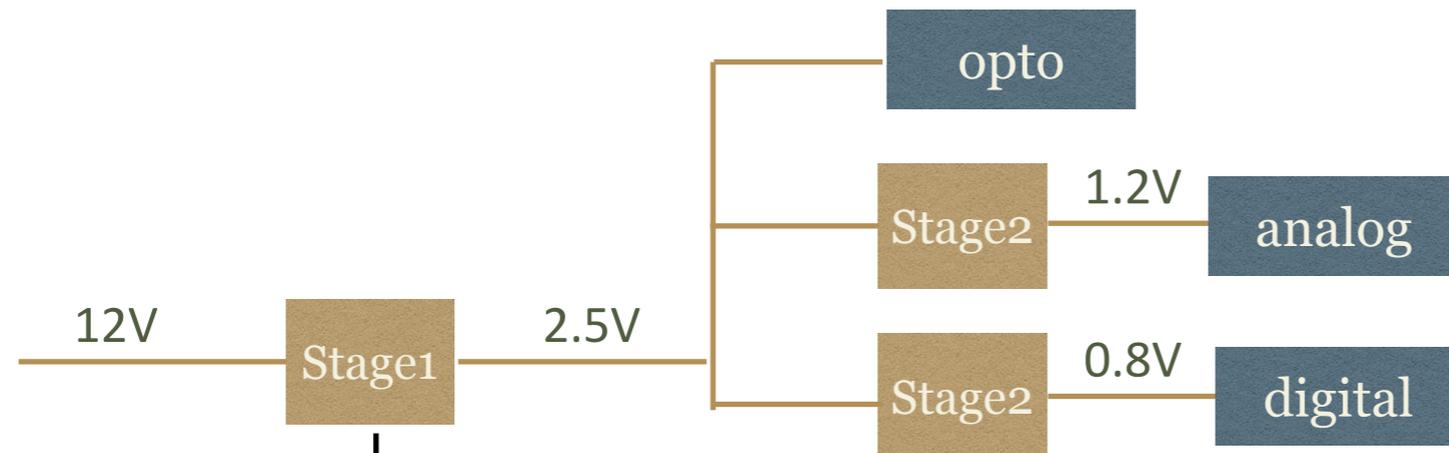


Latest News on DCDC converters

F.Faccio, S.Michelis, G.Ripamonti*, M.Besirli*

CERN, EP-ESE

* also with EPFL



FEAST2.1 In production and deployed, but failures observed in the CMS pixel system in 2017

bPOL12V Advanced prototyping, but delayed by the above problem with FEAST

bPOL2V5 Advanced prototyping, but delayed by the above problem with FEAST

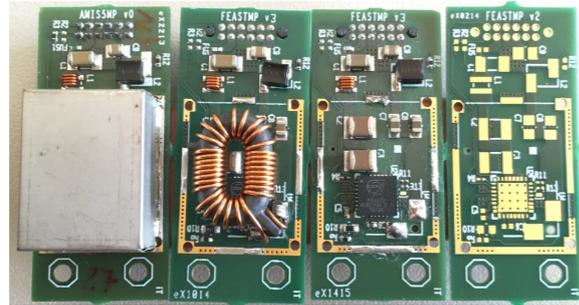
rPOL2V5 Initial prototyping stage

Tally of the damaged DCDC modules (Aachen-type) during 2017 in the CMS pixel detector system

The total number of modules deployed is about 1200



Aachen module



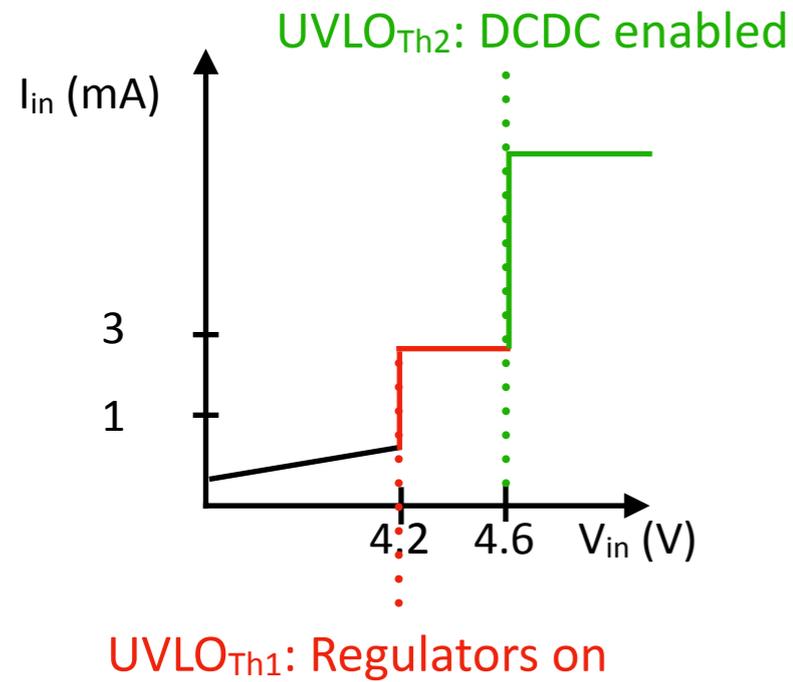
CERN module (FEASTMP)

Perfectly working in the system but found to have anomalous current when tested

	Pixel Names	Number of Converters	Tested Broken	Tested working with High Current	Tested working with normal current	BROKEN	HIGH CURRENT
						% with respect to total	% with respect to total working
		TOTAL	"BROKEN"	"HIGH CURRENT"	"GOOD"		
BPIX (+Z, Near)	BPIX-Bpl	208	4	48	156	1.9	23.5
BPIX (-Z, Near)	BPIX-Bml	208	10	48	150	4.8	24.2
BPIX (+Z, Far)	BPIX-BpO	208	13	70	125	6.3	35.9
BPIX (-Z, Far)	BPIX-BmO	208	11	70	127	5.3	35.5
FPIX (+Z, Near)	FPIX-Bpl	96	7	41	48	7.3	46.1
FPIX (-Z, Near)	FPIX-Bml	96	7	34	55	7.3	38.2
FPIX (+Z, Far)	FPIX-BpO	96	9	23	64	9.4	26.4
FPIX (-Z, Far)	FPIX-BmO	96	6	22	68	6.3	24.4
BPIX - not connected to modules		32	2	8	22	6.3	26.7

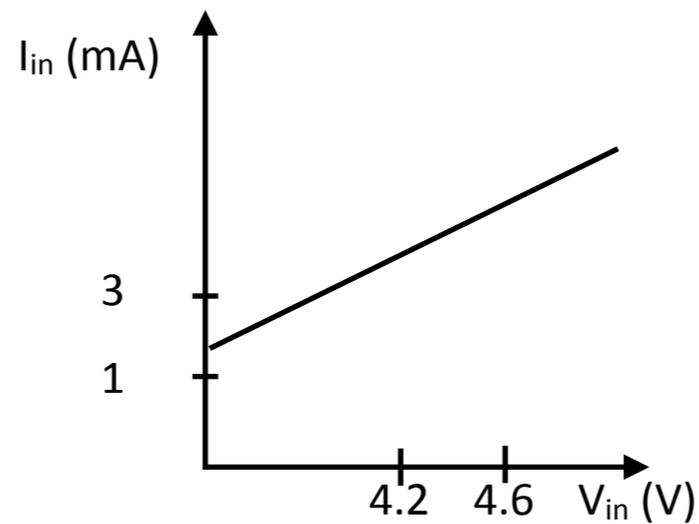
Symptoms of damaged converters: current consumption below UVLO thresholds

“Good”



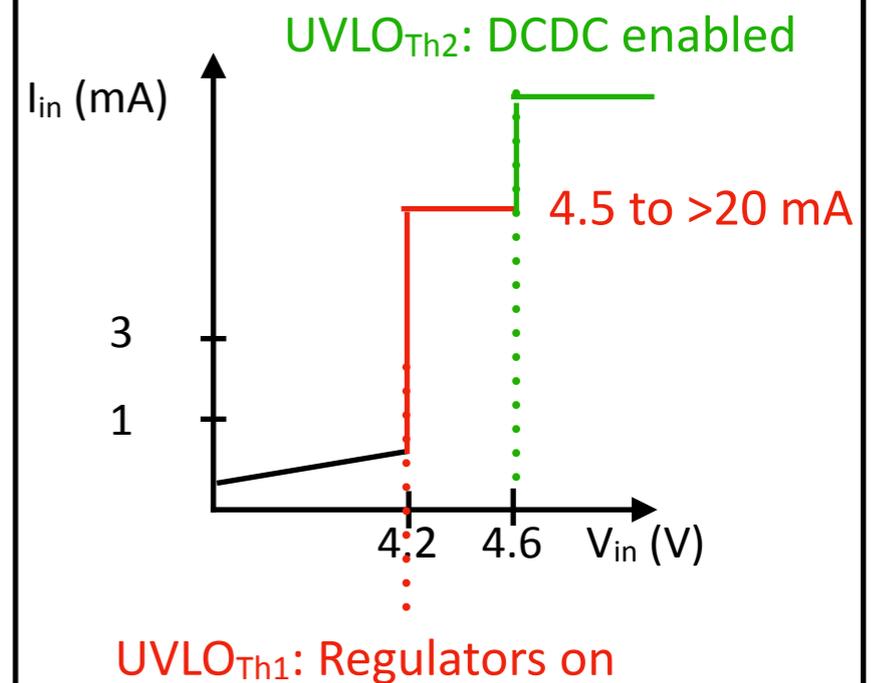
Perfectly working in the experiment

“Broken”



Failed in the experiment

“High current”



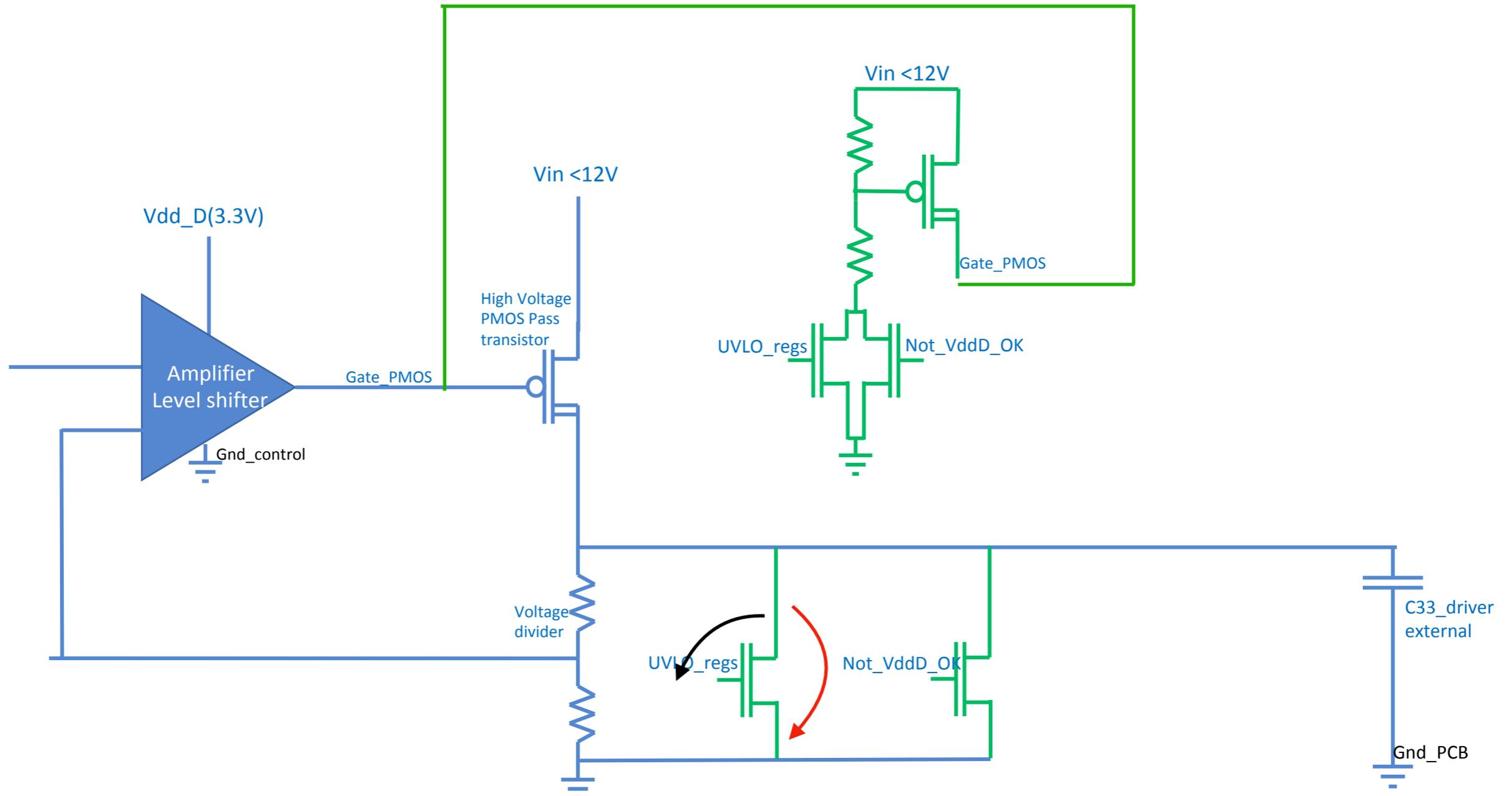
Perfectly working in the experiment

We measured the I-V curve of a large number of samples of FEAST, FEAST2 and FEAST2.1, amongst which some were irradiated with different sources (Heavy Ion, protons, neutrons, pulsed laser)

We found no “High-Current” module, with the exception of:

- 9 of the 33 samples of FEAST exposed to 230MeV protons at PSI**
- 1 sample prepared for HI irradiation but never exposed (different manipulations performed on the test board, including soldering to the V33Dr node)**

The failure appears to be due to damage in clamp transistors in one of the on-chip 3.3V linear regulators.



**Gate current of uA
can block the regulator
“broken”**

**Drain-source current:
no problem as long as $I < 70\text{mA}$
“High current”**

Current plan for further measurements

- **Heavy Ion irradiation of samples previously irradiated with other sources**
- Long term test in the Castor Table (CMS)
- Irradiation at the CERN IRRAD1 facility
- Irradiation at PSI with 230MeV protons
- Failure analysis of samples damaged in CMS
- **Injection of large currents from the supply and control cables, and from ground**

Moreover, a revised version of the ASIC (FEAST2.2) is being manufactured

Heavy Ion irradiation of samples previously irradiated with other sources

Purposes:

- observe if the response of pre-irradiated samples is different than what has consistently been measured for fresh samples
- monitor the V33Dr node in search of anomalous voltage peaks
- expose samples with both 0402 and 0201 SMD capacitors to see if there is any difference

Date scheduled:

- April 18

Modules prepared for the test

- All have been fully measured, including I-V curves
- Samples exposed to 230MeV protons (PSI), X-rays (CERN), neutrons (Ljubljana)

	Board N	Type	
Fresh boards	1	FEAST2	
	34	FEAST2	
	4	FEAST2	
Protons @ PSI	9	FEAST	} Integrated flux $\sim 6.3e13$ p/cm ²
	10	FEAST	
	11	FEAST	
	12	FEAST	
X-rays	30	FEAST2	} Integrated dose 200Mrad
	36	FEAST2	
Neutrons	13	FEAST2	} Integrated flux $\sim 4-5e14$ n/cm ²
	14	FEAST2	
	15	FEAST2	
	16	FEAST2	

Results:

- **no sample has been damaged (either “broken” or “high current”)** by HI exposure with LET of 45 MeV cm² mg⁻¹
- some voltage spikes observed on V33Dr, but limited to about 700mV and lasting only 10ns
- samples exposed: 2 neutrons, 1 protons, 2 X-rays and 1 fresh (with 0201 SMD cap)

Injection of large currents from the supply and control cables, and from ground

Purposes:

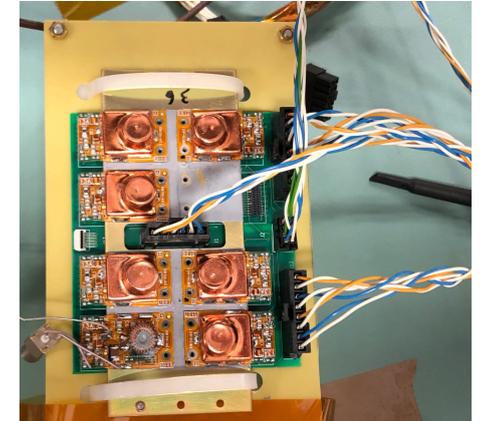
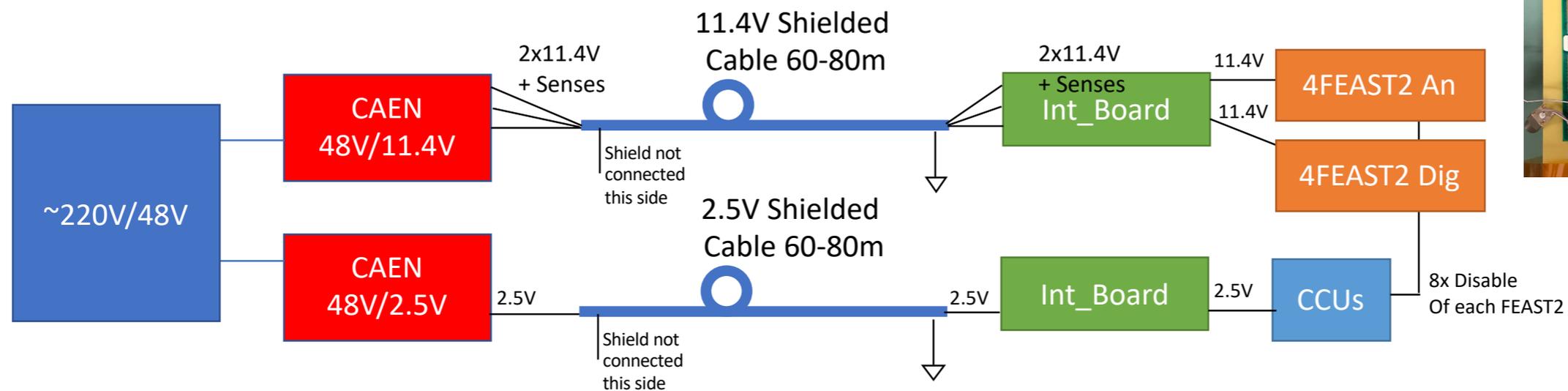
- confirm or rule out the hypothesis that interference via the supply, ground or control cables (EMC) is responsible for the failure

Date scheduled:

- in progress

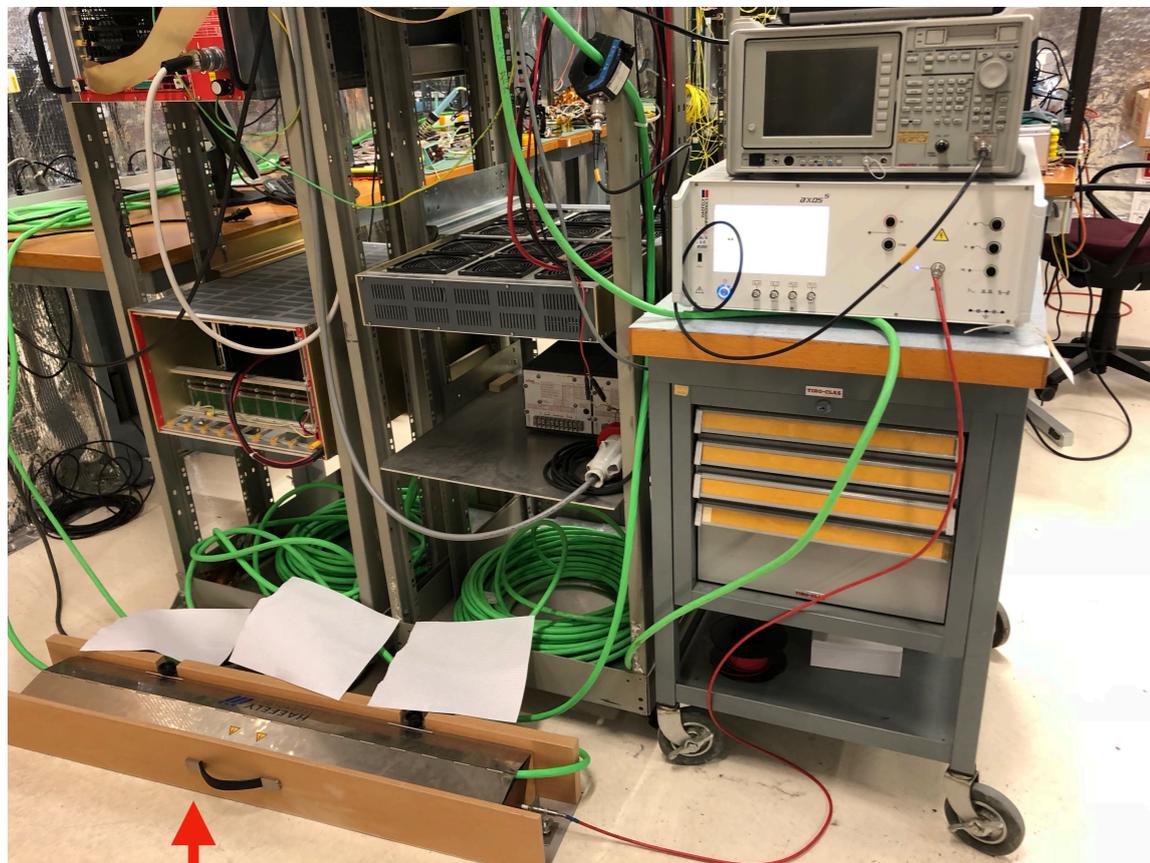
Some details of the study:

- Study driven by our EMC experts at CERN: F. Szoncsó (HSE-DI), D. Valuch (BE-RF-FB)
- Work started at building 186 on a replica of the CMS pixel system

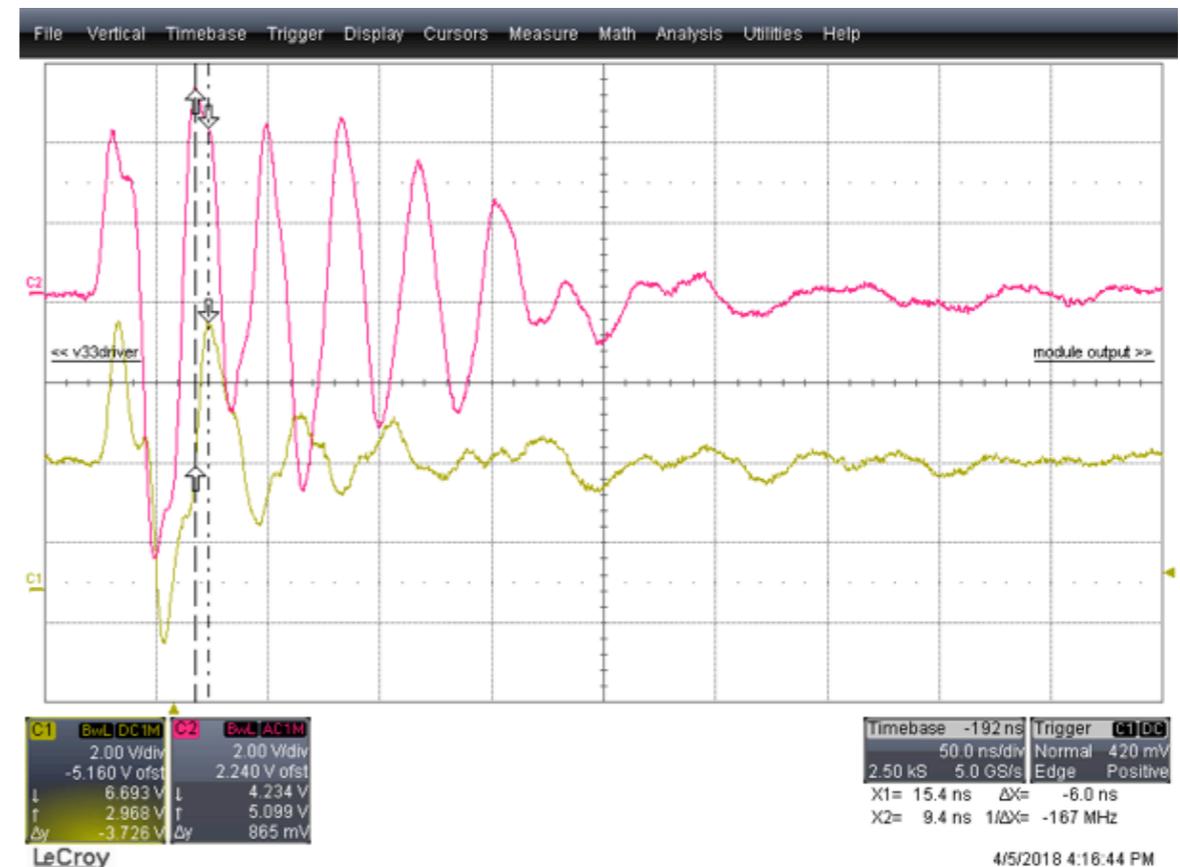


Measurements already done:

- High-frequency capacitive-coupled noise injection on the 11.4V input bus line
- High-frequency injection on the 2.5V output bus line and on the Enable line (capacitively and inductively)
- low frequency observations: disable-enable cycles, short circuit at the output of the converter



Capacitive high-frequency coupler used on the input bus line

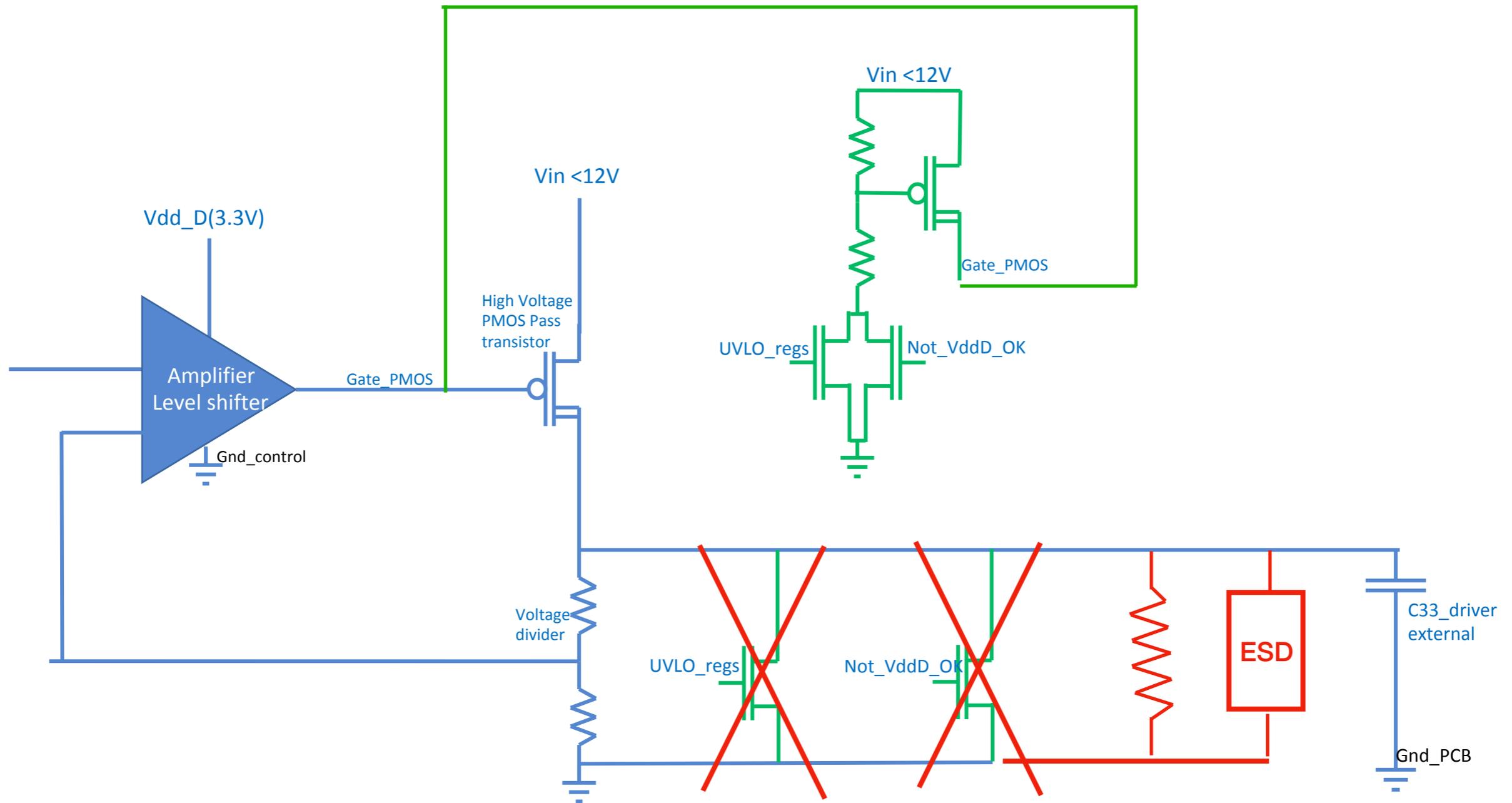


AC-observation of the effect of a 3kV (!) pulse with 50ns duration on V_{in} and V_{33Dr} . The peak is several V above the DC (V_{33Dr} reaches 8V)!

No success so far in provoking neither the failure nor the “High Current” damage of a DCDC. Further measurements will be done with longer pulses, but not in this replica setup anymore.

A revised version of the ASIC (FEAST2.2) is being manufactured

We have modified the design of the ASIC to remove the “weak” low-voltage transistors from the V33Dr node, as well as to add a dedicated ESD protection device to the pad.



Packaged chips should be available in September.

We still have to find a way to demonstrate these are more robust than version 2.1

Conclusion on FEAST

The failure has NOT yet been reproduced outside the CMS detector

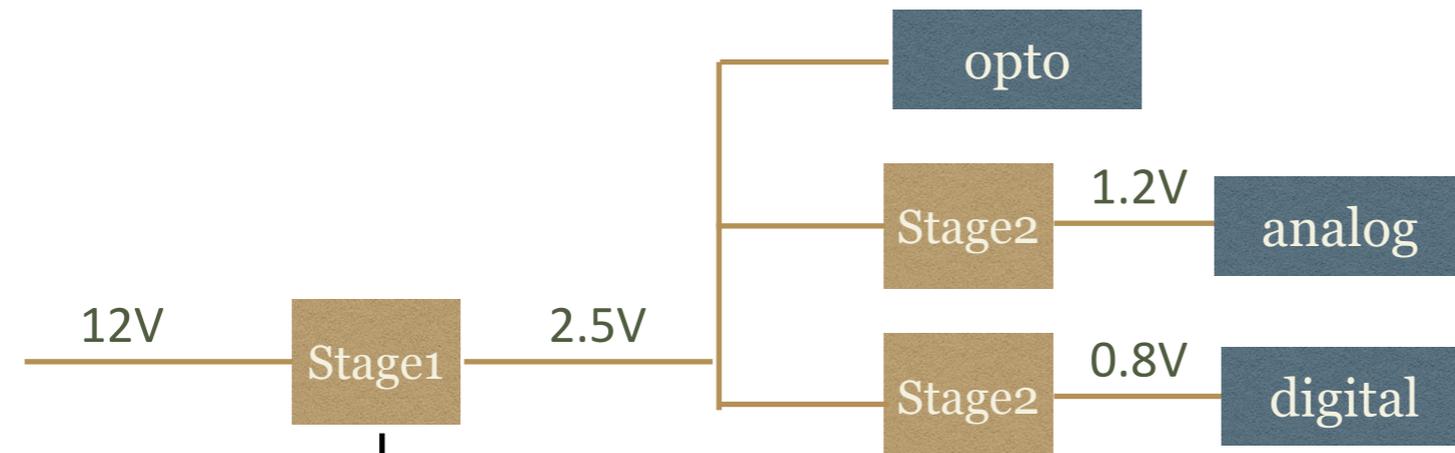
A large range of measurements is planned for the near future, while in parallel a modified version of the ASIC has been prepared

Acknowledgements

Many thanks to the CMS team having taken care of the full development and deployment of the CASTOR Table setup, (N. Bacchetta, S. Cuadrado Calzada, A. Karneyeu, T. Prousalidi, M. Hansen, A. Kaminski, S. Lusin). Their hard work is exploited also for the tests planned in IRRAD1 and PSI.

Many thanks to D.Porret (EP-ESE) for the development of the long-term ageing setups (hardware), to G.Borghello (EP-ESE) for the Labview software, and to S. Cuadrado Calzada for taking care of duplicating one of these systems.

Many thanks to F. Szoncsó (HSE-DI) and D. Valuch (BE-RF-FB) for their exploration of EMC issues.



FEAST2.1 In production and deployed, but failures observed in the CMS pixel system in 2017

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bPOL2V5 Advanced prototyping, but delayed by the above problem with FEAST

rPOL2V5 Initial prototyping stage

The results of the previous prototype (bPOL12V_V25.2) led to the introduction of a number of modifications. Test of V25.3 shows that most issues have been solved.

Modifications needed in version V25.2

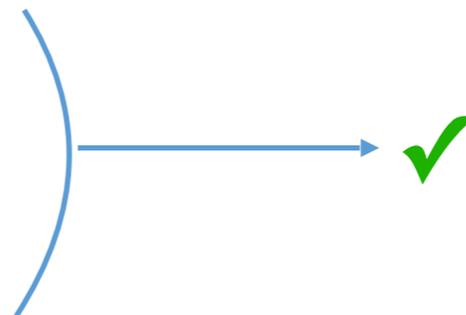
Results in version V25.3

Electrical performance

- Modification of the start-up circuit (some samples do not start reliably)
- Modification of reference voltage for the oscillator (frequency changes with load)
- Increase in the PSRR of the Reference Voltage Generator and improved isolation from substrate to improve noise immunity



OK



The frequency change with load is largely improved, so better noise immunity of the control circuitry. No need for further changes.

Radiation performance

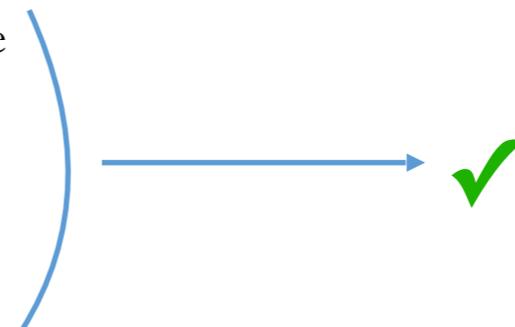
- TID:
 - ▶ Layout change in the Reference Voltage Generator
 - ▶ Modification of the start-up circuit of the HV Reference Voltage Generator
- DD:
 - ▶ Layout change in the compensation network to eliminate the most likely current injection path on the sensitive feedback node
 - ▶ Possibility to remove the remaining current injection paths with FIB to increase the probability of understanding the origin of the current



The post-rad evolution is still observable in some conditions



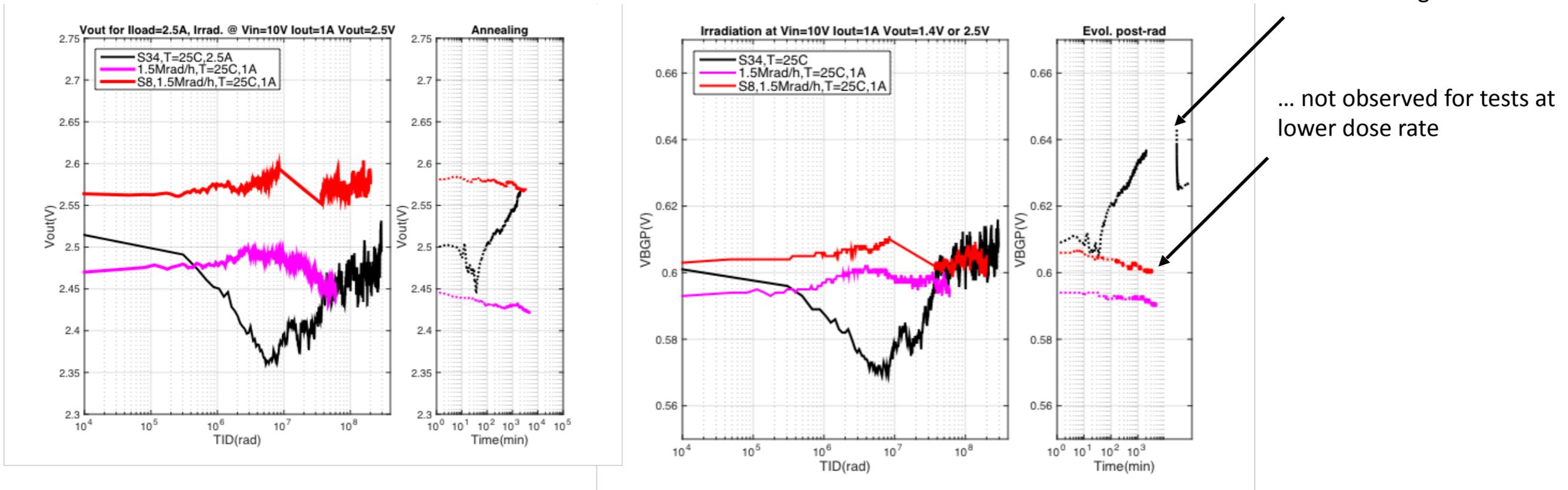
The problem with the start-up at high TID (>200Mrad) has not been observed anymore.



The largest contribution to the injection has been found, and when removed the circuit is not disturbed anymore up to an integrated neutron fluency of $5e15$ n/cm².

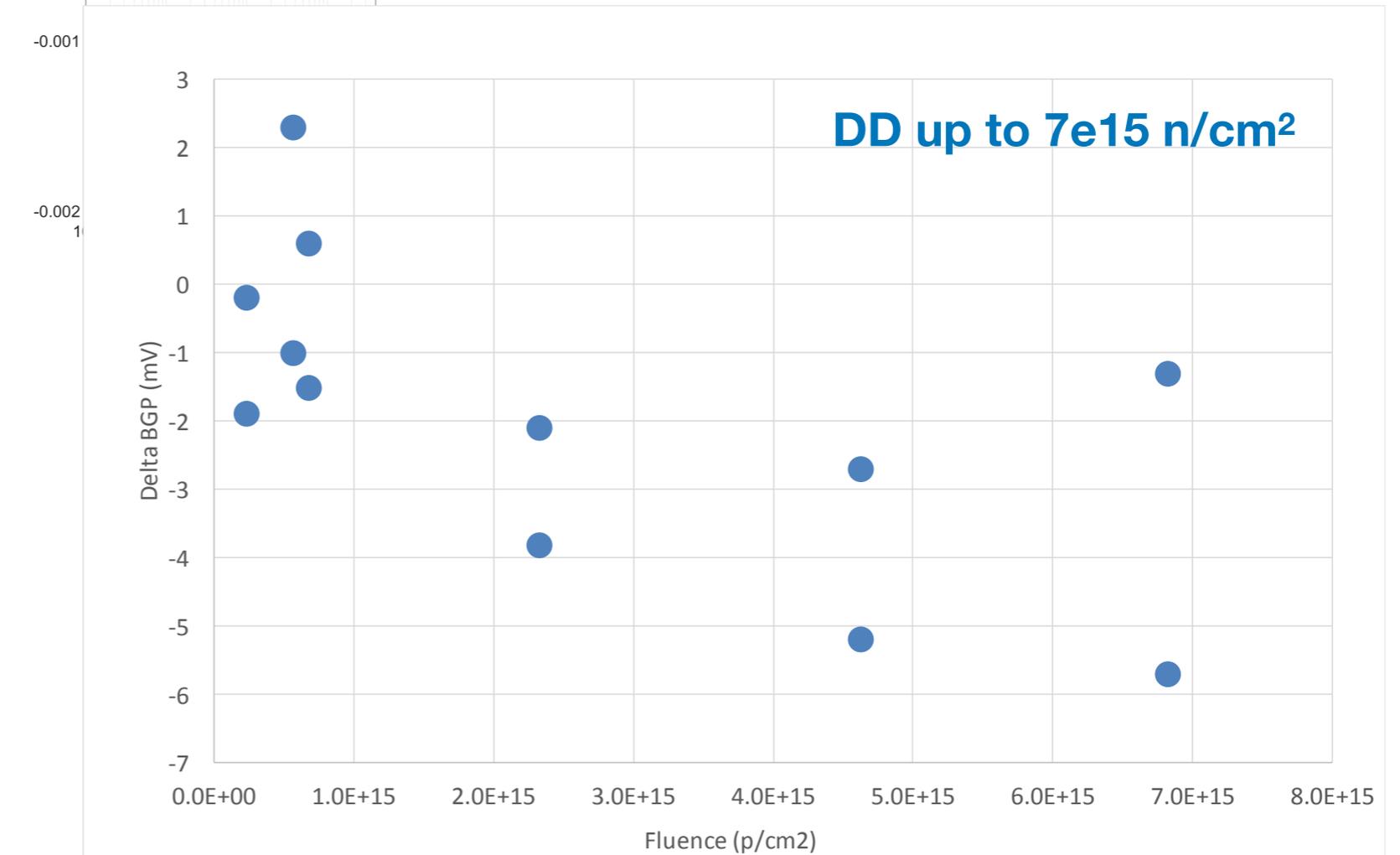
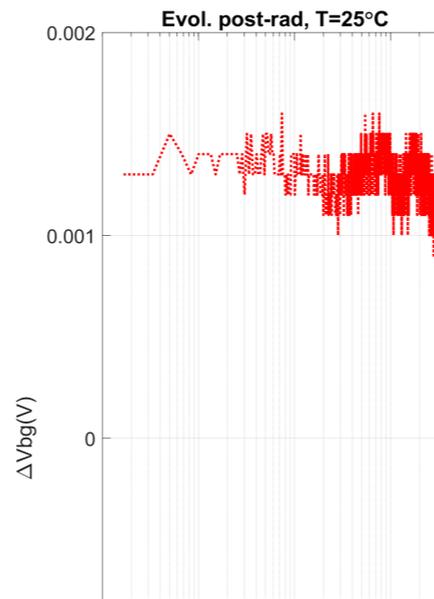
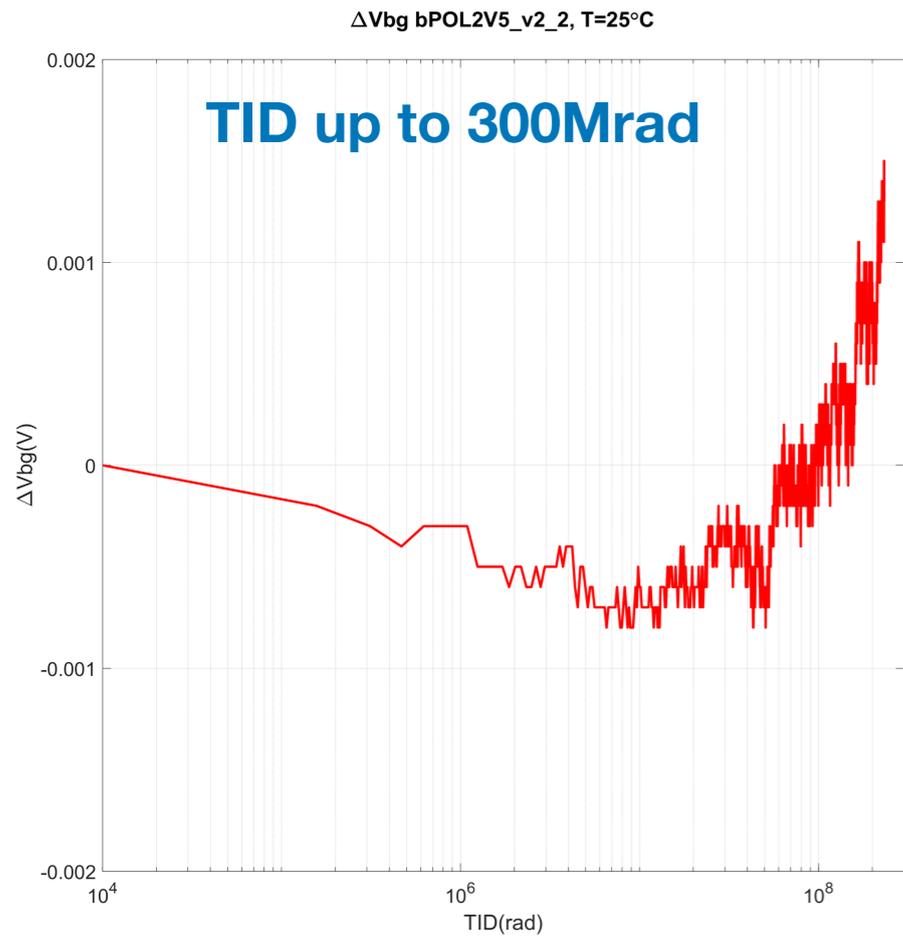
V25.4 will fit in a QFN32 package

The TID tolerance has been verified with X-rays at both room T and -30°C up to 300Mrad



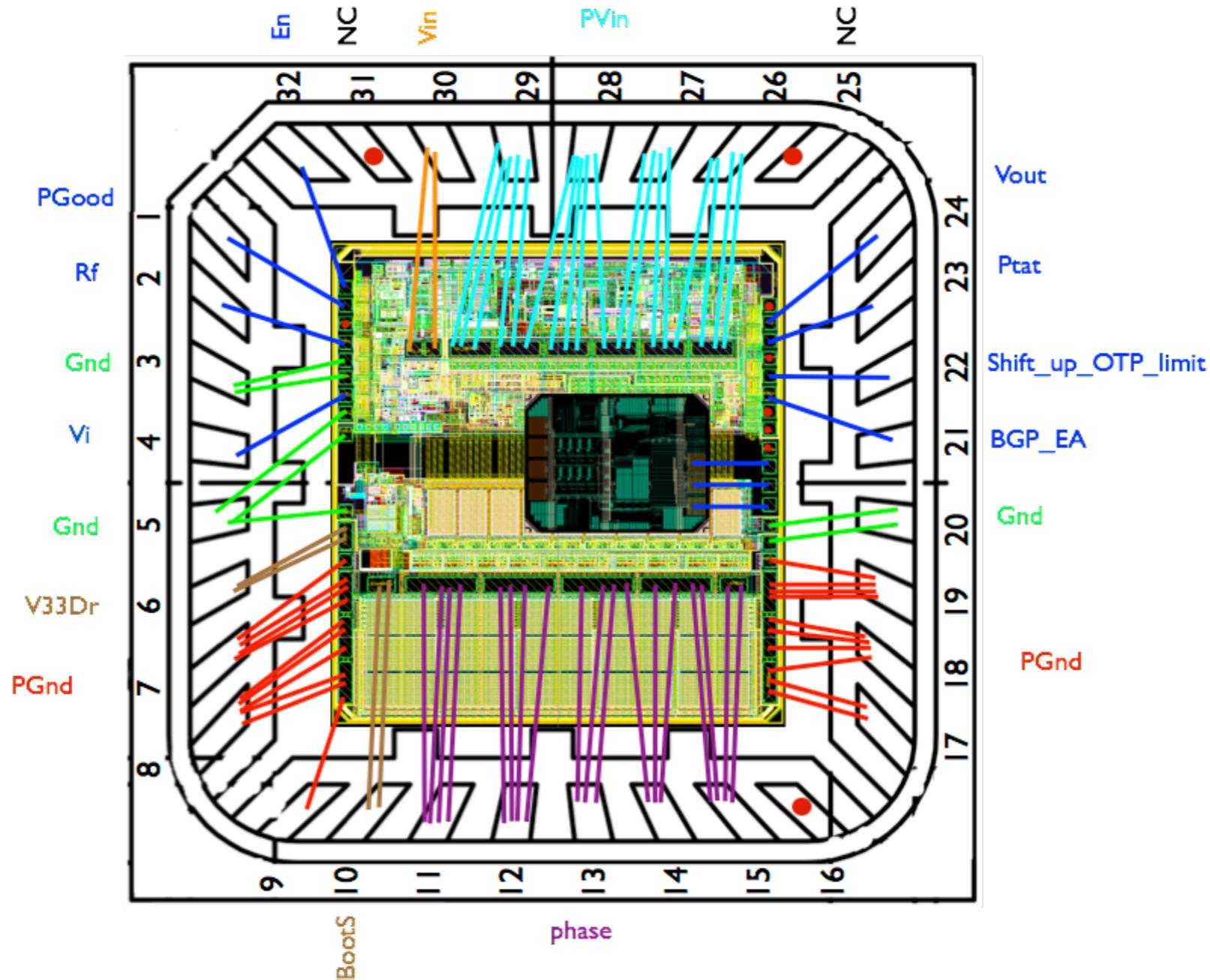
The reference voltage generator stability with TID can not be improved in this technology.
We hence try a different solution.

This is the radiation tolerance of the reference voltage generator designed in the 130nm process

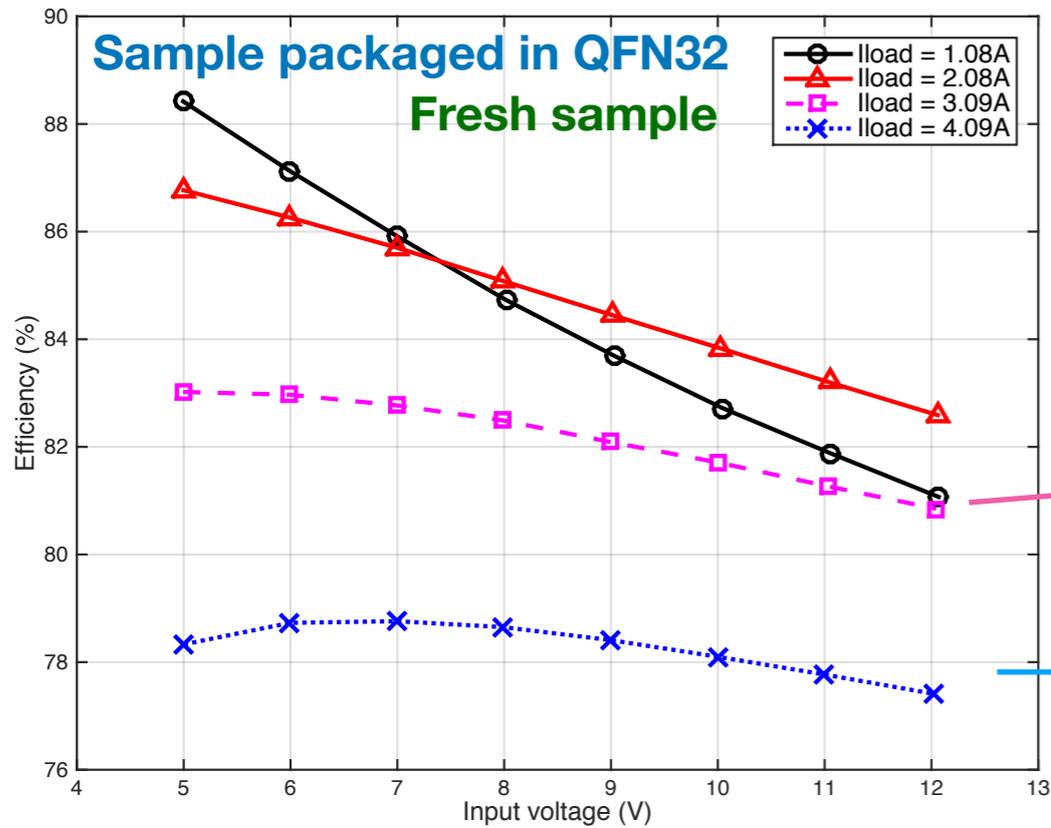


With chip stacking we can provide to bPOL12V_V25.4 a very stable reference voltage from a small chip in 130nm.

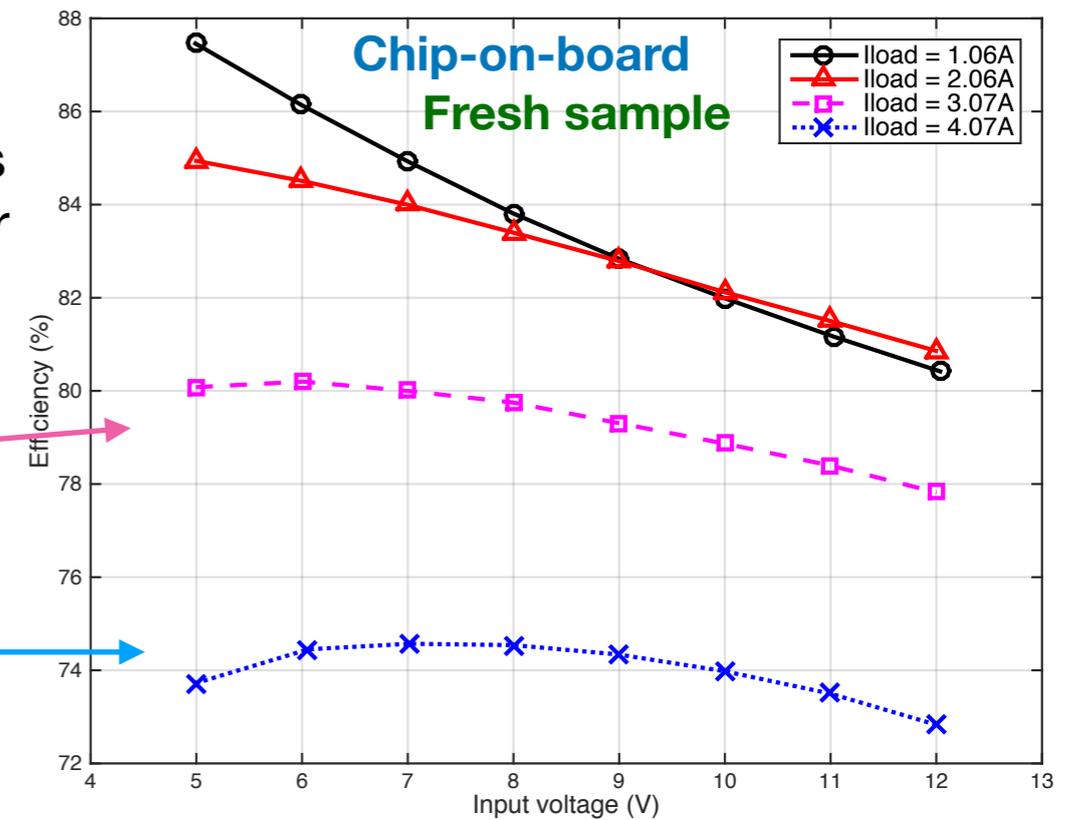
In this way, we can also exploit the availability of OTP devices (e-fuses) to trim the reference voltage, producing a very uniform V_{out} for all converters during production.



Neutron exposure up to $5e15$ n/cm² introduces a marginal efficiency decrease

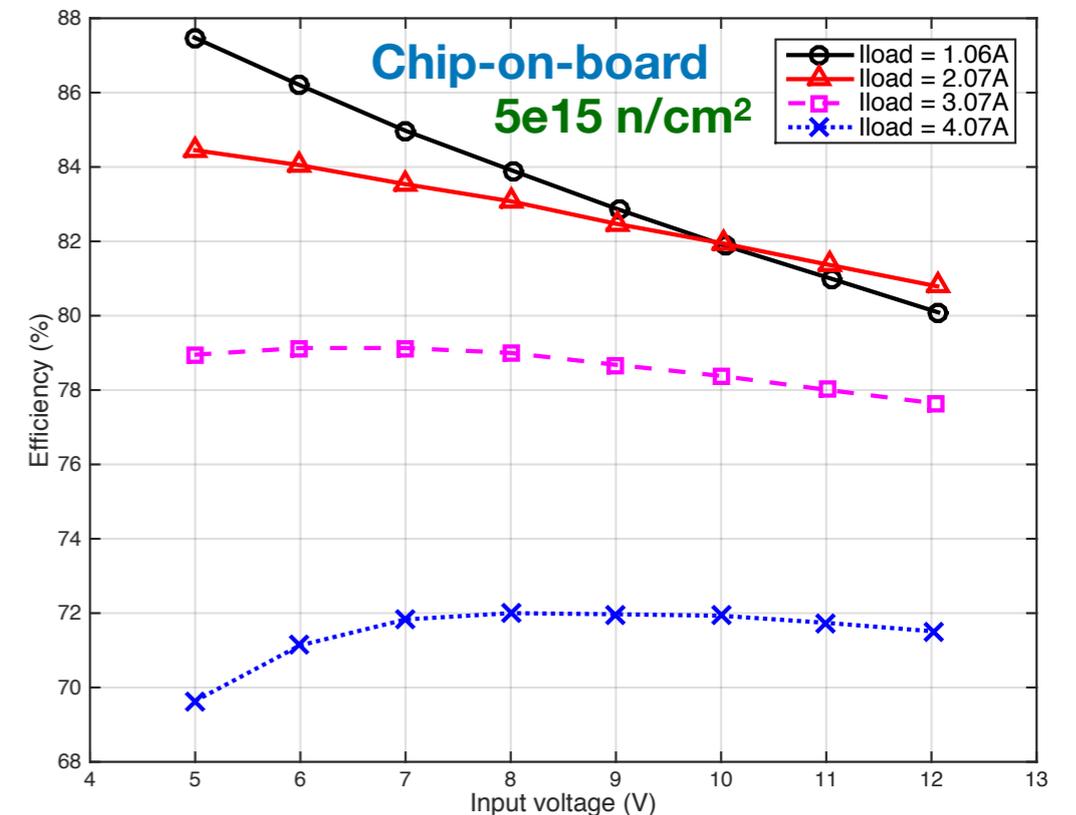


Efficiency at large load drops because of poor cooling.



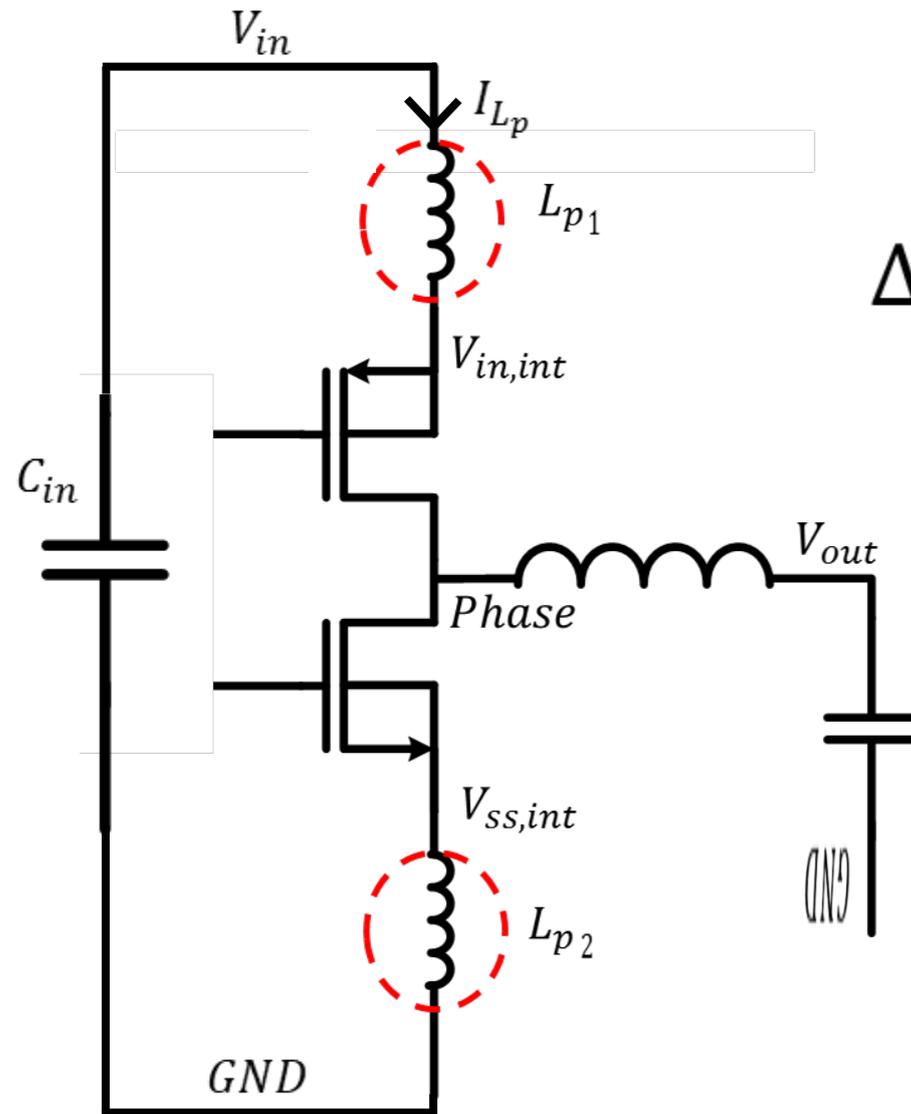
Additional results from the neutron exposure:

- the parasitic leakage in the feedback network can be made negligible
- There is a decrease in OCP threshold, so the initial value has to be properly chosen
- the limit tolerance appears to be between 7 and $8e15$ n/cm²



Main reliability threat (besides radiation): excessive V_{ds} in the power transistors

This is due to the periodic large current flow and the parasitic inductance along the current path



$$\Delta(V_{in,int} - V_{ss,int}) = -(L_{p1} + L_{p2}) \frac{dI_{Lp}}{dt}$$
$$= -(L_{bond} + L_{PCB} + ESL) \frac{dI_{Lp}}{dt}$$

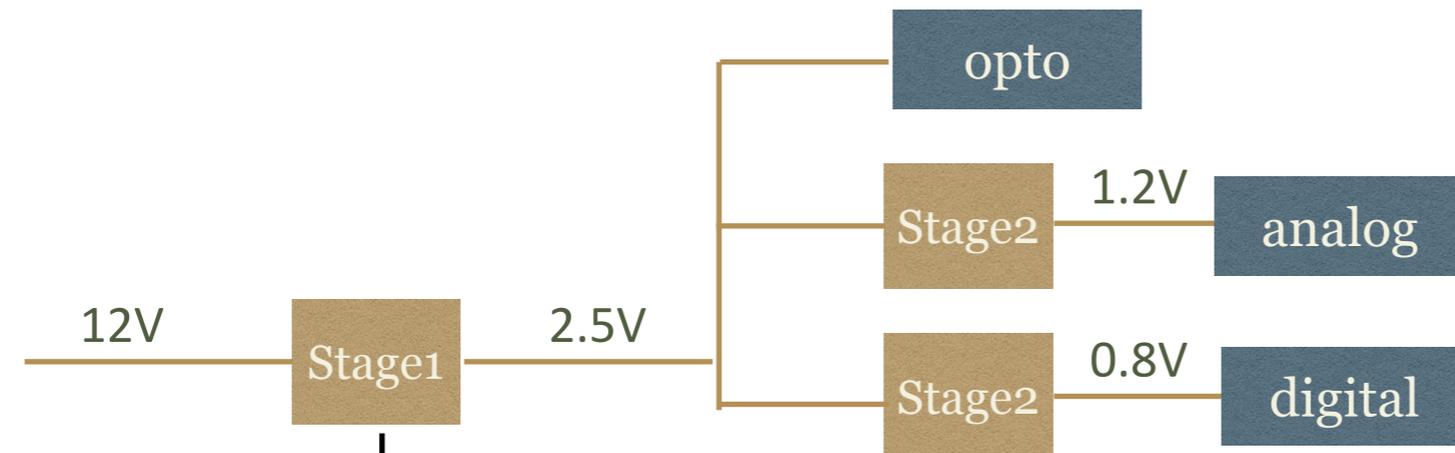
With wire-bonding assembly and the present board design, the inductance is large. Voltage peaks surely exceed specified maximum V_{ds} rating (DC), and can get close to the Breakdown Voltage (BV).

Solution to ensure long-term reliability: maximum voltage de-rating.

Additional measurements planned

- **Additional TID exposures: more samples, larger TID levels**
- **Exposure with protons from the PS (IRRAD1 facility)**
- **Heavy Ion irradiation of samples previously irradiated with X-rays and neutrons**
- **Measurement of the Breakdown Voltage (BV) of the High-Voltage transistors before and after irradiation (X-rays, neutrons)**
- **Long-term ageing test of a large number of samples (exposed to different radiation sources)**

All changes required - including what we will learn from the FEAST2 investigation - will be implemented in version V25.4



FEAST2.1 In production and deployed, but failures observed in the CMS pixel system in 2017

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bPOL2V5 Advanced prototyping, but delayed by the above problem with FEAST

rPOL2V5 Initial prototyping stage

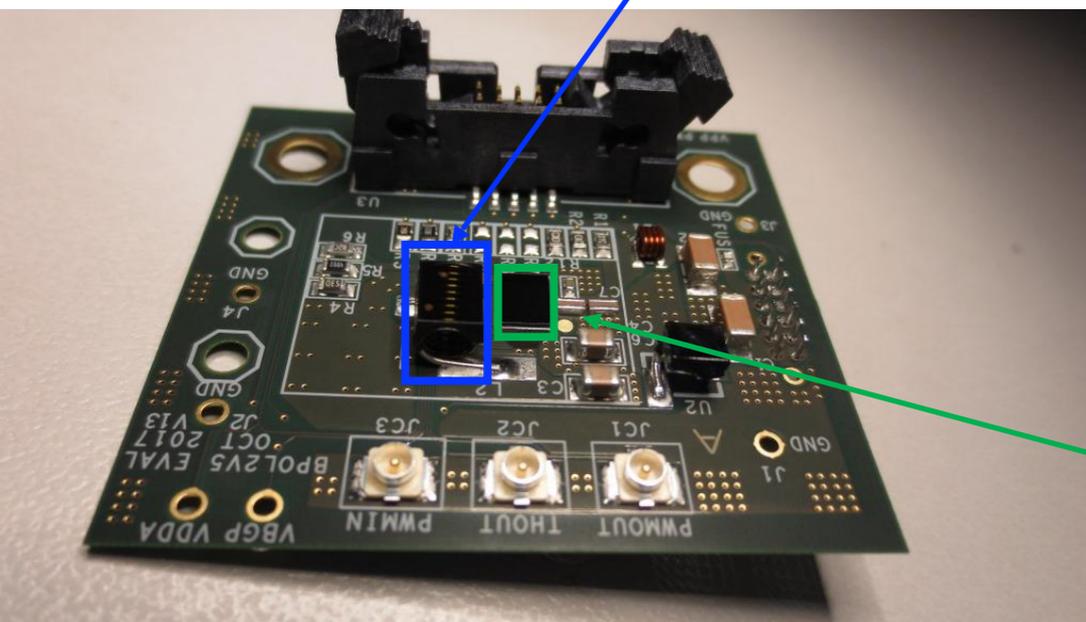
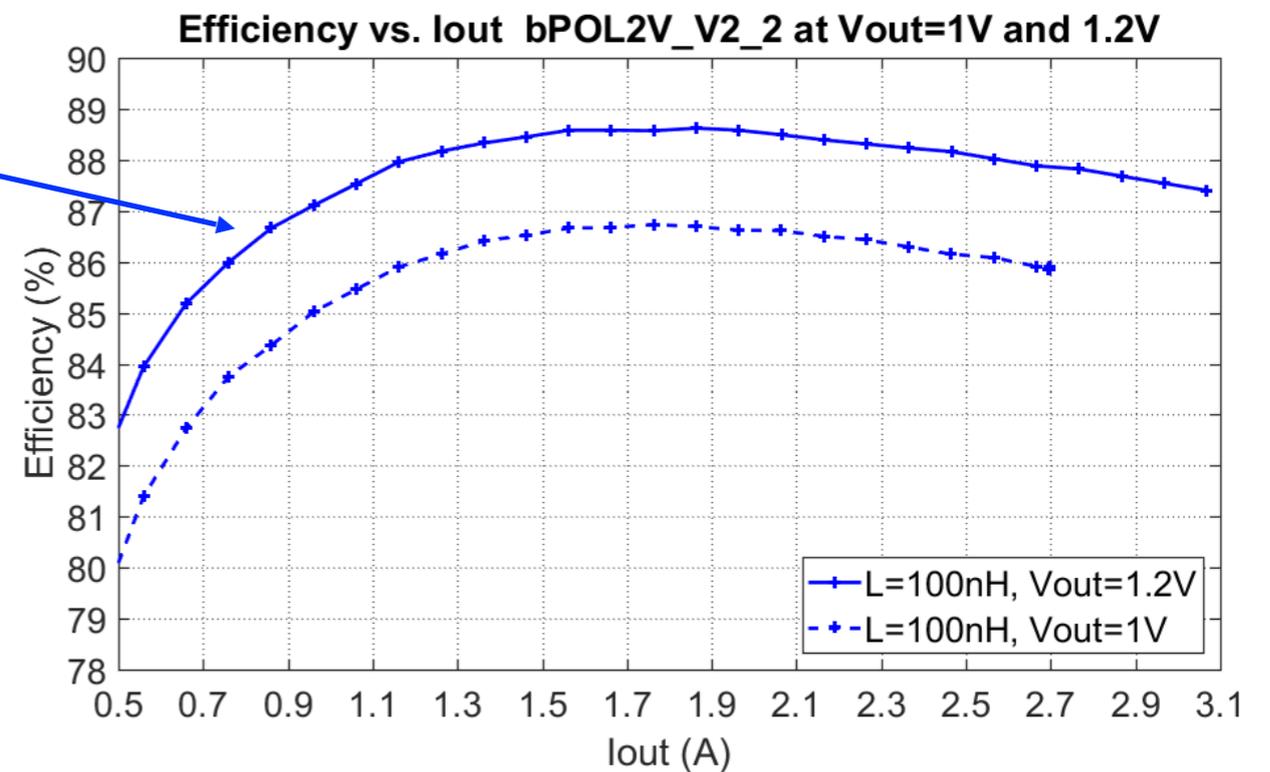
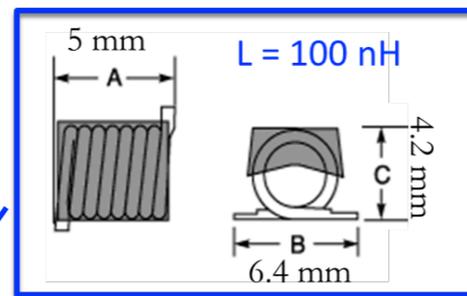
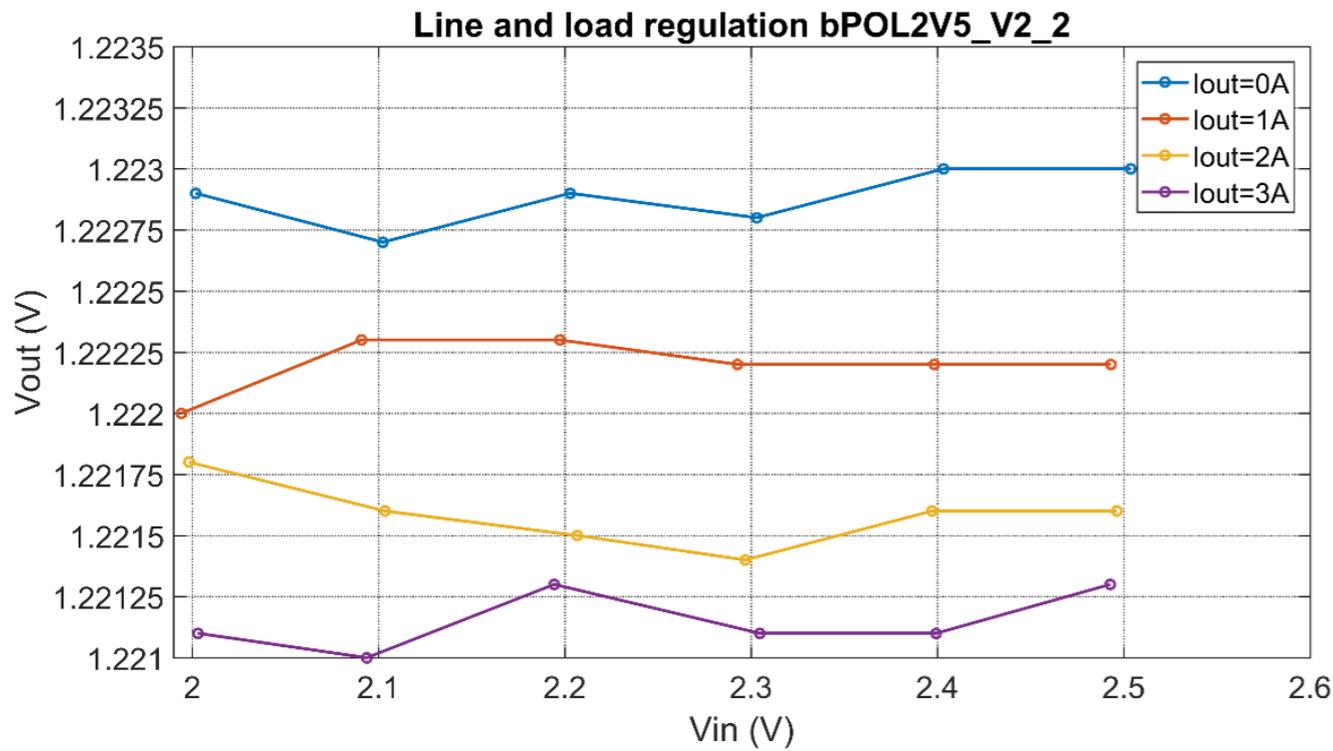
**The first prototype of bPOL2V5 was measured in 2017 and was already working well.
A second prototype has been manufactured and tested.**

Some issues were found and have been corrected

The parasitic inductance along the current path has been reduced

Some missing functionalities have been added (OCP)

The converter shows satisfactory regulation performances and exhibits a peak efficiency of 88.6 %



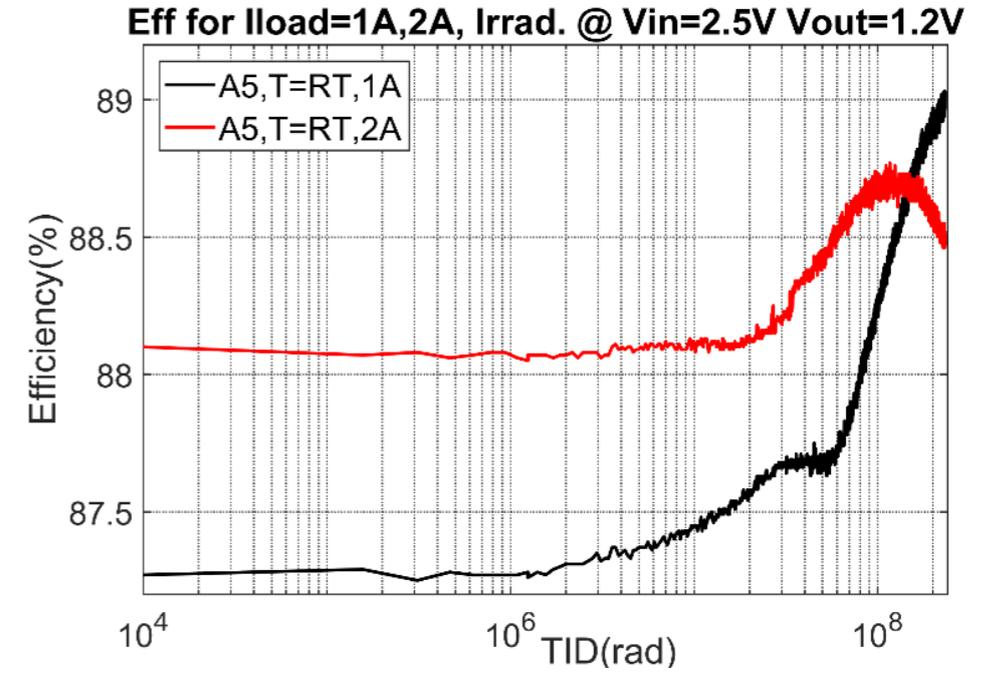
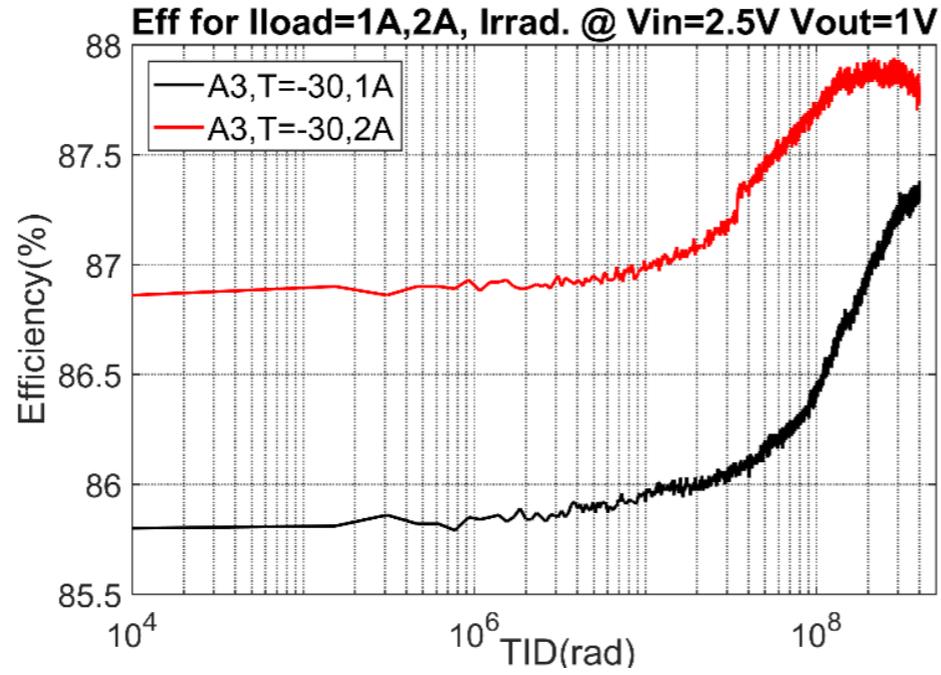
ASIC (3.9 mm X 3 mm)

TID only very marginally affects the functionality of bPOL2V5_V2.2

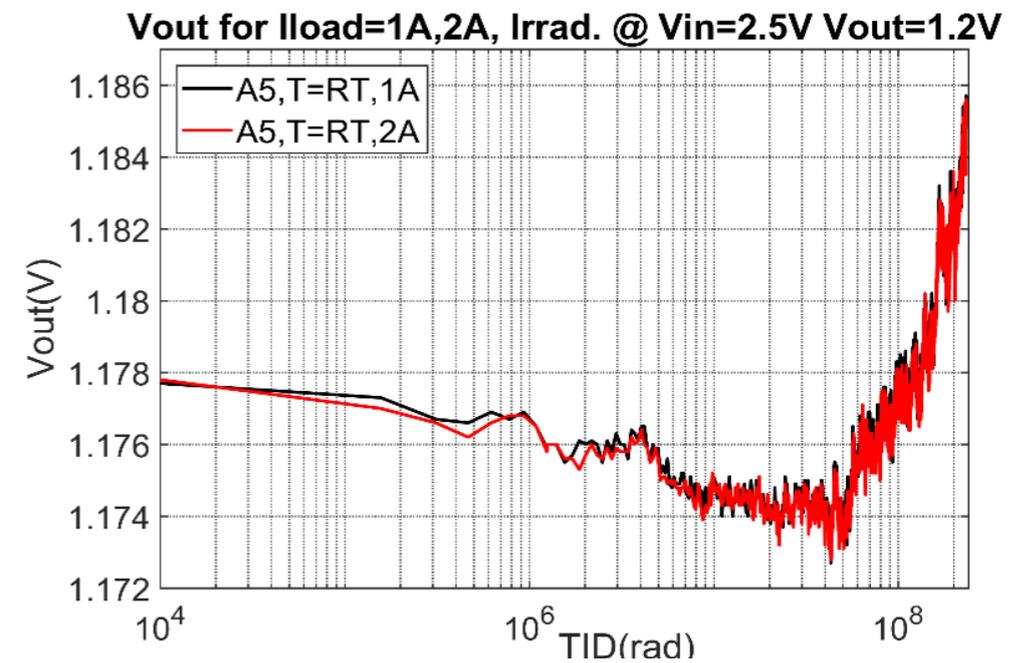
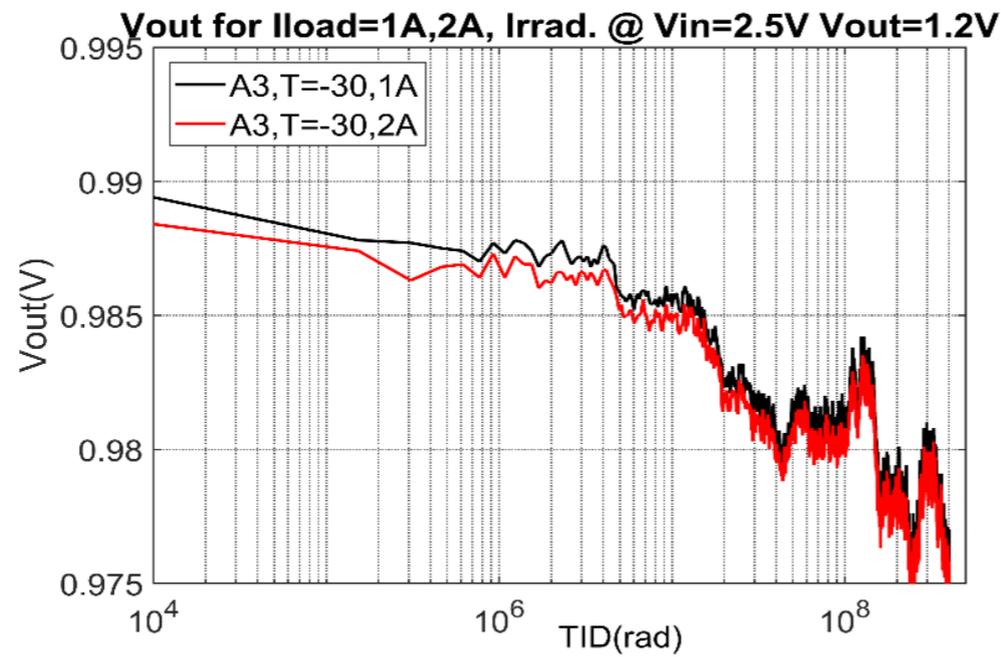
-30°C

25°C

Efficiency



Output Voltage



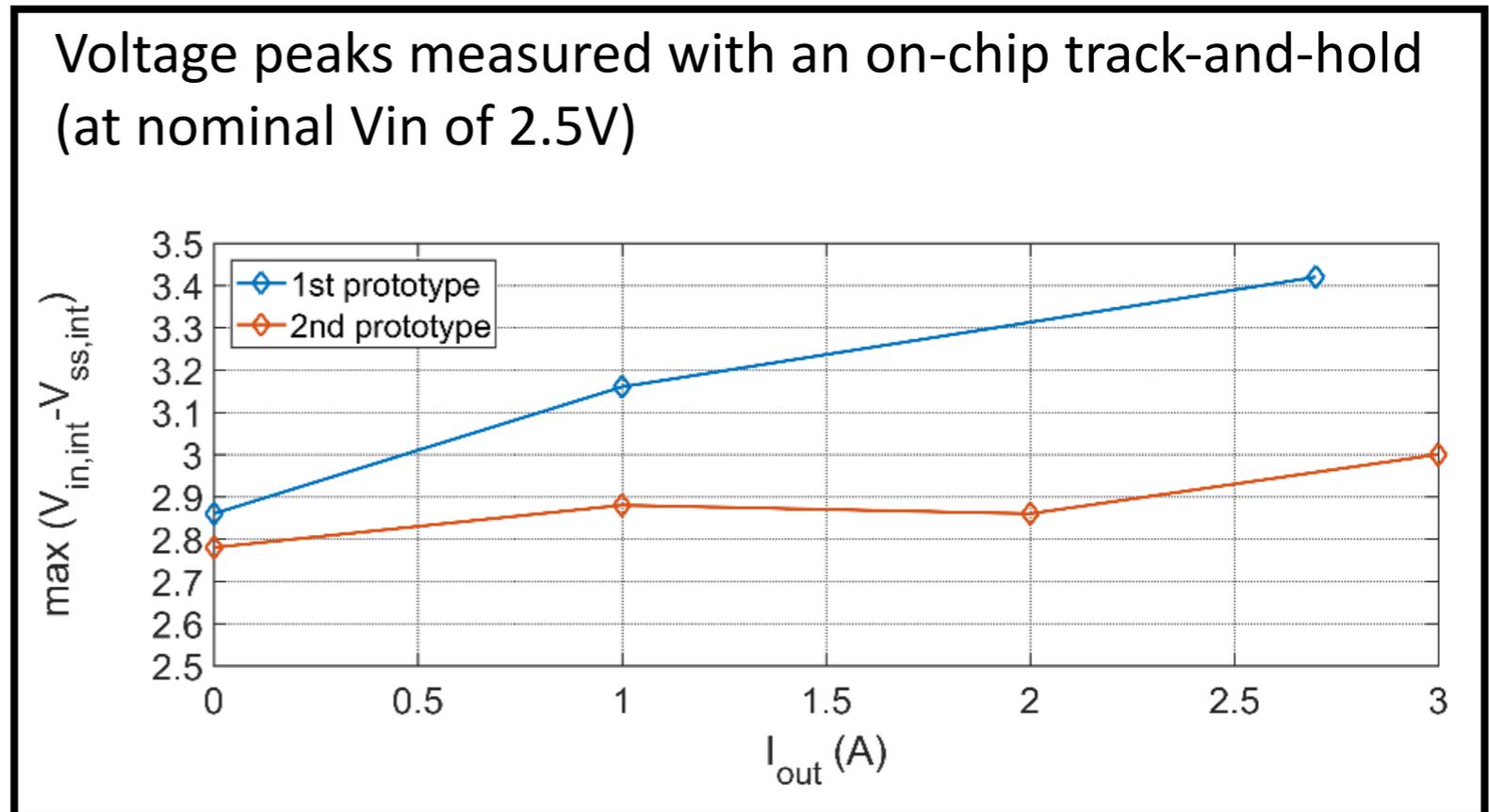
A detailed study of the PCB design and of the components populating it led to a significant decrease of the parasitic inductance along the current path

The voltage peaks during commutation have been considerably reduced

$$\Delta(V_{in,int} - V_{ss,int}) = -(L_{bond} + \underbrace{L_{PCB} + ESL}) \frac{dI_{Lp}}{dt}$$

New PCB layout and different choice of the input capacitors for the second prototype

Estimated parasitic inductance	
	$L_{PCB} + ESL$
2 nd prototype	155 pH
1 st prototype	450 pH

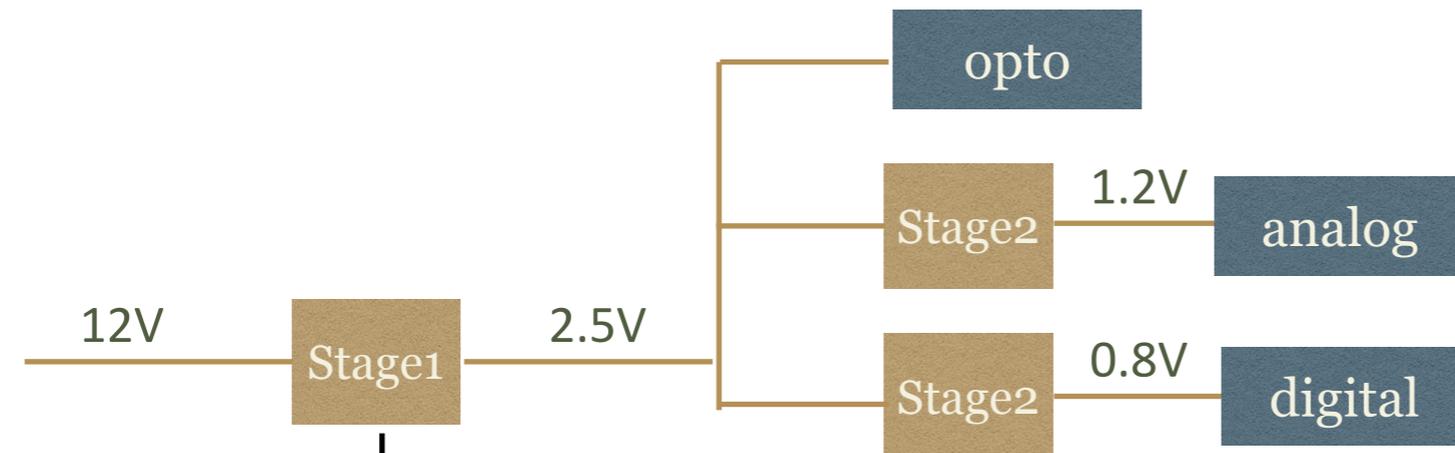


Additional measurements planned

- Neutron or proton irradiation for displacement damage
- Heavy Ion irradiation to confirm SEEs results from first prototype (no issue found), including samples pre-exposed to TID
- Long-term ageing test of a large number of samples (exposed to different radiation sources)

We are completing the design of a new version (V3.1) that uses the 3.3V I/O transistors in the same 130nm CMOS process

- This allows to considerably increase the confidence on the long-term reliability
- This prototype also embeds OTP devices (e-fuses) enabling the trimming of the reference voltage
- All functionalities are included (Over-Temperature protection as well)
- **However, the radiation tolerance of the 3.3V transistors has not been tested yet**



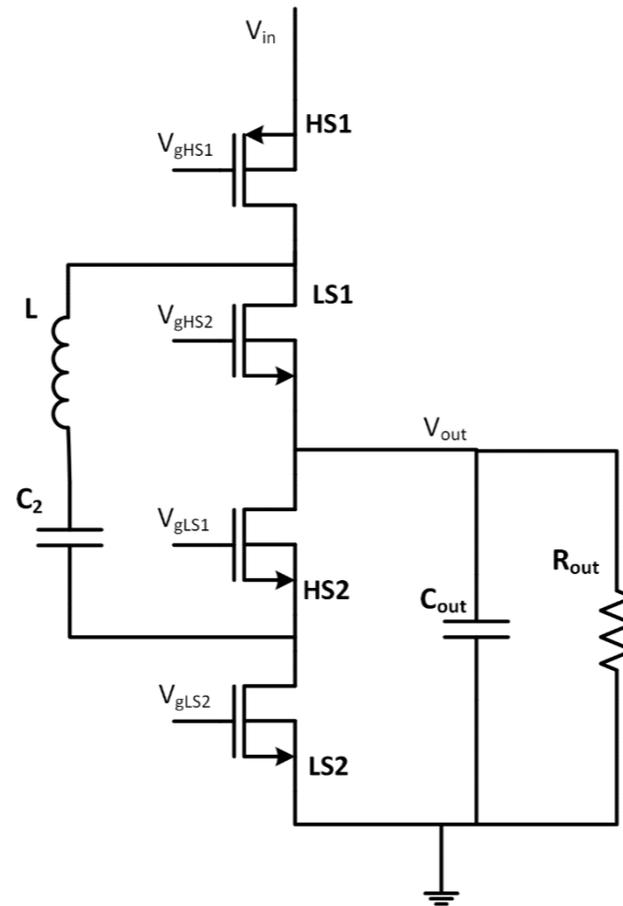
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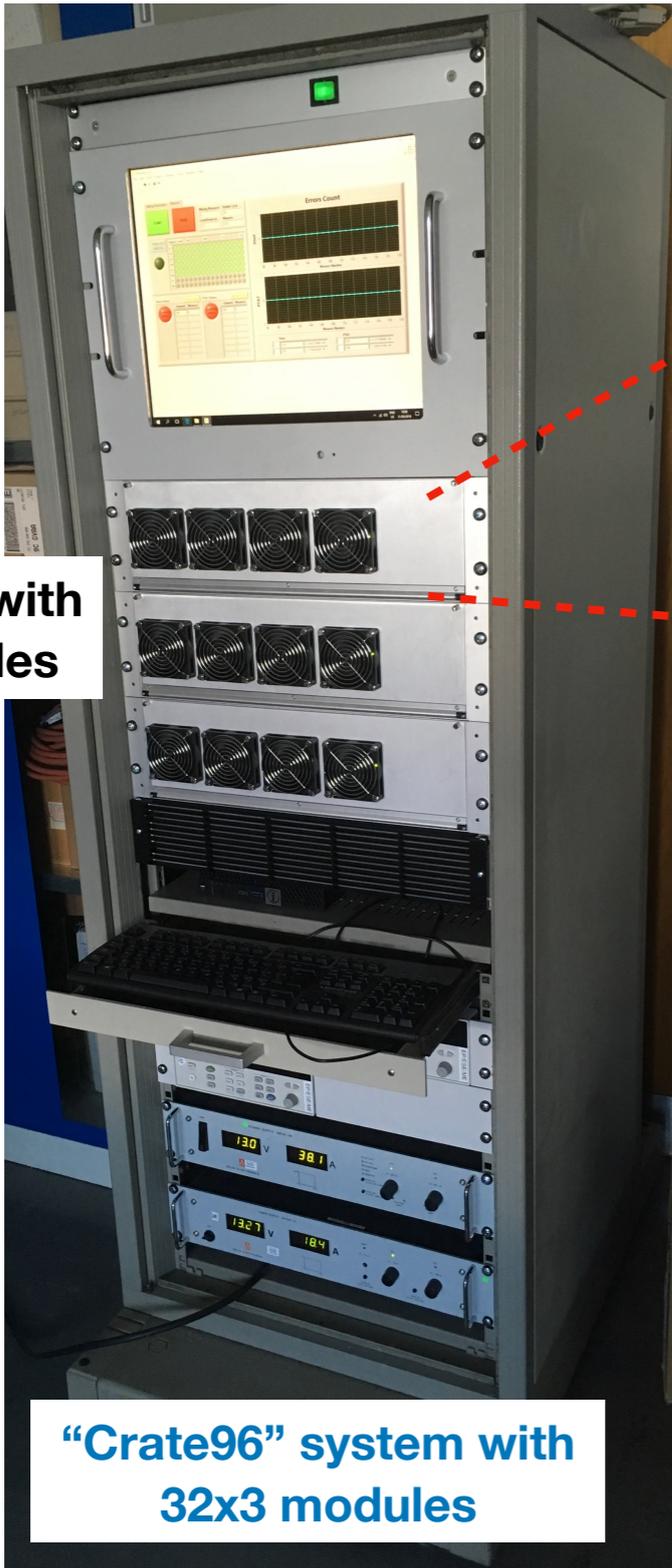
This novel architecture promises a large decrease of the inductor value (from 100 to 10nH)



**The first prototype of the ASIC is in our drawers since December 2017
No assembly in PCB will be ready for testing until June!**

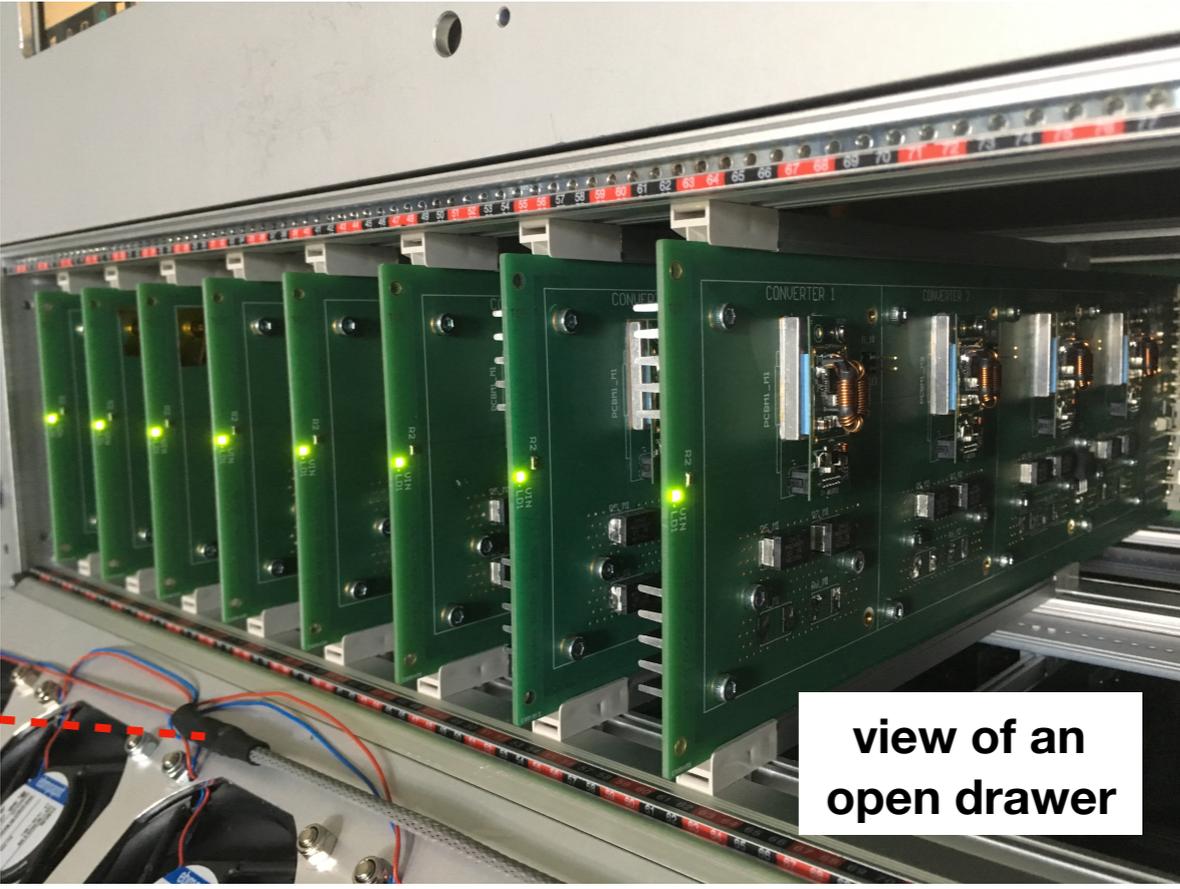
Long-term ageing tests (all converters)

We built two systems to keep DCDC modules in (or beyond) operational conditions for long runs. A total of 124 modules can be powered, loaded and monitored. Another rack capable of 96 modules is being completed.

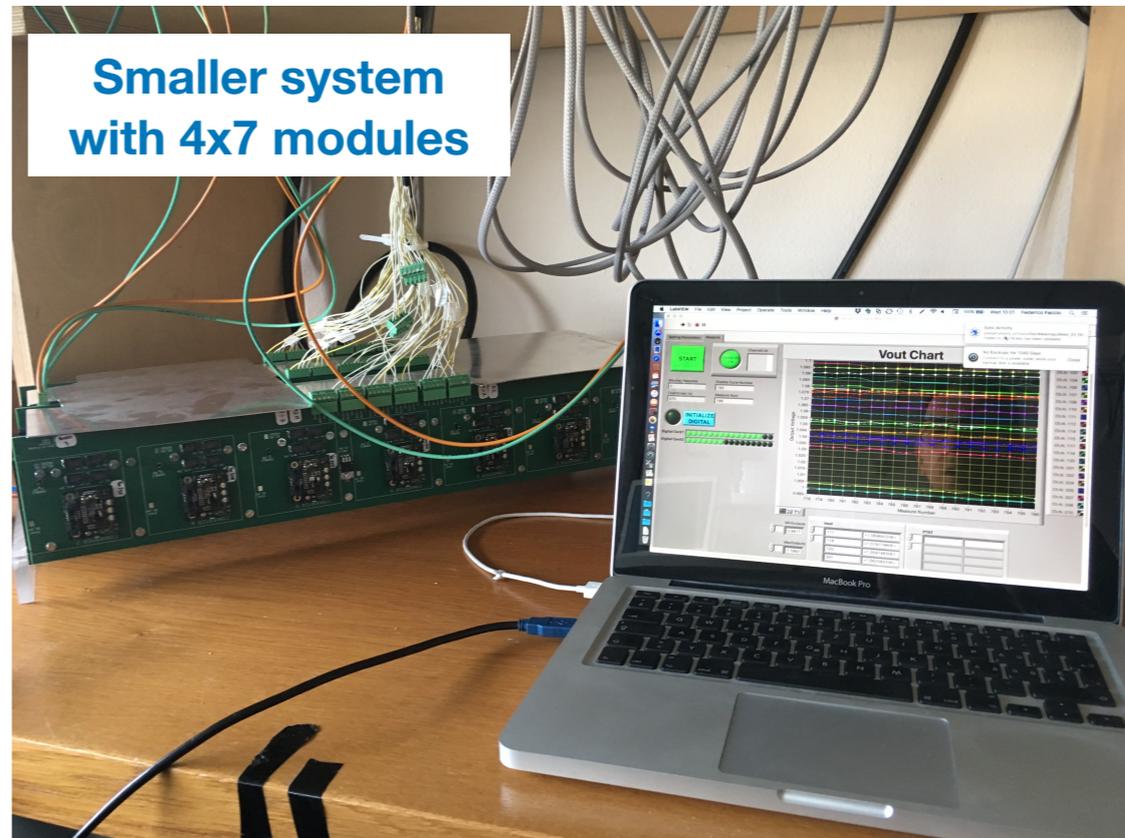


3 drawers with 8x4 modules

“Crate96” system with 32x3 modules



view of an open drawer



Smaller system with 4x7 modules

This is the list of DCDC modules stressed so far (most of the runs are still on-going).

Vout is set to 2.5 or 1.5V, load current 2.5 and 3A respectively.

bPOL12V use different inductors: 460 and 220nH (solenoid), and 200nH flat toroid.

Junction temperature has been measured in 2 points and is close to 54 °C.

	Fresh/ Irradiated	Vin	N. of samples	Stress time	Comment
FEAST2.1	Fresh	14V	7	3 months	Test completed
FEAST2.1	Fresh	12V	20	1.5 months	
FEAST2.1	Fresh	13V	16	1 month	
FEAST2	Protons @ PSI	12V	12	~2 months	7 High-Current
bPOL12.V3	Fresh	12V	14	3 months	Test completed
bPOL12.V3	Fresh	12V	32	~2 months	
bPOL12.V3	Fresh	13V	16	1 month	
bPOL12.V3	Neutrons up to 5e15	10V	7	3 weeks	
bPOL2V5	Fresh	2.7V	21	1 month	

Conclusion

December 2017

FEAST2.1: completed

Large investigation program needed
FEAST2.2

bPOL12V: last small modifications needed

Potentially same problem as FEAST
Reliability to be evaluated in detail

bPOL2V5_V2.1: last small modifications needed

Move to V3.1 to gain in reliability

rPOL2V5: possible alternative

Unless first prototype works remarkably well,
no resources to continue the development

The work plan has expanded, but the resources have (and will) not