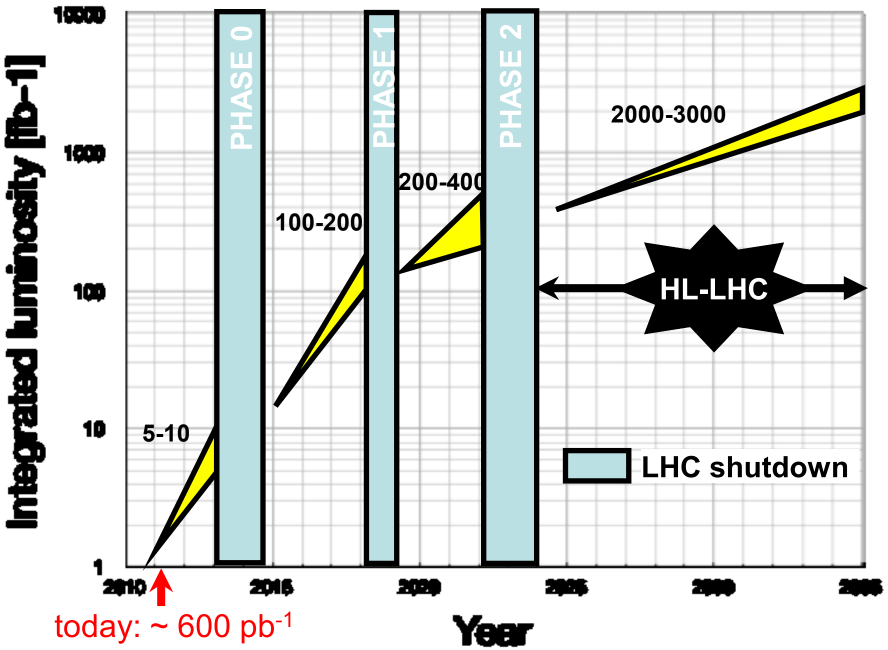
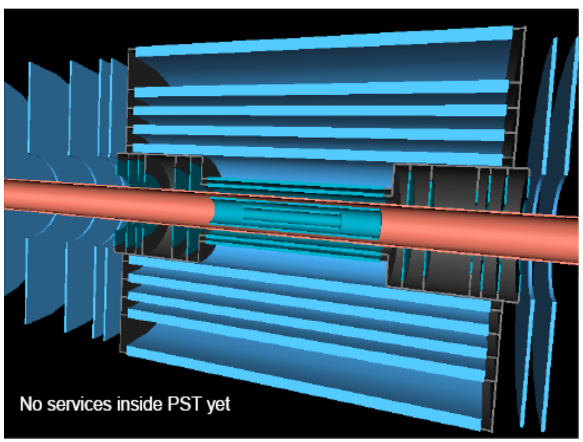
Silicon Strip Detectors for the ATLAS HL-LHC Upgrade

Anthony Affolder
University of Liverpool

On behalf of the ATLAS Upgrade Community

ATLAS Inner Tracker Upgrades



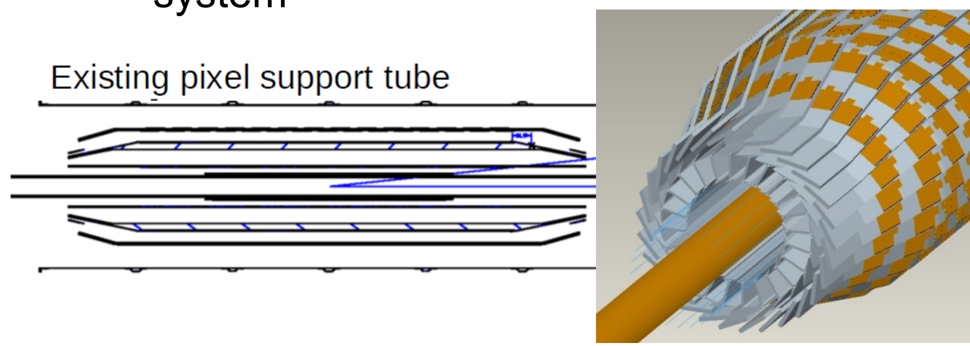


Phase 0

- New beam pipe w/additional pixel layer (IBL)
  - See Philippe Grenier's presentation

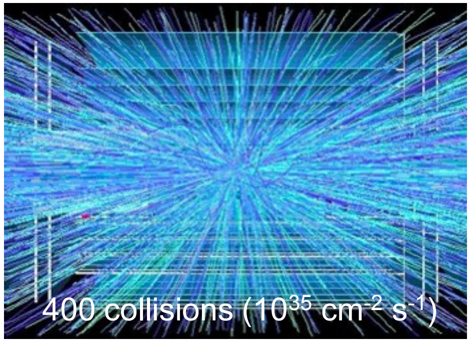
Phase 1

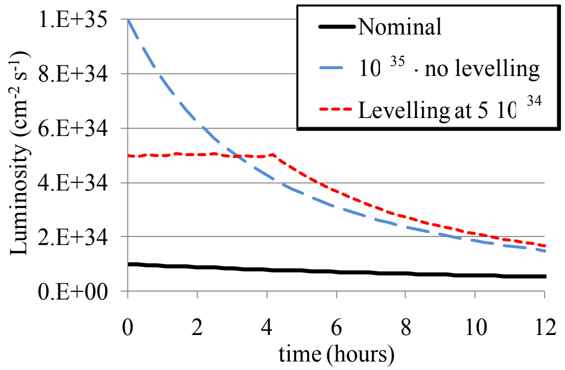
- Possibility of replacement of entire pixel system

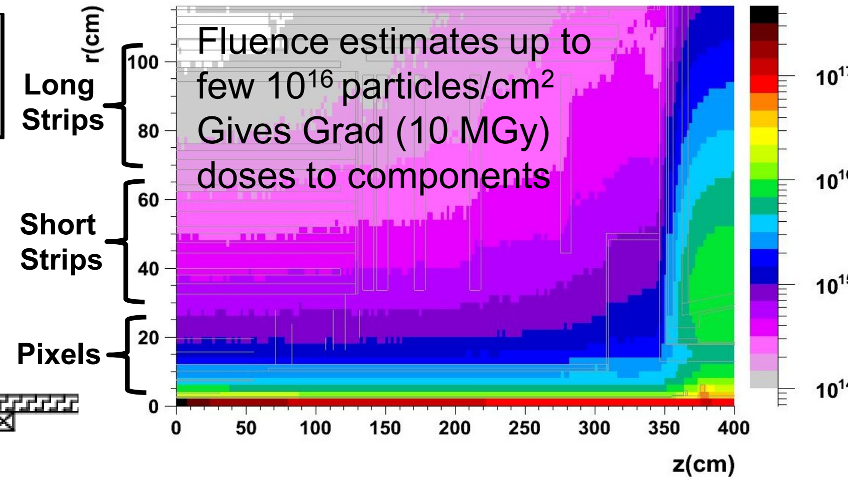


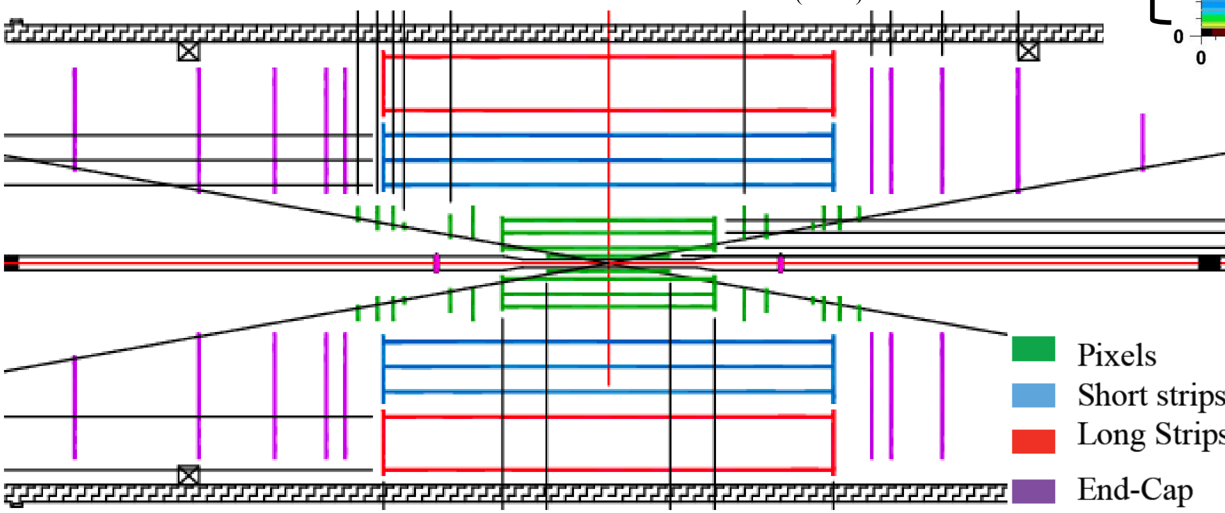
- Phase 2 (HL-LHC, previously sLHC)
  - Replacement of current transition radiation tracker (TRT) and strip tracker with an all-silicon tracker
    - **Focus of this talk**

ATLAS Phase II Tracker Upgrade









Challenges facing HL-LHC silicon detector upgrades:

- Higher occupancies
  - ↳Finer Segmentation
- Higher particle fluences
  - ↳Increase Radiation Tolerance
- Larger Area (~200 m^2)
  - ↳Cheaper Sensors

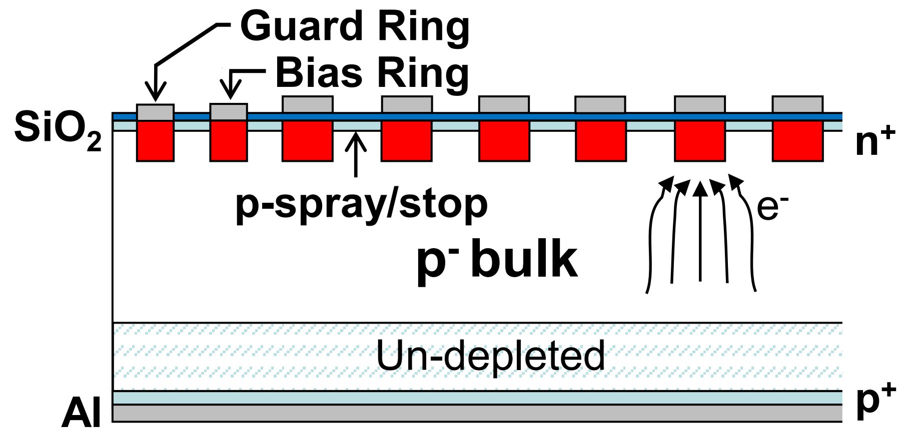
Short Strip (2.4 cm) μ-strips (stereo layers): r = 38, 50, 62 cm — Up to 1.2×10^{15} 1MeV n_{eq}/cm^2

Long Strip (4.8 cm) μ-strips (stereo layers): r = 74, 100 cm — Up to 5.6×10^{14} 1MeV n_{eq}/cm^2

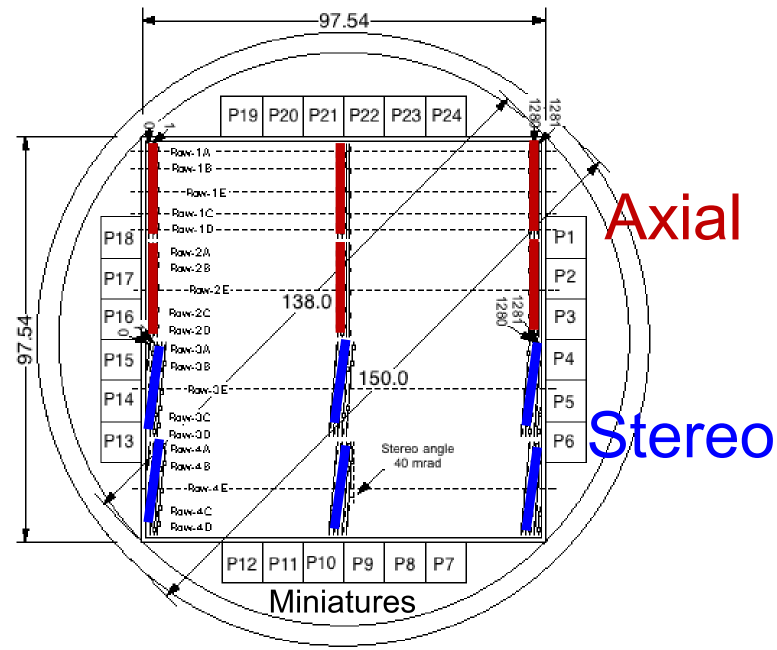
Fluence estimates include a 2x "safety" factor for prediction uncertainties

Radiation Hard Sensors

- **n^+-strip in p-type substrate (n-in-p)**
  - Collects electrons like current n-in-n pixels
    - Faster signal, reduced charge trapping
  - Always depletes from the segmented side
    - Good signal even under-depleted
  - Single-sided process
    - ~50% cheaper than n-in-n
    - More foundries and available capacity world-wide
  - Easier handling/testing due to lack of patterned back-side implant

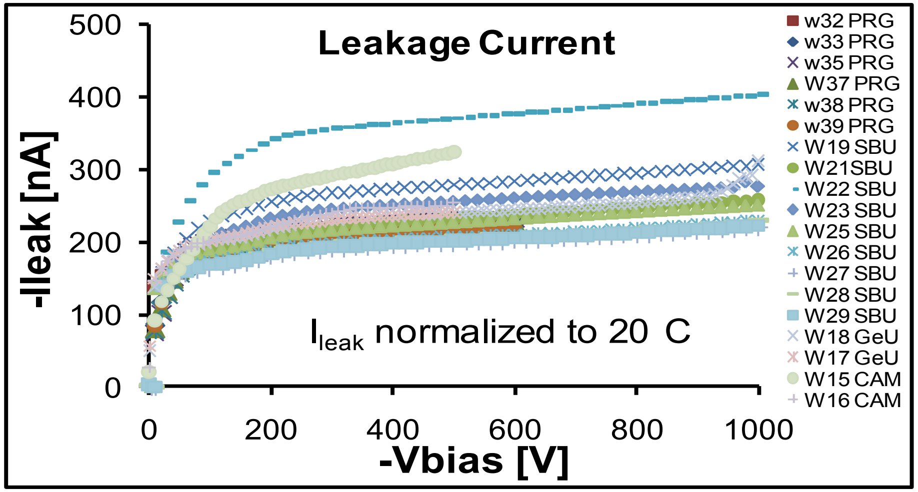


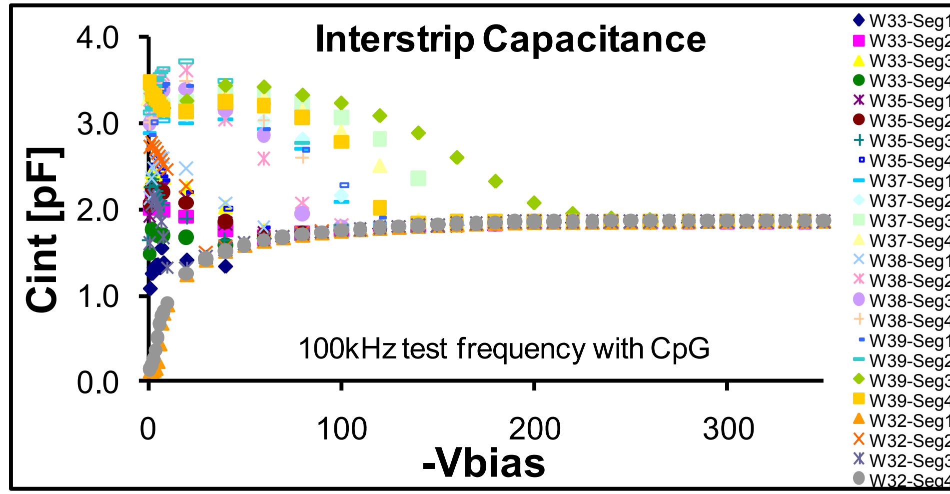
- Collaboration of ATLAS with Hamamatsu Photonics (HPK) to develop 9.75x9.75 cm^2 devices (6 inch wafers)
  - 4 segments (2 axial, 2 stereo), 1280 strip each, 74.5 μm pitch, ~320 μm thick
  - FZ1 <100> and FZ2 <100> material studied
  - Miniature sensors (1x1 cm^2) for irradiation studies

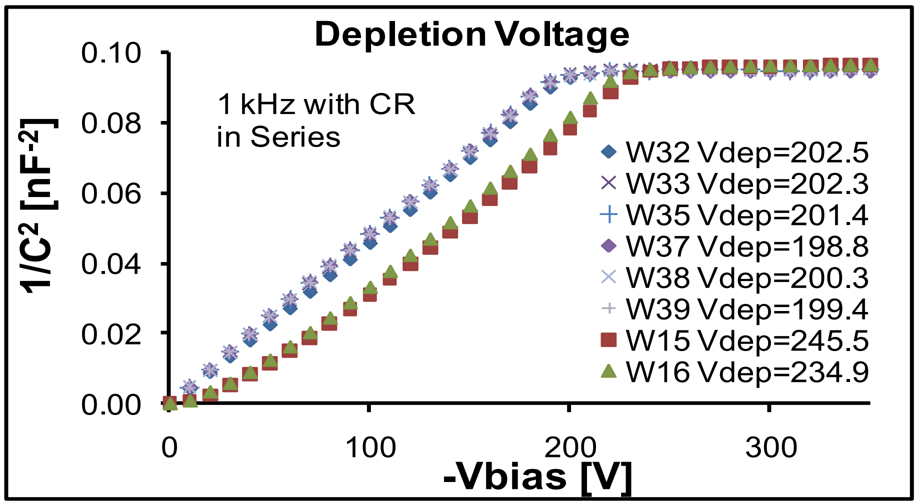


See N. Unno, et. al., Nucl. Inst. Meth. A, Vol. 636 (2011) S24-S30 for details

Full-size Sensor Evaluation





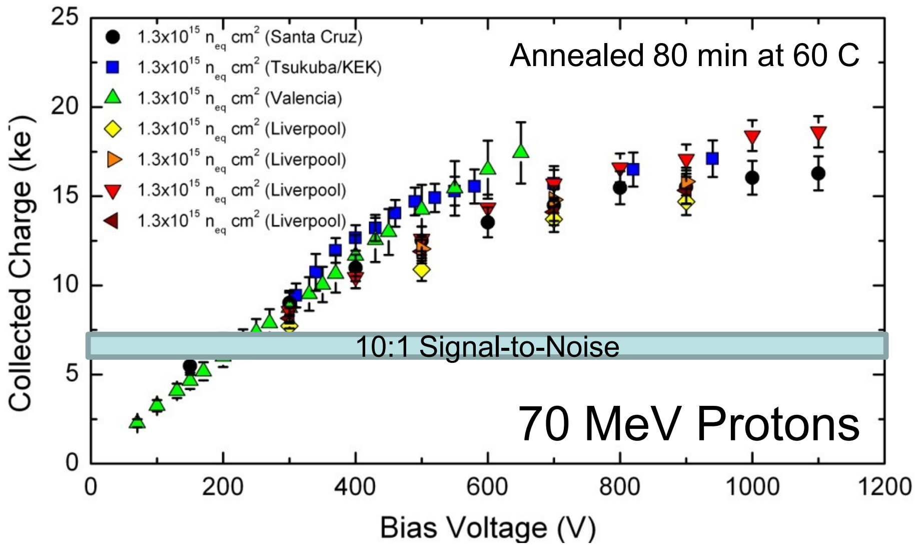


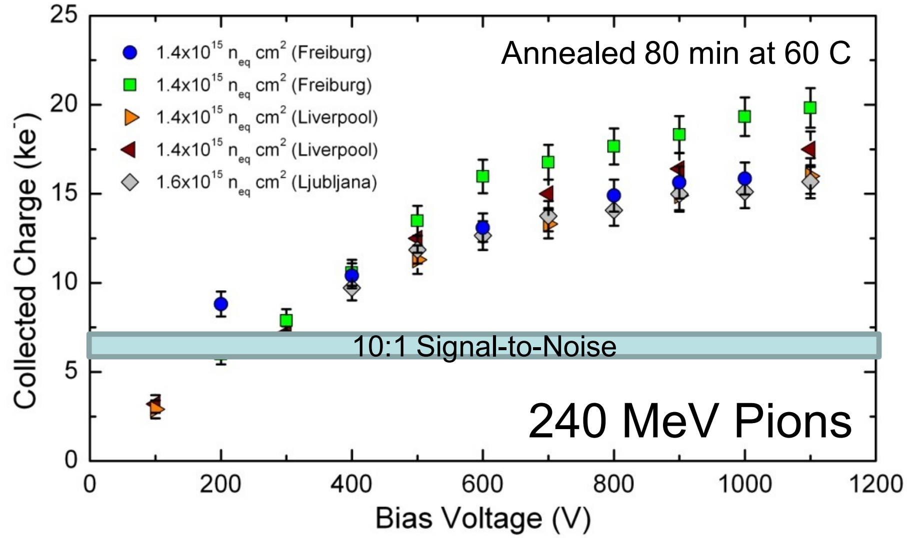
See J. Bohm, et. al., Nucl. Inst. Meth. A, Vol. 636 (2011) S104-S110 for details

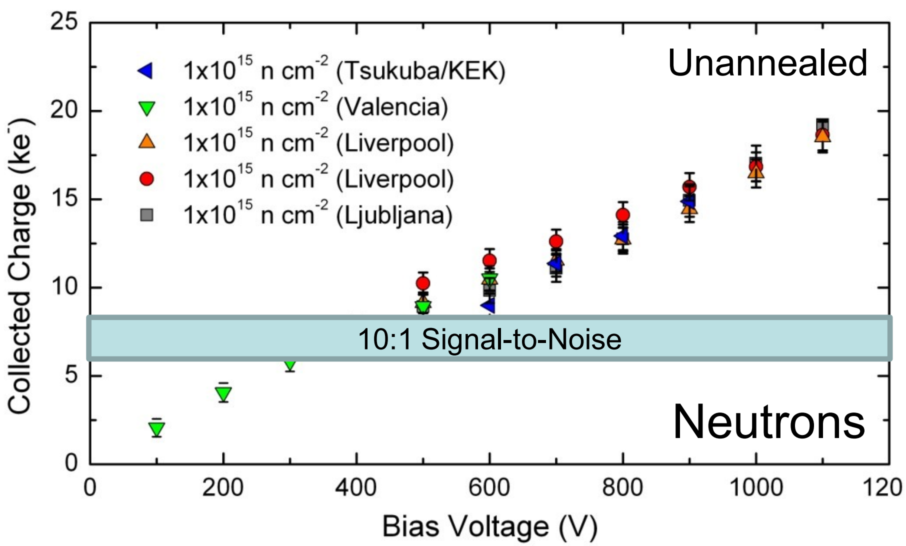
	Specification	Measurement
Leakage Current	<200 µA at 600 V	200– 370nA
Full Depletion Voltage	<500 V	190 – 245V
Coupling Capacitance (1kHz)	>20 pF/cm	24 – 30pF
Polysilicon Resistance	1.5+/-0.5MΩ	1.3 -1.6MΩ
Current through dielectric	I_{diel} < 10 nA	< 5nA
Strip Current	No explicit limit	< 2nA
Interstrip Capacitance (100kHz)	<1.1pF/cm (3 probe)	0.7 – 0.8pF
Interstrip Resistance	> 10x R_{bias}~15 MΩ	>19 GΩ

<u>All specifications already met!!</u>

Charge Collection Results





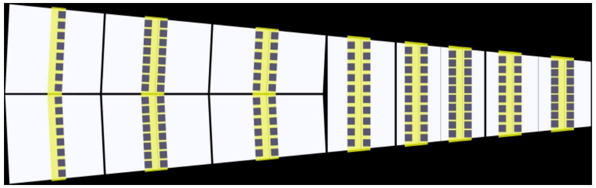


- Miniature devices irradiated to strip barrel fluences with neutrons, pions, protons
- Charge collection measured with ^{90}Sr β-source
  - Consistent results between different groups/equipment
- S/N greater than 10:1 for strip sensor types with expected noise performance
  - ~600-800 e^{-} short strips, ~800-1000 e^{-} long strips
  - See H. Sadrozinski, et.al., Nucl. Inst. Meth. A, doi:10.1016/j.nima.2011.04.0646 for details

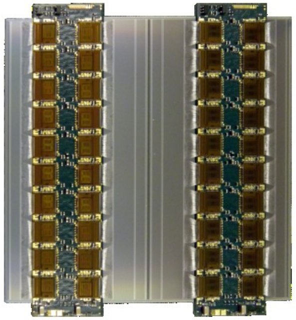
Stave+Petal Programme

- Designed to reduce radiation length
  - Minimize material by shortening cooling path
  - *Glue module directly to a stave core with embedded pipes*
- Requirements of large scale assembly considered from the beginning-
  - *Simplify build as much as possible*
- All components independently testable prior to construction
- Design aims to be low cost-
  - *Minimize specialist components*

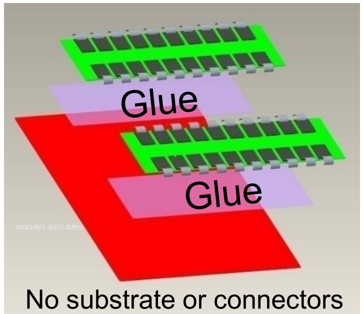
Petal Hybrid

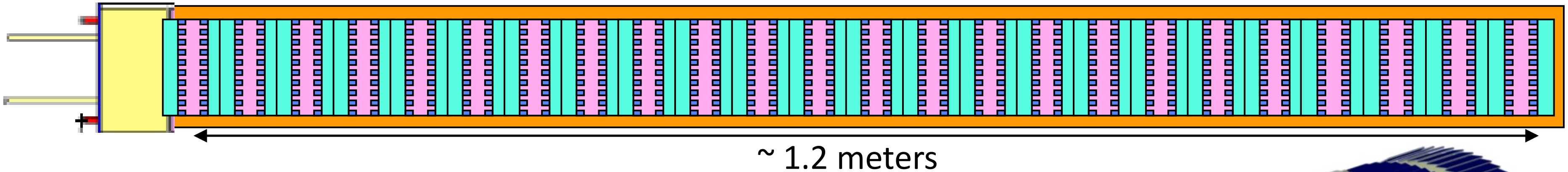


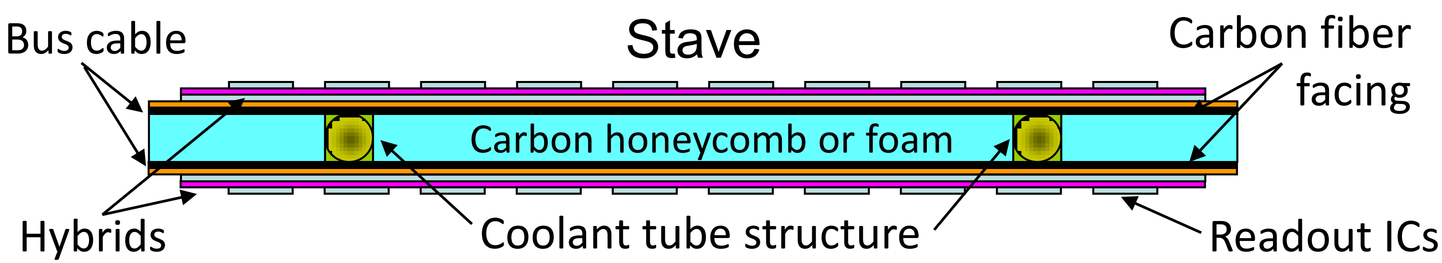
Petal

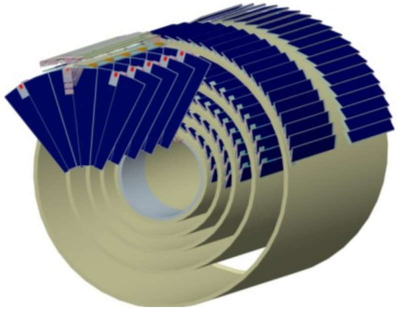


Stave Module





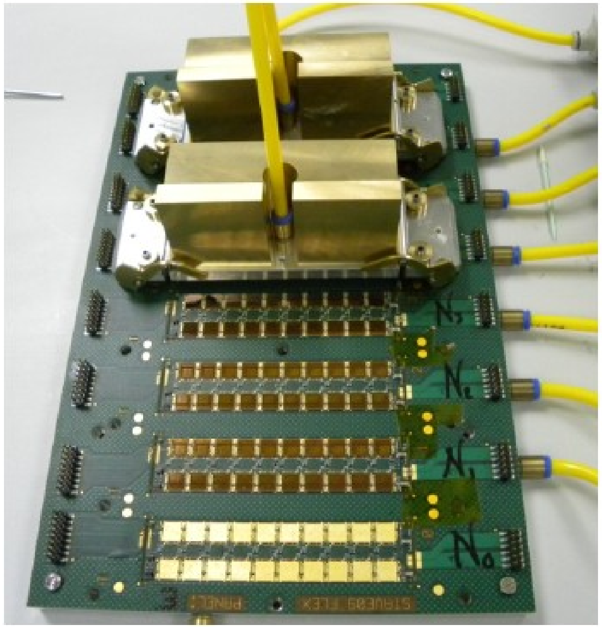




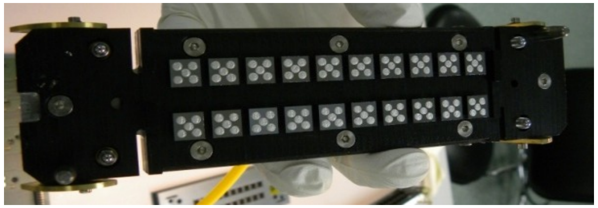
Hybrid Mass Production

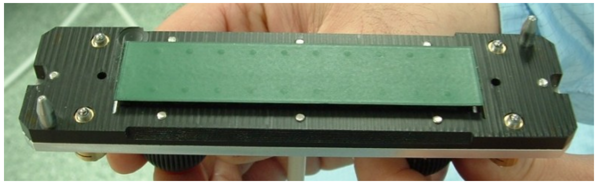
- First pass at industrialization of hybrids:
  - Panelization (8 per panel):
    - Flex selectively laminated to FR4
      - FR4 acts as temporary substrate during assembly, wire bonding and testing
  - Designed for machine placement and solder re-flow of passive components
  - Mass attachment/wire bonding of custom ASICs
- Flex uses conservative design rules (~20000 hybrids to be installed):
  - ↳ High yield, large volume, low price
    - 100μm track and gap, blind vias (375μm lands with 150μm drill) and 50μm dielectrics
- Hybrids+ASICs tested in panel
  - With final ASIC set (ABCn-130nm, HCC, power), all hybrids in the panel tested with one data I/O and one power connection

Fully characterized hybrid cut out of panel ready for module assembly

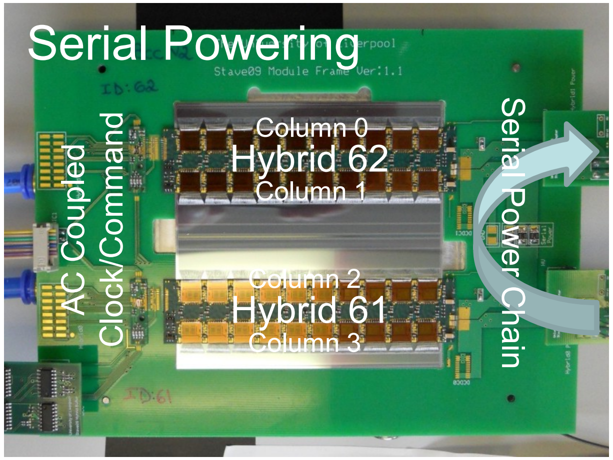


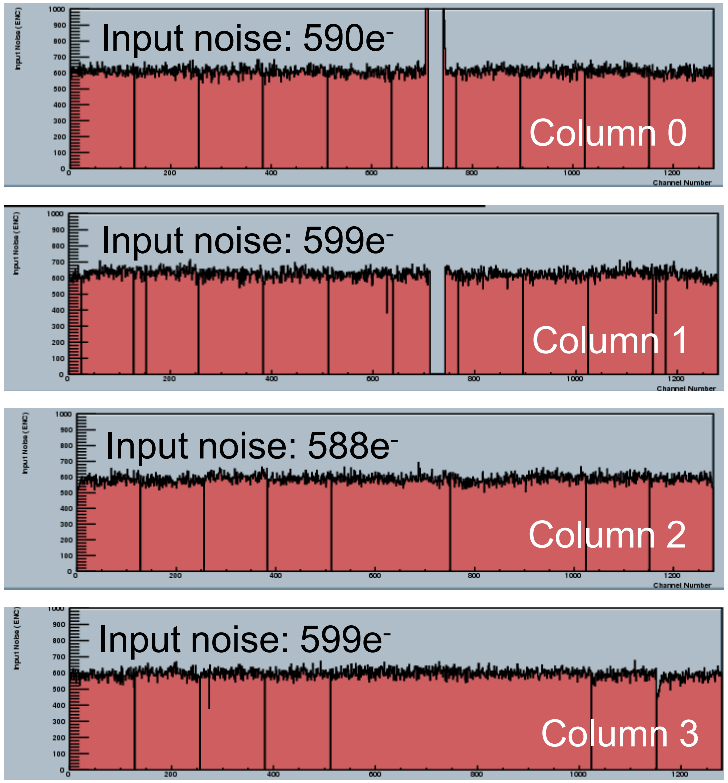
Panel dimensions: 300mm x 200mm
Hybrid dimensions: 24mm x 107.6mm





Stave Module Tests

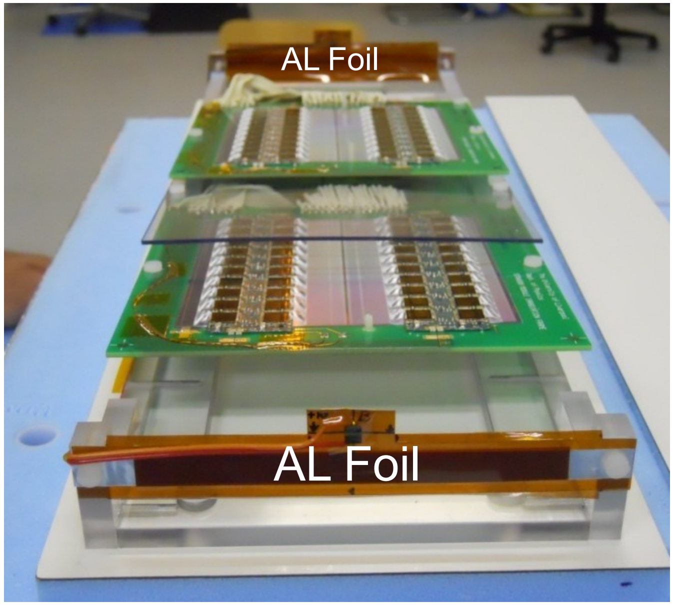




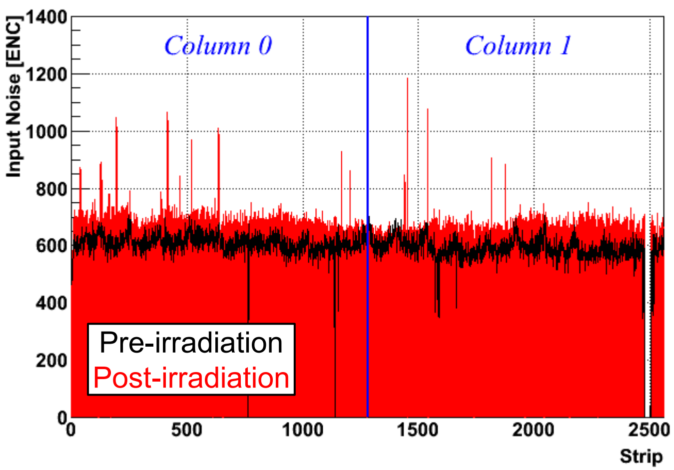
- Stave modules are tested in PCB frames
  - Cheap, flexible test bed for different power/shielding/grounding configurations
- Parallel powering, serial powering, and DC-DC converters have all been evaluated
  - With proper grounding/shielding, all these configurations give expected noise performance

	Parallel	Serial	DC-DC
Hybrid 62	$590\ e^-$ $596\ e^-$	$590\ e^-$ $599\ e^-$	$595\ e^-$ $603\ e^-$
Hybrid 61	$585\ e^-$ $591\ e^-$	$588\ e^-$ $599\ e^-$	$585\ e^-$ $591\ e^-$

Strip Module Irradiation

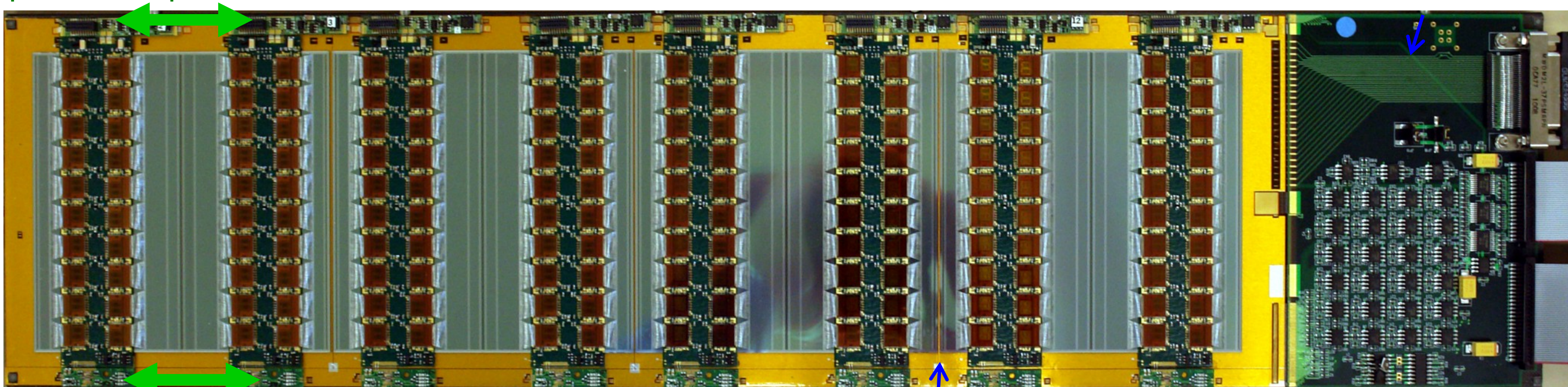


- Irradiated at CERN-PS irradiation facility
  - 24 GeV proton beam scanned over inclined modules
  - Module biased, powered, and clocked during irradiation
  - Total dose of 1.9×10^{15} n_{eq} cm^{-2} achieved
    - Max predicted fluence for barrel modules is 1.2×10^{15} n_{eq} cm^{-2}
- Sensor and module behave as expected
  - Noise increase consistent with shot noise expectations

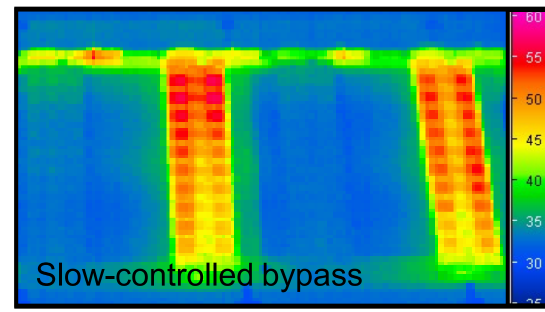


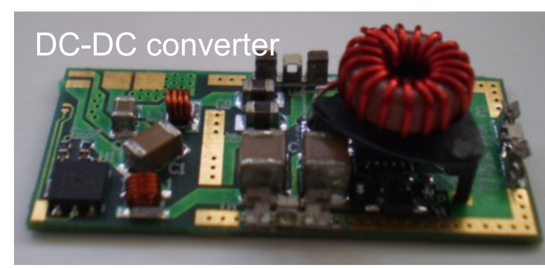
Noise	Column 0	Column 1
Pre-Irrad	610 e^-	589 e^-
Post-Irrad	675 e^-	650 e^-
Difference	65 e^-	61 e^-
Expected	670 e^-	640 e^-

Stavelets



- Shortened stave built as electrical test-bed
  - Shielding, grounding, serial and DC-DC powering, …
- First stavelet serial powered
  - Power Protection Board (PPB) has automated over-voltage protection and slow-controlled (DCS) hybrid bypassing
  - **DC-DC stavelet under construction**
- Uses Basic Control Chip (BCC) for data I/O
  - Generates 80MHz data clock from 40MHz BC clock
  - 160Mbit/s multiplexed data per hybrid

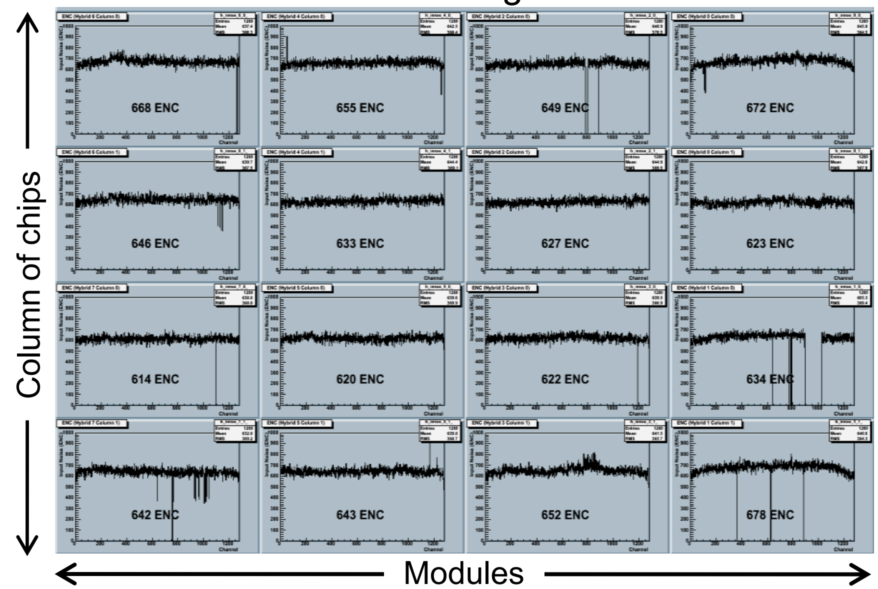


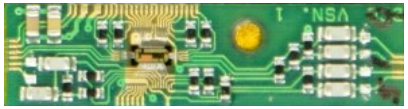


Serial Powered Stavelet Electrical Results

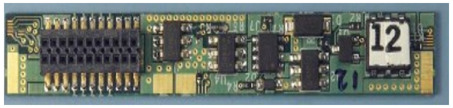
- Uses on-hybrid shunt control circuit
- Stavelet noise approaching single module tests
  - Roughly ~20 e^- higher
  - Bypassing hybrids does not affect noise performance
- All technologies necessary for serial powering of stave have been prototyped and shown to work (and compatible with 130 nm CMOS)
  - Constant current source, SP protection and regulation, multi-drop LVDS
    - Currently optimizing location of components, size of SP chains
- Minimal impact on material budget
  - Estimated to be ~0.03% averaged over the stave

Stavelet Noise using Serial Power



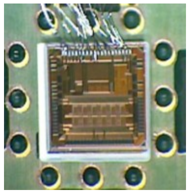


AC-coupled mLVDS



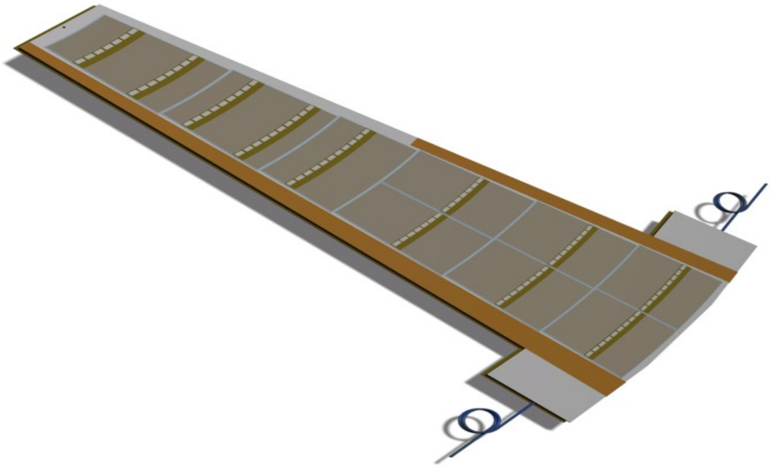
Serial Power Protection
(discrete components)

Custom Current Source

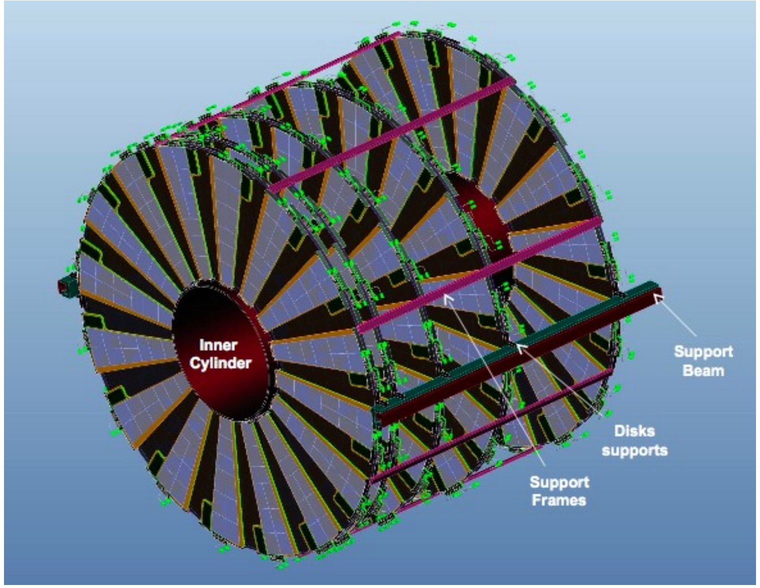


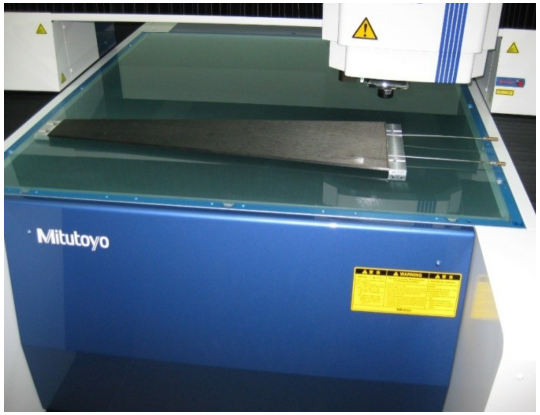
Serial Power Protection
(130 nm prototype)

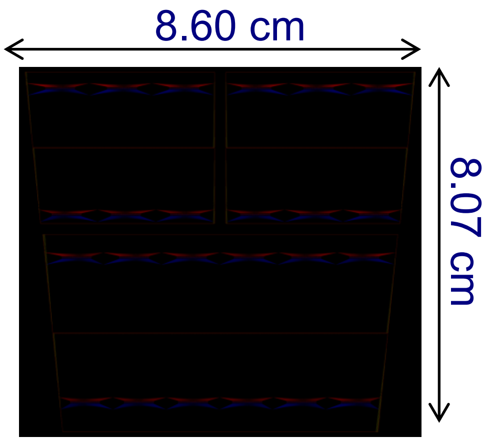
Petal Endcaps



- The petal concept follows closely the barrel stave concept
- 5 discs on each end cap with 32 petals per disc
  - 6 Sensor rings
- First petal cores have been produced
  - Flat to better than 100 μm
- First endcap hybrids tested
  - Same performance as barrel hybrid
- n-in-p sensor prototypes submitted to CNM to make petal-let using 4" wafers

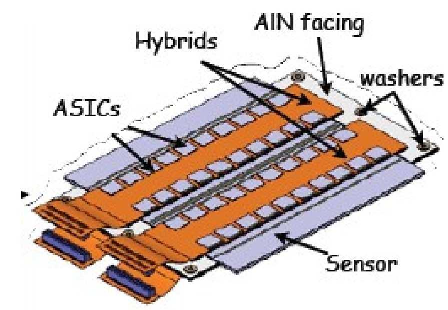


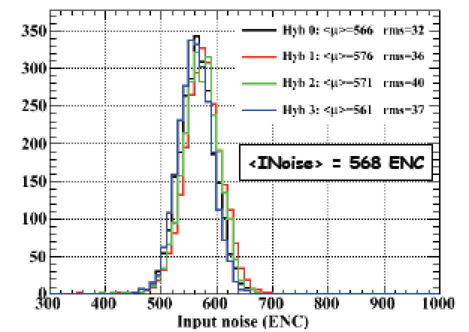


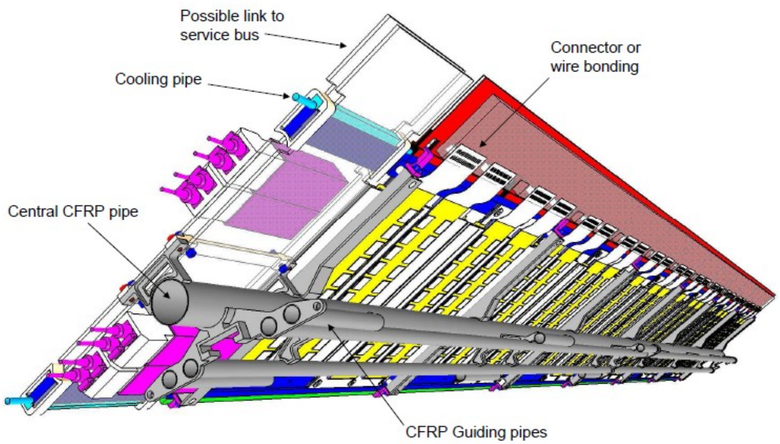


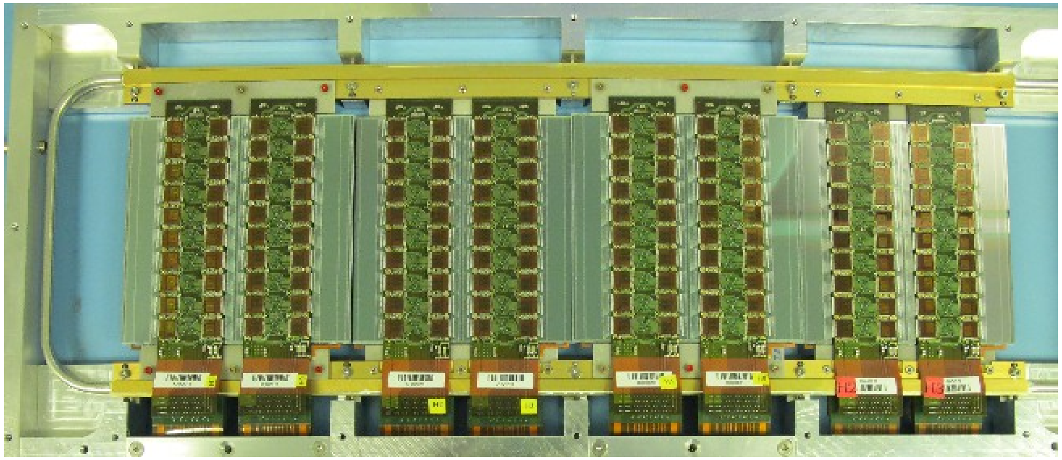
Alternative Solution: Super-Module

- Modular concept: cooling, local structure, service bus, power interface are decoupled from the modules
- Overlapping coverage in Z
- Rework – Possible up to the commissioning after integration
- Design includes carbon-carbon hybrid bridge
  - Hybrid could be also glued as for stave modules to reduce material





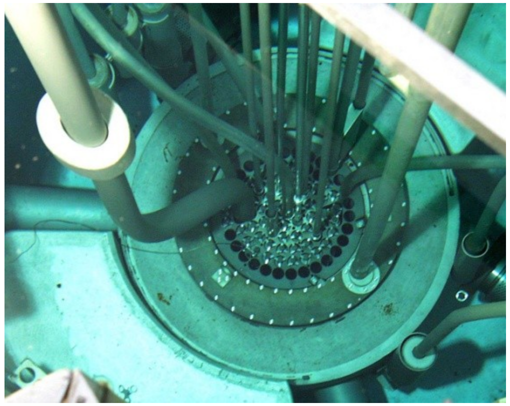




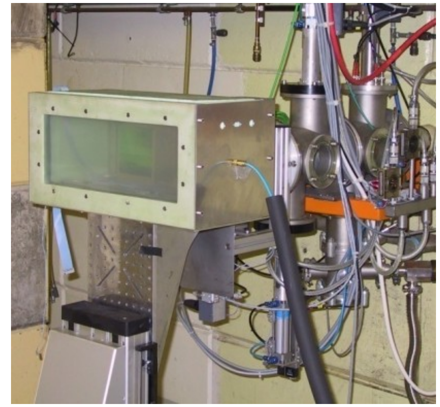
Conclusions

- The current ATLAS TRT and silicon strip tracker must be replaced with an all-silicon tracker for HL-LHC operation (planned to be assembled by 2020)
- The R&D program of components has made significant progress:
  - Full-size prototype planar strip detectors have already been fabricated at Hamamatsu Photonics (HPK) which meet the final specifications
  - Working baseline and alternative module prototypes have been made and shown to work after irradiation larger than the final expected fluence
  - Due to time constraints, we couldn't show the following (see backup slides):
    - n-in-p FZ planar devices have also been shown to collect sufficient charge for the pixel region
    - Thermo-mechanical prototypes perform as expected, meeting the needs of the experiment
- Full-size stave/super-module prototypes are planned to be finished this year with the next generation of the 130 nm ASICs for the strip tracker under design

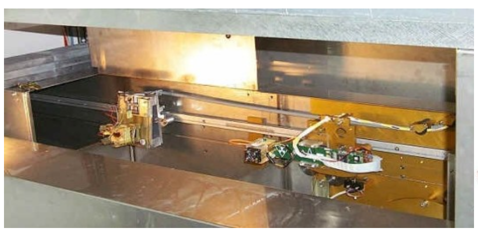
Thank You to Irradiation Sources



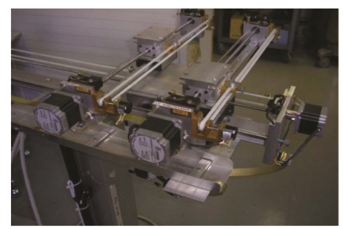
Irradiation and dosimetry (Neutrons):
Triga Reactor, Jozef Stefan Institute,
Ljubljana, Slovenia: **V. Cindro, et. al.**



Irradiation and dosimetry (26 MeV Protons):
Compact Cyclotron, Karlsruhe, Germany:
W. de Boer, A. Dierlamm, et. al.



Irradiation and dosimetry
(24 GeV Protons):
CERN PS Irrad1 facility,
Geneva Switzerland:
M. Glaser, et. al.

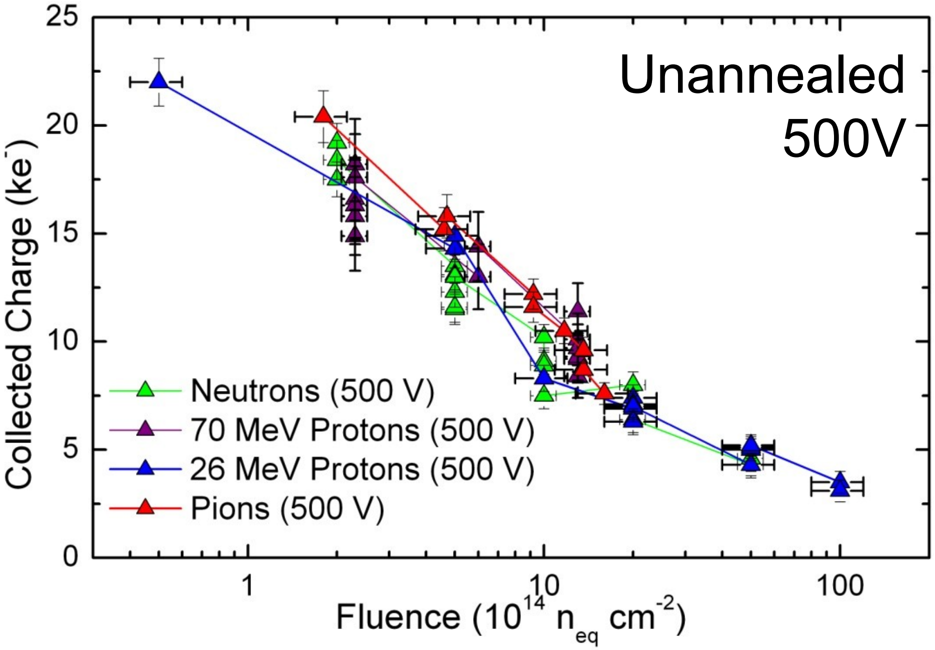


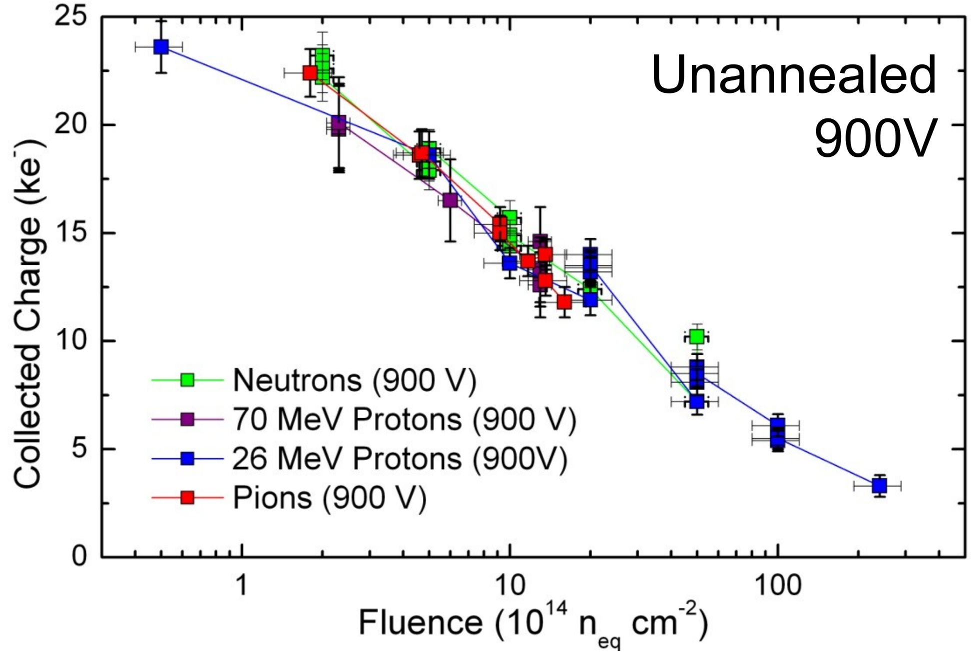
Irradiation and dosimetry
(280 MeV/c Pions):
Paul Scherrer Institut,
Switzerland:
M. Glaser, T. Rohe, et. al.

Irradiation and dosimetry
(70 MeV Protons):
AVF Cyclotron at CYRIC,
Sendai, Japan:
Y. Unno, T. Shinozuka, et. al.

Backup

Charge Collection Summary



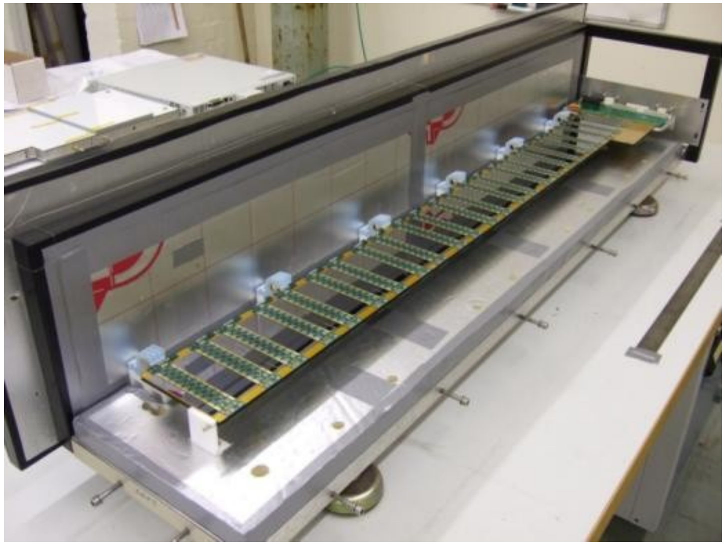


For ATLAS07 miniatures, results from all irradiation sources consistent after non-ionizing energy loss (NIEL) scaling to 1 MeV neutron equivalent fluences

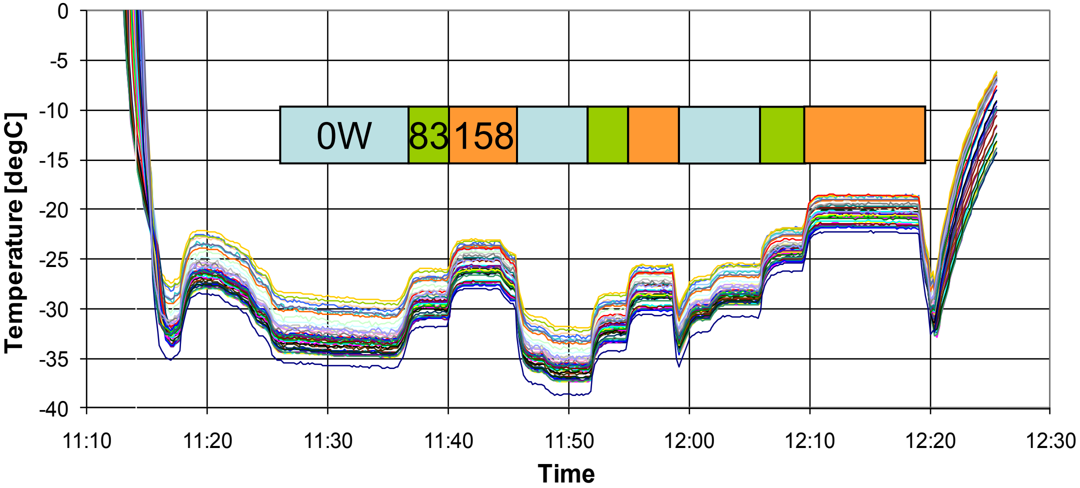
- Annealed measurements corrected to un-annealed state using values derived from I. Mandic, et. al., Nucl. Instr. Meth. A, Vol. 629 (2011) 101-105.

<u>Charge sufficient for pixel layers as long as adequate bias voltage and cooling provided!!!</u>

Thermo-mechanical Demonstrator



Full-size demonstrator made with realistic mechanical modules, stave cores, bus cables and locking mechanism. It is cooled to -35 C° with a CO_2 blow system. During cooling from room temperature to operating temperature, deflections *less than 100 μm* were measured.

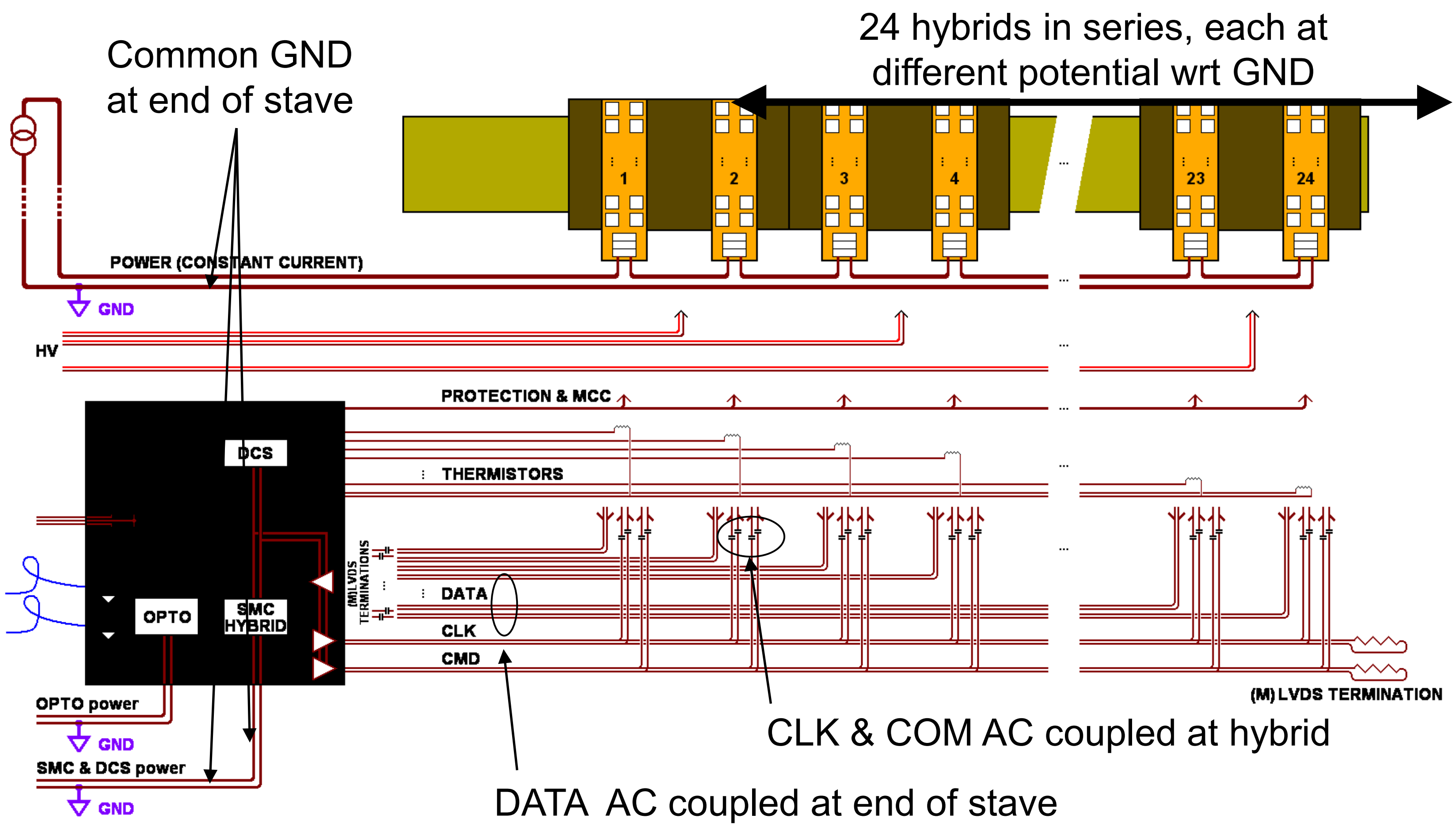


Thermal resistance (hybridΔT/total power):

Top:	0.0425 ± 0.0024 °C/W
Bottom:	0.0474 ± 0.0030 °C/W
All:	0.0449 ± 0.0037 °C/W
Simulation:	0.043 °C/W

Great agreements between measurement and simulation!!

SP Stave Architecture



(DC-DC powered stave would look similar, apart from the absence of AC coupled IO)