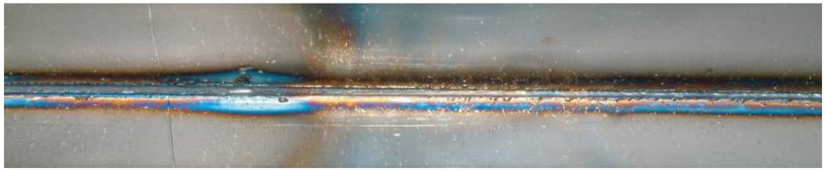
PLANS FOR EXPERIMENT PROTECTION AT LHC

- Introduction:
  - Lessons from the past
  - The **L**arge **H**adron **C**ollider
- LHC protection strategy
  - Beam interlock system
- Failure scenarios
  - Risks for the Expts
- LHC Experiment protection
  - Beam conditions monitors, etc.
- Detectors damage threshold
  - What do we know for silicon ?
- Conclusion and outlook



- Note: I won't address heavy ion beams

Special thanks to:

- Antonello di Mauro, Siegfried Wenig, Richard Hall-Wilton, Richard Jacobsson, Jorg Wenninger, Rudiger Schmidt, Rob Appleby, Daniela Macina, etc.

It happens ...

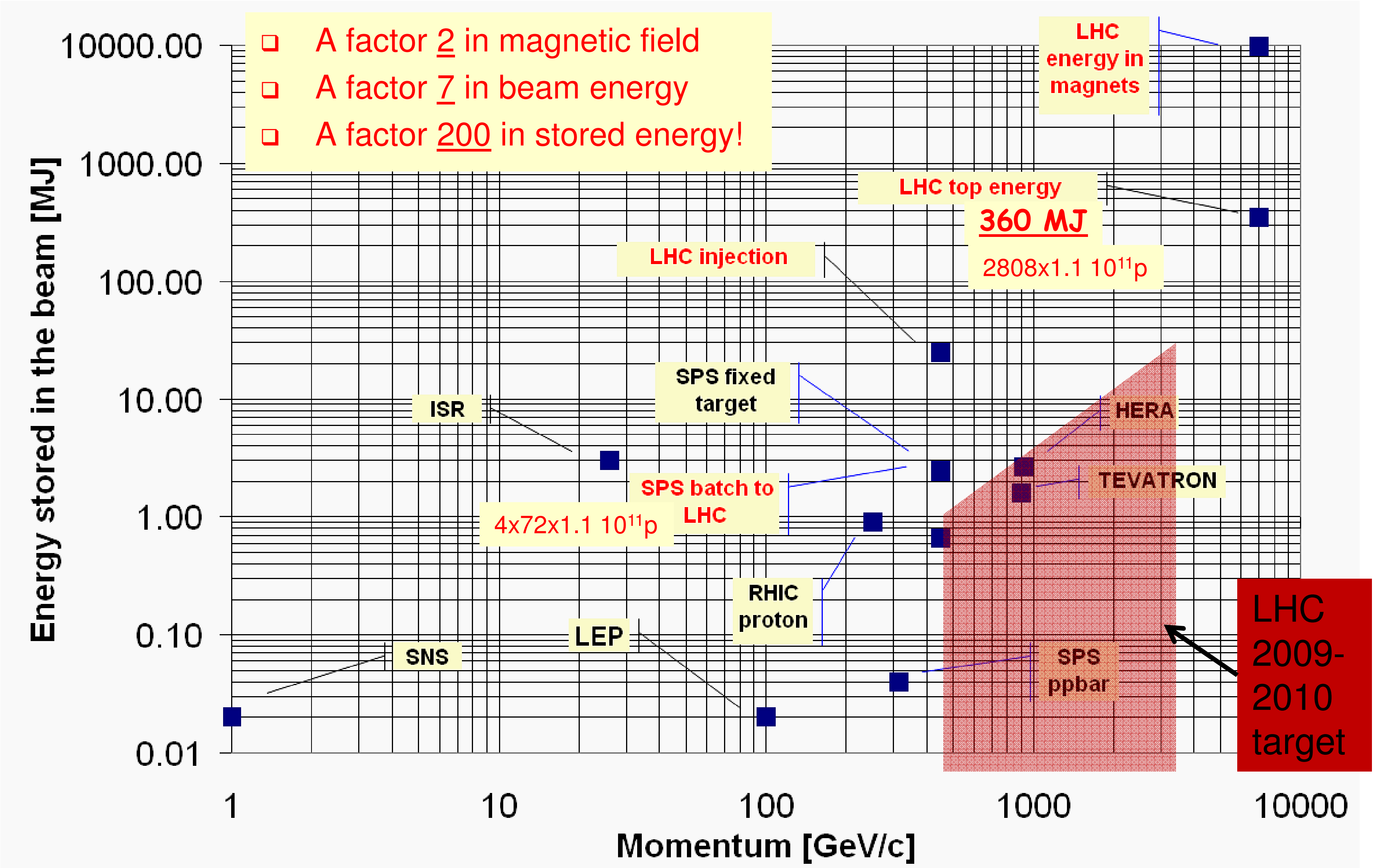
- SppS:
  - 198x: electrostatic separators adjusted for 315 GeV, instead of injection energy of 26 GeV => UA2 gets beam injected repeatedly into detector, no fast feedback from the Expt
- LEP:
  - 1991: Quad polarity switched... consecutive splashes into L3, damage to BGO lumimonitor (later, in 1992, further failures with damage to endcap calorimeter...)
  - 1993: Quad failure ... Aleph loses fraction of VDET due to shorting of AC capacitor chips
- RHIC:
  - 2000: Phobos: several missed aborts, lose 1-2% of their Si pad detector channels (other RHIC experiments affected as well).
- HERA:
  - 2002: damage caused to H1 Si pad and strip detectors (BST) and their electronics.
- Tevatron:
  - 2002: asynchronous dump, CDF loses six ladders of vertex detector due to chip failure

Lessons:

See J. Spalding in TeV4LHC April 2005

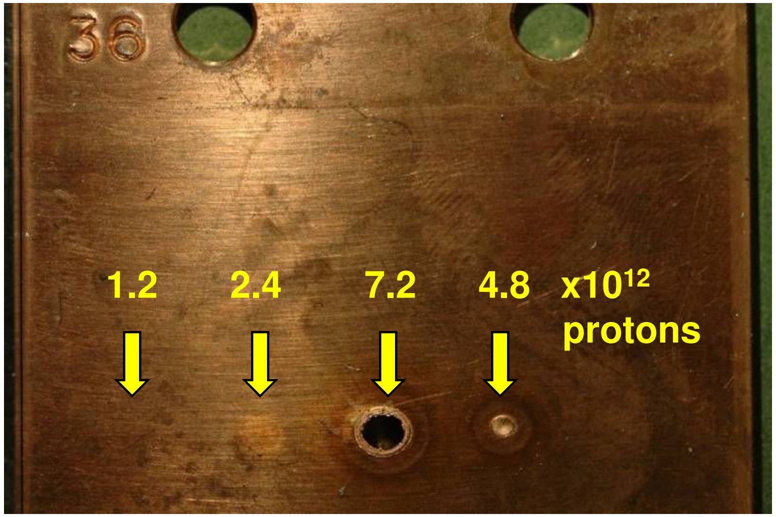
- it does happen!
- better have a protection system in the experiment to trigger beam abort
- better have *some sort of monitor* during injection (fast feed back to machine!)

Stored Energy of the LHC



Damage Potential of LHC Beams

- LHC colleagues performed a controlled experiment with 450 GeV beam shot into a stack target to benchmark simulations.
- Copper:
  - melting point reached at ≈ 2.4×10^{12} p
  - clear damage at ≈ 4.8×10^{12} p
- Good agreement with simulation



See V. Kain et al., *Material damage test with 450 GeV LHC-type beam,* Proc. of 2005 Part. Acc. Conf., Knoxville, Tennessee, and PhD Thesis by V. Kain, CERN-Thesis-2005-047

Definition for the LHC of a "safe" beam limit (setup beam, see later):

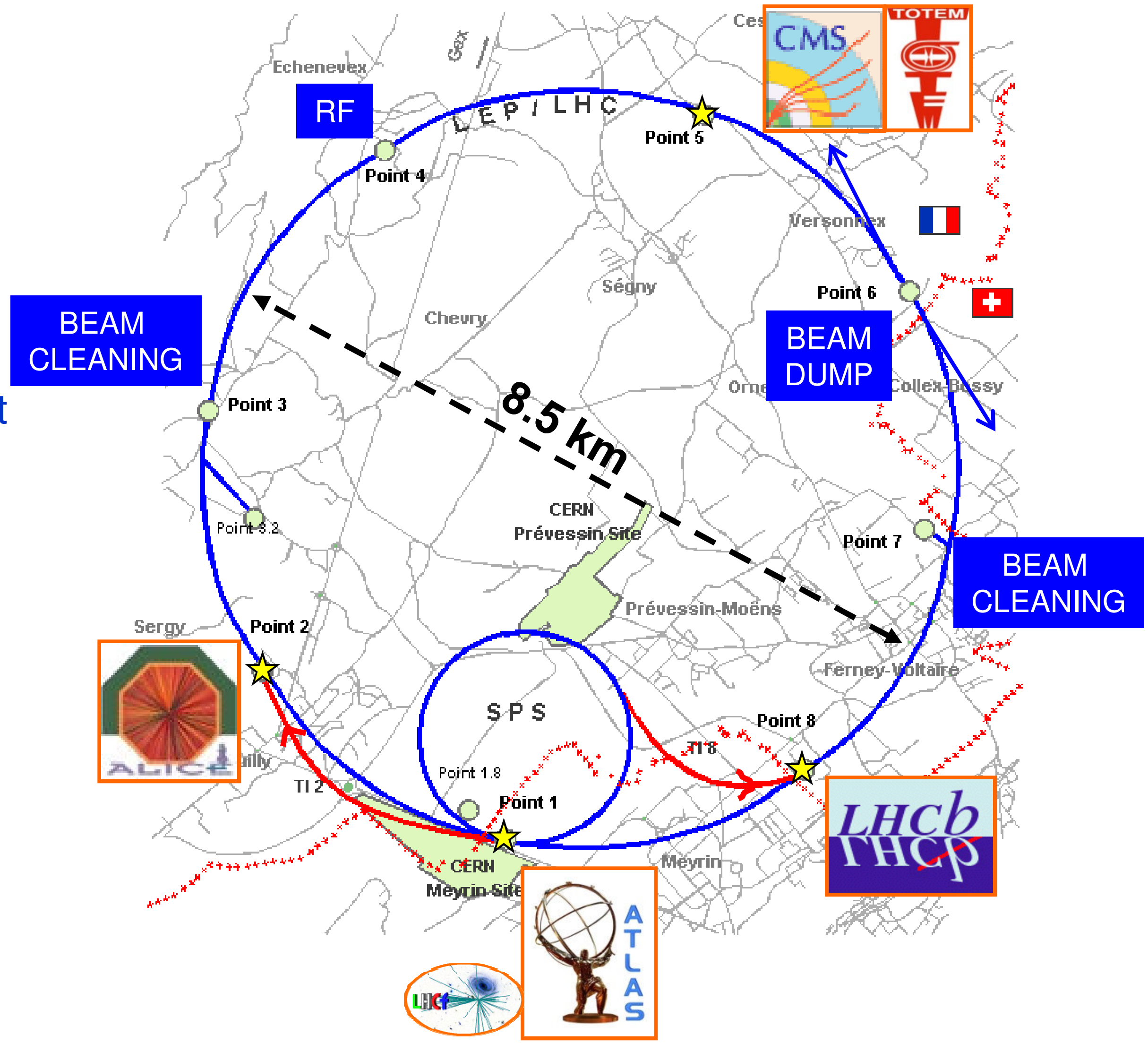
10^{12} protons at 450 GeV ⇨ about 3% of a full SPS batch

10^{10} protons at 7 TeV (scaled from 450 GeV)

Note: tests as described above do not correspond to the most typical impact of beam, there is a safety margin on the 450 GeV "safe beam" for typical accelerator equipment. But what about experiments/detectors ?

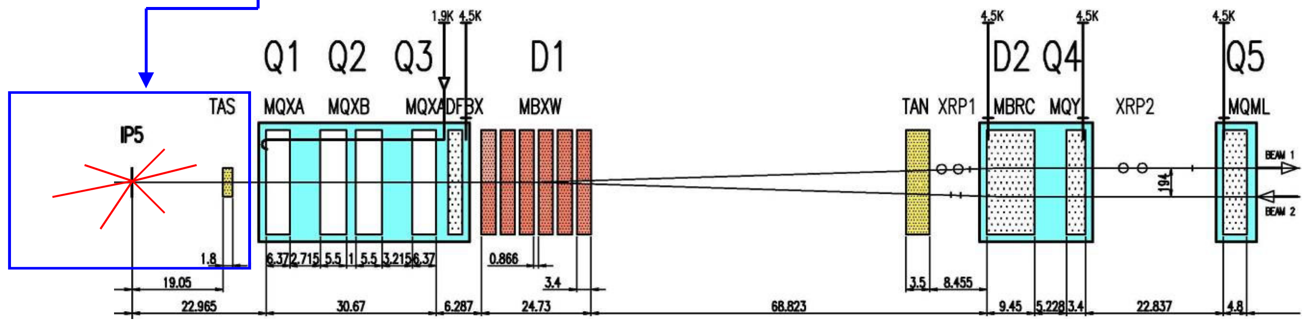
The LHC and the Experiments

- CMS/Totem:
  - near dump
  - roman pots
- LHCb and Alice:
  - just near injection point
  - experimental dipole magnets + correctors
  - no TAS absorbers
  - LHCb VELO, similar to "roman pots"
- ATLAS/LHCf:
  - a cool place to be...



Typical Insertion Region (Region Around Experiment)

- Here is CMS (same for ATLAS), symmetric at IP:



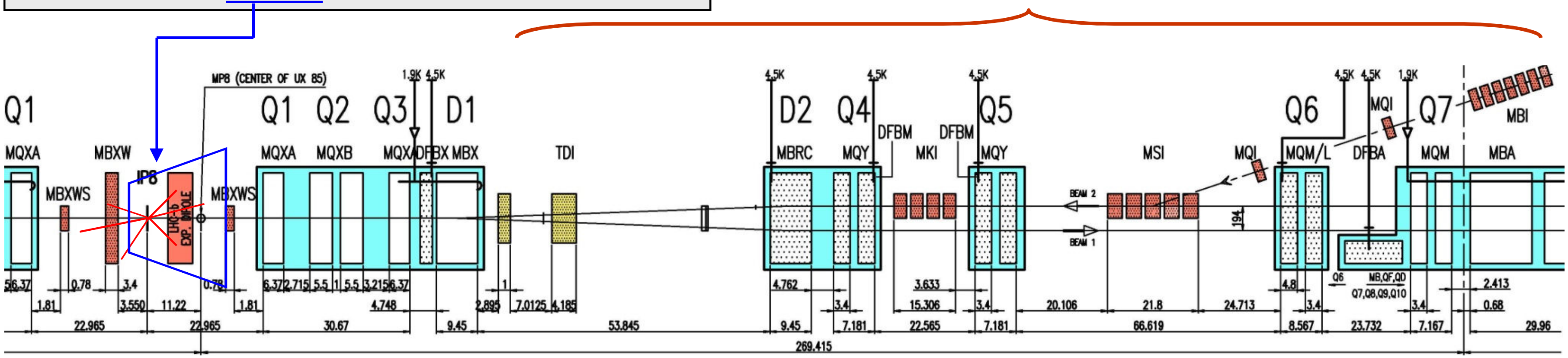
- cryomagnet
- warm magnet
- absorber/ collimator

TAS = absorber to protect triplet from IP primaries

NB: Q1-3 contain also some corrector dipoles

- Here is LHCb (similar for ALICE):

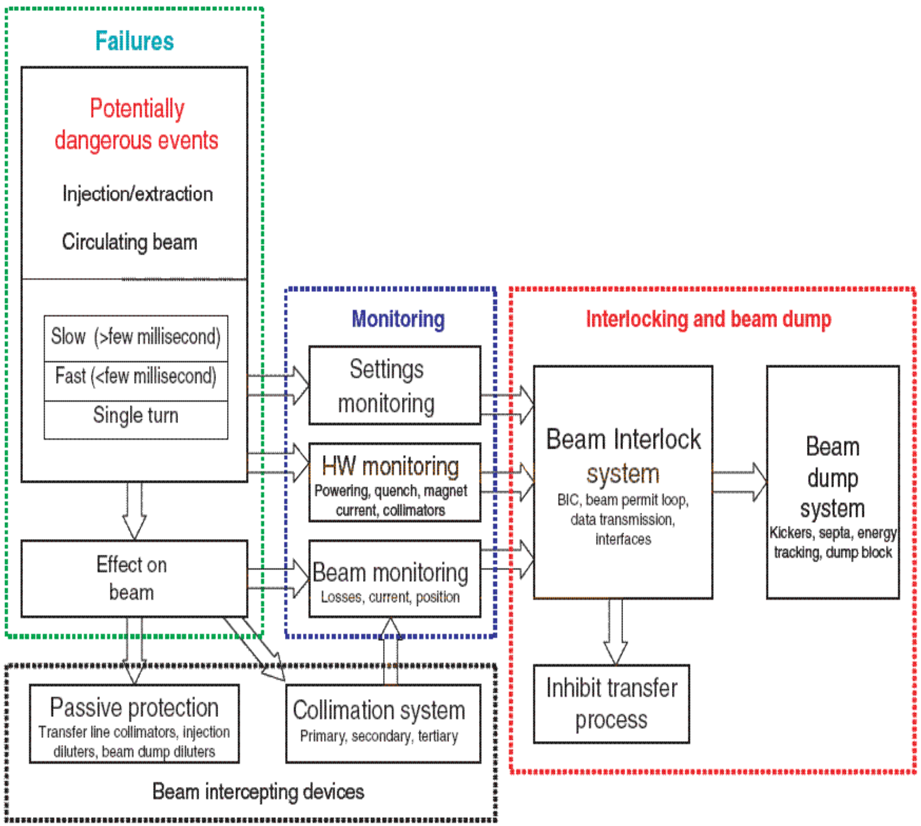
injection from SPS !

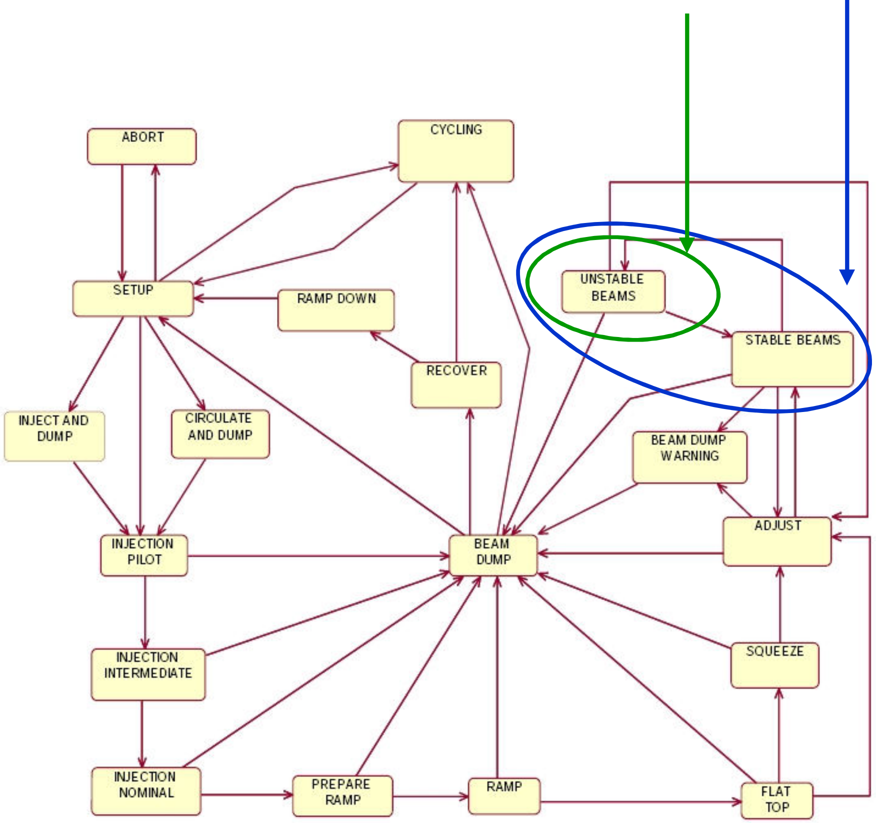


- No TAS
- presence of dipole magnet + correctors MBXW...

Beam modes:

- Outside these two beam modes, movable detectors **must** be OUT
- In this state, they *should* move OUT (but don't dump if not...)

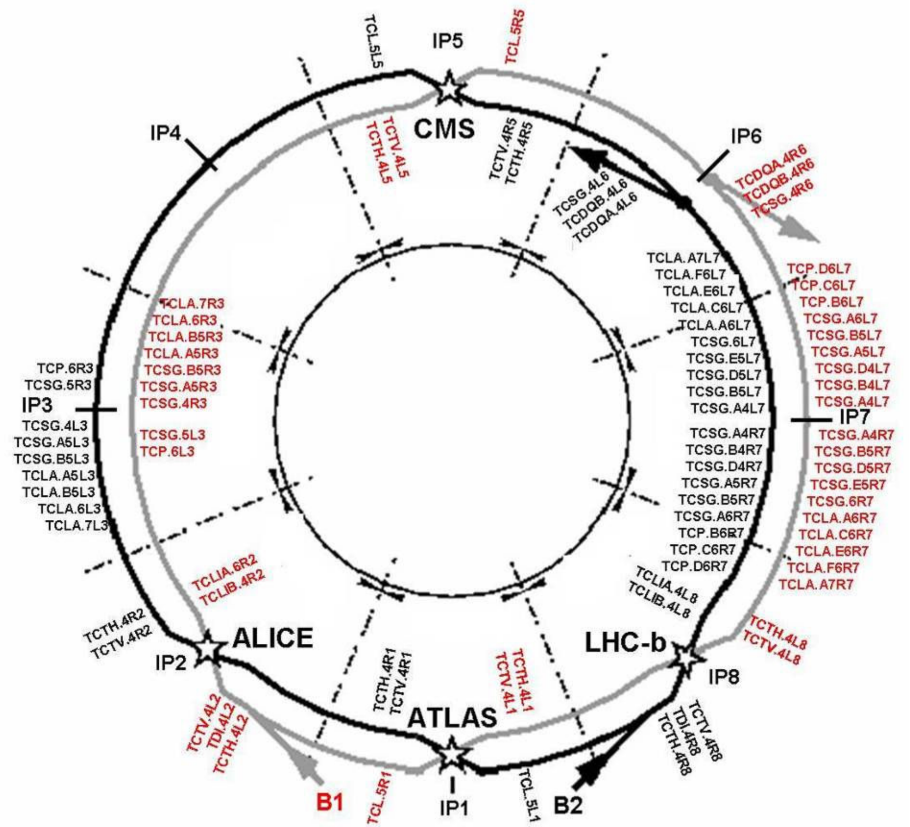




LHC "Passive" Machine Protection : Collimators / Absorbers

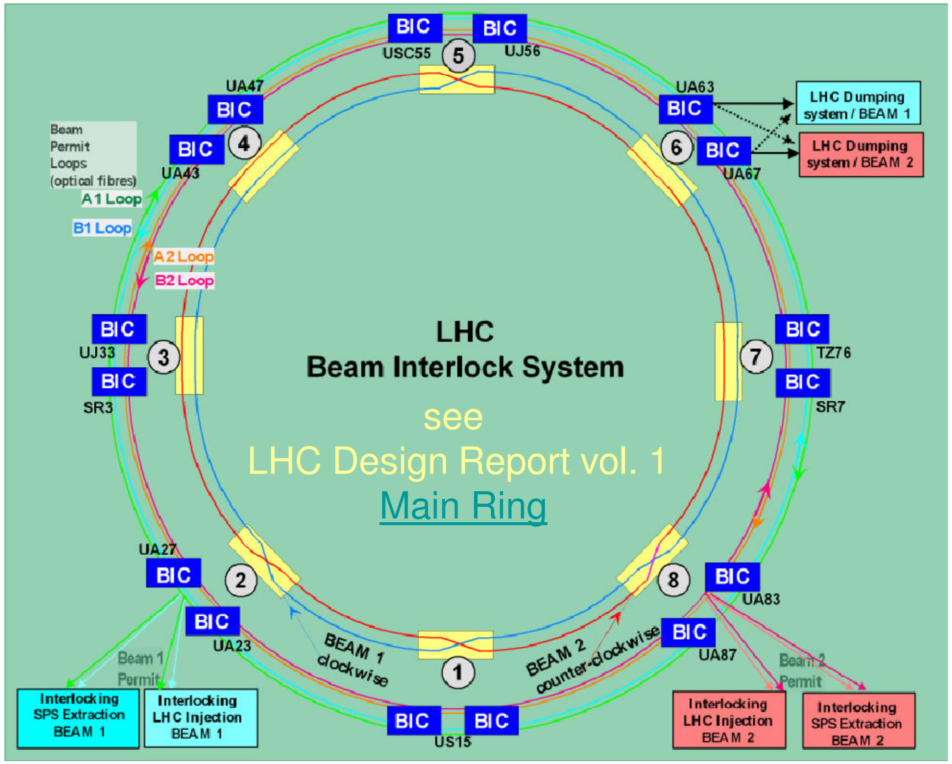
- Almost entirely cryogenic ring
  - more than 20 km of superconducting magnets
- Quench limits impose **collimation**!
  - ⇒ Lost protons must be intercepted with high efficiency before **quench**
    - instantaneous loss in a magnet (~10 m) required < 10^{10} p at 450 GeV, 10^{6-7} at 7 TeV
  - Unlike HERA, TEVATRON, RHIC... the **LHC cannot be operated without collimators** (except at injection with low intensity).
  - At the LHC the collimators must define the aperture (primary + secondary) which has an important impact for Machine Protection: **for most multi-turn failures the beam will hit collimators first !**
- Monitoring:
  - BLM's on collimators, on magnets
  - BPM's, etc.
  - Try avoiding quenches by setting dump thresholds lower than quench values

Energy GeV	Loss rate (10 h lifetime, 3×10^{14} p)	Quench limit (slow losses)
450	8.3×10^{9} p s^{-1}	7×10^{8} p s^{-1} m^{-1}
7000		8×10^{6} p s^{-1} m^{-1}



LHC "Active" Machine Protection : Beam Interlocks

- General strategy:
  - inject probe bunch ($5x10^9$ p)
  - if OK (circulating), inject higher intensity batch
  - on dump trigger => extract beam in < 0.3 ms (1 turn ≅ 0.09 ms)
- Abort gap:
  - continuously monitored, at least 3 us long



- Beam Interlock System
  - Two redundant BeamPermit loops per beam around the ring
  - Beam Interlock Controller:
    - Makes AND of several UserPermit signals
    - More than 3000 LHC user devices of the BICs (BLM's, BPM's, etc.)
    - If UserPermit signal is false, then BeamPermit is false => dump and block injection
- BeamPresence
  - one flag per LHC ring
  - at least 5 uA in the ring (fast AC BCT)
- ProbeBeam
  - True if SPS intensity < limit
    - limit = C x 10^{11} protons (C≤1)
  - if BeamPresence and ProbeBeam are false, then cannot inject into LHC
- SetUpBeam
  - based on LHC current, energy dependent:
    - True if < 10^{12} ($5x10^{10}$) protons at 0.45 (7) TeV.
    - If True, it allows masking some BIS inputs

<u>For the experiments, these are the worries:</u>

- Injection failures:
  - incomplete or unsynchronized kicker fire => mostly Alice & LHCb
  - wrong magnet settings in transfer line => mostly Alice & LHCb
  - wrong magnet settings in the LHC => everybody

- Circulating beam failures: ⇒ mostly caught by collimators
  - magnet failure / mishap => everybody
  - RF failure => everybody
  - collimator failure / mishap => everybody

  } Expect Expts to be protected by "early" cryomagnet quench protection

- Extraction failures:
  - underkick, unsynchronized beam dump => mostly CMS

We'll see some specific examples later

What kind of particle rates ?

- In terms of estimating particle rates to a detector, the only simple (though quite unlikely) LHC failure scenario is
  - Suppose a batch is injected with wrong magnet settings near an experiment (remember: a probe beam has < 10^{11} protons)
  - The batch is shot straight into the detector without traversing much material (little showering, less than x10 multiplication), beam size σ ~ 0.3 mm
  - Potentially, of order **~10^{13} p/cm^2** (in <1ns) depending on the maximum value for the ProbeBeam and on the local shower multiplication
  - Very high flux density, but very local (could be quite catastrophic if readout chips happen to be on the trajectory)
- Other possible failures (with grazing, showering,...) require detailed MC simulations
  - Work in progress
  - A few examples in the next slides

Example 1: TAS Absorber Grazing Case in ATLAS

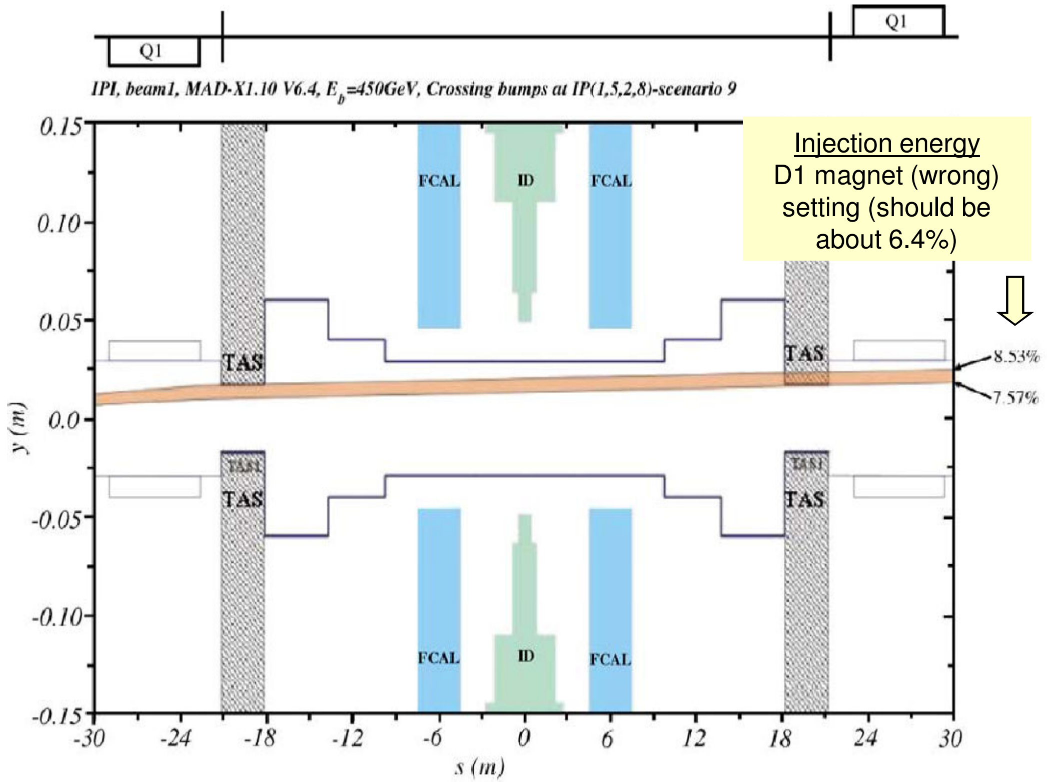
ATLAS beam failures simulation:

See Dariusz Bocian, LHC Project Note 335

- Studied wrong settings of MCBX, D1 and D2: due to presence of TAS absorber, pilot beam can never hit directly the Inner Detector.
- Thus, most dangerous case is when wrong magnet setting is such that beam scrapes first TAS and hits second TAS.
- If a $5x10^9$ bunch is lost in ATLAS due to a single wrongly set magnet, the estimated radiation dose delivered to the b-layer is estimated to be

  < $5x10^{-3}$ Gy or

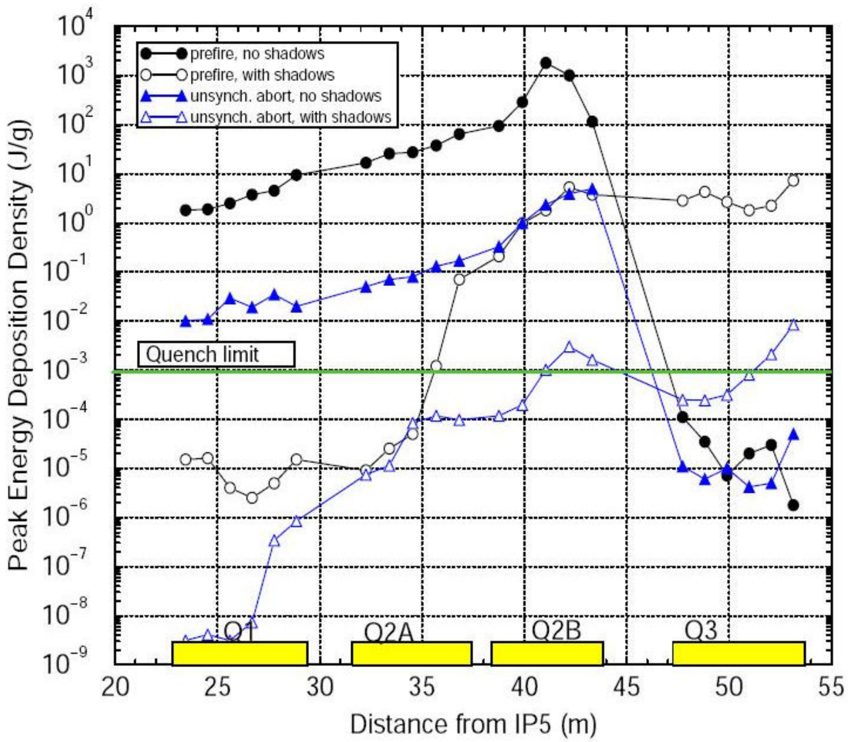
  (Note: in terms of rate this is about 10^7 more than during a nominal bunch crossing, i.e. ~ 10^6 MIP/cm^2)

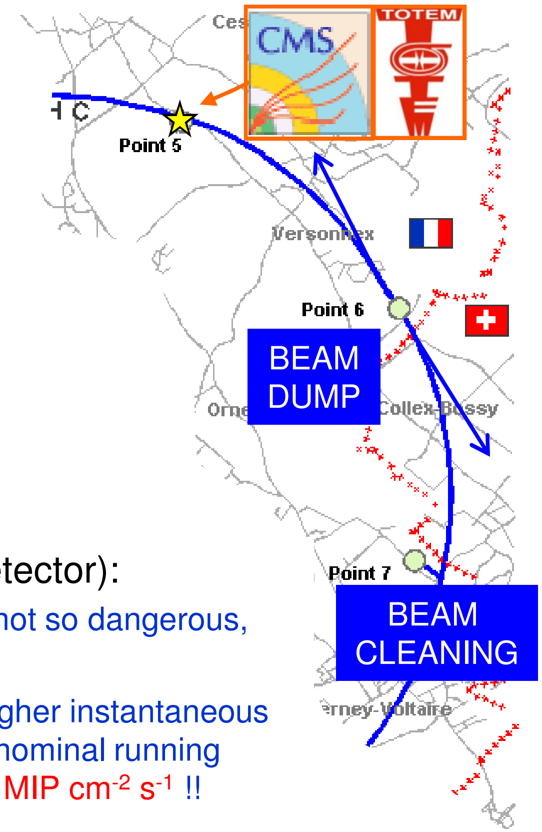


- *Specially searched for* two-magnet failures could deposit much more, but such failures are considered much less likely

Example 2: Extraction Failure and Effect on IP5

- Simulations for effect on CMS / IP5 due to unsynchronized abort and kicker prefire, see Drozhdin, Mokhov, Huhtinen, *1999 Particle Acc. Conference*
  - kicker prefire: one kicker module fires alone; should not happen (system designed such that a firing module fires the other modules)
  - unsynchronized abort: quite likely to happen; kicker rise time ~3us => ~120 bunches swept





- Results (for Pixel detector):
  - Integrated doses not so dangerous,
  - but rates are!
  - Up to 10^8 times higher instantaneous rates than during nominal running $\Rightarrow$ up to 10^8 x 10^6 MIP cm^{-2} s^{-1} !!

- These results led to addition of movable and fixed collimators at IP6 (TCDQ, TCDS) to intercept the bulk of the mis-kicked beam

Example 3: ALICE Beam Failures Simulation Studies

Effect of kicker failures during injection

- See B. Pastirčák et al., *Radiation from Misinjected Beam to LHC,* ALICE Internal Note 2001-03

Failure scenarios:

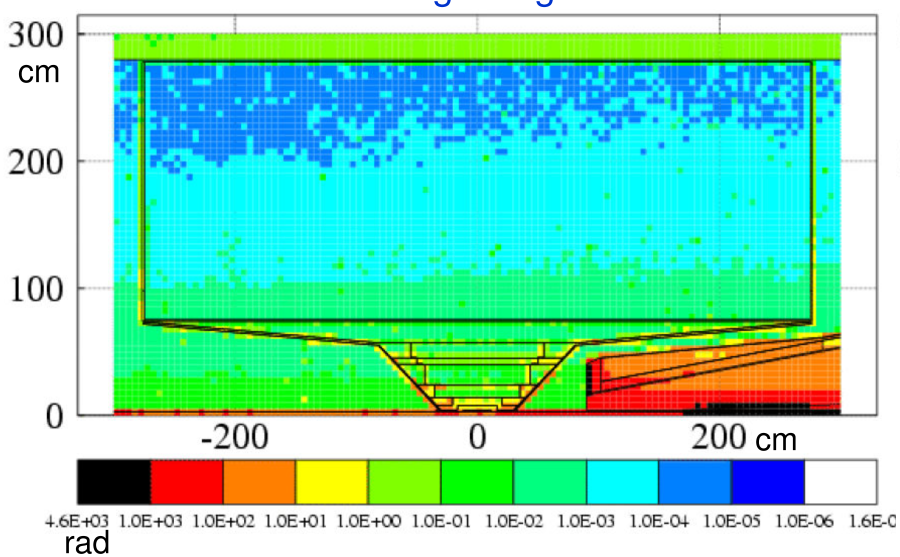
- grazing: full batch (4.1×10^{13} p) missing the TDI beam stopper, worst case but very unlikely
- sweep: prefire of kicker modules, ≈ 20 bunches escape TDI, expected several times/year (?) → main contribution

Results:

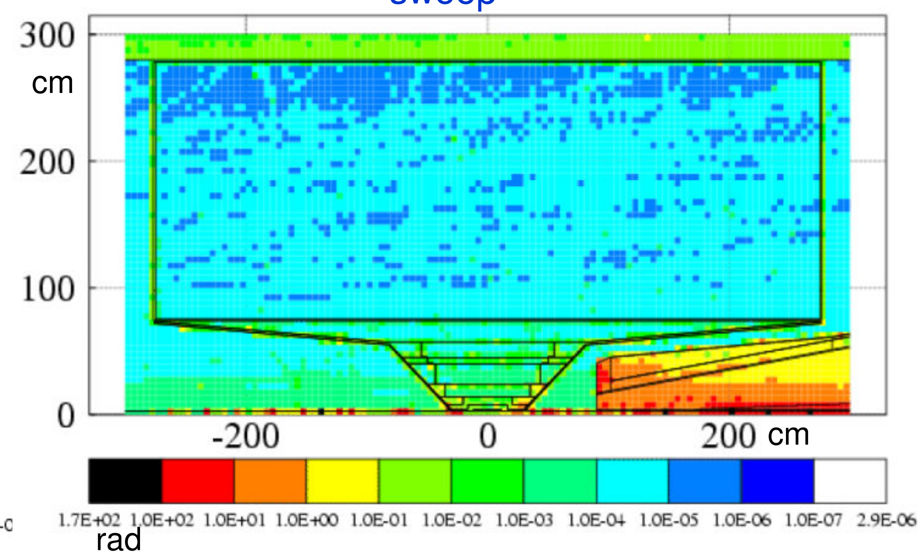
- Accumulated dose during 10 years due to "expected" misinjections is (for Si Pixel Detector and electronics) about 1 krad (1% of total dose from primary collisions)
- Energy deposition maps per accident in Alice detector (vertical section):

Here, for Si, inner tracker: 100 rad ~ 10^{9-10} MIP/cm^2

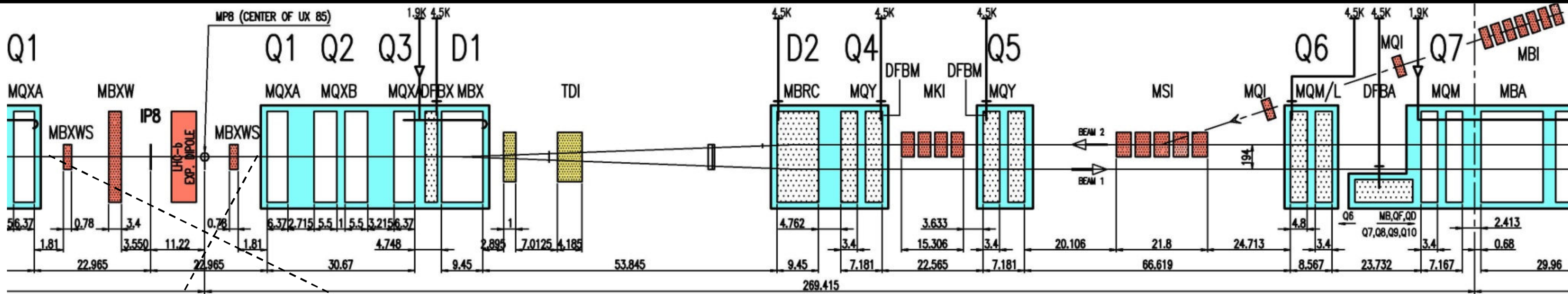
"grazing"

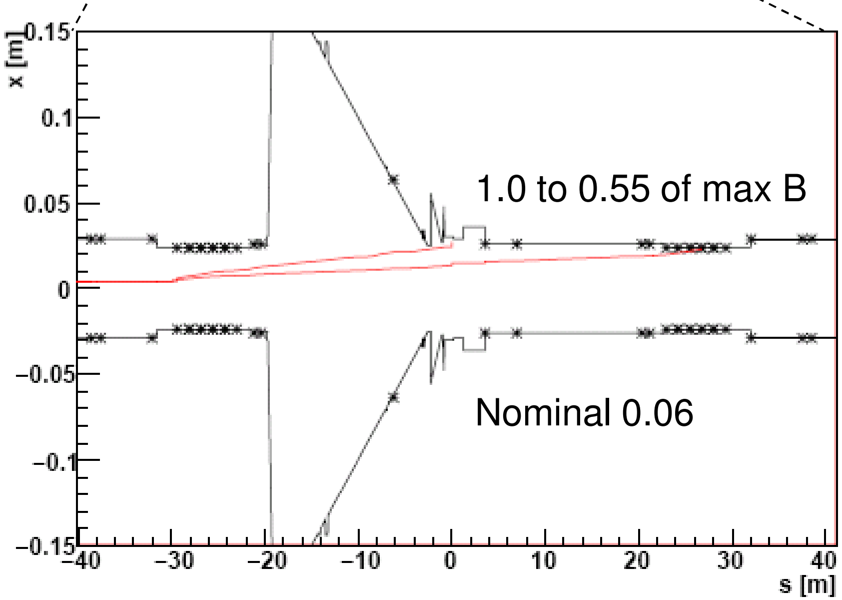


"sweep"



Example 4: Wrong Compensator Setting at Injection (here beam2 IP8)

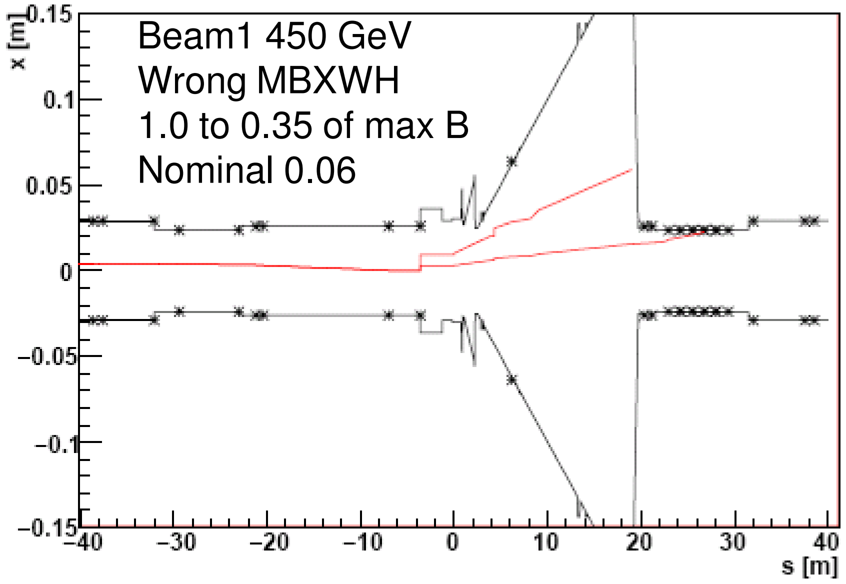


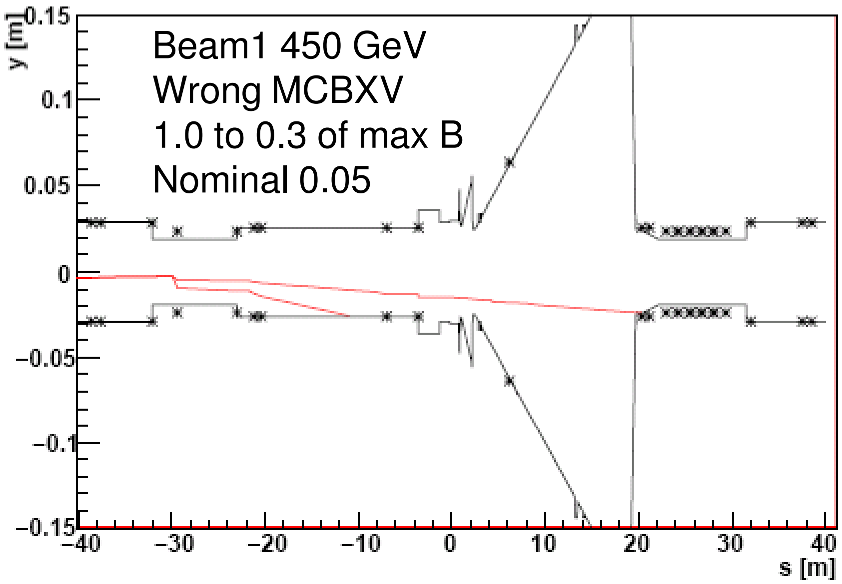


- Beam2, 450 GeV
- Wrong setting of MBXWH (horizontal compensator)
- Beam can hit LHCb detector

LHC Project Report 1174 “LHCb Injected Beam Accidents” R.B. Appleby
LHC Project Report 1175 “ALICE Injected Beam Accidents” R.B. Appleby

Example 5: wrong compensator or corrector settings at injection (here beam1 IP8)



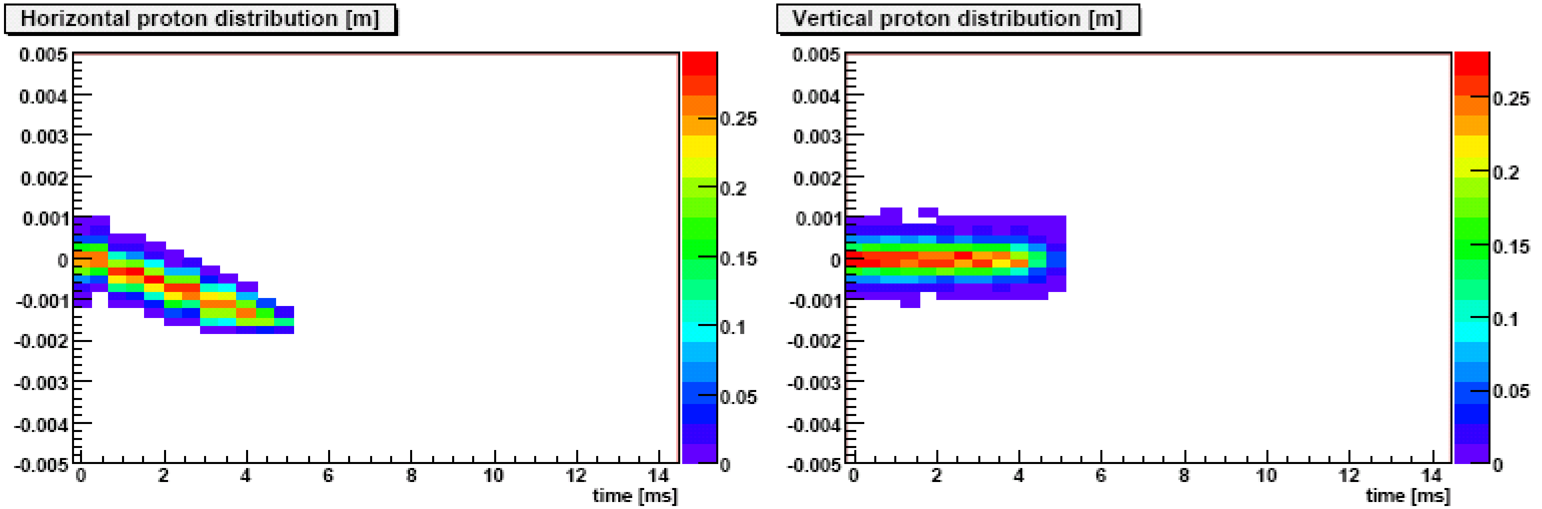


- Injected beam does not need to come from nearby injection line!
- Here beam 1 in LHCb (after almost one turn)
- Valid for all experiments at LHC

LHC Project Report 1174 “LHCb Injected Beam Accidents” R.B. Appleby
LHC Project Report 1175 “ALICE Injected Beam Accidents” R.B. Appleby

Example 6: circulating beam D1 failure at 450 GeV (here IP8)

- Separation magnet D1 going down at 450 GeV
- Beam mostly caught at primary collimators
- Here, LHCb VELO would have an aperture of 5 mm radius around the beams

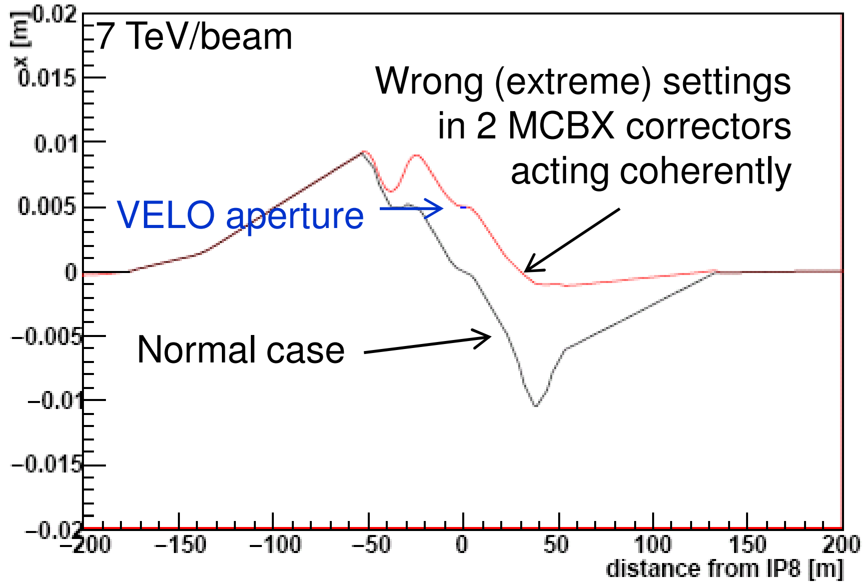


LHC Project Report 1176 “LHC circulating beam accidents for near-beam detectors” R.B. Appleby

Example 7: Wrong Local Bump

<u>Take again IP8 / LHCb</u>

- Beams separated in Y (vertical) during filling, ramping, etc.
  - Typ. ~ 1 mm between beams at 7 TeV before colliding
  - Max. accessible separation at 7 TeV is a few mm

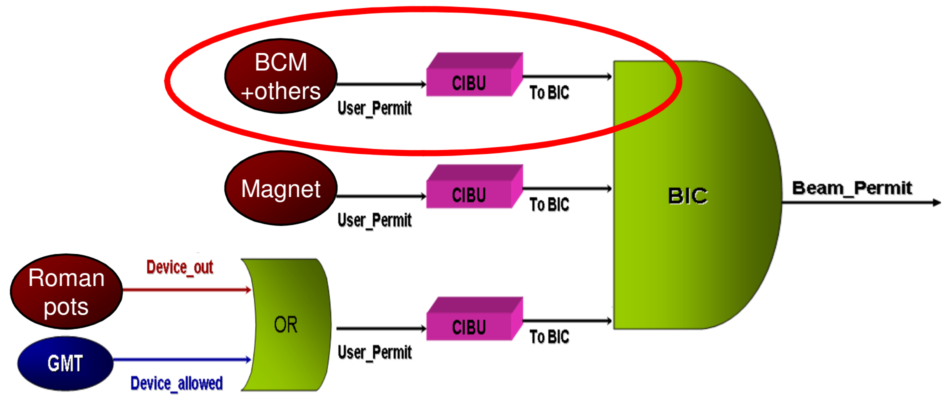


- Bump can be local, transparent to rest of machine!
  - Example here at 7 TeV with two magnets
- The lower the energy, the "easier" to make such a bump
  - At 450 GeV => accessible separation range amplified by factor 15.5, i.e. up to few mm x15.5 !!

LHC Experiment Interlocks

Beam_permit:

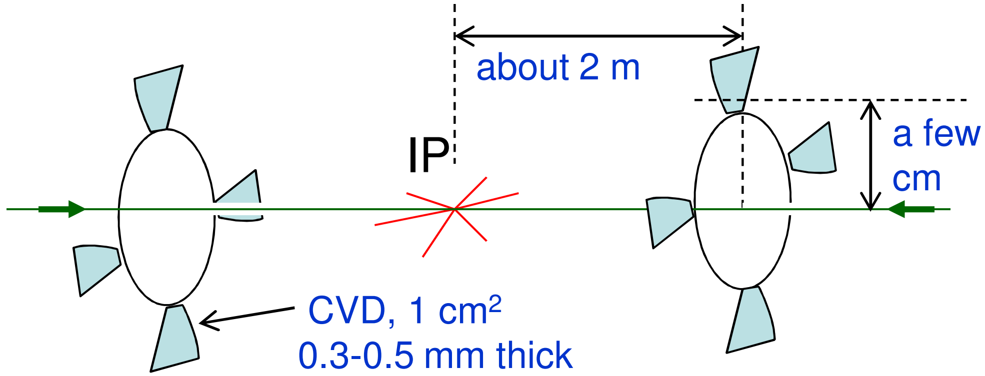
- In each experiment, several systems (typically 3 or 4) in "and" mode must be alive and deliver a User_permit
- If one system remove the User_permit, it triggers a beam dump
- Both beams are dumped
- Recovery procedure after post-mortem data analysis



(emergency buttons are also implemented in some experiments…)

Injection_permit:

- Separate interlock based on same transmission hardware (signals to SPS extraction)
- Allows inhibiting injection into LHC, e.g. when
  - Detector not ready for injection
  - Bad injection detected during a fill, requires stopping injection without dumping the stored beam

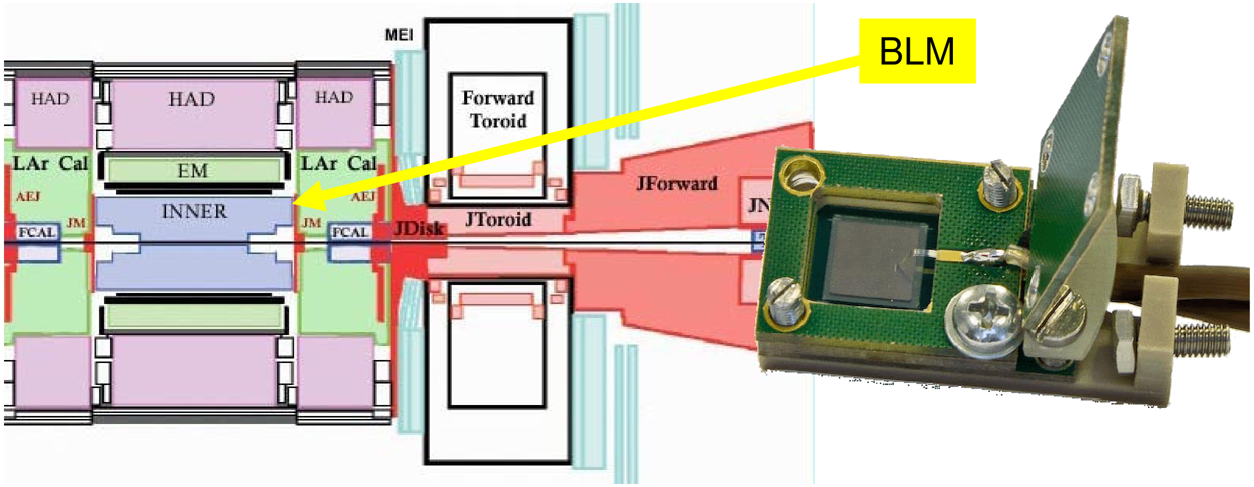


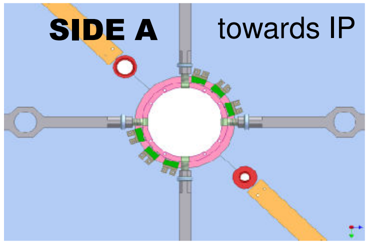
- One set of diamond sensors on each side of IP:
  - Stand-alone system using a few polycrystalline CVD diamond pads
  - UPS powered, with few minutes autonomy
  - Post-Mortem analysis capability
  - FPGA-based dump logic:
    - input: measured rates
    - output: `UserPermit` signal
  - Unmaskable input to local BIC
  - On trigger, dump both beams
  - Expected ready from "day 1"
  - Must have high availability, reliability, efficiency

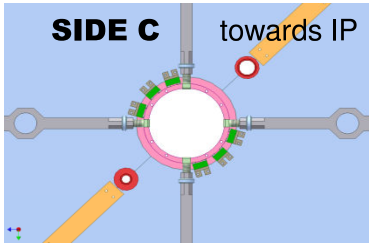
1 MIP ~ 1 fC

- BCM (beam conditions monitor) must protect detectors against circulating beam failures

ATLAS (1)







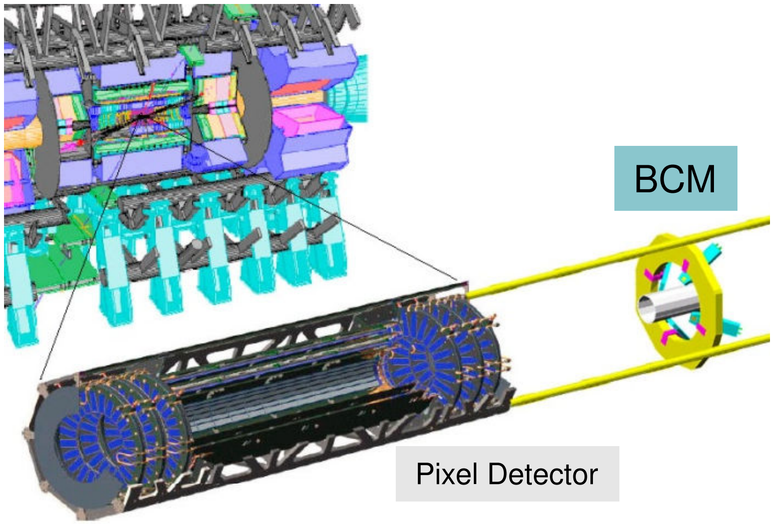
- Beam Loss Monitors (BLMXD.01L1/R1.CH0N_ATLAS)
  - 2 x 6 pCVD diamond detectors (8 x 8 mm^2)
  - z = ± 345 cm and r = 65 mm
  - 40 μs integration time, pA to mA
  - Readout chain of LHC BLM system with modified BLMTC FPGA firmware
    - Abort signal at front panel
    - Receive PM signal

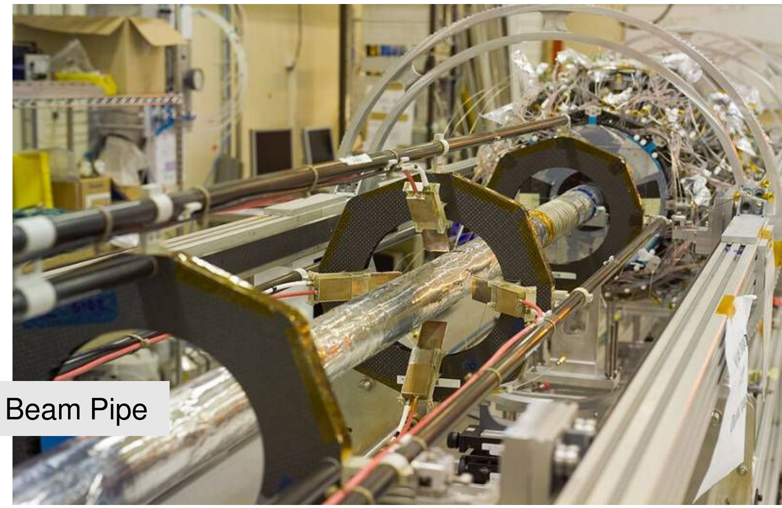
At nominal 1e34 cm^{-2} s^{-1}

Noise	Collisions	Thres.	Damage
~10 pA	~15 nA	50 nA (?)	> 1 uA??

- Beam abort condition
  - 2 in a group of 3 detectors above threshold

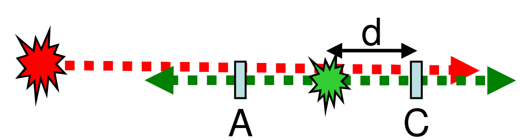
ATLAS (2)





See M. Mikuz et al.,
NIMA 579 (2007) 788-794

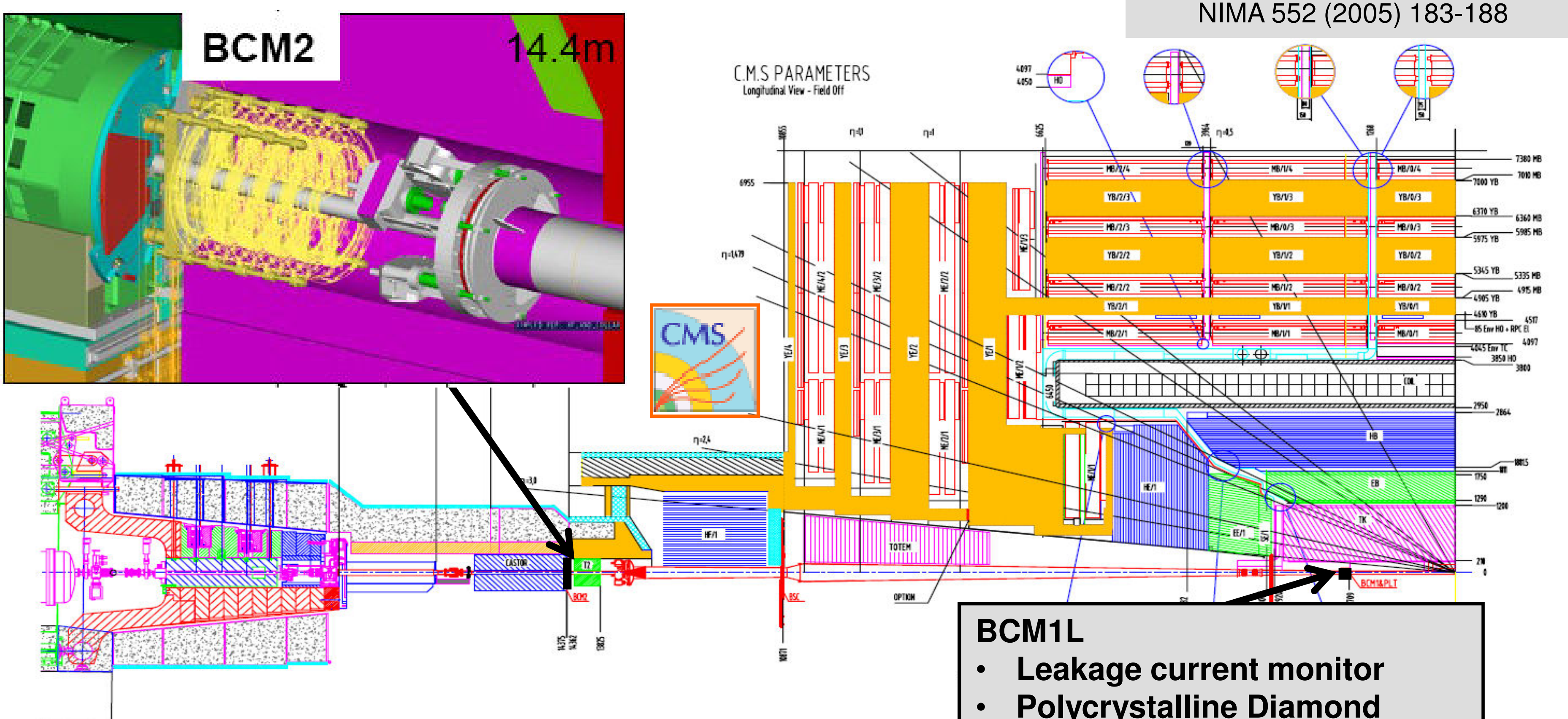
- Beam Conditions Monitors (BCM)
  - 2 x 4 pCVD diamond detectors (8 x 8 mm^2)
  - z = ± 184 cm and r = 55 mm
  - Fast readout time
  - Single MIP sensitivity with sub-ns time resolution ➔ Time of flight measurement ➔ distinguish collisions – background (ΔT(A/C) = 2d/c)
- Beam abort condition (not used at start-up)
  - 3 sensors above high threshold (5 MIPS) AND
  - 4 sensors above low threshold (0.5 MIPS)



d/c = 184 cm/c = 12.2 ns = ~ 25ns / 2
Monitor beam halo by out of time signals vs collisions

CMS (1)

see L. Fernandez-Hernando et al., NIMA 552 (2005) 183-188



BCM2

- **Leakage current monitor**
- **Polycrystalline Diamond**
- **Location: z=± 14.4m, r=29cm, 4.5cm**
- **8 stations in ϕ, 24 sensors total**

BCM1L

- **Leakage current monitor**
- **Polycrystalline Diamond**
- **Usage: Experiment protection**

BCM1F

- **Bunch by bunch monitor**
- **Single crystal Diamond**
- **Usage: Pixel protection**

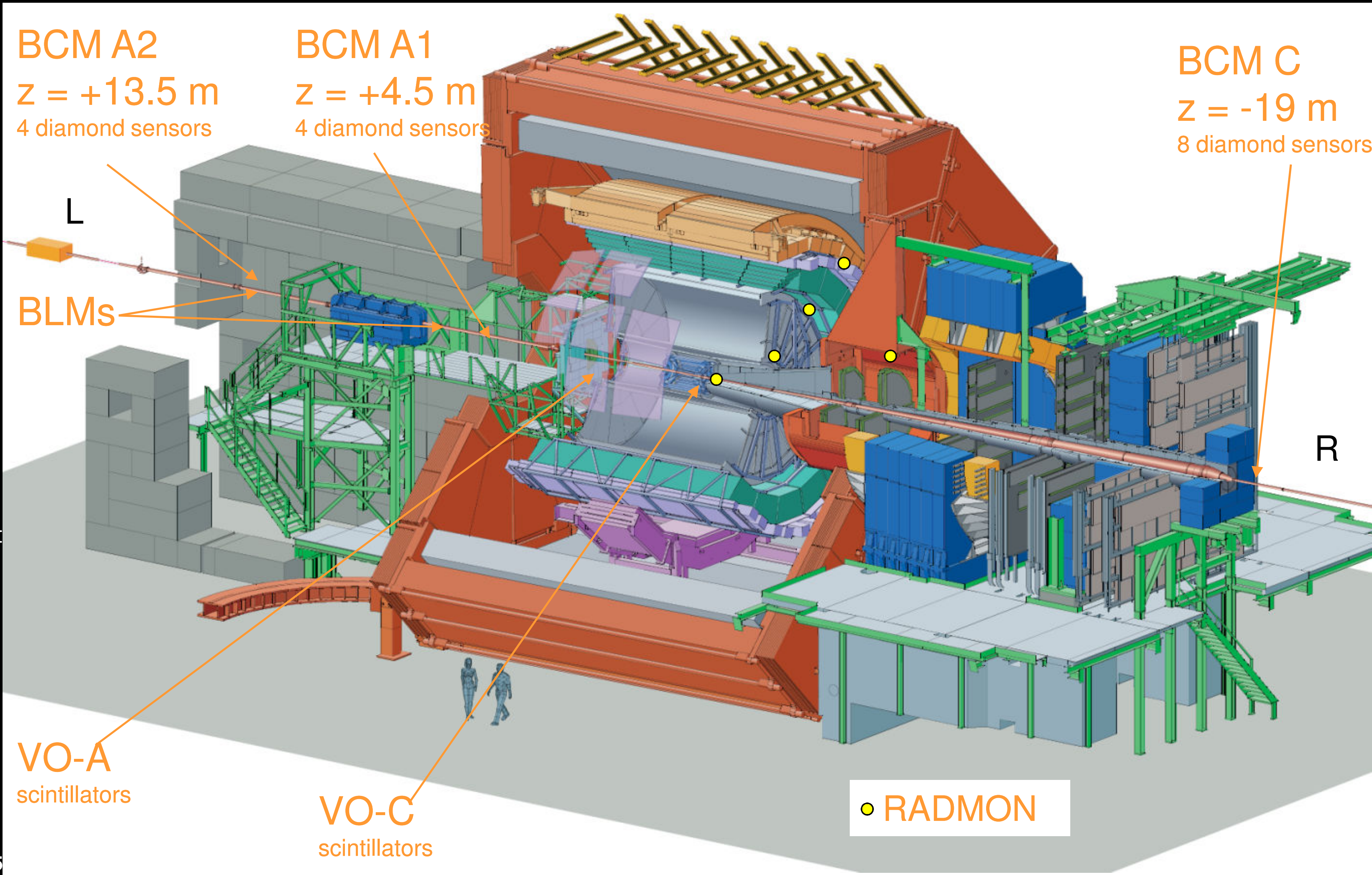
CMS (2)

- Initially only 8 diamonds (4 per end) in inner ring on BCM2 will be “active” in asserting BEAM_PERMIT
- BCM1L hardware will be connected to the ABORT from the beginning, however thresholds will NOT be set until after a suitable commissioning period with beam
- BCM1L detectors and inner ring of BCM2 are at ca. 4.5cm radius, approximately the same as innermost layer of pixel detector
- Initial threshold for BCM2: RS1 ~ 10 uA (40 us)

At nominal 1e34 cm^{-2} s^{-1}

Noise	Collisions	Thres.	Damage
<10 pA	~15 nA	10 uA	> 18 uA

- Thresholds are per diamond. No coincidence required.
  - Has been running stably for > 6 months, w/o spurious triggers


BCM A2
z = +13.5 m
4 diamond sensors
BCM A1
z = +4.5 m
4 diamond sensors
BCM C
z = -19 m
8 diamond sensors
L
R
BLMs
VO-A
scintillators
VO-C
scintillators
RADMON

twepp-09 Paris, France Topical Workshop on Electronics for Particle Physics September 21-25, 2009

- The UserPermit is based on BCM-CFC-TELL1 chain as in LHCb.
  - Fast abort on RS2 (2x40μs CFC integration frames) coincidences:
    Dump beam if 3 of 4 adjacent diamond sensors show current > thr_{RS2}
  - Slow abort on ΣRS32 (32x40μs):
    Sorting out the two highest and the lowest of 8 sensors, dump beam if ΣRS32 > $thr_{\Sigma RS32}$
- Current estimate for dump thresholds (to be x-checked …):
  - thr_{RS2} ~ 5000 nA , $thr_{\Sigma RS32}$ ~ 250 nA

Noise	Collisions	Thres.	Damage
<100 pA	~100 pA	~ 5 uA	~ mA

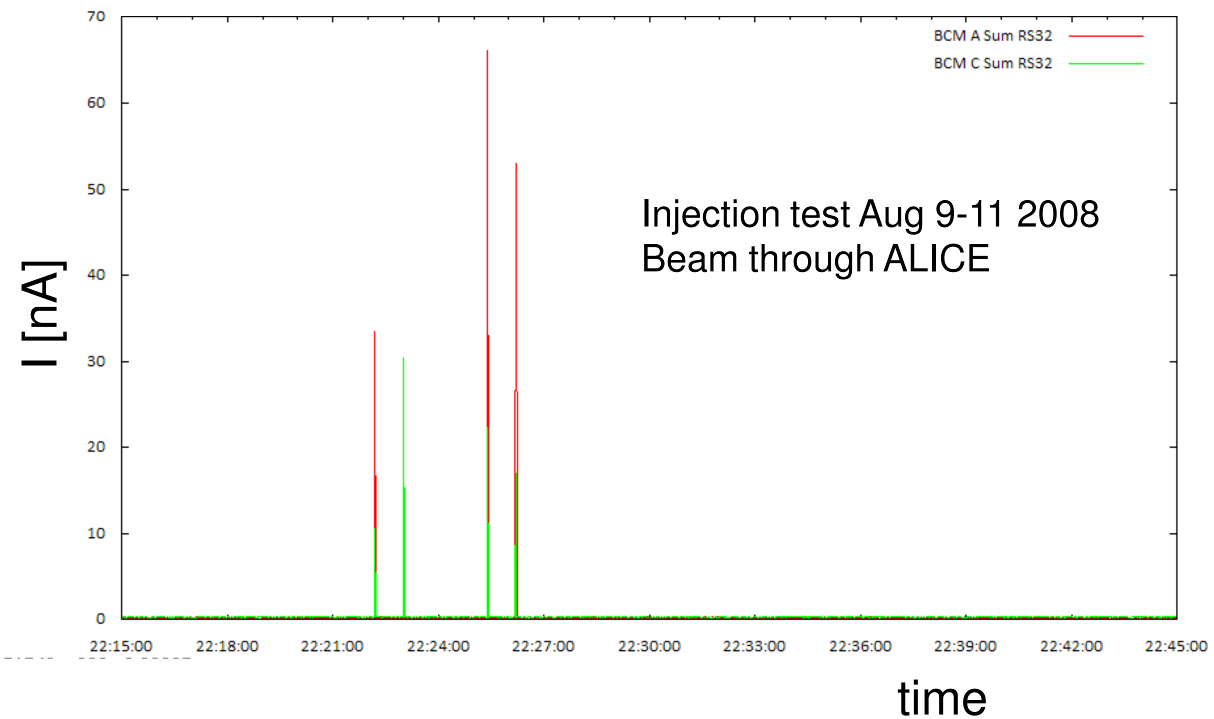
BCM currents from FLUKA simulation of injection failures by B. Pastirčák (ALICE Int. Note 2001-03), updated in Nov 07

(pilot bunch 5 × 10^9 p)

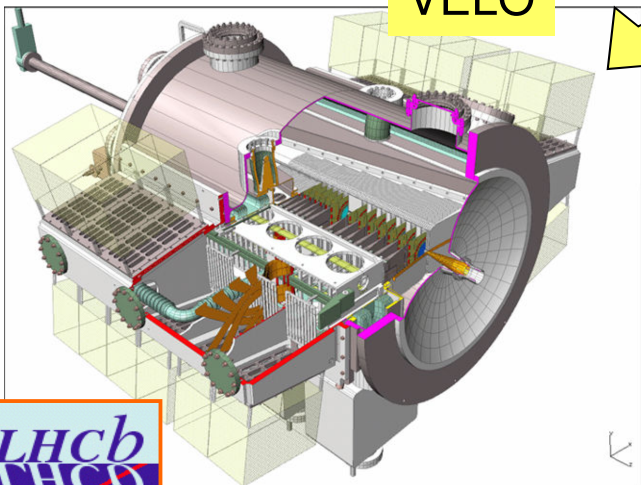
	RS2 [nA]	RS32 [nA]
BCM A	≈500-750	≈30-50
BCM C	≈100	≈6

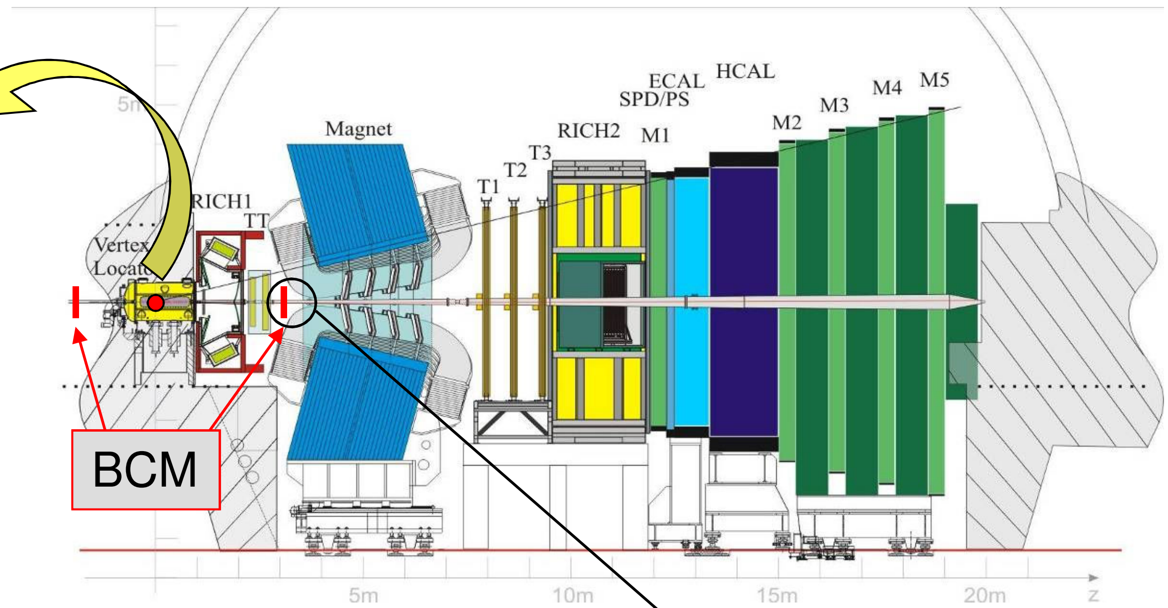
TDI grazing (pilot bunch 5 × 10^9 p)

	RS2 [nA]	RS32 [nA]
BCM A	≈900-2700	≈55-170
BCM C	≈325	≈20

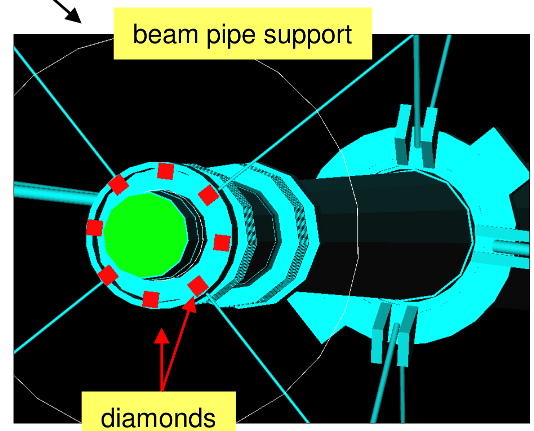


LHCb (1)



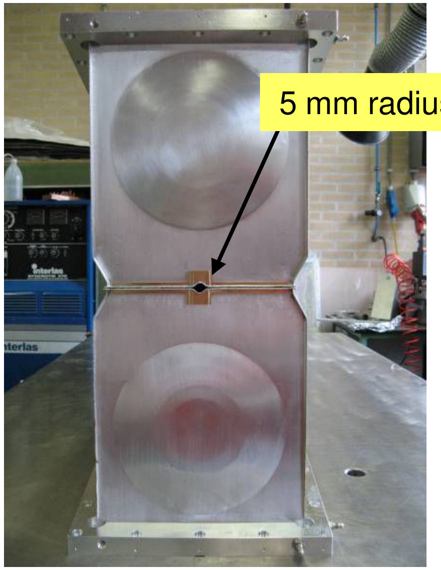


- Each BCM station composed of 4 or 8 CVD diamonds
- Mounted on the beam pipe, about 6 cm away from beam axis
- Asymmetric layout of BCM around IP (space availability)
- Diamonds readout: integrated rates in 40 us (later upgrade to 25 ns ?)
- Use stand-alone readout board for algorithm on dump trigger decision
- Simulations ongoing (relate VELO rates to BCM rates in failure scenarios)

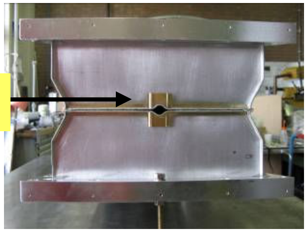


Noise	Collisions	Thres.	Damage
<10 pA	~1 nA	few uA	> ?? uA

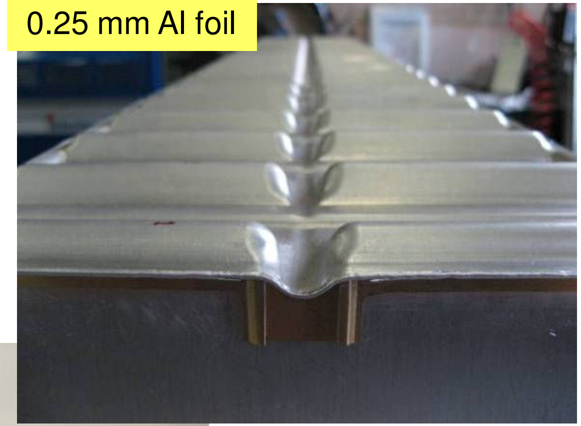
LHCb's Special: Vertex Locator



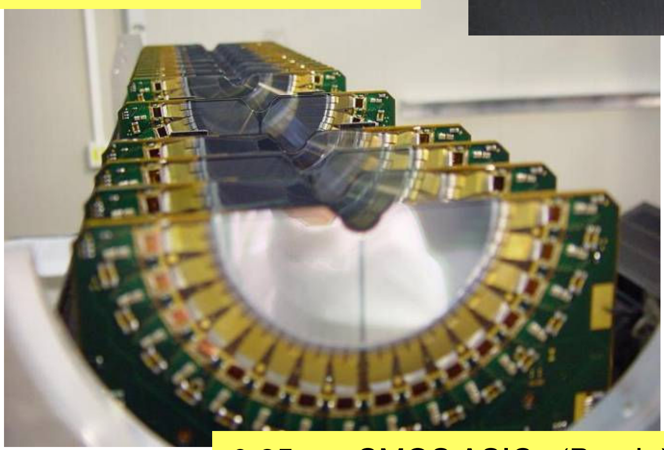
5 mm radius



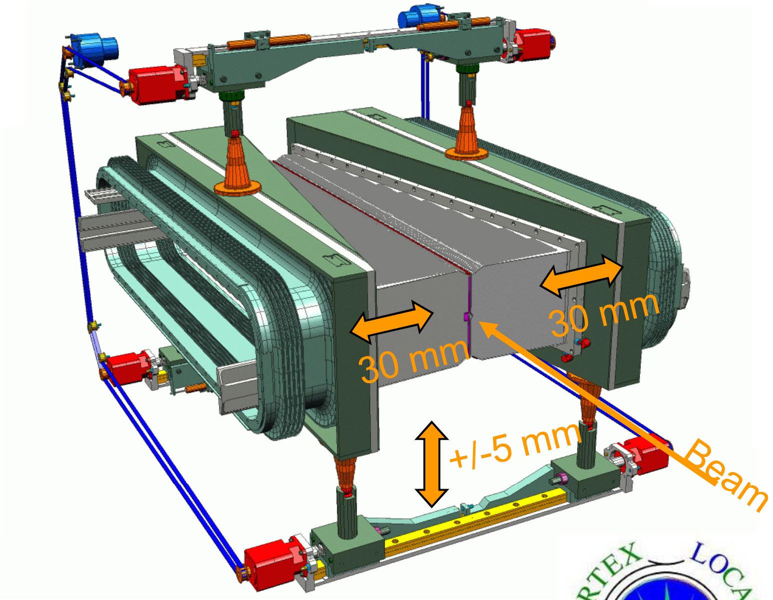
0.25 mm Al foil



21 r-phi Si modules per side



0.25 um CMOS ASICs (Beetle)



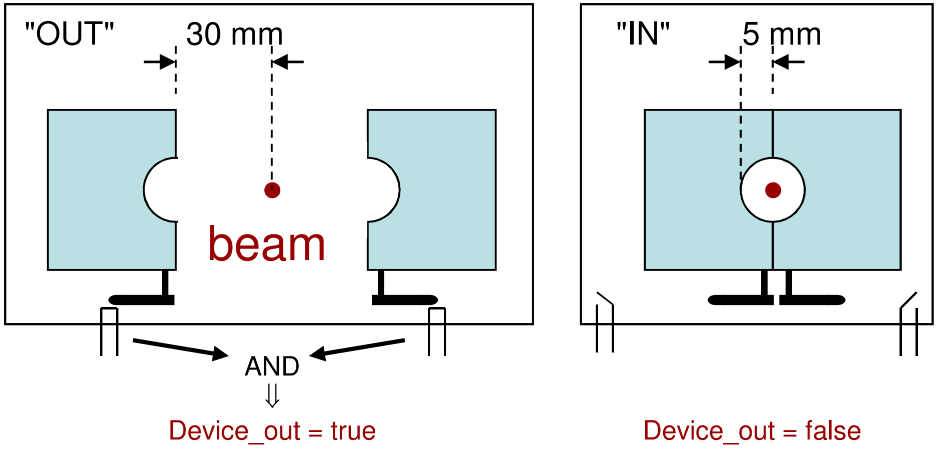
- <u>Injection</u>: no material at r<27 mm $\Rightarrow$ Velo open (OUT)
- <u>During stable beam</u> $\Rightarrow$ Velo closed (IN)
- Final position adjustable in y and in x to center beam in the hole (axial geometry for RZ trigger !)
- It must be possible to adjust "beyond" nominal beam axis (beam position not guaranteed...)
- Microswitches to detect Velo is OUT (both halves)
- Microswitches and hard stops to prevent crashes

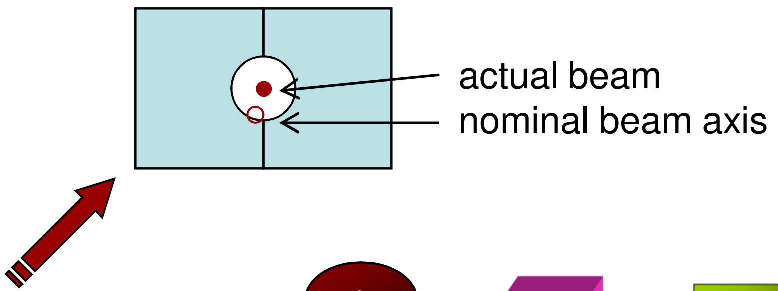
LHCb VELO Protection System

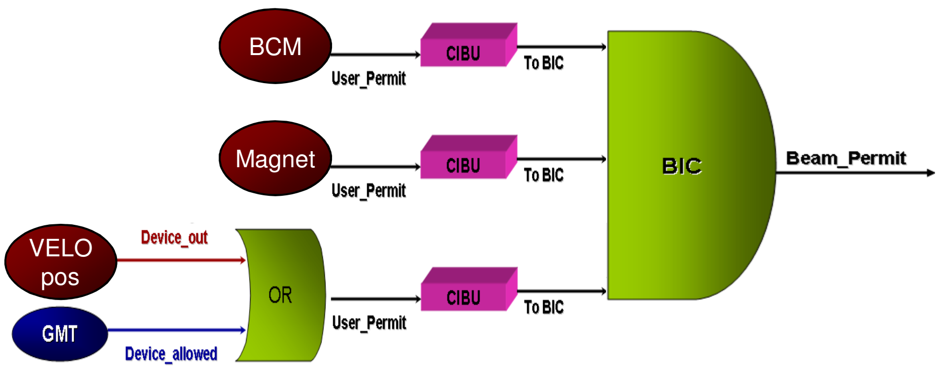
- Microswitches in X on each half to check that VELO is in garage position (OUT)
- Read out by PLC which generates Device_out signal
- LHC flag Device_allowed transmitted via reliable network to the Expts. If False, movable devices must be in OUT position
- If both LHC flag Device_allowed and VELO flag Device_out are false, then LHCb UserPermit is false => dump the beam, prevent injection
- VELO motion is "slow", of order 0.1 mm/s
- Can move over nominal beam axis and/or beam can move to the detector!

  ⇒ fast protection needed !

  ⇒ BCM must detect increase in rate (over normal minimum bias events) due to a possible beam-velo foil scraping, must work for both beams







Damage thresholds for detectors

twepp-09 Paris, France
Topical Workshop on Electronics for Particle Physics
September 21-25, 2009

What are the most exposed / most sensitive detectors ?

What are their damage thresholds ?

Why do we care ?

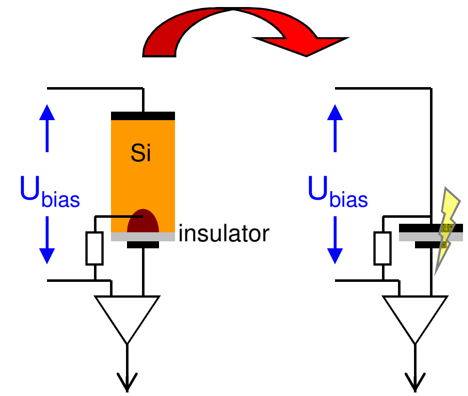
- Detectors are designed, built and installed: but operation procedures can be changed
  - HV and LV on/off at injection or with “non-physics” circulating beam ?
- Feedback to the machine
  - Definition of intensity limit at injection
    - Currently H/W 10^{11} protons and S/W 10^{10}
- Improvements on future detectors (at even higher beam intensities...)

For comparison:

- Atlas/CMS pixel (r=4.3cm): order of 0.02 MIP/cm^2 per pp interaction
- LHCb VELO: order of 0.5 MIP/cm^2 per pp interaction
- MIPs through pixel detectors due to pp collisions in IP1/5 in a nominal year ~ $10^{17...18}$
- One nominal LHC bunch: 10^{11} p
- Full nominal LHC beam: 3 x 10^{14} p

Problems with beam losses for the silicon:

- Heat deposit: not a problem ? (for the likely failures)
  - Thermomechanicql effects ? Seeds for crqcks ?
- Extra radiation damage, eating up the "budget"
  - not so critical: LHC Si detectors designed to sustain "huge" doses (few 10^{14} n_{eq}/cm^2 ~ 10 Mrad) ;
  - but watch out anyway!
- Sudden high rate can induce large voltage in the Si detector
  - becomes essentially conductor => bias voltage boundary moves to another place... zap or no zap ?
    - e.g. SiO_2 breaks at ~ 1V/nm
  - direct hit to FE chip can be even worse (lose full chip, i.e. many channels... see CDF accidents)



The *keep-it-always-on-or-not* dilemma:

- Keep detector always ON for stability ?
  - no charge up effects, no temperature effects, etc.
- Reduce risk during injection by turning OFF HV ? (or even LV off)?
  - unstable at turn-ON

What do we know about LHC Expt Si detector and resistance to high rates ?

ATLAS and CMS tests at CERN PS beam:

- 24 GeV, 1 or few-bunch batch (bunch: 42 ns long, ~10^{11} p, separation 256 ns), with peak bunch density of ~ $3x10^{10}$ p/cm^2.
- Detectors biased and FE electronics ON

- ATLAS:
  - See A. Andreazza, K. Einsweiler, C. Gemme,, L. Rossi, P. Sicho, NIM A 565 (2006) 50–54, *Effect of accidental beam losses on the ATLAS pixel detector*
- CMS:
  - See M. Fahrer, G. Dirkes, F. Hartmann, S. Heier, A. Macpherson, Th. Müller, Th. Weiler, NIM A518 (2004) 328–330, *Beam-loss-induced electrical stress test on CMS Silicon Strip Modules*

Laser tests (not exhaustive):

- Atlas silicon strip: 1064 nm LASER (1 W)
  - K. Hara,T. Kuwano, G. Moorhead, Y. Ikegami, T. Kohriki, S. Terada, Y. Unno, NIM A 541 (2005) 15–20, *Beam splash effects on ATLAS silicon microstrip detectors evaluated using 1-w Nd:YAG laser*
- Atlas silicon strip sensors: LASER (2 types)
  - T. Dubbs, M. Harms, H. E-W. Sadrozinski, A. Seiden, M. Wilson, IEEE Trans. Nucl. Sci. NS47 (2000) 1902, *Voltages on Silicon Microstrip Detectors in High Radiation Fields*

- Andreazza et al., NIM A 565 (2006) 50–54

⇒ « The results of the PS experiment therefore indicate that the loss of a LHC "pilot beam" of 5x10^9 protons should not make any sizeable permanent damage to the performance of the ATLAS pixel detector. This accident will, very likely, require a reloading of the configuration parameters in a large fraction of the pixel detector. »

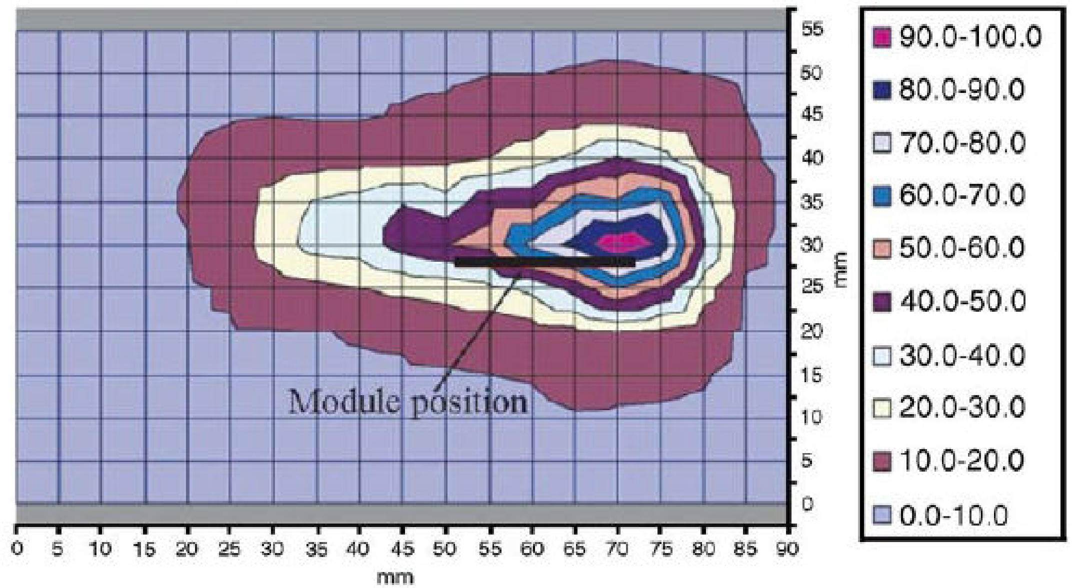


Fig. 3. Beam profile of a 10^{11} proton bunch extracted from the CERN Proton Synchrotron and measured in the vicinity of the ATLAS pixel module, which is also shown. The beam intensity is of $\approx 3 \times 10^{10}\,\mathrm{p/cm^2}$ in a central area of $\approx 5\times3\,\mathrm{mm}^2$. The average flux over the module is of $1.5 \times 10^{10}\,\mathrm{p/cm^2}$.

- M. Fahrer et al., NIM A518 (2004) 328–330

⇒ « There is strong evidence that CMS silicon strip modules will survive a beam loss, because the fast breakdown of bias voltage protects electronics and sensors, especially the dielectric layer and the polysilicon resistors. »

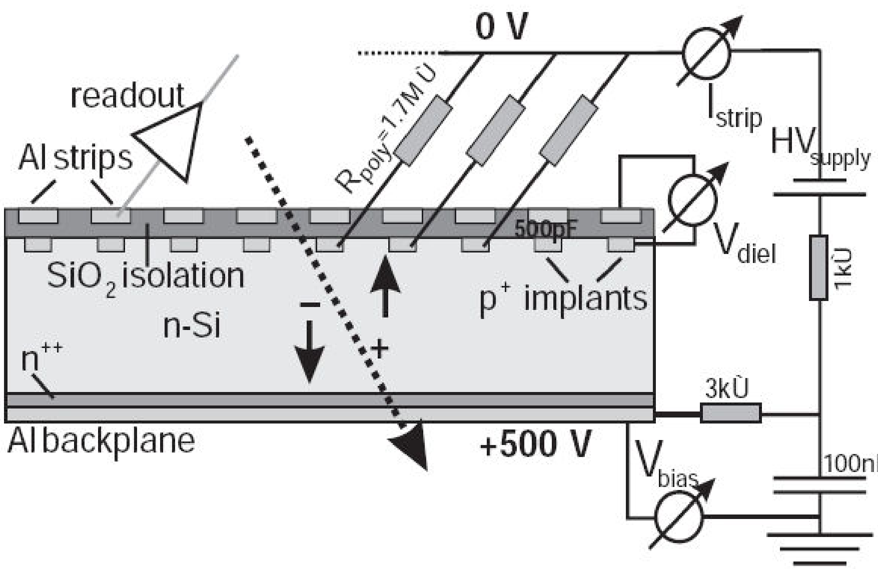


Fig. 1. Sensor schematics with electrical setup.

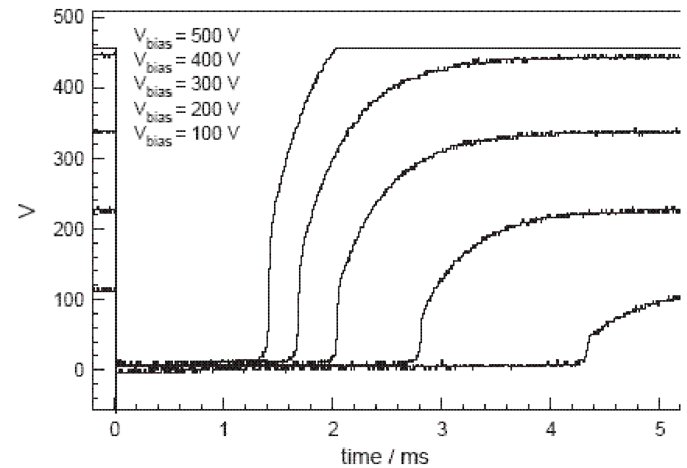


Fig. 2. Time behaviour of bias voltage.

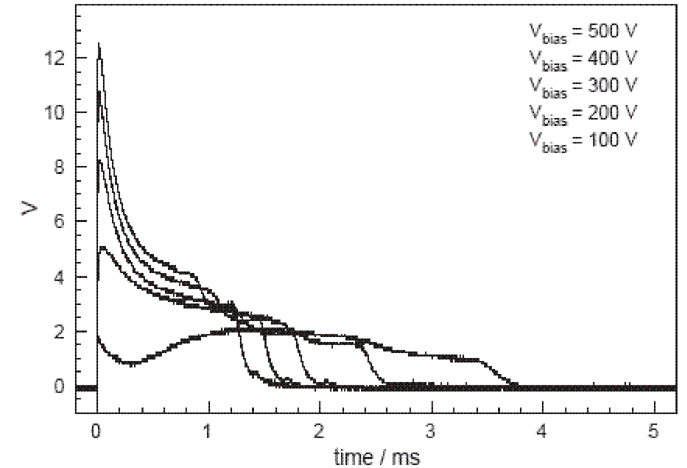
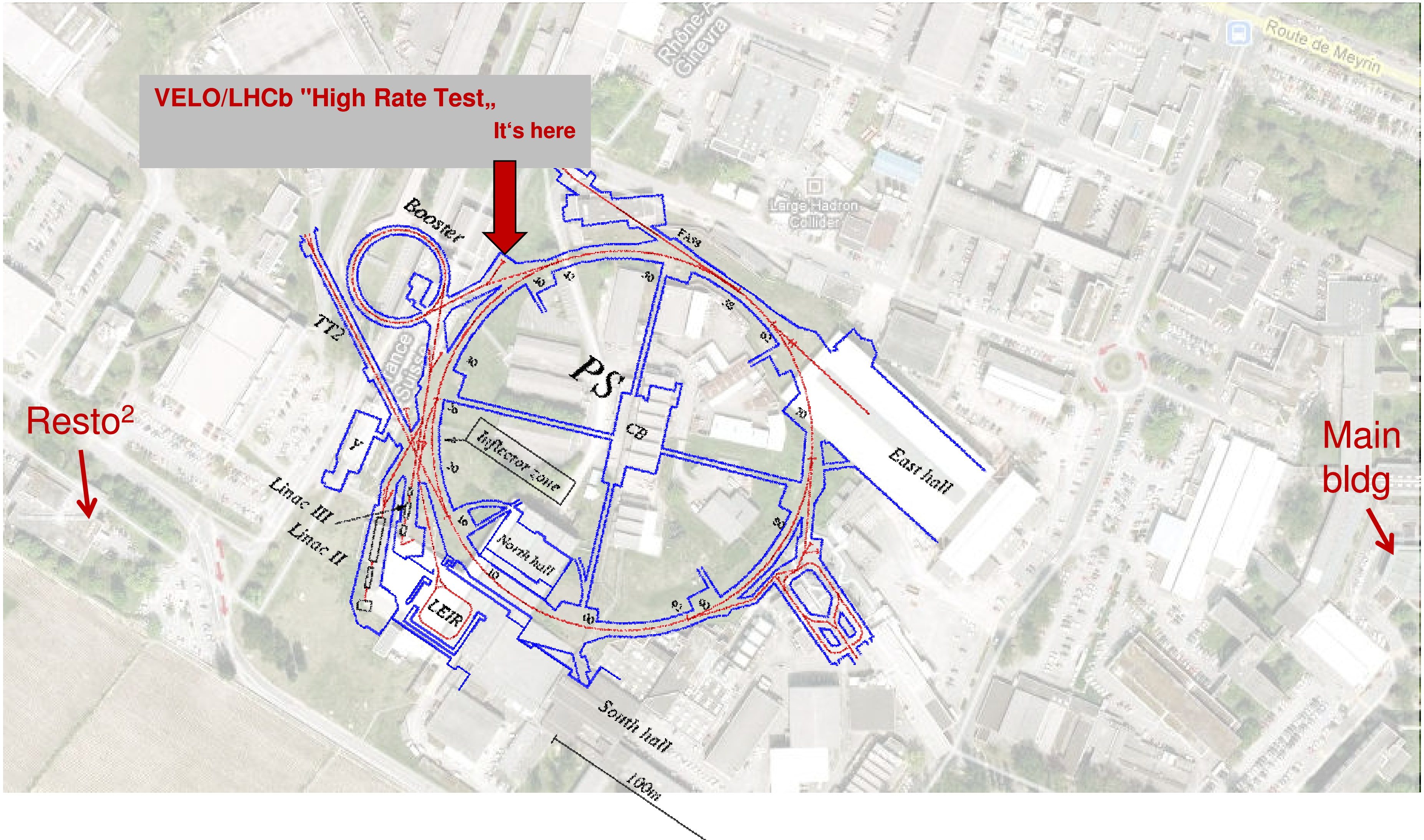


Fig. 3. Time behaviour of voltage over dielectric layer.

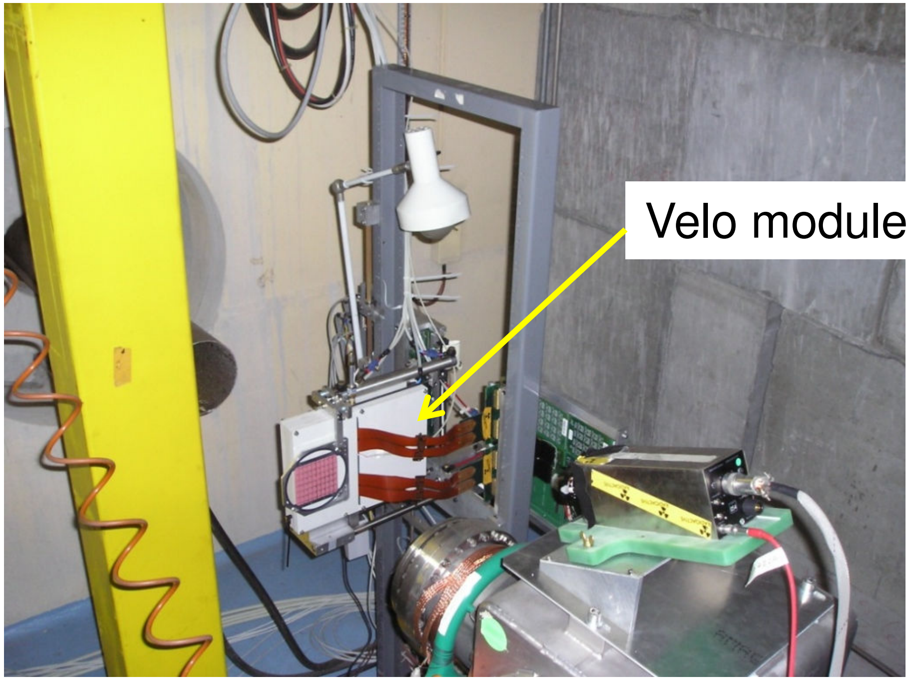
A Recent LHCb VELO High Rate Test



A Small Scale Experiment

Module mounted close to the PS booster (PSB) beam dump

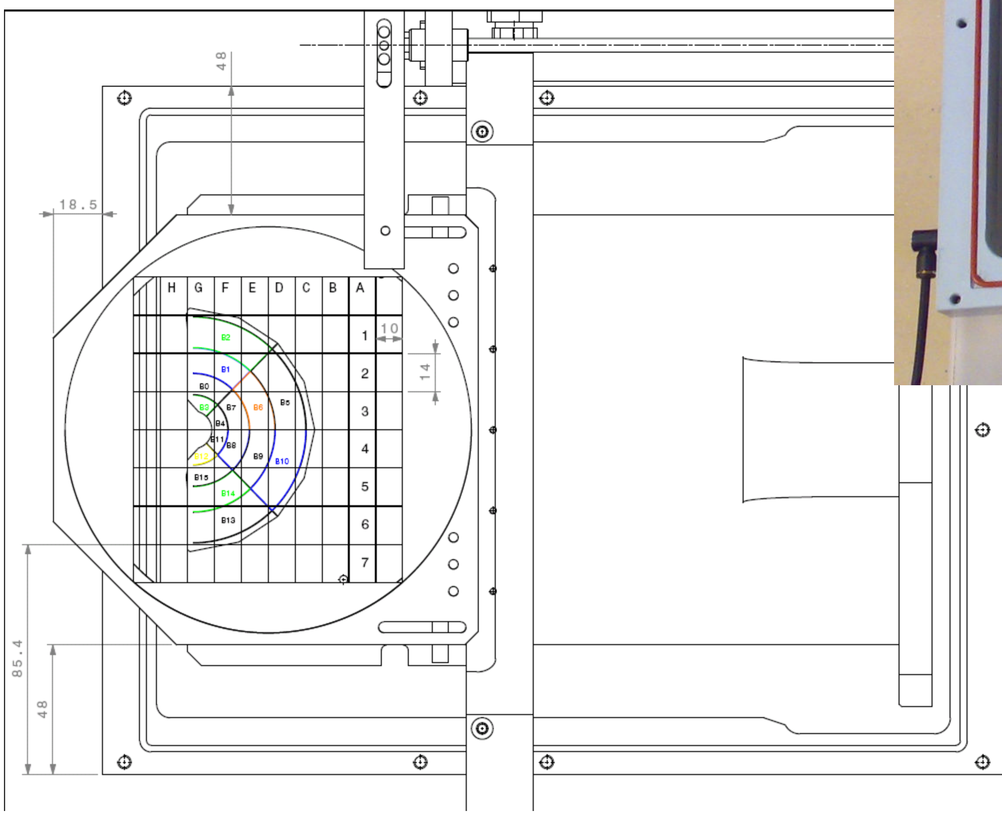
- Proton beam of 1.4 GeV kinetic energy
- Intensity from 2e9 to 9e12 p/bunch
- 1 to 4 bunches (4 rings), we use a single bunch (ring 3)
- Beam spot size rms ~ 2-4 mm , bunch duration rms ~ 20-60 ns

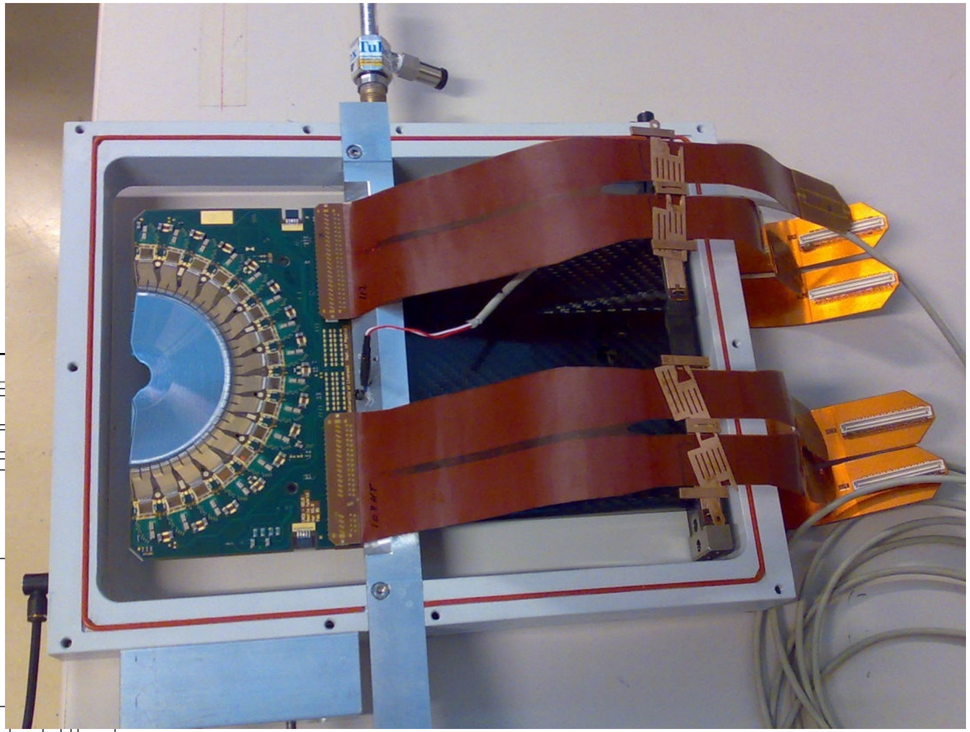


The Victim: "Module 48"

LHCb/Velo spare from production

- Back-to-back R & Phi sensors
- 2048 AC coupled n-on-n strips / side
- 16 FE chips (IBM 0.25 µm) per side, all configured but only 8 per side read out

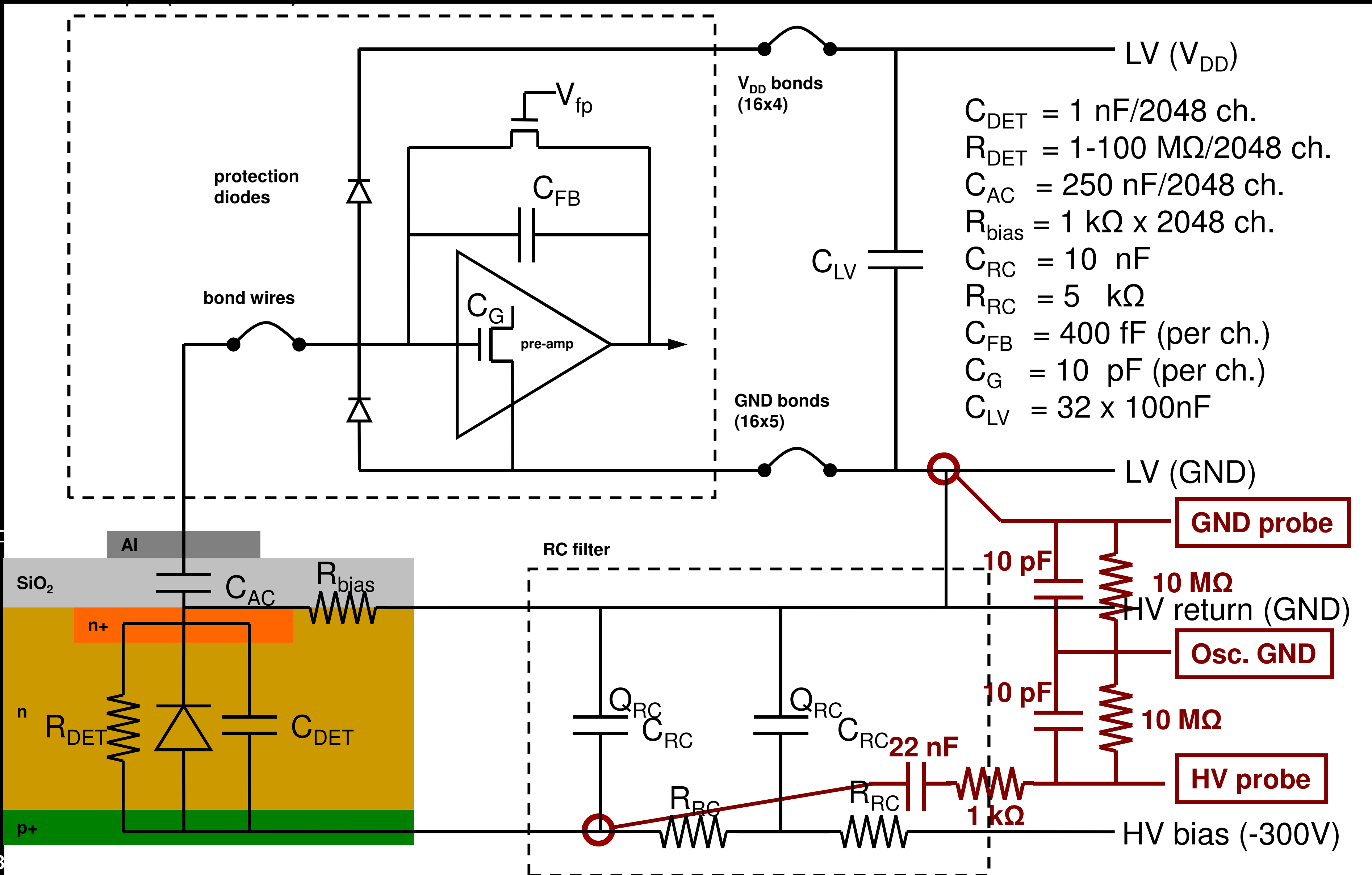




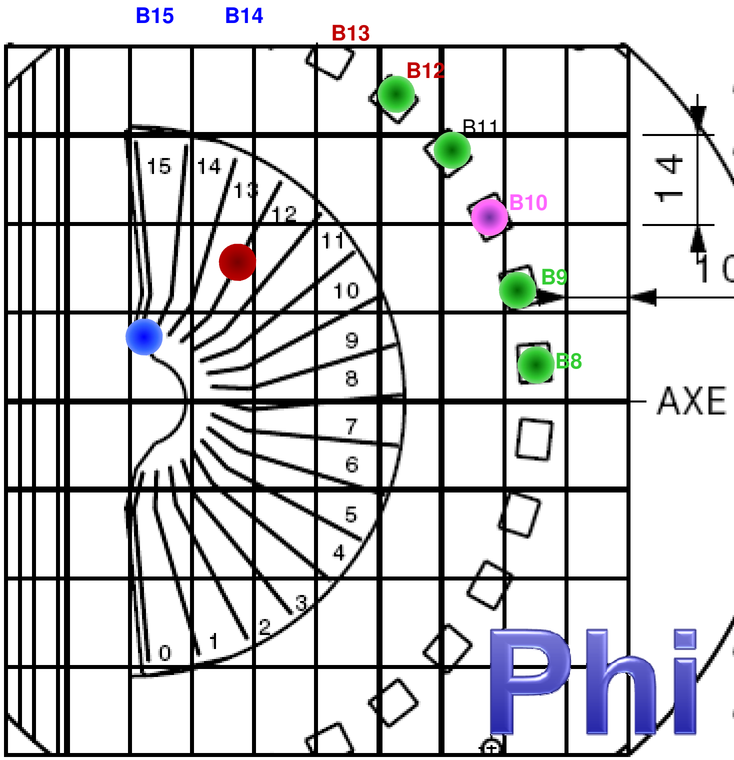
Mounted in the beam line

- Cooled to +1 ˚C (LV on) with vortex tube (8 bar compressed air)
- Fluorescent screen to view the beam
- Insert/retract from beam line
- Remote control and read-out
- Heavy radiation environment !
  - Backsplash at every beam dump
  - ~ 1 kGy in a few months

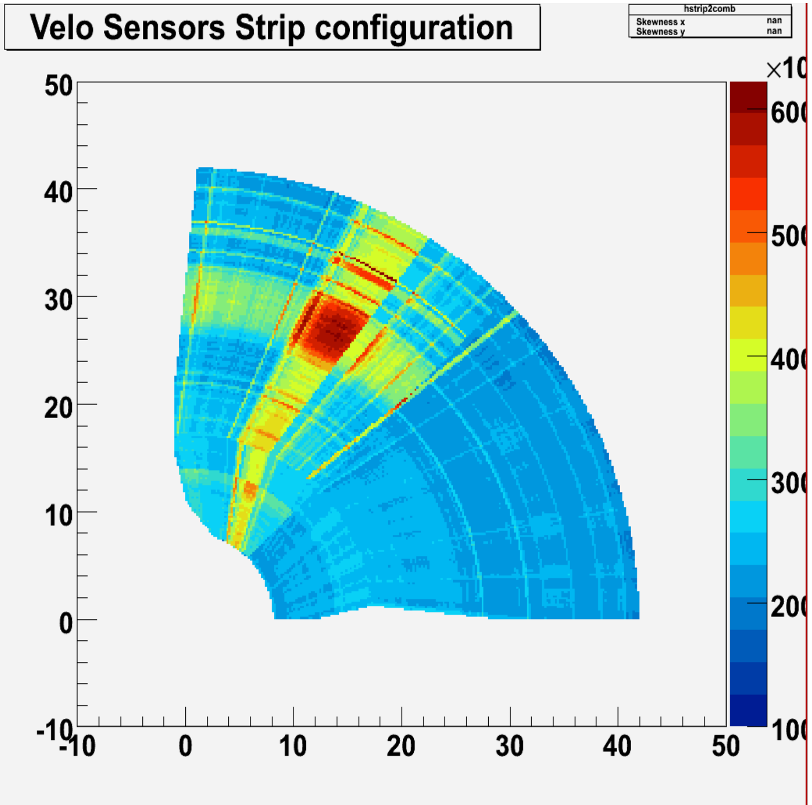
Electrical model – static case



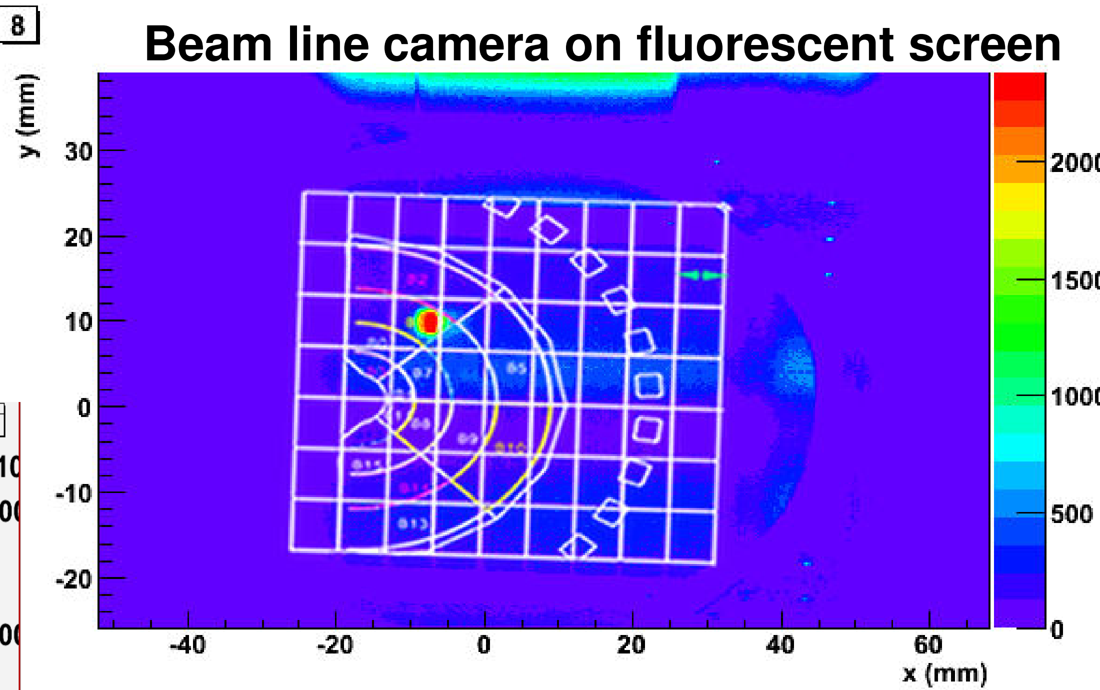
- Intensity steps: $2x10^{9}$, $2x10^{10}$, $2x10^{11}$, $2x10^{12}$ & $9x10^{12}$
- Each step: LV/HV off, LV on/HV off, LV on/HV 150 V & LV on/HV 300V
- Each beam 'shot' follows the same pattern
  - A set of standard measurements
    - I/V of both sensors
    - Noise & pedestal data
    - Test pulse data at +1.5, 0 and -150 V
  - Insert the module, acquire during the shot
    - 14 consecutive triggers of front-end data
    - Voltage on hybrid GND and sensor bias via oscilloscope
    - Beam spot image via a a camera
  - Repeat the same set of measurements
- Shots on two sensor positions
- Shots on five front-end chips
  (here only LV on/off matters)



Combined R-Φ sensor front-end data

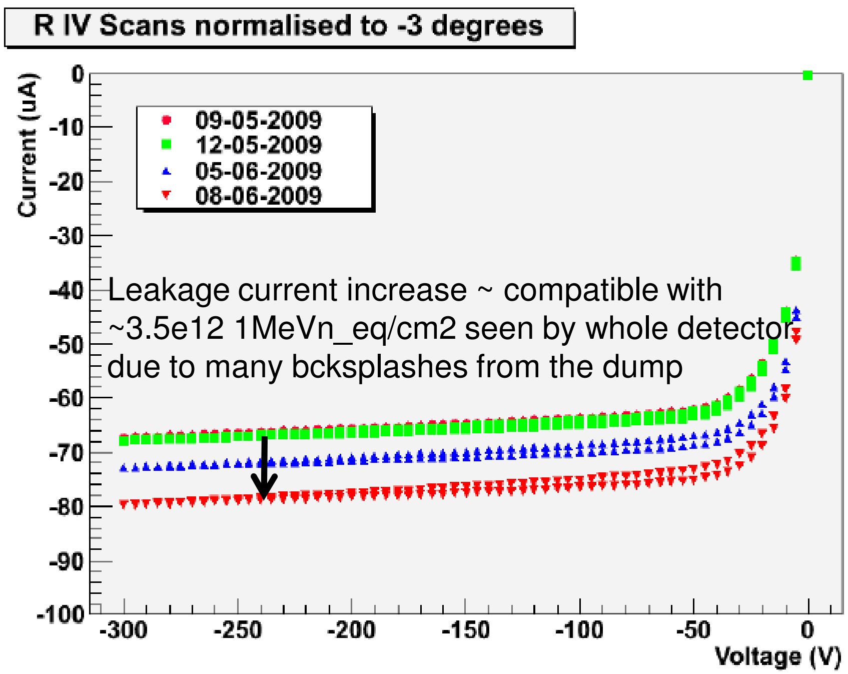


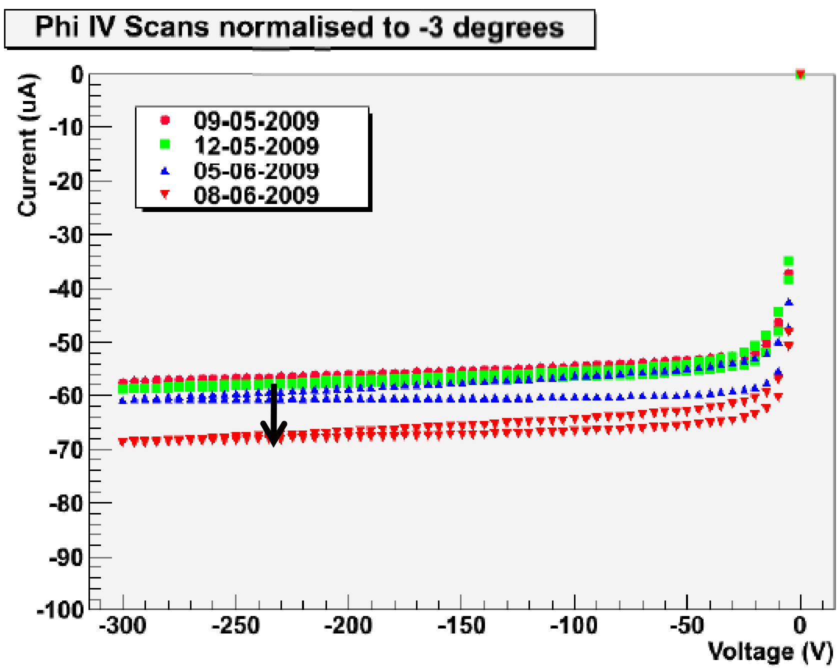
Beam line camera on fluorescent screen



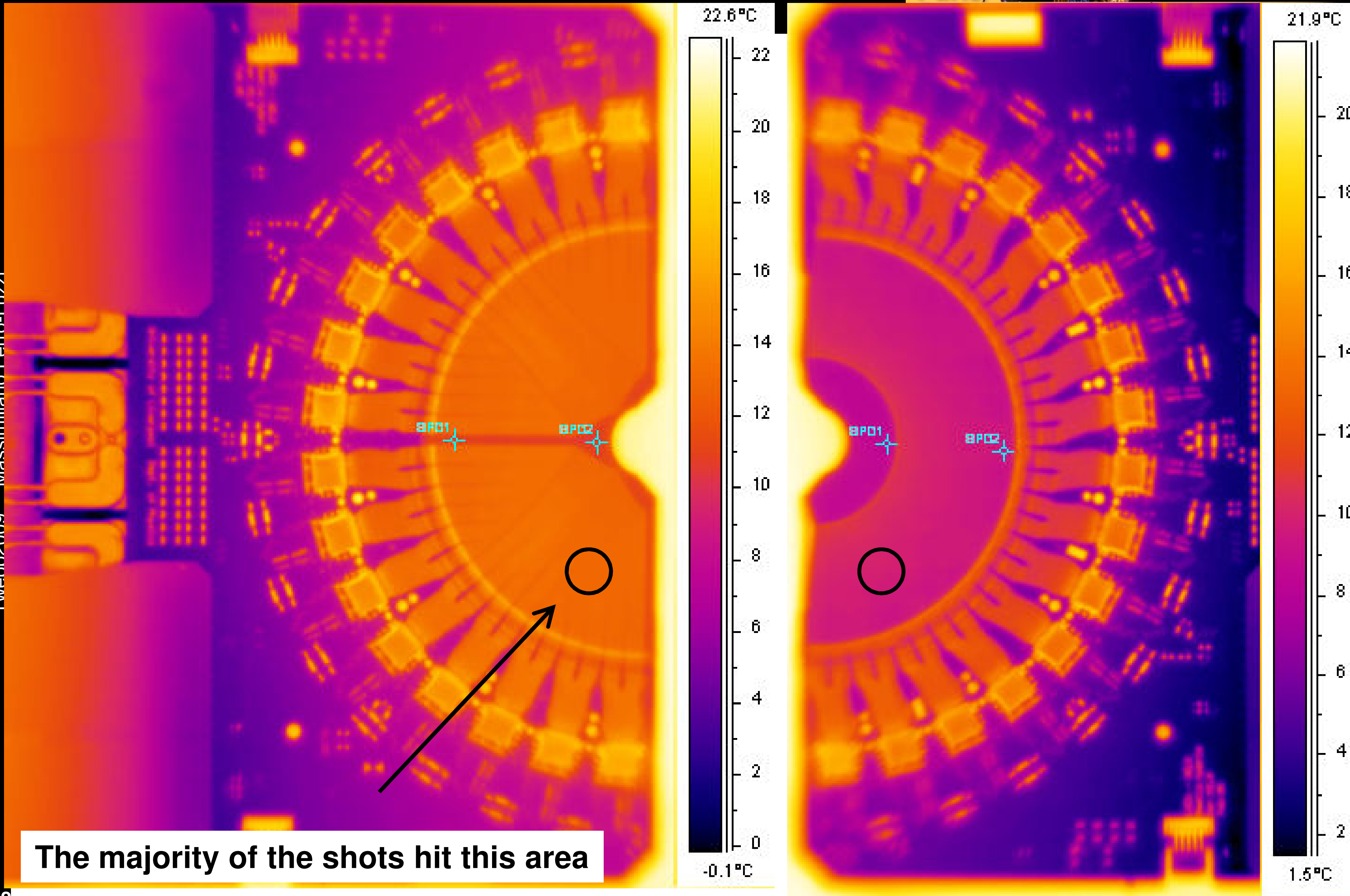
I/V curves

- I/V curves in-situ between each shot
  - Superimpose temperature corrected I/V curves
  - Small increase probably due to accumulated dose
  - Rough estimate between first and last curve: ~3.5×10^{12} 1-MeV-n_{eq} /cm^2 (~1 kGy)
- Work in progress
  - Correlate with radiation monitoring data



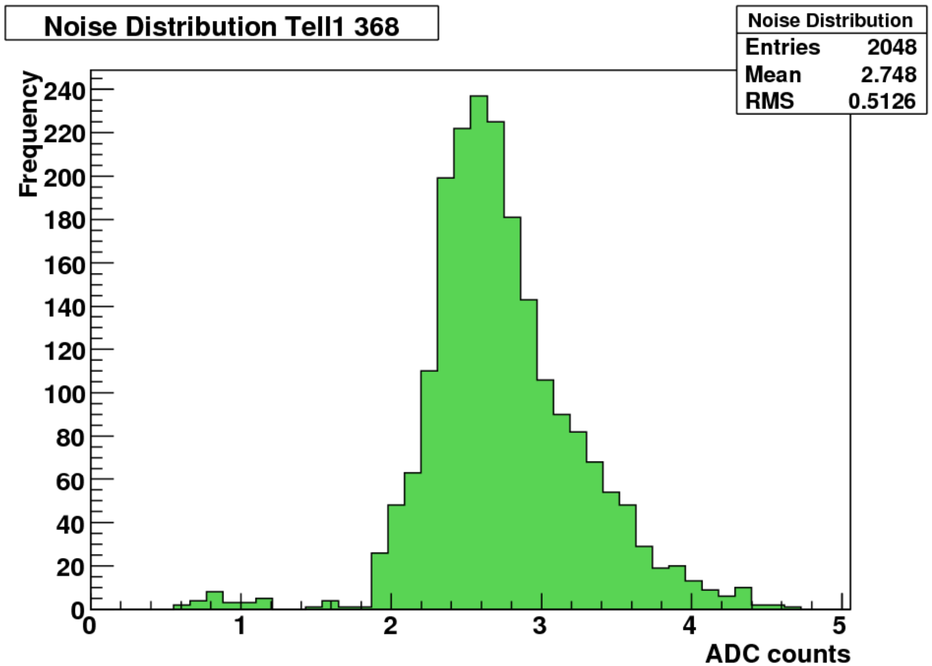


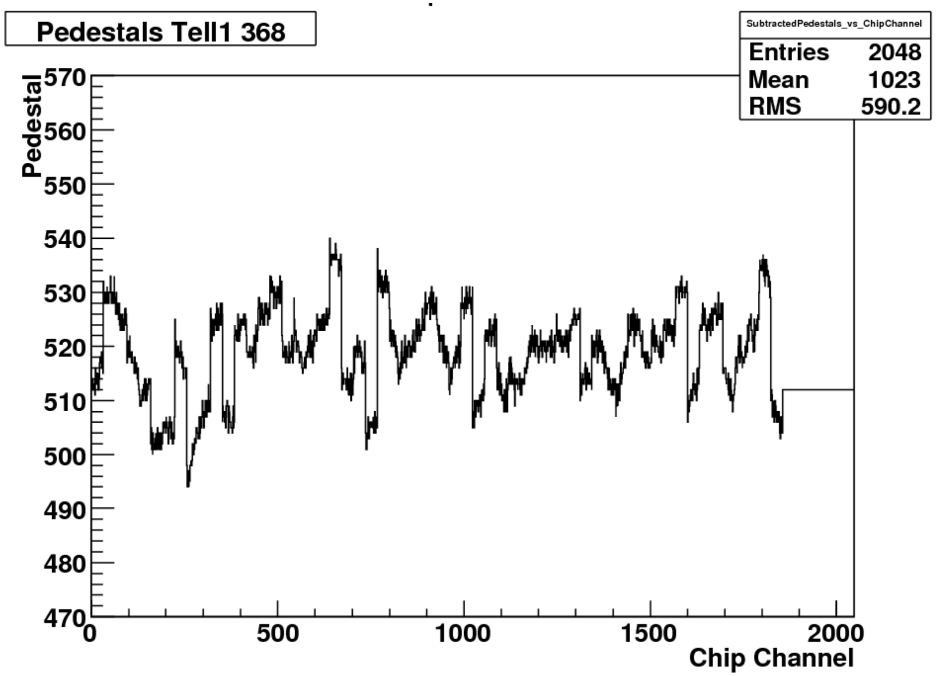
Thermal image: No hot-spots



The majority of the shots hit this area

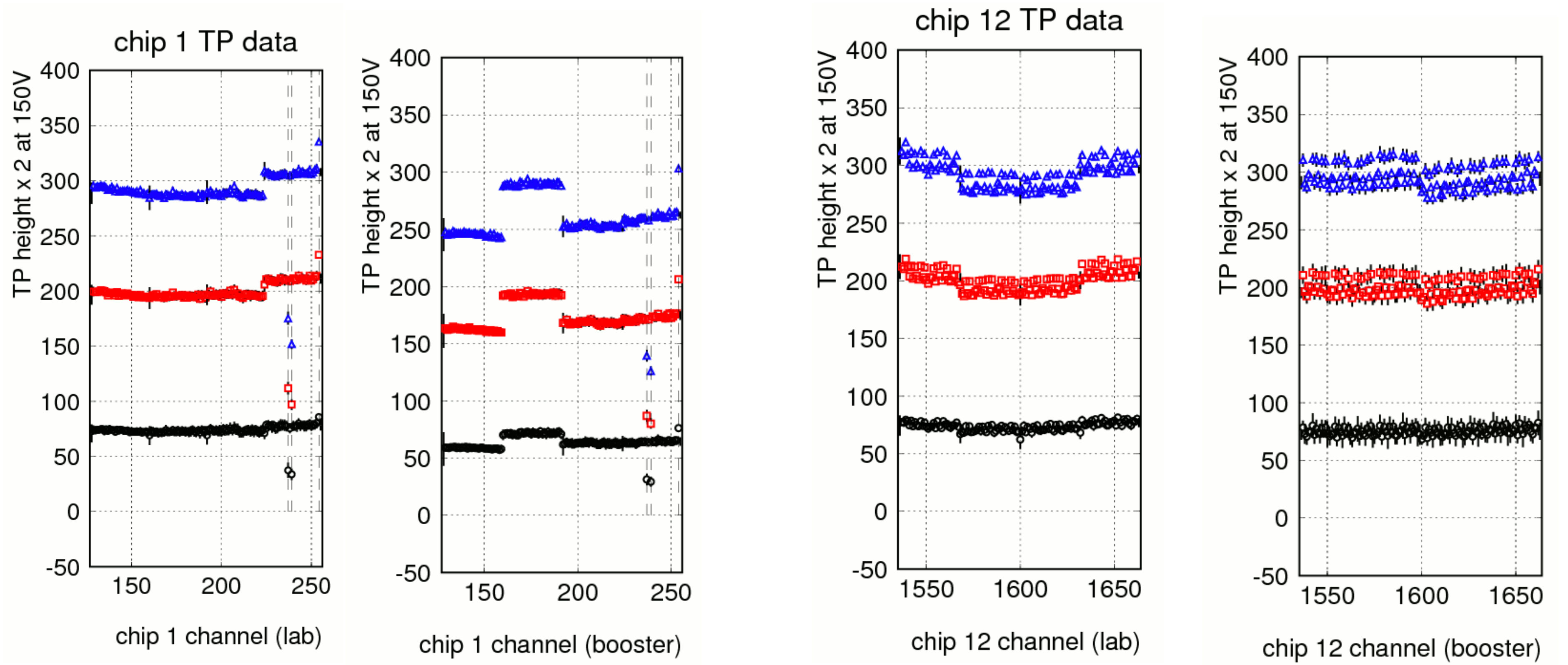
Noise & Pedestals





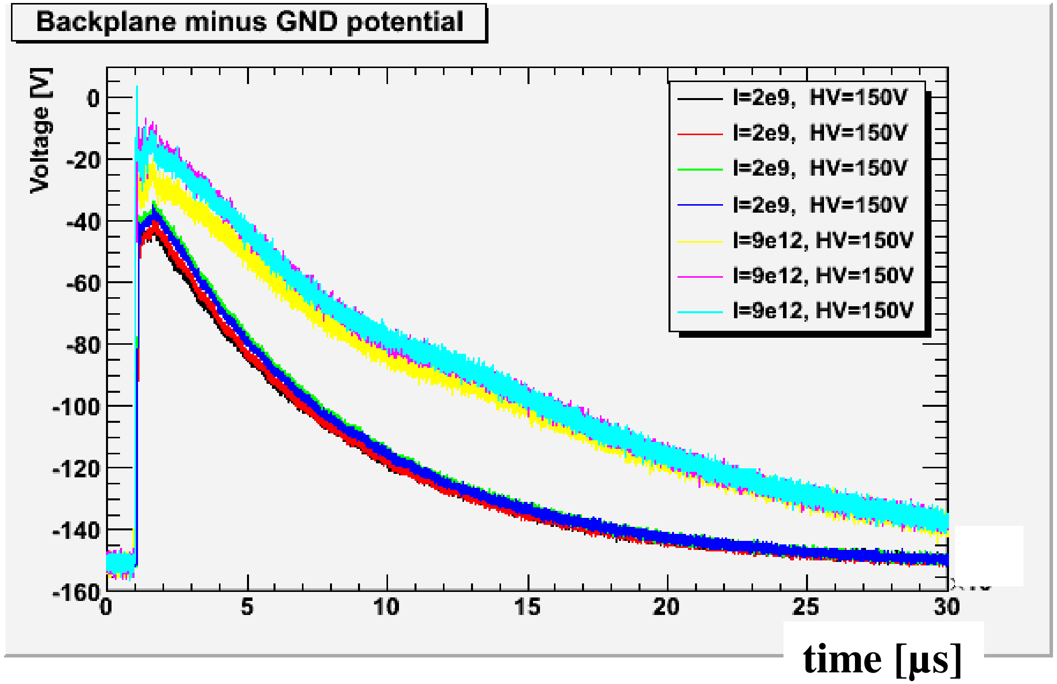
- Noise & pedestals measured in-situ between each shot
  - Plots show date taken towards the end of the program
  - No change visible
- Detailed analysis is in progress

Test pulse response – post-zap



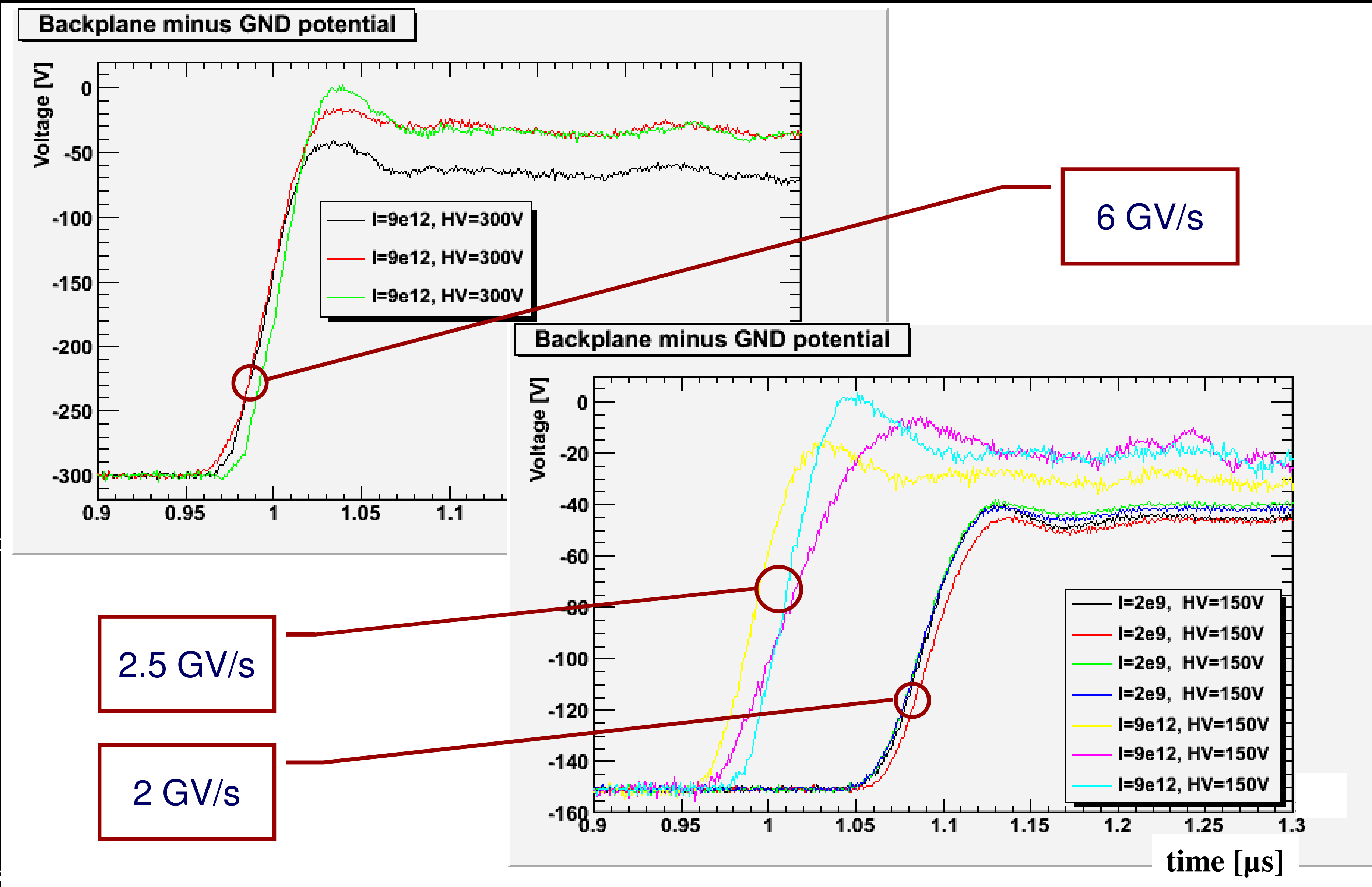
- **Test pulse response**
  - **'booster': in-situ after a couple shots (module almost fresh)**
  - **'lab': lab measurement after the full program**
- **Gain difference due to different analogue drivers/receivers**
- **Bad channels identical to production QA**
- **No significant effect observed due to beam shots**

Voltage across the sensor vs. time



- Oscilloscope measurements
  - Hybrid GND
  - Backplane
  - 1 sample / ns
- Ground reference arbitrary
  - Huge ground bounce
  - Large pick-up
  - Plot $V_{backplane}$-$V_{hybridGND}$
- Two distinct features
  - Sharp rising edge (50 ns)
  - Slow charge-up

The first 50 ns …



Shots on the FE chips

- 56 shots on the FE chips: $2\times10^{9} – 2\times10^{11}$ p/bunch

- No destructive latch-up
  - Design rules include structures to prevent latch-up
  - Seems to be effective!

- SEU analysis in progress: none observed so far
  - Requires large energy deposited in small volume
  - Nuclear reactions necessary
  - Cross-section very low
  - Triple-redundant registers: corrected every 2 ns

Summary of LHCb High Rate Test

- The PS booster provided beam to emulate specific LHC beam injection failures
  - 200 ns shots (+/-2rms), 2×10^9 to 9×10^{12} protons in ~1cm^2
- A VELO strip module was subject to a large number of shots
  - Two positions on the sensor, five FE chips
  - Different conditions on LV and HV
- Survived 9×10^{12} *p* on sensor with 0, 150, 300 V bias, LV on or off
- Survived 2×10^{11} *p* on the FE chip (LV on or off)
- No visible change in performance
  - I/V curves, noise, pedestals, thermal imaging, …
- Saving graces ?
  - The whole sensor responds as a unit
  - Large area sensor – many channels
  - $C_{AC} >> C_{RC}$ $(+C_{DET})$
  - Protection diodes on the FE inputs
  - Triple-redundant registers in FE chips
- Analysis & measurement still in progress

Summary and Outlook

- LHC is very different from what has been seen so far:
  - new (total beam) energy domain
  - cannot run without collimation (cryo/quenches)
- Machine protection will play a key role (especially at turn-on)
  - passive (collimators) , active (beam interlocks, dump/inject)
- Expts have developed own (to some extent, common) protection system
  - Beam Conditions Monitor (CVD diamonds) + other detectors => dump trigger
  - Should take care of circulating beam failures (redundant with machine protection)
  - Must have high availability, reliability, efficiency
  - Feed-back to stop injection is implemented
  - Close collaboration with machine colleagues
- Not all possible failure scenarios for all IP's have been simulated or studied
- Not all exposed detectors have been stress-tested with high particle rates...
  - Showed some recent results on LHCb/VELO damage threshold
- Full chain tests ongoing (some already done)
- Thresholds to be set and fine tuned with beam

Work in progress

Post-~~mortem~~ vivum – why did it survive?

- Deposited energy (in 300 μm Si)
  - $9 \times 10^{12} \times 24000 \times 3.6$ eV => 0.12 Joule in ~200 ns
  - Temperature increase in 1 cm^2 x 0.3mm Si < ~ 2 ˚C
  - Maximum SPS injection train (288×10^{11}): 0.4 Joule / 10 μs
- Local energy store: the RC filter
  - 10 nF @ 300V => 0.5 mJ
  - Absorption volume critical
- Massive ionisation in biased silicon
  - Q_{RC}(300V) = 3 μC
  - Deposited charge @ 2×10^9: 7.5 μC

  } HV bias reduced to 0 V
- Possible transient damage
  - Current through front-end
  - AC coupling diode
  - Voltage on front-end input
  - Fast HV ramp-down