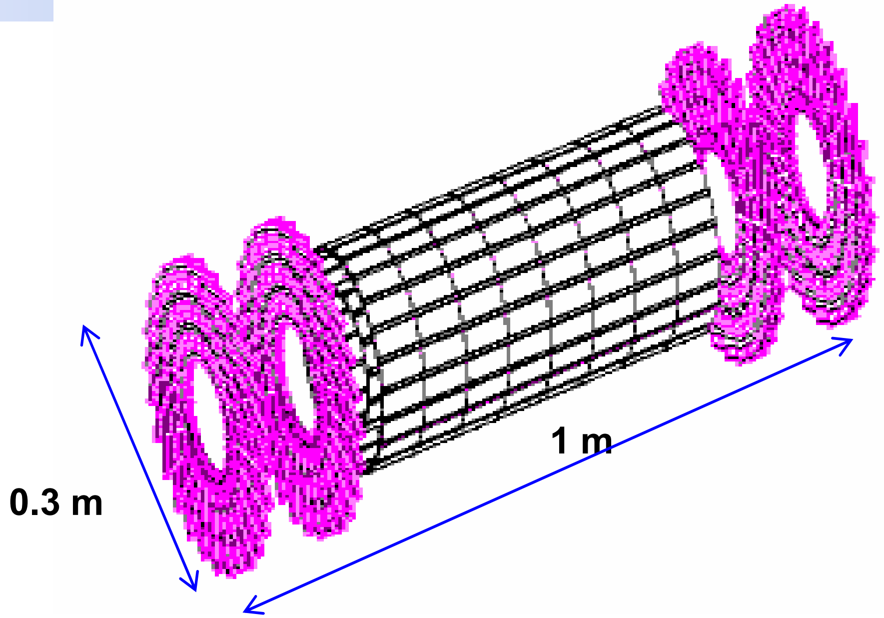
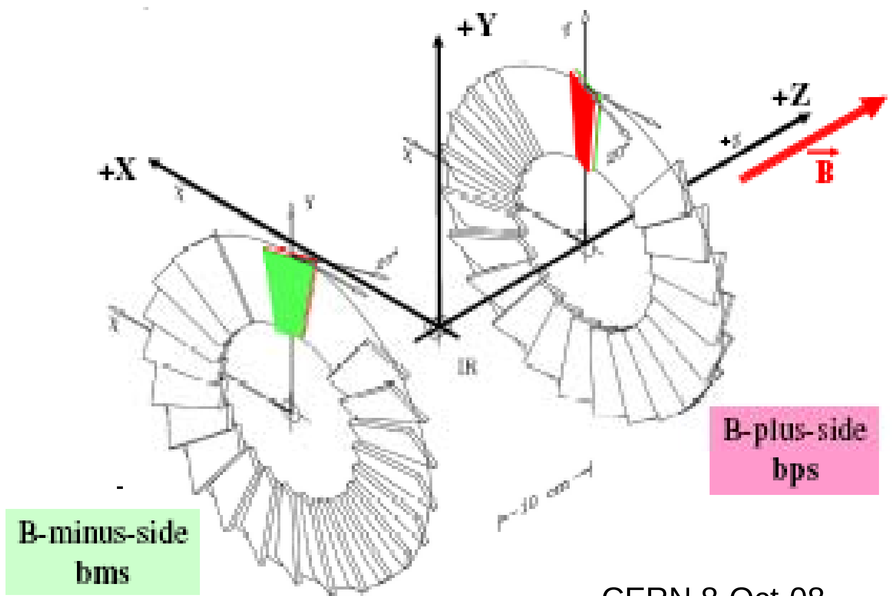
Outline

- Overview of FPix system
  - Technology used
  - Experience in construction and installation
- Limitations at 3×10^{34} $cm^{-2}s^{-1}$
- Technology choices for the upgrade
  - Risks and opportunities
  - Status of R&D
- Cost and schedule
- Summary

FPiX Overview

- The core of the CMS tracking system is a (hybrid) Pixel detector
- 100 × 150 μm^2 pixel size ⇒ excellent spatial resolution ~10-20 μm
- Charge sharing promoted by 4T B field and 20^0 tilt in FPiX
- **4 disks (FPix)**
  - Z=±34.5 and ±46.5 cm
  - (~ 6 cm above beam line)
  - 96 blades with 672 modules
  - 4320 ROCS, 18 Mpixels
  - Total area 0.28 m^2





- Radiation hardness
- Designed for ~6×10^{14} cm^{-2} (300 fb^{-1} @ 4.4 cm)

Pixels

- The pixel 3D hits are ideal seeds for tracking and μ reconstruction
  - Pattern recognition, all 5 track parameters well constrained

- Excellent position resolution makes pixels essential :
  - for primary and secondary vertex reconstruction
  - for b and τ identification

SUSY h -> b $\bar{b}$ event in CMS detector

pp -> $\tilde{u}_L + \tilde{g}$

$\tilde{g}$ -> $\tilde{t}_1 + \bar{t}$

-> $W^- + \bar{b}$ (jet_4, E_t = 113 GeV)

-> s(jet_5, E_t = 79 GeV) + $\bar{c}$

-> $\tilde{\chi}_2^+$ + b (jet_3, E_t = 536 GeV)

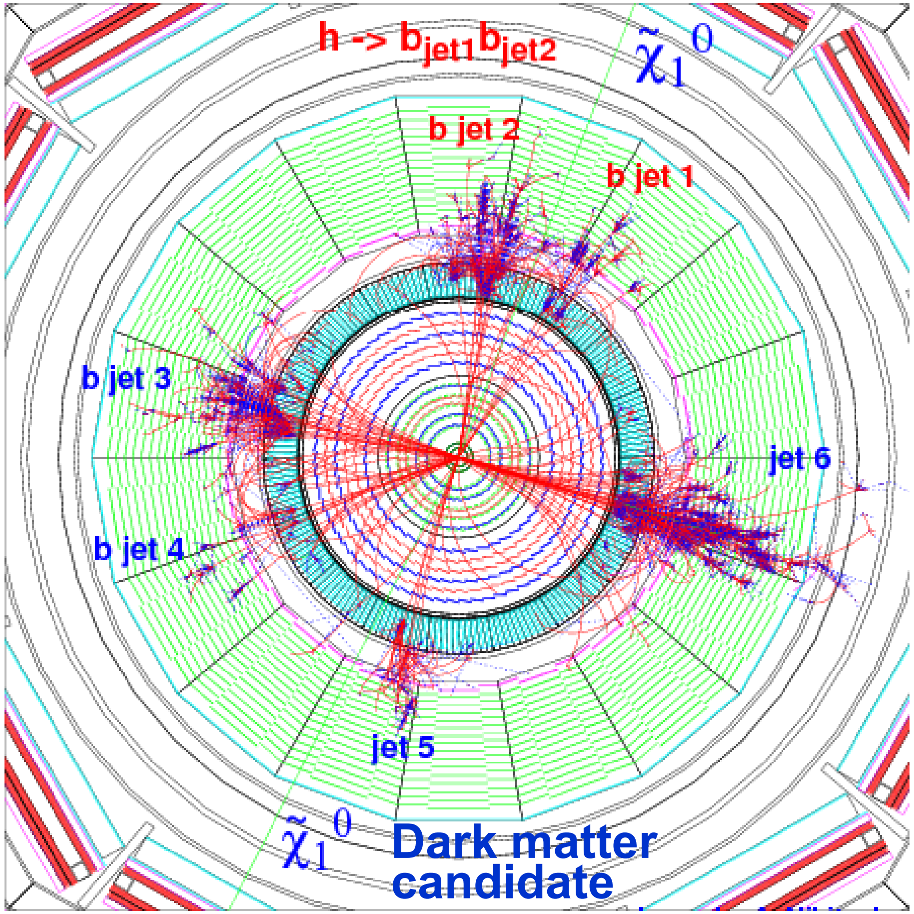
-> $\tilde{\chi}_1^+$ + Z -> $\nu \bar{\nu}$

-> $\tilde{\chi}_1^0$ + W^+ -> $\nu \tau$ -> e ν ν

$\tilde{u}_L$ -> $\tilde{\chi}_2^0$ + u (jet_6, E_t=1200 GeV)

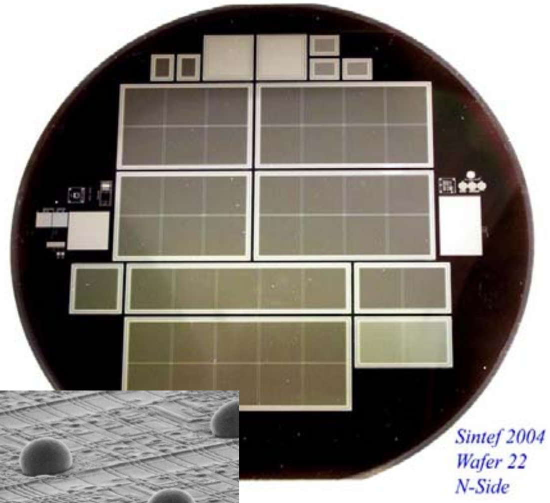
-> $\tilde{\chi}_1^0$ + h -> b $\bar{b}$ (jet_1, E_t=206, GeV; jet_2, E_t=320 GeV)

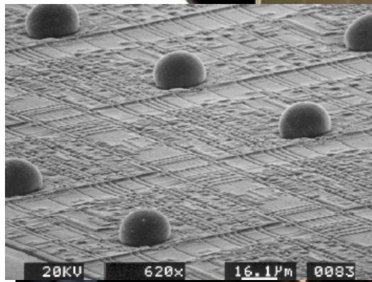
mSUGRA
m_0=1000 GeV, $m_{1/2}$=500 GeV
A_0=0, tan β =35, μ>0
m($\tilde{g}$) =1266 GeV
m($\tilde{u}_L$) = 1450 GeV
m($\tilde{t}_1$) = 1026 GeV
m($\tilde{\chi}_2^0$) = 410 GeV
m($\tilde{\chi}_1^0$) = 214 GeV
m(h) = 119 GeV

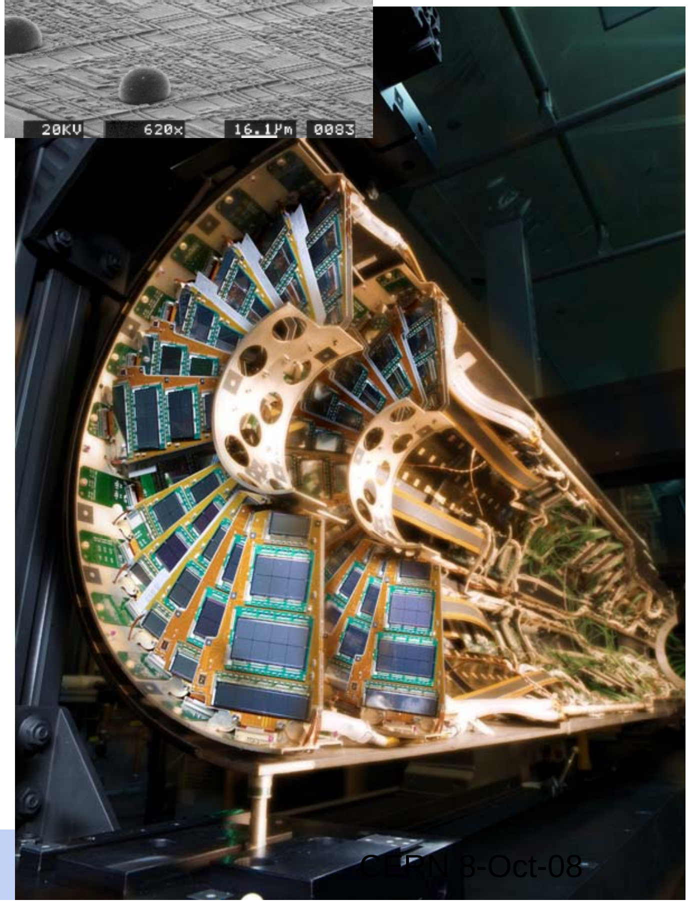


US Role in the FPiX

- **Complete Forward Pixel System $12M** (FNAL, Buffalo, Colorado, Cornell, Davis, Nebraska, Kansas State, Iowa, Johns Hopkins, Northwestern, Mississipi, Puerto Rico, Purdue, Purdue Calumet, Rutgers, Tennessee, Vanderbilt)
  - Development of sensors, module design
  - Development of most readout components with the exception of the readout chip (250 nm CMOS, PSI)
  - Testing of the components at several universities and FNAL
  - Selection of vendors to bump bond the pixel sensors to the Readout chip (IZM, RTI)
  - Modules (plaquettes) construction at Purdue
  - Construction, assembly, and testing of panels, blades, and cylinders at FNAL
  - Transportation
  - Mechanical support structure, cooling pipes
  - Installation and commissioning at CERN
  - DAQ, DCS, data base, infrastructure at CERN

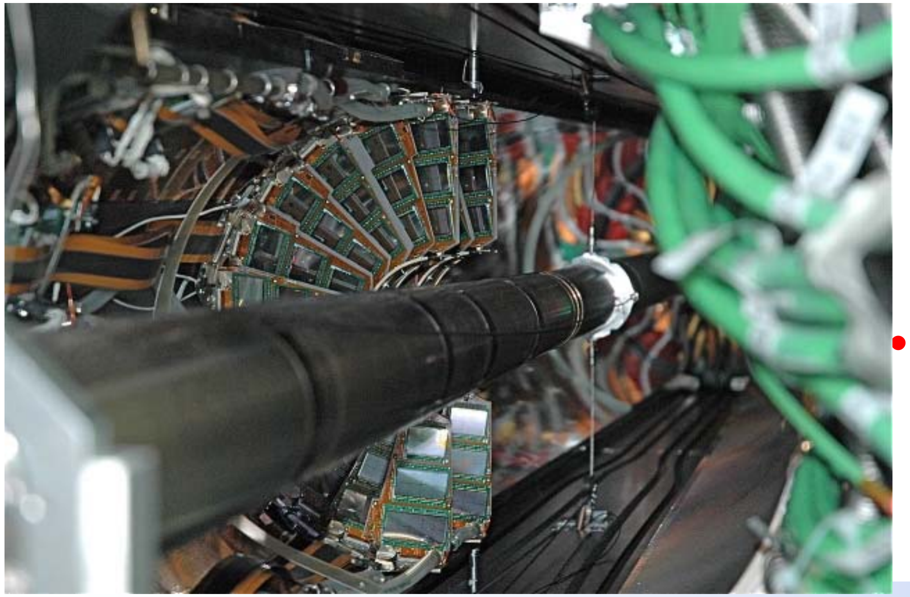






Experience

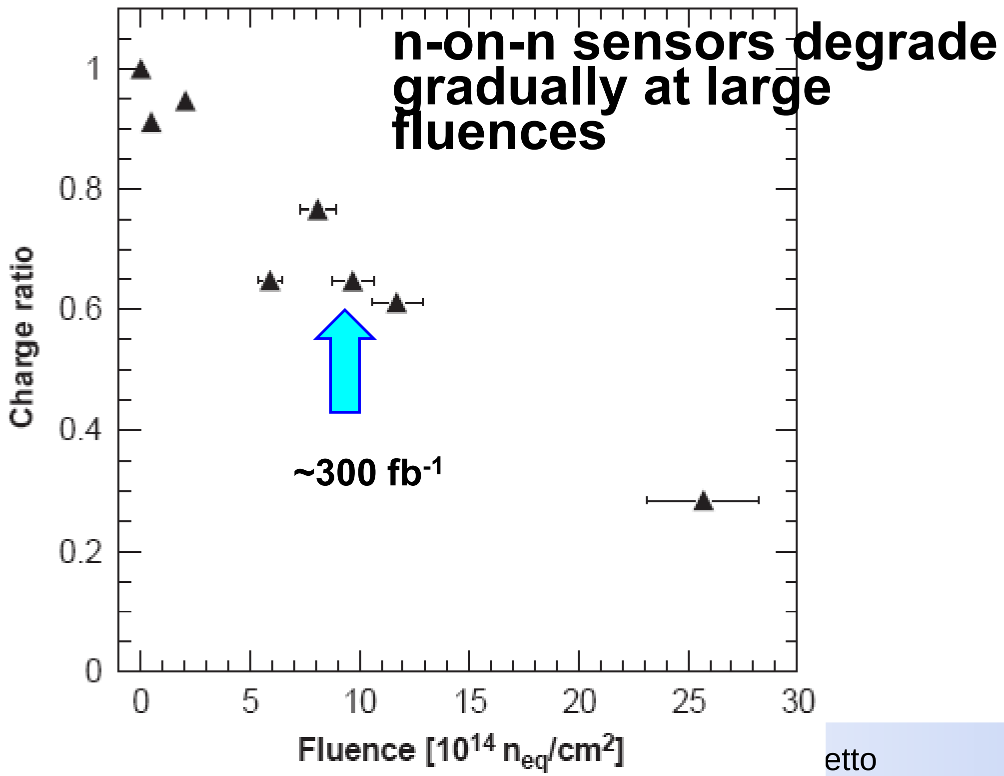
- **Pixel Construction**
  - The final ROC (PSI46 V2) received March 2006
  - Production plaquettes started in June 2006
  - First Production Half Cylinder (HC-Z1) shipped 4/26/07
  - Shipment of last Half Cylinder in Dec 07



- **Pixel Installation (Jul 31 2008)**
  - 9 Hours for each side
  - Night before insertion:
    - Table moved into position and extension rails attached and aligned. Time: 2h
  - Insertion day:
    - Unpack one CTU, raise to table, align, and perform half-push to intermediate position.
    - Repeat for other CTU. Time (total) 4h
    - Perform synch push: 2h
- Despite this success, there were more interferences than anticipated. Improvements are possible and will be important to reduce exposure once the area becomes radioactive.

Limitations in Phase 1

- Radiation damage due to integrated luminosity.
  - Sensors designed to survive $6\times10^{14} n_{eq}/cm^2$.
  - Dose at 1E34 @inner layer $3\times10^{14} n_{eq}/cm^2/year$



Note that the table assumes L=60 fb^{-1} at 1×10^{34} cm^{-2}s^{-1} but if machine works well we could get L=100 fb^{-1}/year at 1×10^{34} cm^{-2}s^{-1} in 2012

Year	Peak Lumi (x 10^{34})	Integrated (fb^{-1})	Integrated (fb^{-1})
2009	0.1	6	6
2010	0.2	12	18
2011	0.5	30	48
2012	1	60	108
2013	1.5	90	198
2014	2	120	318
2015	2.5	150	468
2016	3	180	648
2017	3	0	648
2018	5	300	948
2019	8	420	1428
2020	10	540	2028
2021	10	600	2628
2022	10	600	3228
2023	10	600	3828
2024	10	600	4428
2025	10	600	5028

Garoby LHCC July 1, 2008

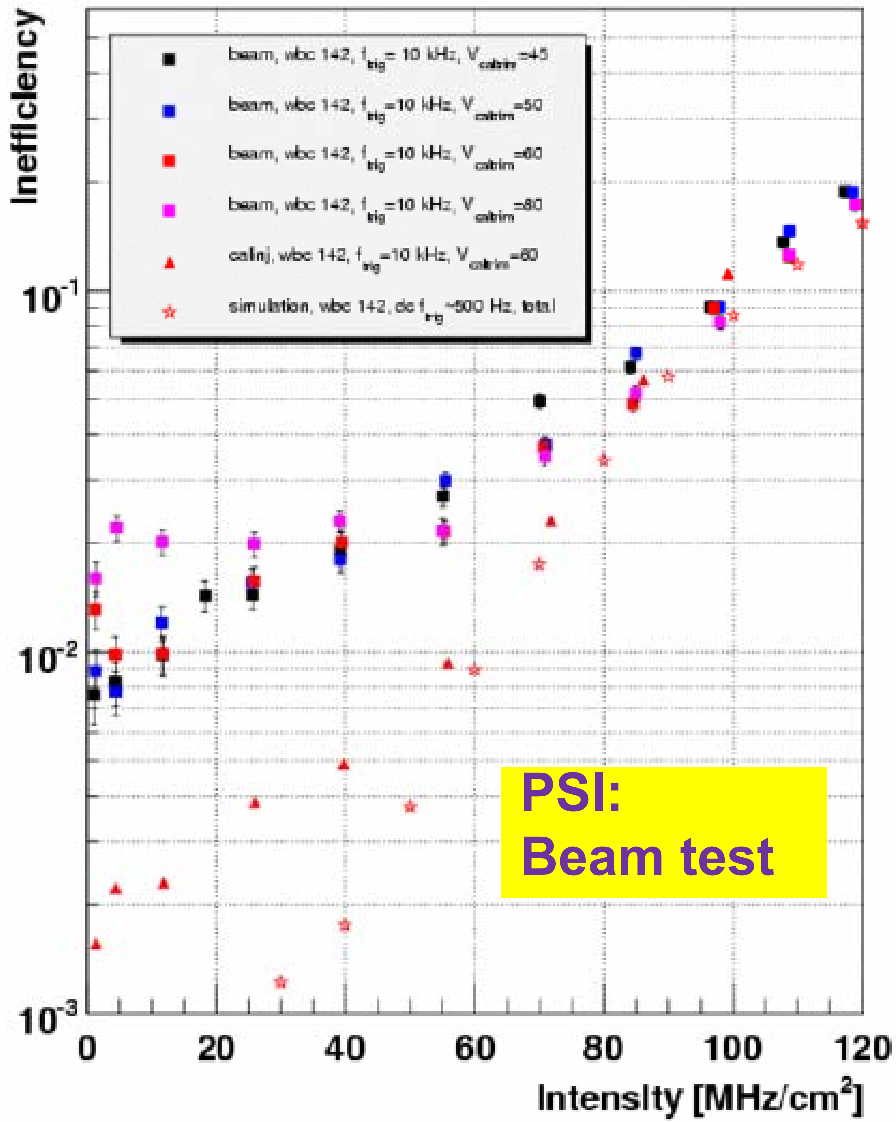
Limitations in Phase 1

- **Instantaneous luminosity**

- **Pixel dead time**
  high luminosity LHC: [10^{34}]
  11 cm / 7 cm / 4 cm layer
  total data loss @ 100kHz L1A:
  0.8%
  1.2%
  3.8%

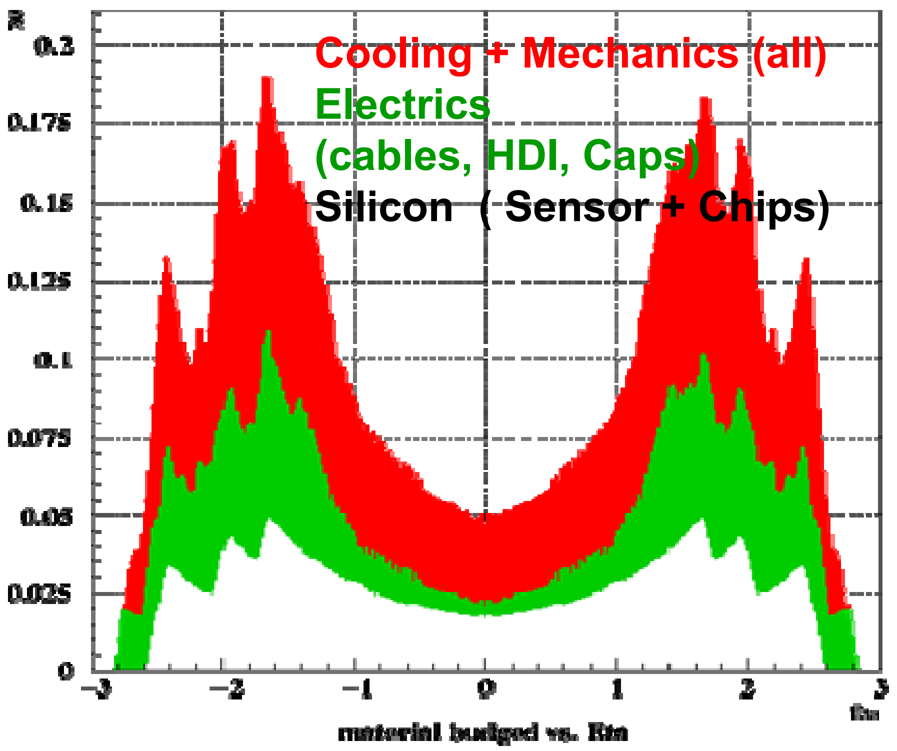
PSI: simulation

- **Dead time will rise to ~12% due to increase in peak luminosity**

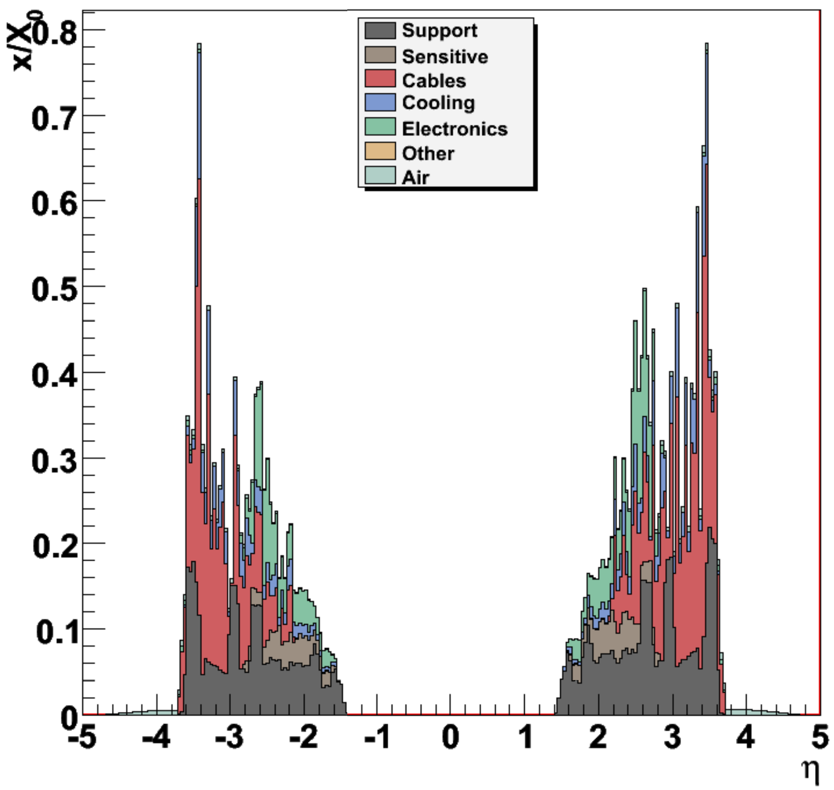


Limitations in Phase 1

BARREL PIXELS



ENDCAP PIXELS



- **Material budget both in endcap and barrel**
  - **Significant contribution from mechanical supports, cables**

Upgrade Plans

- Baseline: 3 layers (4 layer option) 3 disk in each endcap
  - Detector technology
    - Single sided n-on-p sensors (more rad-hard) instead of n-on-n (fallback)
    - Evaluating 3D sensors industrialization for innermost layer at 4 cm.
  - Readout Chip
    - Double buffer size (in 250 nm CMOS extra 0.8 mm needed for chip periphery)
      - Minimal R&D. Design, verification, testing at high beam rates 8-10 months
      - Mechanical changes
    - Further gains possible with 130 nm CMOS but R&D needed
  - Layout, mechanical assembly, and cooling (aim at material reduction of about a factor of 3 in barrel and 2 in forward)
    - $C0_2$ cooling (as in VELO for LHCb)
    - Low mass module construction and simplified thermal interfaces
    - Further material reduction can be acheived with on module digitization:
      - R&D needed: It requires new ADC and Token Bit Manager changes

4^{th} Layer option

- 4 layer system has 1.8x more modules than present 3 layer system
- Severe infrastructure constraints
  - DC-DC step down converters to bring more power through cables
  - high speed links to transmit 3.6x more data through same fibers
  - have advanced bi-phase cooling (e.g. CO_2) in same pipe x-section

Cost estimate for following system: (no half modules)

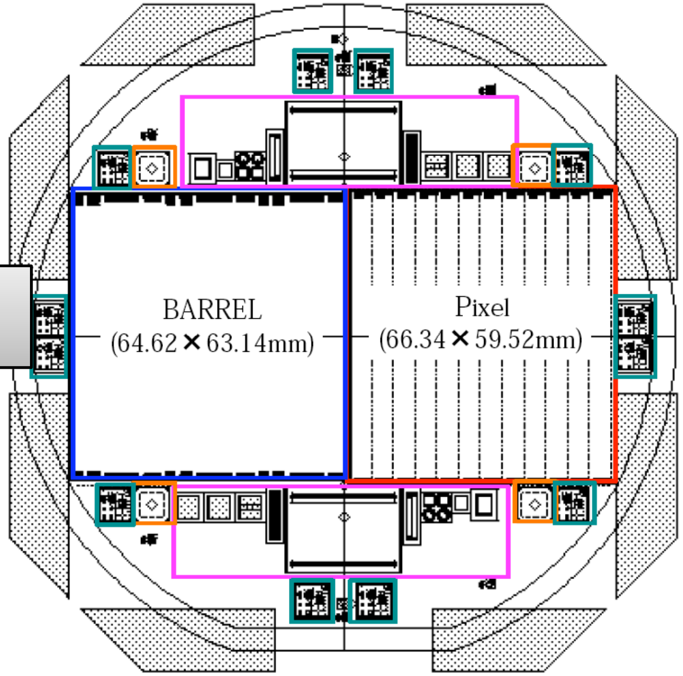
radius [cm]	length [#mod]	faces	#modules
16.0	10	64	640
10.4	8	42	336
7.3	8	30	240
4.4	8	18	144

- Nonetheless 4 layer system could :
  - Solve potential problems if inner silicon tracker layer fails
  - Strengthen pattern recognition in more complex events
  - Decision after we see first LHC data. It could be installed after 2013

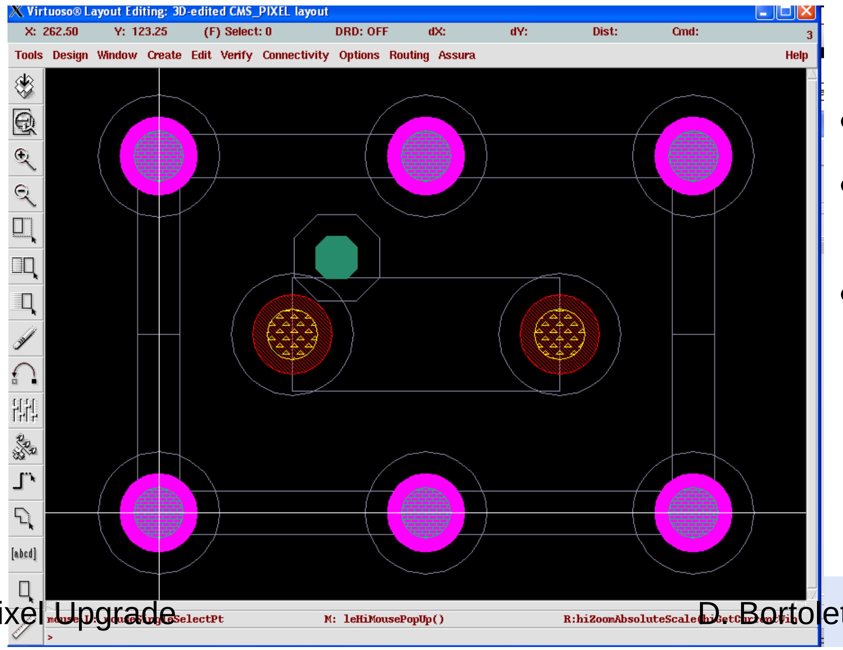
Sensor R&D

- **n-on-p Submission with HPK:**
  - **Test different substrates**
  - **Different thickness**
  - **n-on-p versus n-on-n**
  - **Pixel isolation (p-spray and p-stop)**
  - **Expect delivery February 2009**

n-on-p Rad hard up to ~3×10^{15} cm^{-2}



- **3D - Submission with Sintef**



3D Rad hard up to ~10^{16} cm^{-2}

- **Shared with ATLAS and MEDIPIX**
- **Sintef produced the CMSFPIX sensors**
- **First prototypes for bump-bonding in spring 2009**

A two column pixel implemented in the CMS pixel geometry

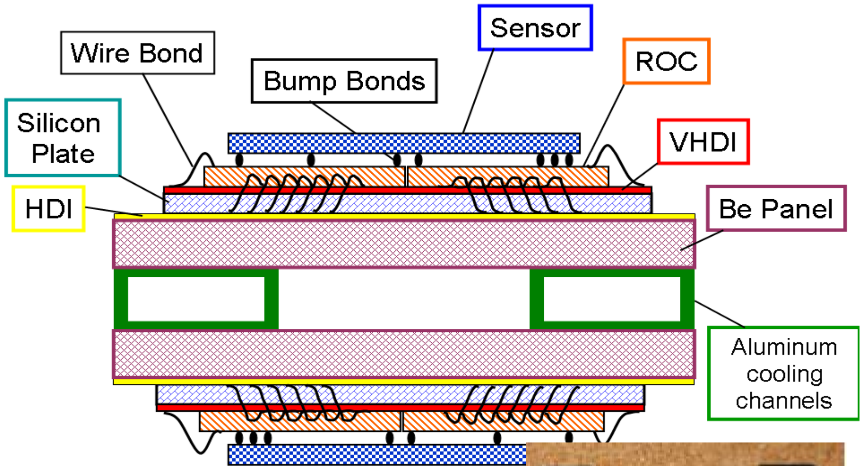
More in Gino's talk

Mechanical R&D

Current FPIX blades have:

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

LARGE MATERIAL BUDGET

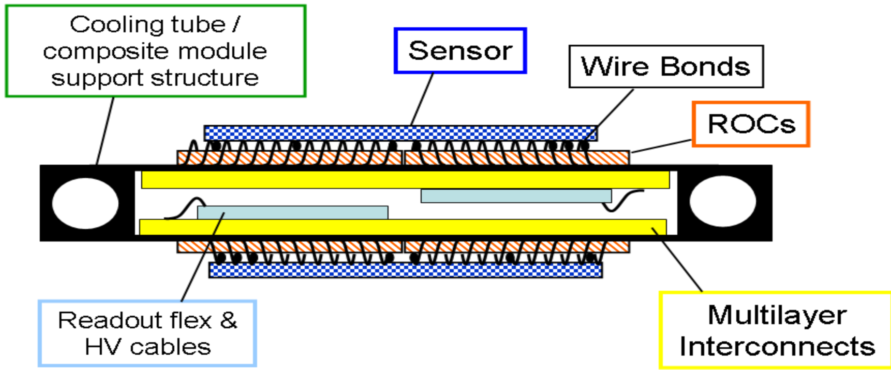


- FPiX: 7 different types of modules

Integrated modules R&D

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

LOW MATERIAL BUDGET



- New system: one module type
- Light support structure

More in Kirk's and Simon's talk

CO_2 R&D

- CO_2 properties match silicon detector applications
  - Low viscosity and low density difference between liquid and vapor is ideal for micro channels (d<2.5mm)
    - Great saving in material budget liquid (CO_2 is ~ 1.03 g/cm^3 compared to 1.76 g/cm^3 of C_6F_{14})
    - Small area for heat transfer → need to route enough tubes for sufficient thermal contact with pixel modules
  - Ideal for serial cooling of distributed heat sources
  - Radiation hard
  - Optimal operation temperature -40°C to +20°C
- "No showstoppers" for existing CMS pipes (aim for maximum of 40 Bar, Pipes rated to 150 Bar)
- CO_2 cooling excellent candidate for upgrade
- We are constructing a CO_2 cooling system for lab bench testing

Already used by LHCb VELO detector

LHCb CO_2 cooling tube

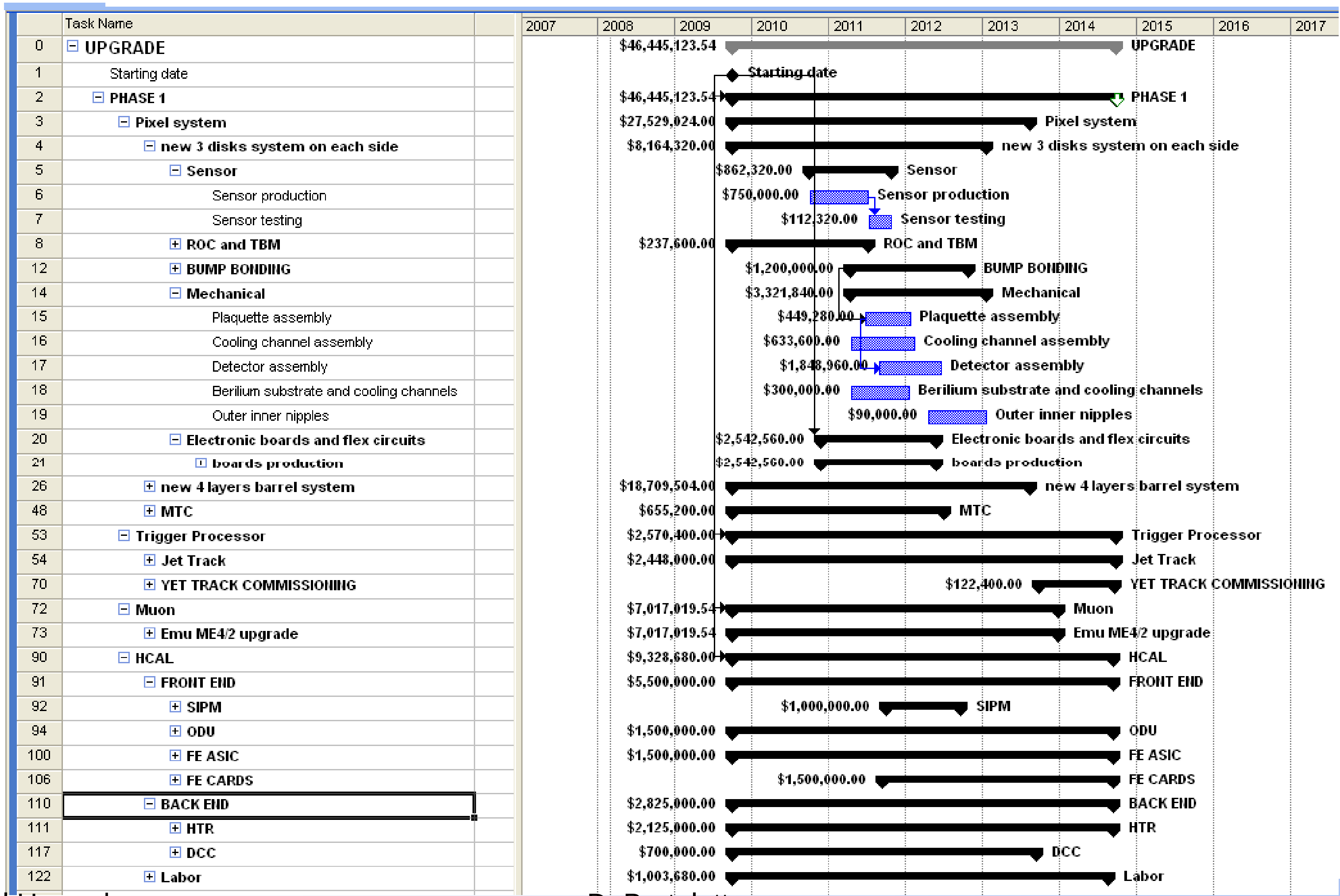
More in Terry's talk

Organization

- Many groups are involved in the planning for the Phase 1 Pixel replacement
  - FNAL (mechanics, sensors, cooling, electronics including power distribution)
  - PURDUE (sensors, modules, cooling integration into modules)
  - PIRE collaboration which includes Kansas, Kansas State, Nebraska, Puerto Rico, UIC (Sensor, ROC, bump bonding)
  - Mississippi (mechanical support)
  - Iowa (cooling), Purdue Calumet (testing)
  - +others?
- Most groups have submitted R&D proposals that have been evaluated by CMS and have received a positive evaluation

Schedule and Budget

- Schedule and cost was developed using the experience of building the FPiX disks



Cost Detail

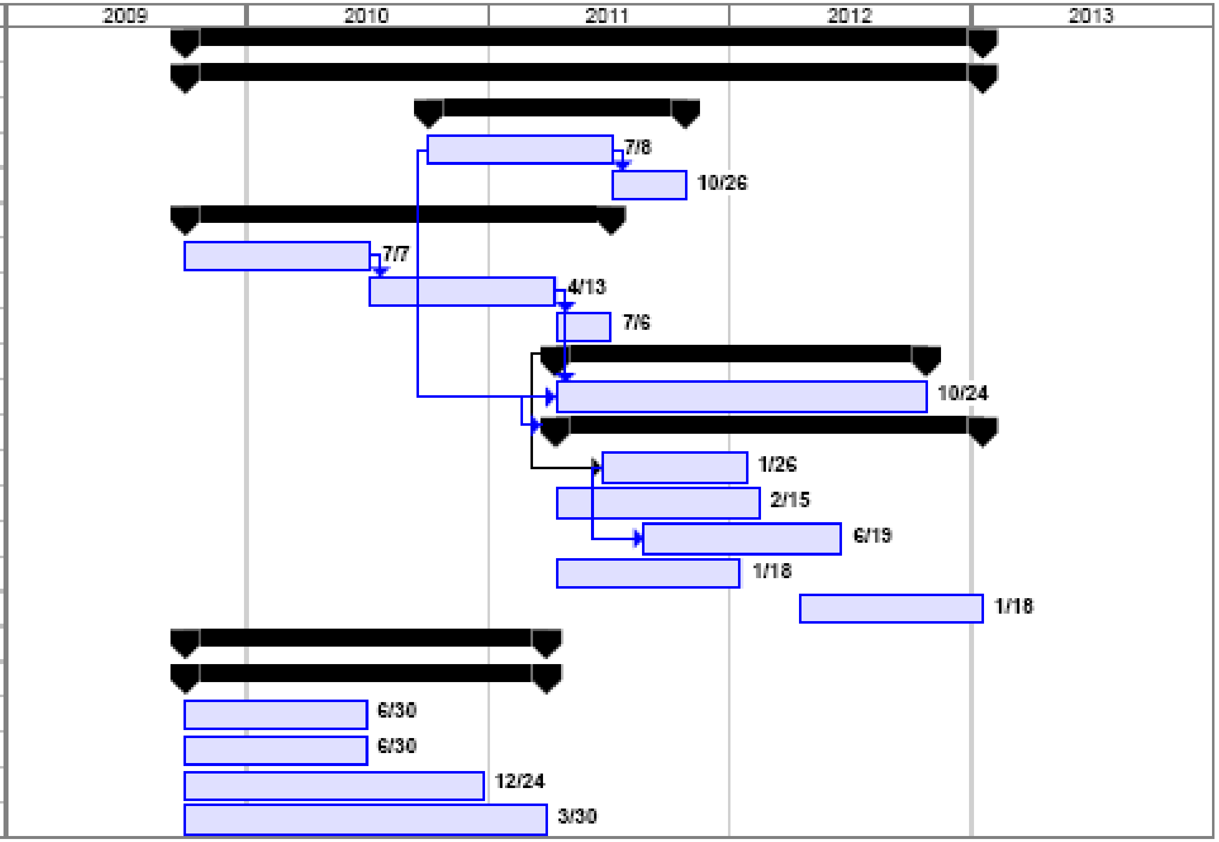
- FY08 total cost $ 30.2M (Labor $19 M, M&S $11 M)
- Use experience from FpiX which was completed in FY08
- 3 disks on each side= 8.16 M$ (including engineering & labor + some contingency):
  - Sensors $ 862,320
  - ROC & TBM $ 237,600
  - Bump Bonding $ 1,200,000
  - Mechanics $ 3,321,840
  - Electronics $ 2,542,560

FY08 dollars

Schedule Detail

- **Expect to finish R&D in mid FY10**
- **Assume Project funding starts FY10**
- **3 disks system completion in 2013**

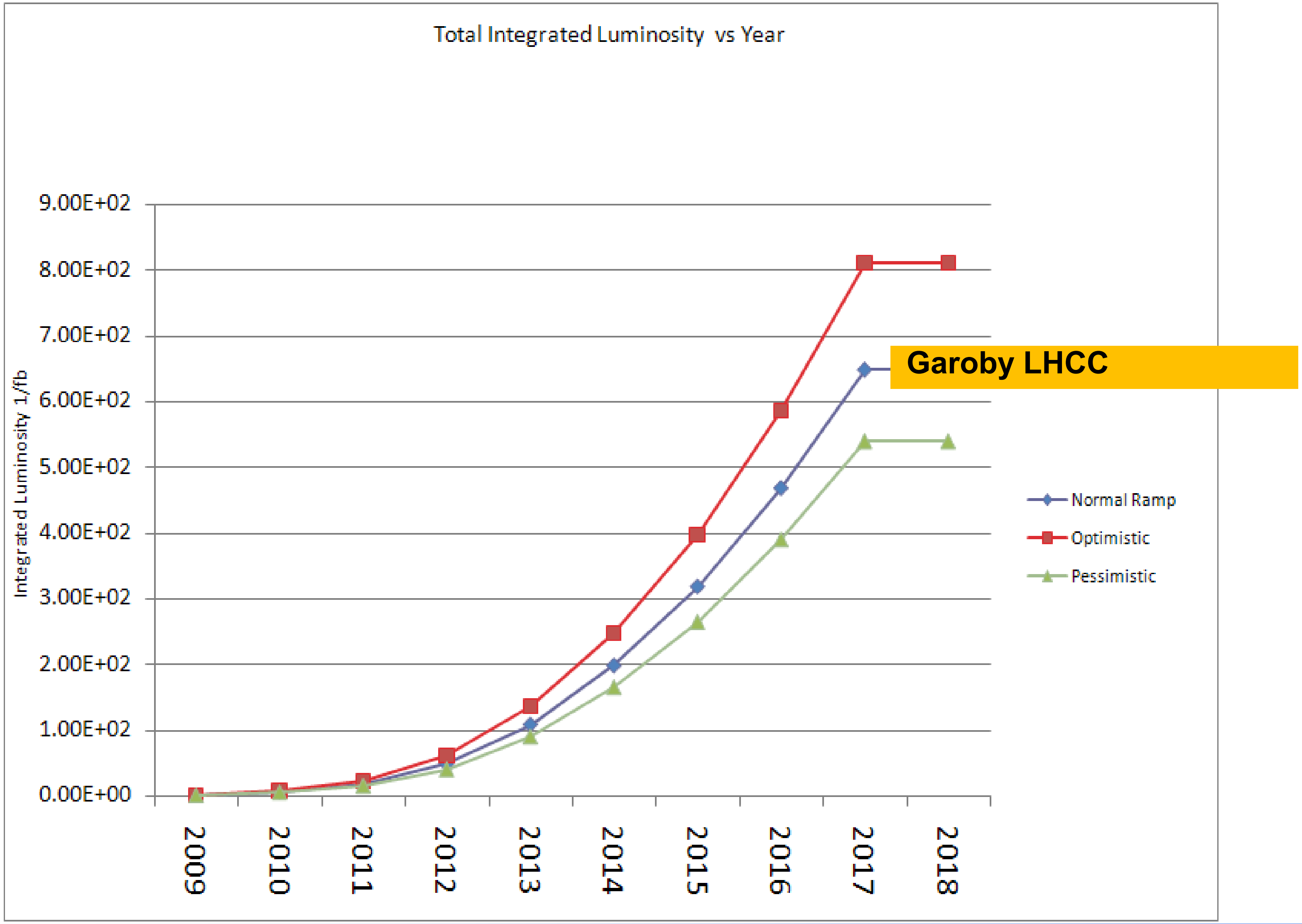
ID	Task Name
1	Pixel system
2	new 3 disks system on each side
3	Sensor
4	Sensor production
5	Sensor testing
6	ROC and TBM
7	ROC and TBM R&D
8	ROC and TBM production
9	ROC and TBM testing
10	BUMP BONDING
11	bump-bonding production
12	Mechanical
13	Plaquette assembly
14	Cooling channel assembly
15	Detector assembly
16	Berilium substrate and cooling channels
17	Outer inner nipples
18	Electronic boards and flex circuits
19	boards production
20	cable connectors and fibers
21	flex circuits and PCB
22	testing of VHDI
23	assembly and testing of PCBs



Conclusions

- SLHC Phase 1 Pixel upgrade is critical to maintain pixel capabilities at the higher luminosity
- The new system will improve:
  - Radiation hardness (integrated luminosity)
  - Data losses (peak luminosity)
  - Reduce material budget ⇒ great for physics
- Phase 1 replacement/upgrade is a stepping stone for the Phase 2 upgrade which will use the same low material budget mechanics & cooling.
- Upgrade needs to be focused since Phase 1 replacement project will have to be done in parallel with Phase 2 upgrade R&D for 10^{35} which is very challenging
- Three disks system ready for installation in 2013.
  - Need finish RD by mid FY10. Construction in FY11 and FY12.

Limitations in Phase 1

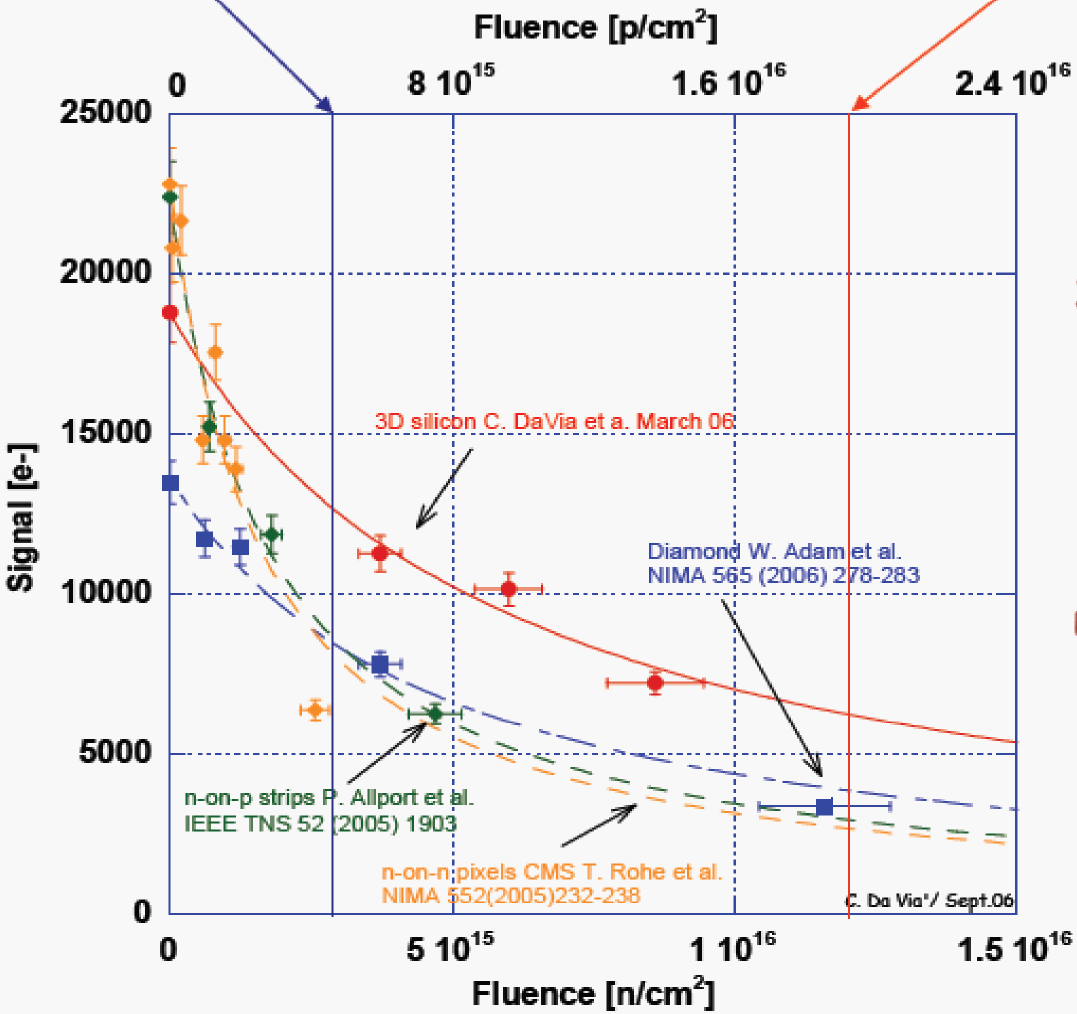


Radiation Hardness

$3x10^{15}$ p/cm^2 =
10 years LHC at 10^{34} cm^{-2}s^{-1}
At r=4cm and target for b-layer replacement

1.8×10^{16}p/cm^2 =
10 years SLHC at 10^{35}cm^{-2}s^{-1}
At r=4cm

Da Via



Fluence [n/cm^2]	Bias voltage [V]	
3D		
3.74×10^{15}	60	**B-layer**
5.98×10^{15}	100	
8.60×10^{15}	160	**upgrade**
n-on-n pixels CMS		
~3×10^{15}	600	

We can expect:

Twice as much charge
Factor 10 less bias