Accelerator Controls
Part1: CERN Accelerator Controls

CAS 2009@Divonne

Hermann Schmickler

What we will do in the next 2 hours…

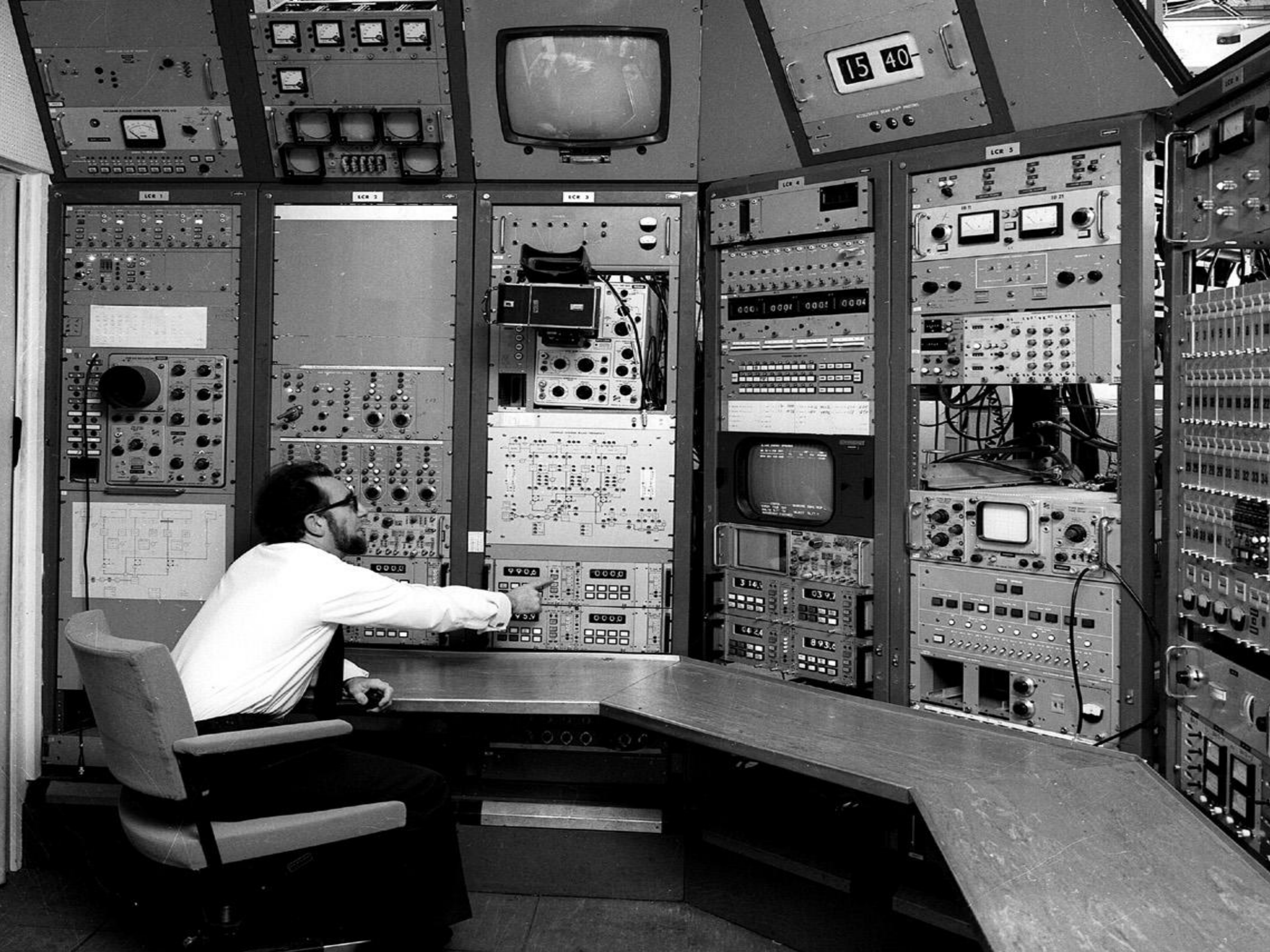
- First hour:
  The good old days…
  Concept of modern controls
  Required functionality - nothing on technology
  examples for settings generation, function trimming and real time feedback
- Second hour (on request of the program committee):
  A fully detailed description of the CERN timing system (= multi accelerator operation)

Outline

- Controls technology (5 minutes)
  → 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
  Examples for:
  static and dynamic control, real time 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.

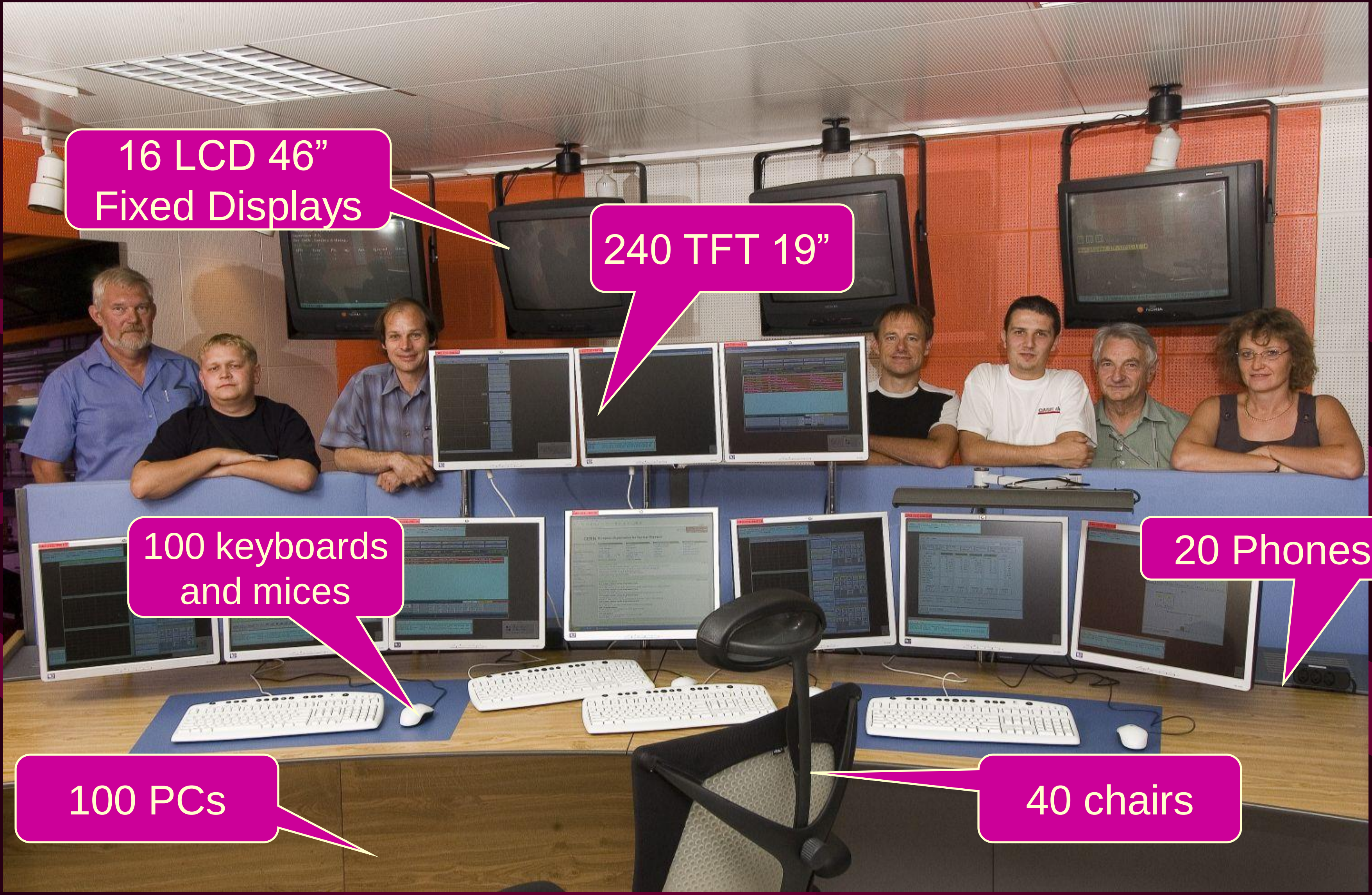

15 40
LCR 1
LCR 2
LCR 3
LCR 4
LCR 5

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 New CERN control center, ready spring 2006

CCC (=CERN Control Center) Working Place

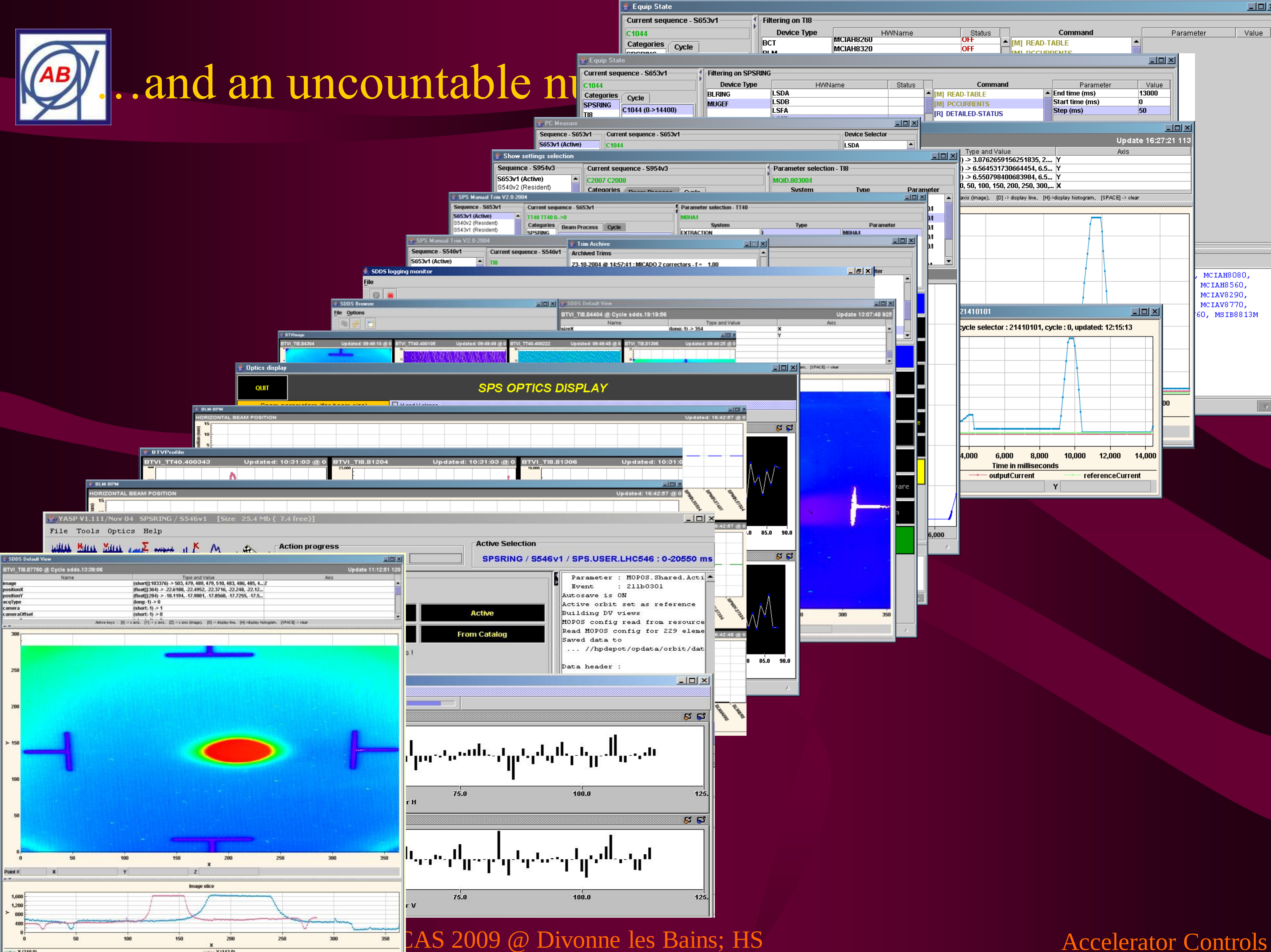


Some keywords for LHC controls technology

- 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,
- 3-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)

...and an uncountable nu



Technical Services

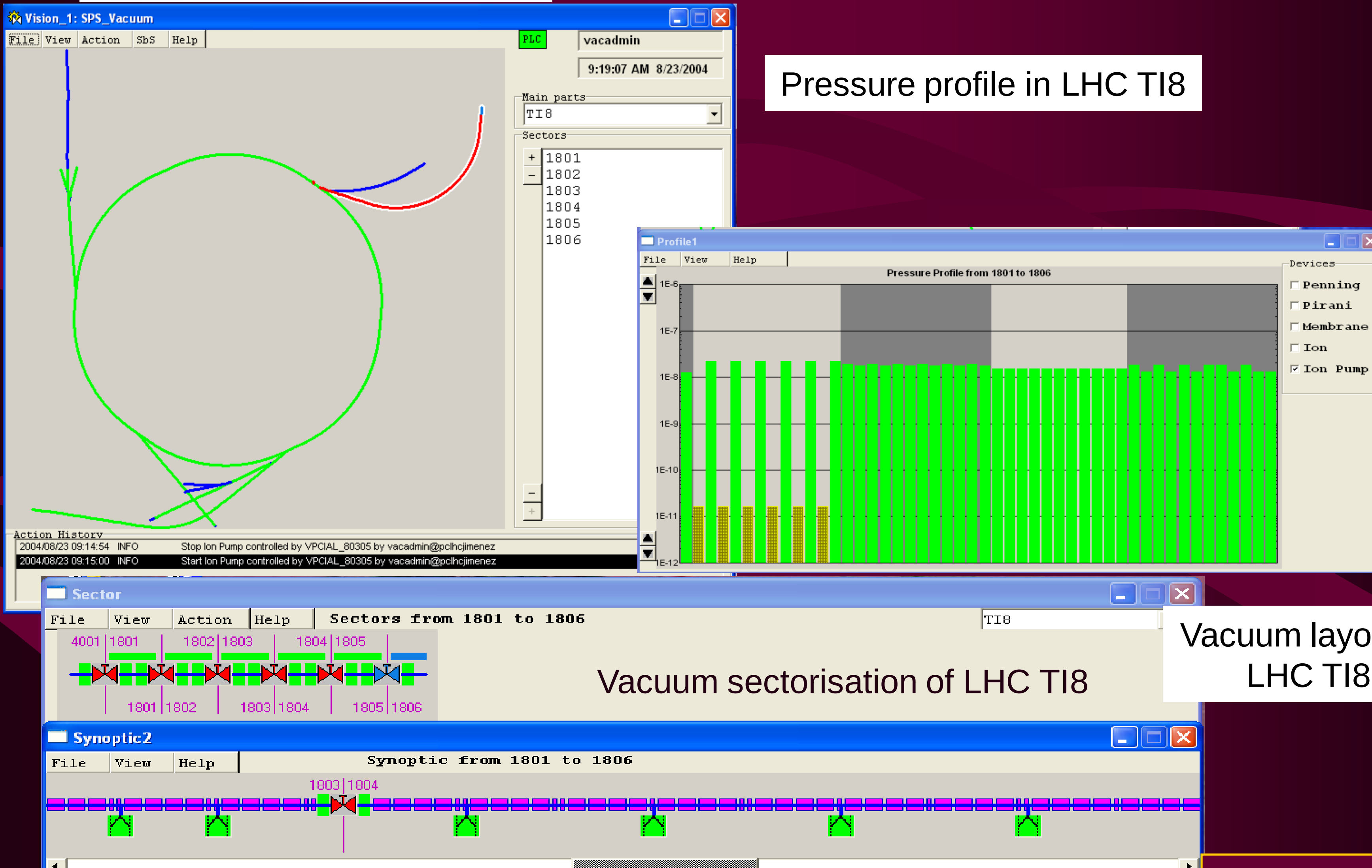
All we need even before thinking of injecting beam:

- 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

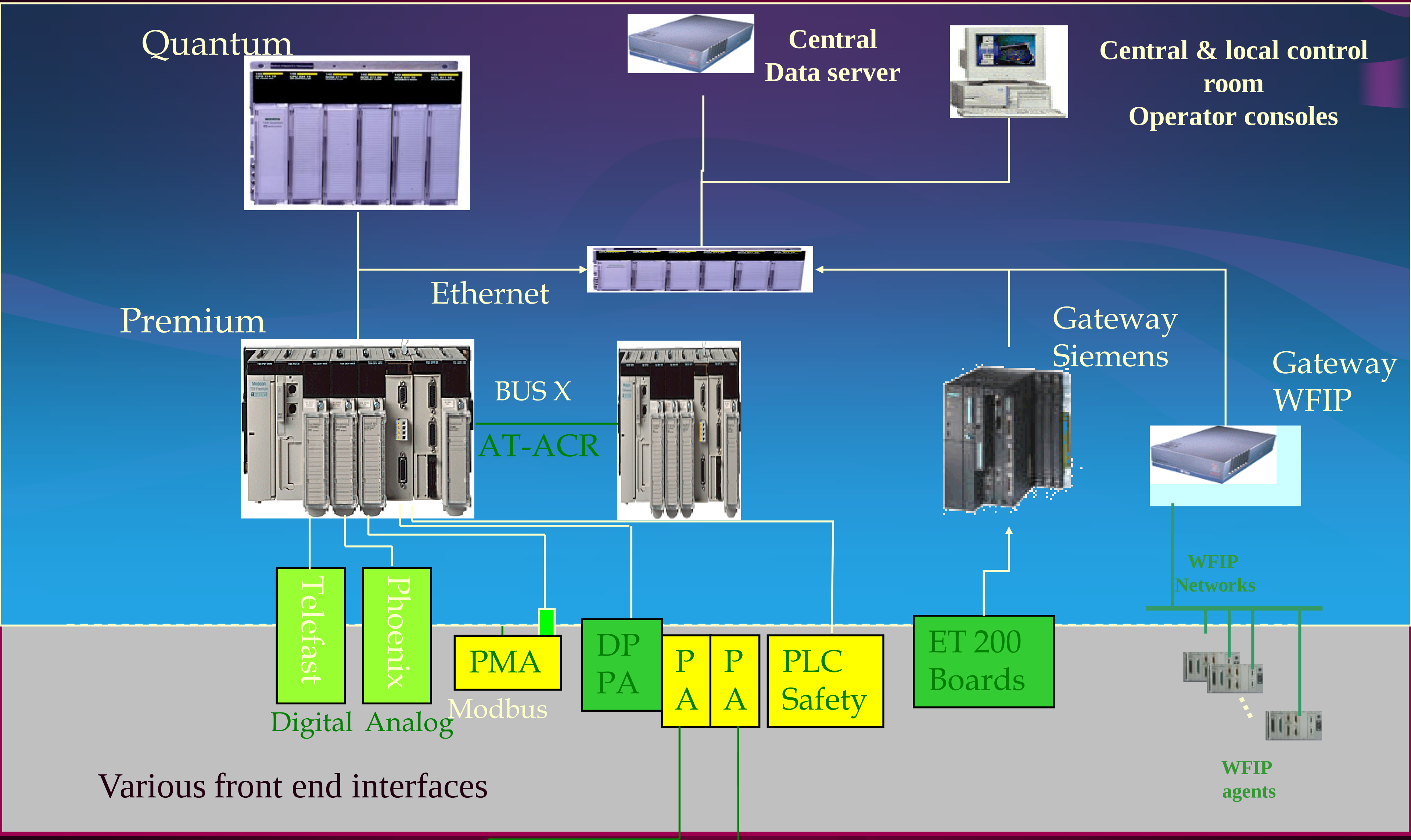
Pressure profile in LHC TI8



Vacuum 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**

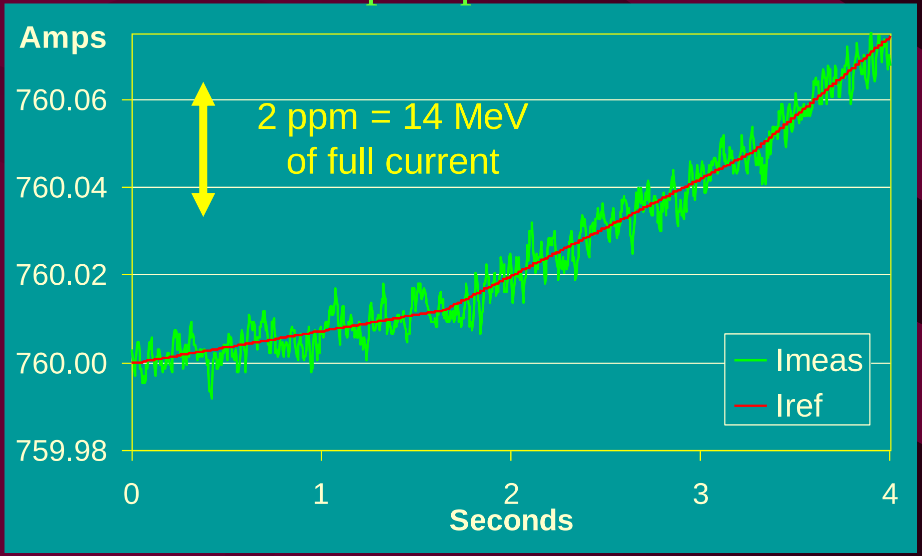
→**Machine Protection**

→**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

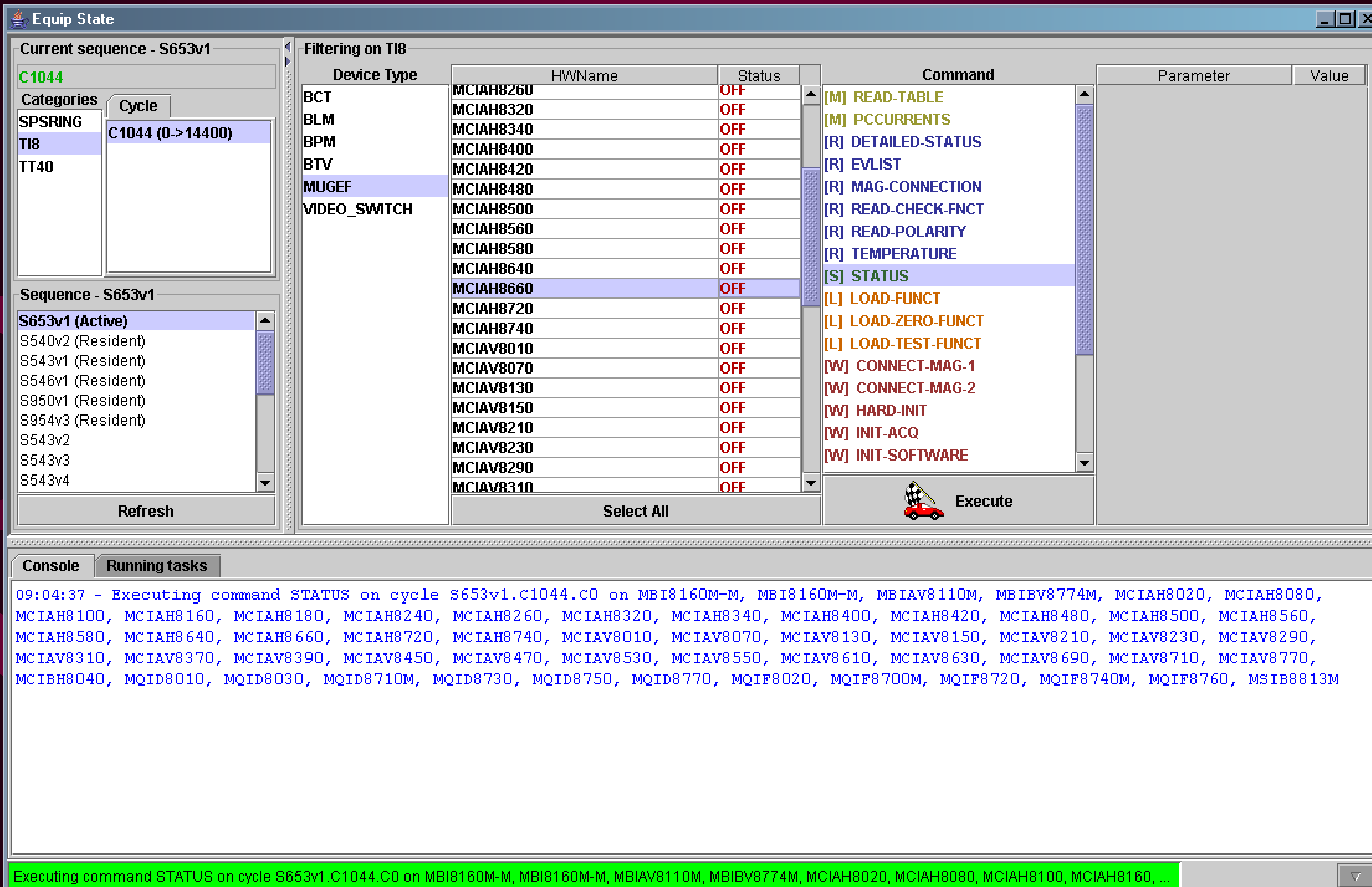


Tools for the control of beam parameters

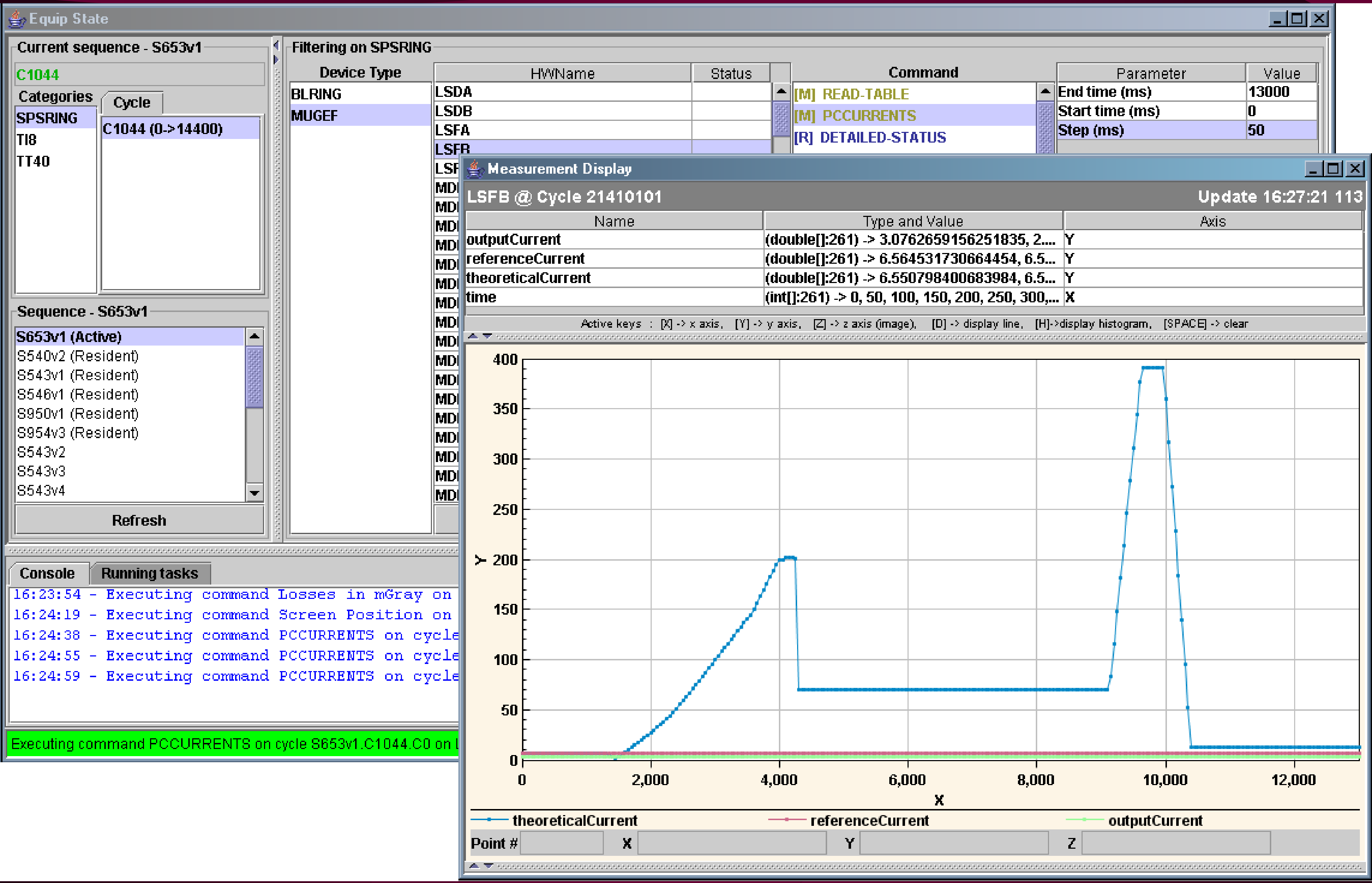
Requested Functionality:

- 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…

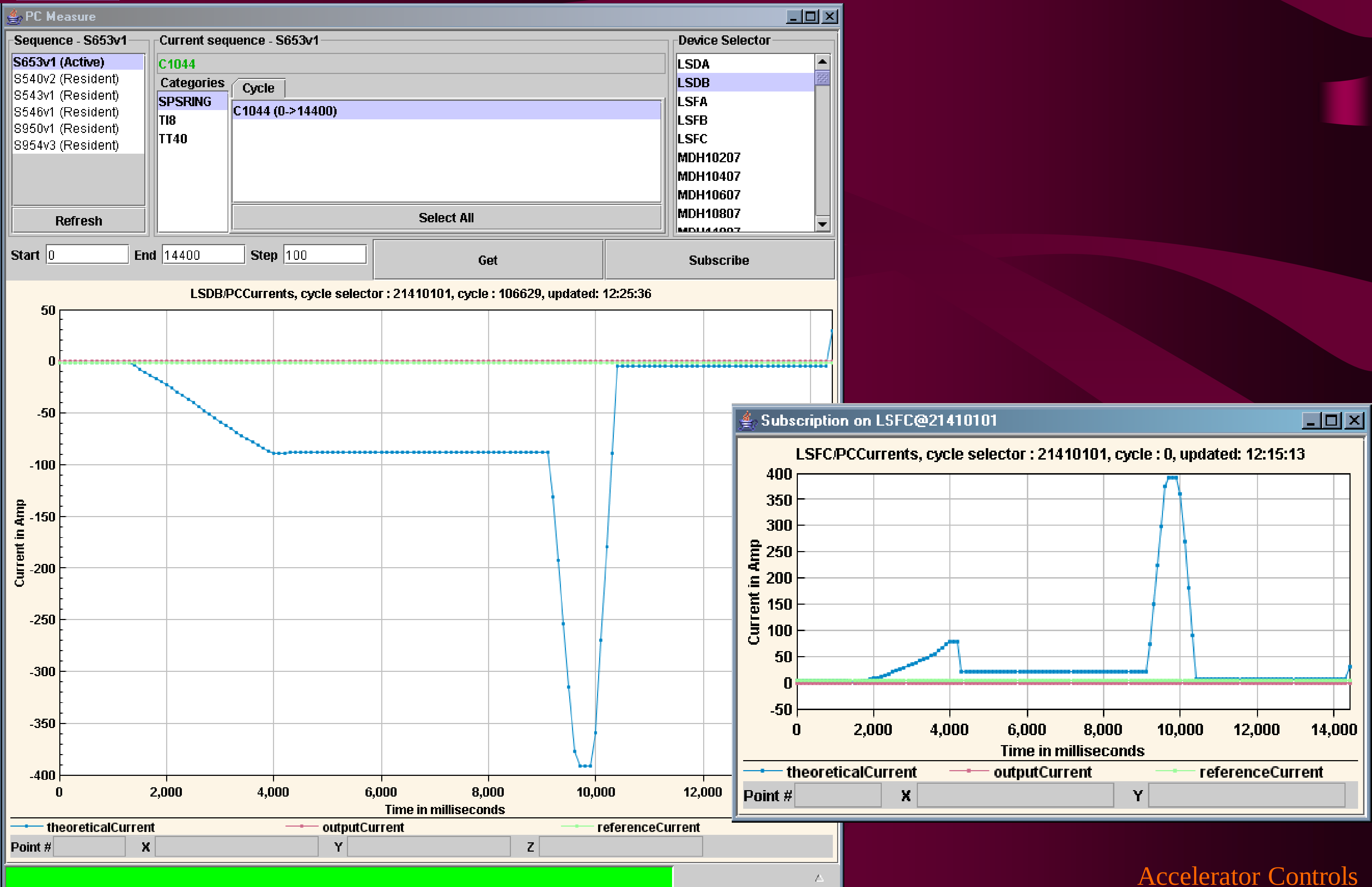
Generic Equipment Control



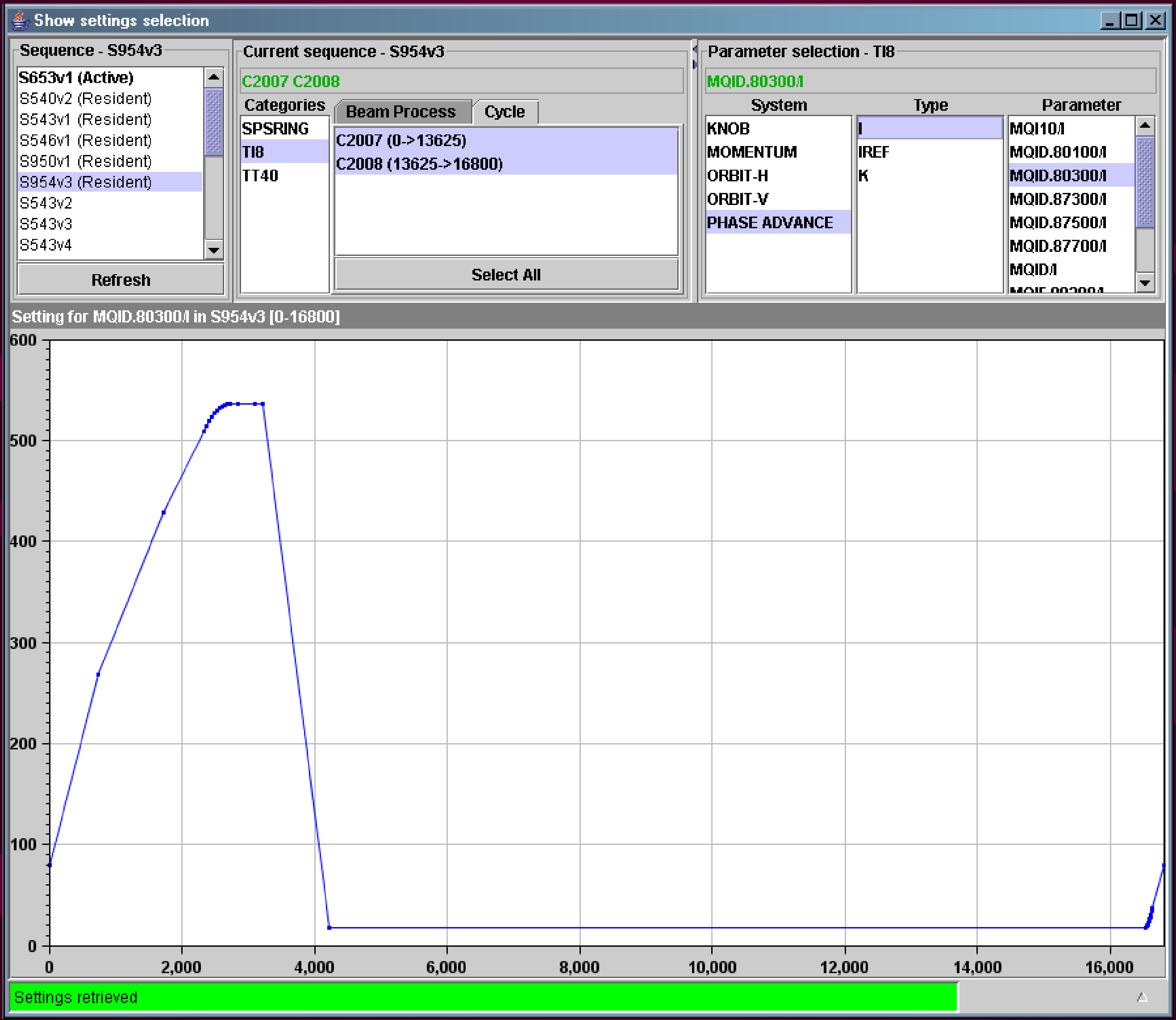
Generic Measurement



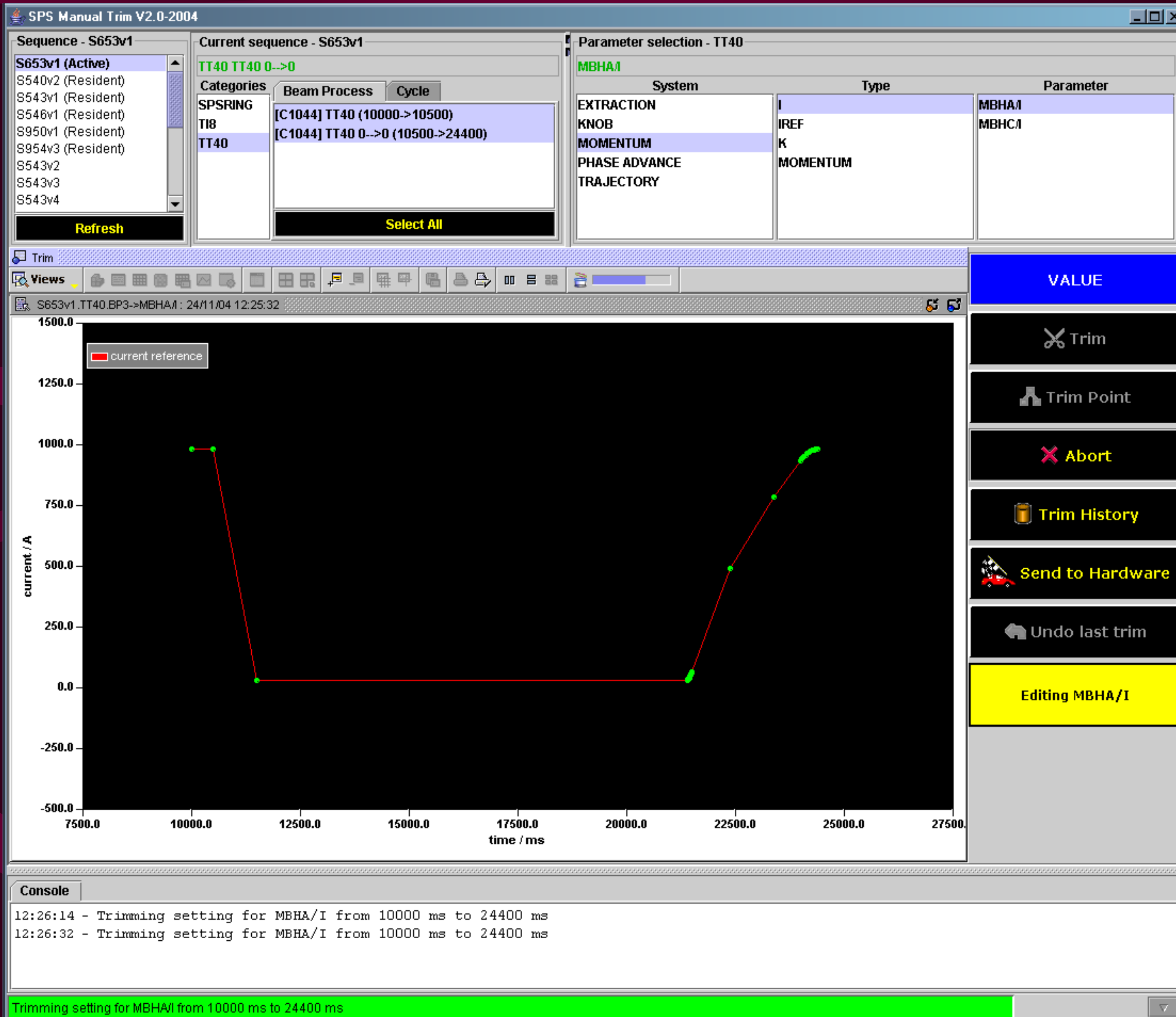
Measurement of power converters



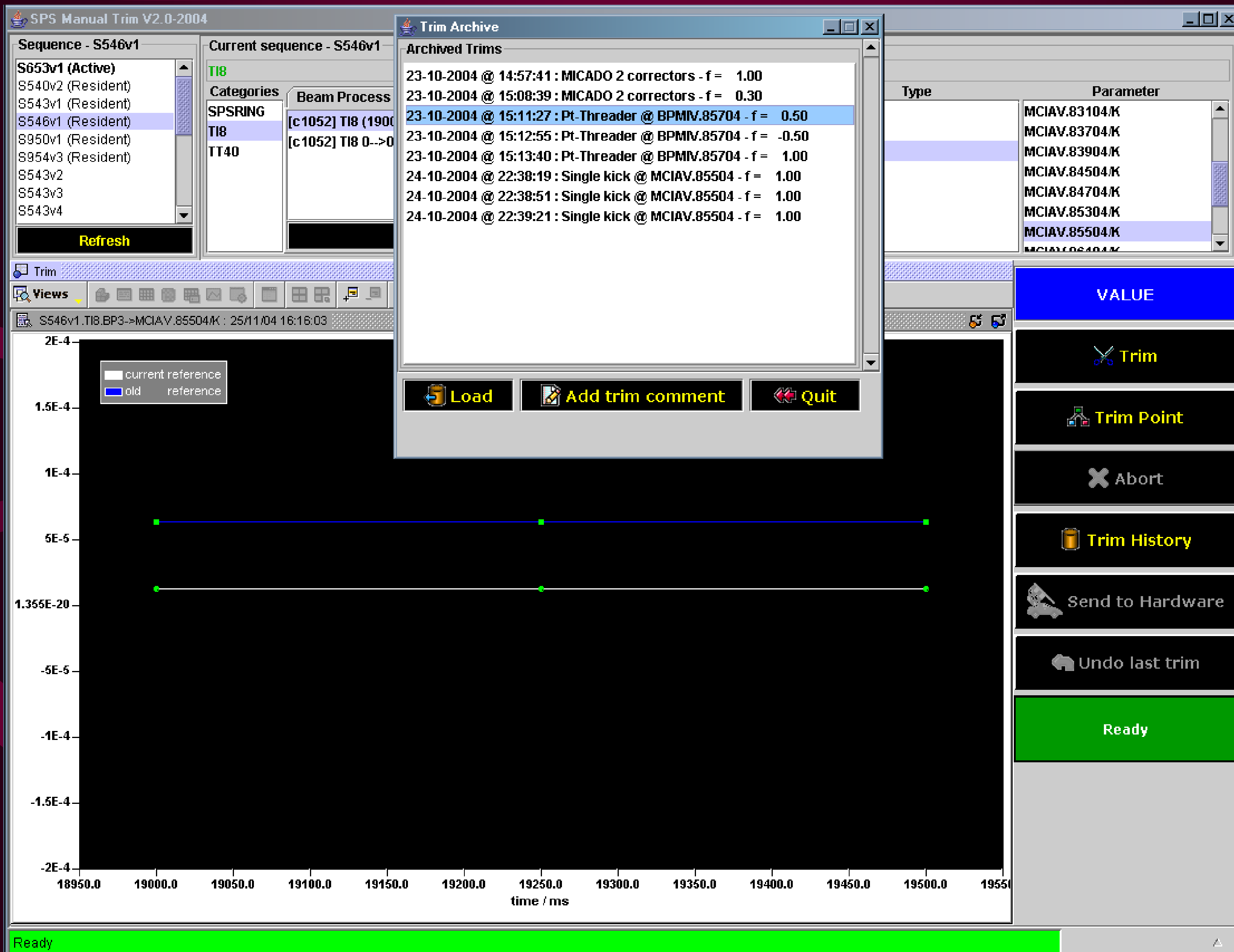
Visualization of the settings



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

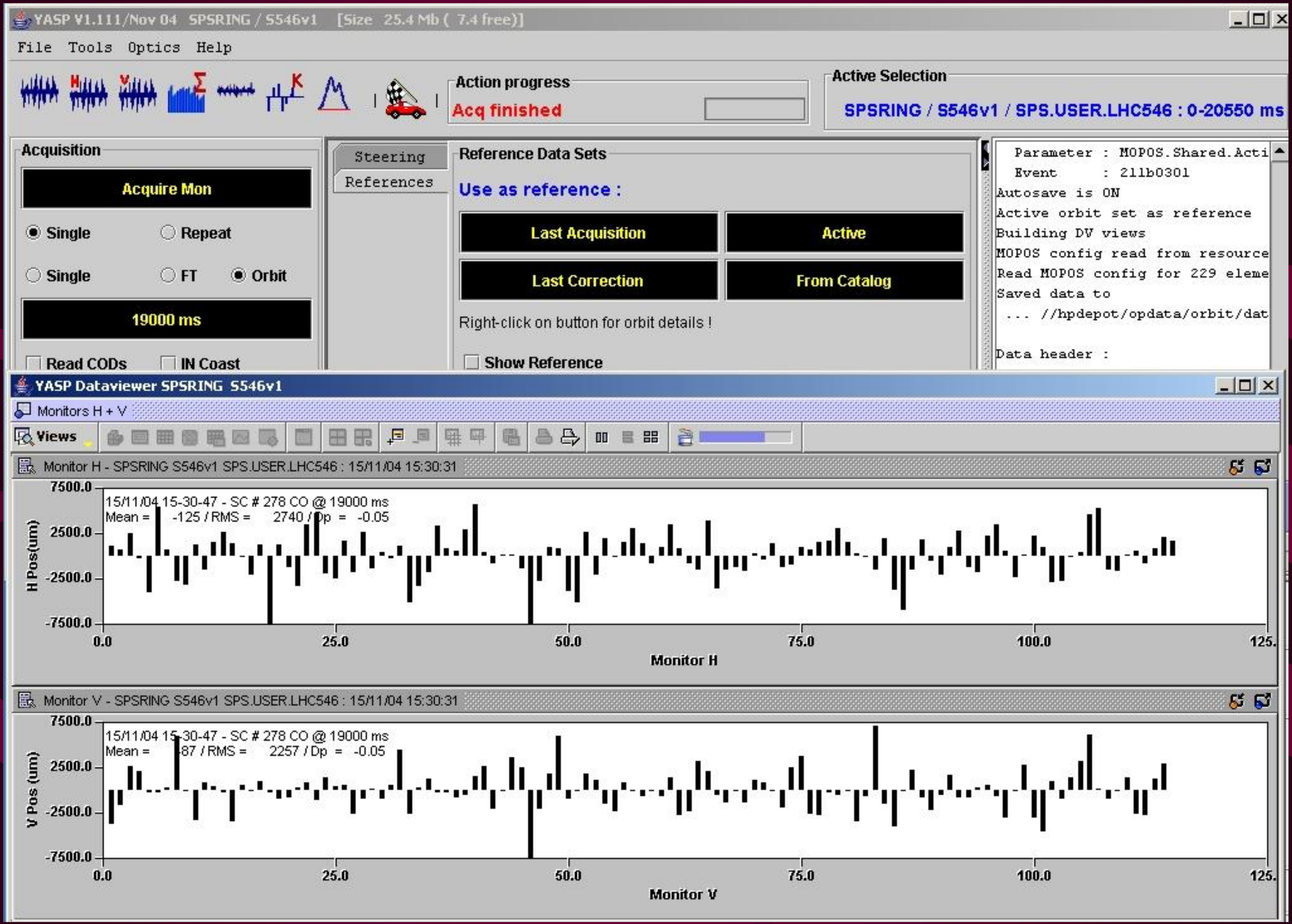
Trim history



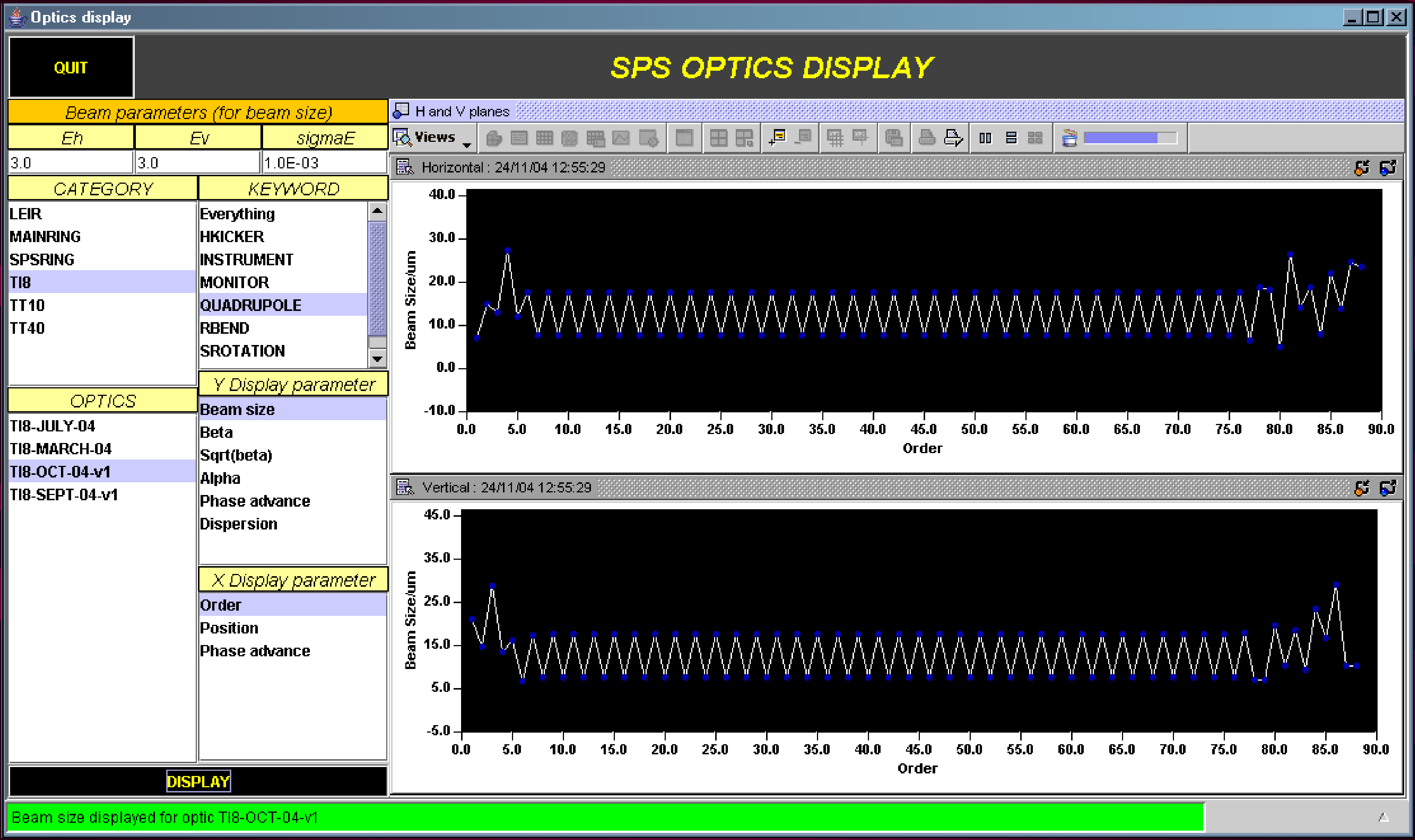
Supporting Tools for Operation

- 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

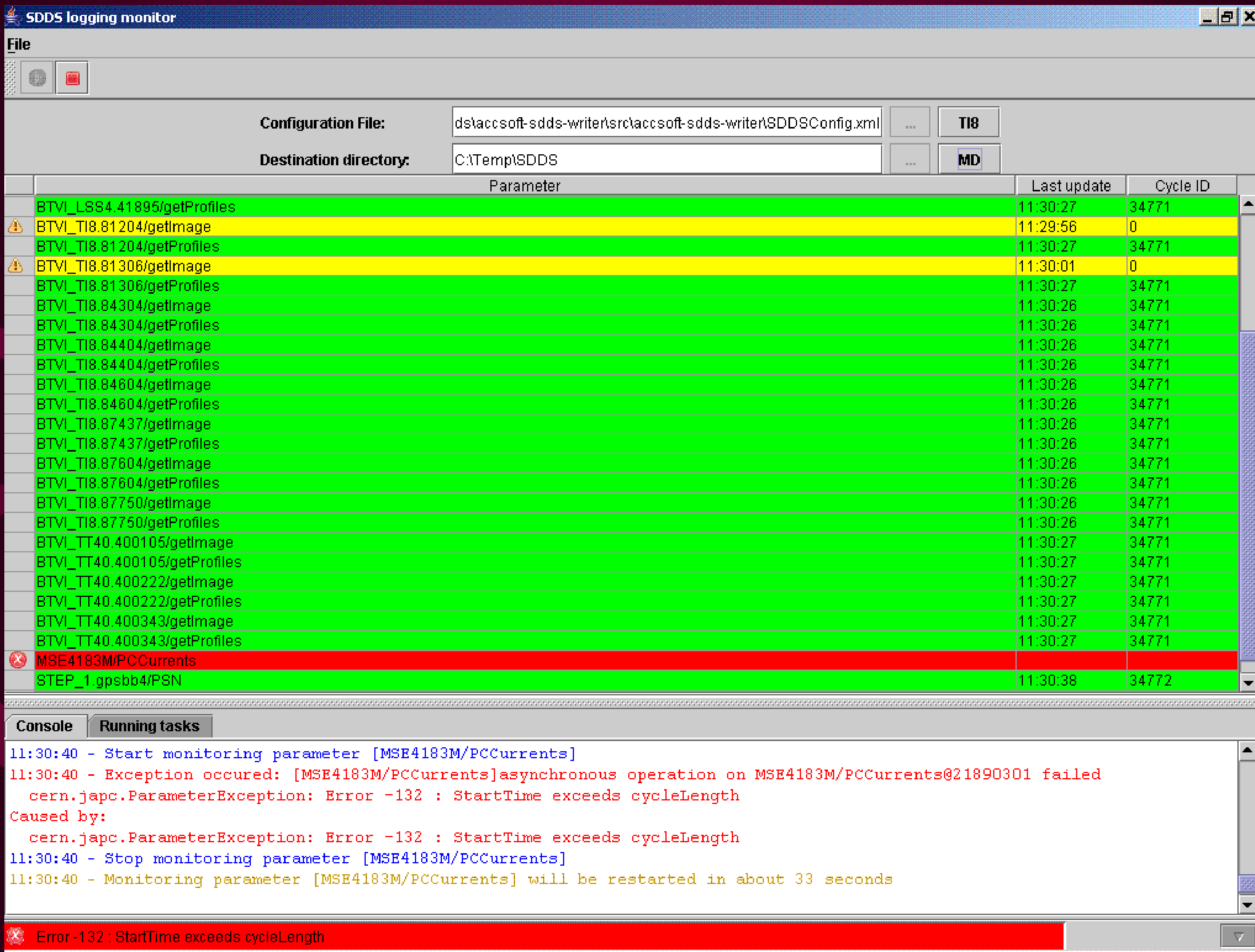
Orbit Steering



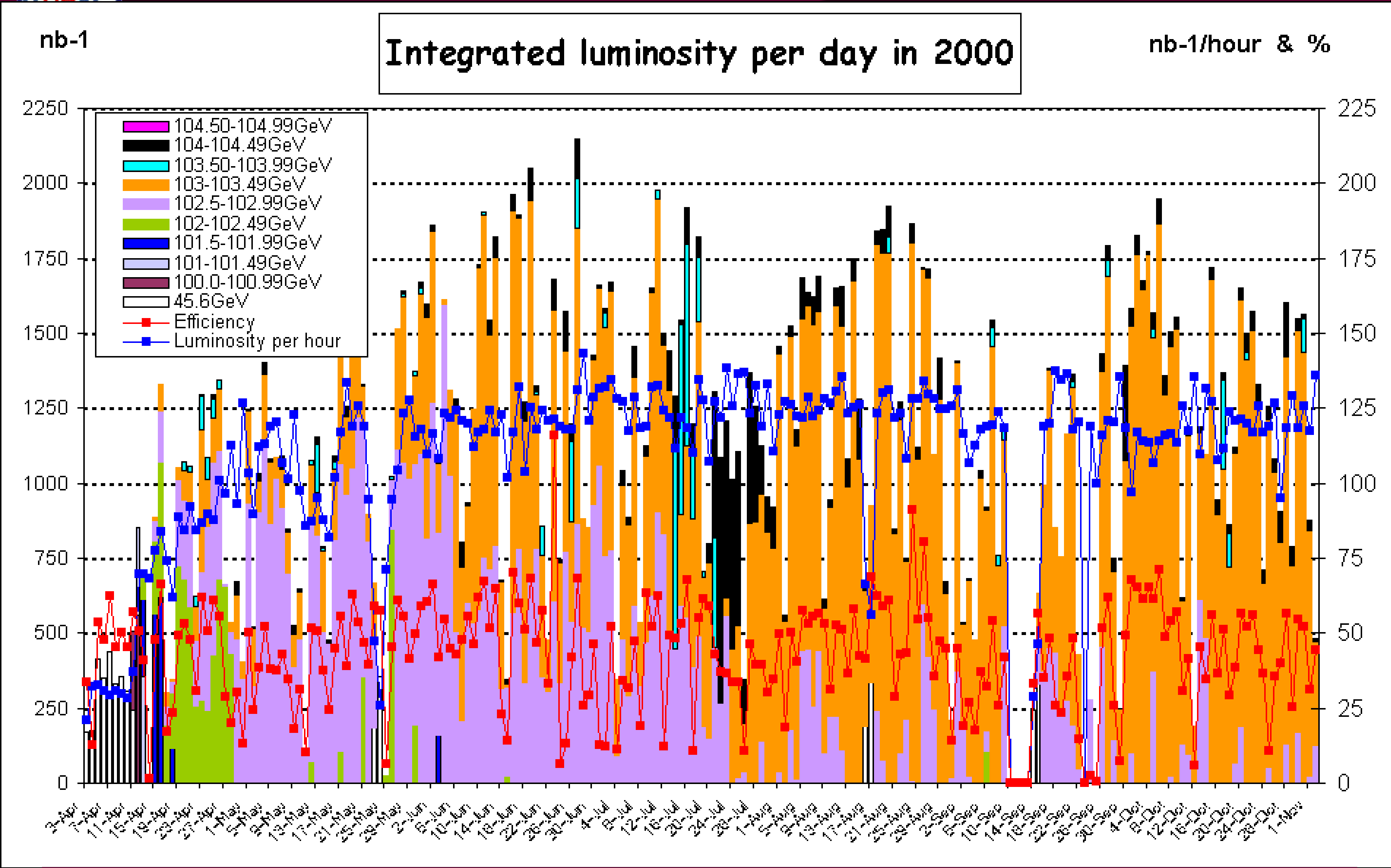
Optics Display



Logging & Monitoring

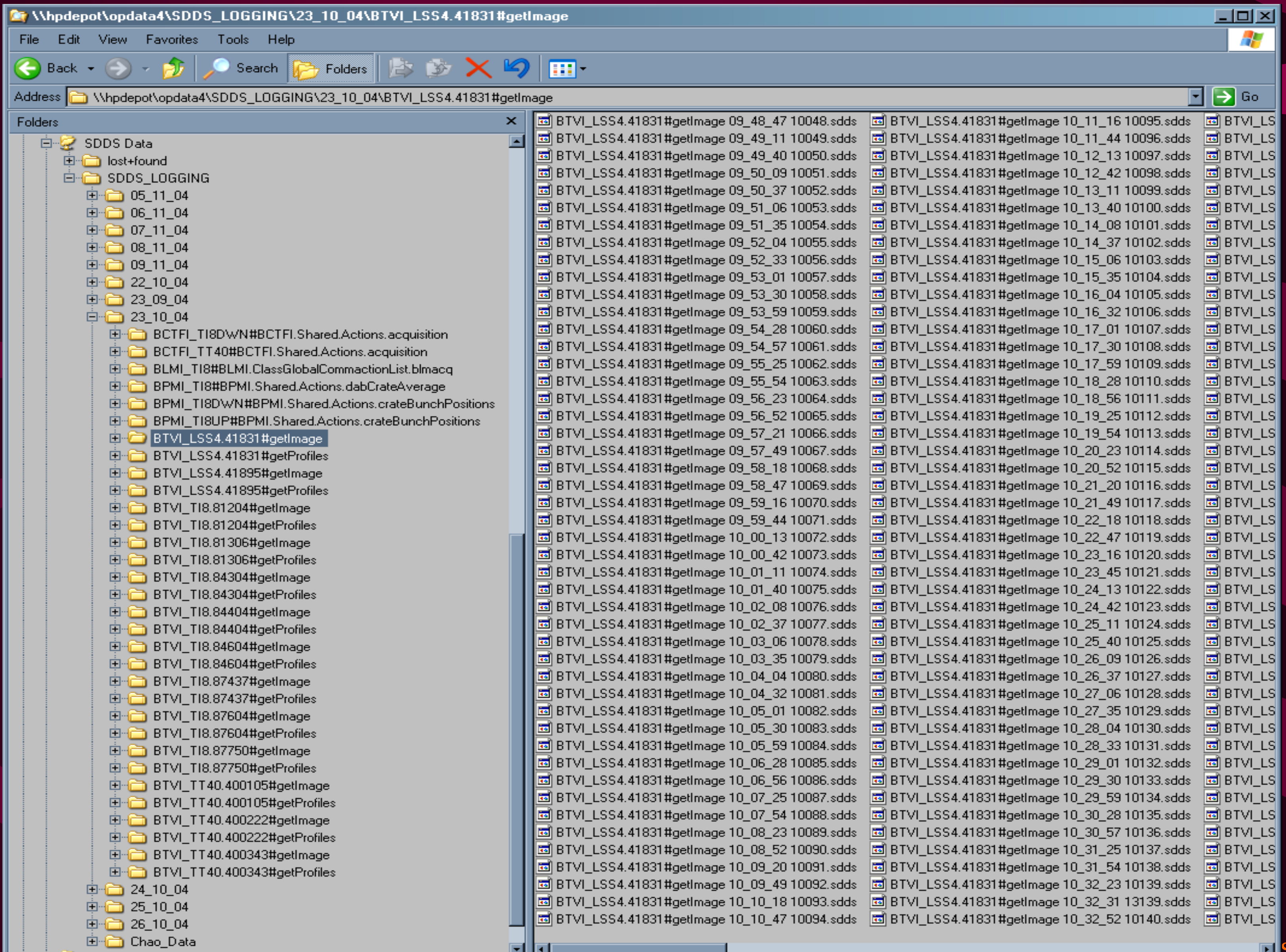


Statistics

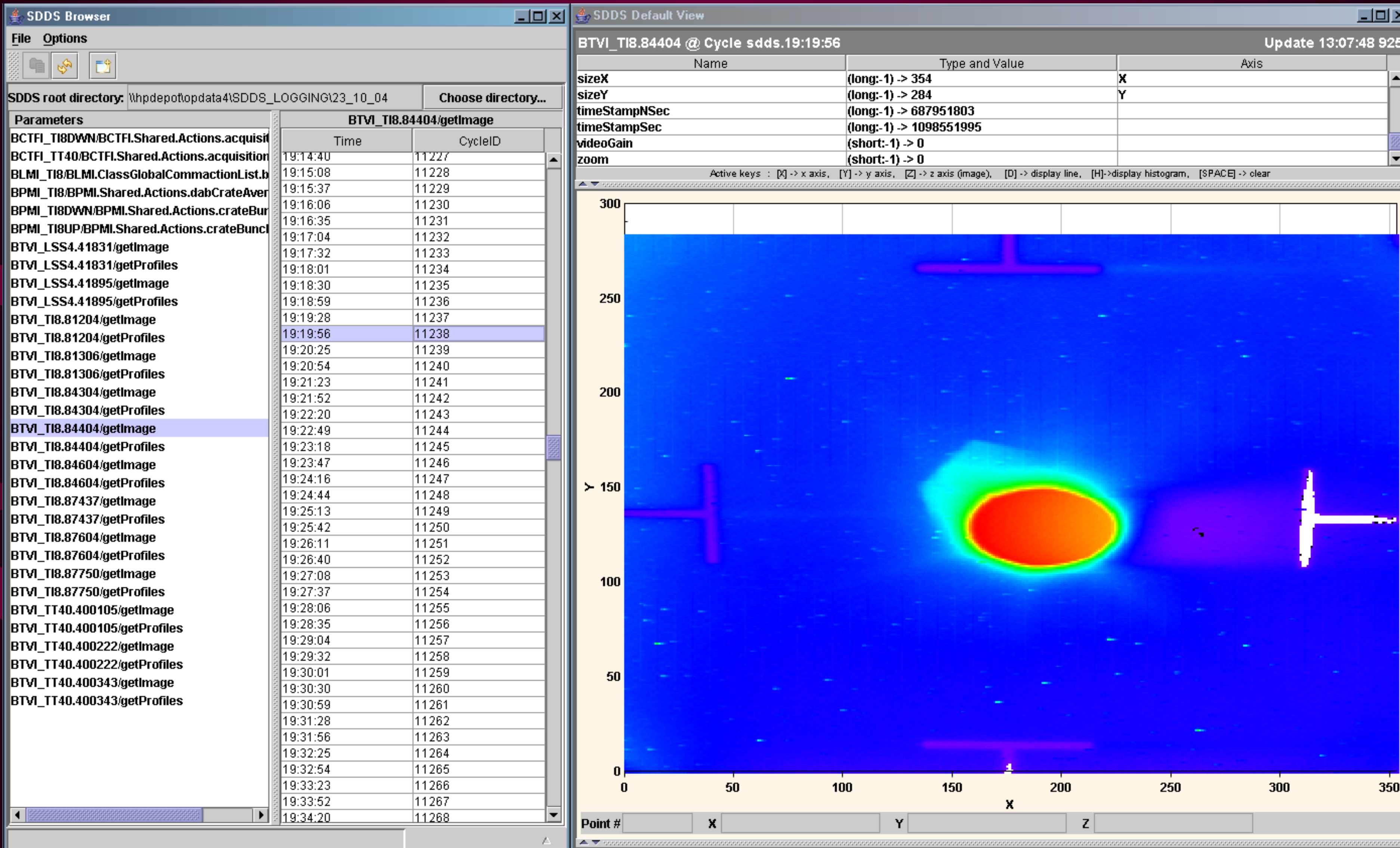


Data hauled from database automatically at end of fill

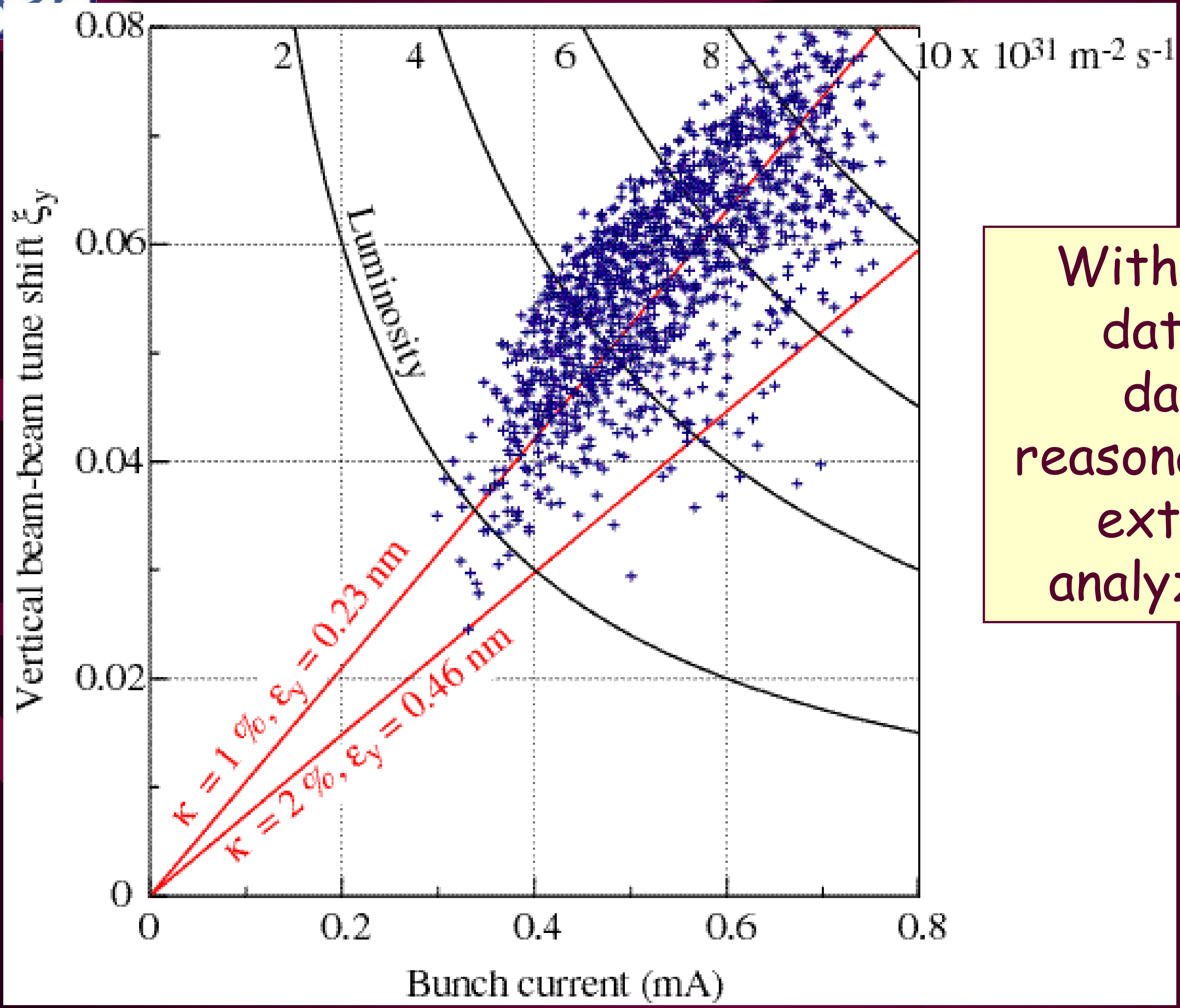
Retrieval of archived measurements



Browser & Viewer

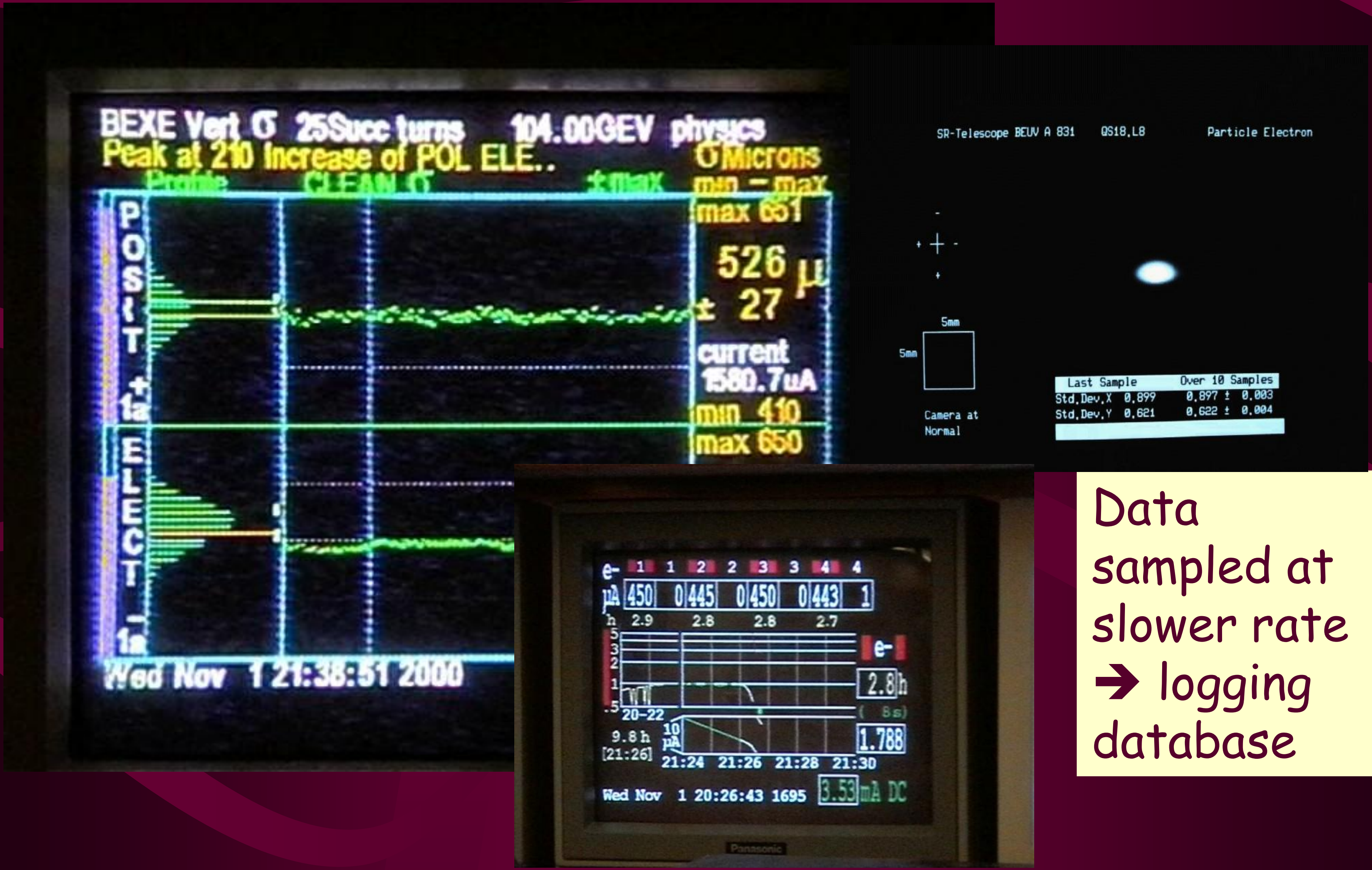


DATA EXTRACTION → POST RUN ANALYSIS



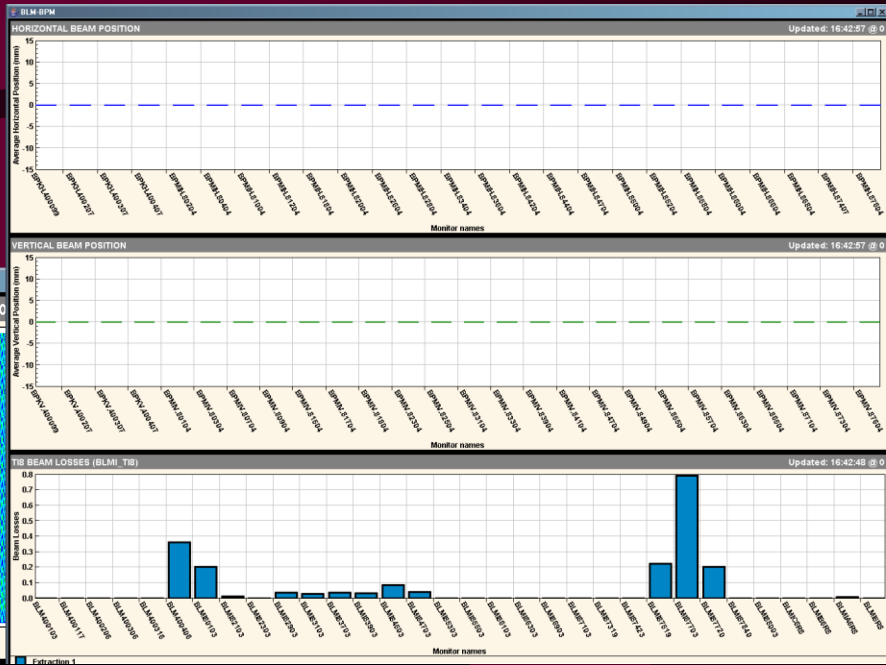
With historical data on the database, reasonably easy to extract and analyze off-line

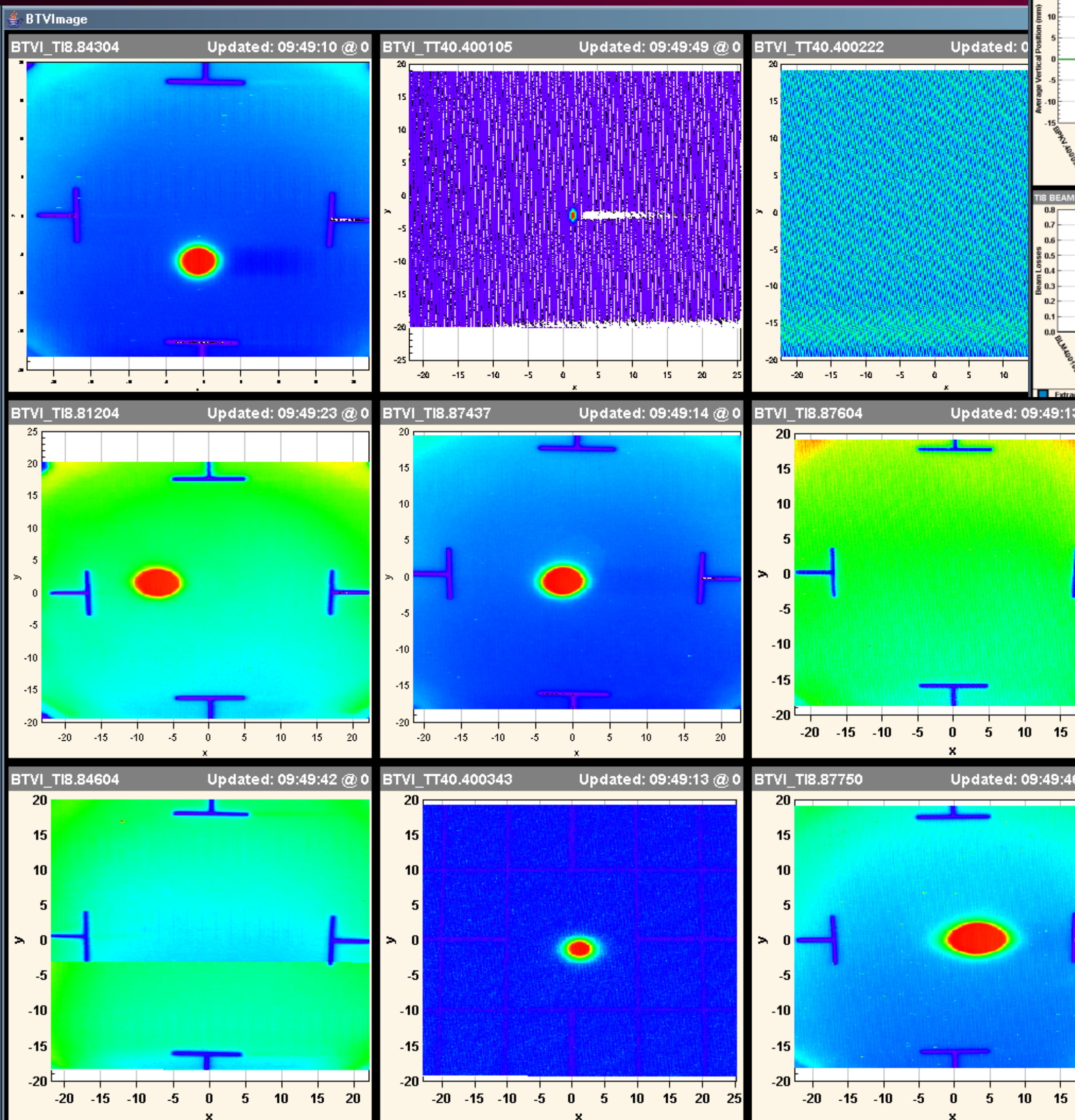
Dedicated Video (FAST) Signals (LEP)

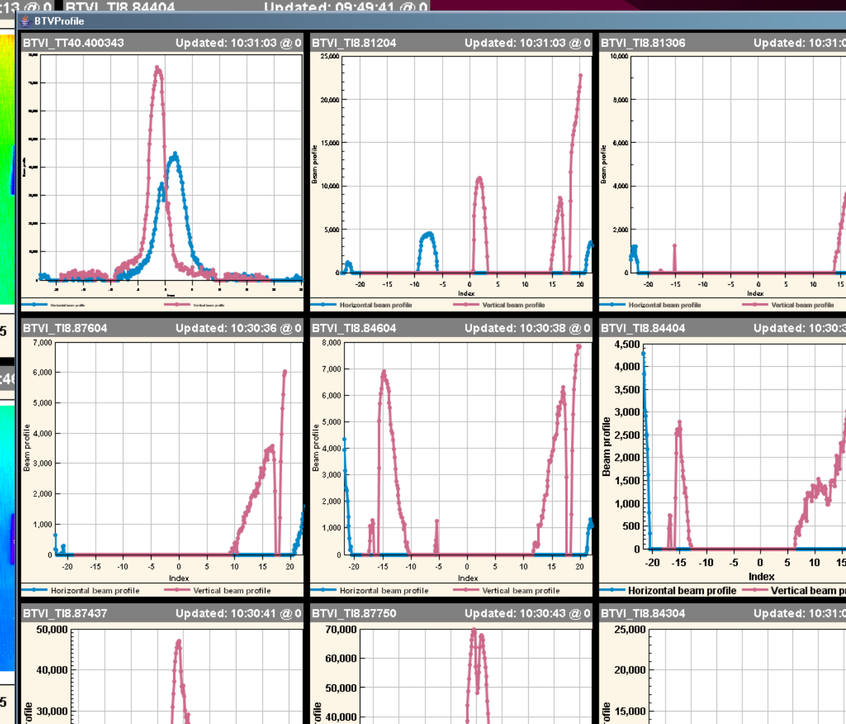


Data sampled at slower rate → logging database

Fixed Displays
Large screens in CCC)







Now we take a closer look:

Ex: Settings generation for the main bend MB

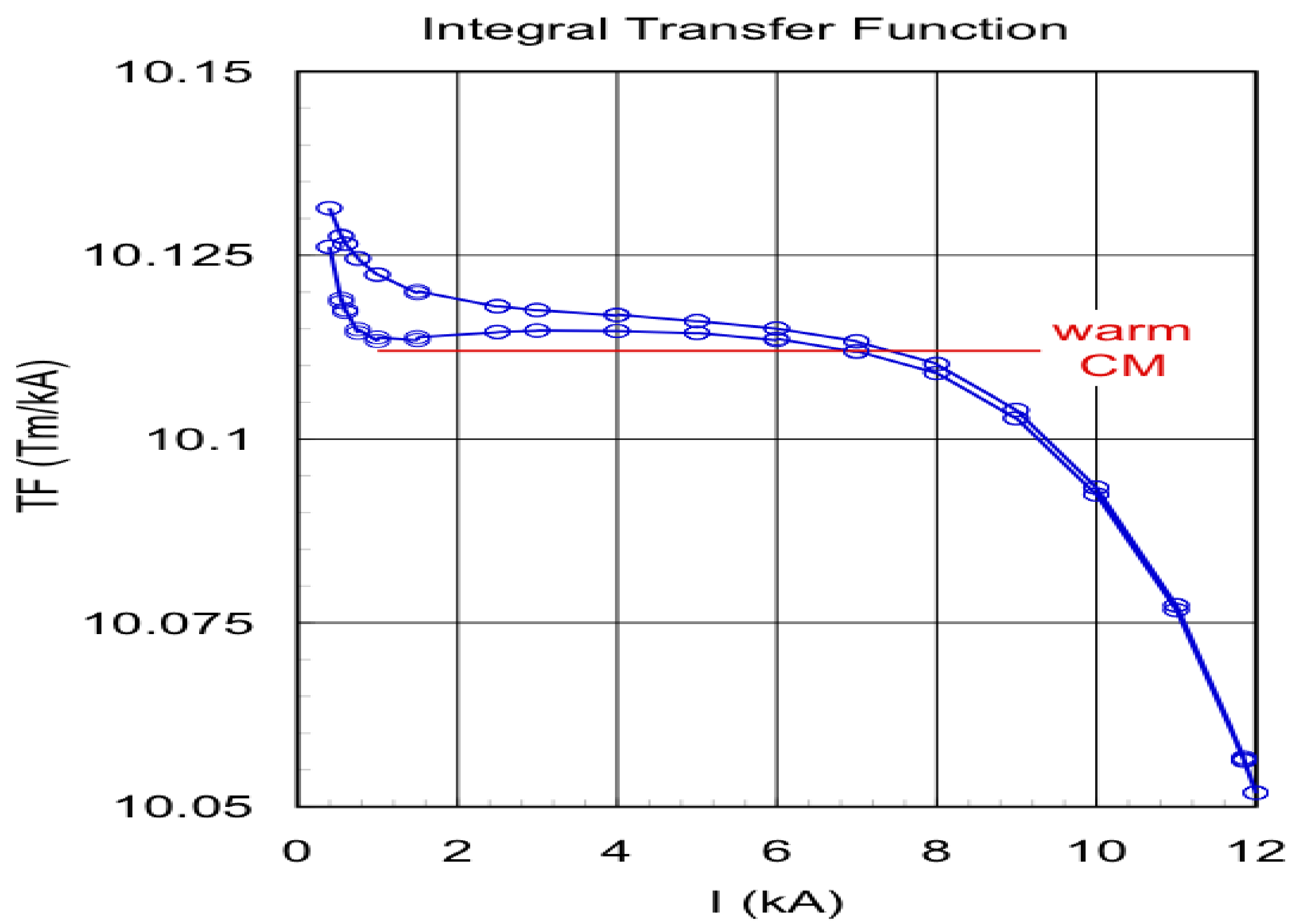
- warm magnets:
  1) injection setting from requested beam momentum setting and calibration curve of Magnet
  2) Magnetic history of dipoles handled via specific hysteresis cycles before injection (called: degaussing…)
  3) Online Feedback to actual setting via reference magnet
  4) Requested beam momentum refined by measuring extraction energy of preinjector
  5) Magnetic Model (or calibration curve) refined by momentum measurement in receiving machine
  6) Other cycle history handled as trim and rollback utility (i.e. "cold machine after shutdown", "warm machine after 1 day of permanent operation"
- cold magnets:
  things are more complicated…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 (about 90% of data available)
  - → all (warm) MQW
  - → a sample (5 to 10) of other warm insertion magnets (MBXW, … measured at the manufacturer before delivery)

- at the present rate, cold measurements on:
  - → ≈ 20 % of MB and ≈ 20 % of 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:

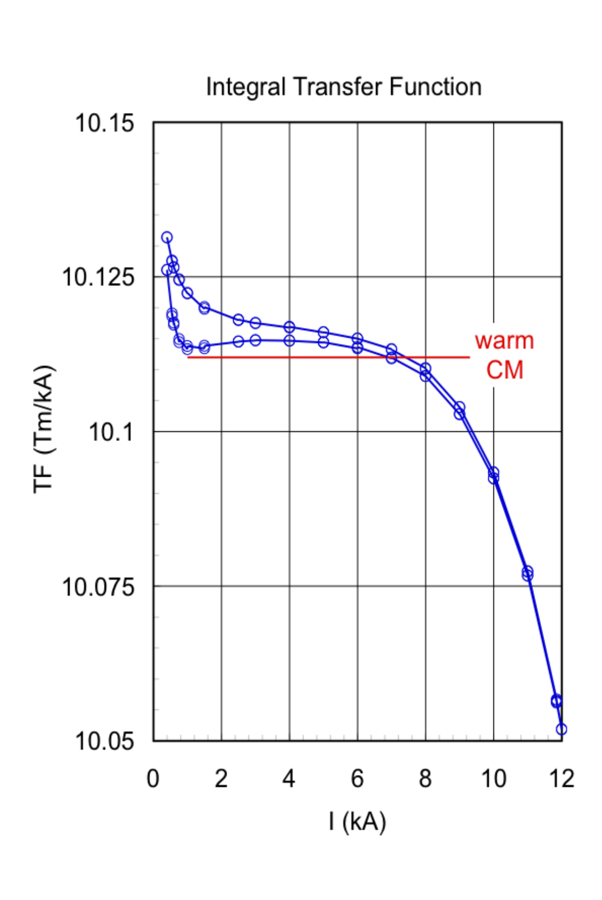
$$\mathbf{C}_n = \mathbf{C}_n^{geom} + \mathbf{C}_n^{MDC} + \mathbf{C}_n^{saturation} + \mathbf{C}_n^{decay} + \mathbf{C}_n^{SB} + \mathbf{C}_n^{def} + \mathbf{C}_n^{MAC} + \mathbf{C}_n^{residual}$$

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 - 1/5



- Determine the current I in the MB to obtain a given integrated field B dl over the sector (as specified by LHC control system). Algorithm:

only if cold data is missing

→ *retrieve warm transfer function TF_W^M for each magnet in the sector*

→ *apply warm-cold scaling f_{TF} and offset $\Delta_{TF}(I)$ and obtain the cold transfer function TF_C^M*

$$TF_C^M(I) = f_{TF}\, TF_W^M + \Delta_{TF}(I)$$

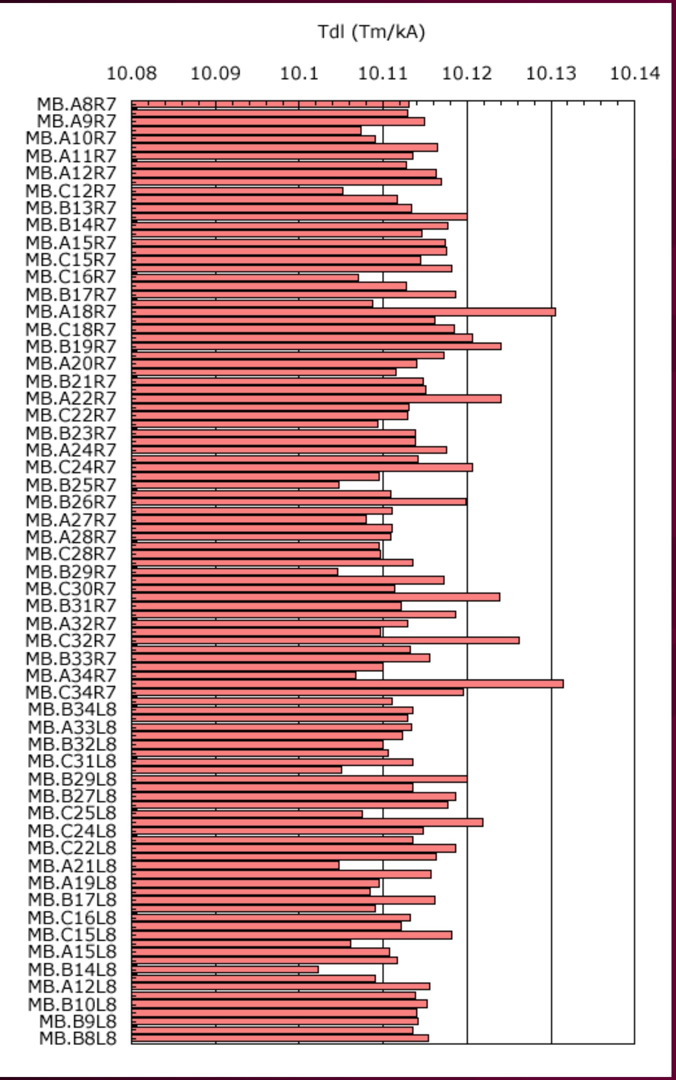
→ integrate the TF_C^M over the sector

$$TF_C(I) = \sum_M TF_C^M(I)$$

→ compute the current by inversion of the (non-linear) TF_C

$$I = (TF_C(I))^{-1}\, B\, dl$$

MB Injection settings - 2/5

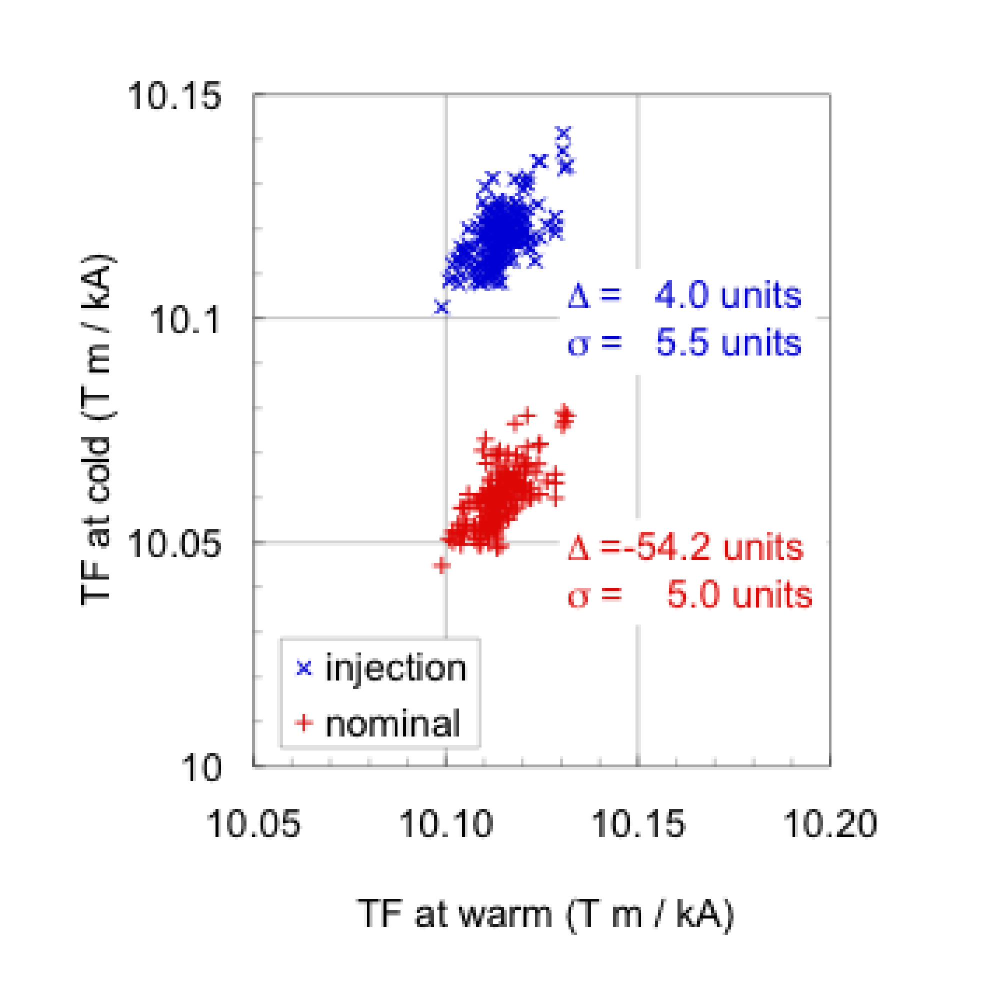


- Warm and cold magnetic data is stored in a database containing separate entries for:
  - → warm data
  - → cold data
    - injection
    - flat-top
  - → warm/cold offsets
    - injection
    - flat-top
  - → components in cold conditions
    - geometric
    - persistent currents
    - decay and snap-back
    - saturation

MB injection settings - 3/5

- warm/cold correlation based on production accumulated so far.
- computed in July 2004 on approximately 100 magnets
- offsets are stable, standard deviation acceptable and comparable with expected measurement accuracy

$$f_{TF} = 1.00\ (-)$$
$$\Delta_{TF} = 5.5(6)\ (\mathrm{mT\ m/kA})$$



MB injection settings - 4/5

NAME	FUNCTION	Polarity	Magnet
LQTAC.7R7	Q7R7	V1F/V2D	
LBARA.8R7	A		3026
LBBRB.8R7	B		1031
LQTBB.8R7	Q8R7	V1D/V2F	
LBARA.9R7	A		3050
LBBRC.9R7	B		1044
LQTEC.9R7	Q9R7	V1F/V2D	
LBARA.10R7	A		1052
LBBRB.10R7	B		1032
LQTBB.10R7	Q10R7	V1D/V2F	
LBARA.11R7	A		3022
LBBRB.11R7	B		1034
LQTCH.11R7	Q11R7	V1F/V2D	
LBARA.12R7	A		2018
LBBRA.12R7	B		1010
LBARB.12R7	C		2039
LQATH.12R7	Q12R7	V1D/V2F	
LBBRA.13R7	A		3041
LBARA.13R7	B		1013
LBBRC.13R7	C		
LQATM.13R7	Q13R7	V1F/V2D	
LBARA.14R7	A		3030
LBBRA.14R7	B		1004
LBARB.14R7	C		2015
LQATH.14R7	Q14R7	V1D/V2F	
LBBRA.15R7	A		3020
LBARA.15R7	B		3010
LBBRC.15R7	C		1022
LQATQ.15R7	Q15R7	V1F/V2D	
LBARA.16R7	A		
LBBRA.16R7	B		1008
LBARB.16R7	C		3028
LQATH.16R7	Q16R7	V1D/V2F	
LBBRA.17R7	A		2008
LBARA.17R7	B		3055
LBBRC.17R7	C		1035
LQATM.17R7	Q17R7	V1F/V2D	
LBARA.18R7	A		3006
LBBRA.18R7	B		1021
LBARB.18R7	C		2029
LQATH.18R7	Q18R7	V1D/V2F	
LBBRA.19R7	A		2004
LBARA.19R7	B		1045
LBBRC.19R7	C		2009
LQATQ.19R7	Q19R7	V1F/V2D	
LBARA.20R7	A		3054
LBBRA.20R7	B		2002
LBARB.20R7	C		3043
LQATH.20R7	Q20R7	V1D/V2F	
LBBRA.21R7	A		3014
LBARA.21R7	B		1012
LBBRC.21R7	C		1024

LQATM.21R7	Q21R7	V1F/V2D	
LBARA.22R7	A		3007
LBBRA.22R7	B		1023
LBARB.22R7	C		2020
LQOAG.22R7	Q22R7	V1D/V2F	
LBBRA.23R7	A		3042
LBARA.23R7	B		1014
LBBRC.23R7	C		1039
LQASE.23R7	Q23R7		
LBARA.24R7	A		
LBBRA.24R7	B		
LBARB.24R7	C		
LQOAG.24R7	Q24R7		
LBBRA.25R7	A		
LBARA.25R7	B		
LBBRC.25R7	C		
LQOAR.25R7	Q25R7		
LBARA.26R7	A		
LBBRA.26R7	B		
LBARB.26R7	C		
LQOAG.26R7	Q26R7		
LBBRA.27R7	A		
LBARA.27R7	B		
LBBRC.27R7	C		
LQASE.27R7	Q27R7		
LBARA.28R7	A		
LBBRA.28R7	B		
LBARB.28R7	C		
LQOAG.28R7	Q28R7		
LBBRA.29R7	A		
LBARA.29R7	B		
LBBRC.29R7	C		
LQOBF.29R7	Q29R7		
LBARA.30R7	A		
LBBRA.30R7	B		
LBARB.30R7	C		
LQOAM.30R7	Q30R7		
LBBRA.31R7	A		
LBARA.31R7	B		
LBBRC.31R7	C		
LQOAV.31R7	Q31R7		
LBARA.32R7	A		
LBBRA.32R7	B		
LBARB.32R7	C		
LQOAG.32R7	Q32R7		
LBBRA.33R7	A		
LBARA.33R7	B		3023
LBBRC.33R7	C		2041
LQOBJ.33R7	Q33R7	V1F/V2D	
LBARA.34R7	A		2016
LBBRA.34R7	B		1003
LBARB.34R7	C		3025
LQOAM.34R7	Q34R7	V1D/V2F	

LBBRA.34L8	C		1025
LBARA.34L8	B		2017
LBBRC.34L8	A		3005
LQOBF.33L8	Q33L8	V1F/V2D	
LBARA.33L8	C		3021
LBBRA.33L8	B		2050
LBARB.33L8	A		2523
LQOAM.32L8	Q32L8	V1D/V2F	
LBARB.23L8	A		
LQOAG.22L8	Q22L8	V1D/V2F	
LBBRA.22L8	C		2065
LBARA.22L8	B		
LBBRD.22L8	A		1029
LQATK.21L8	Q21L8	V1F/V2D	
LBARA.21L8	C		

LBBRA.21L8	B		2007
LBARB.21L8	A		2036
LQATH.20L8	Q20L8	V1D/V2F	
LBBRA.20L8	C		1015
LBARA.20L8	B		2028
LBBRD.20L8	A		2003
LQATO.19L8	Q19L8	V1F/V2D	
LBARA.19L8	C		1011
			3061
			1036
			3012
			2042
			2006
			2056
			3003
			3063
			3009
			2014
			3058
			3018
			2031
			3038
			3065
			3002
			3029
			1017
			1133
			3034
			3066
			3019
			3053
			1030
			3062
LBBRF.9L8	A		3036
LQNCB.8L8	Q8L8	V1D/V2F	
LBARE.8L8	B		3051
LBBRI.8L8	A		3016
LQNFI.7L8	Q7L8	V1F/V2D	

- The magnet installation sequence is determined at the Magnet Evaluation Board (MEB), based on constraints on:
  - → geometry
  - → field quality
  - → other (quench, non-conformities, …)
- The information is collected in an installation map, recorded in the Manufacturing and Test Folder (MTF)

We know which magnet is where

we can build integral field information

MB injection settings - 5/5

- average transfer function at injection for sector 78 (extrapolated from 109/154 magnets allocated)
- warm/cold extrapolation for 44/109 magnets (65 cold measured)

$$TF_1 = 10.117(5)\ (\mathrm{T\ m/kA})$$
$$TF_2 = 10.117(1)\ (\mathrm{T\ m/kA})$$

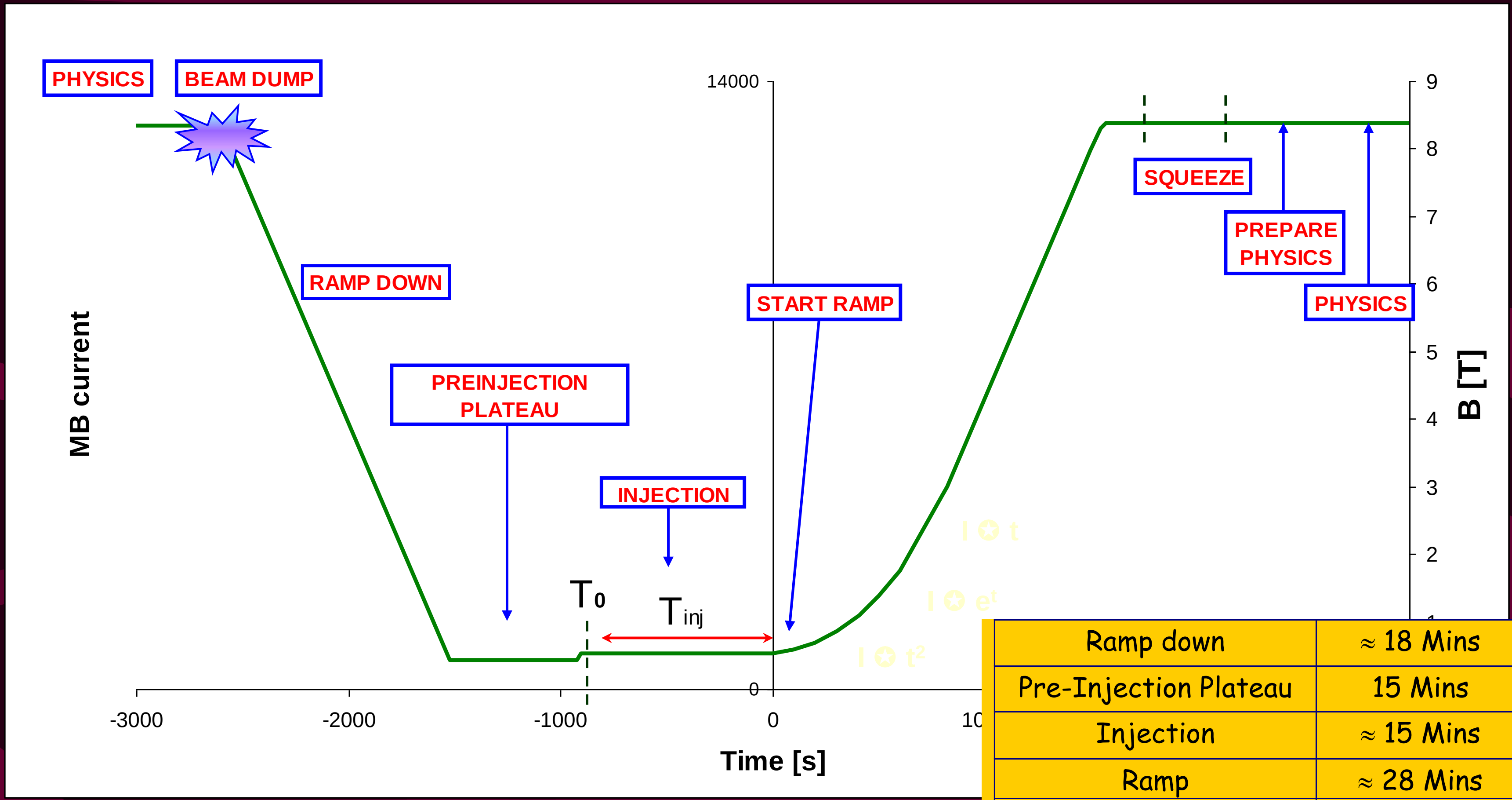
- current in sector 78 for an injection at 450 GeV from SPS (1189.2 T m)

$$I = 763.2(5)\ \mathrm{A}$$

= this corresponds to step 1 in the discussed sequence

The Control system has to help generating these settings and then stores this setting and makes it available for trimming

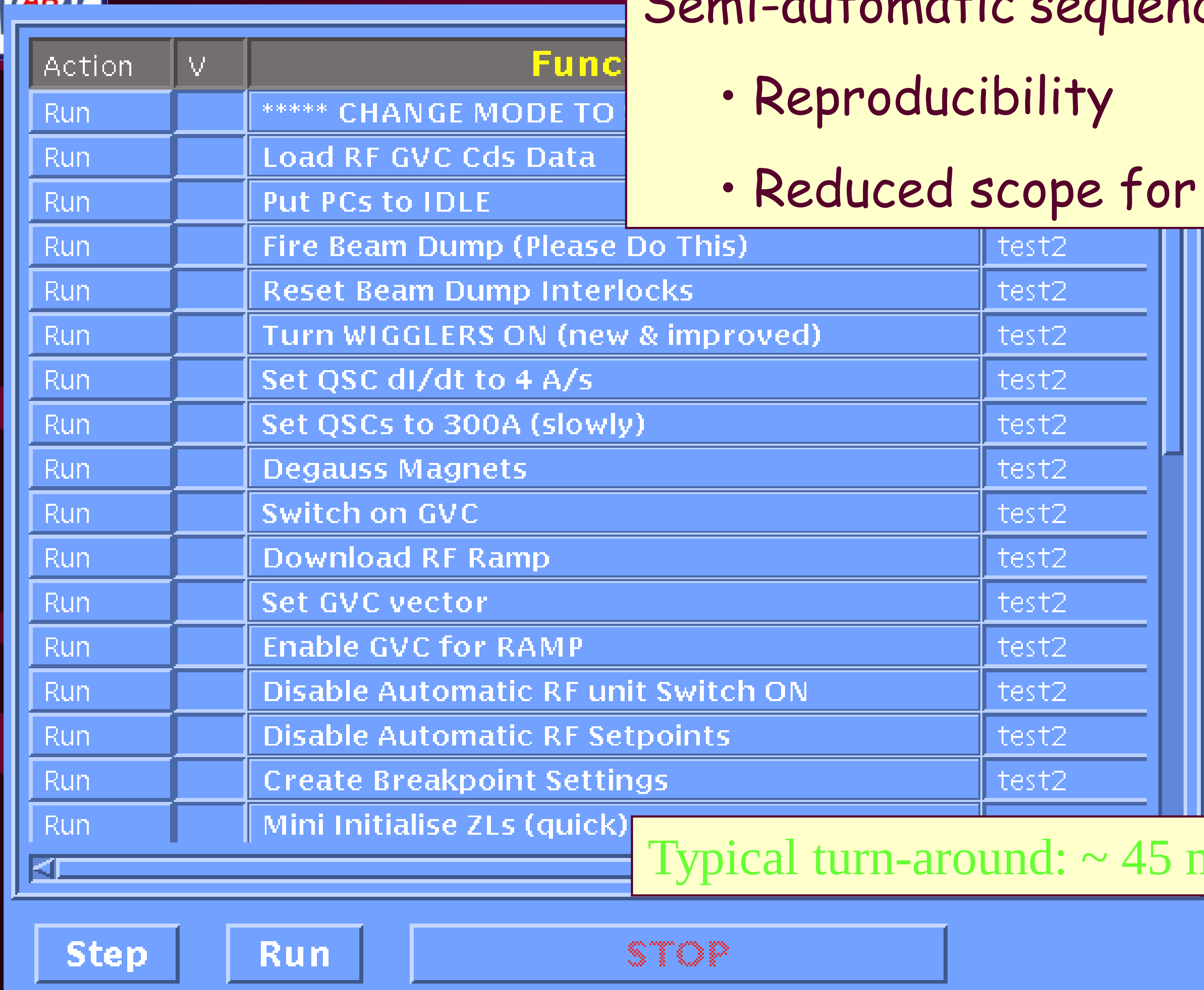
…and now we have to accelerate the whole lot



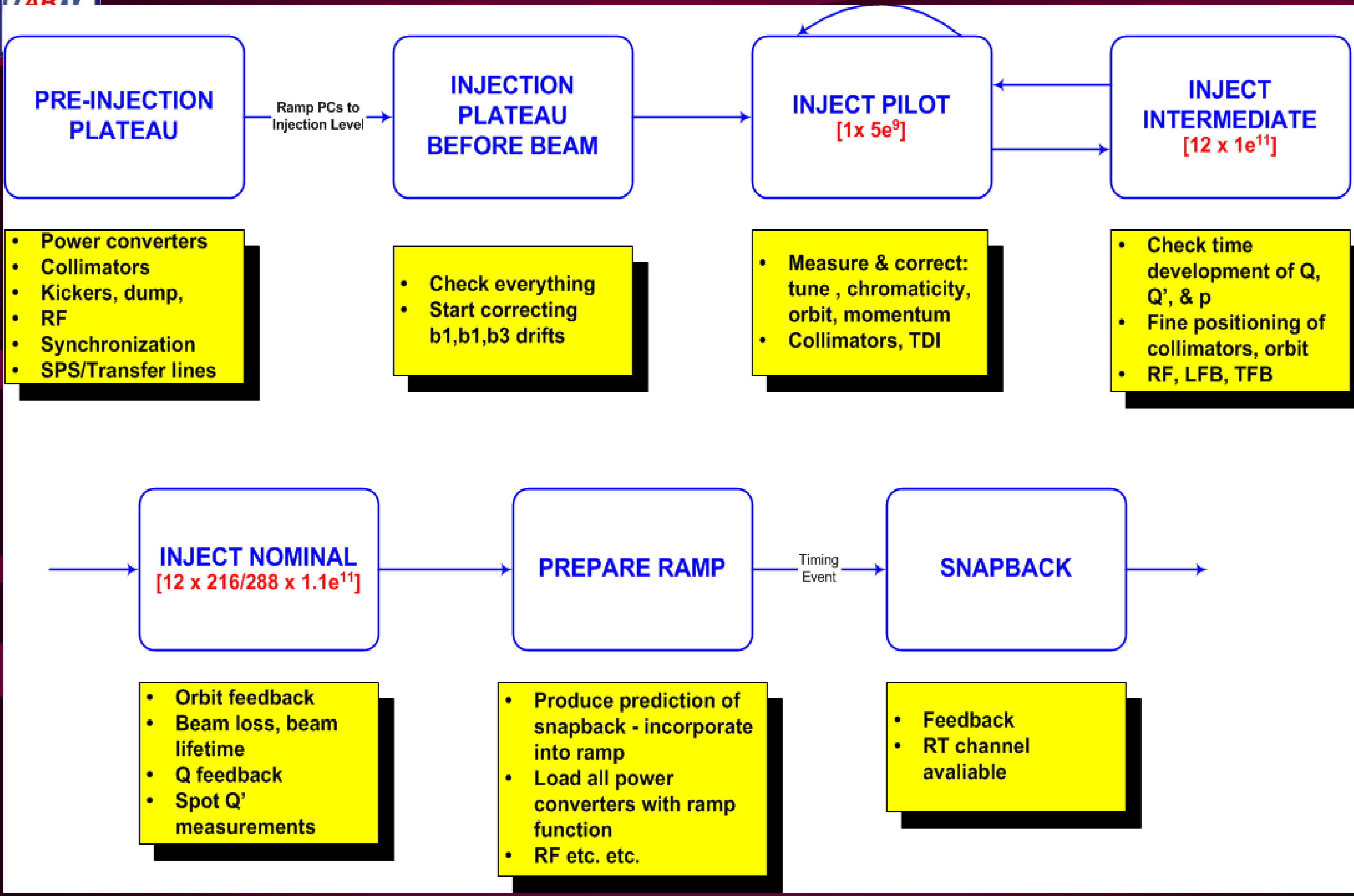
Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	< 5 Mins
Prepare Physics	≈ 10 Mins
Physics	10 - 20 Hrs

Semi-automatic sequencer for LEP

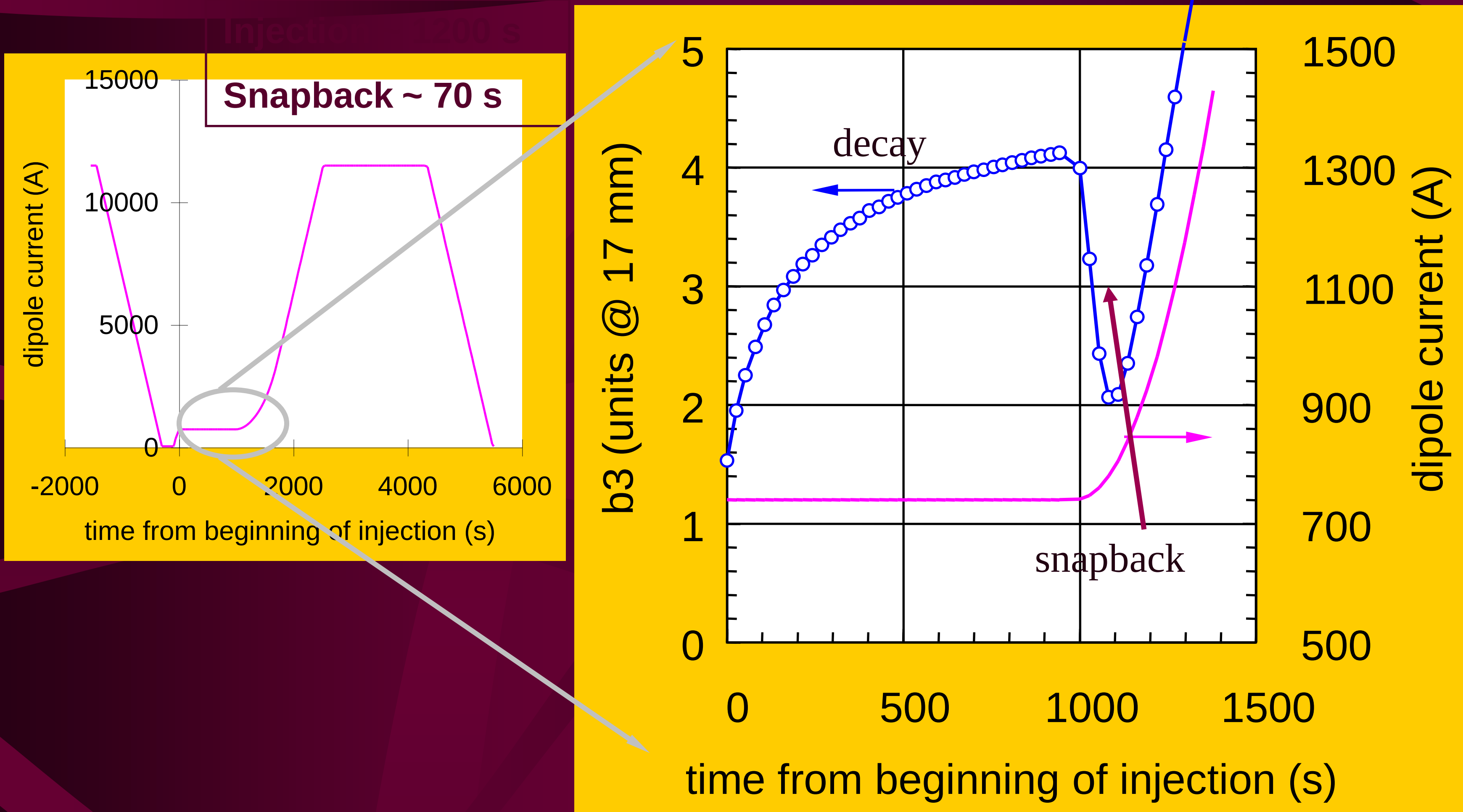
- Reproducibility
- Reduced scope for error



Typical turn-around: ~ 45 minutes


PRE-INJECTION PLATEAU
Ramp PCs to Injection Level
INJECTION PLATEAU BEFORE BEAM
INJECT PILOT
[1x 5e9]
INJECT INTERMEDIATE
[12 x 1e11]
• 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 1.1e11]
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

The most 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

Chromaticity

- The measured chromaticity is the sum of:

$$Q'_{total} = Q'_{meas} = Q'_{natural} + Q'_{lattice-sext} + Q'_{b3-dipole} + Q'_{b3-spool} + Q'_{b3-other}$$

$\rightarrow$Correct natural with lattice sextupoles

$\rightarrow$Would aim to balance Q'-b3-dipole with Q'-b3-spool

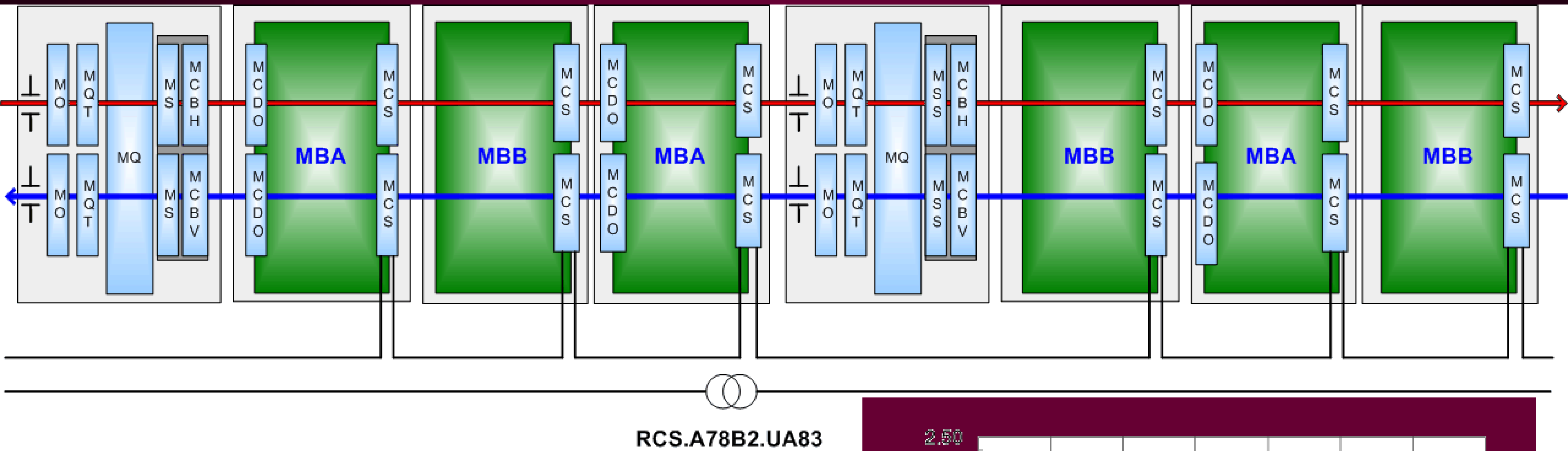
$\rightarrow$Watch other (e.g. insertion quads – own correctors)

- Signature of improperly compensated b_3 error is clear:

$\rightarrow$0.1 unit b3 $\rightarrow$ +3/-3.5 Q'h/Q'v

- We should be able to measure periodically on injection plateau to verify corrections.

Correction elements

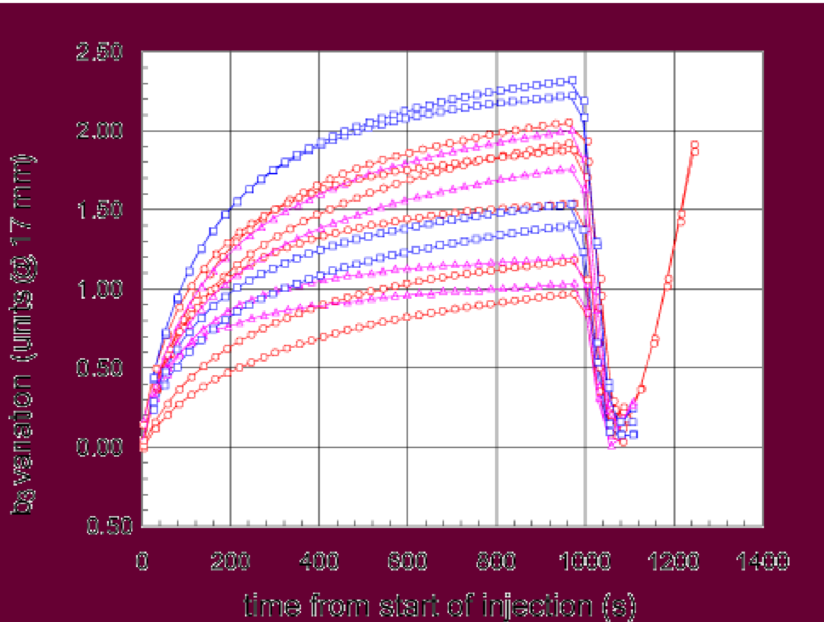


Per aperture:

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



Requirements

- Static errors → controls database
- Eddy currents → controls database
- Transfer functions → controls database
  - → Note: I, I(t) downloaded to front-ends
  - → K to B to I, I(t) done at high level via transfer function look-up
- Hysteresis model
  - → to deal with reversing the direction of the current in e.g. the MCS. This causes crossing of the hysteresis loop with a potentially large chromaticity shift – going to have deal with this control system side

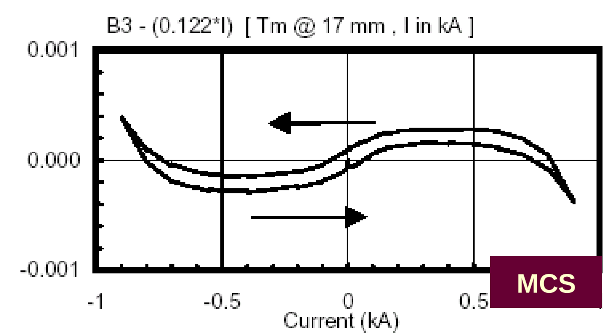
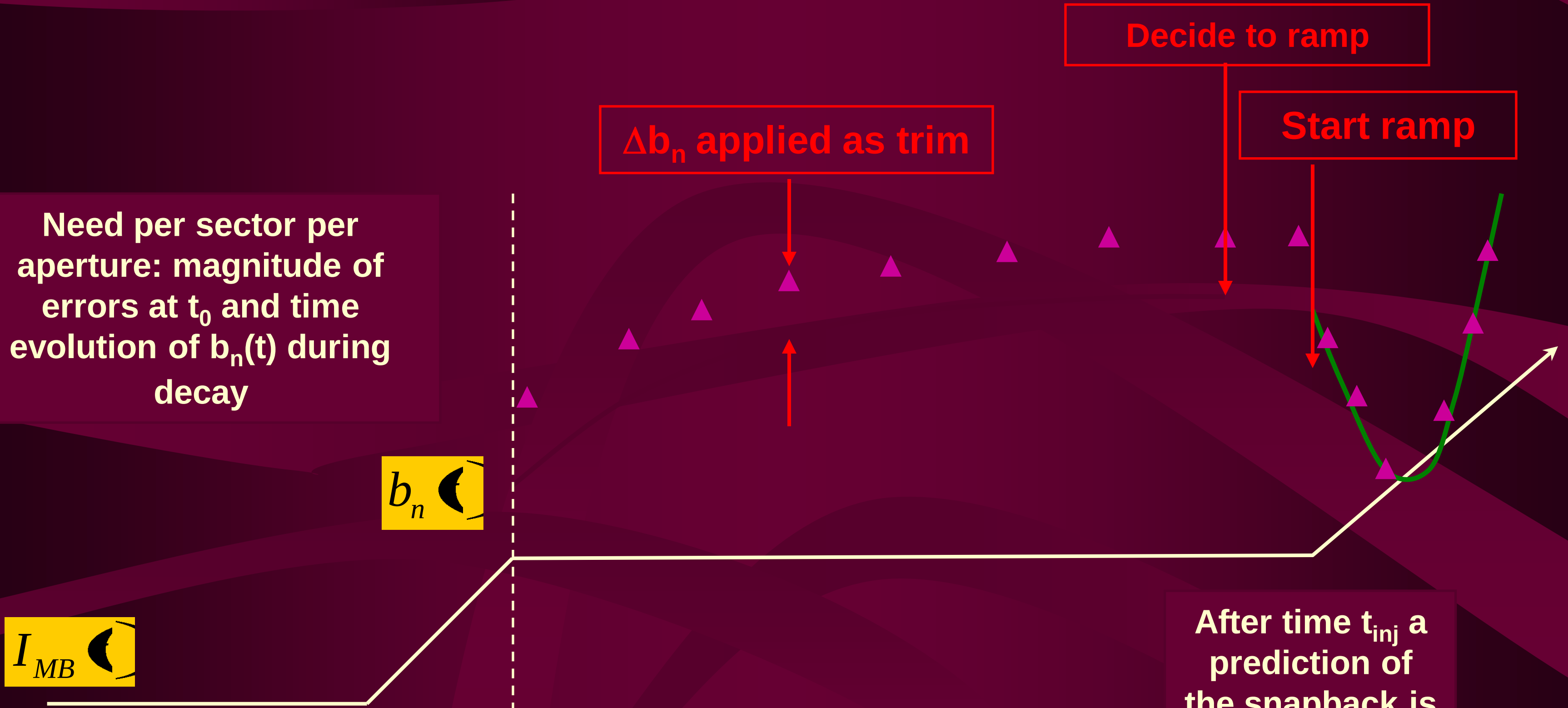


Figure 3 : Field strength of a MCD corrector : difference between the strength and straight line giving the average to enlighten the hysteresis due to persistent currents.

Plus dynamic effects…

Dynamic effects - correction



Need per sector per aperture: magnitude of errors at t_0 and time evolution of $b_n(t)$ during decay

After time t_{inj} a prediction of the snapback is required.

Download.

Control system has "linear" model of multipole behaviour

Incorporating empirical adjustments based on previous experience

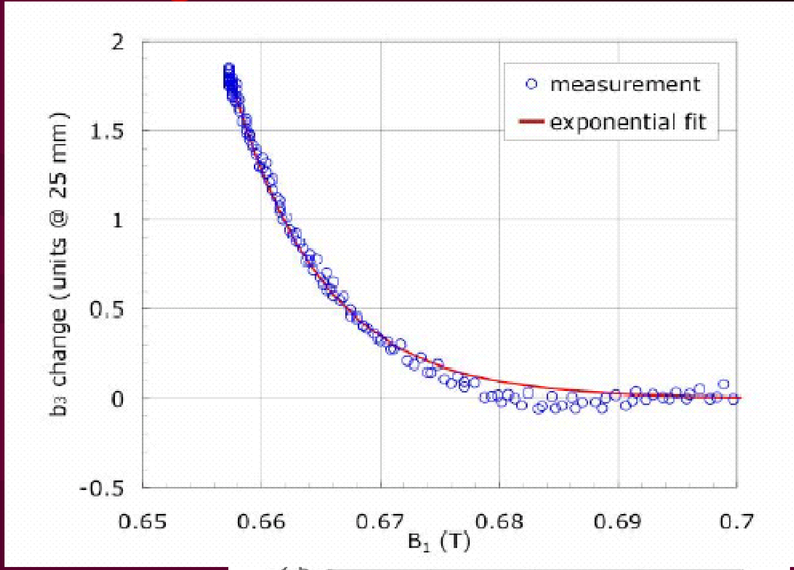
Based on this corrections applied as a function of time during the injection plateau

Snapback – Q'

If b_3 amplitude can be measured "on-line" the SB fit can be predicted w/out use of "multi-parameter" algorithm

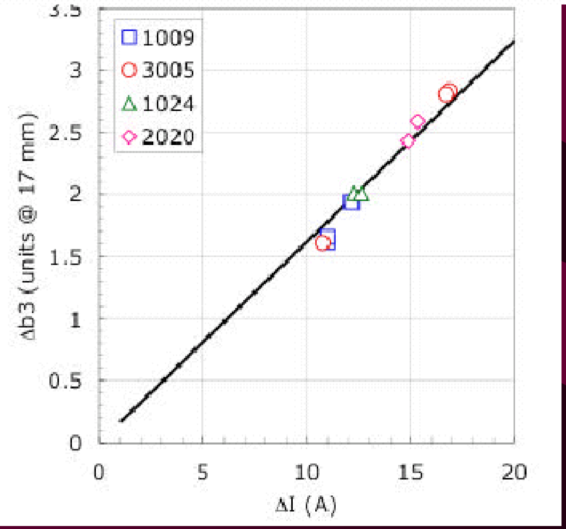
- Fit snapback:

$$b_3^{snapback}(t) = \Delta b_3 e^{-\frac{I(t) - I_{injection}}{\Delta I}}$$



- I(t) – MB current at time t
- $I_{injection}$ – injection value of current
- Δb_3 and ΔI are fitting constants

- Δb_3 and ΔI are correlated



Sextupole compensation during snap-back in collaboration with FNAL – Luca Bottura

Q' - snapback

- 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

…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

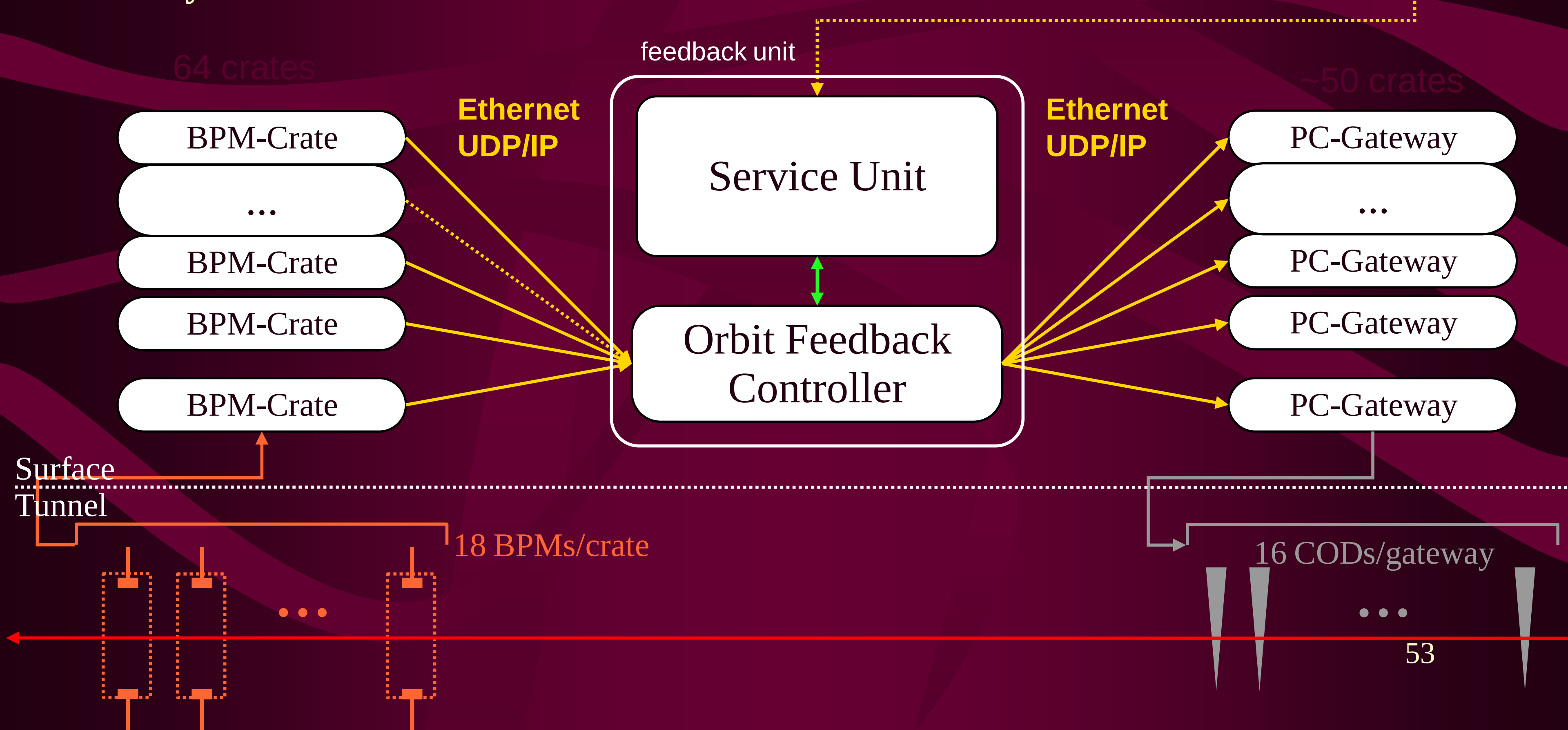
  } Nice Problem for the instrumentation group
- Data centralization and computation of corrections (including error handling, dynamic change of twiss parameters…
- Feedback of corrections to power converters

Orbit FB Control Layout

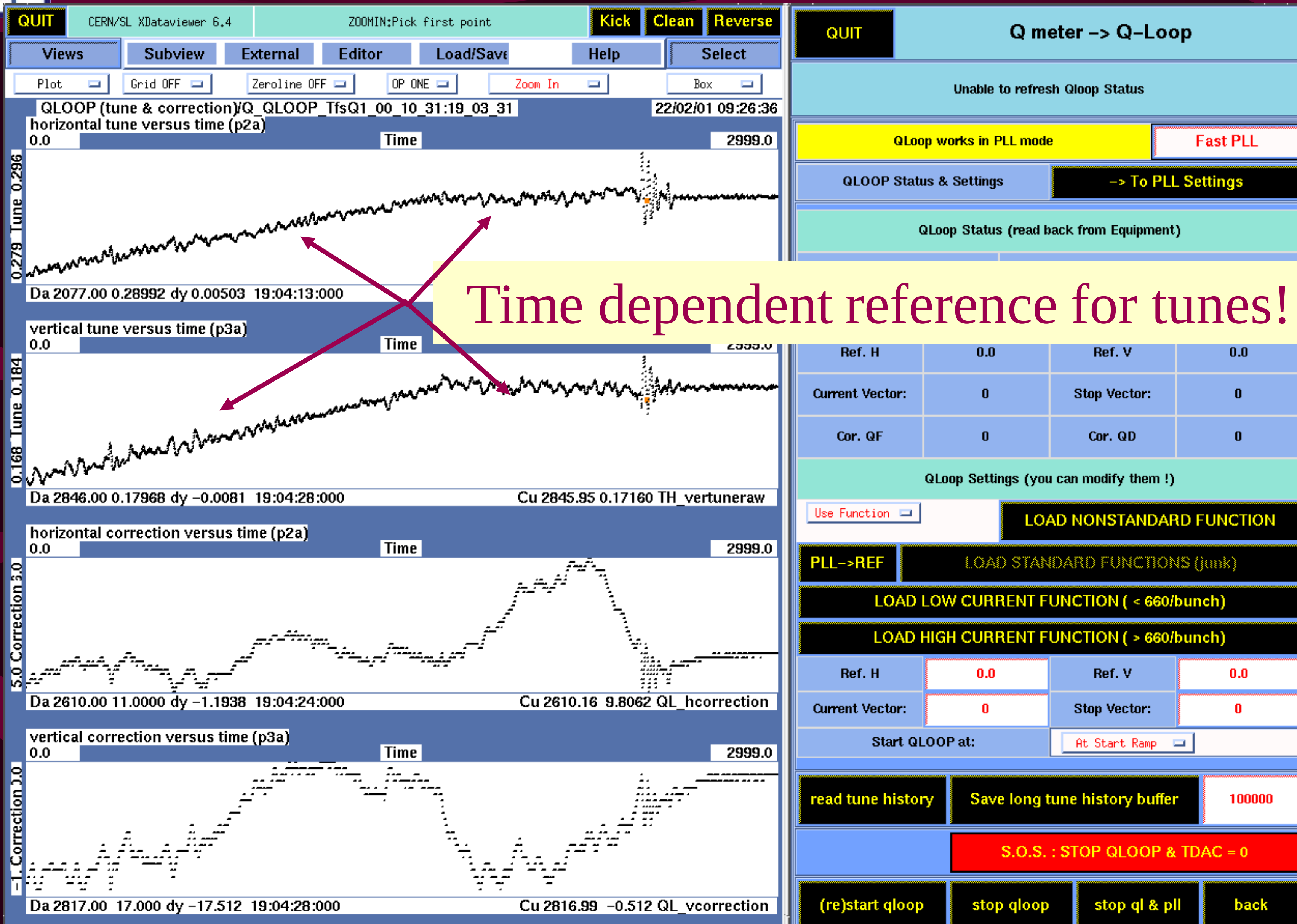
Central FB unit has 2 functional parts

- **Time-critical controller unit to compute the corrections (hard real-time).**
- **A Service Unit for DB and user interfaces, matrix operations, sanity checks..**

The total loop delay is expected to be stable at ~ 60-80 ms



LEP feedback on tunes



Time dependent reference for tunes!

Summary 1st hour

- Accelerator Controls is a vast activity
- Controls Hardware mainly based on commercially available products (COTS)
- Controls Software an incredible suite of tools and applications mainly based on open source technologies and in majority developed at CERN
- Controls of beam parameters makes the link between:
  - accelerator physics
  - beam observation
  - equipment control
- …and is fun to work on…