

EUROPEAN SPALLATION SOURCE



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

Testing Experience and salient features of RFPS

PRESENTED BY MANISH KUMAR POWER ELECTRONICS ENGINEER, ESS, LUND, SWEDEN.

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	\geq 100 kHz 100 kHz \div 1 kHz 1 kHz \div 0.3 kHz
 Max. phase variation 	0.5° 1° 2°
 Max amplitude variation 	0.5% 1% 1.5%
Pulse-to-pulse stability	
- Av. amplitude variation	≤ ± 0.5 %
- Av. phase variation	$\leq \pm 0.5^{\circ}$
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

RFPS



- 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



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DESCRIZIONE/DESCRIPTION YT4P400K-V2 OVERALL VIEWS

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GINA/PAGE

ALA/OUT OF SCALE

ALA/OTHER SCALE:

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A3



- 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;

4.44 (ALIAN ON THE RED distribution, including directional couplers;

RFPS Testing setup and Results Test set up at TS3 and its 3D model



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RFPS Features

Salient Features Related to Power Supplies

400V,

3 Ph +

N + PE

50 Hz

PE

MCB

AC

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



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	Тур	Max	Unit
Turn-On Time	T_r	-	0.8	1	μs S
Turn-On Delay	TD_{on}	-	0.6	0.8	μs S
Turn-Off Time	T_{f}	-	0.8	1	μs S
Turn-Off Delay	TD_{off}	-	1.8	2	μs S
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.

Parameter	Symbol	Conditions/Remark	Min	Тур	Max	Unit	Size I x W x H
Operating voltage	V_{op}		100	18000	18000	V	
Maximum voltage	V_{max}		-	-	30000	V	[■] =425 x 115 x 3
Reverse Voltage	V_{rev}		-	-	30000	V	-+25 X 115 X 5
Nominal Current (resistive)	I_{nom}	Current during pulse flat-top	-	50	80	Α	mm
RMS Current	I_{rms}		-	13	-	Α	111111
Average Current	I_{avg}		-	3	-	Α	
Peak Current	I_{pk}	<10 μ s 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 $\frac{di}{dt}$ @18 $kV = 19.4A/us$	-	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	

5 x 322

Astrol Series HV Switch Testing

HV Switch Test Results



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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





short circuit

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





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RFPS Testing setup and Results

Test Stand 3 setup for testing RFPS



RFPS Testing setup and Results

RFPS HMI screen at full power

200 250 300 1111111111111111111111111111111111	400	,0 kW ,7 kW	OPERATIONS COUNTDOWN OS
EXTERN/ ABO	AL INTERLOCKS: RT OK PERMIT OK	PULSE START: ESS TRIGGE	R PRESENT
206,9 kW	TUBE FWD:	206,6 kW	MAIN VIEW
0,0 kW	TUBE REFL:	0,3 kW	
5581 W	DRIVER FWD:	5084 W	MAIN SET
4 W	DRIVER REFL:	6 W	
8,34 V	FILAMENT VOLTAGE:	8,31 V	EVENTS
176 A	FILAMENT CURRENT:	174 A	
-212 V	G1 VOLTAGE:	-211 V	GENERAL
1307 mA	G1 CURRENT:	1055 mA	
17,2 kV	ANODIC VOLTAGE:	17,2 kV	EXPERT
18,23 A	ANODIC CURRENT:	18,24 A	
900 V	G2 VOLTAGE:	899 V	
185 mA	G2 CURRENT:	218 mA	
	20 25 30 EXTERN/ ABOI 206,9 kW 0,0 kW 5581 W 4 W 8,34 V 176 A -212 V 1307 mA 17,2 kV 18,23 A 900 V 185 mA	400 20 25 30 35 40 45 50 kW 0 EXTERNAL INTERLOCKS: ABORT OK PERMIT OK EXTERNAL INTERLOCKS: ABORT OK PERMIT OK AMP-B TUBE FWD: TUBE FWD: TUBE FWD: TUBE REFL: DRIVER REFL: S581 W 4 W 8,34 V 176 A -212 V 1307 mA 17,2 kV 18,23 A 900 V 185 mA 400 0 15 16 17 17 17 17 17 17 17 17 17 17	20 23 30 35 40 45 50 kW Q,7 kW 20 23 30 35 40 45 50 kW Q,7 kW 20 23 30 35 40 45 50 kW Q,7 kW EXTERNAL INTERLOCKS: PULSE START: ESS TRIGGER ABORT OK PERMIT OK PERMIT OK ESS TRIGGER 206,9 kW 0,0 kW TUBE FWD: 206,6 kW 0,0 kW TUBE FWD: 206,6 kW 0,0 kW DRIVER FWD: 5084 W DRIVER REFL: 6 W FILAMENT VOLTAGE: 8,31 V FILAMENT CURRENT: 174 A -212 V G1 CURRENT: 174 A 1307 mA G1 CURRENT: 175 mA 17,2 kV ANODIC VOLTAGE: 17,2 kV 18,23 A 900 V G2 VOLTAGE: 899 V 185 mA G2 CURRENT: 218 mA





RFPS Testing setup and Results RFPS HMI screen for Tube A

24/11/2021 12.35.03	AMP-A FU	ULL VIEW 24/11/2021 12.35.27	AMP-B FULL VIEW
	SOLID STATE		SOLID STATE
FWD OUT: 207,6 kW	FWD OUT: 5620 W	FWD OUT: 206,7 kW	DRIVER FWD: 5126 W
RFL OUT: 0,0 kW	RFL OUT: 4 W	RFL OUT: 0,3 kW	DRIVER RFL: 6 W
FWD LOAD CIRCULATOR: 53 W GAIN: 15,7 dB	UNDALANCE LOAD FWD: 4 W	FWD LOAD CIRCULATOR: 55 W GAIN: 16,1 dB	UNDALANCE LOAD FWD: 4 W
FILAMENT VOLTAGE: 8,26 V	TEMPERATURE LQD IN: 35,4 °C	FILAMENT VOLTAGE: 8,26 V	TEMPERATURE LQD IN: 35,4 °C
FILAMENT CURRENT: 174 A	TEMPERATURE LQD OUT: 35,3 °C	FILAMENT CURRENT: 173 A	TEMPERATURE LQD OUT: 35,3 °C
G1 VOLTAGE: -212 V	DRIVER LQD FLOW: 11,9 I/min	G1 VOLTAGE: -211 V	DRIVER LQD FLOW: 11,9 1/min
G1 CURRENT: 1337 mA		G1 CURRENT: 1133 mA	
ANODIC VOLTAGE: 17,3 kV		ANODIC VOLTAGE: 17,3 kV	
ANODIC CURRENT: 18,34 A		ANODIC CURRENT: 18,30 A	
G2 VOLTAGE: 899 V		G2 VOLTAGE: 900 V	
G2 CURRENT: 177 mA		G2 CURRENT: 218 mA	
TEMPERATURE LQD IN: 35,7 °C		TEMPERATURE LQD IN: 35,7 °C	
TEMPERATURE LQD OUT: 39,1 °C	RARAMETERS	TEMPERATURE LQD OUT: 37,9 °C	BABAMETERS
TUBE LQD FLOW: 37,6 I/min		TUBE LQD FLOW: 40,0 1/min	
·		·	
		BACK	BACK

RFPS Testing setup and Results RF Pulse

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NultiVie	w =	Spectru	ım	× Pulse	× Pulse 2	×				-
Ref Level	0.50 dBm	n		RBW 3 MHz						
Att	<mark>11 d</mark> E	s 🗢 SWT	5.6 ms	VBW 3 MHz						
TRG:IFP	4									O 1AD Class
zero spa	1	4 0.50	od JD		E.					O TAP CITW
).4 dBm—		1 0.50		1					US[I]	0.08 dE
										-200.00 µs
) 3 dBm—									M1[1]	-61.23 dBm
ils abili										-31.82 μs
).2 dBm—			D3	6	22		8	2		
			ta.	M4						
).1 dBm—			" how	ul						
			11							
) dBm						-	1.0			
0.1 dBm-									-	
									10 X	
0.2 dBm-							14			
0.3 dBm—										
0.4 dBm-			11 1				5			
0.5 dBm-			TRG							
F 352 21 /	MH ₂		#	5		1001 pts	8	8	2000 / Jan	560 0 us/
Marker T	able									
Type	Ref	Tre		X.Value	V-V-alı	10	Function	e	Function Result	
M1		1		-31.82 µs	-61.23 d	Bm	, and for		. and the market of the source	
M2		1		-7.84 µs	-54.00 d	Bm				
D3	M4	1		-200.0 µs	0.08	dB				
M4		1		242.16 µs	0.11 d	Bm				
D6	M4	1		3.285 84 ms	-0.26	dB				
								Measuring		07.01.2021

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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 2







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