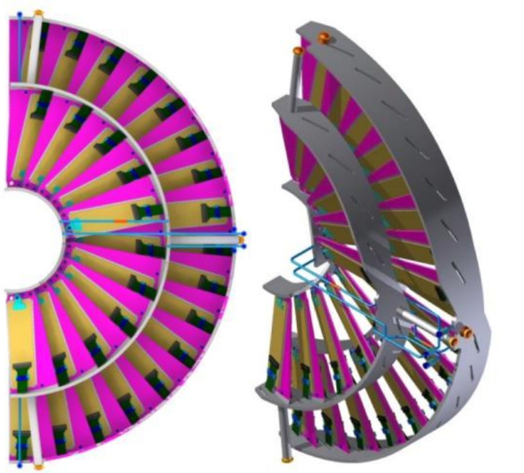
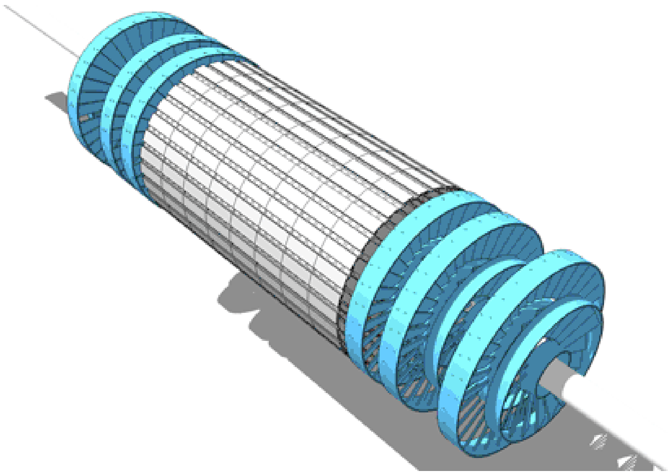
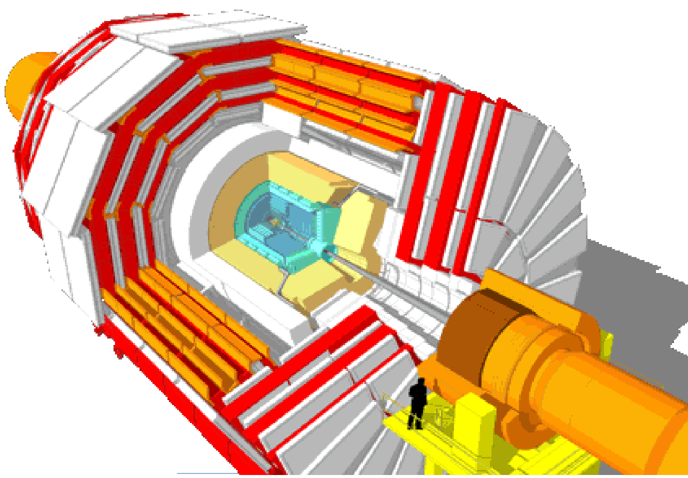
Status of CMS Forward Pixel Mechanics & Cooling

Stefan Grünendahl, Fermilab

Forum on Tracking Detector Mechanics, NIKHEF, June 2015





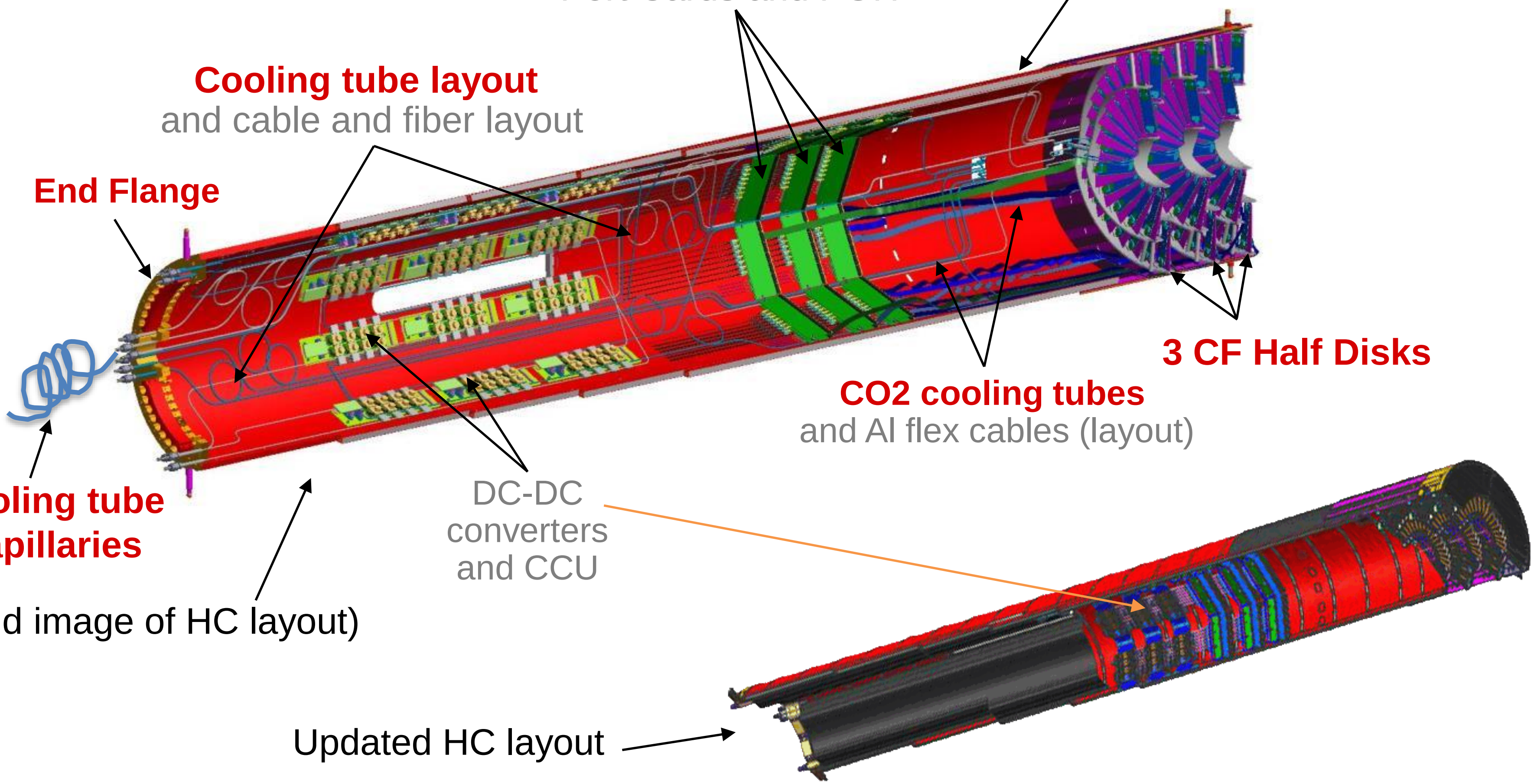


Overview

- CMS FPIX Upgrade Objectives
- Main Features of Mechanics and Cooling
- Recent Developments (last 12 months)
  - Cooling & electronics layout, incl. grounding provisions
  - End flange design with cooling connections
  - Insertion Tests (2014) & adjustable cylinder mounts
  - Module installation procedure
- Production Status

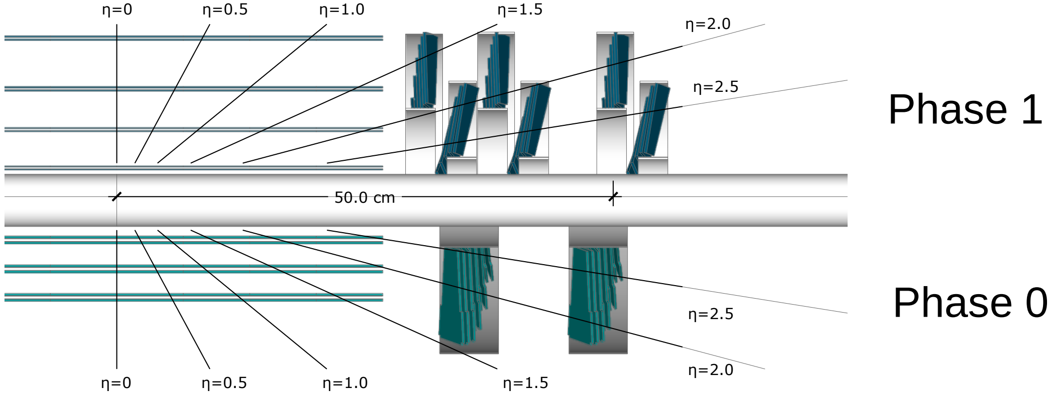
CMS FPIX Mechanics

- Support structure and cooling for pixel modules and electronics (4 Half Cylinders)



Objectives

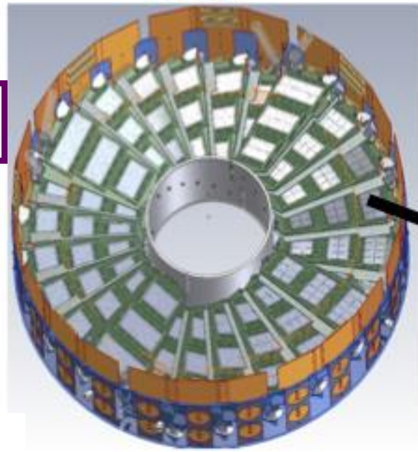
- Motivation for design choices
  - Reduce material budget (despite adding a disk)
    - All CF/graphite support structure
    - CO_2 cooling with small stainless steel tubes
    - Move more of the material/electronics further from the IP
  - Easier production and maintenance
    - One module type (2x8), that can be removed from blade if needed
    - Independently mounted inner and outer half disk, inner half disk can be replaced if needed
    - Modules rotated/tilted to improve hit resolution



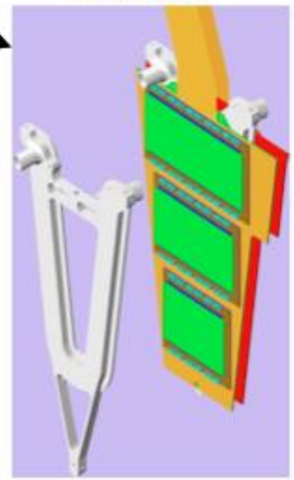
Main Features of Half Disk Structure

Phase 0

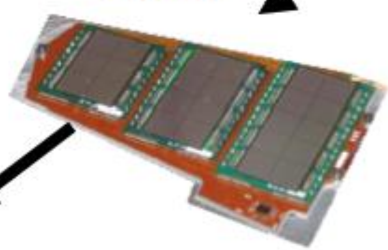
Disk



Blade

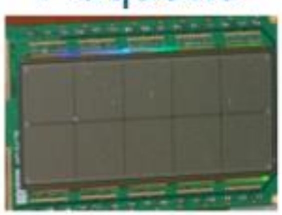


Panel



4 Types

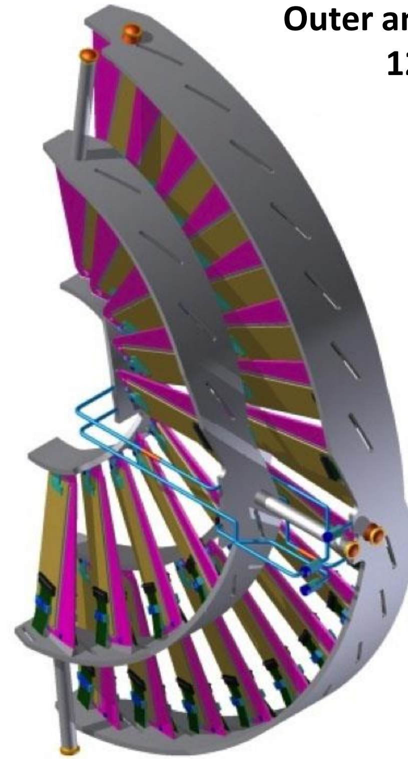
Plaquette



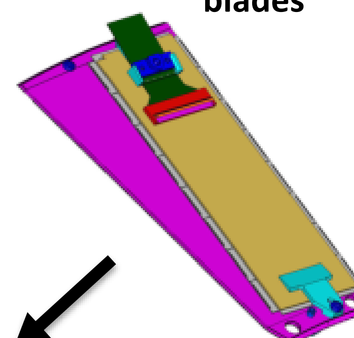
7 Types

Phase 1

Outer and inner half-disks
12 Half-disks



Outer half-disk: 17 blades
Inner HD: 11 blades

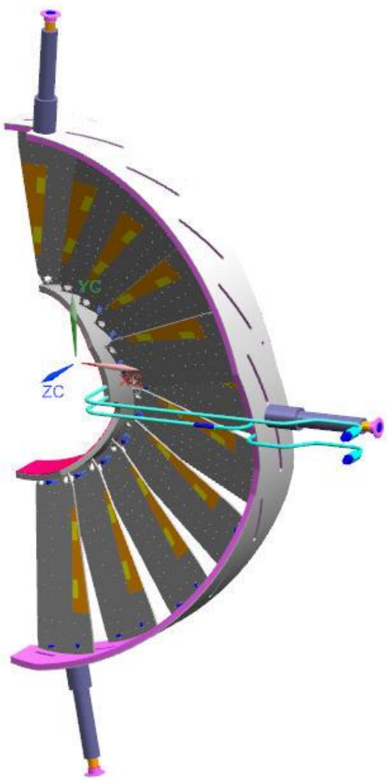


2x8 Module

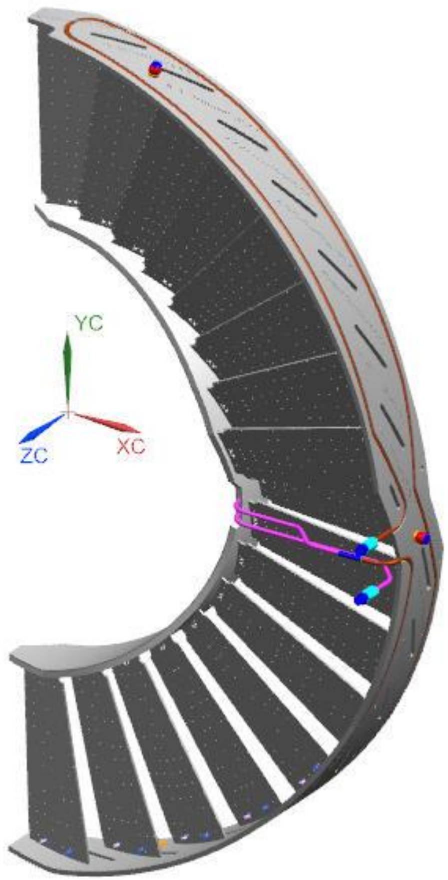
1 Type (672 total)

Half Disk Structure

Inner Assembly

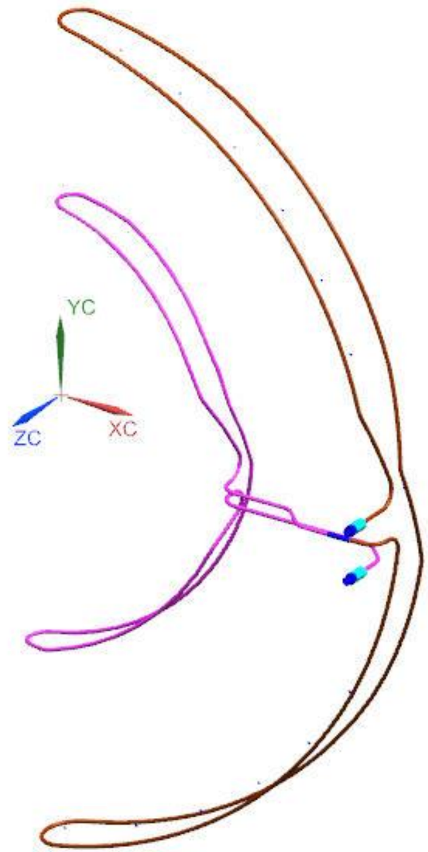


Outer Assembly

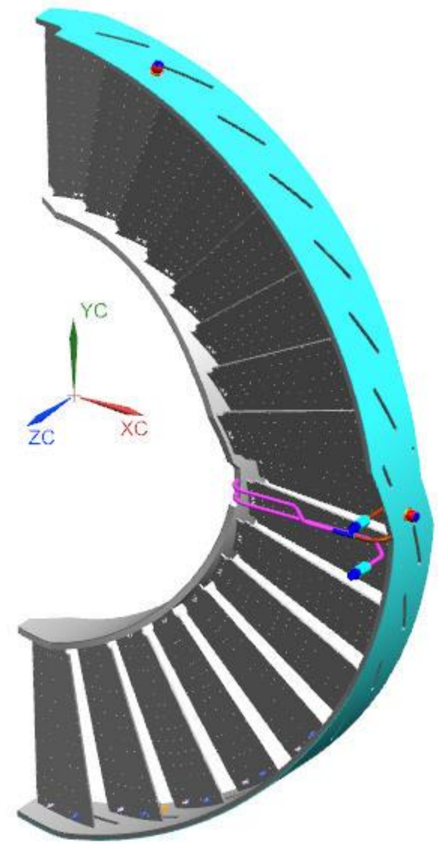


After blades bonded to graphite rings

SS Cooling Tubes



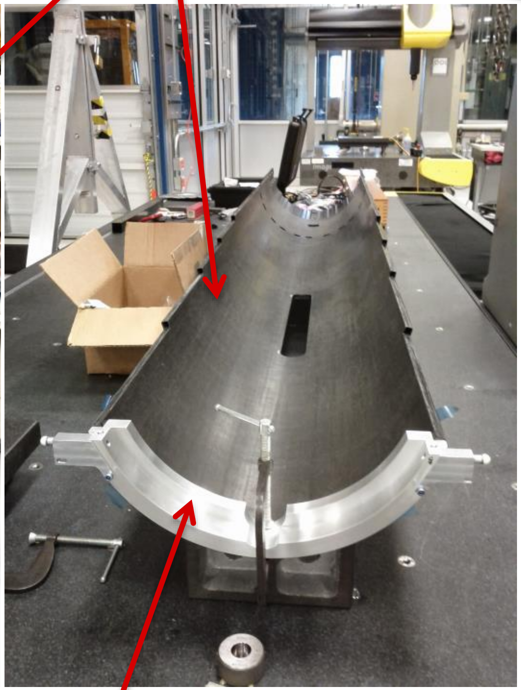
Outer Assembly with tubing and CF facing

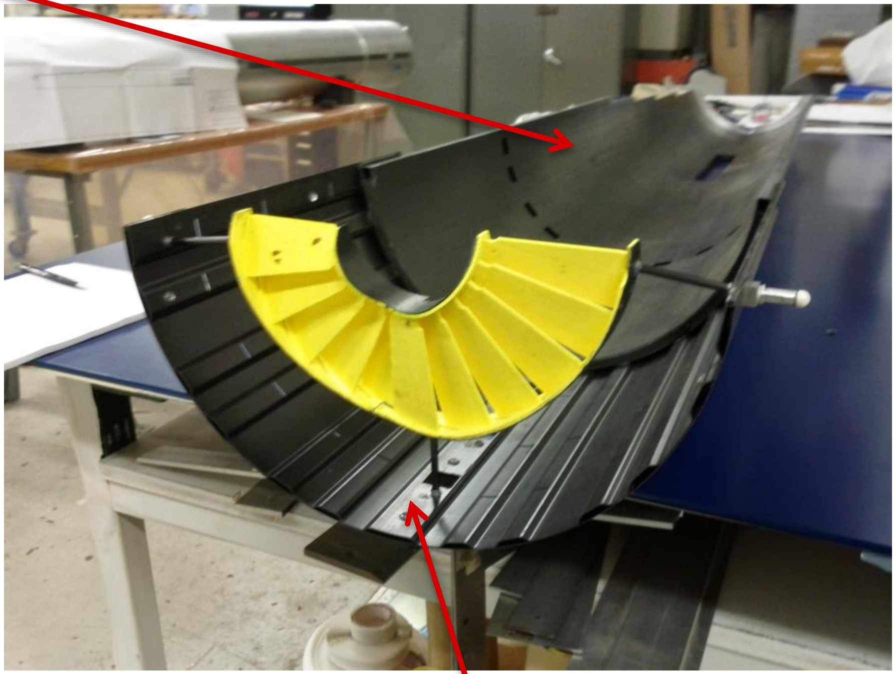


After tubing and facing bonded to graphite rings

Half Cylinder Structure

Double wall CF back section (very similar to Phase 0 HC)



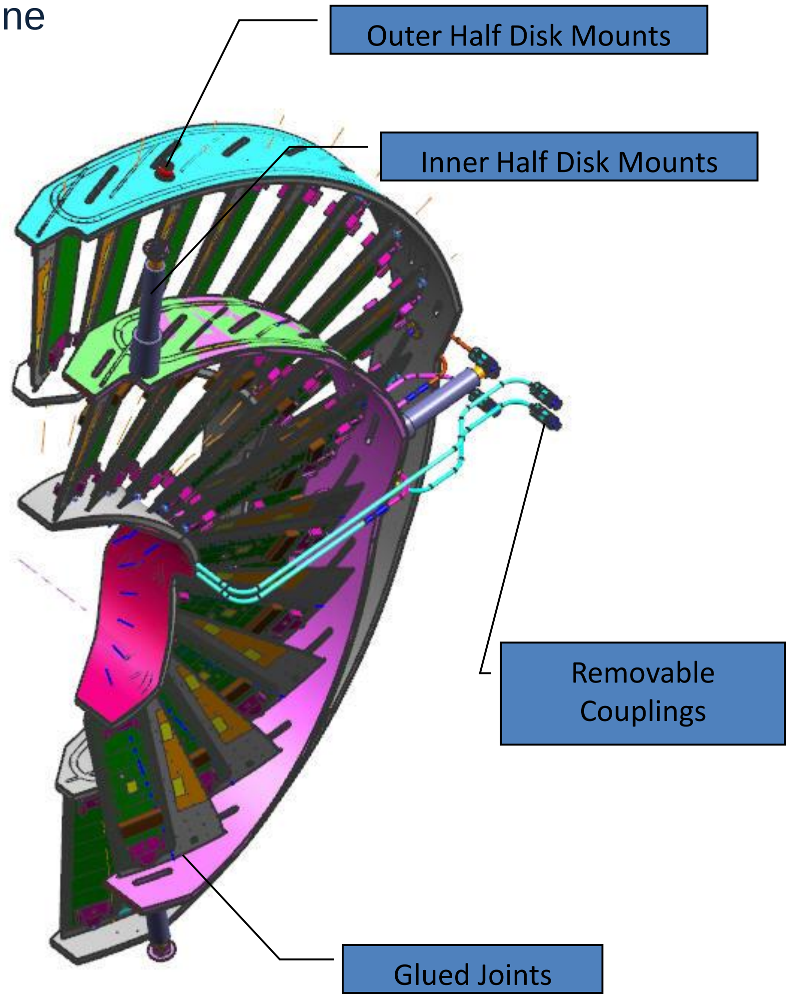


End flange
(very similar to Phase 0)

Single wall corrugated
CF front section

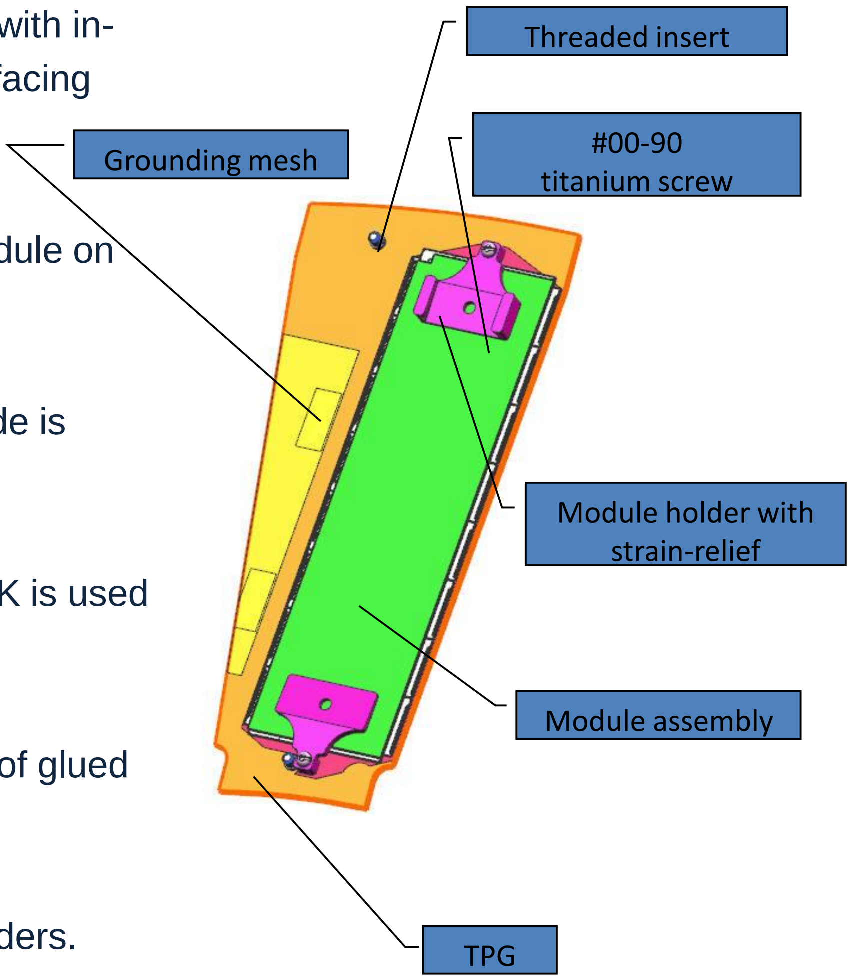
Basic Design of the Half Disk

- Half disk consists of one inner blade assembly and one outer blade assembly.
- Both assemblies are fastened to the half cylinder individually with 3 mounts.
- Outer blade assembly consists of 17 blades.
- Inner blade assembly, with an inverted cone arrangement, consists of 11 blades.
- All blades are glued to 2 supporting half rings that perform as heat sinks as well.
- Cooling tubes are embedded within the rings with removable couplings attached at ends.
- Apply parylene coating on the HD structure to seal all machined surfaces before mounting modules.



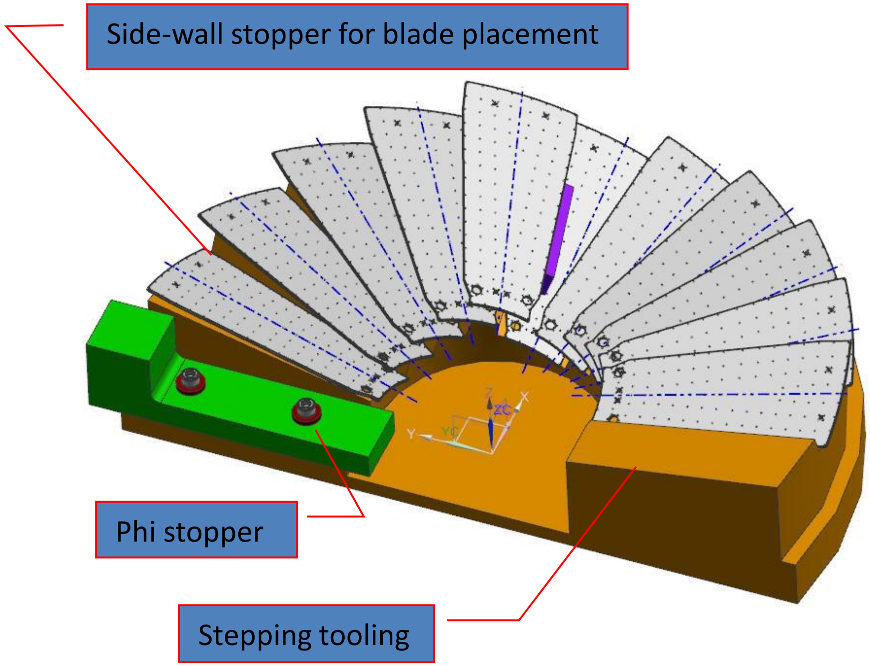
Basic Design of the Pixel Blade

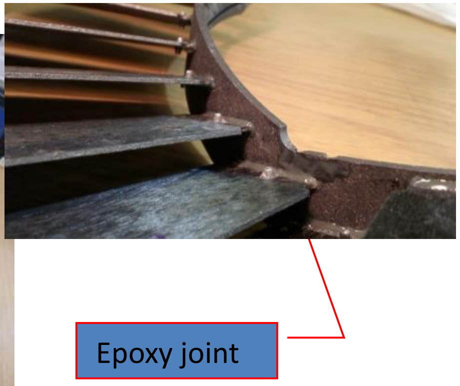
- Solid TPG (0.68 mm thick, highly thermally conductive with in-plane k = 1500 W/mK) encapsulated with carbon-fiber facing (0.06 mm thick).
- All blades within the half disk are identical with one module on each side. (Only 2x8 module is used.)
- Cooling is arranged at the ends of the blade where blade is bonded to the cooling rings.
- Removable silicone thermally interface film with 4 W/mK is used between the module and blade.
- Module assembly is removable with provision of a pair of glued module holders.
- Cable strain-relief is provided by one of the module holders.
- Aluminum #00-90 threaded inserts are glued on the blade for module mounting



Tooling for Half Disk Assembly

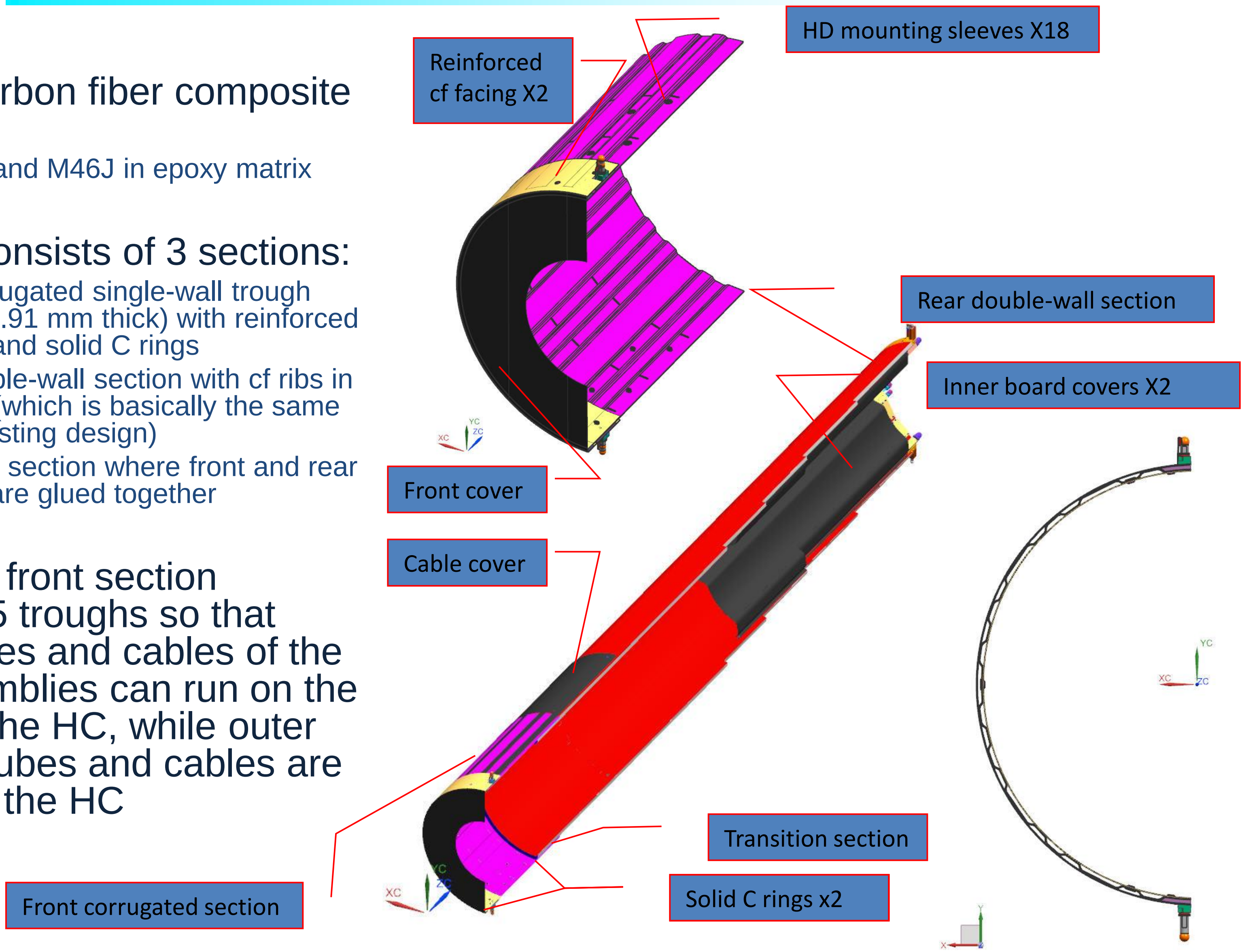
- Use of fixtures sets precision of finished assembly
- TC 5022 thermal compound in blade-to-ring joints is sealed in by DP190 epoxy
- Completed disk assembly is parylene coated



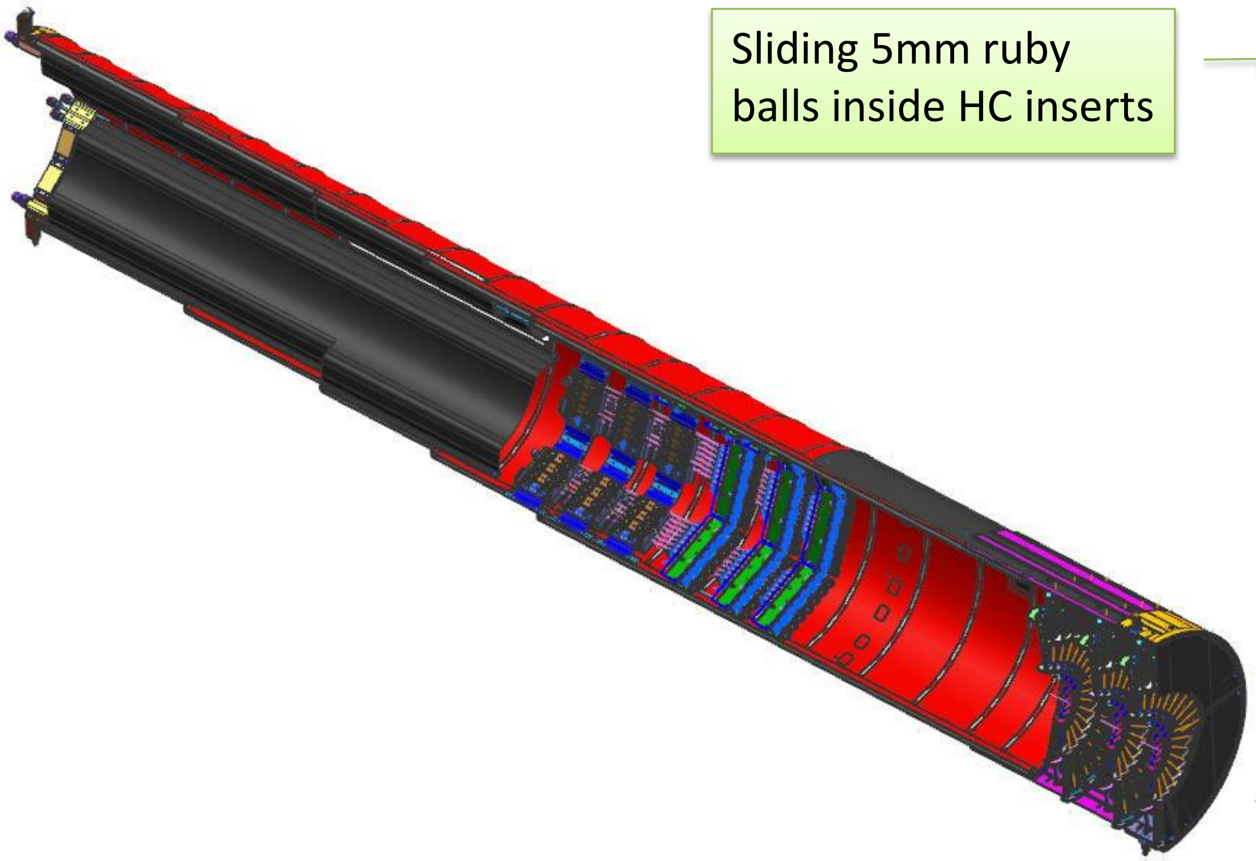


Design of Half Cylinder

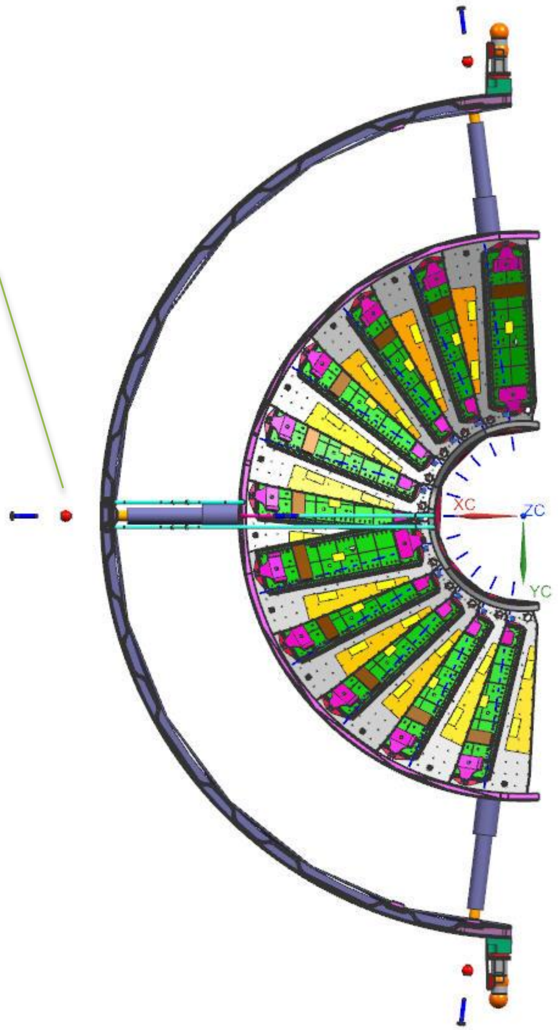
- Made of carbon fiber composite (cf):
  - K13C2U and M46J in epoxy matrix
- Cylinder consists of 3 sections:
  - front corrugated single-wall trough section (0.91 mm thick) with reinforced cf facing and solid C rings
  - rear double-wall section with cf ribs in between (which is basically the same as the existing design)
  - transition section where front and rear sections are glued together
- Single-wall front section provides 25 troughs so that cooling tubes and cables of the inner assemblies can run on the outside of the HC, while outer assembly tubes and cables are kept inside the HC



Half Disk Mount within Half Cylinder



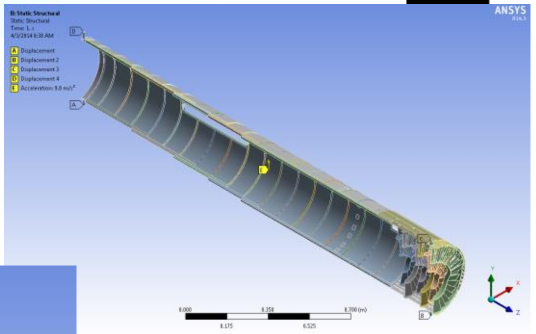
Sliding 5mm ruby balls inside HC inserts

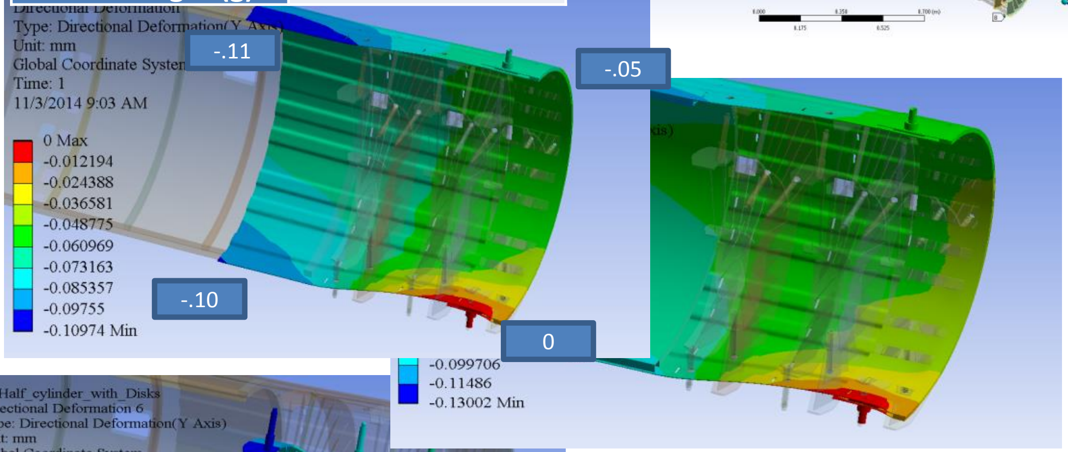


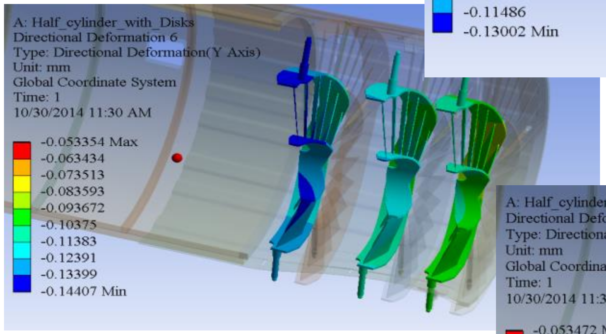
FEA of Half Cylinder with Half Disks

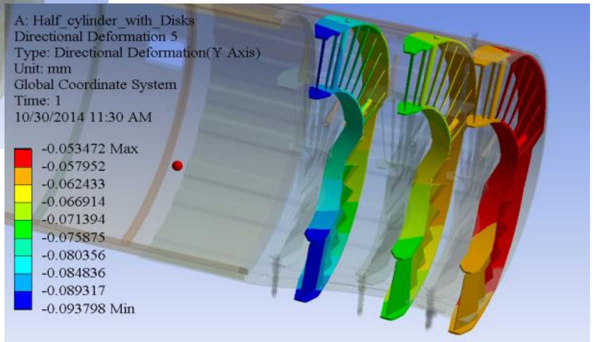
- Simulated HC supports
- Sliding supports for HD mounts
- Distributed load applied ~ 2000g
- Max deflection 0.13mm of HC occurred at rear section
- Max deflection 0.14mm of inner assemblies occurred at 3rd HD
- Max deflection 0.09mm of outer HD assemblies occurred at 3rd HD

Part	Total Weight (g)
End Ring	551
Half Cylinder	2351
Outer Half Disk	873
Inner Half Disk	630
Distributed Load	2086
Total Weight (g)	6491





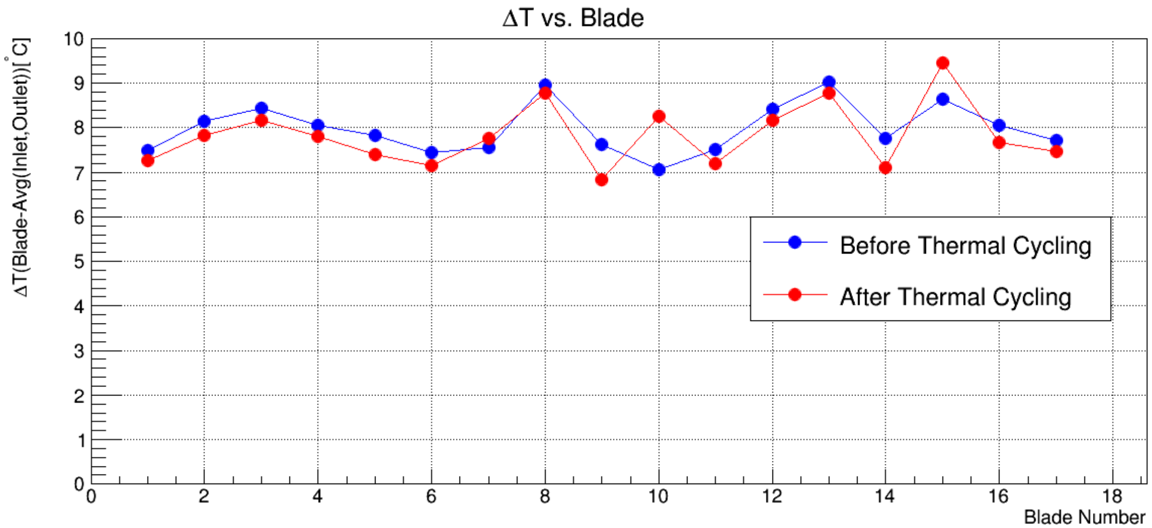




displacements (mm)		HC	Outer Disks	Inner Disks
uy	min	-0.1300	-0.0938	-0.1441
	max	0.0064	-0.0535	-0.0534

Thermal Performance

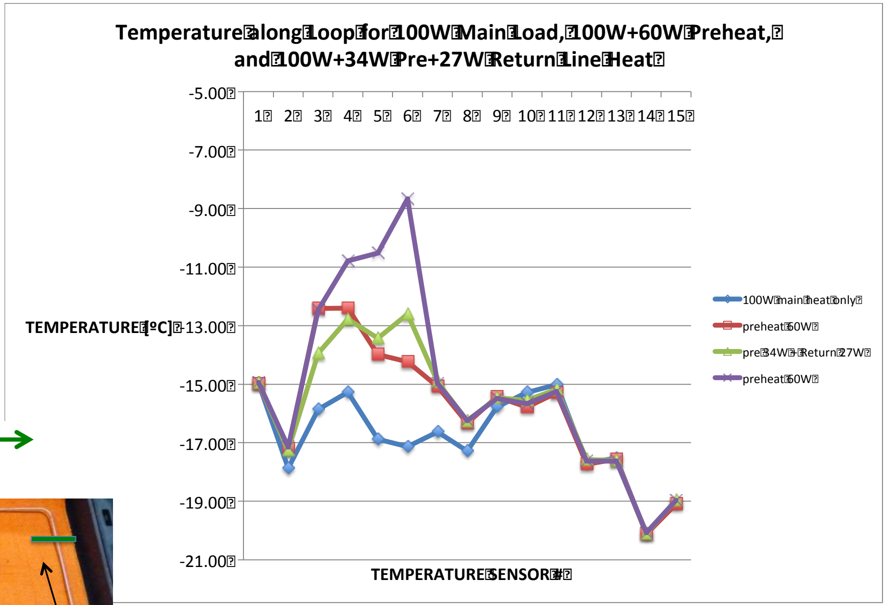
- Design & QC criterion: Every sensor module should run less than 10ºK above coolant temperature under maximum load (3W/module, corresponding to end-of-life irradiation).
  - Verified for full outer and inner prototype. (Inner prototype machined with wrong blade-ring joints; manual rework needed. Delta T found to scale with larger thermal gap; three blades found with Delta T above 10ºK; all below 14ºK.)

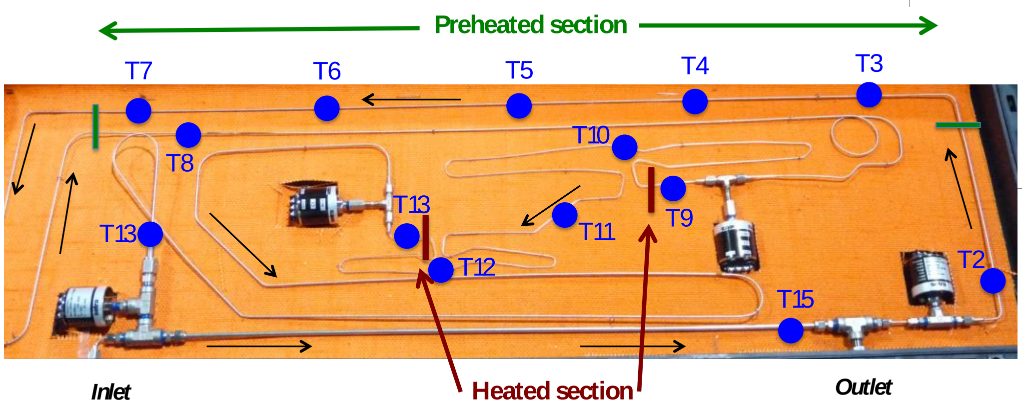


- We will use an automated procedure for measuring all blade temperatures under maximum load for every production disk.

Recent Developments: Final Cooling Layout

- Full loop tests (at FNAL & CERN):
  - loops work ok under max. heat load
  - Return lines can be used for electronics cooling





Apply heat loads estimated after lifetime radiation dose with a 30% safety

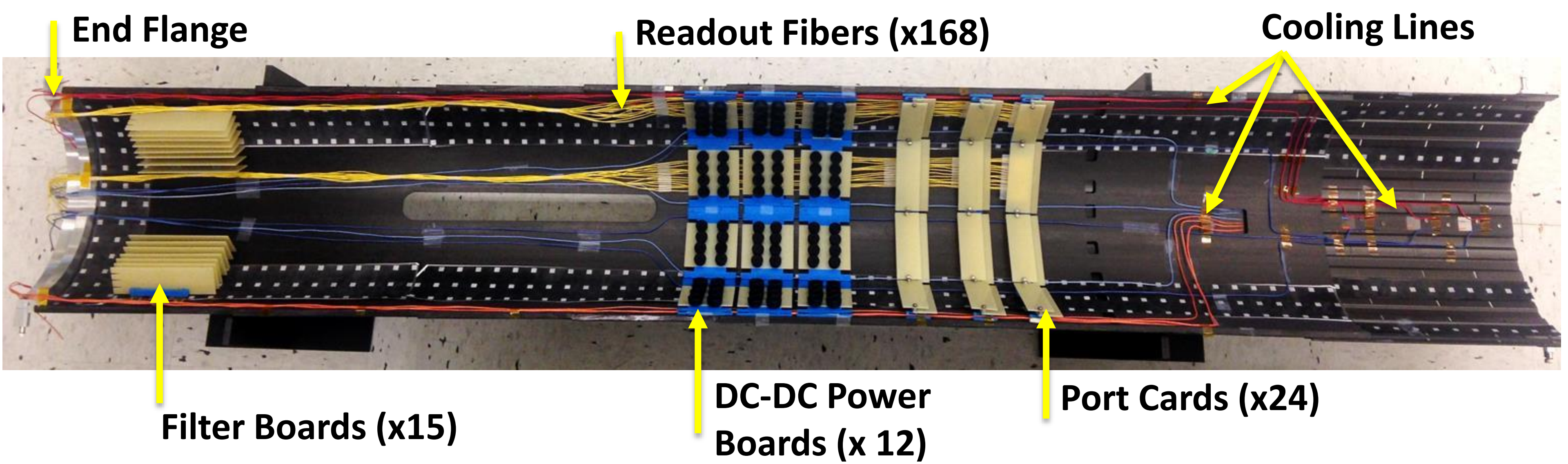
- Preheated section (DC-DC converters, POHs and a single Half Disk) ➞ 60W
- Heated section (3W/module) ➞ 100W

Measure temperatures vs. flow & pressure drop

LHC CMS Detector Upgrade Project

Electronics Integration

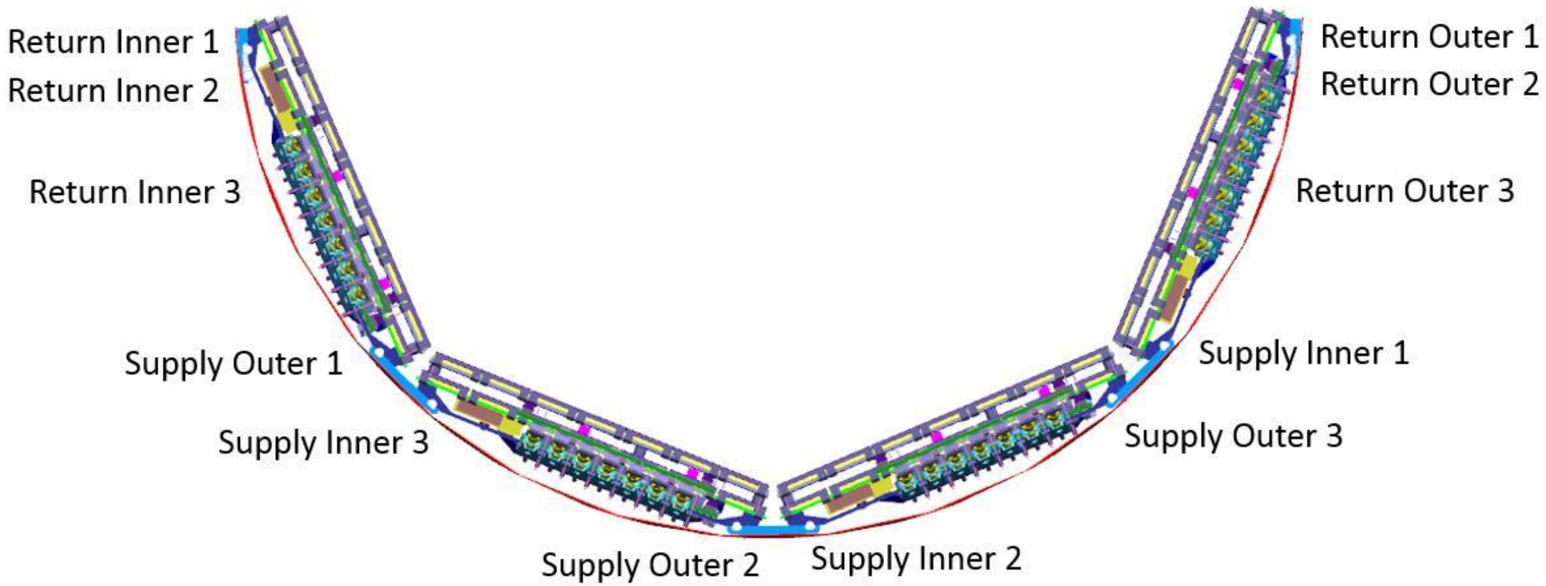
- Filter cards, DC/DC converters, Portcards and CCUs are located in the cylinder
- DC/DC converters & portcards thermally connected to CO2 tubing



Electronics Cooling

- Both feed and return lines are used to cool the DC/DC converters and the portcards

CO_2 layout



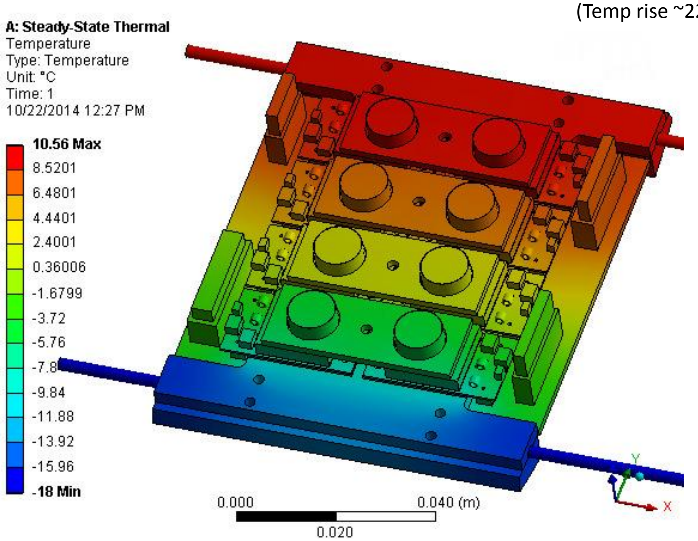
(View from disks)

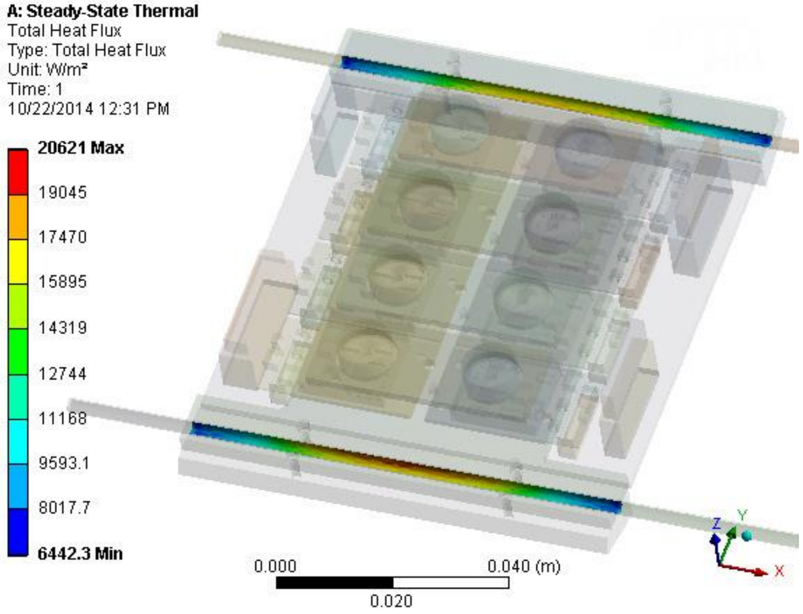
Electronics Cooling

- DC/DC converters have highest power density
- FEA results indicate single ended cooling yields acceptable converter temperature (left graph) and tubing wall power density (two-sided example shown in right graph, max. density=21 kW/m^2).
- Cooling bridge design with common components for converters and portcards

FEA Results with 1 End Cooling

Temp rise ~ 28.5C for 14 W
(Temp rise ~22C if 11W)

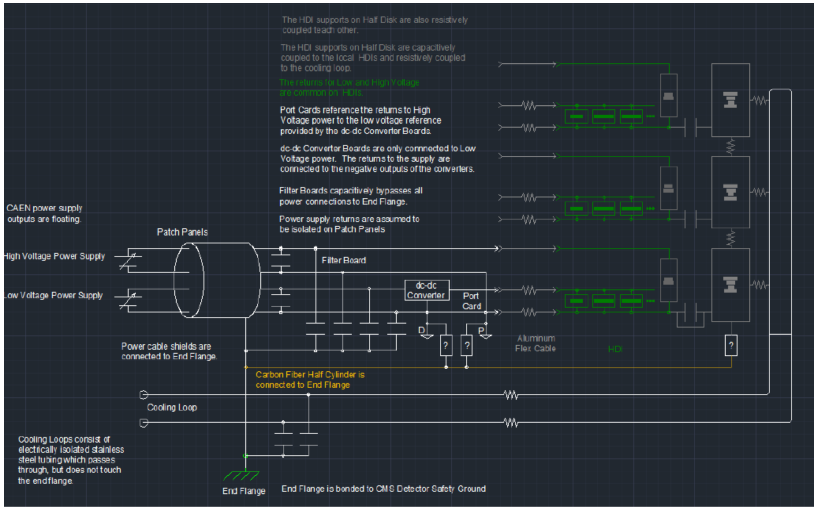




Grounding

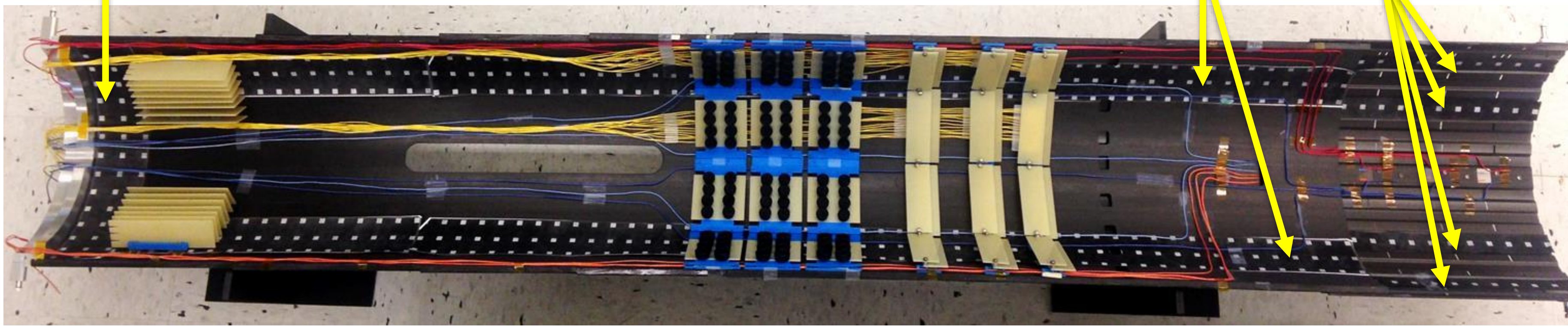
- Grounding mesh is co-cured into the cylinder shells

- provides shielding contact for the carbon structure and contact points for electronics ground reference



(Grounding scheme in additional slides)

Grounding Mesh Locations 



Cabling & Fibers

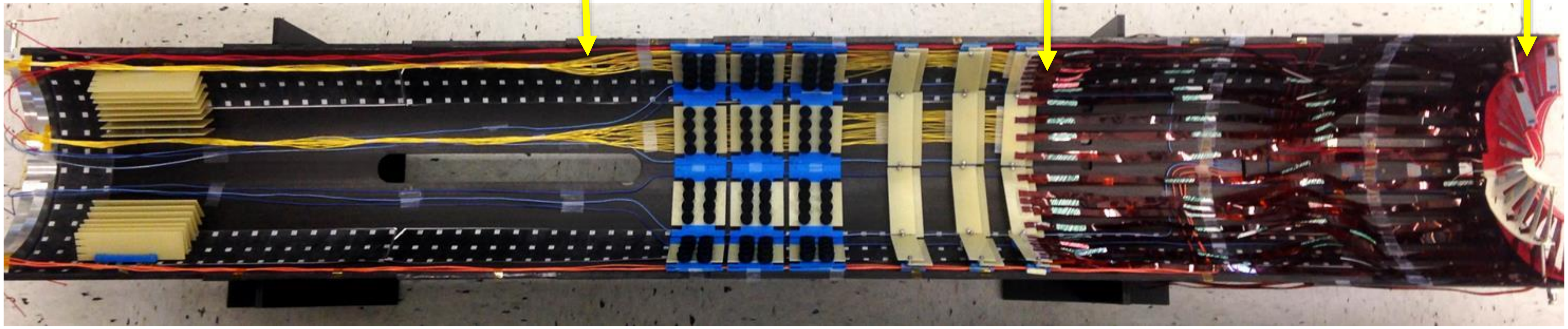
Al flex cable layout from modules to port cards has been developed and tested

The increase in the number of fibers for Phase 1 is significant and requires an organized layout. The fibers will run individually to the end flange. The design of the end flange was recently modified to accommodate fibers on top of the end flange.

Cables per Half Cylinder

Component #1	Component #2	Number and Type of Cable
Modules	Port Cards	168 Al Flex
DC-DC	Port Cards	8 wires (AWG 24) to each PC stack
CCU	Port Cards	I2C 7 wires (AWG 28) to each PC stack
DC-DC	Filter Boards	6 wires (AWG 20) to each DC-DC
Port Cards	Filter Boards	2 wires (AWG 20) power per PC
CCU	Filter Boards	2 wires (AWG 20) per FB to CCU

Readout Fibers (x168) **Al Flex Cables (x168)** **1st Outer and Inner Disks**

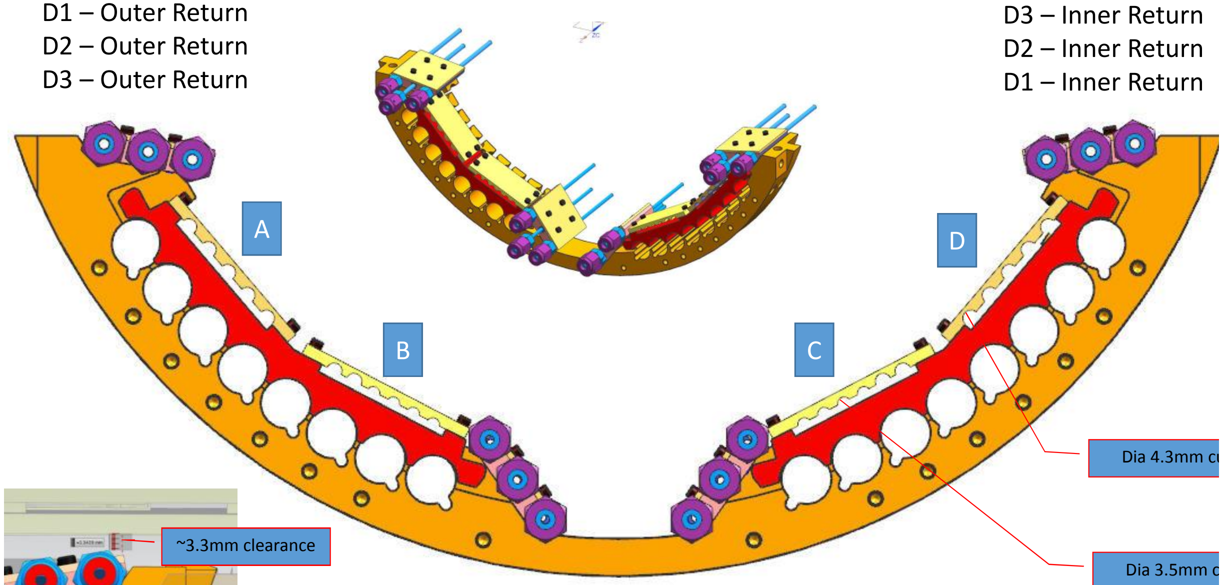


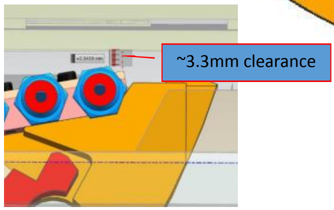
(Not all fibers and cables shown)

End Flange Layout

D1 – Outer Return
D2 – Outer Return
D3 – Outer Return

D3 – Inner Return
D2 – Inner Return
D1 – Inner Return



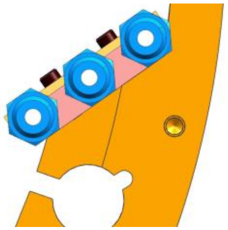


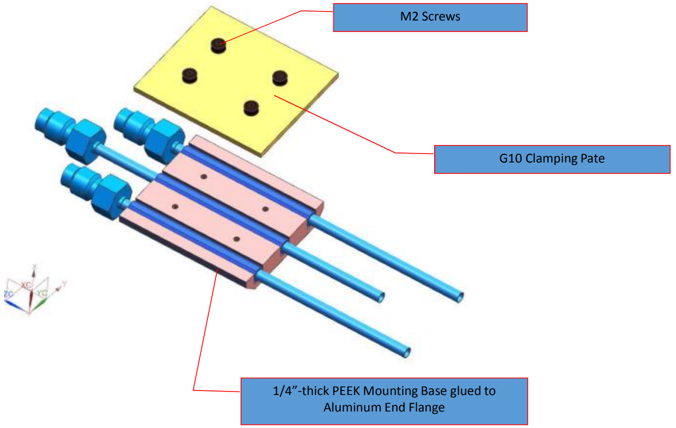
D3 – Outer Supply
D2 – Inner Supply
D1 – Outer Supply

D1 – Inner Supply
D2 – Outer Supply
D3 – Inner Supply

- Individual 1/8" VCR connections for all six cooling loops
- Capillaries outside of pixel volume connect to two main lines per half cylinder

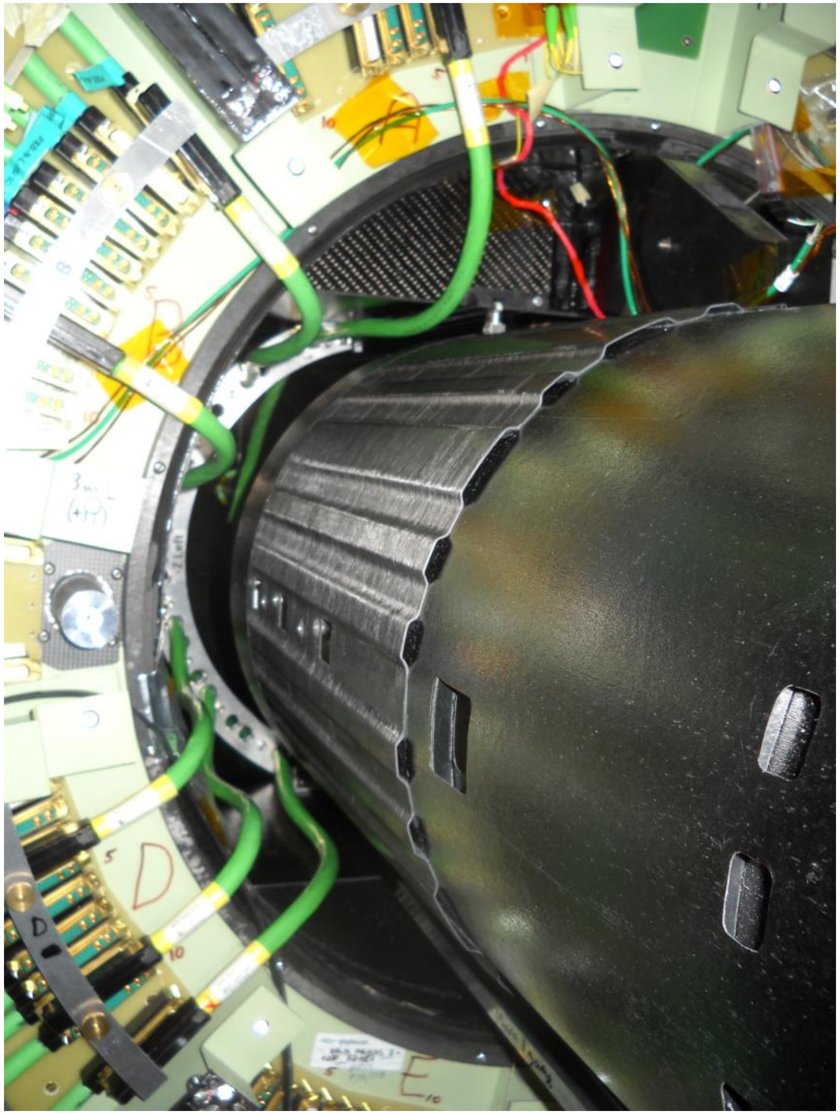
A,B,C,D: fiber locations on top of cable clamps





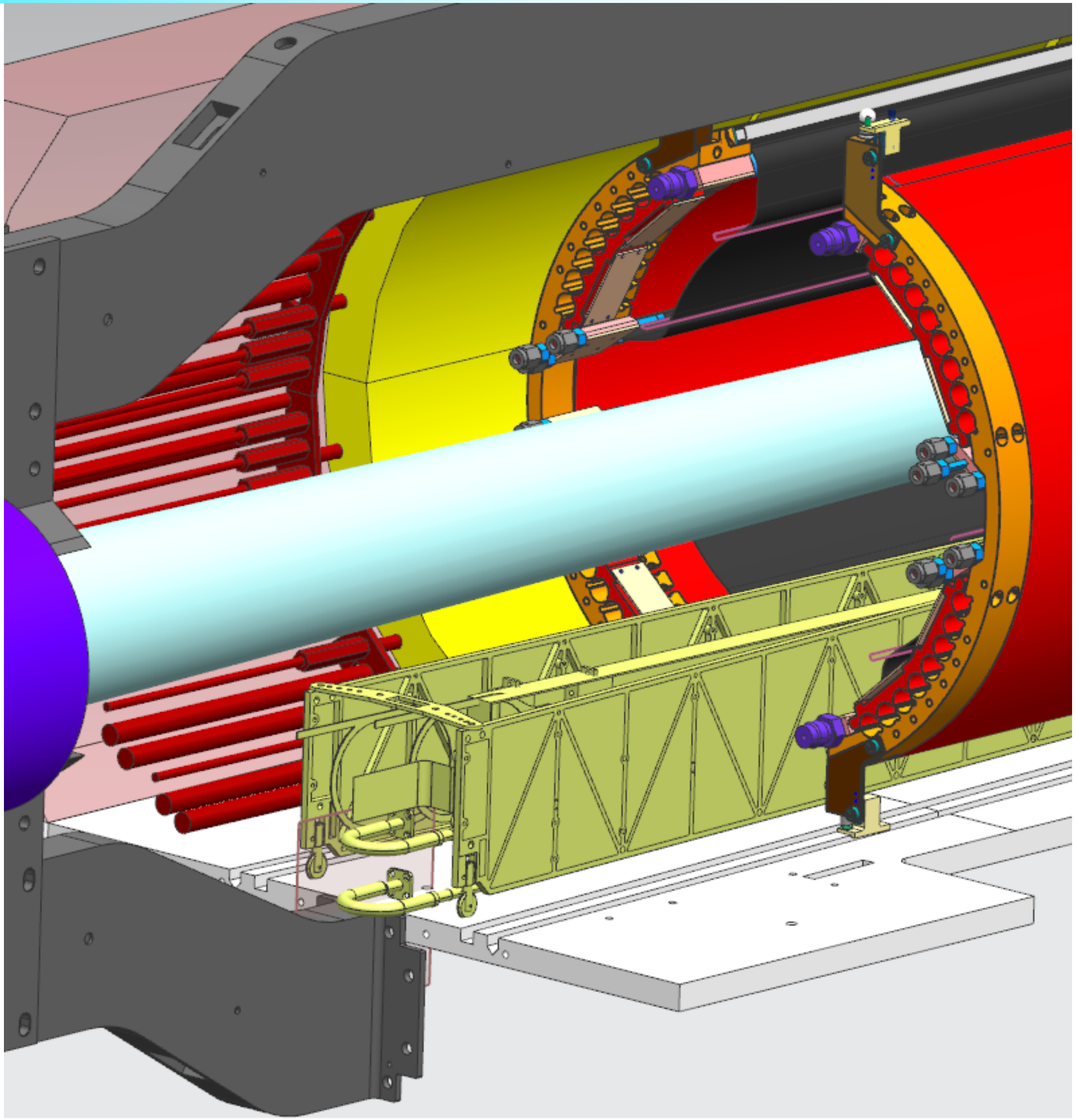
FPIX Support with adjustable HC Mounts

- Based on insertion tests conducted in 2014
  - Phase 1 FPIX mockup
  - New rails (UC-Davis) designed to provide clearance to beampipe lead shield
  - Investigated clearance to latest BPIX cable routing
- Installation clearances studied in CAD
  - BPIX mockup not available
- Adjustability added to HC mounts



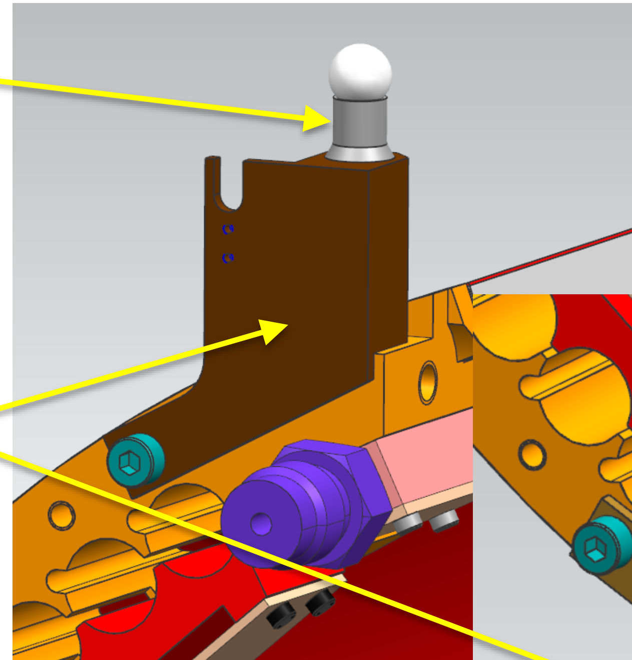
HC End Flange Configuration

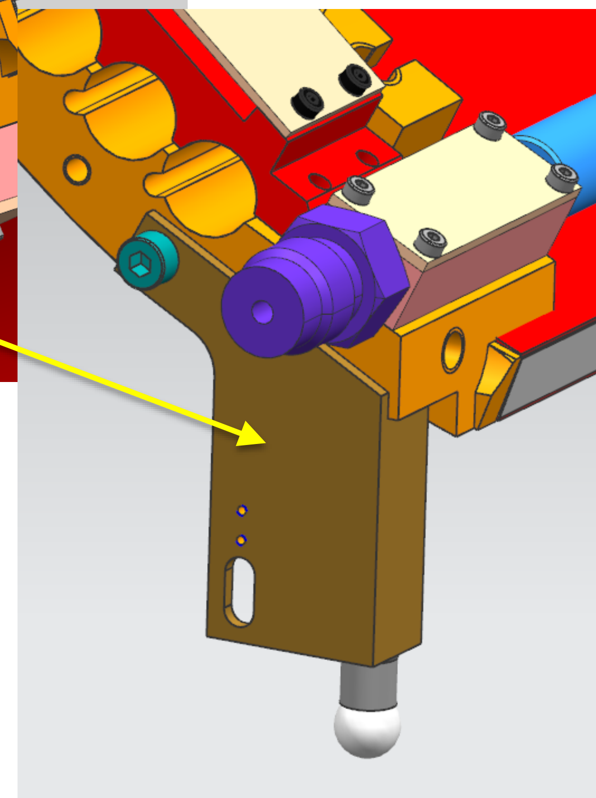
- View aft of the end flange
- BCM shown in place
- Cables, fibers and CO_2 lines not shown

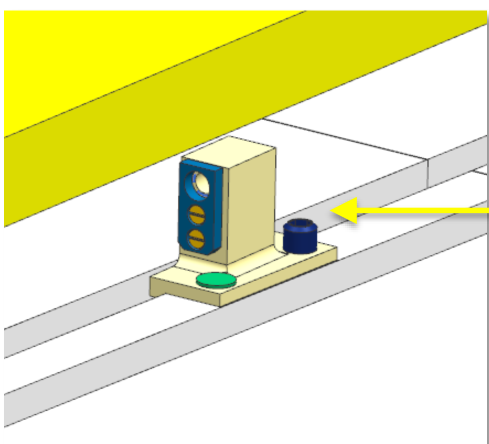


HC Supports – Rear Mounts

- Posts mount to end rings; shims for vertical adjustment
- Z-stop brackets mounted to end ring engage Z-stop blocks mounted to CMS pixel support plate



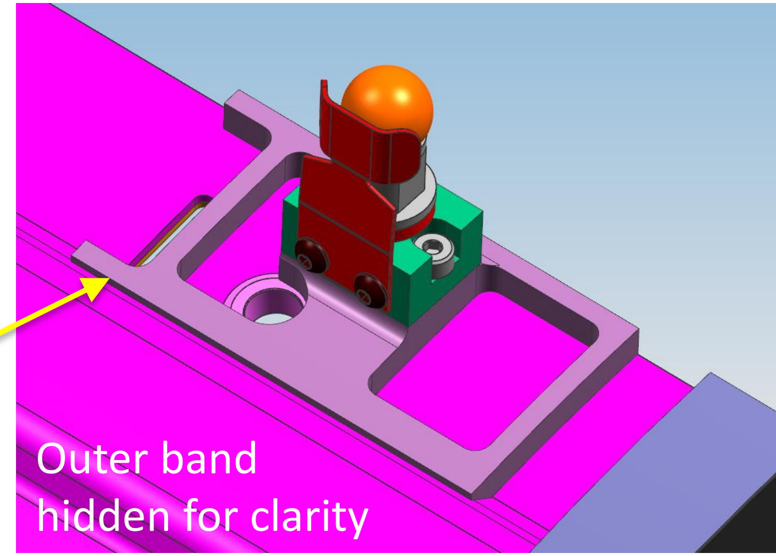


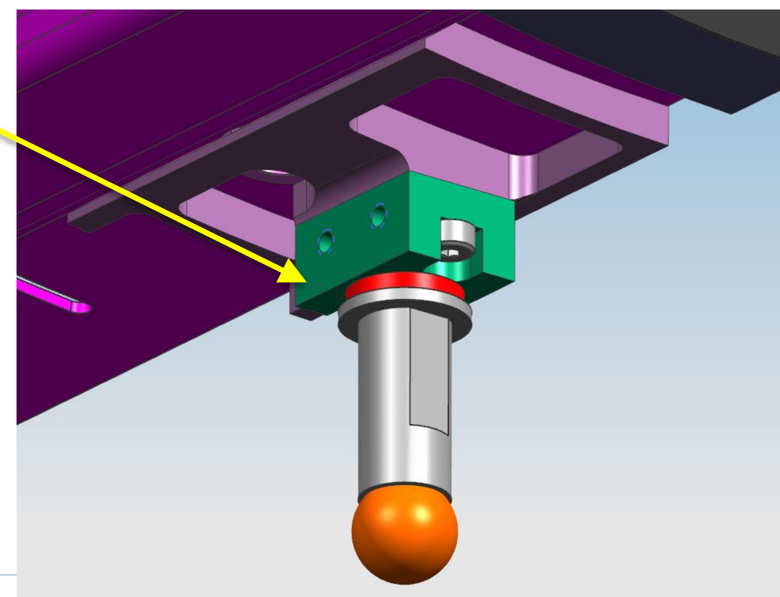


Z-stop block with shim

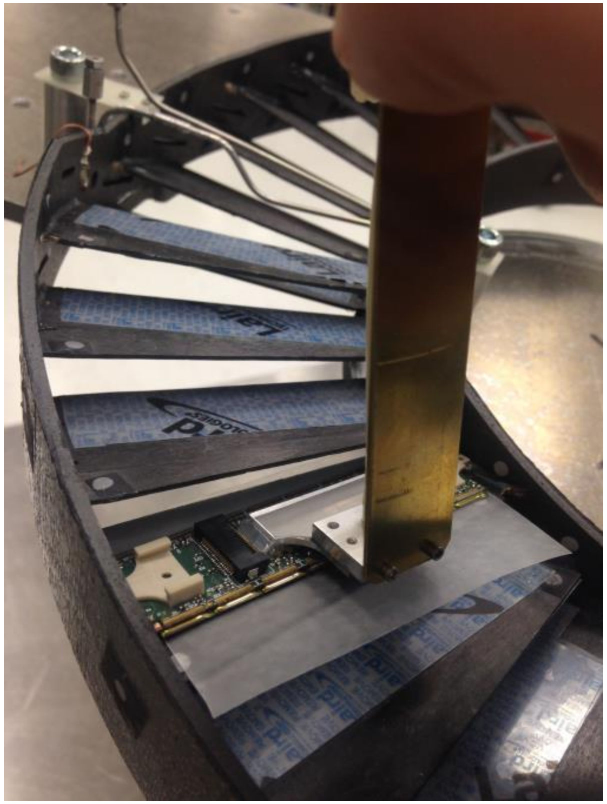
Adjustable Front Mounts

- Added +/-X adjustability
- Bracket glued to CF split into two parts
  - Fixed part sandwiched between corrugation and outer band
    - Pinned to precision mandrel during assembly to control location
  - Replaceable part with different geometries achieve different X offsets in 1mm steps
- Posts mount to bracket block
  - 3.25mm +Y nominal beam center offset
  - ±1.5mm adjustability in 0.5mm steps

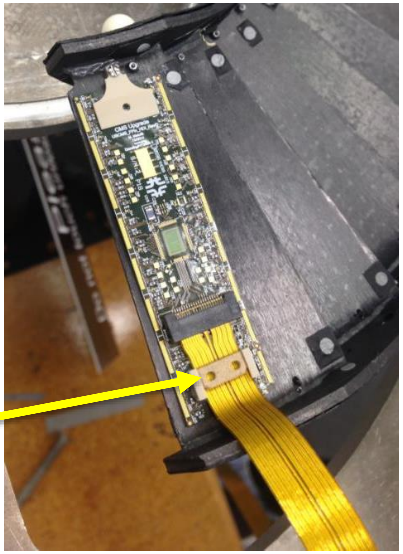




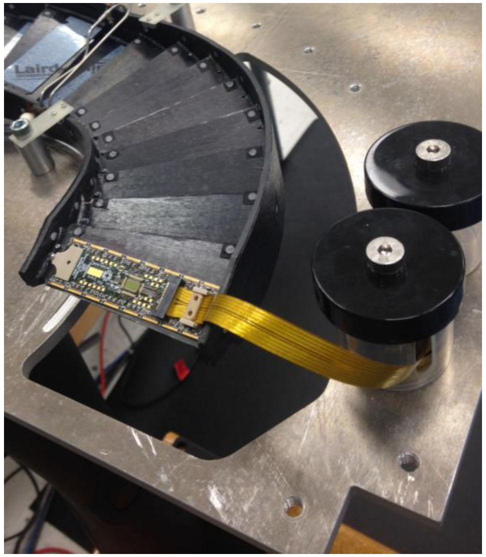
Detailed Module Installation Procedure



- Thermal phase change material and module locating screw inserts already in place on disks
- Custom vacuum tools used to place modules into position
- Cable insertion, and quick electrical checkout during module installation
- Flex cables stored in containers attached to disk carrier base plate

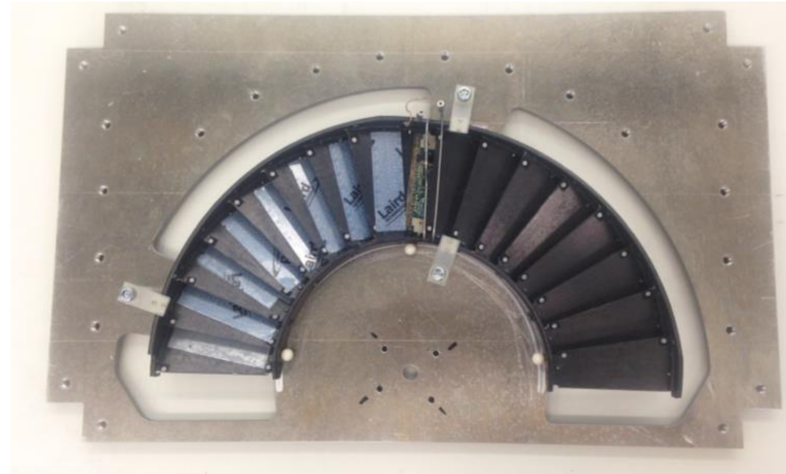


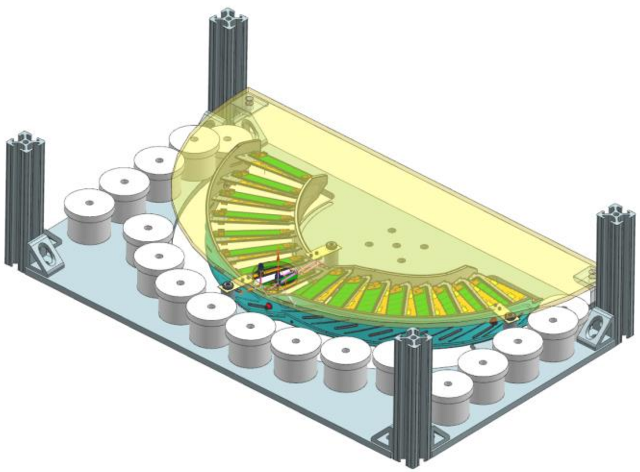
Cable restraint wedge

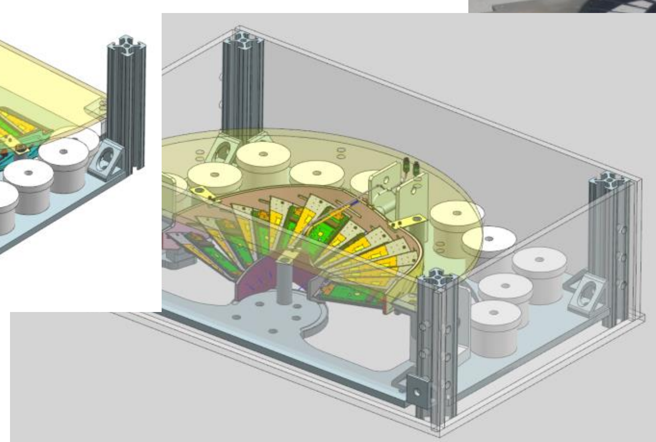


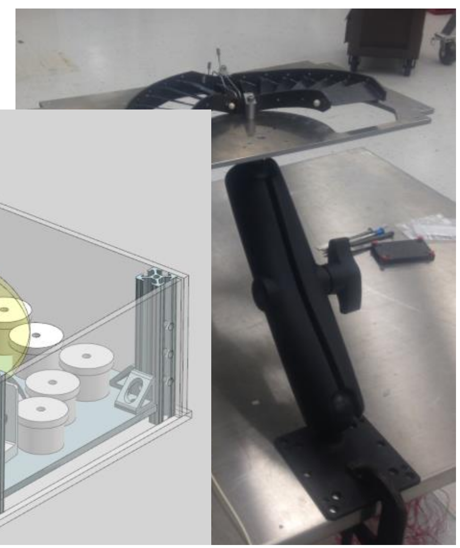
Disk Support & Transport

- Finished mechanical disk structure clamped to aluminum base plate
- Remain on this support structure for module installation, testing and shipping
  - base plate is integrated into storage and shipping containers

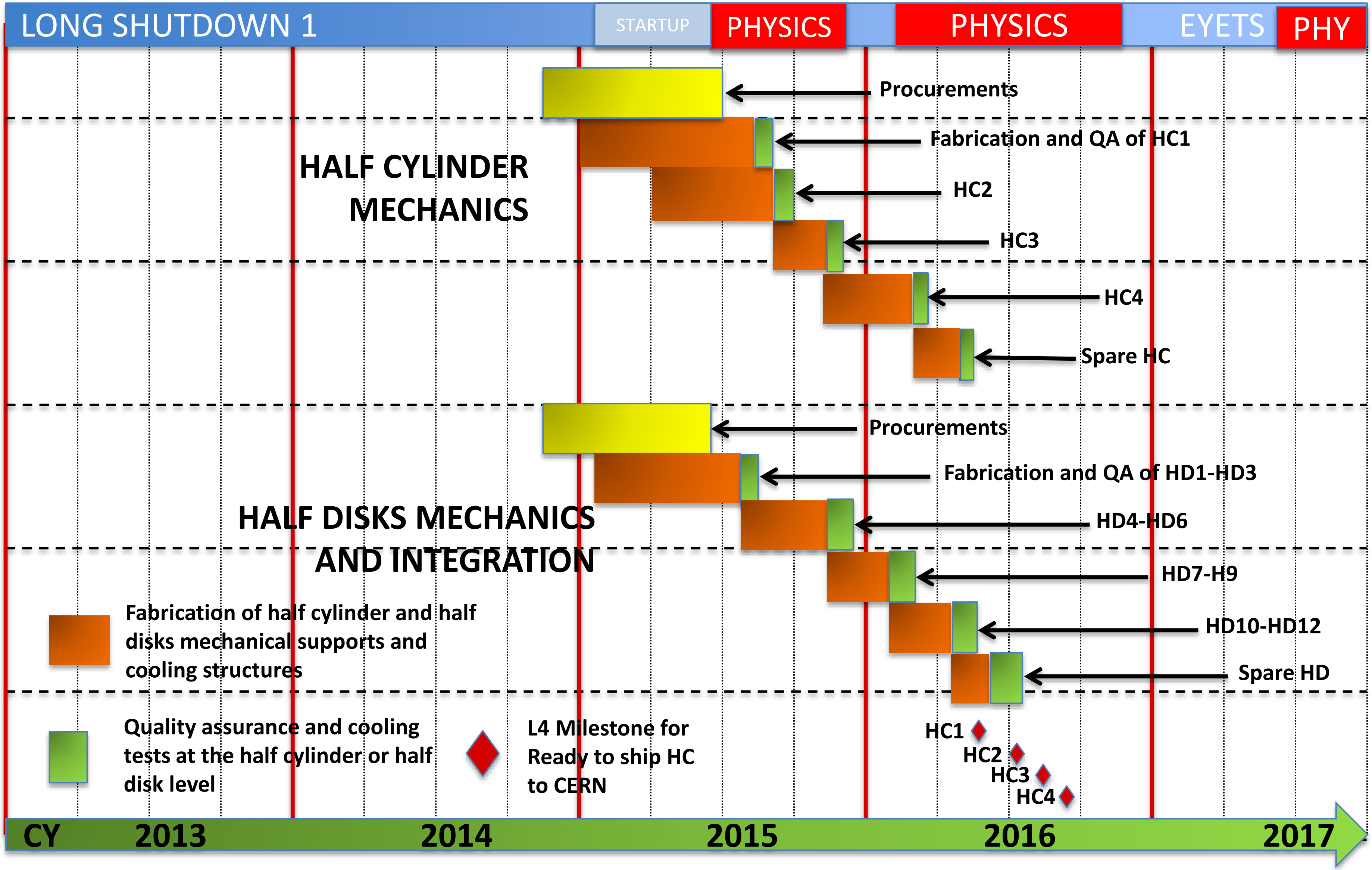








Schedule – Mechanics (Production)



Production Status & Schedule

- Cylinders:
  - 50% of rear shells done
  - 80% of curved ribs done
  - 100% of straight ribs done
  - 100% of solid CF rings done

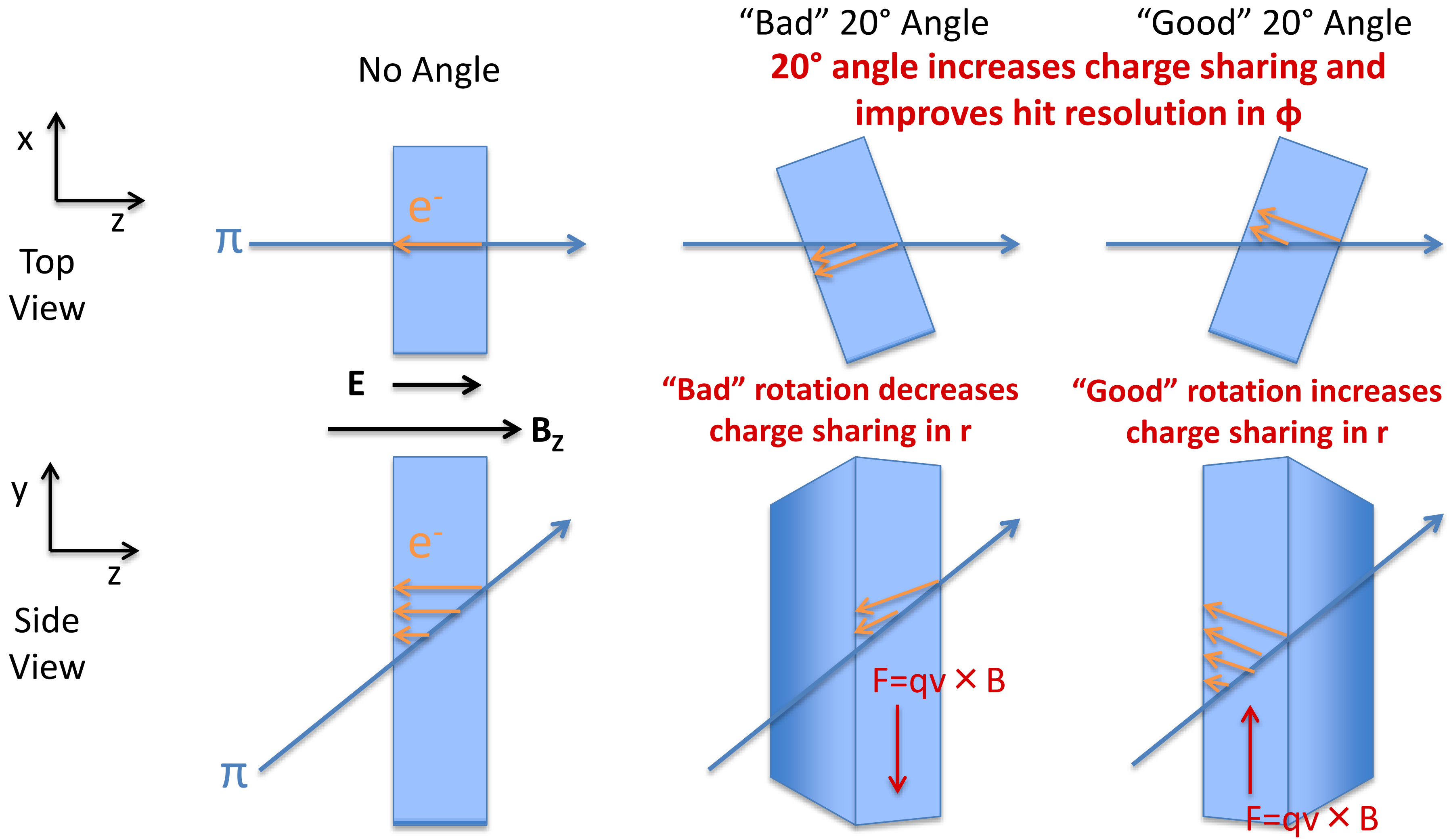
- Disks:
  - 80% of blade lamination done
  - 80% of blade drilling and cutting done
  - Graphite rings for –z rings machined

- Schedule:
  - First cylinder in August; complete with disks in September
  - Then: one cylinder and six disks every two months

Backup

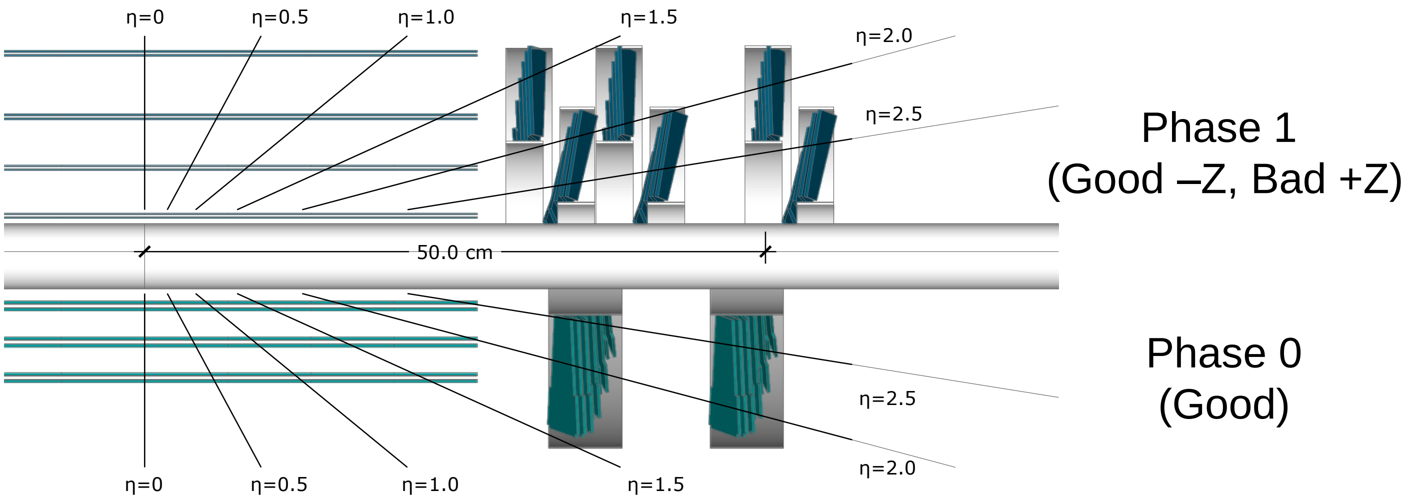
Mirroring of FPIX Disks

- FPIX blades/modules have a 20° turbine angle



Mirroring of FPIX Disks

- Currently installed FPIX have mirrored +z and -z endcaps
  - Both endcaps have a “Good” turbine rotation
  - However the two endcap structure is physically different
  - Means two different mechanical designs and fixtures for fabrication
- We studied (in simulation) what if we built the same mechanics for both +z and –z endcaps
  - E.g. “Good” turbine rotation for -z endcap, “Bad” for +z endcap

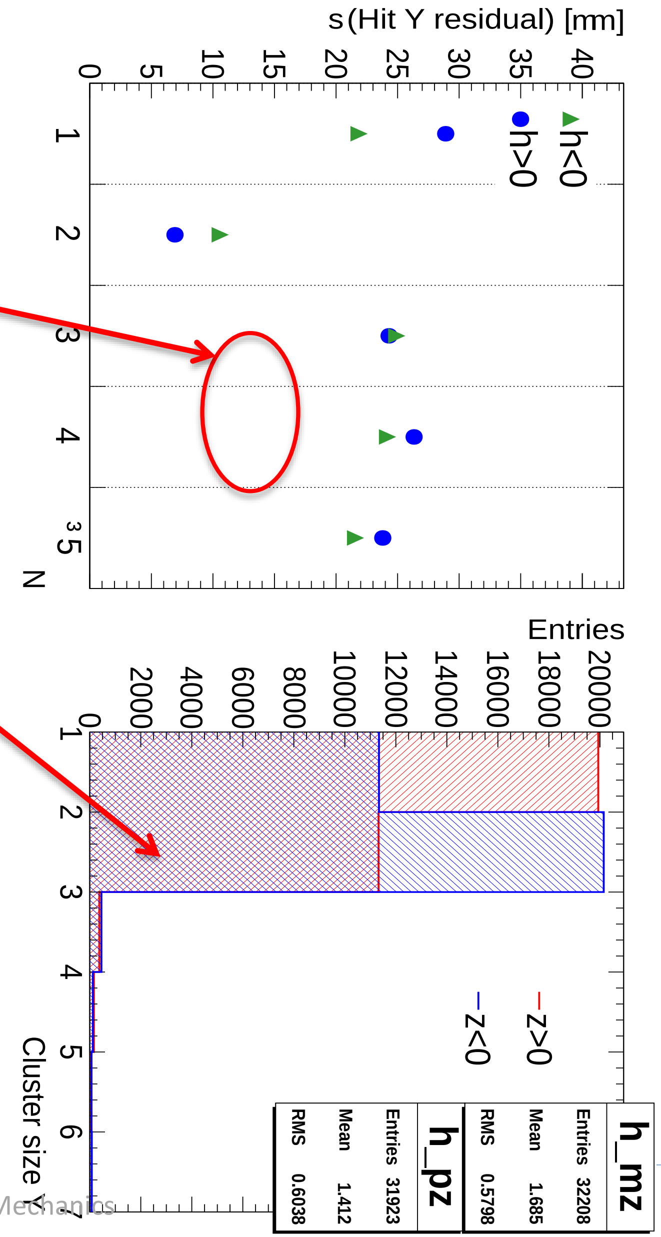


LHC CMS Detector Upgrade Project

σ(Y/ϕ) vs. Cluster Size

Verena Martinez Outschoorn

Larger hits in Z<0 side



1) **More two-pixel hits**, which have the best resolution

➞ Even though resolution for these is slightly worse

2) **Fewer single-pixel hits**

➞ Note the resolution for these is also better

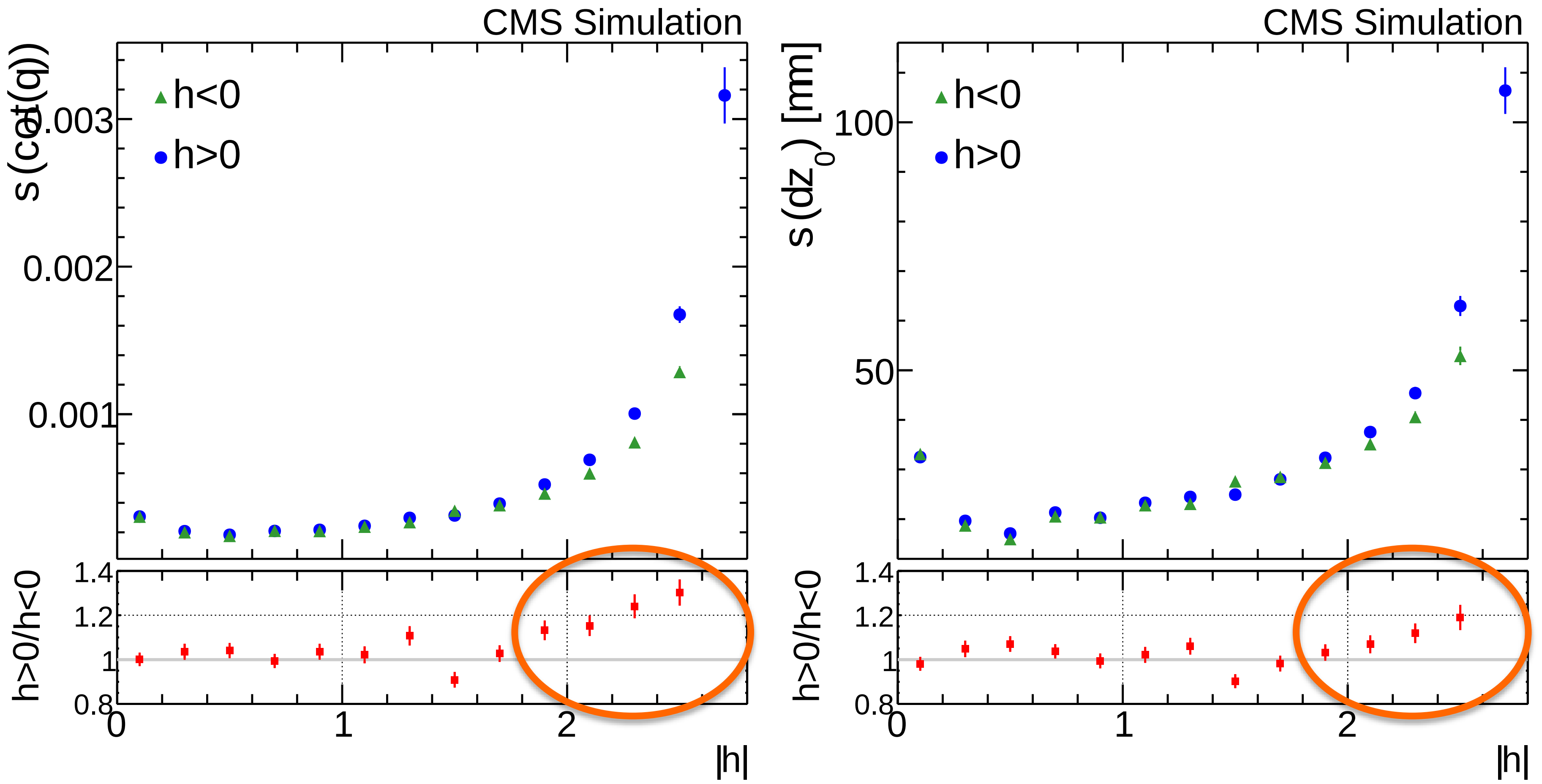
RMS(Z<0) ~ 17µm

RMS(Z>0) ~ 26µm

Overall better single hit resolution in radial direction by ~50% for Z<0 compared to Z>0

Track Parameter Comparison

$\sigma(\cot\theta)$ Verena Martinez Outschoorn $\sigma(\delta z_0)$

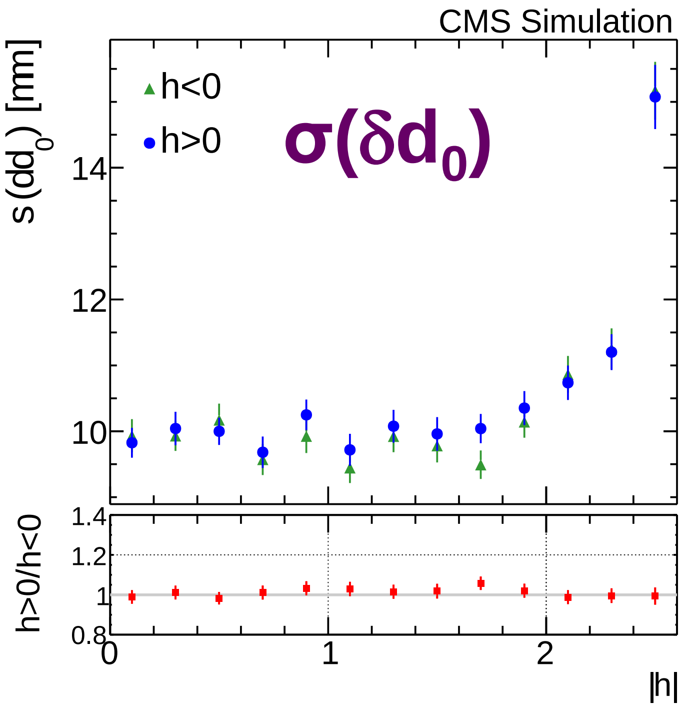


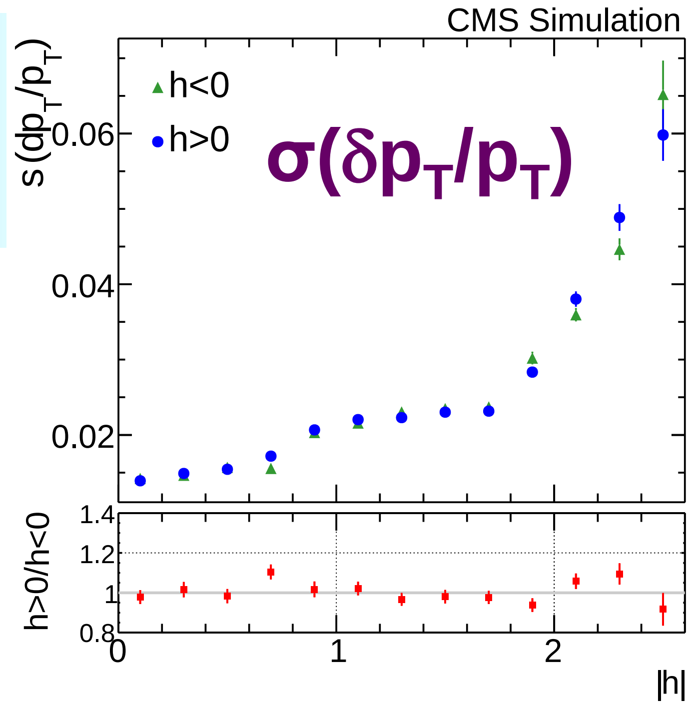
Impact of ~20% in cot(θ) and δZ_0 resolution for ~ |η|> 1.8

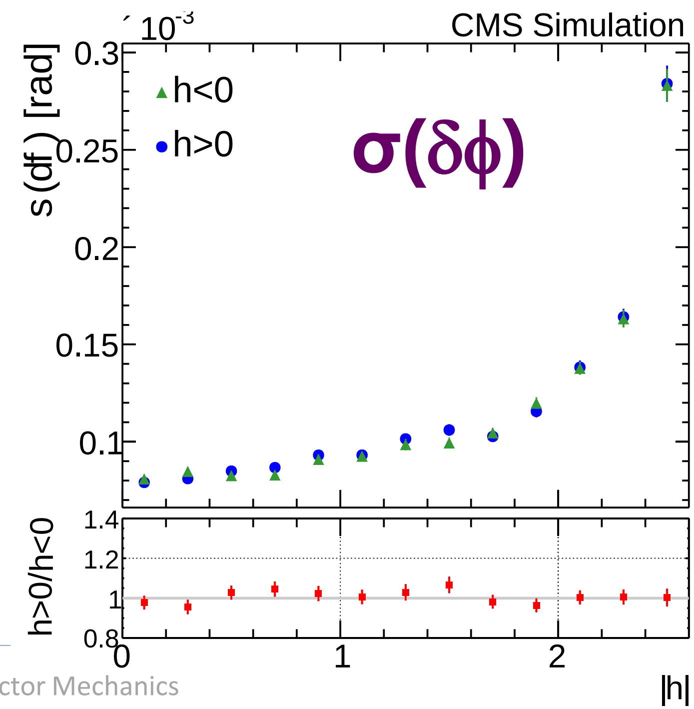
LHC CMS Detector Upgrade Project

Track Parameter Comparison

Verena Martinez Outschoorn







No significant difference for the other track parameters

Summary of MC Study

- Performed studies of impact of +/- Z rotation in the FPIX on the tracking performance in simulation using a sample of muons with p_T 1-200 GeV

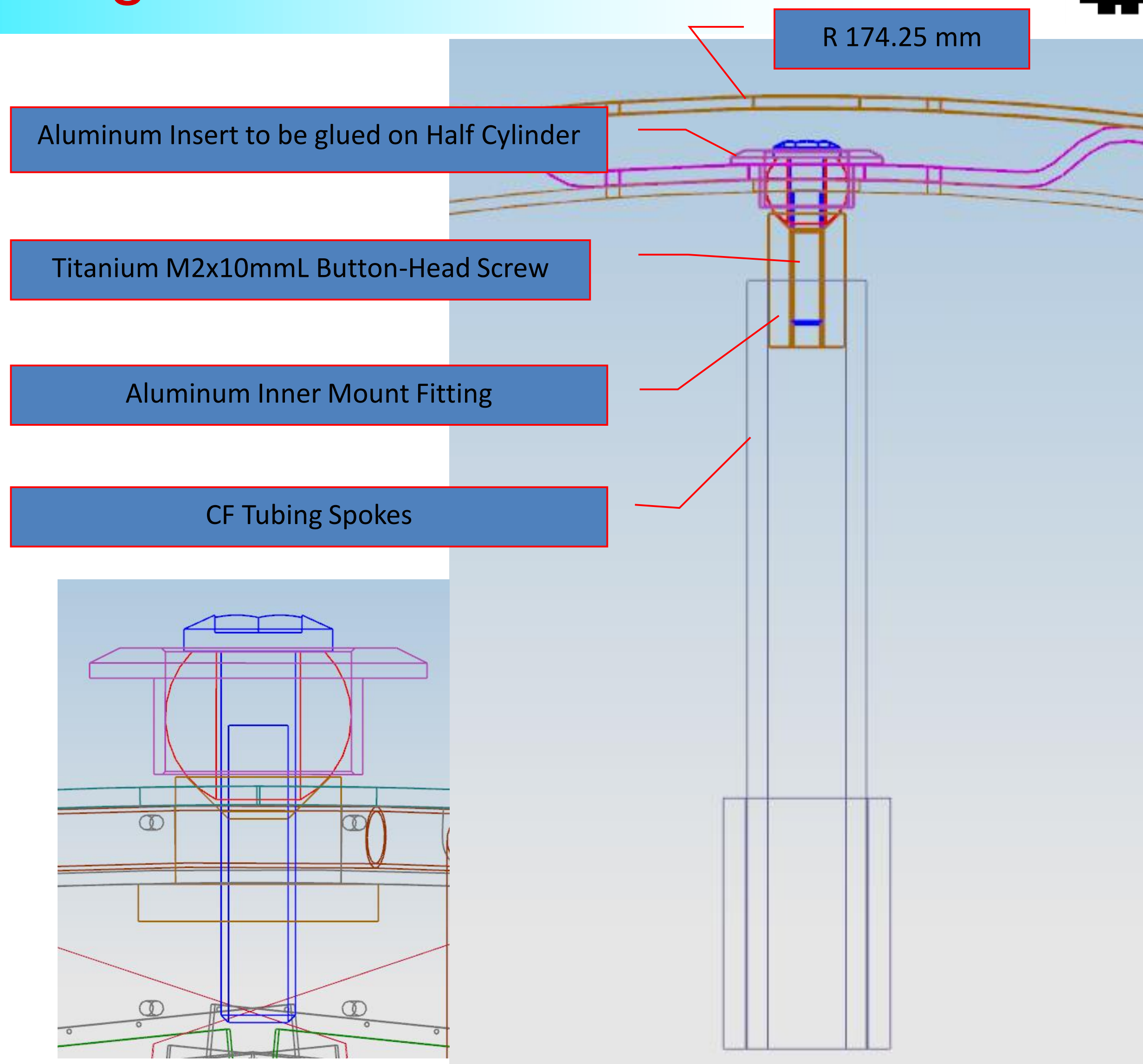
- Preliminary results show degradation in performance for +Z vs. -Z
  - **~50% worse single hit resolution** in +Z side
  - **~20% worse track parameter resolution** in +Z side for the most relevant parameters: cot(θ) and δz

  Mirror of +Z and –Z would remove this asymmetry between the 2 sides

- **We decided to build mirrored (different) +Z and -Z endcaps!**

Basic Design of the Half Disk Mounts

- Outer and Inner Mount Assemblies attached to Half Cylinder Separately
- Existing mount design kept – ball slides inside a sleeve to avoid accidental handling
- CF tubing are used for the supporting spokes for inner HD

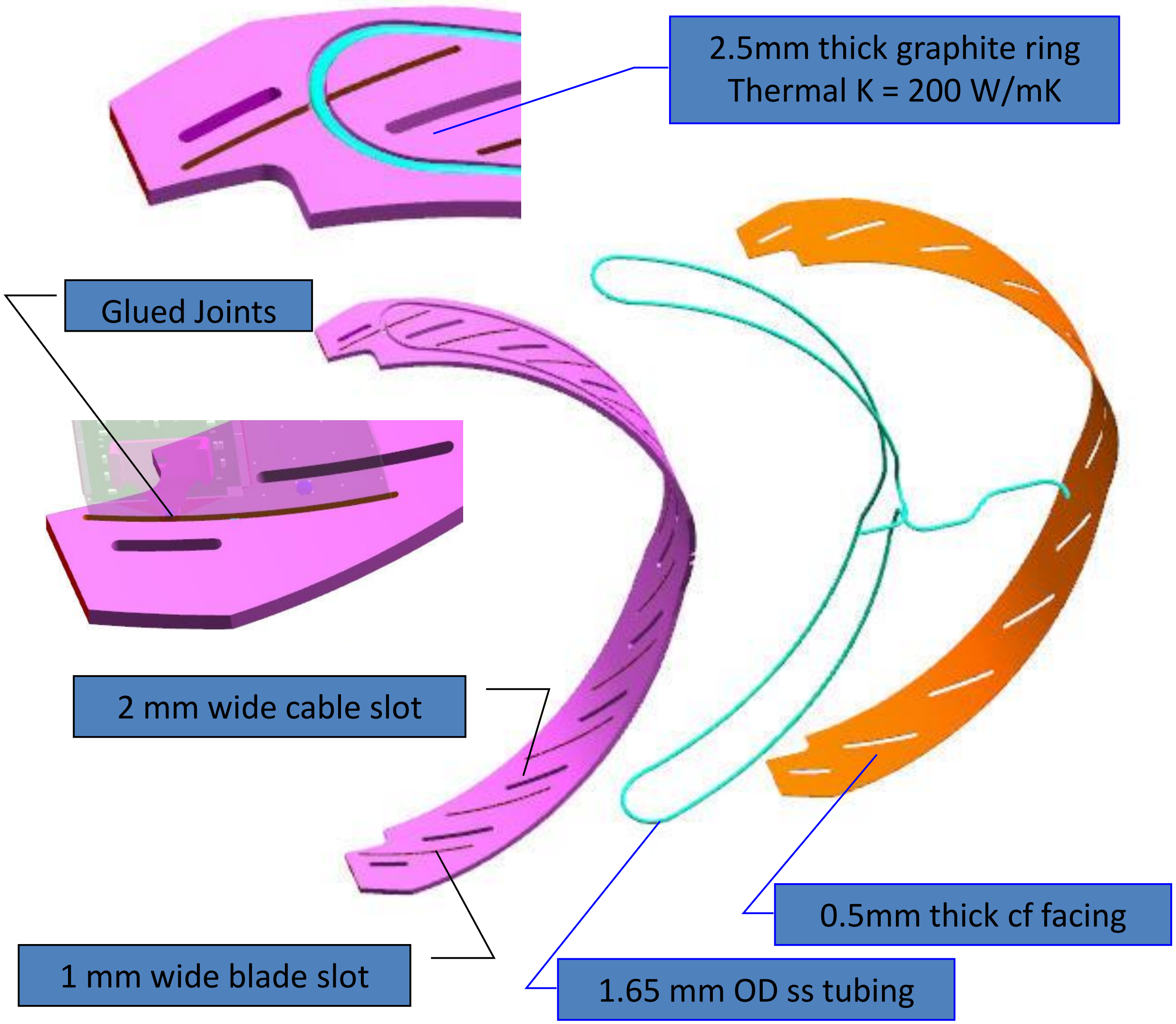


For Outer HD

For Inner HD

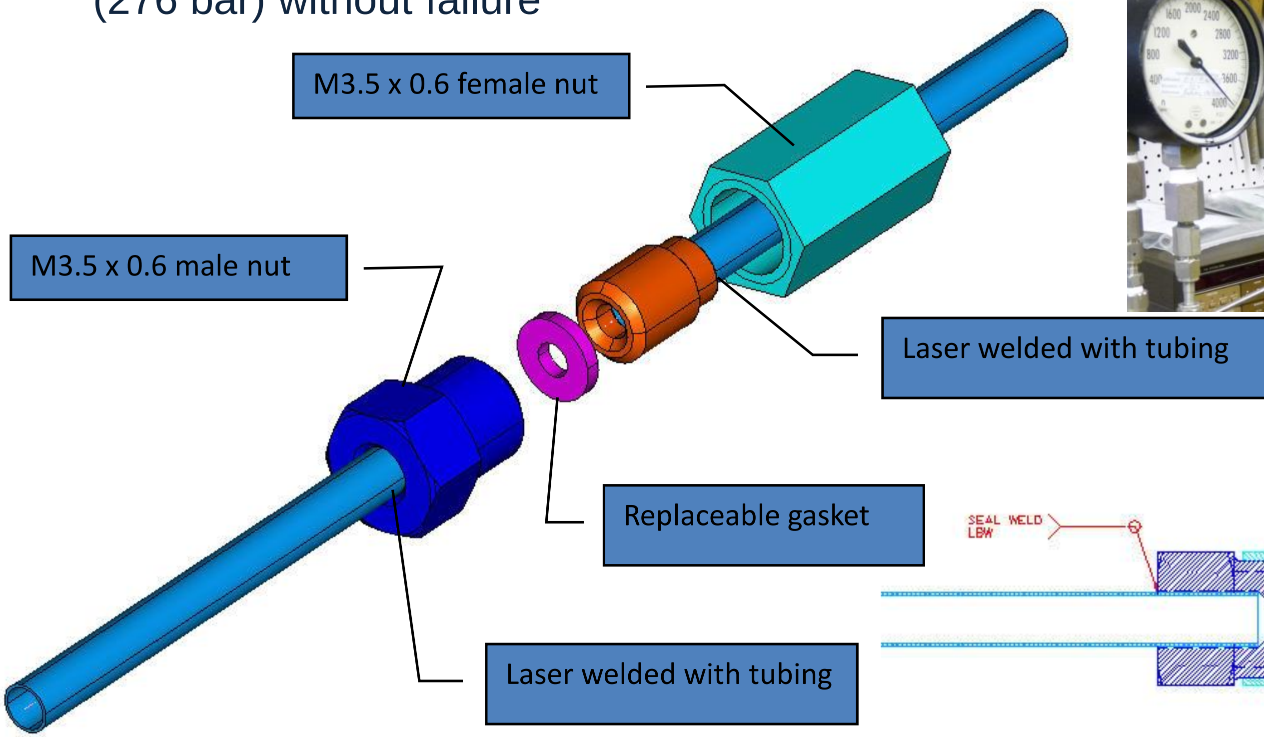
Cooling Arrangement

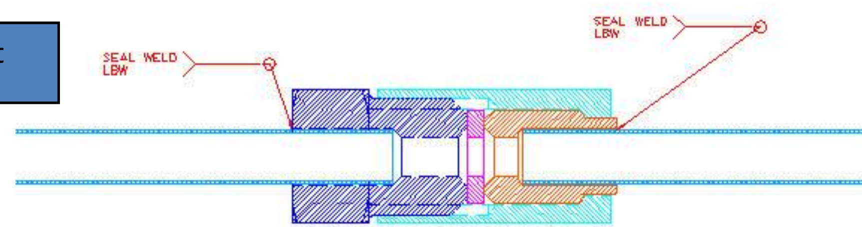
- Use the support half rings as heat sinks
- Embed ss tubing with high K thermal grease.
- Cover the groove/tubing with structural CF facing and glue them
- Embed TPG blade ends into the ring slots with high K thermal grease then glue them



CO_2 Removable Coupling Design

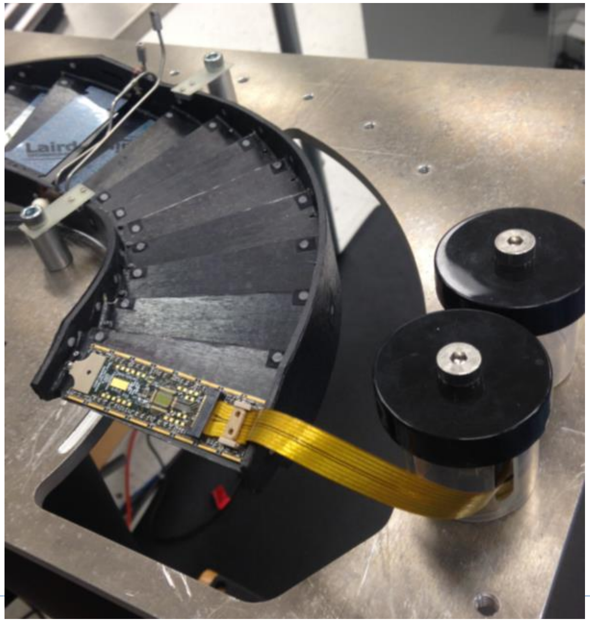
- Design is based on proven VCR metal sealing technology of commercial part
- Parts are made of ss except consumable aluminum gasket
- Prototype being tested and successfully held hydrostatic pressure up to 4,000 psi (276 bar) without failure

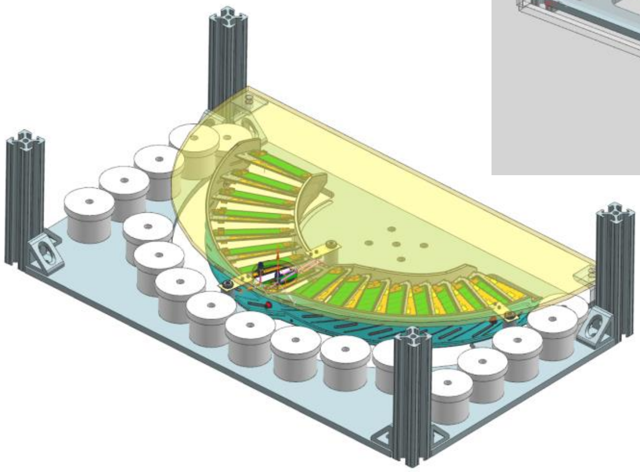


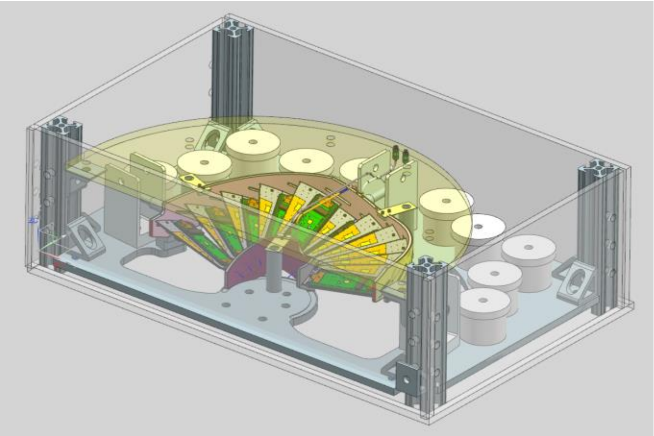


Shipping – Halfdisks

- Phase 1 HDs slightly larger due to flex cables
  - Cables coil up into small captured containers
- HDs fit in same outer case size with a little less foam than before for the outer disk
  - Phase 0 = 43.2 x 26.7 x 14.0 cm
  - Phase 1 outer = 49.5 x 30.6 x 14.0
  - Phase 1 inner = 41.9 x 27.3 x 14.0

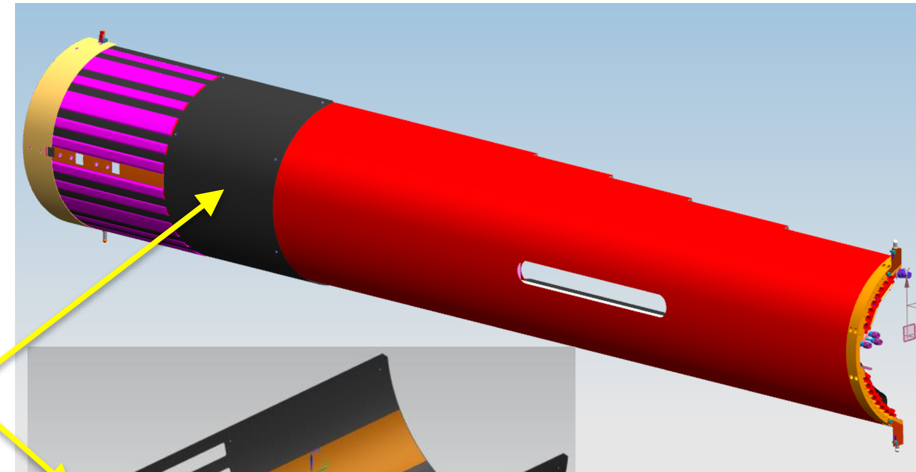


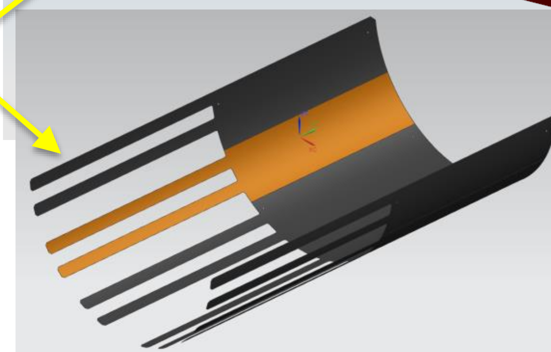




Integration
HC External Covers – Cables

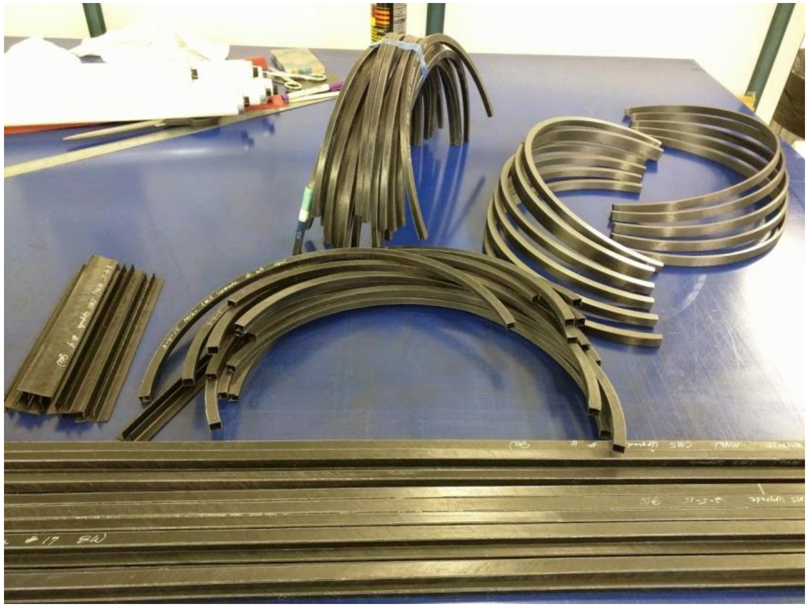
- Module cables from inner halfdisks are routed on the outside surface of the halfcylinder for a large portion of their length
- Carbon fiber cover added to capture cables
  - Profile sits within shadow of front corrugation features
- Cover is co-cured with a grounding mesh to electrically shield the cables
  - Grounded with soldered straps to internal ground mesh
- Phase 0 BPIX appears to have inner aluminum screen
  - This shield presumably repeated for Phase 1

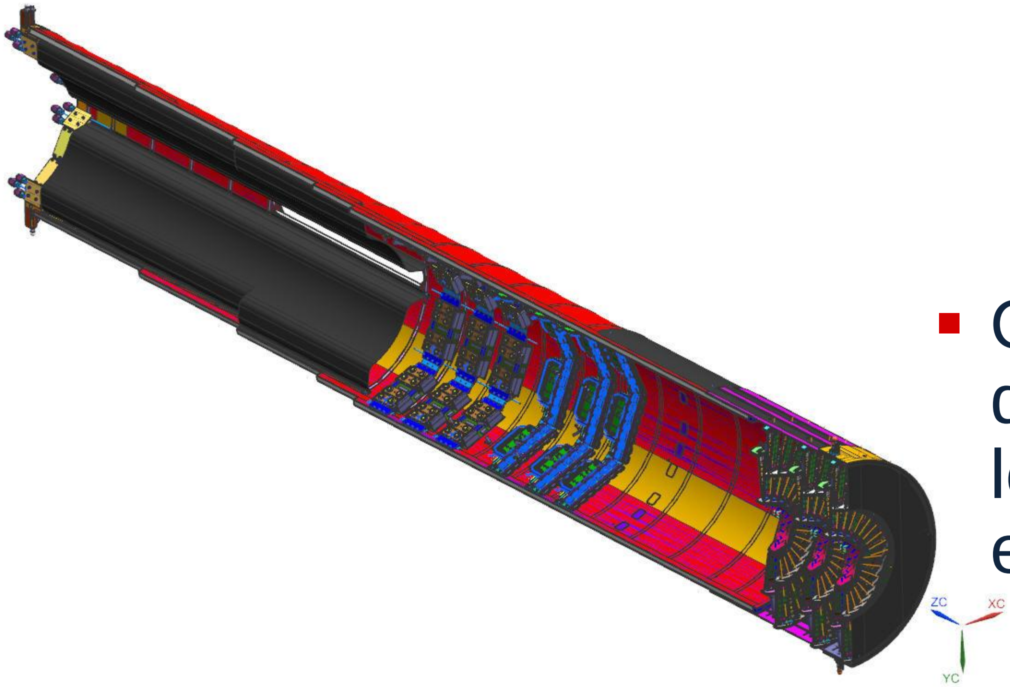




Cylinder Production & QA

- QA during cylinder construction:
  - deflection under load test performed for all straight ribs; single outlier found, removed.
  - All shells and ribs to be visually inspected for lamination defects.





- QA of finished cylinders: deflection test with dummy loads for third disk and electronics point load.

Disk Production & Mechanical QA

- Goal: sensor offset from nominal positions <1mm
  - Sufficient as starting point for track alignment
  - Achievable without optical/CMM measurement of every sensor position

- Critical dimensions for module position in CMS are:
  - Sensor to HDI 50µm
  - HDI to module end holder 63µm
  - Module holder to insert pins to blade edges 100µm
  - Blade edge to disk rings 150µm
  - Disk rings to disk support feet 100µm
  - Disk feet to cylinder inserts 25µm
  - Cylinder inserts to cylinder 125µm
  - Reproducibility of cylinder deflection 15µm (0.1 * max. deflection)
  - Cylinder end flange & foot gluing 20µm (done and measured on CMM)
  - Summed in quadrature: 260µm (linear sum: 650µm)

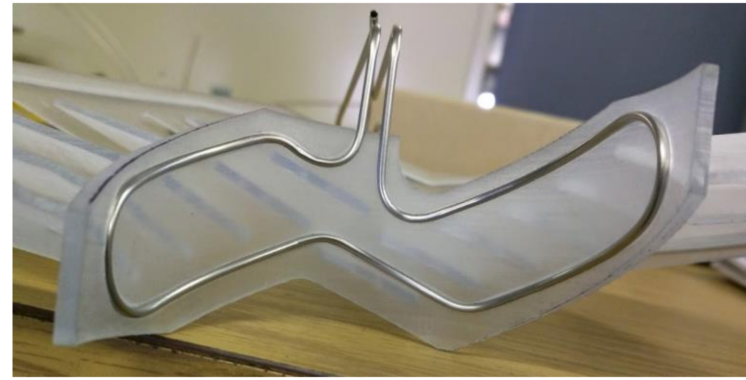
- All assembly steps done on templates
  - Insert gluing fixture references same blade edges that are used for alignment on disk gluing template
  - Disk support feet gluing fixture uses same radial and phi-stop features on disk rings as disk gluing template
  - First production items to be cross-checked on CMM
  - Production QC via template check of finished disk

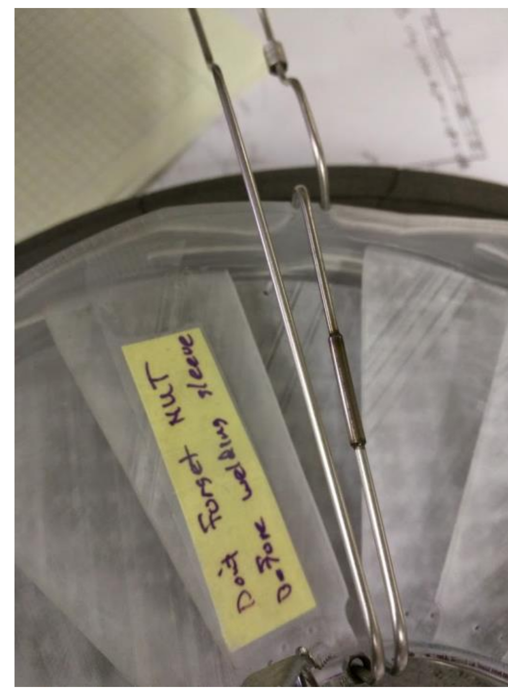
- Finished disks to be parylene coated for carbon sealing

- All disks (& cylinders, PC boards, cables etc.) to be weighed

Disk Cooling Tube Production & QA

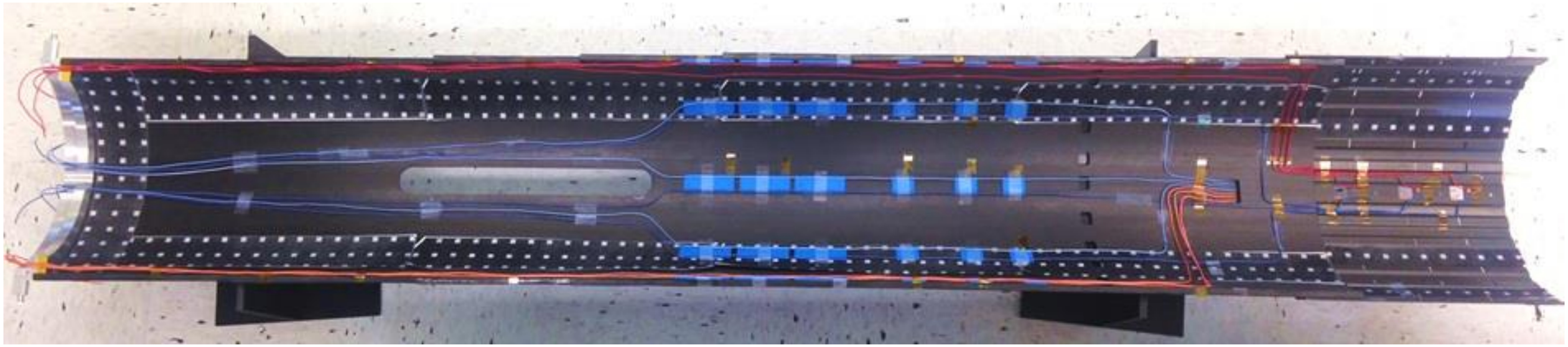
- All disk tubing bent on 2D template, then rolled
- Inner to outer ring joint welded (2 welds) on 3D template
- Finished disk tubing checked against 3D template
- Only three joints, all welded. 4 welds per loop.
- Finished tubing to be tested to 157 bar with hydraulic test stand before embedding into disk structure.





Cylinder Tubing Production & QA

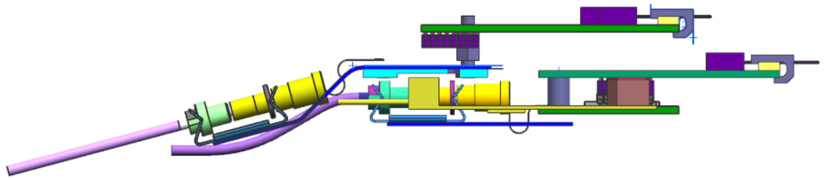
- Tubing bent to fit cylinder prototype
- Small number of joints, all welded:
  - Six loops, each with 2 couplers to disk, 2 tubing transitions in corrugated section, 1 coupler to inlet, and 1 coupler to return. Total of 6*6 = 36 joints in cylinder section, 36 + 24 = 60 joints including disks.
- Finished tubing checked for fit against cylinder prototype
- Standard commercial couplers at end flange
- Finished tubing to be tested to 157 bar with hydraulic test stand

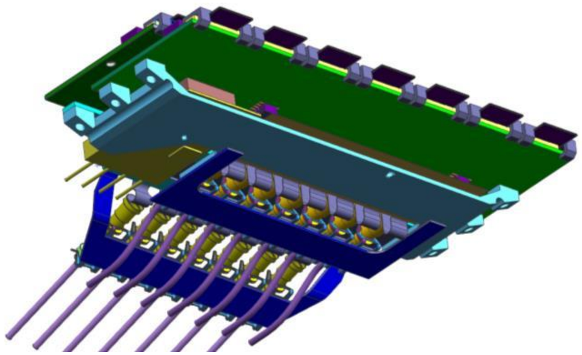


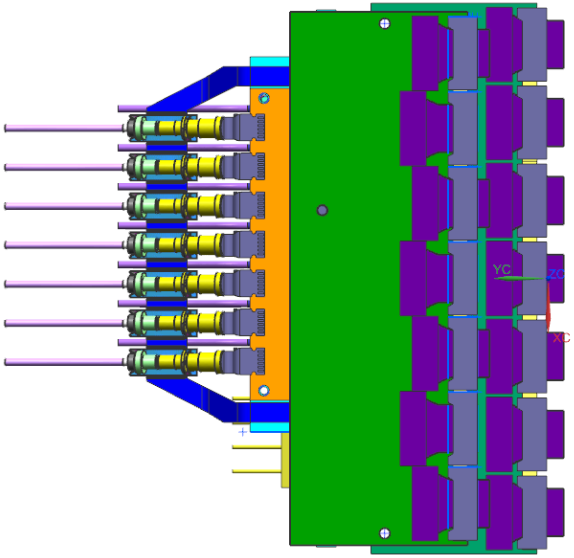
Capillary Production & QA

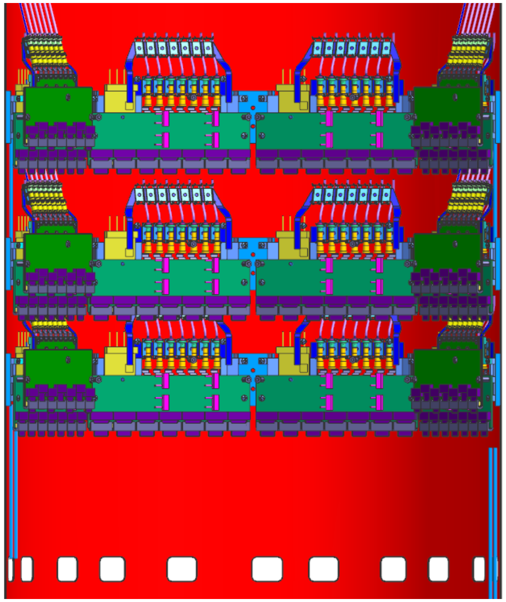
- Small diameter, large wall thickness
  - Standard commercial couplers
  - Can be bent in situ to interface between main lines and FPIX end flange
  - Final length & diameter to be determined to fit CMS integration
- Two welded joints
- Finished tubing to be tested to 157 bar with hydraulic test stand.

Portcard Design & Arrangement

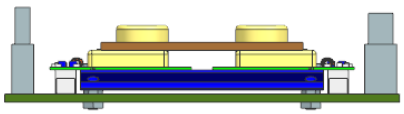


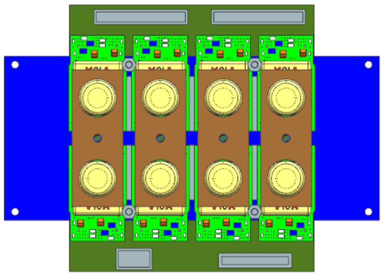


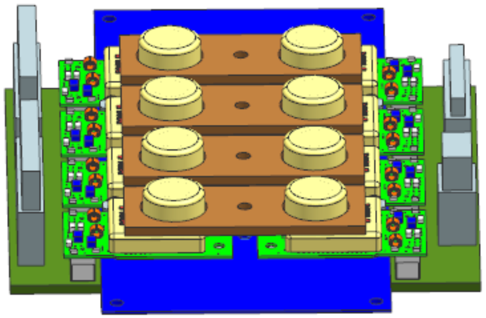


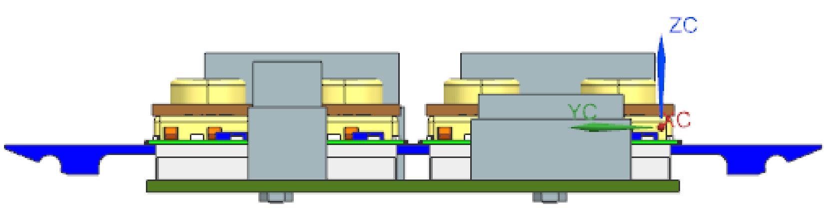


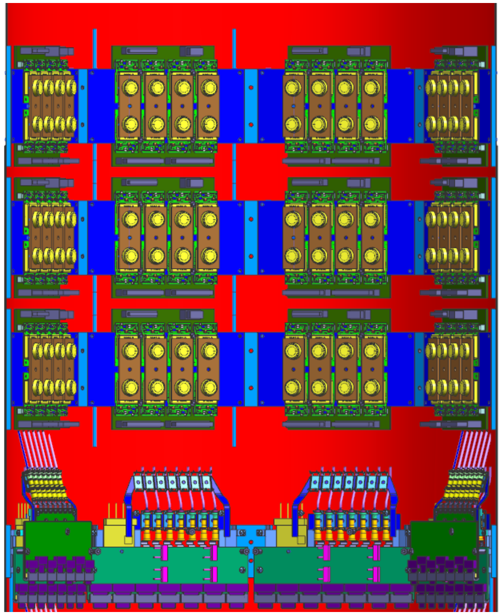
DC/DC Design & Arrangement











(not the latest design – some connectors have been moved to make better use of the width of the cooling bridges)

Grounding Scheme