Precision Mechanics, Thermal Management, and Power

Future Instrumentation Needs

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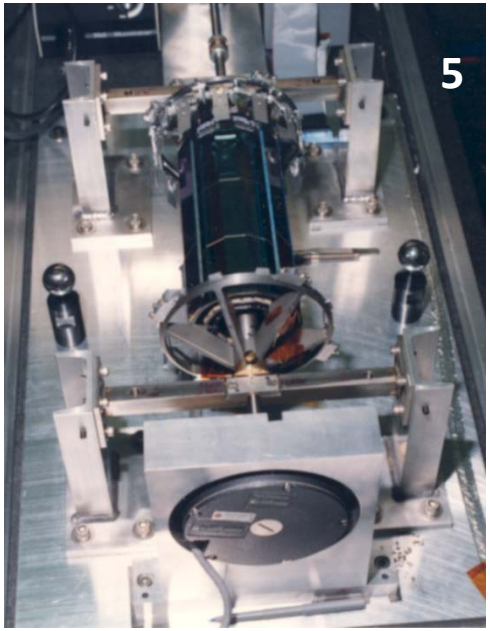
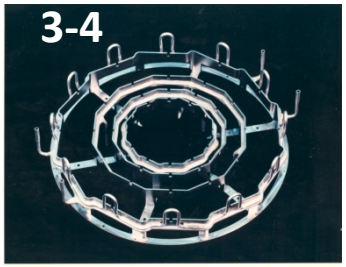
Charge

…not a review…the deliverable of the October workshop will be a report that will be shared with DOE and NSF that will summarize the workshop findings and 'recommend' areas for future investment and formulate potential grand challenges

Acknowledgments: Bill Cooper, David Lynn, Eric Anderssen, Joe Silber, Mitch Newcomer, Georg Vielhauser, Anne Ruminski, Ashley Greenall

Dedication: Aldo Menzione





CDF Silicon Vertex 1992

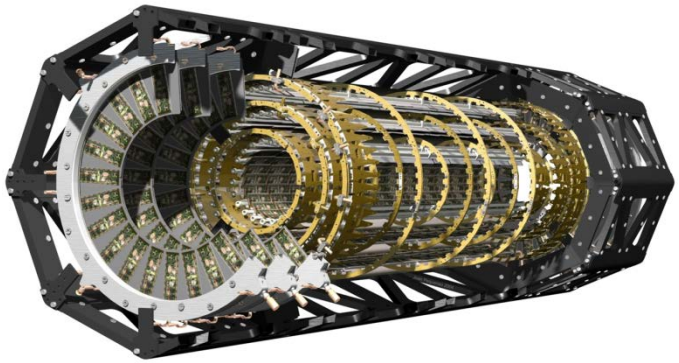
1. Composite support
2. High TC AlN electronics
3. Precision Be support
4. Embedded liquid cooling
5. Metrology
6. Local power regulation and protection

Introduction

- Refers generically to structures and methods which support precision tracking/vertex detectors/imagers and are/may be/have
  - Long radiation length
  - Radiation tolerant
  - Mechanically robust (precise, stable, etc…)
  - High thermal conductivity
  - Provide local and efficient cooling, <0 C.
  - Efficient power delivery, reduced cabling
  - High density electronic interconnects
- Originates from Energy Frontier legacy but also may apply to a variety of Intensity Frontier (vertex detectors….) and Cosmic Frontier (focal planes…) applications

Cont.

- Significant aspects of this are already well established through application to running or recent experiments.



- What is potential for improved performance, what are the needs, are there new directions or capabilities?
- What is natural to develop in the course of a particular experiment and what is of generic interest?

Where have the advances come from?

- Generic R&D
- OPS support for R&D
- LDRD
- SBIR
- KA25
- Industry/Govt/Academic consortia (Europe)
- A diversity of funding sources

Conditions

Operating/Environmental Conditions	
Max Operating Temperatures	40 °C
Min Operating Temperatures	-50 °C
Ionizing Radiation TID	50 - 1000 Mrad
Non-ionizing radiation Levels	1-10 x 10^{15} n_{eq}/cm^2
Magnetic Fields	> 2 T
Typical Sensor Area	100 m^2
Typical Power Densities	~ 100mW/cm^2
Total Power	100 KW
Precision	~10 microns → optical
High Voltage	500-1000 V
Clocking	640 Mbs

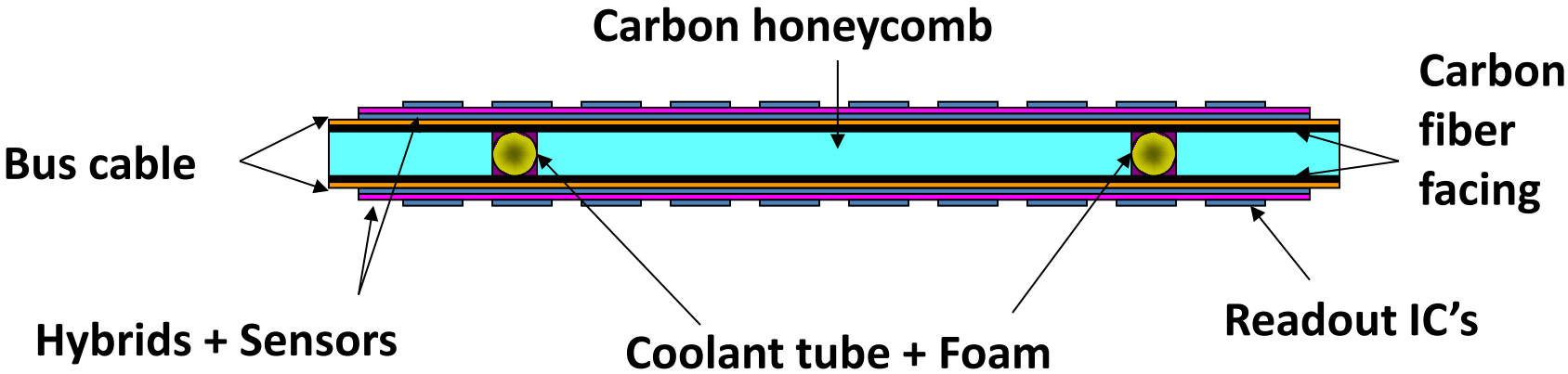
- 1st pass driven by HL/HE hadron colliders
- LC: power cycling, → motion, vibrations, ultra light, thin
- Cosmic: vacuum compliance, lower T, miniaturization, manufacturing

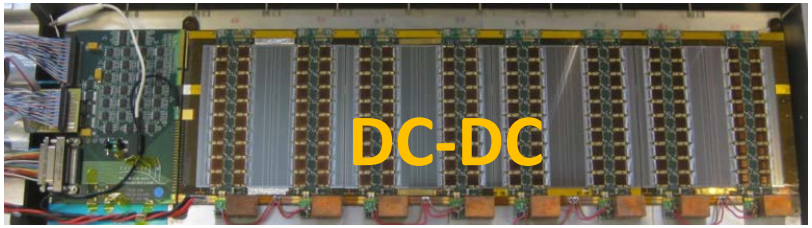
Requirements

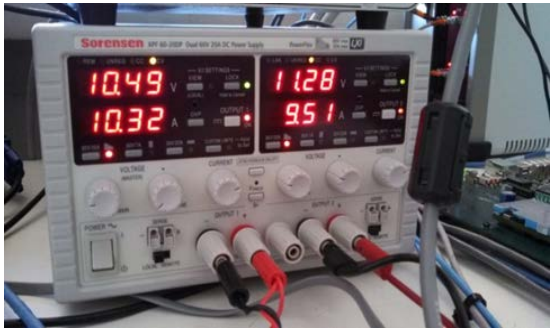
Requirements
Long radiation length materials
High stiffness/mass ratio (i.e. stability)
Radiation tolerant materials
Dual (or triple) purpose elements
Large scale manufacturability
Minimal thermal and humidity effects
Precision placement and survey

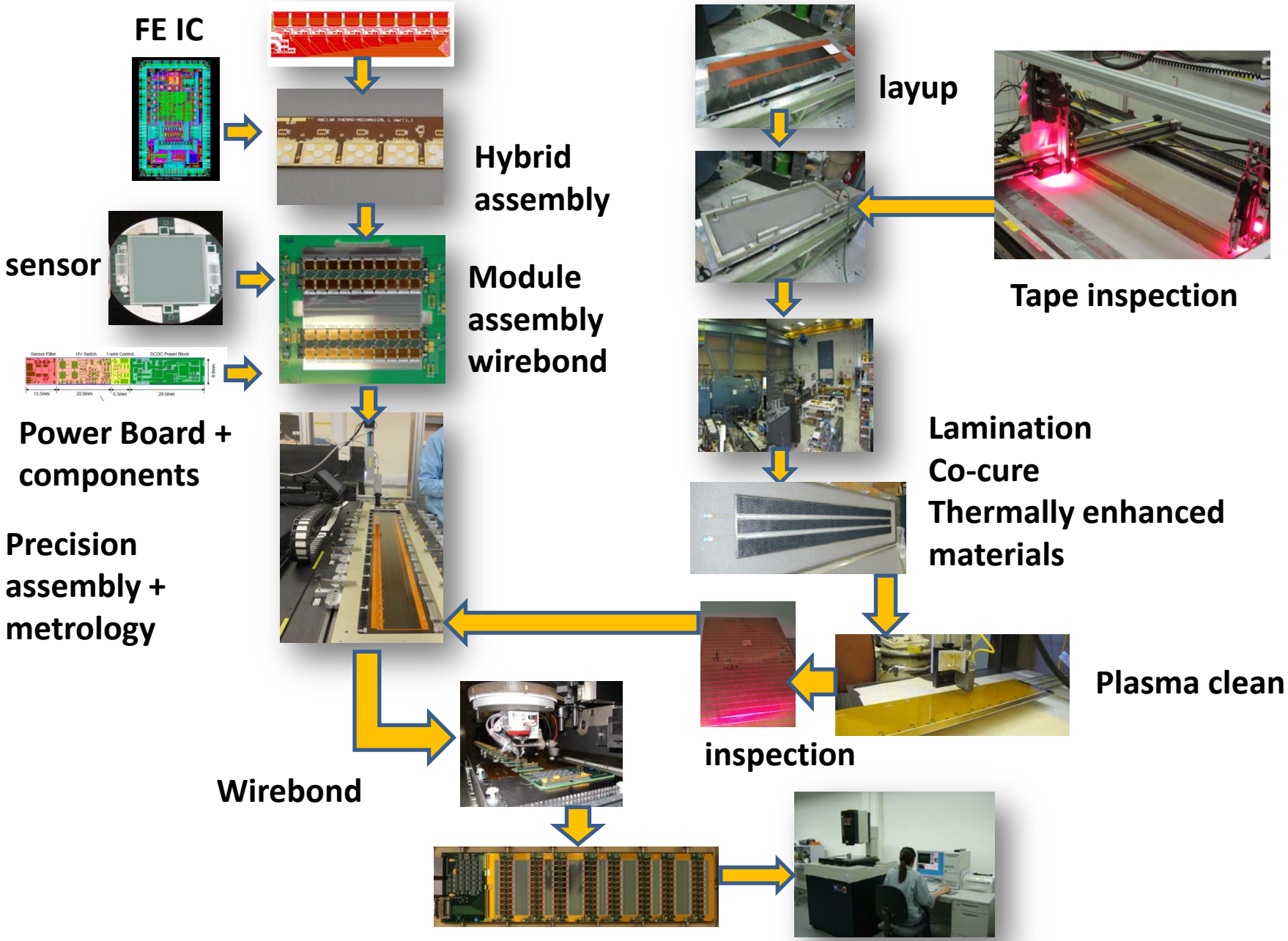
- Low mass to avoid MCS and conversions
- Materials properties
- Integrated functions
- Radiation resistance
- Manufacturing

A Basic Structure








FE IC
Hybrid assembly
sensor
Module assembly wirebond
Power Board + components
Precision assembly + metrology
layup
Tape inspection
Lamination
Co-cure
Thermally enhanced materials
Plasma clean
inspection
Wirebond

Specifics (1)

- Multiple Functions
  - Shielding and grounding
  - integration of electrical components, functions
  - co-cure methods
- Improved materials
  - new ceramics,
  - new carbon or other types of low density foams
  - Adhesives, loading
  - high modulus fibers, among others
  - Thinning methods
- Engineered composites
  - new arrangements and configurations which could yield improved, or even novel, properties
  - laminate orientations and mixed materials.

Specifics(2)

- Materials science and nanotechnology
  - For example, nano-particle dispersions have been shown to improve thermal conductivity and strength of polymers
  - Very dependent on engagement with materials science community
  - Likely to require special processes which we would need to acquire
- Spin-offs
  - other fields may benefit from developments originating in HEP (BES, NP, Accelerators, Astro)
  - Additional funding sources can sustain R&D capabilities through the inevitable funding cycles.
- Measurement techniques and QA
  - Characterization of materials, components, and structures in R&D, fabrication, & in situ
  - 3D metrological methods
  - acoustical microscopy
  - large area automated inspection, thermal imaging
  - precision survey, both static and dynamic.

Specifics(3)

- Cooling methods
  - Further development of liquid and 2-phase methods
  - Gas flow
  - Interaction with materials, interfaces, foams, adhesives
  - Fluidics, plumbing, micro-fluidics
- 3D printing
  - May be of particular interest once materials become more varied
- Simulation and Modeling
  - Can be critical to understanding the behavior of both components and complex structures
  - Understanding performance and reliability
  - Create a well established understanding of basic materials properties in order enable modeling of more complex structures
  - Engagement with industrial and academic collaborators

Specifics (4)

- Alternative LV powering
  - Components
  - System design
  - ASICS
- HV multiplexing
  - Switching transistors
  - System design
  - Irradiation and testing
  - Support of niche technologies
- System design
  - Low mass interconnections
  - Testing and reliability

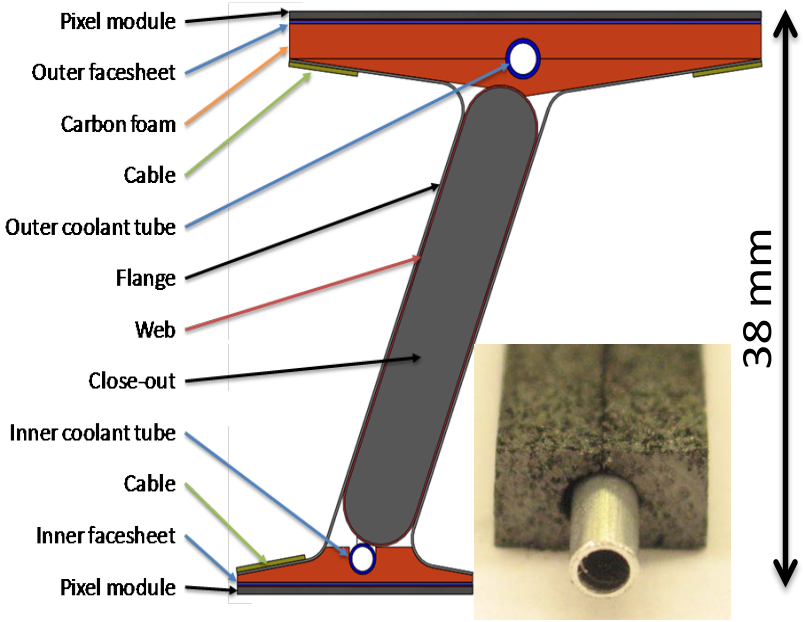
Materials

- Past/present implementations have driven the field mainly to carbon materials/composites, liquid and 2-phase coolants
- Other materials (metals, ceramics, foams, polymers) are found typically in niche applications
- Requires infrastructure – facilities, techs, eng
- Claim additional R&D could lead to capabilities (wrt requirements) which
  - go significantly beyond present state-of-the-art
  - add QA, cost, and/or manufacturing advantages

Present Materials Selection

	Structural (stiff)	Thermally Conductive	Low (long) Radiation Length
Carbon based materials			
Carbon Foam	✓(as core material)	✓✓	✓✓✓
Carbon Fiber Reinforced Plastic	✓✓✓	✓✓✓	✓✓
Carbon Honeycomb	✓✓(as core material)	X	✓✓✓
TGP	X	✓✓✓	✓✓
Polymers/Plastics			
Peek	✓	X	✓✓
Liquid Crystal Polymer	✓	X	✓✓
Ceramics			
Alumina	✓✓✓	✓	✓
Beryllia	✓✓✓	✓✓✓	✓✓
Aluminum Nitride	✓✓✓	✓✓✓	✓
Metals			
Beryllium	✓✓✓	✓✓✓	✓✓
Aluminum	✓✓	✓✓✓	✓
Titanium	✓✓	✓	X
Stainless Steel	✓✓	✓	X

Example Structures



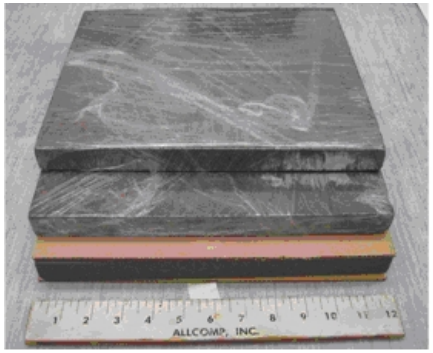
- Typically a cured (or co-cured) structure composed of fibers, a polymer matrix, additional elements such as foam, honeycomb, embedded cooling channels, electrical interconnects
- Low mass CF structure/specialized materials
- Embedded thermal aspect, thin walled pipes, engineered interfaces
- Embedded electrical functions

A Composites Facility

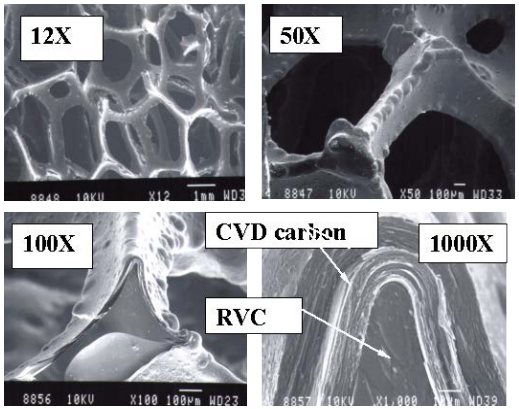
Critical infrastructure needed to serve community

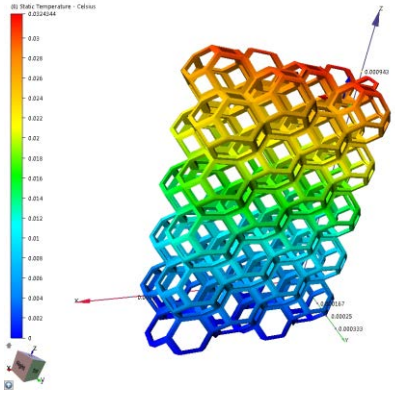
Example: Carbon Foams: Low density, hi conductivity

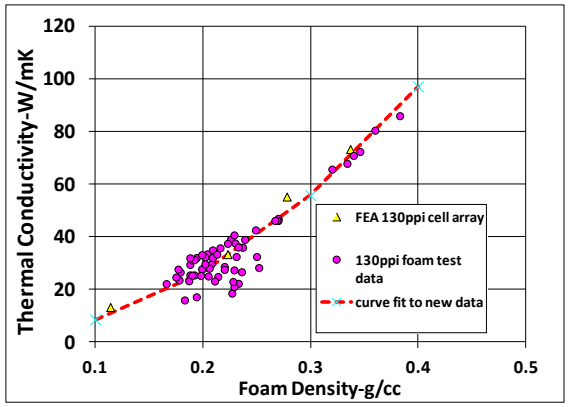
- Developed in collaboration with industry through SBIR
- Qualified for radiation tolerance and thermal/mechanical performance, in use.
- FEA modeling of thermal and mechanical properties.



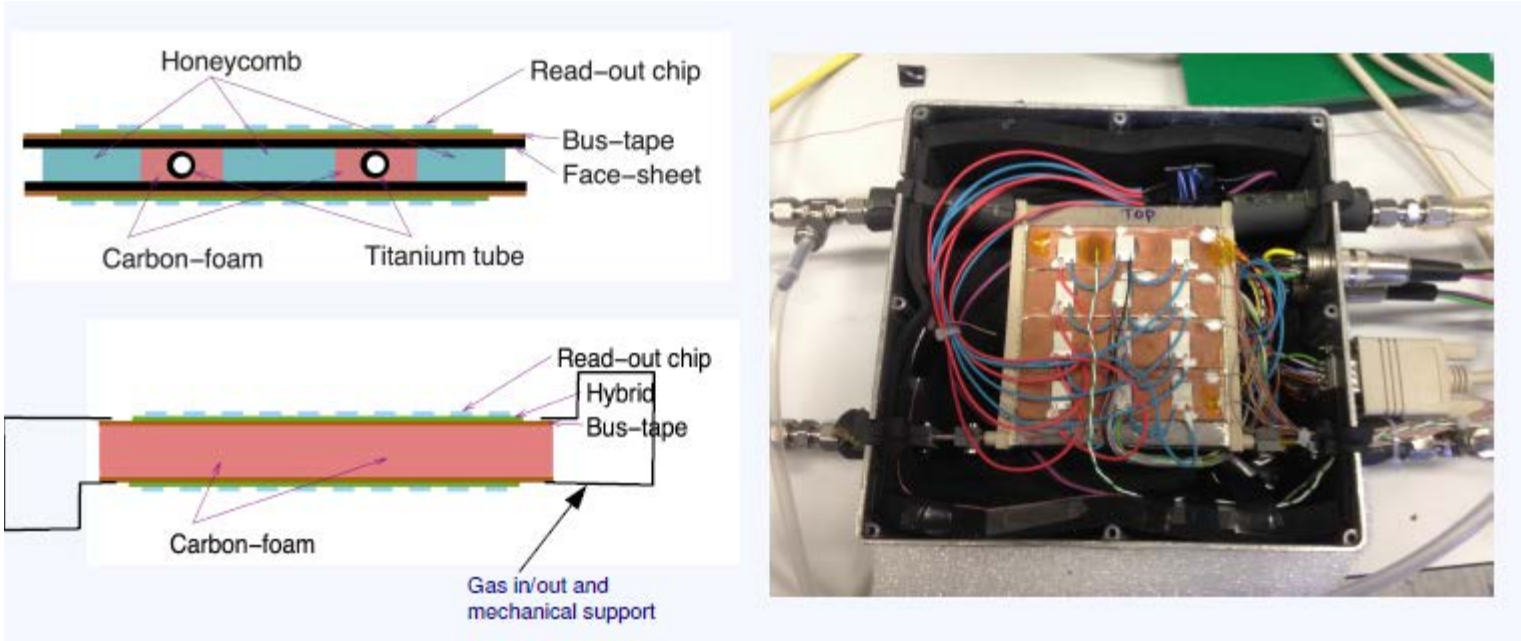
Property	Value(Unit)
Density	~ 0.23 g/cc
Initial porosity	130 pores/inch
Thermal conductivity	30-40 W/m-K
CTE	<2 ppm/°C
Tensile modulus	35ksi
Tensile strength	515psi
Compressive modulus	50ksi
Compressive strength	280psi







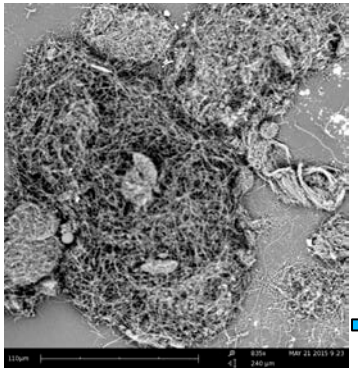
Example: air cooling



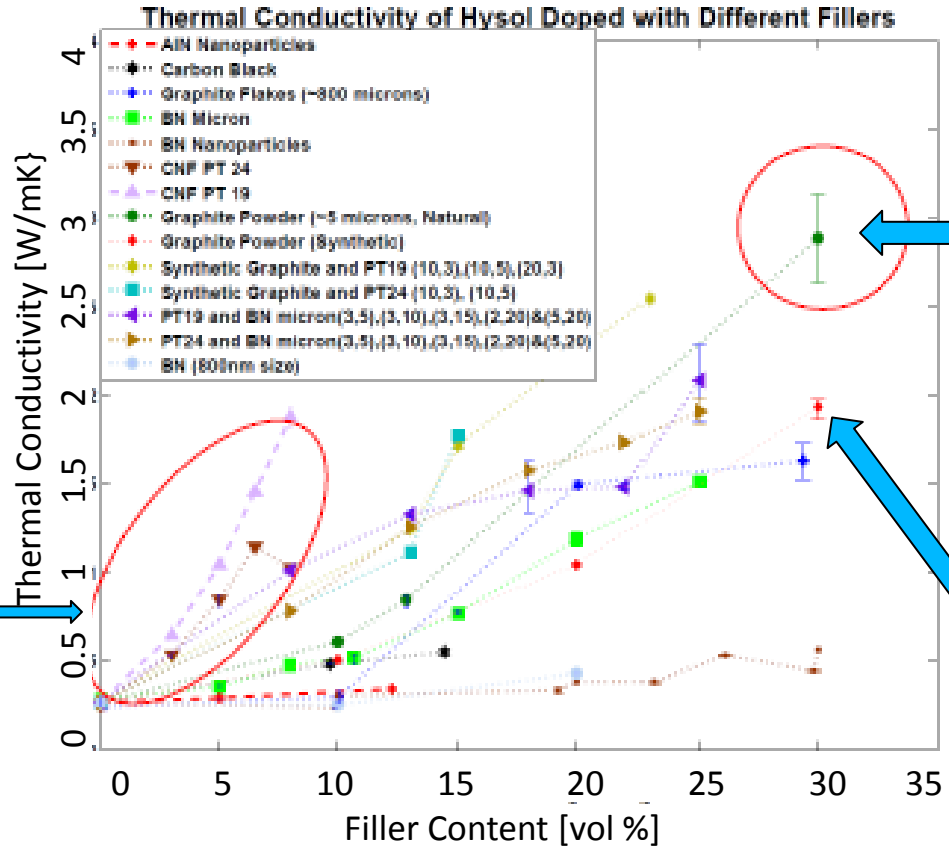
Nigel Hessey (NIKHEF)

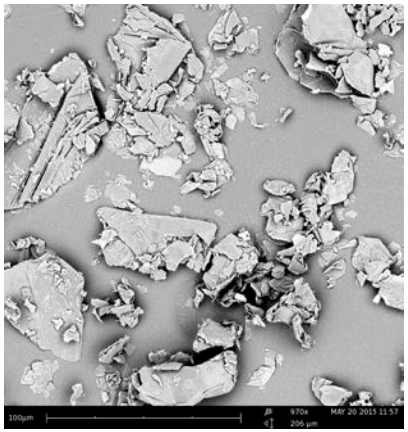
- See also low mass pixels for STAR and ALICE

Example: Thermally Enhanced Materials Survey

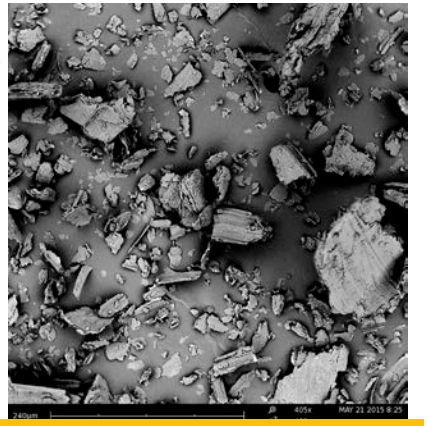


Carbon NanoFiber





Natural graphite



Synthetic graphite

Loading of epoxy or other adhesives

Typical materials in present use for HEP:

1-1.25 W/mK

Database

- Identifying and specifying materials of interest, and their properties, can sometimes be difficult to coordinate.
- For design, modeling, and simulation, it is important that workers use common and agreed upon values.
- A public access database of materials properties should be established.
  - The database would include physical, structural, thermal, and radiation hardness properties.
- The database could later be extended to include specific processes and techniques to match materials to low-mass detector requirements.
- Of value across multiple frontiers

Materials R&D Directions

- Materials
- Processing (co-cure, thinning, loading…)
- Coolants – liquid and gas
- Measurement methods (metrology, thermal…)
- Modeling and simulation
- Structures and integration
- Database

Motion Control and Actuators

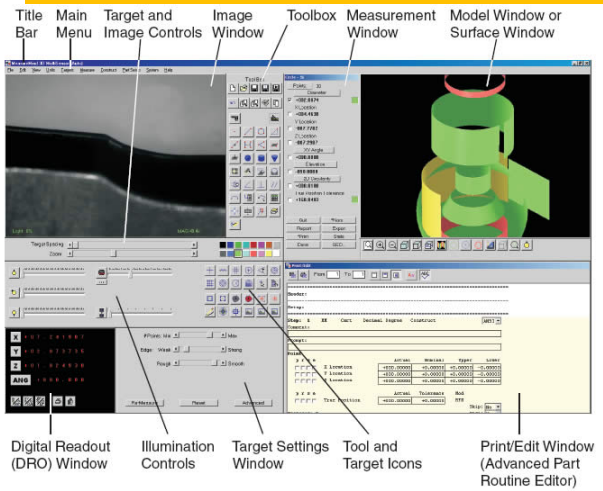
- Well developed commercial aspect driven by photonics, manufacturing, robotics, QA
- Important tool for the fabrication of precision sensor arrays, etc.
  - R&D lies in application to large area and high throughput fabrication
  - Interaction with optical metrology tools
- Use in-situ for alignment, positioning of “layers”
- Custom application to focal planes – fiber positioners

Metrology

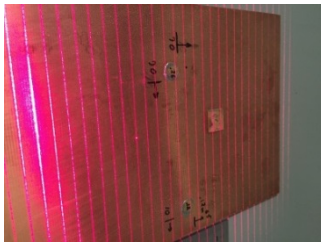
- Precision, non-contact mechanical measurement
- R&D, construction, in-situ alignment & monitoring
- Optical and touch probe CMM's and inspection
- ESPI/TV Holography
- Frequency Scan Interferometer (FSI)
- Laser rangefinding displacement sensor
- Confocal probe
- Vibrometry and acoustic microscopy

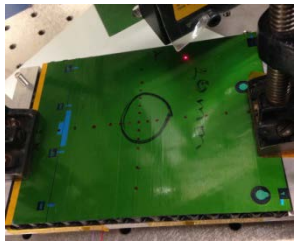
Examples

Coordinate Measurement

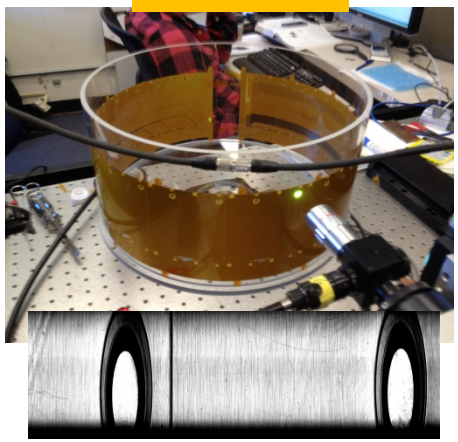


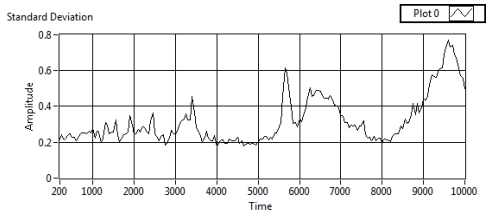
Defects



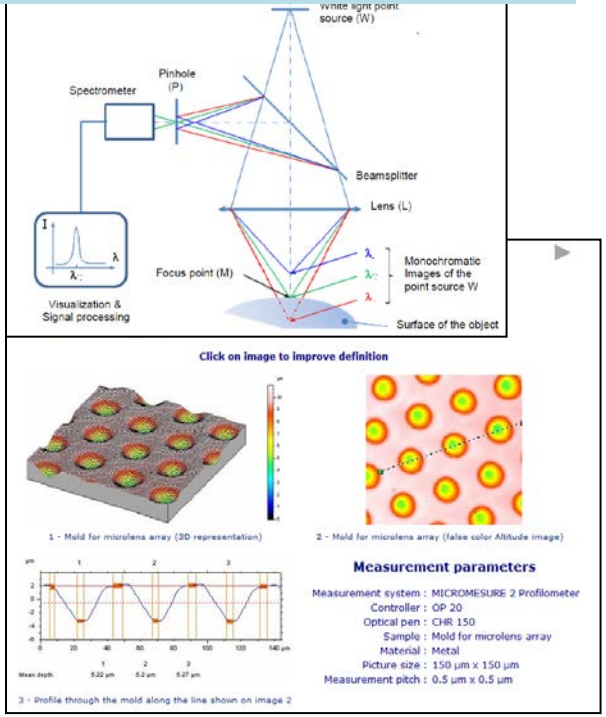


Imaging

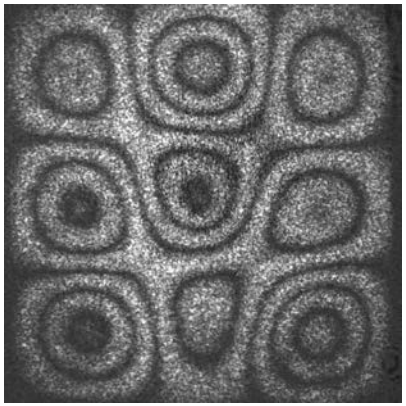


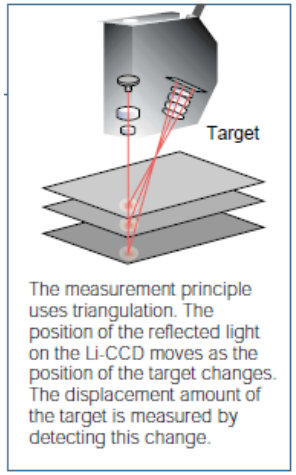


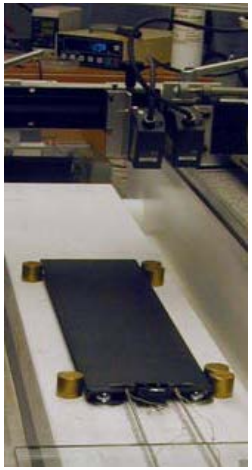
3D Confocal Microscopy



TV Holography/ESPI

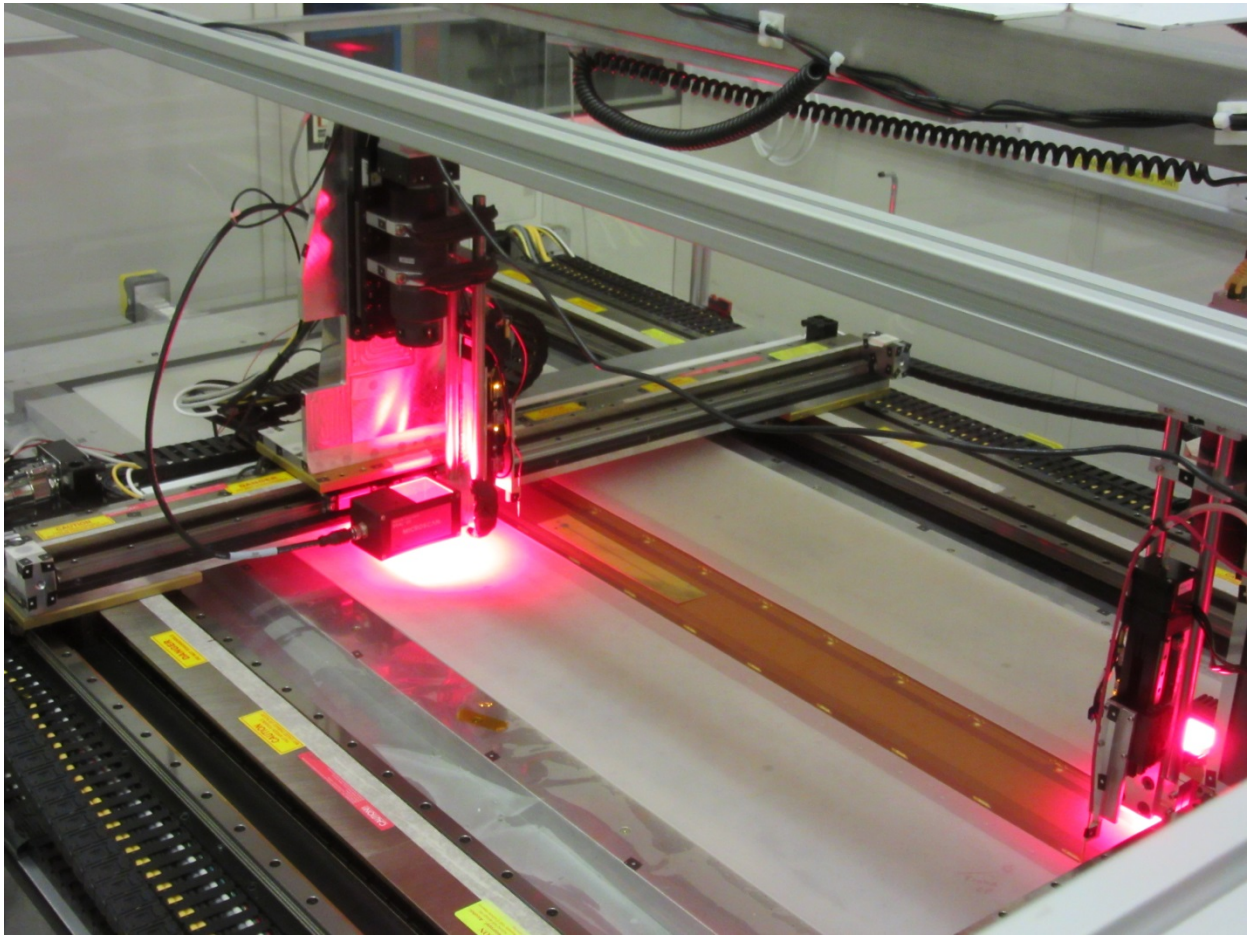






Laser Scanning

Example: custom inspection system



Roy Wastie: Oxford University

Metrology

Technology	Application	Resolution	Interface	Ease/Speed
CMM-touch	Large objects	x/y/z ~ μm's	commercial	Teach mode
CMM-optical Imaging	In plane location Small heights	x/y/z ~ μm's	Commercial or custom	same
ESPI	Dynamics	x/y/z ~ μm's	commercial	R&D tool
FSI	In-situ alignment Stability	One axis	custom	System design
Laser Displacement	Flexible heights R&D tests	z ~ μm's	User defined	User defined, 1 KHz
Confocal Probe	Precision heights Small area	10-100 nm	Limited use commercial or user	User defined, 100 Hz–2 KHz

Research Directions

- Mainly driven by experimental needs
- High throughput inspection systems
  - Commercial vs custom
- 3D imaging over large areas is a rapidly developing field due to industrial QA
  - Understanding the capabilities of this technology may help realize new approaches across frontiers
- Active systems which combine metrology with motion control and actuation
- Time resolved systems to measure vibration and find hidden defects

Power

- All existing trackers have used a very conservative power (LV and HV) distribution systems
- Treat each module as an individual and independently fed system
- In the last ~8 years important alternative architectures have emerged
- Arguably the biggest innovation in the field due to dramatic efficiency and material improvements.

Power Distribution

- For large systems, with limited access space, services cross section can be a major issue
- Mass of services
- Inefficient distribution demands extra cooling
- Required approaches feature
  - DC-DC conversion methods
  - Serial current distribution
  - Multiplexing
  - Monitoring and control functions
  - Power cycling in the LC application
- Must respect demands on reliability, low noise, grounding and shielding, interaction with mechanics and cooling

D.Lynn
M.Newcomer
A.Greenall
P.Phillips
S.Dhawan
G.Blanchot

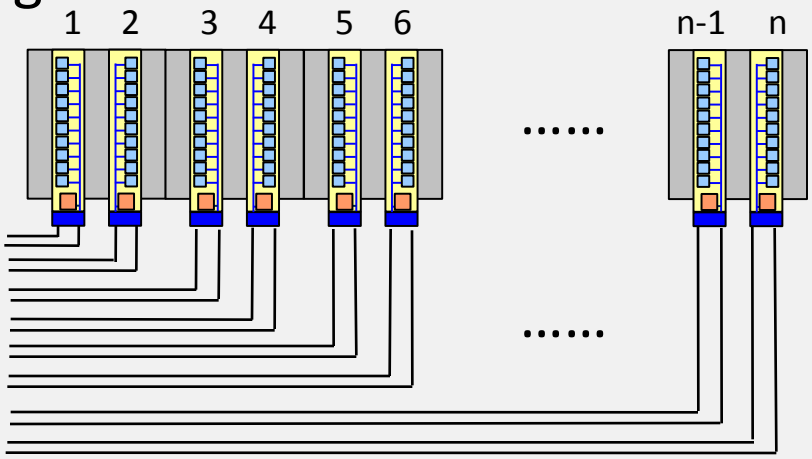
Powering Alternatives

- Independent Power
  - One cable with current I_{mod}, and V_{mod} for each module
- Serial Power
  - Reuse current, connecting N modules in series, one cable carries current I_{mod}, $V=NV_{mod}$
  - Practical implementation utilizes shunt regulation and active bypass protection, requires extensive AC coupling of control and data
- DC-DC Conversion
  - Step down voltage by factor R at each module, one cable carries $I_{tot}=Ni_{mod}/R$ at $V=Rv_{mod}$
  - Practical implementation utilizes switching converters either charge pumps or inductive
- These alternative approaches can be very efficient compared to linear regulation

Power architectures

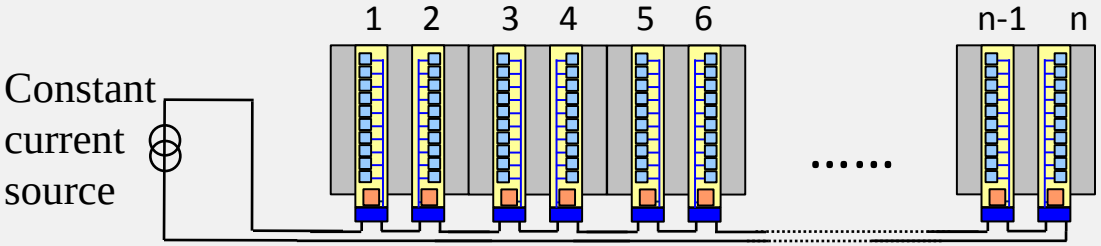
- Independent powering

Hybrid current = I
Number of hybrids =n
Total current = nI
Power lines = n



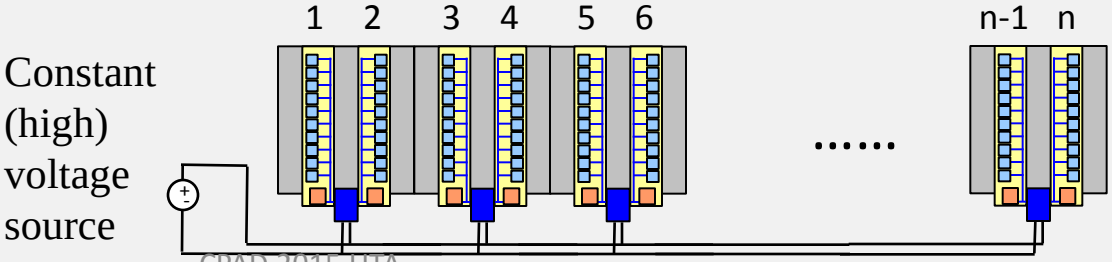
- Serial powering

Hybrid current = I
Number of hybrids =n
Total current = I
Power lines = 1

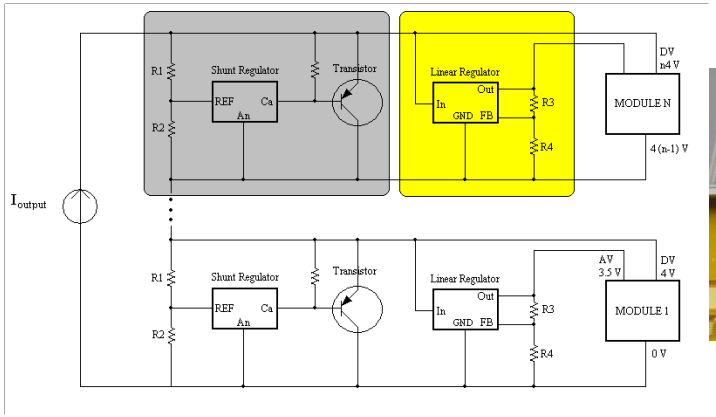


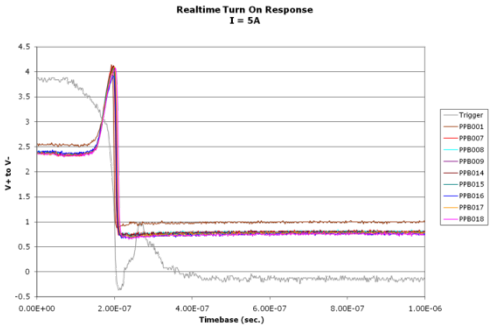
- DC-DC powering

Hybrid current = I
Number of hybrids =n
Total current = n(I/r)
Power lines = 1

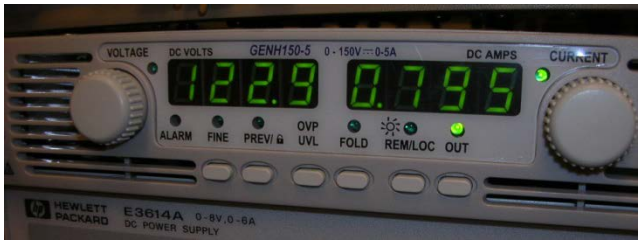


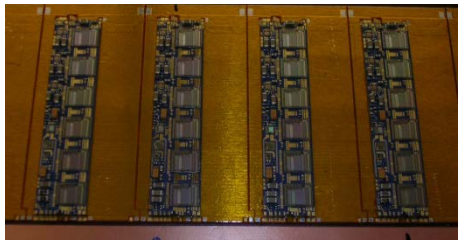
Serial Power



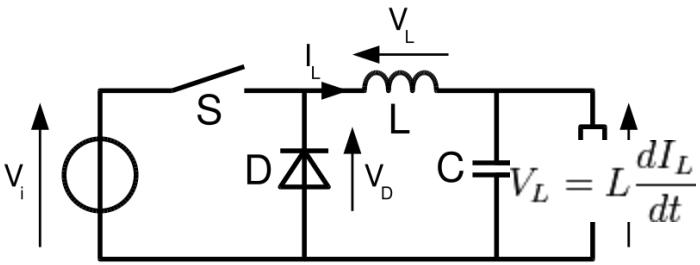


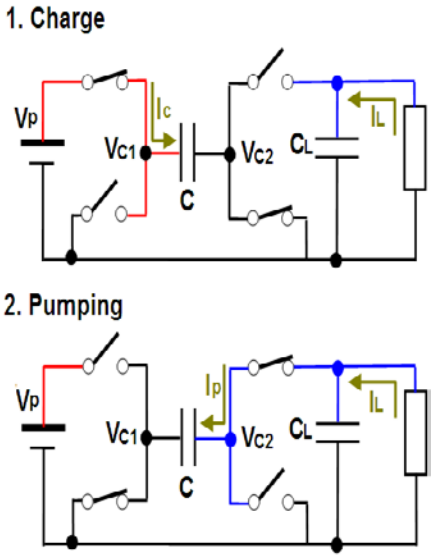
- Many variations on this have been studied in the R&D efforts, custom ASICs exist and are in development
- Large systems (>30 drops) have been operated with AC coupling
- Stable, low noise behavior obtained
- Failure recovery and control circuits have already been tested
- Most efficient when current per module is uniform





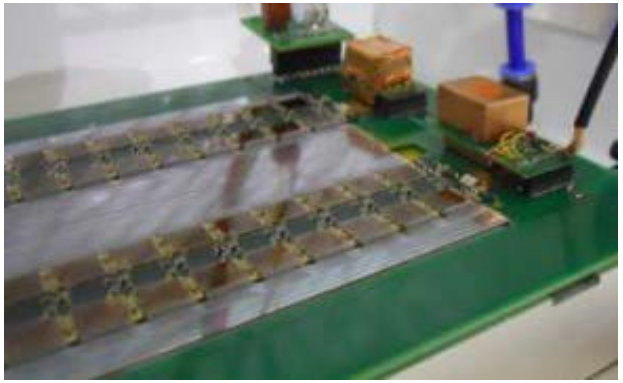
DC-DC Conversion



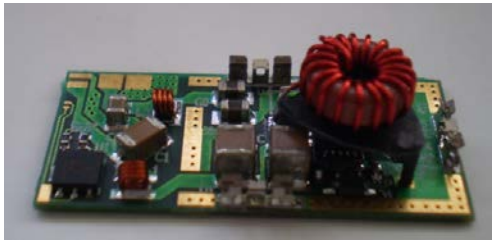


Charge pump

- DC-DC converters require high frequency clocks
- Realistic circuits have been operated in close proximity to sensor/modules with excellent noise performance, when adequately shielded.
- Main concern is the mass and size of required components
- Dramatic improvement in inductor size

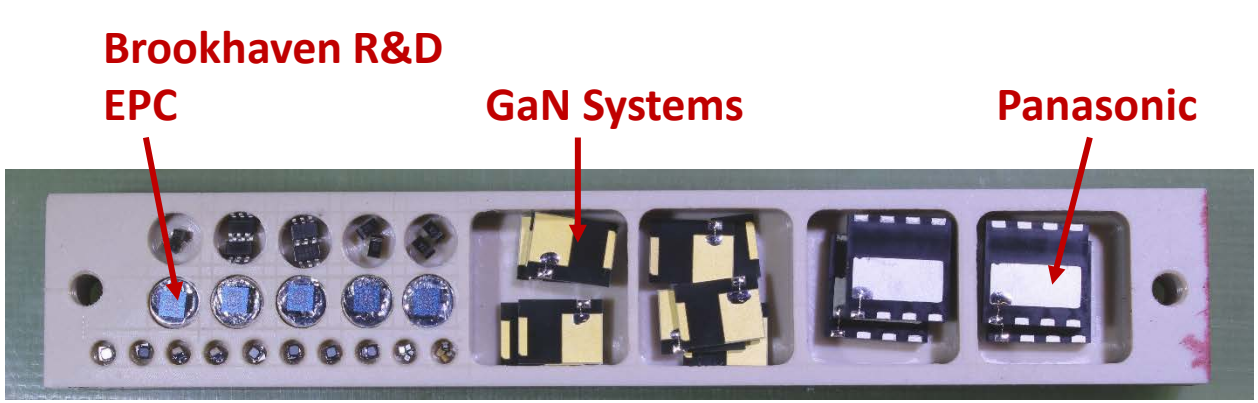


Buck converter with custom air core inductor

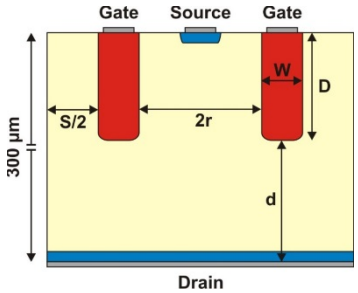


High Voltage Multiplexing

- R&D has focused on
  - Finding a suitable rad hard switch
  - Working in some cases with niche companies
  - Research consortia
  - System implementation
- Compound devices (SiC and GaN) and novel Si



3D Vertical Silicon JFET
CNM Spain



Role of ASIC Design

- Advanced power devices require fully engineered rad-hard systems
  - Clocks and switches
  - Control
  - Monitoring
  - Protection
- ASIC design activities can be as substantial as those aimed at front end readout
- Additional chip sets
- Can require specialized testing and QC

Research Areas and Directions

- Radiation hard regulators, drivers, switching converters, charge pumps, HV low leakage switches
- Low mass inductors, air core inductors, low profile inductors
- Power cycling methods, stabilization, turn-on
- Low mass shields
- Control and monitoring architectures
- System design
- Low mass cables – flexible circuits, aluminum
- Connectors

Collaboration

- Collaboration has already been a hallmark of this area
- Important contributions from universities, labs, and industry (including SBIR)
  - Typically major infrastructure provided at labs
  - New products, capabilities from industry
  - Innovation, ideas, analysis, components, experimental connections at universities
- All should be encouraged and supported
- Possibility to work with other DOE Science offices on common areas

Recommendations for Support

- Physical infrastructure at universities and Nat. Labs
- IC designers – power, protection, and mux and DCS
- Simulation of material properties – collaboration with materials scientists, interdisciplanary
- Exploration of new metrology tools
- Materials studies
- Irradiation facilities
- SBIR: we should review the SBIR topics in this context
- Cooling
  - 2 phase
  - Gas flow

Conclusions

- Already a well established aspect of advanced instrumentation
- A variety of applications across the 3 frontiers
- Potential for important new developments and improvements in materials, structures, methods
- Requires on-going support for infrastructure
- Potential spin-offs to science and industry, good area for collaborative engagement
- Should develop a shared knowledge base which can grow as we learn more