Bunch Current Normalisation Analysis Results

Thilo Pauly (CERN)

on behalf of the BCNWG

$$\mathcal{L} = f_r \cdot \frac{\sum_i N_i^{(1)} N_i^{(2)}}{2\pi \Sigma_x \Sigma_y}$$

LHC BUNCH CURRENT NORMALISATION FOR THE APRIL-MAY 2010 LUMINOSITY CALIBRATION MEASUREMENTS

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Analysis Activity Overview

- VdM scans April/May:
  - fills 1058, 1059, 1089, 1090
    - no crossing-angle

Van der Meer scans, April-May 2010							
LHC fill	Approx. start date	Approx. start time	Approx. stop date	Approx. stop time	IP scanned	Bunch pattern	Approx. bunch population
1058	April 24	11:00	April 24	12:30	IP5	3-bunch	$1.0 \cdot 10^{10} p$
1059	April 26	02:30	April 26	06:00	IP8, IP1	2-bunch	$1.0 \cdot 10^{10} p$
1089	May 8	23:00	May 9	03:30	IP5, IP1	2-bunch	$2.0 \cdot 10^{10} p$
1090	May 10	05:00	May 10	07:00	IP2	2-bunch	$2.0 \cdot 10^{10} p$

Fill 1058 3-bunch pattern					Fills 1059, 1089 and 1090 2-bunch pattern				
Beam1 RF bucket	Colliding Beam2 RF bucket IP1	IP2	IP5	IP8	Beam1 RF bucket	Colliding Beam2 RF bucket IP1	IP2	IP5	IP8
1	1	8911	1	-	1	1	8911	1	-
8941	(8911)	17851	(8911)	1	17851	-	-	-	8911
17851	17851	-	17851	8911					

  - preliminary analysis for ICHEP
  - more detailed analysis
    - establish the methods
    - final numbers to appear in the next days as CERN preprint
- VdM scans October:
  - fills 1386 (ATLAS scans, partial CMS scans), 1422 (LHCb, CMS, ALICE scans)
    - non-zero crossing angle
    - 19-bunch scheme, ~1.5×10^{12} p
  - work in progress, using the same method as before

Systems involved

DCCT: DC current transformer

- 2 (production A and development B) systems with 1 transformer per beam at Point 4
  - both system A and B are used (average)
- measures mean total current of circulating beam (bunched and unbunched)
- calibration winding and known generated current used to calibrate the absolute 'scale factor' α

BPTX: experiments' timing pick-ups

- provides as by-product a per-bunch relative intensity
- ATLAS BPTX data used to cross-check the per-bunch intensity from the FBCT

LHC detectors used to study ghost charge and satellite bunch contributions

FBCT: fast beam current transformer

- 2 (production A and development B) systems with 1 transformer per beam at Point 4
  - only system A is used
- 200 MHz bandwidth channel used for per-bunch measurements
  - only sensitive to bunched beam, not sensitive to unbunched beam
  - measures bunches over threshold (~5e8) per 25ns slot
- absolute calibration currently done via the DCCT

Definition:

- **Ghost charge:** summed charge for all those 25ns slots which are not visible by the FBCT, i.e. unbunched and/or below the FBCT threshold
- **Satellite bunch:** captured charge in RF buckets within a few tens ns around the nominal buckets

Method and Overview

Needed for VdM scans: $N_i^{(1)} \cdot N_i^{(2)}$

Total beam current from DCCT $N_{tot}^{DCCT} = \alpha \cdot S_{DCCT} - N_0^{DCCT}$

- N_0^{DCCT}: baseline offset from DCCT data
- S_{DCCT}: measured DCCT signal
- α: scale factor from DCCT calibration

Per-bunch current via FBCT $N_i^{FBCT} = (N_{tot}^{DCCT} - N_{ghost}) \cdot \frac{S_i^{FBCT}}{\sum_i S_i^{FBCT}}$

- N_{tot}^{DCCT}: absolute calibration via DCCT
- $\frac{S_i^{FBCT}}{\sum_i S_i^{FBCT}}$: relative per-bunch intensity

Outline:

- N_0^{DCCT} Baseline offset correction and uncertainty
- α Scaling factor uncertainty
- $S_i / \sum S_i$ Per-bunch uncertainty
- N_{ghost} Ghost-charge population

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baseline offset
…m DCCT data

Per-b…

…e per-bunch
…ity

via DCCT

In the following,
if not stated otherwise,
all systematic uncertainties are taken as uncertainty bands

i.e. a quantity with a systematic uncertainty of Δ is conservatively assumed to follow a flat distribution in the interval [-Δ, +Δ] around the central value

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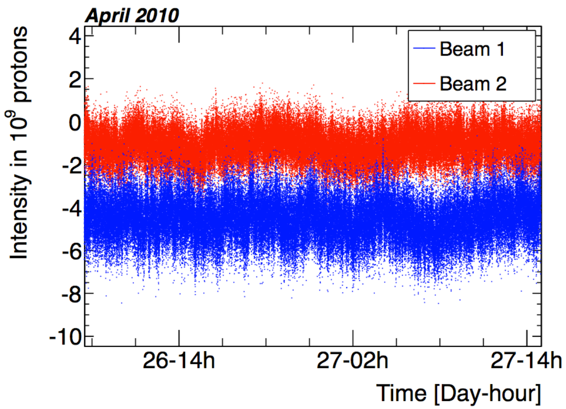
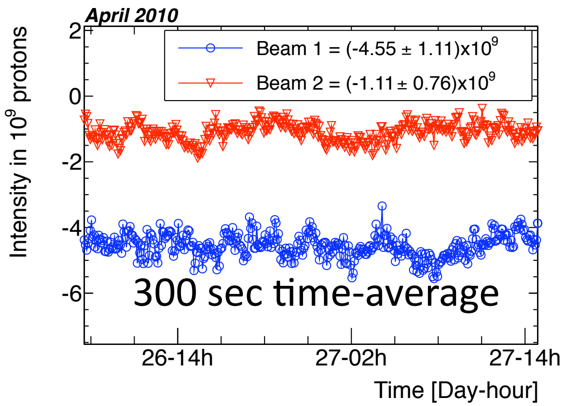
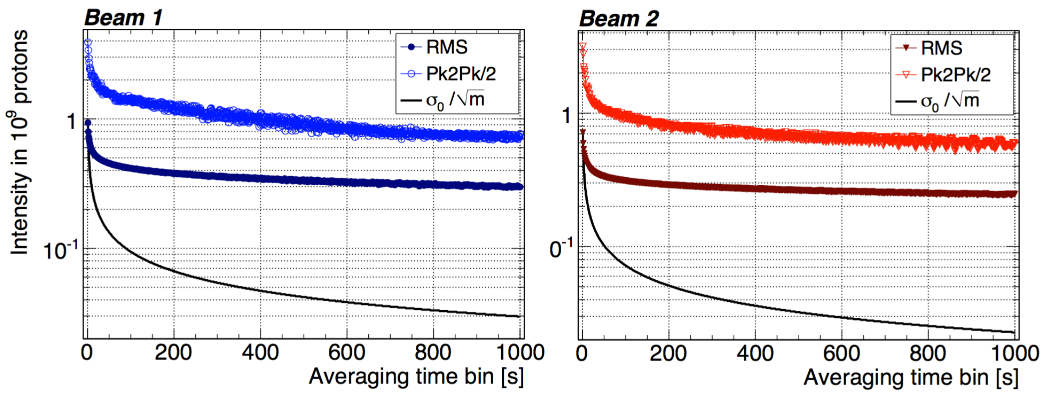
DCCT Baseline Drifts

- Study on periods without beam
- Time-averaging suppresses white noise and reveals slow baseline drift





- Origin of baseline drifts are not known. Possible reasons are:
  - temperature drifts
  - electromagnetic pick-up in cables and electronics
  - mechanical vibrations in the transformer assembly



Averaging window of 300 sec seems an appropriate choice

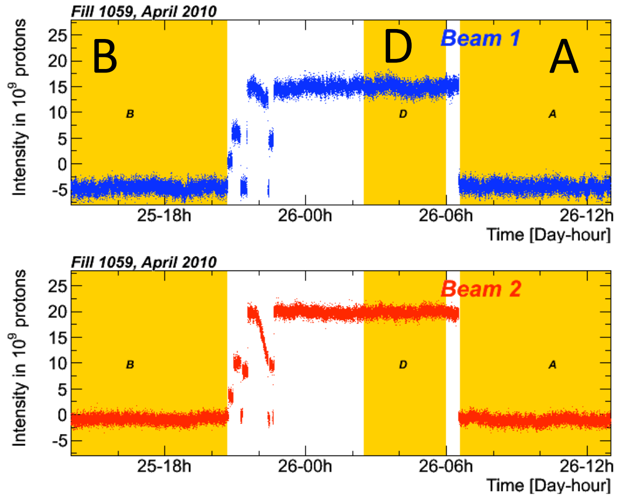
- large enough to suppress white noise
- small compared to the length of a scan

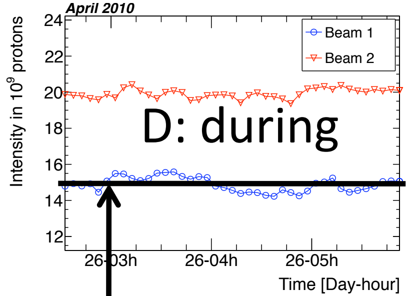
Method for Baseline Correction

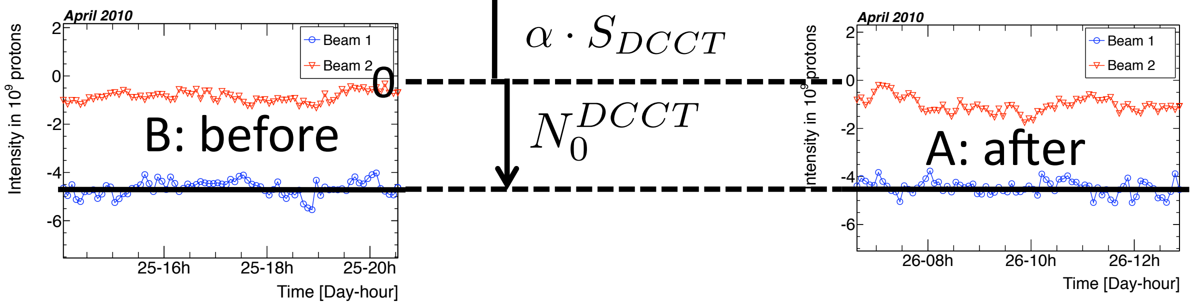
- Define 3 periods
  - B Before: empty before fill
  - D During: during fill (VdM)
  - A After: empty after fill
- Baseline offset during VdM scan determined as interpolation between periods B and A

$$N_{tot}^{DCCT} = \alpha \cdot S_{DCCT} - N_0^{DCCT}$$

- uncertainty is the maximum pk2pk/2 of B or A period



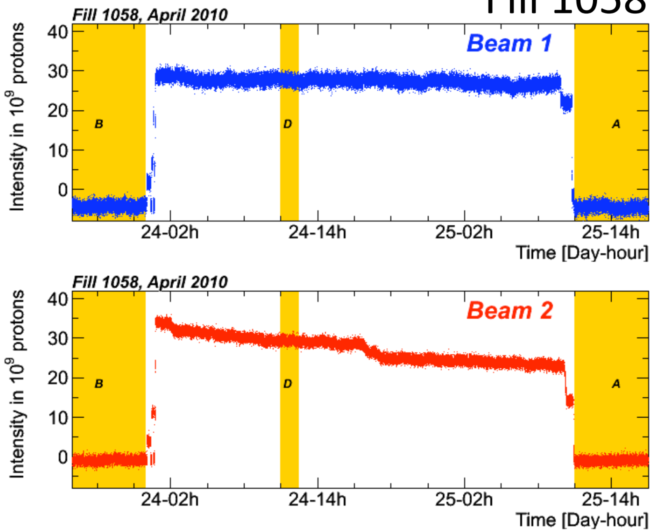




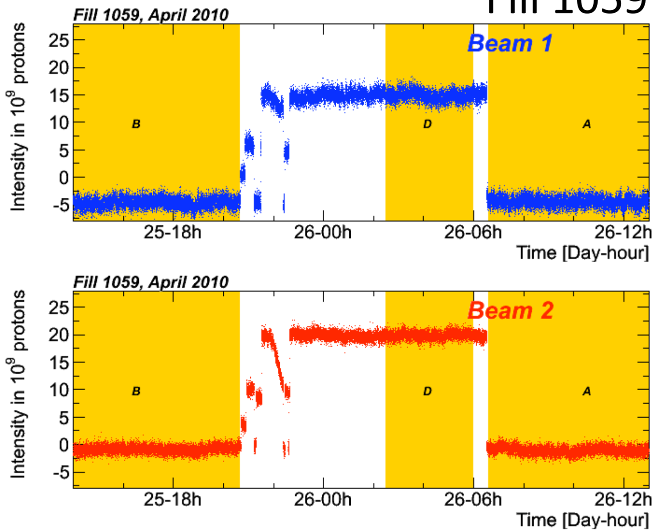
Baseline offset: April/May periods

System A, system B not shown

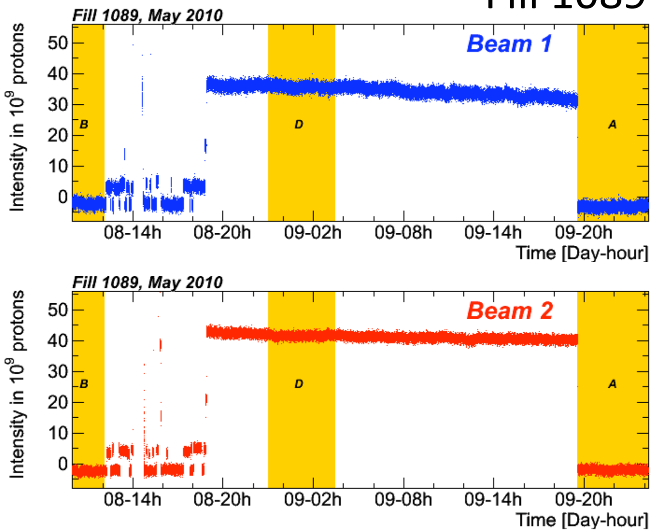
Fill 1058



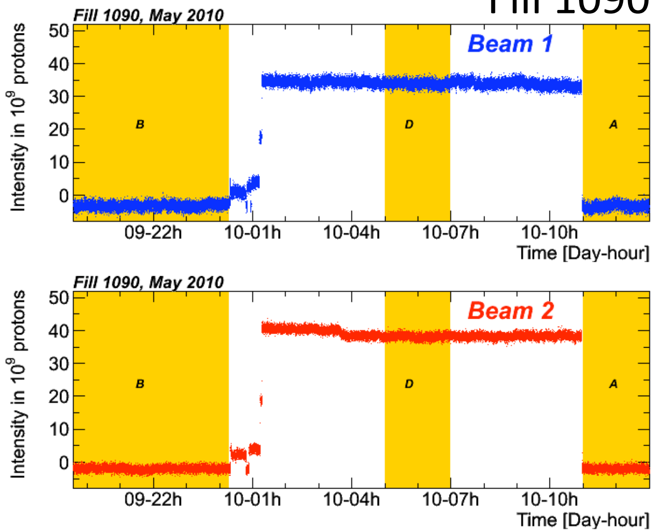
Fill 1059



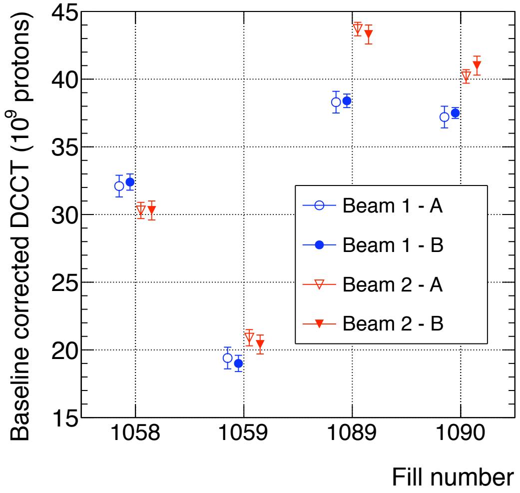
Fill 1089



Fill 1090



Baseline offset results for April/May scans



- use average (System A + B)/2
- fix baseline offset uncertainty to largest uncertainty: 0.8 x 10^9 p

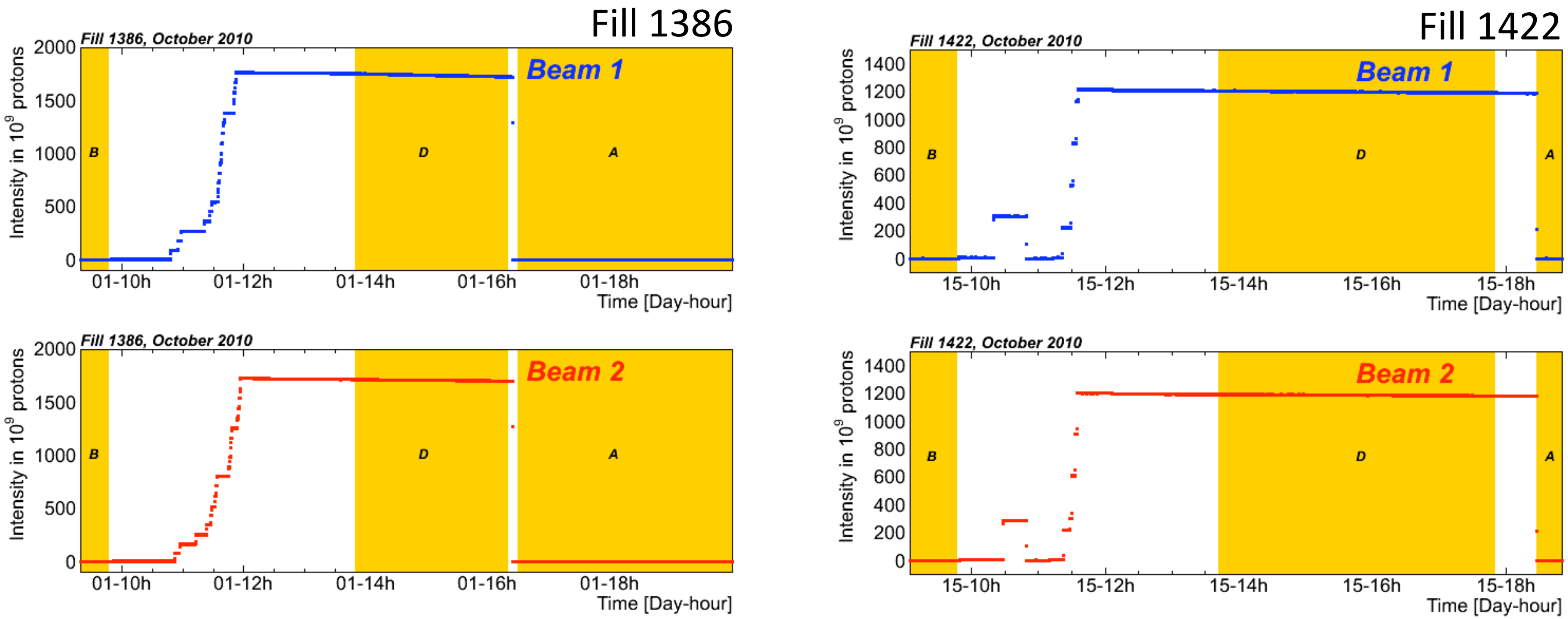
Fill nr.	LHC ring j	Detailed analysis (System A + System B) LHC intensity $N_{tot,j} \cdot 10^{-9}$ baseline-corrected	Preliminary analysis (System A) LHC intensity $N_{tot,j} \cdot 10^{-9}$ baseline-corrected
1058	1	32.3 ± 0.8	31.8 ± 2.0
	2	30.3 ± 0.7	28.4 ± 2.0
1059	1	19.2 ± 0.8	18.9 ± 2.0
	2	20.7 ± 0.7	20.6 ± 2.0
1089	1	38.4 ± 0.8	38.1 ± 2.0
	2	43.5 ± 0.7	43.7 ± 2.0
1090	1	37.4 ± 0.8	37.4 ± 2.0
	2	40.6 ± 0.7	40.0 ± 2.0

baseline offset uncertainty only

unify to 0.8

- baseline offset uncertainty reduced from $2\text{x}10^9$ to $0.8\text{x}10^9$
- some central values changed

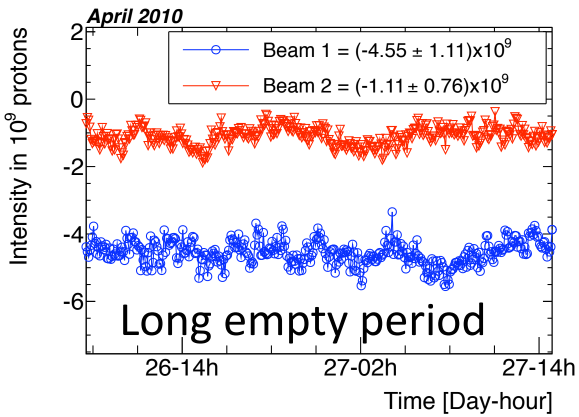
Baseline offset results for October scans

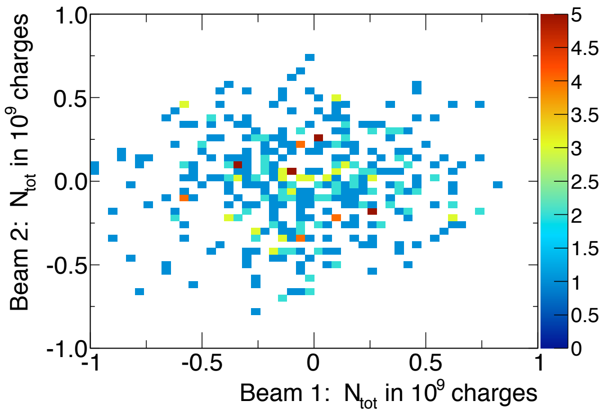


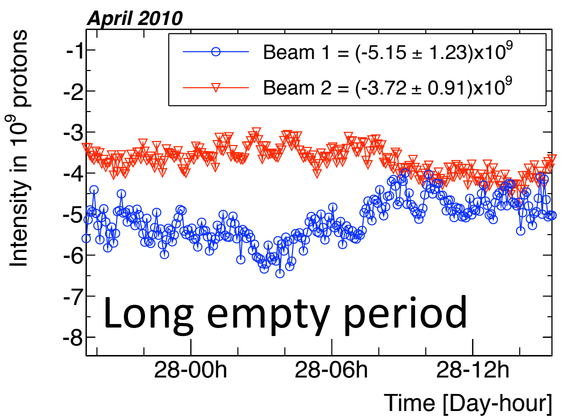
- Absolute baseline uncertainties unchanged (0.8 x 10^9), but intensities now much higher > 10^{12}
- Relative baseline uncertainty negligible (<0.1%)

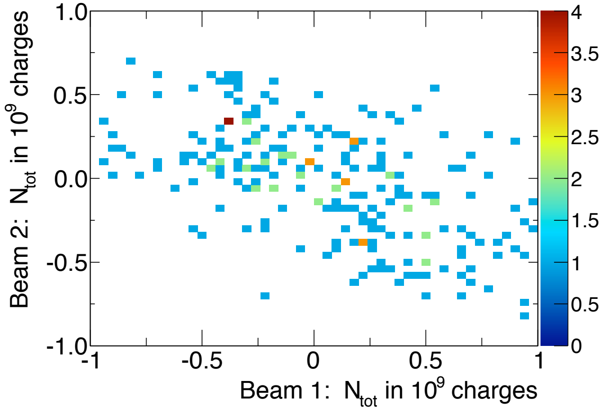
Correlation of baseline drift between the two beams?

Look at periods without beam (System A only)

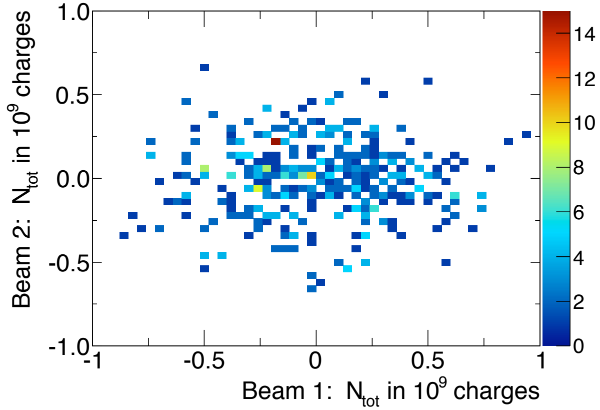








Periods before and after April/May-VdM fills



No correlation visible

can add baseline uncertainties for both beams quadratically

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Outline:

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- α Scaling factor uncertainty
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- N_{ghost} Ghost-charge population

Uncertainty on Absolute Scale Factor α

$$N_{tot}^{DCCT} = \alpha \cdot S_{DCCT} - N_0^{DCCT}$$

- Possible issues:
  - long-term time stability: evolution between calibration periods and VdM scan periods
    - ±2% for each ring, based on 5 precise calibration points during technical stops
  - misbehaviour of the DCCT linked to the LHC filling pattern
    - believed to be negligible
  - inaccuracy of the commercial current generator used for calibration
    - <0.1%
  - non-linearity of measurement system between working point and calibration point
    - <0.1%

- Current uncertainty:
  - for preliminary and detailed analysis

$$\frac{\Delta\alpha}{\alpha} \approx \pm 2\,\%$$

  - correlated between the two beams in a fill
  - uncorrelated between fills

for more information, see JJ Gras' presentation on Friday: "Instrumentation1 : Beam current transformer" for a more detailed discussion

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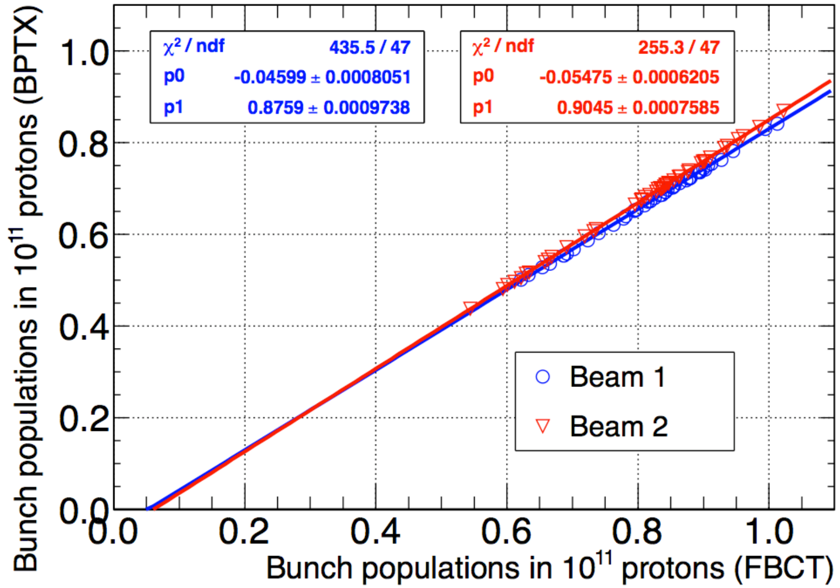
Relative Per-Bunch Populations

$$N_i^{FBCT} = (N_{tot}^{DCCT} - N_{ghost}) \cdot \frac{S_i^{FBCT}}{\sum_i S_i^{FBCT}}$$

- Cross-check of FBCT per-bunch intensities with independent ATLAS BPTX system
- BPTX and FBCT show a linear relationship, but there is an offset, likely in the BPTX, but yet of unknown origin
- Relative per-bunch intensities $r_i = \frac{S_i}{\sum_i S_i}$
- comparison with BPTX shows relative differences of
  - April/May scans:
    - up to 3% without accounting for the offset
    - <1% with accounting for the offset
  - October scans:
    - up to 1% without accounting for offset
    - <1% taking it into account
- Single bunch uncertainties:
  - April/May: 3%
  - October: 1%
- no correlation between two beams, i.e. quadratic sum in the bunch current products



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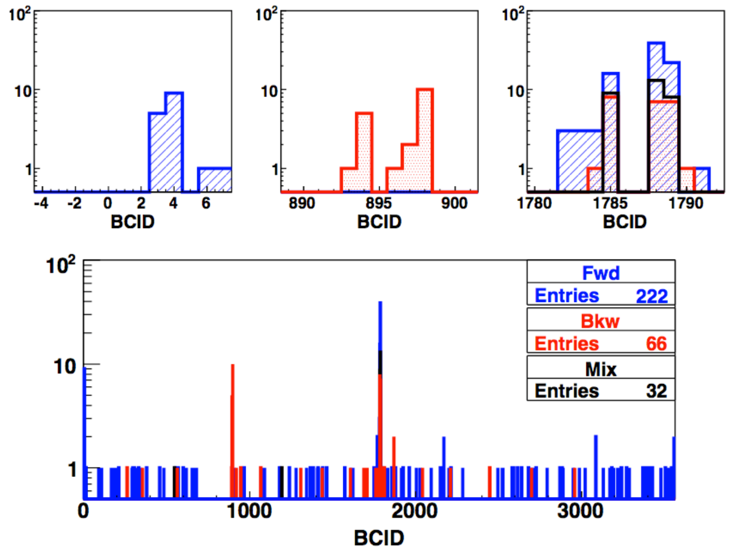
Ghost Charge

- LHCb beam gas analysis
  - Fill 1089: ghost charge close to 1% for beam 1
  - smaller for beam 2 and other fills
- Small (<1%) ghost charge correction was applied to the April/May scans, see table
- October scans are under study
- Need to watch ghost charge carefully in the future and improve measurements

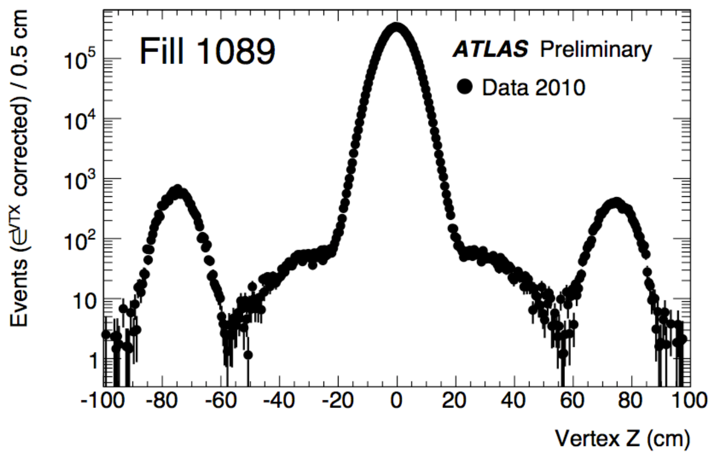
Fill 1089



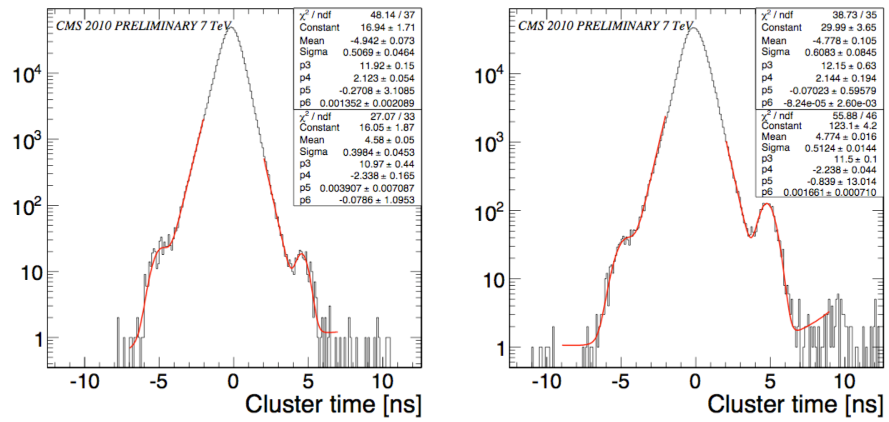
Fill number	Beam1 ghost fraction $f_{\mathrm{ghost},1}$ in % all slots	(near bunch slots)	Beam2 ghost fraction $f_{\mathrm{ghost},2}$ in % all slots	(near bunch slots)
1058	0.08 ± 0.01	(0.04 ± 0.01)	0.03 ± 0.01	(0.02 ± 0.01)
1059	0.12 ± 0.06	(0.12 ± 0.06)	0.00 ± 0.03	(0.00 ± 0.03)
1089	0.85 ± 0.06	(0.36 ± 0.04)	0.26 ± 0.03	(0.16 ± 0.03)
1090	0.42 ± 0.06	(0.24 ± 0.05)	0.41 ± 0.06	(0.36 ± 0.06)

Satellite Bunches

- Analyses by ATLAS/CMS taking advantage of zero crossing angle during April/May scans
- ATLAS/CMS displaced vertices
  - consistent results
  - fill 1089 has satellite populations (5ns distance) of up to 2 permil
  - fill 1090 up to 1 permil



- CMS timing:
  - timing information from endcap electromagnetic calorimeter for minimum bias events
  - consistent with vertexing results



Conclusion:

- April/May scans: satellite contribution <2e-3, negligible
- October scans: under study, but non-zero crossing angle (less impact, more difficult to measure)
- need to watch carefully in future

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- N_{ghost} Ghost-charge population ✔

April/May Per-Bunch Results

(preliminary results in brackets)

		Fill number			
		1058	1059	1089	1090
Populations $N \cdot 10^{-9}$					
	$N(1)$	9.56 ± 0.29	8.98 ± 0.34	18.99 ± 0.54	19.91 ± 0.57
		(9.41 ± 0.36)	(8.85 ± 0.55)	(19.05 ± 0.62)	(20.01 ± 0.66)
Beam1	$N(8941)$	11.70 ± 0.35	-	-	-
		(11.51 ± 0.44)	-	-	-
	$N(17851)$	11.02 ± 0.33	10.20 ± 0.38	19.08 ± 0.54	17.33 ± 0.50
		(10.88 ± 0.41)	(10.05 ± 0.63)	(19.05 ± 0.62)	(17.39 ± 0.57)
	$N(1)$	10.19 ± 0.31	10.35 ± 0.37	22.18 ± 0.61	19.54 ± 0.55
		(9.57 ± 0.40)	(10.30 ± 0.59)	(22.33 ± 0.64)	(19.32 ± 0.60)
Beam2	$N(8911)$	10.66 ± 0.33	10.35 ± 0.37	21.21 ± 0.59	20.89 ± 0.59
		(10.00 ± 0.42)	(10.30 ± 0.59)	(21.37 ± 0.62)	(20.68 ± 0.64)
	$N(17851)$	9.43 ± 0.29	-	-	-
		(8.83 ± 0.37)	-	-	-

April/May Per-Bunch Product Results

(preliminary results in brackets)		Fill number 1058	1059	1089	1090
Population products $P_{ij} \cdot 10^{-18} = N_{i,1} \cdot N_{j,2} \cdot 10^{-18}$					
IP1&5	$N(1) \cdot N(1)$	96.4 ± 4.5 (90.1 ± 9.0)	92.5 ± 5.1 (91.1 ± 12.8)	419.7 ± 18.5 (425.4 ± 34.0)	386.0 ± 17.1 (386.6 ± 32.0)
	$N(17851) \cdot N(17851)$	102.8 ± 4.8 (96.1 ± 9.6)	- -	- -	- -
IP2	$N(1) \cdot N(8911)$	100.8 ± 4.7 (94.1 ± 9.4)	92.4 ± 5.1 (91.1 ± 12.8)	401.3 ± 17.6 (407.1 ± 32.5)	412.5 ± 18.3 (413.8 ± 34.3)
	$N(8941) \cdot N(17851)$	109.1 ± 5.1 (101.7 ± 10.2)	- -	- -	- -
IP8	$N(8941) \cdot N(1)$	117.9 ± 5.5 (110.2 ± 11.0)	- -	- -	- -
	$N(17851) \cdot N(8911)$	116.2 ± 5.4 (108.7 ± 10.9)	105.0 ± 5.8 (103.6 ± 14.5)	403.2 ± 17.7 (407.1 ± 32.5)	359.0 ± 15.9 (359.6 ± 29.8)

NB: Bunch product calculated before averaging

Summary on Per-Bunch Product Uncertainties

Bunch population product $P_{ij} = N_i \cdot N_j$

Preliminary Analysis

$$\frac{\sigma_{P_{ij}}^{\text{baseline}}}{P_{ij}} = \frac{1}{\sqrt{3}} \left(\frac{\Delta N_{\text{tot},1}}{N_{\text{tot},1}} + \frac{\Delta N_{\text{tot},2}}{N_{\text{tot},2}} \right)$$

$$\frac{\sigma_{P_{ij}}^{\text{scale}}}{P_{ij}} = \frac{2}{\sqrt{3}} \frac{\Delta\alpha}{\alpha} = 2.3\%$$

$$\frac{\sigma_{P_{ij}}^{\text{FBCT}}}{P_{ij}} = 0$$

$$\sigma_{P_{ij}} = \sigma_{P_{ij}}^{\text{baseline}} + \sigma_{P_{ij}}^{\text{scale}}$$

Detailed Analysis

$$\frac{\sigma_{P_{ij}}^{\text{baseline}}}{P_{ij}} = 0.682 \cdot \sqrt{\left(\frac{\Delta N_{\text{tot},1}}{N_{\text{tot},1}} \right)^2 + \left(\frac{\Delta N_{\text{tot},2}}{N_{\text{tot},2}} \right)^2}$$

$$\frac{\sigma_{P_{ij}}^{\text{scale}}}{P_{ij}} = 0.682 \cdot 2 \cdot \frac{\Delta\alpha}{\alpha} = 2.7\%$$

$$\frac{\sigma_{P_{ij}}^{\text{FBCT}}}{P_{ij}} = 0.682 \cdot \sqrt{\left(\frac{\Delta N_{i,1}}{N_{i,1}} \right)^2 + \left(\frac{\Delta N_{j,2}}{N_{j,2}} \right)^2}$$

$$\sigma_{P_{ij}} = \sqrt{(\sigma_{P_{ij}}^{\text{baseline}})^2 + (\sigma_{P_{ij}}^{\text{scale}})^2 + (\sigma_{P_{ij}}^{\text{FBCT}})^2}$$

- Converting uncertainty band to confidence intervals:
  - Preliminary: 1-sigma errors, factor 1/√3, corresponds to 58% CL
  - Detailed: prefer to use 68% CL, i.e. factor 0.682
- Baseline:
  - Preliminary:
    - $\Delta N_{tot}=2\times10^9$
    - fully correlated
  - Detailed:
    - $\Delta N_{tot}=0.8\times10^9$
    - uncorrelated
- Absolute scale:
  - unchanged: $\Delta\alpha/\alpha=2\%$, correlated
- Per-bunch populations:
  - Preliminary: 0
  - Detailed:
    - $\Delta N_i/N_i=3\%$ April/May
    - $\Delta N_i/N_i=1\%$ October
- Uncertainty contributions:
  - Preliminary: correlated
  - Detailed: uncorrelated

Summary on Per-Bunch Product Uncertainties

Bunch population product $P_{ij} = N_i \cdot N_j$

	1058	1059	1089	1090	1386	1422
Preliminary Analysis						
$\frac{\sigma_{P_{ij}}^{\text{baseline}}}{P_{ij}} = \frac{1}{\sqrt{3}} \left(\frac{\Delta N_{\text{tot},1}}{N_{\text{tot},1}} + \frac{\Delta N_{\text{tot},2}}{N_{\text{tot},2}} \right)$	7.7%	11.7%	5.7%	6.0%		
$\frac{\sigma_{P_{ij}}^{\text{scale}}}{P_{ij}} = \frac{2}{\sqrt{3}} \frac{\Delta \alpha}{\alpha} = 2.3\%$	2.3%					
$\frac{\sigma_{P_{ij}}^{\text{FBCT}}}{P_{ij}} = 0$	0					
$\sigma_{P_{ij}} = \sigma_{P_{ij}}^{\text{baseline}} + \sigma_{P_{ij}}^{\text{scale}}$	10.0%	14.0%	8.0%	8.3%		
Detailed Analysis						
$\frac{\sigma_{P_{ij}}^{\text{baseline}}}{P_{ij}} = 0.682 \cdot \sqrt{\left(\frac{\Delta N_{\text{tot},1}}{N_{\text{tot},1}} \right)^2 + \left(\frac{\Delta N_{\text{tot},2}}{N_{\text{tot},2}} \right)^2}$	2.5%	3.9%	1.9%	2.0%	<0.1%	
$\frac{\sigma_{P_{ij}}^{\text{scale}}}{P_{ij}} = 0.682 \cdot 2 \cdot \frac{\Delta \alpha}{\alpha} = 2.7\%$	2.7%					
$\frac{\sigma_{P_{ij}}^{\text{FBCT}}}{P_{ij}} = 0.682 \cdot \sqrt{\left(\frac{\Delta N_{i,1}}{N_{i,1}} \right)^2 + \left(\frac{\Delta N_{j,2}}{N_{j,2}} \right)^2}$	2.9%				1.0%*	
$\sigma_{P_{ij}} = \sqrt{(\sigma_{P_{ij}}^{\text{baseline}})^2 + (\sigma_{P_{ij}}^{\text{scale}})^2 + (\sigma_{P_{ij}}^{\text{FBCT}})^2}$	4.7%	5.5%	4.4%	4.4%	2.9%*	2.9%*

*work in progress

Conclusions

- Detailed Beam Current Normalisation Analysis
  - established a measurement procedure
  - updated central values
  - reduced systematic uncertainties of April/May fills considerably
  - main uncertainties are
    - absolute scale (2.7%, studied further)
    - relative per-bunch population
    - baseline offset (negligible for high total intensities)

- NB: ATLAS and CMS results for April/May scans were close to 100% correlated because the main uncertainties are the same