LHC Commissioning with Beam
Overall Strategy

Mike Lamont

AB-OP

6th April 2005

TI8

- Beam down – first shot.
- Full set of measurements
  - optics, aperture etc.

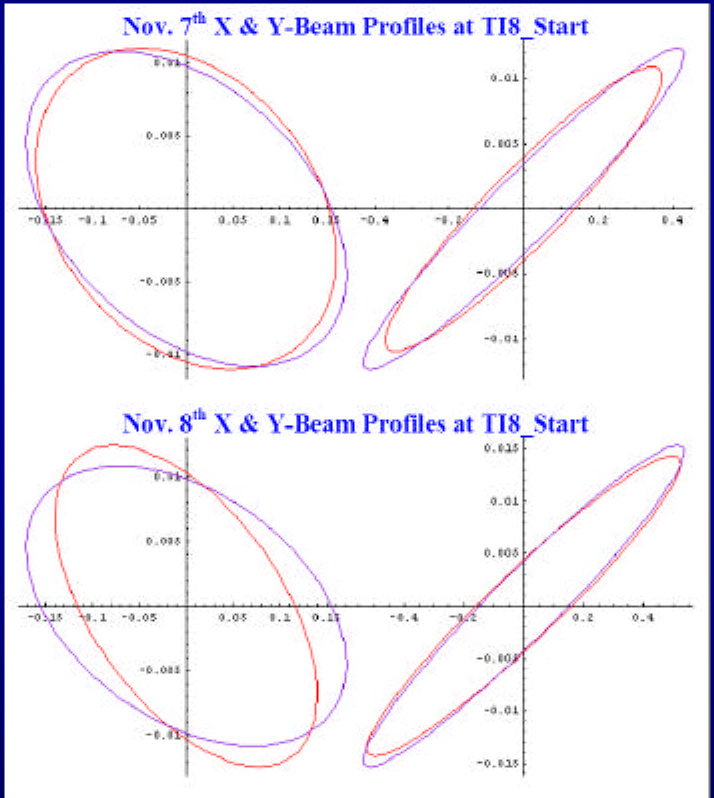
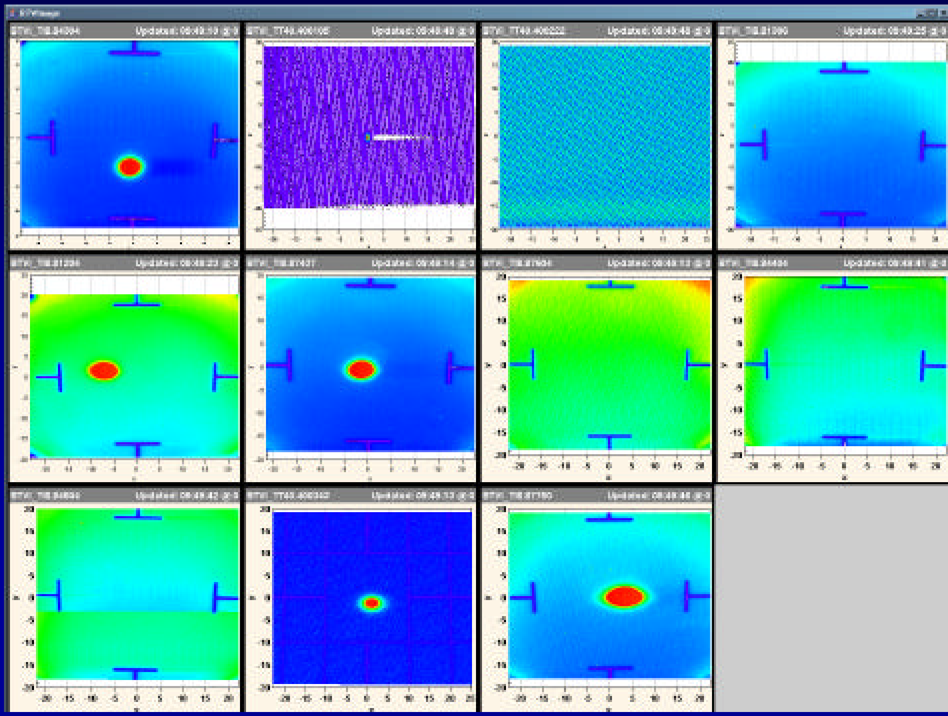


Figure 2. Comparison between Design & Measured Beam Profiles of 07/11 (top) and 08/11 (bottom); Actual beam size; units: mm & mrad (red: measured, blue: design)



Lionel Mestre

What does this tell us?

Yu-Chiu Chao

LHC Beam Commissioning

- OBJECTIVES
- PREPARATION
- PLANNING

- KEEP IT SIMPLE
- STAGE IT
- KEEP IT SAFE

Objectives

Commissioning the LHC with beam - Stage One

- Establish colliding beams as quickly as possible
- Safely
- Without compromising further progress

Take two moderate intensity multi-bunch beams to high energy and collide them.

More Specifically

43 on 43 with 3 to 4 x 10^{10} ppb to 7 TeV

- No parasitic encounters
  - No crossing angle
  - No long range beam
  - Larger aperture
- Instrumentation
- Good beam for RF, Vacuum…
- Lower energy densities
  - Reduced demands on beam dump system
  - Collimation
  - Machine protection
- Luminosity
  - 10^{30} $cm^{-2}s^{-1}$ at 18 m
  - 2 x 10^{31} $cm^{-2}s^{-1}$ at 1 m

and in the process

- Commission
  - the Equipment
  - the Instrumentation
  - the Machine protection system

to the levels required.

Looking for an efficient commissioning path to get us to the above objectives

Stage two definition to follow

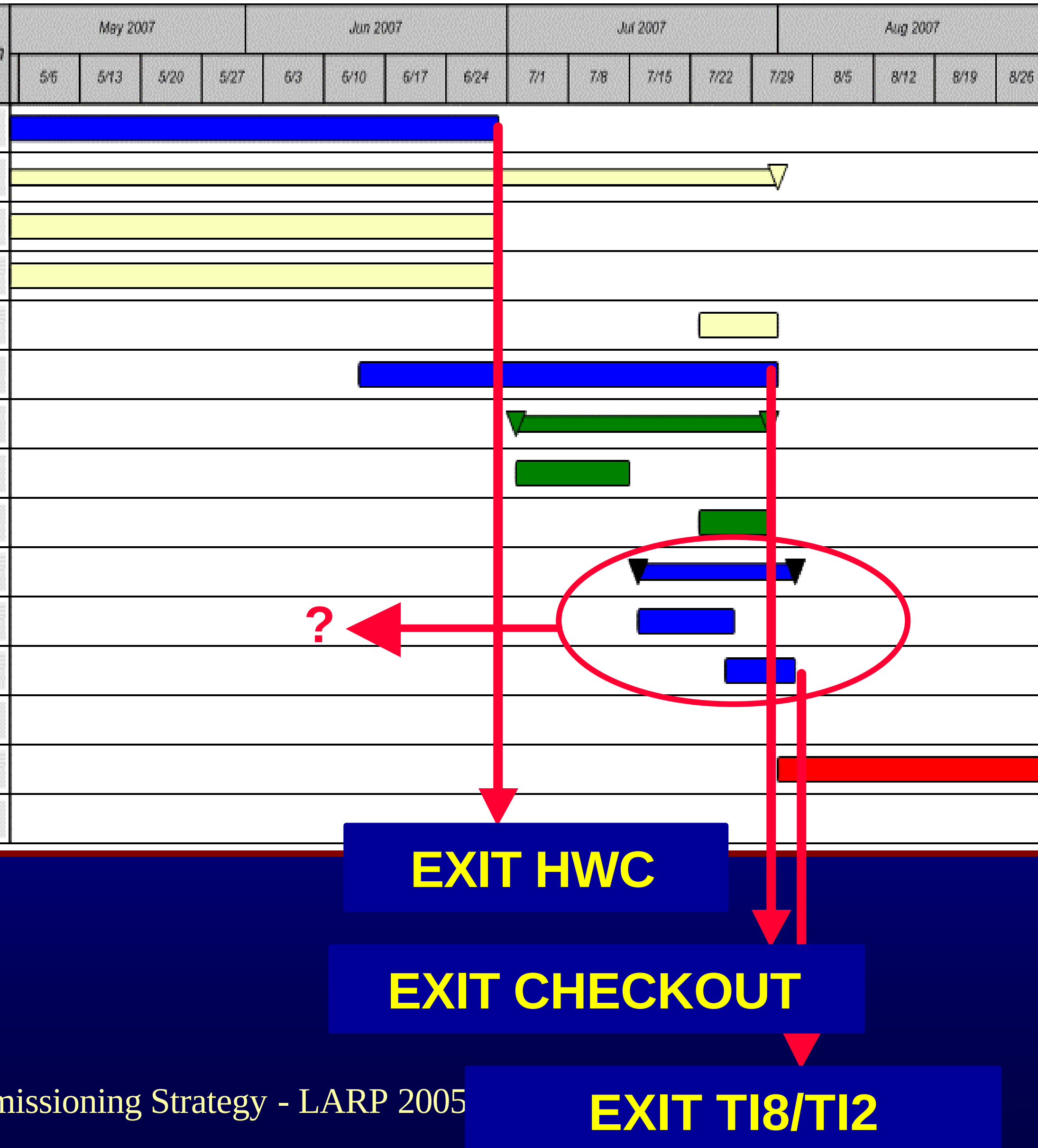
Preparation

Clear aim to commission/fix/test everything that can be:

before beam.

LHC - 2007

ID	Task Name	Start	Finish	Duration
1	**HARDWARE COMMISSIONING**	1/1/2007	6/29/2007	26w
2	**SYSTEM TESTS**	**1/1/2007**	**7/31/2007**	**30.4w**
3	MACHINE PROTECTION	4/2/2007	6/29/2007	13w
4	RF CONDITIONING/COMMISSIONING	1/1/2007	6/29/2007	26w
5	ACCESS/INB	7/23/2007	7/31/2007	1.4w
6	**MACHINE CHECKOUT**	6/14/2007	7/31/2007	6.8w
7	**TI8**	**7/2/2007**	**7/30/2007**	**4.2w**
8	**CHECKOUT**	7/2/2007	7/13/2007	2w
9	**WITH BEAM**	7/23/2007	7/30/2007	1.2w
10	**T12**	**7/16/2007**	**8/2/2007**	**2.8w**
11	CHECKOUT	7/16/2007	7/26/2007	1.8w
12	WITH BEAM	7/26/2007	8/2/2007	1.2w
13				
14	**LHC COMMISSIONING WITH BEAM**	8/1/2007	10/30/2007	13w
15				



Exit HWC - 1

Given installation, technical infrastructure etc. etc.

- **Implicitly:**
  - **Beam Vacuum [warm & cold]**
  - **Cooling and Ventilation**
  - **Cryogenics Plant**
  - **Cryostat Instrumentation**
  - **Electrical Network**
  - **Insulation Vacuum**
  - **Powering Interlock**
  - **QRL Instrumentation**
  - **QRL Vacuum**
  - **Radiation Monitors**
  - **Software Interlock System**
  - **Access**
  - **Survey/Alignment**

MOVE FROM HWC MODE TO OPERATION MODE

↓

- **Monitoring, logging, display, PM, Diagnostics**
- **Control applications**
- **Coupling between systems**
- **Recovery procedures from CCR clearly defined etc. etc.**

Exit HWC - II

- All magnet circuits [warm & cold]
- Power converters
- Kickers, Septa
- Collimators, Absorbers
- Beam dumps
- RF
  - Power systems, low level, cavities, TFB
- Instrumentation
- Machine protection
  - QPS, Energy Extraction, Power Interlock Controllers
- Controls

Machine checkout

- By Operations
- With support of equipment specialists, HWC team etc.
- From the PCR

Drive all relevant systems in a synchronized way through the complete operational sequence

This where operations get serious

Exit machine checkout - 1

- RF
  - Pre-pulses, low level control [cavity control, synchro, beam control, longitudinal damper], transverse damper, power systems. Diagnostics.
  - Synchronisation with injectors
- Power converters
  - tracking
  - control, ramping, squeezing, real-time
- Kickers, septa,
- Collimators, absorbers
- Dump:
  - timing, post-mortem, inject and dump
- Beam Instrumentation
  - pre-commission, timing, acquisition tests, interface to control system

Exit Machine Checkout - 2

- **Interlocks & Machine Protection**
  - Equipment interfaces, links, logic, controls,
  - PIC, WIC, BIC, Safe Beam Flags
  - Software interlocks
  - QPS, Energy extraction
    - displays, diagnostics, post-mortem, recovery
  - Energy meter

Exit Machine Checkout - 3

- **Controls:**
  - Slow timing, fast timing, synchronisation
  - Alarms, logging, post mortem, fixed displays
  - Equipment control & access
  - Analogue acquisition
  - Software: measurements, trajectory acquisition and correction, ramping etc. etc.
  - Controls infrastructure: servers, databases etc.
  - Sequencer, injection management
  - Procedures for sliding bumps etc. etc.

Exit Machine Checkout - 4

- Settings etc.
  - calibrations, optics, transfer functions, ramp, squeeze…
- Radiation monitoring
- Access system
  - INB, EIS
  - Operation
- Experiments
  - Data interchange
  - Beam aborts

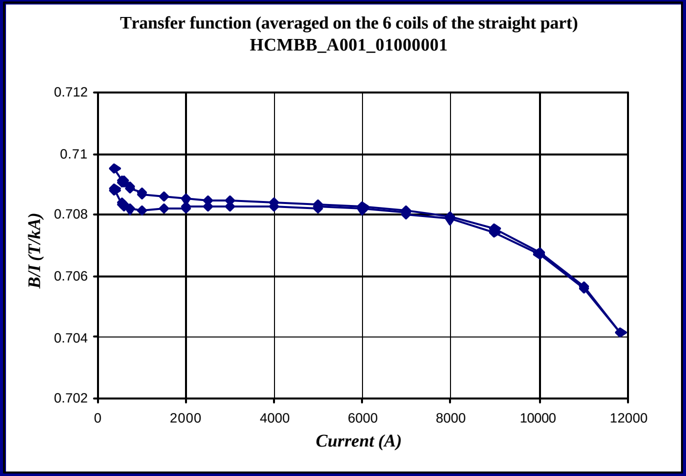
Exit injectors and transfer lines

- **SPS LHC cycle**
  - All requisite beams available
  - Beam quality
  - Delivered when required
- **TI8 & TI2**
  - Fully qualified LHC pilot beams to final TED

Pre-beam: Magnets

- **Errors: all circuits, full cycle**
  - geometric, beam screen, saturation
  - eddy,
  - RMS/Persistent currents
    - static model
    - powering history dependent model
    - on-line reference magnets
- **Cycle path – all magnets**
- **Transfer functions**
  - for all magnet circuits
  - hysteresis behaviour for corrector circuits where appropriate
- **Strategy for:**
  - excitation of nested correctors
  - cycling nested pc/magnets

```
b1pM_MBRS  :=   0.0000;
b1gM_MBRS  :=   0.0000;
b2pM_MBRS  :=  -0.1088;
b2gM_MBRS  :=   0.1904;
b3pM_MBRS  :=  -4.1431;
b3gM_MBRS  :=  -2.1825;
```



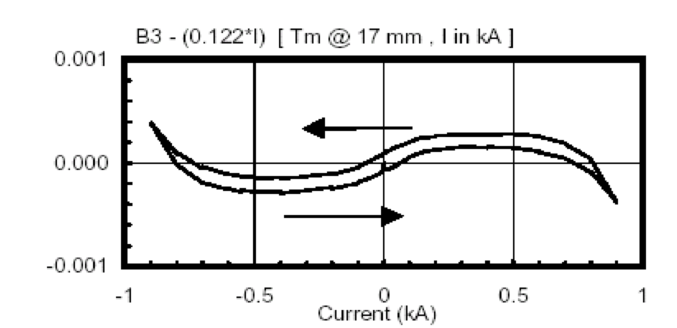


Figure 3 : Field strength of MCS corrector : difference between the strength and straight line giving the average to enlighten the hysteresis due to persistent currents.

Planning: with beam

1	Injection
2	First turn
3	Circulating beam
4	450 GeV: initial commissioning
5	450 GeV: detailed measurements
6	450 GeV: 2 beams
7	Nominal cycle
8	Snapback – single beam
9	Ramp – single beam
10	Single beam to physics energy
11	Two beams to physics energy
12	Physics
13	Commission squeeze
14	Physics partially squeezed

Beam

- **Pilot Beam:**
  - Single bunch, 5 to 10 x 10^9 protons
  - Possibly reduced emittance
- **Intermediate single:**
  - 3 to 4 x 10^{10} ppb
- **4 bunches etc. pushing towards…**
- **43 bunches**
  - 3 to 4 x 10^{10} ppb

Will stepping up & down in intensity/number of bunches through the phases

First turn

- Commission injection region
- Instrumentation
- Threading

PILOT

RING 1
RING2

Establish circulating beam

- Circulating low intensity beam

PILOT

RING 1
RING2

450 GeV Initial

- Polarities and aperture checked.
- Basic optics checks performed.
- First pass commissioning of BI performed.
- Phase 1 of machine protection system commissioning performed. .
- Beam Dump commissioned with beam

SINGLE INTERMEDIATE

RING 1
RING2

450 GeV Detailed

- Well-adjusted beam parameters, detailed optics checks
- Fully functioning beam instrumentation.
- Machine protection as required for ramp
- RF - beam control loops operational and adjusted

SINGLE INTERMEDIATE ++

RING 1
RING2

Two beam operation

- 2 beams, well-adjusted beam parameters,
- beam instrumentation, cross talk etc.

Switch to nominal

- 2 beams, well-adjusted beam parameters,
- beam instrumentation, cross talk etc.

Snapback

- Single beam, good transmission through snapback
- Requisite measurements (orbit, tune, chromaticity)

PILOT++

RING 1
RING2

↓

Ramp Single Beam

- Single beam, good transmission to top energy
- Commission beam dump in ramp
- Stops in ramp - measurements
- RF

PILOT++

RING 1
RING2

↓

Two beams to top energy

- Two beams, good transmission to top energy
- Measurements

43 x 43

COLLIDE

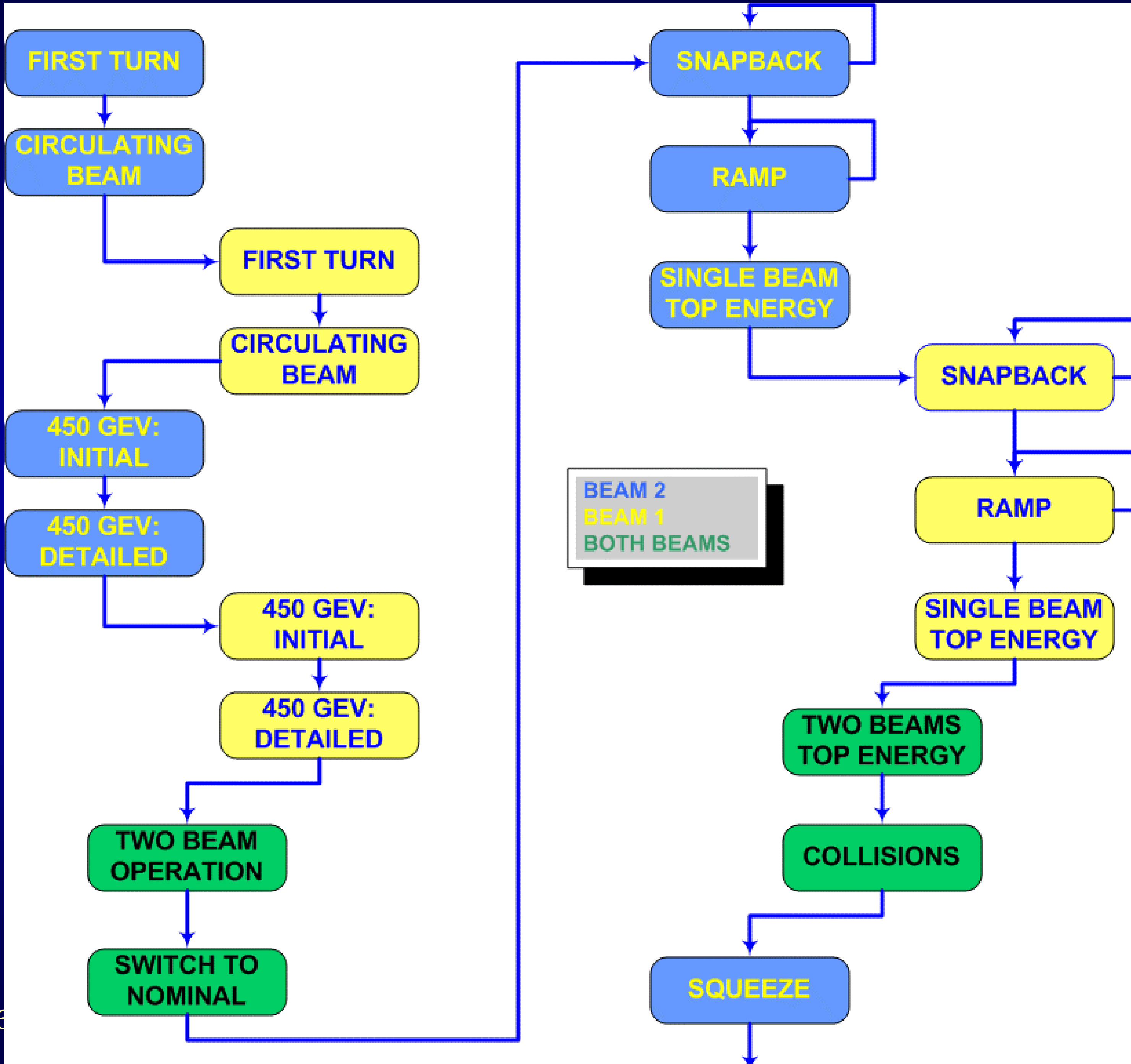
↓

Squeeze

- Single beam - step through squeeze
- Parameter control, measurements

SINGLE INTERMEDIATE

RING 1
RING2

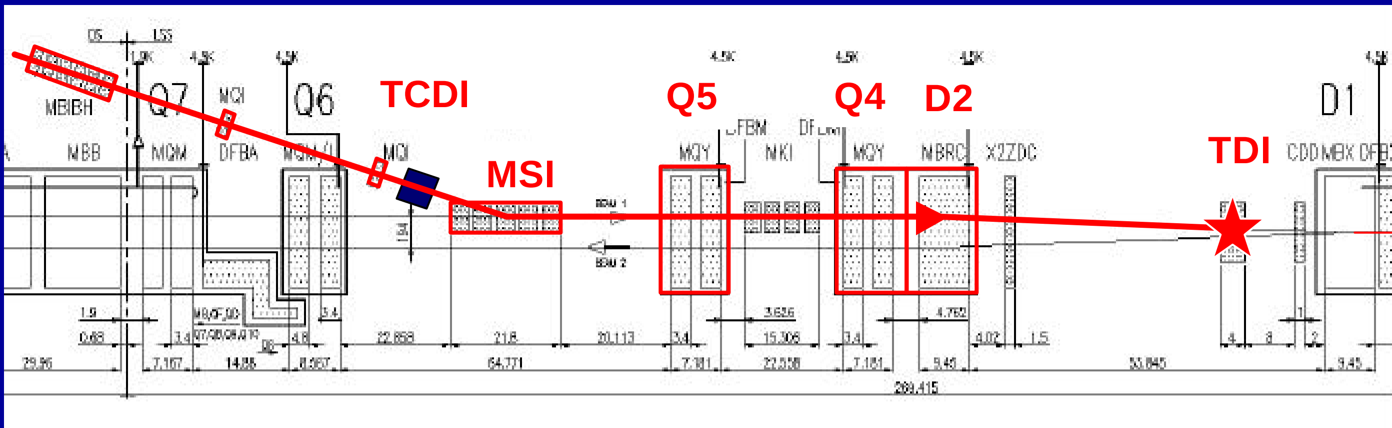

FIRST TURN
CIRCULATING BEAM
FIRST TURN
CIRCULATING BEAM
450 GEV: INITIAL
450 GEV: DETAILED
450 GEV: INITIAL
450 GEV: DETAILED
TWO BEAM OPERATION
SWITCH TO NOMINAL
SNAPBACK
RAMP
SINGLE BEAM TOP ENERGY
SNAPBACK
RAMP
SINGLE BEAM TOP ENERGY
TWO BEAMS TOP ENERGY
COLLISIONS
SQUEEZE
BEAM 2
BEAM 1
BOTH BEAMS

At each phase:

- Equipment commissioning with beam
- Instrumentation commissioning
- Checks with beam
  - BPM Polarity, corrector polarity, BPM response
- Machine protection
- Beam measurements
  - beam parameter adjustment, energy, linear optics checks, aperture etc. etc.

Transfer & Injection

LEFT OF IP2 (H plane)



- **Objectives & importance of preparation [hammered]**
- **System Commissioning:**
  - **Hardware**
  - **Machine Protection**
  - **Beam Instrumentation**
  - **Controls**

Procedure for commissioning with beam

plus time estimate

Transfer & Injection: Issues

- Scheduling of TI2 and IR2
- Keep TI8 operational
- Sector test clearly a big advantage

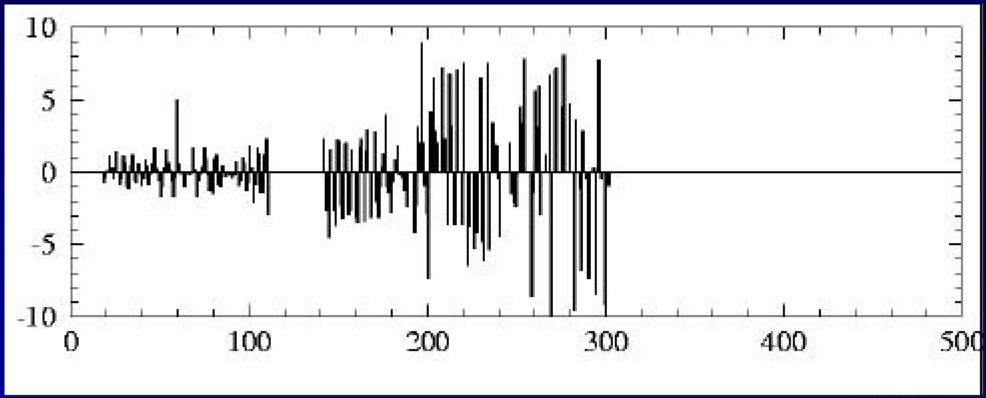
- Machine Protection [general]
  - Including full specification & formal acceptance
  - Imperative that we have a well-defined plan of how to commission the machine protection system with beam.
  - Providing an appropriate level of protection at each commissioning stage.

450 GeV: Initial

Commissioning tunes

Simple machine

De-Gauss cycle



- Threading, First turn, circulating beam, RF capture
- Beam instrumentation:
  - BPM, BCT, Screens, Tune
- Beam parameter adjustment
- First pass optics and aperture measurements
- Equipment:
  - RF, Beam Dump

450 GeV: consolidation

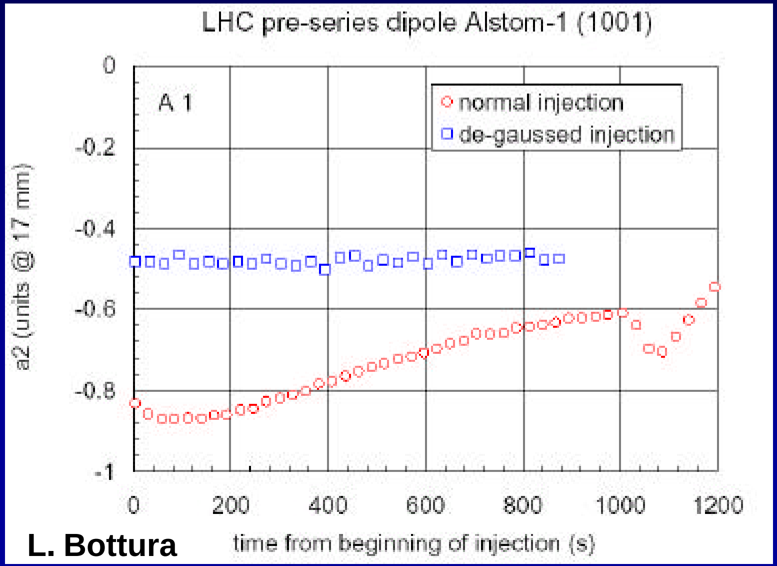
- **Measurements:**
  - Linear optics checks and correction
  - Beta beating, Emittance
  - Non-linear optics, higher orders
- **Equipment**
  - Collimators
  - RF, LFB, TFB
- **Instrumentation**
  - BLMs…
- **Machine Protection system**

Well adjusted 450 GeV machine.

Machine Protection systems fully tested, approved and operational to take beam into the ramp

De-Gauss versus Nominal

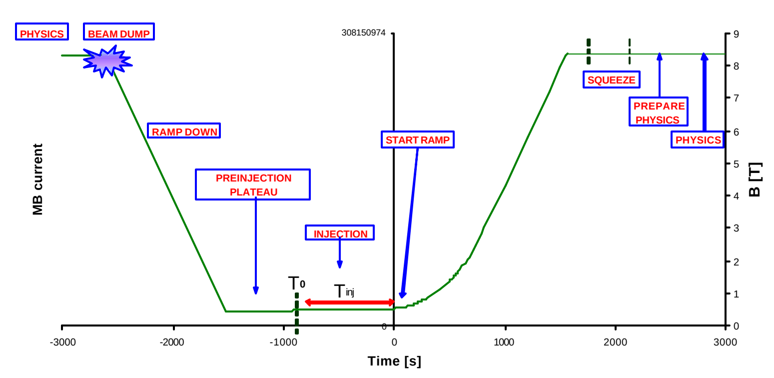
1. Nominal cycle and wait 30 minutes
2. De-Gauss cycle



- Zeros persistent current effects
- Stable in time
- No dependency on the powering history of the magnets
- Get a handle on persistent current amplitudes
- No 30 minutes wait
- HOWEVER:
  - Spend time commissioning a cycle we can't use operationally; plus possibly some beam dynamics issues

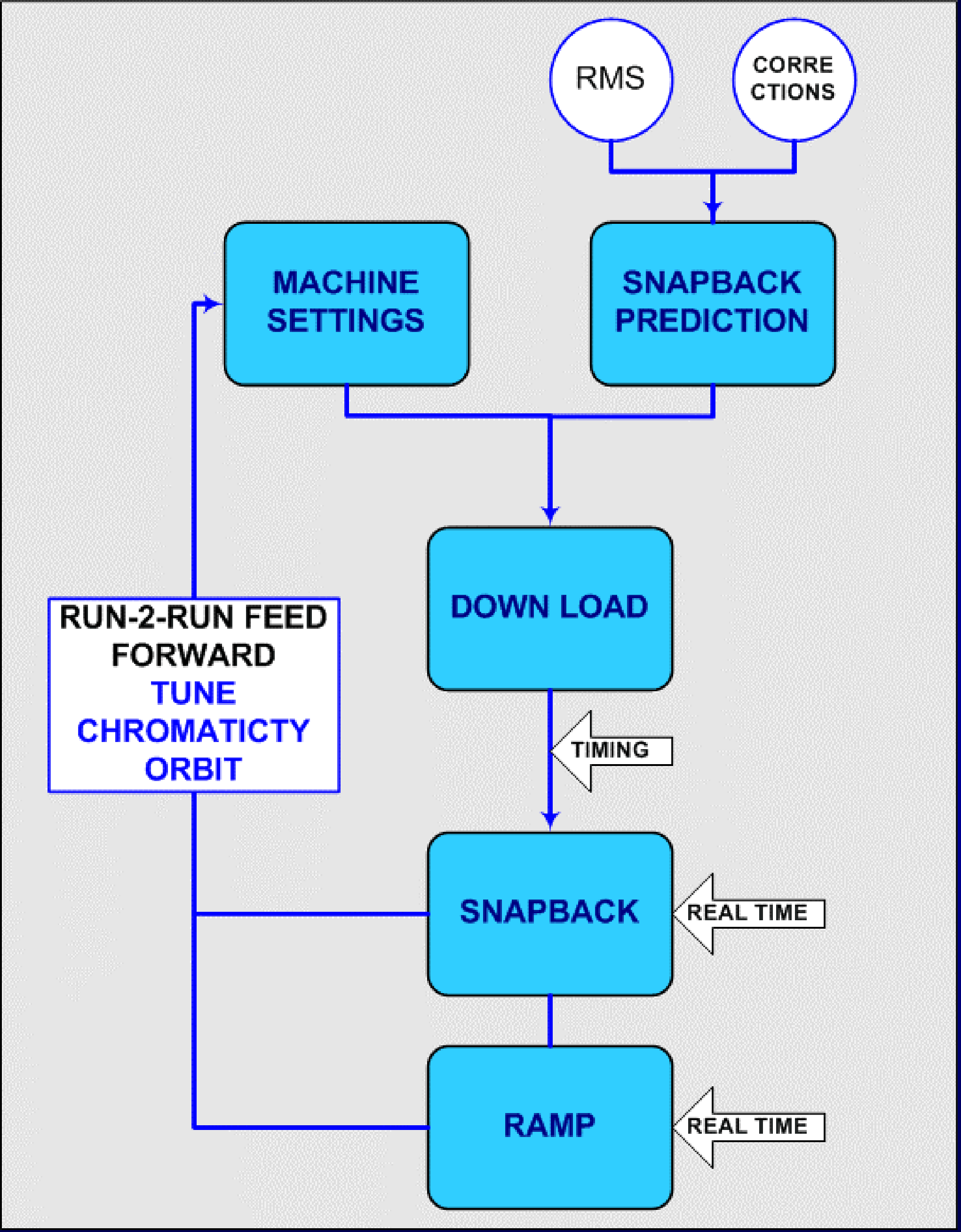
To be followed up

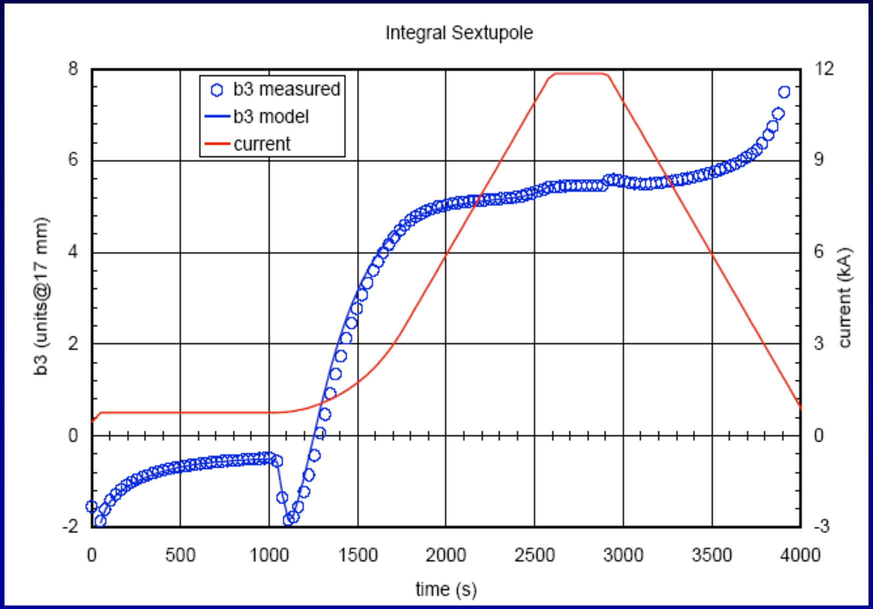
Ramp



- **Procedure detailed:**
  - **Baseline Ramp**
  - **Power converters,**
    - **Pre-loaded functions, Real-time**
  - **RF**
  - **Dump**
  - **Timing**
  - **Stop in Ramp & Squeeze**

- **Prerequisites include:**
  - **Beam Instrumentation**
    - **Tune measurement**
    - **Q' measurement**
    - **Orbit**
  - **RMS:**
    - **predictions of snapback, transfer functions, static errors…**
  - **Machine Protection**

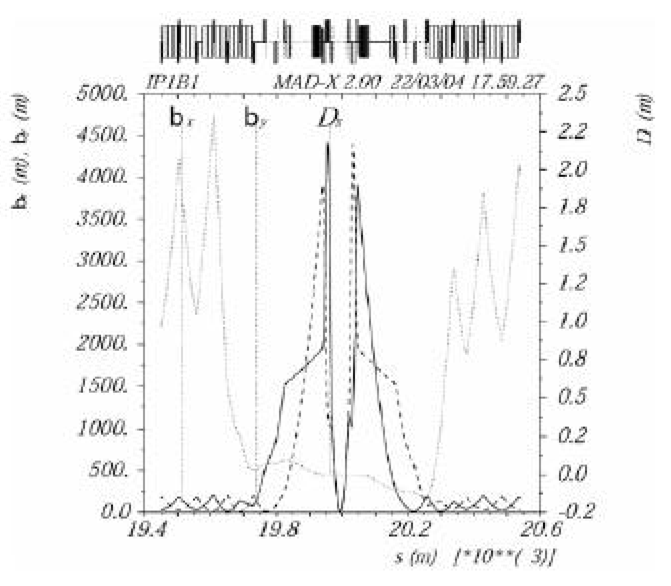




During commissioning:

- **PC Tracking Studies**
- **Beam Dump Commissioning**
- **BLM threshold adjustment**

Squeeze



- **Key Requirements**
  - **Separation**
  - **Aperture**
  - **Smooth powering**
  - **Avoid low gradients and zero crossings**
- **Tight Tolerances**
  - **Interplay between gradient errors and limits on tune, beta beating, dispersion, orbit**
  - **Excellent control required: feedback desirable**
- **Time**
  - **Given by power converter ramp rates**
  - **8.5 minutes per IP**
  - **plus round off & collimator adjustments**

Procedure detailed:

- **Collimators**
- **Power converters**
- **Monitoring**
- **Parameter control**

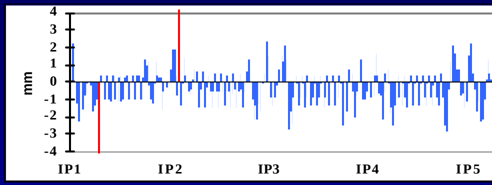
Squeeze

- **Commissioning procedure:**
  - **Squeeze one IP at a time without crossing angle**
  - **One IP at a time with crossing angle**
  - **Minimise intermediate solutions. How many matched intermediate steps are required?**
  - **Parallel squeeze in more than one IP**

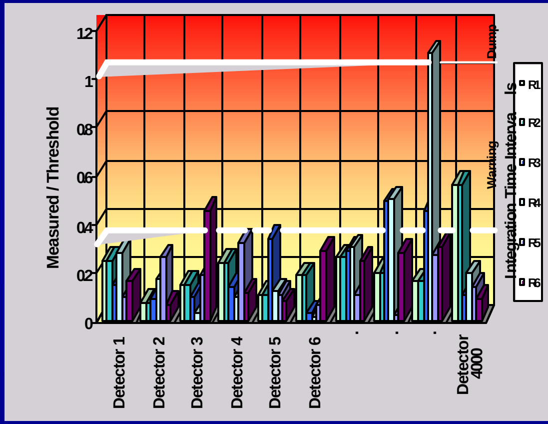
- **Issues**
  - **Triplet correction for b* 🖫 0.7 m.**
  - **Transfer functions and triplet alignment ® errors**
  - **Reproducibility of transfer functions at low powering**
  - **Alignment optics**

Critical systems @ Start-up

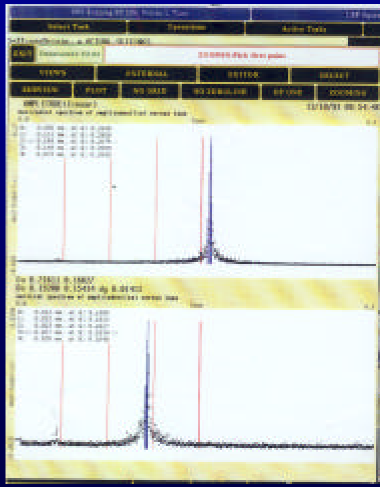
- **BPMs**
  - Day 0: Orbit on pilot – immediate, turn by turn with BST
  - Systematic check for polarity errors etc.
  - System performance – long term



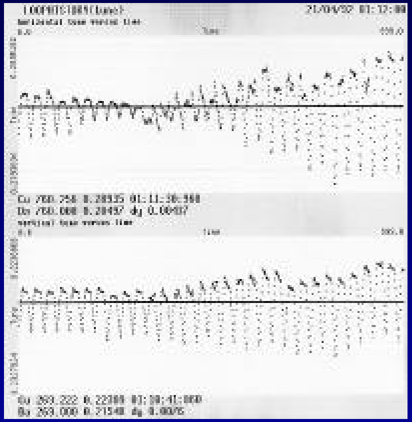
- **BLMs**
  - Day 0: “slow” monitors – immediate
  - BST for fast loss monitors
  - Calibration, Cross talk…
  - Thresholds - considerable effort

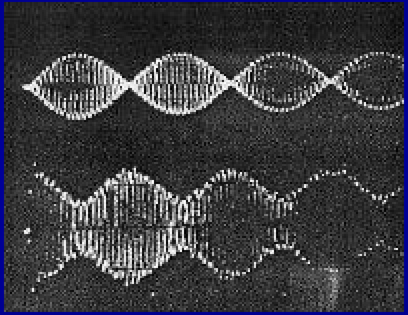


- **BCT**
  - Day 0: DC immediate, bunch to bunch – BST
  - Lifetime calculation – slow!
- **Tune**
  - Tune Day 0: Kick/FFT & multi- FFT
  - PLL – few weeks



Critical systems @ Start-up





- **Chromaticity**
  - **Day 0: Kick/Head-tail (BST)**
  - **Day 0: DQ v Df**
  - **Periodic momentum modulation – PLL**

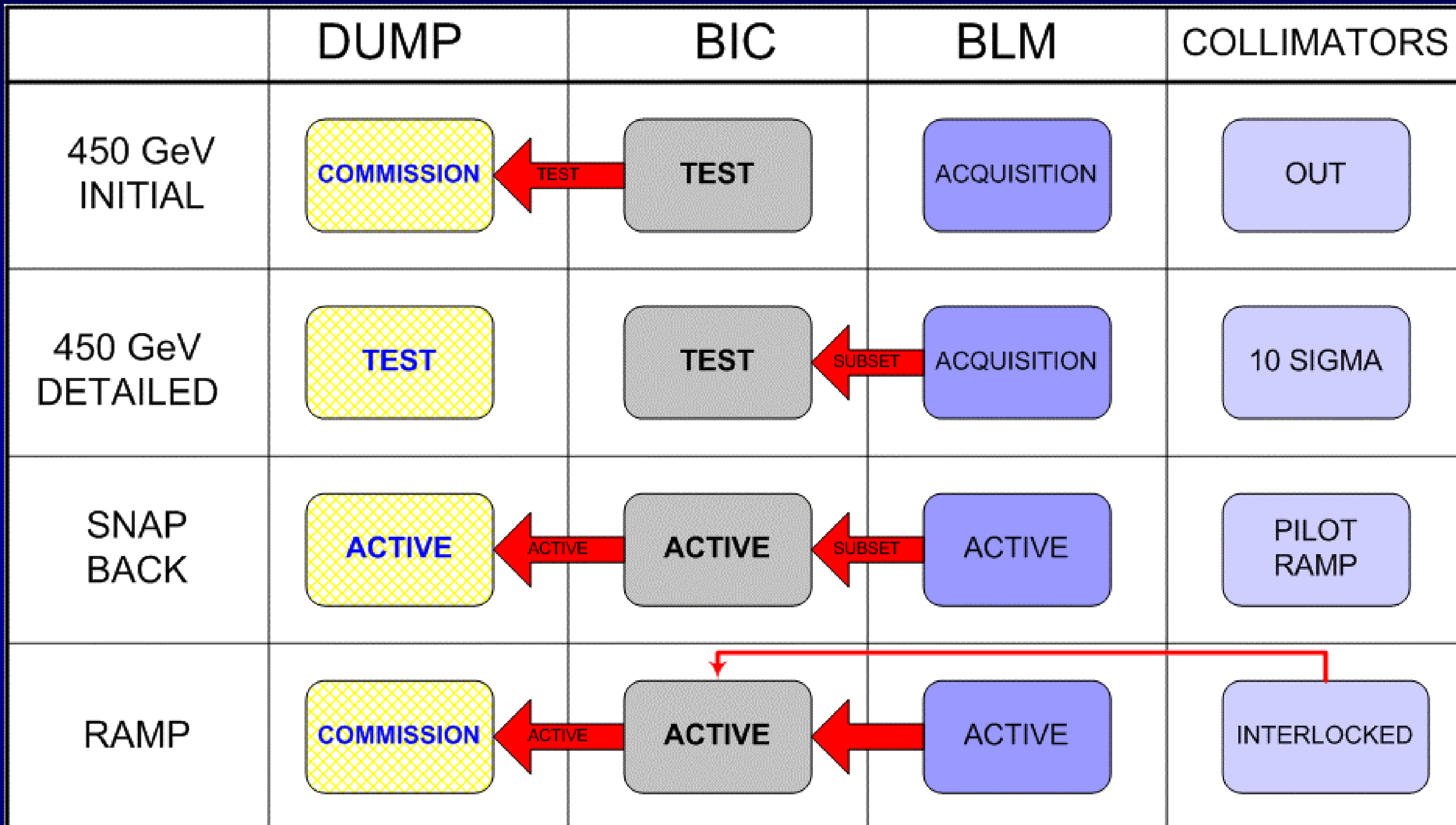
- **Coupling**
  - **Day 0: Kick/Beam response**
  - **PLL: closest tune approach**

Clear need to get PLL (& BST) working ASAP

Good to see that the basics will be there from the start

Plus: SLM, LDM, AGM, RGM, Wire scanners, luminosity monitors.

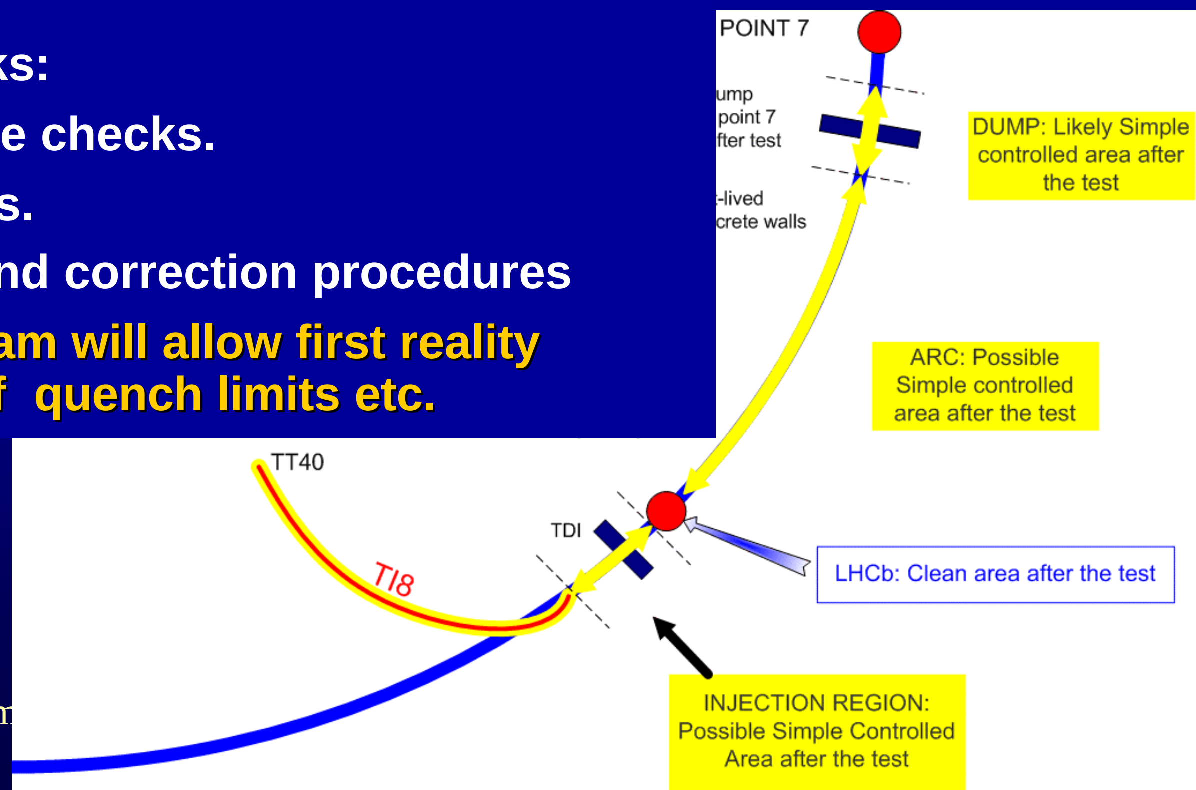
Machine protection



Need a well defined plan for the commissioning and integration of the Machine Protection System

Sector Test

- **Rigorous check of ongoing installation and hardware commissioning**
- **Pre-commission essential acquisition and correction procedures.**
  - **Commission injection system:**
  - **Commission Beam Loss Monitor system**
  - **Commission trajectory acquisition and correction.**
  - **Linear optics checks:**
  - **Mechanical aperture checks.**
  - **Field quality checks.**
  - **Test the controls and correction procedures**
- **Hardware exposure to beam will allow first reality checks of assumptions of quench limits etc.**



How long?

	Phase	R1/2	Time [days]	
	Injection	2	1	2
1	First turn	2	3	6
2	Circulating beam	2	3	6
3	450 GeV: initial commissioning	2	4	8
4	450 GeV: detailed measurements	2	4	8
5	450 GeV: 2 beams	1	2	2
6	Nominal cycle	1	5	5
7	Snapback – single beam	2	3	6
8	Ramp – single beam	2	4	8
9	Single beam to physics energy	2	2	4
10	Two beams to physics energy	1	3	3
11	Physics	1	2	2
12	Commission squeeze	2	4	4
13	Physics partially squeezed	1		
	TOTAL TIME (WITH BEAM)			*60*

Parallelism?

- System tests with HWC ongoing
  - Machine protection
  - Controls
  - RF/Injection/Collimators etc.
- Machine checkout with HWC ongoing
  - Sign over completed sectors to OP
- TI2 commissioning – LHC with beam 2
- HWC – partial LHC with beam 2
  - Implications: dump, radiation protection, access, resources, support etc.
- LHC - partial beam 1 with beam 2

Options need examining

Conclusions

- **PREPARATION**
- **STAGING**
  - **43 x 43 colliding (in 3 months absolute minimum)**
- **PLANNING**
  - **Before beam**
  - **Phases detailed – work in progress**

- ***//cern.ch/lhc-commissioning***
- ***//cern.ch/lhc-injection-test***