國家同步輻射研究中心
National Synchrotron Radiation Research Center

Trends in RF Technology for Applications to Light Sources with Great Average Power

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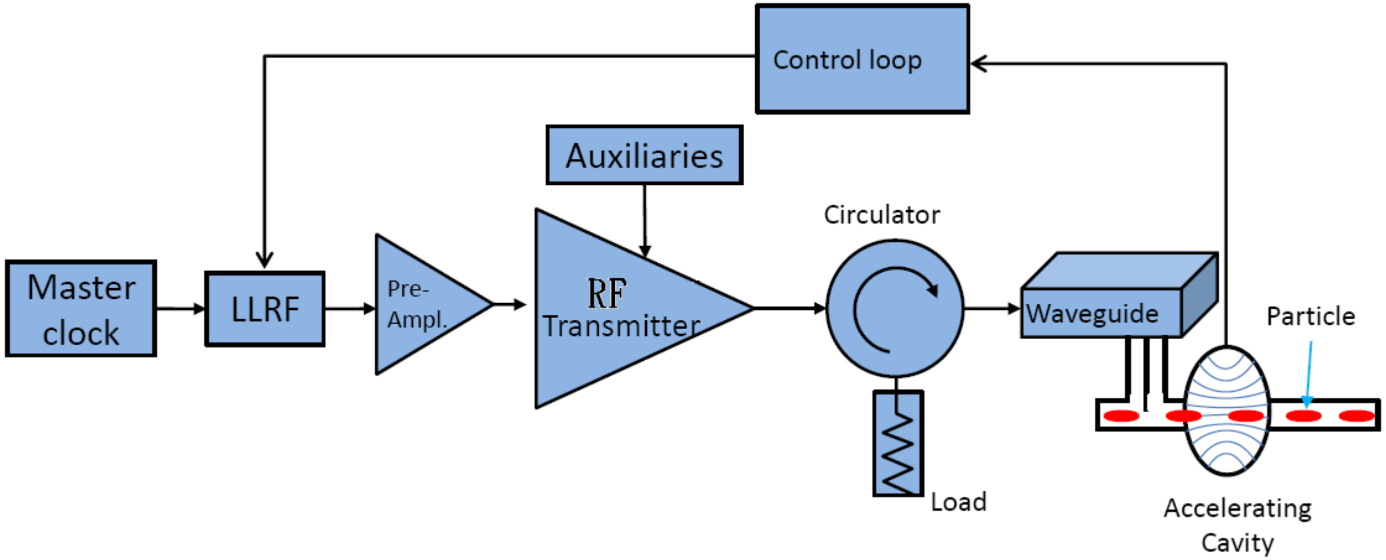
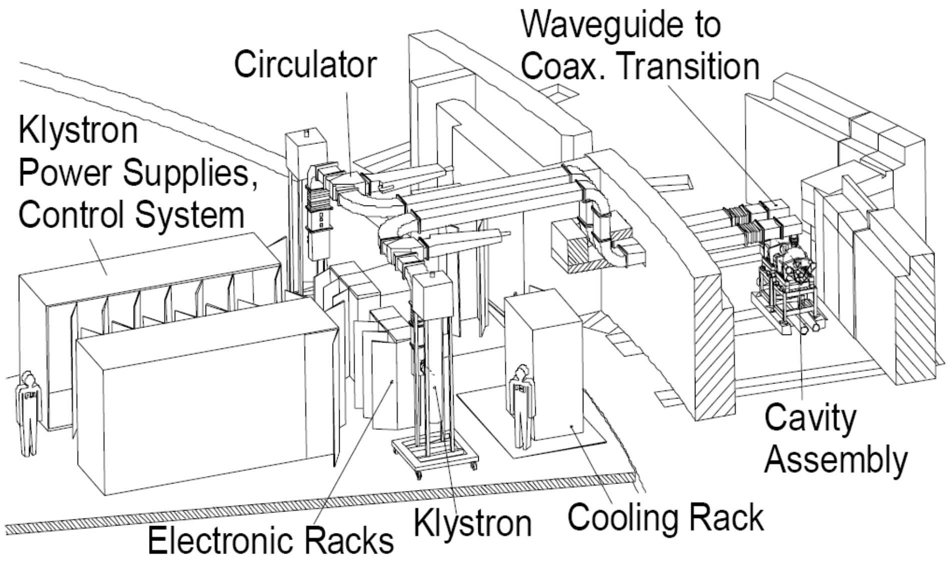
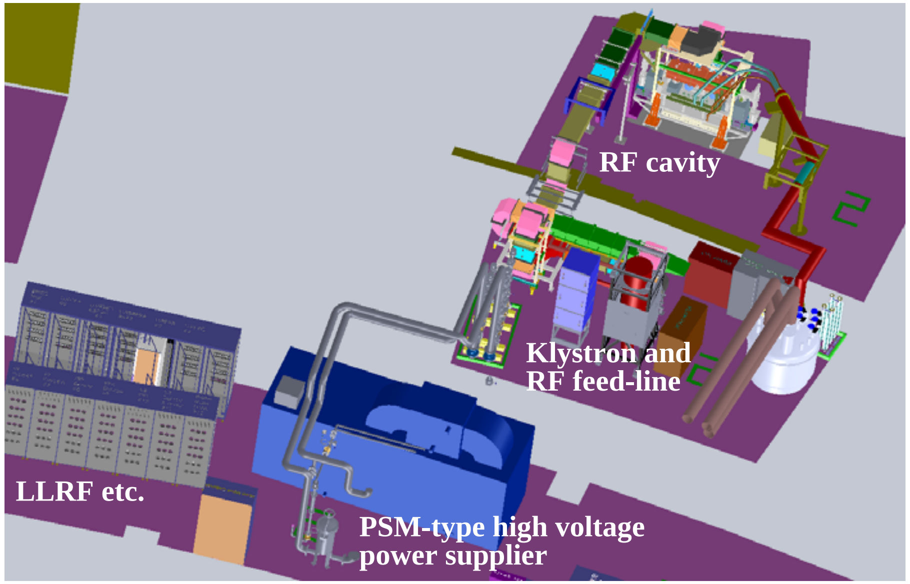
Focus

- Emphasis mainly on RF sources for applications to light sources with great average power with RF frequencies at about 352 and 500 MHz;
- Consideration of the power supply of the RF generator as a non-separated part of RF source;
- Selection of RF sources mainly determined by how to achieve its operational high reliability and availability to satisfy the rigorous experimental demands of users of light sources.

Typical Layout of RF System for Light Sources



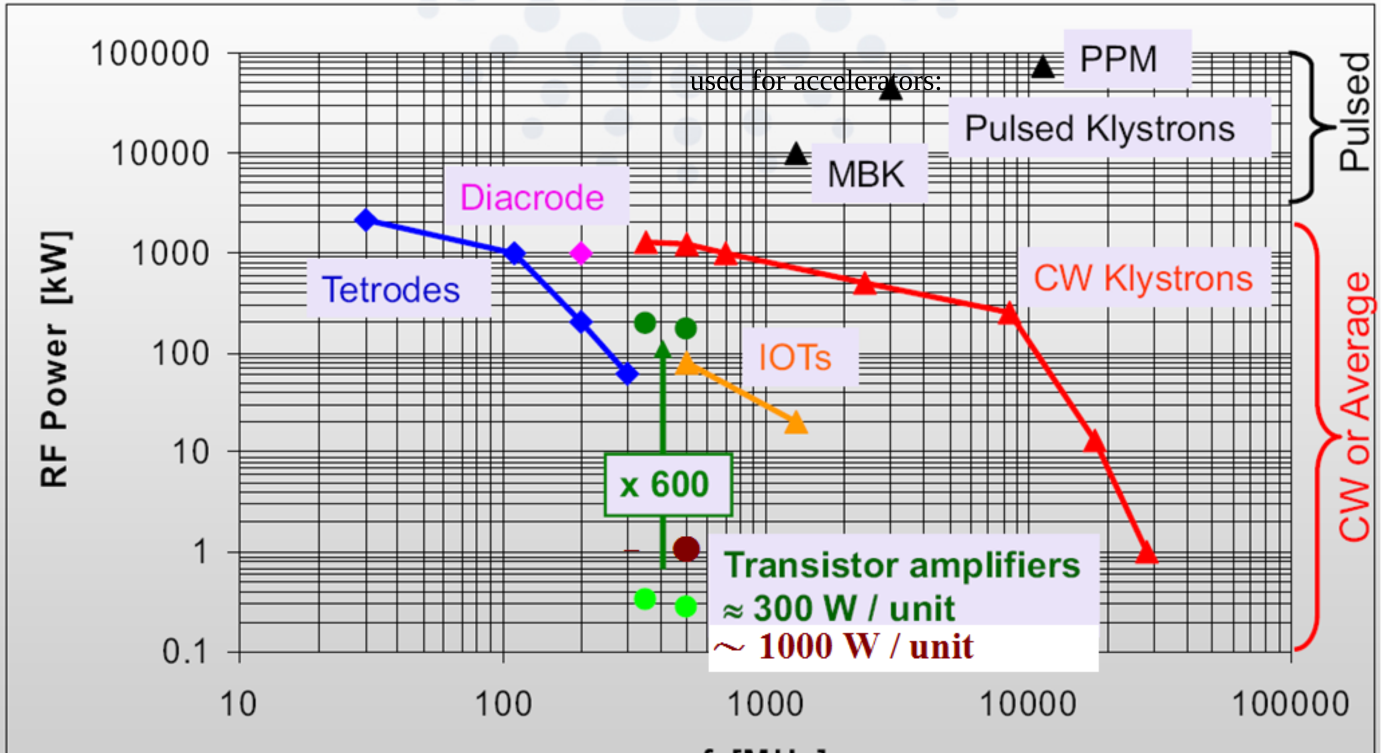




(Images courtesy of SLS, PSI) **(TPS/NSRRC)**

RF Sources for Light Sources

- RF sources
  - **Klystron**, adopted at CLS, SSRF, TPS, PLS-II, NSLS-II, etc.
  - **Inductive output tube** (IOT), adopted at DLS, Elettra (upgraded), ALBA, etc.
  - **Solid-state RF amplifiers**, adopted at SOLEIL, ESRF (upgraded), etc.



Courtesy of Joern Jacob, ESRF (2009)

- RF sources with frequencies at 99-105 MHz, 352.2 MHz, 500-510 MHz, 1.3 GHz, 2.856 GHz, etc. are commonly used for accelerators.
- RF Sources with operational frequency at 352.2 MHz and 500-MHZ are most popular for high average power application at light sources.

How to Make RF System Even More Reliable?

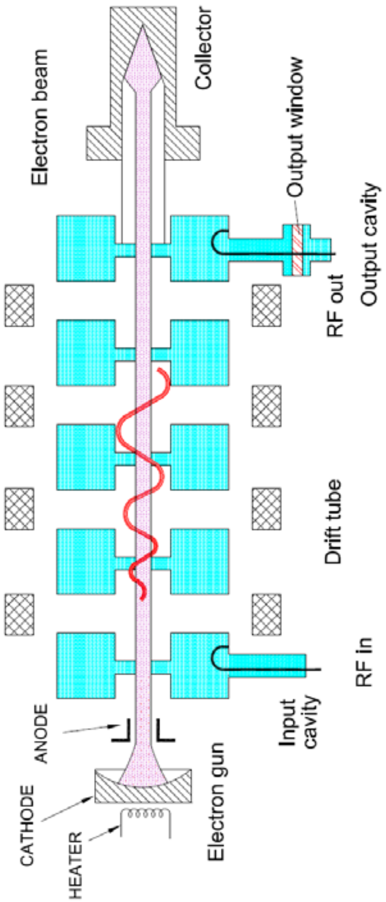
- **Design with over-specification**
  - e.g. Operating a 80-kW, CW IOT with average RF power not more than 40 kW;
  - e.g. Operating a 1000-W RF transistor with maximum RF output less than 600 W;

- **Design with *N+n* redundancy & allowance for a hot swap**
  - e.g. Implementing 86 but required 68 PSM modules for a PSM-type high-voltage power supply;
  - e.g. Implementing 15 % more than the required numbers of solid-state power-amplifier elementary modules for a solid-state RF amplifier;

- **Preventive replacement/maintenance**
  - e.g. Replace a performance-degraded component before it fails.

- **Advanced diagnostic instruments and automatic fault-logging software**.

Klystrons *Velocity modulation (RF drive power) + density modulation (drift tube)*

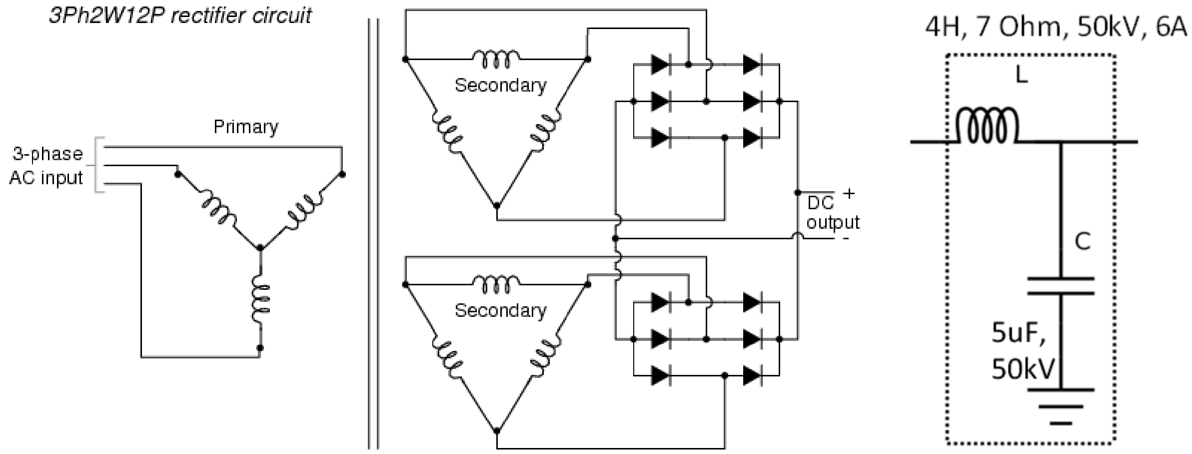


100-kW klystron

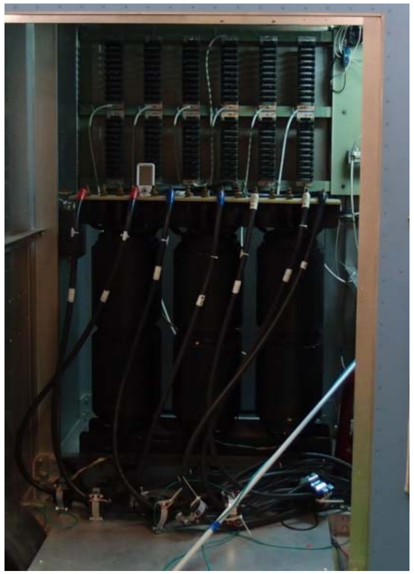
300-kW klystron

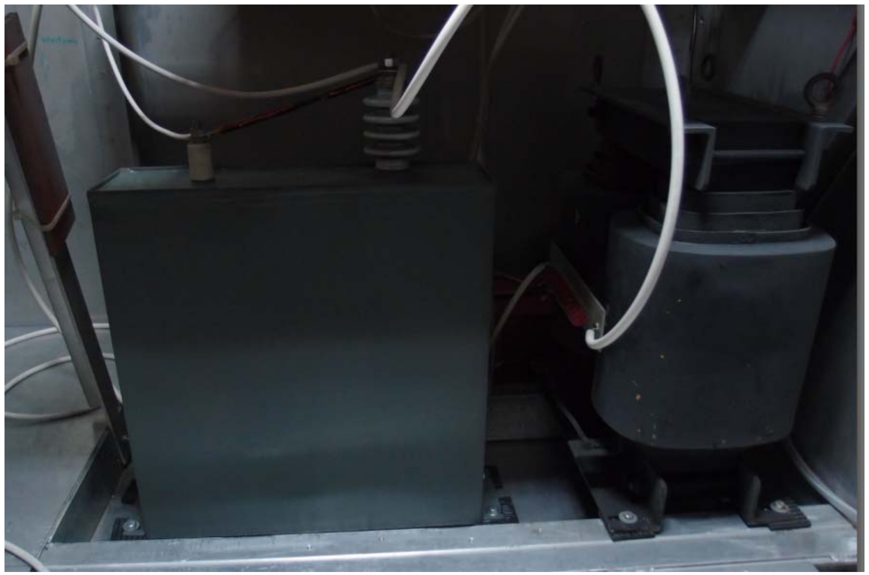
- Vacuum tubes (klystron, IOT, etc.) require a large DC voltage; e.g. -23 kV for 70 kW, -27 kV for 100 kW, and -53 kV for 300 kW RF output.
- The klystron price increases steadily, for example at a rate about 5 % annually in the past ten years continuously for some popular klystrons with limited quantity of procurement.

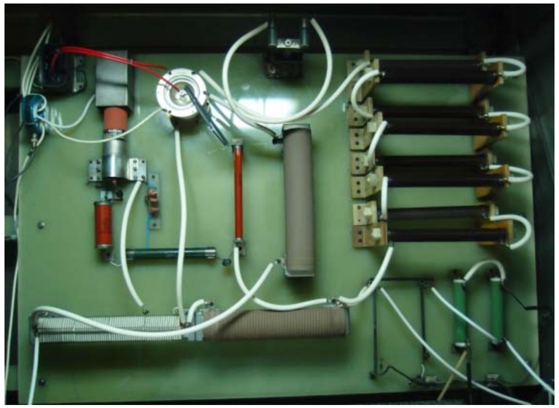
Crowbar-type HVPS *(taking the one used at TLS as example)*



- The high-voltage power supply is classically equipped with a crowbar circuit to ensure a quick dump to ground of the stored energy from the high-voltage power capacitor, which is part of the choke filter, to protect the klystron from damage during, for example, internal arcing.
- Two-stage crowbar circuit at TLS:
  - spark gap: circuit shorted at 35 kV
  - ignitron: circuit shorted at 50 kV







What is the Operational Problem with a Klystron-based RF Transmitter? *Our Solution*

- Technical reasons
  - Capacity of existing design not to fit perfectly the special needs of a light source;

  - Difficulty in troubleshooting with a high-voltage circuit;
  - ➢ **Select high-voltage components over specification, for example with a safety factor 1.5.**
  - ➢ **Use high speed multi-channel transient recorder with large memory to identify the signal of a first trip.**
  - ➢ **Apply regular high-voltage testing to evaluate an increased leakage current under high voltage as an index of preventive replacement**

  - Sensitive to performance of high-power RF circulator;
    - Risk to damage a RF window;
    - Decrease of maximum output power.
  - ➢ **Add a waveguide bridge between the cavity and the circulator to minimize the reverse RF power from the cavity.**

- Budgetary reasons
  - The klystron market shrinking and monopolizing.
  - Increasing cost.
    Eventually difficult to obtain klystrons in the market in the future.
  - ➢ **Purchase spare klystrons, eventually enough for machine operation for 20 years.**

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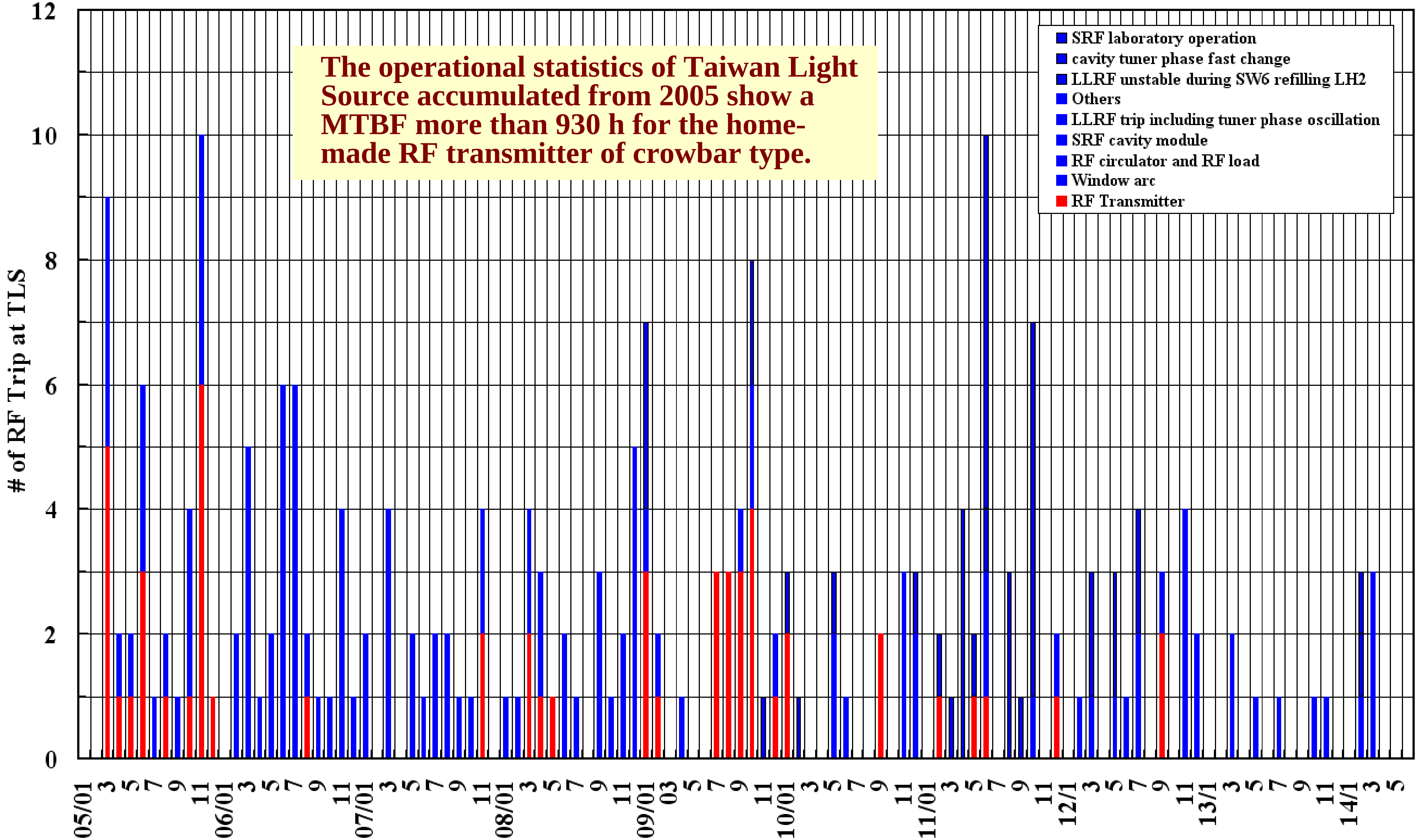
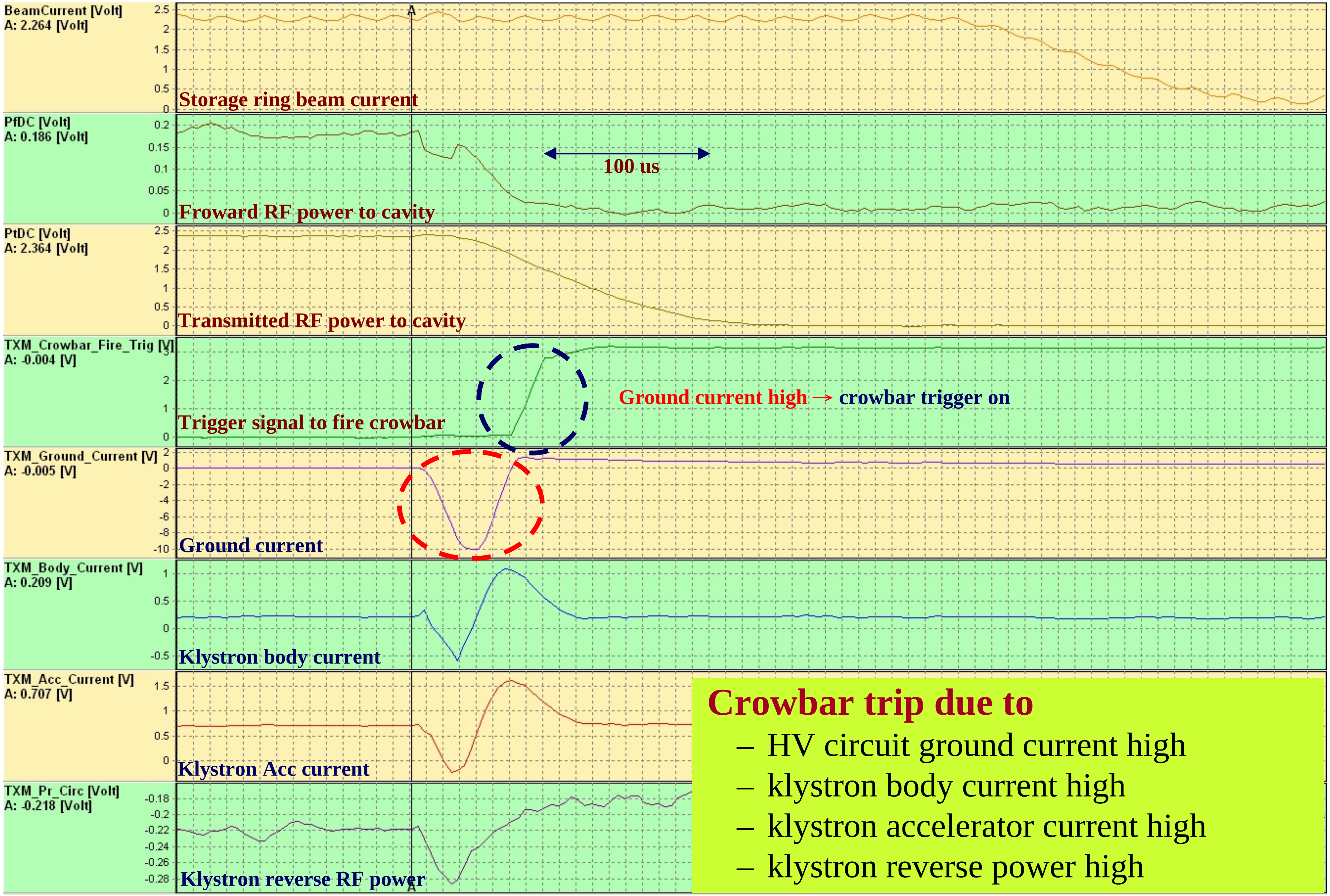
Statistics of SRF Operation at TLS Using Klystron-based RF Transmitter *(2005-2014)*



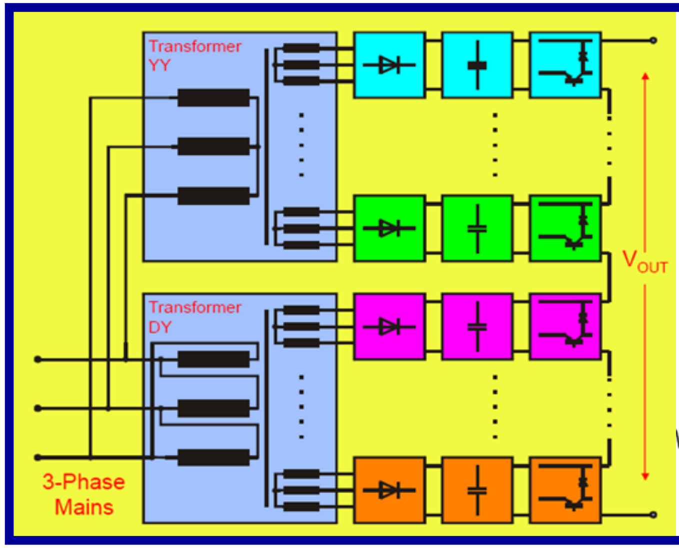
Some Examples of a Crowbar Trip Event *(at TLS)*

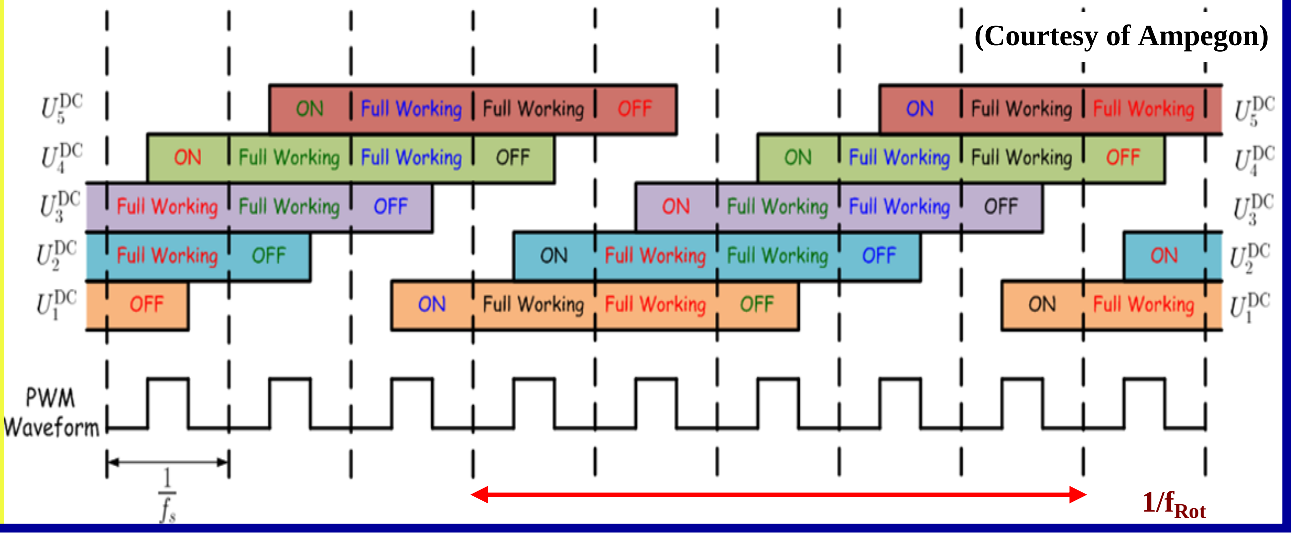


Crowbar trip due to

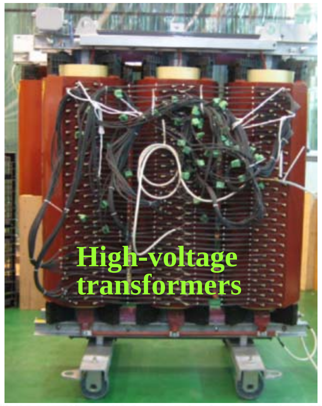
- HV circuit ground current high
- klystron body current high
- klystron accelerator current high
- klystron reverse power high

PSM-type High-Voltage Power Supply





(Courtesy of Ampegon)

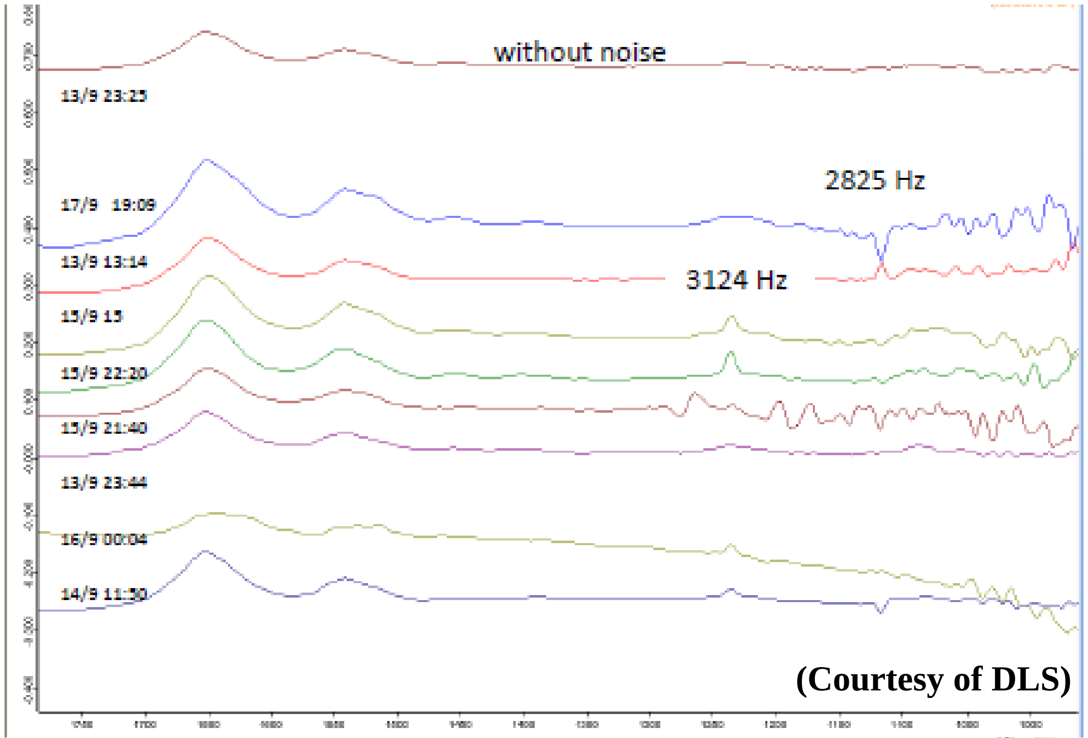


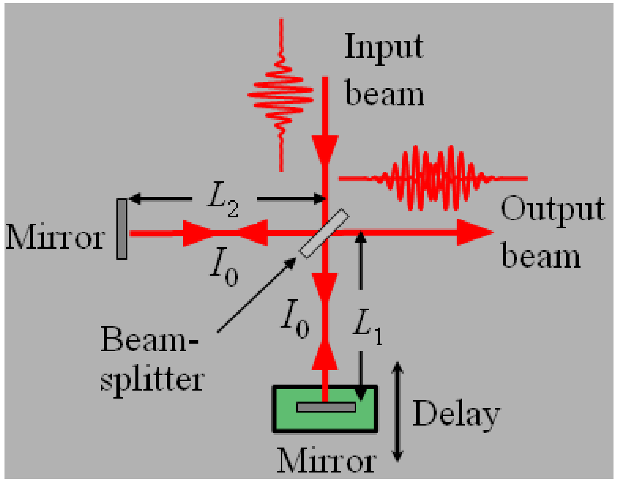
Apply rotation, coarse-step modulation (CSM) and pulse-step modulation (PSM) to PSM modules.

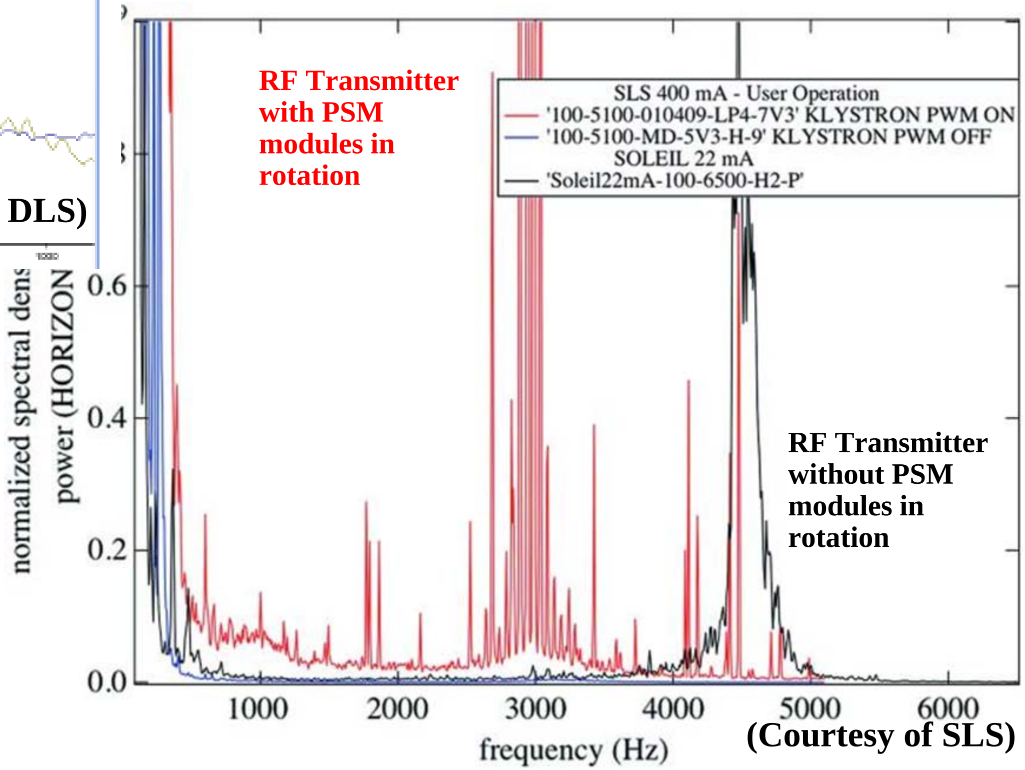
Parameter	[redacted]				PSM	Tube and Croowbar
Reliability	10	6	8	8	10	7
Efficiency	9	7	8	9	10	3
Ripple	8	6	7	4	5	8
SC energy	5	6	7	10	9	6
Space requirement	5	6	6	8	8	8
MTTR	3	5	6	8	10	5
Price	4	6	8	6	7	5
Pulse	1	2	2	10	8	9
System limitations	2	4	8	8	8	5
System integration		-	-	-	-	
Total		**5.9**	**7.2**	**7.4**	**8.3**	**5.9**

(Courtesy Karl Zingre, 2003)

RF Noise on Infrared Beamline (Michelson Interferometer)



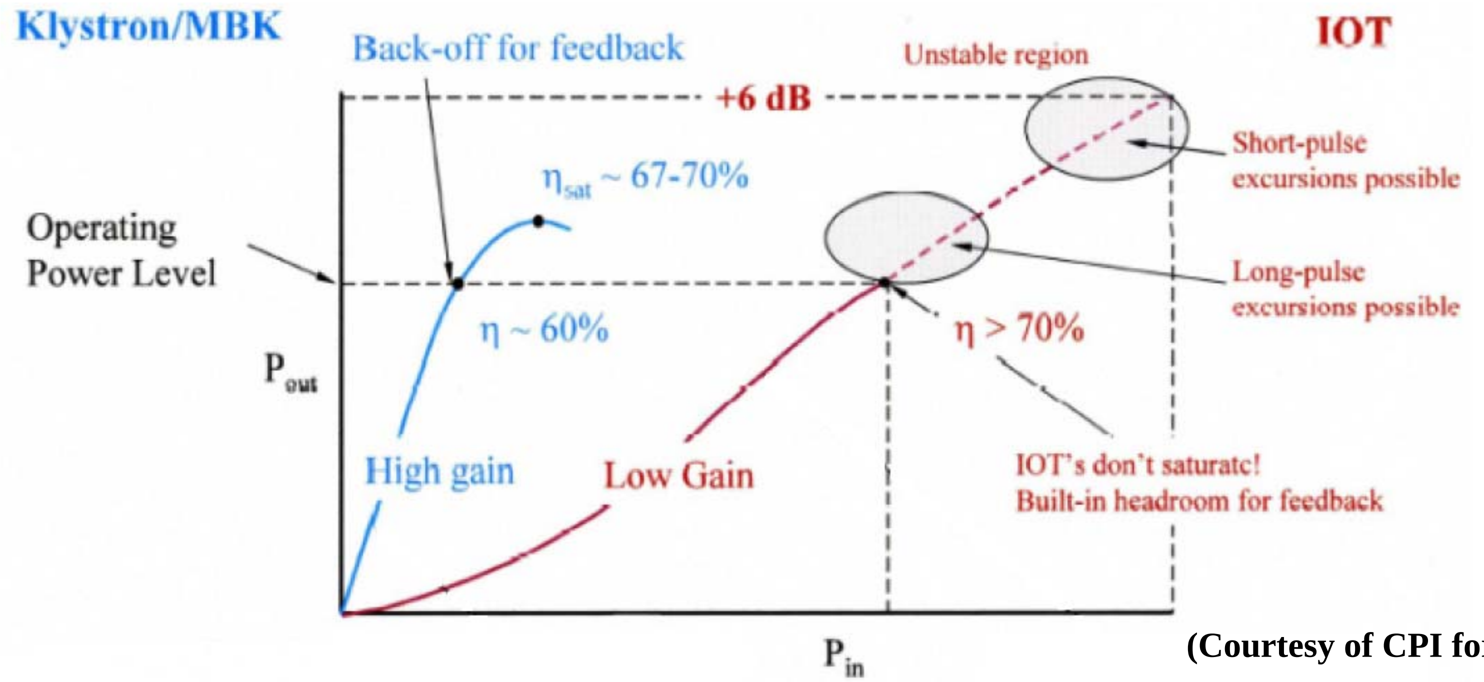




1. **The high-voltage power supply of PSM type generates RF noise from its rotation of the PSM modules and from the harmonics of electric power.**
2. **Their contamination in the infrared beamline remains a major concern that might be cured with a digital low-level RF system.**

Inductive.utput Tubes *(IOTs)*

- **IOT = a hybrid of a grid tube and a klystron**
  - An IOT with maximum RF output power larger than 100 kW is so far commercially unavailable. A multi-beam high-power IOT must have the potential to deliver a few hundred kW with a small cathode voltage, but is not yet commercially available.
  - Relative to a klystron, IOT has high efficiency but low gain (~20 dB).
  - Relative to a klystron, RF output of an IOT is less sensitive to ripples of high voltage.



(Courtesy of CPI for ESS)

- **Operational challenge: IOT has popular applications in television transmission.**
  - Whether the IOT is still highly reliable when operating at high average output power;
  - Whether the IOT has a reasonable life-time time when operating at high average output power.

Inductive-output Tubes *(Cont'd)*

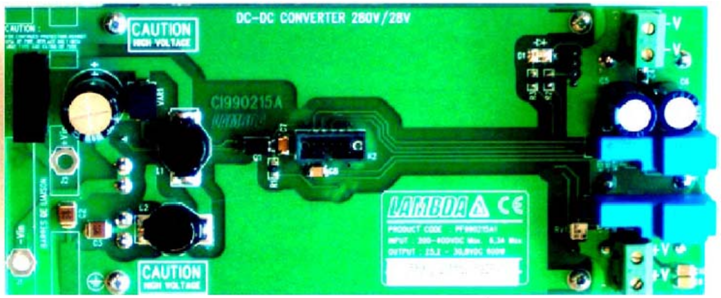
- **Few light sources use IOT for the RF system of the storage ring**
  - DLS: Maximum RF output 300 kW on combining four IOT each 80 kW powered by PSM-type high-voltage power supply.
  - ALBA: Maximum RF output 150 kW on combining two IOTs each 80 kW powered by PSM-type high-voltage power supply.
  - Elettra: Maximum RF output 150 kW on combining two IOT each 80 kW powered with a high-voltage power supply

TH 793-1 LS
(DLS, ALBA, Elettra)
(Courtesy of Elettra)

E2V D2130
(DLS, Elettra)
(Courtesy of Elettra)

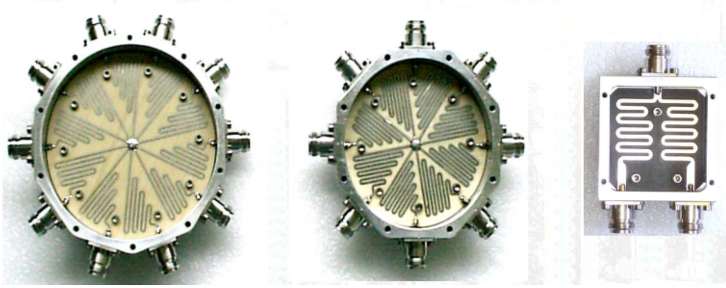
L3 Communications
(booster/NSLS-II)
(Courtesy of NSLS-II/BNL)

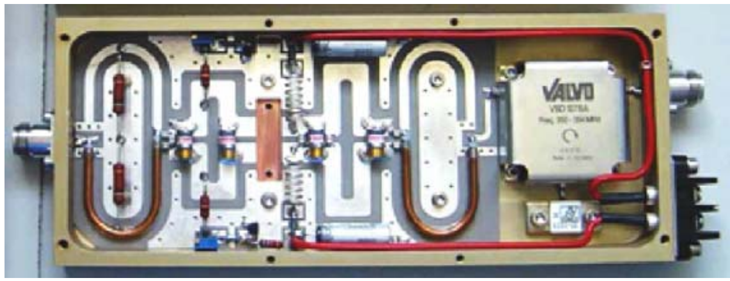
Solid-State RF Amplifier *Pioneered at SOLEIL*



600 W–280 Vdc/28 Vdc converters

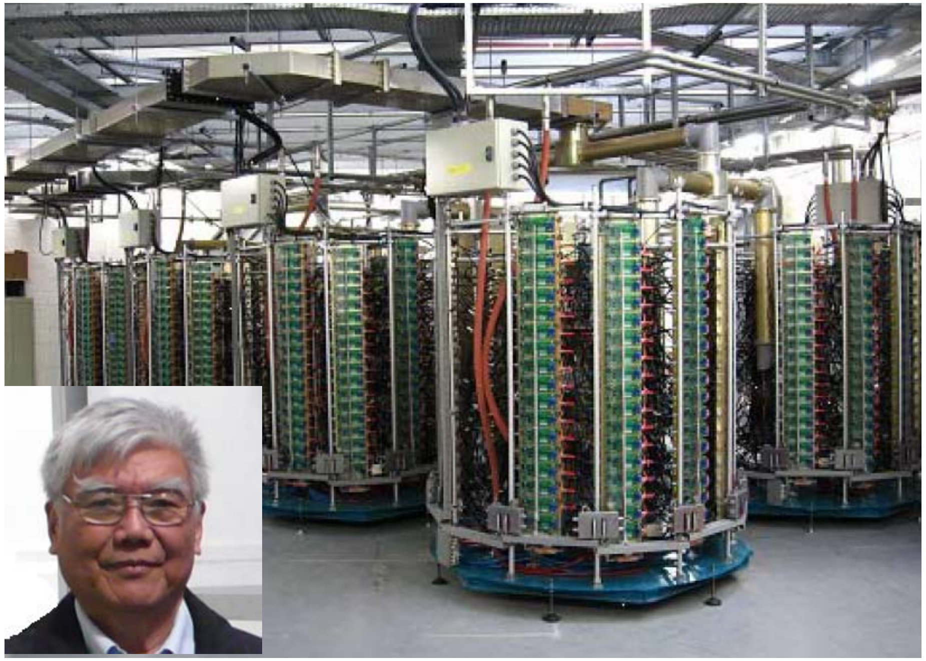
10-Way 8-Way 2-Way

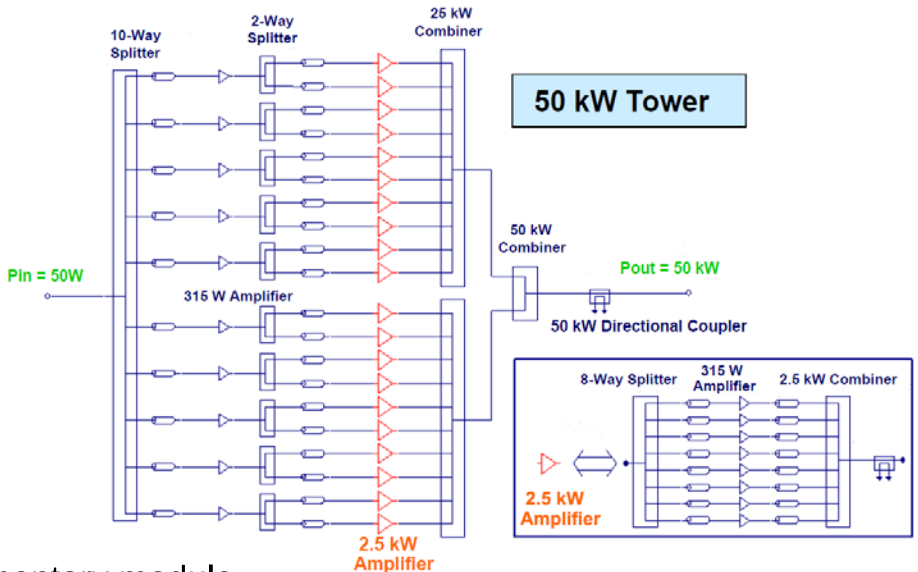




2 x 100 kW 2 x 50 (or 25) kW 10 x 2.5 kW 8 x 315 W

Images courtesy of Synchrotron SOLEIL





- Maximum RF output: 180 kW/RF amplifier and 330 W/elementary module.
- 726 power amplifier elementary modules in four amplifier towers per 180 kW RF amplifier

Solid-state RF Amplifier *Followed at ESRF*

Courtesy of ESRF

- An upgraded version of SOLEIL-type solid-state RF amplifier.
  - Maximum RF output 150 kW/RF amplifier and 650 W/elementary module.
  - 128x2 power amplifier elementary modules in two amplifier towers per 150-kW RF amplifier

Solid-state RF Amplifier *with AC/DC Power Supply*

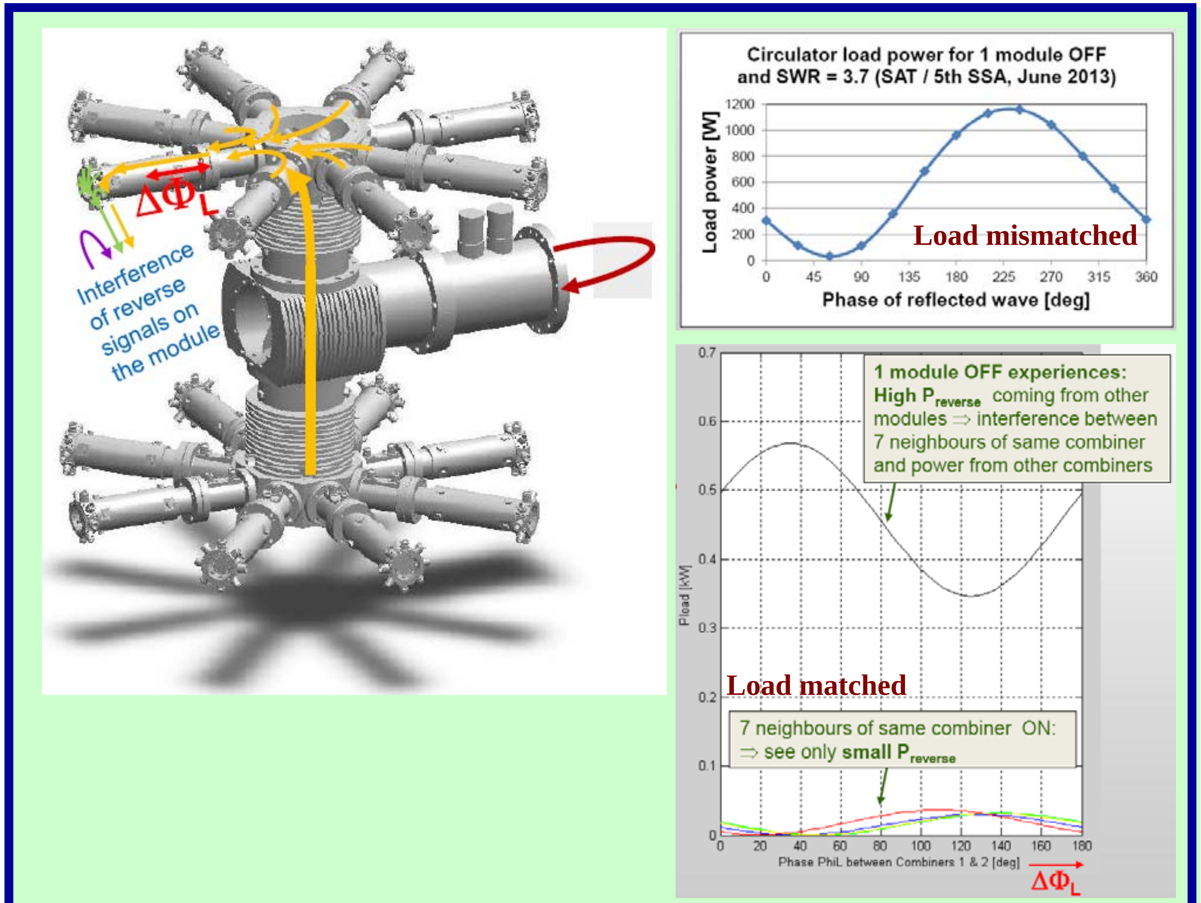
- Each power-amplifier elementary module is biased with its own switching power supply or DC converter of voltage a few tens of volts. Few switching power supplies can be regulated by one controller.
- The power supply requires not only high efficiency but also low noise and low voltage ripples. The ripples of bias voltage contaminate the RF output of a RF power transistor.

e.g. Eaton Product of high efficiency (up to 96 %) 220 V_{AC}/50 V_{DC} power converter.

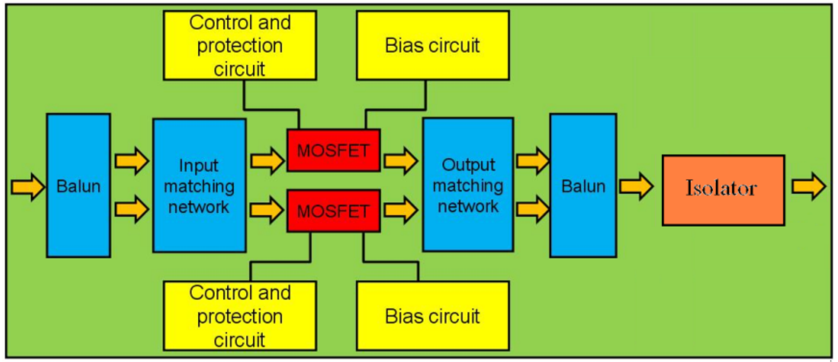
Solid-state RF Amplifier *Operational statistics*

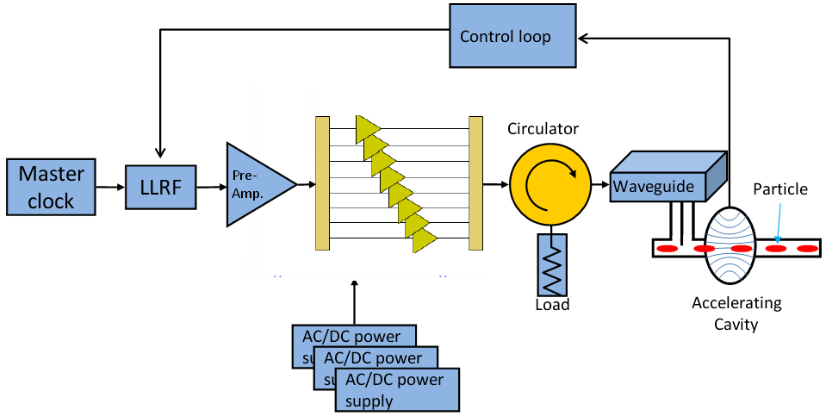
- A design of a high-power solid-state RF amplifier with *N*+*n* redundancy of power-amplifier elementary module ensures a highly reliable operation.
  - **SOLEIL**
    - 4x180 kW SSA = 4x(4x45 kW) = 16 amplifier towers (45 kW) = 3000 SSA elementary modules for storage ring operation;
    - A few tens of thousands of hours gives an annual rate of failure about 3.5 %;
    - Failure is due mainly to thermal fatigue, for example, transistor breakdown or solder damage
  - **ESRF**
    - 3x150 kW SSA = 3x (2x75 kW) = 6 amplifier towers (75 kW) = 768 SSA modules for a storage ring;
    - 14 % of 22 RF trips in 2013 due to solid-state RF amplifier
    - Running time 3600 h

Solid-State RF Amplifier *w/ or w/o High-Power Circulator*



Courtesy of Joern Jacob, ESRF (2014)





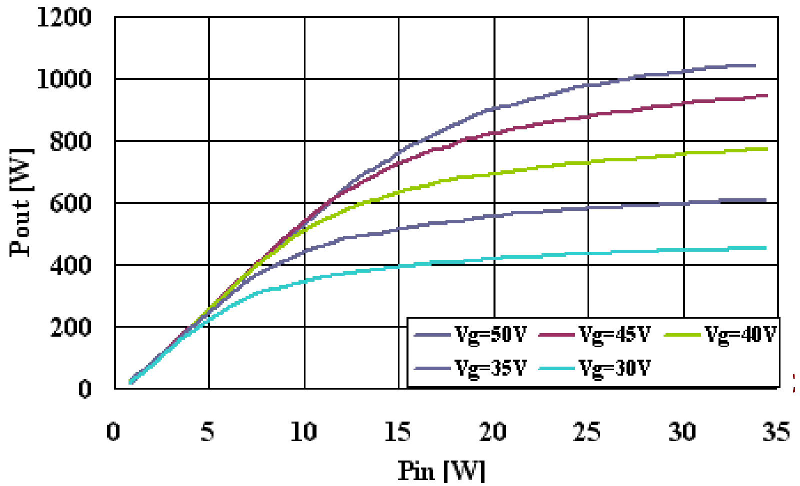
Taking 600-W RF amplifier elementary module used at ESRF as an example when one elementary module is off:

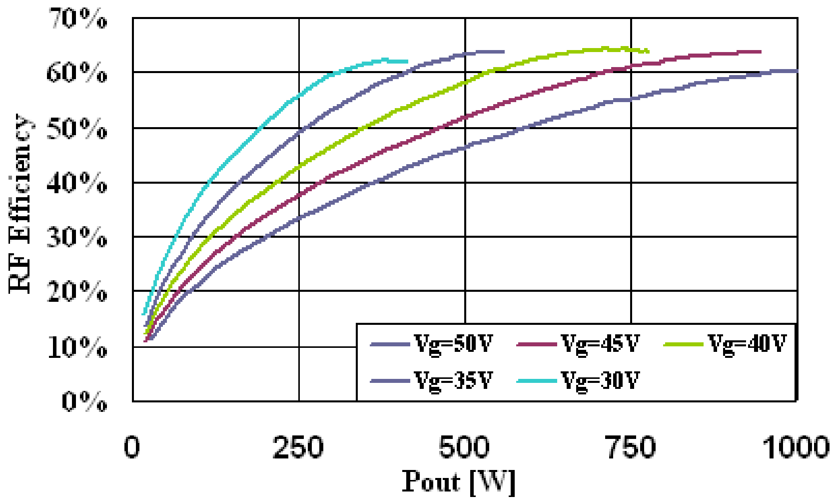
- Under matching conditions, the maximum reverse power is less than 600 W at any combining phase $\Delta\ \Phi_L$;
- Under VSWR 3.7, maximum reverse power back to module can be up to 1500 - 1700 W at worst phase but decreases to 1100 W at the best combining phase.

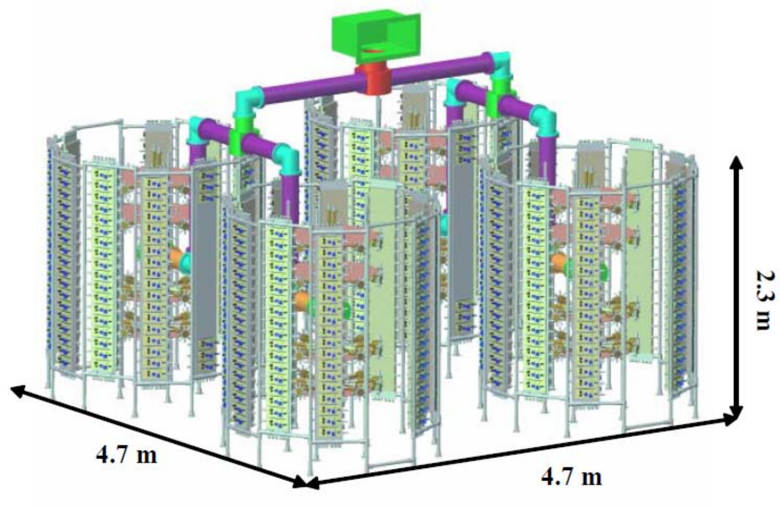
1. **The high-power isolator dedicated for an individual power-amplifier elementary module becomes the most expensive circuit component, apart from its switching power supply.**
2. **Installing a high-power isolator with a full-power dummy load between an accelerating RF cavity of a storage ring and a solid-state RF amplifier, similar to what has been adopted for the klystron or IOT-based RF transmitter, might greatly simplify the design challenge, providing an alternative to the SOLEIL approach.**

Solid-state RF Amplifier *Making it even more attractive*

- Superior efficiency at varied levels of output power;
  - Optimal drain voltage for varied level of output power;
    - Complicated algorithm + remote controllable-switching power supply
  - Optimal power combined with high efficiency at a few output power levels;







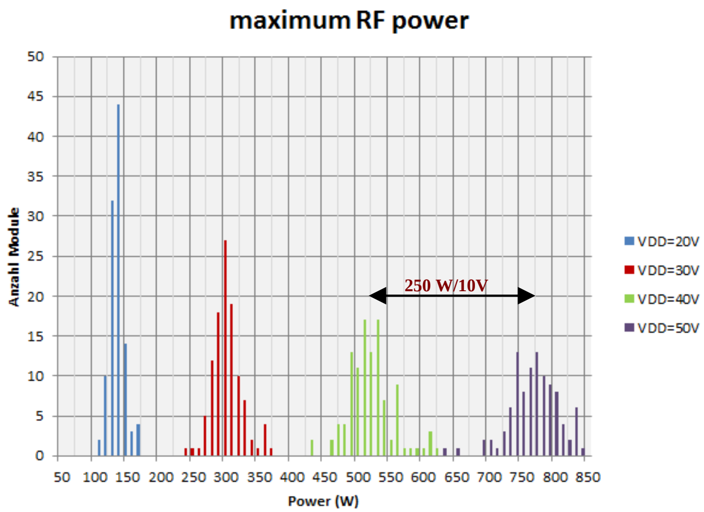
Images courtesy of Synchrotron SOLEIL

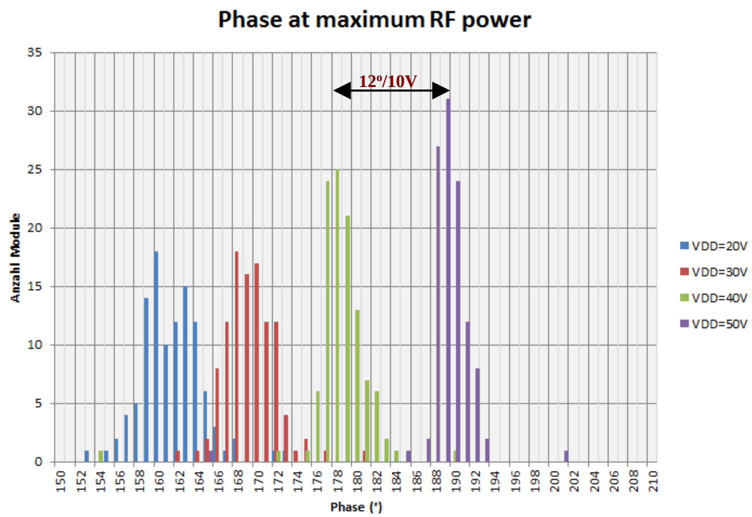
Taking SOLEIL design as example:

1) **45 kW/amplifier tower**
2) **Using a symmetric power combiner (hybrid combiner or magic tee), maximum output powers 90 kW and 180 kW can be effectively delivered.**
3) **Using an asymmetric power combiner, maximum output power 135 kW can be effectively delivered.**

Solid-state RF Amplifier *Making it even more attractive*

- **Cheaper**
  - **Produced in automation, with minimized hand working & tuning;**
    - Integrate most circuit elements into one printed circuit board, for example usage of microstrip balum and circulator.
    - Performance less insensitive to property scattering of transistor, capacitor, etc.

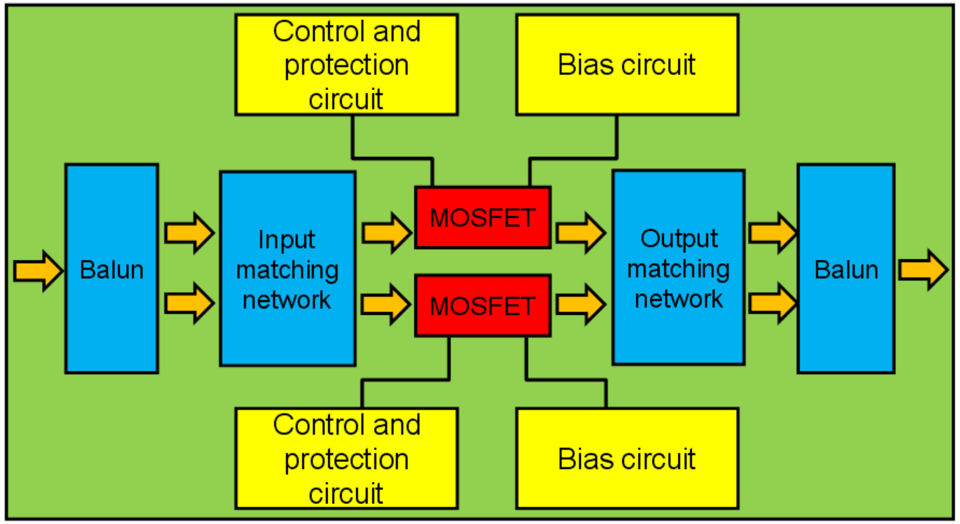


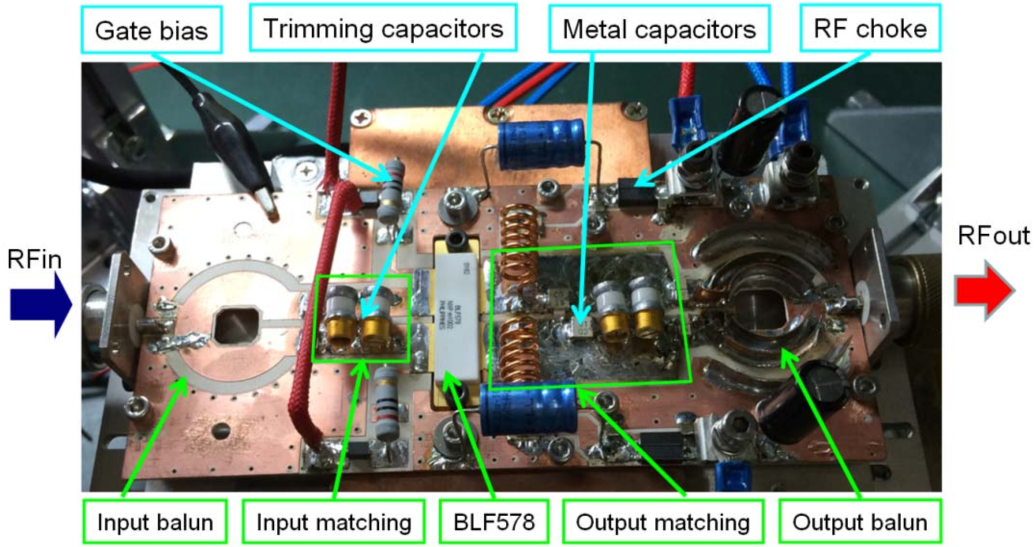


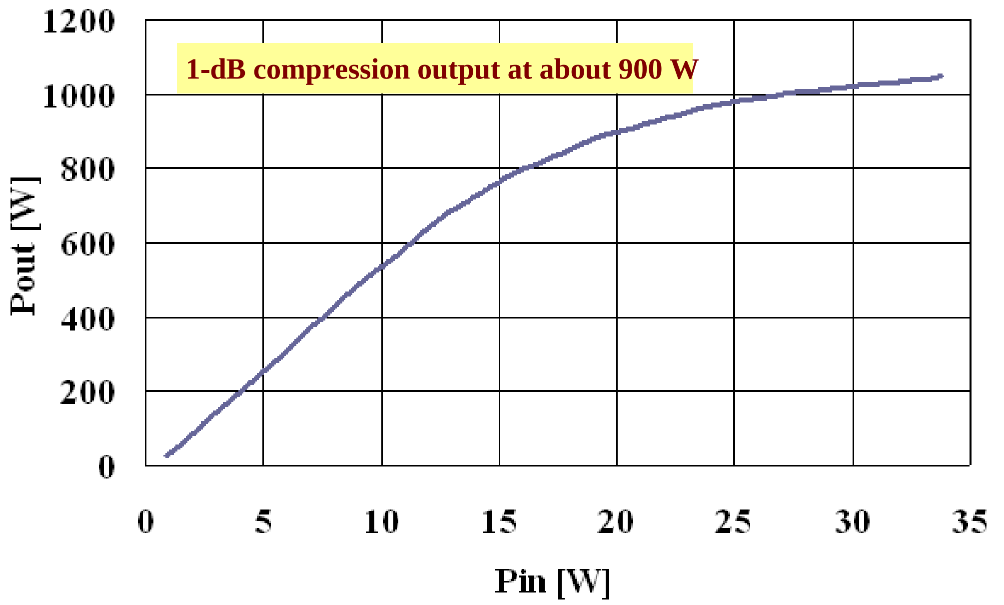
Courtesy of Bodo FRITSCHE (Ampegon)

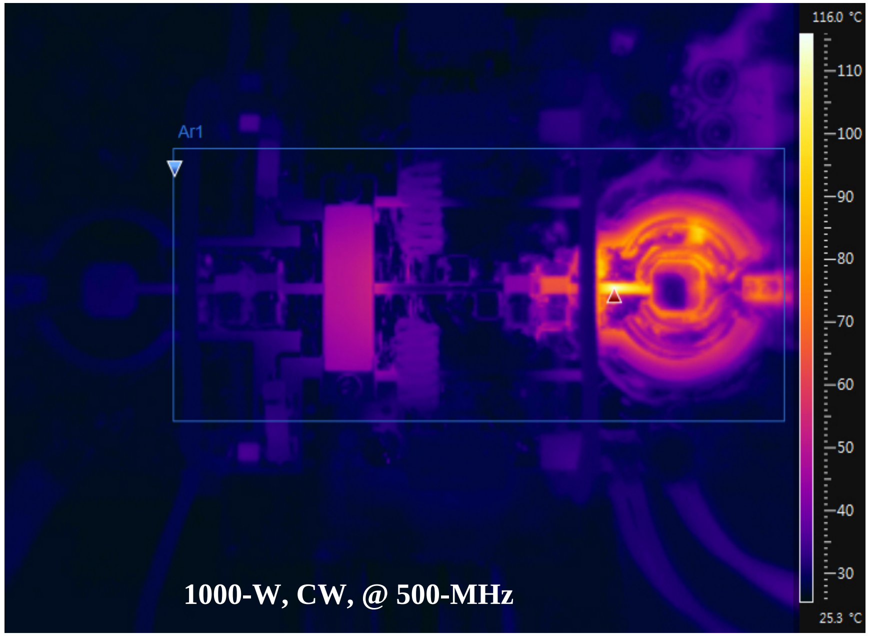
  - **Some possible strategies**
    - Fewer stages of RF power to combine;
    - Larger designed RF output power from single solid-state RF power module;
    - Integrate DC/DC converter into solid-state RF power module using common printed circuit board;
    - Use common water-cooling plate (dissipater) for a few solid-state power modules & DC/DC converters.

Solid-state RF Amplifier *Making it even more attractive*









More than 600 W heat dissipated on the circuit board of solid-state RF power module. The average power density is up to 230 W/cm^2.

The MTBF of the power transistor is exponentially decreased as a function of its die temperature.

Perspective

- The **cost** of a high-power solid-state RF amplifier **might become considerably less** than that of a klystron-based RF transmitter in the near future, so enabling the replacement of klystron-based RF transmitters in many light sources, but a klystron will survive in coming decades because of its applicability for a MW power rating.
- Production of a high-power solid-state RF amplifier operated at **high average power highly reliably** is still a **considerable challenge**.
  - A design depending on working frequency might experience a different outcome.
  - Mastering the details of a power-amplifier elementary module in-house is still essential for highly reliable operation of a solid-state RF amplifier, identically to mastering the knowledge of high-voltage technology for highly reliable operation of a klystron-based RF transmitter.
- Considering the nature of the **graceful degradation of solid-state RF power transistors**, how to realize a solution for the enduring maintenance of a solid-state RF amplifier **on a time scale 20 years** must be carefully considered during the planning phase.
  - The development of an RF power transistor has been much more rapid than that of a high-power vacuum tube.
  - The power RF transistor of best performance available on the market will become extinct more rapidly than those vacuum tubes available already in the past decade.

Acknowledgements

The production of this review has benefited greatly from the papers available in proceedings of accelerator conferences archived on the JACoW website and the transparencies available after the European Synchrotron Light Source Radio-frequency (ESLS-RF) Meetings and CW and High Average Power RF (CWRF) Workshops on their websites. I am deeply grateful for their contribution to the development and application of RF sources to light sources.

Thank You for Your Attention!