LHC Beam Instrumentation

Performance, Issues and Plans

Rhodri Jones on behalf of the

CERN Beam Instrumentation Group

CMAC – 14th March 2013

What Operation Wants!

Jorg Wenninger (BI Day 2012)

We want measurements of all beam parameters that cover the full LHC dynamic range

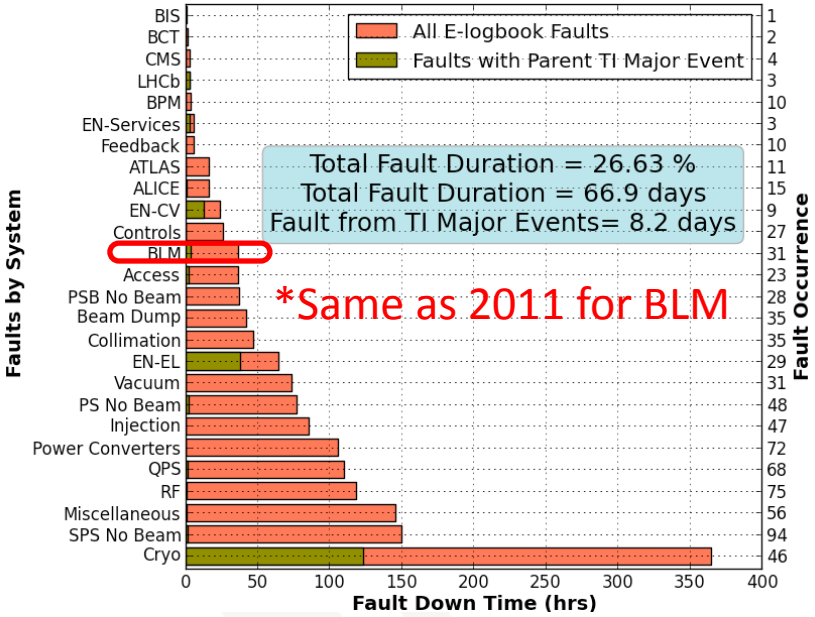
They should be

- *fast,*
- *accurate (give us 10 x better than what we need and we are happy),*
- *cool and cooled,*
- *bunch by bunch (all in //) and turn by turn,*
- *without gain changes or other operational hazards.*

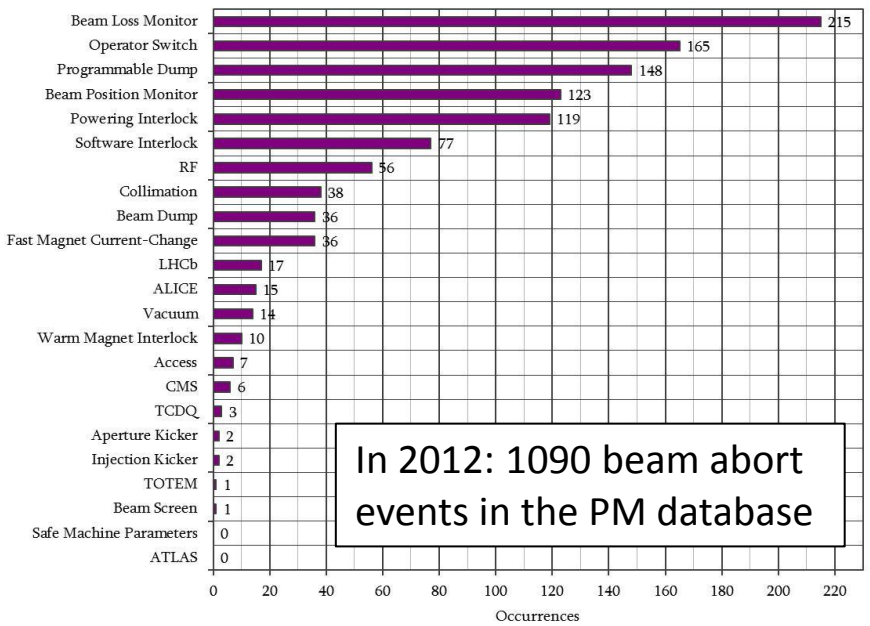
What we Managed to Provide

LHC BLM SYSTEM:
2012 OPERATION

Overall BLM Performance



Fault Down Time System by System

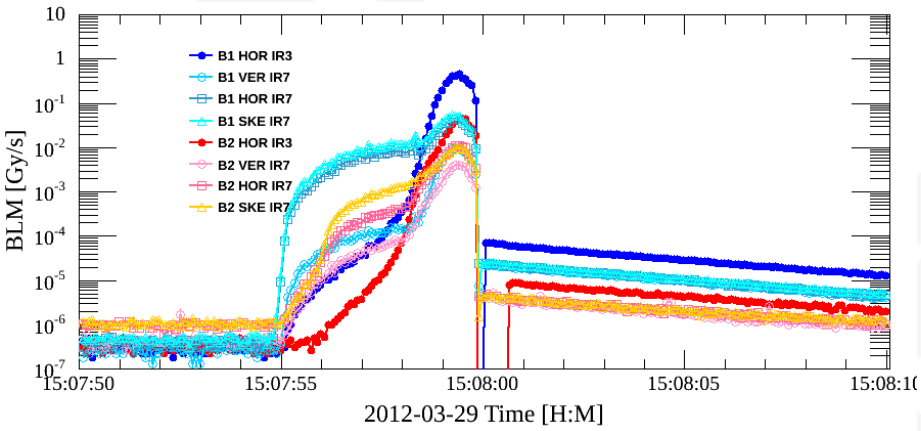


Beam Interlock System First Trigger

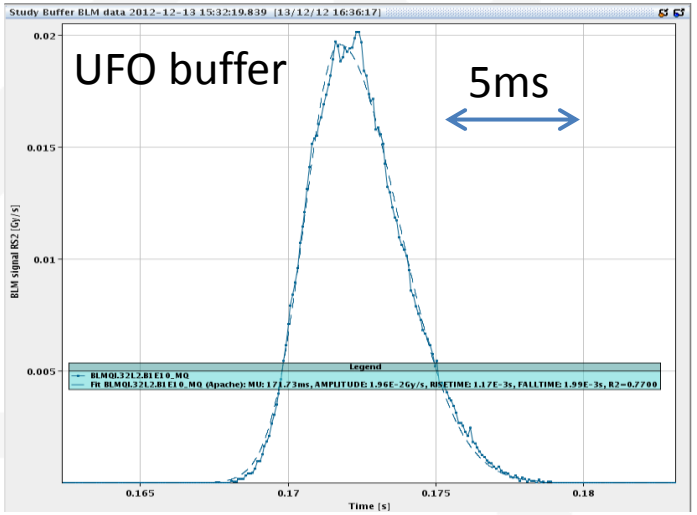
- **Very reliable and central system for safe LHC operation.**
  - At 4 TeV now have very well tuned thresholds.
  - Heavily used in CCC and for analysis under all LHC operational conditions.
- **Known issues to be treated during LS1:**
  - Unavailability due to errors from communication link - failures increased dramatically
    - Daily automatic analysis of all links allowed cards to be exchanged before affecting LHC availability
  - Saturation for very fast losses (mainly injection)
  - High voltage breakdowns

Overall BLM Performance

- **Improvements in 2012**
  - New data buffer for automatic collimator beam based alignment
    - Delivers 82ms integral from each BLM detector at 12.5Hz
    - Allowed much faster collimator set-up
    - Excellent diagnostic tool
      - time evolution of losses, halo population & diffusion rates
  - New UFO Study Data Buffer
    - Capture buffer allowing 80 µs integral with 4396 samples/channel
    - Automatic triggering when abnormal losses detected



Dedicated 12.5 Hz data



LHC BLM SYSTEM:
PLANS FOR LS1

LS1 BLM Actions

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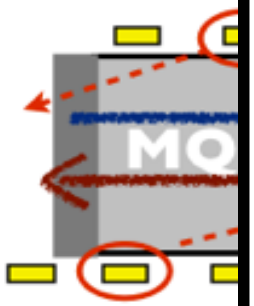
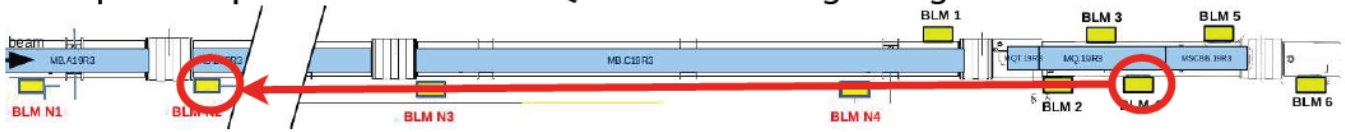
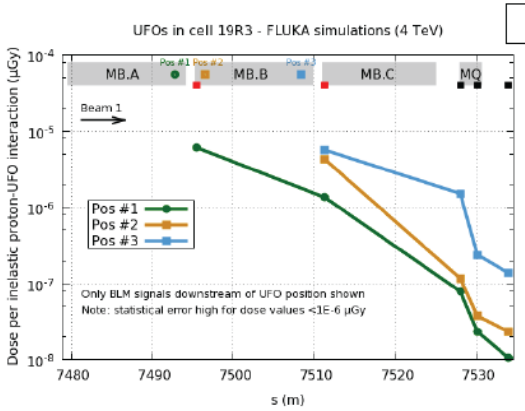
  - 70% of
- **Improve**
  - Exchan
- **Relocati**
  - 816 de



ARC BLM relocation I

- Proposed option. Move 2nd MQ BLM to the beginning of MB.B





A. LECHNER & M. SAPINSKI

Proposed new BLM location based on signal gain

UFO Location	BLM MB.B	BLM MB.C
MB.A	80	13
MB.B beginning	--	50
MB.B end	--	7

- MQ BLM should be reduced by 50 in order to protect against UFOs at MB.B.
- OTHER OPTION. BLM located in the interconnect (vertically and ~ centered between B1 and B2) would cover all possible UFO locations (to be confirmed).

E. Nebot EVIAN 19-12-2012 4

LS1 BLM Actions

- **Additional Tunnel Work**
  - Exchange of 360 acquisition crate backplanes to improve stability
  - Modification of 309 signal distribution boxes
  - Modification of 20 high voltage distribution boxes
    - Adding suppressor diodes and resistors
  - Modification of ~700 modules for HV level detection
  - Connection to WorldFIP
    - Allows additional remote access features
- **Surface Work**
  - Replacement of all racks to add temperature regulation
    - Removal and re-installation of complete system
    - Reconnection of all fibre patchcords (~1600)
  - Maintenance of ~800 processing modules
  - Improvements to the firmware
    - Compatibility with new Linux based CPU
    - Addition of more checks and modifications to buffered data collection

Post LS1 BLM Thresholds

- **Implement outcome of tunnel installation modification**
  - Simulation of losses & calculation of thresholds for new BLM positions
- **Implement outcome of quench tests**
  - Recalculation of interlock thresholds for BLMs protecting cold elements
    - Fast losses (10 ms, ADT + MKQ + Orb. Bump)
      - Signal 5 times larger than estimated quench level before quenching
    - Steady-state (10 s, ADT + coll. system, protons)
      - Signals reached 3.5 times higher than estimated quench level with no quench
    - Steady-state (20s , ADT + Orb. Bump)
      - Quenched at estimated quench level
  - Extrapolation to 7 TeV requires dedicated analysis + simulations
- **Modifications in Threshold Generation**
  - Implement all functionalities inside the LSA database
    - Migration from C++ stand-alone threshold generation
    - Implementation of generation algorithms in PL/SQL (BE-CO)
    - GUI provided to generate, visualise and compare thresholds
  - Should improve reliability, reproducibility and long term maintainability

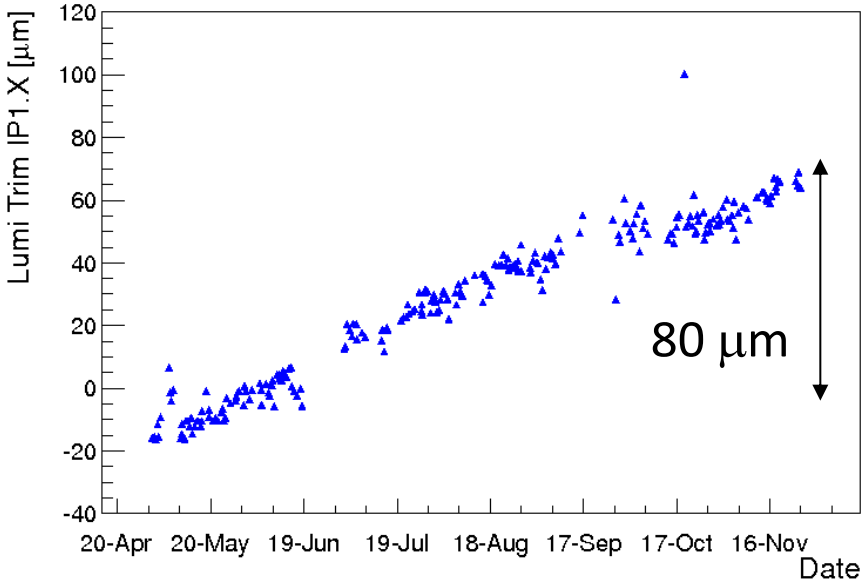
LHC BPM SYSTEM:
2012 OPERATION

Overall BPM System Performance

- **System Performance in 2012**
  - Channel availability greater than 97%
    - Deployment of automatic analysis tool during LS1
      - for improved fault detection for preventive maintenance
  - Orbit Resolution in the order of 10 μm.
    - Automatic configuration of averaging depending on bunch number tested
    - Will be implemented post LS1, pushing resolution below 5μm
  - Orbit Stability
    - Tight collimator settings and lower β* possible with excellent orbit stability
    - Arcs & most of the LSS BPMs
      - Fill to Fill reproducibility of ~50 μm rms.
      - Common regions 1,2,5 & 8, ~ 200 μm rms.
- **Main Issues**
  - Long term stability and reproducibility
    - Dependence on temperature, bunch charge and filling scheme
    - Mitigated for 2012 run but still needs improvement
  - Accuracy of IR BPMs
    - In addition to the above also suffer from directivity of stripline pick-ups

Orbit Feedback System

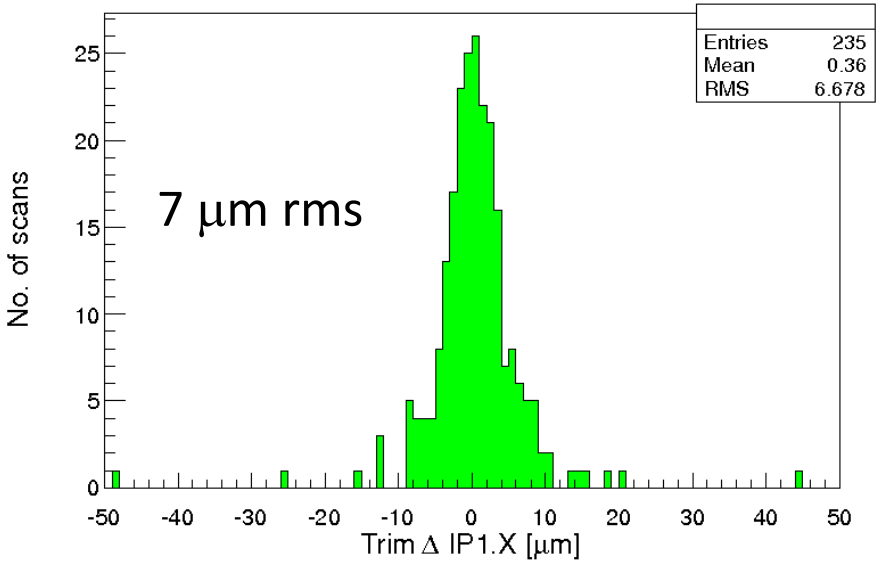
- **System Performance in 2012**
  - LHC does not work without orbit FB and overall performance 2010-2012 has been remarkable (Jorg Wenninger – BI Day 2012)
  - Current correction quality limits (not yet a real problem):
  - Arcs + most of the LSS: BPM Fill to Fill reproducibility – 50 μm rms.
  - Common regions 1,2,5 & 8, ~ 200 μm rms (directivity of stripline BPM)



Fill to fill difference is very small and sufficiently good (↔ squeeze in collision)

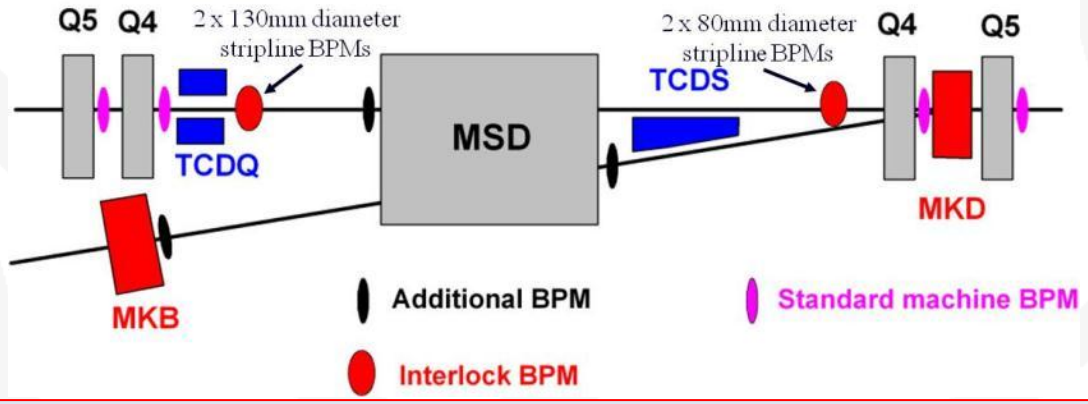
Orbit correction at IP to bring beams head-on (here B1H correction)

Slow drift over the year →not corrected by OFB.



Interlock BPMs

- **Purpose**
  - Ensure orbit at extraction septum stays within ±4mm to keep safe extraction trajectory
  - A single high intensity, high energy bunch can cause damage to the septum
    - System must be capable of reacting on a bunch by bunch basis
- **Layout**
  - 2 redundant BPMs near TCDQ and 2 near preceding Q4
  - 90° phase advance to minimise chance of an unfortunate orbit bump
  - Uses standard LHC BPM analogue electronics BUT specific FPGA firmware
  - All hardware detection and trigger of beam abort



Operational Settings:
- *Single bunch instability* : 70 readings out of limits over 100 turns
- *Fast Full Beam Instability* : 250 readings out of limits over 10 turns

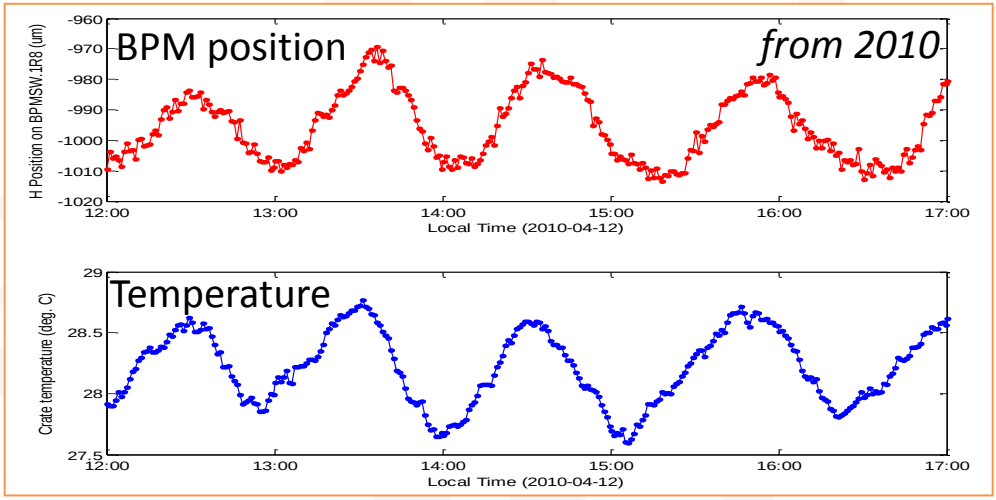
Interlock BPMs

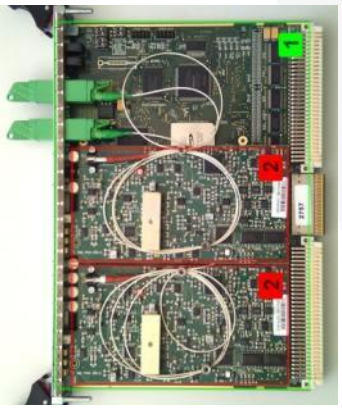
- **Issues**
  - The system suffered from too many false dumps
    - BUT no known case where the interlock did not function when it should have
  - As for standard LHC BPMs – system functions in 2 dynamic ranges
    - High sensitivity 2×10^{9} to 5×10^{10}
    - Low sensitivity 4×10^{10} to $>2\times10^{11}$
  - Originally signal attenuated from each pick-up to match arc BPM signal levels
    - Gave issues when single bunches slowly lost intensity & reached low to high sensitivity transition
  - Removed attenuation to allow interlock BPMs to reach 2×10^{10} in low sensitivity
    - No more issues for high intensity operation
- **Special Machine Conditions**
  - Tuning interlock BPMs for high intensity operation made them incompatible for several MDs and the p-Pb run
  - Difficult to find attenuation to cover low intensity ions & medium intensity protons
  - Non linearity systematically dumped the ion fills once a single bunch reached ~3×10^{9}
- **Work underway for Post LS1 implementation**
  - Study possibility to cover entire dynamic range without gain switching – options:
    - Optimisation of current system, reducing spurious reflections
    - Alternative acquisition electronics : e.g. logarithmic amplifiers
  - Improve diagnostics for this system which hampered understanding in 2012

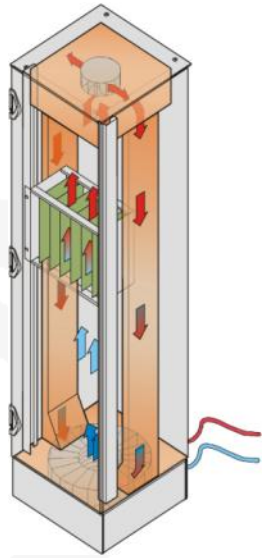
LHC BPM SYSTEM:
PLANS FOR LS1

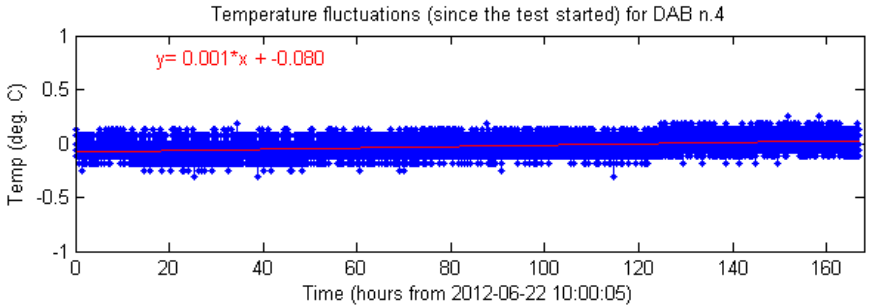
BPM Temperature Dependence

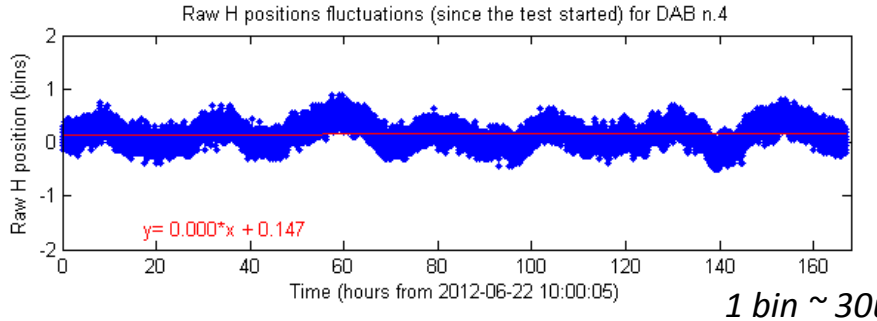
- **Improvements Foreseen**
  - Installation of thermalised racks
  - Maintains temperature within ±0.2°C
  - Prototype successfully tested in 2012









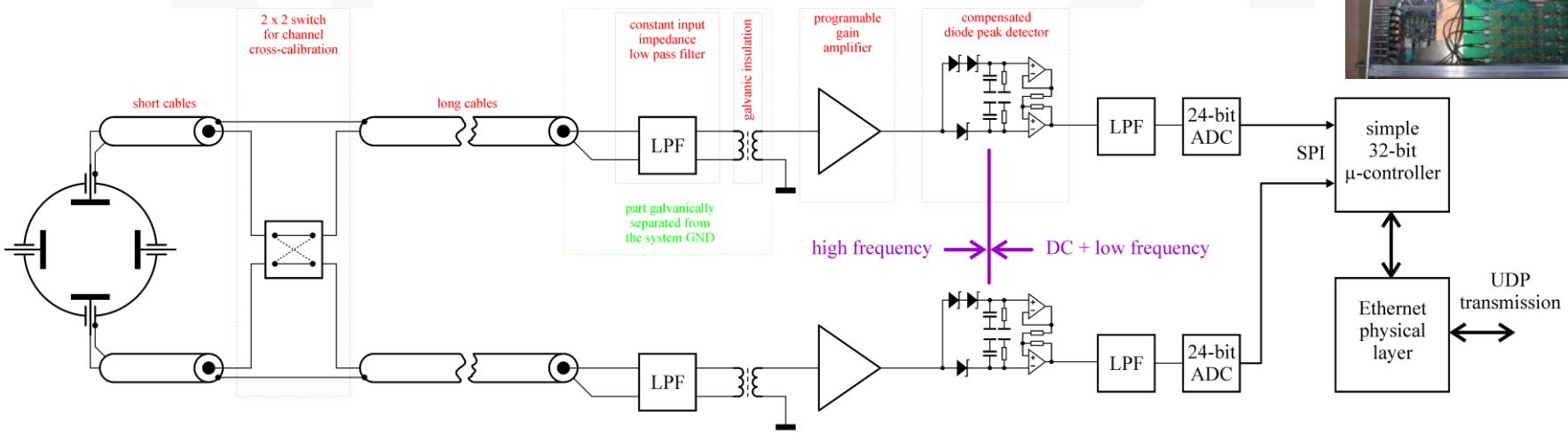


1 bin ~ 30um

Collimator & LSS BPM System

- **Diode ORbit & Oscillation System – DOROS**
  - New technique developed to provide accurate beam position measurements for collimator BPMs

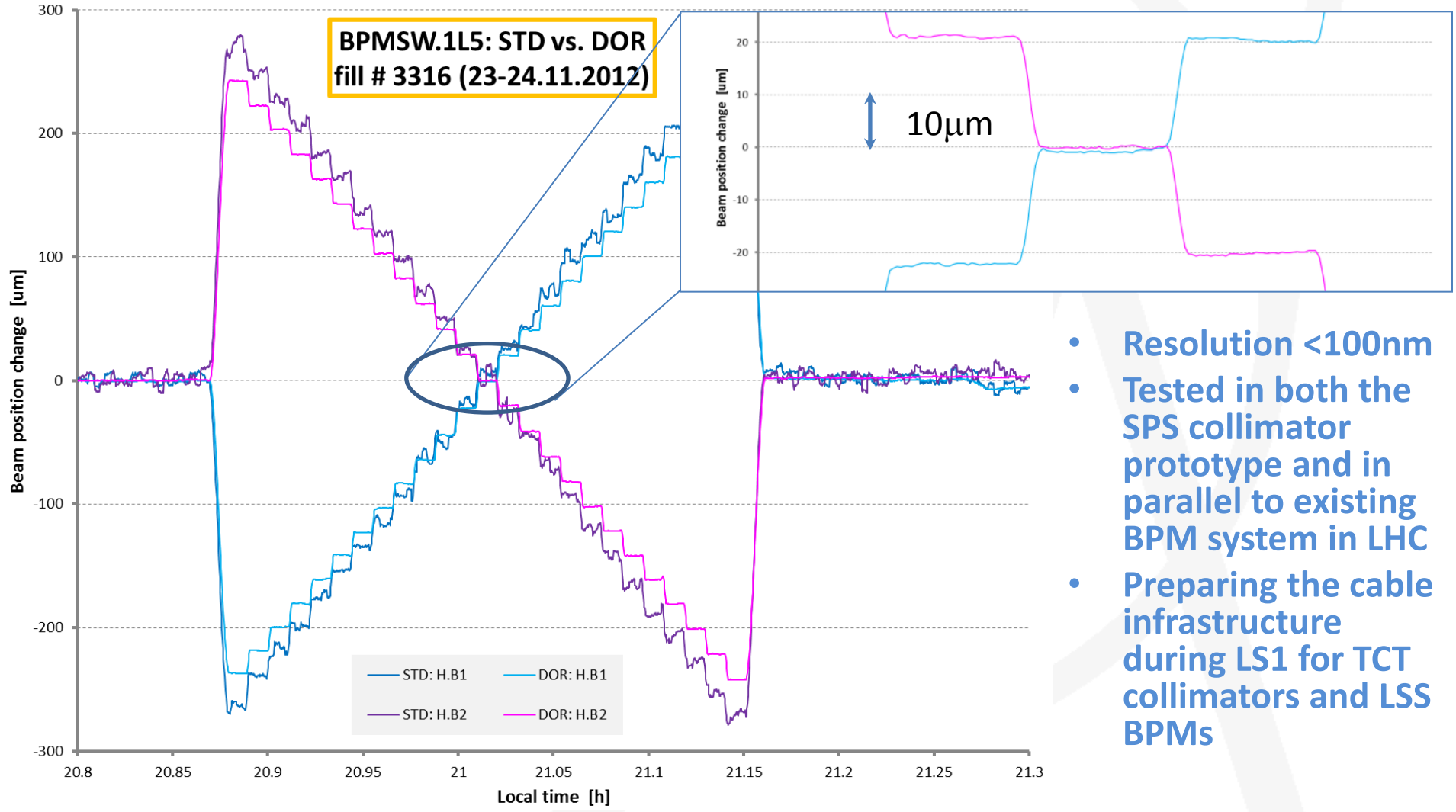
  - Optimised for position resolution, absolute accuracy for centred beams
  - Can also provide phase measurement for continuous local beta-beat calculation with very low oscillation amplitudes
  - No bunch-by-bunch measurement but could be gated



Diode Orbit Measurement

2 channels shown for one pick-up plane, one 19" 1U unit accommodates 8 channels

Results with DOROS



- Resolution <100nm
- Tested in both the SPS collimator prototype and in parallel to existing BPM system in LHC
- Preparing the cable infrastructure during LS1 for TCT collimators and LSS BPMs

LHC SYNCHROTRON LIGHT SYSTEMS
2012 OPERATION

BSRT Operation in 2012

Problems encountered in 2012

Electro-magnetic coupling - heating
- Mirror support failures, coating blistering → needed to replace both mirrors after August

Absolute calibration
- Drifting due to mirror coating damage
- Noisy due to numerous folding mirrors

→ Image blurring

Overall reliability
- auto-steering, auto-gain

Improvements – Upgrades during 2012

New mirrors & mirror holder
- From Si to Fused Silica bulk – reduced EM coupling
- Re-design of holder & springs to ensure mirror cannot fall off in case of spring failure

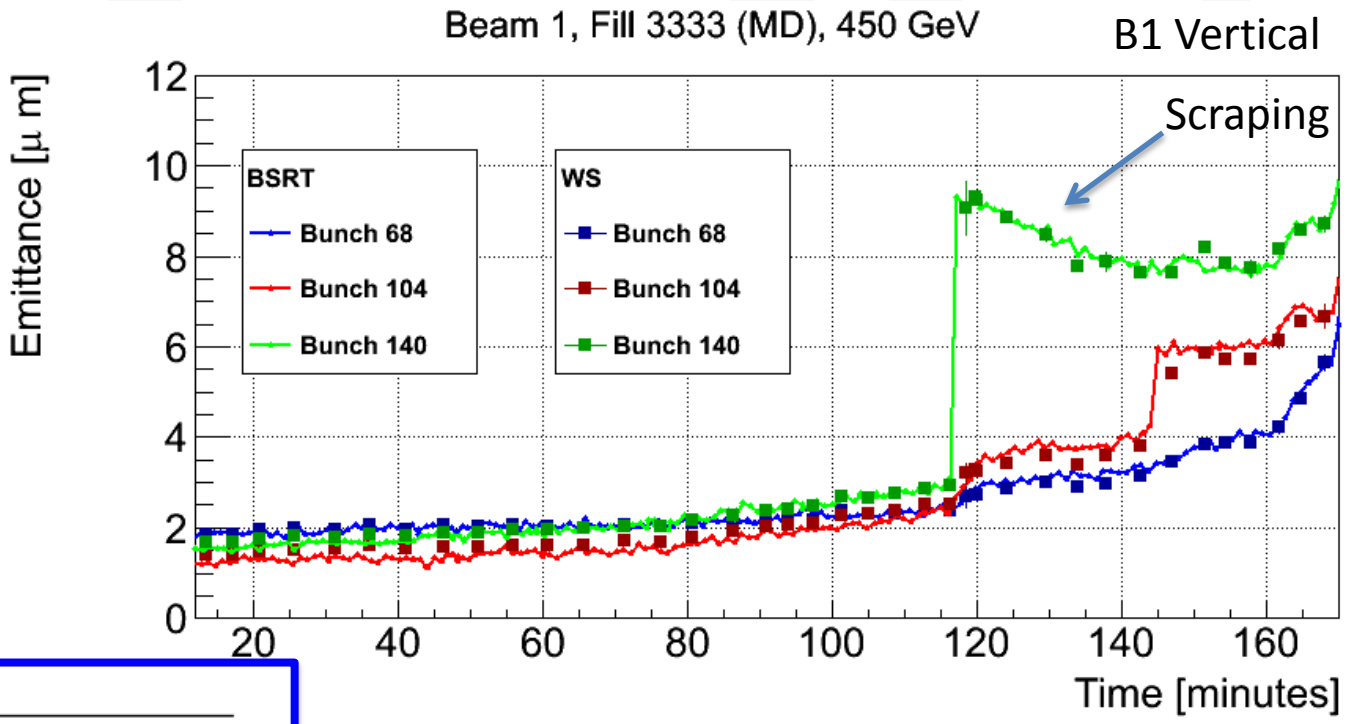
New optics
- Simplified imaging system – lower PSF corrections

New FESA server
- Improved reliability
- Fast bunch per bunch scans (~12Hz)

2012 BSRT Performance

After installation of new optics

- Excellent agreement BSRT – WS over a wide emittance range
- Magnification within 10% w.r.t. nominal
- PSF ~20% smaller than typical values with old optics



$$\sigma = \sqrt{\sigma_m^2 - \sigma_{psf}^2}$$

1 mm = 1.3 mm − 0.8 mm

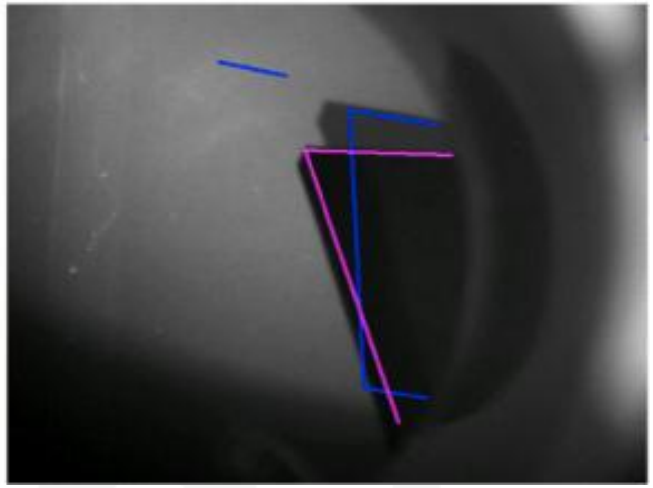
- Developing optics for lower wavelengths (lenses, folding mirrors, camera sensor), i.e 300nm or lower, to reduce diffraction

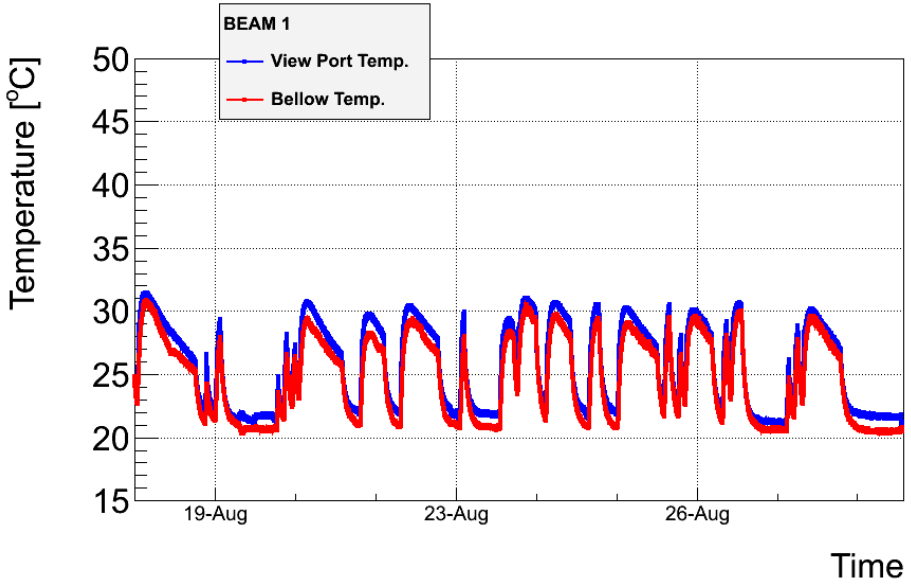
	Correction Factors			
	Old Optics	*New Optics*	*Old Optics*	*New Optics*
450 GeV	~0.9	0.85	~1.1	0.87
4 TeV	~0.6	0.35	~0.7	0.33
	Horizontal Plane		**Vertical Plane**	

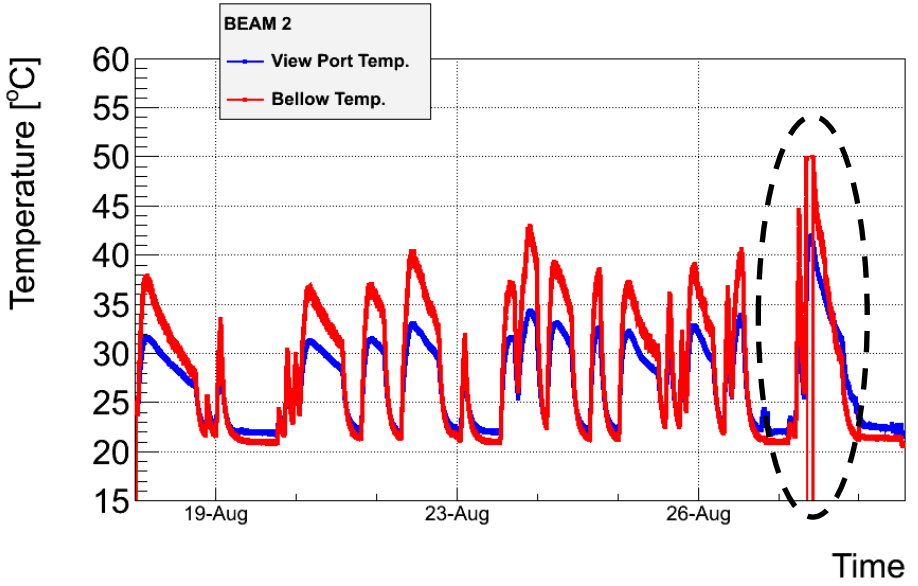
BSRT Mirror Heating

28-Aug-2012

- Light spot observed to be off-centre
- Dumped beam & retracted mirror
- Mirror later dropped down in out position

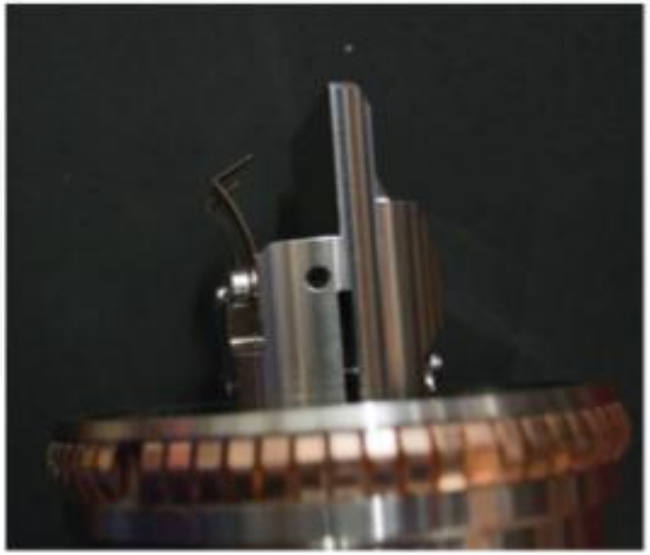






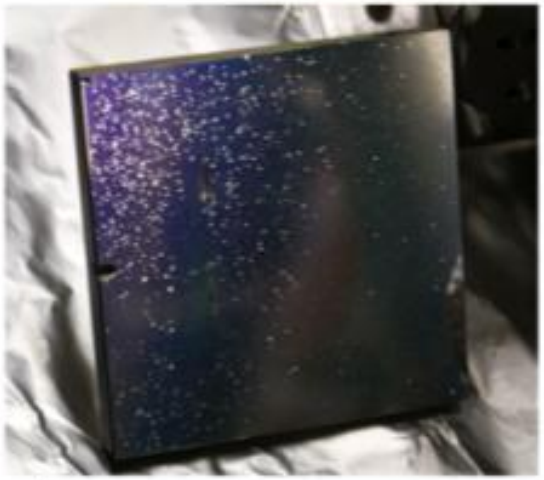
BSRT Heating Issue

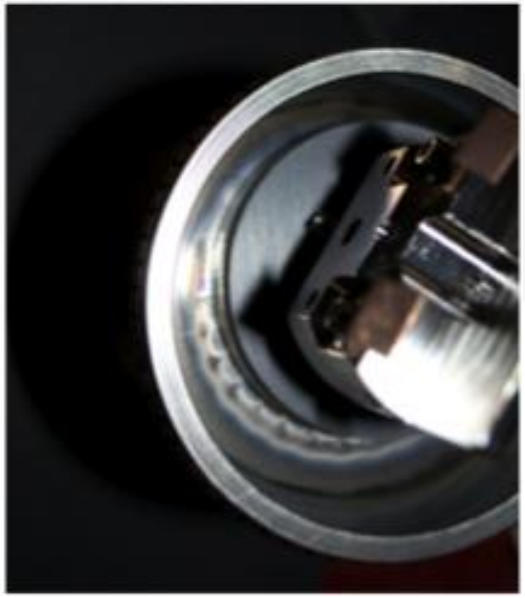
Mirror clamps deformed by heating



Mirror as it would have been in place

Mirror coating damaged by heating?

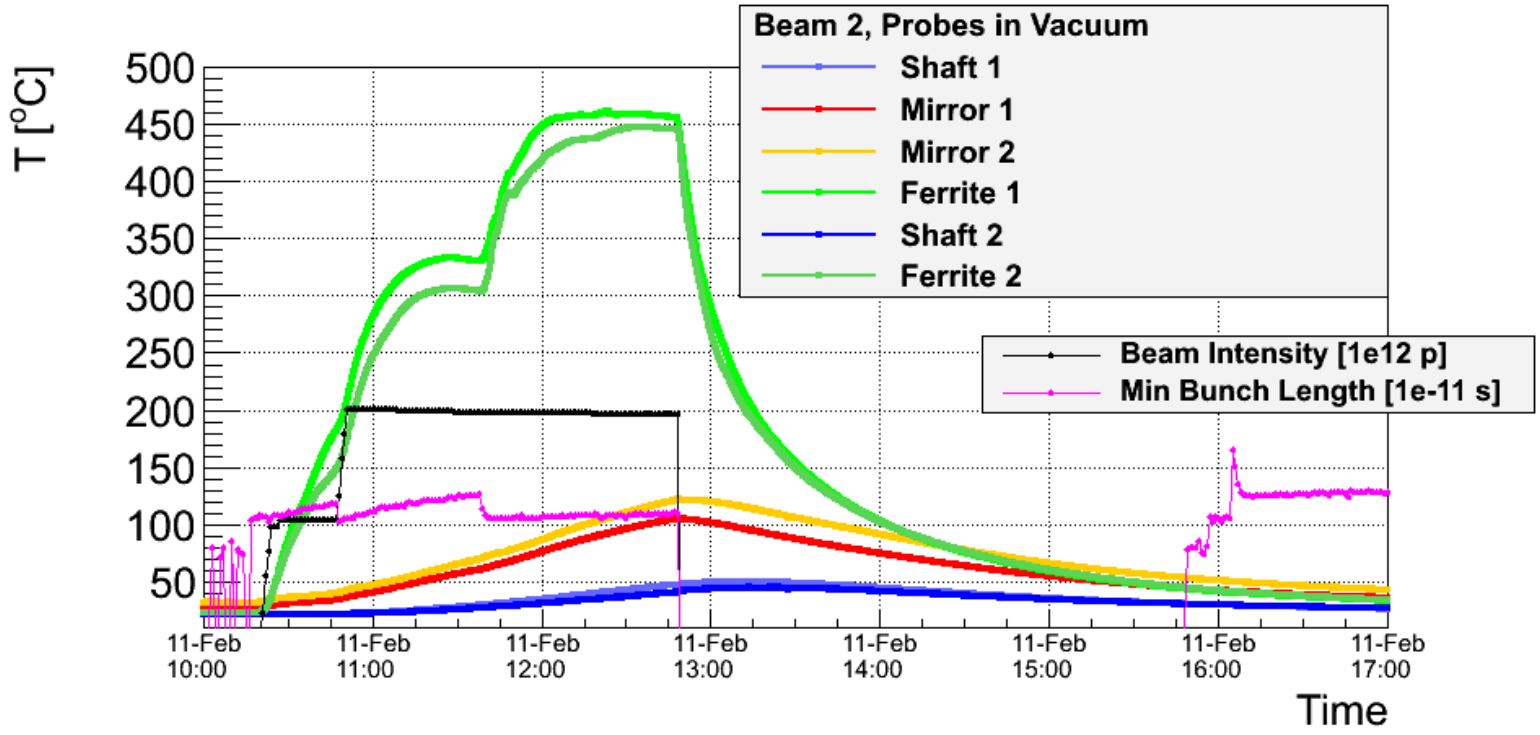




Traces of heating at the ferrite location

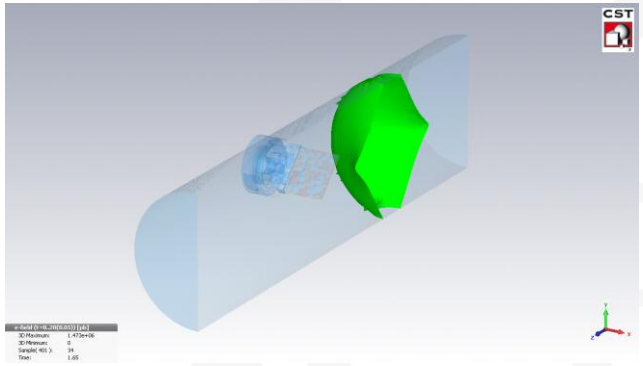
BSRT Heating Issue

- **Installed new assembly during 2012/2013 winter technical stop**
  - Instrumented with 6 thermocouples in vacuum distributed throughout the mirror support
  - Obtained time for 3 hour high intensity proton fill at injection to obtain data to allow further understanding of heating effects as input for FE modelling

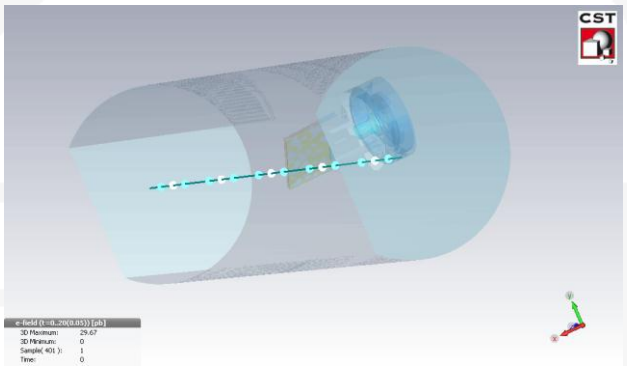


LHC SYNCHROTRON LIGHT SYSTEMS
POST LS1 OPERATION

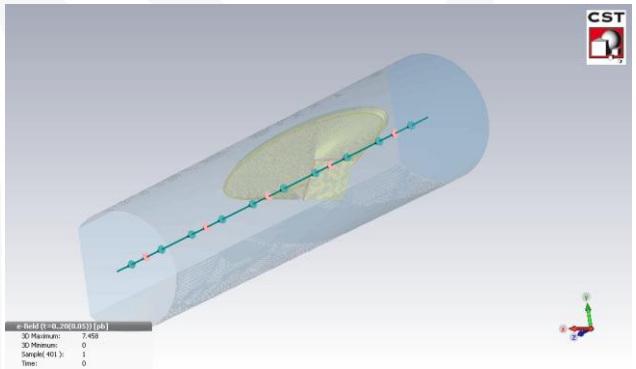
BSRT Mirror Assembly Design



Default design (no ferrite)



Default design with ceramic holder



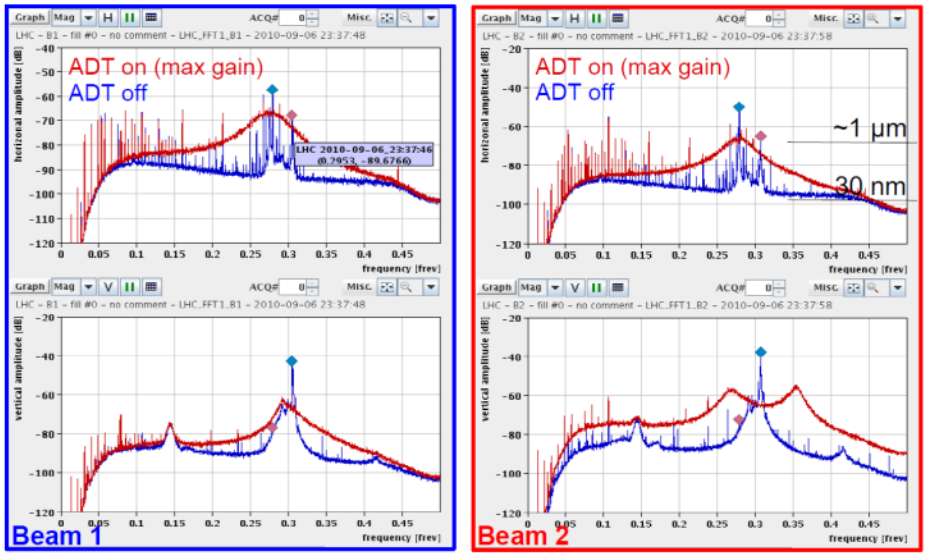
New design with “sheltered” mirror

- **Modifications clearly required to the current design**
  - Several options initially being followed
    - Replacement of metallic mirror holder by ceramic parts, e.g. *Macor* (machinable glass ceramic) or *Shapal* (machinable aluminium nitride ceramic)
    - Alternative designs with fixed mirror position
      - “Sheltered Mirror” designs
      - Elliptical cross-section designs
  - In parallel study ways to obtain efficient heat transfer from ferrites under vacuum conditions

LHC TUNE SYSTEMS:
2012 & POST LS1 OPERATION

Main BBQ Tune Systems

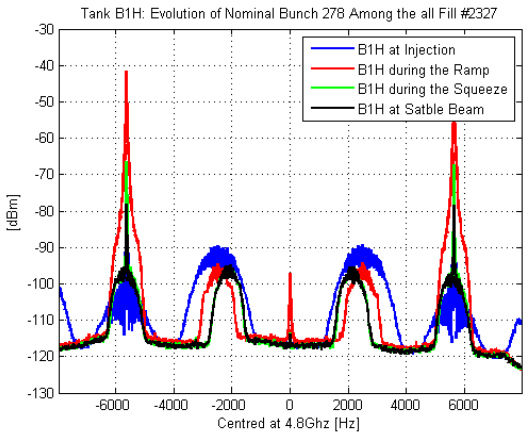
- **Main Issues**
  - Incompatibility of tune measurement with transverse damping
    - Damper operated at high gain suppressing
    - Large octupole currents & chromaticity broadening tune peak
  - 50Hz mains harmonic interference at low oscillation amplitudes
- **Solved in 2012 through implementation of gated BBQ system**
  - Gating on bunches for which the damper operates at lower gain
  - Long, non trivial development resulting in first prototype for summer 2012
  - Operational for rest of 2012 with basic functionality

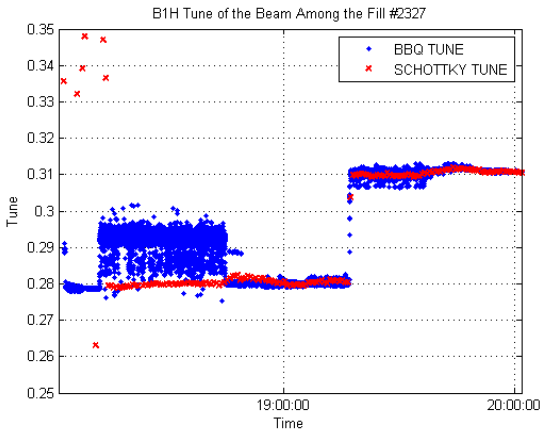


- **Post LS1 Operation**
  - Installation of dedicated pick-ups for gated tune
  - Software upgraded to allow full gated tune functionality
- **Feedback compatibility with QPS**
  - Fast tune changes induce false QPS quench signals
  - TE/MPE considers introducing different threshold levels after LS1
  - Better tune signal with gating should help reduce spurious tune jumps

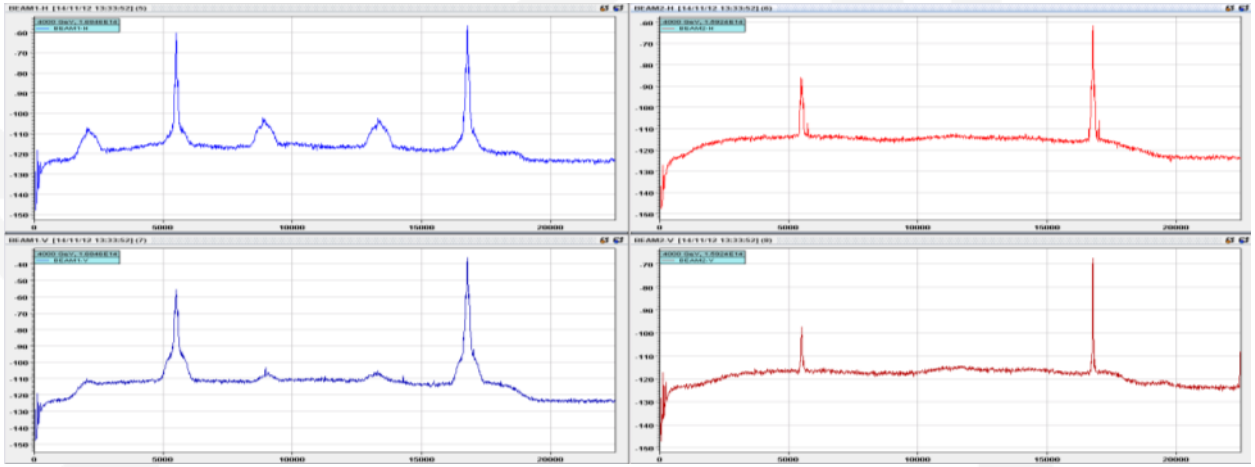
2012 Schottky System Performance

- ***Run with IONS in 2011***
  - Good Schottky signals observed on all ion fills
  - Reliable single bunch measurements for the tune
  - Chromaticity measurements also possible





- ***Run with Protons in 2012***
  - Signal good on B1H for single & multi bunch measurements at injection & stable beams
  - Large coherent signals saturate and destroy the pre-amps in the other systems!
  - Still the only system capable of bunch by bunch tune and chromaticity measurements in a non invasive and transverse damper independent way



Schottky Systems Post LS1

- **Overhaul of all Schottky pick-ups**
  - Reduction of reflections for better return loss on waveguide-to-coaxial transitions
    - New transitions to be manufactured
- **Improve symmetry of opposite electrodes**
- **Replace all internal SiO_2 coaxial cables**
  - Some are leaking argon into vacuum
  - Same issue with collimator BPM cables due to non-adapted material choices and welding procedures
    - Followed up by EN/MME and BE/BI teams directly with manufacturer
- **Overhaul of the RF signal processing**
  - Modify the gating of all front-ends
  - New RF input filter to cope better with amplifier saturation
- **Controls and software**
  - Extend the attenuator & phase shifter control to all systems
  - Adapt the front-end control software to the hardware modifications.
  - Complete replacement of the Java user application software

OTHER BEAM INSTRUMENTATION SYSTEMS
2012 & POST LS1 OPERATION

Other Systems I

- **Wirescanners**
  - Suffered vacuum leak on bellows after 10,000 scans
    - Redesigning of bellows in collaboration with manufacturers to obtain lifetime of >50,000 scans
  - Broke several wires due to control card / software issues
    - Need to be understood & mitigated during LS1
- **Screen Based Beam Size Measurement**
  - Suffered from broken RF fingers on dummy chamber
    - Due to metallic gripping resulting from poor production and assembly procedure
    - Re-design complete and all affected systems will be modified
  - Matching monitor tested but sensitivity needs to be improved
- **Abort Gap Monitor**
  - Depends on light from synchrotron light monitor
  - Data published @1Hz with resolution that varies with energy & species
    - Protons - required resolution (0.1 of the quench level) met at all the energies
    - Pb - required resolution only met from 1.5TeV onwards
  - The present level of reliability doesn't allow for inclusion in the interlock system
- **Longitudinal Density Monitor**
  - Integrating for 5 minutes achieved a resolution of 10^{-4} at flat top
  - LDM important during VdM scans for out of bucket beam evaluation
  - Efforts in LS1 to fully integrate this into the control system

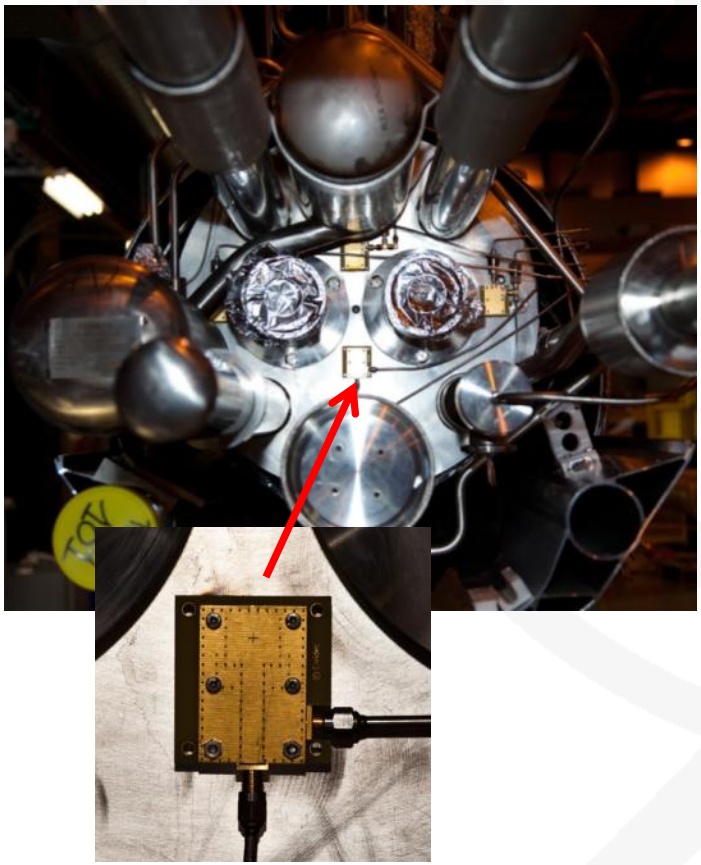
Other Systems II

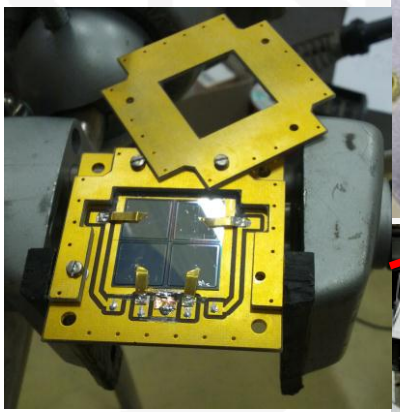
- **Rest Gas Ionisation Monitors**
  - MCP failures in early 2012
    - Reasons understood & protection measures now in place
  - Difficult cross-calibration
    - No intensity overlap with wirescanners during p-p runs + BSRT B2 mirror problem
  - Overall interpretation of results still difficult
    - Evidence of space charge impact on measured profile (especially strong for high-brightness proton beams)
- **Beam Current Monitors**
  - Very important for absolute luminosity calibration
    - Pushed LHC Beam Current Transformer performance to its limits
    - Well beyond requirements for normal operation
    - Uncertainty in the absolute DCCT calibration now at the < 0.3% level
  - Fast BCT monitors
    - Commercial toroids suffer from both position and bunch length dependence
    - Development ongoing to address these issues
    - Implementation of dI/dt system for machine protection also tested
- **Instability Monitors**
  - Ongoing development
    - High sensitivity frequency domain detection system based on bandpass filters and diodes
  - Replacement of fast oscilloscopes
    - More adapted acquisition system for performance & reliability

Studies for HL-LHC

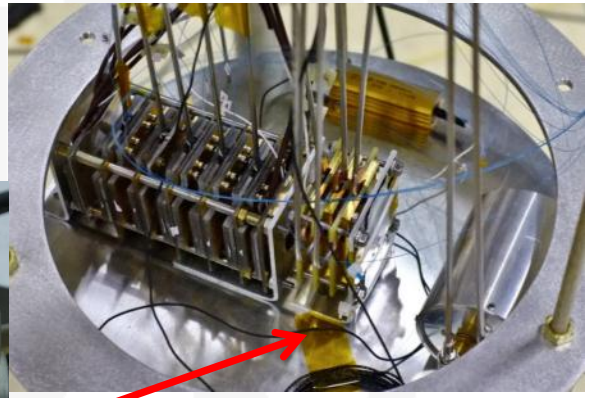
- **Investigating use of diamond, silicon and liquid helium chambers as future BLMs at 1.9 K**

Installation of 2 diamond and 2 silicon detectors on cold mass of Q7R3





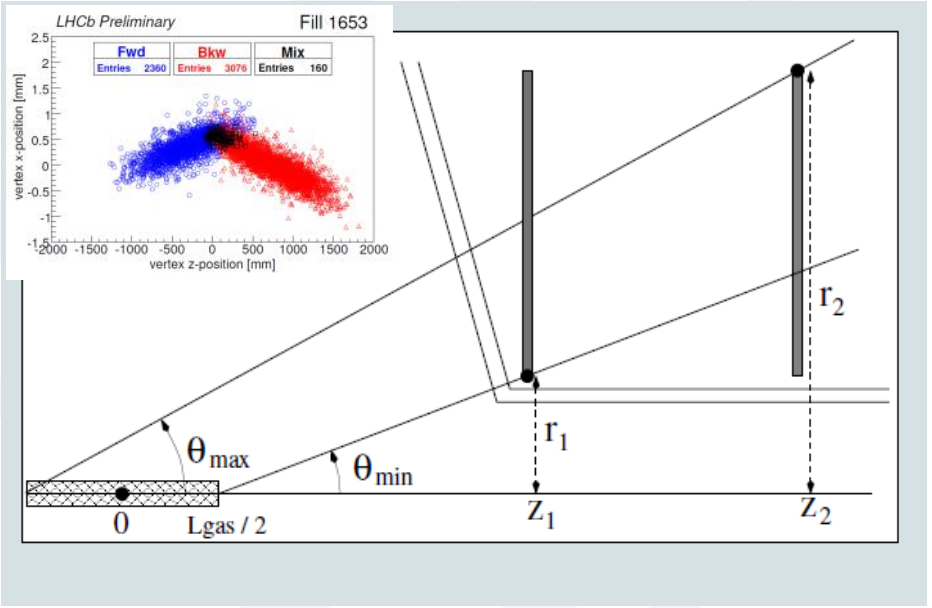
Cold Irradiation in PS T7

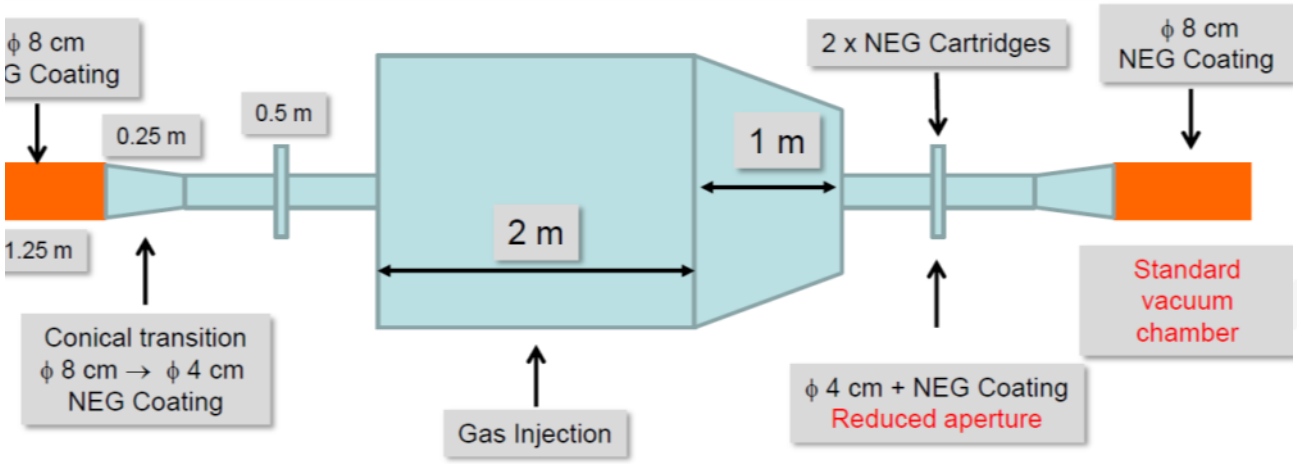


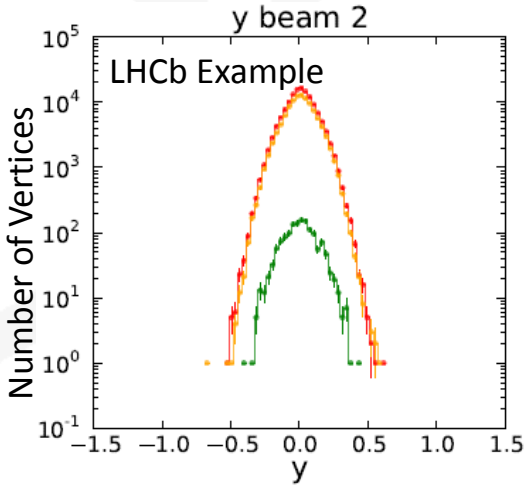
Cryostat at irradiation position

Studies for HL-LHC

- **Beam Gas Vertex Imager for non invasive beam size measurement**
  - Based on experience of LHCb VELO
  - Aims
    - 5 % uncertainty on bunch width in 3 min
    - 5 % uncertainty on beam emittance in 3 min
  - Feasibility study nearly complete
  - Next Steps
    - Approval for installation of prototype after LS1
    - Design of vacuum chamber & RF screen
    - Collaboration with EPFL for detector







Conclusions

- **OP Perspective (J. Wenninger @ BI Day 2012)**
  - The core beam control instruments are doing pretty well, but can profit from quality improvements during LS1
    - We should be careful to preserve the system performance
  - This year the focus has shifted heavily towards bunch by bunch data to diagnose instabilities
    - Further bunch by bunch diagnostics should be developed

- **Main Challenges**
  - Restarting after LS1 with everything back in working order
    - Most of the BLM system dismantled & re-installed
    - Wirescanners, BSRT, BTVs, BCTs, BGI & Schottky systems removed & consolidated
  - Reliable emittance measurements
    - Ideally non-invasive, calibrated and bunch by bunch
    - International workshop to address this planned for April
  - Reliable machine protection systems
    - Maintain BLM system at current or improved performance at higher energy
    - New interlock BPM system
    - Addition of dI/dt system based on beam current measurements