Novel Powering Schemes for SLHC Tracking Detectors

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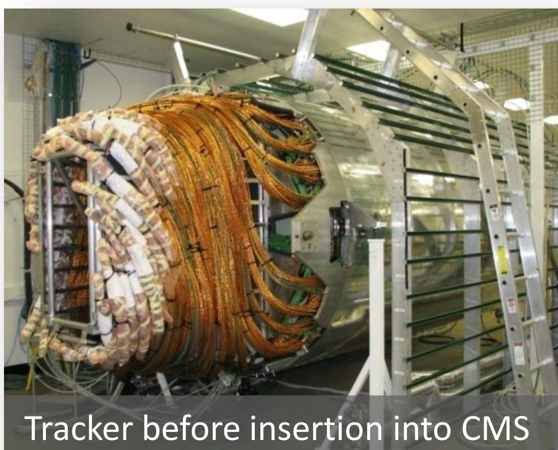
IEEE Special Focus Workshop
Detector Developments for the SLHC
Dresden, 19. 10. 2008

Outline

- Tracker Powering at LHC
- Power Requirements at SLHC
- Strategies for Improved Powering
- Serial Powering
- DC-DC Conversion
- Summary

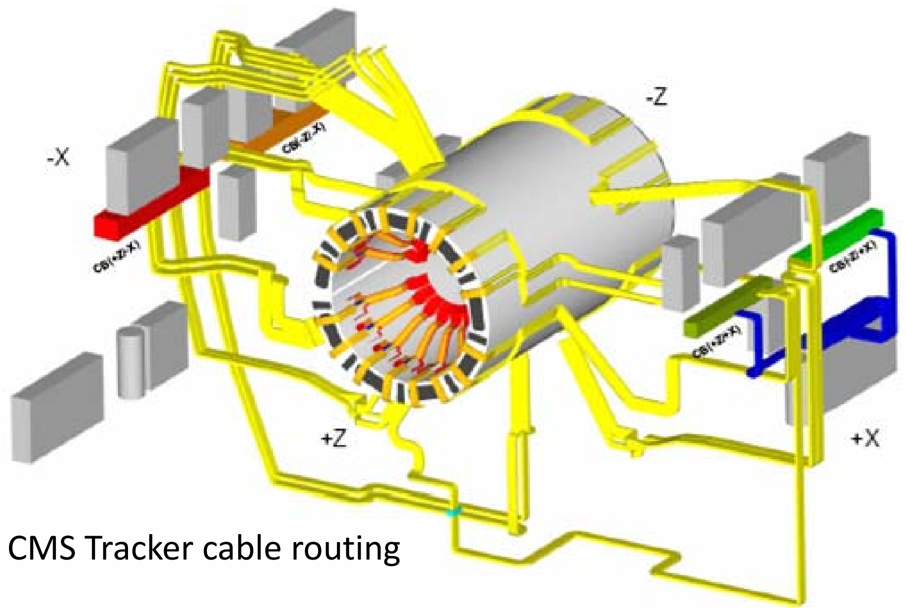
Tracker Powering at LHC

CMS Tracker Endcap TEC+



Tracker before insertion into CMS

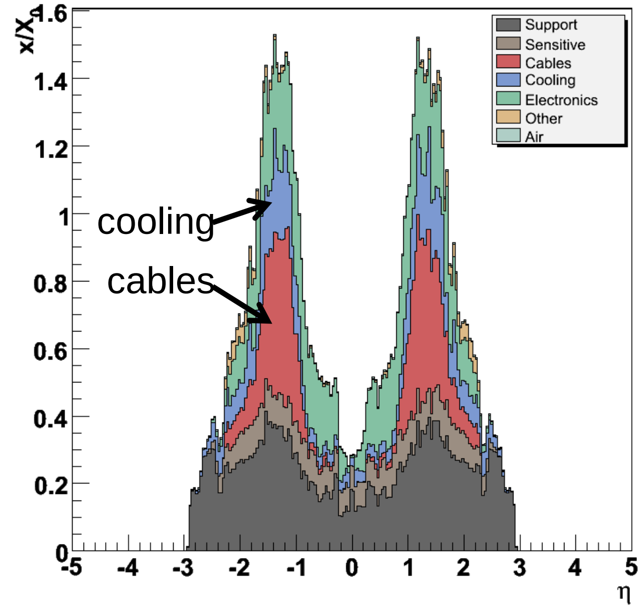
- current silicon strip trackers of ATLAS and CMS burn 50% of power in cables
- CMS strip tracker[1] :
  - ASIC supply voltages: 2.5 V and 1.25 V
  - front-end power: 33 kW
  - total current: 15 kA (ATLAS SCT+TRT: 12 kA)
  - loss in cables: 34 kW
- cables are dimensioned to carry this current



CMS Tracker cable routing

Why do we have to change the powering scheme for SLHC?

- powering will be even more critical at SLHC [2], [3] trackers
  - ASICs run at about 1.3 V (assuming 130 nm CMOS)
  - front-end power consumption estimates: CMS: 35 kW, ATLAS: 43-63 kW [4]
  - total current estimates: CMS: 27 kA, ATLAS: 33-48.5 kA
  - if we need to send 2-4 times more current through same cables -> **4-16 x cable loss** !
- these estimates are driven by the requirement for high granularity, radiation hardness and low noise and take already into account improvements due to smaller ASIC feature size
- cable cross section is fixed:
  - there is hardly any space for more cable cross section in cable channels
  - replacing cables between balconies and tracker is very difficult because of interference with other services and detector components
- since cable loss scales with *current²*: need to transmit power at **lower current**
- this allows to reduce copper cross-sections to save material



CMS Strip Tracker material budget

Strategies for Improved Powering Schemes

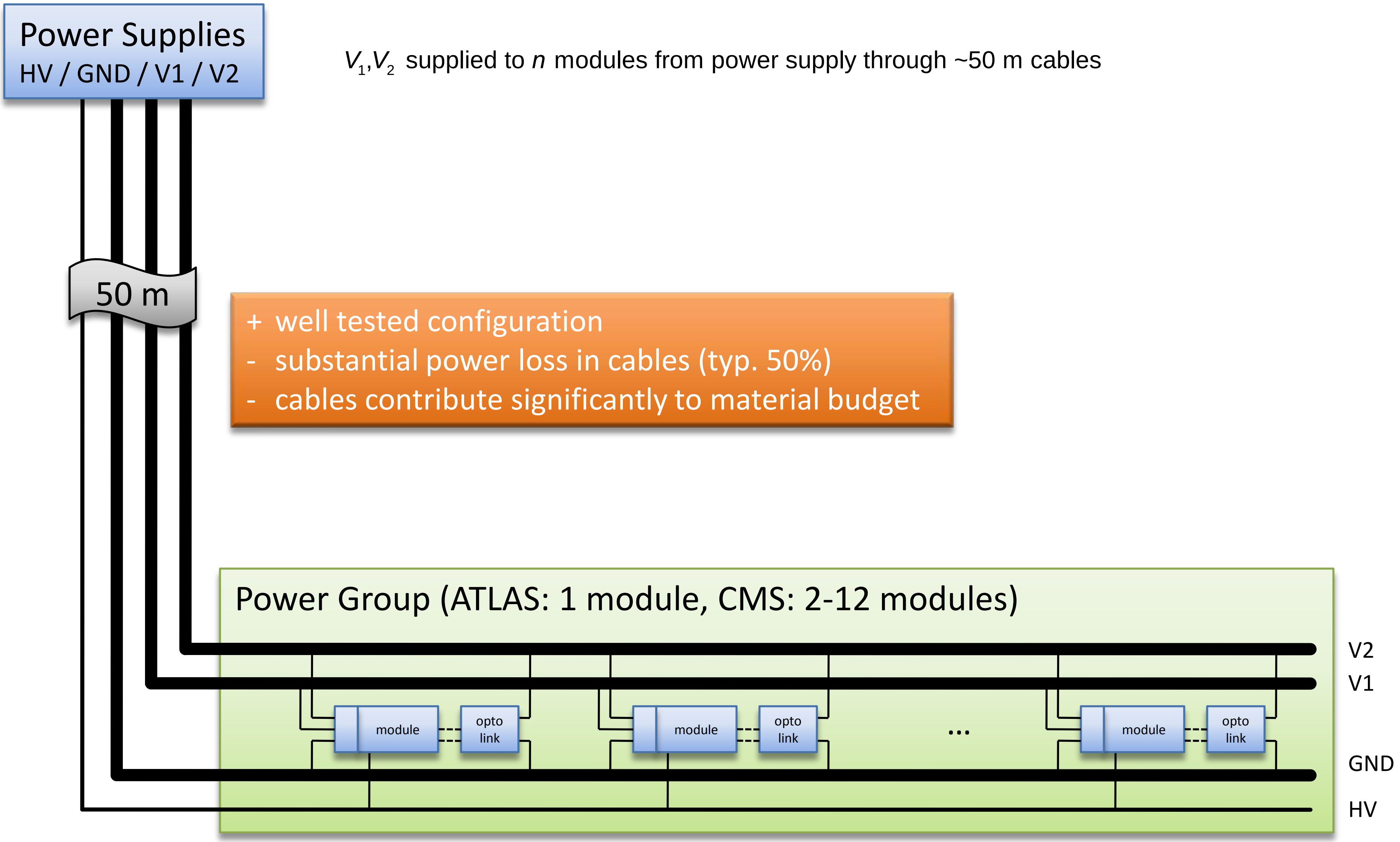
- save power wherever possible
  - take advantage of reduced ASIC feature size
  - take advantage of reduced detector capacitance due to higher granularity
  - optimize read-out scheme for low power
- use $P = U\,I$: bring power at high voltage (10-50 V) to tracker volume and
  - either operate many detector modules in series (re-use current)
  - or use DC-DC converters to convert to low voltage and high current locally
- additional powering circuitry
  - consumes power
  - generates heat
  - adds to material budget

  watch total balance
- the powering scheme has implications for all other parts of the system
  - try to minimize additional system complications due to powering
  - avoid degradation of system performance, in particular in terms of noise
  - need to define powering scheme before the rest of the system can be finalized
- power distribution has to be reliable and flexible in operation

Classical (Parallel) Powering Scheme

V_1,V_2 supplied to *n* modules from power supply through ~50 m cables

- + well tested configuration
- - substantial power loss in cables (typ. 50%)
- - cables contribute significantly to material budget

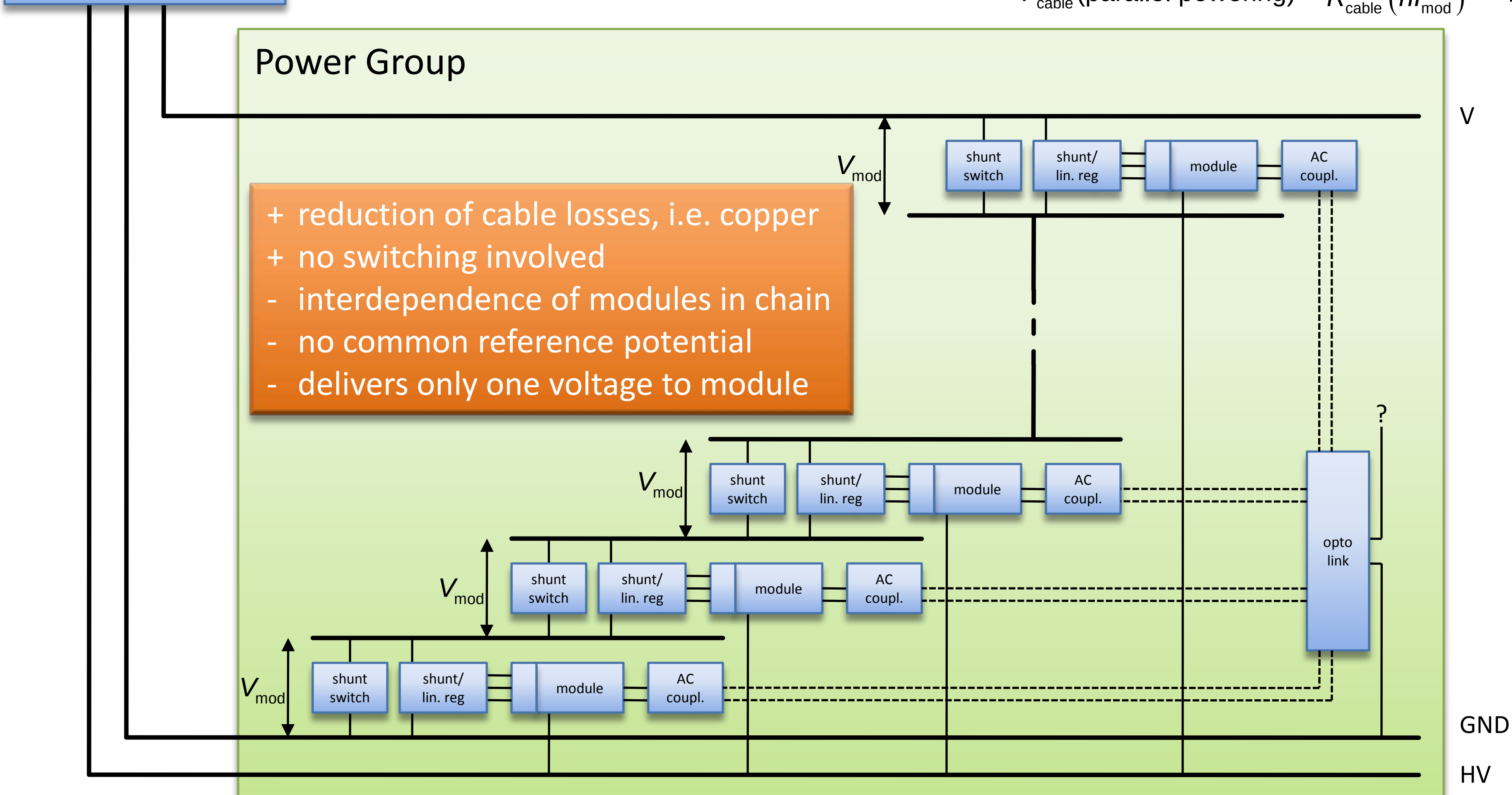


Serial Powering

Power Supplies
HV / GND / V

$V_{mod} = V / n$ with n modules in the chain, supplied by constant curent I_{mod}

current through cables only $I = I_{mod}$ instead of $I = nI_{mod} \rightarrow$ $\frac{P_{cable}(\text{serial powering})}{P_{cable}(\text{parallel powering})} = \frac{R_{cable} I_{mod}^2}{R_{cable}(nI_{mod})^2} = \frac{1}{n^2}$

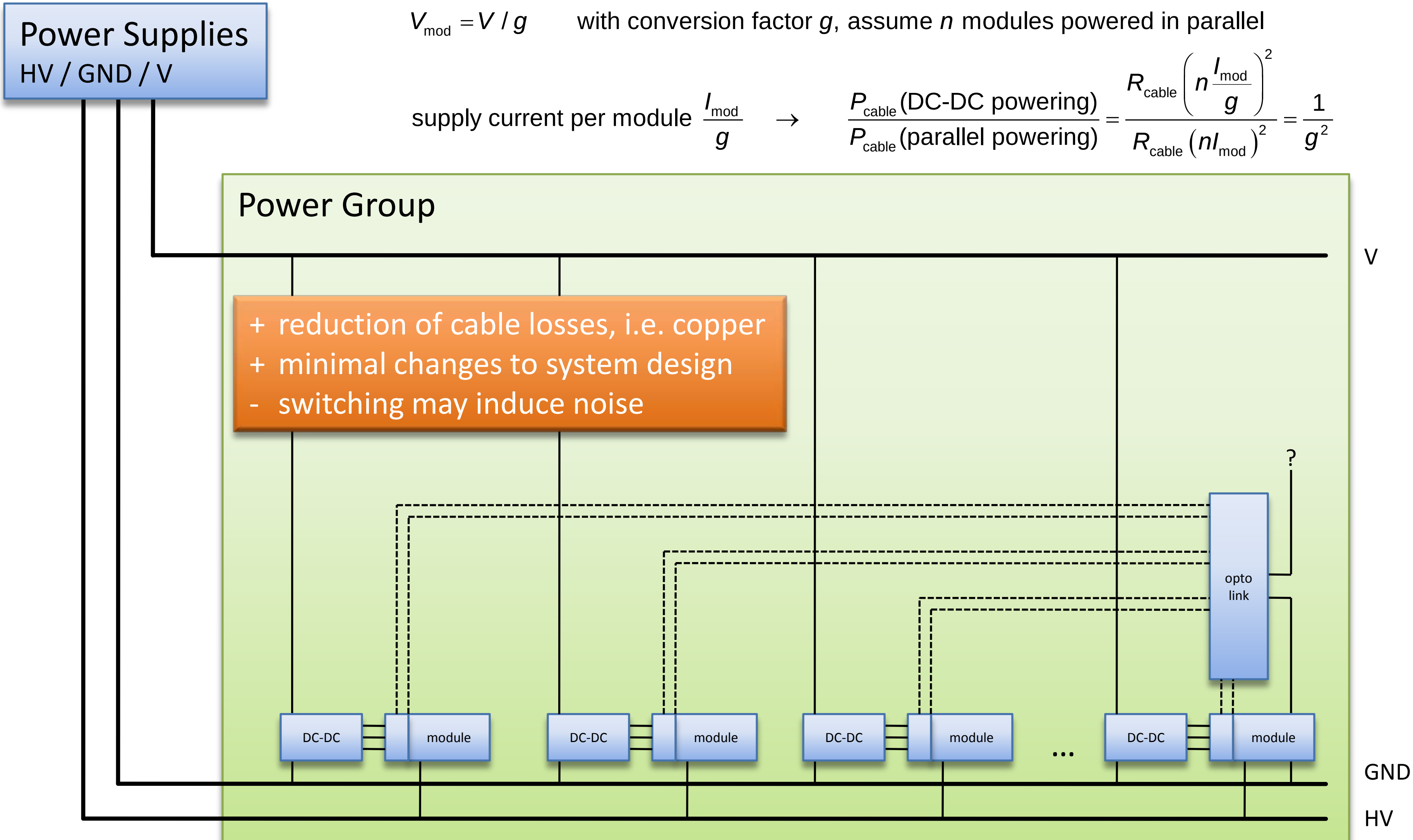


- \+ reduction of cable losses, i.e. copper
- \+ no switching involved
- \- interdependence of modules in chain
- \- no common reference potential
- \- delivers only one voltage to module

DC-DC Power Conversion

$V_{mod} = V / g$ with conversion factor g, assume n modules powered in parallel

supply current per module $\frac{I_{mod}}{g}$ $\rightarrow$ $$\frac{P_{cable}(\text{DC-DC powering})}{P_{cable}(\text{parallel powering})} = \frac{R_{cable}\left(n\frac{I_{mod}}{g}\right)^2}{R_{cable}\left(nI_{mod}\right)^2} = \frac{1}{g^2}$$



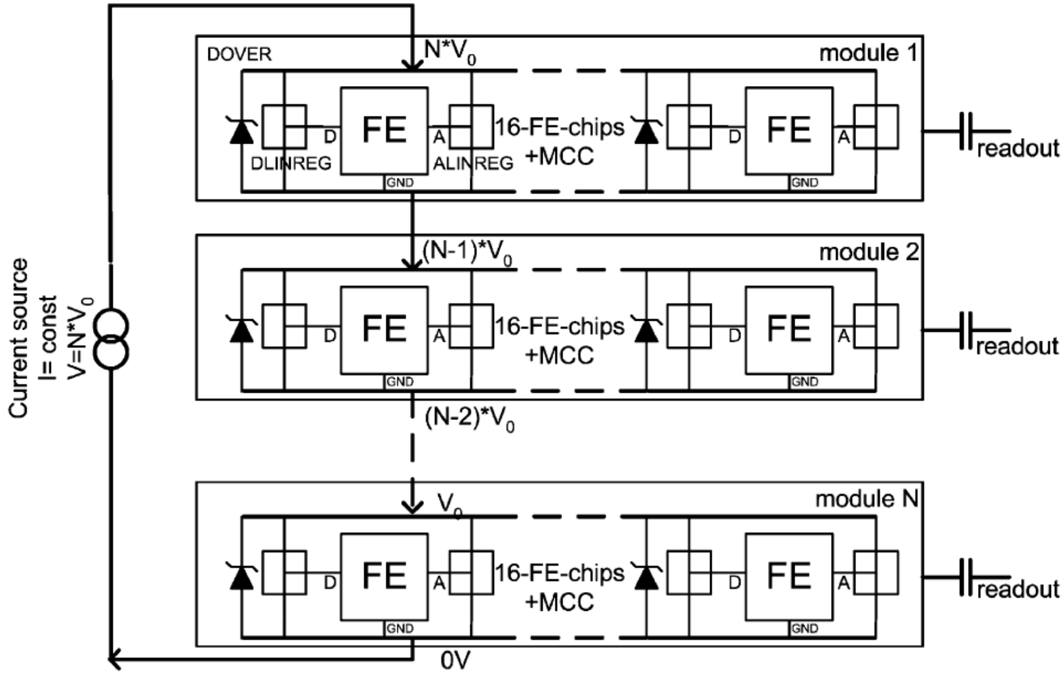
A two step conversion with a first stage at the supermodule level might be a good choice since it moves the bigger converters further outside (see e.g. [12])

Comparison of Serial Powering and DC-DC Conversion

	Serial Powering	DC-DC Conversion
efficiency	65 – 85 % (to be measured on real systems)	
power loss in cables	~(# modules in chain)$^{-2}$	~(conversion factor)$^{-2}$
supply of different voltages	add voltage regulator	add converter
supply of different currents	current = max. needed current	no problem
scalability in #modules	adapt input voltage	add converter or increase current capacity
FE ASIC	shunt and regulation circuitry partly incorporated in FE ASIC	can be fully decoupled from FE ASIC or partly incorporated
system ground potential	different for every module	one ground level
data/control links	need AC coupling	any coupling
slow control (voltage reading, …)	different reference potential for each module	as in conventional systems
reliability	need protection against failure of module or power circuitry in chain + over-voltage protection	converter failure leads to loss of modules possiblity to switch off individual modules
start-up	all modules in chain at once	operation of individual modules possible
noise	voltage fluctuations in chain	switching noise
rad-hard transistors at full input voltage (10-50 V)	bypass transistors (slow)	switching transistors
material budget	shunt/lin. regulators (inside FE ASIC), bypass transistor, AC coupling	converter

Serial Powering of a Pixel System

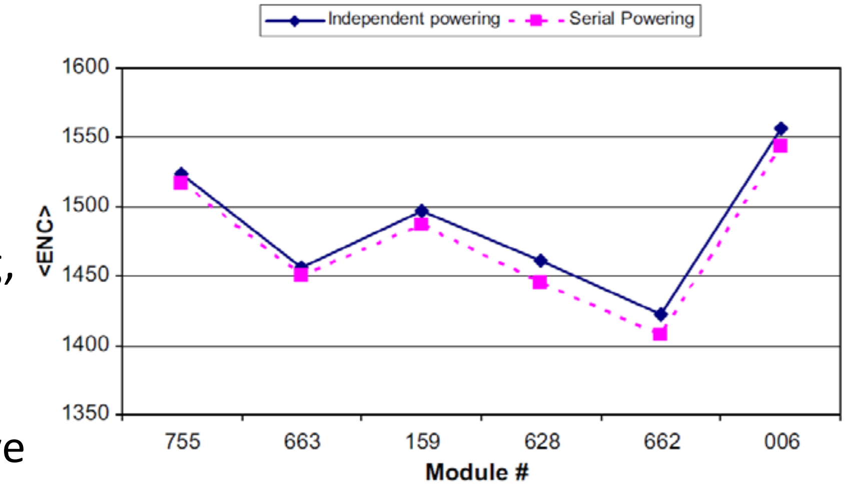
- pioneered and proof of principle by the Bonn group for ATLAS pixel upgrade [5]
- shunt and linear regulators integrated in FE ASICs
- parallel shunt regulators add redundancy but raise issue of matching
- tests with system with 6 serially powered pixel modules
- no significant noise increase even if one module is artificially made noisy (parallel switchable load)

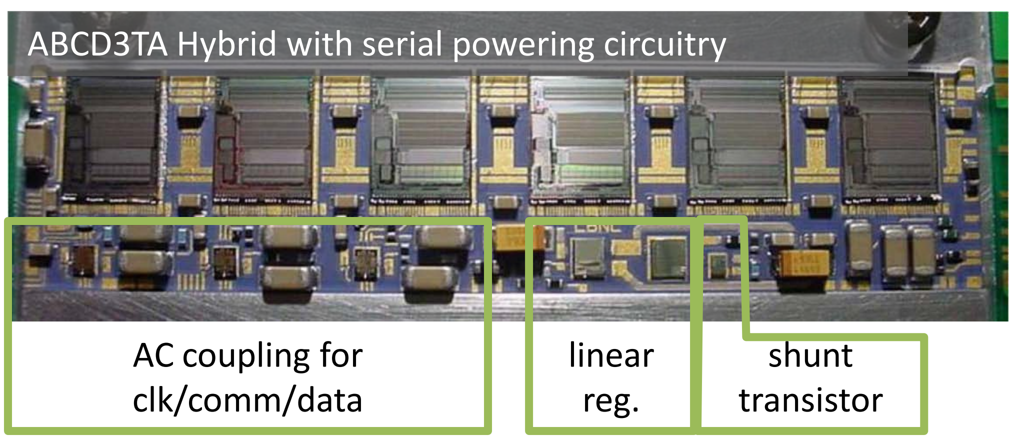


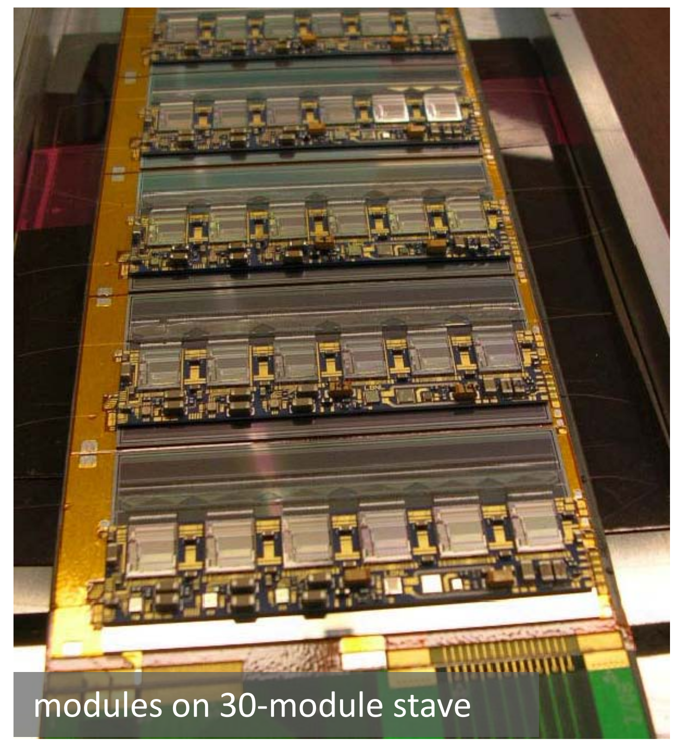
6-module half-stave with serial powering

Serial Powering of Silicon Strip Detectors

- R&D for ATLAS tracker [6]
- serial powering of a six-module stave was tested at LBNL and RAL
- no noise increase w.r.t. independent powering, even with noise currents injected into the chain
- currently assembly and test of 30-module stave with serial powering circuitry integrated onto hybrid (AC coupling would be off hybrid in final system)
- first 7 modules operate reliably





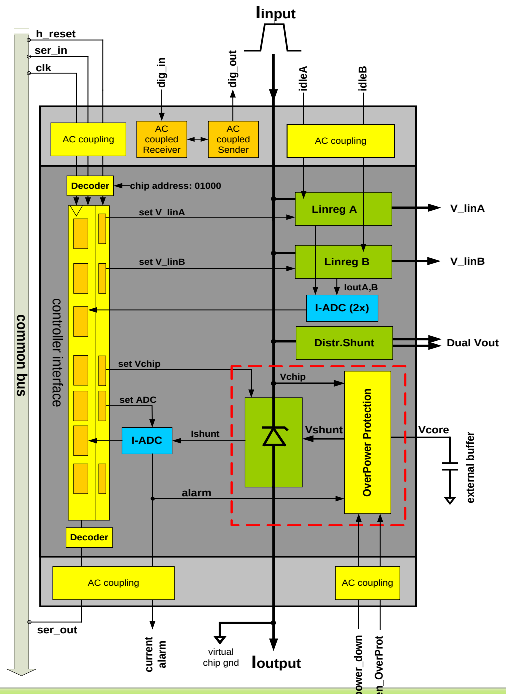


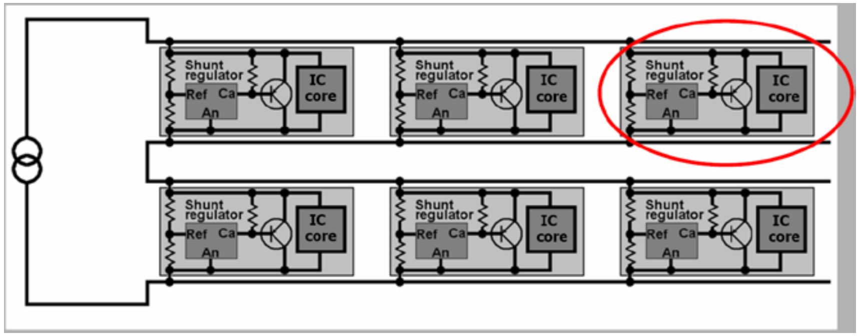
Serial Powering Interface Chip (SPI)

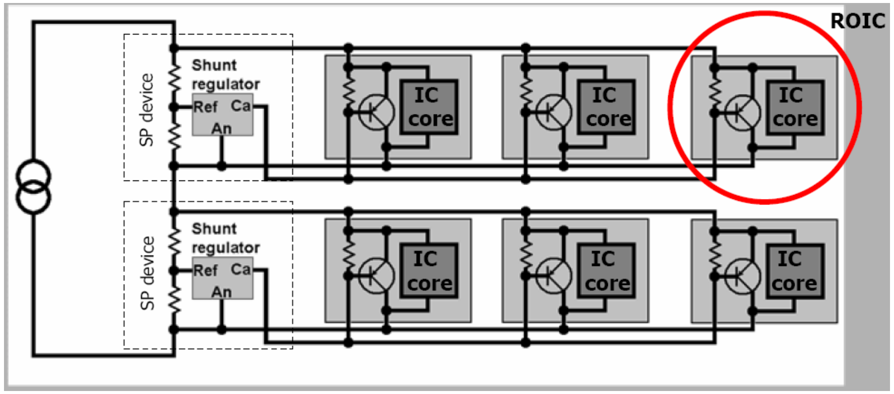
- integrated power management device for serial powering (TSMC 025MM), developed at Fermilab [13]

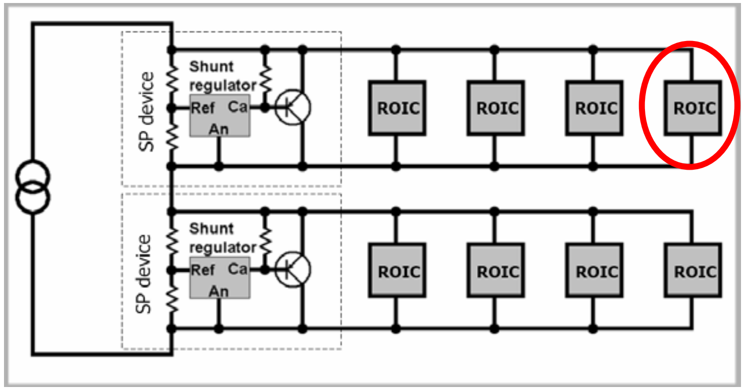
- either use shunt inside SPI chip or use SPI to control shunts inside FE-ASICs

- linear regulators, ADCs and AC coupled control interface



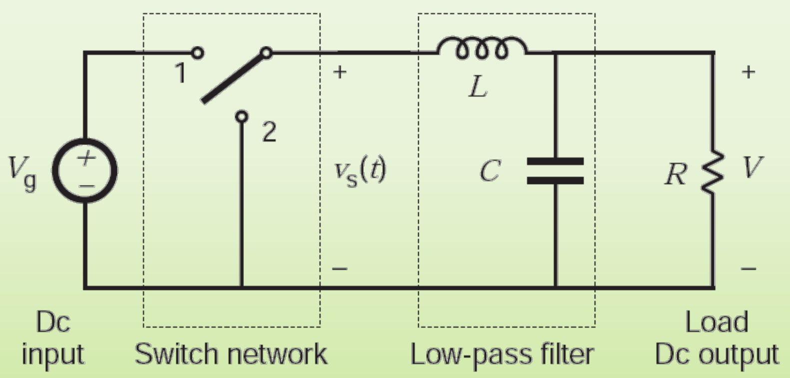




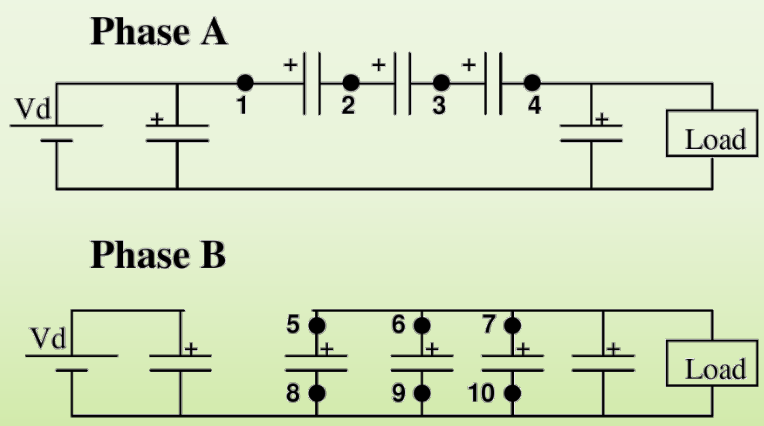


DC-DC Converters

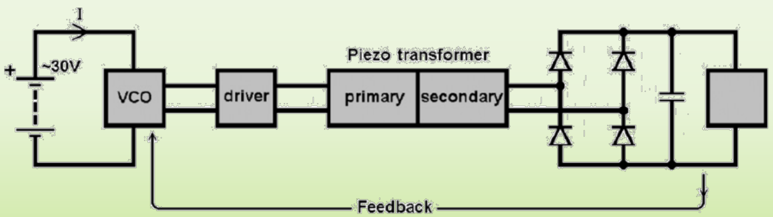
- many different designs
- inductor based converters [7], [8]
  - current capacity up to several amps
  - ferrite cores saturate in 4 Tesla field
    → need to use air core coils
- capacitor based converters [10]
  - are limited in current to few 100 mA at most
  - no inductors needed, can be very compact and may be even included in FE ASIC
- piezoelectric transformers [11]
- all need rad-hard "high voltage" transistors as switches
- efficiency typically 70 – 90 %
- switching noise is a concern



Inductor Based "Buck Converter"



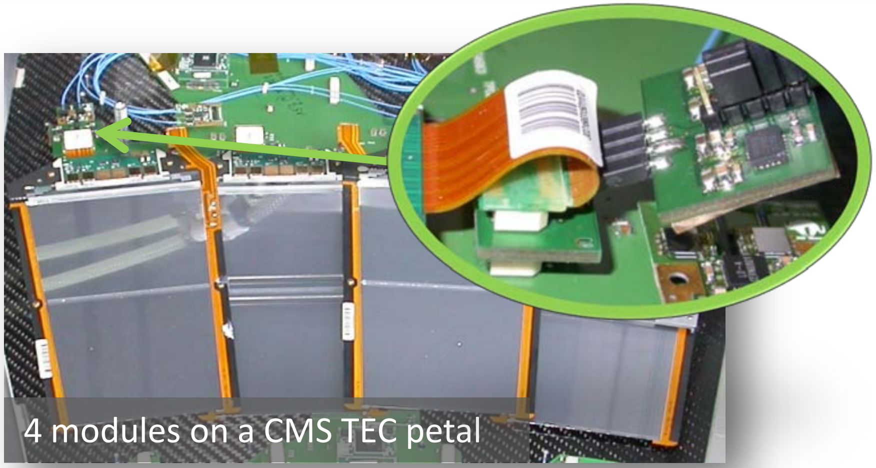
Capacitor Based "Charge Pump" [10]



Converter with Piezo Transformer [3]

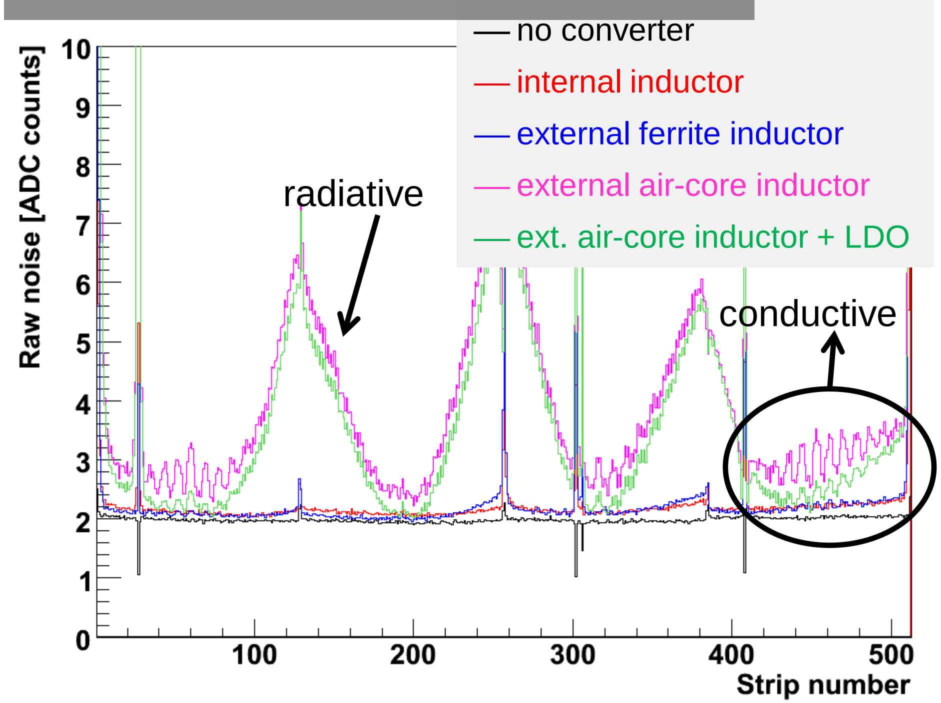
DC-DC Buck Converters for Silicon Strip Trackers

- tests with commercial buck converters have been performed at Yale/BNL/RAL[7] (ATLAS) and Aachen[8] (CMS)
- show here results from Aachen where converters are testes on a 4-module assembly
- Enpirion EN5312QI (integrated planar inductor) and EN5382D with external inductors
  - switching frequency 4 MHz
  - Vin = 2.4V – 5.5V (rec.) / 7.0V (max.)
  - Iout = 1A
- 10% noise increase with internal or ferrite core inductors
- strong radiative interference with air core inductors



4 modules on a CMS TEC petal

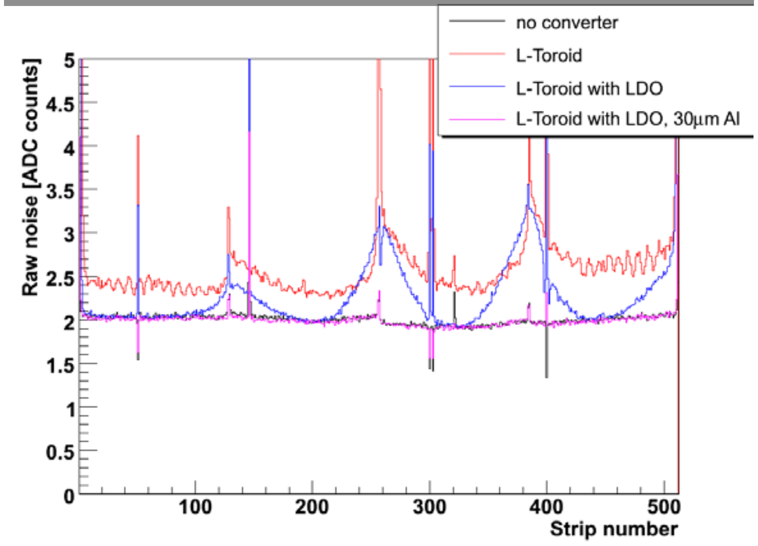
noise measurements with different converters



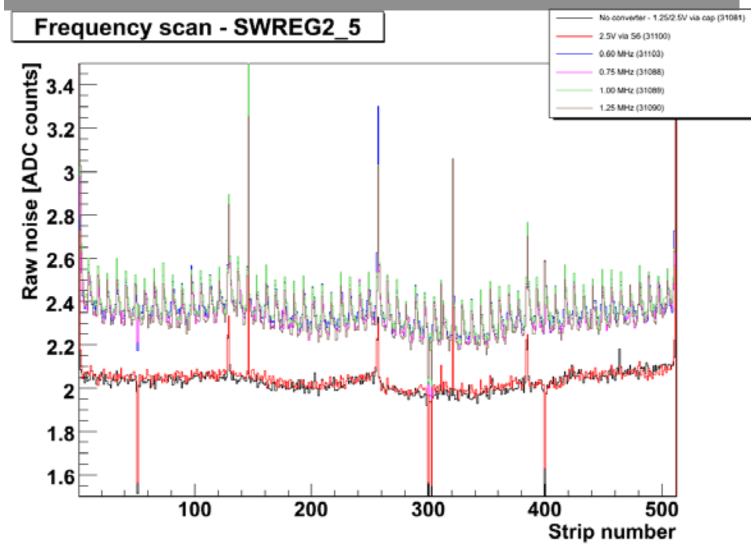
DC-DC Buck Converters for Silicon Strip Trackers

- interference of air core inductors can be reduced by
  - placing the converter a few cm away from hybrid
  - using toroid instead of solenoid inductor
  - using a Low Dropout Regulator (LDO)
  - shielding the converter (30 µm Al is sufficient)
- measurement with converter at the hybrid, toroids, LDO and shielding shows no increase in noise
- DC-DC buck converters can be used at module and/or supermodule level
- radiation hard converter ASIC under development at CERN [9]
  - first prototype SWREG2 available and working, but not rad-hard and shows ~15% noise increase
  - investigate alternative processes

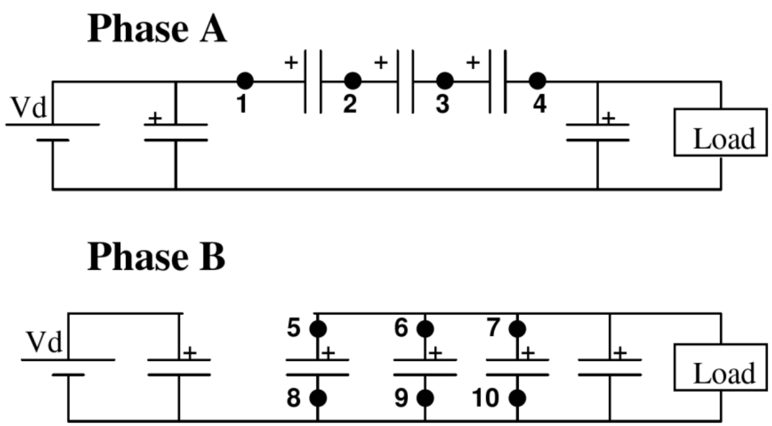
noise measurements with different converters



noise measurements with SWREG2

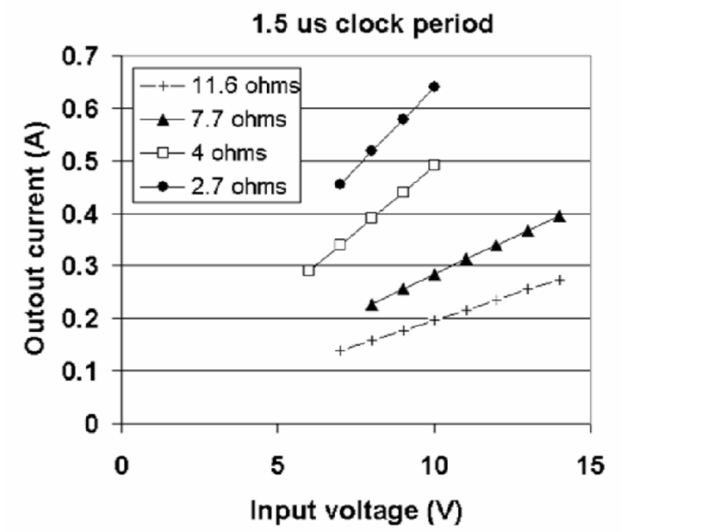


Capacitor Based DC-DC Converter

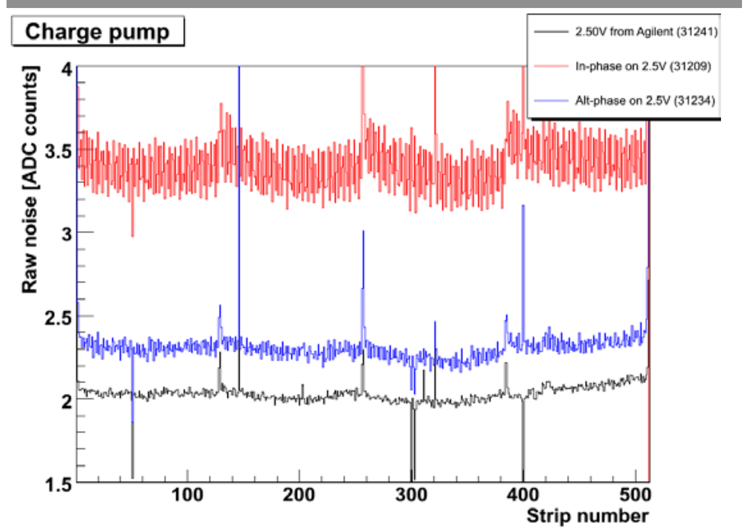


- Chare Pump developed at LBNL [10]
- conversion factor 4
  - IC in 0.35 μm CMOS process (H35)
  - external 1μF flying capacitors
  - output current 0.5A
  - switching frequency 0.5MHz
- proof of principle
- adds 0.02% X_0 to a typical strip module
- measurements with CMS TEC modules show ~10% noise increase when two charge pumps operate with alternating phase

output resistance measurement

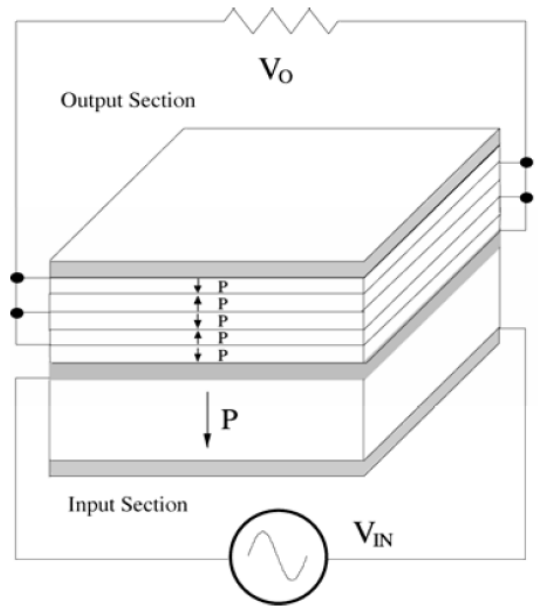


noise measurements with LBNL charge pump

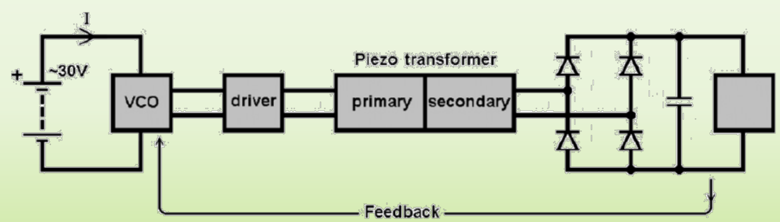


Piezo Transformers for Silicon Strip Trackers

- development of piezo-electric transformers for LV and HV power supply at Tokyo Univ. and KEK [11] together with NEC-Tokin corporation
- HV is an extension of the HV supply that has been developed for the ATLAS thin gap muon chambers
- power specs
  - LV: 2 V - 4 A
  - HV: 1 kV - 10 mA
- typical size: 14 mm x 14 mm x 5 mm
- prototypes are currently being manufactured
- for LV step-down conversion close to the detector module the converter material is a concern (HV step-up converters can be placed further out)



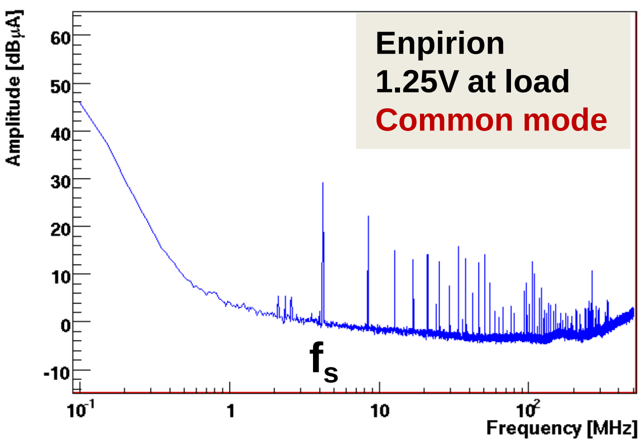
piezo transformer principle

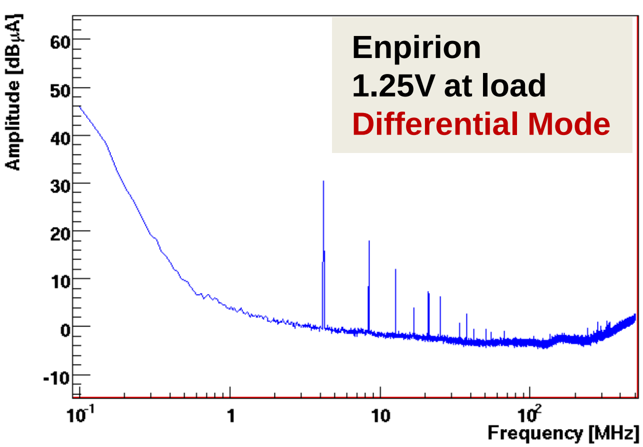


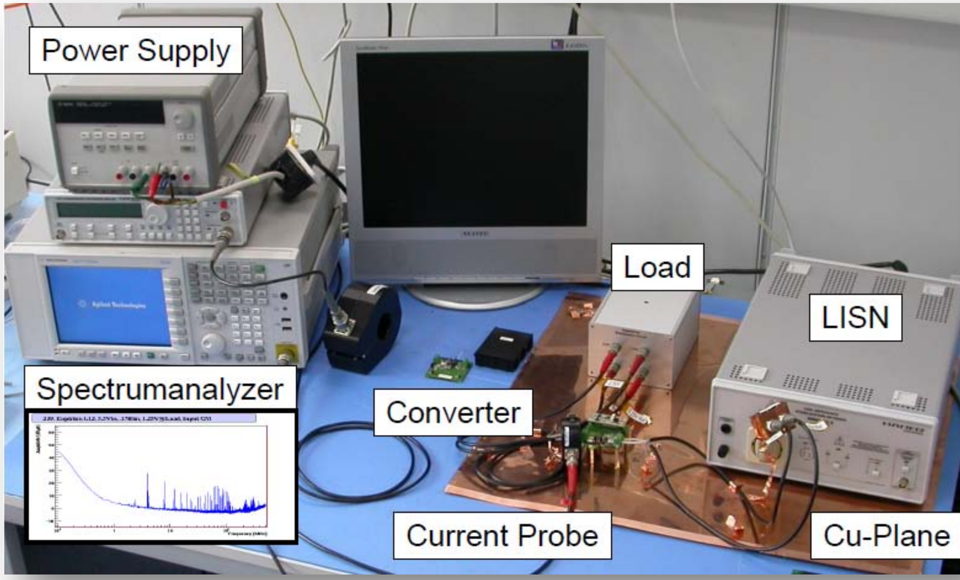
Converter with Piezo Transformer [3]

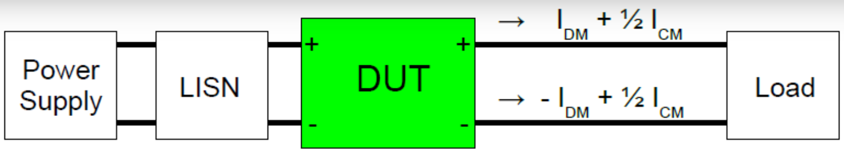
Understanding Electromagnetic Interference

Standardized EMC set-up to measure **Differential & Common Mode** noise spectra (CERN, Aachen, …)

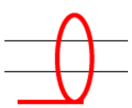








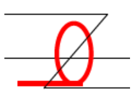
CM-Setup:



Current Probe → Spectrumanalyzer

$I_{DM} + ½\, I_{CM} - I_{DM} + ½\, I_{CM} = \mathbf{I_{CM}}$

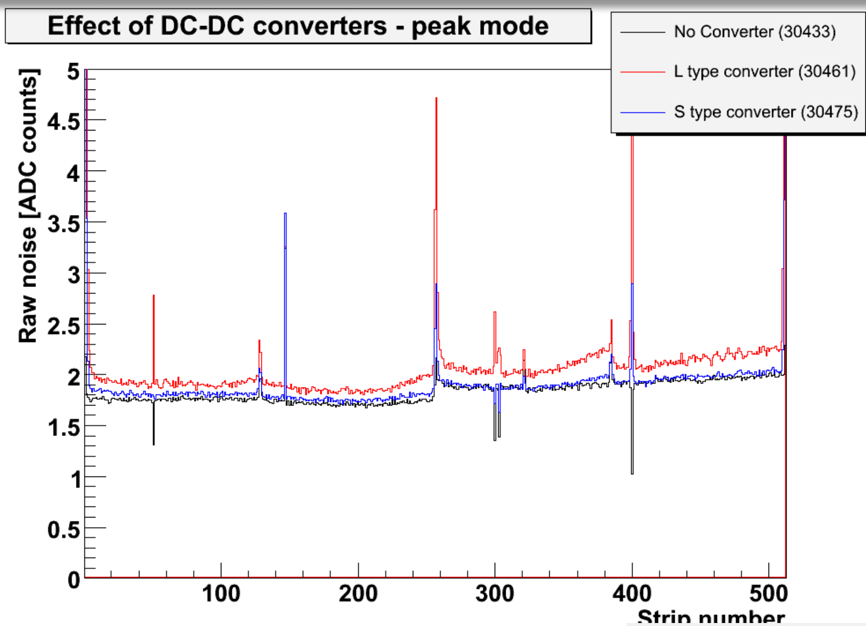
DM-Setup:

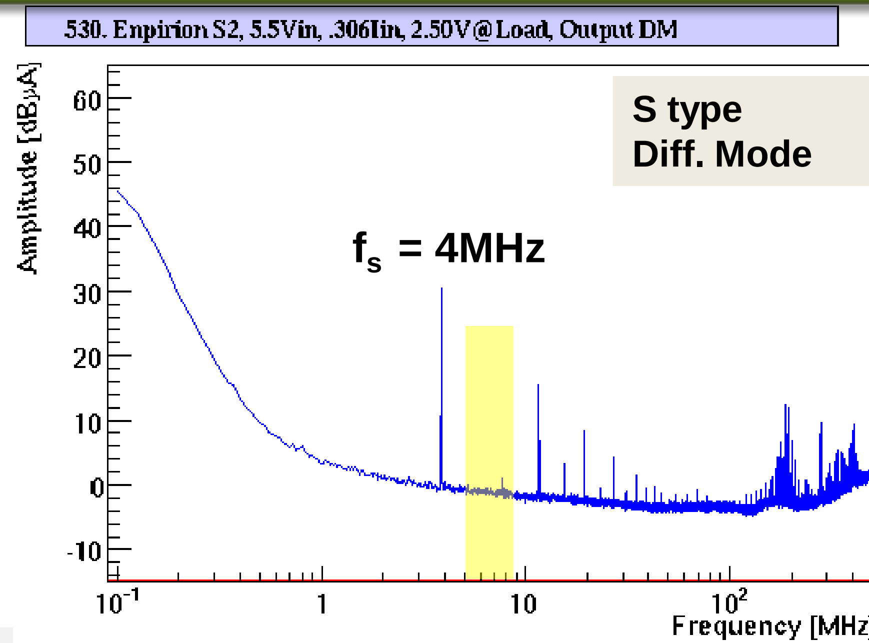


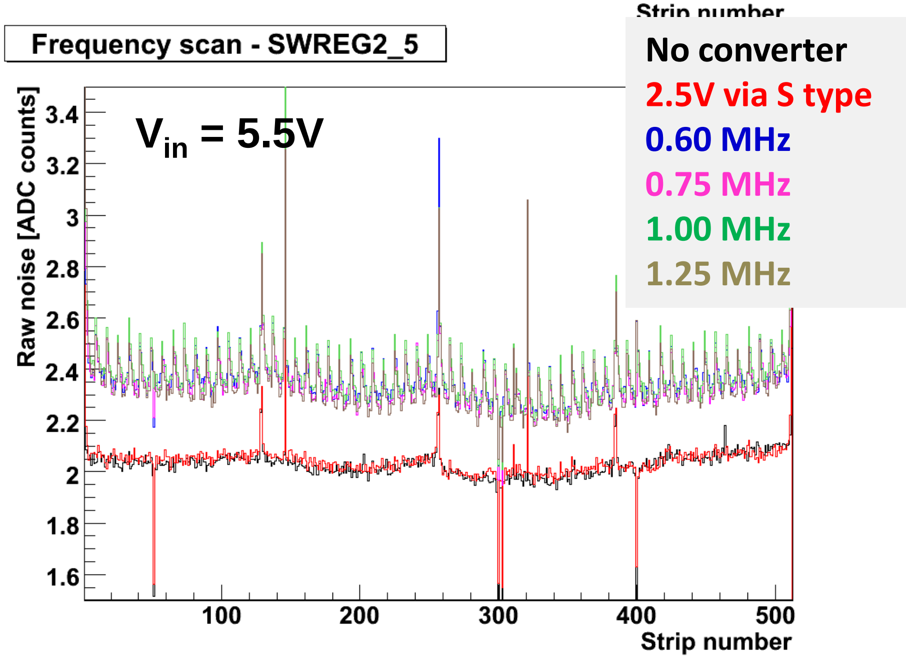
Current Probe → Spectrumanalyzer

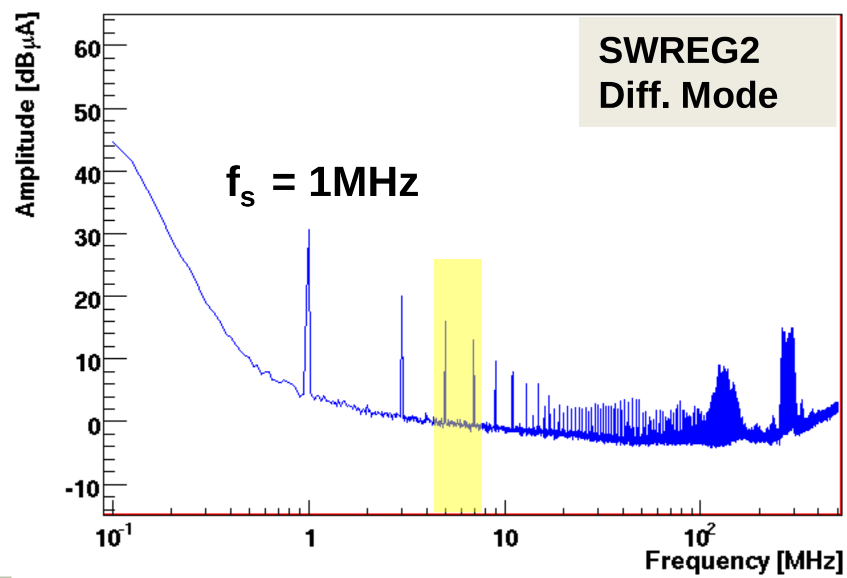
$I_{DM} + ½\, I_{CM} - (- I_{DM} + ½\, I_{CM}) = \mathbf{2 \cdot I_{DM}}$

Frequency Spectrum vs. Noise









Summary

- current consumption of SLHC trackers will require novel powering schemes which allow to supply power to the trackers at higher voltage and reduced current
- improved powering schemes can help to reduce the material budget
- mainly two options are considered
  - serial powering
  - DC-DC conversion
- new approach which has not yet been used in a tracking detector
- full detector system can only be developed once the powering scheme is known
- several groups are currently developing and testing novel powering schemes with promising results
- no fully qualified solution is available today but significant progress is to be expected over the next 1-2 years

References

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