LHC Beam Instrumentation

-

The Experience of Large Scale Beam Instrumentation Design, Manufacture, Test and Installation

CLIC08 Workshop

CERN, 14-17 October 2008

Rhodri Jones
(CERN Beam Instrumentation Group)

Overview

- Introduction to the LHC Instrumentation Systems
- Preparation
  - Specifications
  - Design Issues
- Mechanical Manufacturing
  - Procurement
  - Follow-up
- Collaborations
- Electronic Production & Testing
- Project Management Tools

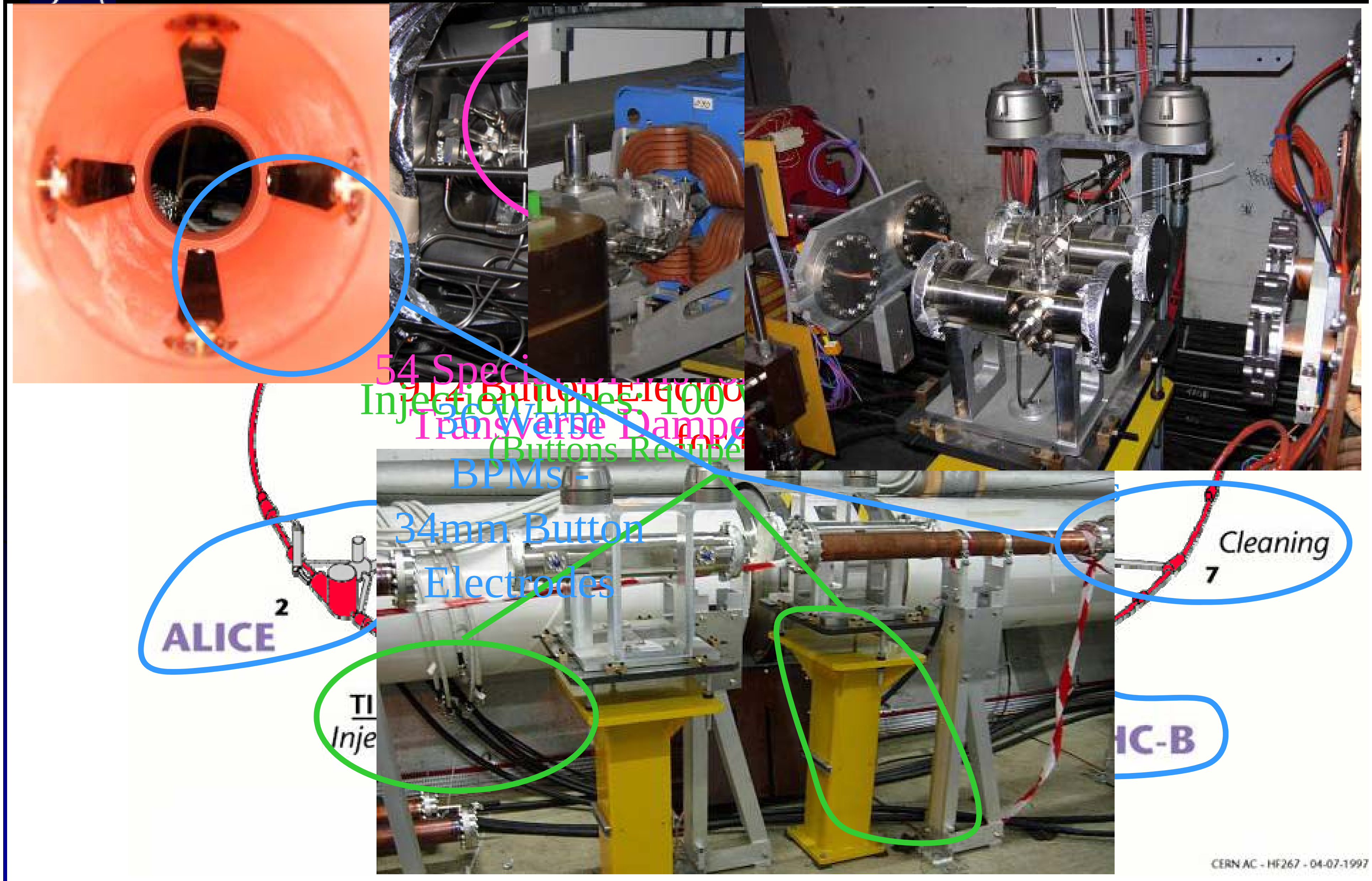
Introduction to LHC Beam Instrumentation

- Two Large Distributed Systems
  - Beam Position System
    - 1136 dual plane BPMs for LHC & Transfer Lines
  - Beam Loss System
    - ~3600 Ionisation chambers
    - ~300 Secondary Emission Monitors
- Many Small Scale Specific Systems
  - Emittance
    - Screens
    - Wire Scanners
    - Synchrotron Light Monitors
    - Ionisation Profile Monitors
  - BCTs
  - Tune Systems
  - Luminosity monitors

Introduction to LHC Beam Instrumentation

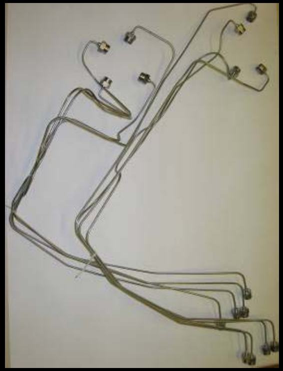
- Budget
  - Total budget of ~40 MCHF
    - Original estimate in 1995 was for 40 MCHF!
    - Many instruments were added & others dropped along the way
  - Main Systems account for 65%
    - BPM – 18.5 MCHF
    - BLM – 7 MCHF
  - Cabling accounts for 28%
    - 5 MCHF : fibre-optic cabling (single contract by TS/EL)
    - 3.7 MCHF : semi-rigid cryogenic coaxial cables (single contract)
    - 2.5 MCHF : cabling (contract by TS/EL)
  - Choice of fibre-optics was instrumental in
    - Reducing the overall cabling cost
    - Enabling most acquisition electronics to be located on the surface
      - No radiation concerns
      - Access possible

LHC Beam Position Monitors

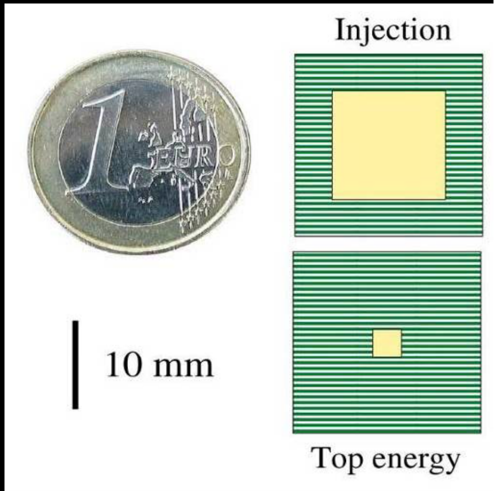


Beam Position System Challenges

- Choice of button electrode pick-up
  - Requires feedthroughs that can operate at ~4K
  - Maximise aperture & signal strength
  - Minimise transverse impedance



- Dynamic Range
  - From 1 bunch of 1×10^{9} charges to 2808 bunches of 1.7×10^{11} charges
    - 114dB dynamic range
- Linearity
  - Better than 1% of half radius, ~130μm for arc BPMs
    - Over whole intensity range
    - Over large fraction of the aperture
- Resolution
  - In the micron range for accurate global orbit control
    - Driven by collimation requirements
    - Over 120 collimator jaws in the LHC



The LHC Beam Loss System

Role of the BLM system:

1. Protect the LHC from damage
2. Dump the beam to avoid magnet quenches
3. Diagnostic tool to improve the performance of the LHC

Name	Type	*Number*	*Area of use*	*Maskable*	*Time resolution*
BLMQI	Ionisation Chamber	~3000	Quadrupole ARC/Straight	yes/no	1 turn
BLMEI BLMES	Ionisation Chamber SEM	~150 ~150	Collimation regions	no	1 turn
BLMEI BLMES	Ionisation Chamber SEM	~400 ~150	Critical aperture limits or positions	no	1 turn
BLMB	ACEM	~10	Primary collimators	yes	bunch-by-bunch

Beam Loss Detectors

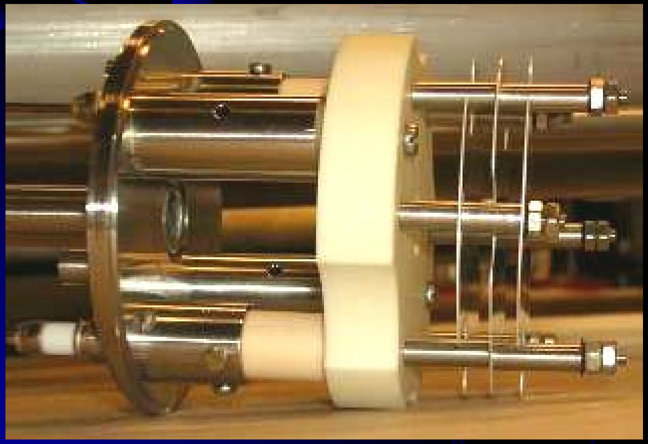
- Design criteria: Signal speed and reliability
- Dynamic range (> 10^9) limited by leakage current through insulator ceramics (lower) and saturation due to space charge (upper)

Ionization chamber:

- N_2 gas filling at 100 mbar over-pressure
- Length 50 cm
- Sensitive volume 1.5 l
- Ion collection time 85 μs

Secondary Emission Monitor (SEM):

- Length 10 cm
- P < 10-7 bar
- ~ 30000 times smaller gain



Both monitors:

- Parallel electrodes (Al or Ti) separated by 0.5 cm
- Low pass filter at the HV input
- Voltage 1.5 kV

Preparation - Specifications

- Traditionally
  - Specifications prepared in ad-hoc fashion
  - Often limited to a few required parameters
    - e.g. global accuracy & resolution
  - Global constraints often determined by very specific end user scenarios

- New approach in BI for the LHC
  - Specification team set-up to collate all information
    - Small team composed of
      - Accelerator physicists
      - General BI representatives
      - Technical expert for each specific instrument
  - Detailed specifications prepared for each instrument
    - All possible end use cases considered
    - Main parameter requirements for each case detailed with reasoning
    - Importance of each requirement judged
    - No specific technology or design pre-defined
  - Document of reference on which design is based
    - Referenced and re-visited with any design changes

Preparation - Specifications

- Documented & approved in EDMS

CERN
CH-1211 Geneva 23
Switzerland

the Large Hadron Collider project

Functional S

ON THE MEASUREM
LOSSES IN TH

Abstr

This functional specification is dedicated to
the LHC main rings. Its use, both for mach
and studies is considered. Taking into accou
quench and damage limits, the functional re

Prepared by :	Check
Bernard Jeanneret Helmut Burkhardt	O. Brü B. Del C. Fis J.J. G J.P. Kou R. Sch J. Wen

Approval gro

BLM's: G.L. Arduini, R. Assmann, L. Bruno, E. Ch
B. Goddard, M. Lamont, R. Jung, R. Lauckner, D
Potter, P. Proudlock, F. Rodriguez Mateos, J.P Ri
Tsesmelis.
MPWG in addition to the above: J.-C. Billy,
Dehavay, R. Denz, E. Gschwendtner, V. Montabon

CERN
CH-1211 Geneva 23
Switzerland

the Large Hadron Collider project

LHC Project Document No.
LHC-BPM-ES-0004 rev 2.0

CERN Div./Group or Supplier/Contractor Document No.
SL/BI

EDMS Document No.
327557

Date: 2002-02-11

Functional Specification

MEASUREMENT OF THE BEAM POSITION IN THE LHC MAIN RINGS

Abstract

This Functional Specification covers the Beam Position Measurement System (BPM System) distributed along the LHC rings. The observables provided by the BPM System are the beam trajectories, the closed orbits, the beam oscillations measured at one azimuth in the machine and optionally the bunch currents. The beam parameters that can be calculated from these observables are identified. The requirements arising from LHC beam dynamics are used to set tolerances on the beam parameters. Given typical LHC operations scenarios, these requirements and tolerances are translated into specifications for the BPM System.

Prepared by :	Checked by :	Approved by:
Jean-Pierre KOUTCHOUK SL/BI jean-pierre.koutchouk@cern.ch	**Oliver Brüning** SL/AP **Claude Fischer** SL/BI **J-Jacques Gras** SL/BI **Rüdiger Schmidt** AC/TCP **Jörg Wenninger** SL/OP	**Hermann Schmickler** SL/BI

Approval group members:

G. Arduini, D. Brandt, E. Chapochnikova, P. Charrue, S. Fartoukh, J.B. Jeanneret, W. Herr, W. Hofle, R. Jung, M. Lamont, R. Lauckner, T. Linnecar, V. Mertens, R. Ostojic, J.P. Potier, P. Proudlock, J.P. Quesnel, K. Potter, F. Ruggiero, K.H. Schindl, H. Schmickler, F. Schmidt, P. Strubin, L. Tavian, T. Taylor, A. Verdier.

LHC Project Document No.
LHC-BPM-ES-0004 rev 2.0

Page 15 of 24

Measurement		P	Range	Accuracy	Scale error	Offset	Non-linearity	Resolution
				peak	*peak*	*peak*	*peak*	*rms*
TR2		*	R2	±2000μm	+	+	+	+
TR3		*	R1	±500μm	+	NR	+	+
TR4		*	R1	±500μm	+	NR	+	+
			R1	±50μm	+	NR	+	+
TR5		*	R1	±1500μm	+	NR	+	+
			R1	±250μm	+	NR	+	+
TR7/TR8		*	± 1 mm ⊂ R1	±400μm	+	NR	+	+
				±50μm	±4%	NR	+	+
TR11			R2		NR	NR	±500μm	50μm
CO2		*	R1	±500μm	+	±250μm (±750μm)	+	+
CO3			± 1 mm ⊂ R1	±20μm	NR	NR	NR	+
CO4			± 1 mm ⊂ R1	±30μm	+	+**	+	+
CO7			R1			±100μm	±200μm over ±4mm	1000μm
CO8			R1	±250μm	+	NR	+	+
CO9	IP		± .1 mm ⊂ R1	±15μm	+	NR	+	+
	other		± 1 mm ⊂ R1	±175μm	+	NR	+	+
CO14			± .1 mm ⊂ R1	±10μm	+	NR	+	5μm

Table 6: Precision required either on the trajectory (TR) or on the closed orbit (CO) according to the measurement goals and conditions.

\+ : component included in the calculation of the accuracy
NR: non-relevant or negligible
**: difference between beam1 and beam2 positions (low-β triplets)

Table 7 summarizes the requirements for the two dynamic sub-ranges relevant to the beam intensity

Precision goal	*Coarse (pilot pulse)*	*High (other beams)*
Scale error	NR	±4%
Roll	NR	±1 mrad
Offset	±750μm	±100μm (relative offset < ±30μm in IR's)
Non-linearity	NR	±200μm over ±4mm, ±500μm over R1
Resolution	200μm rms	50μm rms (traj.), 5μm rms (orbit)

Table 7: Specification for the accuracy of the BPM's

Preparation – Technical Specifications

- Technical Board set-up to follow-up all technical & administrative issues
  - Team composed of project leaders for each individual instrument
    - Responsibility delegated to individuals not regrouped at the GL or SL level
  - Managed evolution of the global BI project from design to installation
    - Emphasis on standardisation
    - Choice of common technologies
    - Global infrastructure management
    - Budget & planning follow-up
    - Forum for distribution of general information
  - Checked the integrity of the technical design versus the requested specifications
    - Peer review of technical choices by board members
    - Feedback to specification team if problems or trade-offs have to be envisaged

Preparation – Design Aspects

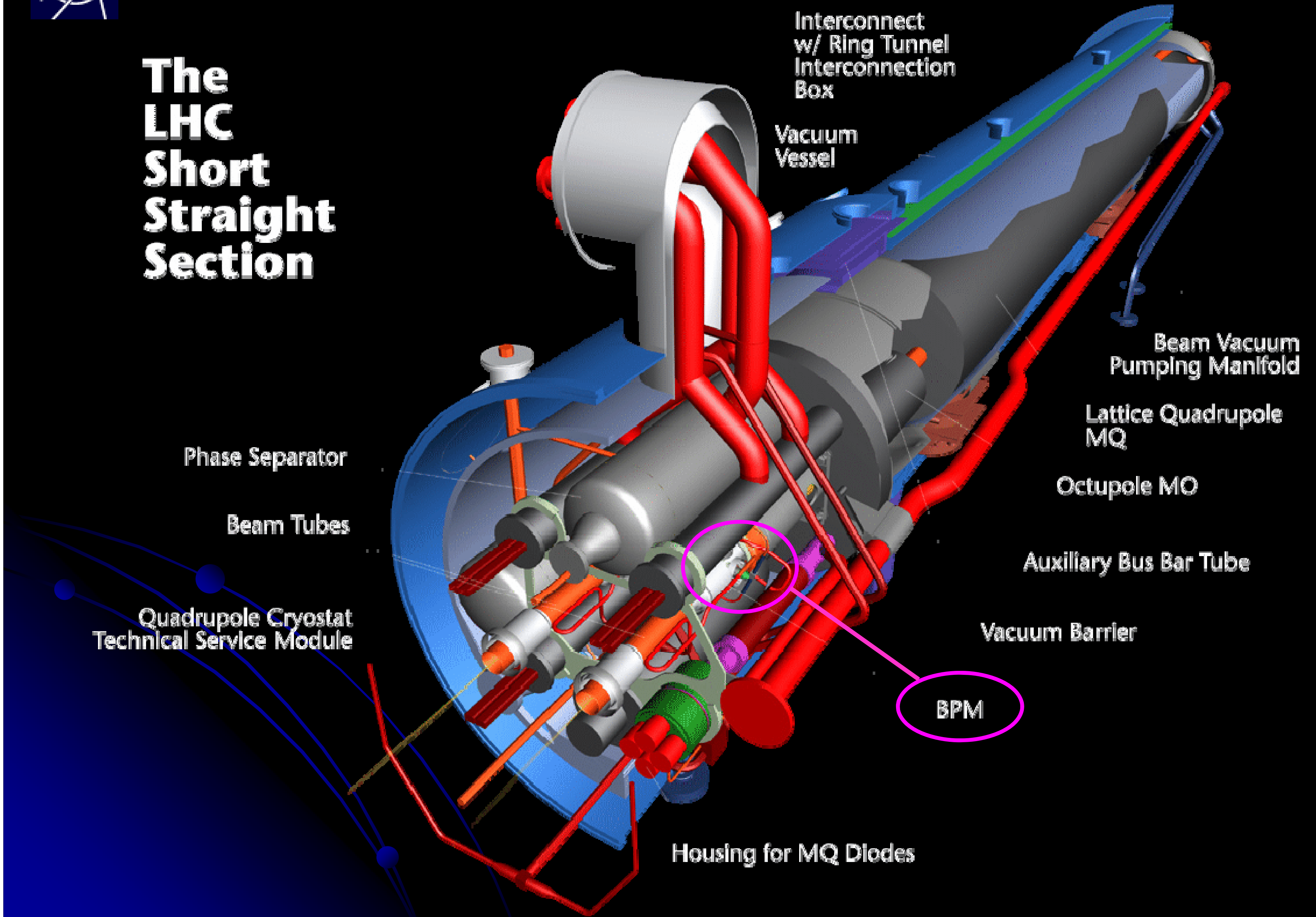
- For large scale distributed systems
  - Simplicity where possible
  - Robustness
  - Standardisation
  - Value for money
  - Final working environment

- The following complicate things
  - Integration
    - Equipment co-habiting with other systems
  - Radiation
  - Multiplicity - small changes can have
    - Large budgetary effects
    - A big influence on planning

Design – A Few Examples

- LHC BPM System
  - Choice of electrode (~4200 required)
    - BPM integrated in cryostat
      - Decision required very early
    - Button
      - Cheaper to produce & test
      - Easy to install
      - Lower signal level (close to limit of detection for pilot bunches)
    - Stripline
      - More signal
      - More complicated to produce, test & install
  - Early work concentrated on ARC monitor
    - Several redesigns required due to layout changes of other systems
    - Once other non-arc regions were considered the number of variants suddenly blossomed

Integration in a Crowded Environment



Design – Standardisation Helps!

- Small scale production of variants posed more problems in terms of delay than that the large series production

BPM	Arc Beam Position Monitor (Arc type+ DS)	864
BPM_A	BPM for Q7R (flange adapted to diam 63 DFBA CWT)	10
BPMR	BPM with Rotated Beam Screen (H-type)	20
BPMRA	BPMR for Q7R	2
BPMYA	Enlarged Aperture BPM	16
BPMYB	Enlarged BPM with Rotated (H-type) B.Screen	20
BPMW	Warm LHC BPM adapted for Elliptic 52x30 / 59x44	16
BPMWA	Enlarged Warm BPM for ADTV/H	8
BPMWB	Enlarged Warm BPM for D2	14
BPMWC	Enlarged Warm BPM for left of Q6R3 and right of Q6L7	4
BPMWE	Enlarged Warm BPM adapted for Elliptic 52x30 / 63	16
BPMWI	80mm Aperture Warm BPM in front of D2 in 2L and 8R	2
BPMWT	80mm Aperture Warm BPM for Roman Pots	12
BPMC	Combined pick-up : 4 Buttons and 4 Strip Lines	14
BPMCA	BPMC for Q7R4	2
BPMD	BPM after MKB Diluter for the Dump lines	2
BPMS	Cryogenic Directional Stripline Coupler (Q2)	8
BPMSA	BPM Aperture 80mm for Interlock System in IR6	8
BPMSB	BPM Aperture 130mm for Interlock System in IR6	4
BPMSE	BPM upstream of TCDS in IR6	2
BPMSW	Warm Directional Stripline Coupler (Q1)	8
BPMSX	Warm Directional Stripline Coupler dehind D1	4
BPMSY	Warm Directional Stripline Coupler dehind DFBX	4

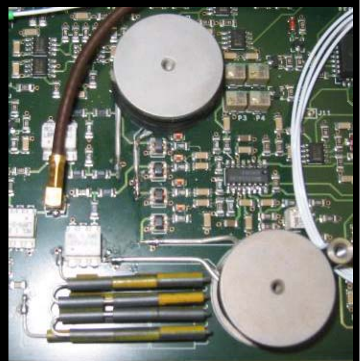
Design – Standardisation Helps!

- Electronic Standardisation
  - Single type of digital electronics acquisition card used for the majority of LHC instruments
    - Disadvantages
      - Needs from many users have to be assimilated
      - Design more complicated
      - Small changes affect many systems
    - Advantages
      - More efficient & cheaper production runs
      - Faults easier to find as many users test a single product
      - Software development much faster

Manufacturing - Procurement

- Best way to qualify firms
  - Include prototype request in Market Survey
  - Can easily eliminate non-conform firms BUT
    - adds at least 6 months to the procurement process
    - Costs can mount up as prototypes are required from all interested companies

- Foresee Long Lead Times for Non Standard Items
  - Button electrodes (4200 units – 1.5MCHF)
    - Market Survey in 1997
    - Prototype qualification during 1998/1999
    - Call for Tender & contract approved in 2000
    - Delivery from 2001 to 2003
    - TOTAL of 5 years from MS to full series reception
  - Delay Lines (7800 custom made units – 0.5MCHF)
    - MS in April 2004
    - Prototypes procured & tested by April 2005
    - Call for tender in June 2005
    - Deliveries from Jan to Dec 2006
    - TOTAL of 2.5 years from MS to full series reception



Manufacturing – Follow-up

- Contract Follow-up
  - Many firms were unable to keep delivery schedules
    - CERN placed many different contacts with the same companies
      - Leads to conflict & ever changing priorities
    - Knock-on effect on other scheduled items
      - Extra cost of maintaining test / assembly teams waiting
- Technical Follow-up
  - Batch by batch verification is essential
    - Quality invariably varies for long production runs
    - UHV cleaning in particular found to be critical
    - Radiation tested components have to come from the same production batch if re-testing is to be avoided

Collaborations – LHC BI Experience

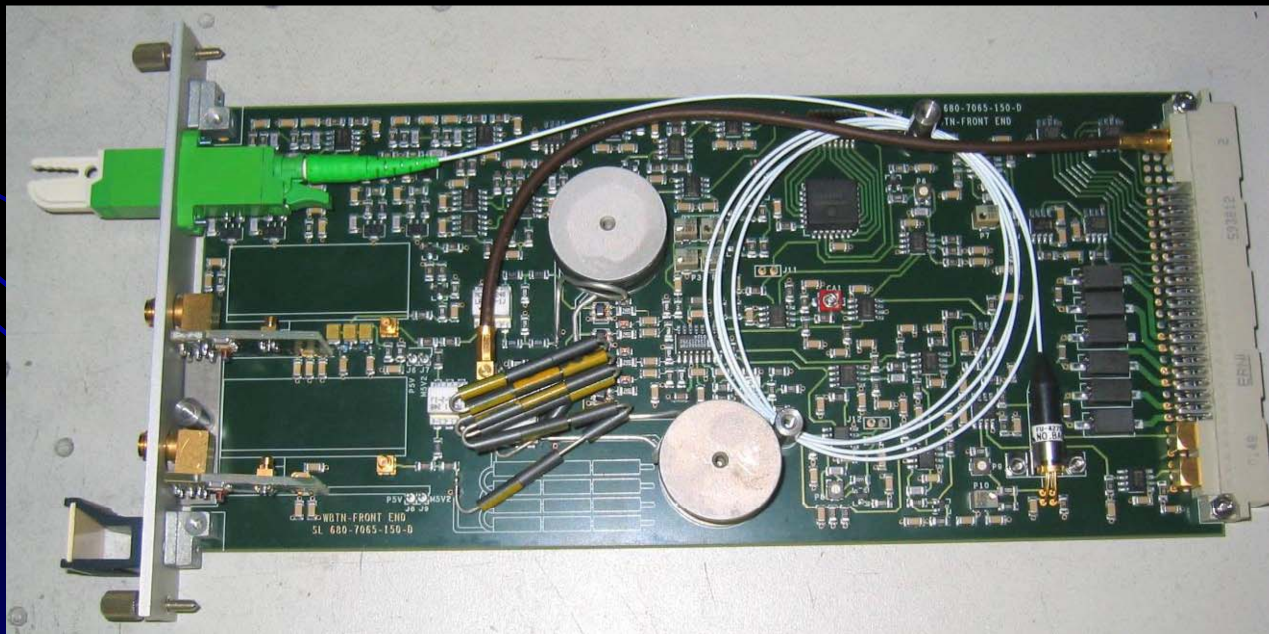
- Russian Collaboration with IHEP for LHC BLMs
  - Collaboration agreement fixed in ~10 contracts
    - All changes documented via new contracts or amendments
  - 4250 Ionisation Chambers & 380 SEM assembled & tested at IHEP
    - CERN designed, produced & tested initial prototypes
    - CERN ordered all components
    - CERN arranged packaging & transport to IHEP
      - Over 1.4 million parts transported
  - All LHC BLMs tested & installed by IHEP team at CERN

Collaborations – LHC BI Experience

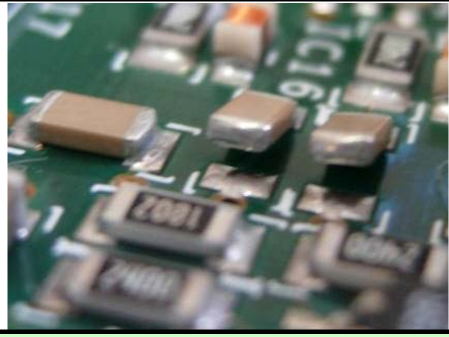
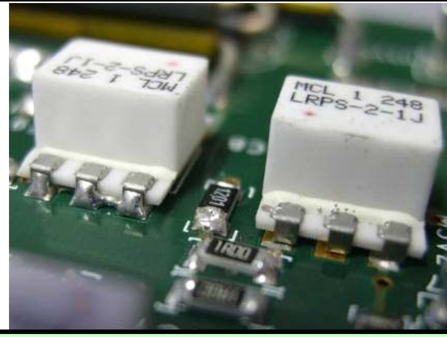
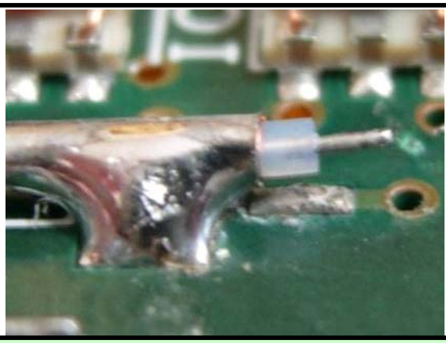
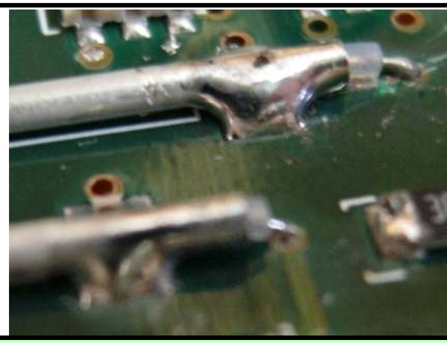
- Essentials for good large scale collaboration
  - Well defined specifications
  - Close follow-up during all project phases
    - Regular visits to collaboration partners
  - One collaboration member full time at CERN
    - Capable of overcoming language barrier & sorting out formalities
    - Responsible for organisation of shipping, testing & reception
  - Provision for continued support
    - BLM test stand at Protvino will be maintained operational for another 2 years to allow additional units to be produced & tested if required

Electronic Production & Testing

- Production & Tests
  - Duration for development largely underestimated
    - True for both BPM & BLM systems by up to 50%
  - Components quickly become obsolete over design period
    - Foresee layout for compatible components where possible
    - Take decision on series components early
  - Production losses for electronics far greater than for mechanical components

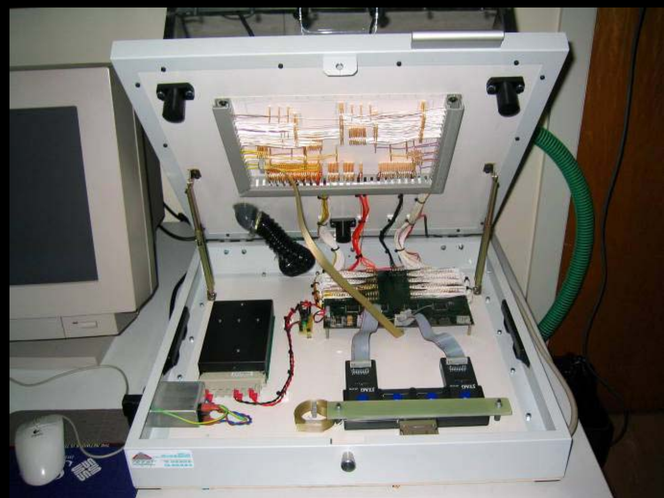


Electronic Production & Testing

		
Picture #13 CARD #209 755 046	Picture #14 CARD #209 758 747	Picture #15 CARD #209 758 747
A huge tin spot causing a short-circuit between several components.	Two resistors have been soldered just on 1 side!	The splitter on the left has a short-circuit between pins #2 and #3. The splitter on the right has 2 out of 3 pins not soldered.
		
Picture #16 CARD #209 758 621	Picture #17 CARD #209 762 075	Picture #18 CARD #209 755 158
The outer conductor is soldered too far and is short-circuited to the inner pad. The inner conductor is floating.	On the board named '7065-160-B' this component have been teared off!	Both ends of L4 component are not correctly soldered.

Electronic Production & Testing

- Production & Tests
  - Automated testing of electronics essential
    - Needle test bench set up with external company for testing of analogue components of completed BPM cards
      - Over 2 million components tested
        - Over 400 components per card for 5000 cards
      - Detected bad solder joints & wrongly mounted or incorrect components
    - JTAG test bench set-up at CERN & provided to manufacturer for quality assurance of digital circuits
      - Allows manufacturer to respond rapidly to production errors
      - Minimises loss of components due to poor procedures
      - Provides check of internal functioning of FPGAs, memories etc
    - Maximum effectiveness ⇒ integration into design at early stage



Electronic Production & Testing

- Radiation Tolerance
  - Adds significant overhead to any design
    - Typically 50% more iterations required
  - Test set–up & beam time needed
    - Adds to the length of the design phase
  - All components need to be tested
    - Reliability only as good as the weakest link
    - Batch number of components must be traced
      - Different production runs of the same components can have very different tolerances to radiation
  - Look to HEP experiments for tested components
    - Gigabit optical link Opto-Hybrid (GOH) produced & tested by CMS used by BLM system
- Traceability
  - Individual serial number chips found to be very useful
    - Can be read-out remotely for complete installation picture
    - Allows individual calibration curves to be selected for specific cards
  - All equipment catalogued & fitted with a bar code
    - A requirement for tracing all equipment leaving a radiation zone

Project Management Tools

- EDMS
  - Used extensively to document all specifications
- MTF
  - Essential for tracking of inventories and maintaining production and installation data
- EVM & CET
  - Differing experiences
    - Depends a lot on how it is initially set-up
      - Work units too coarse gives no useful information
      - Work units too detailed leads to difficult maintenance
    - For LHC no direct link between orders recorded in CET & specific EVM work-units
      - Only global tracking of budget situation was possible
      - Difficult to pinpoint which work units were over budget or behind schedule

Summary

- Large scale projects come along very rarely at CERN
  - SPS ⇒ LEP 13 years
  - LEP ⇒ LHC 19 years
  - LHC ⇒ CLIC ?
- Experience is unfortunately lost along the way
  - Few of the LEP BI construction team saw beam in LHC
  - Similar mistakes were probably made again
    - Hindsight is a wonderful thing
    - However many important lessons were learnt
      - e.g. BPM system made to auto-trigger without external timing!
- Main Points Retained from LHC Experience
  - Clear functional specifications required very early
  - Clear project management structure essential from the outset
  - R&D, design & testing times largely underestimated
    - Especially true when designing for radiation environments
  - Standardisation across domains improves effectiveness as a whole
  - Quality assurance procedures important for large scale production
  - Host laboratory personnel time to be foreseen for collaborations