Abstract
This proposal includes R&D of mechanical aspects for a possible 3rd set of disks for the current CMS Forward Pixel detector, a possible intermediate upgrade pixel detector for CMS at the LHC, and the upgrade pixel detector for CMS at the SLHC.
Talk Overview

• Goals for upgrade pixel mechanics
• Review aspects of the current pixel detector for improvement
• Review what’s in our revised plan
• Mechanical R&D that has been started
• Revised R&D task list and milestones
CMS Forward Pixels at Purdue and FNAL

- The Purdue group developed the tools, materials & techniques for assembly, testing and delivery of ~1000 Pixel modules for the CMS FPIX (~250,000 wirebonds and >25 million pixels) at the planned assembly rate of 6 modules per day.

- Rework techniques were also developed at Purdue to recover faulty modules and maximize the final yield.

- The Fermilab group designed, assembled and tested ~250 Panels on 8 Half-Disks (for Pixel module support and cooling), in 4 Half-Cylinders (with cooling and electronics services) for FPIX.

- Fermilab had overall management responsibility for the construction of FPIX, as well as the transportation of detector assemblies to CERN and commissioning of the detector at CERN.
Phase 1 Upgrade Requirements

It is MANDATORY that the Phase 1 Upgrade
- Contribute to the physics by maintaining or improving performance at higher luminosity
- Fit within the available construction and installation time
- Fit within the available funding

It is also HIGHLY DESIRABLE that
- Each part of the Phase 1 Upgrade should be a significant step on the ROADMAP for the Phase 2 Upgrade
Goals for US CMS Pixel Mechanics R&D at Purdue and Fermilab

• In view of the recent Phase 1 upgrade plan, we have *revised* our mechanics R&D toward a Forward Pixel replacement / upgrade detector in 2013 = 3 *disks* + CO2 *cooling*
  – Reduce material significantly (and distribute more uniformly)
  – Reduce # of components and interfaces = simplify assembly
  – Study alternatives to current disks for detector geometry (i.e. fewer module types)
  – Improve routing of cooling, cables, location of control and optical hybrid boards

• A CO2 cooling system may lead to a design that uses significantly less material, and acts as a “pilot system” for implementation in a Phase 2 full CMS (and ATLAS) tracker upgrade.

• Mechanics R&D compatible with new detector layout and technologies required to maintain or improve tracking performance at higher luminosity + triggering capability
  – Serial powering (or other powering scheme)
  – Longer (possibly thinner) ROC with double buffer size for higher data rate and HV-cap
  – MTC (Module Trigger Chip) for pixel-based trigger at Level 1
Current FPIX Material Budget

Most material between $1.2 < \eta < 2.2$ is in Disks (brazed aluminum cooling loops) and electronics (ZIF connectors and adapter boards) and between $2.2 < \eta < 3.6$ in cables and cooling.
Present Pixel System with Supply Tubes / Cylinders

- BPIX end flange printed circuits
- DOH & AOH motherboard + AOH’s
- Power board
- FPIX service cylinder
- Adapter boards
- Port Cards and AOH
- Cooling manifold

η = 1.18
η = 1.54
η = 2.4
Phase 1 Pixel System Concept

- Replace C6F14 with CO2 Cooling
- 3 Barrel Layers + 3 Forward Disks (instead of 2)
- Pixel integrated modules with long Copper Clad Aluminum pigtail cables
- Move OH Boards and Port Cards out

![Diagram showing the Phase 1 Pixel System Concept with labels for BPIX supply tube, FPIX service cylinder, OH Boards + Port Cards + Cooling Manifold moved out, and η values of 1.18, 1.54, and 2.4.](image-url)
Present Mass Distribution in FPIX Service Cylinder

- Port Cards and AOH
- Coils of fibers
- Disks
- Pipes and Cables Front
- Pipes and Cables Back
- End Electronics
- End Flange
- Service Cylinder
# Weight and Radiation Length estimates for replacement/upgrade FPIX detector

<table>
<thead>
<tr>
<th></th>
<th>Present Fpix</th>
<th></th>
<th>New Fpix</th>
<th></th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass (g)</td>
<td>RL (cm)</td>
<td>Mass (g)</td>
<td>RL (cm)</td>
<td></td>
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<tr>
<td>Service Cylinder</td>
<td>7212</td>
<td>206</td>
<td>5770</td>
<td>256</td>
<td>reduce CF thickness, most of SC is outside FPIX acceptance</td>
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<tr>
<td>End Flanges</td>
<td>2820</td>
<td>13</td>
<td>2136</td>
<td>27</td>
<td>use CF instead Al, outside FPIX acceptance</td>
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<tr>
<td>End Electronics</td>
<td>2456</td>
<td>71</td>
<td>2456</td>
<td>71</td>
<td>outside FPIX acceptance</td>
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<tr>
<td>Coil Fibers</td>
<td>2271</td>
<td>162</td>
<td>1136</td>
<td>314</td>
<td>use custom (actual) length fibers</td>
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<tr>
<td>Pipes and Cables Back</td>
<td>4860</td>
<td>5.8</td>
<td>1480</td>
<td>29</td>
<td>1mm diam. CO2 pipes, CCA cables</td>
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<tr>
<td>Port Cards and OH</td>
<td>1616</td>
<td>19</td>
<td>1616</td>
<td>19</td>
<td>move out of FPIX acceptance</td>
</tr>
<tr>
<td>Pipes and Cables Front</td>
<td>5489</td>
<td>6.3</td>
<td>1647</td>
<td>32</td>
<td>CO2 pipes, CCA cables, move manifold out of FPIX acceptance</td>
</tr>
<tr>
<td>Disks</td>
<td>4512</td>
<td>14.7</td>
<td>2345</td>
<td>31</td>
<td>CO2 cooling, CF structure, high TC heat spreaders, half # of HDI</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>31237</strong></td>
<td><strong>56</strong></td>
<td><strong>18586</strong></td>
<td><strong>103</strong></td>
<td></td>
</tr>
</tbody>
</table>

*~40% less mass overall*

*2X less mass in FPIX acceptance (1.5 < η < 2.5) and 2X RL increase*
Revised Mechanics R&D Proposal

Most of the tasks listed in our earlier proposal remain parts of our new plan, with renewed emphasis on reducing material significantly.

Our revised plan:

– develop a conceptual design early that integrates CO2 cooling and lightweight support
– develop mechanics targeted at the design (+ revisions)
– Goal: optimal mechanical/thermal solution for the replacement/upgrade FPIX in ~2 years
Revised Mechanics R&D Proposal

1. Conceptual design
   – Integrate cooling/support structure into an overall detector package and eliminate redundant features

2. Cooling/Support development
   – Study CO2 cooling, including construction of a CO2 cooling system for lab bench testing of prototype integrated cooling/support structure and prototype pixel detector integrated modules
     • Improved C6F14 is backup cooling solution
   – Investigate new materials and designs for support/cooling structure to lower the material budget
     • Study suitability of composites with high thermal conductivity for fabrication of low mass support frame and thermal management scheme
     • Finite Element Analysis of mechanical stability and thermal performance
     • Composite material combinations (ex: Thermal Pyrolytic Graphite vs. C-F laminate) for integrated module support
     • Investigation of alternative cooling channel materials
     • Design cooling structure in a sparse arrangement that minimizes the number of fluid connection joints
     • Measurements of cooling performance of prototype integrated module-on-support structures, and evaluation of radiation hardness of alternative materials
3. Integrated Module Development

- Evaluation of adhesives for integrated module assembly and rework
- Evaluate state-of-the-art alternatives (ex: ceramic vs. flex-laminated-on-rigid substrates) for dense multilayer interconnects for readout and power circuits
- Development of (semi-robotic) tooling to assemble prototype integrated modules
- Testing of mechanical, thermal and electrical properties of prototype integrated modules with radiation
What has been started at Purdue
Integrated module development - Adhesives study

• Begun a market survey of adhesives for pixel integrated module assembly that meet requirements for SLHC
  – Requirements for adhesive:
    • Thermal conductivity: > 0.2 W/m-K
    • Soft: shear modulus < 50 N/mm^2
    • Radiation hard
    • Electrically non-conductive
    • Curing at room temperature
    • Not flowing during application: adhesive confined within chip
    • Good wetting properties
    • Not creeping after curing
    • Allow integrated module replacement without damaging the support

• Will build mechanical grade integrated modules using candidate adhesives and evaluate the mechanical properties after irradiation.

FPIX adhesive sample tensile tested after irradiation
Recent exploration of parameter space @ Purdue

- We can make rows of fine pitch (100 um) bonds with distance vs. height shown in the area bounded by the blue line, but the resulting loop profiles are inconsistent or neighboring wires sometimes touch.
- We can consistently make double (staggered – inner and outer) rows of fine pitch bonds that do not touch each other with distance vs. height shown in the area bounded by the green line.
- At this time, we conclude that we can consistently make double rows of fine pitch step bonds at a height of 2mm with a nominal lateral distance of 3mm.
Currently, FPIX Disks have a lot of material in:
  – passive Si and Be substrates
  – flex circuits with Cu traces
  – thermal conductive (BN powder) adhesive interfaces
  – brazed aluminum (0.5mm wall thickness) cooling channels
Fpix Blade components and thermal interfaces

- Current design has ~20 component layers for a blade. This allows for “standalone module” testing, but at a material price
- Reduce # of thermal (adhesive) interfaces = less material and thermal impedance
- Need method to evaluate bump bond connections before next assembly step = probe testing BBMs before module assembly
Upgrade Integrated Module Concept

- Flip chip modules mounted directly on high heat transfer/stiff material (ex. pyrolytic graphite).
- Wirebond connections from ROCs to high density interconnect/flex readout cables through holes in rigid support / heat spreader
- Leaves pixel sensors uncovered for scanning with pulsed laser
- Flip chip modules REMOVABLE, leaving multilayer interconnect bus intact for replacement modules.
CO₂ Cooling

- A CO₂ cooling system was designed and constructed for the VELO detector in LHCb and will run in conditions (silicon detector, high radiation) that are comparable to CMS and ATLAS conditions
- CO₂ properties are good for silicon detector applications
  - Low viscosity and low density difference between liquid and vapor is ideal for micro channels (d<2.5mm)
  - Ideal for serial cooling of many distributed heat sources
  - High system pressure makes sensitivity to pressure drops relatively small
  - High pressure (up to 100 bar) no problem for micro channels
  - Radiation hard
  - Environment friendly, ideal for test set-ups
  - Optimal operation temperature range (-40°C to +20°C)
- “No showstoppers” foreseen using existing CMS pipes for CO₂ cooling, but modifications will have to be made to the LHCb CO₂ system to reduce the pressure for CMS pipes
- CO₂ cooling may be the best coolant for any upgrade in the CMS and ATLAS inner detectors
**CO$_2$ Cooling**

Small diameter (1mm) pipes for CO$_2$ cooling:
- much less mass $\sim$1/10
- small area for heat transfer - have to route enough tubes for sufficient thermal contact with pixel modules
- lends to design similar to current FPIX - flat substrates for module support and tubing loops

→ need for material budget optimization -- passive high thermal conductive panels vs. routing small diam. CO$_2$ cooling tubes to heat sources

Consider cooling tube at edge of panel with pixel modules mounted on heat spreader

2D FEA model of the FPIX blade heat sink coolant temp of -15°C

L. Cremaldi, U. Miss.
## Activity Matrix

<table>
<thead>
<tr>
<th>Institution - topic</th>
<th>Activity 1</th>
<th>Activity 2</th>
<th>Activity 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purdue – integrated module assembly</td>
<td>Evaluate adhesives and alternatives for dense multilayer interconnects</td>
<td>Develop prototype integrated module assembly robot</td>
<td>Test prototype integrated modules, evaluation of radiation hardness</td>
</tr>
<tr>
<td>Purdue – integrated support/cooling</td>
<td>Develop conceptual design that integrates CO2 cooling with overall detector design</td>
<td>Evaluate materials for cooling tubes with a minimum of connections</td>
<td>Construction of a CO2 cooling system for lab bench testing</td>
</tr>
<tr>
<td>Fermilab – integrated support/cooling</td>
<td>Study carbon fiber and oriented graphite composites using FEA models and prototypes</td>
<td>Measure cooling performance of prototype integrated module-on-support structures</td>
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<tr>
<td>Task list</td>
<td>FY 2008</td>
<td>FY 2009</td>
<td>FY 2010</td>
</tr>
<tr>
<td>-----------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
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<tr>
<td>Conceptual design cooling/support structure (with revision)</td>
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<td>X</td>
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<tr>
<td>CO2 cooling study - construction of a CO2 cooling system</td>
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<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Study composites with high thermal conductivity for fabrication of low mass support frame</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Investigate cooling channel material alternatives</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Evaluate design and materials support/cooling structure (FEA)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Measure cooling performance of prototype integrated module-on-support structures</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Evaluate adhesives and dense multilayer interconnects</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Develop integrated module assembly robot</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Test prototype integrated modules (mech, thermal, electrical properties with radiation)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
FY08-FY09 R&D Schedule

Evaluate adhesives:

- Q2-Q3 FY08: Identify candidate adhesives (*In progress*)
- Q3-Q4 FY08: Test radiation hardness by measuring mechanical strength of samples at low operating temperature before and after irradiation with fluence up to 10E16 protons/sq cm
- Q4 FY08: Measure thermal conductivity of module samples assembled with candidate adhesives
- Q1 FY09: Evaluate suitability for semi-automated assembly and integrated module repair

**Milestone**

Q1 FY09: Identify reliable, repeatable and reworkable adhesive(s) (robust for SLHC conditions) for pixel integrated module assembly and rework.

Evaluate dense multilayer interconnects:

- Q2-Q3 FY08: Identify candidate state-of-the-art substrates (*In progress*)
- Q3-Q4 FY08: design and fabricate sample substrate multilayer interconnects
- Q1 FY09: test radiation hardness, electrical performance, and wirebondability

**Milestone**

Q1 FY09: Identify optimal product(s) for dense multilayer interconnects.

Conceptual Design of cooling/support structure:

- Q4 FY08: identify requirements for CO2 cooling and low mass/stiff/high thermal conductive support
- Q4 FY08-Q1 FY09: CAD design of conceptual model
- Q2-Q3 FY09: perform mech. and thermal FEA of CAD model – feedback to design revisions

**Milestone**

Q3 FY09: optimal conceptual design for replacement/upgrade FPIX detector, ready to proceed to preliminary design for TDR
FY08-FY09 R&D Schedule (cont.)

Study composites with high thermal conductivity
  Q3 FY08: identify candidate low mass/stiff/high thermal conductive materials
  Q4 FY08-Q1 FY09: fabricate sample structures
  Q1-Q2 FY09: test mechanical and thermal performance of samples
*Milestone* Q2 FY09: Identify optimal composite materials for low mass support structure

FY09-FY10 R&D Schedule

CO2 cooling study
  Q1-Q2: investigate cooling channel material alternatives
  Q2-Q4: construction of CO2 cooling system for bench testing
*Milestone* Q4: reliable CO2 cooling system for testing of prototypes

Evaluate design and materials for support/cooling structure:
  Q1 FY09-Q1 FY10: perform FEA and test performance of integrated modules-on-supports
*Milestone* Q1 FY10: Identify optimal design and construction for low mass support/cooling structure.

Prototype integrated module assembly robot:
  Q1-Q2: design and fabricate tooling for prototype integrated module assembly
  Q3-Q4: motorize and program assembly tooling
*Milestone* Q4: Operation of robot for reliable, repeatable assembly of integrated module prototypes.

Test prototype integrated modules:
  Q2-Q3: testing of mechanical prototype integrated modules
  Q3-Q1 FY10: testing of electrically working prototype integrated modules
*Milestone* Q1 FY10: Demonstrate reliability of assembled prototype integrated modules.
Relation to other WG and R&D activities

- Our R&D plan to develop a lightweight and highly integrated support structure using CO2 cooling for FPIX is a complement to the PSI group proposal for a phase 1 BPIX upgrade including:
  - a very lightweight structure with CO2 cooling
  - streamlined services and integrated modules
  - compatible with existing CMS services

- Our plan to develop a lightweight and highly integrated CO2 cooling/support structure for FPIX is a complement to the R&D at UCSB of an improved cooling scheme for an upgrade tracker

- We share an interest in CO2 cooling with ATLAS upgrade groups, particularly in the development of CO2 cooling for LHCb VELO by NIKHEF. It will be very useful to collaborate with these groups on the development of CO2 cooling for a low-mass Phase 1 pixel upgrade for CMS.
Summary

Plan for upgrade mechanics R&D for next two years at Purdue and Fermilab:

- Addresses aspects of the current pixel detector for improvement
- Goals for upgrade mechanics
- Tasks, schedule and milestones

In the next two years, we plan to be prepare an optimal design solution for structural support and cooling, and plan for assembly of an upgrade FPIX detector for Phase 1 in 2013, including:

- Requirements and specifications
- Preliminary design
- Structural and thermal analysis – performance predictions
- Prototype assembly and testing

→ Preparation for Technical Design Review ~18 months from now
→ Construction phase ~2.5 years from order of components (based on current Fpix experience).
Responses to CMS Upgrade Management Board comments on SLHC Proposal 7.15

1. Reevaluate the timescale to deliver a sound conceptual design, including sufficient feedback from the evaluation phase.

Answer: we will make a conceptual design by Q1 FY09, and focus all development and analysis toward optimizing and completing the conceptual design by Q3 FY09.

2. As a great deal is to be accomplished in a short time, explain more about the linkages between the various tasks in the project.

Answer: we will proceed from an early overall detector conceptual design, to identification of requirements for module, support structure and cooling design, to parallel development of critical items that must be tested to meet the requirements, and feed back the development and test results to the overall conceptual design. A MSProject schedule is being made to clearly show the linkages between tasks and to track progress.

3. Explain the relation of this project to other pixel R&D in CMS and possibly ATLAS.

Answer: see slide 24.
Backup slides
Resolution of Flat Disk VS Turbine at 20°

Fig. 18. A resolution of 46 µm is found along columns for $\alpha = 0^\circ$ using charge sharing. The peak at the center indicates a higher resolution in case charge was shared with neighboring pixels.

Fig. 19. An average resolution of 17 µm is found along columns for $\alpha = 20^\circ$ using charge sharing.

- 20° angle of sensors improve resolution from 46 to 17 microns according year 2000 CERN measurements.
- Improved vertex resolution by factor of ~2 (raw estimation)
Detector design ideas

- R&D will greatly depend on the detector design
  1. Keep 20° tilt angle of sensors
  2. Al cooling channels replaced by small diam. Cu-Ni (if high pressure CO2 is used) or PEEK, LCP, or CF
  3. Consider edge cooling
  4. Inner and outer Al support rings $\rightarrow$ CF
  5. Use HighTC heat spreaders (TPG) and cool from outer ring
  6. Possibly small CO2 tubes running in grooves machined in Be or C-C manifold around the edge

- A “flat disks” Fresnel design may also work (to reduce material), but loss in single hit resolution is troubling.