New generation B-Field and RAD-tolerant DC/DC power converter for on-detector operation

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Why?

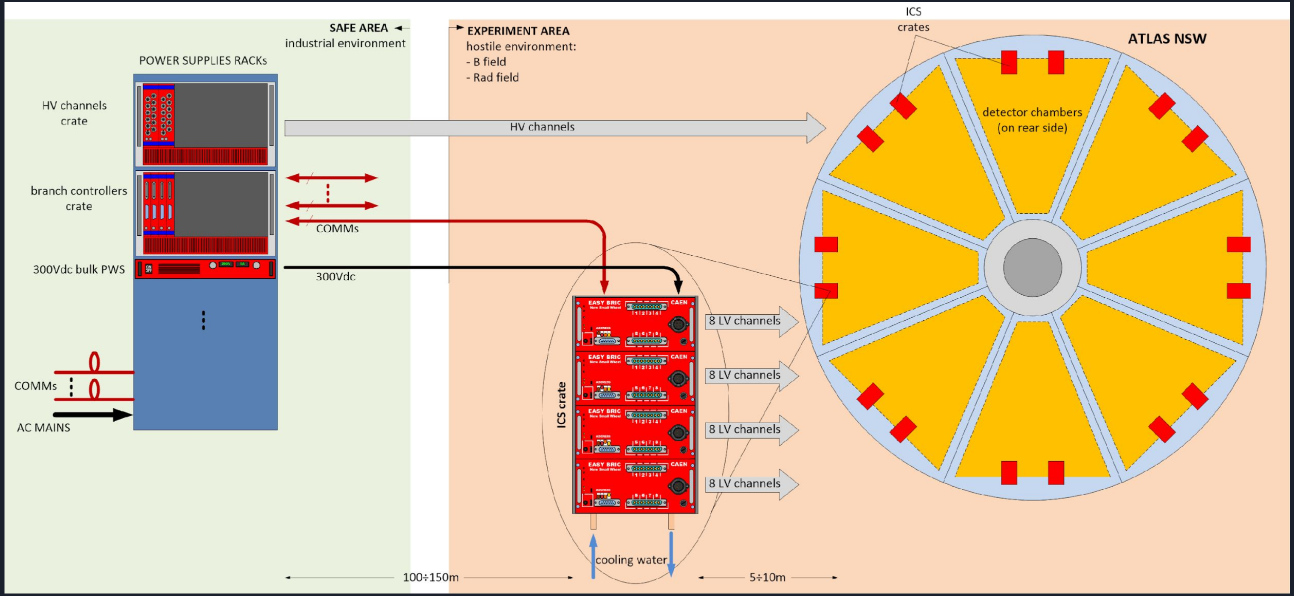
- Most of the recent upgrades in the large physics experiments use new types of detectors, like the Micro Pattern Gaseous Detectors (MPGD).
- This tendency requires upgrading the power distribution strategy by modifying the infrastructure topology:
    - Need of managing a larger number of independent channels;
    - Need of distributing the power with high granularity;
    - Need to deliver low supply voltages (up to few V) with currents up to few A.

Why?

- Advantages:
  - Precise and optimised control;
  - Isolating capability in case of problems;
  - Reducing the mutual interaction of the various sub-parts of the detector electronics.
- But:
  - Lower voltages with higher current result in higher voltage drop and the need for a higher cable cross section.
  - Therefore, in comparison to the standard power distribution strategy, it is not anymore possible to place the power supplies too far from the relative detectors;

New power distribution strategy

- Reconceives the multi-stage conversion:
  - no addition of point of load;
  - no sensing network;
  - provide remotely from the safe area the primary DC power supply (~300V);
  - introduction of intermediate conversion stage "ICS".



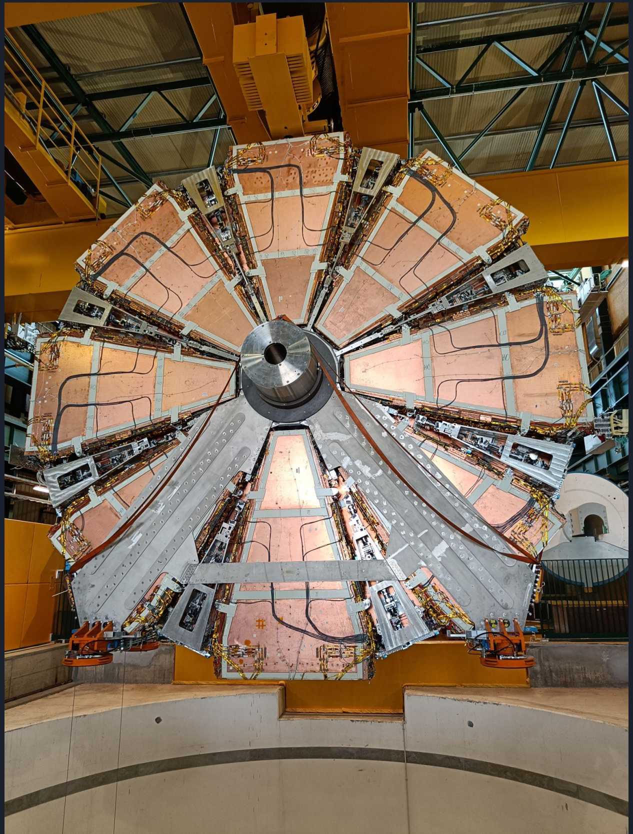
- Integrate the new generation DC/DC converter in the detector.
- Require the new power supplies to be exposed to very hostile environment.
- Opens for new technology challenges, from geometrical and physical constraints to radiation and magnetic field hardness.

The case of ATLAS New Small Wheel

- Guide to the development of such strategy and design of the new converters.
- NSW is composed of two detectors, the Micromegas (MM) for tracking and the sTGC for triggering.
- LV power required by the front-end electronics of both detectors is about 100kW.

- Objectives:
  - Create compact system, with high power density within the limited space available.
  - Maximize efficiency, given the criticality in heat transfer, and integrate its cooling system with the detector.
  - Maximize the reliability, providing mechanical facilitations to assure easy maintenance.

- Tender was awarded to the company CAEN S.p.A., which designed and produced the LV power system Easy6000 BRIC.



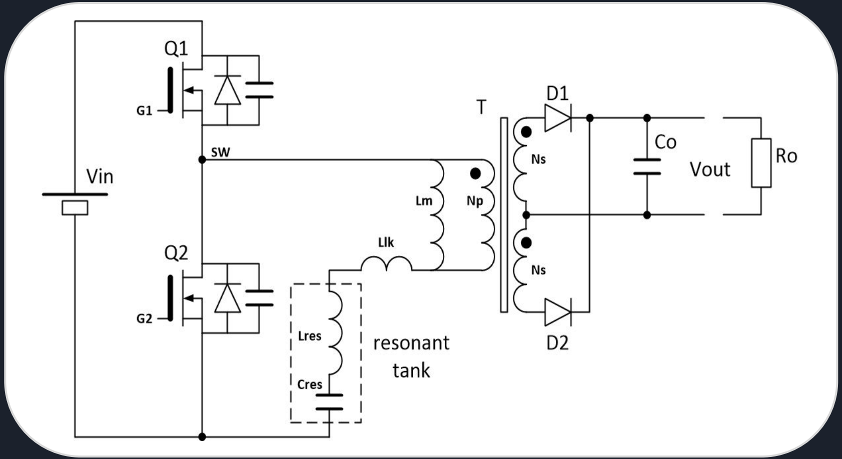
Design of the new ICS - Considerations

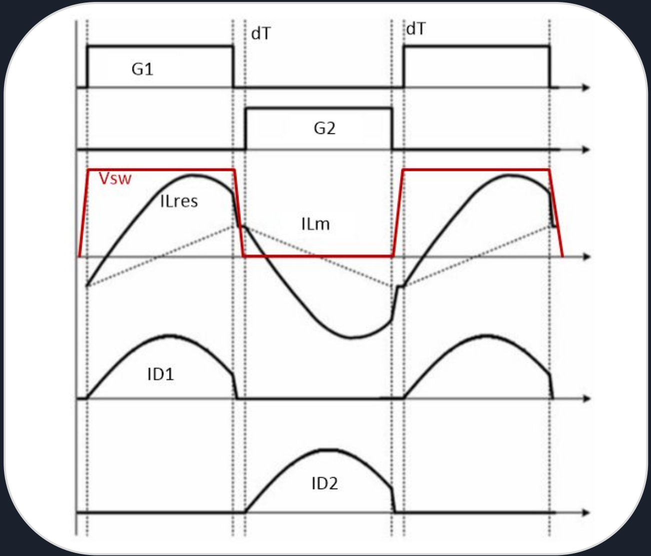
- GaN devices have proven to be effective and were chosen for this design:
  - wider band-gap than silicon devices, which means higher break-down voltages and smaller size;
  - very fast, with low gate charge requirement;
  - able to better tolerate ionising radiation than silicon devices;
- Another criticality is the requirement to create galvanic isolation between input and outputs.
- Necessary to design an isolated DC/DC converter inserting a transformer, which will have to work in the presence of high magnetic fields (transformer design in F. Giordano poster).

Electronics design

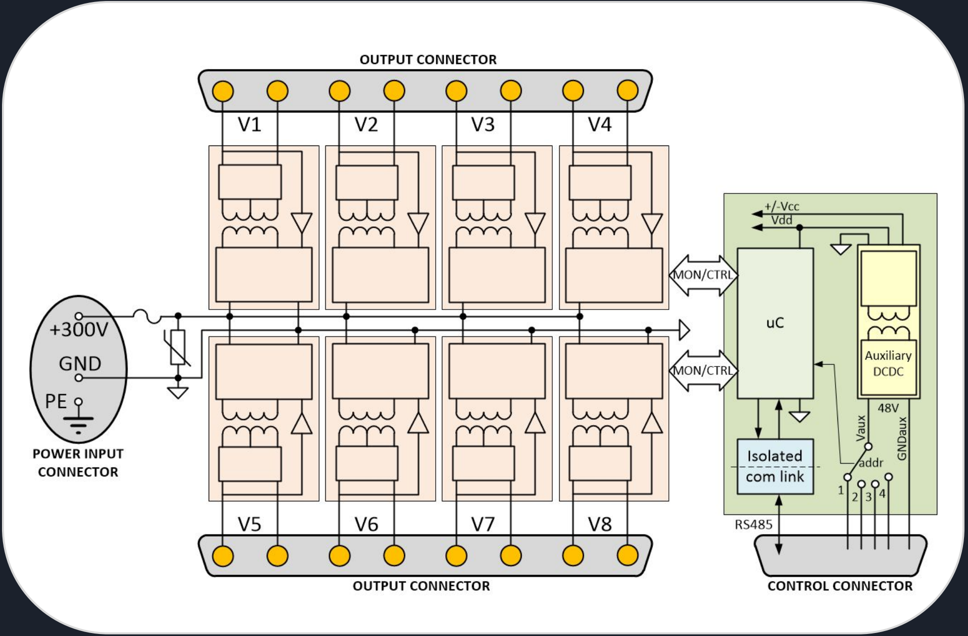
- LLC-HB converter can be a good choice to satisfy the given needs and constraints.
- Key element is a resonant circuit based on a L-C tank.

- Advantages:
    - soft commutation of FETs and Diodes;
    - low inductive component count;
    - voltage applied to FETs defined and limited to Vin;
    - fixed 50% duty-cycle driving;
    - high frequency operation.





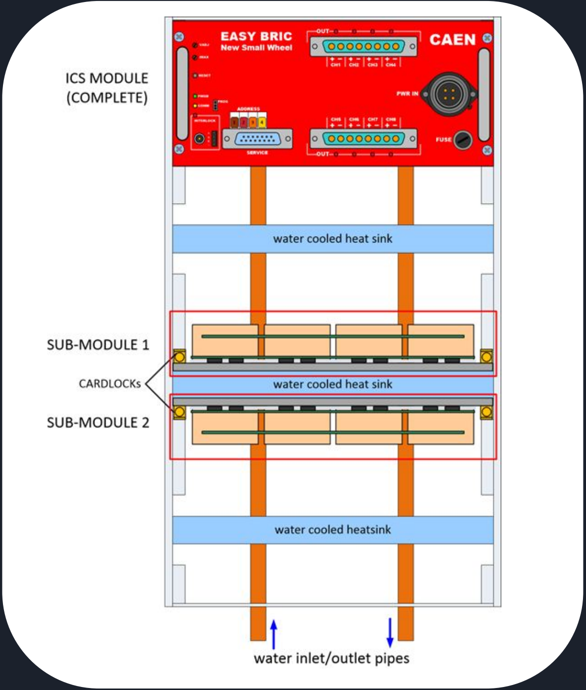
Control

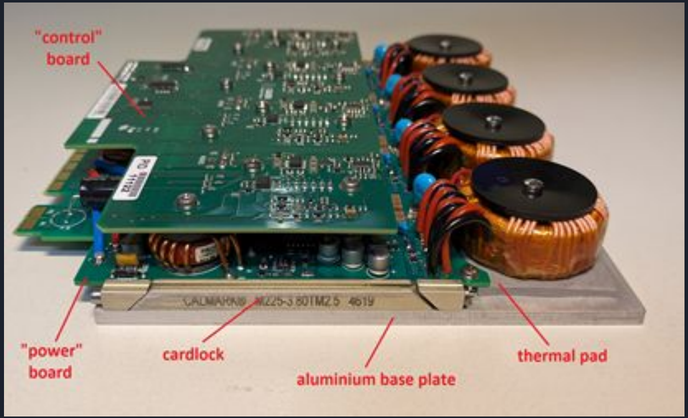


- To meet the requirements, a module containing 8 170W DC/DC was designed: every channel is independently controlled and monitored.
- Local controller implemented, communicate with remote controller via RS-485. Auxiliary power supply for service voltages is provided.
- Both communications and power supply isolated, capacitive barrier digital isolators adopted for communication.
- μC is another critical part of the project: tests were carried out, and a specific one passed preventive radiation tests up to the levels expected.

Mechanics

- Another requirement was the grouping of 4 modules in a unique crate.
- Modules are divided into 2 submodules of 4 channels each.
- The presence of magnetic field prevented the use of fans, the heat transfer was achieved by a liquid cooling system.





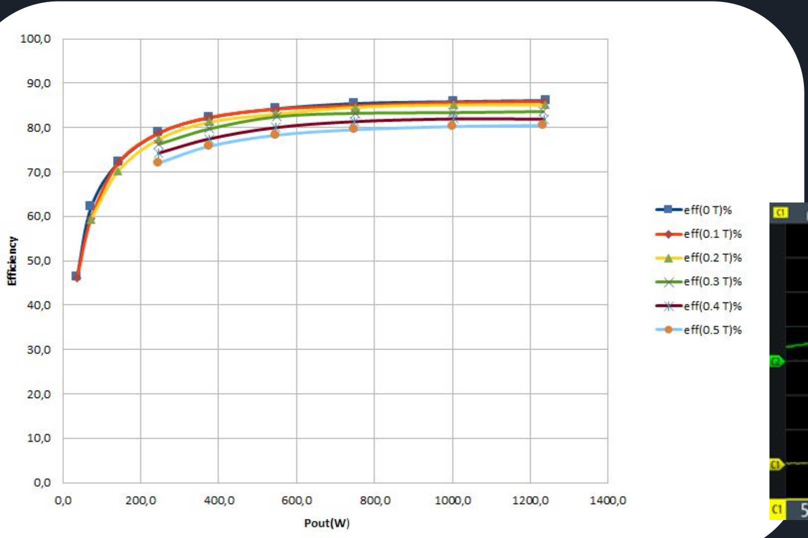
- All components that dissipate heat are in thermal contact with an aluminum plate that at its time is pressed on heatsinks with cardlocks.
- Submodules are independently inserted above and below their heatsink
- A front panel with µC, aux psu, communication and connectors (common for each module) close the structure, allowing quick maintenance operations.

Environmental tests

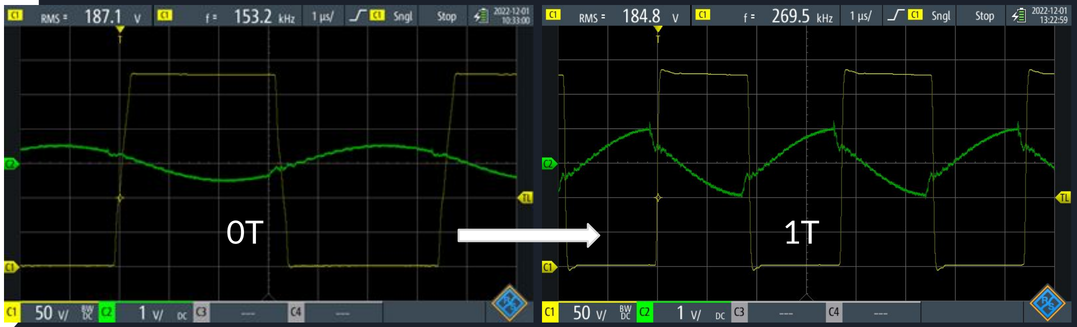
- Radiation hardness: test campaigns of the entire converter were performed in CHARM facility at CERN:
  - Total Ionizing Dose (TID) = 189.6 Gy ;
  - Hadrons (E > 20 MeV) = $6.7 \times 10^{11}/cm^2$;
  - Neutrons (1 MeV equivalent) = $2.1 \times 10^{12}/cm^2$.
- Recorded events:
  - 3 “OFF”, meaning that the channels went OFF and required a manual turn-on;
  - 7 “communications lost”, needed manual reset;
  - 20 self-resets of the microcontroller.
- No destructive events, all channels were still working after the irradiation.
- Microcontroller internal memory kept settings and calibration data without corruption.
- Internal aux voltages, output voltage/current monitor remained constant and stable.

Environmental tests

- B-Field tolerance validation in CERN MNP17 and GOLIATH facilities.
- MNP17: behavioural hardness and efficiency measurements.
- All channels connected to active loads and switched ON at different B-fields, from 0 up to 0.5T in steps of 0.1T, and at different output currents, up to 15A.

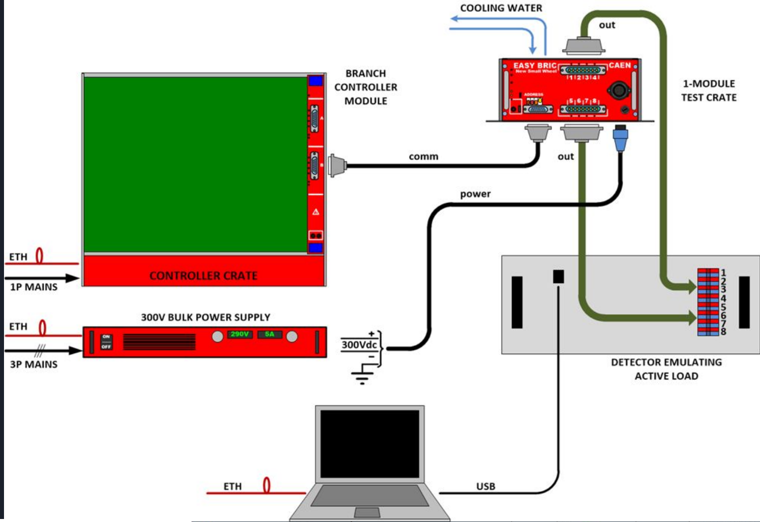


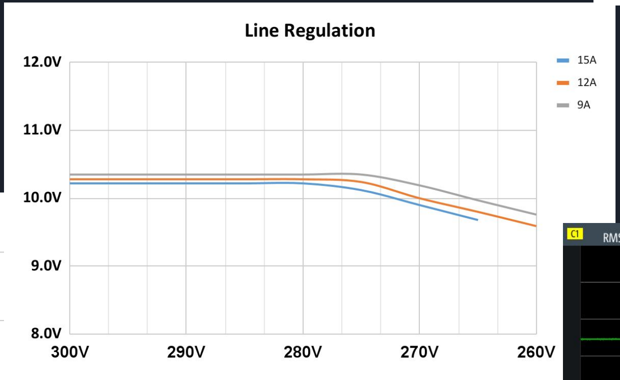
- GOLIATH: test at higher magnetic field, up to 1.3T.
- Check the performances at extreme condition by looking at waveforms.
- Voltage at the switching node SW and current in the primary coil of the transformer.

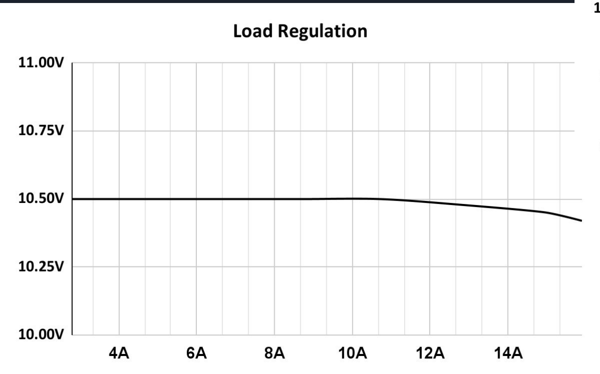


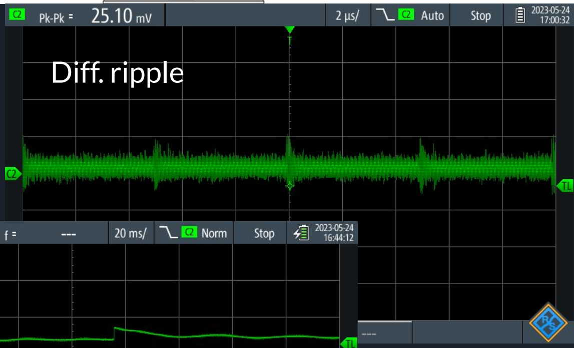
Electrical measurements

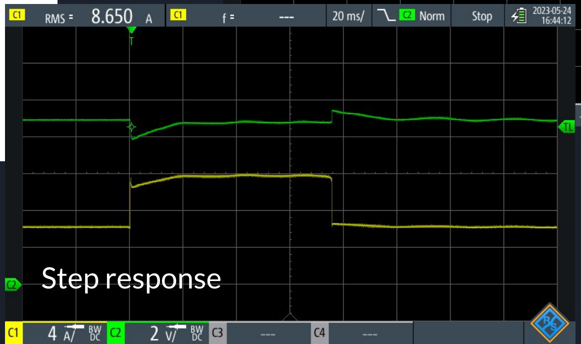
- Line regulation as function of the input voltage and the output current.
- Load regulation as function of the output current.
- Load step response: constant 8A load stepped to 12A and sequentially reduced to 8A in 80ms.
- Output differential ripple, with AC-coupled differential probe.









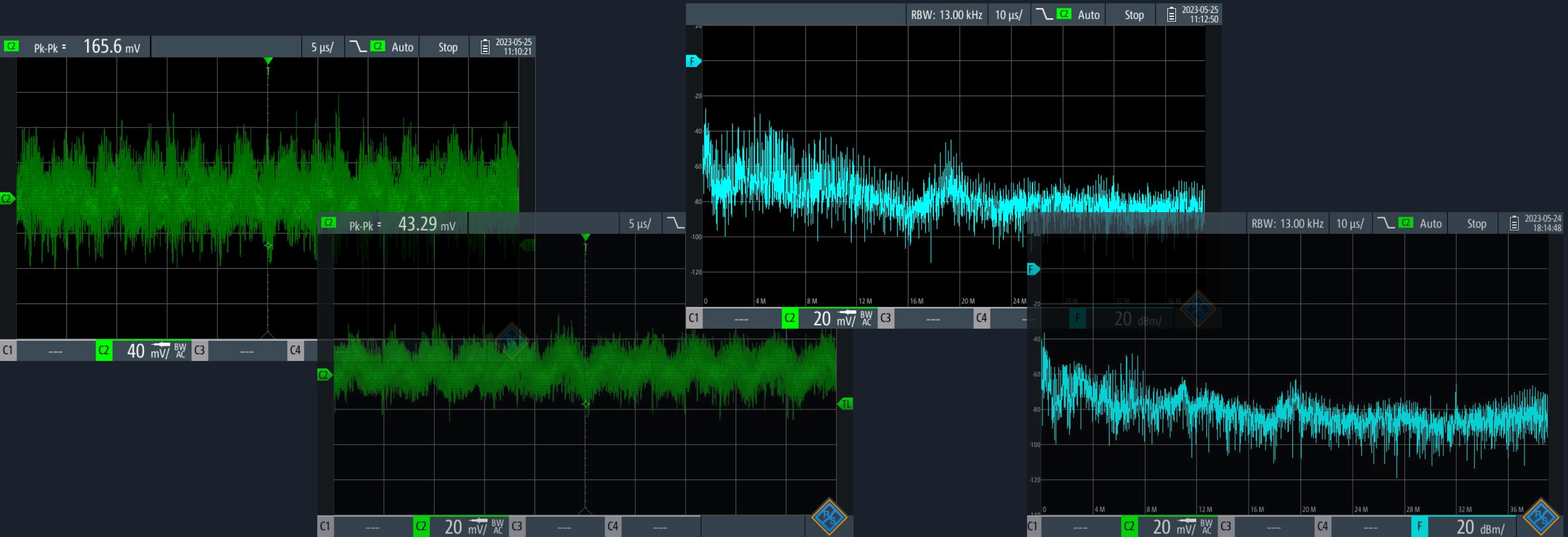


Optimization

- All necessary precautions in matter of filtering must be taken to prevent the noise propagation until the front-end electronics of the detector. Most critical is the common-mode.
- Two refurbishment campaigns were done to converge progressively to the optimum readout noise level:
  - the first campaign was done during the commissioning of the single detectors;
  - the second when the system included all the converters, cabling and all the detectors were installed on the wheels.
- Not possible to implement ferrites and common-mode filters, because of the environmental magnetic field, therefore capacitors were implemented in specific points of the circuit.
- A third campaign was done after the installation in ATLAS. Had as an objective the reduction of the slew rate of the first switching cycles (that happened in hard switching), to improve the reliability of the converter.

Optimization

- With the “capacitors approach”, in one case it was possible to short-circuit the residual noise propagated to the secondary towards ground, and in the other to limit the slew rate of the switching edges.



Conclusions

- New concept of designing and installing LV power systems on large experiment detectors.
- Direct supply the front-end electronics with high power density.
- Working in a harsh radiation and B-field environment.
- Details of the electrical performance are shown, together with the results of the prototype validation in a hostile environment.
- This kind of LV power system will make possible the extensive use of very high-density-channel detectors, like the MPGD.

Acknowledgment

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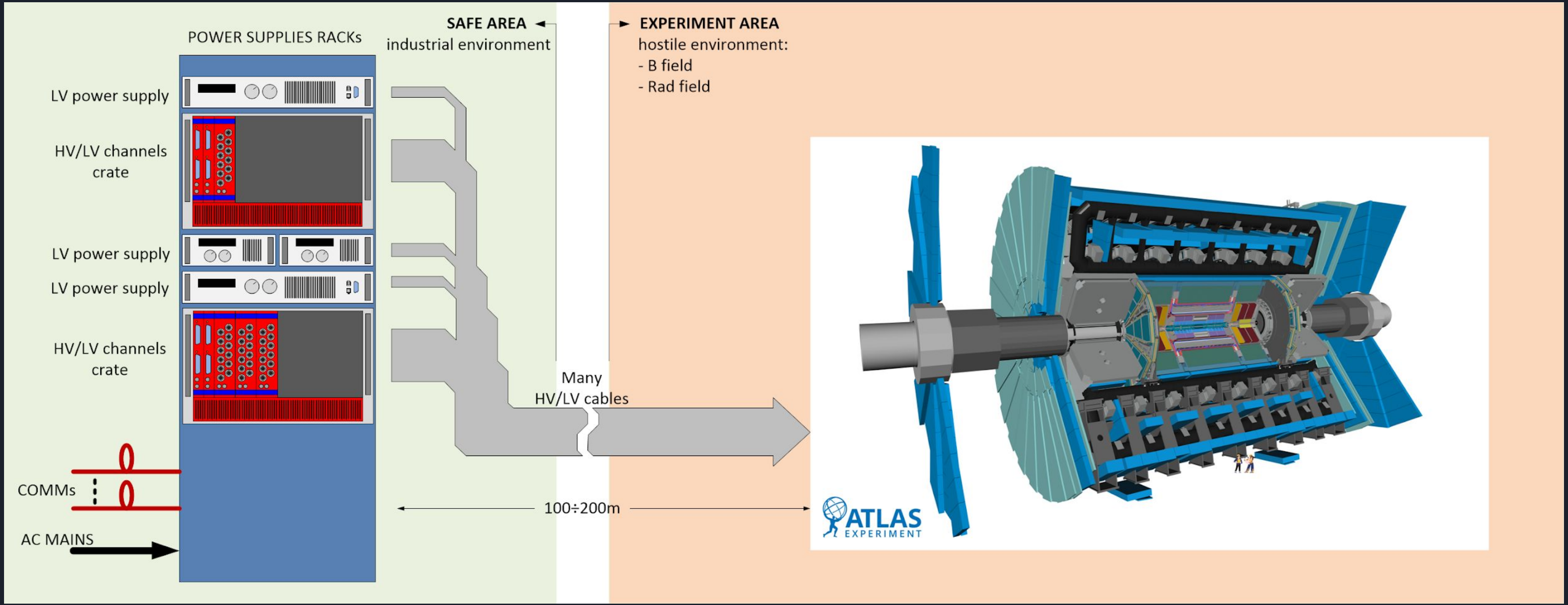
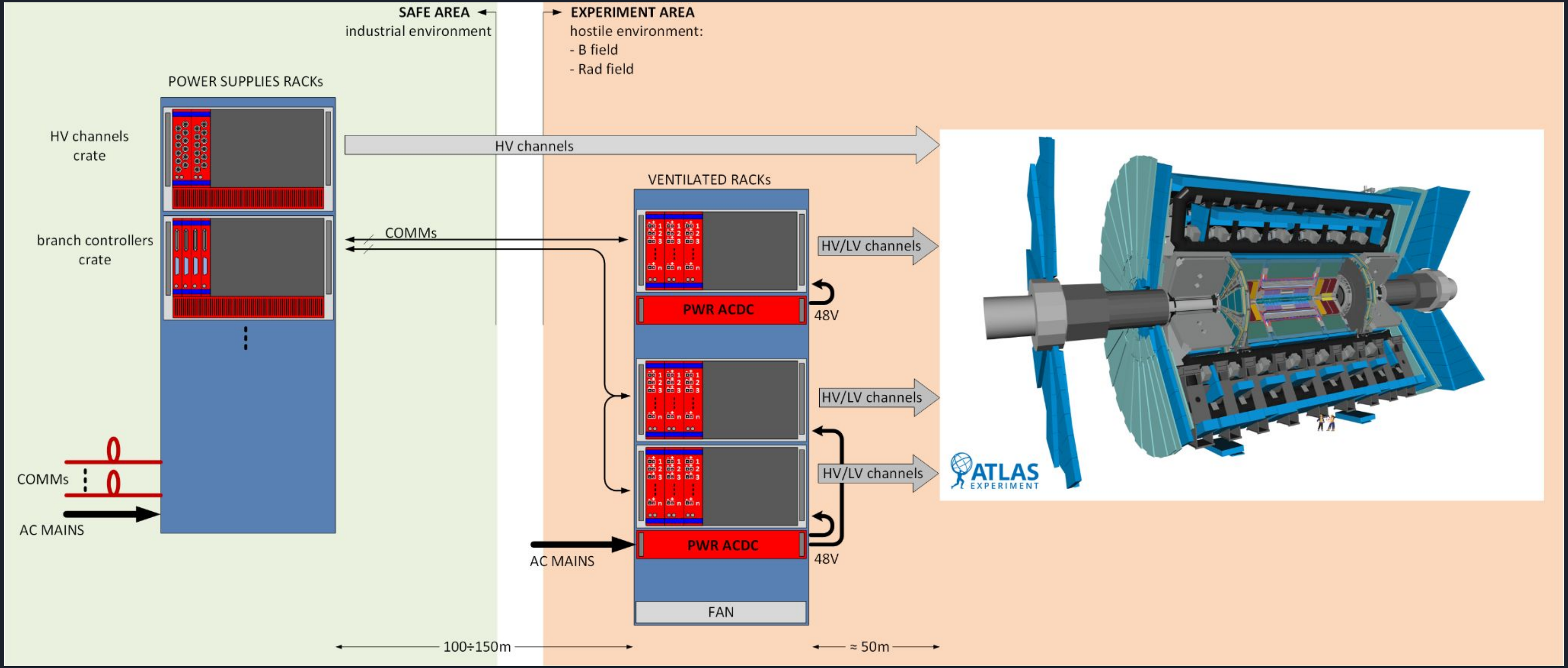
- EMI/EMC measurements on the prototypes:
  - Alam Toro Salas (Department of Physics of Brandeis University).

Backup

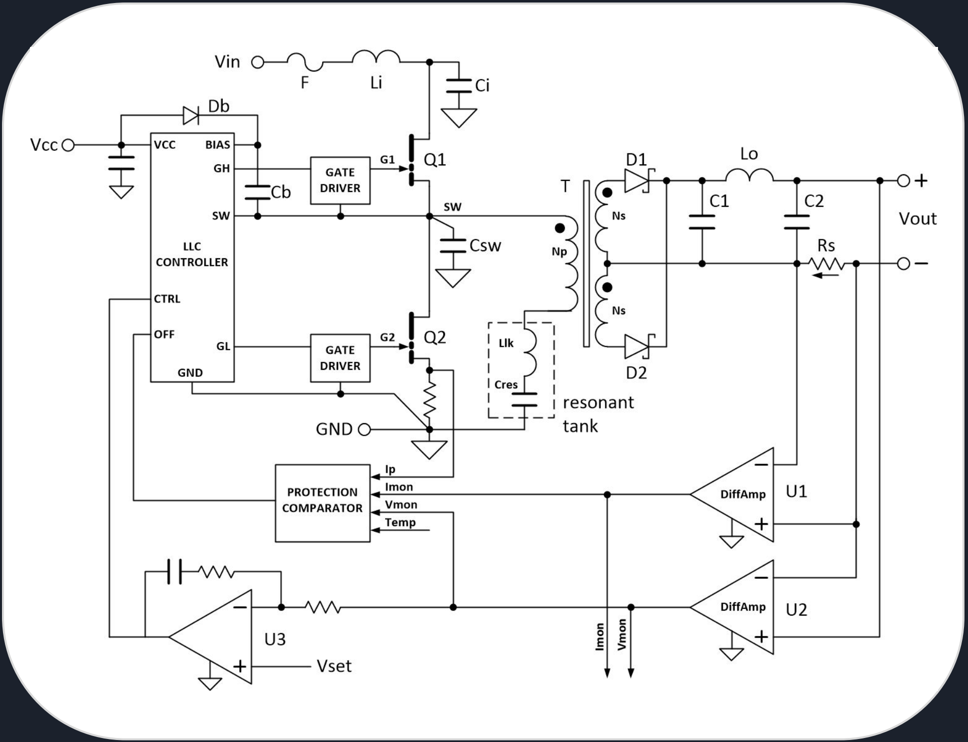
Standard power distribution strategy #1



Standard power distribution strategy #2



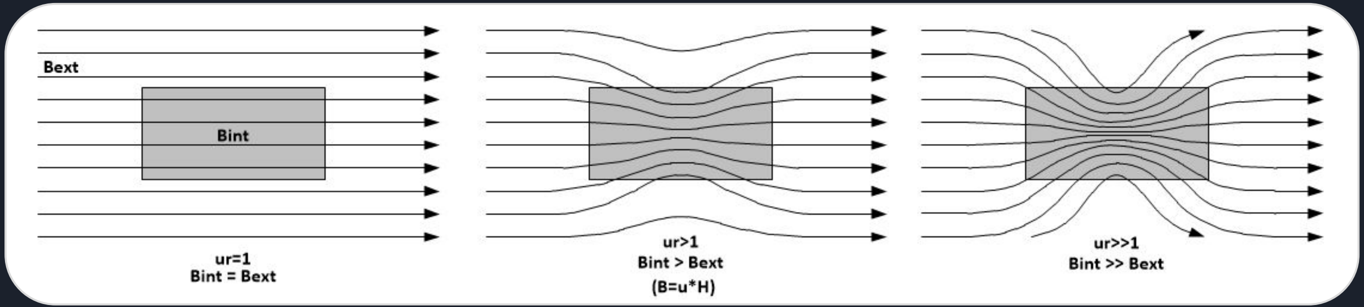
Electronics design (continuation)

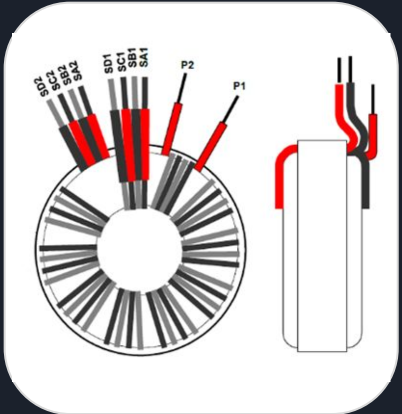


- Take advantage of Llk as the inductive component of the resonant tank.
- The LLC controller driving the FETs change the driving frequency to regulate the output voltage.
- Output voltage and current are monitored via differential amplifiers U1 and U2.
- Vmon is compared with a fixed voltage Vset via the integrator U3, whose output drives the LLC controller.
- The use of GaNs requires some precautions: an additional capacitance Csw is needed on the SW node, to avoid too steep transitions of the voltage.
- Also, they have lower driving voltages, so the output of the LLC controller must be adapted.
- A solid-state “bootstrap” technique (Db-Cb) to properly drive both the lower and the higher FETs.

Transformer design

- It must work with the high external magnetic field existing in the experiments caverns (up to 5-600mT).
- When a material is exposed to an external magnetic field (Bext) the magnetic lines of force of it tend to concentrate inside the material.
- It is not possible to use standard ferrite cores as well as air-core transformers.
- The compromise solution is the use of special materials with low permeability and high saturation levels for the core: this limits the penetration of the external field to the external layers, keeping the magnetic properties in most of the internal section.
- Simple design, simple configuration: toroidal and 1P : 1S .





Equipment connection