Elettra Sincrotrone Trieste

EUROPEAN SPALLATION SOURCE

Radio Frequency Power Station for the ESS Linac Spoke Cavity

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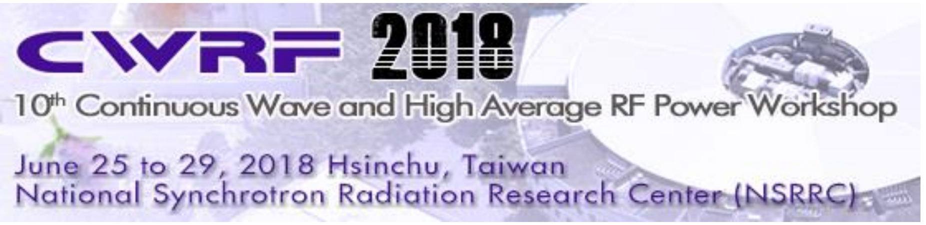
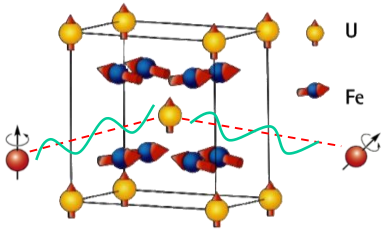
C. Martins, P.Torri, R. Yogi (European Spallation Source)

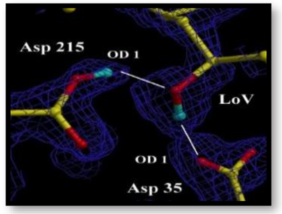


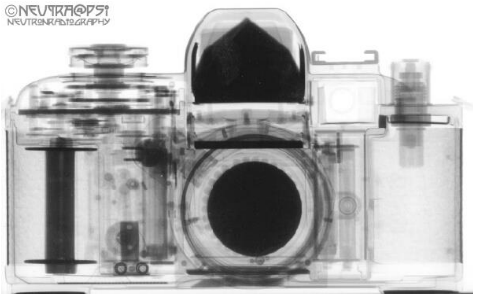
European Spallation Source

Neutron science to investigate:

- magnetic atoms,
- light atoms,
- movement of atoms,
- isotopes,
- materials



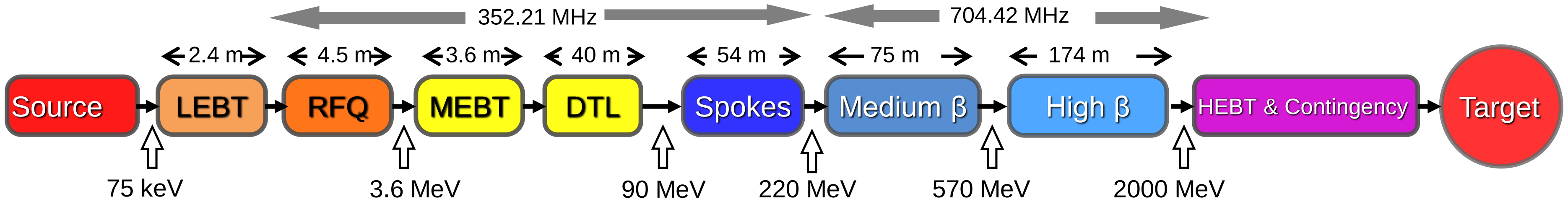




Courtesy of Ian S. Anderson

ESS high neutron flux is generated by SPALLATION:

- high energy protons hit a Wolfram target
- (H^+) Proton Linac, beam power target 5 MW, Linac energy 2.0 GeV
- Linac commissioning will start at lower energy



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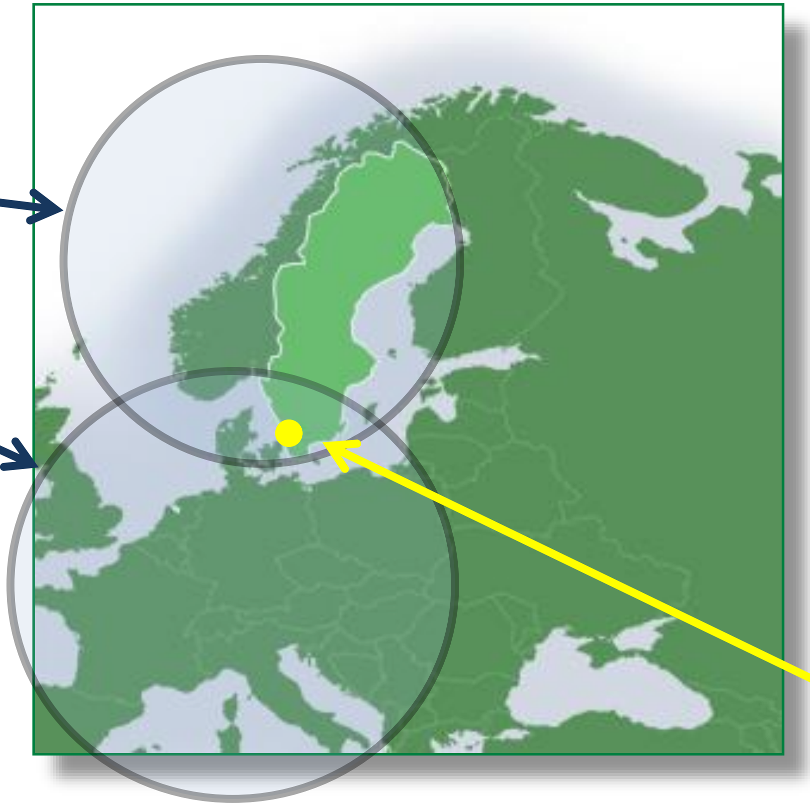
IKC Framework

ESS CONSTRUCTION

Sweden, Denmark and Norway cover the 50% of costs,

Several EU and not EU partners cover the rest, mainly with the In Kind Contribution formula: devices and equipment designed and custom made for the ESS project.



LUND ESS site

Several Partners:

ITALIAN IKC CONTRIBUTION:

Elettra, INFN and CNR are the partners for the Italian IKC to ESS. Elettra contributes with magnets, magnets power converters, diagnostic (wire scannere acquisition system) and

26 equivalent 352 MHz 400 kW peak Radio Frequency Power Stations for the Linac Spoke section.

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Trilateral IKC Agreement

Elettra

- -project management
- -RFPS design and prototypes development
- -technical specification
- -construction follow-up and QA/QC
- -verification and validation

INFN

- -tender documentation
- -performs the tender procedure
- -RFPS purchasing

ESS-ERIC

- -RFPS design and prototypes development
- -technical specification

Scope of Work

26 RFPS units

400 kW

RFPS construction outsourced.
It will be assigned to the successful contractor as required by the Italian public procurement Law

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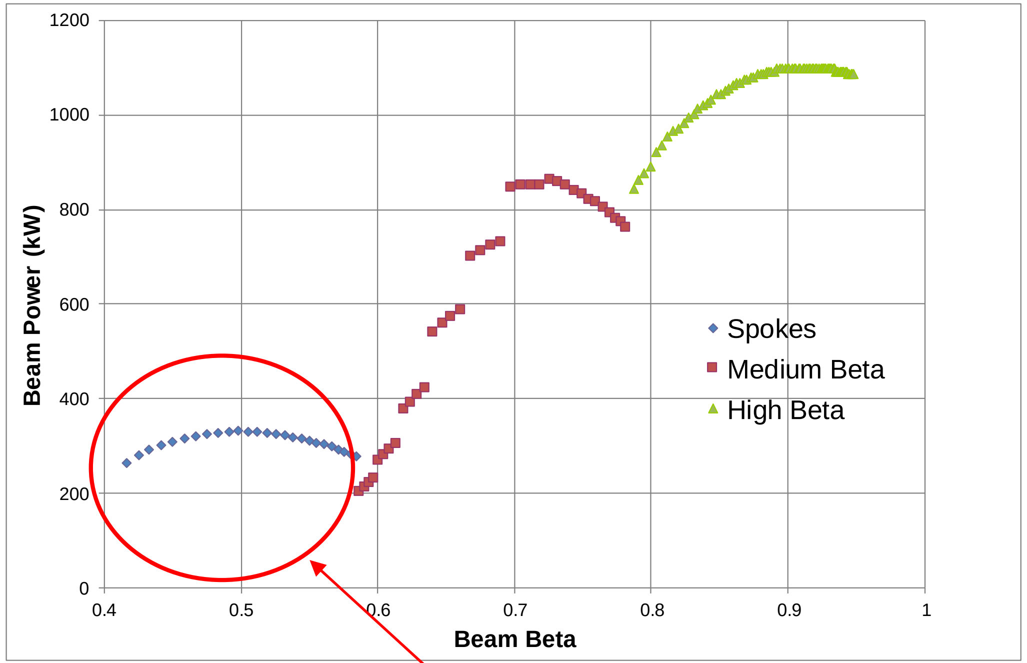
Radio Frequency Power Station

RFPS features:

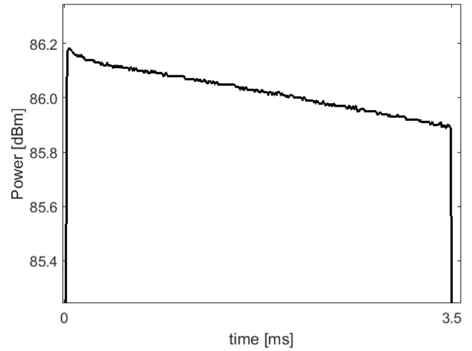
- RF power requirement range per spoke cavity: from 260 kW to 330 kW pep*
- one RFPS will power one spoke cavity to accomplish an independent setting of the RF power level, amplitude and phase regulation
- frequency 352.21 MHz
- periodic pulse operation at 14 Hz, nominal flat-top width 3.5 ms
- non standard flat-top minimum width 140 us only for RF conditioning purpose
- RF power distribution losses downstream each RFPS ≈ 36 kW pep (worst case)

- 400 kW is the nominal RF output power

ESS SC Linac Beam Power need vs Beam β



Spoke section beam energy: 90 MeV - 220 MeV

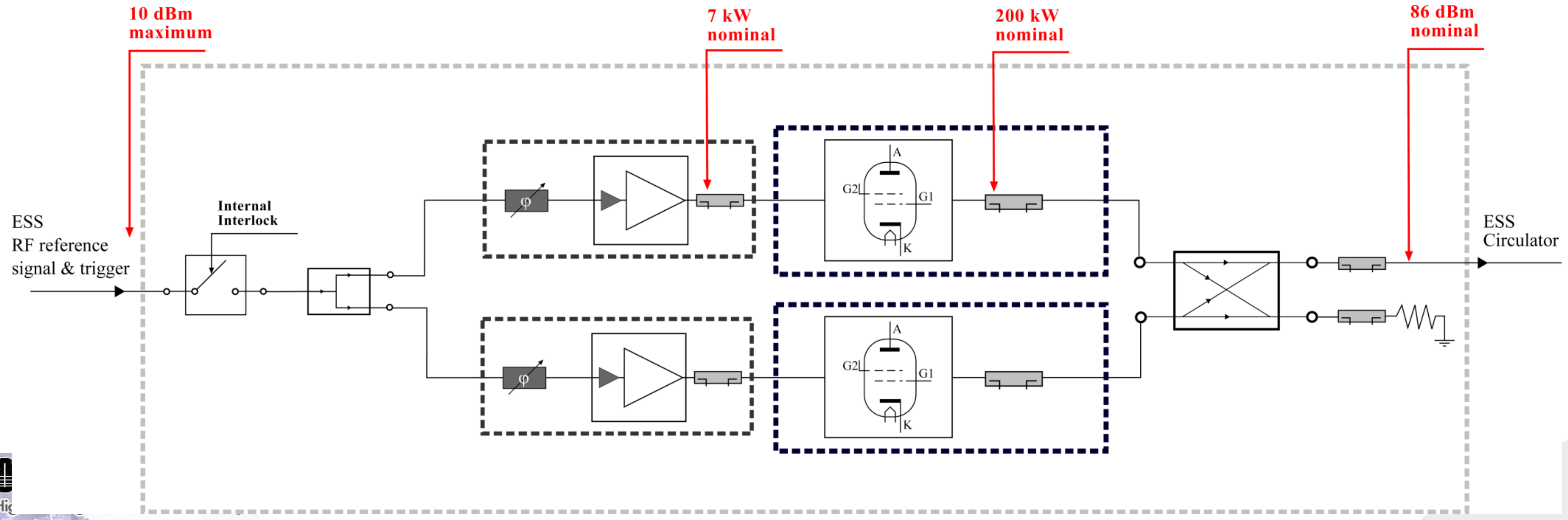


FREIA UPPSALA: envelope of the RFPS pulsed power

* pep = peak envelope power is the average power measured at the crest of the pulse envelope during one repetition cycle.

RFPS Description

- ✓ RF power amplification : two TH 595 A tetrode tubes*, 210 kW each with a 3dB hybrid combiner to add together their output power. Single tetrode branch use not expected.
- ✓ A single HV modulator feds the two anodes in parallel, while heaters and the other electrodes have its own power supply for independent regulation purposes.
- ✓ RF pre-amplifier is based on water cooled solid state transistor technology, 1dB compression point @69 dBm. Static gain adjustment is also foreseen.
- ✓ RF input distribution should also protect the RFPS against internal/external faults and allow the RF phase and amplitude balancing between the two RF branches.
- ✓ Turn key system



*The possibility to achieve the nominal power with solid state transistor base amplifier has been investigated and discounted as costly, needlessy complex and not fully tested

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RFPS pulse quality & stability

RF pulse quality depends:

- on the SSA pre-driver pulse quality
- on the tetrode electrodes power supply dynamic performances and output voltage regulations
- on the heater power supply quality

RF pulse features:

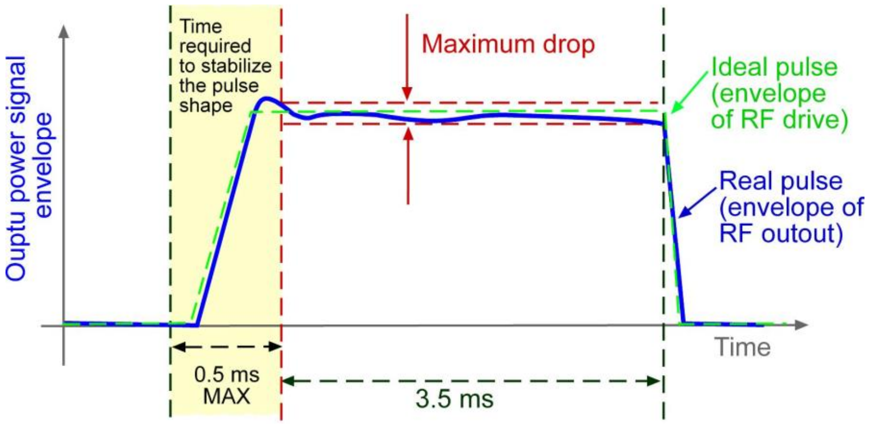
- to be measured after a «warm-up time» at constant external RF drive
- to be measured after a «stabilization time» ,Ts <0.5 ms that shall mask any overshooting and/or following errors

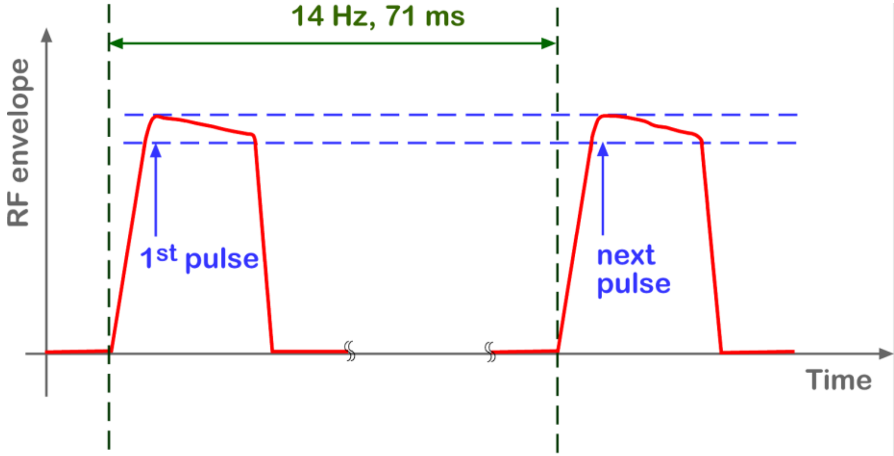
Pulse quality:

- Maximum pulse drop $\leq$ 0.25 dB
- Spectral quality of the amplified signal

Pulse to pulse stability:

- Average amplitude variation $\leq \pm 0.5\%$
- Average phase variation $\Delta\phi \leq \pm 0.5^0$





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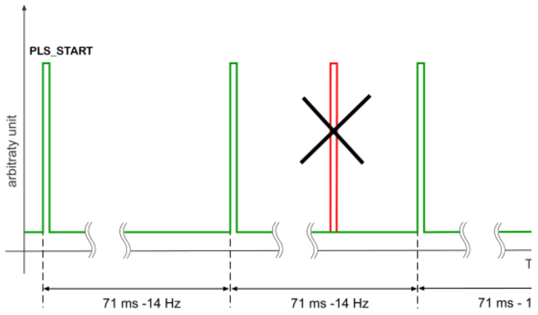
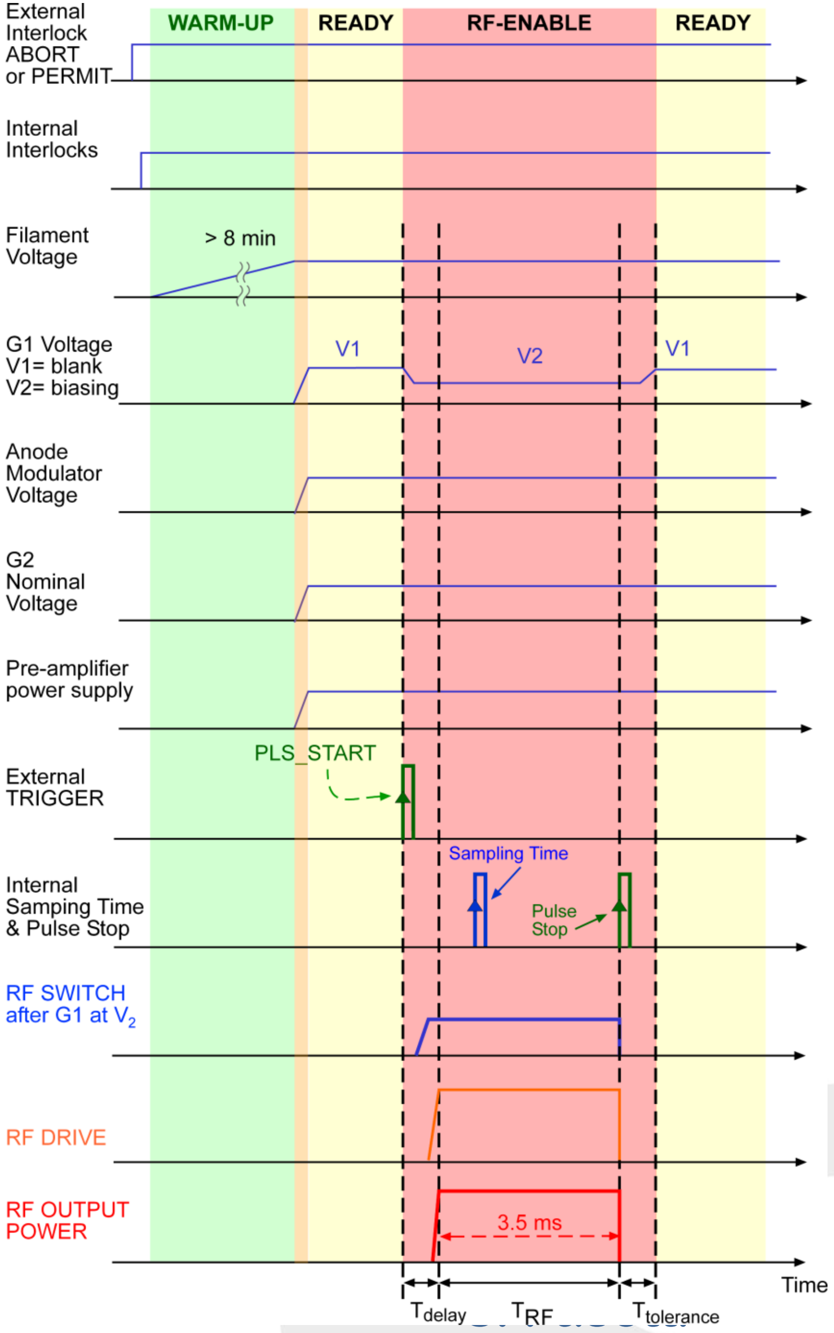
RFPS trigger & timing

ESS will deliver a PLS_START and PLS_STOP trigger signals and a pulse shaped RF driving level

After receiving the PLS_START, the RFPS shall:

- ✓ check the proper RF level (RF overdrive interlock)
- ✓ biase the tetrode tubes, G1 Voltage (ENERGY SAVING!!!)
- ✓ RF drive the amplification chain and deliver the output pulse
- ✓ sample the main RFPS parameters at the flat-top
- ✓ stop the RF output power at PLS_STOP or
- ✓ cut the RF pulse after 3.6 ms any case
- ✓ blank the tetrode, G1 voltage offset
- ✓ ignore any trigger signal if issued within 71 s from the previous one
- ✓ be ready for next output pulse after 71 ms





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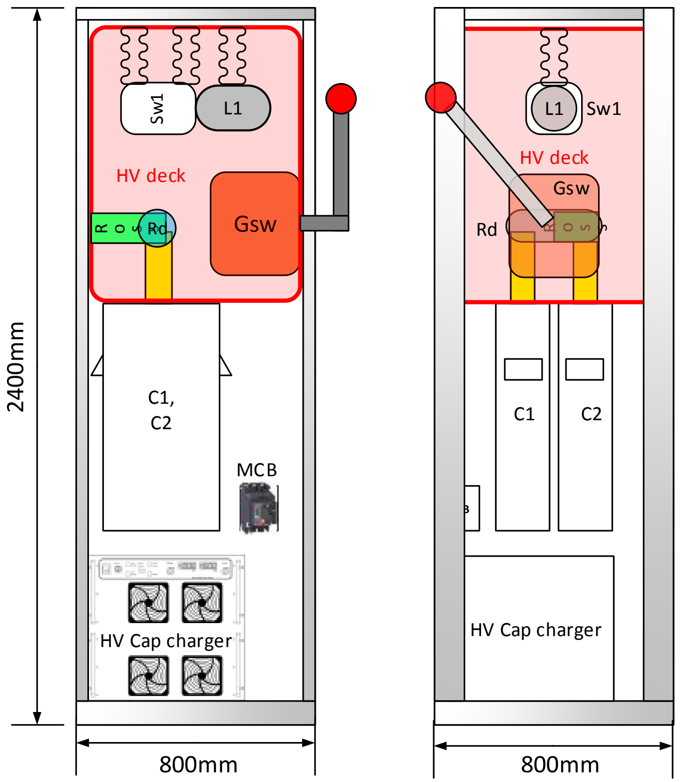
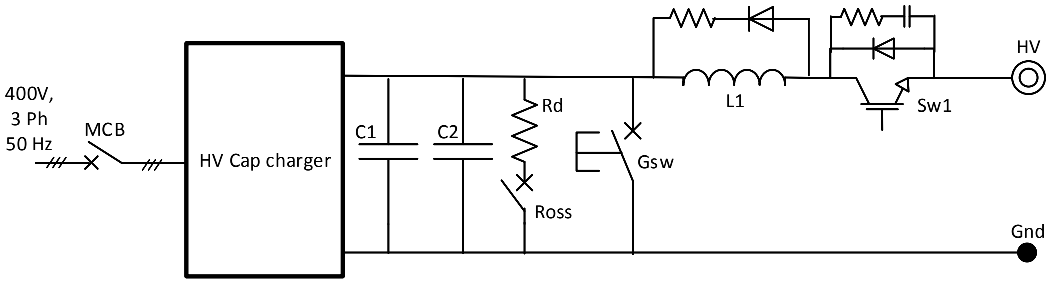
HV Modulator

HV modulator topology and layout STRONGLY RECOMMENDED in the technical specification!

- ✓ based on off the shelf components (cost optimization)
- ✓ both tetrode anodes energy requirement is stored in a capacitor bank, size to allow a maxumum pulse drop, fed by a capacitor charger.
- ✓ Equipped with all the required measurement, control and safety protections devices (no crow bar).
- ✓ Low frequency harmonic emission and AC voltage flicker to preserve the AC grid quality requirement… big issue to be solved!





MCB: Main Circuit Breaker
HV Cap charger: High Voltage capacitor charger
C1, C2: Polypropylene High Voltage capacitors
Rd: High Voltage dump
Ross:
Gsw:
L1:
Sw1:

An example of effectiveness of flicker control implementation provided after placement of the Contract

TH 595 A

Anode Voltage	16.5 kV	
Anode Current (average)	18.9 A	x 2

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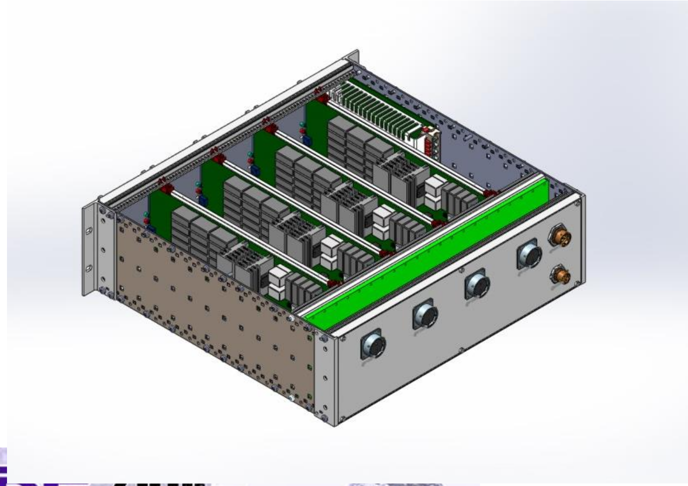
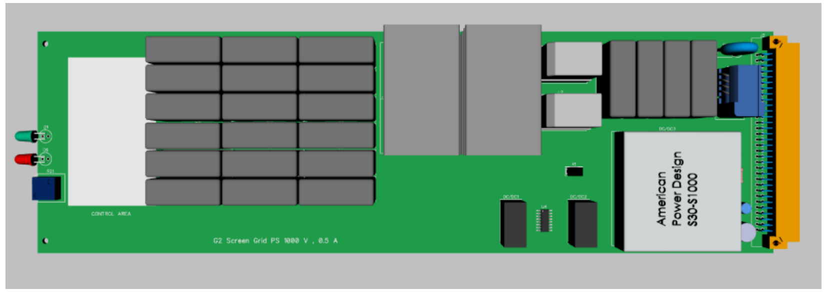
…sotti

Tetrode G1 & G2 power supplies

G1 & G2 topology and layout SUGGESTED in the technical specification!

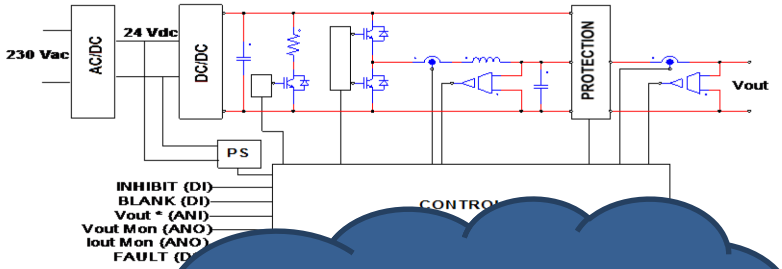
- ✓ off the shelf power supply are expensive and/or do not offer the adequate voltage regulation bandwidth
- ✓ each tetrode will have its own G1 and G2 power supply
- ✓ best solution is a dedicated switch mode power converter having the requestes output voltage regulation and current limitation features
- ✓ At the tender publication day, this solution was only an idea supported by several simulations having good result so that the Tenderers could endorse this idea or propose others solutions.





TH 595 A

G1 Voltage	-210 V	G2 Voltage	900 V
G1 Current	1.7A	G2 Current	0.26 A



These days G2 prototype PS under testing

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Safety

Safety is defined and measured more by its absence than by its presence”

James Reason, Psychologist, UK

The RFPS is to be considered as a system working in connection with other systems, and interfacing human operators in different conditions. The RFPS will be installed in a non-restricted access area.

So it shall be safety-integrated in order to:

- **eliminate the identified hazard,**

informed design steps, according to and compliant with the Regulatory Framework

- **reduce risk of those unavoidable,**

RFPS control system, fail-safe, pro-active, visualizing status to involved personnel

- **signalize the residual risks associated with the machinery**

RFPS safety user guide and related elements

Rules & Standards

- **The RFPS is a system, composed by different elements which relate to different regulatory areas. A list of European Union Directives cover these areas.**
- **Besides, each area is covered also by multiple standards from different International and European Organizations or Committees. However the EU directives covers the National Swedish standards**

Area	EU directives	Topics
Machinery Safety	2006/42/EC	Machinery safety
	89/391/EEC	*Measures to improve safety and health at work*
Electrical Safety Wiring	2014/35/EU	Electrical safety: low-voltage electrical equipment
	2006/95/EU	*Electrical equipment designed for use within certain voltage limits*
Electromagnetic Compatibility	2004/108/EC	Electromagnetic compatibility of electrical and electronic apparatus
Non-Ionizing Radiations	2013/35/EU	Limiting the exposure of workers to risks from electromagnetic fields
Ionizing Radiations	2013/59/Euratom	Basic safety standards for exposure to ionizing radiation (from 2018)
RoHS	2011/65/EC	Restrictions on the use of certain hazardous substances in electrical and electronic equipment
Noise Emissions (audio)	2003/10/EC	Health and safety at work: exposure to noise

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Validation, FAT & SAT

- Twenty-six (26) RFPS units shall be built, tested and commissioned.

- The first RFPS unit will be extensively tested at the Contractor premises (VALIDATION) in order to:
  - check the design and the technical solutions
  - recommend optimizations to best meet the specification if needed
  - finalize the FAT procedure to improve its effectiveness versus time frame

- At this stage, it should be possible to add design optimization and perform minor modifications, which cost, if any, shall be discussed and agreed among the parts (Voltage flicker mitigation, for example).

- Factory Acceptance Tests done on ALL twenty-six (26) RFPS units

- Site Acceptance Tests will be performed on the first unit only at ESS premises in the final installation layout with dedicated care to:
  - mechanical vibration issues, induced by the pulsed regime in continued operation status,
  - thermal fatigue and drift,
  - EMC noise and immunity.

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RFPS roadmap

Three project phases are planned according to ESS standard:

1. contract masterplan
2. RFPS design, at the most detailed level
3. design of engineering activities for RFPS construction,
4. publishing and updating of Technical Design Report
5. main material procurement
6. Critical Design Review meeting, during which the TDR shall be discussed and approved

Phase 1 ≈ 2 months

1. construction of the first RFPS unit,
2. validation and FAT of the first RFPS unit, according to the specifications
3. "as built" documentation update and release from construction and validation sub-phases,
4. Readiness Review Meeting, upon the positive FAT procedure regarding the first RFPS unit,
5. delivery and SAT at ESS premises of the first RFPS unit.

Phase 2 ≈ 1 year

1. construction of the remaining 25 RFPS units,
2. FAT on each RFPS unit and, if successful, shipment approval,
3. delivery of the RFPS units at ESS premises,
4. final assessment and release of the RFPS units' documentation,
5. a System Acceptance Review Meeting

Phase 3 ≈ 1 year

Contract time schedule is really challenging!!!

Quality Control

A contract is successfully when:

- goods fully comply the specifications
- time schedule is met
- cost is reasonable within the expectations

To achieve this goal the Customer shall closely follow the goods design, production and commissioning.

To achieve this goal the Contractor shall have the full understanding of why the requested goods have been so specified and shall have a fabrication expertise (pre-qualification!)

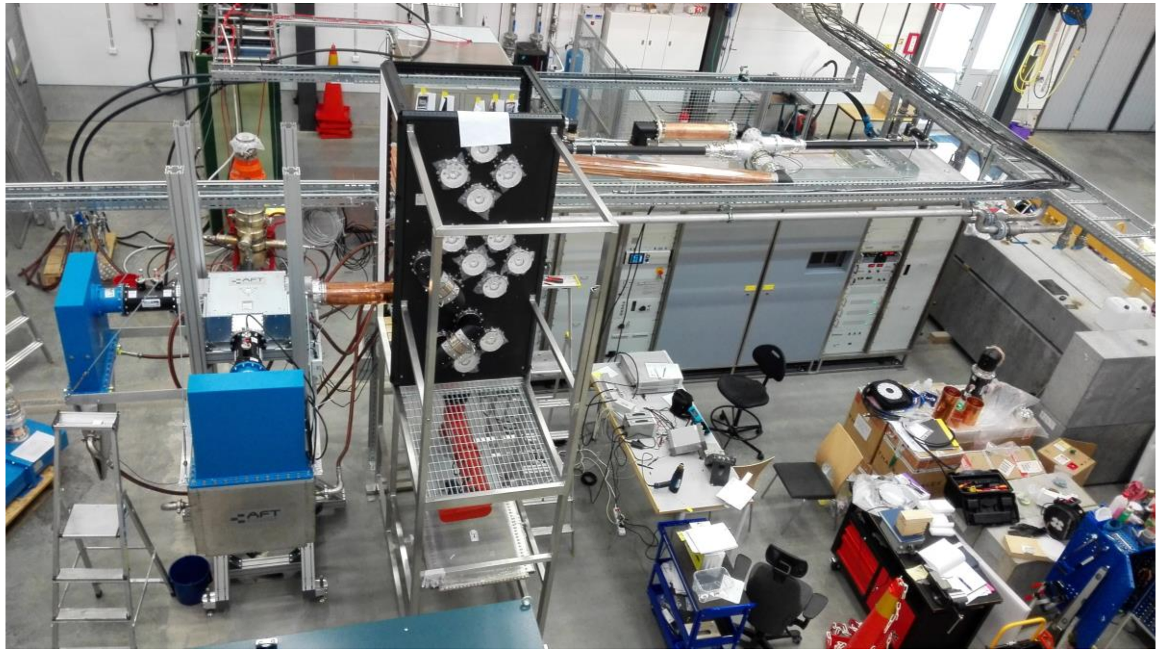
Customer and Contractor <u>shall work together</u> to make successfully the contract

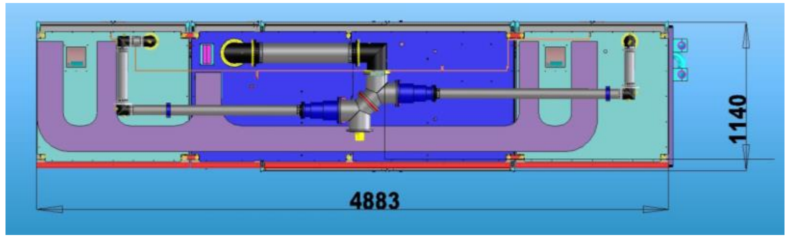
through a clear contract management and a quality assurance program put in place at the design, manufacture, commissioning and installation steps.

FREIA Test Stand

The FREIA laboratory, UPPSALA University (Sweden) , Department of Physics and Astronomy, has a dedicated test facility for studying the performance of superconducting accelerating SPOKE cavities.

FREIA purchased two RFPS 400 kW 352 MHz units from two different companies having performances close to the ESS requirements but 28 Hz and CW capabilities.





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Elettra has performed several measurement campaigns on both the RF stations to assess their performances and finalize the technical specifications.

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TH 595 measured features

Several tests have been reperated to assess the TH 595 performances at Thales premises and at FREIA laboratory

One of the FREIA RFPS was operated slightly changing the tube's tuning parameters (G1, G2 and HV voltages):

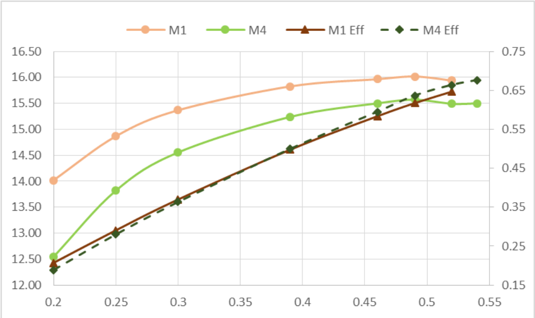
- **TH 595 Matlab model to forecast the tube operating curves developed (V. Ingravallo)**
- **Useful data on gain and efficiency taken**

	Anode (kV)	G1 (V)	G2 (V)	Tube Gain (dB)	RF Power min (kW)	RF Power max (kW)*
M1	17	-200	900	15.94	16.4	177.0
M2	16	-200	900	15.73	15.8	170.0
M3	16	-200	850	15.63	14.2	164.9
M4	16	-220	900	15.49	11.5	161.5
M5	17	-220	900	15.71	11.7	167.3
M6	17	-220	950	15.84	13.3	172.1
M7	17	-240	950	15.52	9.7	158.3
M8	17	-240	950	15.38	8.5	154.6
M9	16	-240	900	15.26	8.2	151.4
M10	17	-240	950	15.52	9.9	160.6
M11	17	-230	900	15.55	11.1	162.0

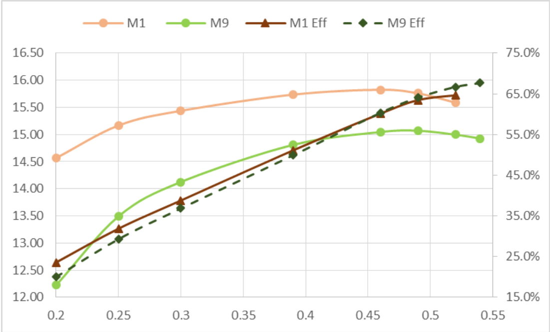
* LL_RF driving signal = 0.52, maximum drive 0.54 from M4 to M11

Factory set parameters

IPA 1



IPA 2



IPA1	Anode (kV)	G1 (V)	G2 (V)	Gain @ max power(dB)	Efficiency @ max power	RF Power min (kW)	RF Power max (kW)
M1	17	-200	900	15.90	65%	16.4	177*
M4	16	-220	900	15.50	68%	11.5	170.6

IPA2	Anode (kV)	G1 (V)	G2 (V)	Gain @ max power(dB)	Efficiency @ max power	RF Power min (kW)	RF Power max (kW)*
M1	17	-200	900	15.60	65%	22.9	189*
M9	16	-240	900	14.90	68%	13.4	175.0

TH 595 + TH 18595 A

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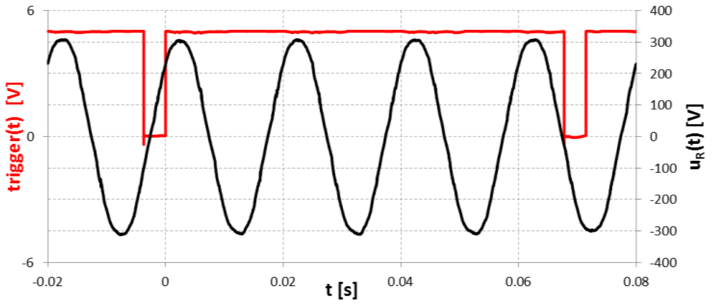
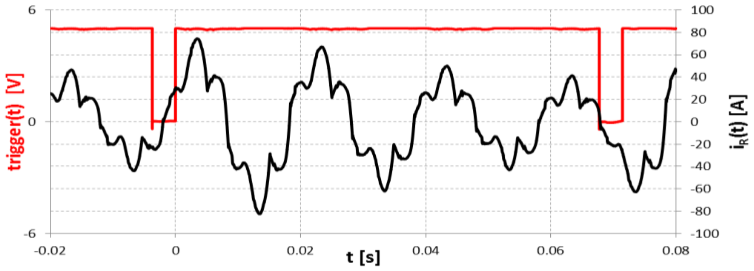
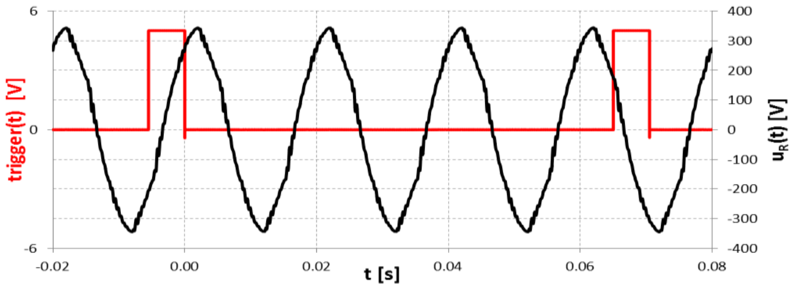
PF and Flicker measurement

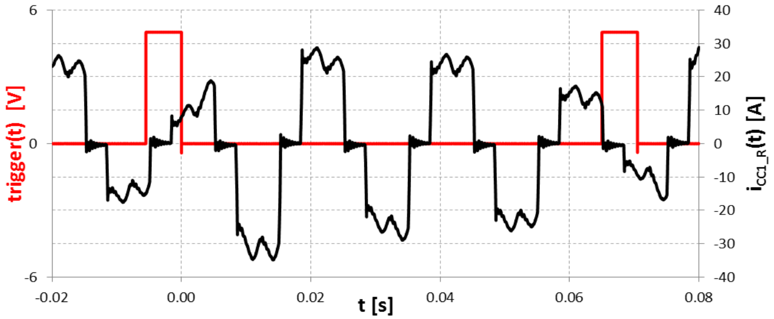
Harmonic distorsion, Power Factor and flicker measurements carried out on both the FREIA RFPS units (T. Ciesla)

Registered waveform and current of R phase









Anode power supply: 6-pulse rectifier with soft start circuit

RF output power: 187 kW per tube .

HV Modulator with capacitor charger.

C. Martins topology

Capacitor charger limited at 37 kW

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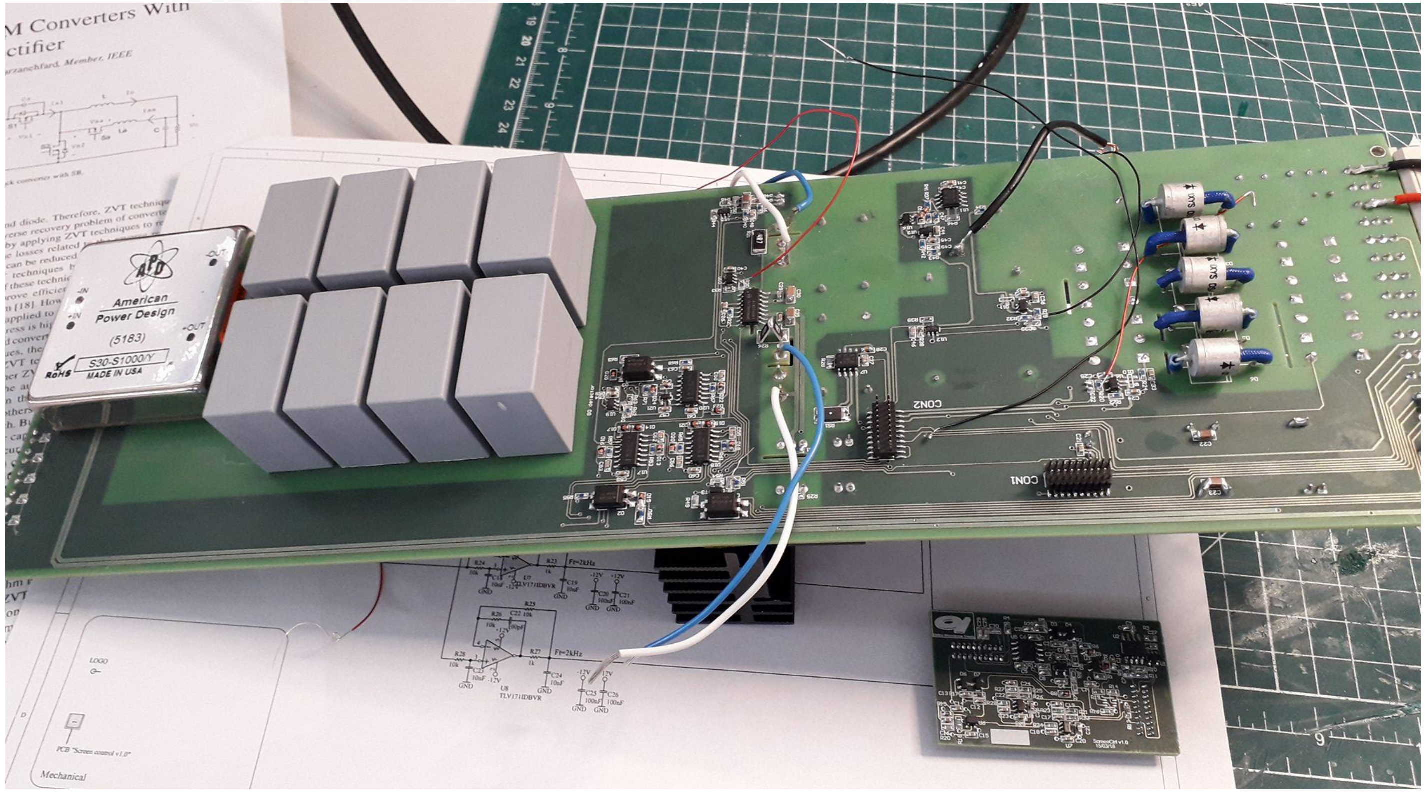
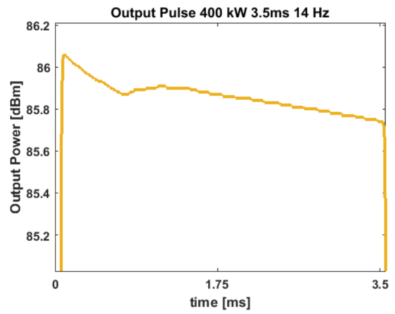
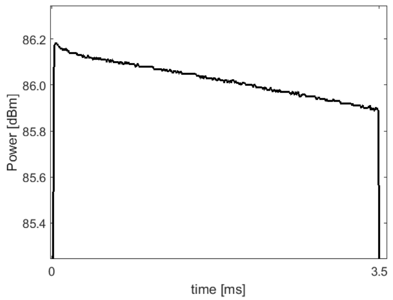
G2 power supply prototype

- At the tender publication time the G2 and G1 power supplies were only an idea supported by numerical simulations.
- Today the G2 prototype has been built and successsfully tested
- BoM and board cost < 1000 Euro
- Some «burn out» time is still required.
- The tender winner can decide to implement it.



G2 impact on the RF pulse envelope shape





Courtesy of M.Jobs , A. Frizzi

Features:

1000 VDC, 0.5 A , Peak Power 500 W

switch mode power converter with voltage regulation and current limitation capabilities

voltage recovery time < 150 μs

C. Pasotti

Conclusion

✓ RFPS manufactures outsourced. The tender's technical specification contains:

- mandatory requirements (Thales tube 595 A)
- strongly recommended solutions (HV modulator topology)
- «suggested» design (G1 and G2 power supplies)

balancing cost versus performances

Any case the final contractual liability belongs to the Contractor

✓ Thanks to the FREIA laboratory the RFPS technical specifications gained ground and feasibility

✓ The main RFPS contract challenge is the PRODUCTION TIME SCHEDULE!

Strong interaction is foreseen between Parties to successfully achieve the Scope of Work!

C. Pasotti

Thank you!

Solid State vs Tube technology

PROS & CONS comparison table between the two technologies for the RFPS project

Rank symbol	*Legenda*
🟢	good
🟡	adequate
🟠	scarce
🔴	bad

RF Source Solid State transistor				*RF Source* **Tetrode TH595**
Comment	***Rank rate***	***Feature***	***Rank rate***	***Comment***
5 - 10 Euro/W, CW RF power cost, but the system becomes very complex and a further cost reduction it is not plausible	🔴	**Cost**	🟢	2 Euro/W, market surveys among three companies
Short and medium term good, it becomes an issue at long term	🟡	**Discontinuity**	🟠	Short term good, it becomes an issue at medium long term
To achieve 400 kW a huge number of modules shall be combined. Gain ad phase dispersion of each module shall be carefully set to avoid unwanted losses and output power reduction	🟡	**Operability**	🟢	Tube very easy to handle and set into operation
Quick replacement possibility providing the right choice of the combining's and connector's technology	🟢	**Servicing**	🔴	Three hours down time to replace the tube
Technology tested on CW machine with larger footprint and power density	🟠	**Availability**	🟢	Robust tube, well known and tested technology. Already running machine.
Good if there is a well done supervisory system	🟢	**Troubleshooting**	🟢	Simple combination of two tubes: easy identification of failure parts
None, but if there is the hot plug option it easily overcomes the lack of redundancy	🟡	**Redundancy**	🔴	None, just tube replacement
Standard safety procedure. Standard training	🟢	**Safety**	🟠	The anode's high voltage requires dedicated safety procedure and standard. Trained people only.
>55% claimed. To be checked	🟢	**Efficiency**	🟡	>45% measured on existing machine
8 months delay for check, test and tendering	🔴	**Schedule**	🟢	Within the ESS project time frame
To be checked if a single supplier	🟠	**Production rate**	🟢	Within the ESS project time frame, verified

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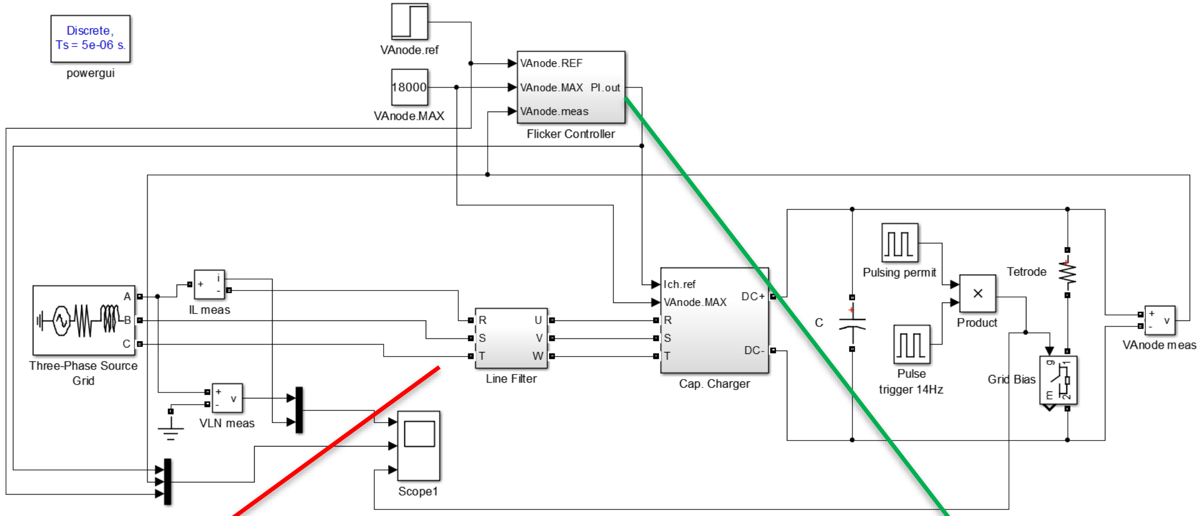
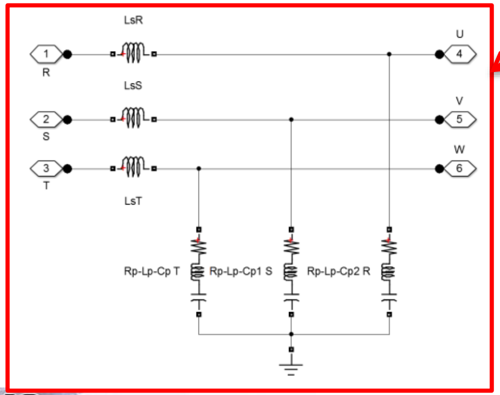
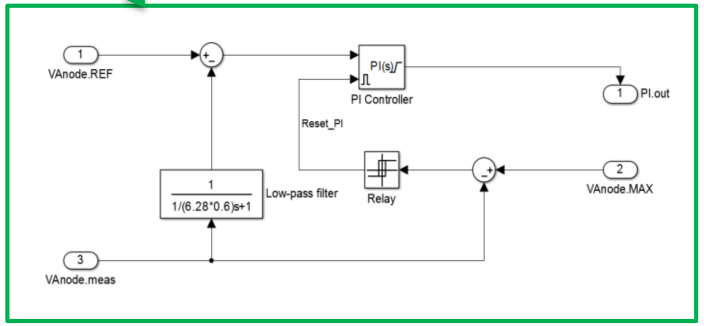
LHD and Flicker PID control







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