# RF Power Station Evaluation FREIA, Uppsala University

Magnus Jobs[1], Rolf Wedberg[1], Roger Ruber[1],

[1]) *Uppsala University, Physics & Astronomy, FREIA*

*Uppsala University, Uppsala, Sweden*

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# Outline

- Introduction to FREIA Laboratory RF Line
- Tetrode Power Stations
- Power Stations Supplies Evaluation
- Power Stations RF Performance
- SSA Development
- Conclusions

# FREIA Uppsala


- UU contribution to the ESS project
- Key goals to validate prototype cavities, cryomodules and RF sources

# FREIA Uppsala

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## RF Source

- 400 kW 3.5 ms pulses at 14Hz
- Dual TH595 tetrodes

## Cryogenics

- Liquid Nitrogen
- Helium liquefaction (150 l/h)
- 2000 l storage dewar

## Spoke Cavity

- Operating at 352.21 MHz
- Q > $10^9$
- Operating gradient 9 MV/m

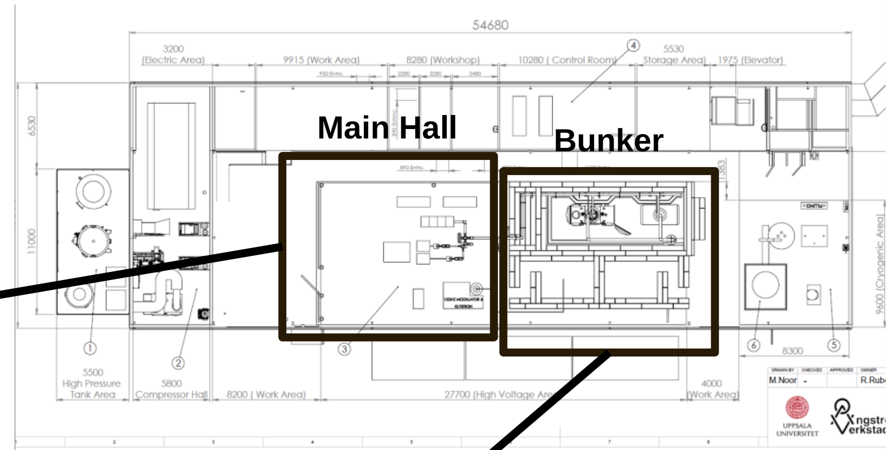
## Cryostat

- Operating at 1.8 K
- 16 mbar pressure

## Control System

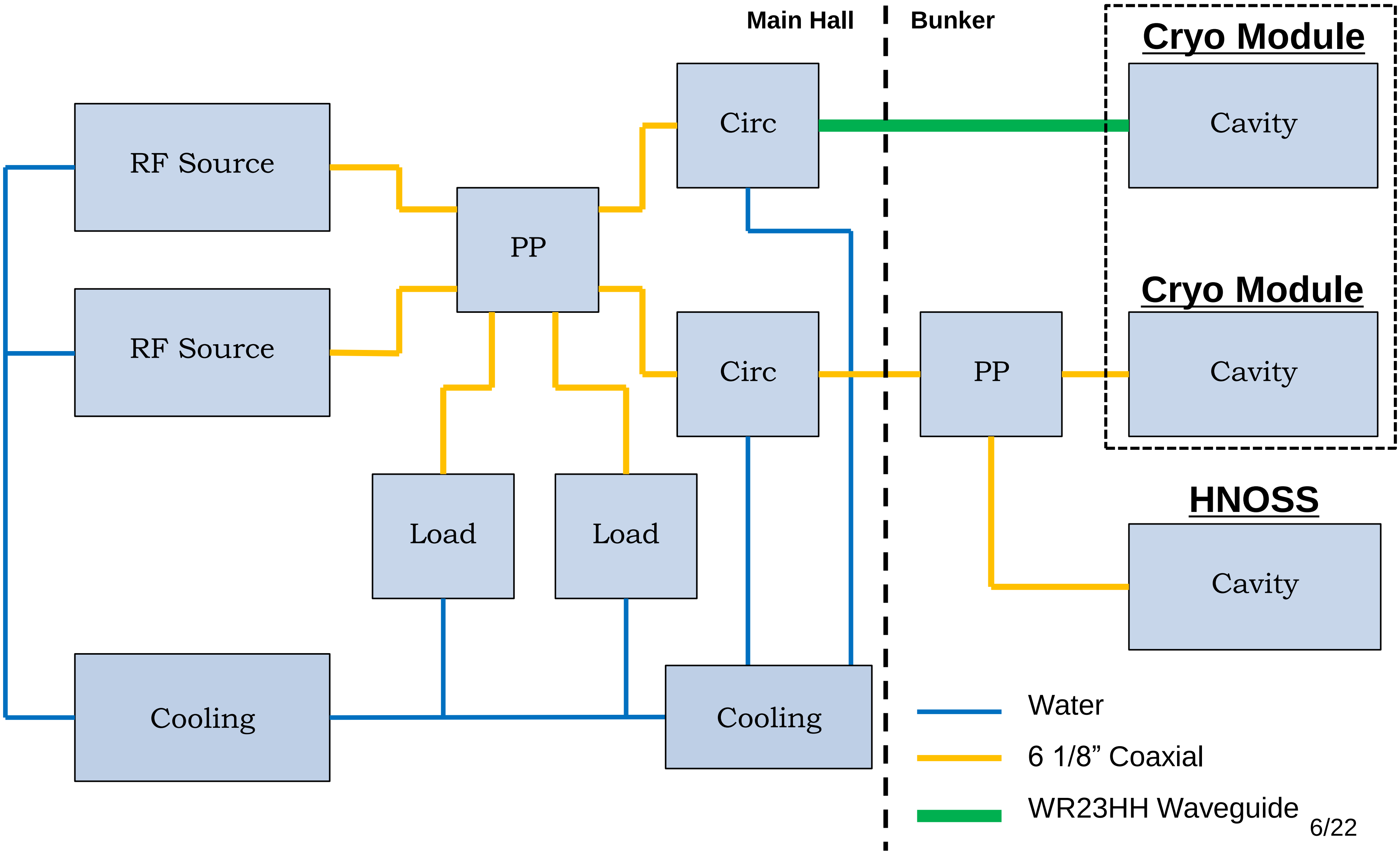
- Closed-loop LLRF system
- Cryogenics control
- Safety Interlocks

# 400kW RF Line




- Two 400kW RF Power Stations
- Main Bulk Outside Bunker
- Coaxial & Waveguide Lines
- Patch-Panels for Rearrangement

# Block Schematic



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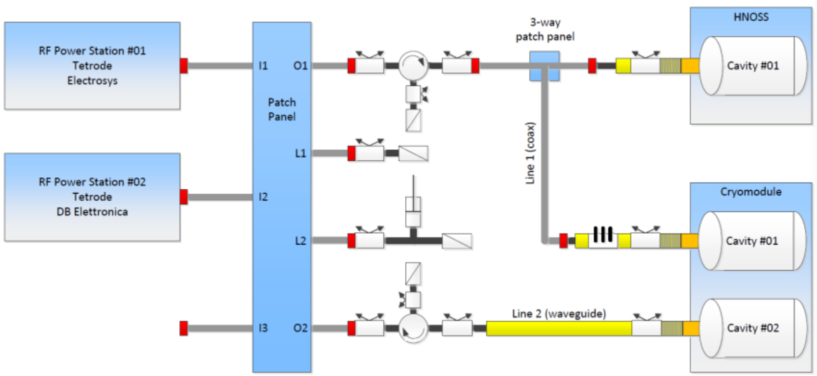
# RF Distribution




- 6-1/8” Coaxial Lines
- WR23HH Waveguides
- Multiple Patch-Panels
- ~90% Installed

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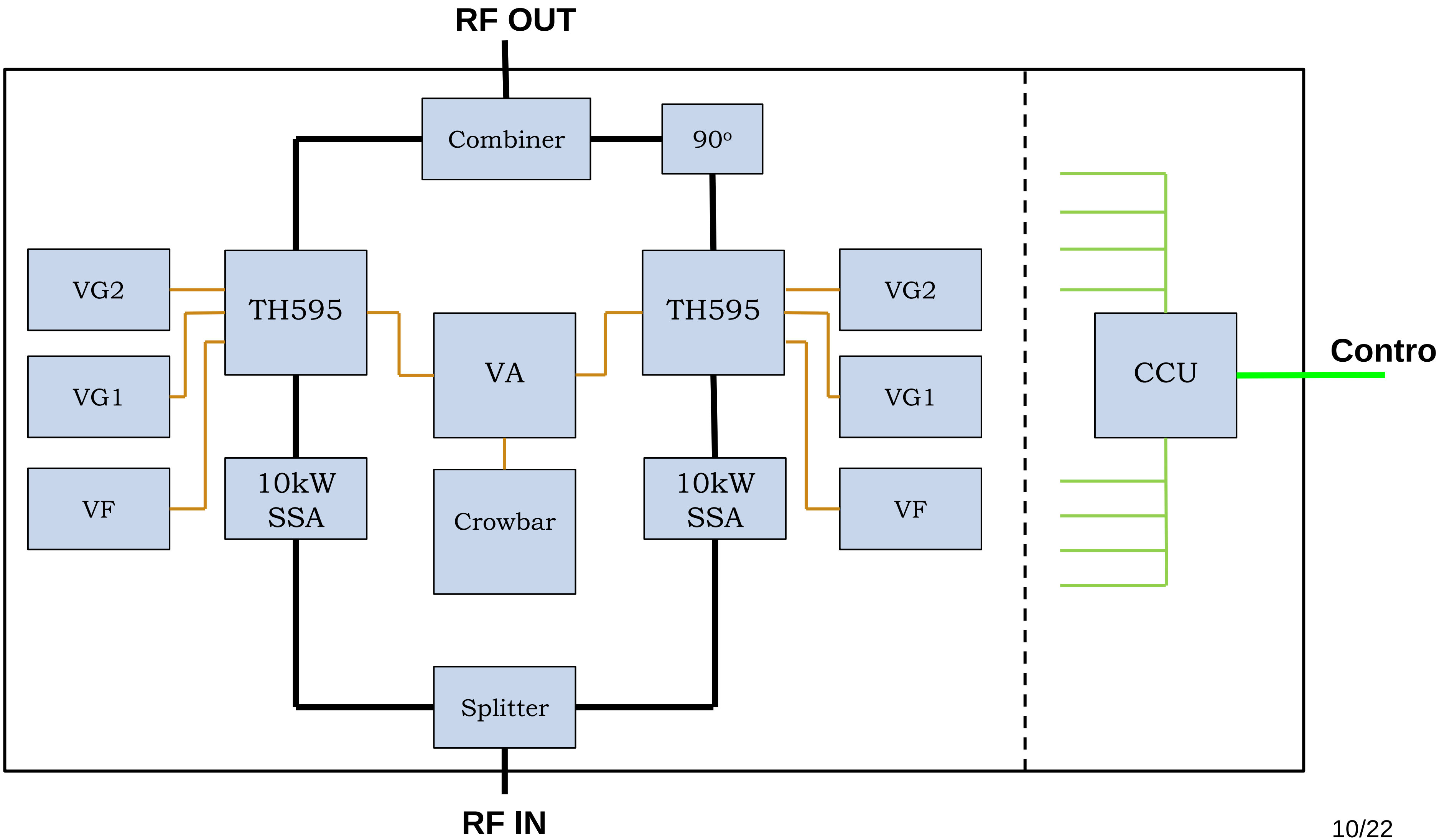
# Industries Included

- Components used and tested in the RF-chain at FREIA include multiple companies
- The use of high power 400kW pulses often presents new applications for involved companies which means that many components are developed and evaluated in collaboration

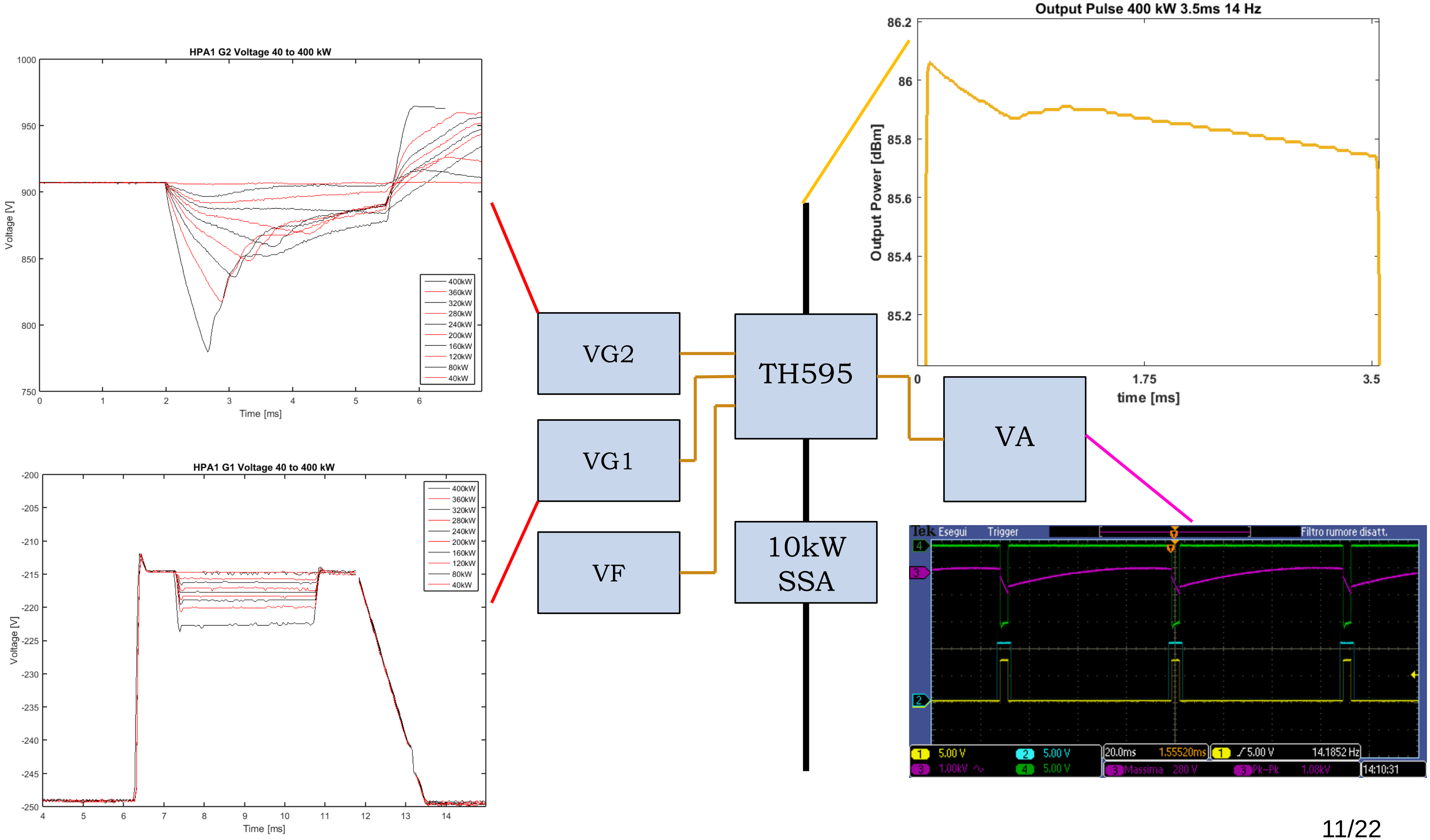
# 400kW RF Stations

- Dual TH595 Per Station
- 400kW Peak at 14 Hz, 3.5ms
- Crowbar & Series Switches
- One Station Commissioned
- One Station in SAT


# Station Schematic



# Tetrode Supplies



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# Parameters

- First RF Station Commissioned
- Only minor deviations
- Improvements Ongoing
- Initial tests in closed-loop configuration performed

| Parameter | Tender Specification | HPA1 | HPA2 | Station Out |
|---|---|---|---|---|
| Frequency of operation | **352.21 MHz** | 352.21 MHz | 352.21 MHz | |
| Output power | **≥ 175 kW** | 200 kW | 200 kW | |
| 3 dB bandwidth | **≥ 250 kHz** | ≥ 2.5 MHz | ≥ 2.5 MHz | |
| Pulse width | **3.5 ms** | 3.5 ms | 3.5 ms | |
| Frequency of pulses | **14 Hz** | 14 Hz | 14 Hz | |
| Input power from driver | **≤ 10 kW** | 6.0 kW | 6.9 kW | |
| Gain | **≥ 14.5 dB** | 15.6 dB | 14.9 dB | |
| Anode Efficiency | **≥ 65 %** | 65% | 60% | |
| Class of operation | **AB** | AB | AB | |
| Harmonics | **< -35 dBc** | | | < -40 dBc |
| Spurious | **< -60 dBc** | | | < -60 dBc |
| Linearity[1] | **± 0.5 dB** | ± 1.25 dB | ± 1.25 dB | ± 1.25 dB |
| Gain amp. stability (time >5 µs) | **± 1 dB** | | | ± 0.3 dB |
| Gain phase stability (time >5 µs) | **± 5degrees** | | | ± 1.5 degrees |
| Driver Gain[2] | **≥ 70 dB** | 69.5 dB | 70 dB | |
| Driver amp. stability (time >5 µs)[3] | **± 0.2 dB** | ± 0.25 dB | ± 0.1 dB | |
| Driver Phase Linearity | **± 5degrees** | | | ± 0.5 degrees |

1: Primarily caused by deviation in linearity in the <50 kW range
2: Controlled by station, could be modified by if required
3: Some minor discrepancy of gain control in HPA1

- Second RF Station Ongoing

# Wire Test

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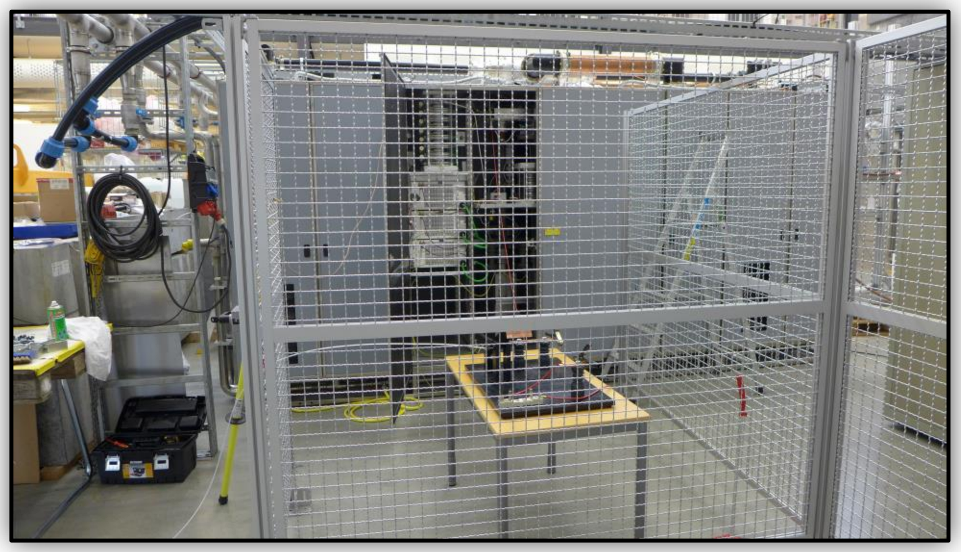
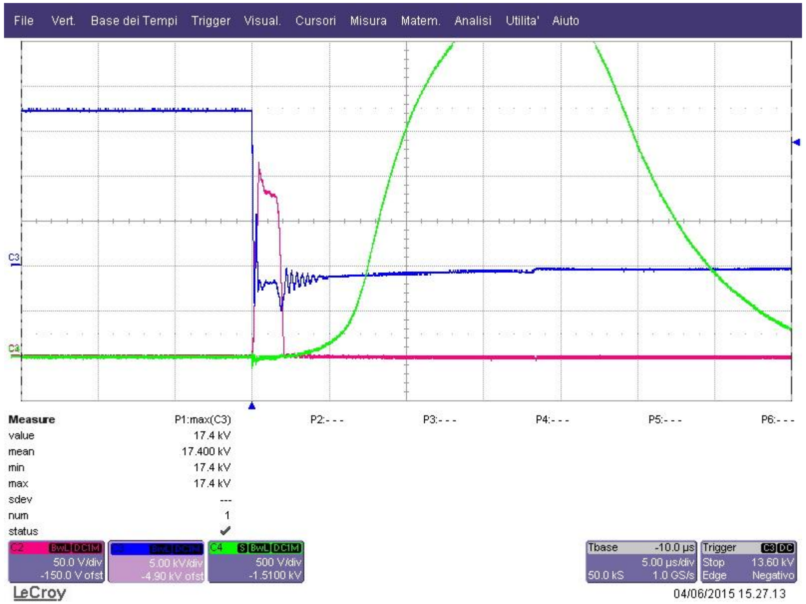
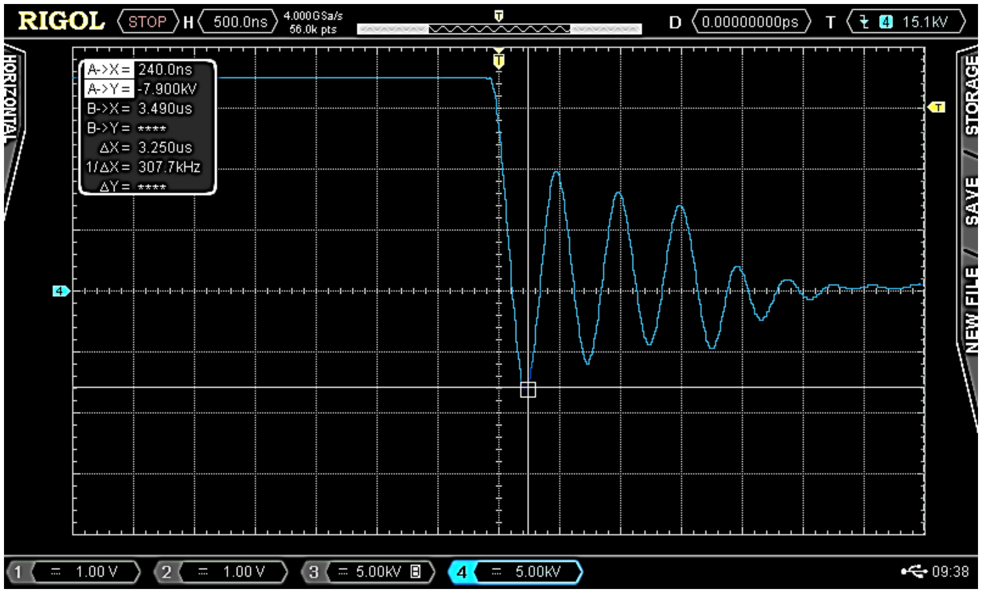





- Test of Crowbar & Series Switches
- Series Switches are IGBT based
- Series Switches testes w/wo Crowbar
- Short Circuit Wire Filament as defined by Thales datasheet

# Series Switches

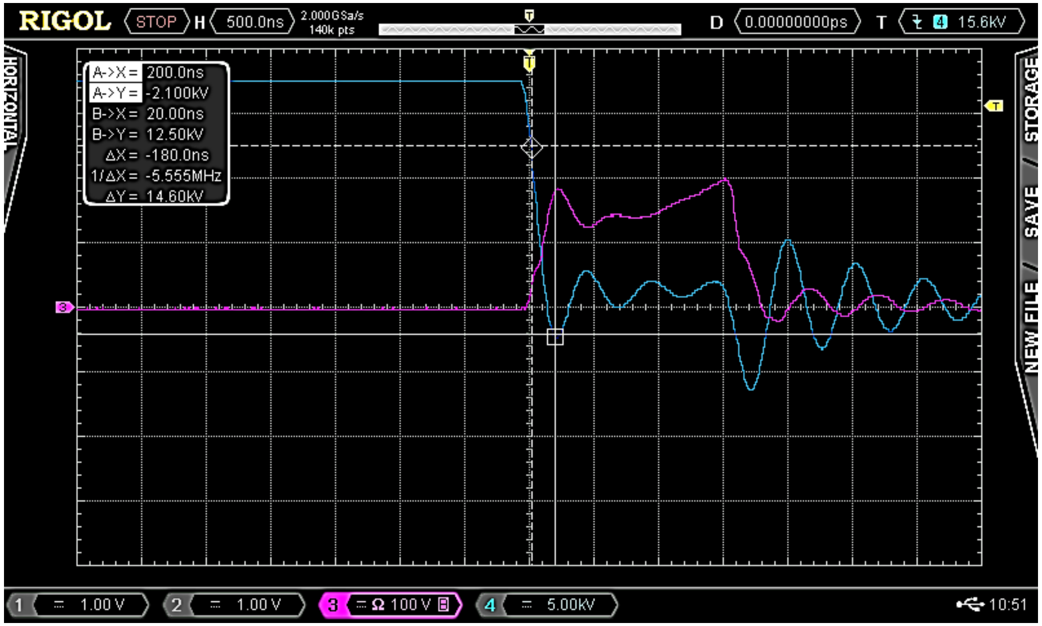



- Significant ringing
- Caused by SRD capacitances & output lead inductance
- Snubber network across IGBT does not remove this effect
- **Flyback 5-diode stack destroyed by 8kV undershoot**

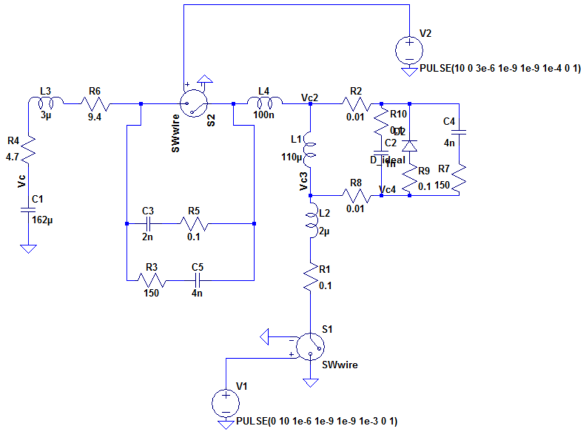
- Undershoot can be reduced by the inclusion of snubber network across diode stack

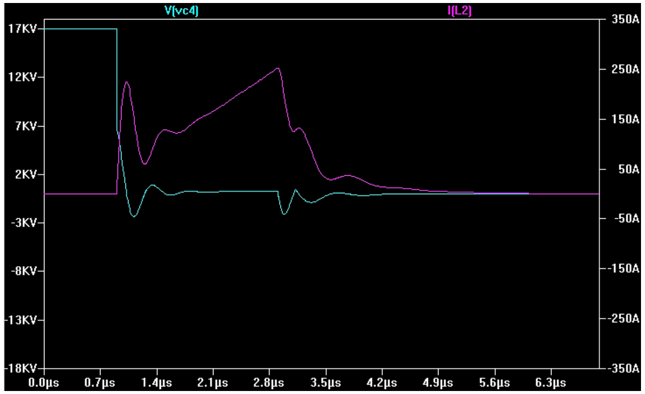
- Proper voltage divider network across diode stack was missing adding to the sensitivity of the design. Proper voltage divider network to be included

# Series Switches

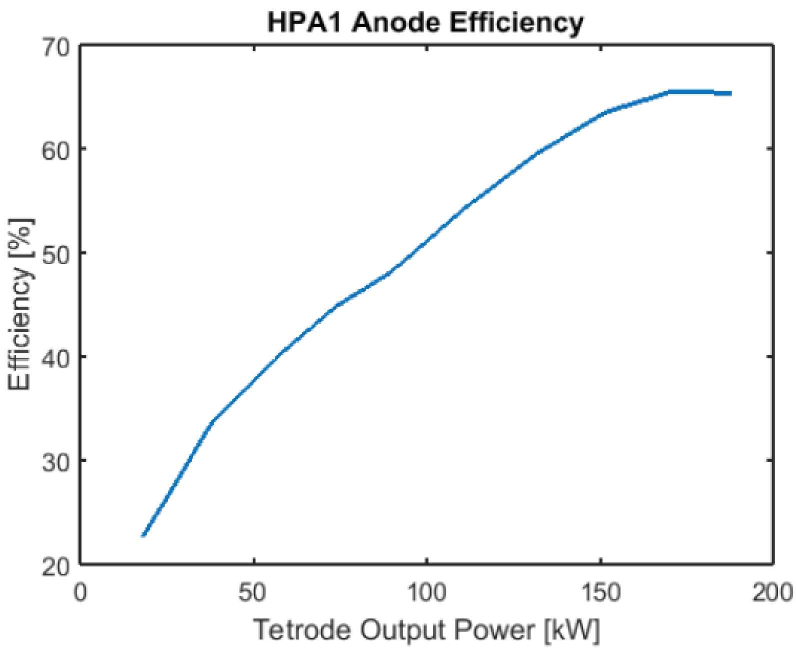


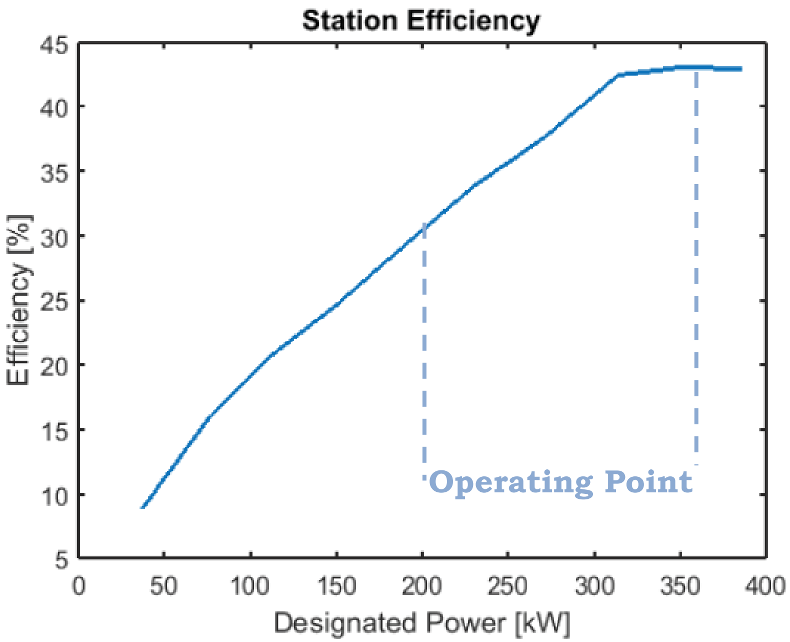

- Snubber network added on diode stack
- Undershoot reduced significantly
- Main cause contributed to overly idealistic modeling of network during design stage
- Good correspondence with simulations



# Efficiency




- Anode Efficiency Peak ~65%
- Tuned for 400kW operation

- Efficiency Peak ~43%

# Tube Performance

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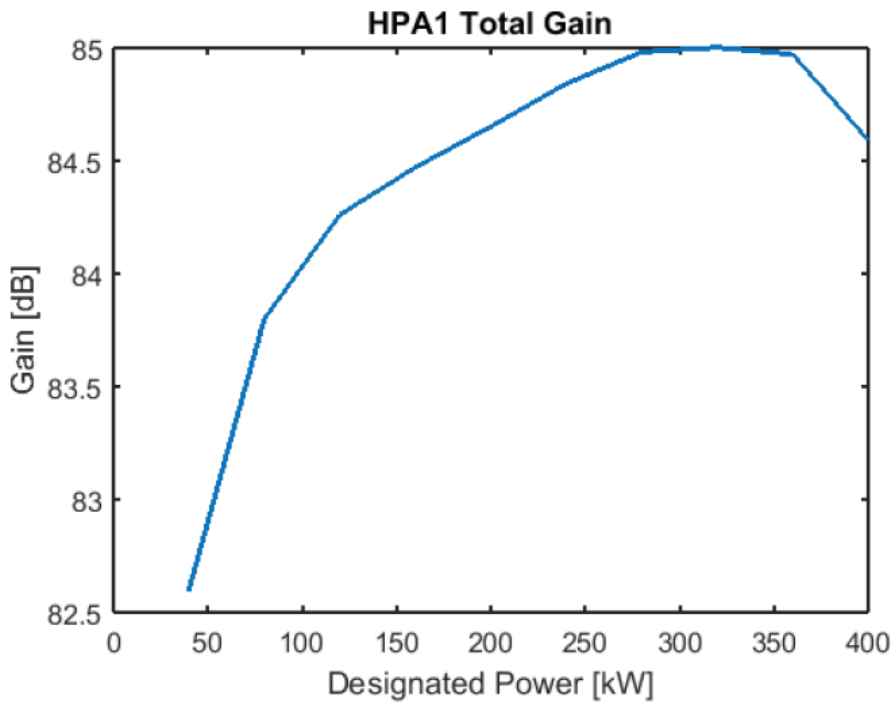
**Amp Section A**

| Station P. Out [kW] | 0 | 40 | 80 | 120 | 160 | 200 | 240 | 280 | 320 | 360 | 400 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Power - In [dBm] | | -9,8 | -7,8 | -6,62 | -5,65 | -5,02 | -4,22 | -3,67 | -3,08 | -2,52 | -1,71 |
| Power - FWD [dBm] | | 1 | 4,2 | 5,84 | 7,02 | 7,83 | 8,82 | 9,51 | 10,12 | 10,65 | 11,08 |
| Power - Out [dBm] | | 72,8 | 83,8 | 77,64 | 78,82 | 79,63 | 80,62 | 81,31 | 81,92 | 82,45 | 82,88 |
| Gain [dB] | | 82,6 | 91,6 | 84,26 | 84,47 | 84,65 | 84,84 | 84,98 | 85 | 84,97 | 84,59 |

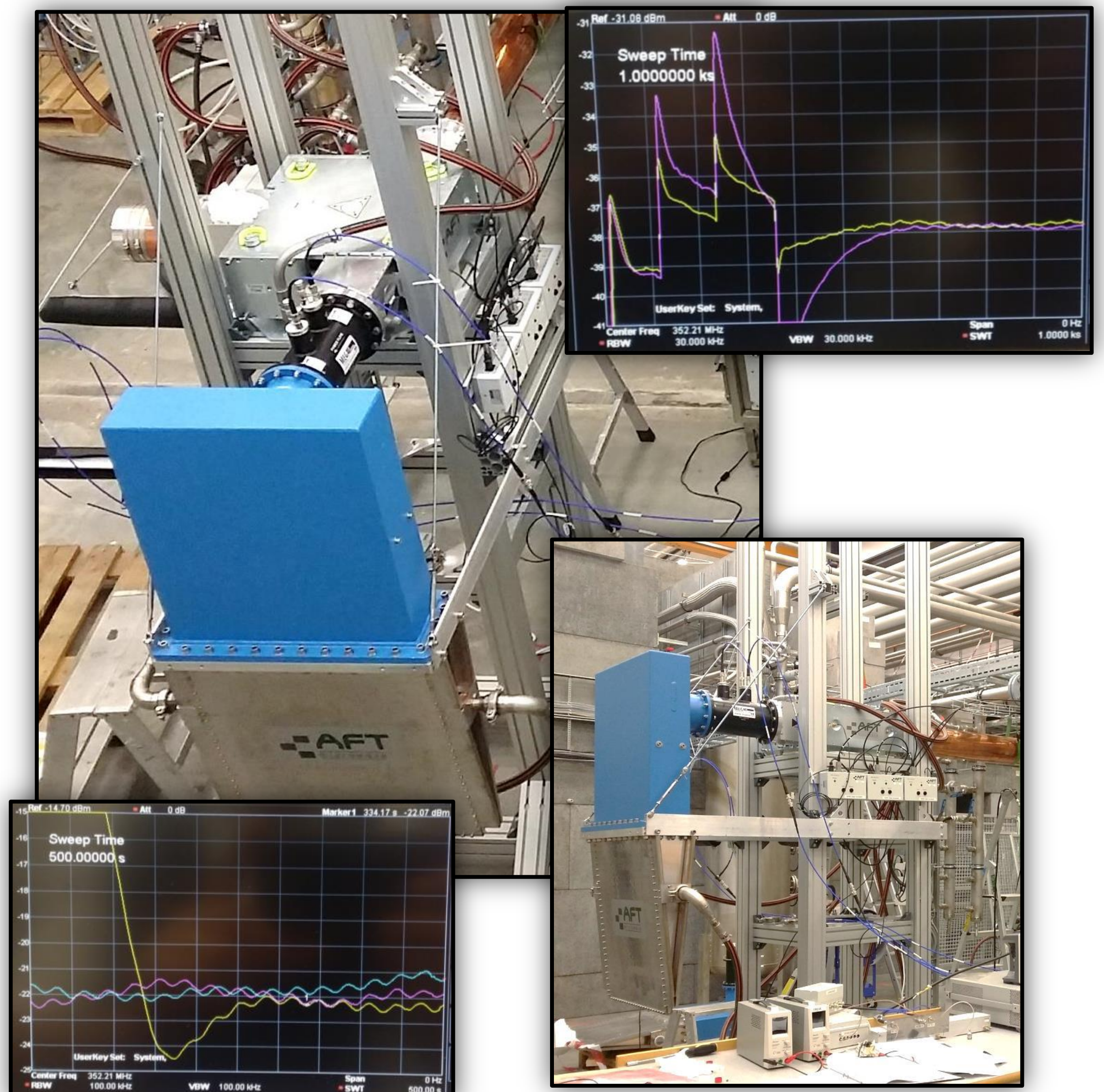
- Initial tube performance close to expected
- Some further tuning can be performed
- Tube gain droop need to be adjusted in order not to exceed G1 limitations



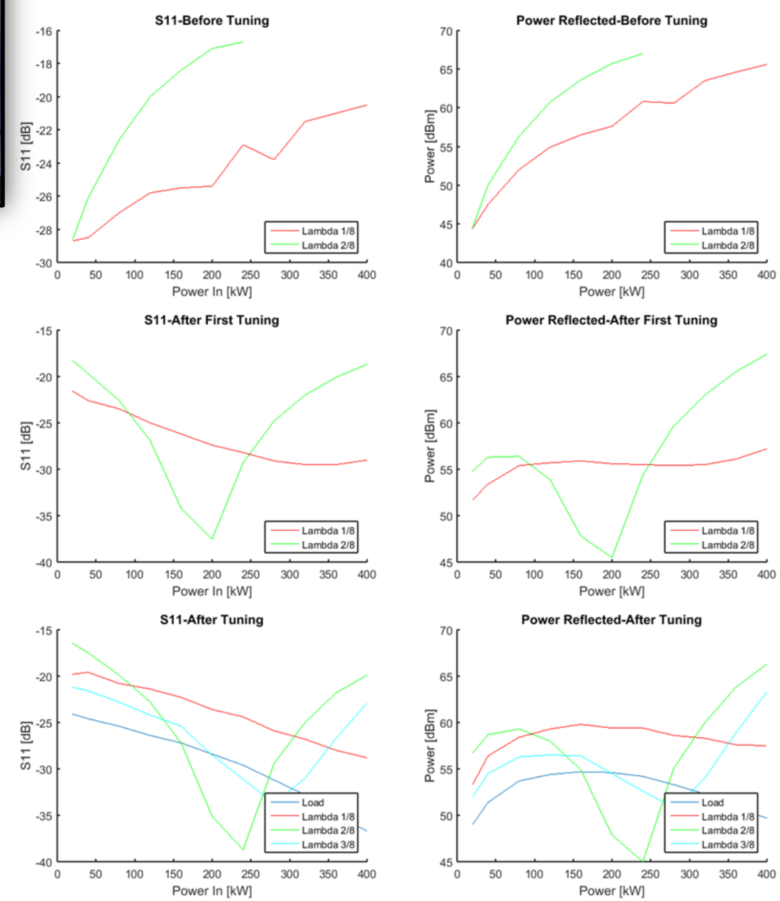

**HPA1**

| Station P. Out [kW] | 0 | 40 | 80 | 120 | 160 | 200 | 240 | 280 | 320 | 360 | 400 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| I_anode [I] | | 4,93 | 6,98 | 8,66 | 10,1 | 11,35 | 12,55 | 13,47 | 14,52 | 15,87 | 17,46 |
| V_anode [kV] | | 16,3 | 16,28 | 16,33 | 16,33 | 16,38 | 16,38 | 16,43 | 16,43 | 16,45 | 16,5 |
| | | | | | | | | | | | |
| Filament Current [I] | | 182 | 182 | 182 | 182 | 182 | 181 | 181 | 181 | 180 | 180 |
| Filament Voltage [V] | | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| | | | | | | | | | | | |
| G1 Current [I] | | 0 | 0,03 | 0,15 | 0,32 | 0,47 | 0,63 | 0,73 | 0,89 | 1,13 | 1,52 |
| G1 Voltage [V] | | -216 | -216 | -217 | -217 | -218 | -219 | -219 | -220 | -221 | -222 |
| | | | | | | | | | | | |
| G2 Current [I] | | 0,023 | 0,03 | 0,072 | 0,08 | 0,096 | 0,117 | 0,14 | 0,175 | 0,24 | 0,357 |
| G2 Voltage [V] | | 899 | 902 | 910 | 924 | 929 | 934 | 935 | 938 | 942 | 947 |

# Circulators




- Thermal Detuning
- Thermal Oscillations



# Reflections

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## "Back of The Envelope" Tube Behavior During Reflections

- -20dB Reflections from circulator
- Unknown Phase
- Effect on Anode Voltage Swing?
- Nominal Anode Impedance 440 Ohm
- Anode Voltage 16kV

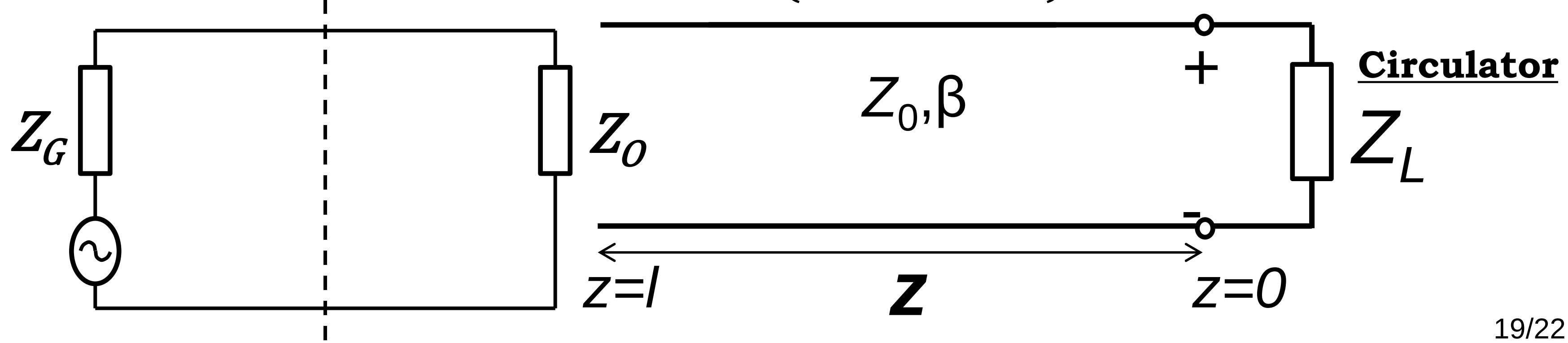
| Gamma | Angle | $R_O$ | $X_O$ | | $V_{A,RF}$ |
|---|---|---|---|---|---|
| 0 | 0 | 440 | 0 | | 13.3kV |
| 0,091 | 0 | 528 | 0 | | 14.5kV |
| 0,091 | 90 | 433 | -79 | | 13.4kV |
| 0,091 | 180 | 367 | 0 | | 12.1kV |
| 0,091 | 270 | 433 | 79 | | 13.4kV |

**High Anode Dissipation**

- **Close to G2!**
- **$V_{peak}$=30.5kV**
- **Affect η/Gain**

$$\boldsymbol{Z_O} = Z_0 \frac{(1+\Gamma e^{-j\alpha})}{(1-\Gamma e^{-j\alpha})}$$

**Tetrode/Cavity**



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# 400kW Load-Pull

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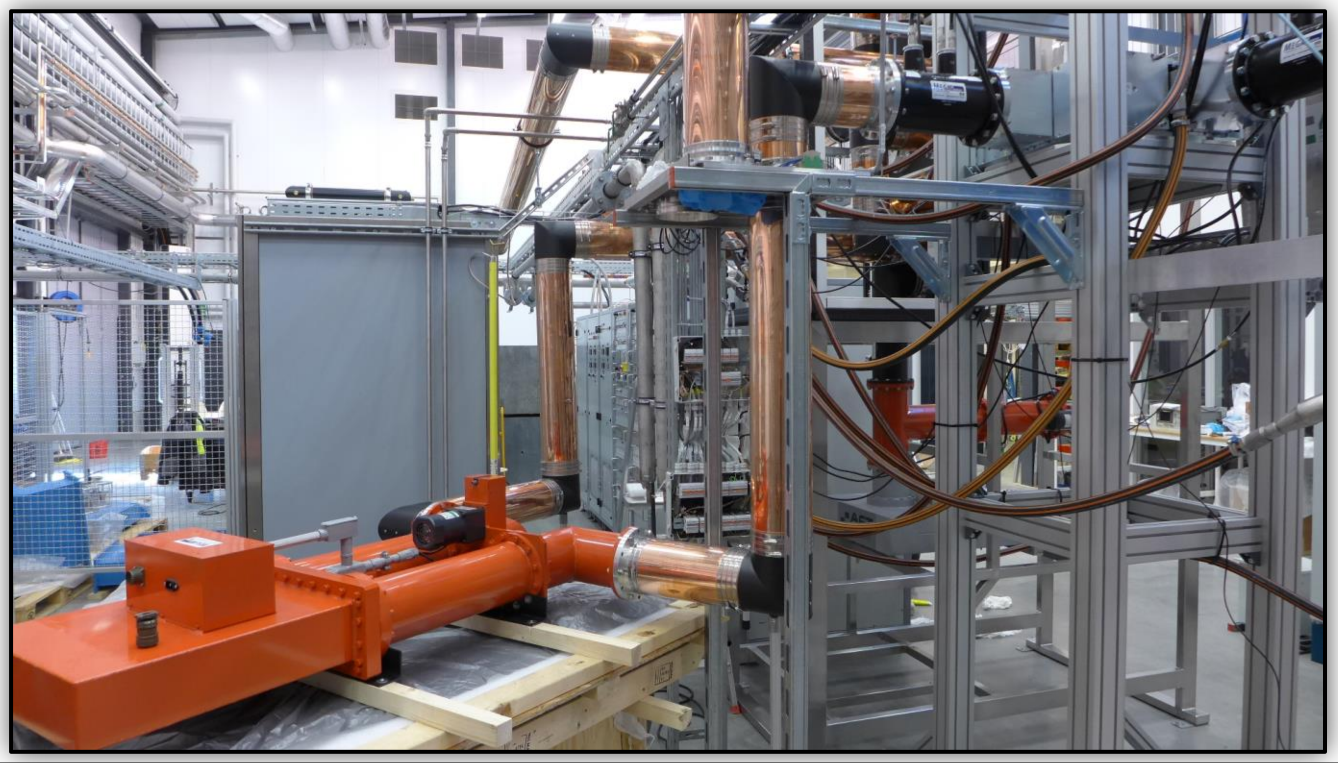
- Even with circulators loading effects must be considered
- Thermal and non-linear effects makes measurements an absolute must
- Using a 6-1/8” variable load setup allows for system evaluation and improvements



# Solid-State RF

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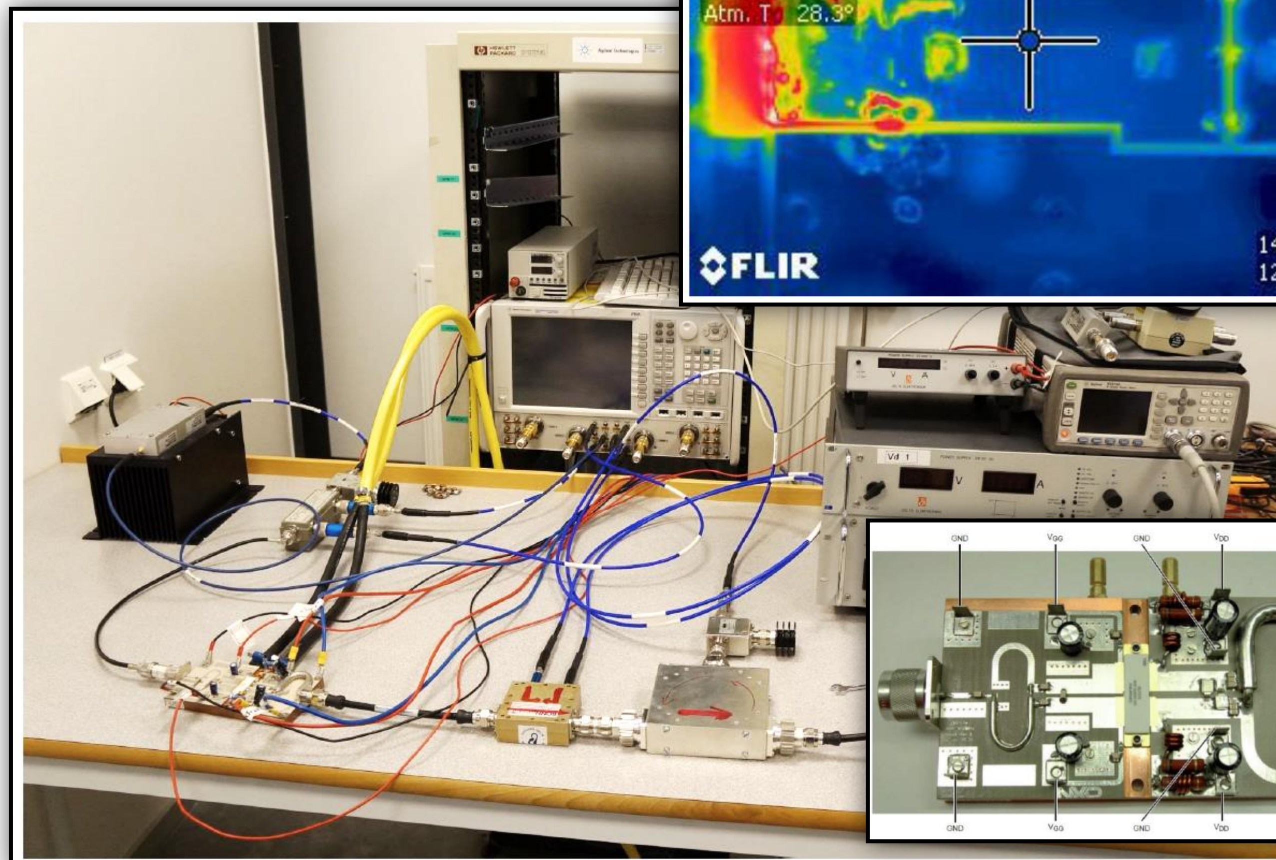
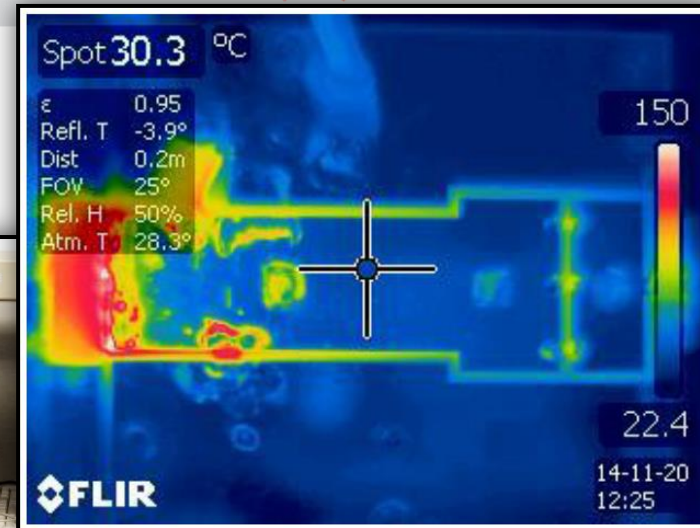
- Work is being done in development of higher power solid state amplifiers

- 1.25 kW Modules
- 352.21 MHz
- Water Cooled
- High Efficiency

- Custom Combiners





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# Conclusions

- First RF station commissioned and in operation at FREIA
- Second RF station currently undergoing on-site acceptance test
- Performance measurement and development of sub-components undergoing
- Performance measurements of station in full RF line undergoing and developed to enhance performance

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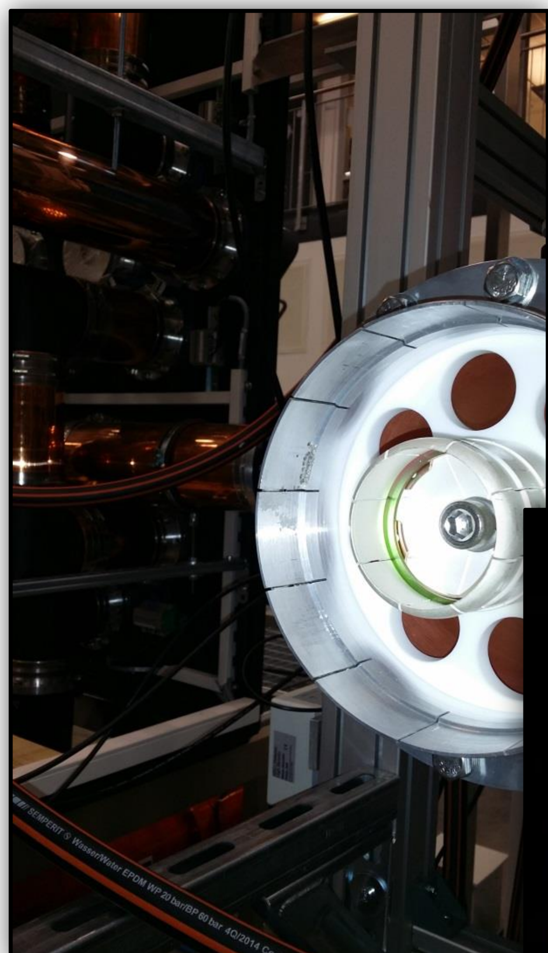
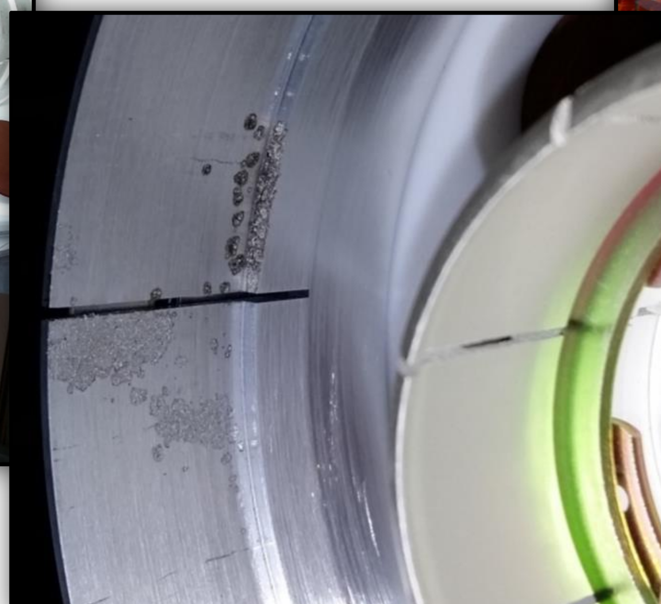
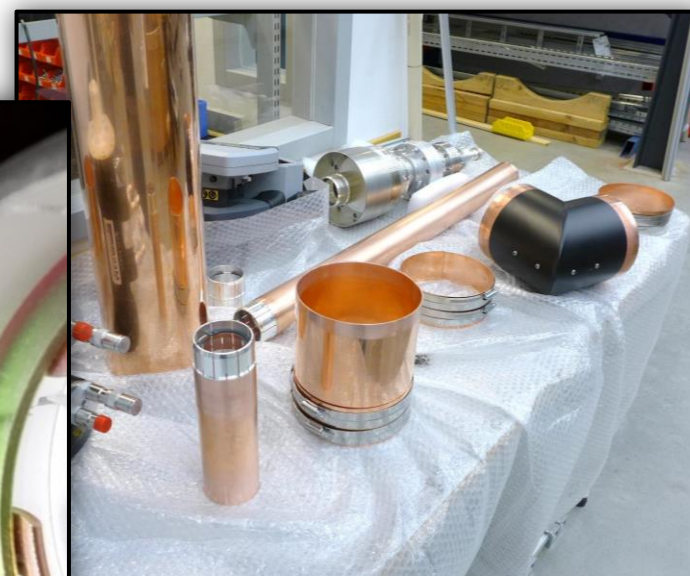
# High Power Arcing

- Arcing in transmission lines and flanges
- Arc-Detectors required at multiple locations
- Some arcing is not easily detectable!
- High reflections must be accounted for





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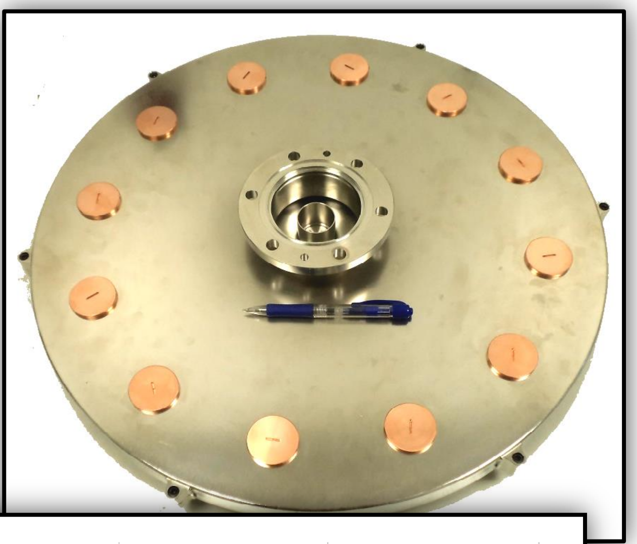
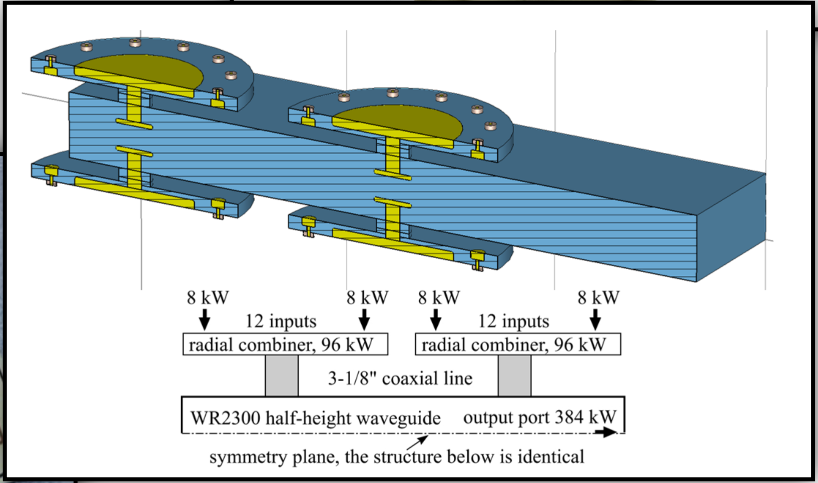
# Solid-State RF

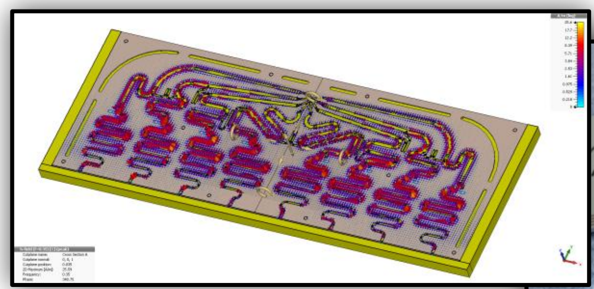
- SSA power combining technology

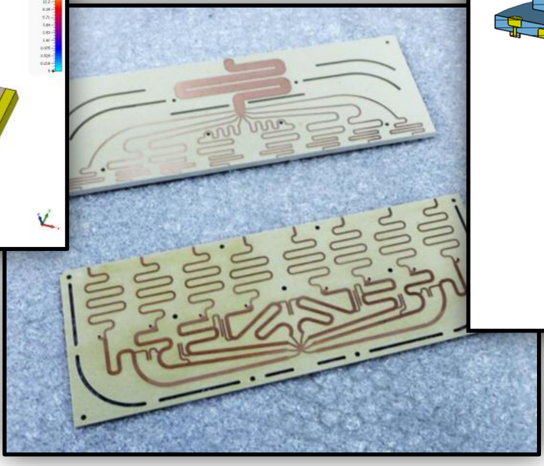
- **Step 1)** 1 kW → 8 kW
- **Step 2)** 8 kW → 96 kW
- **Step 3)** 96 kW → 384 kW

- Low-loss designs are critical







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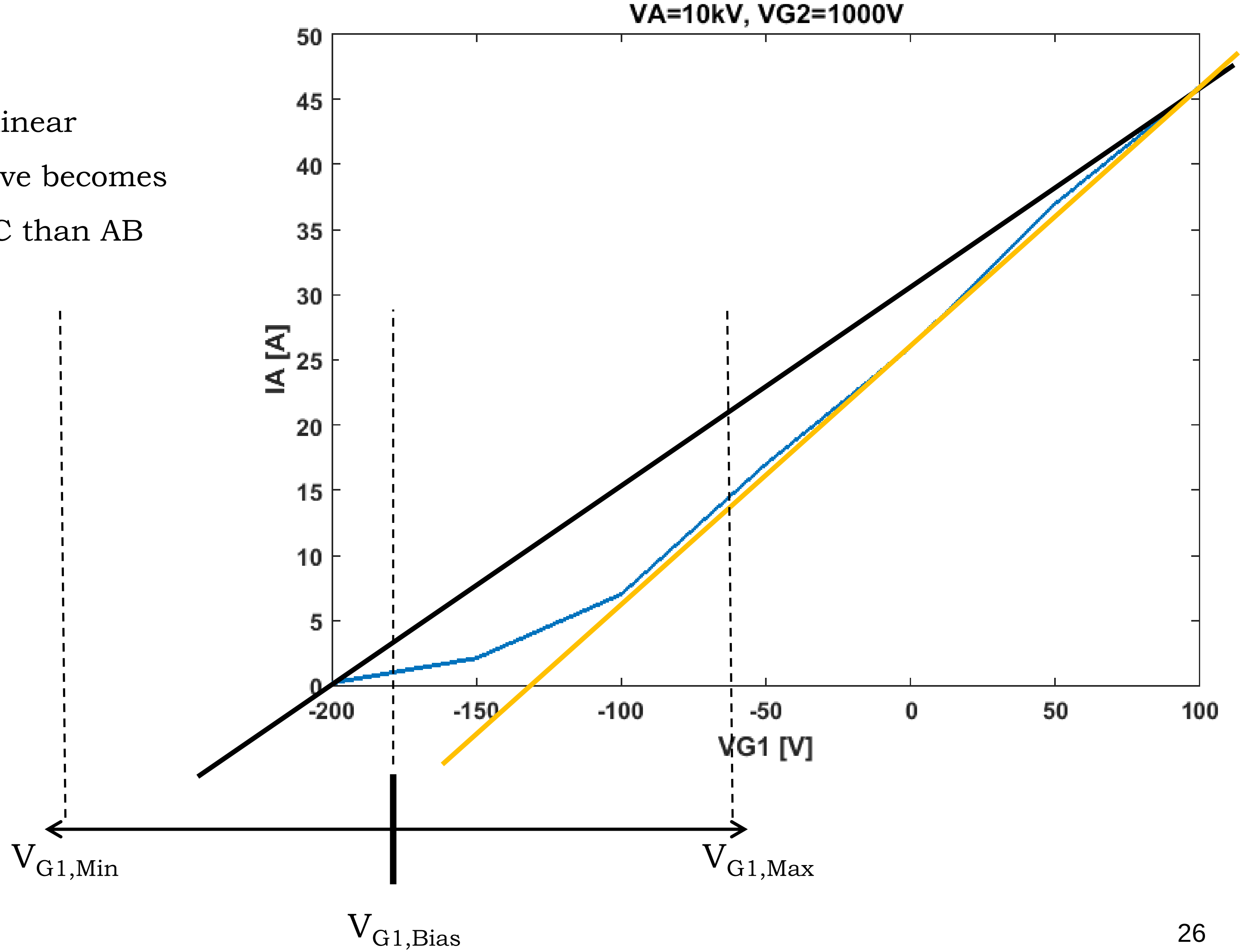
# Why Class C?

- Tube is not linear
- Effective curve becomes more Class C than AB



# TH595 Simulated Load Reflection

| Frequency MHz | Forward Power Kw | Load Power Kw | VSWR: 1,2 phase°[Y] | DC Anode Voltage Kv | Anode residual Voltage KV | Screen grid voltage V | DC IG2 current | DC Anode current A | Peak anode current | Dissipated anode power Kw | Tube Efficiency | Input Power KW | Nominal anode impedance | R e load impedance | JX load impedance | MAX G2 Power Density W/cm2 | Total G2 RF losses W | Total G2 dissipation (G1 si triode) | Peak cathode current density A/cm2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 352 | 202 | 200 | 0 | 16,0 | 1,8 | 900 | 0,48 | 16,8 | 57,5 | 3,2 | 74,26% | 4,97 | 440,0 | 528,0 | 0,0 | 18,7 | 594,9 | 614,8 | 0,98 |
| 352 | 202 | 200 | 45 | 16,0 | 2,2 | 900 | 0,37 | 17,4 | 59,4 | 3,6 | 71,98% | 5,20 | 440,0 | 496,0 | 64,3 | 17,9 | 568,3 | 583,6 | 0,99 |
| 352 | 202 | 200 | 90 | 16,0 | 3,0 | 900 | 0,22 | 18,6 | 63,6 | 4,5 | 67,24% | 5,76 | 440,0 | 432,8 | 79,3 | 15,8 | 504,0 | 513,1 | 1,04 |
| 352 | 202 | 200 | 135 | 16,0 | 3,9 | 900 | 0,15 | 19,7 | 67,5 | 5,3 | 63,32% | 6,32 | 440,0 | 383,8 | 49,8 | 13,8 | 439,8 | 446,0 | 1,09 |
| 352 | 202 | 200 | 180 | 16,0 | 4,3 | 900 | 0,13 | 20,2 | 69,0 | 5,7 | 61,89% | 6,57 | 440,0 | 366,7 | 0,0 | 12,9 | 413,1 | 418,5 | 1,11 |
| 352 | 202 | 200 | 225 | 16,0 | 3,9 | 900 | 0,15 | 19,7 | 67,5 | 5,3 | 63,32% | 6,32 | 440,0 | 383,8 | -49,8 | 13,8 | 439,8 | 446,0 | 1,09 |
| 352 | 202 | 200 | 270 | 16,0 | 3,0 | 900 | 0,22 | 18,6 | 63,6 | 4,5 | 67,24% | 5,76 | 440,0 | 432,8 | -79,3 | 15,8 | 504,0 | 513,1 | 1,04 |
| 352 | 202 | 200 | 315 | 16,0 | 2,2 | 900 | 0,37 | 17,4 | 59,4 | 3,6 | 71,98% | 5,20 | 440,0 | 496,0 | -64,3 | 17,9 | 568,3 | 583,6 | 0,99 |
| **Phase rotation with constant anode voltage** | | | | | | | | | **TH 595 ESS** | | | | | | | | | | |