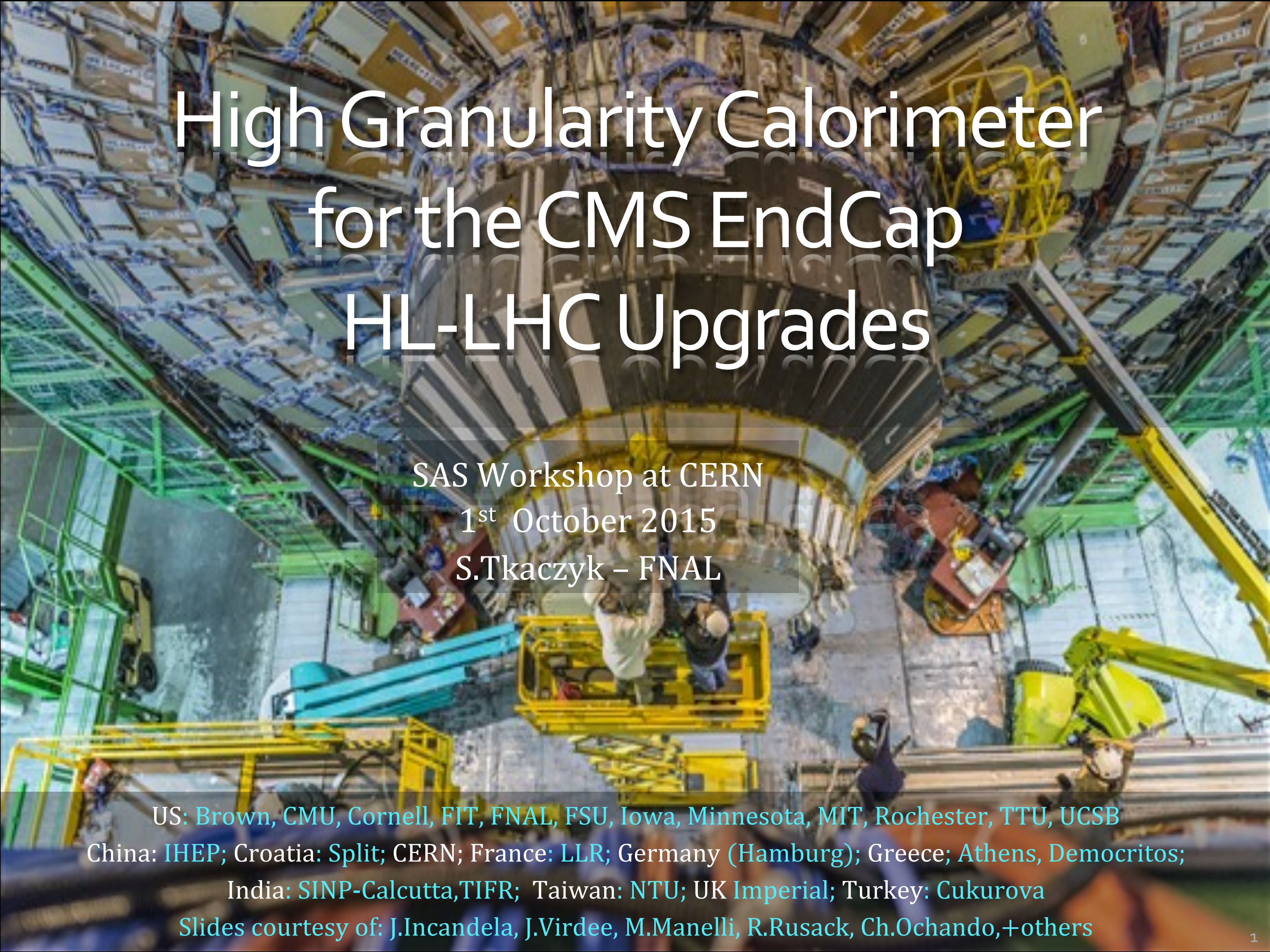


High Granularity Calorimeter for the CMS EndCap HL-LHC Upgrades

SAS Workshop at CERN

1st October 2015

S.Tkaczyk – FNAL

US: Brown, CMU, Cornell, FIT, FNAL, FSU, Iowa, Minnesota, MIT, Rochester, TTU, UCSB

China: IHEP; Croatia: Split; CERN; France: LLR; Germany (Hamburg); Greece; Athens, Democritos;

India: SINP-Calcutta,TIFR; Taiwan: NTU; UK Imperial; Turkey: Cukurova

Slides courtesy of: J.Incandela, J.Virdee, M.Manelli, R.Rusack, Ch.Ochando,+others

End Cap Calorimeter for CMS

- **Physics program at HL-LHC post the Higgs discovery puts emphasis on:**
  - **Traditional channels:** H->γγ and H->4 e (w/ electrons and photons)
  - **Jets**: especially VBF, VBS, **tau-jets**: H->ττ, **boosted jets**
  - **Missing Transverse Energy:** for Dark Matter, BSM searches

- **Challenges:**
  - **Mitigation of high pile-up**
  - **High radiation dose:** signal loss for current EC

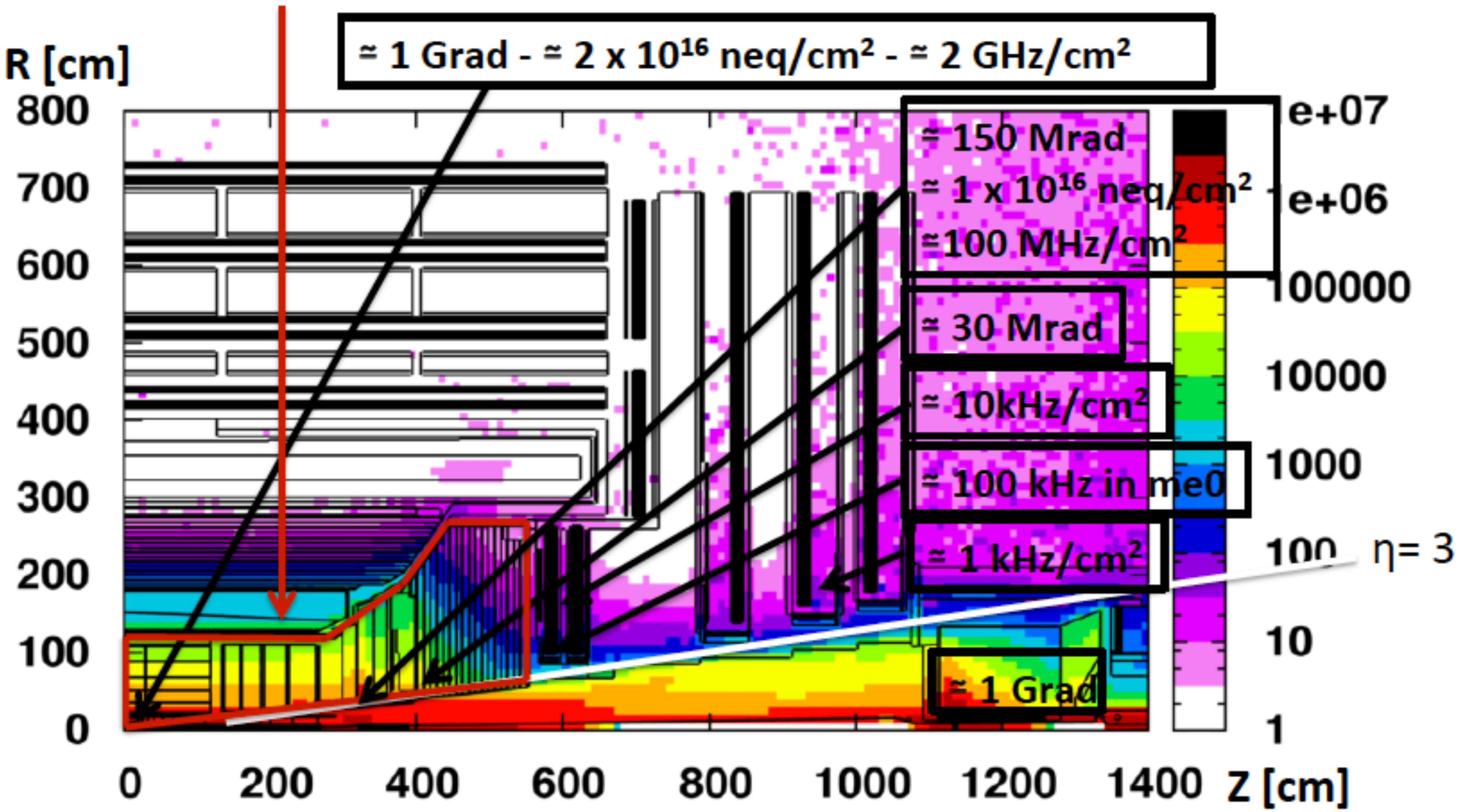
- **New End Cap concept based on mixture of silicon and scintillator samplings**

- **Pioneering work by CALICE R&D and others**

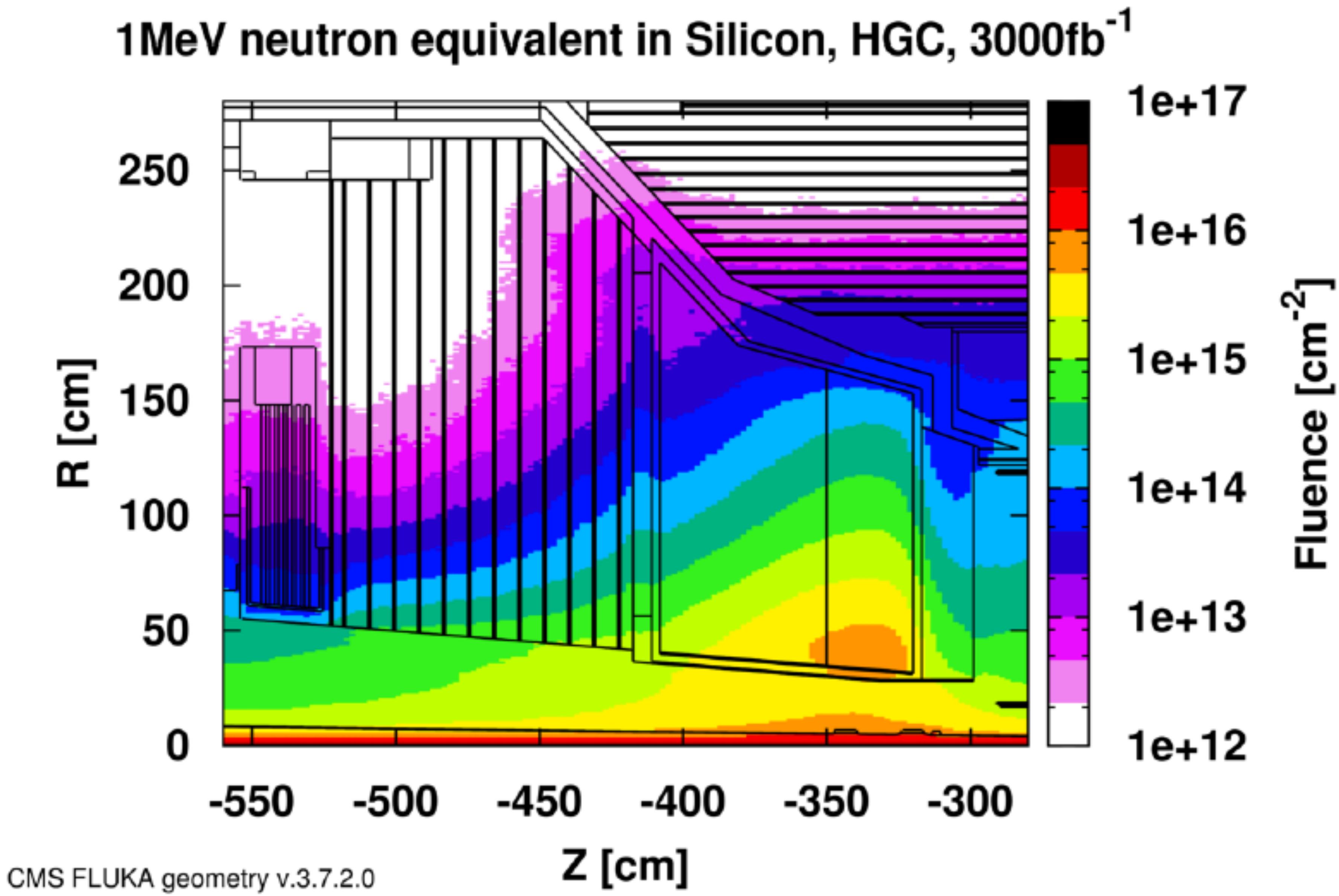
HL-LHC: A Hostile Environment

- 3000 fb-1 Dose map in [Gy] simulated with MARS and FLUKA
- Numbers in boxes indicate maximum doses – neutron equivalent fluence – particle rates (for 5×10^{34} Hz/cm^2) seen by various detectors

Aging studies show that Tracker / Endcap must be replaced



Expected Radiation Levels

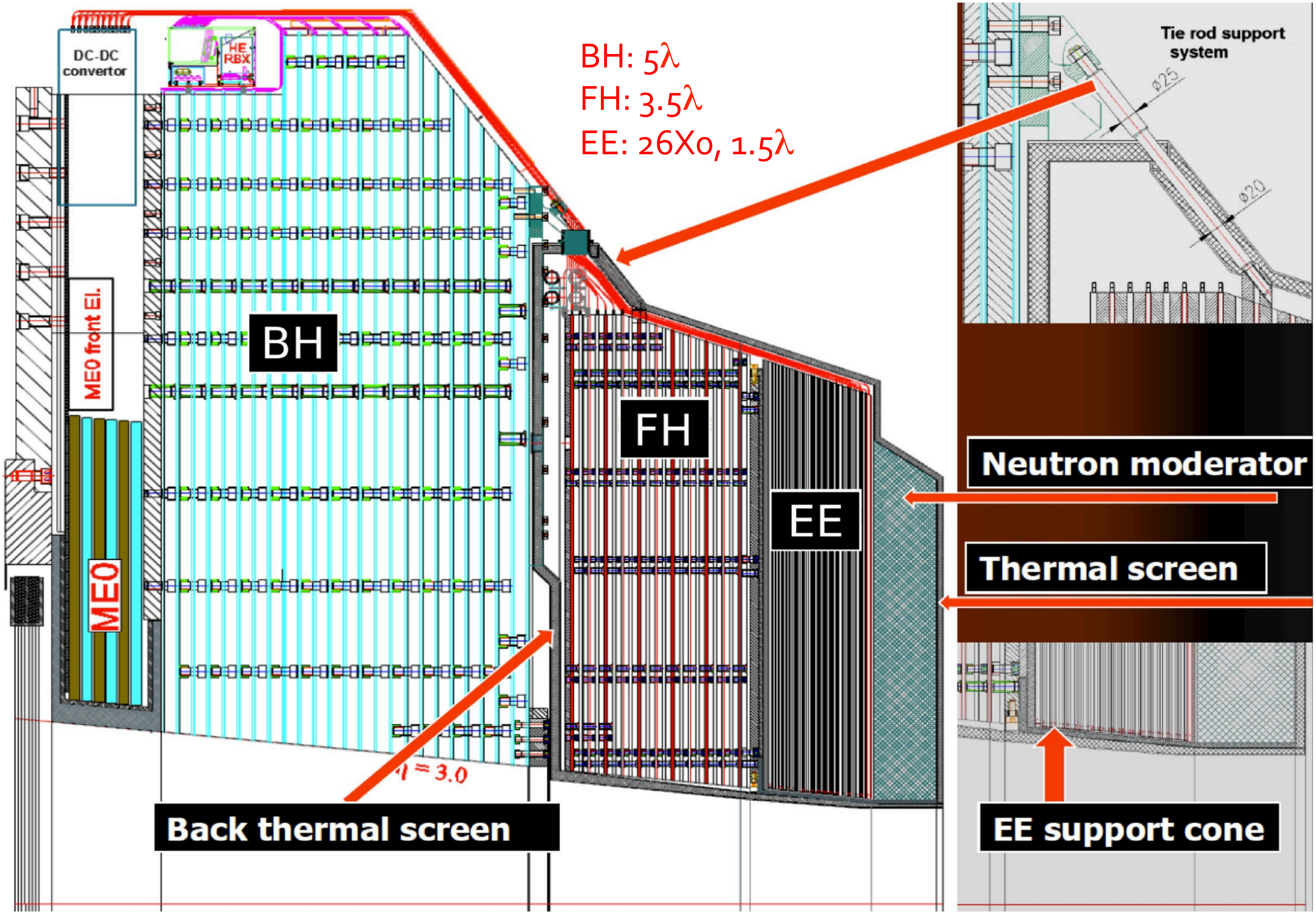


End Cap Calorimeter for CMS

- **High Granularity Calorimeter Proposal:**
  - A dense and compact electromagnetic and hadronic calorimeter with high lateral and longitudinal granularity
  - Combination of topological information and shower tracking capability with energy resolution will aid particles and jet reconstruction with Particle Flow reconstruction in the high occupancy environment of the HL-LHC
  - Proposed techniques and technologies with significant promise for future detectors and accelerators
- **Backing Hadronic Calorimeter Proposal:**
  - Similar to existing HE
  - Plastic scintillator tiles with WLS readout

Endcap Detector Concept

BH: 5λ
FH: 3.5λ
EE: 26X0, 1.5λ



HGC Project Milestones

- **Substantial progress across all aspects of the project during past year**

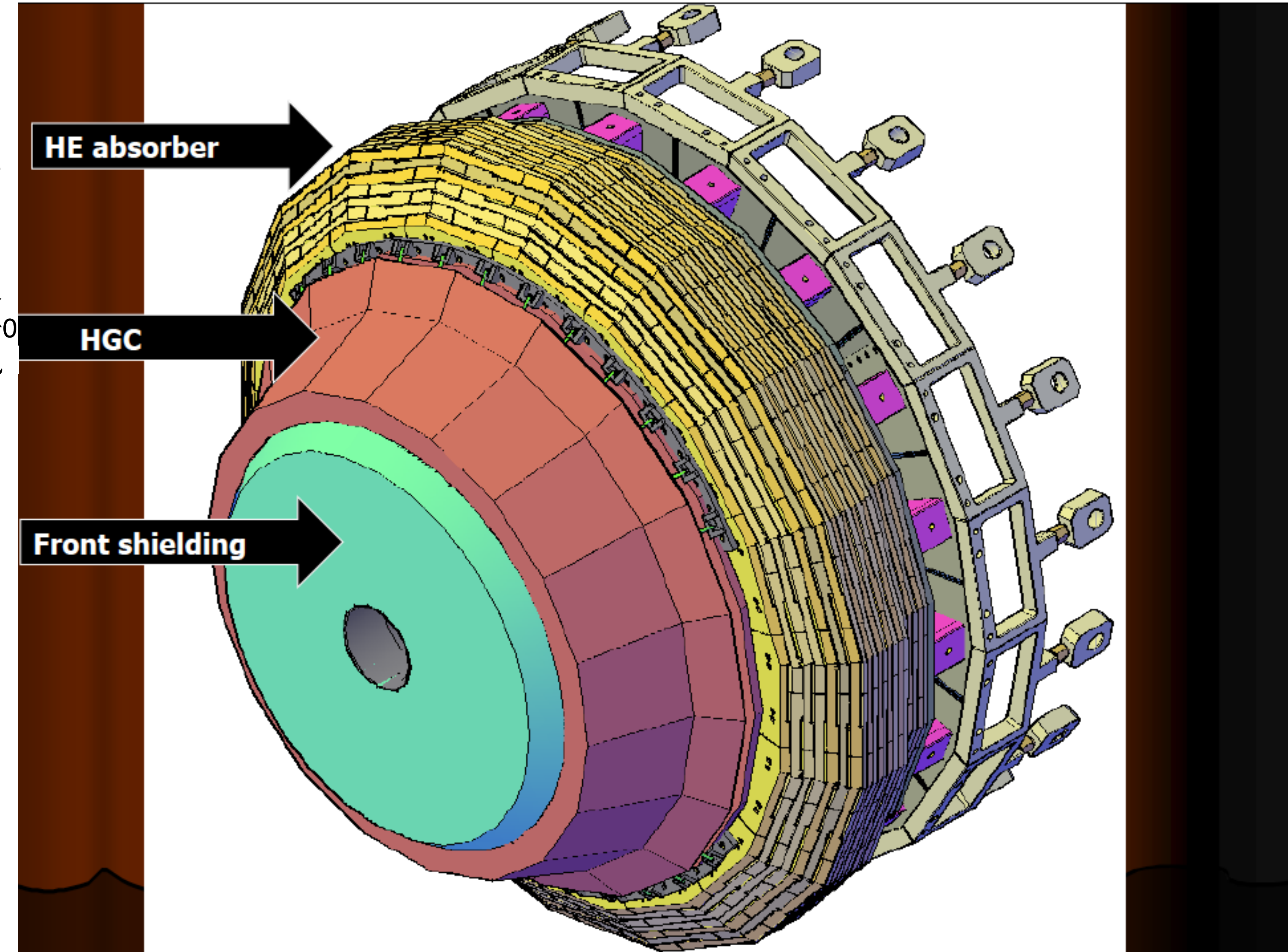
- **A number of major milestones have been achieved**
  - Key questions of radiation tolerance of silicon sensors addressed
  - Essential aspects of the electronics system established
  - Mechanical design of HGC developed
  - Major issues related to mechanics and integration of key detector elements understood and addressed

ENDCAP CONCEPTUAL DESIGN

BH:5.5λ

EH: 26X_0

FH: 3.5λ



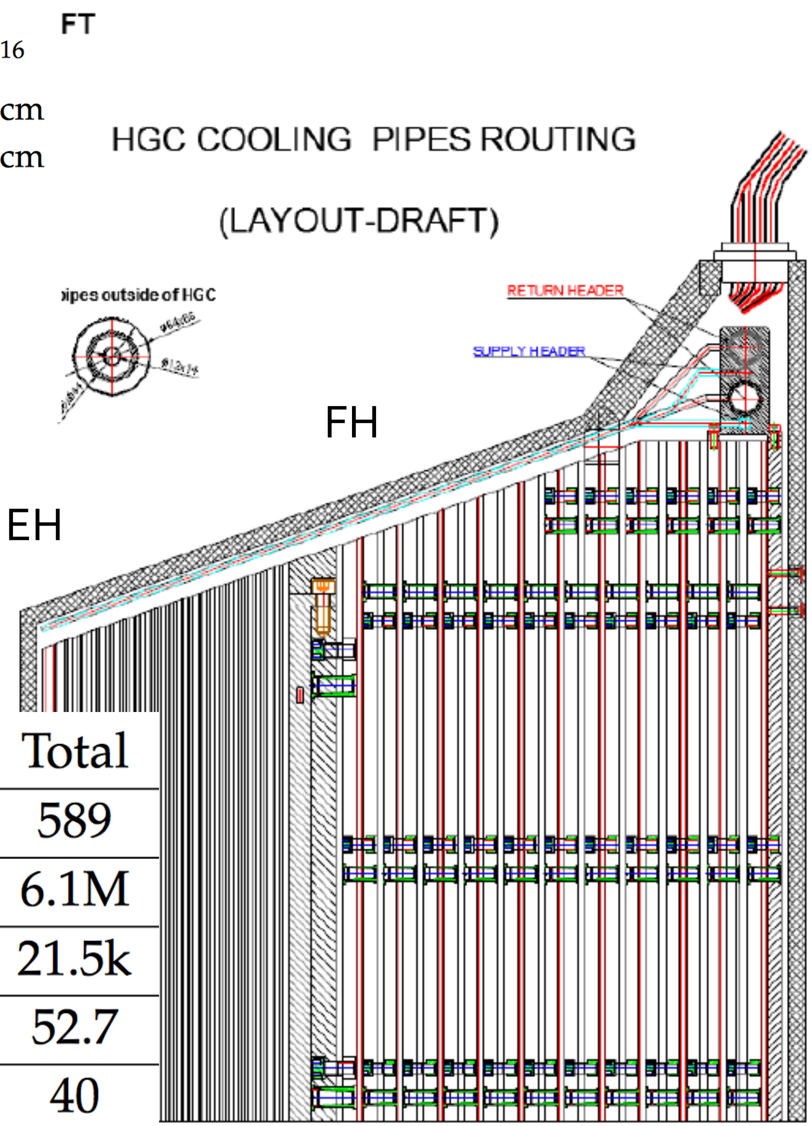
HGC: New Layout & Parameters

Thickness	300 μm	200 μm	100 μm
Maximum dose (Mrad)	3	20	100
Maximum n fluence (cm^{-2})	6×10^{14}	2.5×10^{15}	1×10^{16}
EE region	$R > 120$ cm	$120 > R > 75$ cm	$R < 75$ cm
FH region	$R > 100$ cm	$100 > R > 60$ cm	$R < 60$ cm
Si wafer area (m^2)	290	203	96
Cell size (cm^2)	1.05	1.05	0.53
Cell capacitance (pF)	40	60	60
Initial S/N for MIP	13.7	7.0	3.5
S/N after 3000 fb^{-1}	6.5	2.7	1.7

EH
10 layers: 0.64 X_0,
10 layers: 0.88 X_0,
8 layers: 1.1 X_0

FH
12 layers: 0.3 λ

BH
12 layers: 2 segments



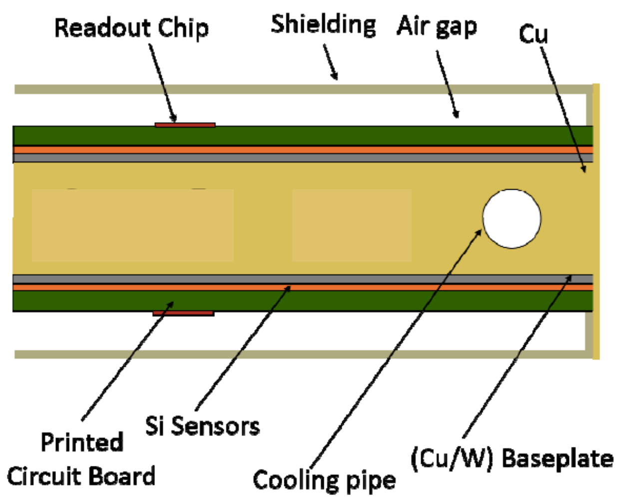
	EE	FH	Total
Area of silicon (m^2)	380	209	589
Channels	4.3M	1.8M	6.1M
Detector modules	13.9k	7.6k	21.5k
Weight (one endcap) (tonnes)	16.2	36.5	52.7
Number of Si planes	28	12	40

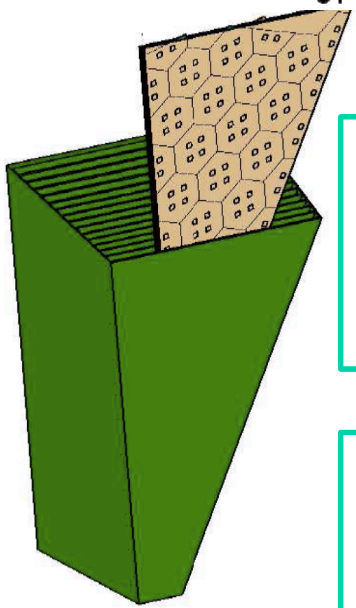
MECHANICAL DESIGN

Wedges and Cassettes

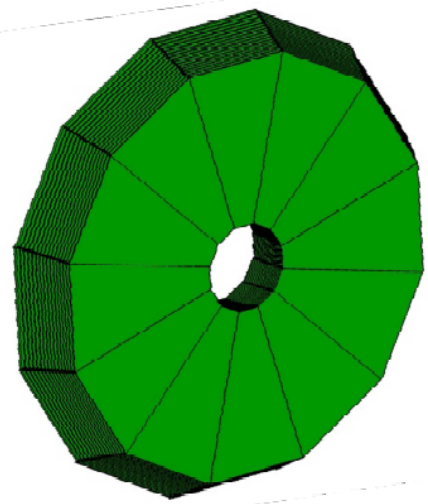
Section Through a Cassette

Design B (currently proposed):

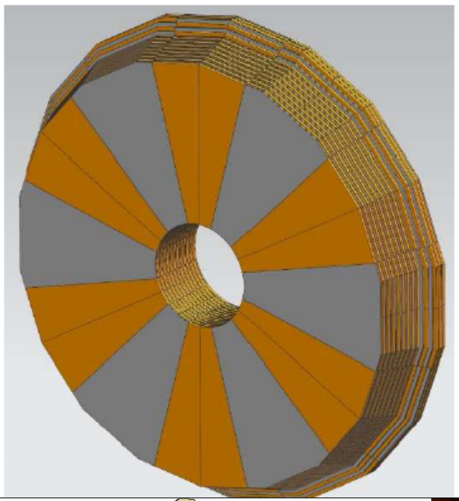




EE Wedges to be glued together to form a monolithic structure

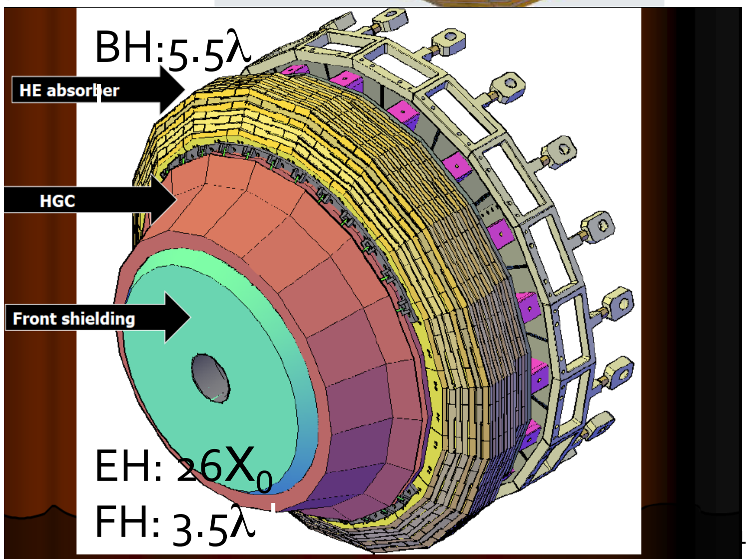


FH Wedges bolted brass plate structure with 30° slots (based on HE design)



Wedge Carbon Fibre Structure with Embedded W Plates (3° tilt)
Cassettes slid into slots

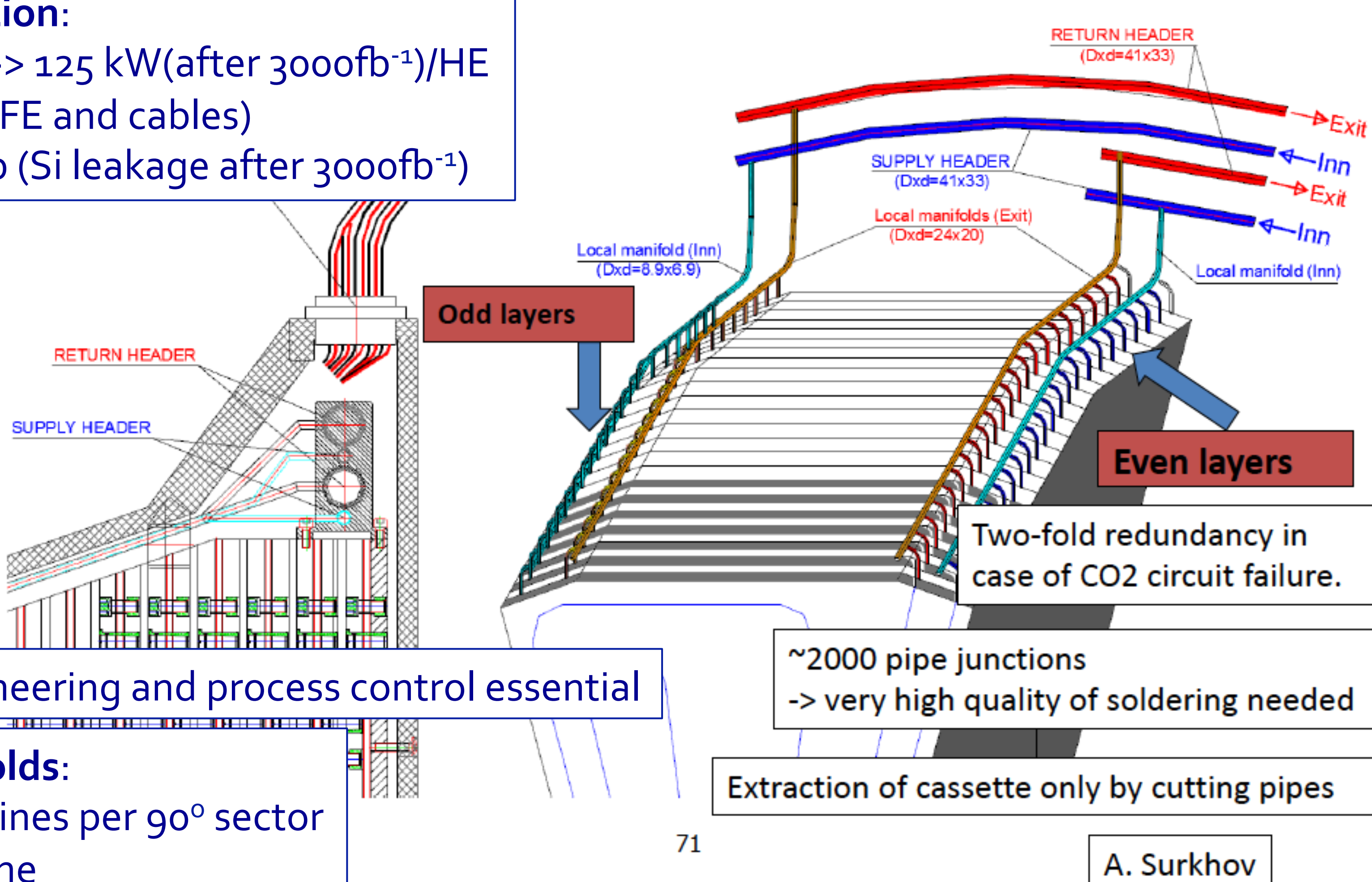
EE Investigating mechanics to make a larger rotation



HGC Services Integration

Cooling of 30 degree sector

Power Dissipation:
100 kW (0 fb^{-1})-> 125 kW(after 3000fb^{-1})/HE
50 kW/endcap (FE and cables)
12.5 kW/endcap (Si leakage after 3000fb^{-1})



Two-fold redundancy in case of CO2 circuit failure.

~2000 pipe junctions
-> very high quality of soldering needed

Extraction of cassette only by cutting pipes

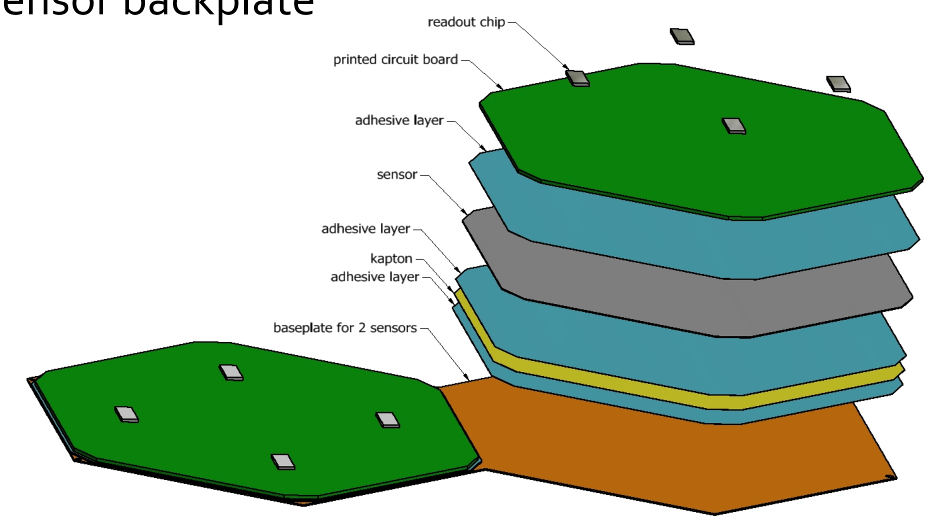
Careful engineering and process control essential

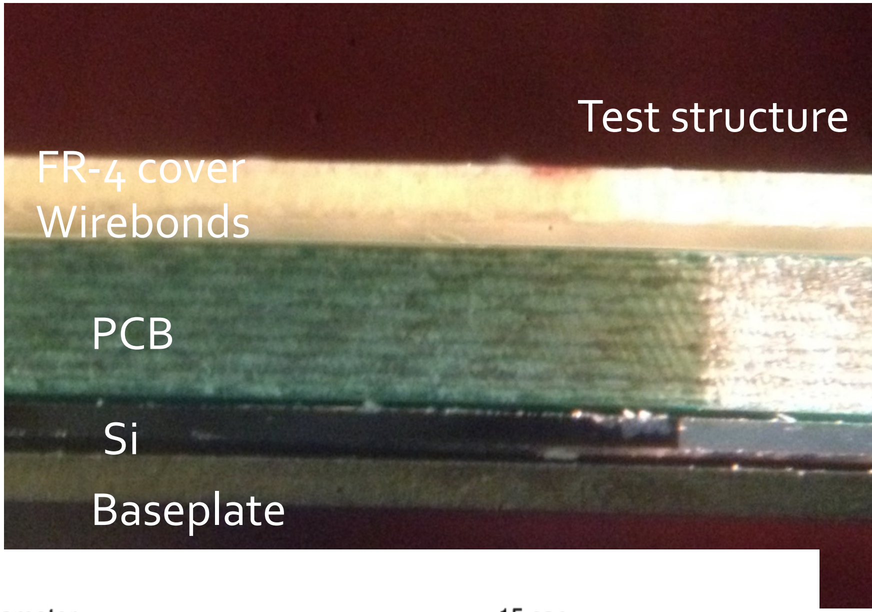
Cooling Manifolds:
2 CO_2 transfer lines per 90° sector
Rating: 15kW/line
Capacity: 120 kW /endcap

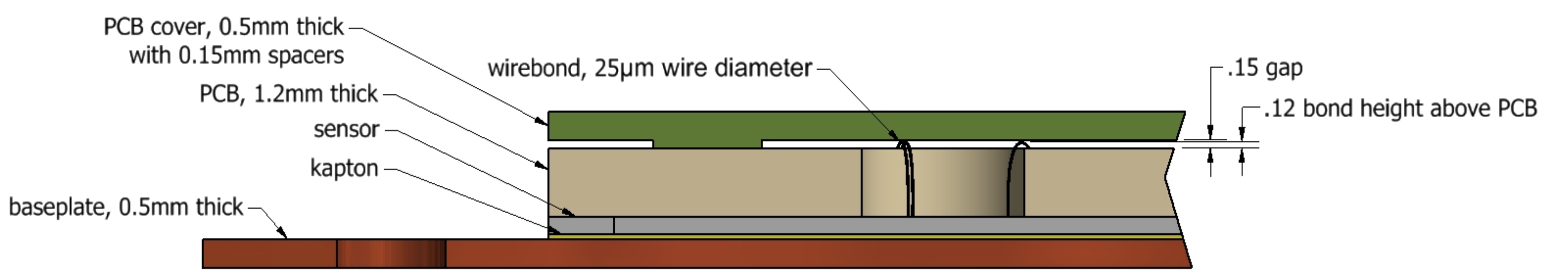
HGC Silicon Sensor Module Design

- **Robust module design suitable for large scale automated assembly developed**
- **Ruggedized design with protected sensors and wire bonds – ease of handling and integration**

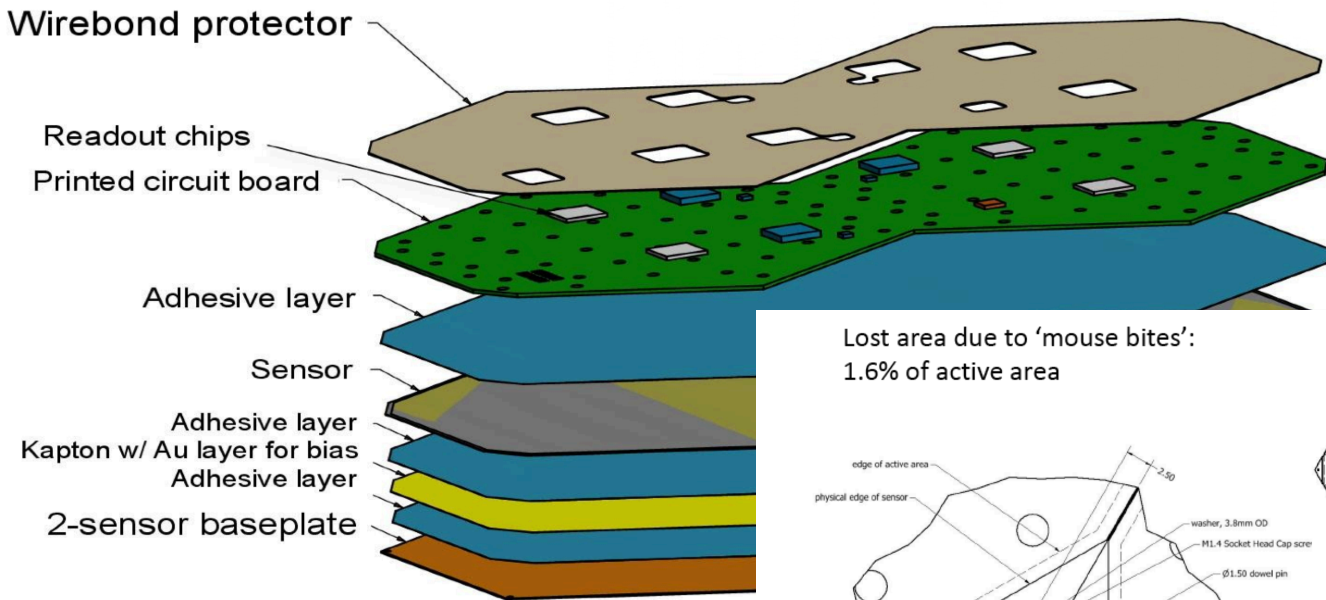
Current Concept 6” wafer
2-sensor backplate



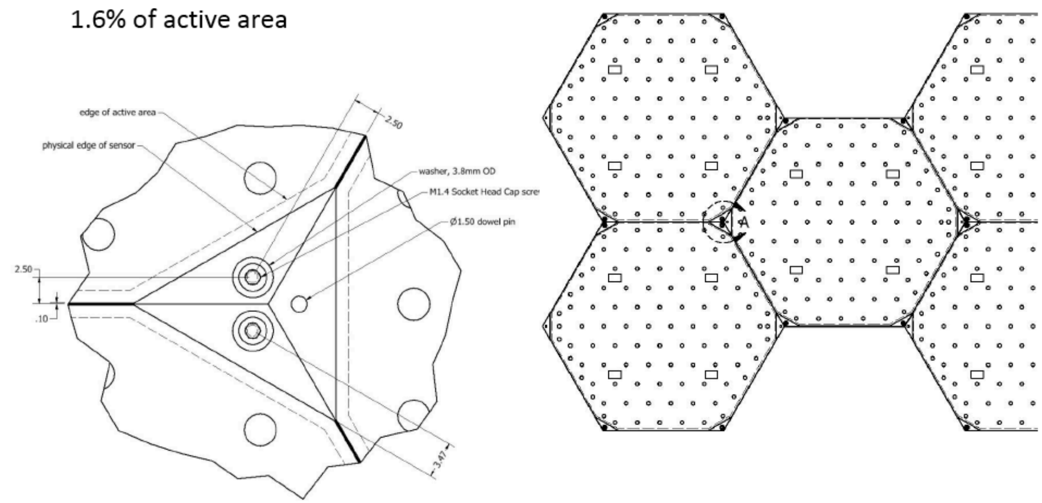




Module Assembly



Lost area due to ‘mouse bites’:
1.6% of active area

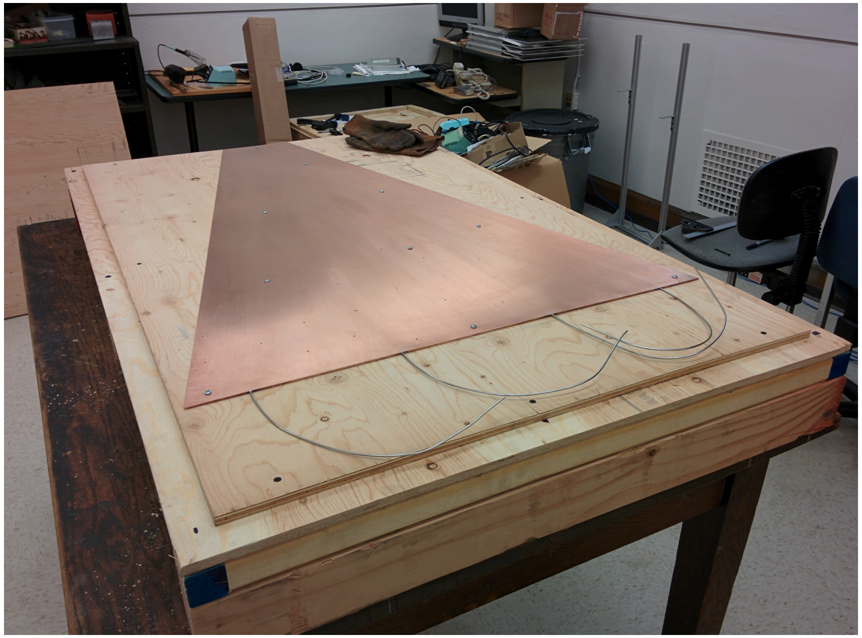


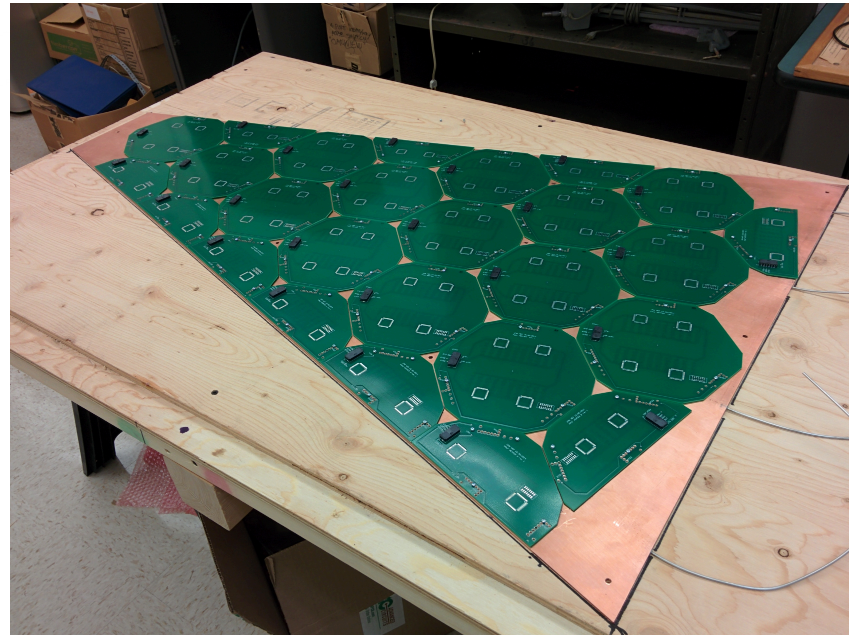
We want to take a first look at how the “module with base plate” can be used for mounting modules on petals, and understand impact on cooling, and thermal expansion issues

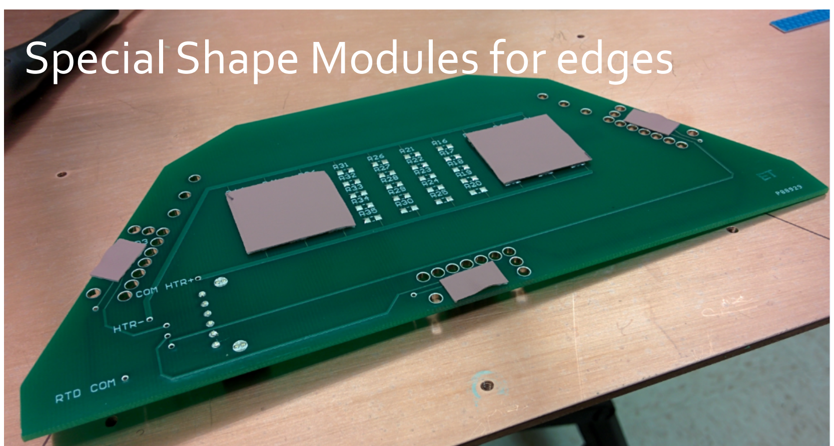
4

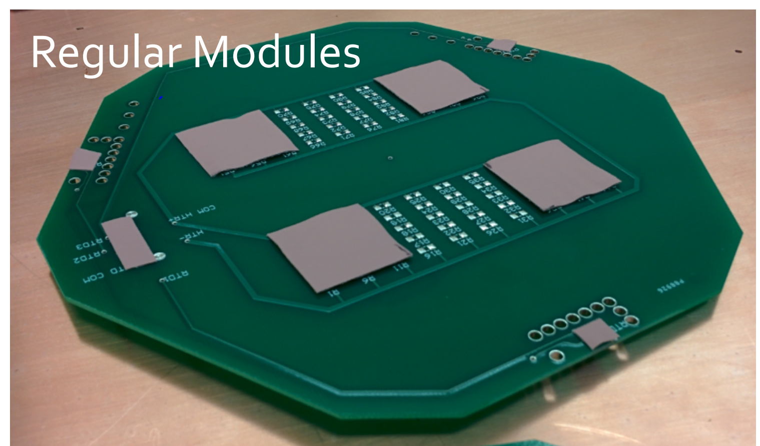
- Modules combine two sensors – ICs placed on PCBs
- Baseline ASIC with Time-over-Threshold and 50ps timing for EM showers

Cassette Assembly



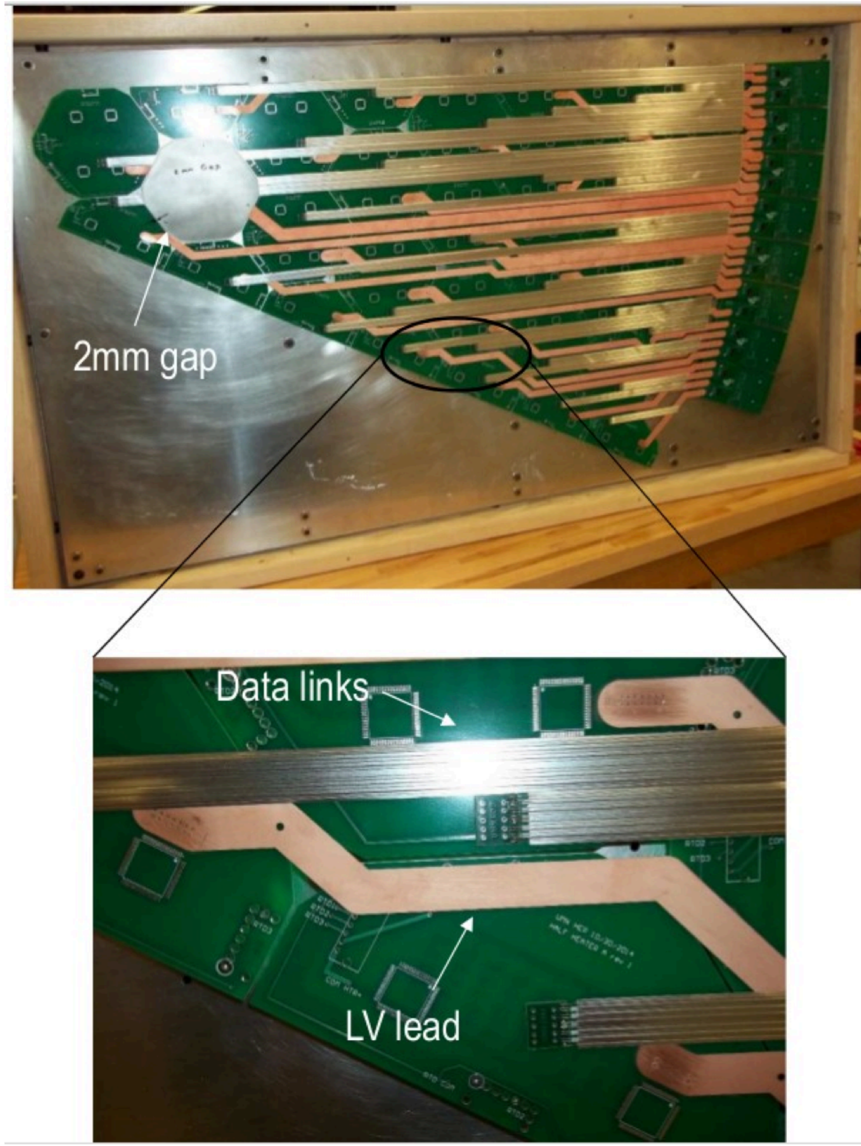


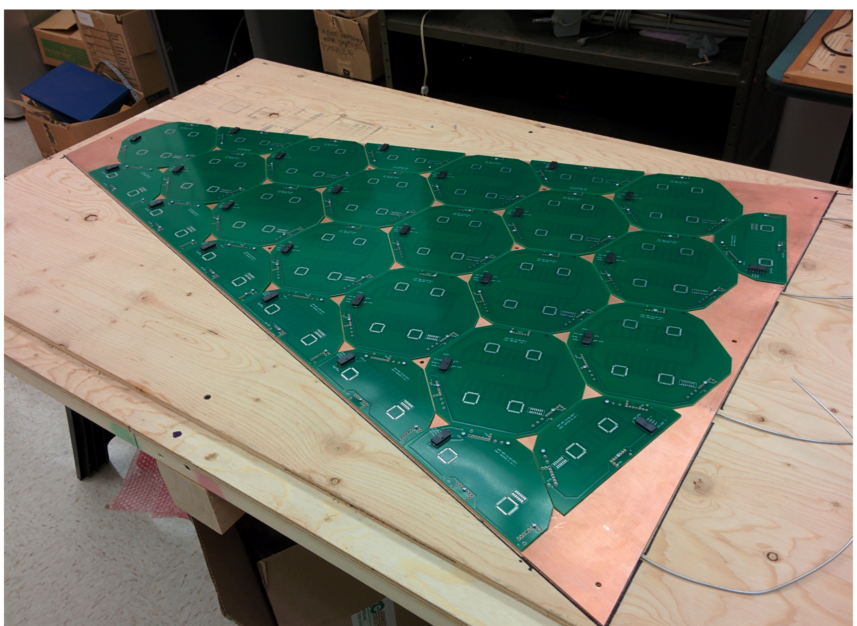




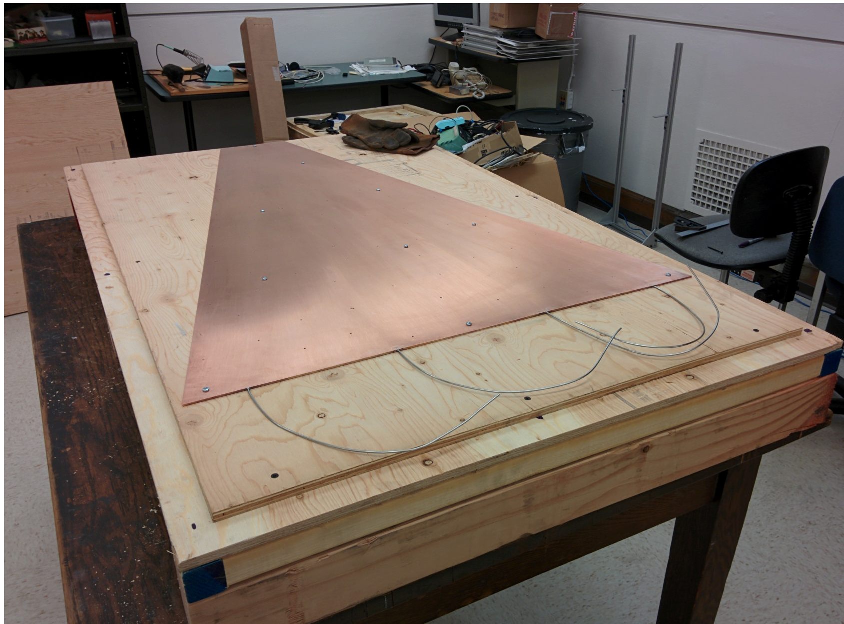
Cassette Mechanics

- Copper plates with integrated CO_2 cooling pipes
- Integrated LV, HV and high speed data readout
- Placed on cassette edge:
  - DC-DC converters, electrical/optical data converters

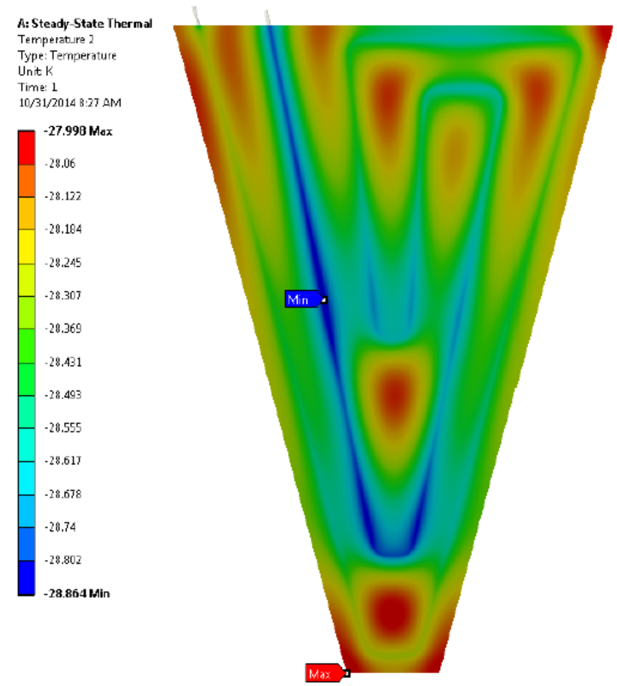




Cassette Thermal Tests



Results of Thermal Model with 250 W/m^2 applied to both sides of plate:

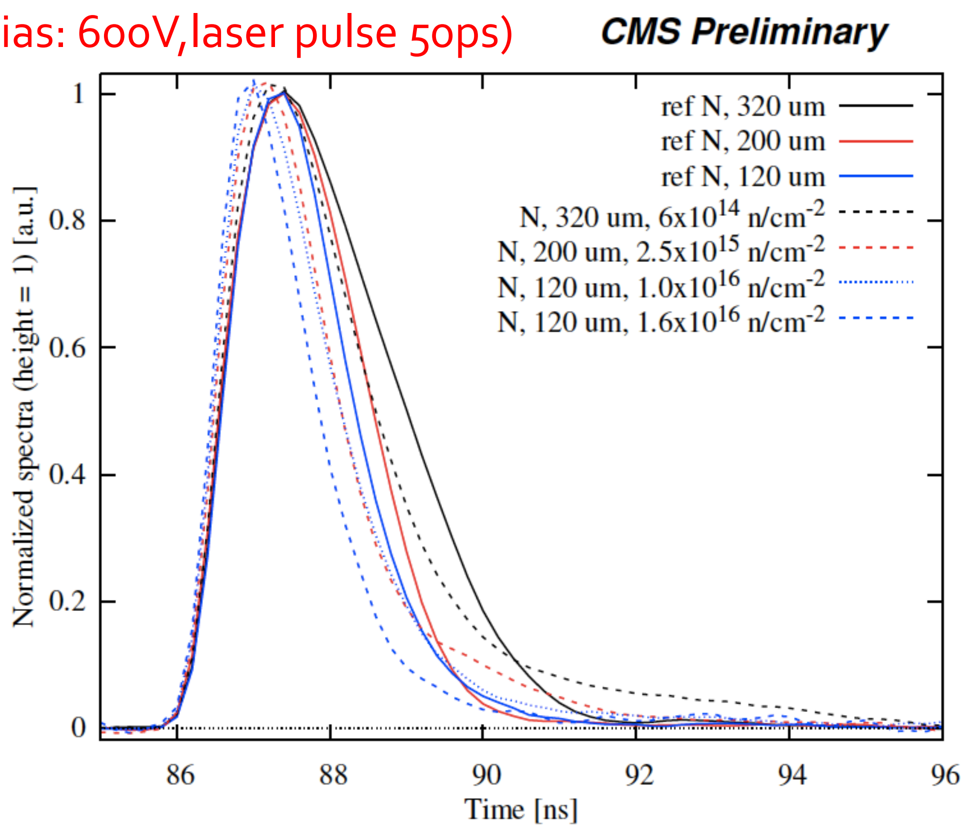


SENSORS

HGC Silicon Sensors

- **Basic sensor characteristics verified with neutron irradiation up to** $1.5*10^{16}$ n/cm² (expected max dose of $1*10^{16}$ n/cm² at 3'000fb^{-1})
  - **Sensor leakage current and charge collection efficiency**

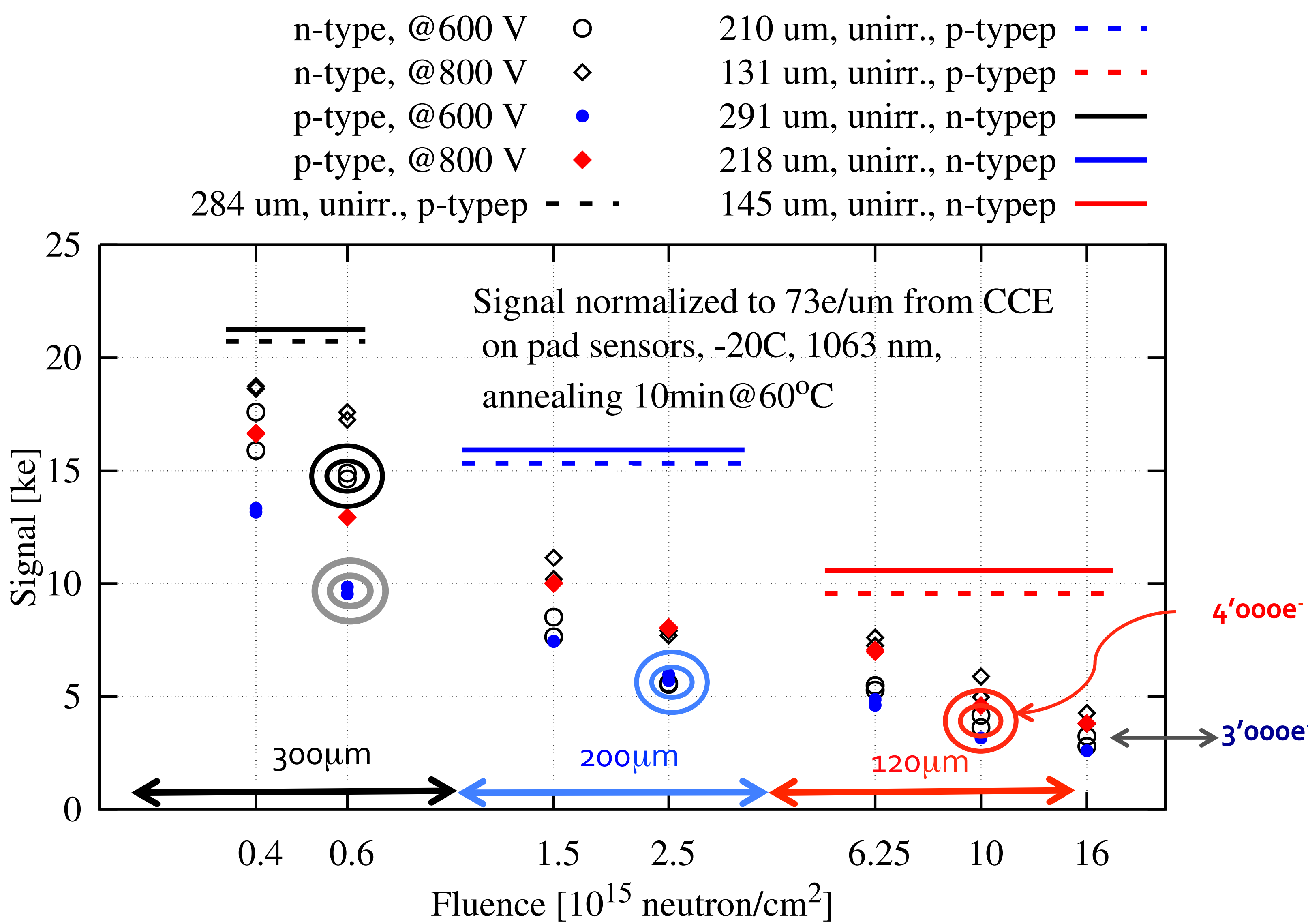
Pulse Shape before/after irradiation
p-in-n diodes;Bias: 600V,laser pulse 50ps)



Shorter rise time and width after irradiation ->relevant for timing

HGC Silicon Sensors

Charge collection efficiency vs neutron fluence



HGC Silicon Sensors

- **Sensor simulations for design optimization advanced**
- **Close collaboration with the CMS Tracker upgrade**

- **HGC sensor prototype submission planned for September 2015**
  - **Includes full size wafer and test structures**

FRONT-END ELECTRONICS

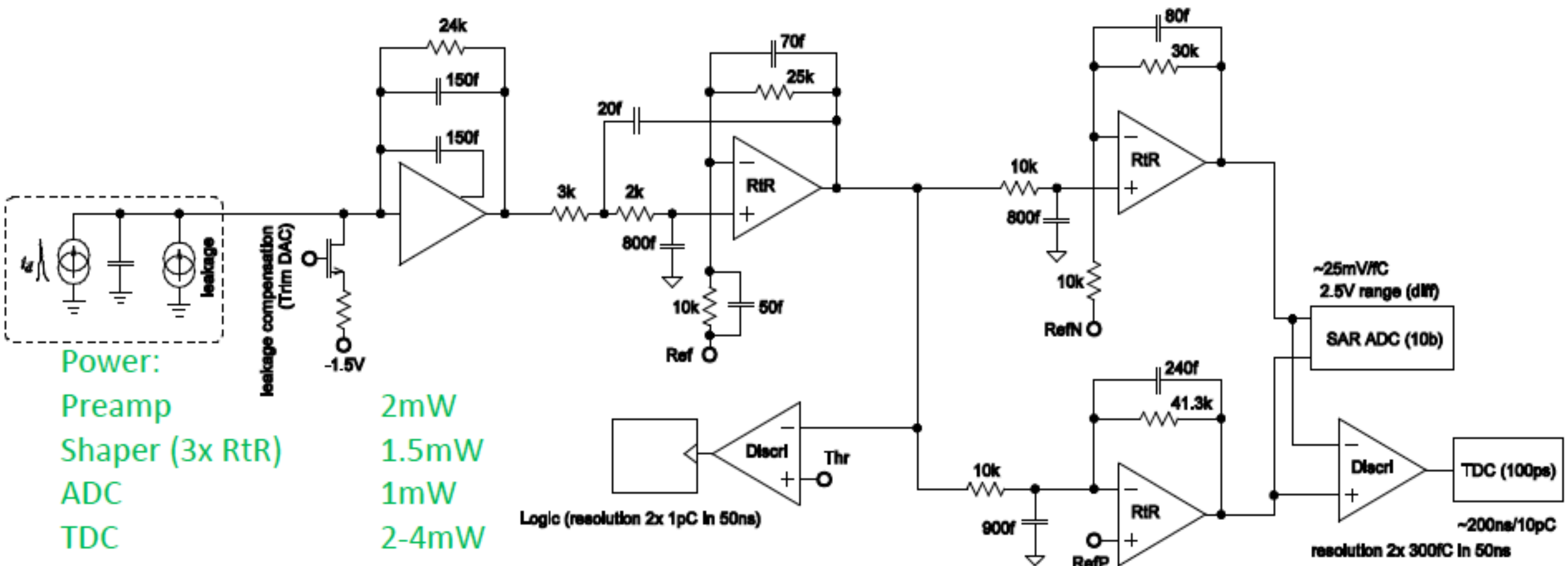
HGC FrontEnd ASIC

- **HGC FE ASIC design which meets the performance requirements developed**
  - Uses Time-over-Threshold scheme to provide low noise (~2000 e-) and to cover full dynamic range (~1:2000Mips)
    - Full SPICE simulation of the analog performance
  - TDC and ADC based on existing designs
  - Possible fast timing for each cell in core of showers with $E_T > 2\sim 3\ GeV$
  - Potential issues related to this design studied
- Simpler backup design exists
  - Lower gain to avoid saturation effects
  - Higher noise (~11000 e-) and lost single MIP sensitivity
    - Requires dedicated channels for MIP calibration
      - Special small sensors on each wafer for redundant tracking of charge collection

HGC ToT FE ASIC Schematic of one channel

Initial studies by Jan Kaplon (CERN)

- Input stage: cascode with PMOS input transistor with resistive feedback (~1V linear range at the output for signals from p^+ on n^- detectors), 2mW @ 1.5V
- Leakage compensation with Trim DAC – current sink strongly degenerated – contribution to the noise negligible (automatic control of the DAC - state machine)
- Shaper : DC coupled, Sallen-Key low pass filter built with RtR amplifier, 3x400uW, 2x 10pF driving capability, Tpeak=20ns (15ns after first stage for double pulse resolution logic)
- TDC for measurement of TOT for signals above 60fC (up to 10pC), 3.6mW/channel (*) for 100ps bin
- 10 bit ADC for measurement of pulses up to 100fC, 1mW/channel (**)



Power:

Preamp	2mW
Shaper (3x RtR)	1.5mW
ADC	1mW
TDC	2-4mW (200-100ps)

(*) 3.6mW for one channel of TDC in TDCPix (NA62), 320MHz coarse clock, 100ps bin from DLL, 2012 JINST 7 C01065
(**) communications with Krakow AGH UST group

Digital Signal Processing/Compression: 20mW

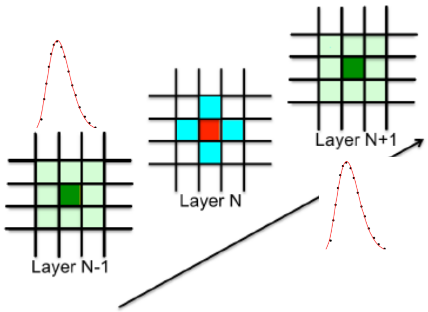
Prototype Chip by Christophe de la Taille (Ecole Polytechnique) based on SKIROC chip

Noise < 2000 e
Good for mip calibration
6.5 – 8.5 mW/ch

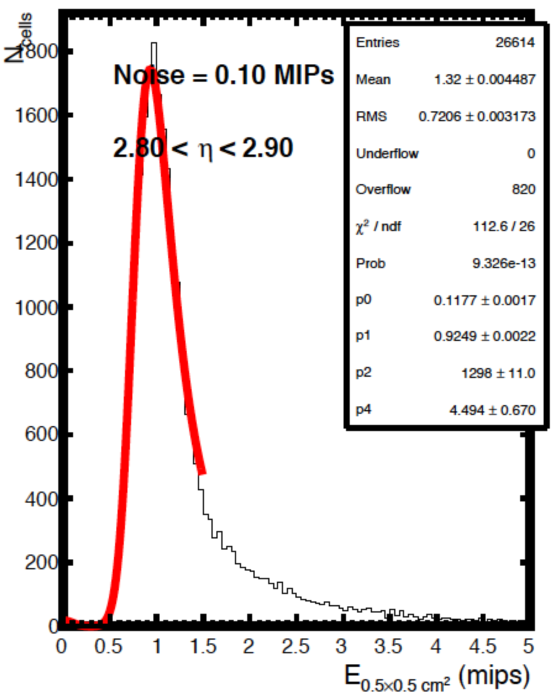
HGC FE ASIC MIP calibration

- **Method for calibration with MIP over full acceptance and detector lifetime developed**
  - **HGC tracking capability allows for isolation of clean MIP signal with S/N=2 for calibration of charge collection**
  - **Dedicated low noise cells provide local calibration with S/N>5**
    - **Used to study the systematics using the same electronics as standard cells**
- **In the backup design MIP calibration requires dedicated high gain amplifier**

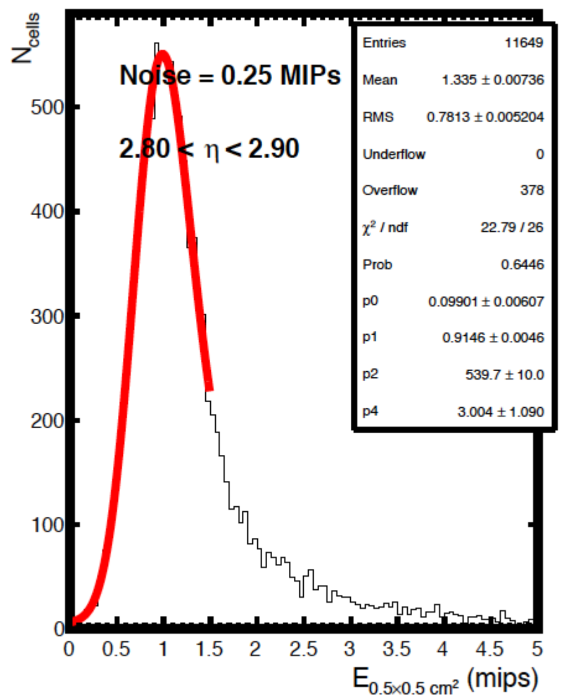
MIP Calibration with S/N -> 2



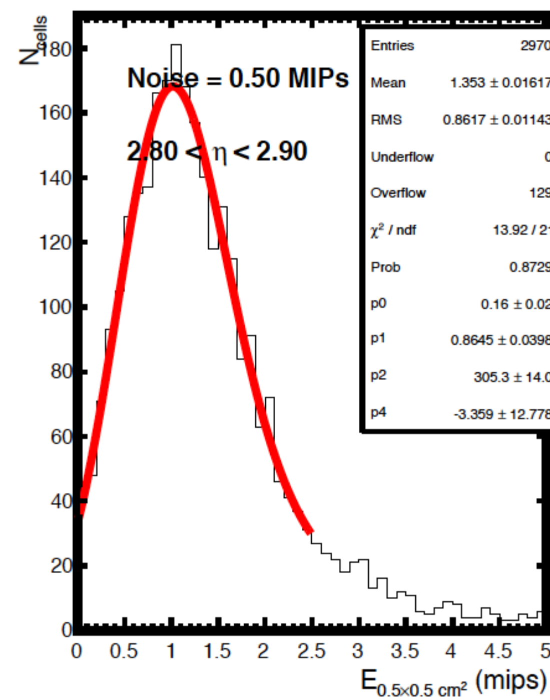
Require isolated MIP signal in previous 2 and following 2 layers
$\Rightarrow$ Achieve very clean MIP signal with local tracking in HGC:
Results below are for $2.8 < \eta < 2.9$ at 200PU



S/N = 10



S/N = 4



S/N = 2

HGC Data Rates

Data coding – with header and error detection

- For each bunch crossing each module starts the event record with
  - BCID (local BX ID) – 12 bits 0 1 0 1 0 1 0 1 0 1 0 1
  - EVID (local event ID) – 12 bits 0 1 0 1 0 1 0 1 0 1 0 1
  - Event record lenght – 12 bits 0 1 0 1 0 1 0 1 0 1 0 1
- At the end of event record
  - Error detection – 32 bits 0 1 0 1 0 1 0 1 0 1 0 1 … 0 1 0 1 0 1 0 1 0 1 0 1
  - We could f.g. use Cyclic Redudancy Check
- Therefore the event record for each module is

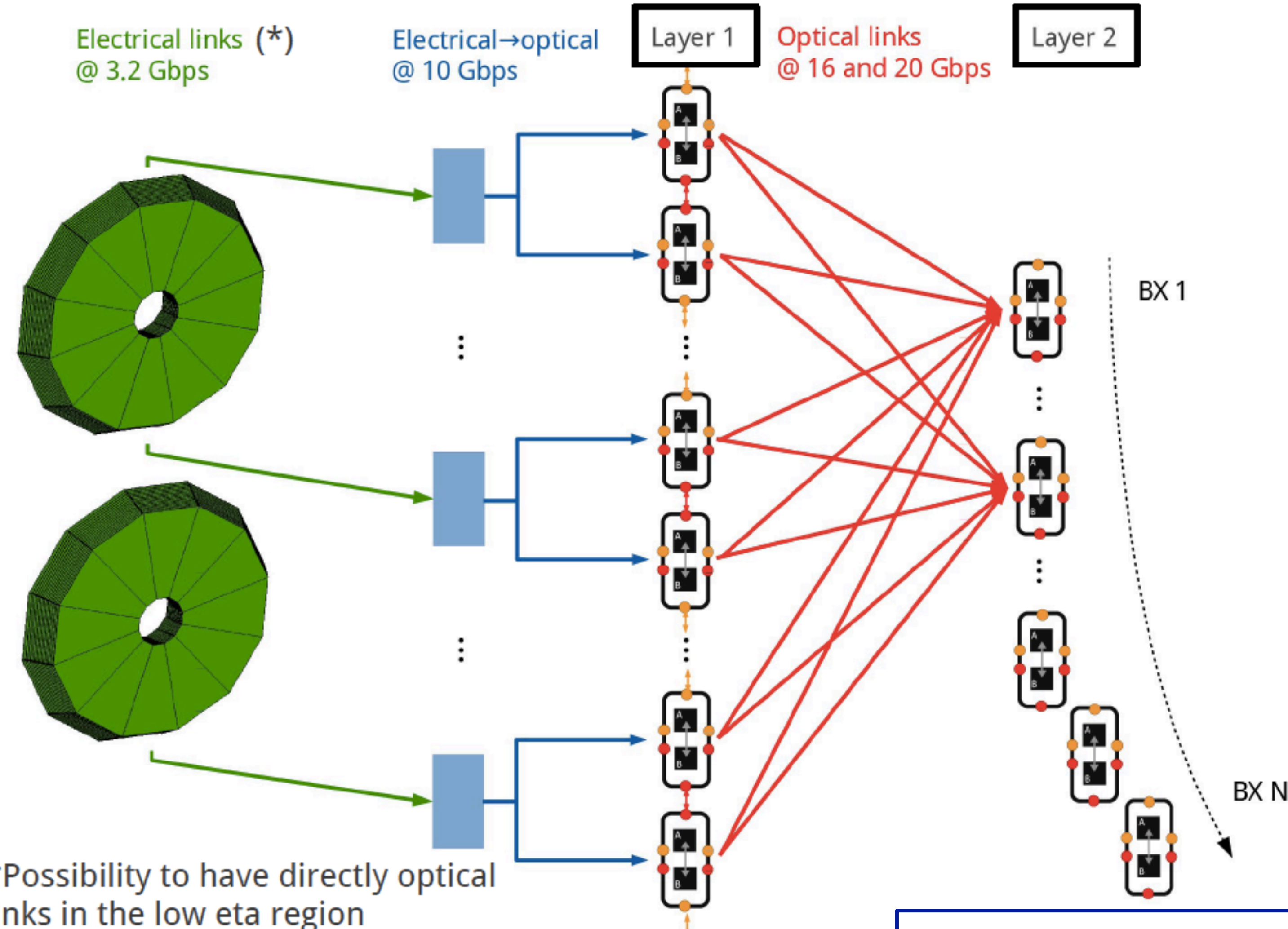
η range	Average data bits/module
1.5 < |η| < 2.0	445
2.0 < |η| < 2.5	862
2.5 < |η| < 3.0	2453

η range	Total bits	Data rate (Gbps)
1.5 < |η| < 2.0	513	**0.51**
2.0 < |η| < 2.5	930	**0.93**
2.5 < |η| < 3.0	2521	**2.52**

Data rates at 200 PU safely below 3.28 Gbps available bandwidth

Level-1 Architecture

Design based on existing or near-existing technology
Similar architecture as Phase I Level1 Calorimeter Trigger

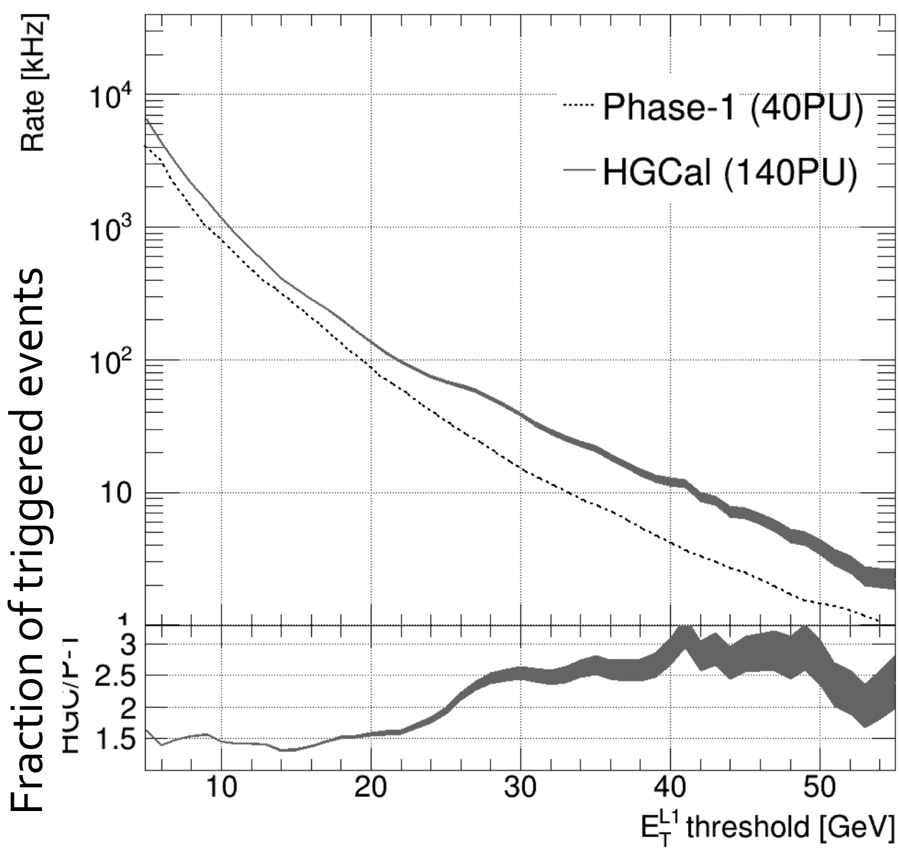


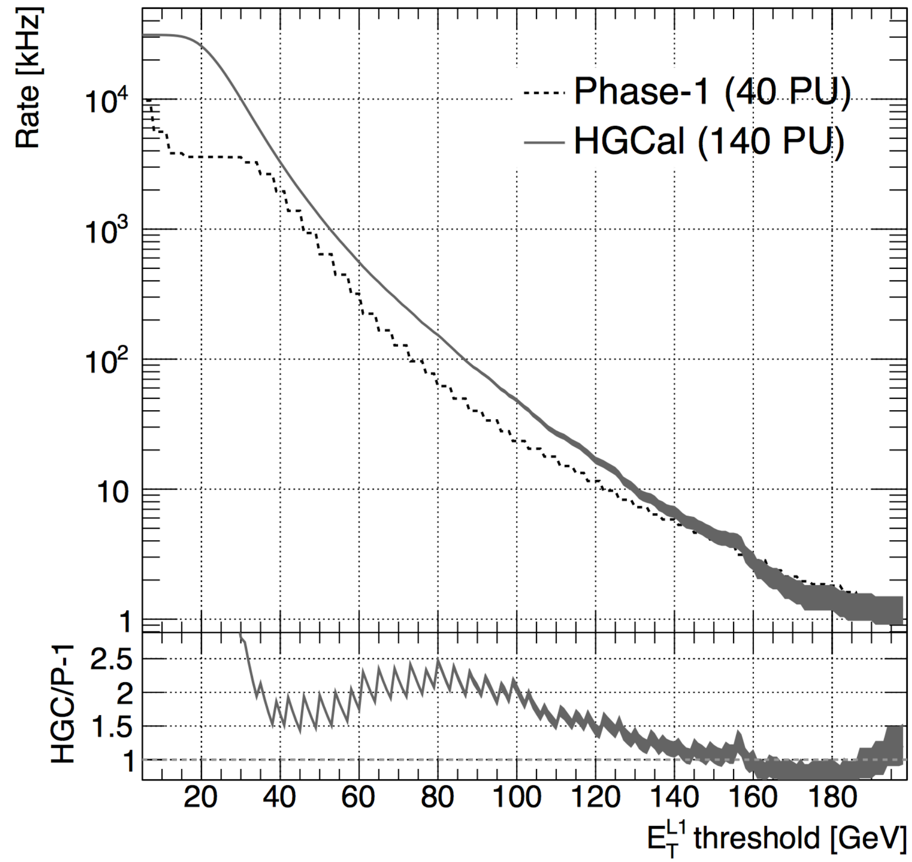
*Possibility to have directly optical links in the low eta region

Jean-Baptiste Sauvan

Level-1 Trigger: e/γ & jet Rates

Comparing Phase 1 and HL-LHC e/γ and jet L1- trigger rates

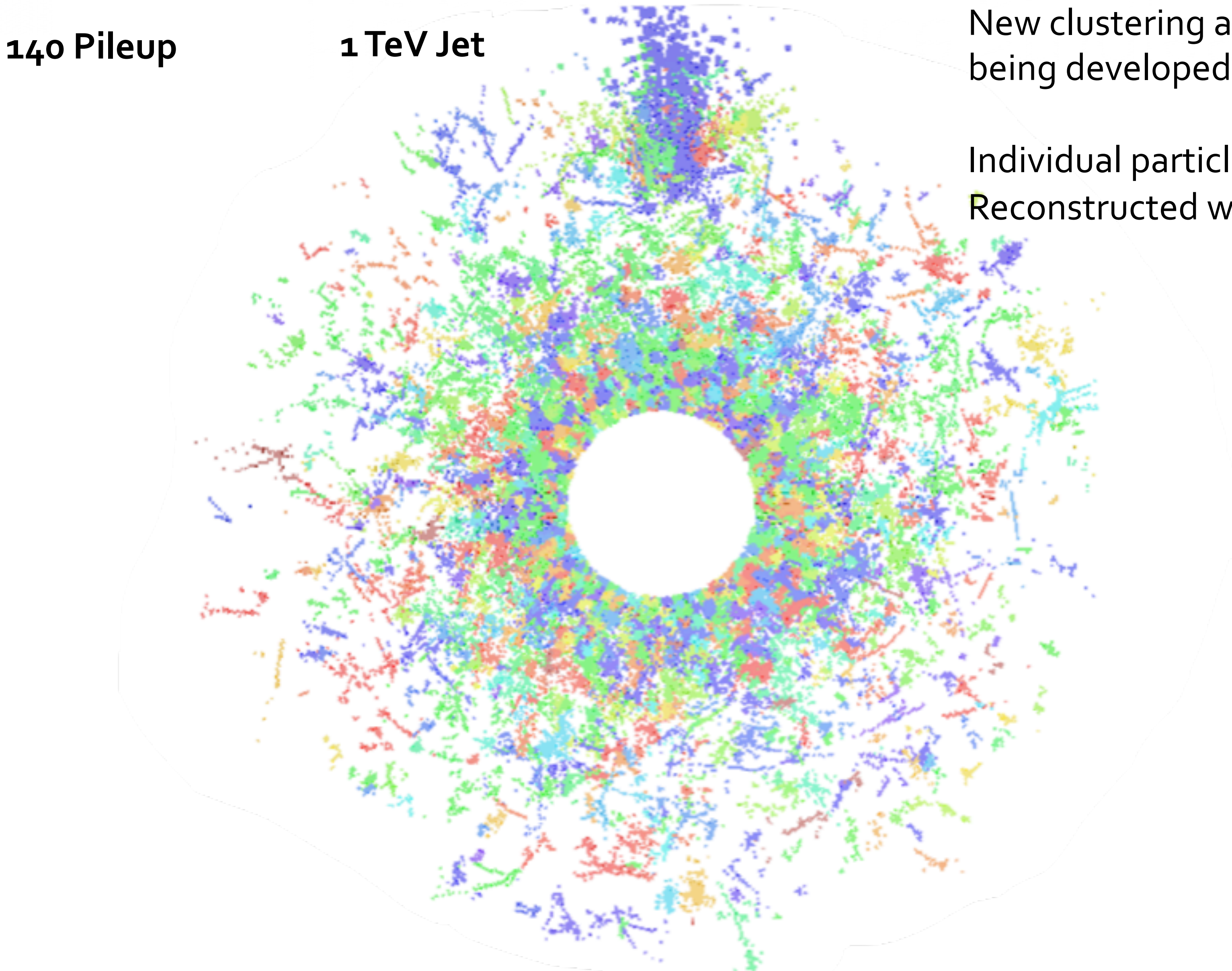




Use of longitudinal information yields a rate reduction of ~ factor 1.7
for an efficiency loss of 1-2%
HGC L1 rates twice the Phase 1 EC while instantaneous lumi is 3.5 higher

SIMULATION: RECONSTRUCTION AND PERFORMANCE

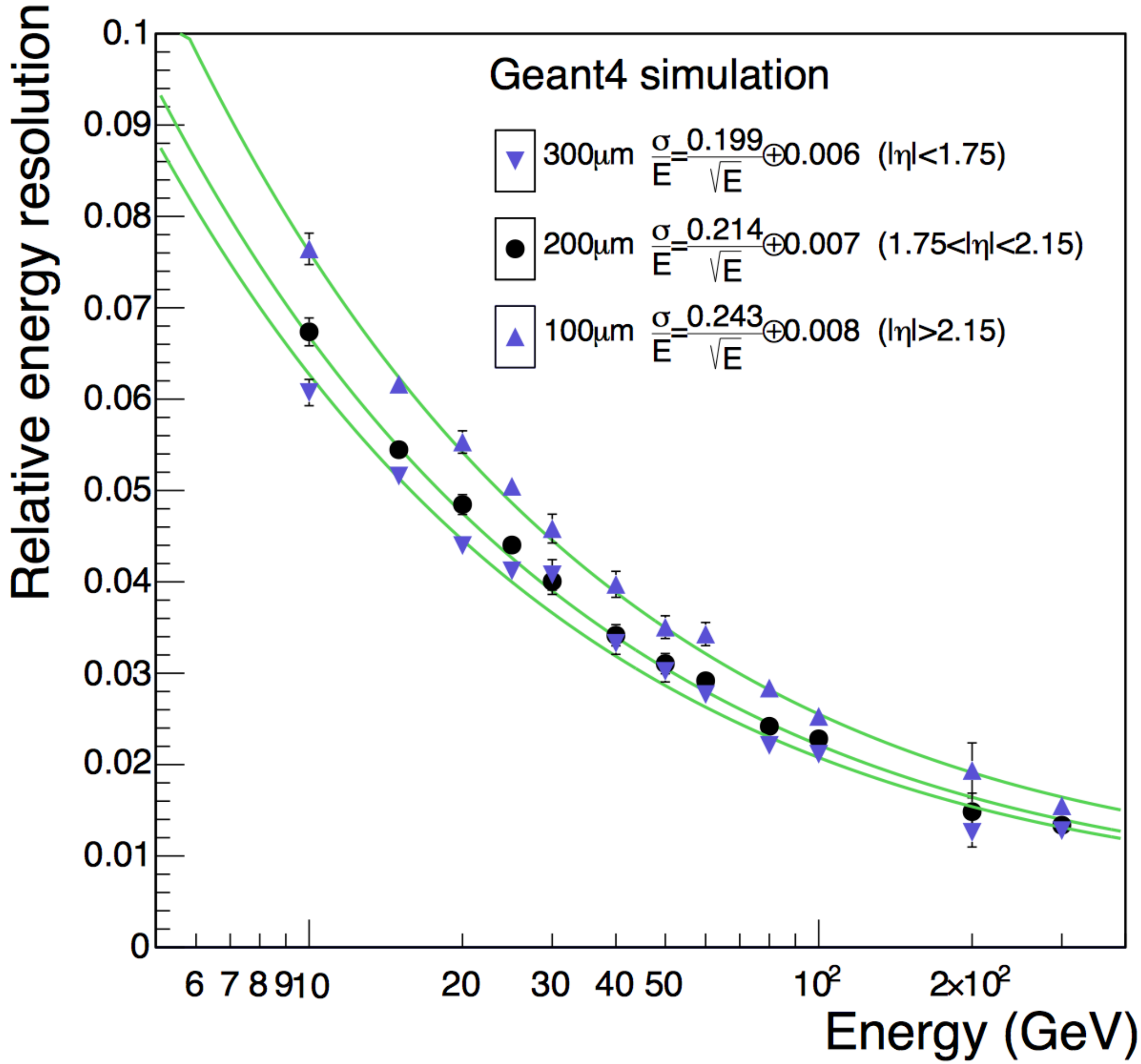
HGC Performance Studies



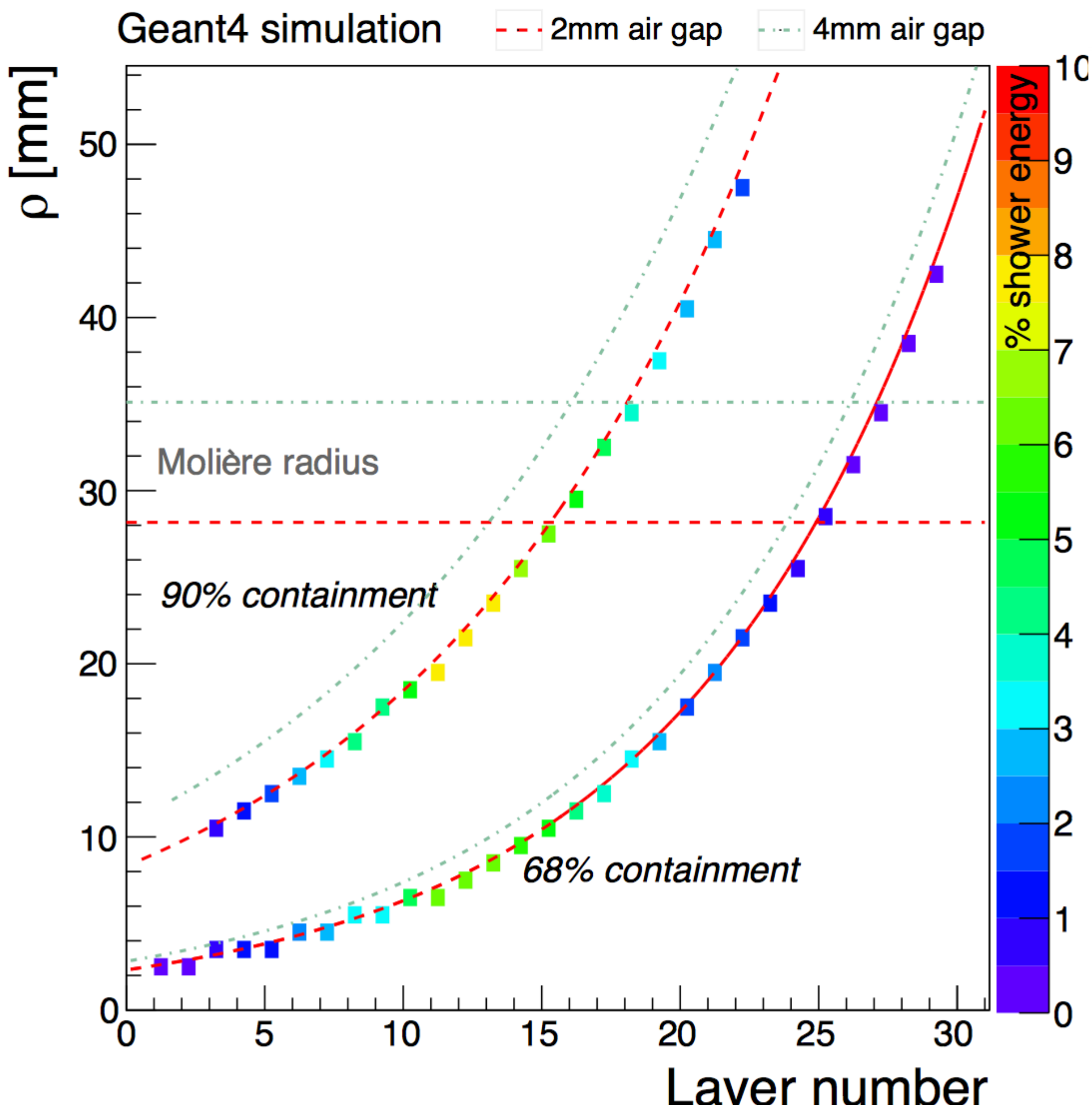
New clustering algorithms being developed

Individual particles Reconstructed with CMS PF

HGCal EM Performance Studies



HGCal EM Performance Studies

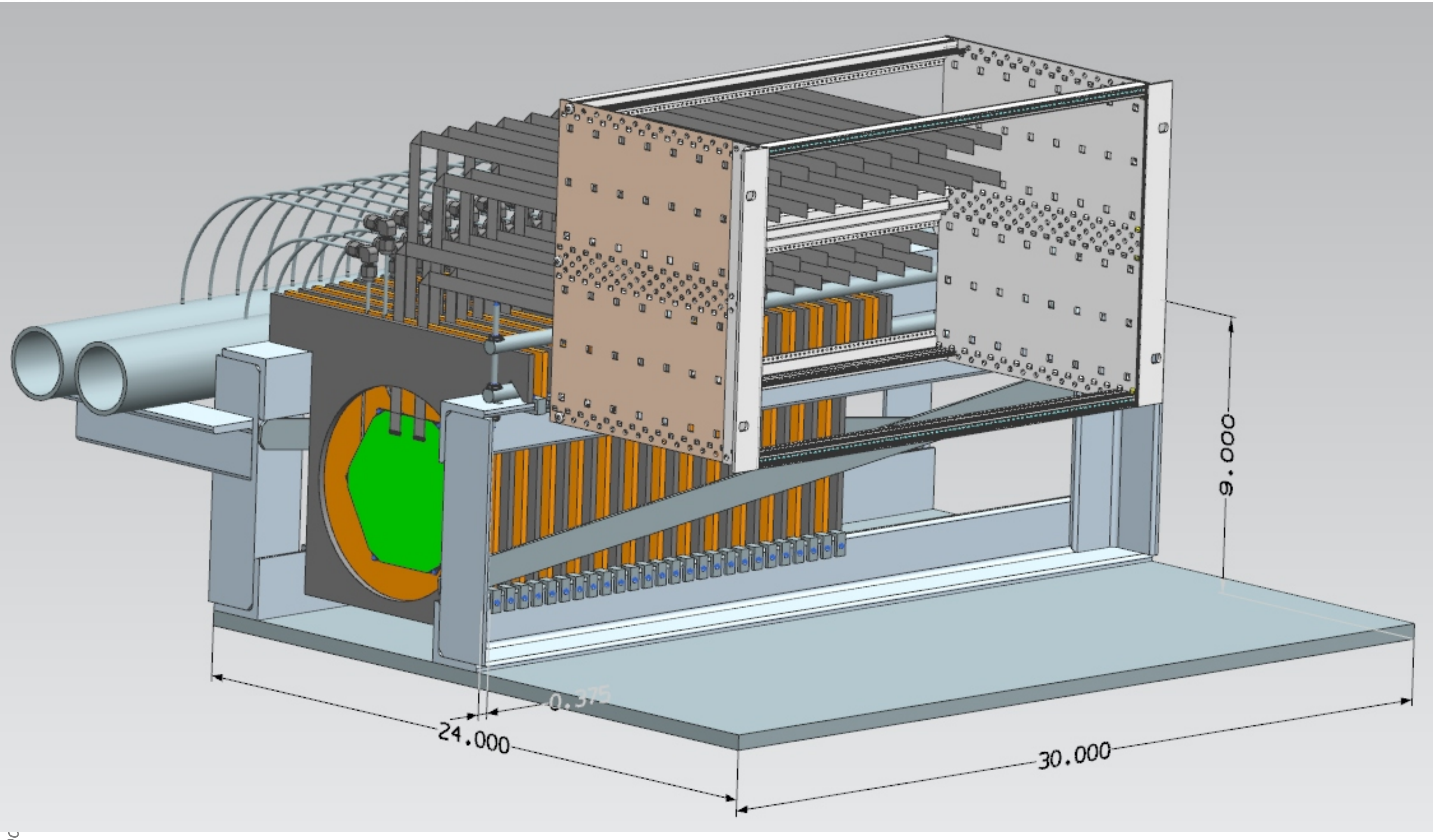


Current Activities

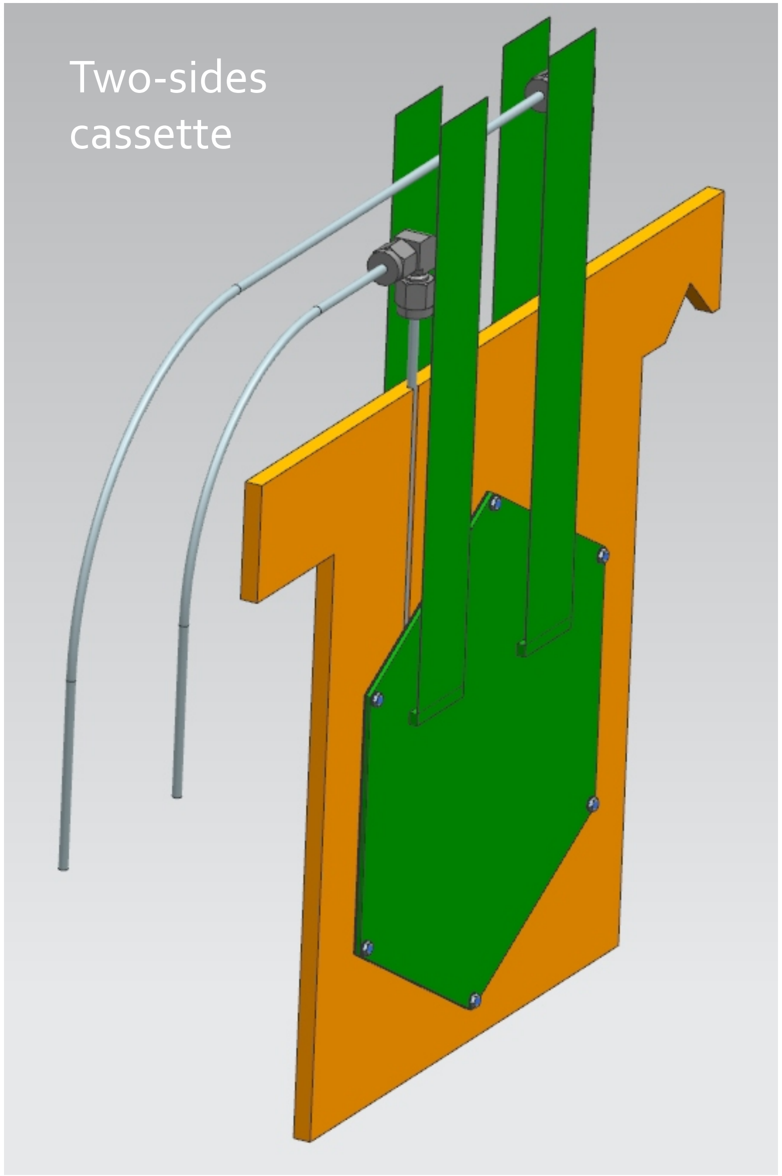
- R&D for silicon calorimeters studied by the CALICE collaboration, SID and others in the ILC context
- Basic understanding of the performance established
- Many results have already been presented

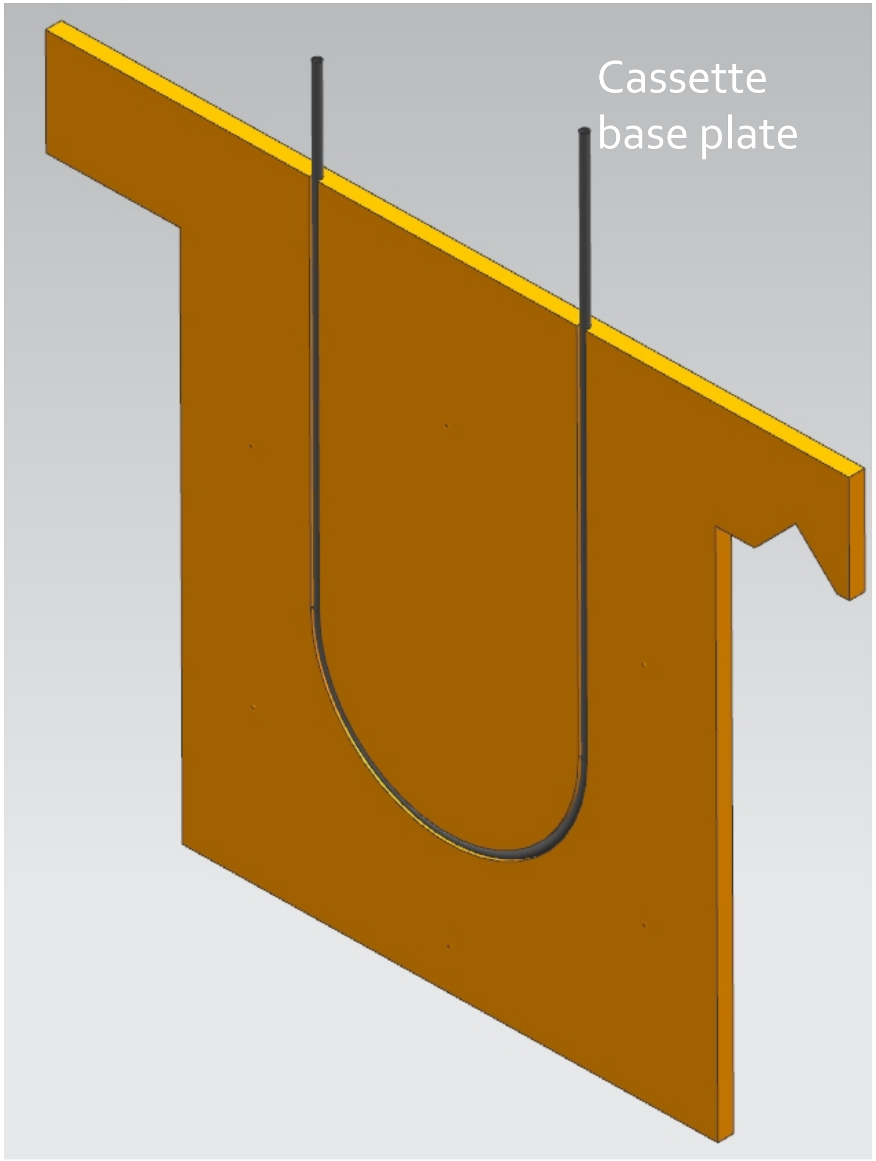
- For the CMS Phase 2 upgrades the specific aspects of the Hl-LHC environment need to be addressed
  - Radiation damage effects ; 25ns pulse structure, high rate readout; reconstruction in presence of high pile-up
- Component prototyping has started to address in the test beams the performance:
  - Sensors ; Modules; Readout chip -SKIROC2 CMS
  - Services (power, cooling)

Testbeam Prototype



Testbeam Prototype





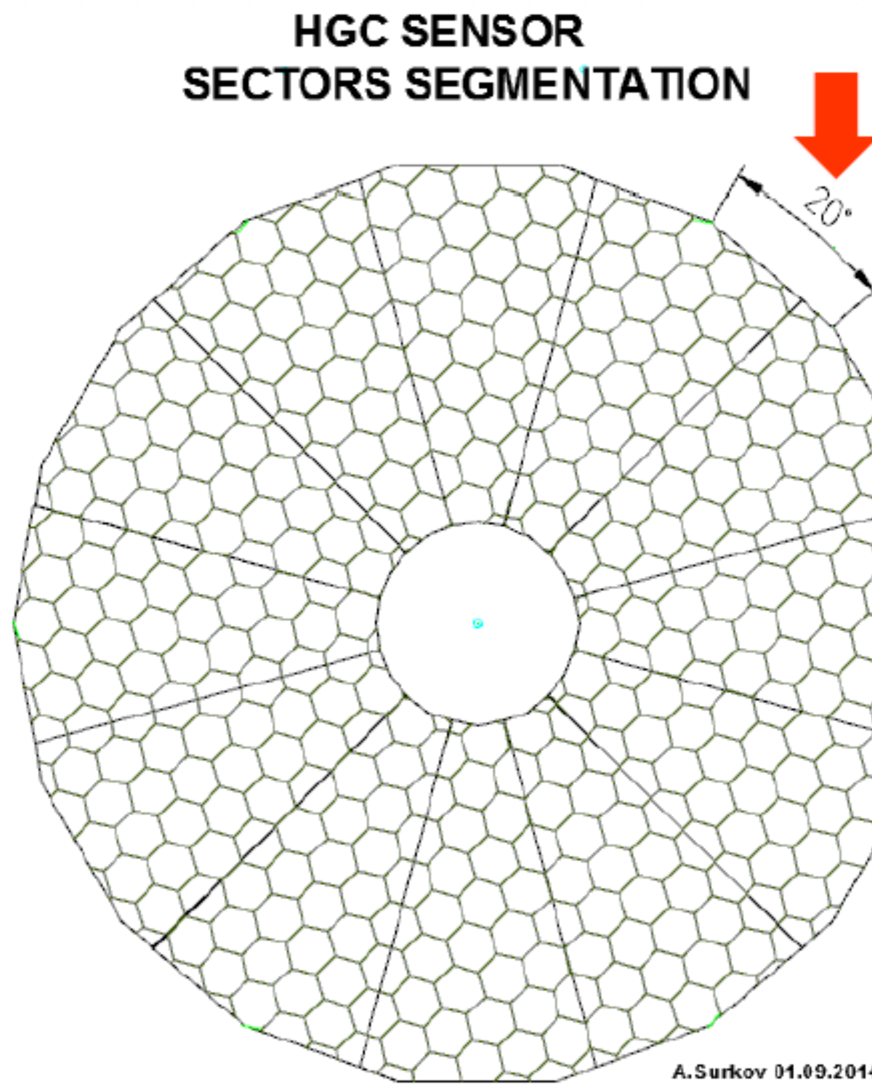
Summary

- Over the past year, the HGC project has progressed from an idea to a viable conceptual design
- Technologies exist to produce sufficiently radiation hard versions of all critical components of the HGC
-
- Technical Proposal with detailed description: https://cds.cern.ch/record/2020886/files/LHCC-P-008.pdf

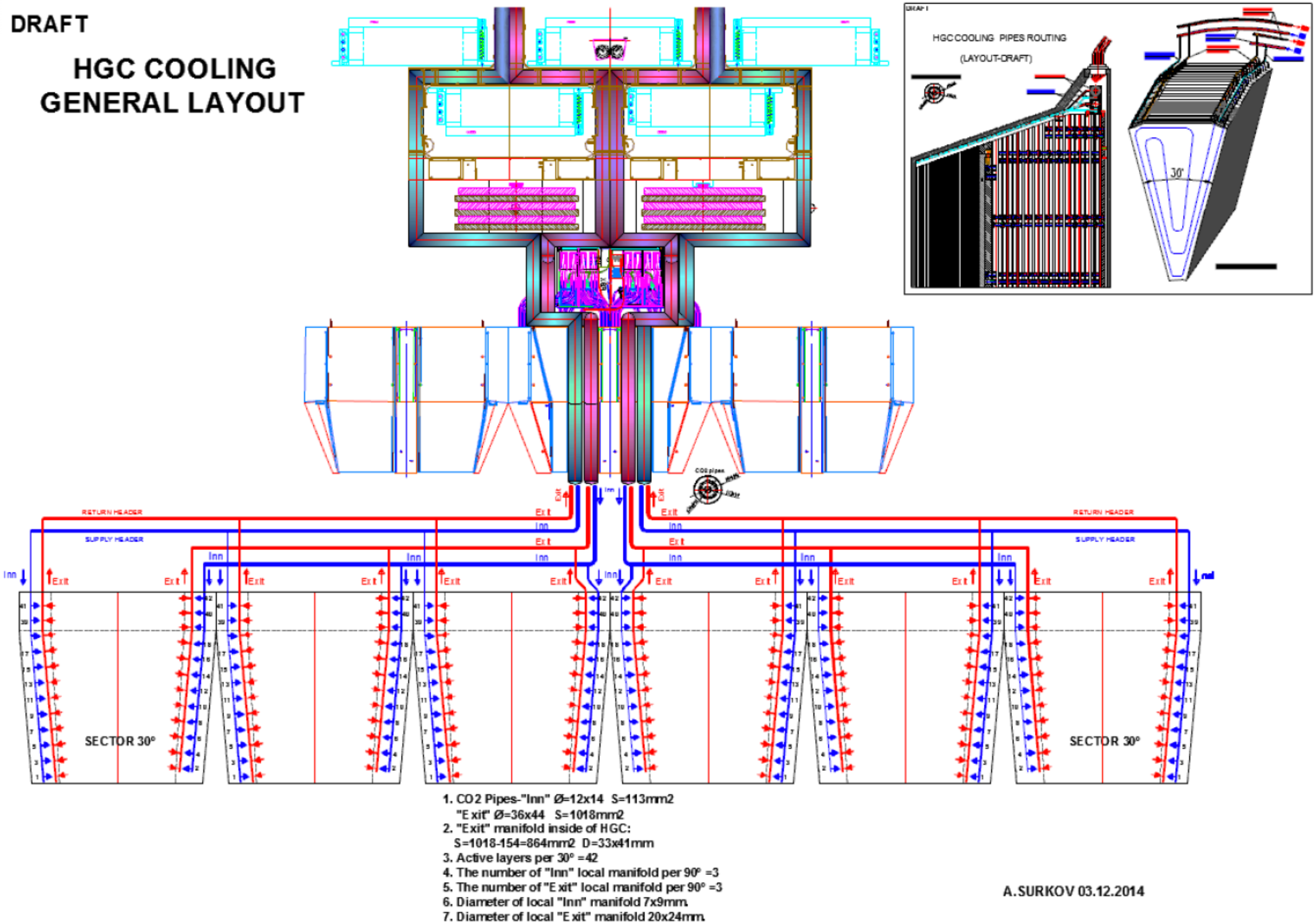
BACKUP

HGCal Mechanics

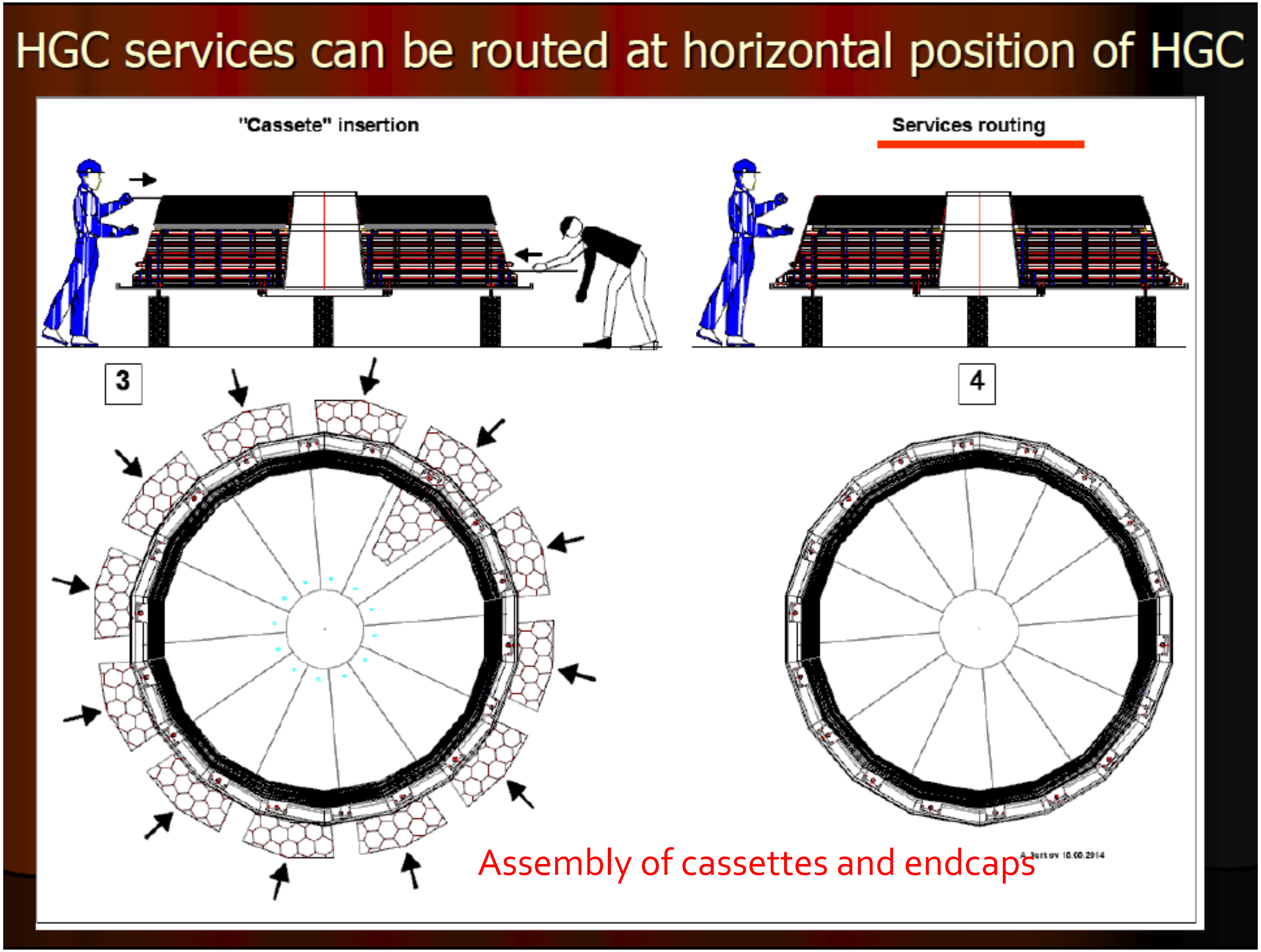
Sum



Example of Services: Cooling Channels

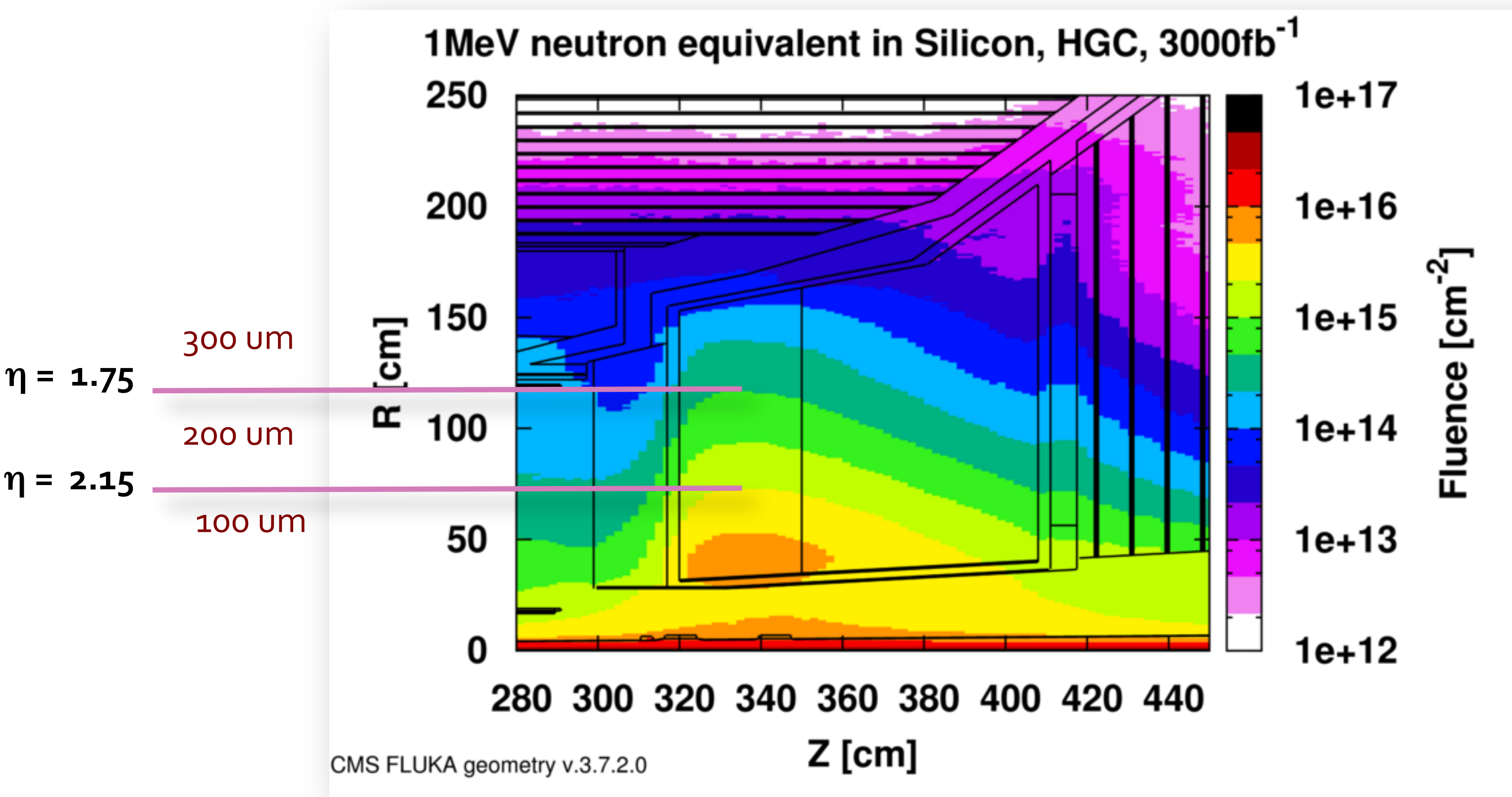


Assembly

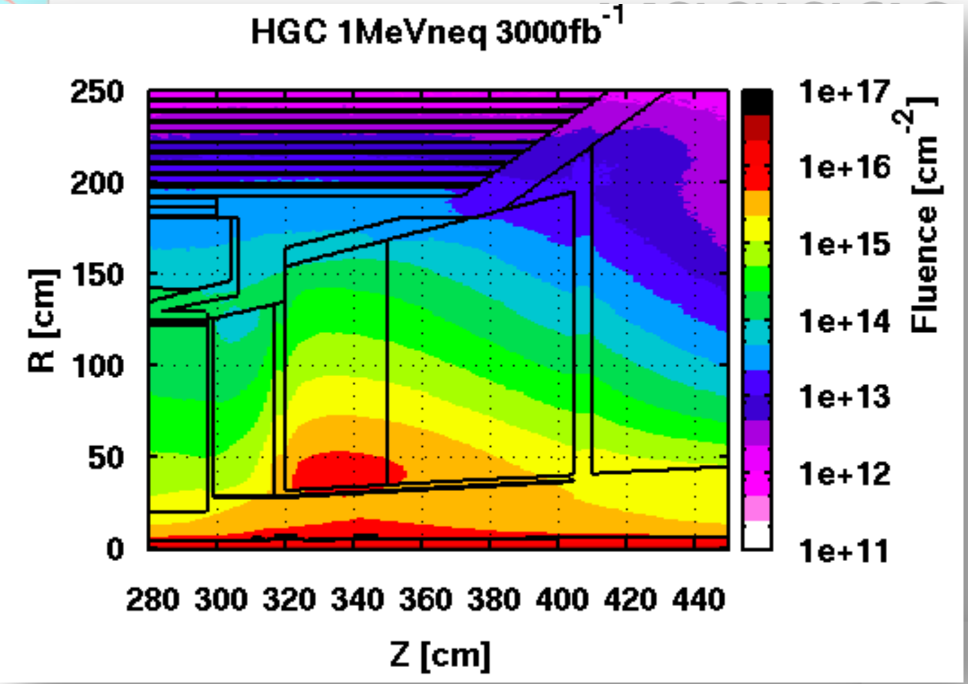

HGC services can be routed at horizontal position of HGC
"Cassete" insertion
Services routing
3
4
Assembly of cassettes and endcaps

Radiation Environment

Thickness	300 μm	200 μm	100 μm
Maximum n fluence (cm^{-2})	6×10^{14}	2.5×10^{15}	1×10^{16}
Maximum dose (Mrad)	3	20	100
E-HG region	$1.48 < \lvert\eta\rvert < 1.75$	$1.75 < \lvert\eta\rvert < 2.15$	$2.15 < \lvert\eta\rvert < 3.0$
H-HG region	$R > 860$ mm	$R < 860$ mm	–
Cell size (cm^2)	1.05	1.05	0.53
Cell capacitance (pF)	33	50	50
S/N after 3000 fb^{-1}	9.6	4.9	2.4
Si wafer area (m^2)	323	161	117



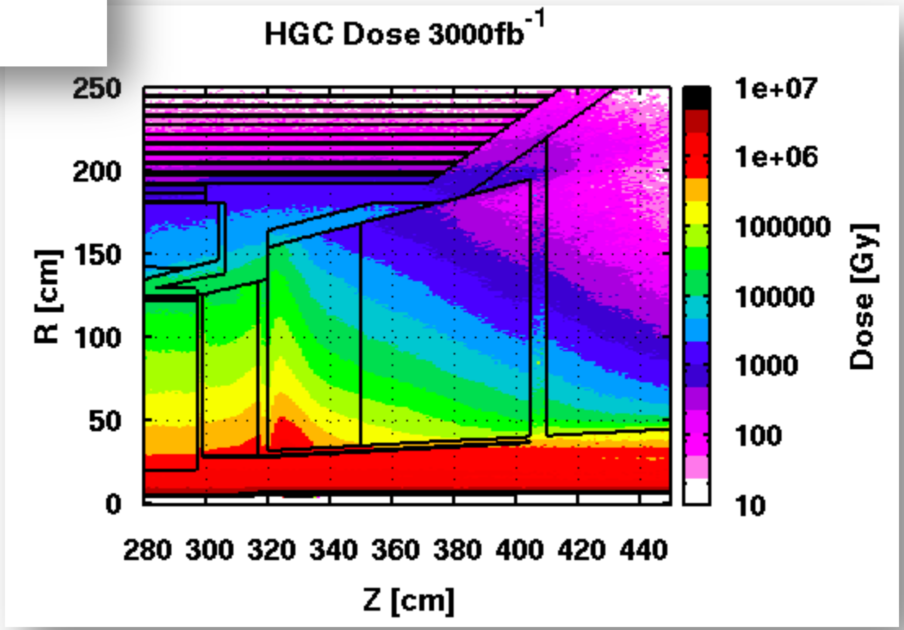
Radiation Maps



3000 fb^{-1}

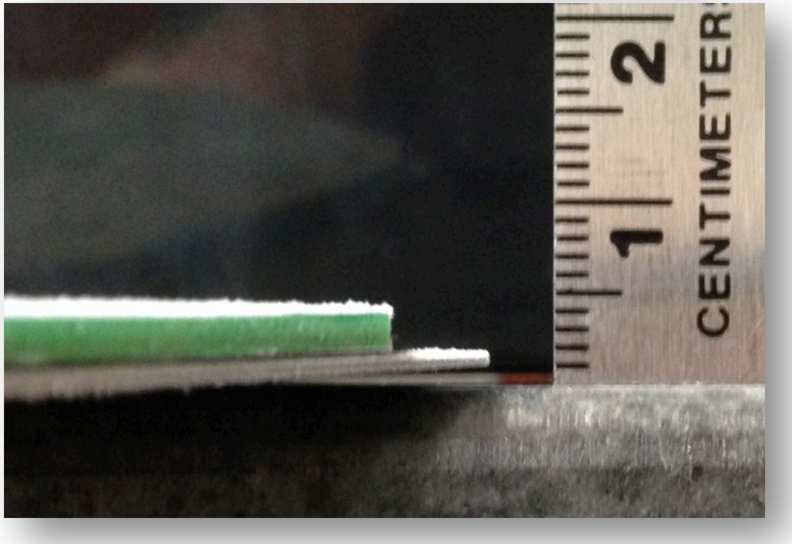
Dose< 100 Mrad

n Fluence < 10^{16} /cm²



HGC Module Stress & Deformations

- Cooled from +23C down to -41C (-30C is nominal so this is a slightly extreme test)
  - Modules screwed/pinned as for petal installation.
  - Check distortion via a capacitance measurement between backplate and Cu cooling plate
  - Release screws and pins to see distortion of 'cold' module.

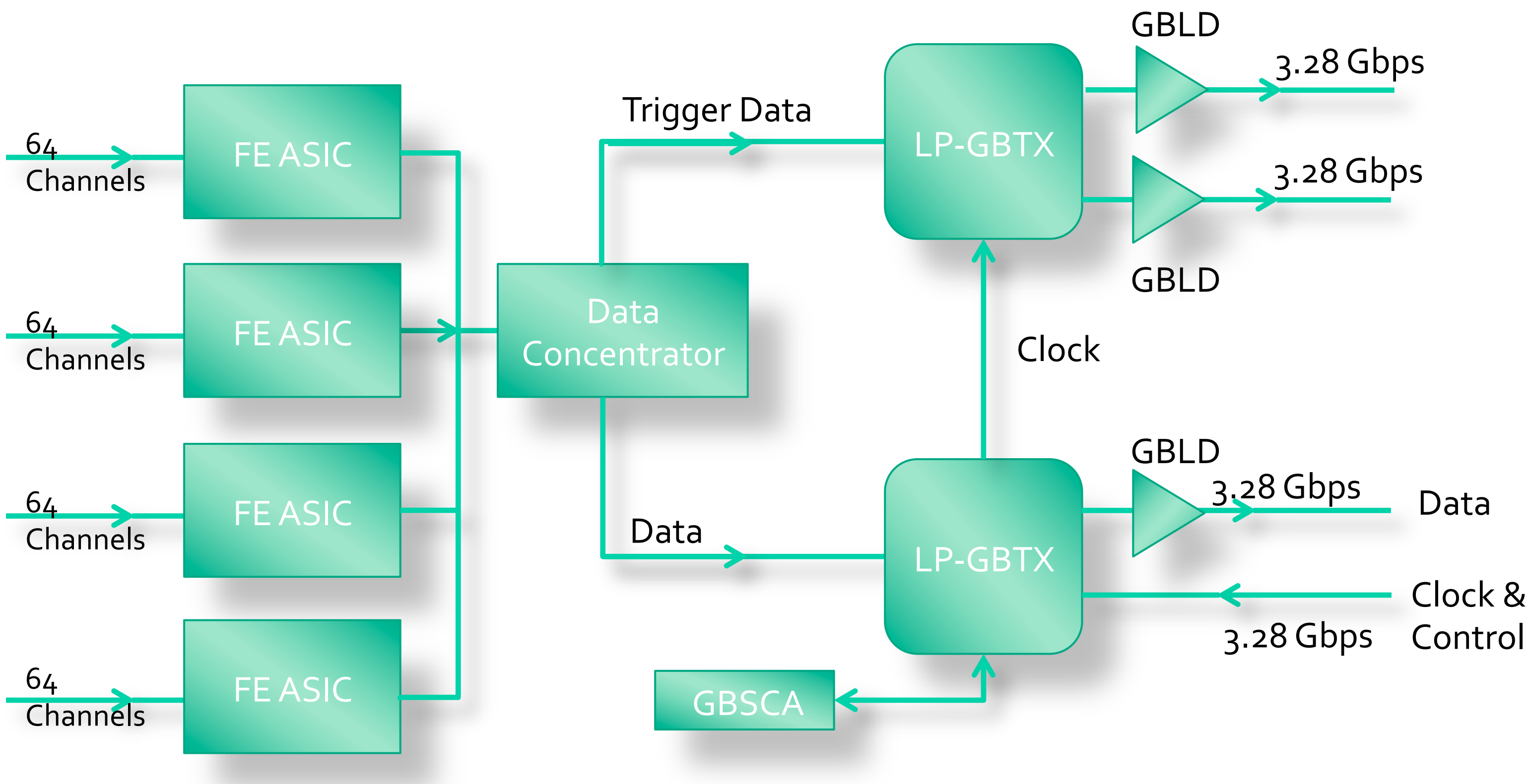


- Findings for 75W/25Cu back-plate.
  - Distortion of dismounted module:
    - Max. deflection = 0.8 mm using precision shims
      - See figure at left
    - Distortion is convex
      - Center of module wants to push ***into*** the Cu base plate as desired
  - Distortion → Stress in sensor

    ⇒ **Stress in the silicon is ~6 MPa.**
    - The Ultimate Tensile Strength of silicon is 7GPa
      - Safety factor > 1000 for breakage
      - Identified a thermally conductive epoxy that is fairly elastic even when cold that could further diminish stress risks. Need to rad-test.
    - Impact on performance?
      - Stress in sensors in CDF ISL, CMS TIB goes as high as 20 MPa (F. Raffaelli, INFN-Pisa)
      - No problems reported for CDF ISL (>10 years of operation) ditto for CMS TIB

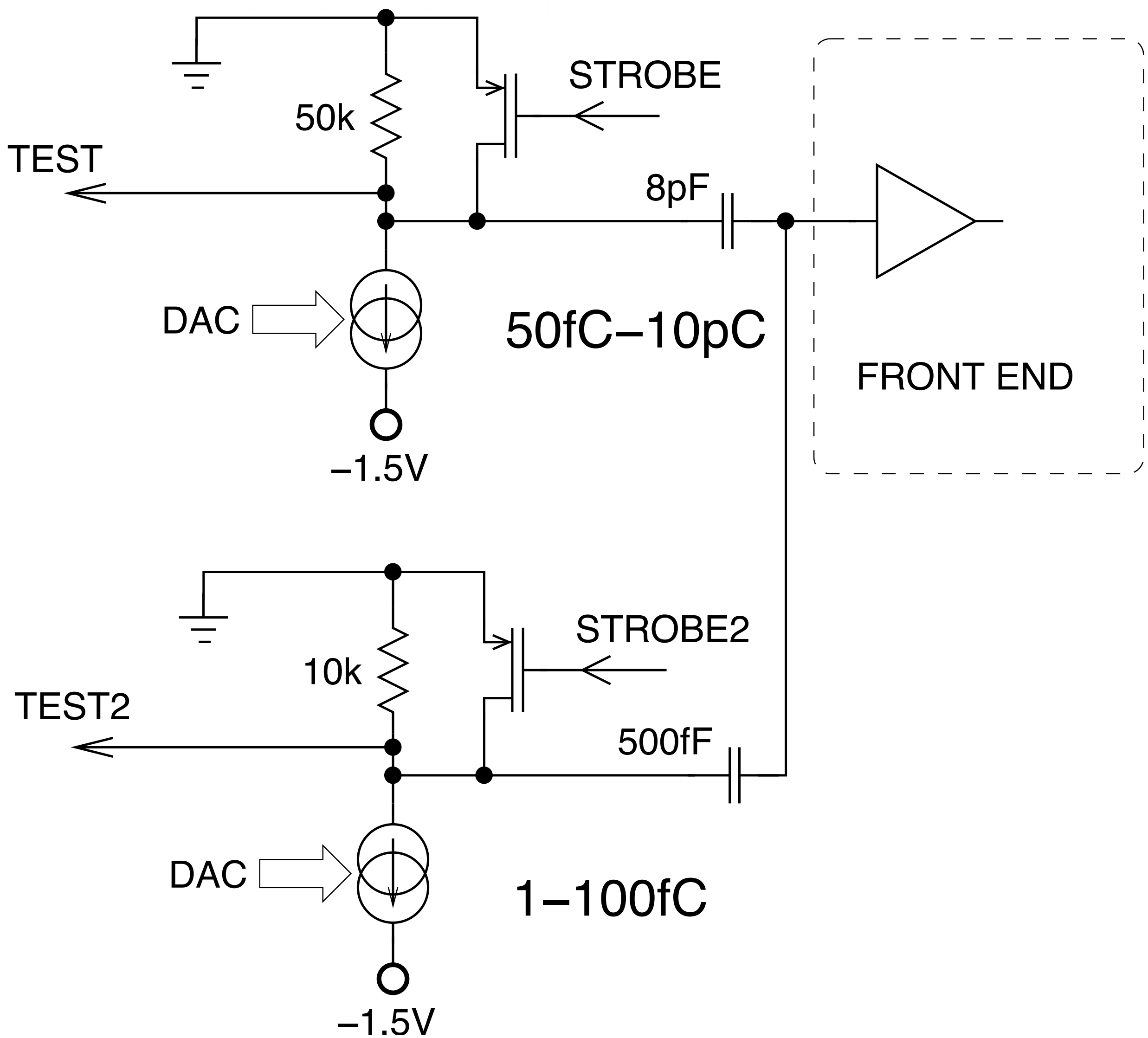
HGC Front End Electronics

- **Data Transfer capacity matched to 120um Si / 512 Channel Modules in high η region**
  - **High radiation forces use o Electrical Links**
- **For 300um Si / 256 Channel Modules (the bulk of the surface) option to combine data from adjacent Modules onto a single Optical Link**



HGC FE Charge Injection

FE Charge injection calibration circuit

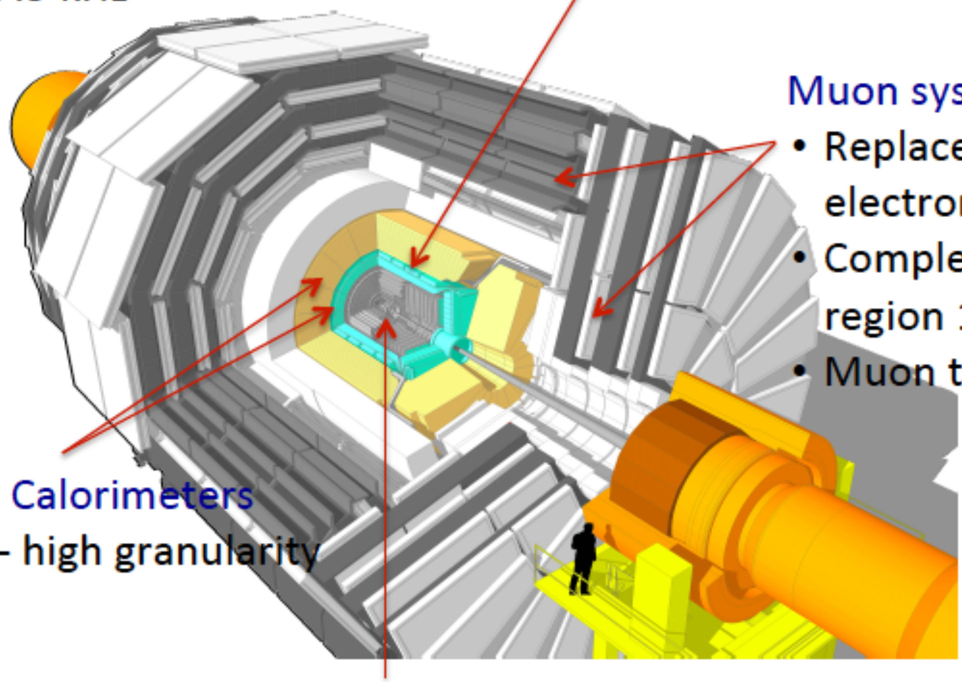


CMS HL-LHC Upgrade: Summary

Trigger/HLT/DAQ
- Track information at L1-Trigger
- L1-Trigger: 12.5 µs latency - output 750 kHz
- HLT output ≈7.5 kHz

Barrel EM calorimeter
- Replace FE/BE electronics
- Lower operating temperature (8∘)

Muon systems
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$



Replace Endcap Calorimeters
- Rad. tolerant - high granularity
- 3D capability

Replace Tracker
- Rad. tolerant - high granularity - significantly less material
- 40 MHz selective readout (Pt≥2 GeV) in Outer Tracker for L1-Trigger
- Extend coverage to $\eta = 3.8$

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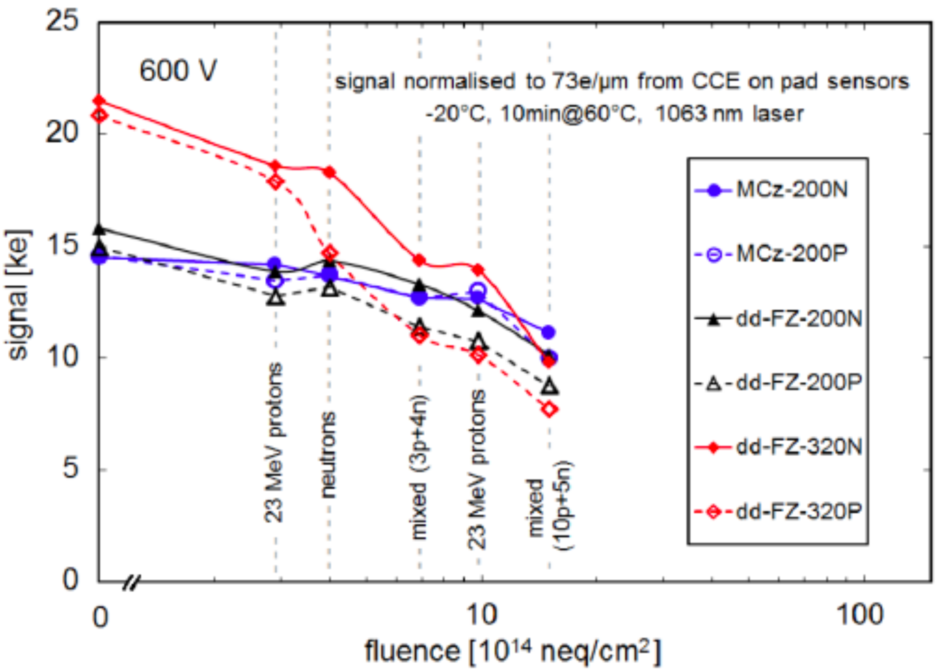
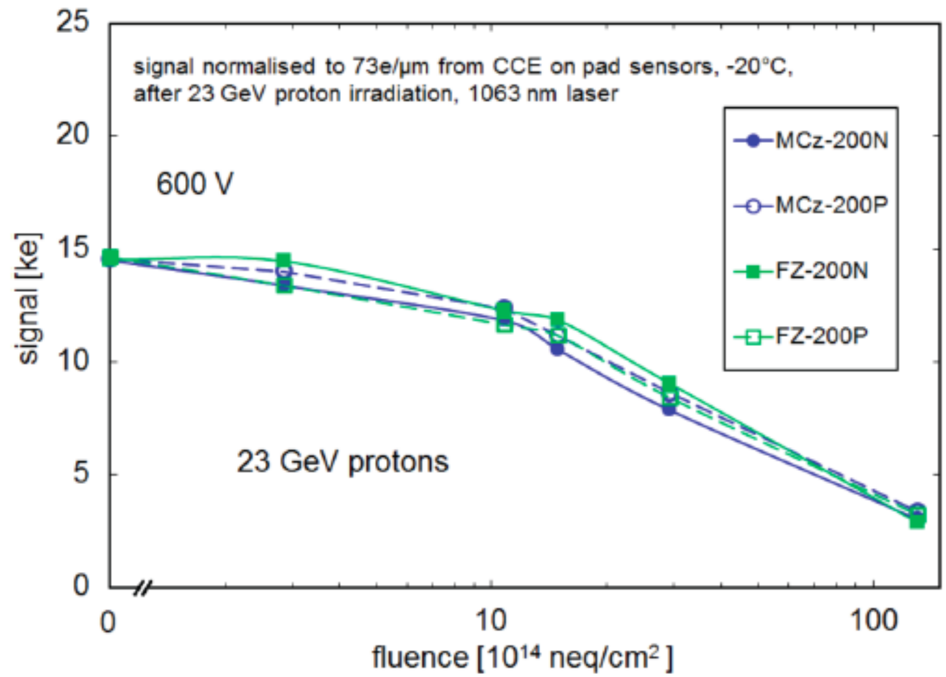
https://cds.cern.ch/record/2020886

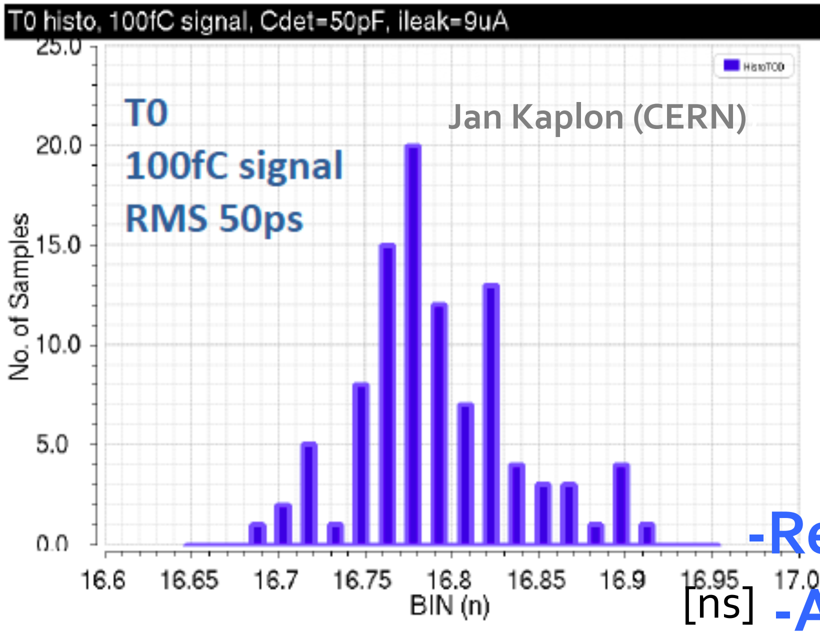
Radiation Studies





- Besides these studies related to tracker, dedicated irradiations have been performed with neutrons on a range of samples
  - Initial results very consistent with experience from tracker sensors
  - Full results will come over the next months, after cool down and annealing steps allow access to the sensors

HGC high precision timing?



Expect > 10~20 cells above 100fC in clusters with E_T > 2~4GeV

Is it useful for pile up mitigation or precision cluster timing?

-Compatibility of cluster timings

-Reconstruct time of hard scatter vertices

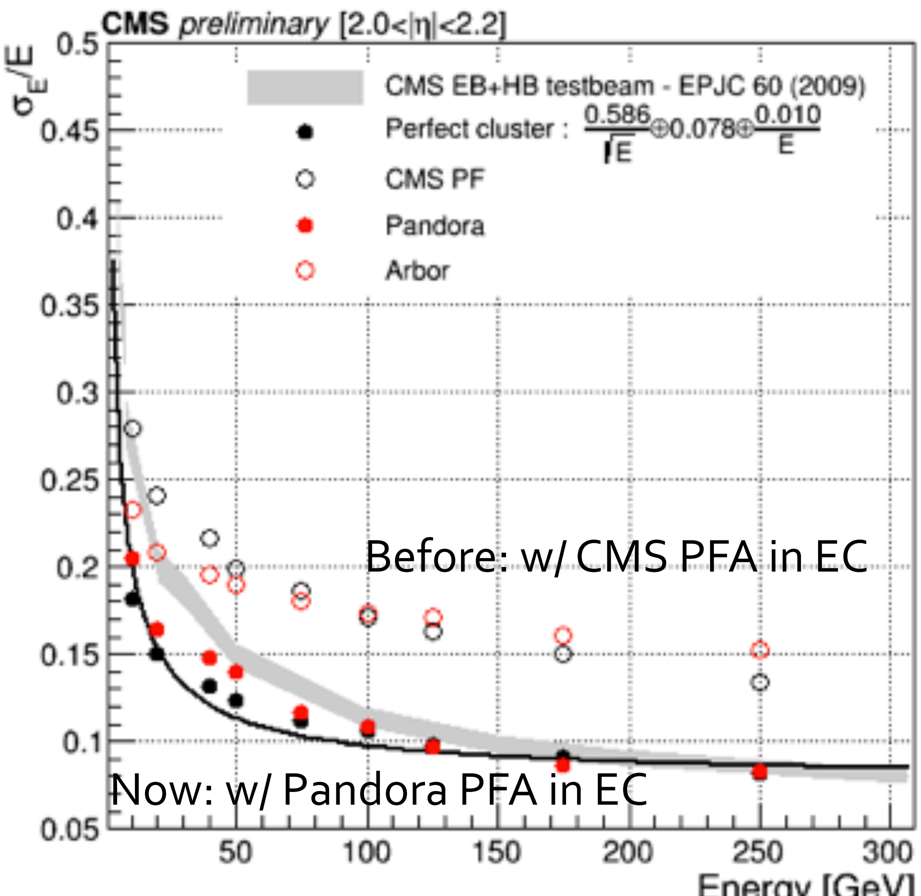
-Associate a photon with reconstructed vertex?

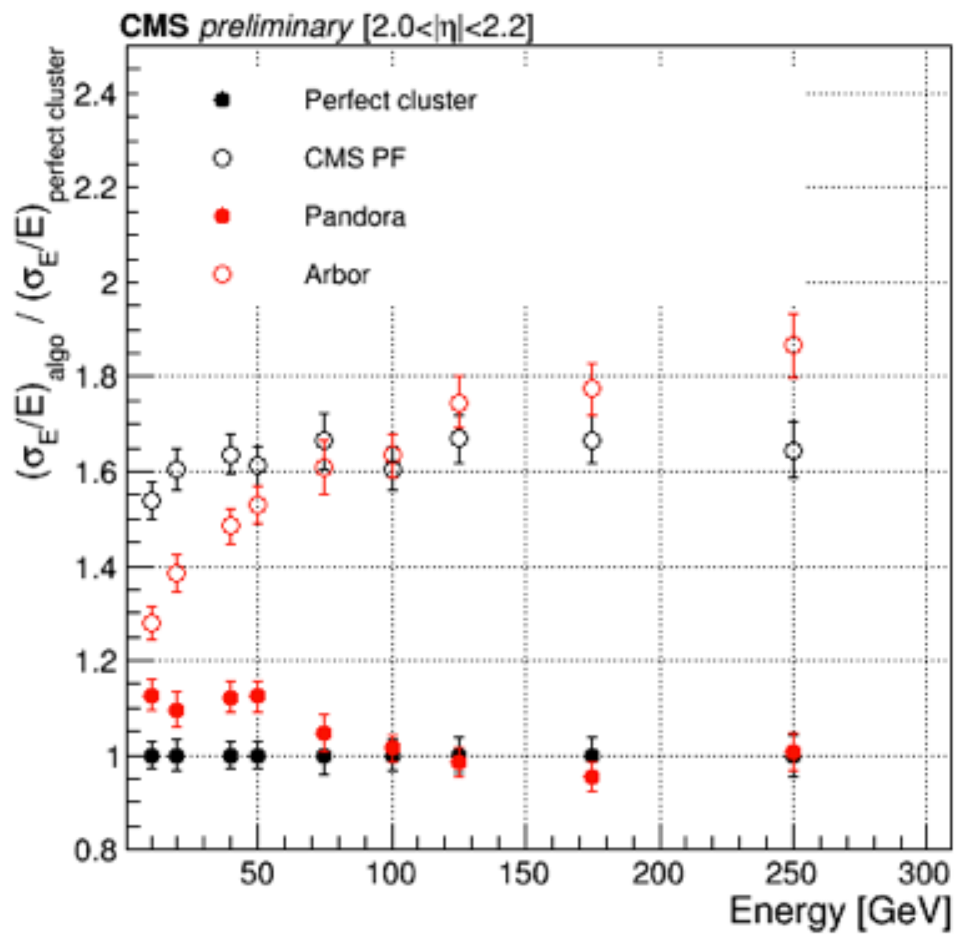
- Detailed studies of systematic effects ongoing
  - Jitter in Silicon sensors
  - TDC binning and non-linearity, time slew,…
  - Clock distribution

HGC Had Performance Studies

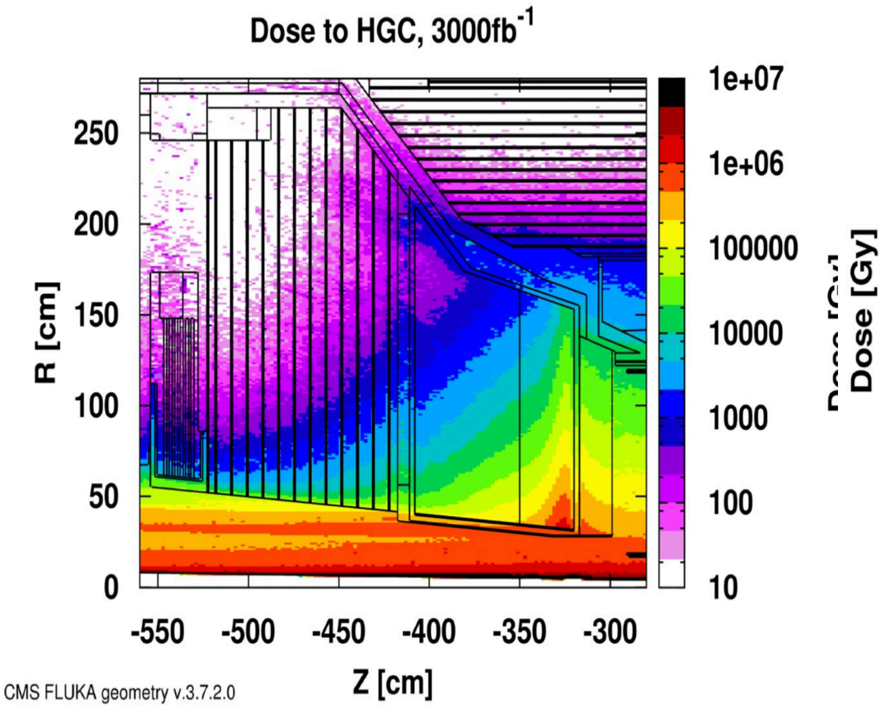
- π+ calibration and resolution –
  - Improved performance with PandoraPFA in EC

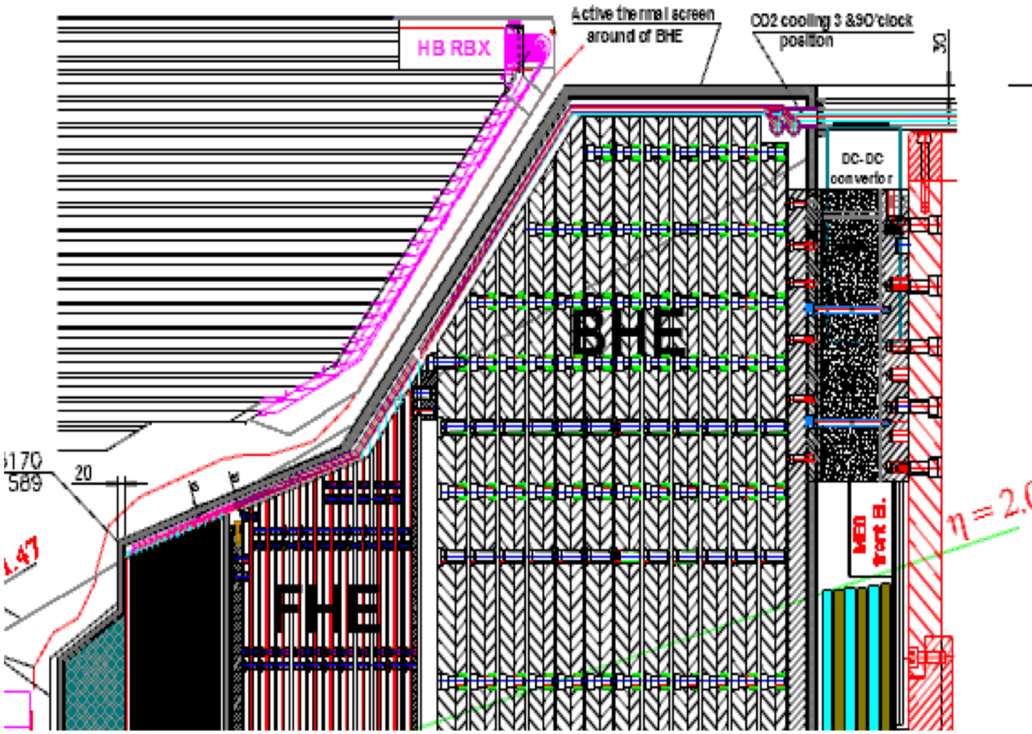
Tkaczyk





Cold Scintillator Concept





- Extend thermal screen to cover full endcap
  - Warm-cold transition deeper
  - Flexible boundary between Si/Scintillator