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RedPitaya applications at the NBTF beam source SPIDER

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Outlines:

- RedPitaya
  - FPGA SoC
  - MDSplus device
- RedPitaya in SPIDER experiment
  - Dual directional couplers
  - Beamlet Current Measure
  - Beam Dump Current Measure
  - Accelerator Grid Power Supply
- Conclusions
  - PROS / CONS

Abstract

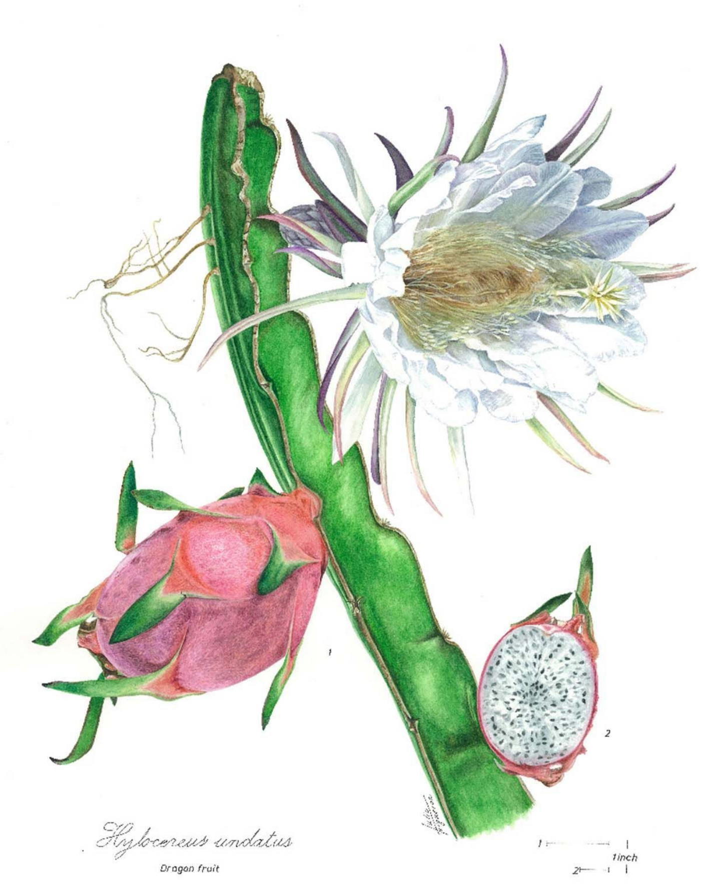
The RedPitaya board represents an alternative to many expensive laboratory measurement and control systems. It hosts a Zynq system composed of an ARM processor deeply integrated into a configurable FPGA, two 125MHz RF inputs and outputs and 14-bit Analog to Digital and Digital to Analog converters.

Due to its flexibility, RedPitaya has been considered for a variety of advanced diagnostic measurements at SPIDER, one of the two experiments being held at the ITER Neutral Beam Test Facility located in Padova (Italy). In particular, high-speed, event-driven data acquisition, i.e. data acquisition during a time window centered on the occurrence time of a given event, possibly repeated during the experiment, represents a common use case in data acquisition at SPIDER. Event driven data acquisition was carried out by a much more expensive commercial device and the RedPitaya solution has been considered not only for its price, but also because not all the requirements could be satisfied with the former solution. For this reason, a project was started, aiming at developing a flexible FPGA configuration capable to satisfy all the requirement, in particular the required flexibility in event definition. Events triggering acquisition can indeed be represented by external triggers, but can also be derived from input signal characteristics such as level and steepness. Moreover, external triggers can be either directly provided or derived from the Manchester encoding of real-time events in the 10 MHz timing highway signal, a signal generated by the central timing system and distributed to all systems to provide in phase clock and asynchronous triggers.

Red pitaya event driven data acquisition has also been used to provide streamed spectral measurement of RF sources. In this case, the boards receive a sequence of triggers (up to 200 Hz) and at the occurrence of every trigger it acquires a bunch of samples at high frequency (up to 125 MHz) that is then streamed to the network via the embedded Zynq CPU. FFT analysis is then performed either inline or offline to derive spectral information at every trigger time, thus implementing continuous spectral information, a measurement would otherwise have required very expensive instrumentation otherwise.

Thanks to this flexibility, RedPitaya – based data acquisition is becoming more and more used at SPIDER, and the developed solutions, including flexible DAC devices, shall also be used at RFX-mod2, the upgrade of the RFX-mod fusion experiment currently under construction in the same laboratory.

Red Pitaya … not the fruit !



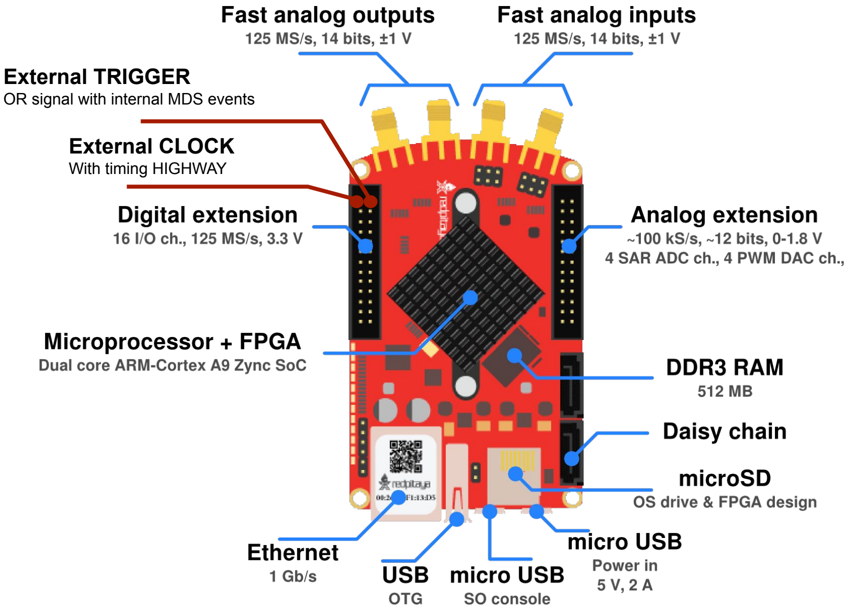
The Pitaya is also commonly known in English as "***dragon fruit***", a name used since around 1963, apparently resulting from the leather-like skin and prominent scaly spikes on the fruit exterior. The names *pitahaya* and *pitaya* derive from Mexico, and *pitaya roja* in Central America and northern South America, possibly relating to pitahaya for names of tall cacti species with flowering fruit. The fruit may also be known as a strawberry pear.

Nutritional value per 100 g (3.5 oz)		
Energy	1,100 kJ (260 kcal)	
Carbohydrates	82.14 g	
Sugars	82.14 g	
Dietary fiber	1.8 g	
Protein	3.57 g	
Vitamins	**Quantity**	**%DV†**
Vitamin C	9.2 mg	11%
Minerals	**Quantity**	**%DV†**
Calcium	107 mg	11%
Sodium	39 mg	3%

Units
μg = micrograms • mg = milligrams
IU = International units

†Percentages are roughly approximated using US recommendations for adults.
Source: USDA FoodData Central

StemLab RedPitaya



	STEMlab 125 - 10	STEMlab 125 - 14
I/O channels	2+2	2+2
Bandwidth	40MHz	40MHz
Resolution	10bit	14bit
ADC	**AD9608**	**LTC2145-14**
DAC	**AD9767**	**AD9767**
Input range	+/- 1V (LV) and +/- 20V (HV)	+/- 1V (LV) and +/- 20V (HV)
Input coupling	DC	DC
Minimal Sensitivity	± 1.95mV / ± 39mV	± 0.122mV / ± 2.44mV
External Trigger	Yes	Yes
External Clock	Yes	Yes

Why SoC FPGA devices

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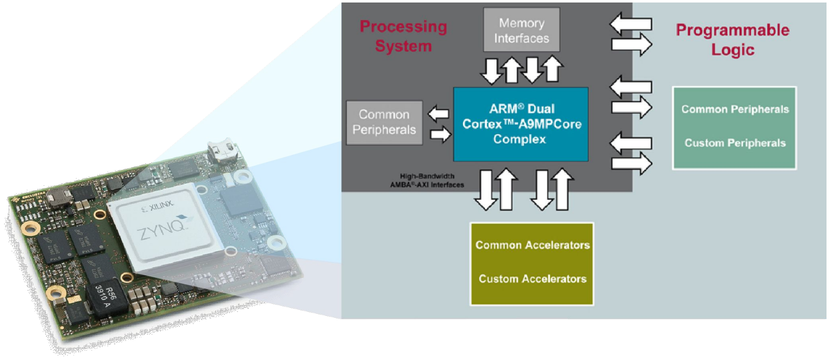
Why choosing FPGA (Field Programmable Gate Arrays) for development in fusion experiments?

The most important aspect of using SoC FPGAs is the interaction with the processing unit.

- With a flexible logic design it becomes **easy to bridge the data with high-level tools** for archiving data (i.e. MDSplus system) or making runtime analysis.
- This leds to a rising attention on SoC boards able to embed a full features **OS like GNU Linux**.
- RedPitaya hosts a Zynq 7K system composed of an ARM processor deeply integrated into a configurable FPGA, two **125MHz** inputs with 14-bit Analog to Digital and 10-bit Digital to Analog converters.



RedPitaya *rfx_stream* implementation

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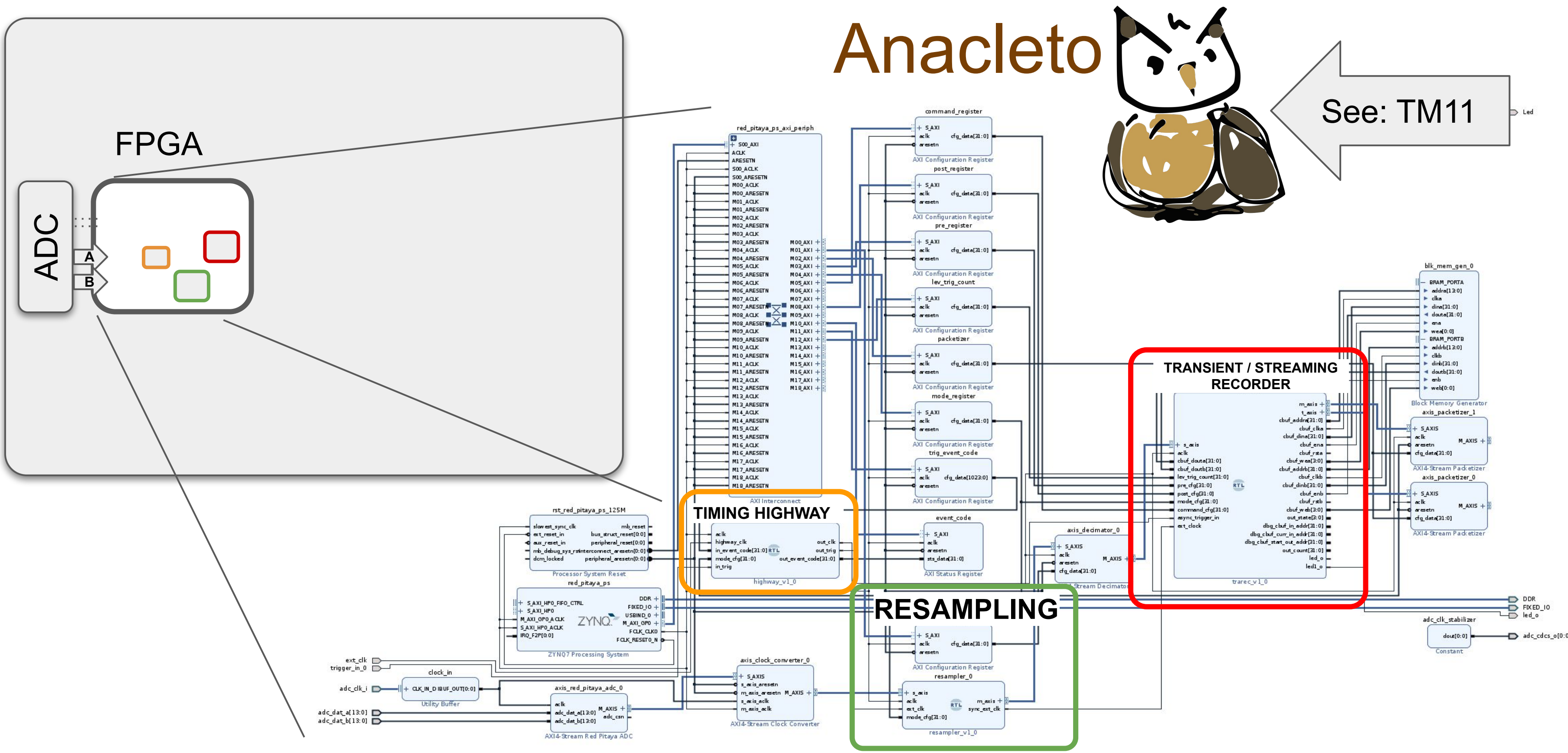
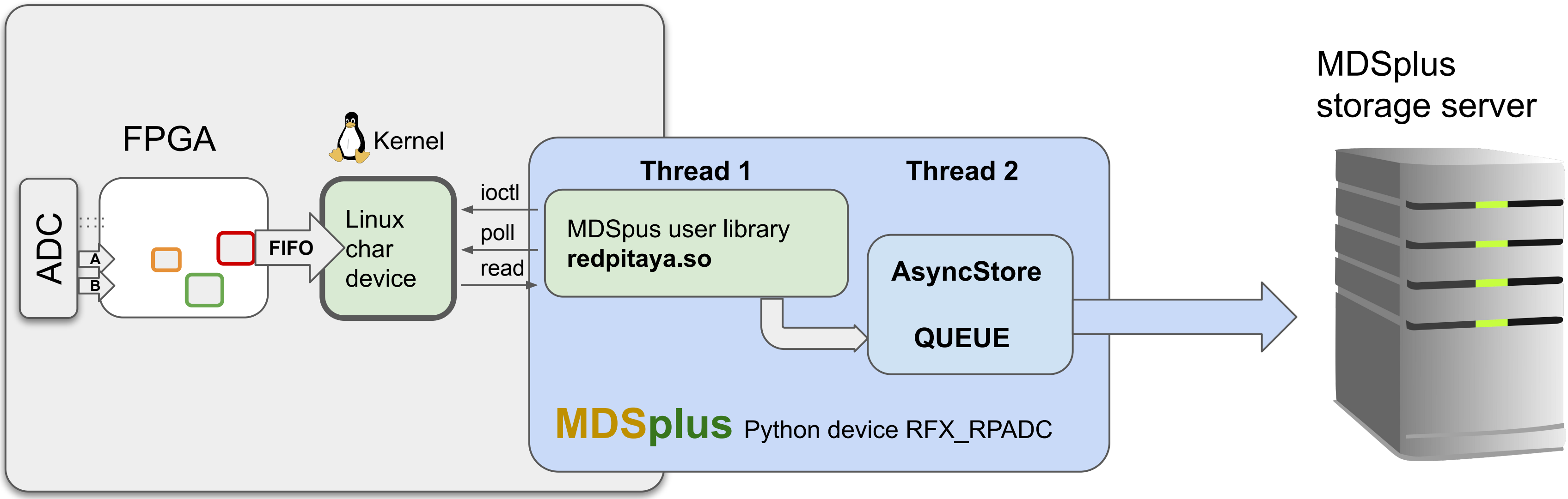
The acquisition driver and the FPGA firmware running in our boards has been completely rewritten to a custom implementation. A set of VHDL ip cores have been designed implementing the recorder features.



RedPitaya *rfx_stream* implementation

The FPGA firmware uses a FIFO element that is spooled by a kernel character device and then read by user library functions.



1. Each chunk of data read by device is already time-stamped in hardware with the clock count (internal or external)

2. The MDSplus device support library converts all the chunks in MDSplus segments

3. Two threads are started within the actual MDSplus device to create a producer/consumer pattern for the network transmission. This copes with either the possible lag writing into a local storage media or the network connection to a storage server.

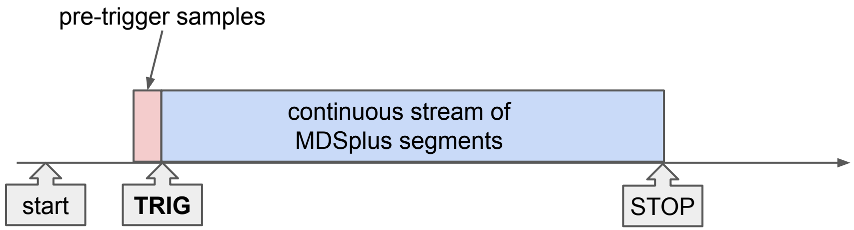
MDSplus device interface

The device support library directly interfaces the firmware with **MDSplus.**

The device can be operated in several different **MODES**:

CONTINUOUS RECORDER

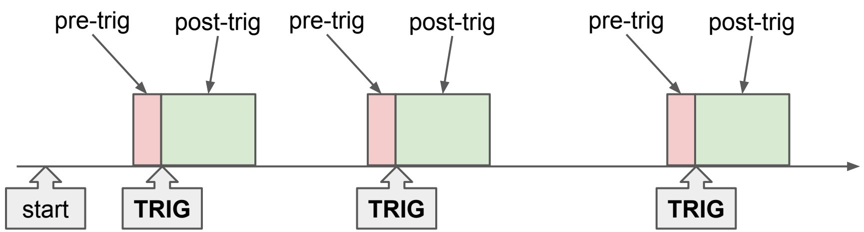
- **STREAMING:**
  The acquisition ends by a direct call of the *stop_acquisition* internal function



TRANSIENT RECORDER

- **EVENT STREAMING / SINGLE:**
  The acquisition is triggered by a threshold on the signal itself. A configurable number of samples over/under a specified level trigger the acquisition.

- **TRIGGER STREAMING / SINGLE:**
  The acquisition is explicitly triggered by an external event that could come from an external electrical TRIGGER input, a timing highway event on external CLOCK, or internal MDSplus multicast UDP events.



MDSplus device interface

The device support library directly interfaces the firmware with **MDSplus.**

The device can be operated in several different **MODES**:

Transient pre-samples
Sample retained before event

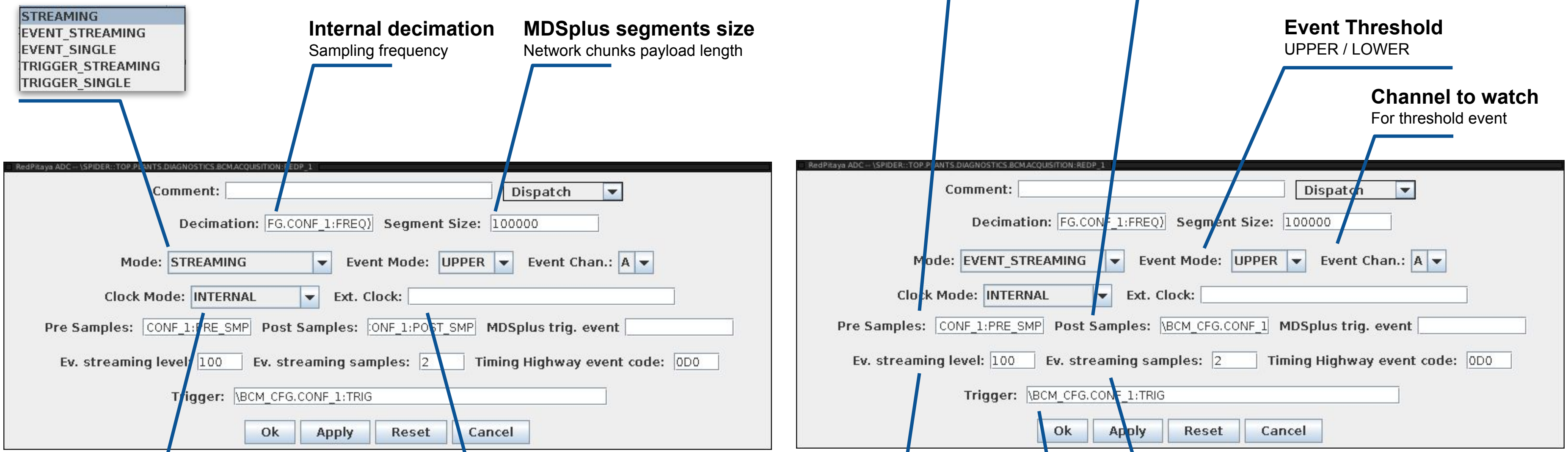
Transient post-samples
Sample recorder after event

Internal decimation
Sampling frequency

MDSplus segments size
Network chunks payload length

Event Threshold
UPPER / LOWER

Channel to watch
For threshold event



Clock source
Internal FPGA clock / External

Clock expression
Custom clock period

Event Threshold level
RAW code of triggering level

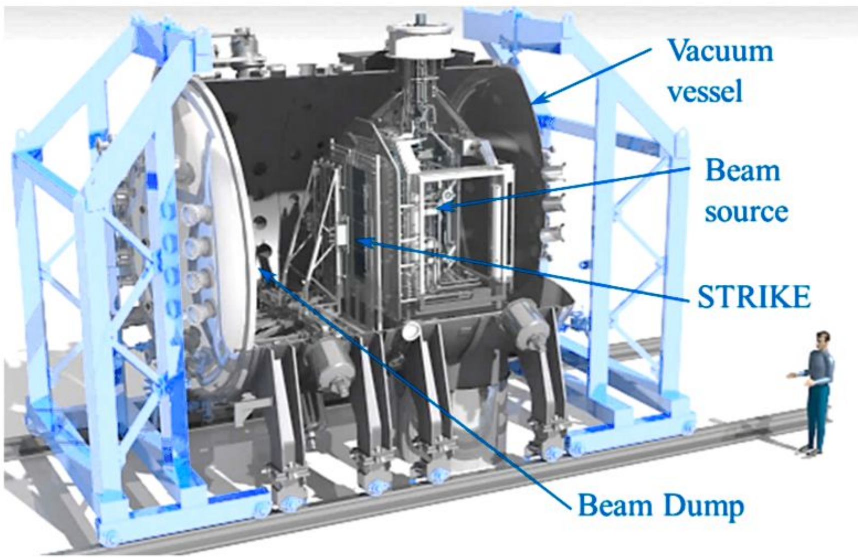
Event Threshold Samples
Number of samples that trigger event

Trigger time expression
Times of all triggers

RedPitaya in SPIDER experiment

SPIDER is the first large experimental device for **Neutral-beam injection** (**NBI**) that serves as a study test bench to improve the ITER neutral beam design.

The strong potential gradients among components and the high currents that flow through the source and the vessel when breakdown events occur require for a strong insulation of all the diagnostics.

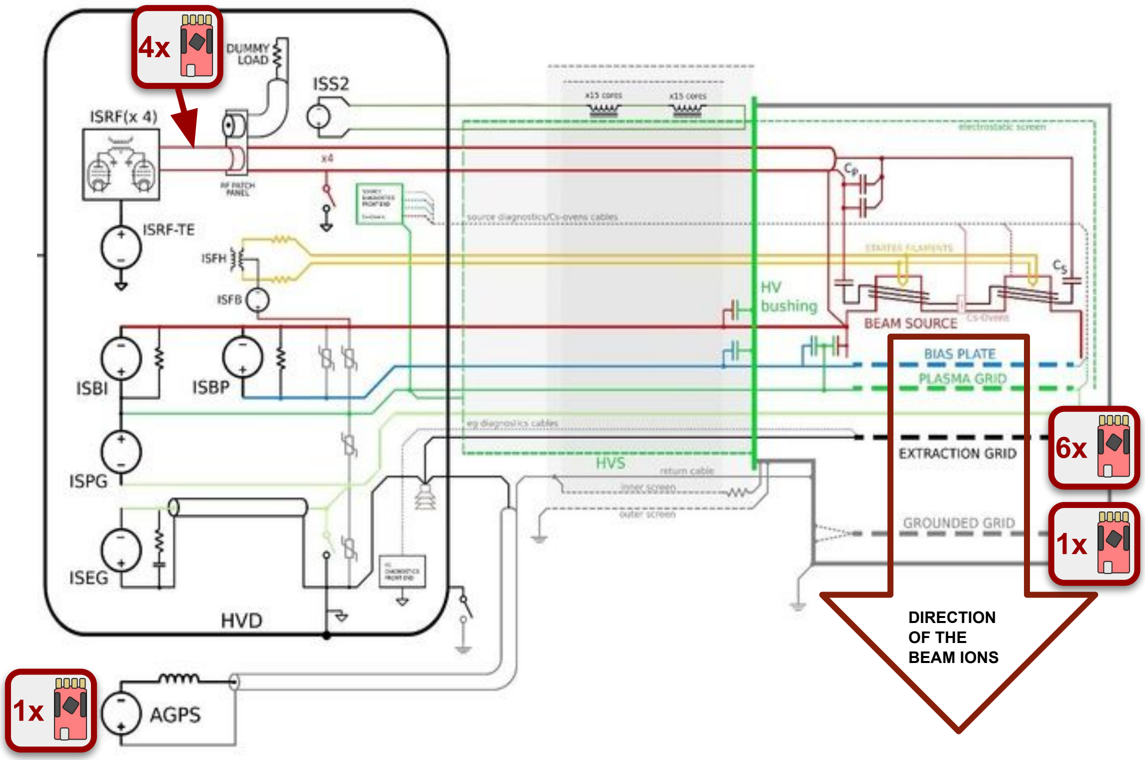


The design parameters of SPIDER are the following:

- ***Type:*** caesiated surface-plasma negative ion source
- ***Plasma source:*** 8 cylindrical RF drivers, operated at 1 MHz
- ***Process gas:*** hydrogen or deuterium
- ***Extracted H^- current:*** 54 A (target value)
- ***Electrodes:***
  - Plasma Grid (-110 kV)
  - Extraction Grid (-100 kV)
  - Grounded Grid (0 V)
- ***Beam:*** 1280 beamlets
  4×4 beamlet groups of 5×16 beamlets each

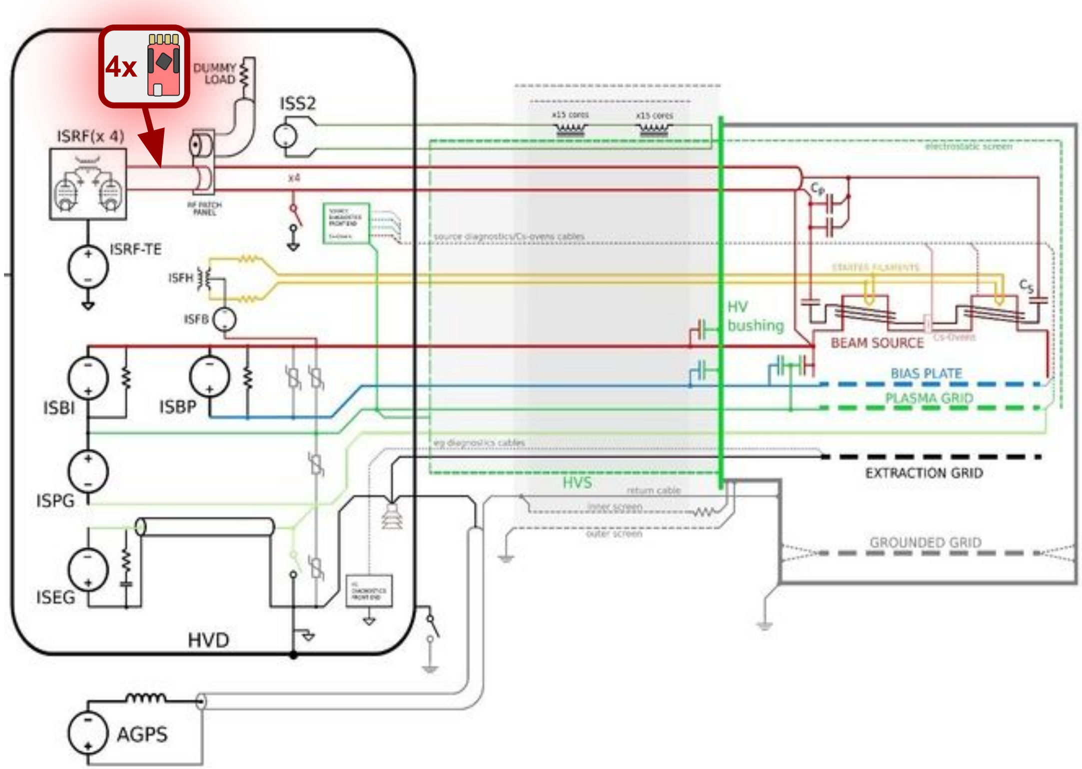
RedPitaya in SPIDER experiment

We currently have 12 Red Pitaya boards that are active for SPIDER diagnostics:



1 - DDC	**Directional Couplers** 8Ch, 60 Msps, FFT
2 - BCM	**Beamlet Current** 10Ch, adjustable rate
3 - BDCM	**Beam Dump Current** 2Ch, adjustable rate, WiFi
4 - AGPS	**Acceleration Grid PS** 1Ch, adjustable rate

RedPitaya in SPIDER experiment



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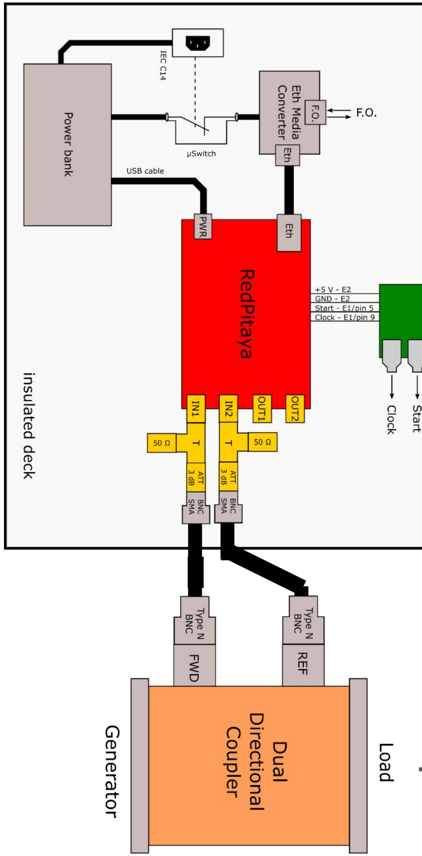
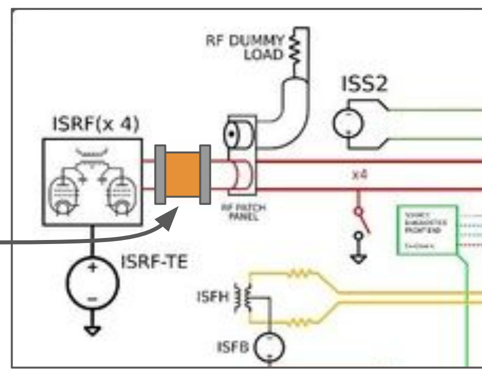
DDC (Dual Directional Couplers)

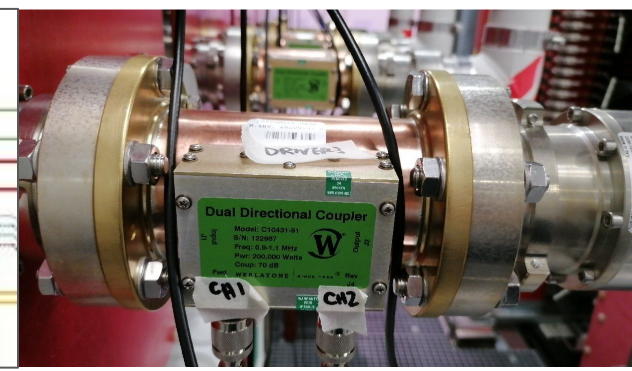
A provisional measurement system to assist the SPIDER experimentation with an **improved RF power estimation** has been adopted.

The transducers adopted for the power measurement are Dual Directional Couplers (DDC), a 4 ports element which provides two output analog signals: **forward voltage and reflected voltage**.

The DDC output signals are not at HVD potential due to the DC voltage applied by ISEG (ISBI and ISPG apply dc voltage too), and furthermore each outer conductor is subjected to a different RF voltage (few kV). Thus the measurement system shall **guarantee the insulation to the HVD and the insulation between each RF line**.



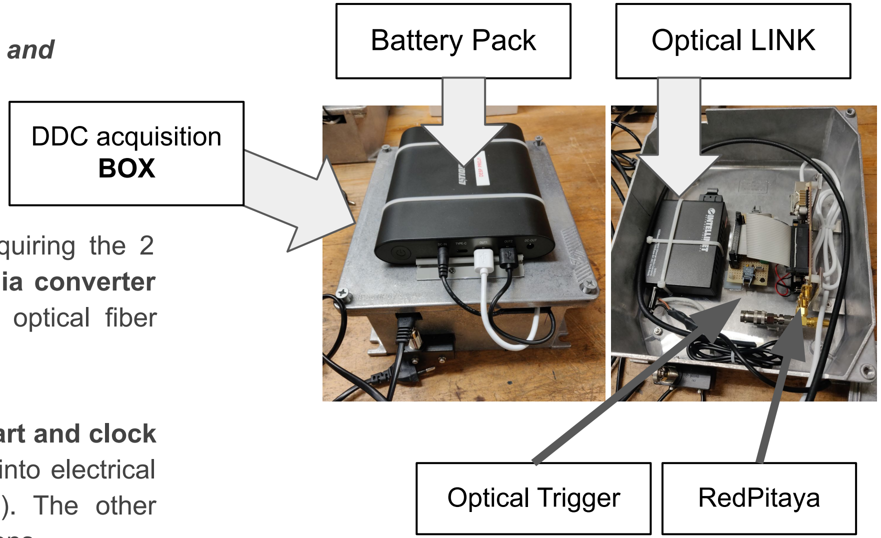




Werlatone model C10431-91

DDC (Dual Directional Couplers)

relatively cheap and not complicating too much the SPIDER activation and deactivation procedures.



They have been equipped with **Redpitaya STEMlab 125-14** boards acquiring the 2 voltage signals provided by each respective DDCs and an **ethernet media converter** for insulating the digital output signals from the Redpitaya through an optical fiber connection.

For synchronizing the acquisition of the 4 Redpitaya, **optical signals of start and clock coming from CODAS are transmitted to the first Repitaya**, converted into electrical signals by means of electronic boards (O/E/O board in the following). The other Redpitaya are connected together by means of IN/OUT fiber optic connections.

Due to the insulation requirements, these components are placed in decks insulated both from the HVD and between each other. The components of each subsystem are **supplied by a power bank guaranteeing the operation for at least 8 hours**.

DDC (Dual Directional Couplers)

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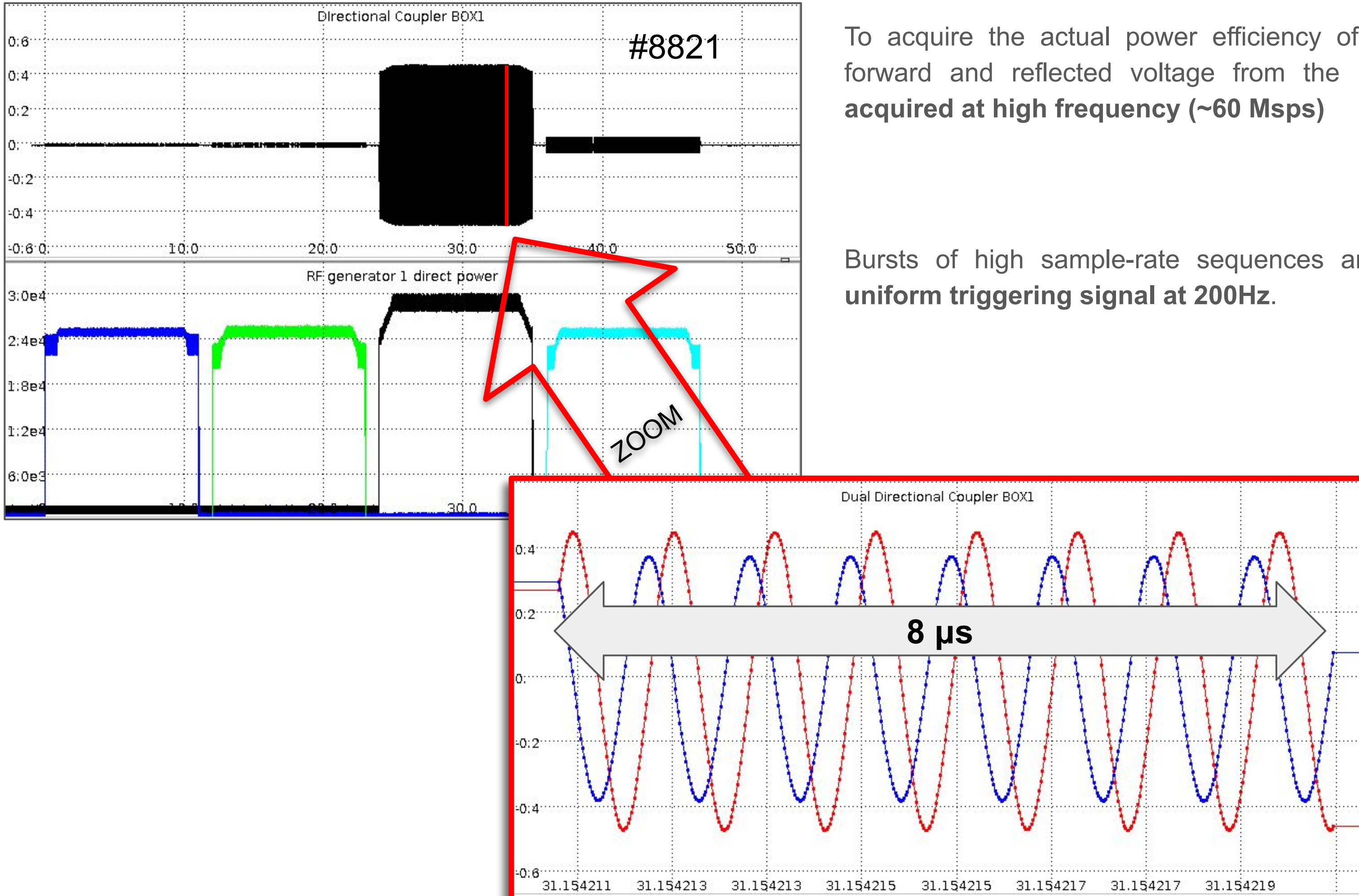
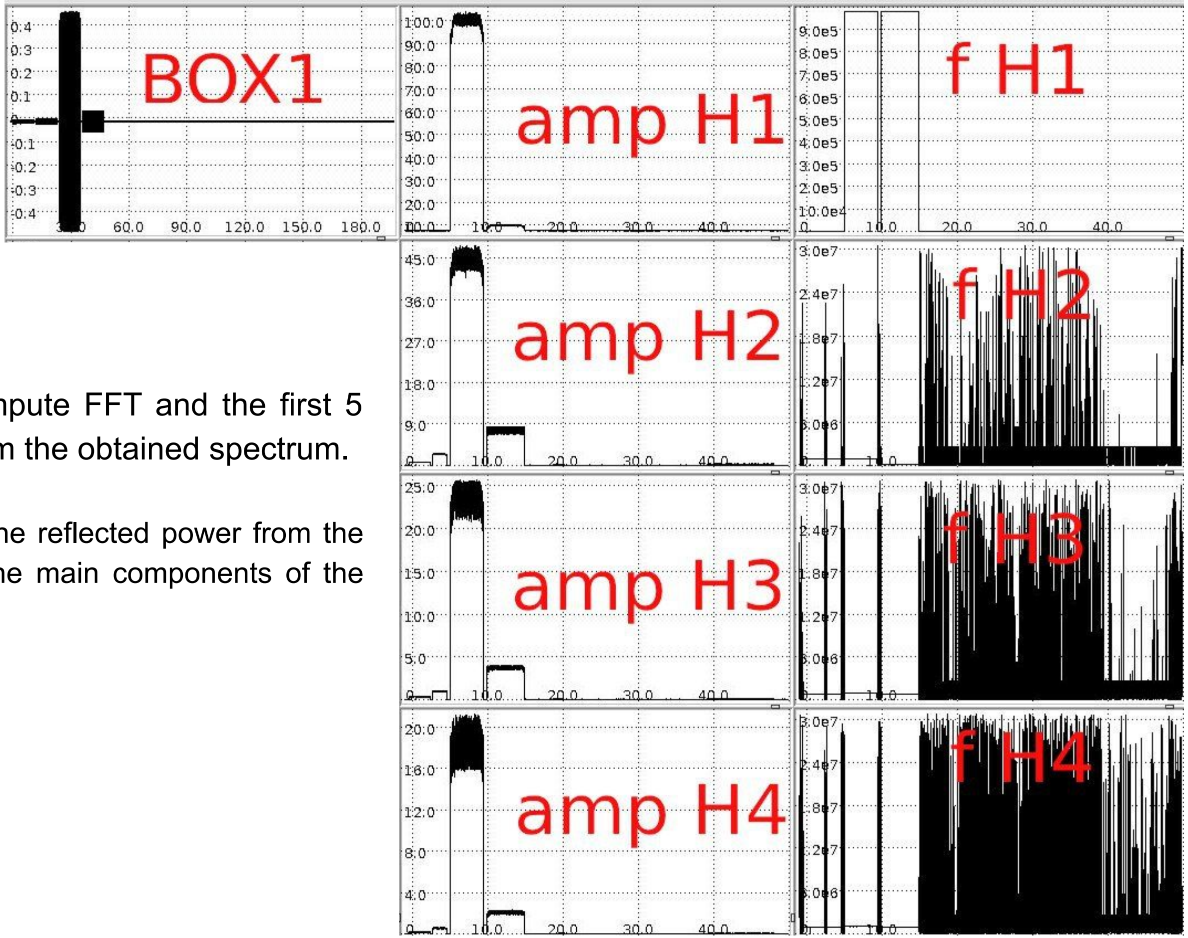


To acquire the actual power efficiency of the system the forward and reflected voltage from the **DDC sensor is acquired at high frequency (~60 Msps)**

Bursts of high sample-rate sequences are stored with a **uniform triggering signal at 200Hz**.

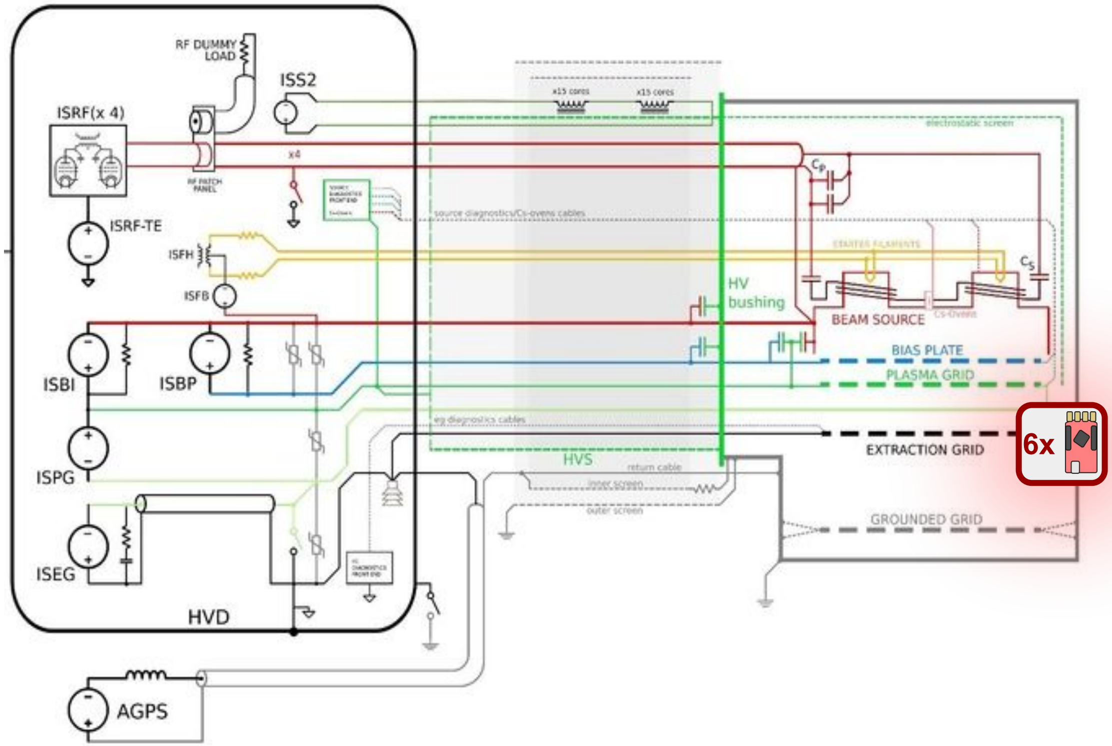
DDC (Dual Directional Couplers)



All signal bursts are then used to compute FFT and the first 5 main harmonics are then evaluated from the obtained spectrum.

This provides the possibility to measure the reflected power from the source and the related SWR signal for the main components of the spectrum under analysis.

RedPitaya in SPIDER experiment



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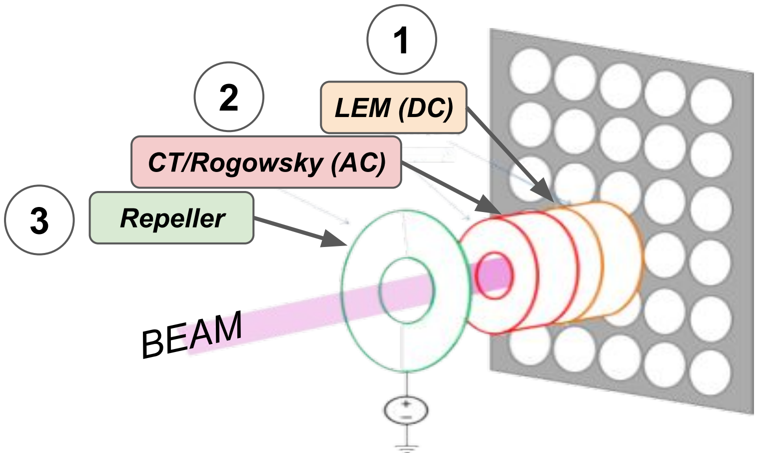
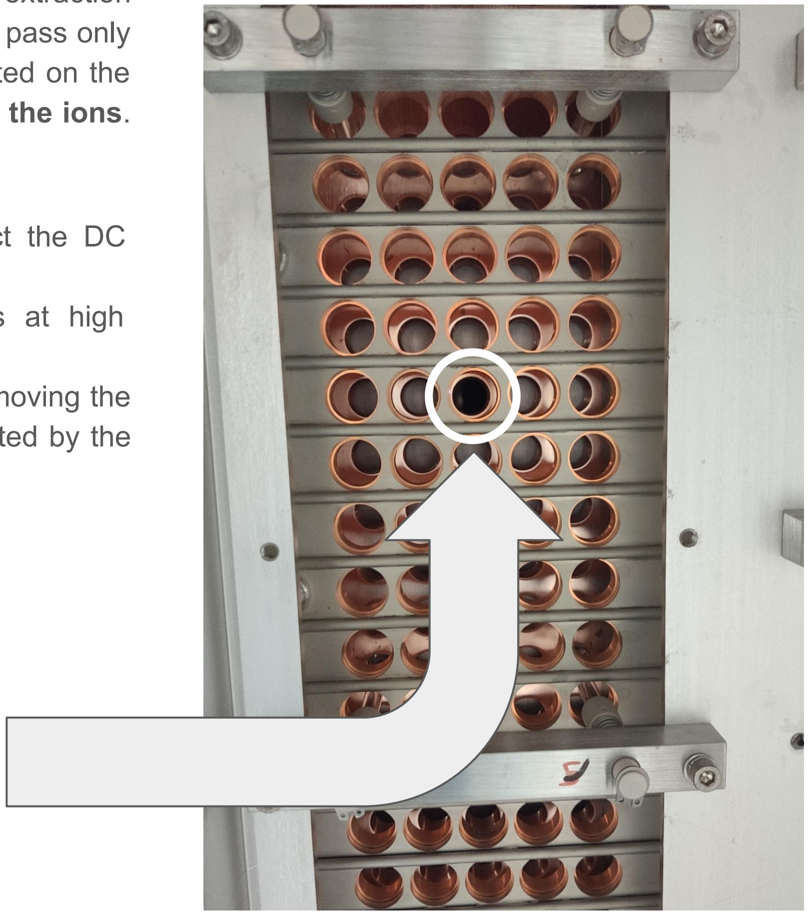
4 - AGPS	Acceleration Grid PS 1Ch, adjustable rate

BCM (Beamlets Current Measures)

As a first operation campaign SPIDER is operating with only a subset of extraction beamlets active. The selection is done using a mask plate that lets the ions pass only through some of the grid apertures. **5 Current sensors** have been mounted on the grid directly concatenating the beam and **measuring the actual current of the ions**. Each sensor assembly is composed by:

1. A LEM sensor: **Closed loop current transducer**, able to extract the DC current component for slow dynamics.
2. A **current transformer** directly measures the current variations at high frequencies.
3. An electrostatic plate that serves as a free positive ions **repeller** removing the current component that does not pertain to the beam but are attracted by the electric field on the grid output.





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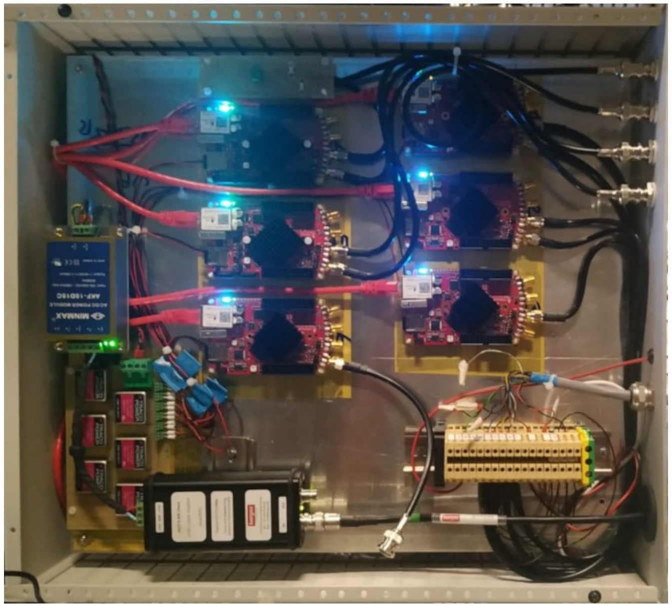
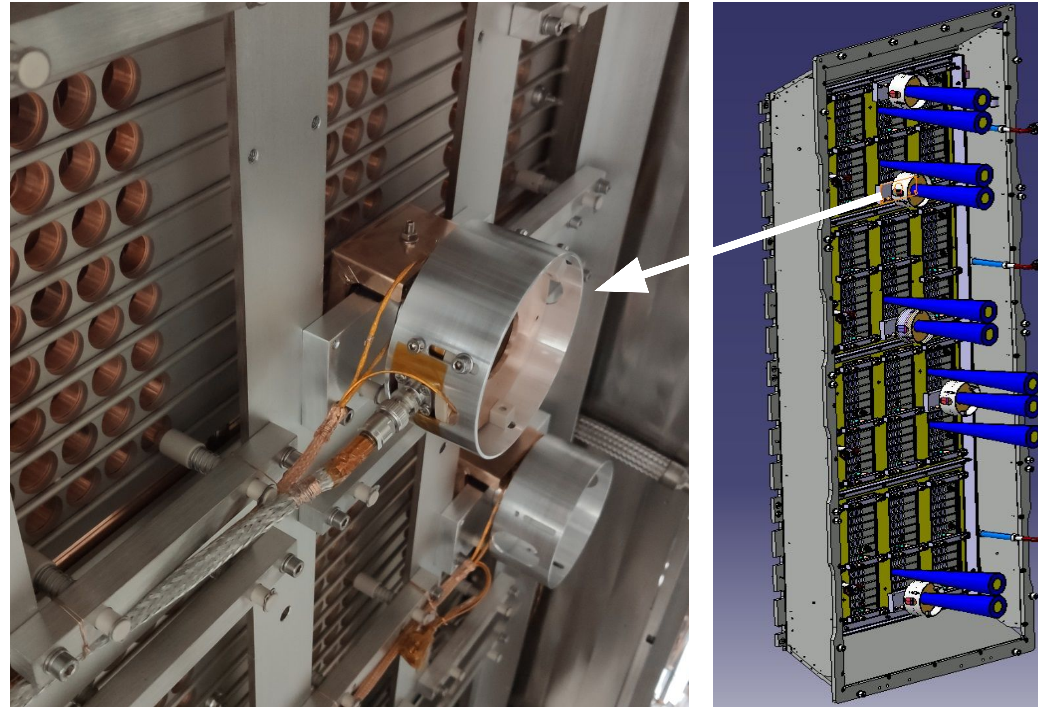
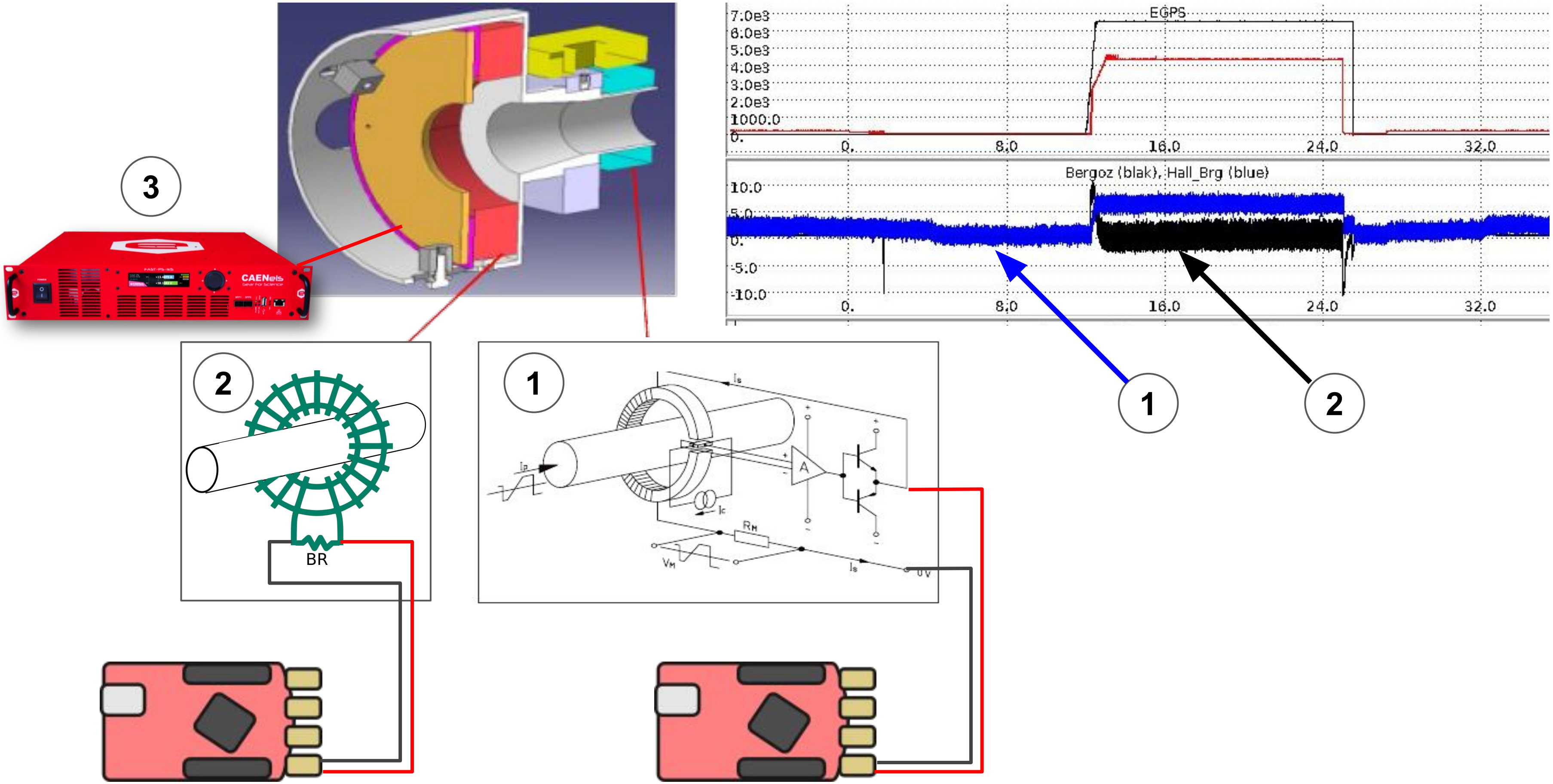


Internal assembly of the acquisition module with the 6 RedPitaya boards acquiring 2 signals from each of the 5 sensors.



Internal view of the sensors mounted on the extraction grid, all insulated lines have been protected with a copper shield to protect the ADC input. Electric overvoltage protections have been mounted before the input link to the Redpitaya.

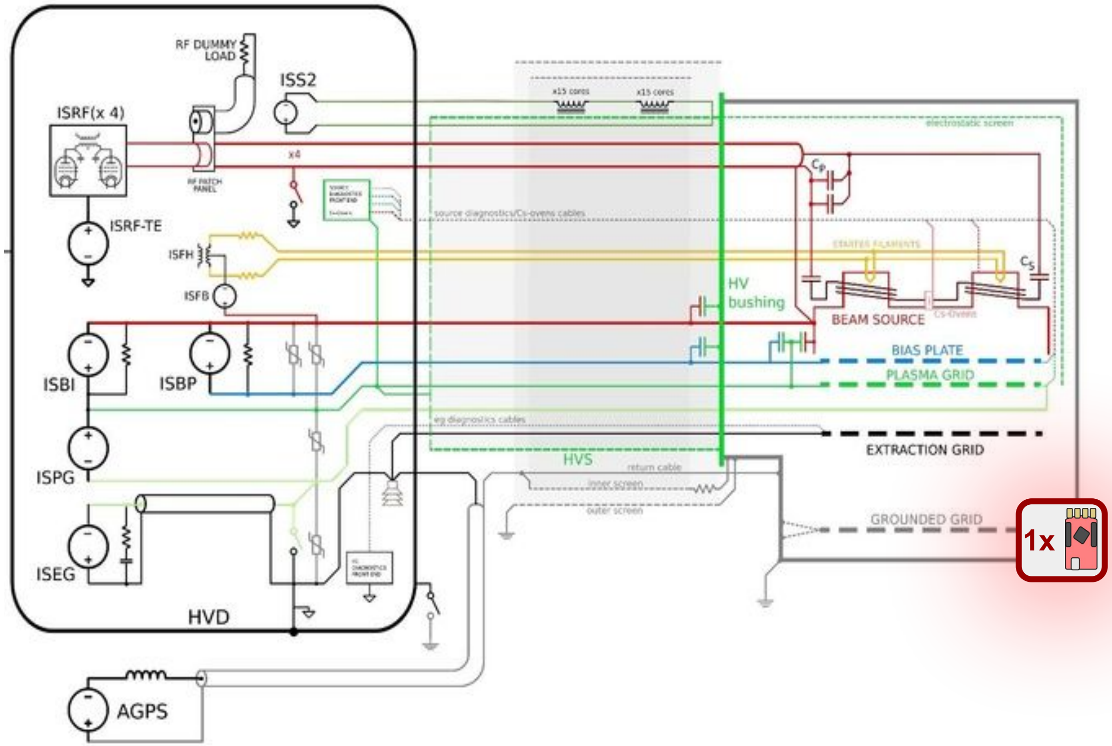
BCM (Beamlets Current Measures)



Current transformer sensor

Closed loop transducer Channel

RedPitaya in SPIDER experiment



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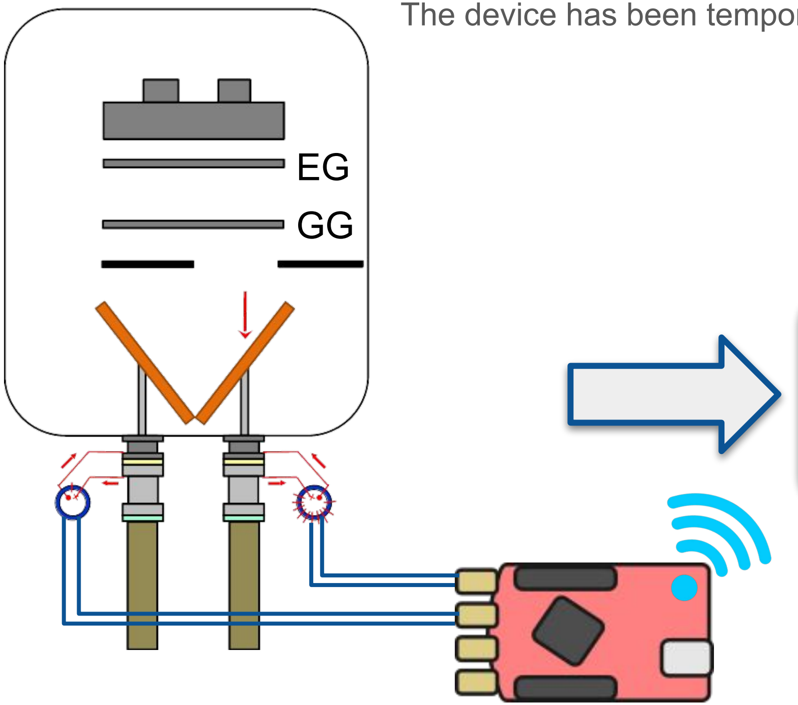
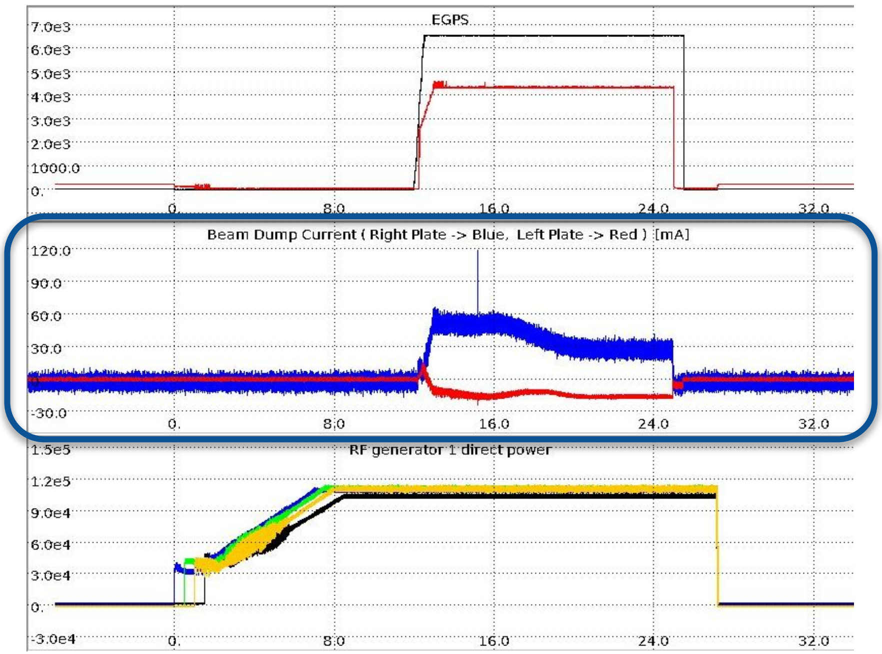
BDCM (Beam Dump Current Measure)

The beam power extracted from RF plasma is mainly absorbed by the **beam dump** component which has been also designed to measure the **total beam current** that flows through the dumper panels.

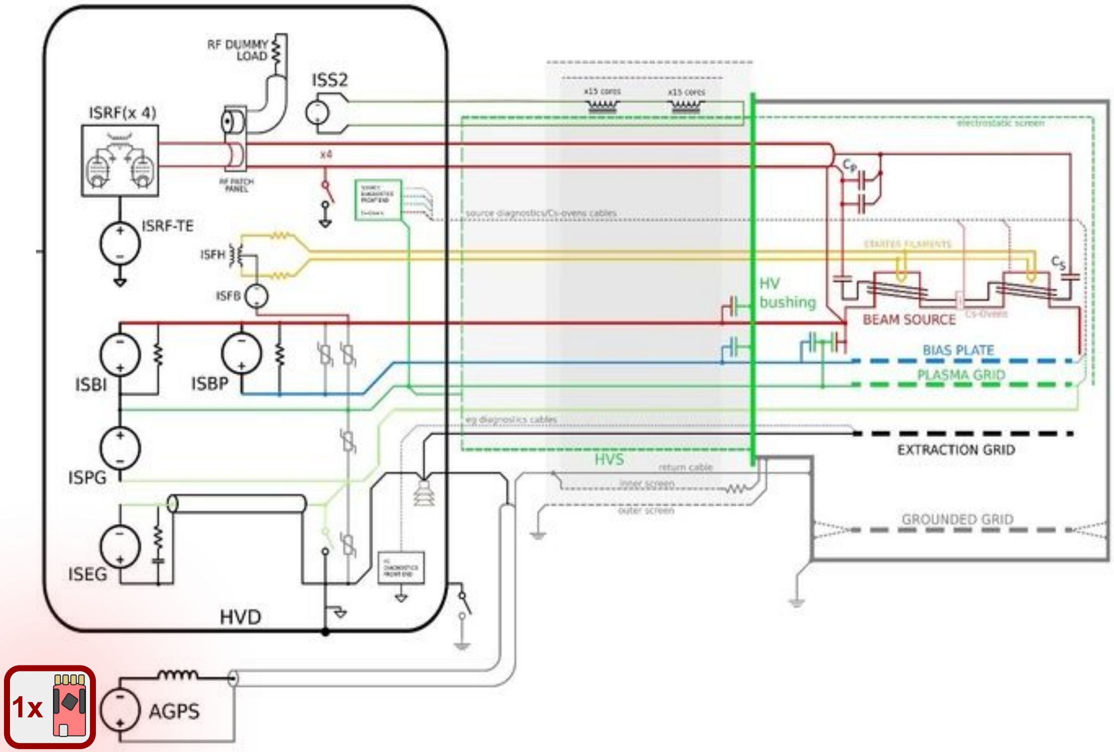
The device has been temporarily WiFi connected to prevent any damage to the network link.





M. Zaupa, M. Dalla Palma, E. Sartori, M. Brombin, *and* R. Pasqualotto , "SPIDER beam dump as diagnostic of the particle beam", Review of Scientific Instruments 87, 11D415 (2016) https://doi.org/10.1063/1.4958906

RedPitaya in SPIDER experiment



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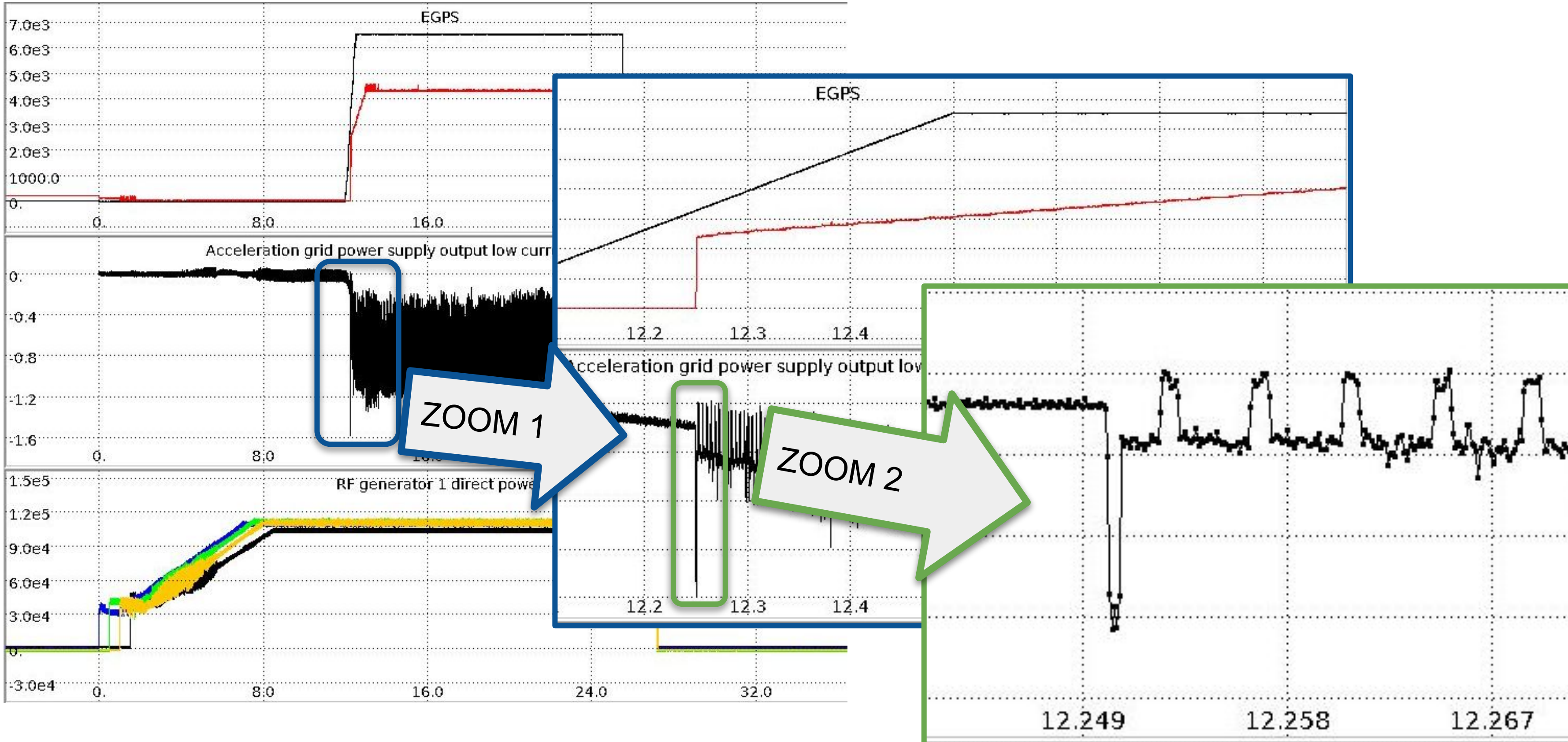
AGPS (Accelerator Grid Power Supply)

Accelerator Grid Power Supply (AGPS) provides 8MW power at (-) 96kV to the beam source for all the internal acceleration grids. Study of low-voltage ripple effect.



CONCLUSIONS

PROS:

- Easy to implement firmware to operate in realtime within the FPGA logic.
- Complex operations can be left be operates by a full-fledged linux environment.

  The MDSplus storage system can be directly deployed inside the recorder device.
- Cheap and easily available.
- Compact and carefully designed to be adapted to many applications:
  - WiFi through dongle if needed
  - Battery powered if necessary for insulation
  - 2 fast ADC/DAC and 8 slow ADCs
  - 16 DIO or 8 P/N dual ports
  - High freq clock output for daisy-chain

CONS:

- Can not be started without an internal SD storage
  The QSPI boot could be added by external flash?
- A version of the board with the defence grade Zynq 7K (temperature and EMC) for critical applications is not yet available in the market.
- Only 3V3 ports can be used for IO due to the single power supply of the FPGA banks. Other boards have also a lower power option that can operate the true 1.8V or 2.5V LVDS.

CONCLUSIONS

The RedPitaya board represents a very good alternative to many expensive laboratory measurement and control systems.

- A successful implementation of a high-speed, event-driven data acquisition for MDSplus has been developed.

  This device is able to operate both in streamed acquisition and as a transient recorder to acquire data during a time window centered on the occurrence time of a given event, possibly repeated during the experiment.

- Due this flexibility, RedPitaya has been considered for a variety of advanced diagnostic measurements at SPIDER, one of the two experiments being held at the ITER Neutral Beam Test Facility located in Padova (Italy).

  12 boards are currently operating in SPIDER for a total amount of 21 channels of either continuous or scattered acquisition.

- RedPitaya–based data acquisition is becoming more and more used at SPIDER, and the developed solutions, including flexible DAC devices, shall also be used for other experiments such as MITICA and RFX-mod2.

REAL CONCLUSIONS

We really want to have such devices close to the sensors !!

WHY?

Embedded FPGA can hold even complex Deep Neural Network topologies via Network quantization.

The proper deployment of embedded devices in an experiment could represent a way to integrate many different diagnostics into a single unsupervised model (VAE composition).

This can be done with simple devices!! Even the Zynq 7K

Checkout my paper (accepted IEEE TNS):

Diagnostic data integration using deep neural networks for real-time plasma analysis

REAL CONCLUSIONS

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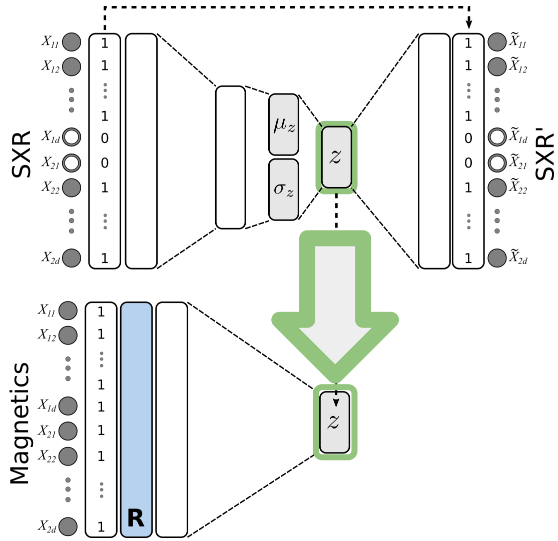

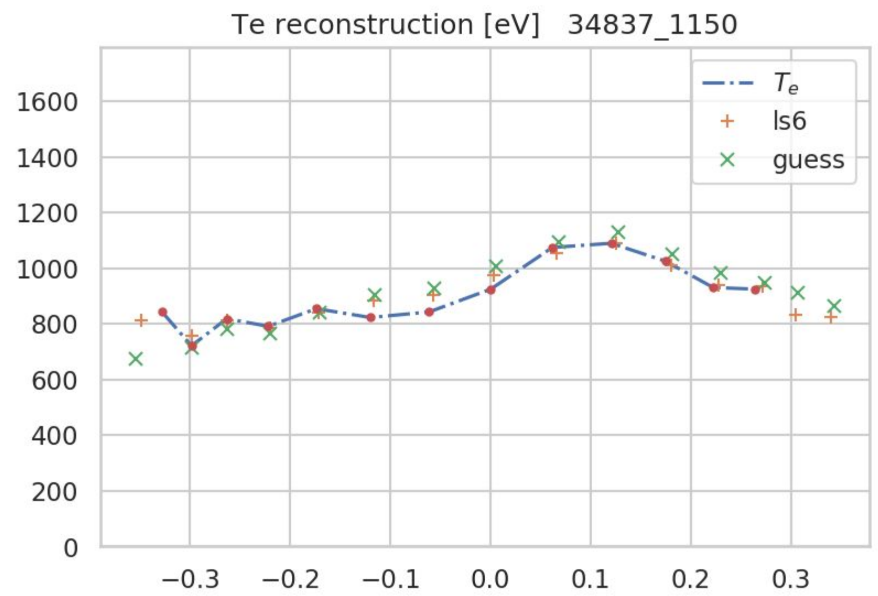

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Thanks for your kind attention.

This work was set up in collaboration and with financial support of Fusion for Energy.

<andrea.rigoni@igi.cnr.it>