EIC All-Silicon Tracker: challenges in the development of the power system

EIC group meeting

May 18, 2021

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Outline

- Considerations on power system development for MAPS detectors
- The ALICE ITS-2 development
- EIC tracker powering options technical note
  - General information
  - Document structure
    - Detector/power system requirements
    - Assumptions on sensors/modules
    - Powering options (Fixed voltage DC-DC converters, Serial powering)
  - Preliminary material budget estimations and development time

Main power system requirements

- Ability to work in magnetic field
  - Limits range of suitable technologies (e.g. can only use air core inductors)
- Radiation hardness
  - Total Ionizing Dose (TID), Non-Ionizing Energy Loss (NIEL), Single Event Effects
  - Implies extensive testing and/or adoption of rad hard by design technologies
- Electrical
  - Voltage stability: affects sensor operation and performance
    - fake-hit rate, detection efficiency
  - Granularity, connection topology, grounding
- Material budget
  - Also affects material budget of mechanical support
- Other:
  - Interface to various systems (RDO board, safety systems, …)

Challenges

General trends in high energy nuclear physics experiments:

- Increasingly higher luminosity
  - higher data rate / higher power required
  - harder to find/design suitable radiation hard components
- Increasingly more stringent material budget/coverage requirements
  - harder to deliver stable power at the detector

Above trends more a problem for power system than readout system:

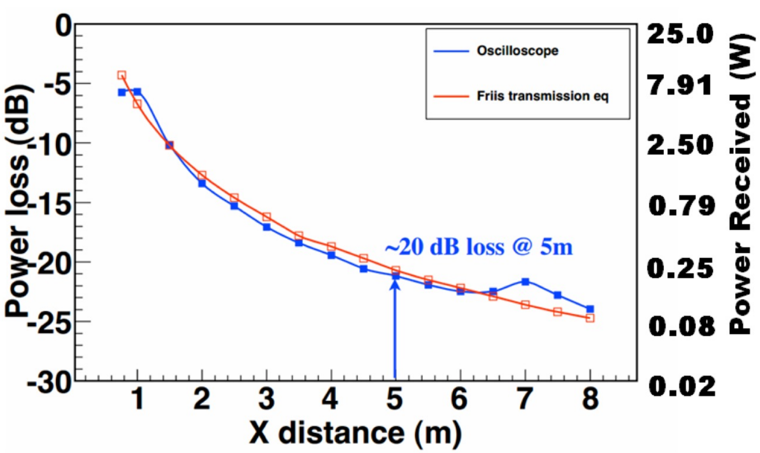
- Reducing material budget not necessarily incompatible with higher RDO rate
  - Reducing cable cross section/distance benefits impedance (although not resistance)
- Reducing material budget conflicts with increasing currents

Transporting power to/through the detector primary issue:

- Done using cables of various types (wires, FPCs, ICs), usually bulky
- Voltage conversion as close as possible to the sensors benefits material budget
  - Highly reduced cable cross section, although at the cost of using additional circuitry
  - Trade-off with radiation hardness requirements

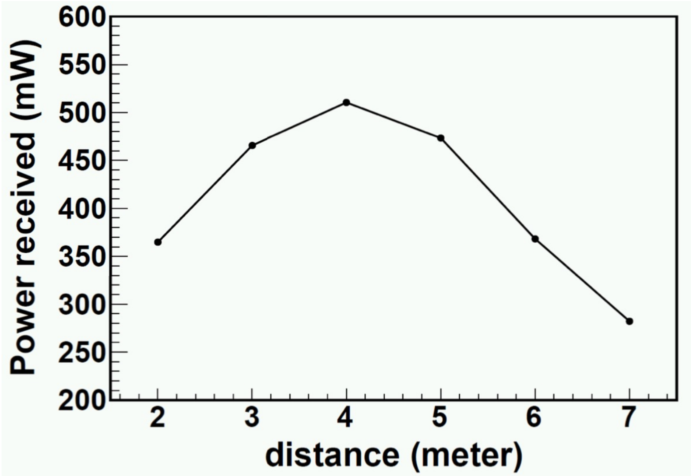
Wireless power transmission?

- Efficient power transmission not possible at large distances (~meter) from transmitter
- Technology suitable for short distances where cables/connectors are not an option



RF transmitter-receiver (multi-directional)

- Power loss (dB) in the RF power transmission as a function of distance (m) from the source (25W).
- Allows crossing obstacles but it provides very low power efficiency (~$1/d^2$)

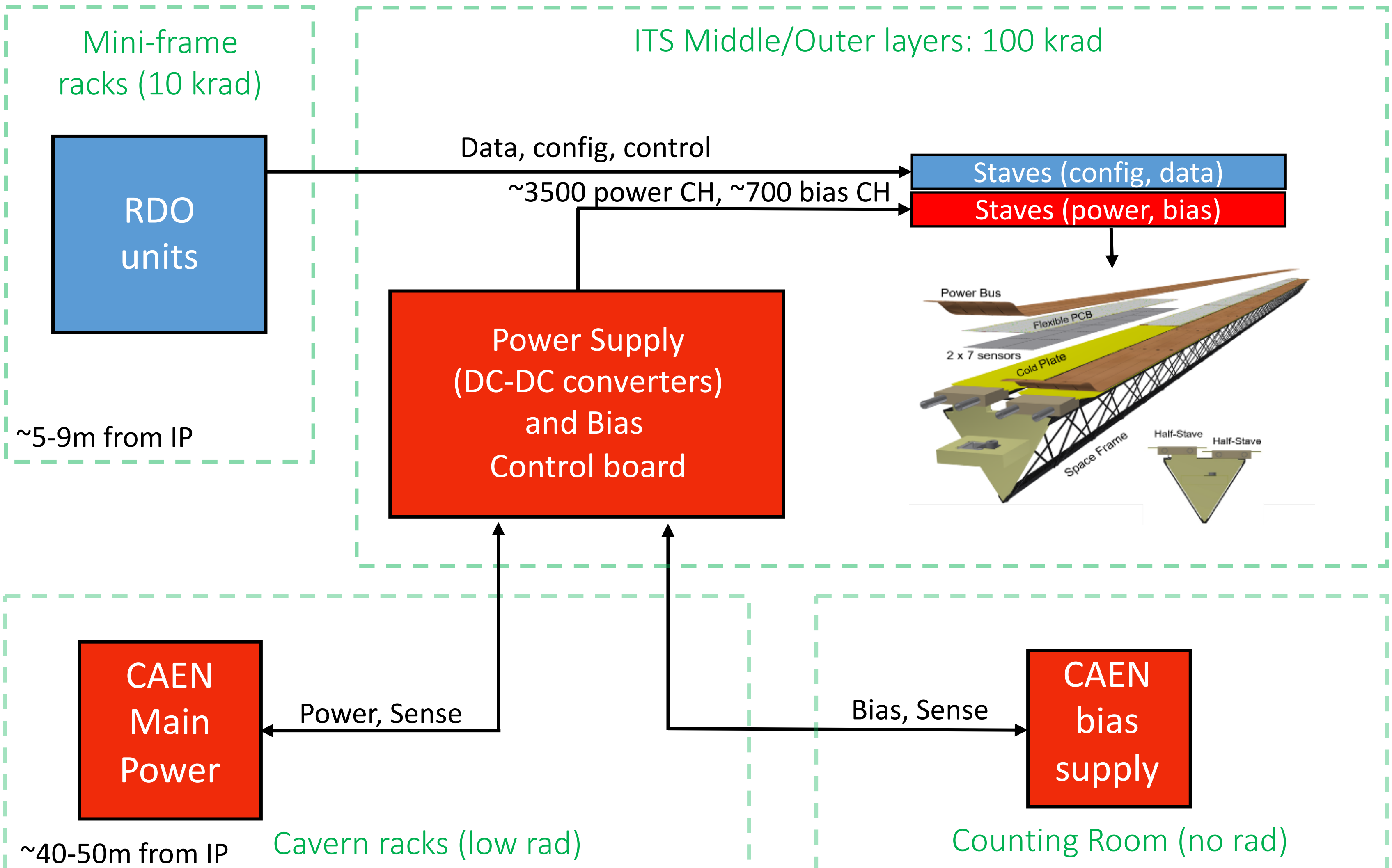


Optical transmitter-receiver (uni-directional)

- Power received (mW) by a photovoltaic panel as a function at distance (m) from an optical source (3.5W LED @940nm + focusing lens)
- More efficient power transfer, however it cannot be used where there are obstacles

https://arxiv.org/pdf/1511.05807.pdf

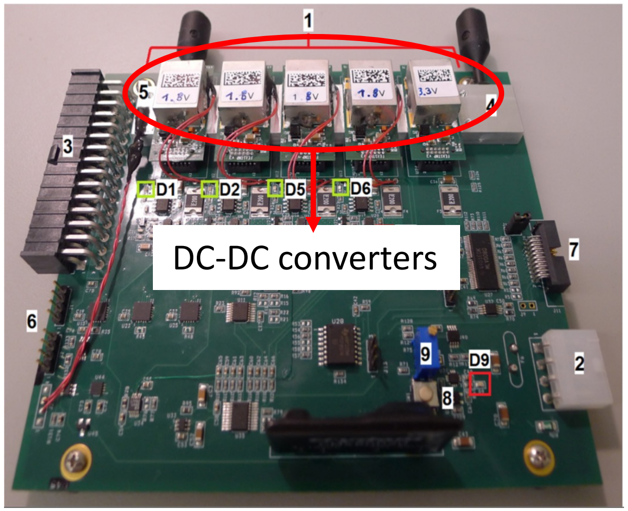
ALICE ITS-2 initial architectural scheme

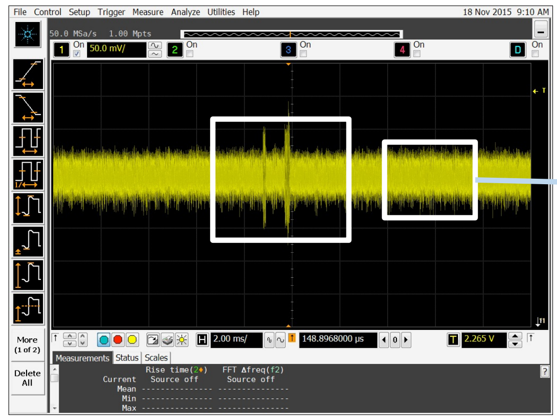


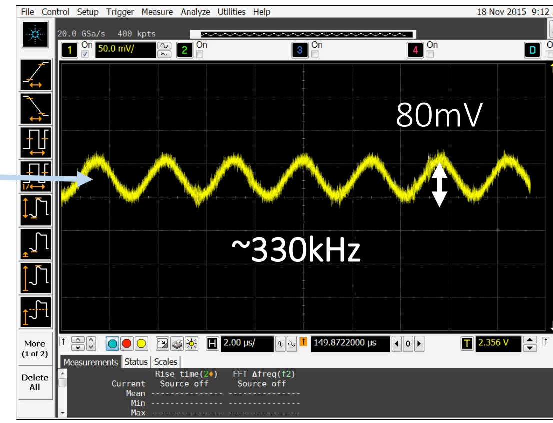
Power system TID: 100 krad at least
Power system must work in 0.5 T magnetic field

ALICE ITS-2: voltage generation

First PB design based on CERN FEASTMP DC-DC converters: high conversion efficiency, high rad hardness



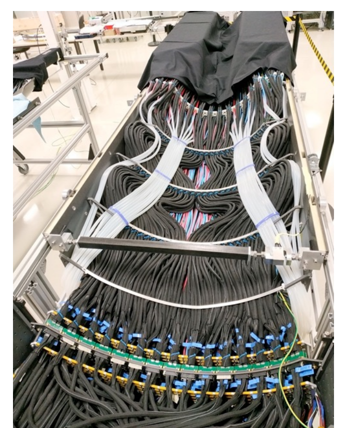




Yield issues in FEASTMP later found by the CMS collaboration. Fixed in new version (late for ALICE ITS-2)

Switched to regulators:

- No testing in magnetic field required
- Low power efficiency
- Large section, heavy cables



High mass power cables at |η| ~> 2.5

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

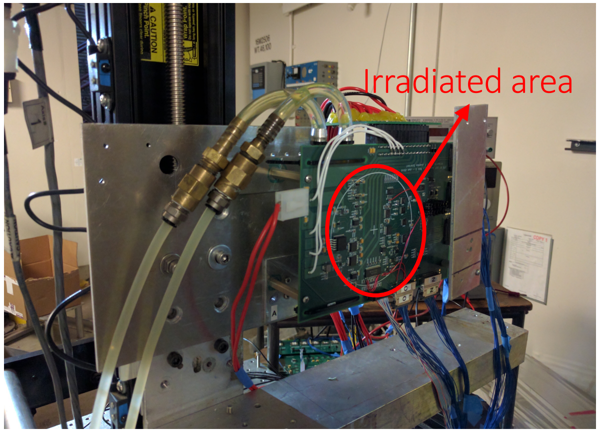
COTS tested:

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

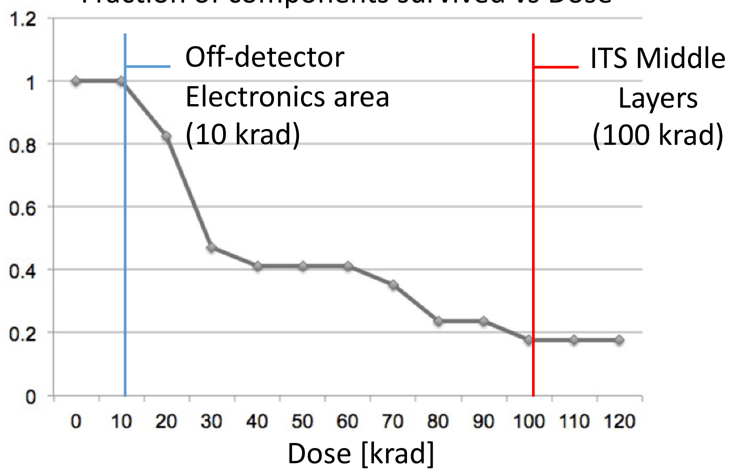
Results:

- 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)

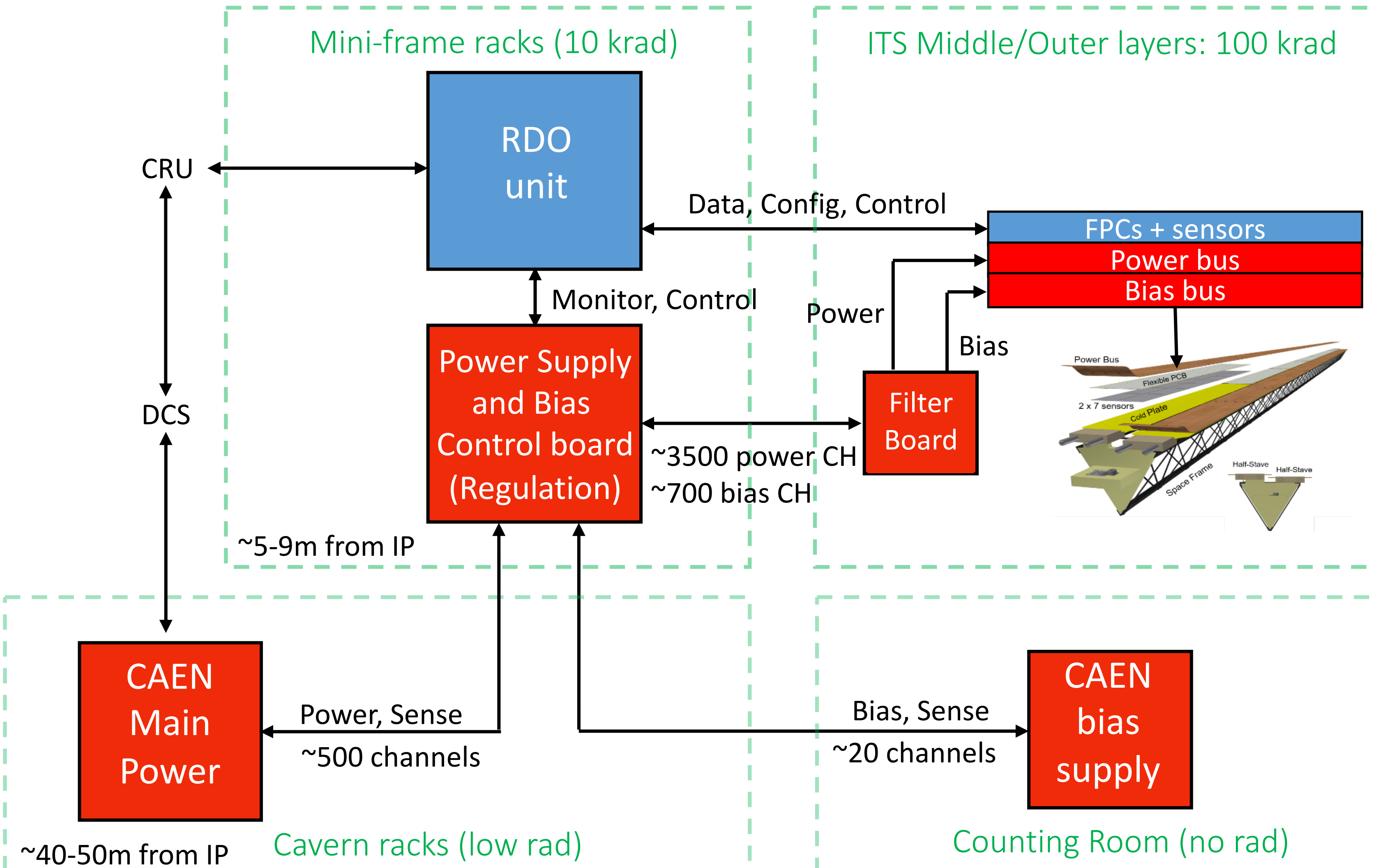
BASE 2016 beam test campaign



Fraction of components survived vs Dose



ALICE ITS-2 power system scheme



Readout and Power systems TID: 10 krad TID at least

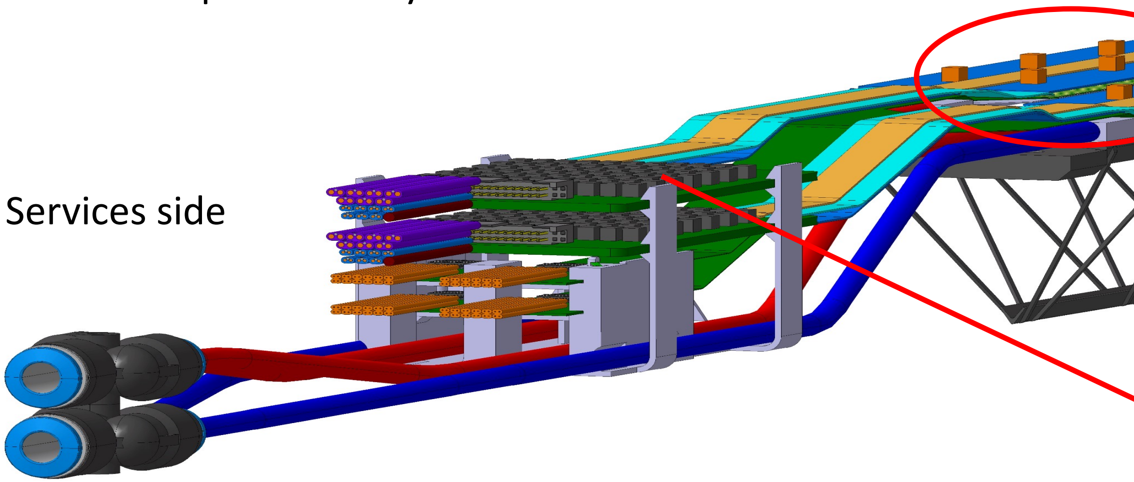
Readout and Power systems must work in 0.5 T magnetic field

End of stave decoupling

Ceramic capacitors only in detector volume

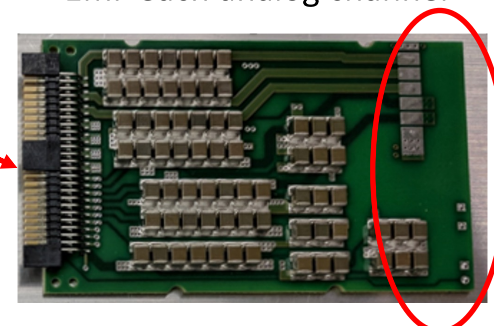
Distributed power bus capacitance

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

EIC tracker powering options technical note: general information

Purpose of the document

- Explore the range of available powering options for a EIC all-silicon tracker
- Determine material budget figures for each configuration

Approach

- Not detailed concerning the underlying technologies
- Mainly oriented toward determining:
  - Material budget vs granularity trade-offs
  - Material budget improvements as compared to state-of-the-art developments

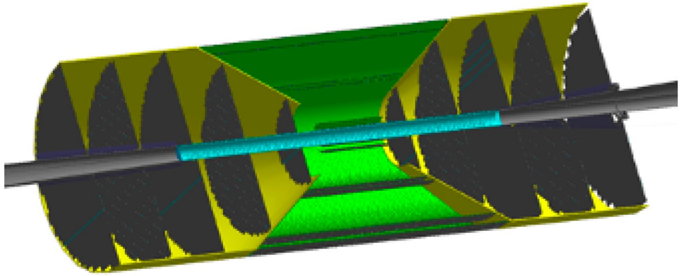
Link

https://www.eicug.org/web/sites/default/files/Powering-options-for-an-EIC-silicon-tracker.pdf

EIC silicon tracker requirements

Requirements that are most relevant to the studies included in the document

Detector geometry from YR



- 6 layer barrel (~7.5m^2)
- 10 disks (~4.5m^2)

Material budget per layer (from Leo's calculations)

- IL: 0.1% X_0
- ML, OL: 0.55% X_0
- Disks: 0.24% X_0

Other requirements

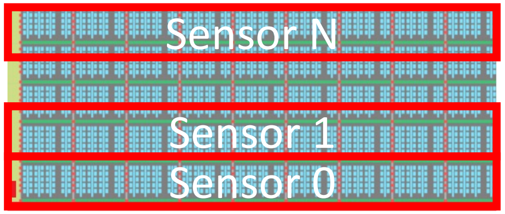
- Magnetic field: up to 3T
- Electrical: input voltage @ 1.2V +/-10%
- Radiation hardness requirements (TID, NIEL, High LET fluence, …)
  - TBD but expected to be lower than ALPIDE sensor radiation hardness specs

Assumptions on sensors/modules

Module dimensions: 300 mm x 30 mm

Each module is made of N sensors (N depends on yield)

All modules powered at 1.2V +/- 10%

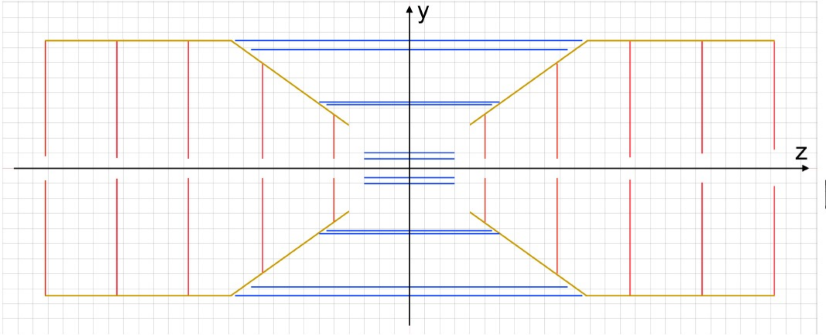


Current figures:

- Digital current: 0.5A (~50% of that of an ALICE ITS-2 module), due to:
    - ~Similar functionality as ITS-2, improved architecture
    - Reduced input voltage 1.8V → 1.2V
    - Reduced gate capacitance
- Additional digital current pessimism: 0.15A
- Analog current: 0.2A (~same as ALICE ITS-2 module)

Central Barrel (~7.5m^2): ~830 modules

Disks side A (~2.25m^2): ~250 modules

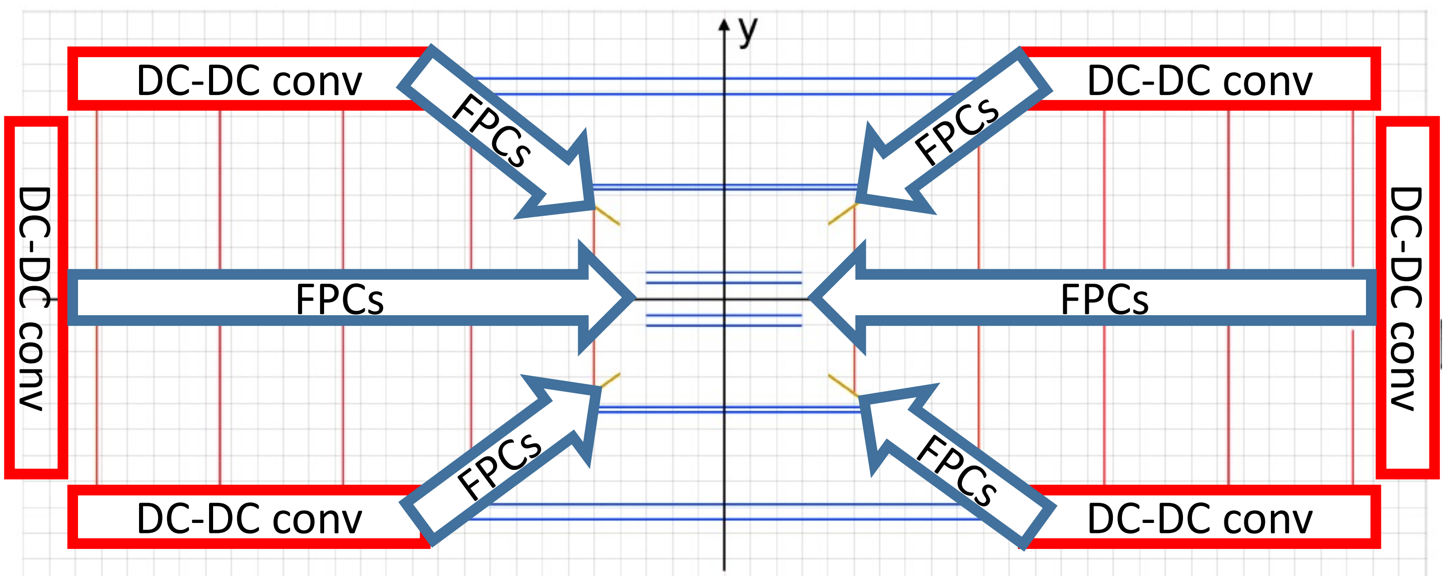


Disks side B (~2.25m^2): ~250 modules

Fixed voltage DC-DC converter powering option

Based on the use of DC-DC converters near the detector volume

- DC-DC converters are bulky:
  - PCB + ASIC + inductor + metallic shield + …
  - A large number (O(1000)) of DC-DC converters is required to power a 12m^2 tracker
- Assumes that the detector is powered from both sides
- Flexible Printed Circuits (FPC) to connect DC-DC converters to detector through gaps
- Location and architecture of DC-DC converter circuitry dependent on:
  - Available space, radiation hardness requirements, material budget requirements, …



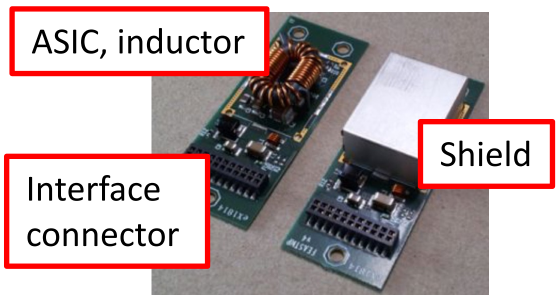
Fixed voltage DC-DC converter powering option

DC-DC circuitry on detector sides kept as simple as possible

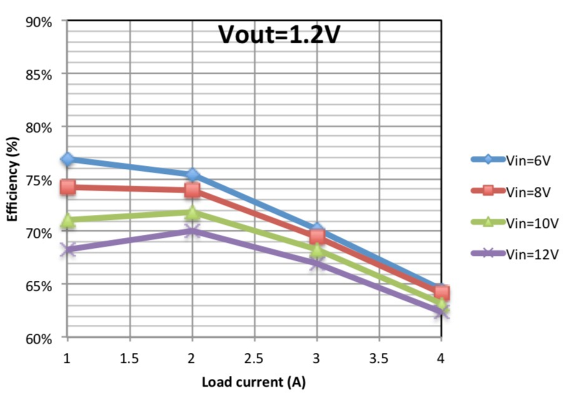
- Segmented into independent units each powering a set of sensor modules
- Each unit: DC-DC converter(s) + current sense(s) + passive components/connectors

Baseline DC-DC converter CERN FEASTMP. Bulky but:

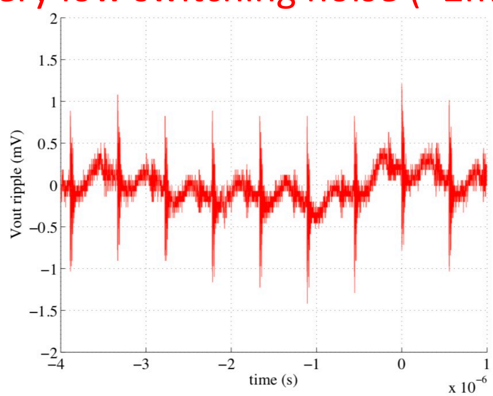
- Testing for radiation hardness and in magnetic field not needed:
  - 200MRad TID by design
  - Works in > 4T magnetic fields
- Will work with sensors in TJ 65nm technology
  - Output voltage range 0.9-5V
  - Max output current 4A
  - Input voltage range 5-12V



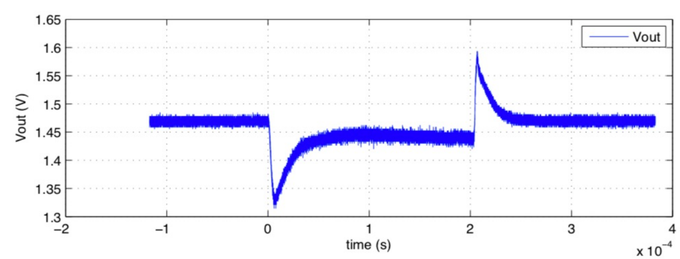
Good efficiency (> 60%)



Very low switching noise (<2mVpp)

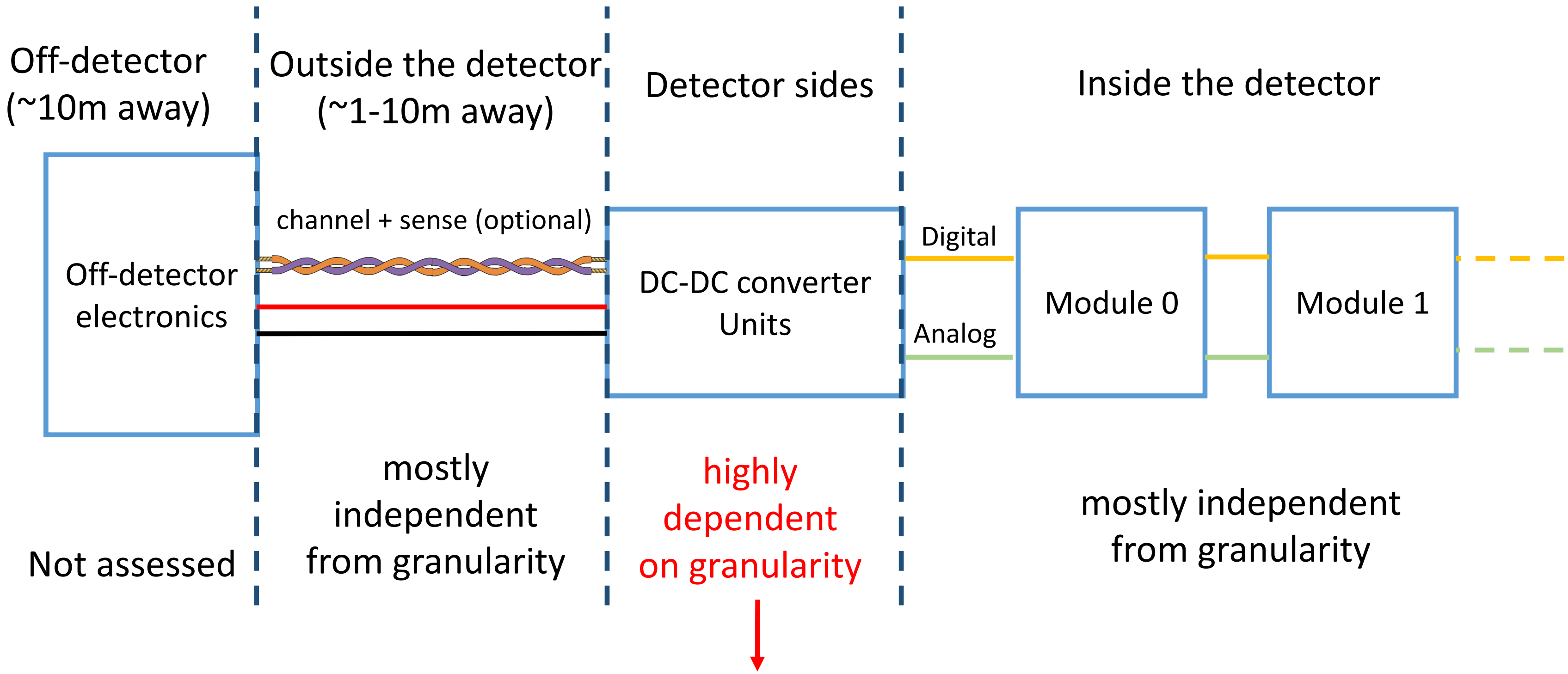


2A step performance



Fixed voltage DC-DC converter powering option

Material budget impacted by granularity in different ways at different locations



Lowest material budget/lowest granularity

4 modules fully powered from a single DC-DC converter:

Disks: ~125 DC-DC converters
Barrel: ~210 DC-DC converters
Total PCB area: ~1.25m^2

Highest material budget/highest granularity

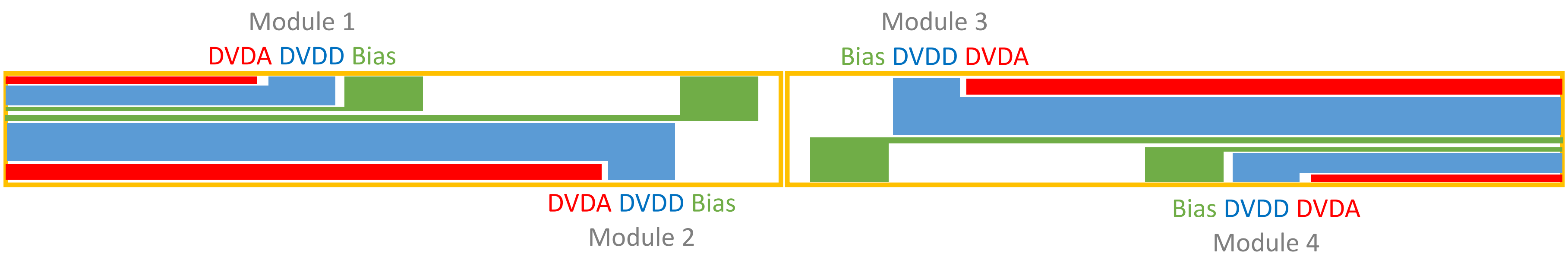
Digital and analog powered independently for each module (ALICE ITS-2-like configuration):

Disks: ~1000 DC-DC converters
Barrel: ~1700 DC-DC converters
Total PCB area: ~3m^2

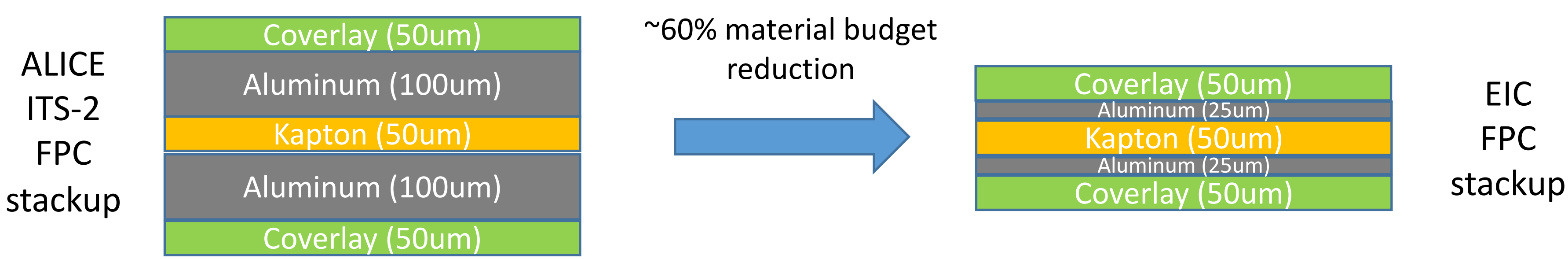
Fixed voltage DC-DC converter powering option

Example implementation of an EIC tracker outer layer stave FPC

- 4 modules
- 2 FPCs back-to-back, powered from the forward and backward regions
- Allows for a lower number of metal traces per FPC as compared to ITS-2
  - wider and shorter metal traces, hence lower material budget
- Traces with equalized voltage drops → Identical and fixed voltage DC-DC converters



Factoring in the projected current figures for ITS-3-like sensors

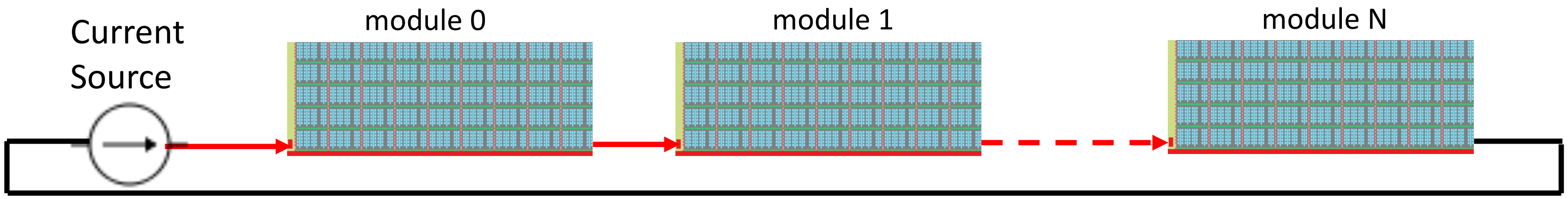


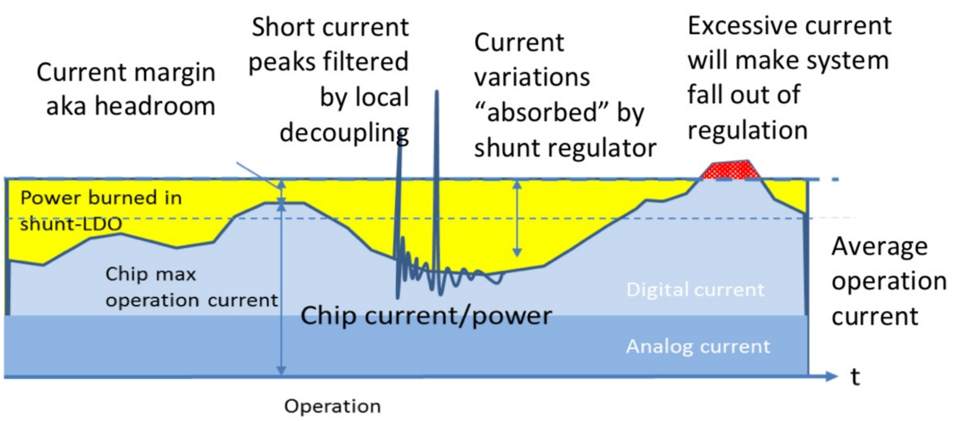
More dramatic improvements can be achieved by integrating data/config FPC with power FPC

Serial powering option

Main features:

- Modules are connected in series (GND_{N-1} → VDD_N) → Reduced number of FPC traces
- Constant chain current forced by current source (off-detector)
- Shunt LDOs integrated in each module drain excess current (I_{chain} - I_{module})



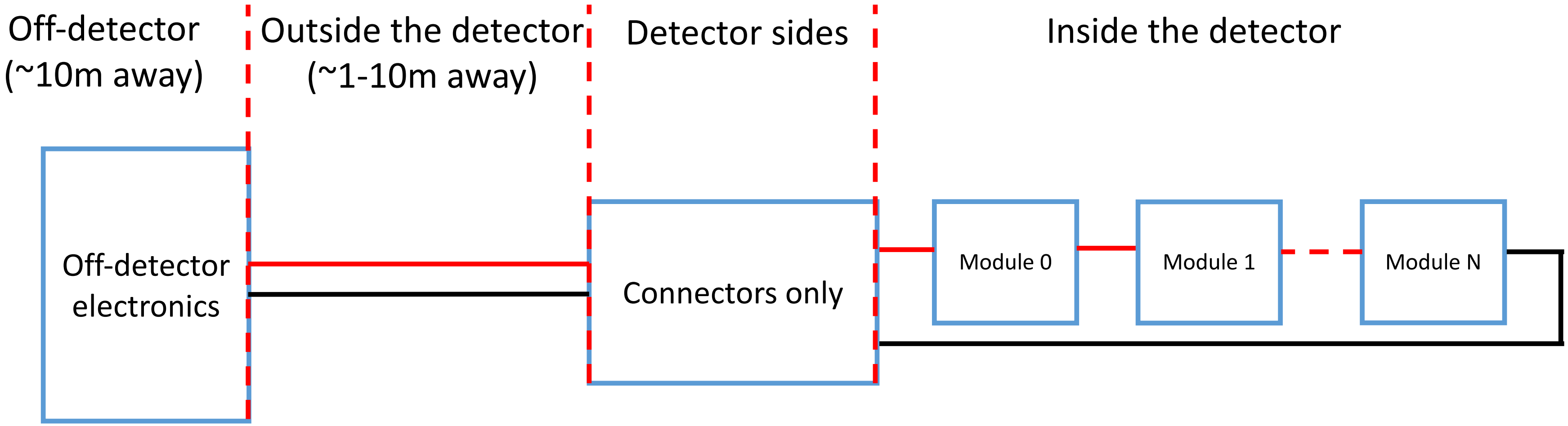


https://indico.cern.ch/event/681247/contributions/2929073/attachments/1640109/2618527/SerialPowerACES2018.pdf

- A serial powering scheme currently in use in the ATLAS experiment inner tracker
- New powering circuits/schemes under development within the RD53 project

Serial powering option

Material budget scales ~linearly with granularity



- Each connection carries the same current regardless of the number of modules connected to it (fixed cable/FPC trace cross sectional dimensions)
- Increasing granularity will increase the number of connections thereby linearly increasing material budget

Material budget figures and development time

	Material budget (as a percentage of reference: ALICE ITS-2)			Development time
	Analog/digital/ground cable mass (outside detector volume)	PCB surface (detector sides)	FPC power bus material budget (inside detector volume)	
ALICE ITS-2 architecture (ITS-3 sensor modules)	50%	100%	~66%	~1.5 years
DC-DC converters	3.125% - 6.25%	87% - 208%	~40%	~1.5 years
Serial powering*	8% - 32%	5% - 20%	~30 - 40%	~5 years

*assumes 10% max voltage drop across cables + FPC traces

Fixed voltage DC-DC converter option could be the baseline:

- Easier implementation, independent from sensor development, DC-DC converters available

Serial powering enables further reductions of material budget in/near detector volume