Brookhaven National Laboratory | Jefferson Lab | U.S. DEPARTMENT OF ENERGY

ePIC Echelon 0 Prototype Timelines, Testing and Challenges

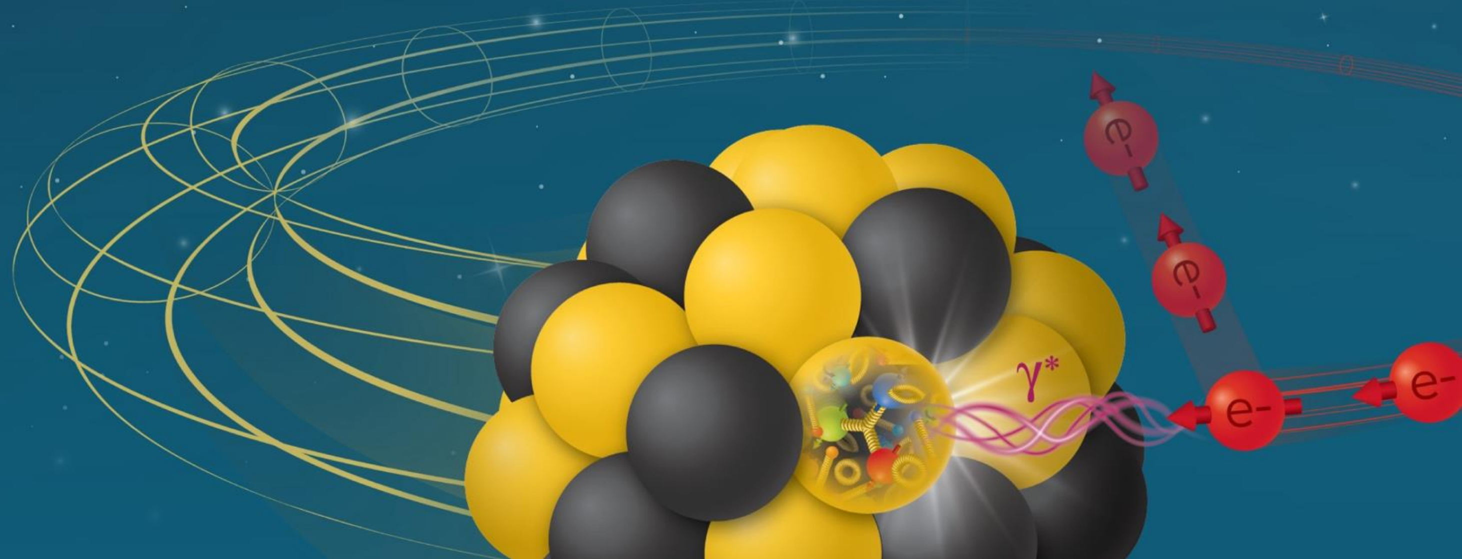
EIC Project DAQ/Computing CAMs

David Abbott(JLab), Jeff Landgraf (BNL)

Echelon 0/Echelon 1 Mini-Workshop

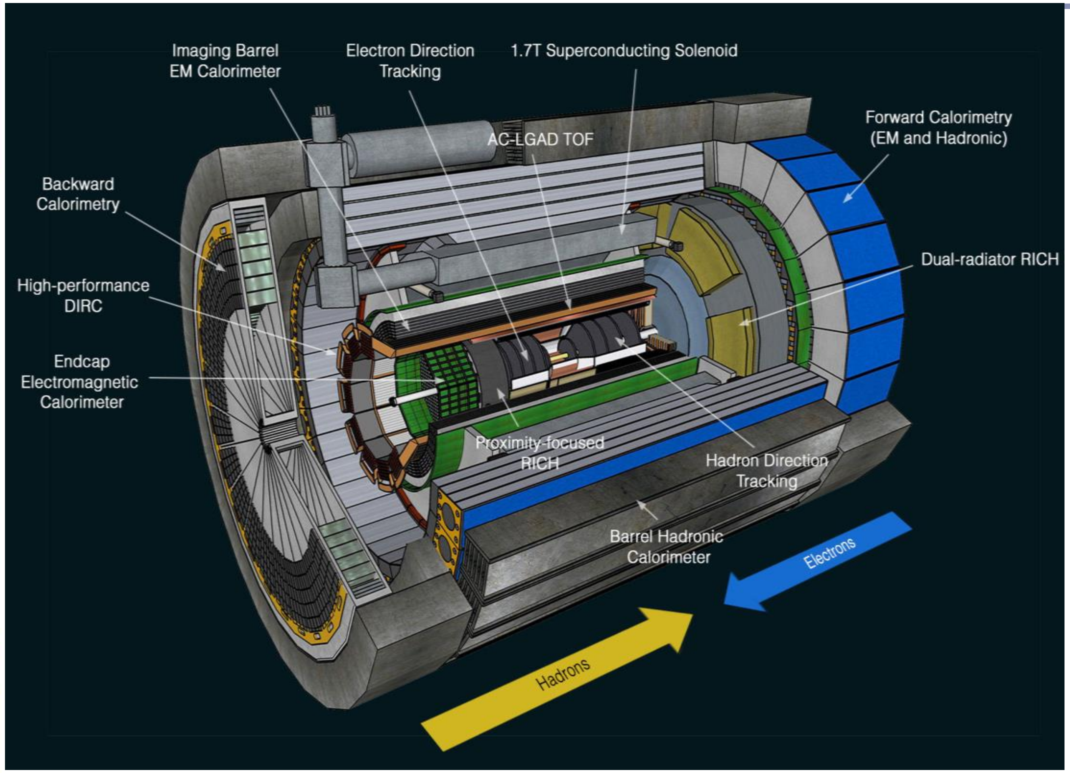
Brookhaven National Lab

July 30-31, 2026

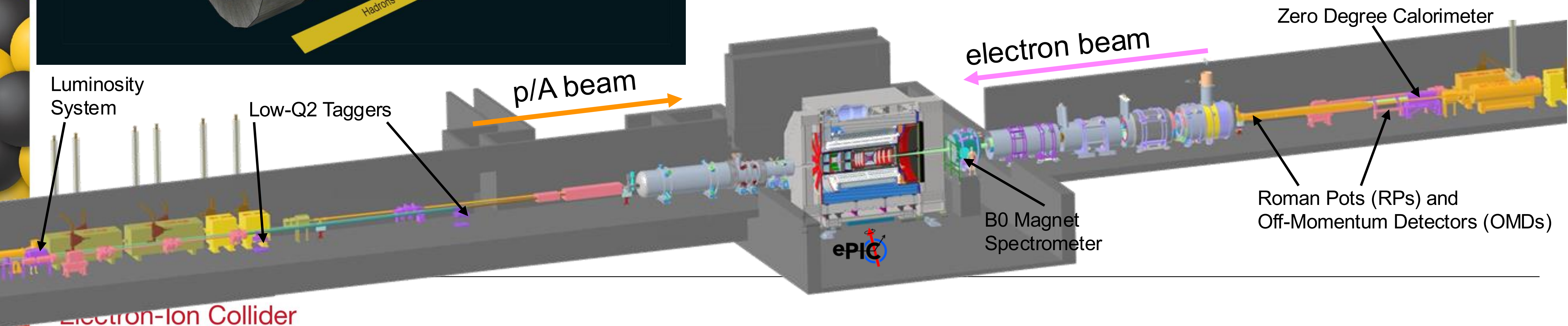


Electron-Ion Collider

ePIC Detector Readout Technologies



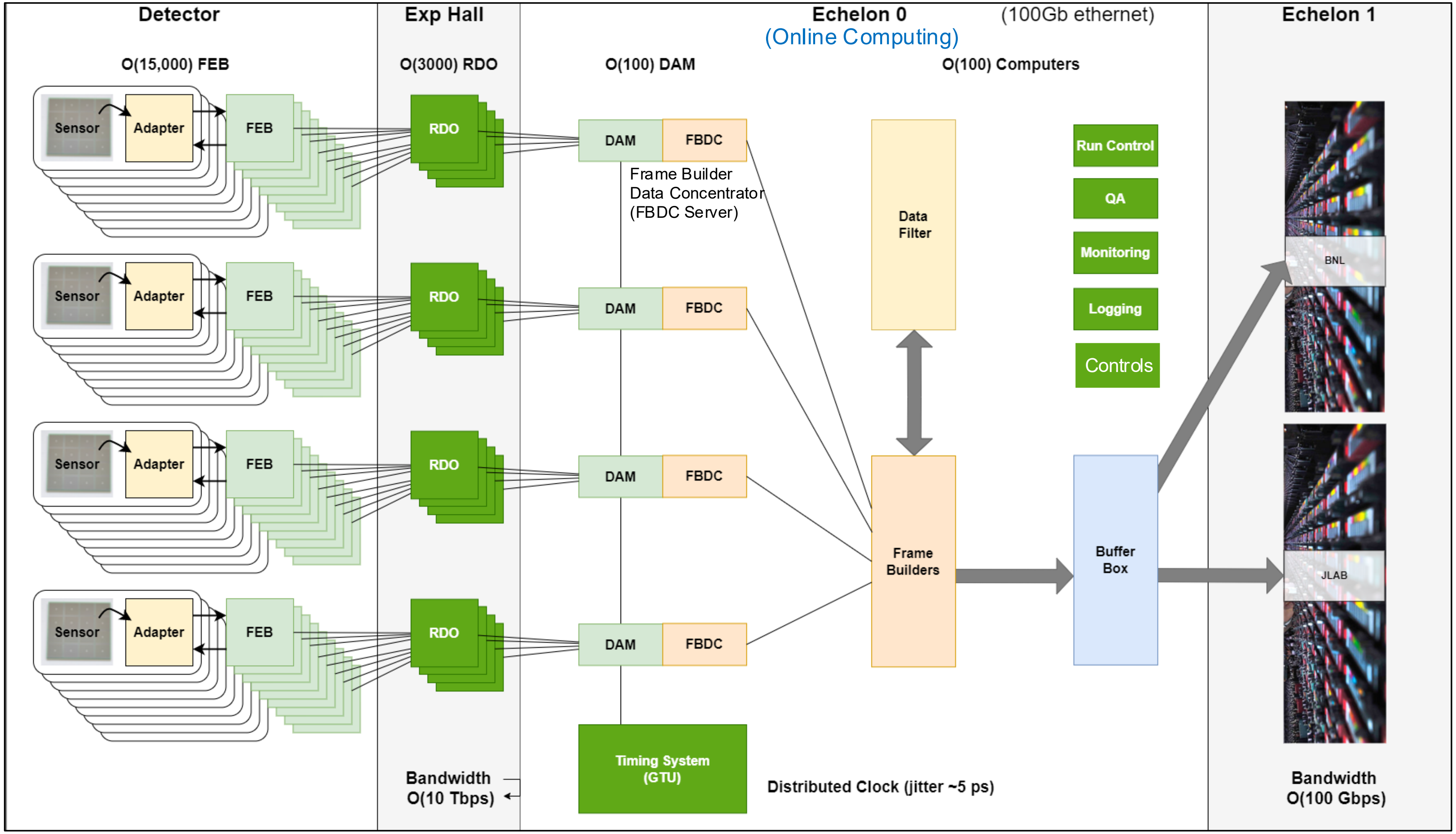
- ~26 Detector Systems
- Spread over +/- 40 meters
- (13 bunch crossings @ *c*)
- 5 main digitization ASICs, 3 digitizing sensors, and discrete readouts
- Many technologies, but effort has been made to make use of possible synergy…



ePIC Streaming DAQ Architecture

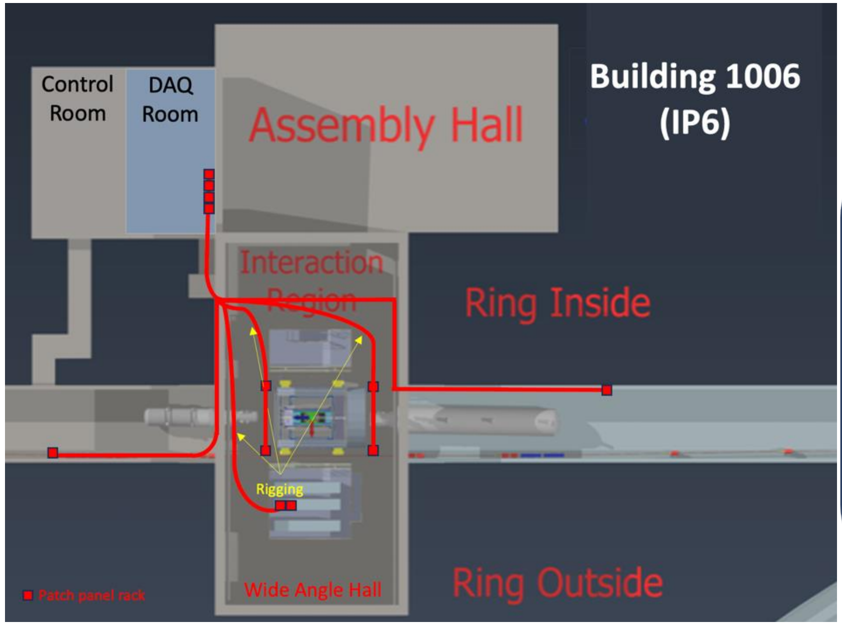
EIC Specs

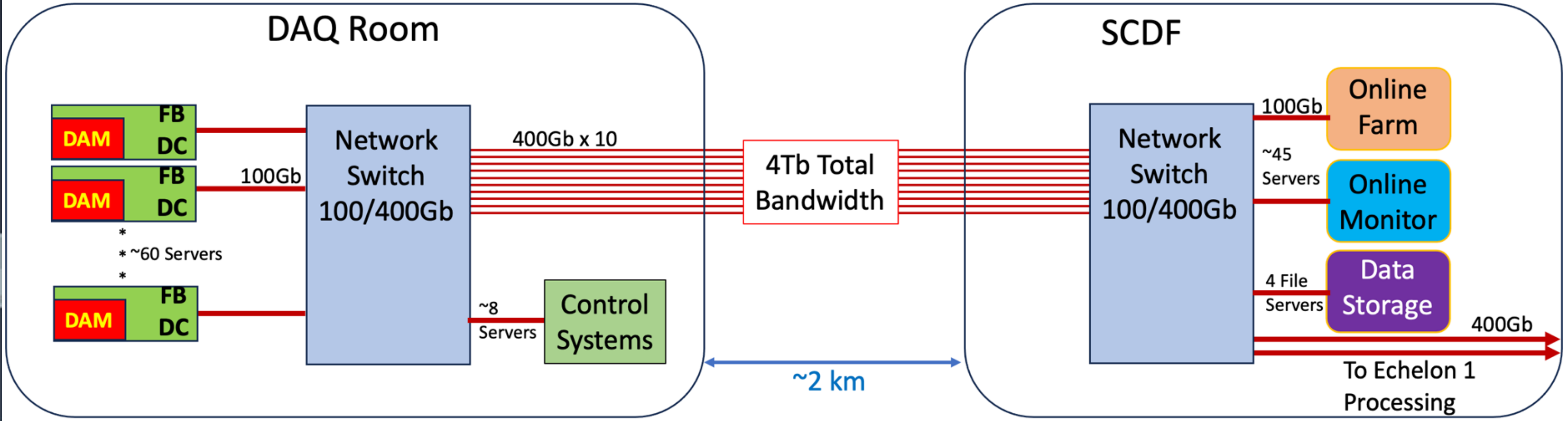
- Bunch Crossing
  ~10.2 ns (98.5 MHz)
- Interaction Rate
  ~ 2 us (500 kHz)
  (one interaction per ~200 bunch crossings)
- High Luminosity
  -- up to 10^{34} $cm^{-2}s^{-1}$
  -- Low occupancy physics signal
  -- Background and noise significant for some sub-systems



Echelon 0 Computing

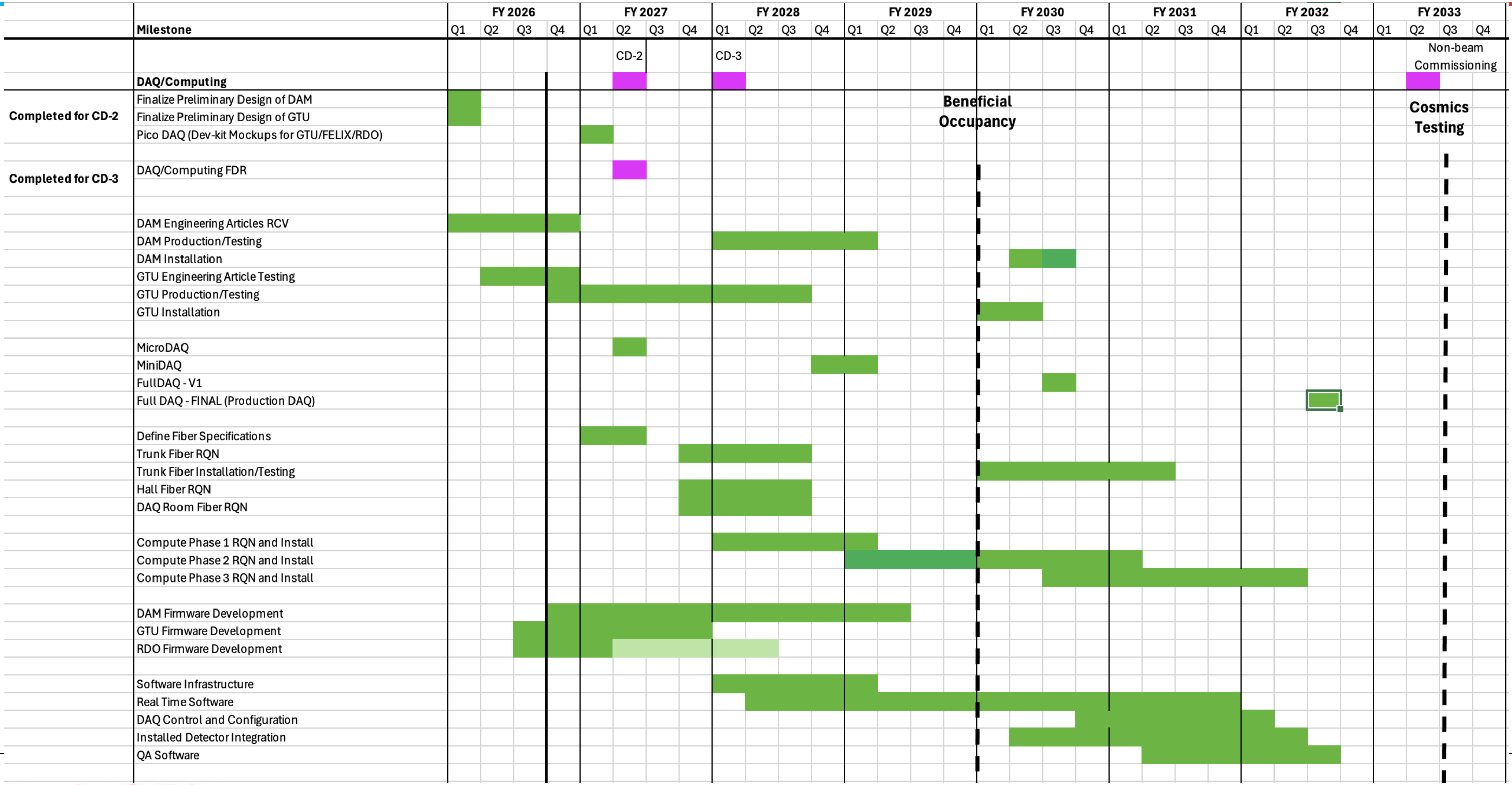
- Echelon 0 enclave plan is to split between Building 1006 and BNL SCDF
- Minimize required power and cooling in the DAQ room. Only online computing requiring direct access to ePIC detector subsystems.
- Take advantage of existing infrastructure at SCDF to support computing for online processing, monitoring and storage, including required access to Echelon 1 resources (calibration, real-time reconstruction and archiving)





Echelon 0 Software Design	**Run Control Model:**	**EIC / LHC clock:**	**Time Frames:**	**Data Banks:**
	• State model incorporates continuously running components (i.e.. scalers) • “Run” structure to configure / select enabled detectors • Slow Control status part of state model	• DAM selects 39.4 MHz or 98.5 MHz • GTU distributes 19.7 MHz to avoid phase problems when dividing clock • Fast commands restricted to EIC bunches at multiple of 5 (2 cycles of 39.4 MHz or 5 cycles of 98.5 MHz)	• 2^{16} Bunch Crossings ~ 667 μs • Not synchronized to Bunch 0 (Minimize correlation between edge effects and spin states) • Build all detector to each time frame • Group O(1000) TF into Super Time Frames	• RDO / lpGBT produced data formatted but not processed produce raw data banks • Processing (data reduction / or additional information) produces new data banks (no modification) • Fraction of raw banks always retained

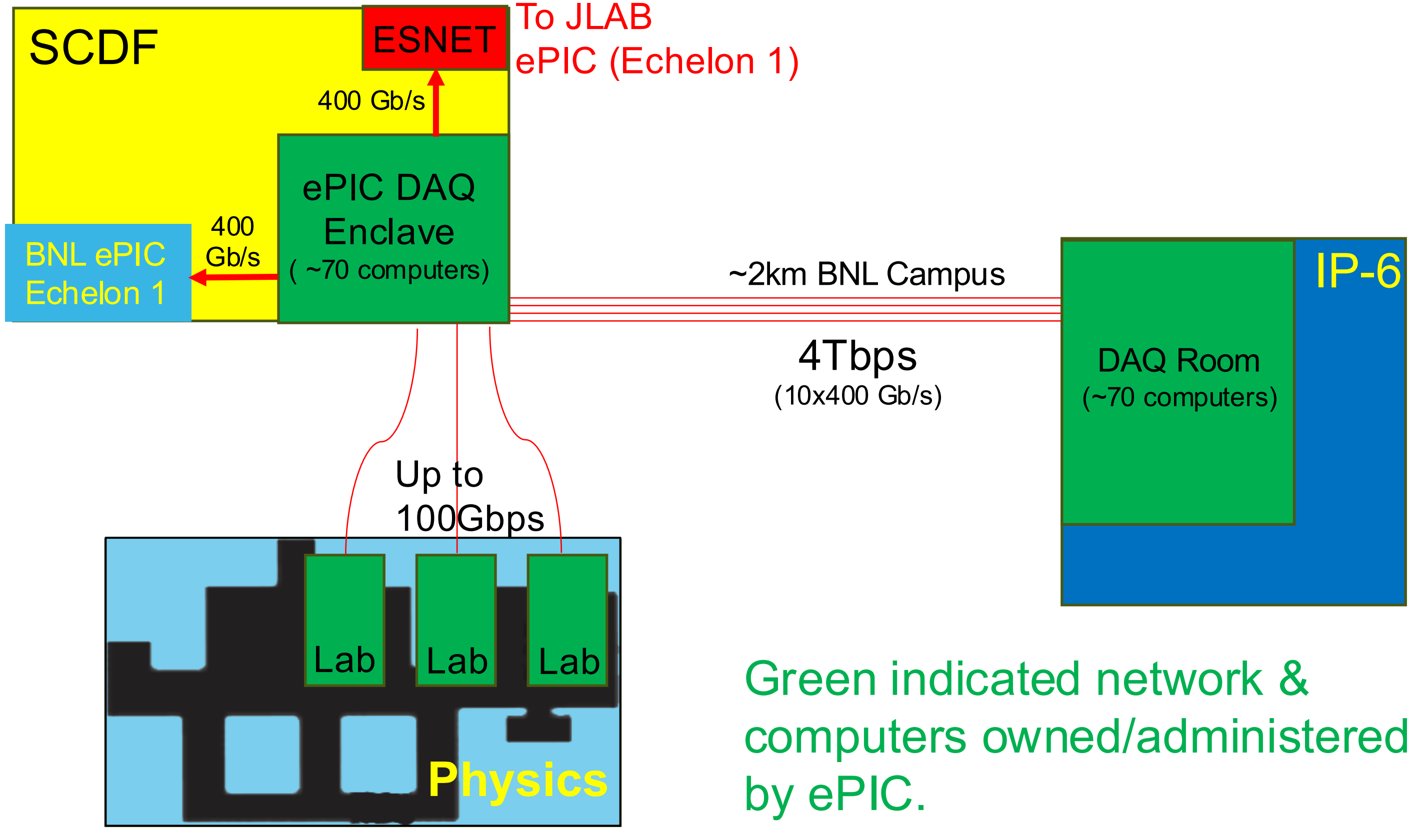
ePIC DAQ/Computing P6 Schedule



Timelines for Echelon 0

ePIC DAQ and computing will require network connectivity at BNL between resources in IP-6, SCDF as well as development labs that is bandwidth guaranteed and minimizes routing.

- Early DAQ & Electronics development has started in labs (Physics Building, in early 2026).
- Initial computing needs for DAQ development would best be placed in a central location (SCDF, initially one rack, preferably late 2026).
- DAQ production and the interface with Echelon 1 can then be developed with test beds in the labs and the SCDF. (between Early 2027 and late 2029)
- When beneficial occupancy at IP-6 is attained, additional Echelon 0 computing resources can be placed in both sites (3-5 racks total at SCDF, early 2030).
- For production running it is important to have all network infrastructure in place (Early 2033) and have equal and transparent network access from Echelon 0 (SCDF) to both Echelon 1 sites (BNL and JLAB)

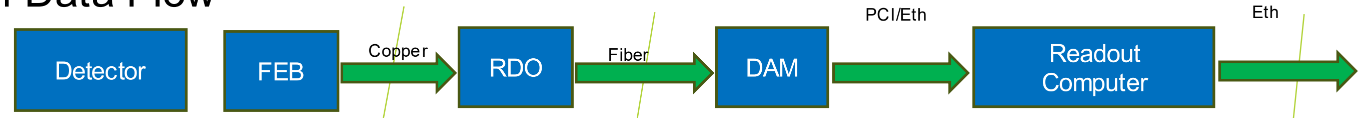


Green indicated network & computers owned/administered by ePIC.

Summary of Channel Counts and Data Flow

Detector Group	Channels					FEB	RDO	Uplink to DAM	DAM
	MAPS	AC-LGAD	SiPM/PMT	MPGD	HRPPD/ MCP-PMT				
Tracking (MAPS)	16B						521	521	14
Tracking (MPGD)				164k		656	56	56	4
Calorimeters	500M		102k			2,224	666	666	18
PID (TOF)		6.1M				500		1364	29
PID Cherenkov			318k		143k	5,060	1240	1332	29
Far Forward		1.5M	10k			529	38	406	12
Far Backward	66M		3.4k			48	36	396	10
Lumi		500k	5k			105	18	51	3
Polarimetry	Independent Electronics, DAQ, & Controls from central detector but expected to build on same technologies								
TOTAL	**16.5B**	**8.3M**	**437k**	**164k**	**143k**	**9,114**	**2,575**	**4,792**	**119**

Summary of Data Flow



Aggregate	**2.0 Tb/sec**
Noise	1.6 Tb /sec
Signal from Physics + Background	400 Gb / sec

Aggregate	**2.0 Tb/sec**
Per RDO (Avg)	0.7 Gb/sec

Aggregate	**109 Gb/sec**
Collision Signal	62 Gb/sec
Synchrotron Rad	Under design
Electron Beam	4.5 Gb/sec
Hadron Beam	1.0 Gb/sec
Noise	41 Gb/sec

Scale of the system:

- Electronics
  - ~ 25 detectors
  - ~ 5 Sensor Technologies
  - ~ 2500 RDOs (on detector/in racks)
  - ~ 120 DAM boards (DAQ room)
  - GTU (with interface boards)
- Detailed simulations of DIS events, Proton and Electron beam gas lead to maximum Data Volume
  - ~ 2 Tb/sec digitized
  - ~ 100Gb/sec recorded
- Dark current rates high for dRICH (SiPM sensitive to single photons) after radiation damage. Need High-Level Filter (ML algorithms under study)
- Synchrotron Radiation Simulations still in flux. Rates at 18GeV with currently simulated beam-line dominate physics rates. Scaling to lower energies is not trivial, and optimized beam line being simulated.

Data Volume Challenges

1	ePIC Data Rate Summary																				
2																					
3	Detector			Readout Limitations						Simulated Rates							Data Volume				
4	System	Detector	Section	Readout / Element	Maximum Data Rate / Element	Maximum Hit Rate / Element	Minimum Distinguishable Hit Separation in Time	Likely Aggregation Limit Source	Hit Rate Capability including Aggregation (pro-rated to readout element)	Max Hit Rate / Readout Element (Physics) (Hz)	Max Hit Rate / Readout Element (SR) (Hz)	Max Hit Rate / Readout Element (Other Backgrounds) (Hz)	Expected Noise Hit Rate / Readout Element (Hz)	Max Hit Rate (All Sources) (Hz / Readout Element)	Avg Hit Rate / Readout Element (Hz)	Total Hit Rate for full Section (Hz)	Bits/Hit	Data Reduction Expected	Readout Elements / Section	Data Rate Full Section (Gb/s)	Allocated Data Volume To Tape (Gb/s)
5	Si Tracking	Inner Barrel (IB)	L0	Mosaix Sensor Fiber Link	7.68 Gb/s		2 us			56,000	17,672,000	200,000	332,000	18,136,000	10,395,139	374,225,000	96.0		36	35.50	15.0
6			L1	Mosaix Sensor Fiber Link	7.68 Gb/s		2 us			80,000	8,812,000	140,000	332,000	9,216,000	5,585,813	268,119,000	96.0		48	25.20	
7			L2	Mosaix Sensor Fiber Link	7.68 Gb/s		2 us			12,000	2,072,000	52,000	332,000	2,416,000	1,620,833	194,500,000	96.0		120	17.40	
8		Outer Barrel (OB)	L3	LAS Fiber Link	3.84 Gb/s		2 us			18,000	1,620,000	36,000	499,000	2,119,000	1,019,991	359,037,000	96.0		352	28.90	
9			L4	LAS Fiber Link	3.84 Gb/s		2 us			15,000	500,000	25,000	416,000	916,000	539,615	604,369,000	96.0		1120	43.10	
10		Backward Disks (EE)	ED0	LAS Fiber Link	3.84 Gb/s		2 us			75,000	7,770,000	420,000	416,000	8,621,000	1,779,271	170,810,000	96.0		96	15.10	
11			ED1	LAS Fiber Link	3.84 Gb/s		2 us			75,000	7,930,000	420,000	416,000	8,621,000	1,113,811	372,013,000	96.0		334	31.30	
12			ED2	LAS Fiber Link	3.84 Gb/s		2 us			50,000	6,510,000	435,000	416,000	7,096,000	1,089,323	363,834,000	96.0		334	30.40	
13			ED3	LAS Fiber Link	3.84 Gb/s		2 us			35,000	1,800,000	485,000	416,000	2,266,000	853,269	284,992,000	96.0		334	22.90	
14			ED4	LAS Fiber Link	3.84 Gb/s		2 us			30,000	250,000	305,000	416,000	791,000	513,689	171,572,000	96.0		334	12.00	
15		Forward Disks (HE)	HD0	LAS Fiber Link	3.84 Gb/s		2 us			140,000	6,840,000	435,000	416,000	7,521,000	1,619,604	155,482,000	96.0		96	13.40	
16			HD1	LAS Fiber Link	3.84 Gb/s		2 us			200,000	6,040,000	475,000	416,000	6,766,000	884,734	295,501,000	96.0		334	23.90	
17			HD2	LAS Fiber Link	3.84 Gb/s		2 us			465,000	430,000	450,000	416,000	1,316,000	528,105	176,387,000	96.0		334	12.50	
18			HD3	LAS Fiber Link	3.84 Gb/s		2 us			610,000	50,000	255,000	416,000	1,266,000	440,620	147,167,000	96.0		334	9.70	
19			HD4	LAS Fiber Link	3.84 Gb/s		2 us			560,000	20,000	240,000	416,000	1,191,000	434,838	145,236,000	96.0		334	9.50	
20	MPGD Tracking	Electron Endcap		SALSA (64 Channel)	1 Gb/s	5.2 MHz	2 us	ASIC output link	5.2 MHz								192.0		160	0.00	5.0
21		Hadron Endcap		SALSA (64 Channel)	1 Gb/s	5.2 MHz	2 us	ASIC output link	5.2 MHz								192.0		160	0.00	
22		Inner Barrel (CyMBaL)		SALSA (64 Channel)	1 Gb/s	5.2 MHz	2 us	RDO	1 MHz								192.0		576	0.00	
23		Outer Barrel		SALSA (64 Channel)	1 Gb/s	5.2 MHz	2 us	RDO	1 MHz								192.0		1536	0.00	
24	Forward Calorimeters	LFHCAL		CALOROC (36 Channel)	2.52 Gb/s	7.8 MHz	125 ns	RDO	975 kHz								320.0			0.00	17.0
25		LFHCAL Insert		CALOROC (36 Channel)	2.52 Gb/s	7.8 MHz	125 ns	RDO	975 kHz								320.0			0.00	
26		EcalEndcapP (W/SciFi)		Discrete FEB (32 Channel)	400 Mb/s	1.6 MHz	100 ns	FEB	1.6 MHz								192.0			0.00	
27	Barrel Calorimeters	HCAL		CALOROC (36 Channel)	2.52 Gb/s	7.8 MHz	125 ns	RDO	975 kHz								320.0			0.00	
28		Ecal (SciFi/PB)		CALOROC (36 Channel)	2.52 Gb/s	7.8 MHz	125 ns	RDO	975 kHz								320.0			0.00	
29		Ecal (Astopix)		ASTROPIX (? pixels)																0.00	
30	Backward Calorimeter	NHCAL		CALOROC (36 Channel)	2.52 Gb/s	7.8 MHz	125 ns	RDO	975 kHz								320.0			0.00	
31		EcalEndcapN (PWO)		Discrete FEB (32 Channel)	400 Mb/s	1.6 MHz	100 ns	FEB	1.6 MHz								192.0			0.00	
32	Far Forward	B0 Calorimeter		CALOROC (36 Channel)	2.52 Gb/s	7.8 MHz	125 ns	RDO	975 kHz	No/Estimate	No/Estimate	No/Estimate	No/Estimate	36,000	36,000	135,000	320.0		4	0.04	12.0
33		B0 Tracker		EICROC (1024 Channel)	256 Mb/s	204 kHz	100 ns	EICROC	204 kHz	No/Estimate	No/Estimate	No/Estimate	No/Estimate	102,000	51,200	34,400,000	100.0		672	3.44	
34		2x Roman Pots		EICROC (1024 Channel)	256 Mb/s	204 kHz	100 ns	EICROC	204 kHz	No/Estimate	No/Estimate	No/Estimate	No/Estimate	50,000	50,000	26,100,000	100.0		512	2.61	
35		2x Off Momentum		EICROC (1024 Channel)	256 Mb/s	204 kHz	100 ns	EICROC	204 kHz	No/Estimate	No/Estimate	No/Estimate	No/Estimate	50,000	50,000	14,700,000	100.0		288	1.47	
36		ZDC Crystal Calorimeter		Discrete FEB (32 Channel)	400 Mb/s	1.6 MHz	100 ns	FEB	1.6 MHz	No/Estimate	No/Estimate	No/Estimate	No/Estimate	11,000	6,200	180,000	192.0		28	0.03	
37		ZDC HCAL		CALOROC (36 Channel)	2.52 Gb/s	7.8 MHz	125 ns	RDO	975 kHz								320.0			0.00	
38	Far Backward	2 x Low Q2 Tagger Tracker		TimePix																0.00	16.0
39		2 x Low Q2 Tagger Calorimeter		CALOROC (36 Channel)	2.52 Gb/s	7.8 MHz	125 ns	RDO	975 kHz								320.0			0.00	
40		Lumi PS Calorimeter		CALOROC (36 Channel)	2.52 Gb/s	7.8 MHz	125 ns	RDO	975 kHz								320.0			0.00	
41		Lumi PS Tracker		EICROC (1024 Channel)	256 Mb/s	204 kHz	100 ns	EICROC	204 kHz								100.0			0.00	
42		Direct Photon Calorimeter		CALOROC (36 Channel)	2.52 Gb/s	7.8 MHz	125 ns	RDO	975 kHz								320.0			0.00	
43	PID-TOF	Barrel		FCFD (32 Channel)	80 Mb/s	3 kHz	200 ns	FCFD	3 kHz								160.0			0.00	12.0
44		Endcap		EICROC (1024 Channel)	256 Mb/s	204 kHz	100 ns	EICROC	204 kHz								100.0			0.00	
45	PID-Cherenkov	dRICH		ALCOR (64 Channel)	1.7 Gb/s	21.1 MHz	125 ns	DAM	78 MHz				19,200,000				80.0		4968	0.00	32.0
46		pfRICH		FCFD (32 Channel)	80 Mb/s	3 kHz	100 ns	FCFD	3 kHz	14,100	No/Estimate	113,000	320	640,000	41,700	90,700,000	160.0		2176	14.51	
47		hpDIRC		FCFD (32 Channel)	80 Mb/s	3 kHz	100 ns	FCFD	3 kHz								160.0			0.00	
48																					
49	Sum																			352.91	109.0

Data Volume Challenges

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6			L1	Mosaix Sensor Fiber Link	7.68 Gb/s		2 us			80,000	8,812,000	140,000	332,000	9,216,000	5,585,813	268,119,000	96.0		48	25.20	
7			L2	Mosaix Sensor Fiber Link	7.68 Gb/s		2 us			12,000	2,072,000	52,000	332,000	2,416,000	1,620,833	194,500,000	96.0		120	17.40	
8		Outer Barrel (OB)	L3	LAS Fiber Link	3.84 Gb/s		2 us			18,000	1,620,000	36,000	499,000	2,119,000	1,019,991	359,037,000	96.0		352	28.90	
9			L4	LAS Fiber Link	3.84 Gb/s		2 us			15,000	500,000	25,000	416,000	916,000	539,615	604,369,000	96.0		1120	43.10	
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12			ED2	LAS Fiber Link	3.84 Gb/s		2 us			50,000	6,510,000	435,000	416,000	7,096,000	1,089,323	363,834,000	96.0		334	30.40	15.0
13			ED3	LAS Fiber Link	3.84 Gb/s		2 us			35,000	1,800,000	485,000	416,000	2,266,000	853,269	284,992,000	96.0		334	22.90	
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20	MPGD Tracking	Electron Endcap		SALSA (64 Channel)	1 Gb/s	5.2 MHz	2 us	ASIC output link	5.2 MHz								192.0		160	0.00	
21																				0.00	
22																				0.00	5.0
23																				0.00	
24	Forward Calor																			0.00	
25																				0.00	
26																				0.00	
27	Barrel Calorim																			0.00	
28																				0.00	17.0
29																				0.00	
30	Backward Cal																			0.00	
31																				0.00	
32	Far Forward																			0.04	
33																				3.44	
34																				2.61	
35																				1.47	12.0
36																				0.03	
37																				0.00	
38	Far Backward																			0.00	
39																				0.00	
40																				0.00	16.0
41		Lumi PS Tracker		EICROC (1024 Channel)	256 Mb/s	204 kHz	100 ns	EICROC	204 kHz								100.0			0.00	
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43	PID-TOF	Barrel		FCFD (32 Channel)	80 Mb/s	3 kHz	200 ns	FCFD	3 kHz								160.0			0.00	12.0
44		Endcap		EICROC (1024 Channel)	256 Mb/s	204 kHz	100 ns	EICROC	204 kHz								100.0			0.00	
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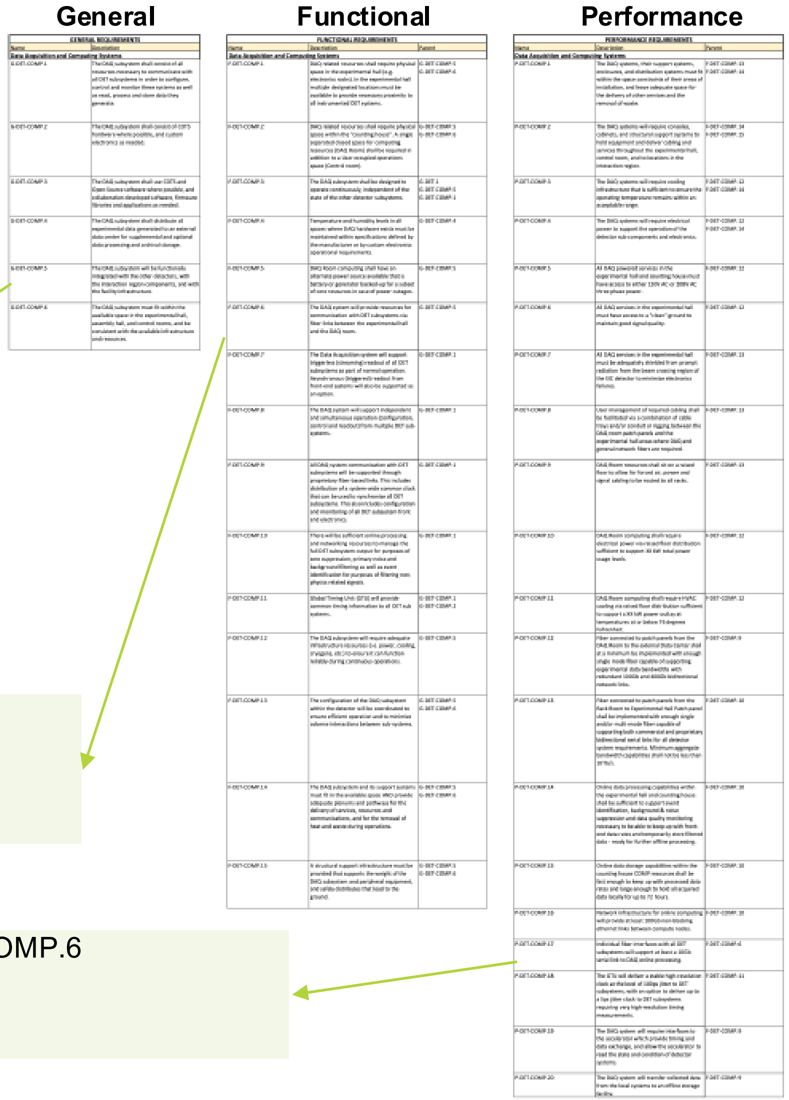
46		pfRICH		FCFD (32 Channel)	80 Mb/s	3 kHz	100 ns	FCFD	3 kHz	14,100	No/Estimate	113,000	320	640,000	41,700	90,700,000	160.0		2176	14.51	
47		hpDIRC		FCFD (32 Channel)	80 Mb/s	3 kHz	100 ns	FCFD	3 kHz								160.0			0.00	
48																					
49	Sum																			352.91	109.0

Data volumes directly affect requirements, and are being studied:

- Few issues with data volume through electronics chain (we are identifying hot spots)
- Highest luminosity rates into DAQ computing could reach **450 Gbps** (Synchrotron radiation in SVT) >> Output requirement 100 Gbps.
- Some detector's readout are more compressible than others. SVT in particular is not very compressible so we may need to be open to Echelon 0 (or early Echelon 1) data reduction techniques including software trigger.

Backup

Requirements



- Project level requirements are broken down and linked into categories: General, Functional and Performance.
- An example of data performance for fibers in DAQ/Computing is listed below:
- This concept helps avoid “feature creep”. The idea is that the job of the project is to achieve a defined level, and not pay for anything more…

G-DET-COMP.5	The DAQ subsystem will be functionally integrated with the other detectors, with the interaction region components, and with the facility infrastructure.

F-DET-COMP.6	The DAQ system will provide resources for communication with DET subsystems via fiber links between the experimental hall and the DAQ room.	G-DET-COMP.5

P-DET-COMP.17	Individual fiber interfaces with all DET subsystems will support at least a 10Gb serial link to DAQ online processing.	F-DET-COMP.6

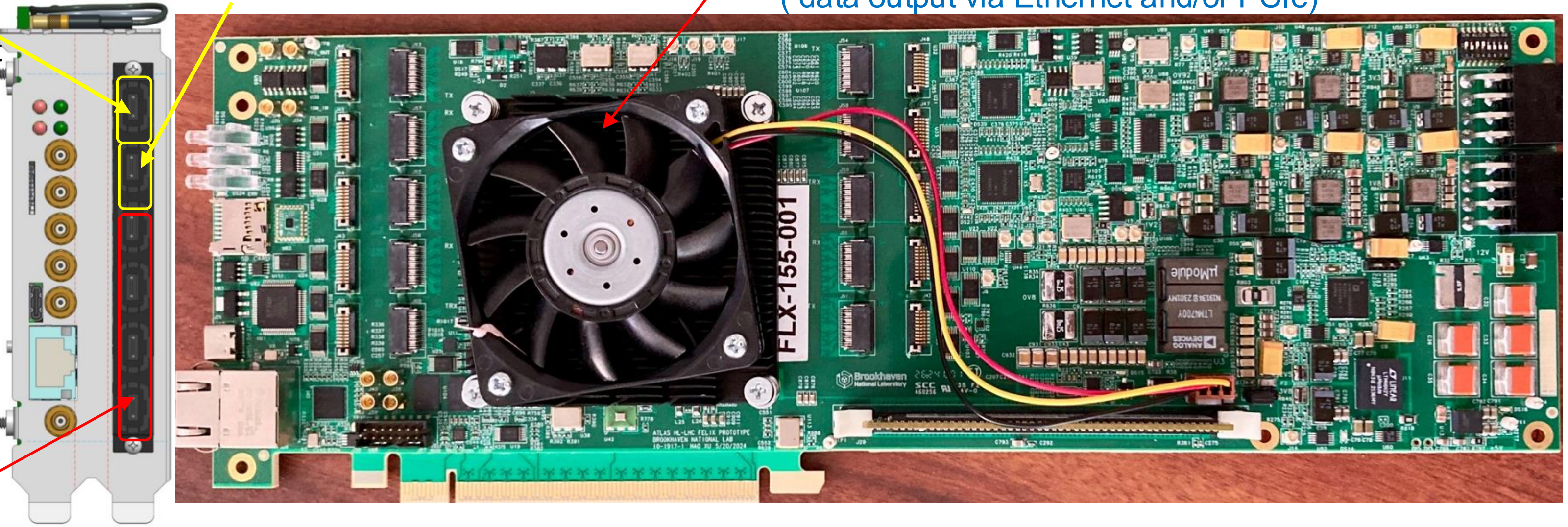
AI Requirements

- Focus on AI is intensifying
- AI is not a project requirement for the DAQ
- AI is a potentially enormously useful tool for attaining the project requirements
- Searching for concrete ways to make the Electronics / DAQ "AI ready"

- As of now there are a few specific answers to this:
  - Specific ML algorithms for specific features (e.g. dRICH dark current reduction in firmware)
  - MCP Servers to make data accessible to LLMs
    - Slow controls readout
    - DAQ Monitoring / Logging
    - Run Log Database information
  - MCP Servers to provide API's to allow LLMs (potentially) control DAQ
    - Run Control features
    - Use SRO WG orchestration test bed (Dmitrii's Talk) as a model

FELIX Updates – FLX-155 – DAM Status

Front-End Link eXchange

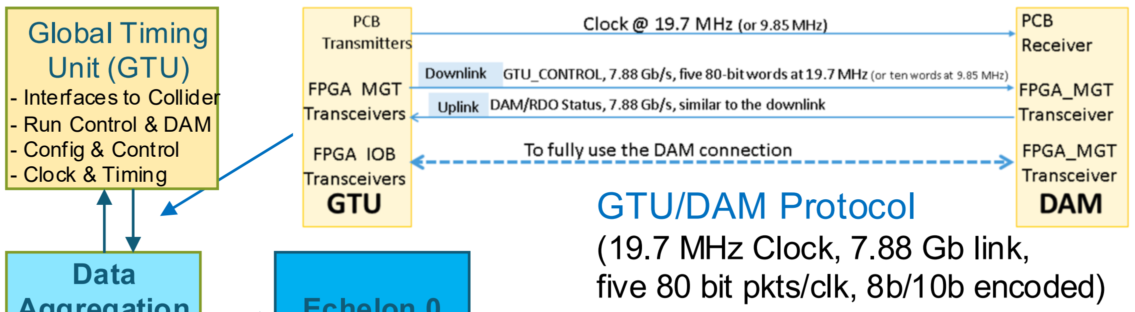


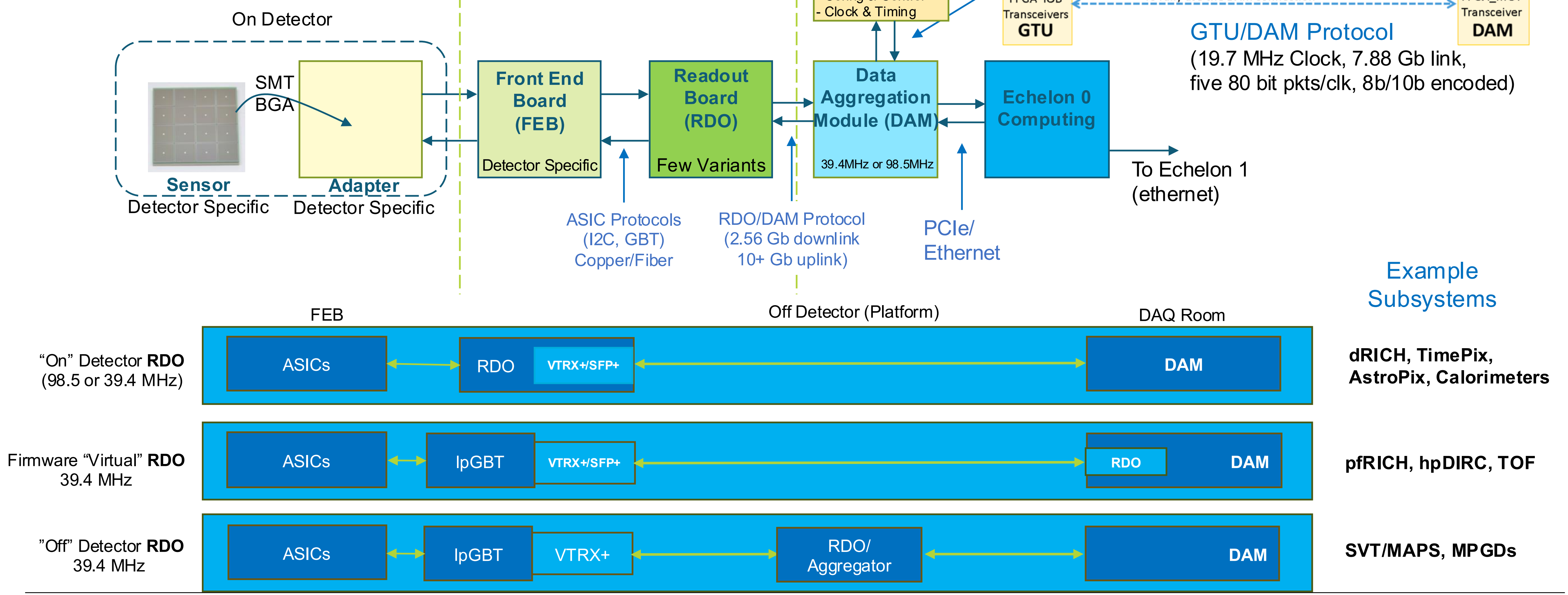
- FELIX hardware for future ATLAS experiments at HL-LHC is being developed at BNL (Omega Group)
  - ePIC is collaborating with Omega to use this design as our DAM board.
- Initial engineering articles were tested in early 2025. Updated PCB design (FLX155A) sent out for fabrication/population
  - Final design board FLX155B will be tested this Fall (2026).
- We are planning to produce at 2-3 boards for ePIC use. Availability anticipated end of 2026.
  - Currently we have two 24-port versions (FELIX 182) being used for developmen

ePIC Readout Chain – RDO options

Charges 2,3

- RDOs are implemented in several forms depending on the detector sub-system.
- The communication protocol to the front-end is standardized





Readout Chains

Detector System	Sensor	ASIC / Digitization	Digitization Clock	FEB	FEB-RDO Protocol	RDO Type	RDO Location	Notes
Si Tracking --- (ITS3 / LAS): (IB, OB, EE, HE)	ITS3/LAS	Integrated /w sensor	39.4 MHz (2-8 us time)	Integrated (Schambach)	GBT	Fiber Aggregator GenericRDO	South Platform	• J. Schambach Presentation
MPGD tracking: (SAMPA): (IB, OB, EE, HE)	urWELL / uMegas	SALSA	39.4 MHz	lpGBT / VTRX+	GBT	4 → 1 GenericRDO	South Platform	• RDO – N. Novitzki Presentation • FEB – F. Barbosa Presentation
Calorimeters (CALOROC): BarrelHCAL, Backward HCAL, Barrel ECAL, Backward ECAL, Backward HCAL	SiPM	CALOROC	39.4 MHz	lpGBT / SFP+	GBT	4 → 1 GenericRDO	South Platform	• N. Novitzki Presentation
Calorimeters (CALOROC): LFHCAL, HCAL Insert	SiPM	CALOROC	39.4 MHz	lpGBT / SFP+	GPT	4 → 1 GenericRDO	East HCAL Platform	• N. Novitzki Presentation
Calorimeters (Discrete): FwdEcal	SiPM	Discrete	98.5 MHz	FPGA / SFP+ / Cu	Internal	16 → 1 GenericRDO	South Platform	• G. Visser Presentation • Planned RDO similar to existing designs
Far Forward (AC-LGAD / EICROC): B0 tracking, Roman Pots, Off Momentum	AC-LGAD	EICROC	39.4 MHz	lpGBT / VTRX+	GBT	Direct to FELIX	N/A	• Same as per Endcap TOF
Far Backward: (AC-LGAD / FCFD): Lumi photon spectrometer tracker	AC-LGAD	FCFD	39.4 MHz	lpGBT / VTRX+	GBT	Direct to FELIX	N/A	• Same as per Barrel TOF
Central Detector (AC-LGAD / EICROC): Endcap TOF	AC-LGAD	EICROC	39.4 MHz	lpGBT / VTRX+	GBT	Direct to FELIX	N/A	• F. Barbosa Presentation
Central Detector (FCFD): Barrel TOF, pfRICH, DIRC	HRPPD / MCPMT	FCFD	39.4 MHz	lpGBT / VTRX+	GBT	Direct to FELIX	N/A	• F. Barbosa Presentation
Far Forward/Backward (CALOROC / Discrete): B0 Crystal Calorimeter, ZDC Crystal Calorimeter, ZDC HCAL, Lumi Photon Spectrometer Calorimeter	SiPM	Discrete	39.4 MHz (or) 98.5 MHz	FPGA / SFP+ / Cu (or) lpGBT / SFP+	Internal GBT	16 → gRDO (or) 4 → 1 gRDO	East/West Tunnel Near Detectors	• Small channel count detectors • Expect to copy either CALOROC or Discrete
Far Backward: (Discrete): Direct Photon Lumi Calorimeter*	SiPM	Flash-250	197 MHz	FADC 250	Streaming ADCs	(N/A)	West Tunnel	• Special FELIX processing to histogram / Sum bunch by bunch luminosity data
Far Backward: (TimePix): Low Q Tagger	TimePix	Integrated / w sensor	98.5 MHz	Integrated / w sensor	Internal	SPIDR4 Variant (NIKEF)	West Tunnel Under Detector	• K. Livingston Presentation • Planned RDO similar to existing designs
Imaging Calorimeter (Astropix):	AstroPix	Integrated / w sensor	98.5 MHz	Integrated / w Sensor	Astropix Internal	End of Stave Card (NASA)	On Detector	• J. Metcalfe Presentation • Planned RDO similar to existing designs
Central Detector (ALCOR): dRICH	SiPM	ALCOR	39.4 MHz	FPGA / Cu	Internal	FPGA / VTRX+	On Detector in PDU	• Pietro Antonioli Presentation

Electronics design pending
Planned variants of GenericRDO
Scope of outside Electronics/DAQ