POCPA 7

31rst May – 2nd June 2023

Reliability of ESRF power supplies and Hotswap System

L. Jolly

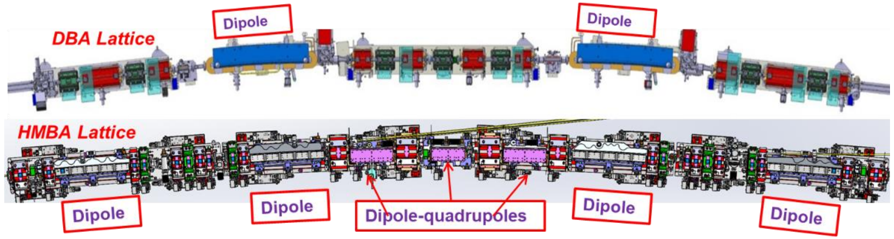
On behalf of the ESRF Power Supply Group

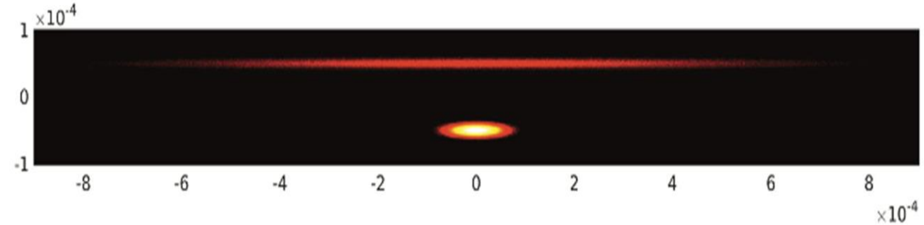
ESRF | The European Synchrotron

OUTLINE

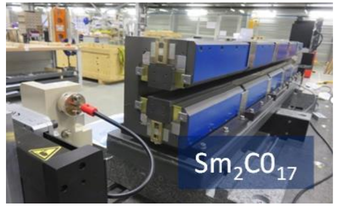
- Extremely Brillant Source (EBS) Upgrade
- Overview of Storage Ring Main Power Supplies
- Evolution of PS reliability 2020-2023
- Hot Swap Redundancy System

THE EBS UPGRADE (DEC 2018 – DEC 2019)





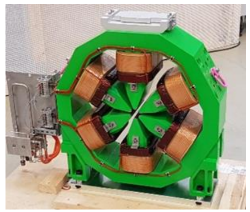
- Old DBA lattice replaced with a new HMBA lattice to increase X-ray beam brilliance and coherence by a factor 100
- Replacement of old SR magnets with 864 new magnets
- Installation of 1056 new main PS rated 4kW (single type of design) for
  - 96 x Dipole-Quadrupole combined magnets
  - 512 x Quadrupole
  - 192 x Sextupole magnets
  - 64 x Octupole magnets
- Hot Swap Redundancy System to keep PS system reliability same as previous machine (<4 beamloss per year ??)

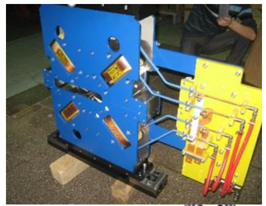


Dipole PM

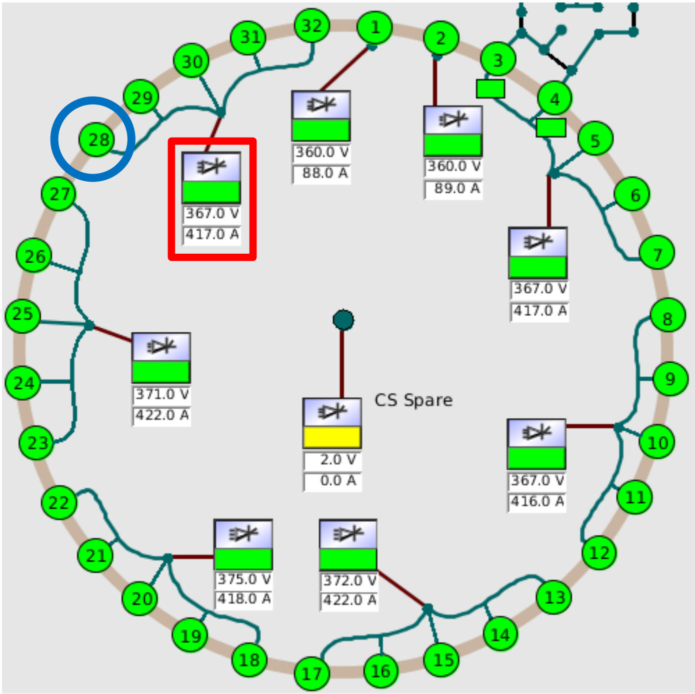

DQ Magnet

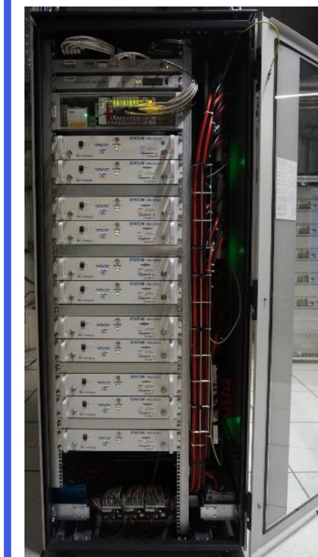

Quad Magnet


Sextu Magnet


Octu Magnet

MAIN MAGNETS: POWER CONVERTERS ARCHITECTURE

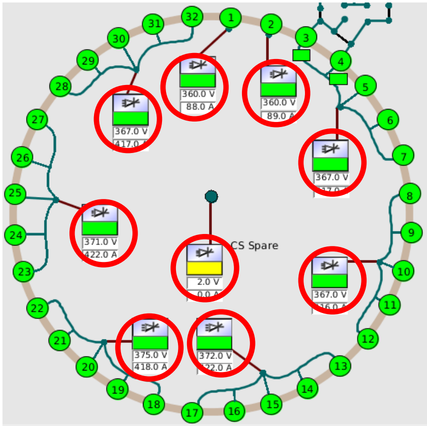




Magnet powered using 2-stages power conversion system

- AC/DC (400V AC => 360V DC) conversion: Common Sources 360Vdc (8+1 PS)
- Total 8 off 360Vdc network distributed all along the technical gallery
- DC/DC magnet PS: STATUM PS (864 PS running+ 192 PS stby)

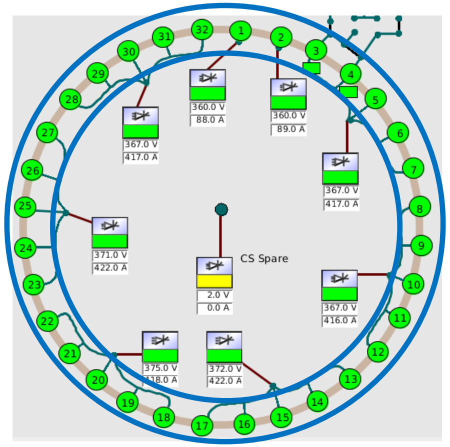
MAIN MAGNETS: COMMON SOURCE 360V CONVERTER (CS-360VDC)

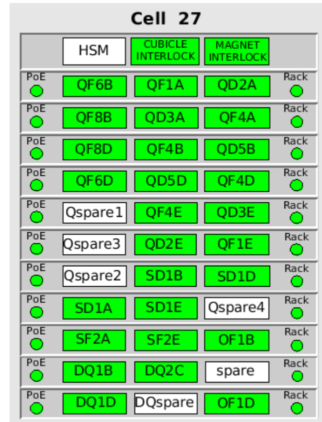


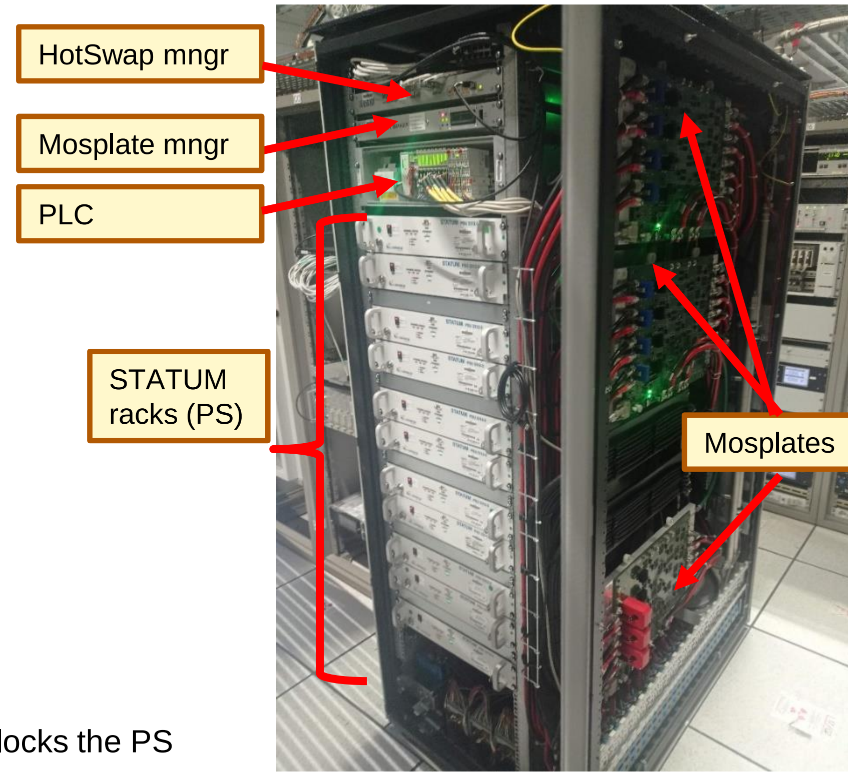
Function: Elec sources of 360Vdc networks powering downstream 4kW magnet PS

- 8 converters in operation + 1 spare for cold redundancy
- Switching matrix to quickly replace a faulty converter with the spare (<30min)
- 12 pulse thyristor rectifiers with passive LC filter, Water-cooled
- 2 sizes: 200kW (feeding 135 magnet PS) / 40kW (feeding 27 magnet PS)
- Inherited from the old ESRF machine (used as magnet family PS since early 1990’s) BUT control upgraded in 2019 with digital regulation (PLC + DSP + FPGA)

MAIN MAGNETS: HOTSWAP CUBICLE (HSC)



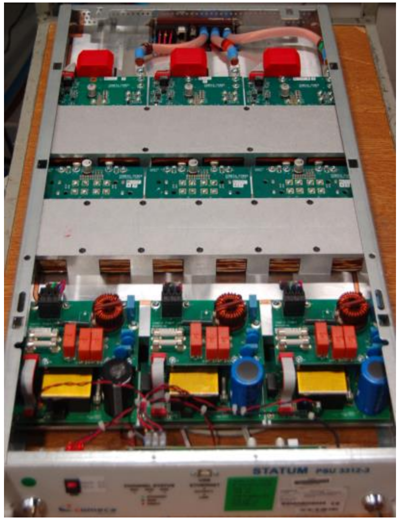


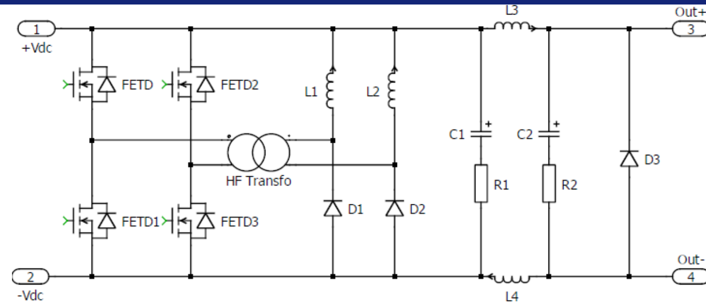


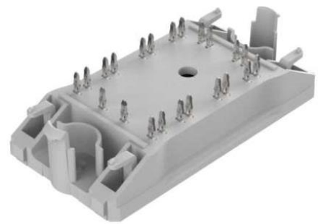
Standard cubicle (800mmW x 1200mmD) for all 32 cells, containing

- 33 x PS channels
  - 27 x PS feeding magnets
  - 6 x standby PS for hot redundancy
- A PLC monitors the magnet safety (flow/temp switches) and interlocks the PS
- A hot swap system monitoring magnet current and swapping PS in case of current deviating from declared setpoint
- All above devices controlled by TANGO with Ethernet links

MAIN MAGNETS: MAIN (STATUM) PS



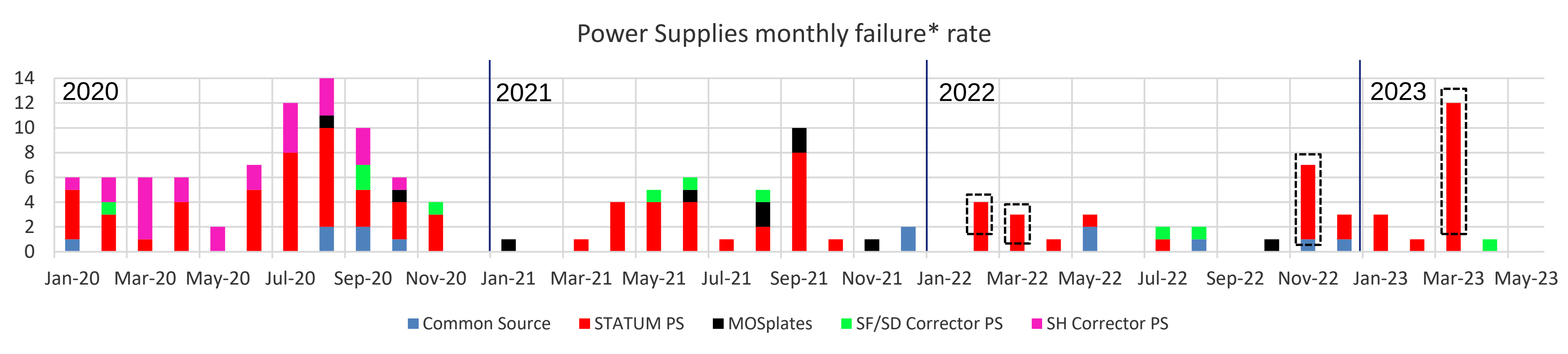




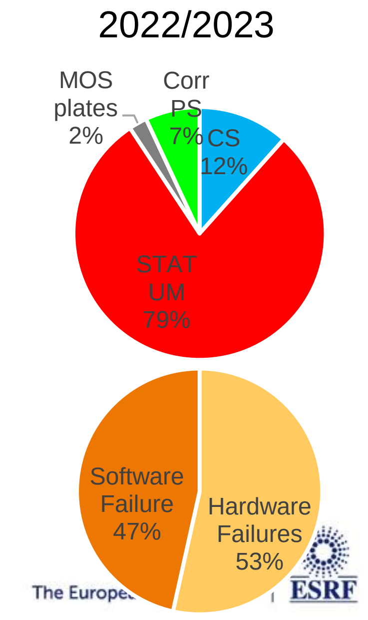
One crate containing 3 PS channels rated 33Vdc / 120Adc / 4kW each

- Designed and manufactured by COMECA Power (France)
- Water-cooled, Zero Voltage Switched PWM converter + planar magnetics => high efficiency and power density (3 x 4 kW in a 19'' wide - 2U high - 750mm deep crate)
- DSP based digital regulation using MAC150 DCCT => current stability < 20ppm
- Remote communication links: (Slow) Ethernet and (Fast) CANbus links
- Control Electronics is Powered Over the Ethernet (PoE) from the Ethernet switches using Ethernet cable
- Easy rack-in/out mechanism (Combitac elec. connector + water hose quick connect) => rack replaced in few minutes

STORAGE RING PS RELIABILITY (PSG PERSPECTIVE)



(*) hardware failure or software/communication malfunction



<u>2020</u>: Firefigthing period, high failure rate => stock of spare STATUM PS running dangerously low!

<u>2021</u>: In-house repair of STATUM **+** Fixing STATUM firmware problem + Development of Hotswap Control

<u>2022</u>: End of infant failure phase + Improvement of STATUM firmware + Development of Hotswap Control

<u>2023</u>: Activation of hotswap system

REX of 2022/23 period - Factors having a significant impact on PS failure rate:

"Shutdown effect" on PS <u>hardware</u> reliability

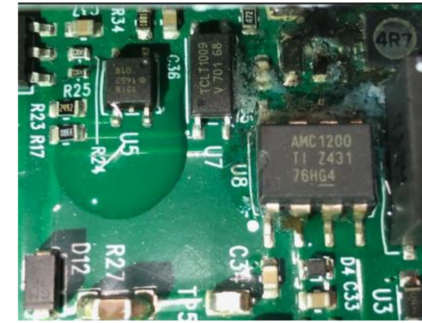
- 33% of all hardware failures occurred right after / during shutdowns (8 failures)
- Stressful environment for electronics (cycling of main and auxiliary power)

Release of new STATUM <u>software</u> version introducing/revealing latent bugs:

- 20 events, accounting to almost 50% of all PS failures.
- Recurring difficulties in proofing in the lab a new version with 100% confidence

RELIABILITY ISSUES

STATUM

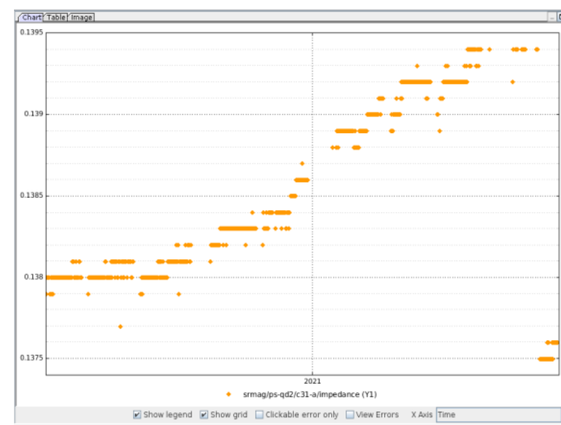


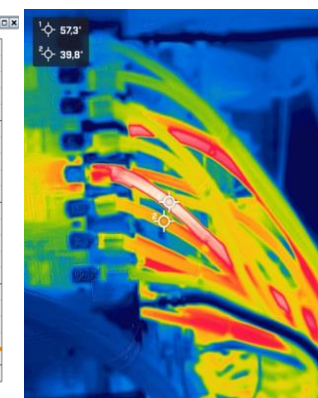
- Bugs in embedded software of Channels' DSPs and Rack's Interface Controllers
  - Random hiccups (trip by overcurrent) of PS channels when starting or stopping
  - Large error in magnet current regulation in some conditions
  - Communication board crippled with problems (Eth link unreliable, NTP synchronization crashing)
- Hardware reliability issues
  - Design issues: PoE stage ill-designed leading to a cascade of problems (control electronic not starting, boards failure, loss of calibration parameters)
  - Quality issues: Electronic board failures, Loose electrical connections, Water leaks, …
  - Unexplained incident: fuses blowings, EMIs, and many others

HOT Swap Cubicles

- Total of >6000's of electrical power connections
- Live magnet resistance monitoring allowed detecting just in time quite a few loosely crimped cables overheating

⇨ Crimping and retighten of the lugs before failure



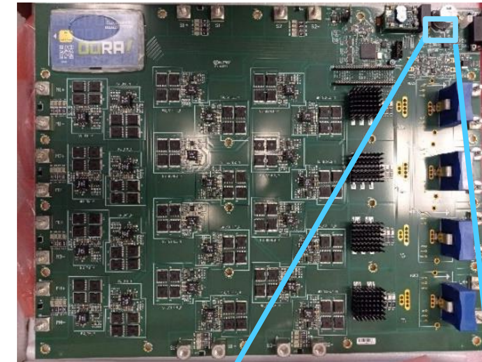


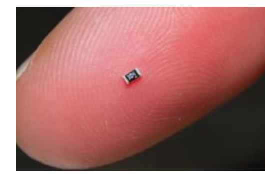
RELIABILITY ISSUES

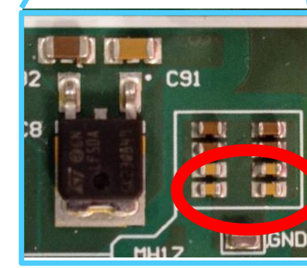
MOSPLATES

- From June 2021 MOSplates started failing at a rate of about 1 per month (Power MOSfet suddenly turning off disconnecting PS from magnet!)
- Rootcause identified: Premature failure of tiny filtering capacitors

  => Modification campaign in Winter 2021 to unsolder capacitor from MOSplate (640 capacitors!)





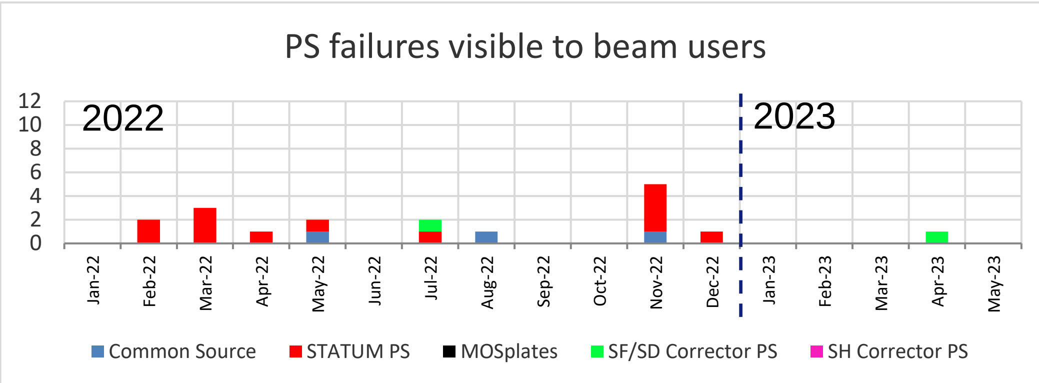


Corrector PS:

- Crash of the rack’s µcontroller, freezing the PS’s current setpoint
- 2-3 crash per month, almost never twice on same rack over a 10 month period!
- Strong suspicion that these crash were caused by the environment, more specifically the Ethernet link.
- Rootcause found with help of Network team: bad auto-negociation of Ethernet link at start-up

=> reconfiguring the CISCO Ethernet switch to force the Eth link to full-duplex mode solved the issue.

STORAGE RING PS RELIABILITY 2022-23 (BEAM USERS' PERSPECTIVE)



Main PS System	MTBF [h]
8 x CS 360Vdc	3200
864 x Main PS (STATUM)	738
32 x Hotswap system	No Failure
Overall System	**600**

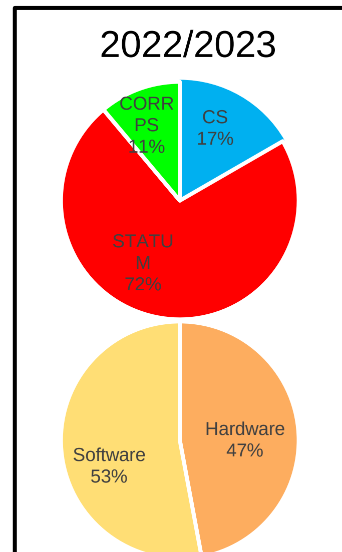
Corrector PS System	MTBF [h]
2 x CS 48Vdc	No Failure
864 x SF/SD Corr PS	4800
294 x SH Corr PS	No Failure
Overall System	**4800**

Excluding failures that happened during shutdown (SD) and associated restart period

=> 18 failures "only" visible to users these last 18monthes

For comparison, **MTBF of old ESRF machine (period 2007-2014)** was

- 2400h for Main PS System (total of 14 PS)
- 2300h for Corrector PS System (total of 410 PS)



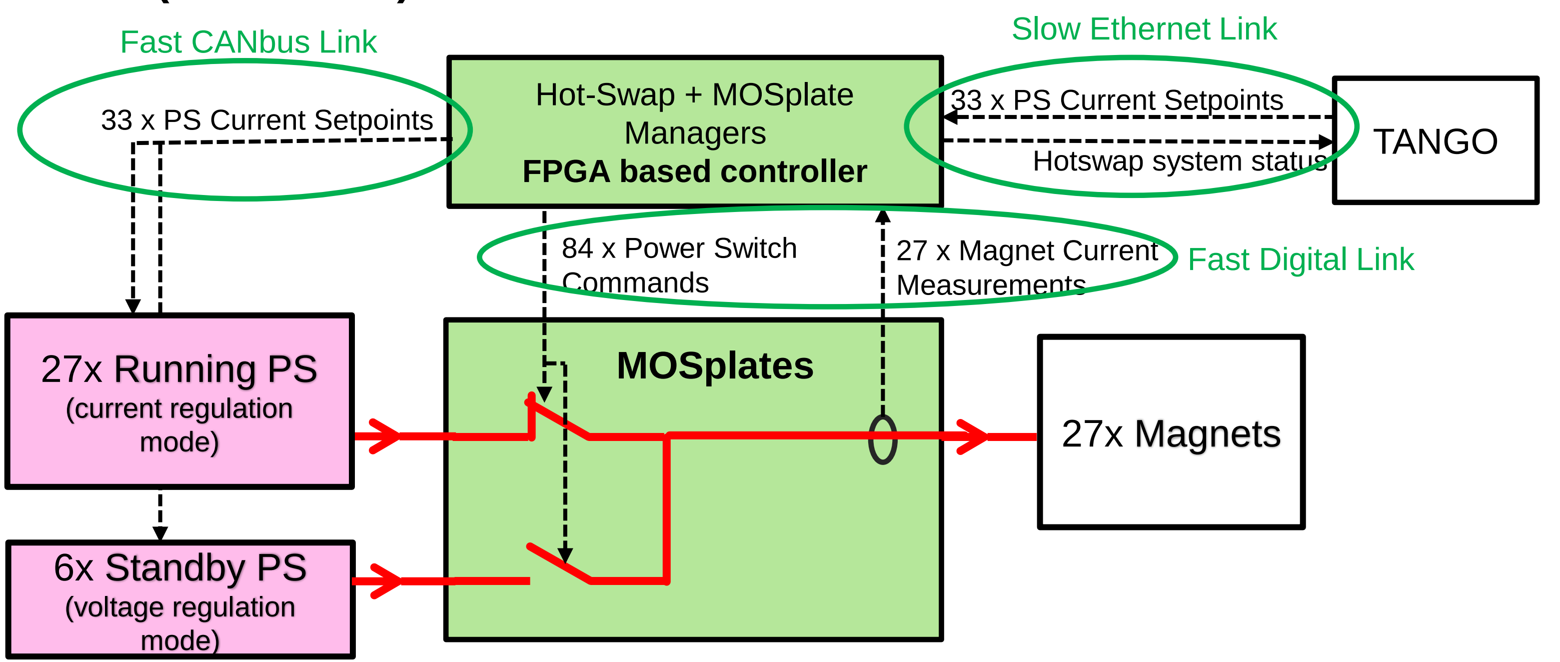
Note: no impact of Hotswap system on accelerator reliability so far, see next slide.

Function

Automatically swaps a faulty PS with a healthy one without noticeable drop in magnet current

- PS Fault detection by comparing magnet current setpoint and current measurement
- “Hot” disconnection / reconnection of power supplies from/to magnet via a matrix of power MOSfet switches

Architecture (for one cell)



Hotswap and Mosplates managers

=> the low level fast controller of the system,

ensuring the following functions

- Hotswap sequencer
  - Monitors magnet current and initiate hotswap if departure from setpoint (0.15% for DQ mag, 5% for Quad mag)
  - Send voltage and current setpoints to spare PS (+ PI current regulator gains)
  - Ask MOSplates to disconnect faulty PS from Magnet and connect spare PS instead

- Communication with TANGO (remote control)
  - TANGO->HSM (Command):
    - Current Setpoints
    - Hotswap inhibition command
  - HSM -> TANGO (Feedback to user)
    - system status, alarms/events history
    - current waveform recordings for post mortem analysis

MOSPlates (power part)

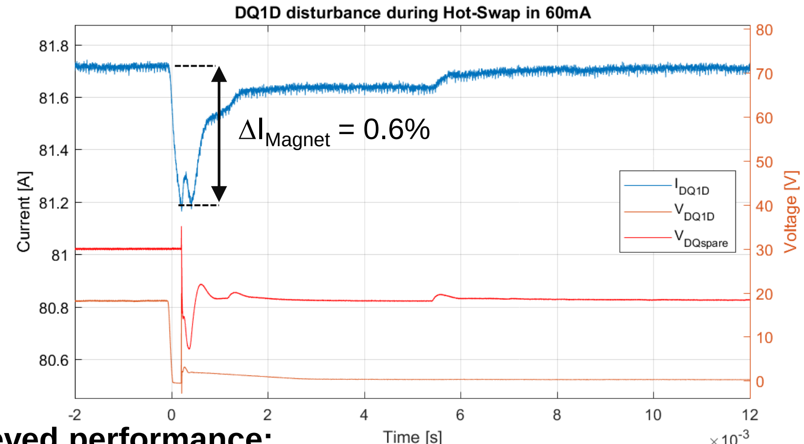
- Water cooled electronic board 500mmx350mm
- 4 channels rated 120A to feed **4 magnets**, from **4 running PS** and **2 standby PS**
- 12 pairs of **MOSfet switches + FW diodes**
- **Current sensors** (Hall Effect current sensors or DCCT)
- **FPGA control circuit** for communication link with MOSplate managers and control of MOSFET

HOTSWAP SYSTEM: PERFORMANCES

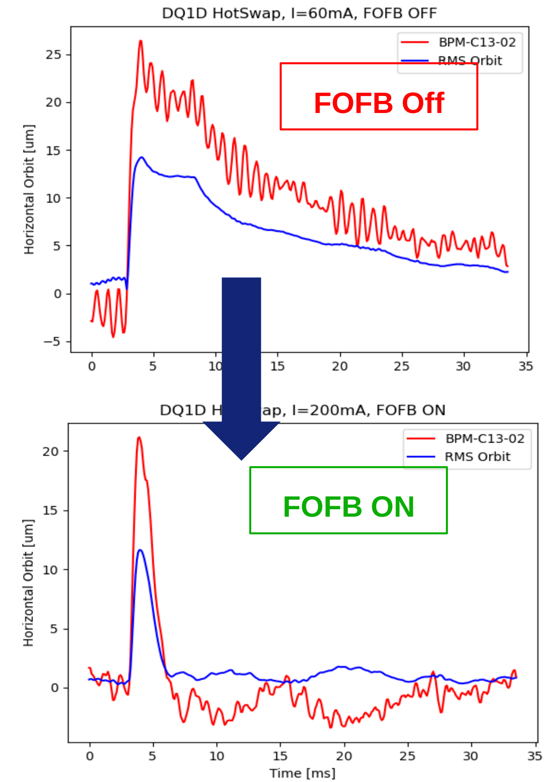
Switching off manually DQ1D PS (simulation of PS failure) – stored electron beam current at 60mA

:

Magnet Current



e- BEAM horizontal deviation



Achieved performance:

- ΔI Magnet = 0.6%, ΔB Magnet = ????
- No beam loss, Δx Beam = 30um / 2ms (with FOFB turned ON)
- Performance in terms of ΔI Magnet limited by
  - Magnet's electrical time constant (di/dt)
  - Hotswap manager reaction time (#100us)
  - PS's voltage regulation bandwidth (150Hz => #1ms)
- Impact on Beamlines (X-ray beam deviation) unknown at the moment

HOTSWAP SYSTEM: STATUS

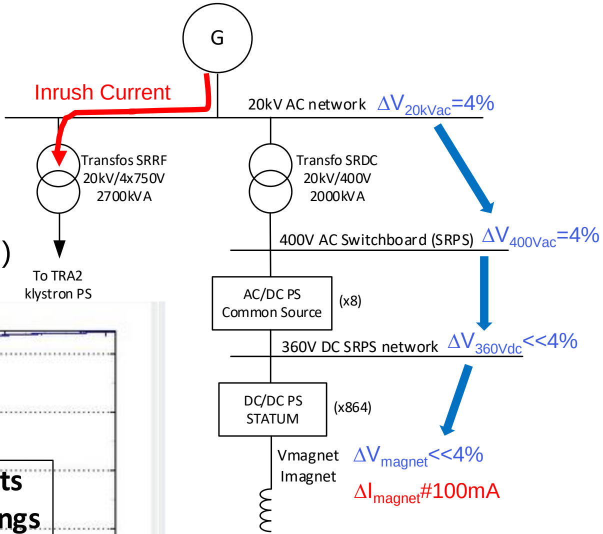
Status

- System **in service since 16 Jan 2023**, covering the 576 Quad and DQ magnets
- Manufacturing of additional MOSplate to cover the 192 Sextupoles in progress since Jan 2022 (heavy delays due to shortage of electronic components)

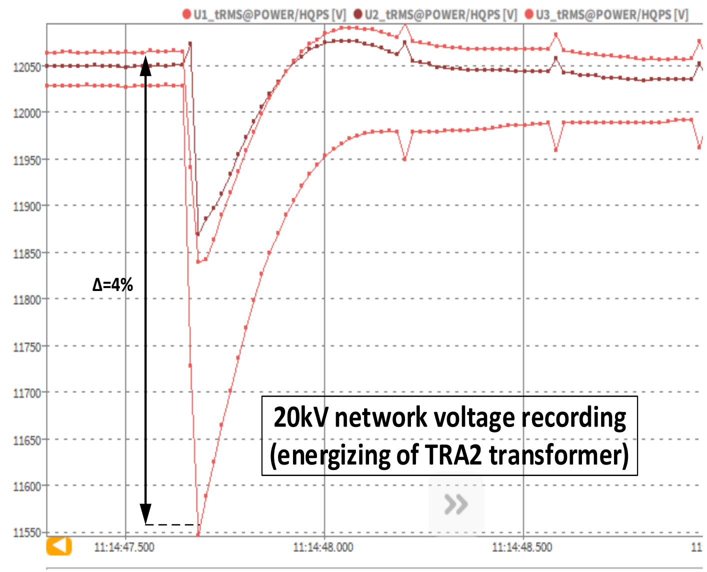
Return of experience after 4 months operation in User Service Mode (USM)

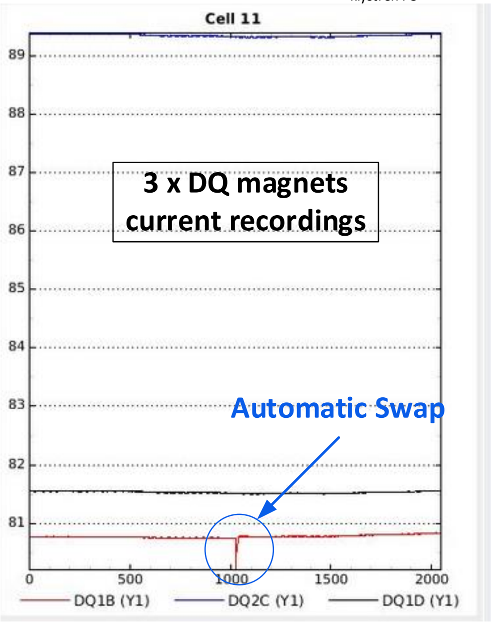
- No negative impact of HOTSWAP system on accelerator reliability so far
- Unfortunately, no main PS failure in USM in 2023 => no chance yet for proving hotswap system's added value
- Yet some unexpected swaps did occur in USM…. caused by disturbances coming from the 20kV AC network!
  - Energizing of large ESRF transformer
  - Incidents on Grenoble utility grid

Energizing of large ESRF transformers



1. Large Tx inrush current causes transient voltage dip on the 20kV electrical network
2. Voltage dip propagates down to the main PS output voltage
3. Automatic swap of some DQ magnet PS (swap activation threshold set to 0.15% of setpoint!)

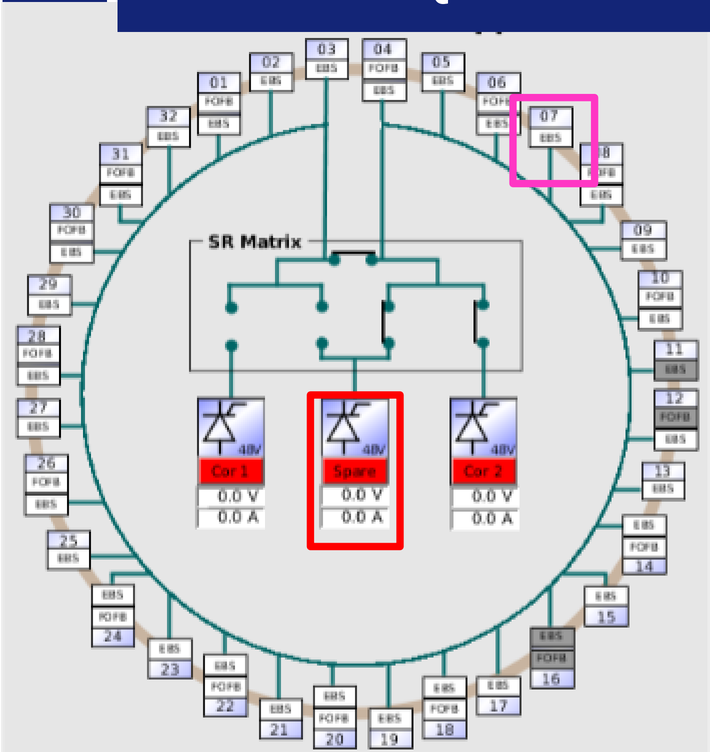


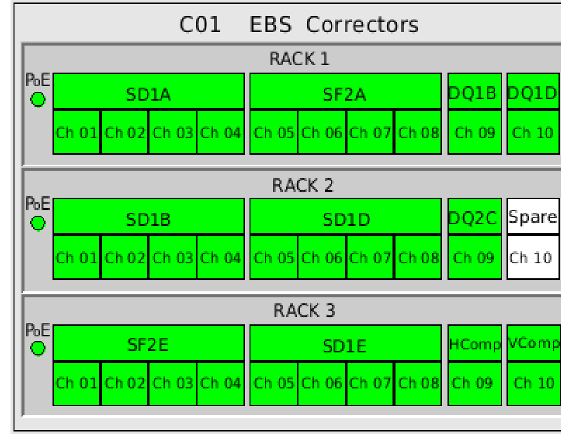


⇒ Mitigated by precise calibration of all current sensors of the Hotswap System / high BandWidth of PS current regulation

MANY THANKS FOR YOUR ATTENTION

SEXTU AND DQ CORRECTORS: CS-48V AND DC CORRECTOR PS (BILT EBS)





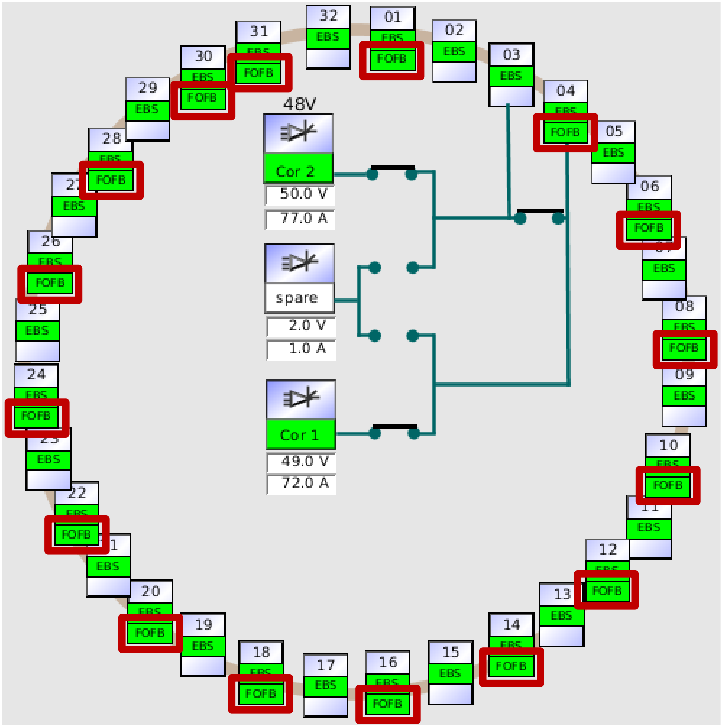
Ch Ratings
+/- 2.4Adc
(+/-18V)
40W

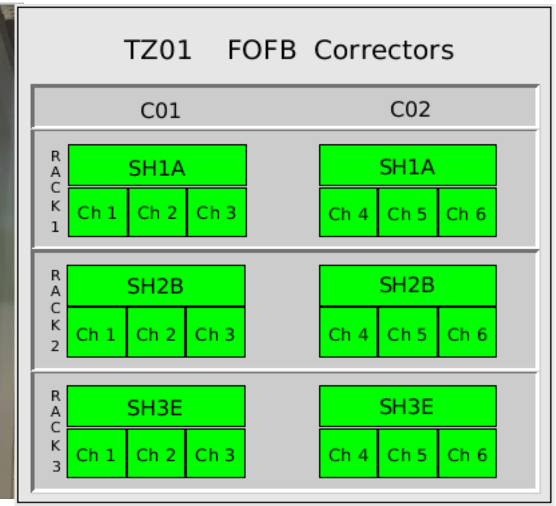
CS Ratings
48 Vdc
30 kW

Corrector Magnet powered using 2-stages power conversion system

- **Common Source 48Vdc : 400V AC => 48Vdc (2 + 1 PS)**
- **One single 48Vdc distributed network**
- **DC Corrector PS : DC/DC magnet PS (864 PS)**

SH CORRECTORS: DC+AC CORRECTOR PS (BILT FOFB)





Ch Ratings
+/- 1.8A dc
0.2 A ac
100W peak

Total number of DC + AC Corrector PS

294 channels in operation
(housed in 48+1 racks of 6 channels)