Slow extraction (in)efficiency measurements

2nd Slow Extraction Workshop, 9 - 11th November 2017

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Overview

- Why measure the extraction efficiency?
- Why is it so difficult to measure?
- Common techniques for measurements:
  - Direct measurements: *limitations*
  - Indirect measurements: *inefficiency (losses)*
- Recent measurements at CERN SPS:
  - Results and problems encountered
  - Goal: development of an online (in)efficiency tool
- Conclusion

Why measure extraction efficiency? (1)

- At high energy and intensity we are concerned about the Induced Radioactivity (IR) of the slow extraction region:
  - Hands-on maintenance is (almost) unavoidable
  - Ever tightening regulatory dose limits to personnel
  - Longer cool-down times will mean longer machine downtime when…
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- The IR is proportional to the number of protons lost in the extraction process:

$$\mathrm{IR} \propto 1 - \epsilon, \quad \text{where the efficiency is } \epsilon = \frac{I_{ext}}{I_{acc}}$$

  - I_{ext} : extracted beam intensity measured in the extraction line, e.g. on a SEM
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i.e. the inefficiency

The constant of proportionality will be discussed tomorrow afternoon:
Session 4: Hardware, reducing loss, activation and dose
chaired by M. Tomizawa

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  - …**performance** of extraction systems at **different laboratories**:
    - *Relative measurements of prompt extraction losses can be used to compare the performance of different systems or loss mitigation techniques*
    - *In the same machine this works well, however a well-defined extraction efficiency is needed to compare systems from lab-to-lab*
    - *We all have different ways of calibrating the extraction losses with their own intrinsic uncertainty and particularities …often confusing or misleading*

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- As $\epsilon \longrightarrow 1$ it becomes harder to measure accurately
  - Considering small **systematic** calibration errors in different beam intensity monitors:
  - $\delta_{ext} \ll I_{ext}$ and $\delta_{acc} \ll I_{acc}$:

$$\epsilon' = \epsilon \pm \frac{\delta_{ext}}{I_{ext}} \mp \frac{\delta_{acc}}{I_{acc}} + \cdots$$

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- Extraction efficiency measurements are an age-old problem…
  - Limited number of publications from the 60's and 70's on extraction efficiency measurements: such topics are usually hidden in internal MD notes/reports

Direct efficiency measurements (1)

- High extraction efficiencies cannot be measured accurately using direct intensity measurements: limited by the absolute calibration errors:

$$\epsilon \approx \frac{I_{ext}}{I_{acc}} \pm \frac{\delta_{ext}}{I_{ext}} \mp \frac{\delta_{acc}}{I_{acc}}$$

Device	Calibration Technique	Observable	Typical Calibration Accuracy [%]	Example Ref.
Ring-DCCT	electronic	I_{acc}	$\approx$1	
Fast-BCT	electronic	I_{ext}	$\approx$1	
Activation foils	assumption on nuclear cross-section	I_{ext}	$\approx$15	[1]
Activation foils	**using fast-BCT**	$\boldsymbol{I_{ext}}$	$\boldsymbol{\approx 3}$	
SEM	**using fast-BCT**	$\boldsymbol{I_{ext}}$	$\boldsymbol{< 3}$	
Scintillators/ionization chambers (rate limited $\lesssim 10^{10}$ Hz)	**using fast-BCT**	$\boldsymbol{I_{ext}}$	$\boldsymbol{< 3}$	[2]

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  - Lossless fast-extraction, i.e. 100% efficient (check losses on BLMs)
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  - At the SPS we can, but it’s a rather special extraction using kickers 2.3 km away!
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  - Not easy to set-up/repeat online: it’s a dedicated, one-off measurement
- Note that no absolute calibration measurements are required:
  - Limited mainly by the assumption of loss-less FE, typical error $\sim$ few %

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Measurement type	Quantity	Systematic error on the inefficiency $\bar{\epsilon}$ [%]	Systematic error on efficiency ϵ or $(1-\bar{\epsilon})$ [%]
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- As the inefficiency is proportional to the number of protons lost, the prompt beam loss during extraction (BLMs) can be used:
  - The challenge is to find a way to carefully calibrate the measured beam loss in a linear way to the number of protons lost
  - Most laboratories use beam loss to quantify the extraction efficiency

Indirect efficiency measurements (2)

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    …BLMs, SEMs in extraction line and ring BCT:

$$\bar{\epsilon} = 1 - \epsilon$$

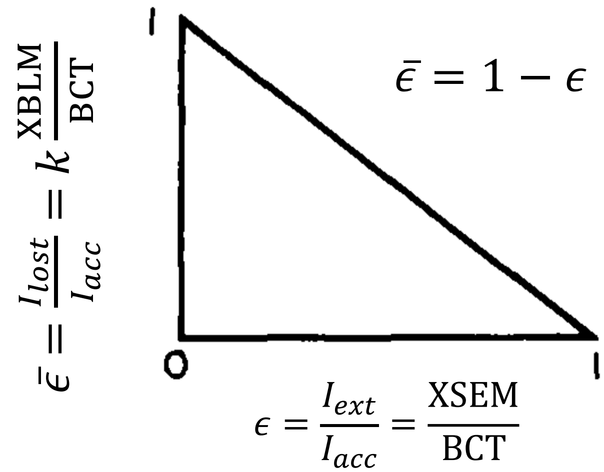

Fig. 1. Inefficiency as a function of efficiency.

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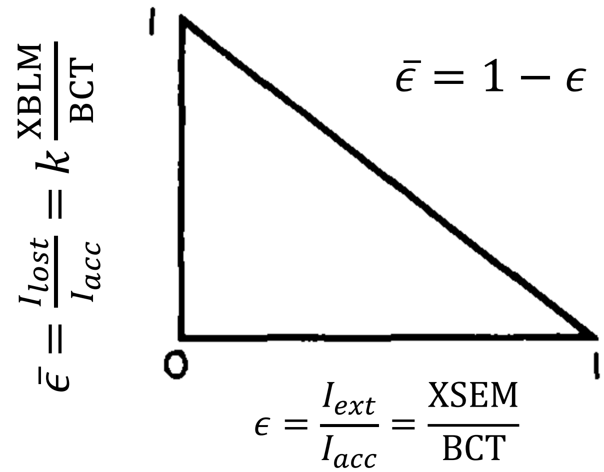

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Calibration of instrumentation

- One can also compare the calibration of the intensity measurements made on the BCT and SEM [4, 5]:

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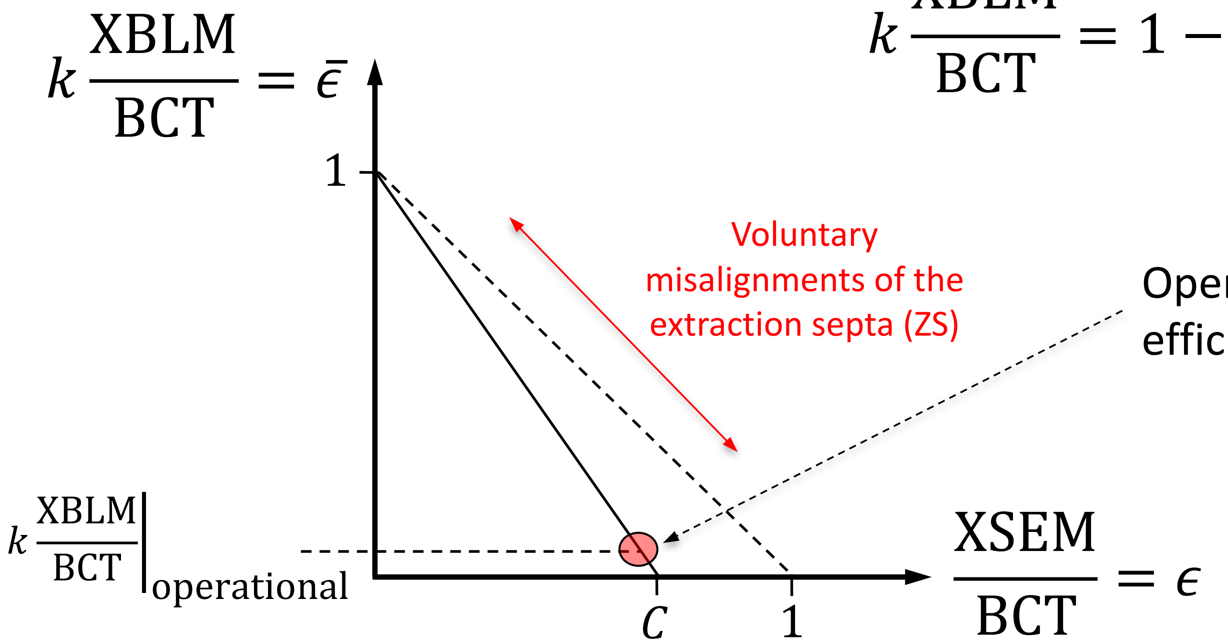

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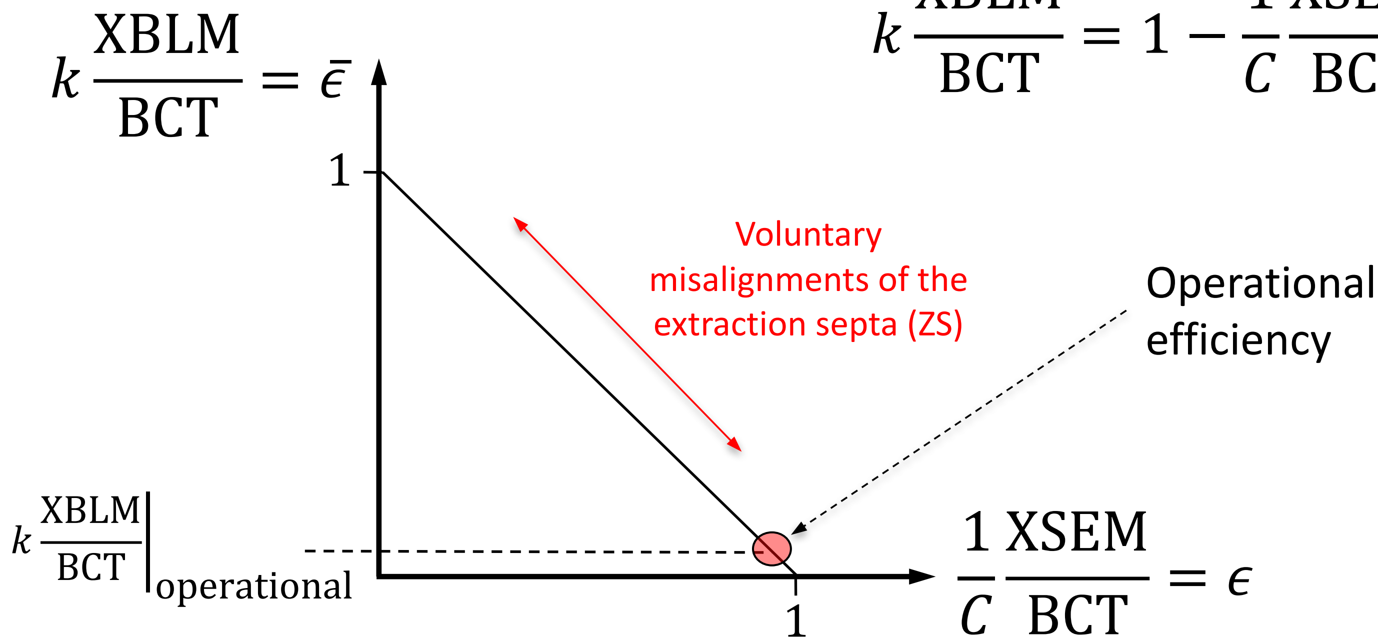
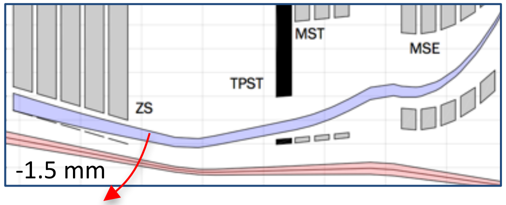


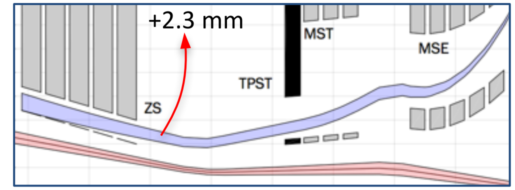
- Once the calibration constants k and C are known one can monitor the extraction efficiency online:

$$\epsilon \approx 1 - kC\frac{\mathrm{XBLM}}{\mathrm{XSEM}} \quad \text{assuming that} \quad k\mathrm{XBLM} \ll C\mathrm{XSEM}$$

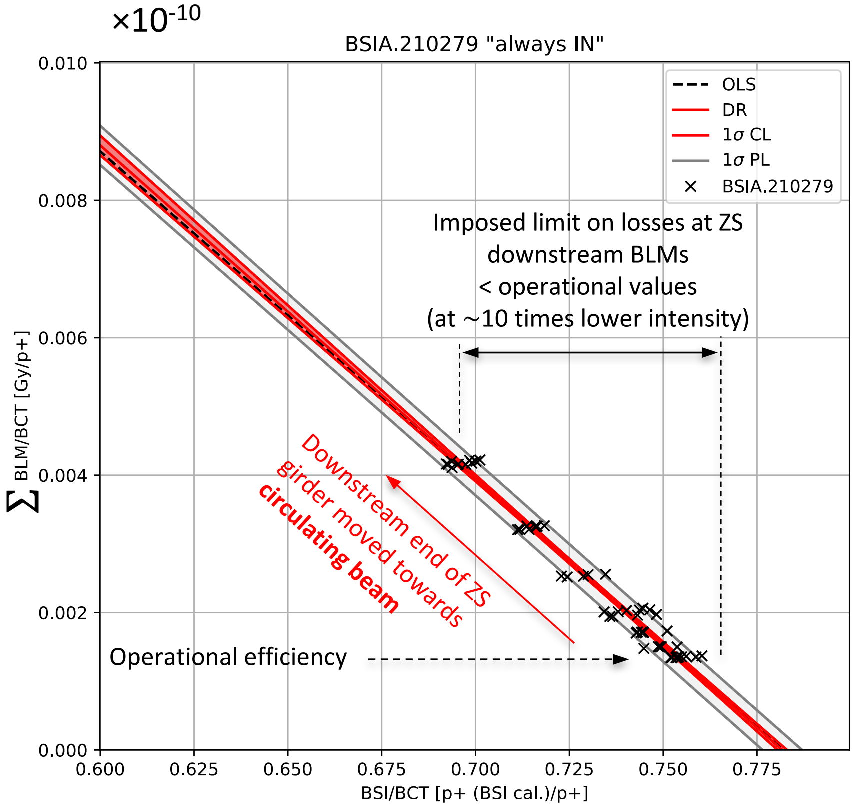
SPS measurement results (1)



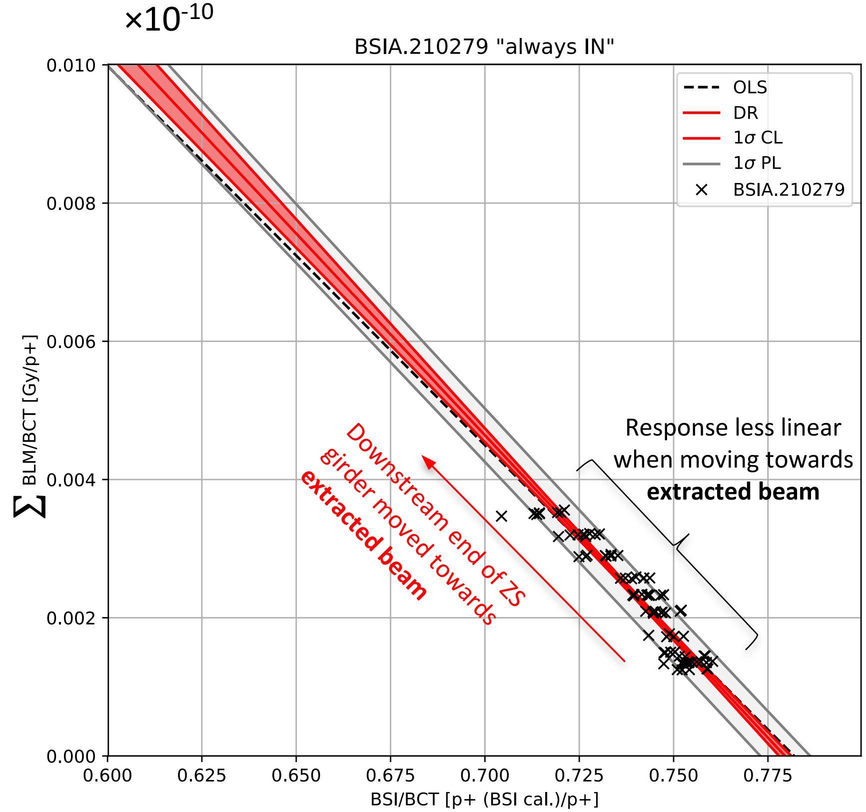
$\Delta x'_{ZS} \sim \pm 160\ \mu\text{rad}$



Electrostatic septum moved towards the **circulating beam:**



Electrostatic septum moved towards the **extracted beam:**



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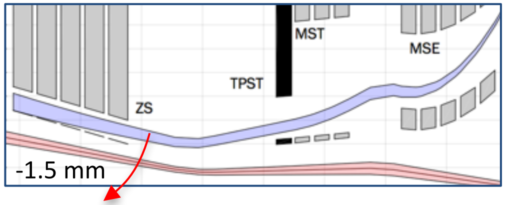

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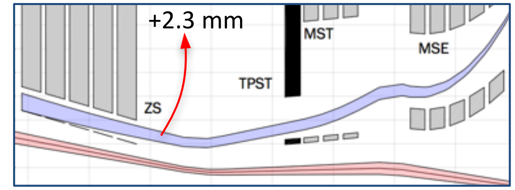

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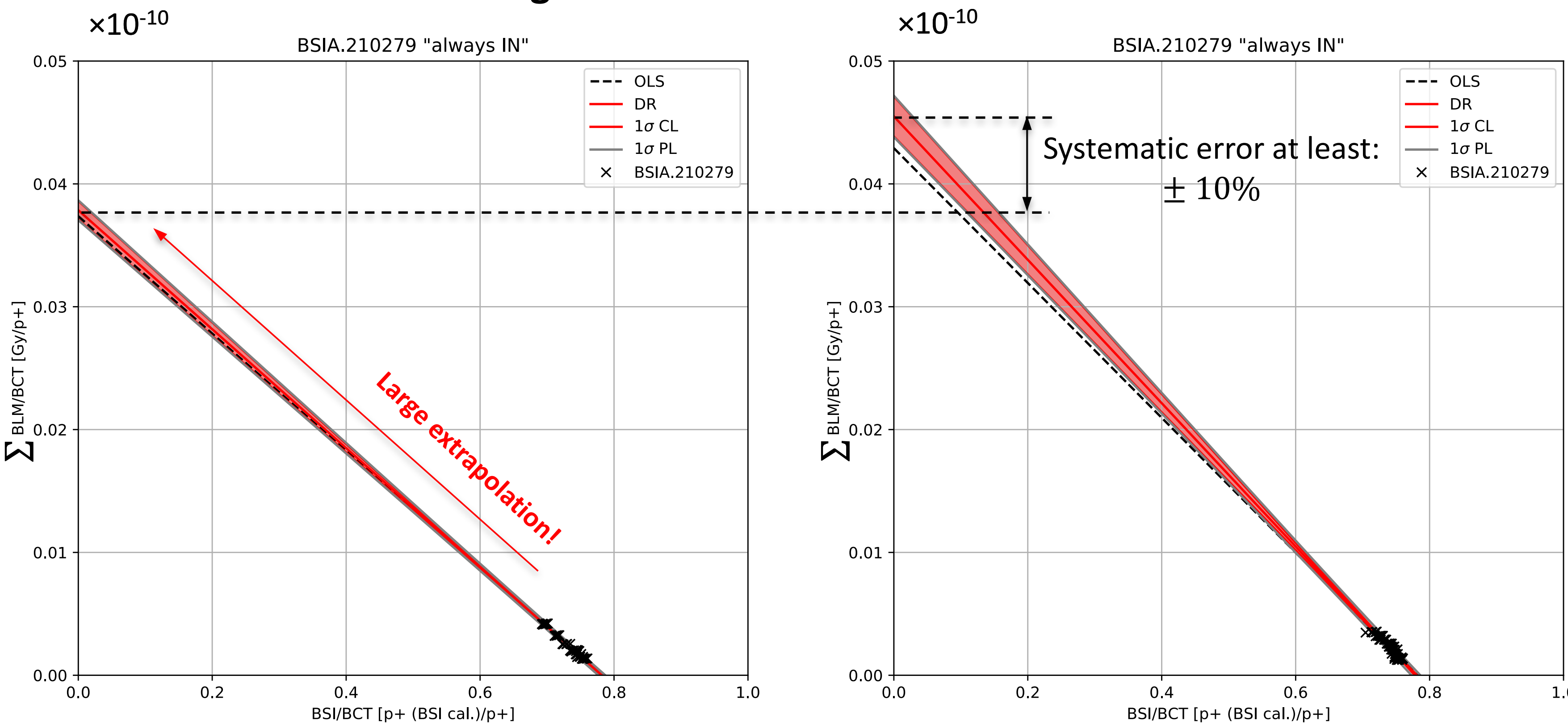

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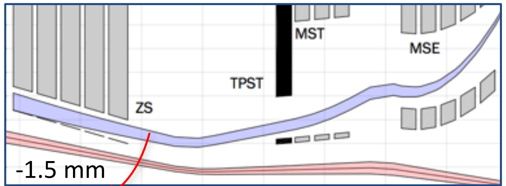

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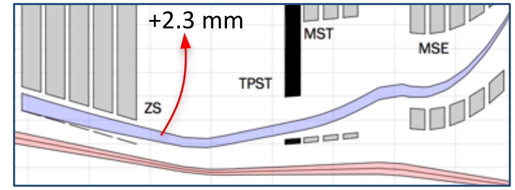

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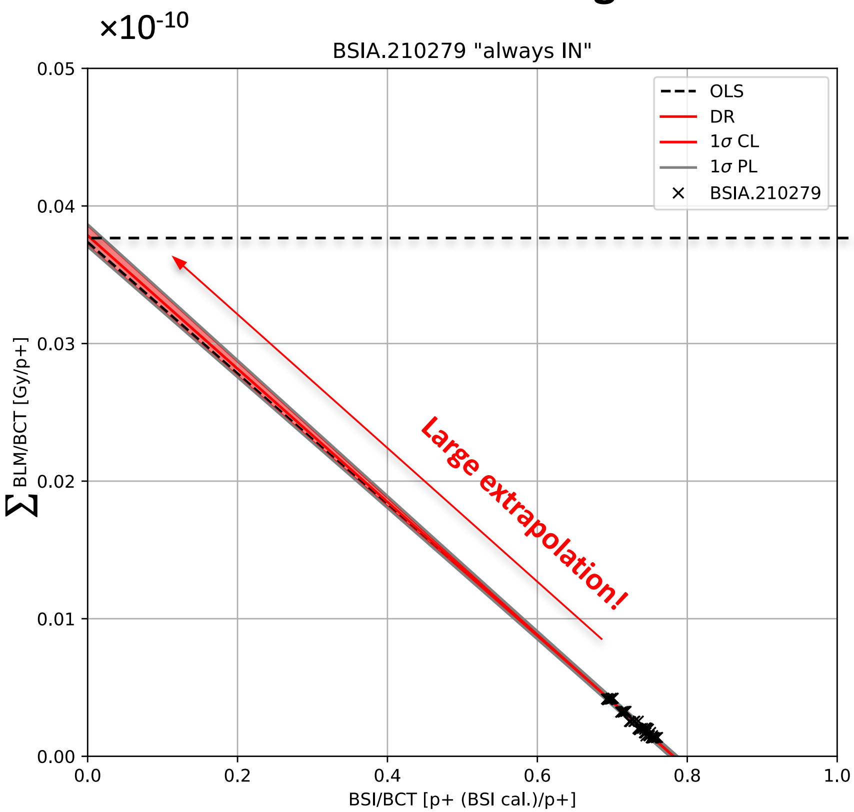
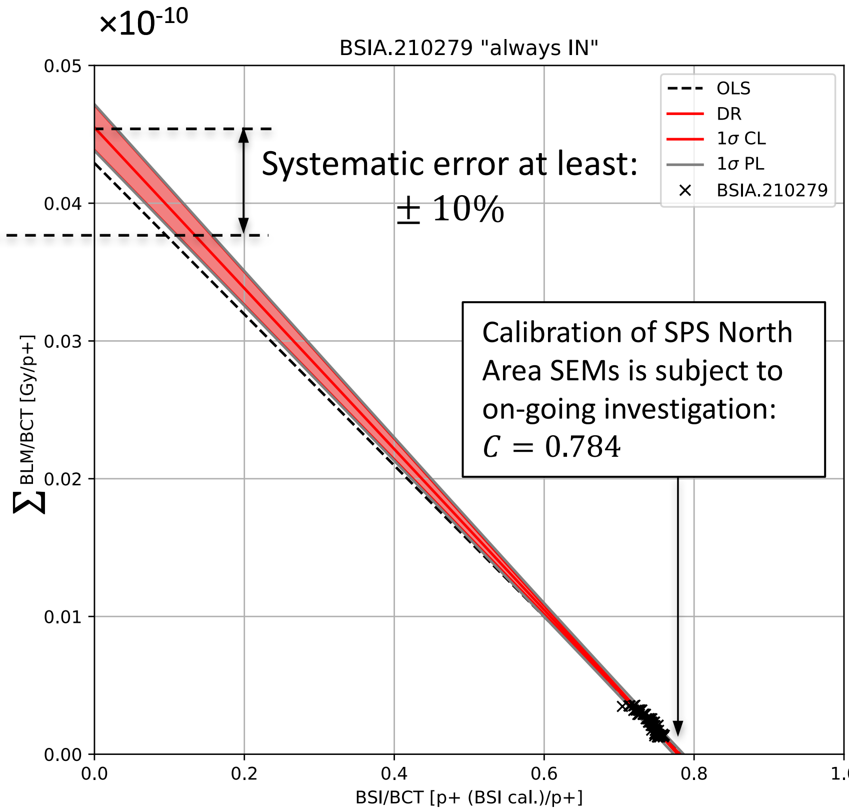




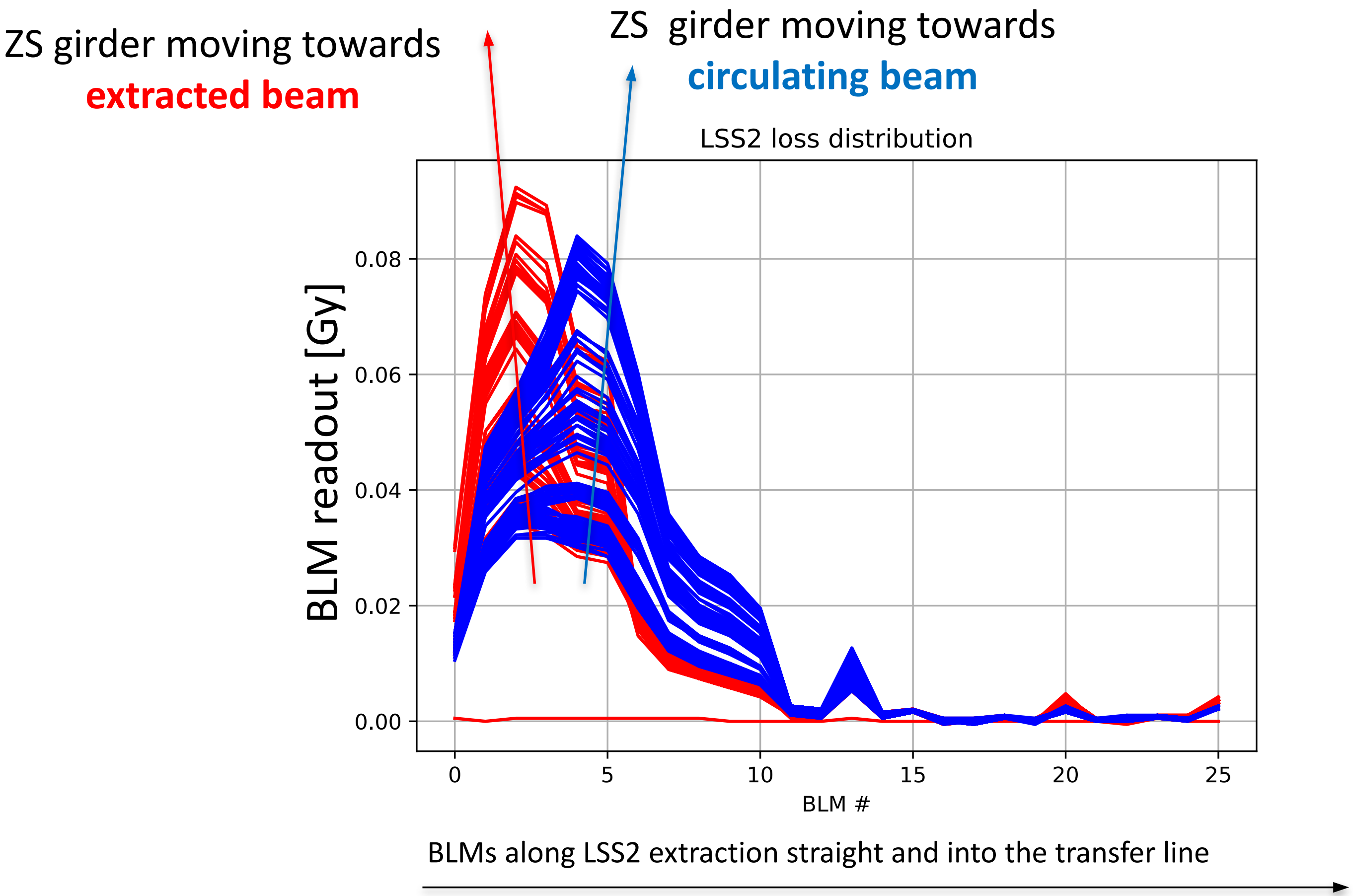
SPS measurement results (2)

Year	SEM [Ti Foil]	ZS Downstream Scan Direction	k [10^{13} p^+/mGy]	C $\left[\frac{\text{XSEM}}{\text{XBCT}}\right]$	$\bar{\epsilon}$ [% ± $\delta_{\bar{\epsilon}}$] $\delta_{\bar{\epsilon}} = 20\%$ *	ϵ [% ± δ_{ϵ}] $\delta_{\epsilon} = 20\%$ *
2016	BSIA 210279	**All data**	**24.0**	**0.66****	**4.3 ± 0.8**	**95.7 ± 0.8**
2017	BSIA 210279	Towards extracted beam	21.7	0.78	3.0 ± 0.6	97.0 ± 0.6
		Towards circulating beam	26.3	0.79	3.6 ± 0.7	96.4 ± 0.7
		All data	**23.8**	**0.78****	**3.4 ± 0.7**	**96.6 ± 0.7**

* Systematic error is difficult to quantify $\delta_{\bar{\epsilon}}$ a smaller extrapolation would be preferable

** BSIA.210279 foil was exchanged for a new one during 2016-17 End of Year Technical Stop

SPS Longitudinal BLM distribution

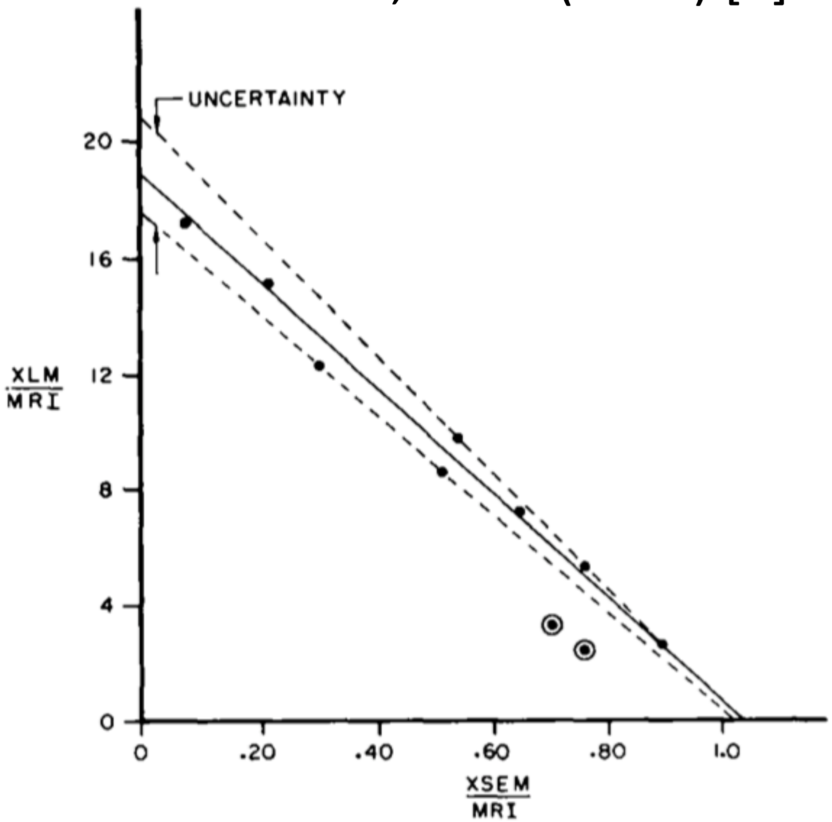


- Longitudinal form factor changes significantly over measurement:
  - In SPS we have a limited number of small BLMs distributed along LSS2, not a continuous BLM like a fiber-optic or coaxial cable

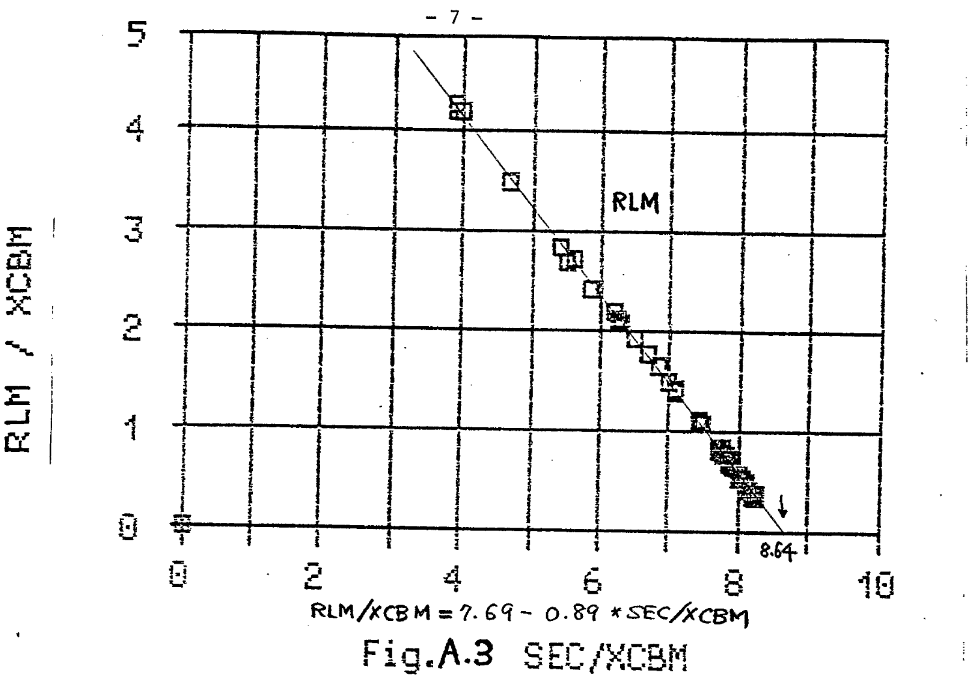
Linearity achieved in practice

- Linearity across a wide range has been achieved **using coaxial-type BLM monitors** running the length of the extraction region:

MR, FNAL (1973) [4]



AGS, BNL (1987) [6]



Conclusion

- Measurement of the extraction inefficiency via calibration of BLM signals is far more accurate as we approach efficiencies of 100%
- The slow extraction efficiency at the CERN SPS has been measured at 96.6 ± 0.7 % in 2017 using the FNAL approach:
  - We expect about 98.5 % efficiency for a 200 μm effective septum thickness
  - The systematic error from the large extrapolation dominates the estimated uncertainty in our case
  - A very low intensity beam has been developed (100x lower than operational) and will be used in the future to reduce the extrapolation
  - A better longitudinal BLM coverage might improve the linearity
  - The extraction efficiency since 2016 has improved by 20%, consistent with the measured improvement of the extraction BLM signal (per p^+)
  - This approach could be extended to understand splitting losses in the CERN North Area transfer lines (BLM coverage here is presently very poor)
- The measurements have confirmed a large calibration offset between the ring DCCT and SEM monitors in the CERN North Area

Thank you!

- Any questions?

References

[1] K. Bernier et al., *Calibration of secondary emission monitors of absolute proton beam intensity in the CERN SPS North Area*, CERN-97-07, Geneva, CERN, 1997

[2] P. Forck, T. Hoffmannm A. Peters, *Detectors for slowly extracted heavy ions at the GSI Facility*, DIPAC 97: Beam diagnostics and instrumentation for particle accelerators, 1997

[3] D. Dekkers et al., *Slow extraction efficiency at 19.2 GeV/c*, CERN-MPS-CO-Note-69-32, Geneva, CERN, 1969

[4] F. Hornstra, *The system for precise measurement of accelerator extraction efficiency*, Nucl. Instum. Meth. 128, pp. 435-440, 1975.

[5] F. Hornstra and E. Bleser, *A method and a simple device to precisely measure accelerator extraction efficiency and beam line transport efficiency*, FN-252, Batavia IL, FNAL, 1973

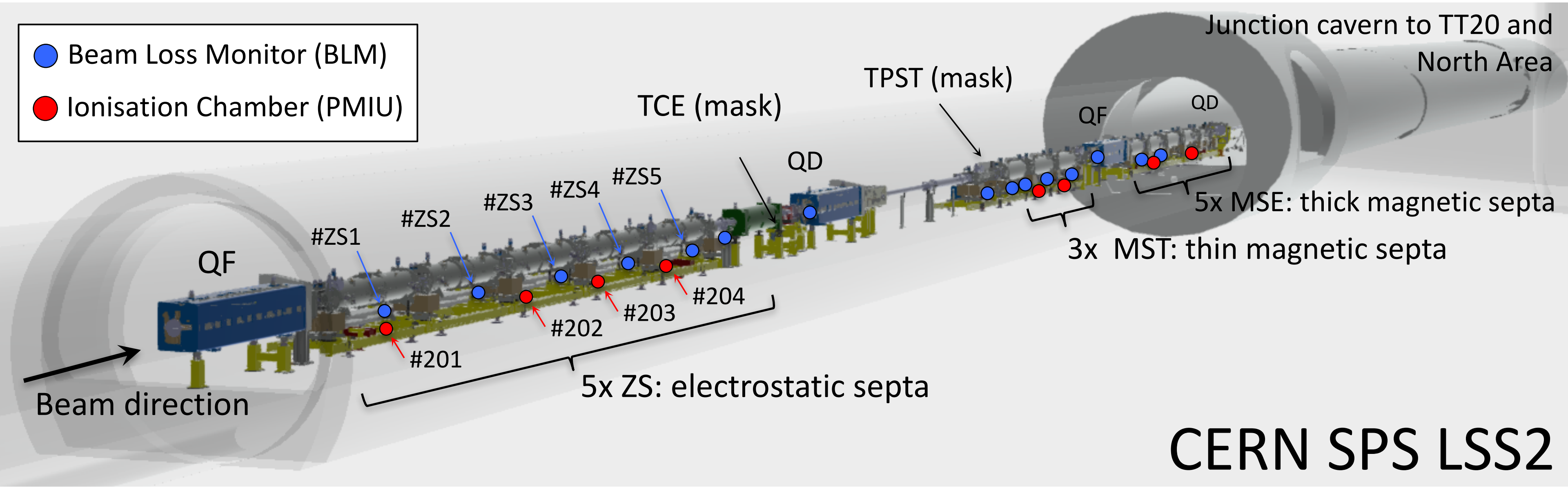
[6] M. Tanaka et al., *SEB Extraction Study II – Investigations of the apparent beam intensity dependence of extraction efficiency*, AGS Studies Report 222, BNL, 1987

Other papers:

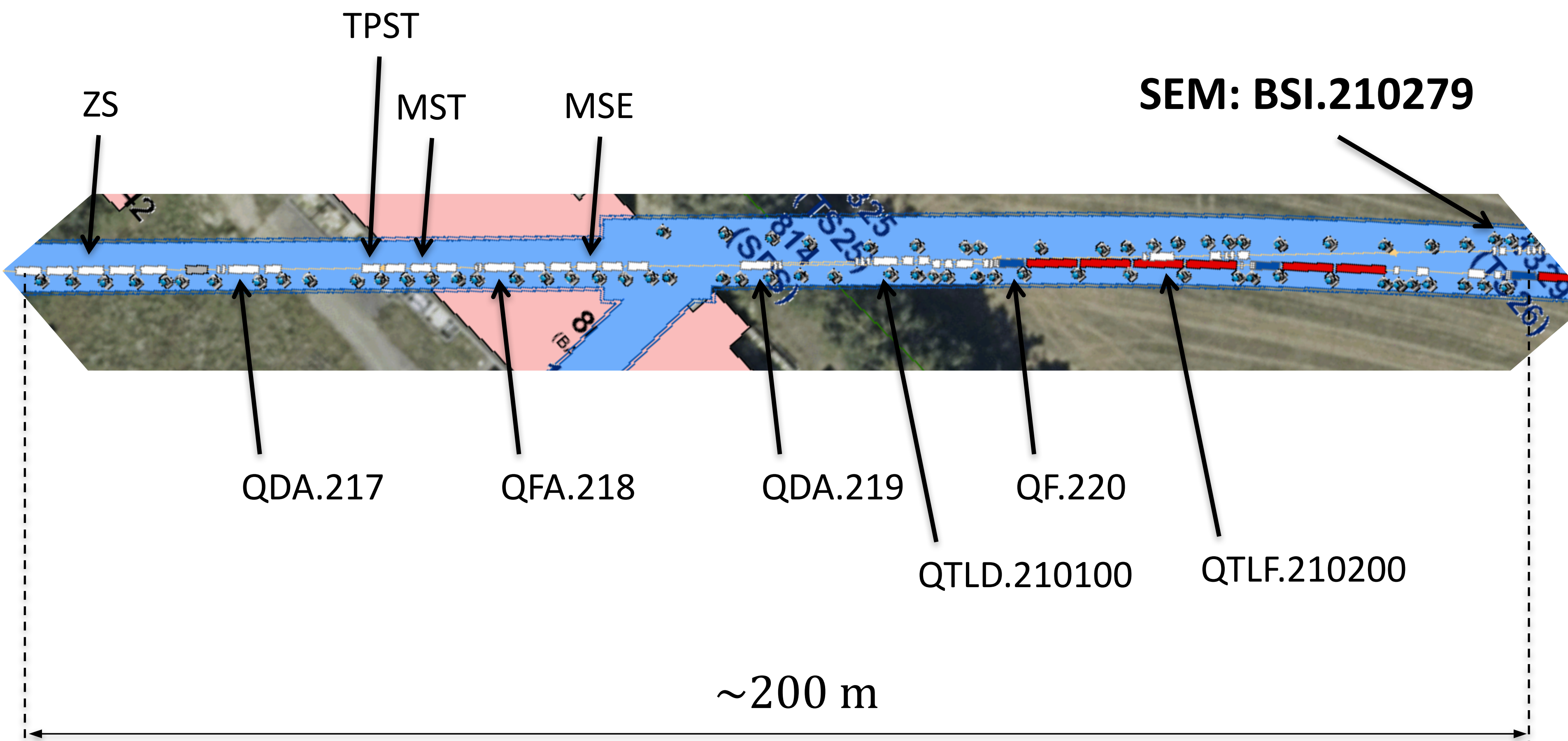
- Y. Baconnier, O. Barbalat, F. Scheck, *Status of studies of the CPS slow extraction*, 7th International Conference on High-Energy Accelerators, Yerevan, USSR 1969
- V. Gvozdev, *Measurement of the synchrophasotron slow-extraction efficiency*, Particle Accelerators Vol. 6, pp. 53-55, 1974
- M. Tanaka et al., *SEB Extraction Study I – Calibrations of the Ring Loss Monitor (RLM) and the Secondary Emission Chamber (SEC) by changing the electrostatic septum position and skew*, AGS Studies Report 219, BNL, 1987
- M. Tanaka et al., *SEB Extraction Study III – Measurement of extraction efficiency during the spill,* AGS Studies Report 229, BNL, 1987
- R.A. Andrews et al., *Extraction for the Main Ring at NAL*, Proceedings, Ninth International Conference On High Energy Accelerators, pp. 456-461, 1974

Extra slides

SPS BLM locations

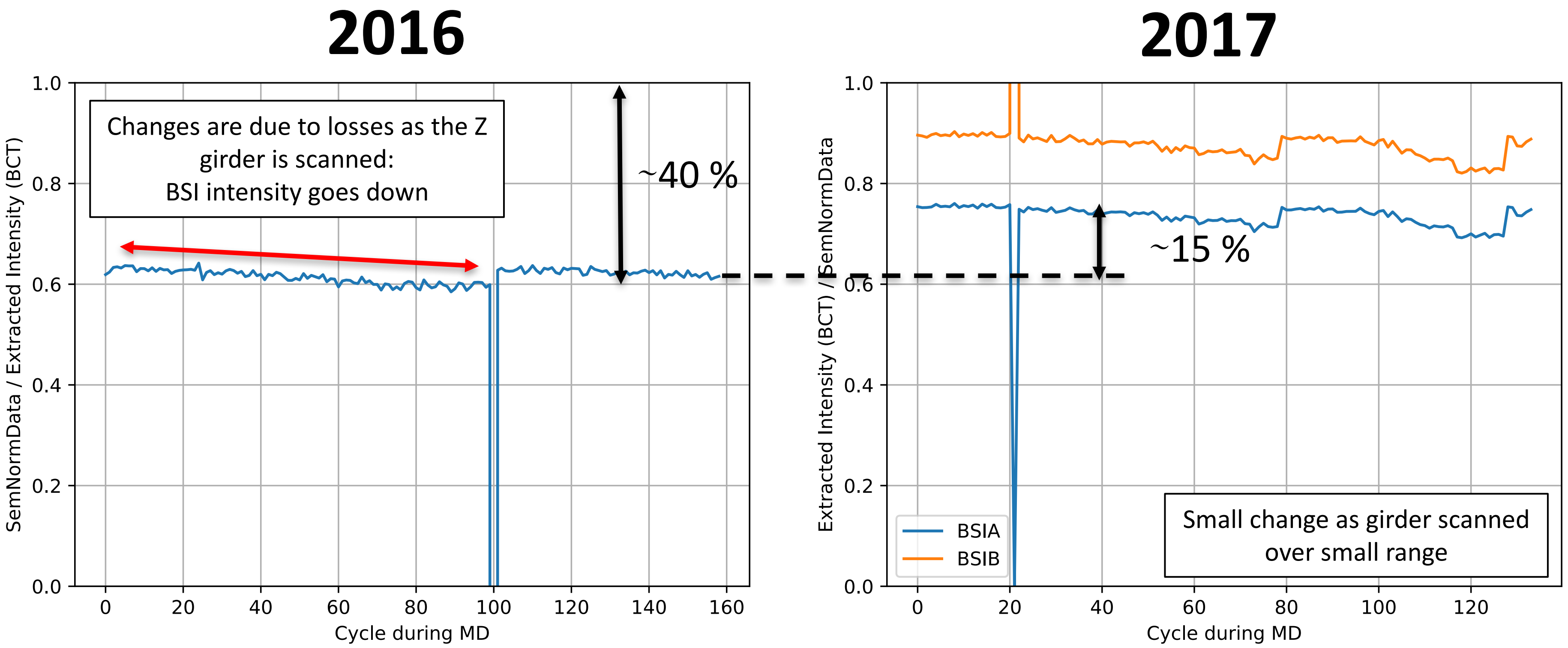


BSI SEM location in LSS2



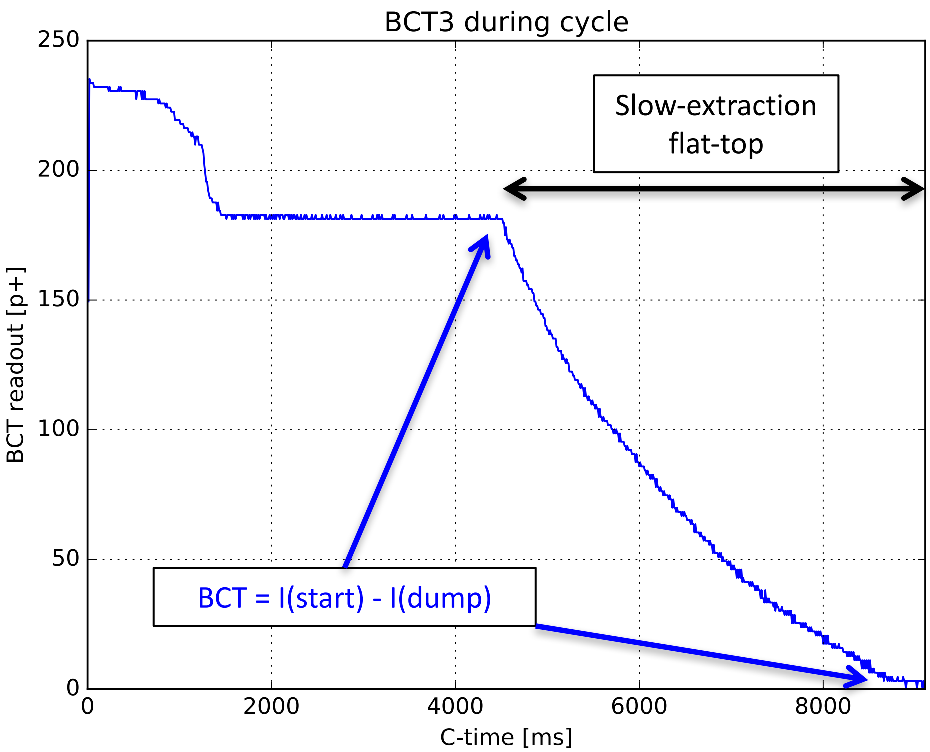
SEM vs. BCT data: 2016 vs. 2017

- Using data acquired during MD's (*semNormData*) we can check change in calibration due to the change of foil:
  - BSIA foil response has increased by about 15 %
  - No signal from BSIB in 2016



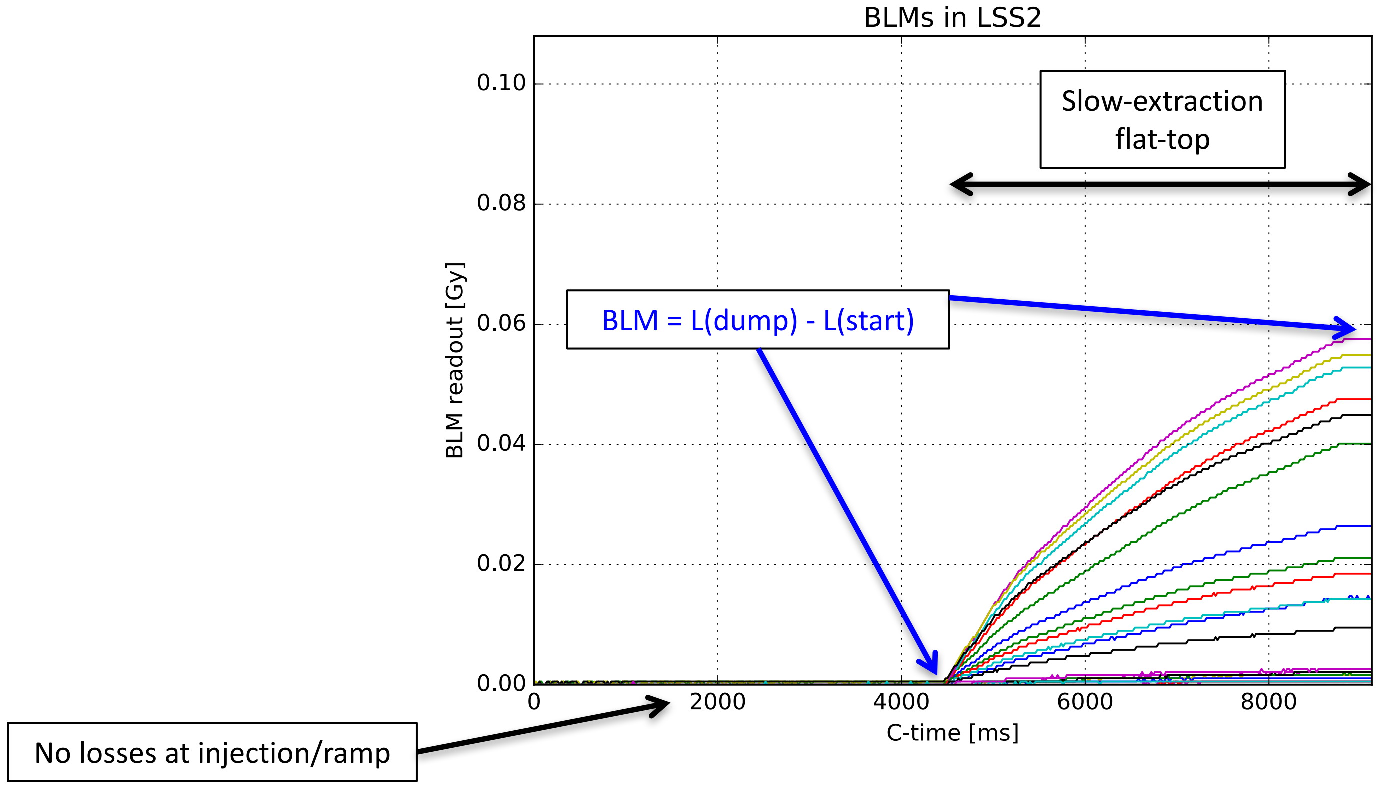
Intensity correction on BCT

- Important to remove beam intensity lost at injection and dumped from the normalization of the BLM and SEM signals



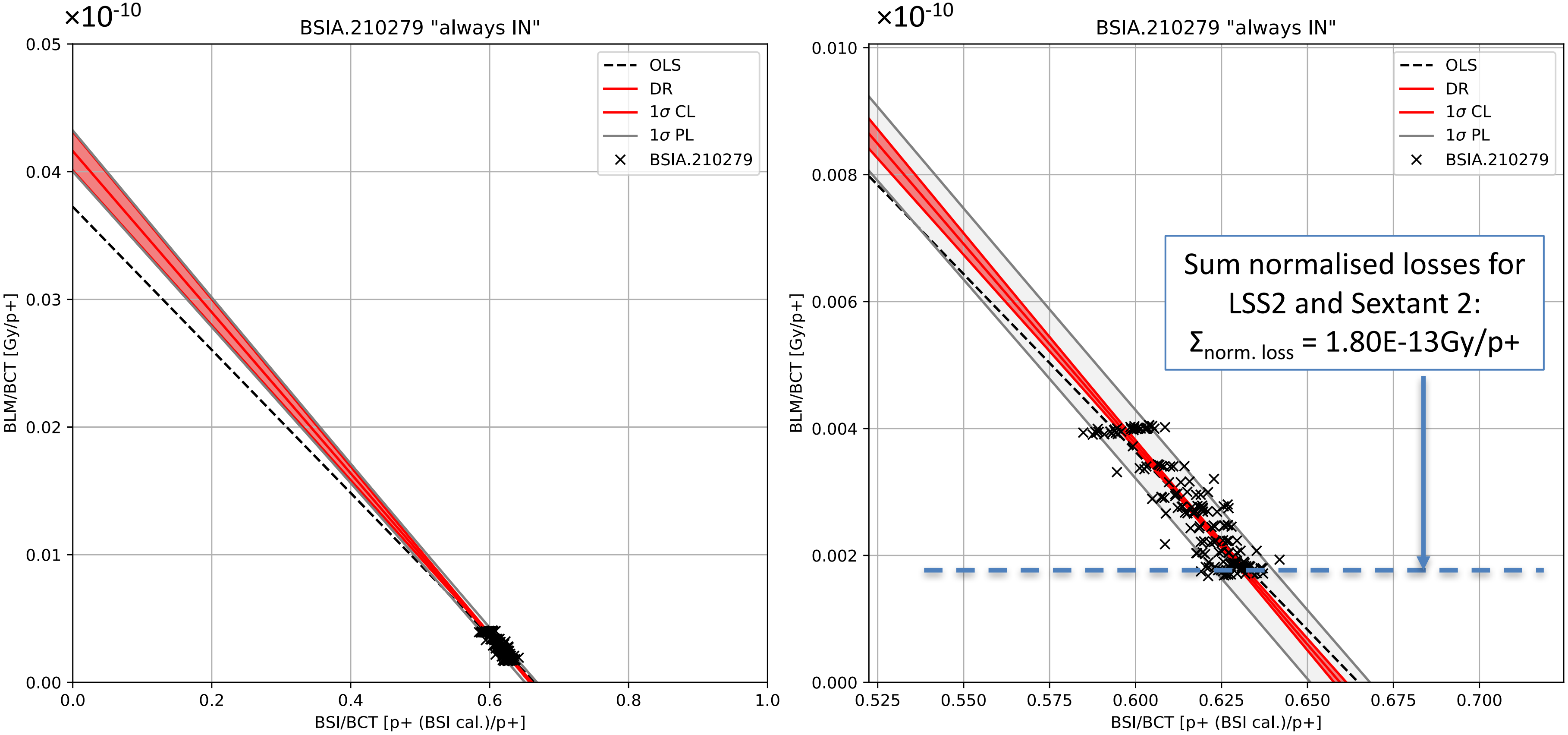
Loss correction: BLM losses vs. time

- Only integrated losses during extraction were considered, which dominate anyway, other losses in the ring are negligible:



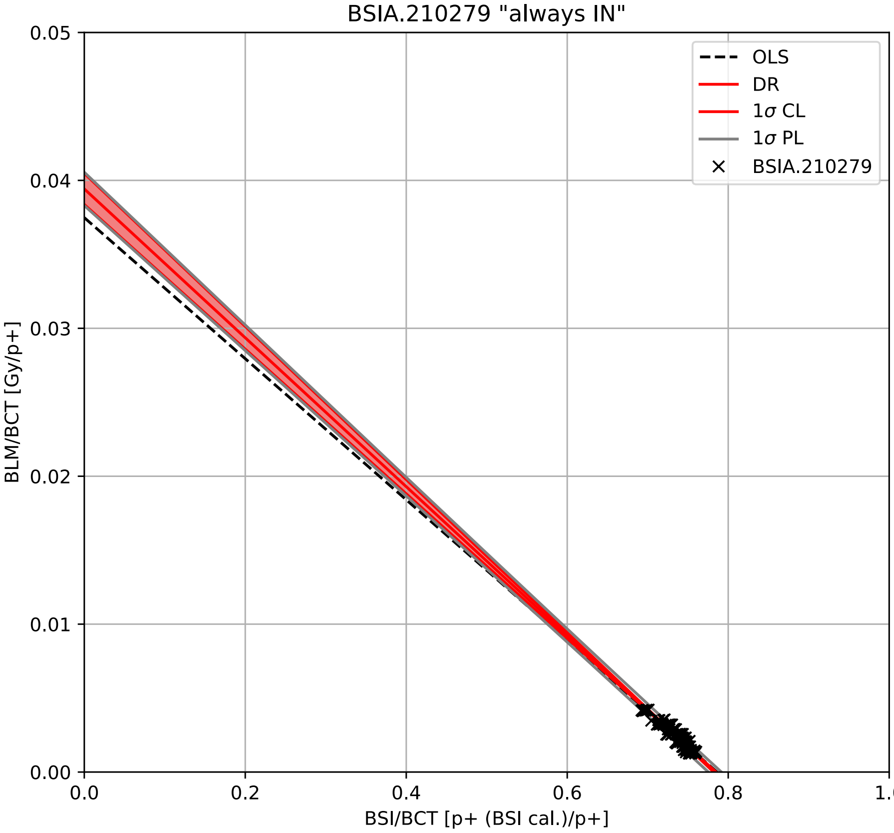
Results in 2016: BSIA 210279

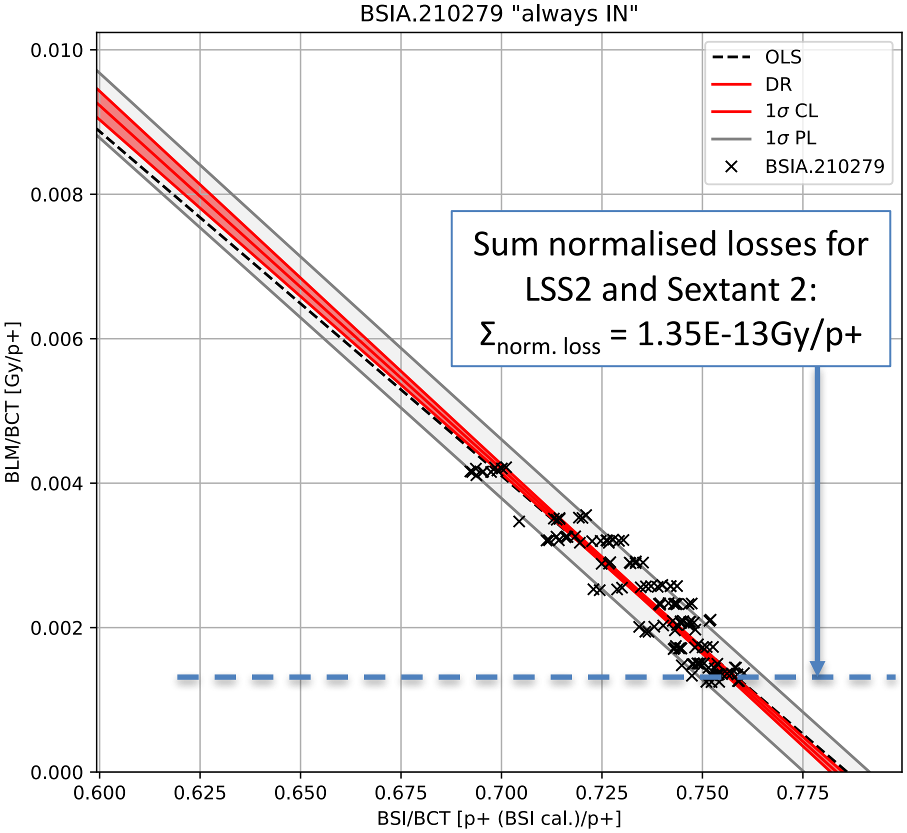
- Using ***semNormData*** field published by the front-end:



Results in 2017: BSIA 210279

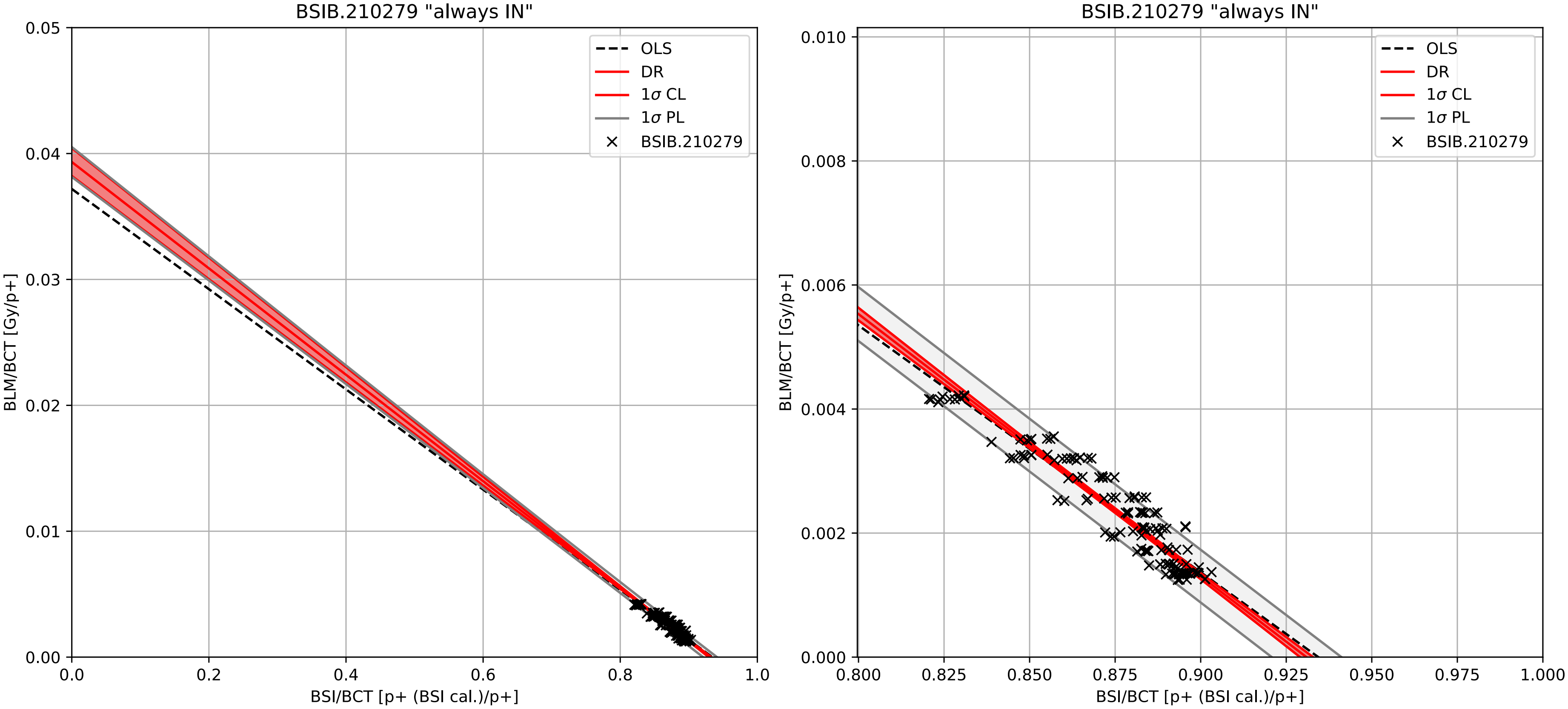
- Using ***semNormData*** field published by the front-end:





Results in 2017: BSIB 210279

- Using ***semNormData*** field published by the front-end:



SPS measurement results (3)

Year	SEM [Ti Foil]	ZS Downstream Scan Direction	k [10^{13} p$^+$/mGy]	C $\left[\frac{XSEM}{XBCT}\right]$	$\bar{\epsilon}$ [% ± $\delta_{\bar{\epsilon}}$] $\delta_{\bar{\epsilon}} = 20\%$ *	ϵ [% ± δ_{ϵ}] $\delta_{\epsilon} = 20\%$ *
2016	BSIA 210279	**All data**	**24.0**	**0.66****	**4.3 ± 0.8**	**95.7 ± 0.8**
2017	BSIA 210279	Towards extracted beam	21.7	0.78	3.0 ± 0.6	97.0 ± 0.6
		Towards circulating beam	26.3	0.79	3.6 ± 0.7	96.4 ± 0.7
		All data	**23.8**	**0.78****	**3.4 ± 0.7**	**96.6 ± 0.7**
2017	BSIB 210279	Towards extracted beam	21.3	0.94	2.9 ± 0.6	97.1 ± 0.6
		Towards circulating beam	27.0	0.93	3.6 ± 0.7	96.4 ± 0.7
		All data	**25.9**	**0.93**	**3.4 ± 0.7**	**96.6 ± 0.7**

* Systematic error is difficult to quantify $\delta_{\bar{\epsilon}}$ a smaller extrapolation would be preferable

** BSIA.210279 foil was exchanged for a new one during 2016-17 End of Year Technical Stop