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Radio Frequency Power Station at the European Spallation Source, Lund, Sweden

Testing Experience and salient features of RFPS

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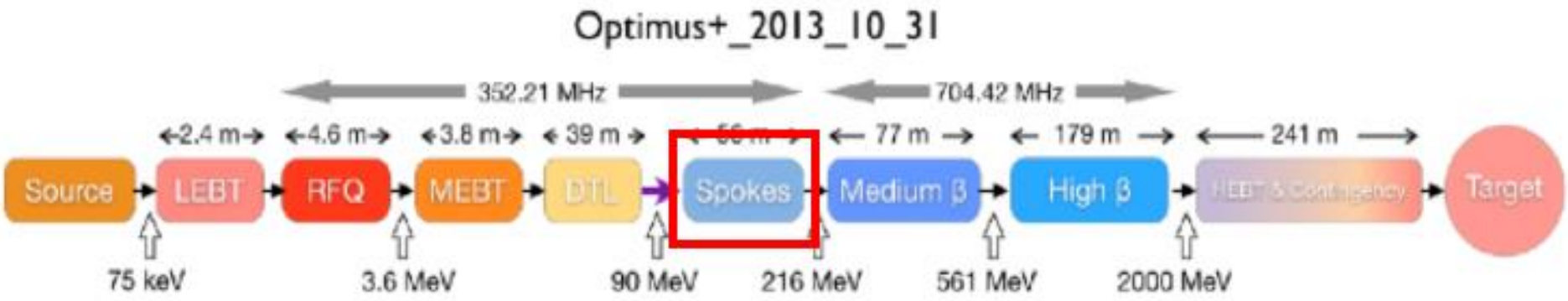
2022-07-05

RFPS Overview

26 RFPS for the SPOKE LINAC at ESS

Overall view of the system



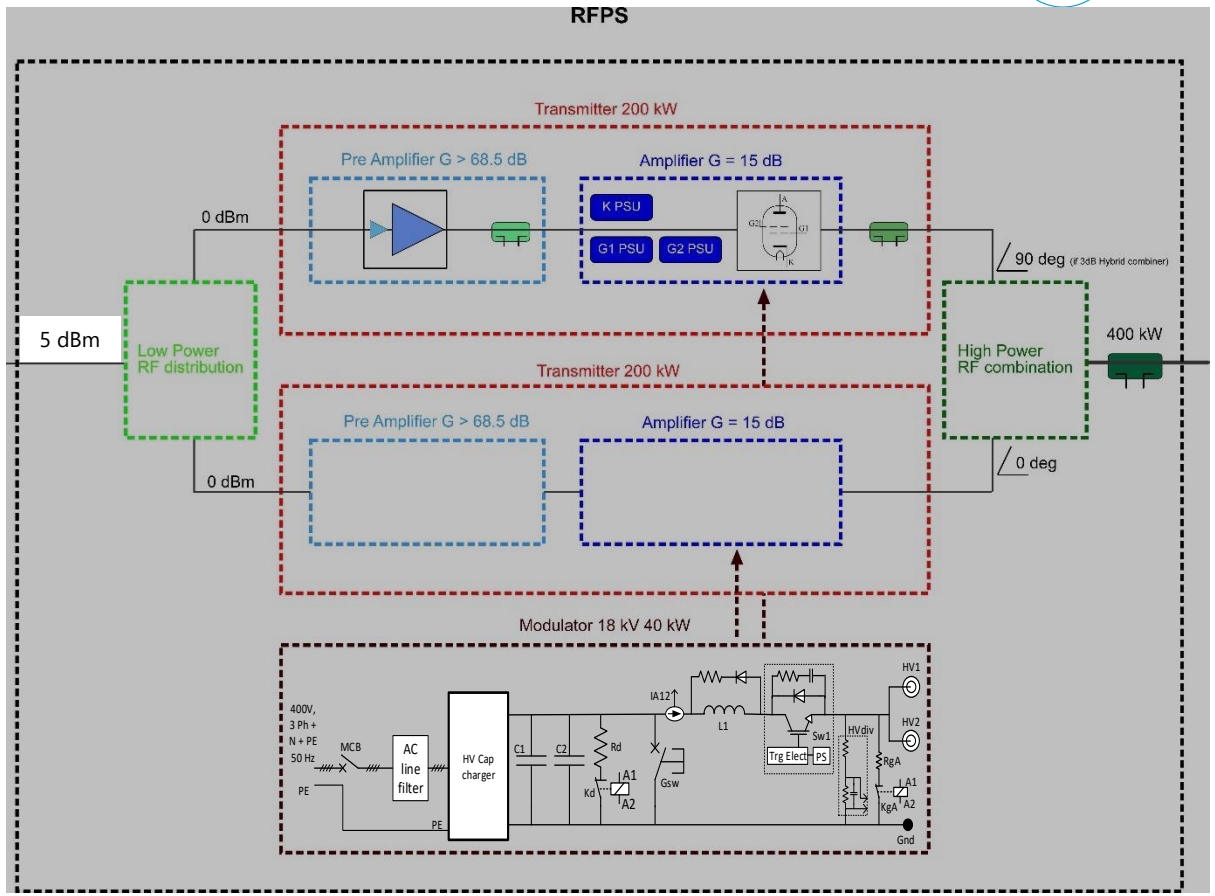
Recall on RFPS for Spokes' requirements and topology

- Main parameters of RFPS for Spokes (as from SoW)

Parameter	Value
CF (monotonic)	**352.21 MHz**
P_N	**400 kW**
RF Drive $_M$	5 dBm
Gain @ P_N	> 76 dB
BW	≥ 2 MHz
Operation	Pulsed, at 5% duty cycle
Pulse repetition rate	**14 Hz**
PW_N	**3.5 ms**
Input & Output impedance	50 Ω
RF output line	6 1/8 " EIA rigid coaxial line flange
Electrical grid Power Line	AC 400 V, 50 Hz, 3 Phases + Neutral + PE
Electrical grid Control Line	AC 400 V, 50 Hz, 3 Phases + Neutral + PE
Cooling	Forced air and water
RF flat-top stability	≥ 100 kHz 100 kHz÷1 kHz 1 kHz÷0.3 kHz
- Max. phase variation	0.5^0 1^0 2^0
- Max amplitude variation	0.5% 1% 1.5%
Pulse-to-pulse stability	
- Av. amplitude variation	≤ ± 0.5 %
- Av. phase variation	≤ ± 0.5^0
Power Quality	
- Harmonic distortion, THD	< 10% (*)
- Flicker on AC line current	< 10% (*)
- Power factor	> 0.95 (*)
- Efficiency, during flat-top	≥ 55%

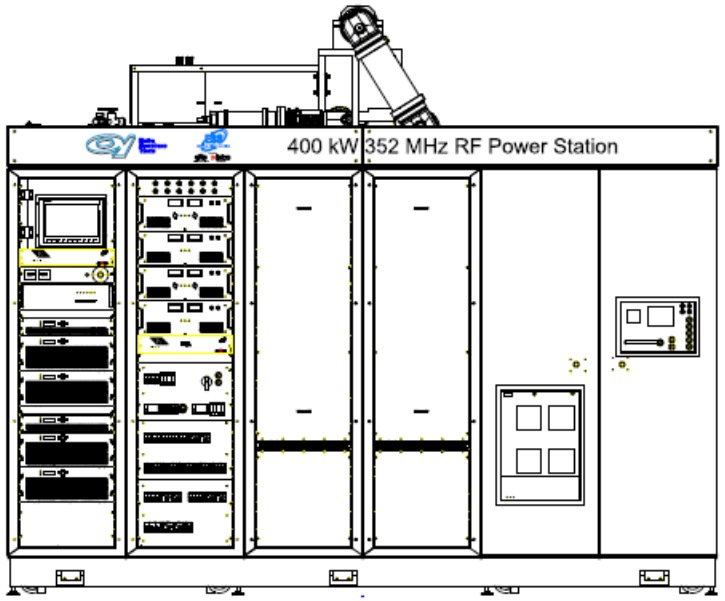
(*)-*not specified, but achieved by Modulator design*

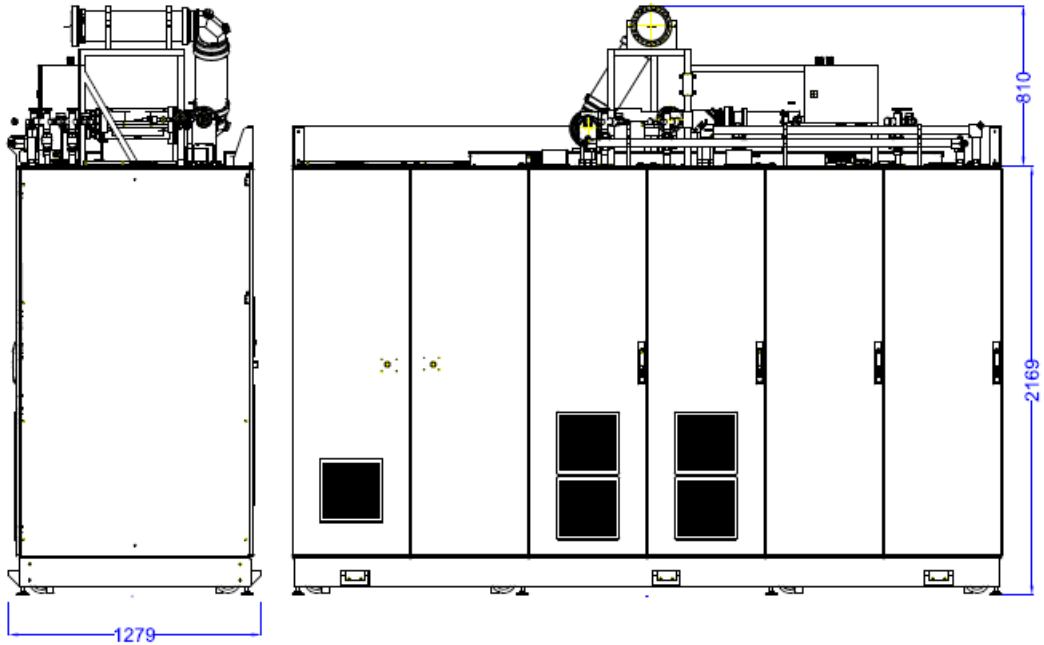
- Topology simplified schematic

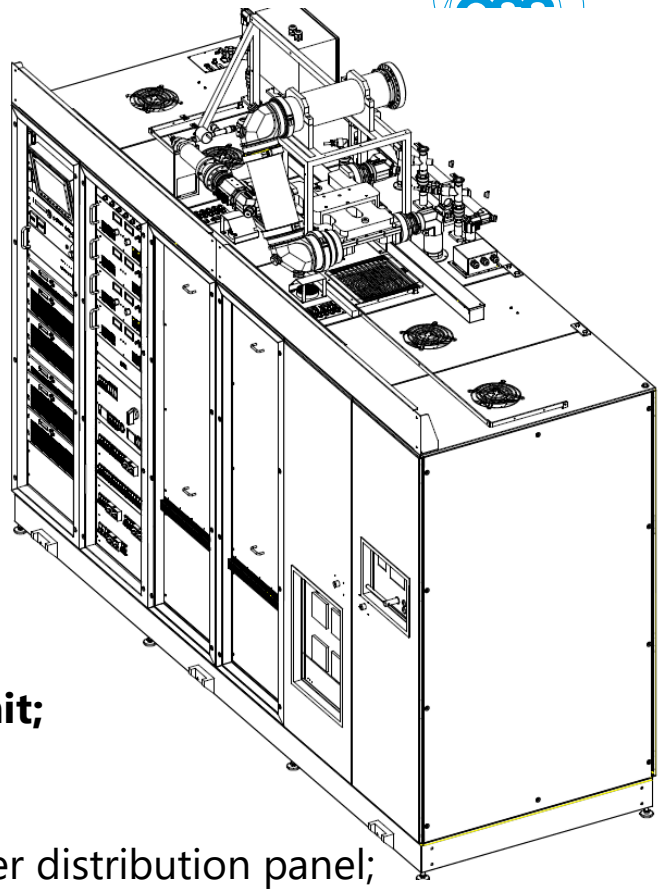


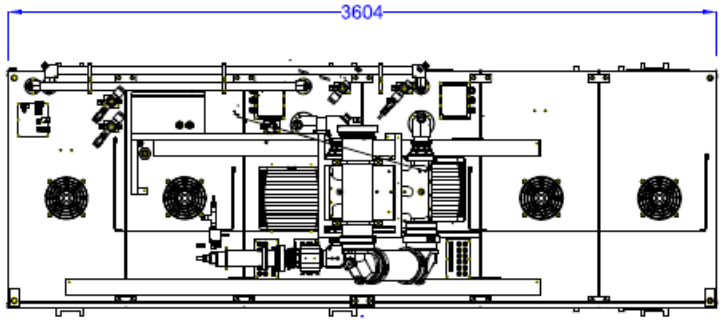
- Transmitters & RF distribution: design and component selection by the contractor;
- G1, G2 PSU's: design and component selection by the contractor;
- Modulator 18kV 40kW: design, component selection, prototype construction & validation by ESS Lund

RFPS for Spokes' design







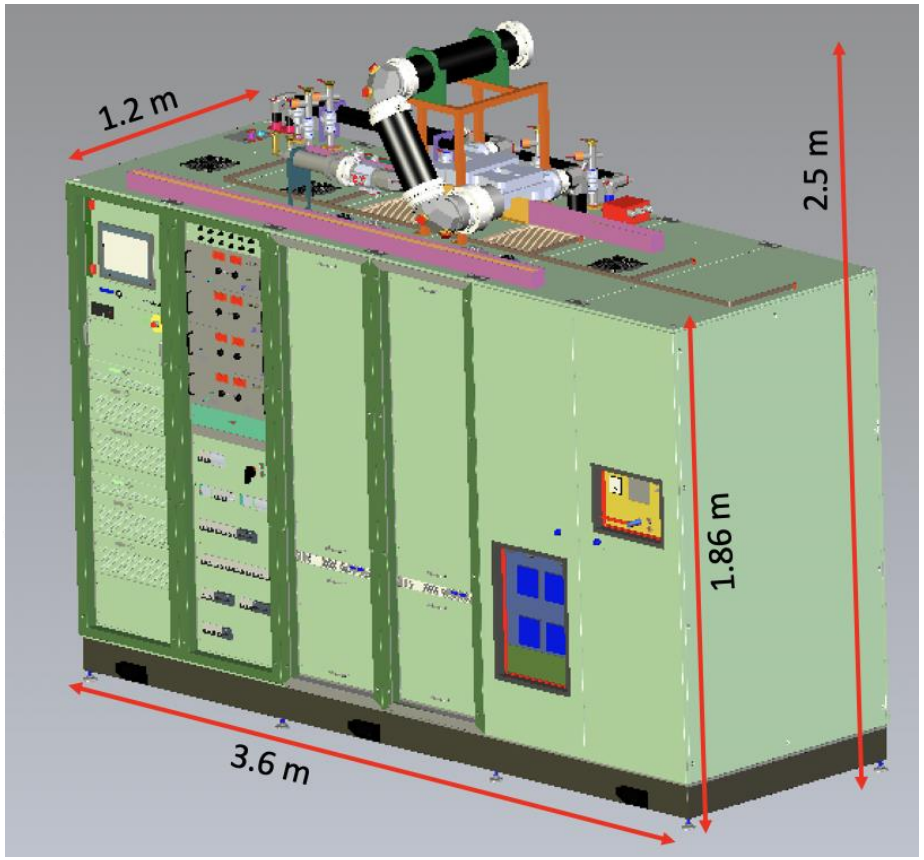


- **All-in-one system, transportable as a single unit;**
- **5 racks, each for a separated function**
  - Rack #1: Central controls & SS pre-drivers;
  - Rack #2: Grid G1, G2 power supplies, AC power distribution panel;
  - Rack #3: Tetrode A, RF cavity A, blower A, filament PS A, RF distribution A;
  - Rack #4: Tetrode B, RF cavity B, blower B, filament PS B, RF distribution B;
  - Rack #5: HV modulator (cap. charger, cap. bank, SS series switch, safety devices);
- **Output RF stage mounted on the roof**
  - RF combiner;
  - RF reject load;
  - RF distribution, including directional couplers;

SCALA/OUT OF SCALE ☐ 1:2 ☐ 1:1 SCALA/OTHER SCALE: _ ☐ 2:1 ☐ 5:1			db Elettronica Telecomunicazioni S.p.A.	▶itelco	ESS
FIRME/SIGNATURES		DATA/DATE	DESCRIZIONE/DESCRIPTION		
Mancini Averino		13-07-2020	YT4P400K-V2 OVERALL VIEWS		
Andrea Stefani		13-07-2020			
Massimo Rossi		13-07-2020	DWG. n. 2.1.a		
A3	PAGINA/PAGE 1 / 2		PART NUMBER 69304401 0		

RFPS Testing setup and Results

Test set up at TS3 and its 3D model



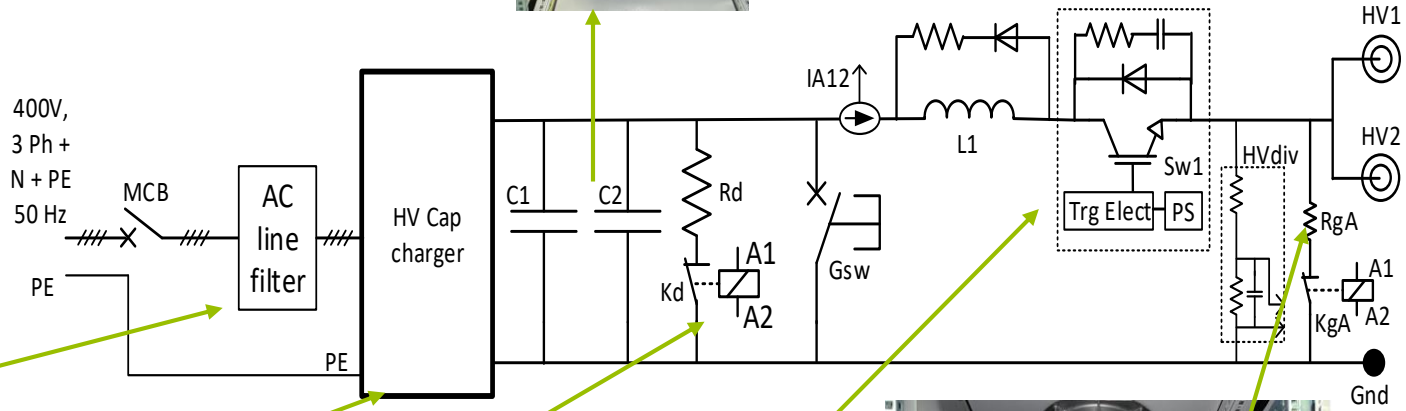
RFPS Features

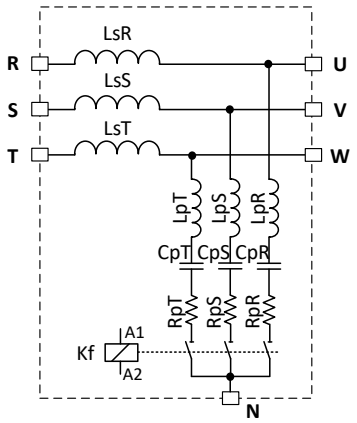
Salient Features Related to Power Supplies

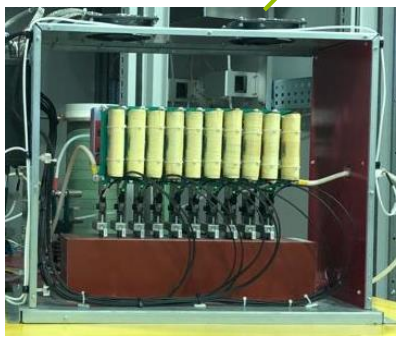
Series HV switch instead of the parallel crowbar

18 kV Anode power supply for Thales 595A tetrodes and Flicker control for the anode power supply

10 switches

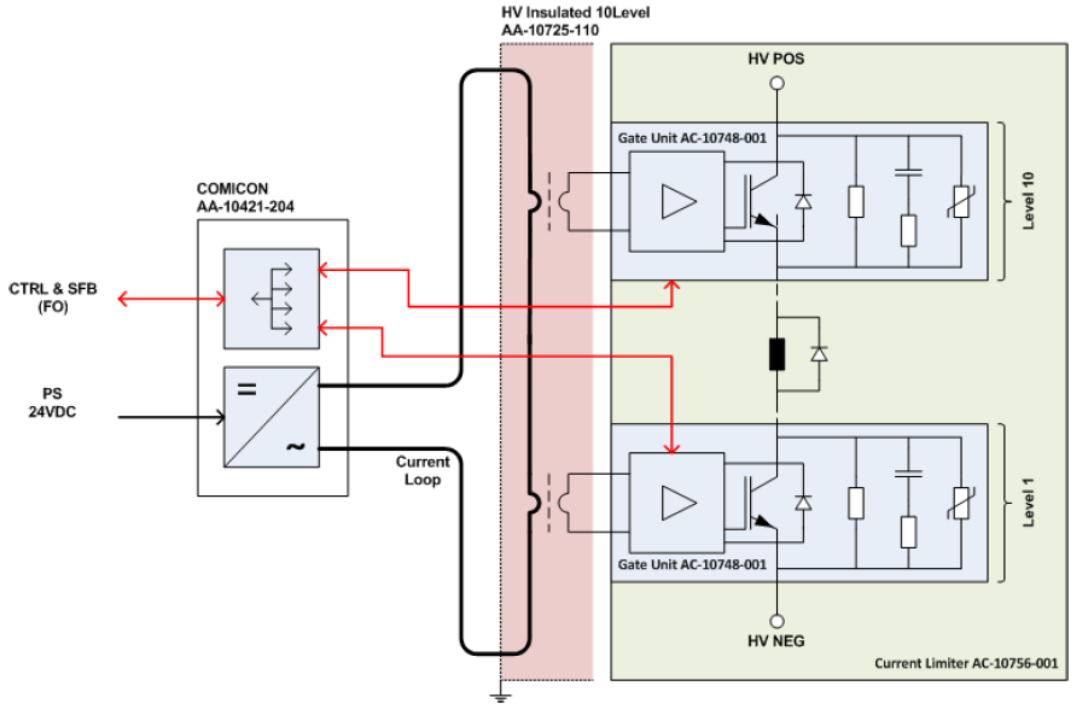


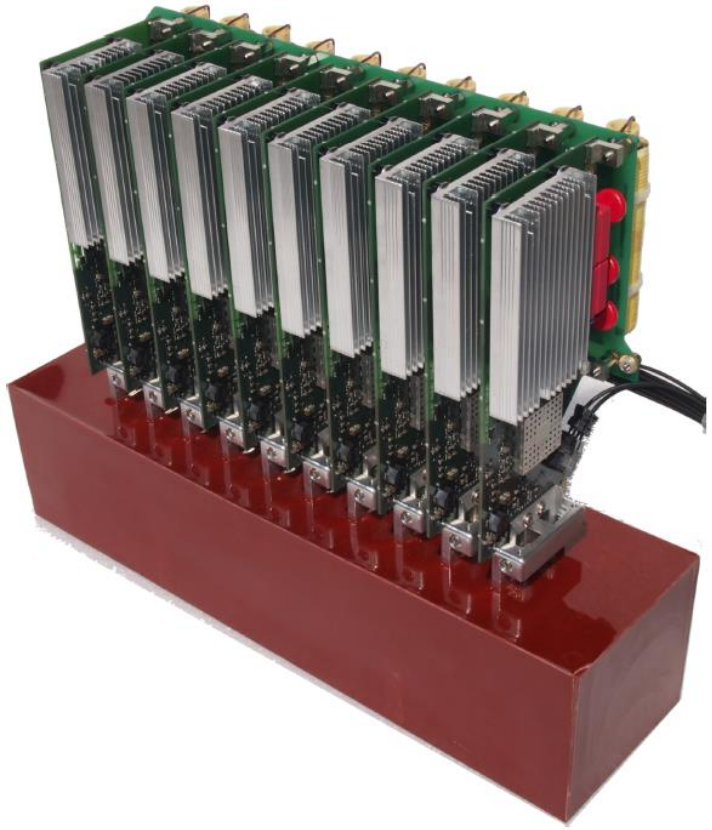




Astrol Series HV Switch

Block Diagram of HV Series Switch





10 IGBTs is series to withstand 18 kV.
Each IGBT is protected against overvoltage
by RC snubber and varistor.

Astrol Series HV Switch

Time and Electrical Specifications

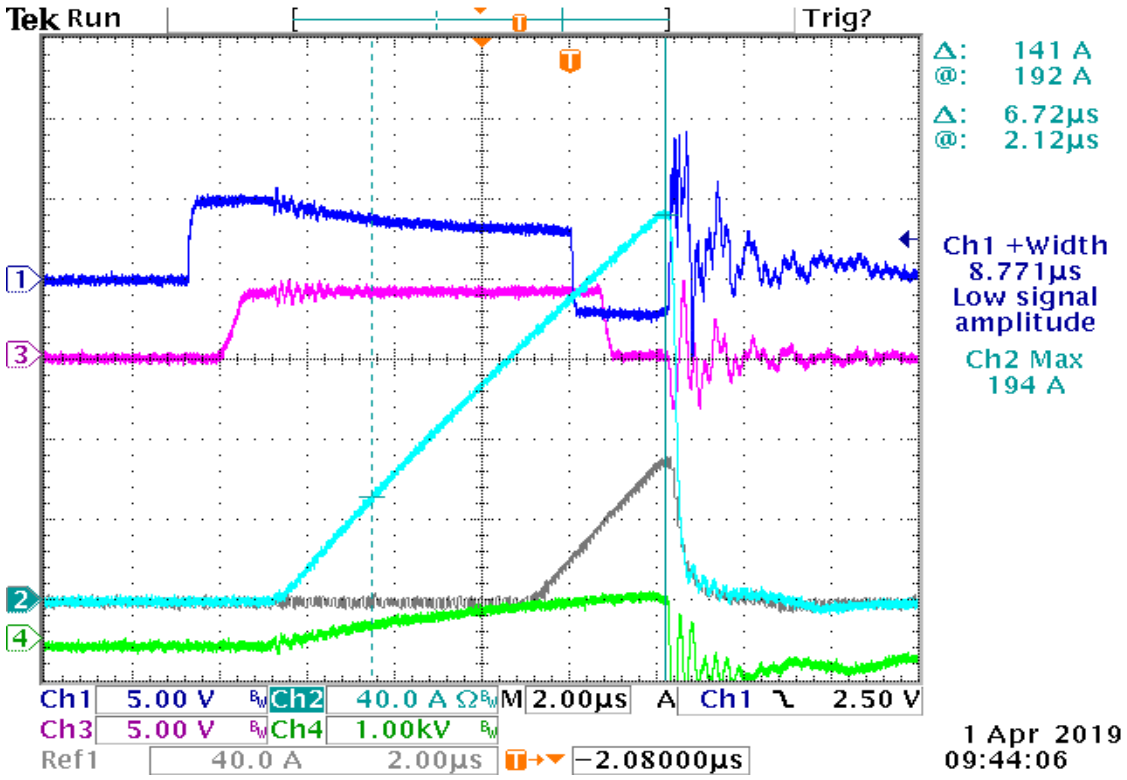
Parameter	Symbol	Min	Typ	Max	Unit
Turn-On Time	T_r	-	0.8	1	μss
Turn-On Delay	TD_{on}	-	0.6	0.8	μss
Turn-Off Time	T_f	-	0.8	1	μss
Turn-Off Delay	TD_{off}	-	1.8	2	μss
On Time	T_{on}	-	-	4	ms
Pulse Repetition Frequency	f_{rep}	-	-	14	Hz

- Series Switch instead of crowbar for the anode HV supply.
- Fast response of the order of 1.0 µs.
- Size L x W x H =425 x 115 x 322 mm

Parameter	Symbol	Conditions/Remark	Min	Typ	Max	Unit
Operating voltage	V_{op}		100	18000	18000	V
Maximum voltage	V_{max}		-	-	30000	V
Reverse Voltage	V_{rev}		-	-	30000	V
Nominal Current (resistive)	I_{nom}	Current during pulse flat-top	-	50	80	A
RMS Current	I_{rms}		-	13	-	A
Average Current	I_{avg}		-	3	-	A
Peak Current	I_{pk}	<10μs Non repetitive. Note: The HVS[3] has no integrated current measurement the system integrator has to ensure that this current level is not exceeded. An independent current measurement system could be integrated on request.	-	-	250	A
On-State voltage drop	V_{drop}	@50A	-	28	34	V
Leakage Current	I_{leak}	@18kV Input-Output	-	2	-	mA
Switch Inductance	L_{sw}	Maximum $\frac{di}{dt}$@$18kV = 19.4A/us$	-	0.93	-	mH
Total Power Dissipation	P_{vtot}	@(50A/4ms/14Hz) incl. CSINT	-	100	-	W
Power Consumption	P_{in}		-	-	20	W
Power Supply	V_{PS}	DC	22	24	26	V

Astrol Series HV Switch Testing

HV Switch Test Results



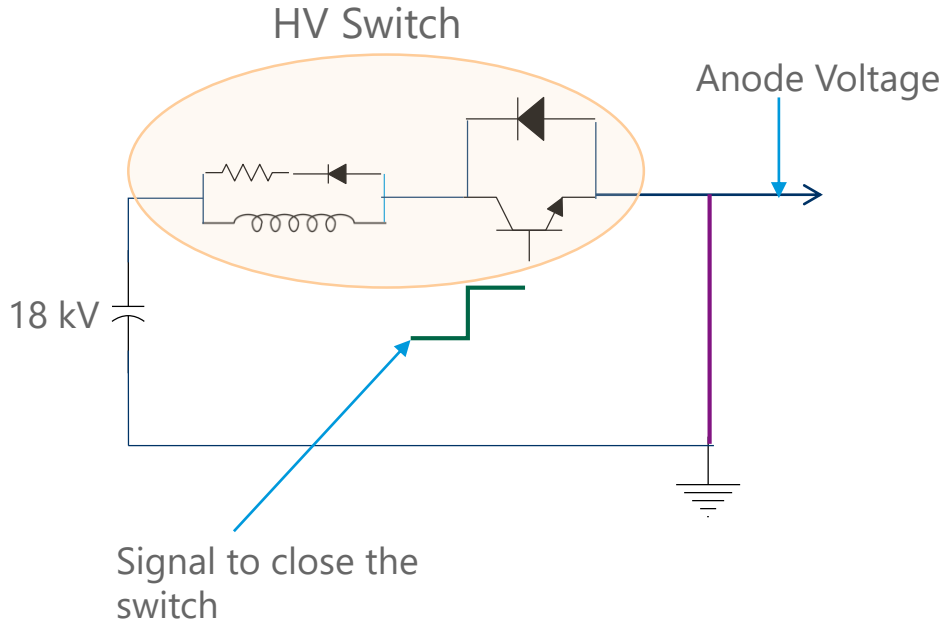
Ch1=control pulse from controller

Ch3=pulse to fibre-optic driver after MOSFET

Ch2=current through Astrol Switch

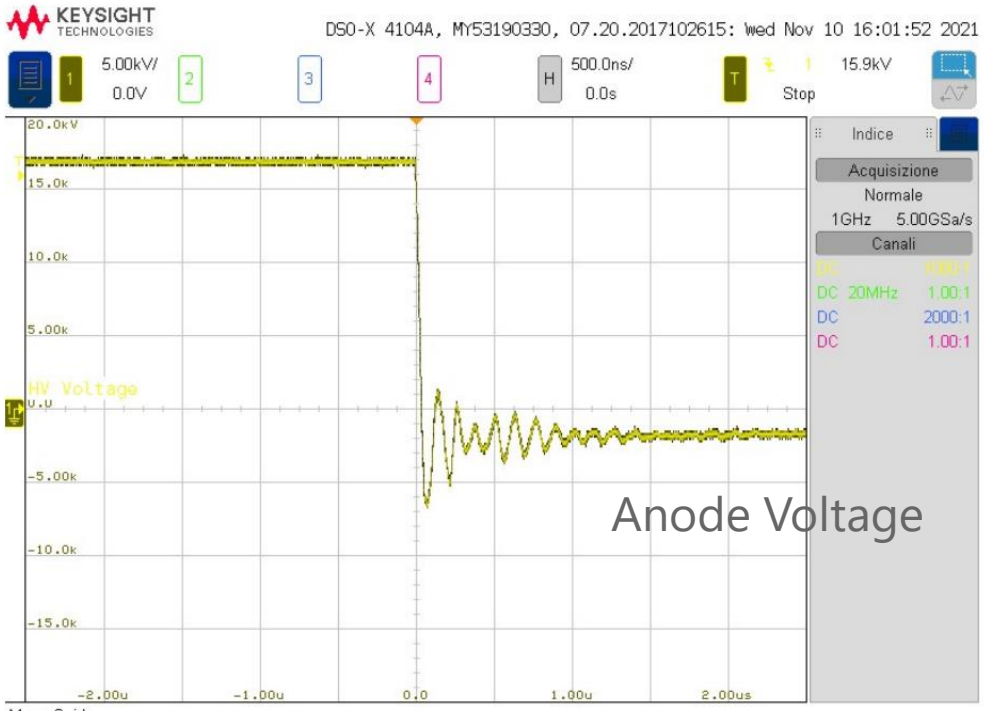
Ch2 Reference=current while finding t_0 to calculate safe pulse width for testing purposes

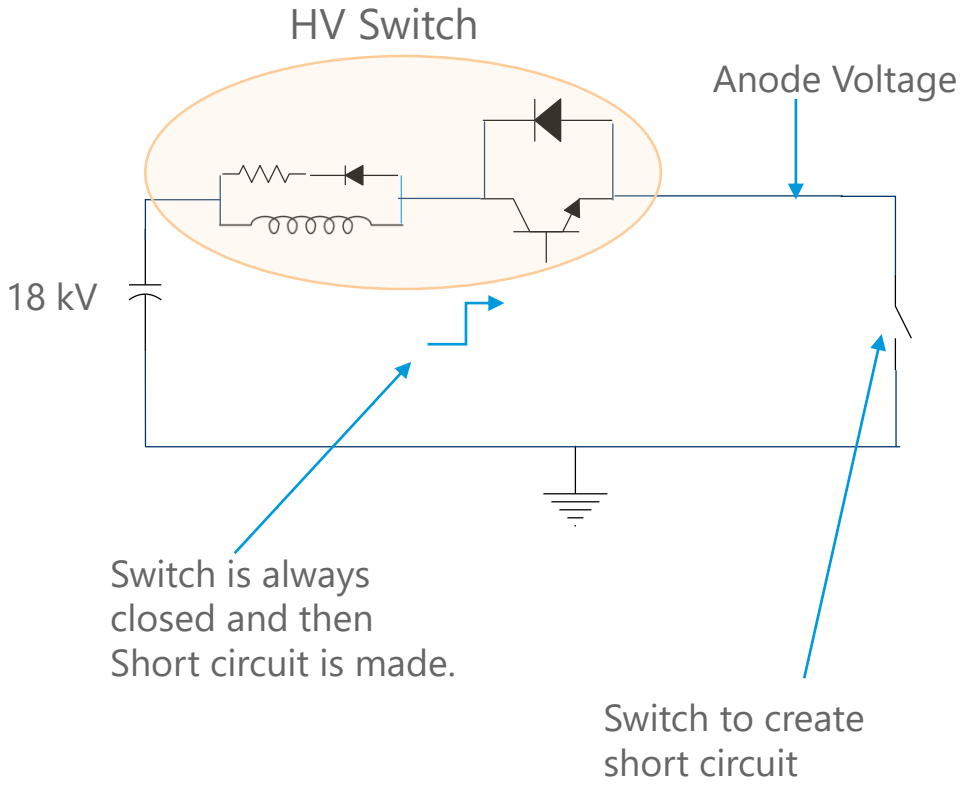
Ch4= Voltage across Dummy Loads(Short Circuit)



Astrol Series HV Switch Testing

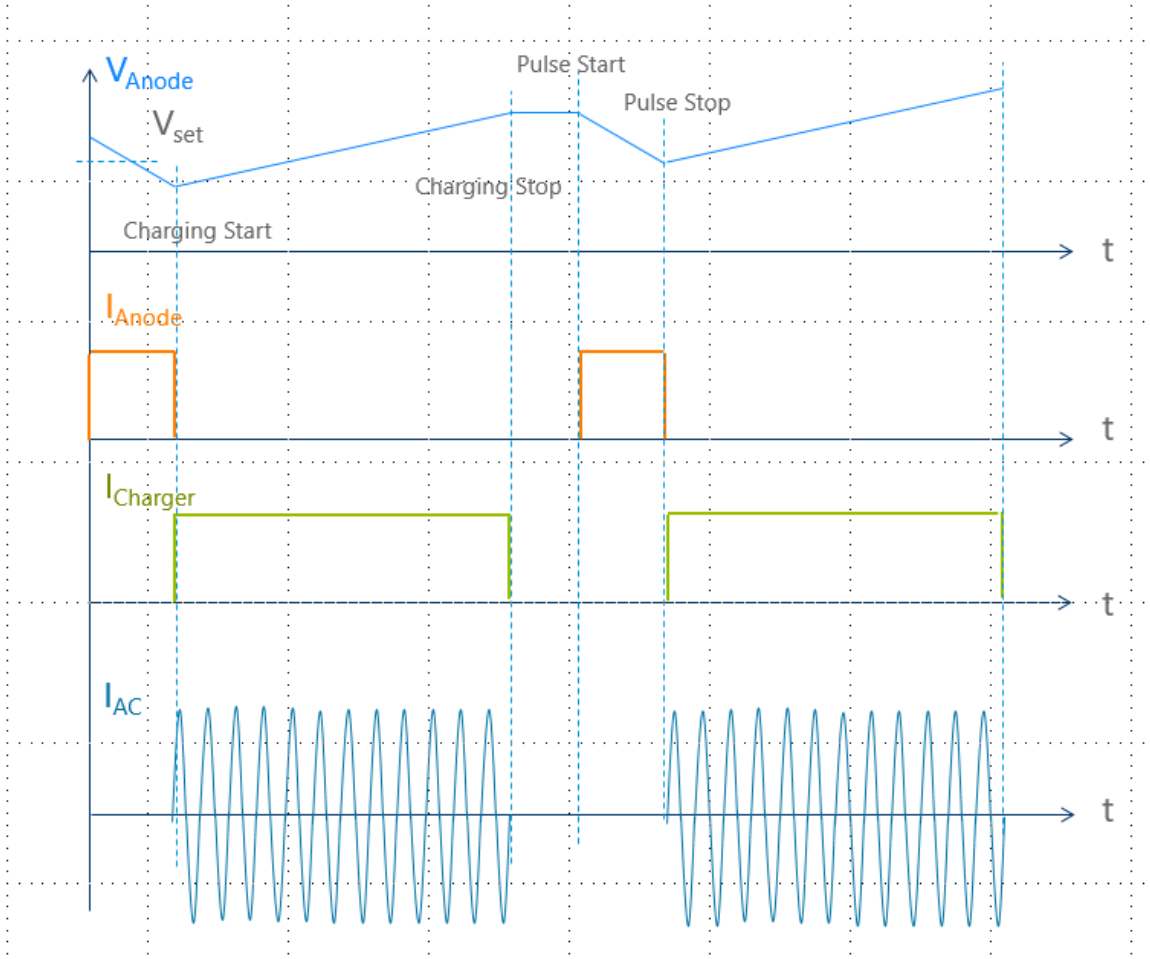
HV Switch Test Results

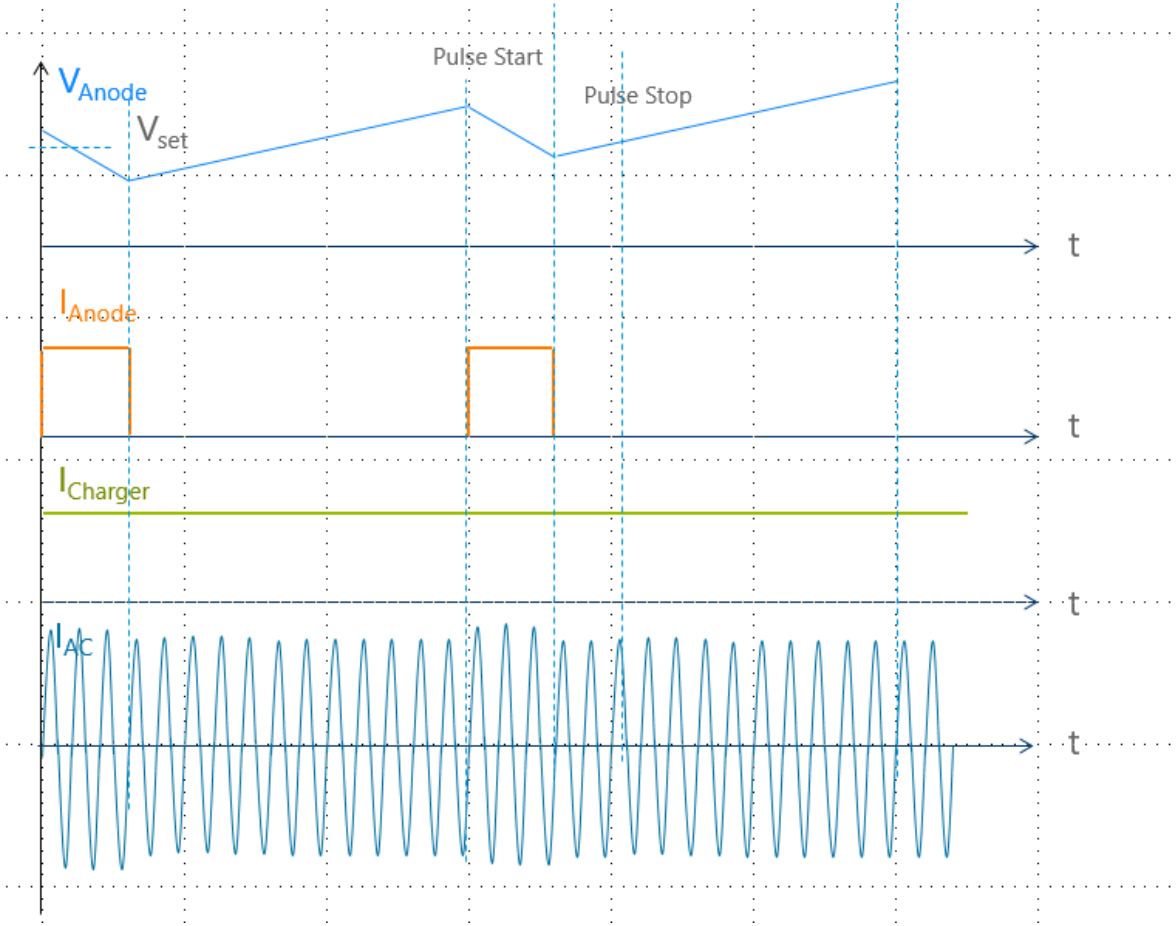




RFPS for Spokes' design – Capacitor charging schemes

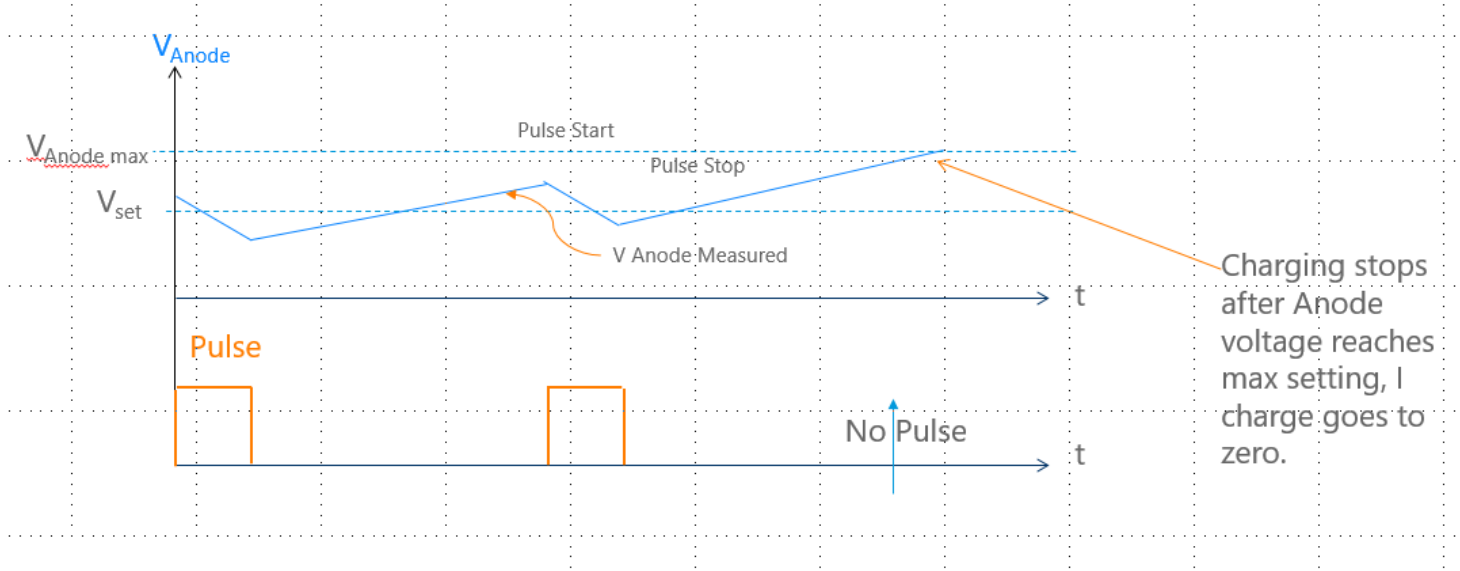
Conventional vs flicker free charging scheme

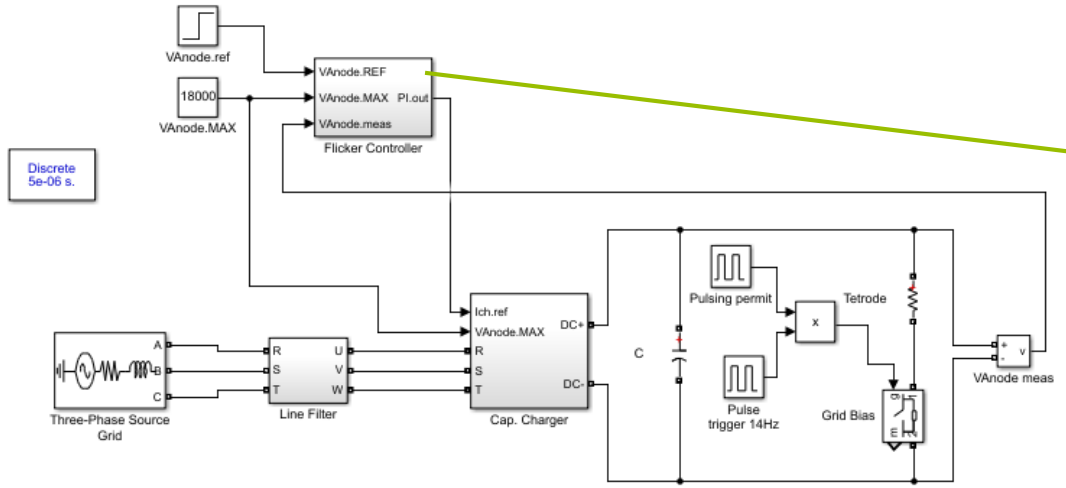


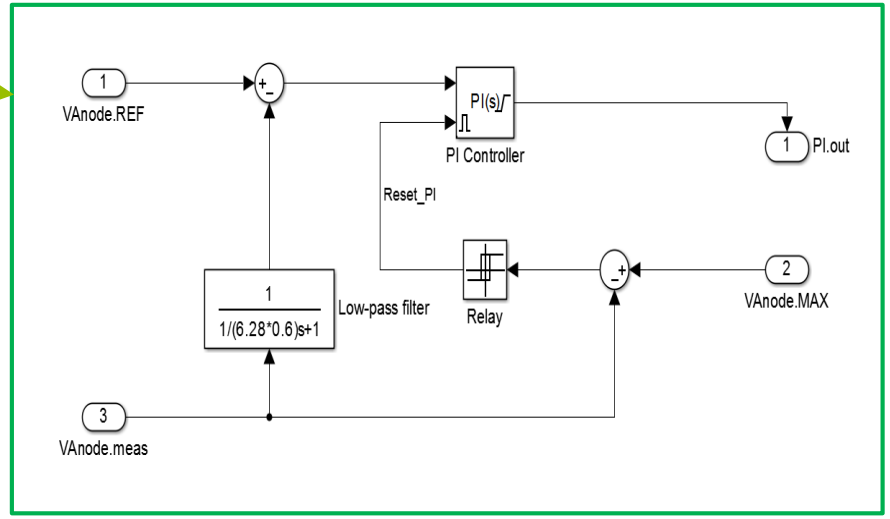


Flicker Control

- Standard off the shelf industrial capacitor charger is used.
- External flicker control loop is introduced to set the output current reference for the charger.

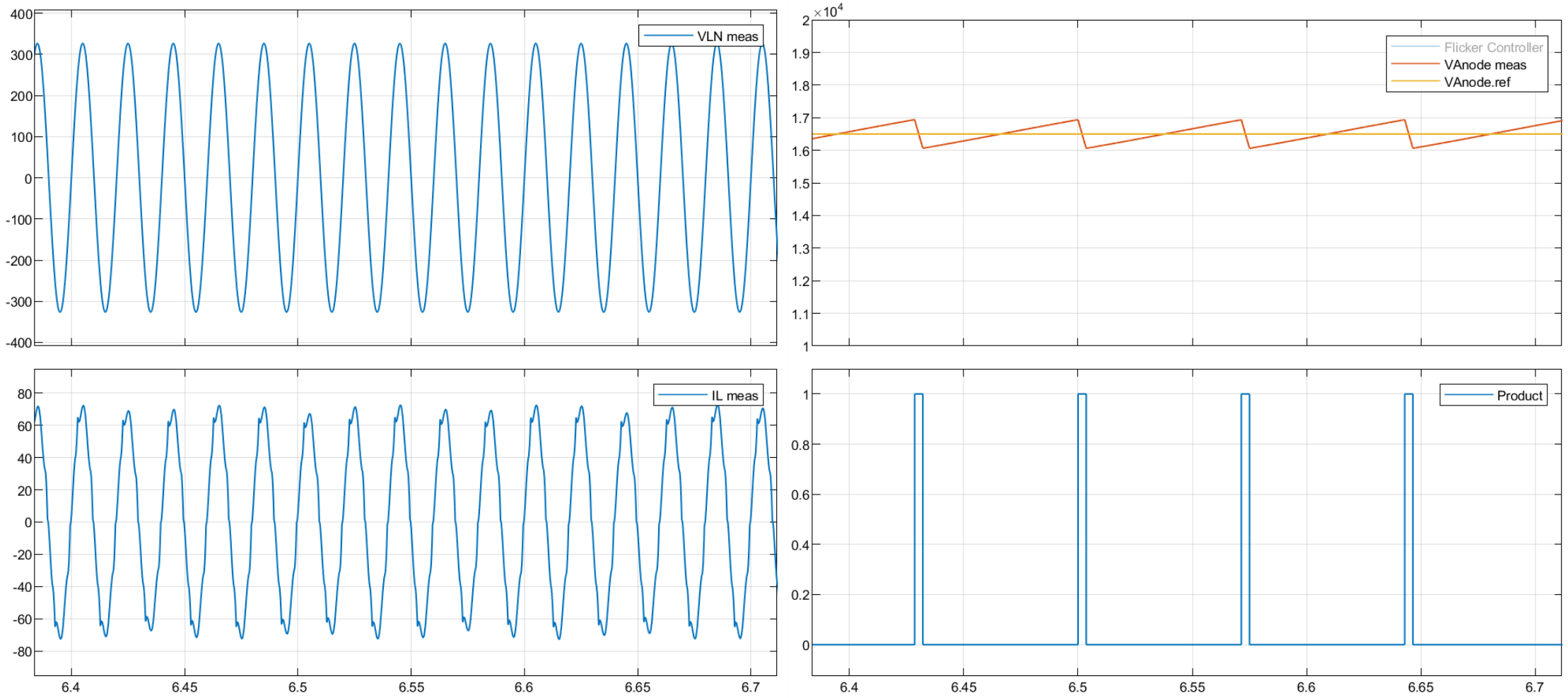






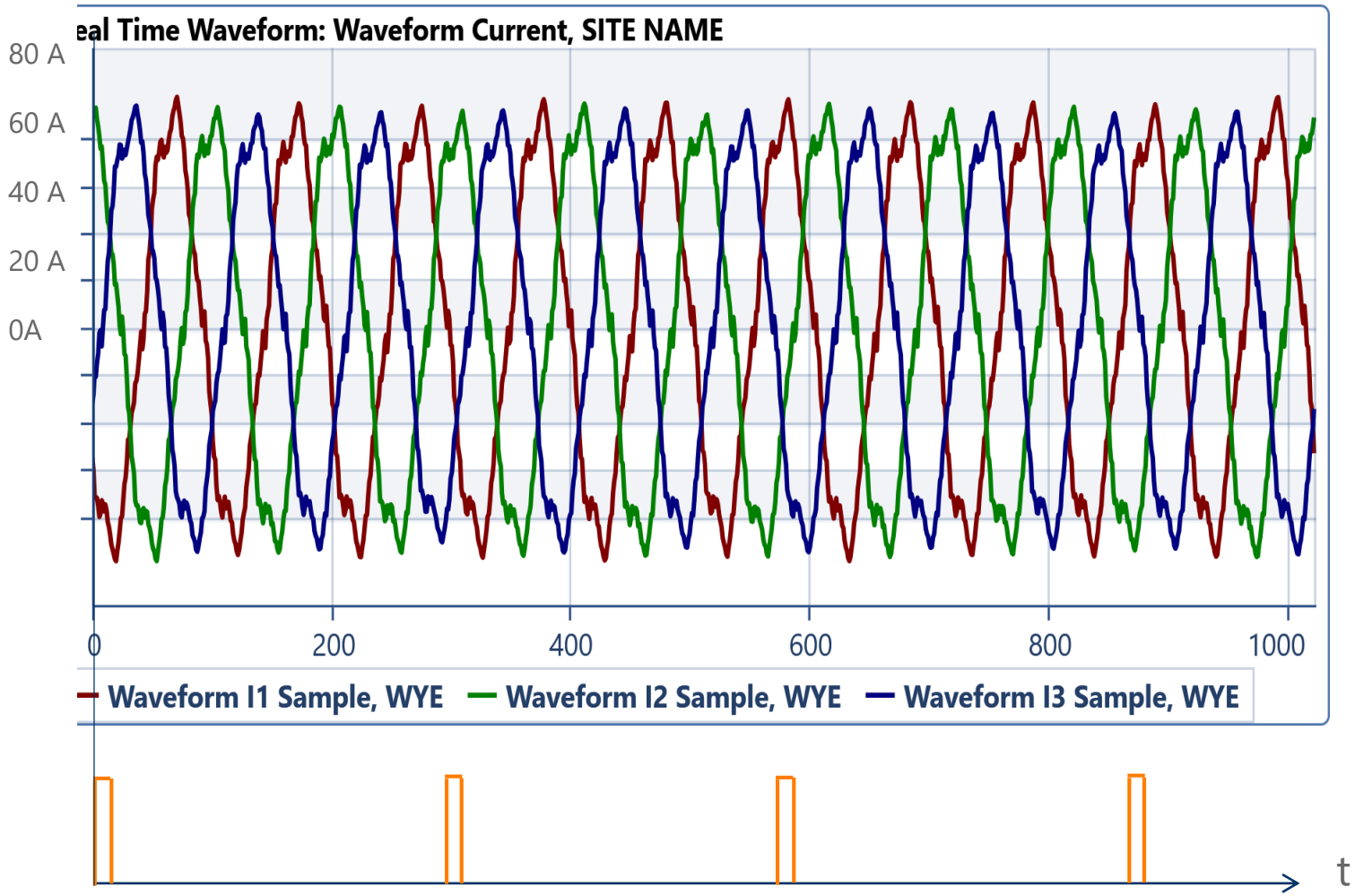
Simulation Results of Flicker Control

Simulation Results - Current waveforms with Flicker control



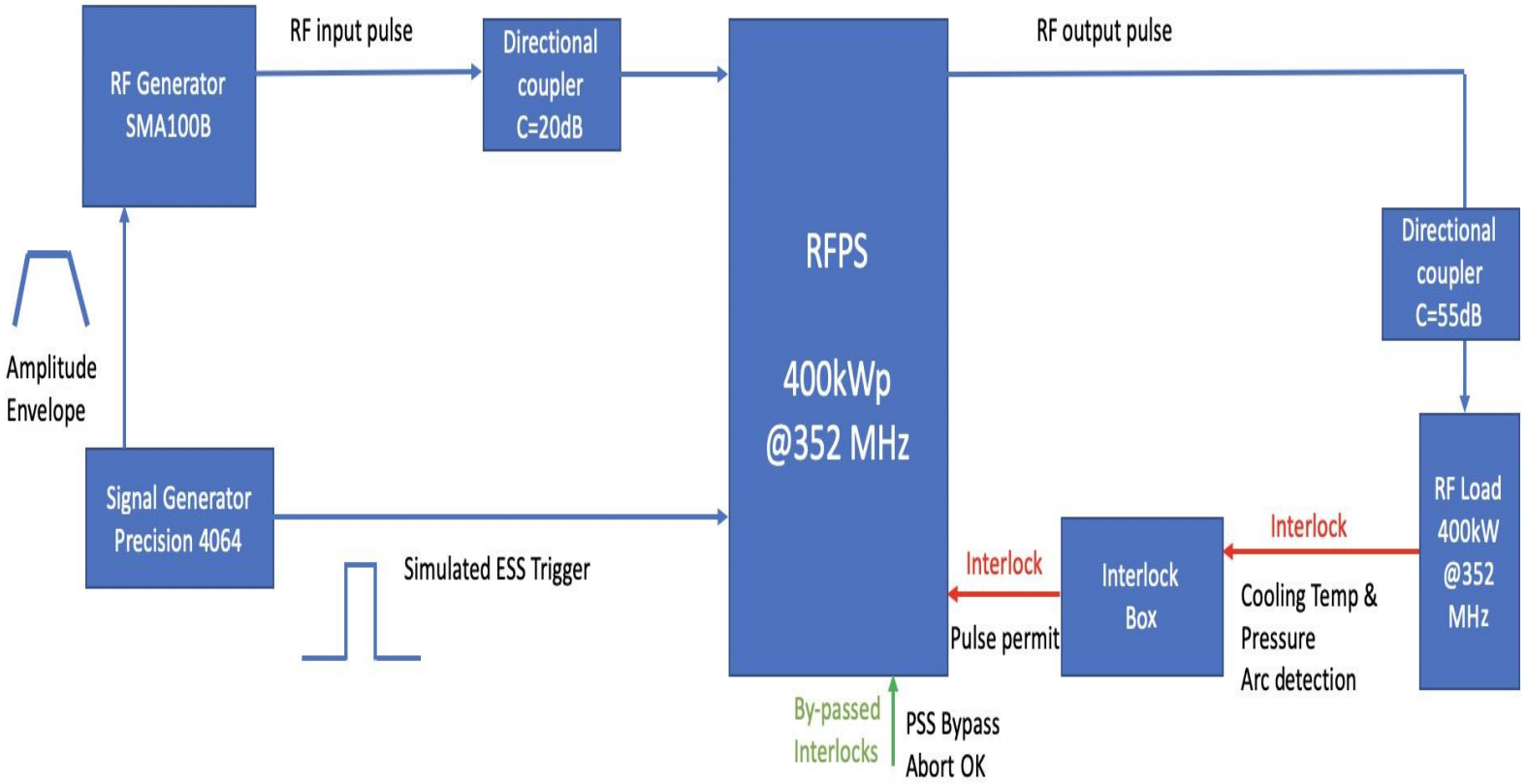
RFPS Cap charging and Line Currents

Actual Measurements of Line Currents



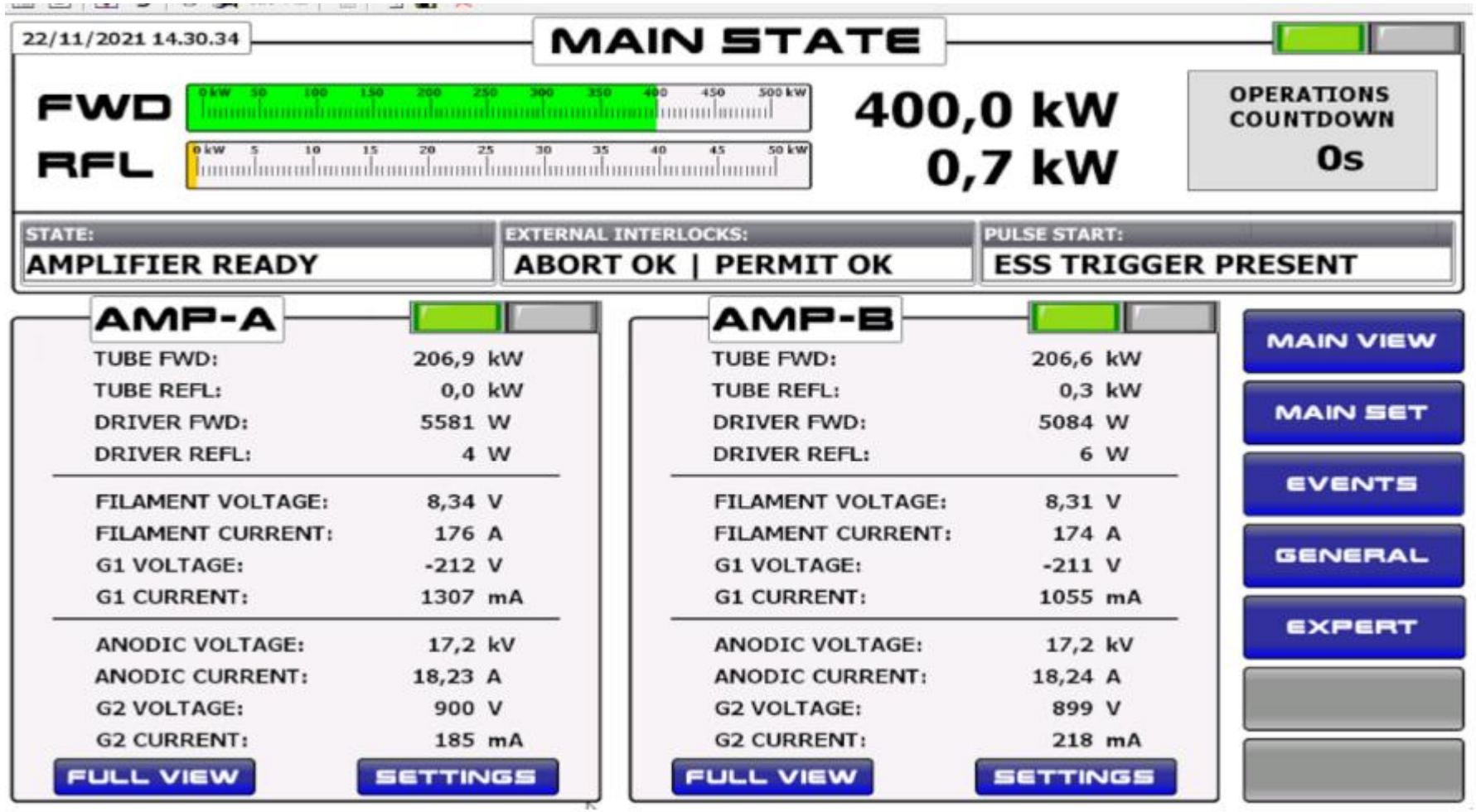
RFPS Testing setup and Results

Test Stand 3 setup for testing RFPS



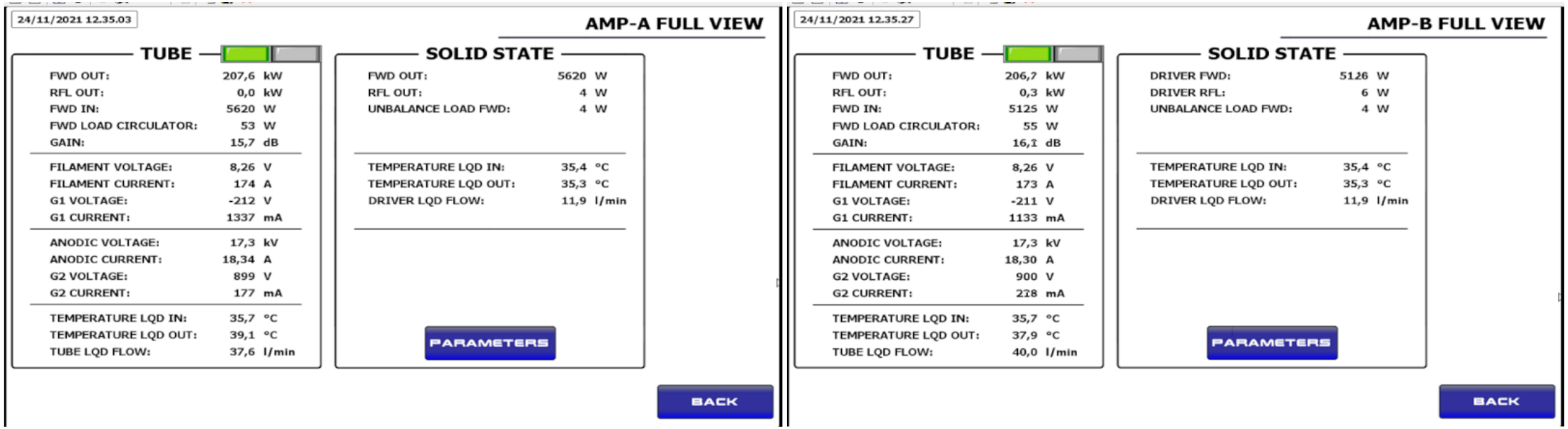
RFPS Testing setup and Results

RFPS HMI screen at full power



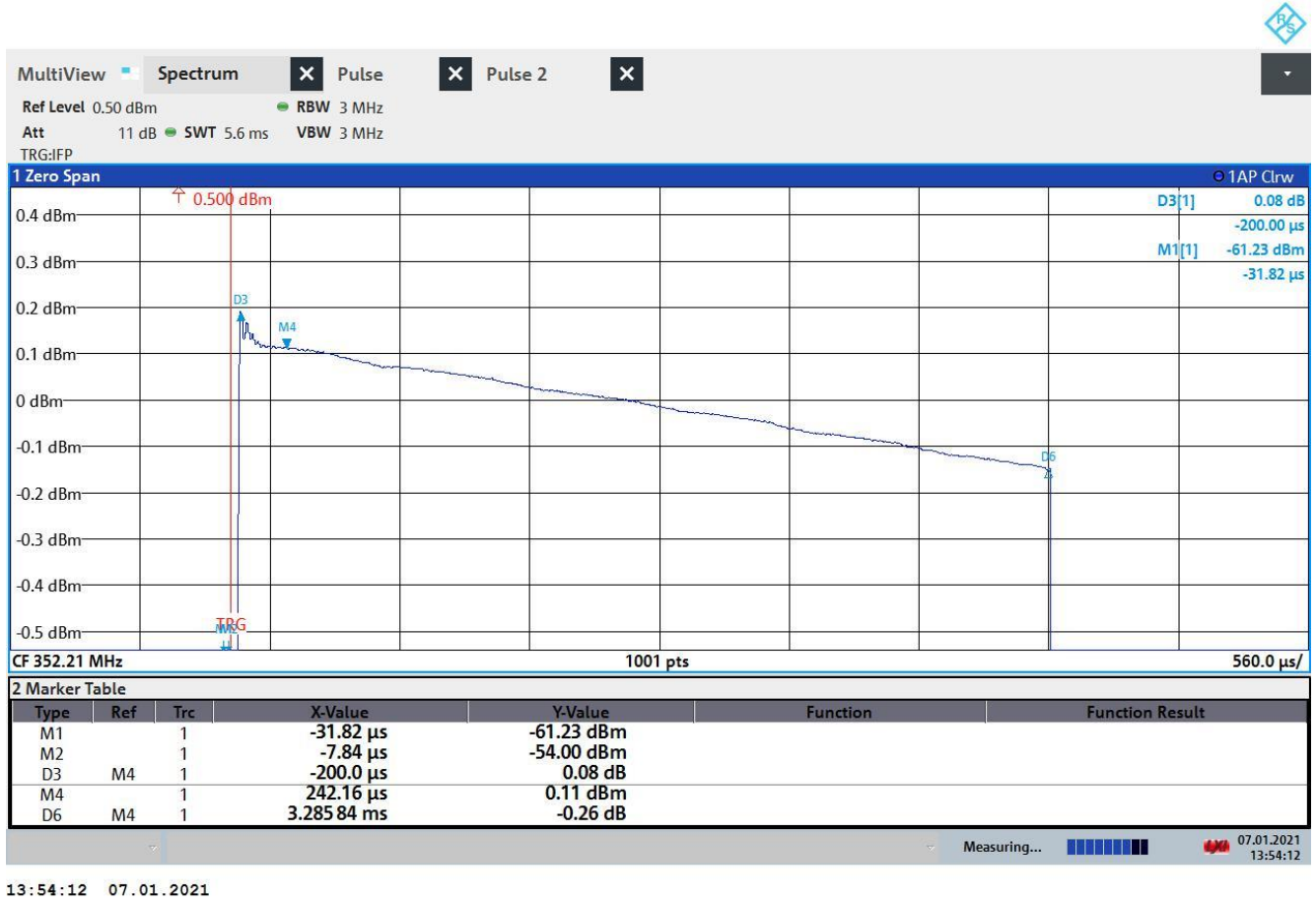
RFPS Testing setup and Results

RFPS HMI screen for Tube A



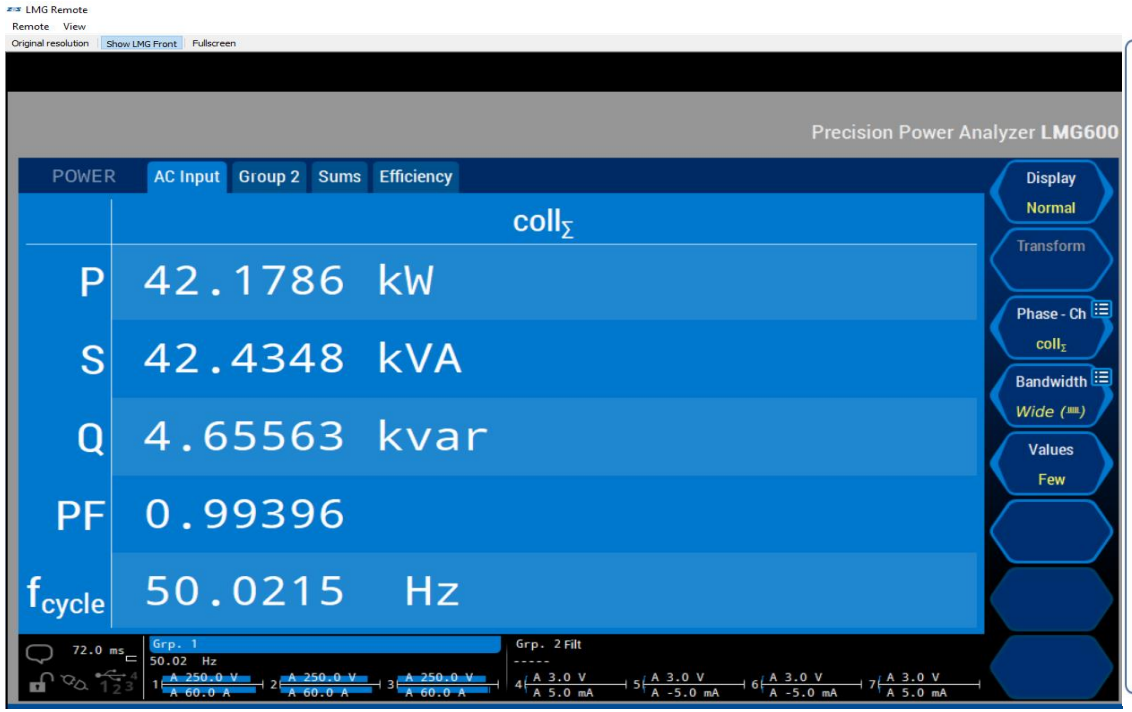
RFPS Testing setup and Results

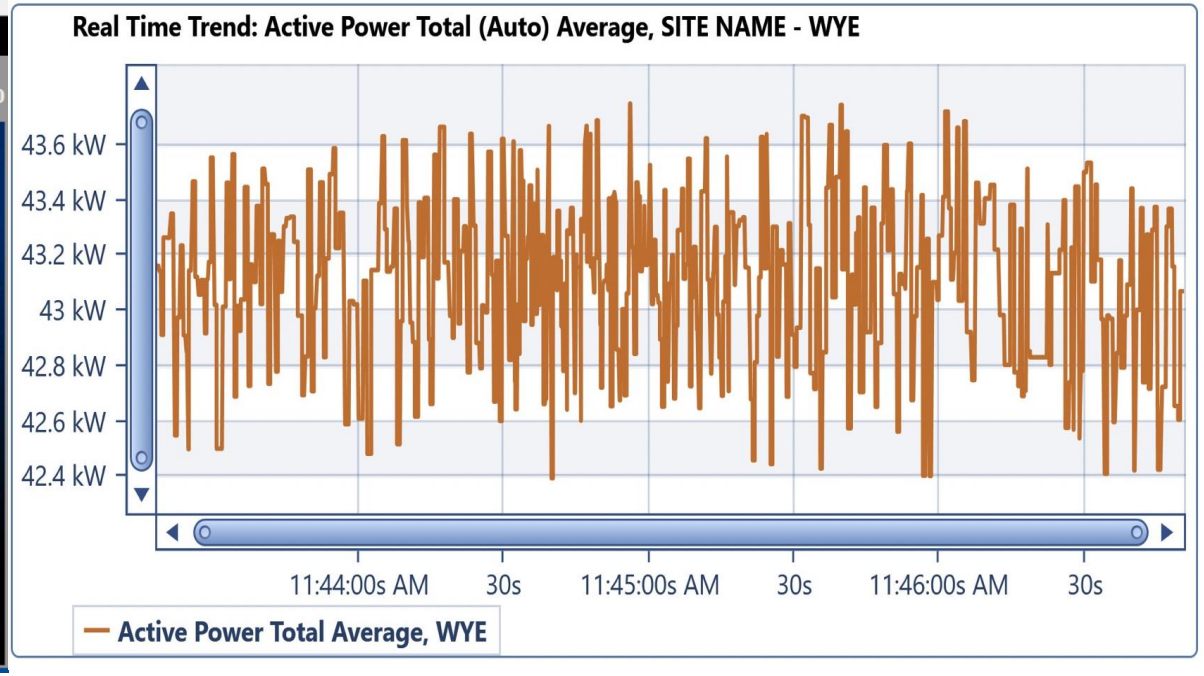
RF Pulse



RFPS Power Measurement at TS3

Power and efficiency for the RFPS

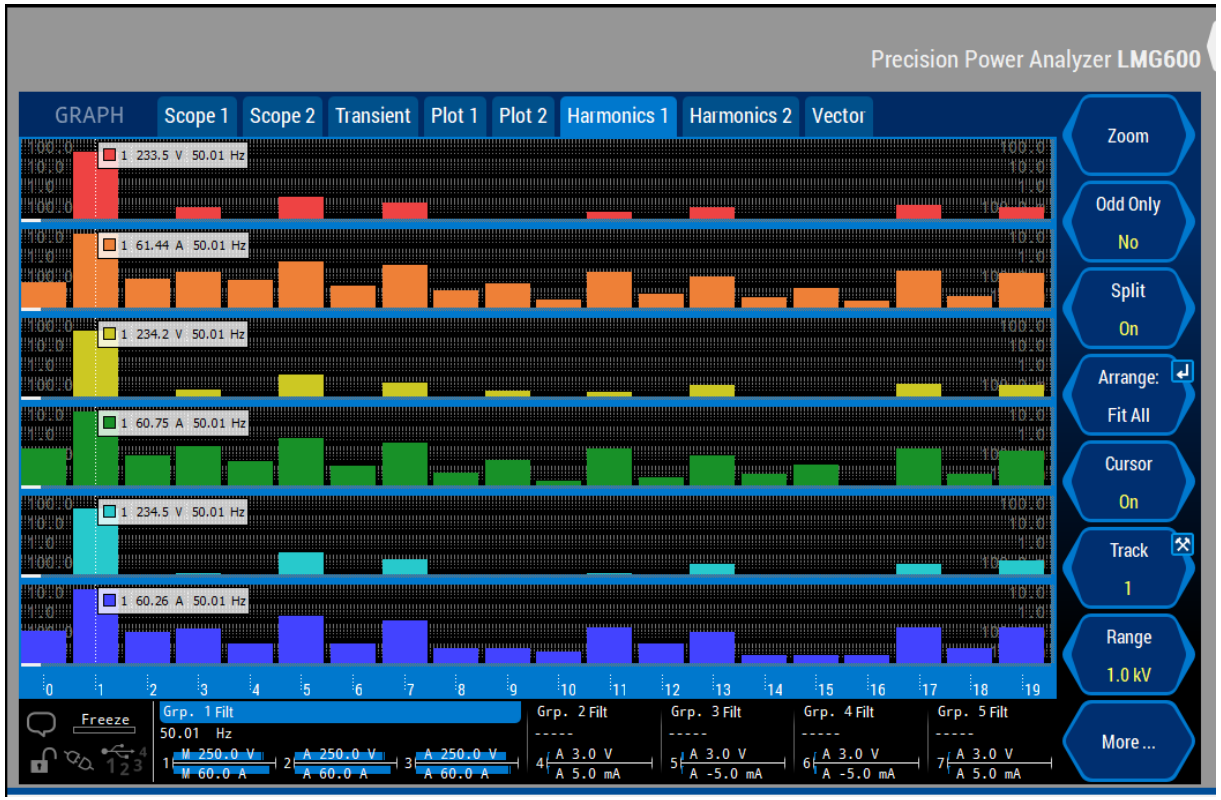




Wall plug to RF Efficiency approx. 44 %
PF of approx. 1.
42-43 kW power consumption

RFPS Power Measurement at TS3

Harmonics and THD

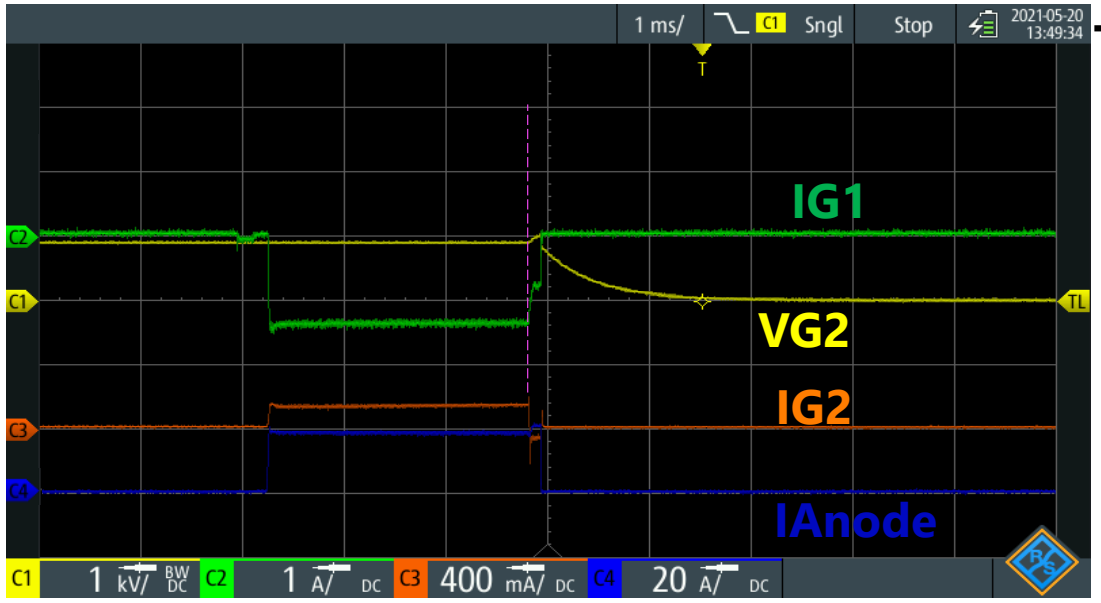


The measured THD on the system is around 6 to 7 %

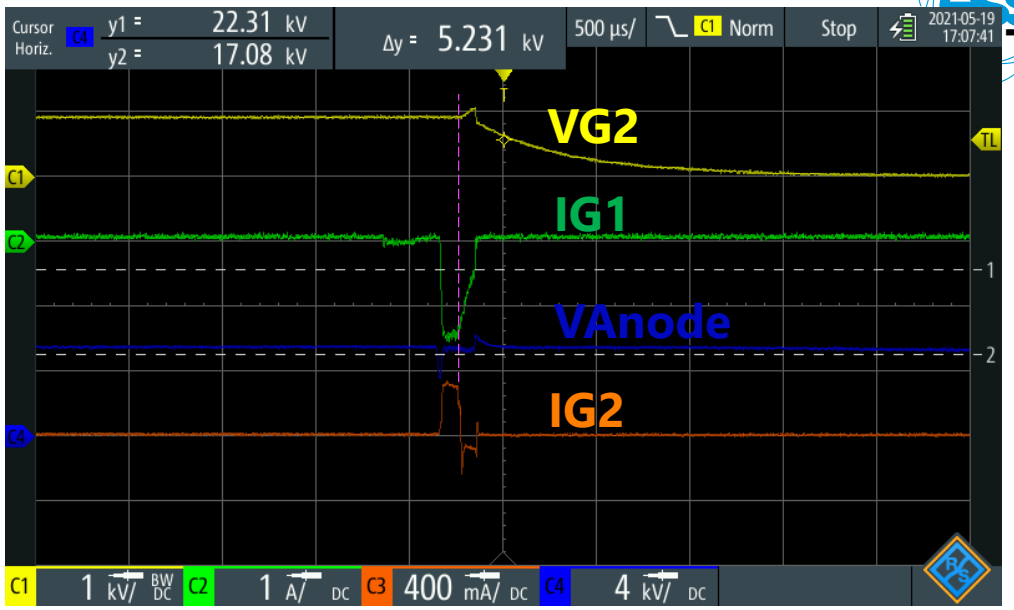
Anode PS efficiency = 90 %

Tetrode TH595A (T4) failure at ESS

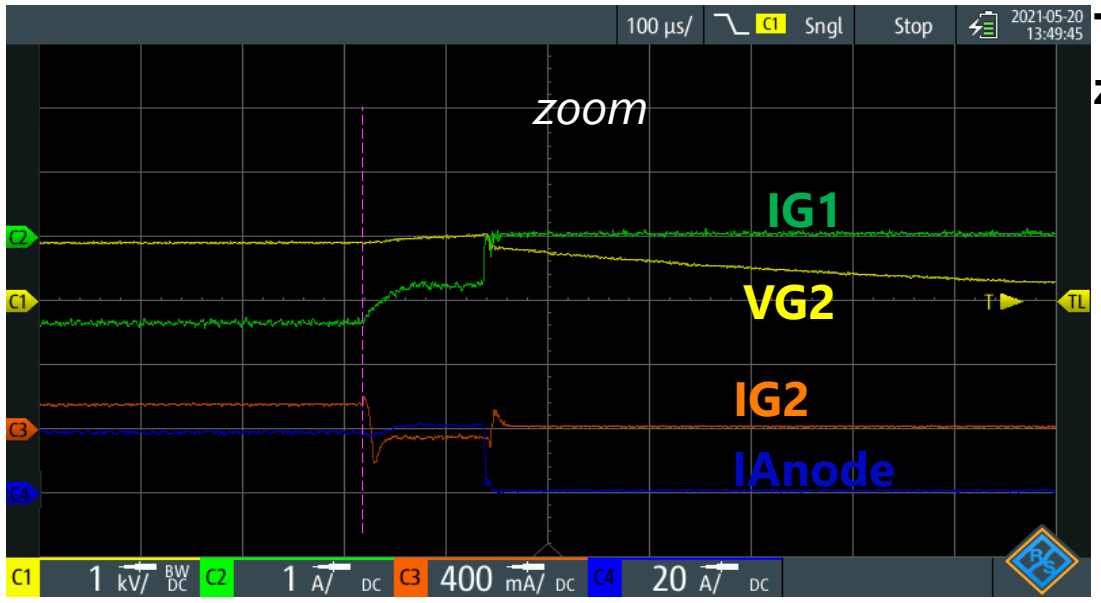
May 2021



Trip 1



Trip 2



Trip 1 zoom

Observations:

- One tetrode TH595A (**T4**) has failed after few hundred hours of operation;
- Trip is due to a reverse current on screen grid (IG2), which leads to a rise on screen grid voltage (VG2);
- It occurs systematically when RF power of RFPS is >360 kW approx. (i.e. >180kW per tetrode);

RFPS Future plans

Future options for RFPS upgrades

We have had some issues with tetrode operations and efforts are in progress to understand and mitigate the issues.

The options for using Klystrons for the RFPS is being investigated.

Conclusions

Electrical power quality can be greatly improved with advanced and modern power electronics controls.

Better equipment protection can be achieved using series switch instead of parallel crowbar conventional scheme.

Efficiency improvements can be attempted with better capacitor chargers using AFE

Thank You and Questions