Serial Powering in the CMS silicon tracker detector for High-Luminosity LHC

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Outline

- Motivation for serial powering
- Implementation for the CMS pixel tracker upgrade
- The Shunt-LDO regulator on RD53A
- Main challenges of the system
- Improvements after RD53A
Motivation for Serial Powering
Inner tracker challenges at high luminosity

**Increased radiation levels**
- Innermost layer at 3 cm from beam
- Up to $2.3 \times 10^{16} \text{n}_{\text{eq}} \text{cm}^{-2}$ fluence
- Total dose of 1.25 Grad max

**Higher granularity**
- More pixels to read out

**Increased hit rate**
- Higher bandwidth

**65 nm CMOS technology**
- 1.2V operating voltage $\Rightarrow$ higher current

**Low material budget**
- Low mass cabling
- Avoid substantial power loss/voltage drop on cables

**Radiation hard components**

**High current consumption**

**Limit current on cables**
CMS IT upgrade—powering requirements

Powering specific requirements

- 50 kW on detector power
- High current required by ROCs
- 3900 readout modules

More detail on the overall design in the talk by Jory Sonneveld

Serial Powering only viable solution

Low material budget
Advantages of serial powering

Direct parallel powering
- 2 cables per module
- Total power consumption: \( nIV + n^2I^2R \)

POL conversion with DC/DC converters
- 12V → 1.2V conversion
- Not radiation hard enough (150 Mrad max)
- Component size, hefty material addition

Serial Powering
- 2 cables per chain
- 1.5V → 1.2V POL conversion
- Total power consumption: \( nIV + I^2R \)
Serial Powering implementation

CMS IT Phase II
Chain layout – low voltage distribution

- Constant current supplied to readout chips
- Voltage conversion on ROC, no additional power electronics on modules
- Lower supplied current $\Rightarrow$ reduced dissipation on cables
- Allows for reduced cabling (one line per chain)

Voltage drop on cables not an issue in constant current mode

Up to 12 modules per chain
Chain layout – low voltage distribution

- Local GND reference changes along the chain
- Each module comprised of 2 or 4 chips powered in parallel and bump-bonded to a single sensor
- Variations in digital power consumption compensated by shunt
- Separate regulators for analog and digital domains to keep analog part immune from digital activity
Chain layout – high voltage distribution

- High voltage for sensor biasing provided in parallel
- Common return with low voltage line

- HV referenced to local chip ground potential
- Effective bias voltage changes by up to ~20V between upstream and downstream modules
- Mitigated with 2 separate HV lines per chain
- Grand total of 500 serial lines
- 164 “4A” lines for double modules
- 336 “8A” lines for quad modules

- LV: 200W power at ~25V
  - 1.5V × 12 modules + 7V (MAX) drop on cables
  - HV: 1000V, ~20mA (TBD)
The Shunt-LDO on RD53A
ROC and SLDO roadmap

**Pixel chips**

- FEI4 (130nm)

**Dedicated test chips (only regulator)**

- 2A SLDO test chip (65nm) ➢ Moved to 65nm technology

**2017**

- RD53A

**2018**

- RD53A Quad-modules

**2019**

- ATLAS ROC
- CMS ROC

**2020**

- SLDO test chip A
- SLDO test chip B
- SLDO test chip C

- RD53B

**Improved performance** (Startup, voltage accuracy, ..)

**New features** (Overvoltage/overload protection, ..)
The RD53A readout chip

- Designed by the RD53 collaboration
- RD53A: 3 different front ends for prototyping
- Built in 65nm CMOS technology
- Half size w.r.t. final CMS ROC
- 400x192 pixels (50x50 $\mu m^2$ each)
- Highly radiation resistant (above 500 Mrad)

Linear front end chosen by CMS

Shunt-LDO components on chip bottom
The Shunt-LDO regulator

- Constant input current is converted to constant voltage on the chip
- Power consumption (digital in particular) highly variable
- Enough current must be supplied to avoid failures
- Need to “burn” excess current

Shunt-LDO solves both issues

- LDO provides constant voltage (~1.2 V) drawing the required current $I_{load}$
- Residual current $I_{in} - I_{load}$ is shunt
- While $I_{load} < I_{in}$ the system is seen by the power supply as a constant load ⇒ crucial for a serially powered system
- Voltage divider + A1-M1 complex ensure \( V_{DD} = 2V_{ref} \)
- \( V_{in} \geq V_{DD} + 0.2V \) needed

- Shunt determines how chip is seen by PS
- \( V_{in} = V_{ofs} + \frac{R_3}{1000} I_{in} \equiv V_{ofs} + R_{eff} \cdot I_{in} \)
- Power supply sees a constant load
- Independent form power consumption as long as \( I_{load} < I_{in} \)
Known Issues and challenges of the system

RD53A SLDO
Current sharing and headroom

Current sharing between chips in same module not trivial
- Chips in same module powered in parallel
- Current split determined by $V_{ofs}$, $R_{eff}$ of each SLDO, startup
- Measured on 4 RD53As in parallel powered with current source

Headroom optimization
- A headroom is provided, i.e. $I_{in} = I_{load}^{max} + I_{headroom}$
- Covers potential current consumption spikes
- Accounts for mismatch in $V_{ofs}$, $R_{eff}$ between chips

First studies indicate 20% headroom can cover estimated mismatches
Basic failure scenarios

Normal operation

Open on one chip

Short on one chip

Open on one chip:
- Remaining chip must take full current
- Power burnt on chip strongly increases
- Operational margin limited by thermal issues and input voltage
- Other modules can operate

Short on one chip:
- Module completely loses functionality
- Other modules in the chain can operate
Stress tests

Tests have been performed stressing SLDO system on the RD53A chip
- 4.5A, 1.8V (high current) for a week (with cooling)
- 5A, 1.9V (high current) for a week (with cooling)
- 1.8A, 2.2V (high voltage) for a week
- 130000 continuous power cycles at nominal operating point
- One week at nominal operation with 1/4 of wire bonds carrying $I_{in}$ removed
- 3 days at 4.5A with removed wire bonds (with cooling)

No anomalous behavior observed

✓ SLDO design appears sturdy

✗ No info on possible failure modes

Design limits:
- 4A, 2V max
Improvements over RD53A SLDO
The SLDO test chip version C

- New standalone test chip for shunt LDO available in summer 2019
- Includes many improvements w.r.t. RD53A SLDO

**Undershunt protection**
- If $I_{load} > I_{in}$ on one chip the regulator fails and the voltage across the module collapses $\Rightarrow$ whole chain affected
- To prevent this, dedicated circuitry reduces $V_{out}$ in case $I_{shunt}$ gets too low

**Improved startup behavior**
- Common bandgap regulator for Analog/Digital SLDOs
- Dedicated startup circuit allows for much improved behavior

**Overvoltage protection**
- Voltage clamp to avoid exceeding 2V input
- Cut off voltage can be set
Dynamic startup behavior

- 4 RD53A chips (i.e. 8 SLDOs) in parallel to emulate quad module
- Current source with 100A/s ramp

RD53A internal SLDOs

RD53As powered with SLDO test chips C

Startup behavior shows great improvement, better current sharing
Conclusions

- Serial powering concept proven to be reliable
- Allows to meet the powering challenges faced by the CMS Phase II pixel tracker
- Many tests have been performed and more are ongoing
- Further improvements w.r.t. RD53A have been implemented and tested in dedicated SLDO test chips
- Quad RD53A modules (with and without sensors) are now available for testing
- RD53B-based CMS-ROC will be available in late 2020
- More studies to be done on the optimization of working points and headroom
Thank you for your attention

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The HL-HLC update plan

Today

Factor ~10 increase in integrated luminosity

Roberto Seidita - Serial Powering in the CMS silicon tracker detector for High-Luminosity LHC
Up to 12 modules per chain
Potential issue with HV

- An issue may arise when HV is off and LV is on.
- If HV PS has high ohmic behavior in its off state, difference in local grounds causes leakage currents to flow in downstream module.
- Sensor becomes forward biased.
- Solved bypassing the HV PS with a diode and/or crowbar.
RD53A with SLDOc setup

Input from current source

Two SLDO test chips power each RD53A (one each for analog/digital domains)
Shunt-LDO is fully functional after 600Mrad at 0C:

- Output behavior is very stable
- Some variations of input behavior
- Reference voltages change due to internal resistor
  - Improved design in RD53B
Detector-like structure tests

- Electrical connections similar to final detector
- Aluminum structure with water cooling pipe inside
- Cooling is essential: ~10 W per module are dissipated