Low-Energy Electron Beam Dosimetry and Applications

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Classification of electron accelerators used in radiation processing

- Important parameters are energy and beam current
- Energy determines the thickness of product that can be uniformly processed
- Current dictates product throughput or efficiency
  - Low energy accelerators– typically range from 150 keV to 500 keV, usually self-shielded
  - Medium energy accelerators– 0.5 MeV to 5 MeV, beam powers up to 500 kW
  - High energy– 5 MeV to 10 MeV, typical powers up to 50 kW, some units up to 500 kW
- Self-shielded laboratory units
  - Used for research, process development, dosimetry studies

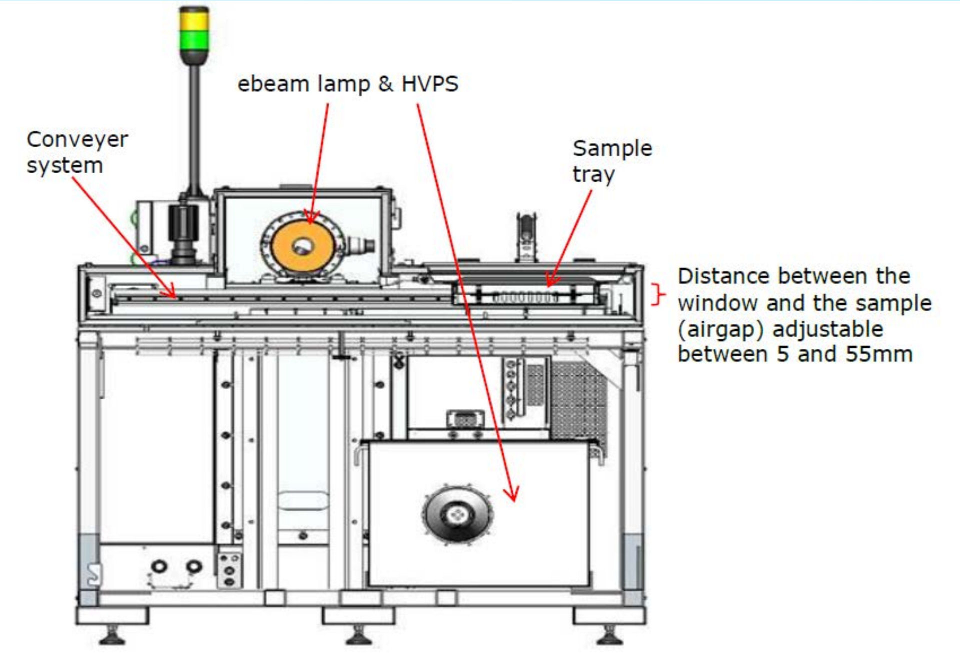
Comet EBLab-300 Laboratory Unit

- Self-shielded, self-contained electron beam unit
- Semi-custom design, extended energy range from 100 keV to 300 keV
  - Covers most LEEB radiation processing applications
- Additional shielding, R&D required during design and development
  - Extensive testing procedures
- Delivery to NIST expected January 2019
- To be located in new laboratory space (H-wing) in Radiation Physics Building

Comet EBLab-300 Detailed Specifications

ebeam Engine

- Acceleration voltage adjustable between 100 and 300 kV
- Beam current adjustable up to 20 mA through user interface (4.5 kW power limit)
- Dose uniformity, +- 10% at 30 mm from window
- Field width 230 mm
- Surface dose rate at 300kV, 15 mA (at 30 mm distance) > 1150kGy x m/min
- Surface dose rate at 100 kV, 20 mA (at 10 mm distance) > 2700kGy × m/min
- Dose rate adjustable through user interface
- Doses up to 450 kGy in a single pass

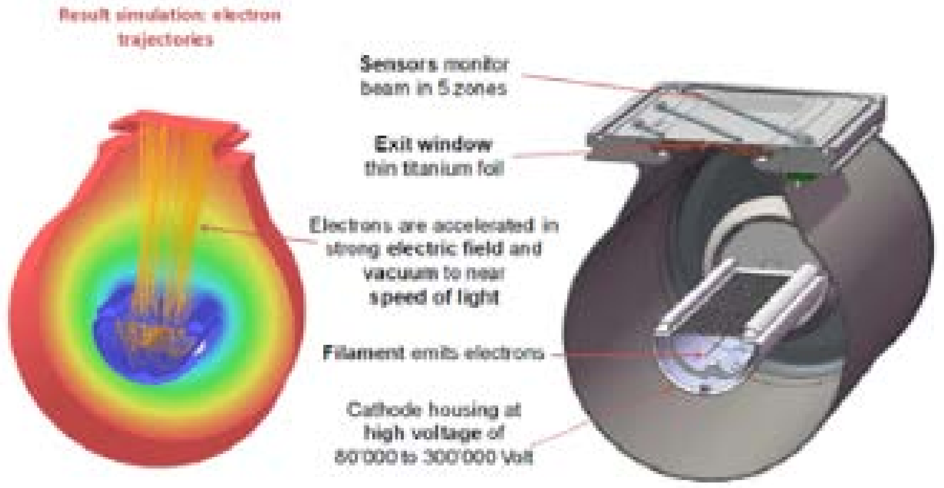


Sample Handling

- Sample tray can accommodate samples up to 21 cm x 30 cm, and 50 mm thick
- Transport speeds variable from 3 m/min to 30 m/min

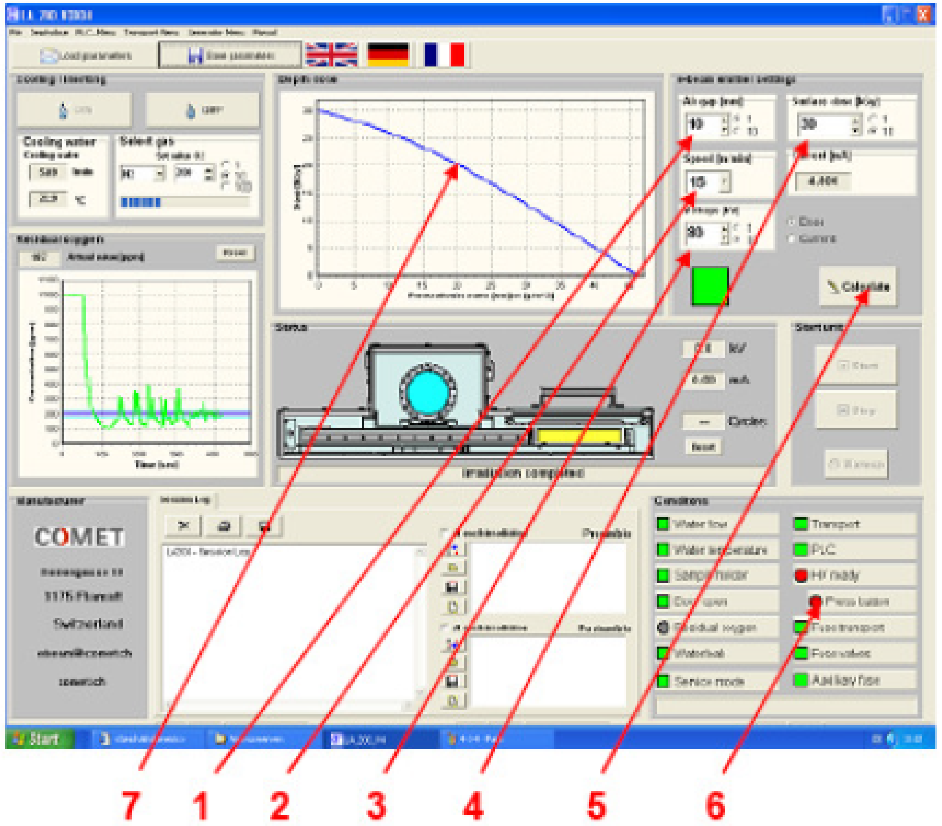
Comet ebeam Lamp

- Vacuum-sealed beam emitter
- Electron “shower”
- Grounded anode
- Thin (10 micron) Ti exit window to maximize transmission



EBLab-300 User Interface

Setting the desired parameters

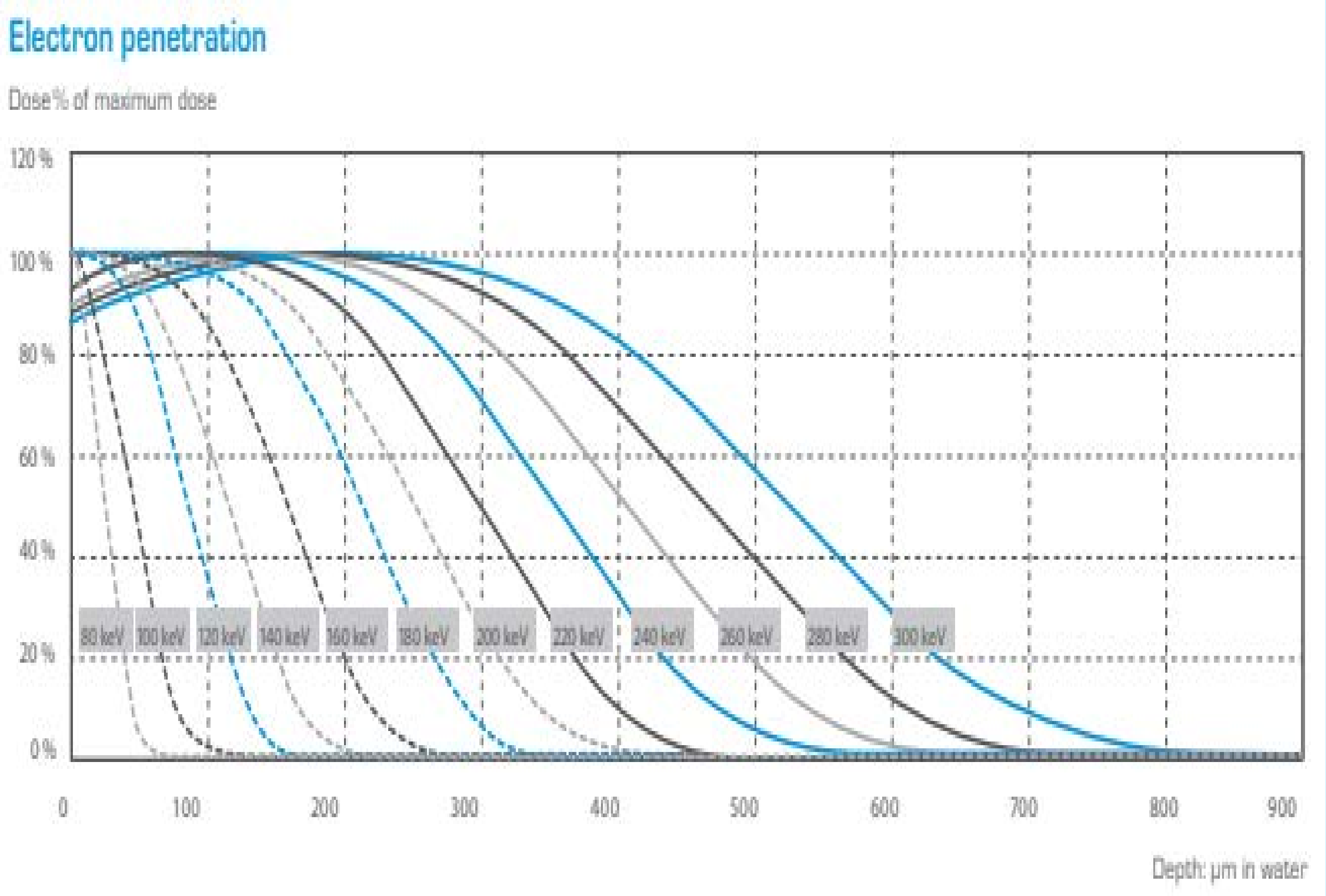


1. Air gap between ebeam lamp window and sample material (where dose is deposited)
   Air gap to the floor of the variable pattern holder: 60mm
   Air gap to the pattern holder with fixed height: 10mm
2. Speed at which the sample material passes by ebeam Lamp electron window
3. Voltage at the ebeam Lamp
4. Estimated surface dose on the sample material
5. Command to calculate the required electric current of the ebeam Lamp - select after parameter modification
6. HVPS not yet ready (action: press the red button on the control panel)
7. Estimated process of the depth dose, assuming that the sample material has a density of $1 g/cm^3$. In case of greater density, the penetration depth is smaller, and vice versa.

Courtesy: Anthony Carignano, ebeam Technologies

Low-Energy Electron Beam Penetration

- Low-energy electron beams have an extremely steep dose gradient
- Even at 300 keV, penetration depth in products and materials is less than 1 mm (unit density)
- This makes the quantification of dose extremely difficult



Low-energy e-beam advantages

- Simpler components
  - Maintenance free electron source
  - Ebeam emitter is vacuum-sealed, customer replaceable
- Very high surface dose rates
- Minimal radiation shielding compared to higher energy accelerators or cobalt-60 irradiators

https://ebeamtechnologies.com/products/ebeam-engines/

Low-Energy Radiation Processing Applications

- Sterilization
  - Surface sterilization of food and packaging materials
- Food-safe packaging
  - Curing of inks, crosslinking
- Materials Modification
  - Crosslinking
  - Radiation grafting
  - Protective coating for metal coils
  - Pressure-sensitive adhesives

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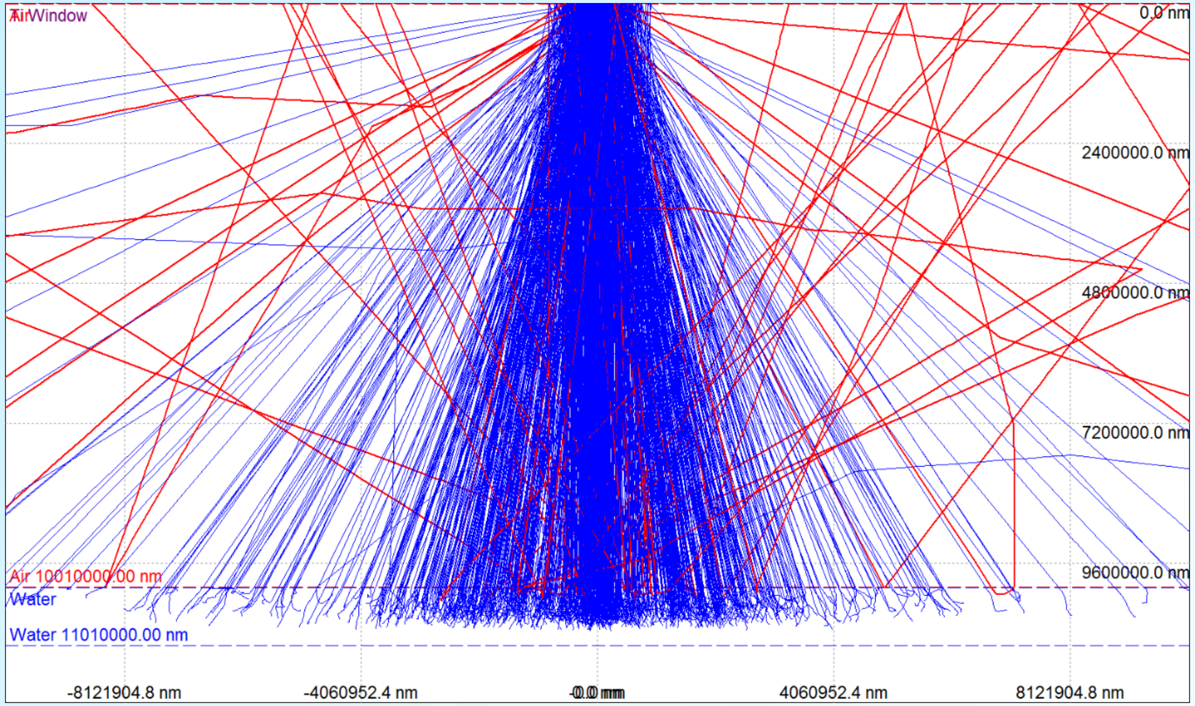
http://www.packworld.com

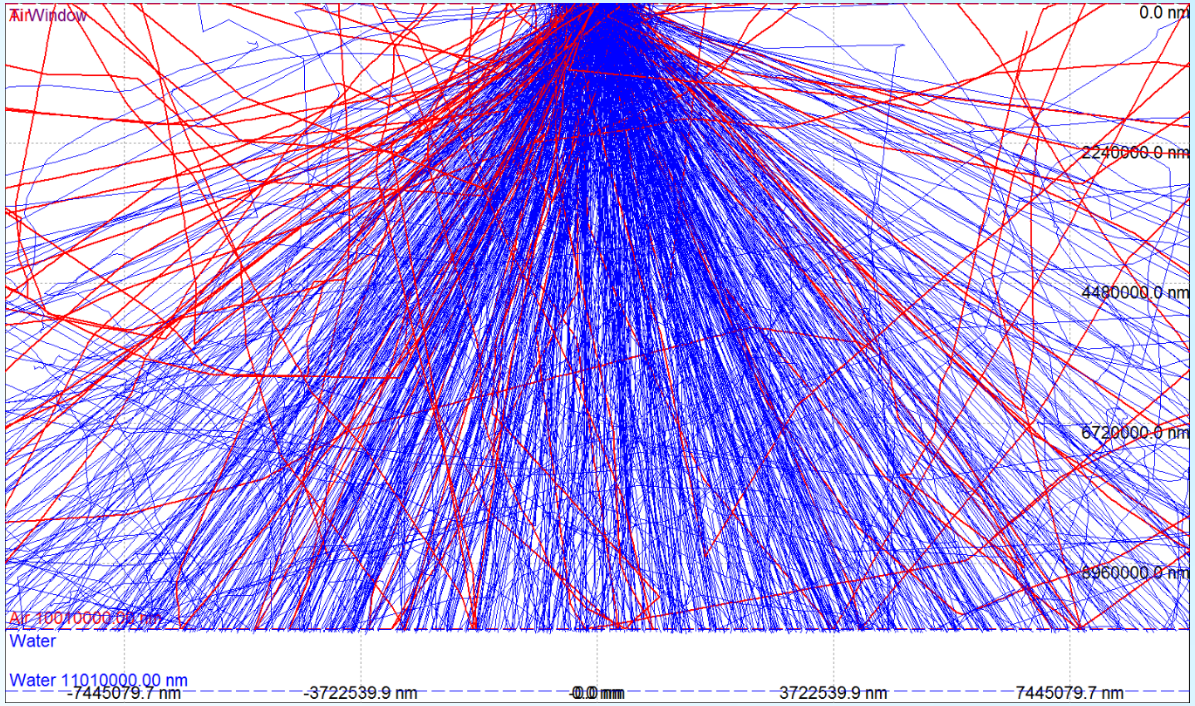
* Does not imply endorsement by NIST

LEEB Dosimetry Challenges

Electron beam penetration into water—10 micron Ti window, 10 mm air, 1 mm water



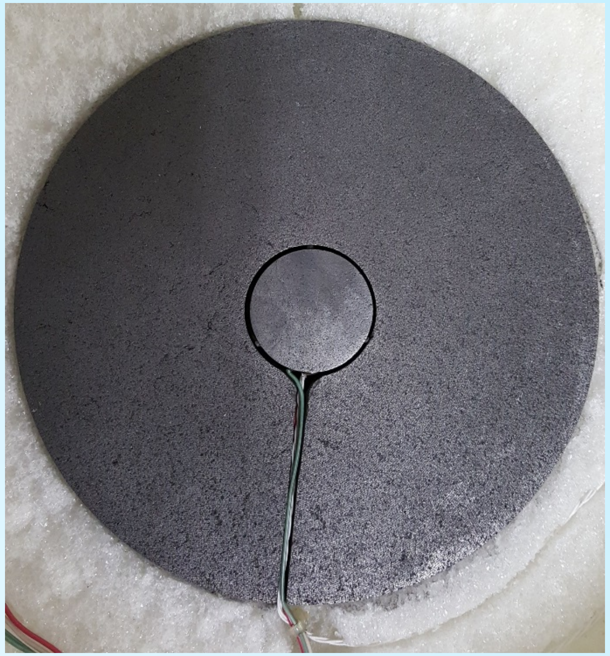
300 keV



100 keV

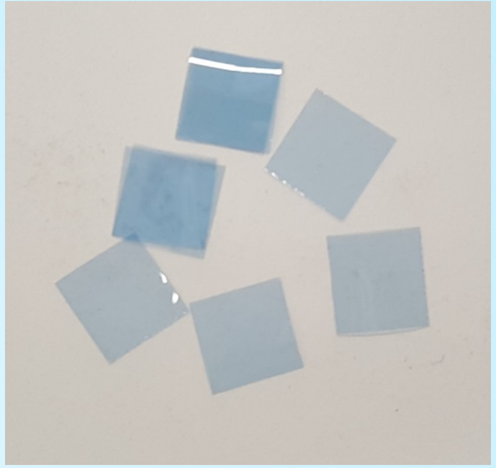
LEEB Dosimetry Challenges

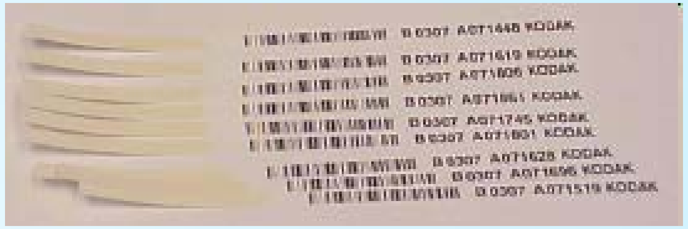
- Thermal effects
  - Significant heating of the exit window and the air surrounding the samples/dosimeter
    - This heat transfer can have a significant effect on the measurement of dose using calorimeters
    - Thermal shields can cause additional attenuation of the primary beam
  - The response of most thin film dosimeters can vary significantly with ambient temperature
- Dose rate effects
  - Dosimeter response may vary with dose rate
- Radiation damage of components

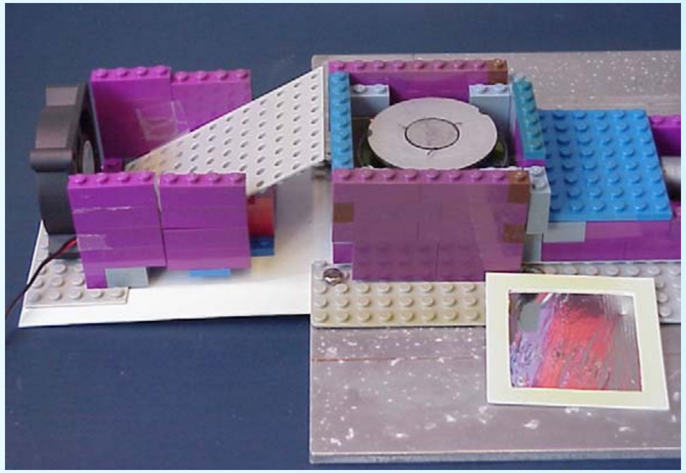


Approaches to Low-Energy dosimetry

- Thin film dosimeters (radiochromic)
  - Response dependent on temperature and humidity during irradiation
  - Dose rate dependence
- Alanine film dosimeter
  - Relatively insensitive to influence quantities
  - Large dose gradient due to thickness of coating
- Graphite calorimeters
  - Sensitive to environmental heating
  - Steep dose gradient
  - Totally absorbing



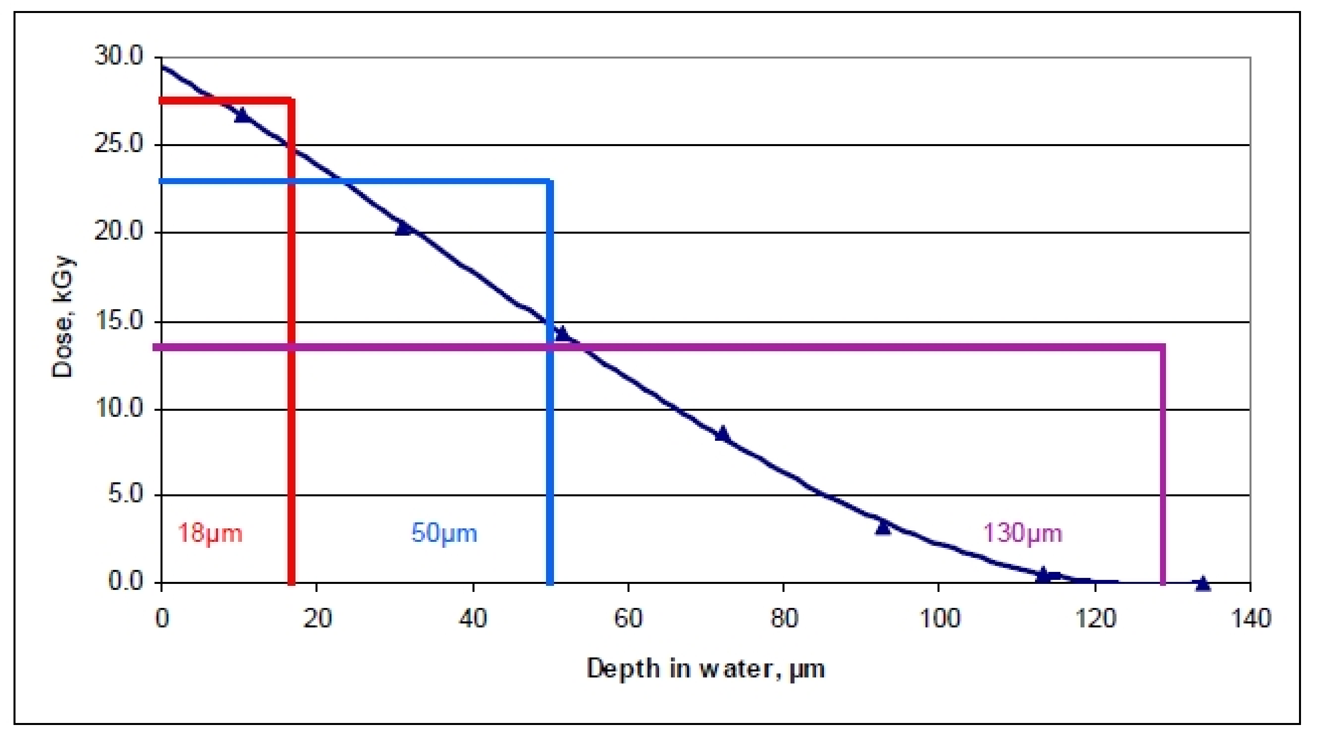




J. Helt-Hansen et al. / Radiation Physics and Chemistry 74 (2005)

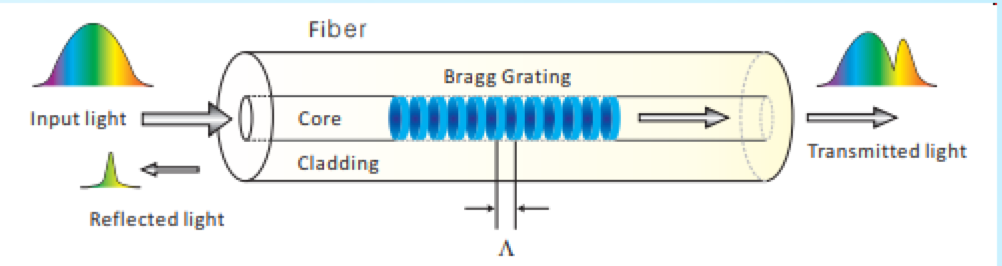
Low Energy Dosimetry— D_μ Concept

- Account for dose gradient in dosimeter
- Reference alanine dosimeter totally absorbing
- D_μ – average dose to water in first micron of water-equivalent absorber
- Dosimeter calibrations performed at high energy– transferred to low energy -> traceability
  - Need response function, dosimeter depth-dose, Monte Carlo (backscatter correction)
  - Derive surface dose from apparent (measured) dose
    - Gradient correction factors can be as high as 5

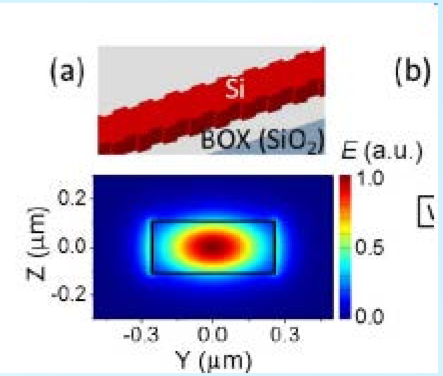


Novel Approaches to Low-Energy Dosimetry

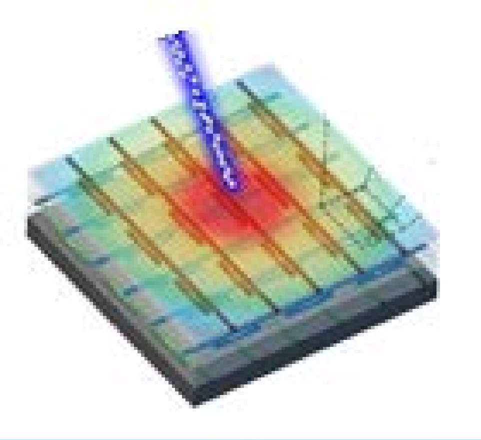
- Avoid limitations posed by traditional methods
  - Photonic sensors
    - Fiber-Bragg gratings (FBG)
      - Temperature-dependent resonant condition due to changes in refractive index
      - Resolution ~100 mK
      - Probed photonically with a laser
      - Immune to electromagnetic interference
      - Compact size
    - Photonic crystal cavity sensors
      - Nano-fabricated silicon cavities
      - Spatial resolution ~1 μm
      - Temperature resolution ~ a few μK
      - Can be imbedded, multiplexed -> sensor arrays
  - Goal is to design, develop and validate a system aided by the EBLab-300 unit



L. Wang, N. Fang and Z. Huang http://dx.doi.org/10.5772/53551

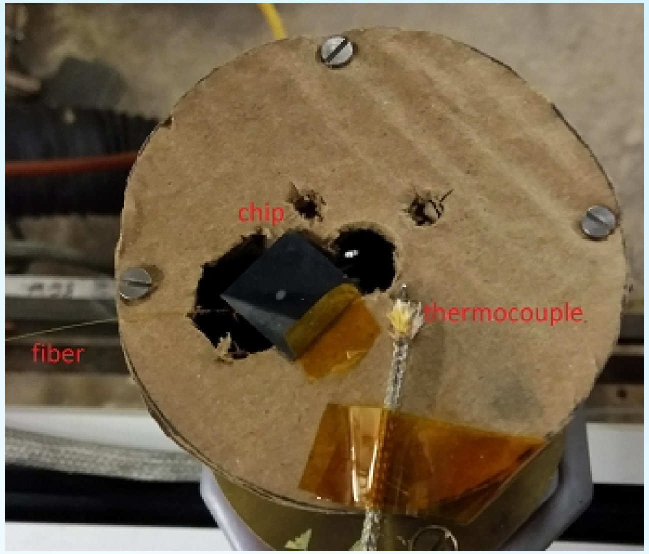


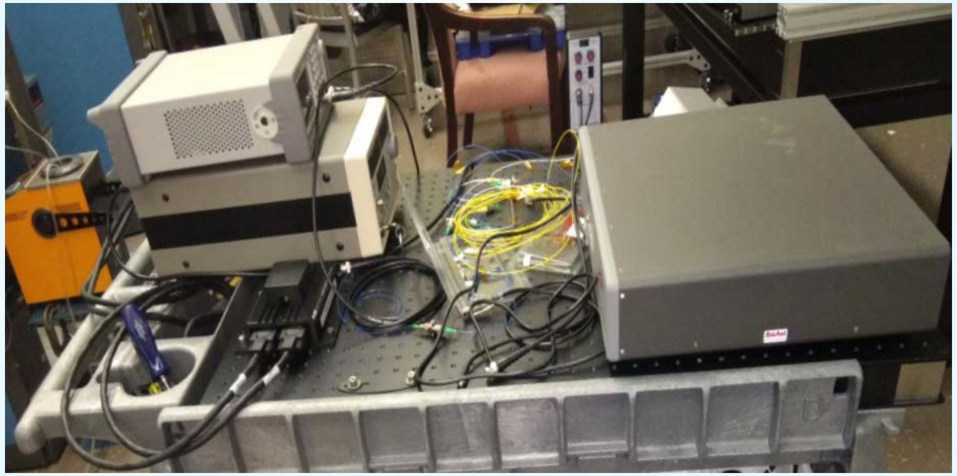
N. Klimov et al., Vol. 40, No. 17 Optics Letters (2015)

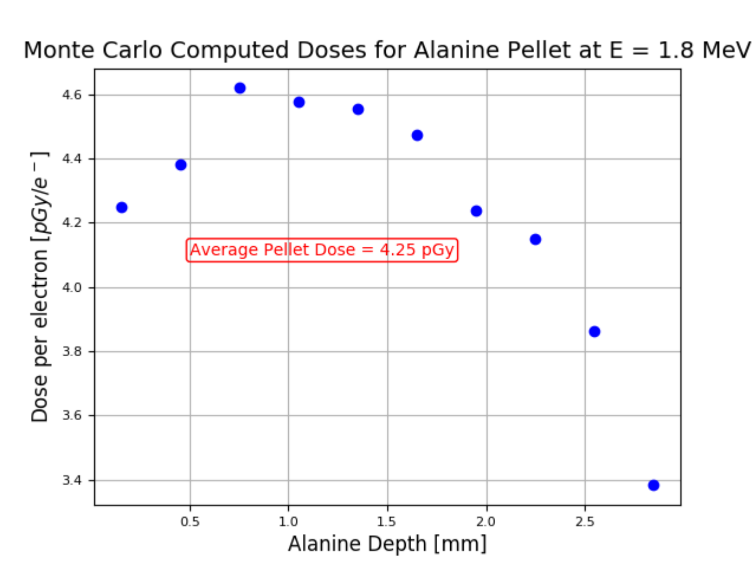


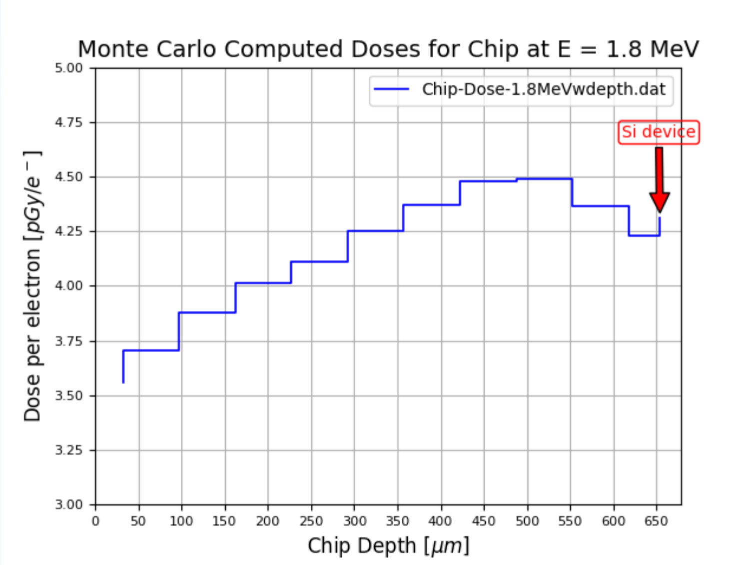
Electron beam testing of FBG sensor

- Real-time irradiation of FBG silicon chip photonic sensing system
- Interrogated with an ~1550 nm laser coupled through fiber-optic cable
- 1.8 MeV electron beams, cycled on and off in 30 s intervals
- Record temperature at chip location with thermocouple
- Measure system response as a function of temperature (dose)
- Use alanine pellets to determine dose to sensor

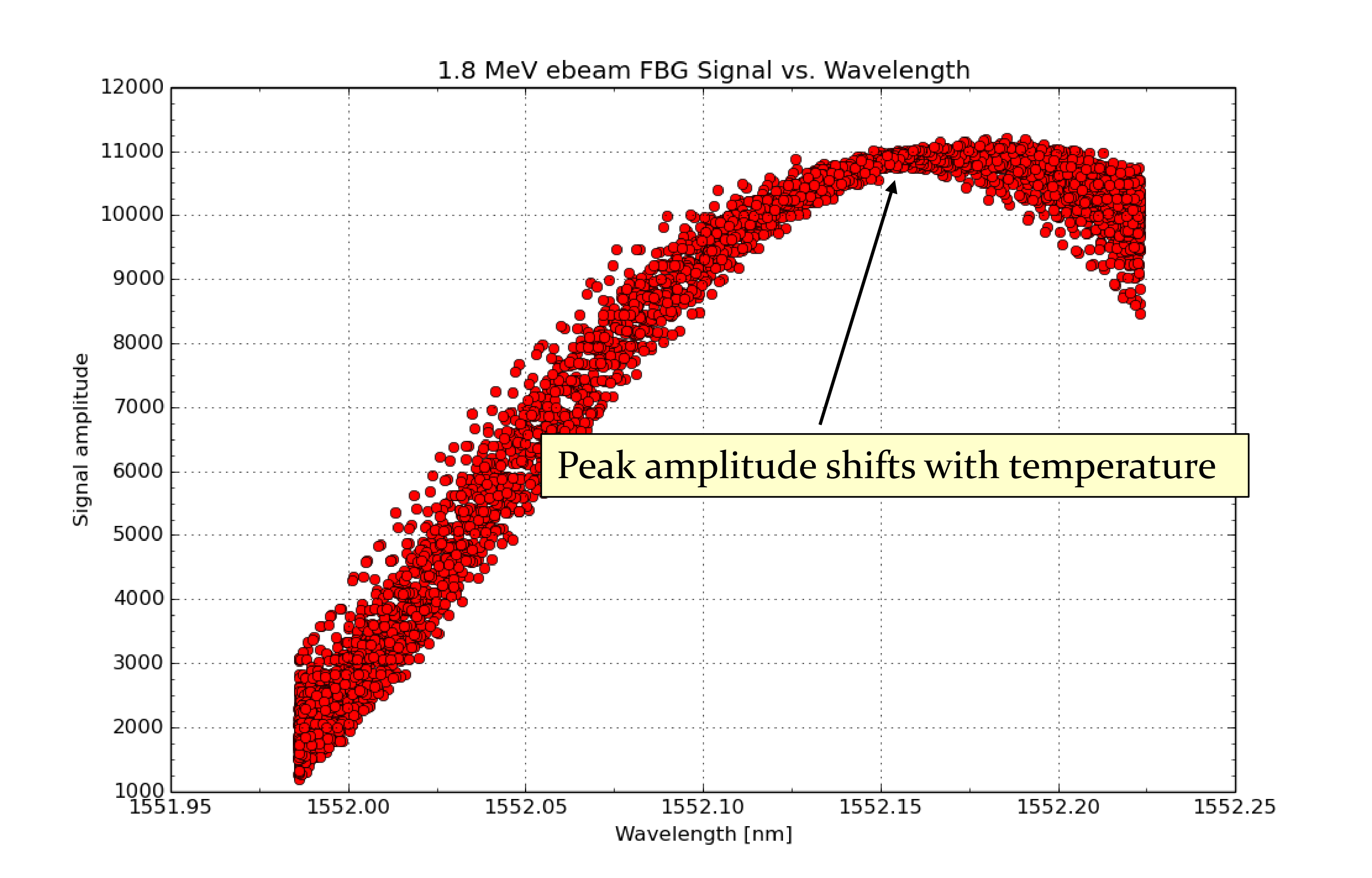




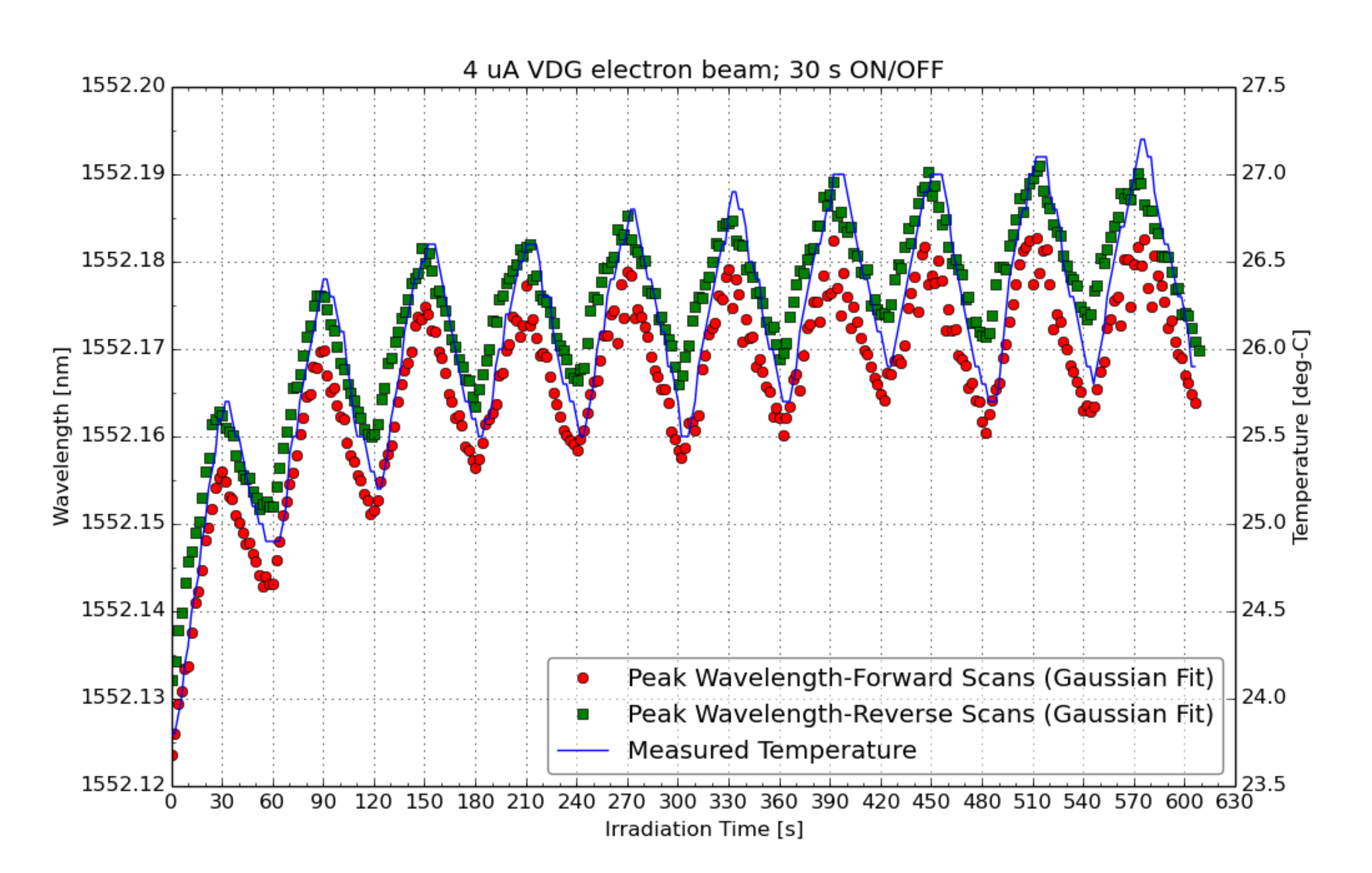




FBG Raw Signal vs. Wavelength Under 1.8 MeV electron irradiation

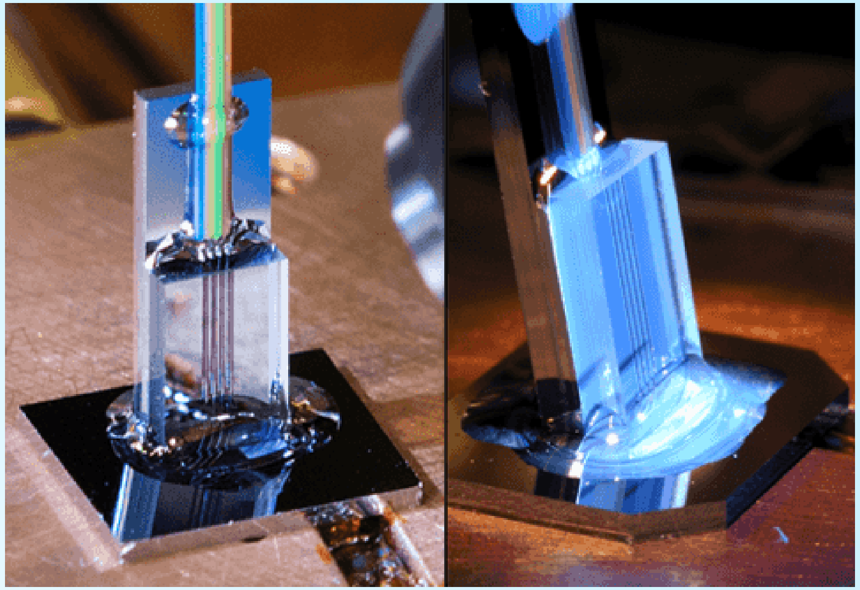


FBG sensor response to 1.8 MeV electron beam

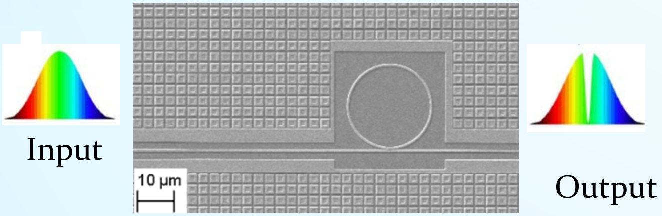


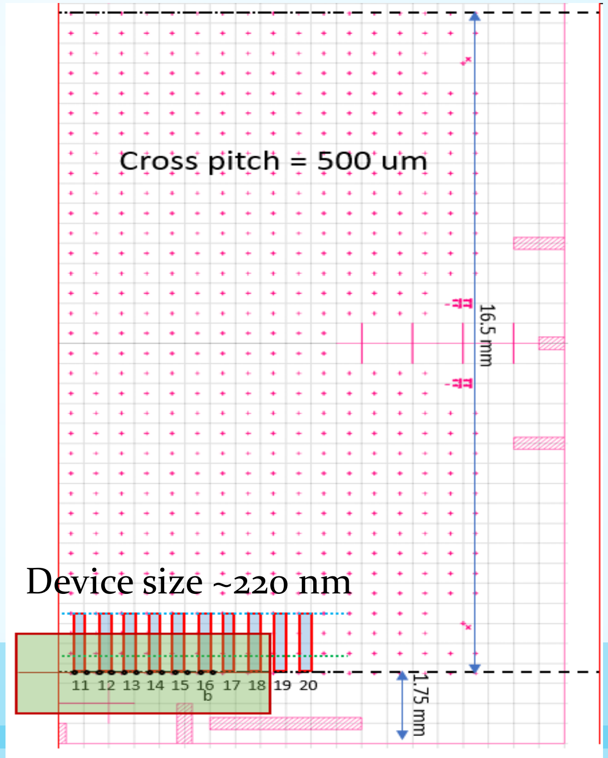
- Check of system functionality
- Ten beam cycles, 30 s on, 30 s off
- Nominal dose rate = 13 Gy/s
- Very little thermal insulation– heat exchange with surroundings
- FBG sensor’s thermal response on the order of 10-15 pm/˚C

Nano-fabricated photonic crystal ring resonators and cavities

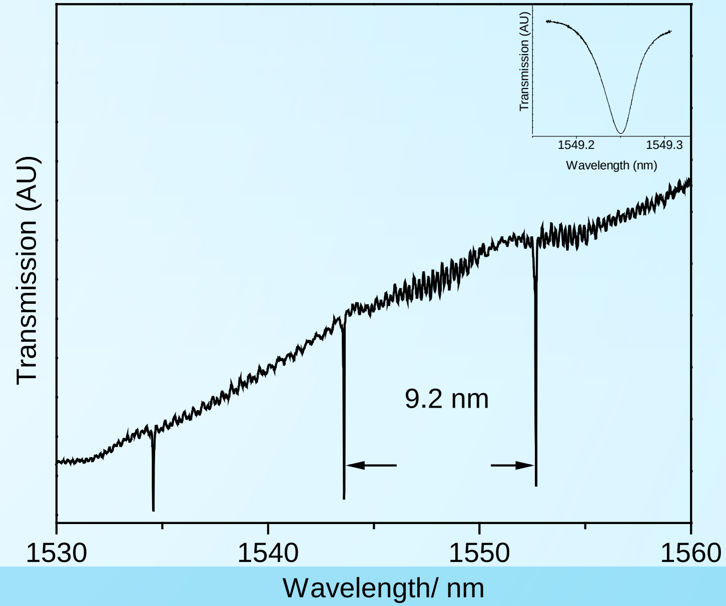


- Changes in refractive index cause a shift in resonant wavelength
- Very narrow resonances, temperature resolution ~1 mK
- Electron-beam testing planned in coming weeks





Courtesy: Zeeshan Ahmed



Future Plans

- Install and test EBLab-300 unit
- Develop testing protocols
- Determine operating parameters
- Monte Carlo modeling
- Develop methods for low-energy dosimetry
- Materials testing