Synchrotron radiation measurements at the CERN LHC

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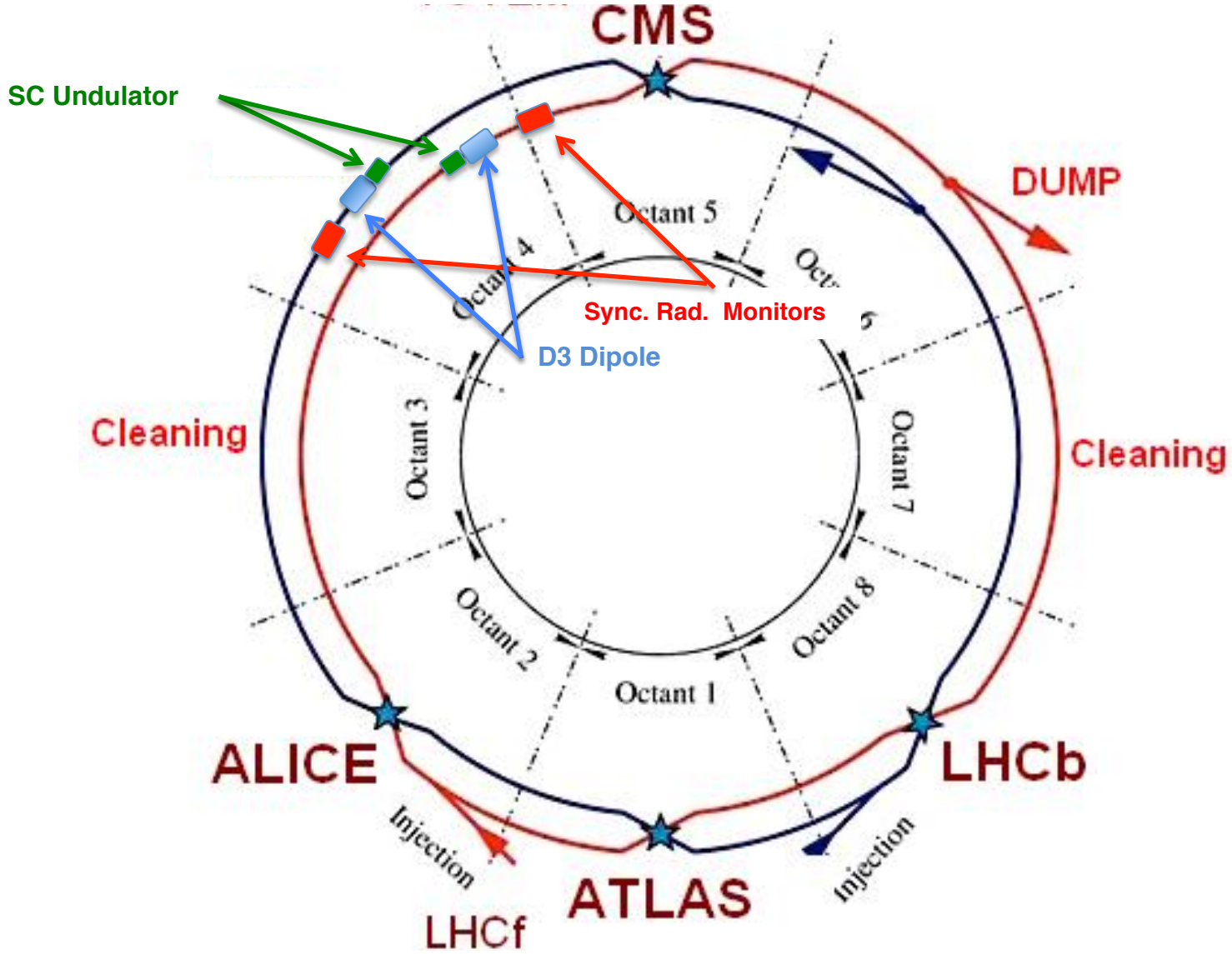
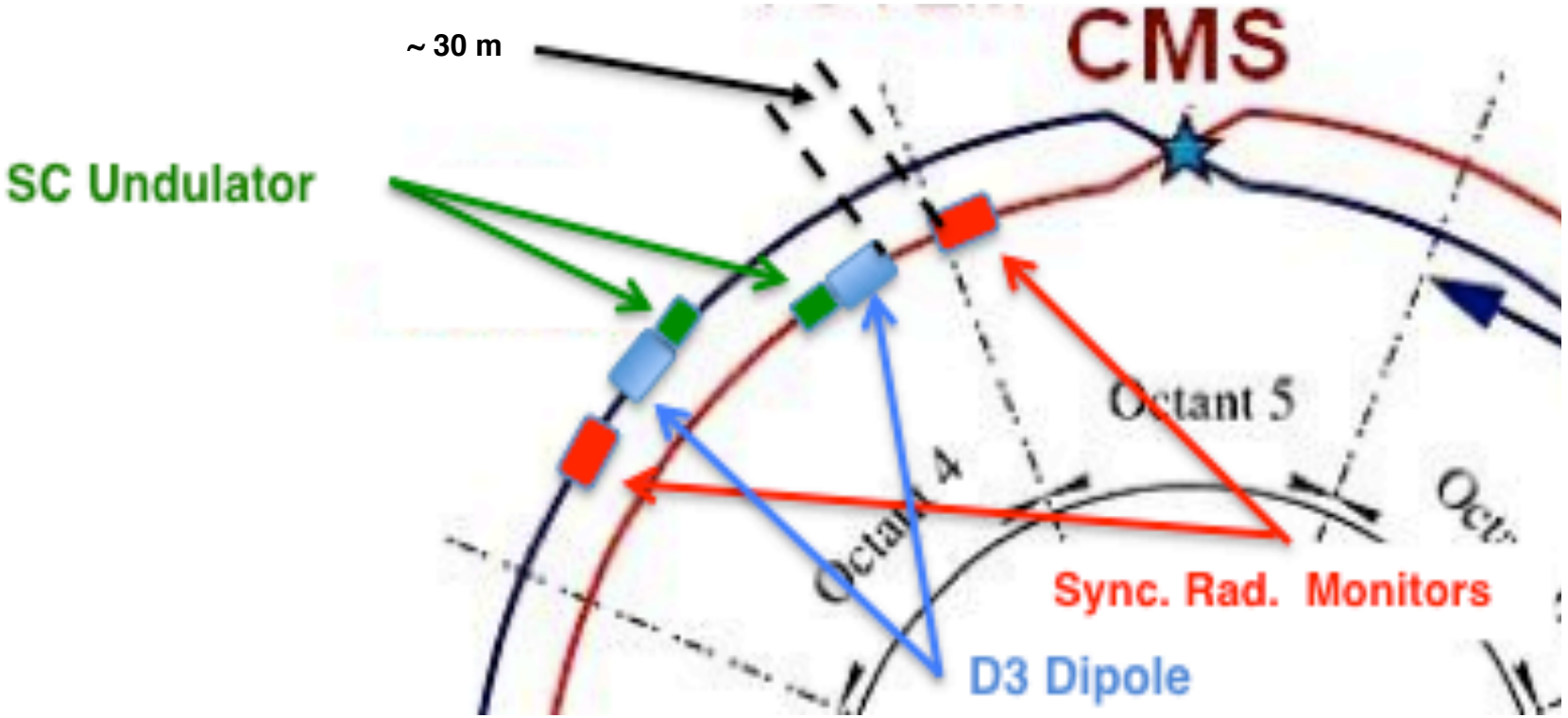
CONTENTS

- Introduction to BSR systems at LHC
- Transverse profile measurements
- Longitudinal profile measurements

Synchrotron Radiation Monitors @ LHC

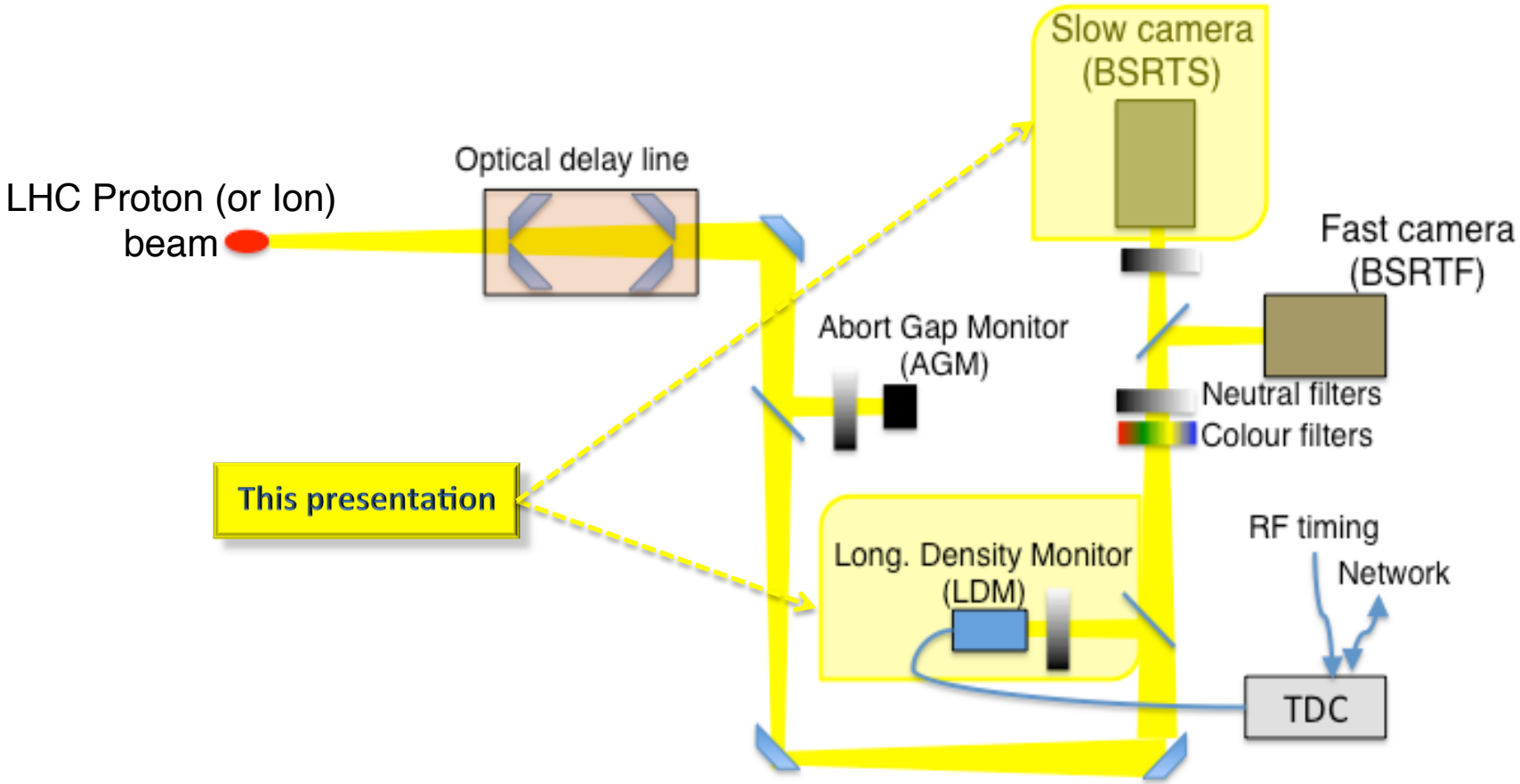


Synchrotron Radiation Monitors @ LHC



Synchrotron radiation is generated by the SC undulator up to proton energies of ~ 1.5 TeV and by the D3 dipole for higher energies

BSR System Schematic Layout



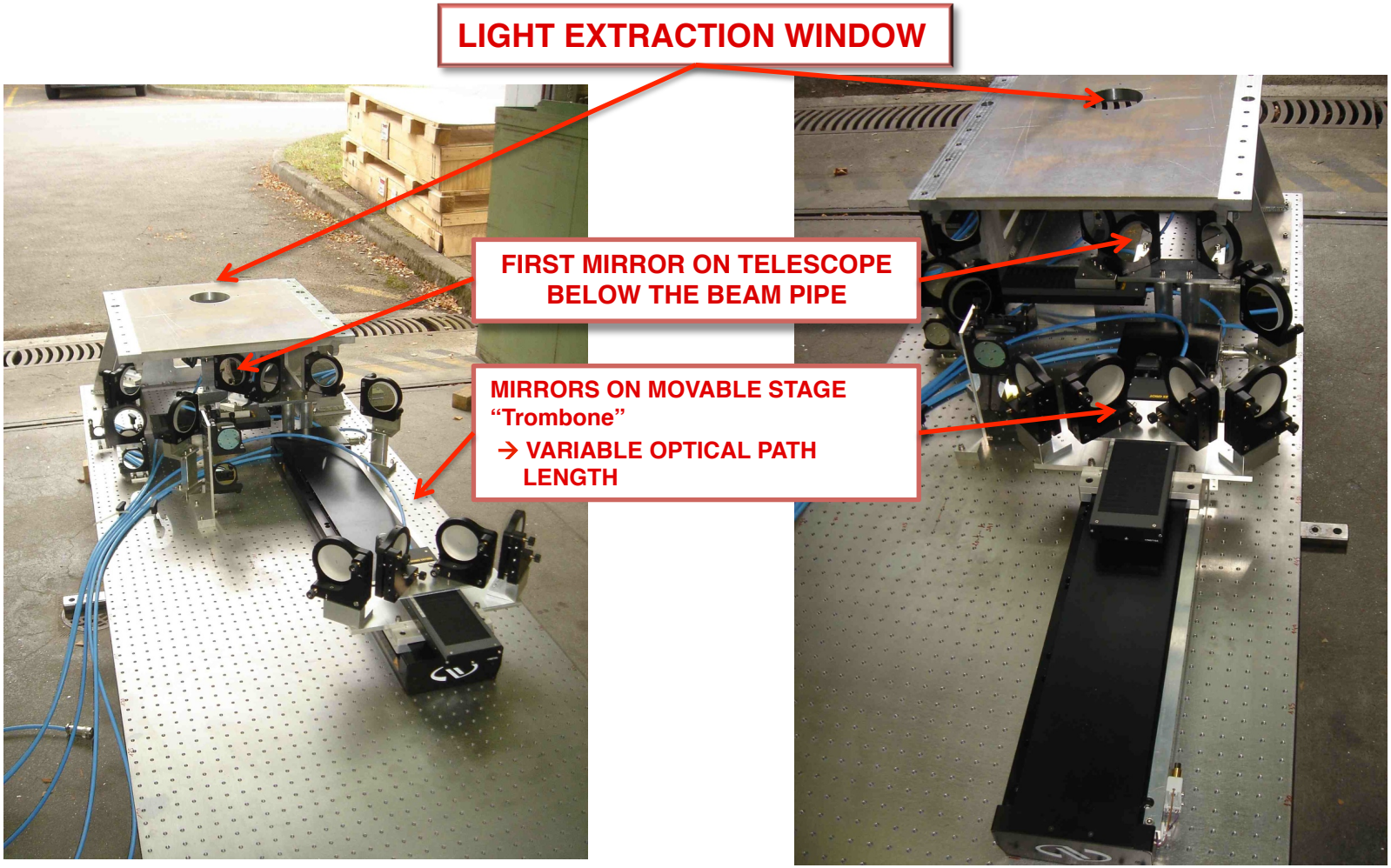
Beam Synchrotron Radiation (BSR) Systems

System	Aim	Hardware	Main Features
AGM	Abort Gap population	-Hamamatsu R5916U-51 Photomultiplier -C5594-14 amplifier	-10 Hz acquisition ~1e6 dynamic range (without considering optical filters) -100ns resolution (25ns possible)
BSRTS	Transverse profile	-Proxitronic Nanocam HF4 S 25N NIR (intensified)	-50Hz Acquisition -gating down to 25ns -max gate trigger rate 200 Hz **→ single bunch, single turn (every 55 turns)**
BSRTF	Transverse profile	-Camera Redlake HG-100K -Photek MCP125 intensifier (coupled via optical fibers to camera) -GM200-3 gate module	-Acquisition up to 100 kHz -gating down to 3ns **→ single bunch turn-per- turn**
LDM	Longitudinal profile, satellite and ghost bunches	-MPD Photodiode - 77ns dead time (Beam 1) -idQuantique Photodiode - 46ns dead time (Beam 2) -Agilent TDC	**-90ps resolution** **-1e5 dynamic range**

Will mainly talk about BSRTS and LDM

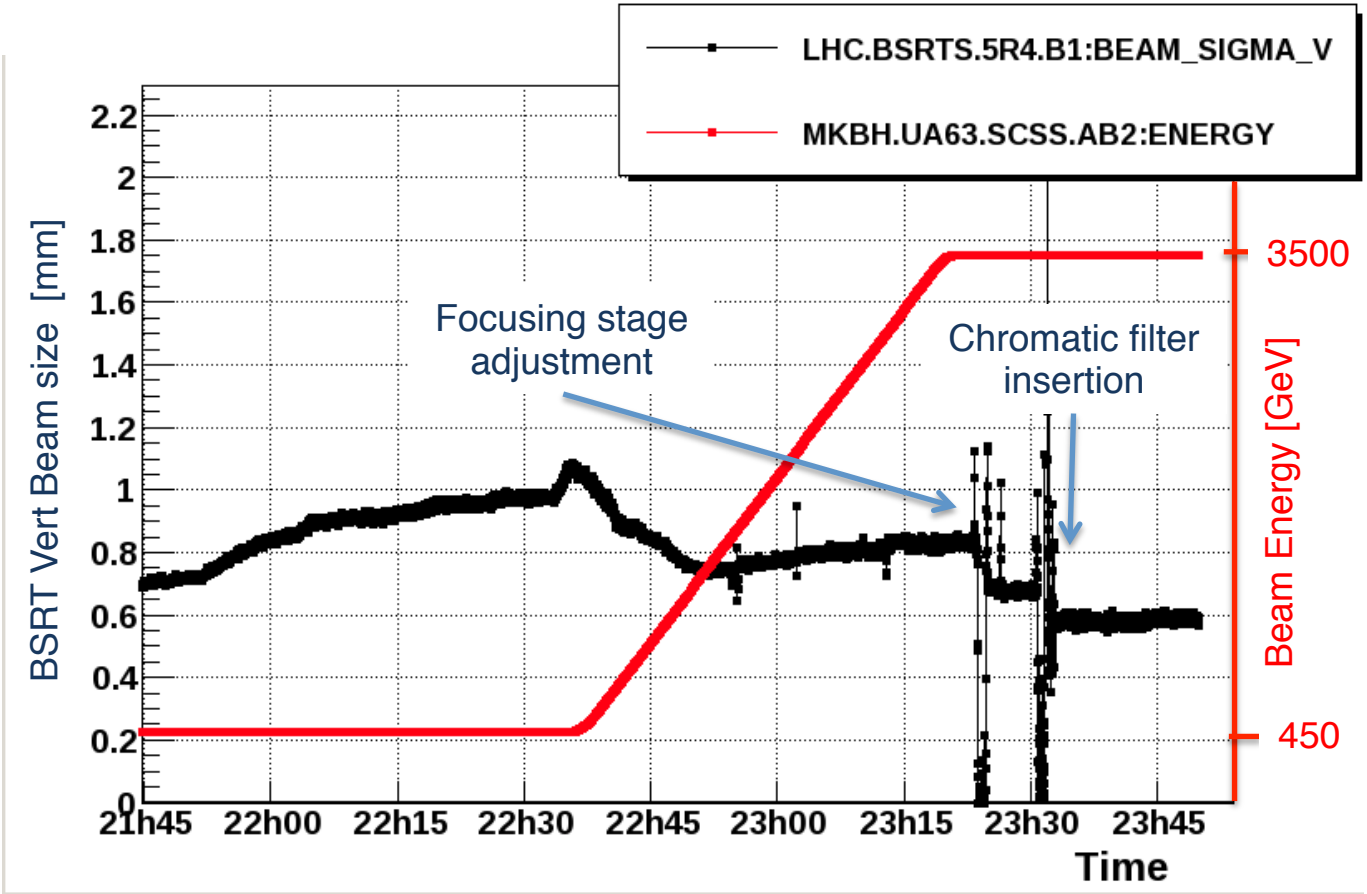
BSR Telescope

- Pictures showing only part of the optical path



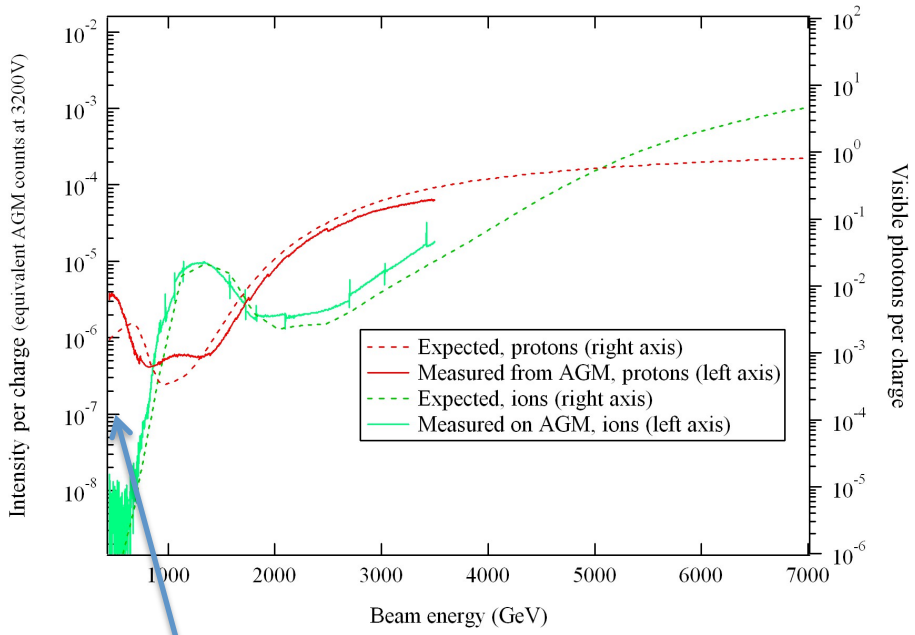
BSRTS -Effect of optical path length and color filter

Protons beam, injection and ramp to 3.5 TeV (I = ~ 2e10 p)

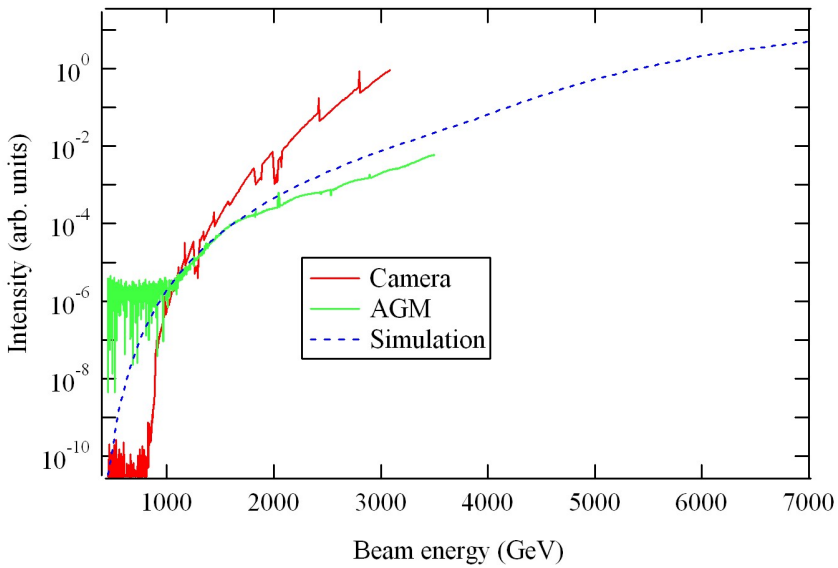


AGM and BSRTS - Simulated vs Measured light intensity

Proton an Pb ions,
AGM meas. and Simulations



Pb ions
AGM meas., BSRT meas. and Simulations



At least a factor 1e4 difference between protons and ions at injection energy

Nevertheless: we managed to see light at injection with ions

BSRT vs Wire Scanners

Wire Scanners (WS) are used as **reference** for transverse profile meas. at the LHC,

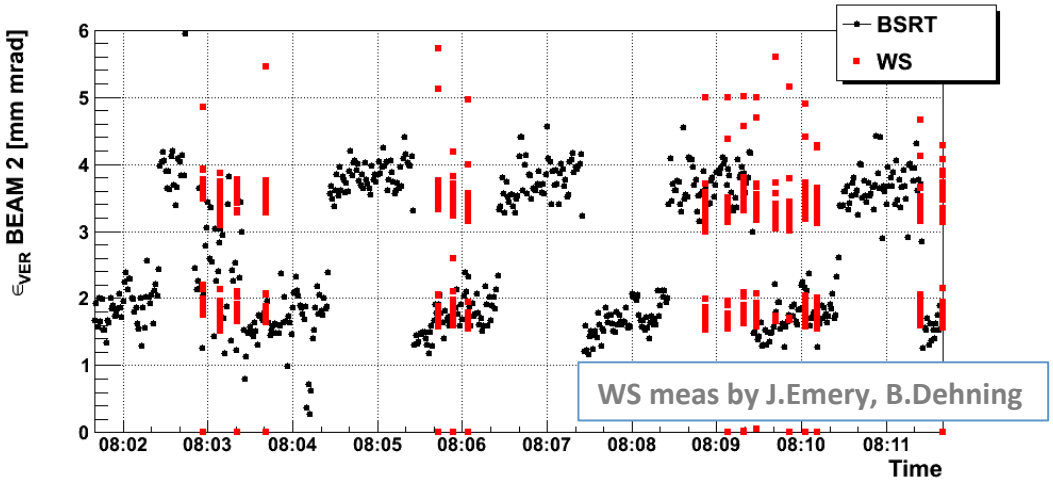
- but can be used up to few 10**13 circulating protons
  - then wire damage or quench of SC elements

BSRT calibration vs WS

- Calibration factors for each beam, for each plane, function of energy
  - From 300 to 900 um in quadrature on the measured beam size

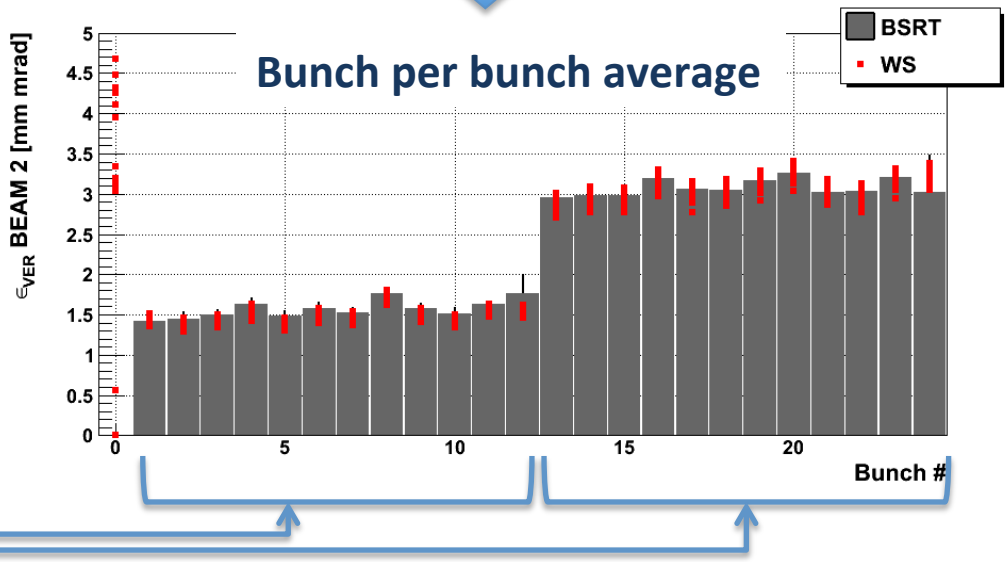
BSRTS vs Wire Scanners (example)

Bunch per bunch meas lasted ~ 10 minutes
-17 WS meas per bunch
-15 BSRT acq. Per bunch



Beam 2 Vertical 450 GeV

- 12 'small' emittance bunches
- 12 'large' emittance bunches

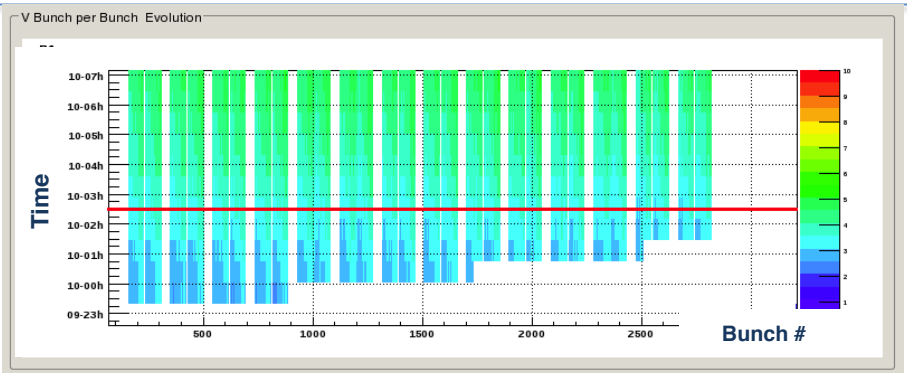


CONCLUSION

- WS – BSRT b-to-b agreement ~ 1%
- Obtained during special MD period (BI experts optimization)

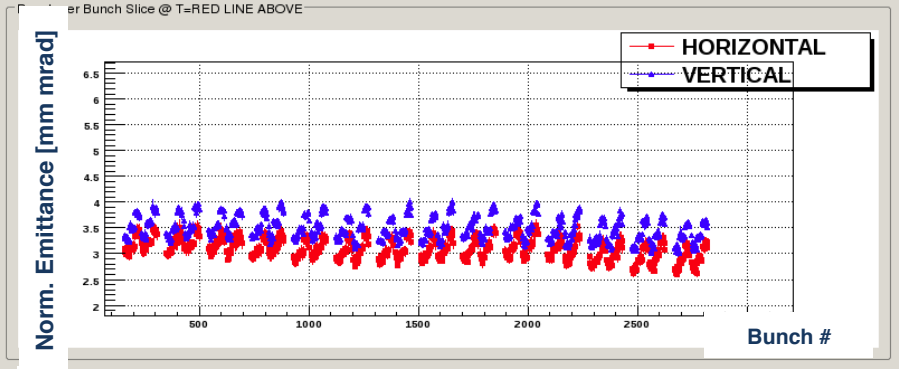
BSRTS as used during LHC operation

Vertical emittance vs bunch vs time



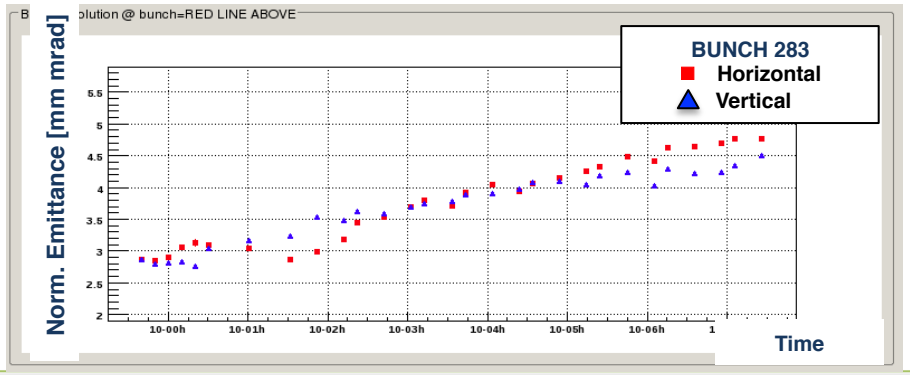
Bunch per Bunch emittance @ fixed time

Structure comes from Injectors (e.g. bunches from different PSB rings)



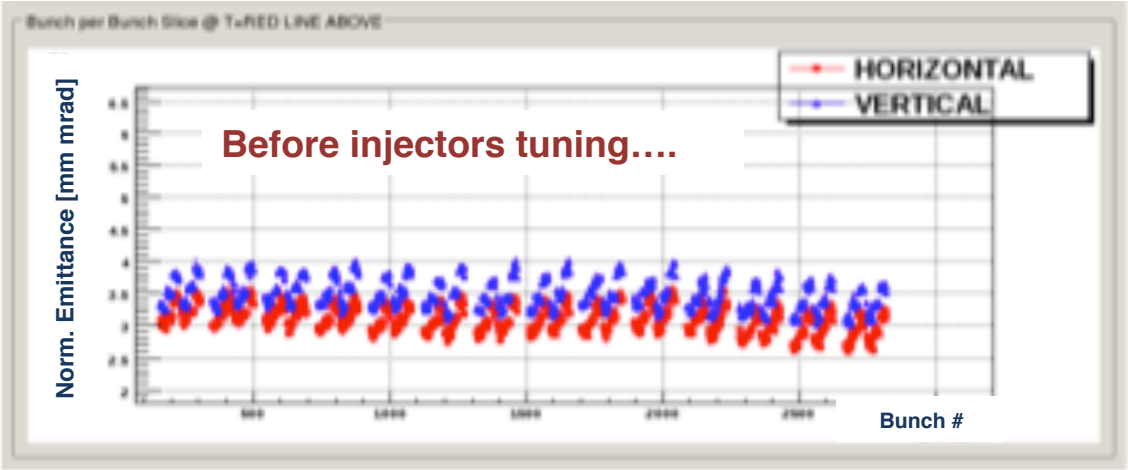
Single bunch Hor and Ver emittance vs time

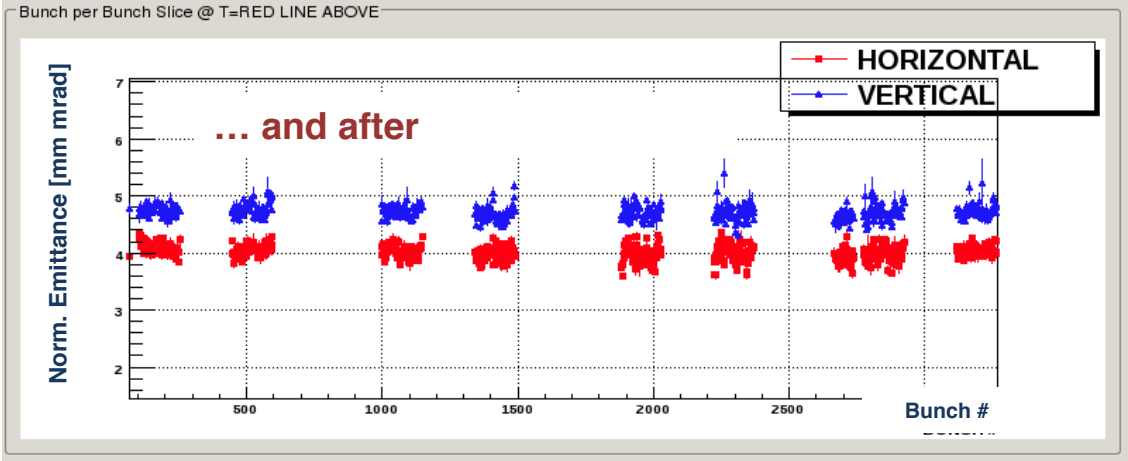
Unphysical emittance reduction between two periods on the same bunch → order of magnitude of measurement statistical error



LHC improvement thanks to BSRTS meas.

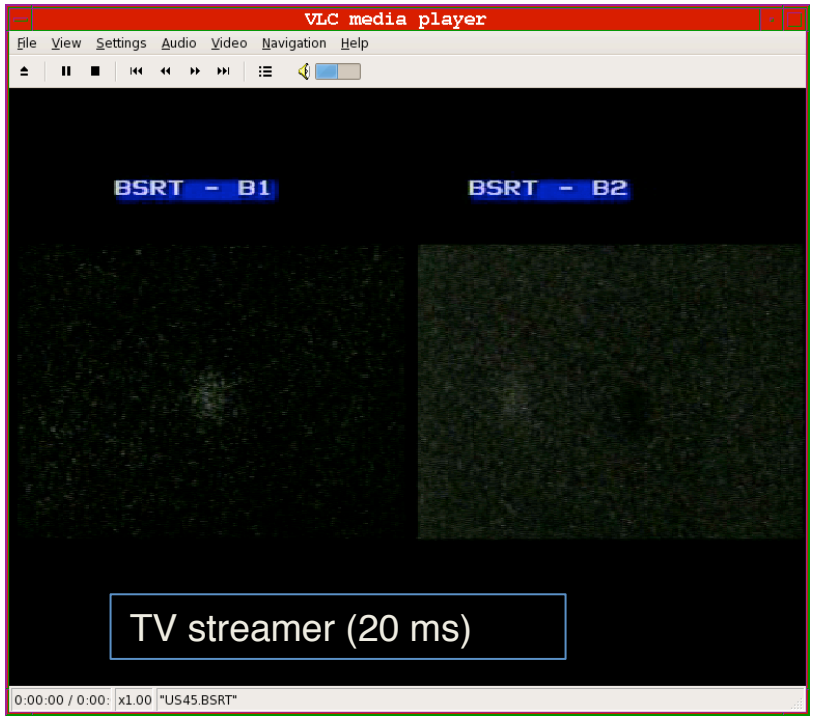
Bunch per Bunch emittance @ fixed time → structure coming from Injectors improved → Emittance along trains much more uniform

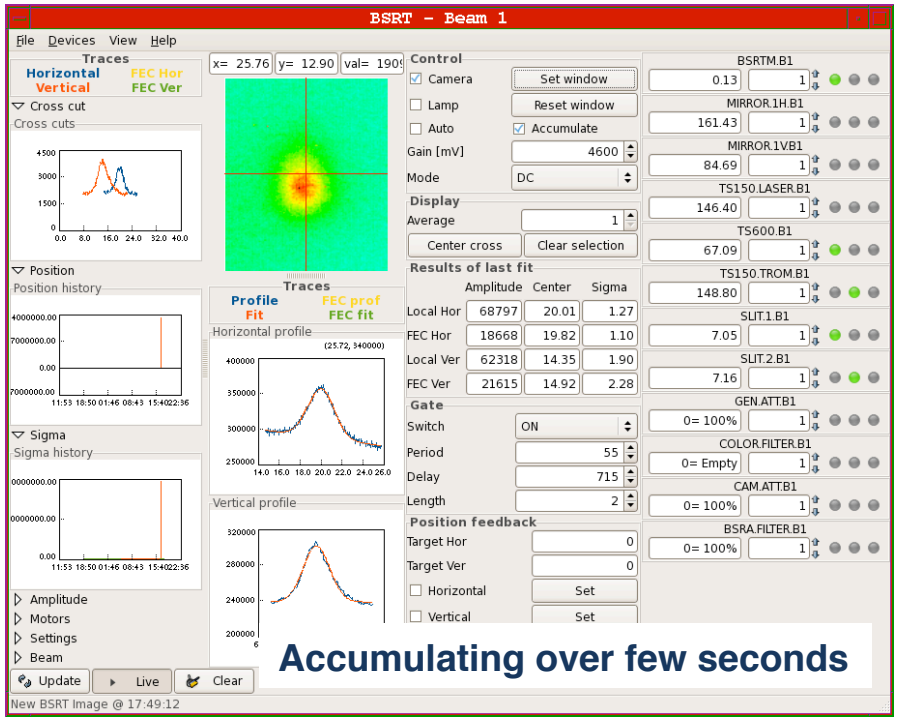




BSRTS - Pb Ions @ 450 GeV

- 10 November 2010, 17 Ion bunches at 450 GeV
- Likely first time in the world with heavy ions at such energy



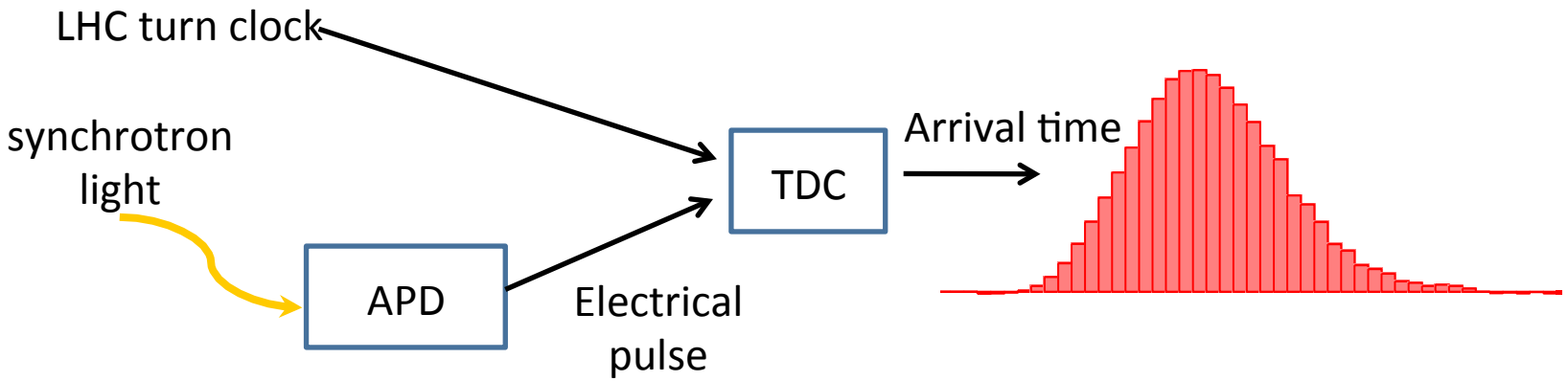


BSRTS - Conclusions

- System commissioned and almost fully operational (not mentioned here: all automatisms…)
- Bunch to bunch scans : not fully operational yet, available on demand to experts, 2-5 sec per bunch enough to have low statistical error
- Relative accuracy : better than 5 %
- Absolute accuracy:
  - better than 10% after cross calibration w.r.t. WS
  - Stability of cal factors w.r.t. WS to be studied more
- Ultimate resolution : still to be studied in detail

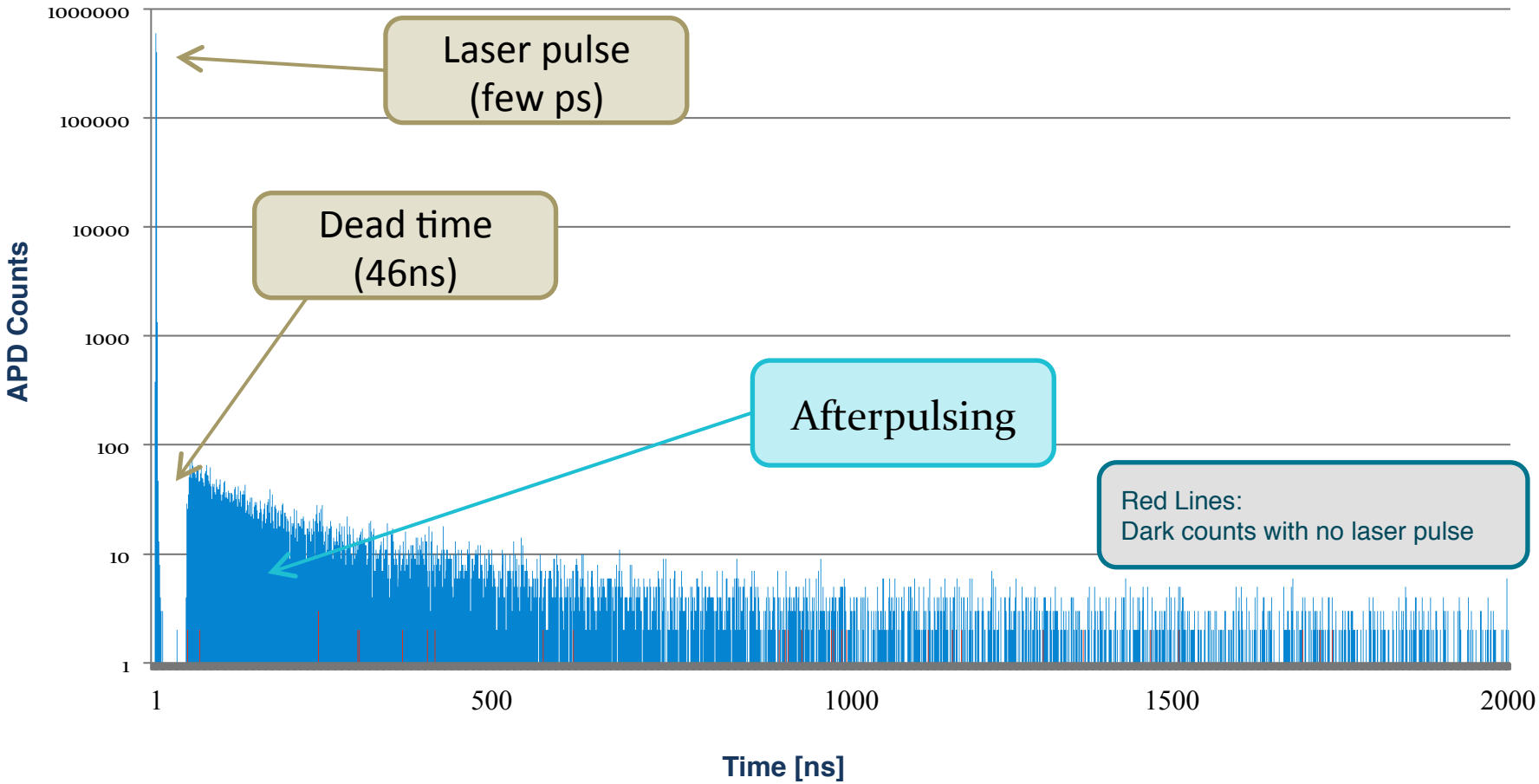
LDM - System

- Photon counting with Geiger-mode Avalanche Photo-Diode (APD)
- Integration over many turns to build up profile



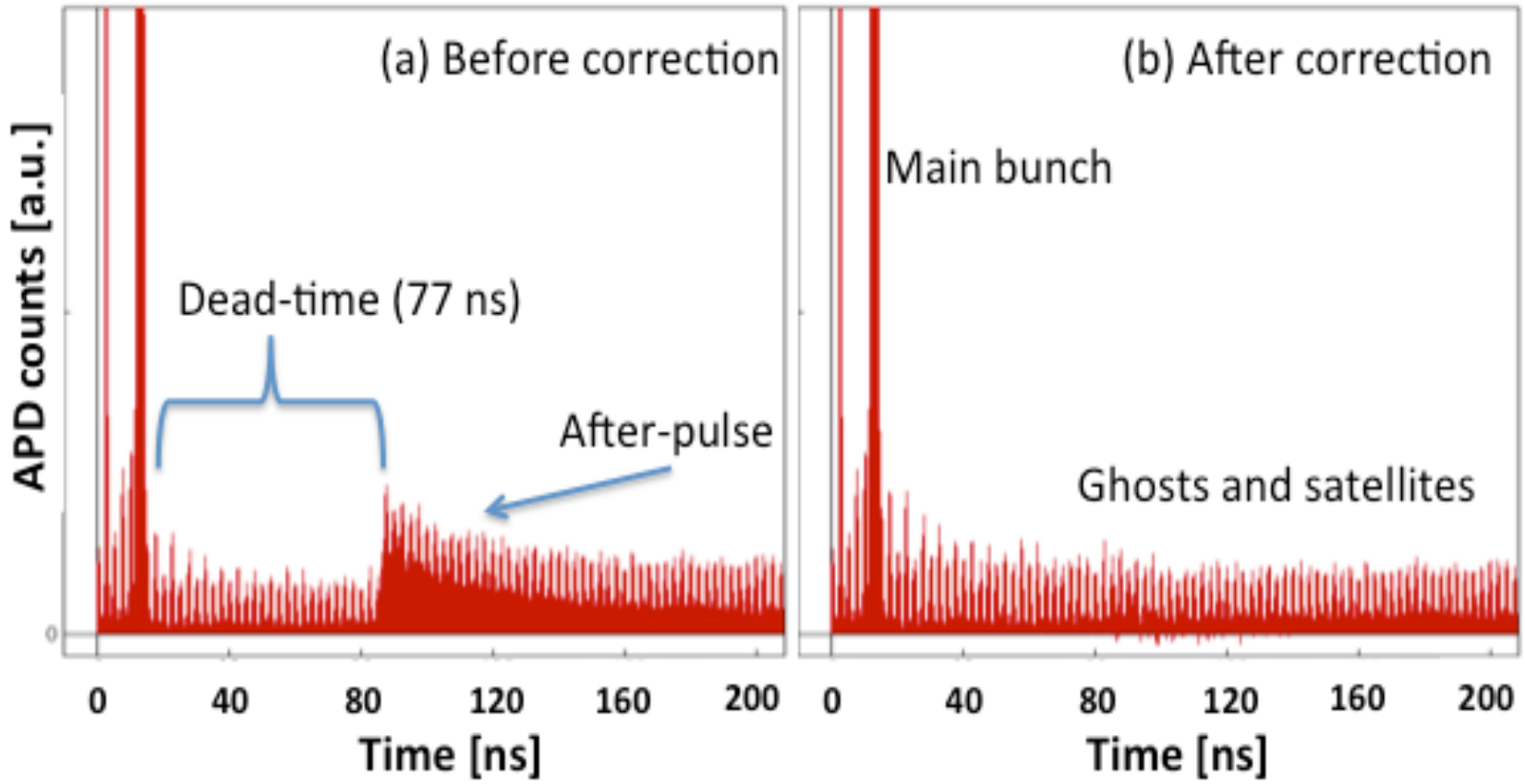
LDM – APD Response

- Laboratory measurement setup and calibration via pulsed laser



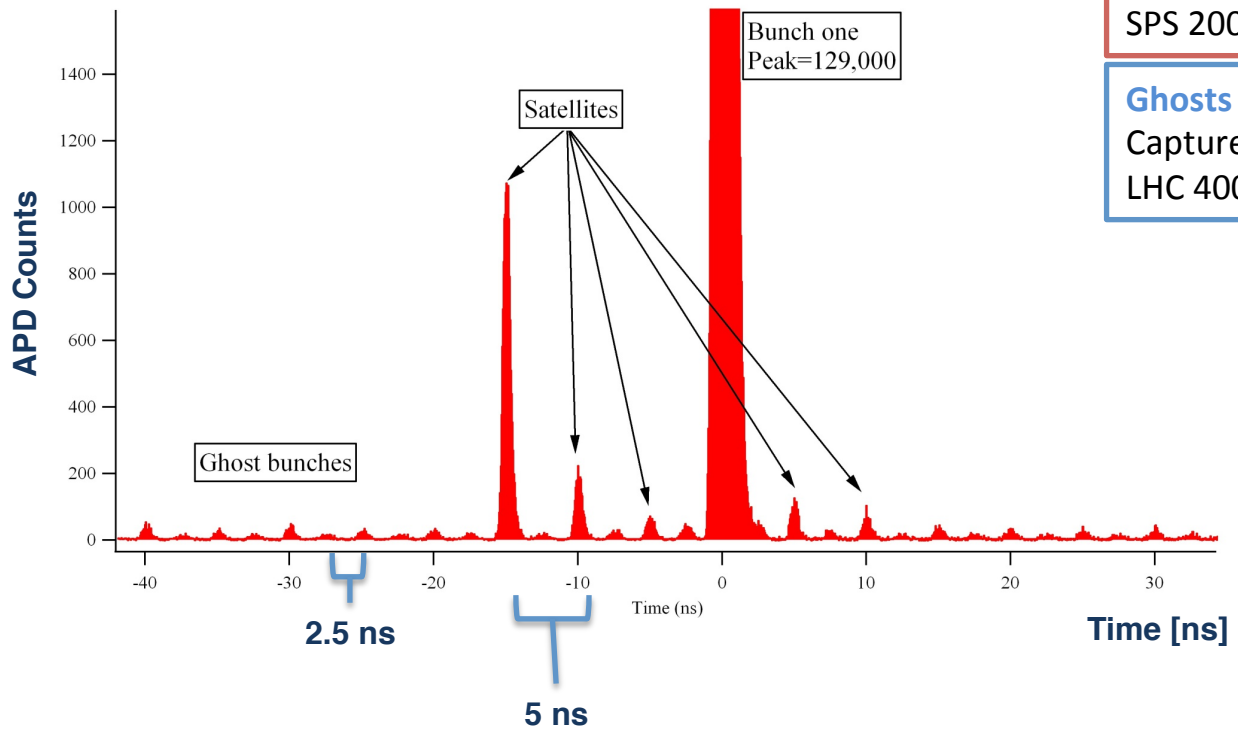
LDM – After pulse correction

- LHC Beam measurement



LDM – Measurement Example

- Lead Ions beam
- Integration time ~ 10min



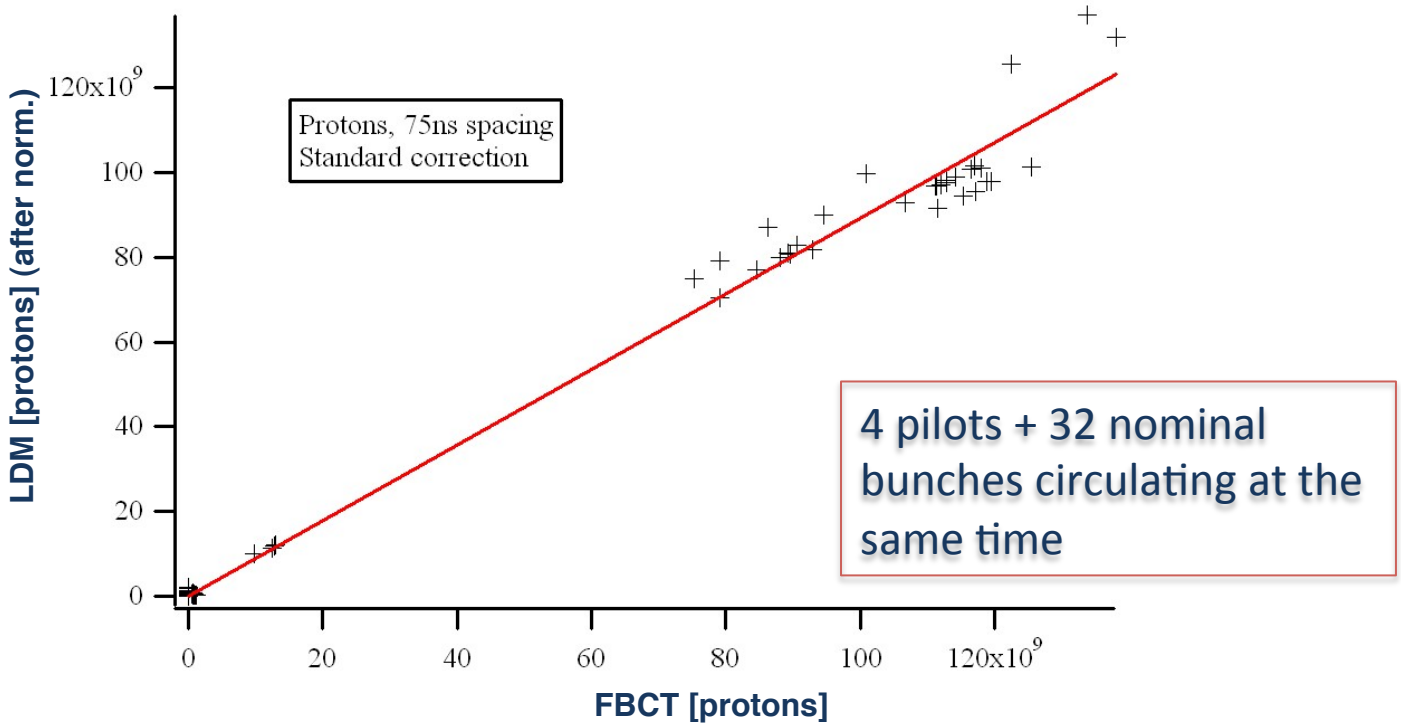
Satellites
Capture/splitting errors in the injectors
SPS 200 MHz → 5 ns

Ghosts
Capture/splitting errors in the LHC
LHC 400 MHz → 2.5 ns

LDM is the only LHC system able to see all structures from RF, with enough **dynamic range** and **time resolution** for monitoring satellites and ghosts

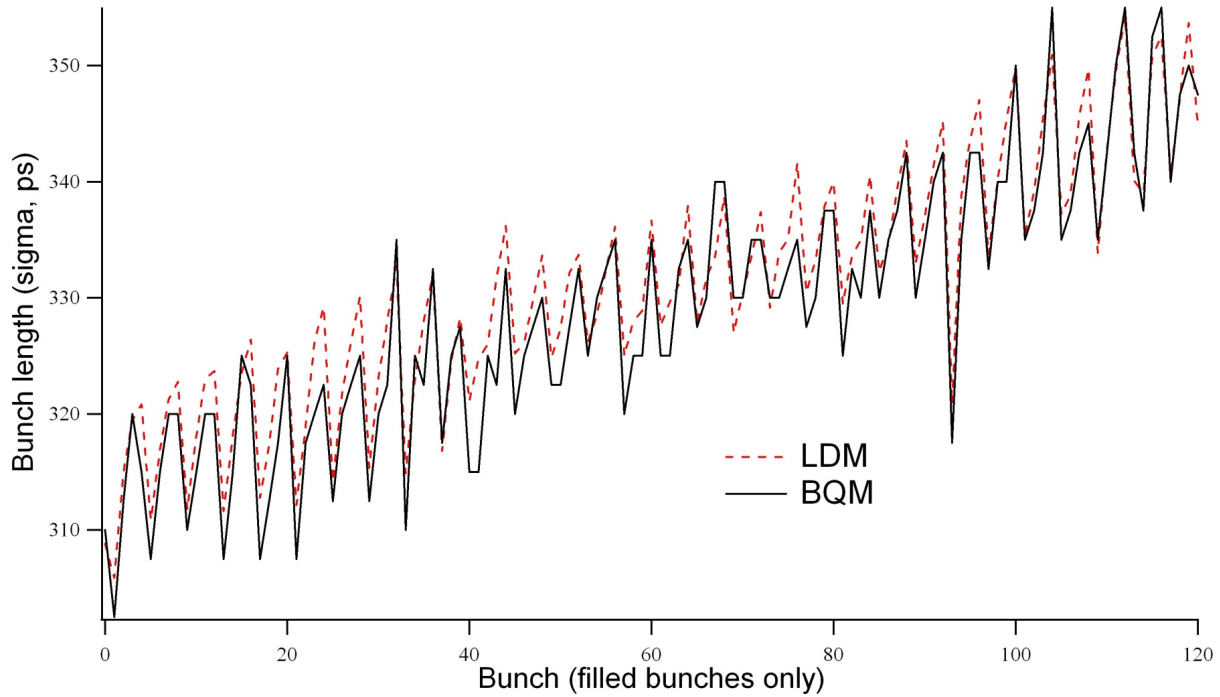
LDM vs Fast Beam Current Transformers (FBCT)

- FBCT measure single bunch beam current (25ns slots)
- LDM can be used to estimate the relative bunch intensity difference and compared to FBCT



LDM vs Beam Quality Monitor (BQM)

- BQM measures bunch length, but with poor dynamic range → can't detect satellites and ghosts

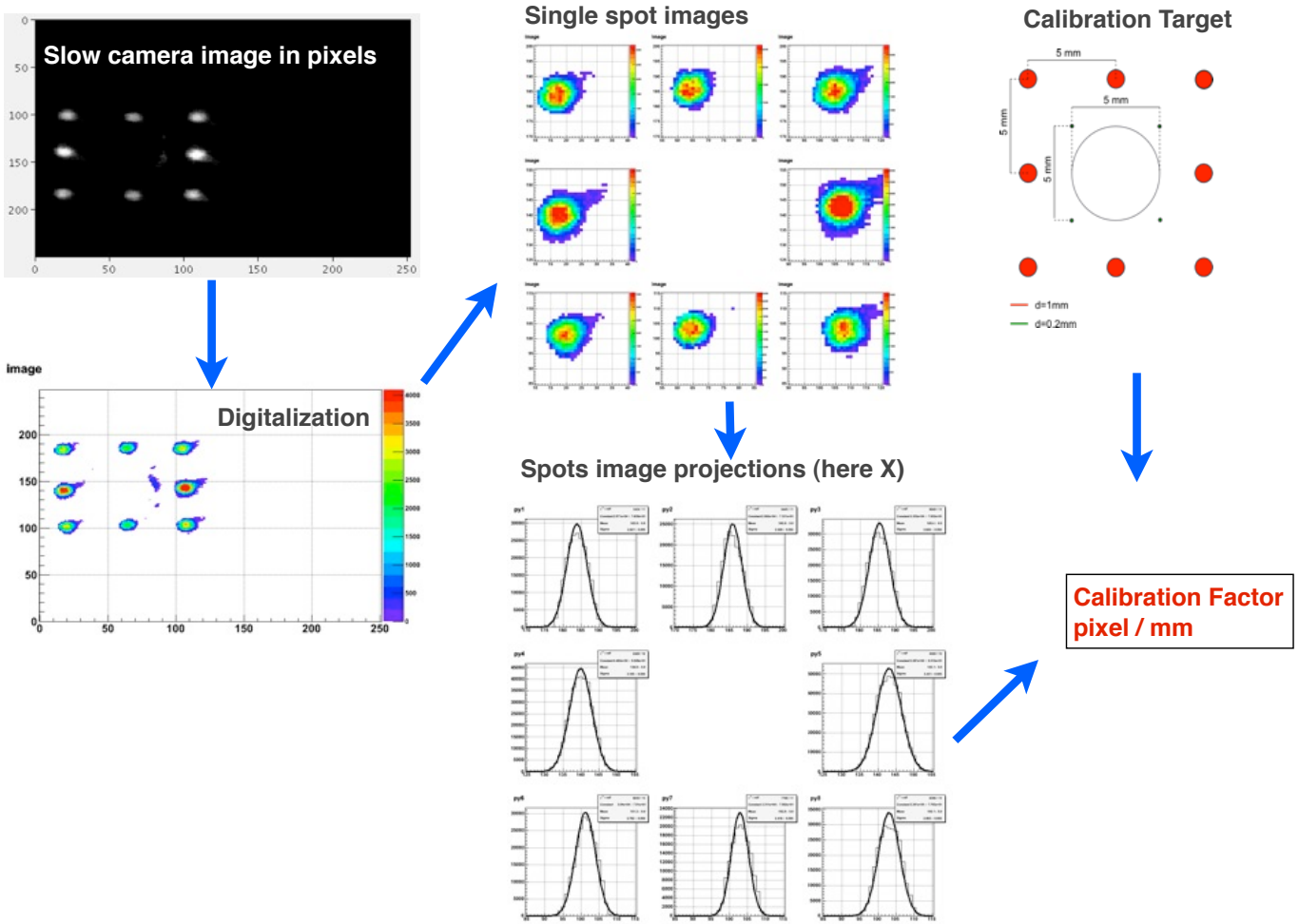


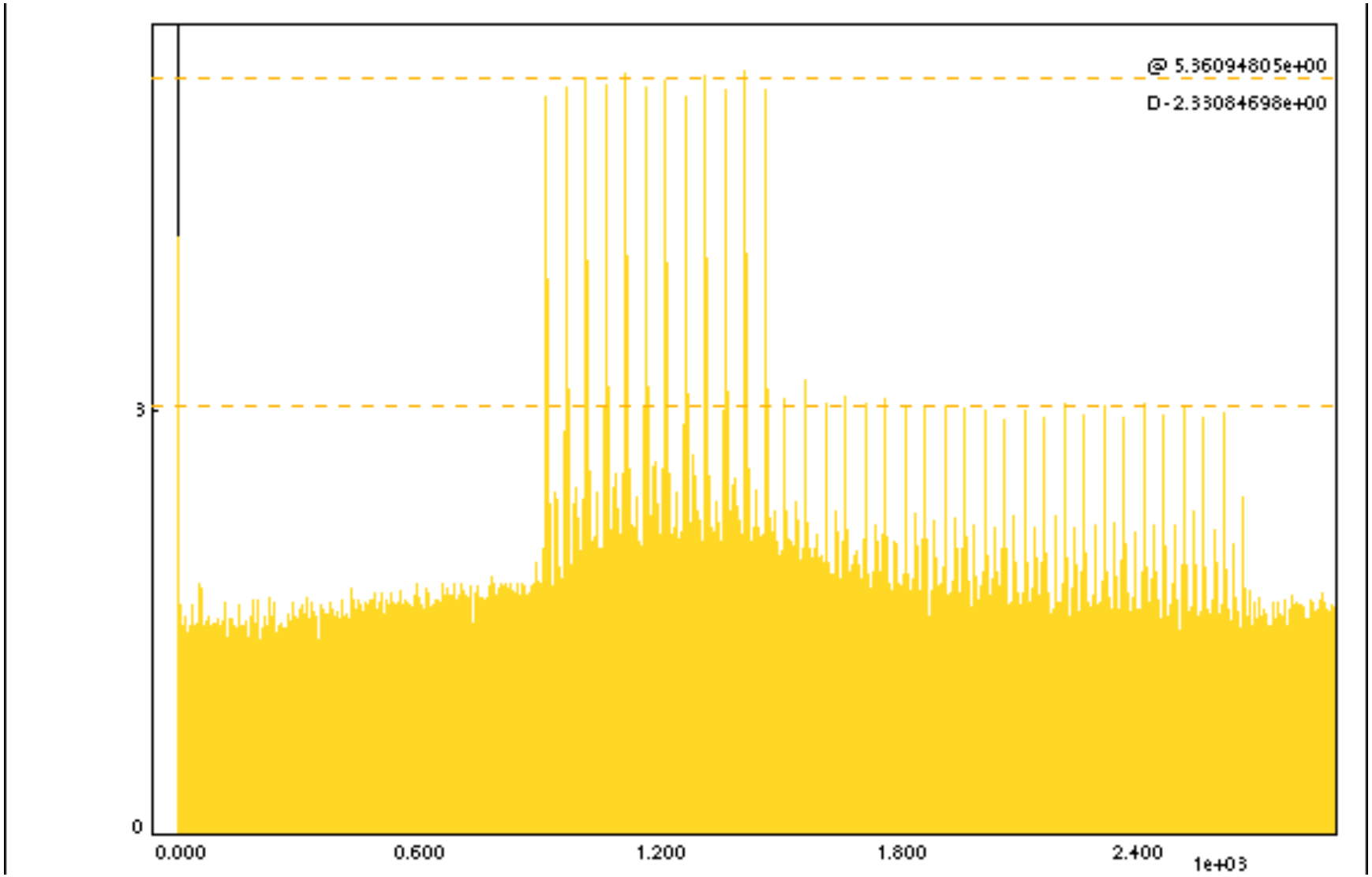
Conclusions (LDM)

- System is still in commissioning phase
- Very promising results , already used during LHC special runs
  - Allowed monitoring and correcting capture/splitting errors
- Low and high level operational software under development

SPARE

BSRT Calibration via reference target image




@ 5.36094805e+00
D-2.33084698e+00
3
0
0.000
0.600
1.200
1.800
2.400
1e+03

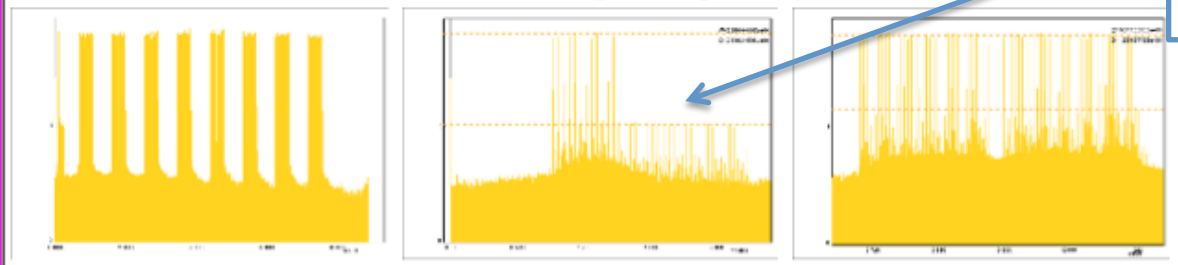
LDM – LHC OP logbook

12 Bunches injected using 36 bunch-train scheme
→ Protons leakage over empty buckets

10:41 BI

LDM B1

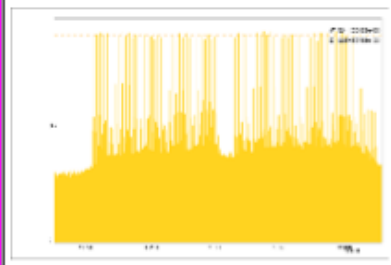
Satellites are still there, PS had however adjusted splitting for last injections.



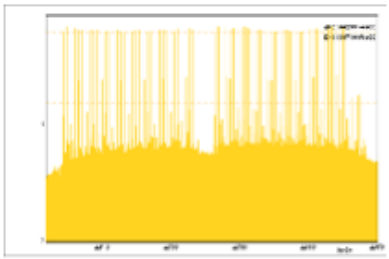
B1 log full ring.png

B1 log 1st batch.png

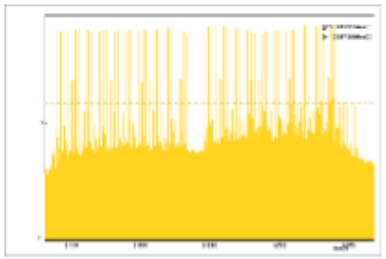
B1 log 2nd & 3rd.png



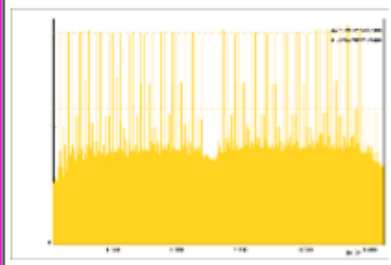
B1 log 4th & 5th.png



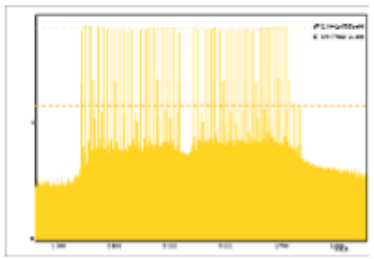
B1 log 6th & 7th.png



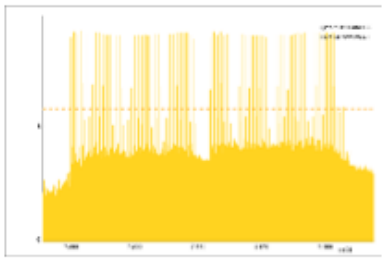
B1 log 8th & 9th.png



B1 log 10th & 11th.png

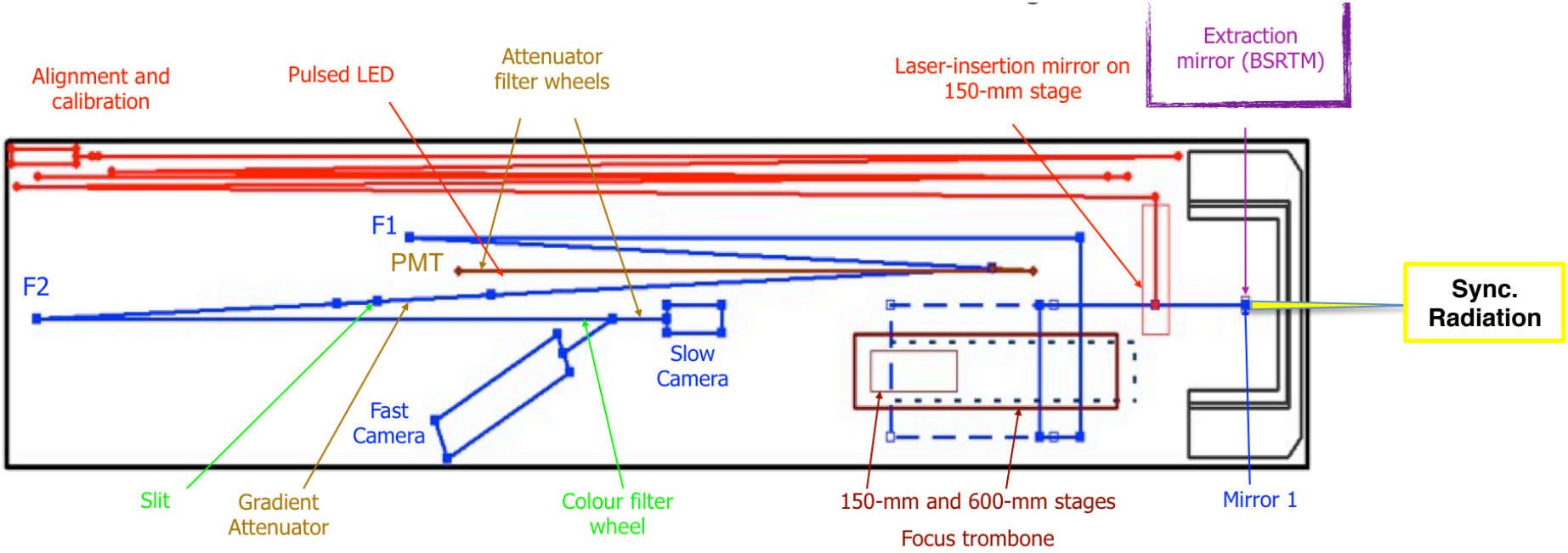


B1 log 12th & 13th.png

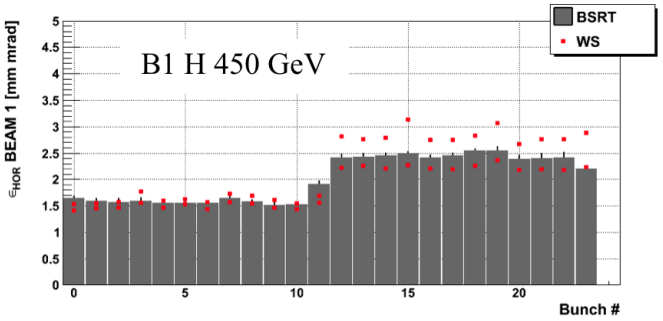


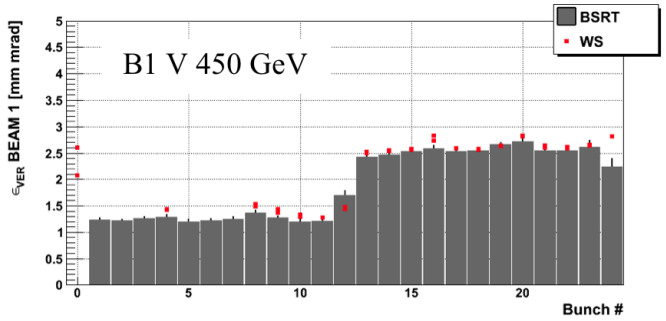
B1 log 16th & 17th.png

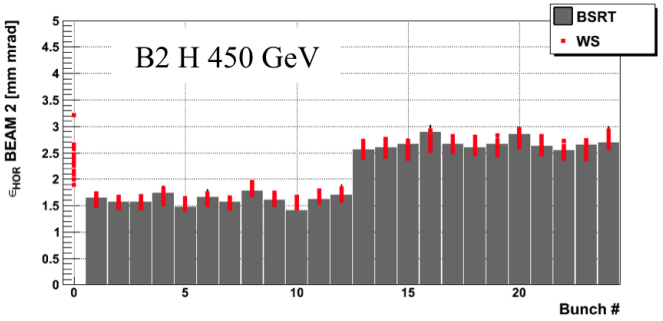
BSR Telescope layout

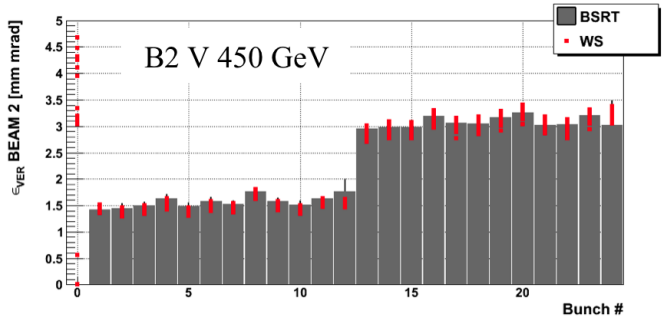


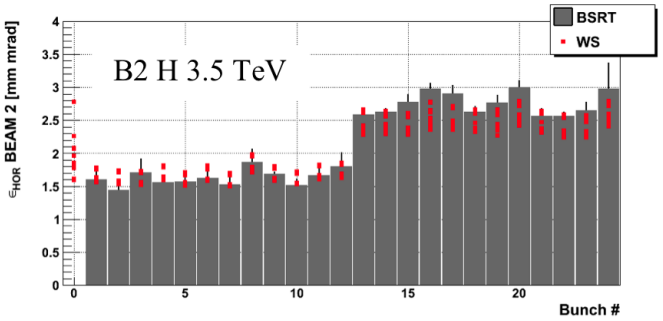
BSRT - WS

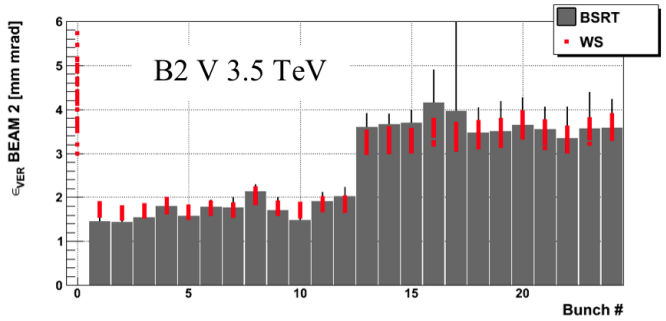

B1 H 450 GeV
BSRT
WS
ϵ_{HOR} BEAM 1 [mm mrad]
Bunch #


B1 V 450 GeV
BSRT
WS
ϵ_{VER} BEAM 1 [mm mrad]
Bunch #


B2 H 450 GeV
BSRT
WS
ϵ_{HOR} BEAM 2 [mm mrad]
Bunch #

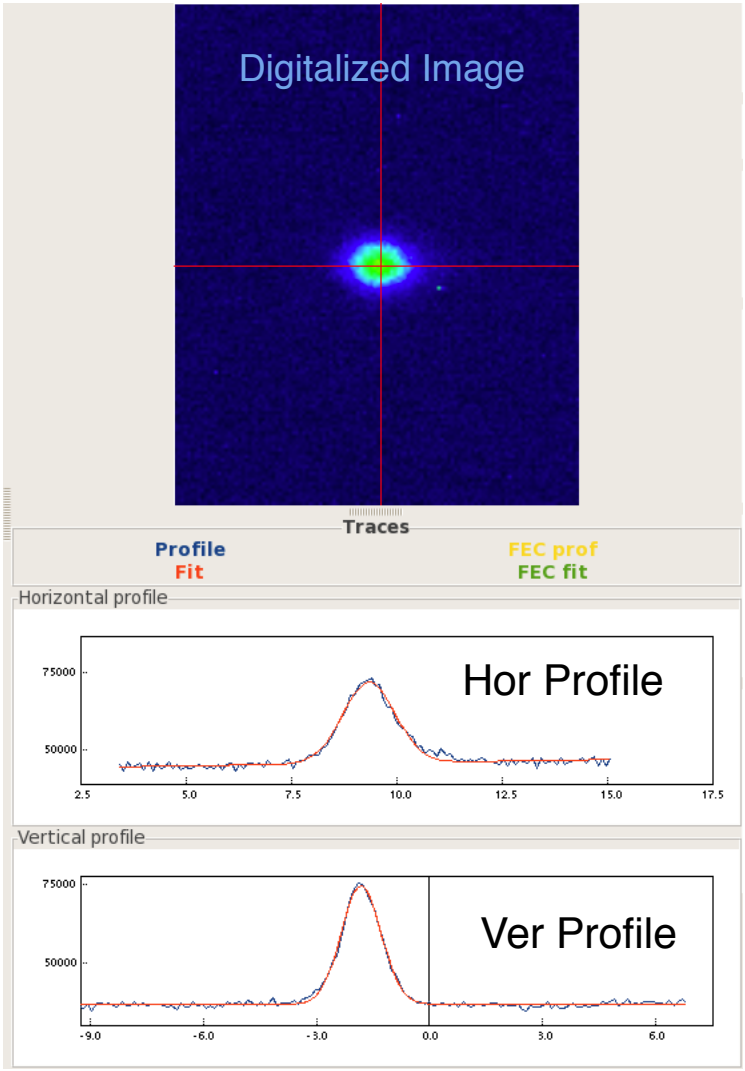

B2 V 450 GeV
BSRT
WS
ϵ_{VER} BEAM 2 [mm mrad]
Bunch #


B2 H 3.5 TeV
BSRT
WS
ϵ_{HOR} BEAM 2 [mm mrad]
Bunch #


B2 V 3.5 TeV
BSRT
WS
ϵ_{VER} BEAM 2 [mm mrad]
Bunch #

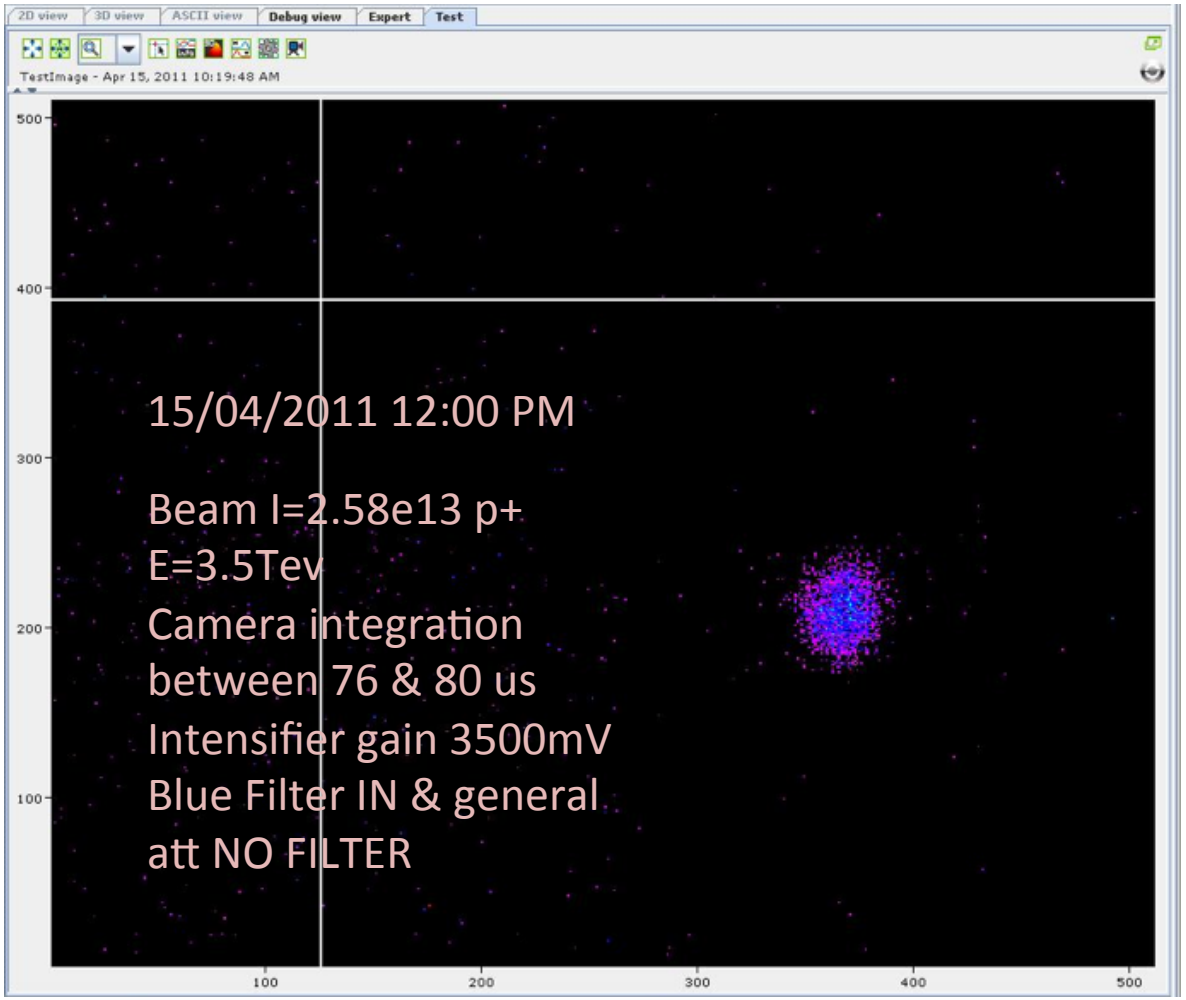
BSRTS - Proton Image Example

- Single bunch ~1.1e11p @ 3.5 TeV
- Accumulated over 4 turns separated of 55 turns (200 Hz trigger rate limit on image intensifier)



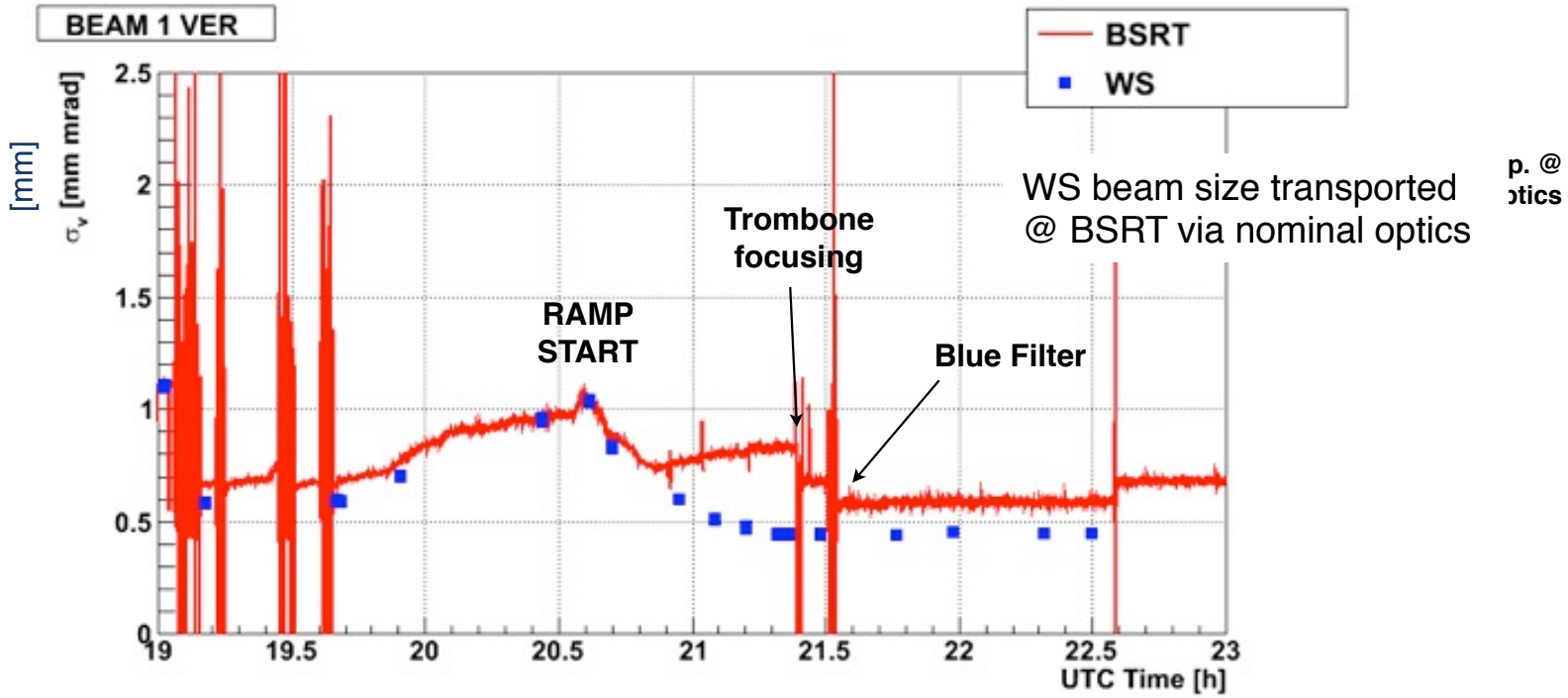
BSRTFast

- Redlake camera
- System designed for bunch-per-bunch, turn-per-turn
- Commissioning on going
- Real intensification via optical fiber coupling to be investigated with beam



BSRTS -Effect of optical path length and color filter

29-03-10, protons, ramp to 3.5TeV



Here: sigma measured by BSRT corrected (in quadrature) with a constant factor at 450 GeV and 3.5 TeV