Instrumentation for space charge effects

Eva Barbara Holzer CERN BE/BI

With the kind support of:

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Outline

Performance of

- BLM – Beam Loss Measurements
- WS – Wire Scanner
- Synchrotron Light Monitor
- IPM – Ionization Profile Monitor
- BCT – Beam Current Transformer
- BPM – Beam Position Monitors
- WCM – Wall Current Monitors
- ?Halo Measurements?

In the

- PS
- PSB
- SPS
- LHC (sometimes shown for comparison)

- For new or updated instruments: **target parameters** given in green color

Beam Loss and Measurement

2012 PS Ring Radiation Survey

PS Ring inside Radiation Survey 2012

Débits de dose en µSv/h à 40 cm de la ligne de faisceau côté intérieur (18/12/2012, ~32h après arrêt faisceau)

Dose rates in µSv/h at 40 cm of the beam line inside of the ring (18/12/2012, ~32h after beam stop)

Section droite Straight section	Amont Upstream	Aval Downstream
1	179	118
2	44	46
3	99	91
4	38	121
5	42	43
6	47	64
7	39	95
8	19	47
9	233	168
10	20	20
11	31	27
12	43	76
13	73	93
14	[illegible]	[illegible]
15	49	130
16	6636	2129
17	577	584
18	199	187
19	[illegible]	[illegible]
20	53	50
21	68	35
22	14	42
23	178	338
24	42	46
25	72	84
26	133	118
27	63	43
28	84	80
29	88	115
30	382	387
31	1076	2533
32	622	603
33	497	613
34	660	704
35	1098	936
36	165	216
37	2324	1904
38	311	244
39	[illegible]	[illegible]
40	121	229
41	[illegible]	[illegible]
42	374	992
43	710	655
44	286	225
45	266	40
46	[illegible]	[illegible]
47	271	207
48	53	109
49	100	100
50	49	53

Section droite Straight section	Amont Upstream	Aval Downstream
51	46	32
52	41	40
53	51	54
54	17	138
55	107	95
56	[illegible]	[illegible]
57	814	2203
58	[illegible]	[illegible]
59	108	70
60	116	107
61	138	133
62	45	48
63	173	134
64	35	37
65	88	146
66	31	25
67	75	42
68	20	21
69	45	67
70	24	24
71	32	17
72	26	25
73	22	60
74	31	45
75	1955	1246
76	187	69
77	87	96
78	22	22
79	34	41
80	7	8
81	6	5
82	23	120
83	60	69
84	45	46
85	79	95
86	18	46
87	111	59
88	19	40
89	30	47
90	18	18
91	36	30
92	5	17
93	16	47
94	9	7
95	36	38
96	4	4
97	27	25
98	12	11
99	79	63
100	10	40

Color Code:
- > 100 µSv/h
- > 200 µSv/h
- > 500 µSv/h
- > 2000 µSv/h

If you have any questions concerning radiation protection, please call:
Pour tout renseignement concernant la radioprotection, veuillez contacter: Phone: 72504

L. Bruno et al., *Final Report of the PS Radiation Working Group*, CERN-ATS-2011-007

R. Steerenberg et al., Func. Spec: PS Beam Loss Monitor System renovation and upgrade (in work)

Transition gamma jump

Extraction

Losses at injection and at flat bottom

Internal dump

Typical PSB activation pattern from 2010

Débits de doses mesurés en µSv/h à 40 cm (07/12/2010)

Anneau Booster

Section	Element	Amont	Aval
BR 1	BHZ 11	1538	724
	QDE 1	147	109
	BHZ 12	133	44
BR 2	QDE 2	10	9
	BHZ 22	25	8
BR 3	BHZ 31	8	420
	QDE 3	98	68
	BHZ 32	95	137
BR 4	BHZ 41	291	47
	QDE 4	16	17
	BHZ 42	37	27
BR 5	BHZ 51	6	19
	QDE 5	5	6
	BHZ 52	8	8
BR 6	BHZ 61	12	238
	QDE 6	18	9
	BHZ 62	314	22
BR 7	BHZ 71	20	18
	QDE 7	5	4
	BHZ 72	6	4
BR 8	QDE 8	49	128
	BHZ 82	84	43
BR 9	BHZ 91	48	782
	QDE 9	115	69
	BHZ 92	78	24
BR 10	QDE 10	20	23
	BHZ102	95	23
BR 11	BHZ111	25	27
	QDE 11	8	6
	BHZ112	47	13
BR 12	BHZ121	4	5
	QDE 12	3	2
	BHZ122	3	2
BR 13	BHZ131	2	13
	QDE 13	2	2
	BHZ132	2	2
BR 14	BHZ141	2	52
	QDE 14	27	26
	BHZ142	134	374
BR 15	BHZ151	162	45
	QDE 15	20	20
	BHZ152	46	18
BR 16	BHZ161	19	38
	QDE 16	15	35
	BHZ162	139	60

Color code: > 100 µSv/h; > 200 µSv/h; > 500 µSv/h

Secti			
BI	QNO30	12	80
	QNO40	200	194
	DIS	322	416
	DIS.Pb	365	34
	SMV	170	274
	BVT		97
	QNO50		64
	QNO60		64
	UMA40		38
	TRA20		60
	UMA50		61
	UMA50+		43
	BVT10	86	63
	SMV10	42	87
	QNO10	108	
	QNO20	187	75
	KFA10	46	22
	DVT30		15
BTM	SGV1	6	
	SGV2	5	
	SGV3	6	
	DUMP	64	
BTY	BVT101	19	7
	QDE104	6	6
	QFO108	4	3
	QDE113	2	2
	BVT116	2	2
	QFO119	2	3
	QDE120	3	2
	QFO122	2	2
	QFO148	0	1
	QDE151	8	5
	QFO153	4	3

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Injection

Global aperture restriction: BR8 – loss peak BR9

PSB activation 2012

Débits de doses mesurés le 18/12/2012

Anneau Booster

Unité		µSv/h		
Distance		2 m	40 cm	
BR 1	BHZ 11	150	1767	761
	QDE 1	58	199	138
	BHZ 12	34	169	79
BR 2	QDE 2	12	20	10
	BHZ 22	9	61	9
BR 3	BHZ 31		19	634
	QDE 3	38	155	98
	BHZ 32	151	162	104
BR 4	BHZ 41		172	45
	QDE 4	17	8	10
	BHZ 42	6	89	25
BR 5	BHZ 51		6	115
	QDE 5	7	22	21
	BHZ 52	4	24	6
BR 6	BHZ 61		17	248
	QDE 6	12	24	13
	BHZ 62	8	417	28
BR 7	BHZ 71		22	24
	QDE 7	6	13	9
	BHZ 72	4	9	5
BR 8	BHZ 81		29	60
	QDE 8	29	51	73
	BHZ 82	24	53	37
BR 9	BHZ 91		37	463
	QDE 9	25	60	35
	BHZ 92	8	43	14
BR 10	BHZ101		13	193
	QDE 10	10	19	23
	BHZ102	21	166	0
BR 11	BHZ111		34	17
	QDE 11	5	7	6
	BHZ112	8	104	24
BR 12	BHZ121		11	3
	QDE 12	1	3	2
	BHZ122	1	2	2
BR 13	BHZ131		2	3
	QDE 13	1	3	2
BR 14	BHZ141	2	3	147
	QDE 14	28	69	52
	BHZ142	158	107	755
BR 15	BHZ151		212	53
	QDE 15	21	27	25
BR 16	BHZ161	20	30	35
	QDE 16	21	17	43
	BHZ162	150	155	96

Color code: > 100 µSv/h; > 200 µSv/h; > 500 µSv/h; > 2000 µSv/h

Autres lignes

Ligne	Element	Amont	Aval
Unité		µSv/h	
Distance		40 cm	
BI	UMA20	8	7
	DVT30	7	
	QNO30	31	239
	QNO40	560	340
	DIS		247
	DIS.Pb	128	78
	SMV	266	416
	BVT		147
	QNO50		66
	QNO60		68
	UMA40		44
	TRA20		72
	UMA50		64
BT	BVT10	141	81
	SMV10	87	174
	QNO10	244	
	QNO20	278	113
	KFA10	68	34
	DVT30		34
	SMV20	235	292
	QNO30		116
	TRA	218	150
			119
		141	63
		52	24
		22	16
		16	10
	MTV10		16
BTM	BHZ10	16	10
	BHZ10	50	27
	QNO10		15
	QNO20	15	14
	SGV1	9	
BTY	SGV2	8	
	SGV3	9	
	DUMP	118	
	BVT101	16	5
	QDE104	6	6
	QFO108	6	5
	QDE113	3	3
	BVT116	3	2
	QFO119	1	1
	QDE120	1	1
	QFO122	1	1
	QFO148	1	1
	QDE151	1	1
	QFO153	1	1

?

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Beam Loss Monitoring – PSB

- Monitor type ACEM (**PSB and PS)**
- No logging
- Signal per lost proton
  - Strongly depends on beam energy
  - Signal not converted to absolute units (like Gy/sec, lost protons/sec)
  - Integral over cycle OR ms-sampling
- 2 rings share the same monitors (→ ring 1/2 and ring 3/4 cannot be distinguished)
- 16 longitudinal positions at vertical aperture restrictions (one per section)
- New system (Ionization Chambers, IC, and new readout):
  - LS1: Additional 16x2 ICs (LHC type) at the same locations as the ACEMs
  - LS2 (LINAC4 connection): 16x2 Flat ICs at horizontal aperture restrictions – 5 times less sensitive

Beam Loss Monitoring – PSB cont.

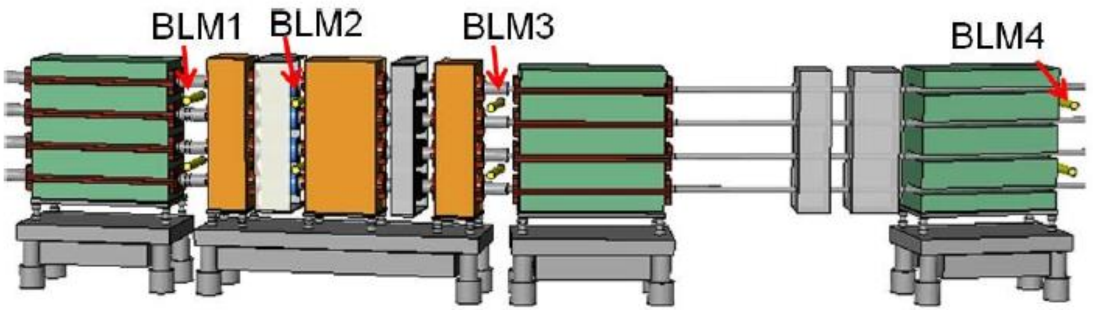
- New BLM system with ionization chambers → will allow to display losses in Gy/s
- Extensive simulation studies (CERN-ATS-Note-2012-096 TECH) will allow to calculate the number of lost protons (guess of the achievable precision: factor 2-5).

- Simulated proton beam energies Ek=160 MeV (future injection energy with LINAC4), 1.4 GeV (present extraction energy) and 2 GeV (future extraction energy) at vertical and horizontal aperture restrictions

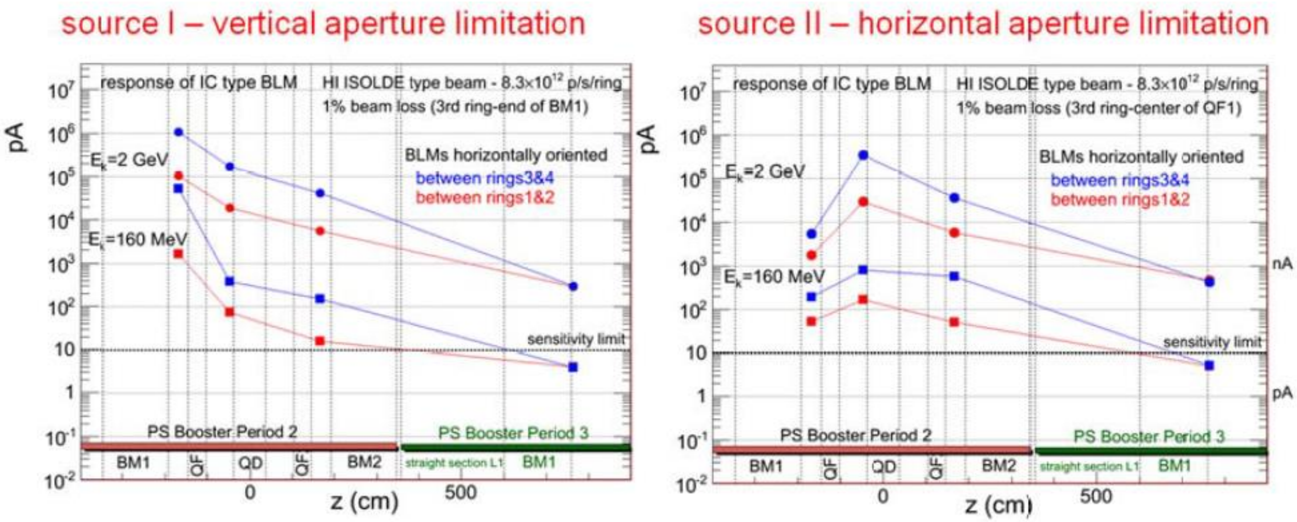
- Lower measurement limit approximation in 2 μs (shortest integration interval with a measurement limit 31nA) for losses at a single location:
  - 160 MeV (V / H loss): 6E4 / 1E6 protons
  - 2 GeV (V / H loss): 6E3 / 6E4 protons

PSB BLM simulation studies   Sanja Damjanovic

- Currently installed locations: “BLM1” and “BLM4”
- Additional location for horizontal loss (LS2): “BLM2”



- 1% beam loss of a HI ISOLDE type beam (8.3E12 protons):



New Readout system for injector BLM (LINAC4, PSB, PS, SPS)

- Generic, highly configurable, able to accept several detector types
- Integration time 2μs, plus moving sums up to a full cycle
- Dynamic range = 10^{11} for integration times >=10ms: 10pA to 200mA
- Comparison with predefined thresholds
  - Machine protection with hardware implementation
  - Limit radiation levels with software implementation
- Online display and logging of max losses
- Capture data with consecutive loss integrals

- Additional: possibility of high time resolution measurements with diamond detectors (time resolution ~ns range) at few selected locations
- Timescale:
  - LINAC2 and PSB: after LS1
  - PS and SPS: LS2

Transverse Profile

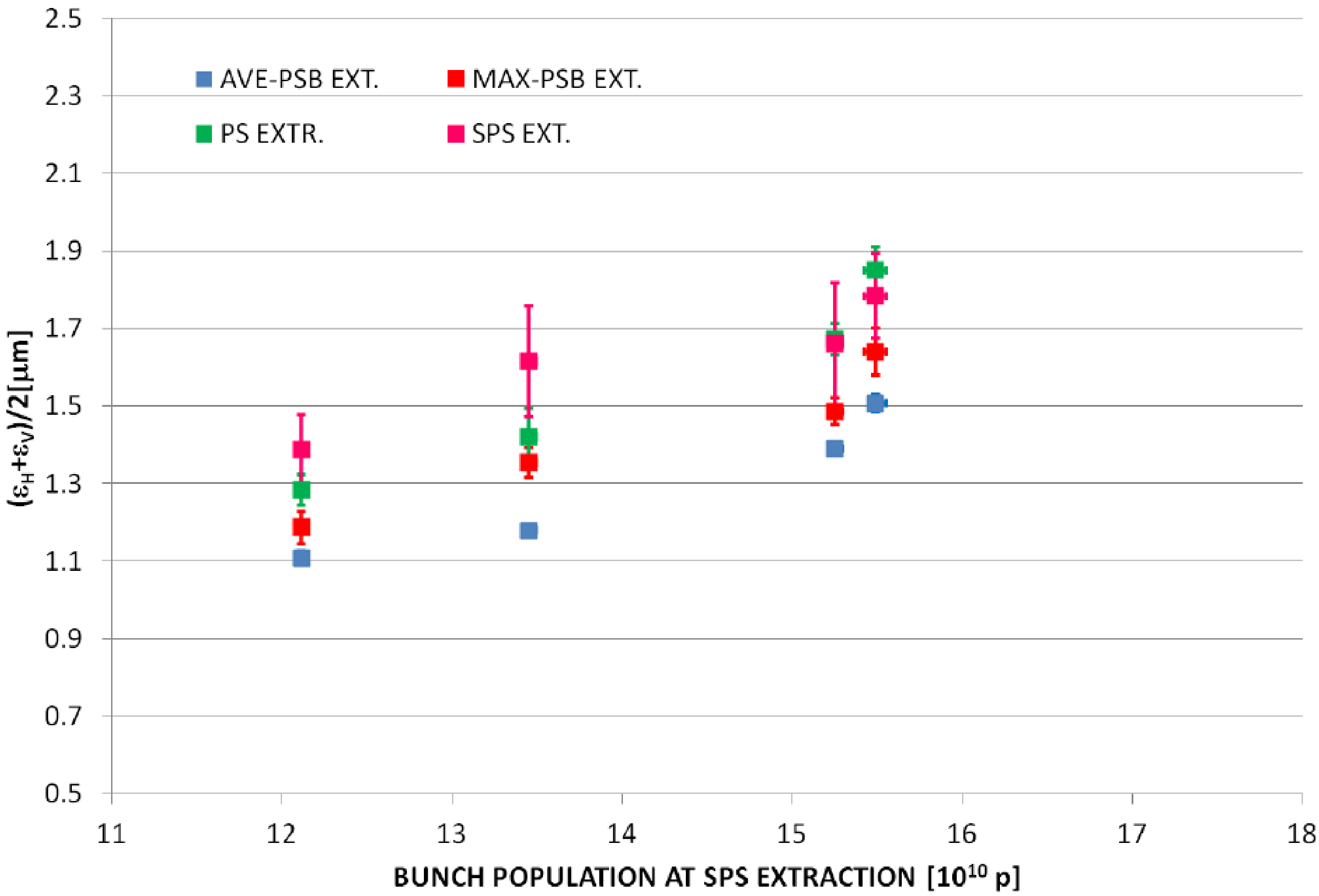
Transverse Profile Measurements – Wire Scanners

	Wire speed	Number of equipment	Dynamic range	Absolute accuracy on emittance	spatial resolution	Meas. range in Δx and Δy	Bunch selection
PSB	rotational 15 m/s	1 H / ring 1 V / ring	100	20%	200μm	calibrated to +/- 5 cm	Could be made b-p-b ?
PS	rotational 15 m/s	3 H 2 V	100	20%	200μm	calibrated to +/- 5 cm	Could be made b-p-b ?
SPS	rotational 6 m/s	3 H 3 V	100	20%	200μm	+/- 5 cm	Bunch-per-bunch
	Linear 1/0.6 m/s	2 H 2 V	100	20%	50μm	~ +/- 4 cm	Bunch-per-bunch
Future SPS 2014	rot. 20 m/s	1 V	10^4 (spec)	< 10%	<10 μm	+/- 4 cm (full aperture)	Bunch-per-bunch
LHC	linear 1 m/s	1 H / ring 1 V / ring + 2 dev./ring	100	2013: 10-50% 2014: 10%	50μm	Full aperture	Bunch-per-bunch

- It typically takes a few 100 turns for one profile (e.g. PSB ~600 turns)
- LS1: systematic simulation study to improve WS accuracy

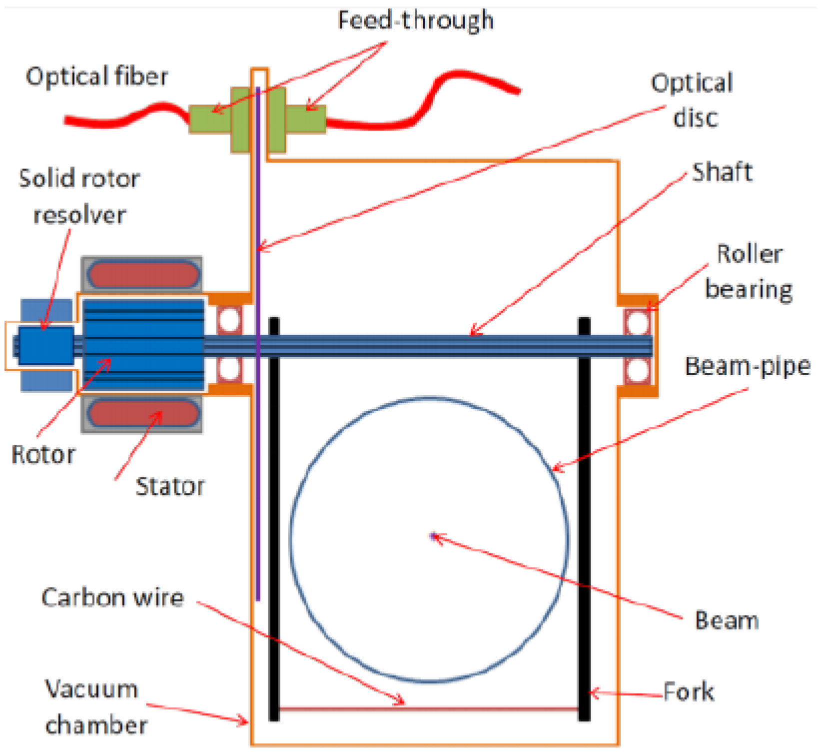
WS measurement across the accelerator chain

- G. Arduini: “Emittance vs. intensity along the chain”, LMC Meeting 12 October 2011



New Wire Scanner Development

- Design goals:
  - Spatial resolution of few µm (using high resolution angular position sensor)
  - Dynamic range: 10^4
    - Usage of sensor with large dynamic (diamond)
    - Automatic electronic switching of gain ranges
  - Minimize fork and wire deformations
    - Study of dynamic behavior of fork/wire system
    - Vibration mode optimized acceleration profile



Transverse Profile Measurements - others

- Relative measurements, they need to be calibrated against the wire scanners

		Number of equipment	Dynamic range	Absolute accuracy on beam size measurement (after cross calibration)	relative accuracy emittance / beam size	spatial resolution	measurement rate	Bunch selection
SPS Synch. 2014 (refurbished)	Only above 300GeV	1	200 or 10^5 by changing attenuation	30% on emittance – hope to improve	10%/5% (same setting, 2 bunches in the machine for example)	~50µm (expected)	10Hz (flexile gating time width)	72 bunches – 1 PS batch
LHC Synchrotron Light	BSRT	1 / beam	200 or 10^5 by changing attenuation	30% on emittance – hope to improve	10%/5%	50µm	10Hz (flexile gating time width)	Bunch-per-bunch
SPS 2015	IPM	2: H,V	10^3	20%	5% / 2.5%	100µm	10 bunches in 0.1 s	Sum of all beam, maybe indiv. bunches)
LHC 2015	IPM	2 / beam	10^3	20%	5% / 2.5%	100µm	10 bunches in 0.1 s	

Transverse Profile Measurement cont.

- G. Arduini et al., *Measurement of the Transverse Beam Distribution in the LHC Injectors (Func. Spec.)*. EDMS 772786. Extensive document including:
  - Measurement techniques
  - Measurement devices (specifications, parameters)
  - Parameters of beams and optics at location of devices
- Timescale for new design WS:
  - PSB: requested, no installation date confirmed
  - PS: requested, planned for LS2
  - SPS: requested, one test system installed LS1, full installation not before LS2
  - LHC: new system not (yet) requested
- Possibility of a PS IPM being investigated (presentation by M. Sapinski; workshop for non-invasive beam size measurement 16. April 2013, CERN)

Intensity Measurement

Fast Beam Current Transformers - FBCT

	State of the Art	PSB	NEW PS, LS1	SPS	LHC
Number of instruments		1	1 (to be replaced LS1)	1 (replaced later than LS1)	2 / ring
Absolute accuracy	1%	No precise calibration, used only for observation and RF synchronisation	1%	5% (bunch position dependence and tail effects)	1% + 1% per mm of beam displacement
Reproducibility (typically averaged over several hundreds of turns)	0.1%		0.1%	~1%	0.5%
Dynamic range	10^3 – 10^4		5 10^3	5 10^3	5 10^3
			Bunch-by-bunch	Bunch-by-bunch	Bunch-by-bunch

- In addition: many FBCT replaced in transfer lines during LS1 (TT2, PSB extraction, ISOLDE line)

DC Beam Current Transformers

	PSB	PS	SPS	LHC
Number of instruments	1 / ring	1	2	2 / ring
Absolute accuracy	1%	1%	1%	0.2%
Noise floor	50µA	50µA	2 µA	2 µA
Dynamic range	10^4 (1 10^9 – 1.4 10^{13} p)	5 10^4 (1 10^9 – 5 10^{13} p)	10^5 (1 10^9 – 1.5 10^{14} p)	10^6 (µA – 1A)

Orbit Measurement

BPMs for orbit measurement

	PSB	NEW PSB – all 4 rings after LINAC4 connection, for >1E11 ppb	PS	SPS	LHC
Design	Cylindrical (dual plane)	Stay the same	Shoebox (dual plane)	Mostly shoebox (single plane)	Button (dual plane)
Number of BPMs	16/ring	16/ring	40 43 (LS1)	~230	~1100 2 per cell per ring
Turn-by turn	no	yes	yes	yes	yes
Position res.	0.1 mm	0.2 mm (better when averaging turns)	0.2 mm (better when averaging turns)	0.5/1mm for high/low intensity bunches	Arc: 5-10µm (nom. bunches, averaging turns), 100µm (very low intensity) IR: ~50µm nom. bunches
Accuracy of offset corr.	No offset correction	El. offset corr. can be applied; Mech. offset not well known	~0.1 mm (el. and mech.)	~0.1mm mech. ~0.5mm el. (radiation ageing of cables)	0.1mm mech. <0.2 mm el.

- Current PSB system: Cannot resolve individual bunches nor rapid beam movement (4MHz acquisition system bandwidth)

BPMs for orbit measurement cont.

	PSB	NEW PSB – all 4 rings after LINAC4 connection for >1E11 ppb	PS	SPS	LHC
Design	Cylindrical el.stat.	Stay the same	Shoebox el.stat.	Mostly shoebox	button
Linearity corrections	No (mech. design linear)	No (mech. design linear)	No (mech. design linear)	No; only BPCE (large aperture at extraction regions)	Yes (no cross terms)
Linearity error	?	?	1% over +/-40mm	BPCE: 1% over +/-80mm	~1% over 1/3 of the aperture

- Linearity corrections: 5th order polynomial (for LHC: cross terms are calculated, but not yet applied)
- Linearity correction of the electronic: simulated and tested in the lab
- Linearity correction due to the BPM geometry: simulated using CST particle studio and tested with beam

Longitudinal

Longitudinal Profile with Wall Current Monitor, WCM

- Resolution and error depends on: bunch shape, bunch length, beam energy, leading or trailing tail, and on the system (bandwidth, readout resolution, cable reflections, whether the WCM is used as dedicated device)

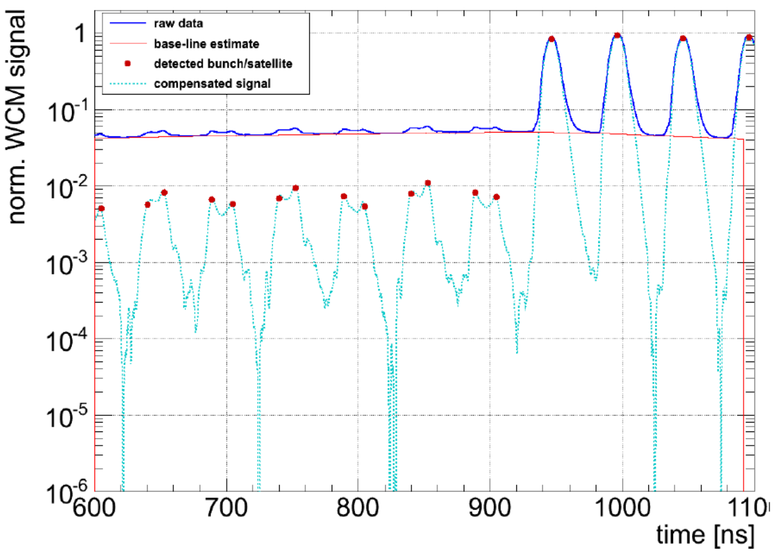
  → numbers are only guidance levels for e.g. LHC beams

- **SPS:** Readout by 8 bit scope, resolution frequency dependent (~ 5 bit for higher frequencies):
  - 1 – 10 turn measurements: bunch shape changes quickly
  - Resolution of tails: 1-3% of the peak value
  - Systematic error (pick-up response): percent region (same order of magnitude as the resolution)
- **PS:** Readout by 8 bit scope
  - Extraction 4ns beam: similar to SPS

Precision on satellite bunch measurements

- G. Papotti et al., *The SPS Beam quality monitor, from design to operation*, IPAC 11 :
  - Automatized satellite bunch detection algorithms reliably detects signals that are about 3% of the main bunches, better precision can be reached by hardware improvements

- R. Steinhagen et al., *Wall-Current-Monitor based ghost and satellite bunch detection in the CERN PS and LHC accelerators*, BIW 12:
  - Investigations and prove of principle in PS and LHC for WCM based system:
  - Measure ghost and satellite bunches with a resolution of 10^{-4} with respect to the main bunches
  - Systematic error < 10^{-3}
  - Precision measurement of the steady-state bunch profile



Literature Longitudinal courtesy T. Bohl

BQM:

- G. Papotti et al. The SPS Beam quality monitor, from design to operation. International Particle Accelerator Conference, 2011. CERN-ATS-2011-219.
- G. Papotti. SPS Beam Quality Monitor. Status and experience. MSWG 2011-04-29, presentation.
- G. Papotti. SPS Beam Quality Monitor. Update on the project. MSWG 2009-09-04.
- G. Papotti. Fast (and reliable) detection of longitudinal instabilities. CERN/GSI Meeting on Longitudinal Beam Dynamics and RF Manipulations, September 2009.
- G. Papotti. SPS Beam Quality Monitor. Machine Studies Working Group (MSWG) Meeting 2009-04-24.

APWL WCM:

- T. Bohl, J.F. Malo. The APWL Wideband Wall Current Monitor. CERN-BE-2009-006.

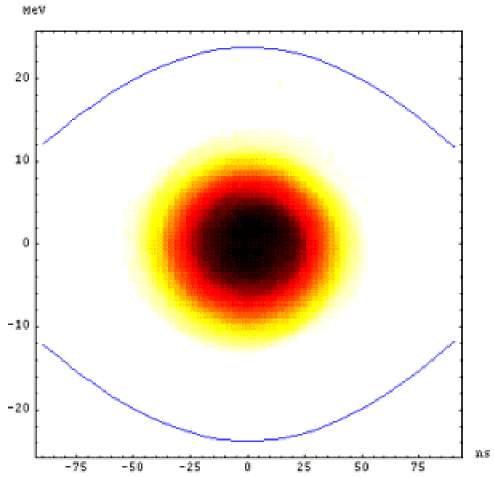
Ghosts/satellites:

- R.J. Steinhagen. Wall-Current-Monitor based Ghost and Satellite Bunch Detection in the CERN PS and LHC Accelerators. 2012 Beam Instrumentation Workshop, CERN-ATS-2012-151.
- R. Steinhagen et al, WCM-based Satellite Measurements during the November'12 VdM scans, LHC Luminosity Calibration and Monitoring Working Group Meeting.

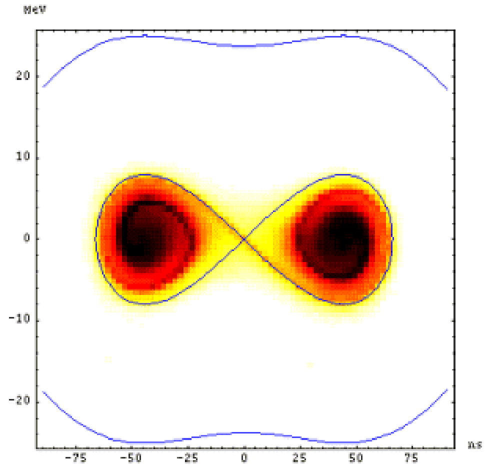
Longitudinal Tomography

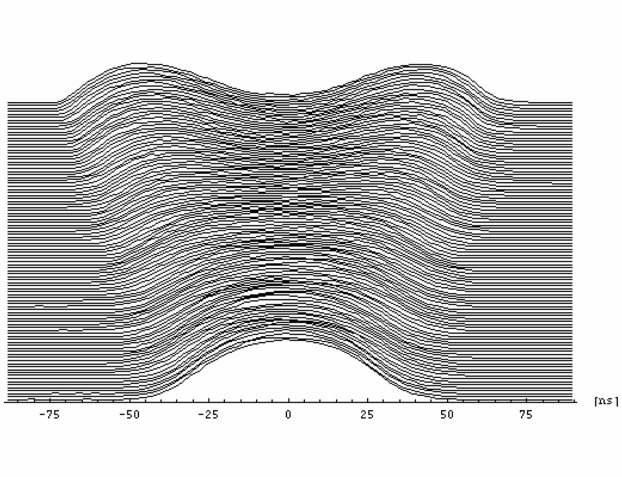
Longitudinal Tomography (S. Hancock, M. Lindroos et al.)

- Available in: PSB, PS, LEIR, AD
- http://tomograp.web.cern.ch/tomograp/



Bunch splitting at 3.5GeV/c in the CERN PS (1999/06/03). The measured data span 10ms.





Longitudinal Tomography (S. Hancock, M. Lindroos et al.)

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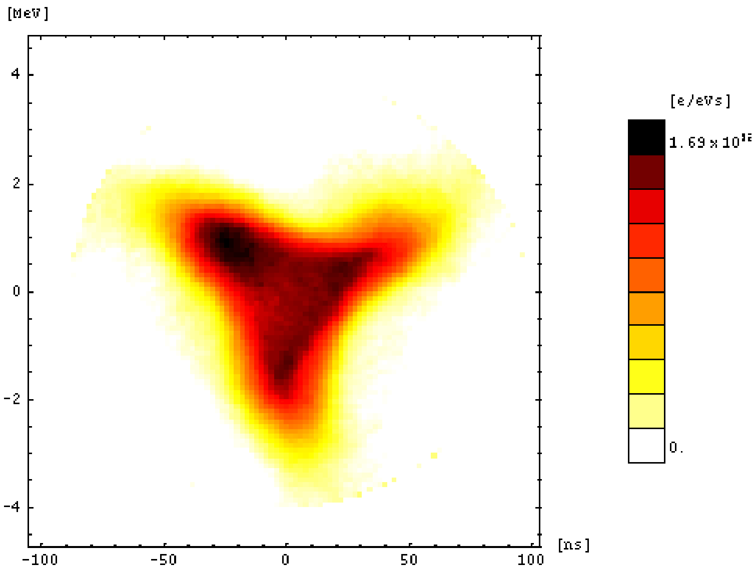

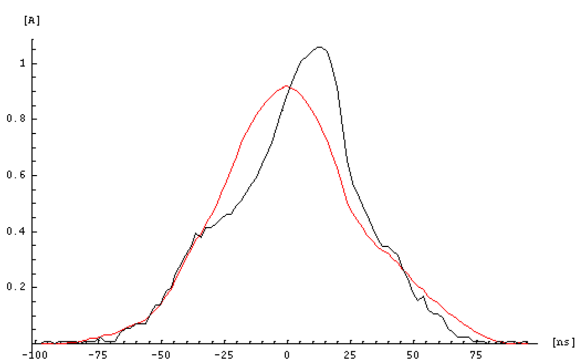

"Longitudinal instability towards the end of acceleration in the PSB (2000/11/23). The projection (in red) of this distribution shows atypically poor convergence towards the corresponding measured profile (in black). The reconstruction includes none of the terms driving the instability, so it is not surprising that tomography cannot reproduce the fine detail. Nevertheless, it is a testament to the robustness of the method that the underlying nature of the instability is revealed so unequivocally as sextupolar."

Transverse Halo Measurements

Transvers Halo Measurement

- **Beam tails (10^{-2} –10^{-3})** are just within range of standard profile measurements
- **Halo (< 10^{-4}):** need very high dynamic range >10^5

Methods:

- Wire scanners and scrapers (linear machine) $\rightarrow$ slow
  - A Browman et al. PAC 2003: dynamic range of 10^5
  - A.P Freyberger, Jefferson Lab, PAC'03, DIPAC'05: dynamic range of 10^8
- Optical Methods $\rightarrow$ faster
  - Light generated by synchrotron radiation or screens
  - Large dynamic range readout
    - CID (Charge Injection Device) cameras with RAI (random access integration) mode (automatically adjusted integration time for each pixel): dynamic range of up to 10^6
    - Micro Mirror Arrays (adaptive masking method), HB2012, *Hao Dai Zhang et al.*
  - Blocking the core with coronagraph

Transvers Halo Measurement cont.

Synchrotron: collimator or scraper or wire in the halo →

- Measure (precise relative measurement) and destroy the halo at the same time
- e.g. LHC, HERA collimators, SPS scrapers, former CERN Beamscope (orbit bump and stationary target)
  - G. Valentino et al., *Beam diffusion measurements using collimator scans in the LH*, Phys. Rev. ST Accel. Beams 16 (2013).
  - F. Burkart, *Beam Loss and Beam Shape at the LHC Collimators*, CERN-THESIS-2012-046.
  - K.-H. Mess, M. Seidel, Collimators as diagnostic tools in the proton machine of HERA, Nucl. Instrum. Methods Phys. Res., Sect. A351, 279 (1994).
  - M. Seidel, M. Seidel, DESY Report No. 94-103, 1994.

- Further Reading on Halo Measurements:
  - Kay Wittenburg, Beam Halo and Bunch Purity Monitoring, CAS on beam Diagnostics, Dourdan, CERN-2009-005 (2009).
  - 29th ICFA Advanced Beam Dynamics Workshop on Beam Halo Dynamics, Diagnostics, and Collimation, HALO’03, Montauk, Long Island, New York.
  - Proceedings ICFA workshops: HB2004, Bensheim, Germany; HB2006, Tsukuba, Japan.

Summary of scheduled updates (PSB, PS, SPS, LHC)

LS1:

PSB	BLM part1
SPS	WS, IPM
LHC	IPM

LS2:

PSB	BLM part2, BPM
PS	BLM, Fast BCT, WS
SPS	BLM, WS
LHC	?WS?

END

CERN: Transverse Size

- **OTR & Scintillation screens**
  - Scintillation typically for set-up (thick screens -> emittance blow-up) or for low energy where OTR cannot be used for hadrons. Meeting last year at GSI to look at resolution possible with various screen materials. Not obvious to find right material for particular beam conditions. http://www-bd.gsi.de/ssabd/home.htm
  - OTR. Good for high energy hadron beam measurements. Little emittance blow-up. Typically used in injection/ejection lines for 3 screen emittance measurement. Very thin foils Ti or C used can withstand fairly high beam powers.
- **Wirescanners**
  - Reference for all other beam size measurements in circular machines.
  - Issues with sublimation of wires for high brightness (low emittance & high charge) beams.
  - Limited by number of points during scan for small beams. Increasing scan speed allows higher intensity to be scanned but reduces # points. Decreasing speed gives nice profiles (many points) but severely limits beam intensity that can be scanned

Transverse Size cont.

- **Rest Gas ionisation monitors**
  - Installed in SPS & LHC
  - Needs moderate pressure bump
  - Issues to understand size evolution during ramp. Space charge, electron/ion gyration radius, electron cloud.
- **BSRT**
  - Only above 400GeV for protons – SPS at extraction & LHC (with dedicated undulator for low energy)
  - Only with many bunches at 450GeV LHC injection energy for lead ions
  - Needs cross calibration and very good knowledge of optics & emission scenarios for absolute calibration
  - Good for relative bunch by bunch size measurements. In LHC now capable of acquiring profiles at 20Hz -> for 1350 bunches, averaging over 5 images, manage to scan all bunches in ~5mins.

Longitudinal Distribution & Transverse Position

- **Wall current monitors.** Frequency up to GHz to look at longitudinal structure. Correction of pick-up & cable response required to obtain sufficient dynamic range to allow detection at below the 1% level. Limited by acquisition electronic dynamic range (typically 8bit ADC for these frequencies). Also play tricks with clamping circuits to look only at satellite populations (i.e. ignoring the core of the bunch) – recovery time from clamping fast enough to look even directly after a main bunch.
- **Stripline pick-ups.** Used to look at intra-bunch transverse instabilities (head-tail etc). Bandwidth up to few GHz.
- **LDM – used in LHC.** Single photon detection. Uses statistics & correction of dead-time & after-pulsing to give near limitless dynamic range. Resolution basically determined by the time you're willing to wait and dark current of avalanche photodiode detector. Temporal resolution some 50ps.

Phase Space Reconstruction

Transverse Phase space reconstruction

Turn by turn BPM data from 2 BPMs with 90 phase separation. Used in PS for multi-turn extraction optimisation, where the main bunch is split into a core with 4 islands which all have different trajectories. - Belleman

Longitudinal

Tomography using data from wall current monitors is used to look at full longitudinal phase space in the PS – basically reconstructing slices of the longitudinal profile over several synchrotron periods. This is a very useful diagnostic for the bunch splitting that is employed in the PS. Hancock

BLM, WS, BSRT, LDM

	Dynamic range	accuracy	Temp. resolution
BLM: Ionization chambers electronics	2 x 10^5 in 40 µs (10^6 under developement: 1nA – 1mA) 10^8 in ≥ 1.3 s	10% on measurement of ionisation; 50 -200% on the number of lost protons	100us
Diamond BLM	Electronics: 10^3; Diamond: 10^9 DC, 1pA – 1mA	n.a.	Few ns

	Dynamic range	accuracy	spatial resolution	temporal resolution
WS	100	5-10%	50um linear WS LHC/SPS 200um rot. WS SPS/PS/PSB	--
BSRT	200 10^5 by changing attenuation	30%	50um 10% on emittance (?)	--
LDM	At LHC at least 10^3 10^3. Theoretically 10^4- 10^5; but limited by deadtime and afterpulse.		--	50 ps