

# The ELBE RF-System based on Solid State Power Amplifiers

## Status and 2-years of operation

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for

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# TOPICS

- 1: Short Remarks on ELBE
- 2: ELBE RF System
- 3: 10kW @ 1300MHz SSPA
- 4: 20kW With Two Combined SSPA
- 5: Two Years Experience With SSPAs
- 6: Work in Progress

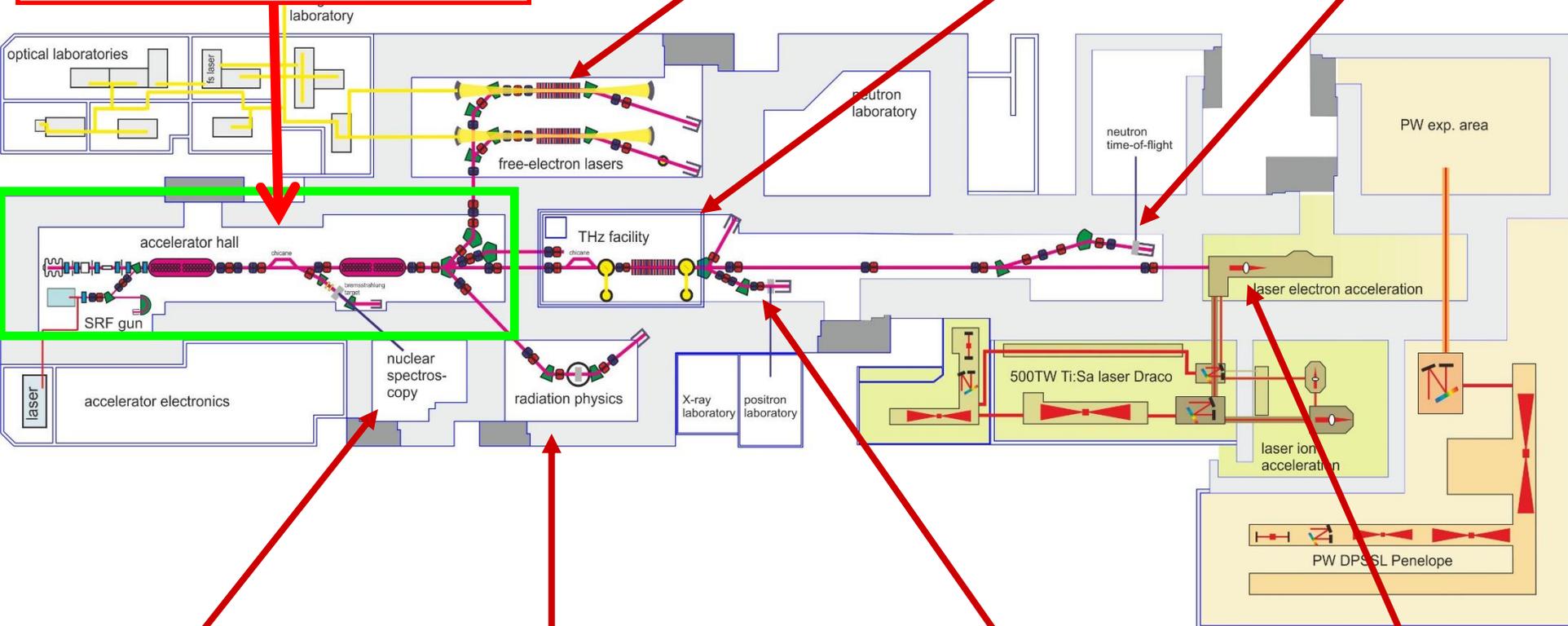
# ELBE LK2 UPGRADE - USER FACILITY

**40 MeV 1.6 mA CW  
SC Electron Linac  
(from 40MeV, 0.8mA)**

**Coherent IR-radiation  
3 – 230  $\mu\text{m}$**

**THz radiation  
100  $\mu\text{m}$  – 3 mm**

**Neutrons**



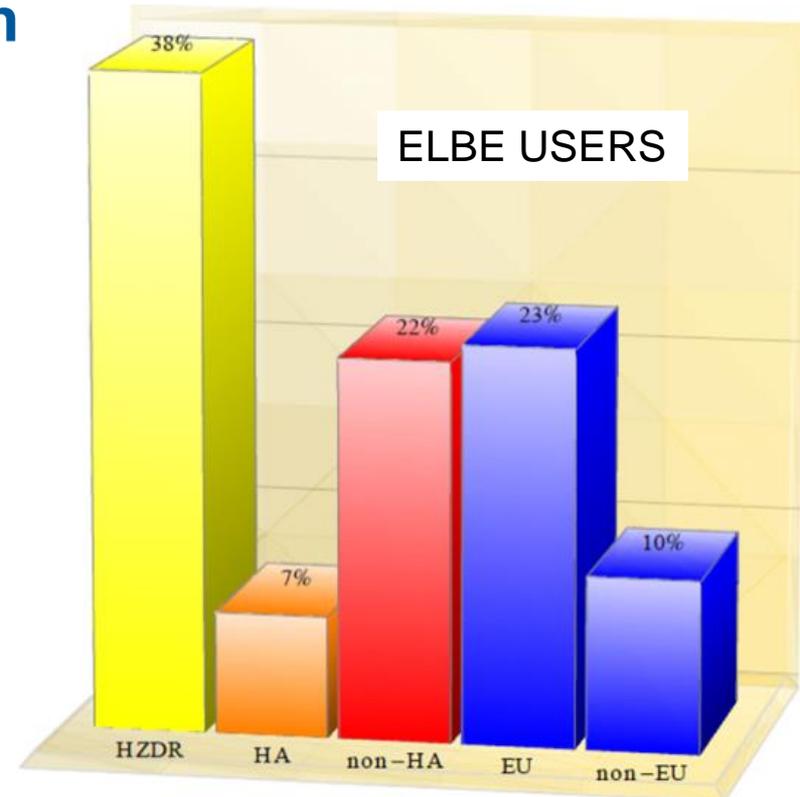
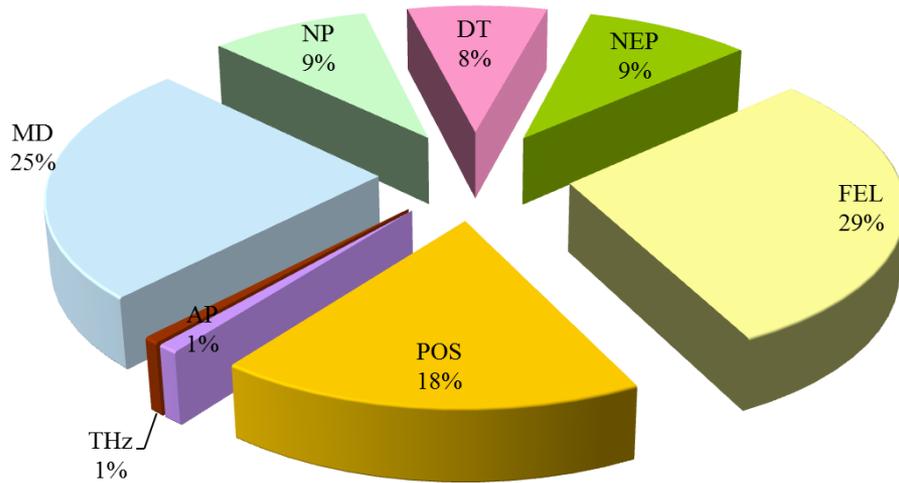
**Bremsstrahlung  
0 – 17 MeV**

**Monochromatic X-rays  
30 – 34 MeV/10 – 100 keV**

**Pulsed, Mono-Energetic  
Positrons 0.2 – 30 keV**

**Electron-Laser  
Interaction**

# Annual Beam Time ~ 6000 h (Example 2013)



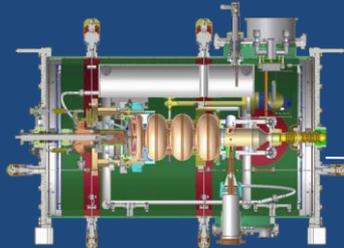
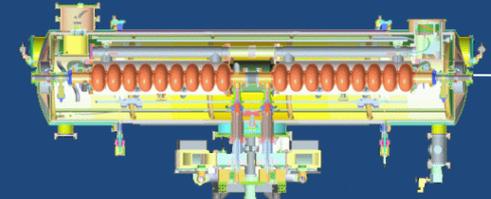
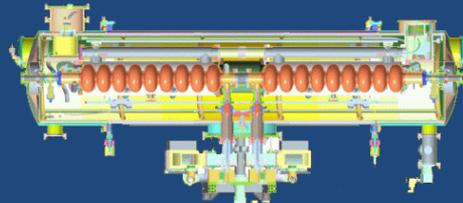
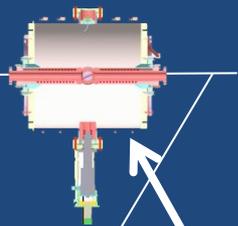
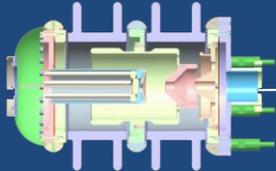
- ELBE (Electron and Laser Beam Center) provides a variety of secondary beams for many research fields
- due to the superconducting accelerator technology all sources can be operated in a high average power continuous wave (CW) mode
- radiation pulses are short (ps to sub ps), with flexible temporal structure (single pulse – CW) and can be synchronized to external lasers

Thermionic  
DC Gun  
250 kV  
 $\leq 260$  MHz  
125pC  
(1.6mA\*13MHz)  
 $\sim 500$ ps  
 $\sim 10$  mm mrad

RF Bunchers  
260 MHz  
+1,3GHz  
compr.  $\sim 100:1$

Linac  
1,3 GHz  
 $\sim 20$ MeV@10 MeV/m  
 $< 1.6$  mA CW

Linac  
1,3 GHz  
 $\sim 20$  MeV@10MV/m  
 $< 1.6$  mA CW



SRF photo gun

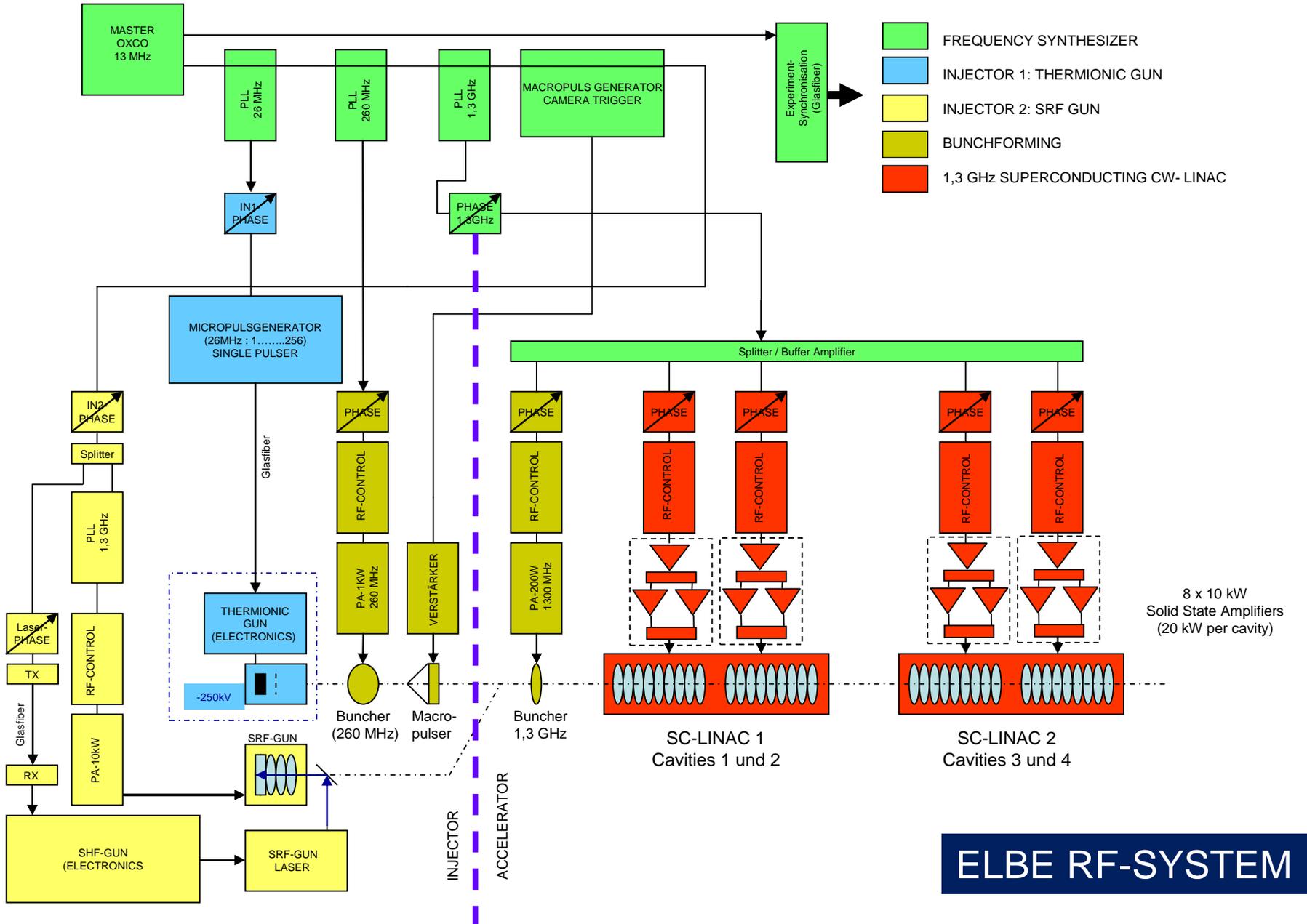
9.5 MeV  
 $\leq 13$  MHz  
77pC / 1nC /  
 $\sim 3-15$  ps (FWHM)  
 $\sim 1-2.5$   $\pi$  mm mrad

1 x 10kW SSPA

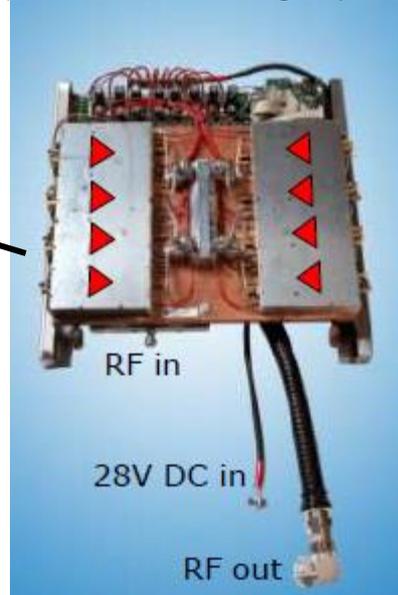
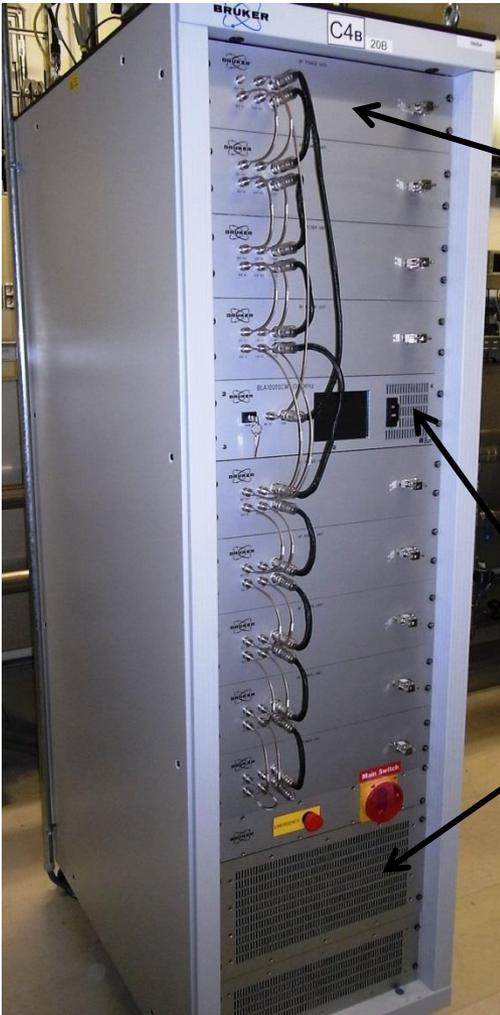
260 MHz: 1 kW SSPA  
1300MHz: 200 W SSPA

4 x 20 kW CW  
(8 x 10 kW SSPA)

## ELBE RF-REQUIREMENT

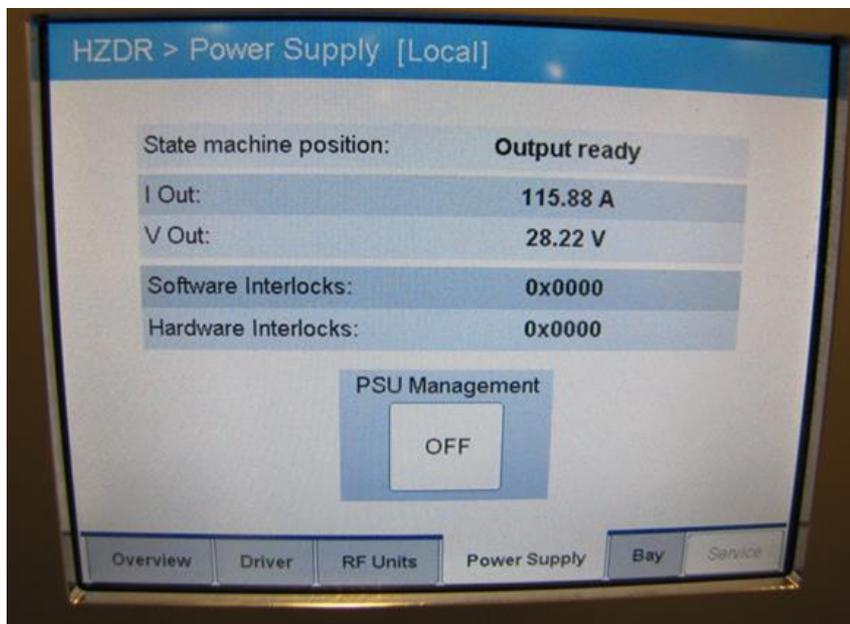
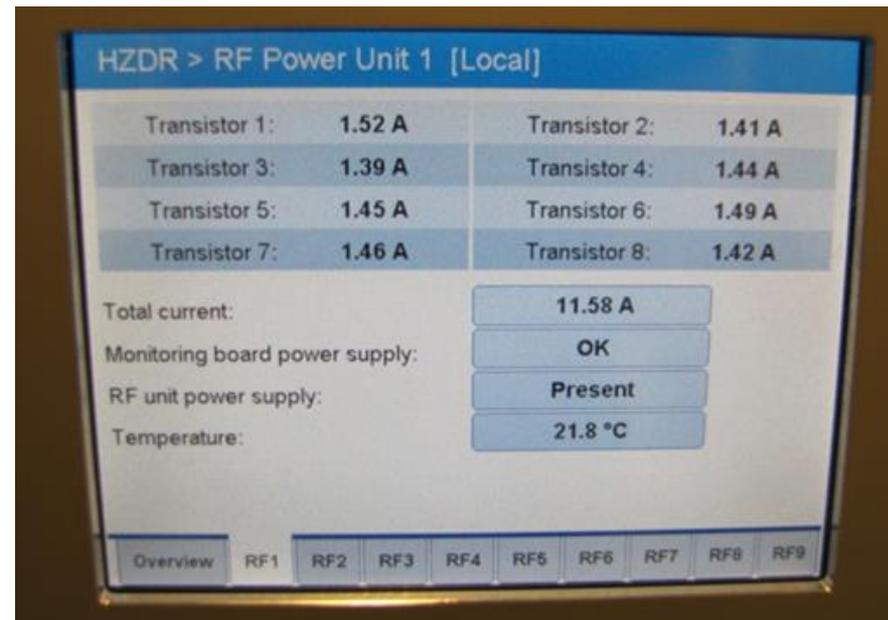
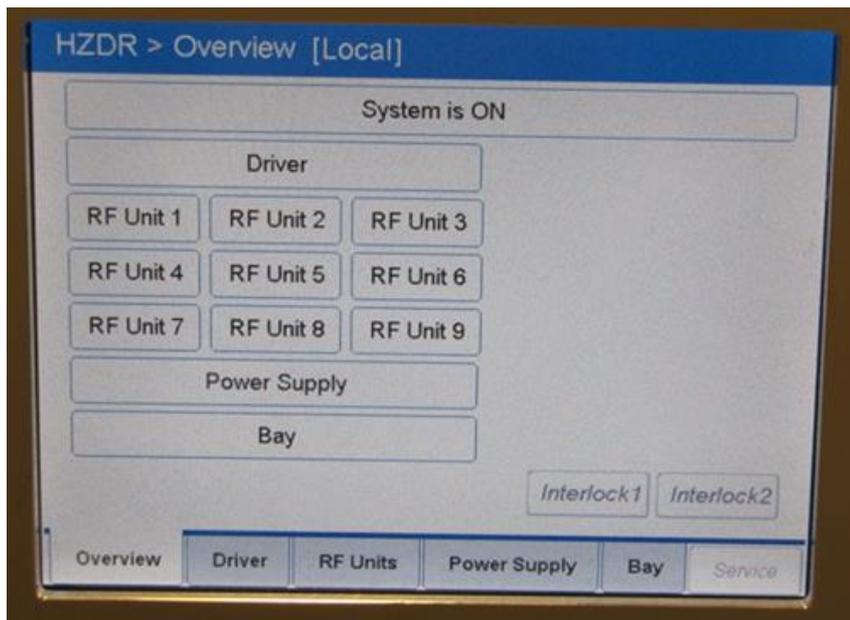


# ELBE RF-SYSTEM



- 9-power modules with 8 Transistors PTF141501E
- 1 kW Driver + Controller,  $P_{out} = 60 \text{ dBm}$  at  $P_{in} = 0 \text{ dBm}$
- Inbuilt 28V 800A SMPS
  
- Safety:
- CAN Bus interlock (Internal IP)
- Control:
- -local (display controlled) or by
- -external status signals (customer solution)
- Monitoring via Internet (IP)

10 kW@1300MHz SSPA



Vacuum Beam Ctrl. MIS PSS Cool.S. Media IN1 → Beam on >FL1 Pic.1 Beam\_Ctrl\_Linac1 close  
 Accel IN1 IN2 BL LA1 NP BL LA2 RP FSL 1 2 BL THz/PP Neut.BL LP Diagnostic Mode Pic.2 Beam\_Ctrl\_Linac2 open

Failure Close Gate: On Off Pulse Gen: On Off PGM MacroPulse CW Mode MP Mode P. Period 200 ms P. Duration 0.2 ms Beamloss Res Light Vacuum Coolant

Beam Control - Linac1 (Release: 12.01.2012)

RTM HF LA1 68913 h

SSPA LA1 - RC.01 Coolant SSSPA Interlock SSSPA Ready MBox Ready Reset ON OFF

SSPA LA1 - RC.11 Coolant SSSPA Interlock SSSPA Ready MBox Ready Reset ON OFF

Phase LA1-RC.01 +0.2 ° WP 0V 1 2 3 4 5V

Gradient LA1-RC.01 9.500 MV/m WP -5V 0V +5V

Phase LA1-RC.11 +40.7 ° WP 0V 1 2 3 4 5V

Gradient LA1-RC.11 4.959 MV/m WP -5V 0V +5V

Phase Loop WP +0.013 V Range Monitoring Enable

9.337 MV/m Pause Ramp 700 kV/m/s RF On RF Off RF Pulse Mode

Phase Loop WP -0.008 V Range Monitoring Enable

4.871 MV/m Pause Ramp 600 kV/m/s RF On RF Off RF Pulse Mode

System Phase Shift +0.2 ° Loop Phase Shift +22.6 °

PH 9103 W PR 1796 W Reset Power Meas. Averaging

System Phase Shift +40.7 ° Loop Phase Shift -8.4 °

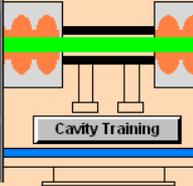
PH 9120 W PR 2604 W Reset Power Meas. Averaging

Phase loop fine tuning -0.3 % open loop ph. set +0.00 V

open loop Grad. set -1.87 V

Phase loop fine tuning +0.0 % open loop ph. set +0.00 V

open loop Grad. set -2.71 V



WG-Tuner RC.01 3 0 2 84 1 57

Tuning LA1-RC.01 11 Steps 999 Ready Frequency +4369

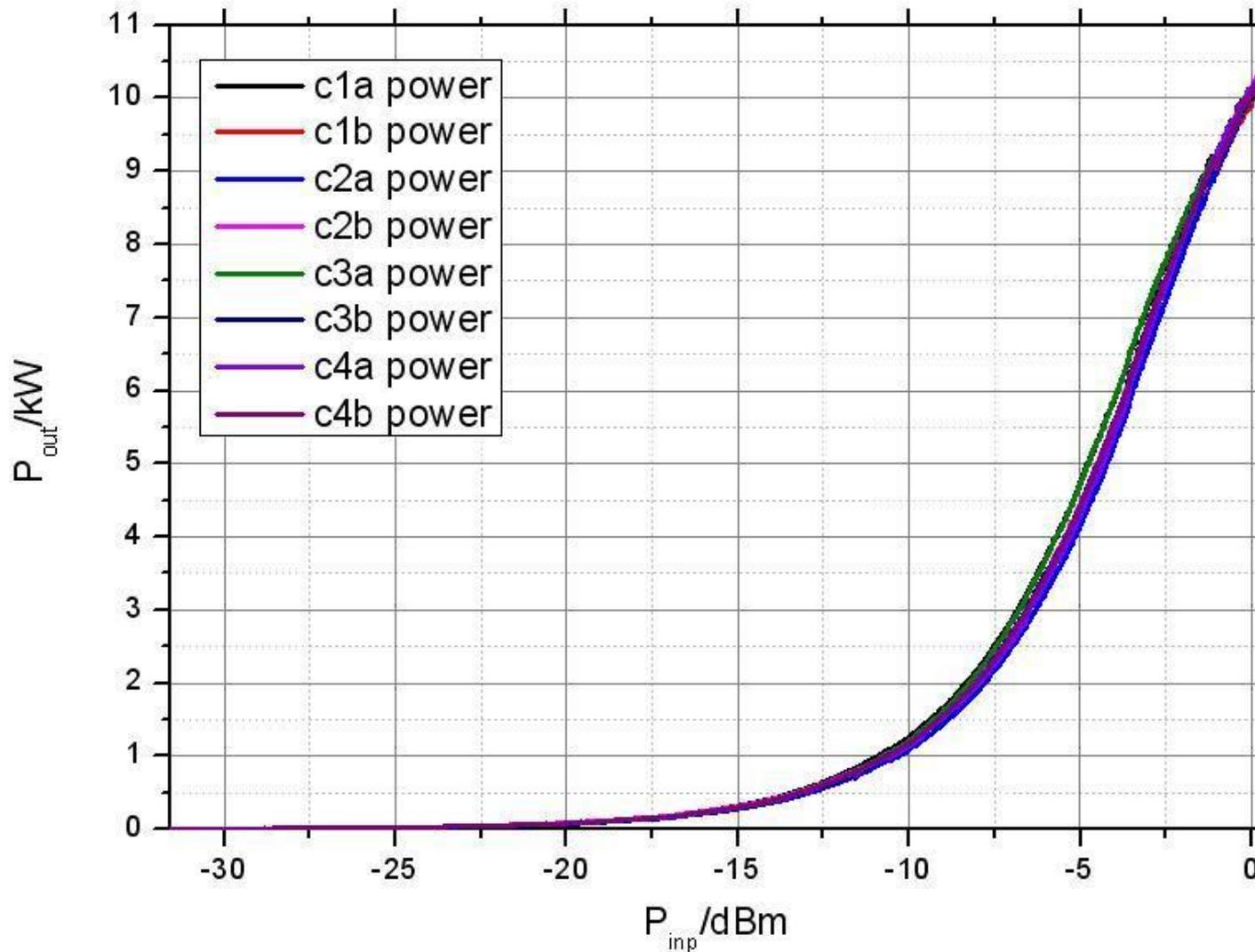
Tuning LA1-RC.11 10 Steps 999 Ready Frequency -16394

WG-Tuner RC.11 3 0 2 32 1 40

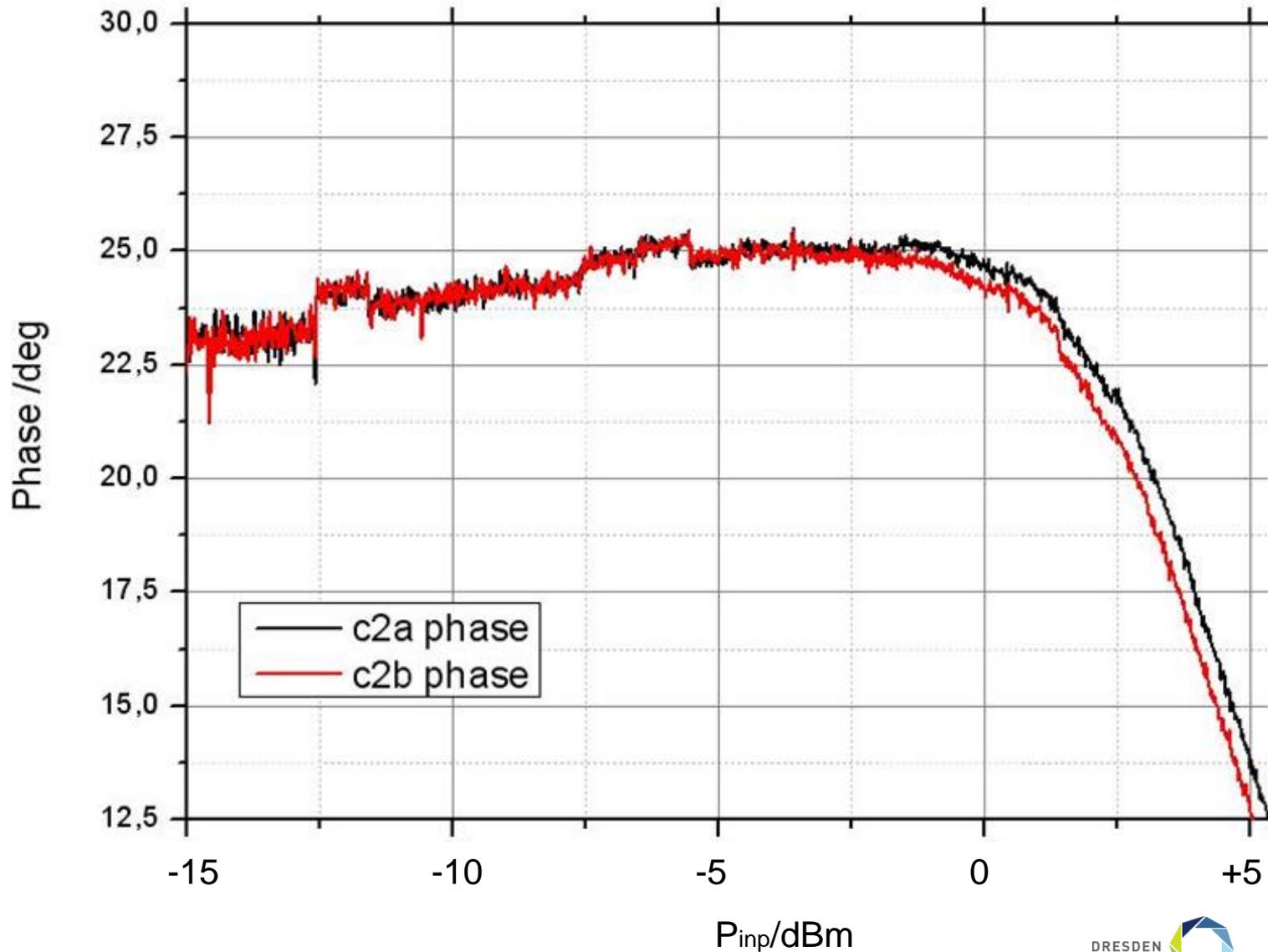
|   |                                |                                      |                                       |                        |
|---|--------------------------------|--------------------------------------|---------------------------------------|------------------------|
| W C1...4                                | 1 C Ug MG.01                   | 2 C [no assignment]                  | 3 C LA2-RC.01-Gradient                | 4 C LA2-RC.11-Gradient |
| Glob.Var. C Linde P14300 [mbar]: +31.01 | C Dosis DLM 7.B [mSv/h]: +7.16 | C I_Cathode IN1-MG.01 [µA]: +1600.24 | C Gate (Offset) IN1-MG.01 [V]: +34.77 |                        |
| Mem.Var. C +0.00                        | C +0.00                        | C +0.00                              | C +0.00                               |                        |
| CLR MV1...8 C +0.00                     | C +0.00                        | C +0.00                              | C +0.00                               |                        |

Data connection AK1 ok AK2 ok AK3 STF1 ok STF2 ok STF3 ok LKA ok DK1 ok DK2 Err. PSS1 ok PSS2 ok OPC ok GW MD GP GP2 IF OM VM LB BPM  
 ELBEWS2 E12: hentzu E15 E18: none E19: seidel E22: none E26: hentzu E31: none E47: none E48: hentzu E54: schurig

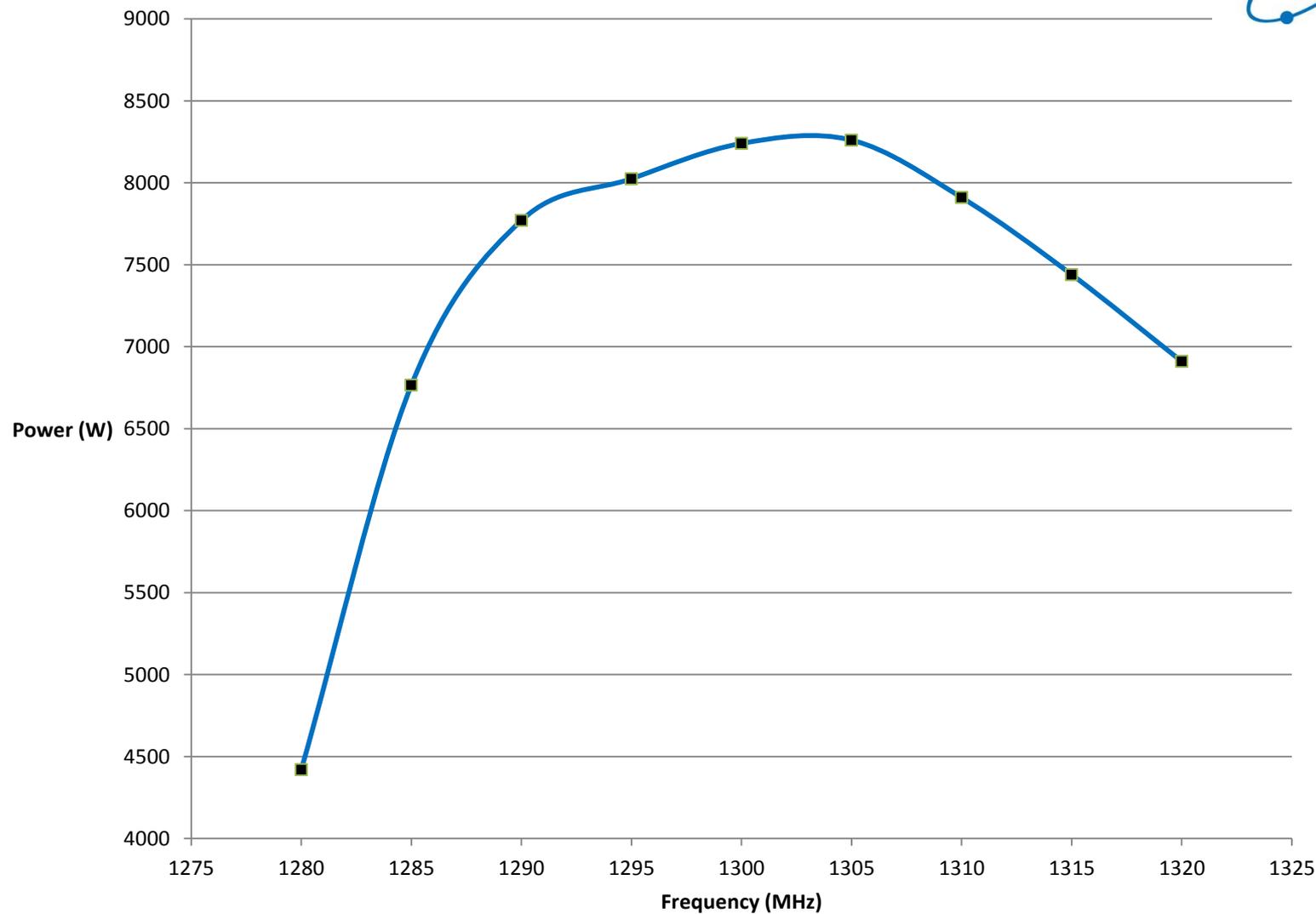
# S21 of all amplifiers used for the ELBE LINAC



# Phase response of the two SSPAs used for cavity C2



# Bandwidth (SSPA prototype)



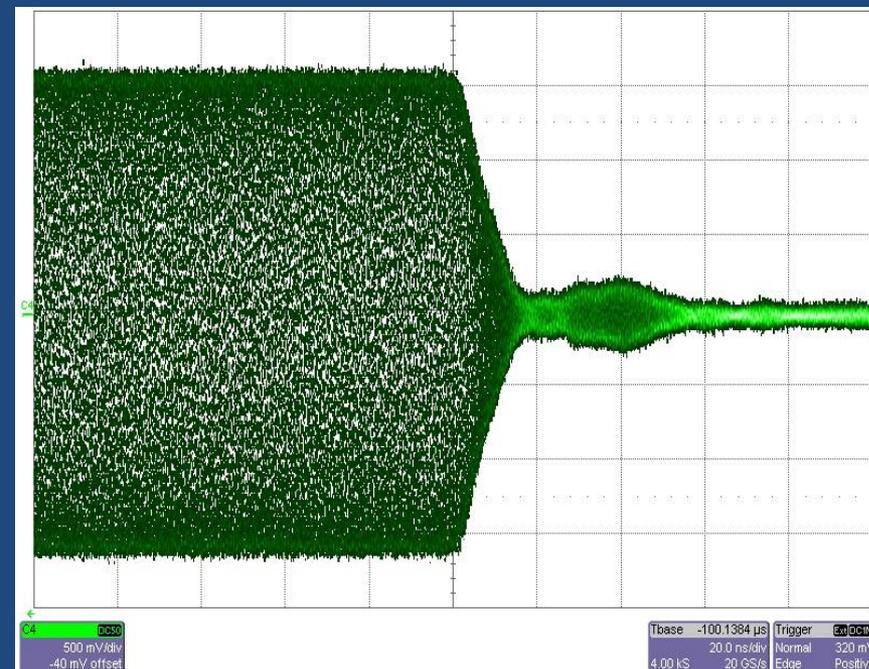
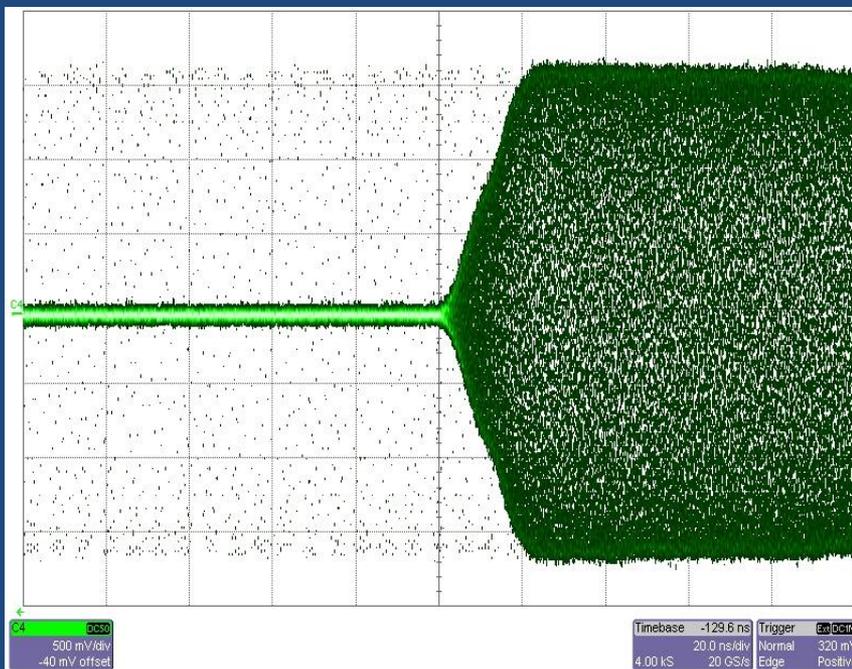
(Laurent.Martinache@Bruker.fr)



Member of the Helmholtz Association

Hartmut Buettig | Institut Radiation Physics FWKE (ELBE) | www.hzdr.de

# Pulse Response (SSPA Prototype)



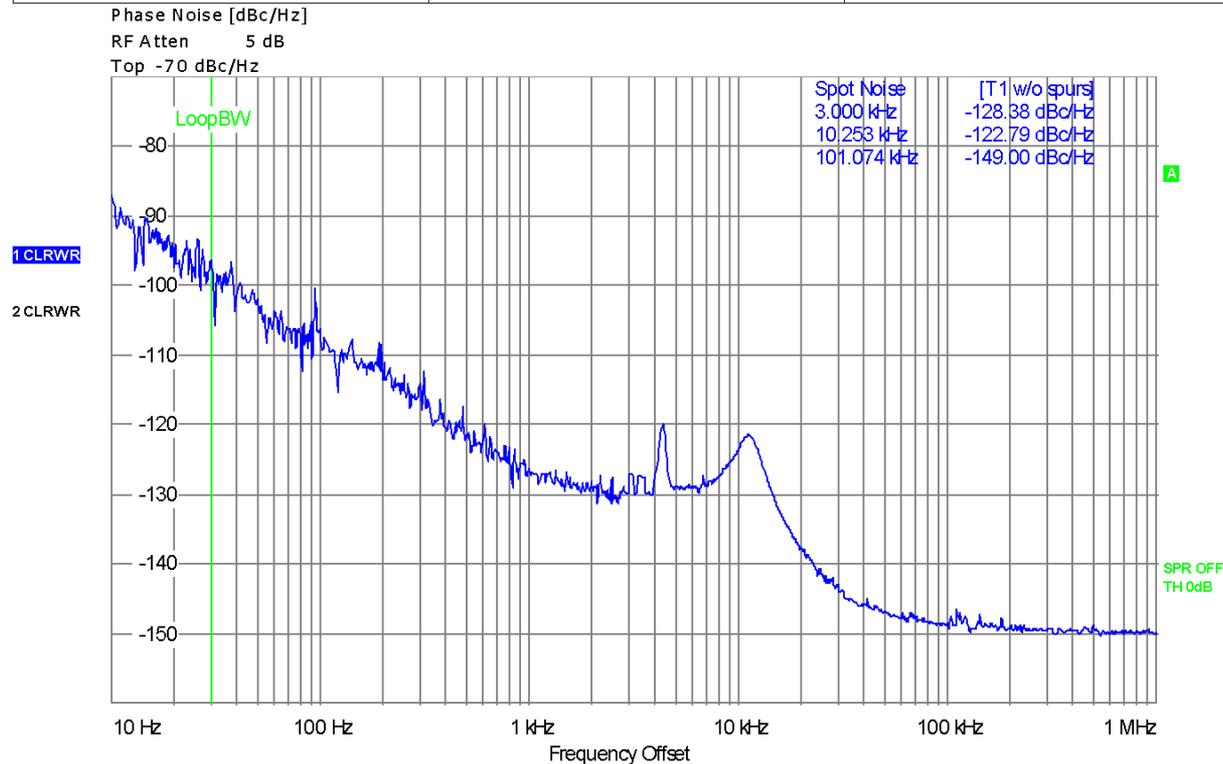
Measured at 8kW output power, rise time  $\approx 20\text{ns}$  fall time  $\approx 60\text{ns}$

(Laurent.Martinache@Bruker.fr)



# Phase Noise (RF-OUT of C3, P <sub>fwd</sub>)

| R&S FSUP 26 Signal Source Analyzer |                    | LOCKED                        |           |           |            |
|------------------------------------|--------------------|-------------------------------|-----------|-----------|------------|
| Settings                           |                    | Residual Noise [T1 w/o spurs] |           | Spur List |            |
| Signal Frequency:                  | 1.300000 GHz       | Int PHN (10.0 .. 1.0 M)       | -77.3 dBc | 30.326 Hz | -85.86 dBc |
| Signal Level:                      | -0.59 dBm          | Residual PM                   | 11.067 m° | 35.453 Hz | -89.04 dBc |
| Cross Corr Mode                    | Harmonic 1         | Residual FM                   | 26.735 Hz | 49.992 Hz | -86.89 dBc |
| Internal Ref Tuned                 | Internal Phase Det | RMS Jitter                    | 0.0236 ps | 70.909 Hz | -96.25 dBc |



Running ...

Tracking disabled, cannot follow DUT drift

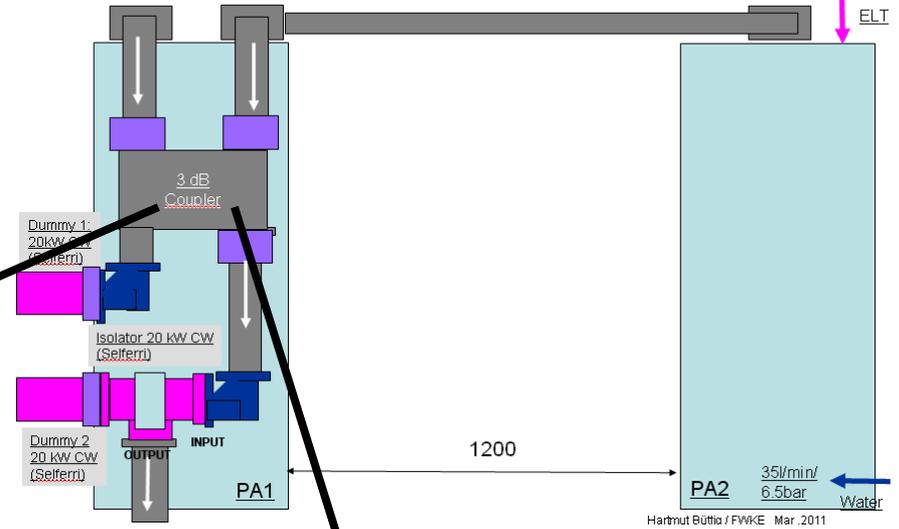
Date: 25.APR.2012 11:20:07

# TWO COMBINED SSPAs

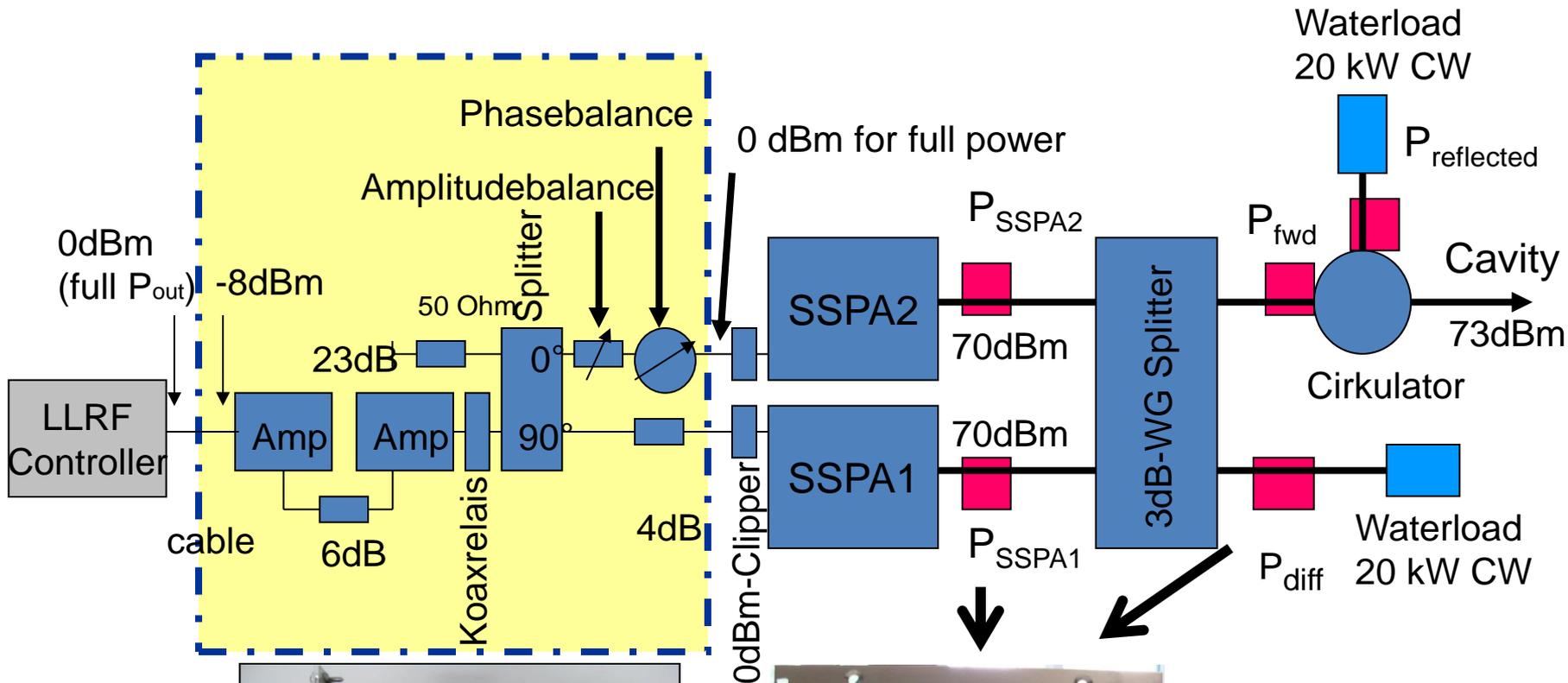


Assembly of two Solid State 10kW PAs

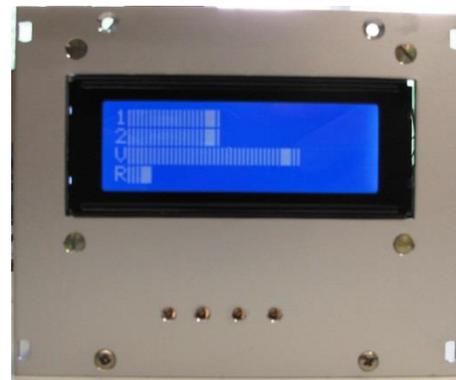
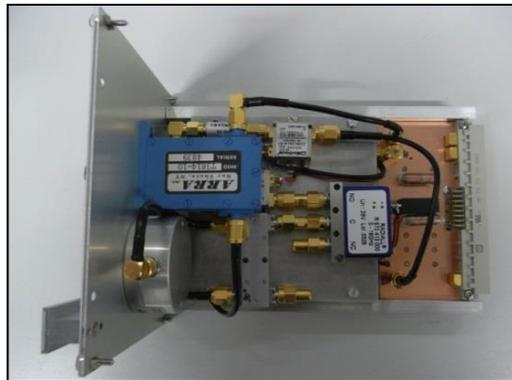
SIDEVIEW (PRINCIPLE)  
Cabinet R106 ELBE



# Balanced SSPAs based on 3dB Splitters

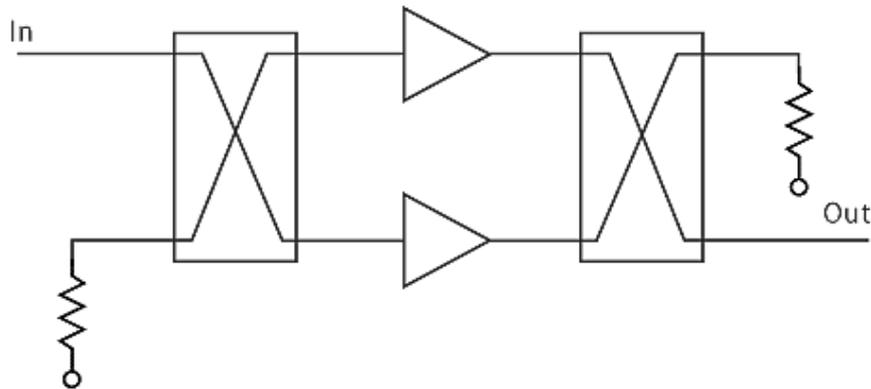


SSPA DRIVER / SPLITTER



Simple adjustment  
4 ch. powermeter  
(with ATMEGA 32)

## Test: LINAC Operation with one SSPA „switched-off“



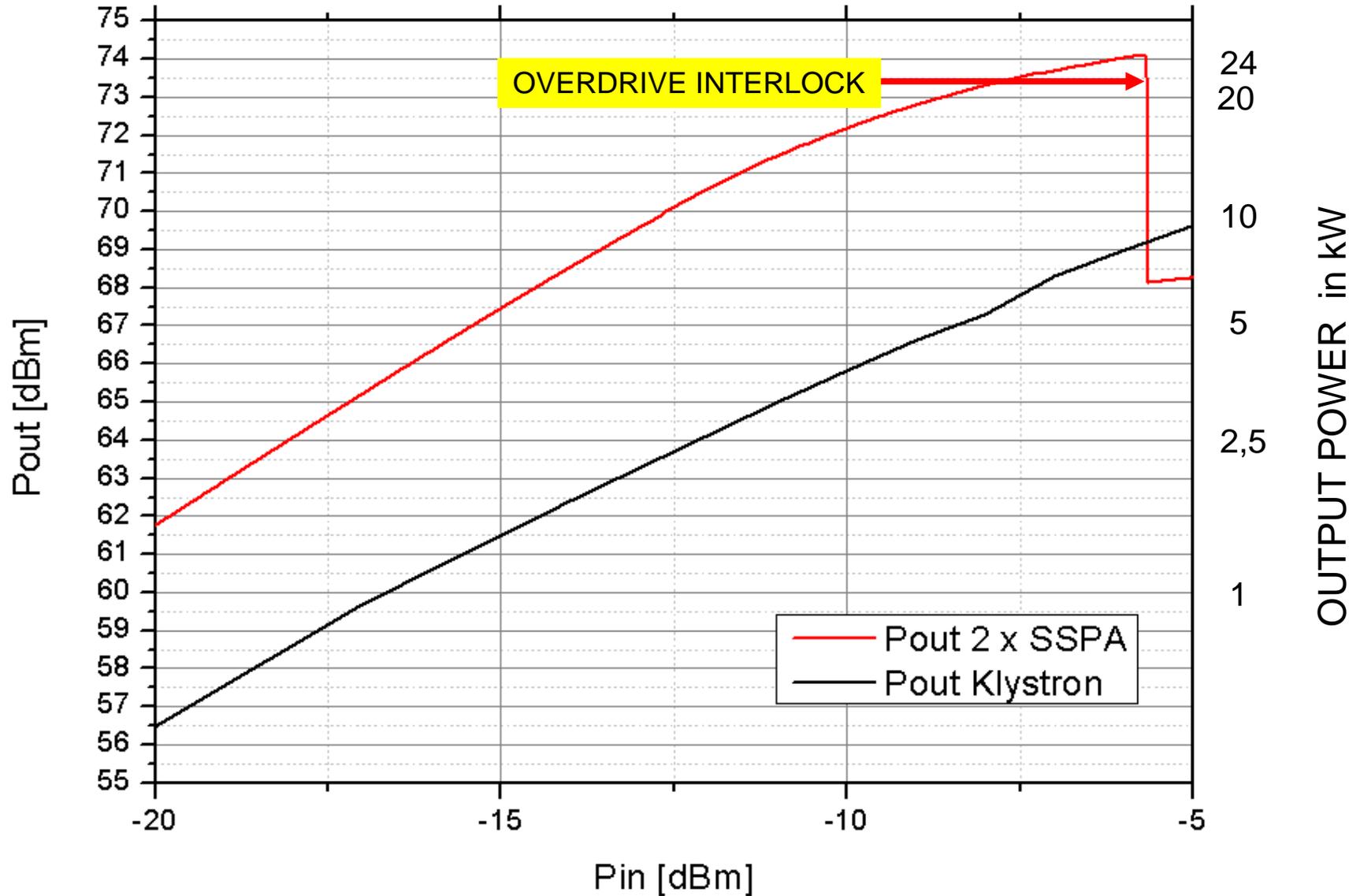
- If one SSPA fails one get -6dB power drop.
- It is possible to continue LINAC operation if  $\frac{1}{4}$ -th of the maximum available RF-power provide sufficient gradient in the cavity.
- First: Protect the unused SSPA output with a wave guide short (metal sheet)
- The 3dB higher drive power can easily deliver the LLRF system
- Use a „dummy connector“ to simulate the proper status signals of the unused SSPA to unblock the interlock.
- During the test we reallocated the gradients of the four cavities to keep the right beam energy.

# INPUT POWER

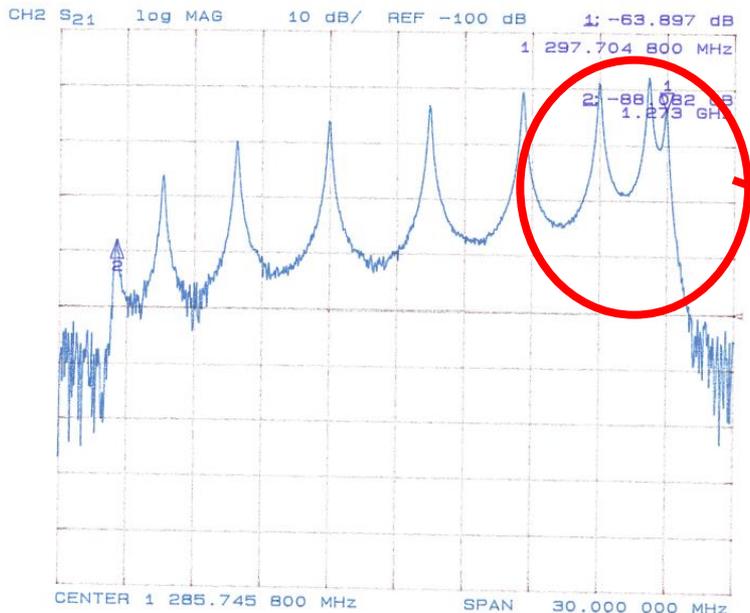
0,032mW

0,1mW

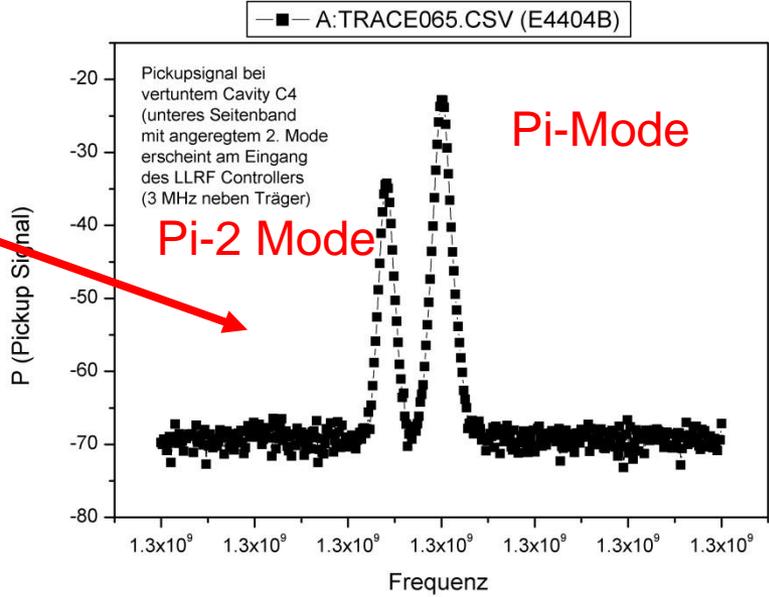
0,32mW



# Observation: Excitation Of Unwanted Cavity Modes



Passband of a 9-cell cavity

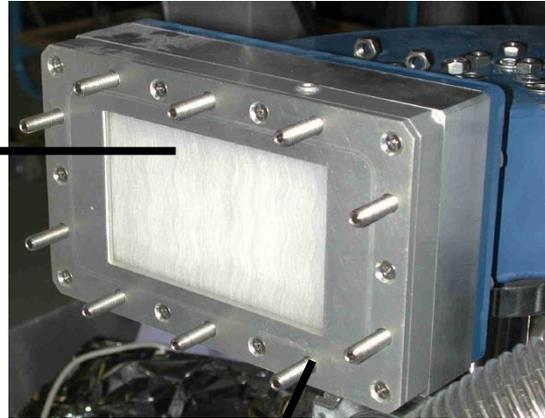
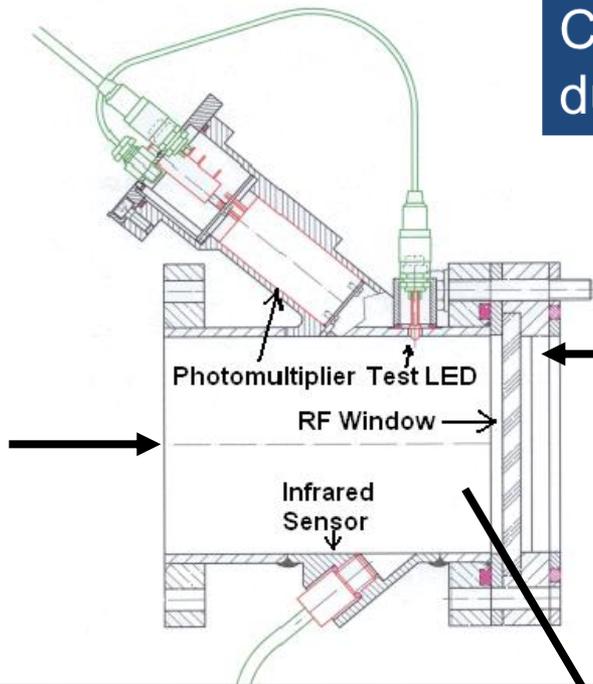


Pickup Signal at Cavity C4

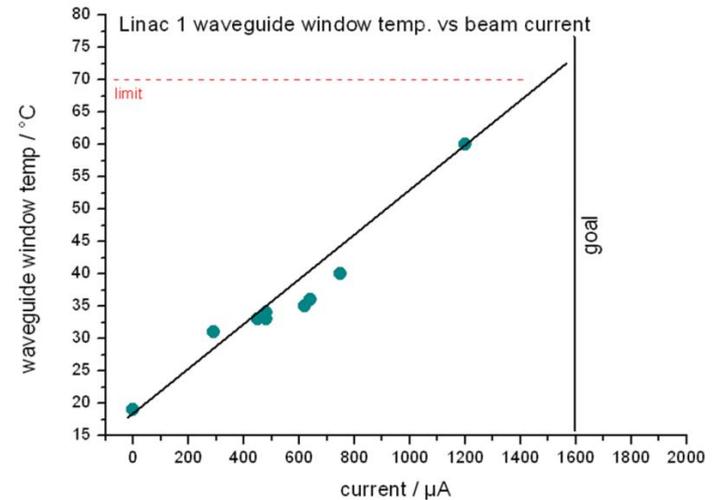
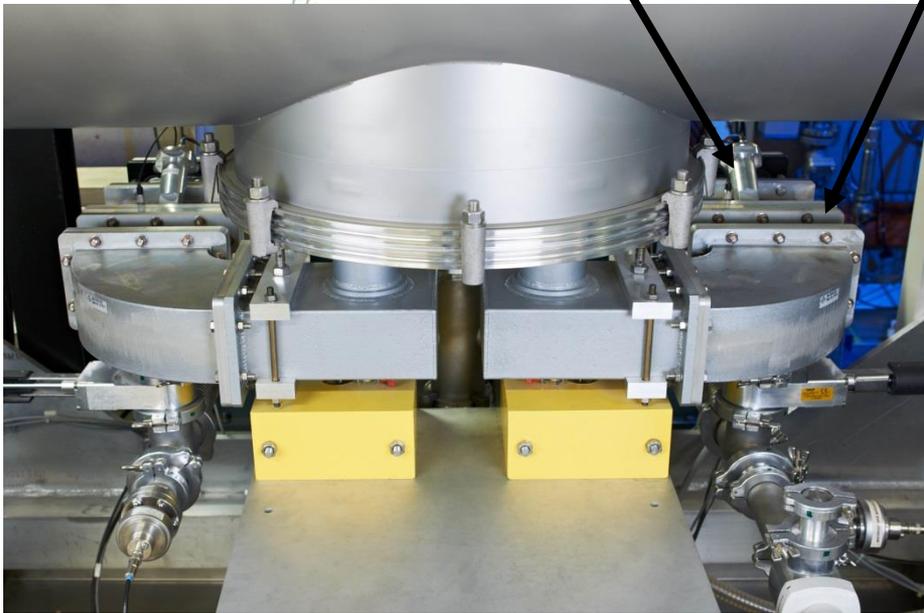
Due to a 10 times higher RF- bandwidth of the SSA at certain circumstances (e.g. detuned cavities, high loop gain) the LLRF controller locked not only on the Pi-mode but also on (Pi-1) or / and (Pi-2). The system became instable.



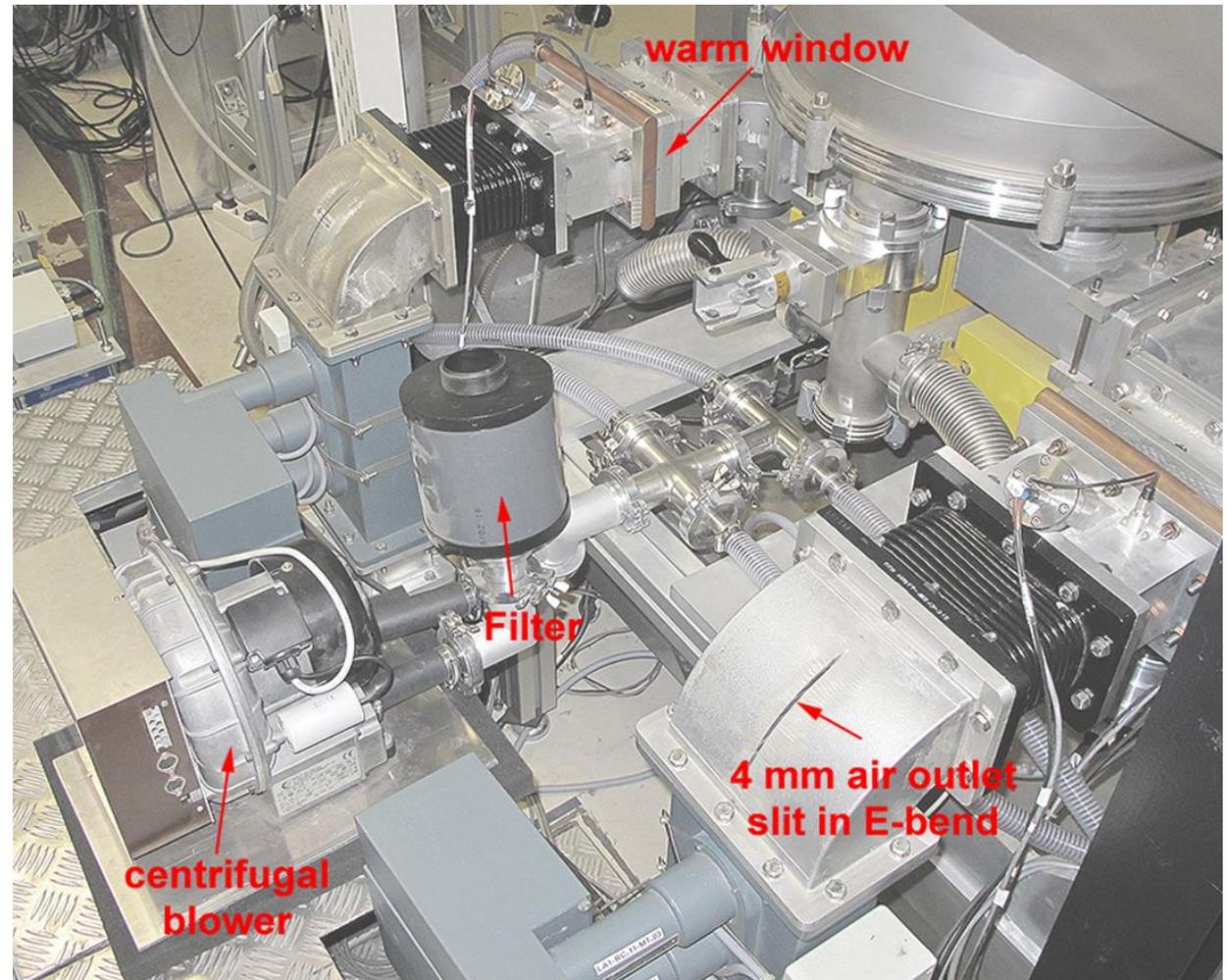
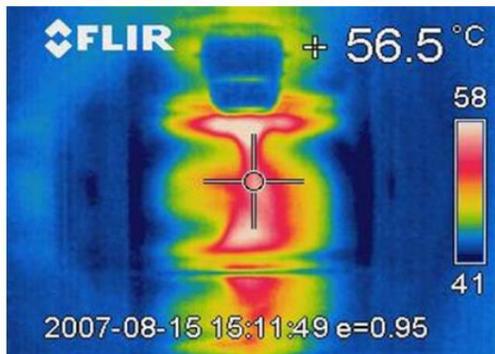
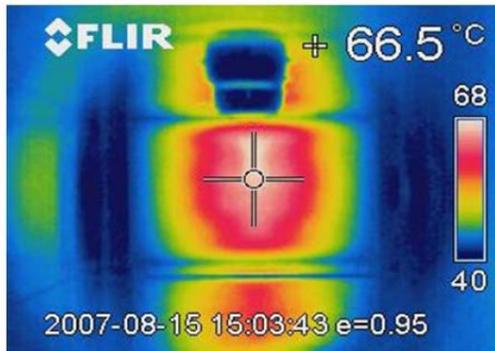
# Critical Temperature at ELBE Waveguide Window during high power operation



**Rexolite**  
 Cross linked Polystyrene  
 Tensile strength: 62 Mpa  
 Thermal conductivity 1.2 W/m x K  
 Diss. factor: 0.0002 @ 1 GHz  
 (4 W @ 20 kW)



# Air cooled waveguide windows (Rexolite) provide more safety



# SSPA FAILURES (Feb.2012 - April 2014)

| Year | Rack | Failure                               | Cause                                      | Repair                              |
|------|------|---------------------------------------|--|-------------------------------------|
| 2012 | C3A  | SMPS primary failed                   | Wrong machined insulator                   | Spare part, (1 hr.)                 |
| 2013 | C4B  | CAN Bus astable                       | Watersensor,<br>Wire not fixed             | Took a long time to fix the problem |
| 2013 | All  | Overdrive (at LLRF interlocks)        | Spikes caused by GaS switches at ELBE LLRF | Limiters added at all RF inputs     |
| 2014 | C4A  | High spurious sigs on RF caused by PS | Not really found                           | Spare part. (1hr)                   |

**LOST TRANSISTORS: 2012: 5 Transistors of 576 , 2013/14: no failures so far**

| Model | Slide | Transistor |
|-------|-------|------------|
| SN007 | RF2   | T8         |
| SN007 | RF3   | T6         |
| SN006 | RF8   | T8         |
| SN001 | RF8   | T5,T8      |

- Without interruption of ELBE operation
- Repair during shutdown assisted by SigmaPhi

# SSPA Spareparts at ELBE

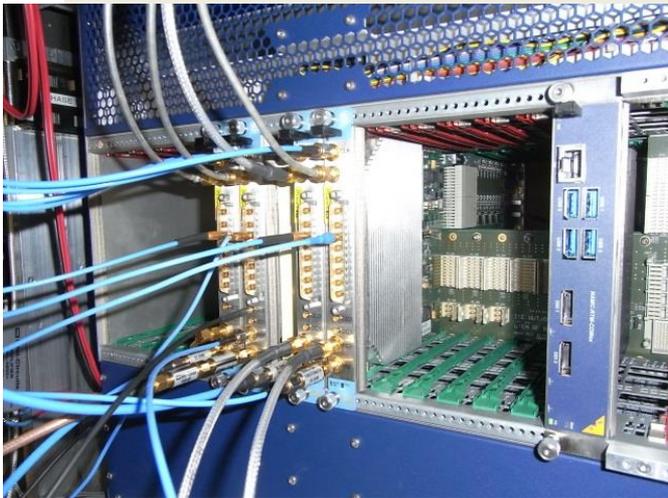
- In Use: 8x 10 kW SSPA (with 28V transistors PTF141501E)
- 1x 8.5 kW SSPA (Prototype)
- 1x 4.2 kW SSPA (not fully equipped, used at Teststand)
  
- Spareparts: 100 x PTF14150E Transistors
- 1 Driver-Controller
- 1 SMPS (2 boxes)
- 3 „slices“: 1,25kW with 8 transistors

# WORK IN PROGRESS

## In collaboration with DESY:

- First successful tests with the DESY
- Digital Single RF Control based on MTCA.4U.
- FEL U27 was operated with all 4 single RF systems controlled by the MTCA. The work is in progress.

Ref.: Rutkowski, Kuntzsch et al., MTCA.4 based LLRF system tests at ELBE  
2nd MTCA Workshop for Industry and Research, MTCA 2013,  
Hamburg, Germany,



MTCA.4U at ELBE

# Summary

## after two years of SSPA operation

- 1,3 GHz CW SSPA installation provide:
- Smooth and stable operation,  
We have lost 5 of 576 transistors (of 8 SSPAs) in 2012 but became not aware of that during operation
- For ELBE UPGRADE: we saved about 40 % costs against a klystron driven system

# 5<sup>th</sup> INTERNATIONAL PARTICLE ACCELERATOR CONFERENCE

JUNE 15 - 20, 2014 | DRESDEN, GERMANY



[www.ipac14.org](http://www.ipac14.org)

