Luminosity Optimization and Calibration at the LHC

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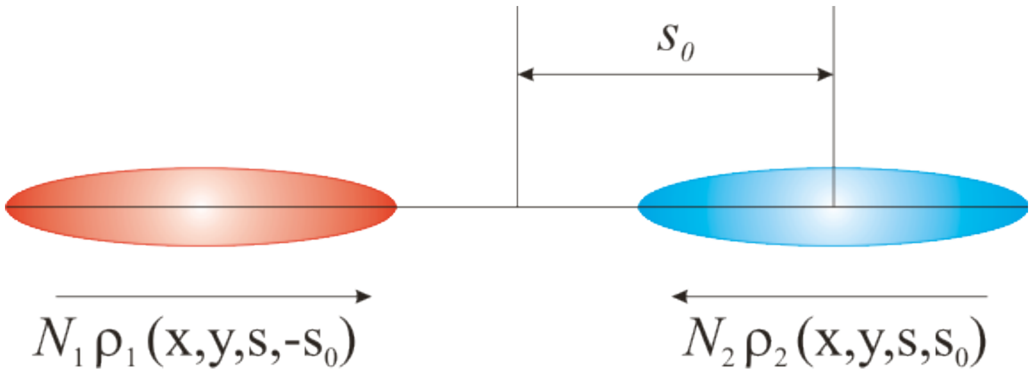
Outline:

Introduction
Luminosity Optimization
Luminosity Calibration
High-β Optics

25 October 2010
LBNL, Berkeley

Luminosity and Collision Rate



- **LHC:** **bunched beams.**
⇒ Consider two bunches going opposite direction with density distribution ρ and number of charges N.

- **For a given process the luminosity is the proportionality factor between of cross section σ and interaction rate dN/dt:**

$$L = N_1 \, N_2 \, f \, K \iiiint \rho_1(x,y,s,-s_0) \, \rho_2(x,y,s,s_0) \, dx \, dy \, ds \, ds_0 = \frac{\dot{N}}{\sigma}$$

- **In the LHC the beams are round and equal by design. The beam is well described by a Gaussian distribution. In this case:**

$$L = \frac{N_1 \, N_2 \, f \, n_b}{4 \, \pi \, \sigma^2}$$

- **High bunch charge and low IP beam sizes increase luminosity.**

Correction Factors

• **Various effects can affect the luminosity:**

• **Un-equal elliptical beams:**

$$L_0 = \frac{N_1 \; N_2 \; f \; n_b}{2 \; \pi \; \sqrt{\sigma_{1x}^2 + \sigma_{2x}^2} \; \sqrt{\sigma_{1y}^2 + \sigma_{2y}^2}}$$

• **Transverse separation:**

$$\frac{L}{L_0} = \exp\left[-\frac{\delta x^2}{2 \; \sqrt{\sigma_{1x}^2 + \sigma_{2x}^2}} - \frac{\delta y^2}{2 \; \sqrt{\sigma_{1y}^2 + \sigma_{2y}^2}} \right]$$

• **Crossing angle:**

$$\frac{L}{L_0} = \left(\sqrt{1 + \frac{\sigma_{1s}^2 + \sigma_{2s}^2}{\sigma_{1x}^2 + \sigma_{2x}^2} \left(\tan \frac{\varphi}{2} \right)^2} \right)^{-1}$$

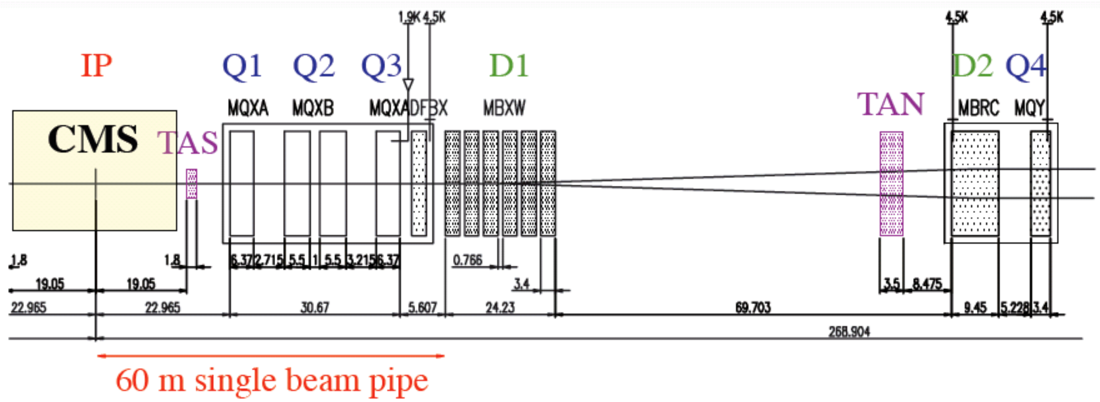
• **Hourglass Effect:**

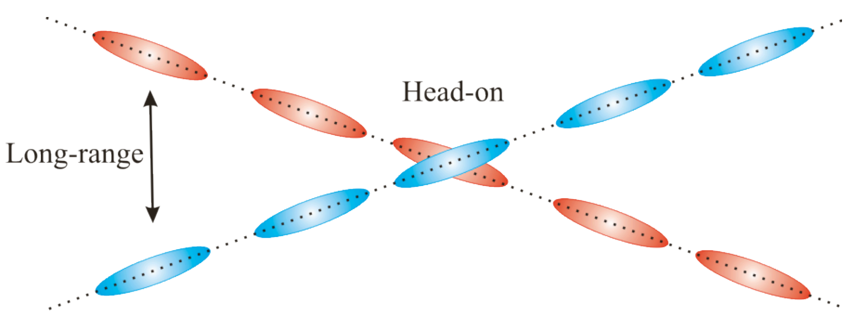
$$\frac{L}{L_0} = \int \frac{1}{\sqrt{\pi}} \; \frac{e^{-t^2}}{\sqrt{(1 + t^2 / t_x^2) \; (1 + t^2 / t_y^2)}} \; dt$$

• **Most of the time all these effects are combined.**

Interaction Region

• **Example of IP5:** **beams share the same beam pipe up to D1.**
⇒ Need to separate them in the common region.





• **Without crossing angle limited to 156 bunches.**
• **Nominal LHC 2808 bunches colliding with an angle ~300 µrad in IP1 and IP5, now ~200 µrad**

• **Operating with a crossing angle reduces the luminosity:**

$$R_X = \left(\sqrt{1 + \frac{\sigma_s^2}{\sigma_x^2} \left(\tan \frac{\varphi}{2} \right)^2} \right)^{-1}$$

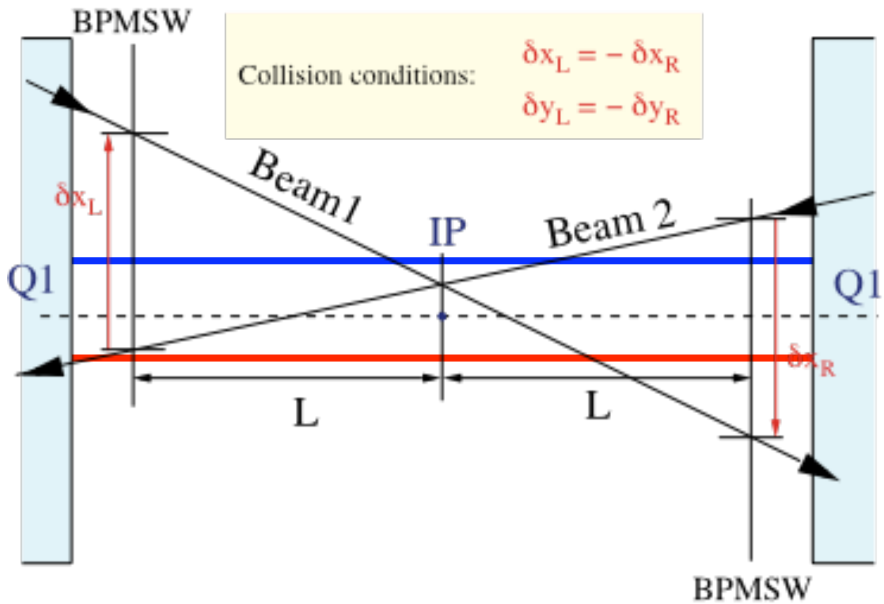
3.5 TeV. Lumi reduction by ±100 µrad crossing angle

β* [m]	L_0/L
11	1.003
3.5	1.008
2	1.014

Get LHC Beams Colliding : BPM Resolution

measured with special (beam-) directional stripline couplers BPMSW
at about 21 m L/R from IP in front of Q1, 2 each in IR

adjust orbits such, that the beam 1 and 2 difference left/right of the IP is the same
beams must then collide. This is independent of mechanical offsets and crossing angles



Beam sizes at the IP @ 3.5 TeV

β* [m]	σ* [μm]
11	**103**
3.5	**58**
2	**44**

Luminosity reduction with separation

δx [σ]	L/L_0
1	**0.7788**
2	**0.3679**
3	**0.1053**

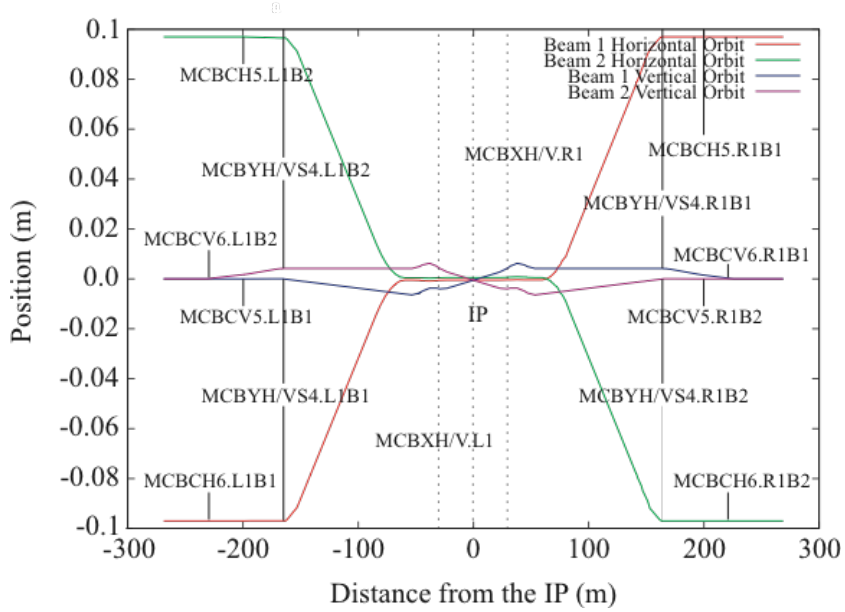
Both beams move with MCBX : First collapse the separation bumps and then optimize with BPMs.

Expected resolution for small separation and 0 crossing angle ; in each plane.

~ 50 μm: using selected, paired electronics ; otherwise ~ 100 - 200 μm
beam 1 and beam 2 have separate electronics

~ 10 μm: with extra BPMWF button pick-ups. Installed in 1&5, for large bunch spacing.

Orbit Bumps



MCBX in triplet - important for crossing angle and aperture at injection. Act on both beams and planes at the same time.

MCBC and MCBY only for one beam allow to drive the beams independently.

⇒ A bump including MCBX magnets will either separate or bring the beams together.

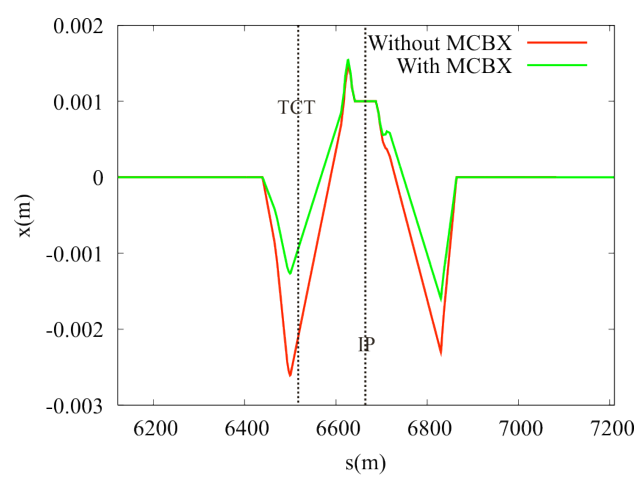
Example of an IP bump with and without MCBX:

⇒ Creates a large offset in the TCT region.

⇒ This offset can be reduced by using MCBX.

⇒ Split the amplitude between beams.

⇒ Characterize performances of the magnets: MCBX subject to large hysteresis. Not used for precision measurements.



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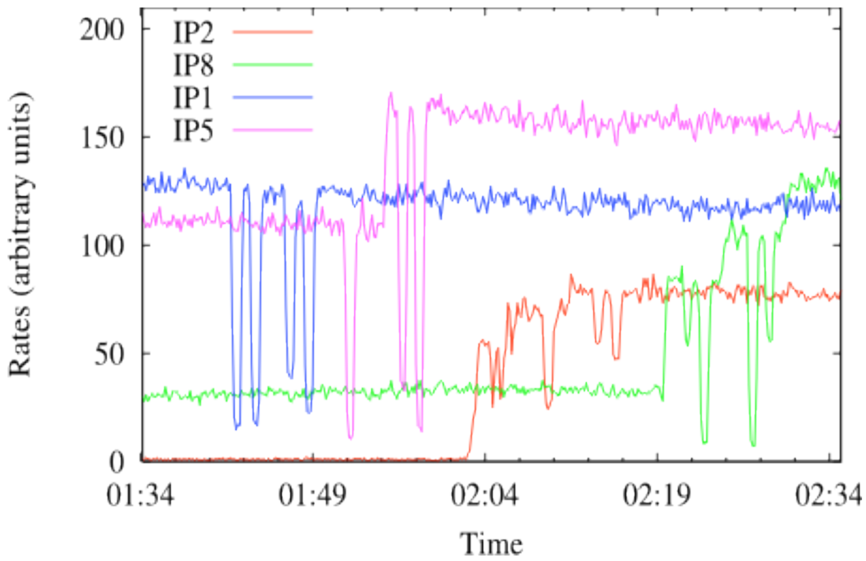
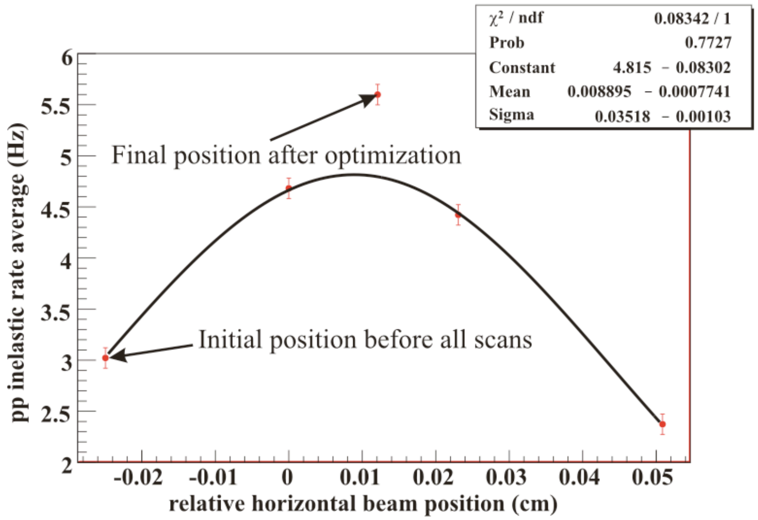
Luminosity Optimization

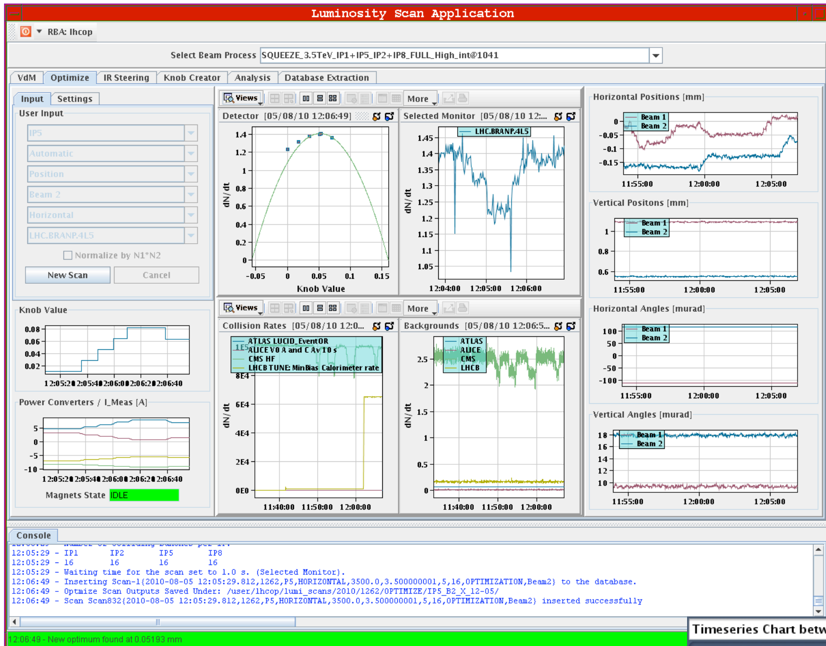
• BPM based alignment not sufficient to find the optimum settings. Use the Van Der Meer scans as an optimization tool.
⇒ Few points around the maximum to find the peak.





• BRAN data during optimization:
⇒ Three points per scan in the horizontal and vertical plane.
⇒ IP optimized in series. Full procedure: ~45 minutes.
⇒ Very lengthy need to improve efficiency.

Automated IR Steering



- **Optimize panel:**

⇒ **Automated IR steering / peak finder.**

⇒ **Select IP / beam / plane / detector.**

⇒ **User input: step size / time per step.**

⇒ **Defaults: 0.5σ / 5s.**

⇒ **Limit on the trim amplitude +/-2σ. Can be changed if really far off.**

⇒ **Optimum given by a parabola calculated on the last three points.**

⇒ **Allows for fast automatic optimization.**

- **First tests (end of fill):**

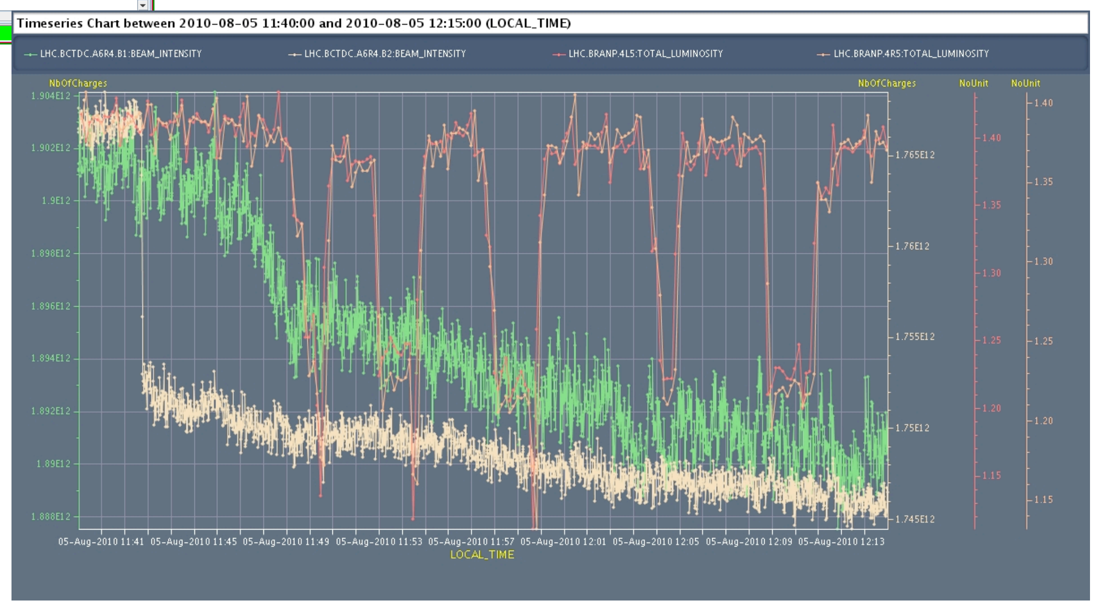
⇒ **Done for IP5.**

⇒ **Separate the beams and launch routine to re-align.**

⇒ **Small losses observed on B1 when separating beams the first time.**

⇒ **No losses afterwards.**

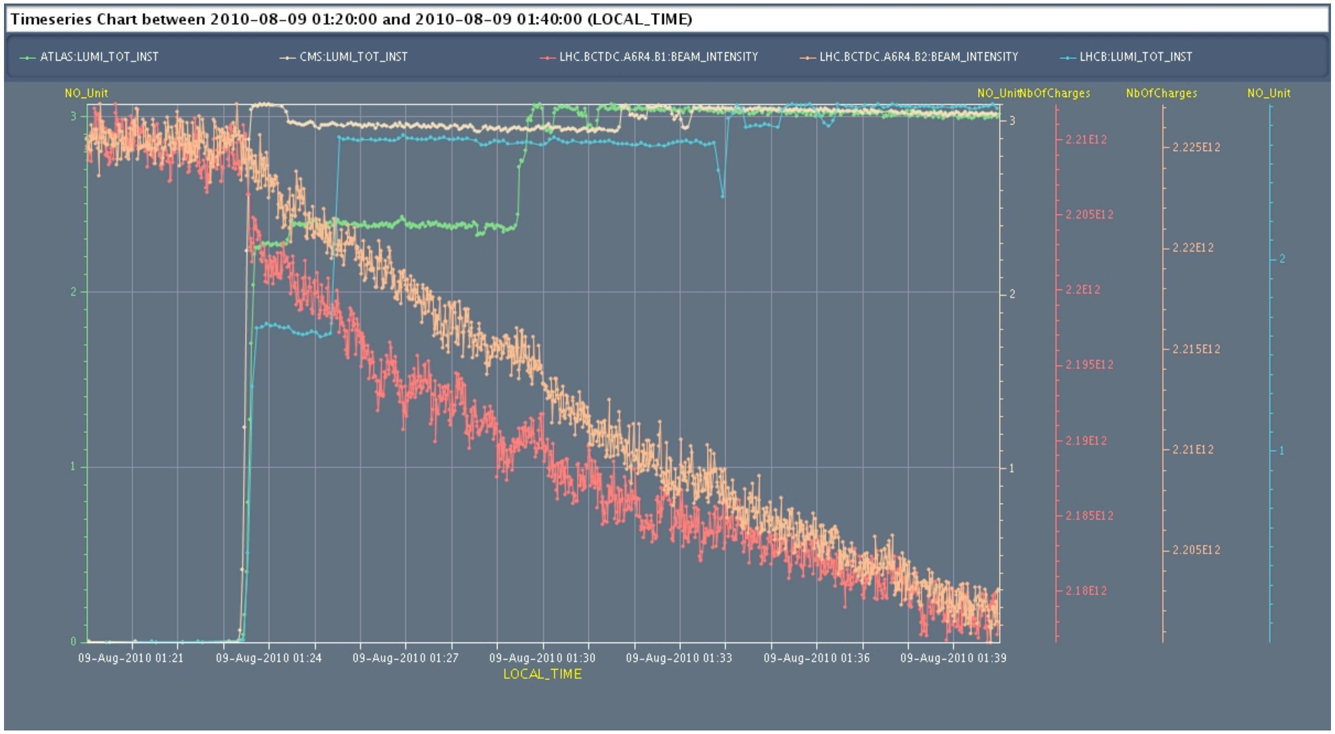
⇒ **Losses on B2: tune swap.**



Regular Operation

- **Fill 1268**

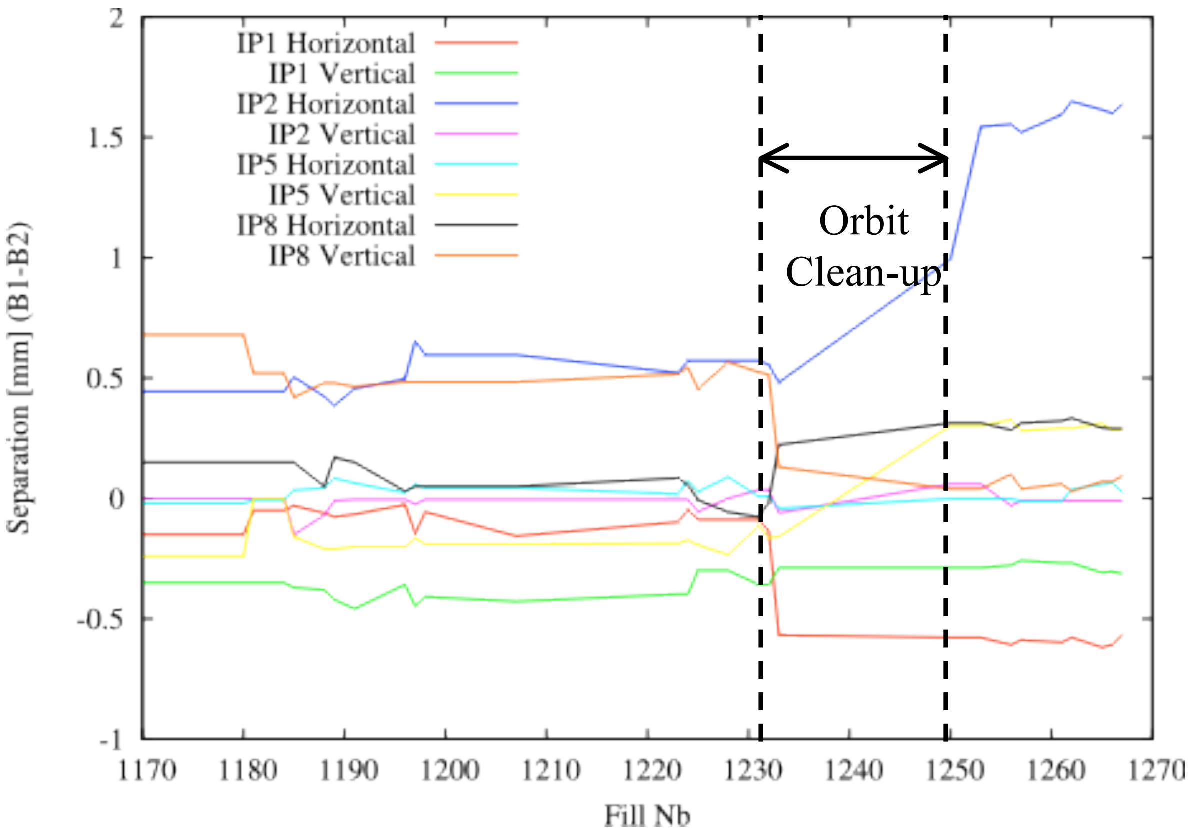
⇒ Losses when bringing beams into collisions.
⇒ No losses during optimization.
⇒ Optimizing IP1+IP5+IP8: ~10 minutes.
⇒ No significant effects or losses with high intensity.



- **New procedure used at the beginning of each fill for several months without issues.**
- **Significantly improved the operation efficiency.**

- **Further improvements:**
- **New routine developed to optimize the four IPs in parallel.**
- **Time reduced to a few minutes to optimize the four IPs.**

Reproducibility



- **Corrections for 3.5 m optics:**

⇒ Before 1232: good stability. Max 200 µm.

⇒ 1232: Jump. Cleaning up of the orbit. Change of reference.

⇒ After 1232: Good stability. Max 50 µm.

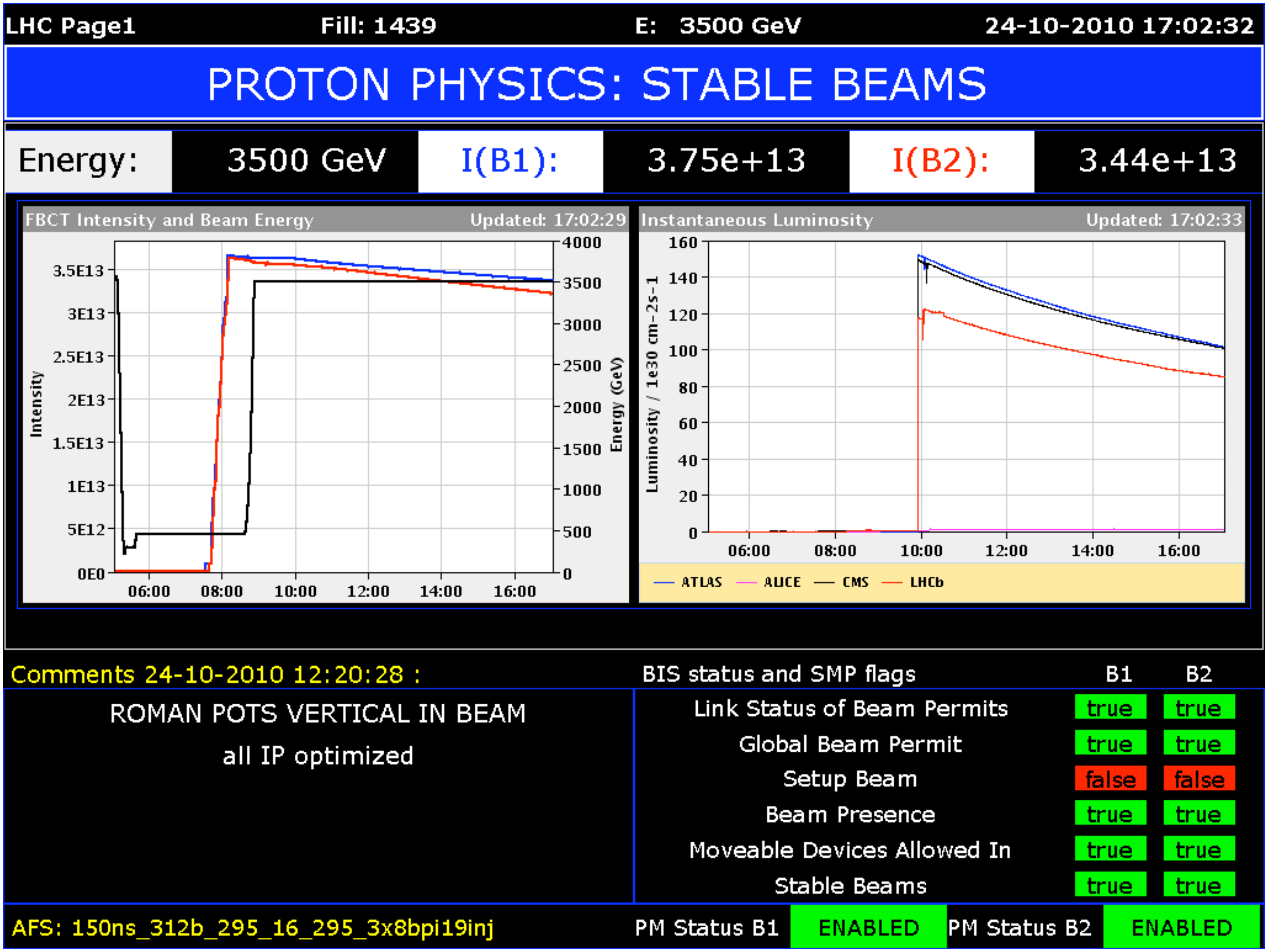
⇒ IP2 seems more difficult to control.

⇒ In general good stability with actual beam parameters.

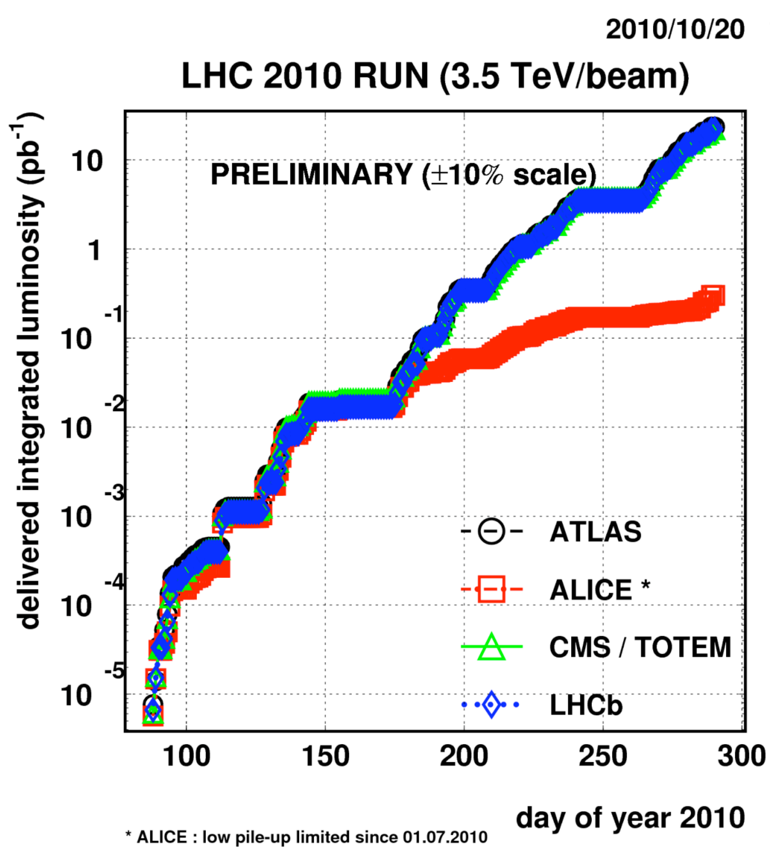
⇒ When reference is the same and orbit is well corrected the collision point is found directly from the optimum settings of the previous fill.

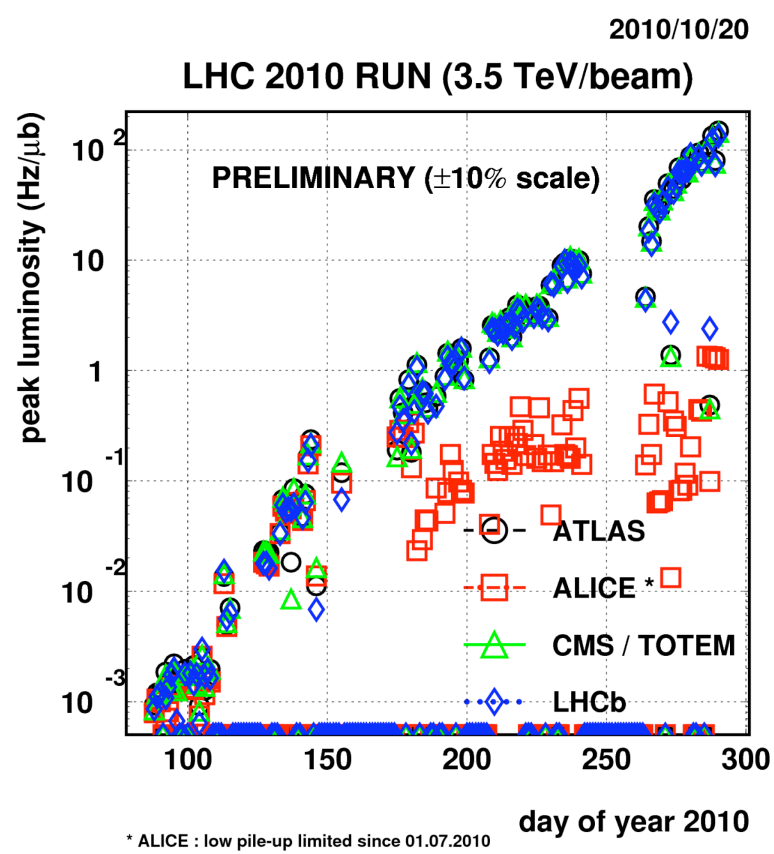
⇒ Not sufficient for nominal LHC beam parameters (σ ~ 16 µm).

24th of October 2010



Luminosity Performance





Luminosity performance on the 20/10/2010:

⇒ Already several fills > 1.00×10^{32} $cm^{-2}s^{-1}$. Reached target for 2010.

⇒About 25 pb^{-1} integrated luminosity. Expect to reach 50 pb^{-1} by the end of this year.

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Methods for Absolute Luminosity Determination

• Knowledge of the absolute luminosity is essential for the experiments to normalize the physics data:

$$\dot{N} = L\sigma$$

• Various method have been used in the past:

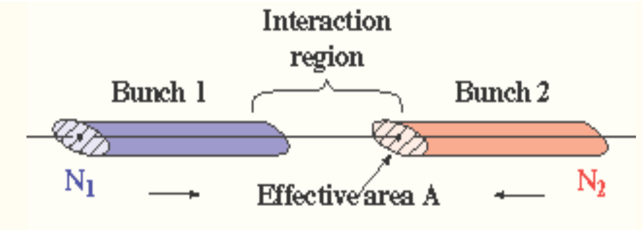
⇒ Use a theoretically well know process: in $e^+ e^-$ collider Bhabba scattering . In hadron colliders, there exist processes like W and Z production which can be calculated to several %. Fragmentation model dependent.

⇒ Elastic scattering of protons at small angles (TOTEM and ATLAS). Requires dedicated optics. Not suitable for early operation.

⇒ Luminosity from machine parameters. Either with the Van Der Meer scans method (ISR) or with reconstruction of the individual beam sizes using beam gas events (LHCb). Independent from the model. Compatible with early LHC operation.

The Van Der Meer Method

$$L_0 = \frac{N_1 \; N_2 \; n_b \; f}{A_{\text{eff}}}$$



Revolution frequency known with good accuracy, intensity measured with BCTs. The effective overlap area can be determined by scans in separation.

- **Regardless of the beam density distribution (uncorrelated x/y distributions):**

$$L(\delta x,\delta y) = L_0 \; F(\delta x,\delta y) = L_0 \; F_x(\delta x) \; F_y(\delta y) \qquad A_{\text{eff}} = \frac{\int_{-\infty}^{+\infty} F_x(\delta x) d\delta x \; \int_{-\infty}^{+\infty} F_y(\delta y) d\delta y}{F_x(0) \; F_y(0)}$$

- **Perfect Gaussian:**

$$F(\delta u) = \exp\left[-\frac{\delta u^2}{2 \; (\sigma_{u1}^2 + \sigma_{u2}^2)} \right]$$

⇒ Measuring the collision rates as a function of the separation provides a direct measurement of the overlap area. Critical parameters: intensity, beam displacement.

Past Experience

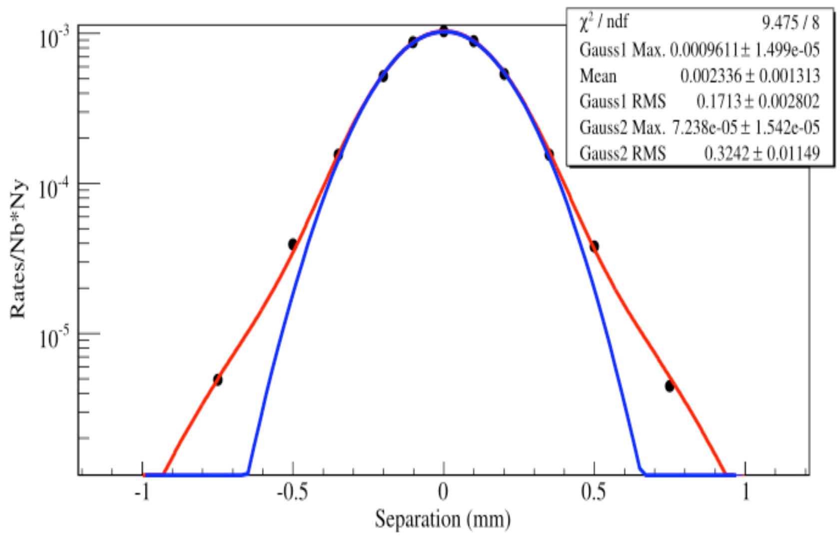
- **Method pioneered at ISR by S. Van Der Meer:**

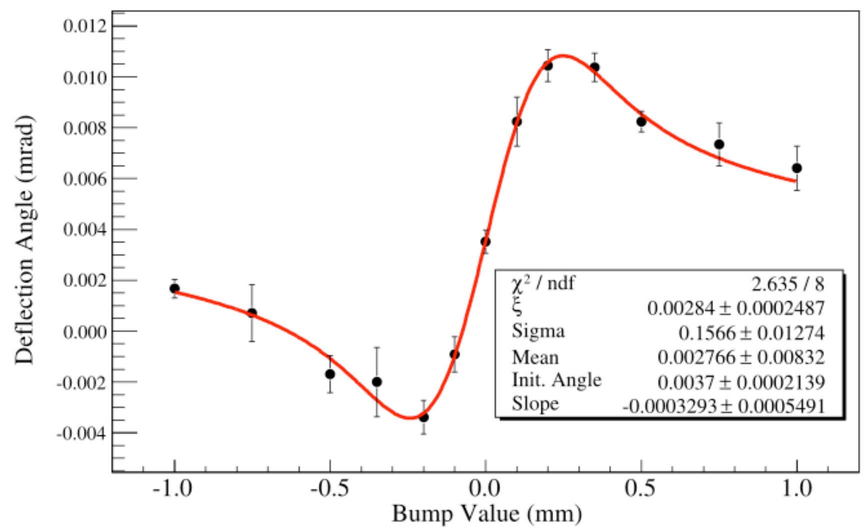
⇒ **1% precision (**K. Potter, "Luminosity measurements and calculations"**).**
⇒ **Conditions different from LHC: Continuous beam, displacement calibrated with scraper.**

- **More recently done at RHIC with a bunched machine:**

⇒ **About 7% precision. Beam conditions not optimized, strong beam-beam, hourglass.**

Measurements done in 2009. 250 GeV RHIC proton run with A. Drees. Presented at IPAC10.





⇒ At the LHC: aim for 10%. Expect to do better with dedicated beam conditions.

Some Beam Parameters

Pile-up and Statistical Accuracy

Statistical error $(N)^{1/2}$. 72 mb cross section, 3.75 μm emittance and one bunch.
⇒ 1% statistical accuracy easily reachable.

β* [m]	N [p/bunch]	L [$cm^{-2}s^{-1}$]	dN/dt	dN/dt / BX
11	2.0×10^{10}	3.58×10^{27}	258	0.023
2	2.0×10^{10}	1.76×10^{28}	1270	0.113
3.5	1.15×10^{11}	3.29×10^{29}	23682	2.106

Crossing Angle

- Only necessary for a large number of bunches (>156).
- For LHC, no additional systematic uncertainty from the crossing angle.
- Actual beam conditions no aperture limitations. Could become more difficult for fully squeezed optics.

Hour Glass Effect

$$H(r) = \sqrt{\pi}\ r\ e^{r^2}\ Erfc\ (r)$$

where $r = \beta^* / \sigma_z$

for round beams and nominal σ_z = 7.55 cm.

β* [m]	r	H(r)
10	132	0.999972
2	26.5	0.999289
1	13.2	0.9971774
0.55	7.28	0.990833

Beam-Beam Effects

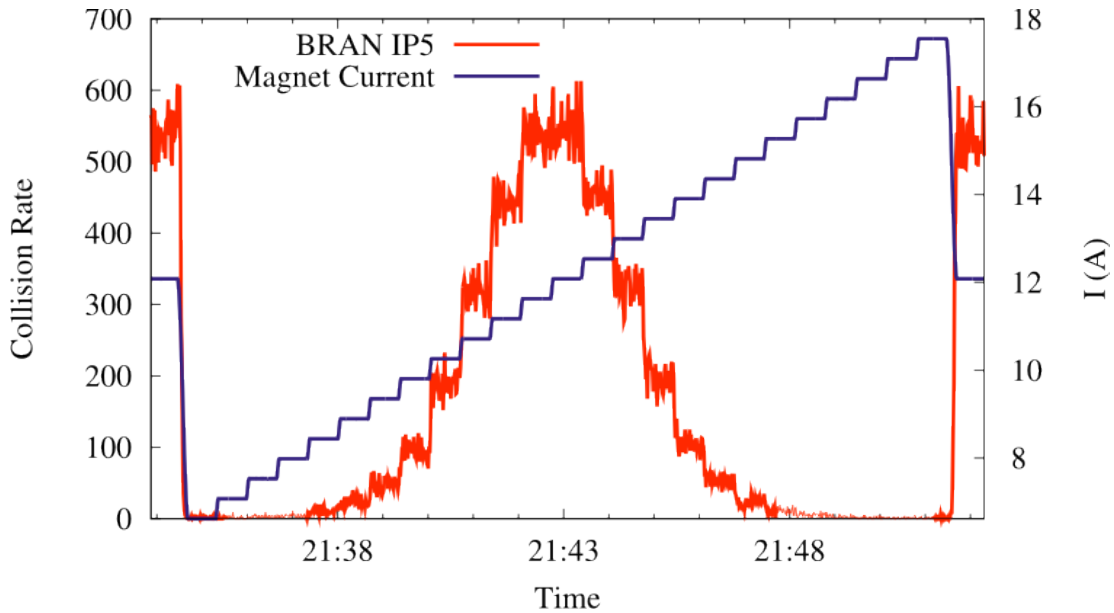
Beam-beam tune shift parameter ξ for head-on collisions depends on intensity (not energy, β*):

$$\xi = \frac{r_c N}{4\pi\varepsilon_N}$$

N [p/bunch]	ξ
5×10^9	0.000163
4×10^{10}	0.00130
1.15×10^{11}	0.00374

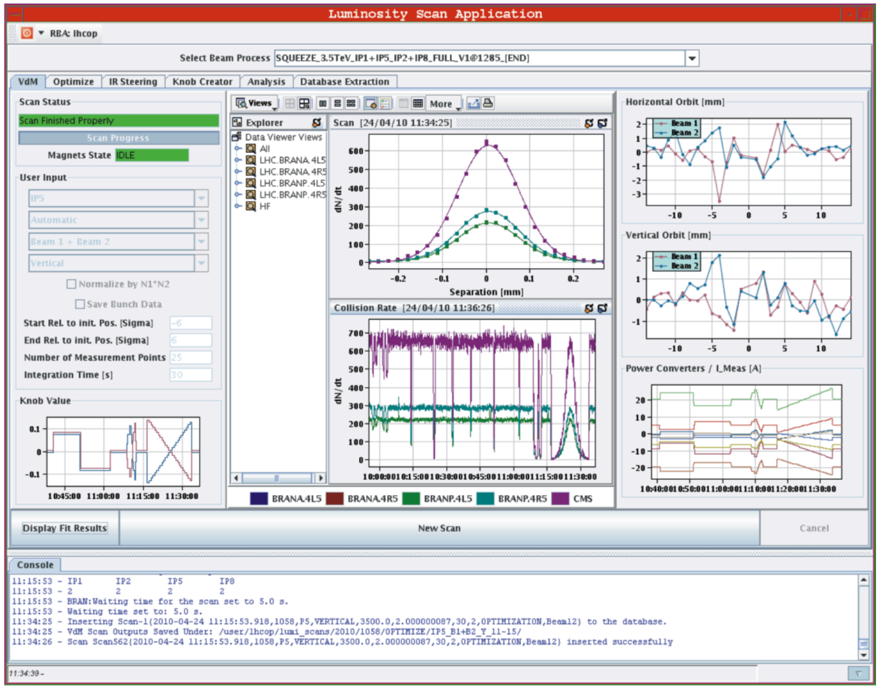
Calibration Scans

- Move the beams stepwise across each other and measure the collision rates as a function of the beam displacement. Repeat in both planes to compute the effective overlap area.



- **Rates:** given by any luminosity monitor (LHC: BRAN, experiments)
- **Statistical accuracy:** not an issue. Step length is a user input. It can be changed depending on beam parameters.
- **Beam displacement:** done with closed orbit bump. Subject to non-closure due to optics errors, hysteresis, etc
- **Beam intensity:** requires bunch by bunch measurements (FBCTs). Collision pattern.
- Other parameters like emittance should be stable in order to avoid additional errors.

Implementation



- **Software developed in Java within the LSA (LHC Software Architecture) framework:**

⇒ Automated / manual IR steering

⇒ Online analysis

⇒ Automated calibration measurement

⇒ Database access

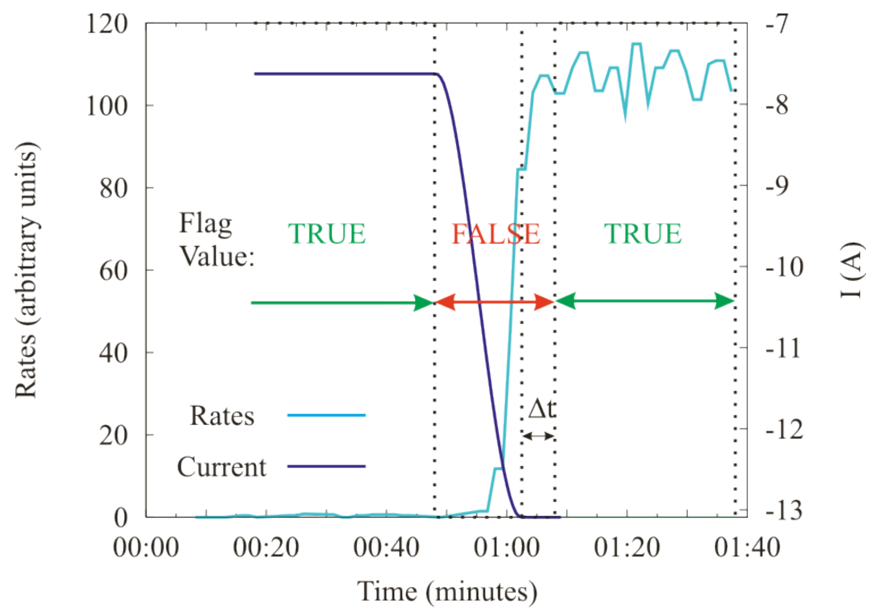
⇒ **Fully operational and used on a regular basis in the CCC.**

- **Data exchange with experiments:**

⇒ Publishes the scan status and progress in real time.

⇒ Allow for experiments to perform online analysis.

⇒ Flag used as trigger by the experiments.



Beam Profile

- Van Der Meer scans performed in all IPs. Move both beams opposite directions to allow +/- 6 σ scan range (limits the offset at the TCT). Done with 2.0×10^{10} p/bunch.

- **Non Gaussian tails observed for all scans:**

⇒ **Fit with a double Gaussian.**

$$L(\delta x, \delta y) = L_0 \; F_x(\delta x) \; F_y(\delta y) \qquad A_{\mathrm{eff}} = \frac{\int_{-\infty}^{+\infty} F_x(\delta x) d\delta x \; \int_{-\infty}^{+\infty} F_y(\delta y) d\delta y}{F_x(0) \; F_y(0)}$$

- **Double Gauss:**

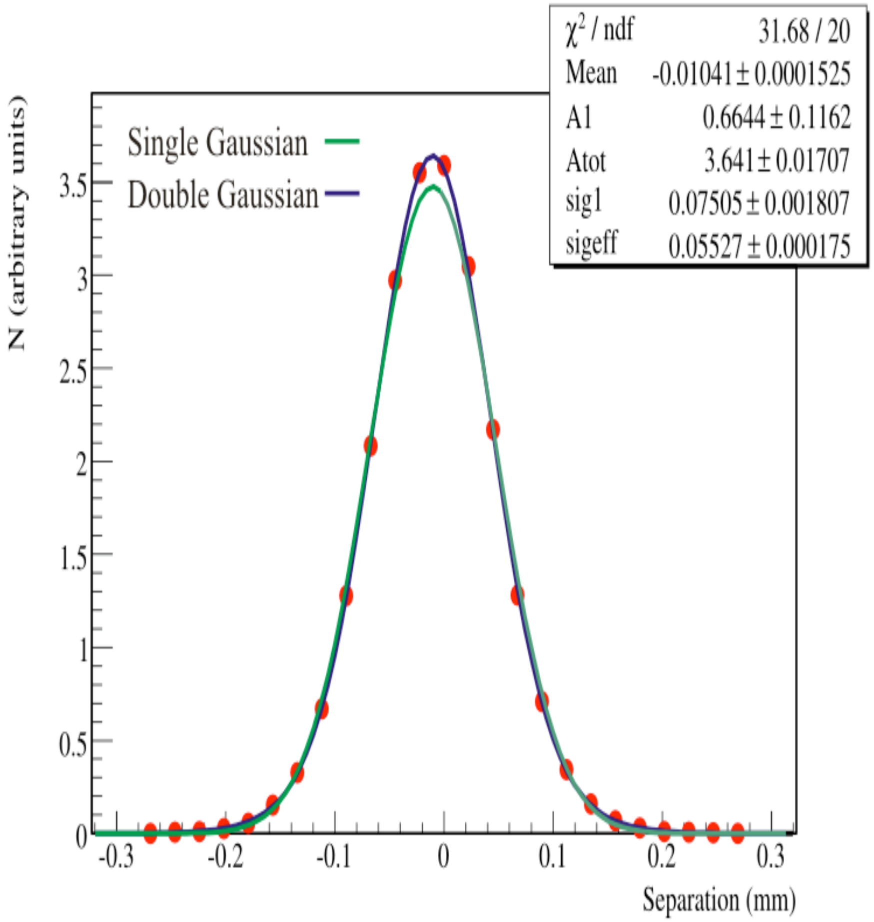
$$F(\delta u) = A_{u1} \exp\left[-\frac{\delta u^2}{2\sigma_{u1}^2}\right] + A_{u2} \exp\left[-\frac{\delta u^2}{2\sigma_{u2}^2}\right] \qquad \sigma_{\mathrm{eff}u} = \frac{A_{1u}\sigma_{1u} + A_{2u}\sigma_{2u}}{A_{1u} + A_{2u}}$$

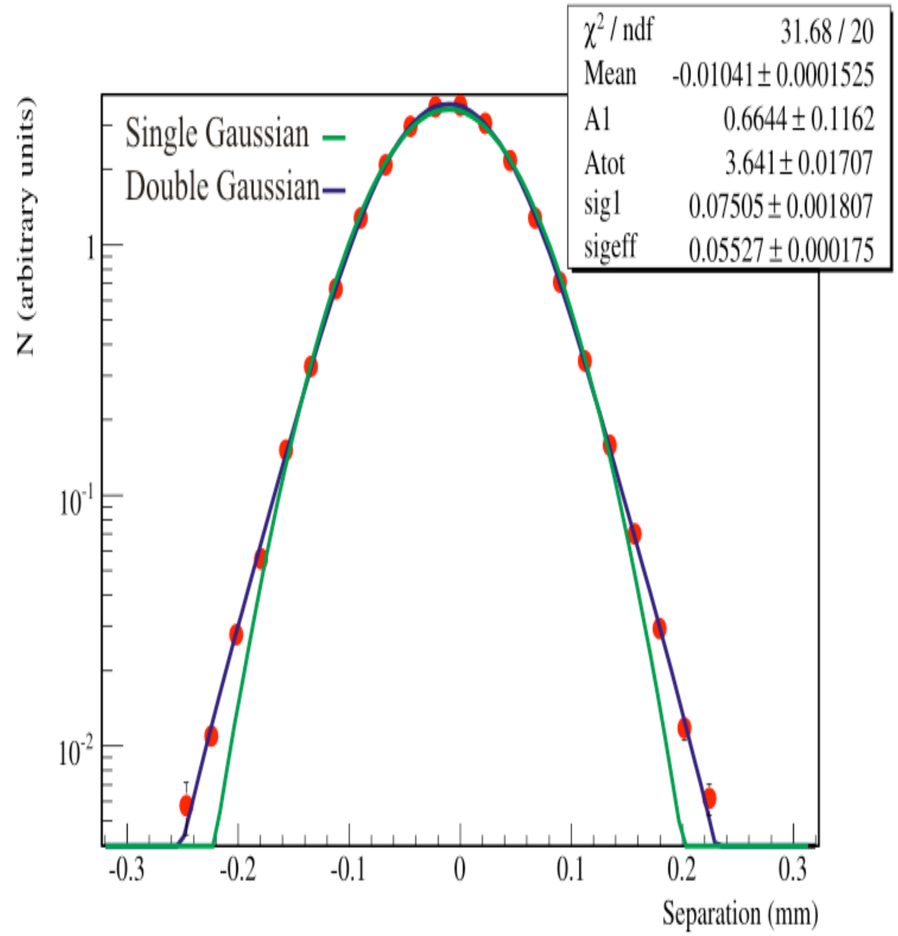
⇒ **Allows analytical approach.**

⇒ **Distribution falling to zero for infinite separation.**

⇒ **Fit function gives directly the effective beam size and statistical error.**

Single Gaussian vs Double Gaussian



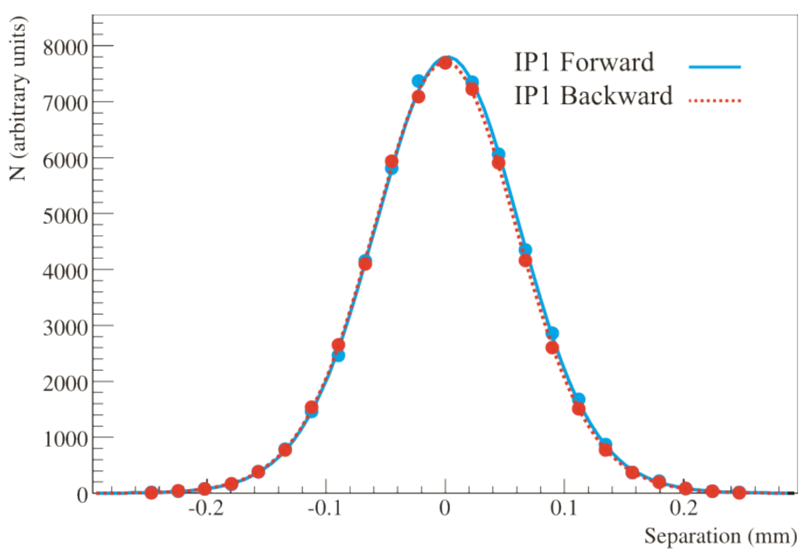


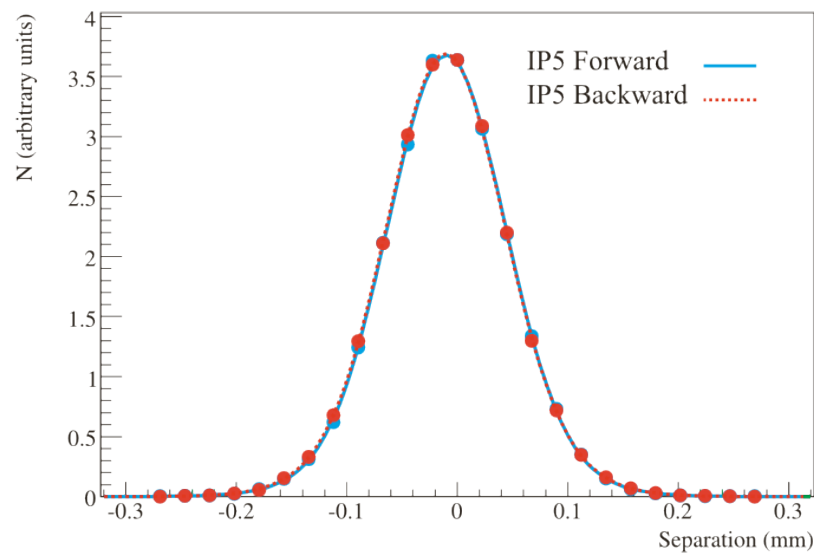
⇒ **Profile is better described by the double Gaussian.**
⇒ **Statistical uncertainty < 1%.**
⇒ **Example of IP5 (HF) but seen for all scans.**

Hysteresis During the Scans

• For each plane scan in opposite directions (opposite hysteresis branch) to check for consistency and hysteresis: effect given by the shift of the distribution.
• Done for ATLAS and CMS.

	$\Delta\sigma_x/\sigma_x$ (mm)	$\Delta\sigma_y/\sigma_y$ (mm)	Δx_{mean} (mm)	Δy_{mean} (mm)
IP1	0.004	0.006	0.002	0.002
IP5	0.004	0.01	0.001	0.002

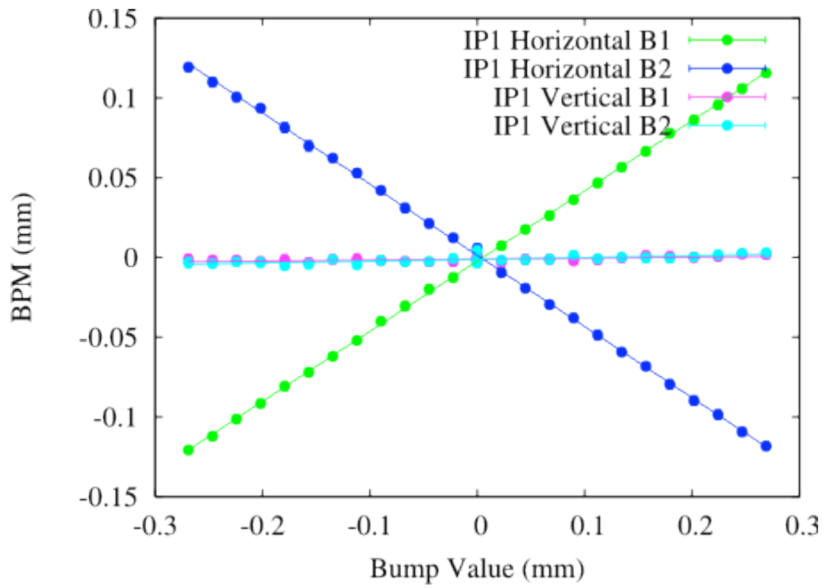


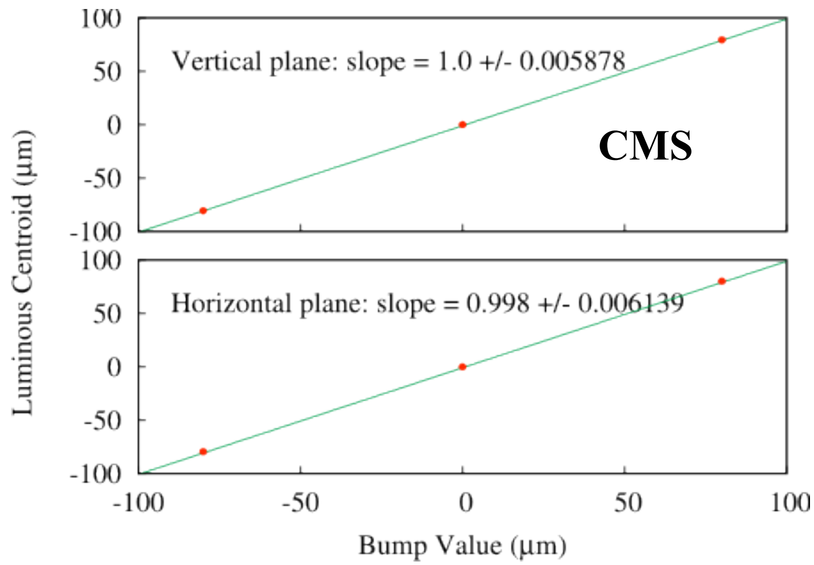


⇒ Largest shift seen in ATLAS vertical ~0.002 mm: negligible effect on the rates.
⇒ Effective beam size measurement very consistent from one scan to the other.
⇒ Hysteresis effects can be considered negligible. 0.002 mm ~ 0.05 σ → 0.1% loss in luminosity.
⇒ Further reduced by scanning always on the same hysteresis branch (direction).

Bump Calibration and Linearity

• **Relative beam displacement essential for effective beam size measurement.**





• **Method:**

⇒ **Displace the IP transversally by moving the two beams in the same direction. Compare value given by magnet settings with luminous region position.**

⇒ **Agreement of less than 1% in CMS and ALICE. About 1-2% in ATLAS.**

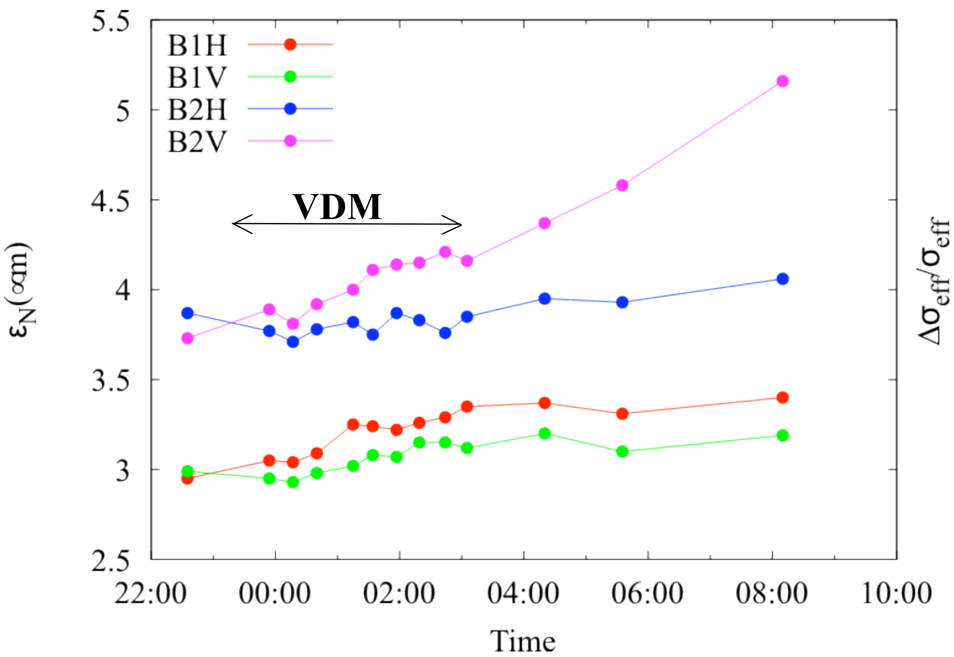
⇒ **LHCb: scan with only one beam and compare with luminous region centroid displacement . Similar results.**

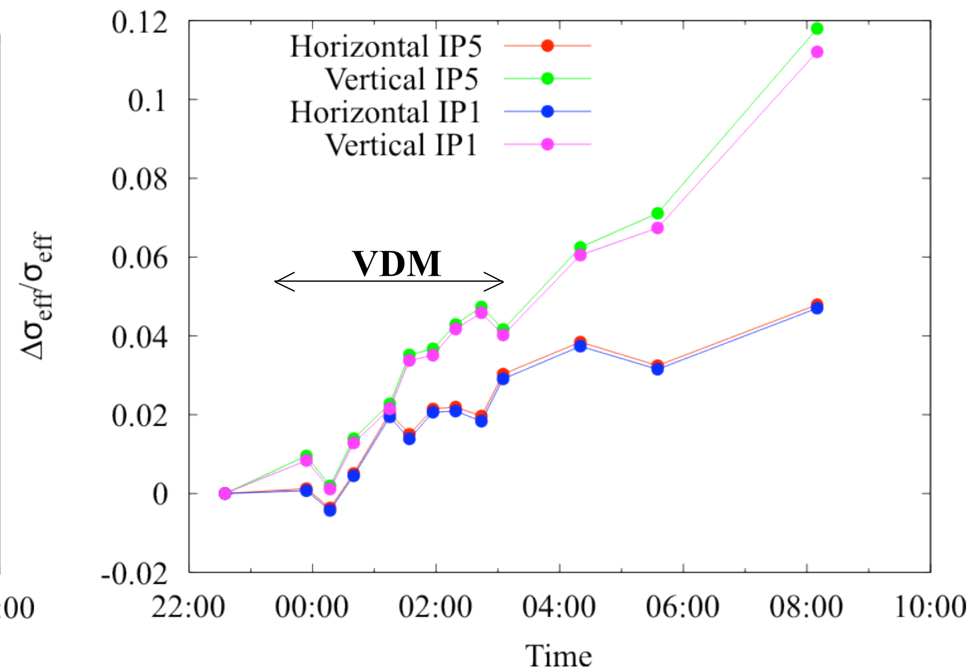
⇒ **In general, very good agreement which confirms the good status of the optics.**

⇒ **Bump linear. No significant coupling observed**

Emittance

Wire scanner emittance measurements during calibration scan session.

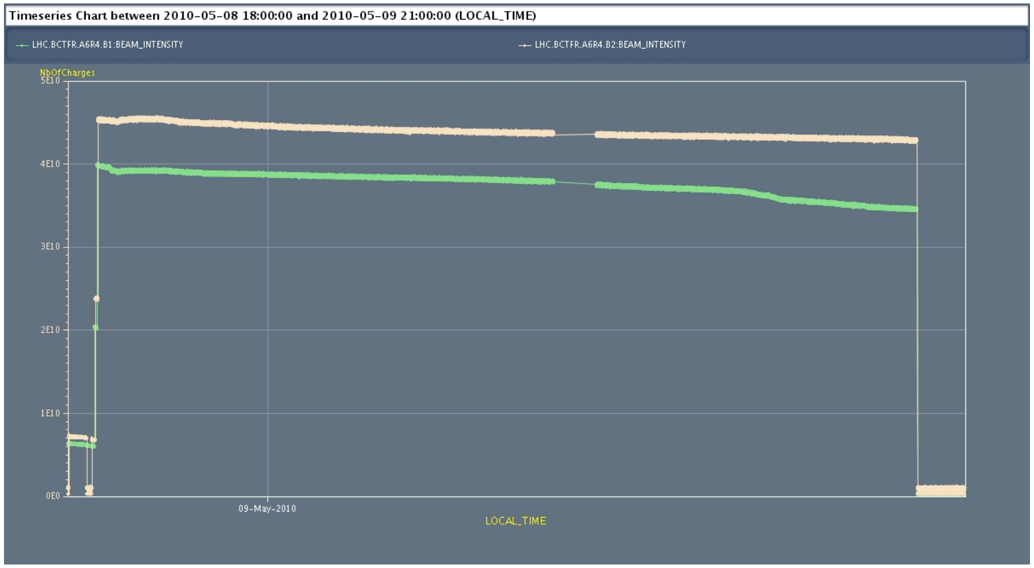




⇒ **Emittance blow up during the scan (left) : the effective beam size (right) measured during the scan is also affected.**
⇒ **The duration of a scan is about 20 minutes: the growth of the effective beam size during one scan is ~1%. In the worst case: full calibration 1-2%.**
⇒ **Looking at the trend over the fill there could be a small blow-up due to the scan itself .To be confirmed with higher intensity.**

Intensity Measurements

- Two systems available in LHC: FBCT (bunch by bunch) and DCCT (full beam).
- Luminosity calibration requires bunch by bunch measurements.

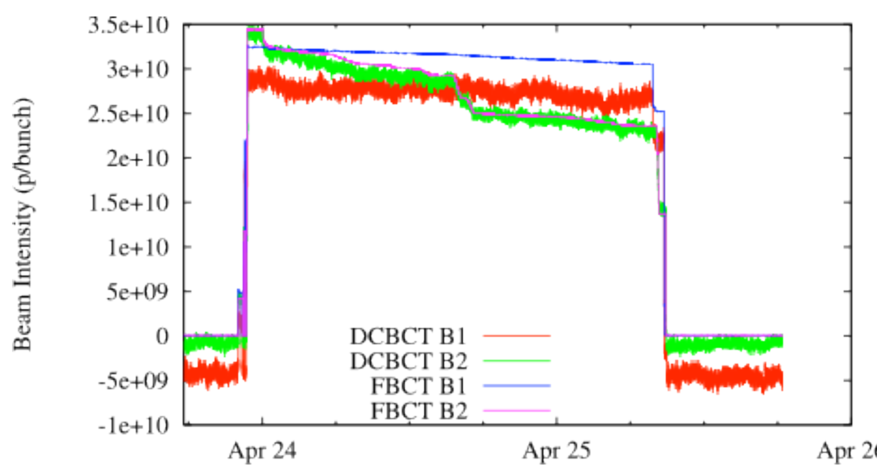


- Intensity over the fill 1089:

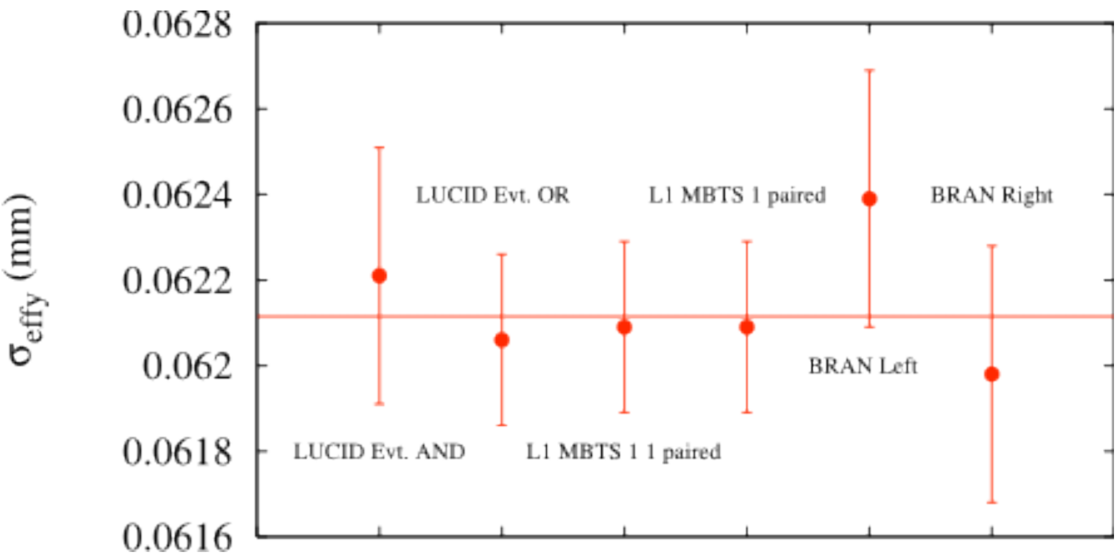
⇒ Intensity very stable, lifetime of several hundred hours.
⇒ Scan ~20 minutes. Intensity variations of the order of 0.1% over the duration of the scan.
⇒ No corrections required from intensity variations over the scans.

- **FBCT and DCCT measurements:**

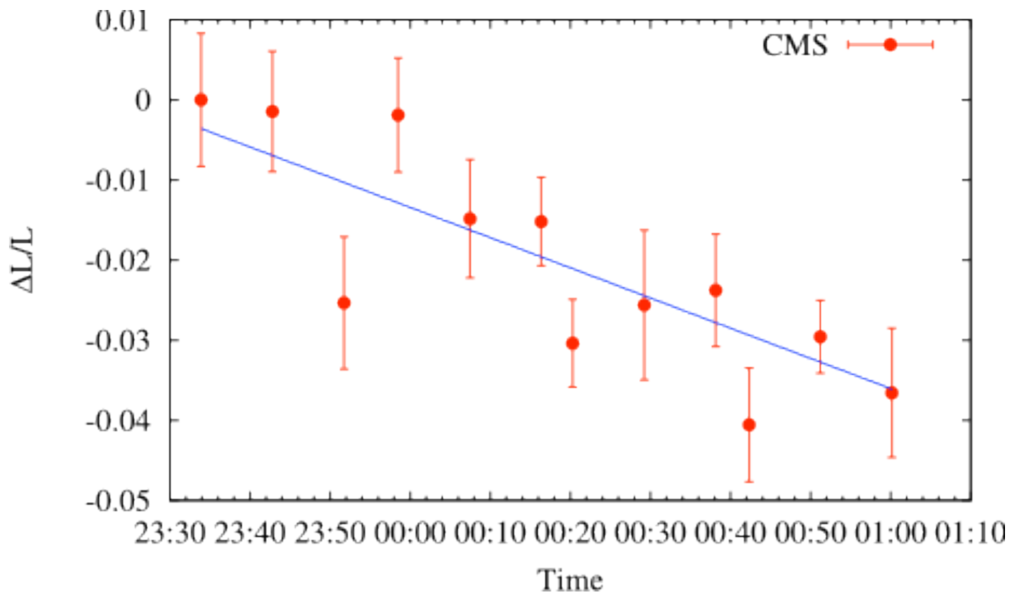
⇒ DCCT easier to calibrate. Cross calibrate FBCT with DCCT.
⇒ DCCT: negative offset, noisy at low intensity.
⇒ Systematic error: includes DCCT+FBCT (FBCT phase shift, drift…)
5% per beam, 10% for the product.



Consistency Checks (I)



- **Fit results comparison between BRANs and experiments:**
- **Example of IP1.**
- **All monitors agree within error bars.**



- **For each an acquisition at zero separation is taken at the beginning, middle and end.**
- **Example of CMS:**

⇒ Consistent with a decay.
⇒ Not due to intensity.
⇒ Same order of magnitude as wire scanners measurements.

Consistency Checks (II)

• **Effective beam size can be derived from emittance and β* (assumes Gaussian beams): as a cross check compare with results from the scans.**

	Horizontal Plane [mm]		Vertical Plane [mm]	
	Scan	Optics	Scan	Optics
IP1	0.0585+/-0.0002 0.0587+/-0.0003	0.0610+/-0.0098 0.0613+/-0.0098	0.0622+/-0.0003 0.0619+/-0.0003	0.0641+/-0.0038 0.0640+/-0.0038
IP5	0.0551+/-0.0002 0.0553+/-0.0002	0.0604+/-0.0078 0.0603+/-0.0078	0.0593+/-0.0002 0.0598+/-0.0002	0.0595+/-0.0130 0.0601+/-0.0132

⇒ Large uncertainty on optics method (~10% uncertainty on emittance and β).
⇒ Optics seem to overestimate the effective beam sizes: calibration of the wire scanner was found to be wrong.

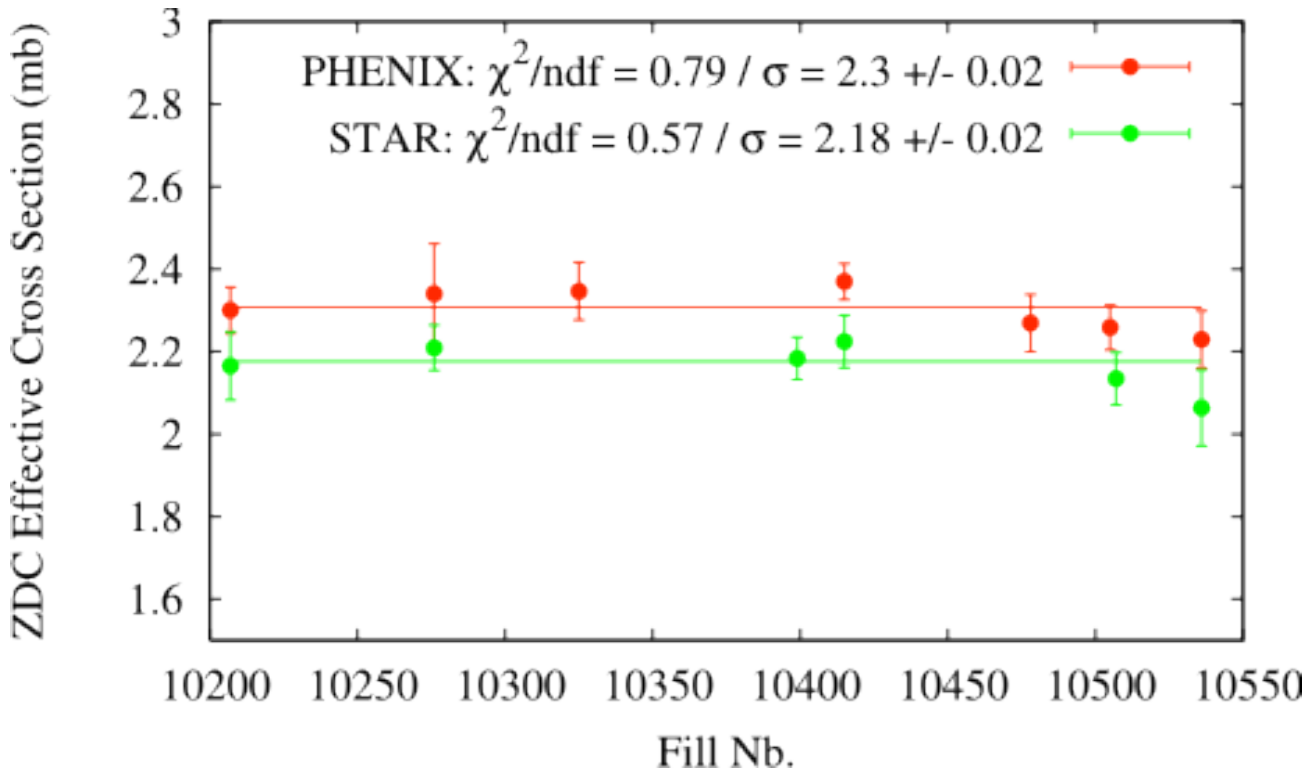
• **Fill-to-fill consistency:**

$$\dot{N} = L\sigma$$

• **Regardless of the beam conditions σ should be constant:**
⇒ ATLAS : 4.8% maximum (depends on the detector)
⇒ CMS : 5%

RHIC Cross Sections

- RHIC scans show a good fill-to-fill reproducibility. All cross section agree within error bars.
- Different between the PHENIX and STAR ZDC explained by different configurations.



- Need more statistics at the LHC to draw real conclusions.
- The visible cross section calculation include intensity measurements:

⇒ At RHIC it can be trusted to at least 2%

⇒ For the LHC the uncertainty is of 5% in the actual configuration.

⇒ The method proved to be reproducible at RHIC. The fill-to-fill discrepancy observed in the LHC could explained by our poor knowledge of the intensity.

Systematic Errors for Luminosity Calibration

- **The main sources of systematic errors were identified and quantified:**

Source	Uncertainty
Fit errors	1%
Hysteresis	Negligible
Emittance blow-up	2-3%
Beam displacement	2%
Intensity	10%
Beam-beam/coupling/pile-up	Negligible
Total	11%

- **Beam-beam/coupling/pile-up very small effect for this measurements (low intensity, round beams).**
- **The accuracy of the measurement is 11% from which 10% are from beam intensity measurements. (MC 20-30%).**
- **Excellent results for a very first try in the LHC.**
- **The results are used as new reference for online luminosity normalization.**

Future Measurements and Expectations

• **Possible improvements for optimal conditions:**

⇒ **If emittance blow-up is still a problem: scan faster / less points.**

⇒ **Calibrate the bumps of beam 1 and beam 2 independently: error down to the vertex position resolution (< 1%).**

⇒ **Scan with only one beam (work ongoing to allow large beam displacements at the IP).**

⇒ **Increased bunch intensity: reduces the uncertainty from the BCT while keeping pile-up and beam-beam small.**

• **Complementary measurements:**

⇒ **Scans in physics conditions: provide useful information on beam-beam and pile-up and help understand the impact of these effects on the measurement.**

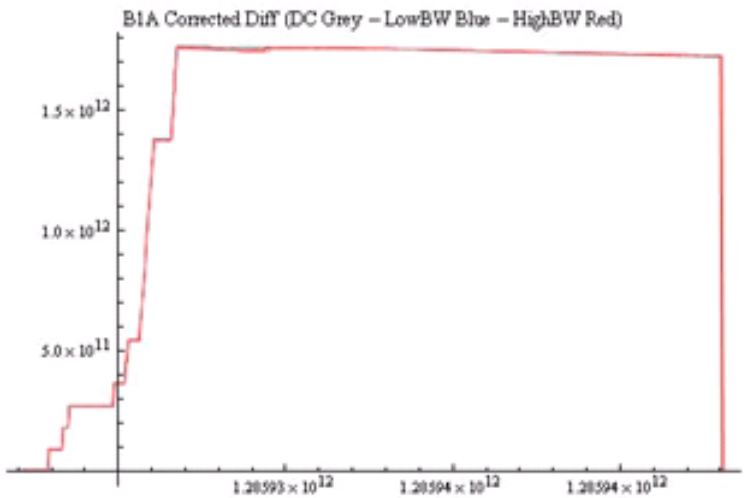
• **Expectations:**

⇒ **Based on this first experience we expect to reach an uncertainty of 5% for future measurements.**

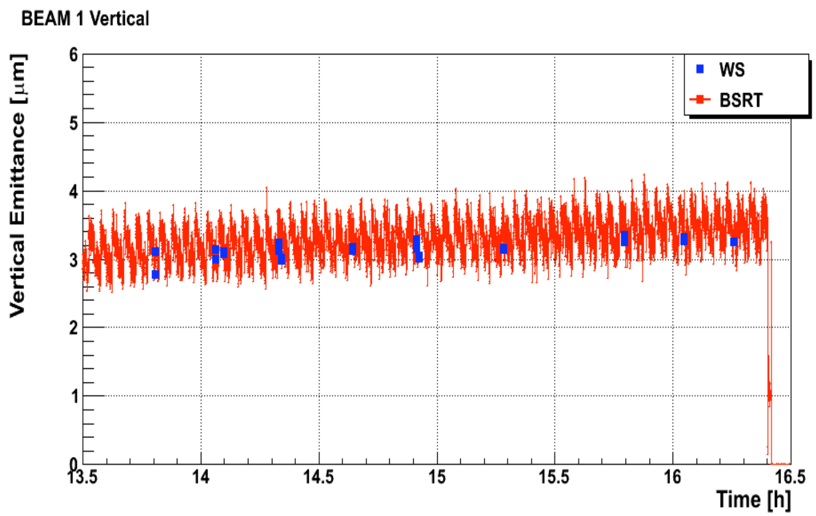
Latest News

- **Dedicated fill: 6 bunches of 8.0×10^{10} p/bunch with crossing angle.**
- **Full set of scans and bump calibration done in all IPs.**

- **Special effort made to recalibrate and check instrumentation before the scans.**



Excellent agreement between DCCT and FBCT *(J. J. Gras)*.



No significant emittance blow-up over the duration of a scan (*F. Roncarolo)*.

⇒ **We are confident we can reach a precision of better than 10% (maybe 5%??).**

Luminosity Optimization and Calibration at the LHC

S. White

Outline:

Introduction

Luminosity Optimization

Luminosity Calibration

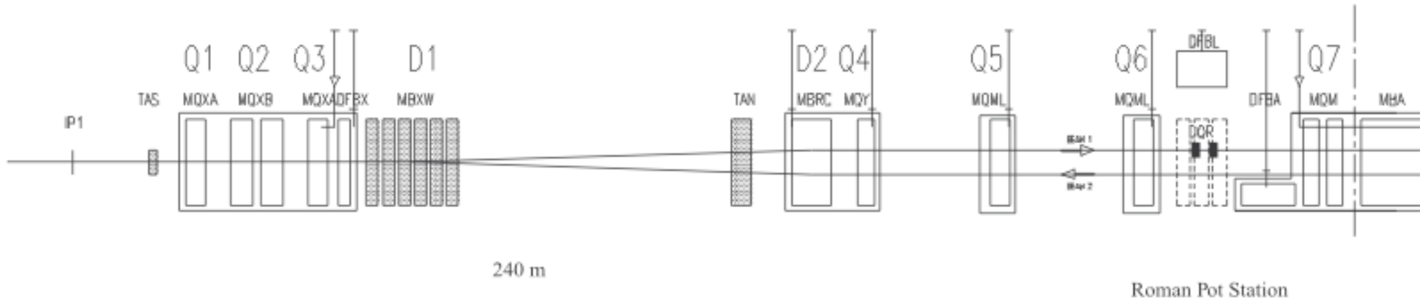
High-β Optics

25 October 2010

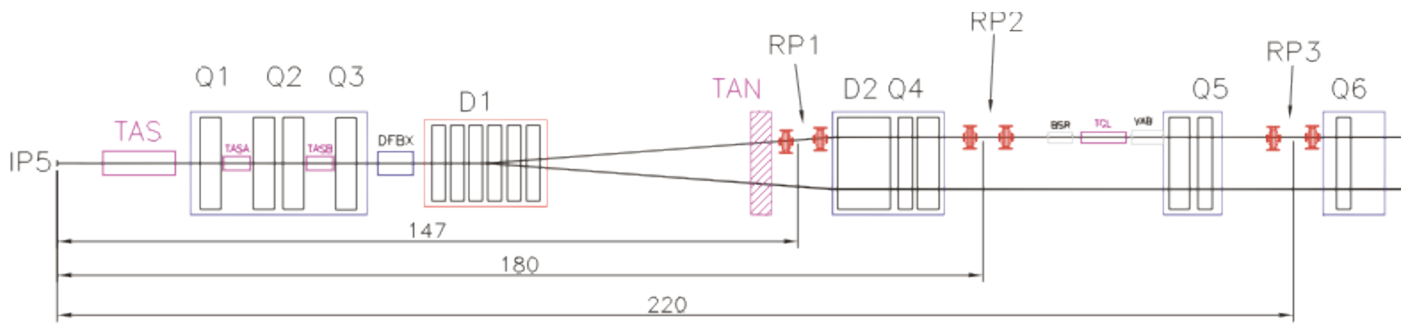
LBNL, Berkeley

Towards Higher Resolution

• Two experiments are foreseen in the LHC, ATLAS (IP1) and TOTEM (IP5), to determine the total proton proton cross section from the measurement of elastic scattering angles.



ATLAS IR layout



TOTEM IR layout

• **Dedicated detectors were installed in both IRs.**
• **Measurement very small scattering angles requires dedicated optics.**
• **Expected precision on the cross section: few percents.**

Optics Constraints

• **The scattering angle at the IP can be expressed as a function of the displacement at the observation point and the particle vertex position at the IP.**

$$\theta^* = \frac{u(s) - M_{11}u^*}{M_{12}} \qquad M_{11} = \sqrt{\frac{\beta(s)}{\beta^*}}\cos\Delta\mu(s) \qquad M_{12} = \sqrt{\beta(s)\beta^*}\sin\Delta\mu(s)$$

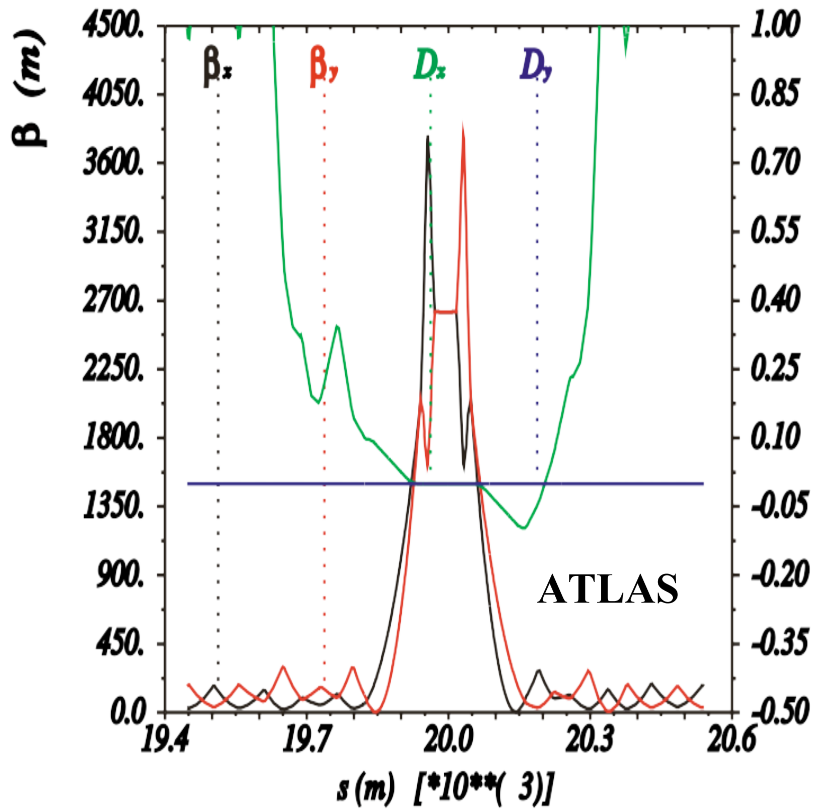
$\Rightarrow \Delta\mu(s) = \pi / 2$: **allow for the displacement at the observation point to be independent from the position at the IP.**

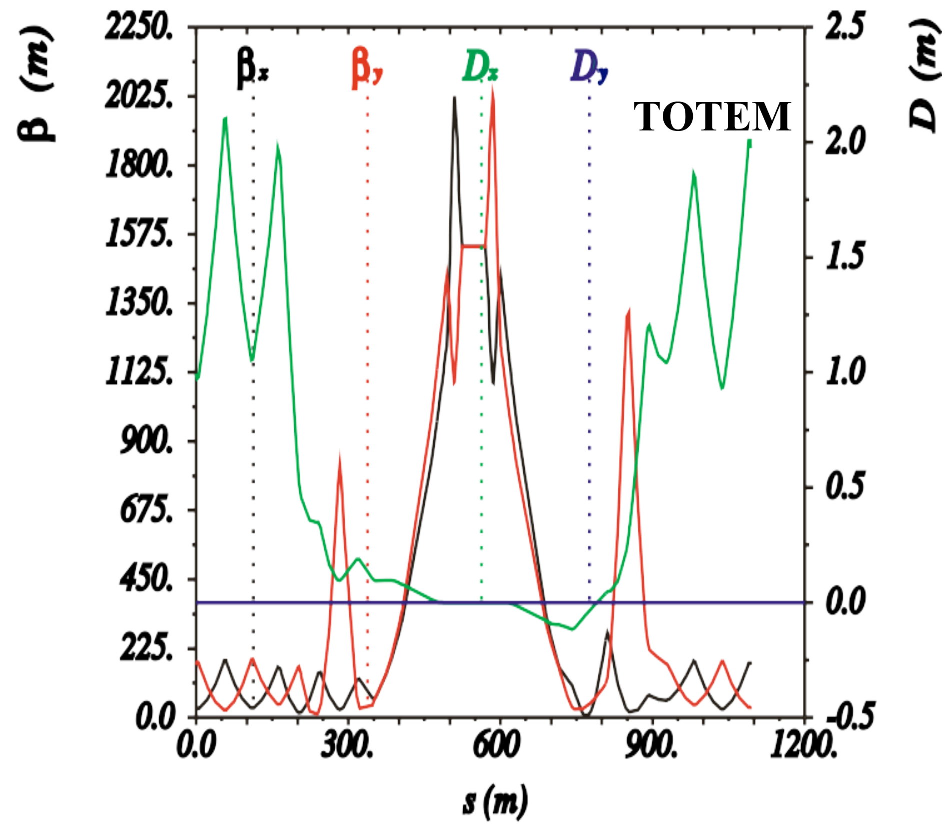
• **Minimum distance of a detector from a beam:** $d \propto \sqrt{\varepsilon \ \beta(s)}$

• **Smallest detectable angle:** $\theta_{\min} \propto \sqrt{\frac{\varepsilon}{\beta^*}}$

$\Rightarrow$ **Additional constraints: low emittance, large β^* and $\beta(s)$ not too small.**

High-β optics





- Two optics developed based on initial studies from A. Verdier and A. Faus-Golfe:

⇒ ALFA: β*= 2625 m, Q4 with inverted polarity, requires dedicated injection.

⇒ TOTEM: β*= 1535 m, compatible with nominal injection. Hardware changes required.

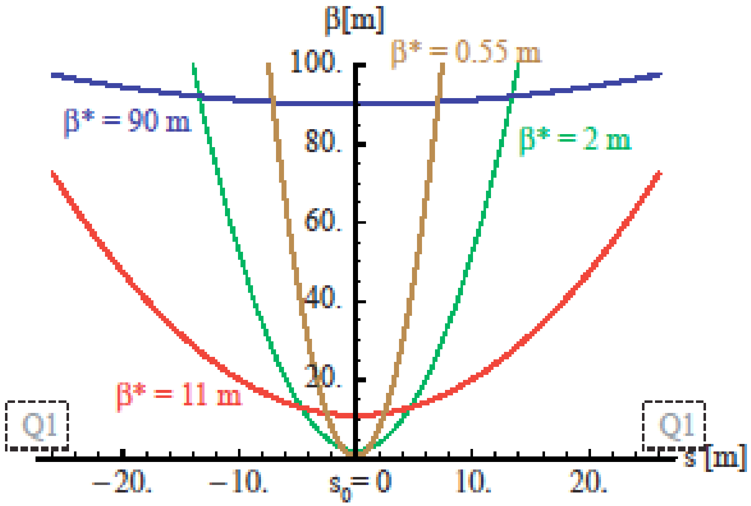
⇒ Both optics designed for emittance of 1 µm (required to reach % level resolution).

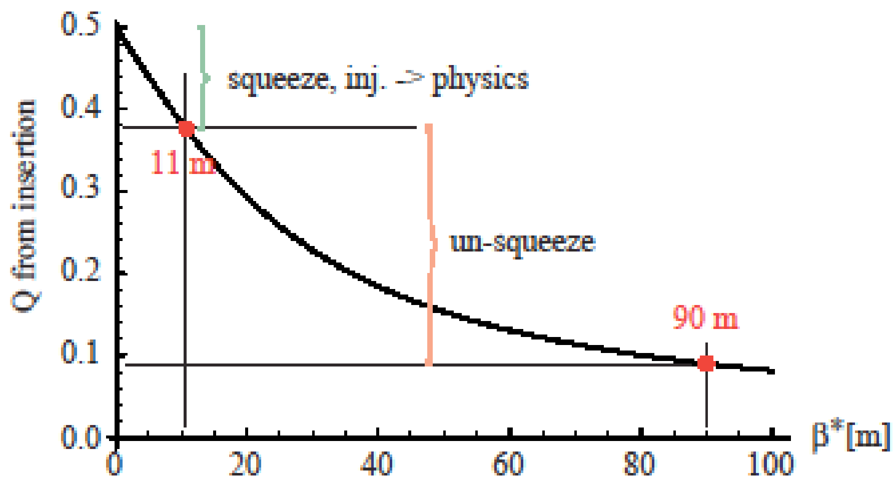
Tune Compensation

• **The betatron phase advance is expressed as:**

$$\mu(s) = \int \frac{1}{\beta(s)} ds$$

⇒ Increasing β* would then reduce the tune contribution of the IR.

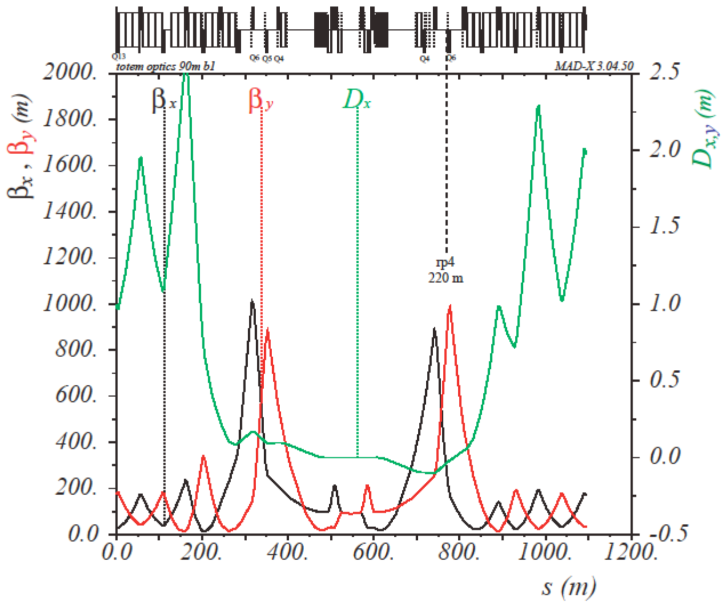




• **We would then loose ~0.5 in tune when un-squeezing the beam to the high-β optics.**
⇒ Some of it could be recovered with the matching.
⇒ The rest should be compensated for with other IRs. IR2, IR8, IR4 have been studied.

Commissioning

• **Intermediate 90m optics have been studied to test the process of un-squeezing and the tune compensation.**



• **Optics designed by H. Burkhardt for IP5**
⇒ **Fully compatible with actual machine layout.**
⇒ **Required tune compensation smaller.**
⇒ **Compatible with nominal emittances at 3.5 TeV.**
⇒ **Commissioning foreseen this year (?).**

• **Very challenging program both for physics and machine operation:**

⇒ **Emittance control (1 μm only required for nominal optics).**
⇒ **Crossing angle and β* determination with very high precision (few μrad on the angle, 1% on the β*).**
⇒ **Will provide very useful information on the flexibility of LHC.**

Conclusion

• **Operation in collision and optimization:**

⇒ **Software fully commissioned and used on a daily basis.**

⇒ **Good fill to fill reproducibility of the machine. Should be further improved for nominal beam parameters.**

• **Luminosity calibration:**

⇒ **First scans gave excellent results in all IPs.**

⇒ **The main sources of errors have been quantified. Main contributor is the beam intensity.**

⇒ **Overall error of 11%. Need more experience and statistics to fully understand the systematic uncertainties.**

⇒ **Actual machine: we hope to get the uncertainty down to 5%.**

• **High-β Optics:**

⇒ **Future high precision cross section measurement (few percents).**

⇒ **Until now no measurements to really assess the operational challenges.**

⇒ **Optics solutions available for IP5 and IP1 fulfilling all requirements.**

⇒ **Intermediate solution at 90 m for IP5 ready for first tests.**

Backup Slides

Van Der Meer Method

- **At separations δx and δy:** $\dot{N} = C \iint \rho_1(x-\delta x, y-\delta y)\ \rho_2(x,y)\ dx\ dy$
- **Uncorrelated x/y distributions:** $\dot{N} = C \int \rho_1(x-\delta x)\rho_2(x)dx \int \rho_1(y-\delta y)\rho_2(y)dy$
- **Areas under the counting curve:**

$$A = C \iint \rho_1(x-\delta x)\ \rho_2(x)\ dx\ d\delta x \iint \rho_1(y-\delta y)\ \rho_2(y)\ dy\ d\delta y$$

- **Counting rate at zero:** $\dot{N}(0) = C \int \rho_1(x)\rho_2(x)dx \int \rho_1(y)\rho_2(y)dy$
- **Integral taken over the whole non-zero region:**

$$\int \rho_1(u-\delta u)\ d\delta u = \int \rho_1(u)\ du \quad \text{and} \quad \int \rho_1(u)\ du = 1 \quad \text{with} \quad u = x, y$$

- **The ratio of the area divided by the rate at zero is:**

$$\frac{A}{\dot{N}(0)} = \frac{C \int \left[\int \rho_1(x-\delta x)\ \rho_2(x)\ dx\right] d\delta x \int \left[\int \rho_1(y-\delta y)\ \rho_2(y)\ dy\right] d\delta y}{C \int \rho_1(x)\rho_2(x)dx \int \rho_1(y)\rho_2(y)dy}$$

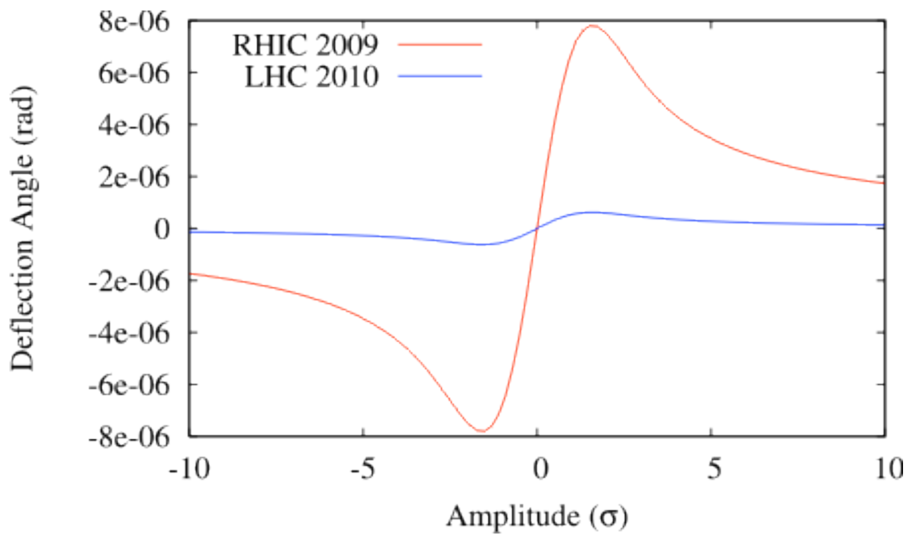
$$\frac{A}{\dot{N}(0)} = \frac{1}{\int \rho_1(x)\rho_2(x)dx \int \rho_1(y)\rho_2(y)dy} = A_{\text{eff}}$$

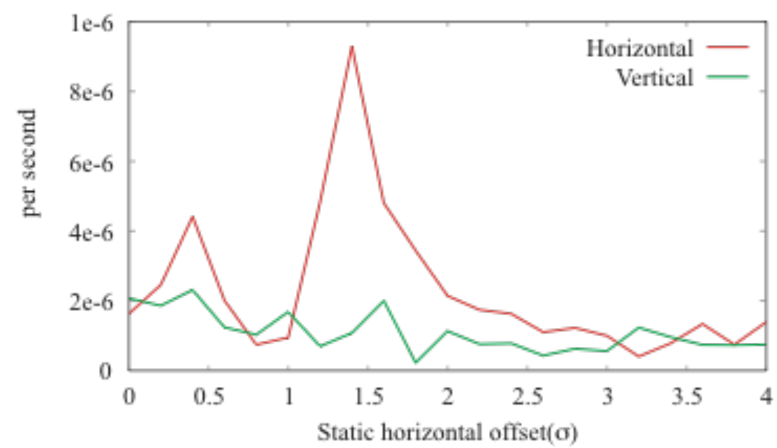
Beam-Beam Effects

- **For round Gaussian beams ($\sigma_x = \sigma_y = \sigma$), the beam-beam deflection angle depends on the separation *r*:**

$$\Delta r' = \frac{2\ N\ r_0}{\gamma}\ \frac{1}{r}\left[1-\exp\left(-\frac{r^2}{2\ \sigma^2}\right)\right]$$

- **Observed at RHIC (250 GeV):**
⇒ Angle ∝ $1/\gamma$: very small for LHC
- **Filling scheme: bunches have different collision pattern: different orbit and tune.**





Emittance growth vs separation. Nom. LHC.

⇒ Luminosity calibration scans: avoid large number of bunches (long-range interactions) and perform at reduced intensity (emittance blow-up).

Crossing Angle

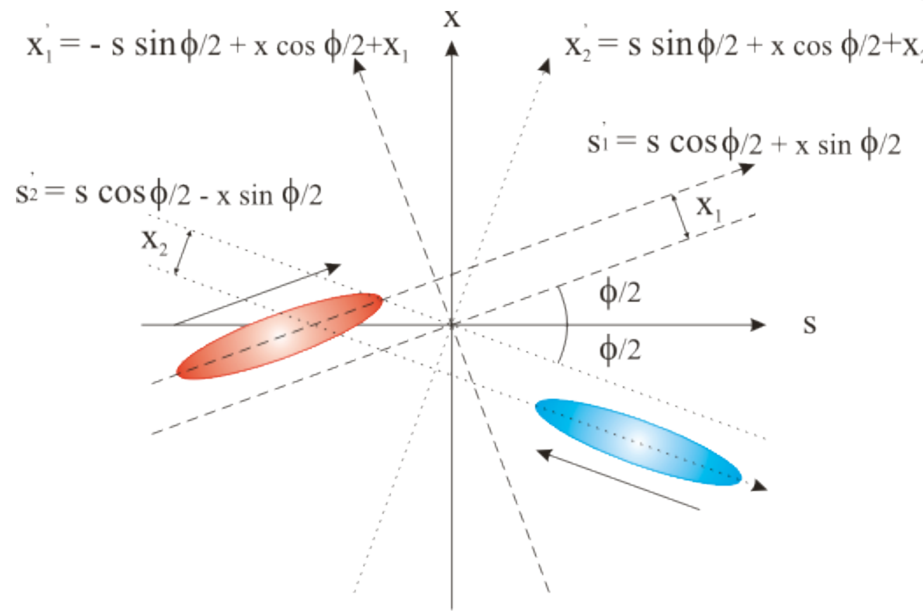
$$\frac{L}{L_0} = S.T.U$$

$$T = \exp\left[-\frac{\delta x^2}{2\ (\sigma_{1x}^2 + \sigma_{2x}^2)}\right]$$

$$S = \left(\sqrt{1 + \frac{\sigma_{1s}^2 + \sigma_{2s}^2}{\sigma_{1x}^2 + \sigma_{2x}^2}\left(\tan\frac{\varphi}{2}\right)^2}\right)^{-1}$$

$$U = \exp\left[S^2\,\frac{\sigma_{1s}^2 + \sigma_{2s}^2}{2}\left(\frac{\delta x\ \tan(\varphi/2)}{\sigma_{1x}^2 + \sigma_{2x}^2}\right)^2\right]$$

$$F(\delta x) = T.U = \exp\left[-S^2\,\frac{\delta x^2}{2\ (\sigma_{1x}^2 + \sigma_{2x}^2)}\right]$$

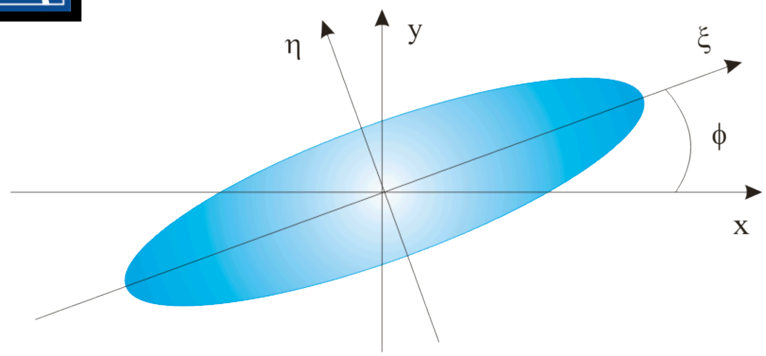


$$\sigma_{\mathrm{eff}} = \frac{\int_{-\infty}^{+\infty} F(\delta x)\,d\delta x}{F(0)}$$

$$\sigma_{\mathrm{eff}} = \frac{\sqrt{\sigma_{1x}^2 + \sigma_{2x}^2}}{S}$$

⇒ If the scan is done in the crossing angle plane correction factor fully determined.

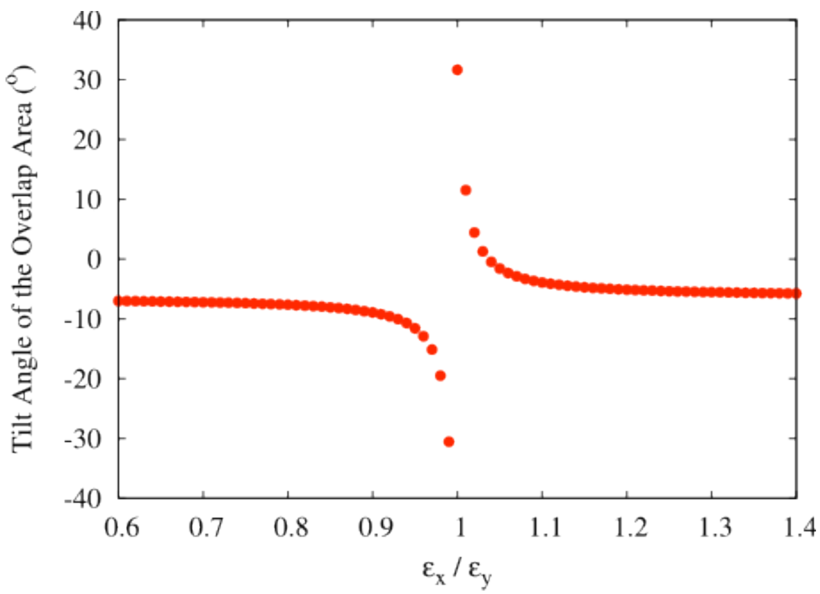
Linear Coupling

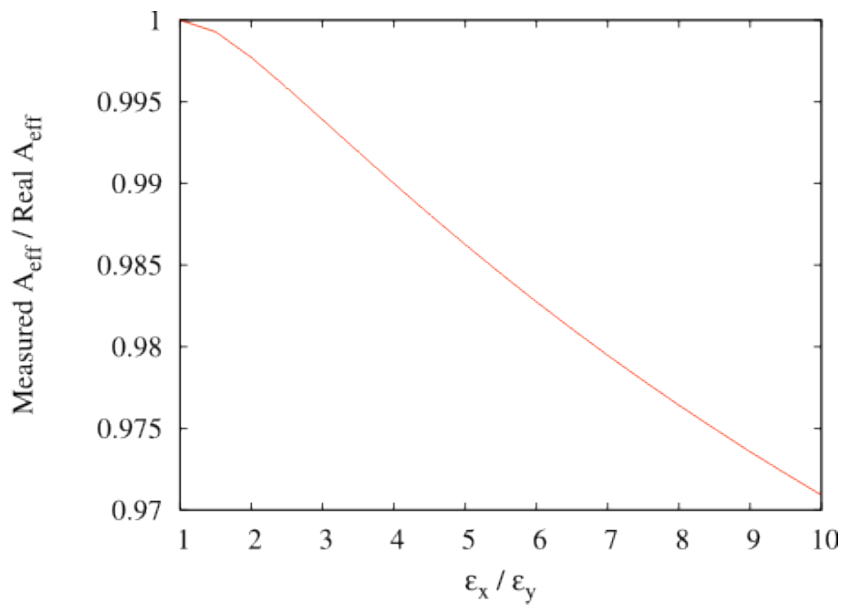


$$\tan 2\phi = \frac{2\sigma_{xy}}{\sigma_{xx} - \sigma_{yy}}$$

$$A_{\text{eff}} = 2\ \pi\ \sigma_{\xi}\ \sigma_{\eta}$$

- **Tilt angle determined from emittance and optics measurements. Undefined for round beams. For round beams no error from coupling** ($\sigma_x = \sigma_y = \sigma_\zeta = \sigma_\eta$).



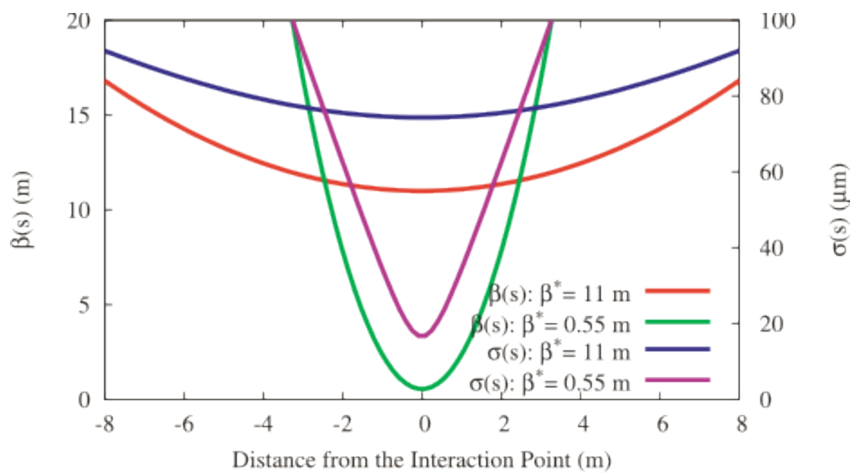


- **If significant perform raster scan to measure the beam sizes along the ellipse axes.**

Hourglass Effect

$$\beta(s) = \beta^*\left(1 + \frac{s^2}{\beta^*}\right)$$

$$\sigma(s) = \sigma^*\sqrt{1 + \frac{s^2}{\beta^*}}$$



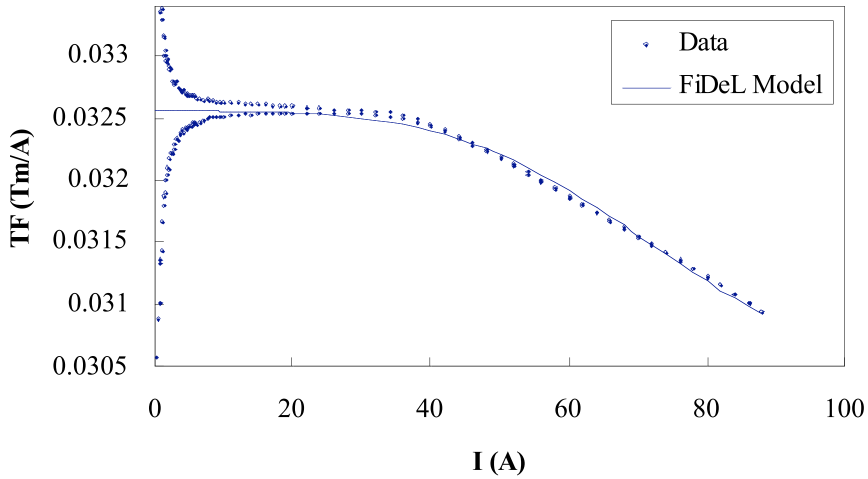
- **Effect becomes relevant when β^* equal or smaller than σ_s.**
  ⇒Include dependency in overlap integral.

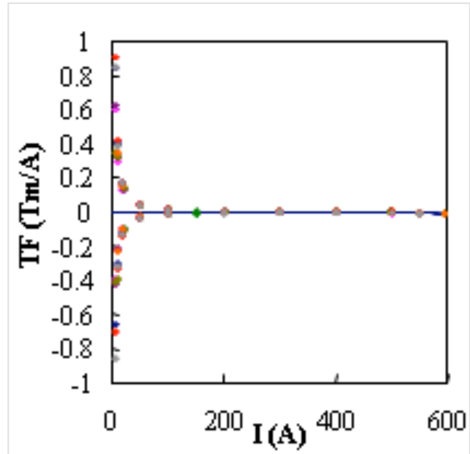
- **Change of variable:** $t^2 = \frac{2\ s}{\sigma_{1s}^2 + \sigma_{2s}^2}$ and $t_u^2 = \frac{2(\sigma_{1u}^{*2} + \sigma_{2u}^{*2})}{(\sigma_{1s}^2 + \sigma_{2s}^2)(\sigma_{1u}^{*2}/\beta_{1u}^{*2} + \sigma_{2u}^{*2}/\beta_{2u}^{*2})}$

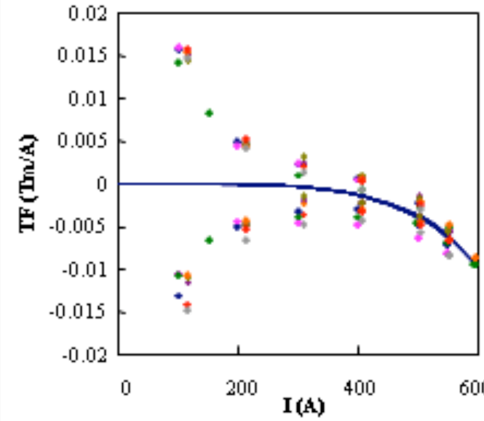
- **General expression:** $$\frac{L}{L_0} = \int \frac{1}{\sqrt{\pi}} \frac{e^{-t^2}}{\sqrt{(1 + t^2/t_x^2)\ (1 + t^2/t_y^2)}}\ dt$$

- **Round beams:** $$\frac{L}{L_0} = \sqrt{\pi}\ t_r\ e^{t_r^2}\,\mathrm{erfc}(t_r) \quad \text{where} \quad t_r^2 = \frac{2\beta^{*2}}{(\sigma_{1s}^2 + \sigma_{2s}^2)}$$

Hysteresis Effects

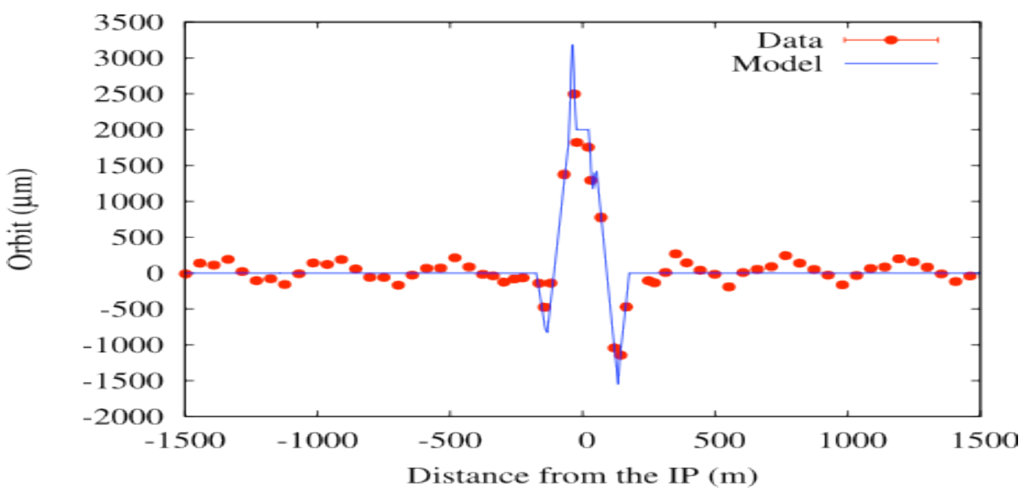






- **Hysteresis measurements and model for MCBY (right) and MCBX (left) magnets.**

⇒ Simulation based on estimates from lab measurements showed large effect on the orbit for MCBX magnets, negligible for MCBC and MCBY.



- **Orbit measurement with MCBX.**

⇒ Orbit data confirm simulations.

⇒ Decided not to use the MCBX magnets for fine tuning and precision measurements.