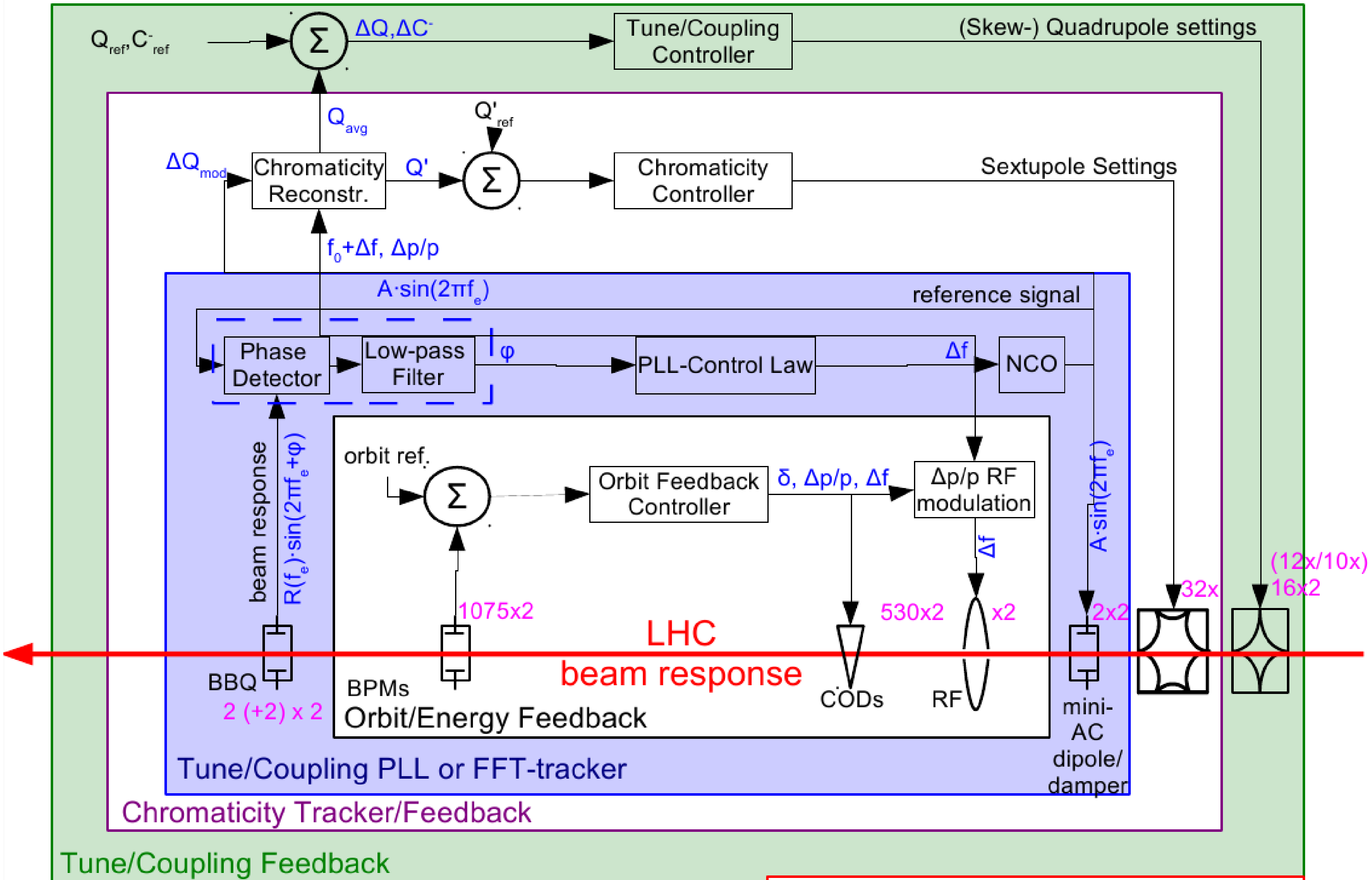
2006

2007

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

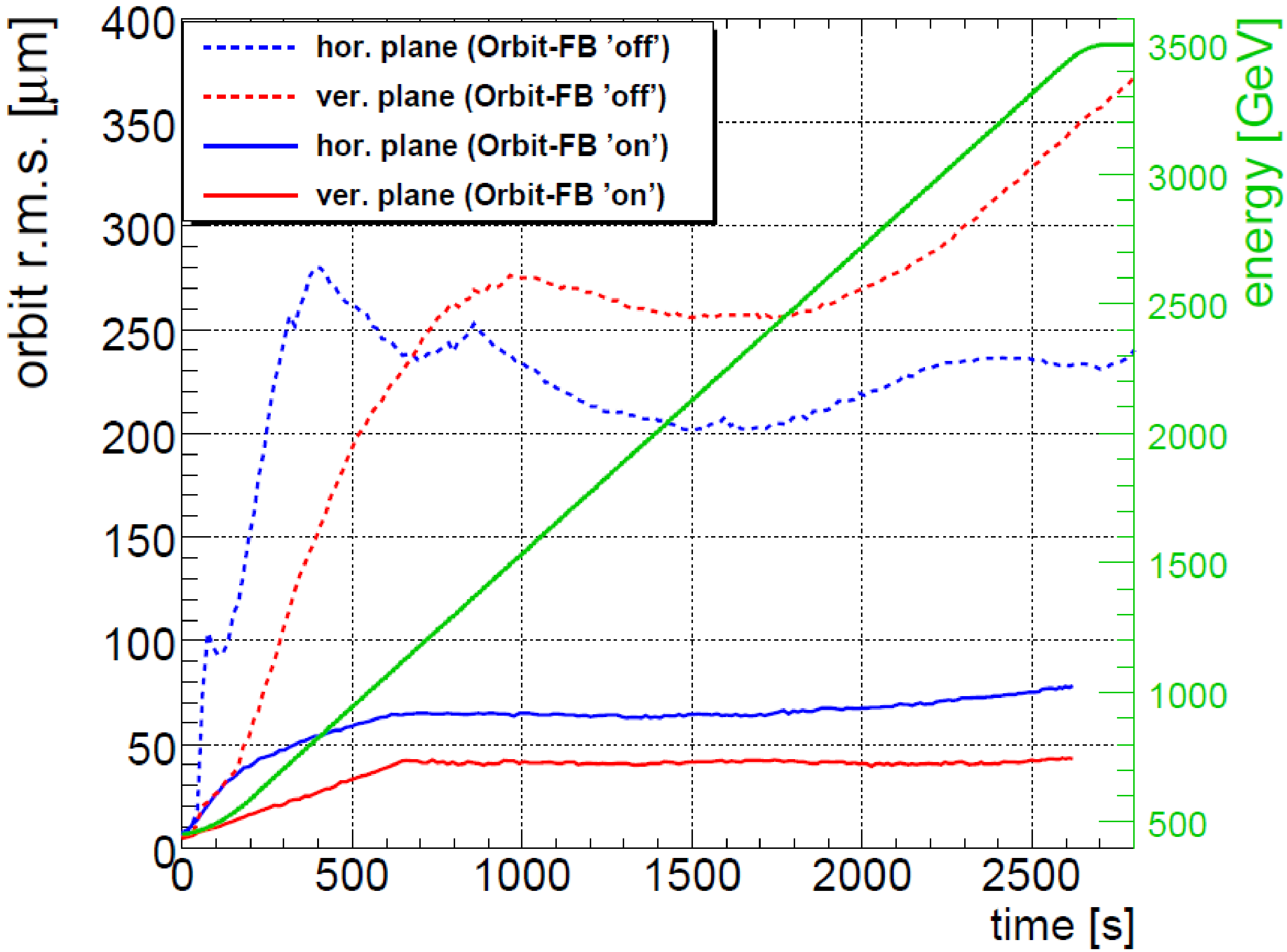


further: $f_{BW}(PLL) \gg f_{BW}(Q') \geq f_{BW}(Q, C^-)$

9

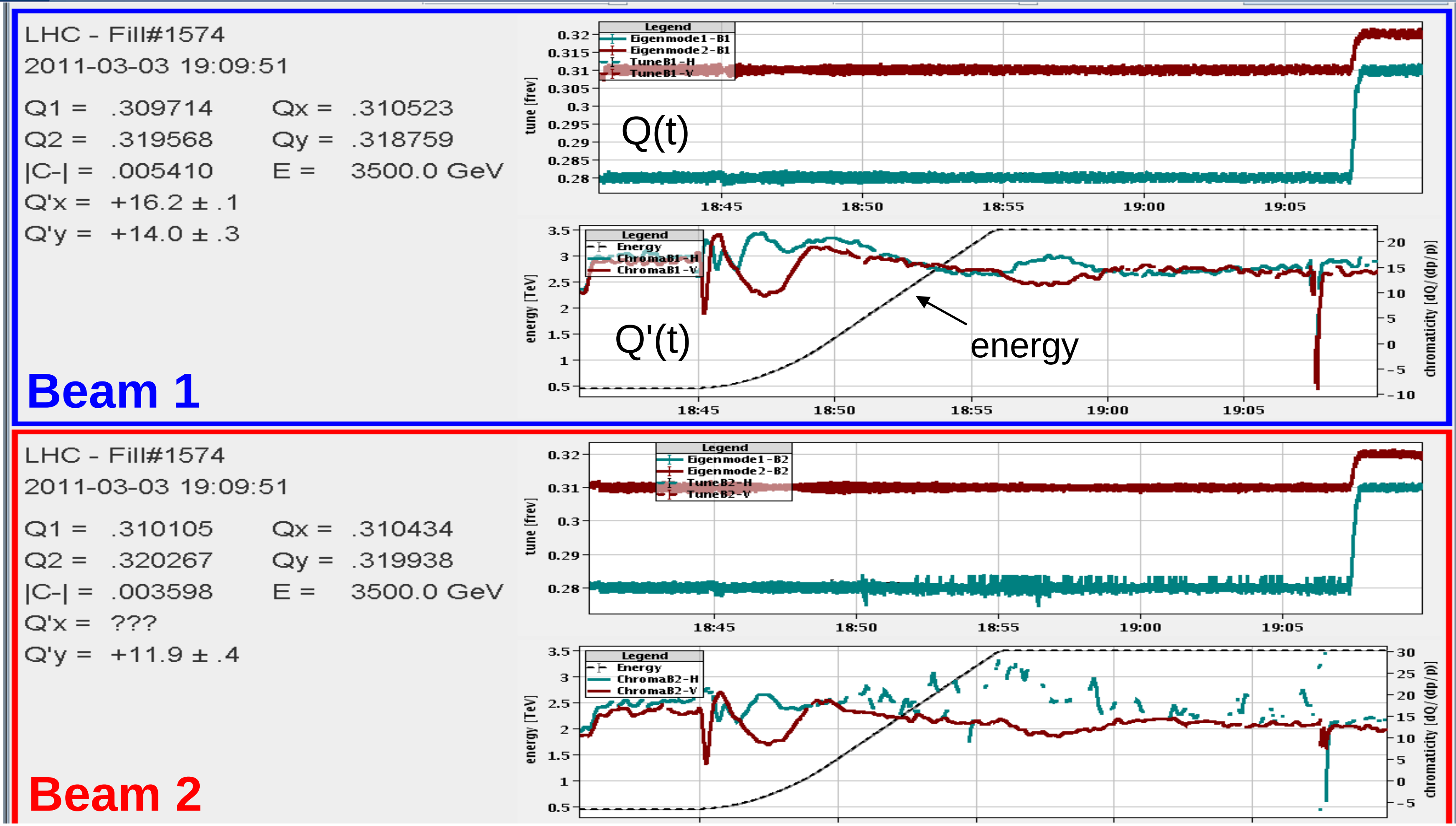
Orbit Feedback Performance

- Orbit feedback used routinely and mandatory for nominal beam



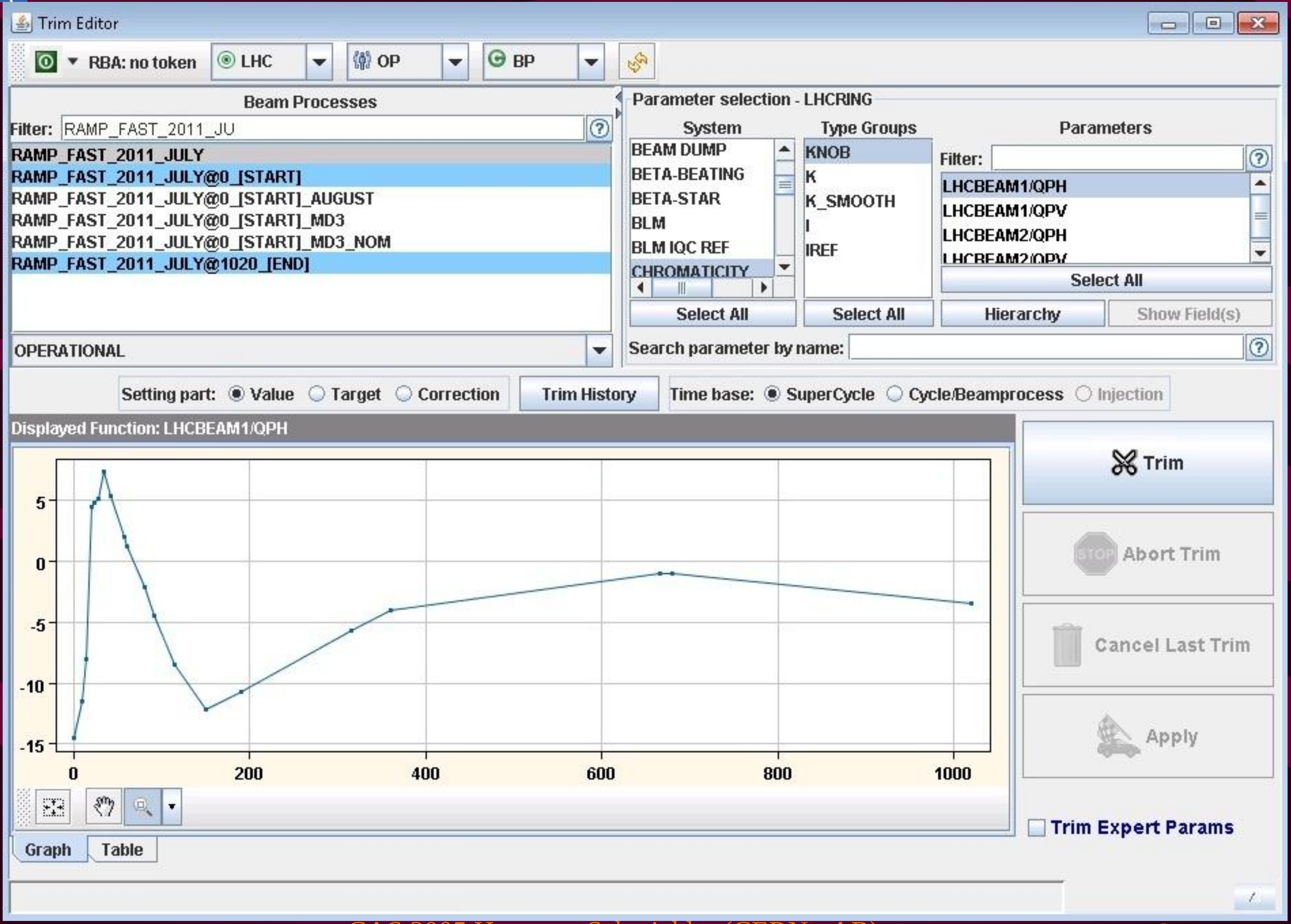
- Typical stability: 80 (20) µm rms. globally (arcs)
- Most perturbations due to Orbit-FB reference changes around experiments

2010 Statistics: Out of 191 Ramps...

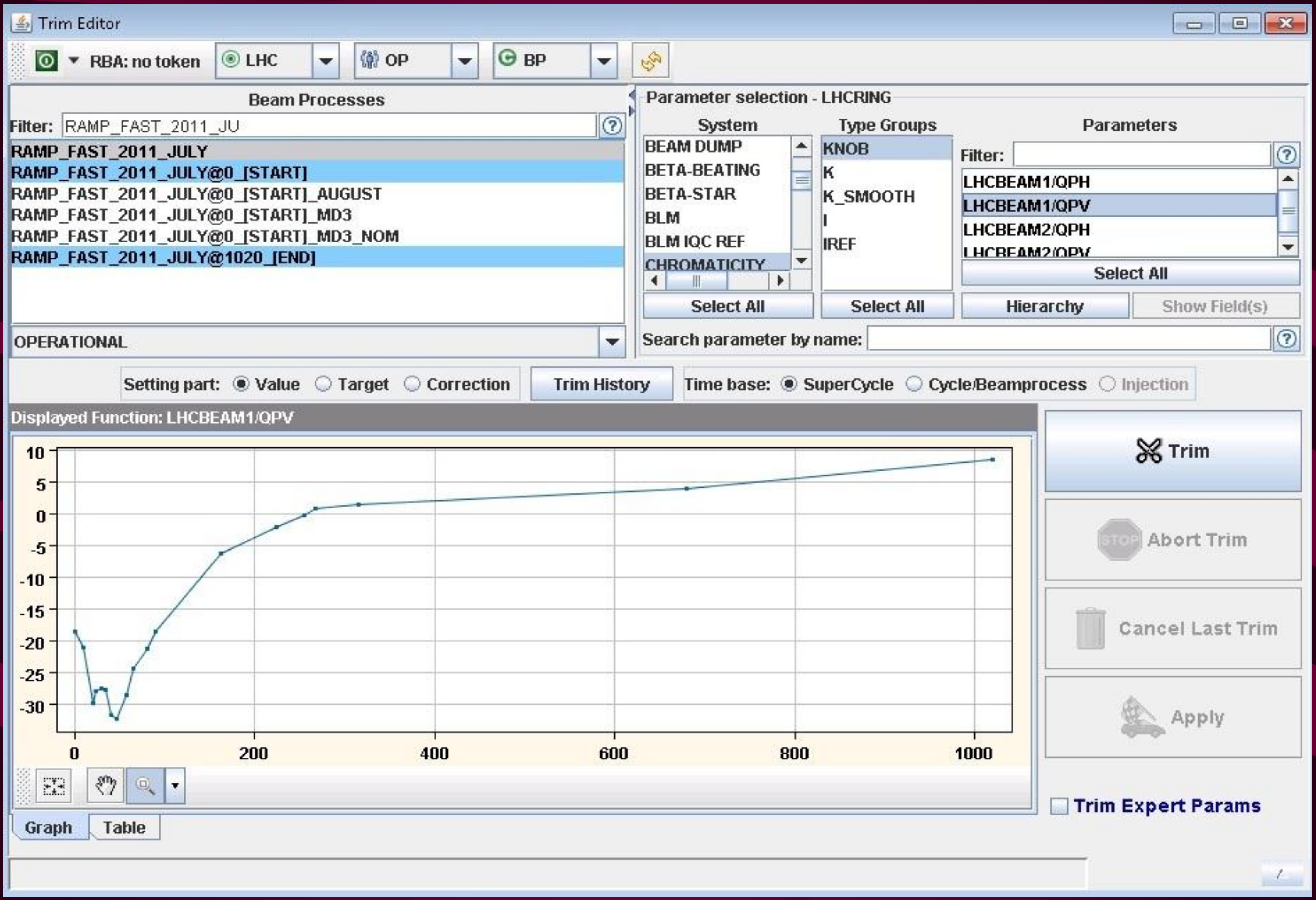


- … 155 ramps with > 99% transmission, 178 ramps with > 97% transmission
- … only 12 ramps lost with beam (6 with Tune-FB during initial 3.5 TeV comm.)
- … "if without FBs": 83 crossings of 3rd, 4th or C- resonance, 157 exceeded |ΔQ|>0.01
- Impressive performance for the first year of operation and low-ish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

Available trim functions for Qh'



Available trim functions for Qv'



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…