Cryo DC-DC boost converter development

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FD2-VD Photon Detector Cold Electronics Workshop at BNL

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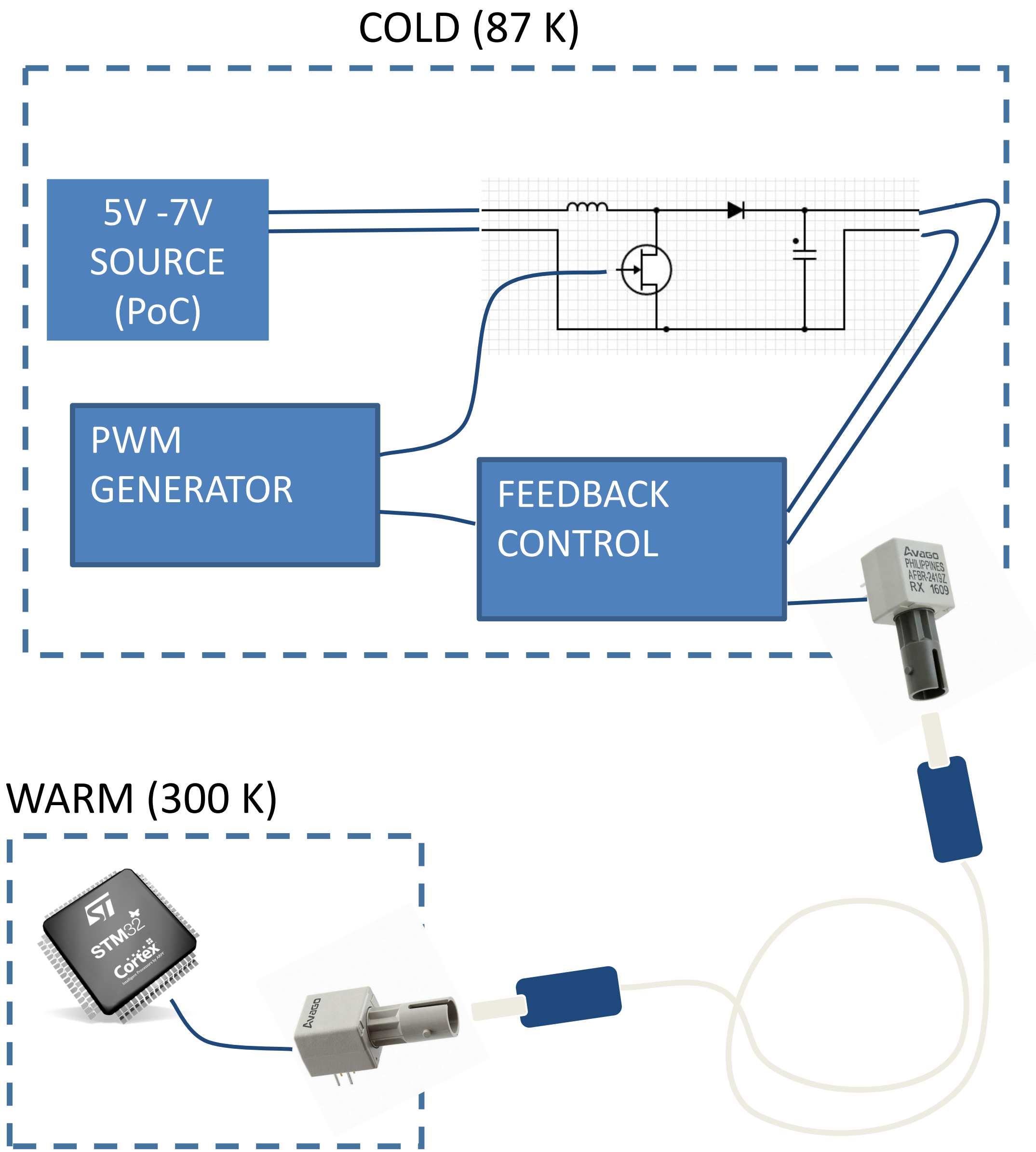
- System overview
- GaAs Power optical Converter (PoC)
- DC-DC boost design
  - Component characterization
  - Performance
- Control
  - Design
  - Component qualification
- Conclusions

System overview

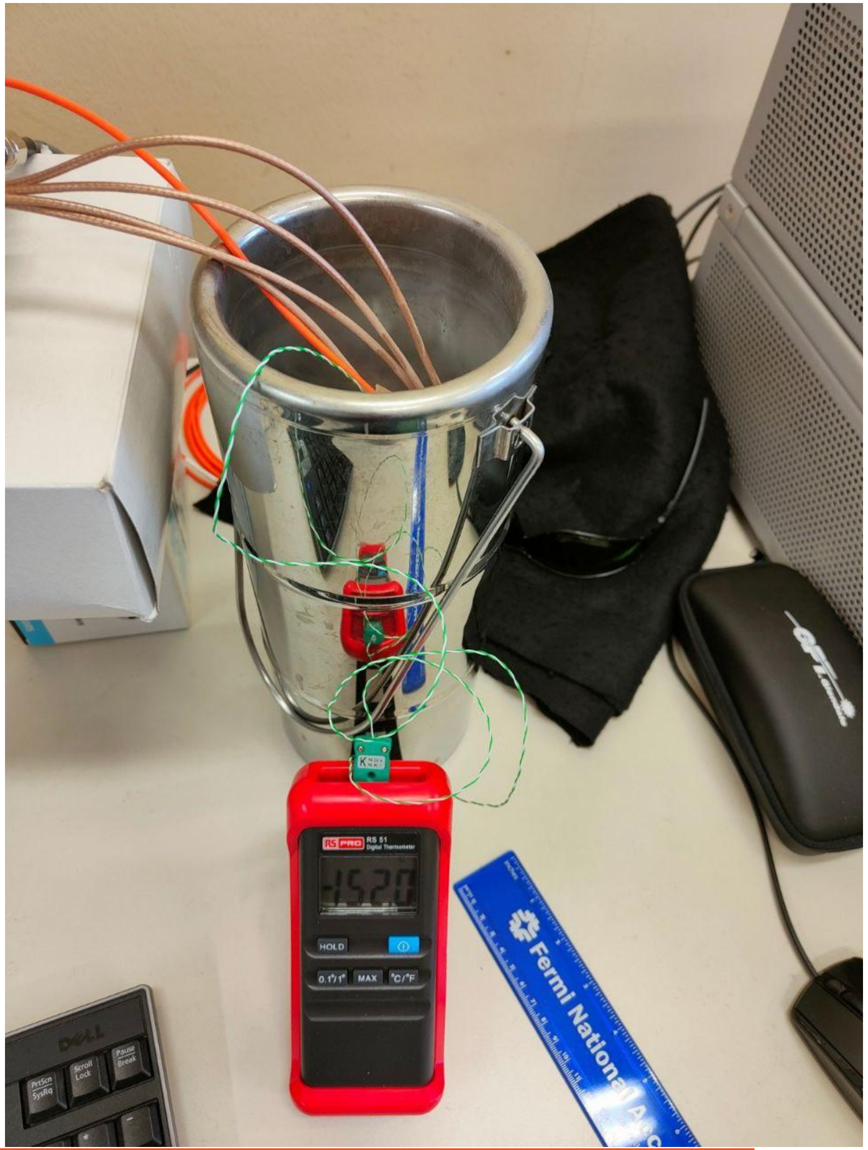
- The system evolved with the needs / possibilities in the DUNE collaboration
- Produce the HV for SiPM bias at cold by the means of a DC-DC boost converter
- A **power supply provided by a PoC** (Power optical Converter) with a 5V - 7V range will give voltage/current for the DC-DC converter
- ***A typical boost configuration with a MOS*** transistor, to increase the output voltage up to 50V
- A **PWM generator drives the MOS** switch with two possible controls:
  - Inner feedback setting the output voltage at a nominal point (e.g. 48 V)
  - Optical input to change the setting voltage within few volts



GaAs PoC

In order to power the DC-DC system a PoC is used.

- We tested a **Broadcom AFBR-406L** based on GaAs technology
- Powered through a **808 nm Lumics laser** (8W max)
- We used a **multimode 200 µm** core fiber connected to the pig-tailed laser with an SMA/FC-PC connector, and to the PoC on the other side
- A **B1505A Semiconductor Analyzer** is used to fix the output voltage and **measure the current**
- The PoC is slowly cooled down checking its temperature with an RTD sensor.



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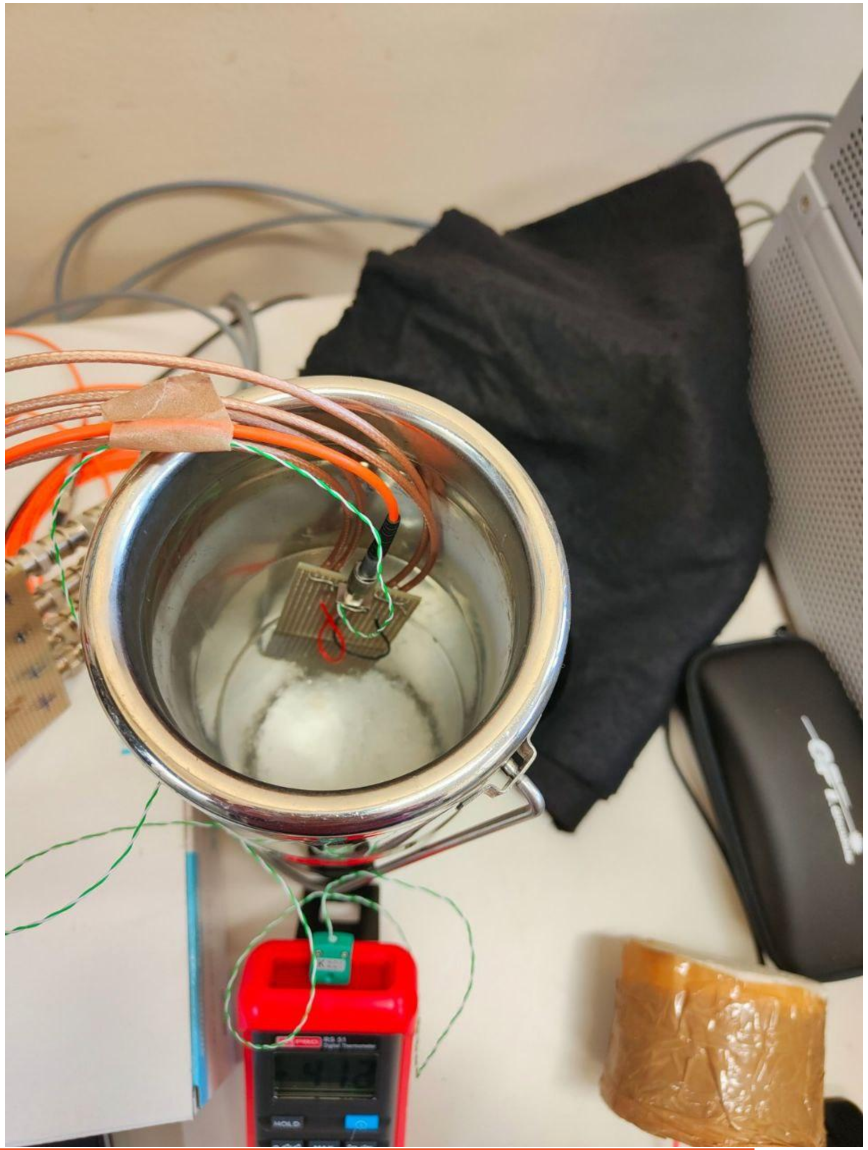

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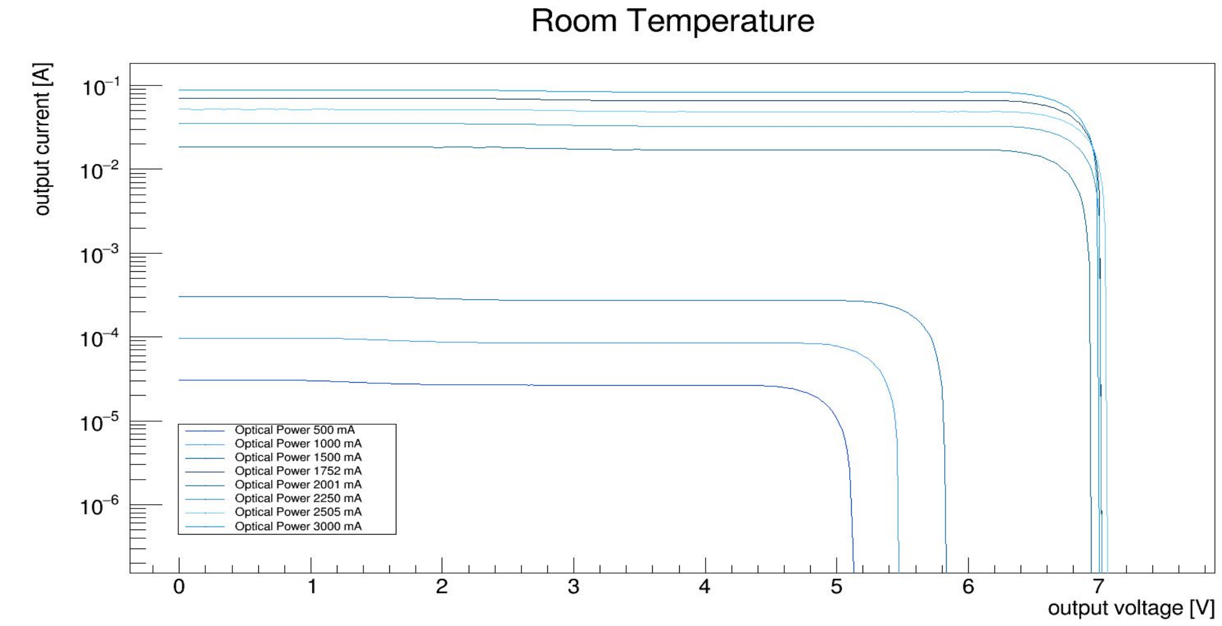
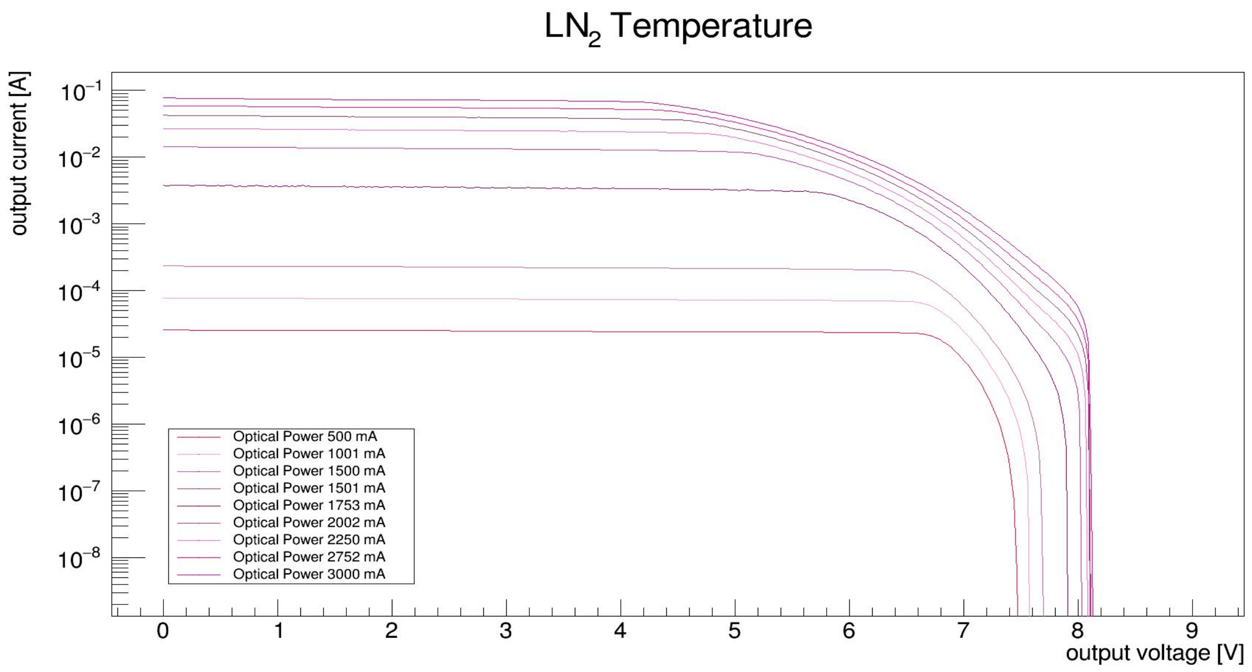
GaAs PoC

In order to power the DC-DC system a PoC is used.

- The **curves are labelled** according to the **laser input current** ($P_{opt} \propto I$)
- As reference 3A →1.5 W_{opt}
- Measurements are take both at RoomT (temperature not fixed but monitored during measurement) and at LN_2 temperature
- A slightly increase in the "open" voltage is observed going **from 7 V to 8V** for 3000 mA between Room and LN_2 temperature





DC-DC boost converter

We selected and characterized many components to check their operability at cryogenic temperature, their characteristics and to select the most suitable.

- MOSFET: *NTF3055L108T1G*, ***ZXMN10A07FTA***, *VN2460N8, 2N7002H6327XTSA2, 2N7002CK*
  - *Lowest on resistance*
- Switching Diode: ***BAV16W***, *BAS16LD*
  - *Very similar device, slightly better max current*
- Inductor: *B82442T1125K000 (680 uH)*, ***B8244T1106K050 (10 mH)***
  - *Good to mitigate ripple*
- Capacitor: ***C1812C104J1GACTU (C0G 100 nF)***
  - *C0G for cryogenic use*

DC characterization of MOSFET and diode

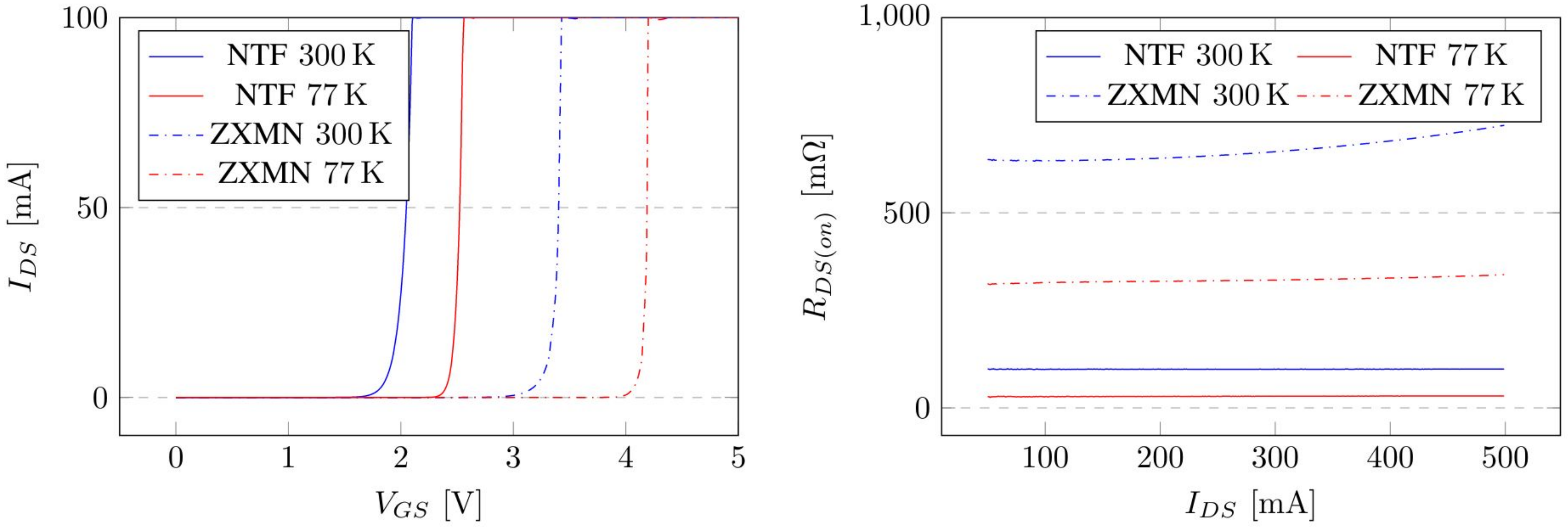
All **MOSFETs** have been characterized at Room Temperature and a LN2 temperature, with a B1505A Semiconductor Analyzer:

- I_D vs V_{GS} (at various V_{DS}) to measure the **threshold**
- V_{DS} vs I_D (at various V_{GS}) to measure the **on resistance $R_{DS(on)}$**

We will just show results for a couple of them, the most suitable for the application.

For the **diode** only the forward I-V curve was measured at both Room Temperature and LN2 temperature to measure the **junction voltage V_D**.

MOSFET results



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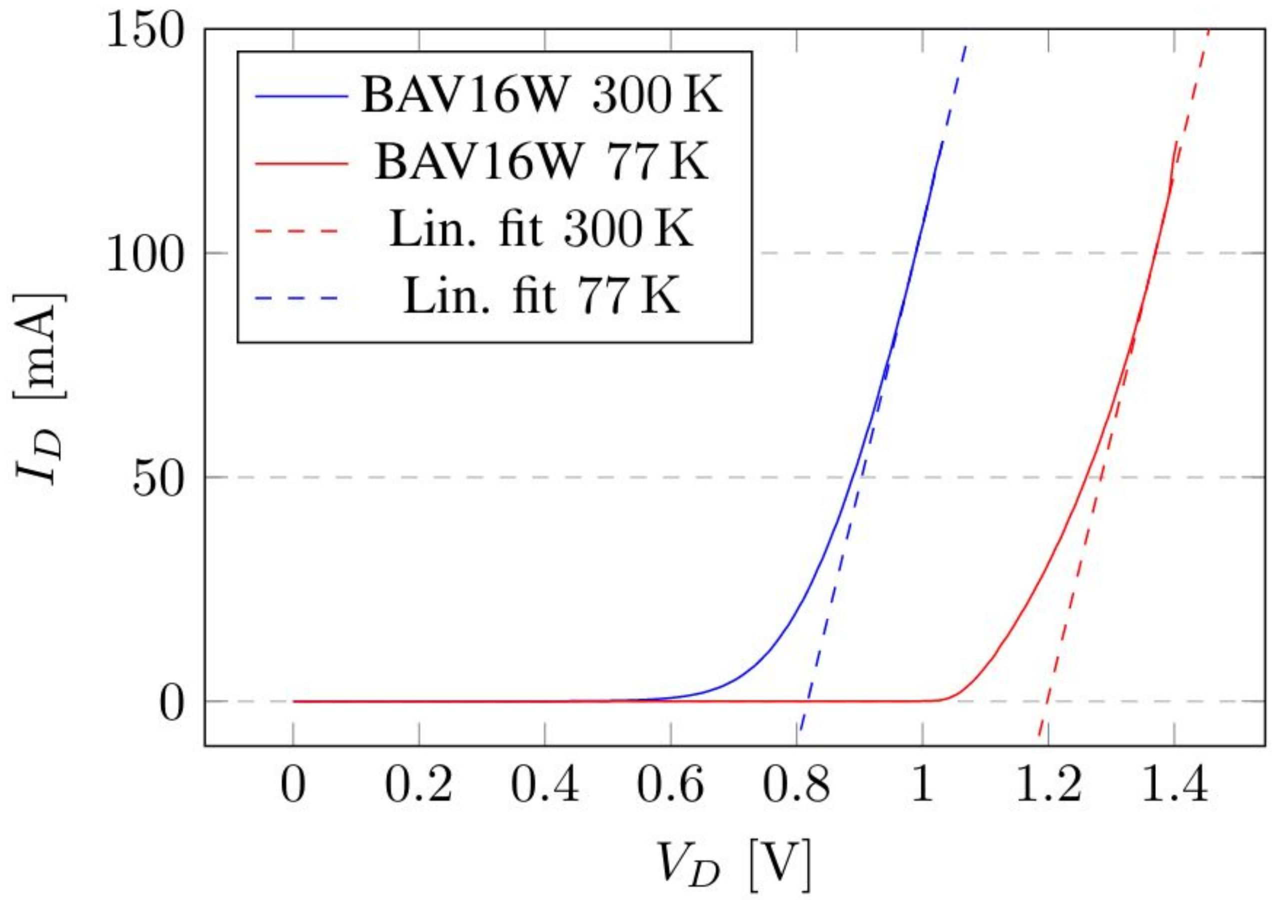
- Drain current vs Gate-to-Source voltage: at 77 K the **threshold increases** of about **0.6 V**
- **On resistance reduces** considerably at 77 K, for NTF resulting in 30 mΩ.

Diode results

- Diode current vs applied voltage in forward bias mode. The **junction voltage increases** of about **0.4 V**
- The two selected diodes model exhibit the same behavior.

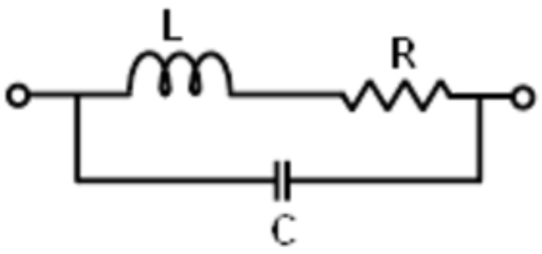


AC characterization of inductor

- The **10 mH inductor** has been tested as it is the most suitable for the application
- An **HP 4395A Impedance Analyzer** has been used in Reflection mode to analyze the impedance as a function of frequency

Model:

$$Z_L = (R + j\omega L) \parallel (j\omega C)^{-1}$$



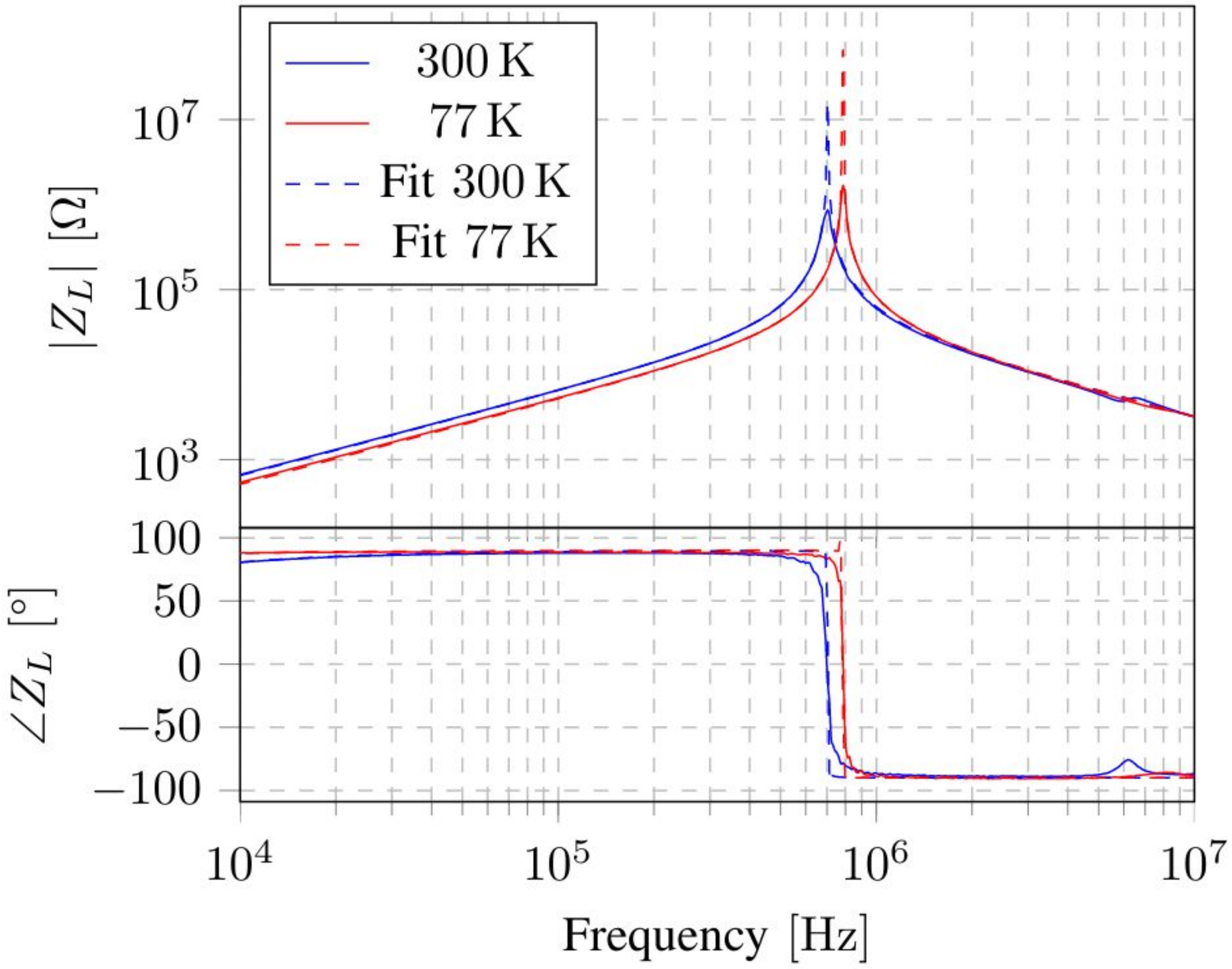
Results are fitted and parameter extracted

Inductor results

- Fitted parameters are:

T [K]	R [Ω]	L [mH]	C [pF]
300 K	106	10	5
77 K	20	8	5

- Resonance frequency is 700 kHz (**800 kHz**) at 300 K (**77 K**) , thus f_{SW} = 100 kHz is a good value
- Series resistance drops drastically at 77 K, giving much better performance to the DC-DC converter



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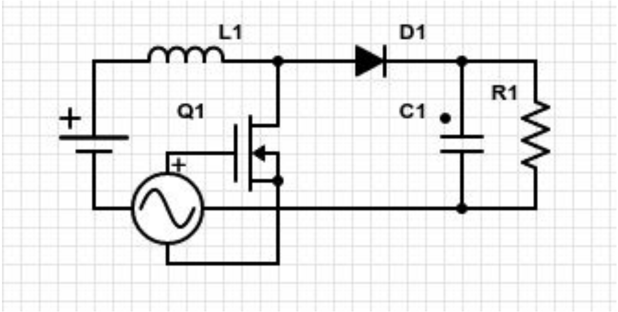
DC-DC boost prototype test bench

- A matrix board is equipped with L1, D1, R1, C1:
  - **Load** is a **10 kΩ** resistor
- The Q1 (**NTF**) **transistor** can be changed to test all models
- **DC input** provided by a **linear supply** (AimTTi PL303QMD-P)
- The input current is monitored with a multimeter (HP 971A)
- The **control signal** is produced by a **Pattern Generator** (HP HP 81104A), High-level = 5 V, Low-Level = 0 V and rise/fall time = 3 ns with **100 kHz of period.**

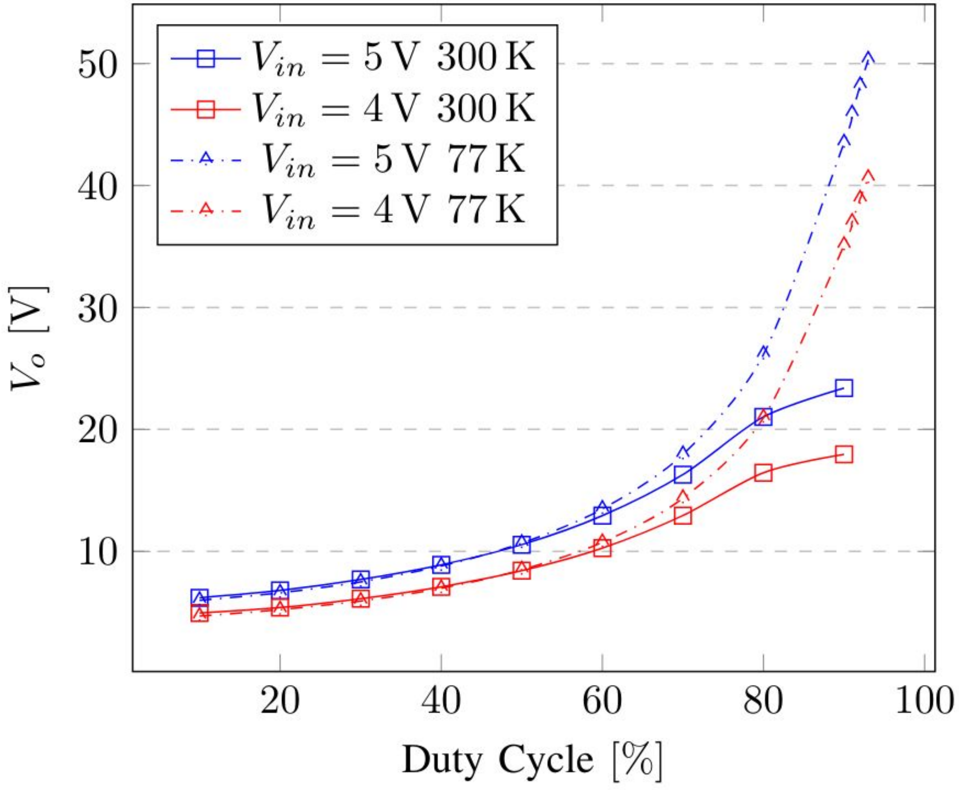


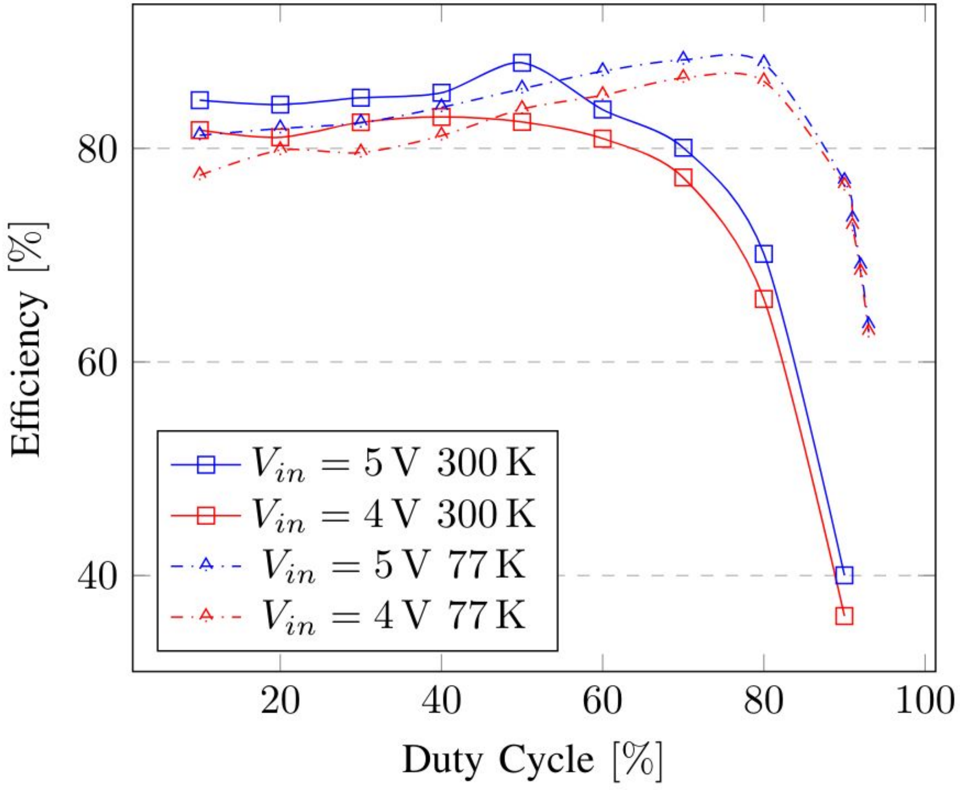
L1	10 mH
D1	BAV16W
C1	C0G 100 nF
R1	10 kΩ
Q1	NTF3055L108T1G

The system is tested at room and LN2 temperature, with different inputs (4V, 5V) and different duty cycle [0.1, 0.93].

- Output readout with a Lecroy HDO6104A oscilloscope.

DC-DC prototype results





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- **On the left the output voltage**, at RoomT it is limited by the inductor series resistor. At LN2 T, it is possible to reach 50 V at 93% of Duty Cycle.
- The **efficiency at LN2** is always **greater than 60%**

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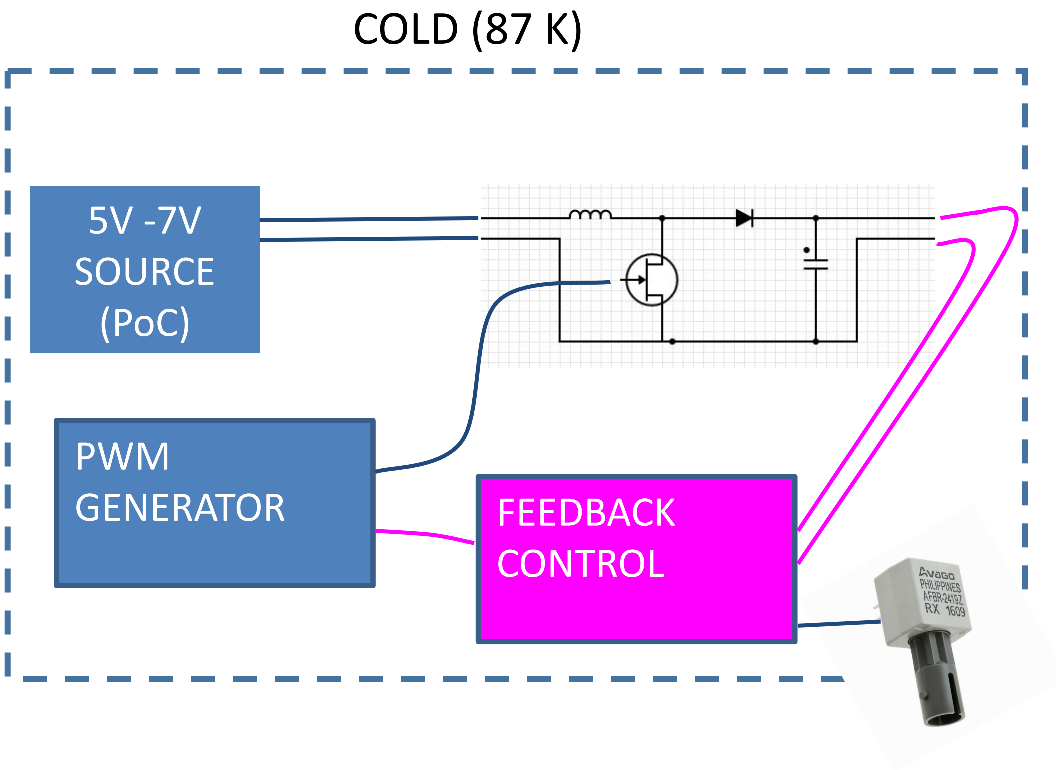
Control design

The idea is to have an **internal feedback** that keeps the output of the DC-DC boost design at the desired set point through the control of the PWM generator

The **set point** can be:

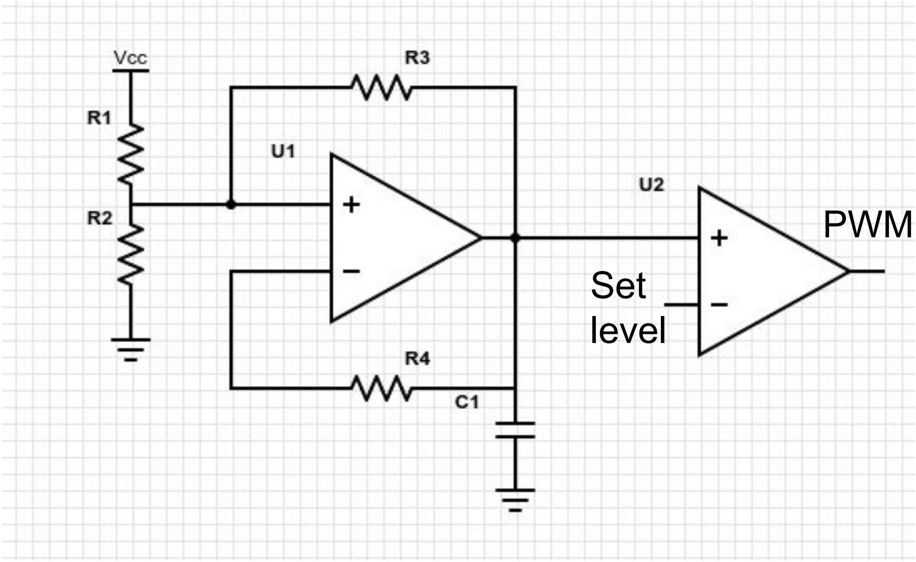
- **Nominal**: Set at the design stage and fixed throughout the entire run. It works in standalone mode
- **External**: The set point can be adjusted with an external communication.

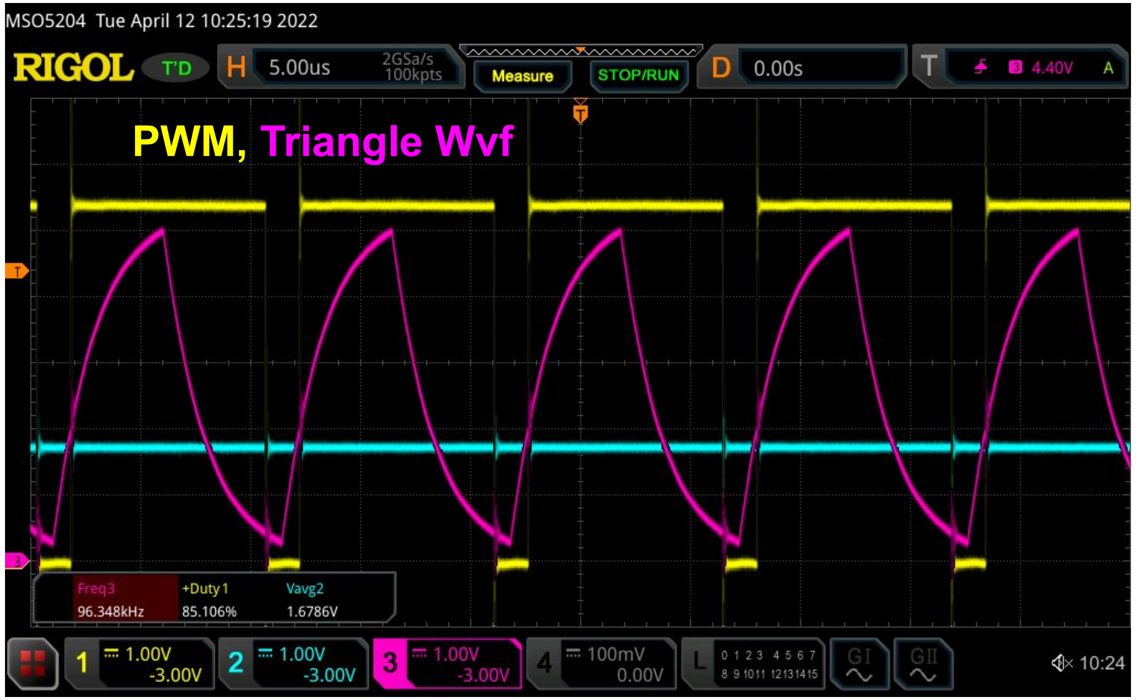
In this way the voltage can be adjustable, but in case of failure of the communication system and/or interfaces, the DC-DC converter will continue working at the nominal set-point.



PWM generator

- To drive the MOS switch we built a **PWM (Pulse Width Modulator) generator** based on **two comparators.**
- Some comparators have been tested to work in LN_2
- The first is set in a positive feedback circuit that makes it oscillate, creating a triangle-like waveform
- The **second comparator** produces the PWM taking as input the **triangle waveform and a level** that is used **to select** the output **duty cycle.**
- The working frequency is ~100 kHz





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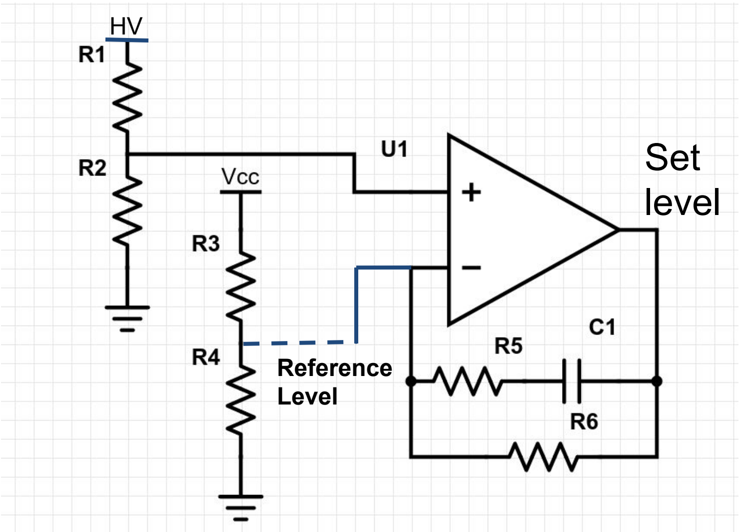
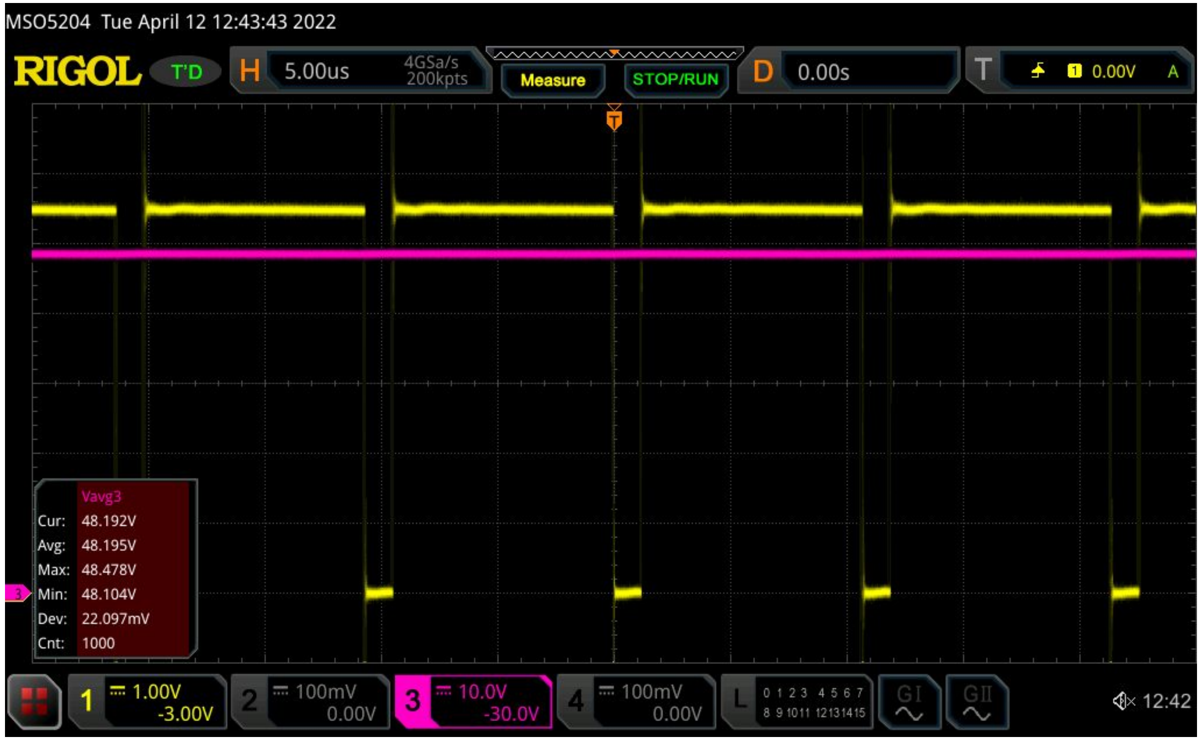
Control feedback

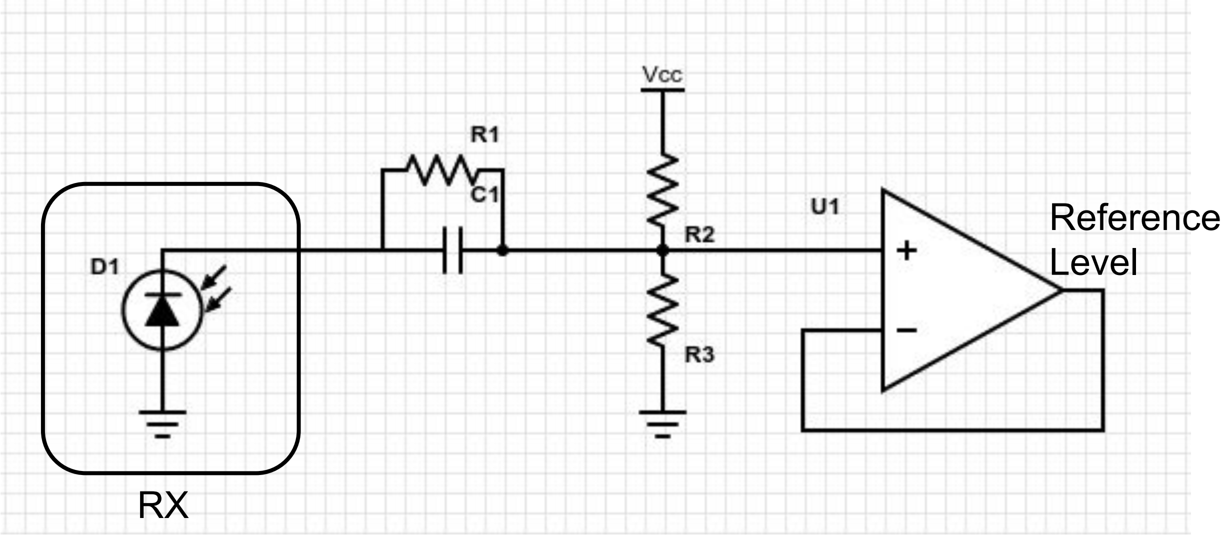
- The **output of the DC-DC** boost converter is **compared with the nominal** working point with an error amplifier
- Some operational amplifier have been tested to work in LN_2
- The error amplifier output controls the set level of the PWM generator
- **48.2 V** generated and kept constant by the internal feedback at LN_2 temperature (5.5 V input)
- 100 kΩ load → 485 μA
- Efficiency = (48.5 x 0.485)/(5.5 x 10.3) ~ 50% mainly because of control electronics.

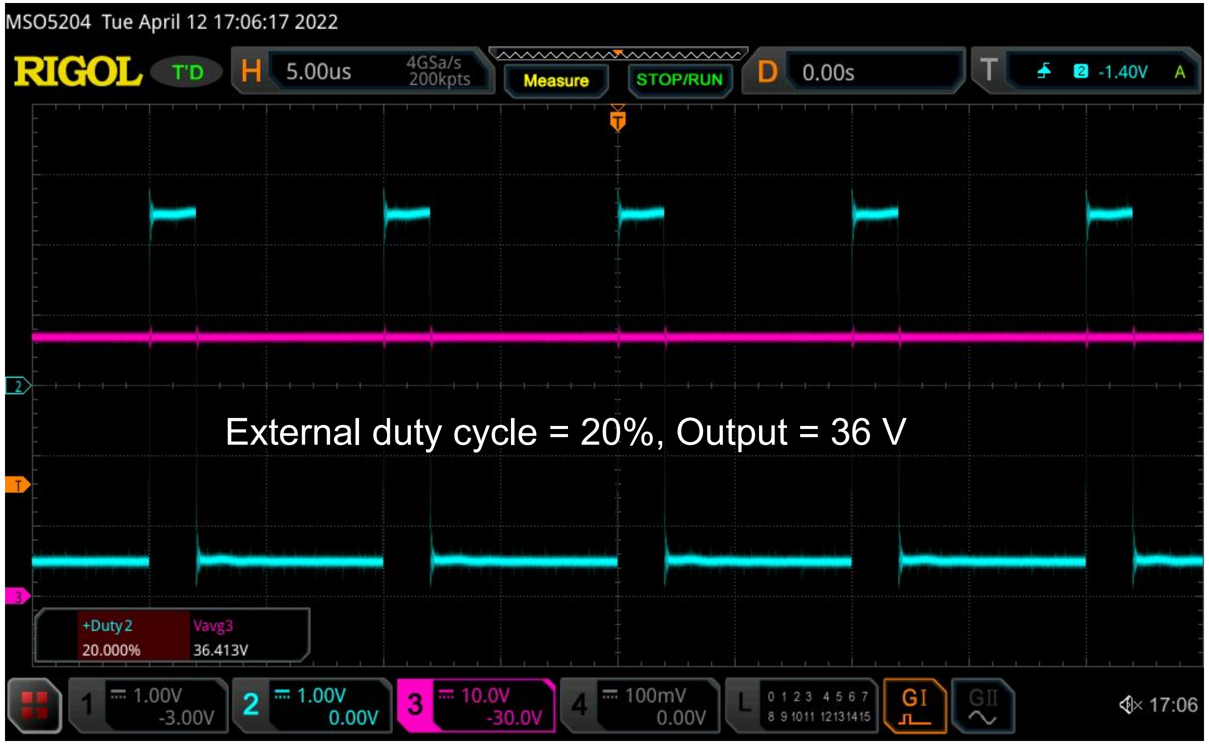




External set point

- An external PWM signal drove through an optical fiber can provide an **external working point** to adjust the nominal one
- The output signal of the buffer stage **is summed to** the one of **the internal working point**
- The signal is AC-coupled and in case of absence of communication the R2-R3 divider will bring the DC-DC output back to the pre-set nominal point.
- With the current configuration (5.5 V input) the output can vary in **[35V, 51V]**





Integration considerations

- Next step is the refinement of components values and the design of a PCB
- The **PCB will be fully integrated** with the **DUNE VD Cold Electronics board**, we target the DC-DC test in ColdBox #3
- The communication receiver to adjust the working point will be implemented as a daughter board

Assuming a max saturation of 2000 PE per channel, that would correspond to:

$$2000\ [PE/Ch] \times 5 \cdot 10^{-6} [A] \times 200\ [Hz] \times 20 \cdot 10^{-6} [s] = 40\ \mu A/Ch$$

PoC / Power fibers	Communication fiber	DC-DC	X-ARAPUCA*	Tot. Fibers
1	1	1	Up to 5 Ch	2
2	1	1	Up to 10 Ch	3
2	2	2	Up to 10 Ch	4

*Assuming 50% efficiency

Conclusions

- A multi stage circuit for bias generation in cryogenic environment (LN_2) has been developed with discrete components
- The different stages have been tested independently and in-sequence, while adding functionalities to the circuit:
  - Typical design for the DC-DC boost converter, fully characterized and operational at LN_2 temperature
  - PWM generation tested in cold, and integrated successfully in the DC-DC design
  - Internal feedback control implemented and tested in LN_2 for internal pre-set working point
  - External control increase flexibility and does not add risk. The optical communication was emulated with an electrical signal and managed to adjust the output voltage [35V, 51V].

and steps forward

- Develop the optical communication at the cryogenic level
- Develop a PCB to be integrated in the DUNE VD Cold Electronics board