The powering systems of the CMS tracker for HL-LHC

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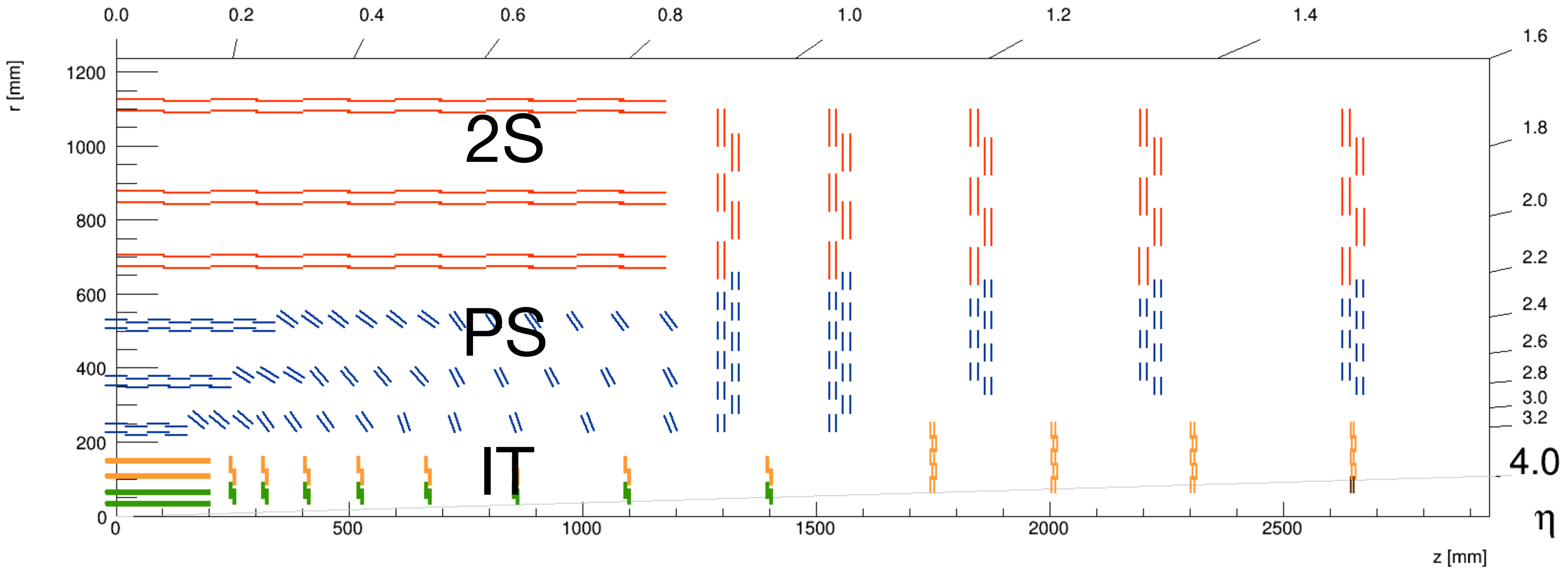
on behalf of the CMS Collaboration

TWEPP 2022 - Bergen - 19-23 September 2022

The CMS Tracker for HL-LHC



Major differences w.r.t the present tracker:

Participates to L1 trigger

Higher granularity

Lower material budget

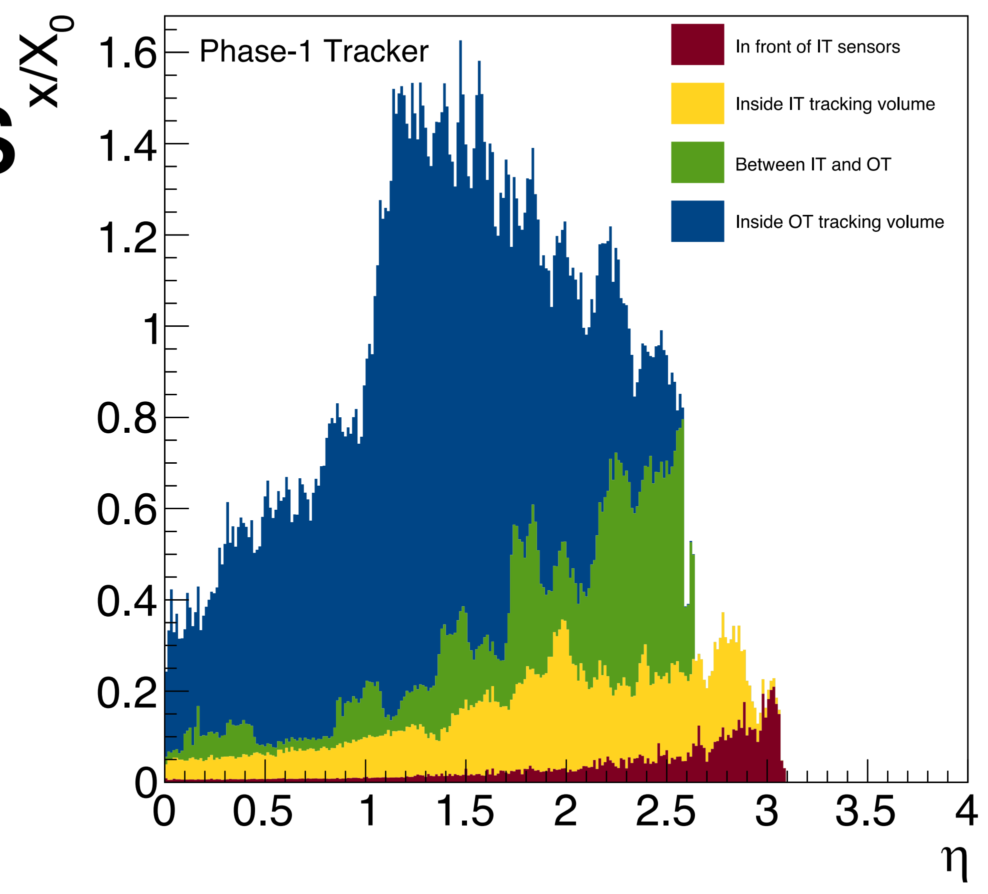
Outer Tracker:

- 13200 modules of two kinds: Strip-Strip (2S) and macro pixel-Strip (PS)
- 42M strips, 170M macro-pixels

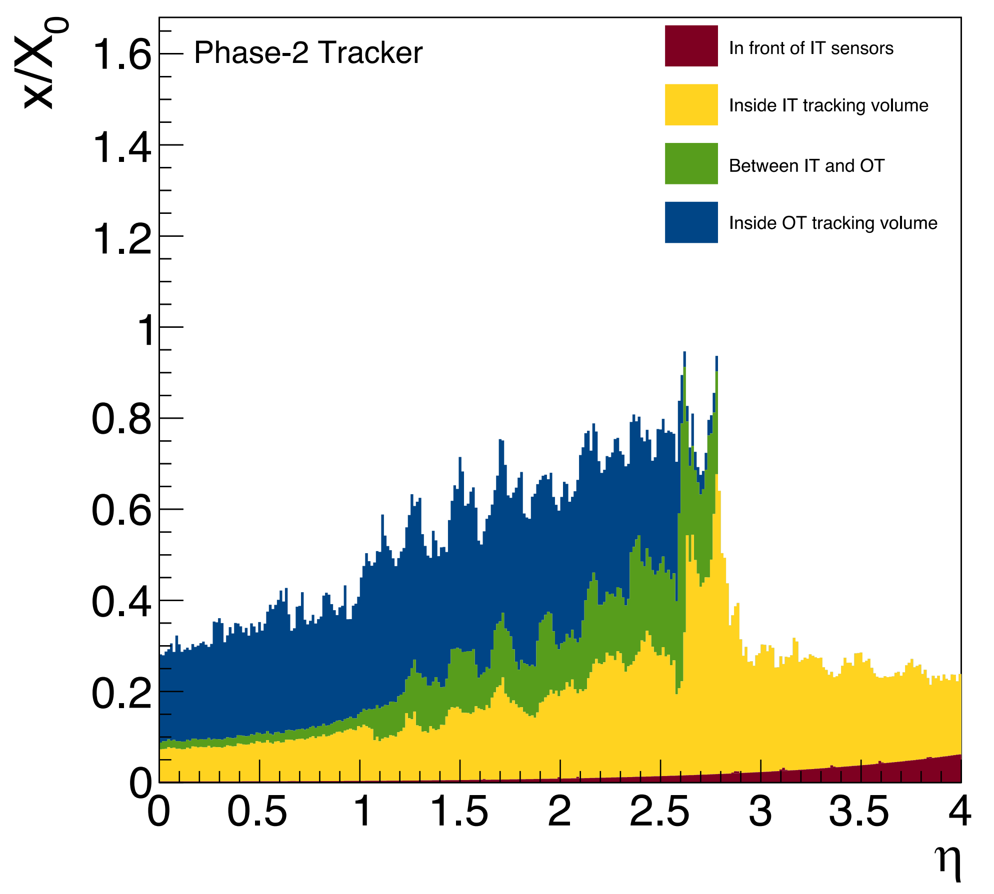
Inner Tracker:

- 3900 pixel modules with 2 (1x2) or 4 (2x2) r/o chips
- 9000 M pixels

actual



HL-LHC



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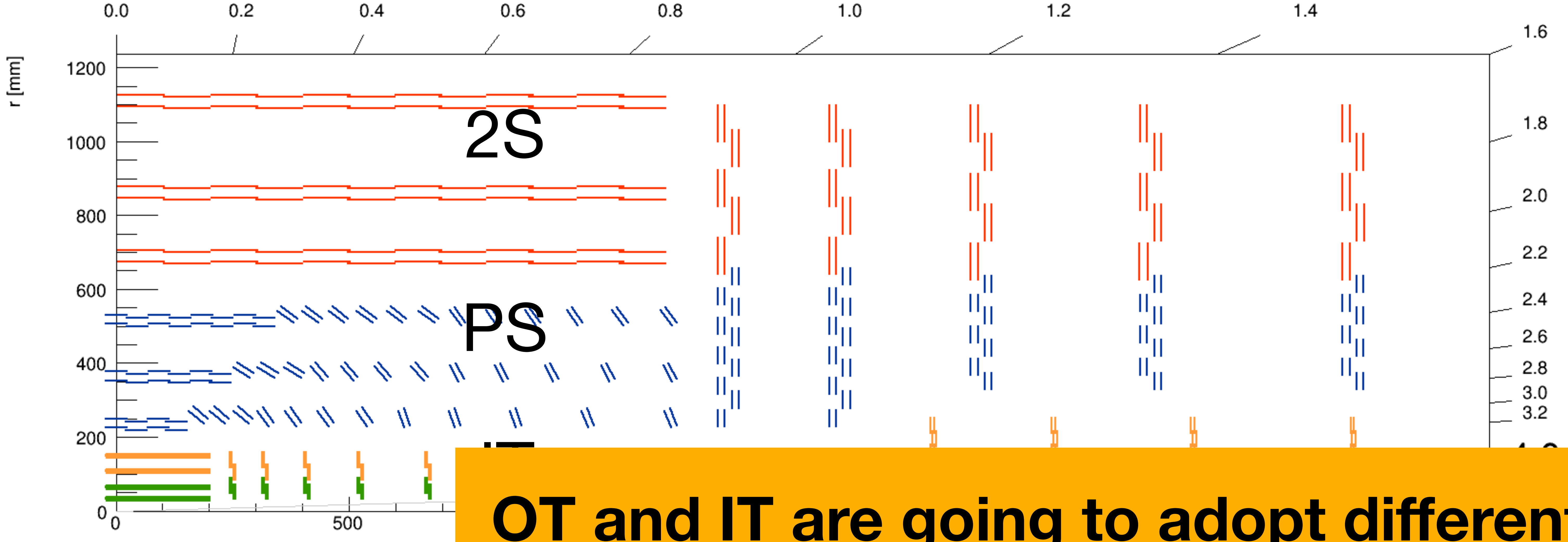

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OT and IT are going to adopt different powering schemes

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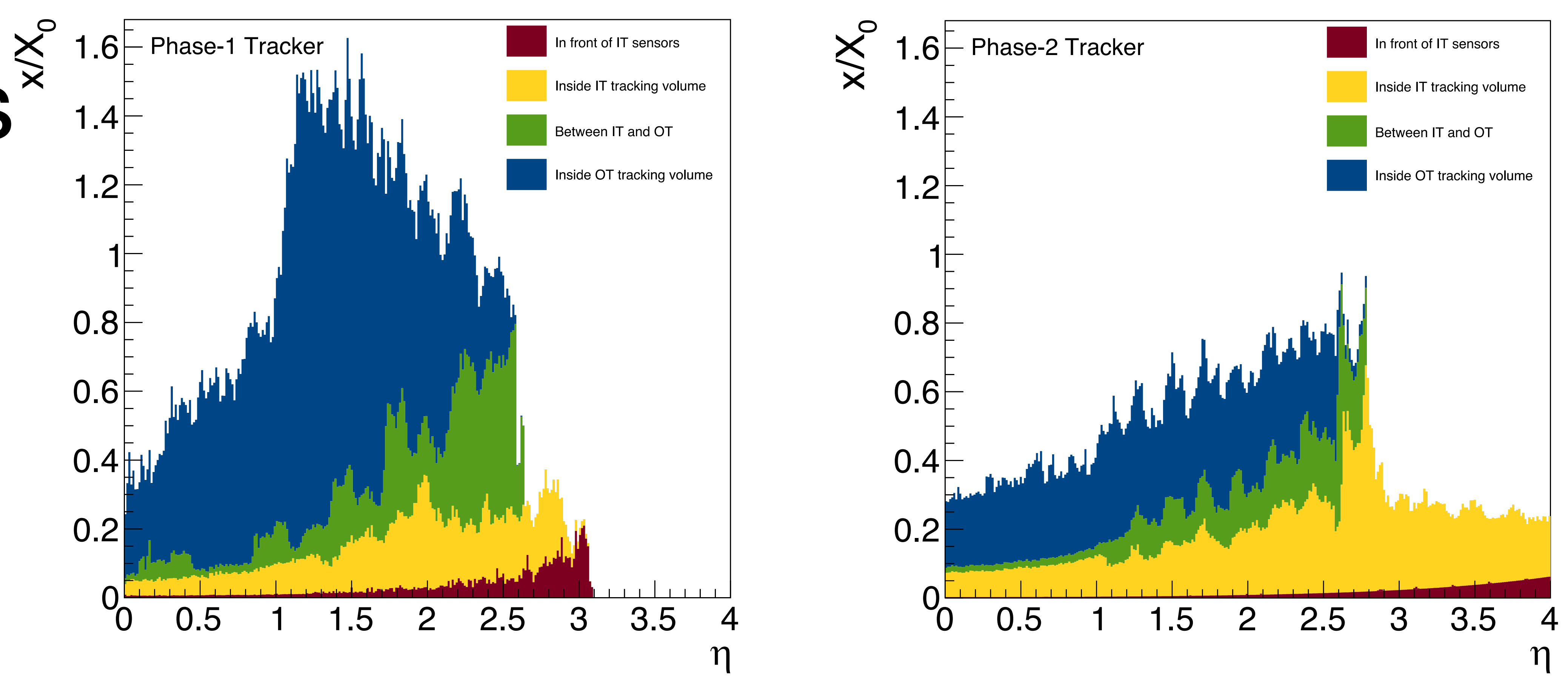
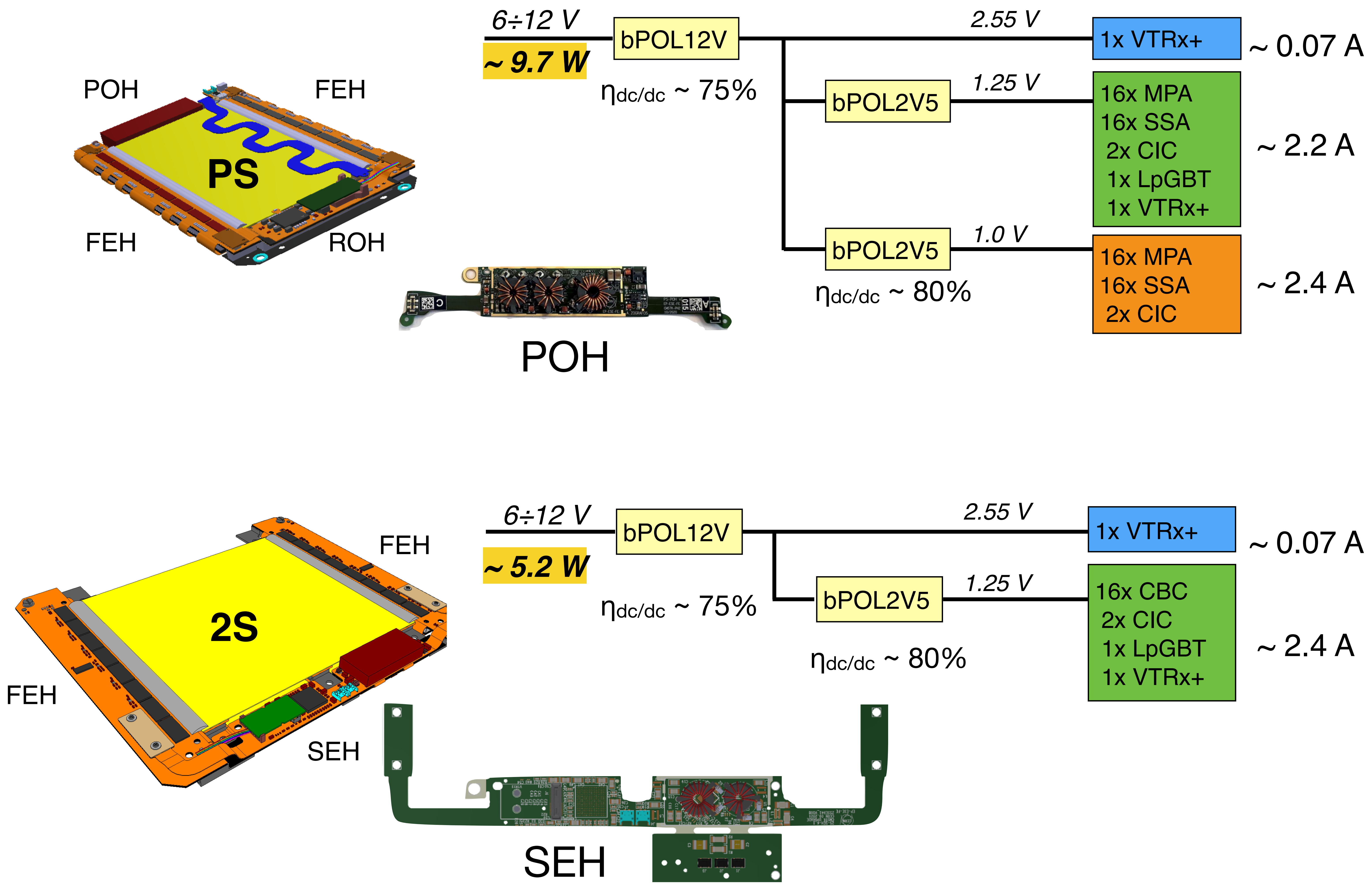


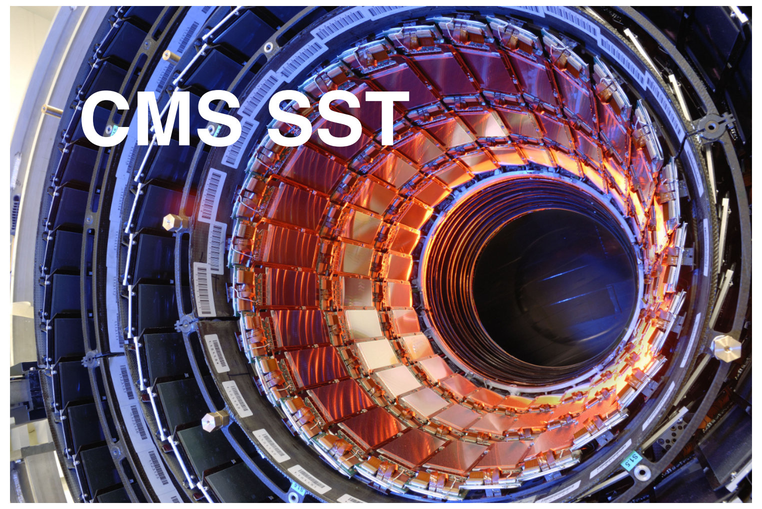
Powering the CMS Outer Tracker

On-module power distribution



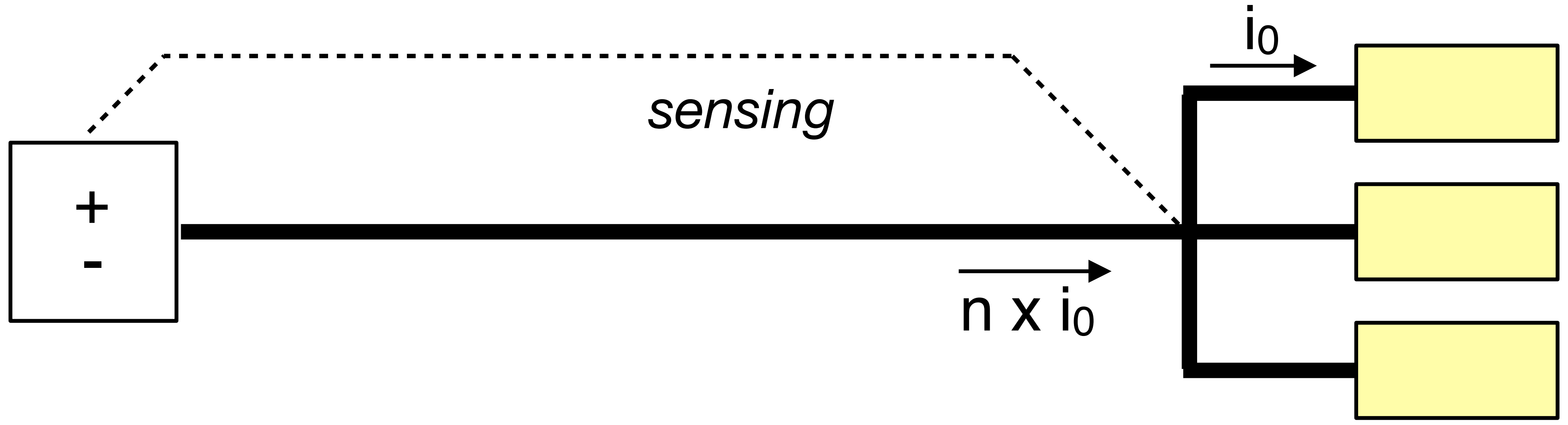
Every OT module is a functional unit individually connected to the power source and to backend system for data, trigger and control

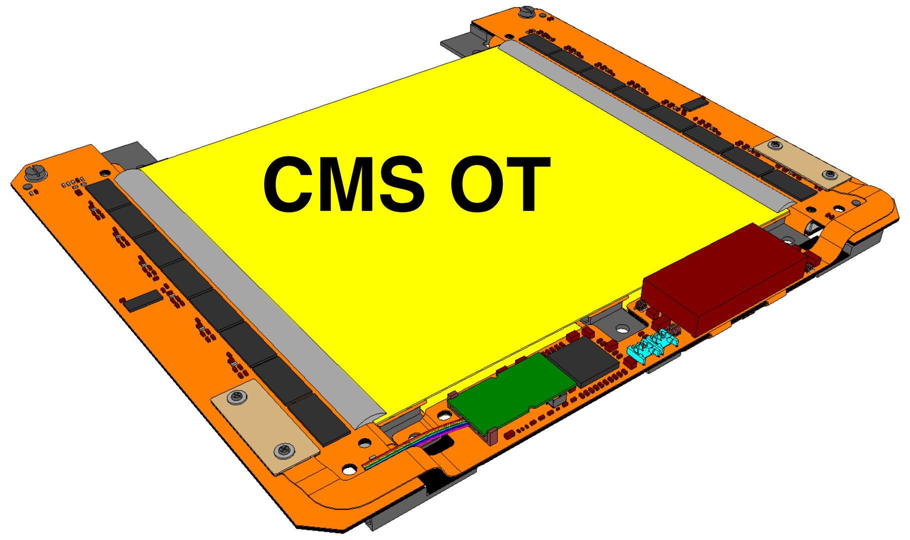
Power distribution choices



Module groups are the basic functional unit

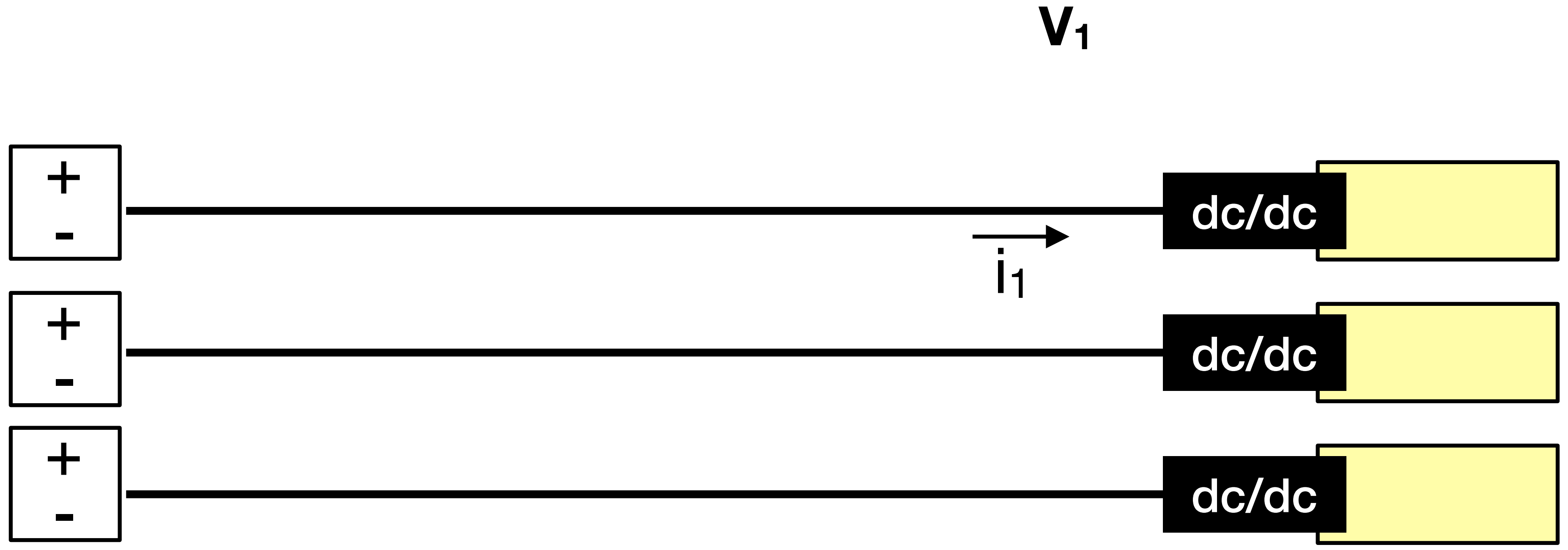
→ **Direct powering with sense wires**





The module is a functional unit

→ **Individual connection to power source with on-module dc-dc conversion**



Cabling defines the power groups.
Optimal grouping reached with up to 12 detector modules per cable
→ LV, HV and services for 12 modules are grouped into one power cable

~50k wires (LV+HV)
No sensing point on detector
→ no V_{drop} compensation

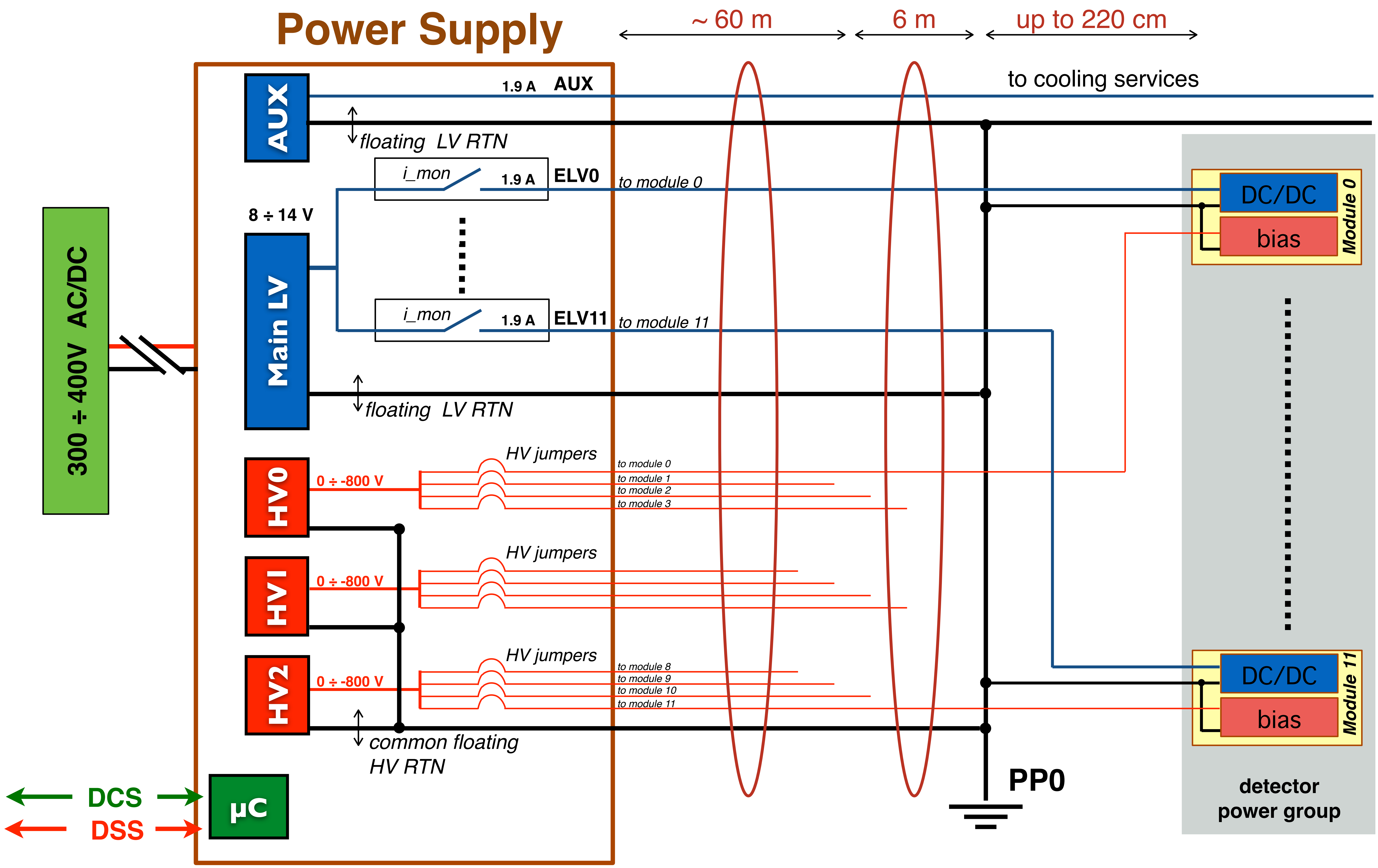
The power supply unit

LV and HV combined units which provide all voltages associated with one cable

1220 of these units:

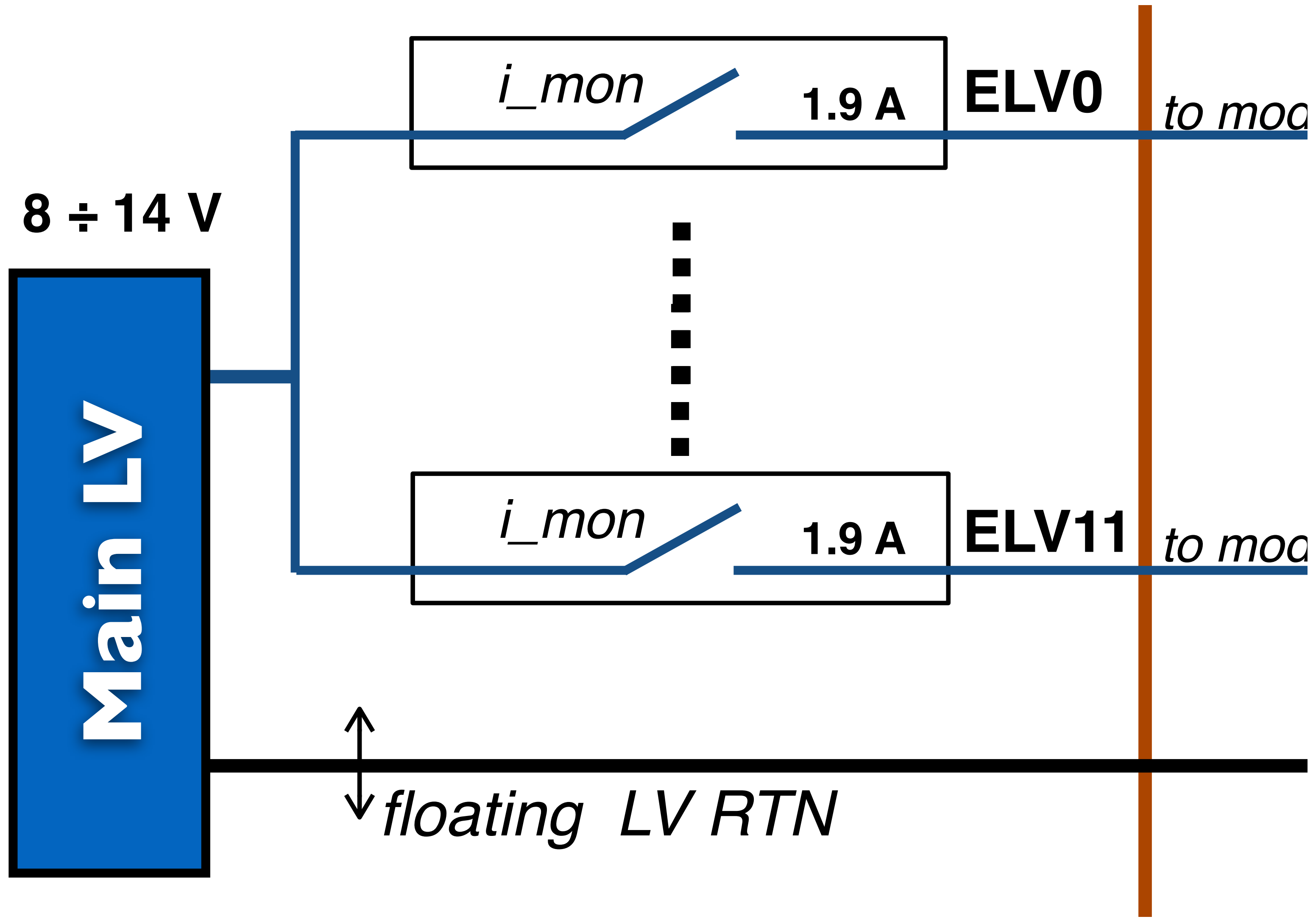
- 12 LV channels (8÷14 V, 1.9 A)
- 3 HV channels (0 ÷ -800 V, 15mA) with 1→ 4 fan out
- 1 AUX LV channel (8÷14 V, 1.9 A)
- 330 W total power
- Input power@ ~ 400Vdc

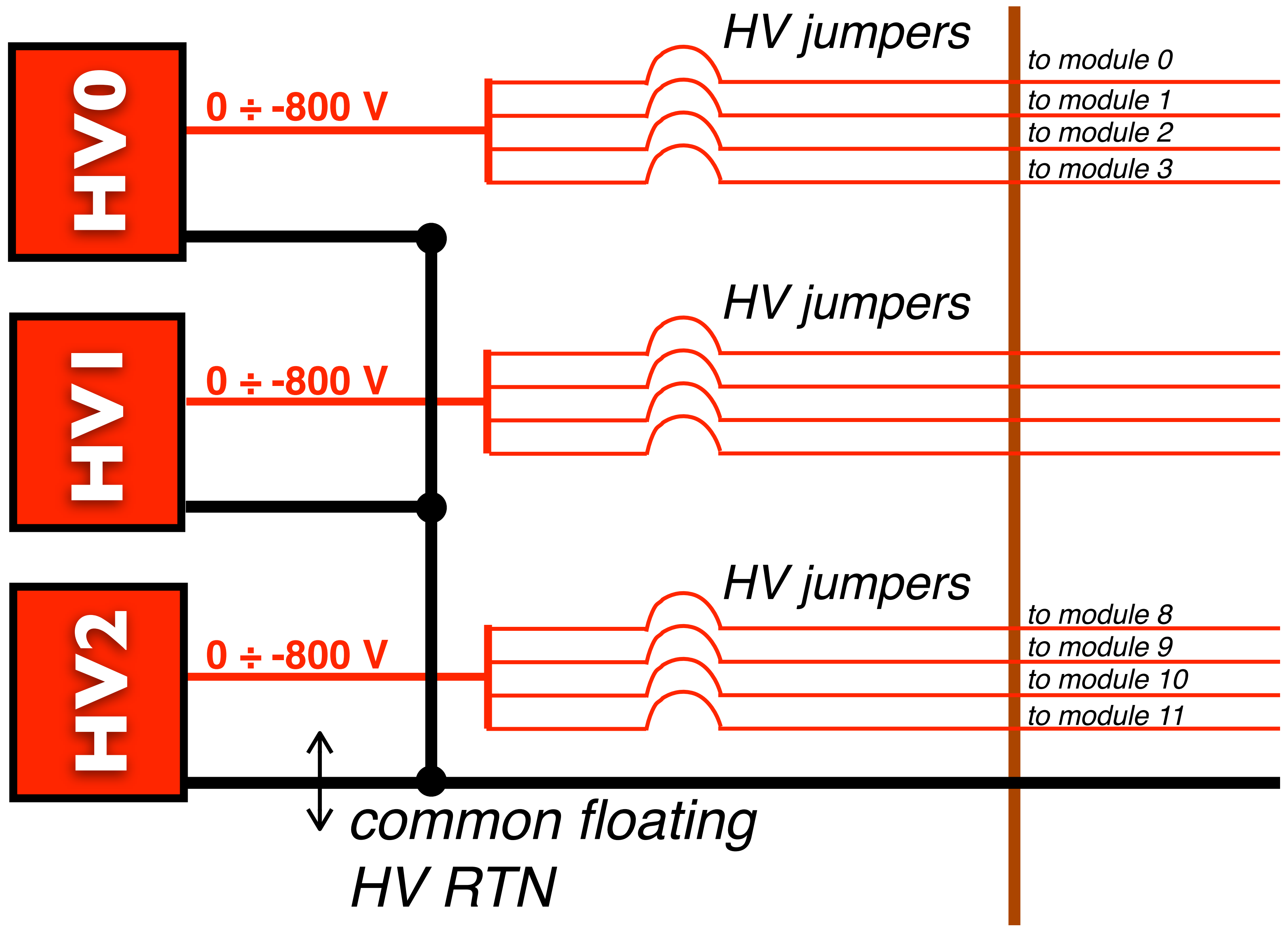
provided by a source in the CMS service cavern



2 interlock lines
1 RESET line

... a few details





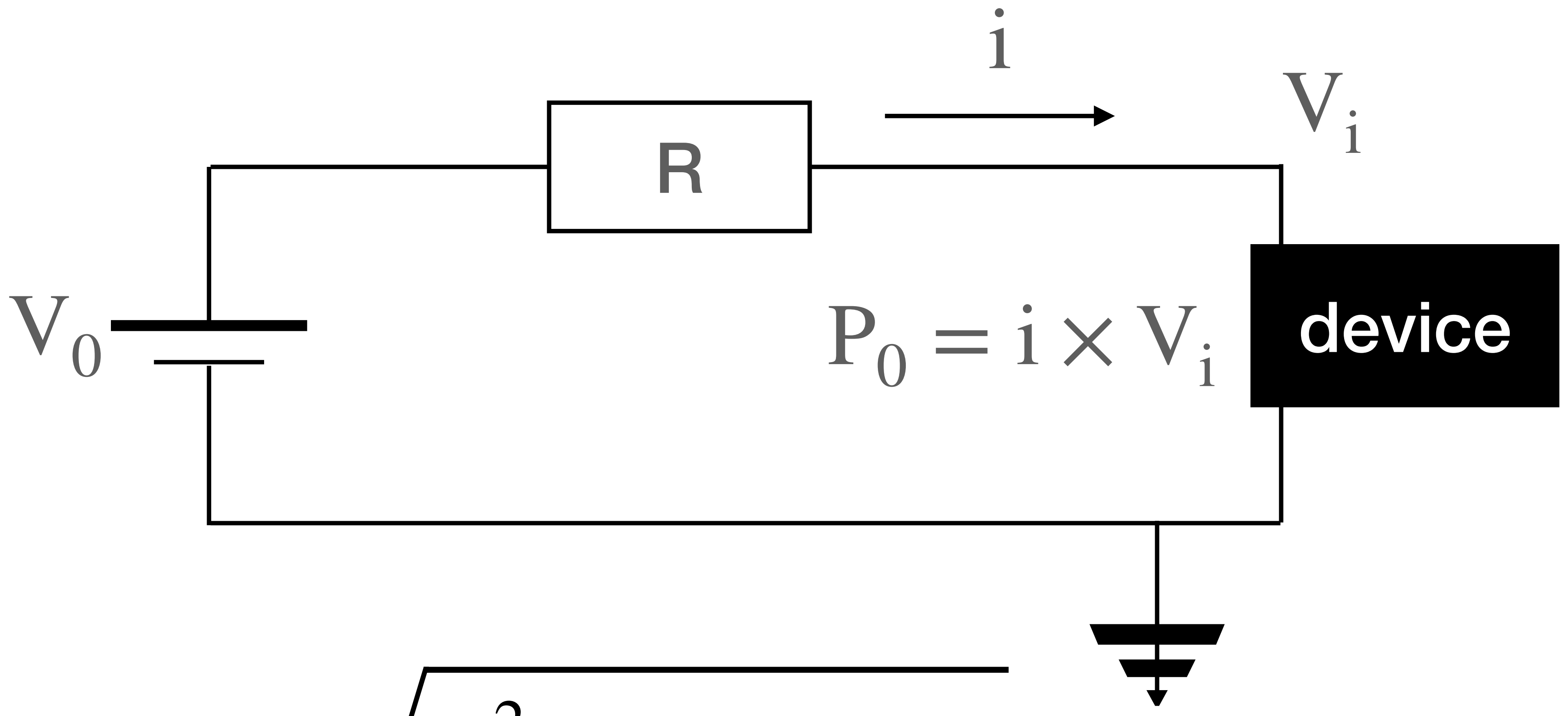
- switch time O(10÷20 ms)
- Common floating RTN
- per channel Voltage and Current monitoring with HW protections

- common floating RTN
- wired HV fan-out with jumpers
- HW current and voltage protections

HV Veto Map:

LV0, LV1, LV2, LV3 → HV0
LV4, LV5, LV6, LV7 → HV1
LV8, LV9, LV10, LV11 → HV2

R is the enemy …



$$i = \frac{V_0 \pm \sqrt{V_0^2 - 4 \times R \times P_0}}{2 \times R}$$

No V_{drop} compensation → $P_0 < \dfrac{V_0^2}{4 \times R}$

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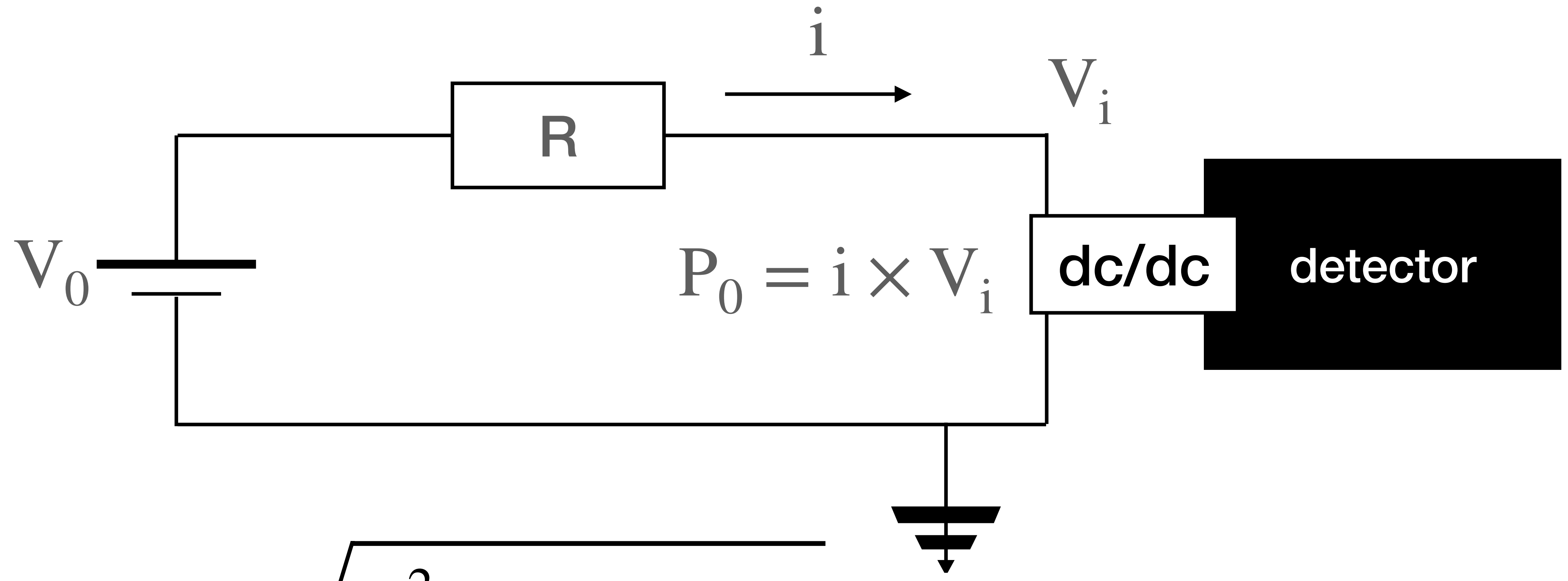

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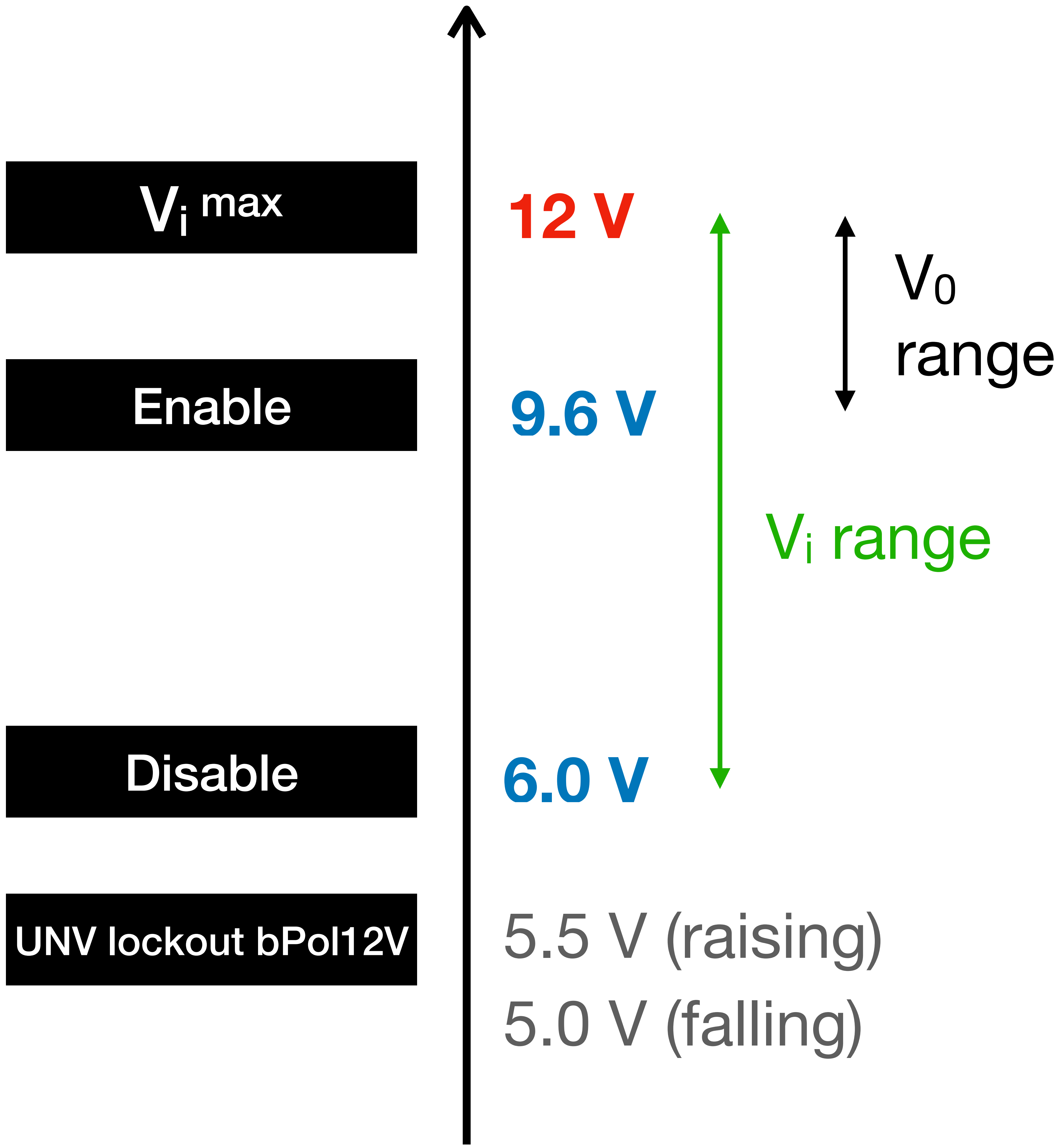
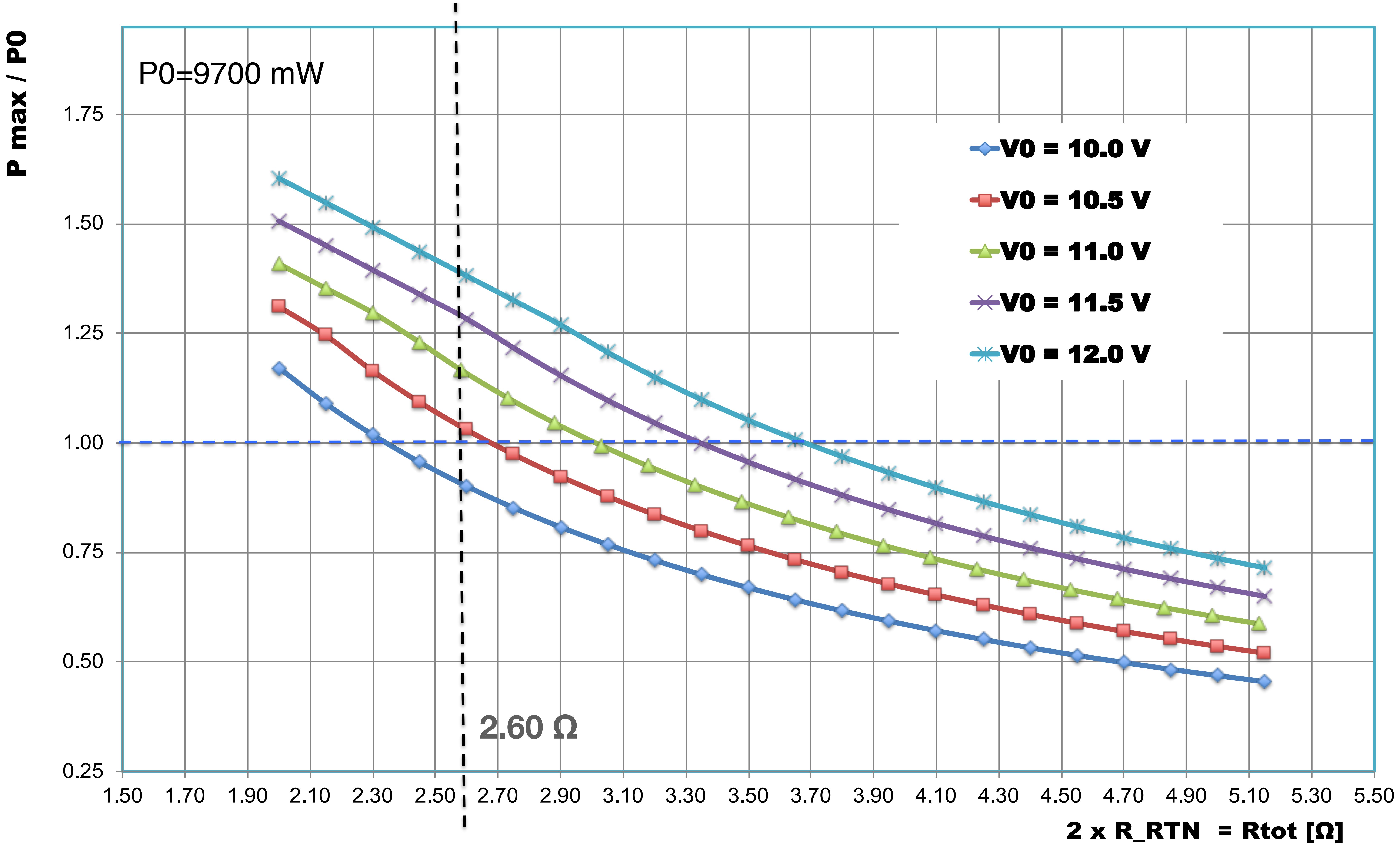
$$P_{Detector} = \eta_{dc/dc} \times P_0$$



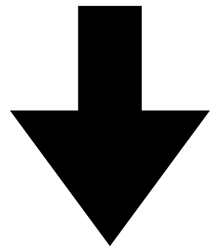
Power to a detector module



Maximum power delivered to a module vs total line resistance
(assuming i_max = 1.9 A and V_dis = 6.5V)

Total OT power

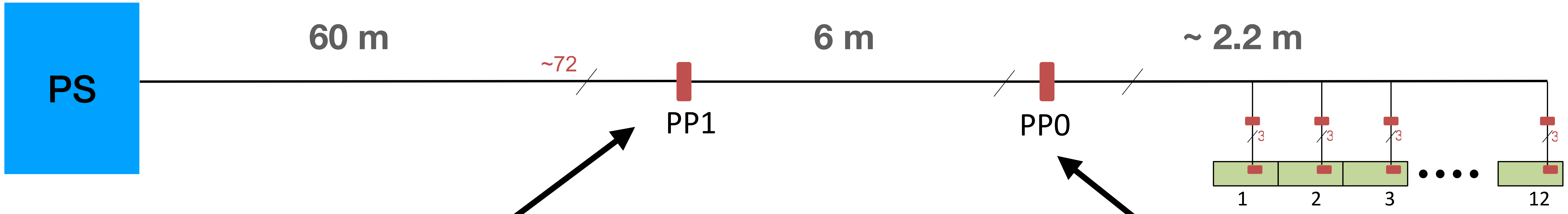
152 kW
Power Supply output

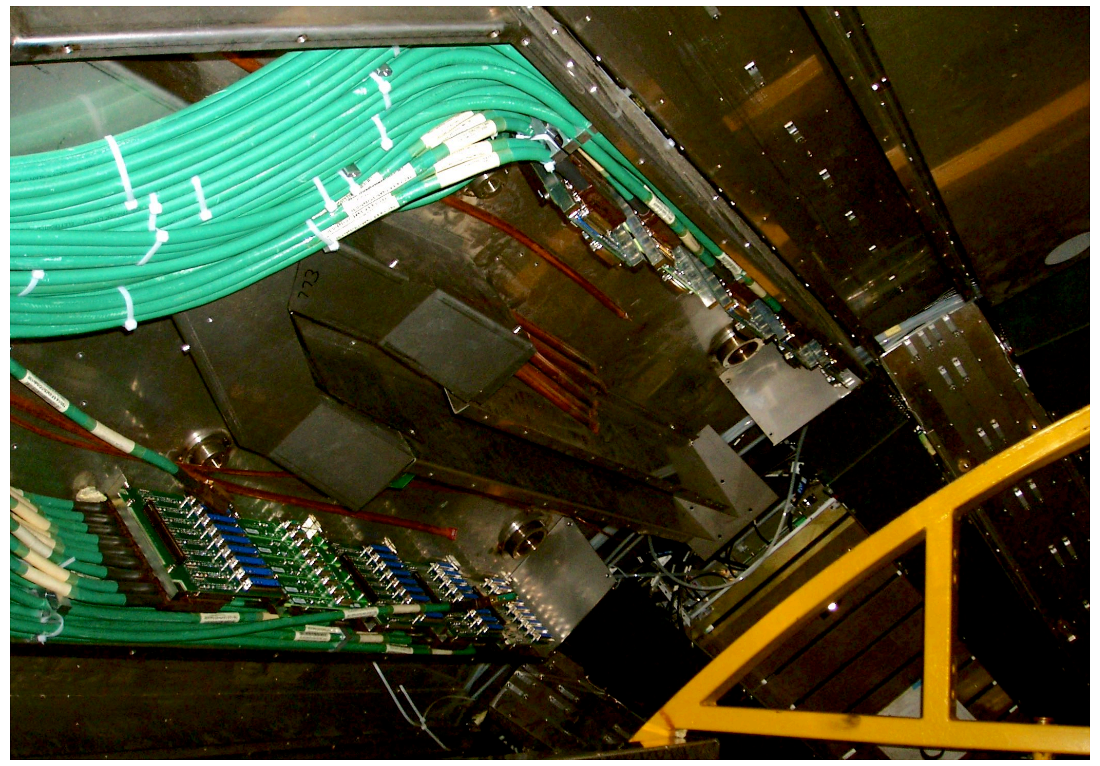


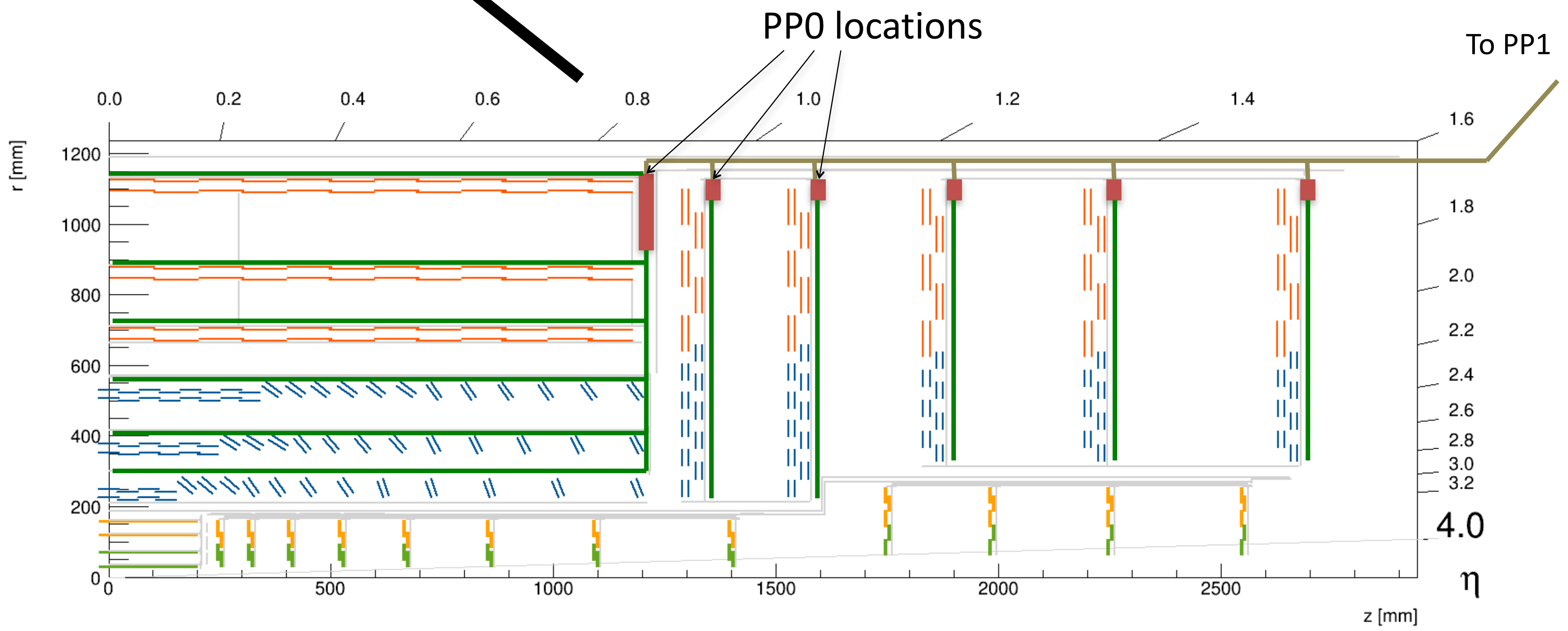
115 kW
to OT detector

Tackling the cable …

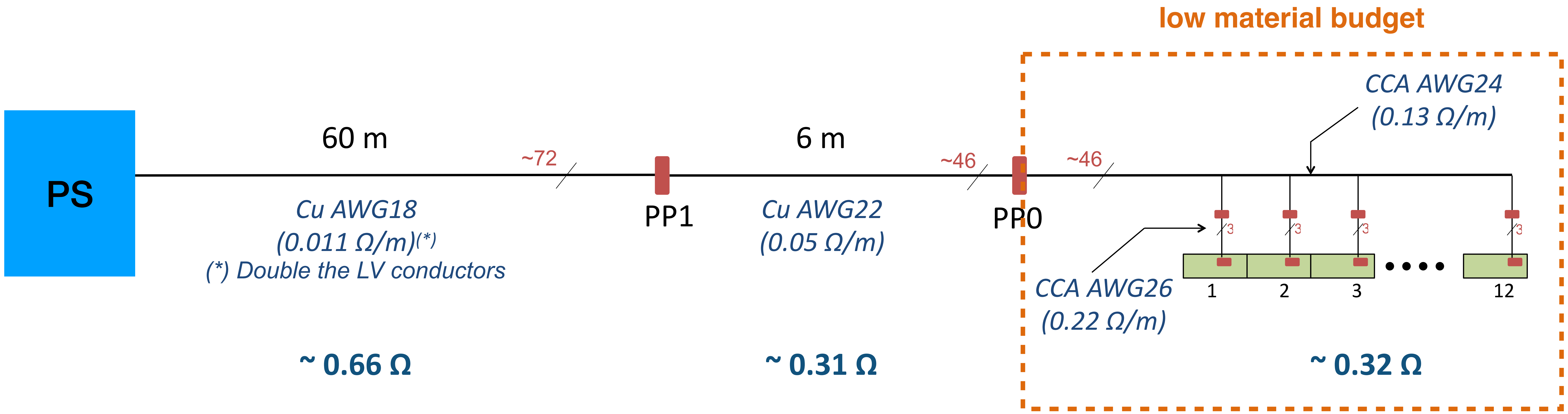
power supplies are located inside the experimental cavern







… the tiny



CCA (15%)
AWG24 (LV)
AWG26 (LV)
AWG 28 (HV)

very light and thin …

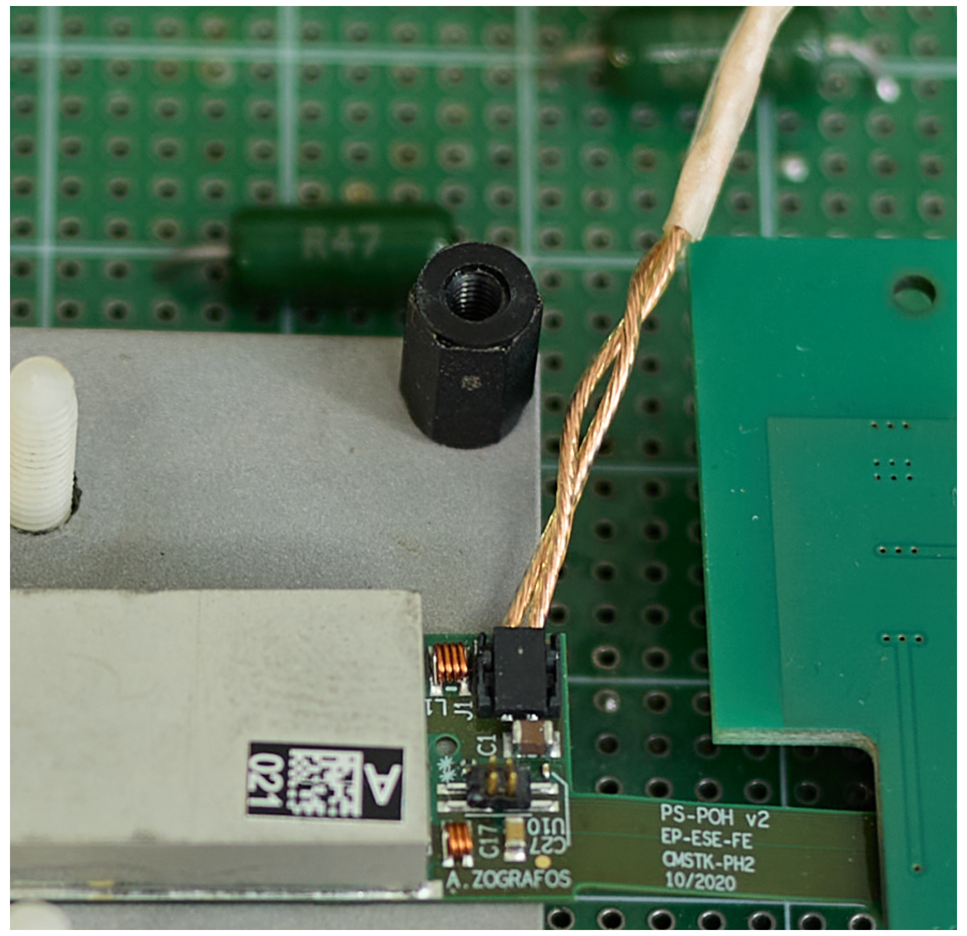
AWG26 CCA(15%) stranded

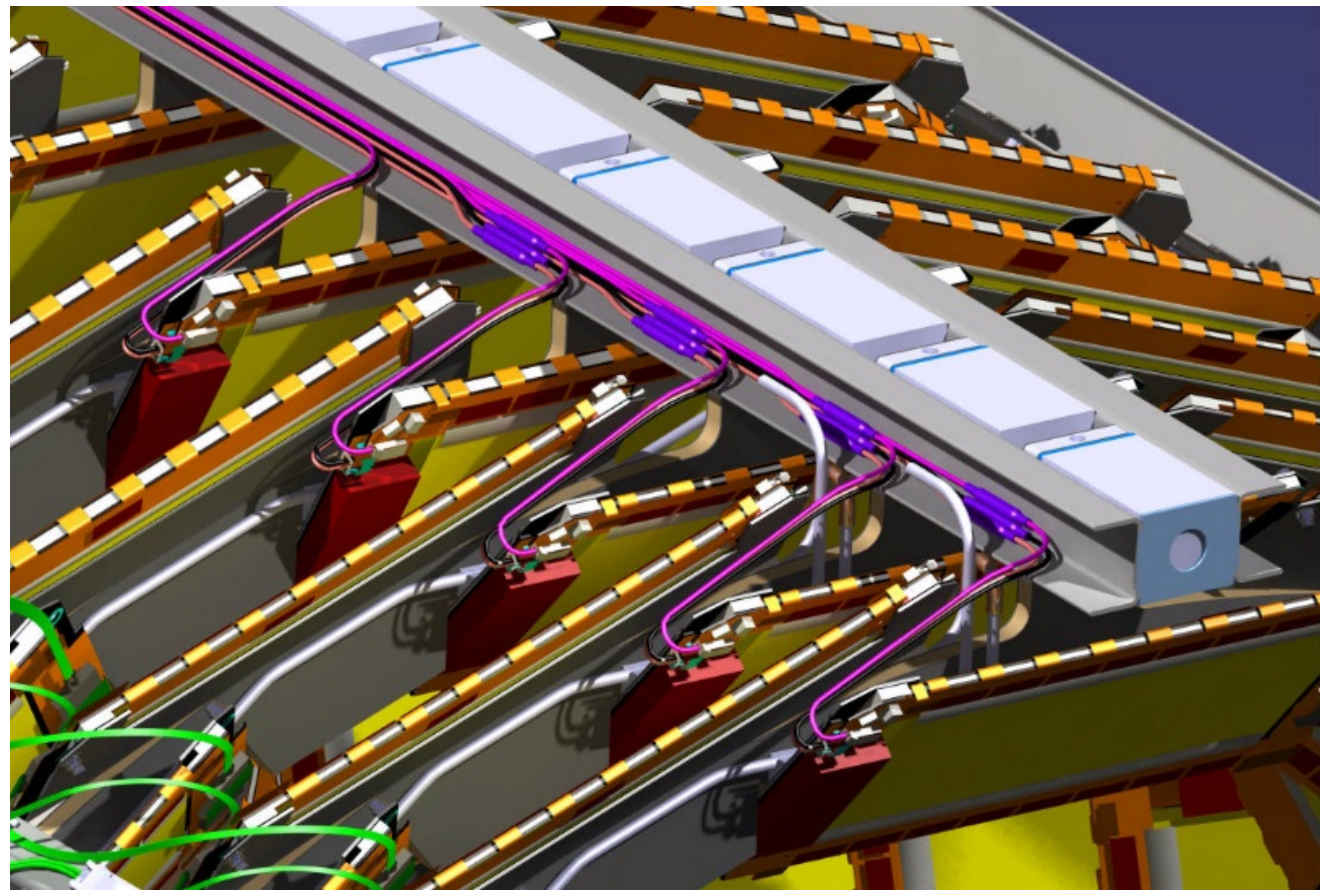
Siltem insulation

2 x 0.68mm diameter

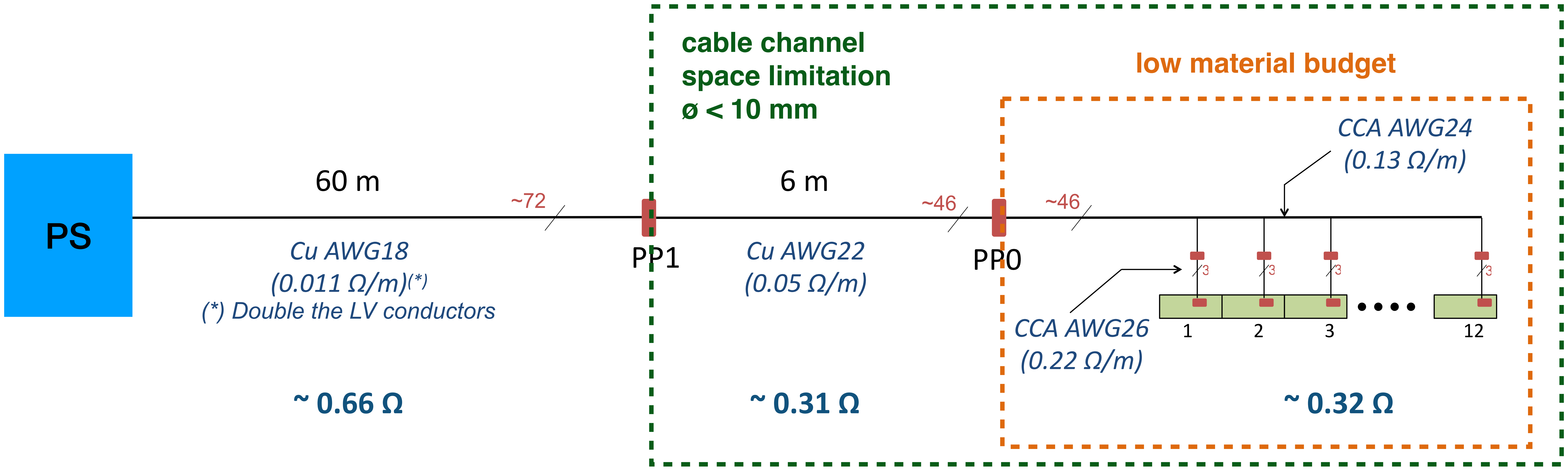
1.7 g/m

1.3 A typical (1.9 A max)

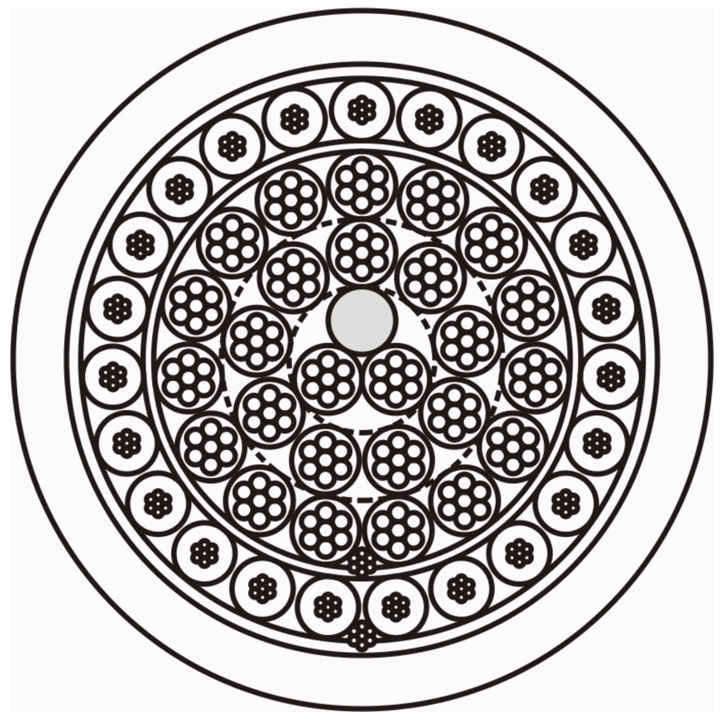




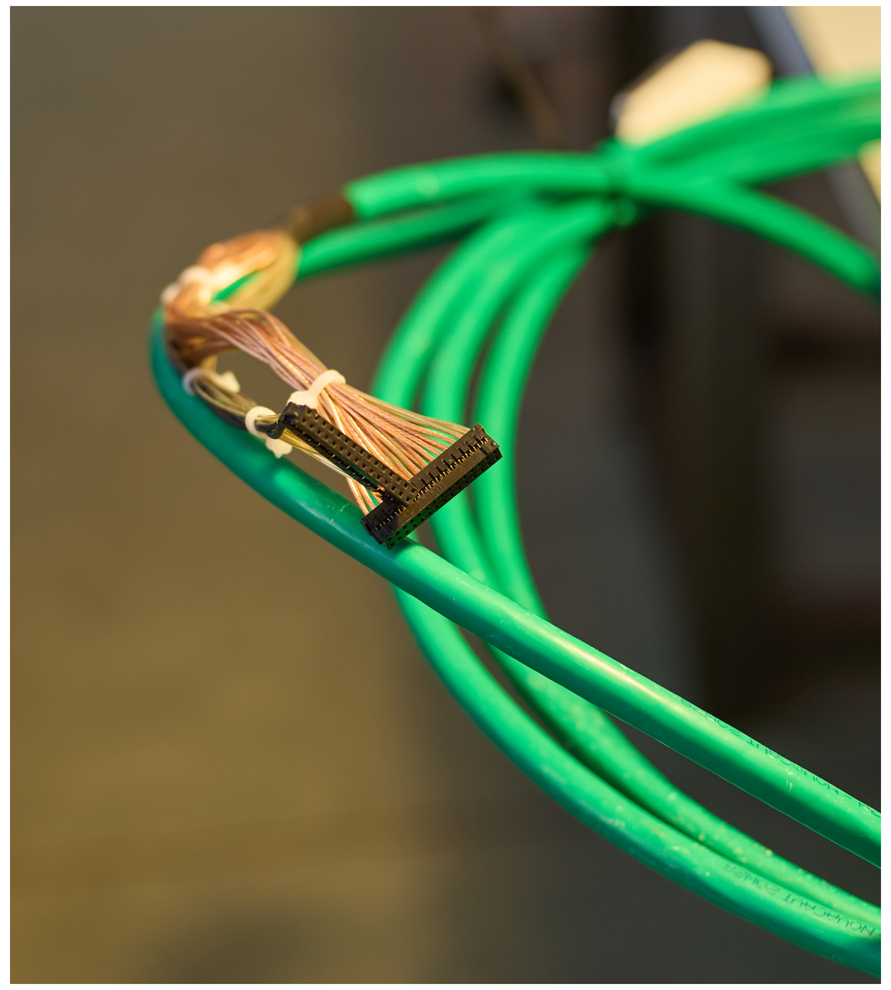
… the short



26 wires (AWG 22)
23 wires AWG28



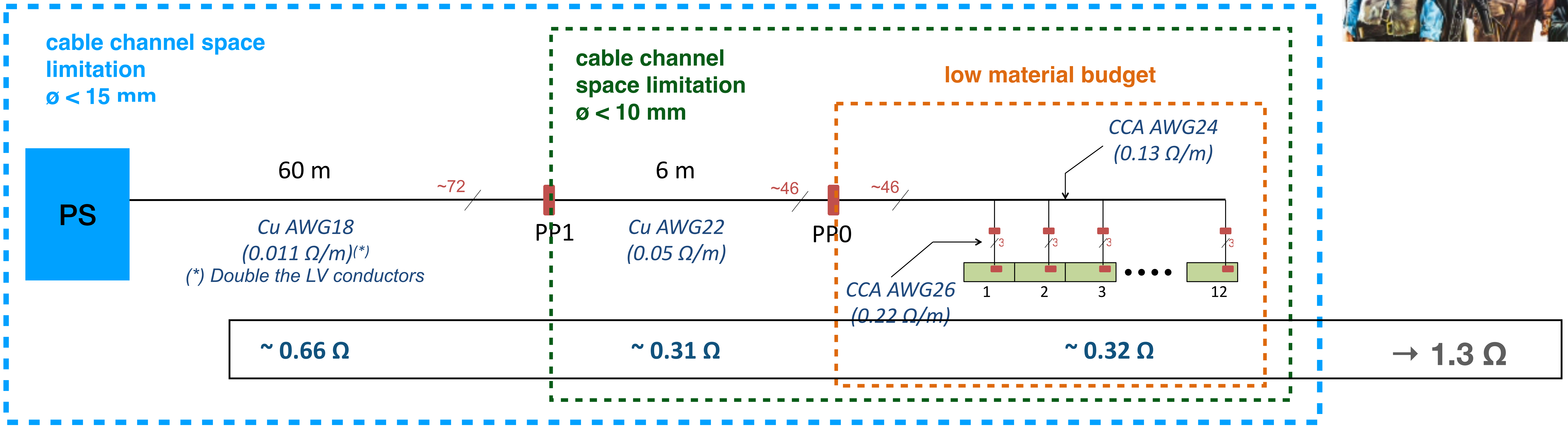
ø = 10mm

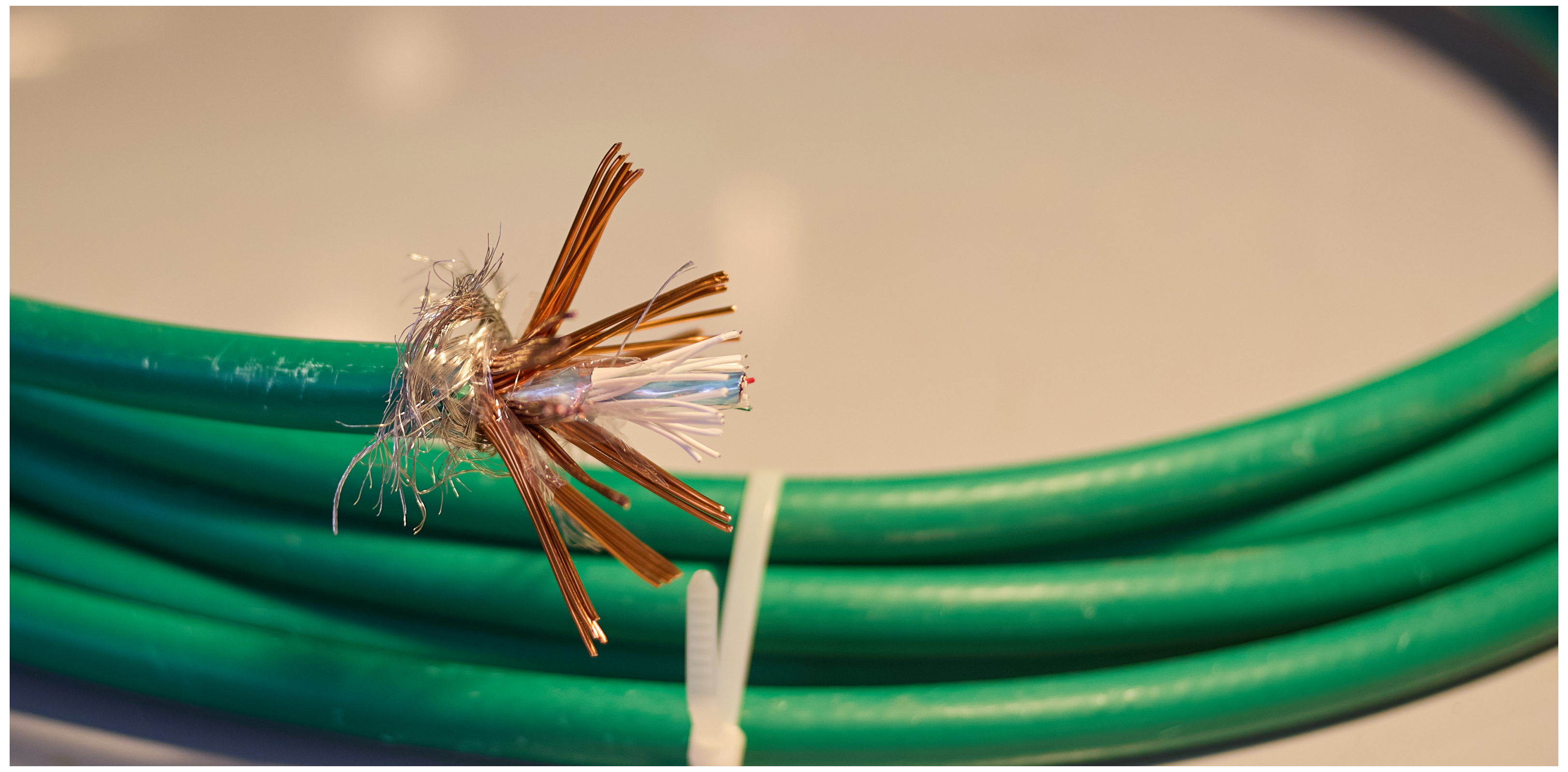


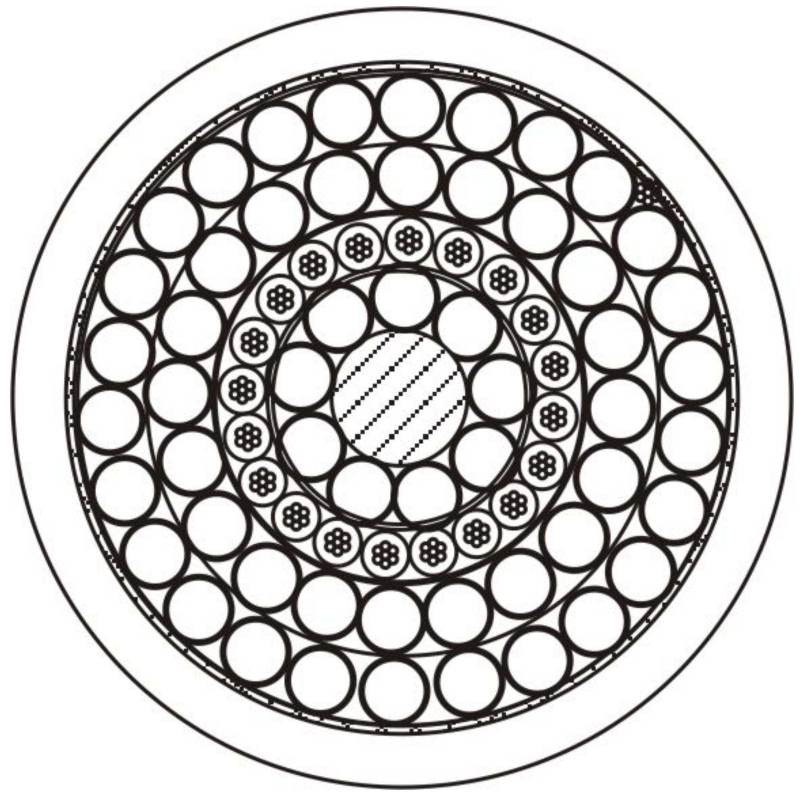
For each cable:

- 12 LV lines
- 12 HV lines
- 1 AUX LV line (pre-heaters for CO_2 cooling system)
- 4 RTD

… the long





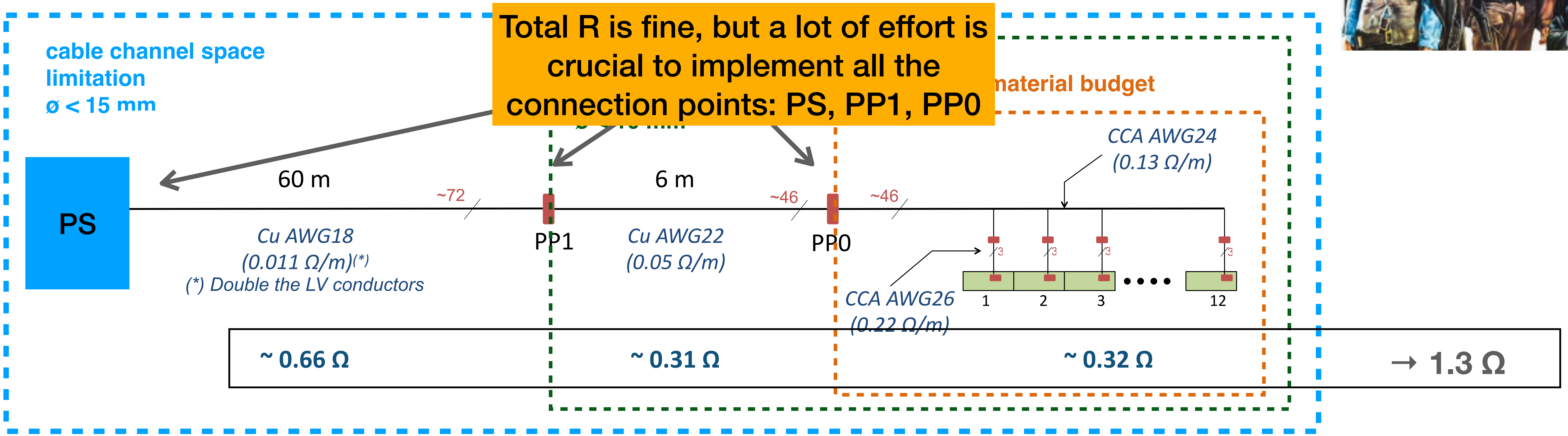


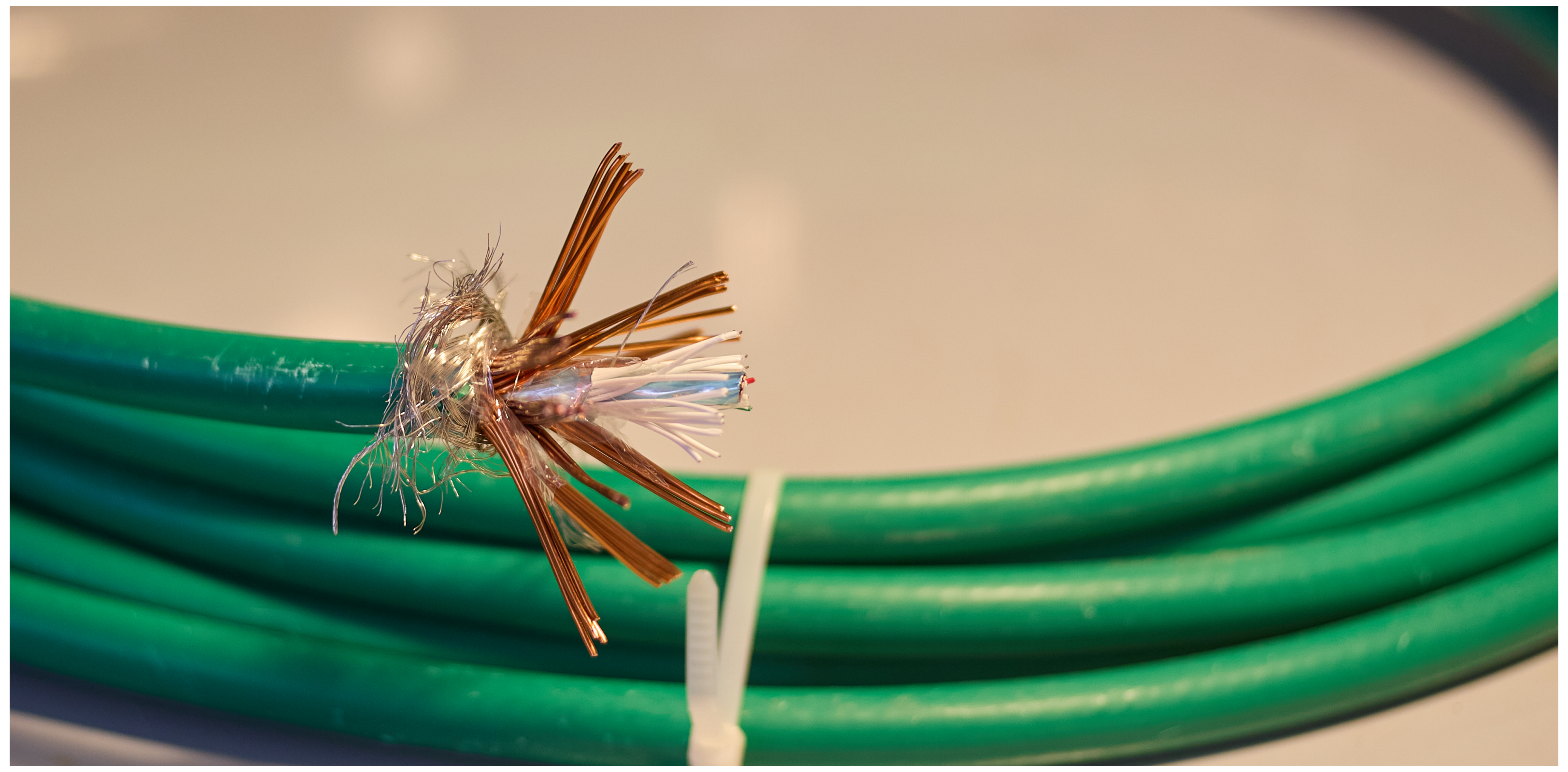
ø = 14.8mm

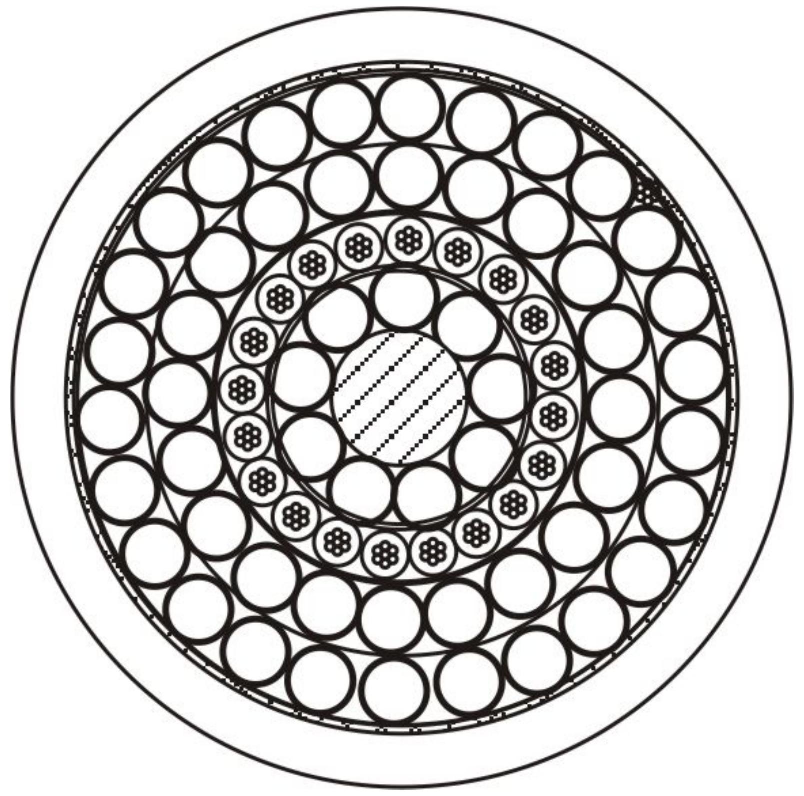
52 Cu enamelled wires (AWG 18)
4+15 AWG28 wires (HV and RTD)
———-
71 wires (+drain connections)

by using solid enamelled Cu wires a very dense cable structure can be obtained

… the long







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OT power supply prototype

In order to test and develop the system, CMS ordered the design and production of two prototype units, within the CERN Framework Market Survey (MS-4492/EP)

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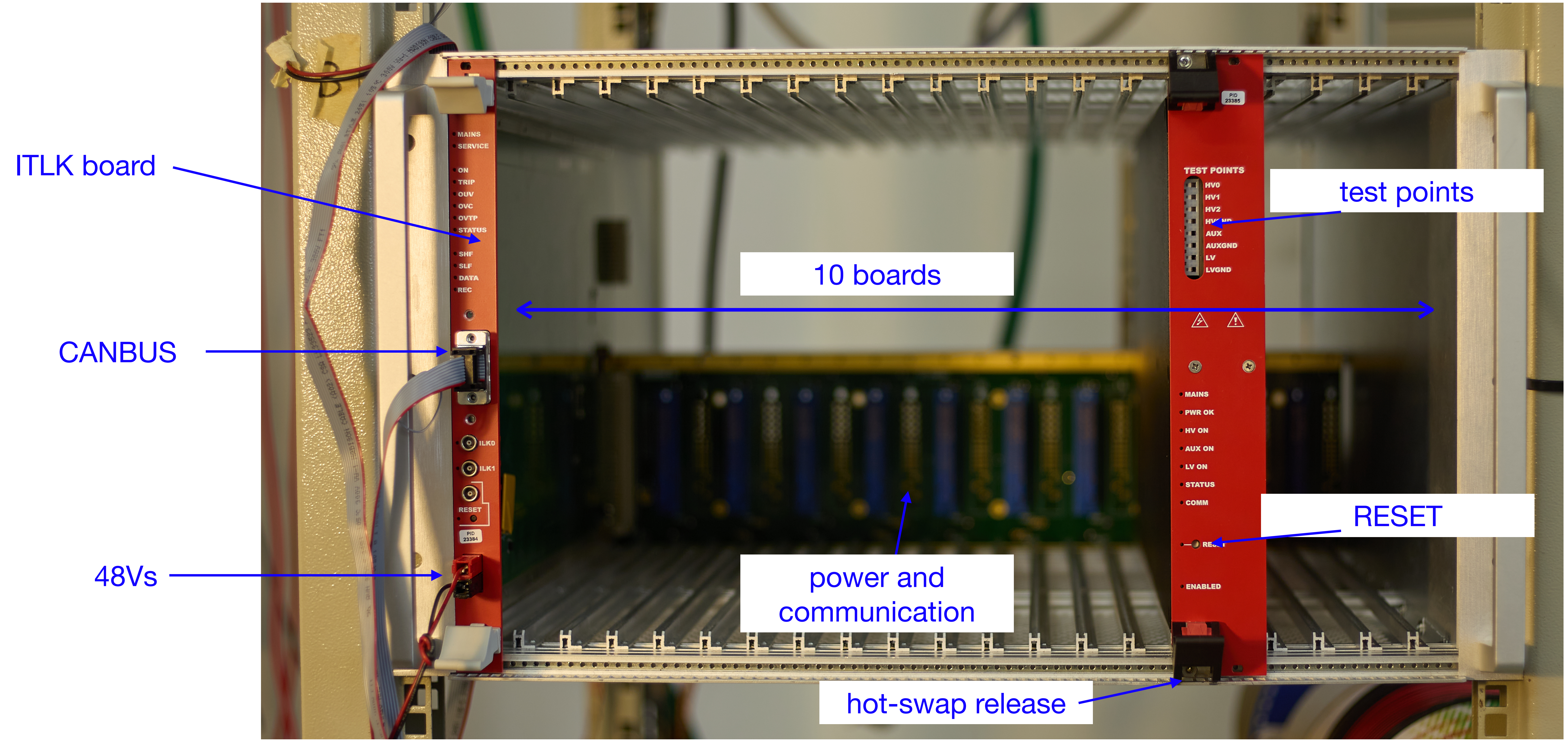
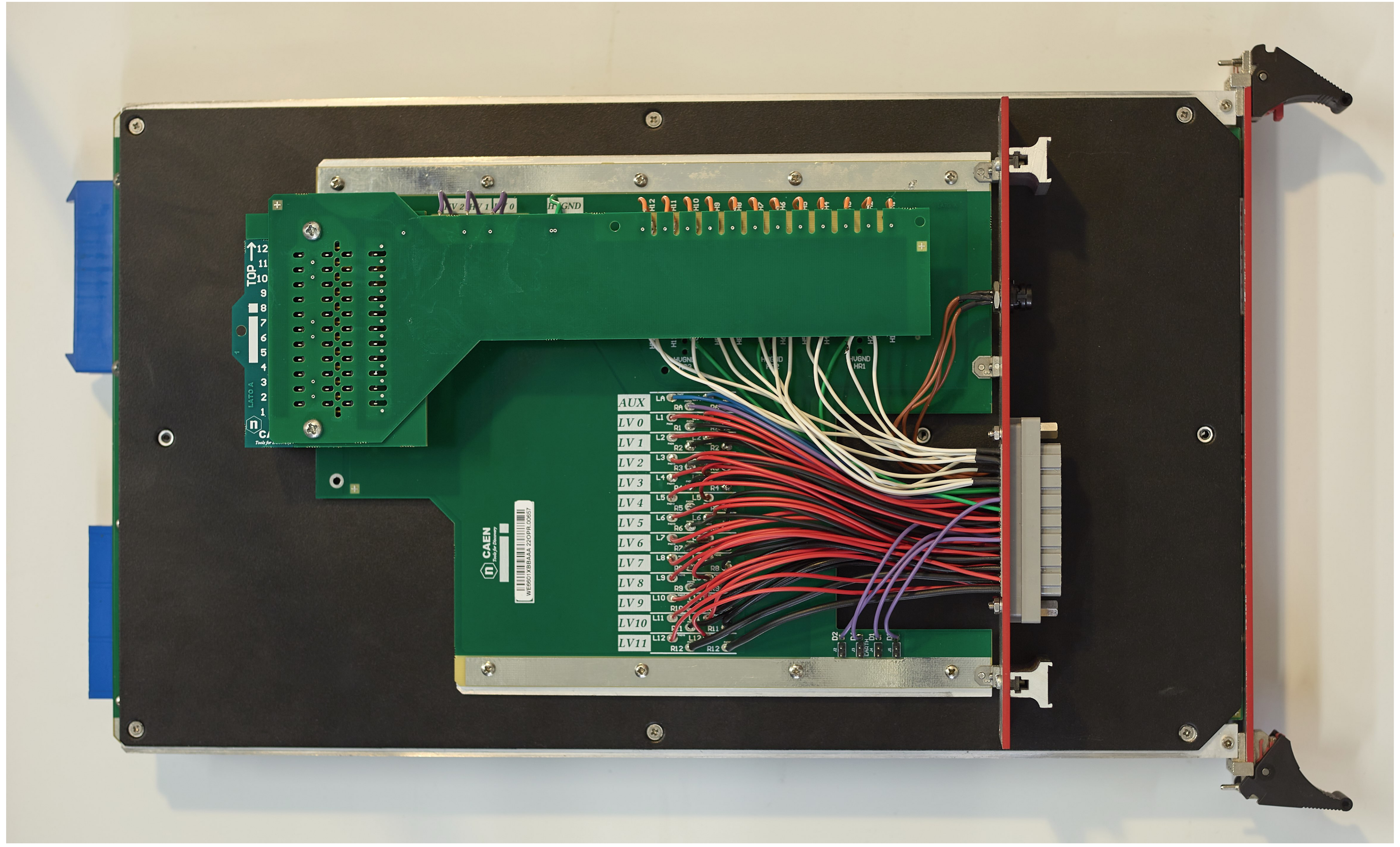
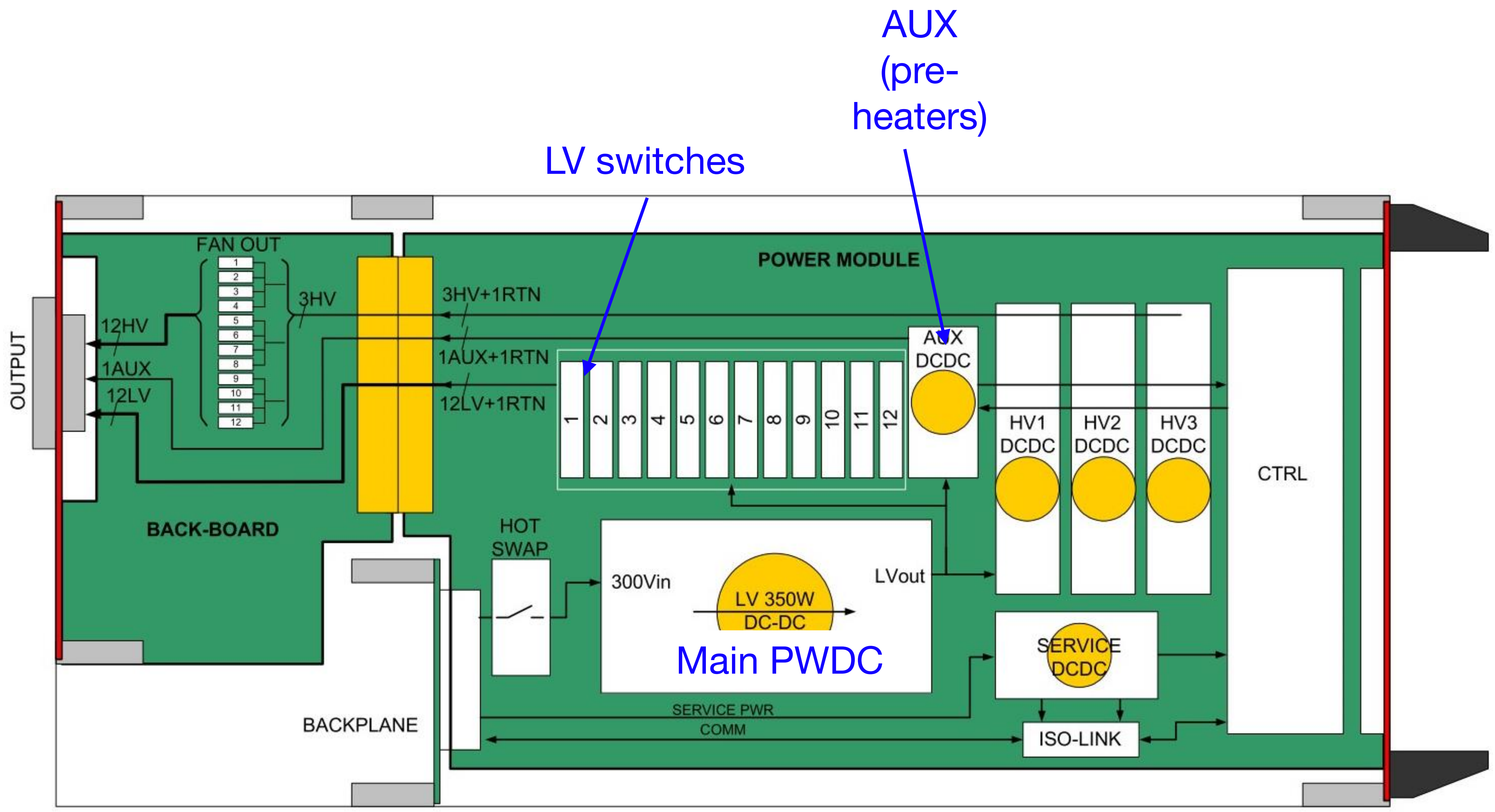


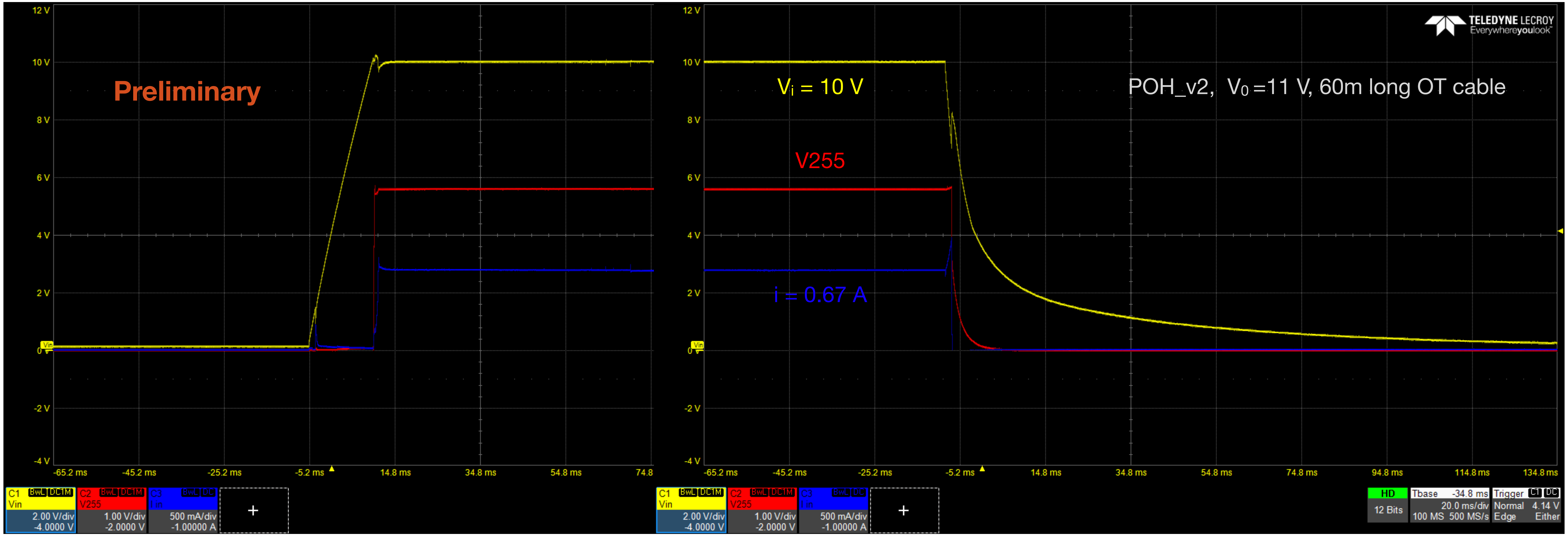
The A6601 prototype board





Functional sketch courtesy of CAEN SpA

Powering test with one POH



Radiation environment

Inside the CMS experimental cavern, in 10y of HL-LHC (4000 fb^{-1}):

- 5 Gy TID; $5x10^{-5}$ Gy/s
- $3x10^{11}$ n/cm^2 (1-MeV eq); 750 $n/cm^2/s$
- $5.6x10^{10}$ HEH/cm^2 (E>20MeV); 140 $HEH/cm^2/s$

+ 100mT fringe B field

In order to verify the performance of the components being deployed, CAEN performed irradiation tests at diverse facilities [1]:

- PSI (200 MeV protons) ← access to facility coordinated by CERN/PSI
- NPI-CAS (0÷30 MeV neutrons)
- RADEF (55 MeV protons) ← INFN proposal to the EU-funded RADNEXT program for transnational access to irradiation facilities: https://radnext.web.cern.ch/#about
- ENEA (~1MeV gamma)

[1] F. Giordano (CAEN), ICHEP2022 : https://agenda.infn.it/event/28874/contributions/169233/

Test at PSI

<u>Proton Irradiation Facility (PIF)</u>
Energy: 230 MeV
~ 5cm beam diameter

Two boards tested:
- micro controllers
- memories (FRAM)
- communication interfaces (serial, CAN)
- Power regulators
- FPGA with memories
- communication interfaces (CAN)
- ADCs and DACs

The logic components for CMS tracker passed the target HEH fluence and exceeded by orders of magnitued the target flux.

Credits to R. Ferraro and S. Danzeca for coordinating the test

Test at RADEF

<u>RADEF proton facility</u>
Energy: 53 MeV
7 ÷ 10 cm beam diameter

Three boards with power components:
- Main LV channel
- LV switches
- HV and AUX channel

Program for each board

Flux p/cm2/s	h	Fluence p/cm2
1E+06	3	1.08E+10
3E+07	3	3.2E+11
1E+08	3	1.08E+12

Some of the channels started to show problems just beyond the fluence of ~10^{11} p/cm^2

Post mortem analysis revealed that a few MOSFET started failing because of the excessive TID received (~ 150 Gy)

Credits to H. Kettunen (RADEF) for coordinating the test and RADNEXT for providing access to the facility

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OSFET started
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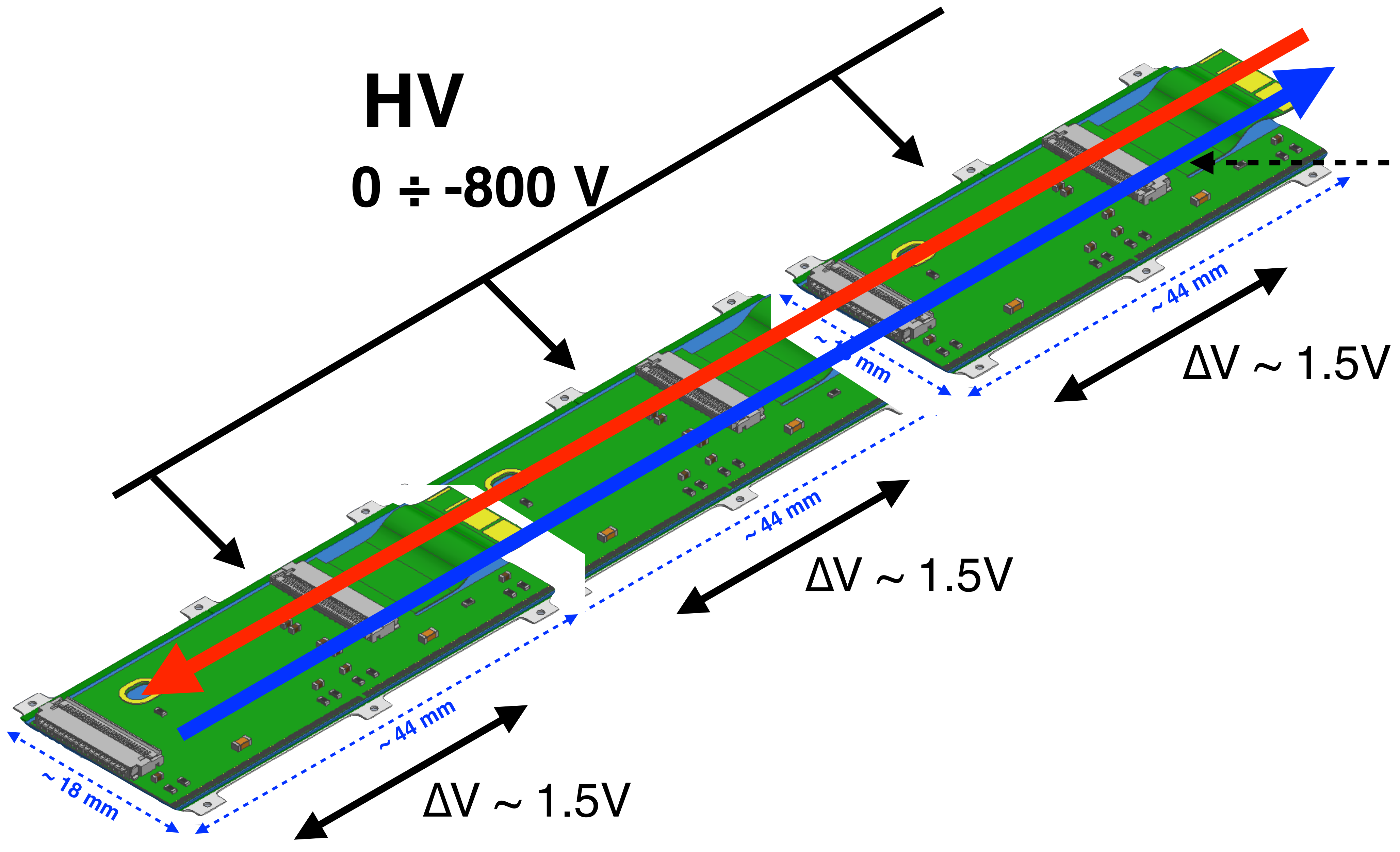
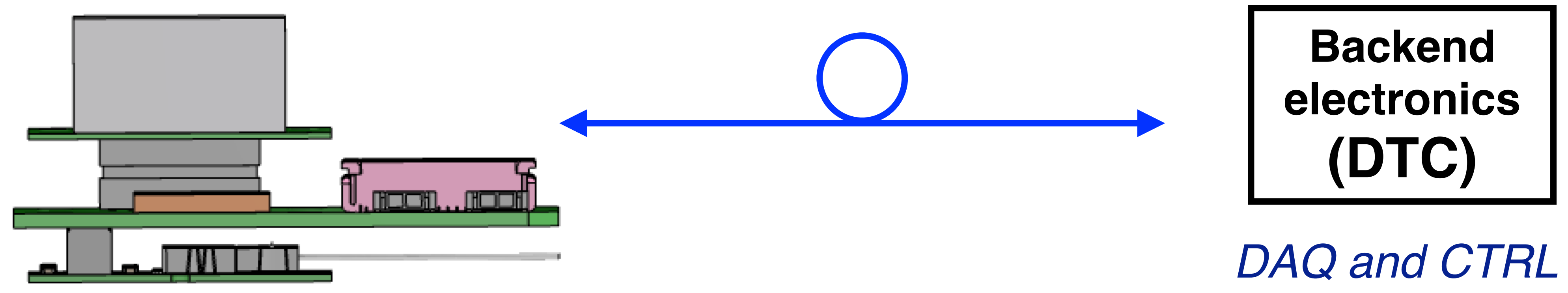
nating the test
and RADNEXT for providing access to the facility

A test of the power supply board in a facility with a mixed radiation field similar to the LHC spectrum will be crucial to qualify the prototype

Powering the CMS Inner Tracker

The architecture of the system





680 portcards ↓

- 3 LpGBT + 3 Vtrx+ per portcard
- AC coupled e-links to modules
- modules in separate serial chains never connect to the same portcard
- on-board dc/dc conversion: → bpol12V → bpol2v5
- power request ~ 2.8 W

500 serial chains

- 164 "4A" chains (1x2 modules)
- 336 "8A" chains (2x2 modules)
- 5 to 11 modules per chain
- Sensor bias within one SP chain with 1 or 2 HV lines per SP chain

The Power Supply Module

PSU (power supply unit):

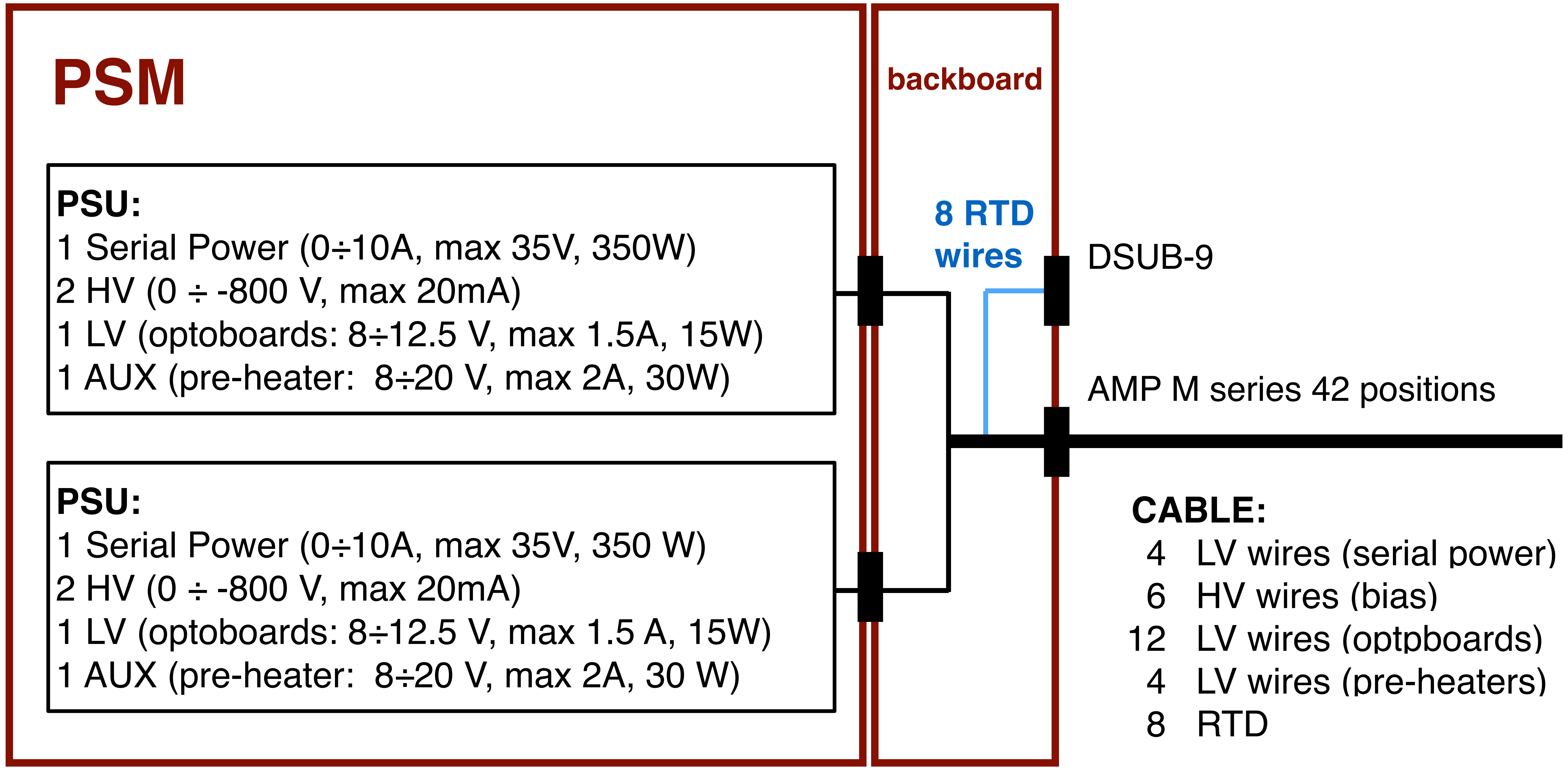
provides all the power services needed by one serial chain

Detector integration limits the number of cables which can be used to power the IT

One cable → 2 serial power chains

PSM → 1 Cable → 2 independent PSU

PSM will be located inside the CMS experimental cavern



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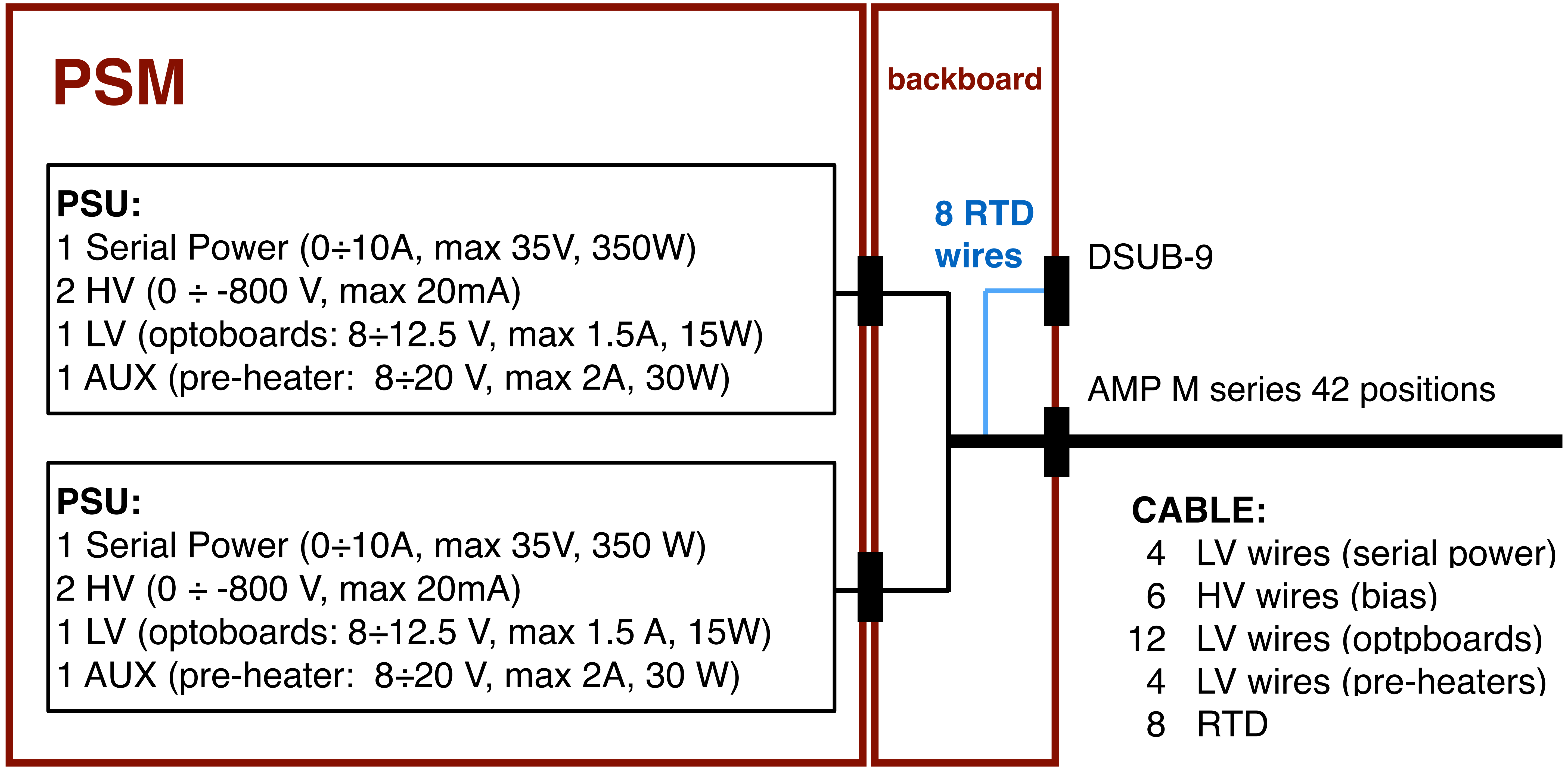


PSM will be located inside the CMS experimental cavern

Procurement of prototype units, within the CERN framework Market Survey (MS-4492/EP) has been initiated by CMS

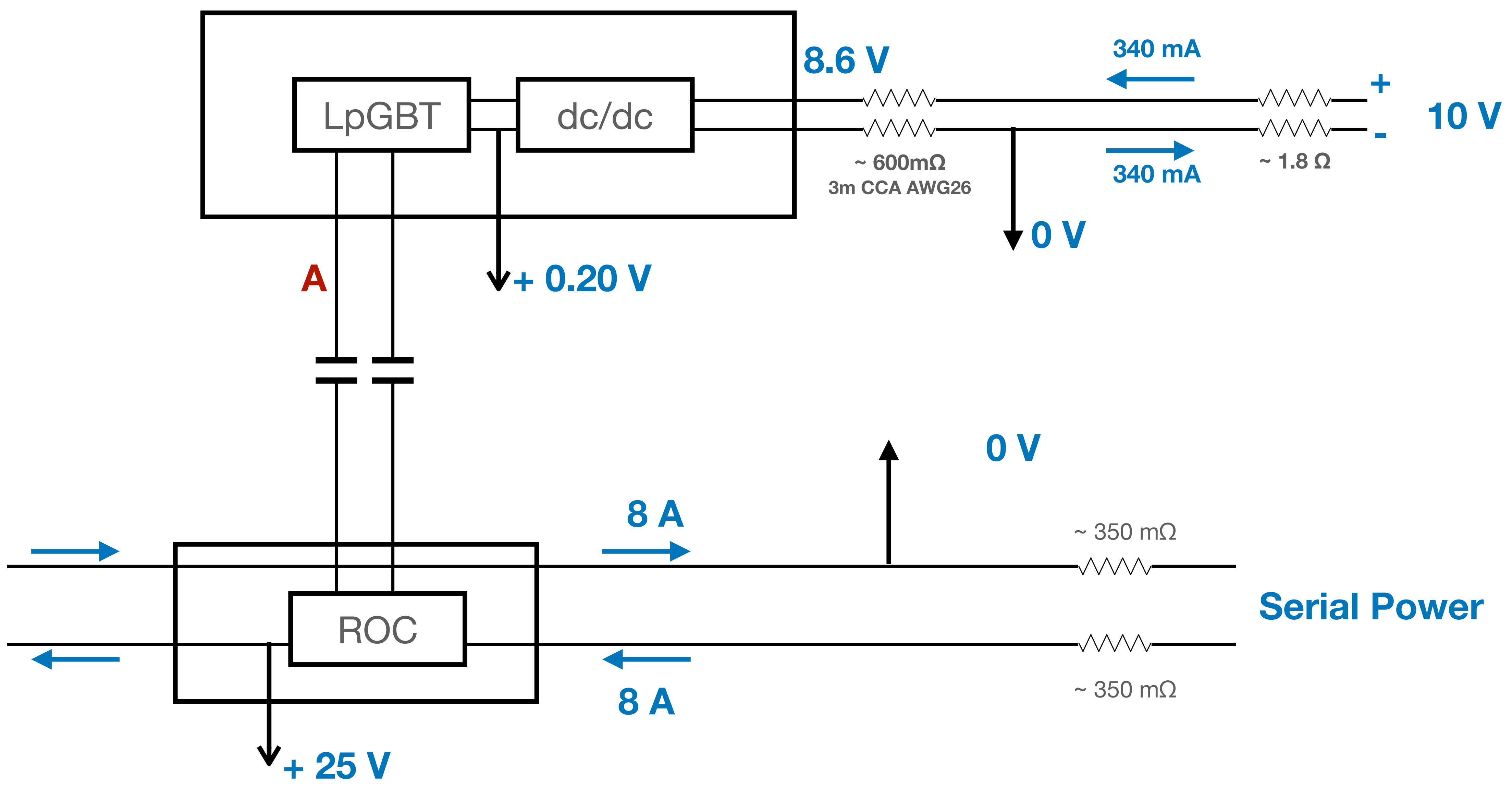
Channel interdependencies

HV veto: forbids sensor biasing when serial power is OFF

- protects the front-ends of the readout chips

Serial Power veto: forbid serial power when portcards are not powered

- prevents voltages in the serial chain from potentially damaging non-biased parts through the e-links

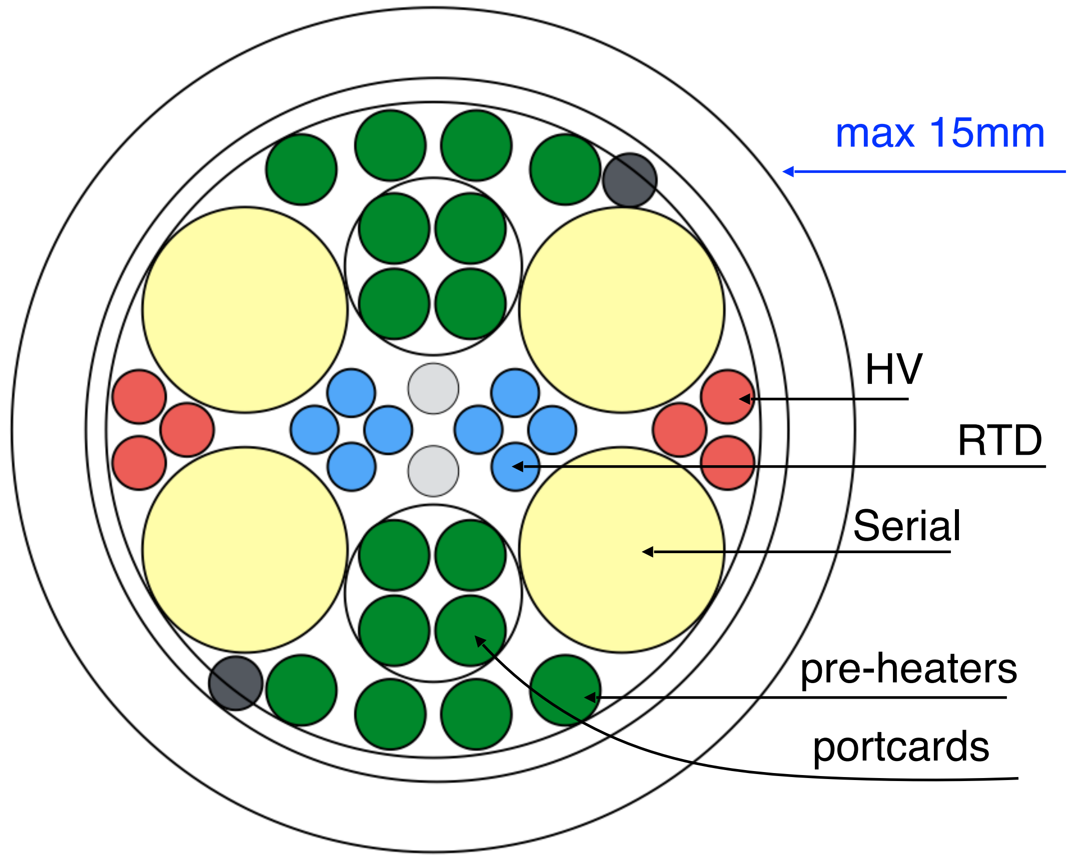


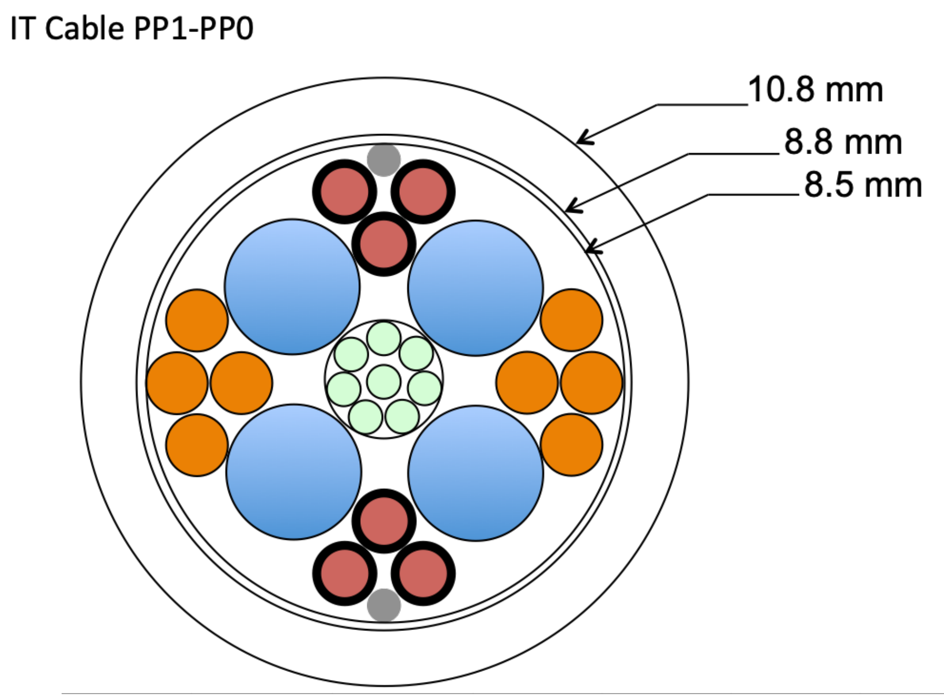
Inner Tracker Cables

Cu outside detector volume

Power-Supply - PP1
60m

PP1-PP0
~ 4 m





- Multiservice cables: various stranded Cu wires with gauges AWG12 ÷ AWG30
- up to 34 conductors (+2 drains)

Al inside detector volume

PP0-modules and PP0-Portcards

CCA wires of various gauges:

- AWG18 serial powering (4A chains)
- AWG16 serial powering (8A chains)
- AWG26 LV portcards
- AWG28 HV modules
- AWG30 RTD

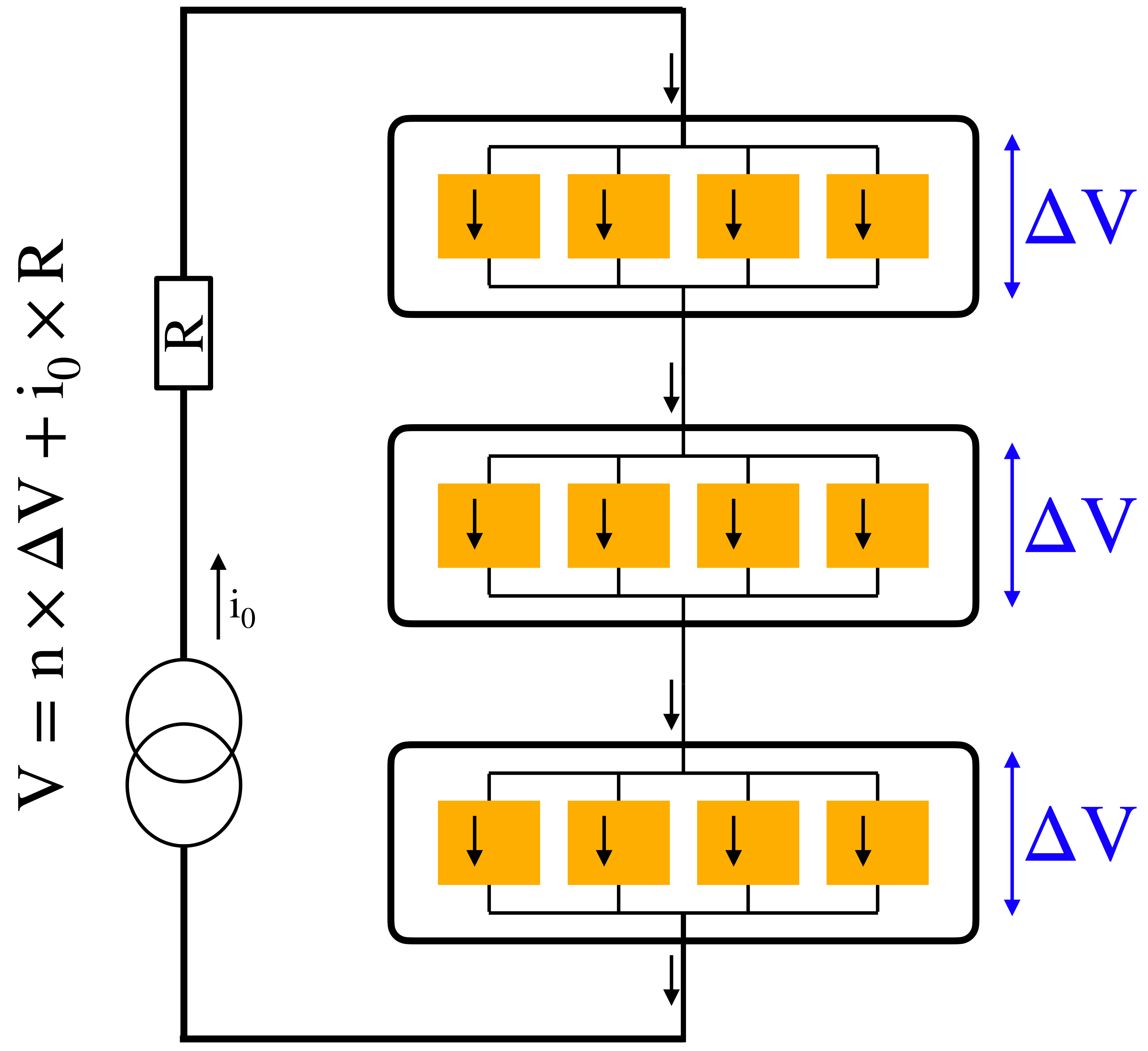
IT power request

😀 Serial powering does not pose stringent requirements on R

🧐 The most demanding chip in the chain determines the power to be delivered

Several factors contribute to the total power request:
- current in the serial chain
- ΔV across modules
- resistive parts in detector integration

Present (very preliminary) estimate of the IT power demand is around 67 kW (46 kW on detector + 21 kW on cables) delivered via 260 PSM and cables:
- 88 PSM for 2x1 modules
- 172 PSM for 2x2 modules



Racks and system integration

One 19” x 6U crate contains up to:

- 10 Outer Tracker PS
- 5 Inner Tracker PSM

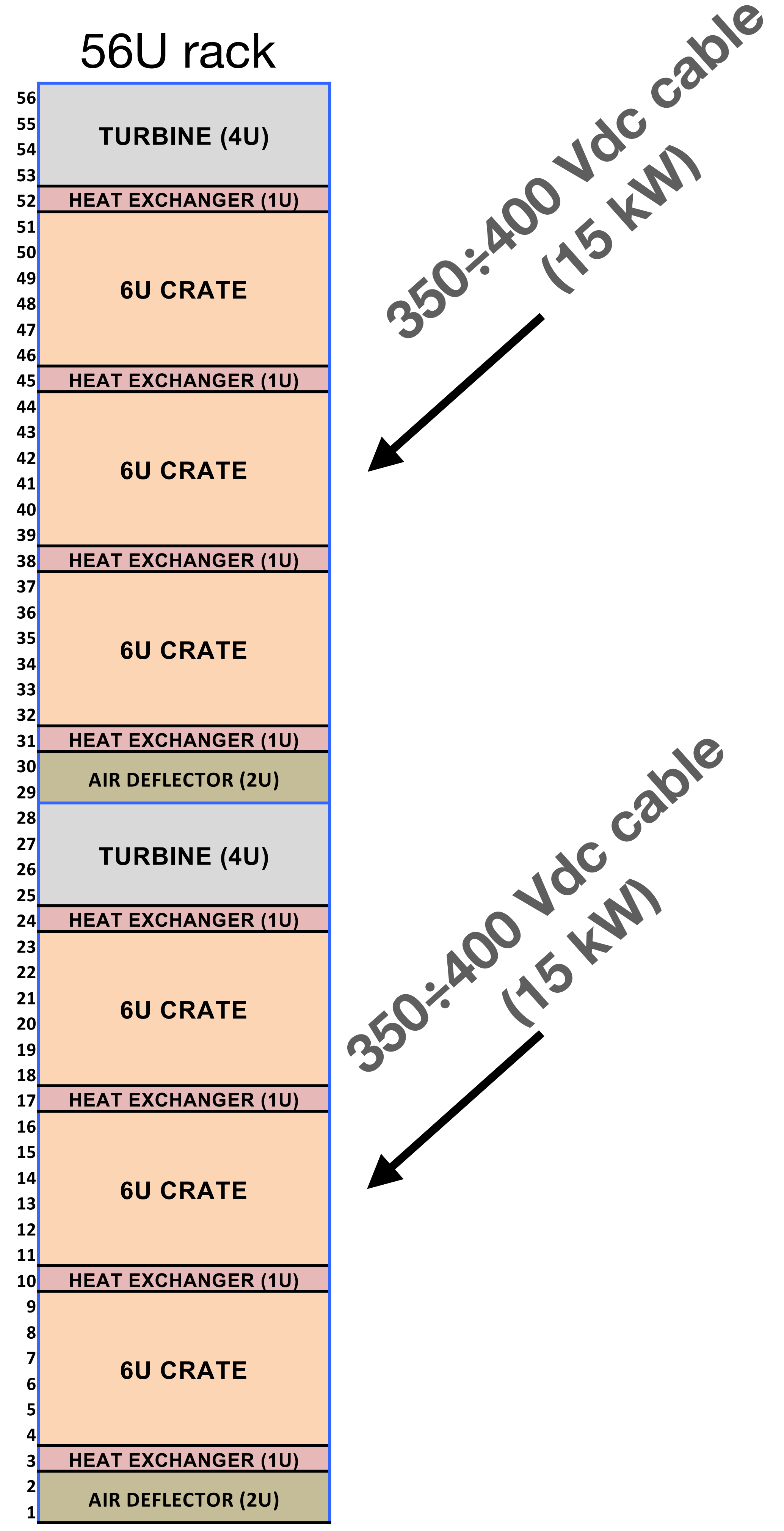
Each group of three crates is powered by one 350÷400 Vdc source (up to 15 kW)

Six crates are hosted inside a 56U high rack

IT: total of 260 PSM hosted inside 12 racks

OT: total of 1220 PSU hosted inside 24 racks

Racks located on balconies in the CMS experimental cavern



Conclusions

The CMS Tracker for HL-LHC will feature a very high number of r/o channels and chips, while keeping very low material budget. The power demand is going to be more than three times the present CMS tracker

The powering systems for IT and OT are designed and components are being prototyped. The adopted powering schemes are:

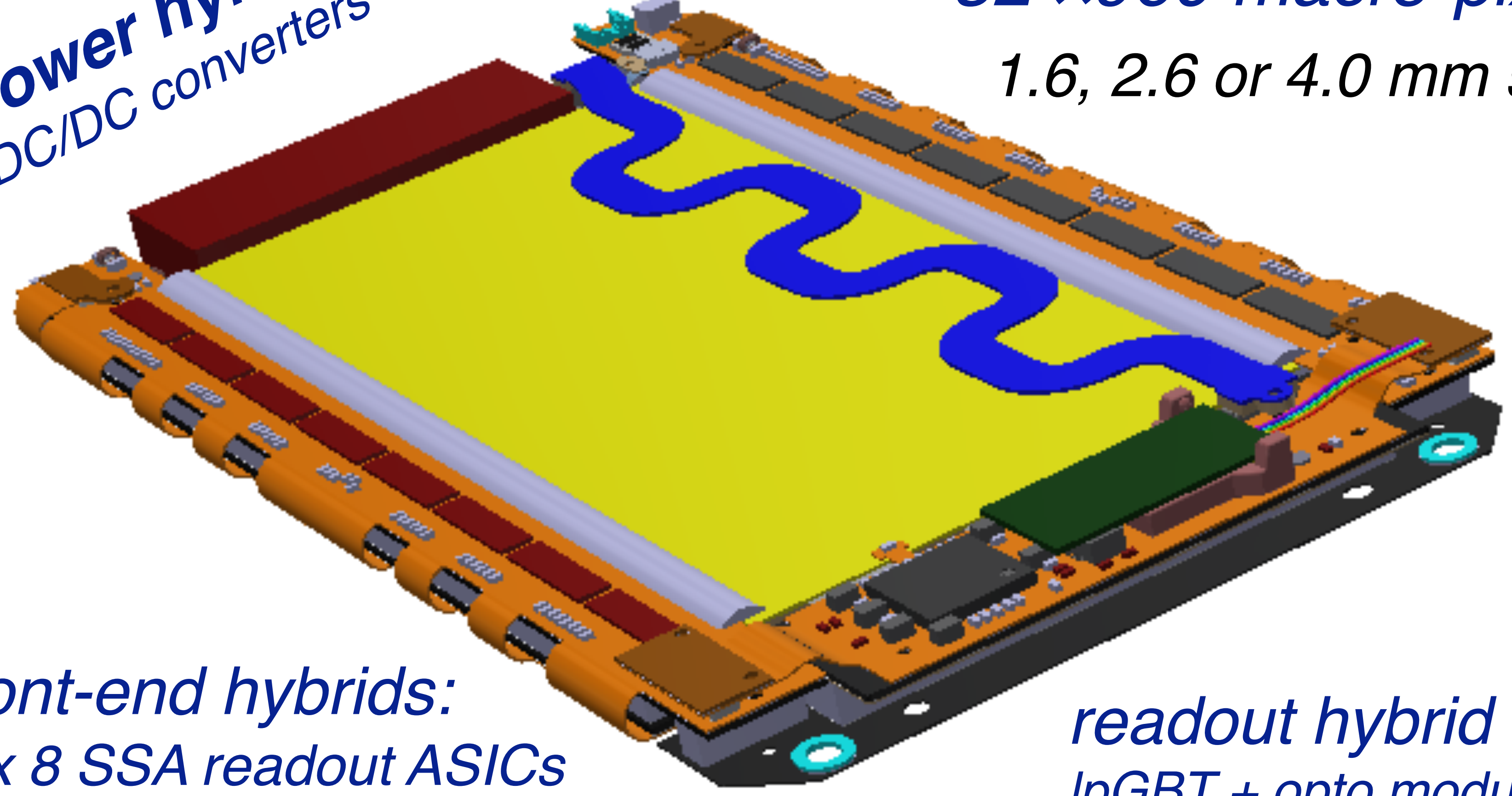
- OT: parallel powering with on-module dc/dc conversion
- IT: serial powering

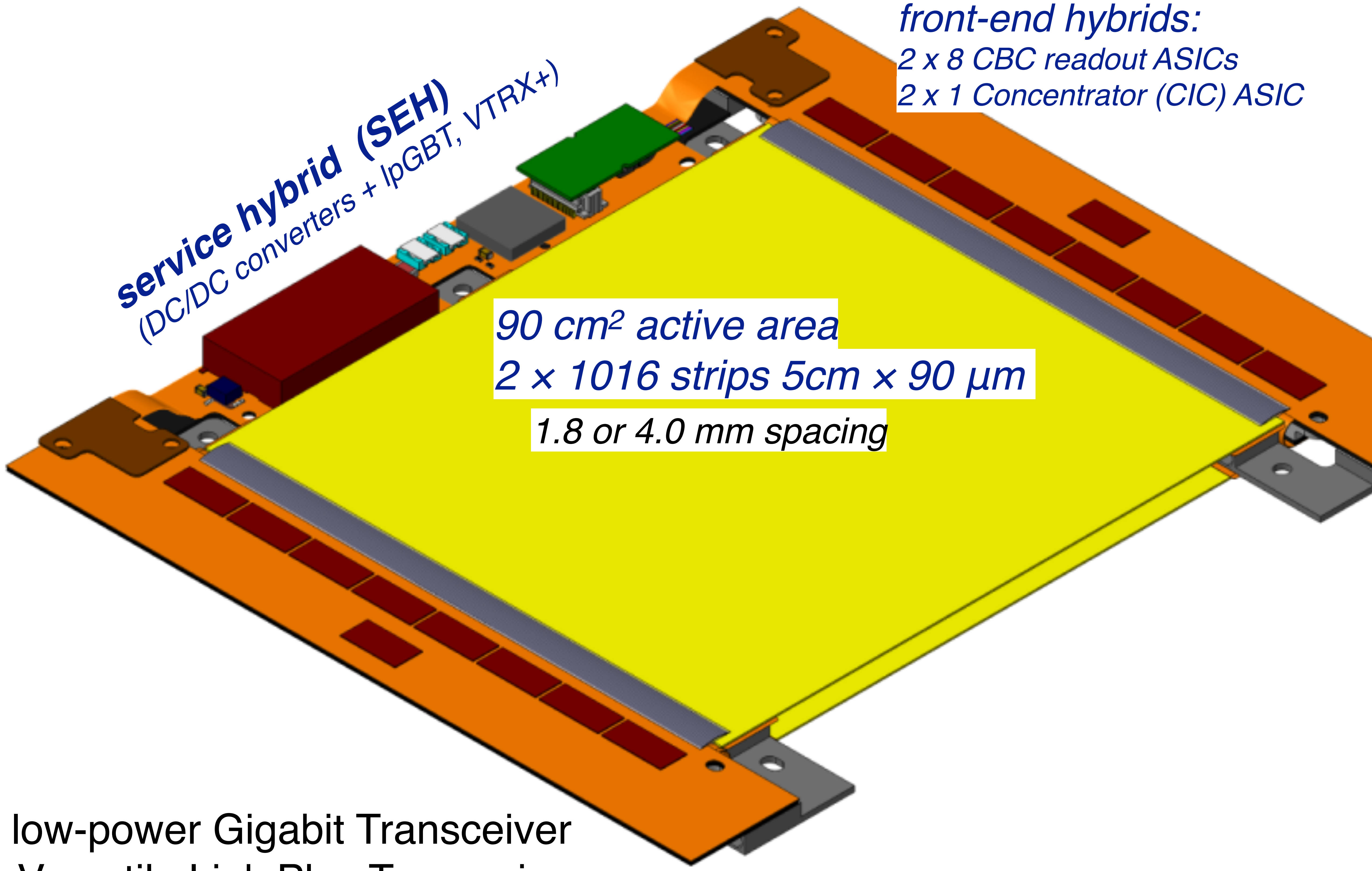
Both systems are challenging and require innovative solutions

Higher and higher power densities are demanded by new HEP detectors → the powering scheme is going to be one of the crucial elements in detector design.

Backup

The CMS Pixel-Strip (PS) and Strip-Strip (2S) Modules



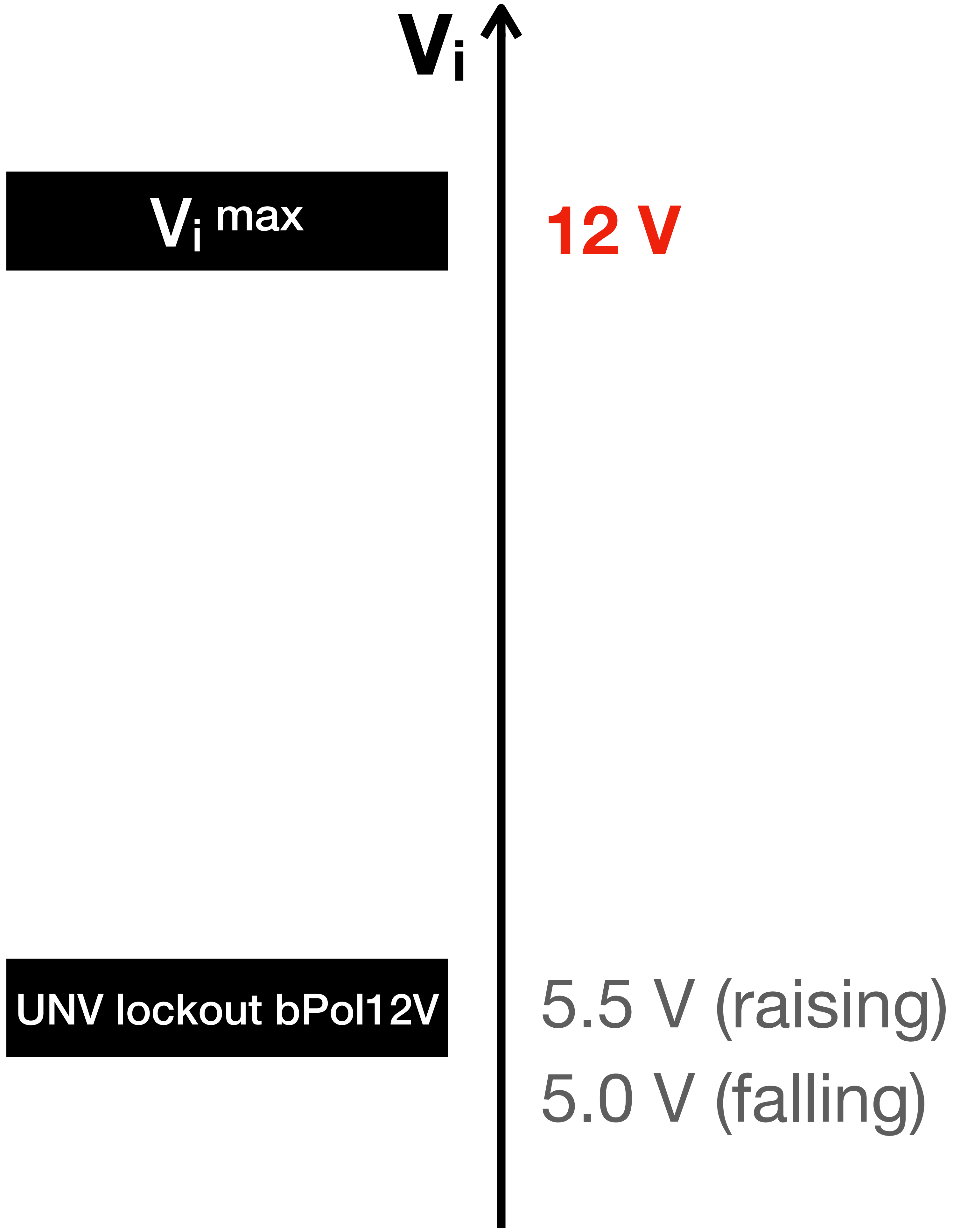


SSA = Short Strip ASIC → readout of short strip sensors
MPA = Macro Pixel ASIC → readout of Macro Pixel sensors
CBC = CMS Binary Chip → readout 2S sensors

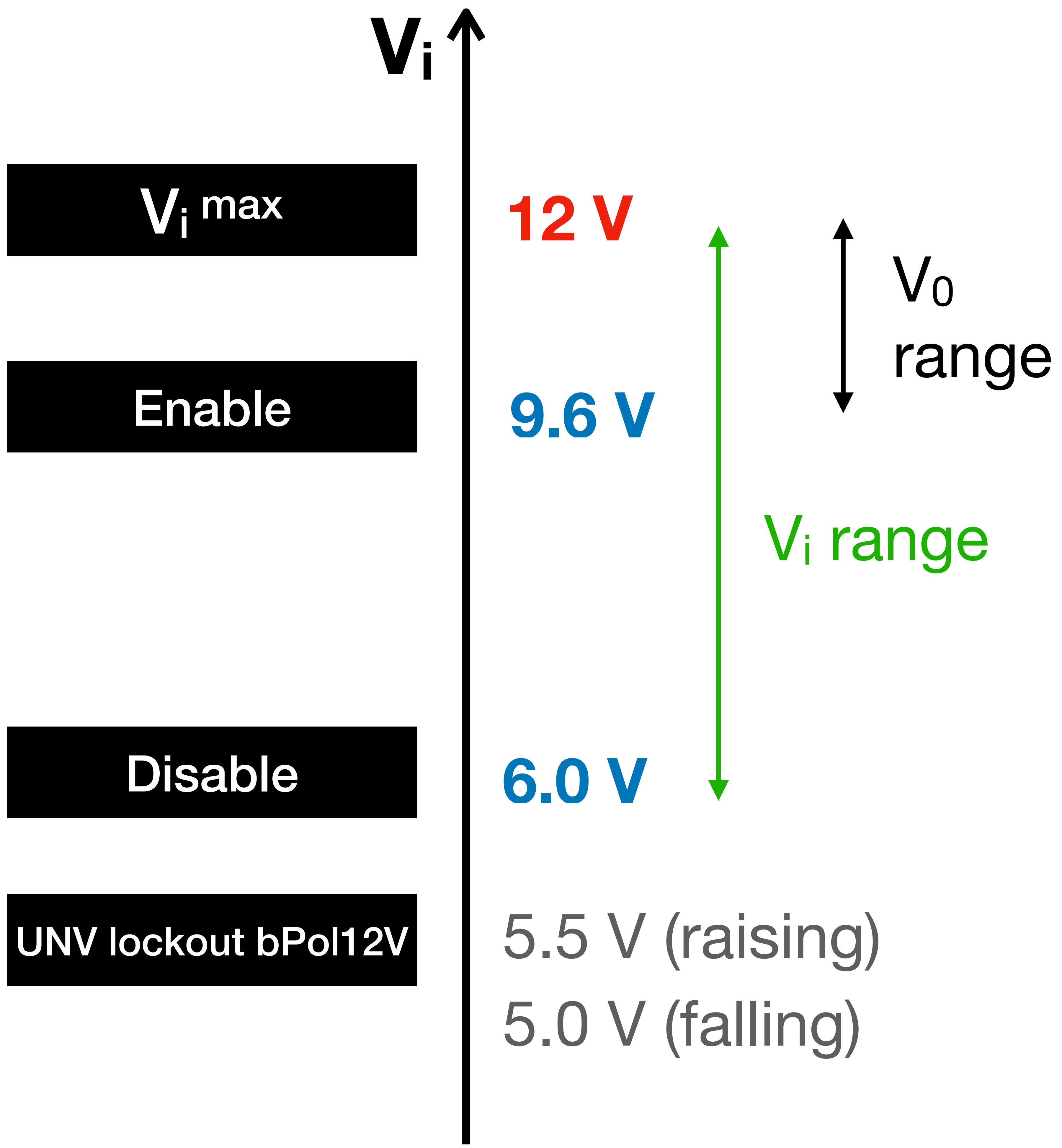
lpGBT = low-power Gigabit Transceiver
VTRx+ = Versatile Link Plus Transceiver

CIC = Concentrator Integrated Circuit
(Receives L1 information and readout data
"Data hub" to service hybrid)

Voltage range



Voltage range



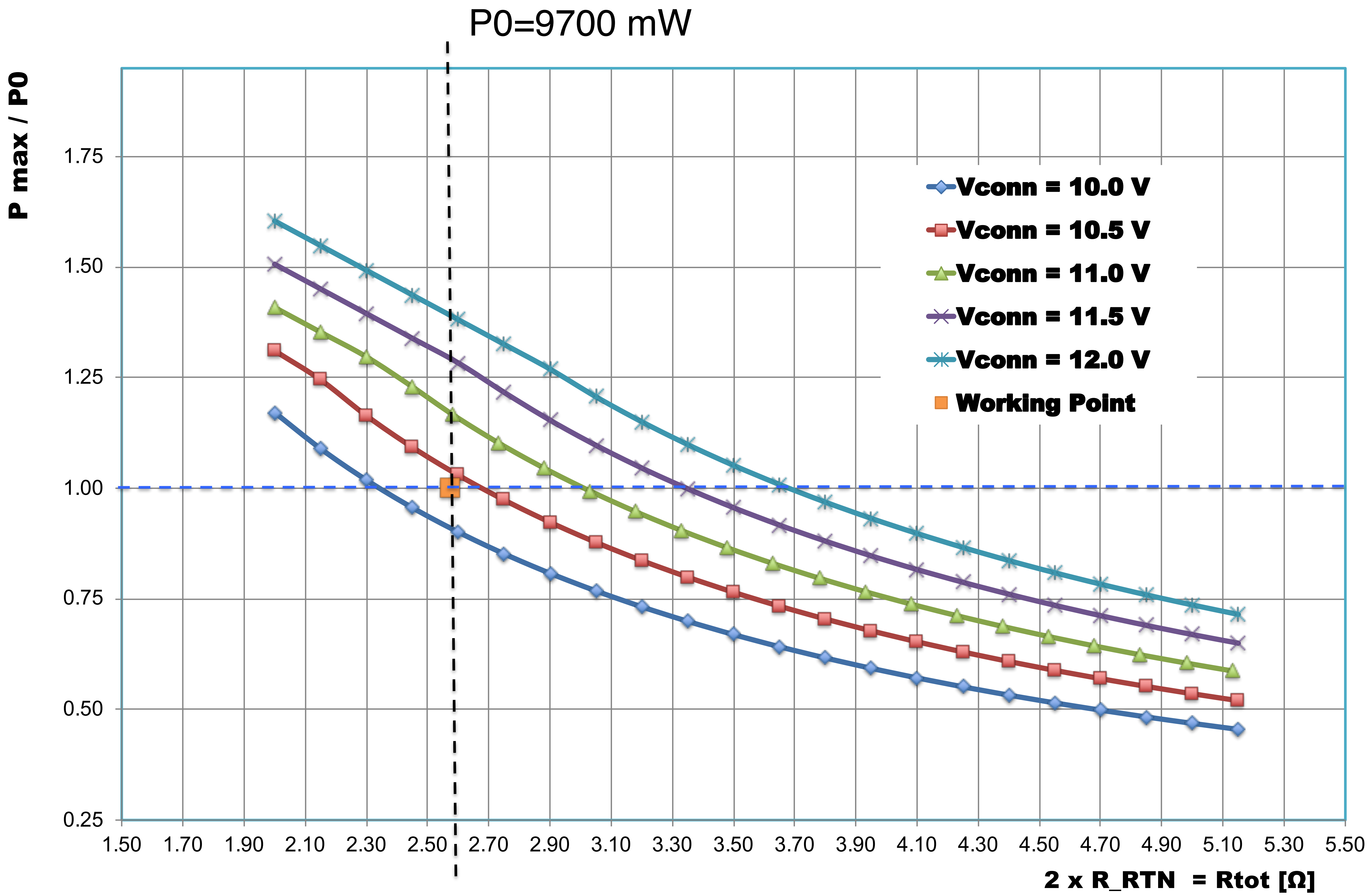
bPol12V and bPol2V5 require an enable signal

The bPol12V enable voltage is supplied by V_i via a 1/12 voltage divider inside the POH and the SEH.

- enable level (raising): 800mV x 12 = 9.6 V
- disable level (falling): 500mV x 12 = 6.0 V

The V_0 useful operational range is between 10V and bPol12V max rating (12V).

Power to the detector



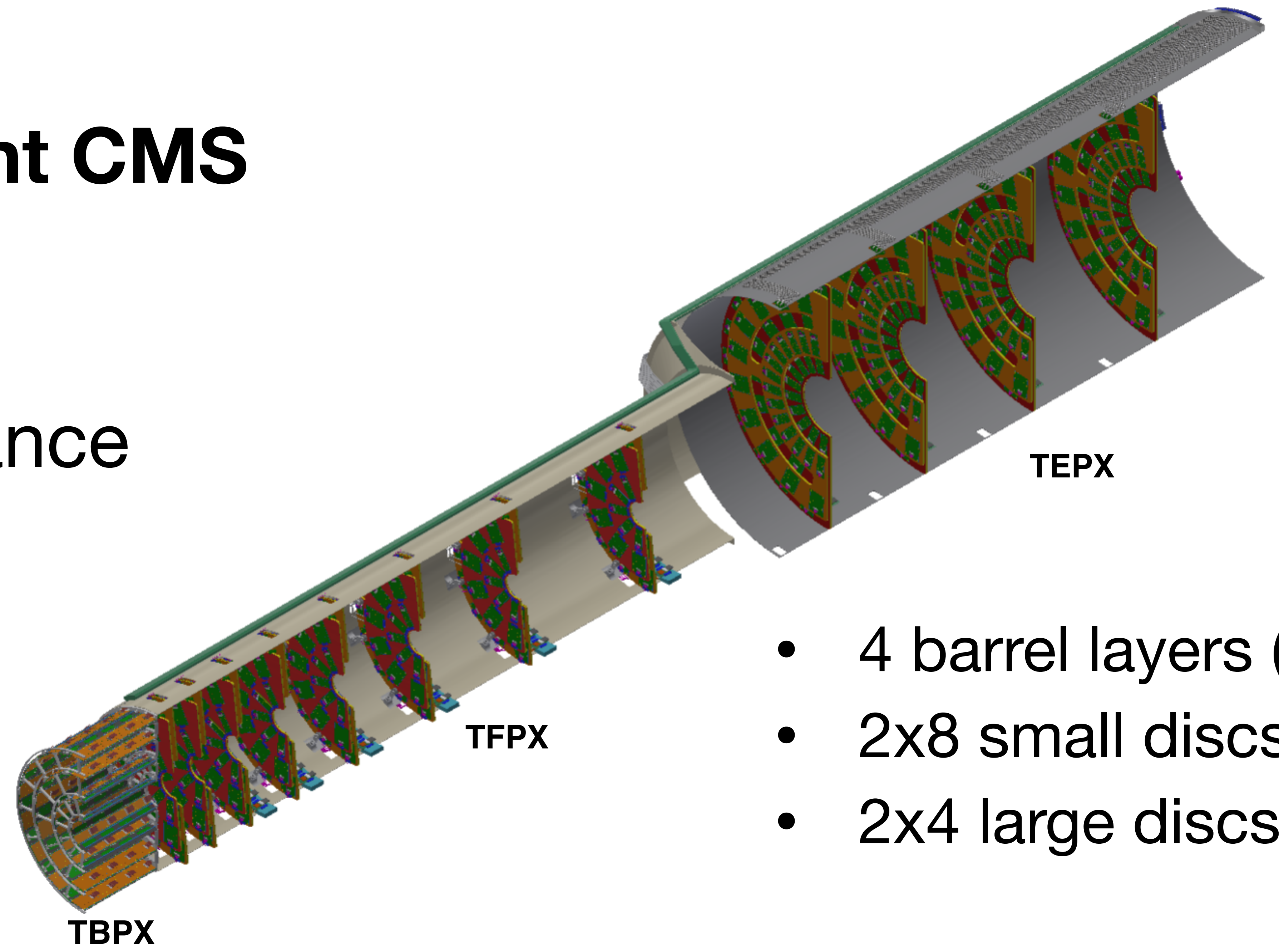
Nominal	Power delivered to each Module [mW]	Total Power Supplies [kW]	total inside cold volume [kW]	Cable power [%]	DC/DC power [%]
5592 **PS modules**	**9709**	83	62	35%	26%
7608 **2S modules**	**5159**	46	41	14%	34%
1032 **pre-heaters**	**6969**	9	8		
13200 **HV power**	**1040**	14	14		
	TOTALS	**152**	**124**	**23%**	**30%**

25% Safety	Power delivered to each Module [mW]	Total Power Supplies [kW]	total inside cold volume [kW]	Cable power [%]	DC/DC power [%]
5592 **PS modules**	**12136**	110	78	38%	24%
7608 **2S modules**	**6449**	58	51	15%	34%
1032 **pre-heaters**	**8360**	11	9		
13200 **HV power**	**1040**	14	14		
	TOTALS	**192**	**153**	**25%**	**30%**

The CMS Inner Tracker for HL-LHC

It will replace the present CMS pixel detector featuring:

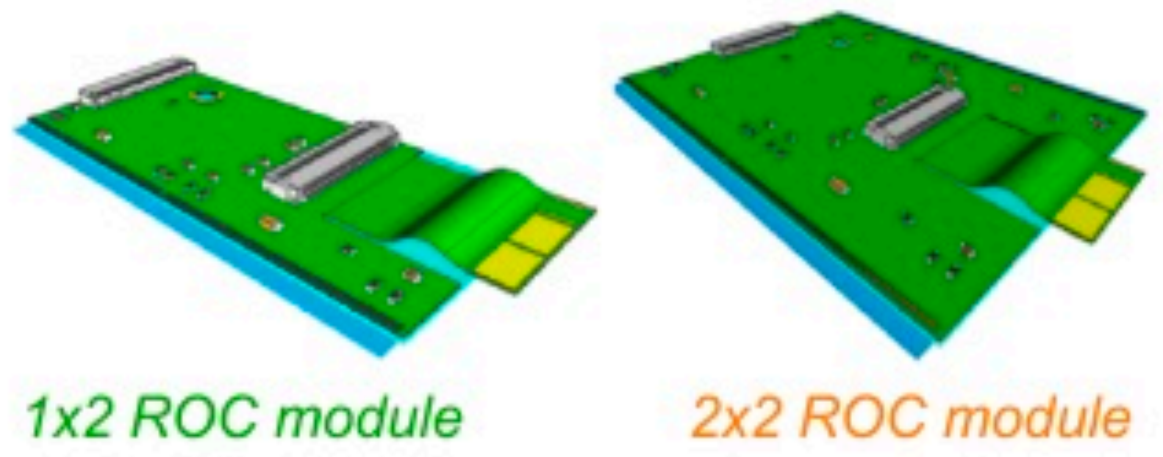
- reduced pixel cell size
- improved radiation tolerance
- reduced material budget
- coverage up to $|\eta| = 4$



- 4 barrel layers (**TBPX**), 4 or 5 modules per ladder
- 2x8 small discs (**TFPX**), 4 rings per disc
- 2x4 large discs (**TEPX**), 5 rings per disc

Readout chip: CROC (RD53 Collab.)
→ supports serial powering

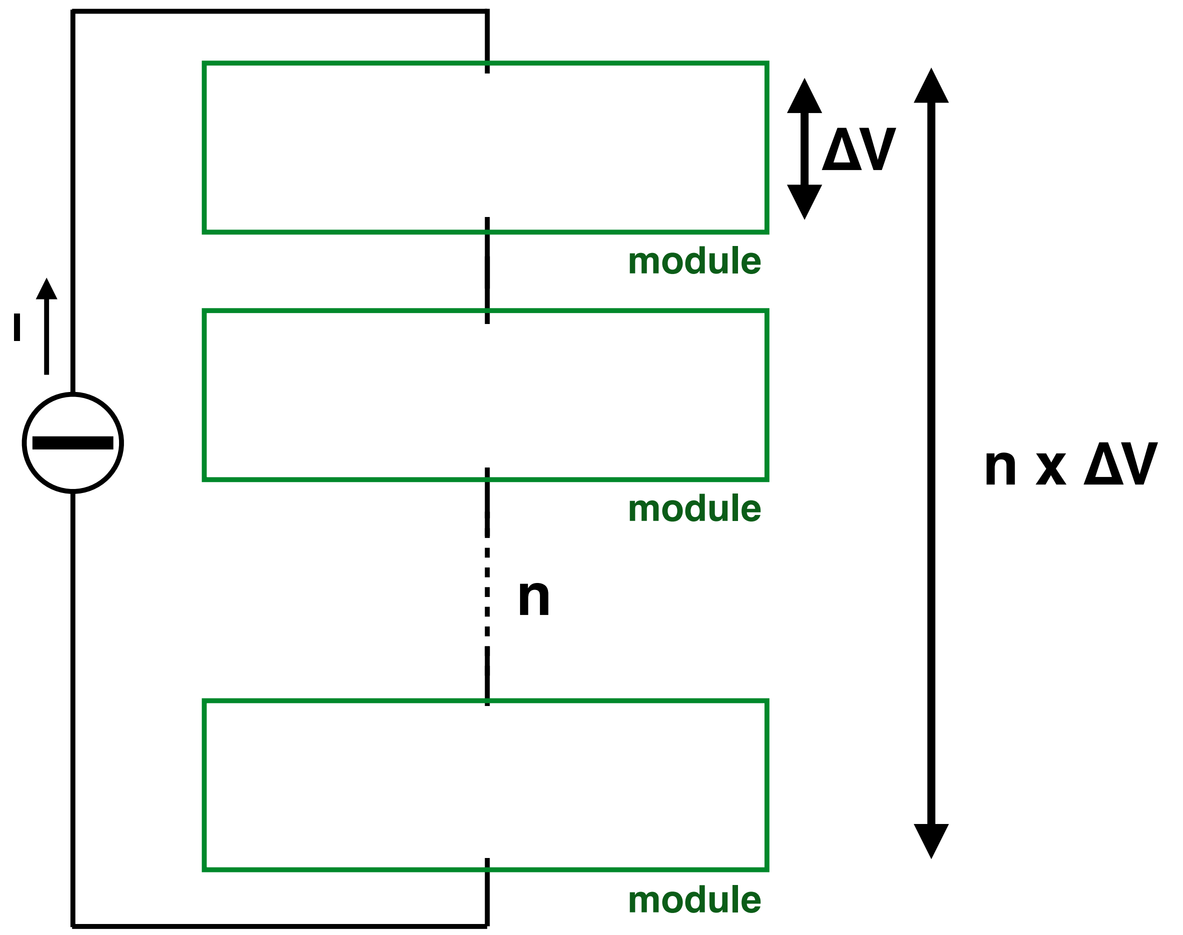
Two main hybrid pixel module types: 1x2 and 2x2 readout chips per module



Serial Powering

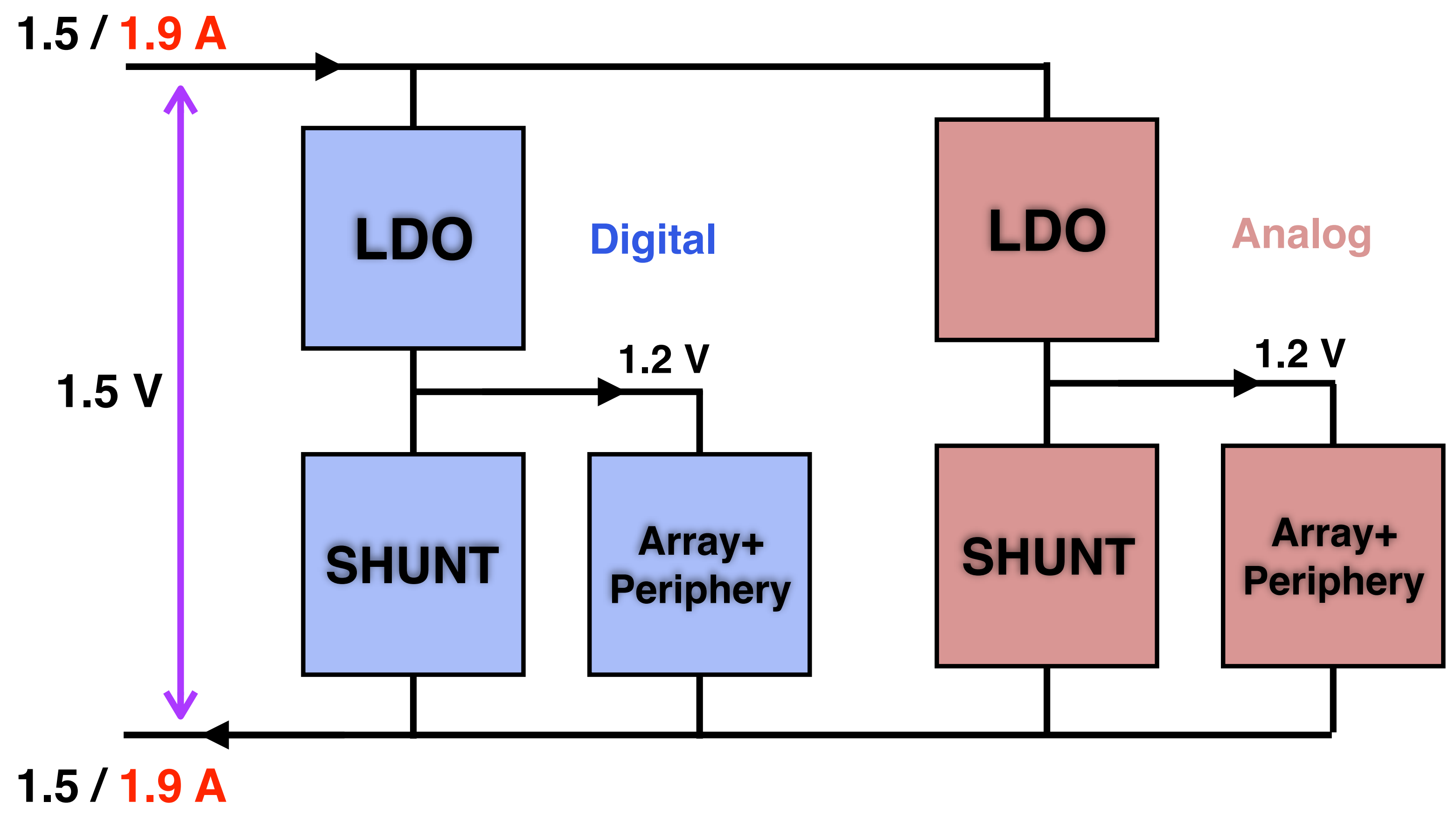
Up to 11 modules connected in one serial chain

Current is shared in parallel b/w r/o chips inside the same module



Serial powering is supported by the r/o chip via the shunt-LDO IP block, providing:

- ➡ shunt functionality: needed to implement the serial scheme
- ➡ LDO regulation: ensure correct voltage (~1.2V) to the electronics

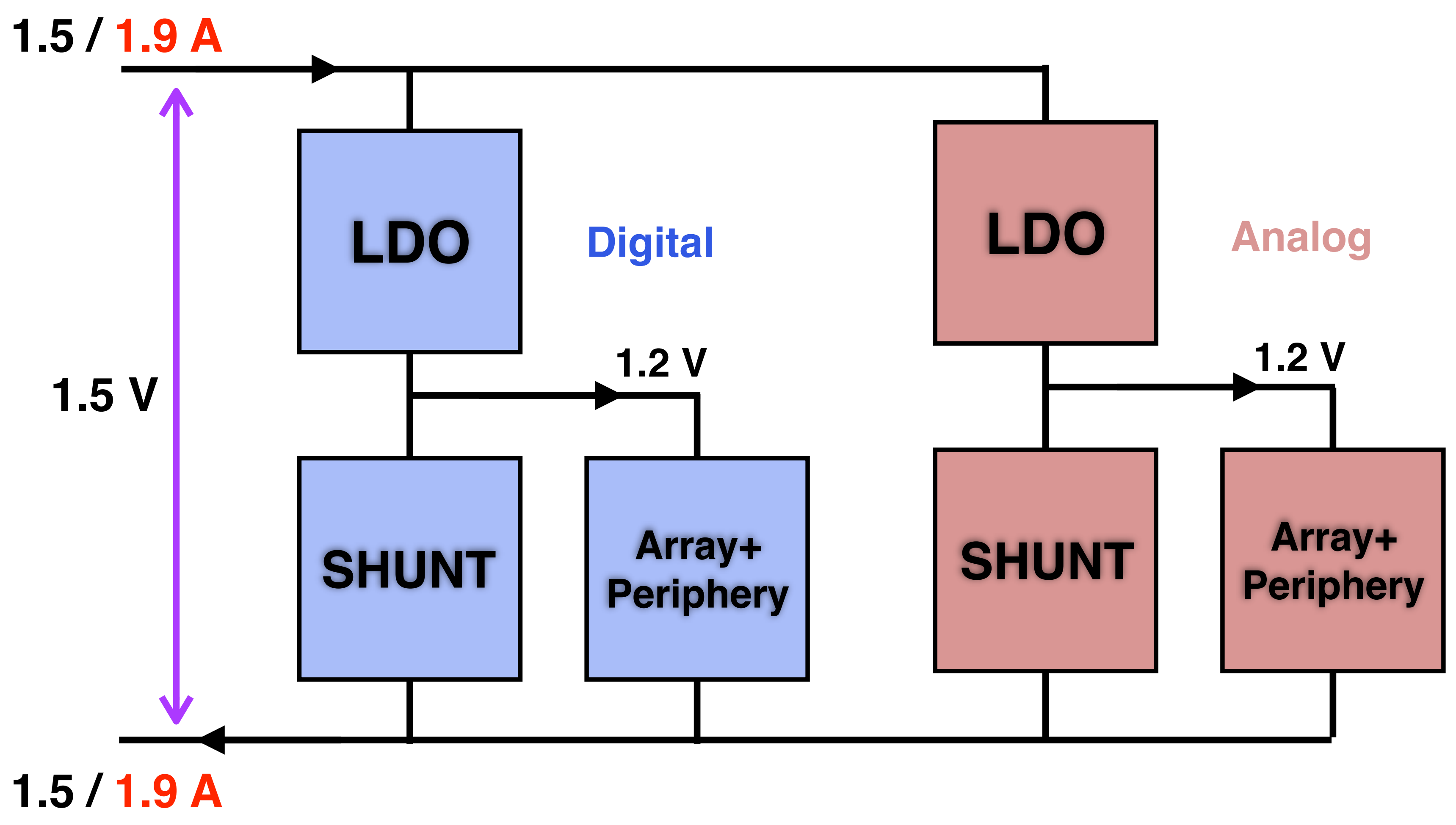


- the Shunt-LDO configuration defines ΔV=f(I)
- aiming at ΔV~1.5 V (1.2V + 0.3V for LDO)
- the chain has to provide enough power for transients: considered ~ 25% current headroom w.r.t. "typical" conditions

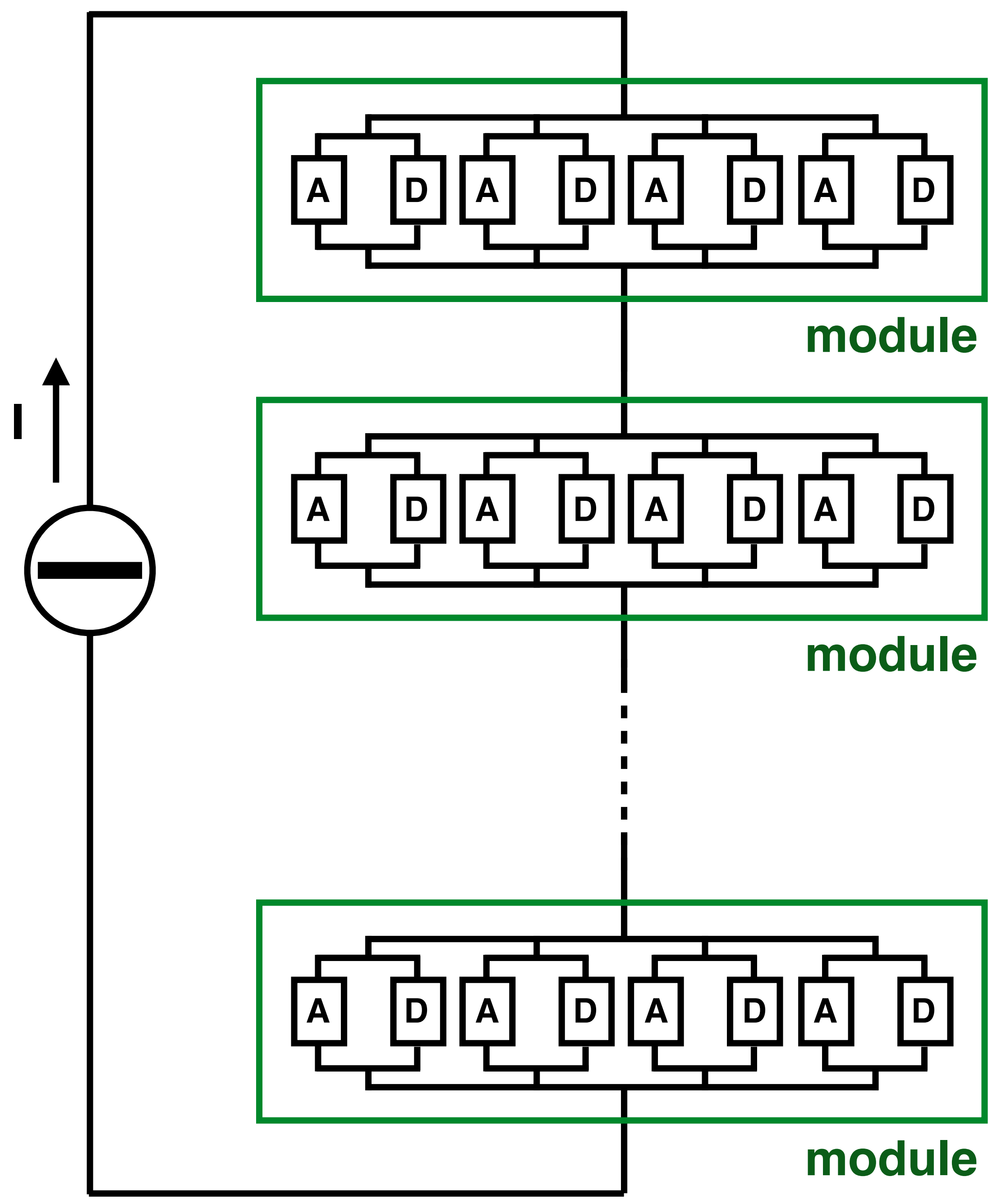
Few crucial aspects for power consumption

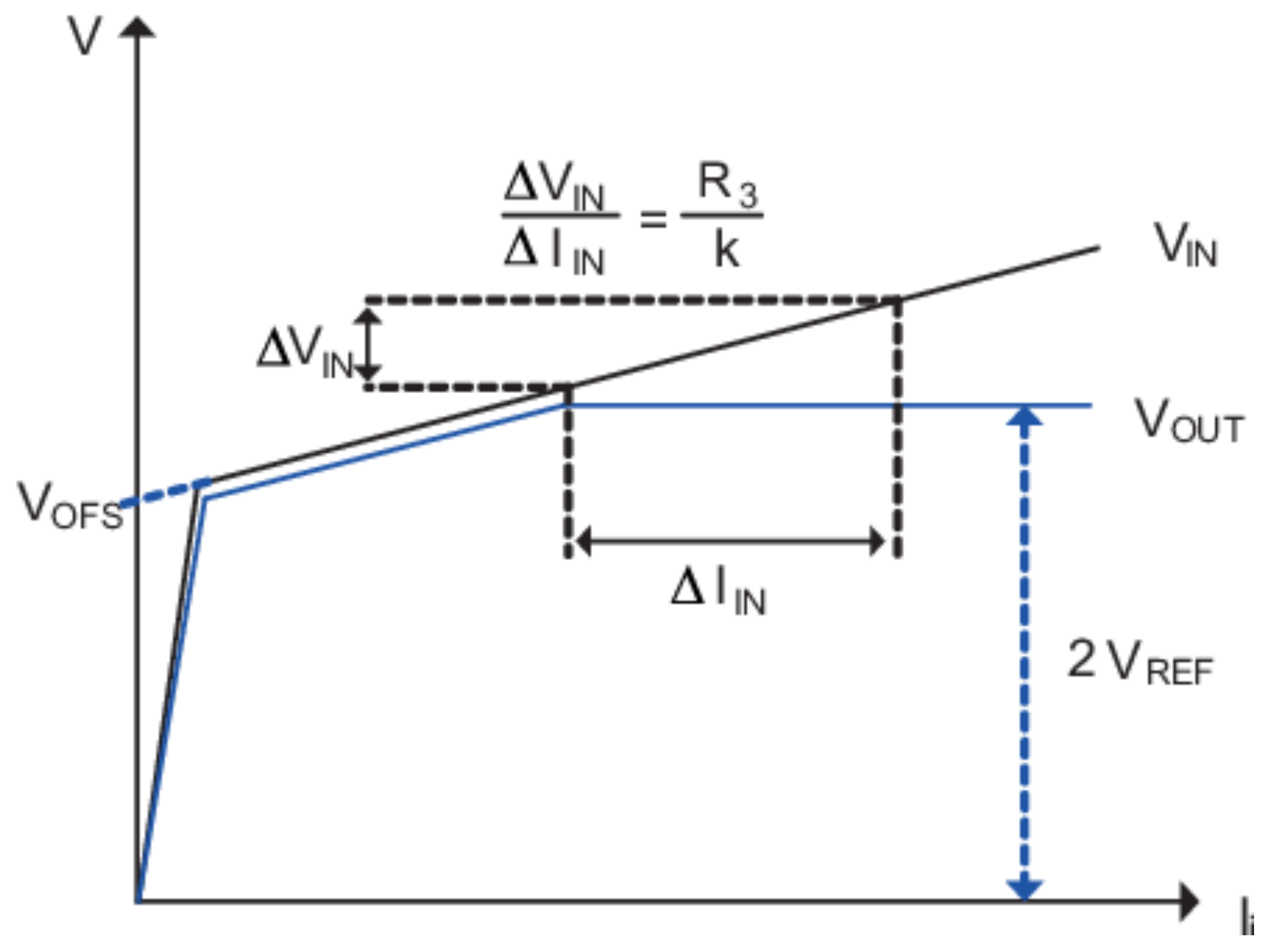
Serial powering is supported by the r/o chip via the shunt-LDO IP block, providing:

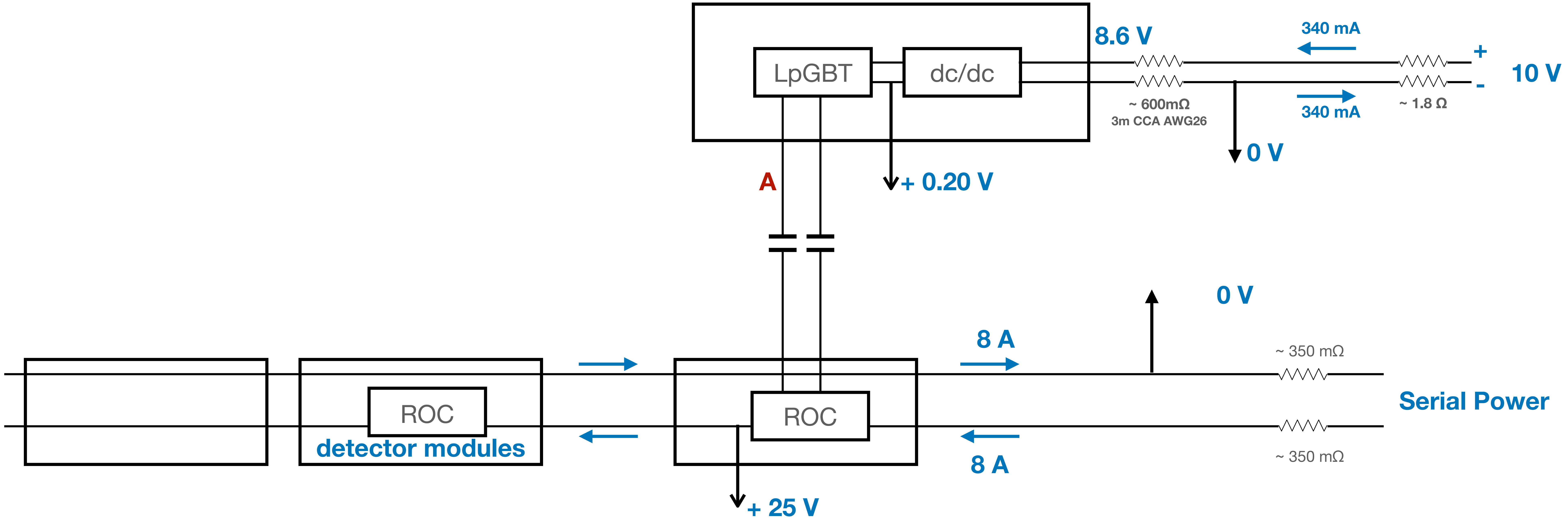
- ➡ shunt functionality: needed to implement the serial scheme
- ➡ LDO regulation to ensure correct internal voltage



Current is shared in parallel b/w r/o chips inside the same module







LpGBT
dc/dc
8.6 V
340 mA
+
10 V
-
~ 600mΩ
3m CCA AWG26
340 mA
~ 1.8 Ω
0 V
A
+ 0.20 V
0 V
8 A
~ 350 mΩ
ROC
detector modules
ROC
Serial Power
8 A
~ 350 mΩ
+ 25 V

Sensors forward biasing

Low resistivity path: HV to RTN when HV OFF

- avoid sensor forward biasing
- either a crowbar or a diode-like structure