

Beam Quality Assessment for LHC beams

Real Time and Post-Pulse

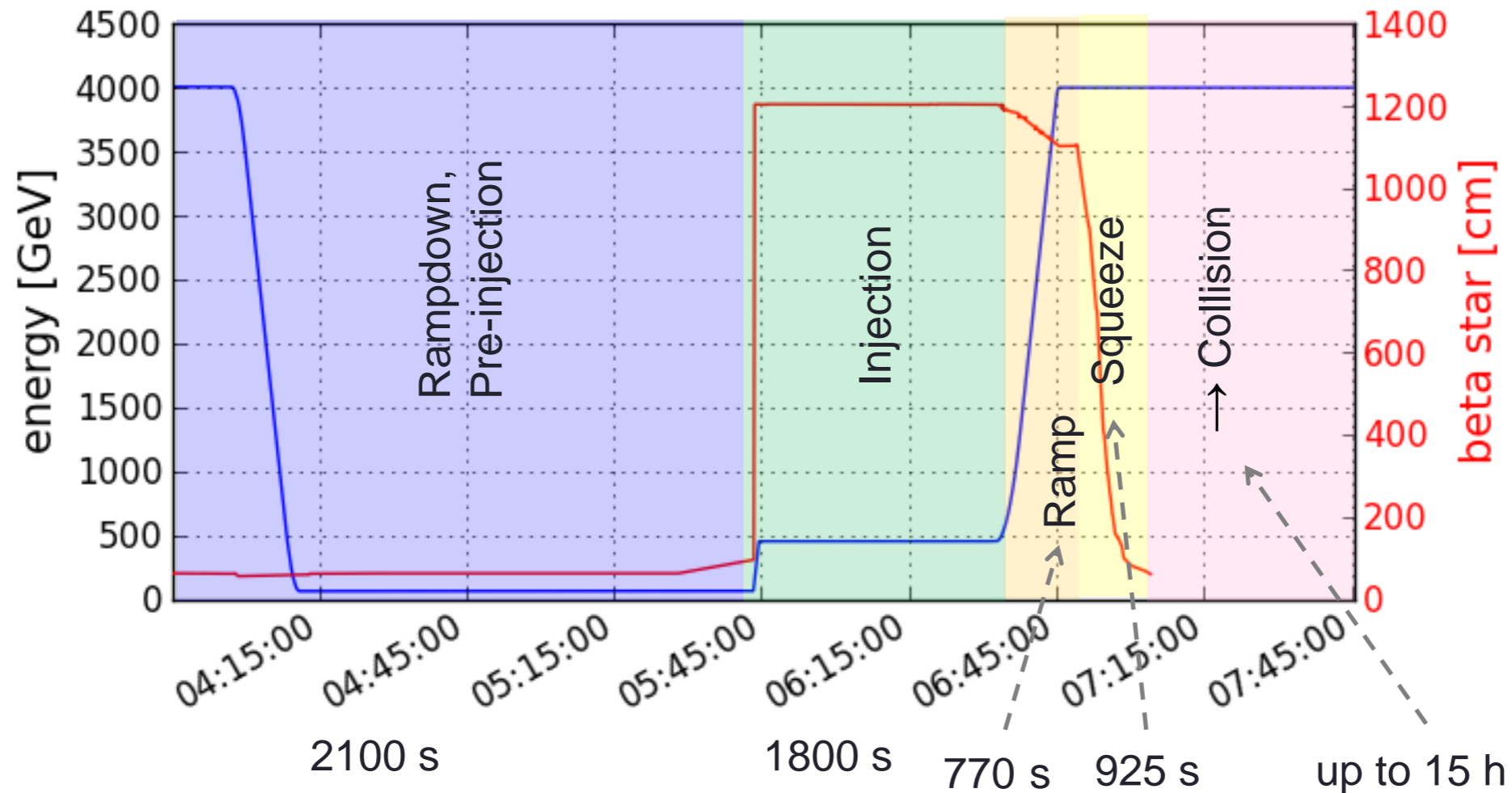
V. Kain, LHC Operation

Special thanks to:

C. Bracco, K. Cornelis, L. Drosdal, D. Jacquet, G. Papotti, B. Puccio, E. Veyrunes, J. Wenninger, M. Zerlauth,...

LHC cycle is long.

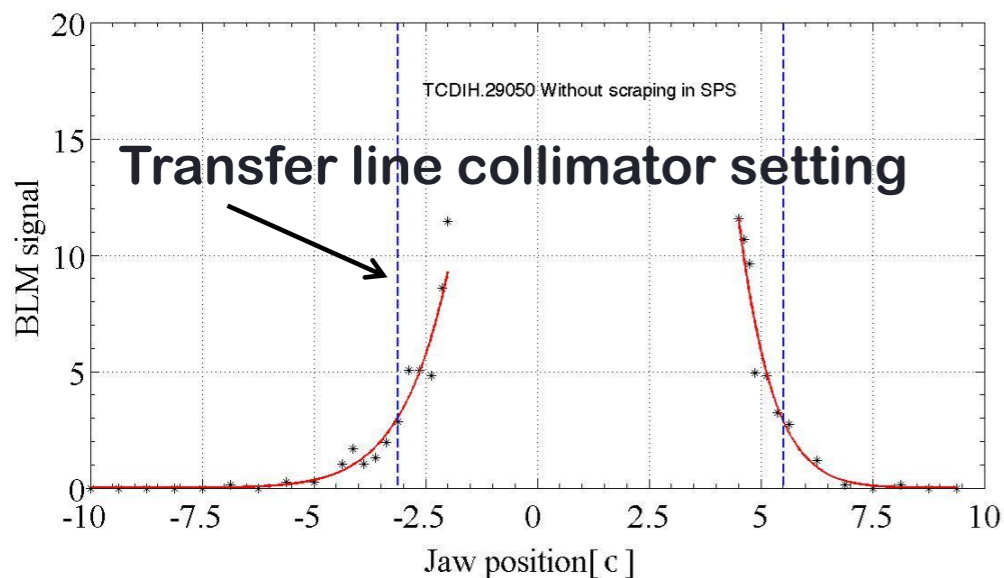
LHC cycle in 2012, 4 TeV collision energy, $\beta^* 0.6$ m:



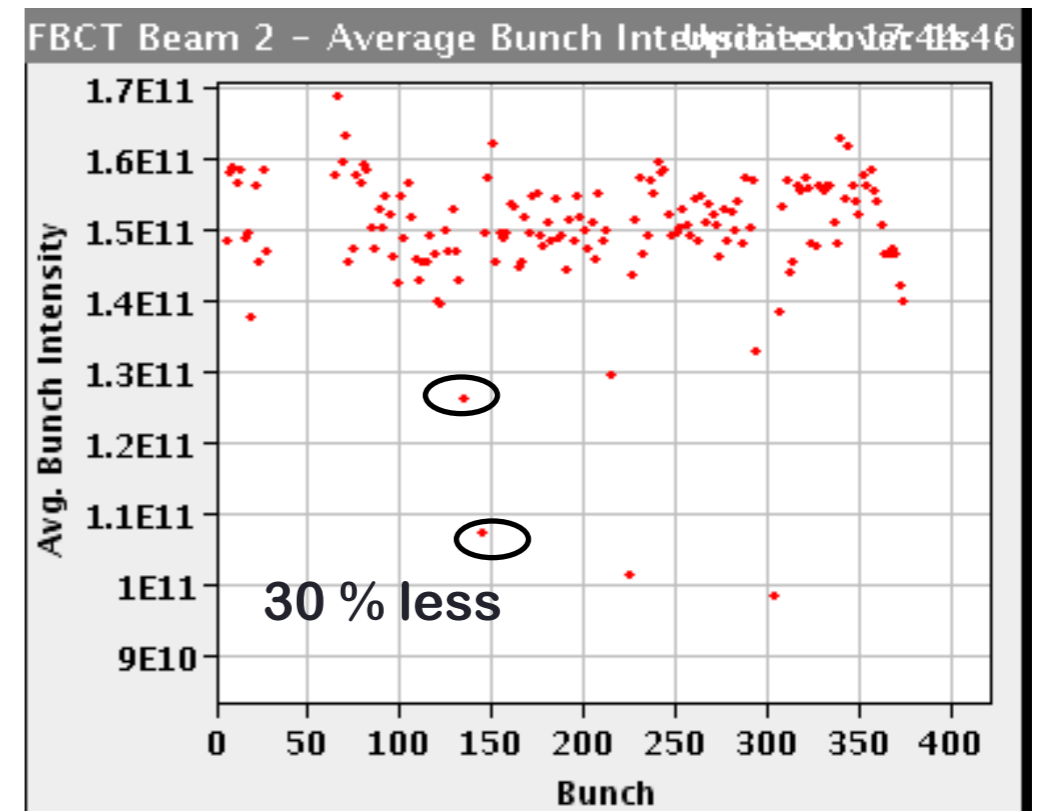
- o All parts of cycle except of injection are driven by functions
 - Once execution started cannot/should not be stopped
 - o Need to go through cycle (e.g. ramp+ rampdown): reproducibility
- Check beam quality before/at injection. Afterwards: live with it.

Requirements:

- o Small emittances: 1.5×10^{11} , $1.5 \mu\text{m}$
- o Uniform bunch intensities ($< \pm 10\%$)
- o Equal beam intensities for beam 1 and beam 2
- o Low tail population
- o Satellite population reasonable
- o Low losses
- o Bunches in the correct buckets
- o ...



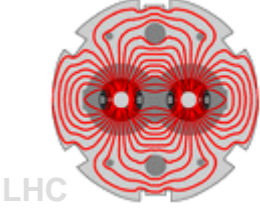
Tail population beyond transfer line collimator opening → scraping in the SPS



12 + 144 bunches at injection in the LHC: Problem with injection kicker timing in the SPS



Beam Quality Checks

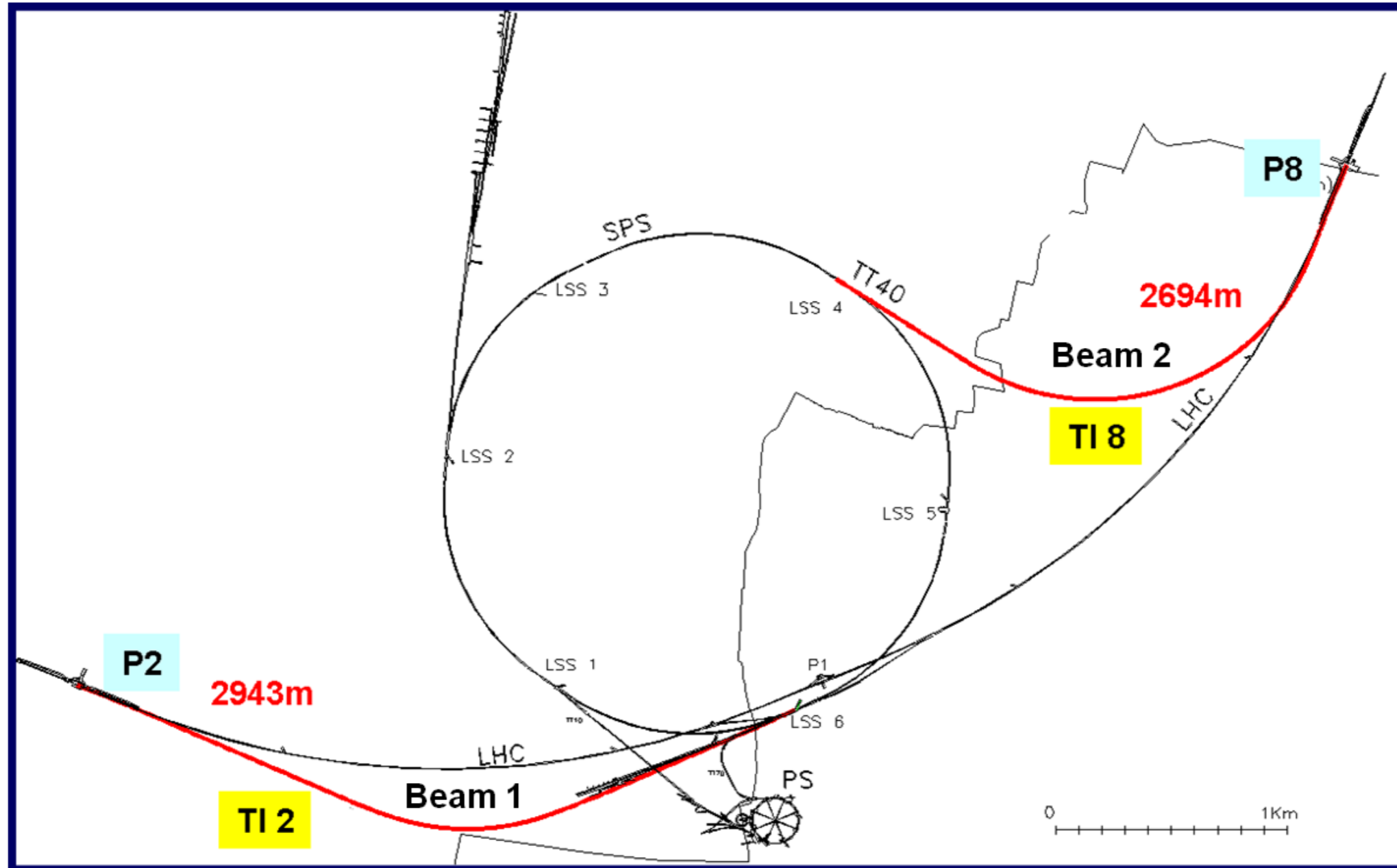


2 types of online active Beam Quality Check Systems:

Beam Quality Monitor (BQM) in the SPS

Injection Quality Check (IQC) in the LHC

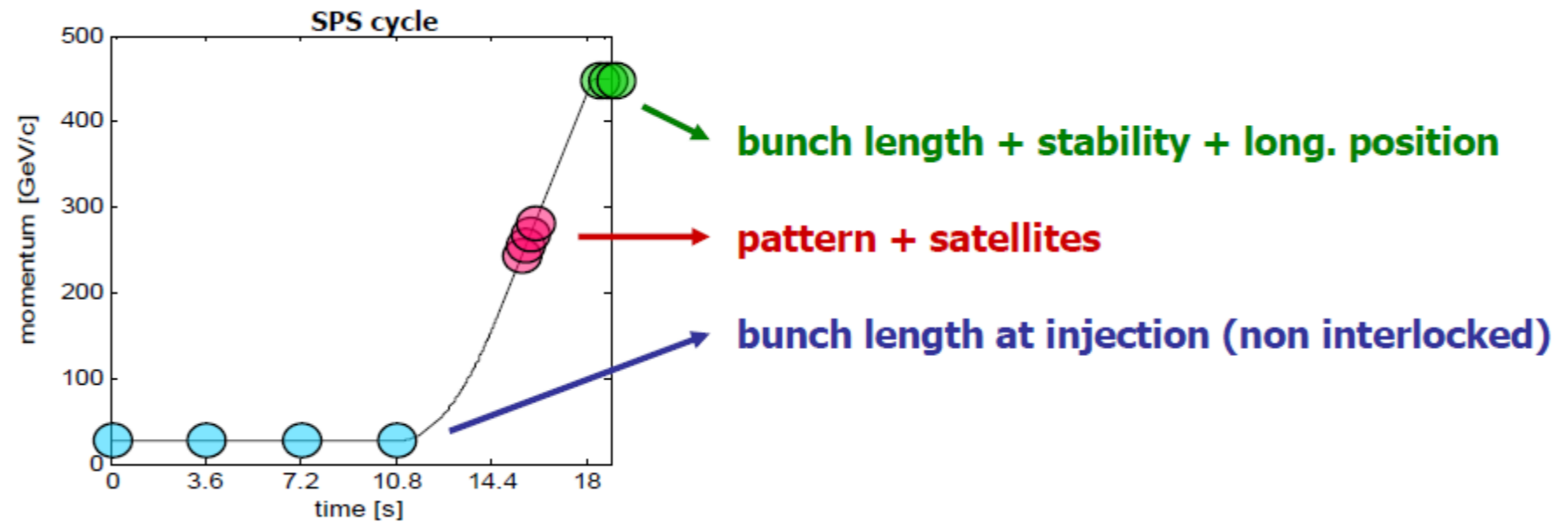
- o 2 3 km long transfer lines to fill the LHC from the SPS



- o Need ~ 12 injections per ring to fill LHC; LHC cycle in the SPS ~ 20 s.
- o Fast extraction from the SPS
- o As soon as extraction launched cannot stop it anymore

- o Beam Quality Monitor (BQM) – checks longitudinal quality of beam in the SPS

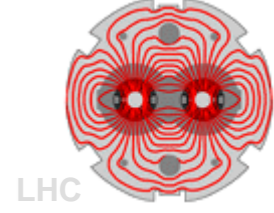
BQM measurements



- o Based on **Wall Current Monitor Beam Profile**. Analysis running on FESA class.
- o Dumps beam in the SPS in case of bad quality. Last check ~ 20 ms before extraction.
- o Analysis speed: 10 ms data acquisition + 10 ms analysis
- o Typical errors caught:
 - Rephasing not working correctly
 - Fully debunched (PS cavity missing)
 - Bad injection phase or bad PS bunch splitting
 - Injections in wrong bucket or missing injections in the SPS
 - Bunch intensity spread too large



Beam Quality Monitor in the SPS



- The BQM analyses each SPS cycle, no matter whether beam requested by LHC or not.

SPS Beam Quality Monitor - SPS.USER.LHC1

01 Jun 2012 01:59:15 SPS - LHC1, 36 CNGS1 - 02 Auto Select LHC Cycle

Expected Beam Pattern: SPS LHC

Bunch Spacing: 50 ns

Number of Bunches per Batch: 36

Number of Batches: 4

Batch Spacing: 250 ns

Inj Bucket Selector Calc.

Settings:

BQM Beam Dump: Enabled

Verify Pattern: Enabled

Acquisition Full Scale: 2 V

Bunch Length Min Threshold: 1.00 ns

Bunch Length Max Threshold: 1.81 ns

Bunch Length Standard Deviation: 0.18 ns

Bunch Peak Standard Deviation: 0.050 V

Bunch Peak Min Threshold: 1.200 V

Bunch Peak Max Threshold: 1.500 V

Bunch Peak Modulation Index Threshold: 1.00

Satellites Intensity Threshold: 4%

Satellites Mid Bucket Threshold: 4%

Results: SPS Mastership SSC Number: 5279 2012.06.01 01:58:54

Time	Cycle ...	Master	Dump	Beam	1st Bu ...	Bu length	Bu Leng...	Bu Peak	Bu Peak Std	Stability	Satelli...	Pattern	Warnings
01:58:54	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:58:10	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:57:27	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:56:44	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:56:01	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:55:18	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:54:34	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:53:51	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:53:08	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:52:25	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:51:42	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:50:58	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:50:15	LHC1	SPS	Enabled	Error	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Error	Could r...
01:49:32	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:48:49	LHC1	SPS	Enabled	Error	Ok	Ok	Ok	Ok	Ok	Ok	Error	Ok	Could r...
01:48:06	LHC1	SPS	Enabled	Error	Ok	Error	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:47:22	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:46:39	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:45:56	LHC1	SPS	Enabled	Error	Ok	Ok	Ok	Ok	Ok	Ok	Error	Ok	Could r...
01:45:13	LHC1	SPS	Enabled	Error	Ok	Error	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:44:30	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:43:46	LHC1	SPS	Enabled	Error	Ok	Error	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:43:03	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:42:20	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:41:37	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:40:54	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:40:10	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:39:27	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:38:44	LHC1	SPS	Enabled	Error	Ok	Ok	Ok	Ok	Ok	Ok	Error	Ok	Could r...
01:38:01	LHC1	SPS	Enabled	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:37:18	LHC1	SPS	Enabled	Error	Ok	Error	Ok	Ok	Ok	Ok	Ok	Ok	Could r...
01:36:34	LHC1	SPS	Enabled	Error	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Error	Could r...
01:35:51	LHC1	SPS	Enabled	Error	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Error	Could r...
01:35:08	LHC1	SPS	Enabled	Error	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Error	Could r...
01:34:25	LHC1	SPS	Enabled	Error	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Error	Could r...
01:33:42	LHC1	SPS	Enabled	Error	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Error	Could r...
01:32:58	LHC1	SPS	Enabled	Error	Error	Error	Error	Ok	Error	Error	Ok	Error	No bea...
01:32:15	LHC1	SPS	Enabled	Error	Error	Ok	Ok	Ok	Ok	Error	Ok	Error	Could r...
01:31:32	LHC1	SPS	Enabled	Error	Error	Ok	Ok	Ok	Ok	Error	Ok	Error	Could r...
01:30:49	LHC1	SPS	Enabled	Error	Error	Error	Error	Ok	Error	Error	Ok	Error	No bea...
01:30:06	LHC1	SPS	Enabled	Error	Error	Ok	Ok	Ok	Ok	Error	Ok	Error	Could r...
01:29:22	LHC1	SPS	Enabled	Error	Error	Ok	Ok	Ok	Ok	Error	Ok	Error	Could r...
01:28:39	LHC1	SPS	Enabled	Error	Error	Ok	Ok	Ok	Ok	Error	Ok	Error	Could r...

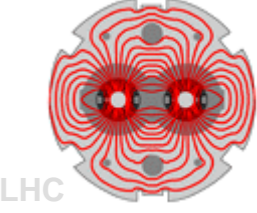
Start Monitoring Stop Save Continuous Saving /user/slops/data/SPS_DATA/OP_DATA/SPSBQM

01:59:13 - Results warnings: Could reduce vertical full scale (fstop).

- Logical “AND” of all analysis results, if FALSE beam dumped before extraction 7



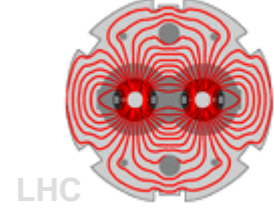
Injection Quality Check in the LHC



- o Analysis carried out after each LHC injection – Interlocks next injection in case of bad result
- o Collects and analyses data from many systems – BLMs, transfer lines, BPMs, LHC BQM, injection kickers, RF phase error, (SPS scraping)
- o Uses LHC Postmortem framework
 - Framework for analysis modules – plugin
 - Partly postmortem push of frontends, partly subscription through CMW
 - All raw data and analysis results stored on Postmortem server
- o Running on a JAVA server
- o Analysis is triggered by LHC injection event. Data is collected and stored as “Event”
- o Modules individually maskable – special LHC modes, tests (e.g. inject & dump)
- o Result available after ~ 8 s



Injection Quality Check in the LHC



- o 4 possible overall results for injection sequencer: repeat, no kick, bad, success
 - No kick and bad also interlock the injection

LHC Injection Quality Check

File Mask Help

RBA: lhcop Beam 1: ✓ Beam 2: ✓ Last injection: Beam 2

Injection IR2 Injection IR8

2012-05-30 19:33:09.950: Beam injected! BQMs: Injected 144 bunches(156 bunches circulating).

BEAM EXTRACTION INJECTION KICKER BEAM LOSS MONITO... RF BUCKET CHECK INJECTION OSCILLAT... TRANSFER LINE RF PHASE

2012-05-30 19:33:09.966: Beam losses are within thresholds.

Monitor name	Max loss	Applied thre...	IQC ref	Dump thres...	Filter factor	Ratio to du...
BLM01.03R8.B2E10_MQNA	0.1869	0.0	0.0	2.3168	1.0000	8.07%
BLME1.04R8.B2E10_MBNB	1.7740	0.0	0.0	23.1431	1.0000	7.67%
BLME1.06R7.B2I10_TCP.C6R7.B2	1.7751	0.0	0.0	23.1680	1.0000	7.66%
BLM01.06L8.B1E30_MQML	0.1520	0.0	0.0	2.3168	1.0000	6.56%
BLME1.06R7.B2I10_TCP.D6R7.B2	1.1250	0.0	0.0	23.1680	1.0000	4.86%
BLME1.04L8.B2I10_TCLIA.4L8	1.0793	2.3150	4.63	23.1680	1.0000	4.66%
BLM01.06L8.B2I10_MOML	0.1070	0.0	0.0	2.3168	1.0000	4.62%
BLME1.06R7.B2I10_TCP.B6R7.B2	1.0463	0.0	0.0	23.1680	1.0000	4.52%
BLME1.06L8.B2I10_TCLIB.6L8.B2	1.0026	2.3150	4.63	23.1680	1.0000	4.33%

Max plot Per slot Per BLM

Losses at injection collimators Losses at injection stopper Transfer line losses

Max larger than reference. The Gy factor was 2.53E-4

Slot: 0 Select slot find: Get LSA references Set references Read references from a file Write references to file

Get last result: B1 Get last result: B2 Stop monitoring: B1 Stop monitoring: B2 Unlatch: B1 Unlatch: B2

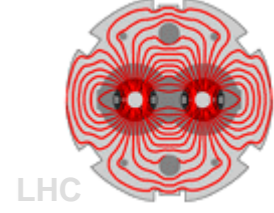
19:33:16 - Beam injected! BQMs: Injected 144 bunches(156 bunches circulating).

IQC GUI:

LHC BLM module



Injection Quality Check in the LHC



- o If injection oscillations are above limit – can only re-inject with maximum 12 bunches. Aperture conservation in LHC and Damper good damping range.
- o Injection oscillation injection interlock

L. Drosdal

LHC Injection Quality Check

File Mask Help

RBA: Ihcop Beam 1: ✓ Beam 2: ✓ Last injection: Beam 2

Injection IR2 Injection IR8

2012-05-30 19:33:09.950: Beam injected! BQMs: Injected 144 bunches(156 bunches circulating).

BEAM EXTRACTION INJECTION KICKER BEAM LOSS MONITORS RF BUCKET CHECK INJECTION OSCILLA... TRANSFER LINE RF PHASE

2012-05-30 19:33:09.956: BPM analysis was good: injection oscillations are within thresholds.

Bunch ID \ Thresholds:	RMS_H	MAX_H	RMS_V	MAX_V
66	0.1486	0.4643	0.2178	0.4465
68	0.1537	0.3969	0.1520	0.3521
70	0.1532	0.3718	0.1717	0.3507
72	0.1674	0.4419	0.1937	0.3988
74	0.1739	0.4663	0.2233	0.5308
76	0.1742	0.4175	0.2575	0.6353

Per bunch Trends

Horizontal parameters over bunches

Vertical parameters over bunches

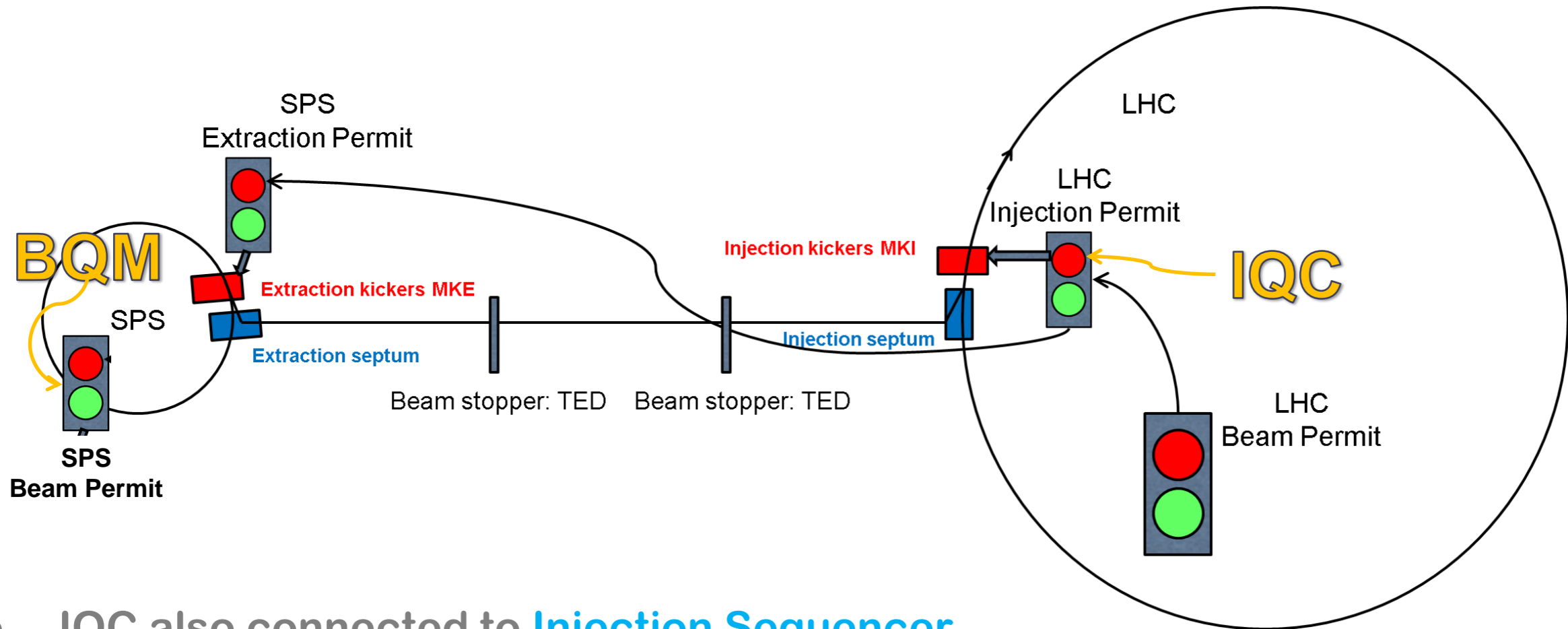
Bad bunch acceptance: 0.25 Bad BPMs acceptance: 0.5

Get LSA references Set references Interlock Reset

Get last result: B1 Get last result: B2 Stop monitoring: B1 Stop monitoring: B2 Unlatch: B1 Unlatch: B2

19:33:16 - Beam injected! BQMs: Injected 144 bunches(156 bunches circulating).

- o BQM connected to SPS Beam Permit
- o IQC connected to injection Software Interlock System (SIS), the injection SIS is connected to the injection permit



- o IQC also connected to **Injection Sequencer**
 - Programs the next injection in the injector timing system
 - Programs all the equipment with required settings for next injection:
 - Pattern of BQM
 - Next injected bunches for bunch-by-bunch measurement systems
 - ...

- o Injection sequencer: pre-programmed series of different shots
 - Different number of bunches, different RF bucket, ...
- o Injection sequencer only plays next request if IQC result was good.

INJECTION SEQUENCER v0.3.3

▼ RBA: lhcop

Injection schemes 50ns_1380b_1380_0_1274_144bpi12inj

Filter: 1380 LOAD **OVER_INJECTION** PILOT R1 : 5791 PILOT R2 : 5791

GRP : 50ns Select

INJECTION RING1						INJECTION RING2					
RFBucket	NbrBch...	BnchSpac(ns)	PS btchs	BnchInt[E9]	I level	RFBucket	NbrBch...	BnchSpac(ns)	PS btchs	BnchInt[E9]	I level
61	12	50	1	100	INTR	61	12	50	1	100	INTR
651	144	50	4	100	NOM	651	144	50	4	100	NOM
4121	144	50	4	100	NOM	4121	144	50	4	100	NOM
7721	72	50	2	100	NOM	7721	72	50	2	100	NOM
9591	144	50	4	100	NOM	9591	144	50	4	100	NOM
13061	144	50	4	100	NOM	13061	144	50	4	100	NOM
16661	72	50	2	100	NOM	16661	72	50	2	100	NOM
18531	144	50	4	100	NOM	18531	144	50	4	100	NOM
22001	144	50	4	100	NOM	22001	144	50	4	100	NOM
25481	72	50	2	100	NOM	25481	72	50	2	100	NOM
27351	144	50	4	100	NOM	27351	144	50	4	100	NOM
30821	144	50	4	100	NOM	30821	144	50	4	100	NOM

Scheme active when loaded
 Allows online buck modif
 Disable inj trims

Display circ bu conf
 Clear active scheme
 Refresh list

INJECTION_SUCCESS **INJECTION_SUCCESS**

RESET Start Step STOP DB/BQM check Enable inj cleaning Clear bch conf set Bu int MD OPTIONS

check reservation Take the reservation cwo-ccc-d4lc.cern.ch Request LHC mastership Remove LHC mastership LHC mastership

12:44:18 : IQC_RESULT BEAM1 >>> INJECTION OK
 Beam injected! BQMs: Injected 144 bunches(1380 bunches circulating).

12:43:35 : IQC_RESULT BEAM2 >>> INJECTION OK
 Beam injected! BQMs: Injected 144 bunches(1380 bunches circulating).

12:44:19 - INJECTION RING 1 : IQC analysis OK

UNLATCH B1 LATCH STATUS B1
 UNLATCH B2 LATCH STATUS B2

1. No **transverse quality monitor** in injectors.
 - Typical issues: **tails and larger emittances**
 - ❑ Noticed due to problem with losses in the transfer lines and later in cycle
 - ❑ Lower peak luminosity
 - ❑ (profile measurements in the LHC have limitations)
 - No continuous emittance measurement in the injectors
 - ❑ Only wire scanners

2. Injector and LHC beam parameter evolution as function of LHC fill number
 - Supertable
 - See trends and catch deterioration
 - We are putting a framework in place

- o The LHC injection process is now well understood due offline analysis
- o IQC comes with all the LHC postmortem infrastructure
 - E.g. Replay of stored events with the same tools
 - Re-analyze stored

The extracted

- o The LHC performance **depends on excellent beam quality** from the injectors and conservation through the LHC cycle.
- o Only before or after injection, beam can be rejected due to quality issues because of the LHC cycle length and execution of functions
- o The **Beam Quality Monitor in the SPS** stops beam with bad longitudinal quality
- o The **Injection Quality Check in the LHC** stops from continuing with injection in case quality is bad
- o The LHC online quality checks cover many possible quality issues. Automatic checks of the **transverse emittance and tails** before injection are still **missing**
- o Storing of and tools to display all relevant beam parameters in the injectors and LHC as function of fill number is necessary to catch deterioration early or push performance further.