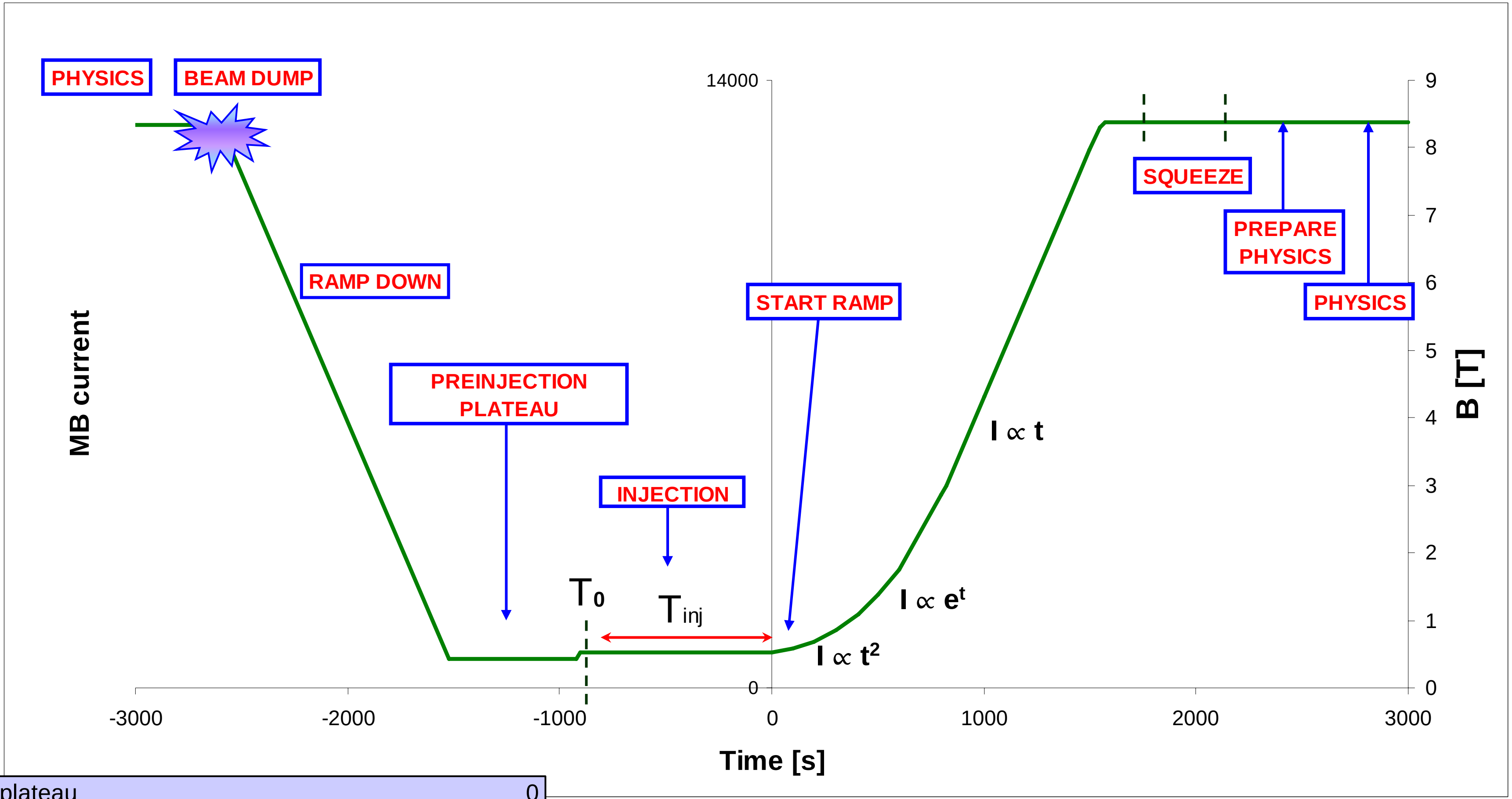
Commissioning the ramp

- **Baseline**
- **Magnets**
  - **Main circuits**
  - **Harmonic correction**
  - **Decay and snapback**
- **Power Converters**
- **Collimators**
- **Beam Instrumentation**
- **Etc.**

Nominal cycle



Injection plateau	0
alpha	5.92105E-06
current rate end snapback	0.6
current at injection	760
current variation during snapback	20
parabolic segment duration	405.333
current at end exp	4110.000
b at end exp	3.000
current to field scaling factor	1370.000
max current rate	10.000
current rate end parablolic	3.648
exp time constant inverse	2.433E-03

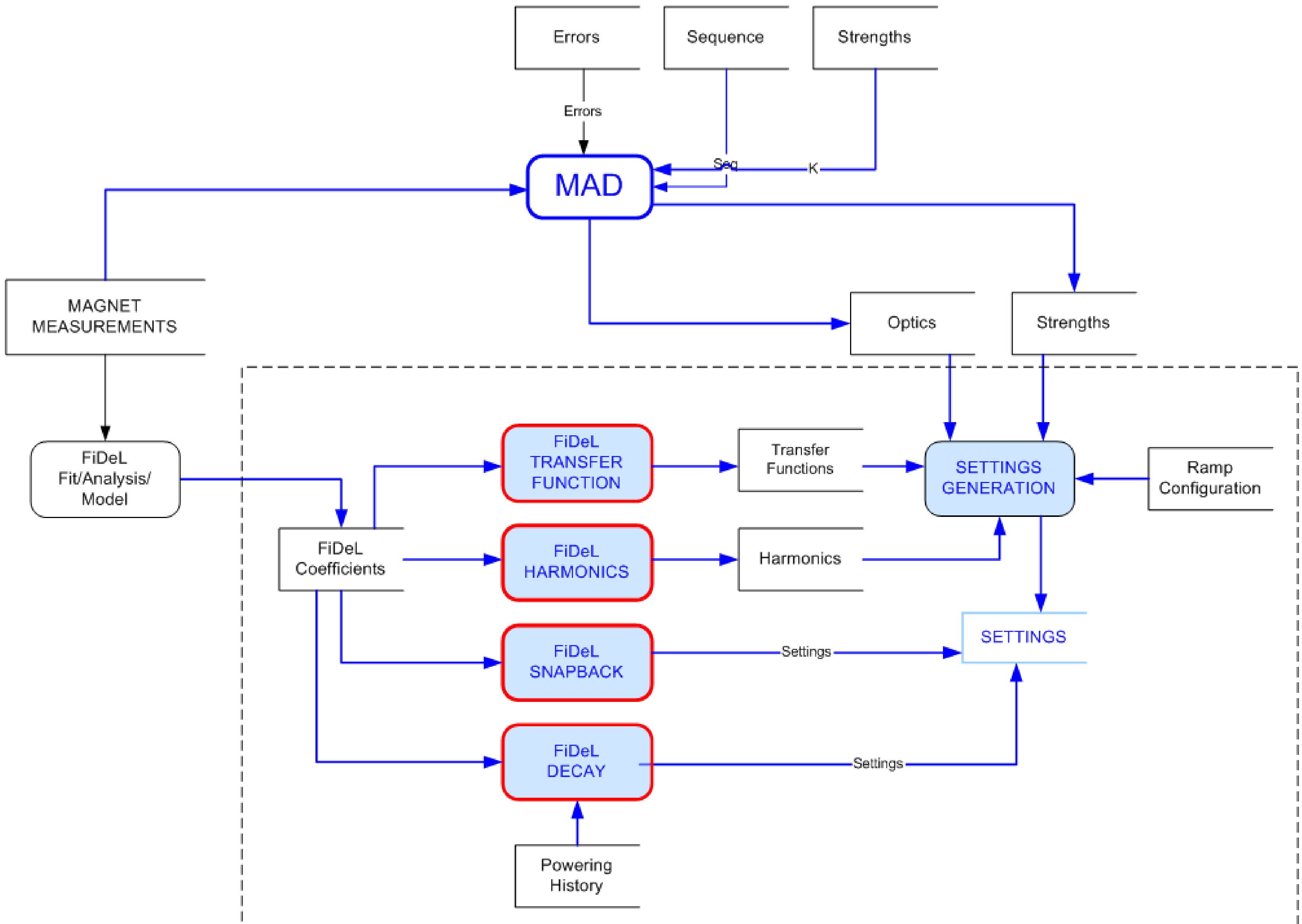
Ramp

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

Settings Generation

- **Main stuff**
  - **Transfer Functions**
  - **DC error components**
    - Geometric
    - DC magnetization
    - Saturation
    - Residual
  - **MAD strengths**
  - **Optics parameters**

Steady state, reproducible from cycle to cycle, depending only on current



MAD – standard transfer of Kn

FiDeL: Harmonics

$$c_m^{geometric} = \gamma_m I$$

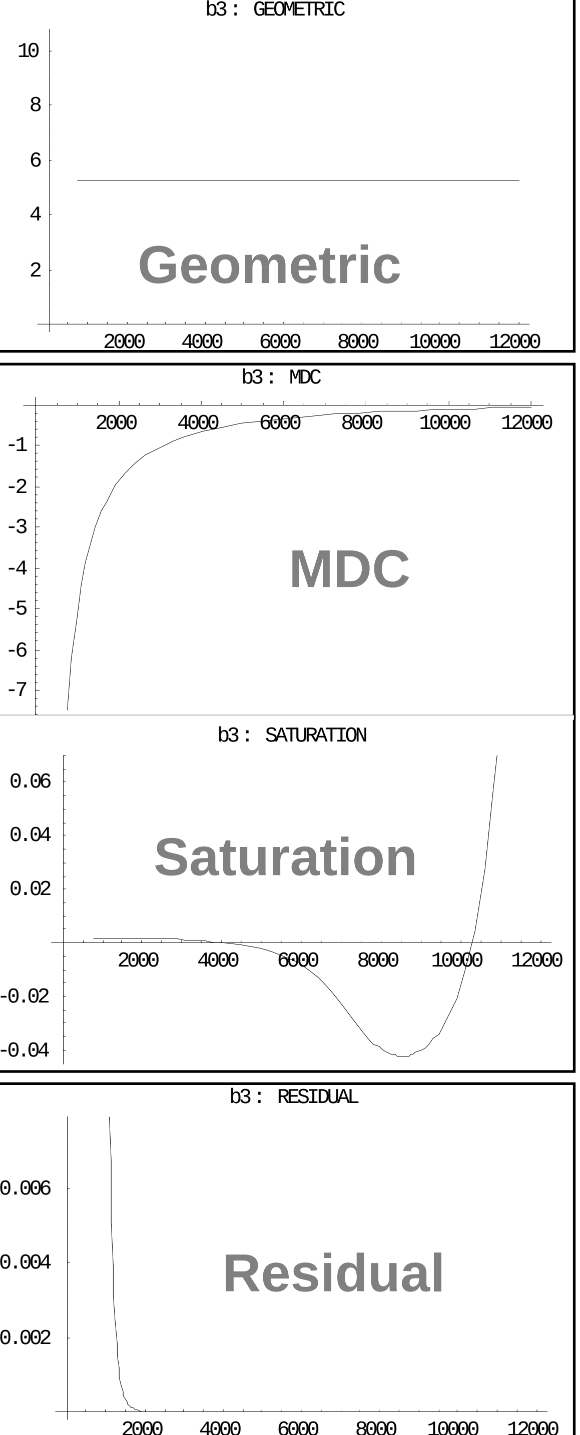
$$c_m^{MDC} = \mu_m I_{inj} \left(\frac{I}{I_{inj}} \right)^{p_m} \left(\frac{I_c - I}{I_c - I_{inj}} \right)^{q_m} \left(\frac{T_{co}^{1.7} - T^{1.7}}{T_{co}^{1.7} - T_{meas}^{1.7}} \right)^{m_m}$$

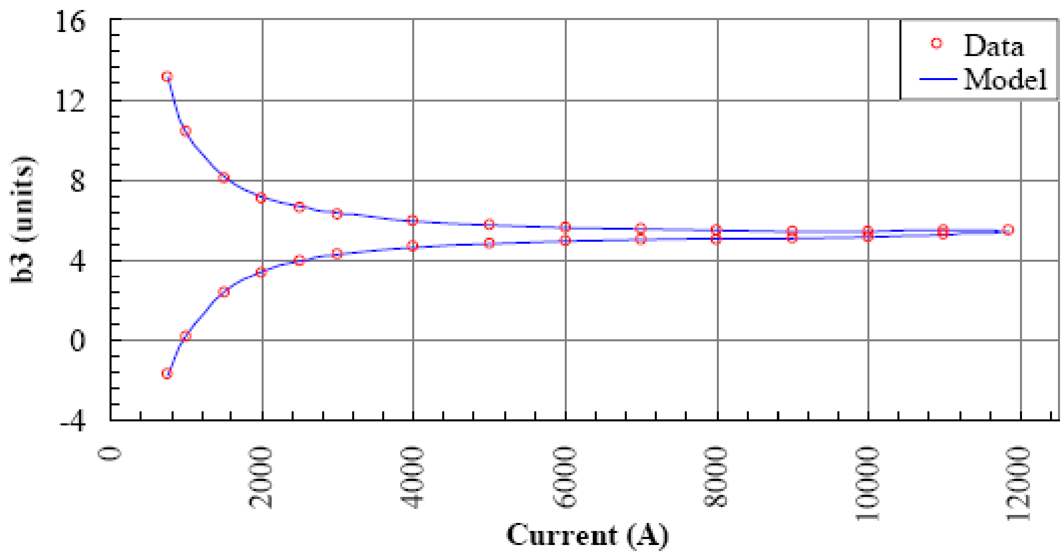
$$c_m^{saturation} = \sum_{i=1}^{N} \sigma_m^i I \, \Sigma\left(I, S_m^i, I_{0m}^i, I_{nom}\right)$$

$$\Sigma\left(I, S_m, I_{0m}, I_{nom}\right) = \frac{1}{\pi} \operatorname{atan}\left(S\left(\frac{I - I_0}{I_{nom}} \right) \right) + \frac{1}{2}$$

$$c_m^{residual} = \rho_m I \left(\frac{I_{inj}}{I} \right)^{r_n}$$

Coefficient	Value							Component
	TF	b2	a2	b3	a3	b4	b5	
γ	10.119	0.142	-0.040	5.276	-0.236	0.004	0.245	geometric
μ	-0.005	0.154	-0.031	-7.466	0.026	-0.002	0.931	magnetisation
p	1.11	1.54	1.46	0.63	1.11	-1.28	0.12	
q	-0.29	0.96	11.52	0.55	0.98	0.57	-0.39	
m	2	2	2	2	2	2	2	
σ^1	0.247	-3.241	-0.118	-0.095	-0.008	0.207	-0.142	saturation
I_0^1	10739	8569	11090	7224	10256	10056	9214	
S^1	1.691	8.088	32.181	9.760	10.453	12.985	8.150	
σ^2	-0.545	20.131		0.347				
I_0^2	13599	14107		11031				
S^2	3.230	25.551		16.923				
ρ	0.003	-0.182	-0.008	0.340	-0.018	-0.011	0.126	residual
r	1.86	1.95	2.82	10.00	2.52	1.36	2.85	


b3 : GEOMETRIC
Geometric
b3 : MDC
MDC
b3 : SATURATION
Saturation
b3 : RESIDUAL
Residual
2000
4000
6000
8000
10000
12000


Data
Model
b3 (units)
Current (A)
16
12
8
4
0
-4
0
2000
4000
6000
8000
10000
12000

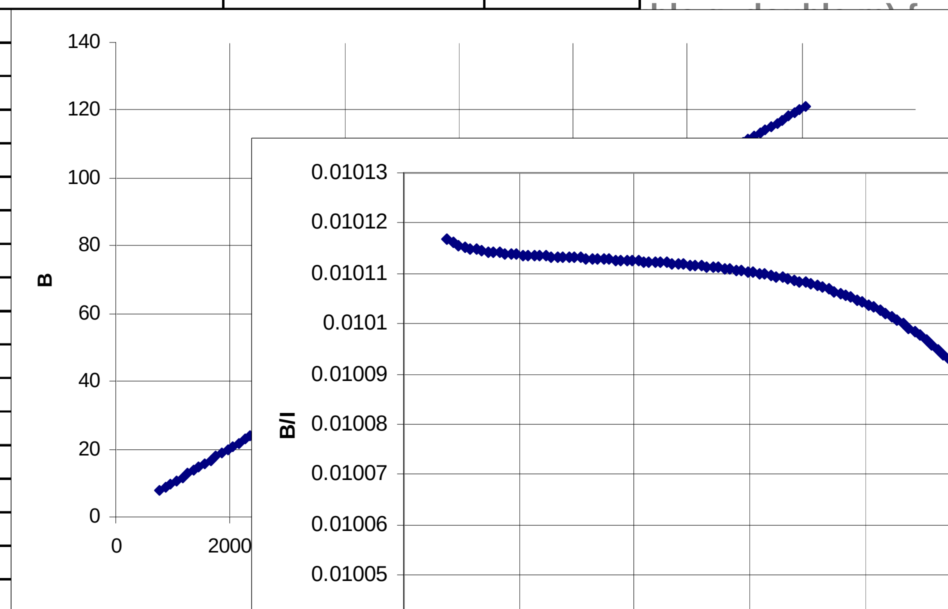
Generate Transfer Functions - Implementation

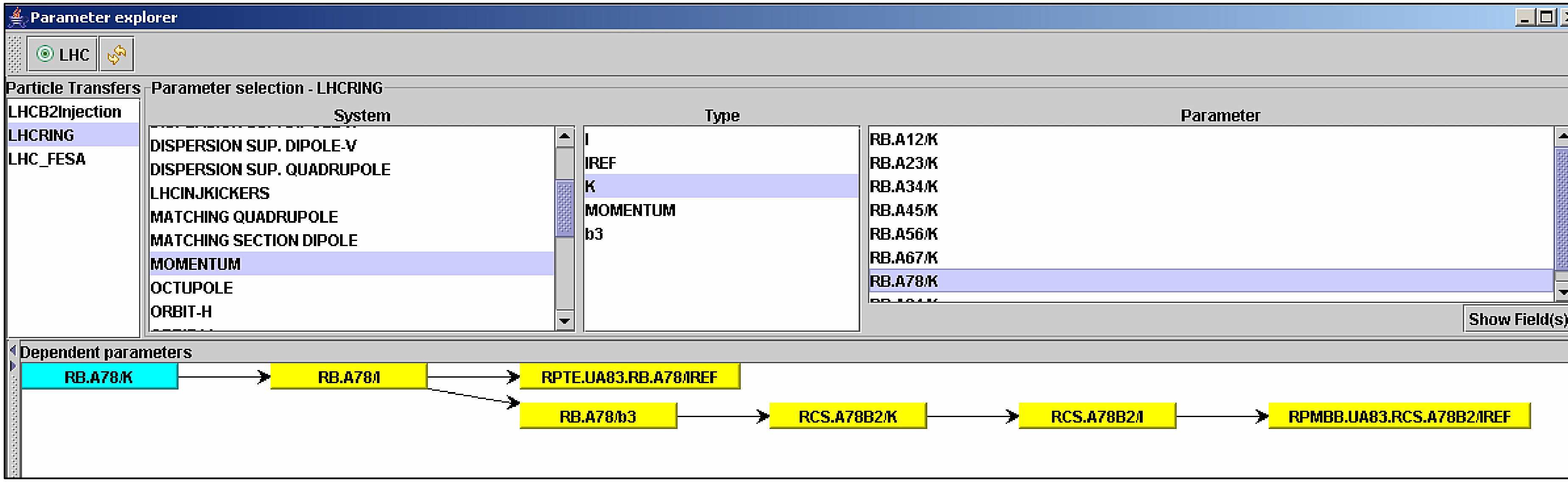
HW_NAME	COMPONENT_NAME	COEFFICIENT_NAME	COEFFICIENT_VALUE
MB.A78	TF	gamma	10.119
MB.A78	TF	mu	-0.005
MB.A78	TF	p	1.11
MB.A78	TF	q	-0.29
MB.A78	TF	m	2
MB.A78	TF	sigma_1	0.247
MB.A78	TF	S_1	1.691
MB.A78	TF	I0_1	10739
MB.A78	TF	sigma_2	0.545
MB.A78	TF		
MB.A78			
MB.A78			
MB.A78			
MB.A78			
MB.A78			
MB.A78			
MB.A78			
MB.A78			

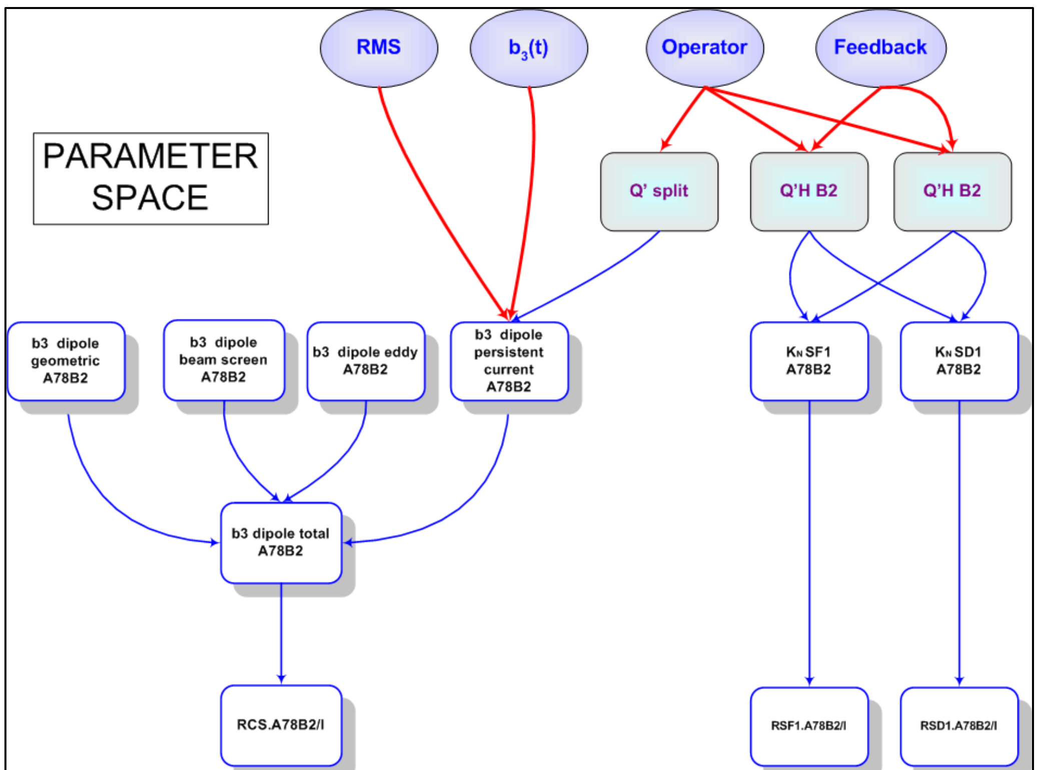
```
// DC Magnetisation

  double getBMDC(d
  
   double mdc = mu *
       * M
         /
         
   retur
  }
```

$$B_m^{MDC} =$$

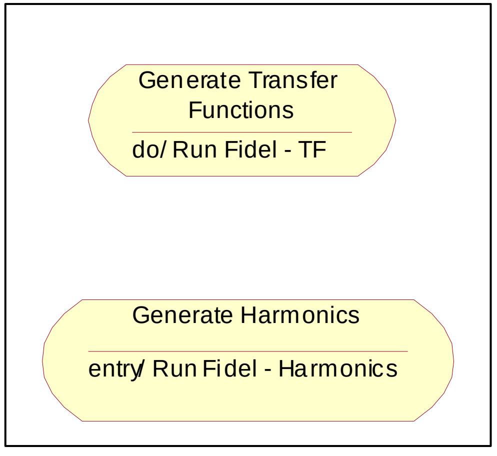
CALIBRATION_NAME	B_FIELD	I
MB.A78	7.688806312	760
MB.A78	8.699903331	860
MB.A78	9.711037605	960
MB.A78		
MB.A78		
MB.A78		
MB.A78		
MB.A78		
MB.A78		
MB.A78		
MB.A78		
MB.A78		
MB.A78		
MB.A78		
MB.A78		
MB.A78		
MB.A78		
MB.A78		
MB.A78		
MB.A78		
MB.A78		
MB.A78		
MB.A78		
MB.A78		

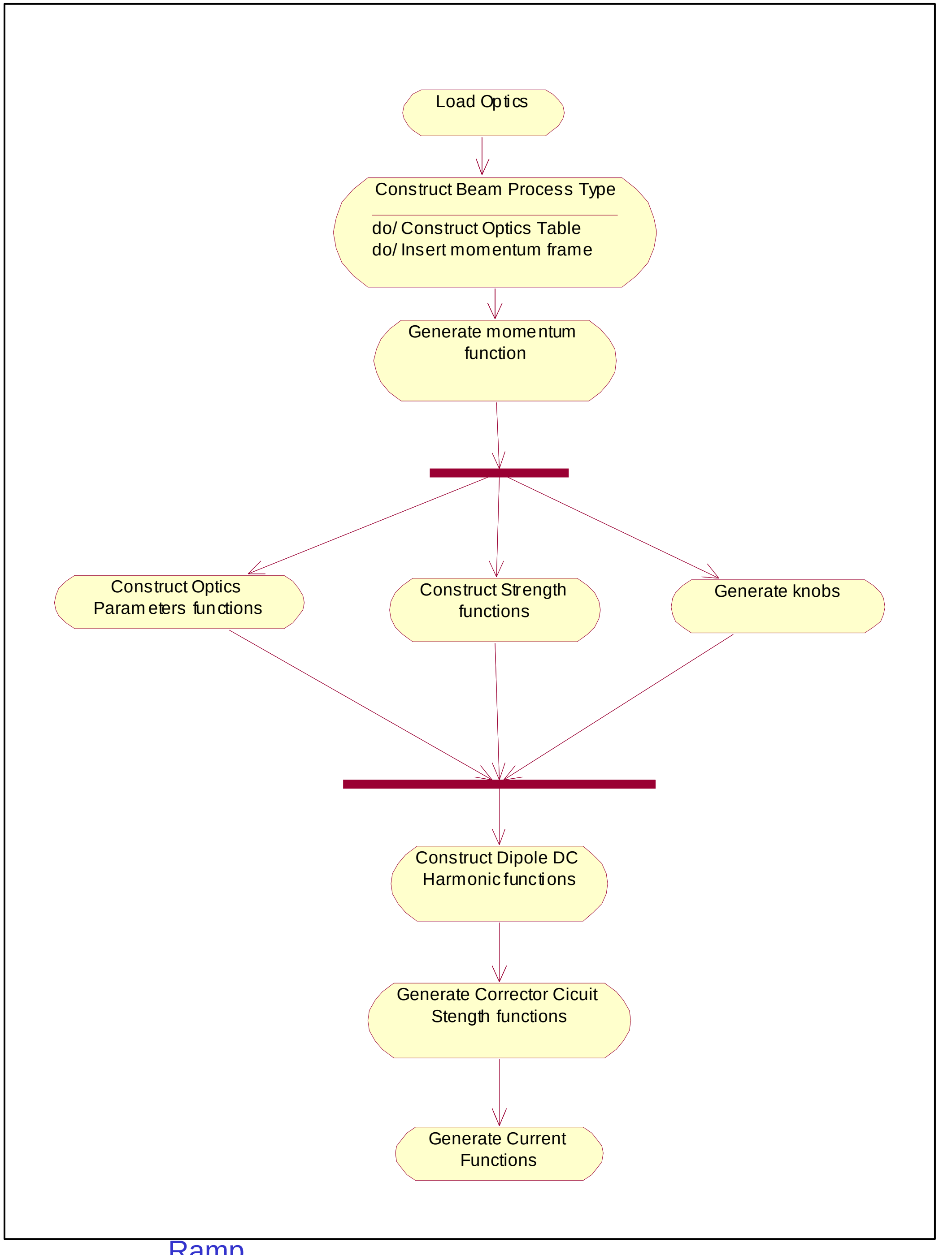


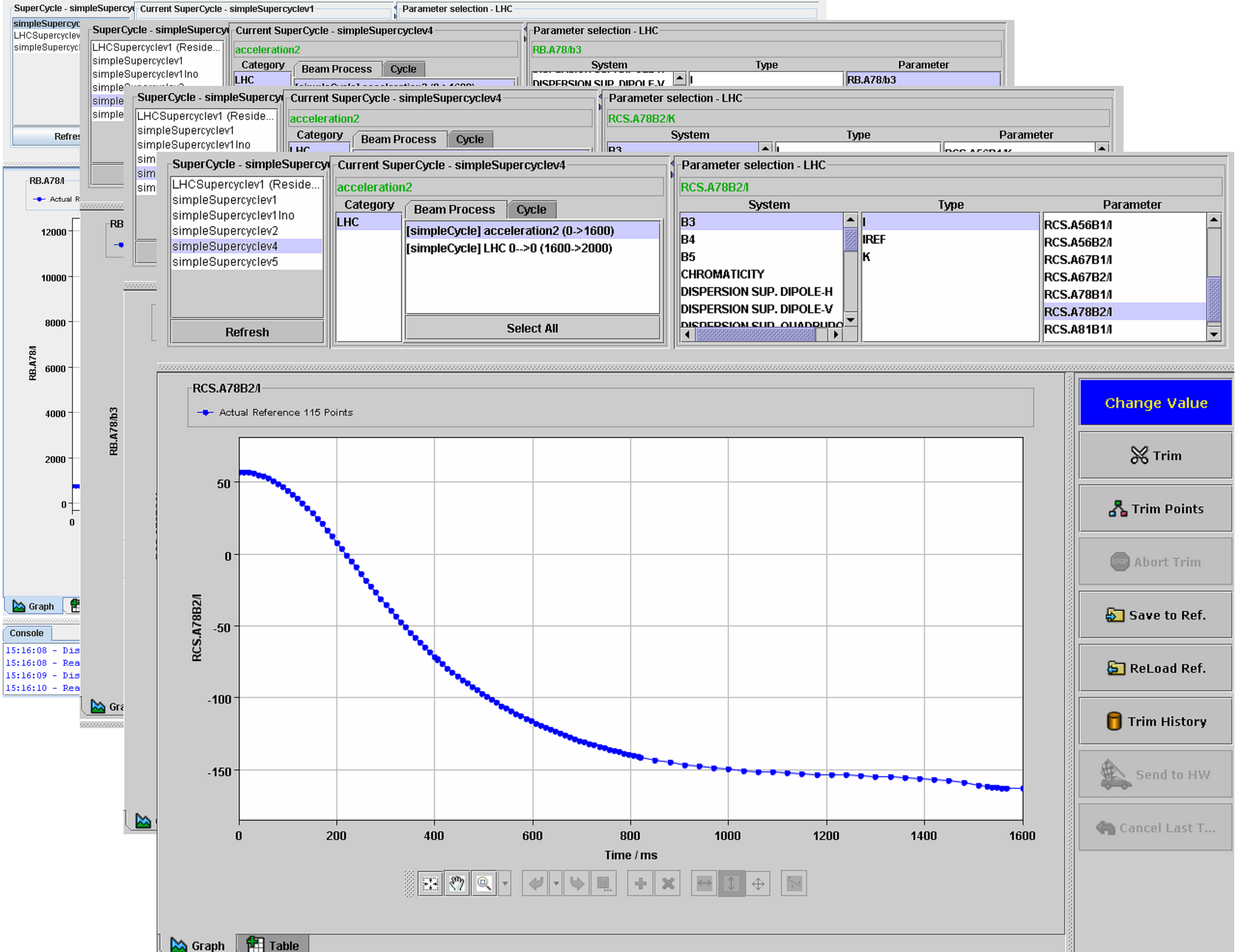

Parameter explorer
LHC
Particle Transfers
LHCB2Injection
LHCRING
LHC_FESA
Parameter selection - LHCRING
System
DISPERSION SUP. DIPOLE-V
DISPERSION SUP. QUADRUPOLE
LHCINJKICKERS
MATCHING QUADRUPOLE
MATCHING SECTION DIPOLE
MOMENTUM
OCTUPOLE
ORBIT-H
Type
I
IREF
K
MOMENTUM
b3
Parameter
RB.A12/K
RB.A23/K
RB.A34/K
RB.A45/K
RB.A56/K
RB.A67/K
RB.A78/K
Show Field(s)
Dependent parameters
RB.A78/K
RB.A78/I
RPTE.UA83.RB.A78/IREF
RB.A78/b3
RCS.A78B2/K
RCS.A78B2/I
RPMBB.UA83.RCS.A78B2/IREF

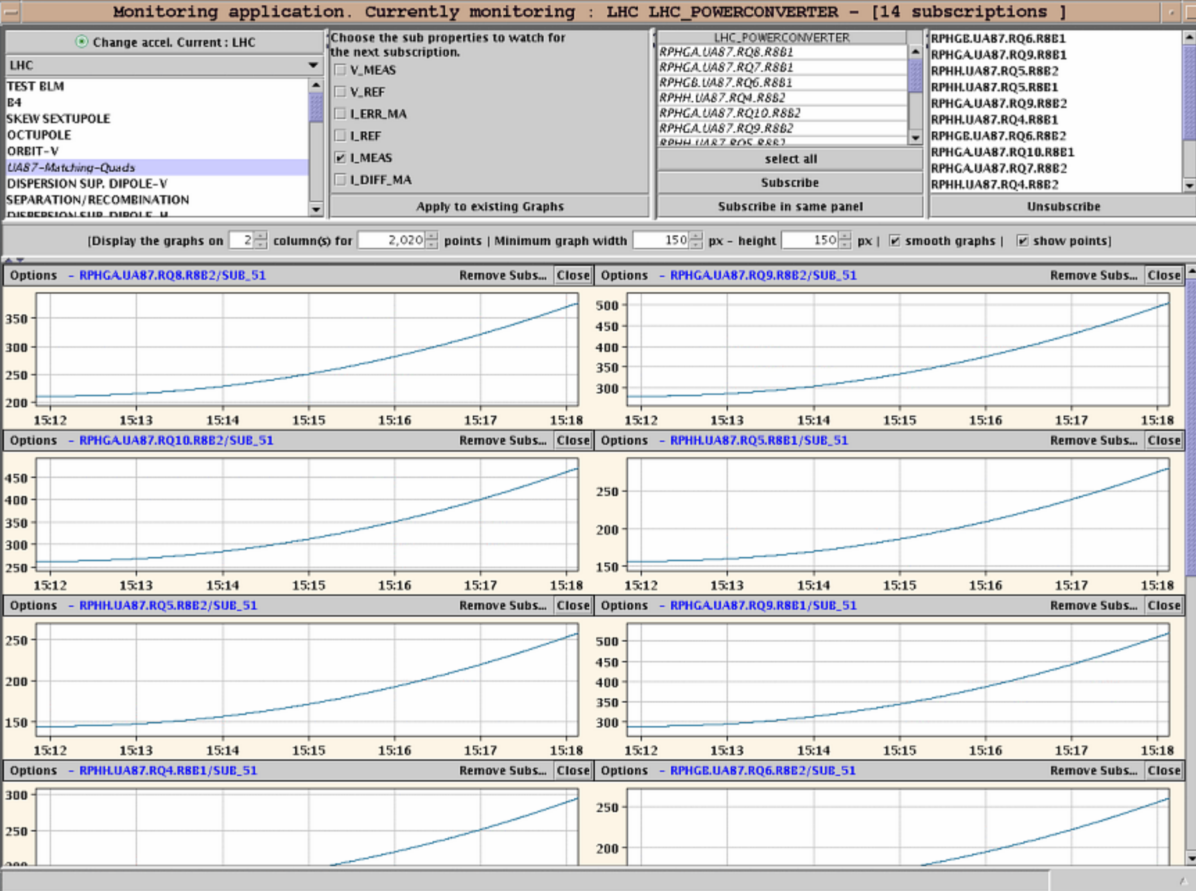

PARAMETER SPACE
RMS
b3(t)
Operator
Feedback
Q' split
Q'H B2
Q'H B2
b3 dipole geometric A78B2
b3 dipole beam screen A78B2
b3 dipole eddy A78B2
b3 dipole persistent current A78B2
KN SF1 A78B2
KN SD1 A78B2
b3 dipole total A78B2
RCS.A78B2/I
RSF1.A78B2/I
RSD1.A78B2/I

Generation


Generate Transfer Functions
do/ Run Fidel - TF
Generate Harmonics
entry/ Run Fidel - Harmonics


Load Optics
Construct Beam Process Type
do/ Construct Optics Table
do/ Insert momentum frame
Generate momentum function
Construct Optics Parameters functions
Construct Strength functions
Generate knobs
Construct Dipole DC Harmonic functions
Generate Corrector Cicuit Stength functions
Generate Current Functions


SuperCycle - simpleSupercy
LHCSupercycle1 (Reside...
simpleSupercycle1
simpleSupercycle1lno
simpleSupercycle2
simpleSupercycle4
simpleSupercycle5
Refresh
Current SuperCycle - simpleSupercycle4
acceleration2
Category
LHC
Beam Process
Cycle
[simpleCycle] acceleration2 (0->1600)
[simpleCycle] LHC 0-->0 (1600->2000)
Select All
Parameter selection - LHC
RCS.A78B2/I
System
B3
B4
B5
CHROMATICITY
DISPERSION SUP. DIPOLE-H
DISPERSION SUP. DIPOLE-V
Type
I
IREF
K
Parameter
RCS.A56B1/I
RCS.A56B2/I
RCS.A67B1/I
RCS.A67B2/I
RCS.A78B1/I
RCS.A78B2/I
RCS.A81B1/I
RCS.A78B2/I
Actual Reference 115 Points
RCS.A78B2/I
Time / ms
Change Value
Trim
Trim Points
Abort Trim
Save to Ref.
ReLoad Ref.
Trim History
Send to HW
Cancel Last T...
Graph
Table
Console
15:16:08 - Dis
15:16:08 - Rea
15:16:09 - Dis
15:16:10 - Rea



Rampin'

Squeezin'

Commissioning ramp – zeroth order

- Design optics
- Fidel Transfer functions

- MB Fidel DC harmonics
- MB spool piece correction

- MQ Fidel DC harmonics
- MQ correction

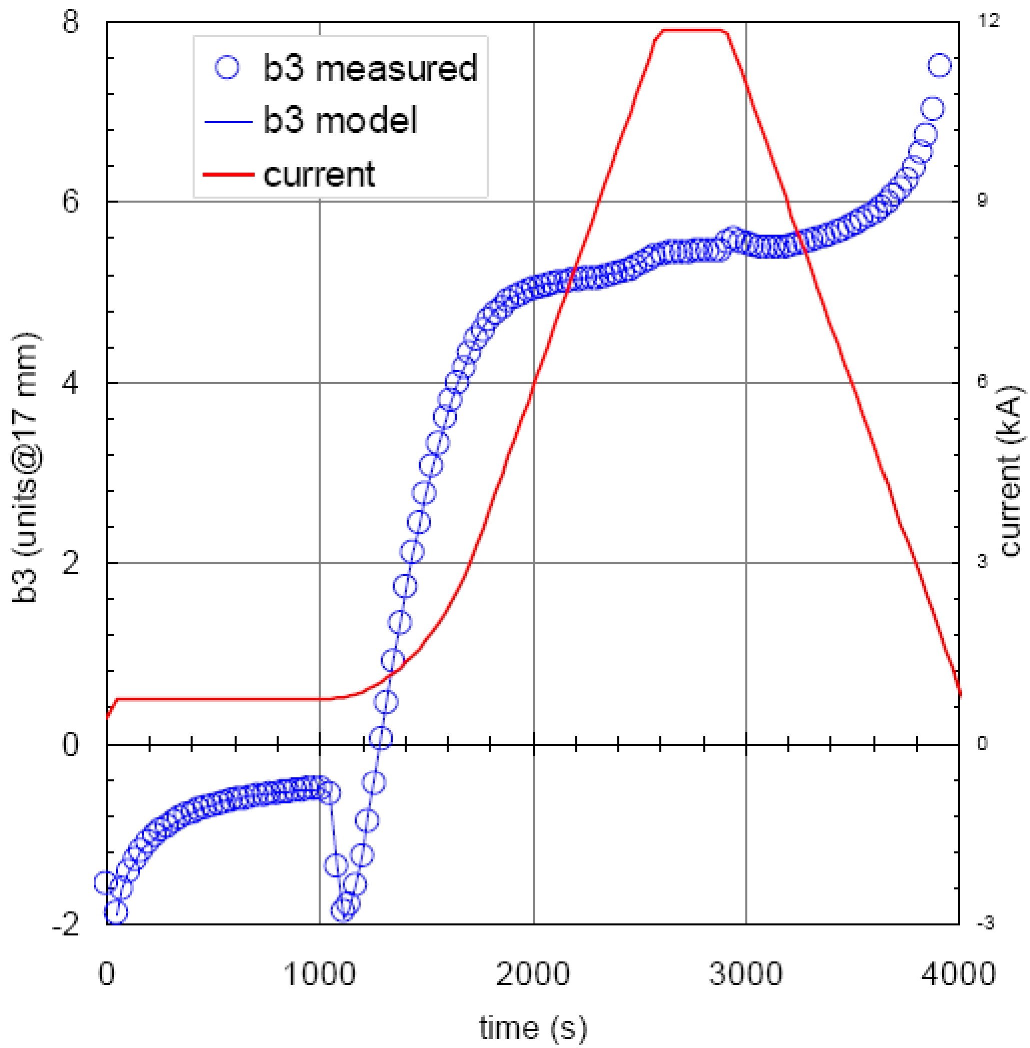
- MQM, MQMC, MQML, MQTH, MQY, MQT, MQTL - geometric and MDC
- Hum…

FIDEL AND MAD

- Also need to deal with hysteresis

Decay and Snapback

Integral Sextupole



Bottura & Sammut – Cham XIV

Decay

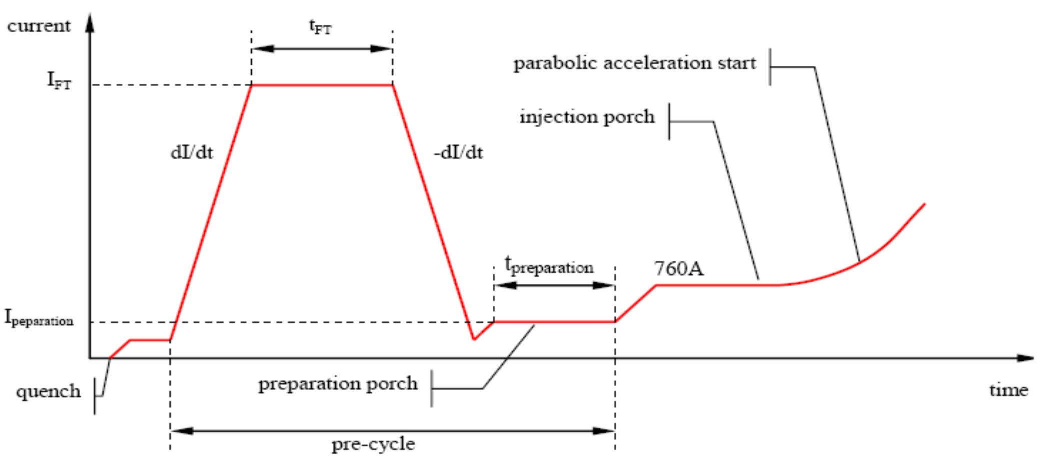
$$\Delta\left(t, t_{inj}, \tau, a^{\Delta}\right) = d\left(1 - e^{\frac{t-t_{inj}}{\tau}}\right) + \left(1-d\right)\left(1 - e^{\frac{t-t_{inj}}{9\tau}}\right)$$

$$c_n^{decay} = \delta_m \frac{\Delta\left(t, t_{inj}, \tau_m, d_m\right)}{\Delta\left(t_{inj}^{std}, t_{inj}, \tau_m, d_m\right)}$$

^{std} – normalization parameters

E, T_0, T_1, τ_T, P_0, P_1, τ_P – fitting parameters

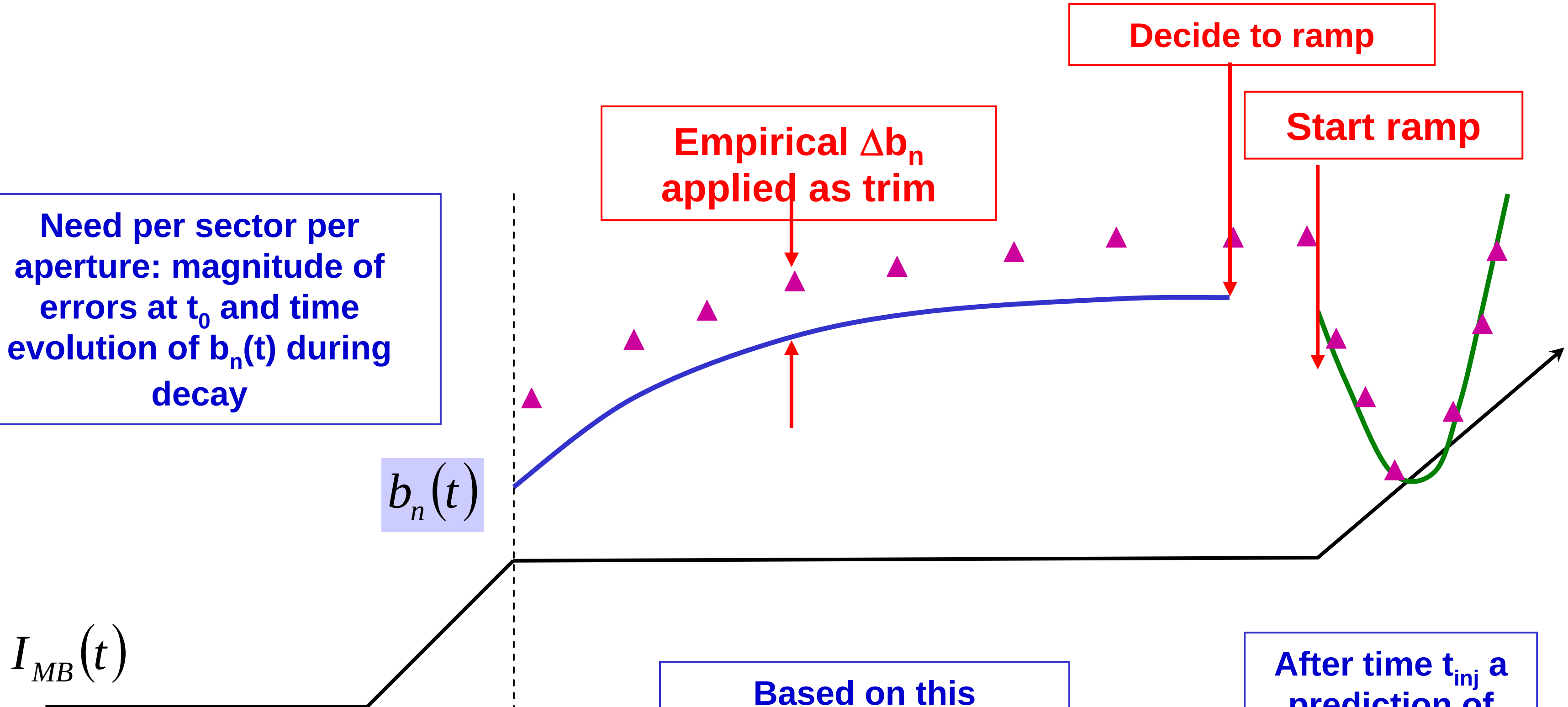
$$\delta = \left(E \frac{I_{FT}}{I_{FT}^{std}}\right)\left(\frac{T_0 - T_1 e^{\frac{t_{FT}}{\tau_T}}}{T_0 - T_1 e^{\frac{t_{FT}^{std}}{\tau_T}}}\right)\left(\frac{P_0 + P_1 e^{\frac{t_{preparation}}{\tau_P}}}{P_0 + P_1 e^{\frac{t_{preparation}^{std}}{\tau_P}}}\right)$$



MOP THIS UP IN LSA

Dynamic effects - correction

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



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

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

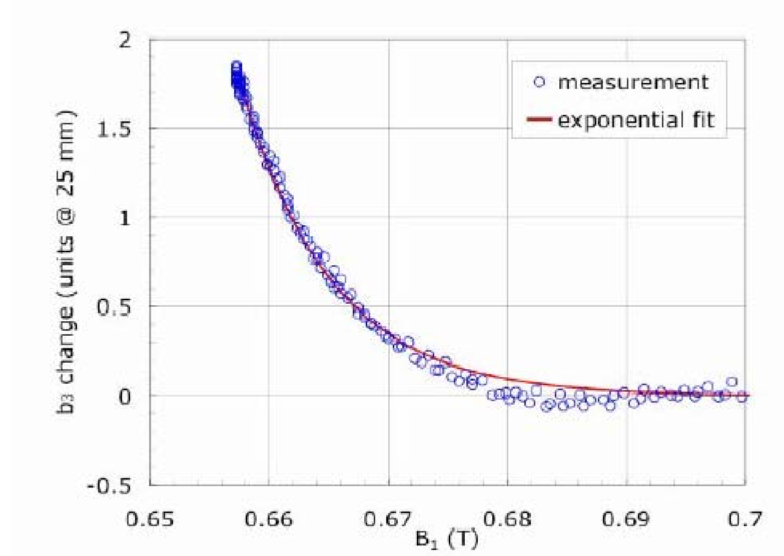
Plus coupling current compensation etc.

Snapback – Q'

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

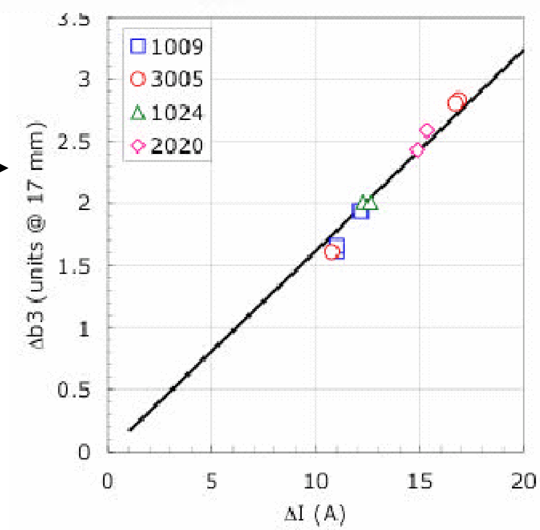
- **Fit snapback:**

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



- **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

e.g. Chromaticity

→ talk: L. Bottura

Extract sextupole change in dipoles Δb_3

slow Q' measurements and b_3 corrections during injection

↓

Infer persistent current change ΔI

since Δb_3 and ΔI are correlated

Just before ramping…

↓

Extract total b_3 correction

↓

Invoke fit for snapback prediction

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

↓

Convert to currents for b_3 spool pieces

↓

Incorporate into ramp functions & download

Timing event

↓

Functions invoked at ramp start

RT corrections still possible

Power Converters

QK's FGCs

- The control system for the LHC power converters has dedicated controller embedded in every converter
  - function generation (current versus time)
  - current regulation
  - state monitoring and control (on, off, reset etc.)
- The same function generator module is also used in the RF systems
  - voltage & phase, frequency, radial position, power coupler position etc.

Power Converters

- **Asynchronous PELPs**
  - **Setup, tests**
- **Synchronous TRIMs   (CTRIM of LTRIM)**
  - **Discrete trims e.g. orbit corrections**
- **Time dependent functions [ramp, squeeze etc.]**
  - **Times are in seconds relative to the start of the table and the granularity is 100us. The first element of the time vector must always be zero and the times must always increase by a minimum of 2ms.**
  - **When arming the table, the first reference value must be within 0.01 A of the actual reference value for the table to be accepted.**

    The level of the reference and the rate of change of every segment will be checked against the appropriate I, V, dI/dt and dV/dt limits.

    Linear interpolation of supplied points
- **Real-time channel**
  - **Corrections up to 50 Hz**
  - **In parallel with time dependent functions**

Triggered by timing or explicit command to FGC

NB: I, ΔI, or I(t) ONLY

Ramp implementation: functions & timing

- Ramp is driven by current, voltage and frequency as functions of time, pre-loaded to the power converters and RF
  - As an array of points (time, reference [absolute])
  - 100 μs granularity
  - Arbitrary time spacing
  - Linear interpolation of supplied points
  - Maximum 5000 point
- for all powering circuits - 1700 power converters
  - mains, quads, triplets, insertions, spool pieces, orbit correctors...

Functions & timing (contd.)

- **Execution of functions is triggered by a "start ramp" timing event**
  - **the operator decides when to ramp and requests the timing system to send the event**

- **The ramp stops naturally when the functions come to an end**
  - **not possible to stop while the functions are executing**
    - a stop "during the ramp" means generating functions which stop at the desired time

RF

- Control acceleration through snapback
  - single bunch pilot, accelerate
  - dump at progressively higher energies
- Measure:
  - capture losses (flash loss of out-of-bucket beam at start of ramp)
  - continuous measurements of frequency response of loops during ramp
  - bunch length (emittance growth) - injection mismatch, RF noise
  - beam losses
- Feed-forward of measured frequency offset
  - for eventual switch to synchro loop operation
- In preparation for physics beams:
  - Commissioning of programmed longitudinal emittance blow-up via RF noise

RF

- **Normally ramp with synchro loop (both rings locked to the same reference) to avoid a big re-phasing before physics, and to ensure correct crossing point for maximum separation for long-range beam-beam.**

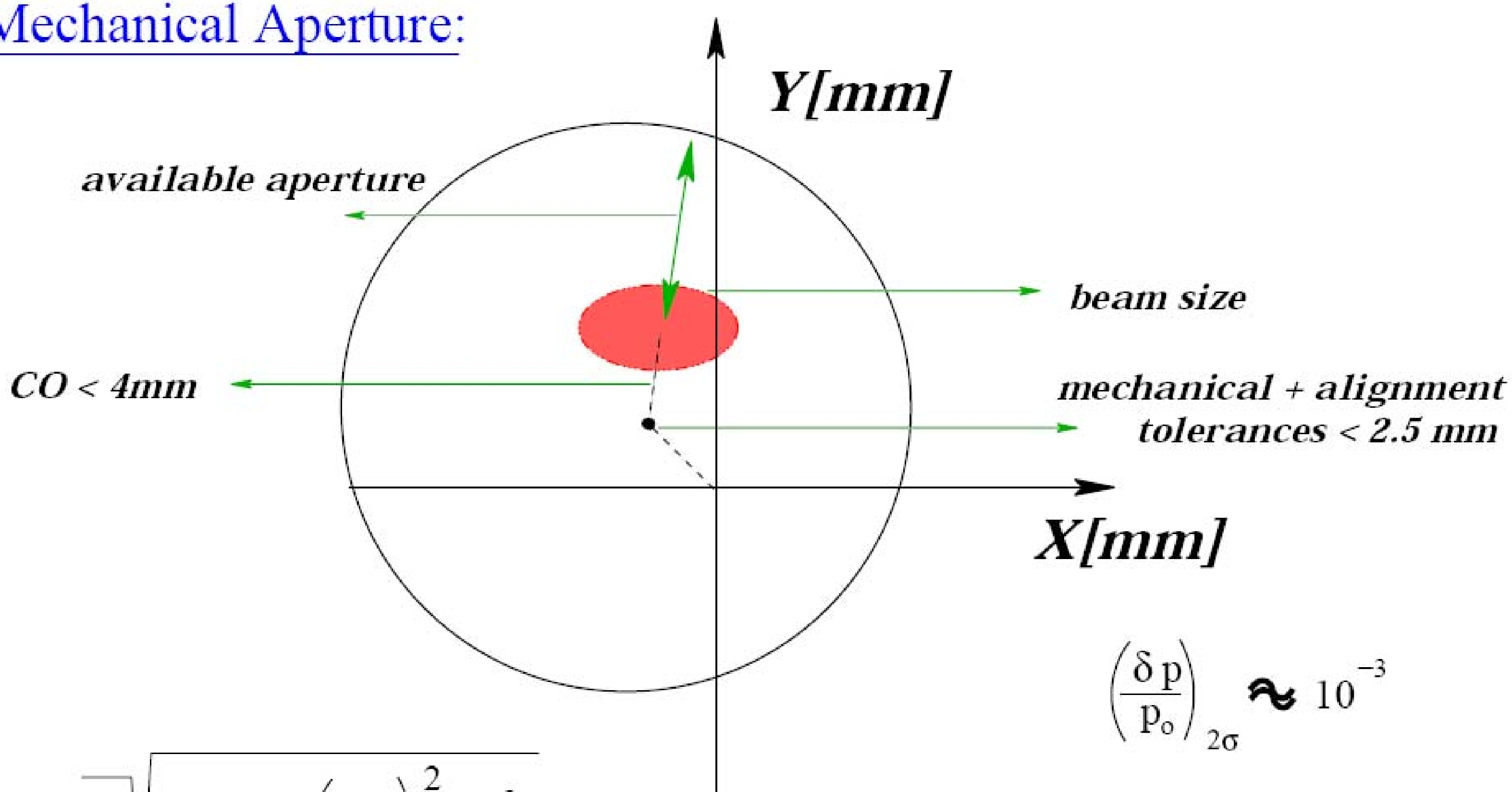
  However, this requires an accurate frequency function derived from the true machine energy. So during commissioning we ramp with radial loop (i.e. fixed radial position, variable frequency) and we can feed forward the measured frequency corrections into the function.
- **Download frequency function versus time**
- **Radial loop on (for commissioning only). In operation we remain on synchro-loop. Needs to be done after last injection and before start ramp**
- **At injection we use high synchro loop gain for accurate positioning of incoming beam in bucket. At top energy we use high phase loop gain to avoid emittance blowup.**
- **Vary the gain of the phase loop amplifier during the ramp**
- **Vary the gain and time constant of the synchronization loop amplifier during the ramp**
- **400 MHz: 2 voltage functions per cavity through the ramp**
- **Transverse feedback – not in the first instance**

Beam - Tolerances – 450 GeV

	Commissioning	First Year	Nominal
Q	$\Delta Q \approx \pm 0.03$	$\Delta Q \approx \pm 0.01$	$\pm 3 \times 10^{-3}$
Q’	> -15	$\Delta Q' \approx \pm 5$	$Q' \approx 2 \;\; \Delta Q' \approx \pm 1$
Orbit	4 mm	4 mm	4 mm.
Momentum	$\pm 2 \times 10^{-4}$	$\pm 2 \times 10^{-4}$	$\pm 10^{-4}$
Coupling	|c-| < 0.1	|c-| < 0.03	|c-| < 0.003
Beta beating	≈ 20% [static]	≈ 20%	20%

	Commissioning	First Year	Nominal
b1	± 2	< ± 1	≪ ± 1
b2 MB	± 0.2	± 0.03	± 0.01
b2 MQ	± 4	± 0.75	± 0.25
b3	± 0.5	± 0.15	± 0.02

Mechanical Aperture:



$$\left(\frac{\delta p}{p_o}\right)_{2\sigma} \approx 10^{-3}$$

$$\sigma = \sqrt{\beta \cdot \varepsilon + \left(\frac{\delta p}{p_o}\right)^2 \cdot D^2}$$

$\varepsilon = \varepsilon_n / \gamma$; $\varepsilon_n = 3.75\ \mu m$ (3.5 μm in SPS)

Updated Table

	Energy [GeV]	Bunches	Bunch Intensity	Total Intensity	τ min [h]	Max orbit (stat)[mm]	Max orbit (dyn) [mm]	Max δβ/β (stat) [%]	Max δβ/β (dyn) [%]	Aperture [σ]	Collimators	TCDQ	BLMs
pilot	450	1	5 e9	5 e9	?	?	?	?	?	?	All out	Out	Passive
	7000												
super pilot	450	1	3 e10	3 e10	?	?	?	?	?	?			
	7000												
intermediate	450	12	3 e10	3.6 e11	?	?	?	?	?	?			
	7000												
43x43 initial	450	43	1 e10	4.3 e11	?	?	?	?	?	?			
	7000												
43x43	450	43	3 e10	1.2 e12	?	?	?	?	?	?			
	7000												

Collimators

	Energy [GeV]	Bunches	Bunch Intensity	Total Intensity	Collimators	TCDQ	TDI	BLMs
pilot	450	1	5 e9	5 e9	All out	Out	Out	Passive
	7000	1	5 e9	5 e9				
super pilot	450	1	3 e10	3 e10	All out	Out	Out	
	7000	1	3 e10	3 e10			-	
intermediate	450	12	3 e10	3.6 e11	n_1 = 6 n_2=out? n_a = out? n_3 = 30	n_{tcdq} = 10	Out	
	7000	12	3 e10	3.6 e11			-	
43x43 initial	450	43	1 e10	4.3 e11	as above	as above	Out	
	7000						-	
43x43	450	43	3 e10	1.2 e12	n_1 = 5.7 n_2= 6.7 n_a = 10.0 n_3 = 30	n_{tcdq} = 9	N_{tdi} = 6.8	
	7000						-	

Measurements

- **Orbit**
  - **Synched Acquisition & feedforward**
  - **GOFB ASAP**
- **PLL: Continuous Tune, Chromaticity & Coupling**
  - **High priority - feedforward**
- **Tune feedback**
- **Coupling feedback**

Question: Do we go all out for tune and coupling feedbacks?

If so, then this is the time to commission them

Coupling control is critical for orbit & tune feedbacks

Spending some time here to commission these systems early on may significantly reduce the time required for ramp development

Measurements

- **Tracking**
- **Transfer Functions**
- **Chromaticity**
  - **RF modulation**
    - Synch with orbit -> dispersion
  - **Ramp – different f_{rf}**
- **Beta beating**
- **Field errors – optics – intermediate energy?**

- **BLMs to beam interlock controller etc.**
- **Continuous emittance monitoring: synchrotron light**

Feedback using the PLL tune system

- **Tune feedback requirements**
  - **Stable PLL tune measurement system**
  - **Knowledge of correction quad transfer functions**
    - already known from initial tune corrections
  - **Implementation of feedback controller**
- **Coupling feedback requirements**
  - **Stable PLL tune measurement system**
  - **Knowledge of skew quad transfer functions**
  - **Implementation of feedback controller**
- **Chromaticity feedback requirements**
  - **Stable PLL tune measurement system**
  - **RF frequency modulation**

All of these will require dedicated beam time for testing the control loop response and the final closing of the loop.

Rhodri Jones

Operations

Strategy – prepare ramp

- **Prepare ramp**
  - Snapback prediction – incorporation into functions
  - 450 GeV trim incorporation [strategy?]

  - Load power converters
  - Load RF
  - Load collimators
  - Tune feedback [?]
  - Energy compensation with horizontal orbit correctors [?]
  - BLM thresholds up the ramp - check
  - Experiments' dipole compensation – not initially
  - Separation bumps – not single beam
  - Crossing angle – not initially

  - Arm data acquisition - timing

Initial Commissioning – Nominal Cycle

- **Pilots to start**
- **Relaxed tolerances on key beam parameters**

- **Cycle to cycle variations**
  - **pre-injection plateau length, length of time at injection**
  - **Wait 15-20 minutes on injection plateau before injecting**
  - **Limited further decay**
- **Indeterminate, and possibly long, time before ramping**
- **Nominal snapback**

- **Ramp to reduced energy…**
- **Recycle after every attempt**

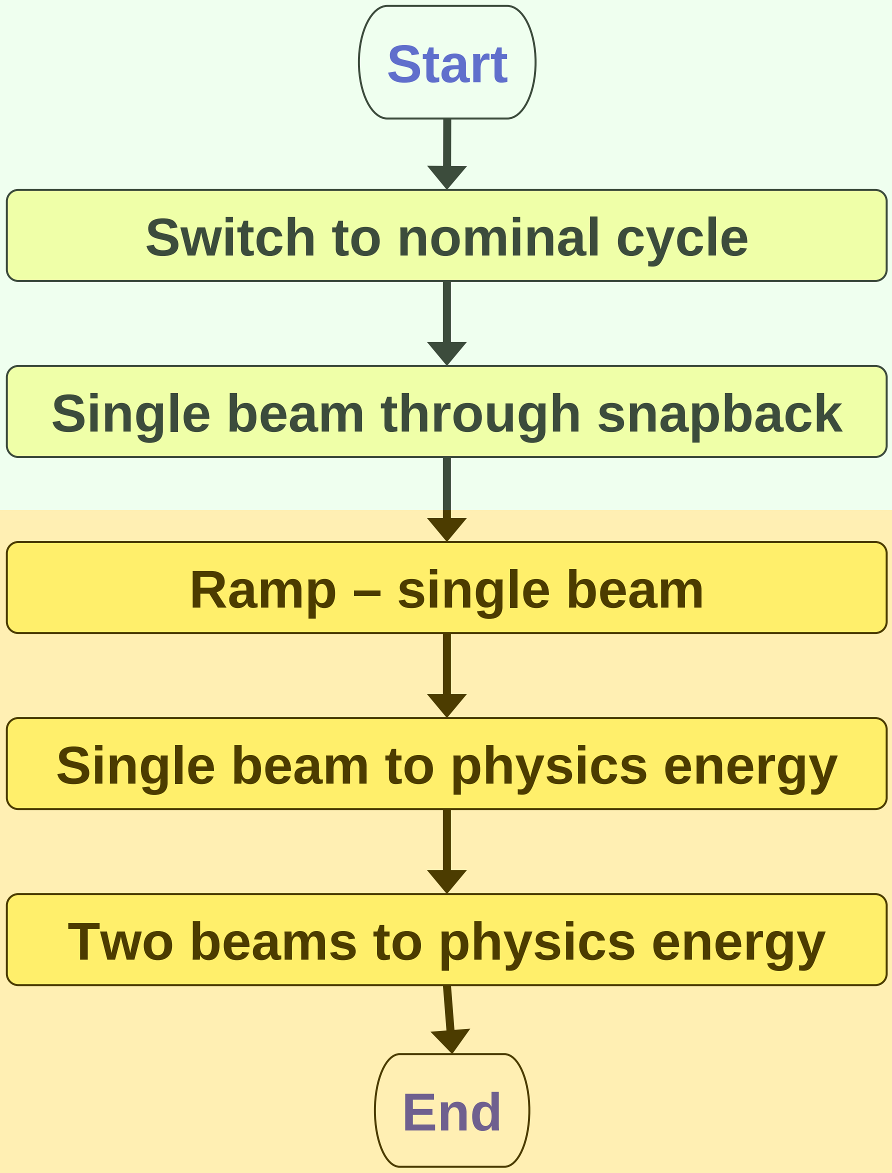
Stopping with beam in the ramp

Used for commissioning of beam dump, beam loss monitors, beam measurements, optics checks, physics...

- **Must be programmed before starting the ramp**
  - **with appropriate round-off behaviour of the functions**
  - **Might need to handle decay after the stop**

- **Restart with beam is possible in theory, but problematic**
  - **requires a new set of functions to be loaded**
  - **including corrections for handling the associated snapback**

Machine Protection

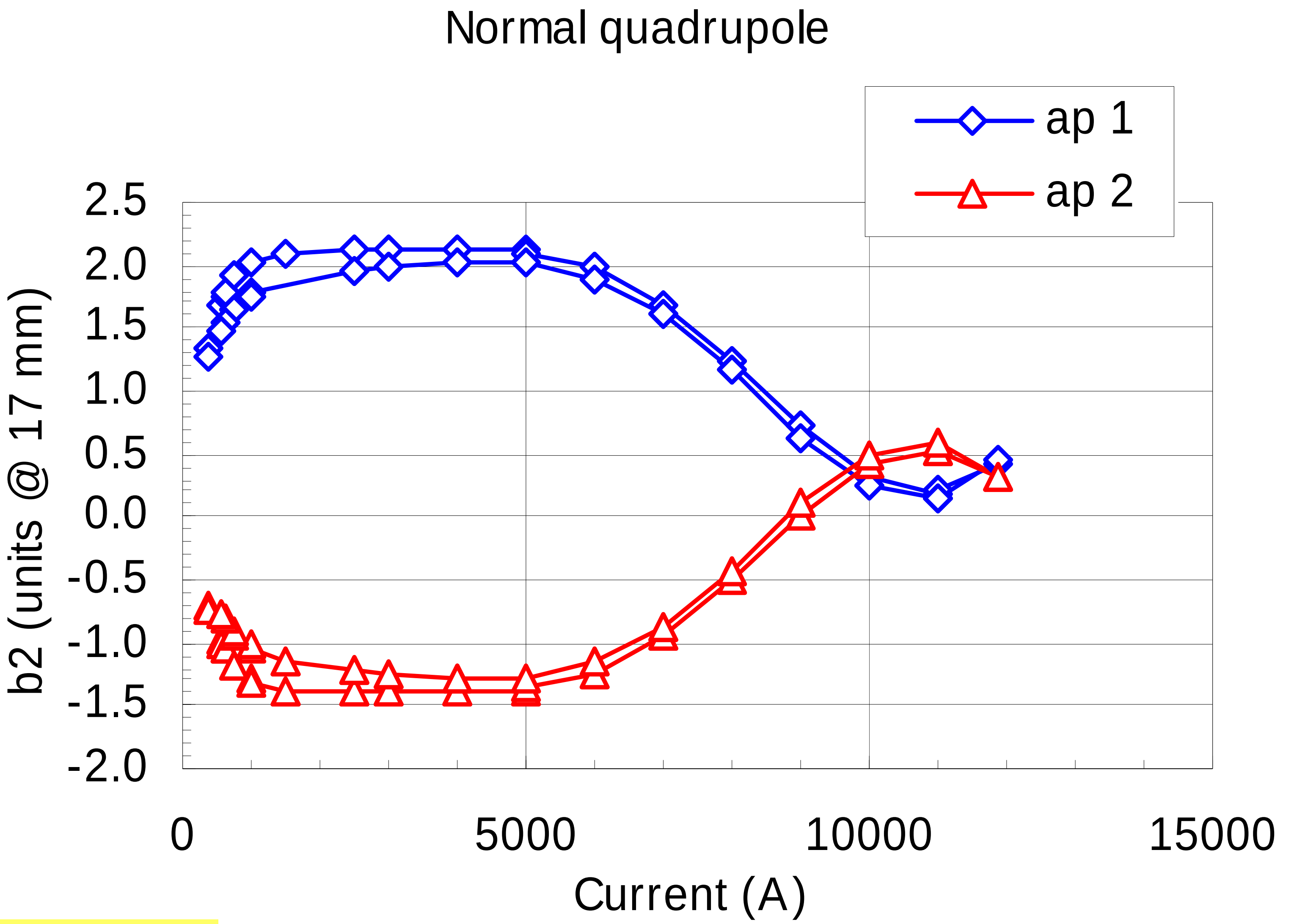


Low intensity, single bunch, low energy... same as at 450 GeV

- BLMs: acquisition – no dump, check losses against thresholds
- collimators & TDCQ coarse settings

Critical machine protection systems must **be in place**

- minimum subset of BLMs connected to beam interlock system
- collimators interlocked in place
- local orbit stabilisation around beam cleaning insertions and dump region
- further commissioning of beam dump & BLMs



Courtesy of N. Sammut