Overview of Sirius' Power Supplies

6th Power Converters for Particle Accelerators

September 24th – 26th | 2018

LNLS/CNPEM | Campinas - Brazil

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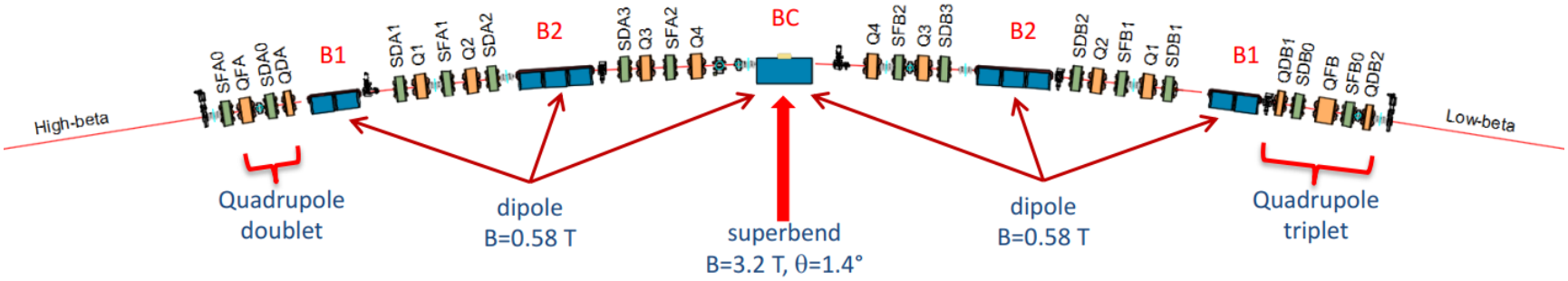
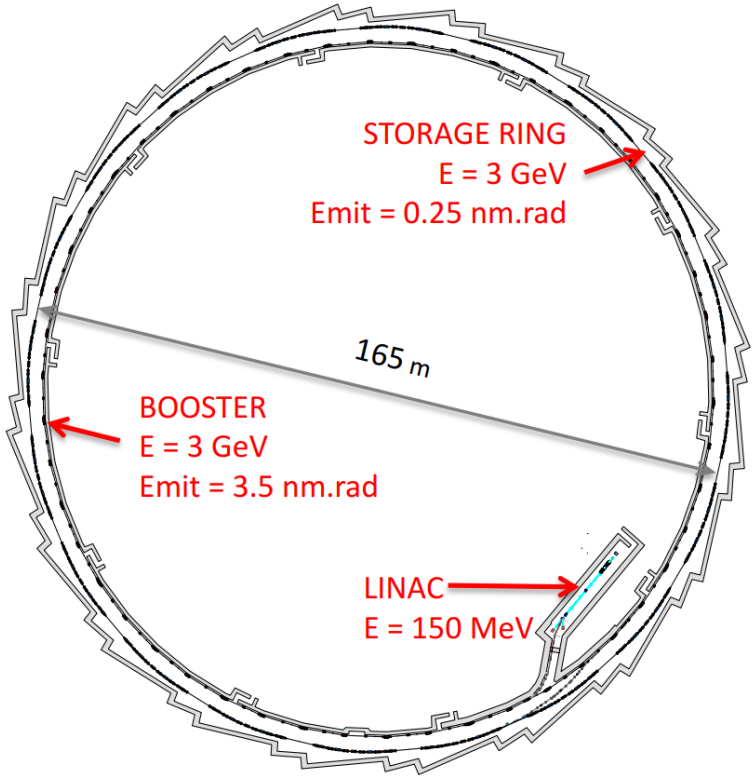
Power Electronics Group – LNLS/CNPEM

OUTLINE

- Sirius project
- Power supplies families
- Digital controllers
- Production status

SIRIUS PROJECT

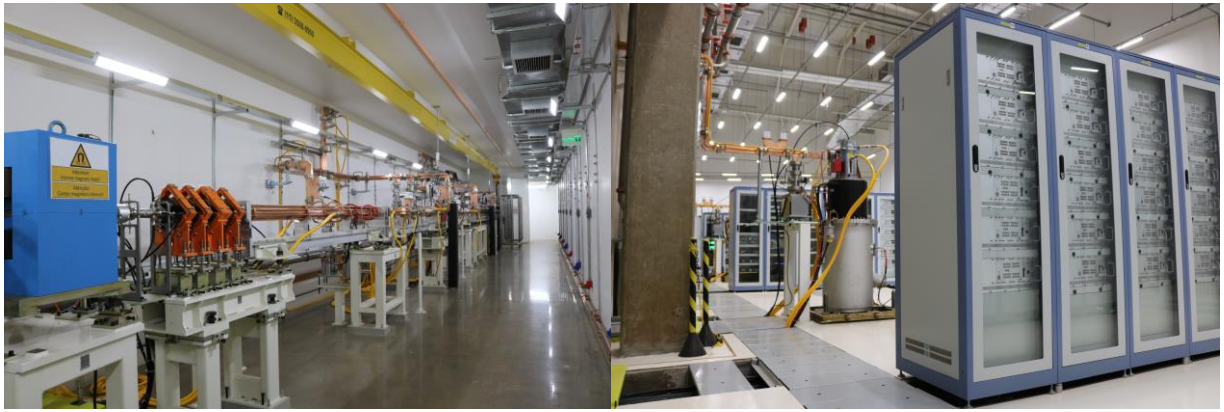




Beam Energy	3.0 GeV
SR Circumference	518.4 m
Lattice	20 x 5BA
Hor. Emittance	0.25 nm.rad
Nominal current (top up)	350 mA
Booster cycling freq	2 Hz
Beamlines (1st budget)	13

SIRIUS PROJECT

- Building construction complete, infrastructure and finishing in progress
- 150 MeV LINAC from SSRF (turn-key) installed and commissioned
- Installation of booster vacuum chamber and magnets on going
- TL's and booster PS's start in mid October



POWER SUPPLIES FAMILIES

- **Effort to standardize PS's from transport lines, booster and storage rings into only three *families***
  - Ease development, production and maintenance
  - Modular approach allows different combinations to fulfill all load specs

- **Converters topology:**
  - Bipolar (correctors, trim coils and booster magnets): *H-bridge + unipolar switching*
  - Unipolar (quadrupoles, sextupoles, dipoles): *Buck + coupled inductors*
  - Associated modules interleaved (lower ripple and controller delay)

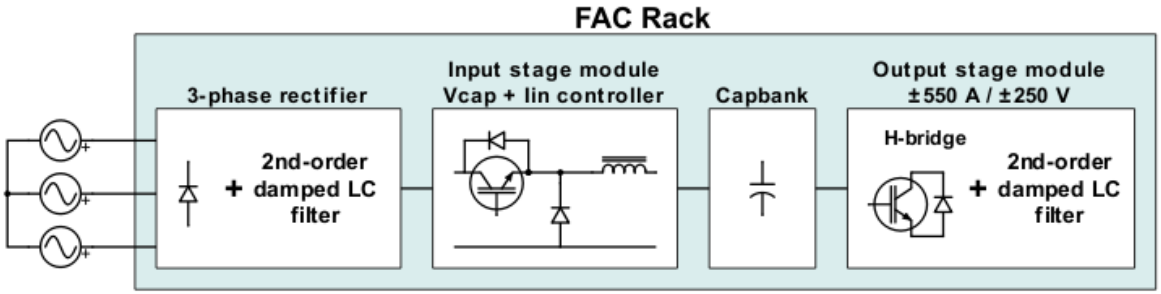
PS Families	FAC AC High Power	FAP DC High Power	FBP Low Power
Module topology	IGBT Buck + Capbank + IGBT H-Bridge	Buck with Two-Interleaved IGBT	MOSFET H-Bridge
Module specs	± 550 A / 50 kW	300 A / 45 kW	± 10 A / 100 W
Power range @ Sirius	0.6 – 333.5 kW	1.5 – 180 kW	15 - 100 W
Total # of PS	6	45	732

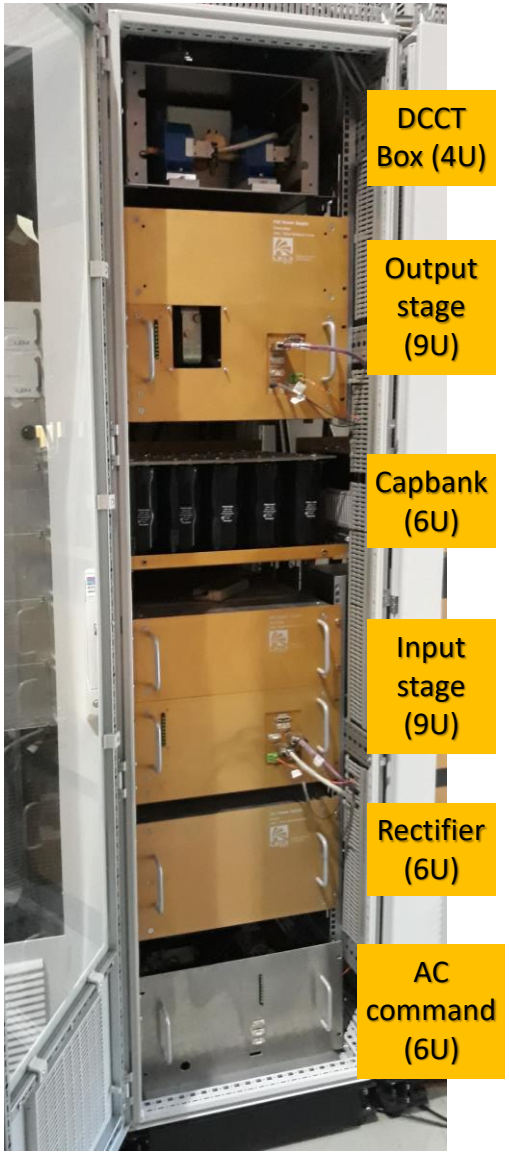
PS REQUIREMENTS

Magnets			Quadrant number	Load inductance [mH]	Load resistance [mΩ]	Nominal current [A]	Nominal voltage [V]	Nominal output power [kW]	PS model	PS Quantity
LTB	DIPOLES		1Q	?	56.3	300	20	6	FAP	1
	QUADRUPOLES		4Q	112.4	754.2	10	10	0.1	FBP	10
	STEERING MAGNETS		4Q	?	354.2	10	5	0.05		11
BTS	DIPOLES		1Q	13.8	427,125	750	35	26.25	FAP-4P	1
	QUADRUPOLES	QF	1Q	11.6	67.03	150	10	1.5	FAP	3
		QF/QD	1Q	6.3	55.7	150	10	1.5		5
	STEERING MAGNETS	HORIZONTAL	4Q	3.4	423	10	5	0.05	FBP	5
		VERTICAL	4Q	3.4	423	10	5	0.05		5
Booster	DIPOLES		4Q	115	333.5	1000	800	333.5	FAC-2P4S	2
	QUADRUPOLES	QF	4Q	540	2265.3	120	500	32.6	FAC-2S	1
		QD	4Q	135	651.5	30	40	0.586	FAC	1
	SEXTUPOLES	SF	4Q	50	253.8	150	70	5,710		1
		SD	4Q	20	216	150	50	4,859		1
	STEERING MAGNETS		4Q	3.4	329.2	10	5	0.05	FBP	50
	SKEW QUADs		4Q	?	256.3	?	5	?		1
Storage Ring	DIPOLES		1Q	316	1060.5	400	450	180	FAP-2P2S	2
	QUADRUPOLES (Main Coils)	QFB (Q30)	1Q	348	942	160	160	25.6	FAP	1
		QFP (Q30)	1Q	174	496.9	160	90	14.4		1
		QFA (Q20)	1Q	116	377.1	160	70	11.2		1
		Q1, Q2, ...(Q20)	1Q	464	1353	160	225	36		4
		QDA, QDP1 ...	1Q	63	263.5	160	50	8		3
		QDB1, QDB2	1Q	126	475.2	160	80	12.8		2
	SEXTUPOLES	SDB0, SDB1, ...	1Q	116	699	160	120	19.2		7
		SDA0, .SDA1, ...	1Q	58	375.4	160	70	11.2		14
	QUADRUPOLES (Trim Coils)	Q30	4Q	10.7	425.4	10	5	0.05	FBP	30
		Q20	4Q	7.2	395.4	10	5	0.05		170
		Q14	4Q	5	415.4	10	5	0.05		70
	STEERING MAGNETS	SLOW Horiz.	4Q	142	378.96	10	5	0.05		120
		SLOW Vertic.	4Q	103	326.46	10	5	0.05		140
		SLOW Vertic. Ext	4Q	6.8	357.56	10	5	0.05		20
	SKEW QUADs	SLOW (Sext.)	4Q	89.6	337.06	10	5	0.05		80
		SLOW (Fast St.)	4Q	6.32	1411.36	3	5	0.015		20
									TOTAL:	783

FAC – AC High Power PS

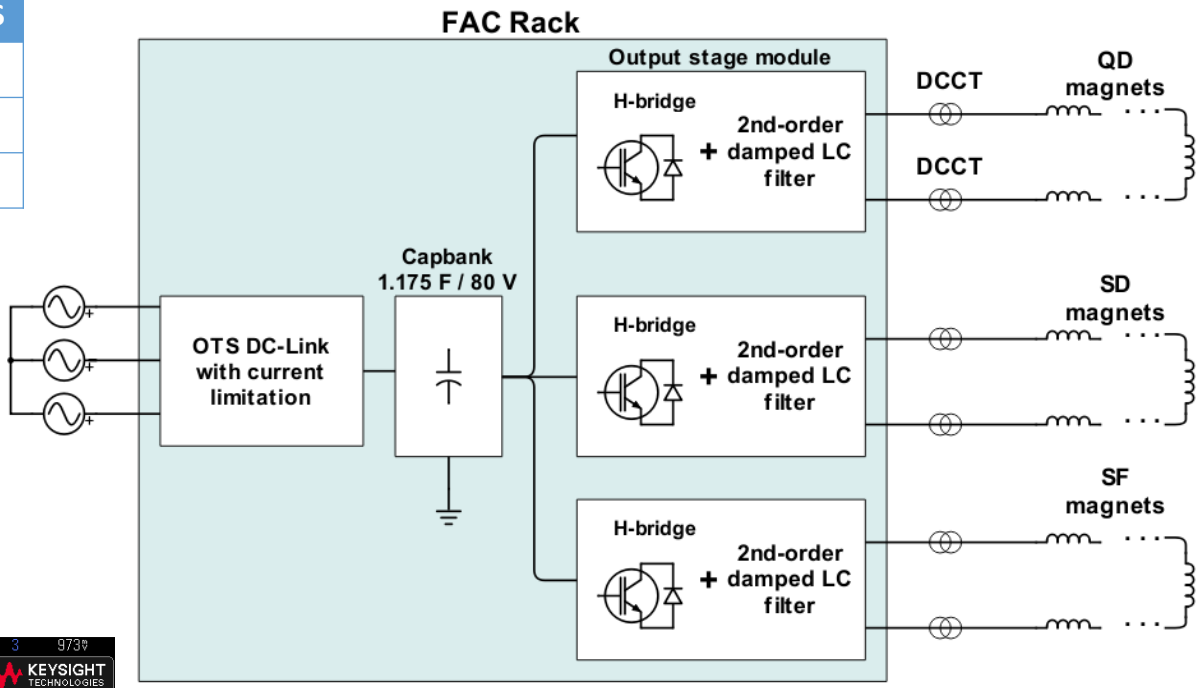
- Booster high-power cycling current sources
- Water-cooled IGBT's heatsinks and inductors
- 2 Hz triangular waveform (sync @ 8 kHz)
- Suppression of AC grid oscillation:
  - ***Capbank voltage control:*** *PI + notch filters @ 2 x n Hz*
  - ***Input current:*** *PI + resonant controllers @ 2 x n Hz*
- Reference & capbank voltage feedforward to improve tracking error on load current

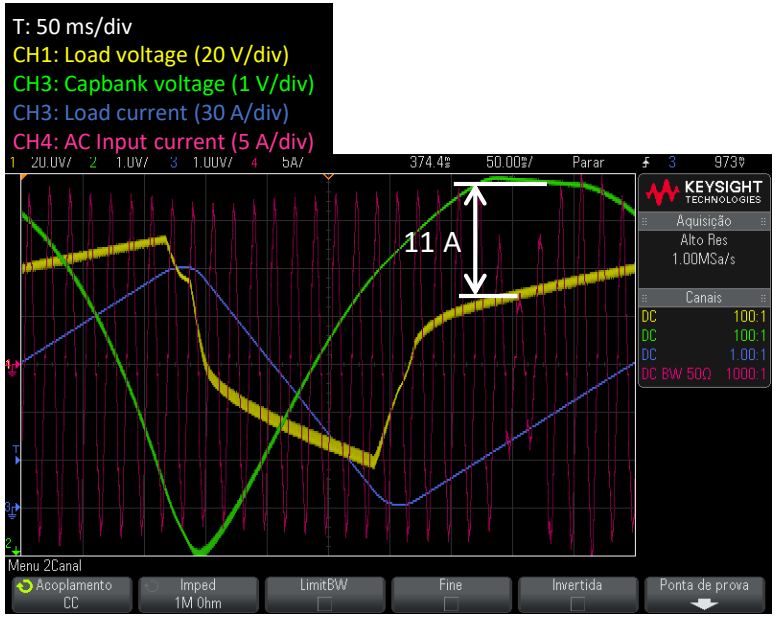




BOOSTER QD/SD/SF PS's

Nominal ratings	Magnets	L [mH]	# PS
30 A / 40 V	QD	135	1
150 A / 50 V	SD	20	1
150 A / 70 V	SF	50	1





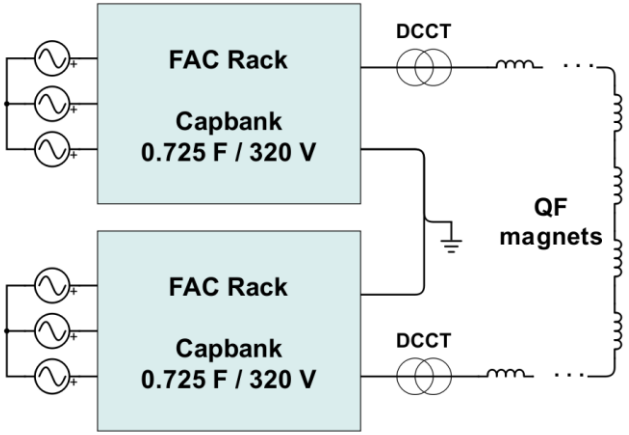
Peak load current: 150 A

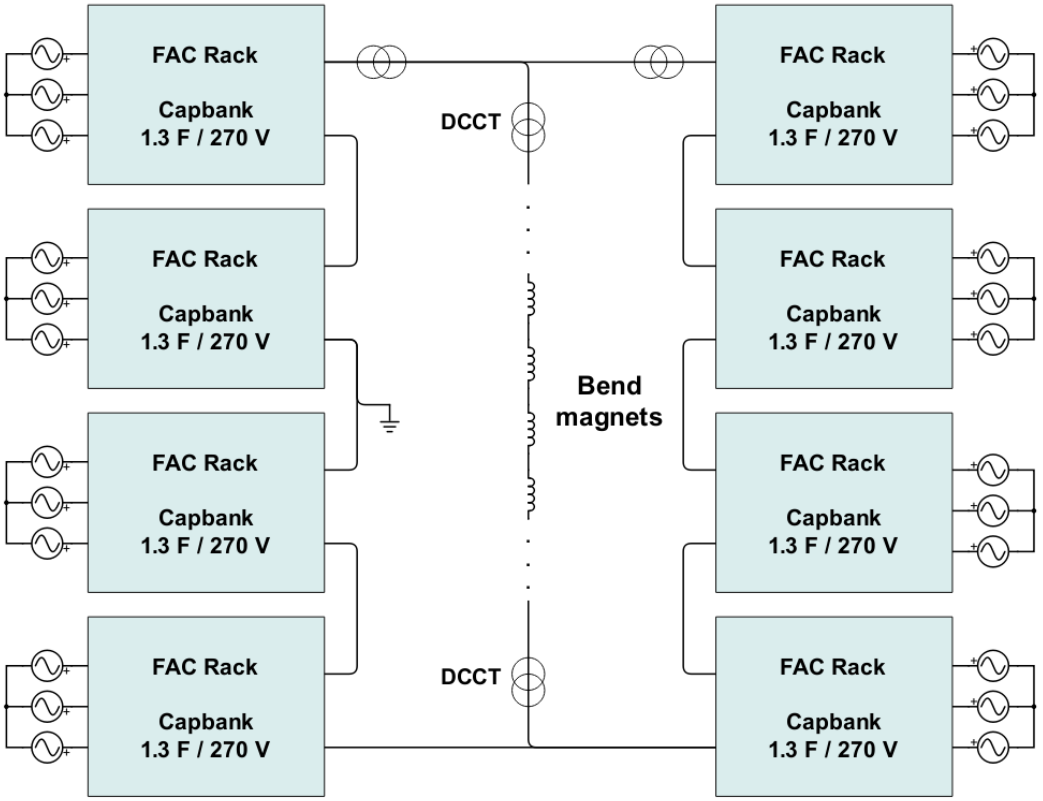
Load: 39 mH / 0.250 Ω

Capbank: 80 V_{DC} / 8 $V_{pk\text{-}pk}$

DC-Link current limitation: 28 A

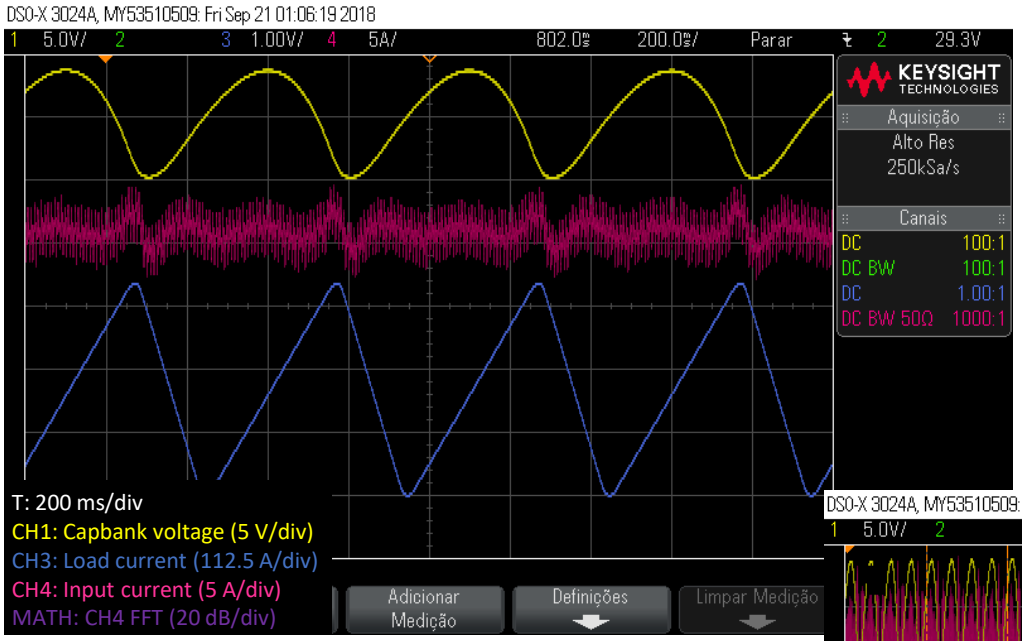
BOOSTER QF AND DIPOLES PS'S





PS Topology	Nominal ratings	Magnets	L [mH]	# PS
FAC-2S	120 A / 500 V	QF	540	1
FAC-2P4S	1100 A / 800 V	Dipoles	115	2

FAC – AC High Power PS

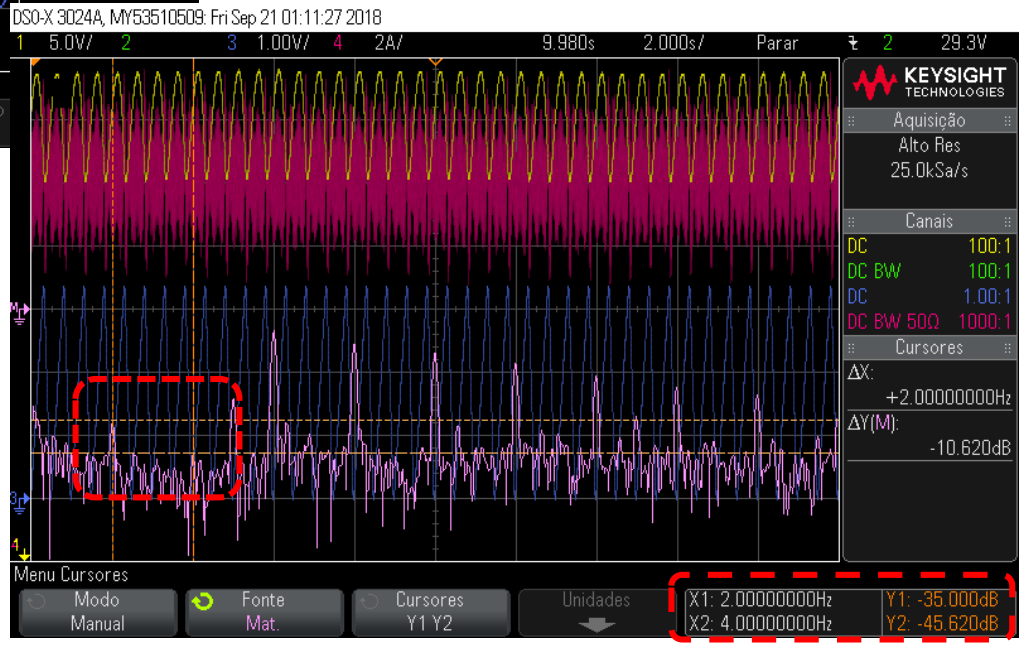


Peak load current: 380 A

Load: 11.5 mH / 0.157 Ω

Capbank: 195 V_{DC} / 8.6 $V_{pk\text{-}pk}$

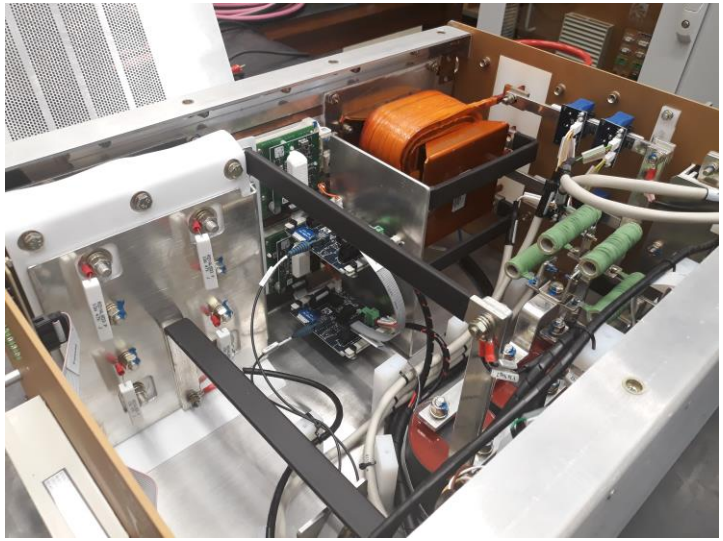
Buck input current: 40.1 A_{DC} / 5.6 $A_{pk\text{-}pk}$



Notch filters and ressonant controllers on 2 Hz and 4 Hz

FAP – DC High Power PS

- Transport lines and storage ring high-power converters
- Buck converter with 2 interleaved IGBTs connected by coupled inductors (developed in-house).
- Water-cooled heatsink and inductors. Manifold installed inside racks to distribute between different power modules
  - *98% eff typ.*
  - *IGBT's temp: 49ºC*
  - *Inductors temp: 68ºC*
- Off-the-shelf adjustable DC-links optimize output stage to work at 50% duty-cycle
  - *High voltage: Regatron TopCon*
  - *Low voltage: TDK Lambda HFE*

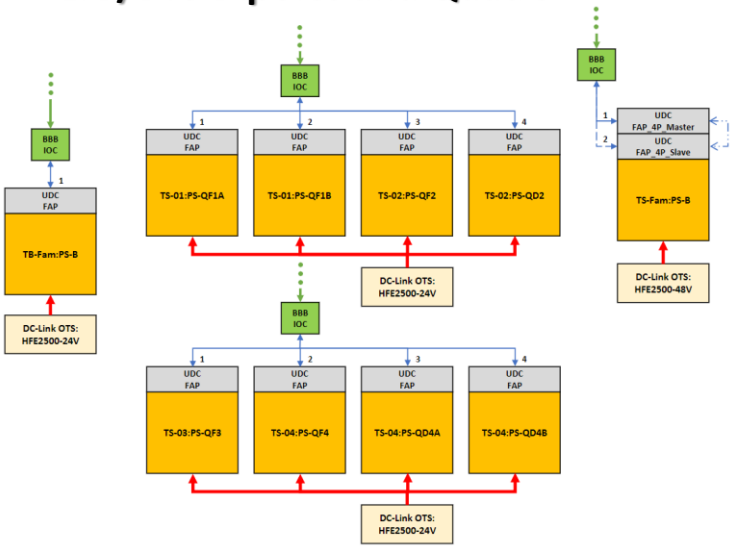


FAP – DC High Power PS

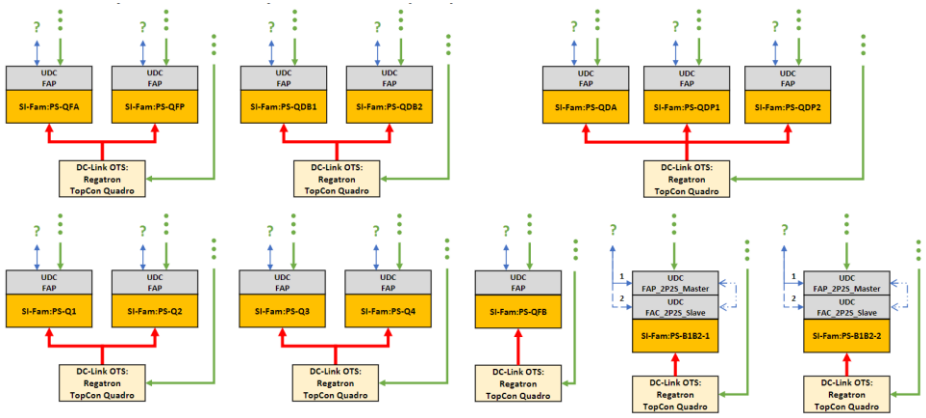
BTS Quadrupoles PS's

FAP – DC High Power PS

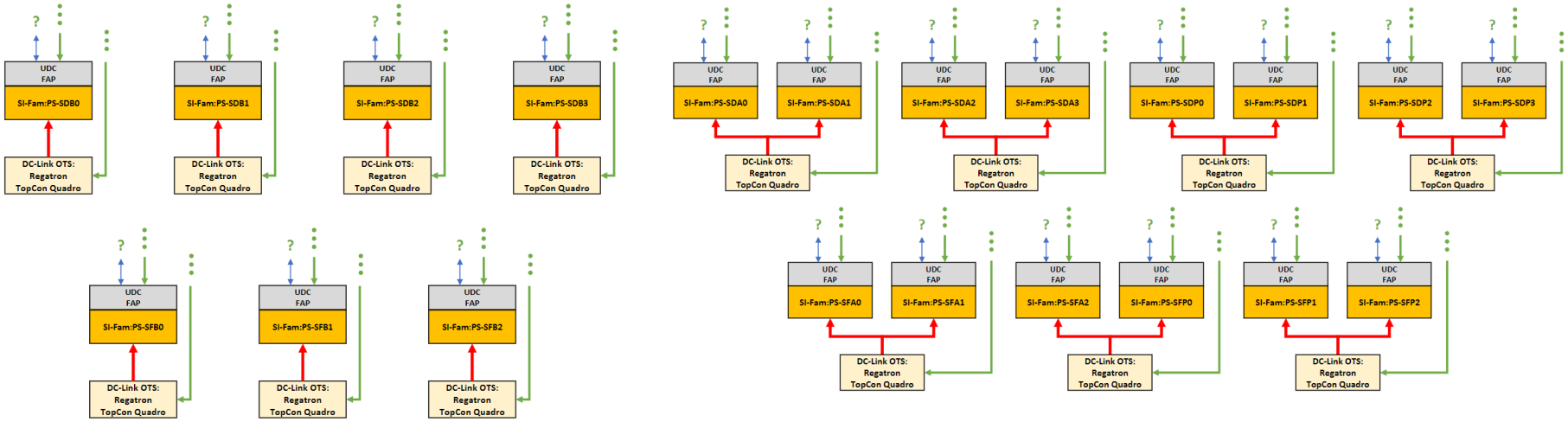
LTB/BTS Dipoles and Quad's



Storage Ring Dipoles and Quad's



Storage Ring Sextupoles



FBP – Low Power PS

Storage Ring			Booster		LTB		BTS
Quad Trim Coils	*Corrector Magnets*	*Skew Quad*	*Corrector Magnets*	*Skew Quad*	*Quad*	*Corrector Magnets*	*Corrector Magnets*
270	280	100	50	1	10	11	10

- 3U crate houses up to 4 individual ±10 A / ±10 V
  - *Air-cooled forced by rack exhaustor (except TL)*
  - *> 4 kHz bandwidth*

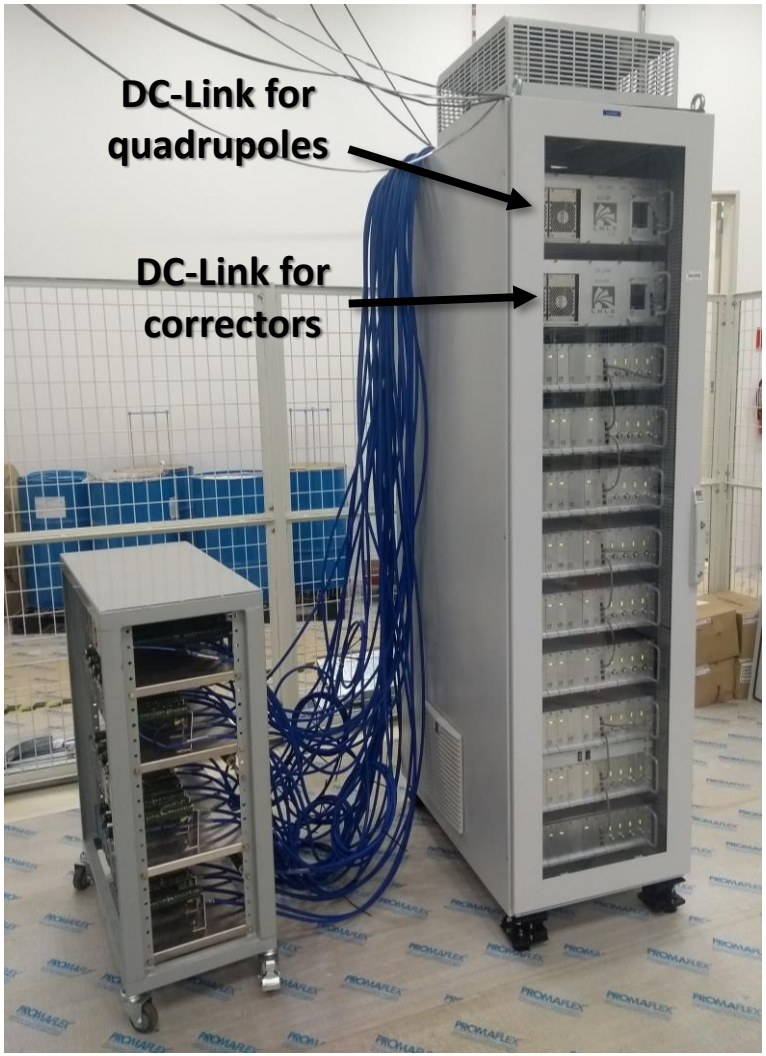
- MOSFETs H-Bridge (f_{PWM} = 50 kHz) + 2nd order LC-damped filter - 89% eff typ.

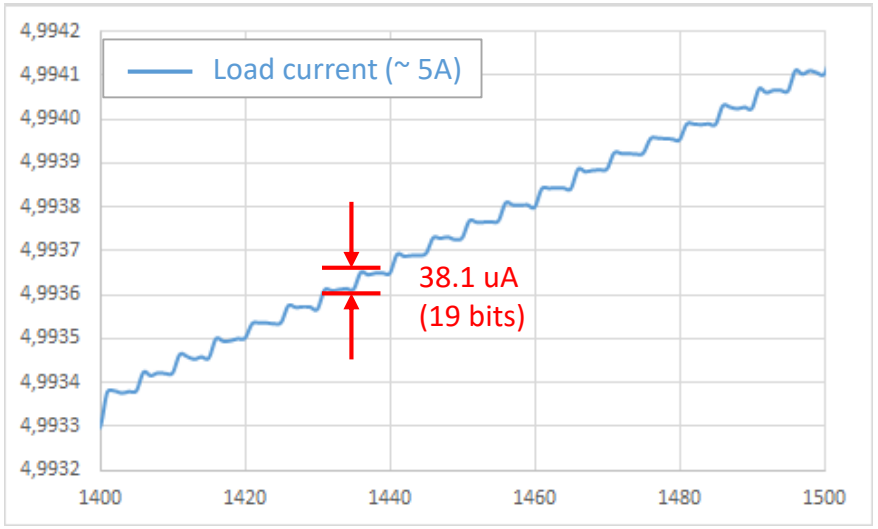
- Off-the-shelf AC/DC converters for shared DC-link among crates from same rack (adjustable for different set of loads)

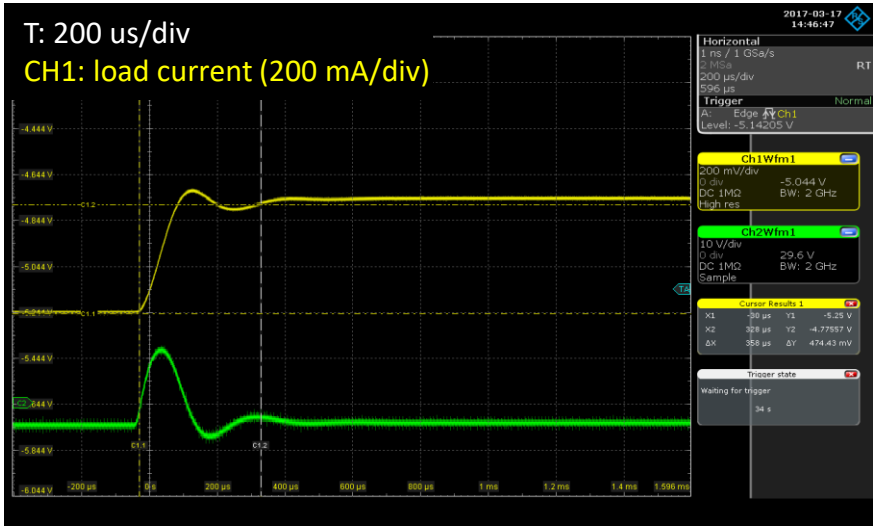
- First prototypes installed at UVX's LINAC two years ago and 10 units of final version installed this year. FBP rack for TL's already in place at Sirius

FBP – Low Power PS

LTB/BTS FBP power supplies





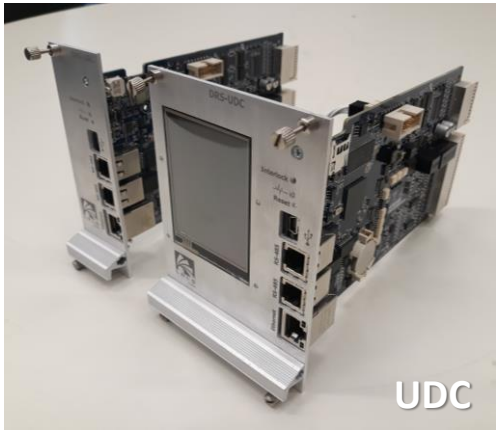


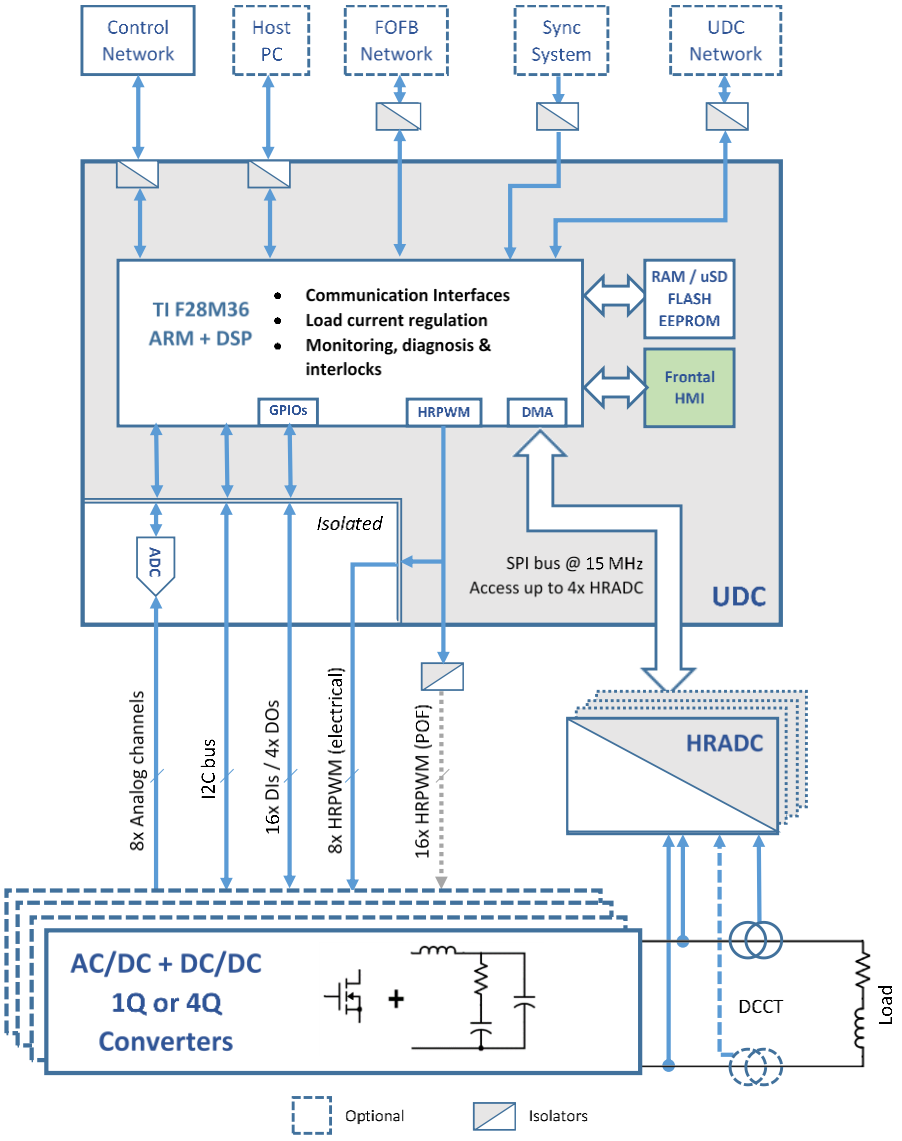
DRS – DIGITAL CONTROLLER

- 3U based in-house development, with initial partnership with University of Campinas

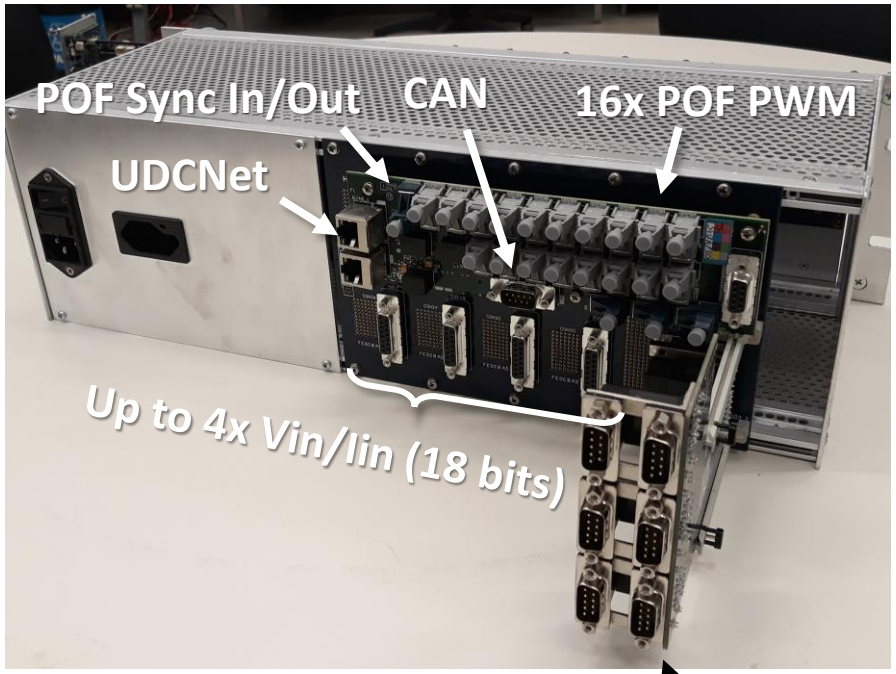
- UDC (Universal Digital Controller):
  - *Dual-core TI F28M36P63C2: ARM + DSP*
  - *Up to 4 indepen. PI controllers @ 100 kHz*

- HRADC (High-Resolution A/D Converter):
  - *18 bits @ up to 600 kSPs*
  - *Voltage / current input (Vishay VPR burden)*



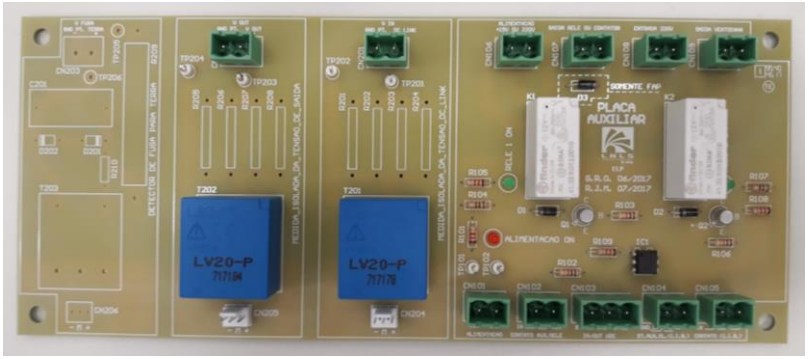


DRS ECOSYSTEM



Interlock board (CAN with UDC)

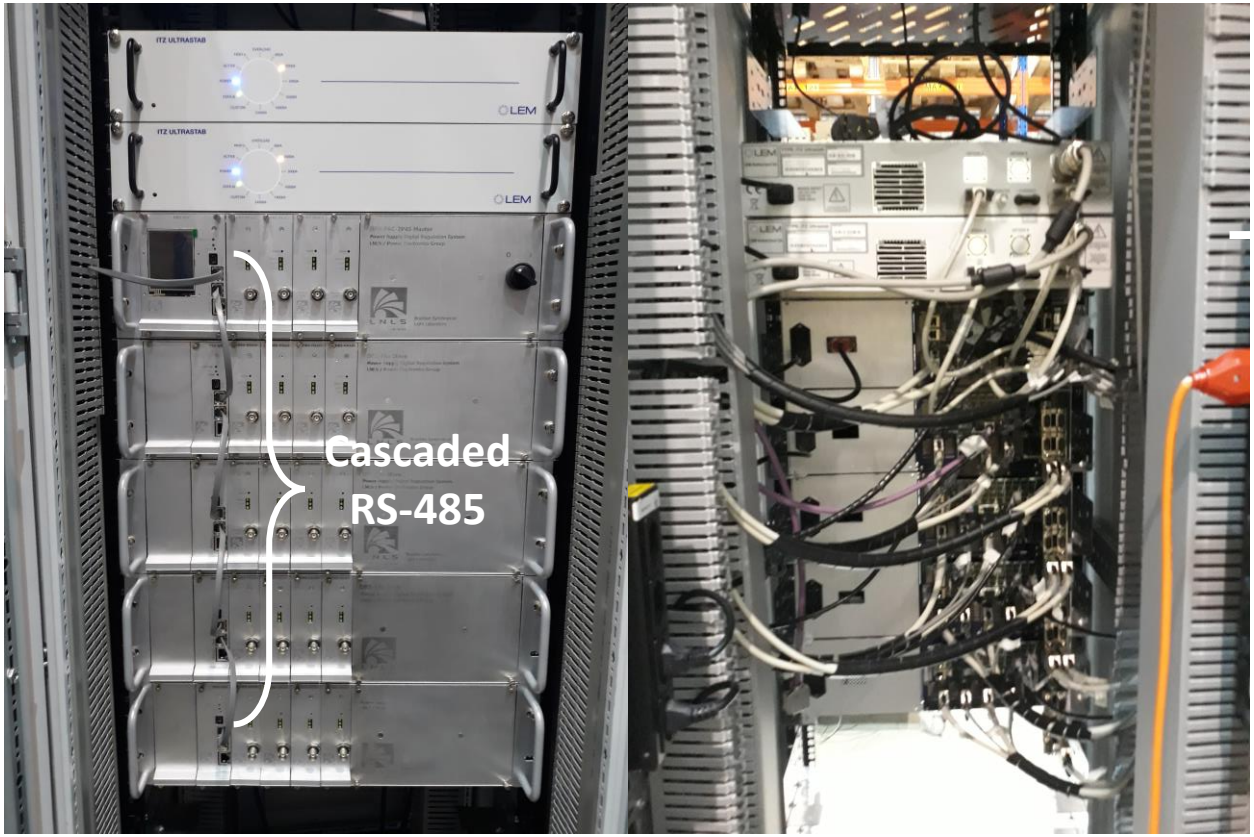
Auxiliary board (AC contactor/relays, isolations, etc)



Expansion board with isolated AIN + DI/O's from/to multiple PS power stages

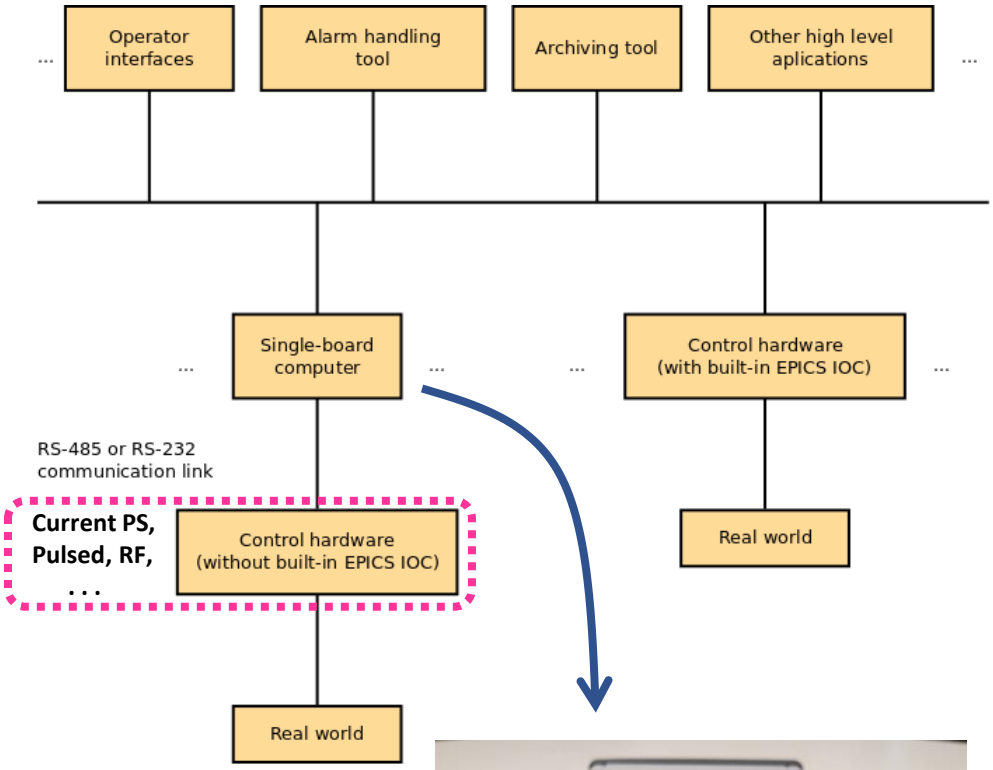
DRS FAx CONTROLLERS

Booster Dipole Controller



LTB/BTS PS Controllers

HIGH-LEVEL INTERFACE

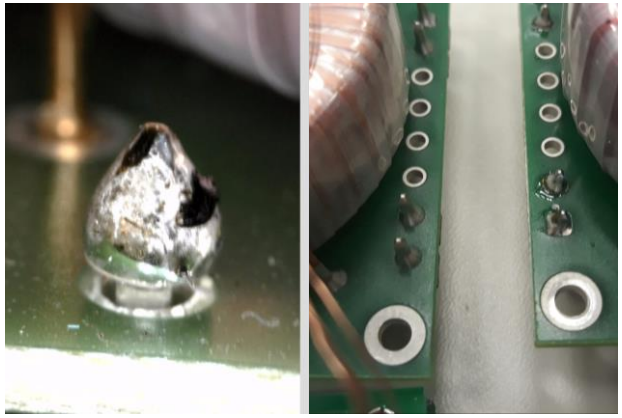


- EPICS plataform (pydm, CCS, ...)
- Power supplies IOC's implemented on SBC modules based on BeagleBone Black:
  - RS-485 @ 6Mbps
  - BSMP protocol (in-house)
  - Synchronization by serial interface, instead on direct pulses

PRODUCTION & TESTS

- FAC
  - 100% modules manufactured, ~90% tested
  - Racks integration and tests in progress
- FAP
  - 100% modules manufactured
  - All LTB/BTS modules tested, racks integration finish on next fews days
- FBP
  - 1 rack (LTB/BTS) installed and operating with dummy loads
  - 380 power supplies (95 crates) delivered and tested – sufficient for Sirius operation without trim coils and QS
  - DCCTs recall (~50% !!)
- DRS (FAC/FAP)
  - > 90% electronics completed (in-house HW customization)
  - LTB, BTS and Booster PS controllers assembled, under tests
  - Cabling and rack integration on going
  - Firmware in progress

PRODUCTION & TESTS



PRODUCTION & TESTS

THANK YOU!

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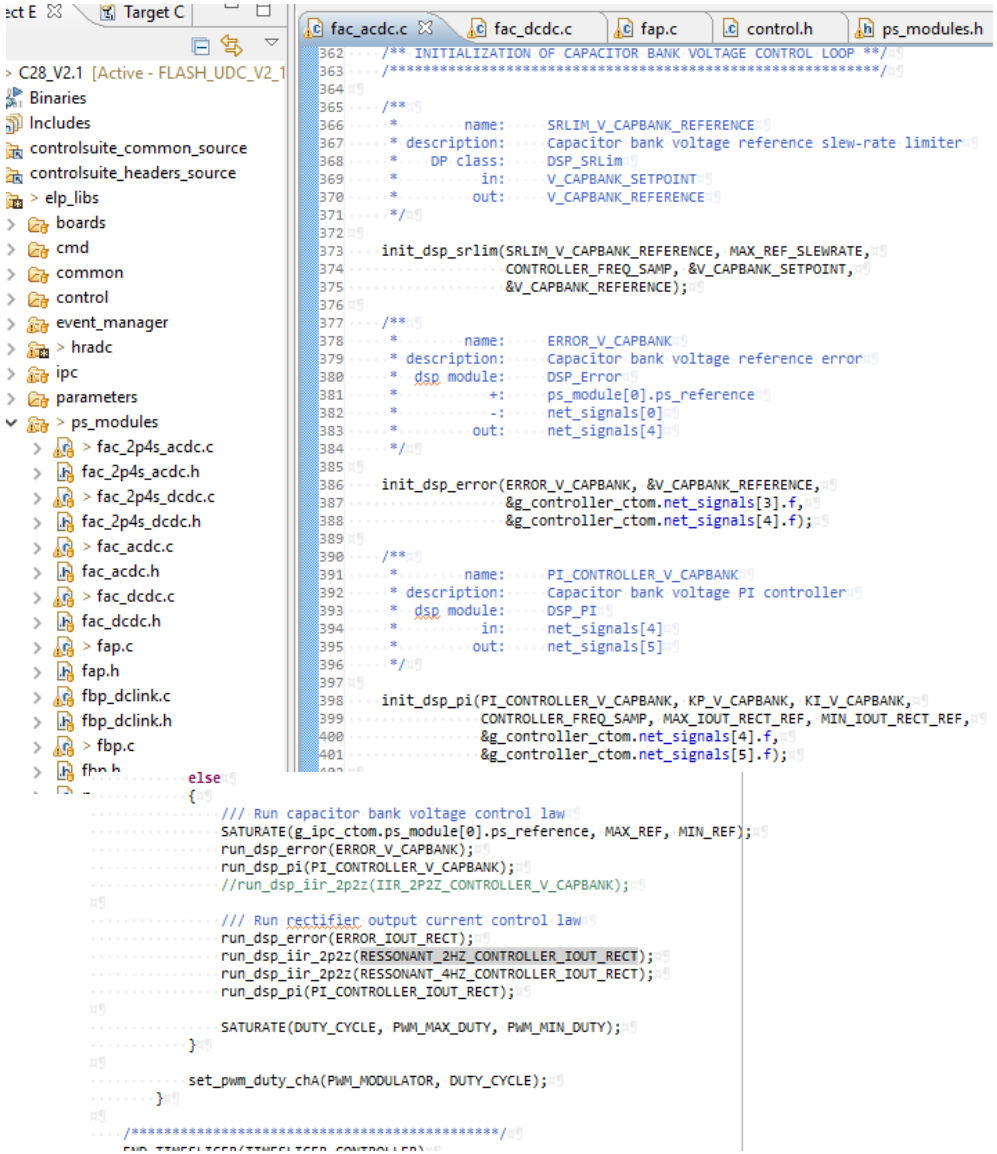

- One project/core to maintain (Git)
- New PS models require only 2 files:
  - ***new_model.c (source)***
  - ***new_model.h (header)***
- Completely parameterized
  - PWM settings (freq/dead-time/sat)
  - Communication settings
  - Control parameters
  - Interlocks thresholds
  - # PS (FBP only)
  - . . .
- Control laws are built and run '*blockwise*' inside each PS module

BOOSTER DIPOLE INPUT CONTROL