Collimator Settings Generation, Management and Verification

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with input from:

R. W. Assmann, D. Jacquet, G. J. Müller

LHC Machine Protection Workshop, 12th March 2013, Annecy.

Outline

- Introduction and Motivation
- Recap of Collimator Settings
- Settings Generation Cycle
- Review of Collimator Status Monitoring
- Errors encountered and Measures taken
- MAD-X Online
- Results and Status of BPM Collimator Operation
- Summary

Introduction and Motivation

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- In the LHC, collimation is required **at all phases** (injection, ramp + squeeze, physics) due to high beam energy.
- The collimator settings depend on key beam parameters e.g. **energy, orbit and β-functions** as a function of time, energy and/or β^*.
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- Overall system performance depends critically on the correct positioning w.r.t. the beam.
- **Unprecedented complexity:** function-based settings, redundant interlocking strategy that change with time.
- **Monitoring of settings** and comparison to the "desired" values is critical.

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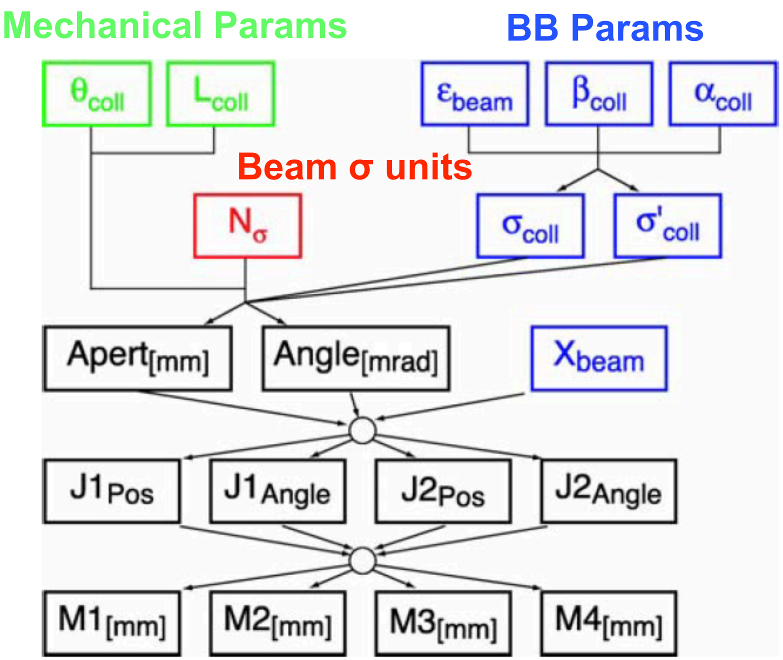
Scope of the talk:

- **To review the settings generation, the errors that occurred and measures taken**
- **To review the present collimator status monitoring system, including MAD-X online**
- **To present the current status of achieving operability of the new BPM collimators**

Recap of Collimator Settings

- The jaw corner positions in mm for any point in the operational cycle are determined from the **local beam-based parameters** and **half-gap opening in beam σ units** at each collimator.

Settings Parameter Space



Jaw Corner Positions

S. Redaelli et al.
EDMS LHC-TCT-ES-0001

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- Typically, the **BB Params** are measured at 4 points: Injection, Flat Top, End of Squeeze, Collisions.

- Functions are generated for a smooth transition of the jaw positions from one point to another.

- The jaw positions are interlocked at all times (typically ± 400 μm or 1 σ):

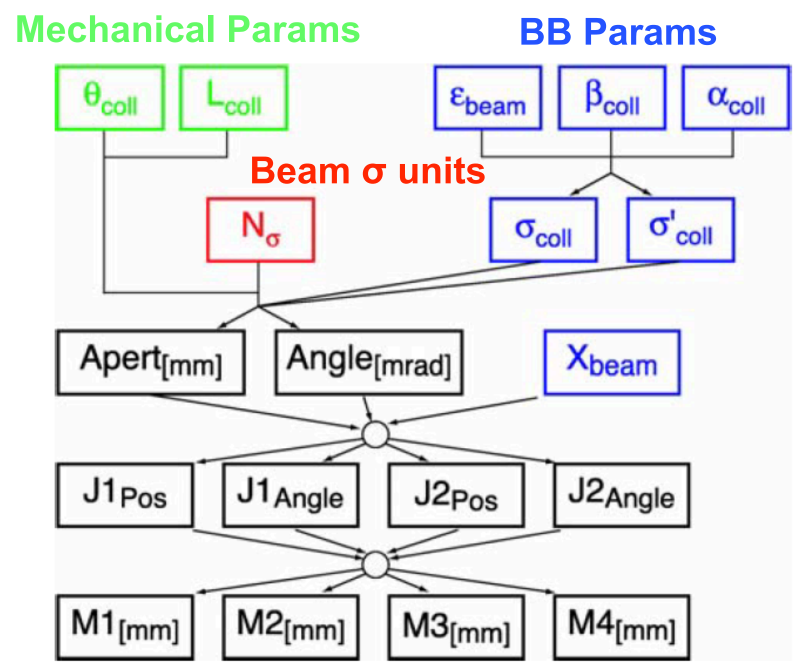
(a) inner/outer limits for each jaw corner (actual/fn BP)

(b) inner/outer β^* limits on the jaw gap (discrete BP)

(c) energy limits on the jaw gap (discrete BP)

- Exceeding the limits triggers a beam dump.

Settings Parameter Space



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Settings Generation Cycle

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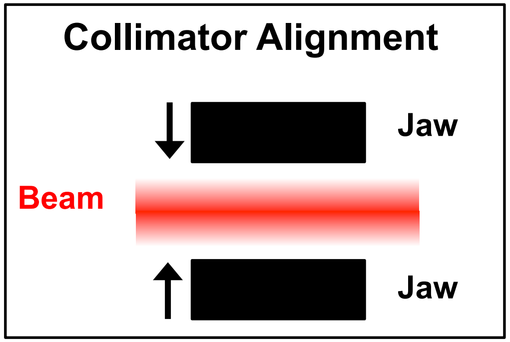

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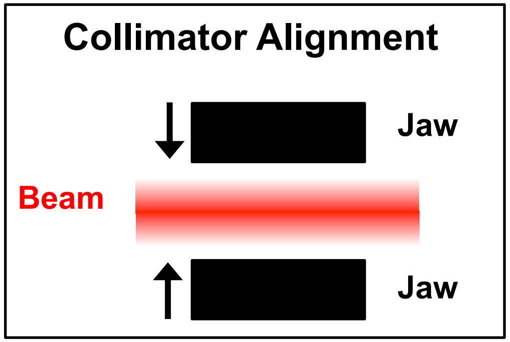


Potential Errors!

Excel Setup Sheet

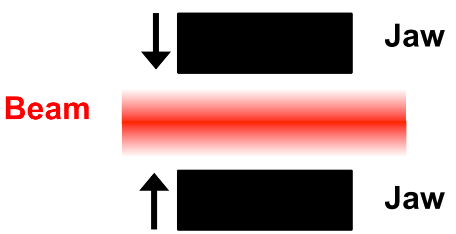
Block 2: Perform beam-based alignment of all collimators sequentially

		IN	MEAS	MEAS	MEAS	RES	RES	RES	OUT	OUT	IN/RES
	Collimator Name	angle [deg]	JAW L calib [mm]	JAW R calib [mm]	LVDT gap	Gap Offset [mm]	Half Gap Meas [mm]	Eff sigma in coll plane [mm]	JAW L setting [mm]	JAW R setting [mm]	Target HALF GAP [sigma]
7	TCP.C6L7.B1	0	4.420	-4.805		-0.193	4.613	n/a	n/a	n/a	4.40
8	TCP.6L3.B1	reduce gap by 25% (reduce energy tails)									
9	TCP.C6L7.B1	0	3.295	-3.530		-0.118	3.413	n/a	n/a	n/a	3.26
10	TCSG.4R6.B1	0	5.670	-5.450		0.110	5.560	1.793	12.663	-12.443	7.00
10	TCP.C6L7.B1	0	2.960	-3.210		-0.125	3.085	n/a	n/a	n/a	2.94
11	TCP.C6L7.B1	0	2.960	-3.210	0.000	-0.125	3.085	n/a	n/a	n/a	2.94
12	TCDQA.B4R6.B1	0	4.900			2.450	2.450	0.858	14.280	0.000	8.00
13	TCP.C6L7.B1	0	2.760	-3.035		-0.138	2.898	n/a	n/a	n/a	2.77
13	TCP.C6L7.B1	0	4.340	-4.540	0.000	-0.100	4.440	n/a	n/a	n/a	4.24
14	TCL.5R5.B1	0	4.205	-4.325		-0.060	4.265	1.039	25.916	-26.036	25.00
15	TCP.C6L7.B1	0	3.990	-4.335		-0.173	4.163	n/a	n/a	n/a	3.97
15	TCP.C6L7.B1	0	4.380	-4.670	0.000	-0.145	4.525	n/a	n/a	n/a	4.32
16	TCTH.4L5.B1	0	1.030	-8.270		-3.620	4.650	1.105	10.739	-17.979	13.00
17	TCP.C6L7.B1	0	4.155	-4.440		-0.143	4.298	n/a	n/a	n/a	4.10
17	TCP.C6L7.B1	0	4.155	-4.440	0.000	-0.143	4.298	n/a	n/a	n/a	4.10
18	TCLA.7R3.B1	0	3.095	-3.065		0.015	3.080	0.757	7.589	-7.559	10.00

Saved on CCC machines after every alignment

Settings Generation Cycle

Collimator Alignment



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15	TCP.C6L7.B1	0	4.380	-4.670	0.000	-0.145	4.525	n/a	n/a	n/a	4.32
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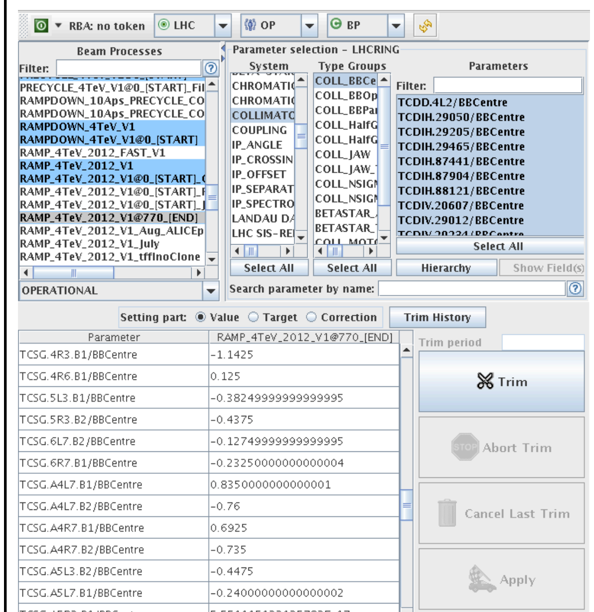
Saved on CCC machines after every alignment

Potential Errors!

Beam Process Settings



Settings Generation Cycle

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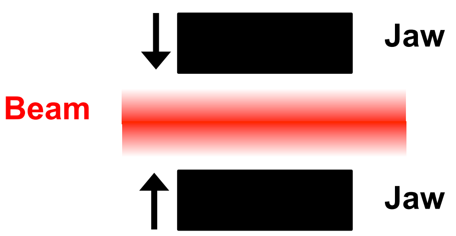


~~Potential Errors!~~

Excel Setup Sheet

Block 2: Perform beam-based alignment of all collimators sequentially

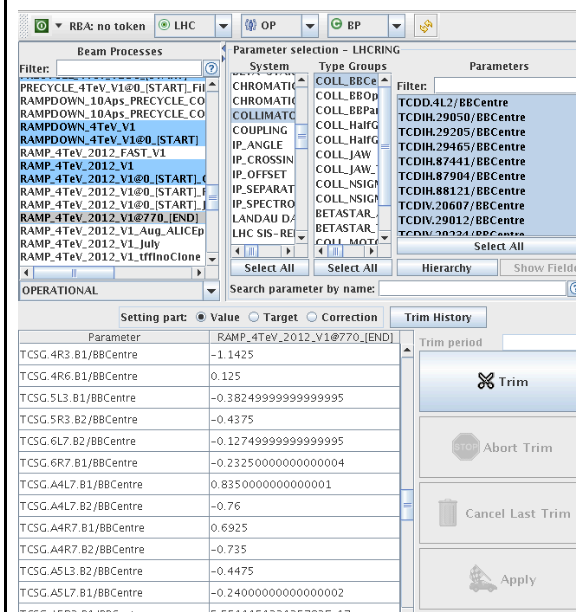
As of 2012: setup sheet now generated automatically by alignment application

							f sigma in coll plane	JAW L Setting (mm)	JAW R Setting (mm)
							n/a	n/a	n/a
							0.551	-0.431	-13.649
							n/a	n/a	n/a
							0.352	1.860	-0.655
							0.942	8.747	-10.087
							n/a	n/a	n/a
TCP.C6R7.B2	0.00	1.830	-0.630	2.376	0.600	1.230	0.352	1.830	-0.630
TCTH.4R2.B2	0.00	1.450	-3.020	4.519	-0.785	2.235	0.791	7.126	-8.696
TCP.C6R7.B2	0.00	1.810	-0.605	2.332	0.602	1.208	n/a	n/a	n/a
TCP.C6R7.B2	0.00	1.810	-0.605	2.331	0.602	1.208	0.352	1.810	-0.605
TCTH.4R5.B2	0.00	4.820	-0.280	5.065	2.270	2.550	0.942	11.687	-7.147
TCP.C6R7.B2	0.00	1.795	-0.580	2.293	0.607	1.188	n/a	0.607	0.607
TCP.D6R7.B2	90.00	1.575	-0.175	1.722	0.700	0.875	n/a	n/a	n/a
TCTVB.4R8	90.00	3.130	-1.720	4.836	0.705	2.425	0.650	8.502	-7.092
TCP.D6R7.B2	90.00	1.535	-0.145	1.651	0.695	0.840	n/a	n/a	n/a
TCP.D6R7.B2	90.00	1.535	-0.145	1.651	0.695	0.840	n/a	n/a	n/a
TCTVA.4R1.B2	90.00	4.380	0.030	4.340	2.205	2.175	0.600	8.202	-3.792
TCP.D6R7.B2	90.00	1.510	-0.110	1.592	0.700	0.810	n/a	n/a	n/a
TCP.D6R7.B2	90.00	1.510	-0.110	1.592	0.700	0.810	n/a	n/a	n/a
TCTVA.4R2.B2	90.00	-0.720	-6.350	5.576	-3.535	2.815	0.840	4.867	-11.937
TCP.D6R7.B2	90.00	1.465	-0.070	1.509	0.698	0.768	n/a	n/a	n/a
TCP.D6R7.B2	90.00	1.465	-0.070	1.509	0.698	0.768	n/a	n/a	n/a
TCTVA.4R5.B2	90.00	2.240	-1.520	3.721	0.360	1.880	0.600	6.357	-5.637
TCP.D6R7.B2	90.00	1.435	-0.040	1.449	0.698	0.738	n/a	0.698	0.698

Saved on CCC machines after every alignment

Potential Errors!

Beam Process Settings



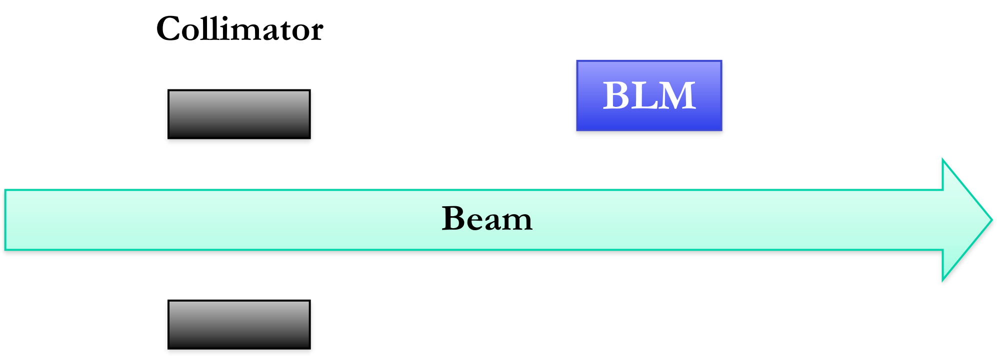
Settings Generation

- Alignments are done at four points to measure the beam centers and beam sizes.
- Functions during squeeze or collisions determined from simulations, and are created with Mathematica or LSA.

Beam Mode	Beam Process	
Injection	Ramp@start	← Alignment (All colls)
Ramp	Ramp function	← $f(\gamma, t)$
Flat Top	Ramp@end / Squeeze@start	← Alignment (All except inj. prot.)
Squeeze	Squeeze function	← $f(\beta^{*}, t)$
Adjust	Squeeze@end / Collisions@start	← Alignment (TCTs)
Adjust	Collisions function	← f(Xing/Sep, t)
Stable Beams	Collisions@end	← Alignment (TCTs + TCLs)

Settings Generation

- Collimator beam-based alignment procedure:



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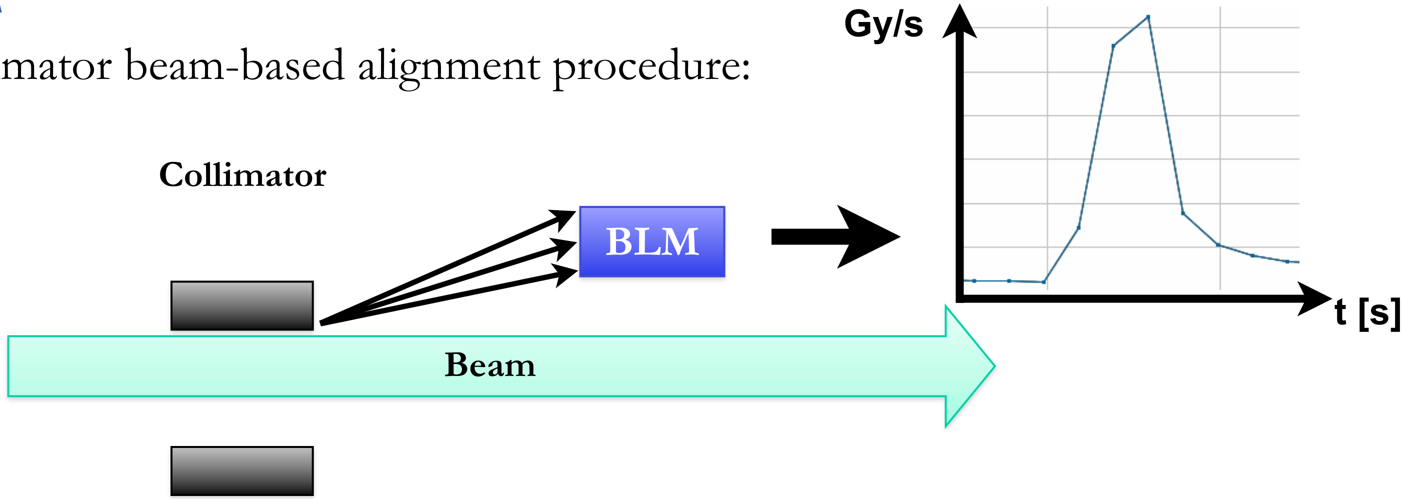

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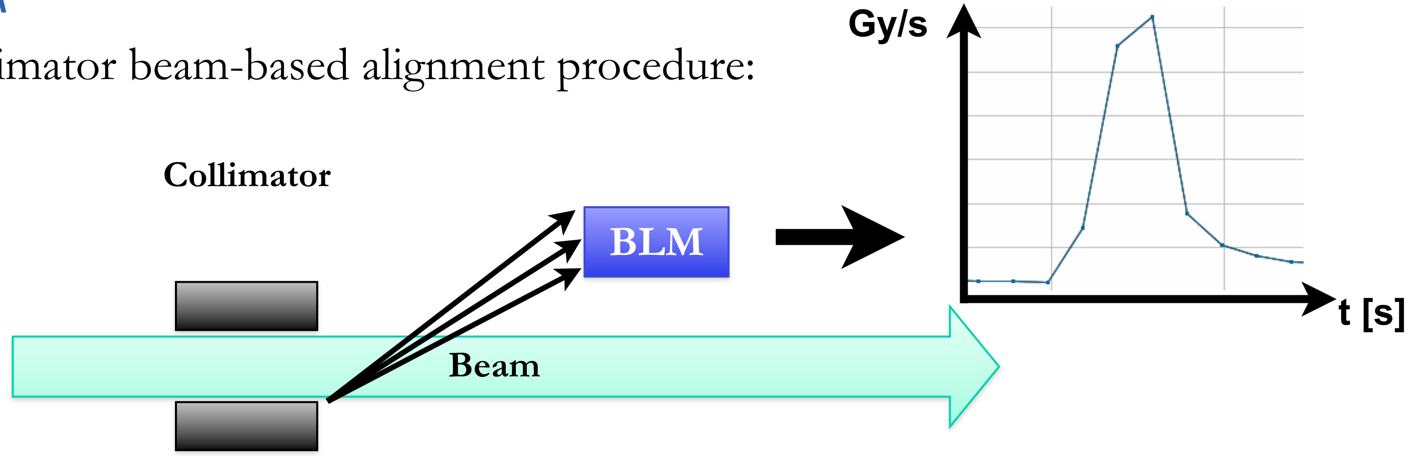

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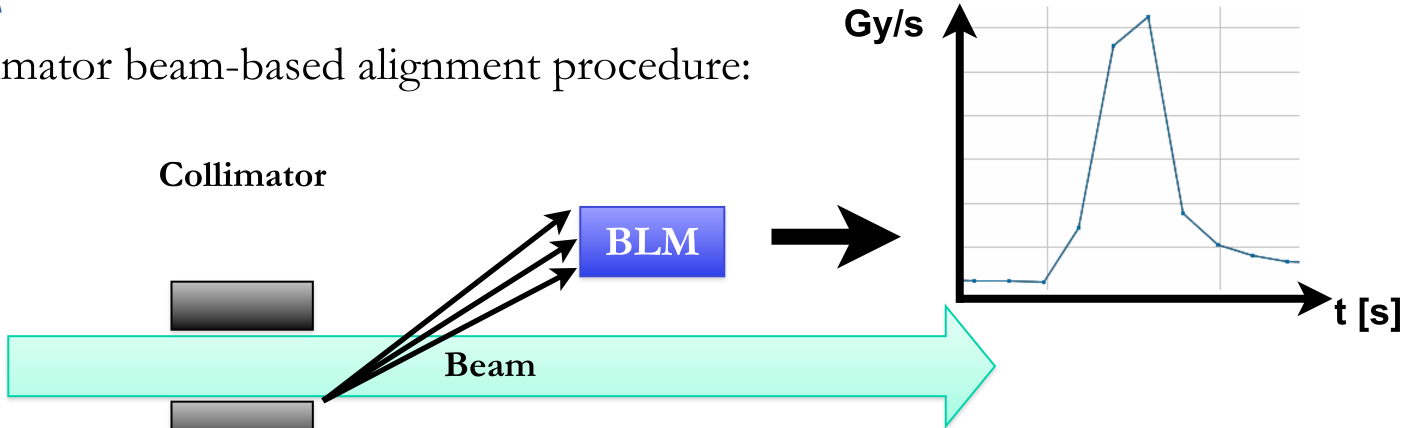

- N is the number of beam σ of the jaw half gap.
- Depends on the collimator family, e.g. TCP IR7, TCSG IR7, TCLA IR7, TCT, TCP IR3….

Beam Centre

$$\Delta x_i = \frac{x_i^{L,m} + x_i^{R,m}}{2}$$

Beam Size

$$\sigma_i^{\text{inf}} = \frac{x_i^{L,m} - x_i^{R,m}}{n_1^{k-1} + n_1^k}$$

New Settings

$$x_i^{L,\text{set}} = \Delta x_i + N_i \sigma_i^{\text{inf}} \qquad x_i^{R,\text{set}} = \Delta x_i - N_i \sigma_i^{\text{inf}}$$

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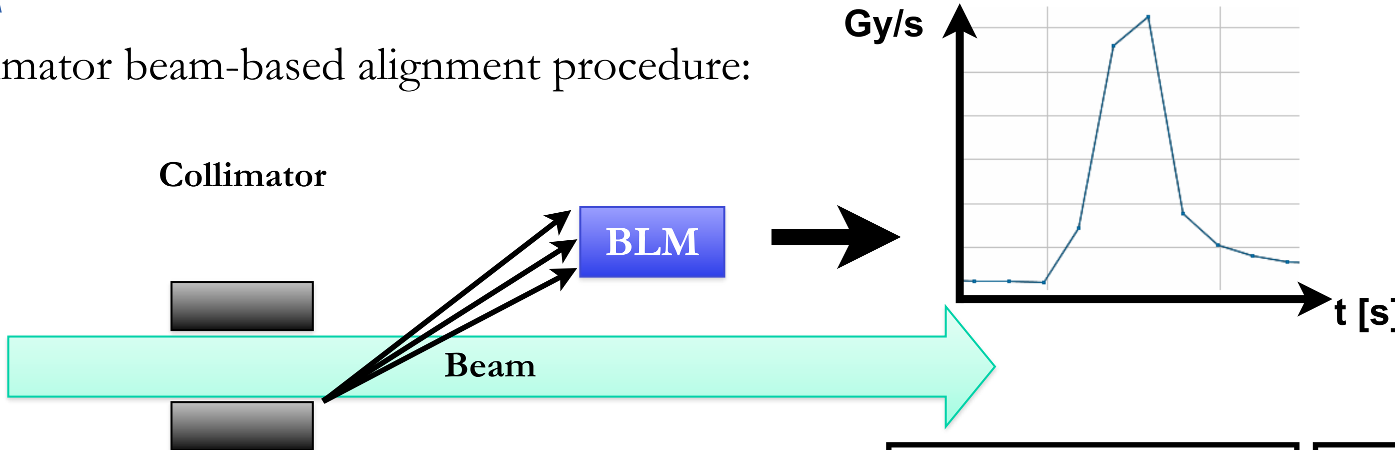

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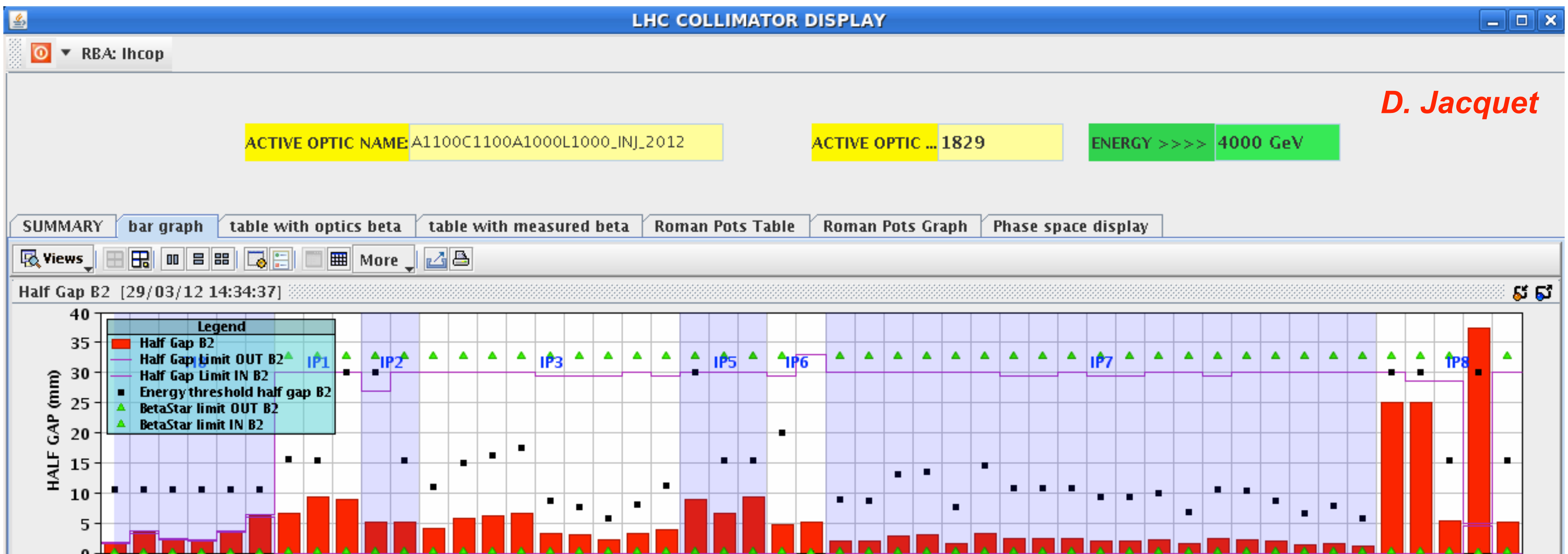
- N is the number of beam σ of the jaw half gap.
- Depends on the collimator family, e.g. TCP IR7, TCSG IR7, TCLA IR7, TCT, TCP IR3….
- At **injection**: the **measured beam size** is used.
- At **top energy**: collimator gaps are smaller in mm and beta-beat < 10 %, hence the **nominal beam size** is used.
- In 2011-2012, several algorithms were introduced to speed up and automate the alignment.
- Time for full alignment: 30 hours (2010) ⟶ 5 hours (2012).

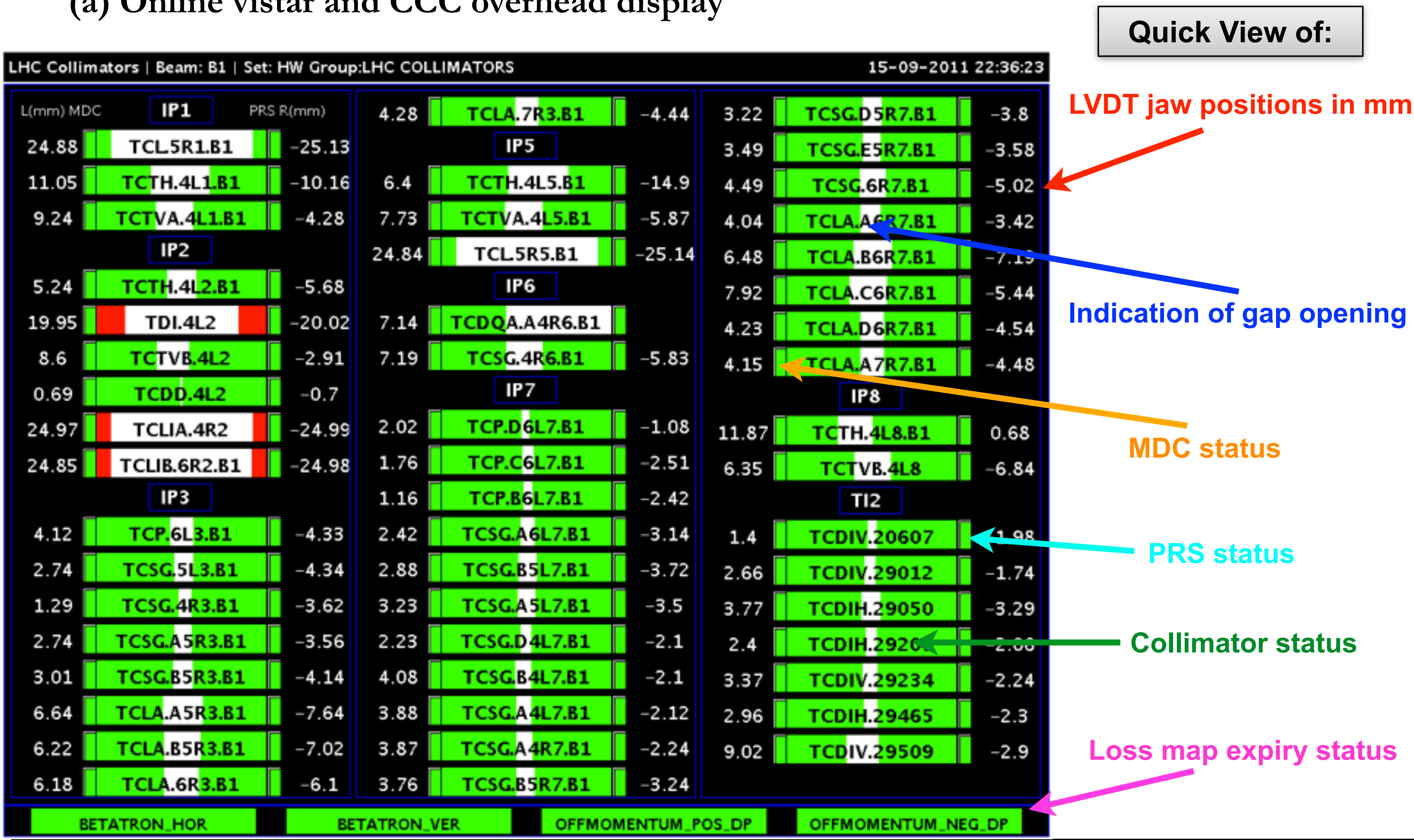
Settings Verification

- Manual verification of generated values by experts.
- Systematic checks of the settings transitions (e.g. ramp to squeeze).
- Low-intensity fill to validate sequencer operation in shade of fills for loss maps or Q/OFB checks.
- All machine configurations are validated by loss maps.
- Online tool to verify the gaps in mm and beam σ + limits:



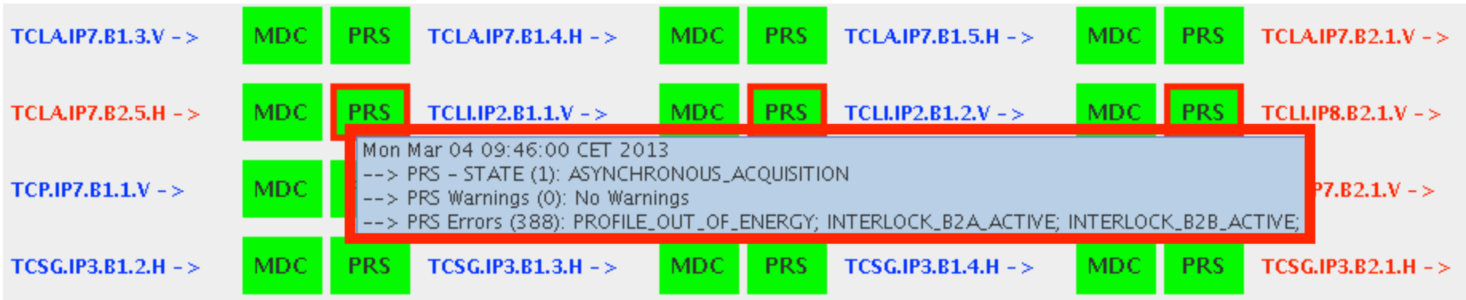
Review of Collimator Status Monitoring

(a) Online vistar and CCC overhead display

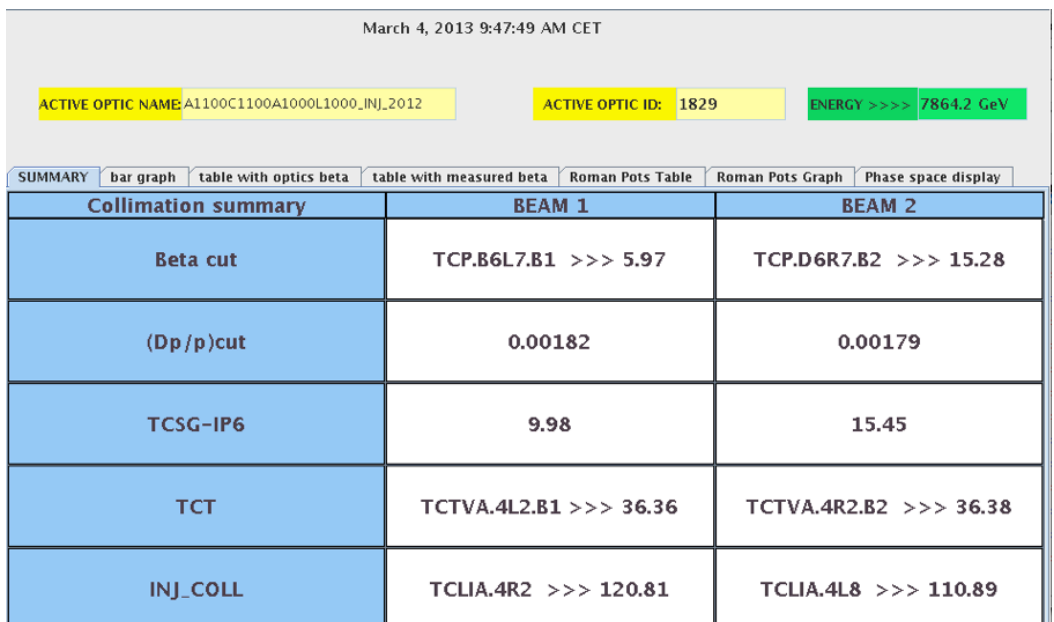


Review of Collimator Status Monitoring

(b) Collimator display for detailed view of the MDC/PRS warnings/errors (S. Redaelli)



(c) Higher-level collimator display, settings in σ units, limits + β-functions (D. Jacquet)



March 4, 2013 9:47:49 AM CET

ACTIVE OPTIC NAME: A1100C1100A1000L1000_INJ_2012 | ACTIVE OPTIC ID: 1829 | ENERGY >>>> 7864.2 GeV

SUMMARY | bar graph | table with optics beta | table with measured beta | Roman Pots Table | Roman Pots Graph | Phase space display

Collimation summary	BEAM 1	BEAM 2
Beta cut	TCP.B6L7.B1 >>> 5.97	TCP.D6R7.B2 >>> 15.28
(Dp/p)cut	0.00182	0.00179
TCSG-IP6	9.98	15.45
TCT	TCTVA.4L2.B1 >>> 36.36	TCTVA.4R2.B2 >>> 36.38
INJ_COLL	TCLIA.4R2 >>> 120.81	TCLIA.4L8 >>> 110.89

Review of Collimator Status Monitoring

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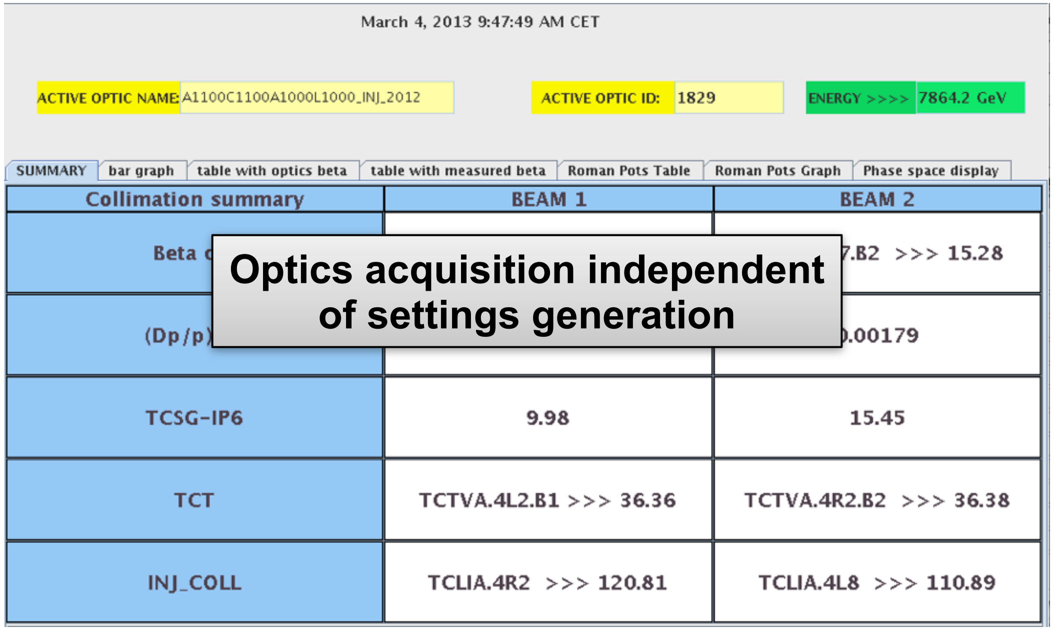

Settings errors in the 2010-2013 run

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1. **March 2012:** TCTVA.4R1.B2 (flat top), TCTVA.4R2.B2 (collisions)
   - **Error:** TCTVA.4R1.B2 center shifted by 1.8 σ at a gap of 26 σ
     TCTVA.4R2.B2 center shifted by 3.8 σ at a gap of 12 σ
   - **Action:** trimmed in the new values

2. **March 2012:** 2 IR3 collimators (ramp function)
   - **Error:** when calculating functions, centers set to 0
   - **Action:** no action necessary (errors small compared to IR3 gap openings, no need to repeat loss maps)

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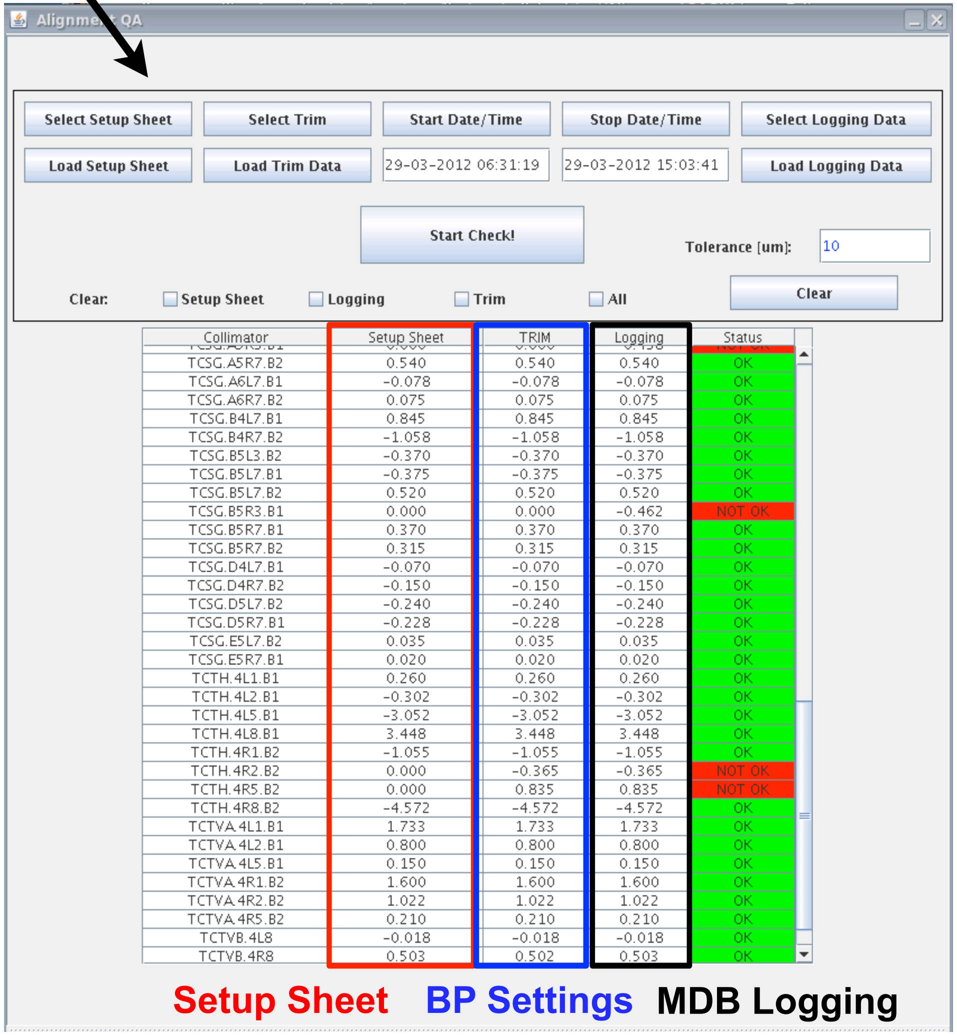
- Belen will discuss the beam-based validation of the settings in greater detail.

- For 1097 collimators aligned in 41 alignment campaigns ⟶ error = 0.36 %

Measures taken to avoid similar errors

- Following the settings errors in March 2012, a **tool** was developed for post-alignment checks.
- Used systematically since, although no further errors were detected.



Collimator	Setup Sheet	TRIM	Logging	Status
TCSG.A5R7.B2	0.540	0.540	0.540	OK
TCSG.A6L7.B1	-0.078	-0.078	-0.078	OK
TCSG.A6R7.B2	0.075	0.075	0.075	OK
TCSG.B4L7.B1	0.845	0.845	0.845	OK
TCSG.B4R7.B2	-1.058	-1.058	-1.058	OK
TCSG.B5L3.B2	-0.370	-0.370	-0.370	OK
TCSG.B5L7.B1	-0.375	-0.375	-0.375	OK
TCSG.B5L7.B2	0.520	0.520	0.520	OK
TCSG.B5R3.B1	0.000	0.000	-0.462	NOT OK
TCSG.B5R7.B1	0.370	0.370	0.370	OK
TCSG.B5R7.B2	0.315	0.315	0.315	OK
TCSG.D4L7.B1	-0.070	-0.070	-0.070	OK
TCSG.D4R7.B2	-0.150	-0.150	-0.150	OK
TCSG.D5L7.B2	-0.240	-0.240	-0.240	OK
TCSG.D5R7.B1	-0.228	-0.228	-0.228	OK
TCSG.E5L7.B2	0.035	0.035	0.035	OK
TCSG.E5R7.B1	0.020	0.020	0.020	OK
TCTH.4L1.B1	0.260	0.260	0.260	OK
TCTH.4L2.B1	-0.302	-0.302	-0.302	OK
TCTH.4L5.B1	-3.052	-3.052	-3.052	OK
TCTH.4L8.B1	3.448	3.448	3.448	OK
TCTH.4R1.B2	-1.055	-1.055	-1.055	OK
TCTH.4R2.B2	0.000	-0.365	-0.365	NOT OK
TCTH.4R5.B2	0.000	0.835	0.835	NOT OK
TCTH.4R8.B2	-4.572	-4.572	-4.572	OK
TCTVA.4L1.B1	1.733	1.733	1.733	OK
TCTVA.4L2.B1	0.800	0.800	0.800	OK
TCTVA.4L5.B1	0.150	0.150	0.150	OK
TCTVA.4R1.B2	1.600	1.600	1.600	OK
TCTVA.4R2.B2	1.022	1.022	1.022	OK
TCTVA.4R5.B2	0.210	0.210	0.210	OK
TCTVB.4L8	-0.018	-0.018	-0.018	OK
TCTVB.4R8	0.503	0.502	0.503	OK

Tool operation:

1. Reads the centers from the setup sheet.
2. Automatically calculates the centers at the time of alignment from the MDB.
3. Exports the LSA settings used by the operational sequence for the appropriate beam process.
4. Compares the different values.

Future work:

- Comparison also between the jaw corner positions ("external parameters") that are sent to the hardware.
- Possibility to select MDB or LDB (for previous fills).
- Could be used to compare LSA and Timber jaw settings after power cuts.

Possible Improvements in Collimator Status Monitoring

- **LHC Alarms SERvice (LASER):** should be used more by the OP crews for diagnostic purposes, e.g. for identifying warnings (orange colour) in collimator status display.

- Assign actions to be taken by OP for the different collimator errors / warnings.

- Plan to **develop further the post-mortem collimation buffer** so that expert does not need to dig through the data when called by OP in case of errors.

- **Better interlock colour-coding:** e.g. energy interlocks for injection protection collimators should not show up in red after the start of the ramp.

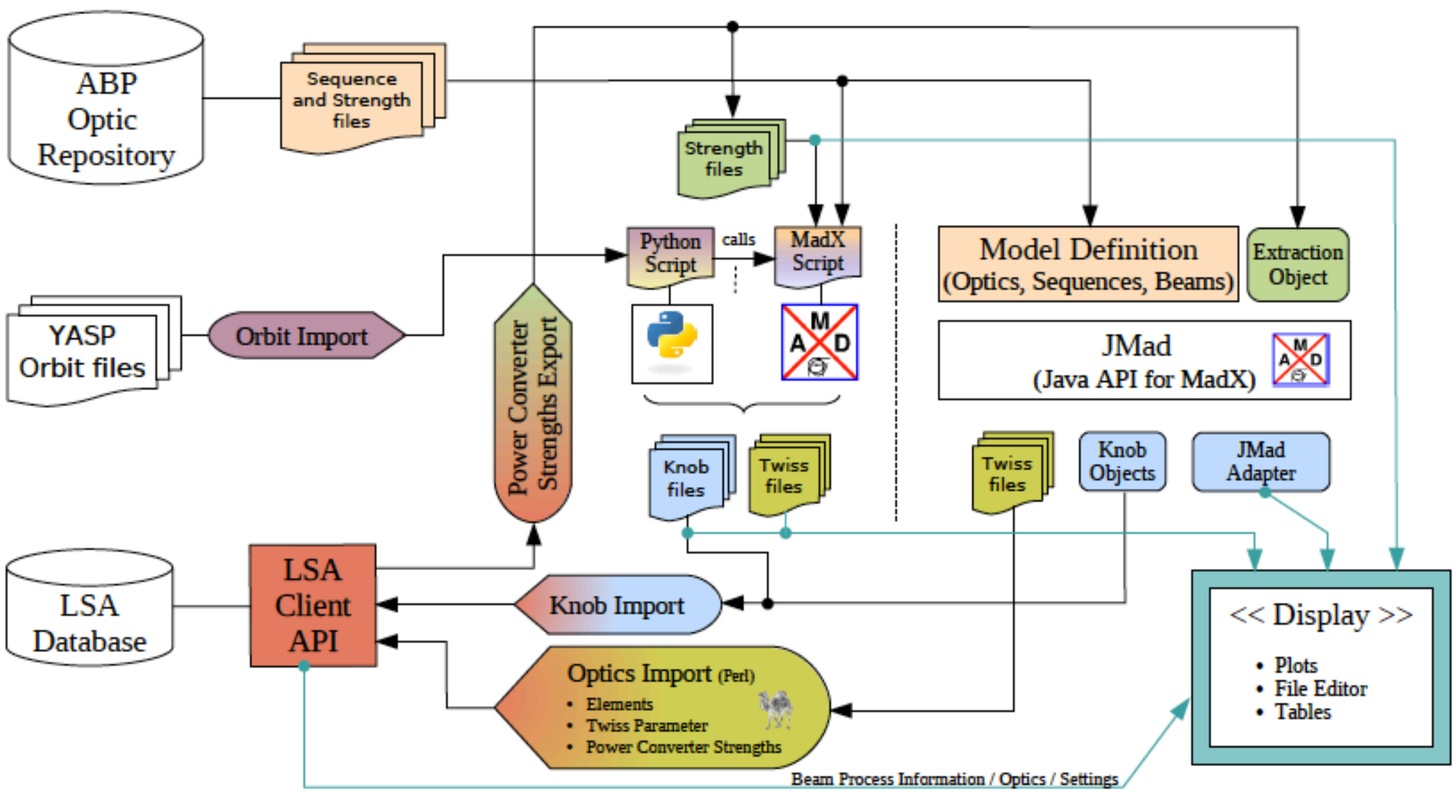
- The **State Machine** checks that the TCTs are at the correct stable beams settings, i.e. make sure that the collision functions were executed correctly
  - could be possibly improved to detect any problems at the start of collisions process.

- Acquisition of the measured β-functions in the collimator settings display.

MAD-X Online

- The online model provides an environment to support:
    - the use of MAD-X simulations and calculations as control system inputs
    - operators while coping with the complexity of the machine
    - simulation of machine manipulations

➢ How does it work? ⇨ Online Model System Overview



G. Müller, Gentner Day'10

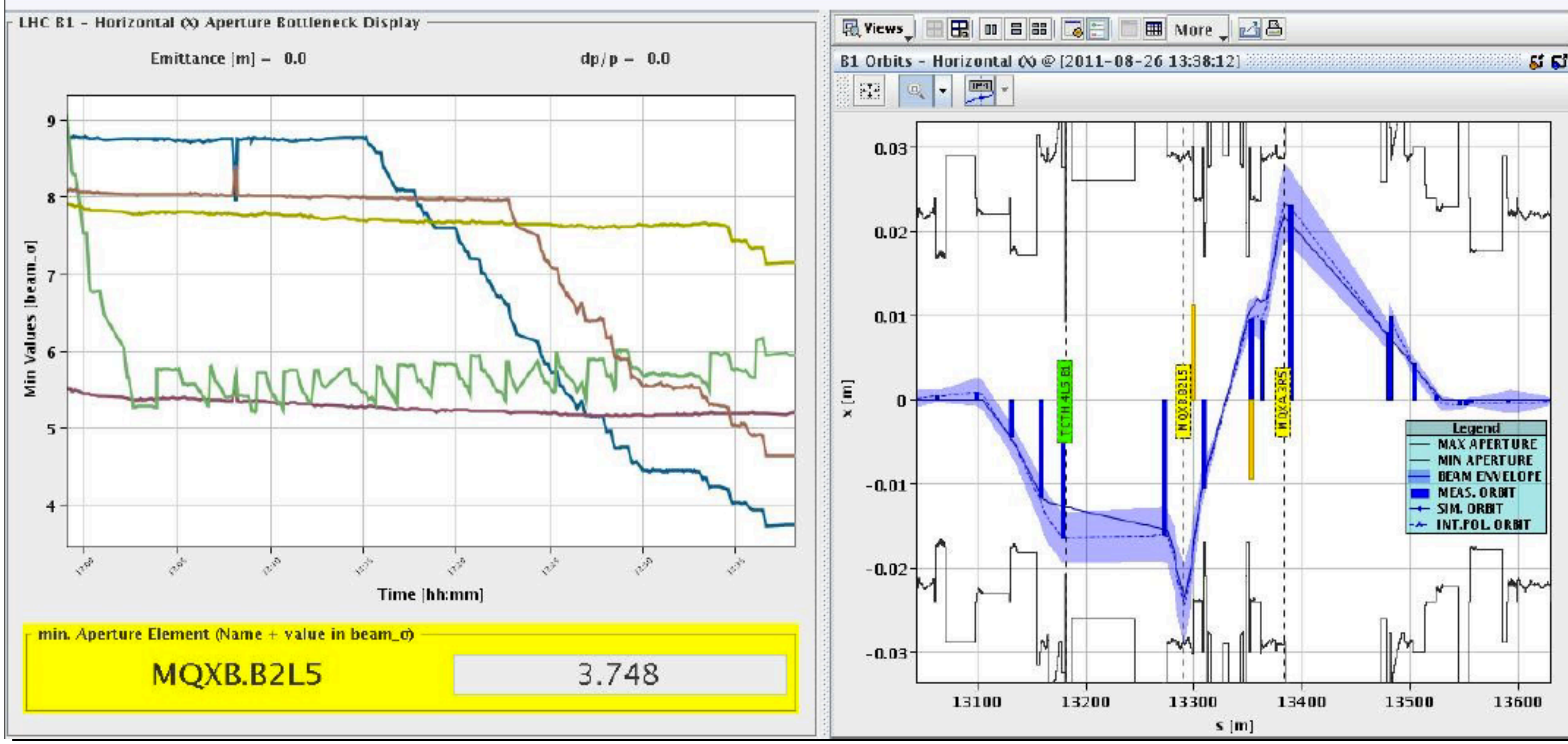
LHC Aperture Meter

LHC Collimation Project CERN

Usage:

- online acquisition of BPM-interpolation to speed up collimator alignment (see HB 2012 paper)
- playback of settings during ramp and squeeze, possibility to catch settings errors (work in progress)
- orbit checks (incl. ATS, 90 m) and **aperture measurements:**

minimal aperture evolution (beam 1 horizontal) during triplet aperture scan in IP5 (CMS) to determine the maximal available aperture before the decision was take to further reduce the β* to 1.0m



G. Müller, ICALEPCS'11

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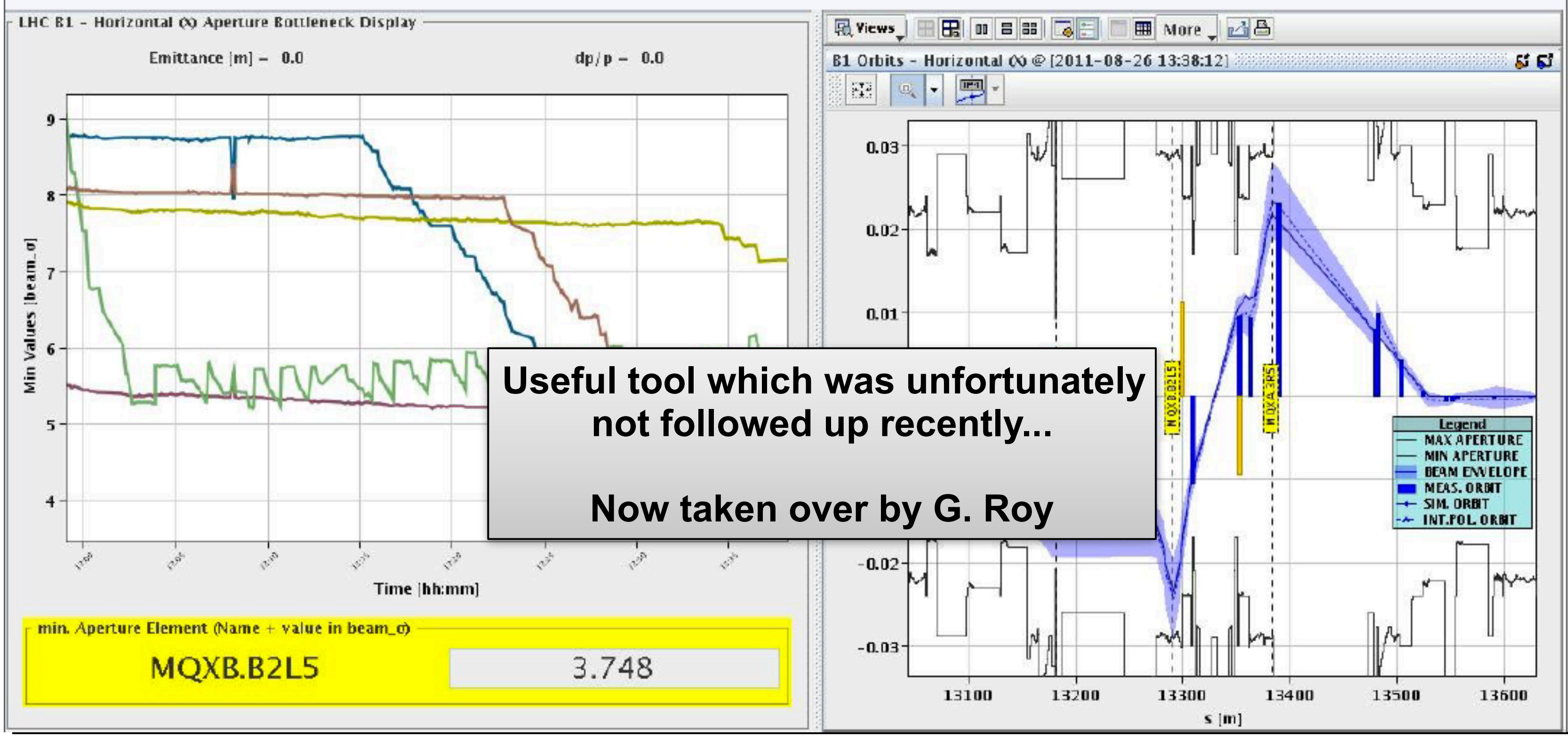


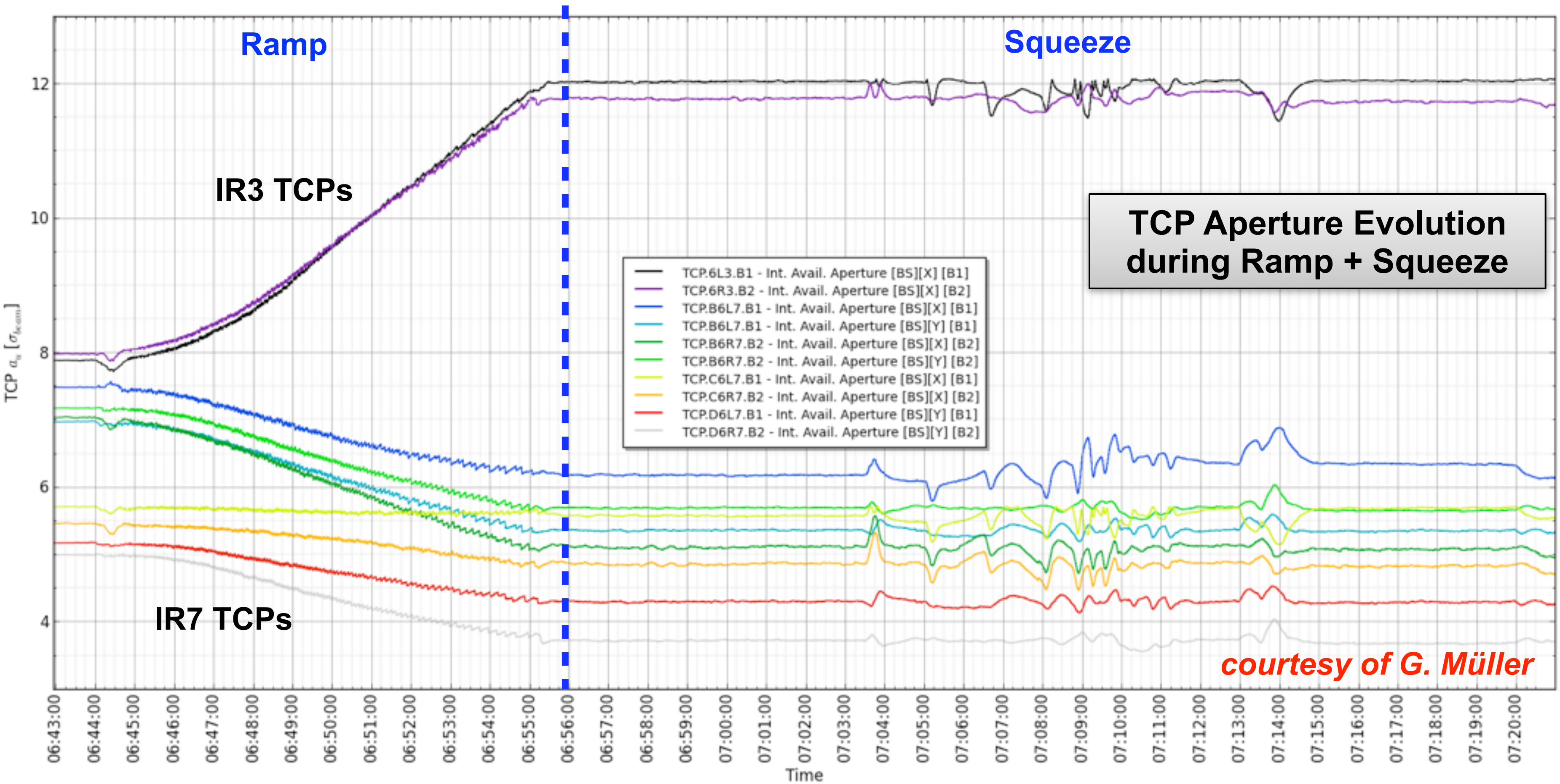
Useful tool which was unfortunately not followed up recently...

Now taken over by G. Roy

G. Müller, ICALEPCS'11

TCP Aperture Evolution

- Aperture calculation not accurate to < 1 σ, but can provide an independent check of the settings.
- **Inputs:** orbit, current collimator positions and optics (**NOT** LSA collimator settings).

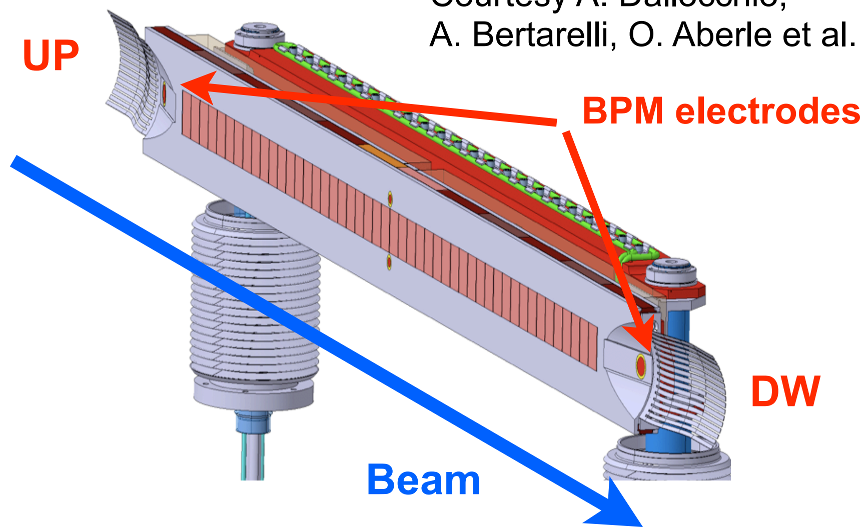


Results and Status of BPM Collimator Operation

Results and Status of BPM Collimator Operation

- Collimators with embedded BPM buttons will replace current TCTs and IR6 TCSGs in LS1.

Courtesy A. Dallocchio, A. Bertarelli, O. Aberle et al.



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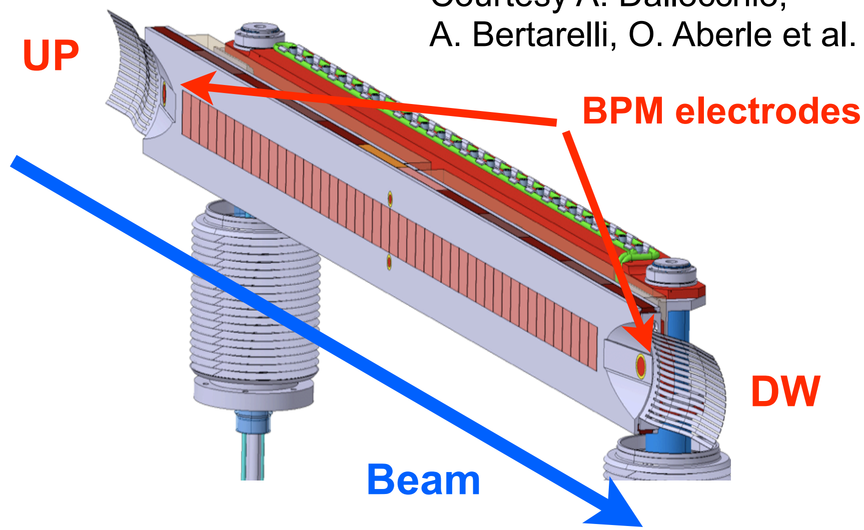

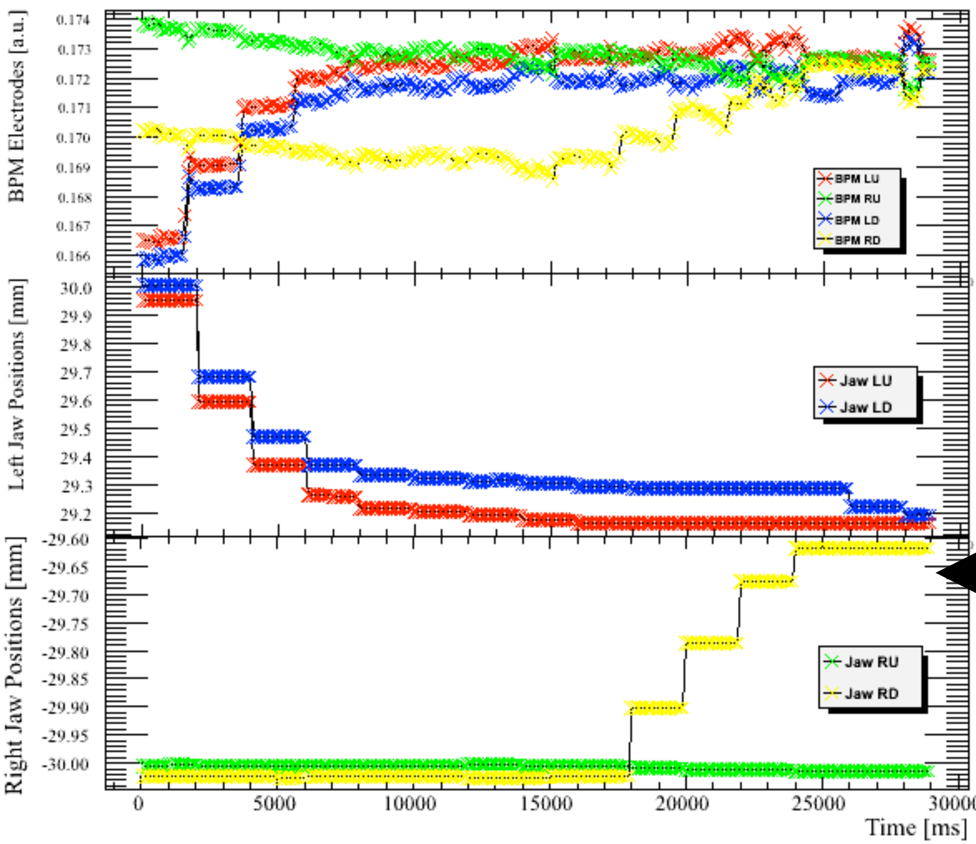

< 30 s alignment time!

After proof-of-principle SPS tests in 2010-2011, automatic alignment algorithm tested in 2012.

$$J_i = \frac{Gap_{BPM}}{4} \times \frac{V_A - V_B}{V_A + V_B} + J_{i-1}$$

Successive approximation algorithm

Results and Status of BPM Collimator Operation

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- 1 hour is currently required for an alignment of 16 TCTs ⟶ **factor 120 improvement!**
- In 1 year of operation (e.g. 2012): gain of 8 hours (8 TCT alignments).
- Gain in β^* reach (see talk by Roderik for more details).

Results and Status of BPM Collimator Operation

LHC Collimation Project CERN

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- In 1 year of operation (e.g. 2012): gain of 8 hours (8 TCT alignments).
- Gain in β^* reach (see talk by Roderik for more details).

- **Alignment accuracy:**
  - BPM non-linearities are a function of the jaw gap and beam center.
  - Correction polynomial developed by A. Nosych based on CST Particle Studio simulations (for more details see my talk in Collimation Working Group, 26.11.2012).
  - Accuracy of < 1% of the BPM aperture for beam offsets of up to 50 % and jaw gaps from 2 - 60 mm.
  - Tested during SPS MDs and cross-checked with standard BLM-based alignment.

Results and Status of BPM Collimator Operation

- **Main goal:** elimination of all orbit-related settings errors at the TCTs and IR6 TCSGs!
- BPMs will **improve collimator operation** by providing:
  - online monitoring of beam centres
  - possibility of interlocks on orbit measurements (should always be 0 with centered jaws)
  - fast fill-to-fill TCT alignments, or as frequently as required
- Possible future usage for **transfer line collimators** (SPS measurements done with single pass).
- **Better monitoring in IR6:**
  - find out earlier on possible problems rather than waiting for the infrequent loss maps
  - can also be used for the SIS interlock of the TCDQ centering/retraction (J. Wenninger)
- **Commissioning with beam** will be required to ensure calibration of electronics for correction of noise and BPM non-linearities.
- **Engineering specification** to be drawn up in collaboration with BI team.

Summary

- The collimator settings generation and verification cycle was presented.
- **Potential error locations** in the cycle and tools developed to verify the settings were identified.
- The different components of the present top-level collimator monitoring system were discussed, highlighting the different layers of abstraction.
- A settings error occurred in **4 out of 1097 (0.36 %)** cases in 4 years of operation. A tool was developed to ensure consistency between alignment measurements and LSA settings.
- Possible improvements in the current collimator status monitoring and the status of MAD-X online tools was reviewed.
- Test results for a fast alignment in **< 30 sec** with an accuracy of **< 10 µm**, and the status of current work towards **maximizing the operational potential** with BPM button collimators were presented.

Reserve Slides

Collimator Settings 2010-2013

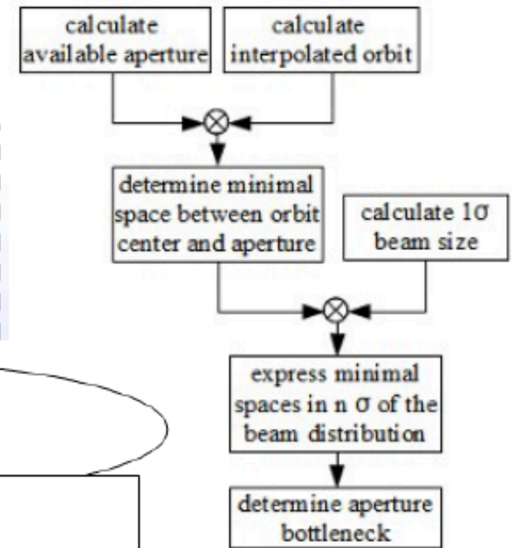
Coll Family	Injection [σ]	Physics Relaxed [σ]	Physics Tight [σ]
TCP IR3	8	12	12
TCSG IR3	9.3	15.6	15.6
TCLA IR3	10	17.6	17.6
TCP IR7	5.7	5.7	4.3
TCSG IR7	6.7	8.5	6.3
TCLA IR7	10	17.7	8.3
TCT	15	11.8	9 / 12 (IP1,5/2,8)
TCL	20	out	10

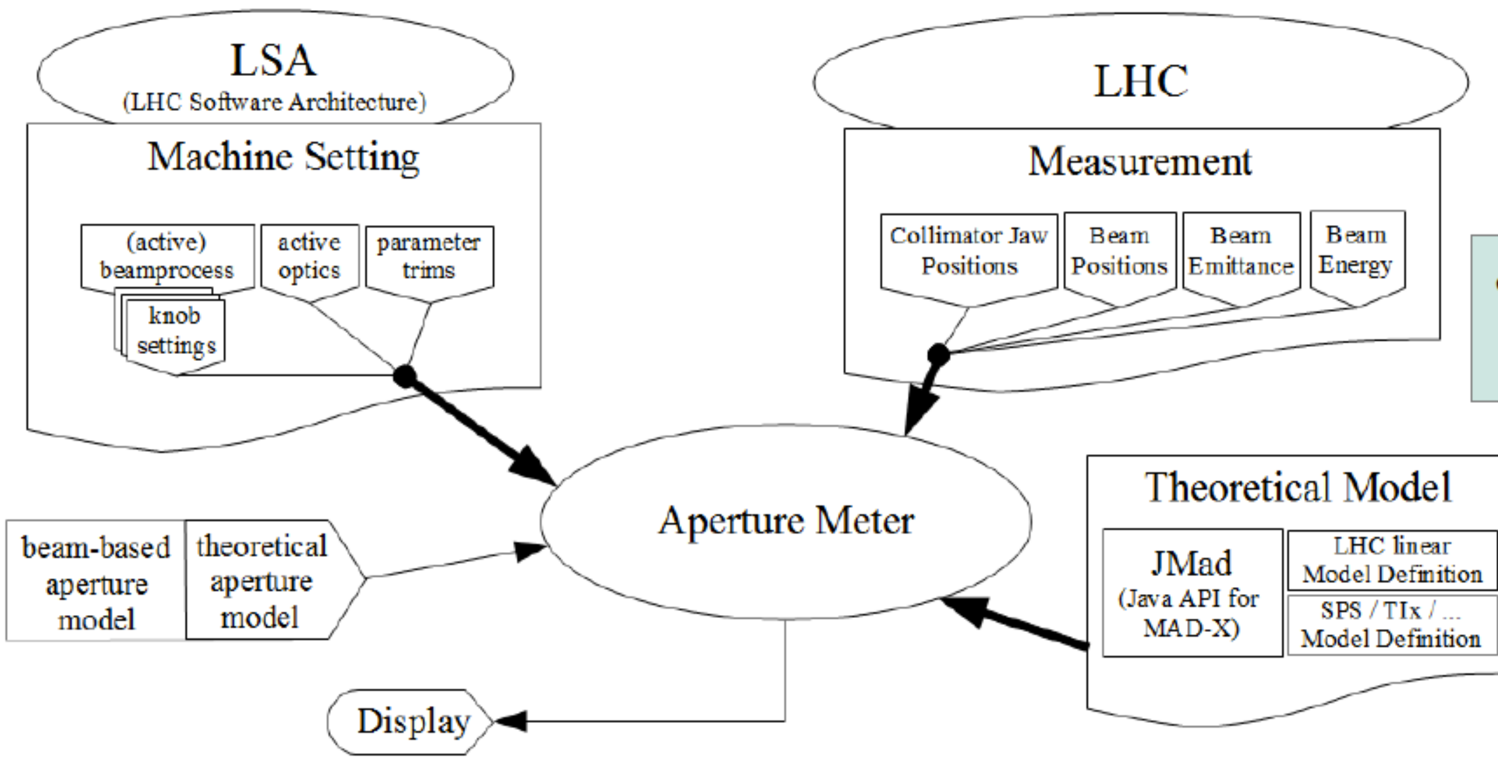
LHC Aperture Meter

Solution / Design

The Aperture Meter as a fixed display in the Control Room

Calculate the available free space for the beam by merging measurements and online simulation data





$$\sigma_u = \sqrt{\beta_u \epsilon_u} \qquad u = x, y$$

β_u ... *beta function*

ϵ_u ... *normalized emittance*

G. Müller, ICALEPCS'11