Specification of the LHC BPM System

LHC-BPM-ES-0004

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- scope
- methodology and beam observables
- beam and machine parameters
- functional requirements

Scope and Activity

specification for the beam position measurement system (BPM) distributed along the 2 LHC rings

- ***identify measurement scenarios:***

  range of bunch parameters and beam patterns

- ***glossary: define what is meant by 'precision'***

  resolution; offset; scale error; non-linearity

  [JJ Gras and JP Koutchouk; SL-Note-2001-039]

Methodology

- select a beam observable

- list all beam parameters which can be derived from the observable and rate their usefulness and potential

  → describe measurement procedures

- select the beam parameters which are most interesting for the machine operation and performance

- derive a BPM specification from the above list of measurement procedures

Beam Observables

- ***single pass trajectory*** TR

  what needs to be measured with a single pas trajectory

  what are potential extended applications

- ***beam oscillations sampled at one or several locations*** TR

- ***closed orbit measurements*** CO

Trajectory and Oscillation Cases

Parameters	Use	Symbol
trajectory	visual inspection	TR1
single pass trajectory	beam threading	TR2
	close trajectory on itself	TR3
injection error	subtract trajectory from CO	TR4
momentum error	average 1. turn trajectory	TR5
focusing errors	cell to cell trajectory	TR7
local chromaticity	cell to cell trajectory $+\delta_p$	TR8
transverse spectrum	driving terms	TR11
fast tune measurement	FFT	TR12

Closed Beam Orbit Cases

Parameters	Use	Symbol
closed orbit	visual inspection	CO1
closed orbit	orbit correction	CO2
local orbit at critical points	orbit stabilisation	CO3
	collision steering	CO4
closed orbit at injection	injection correction	CO7
momentum error	average closed orbit	CO8
dispersion	closed orbit + δ_p	CO9
optics model	measure β and μ	CO11
measure multipole error	feed down	CO13/CO14

Beam Parameters I

- ***pilot bunch:***

  $N_{bunch} = 5.0 \cdot 10^{9}$ → save operation with minimum setup

- ***nominal bunch:***

  $N_{bunch} = 1.1 \cdot 10^{11}$ → nominal operation

- ***ultimate bunch:***

  $N_{bunch} = 1.7 \cdot 10^{11}$ → only for well understood machine

- ***Pb ion bunch:***

  → bunch charge equivalent to proton pilot bunch

Beam Parameters II

- ***pilot bunch:***

  $n_{bunch} = 1$ → save operation with minimum setup

- ***nominal proton operation:***

  $n_{bunch} = 2808$ → 25nsec bunch spacing

- ***limited filling schemes:***

  electron cloud effects → 50nsec / 75nsec bunch spacing

- ***Pb ion bunch:***

  → 125nsec / 100nsec bunch spacing

Operation Scenarios

- ***circulating beam is established with the pilot bunch***
  - → threading; 1. and 2. turn closure
  - → momentum adjustment
  - → closed orbit adjustments
  - → collimators are positioned
- ***increase beam intensity to facilitate measurements:***

  intermediate beam parameters → final orbit correction

  → final collimator settings
- ***operation with nominal beam parameters***

  → safe injection into a well adjusted machine

Beam Parameters III

intermediate beam parameters:

- intensity should be upgradable to nominal beam parameters
- bunch structure should not prevent long-range beam-beam
- should be quick and easy to be produced by the injectors
- should provide precision close to the one for nominal operation

Beam Parameters IV

intermediate beam parameters:

→ assuming coarse setting of the collimators and decent

we can increase the total intensity to approximately

→ (distributed losses only, increased heat reserve in He)

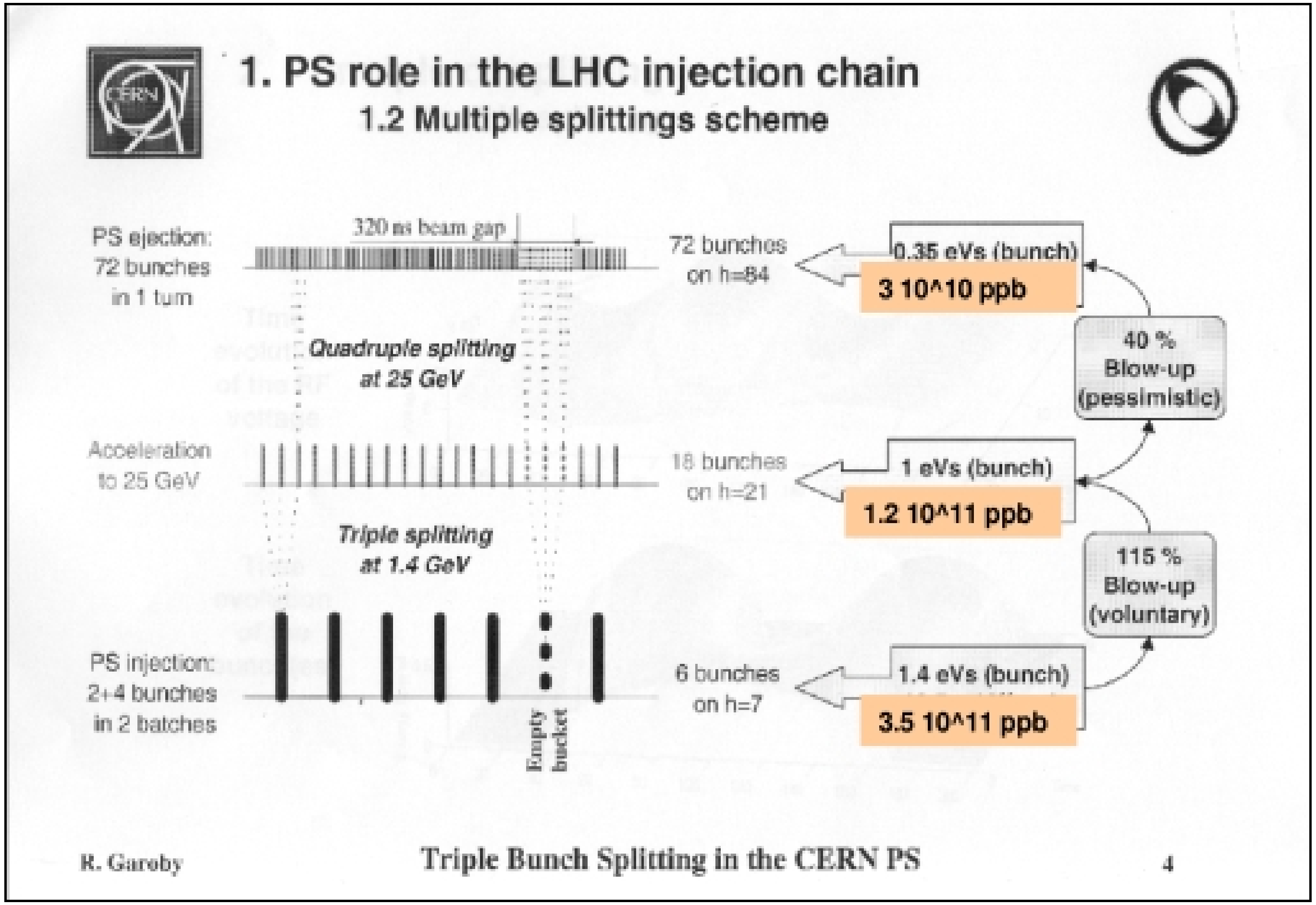
→ $N = 2.5 \cdot 10^{12}$ protons

→ 1% of nominal intensity

→ 30% of nominal PS batch intensity (injected bunch train)

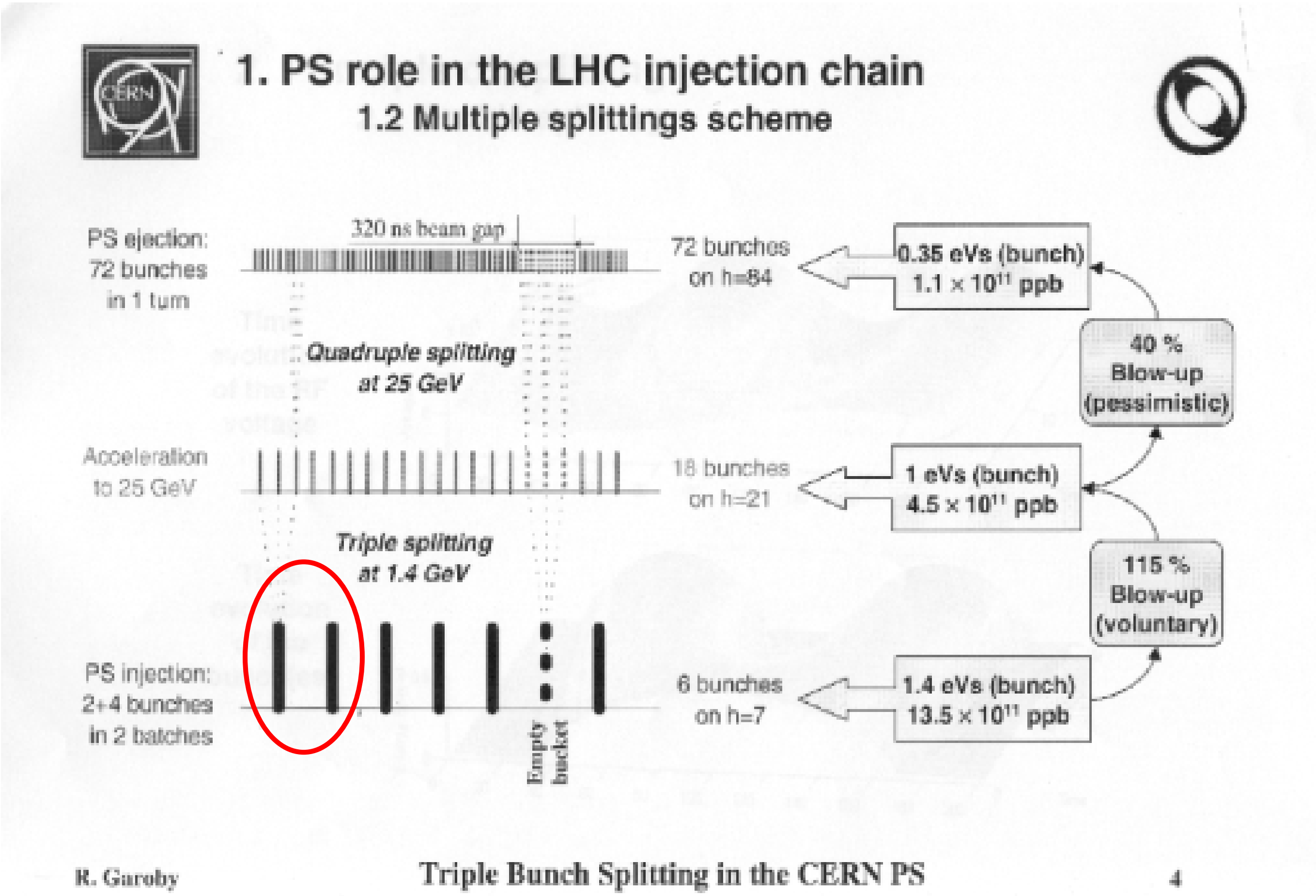
Intermediate Beam Parameters

- ***72 intermediate bunches:*** N = $3.0 \cdot 10^{10}$ protons / per bunch



Intermediate Beam Parameters

24 nominal bunches: $N = 1.1 \cdot 10^{11}$ protons / per bunch



Oliver Bruning/SL-AP

Beam Parameters V

summary of beam types:

Beam	# Bunches	#Charges/ Bunch	Bunch Spacing
pilot	1	$5 \cdot 10^{9}$	88925ns
intermediate 25	72	$5 \cdot 10^{9} \leftrightarrow 1.1 \cdot 10^{11}$	25ns
intermediate 75	24	$5 \cdot 10^{9} \leftrightarrow 1.1 \cdot 10^{11}$	75ns
nominal 25	2808	$1.1 \cdot 10^{11}$	25ns
nominal 75	936	$1.1 \cdot 10^{11}$	75ns
ultimate	2808	$1.7 \cdot 10^{11}$	25ns
TOTEM	36	$1.1 \cdot 10^{11}$	2470ns
Pb Ion	608	$5 \cdot 10^{9}$	125ns/100ns

Specification Criteria I

mechanical aperture:

- $\varepsilon_n = 3.75 \cdot 10^{-6}$ m → σ = 1.2mm at injection energy
- collimator jaws at 7σ and 8.2σ

→
- β -beat < 21% (25%)
- closed orbit (horizontal and vertical) < 4mm (3mm at 7TeV)
- parasitic dispersion: $\Delta D_{x,y} < \sqrt{\frac{\beta_{x,y}}{\beta_{F,QF}}} \cdot D_{x,QF} \cdot 0.3$ (0.28)
- momentum spread: $\frac{\Delta p}{p_0} < +/-1.0 \cdot 10^{-3} \; (0.36 \cdot 10^{-3})$
- momentum deviation: $\frac{\Delta p}{p_0} < +/-2.0 \cdot 10^{-3} \; (0.5 \cdot 10^{-3})$

Specification Criteria II

collimator positions:

- operation with collimators at all operation modes:

  collimator positions: $n_1 = 7\sigma$; $n_2 = 8.2\sigma$

- arc aperture:

  $\delta = 2.5$ mm; CO = 4.0 mm ⟶ MA(MB) = 8.5 σ

- dedicated collimators for injection protection:

  collimator positions: $n_2 < n_{col,inj} < MA(MB)$

⟶ collimator positions must be controlled within 0.2 σ

Functional Specification I

distribution in the 2 machines:

- arc BPM's: each arc quadrupole is equipped with a horizontal and vertical BPM → 45^{o} sampling

→ peak CO < 4mm [J. Miles LHC Project Note 76]

→ identical misalignment for successive QF and QD [LEP]

→ measurement of β-beat in a 90^{o} lattice

[P. Castro-Garcia, CERN SL/96-70]

Functional Specification I

distribution in the 2 machines:

- triplet BPM's: each triplet quadrupole is equipped with a horizontal and vertical BPM

LHC: small phase advance but large change in β

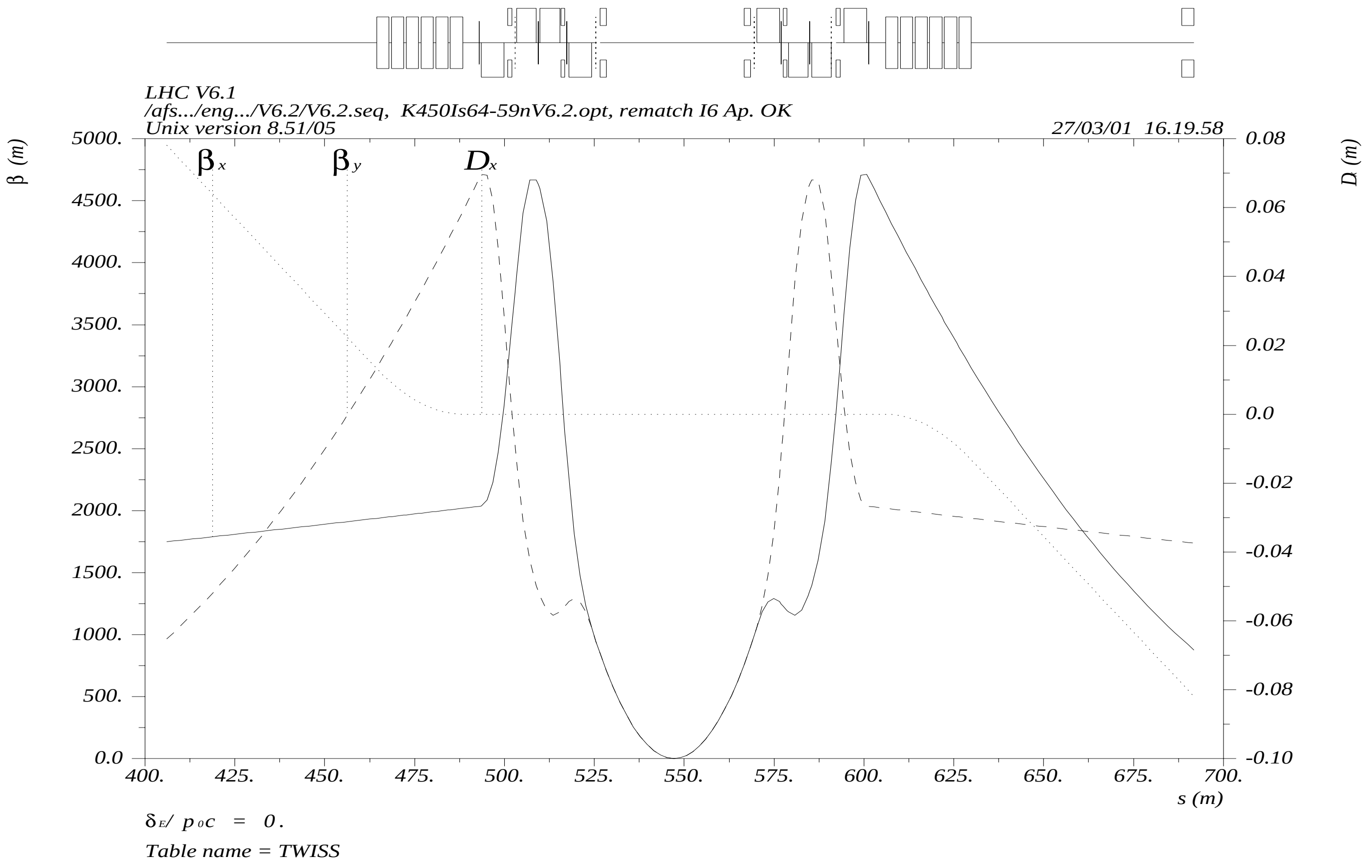
→ Q1: measurement of crossing angle [S. Fartoukh]

→ Q2: measuring the maximum orbit in one plane

→ Q3: measure the orbit maximum in the other plane

Optic Functions at the IP's

- ***the collision optics in IR5:*** $\beta^* = 0.5\,\text{meter}$



Functional Specification I

distribution in the 2 machines:

- D1/D2: two BPM's are installed in the long drift space between D1 and D2

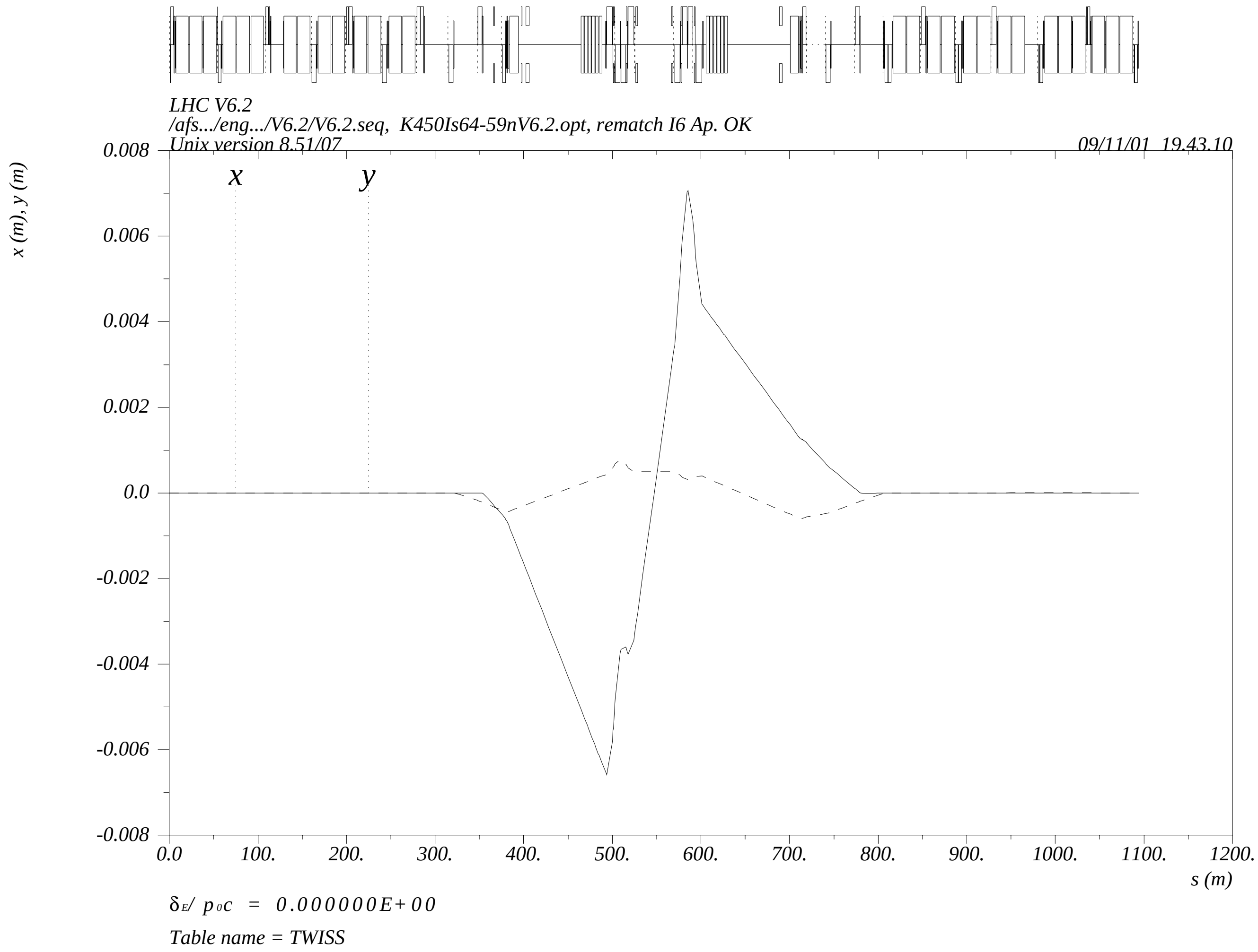
LHC: small phase advance but large change in β

→ tune accurately the crossing angle bump

→ decouple the closed orbit correction in the rings and the common sections of the two beams

IR5 Crossing Angle Bump

mixed crossing angle scheme: 30% independent + 70% common



Functional Specification I

distribution in the 2 machines:

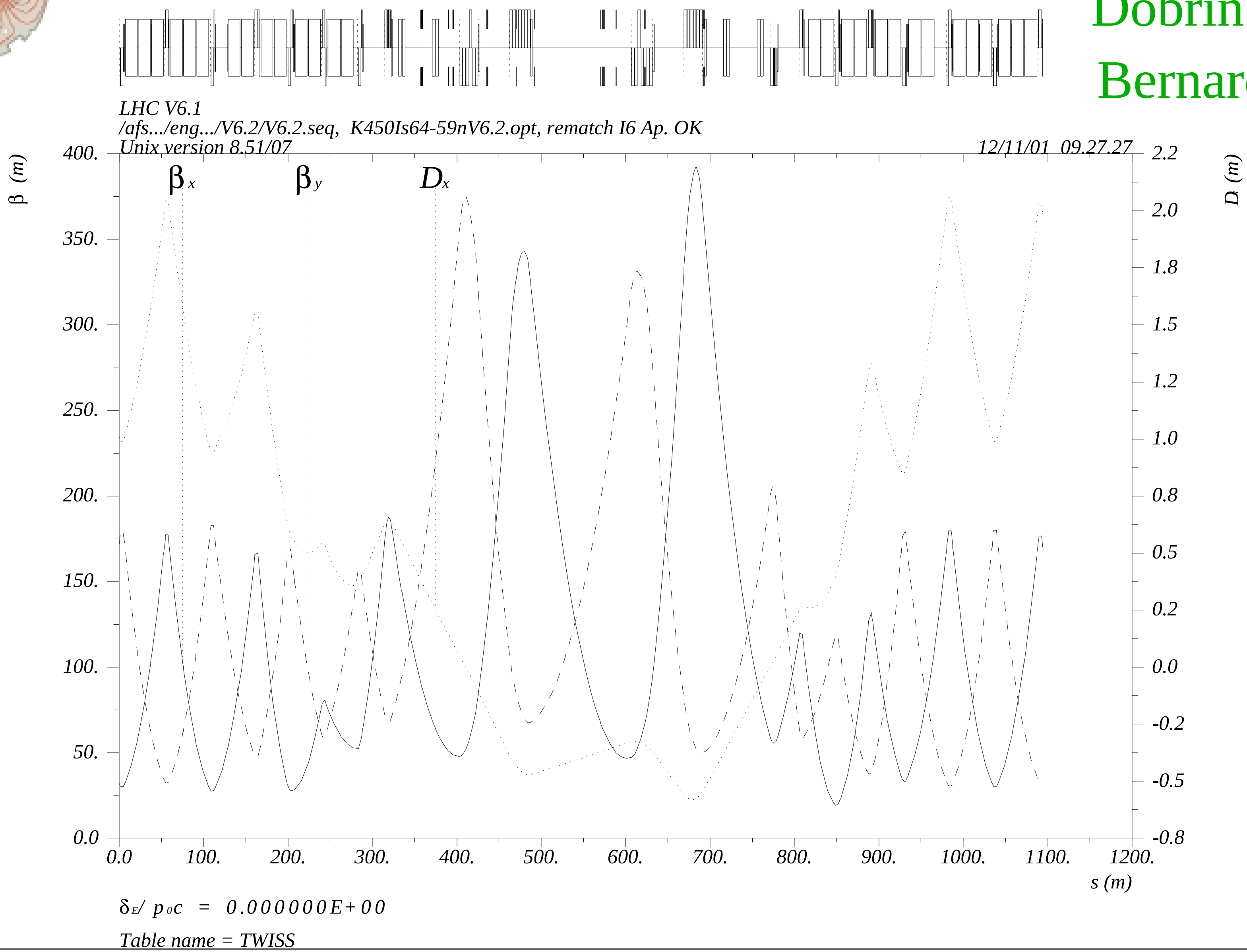
- collimator regions: BPM's are installed on each side of each warm quadrupole

→ (e.g. at the drift spaces were collimators are installed)

→ minimum configuration that allows a linear interpolation of the closed orbit, dispersion and β - functions

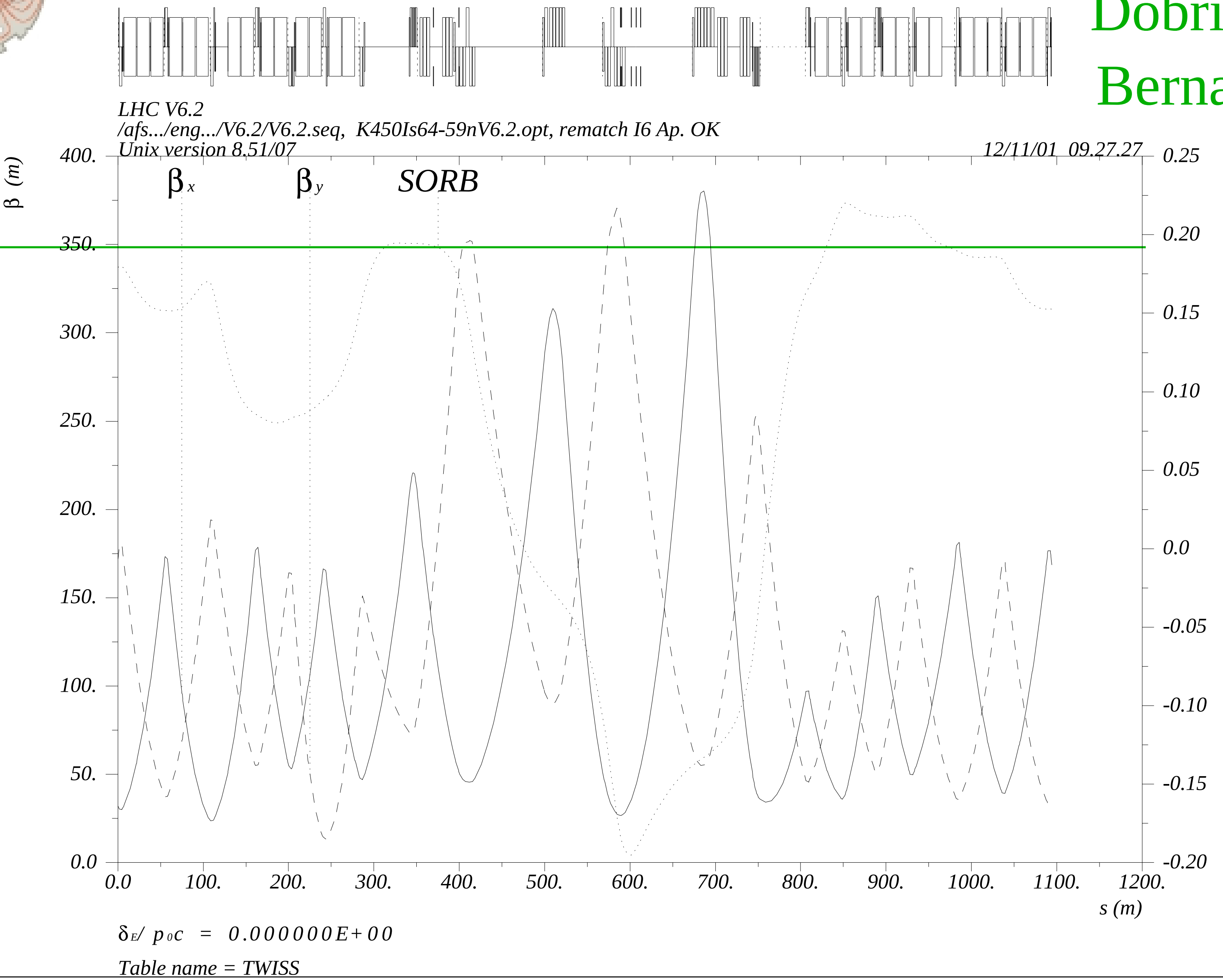
β-cleaning in IR7: Optics for Ring1

Dobrin Kaltchev
Bernard Jeanneret



Momentum-cleaning in IR3: Ring1

Dobrin Kaltchev
Bernard Jeanneret



$D_x / \sqrt{\beta_x}$

Functional Specification I

distribution in the 2 machines:

- special BPM's:

  if all BPMs do not turn out to be equally performing

  the 'best' BPMs will be installed in key positions

  → at the junctions between arc and insertions

  (BPMs with lowest non-linearity)

  → at the junctions of the two rings

  (BPMs with largest accuracy)

Functional Specification II

time resolution of the BPMs:

- bunch to bunch (40MHz):
  → possibility of measuring beam parameters over one batch
  (detuning with amplitude in 1 shot, beam-beam etc)
  → required only at a few locations of the machine: Q4, Q6, Q7
- batch to batch (140kHz):
  → injection constraints
  (injection fluctuations / drifts)
- single bunch (11.3kHz)

Functional Specification III

transverse dynamic range of the BPMs:

	closed orbit	momentum deviation	x-ing angle	beam σ	range 1	range 2
standard BPM's	+/- 4 mm	+/- 2 mm		+/-1.2 mm	+/-15 mm	+/-18 mm
triplet BPM's	+/- 4 mm	+/- 1 mm	+/- 7 mm	+/-1.5 mm	+/-23 mm	+/-27 mm

Functional Specification IV

longitudinal dynamic range of the BPMs:

- ***bunch length:***

the BPM reading must not be sensitive to the bunch length for:

$$0.2\text{ns} < t_{\text{bunch}}\ (\text{rms}) < 0.8\text{ns}$$

Functional Specification V

dynamic range of the BPMs:

- **bunch intensity:**

coarse precision for injection: $5 \cdot 10^{9} < N_{bunch} < 3 \cdot 10^{10}$

high precision: $3 \cdot 10^{10} < N_{bunch} < 1.7 \cdot 10^{11}$

Functional Specification VI

precision:

$$x_{measured} - x_{true} = \Delta + k x_{true} + \psi y_{true} \sum_{k=2}^{\infty} \sum_{j \leq k} \alpha_{kj} \, x_{true}^{k-j} \cdot y_{true}^{k} + \varepsilon$$

Δ: offset

k: scale error

ψ: roll error

α: non-linearity

ε: noise

- uncertainty -> rms error
- peak error = 2• rms error
- in calculating tolerances the maximum perturbation is retained

Functional Specification VII

Measurement	pilot	accuracy	scale	offset	non-linear	resolution
TR4	*	500µm	+	NR	+	+
TR5		250µm	+	NR	+	+
TR7	*	400µm	+	NR	+	+
TR8	*	50µm	4%	NR	+	+
TR11			NR	NR	500µm	50µm
CO2	*	500µm	+	250µm		+
CO3		20µm	NR	NR	NR	+
CO7			+	100µm	200µm	1000µm
CO14		10µm	+	NR	+	5µm

Functional Specification VII

precision:

Goal	Coarse (pilot pulse)	high (other than pilot)
scale error	not relevant	+/- 4%
roll error	not relevant	+/- 1 mrad
offset	+/-750 μm	+/-100 μm arc / 30 μm IR
no-linear	not relevant	200μ m / (500μ m R1)
resolution	200 μ m	50 μ m traject / 5μ m orbit

Functional Specification VIII

repeatability and reproducibility:

- bunch to bunch (due to transients in the BPM electronics):
  - → +/-400 μm for the coarse accuracy (-> 10% of closed orbit)
  - → +/-100 μm for the coarse accuracy (-> 0.1 σ ; pacman bunch)
- run to run:
  - → +/-100 μm for coarse collimator settings (-> 0.5 σ)
  - → +/-20 μm for precise collimator settings

Functional Specification IX

response time:

Measurement	Information block	Response	Methods
single shot	1 orbit / trajectory	1 sec	TR2,3,5,7,11 CO2,5,8
difference	2 orbits/ trajectories	2 sec	TR4,8; CO9
repeated diff	n orbits/ trajectories	n sec	TR9
monitoring	orbit	5 msec	TR7,8,11; CO2
snapshot (224)	orbit / trajectory	2 sec	CO9,13,14