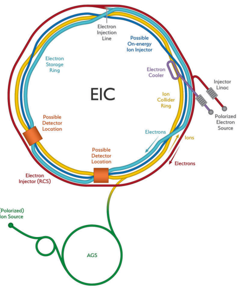


Silicon vertex detector power distribution

SVT EIC workshop

2 – 4 September 2020

Alberto Collu

Lawrence Berkeley National Laboratory

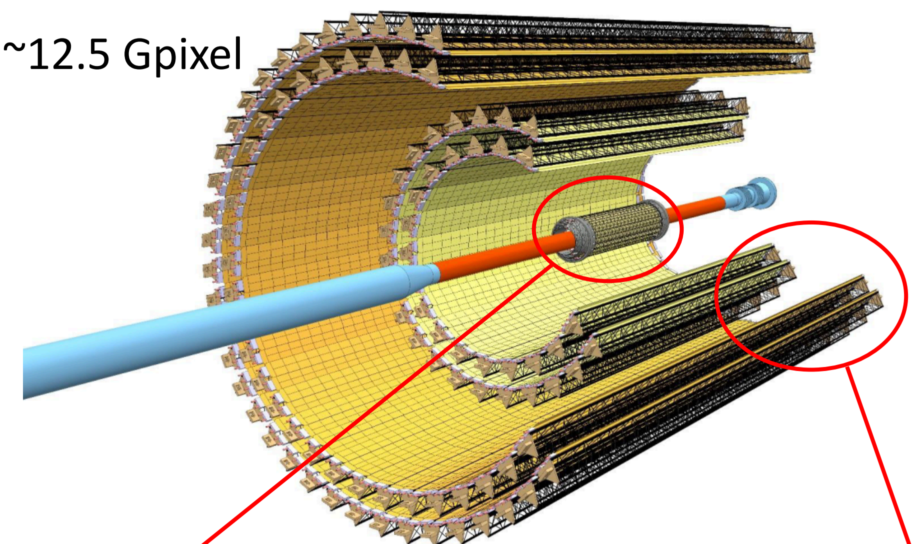
U.S. DEPARTMENT OF ENERGY

Outline

- Power system for last-gen MAPS-based detectors: ALICE ITS-2
  - Overview and power system requirements
  - Power system development
  - Power system production
- Electron-Ion Collider
  - Constraints on power due to material budget
  - Possible power system implementations

ALICE Inner Tracking System Upgrade (ITS-2)

~12.5 Gpixel



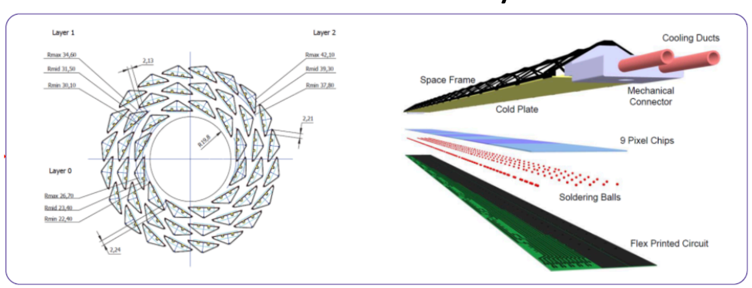
Geometry:

- Surface coverage ~ 10 m^2
- 7 layers of MAPS, 192 staves
- $|\eta| < 2.5$

Power characteristics:

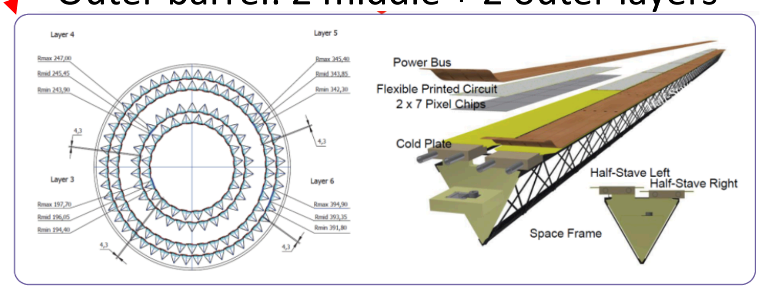
- Operating voltage: 1.8V±10%
- Module power consumption: ~1.8W (D), ~0.36W (A)
- Power density: ~30 mW cm^{-2}
- Total power consumption: ~3 kW
- Analog + digital channels: ~3500
- Bias channels: ~700

Inner barrel: 3 layers



Radius (mm): 23,31,39
X/X_0 (per layer) ~ 0.35%
48 staves
432 sensors (9 per stave)

Outer barrel: 2 middle + 2 outer layers



Radius (mm): 194,247,353,405
X/X_0 (per layer) ~ 1%
144 staves
1692 modules, 23688 sensors

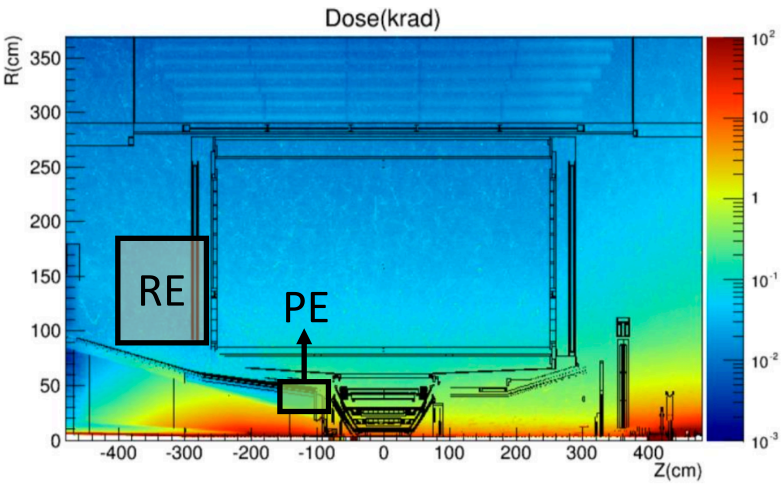
ALICE ITS Power system requirements

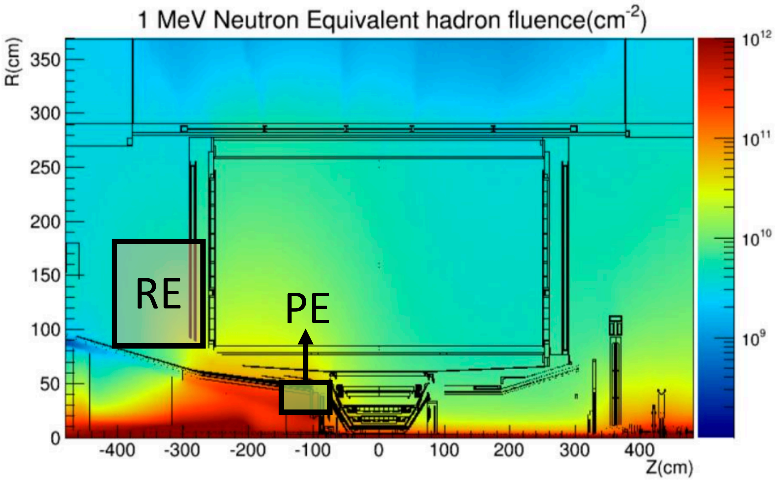
- Supply power (sensor supply and bias) to the staves such that:
  - Module sensor fake-hit rate < 10^{-6} event^{-1}
  - Module sensor detection efficiency ≥ 99%
- Survive the radiation load at the power board location
  - Total Ionizing Dose (TID)
  - Non-Ionizing Energy Loss (NIEL)
  - Single Event Effects (SEL, SEU, SET, …)
- Material budget of the power bus in outer layers in the fiducial volume < 0.4% X_0
- Interface to the ALICE ITS RDO board for control
  - I^2C interfaces
  - Grounding
- Fit into the space allocated in the ITS upgrade integration envelopes

ALICE radiation load: Run 3 + Run 4

A. Alici et al., Radiation dose and fluence in ALICE after LS2, 2018

L_{int} = 10 nb^{-1} (Pb-Pb)

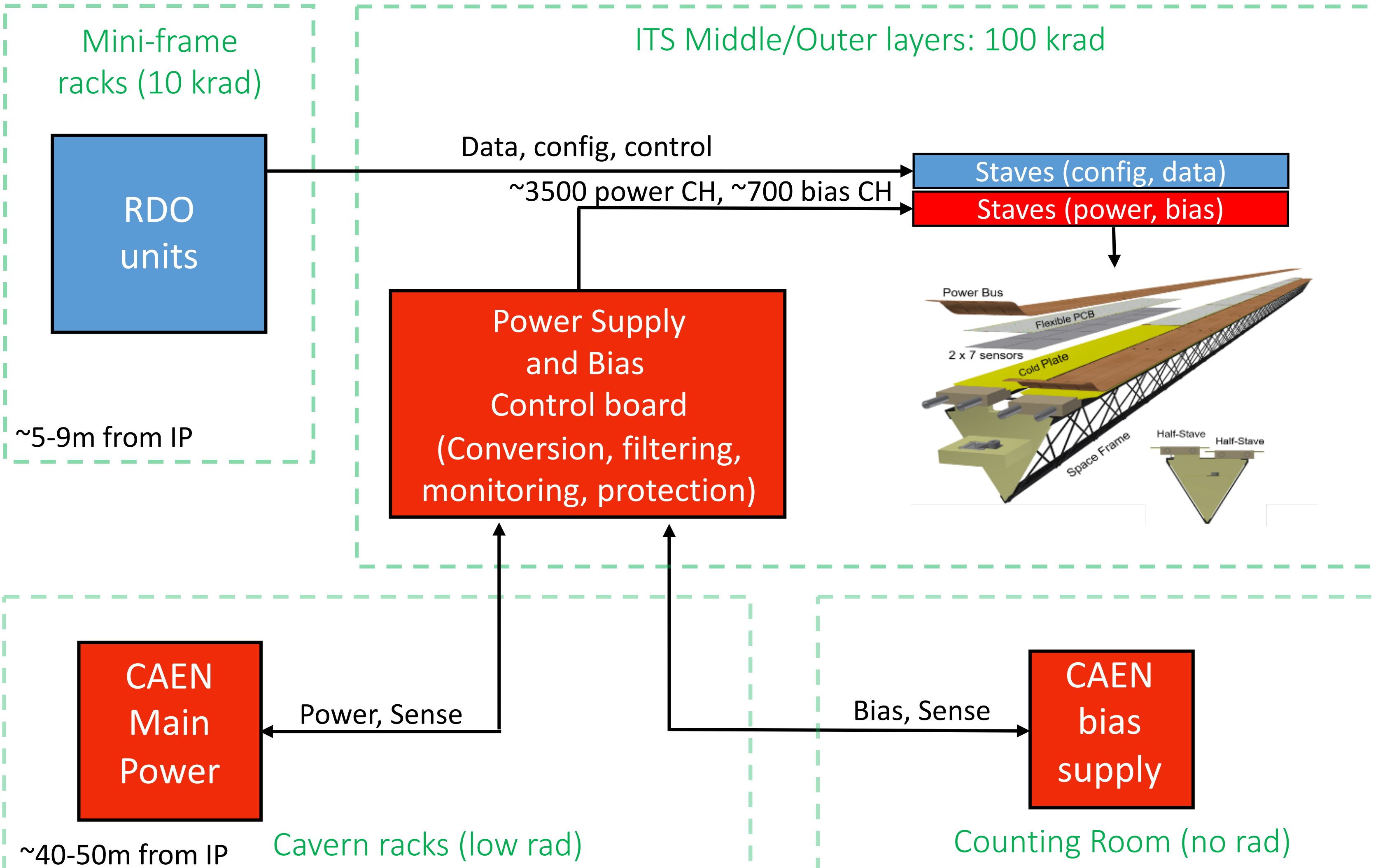




Values in table include a safety factor of 10

Position wrt beam			Radiation level			
r [cm]	z [cm]	Ref name	TID [krad]	1MeV n_{eq} fluence [cm^{-2}]	High energy hadron flux [kHz cm^{-2}]	Charged particle flux [kHz cm^{-2}]
2.2	-13.5 ; 13.5	ITS L0	2734	$1.7 * 10^{13}$	770	910
20	-42.1 ; 42.1	ITS L3, Power Electronics (PE)	101	$1.0 * 10^{12}$	14.2	17.1
43	-73.7 ; 73.7	ITS L6, Power Electronics (PE)	20	$8.1 * 10^{11}$	4.9	6.7
100	330	RDO Electronics (RE)	~5	$1.6 * 10^{11}$	0.86	1.7
258	-260 ; 260	TPC Out	0.86	$1.4 * 10^{11}$	0.37	0.3

ALICE ITS initial architectural scheme

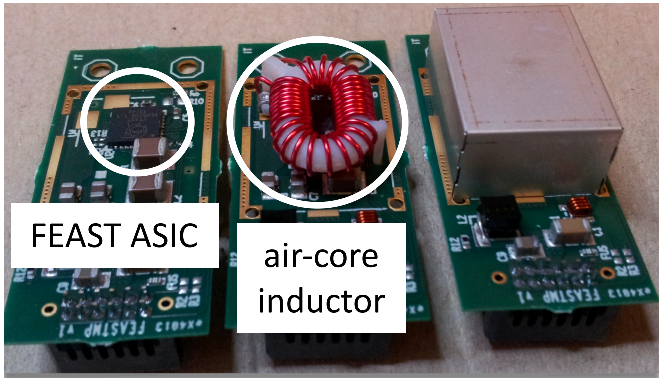


Power system TID: 100 krad at least

Power system must work in 0.5 T magnetic field

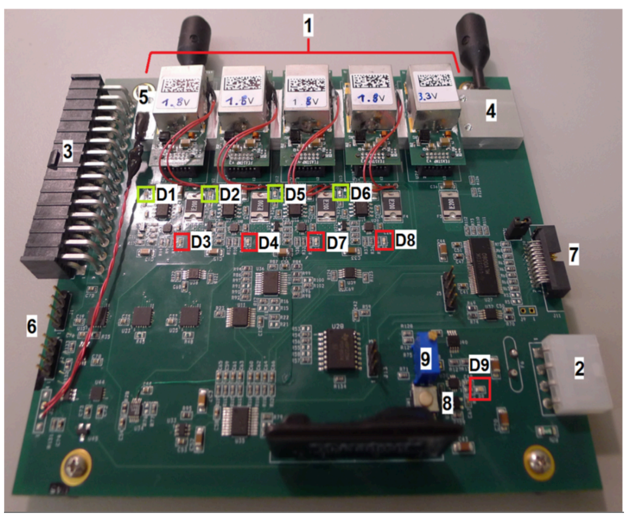
Power board prototype using DC-DC converters

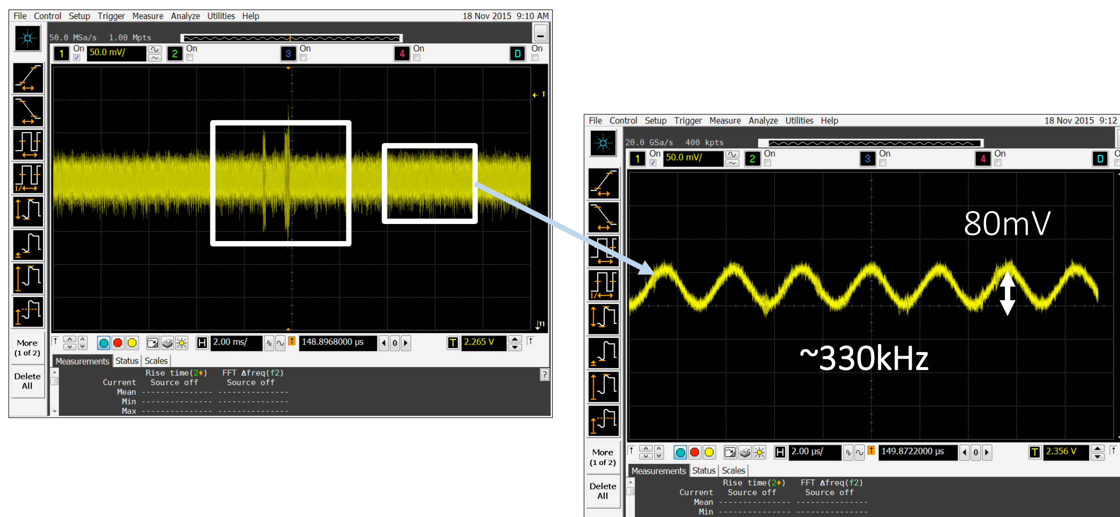
CERN DC-DC converter (FEASTMP)



Max external magnetic field: > 4 T
Total Ionizing Dose (TID): > 200 Mrad
NIEL: > 5 * 10^{14} 1MeV n_{eq} cm^{-2}
Input Voltage: 5-12V
Output Voltage: 0.9-5V (fixed at production)
Output Current: 0-4A
Output Power: 10W
Efficiency range: 40-80% (80% @ I_{out} > 800mA)
Switching frequency: 1.5-2MHz, settable

Many channels on first developed power board prototypes showed high output noise





Yield issues in FEASTMP later found by the CMS collaboration. Fixed in new version (late for ALICE ITS-2)

Radiation testing at the LBNL 88” Cyclotron (BASE)

ALICE ITS Readout and Power System commercial-off-the-shelf (COTS) components

Four campaigns: April 2016, October 2016, June 2017, March 2019

Beam:

- Particles: 55 MeV Protons (can penetrate thick packages)
- Typical flux: ~10^8 cm^{-2} s^{-1}, attenuated if needed
  - ~100 krad in Si in 1h at the Cyclotron
  - Also integrated ~10^{12} 1 MeV n_{eq} cm^{-2} NIEL

COTS tested:

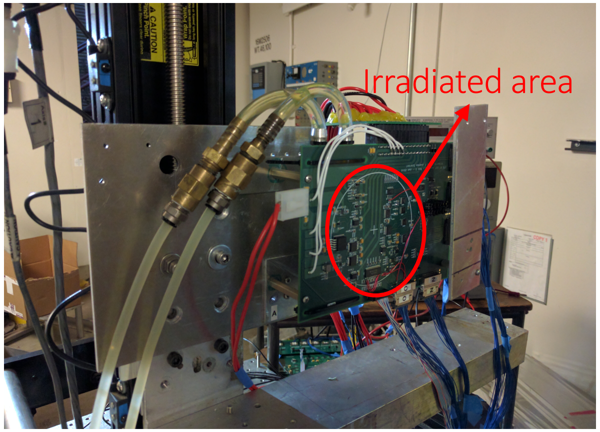
- Switching DC-DC converters, regulators, ADC, DAC, Negative voltage regulators, switches, I2C isolators, …

Results:

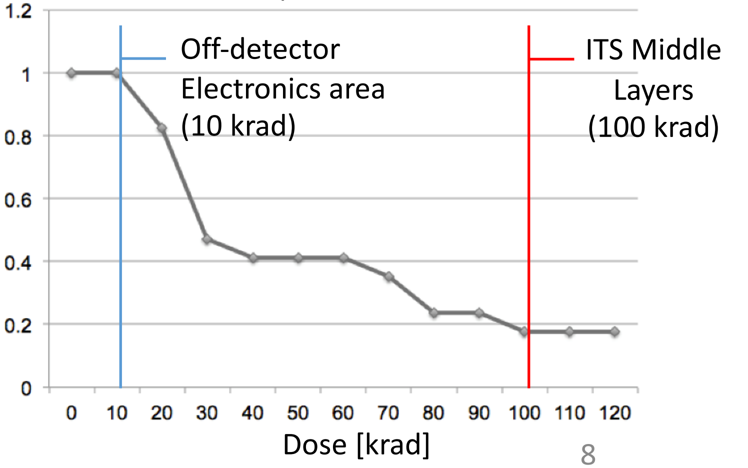
- Somewhat pessimistic, annealing observed
- Most tested COTS do not work past 100 krad
- Components with large transistor structures are more sensitive (larger gate oxide, e.g. voltage regulators)

See Barbara’s presentation on the 88” Cyclotron, Friday September 4th

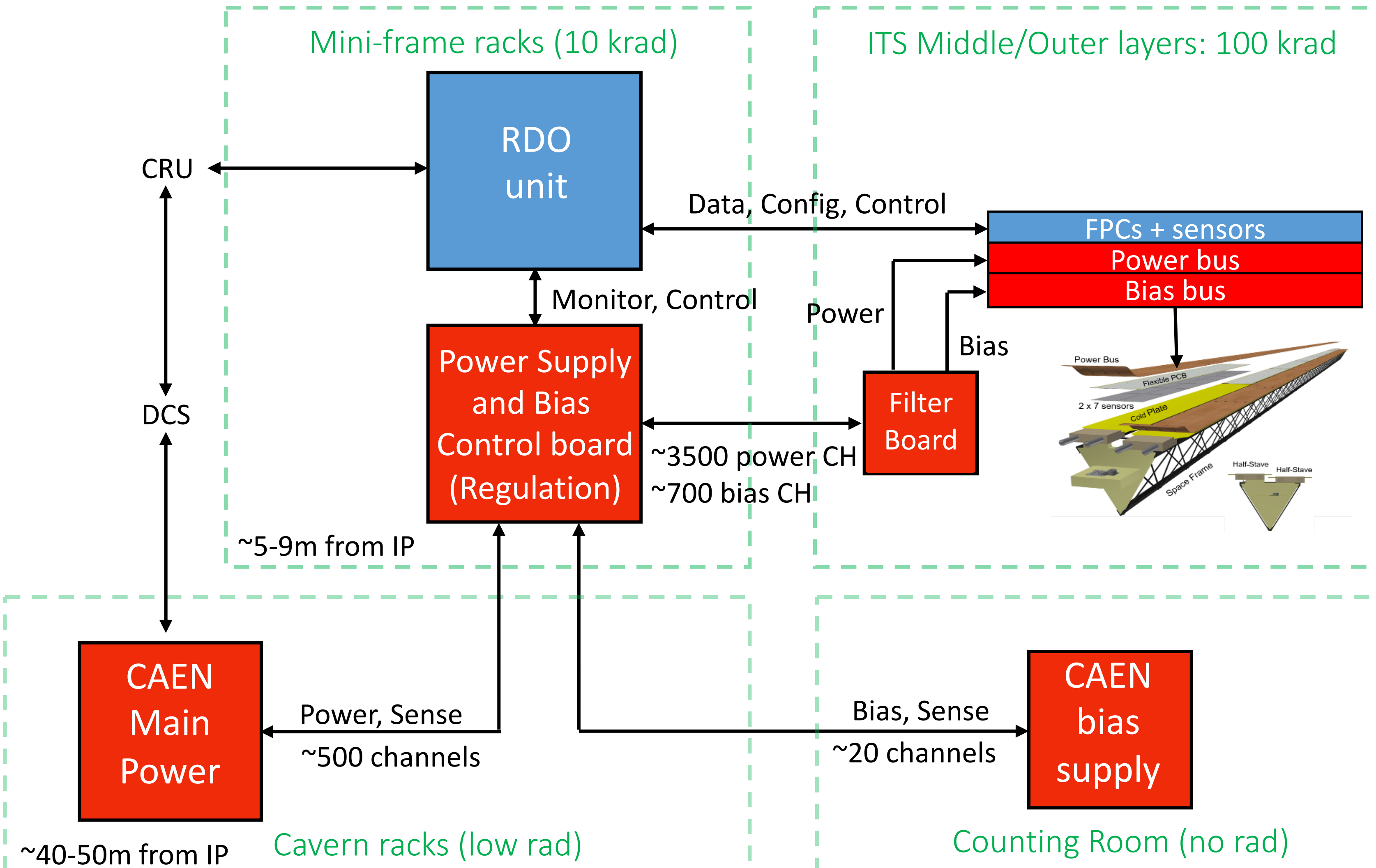
BASE 2016 beam test campaign



Fraction of components survived vs Dose



ALICE ITS final architectural scheme

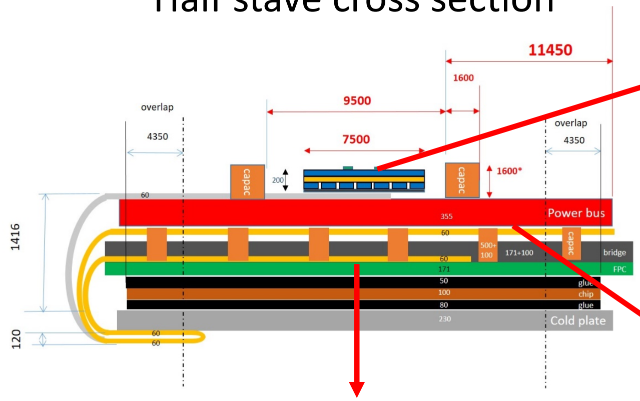


Readout and Power systems TID: 10 krad TID at least

Readout and Power systems must work in 0.5 T magnetic field

OL stave power distribution structures

Half stave cross section



Bias bus

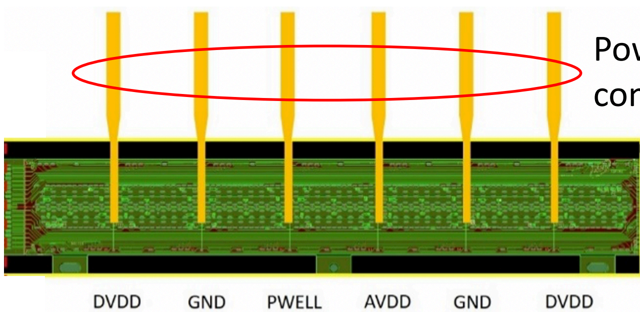
Designed at LBNL
Fabricated in Kharkiv, Ukraine

Bias connections to up to 7 modules

Materials: Aluminum + Kapton

Dimensions (mm):
1500 (L) x 11 (W) x 0.2 (H)

Flexible Printed Circuit (FPC)



Power bus
connections

Designed at INFN Torino, production by INFN Trieste (Italy)
Power + data connections to 14 ALPIDE sensors (module)
Dimensions (mm): 210 (L) x 30 (W) x 0.2 (H)
Materials: Copper + Kapton

Power bus

Designed at LBNL
Fabricated in Kharkiv, Ukraine

Ana/Dig connections to up to 7 modules

Materials: Aluminum + Kapton

Dimensions (mm):
1500 (L) x 30 (W) x 0.3 (H)

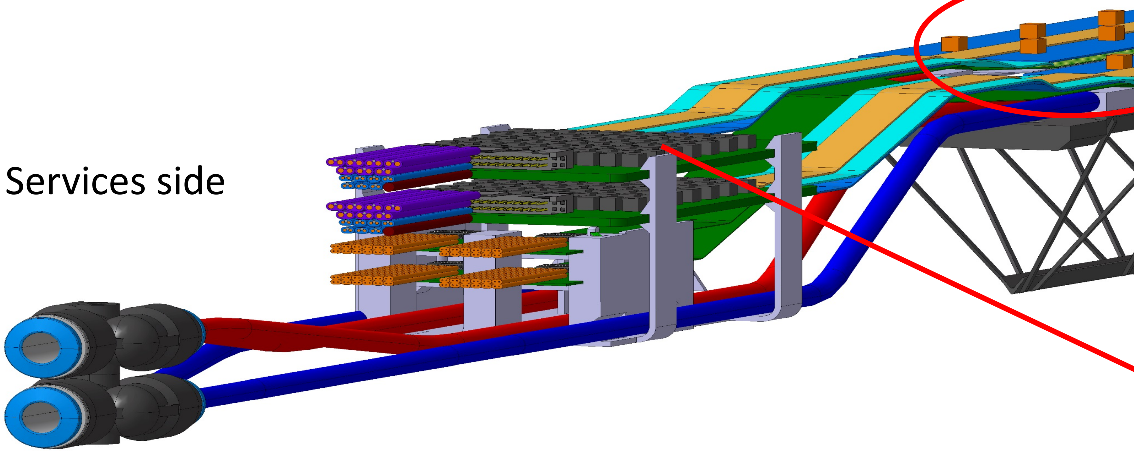
See Nikki's presentation on stave assembly, Friday September 4th

End of stave decoupling

Ceramic capacitors only in detector volume

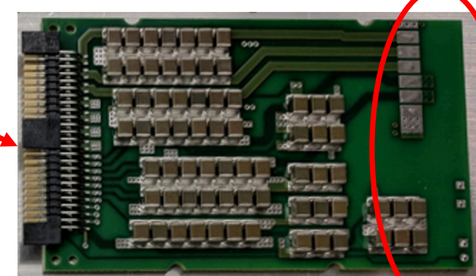
Distributed power bus capacitance

Services side



Filter board

~2.3mF each digital channel
~1mF each analog channel



Power/bias
from power board
(5-9 m away)

Half stave
power/bias interfaces

- Optimization of capacitance based on:
  - SPICE simulations
  - Testing with prototypes of modules
- Large amount of capacitance on filter board required to:
  - Damp voltage oscillations due to sudden variations in current consumption
  - Provide sufficient decoupling to reduce ground bounce/rail collapse upon data transmission

Power board design based on regulators

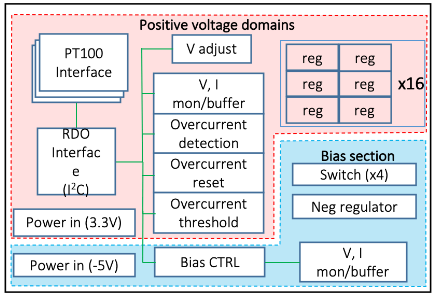
Choosing regulators vs DC-DC converters:

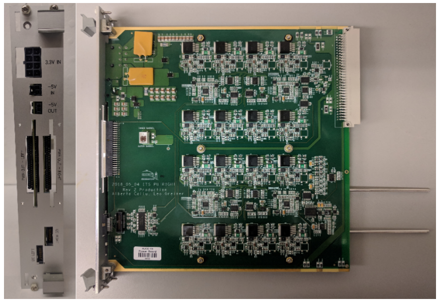
- No testing in magnetic field required
- More power dissipated in the power system
- Large section, heavy cables

5 tons of cables between main CAEN PS and power boards only

Power board main features:

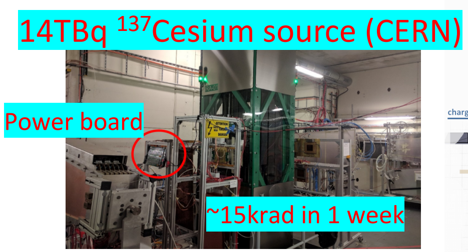
- Positive, negative (bias) voltage adjustment
- Voltage, current monitoring
- Temperature measurements
- Over-temperature, overcurrent protection

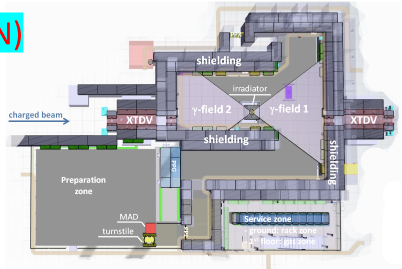




Power board development:

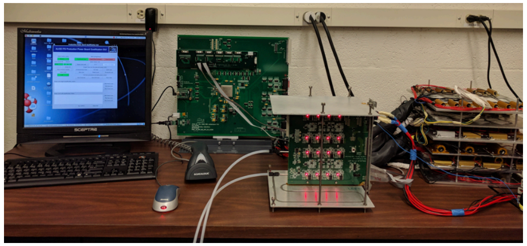
- Extensive prototyping (3 iterations)
- Radiation testing with gamma source, mixed field





Power board production, QA and QC:

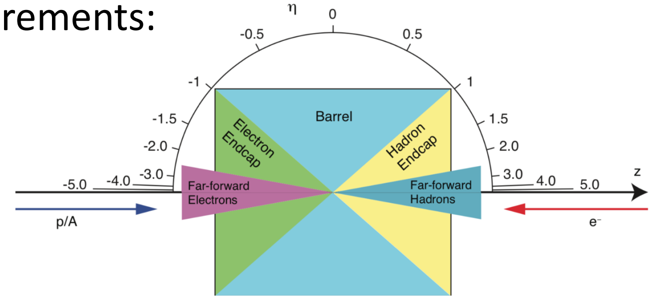
- ~200 units produced and tested at LBNL
- ~6000 channels



Powering an EIC Silicon vertex detector

EIC vertex detector expected operating conditions/current requirements:

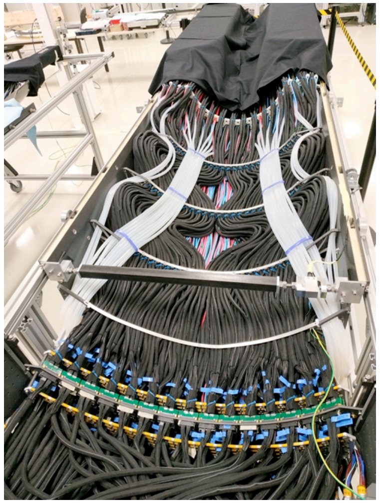
- Event rate: ~500kHz
- Particle multiplicity: ~10/event (does not include background)
- Momentum resolution: ~2%
- Material budget: few % of radiation length
- Pseudo-rapidity coverage (central + auxiliary): |η| <~ 4



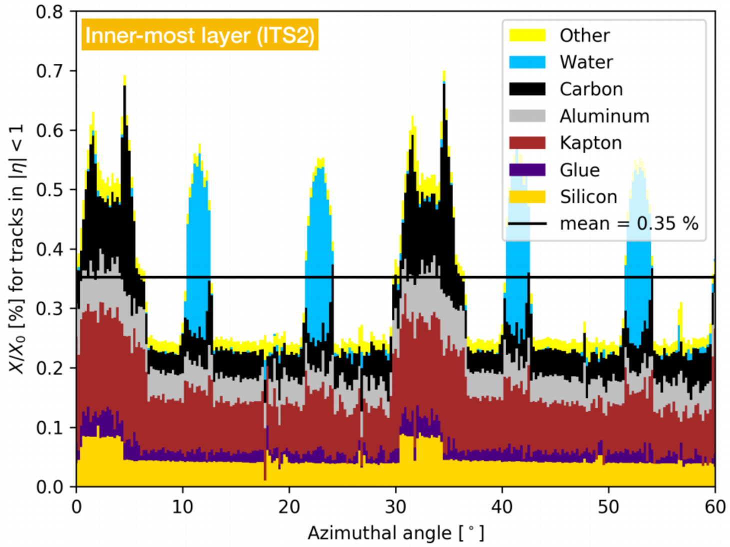
EIC detector Handbook, figure 2

ALICE ITS-2 power system architecture may not be a suitable option for the EIC

Detector services: cabling, cooling



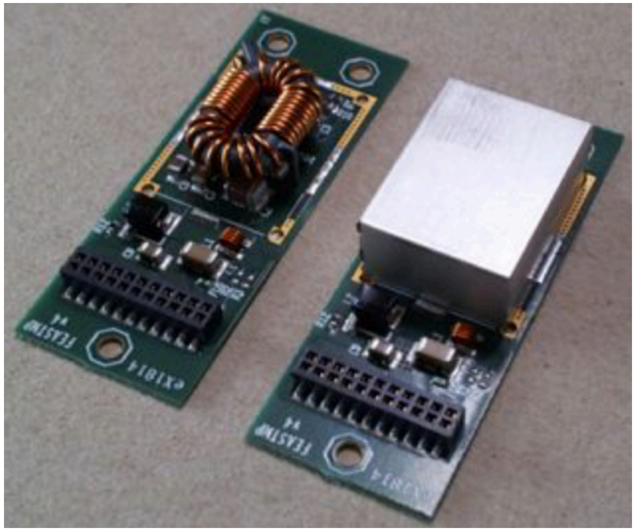
Innermost layer material budget: Si, FPCs, mechanics, cooling (|η| < 1)



Need to move voltage conversion closer to the detector to reduce the mass of services

DC-DC converters outside the detector volume

http://project-dcdc.web.cern.ch/public/Documents/FEAST2%20datasheet.pdf

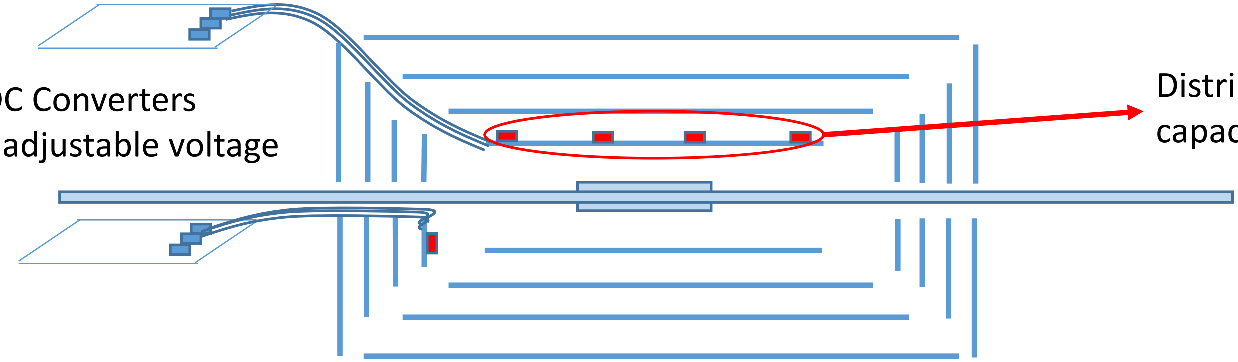


Pros:

- Radiation hard CERN DC-DC converter available
- Reduced development time

Cons:

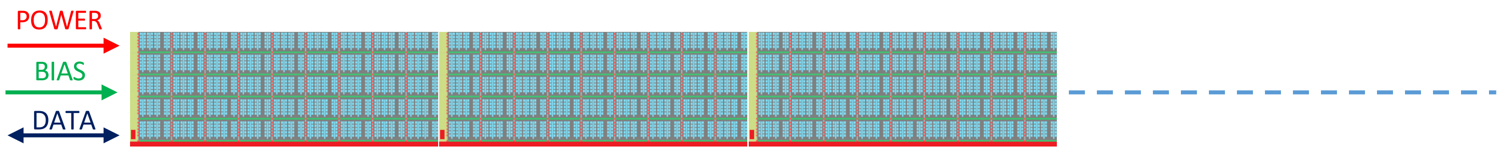
- Bulky, must to be placed outside detector volume
- May require developing voltage adjustment circuitry
- May require large decoupling capacitors in the detector volume



Could be used in conjunction with serial powering, see next slide

Serial powering with integrated regulators

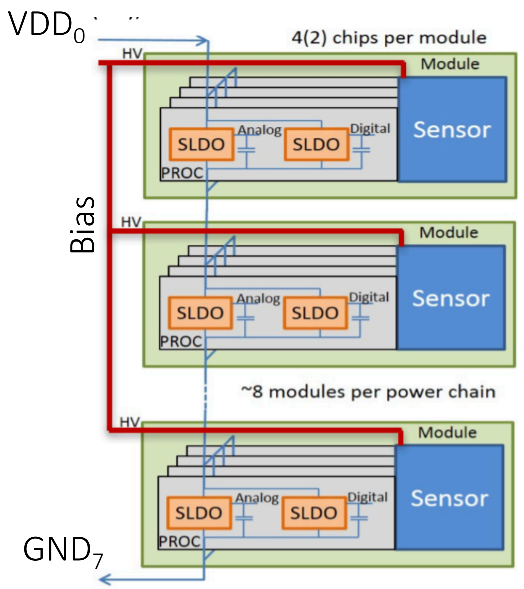
Serial powering allows delivering power to sensors in a chain with minimal FPC material



A serial powering scheme currently in use in the ATLAS experiment inner tracker:

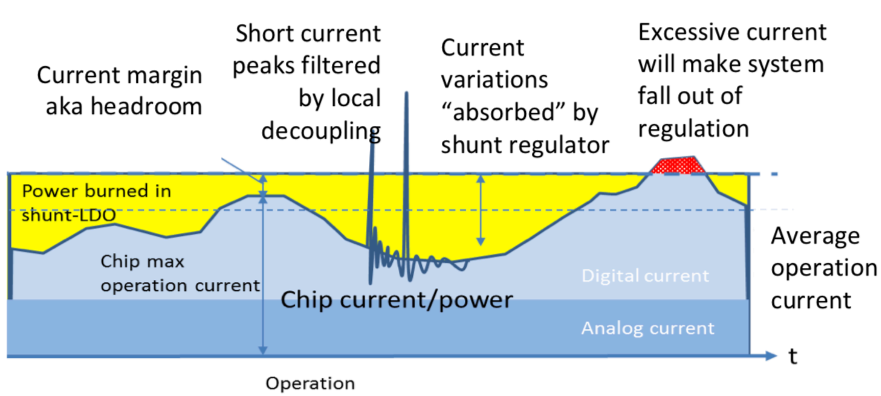
- Modules are series connected ($GND_{N-1} \rightarrow VDD_N$)
- Constant module voltage and constant chain current
    - SLDO drains excess current ($I_{chain} - I_{module}$)
- Chain of N modules powered at $N * V_{module}$

https://indico.cern.ch/event/681247/contributions/2929073/attachments/1640109/2618527/SerialPowerACES2018.pdf



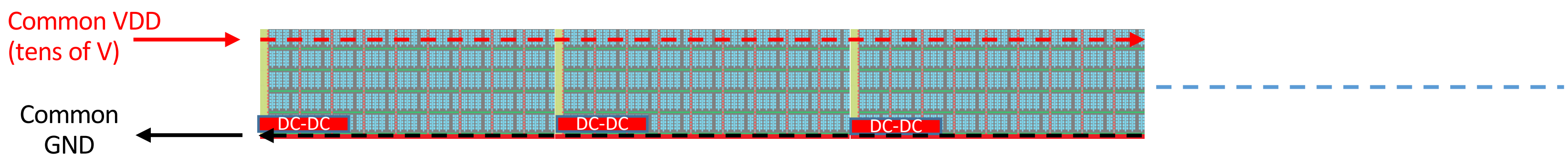
Limitations:

- Failure in one module leads to failure of a full chain
- Power inefficient with high dynamic power consumption sensors



Parallel powering with integrated DC-DC converters

- All modules on a stave connected to the same input voltage (~tens of V)
- Switching DC-DC converters integrated in the sensors (output voltage ~V)



Pros:

- Can efficiently accommodate large dynamic power consumption
- No need for voltage adjustment
- Failure in power circuitry in one module does not compromise a full stave

Cons:

- Might require external discrete components
- Switching noise may be an issue

Could be an interesting option to explore if ALPIDE-like sensors are used in SVT:

- Asynchronous hit-driven readout, clock gating will produce large dynamic power consumption

Summary

ALICE ITS-2 power system development:

- Driven primarily by unavailability of radiation tolerant components and geometry requirements
- Voltage regulation far from detector to reduce radiation load (to 10 krad TID)
    - Low voltage system (~V) requires high material budget cables
    - Voltage drop compensation required
    - Large passive decoupling circuitry near/inside the detector volume to achieve sufficient voltage stability

EIC Silicon vertex detector power system:

- Wide detector acceptance, low material budget requirements highly constrain architecture
    - Replicating ALICE ITS power system may be detrimental to EIC physics goals
- Delivering higher voltage, i.e. lower current, to detector structures benefits material budget
    - Voltage conversion must be as close as possible to the detector, possibly inside sensors
    - Requires adopting or developing circuitry that can cope with high radiation and magnetic fields
- Ideas for possible architectures:
    - CERN FEAST2 DC-DC converters near detector + passive filtering in detector volume
    - Truly serial powering with Shunt LDOs integrated in the sensors (ATLAS-like)
    - Parallel powering with DC-DC converters integrated in the sensors + discrete components