Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Photonics-Based Readout and Power Delivery by Light for Large-Area Monolithic Active Pixel Sensors

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October 30, 2023

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Outline

- Response to reviewer questions
- Introduction to the proposed R&D effort
- Q&A session

Responses to review questions

Review comment #1

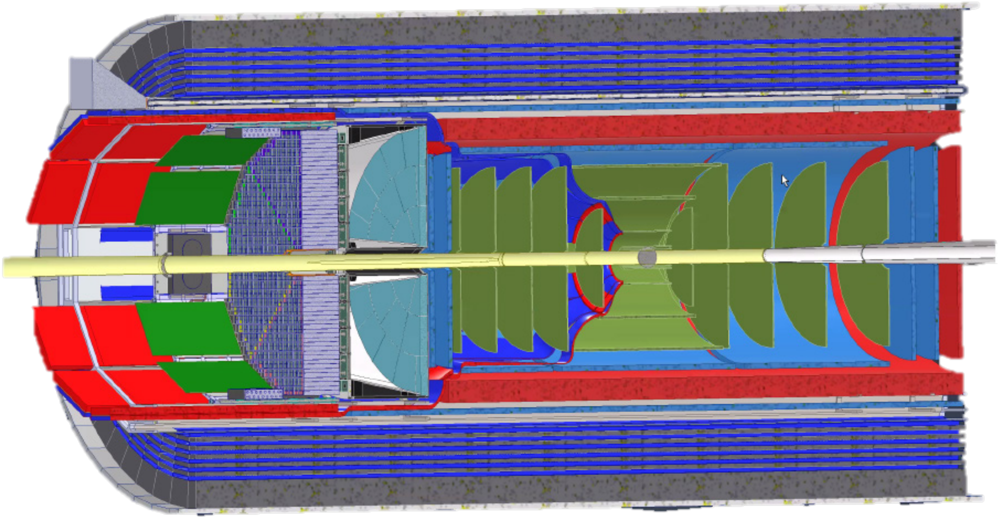
- Please explain how higher power levels for the amplifier input stage can lead to improved timing performance. Is this generally true for existing MAPS designs, or does this require a new design such as that in the separate proposal (Generic R&D proposal #10)?
- **Response:**
  - The photonic power and data delivery approach described in this proposal is agnostic of the front-end design.
  - It is generally true that improved front-end timing performance requires increased in-pixel power consumption. However, the details are highly design-dependent.
  - A further discussion on this point is outside the scope of this proposal. For a more detailed explanation, please see the discussion related to Generic R&D proposal #10 (which is focused on exactly this topic).

Review comment #2

- What is the proposed reduction in radiation length in the proposed optical solution compared to conventional power distribution? Have simulations been done to demonstrate what gains are obtained for some physics observable if the proposed reduction in radiation length is achieved?
- **Response:** A limited amount of simulation has been performed on the effects of intermediate material on the energy resolution of the electromagnetic calorimeter (EMCal). Further analysis is underway.

Material budget of the ePIC detector

- Material budget plays a crucial role in deep inelastic scattering (DIS), which is the basic process at the EIC because of its unmatched precision in studying the inner structure of nuclear matter.



SVT

MPGDs

TOF (fiducial volume)

FFC

Silicon Barrel Layers			
	Radius [mm] (min, max)	Length [mm]	X/X0 [%]
VX 1 (L0)	36	270	0.05
VX2 (L1)	48	270	0.05
VX3 (L2)	120	270	0.05
Sagitta1 (L3)	270	540	0.25
Sagitta2 (L4)	420	840	0.55
Silicon Hadron Endcap (wheels)			
	Distance [cm]	Radius [mm] (min, max)	X/X0 [%]
HD1	25	(36.76, 230)	0.24
HD2	45	(36.76, 430)	0.24
HD3	70	(38.42, 430)	0.24
HD4	100	(54.43, 430)	0.24
HD5	135	(70.14, 430)	0.24
Silicon Electron Endcap (wheels)			
ED1	-25	(36.76, 230)	0.24
ED2	-45	(36.76, 430)	0.24
ED3	-65	(36.76, 430)	0.24
ED4	-90	(40.0614, 430)	0.24
ED5	-115	(46.3529, 430)	0.24

- Detector granularity and multiple scattering arguments of interest for physics in the sub ~5 GeV momentum range are hard to achieve.
- Expected physics-related signal rate is outmatched by the background (beam-induced DIS, synchrotron radiation, bremsstrahlung X-rays, electron and hadron beams gas, and electronics).

Effect of material on the way

- Material on the way to EMCal is inevitable

  Other detectors, cables, pipes, frames, etc

- It degrades the performance of the high resolution EMCal

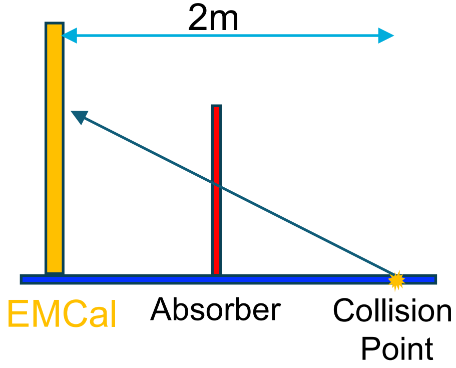
  Photon conversion

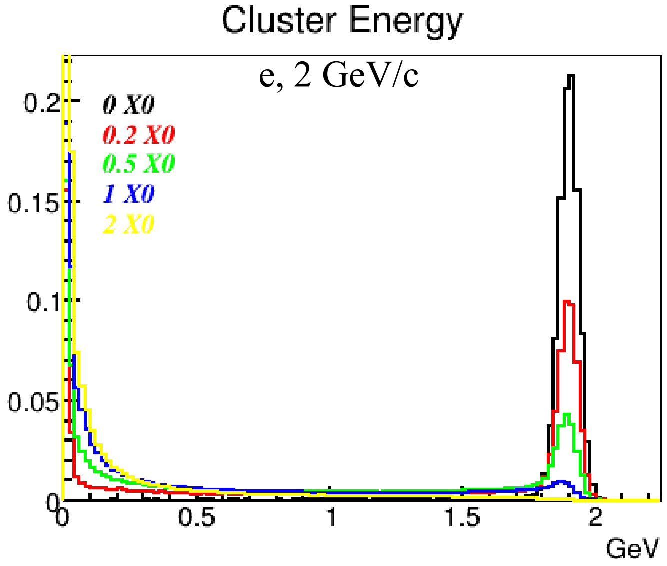
  Bremsstrahlung radiation by electron

  Early shower

- Energy gets absorbed in the material
- Energy gets distributed in the EMCal, e.g., due to Bremsstrahlung radiation by electron
  - Single cluster reco leads to eff. loss
  - The eff. can be recovered by radiated photon reco
  - The closer to the EMCal the smaller the effect
  - The higher Bdl the larger the effect
  - Rad. photons are localized in arcs with the same polar angle as a parent electron => topological search window

GEANT simulation for a single electron





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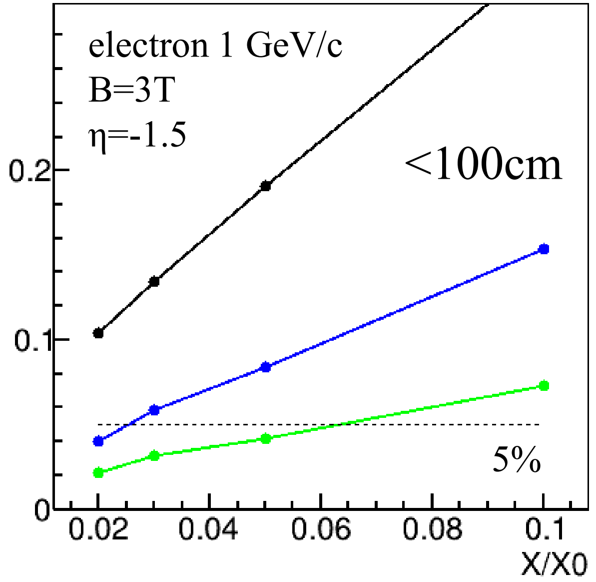
Effect of material on the way

The most extreme case:

Highest Bdl, lowest *e* momentum, close to coll. point

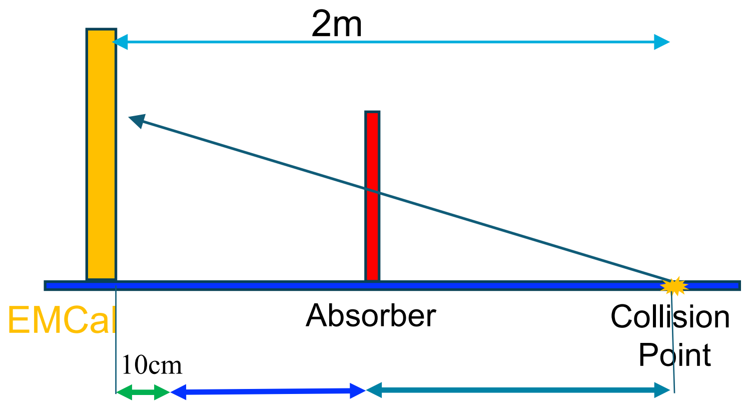
Efficiency loss (with 2σ cut) vs X/X_0



e cluster energy

e cluster and rad γ energy from Ecl>50MeV

e cluster and rad γ energy from Ecl>50MeV and $\Delta\eta$=±0.2, $\Delta\varphi$=±0.5



$<50\%X_0$	$<20\%X_0$	$<(3\text{-}6)\%X_0$	Electron > 1GeV
$<30\%X_0$	$<10\%X_0$	$<10\%X_0$	Photon > 0.1GeV

Exclusive requirements
(the whole effect assumed from one region)

The amount and localization of tolerable material formulated

- 10 μm copper ≈ 0.01 X0
- The requirements are relaxed for B=1.7-2T

A. Bazilevsky

Review comment #3

- What, in practice, will be the advantage from the point of view of the physics measurement in the end? Will the decrease in material budget using optical links significantly impact the physics?
- **Response:** This is a repeat of comment #2.

Review comment #4

- The budget is entirely labor and split over many people with small fractions of each person’s time. Even in Scenario 1 the person spending the most time on this only has 80 hours or 2 weeks of effort for the full year. Are there other resources for labor allocated at BNL to perform this ambitious work? If not, is this level of effort viable with so little effort from each individual? E.g., the time required to prepare safety documentation and train a group of people to safely work with Watt-scale laser fibers should not be underestimated.
- **Response:**
  - The budget was split up between multiple investigators due to the interdisciplinary nature of the R&D effort.
  - Nevertheless, we agree that it was probably divided between too many contributors.
  - If awarded, the project budget will be modified to reduce small contributions and increase the effort levels of the PI and co-PI (Mandal and Rescia).
  - A modest amount of funding (<$5k) will also be included to purchase COTS optical components.
  - The ASIC group at BNL is currently setting up a photonics lab to support other research projects. Thus, the time required to prepare safety documentation and train individuals will not need to be charged to this project.
  - If required, training requirements will be simplified by performing the initial optical power delivery experiments with lower-power lasers (Class 3B instead of Class 4).
  - The proposed work is a feasibility study. We will actively seek follow-on funding to continue the project.

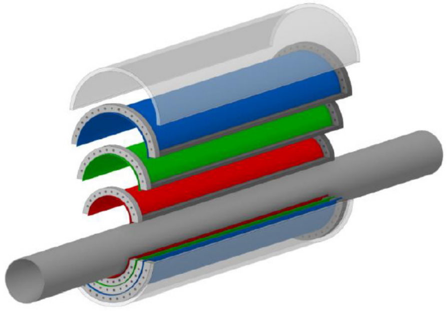
Proposed R&D project

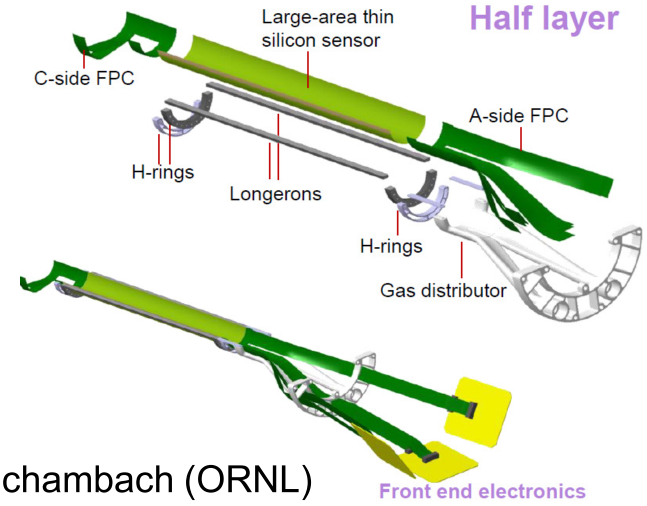
Benefits of optical power/data delivery

- Flat flexible copper cables (FFC) are widely used to deliver SVT resources (power, bias voltages, data).
  - Requires use of connectors and optical-electrical conversion boxes.
  - Both are significant contributors to the overall material budget.
- Serial powering somewhat reduces the material budget but adds significant technical risks.
- Optical power/data links provide Galvanic isolation, eliminate ground loops, localize the effects of failures, eliminate radiation hardness for lasers, and reduce the material budget.

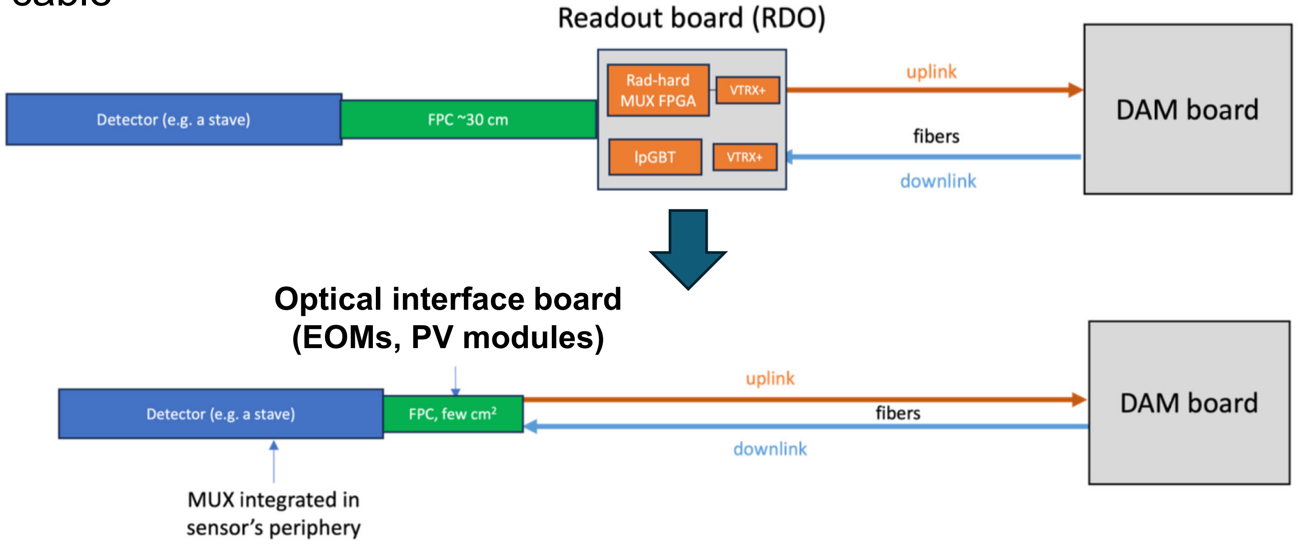
Tabulated radiation lengths (for electrons)

- X0 (silicon) = 22 g/cm^2 = 9.4 cm ← Optical fiber
- X0 (copper) = 12.9 g/cm^2 = 1.43 cm ← FFC cable





J. Schambach (ORNL)



Overview of ePIC SVT readout services

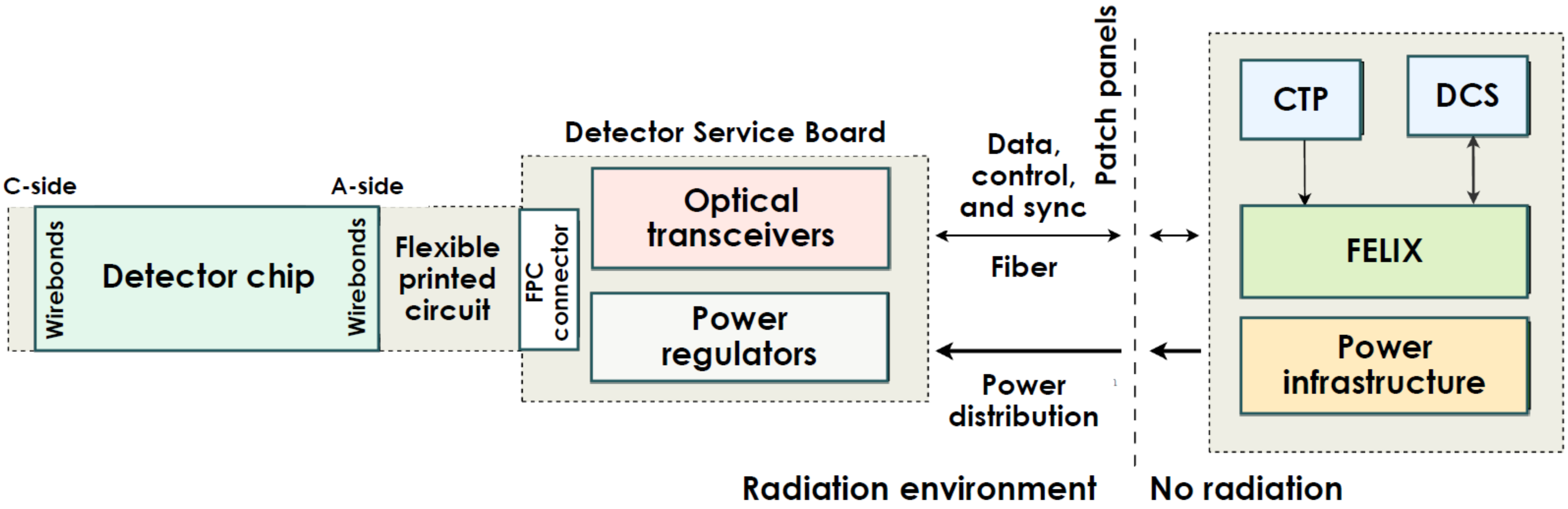


Figure 1: Overview of the ePIC silicon vertex tracker (SVT) readout services architecture. Adapted from a figure by J. Schambach, ORNL. Acronyms: CTP: Central Trigger Processor; DCS: Detector Control System; FELIX: FrontEnd LInk eXchange; FPC: Flexible Printed Circuit.

Overview of the power management section

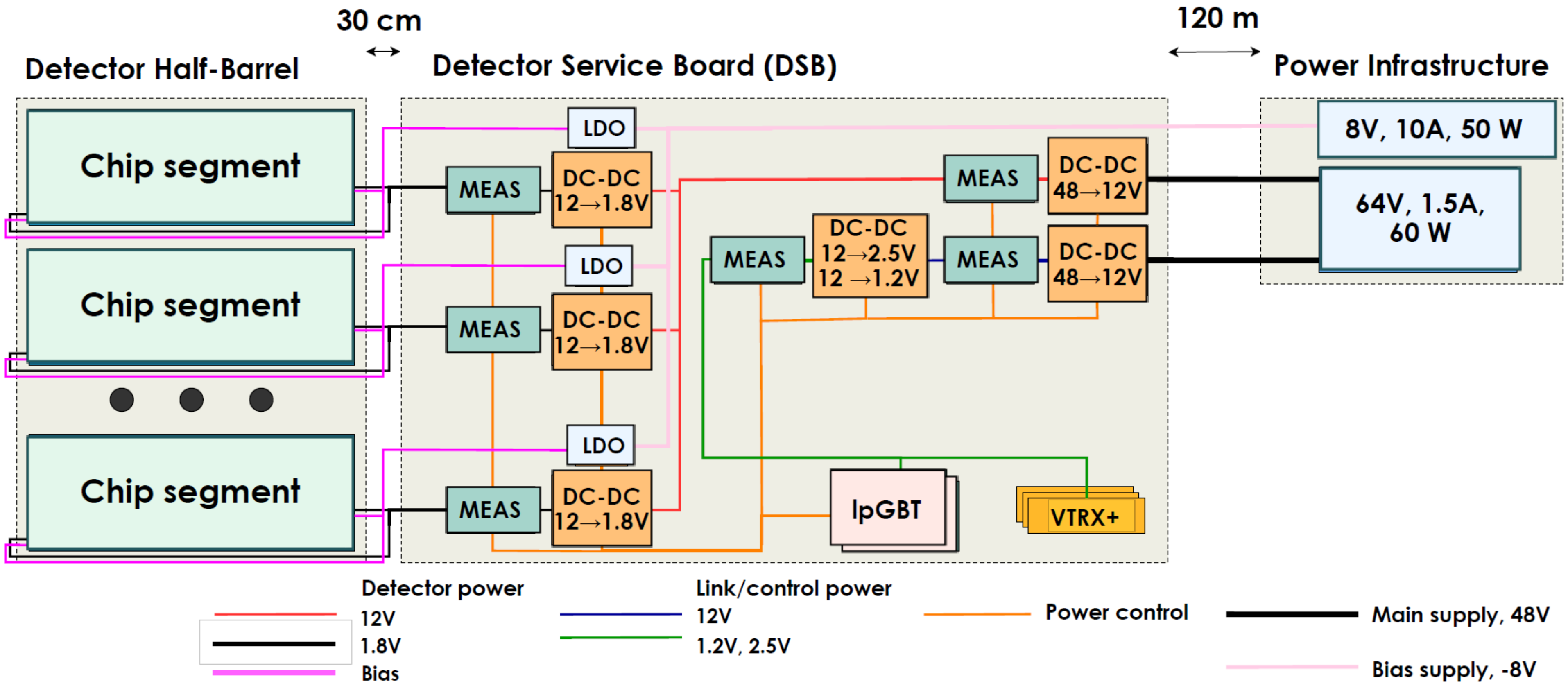
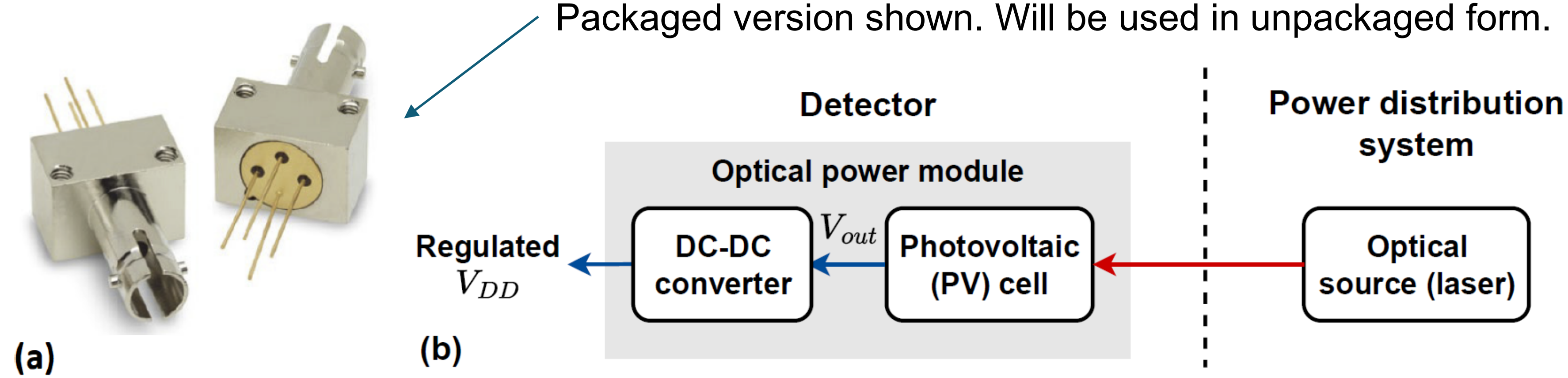


Figure 2: Overview of the power management section of the ePIC SVT readout services architecture. Adapted from a figure by J. Schambach, ORNL. Acronyms: MEAS: Measurement block, LDO: low-dropout linear regulator.

- This is a complex design that can be significantly simplified with optical power delivery.

Optical power link



Packaged version shown. Will be used in unpackaged form.

Figure 8: (a) Photograph of the Broadcom AFBR-POC306A1 optical power converter. (b) Overview of the proposed optical power link architecture.

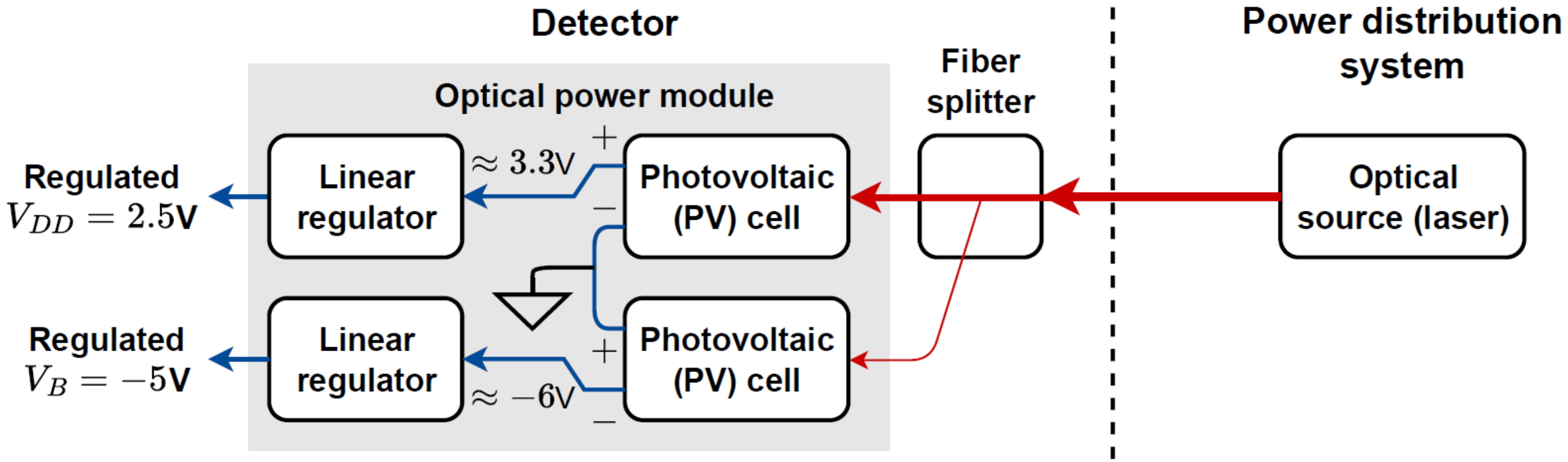
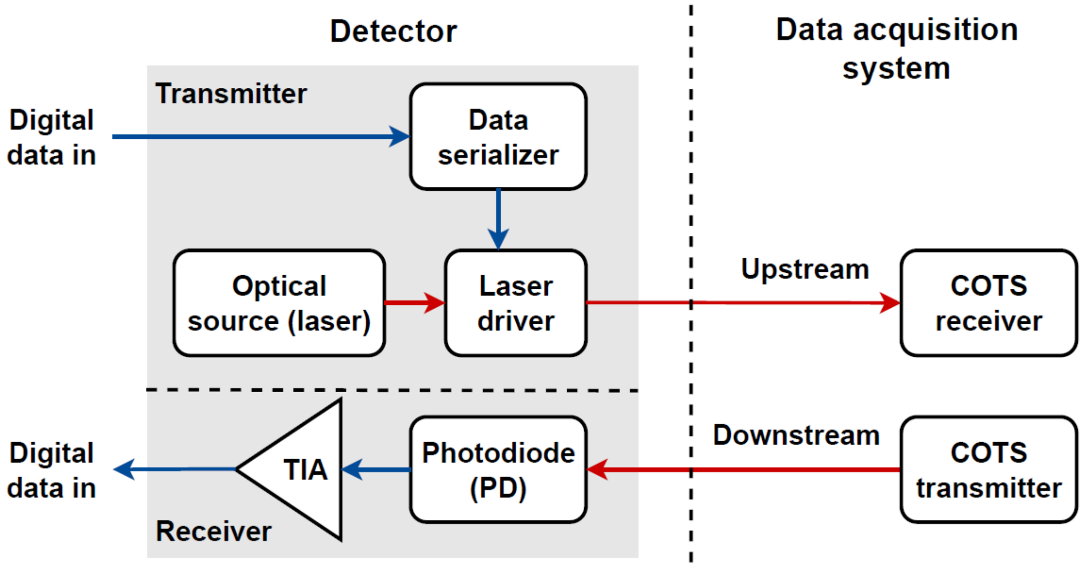
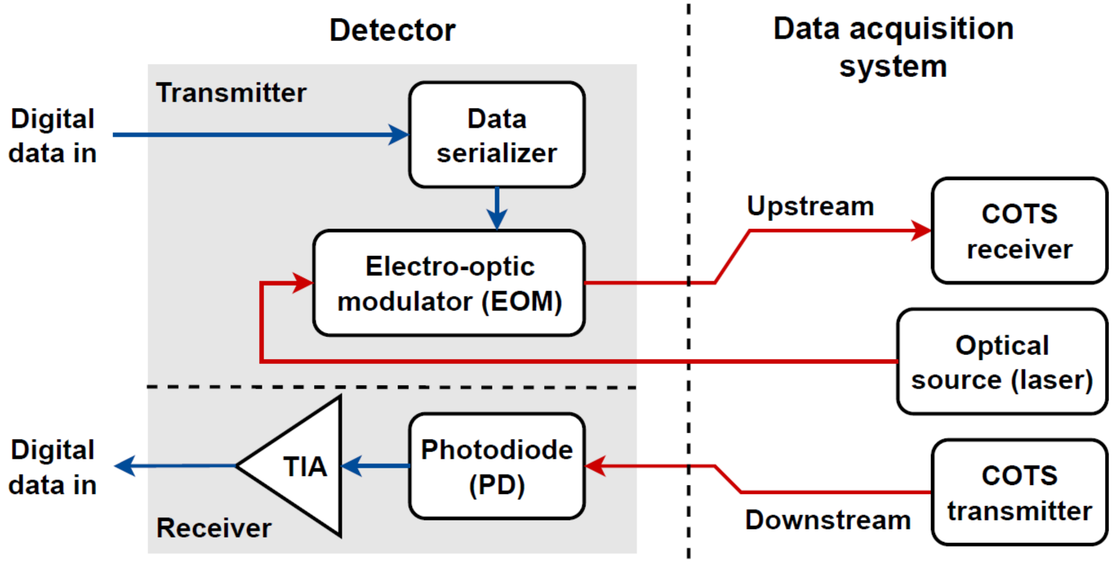


Figure 9: Modified optical power link architecture. Two independent PV modules are used to generate a split DC power supply for both powering and biasing RSUs.

Optical data link



Conventional



Proposed

Integrated silicon photonics

- Leverages the availability of low-cost multi-project wafer (MPW) access to a variety of photonic integrated circuit (PIC) processes.
- Plan: Use the GlobalFoundries (GF) 45SPCLO Silicon-Photonics process (available through the DMEA TAPO program, NDA being processed).
  - 45 nm silicon-on-insulator (SOI) CMOS back-end with a full set of transistors, capacitors, resistors, and diodes.
  - Wide variety of integrated optical components (low-loss waveguides, high-speed photodiodes, electro-optic modulators, vertical and edge couplers) available in the process design kit (PDK).
  - Also of interest for ongoing and planned QIS and AI projects.

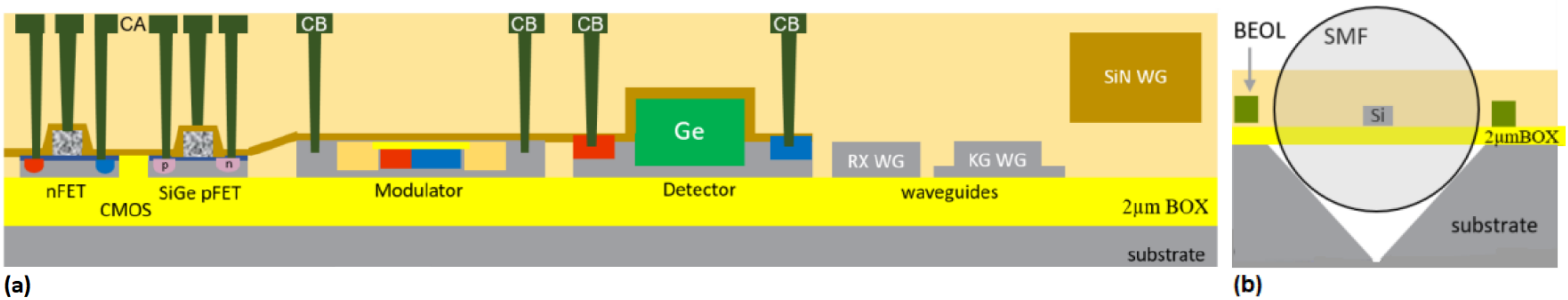
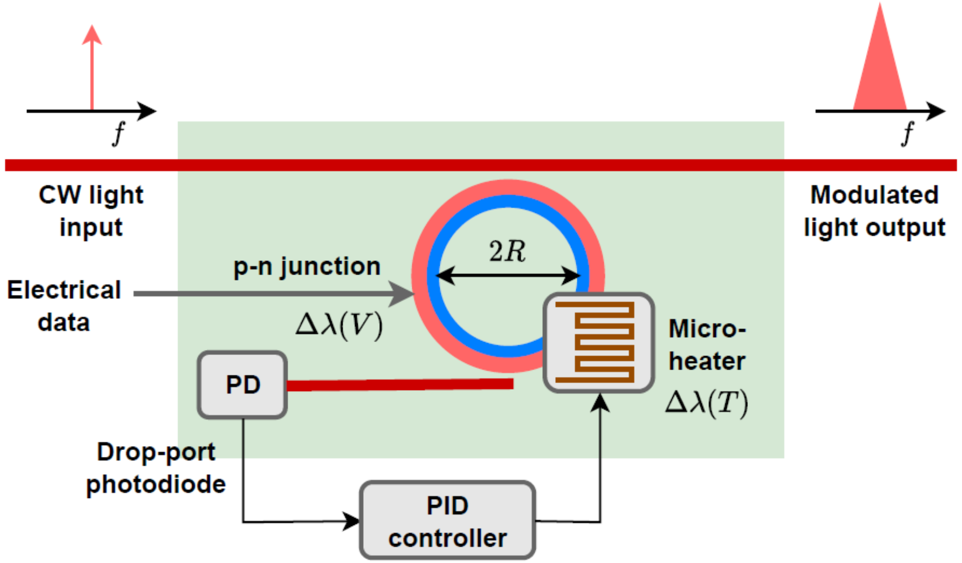
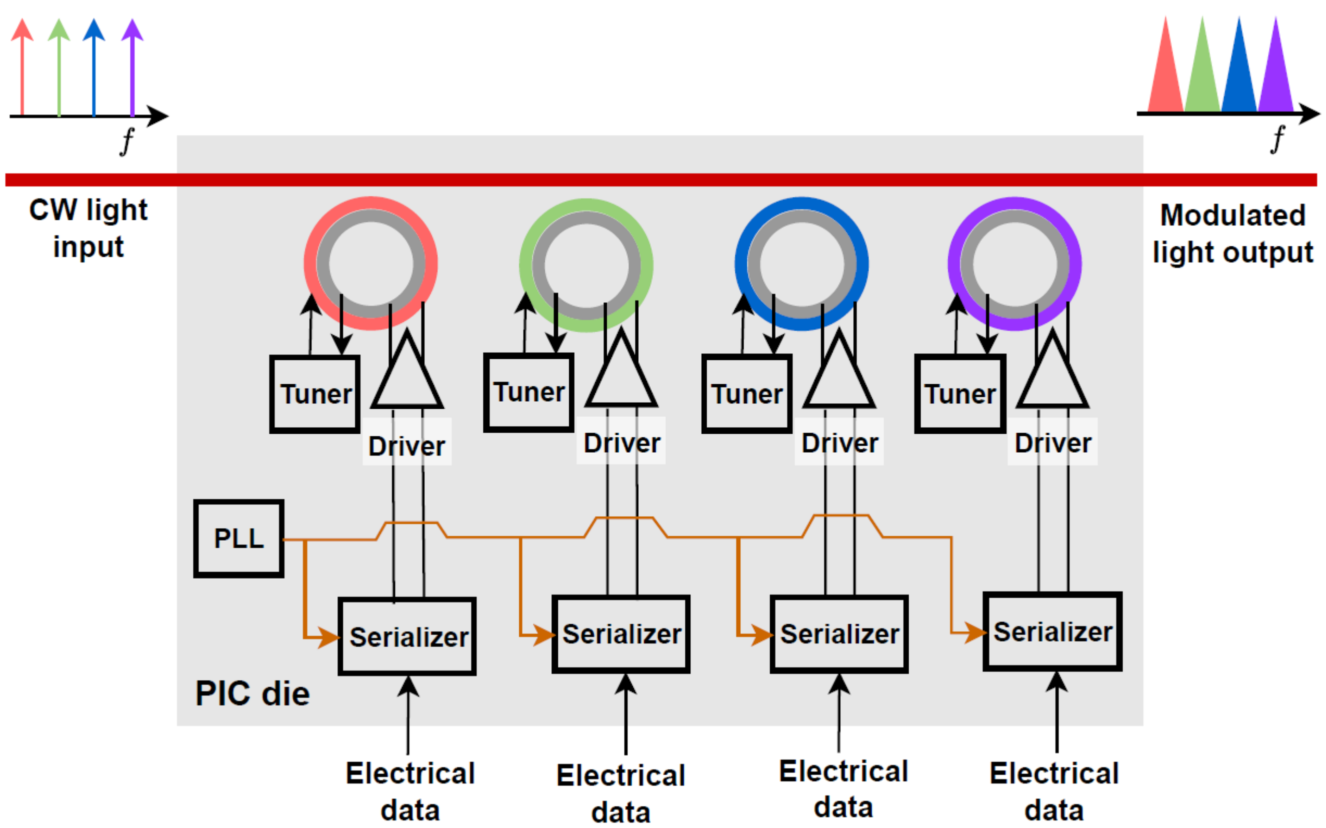


Figure 7: Cross-sections of (a) the front- and middle-end of line (FEOL/MEOL) technology, and (b) the edge coupling module used in the GF 45SPCLO process. Acronyms: CA: Active area contact, CB: gate contact, WG: Waveguide, BOX: Buried oxide, SMF: single-mode optical fiber. Figures adapted from [17].

Integrated electro-optic modulators (EOMs)



Design of a practical ring modulator (RM) with built-in temperature tuning to ensure stability of the resonant frequency versus temperature.



- Single RM will be realized first.
- Multiplexed RM design is a stretch goal.

Block diagram of a 4× multiplexed EOM using RMs and wavelength-division multiplexing (WDM)

Proposed R&D tasks and timeline

Task 1: Develop a flexible PCB to hold COTS optical components with a form factor suitable for deployment at ends of ePIC staves.

Task 2: Test the radiation hardness of the COTS modulator and power-over-fiber (PoF) modules using a suitable radiation source.

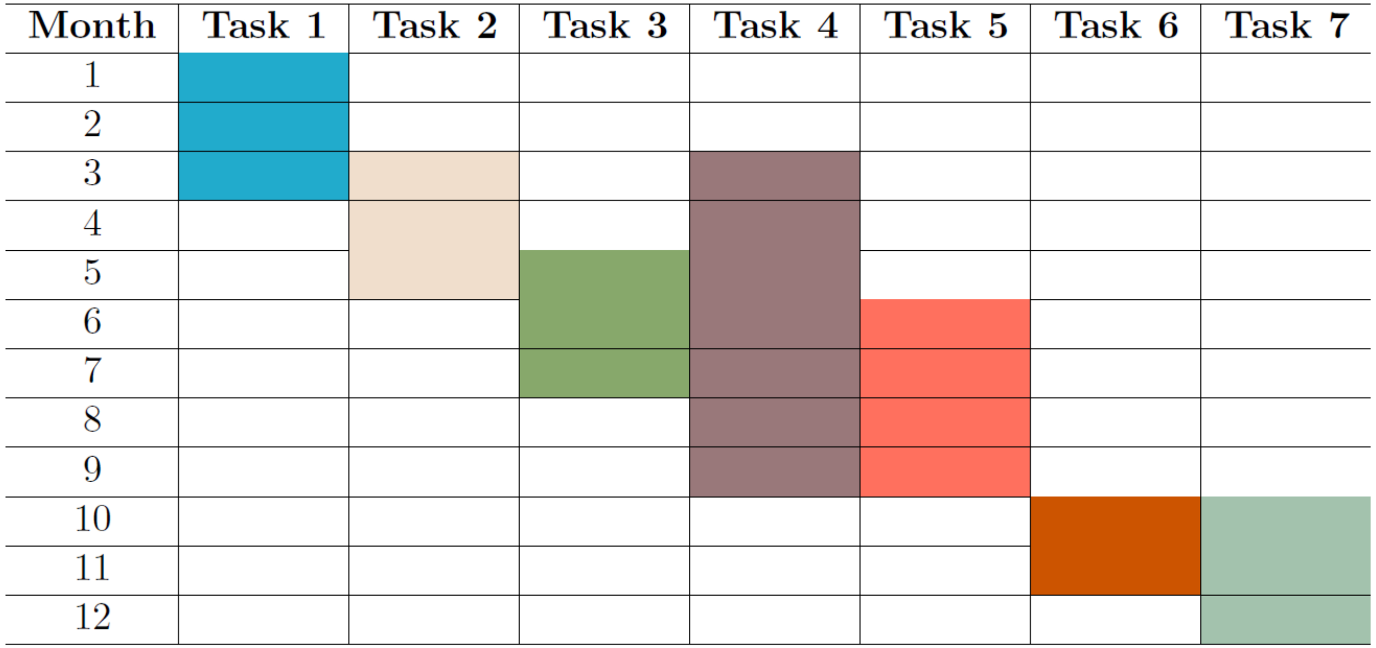
Task 3: Experimentally measure light leakage levels from the optical modules.

Task 4: Gain familiarity with the GF 45SPCLO process and simulate the built-in electro-optic modulators (EOMs).

Task 5: Evaluate feasibility of using multiple on-chip EOMs to implement wavelength division multiplexing (WDM).

Task 6: Evaluate the performance of optical coupler modules available in the GF 45SPCLO process.

Task 7 (stretch goal): Explore methods for optical transmission of slow control data.



Month	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7
1	■						
2	■						
3	■	■		■			
4		■		■			
5		■	■	■			
6			■	■	■		
7			■	■	■		
8				■	■		
9				■	■		
10						■	■
11						■	■
12							■

Milestones:

Milestone 1 (month 3): Complete Task 1
Milestone 2 (month 7): Complete Tasks 2-3
Milestone 3 (month 12): Complete Tasks 4-6

Budget scenarios:

Scenario 1 (nominal budget): Complete Tasks 1-6
Scenario 2 (80% of nominal budget): Complete Tasks 1-4
Scenario 3 (60% of nominal budget): Complete Tasks 1-3

Summary

- Optical power/data delivery to the ePIC SVT has a strong physics motivation.
  - Will reduce the materials budget required for resource delivery to the SVT (power, bias voltages, and data).
  - Will improve integrity of power and data transfer to/from the SVT.
  - Mechanical flexibility of optical fibers will simplify power/data routing.
- Will be implemented in two phases:
  - Initial solution will rely on COTS optical components.
  - The proposed photonics add-on board can be shared with other institutions involved in testing the SVT sensors (for initial evaluation).
  - Final solution will use a photonic IC (PIC) to miniaturize the data link.
- Parts of the concept are being studied at other institutions (such as CERN).
  - To the best of our knowledge, our proposal is the first combine optical power/data transfer.

Any questions?