rPOL2V5: a compact radiation-hard resonant switched-capacitor DC-DC converter for the CMS HGCAL

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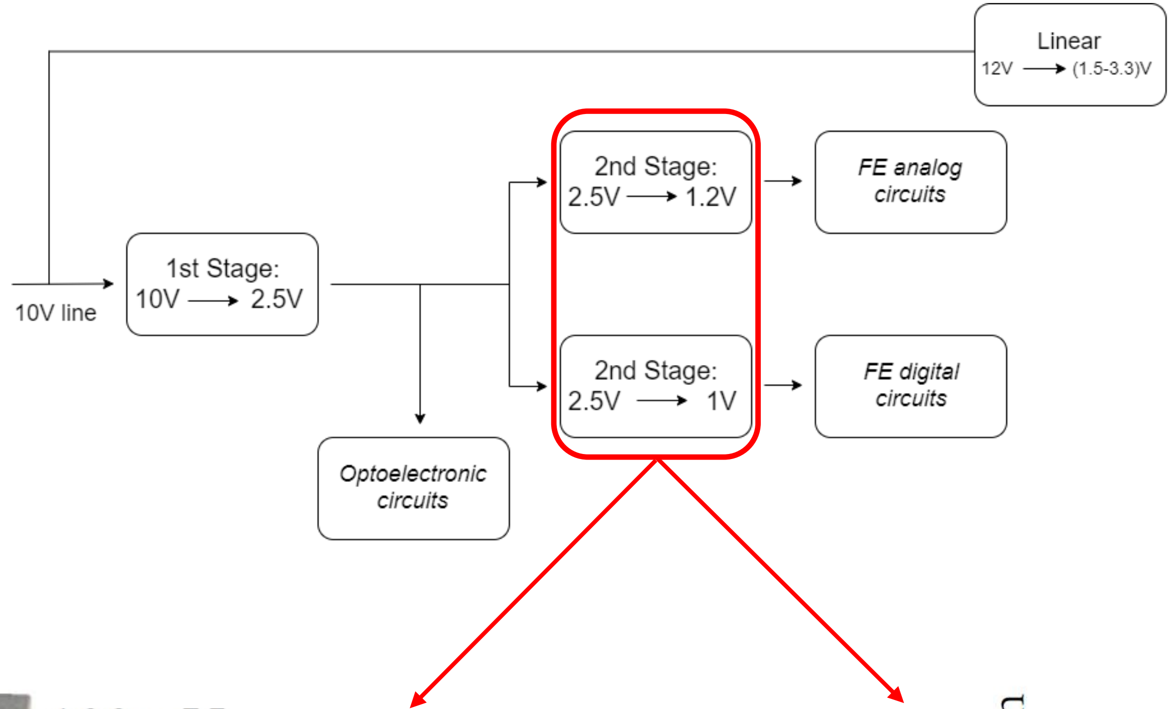
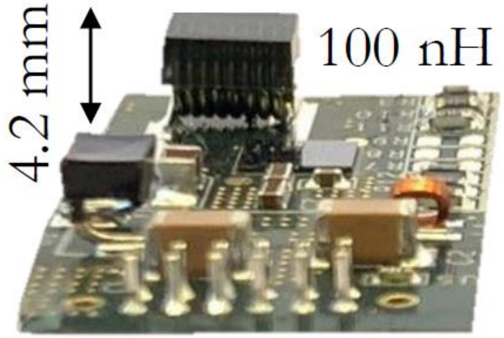
On behalf of the CMS Collaboration

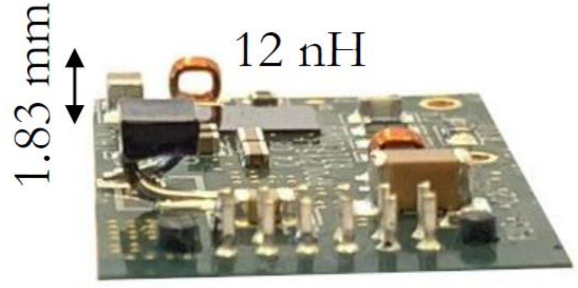
TWEPP, September 21, 2021

CERN / EP-ESE-ME Development of DCDC converters



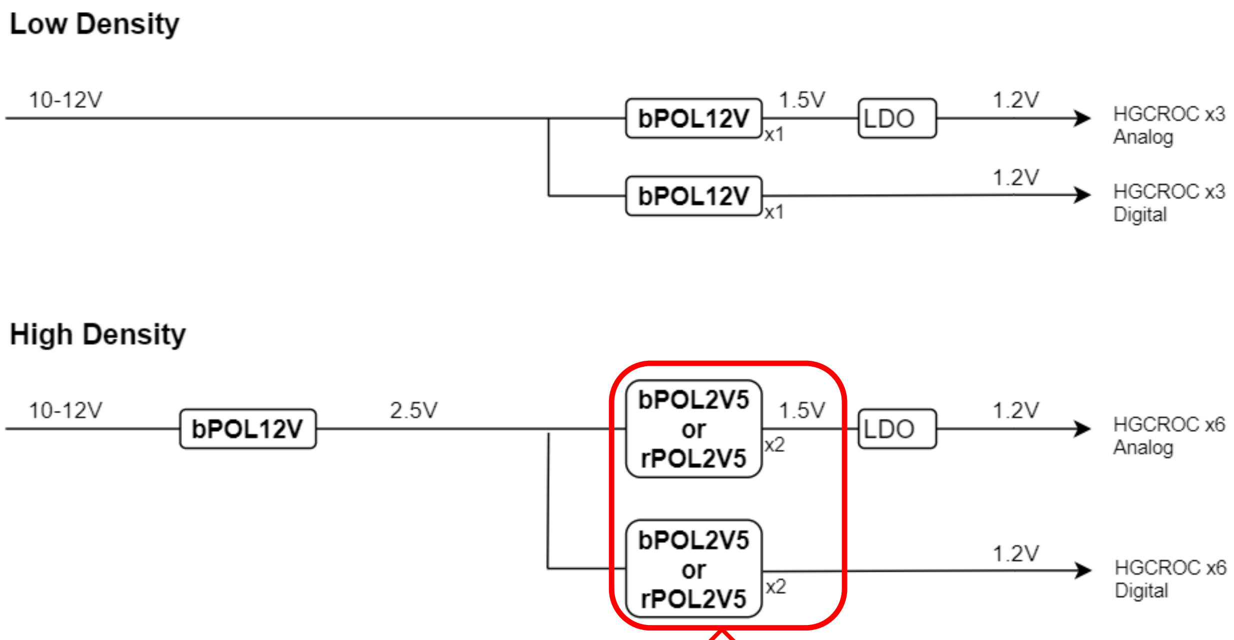


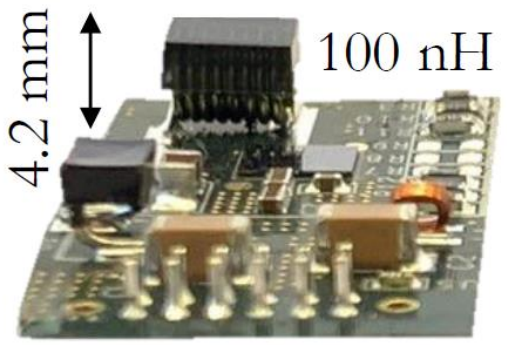
bPOL2V5



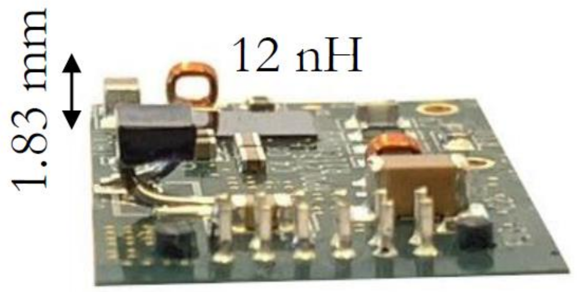
rPOL2V5

HGCAL powering scheme (now obsolete)



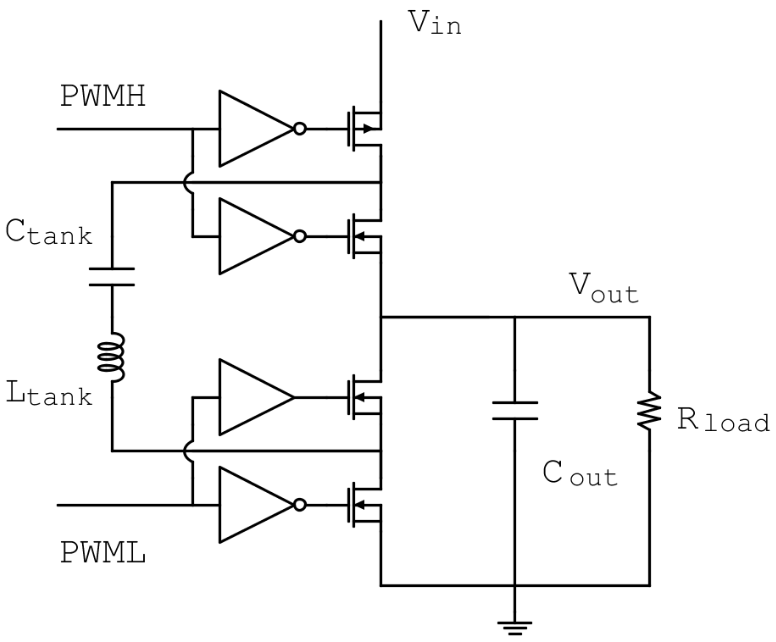


bPOL2V5



rPOL2V5

rPOL2V5: Characteristics



Input voltage	2.5 V
Output voltage	1 V ÷ 1.5 V
Output current	≤ 3 A
Rating IO transistors	2.5 V

rPOL2V5 is a Resonant Switched-Capacitor (ReSC) converter, whose profile can be as low as 2 mm.

While in a buck converter the only component used to store the energy needed for the voltage conversion is an inductor, rPOL2V5 employs both an inductor and a capacitor (tank circuit).

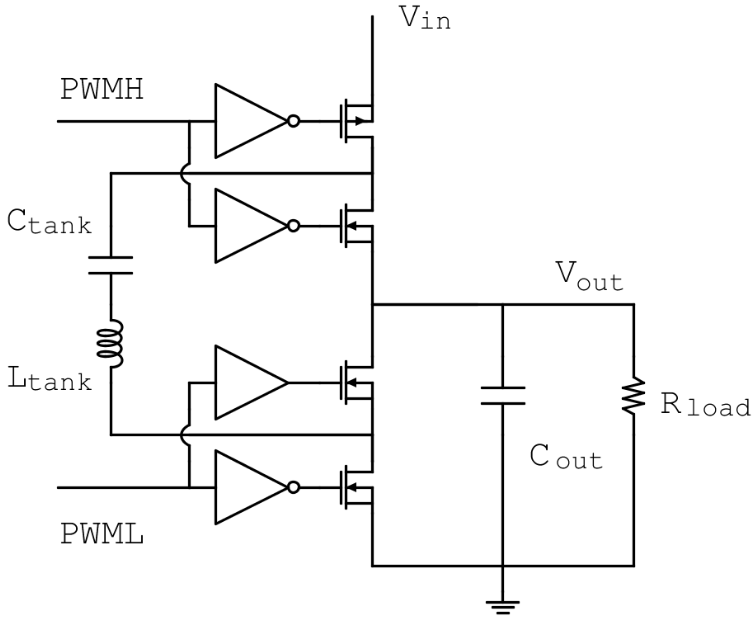
Therefore the inductance required by rPOL2V5 is smaller than the one required by bPOL2V5, and thanks to the high energy density of capacitors (compared to air core inductors) rPOL2V5 represents a valid solution where space constraints are critical, as for example in the CMS High Granularity Calorimeter

rPOL2V5: Output regulation

Output voltage regulation is achieved through the modulation of the phase shift between $PWML$ and $PWMH$, which in turn tunes the switching frequency.

rPOL2V5 exploits Zero Voltage Switching (ZVS), which reduces the frequency-dependent losses, allowing efficient operation at high frequencies.

The controller uses different operation modes to achieve regulation for a wide range of conversion ratios and to boost the light-load efficiency.

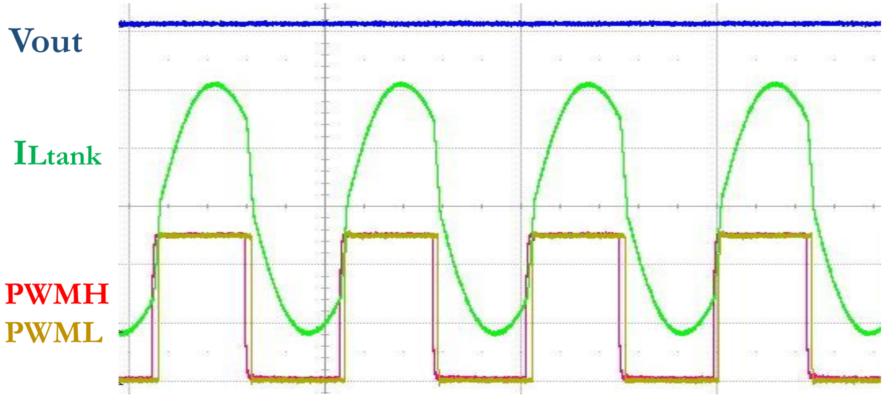


Three modes of operation:

- α mode (lower $\frac{V_{out}}{V_{in}}$, high loads)
- β mode (higher $\frac{V_{out}}{V_{in}}$, high loads)
- Burst mode (light loads)

α-β and burst modes

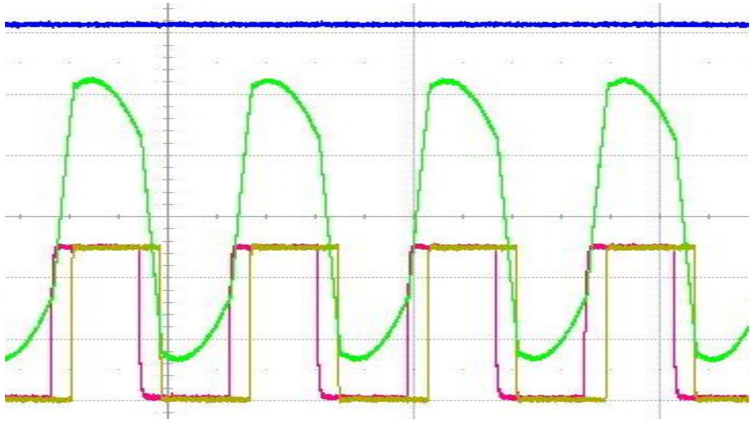
α Mode



$PWML$ coincides with the sign of I_{Ltank} while $PWMH$ has a phase lead α from the zero crossing of I_{Ltank}.

α is tuned to achieve regulation.

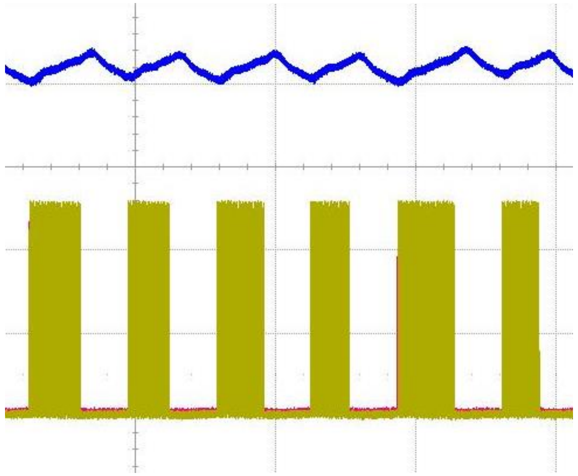
β Mode



$PWMH$ coincides with the sign of I_{Ltank} while $PWML$ has a phase lag β from the zero crossing of I_{Ltank}.

β is tuned to achieve regulation.

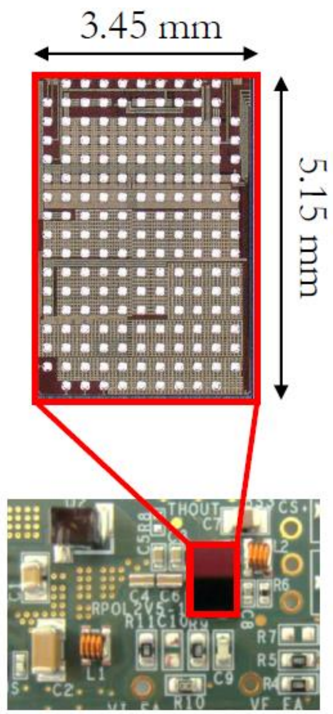
Burst Mode



Burst mode is an intermittent α mode used to guarantee regulation and boost the efficiency for light loads: the converter periodically stops switching to limit the frequency-dependent losses.

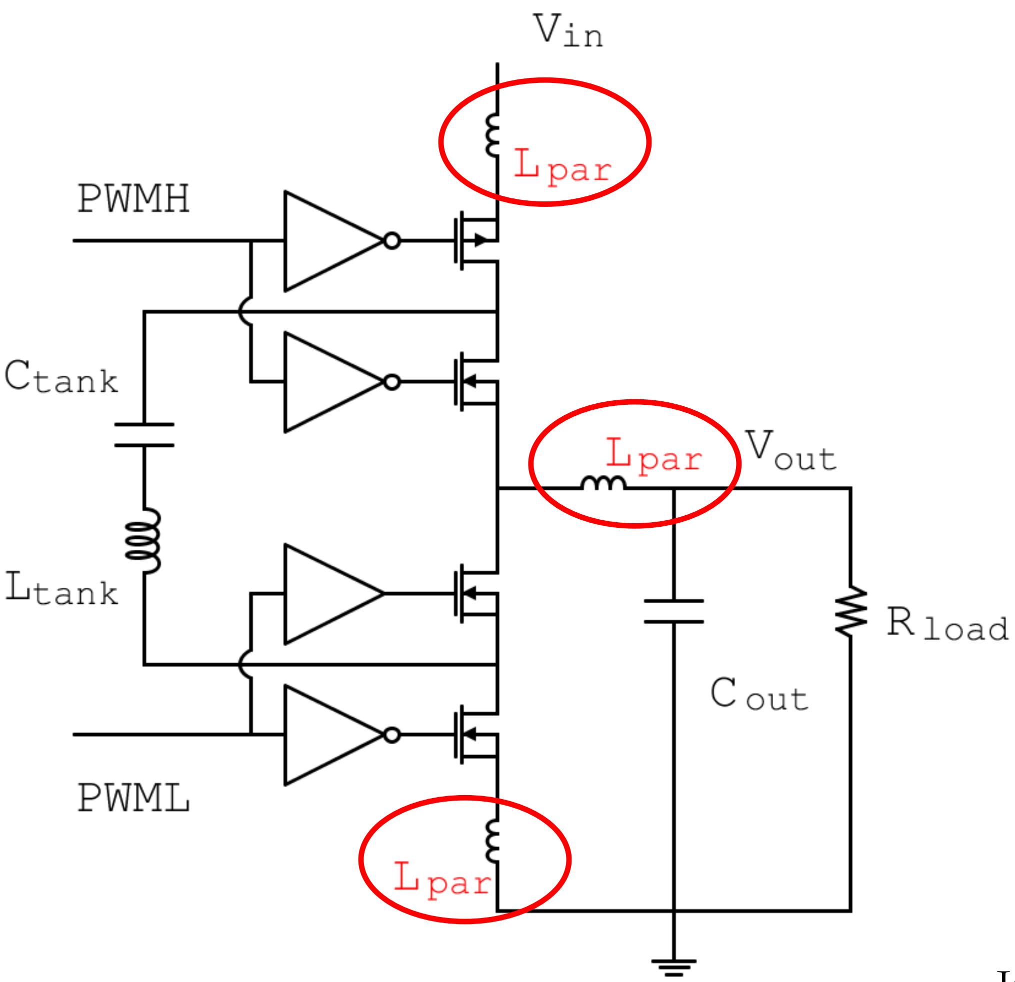
From the first prototype to production readiness

First prototype issues	Solutions implemented at ASIC design level
Unreliable transition between α/β and light load modes	Simplified operation: reduced number of modes, ensuring a smooth transition between α/β-burst modes
Malfunctioning in β-mode, the converter does not work for $Vout>Vin/2$	The controller has been adapted to guarantee a reliable operation in β-mode
Startup at very light loads leads to overshoots on V_{out}	Burst-mode can now be used also during the soft-start avoiding overshoots on V_{out} for low loads.



The second version of rPOL2V5 was submitted in August 2020

ASIC reliability is dependent on the PCB design



During each switching operation, the power transistors experience voltage spikes that exceed their voltage rating (2.5V).

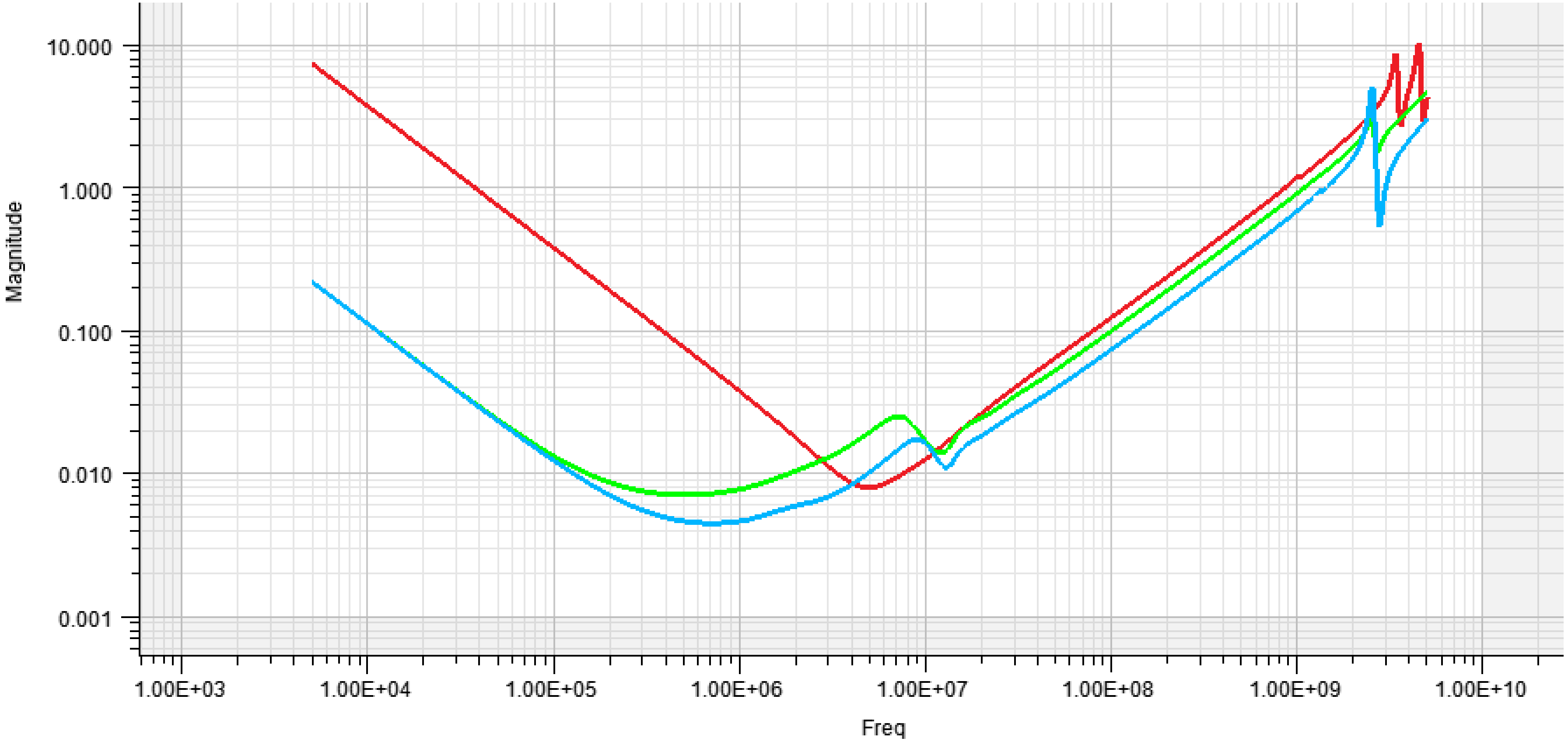
These spikes are generated by the large dI/dt experienced by the parasitic inductance of the ASIC bonding and of the PCB traces.

In particular the parasitic inductances responsible for these spikes are the ones associated to the $Vin - GND$ and $Vout - GND$ loops on the PCB, which includes the parasitic series inductances of the input and output capacitors.

$$V_{Lpar} = L_{par} \frac{dI_{Lpar}}{dt}$$

Therefore, in order to guarantee a reliable operation of the converter,
It is important to limit these voltage spikes by minimizing the parasitic impedances.

PCB parasitic extraction: $Vin - GND$



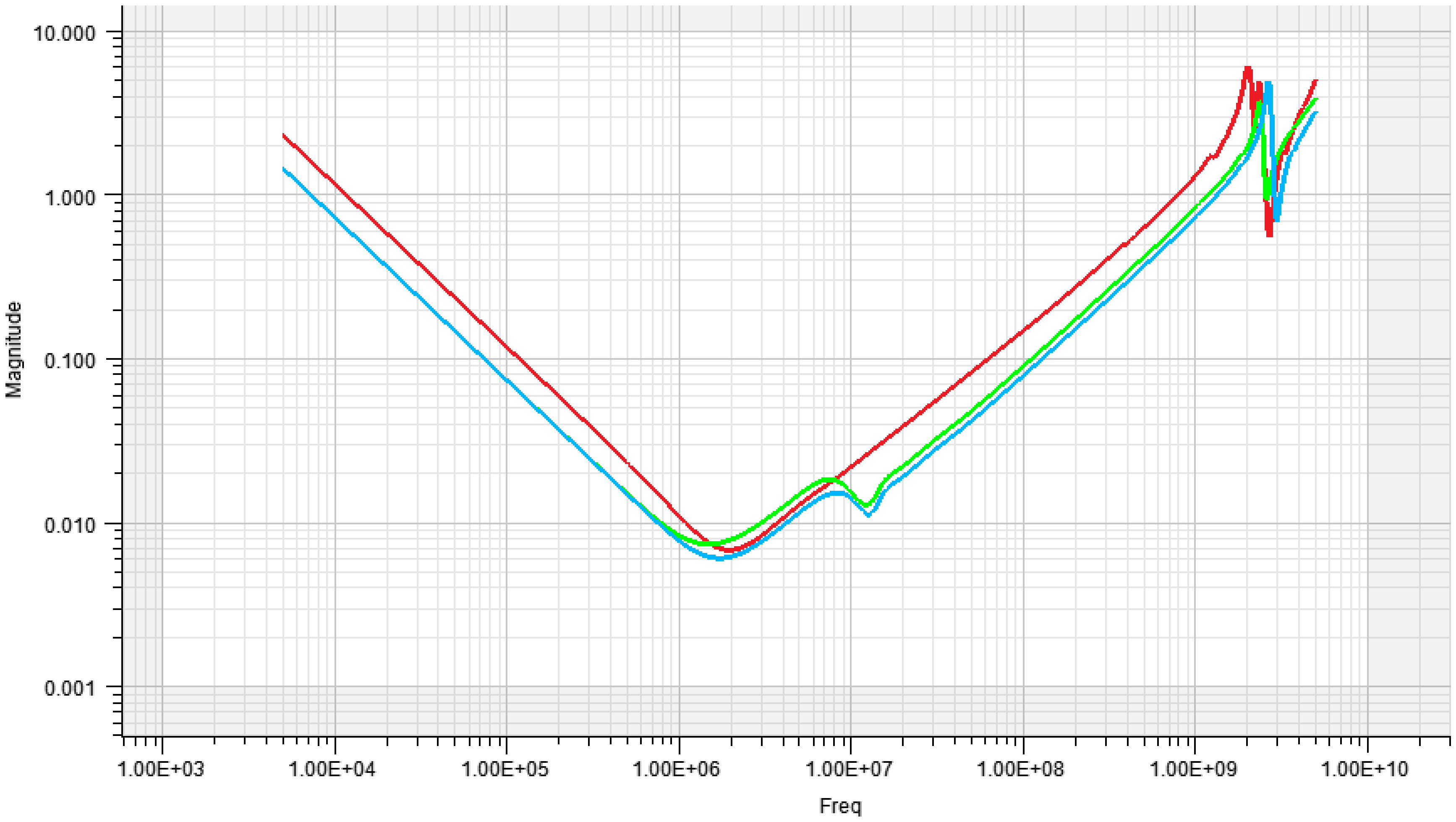
First prototype   New - Mech via   New - Laser via

$Lin = 188pH$

$Lin = 145pH$

$Lin = 109pH$

PCB parasitic extraction: $Vout - GND$



$Lout = 207pH$

$Lout = 133pH$

$Lout = 116pH$

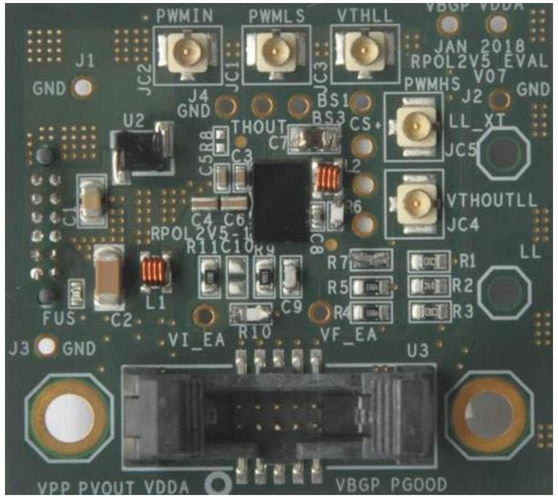
First prototype **New - Mech via** **New - Laser via**

Test PCB modifications

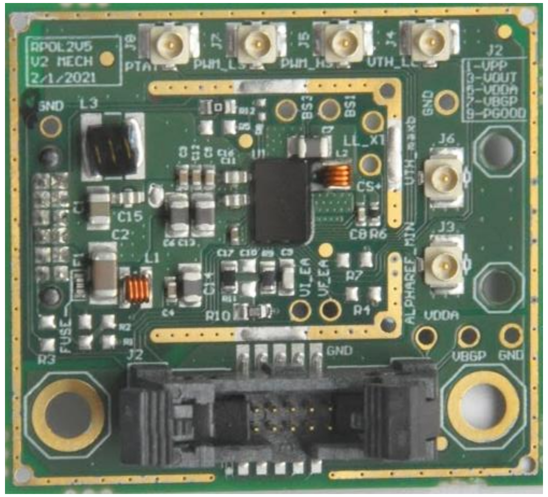
- Improved input filter to guarantee stability and reduce input parasitic inductance
- Improved output filter to reduce voltage ripple and output parasitic inductance.
- Improved tank series resistance to enhance the converter efficiency

Two different variants of the PCB have been designed:

- Laser via: features copper filled microvias in pad to achieve an optimal reduction of the parasitics,
- Mechanical via: features only simple mechanically drilled through vias to ease the manufacturing constraints of the PCB and to decrease its production price (resulted to be >30% cheaper and ensuring higher production yield)



rPOL2V5_V1



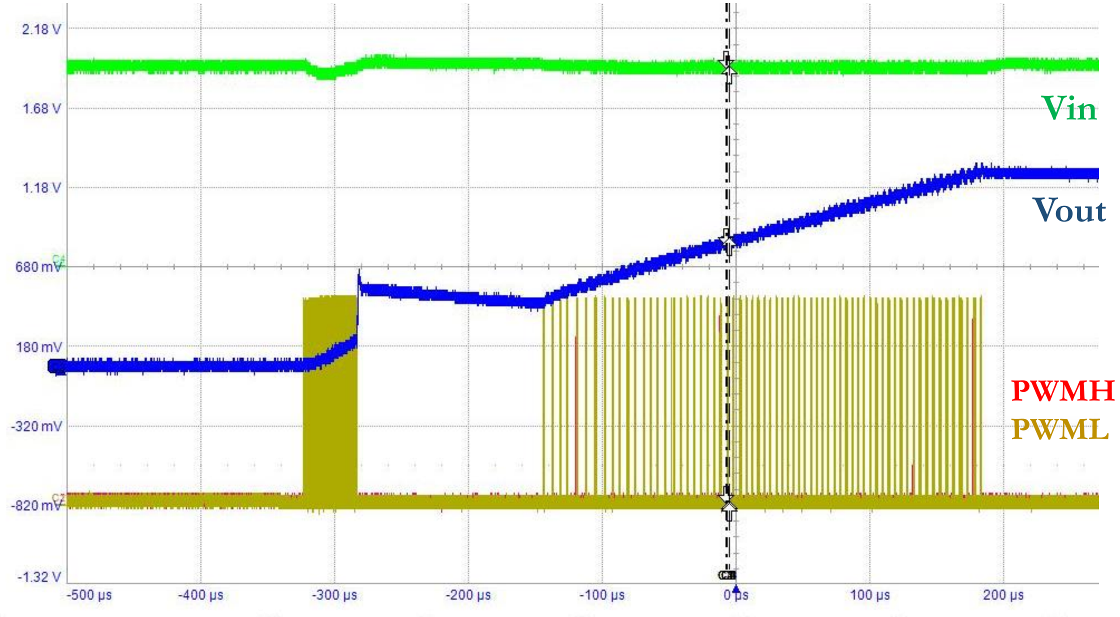
rPOL2V5_V2

Twelve modules of rPOL2V5
(6 Laser vias and 6 Mechanical vias)
have been assembled in June 2021.

rPOL2V5_V2: characterization results

Solutions implemented at ASIC design level
Simplified operation: reduced number of modes, ensuring a smooth transition between α/β-burst modes
The controller has been adapted to guarantee a reliable operation in β-mode
Burst-mode can now be used also during the soft-start avoiding overshoots on V_{out} for low loads.

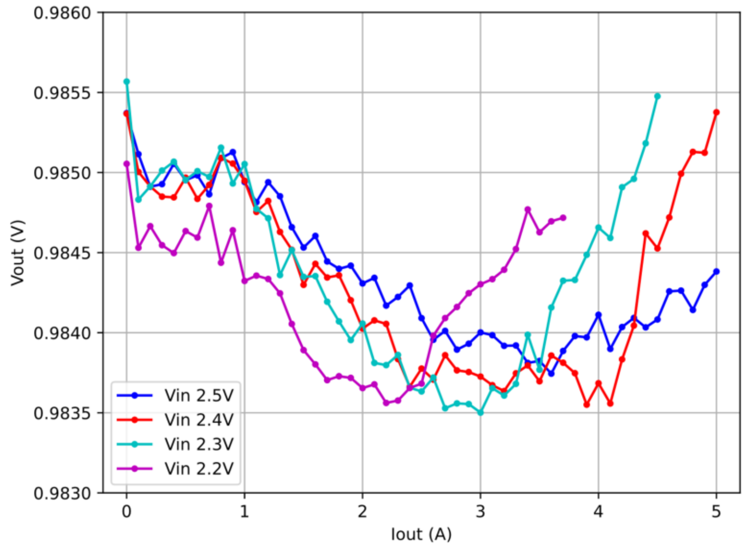
Burst mode during soft start with 0A load current



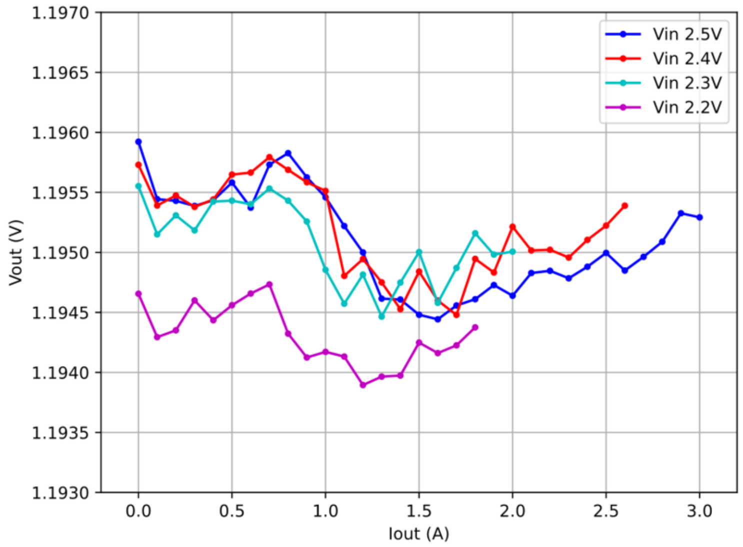
Observed issue: Malfunctioning of the converter detected in few modules (related to mismatch) when operating in β mode: the issue has been understood and reproduced in simulations.
It can be corrected at the ASIC design level by introducing a minor modification.

Experimental results: line and load regulation

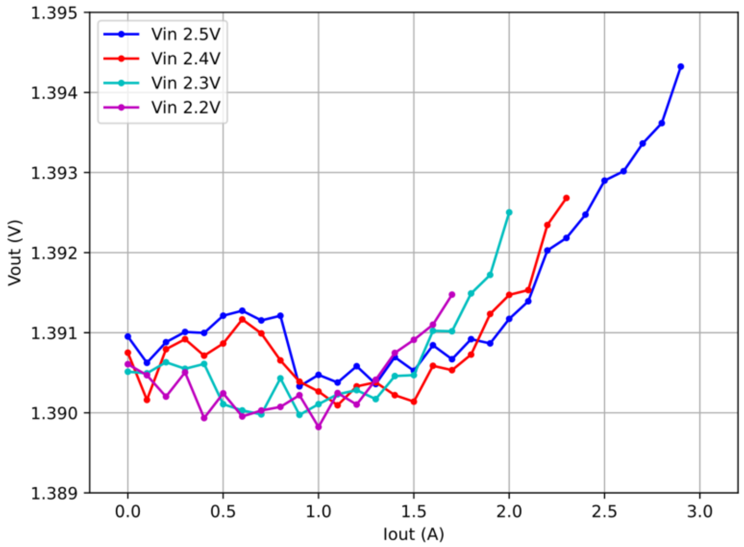
$V_{out} \sim 1V$



$V_{out} \sim 1.2V$



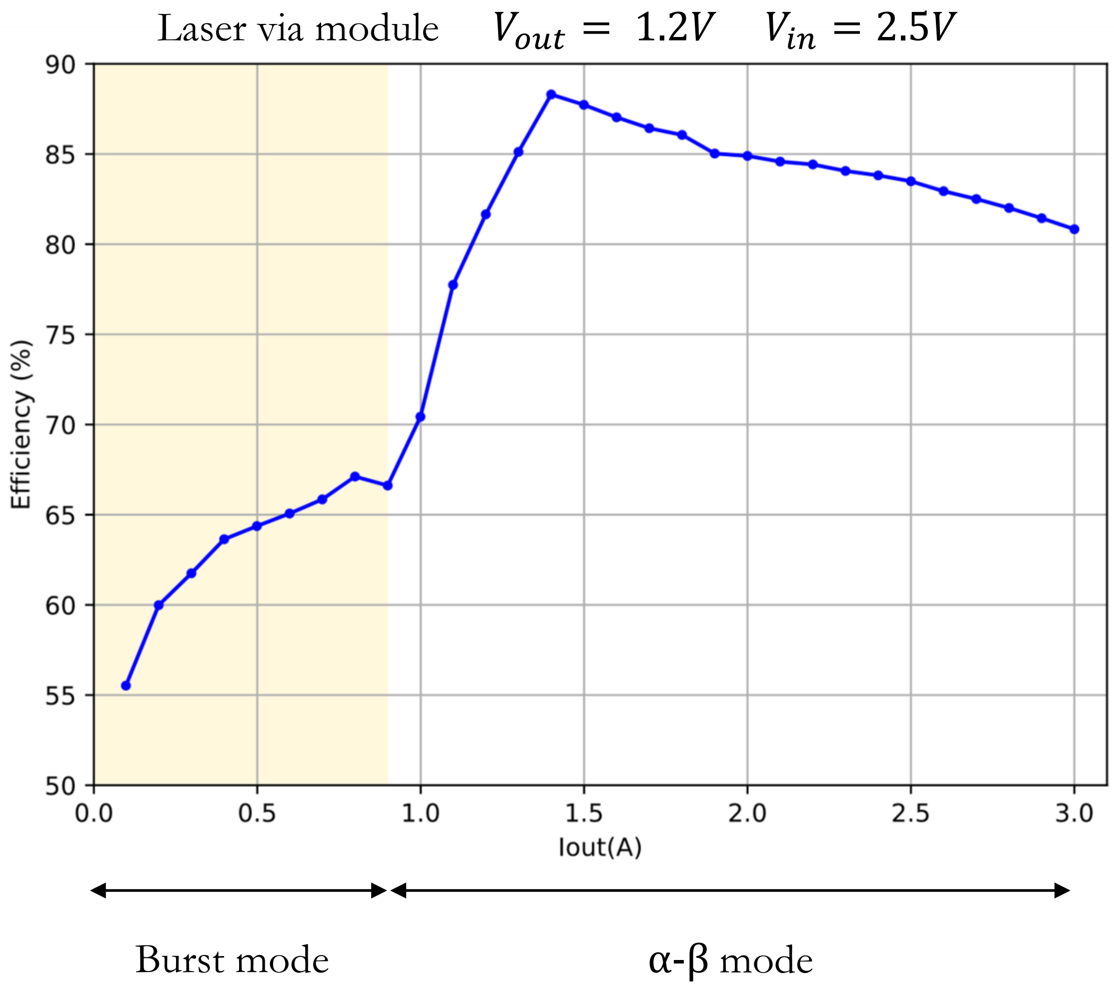
$V_{out} \sim 1.4V$

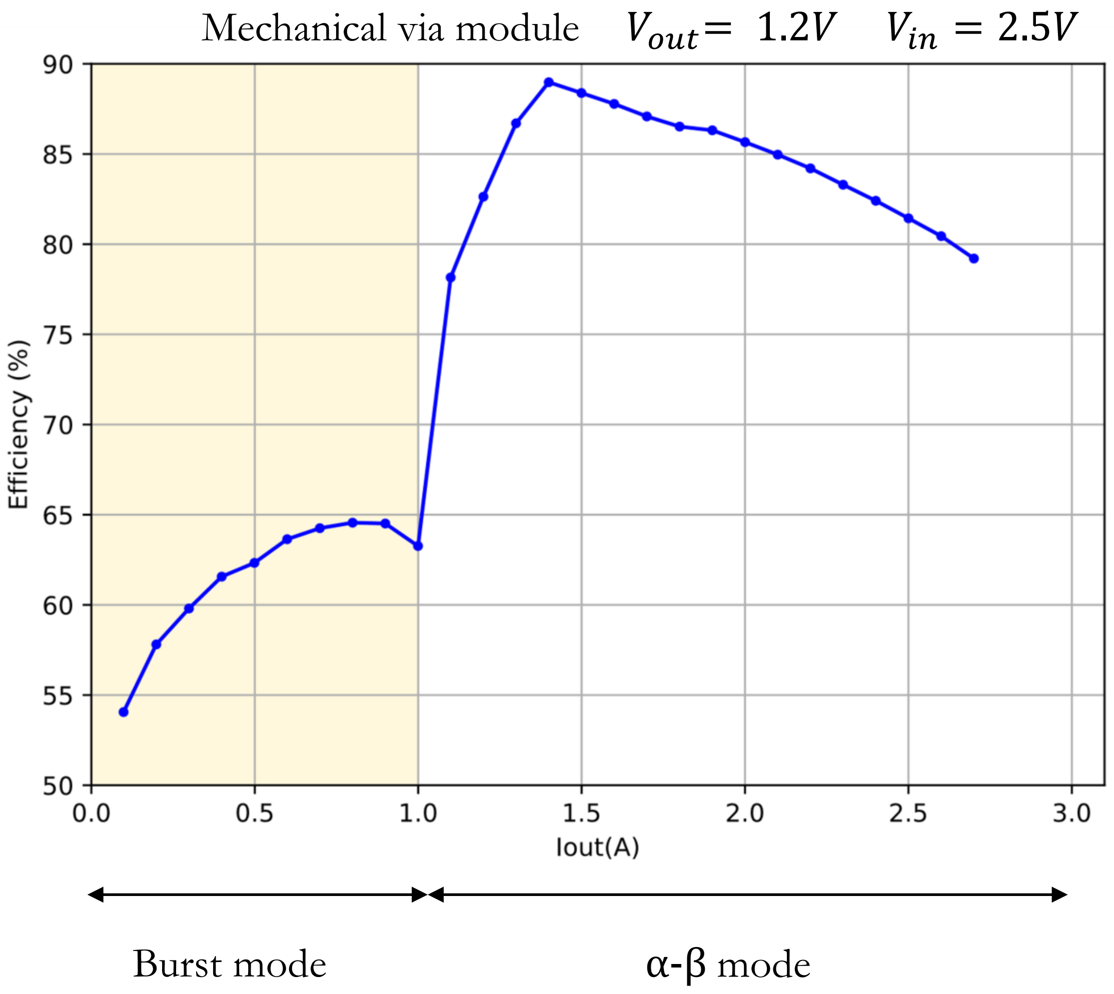


The ASIC features a protection that limits the amplitude of the current flowing in the tank circuit to ensure the reliability of the chip. The triggering of this protection reduces V_{out}, and the converter stops regulating.

Since the protection intervenes at different load current points depending on the values of V_{out} and V_{in}, the maximum current provided by the converter depends on V_{out} and V_{in}.

Experimental results: efficiency curves for $V_{out} = 1.2V$ $V_{in} = 2.5V$



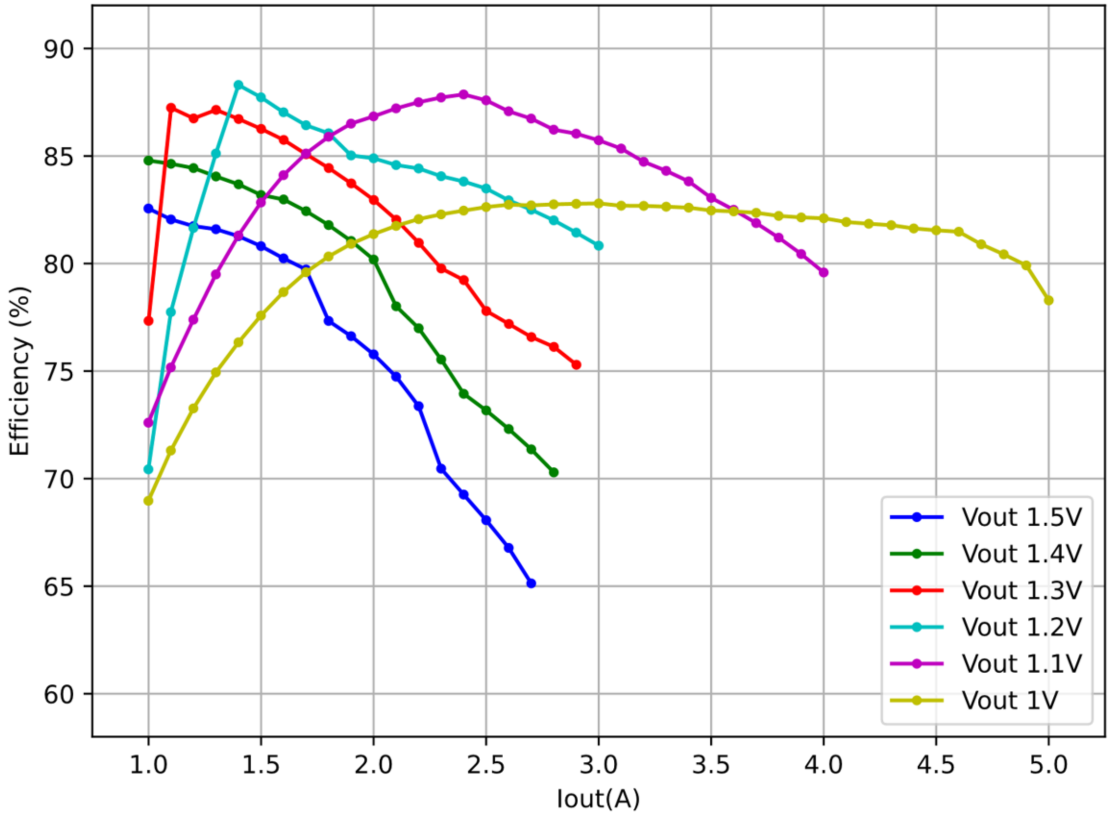


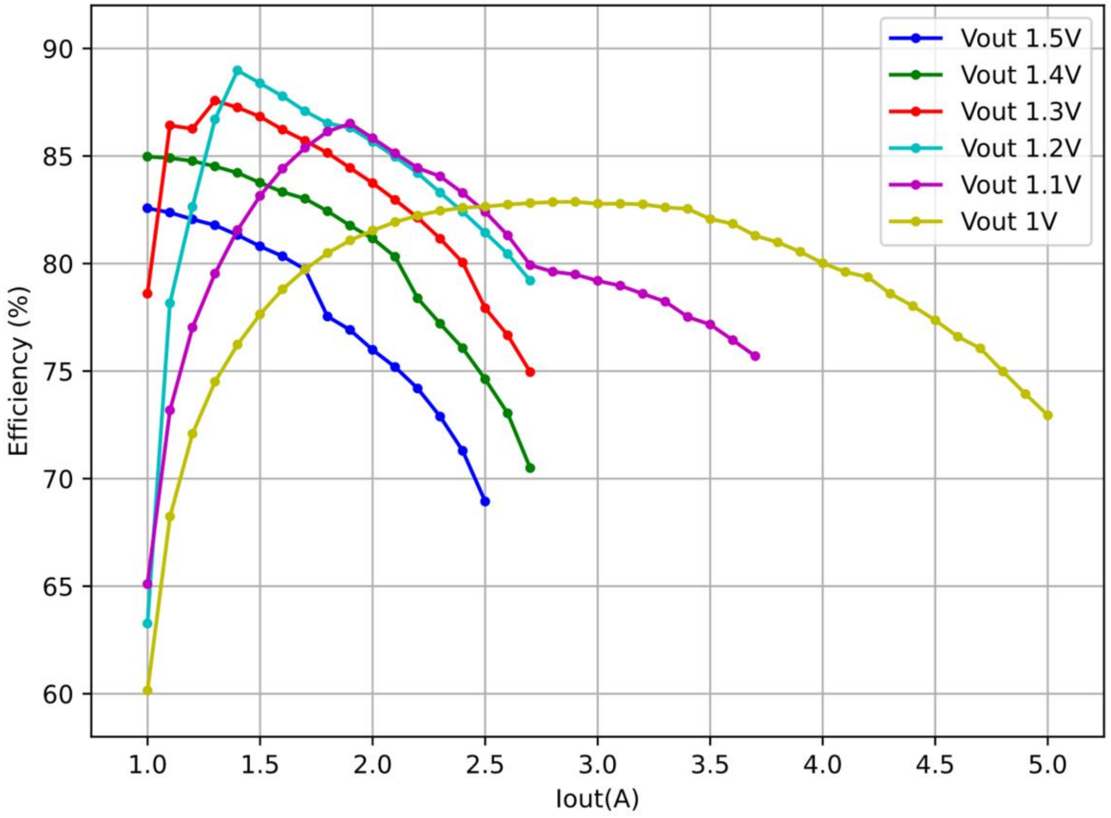
The efficiency measured with both PCB variants is similar, still the Laser via variant provides slightly higher efficiencies.

Experimental results: efficiency curves for various V_{out}

Laser via module $V_{in} = 2.5V$

Mechanical via module $V_{in} = 2.5V$

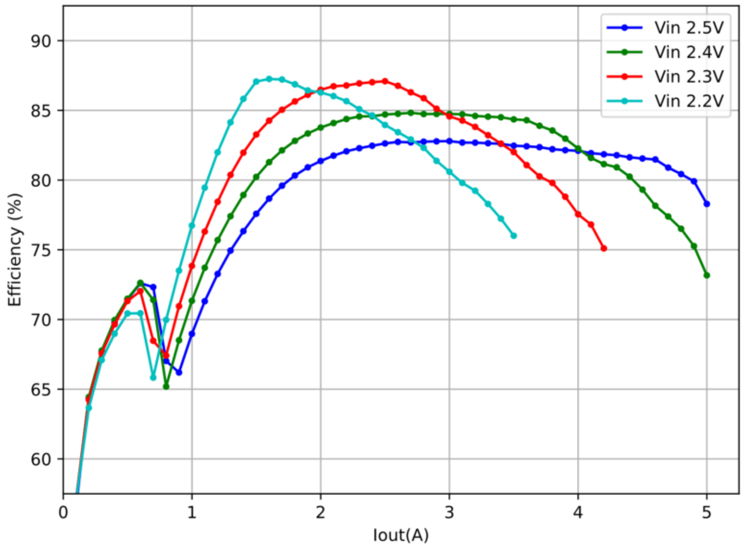




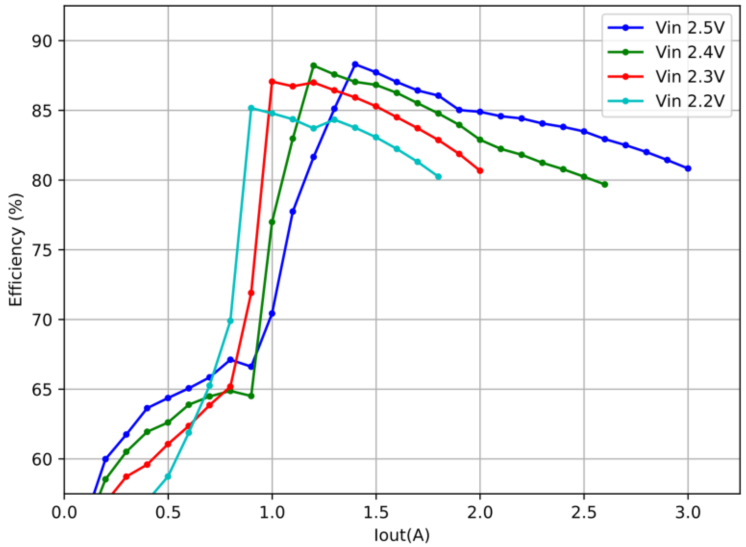
rPOL2V5 ensures high efficiency when the conversion ratio V_{out}/V_{in} is equal to ½ or slightly lower, therefore considering $V_{in} = 2.5V$ the converter achieves higher efficiency when $V_{out} \leq 1.2V$, in these conditions also the maximum load current increases: for $V_{out} = 1V$ rPOL2V5 can reach $I_{out} = 5A$

Experimental results: efficiency curves for various V_{in}

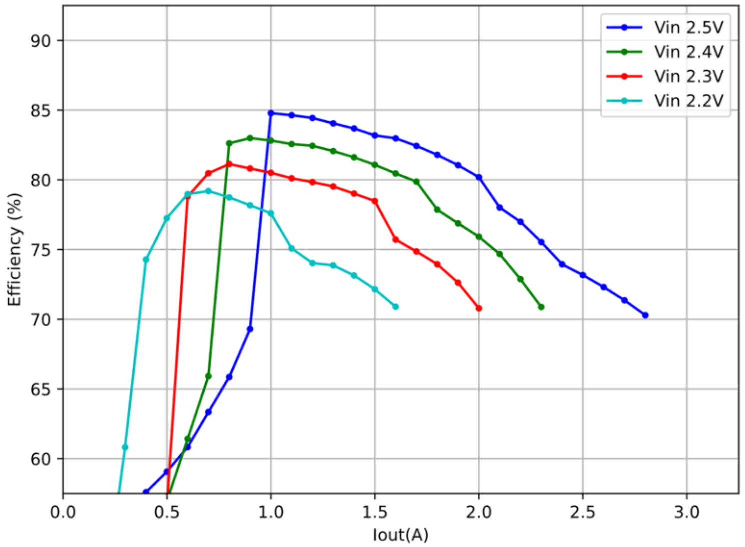
$V_{out} \sim 1V$



$V_{out} \sim 1.2V$



$V_{out} \sim 1.4V$



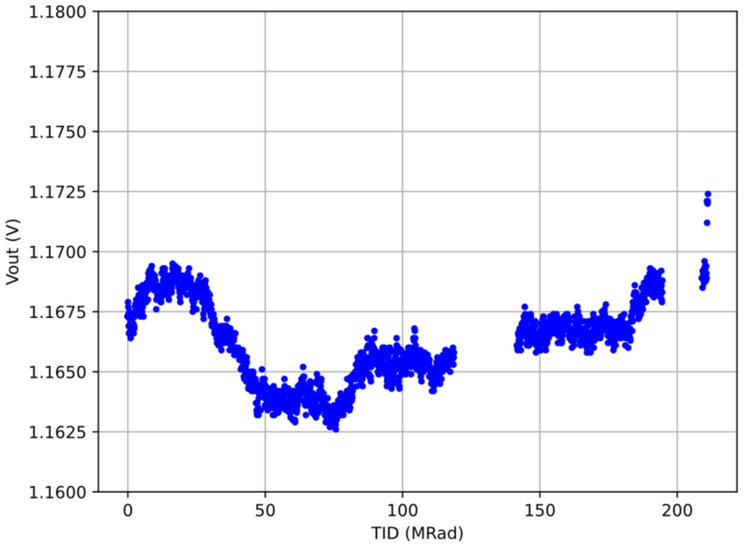
rPOL2V5 works better when the conversion ratio V_{out}/V_{in} is equal to ½ or slightly lower.

For $V_{out} < 1.2V$, the converter shows good regulation and high efficiency also with $V_{in} < 2.5V$.

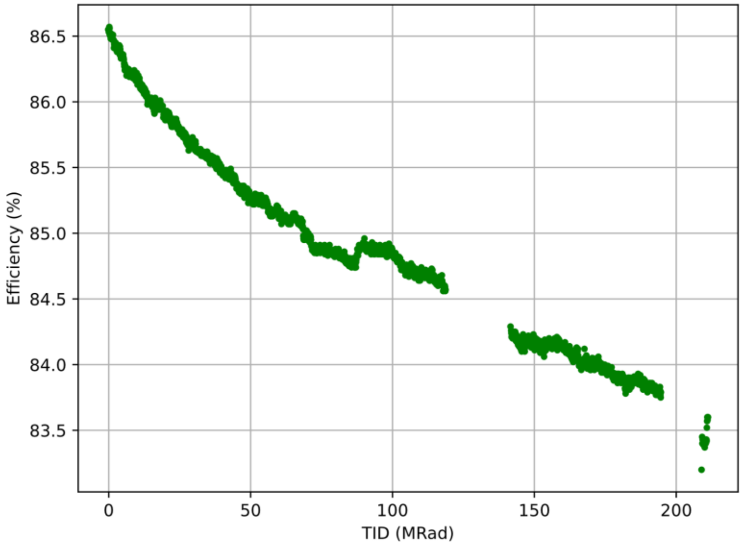
Considering $V_{out} > 1.2V$, the efficiency and the max I_{out} drop when lowering V_{in} below $2.5V$.

Experimental results: TID irradiation campaign $\text{T} = -30^{\circ}C$ Mechanical via module

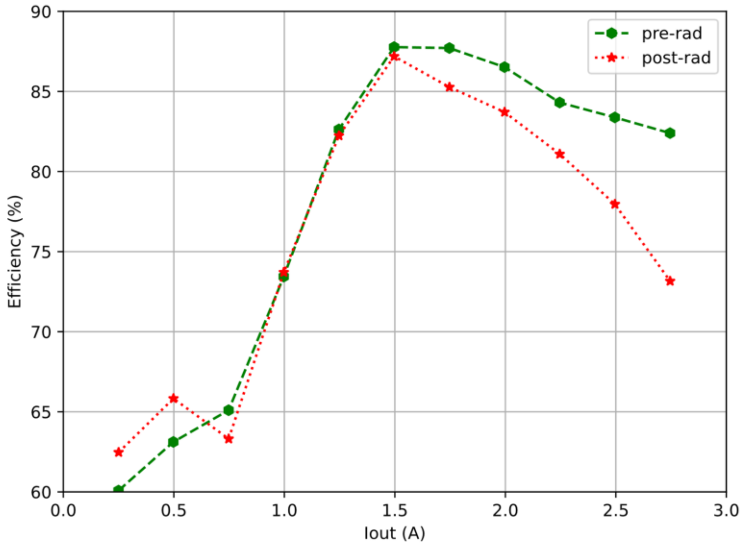
TID X-ray irradiation campaign has been performed at the ObeliX facility,
Mechanical via module $V_{in} = 2.5V$ $V_{out} \sim 1.2V$ $\text{T} = -30^{\circ}C$



Output voltage monitoring



Efficiency monitoring at $I_{out} = 2A$

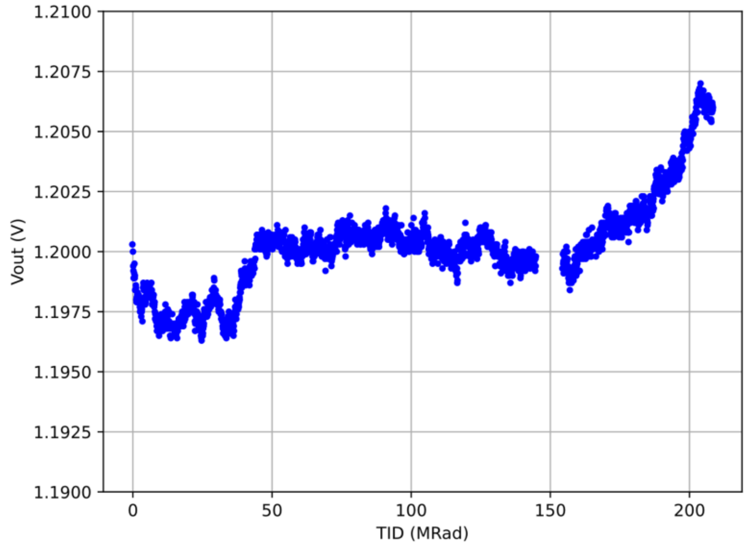


Efficiency degradation induced by TID

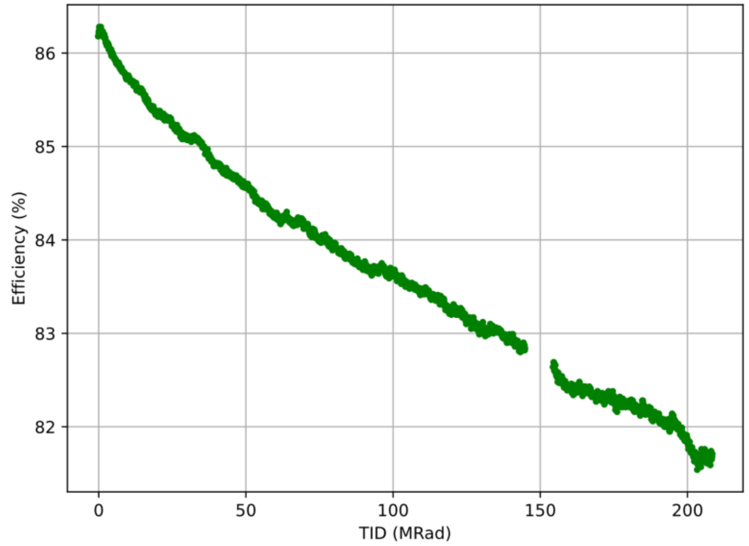
rPOL2V5 was fully functional after 200Mrad
Total Ionizing Dose affects rPOL2V5 efficiency in β mode:
for $V_{out} = 1.2V$ rPOL2V5 enters β mode approximately when $I_{out} > 1.5A$

Experimental results: TID irradiation campaign T $= 25^{\circ}C$ Laser via module

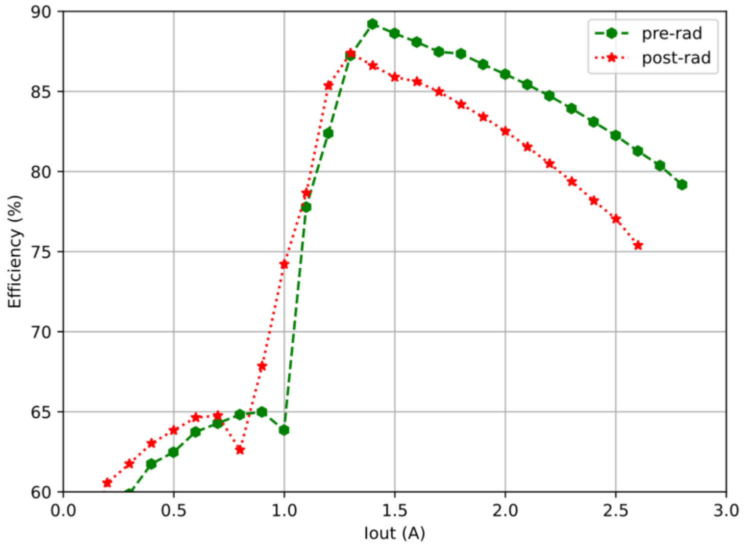
TID X-ray irradiation campaign has been performed with the ObeliX facility,
Laser via module $V_{in} = 2.5V$ $V_{out} \sim 1.2V$ T $= 25^{\circ}C$



Output voltage monitoring



Efficiency monitoring at $I_{out} = 2A$



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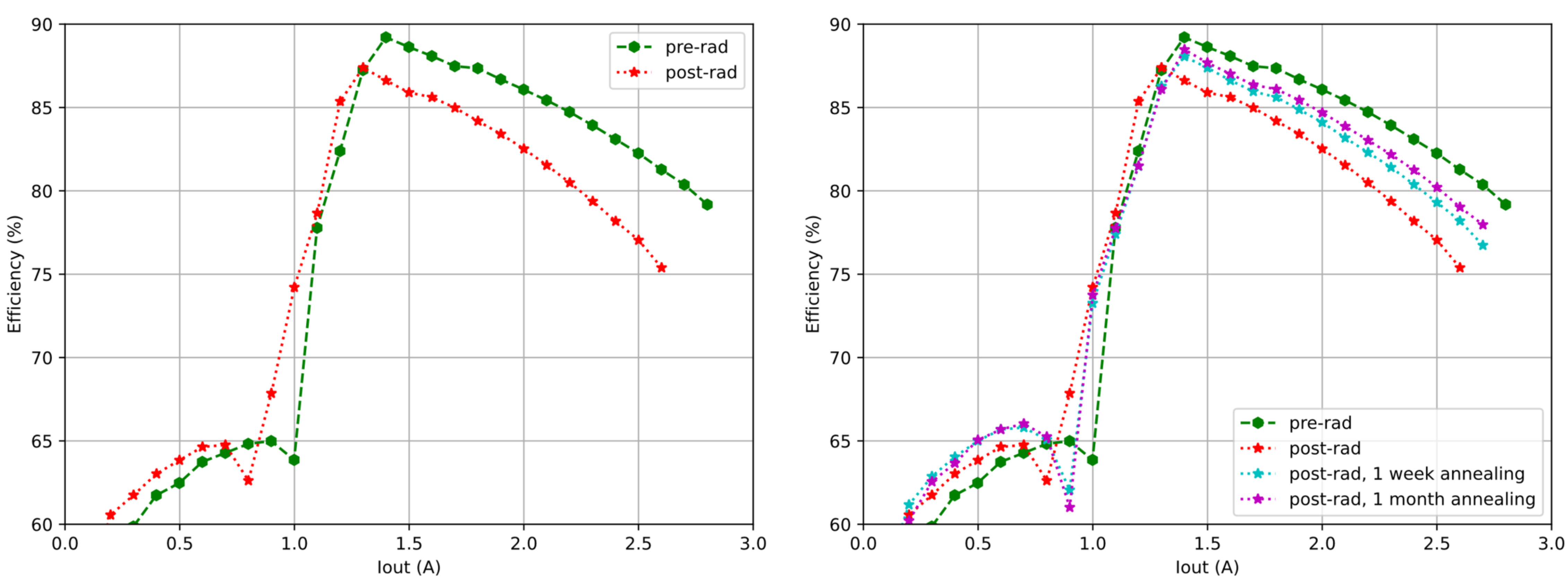
rPOL2V5 was fully functional after 200Mrad
Total Ionizing Dose affects rPOL2V5 efficiency in β mode:
for $V_{out} = 1.2V$ rPOL2V5 enters β mode approximately when $I_{out} > 1.5A$

Experimental results: TID irradiation campaign, post-rad recovery at room temperature

TID X-ray irradiation campaign has been performed with the ObeliX facility,

Laser via module $V_{in} = 2.5V$ $V_{out} \sim 1.2V$ $T = 25^{\circ}C$



The rPOL2V5 efficiency curves monitored after 1 week and 1 month of annealing show a significant recovery of the TID induced degradation.

Summary

The second version of rPOL2V5 is close to production readiness,
all the issues highlighted by the characterization of the first prototype are solved:
the converter ensures a reliable operation in all working conditions.

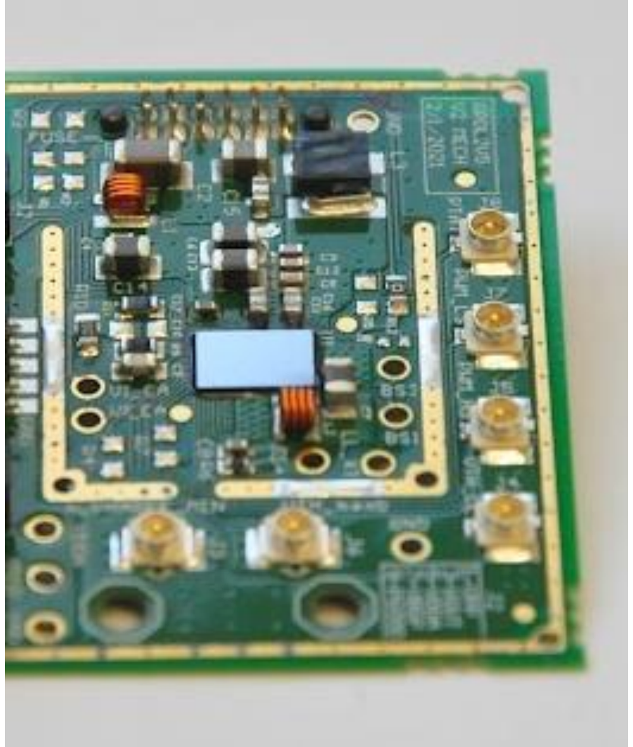
Moreover, the PCB hosting the ASIC has been studied and improved to guarantee the chip reliability,
two different variants of the module have been successfully tested:

- The laser microvia PCB allows the converter to reach the best results in terms of efficiency,
- The mechanical via PCB represent a cheaper, still fully functional solution.

The converter is still affected by a malfunctioning
that can be easily solved by introducing a minor modification in the ASIC.

rPOL2V5 is still to be tested with neutrons and for SEE,
while it has been successfully tested with TID up to 200MRad.

In the meantime, the powering baseline scheme of HGCAL has evolved,
and at the moment it is based only on bPOL12V and the development of rPOL2V5 will not continue.



Nevertheless, rPOL2V5 is now mature and can be considered as an interesting alternative to bPOL2V5
for future applications, specifically for its reduced volume and high efficiency even at high loads when $V_{out} < 1.2V$.