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Simulation and material budget of the CMS Forward Pixel detector

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Abstract

The quality of the physics analysis at CMS is highly correlated with the accuracy of its detector simulation which is written in GEANT4 and the CMS object-oriented framework CMSSW. In order to ensure high performance in track and vertex reconstruction, an accurate knowledge of the material budget is therefore necessary since the passive materials, involved in the readout, cooling or power systems, will create unwanted effects during the particle detection, such as multiple scattering, electron bremsstrahlung and photon conversion. We present the implementation of the CMS Forward Pixel detector geometry in CMSSW framework. We also give a comparison between the simulated objects and the real detector and show that the weight agreement between the simulation and the real detector is better than a few percent.

1 The Forward Pixel detector design

The CMS Pixel detector is part of the tracking system which is closest to the interaction point as shown on Figure 1. It covers a pseudo-rapidity range of $-2.5 < \eta < 2.5$, corresponding to the geometric acceptance of the central tracker. It consists of three barrel layers (BPix) and two end-cap disks (FPix) on either side of the interaction region.

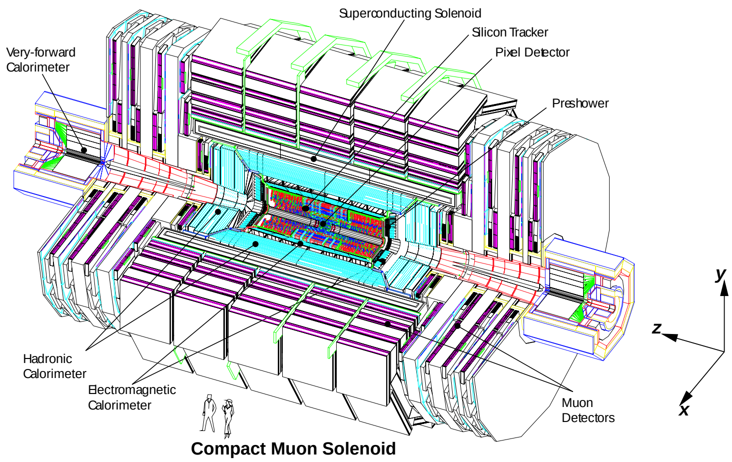


Figure 1: CMS global reference frame.

The FPix detector is made of eight half-disks as shown in Figures 2 and 3. The service cylinder is not shown in this picture. The disks are located at the Z positions ± 35.5cm and ± 48.5cm and contain twenty four blades, made of an aluminum base with a cooling channel and two panels. Cooling channels of adjacent blades are connected by the so-called nipples. There is a shift along the Z axis between the adjacent blades and each blade is tilted by 20 ° around its axis to provide overlap in angular coverage and enable the charge sharing induced by the large Lorentz drift in the 4 Tesla magnetic field.

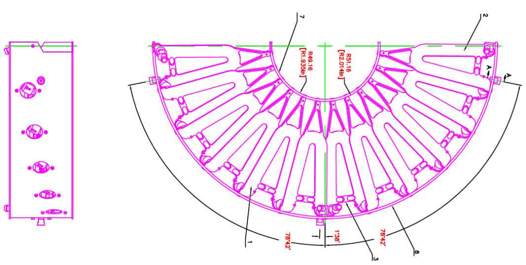


Figure 2: Forward pixel half-disk design.

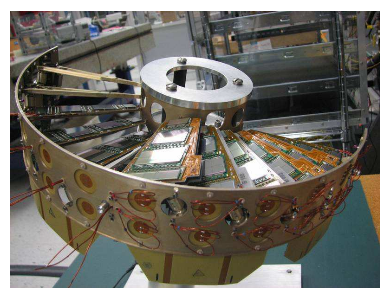


Figure 3: One of the eight full populated Forward Pixel half-disks assembled at Fermilab.

Each panel has a beryllium base plus a High Density Interconnect (HDI) and three or four sensor plaquettes as shown on Figure 4. A total of 96 double sided blades and 672 plaquettes are needed for the FPix assembly. Due to the geometrical constraints of the trapezoidal panels, five types of plaquettes are needed.

The charged particles going through the detector release their charge in the pixel cells. The charge is amplified and analyzed by the Read Out Chip (ROC), which includes 4160 readout channels. To assemble a pixel module, the ROC and the sensor are connected by tiny soldering contacts, called bump bonds. A plaquette is then formed by gluing the pixel module on top of a Very High Density Interconnect (VHDI) flex-circuit which is laminated on a thin layer of silicon substrate. The FPix detector contains 18 millions $150 \times 100\ \mu m^2$ pixels covering a total area of 0.28 m^2.

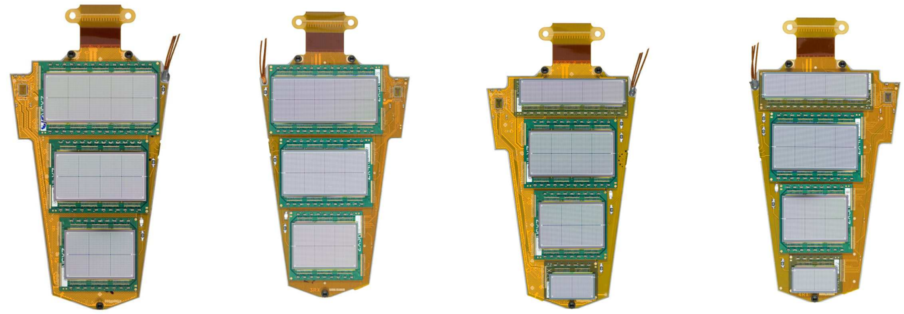


Figure 4: Forward Pixel left and right panels populated with three or four plaquettes. The *yellow* layer is the High Density Interconnect flexible circuit. A panel will be designated as right when its ear, where the Token Bit Manager (TBM) is positionned, is on the right when looking from the assembled plaquette.

2 New geometry description

A first descrition of the FPix geometry was written in FORTRAN/GEANT3 [4]. It was not a flexible description and knowing that some components of the detector were not yet designed, the CMS collaboration decided to re-write the new geometry description in C++/GEANT4 [2] using the Detector Description Language (DDL) [5] based on eXtensive Markup Language (XML). This description is flexible, easily extensible and based on the latest engineering drawings. Keeping the description in XML avoids shifting complex placements into C++ algorithms. Only one custom algorithm `DDPixFwdBlades.cc` has been introduced. This algorithm places the panels and blades on the disks and also computes the parameters necessary for defining the nipple geometry. This algorithm assumes that the axes of `Z+` disk are aligned with the CMS global reference frame of Figure 1. It also assumes that the `Z-` disk is rotated around Y by 180 °. One of the important requirement for an optimized description of the detector is a maximum use of symmetry and minimum duplication of the code. The CMS detector description possesses a geometrical hierarchy defined by volumes and placements, which associates two volumes in a PARENT-CHILD relationship with a relative geometrical transformation between their local reference frames. Reference frames for all sensitive volumes are right-handed, with Y axis pointing along the longer side of the sensor, Z in the direction of the electric field and X away from the beam line for 3-plaquette panels and towards beam line for 4-plaquette panels as shown in Figure 5.

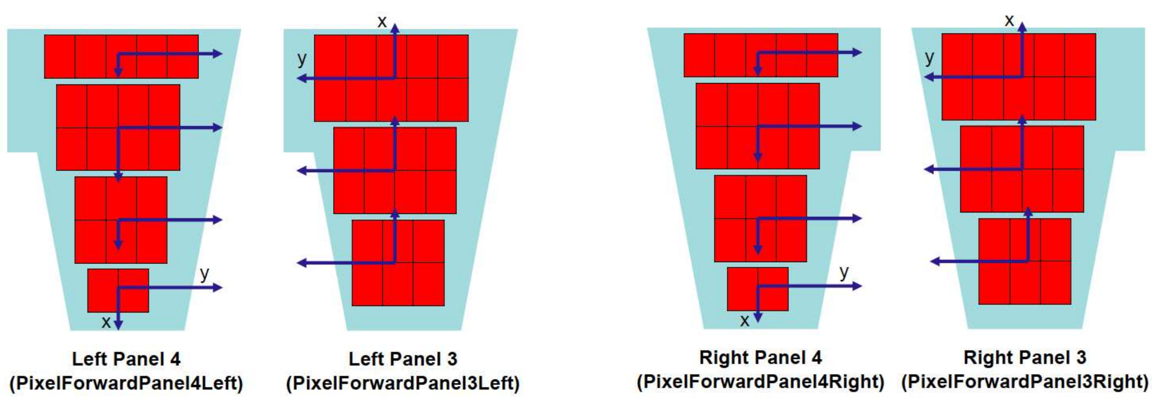


Figure 5: Local reference frames for the Forward Pixel plaquettes.

This requirement is imposed by digitization and reconstruction software that directly uses local reference frames of sensitive volumes as seen by GEANT4 tracking, without any conversions.

3 The FPix geometry package structure

The description of the FPix geometry is included in two packages: `Geometry/TrackerCommonData` and `Geometry/CMSCommonData`. Its schematic view is shown in Figure 6. Each `xml` file describes one detector sub-system, and does not use any references from files higher in the volume tree, such as constants, volume... Therefore, each sub-system can be visualised and tested independently. Each sub-system has a single entry point (*root volume*) and is assigned an *anchor point*. Sub-systems are positioned using the algorithm `DDPixFwdBlades.cc` which places their anchor point. Any change in one sub-system does not affect the code in other parts of the description. In the sections from 3.1 to 3.7, we respectively describe the service cylinder, the plaquette, the panel base, the blade, the nipple and the disk.

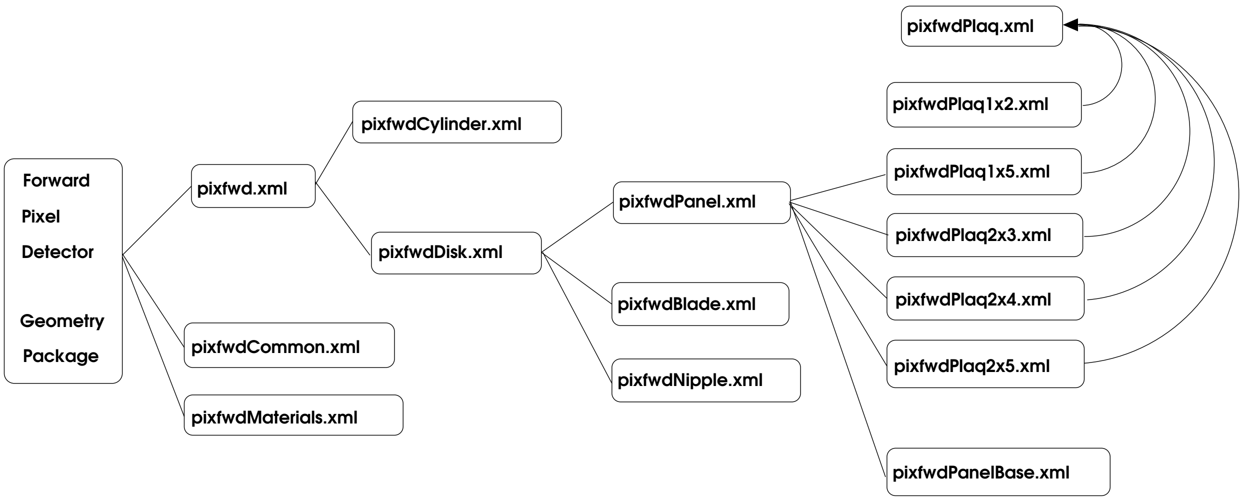


Figure 6: Schematic view of the package structure which describes the FPix detector.

3.1 Service cylinder

The implementation of the FPix service cylinder [7] is divided into eight basic volumes as shown in Figures 7 and 8: service cylinder, end flange, end electronics *1*, end electronics *2*, coil fibers, port cards and Optohybrids (OH), pipes and cables *front* and *back*.

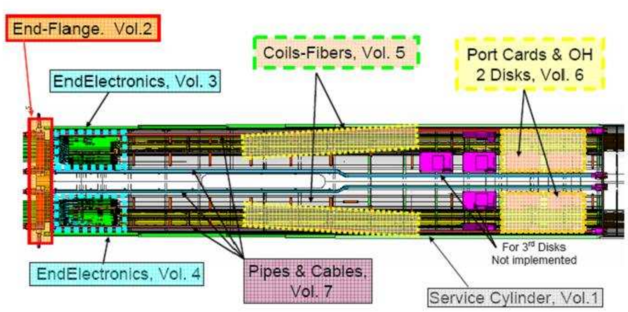


Figure 7: The definition of the 8 volumes of the simplified FPix service cylinder.

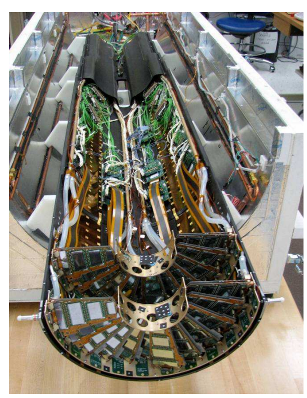


Figure 8: One of the four Forward Pixel half-cylinders in its cold box assembled at Fermilab.

The service cylinder is mostly made of carbon fiber (96.3%). The end flanges (41mm width) are made of Aluminium. The electronic boards (Figure 9) are made of a laminate material G10® which represents 33% of the total electronics mass. The composition was taken to be half epoxy ($C_{14}H_{12}O_3$) and half glass (SiO_2). Power cables and cable conductors that are made of Copper and Tin represent 35% of the total electronics mass, whereas cable isolation is made of POLIAX ($C_{37}H_{24}O_6N_2$) and represents 15%. The mounting brackets are made of carbon fiber. The coil fibers device is principaly composed of G10 (9.8%) and a modified polyphenylene oxide Noryl® (5%). The optical fibers were assumed to be made of a polymethyl methacrylate (PMMA) and the isolation of POLIAX. Connectors and adapters were assumed to be polyester. The port cards, CCU boards and OHs are made of G10® (43.3% of total mass). The capacitors, resistors and chips on the port card were assumed to be made from $BaTiO_3$, Al_2O_3 (Alumina) and silicon respectively. The extension cables, which are included in the port card and OHs volume, are made of copper and isolated with polyimide. Copper represents 24.3% of the total mass and polyimide 11.6%. Cooling pipes are made of aluminium. The coolant is C_6F_{14}. The cables conductor is a mix between Tin and Copper and represents 47.6% (48.2%) of the pipe and cables *front* (*back*), whereas the isolant is made of POLIAX.

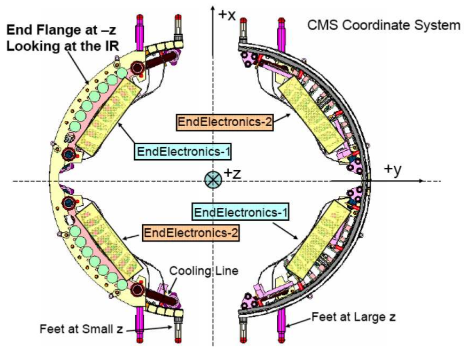


Figure 9: Transverse view of the FPix electronic volumes of the service cylinder.

Unlike files for all other subsystems, the `pixfwdCylinder.xml` does not define a `ROOT` volume and an anchor point, but instead all volumes are positioned directly in the polycone `PixelForwardServiceCylinder`. Figure 10 shows an exploded view of the simulated service cylinder.

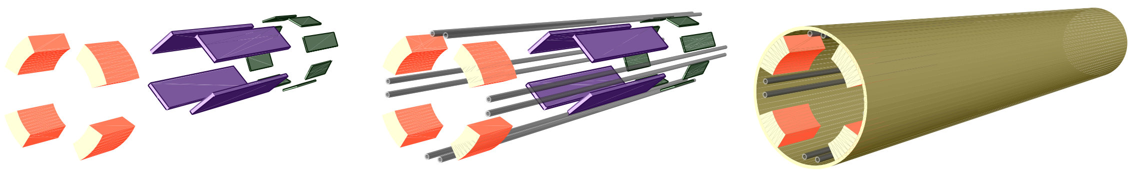


Figure 10: The left picture shows the port cards and opto-hybrid, the coil fibers, electronics and end-flanges. The picture in the middle shows the cooling pipes and the right picture shows the carbon-fiber cylinder.

3.2 Plaquette

A plaquette is a superposition of `Chotherm®`[1)], silicon substrate, adhesive film from `3M®`[2)] and `VHDI` made of Polyimide(`kapton®`) and Copper. The sensor is bump bonded on the ROCs with tiny solderings made of 63% of Tin and 37% of Lead as shown on Figure 11.

The detailed description of the materials which compose a plaquette is given in Tables 14 and 15 following the engineering calculations and measurements. Six `xml` files describe the five types of plaquettes [10] and parameters common to all types of plaquettes, particularly the thicknesses of various layers. Table 1 shows the different sizes of the various plaquettes. Table 2 defines the ten `ROOT` volumes necessary to describe all types of plaquettes. For each of these volumes, the Y axis is in the plane of the plaquette and will be aligned with the panel axis once the plaquette is mounted. The Z axis is perpendicular to the plaquette, pointing to the sensor side.
The `pixfwdPlaq`AXB`.xml` defines a `ROOT` volume `PixelForwardPlaquette`AXB made of Air. An active silicon volume `PixelForwardActive`AXB is positionned in the `PixelForwardSensor`AXB silicon vol-

[1)] Chotherm® is composed of Acrylic, Boron Nitride powder which is a type of ceramic, Silicone gel and polyimide

[2)] which is assumed as Acrylic and Boron Nitride powder

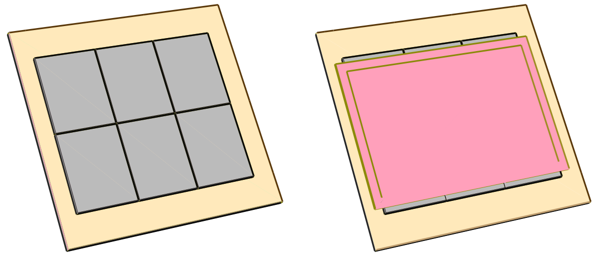


Figure 11: Multi-layered structure for a 2x3 plaquette. The left structure is made of the following layers: chotherm, silicon substrate, adhesive film, vhdi and ROCs. The structure on the right shows the sensor bump bonded on the ROCs with tiny solderings.

ume. The volumes: `PixelForwardAdhFilm`AXB, `PixelForwardFlexCircuit`AXB, `PixelForward-Backing`AXB, `PixelForwardChoTherm`AXB and `PixelForwardBumpROChipEpoxy` are positionned in a passive volume `PixelForwardPassive`AXB. The file `pixfwdPlaq`AXB`.xml` defines an anchor point coordinates `AnchorXRight`, `AnchorXLeft` and `AnchorY` that are used when placing the plaquette on its panel in the `pixfwdpanel.xml` file following the positionning defined in the Table 3.

`Plaquette`	Silicon substrate length x width x thickness (mm)	Sensor length x width x thickness (mm)
`1x2`	21.36 x 15.05 x 0.3	18.49 x 10.39 x 0.27
`1x5`	45.66 x 15.05 x 0.3	42.79 x 10.39 x 0.27
`2x3`	29.46 x 27.77 x 0.3	26.59 x 18.49 x 0.27
`2x4`	38.56 x 27.77 x 0.3	34.69 x 18.49 x 0.27
`2x5`	45.66 x 27.77 x 0.3	42.79 x 18.49 x 0.27

Table 1: Dimensions of the various forward pixel plaquettes.

`PixelForwardPlaquette1x2Left`	`PixelForwardPlaquette1x2Right`
`PixelForwardPlaquette1x5Left`	`PixelForwardPlaquette1x5Right`
`PixelForwardPlaquette2x3Up`	`PixelForwardPlaquette2x3Down`
`PixelForwardPlaquette2x4Up`	`PixelForwardPlaquette2x4Down`
`PixelForwardPlaquette2x5Up`	`PixelForwardPlaquette2x5Down`

Table 2: Plaquette `ROOT` volumes.

3.3 Panel base

The `pixfwdPanelBase.xml` file describes a beryllium panel with a VHDI and no plaquettes [10]. It defines one `ROOT` volume `PixelForwardPanelBase`. For the geometry implementation purpose, the panel base is made of three volumes as shown on Figure 12: the `Main` trapezoidal volume, the `Nose` and the `Ear`.

The panel base is composed of consecutive layers of Berrylium, adhesive film and HDI. The Y axis is along the axis of the panel and points from the narrow to the wide end, the X axis is in the plane of the panel and the Z axis is perpendicular to the panel and points towards the HDI side. The `anchor` point in the panel base `ROOT` volume reference frame is currently such as [`AnchorX`] = [`AnchorZ`] = 0.

3.4 Panel

The `pixfwdPanel.xml` file describing panels [10] defines four `ROOT` volumes: `PixelForwardPanel3Left(Right)` and `PixelForwardPanel4Left(Right)`. The Y axis is along the panel axis and points from narrow to wide end, the X axis is in the plane of the panel and the Z axis is perpendicular to the plane of the panel and

plaquette	panel	rotation angle around Z
`PixelForwardPlaquette1x2Right`	`PixelForwardPanel4Right`	-
`PixelForwardPlaquette1x2Left`	`PixelForwardPanel4Left`	-
`PixelForwardPlaquette1x5Right`	`PixelForwardPanel4Left`	-
`PixelForwardPlaquette1x5Left`	`PixelForwardPanel4Right`	-
`PixelForwardPlaquette2x3Up`	`PixelForwardPanel3Right`	-
`PixelForwardPlaquette2x3Up`	`PixelForwardPanel4Left`	180 °
`PixelForwardPlaquette2x3Down`	`PixelForwardPanel4Right`	-
`PixelForwardPlaquette2x3Down`	`PixelForwardPanel3Left`	180 °
`PixelForwardPlaquette2x4Up`	`PixelForwardPanel3Right`	-
`PixelForwardPlaquette2x4Up`	`PixelForwardPanel4Left`	180 °
`PixelForwardPlaquette2x4Down`	`PixelForwardPanel4Right`	-
`PixelForwardPlaquette2x4Down`	`PixelForwardPanel3Left`	180 °
`PixelForwardPlaquette2x5Up`	`PixelForwardPanel3Right`	-
`PixelForwardPlaquette2x5Up`	`PixelForwardPanel4Left`	180 °
`PixelForwardPlaquette2x5Down`	`PixelForwardPanel4Right`	-
`PixelForwardPlaquette2x5Down`	`PixelForwardPanel3Left`	180 °

Table 3: Positionning of plaquettes onto panels. Both `PixelForwardPlaquette2xnUp` and `PixelForwardPlaquette2xnDown` plaquettes, with $n = 2, 3, 4$ and 5, contain identical geometry, but differ in the directions of X and Y axes of the sensitive volume.

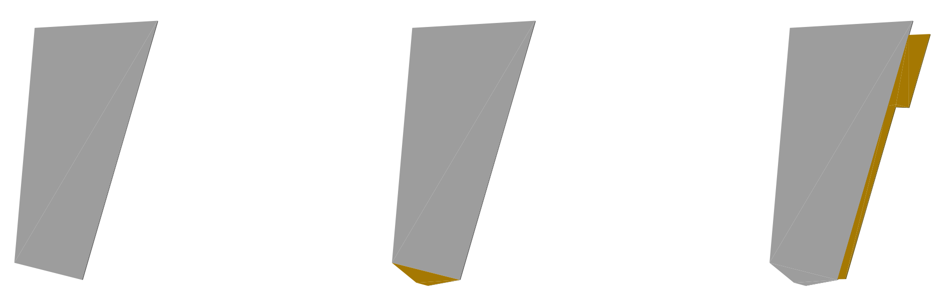


Figure 12: Visualisation of a beryllium panel with only a VHDI layer and no plaquettes. From left to right, the panel base is made of a main volume, a nose and an ear.

points to plaquettes side. Left(Right) panels are defined such as its `ear` is on the X-negative (positive) side. The anchor point in the panel `ROOT` volume reference frame is currently such as [`AnchorX`] = [`AnchorZ`] = 0. The `pixfwdPanel.xml` file positions the plaquettes on panels. Table 3 shows the position of the plaquettes onto the panels with its rotation angle around the Z axis.

3.5 Blade

The `pixfwdblade.xml` file describing the blade [8] defines one `ROOT` volume `PixelForwardBlade`. The blade is implemented so that it consists of a `body` (narrow aluminum side), a `cover` (wide aluminum side) and a `tip` (part close to inner ring, common to both sides) as shown on Figure 14. Cooling channel then goes into both `body` and `cover`. Multiple boolean operations are used in describing the `tip` of the blade and the crossbar. As a result, IGUANA sometimes fails to visualize it properly. The Y axis is along the axis of the blade, from narrow to wider end. Once the blade is positioned, its Y axis will be pointing away from the beam line. The Z axis is perpendicular to the plane of the blade, pointing from `body` to `cover` side. The anchor point in the blade `ROOT` volume reference frame is currently such as [`AnchorX`] = [`AnchorZ`] = 0. Since the origin of the blade frame coincides with the blade anchor point, the `child translation` vector passed to

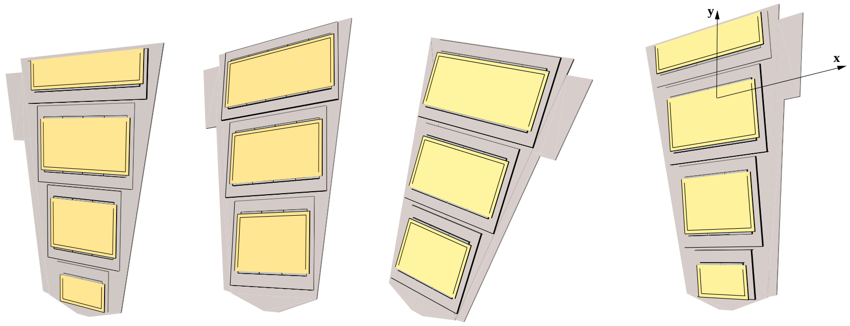


Figure 13: Visualisation of the four types of full populated panels necessary for the assembly of the FPix disks.

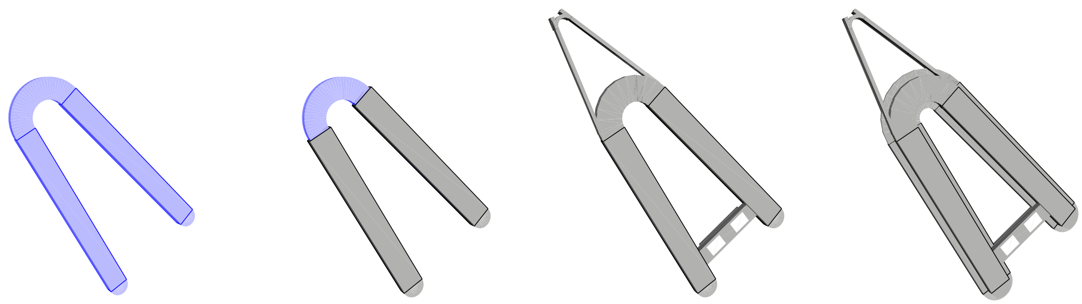


Figure 14: Visualisation of the description of a blade. The blue color represents the coolant used in CMS: C_6F_{14} and it circulate inside the blade. The third picture shows the aluminium parts that make the `body` and `tip`. The fourth picture adds the aluminium `cover` (which is wider than the `body`) to the blade.

the `DDPixFwdBlades` algorithm should be (-[`pixfwdBlade:AnchorX`], -[`pixfwdBlade:AnchorY`], -[`pixfwdBlade:AnchorZ`]).

3.6 Nipple

The `pixfwdnipple.xml` file describing the nipple [8] defines two `ROOT` volumes: `PixelForwardNippleZPlus` (nipple for +Z disk) and `PixelForwardNippleZMinus` (nipple for -Z disk). These two versions of the nipple are reflections of each other, but they are defined separately because GEANT4 visualization doesn't support polycone reflection. The origin coordinate is at the middle of the segment connecting points J and K from the engineering drawings [8]. Z axis is along the nipple axis, pointing from J to K. Nipples are positionned automatically by the `DDPixFwdBlades` algorithm, which recognizes this component by its volume name, and applies appropriate rotations and translations. The call to `DDPixFwdBlades` algorithm calculates parameters needed for constructing the nipple: rotations and constants.

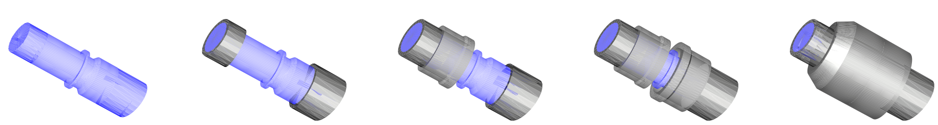


Figure 15: Visualisation of the nipple which connects two adjacent blades. The blue color represents the coolant C_6F_{14}. The second picture shows the `body` on the top and `cover` on the bottom which are made of Aluminium. The third and fourth pictures show two other pieces which partially cover the `body` on the top and `cover` on the bottom, and are made of Epoxy. The last picture adds the `sleeve` part made of Aluminium.

3.7 Disk

The pixfwdDisk.xml file describes the FPix disks [8] [9] and defines two ROOT volumes: disks for the Z+ endcap PixelForwardDiskZPlus and disks for the Z- endcap PixelForwardDiskZMinus. The coordinate origin is located at the center of the disk. The anchor point coincides with the ROOT reference frame origin and the disks are positioned into endcaps without any rotations. In the current version, the disk consists of inner and outer support rings, blades with panels and nipples connecting cooling channels in adjacent blades as shown in Figure 16.

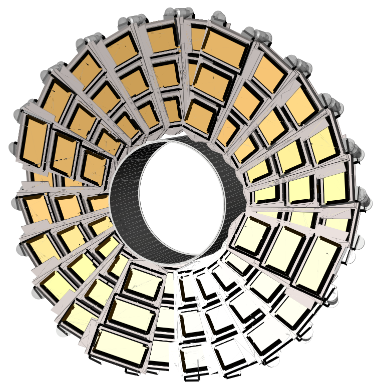


Figure 16: IGUANA visualisation of one of the PixelForwardDiskZPlus disk. The outer support ring is not shown on the picture.

The pixfwdDisk.xml file describes the inner and outer rings and their corresponding edges made of aluminium: PixelForwardDiskInner(Outer)Ring and PixelForwardDiskInner(Outer)RingEdge. Rings and edges are positionned on PixelForwardDiskZPlus and PixelForwardDiskZMinus. Blades, panels and nipples are positionned using the DDPixFwdBlades.cc algorithm. The nature of panels on disks is either left (L) or right (R). Figures 17 and 18 show the 4 different panel layouts for the FPix disks.

As the DDL description doesn't support string constants, layouts are directly written in the algorithm calls as shown in Table 4.

```
<Algorithm name="track:DDPixFwdBlades">
    <rParent name="pixfwdDisk:PixelForwardDiskZPlus"/>
    <Numeric name="Endcap" value="1." />
    <String name="Child" value="pixfwdPanel:PixelForwardPanel3Right"/>
    <Vector name="ChildTranslation" type="numeric" nEntries="3"> 0.,
            -[pixfwdPanel:AnchorY], [zPanel] </Vector>
    <String name="FlagString" value="RLLLLRLLLLLRRLLLLRLLLLLR" />
    <String name="FlagSelector" value="R" />
</Algorithm >
```

Table 4: Algorithm call for panels positioning on a disk.

Blades are numbered in increasing ϕ order in the disk frame. Therefore, in the global frame they are numbered in increasing ϕ order for the ZPlus disks, in decreasing ϕ order, starting with blade 12, for the ZMinus disks. In the algorithm call, Endcap is equal to +1 if placing the child volume into +Z disk or -1 if placing into -Z disk. Child is the name of a child volume being placed and should be in the form FILE:VOLUME. If no child name is given, the algorithm simply calculates nipple parameters. ChildRotation is optional and represents the rotation of the child volume with respect to the blade frame. ChildTranslation is optional and is a vector defining translation of the child volume with respect to the blade frame. FlagString is optional and is a string of 24 characters, used to indicate blades into which the child volume should be placed. FlagSelector is a one character string, key to interpreting FlagString. Positions in BladeFlag that have this character will get the child volume. If the Child parameter is omitted, the algorithm computes the rotation needed for describing the coolant in nipples but does not do any placements. The blade frame origin is on the axis of the blade at a distance anchorRadius from the beam line. It therefore coincides with the anchor point of a blade. The Y axis is along

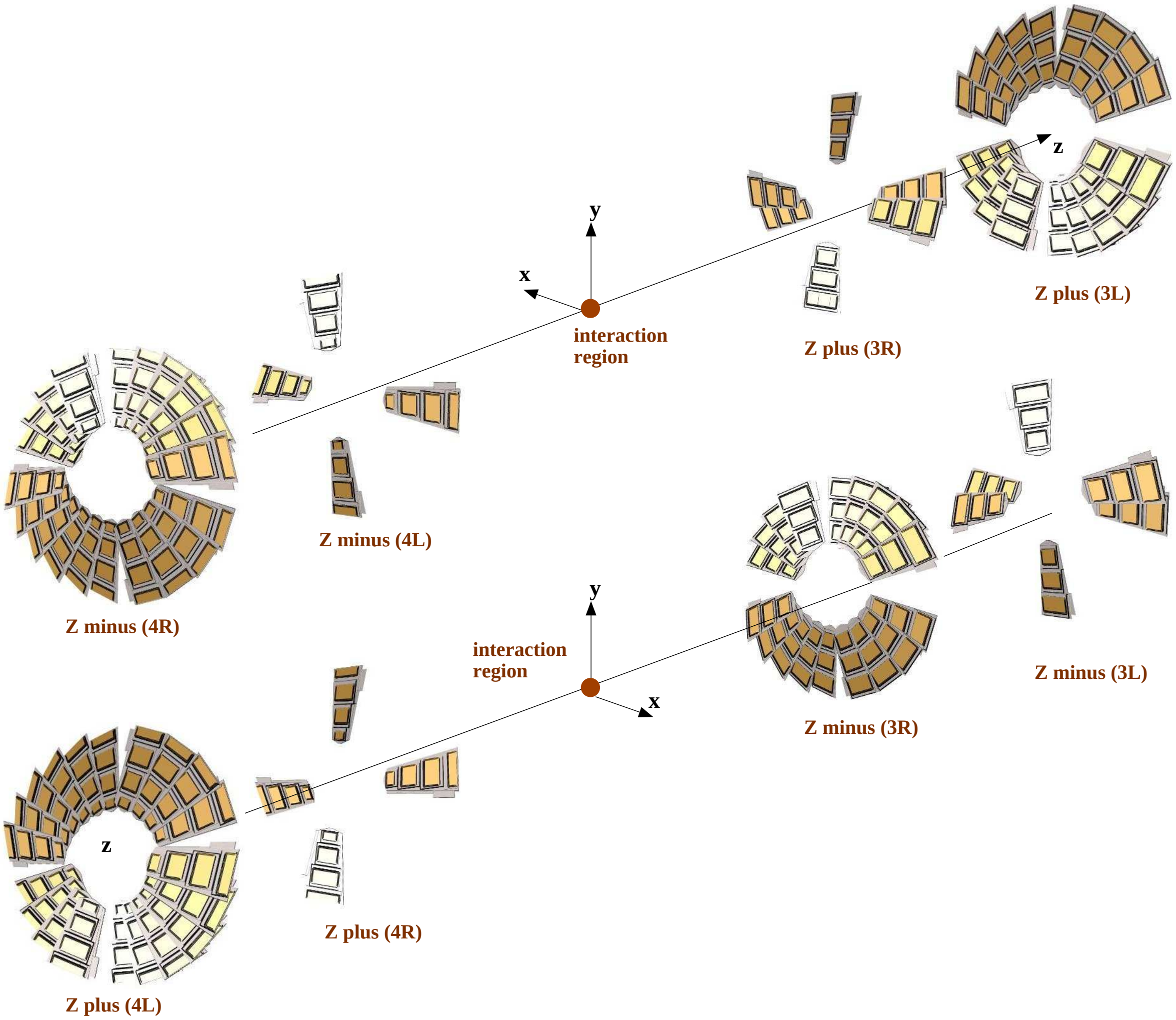


Figure 17: Position of the panels for the FPix disks with respect to the interaction region. The figure shows the layout of each of the 4 FPix disks. From the interaction region, the first panels that are crossed by particles are 3-plaquette type panels. For a better understanding of the different layouts, the *right* and *left* panels are separated. Each 4-plaquette type disk is next to a 3-plaquette type disk.

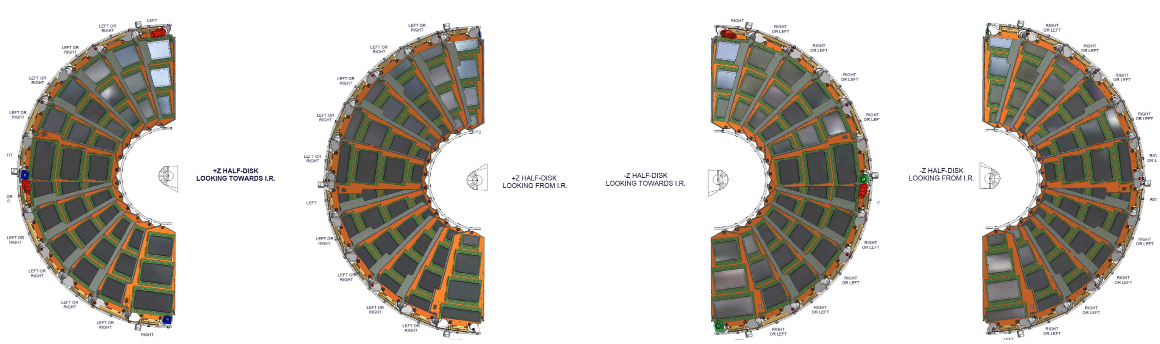


Figure 18: Engineering drawing of the panel position on each forward pixel half-disk.

the blade axis pointing away from beam line and the Z axis is perpendicular to blade plane and points away from IP. That assumes the axes of `ZPlus` disk are aligned with CMS global reference frame, and `ZMinus` disk is rotated around Y by 180 °.

4 Numbering Scheme

All the pixel sensitive components must be univocally identified within the CMS software framework `CMSSW` [3]. A 32-bit integer value identifies each CMS detector component. This identifier is commonly called “geographical identity number” or “detector identity number” and will be referred to as detid throughout this document. The detid bits are filled with a common path for all the CMS detectors: 4 bit long to indicate the main detector, 3 bits to enumerate the subdetector and the remaining 25 bits to identify the subdetector structures.

The numbering scheme [11] which was developed for the pixel forward subdetector respects the convention proposed for the entire Tracker system. All the variables used to identify the Tracker components in the geometrical space are defined within the global CMS reference system of coordinates [12]. The polar radius is defined in cylindrical coordinates as the distance from the z axis in the transverse plane (x, y), $R = \sqrt{x^2 + y^2}$.

The ROC numbering is not present in CMSSW but in the hardware these are numbered from 0 to n-1 (n up to 2,6,8 or 10 for 1x2, 2x3, 2x4 or 2x5 plaquettes, respectively). On each plaquette, the ROC which is on the lower left corner is numbered as zero and the ROC numbers increment from left to right. If the plaquette is made of a second row, the ROC numbering continues from right to left.

Instead of using ROC numbering, the data analysis within the `CMSSW` framework is possible only after mapping the I^{2}C address used to electronically identify the pixel detector components with the corresponding detid. The rules to define a unique detid for the pixel forward (PXF) sensitive components, whose detid encoding is listed in Table 5, are the following:

1. The *Detector* is the Tracker, which is assigned the value 1.
2. The PXF is the Tracker *Subdetector* number 2.
3. The two *Sides* of the subdetector are ordered from $z < 0$ (PXF-, value 1) to $z > 0$ (PXF+, value 2). The value 0 is reserved to select the whole PXF subdetector.
4. The 2 *Disks* of each PXF side are sorted in ascending order of $|z|$, smaller values closer to the interaction point and increasing with distance from the interaction point. The value 0 is reserved for a whole PXF+ or PXF- endcap.
5. The 24 *Blades* of each disk are sorted in ascending order of the φ value in the range $[0, 2\pi)$. The value 0 indicates all the blades of the disk.
6. The 2 *Panels* of each blade are sorted in ascending order of $|z|$, smaller values closer to the interaction point and increasing with distance from the interaction point. The value 0 is reserved for a whole blade.
7. The *Plaquettes* are sorted from 1 to 3 (or 4) in ascending order of the polar radius. The value 0 indicates all the rings of a PXF panel.

Field name	Bit size	Description	Hex mask	Start bit
Detector	4	1 = Tracker (0001)	0xF	28
Subdetector	3	2 = PXF (010) [0=All]	0x7	25
Subdtector Side	2	1=PXF- 2=PXF+ [0=All]	0x3	23
not used	3	···	0x7	20
Disk Number	4	1,...,2 [0=All]	0xF	16
Blade Number	6	1,...,24 [0=All]	0x3F	10
Panel Number	2	1,2 [0=All]	0x3	8
Plaquette Number	6	1,...,4 [0=All]	0x3F	2
not used	2	···	0x3	0

Table 5: Pixel Forward (PXF) detid bit encoding.

5 Material Description in `CMSSW`

Many materials used in the FPix geometry description are composites of various other materials [6][7]. To calculate mixtures, CMS collaboration uses a FORTRAN program `mixture.f`[3]. Composite materials in GEANT4 can be

[3] `Geometry/TrackerCommonData/data/Materials`

defined as mixtures by weight, by volume or by atomic proportions. For the DDD description, however, everything is translated into mixture by weight. The input file for the calculation declares the mixture as: Name of Mixture which is the one assigned in the `xml` files, Name of mixture for title file, Monte Carlo Volume and Monte Carlo Area. The Monte Carlo volume is the volume (in cm^3) of the simulated shape filled with the mixture. The mixture program is taking into account the air and the different materials that compose the simulated object. Items in a compound are defined as: Item number, Comment, Material, Volume, Multiplicity and Type. The item in a compound has to be given a type: `SUP` for support, `SEN` for sensitive volumes (pure silicon volumes), `CAB` for cables, `COL` for cooling, and `ELE` for electronics. This distinction is used to attribute the radiation length to the various functions. In addition to the sub-detector related input file, predefined materials are necessary, such as pure and mixed materials. In these files, the content is in the format: Material name, Atomic weight, Atomic number, Density, Radiation length and Absorption length. For the program, only the name, Density and Radiation length are used and necessary.

The example of the VHDI description defined in `pixel_fwd.in` is shown in Table 6. Using engineering measurements from Tables 14 and 15, the total area of VHDI on a blade is 60.5326 cm^2. The composition of VHDI is 0.5448 cm^3 of Kapton® and 0.1453 cm^3 of Copper. There are 135 capacitors made of Barium Titanate, which dimensions are L=1 mm, W=0.5 mm and Thickness=0.25 mm. Solders are made of Tin and Lead in proportion of 63% and 37%. The total volume of a solder is 0.0054 cm^3.

# "Pixel Forward VHDI"	"Pix_Fwd_VHDI"	0.7124	60.5326	
* 1 "VHDI: Kapton"	"FPix_Kapton"	0.5448	1	ELE
* 2 "VHDI: Copper"	"Copper"	0.1453	1	ELE
* 3 "Capacitors"	"Barium_Titanate"	0.000125	135	ELE
* 4 "Solders"	"FPix_TinLeadSolder"	0.0054	1	ELE

Table 6: VHDI description in the input file used for mixture calculations in CMS.

Table 7 illustrates the mixture result for the VHDI. The output from `mixture.f` is a table showing the different components with their contribution in percentage to the mixture volume, weight and radiation length. In the description of materials, we use the normalised density which takes into account that the Monte Carlo volume is also filled with air. The volume of the various components of a mixture does not necessarily add up exactly to the volume that is used in the simulation, so this normalization factor corrects for it. In the ideal case, it should be close to 1. In order to define the new material in `CMSSW`, `mixture.f` provides the calculated X_0, corrected for normalization, the normalised density $\hat{\rho}$ and the weight fraction of each material in a compound. The normalised density and radiation lengths are defined as:

$$\hat{\rho} = \sum_i \rho_i \frac{V_i}{\sum_i V_i} \quad \text{and} \quad \frac{1}{\rho X_o} = \sum_i \frac{p_i}{\rho_i X_{oi}}$$

with ρ_i and V_i are the density and volume of the i-th item of the compound and p_i is the proportion by weight. Using the results from the mixture program, we finally describe the VHDI material in the `pixfwdMaterials.xml` file as shown in Table 8.

6 Material budget review

The material budget is an important step in the detector implementation. As mentioned before, the FPix detector contains 18 millions pixels which will require a substantial amount of passive materials that are involved in the readout, cooling or power systems. Passive materials will create unwanted effects during the particle detection, such as multiple scattering, electron bremsstrahlung and photon conversion. An accurate knowledge of the material budget is therefore necessary. The fraction of radiation length as a function of psedorapidity, seen by particles originating from the interaction point and passing straight through the Tracker, is shown in Figure 19 for the different tracker structures (a) or material categories (b).

The geometry validation software allows us to study the material budget in terms of radiation length X/X_0 or nuclear interaction length λ/λ_o as function of η and ϕ as shown in Figures 20 and 21. Figure 22 shows the 2-dimensional *r*-*z* profile of the FPix detector as it is implemented in the Monte Carlo simulation in CMSSW_3_1_0/. Figure 23 shows the integrated radiation length x/X_0 experienced by particles emerging from the interaction point as function of the pseudo-rapidity, η. In Figures 22 and 23, the material budget is averaged over the azimuthal

Pixel Forward VHDI (Material name: Pix_Fwd_VHDI)

	Component	Material	Volume [cm^3]	%	Weight [g]	%	Density [g/cm^3]	X_0 [cm]	%	λ_0 [cm]	%
1	VHDI: Kapton	FPix_Kapton	0.5448	76.477	0.7627	34.454	1.400	28.983	13.865	56.623	47.497
2	VHDI: Copper	Copper	0.1453	20.397	1.3019	58.810	8.960	1.435	74.672	15.056	47.641
3	Capacitors	Barium_Titanate	0.1688E-01	2.369	0.1016E+00	4.589	6.020	1.854	6.714	23.039	3.616
4	Solders	FPix_TinLeadSolder	0.5400E-02	0.758	0.4752E-01	2.147	8.800	0.839	4.749	21.380	1.247

Mixture density [g/cm^3]	3.10751
Norm. mixture density [g/cm^3]	3.10740
Mixture Volume [cm^3]	0.71237
MC Volume [cm^3]	0.71240
MC Area [cm^2]	60.53260
Normalization factor	0.99996
Mixture X_0 [cm]	5.25464
Norm. Mixture X_0 [cm]	5.25482
Norm. Mixture X_0 (%)	0.22396
Mixture λ_0 [cm]	35.16663
Norm. Mixture λ_0 [cm]	35.16787
Norm. Mixture λ_0 (%)	0.03346
Total weight (g)	2.21372

X_0 contribution	
Support:	0.000
Sensitive:	0.000
Cables:	0.000
Cooling:	0.000
Electronics:	1.000

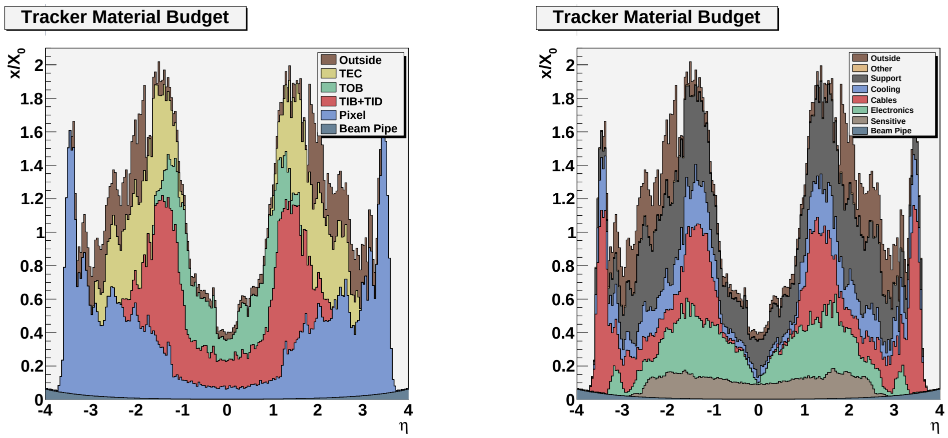
λ_0 contribution	
Support:	0.000
Sensitive:	0.000
Cables:	0.000
Cooling:	0.000
Electronics:	1.000

Table 7: Mixture results for the Pixel Forward VHDI description (Material name: Pix_Fwd_VHDI). For each material in the mixture, we obtain its volume, weight, density, radiation length (X_0) and interaction length (λ_0). The mixture is given a category, in the example of the VHDI, the mixture is 100% Electronics. A summary gives the normalised density, radiation and interaction lengths that are used in the xml file describing the materials.

```
<CompositeMaterial name="Pix_Fwd_VHDI" density="3.10740*g/cm3" symbol=" "
method="mixture by weight">
  <MaterialFraction fraction="0.34454">
   <rMaterial name="pixfwdMaterials:FPix_Kapton"/>
  </MaterialFraction>
  <MaterialFraction fraction="0.58810">
   <rMaterial name="materials:Copper"/>
  </MaterialFraction>
  <MaterialFraction fraction="0.04589">
   <rMaterial name="materials:Barium_Titanate"/>
  </MaterialFraction>
  <MaterialFraction fraction="0.02147">
   <rMaterial name="pixfwdMaterials:FPix_TinLeadSolder"/>
  </MaterialFraction>
</CompositeMaterial>
```

Table 8: XML description of the VHDI. The materials names, weight percentage for the mixture and the normalised mixture density are taken from Table 7.

angle, ϕ.



(a) Material Budget for the different subdetectors and structures: the beam pipe, the pixel vertex detector, the inner Tracker (TIB+TID), the outer barrel (TOB) and endcaps (TEC), the outer structures (support tube, thermal screen and bulkheads)

(b) Material Budget for the different material categories: beam pipe, silicon sensitive volumes, electronics, cables, cooling pipes and fluid, support mechanics and outer structures.

Figure 19: Material budget profile of the Tracker simulation: fraction of radiation length x/X_0 as a function of pseudorapidity η. The CMSSW release that was used to produce these results is CMSSW_3_1_0.

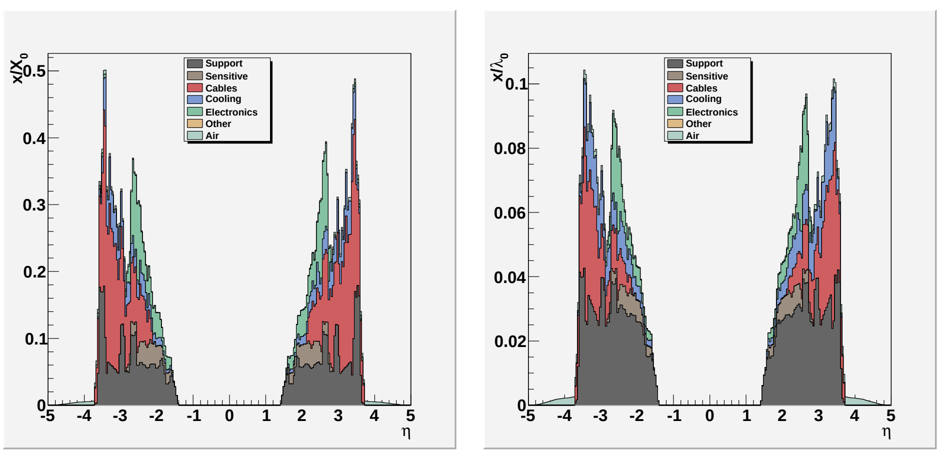


Figure 20: Radiation length as function of the pseudo-rapidity for the Forward Pixel detector. The CMSSW release that was used to produce these results is CMSSW_3_1_0.

7 Comparison between the simulated objects and the real detector

The FPix detector was weighed at Fermilab [13], where the detector was assembled. A study of the comparison between the simulated objects and the real detector was performed, using a class `/SimG4Core/PrintMaterialBudgetInfo` which prints the characteristics of the volumes belonging to a chosen GEANT4 mother volume. Tables 12 and 13 show a part of the comparison between the simulated objects and the real detector. Using the engineering results from Tables 14 and 15, the mass of the volumes from a 1x2 plaquette is extracted and compared with the simulation results from Table 12. The compatibility between the measured and simulated volumes from a 1x2 plaquette is 0.3%, 5.3%, 1.8%, 11%, 1.9%, 0.15% and 1.7% for the silicon sensor, the ROC, the epoxy layer between the ROC and the VHDI, the flexible circuit (VHDI), the adhesive film layer between the VHDI and the silicon substrate, the silicon substrate and the epoxy layer between the plaquette and the HDI flexible circuit respectively. Using the results from Table 13, the compatibility between the measured and simulated service cylinders volumes is 2.6%, 2.8%, 6%, 9%, 2.6%, 1%, 11.5% and 6.5% for the EndFlange, ServiceCylinder, Electronics1, Electronics2, CoilFibers, PortCards, Pipes1 and Pipes2 volumes respectively. The simulation of the

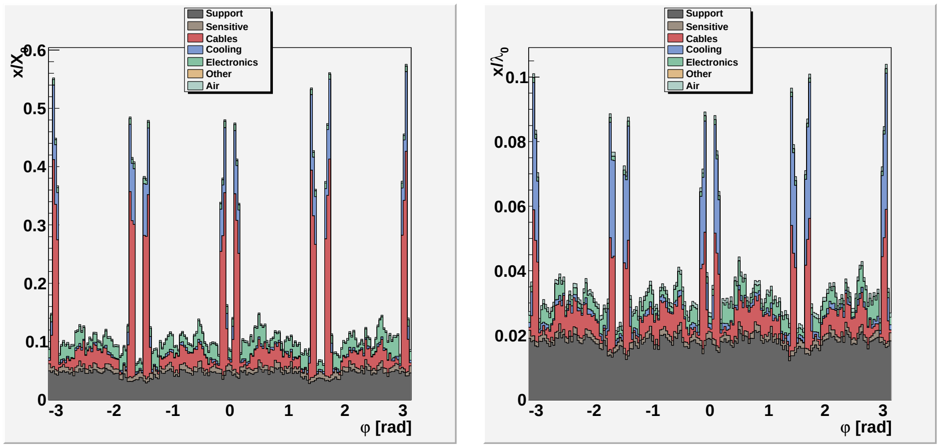


Figure 21: Interaction length as function of ϕ for the Forward Pixel detector. The CMSSW release that was used to produce these results is CMSSW_3_1_0.

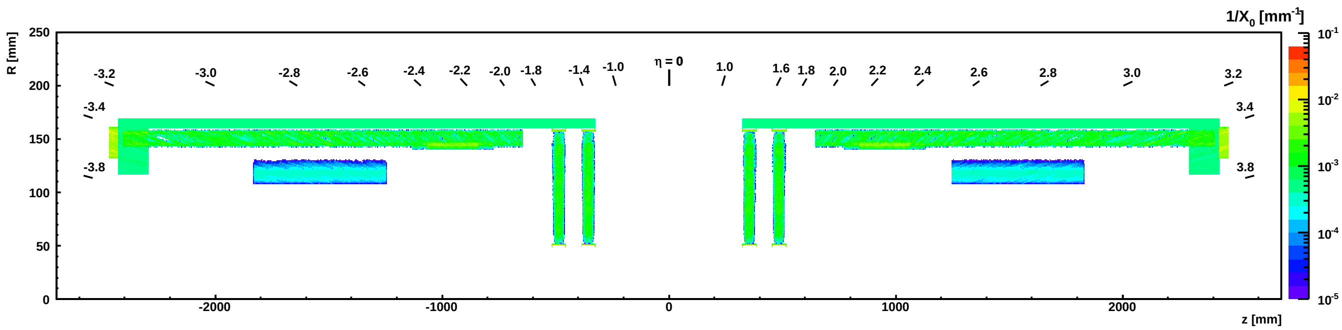


Figure 22: r-z profile of the FPix detector as implemented in the Monte Carlo simulation. The grayscale indicates the inverse of the radiation length $1/X_0(r, z, /phi)$ as function of the pseudo-rapidity η. The CMSSW release that was used to produce these results is CMSSW_3_1_0.

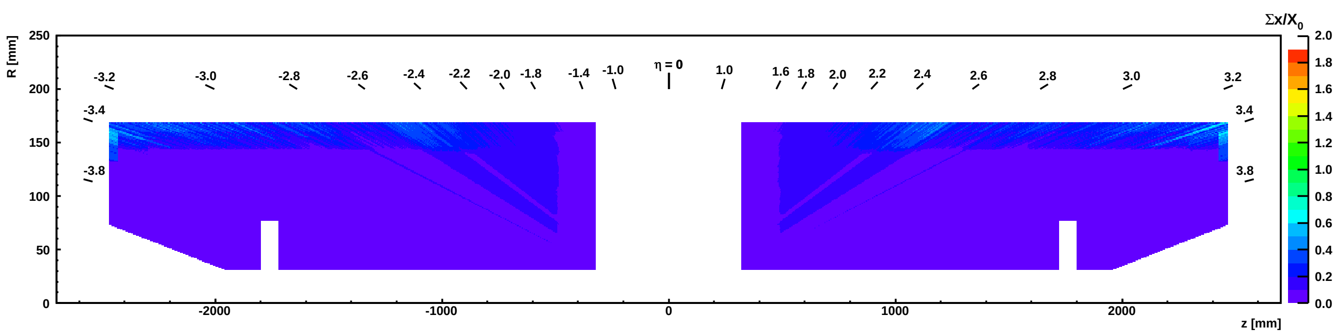


Figure 23: Integrated radiation length x/X_0 experienced by particles emerging from the interaction point as function of the pseudo-rapidity, η. The grayscale indicates the number of radiation lengths X_0 traversed by the particle propagating on a straight line. The CMSSW release that was used to produce these results is CMSSW_3_1_0.

Forward Pixel detector reproduces the real detector weights with a remarquable accuracy. The full populated 3-plaquette (4-plaquette) type panel weights 13g (12.5g) in the lab and is to be compared with a simulated object which weights 14g (13.4g). The nipple which connects two adjacents blades weights 1.5g whereas the simulated object weights 1.7g. The cooling channel made of aluminium weights 8.2g whereas the simulated objects weights 11.3g.The inner (outer) ring weights 38g (115g) whereas the simulated object weights 37.7g (113.4g). The inner ring weight from Table (15) was calculated from the drawing in [8] but its value differs from the lab measurement

[13] because the layout was modified in a later stage. The new drawing included additional holes to remove some of the weight from the inner ring. The half-disk (inner ring, outer ring, cooling channels, cooling channel screws and sleeves, nipples and full populated panels) weight is measured in the lab at 503g. The simulated half-disk weights 524g. The accuracy in the comparison between the real and the simulated half-disk is better than 4%.

	Simulation	Real detector
1 PixelForward Zplus or ZMinus	13.9774 kg	17.506 kg
2 PixelForward disk	2 x 1.1124 kg	2 x 1.006 kg
1 PixelForward service cylinder	10.3734 kg	15.494 kg
1 PixelForward outer carbon fiber cylinder	3.707 kg	3.606 kg
2 PixelForward electronics	2 x 127.225 g	2 x 139.6 g
2 PixelForward electronics	2 x 156.791 g	2 x 167.35 g
4 PixelForward coil fiber	4 x 145.7 g	4 x 141.95 g
8 PixelForward pipe	8 x 303.6 g	8 x 343 g
8 PixelForward pipe	8 x 283.79 g	8 x 303.75 g
6 PixelForward port card	6 x 88.9178 g	total of 8 volumes
2 PixelForward port card + CCU	2 x 141.46 g	= 808 g
2 PixelForward end flange	2 x 689.505 g	2 x 705.1 g

Table 9: Comparison between the simulated weights of the various parts of the forward pixel detector and their weights measured in the laboratory.

8 Pixel supply tube cabling to patch panels and tracker bulkhead

Picture 24 shows the pixel cables that connect the pixel supply tubes to the tracker patch panels. These cables where impelemented in CMSSW software starting release CMSSW_3_1_0.

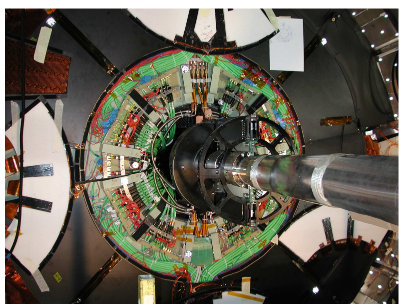


Figure 24: Picture taken at P5 showing the power cables going from the Pixel supply tubes to the tracker patch panels.

The total amount of power cables (which composition is detailed in Table 10) is distributed equally (50%) in a cylinder between pixel (Fpix and Bpix) supply tube and PP0, and the disks in the bulkhead. This material is also used in the bulkhead PixelCables disk, but with a different MC volume.

	Copper	Polyethylene (insulation)
barrel pixel power cables	2328.5 g	1283 g
forward pixel power cables	1671 g	1114 g
pixel cooling pipes	1262 g (steel)	
pixel coolant in pipes	770g of C_6F_{14}	

Table 10: Pixel cables and pipe composition: The number quoted correspond to a barrel pixel half-shell and forward pixel half cylinder. A single power cable for the forward pixel service cylinder was weighted to be 278.5 g. It is assumed to be made of 60% copper and 40% insulation. One steel cooling pipe is 30cm length and has an inner(outer) diameter of 10(12)mm. A total of 20 pieces are necessary per half-detector.

The pixel cables and pipes run from the pixel supply tubes to the PP0. First a cylinder in the pixel barrel volume is composed of half of the pixel cables and pipes. The volume of the cylinder is 13757 cm^3. The second part of the pixel cables and pipes is a disk inside the bulkhead. This disk has a volume of 3742 cm^3. The detailed definitions of the two mixtures is described in Table 11, where the *MC volume* has to be replaced by either 3743 or 13757 cm^3.

# "PixelBarrelSupTubcables"	"PixelBarrelSupTubCables"	*MC volume*		
* 1 "power cable copper"	"Copper"	260	1	CAB
* 2 "power cable PE"	"Polyethylene"	1350	1	CAB
* 3 "forward pixel cable copper"	"Copper"	186.5	1	CAB
* 4 "forward pixel cable PE"	"Polyethylene"	1172	1	CAB
* 5 "cooling pipes steel"	"Steel-008"	161	1	COL
* 6 "coolant"	"C_6F_{14}"	424	1	COL

Table 11: Pixel cables and pipe to PP0 mixtures compositions.

The tracker material which describes the tracker cables to PP1 was updated with pixel barrel and pixel forward cables and copper from cooling pipes[4]. The volume for the pixel cables in the tracker bulkhead was also updated. In total, more than 20kg of material (copper, steel, cooling) were added to the PP0 region, even more to the PP1 region. All this affects the region $|\eta| > 3.2$. The pixel barrel mother volume needed some change in radius at $z >$ 2.4m to allow for a realistic description of the cable distribution.

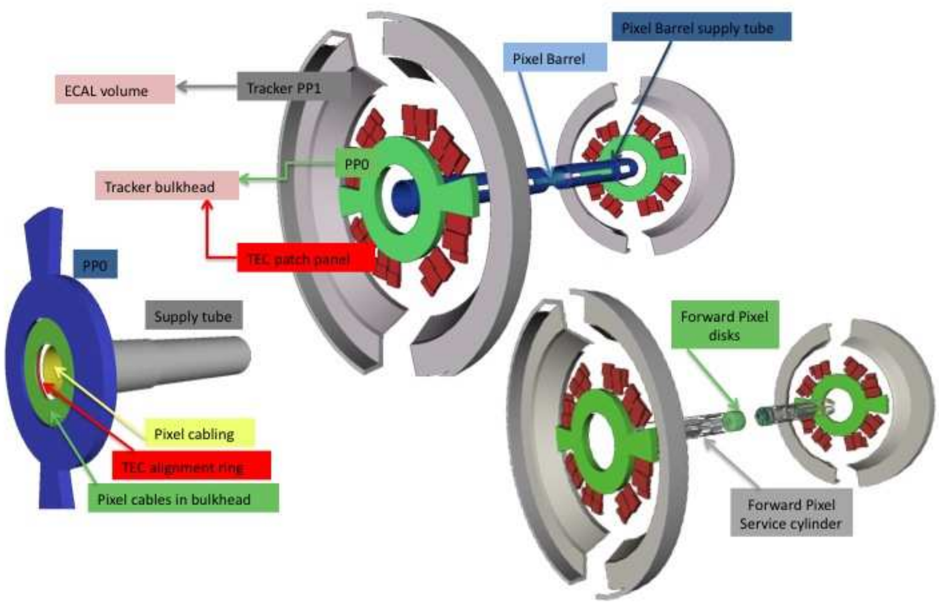


Figure 25: Simulation of the pixel cables going from the pixel supply tubes to the tracker patch panels.

9 Conclusion

The forward pixel geometry is completely implemented and a review of its material budget has been performed. The comparison between the simulated and real detector has shown a weight compatibility better than a few %.

The average weight of a completed half-disk (inner ring, outer ring, cooling channels, cooling channel screws and

[4] see *Geometry/TrackerCommonData/data/trackermaterial.xml*

sleeves, nipples and full populated panels) was measured (without coolant) to be 503g.

Figures 19(a) and 19(b) show the Tracker material budget profile as a function of pseudorapidity η. The contribution from the FPix detector is located in the region $1.5 <| \eta |< 3.8$.

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[8] *CMSpix-doc-573-v1 ("+Z Halfdisk Drawings") and CMSpix-doc-506-v1 ("-Z Halfdisk Drawings")*

[9] *CMSpix-doc-583-v1 ("Panel Layout")*

[10] *CMSpix-doc-458-v5 ("Panels and Plaquettes")*

[11] *CMSpix-doc-901-v9* Pixel group "Naming Convention for Pixel Detector Control"

[12] H. Breuker and P. Petagna, *"The CMS parameter booklet"*, CMS-TK-GN-0001 ver. 2, EDMS Id. 367936, available at https://edms.cern.ch/document/367936; P. Ingenito, CMS-DIGEP-ES-0001 ver. 3, EDMS Id. 90485, available at https://edms.cern.ch/document/90485.

[13] *CMSpix-doc-1858-v3* Pixel group "Half-Disk Assembly Spreadsheet"

Geom. Level	Volume Name	Copy Number	Solid Name	Material Name	Density	Simulated Mass	Measured Mass
6	PixelForwardPlaquette1x2Right	1	PixelForwardPlaquette1x2	Air	1.214 mg/cm^3	0.0423389 mg	
7	PixelForwardSensor1x2	1	PixelForwardSensor1x2	Silicon	2.33 g/cm^3	38.3793 mg	
8	PixelForwardActive1x2	1	PixelForwardActive1x2	Silicon	2.33 g/cm^3	82.5505 mg	121 mg
7	PixelForwardPassive1x2	1	PixelForwardPassive1x2	Air	1.214 mg/cm^3	0.0794215 mg	
8	PixelForwardBumpROChipEpoxy	2	PixelForwardBumpROChipEpoxy	Silicon	2.33 g/cm^3	37.0608 mg	35.2 mg
9	PixelForwardBump	1	PixelForwardBump	Pix_Fwd_Bump	413.91 mg/cm^3	0.822953 mg	
9	PixelForwardEpoxy	1	PixelForwardEpoxy	Pix_Fwd_AgEpoxy	1.60005 g/cm^3	22.6508 mg	22.24 mg
8	PixelForwardBumpROChipEpoxy	1	PixelForwardBumpROChipEpoxy	Silicon	2.33 g/cm^3	37.0608 mg	35.2 mg
9	PixelForwardBump	1	PixelForwardBump	Pix_Fwd_Bump	413.91 mg/cm^3	0.822953 mg	
9	PixelForwardEpoxy	1	PixelForwardEpoxy	Pix_Fwd_AgEpoxy	1.60005 g/cm^3	22.6508 mg	22.24 mg
8	PixelForwardFlexCircuit1x2	1	PixelForwardFlexCircuit1x2	Pix_Fwd_VHDI	3.10741 g/cm^3	124.838 mg	112.3 mg
8	PixelForwardAdhFilm1x2	1	PixelForwardAdhFilm1x2	Pix_Fwd_AdhFilm	1.57984 g/cm^3	25.8954 mg	25.4 mg
8	PixelForwardBacking1x2	1	PixelForwardBacking1x2	Silicon	2.33 g/cm^3	224.655 mg	225 mg
8	PixelForwardChoTherm1x2	1	PixelForwardChoTherm1x2	Pix_Fwd_AgEpoxy	1.60005 g/cm^3	91.5362 mg	90 mg

Table 12: This table shows the weight comparison between the simulated 1x2 plaquette and its corresponding measurements in the laboratory.

Geom. Level	Volume Name	Copy Number	Solid Name	Material Name	Density	Simulated Mass	Measured Mass
4	PixelForwardServiceCylinder	1	PixelForwardServiceCylinder	Air	1.214 mg/cm^3	97.3117 g	
5	PixelForwardCylinderOuterCyl	1	PixelForwardCylinderOuterCyl	Pix_Fwd_Servi_Cylind	201.13 mg/cm^3	3.70703 kg	3.606 kg
5	PixelForwardCylinderElectronics1	1	PixelForwardCylinderElectronics1	Pix_Fwd_End_Electro_1	293.69 mg/cm^3	156.791 g	167.35 g
5	PixelForwardCylinderElectronics2	1	PixelForwardCylinderElectronics2	Pix_Fwd_End_Electro_1	293.69 mg/cm^3	156.791 g	
5	PixelForwardCylinderElectronics3	1	PixelForwardCylinderElectronics3	Pix_Fwd_End_Electro_2	277.14 mg/cm^3	127.225 g	139.65 g
5	PixelForwardCylinderElectronics4	1	PixelForwardCylinderElectronics4	Pix_Fwd_End_Electro_2	277.14 mg/cm^3	127.225 g	
5	PixelForwardCylindersCoilFiber	4	PixelForwardCylindersCoilFiber	Pix_Fwd_End_Coil_Fiber	199.83 mg/cm^3	145.7 g	
5	PixelForwardCylindersCoilFiber	3	PixelForwardCylindersCoilFiber	Pix_Fwd_End_Coil_Fiber	199.83 mg/cm^3	145.7 g	141.95 g
5	PixelForwardCylindersCoilFiber	2	PixelForwardCylindersCoilFiber	Pix_Fwd_End_Coil_Fiber	199.83 mg/cm^3	145.7 g	
5	PixelForwardCylindersCoilFiber	1	PixelForwardCylindersCoilFiber	Pix_Fwd_End_Coil_Fiber	199.83 mg/cm^3	145.7 g	
5	PixelForwardCylinderPipe1	8	PixelForwardCylinderPipe1	Pix_Fwd_End_Pipe_1	2.87036 g/cm^3	303.605 g	343 g
5	PixelForwardCylinderPipe1	7	PixelForwardCylinderPipe1	Pix_Fwd_End_Pipe_1	2.87036 g/cm^3	303.605 g	
5	PixelForwardCylinderPipe1	6	PixelForwardCylinderPipe1	Pix_Fwd_End_Pipe_1	2.87036 g/cm^3	303.605 g	
5	PixelForwardCylinderPipe1	5	PixelForwardCylinderPipe1	Pix_Fwd_End_Pipe_1	2.87036 g/cm^3	303.605 g	
5	PixelForwardCylinderPipe1	4	PixelForwardCylinderPipe1	Pix_Fwd_End_Pipe_1	2.87036 g/cm^3	303.605 g	
5	PixelForwardCylinderPipe1	3	PixelForwardCylinderPipe1	Pix_Fwd_End_Pipe_1	2.87036 g/cm^3	303.605 g	
5	PixelForwardCylinderPipe1	2	PixelForwardCylinderPipe1	Pix_Fwd_End_Pipe_1	2.87036 g/cm^3	303.605 g	
5	PixelForwardCylinderPipe1	1	PixelForwardCylinderPipe1	Pix_Fwd_End_Pipe_1	2.87036 g/cm^3	303.605 g	
5	PixelForwardCylinderPipe2	8	PixelForwardCylinderPipe2	Pix_Fwd_End_Pipe_2	3.05434 g/cm^3	283.79 g	
5	PixelForwardCylinderPipe2	7	PixelForwardCylinderPipe2	Pix_Fwd_End_Pipe_2	3.05434 g/cm^3	283.79 g	
5	PixelForwardCylinderPipe2	6	PixelForwardCylinderPipe2	Pix_Fwd_End_Pipe_2	3.05434 g/cm^3	283.79 g	
5	PixelForwardCylinderPipe2	5	PixelForwardCylinderPipe2	Pix_Fwd_End_Pipe_2	3.05434 g/cm^3	283.79 g	303.7 g
5	PixelForwardCylinderPipe2	4	PixelForwardCylinderPipe2	Pix_Fwd_End_Pipe_2	3.05434 g/cm^3	283.79 g	
5	PixelForwardCylinderPipe2	3	PixelForwardCylinderPipe2	Pix_Fwd_End_Pipe_2	3.05434 g/cm^3	283.79 g	
5	PixelForwardCylinderPipe2	2	PixelForwardCylinderPipe2	Pix_Fwd_End_Pipe_2	3.05434 g/cm^3	283.79 g	
5	PixelForwardCylinderPipe2	1	PixelForwardCylinderPipe2	Pix_Fwd_End_Pipe_2	3.05434 g/cm^3	283.79 g	
5	PixelForwardCylindersPortCards2	2	PixelForwardCylindersPortCards2	Pix_Fwd_Port_Cards	1.2278 g/cm^3	141.46 g	
5	PixelForwardCylindersPortCards2	1	PixelForwardCylindersPortCards2	Pix_Fwd_Port_Cards	1.2278 g/cm^3	141.46 g	
5	PixelForwardCylindersPortCards1	6	PixelForwardCylindersPortCards1	Pix_Fwd_Port_Cards	1.2278 g/cm^3	88.9179 g	
5	PixelForwardCylindersPortCards1	5	PixelForwardCylindersPortCards1	Pix_Fwd_Port_Cards	1.2278 g/cm^3	88.9179 g	101 g
5	PixelForwardCylindersPortCards1	4	PixelForwardCylindersPortCards1	Pix_Fwd_Port_Cards	1.2278 g/cm^3	88.9179 g	
5	PixelForwardCylindersPortCards1	3	PixelForwardCylindersPortCards1	Pix_Fwd_Port_Cards	1.2278 g/cm^3	88.9179 g	
5	PixelForwardCylindersPortCards1	2	PixelForwardCylindersPortCards1	Pix_Fwd_Port_Cards	1.2278 g/cm^3	88.9179 g	
5	PixelForwardCylindersPortCards1	1	PixelForwardCylindersPortCards1	Pix_Fwd_Port_Cards	1.2278 g/cm^3	88.9179 g	
4	PixelForwardCylinderEndFlange	2	PixelForwardCylinderEndFlange	Pix_Fwd_End_Flange	1.66566 g/cm^3	689.505 g	

Table 13: This table shows the weight of the simulated service cylinder parts and the same parts as they were weighted in the laboratory.

Table 14: *Forward Pixel Blade Radiation Length Estimate* (G. Derylo) - part I

		Volume Fract.	Length (mm)	Width (mm)	Thickness (mm)	SubAssy Volume (mm^3)	Qty	Total Volume (mm^3)	Density (g/mm^3)	Mass (g)	Matl Rad Length (g/cm^2)	%RL	Percent of Total %RL
Sensors										**4.9**		**0.50**	**12.0**
1x2		1.00	18.49	10.39	0.270	51.9	1	51.9	0.00233	0.121	21.82	0.01	0.3
1x5		1.00	42.79	10.39	0.270	120.1	1	120.1	0.00233	0.280	21.82	0.03	0.7
2x3		1.00	26.59	18.49	0.270	132.8	2	265.6	0.00233	0.619	21.82	0.07	1.6
2x4		1.00	34.69	18.49	0.270	173.2	2	346.5	0.00233	0.807	21.82	0.09	2.1
2x5		1.00	42.79	18.49	0.270	213.7	1	213.7	0.00233	0.498	21.82	0.05	1.3
PSI-46 chip		1.00	9.94	8.01	0.190	15.1	45	680.0	0.00233	1.584	21.82	0.17	4.1
Bump Bonds	(63/37 Tin/Lead)	1.00	0.03	0.03	0.025	0.0	187200	2.9	0.00880	0.026	7.72	0.01	0.2
Chotherm1680	Acrylic	1.00	9.94	8.01	0.025	2.0	45	89.5	0.00110	0.098	40.00	0.01	0.1
(VHDI-to-chip)	BN powder	0.20	9.94	8.01	0.125	2.0	45	89.5	0.00350	0.313	43.39	0.02	0.4
	Silicone	0.80	9.94	8.01	0.125	8.0	45	357.9	0.00130	0.465	25.13	0.04	1.0
	Polyimide	1.00	9.94	8.01	0.025	2.0	45	89.5	0.00140	0.125	38.39	0.01	0.2
VHDIs										**8.7**		**0.93**	**22.4**
Substrates	1 x 2	1.00	21.36	15.05	0.300	96.4	1	96.4	0.00233	0.225	21.82	0.02	0.6
	1 x 5	1.00	45.66	15.05	0.300	206.1	1	206.1	0.00233	0.480	21.82	0.05	1.2
	2 x 3	1.00	29.46	27.77	0.300	245.4	2	490.8	0.00233	1.143	21.82	0.12	2.9
	2 x 4	1.00	38.56	27.77	0.300	321.2	2	642.4	0.00233	1.497	21.82	0.16	3.9
	2 x 5	1.00	45.66	27.77	0.300	380.3	1	380.3	0.00233	0.886	21.82	0.09	2.3
3M 9882 tape	Acrylic assumed	0.80	Tot Area =	6053.26	0.050	242.1	1	242.1	0.00110	0.266	40.00	0.02	0.4
(VHDI to substrate)	Ceramic (BN assumed)	0.20	Tot Area =	6053.26	0.050	60.5	1	60.5	0.00350	0.212	43.39	0.01	0.3
VHDIs	Kapton	1.00	Tot Area =	6053.26	0.090	544.8	1	544.8	0.00140	0.763	38.39	0.05	1.1
	Copper	0.60	Tot Area =	6053.26	0.040	145.3	1	145.3	0.00930	1.351	12.86	0.25	5.9
Capacitors	(BaTiO3 assumed)	1.00	1.00	0.50	0.250	0.1	135	16.9	0.00608	0.103	11.31	0.02	0.5
Resistors	(Alumina assumed)	1.00		Volume =	0.000	0.0	0	0.0	0.00326	0.000	27.46	0.00	0.0
Solder	(63/37 Tin/Lead)	1.00	0.20	0.20	0.500	0.0	270	5.4	0.00880	0.048	7.72	0.01	0.3
Chotherm1680	Acrylic	1.00	Tot Area =	6053.26	0.025	151.3	1	151.3	0.00110	0.166	40.00	0.01	0.2
(HDI-to-plaquette)	BN powder	0.20	Tot Area =	6053.26	0.125	151.3	1	151.3	0.00350	0.530	43.39	0.03	0.7
	Silicone	0.80	Tot Area =	6053.26	0.125	605.3	1	605.3	0.00130	0.787	25.13	0.07	1.8
	Polyimide	1.00	Tot Area =	6053.26	0.025	151.3	1	151.3	0.00140	0.212	38.39	0.01	0.3

Table 15: *Forward Pixel Blade Radiation Length Estimate* (G. Derylo) - part II

		Volume Fract.	Length (mm)	Width (mm)	Thickness (mm)	SubAssy Volume (mm^3)	Qty	Total Volume (mm^3)	Density (g/mm^3)	Mass (g)	Matl Rad Length (g/cm^2)	%RL	Percent of Total %RL
HDIs										**12.5**		**0.80**	**19.2**
Substrates	(Be)	1.00	Area =	4278.00	0.508	2173.2	2	4346.4	0.00185	8.032	65.19	0.29	6.9
HDI	Kapton	1.00	Area =	4278.00	0.100	427.8	2	855.6	0.00140	1.198	38.39	0.07	1.8
	Internal flex adhesive	1.00	Area =	4278.00	0.050	213.9	2	427.8	0.00125	0.535	40.00	0.03	0.8
	Copper	0.28	Area =	4278.00	0.057	67.5	2	134.9	0.00930	1.255	12.86	0.23	5.5
Capacitors	(BaTiO3 assumed)	1.00	0.75	0.50	0.640	0.2	8	1.9	0.00608	0.012	11.31	0.00	0.1
Resistors	Alumina	1.00	0.75	0.50	0.640	0.2	9	2.2	0.00326	0.007	27.46	0.00	0.0
	(RTD added as 2 extra)												
Solder	(63/37 Tin/Lead)	1.00		Volume =	0.500	0.5	17	8.5	0.00880	0.075	7.72	0.02	0.5
TBM Chip	Silicon	1.00	4.43	3.20	0.600	0.6	2	1.2	0.00233	0.003	21.82	0.00	0.0
3M 9882 tape	Acrylic assumed	0.80	Area =	4278.00	0.050	171.1	2	342.2	0.00110	0.376	40.00	0.02	0.5
(HDI to substrate)	Ceramic (BN assumed)	0.20	Area =	4278.00	0.050	42.8	2	85.6	0.00350	0.299	43.39	0.02	0.4
Bias/Ground Wires	Copper	1.00	Area =	0.08	80.000	6.0	6	36.2	0.00930	0.337	12.86	0.06	1.5
	Kapton	1.00	Area =	0.23	80.000	18.1	6	108.7	0.00140	0.152	38.39	0.01	0.2
	Solder (63/37 Tin/Lead)	1.00		Volume =	1.000	1.0	12	12.0	0.00880	0.106	7.72	0.03	0.8
	Epoxy	1.00		Volume =	15.000	15.0	2	30.0	0.00110	0.033	40.00	0.00	0.0
	In Solder (52In 48Sn)	1.00		Volume =	3.000	3.0	2	6.0	0.00730	0.044	8.93	0.01	0.3
Support Hardware										**20.9**		**1.92**	**46.3**
Screws	(Ti, M1.6)	1.00		Volume =	13.624	13.6	9	122.6	0.00454	0.557	16.17	0.08	1.9
Cooling Channel	(Al, includes 1 jumper)	1.00		Volume =	3261	3261.0	1	3261.0	0.00270	8.805	24.01	0.86	20.6
Outer Ring	(Al, model vol. / 12)	1.00		Volume =	1774	1773.9	1	1773.9	0.00270	4.790	24.01	0.47	11.2
Inner Ring	(Al, model vol. / 12)	1.00		Volume =	796	796.1	1	796.1	0.00270	2.150	24.01	0.21	5.0
Coolant	C6F14	1.00		Volume =	15530	15530.0	0.1667	2588.3	0.00179	4.638	34.82	0.31	7.5