FPIX Mechanical Design & Module Development

Alternative layouts of pixel modules on disks to spur discussion about optimal mechanical design (also cooling tube and electronics layouts)

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Phase 1 Upgrade Mechanics Goals

This work is part of our R&D plan described in:

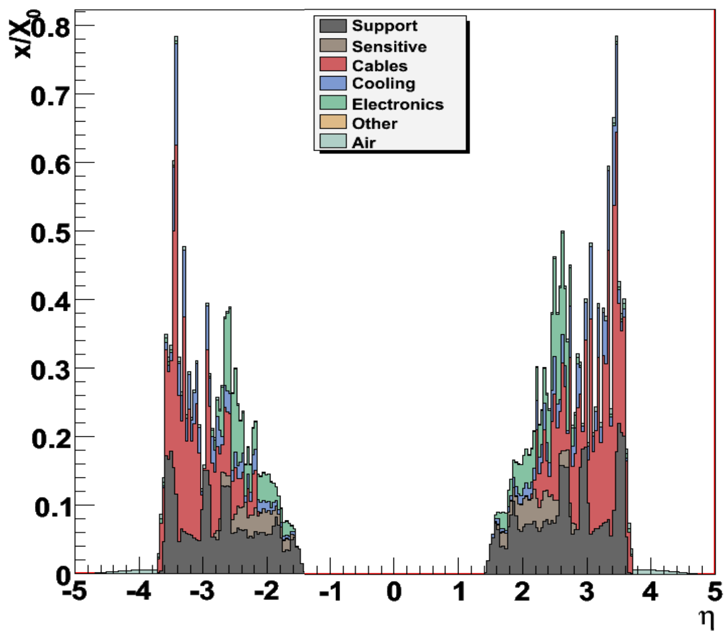
Proposal for US CMS Pixel Mechanics R&D at Purdue and Fermilab

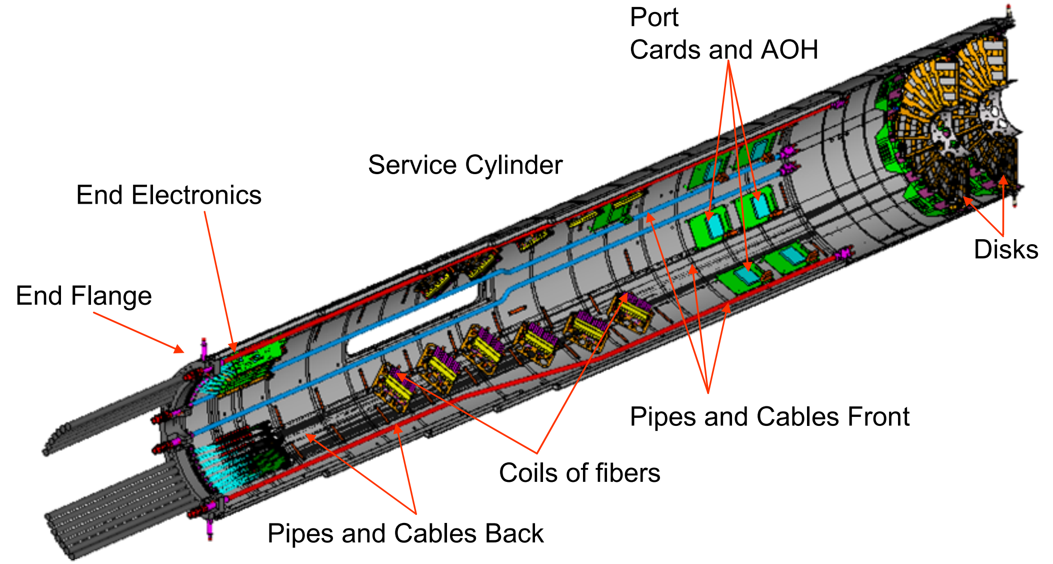
Daniela Bortoletto, Petra Merkel, Ian Shipsey, Kirk Arndt, Gino Bolla, Simon Kwan, Joe Howell, C.M. Lei, Rich Schmitt, Terry Tope, J. C. Yun with valuable input from Lucien Cremaldi, Greg Derylo, Mikhail Kubantsev, Vesna Cuplov (http://indico.cern.ch/conferenceDisplay.py?confId=28746)

We've identified three objectives for the Phase 1 FPIX detector in order to reduce material significantly (and distribute more uniformly):

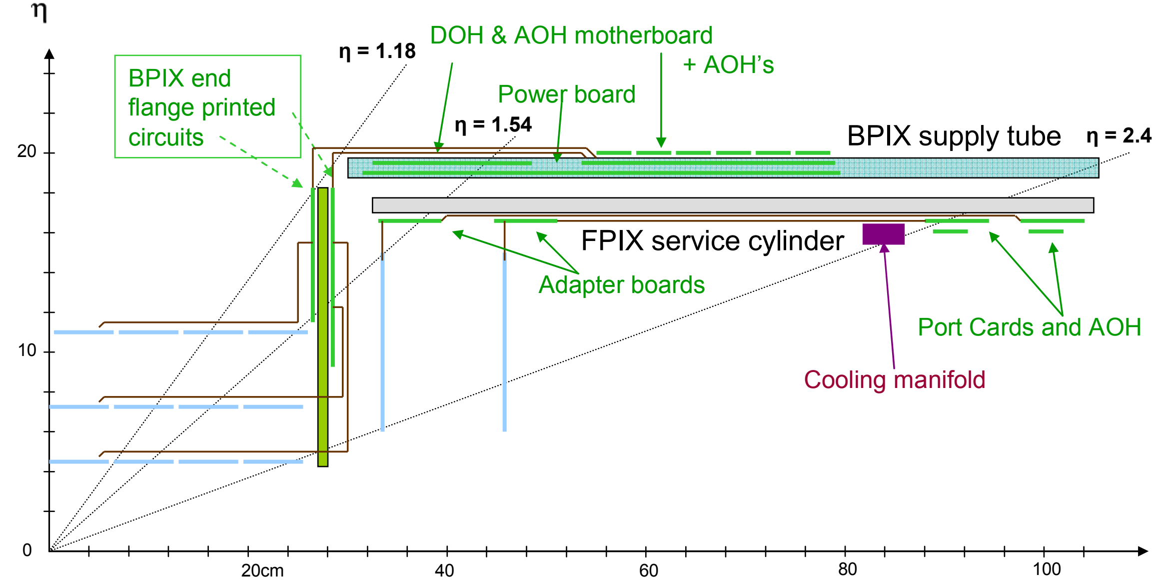
1) **Integrate CO2 cooling and lightweight support**
2) **Reduce # of module types and interfaces**
3) **Improve cooling and cable routing, move control and optical hybrids out to higher η**

Present Material Distribution in FPIX Service Cylinder





Most material in the current Fpix detector between **1.2 < η < 2.2** is in **Disks (brazed aluminum cooling loops)** and electronics (connectors and adapter boards) and between 2.2 < η < 3.6 in cables and cooling



Mechanical R&D

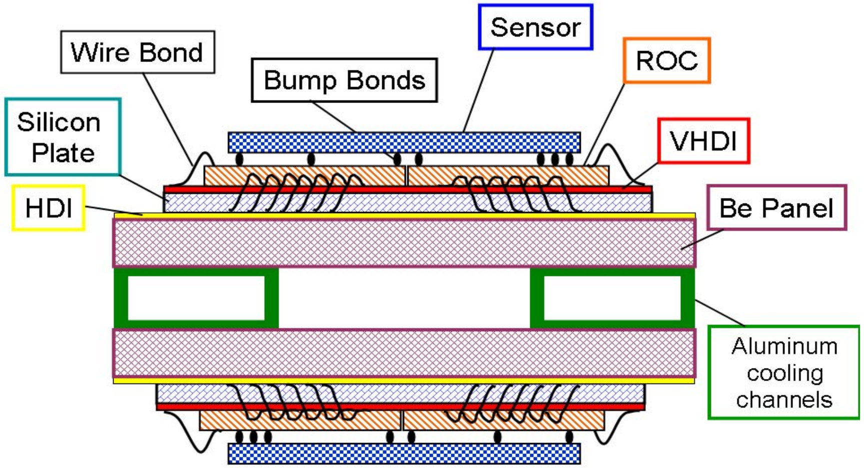
Current FPIX blades have:

- passive Si and Be substrates
- brazed aluminum (0.5mm wall thickness) cooling channels

Integrated modules concept

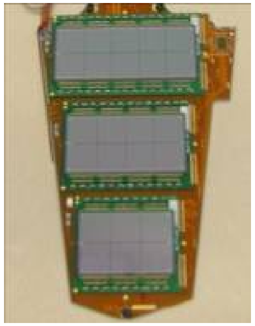
- Flip chip modules mounted directly on low mass/high heat transfer/stiff material (ex. pyrolytic graphite)

LARGE MATERIAL BUDGET

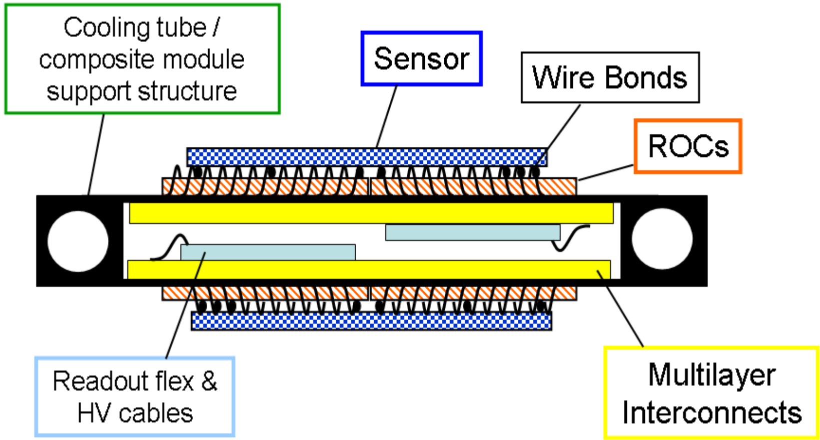


FPix blades have 7 different modules

(we assembled ~1000 modules to yield 672 for installation + spares)



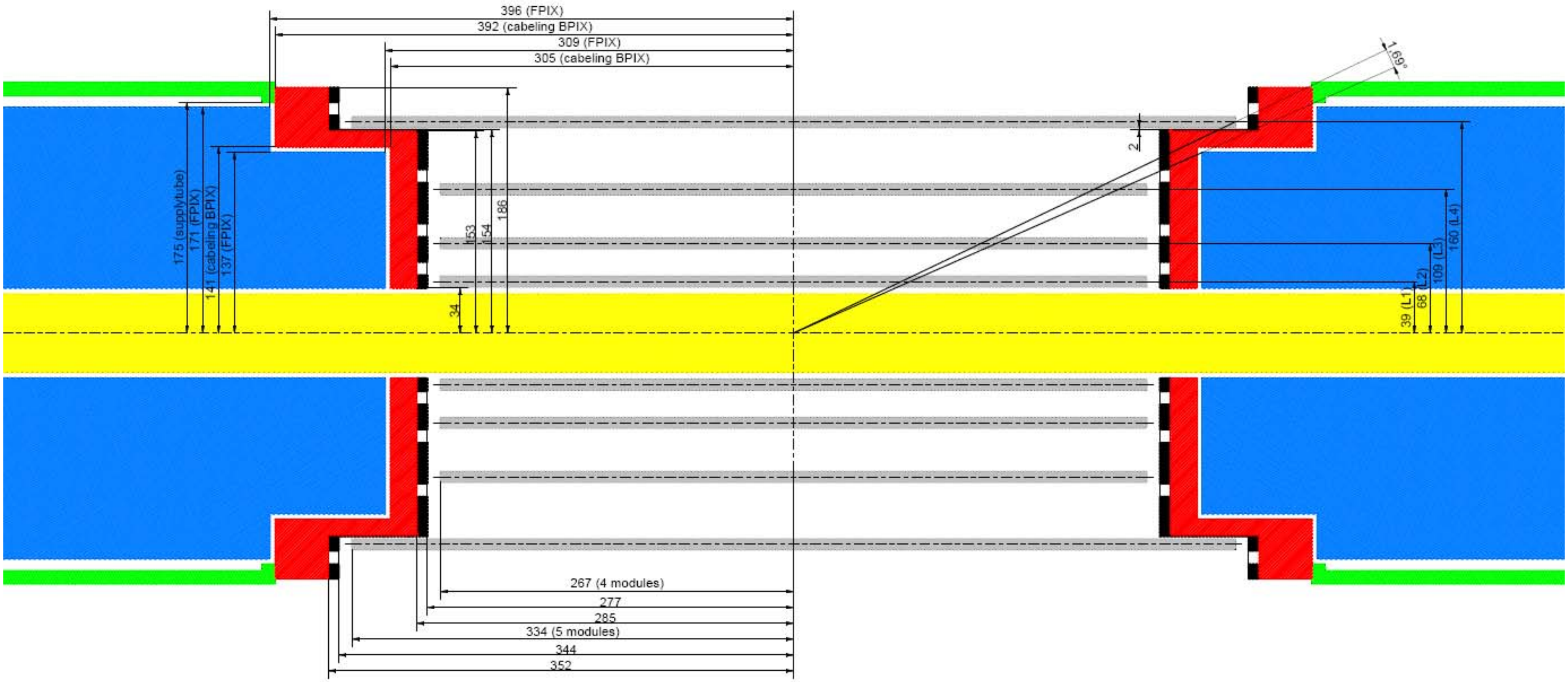
LOW MATERIAL BUDGET



- New system: fewer module types
- Lightweight support structure
- CO2 cooling

Side view of BPIX 4 layer proposal

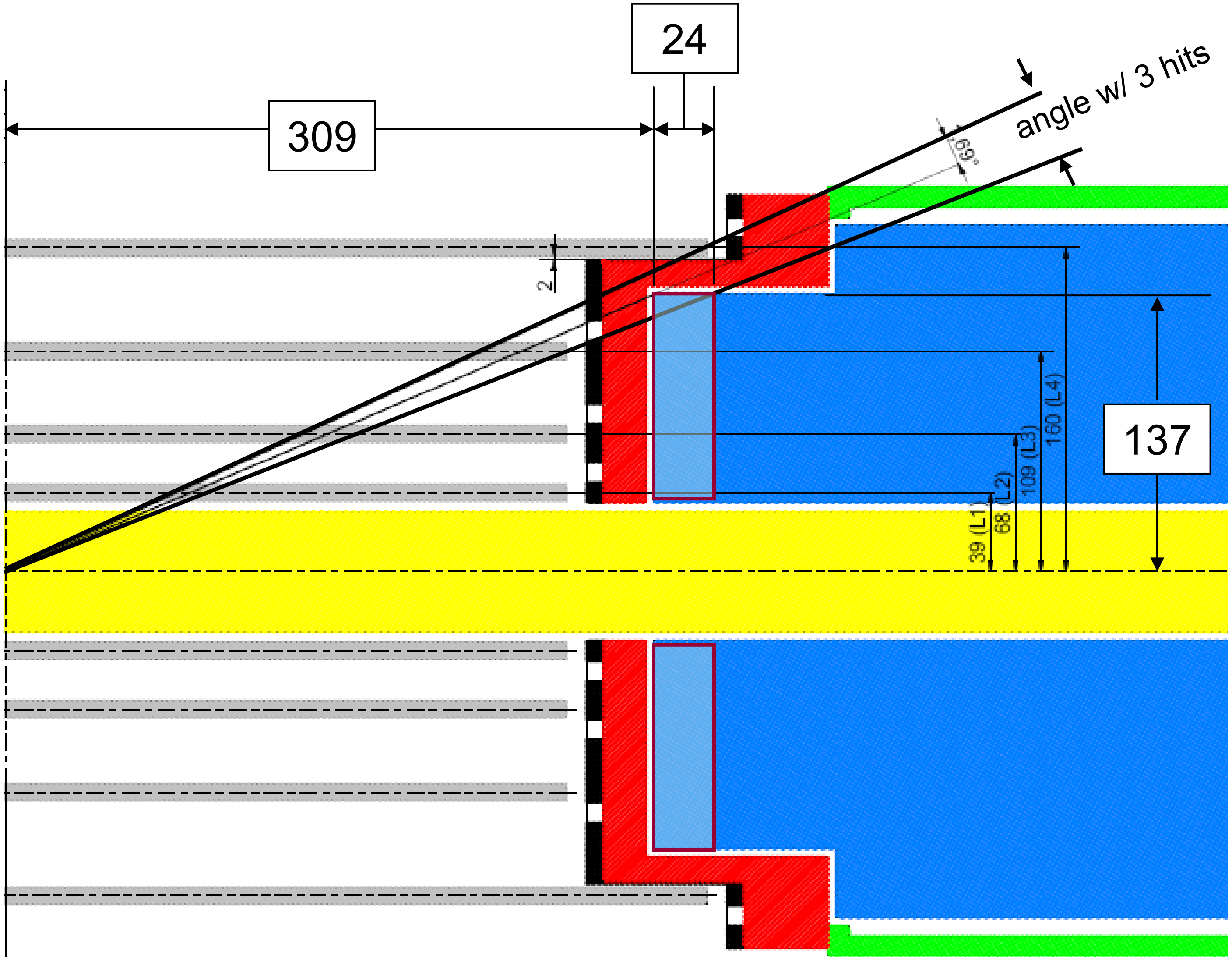
Current FPIX 4 disks at Z: ±345 and ±465 mm
sensor inner radius: 59   outer radius:145



Dimensions for forward-most disk sensors in "Piston Region"

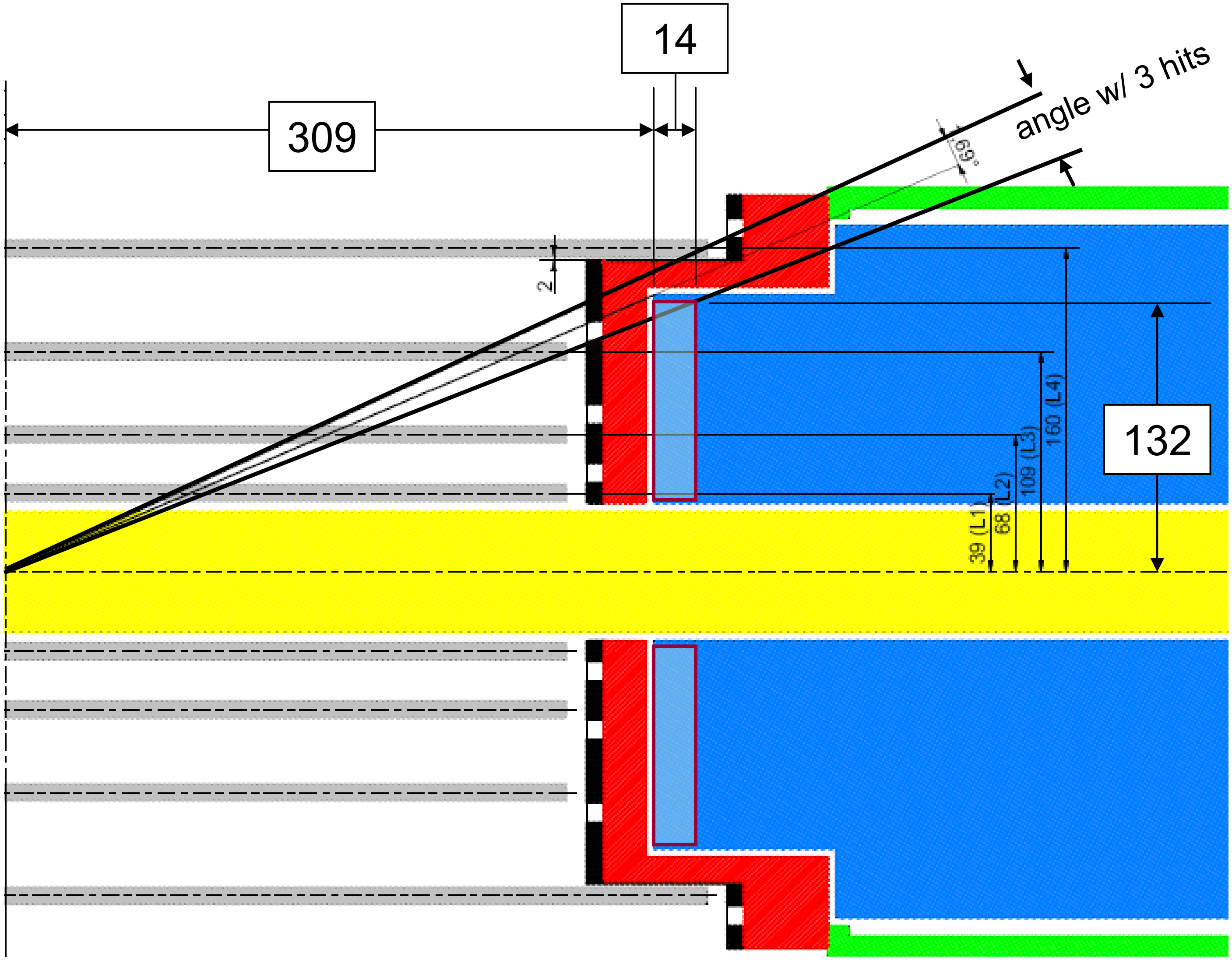
to ensure three hits as acceptance angle increases beyond the third barrel layer

*Max Z dimension for modules at R=137mm is **24 mm***



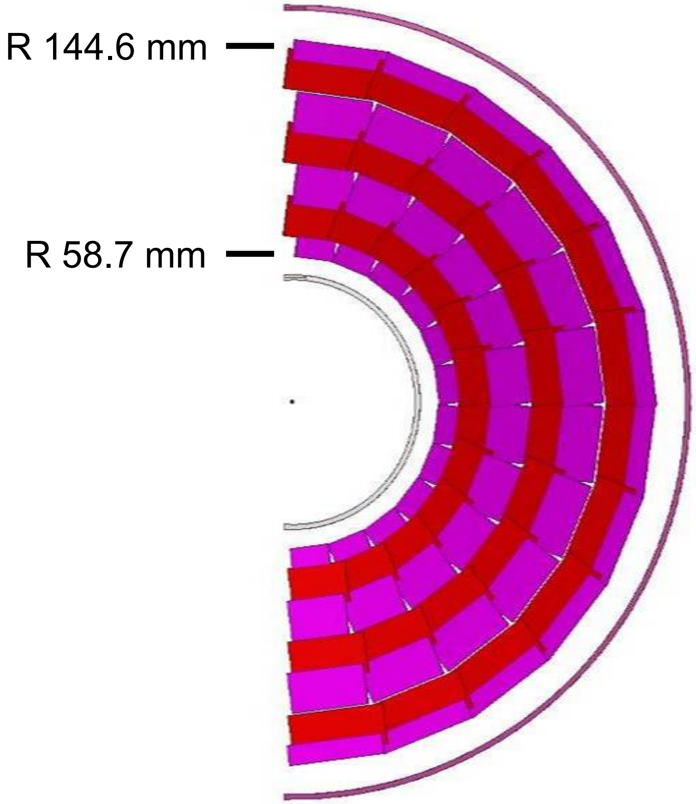
Dimensions for sensors in PRACTICAL forward-most disk in Piston Region

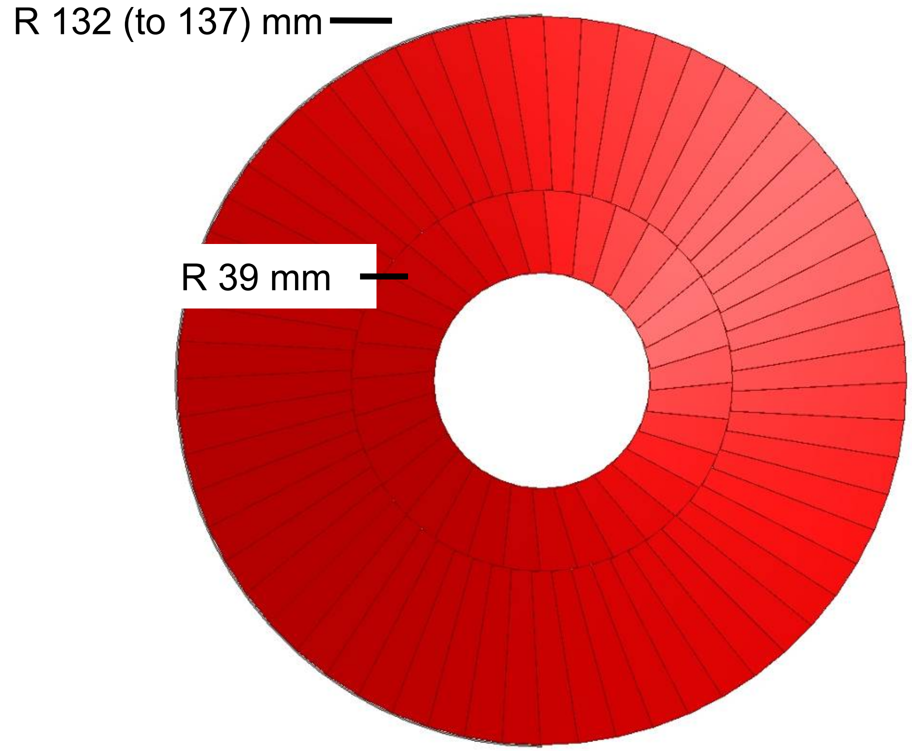
*Max Z dimension for modules at Practical R=132 mm is **14 mm***



Conceptual "Small Disk" Module Layout

radial and ϕ overlaps (and 20° tilt of sensors) to fit Piston Region for Long 4th layer BPix





Current Fpix module layout

7 module geometries
168 modules per disk
(1080 ROCs per disk)

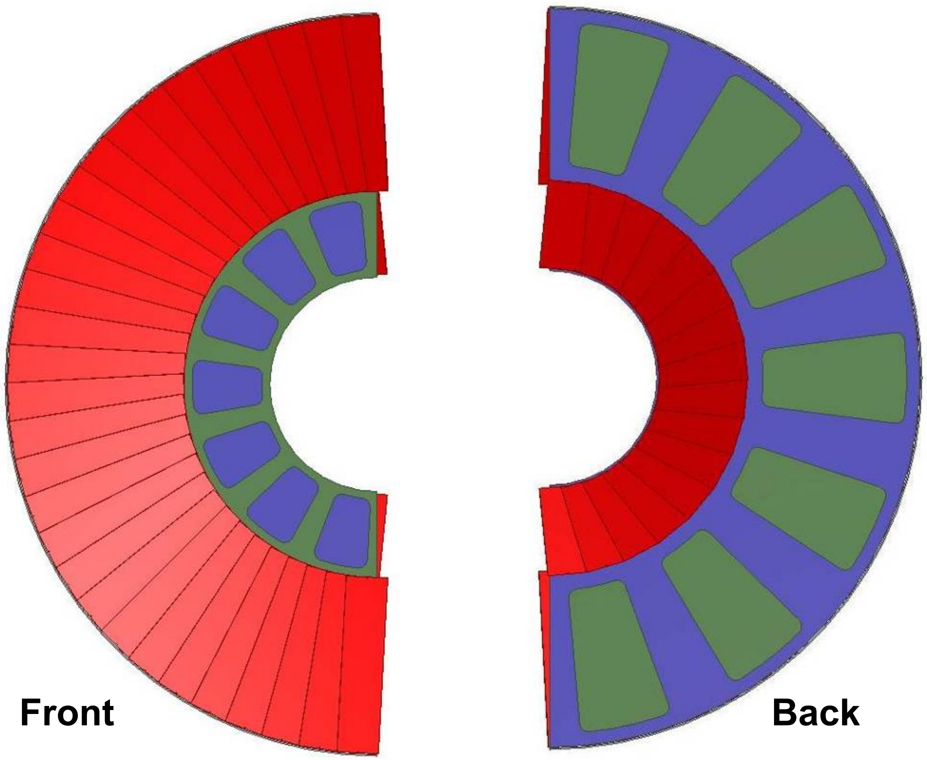
Radial layout of (60) 2x8 and (32) 2x4 modules

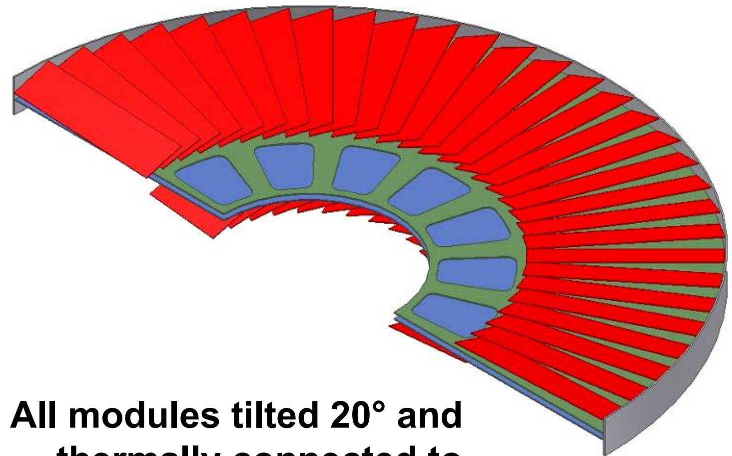
2 module geometries
92 modules per disk
(1216 ROCs per disk)

Small Disk Concept 1 - Shingles on single bulkhead

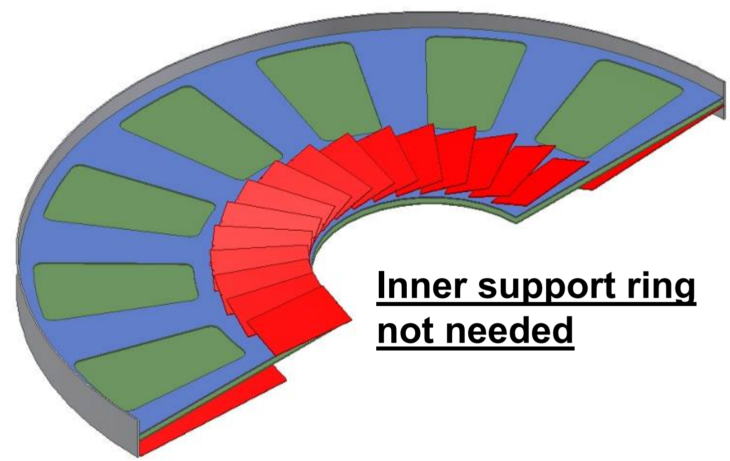
All 2x8 modules "shingles" along outer radius on front side of half-disk

All 2x4 modules "shingles" along inner radius on back side of half-disk





All modules tilted 20° and thermally connected to (actively cooled) bulkhead



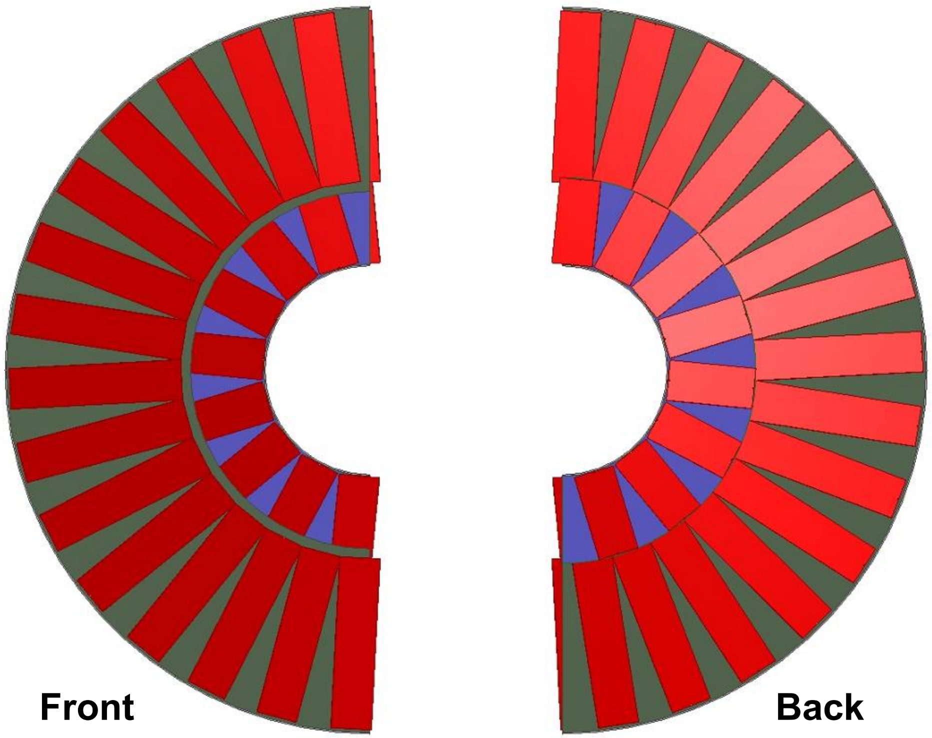
Inner support ring not needed

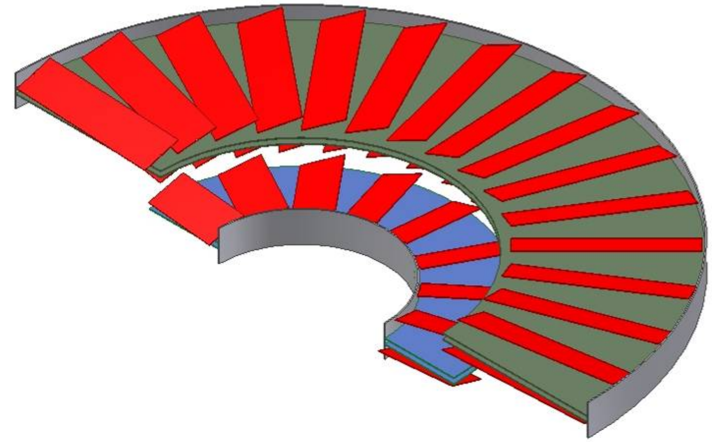
Insufficient clearance between neighboring modules for wirebonds and interconnects

Small Disk Concept 2 – Shingles on two bulkheads

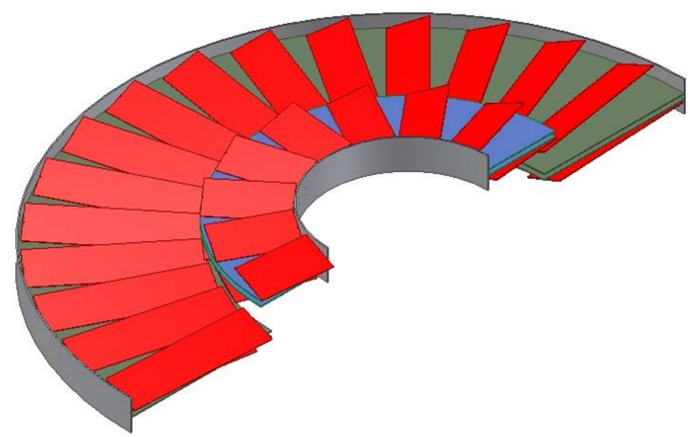
2x8 module "shingles" on outer radius bulkhead alternate on both sides of half-disk

2x4 module "shingles" on inner radius bulkhead alternate on both sides of half-disk





Modules tilted 20° on both sides of inner and outer radius (actively cooled) bulkheads

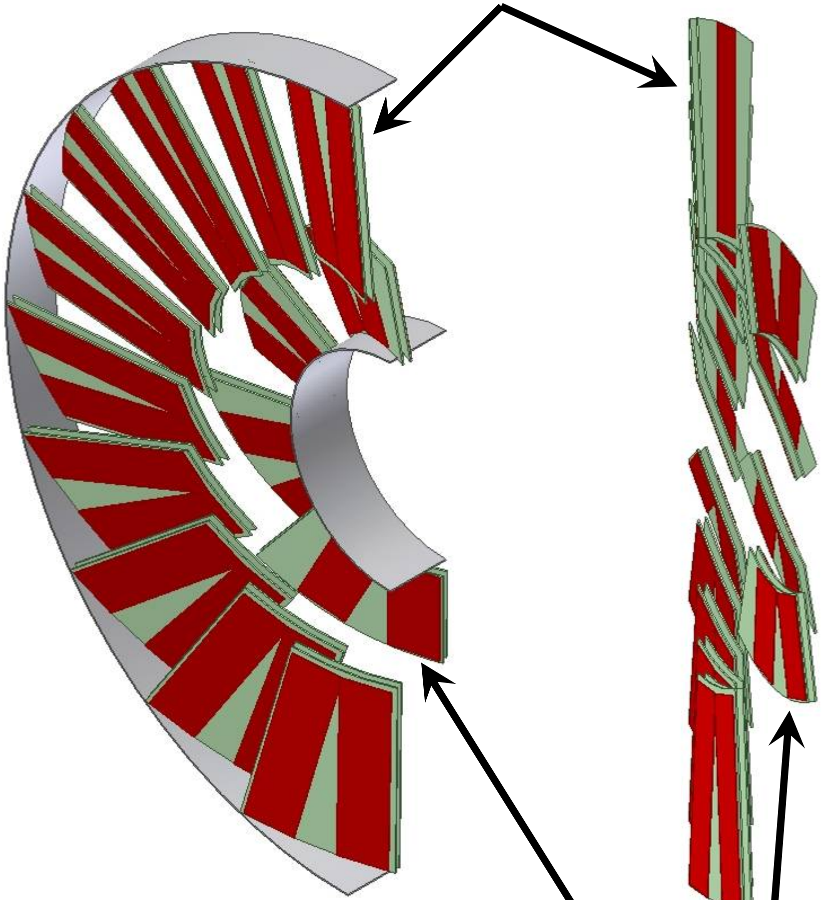


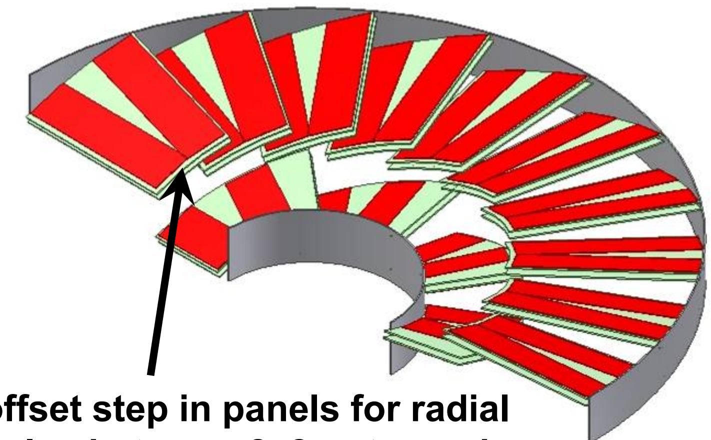
<u>Outer and Inner Radius modules mounted on separate structures for replacement of radiation damaged (inner radius) modules</u>

Small Disk Concept 3 - Modules on tilted Blades

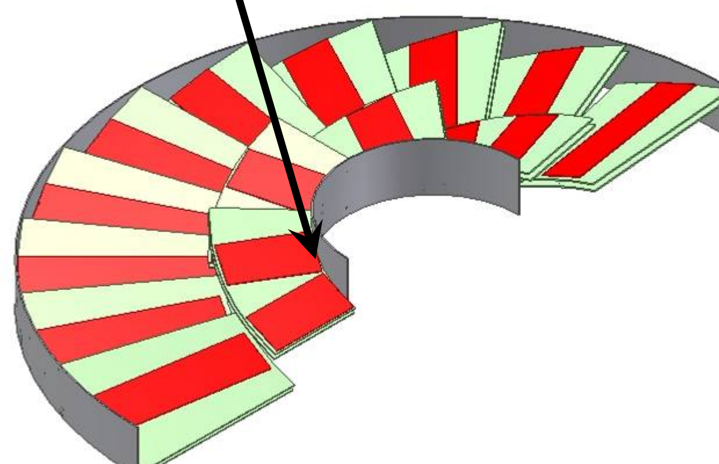
2x8 modules alternate on both sides of 10 outer radius Blades

(3) 2x8s and (4) 2x4s on each actively cooled Blade (Front Panel + Back Panel) tilted 20° in half-disk





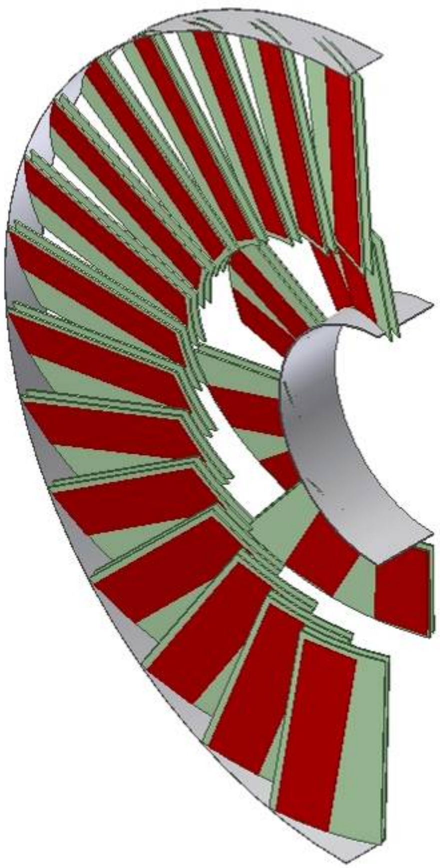
Z-offset step in panels for radial overlap between 2x8 outer and 2x4 inner radius modules



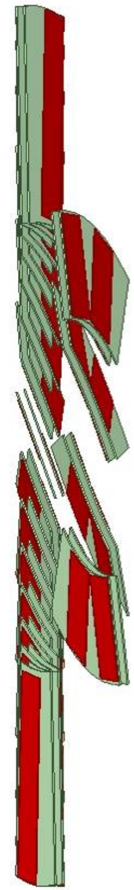
2x4 modules alternate on both sides of 4 inner radius Blades

Small Disk Concept 4 - Modules on tilted Blades

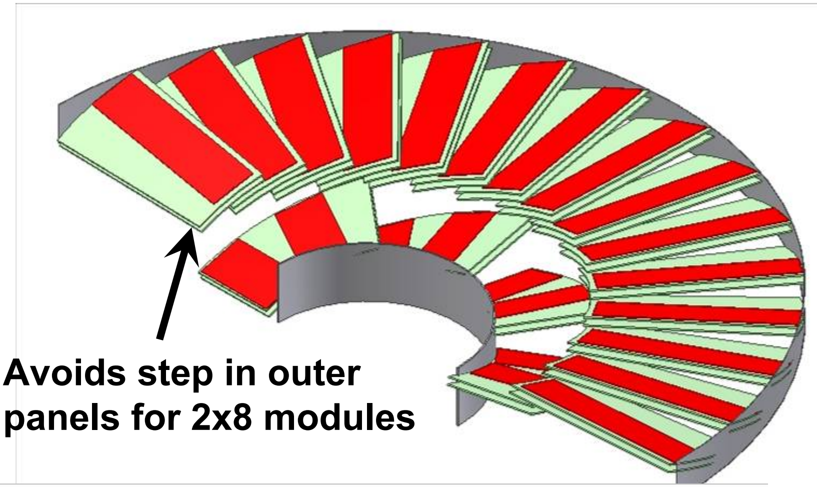
2x8 modules alternate on both sides of 15 outer radius Blades



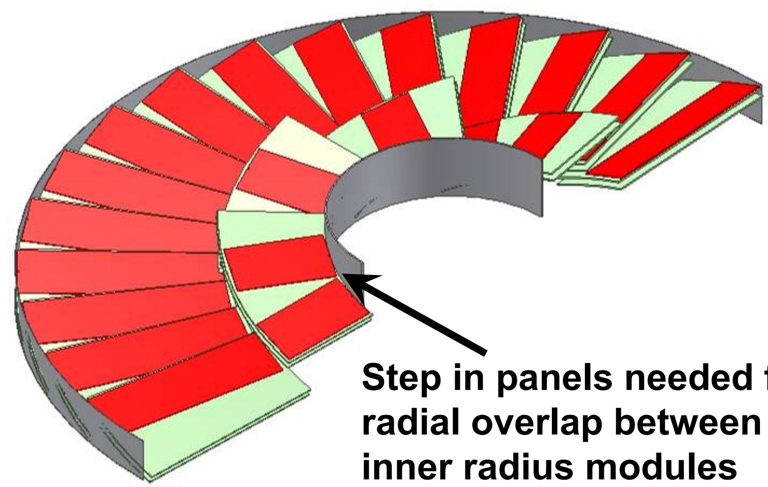
2x4 modules alternate on both sides of 4 inner radius Blades



(2) 2x8s and (4) 2x4s on each actively cooled Blade tilted 20° in half-disk



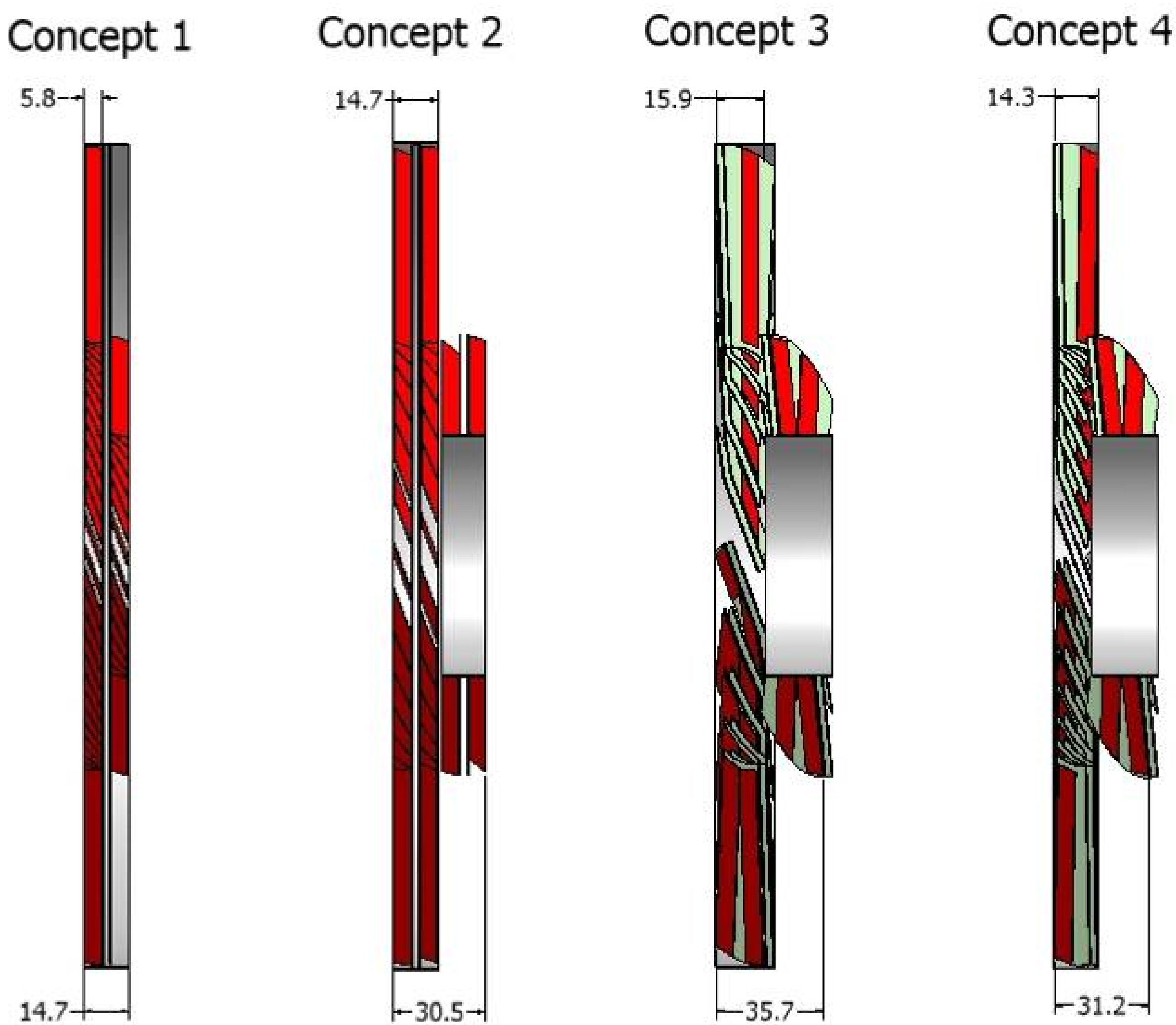
Avoids step in outer panels for 2x8 modules



Step in panels needed for radial overlap between 2x4 inner radius modules

Z axis dimensions of Small Disk Concepts for Piston Region

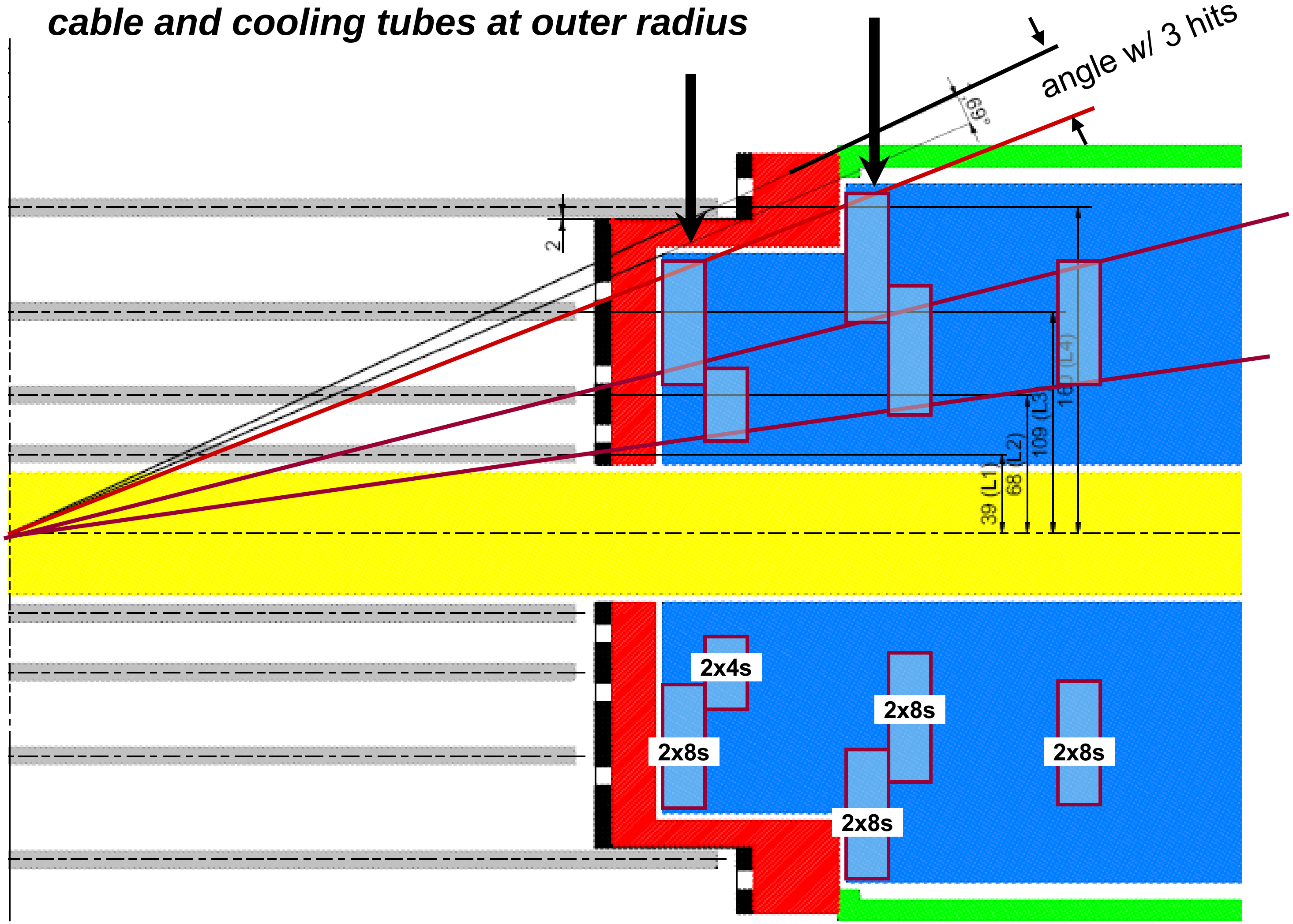
Z dimension of outer (2x8) module arrays is < 24 mm
BUT > 14 mm practical width in Concepts 2-4



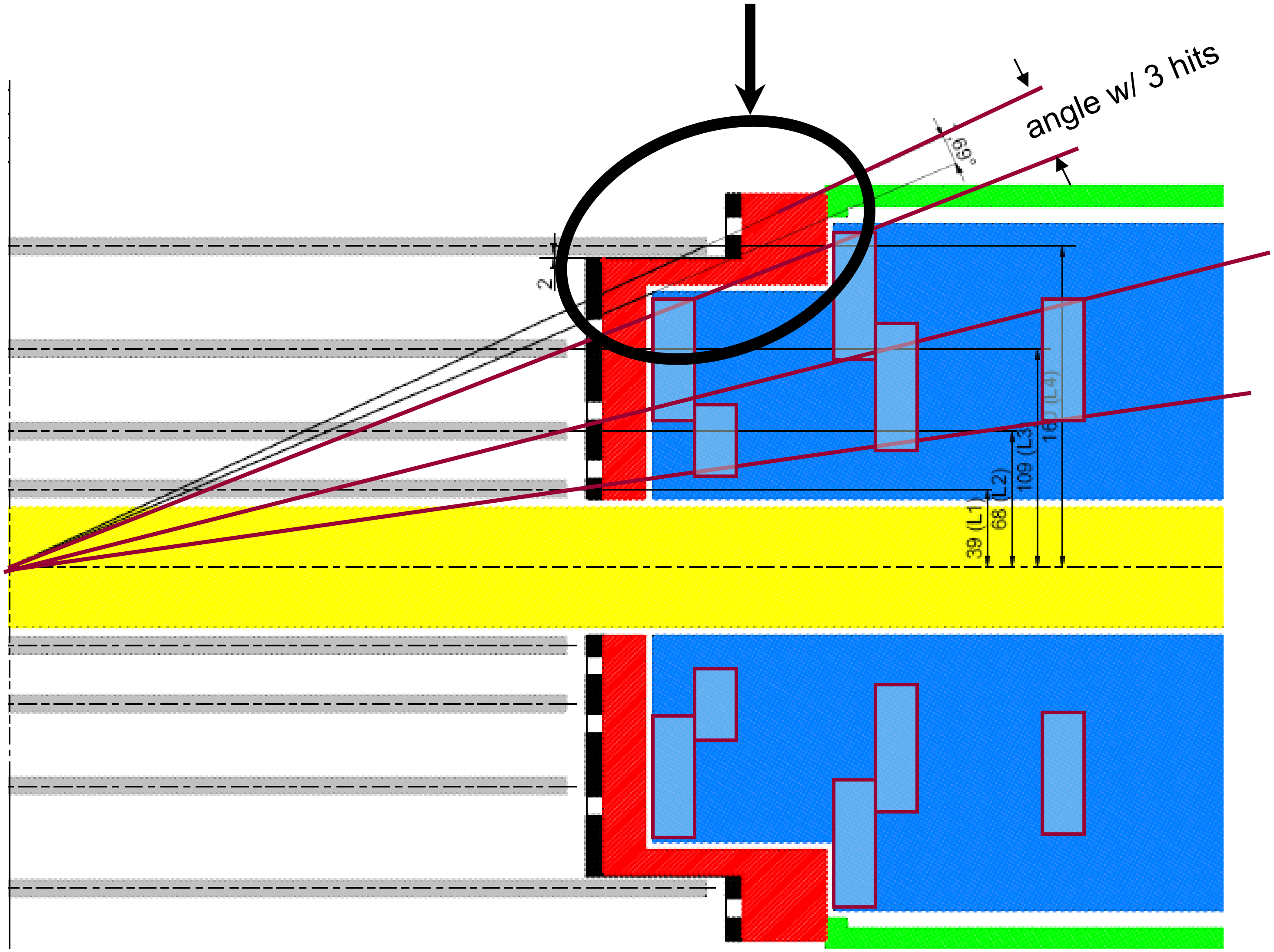
Outer radius locations required for 1st and 2nd disk sensors

(to ensure four hits as acceptance angle increases beyond the third barrel layer)

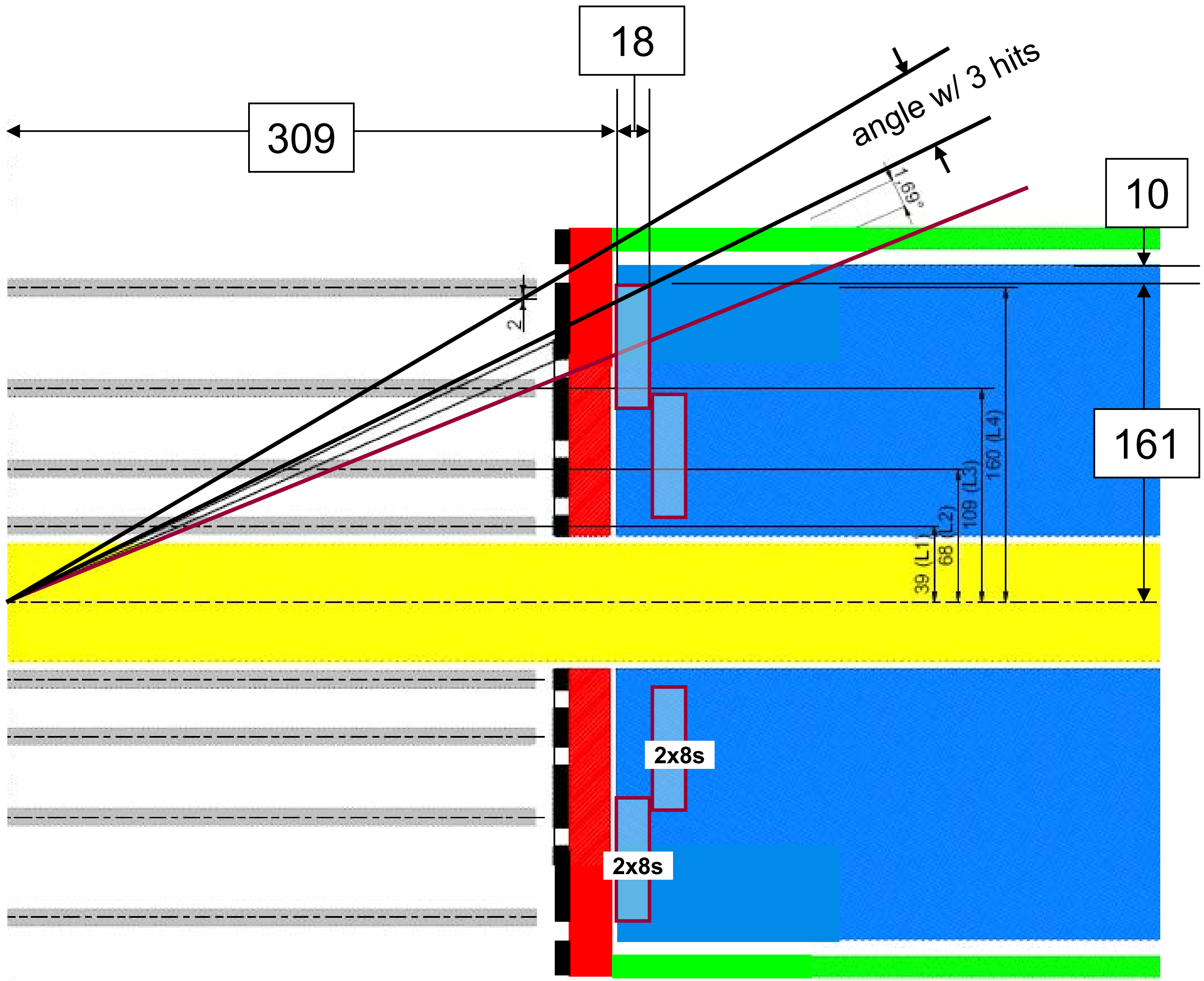
- ***Insufficient "depth" in Z for width of disk sensor arrays***
- ***Insufficient space for outer ring, service cylinder, cable and cooling tubes at outer radius***



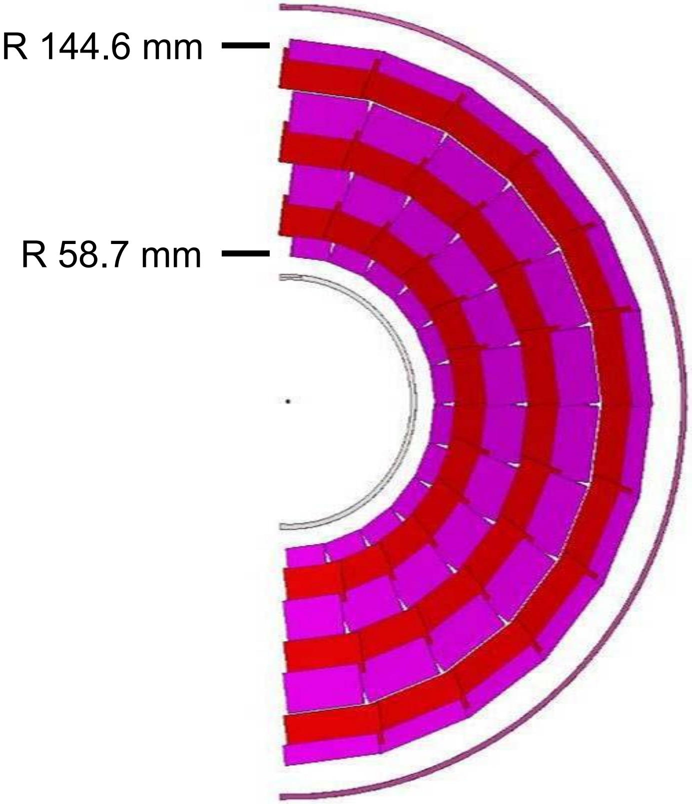
A lot of material due to folding of cables and cooling in this region



Dimensions for sensors in PRACTICAL forward-most LARGE DISK for Short 4th Layer BPIX

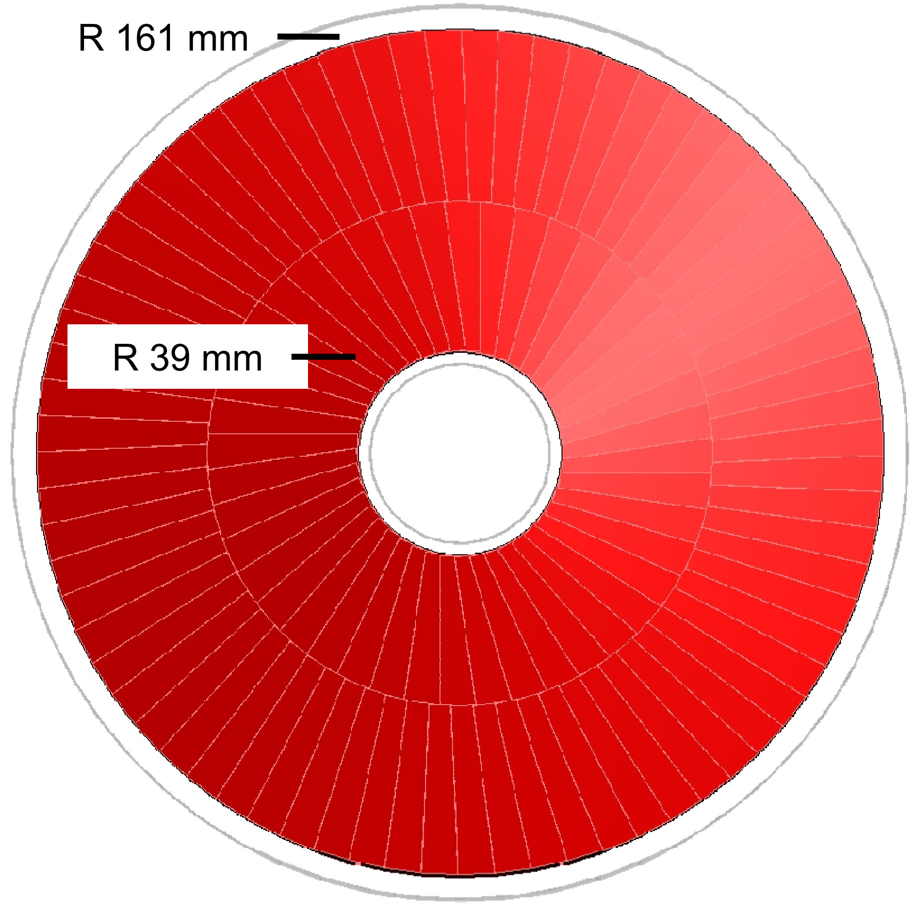


Conceptual Large Disk Module Layout for Short 4th layer BPix



Current Fpix module layout

7 module geometries
168 modules per disk
(1080 ROCs per disk)



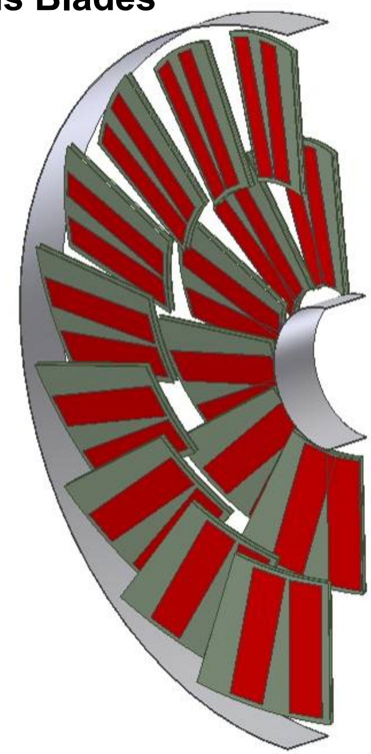
Radial layout of (72) 2x8 outer and (48) 2x8 inner radius modules

1 module geometry
120 modules per disk
(1920 ROCs per disk)

Large Disk – Module layout options

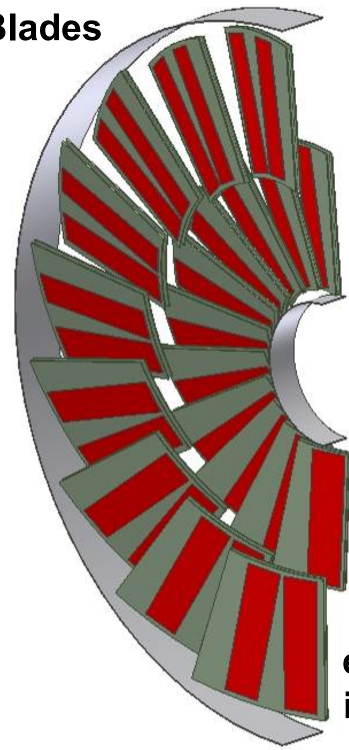
Option 1:

(2) 2x8 modules on each side of all outer and inner radius Blades



Option 2:

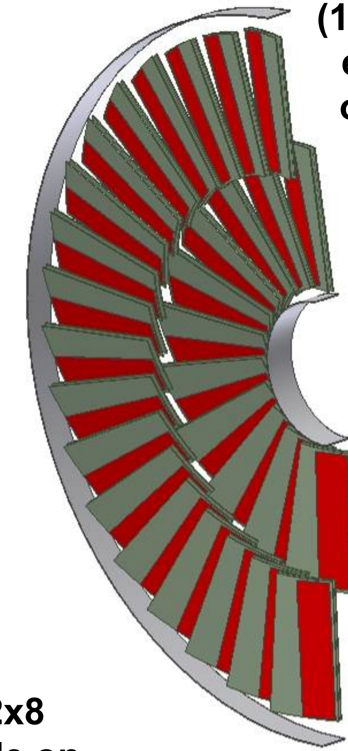
(2) 2x8 modules on each side of outer radius Blades



(1) 2x8 module on each side of inner radius Blades

Option 3:

(1) 2x8 module on each side of all outer and inner radius Blades

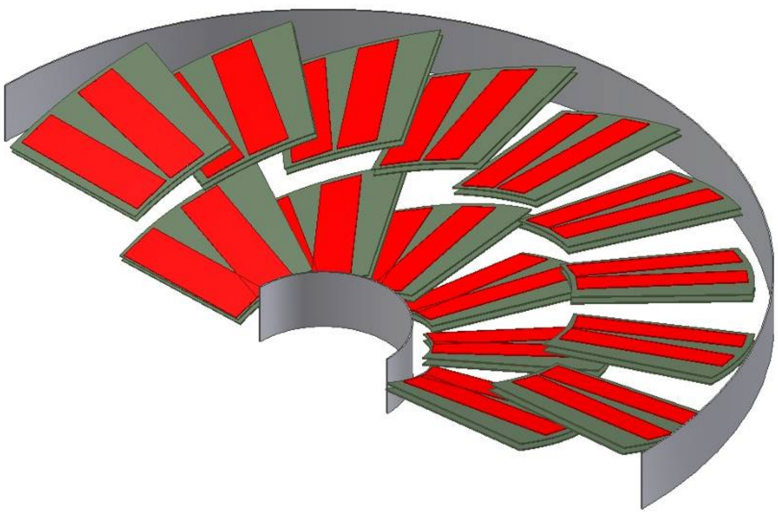


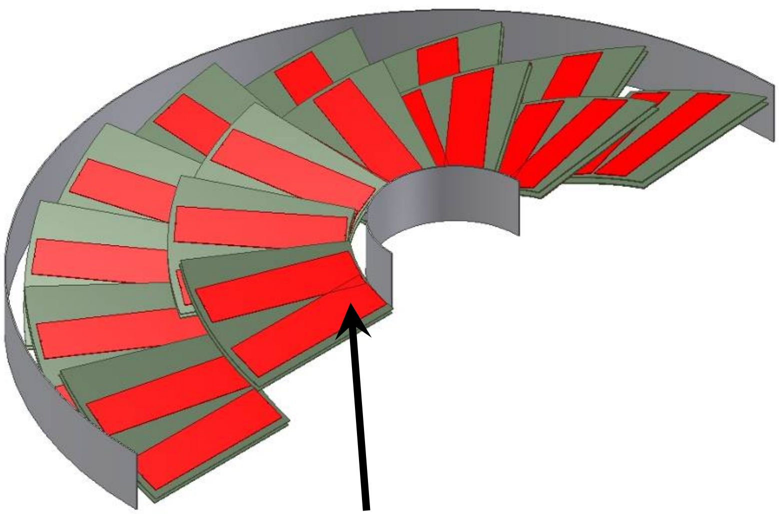
Outer and Inner Radius Blades mounted on separate structures for replacement of radiation damaged (inner radius) modules

Large Disk Option 1

(2) 2x8 modules on each side of all outer and inner radius Blades

Front





Back

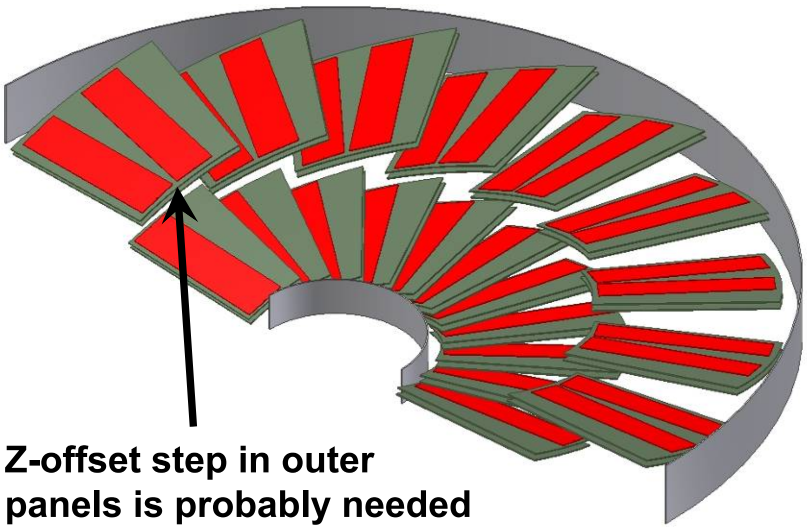
Large overlap between neighboring modules - too large a step in panel needed to alleviate this interference

Large Disk Option 2

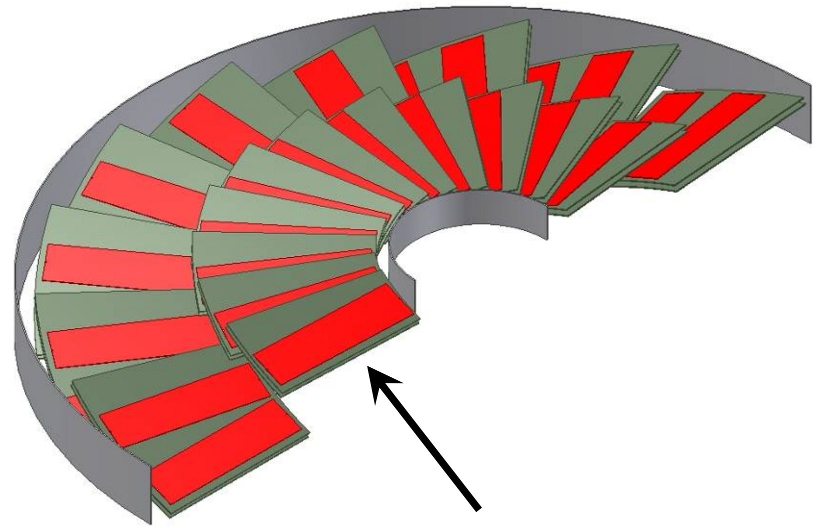
(2) 2x8 modules on each side of outer radius Blades

(1) 2x8 module on each side of inner radius Blades

Front



Z-offset step in outer panels is probably needed to alleviate interference between neighboring modules



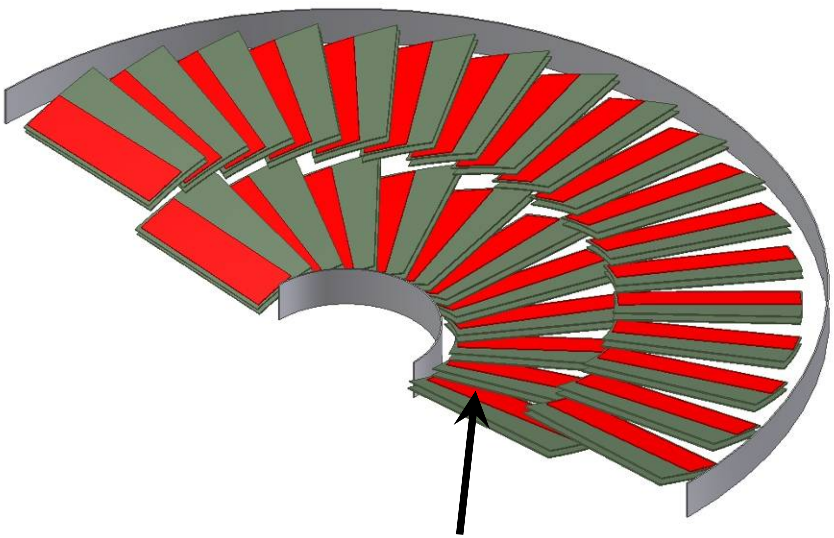
Back

Avoids step in inner panels for 2x8 modules

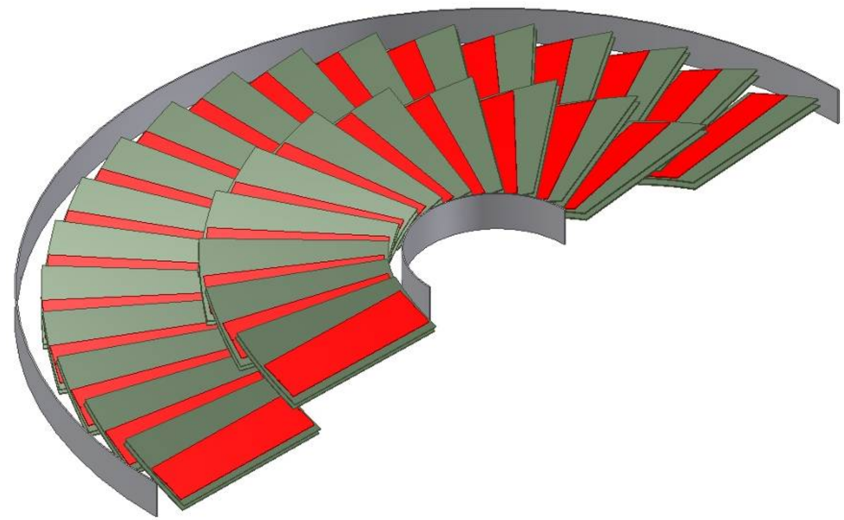
Large Disk Option 3 - Modules on tilted panels

(1) 2x8 module on each side of all outer and inner radius Blades

Front

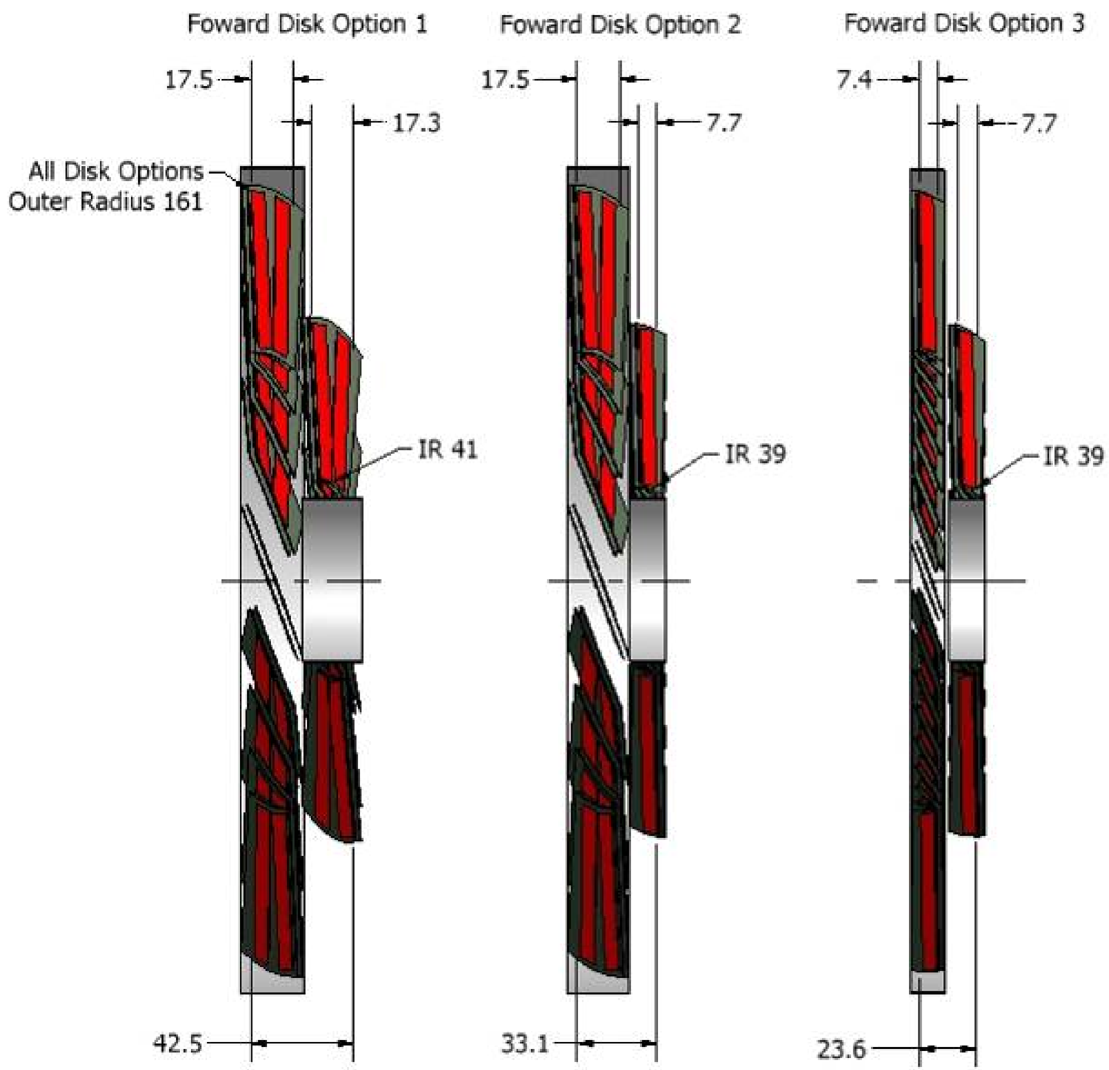


More Z-axis separation is probably needed to alleviate interference between neighboring inner Blades at inner radius



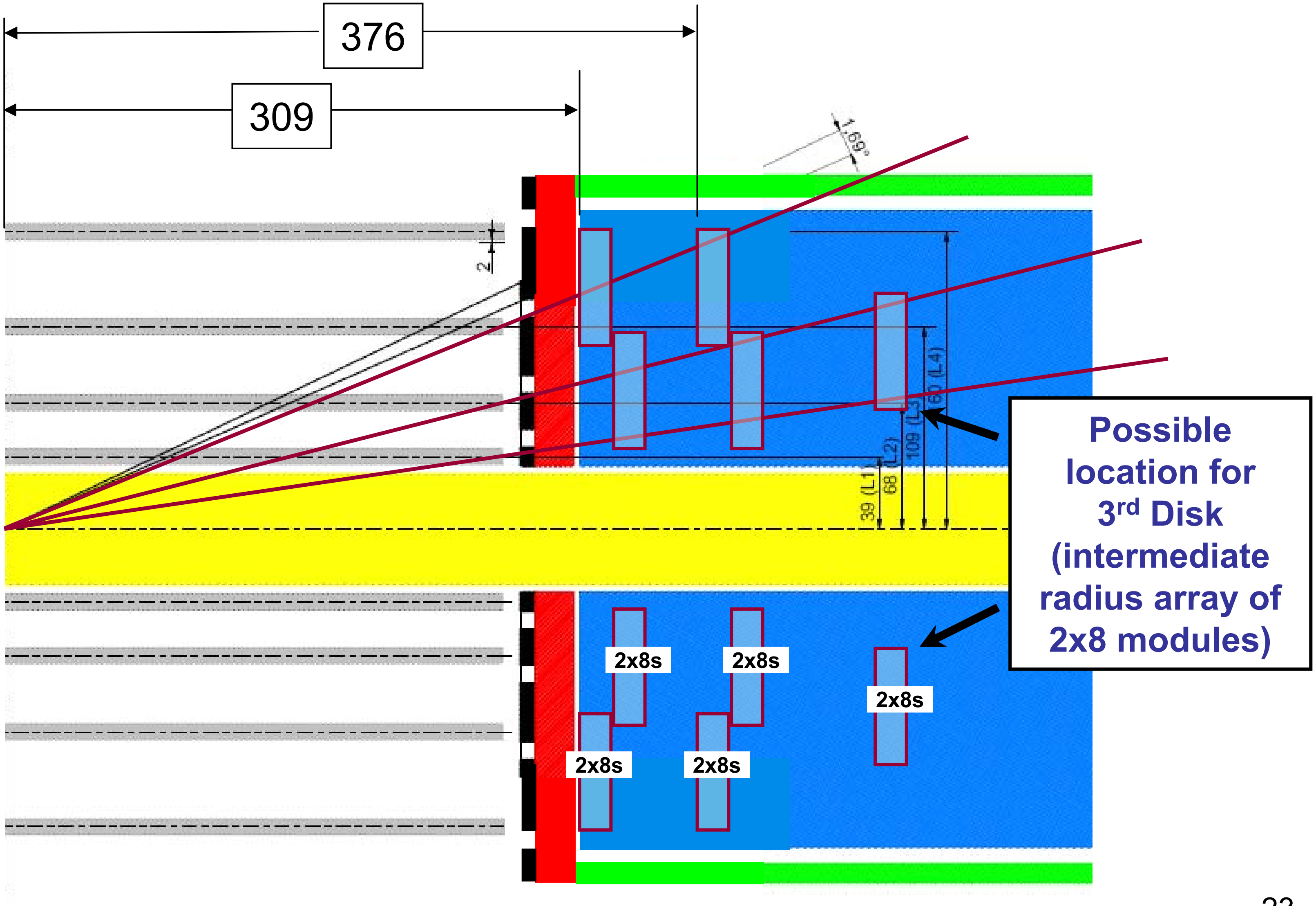
Back

Z axis and Radius dimensions of Large Disk Concepts for Short 4-layer BPIX



Locations for 1st and 2nd Large Disks

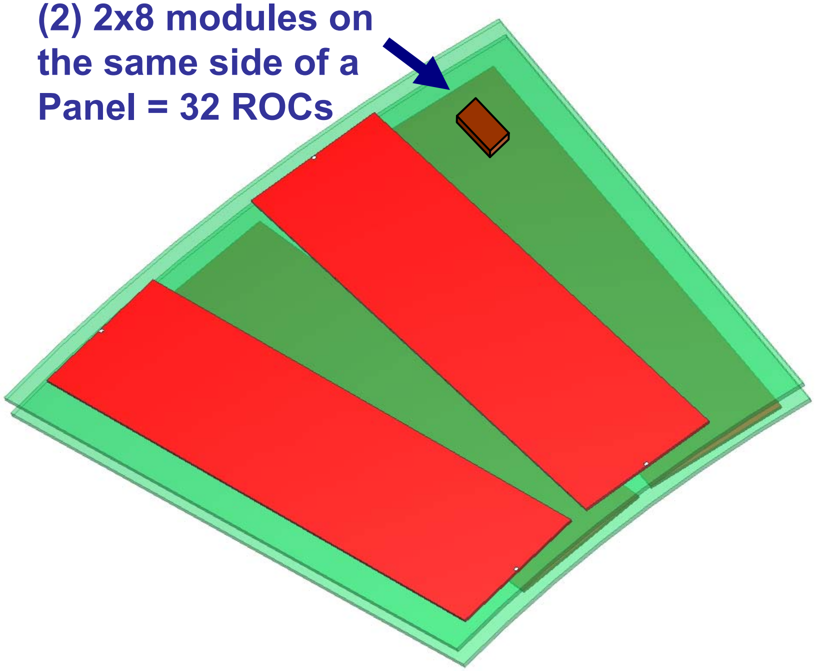
(to ensure four hits as acceptance angle increases beyond the third barrel layer)



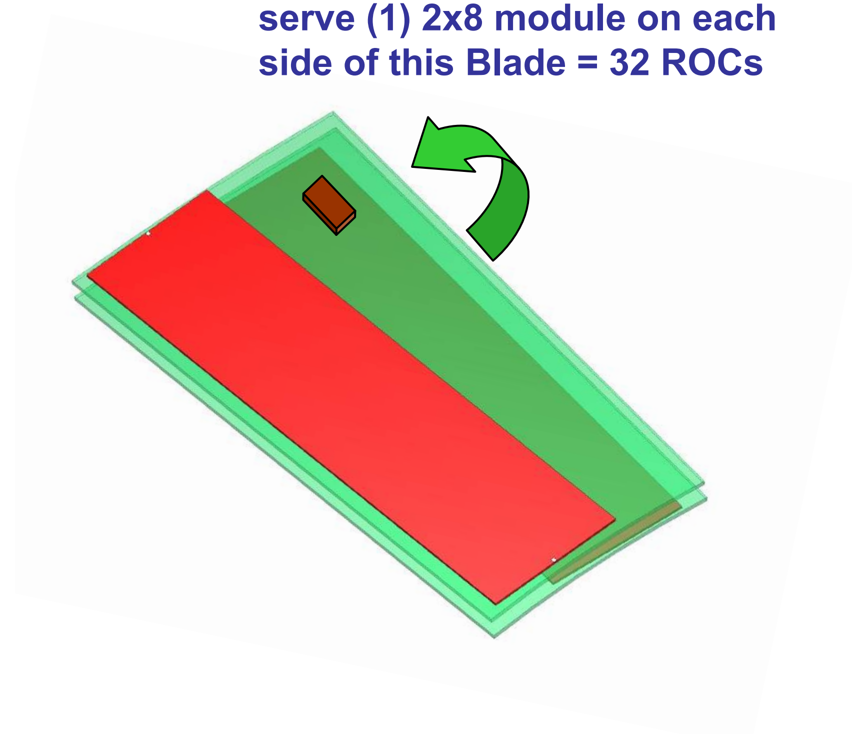
Readout chain unit

A single TBM channel / readout chain can support the readout / manage signals from 32 ROCs

One TBM can serve (2) 2x8 modules on the same side of a Panel = 32 ROCs



If signals can be passed from one side to the other side of a Blade, then one TBM can serve (1) 2x8 module on each side of this Blade = 32 ROCs



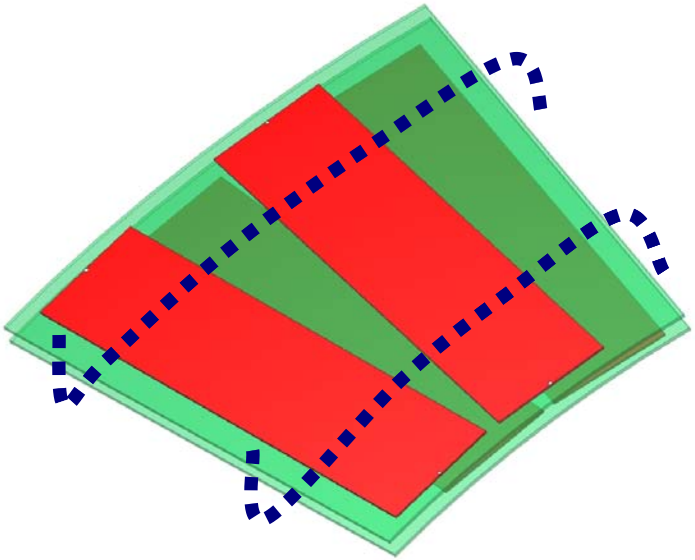
FPIX Options for 2013 replacement/upgrade

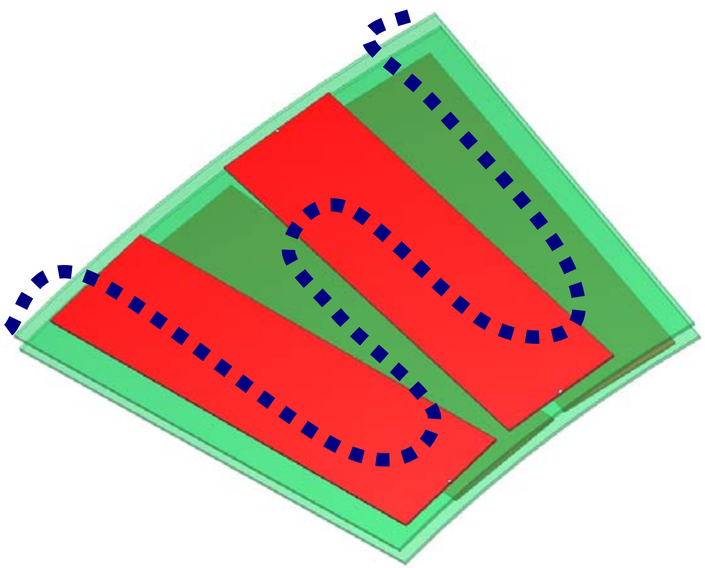
November 2008

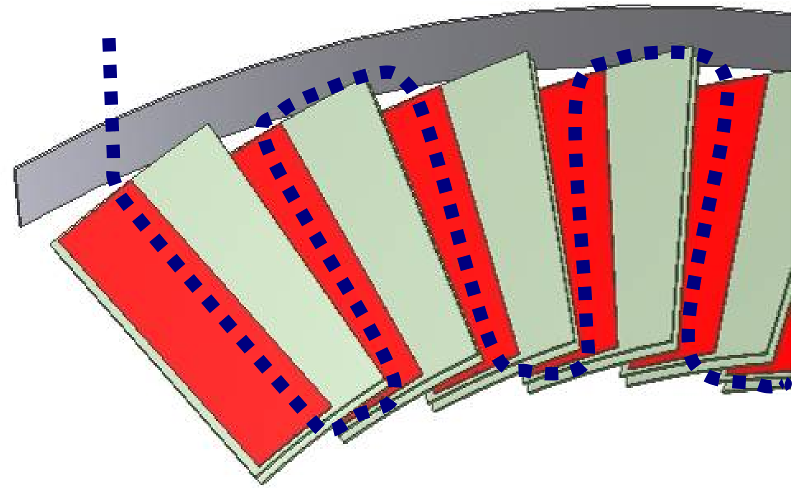
Option	Disks	Modules	Cooling	Pixel ROC (total #)	# of TBM readout chains	Readout	Power
0	Current 2-3	672-1008	C_6F_{14}	PSI46 as now (4320 – 6480)	288	analog 40MHz	as now
1	Current 2-3	672-1008	C_6F_{14}	2x buffers (4320 – 6480)	288	analog 40MHz	as now
2	3 new disks for Long 4th layer BPIX	536	CO_2	2x buffers (8064)	264 *	analog 40MHz μ-tw-pairs?	as now
3	3 new disks for Short 4^{th} layer BPIX	592	CO_2	2x buffers (9472)	288 *	analog 40MHz μ-tw-pairs?	as now DC-DC new PS?

** assumes each TBM serves 32 ROCs*

CO2 cooling tube routing options for Blades

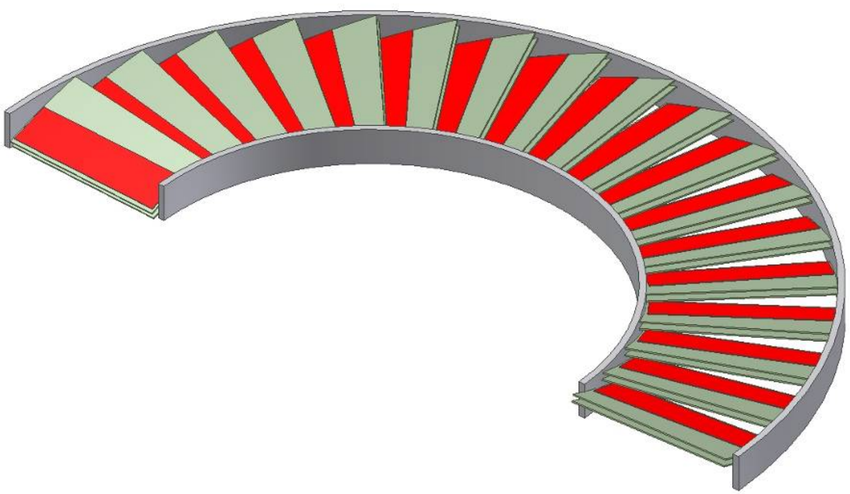


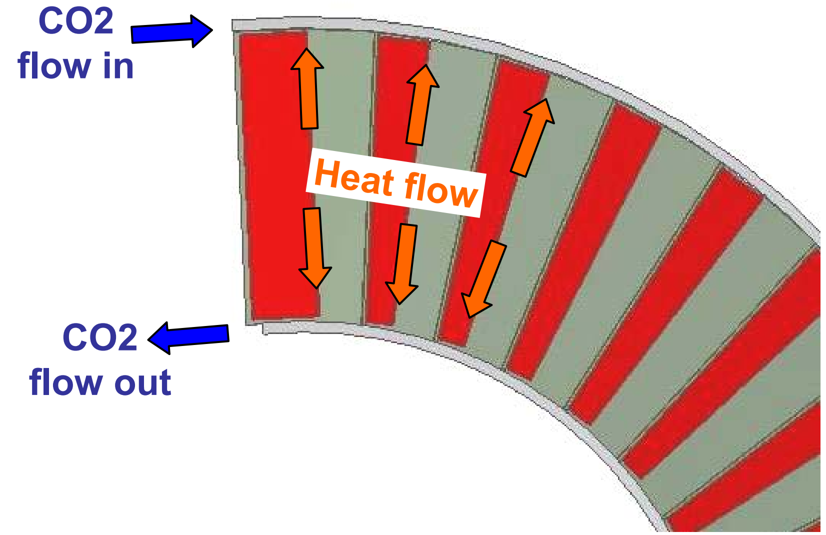




Panels cooled from edges (Rings)

Consider CO_2 cooling tubes in outer and inner rings to cool edges of Panels with pixel modules mounted on heat spreaders

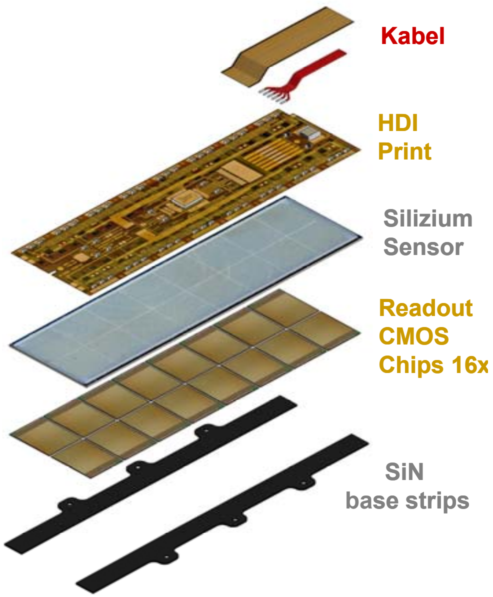




Three alternative module designs

"BPIX"

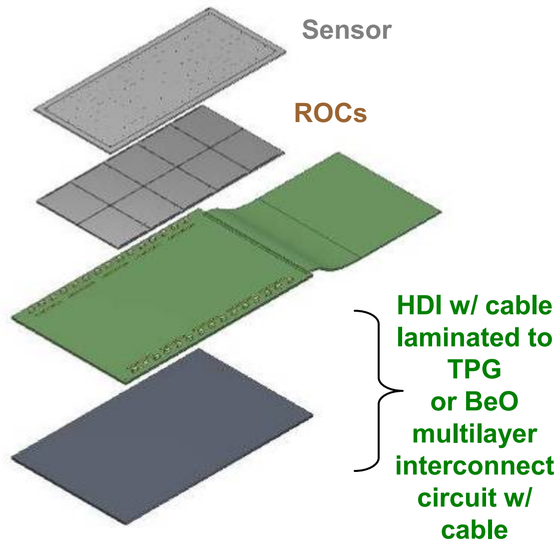
HDI flex on top of sensor



+ Only 1 passive layer between ROCs and cooling/support structure
+ Screw fastened to support structure
- Inhibits scanning with light for bump conductivity test
- Cable strain applies force on sensor
- ▪ Possible bi-metal bowing due to mismatched CTE

"FPIX"

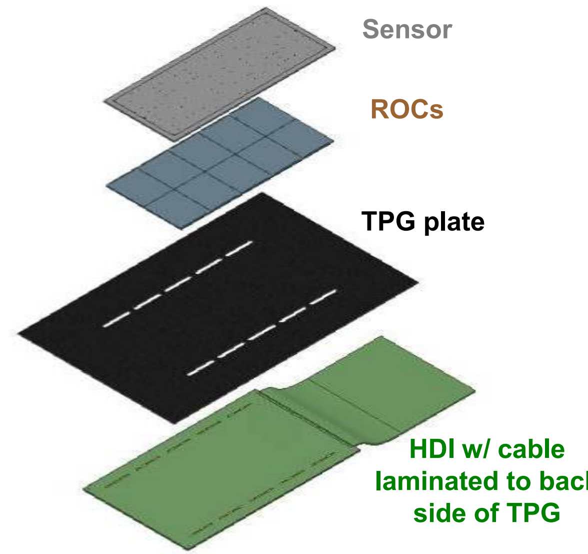
HDI under ROCs



+ Allows scanning sensor with light for dead channel/bump connection tests
+ Allows for removal of flip chip module for ROC rework
+ Strain on cable not transferred to sensor or ROCs
- Multilayer interconnect layer between ROCs and cooling

"Integrated Module"

HDI under and ROCs on top of high thermal conductive plate with thru holes for wirebonds



+ Flip chip modules mounted directly on high heat transfer material
+ Leaves sensors uncovered for scanning with light (pulsed laser)
+ Flip chip modules removable, leaving HDI intact for replacement modules
+ TPG provides cable strain relief

Mass and Radiation Length estimates for replacement/upgrade FPIX Disk

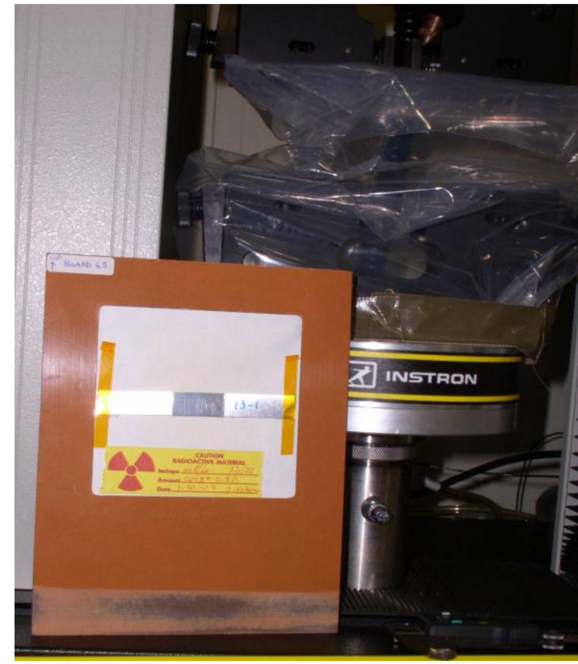
	Present disk		**New disk**		
	Mass(g)	Rad L%	Mass(g)	Rad L%	Comments
Flip chip modules	118.5	0.50	173	0.77	more ROCs, use thinner adhesive to mount to HDI
VHDI	208.0	0.93	0.0	0.00	mount modules directly on HDI
HDI	291.1	0.80	338	1.02	combine function of VHDI and HDI, TPG with CF facing instead of Be
Support Hardware	171.1	0.76	124	0.34	CF instead of Alum for Inner and Outer Rings
Cooling channel	322.6	1.17	**12**	**0.20**	**CO2 coolant + small diameter SS pipes** instead of brazed Alum channels
Total per disk	1112	6.70	**647**	**2.33**	

~40% less mass per disk

~3X reduction in %RL per disk

Integrated module development - Adhesives study

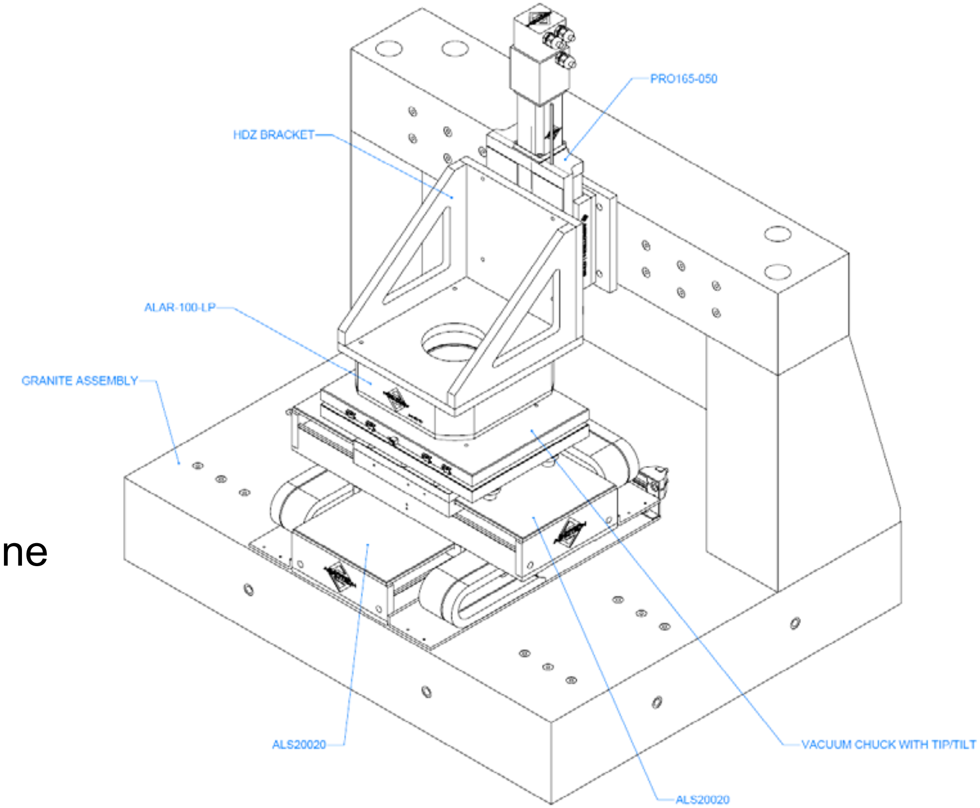
- Begun a market survey of adhesives for pixel integrated module assembly that meet requirements for SLHC
  - Requirements for adhesive:
    - Thermal conductivity: > 0.2 W/m-K
    - Soft: shear modulus < 50 N/mm^2
    - Conformable to 50 micron non-flatness
    - Radiation hard
    - Electrically non-conductive
    - 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
- Building mechanical grade integrated modules using candidate adhesives for evaluation of mechanical properties after irradiation.



FPIX adhesive sample tensile tested after irradiation

Automated module assembly

- Robotics will help in almost all large scale (>1000 module) Phase 2 Inner Detector upgrade scenarios
- Smaller 'standing army', shorter production time
- Leads to uniformity of production techniques
- Current FPix module assembly used fixtures + techs (1000 modules, 1.5 years, 4 FTE's)
- Will use robotic 'pick-and-place' machine with optics and glue dispensing for upgrade module assembly
- Could also be used for module placement on upgrade panels/disks

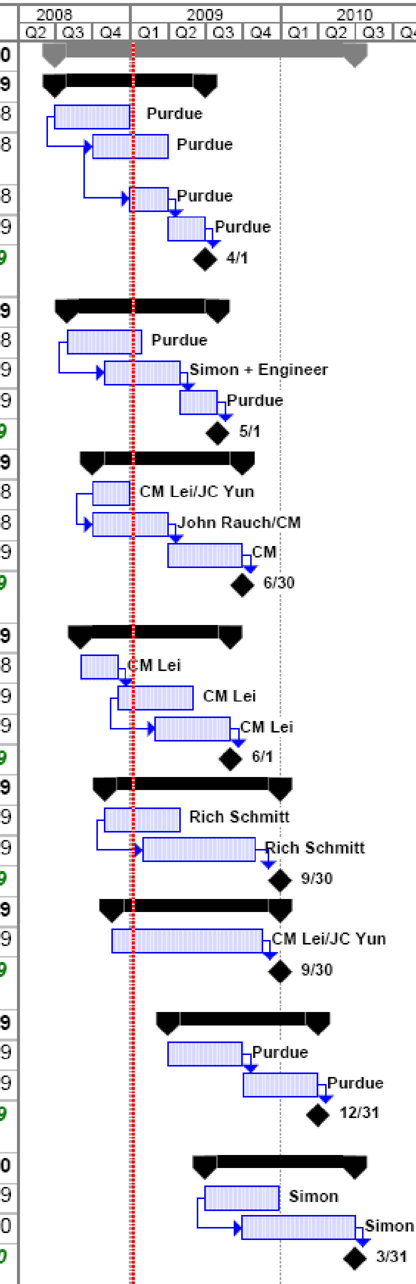


- Purchasing hardware now, will integrate optics, vacuum, and glue dispensing to an off-the-shelf motion control system
- Module design must lend itself to automated assembly
- Lots of code development, process development, and prototyping before production begins

Mechanical Design optimization

- Goals
  - Early conceptual design
  - Model thermal gradients and distortions
  - Minimize material and meet thermal requirements
  - Overall optimal design (mechanics, power and readout)
- Small mechanical prototypes for measurements of thermal performance vs. material
  - Module prototypes – to evaluate adhesives, interconnects, develop assembly tooling and procedure
  - Support prototypes – to evaluate
    - TPG and facing materials - none (just epoxy), carbon fiber, carbon-carbon
    - Mix of low (i.e. Pocofoam) and higher density materials
  - CO_2 cooling – evaluate tube types and size, number of tubes per module
- Ambitious goal would be to build full-scale disk prototype for thermal and mechanical tests by early 2010 based on design and small prototype studies

Task Name	Duration	Start	Finish
Upgrade Pixel Mechanics R&D	**522 days**	**4/1/08**	**3/31/10**
Evaluate adhesives	**262 days**	**4/1/08**	**4/1/09**
Identify candidate adhesives (In progress)	131 days	4/1/08	9/30/08
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	131 days	7/1/08	12/30/08
Measure thermal conductivity of module samples assembled with candidate adhesives	66 days	9/30/08	12/30/08
Evaluate suitability for semi-automated assembly and integrated module repair	66 days	12/31/08	4/1/09
Milestone: Identify reliable, repeatable and reworkable adhesive(s) (robust for SLHC conditions) for pixel integrated module assembly and rework.	***0 days***	***4/1/09***	***4/1/09***
Evaluate dense multilayer interconnects:	**262 days**	**5/1/08**	**5/1/09**
Identify candidate state-of-the-art substrates (In progress)	130 days	5/1/08	10/29/08
Design and fabricate sample substrate multilayer interconnects	131 days	7/31/08	1/29/09
Test radiation hardness, electrical performance, and wirebondability	66 days	1/30/09	5/1/09
Milestone: Identify optimal product(s) for dense multilayer interconnects.	***0 days***	***5/1/09***	***5/1/09***
Conceptual Design of cooling/support structure	**261 days**	**7/1/08**	**6/30/09**
Identify requirements for CO2 cooling and low mass/stiff/high thermal conductive support	66 days	7/1/08	9/30/08
CAD design of conceptual model	132 days	7/1/08	12/31/08
Perform mech. and thermal FEA of CAD model – feedback to design revisions	129 days	1/1/09	6/30/09
Milestone: optimal conceptual design for replacement/upgrade FPIX detector, ready to proceed to preliminary design for TDR	***0 days***	***6/30/09***	***6/30/09***
Study composites with high thermal conductivity	**261 days**	**6/2/08**	**6/1/09**
Identify candidate low mass/stiff/high thermal conductive materials	66 days	6/2/08	9/1/08
Fabricate sample structures	131 days	9/2/08	3/3/09
Test mechanical and thermal performance of samples	130 days	12/2/08	6/1/09
Milestone: Identify optimal composite materials for low mass support structure	***0 days***	***6/1/09***	***6/1/09***
CO2 cooling study	**304 days**	**8/1/08**	**9/30/09**
Investigate cooling channel material alternatives	130 days	8/1/08	1/29/09
Construction of CO2 cooling system for bench testing	196 days	10/31/08	7/31/09
Milestone: reliable CO2 cooling system for testing of prototypes	***0 days***	***9/30/09***	***9/30/09***
Evaluate design and materials for support/cooling structure:	**293 days**	**8/18/08**	**9/30/09**
Perform FEA and test performance of integrated modules-on-supports	261 days	8/18/08	8/17/09
Milestone: Identify optimal design and construction for low mass support/cooling structure	***0 days***	***9/30/09***	***9/30/09***
Prototype integrated module assembly robot:	**261 days**	**1/1/09**	**12/31/09**
Design and fabricate tooling for prototype integrated module assembly	130 days	1/1/09	7/1/09
Motorize and program assembly tooling	131 days	7/2/09	12/31/09
Milestone: Operation of robot for reliable, repeatable assembly of integrated module prototypes	***0 days***	***12/31/09***	***12/31/09***
Test prototype integrated modules:	**261 days**	**4/1/09**	**3/31/10**
Testing of mechanical prototype integrated modules	129 days	4/1/09	9/28/09
Testing of electrically working prototype integrated modules	197 days	6/30/09	3/31/10
Milestone: Demonstrate reliability of assembled prototype integrated modules.	***0 days***	***3/31/10***	***3/31/10***



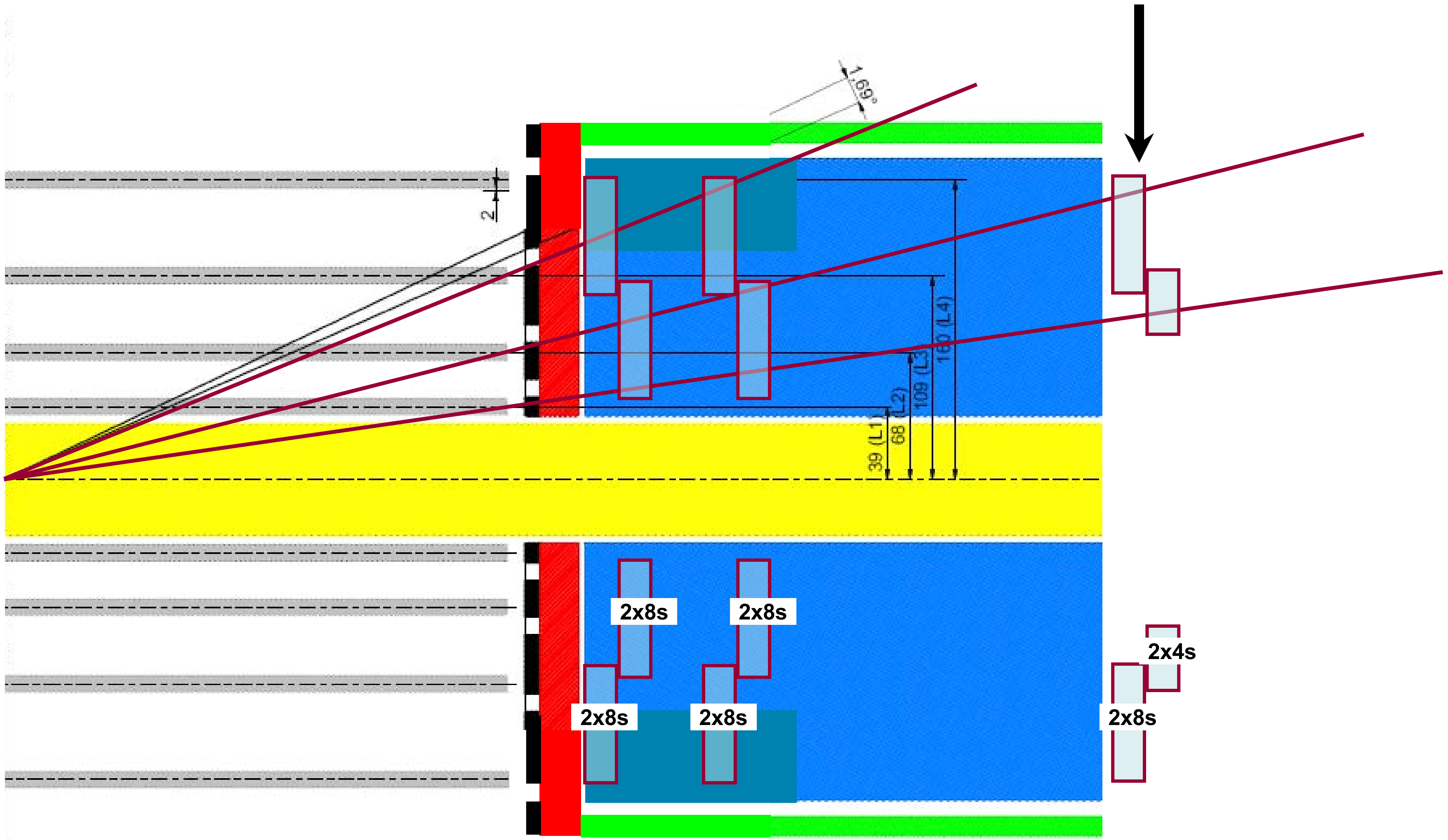
Summary

- Reduction in # of module types, components and interfaces + integration with lightweight support and CO_2 cooling reduces material *SIGNIFICANTLY* *(and may simplify assembly)*
- Module and disk conceptual design and studies have begun
- Small prototype development for testing will follow
- Goal to build full-scale prototype for thermal and mechanical tests in ~1.5 years from now

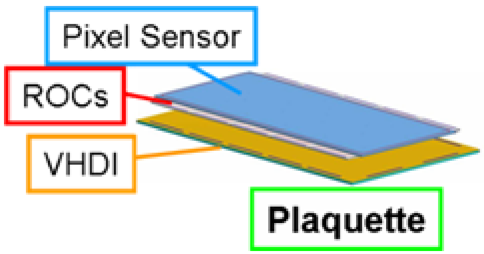
Backup slides

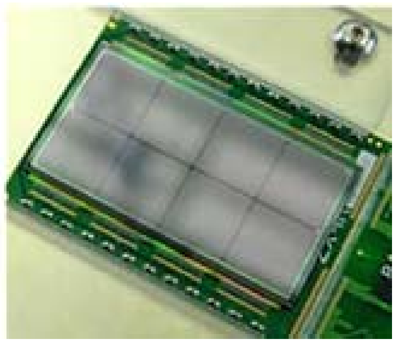
Alternative 3rd Disk

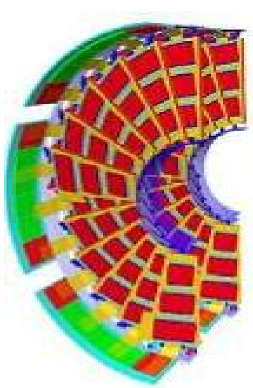
Same outer radius array of 2x8s as in the Large Disk concept
+ an intermediate radius array of 2x4 modules

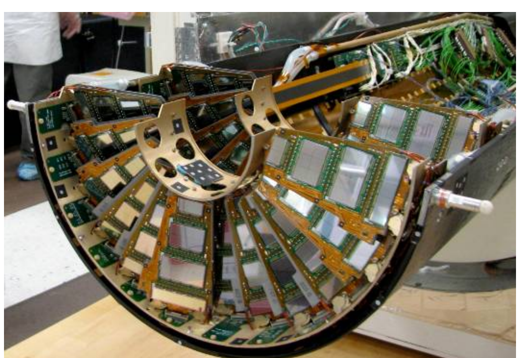


CMS Forward Pixels at Purdue and FNAL









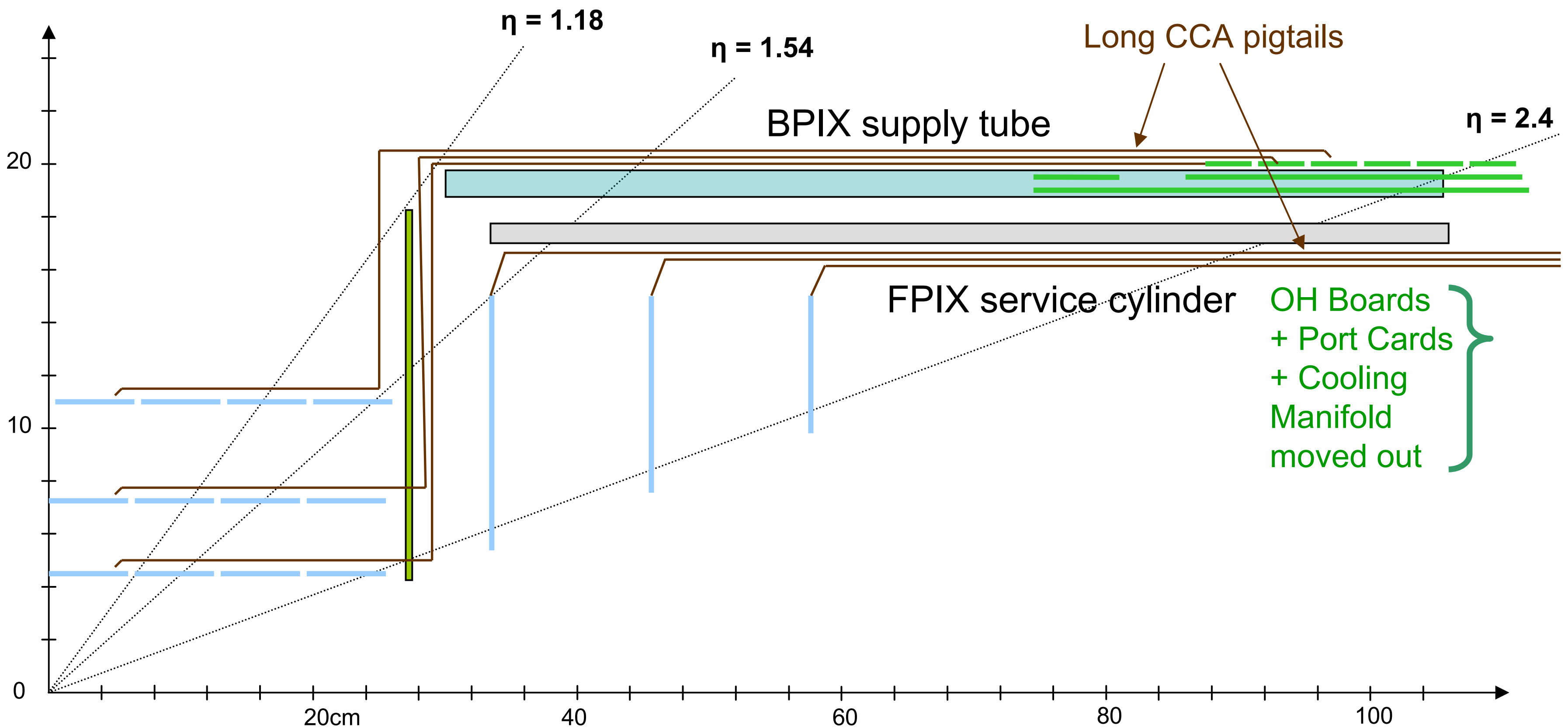
- The Purdue group developed the tools, materials & techniques for assembly, testing and delivery of ~1000 Pixel modules for the CMS FPIX (~250,000 wirebonds and >25 million pixels) at the planned assembly rate of 6 modules per day.
- Rework techniques were also developed at Purdue to recover faulty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

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

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



Revised Mechanics R&D Proposal

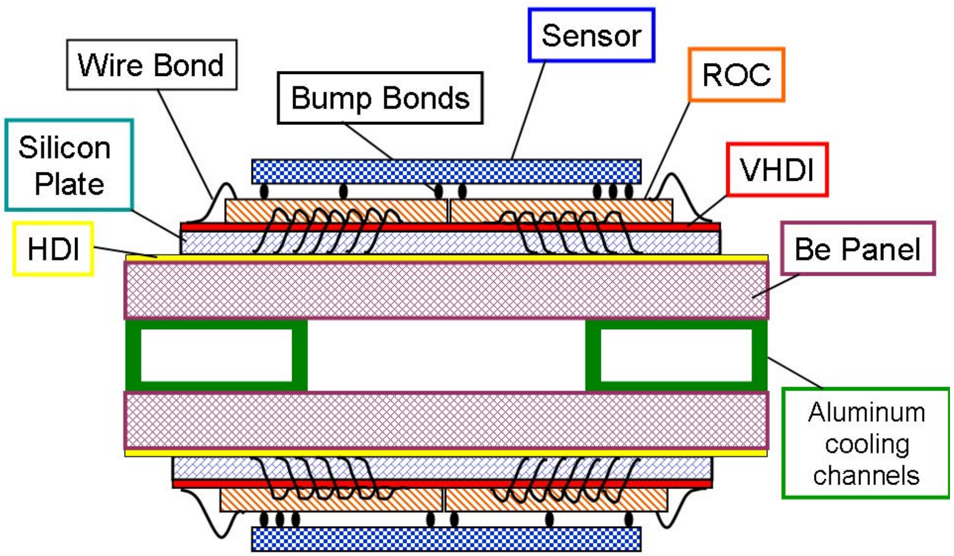
1. **Conceptual design**
   – Integrate cooling/support structure into an overall detector package and eliminate redundant features
2. **Cooling/Support development**
   – Study CO2 cooling, including construction of a CO2 cooling system for lab bench testing of prototype integrated cooling/support structure 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

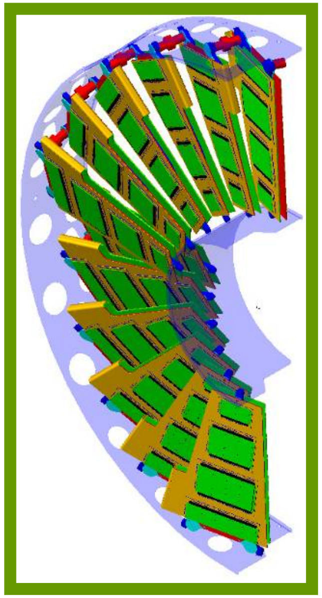
Revised Mechanics R&D Proposal

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

Current Fpix components stack-up

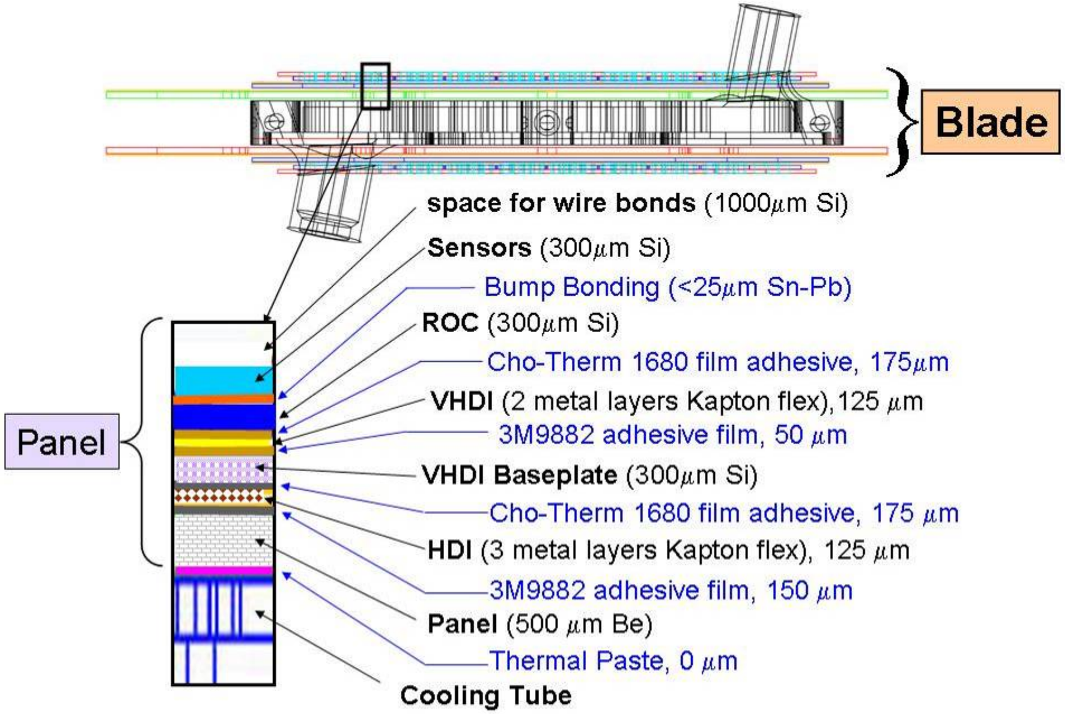




Currently, FPIX Disks have a lot of material in:

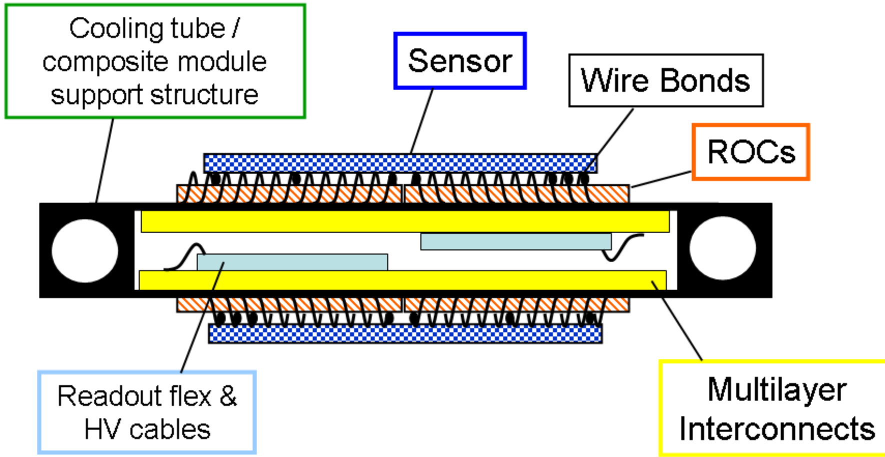
- passive Si and Be substrates
- flex circuits with Cu traces
- thermal conductive (BN powder) adhesive interfaces
- brazed aluminum (0.5mm wall thickness) cooling channels

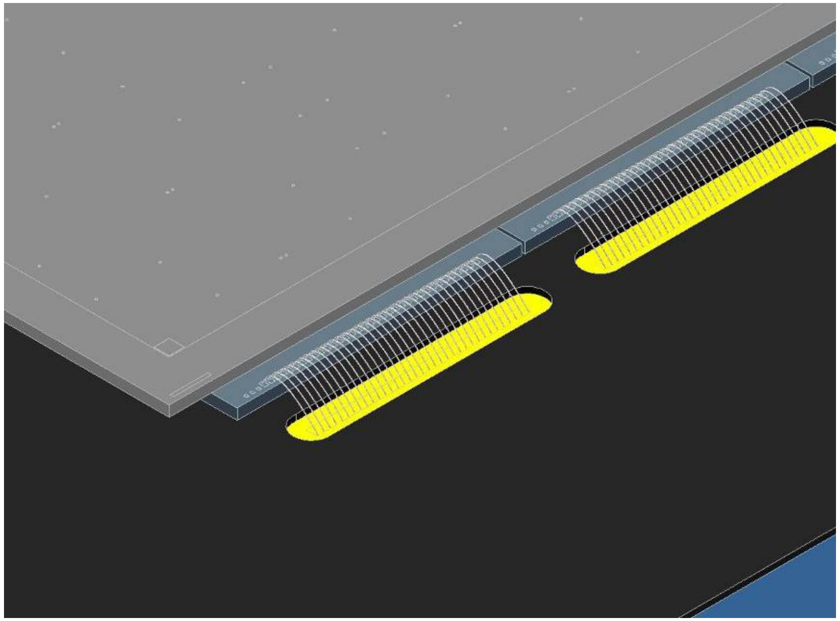
Fpix Blade components and thermal interfaces



- 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.

CO_2 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

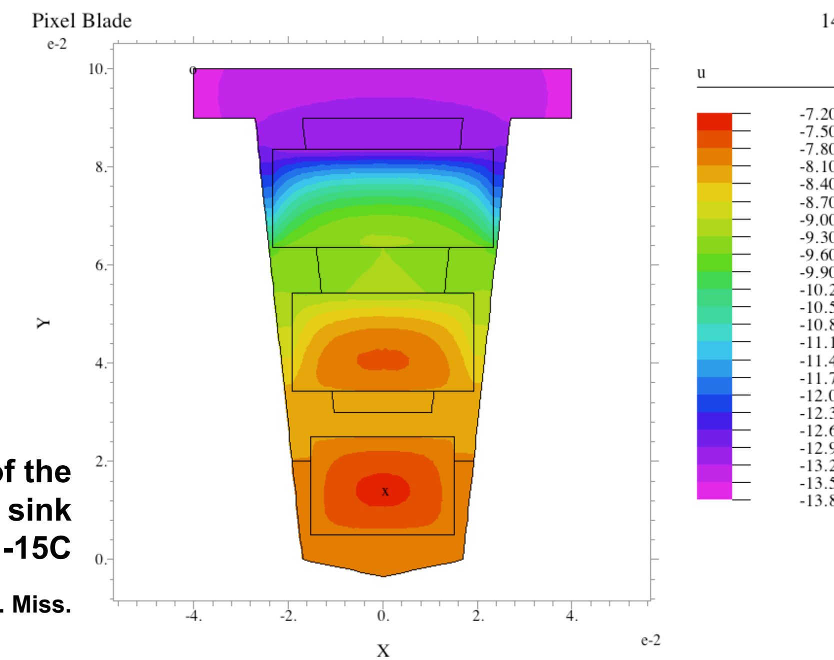
CO_2 Cooling

Small diameter (1mm) pipes for CO2 cooling:

- much less mass ~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. CO2 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 -15C

L. Cremaldi, U. Miss.

Resolution of Flat Disk VS Turbine at 20°

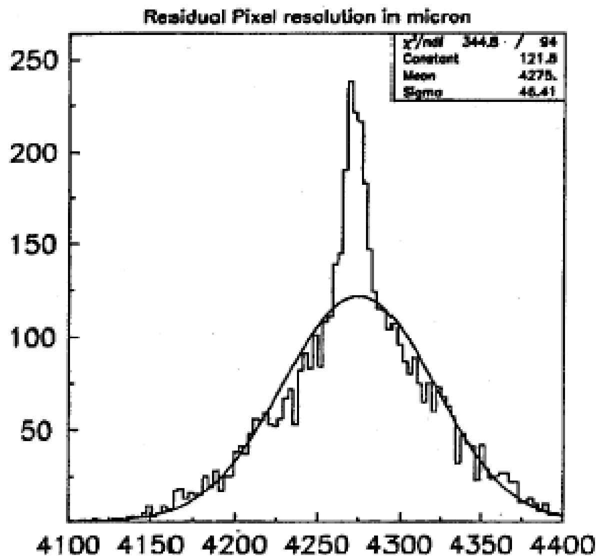


Fig. 18. A resolution of 46 μm is found along columns for $\alpha = 0°$ using charge sharing. The peak at the center indicates a higher resolution in case charge was shared with neighboring pixels.

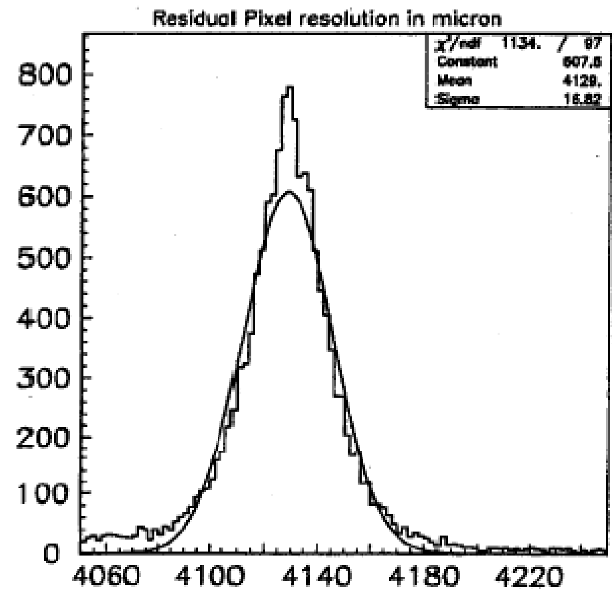


Fig. 19. An average resolution of 17 μm is found along columns for $\alpha = 20°$ using charge sharing.

- 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)