Summary and conclusions

Tracking Systems and Associated Electronics and Readout

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The upgrade of the LHC trackers

- ALICE – LHCb
  - Extend physics program by substantially increasing luminosity
    - e.g. 50 kHZ of Pb–Pb collisions in ALICE; $L=2\times10^{33}\ cm^{-2}s^{-1}$ in LHCb
  - Require new trackers to cope with much higher event rates
  - Upgrades planned for LS2
- ATLAS – CMS
  - Longevity limited by integrated radiation damage
    - Present trackers designed to operate efficiently up to about 500 fb^{-1}
    - Monitoring of critical sensor parameters confirms design goals
    - Large fractions of the detectors would become inoperable well before 1000 fb^{-1}
  - High pile-up requires enhanced functionalities
    - More robust pattern recognition capabilities
    - Enhanced contribution to event selection (trigger)
  - Upgrades planned for LS3
- All trackers
  - Take advantage of novel technologies to improve basic performance
    - Lower material, improved tracking precision
  - Added value to the luminosity delivered by LHC!

Silicon sensors

- Key element of all tracker upgrades to achieve enhanced radiation tolerance and improved performance

- ALICE
  - Extensive use of monolithic pixels, produced on CMOS process
- LHCb
  - Small pixel size (55×55 μm^2) and very thin sensors (150 μm) in the VELO
- ATLAS and CMS
  - ★ Enhance radiation hardness by one order of magnitude!
  - Outer Trackers: n-in-p sensors chosen as baseline; thin sensors (possibly 200 μm) and lower operating temperature (−20°C) required to control bias current
  - Inner pixel detectors: extreme radiation environment is very challenging; 3d sensors may offer enhancement of radiation tolerance further than thin planar sensors

Silicon sensors – key activities

- R&Ds on novel solutions
  - CMOS monolithic pixels
    - ★ High granularity, low material, relatively affordable
    - ★ Baseline for ALICE ITS – may become useable more widely if rad hardness is improved
  - 3d sensors
    - ★ Potentially the option with highest radiation hardness
    - ★ Could be the optimal choice for inner regions of ATLAS and CMS pixel detectors
    - ★ Work with vendors to assess feasibility (quality, throughput, cost…)
- Selection of vendors and quality control
  - Sensors procurements are critical for all Trackers upgrades
  - Large investment of resources and high-level technical expertise required to qualify vendors and monitor quality during production
    - ★ Same level of difficulty as an R&D on a new technology!
    - ★ Crucial for the success of the projects
- Large procurements for the ATLAS and CMS Outer Trackers
    - ★ 2×200 m^2 trackers based on n-in-p sensors, with same timeline
    - ★ Very difficult to find vendors with suitable production capacity and quality
  - A coordinated effort could be highly beneficial
  - Possibility of production on 8” wafers needs to be explored
    - ★ Requires dedicated R&D – may bring substantial financial saving

Electronics

- Front-end
  - Specs
    - ★ Low power / channel
    - ★ Low noise
    - ★ High-density interconnections
    - ★ High radiation tolerance
  - Technologies
    - ★ Deeper (and deeper) sub-micron ASICs technologies
      - 130 nm for strips, 65 nm for hybrid pixels
    - ★ High-density technologies for hybrids substrates
    - ★ Coarse bump-bonding for flip-chip of ASICs to hybrids, and for large pixels
    - ★ Fine-pitch bump-bonding and TSVs for small hybrid pixels

- Back-end
  - Specs
    - ★ High processing power
    - ★ High interconnectivity
  - Technologies
    - ★ xTCA standards
    - ★ Possibly custom-design ASICs for fast pattern recognition (track trigger)

- Services
  - Specs
    - ★ High-speed, low-power links
      - Special requirements for trackers
    - ★ Small-size opto components
    - ★ Power conversion
    - ★ Rad hardness
  - Technologies
    - ★ DC-DC conversion, serial powering
    - ★ 65 nm ASICS for next generation links
    - ★ Low-power low-mass electrical links

Electronics – key activities

- ASICs development
  - ASICs in 130 nm – good progress already, but still a lot of work ahead
  - New (for HEP) 65 nm – huge amount of work, including special radiation qualification for extreme conditions (ATLAS/CMS pixels)
    - Must be a collaborative effort – **RD53 established**
- High density interconnects (hybrid substrates, bump-bonding, TSVs…)
  - Investigate and qualify vendors with suitable products, interested in our volumes and budgets
    - Often project-specific. Share information and experience.
- Power distribution and data links
  - Further developments needed beyond the "phase-1" devices
    - Must continue as common projects
    - Accommodate specific requirements for trackers
    - These developments are critical for the design of the upgraded trackers

Thermal management

Thermal management is of unprecedented importance and difficulty in the HL-LHC trackers

- ★ Higher power and lower operating temperatures; lower mass highly desirable

On-detector thermal management requires novel materials and solutions to achieve better performance, and in general higher radiation tolerance

- ★ Thorough R&D program to be carried out; even "known solutions" need to be re-qualified
- ★ Implementations linked to specific detector design, but most issues are of common interest

Promote exchange of information and experience across experiments

CO_2 cooling is the technology of choice for future Tracker cooling plants

- ★ Positive experience with LHCb VELO; ATLAS IBL and CMS Pixel systems under construction
- ★ Large step forward needed for the ATLAS/CMS phase-2 trackers
- ★ Reliable and affordable lab systems are required (also for common testing infrastructure)

Centralized development for the cooling plants (big systems as well as lab systems) is a must; organization already in place, centered at CERN in PH-DT; needs to be strengthened and fed with resources

Looking forward to:

- Exciting challenge to build the high-luminosity trackers
- Exciting physics!

Thanks in advance to the LHC for all the luminosity

Thank you for your attention