CERN
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the Large Hadron Collider project

LHC Project Document No Draft?
CERN Div /Group or Supplier/Contractor Document No
EDMS Document No

Date: 2004-03-01

D R A F T

Functional Specification

MEASUREMENT OF THE BEAM CURRENT IN THE LHC RINGS

Abstract

This document presents an analysis of the expected use of the beam current knowledge for machine operation and studies. The beam parameters to be derived from the beam current measurement are identified and their required accuracy estimated. These requirements are converted into functional specifications for the beam diagnostics instruments. The whole spectrum of possible beams is considered as well as design constraints.

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Approval group members:

Current Monitoring in LHC

2 types of current monitors

- **FBCT: to monitor the current of individual bunches**

1 at the end of each TI2 and TI8 transfer line, before the TED (2)

2/ring on each side of IP4 in the drift between Q7 and Q6 (4)

2 / at the beginning of each dump line (4)

(2 others presently discussed for injection kicker timing)

- **DCCT: to integrate the circulating current**

2/ring on each side of IP4, in the midle of the dogleg D3-D4 (4)

DCCT(1)

- **Basic parameters :** sampling frequency n x 50 Hz
  sampling time ⩽ 10 s

  3 ranges proposed: 4 μA → 1 mA (250)
  1 mA → 100 mA (100)
  100 mA → 1000 mA (10)

- **Accuracy:** ± 1‰ of full scale on range 1 = ± 1 μA
  ± 1‰ of readings on ranges 2 and 3

- **Resolution (noise):** 1 μA/ s → 0.3 μA/ 10 s by sampling
  ± 2μA/ s → ± 0.6 μA/ 10 s

- **Global accuracy:**

  Range 1 (4 μA → 1 mA)**:** ± $(1^2 + 0.6^2)^{1/2}$ = ± 1.2 μA
  Range 2 (1 mA → 100 mA)**:** ± 1.2 μA → 100 μA (± 1‰)
  Range 3 (100 mA → 1000 mA)**:** ± 100 μA → 1 mA (± 1‰)

DCCT(2)

	Pilot & low ions (9 µA) r1	Nominal ions (0.6 mA) r1	Ions (6mA) r2	Intermed. (55 mA) r2	Intermed. (200 mA) r3	Nominal (550 mA) r3
Resolution	± 0.6 µA /10s ± 7 %	± 0.6 µA /10s ± 10^{-3}	± 0.6 µA /10s ± 10^{-4}	± 0.6 µA /10s ± 10^{-5}	± 0.6 µA /10s ± 3.10^{-6}	± 0.6 µA /10s ± 10^{-6}
Requested circulating	± 10 % & ± 10 %	± 1 %	± 1 %	± 1 %	± 1 %	± 1 %
lifetime	≤ 10 %	≤ 10 %	≤ 10 %	≤ 10 %	≤ 10 %	≤ 10 %
dI/dt interlocks most demanding	?	?	?	?	?	?
Accuracy	± 1.2 µA ± 13 %	± 1.2 µA ± 0.2 %	± 6 µA ± 0.1 %	± 55 µA ± 0.1 %	± 200 µA ± 0.1 %	550 µA ± 0.1 %
Requested circulating	± 10 % & ± 10 %	± 1 %	± 1 %	± 1 %	± 1 %	± 1 %
absolute calibration FBCT	± 5 %					± 1 %

DCCT(3)

Lifetime processing with a resolution of ±0.6 μA:
Pessimistic as without processing

Ion beam of 10 μA - **with τ = 10h** - $\Delta\tau / \tau \leq \pm 100\%$ /30 mn

Nominal ion beam of 0.6 mA - **with τ = 10h** - $\Delta\tau / \tau \leq \pm 10\%$ /5 mn

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Ion beam of 6 mA - **with τ = 10h** - $\Delta\tau / \tau \leq \pm 10\%$ /30 s

intermediate beam of 55 mA - **with τ = 10h** - $\Delta\tau / \tau \leq \pm 4\%$ /10 s
(1/10 of nominal)

with τ = 100h - $\Delta\tau / \tau \leq \pm 40\%$ /10 s
$\pm 10\%$ /40 s

FBCT (1)

Basic parameters : integrator rms noise : 800 µV on 1 V (1/ 1250)
global noise level : * 5 ?? / 5 sampling
calibration : 1 ‰
2 ranges proposed : 0 → 10^{10} p (16 µA)
0 → 1.7 10^{11} p (272 µA)
(1.15 10^{11} p = 184 µA)

- **Accuracy:** ± 1‰ of readings

- **Resolution (noise):** ± 2 x (F.S./ 1250 (rms)) * 5 / 5
pilot: ±8.10^{7} ± 1.6 10^{7}
nominal: ± 1.4 10^{9} ± 0.27 10^{9}

- ***Global accuracy:***
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Range 1 (0 →10^{10} p (16 µA)**):**

pilot:

1 passage: ± ((5. 10^{6})^2+ (2*8.10^{6} * 5)^2) $^{1/2}$ = ±80.10^{6} = ±8.10^{7} p (±2 %)

sampling:± ((5. 10^{6})^2+ (2*8.10^{6} * 5 / 5)^2) $^{1/2}$ = ±17.10^{6} = ±1.7 10^{7} (±0.3 %)

Range 2 (0 →1.7 10^{11} p (272 µA)**):**

Nominal:

1 passage: ± ((1.15. 10^{8})^2+ (2*1.4.10^{8} * 5)^2) $^{1/2}$ = ±14.10^{8} = ±1.4.10^{9} p (±1.2%)

sampling: ± ((1.15. 10^{8})^2+ (2*1.4.10^{8} * 5 / 5)^2) $^{1/2}$ = ± 3. 10^{8} p (±0.3%)

FBCT (2)

	Pilot		Nominal	
	one passage	averaging	one passage	averaging
RESOLUTION	**$\pm 8.10^7$ p** **± 1.6 %**	**± $1.6\ 10^7$ p** **± 0.3 %**	**± $1.4\ 10^9$ p** **± 1.2 %**	**± $0.27\ 10^9$p** **± 0.23 %**
requested injection ε (relative)	**± 20 %**		**± 1%**	
dump ε	**± 5 %**		**± 1 %**	
circulating		**± 5 %**		**± 1 %**
] cross-calibration		**± 5 %**		**± 1 %**
lifetime		**≤ 10 %**		**≤ 10 %**
ACCURACY	**$\pm 8.10^7$ p** **± 1.6 %**	**± $1.7\ 10^7$ p** **± 0.3 %**	**± $1.4\ 10^9$ p** **± 1.2 %**	**± $0.3\ 10^9$p** **± 0.3 %**
requested injection ε (absolute)			**± 3 %**	
dump ε			**± 2 %**	
circulating		**± 5 %** (17% for 10^8 c)		**± 1 %**
absolute calibration		**± 5 %**		**± 1%**

FBCT (3)

Lifetime processing: same for pilot and nominal (same resolution)
Case of nominal: $N=1.15\ 10^{11}$ p

τ	1 h	10 h	100 h
dN/dt	$3.2\ 10^{7}$ p/s $= 1.9\ 10^{9}$ p/mn	$3.2\ 10^{6}$ p/s	$3.2\ 10^{5}$ p/s
$d\tau/\tau$	$\leq \pm 10$ % /mn	$\leq \pm 10$% /10 mn ?	$\leq \pm 100$% /10mn ?

Usage	Threshold	Accuracy
Beam presence flag	$I_{tot} > n \times 10^9$ n=2-4	$(0.5\text{-}1) \times 10^9$ p
Safe beam flag	$I_{tot} < n \times 10^{11}$ n=2-10	10%
Beam intensity limit	Any value $> n \times 10^9$ n=5	5% at high I ($> 10^{12}$) 10% at lower I
Loss rate – slow	$dI/dt > 10^{11}$ p/s	5-10%
Loss rate – fast Turn by turn	$dI/dt > n \times 10^{11}$ p/turn n=3-6 $3.\ 10^{11} = 540$ μA	20% = 100 μA

measured in the lab. 1 mA rms (± 3 mA pktpk)

Table 5: Thresholds values for beam intensity related interlocks and flags.

Monitor tye/mode		Beam scenario	Current range	Observ-ation mode = sampling frequency	Observ-ation range (gating)	Integra-tion time per acquisi-tion	Pilot accuracy	Pilot resolution	Nominal bunch accuracy	Nominal bunch resolution
Single-pass to few (100) pass	**Bunch charge,** **injection efficiency,** **extraction efficiency**	pilot bunch to ultimate SPS batch	2.10^9 p/bunch to $1.7\ 10^{11}$ p/bunch	Turn-by-turn	Bunch by bunch	1 turn	±20% = $\pm 10^9$ p ±10% = $\pm 0.5\ 10^9$ p	±20% = $\pm 10^9$ p ±10% = $\pm 0.5\ 10^9$ p	± 3% = $\pm\ 3.10^9$ p ± 2% = $\pm\ 2.\ 10^9$ p	± 1% = $\pm\ 10^9$ p ± 1% = $\pm\ 10^9$ p
Circula-ting bunch monitor	**Extraction efficiency**	pilot bunch & ion bunches to ultimate beam	2.10^9 p/bunch to $1.7\ 10^{11}$ p/bunch	Turn-by-turn	Bunch by bunch	2.10^2 turns	±10% = $\pm 0.5\ 10^9$ p	±10% = $\pm 0.5\ 10^9$ p	± 2% = $\pm\ 2.\ 10^9$ p	± 1% = $\pm\ 10^9$ p
	Normal mode					2.10^2 to 10^4 turns	±10% = $\pm 0.5\ 10^9$ p	±10% = $\pm 0.5\ 10^9$ p	± 1% = $\pm\ 10^9$ p	± 1% = $\pm\ 10^9$ p
	Bunch lifetime (1mn to 20 hours)					10^4 turns to 10^5 turns	Pilot lifetime of 10h within 10s with 10% accuracy ↔ resolution $1.5\ 10^5$ p/10s		Nominal bunch lifetime of 10h within 10s with 10% accuracy ↔ resolution $3.2\ 10^6$ p/10s	
	Absolute calibration						±5% of pilot = ±0.5 μA		±1% of nominal bunch = ±2 μA	
	Cross calib ring – tr. lines						±10%		±2%	
Circula-ting beam monitor	**Normal mode**		4 μA to 860 mA	N turns	Whole beam	2.10^2 to 10^4 turns	I ≈ 10 μA: accuracy: ± 10% resolution: ± 10% I ≥ 500 μA: accuracy: ± 1% resolution: ± 1%			
	Cross-calib DCCT-FCT					10^4 turns	±10% at pilot current ±1% at nominal bunch current			
	Beam lifetime (1mn to 100 hours)					10^4 turns to 10^5 turns	Beam lifetime of 100h within 10s with 10%accuracy ↔ resolution 1.8 μA			
	Machine interlocks : I						**±10% accuracy at pilot current** **±5% accuracy for N > 10^{12} protons**			
	Machine interlocks:dI/dt						**?**			

Table 6: Acquisition parameters and necessary accuracy and resolution.