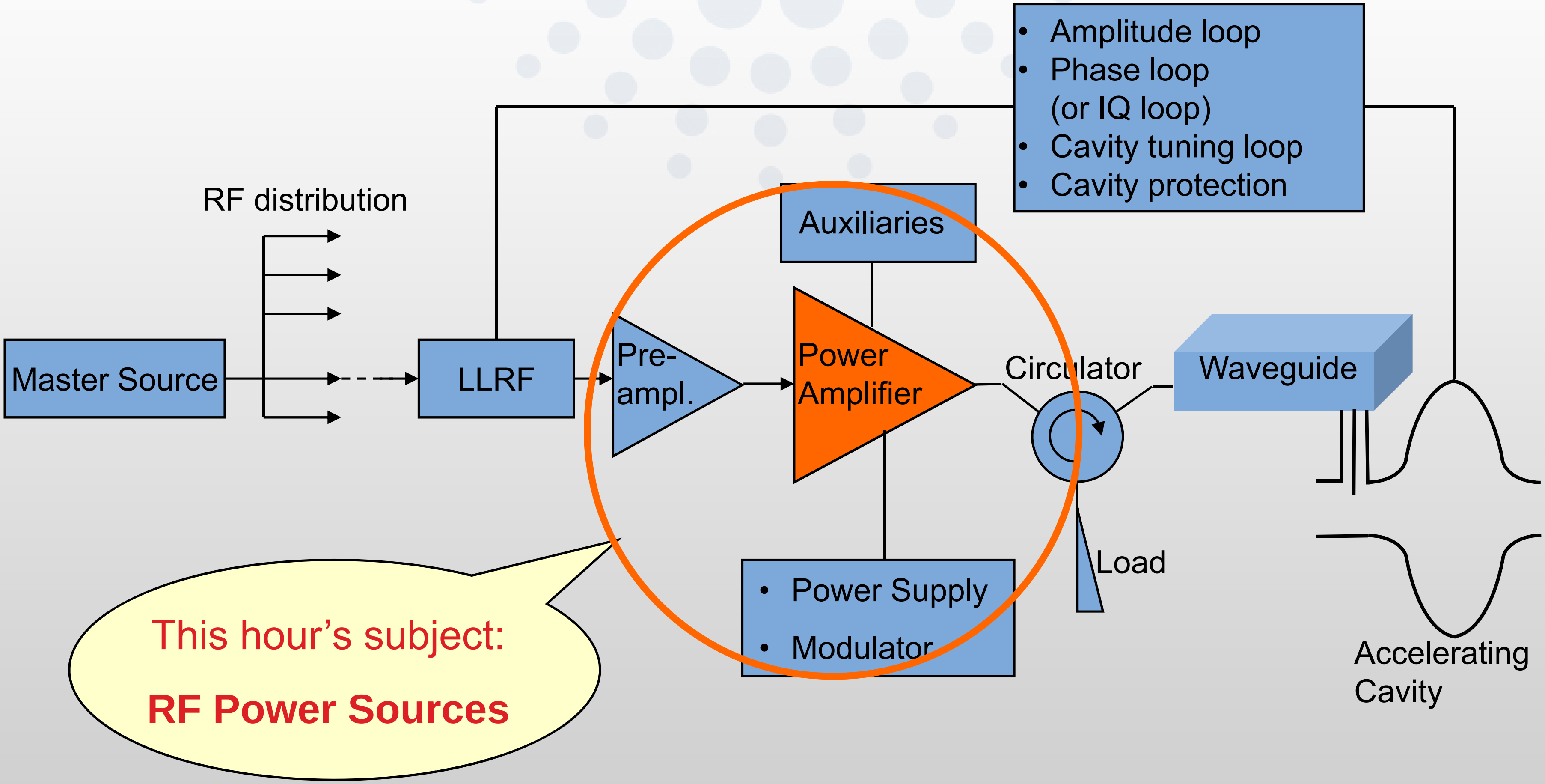
SRF'2009 tutorial program

RF Power Sources

Jörn Jacob, ESRF

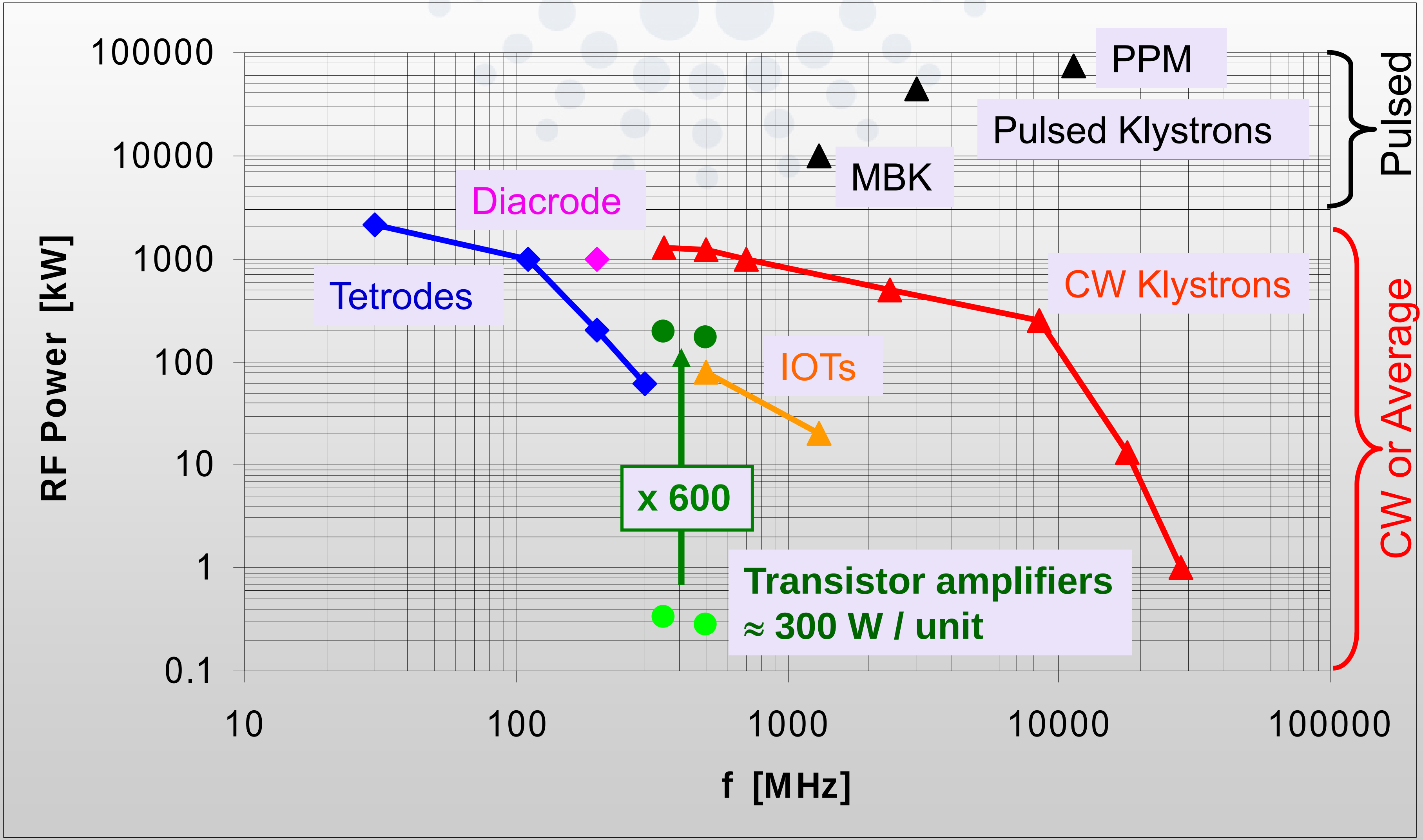
RF transmitters for accelerating cavities



Starting point: specification

- Frequency: *100 MHz … 10 GHz*
- Operation: *cw or pulsed*
- Power: *10 kW (cw)… 100 MW (pulsed)*
- Gain
- Efficiency [mains to RF conversion]
- Stability, Phase noise: amplifier & power supply / modulator
    - For instance, modern light Sources, in particular FEL require extremely small phase jitter (< 0.1…0.01 deg) and voltage ripple (< 0.1…0.01 %)
- Reliability, MTBF
- Durability
- Availability
- Cost: procurement, operation, maintenance

RF power sources for accelerating cavities



Other RF power sources

Other sources generally not used to power accelerating cavities

- Gyrotrons: typically 90…170 GHz, 1 MW, 5 …10 s pulses for plasma heating (fusion) and industrial applications
- TWT: broadband RF tube, used in some broadband feedback systems
- Magnetrons: RF oscillator source
- …

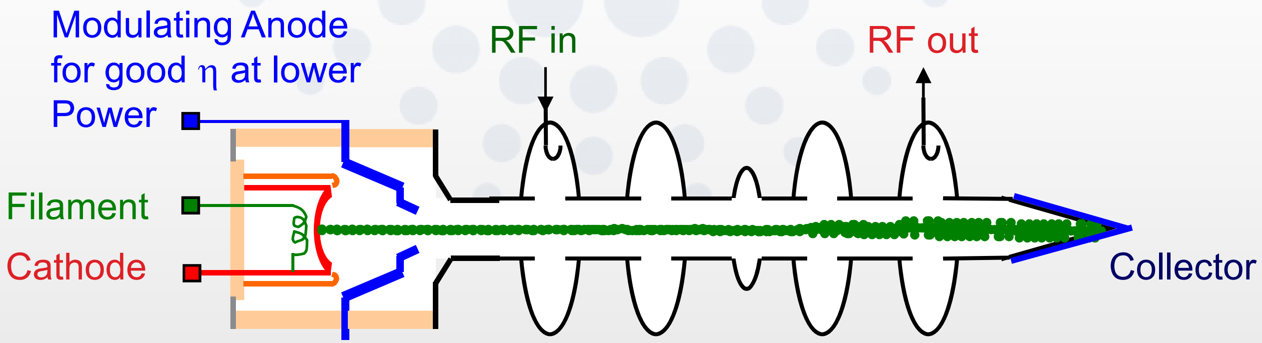
Tetrode

- Tetrode:
  - Vacuum tube with intensity modulation of the electron beam
  - Accelerator applications up to 300…400 MHz: finite electron drift time limits the achievable gain at much higher frequencies
  - Tetrode transmitters deliver between 10 kW and 2 MW CW or average power, correspondingly more in pulsed mode.

- Diacrode TH 628 / Thales:
  - With its symmetric geometry optimized for the coupling to a λ/2 coaxial resonator, the *diacrode achieves twice as much frequency-power product* as a conventional tetrode
  - 200 MHz: 1 MW cw

    4.5 MW in 500 μs pulses / 1 % duty cycle

Klystron

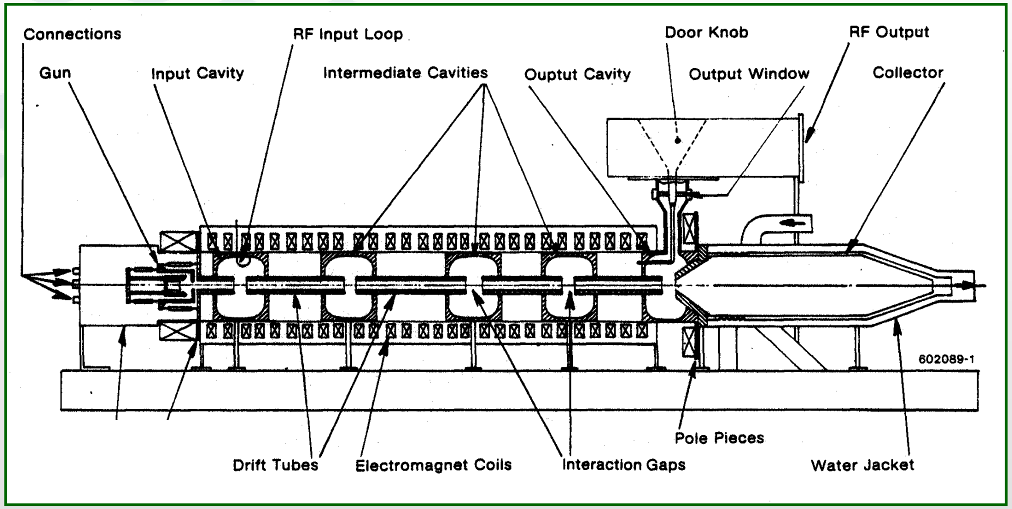


- Low power Velocity modulation with input cavity
- Drift space exploited in conjunction with several idle cavities to achieve bunching and therefore high efficient DC to RF power conversion:
- High gain
- $I_{dc} = K\, V_{dc}^{3/2}$, for reasonable efficiency: beam perveance $K < 1\ \mu$Perv
  - High RF power ⇒ High Voltage
  - Increased effective perveance ⇒ Multibeam klystron
- CW klystrons often have a modulating anode for:
  - gain control
  - while RF drive power in saturation
  - allowing high efficiency operation over large dynamic range
  - However: anode modulation has low bandwidth (typically < 10 Hz)

CW klystrons

Typical CW klystrons:

- Smaller accelerators: TV klystrons
  - → *60 kW / 500 MHz*
- Larger Machines: Super klystrons
  - → *1…1.3 MW*
  - → *352, 500, 700 MHz*
  - → $\eta_{typ} = 62\ \%$
  - → $G_{typ} = 42\ dB \Rightarrow P_{in} \lesssim 100\ W$



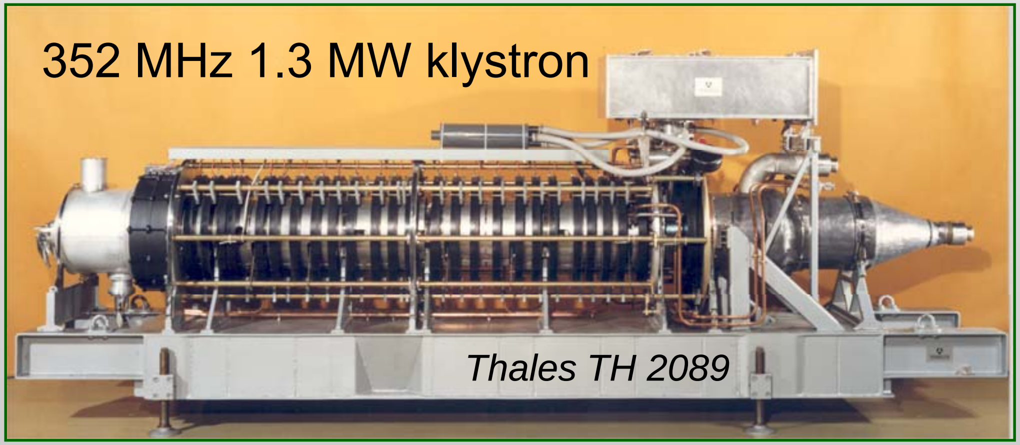
Requires:

- 100 kV, 20 A dc High Voltage Power Supply

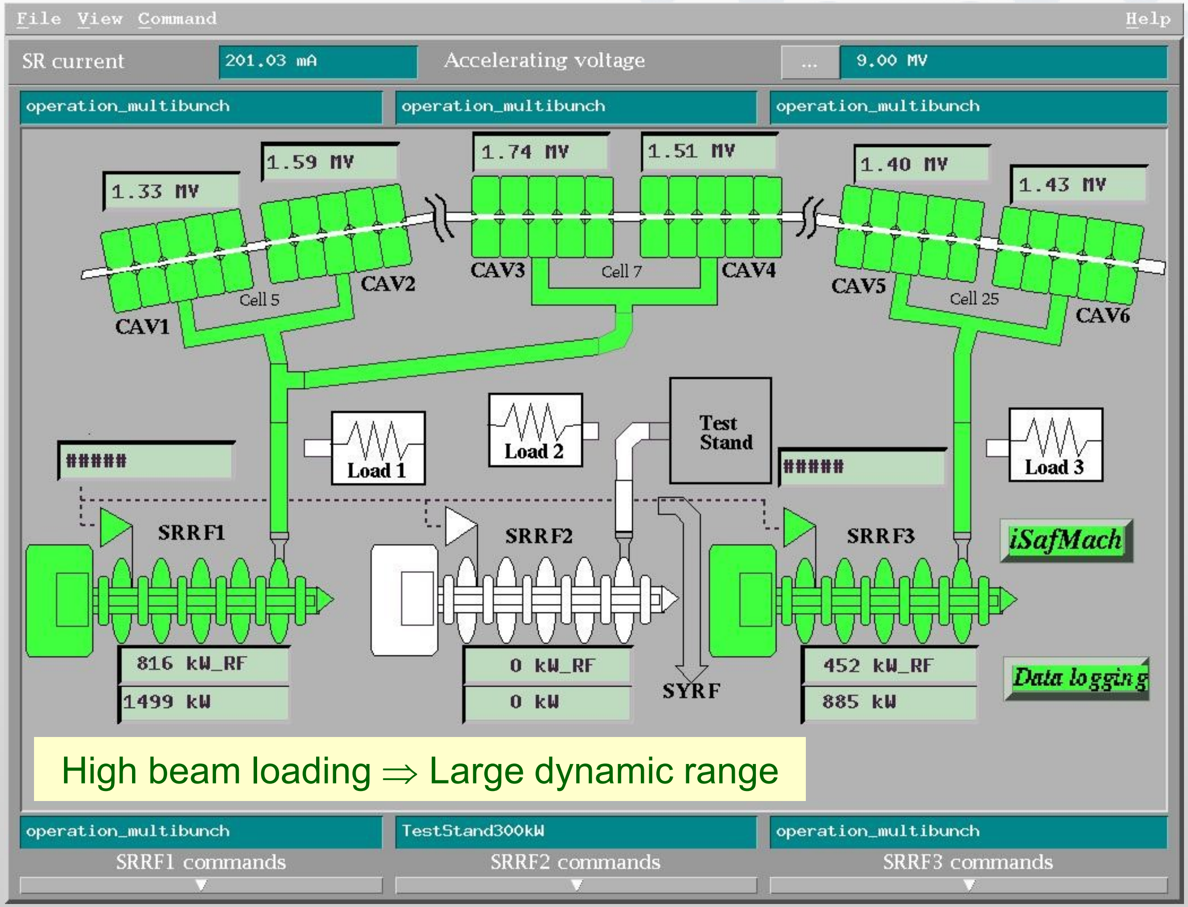
  With Crowbar protection (ignitron, thyratron)

- Modern alternative: IGBT switched PS
- High voltage ⇒ X-ray shielding

⇐



Example - ESRF Storage Ring: RF system in operation



- 1980's: 1.3 MW - 352.2 MHz klystrons developed for LEP/CERN
- Late 1980's:
  - ESRF = first 3rd generation light source
  - Power in the MW range
  - No alternative to klystrons:
    - ☞LEP RF system ⇒ reference design for ESRF (transmitters & cavities)
  - Similar choices by APS, Spring-8, others…
- ESRF: 14 years experience with these tubes from Philips, EEV, Thales

1.3 MW Klystrons: delicate to define working point

Problem	Way out
Harmonic 2 ☞ up to 1 kW on probe	klystron / circulator distance
Multipactoring in input cavity ☞ reduces usable dynamic range	drive power, focusing
Gun breakdowns ☞ backwards ions, e^- ⇒ x-rays, ceramics charging up	focusing, conditioning
HV breakdowns	conditioning
RF breakdowns ☞ in output coupler	
Barium pollution from cathode overheating ☞ anode current, breakdowns	• regular heating adjustment • low heating when no beam
Sometimes	retuning of cavities

Once stable conditions ⇒ 1000's of hours reliable operation

High Power Klystrons at ESRF, continued…

Trip statistics:

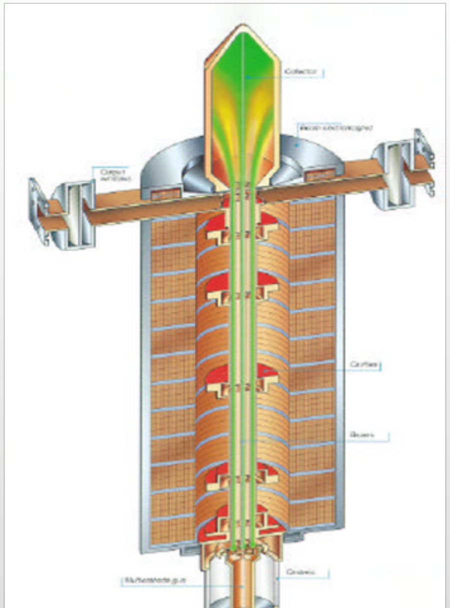
- Total RF system: 25% … 30% of machine trips (ESRF: MTBF > 2 days, availability > 98%)
- Klystron failure rate < auxiliaries' failure rate:
  - Argument for small number / high power tubes
- 900 kW / 450 kW operation: same trip rate
  - Not much linked to power level

Typical klystron drawbacks:

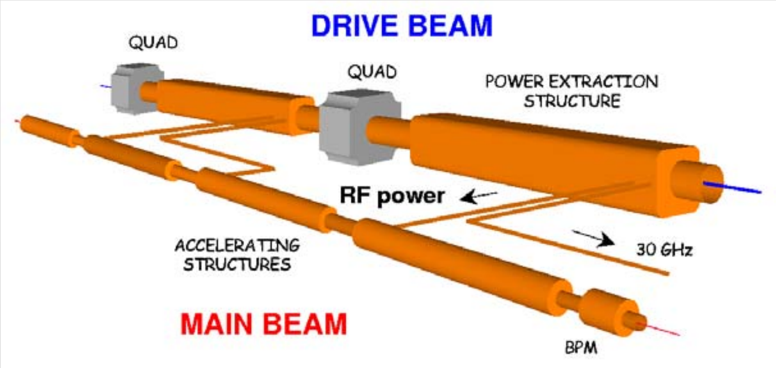
- $d\Phi/d(HV) \approx 7\,°$ per % HV
  - Phase noise up to -50 dBc at multiples of 300 Hz / HVPS ripples
  - Beam sensitive ($f_{synchrotron}$ = 1.2 to 2 kHz)
  - Fast phase loop → -70 dBc
  - Better (in future): switched PS, high switching frequency
- Drive power close to saturation ⇒ reduced gain for fast RF feedback for high beam loading → at PEP II: digital klystron lineariser [J. Fox et al.]
- Today only one klystron supplier for 352 MHz 1.3 MW klystrons

Pulsed Klystrons - examples

- S band klystron
  - 35 … 45 MW at 3 GHz, pulses < 10 μs
  - SLAC and pre-injectors of many machines, including light sources
- Recent developments:
  - Multi Beam Klystron for high efficiency, ex: 1.3 GHz (Thales, CPI, Toshiba)
    - Low Perveance to maximize η: 45 % → 65 %
    - High power: 10 MW / 1.5 ms pulses at "low" HV: 120 kV
      ⇒ cathode for several beams
    - TESLA, X-FEL, … *[see e.g. XFEL TDR]*
  - Periodic Permanent Magnet – PPM klystrons
    - Example: 75 MW / 11.4 GHz for NLC: saving 80 MW of focus supply !



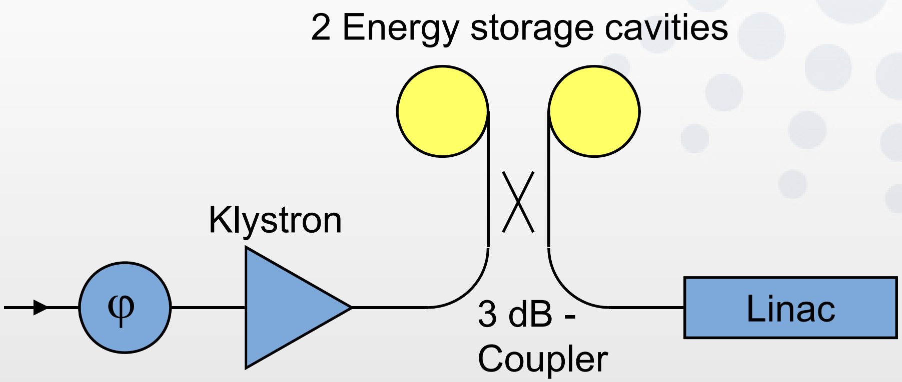
[Thales MBK] 7 beams



- Future: CLIC concept = very dedicated RF source
  - 3 GHz / 937 MHz (CTF3/CLIC) high intensity drive beam
  - → PETS: transfer ≈ 10 MW/cm at 30 GHz to high energy 3 TeV Linac
    (recent modification: 12 GHz Linac achieving 100 MV/m)

[http://clic-study.web.cern.ch]

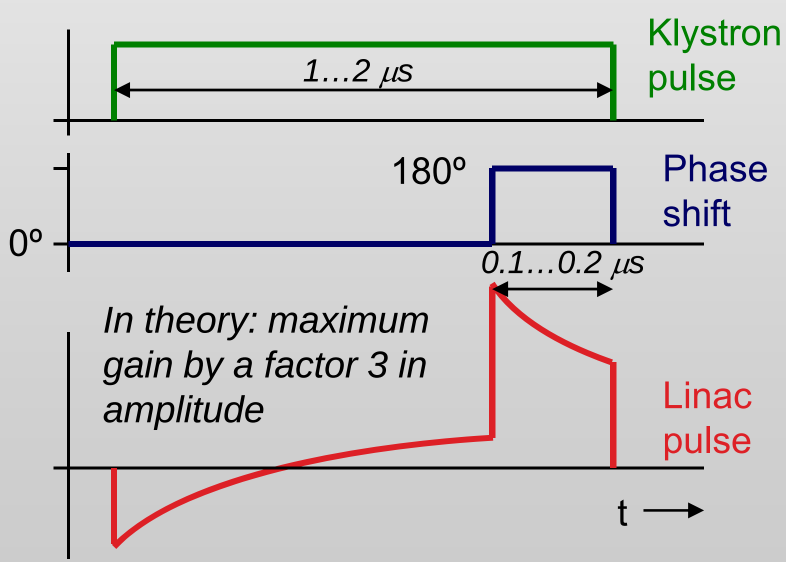
SLED – Pulse Compression

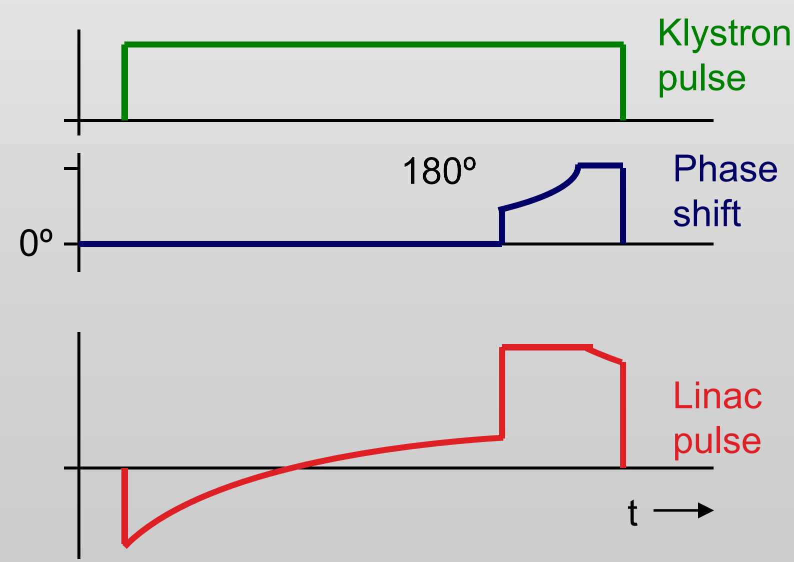


SLED = Stanford Linac Energy Doubler

- SLED II: flatten pulses by replacing cavities with long resonant delay lines [Kroll et al., SLAC]

- Continuous phase shift [Fiebig & Schieblich, CERN]:

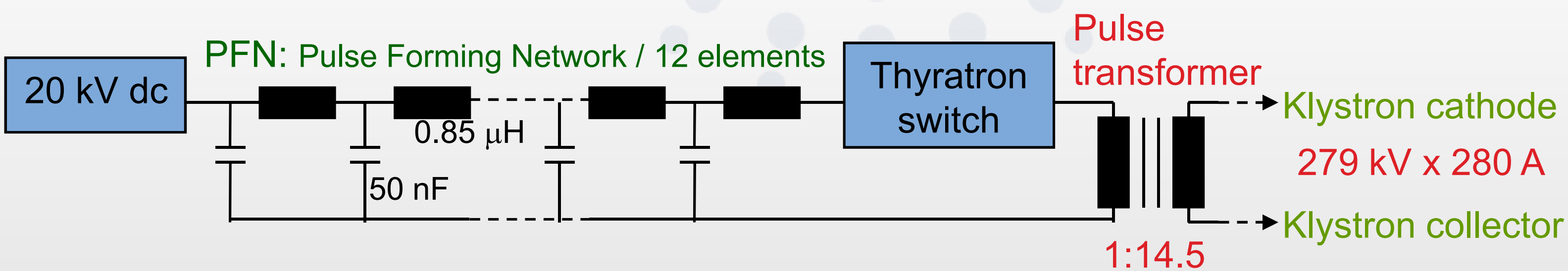




Examples of Modulators for pulsed Klystrons

- PFN modulator of ESRF 3 GHz Linac:

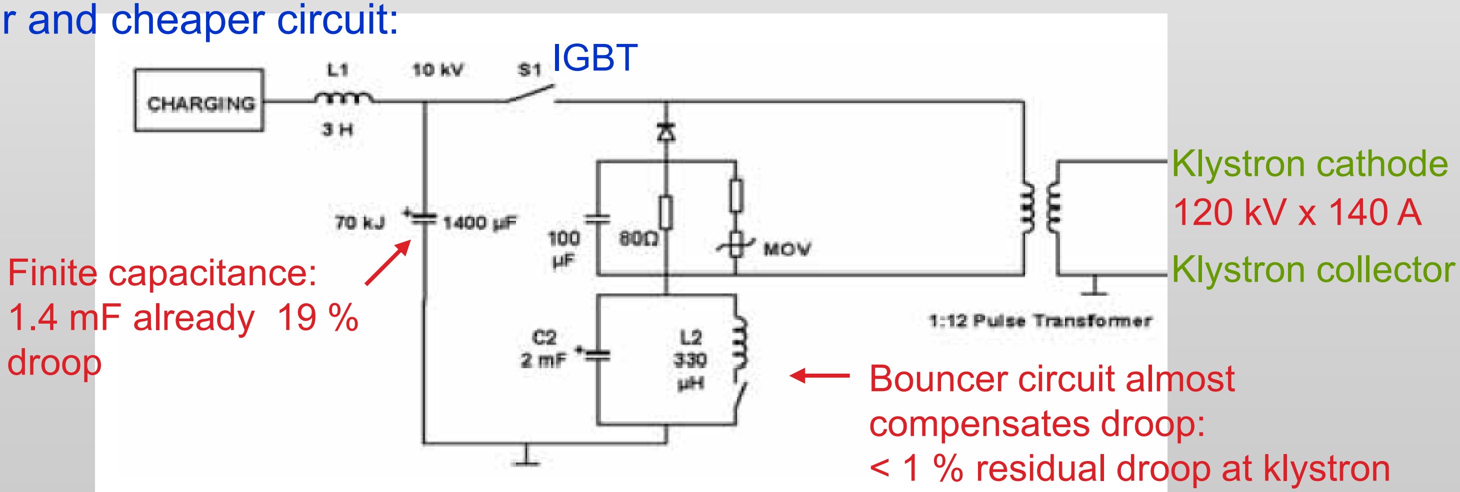
  10 Hz - 78 MW HV pulse / 3.5 μs flat top / ripple < ± 0.5 % ⇒ 37 MW RF pulse



- Bouncer modulator for FLASH or XFEL 1.3 GHz klystrons [XFEL TDR]

  10... 30 Hz - 17 MW HV pulse / 1.5 ms flat top / 10 MW RF pulse

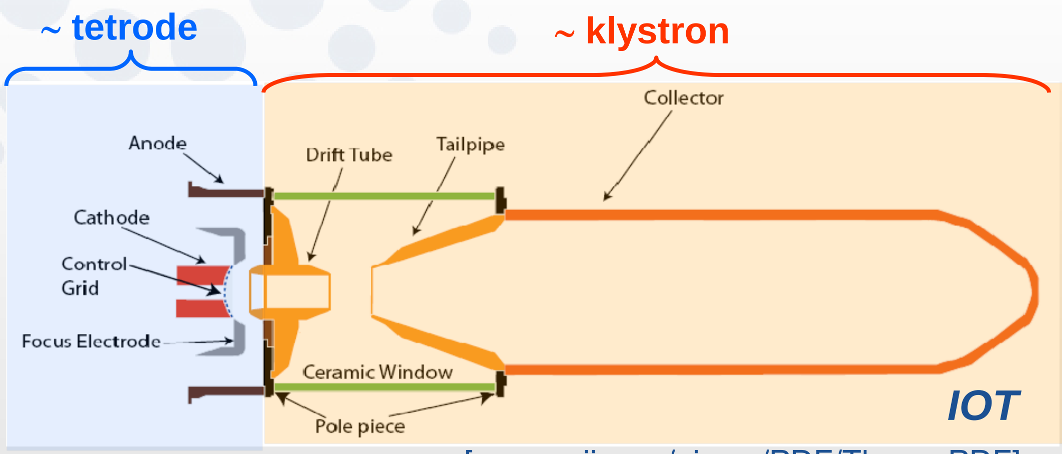
  Simpler and cheaper circuit:



IOT - Inductive Output Tubes or klystrodes

TV-IOT from E2V

TV –IOT from CPI



[www.cpii.com/eimac/PDF/Theory.PDF]

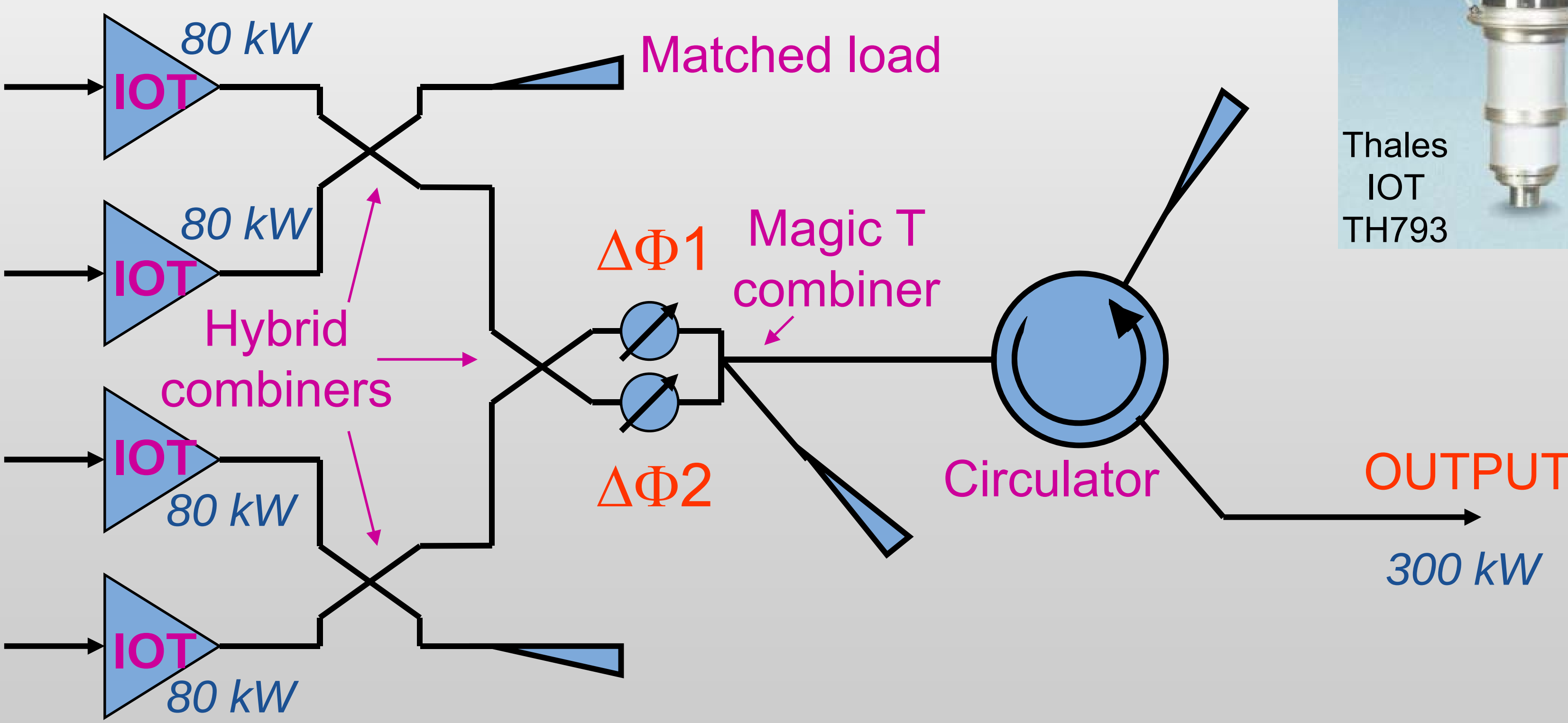
☞ Often with external in-air cavities allowing easy IOT exchange

- TV IOT: typically 60 kW at 460 – 860 MHz
- IOT developed for accelerators [Thales, CPI]:
  - 80 kW CW at 470 – 760 MHz
  - η ≈ 70% ☞ *operation in class B*
  - Intrinsic low Gain = 20 … 22 dB ⇒ P_{in} = 1 kW
  - Compact, external cavity ⇒ easy to handle
  - BUT: low unit power ⇒ power combiners

- 1.3 GHz IOT for cw X-FEL Linacs & ERLs
  - 16…20 kW
  - η ≈ 55 to 65% [Thales, CPI, E2V]
  - No adequate klystron on the market
  - Superiority of IOTs:
    - ☞Higher efficiency
    - ☞Less amplitude & phase sensitivity to HV ripples
    - ☞No collector overheating after loss of drive
    - ☞Expected lower costs

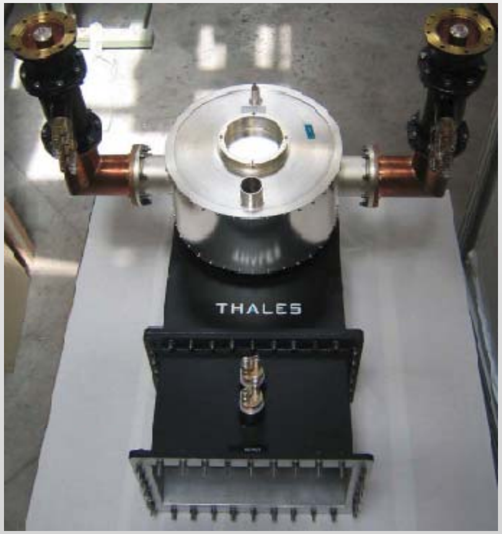
Example: IOT transmitters for SC-Cavities of DIAMOND

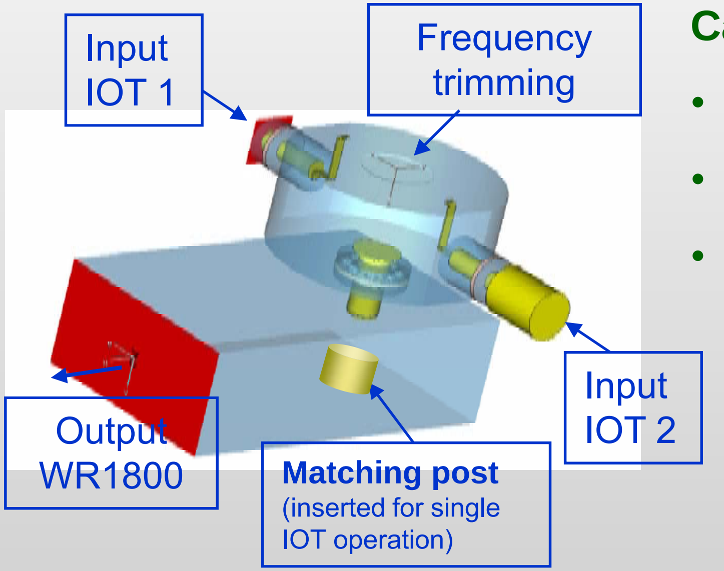
- **First Storage Ring in the world powered with IOTs**
  - 300 kW / SC cavity *(2, ultimately 3 cavities)*
  - **Waveguide type** power combiner 4 x 80 kW
  - One IOT failure ⇒ still 188 kW if ΔΦ1 and ΔΦ2 are set properly
  - Turn key transmitters & TH793 IOTs from Thales



Example: IOTs with cavity combiners for ALBA

- 150 kW / NC cavity *(6 cavities)*
- Compact **Cavity type** power combiner 2 x 80 kW
- Turn key transmitters & TH793 IOTs : from Thales





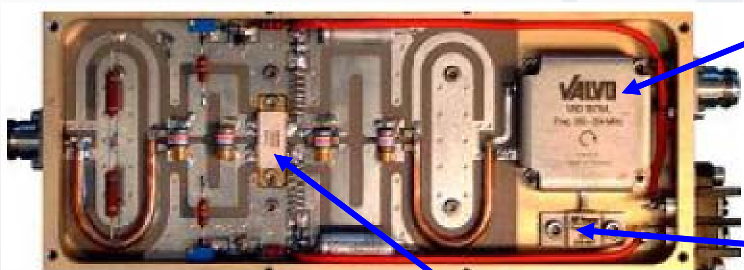
Cavity Combiner - "CaCo"

- MWS design / ALBA
- 100 % match for 2 IOTs
- One IOT off and detuned:
  - ⇒ Adjust tuning plunger in output waveguide
  - ⇒ Re-establish match > 99%

- Compact and modular design
- Unit power of IOT & Cavity well matched (factor 2)
- Extendable: 1 Caco to combine many more IOT's

[P. Sanchez & M. Langlois, ALBA, ESLS RF, Oct. 2006]

SOLEIL 352 MHz Solid State Amplifier



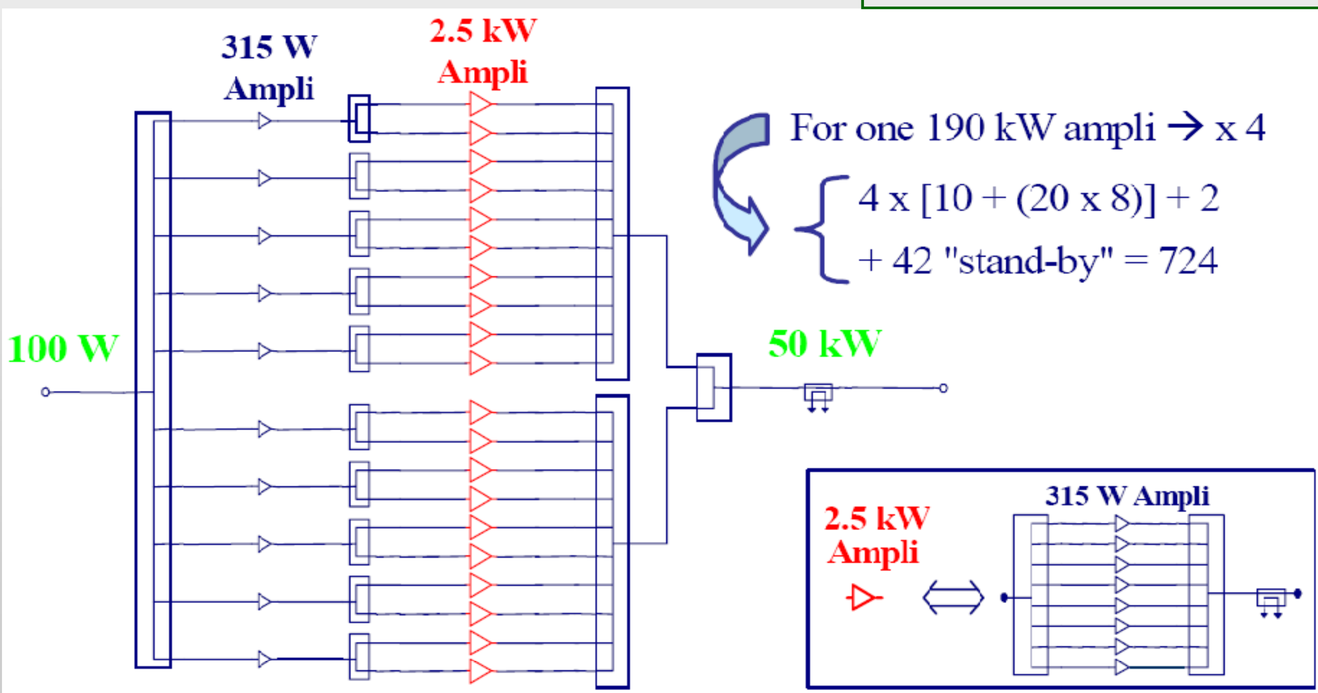
Circulator

500 W load

315 W module

Push pull transistor

300 V / 30 V dc-dc converter



[P. Marchand, Ti Ruan et al., see e.g. PRST AB, 2007]

RF Power Combiners and Splitters

Power Combiner

200 kW | 100 kW | 25 kW | 2.5 kW

Power Splitter

SOLEIL 352 MHz Solid State Amplifier

First 2 SSA powering
2 SC SOLEIL cavities:

1 SSA = 4 x 45 kW towers → max: 180 kW

SOLEIL storage ring:

- no IOT at 352 MHz,
- no klystron for 160 kW / SC cavity

⇒ Development of tailored solid state amplifiers for each of the 4 cavities

- Features confirmed after 3 years of operation of the storage ring
  - Extreme modularity
  - High redundancy: no interruption if some modules fail ⇒ reliable operation
  - No need for HV
  - No need for a high power circulator
  - Simple start up procedures
  - Easy operation and maintenance

Upgrade of ESRF 352.2 MHz RF system

Existing Operation at 200 mA

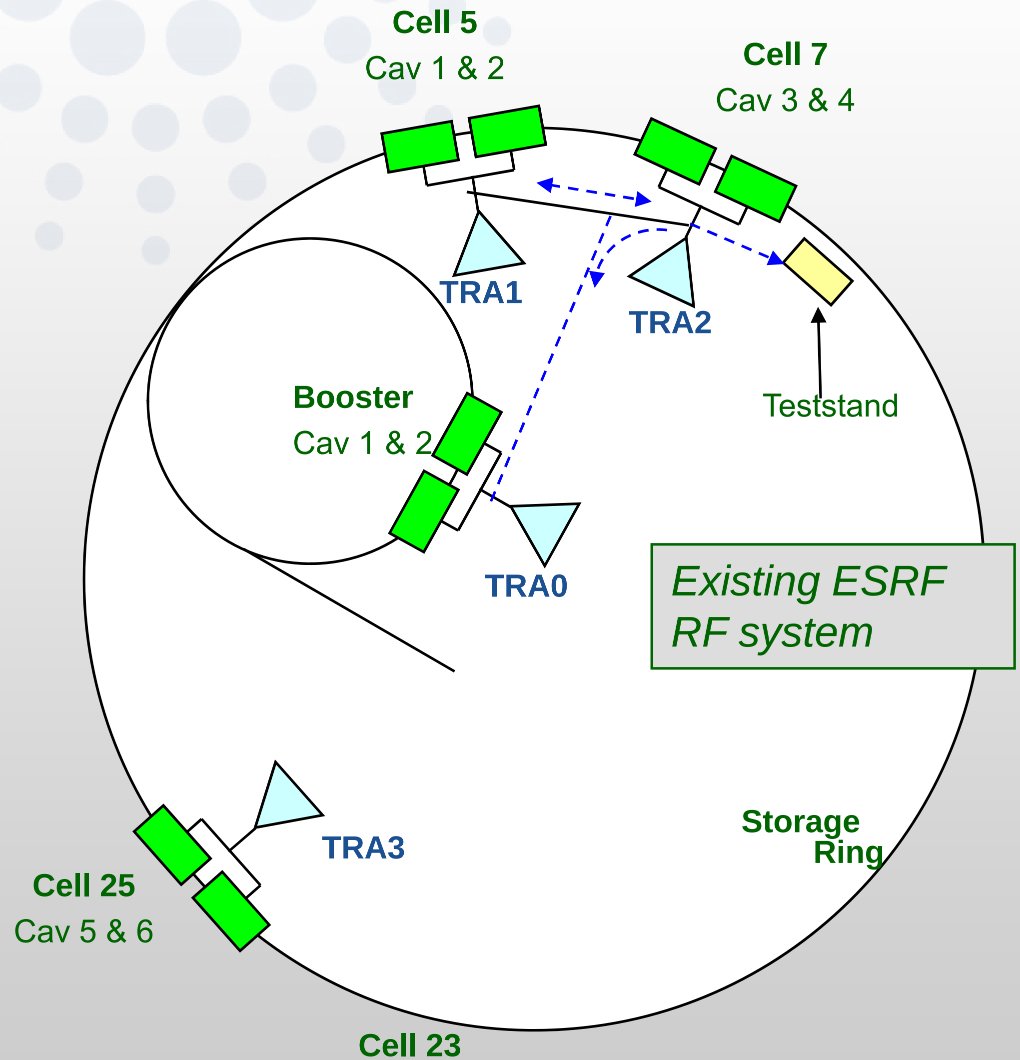
- Redundancy in case of any transmitter failure
- Suppression of HOM driven Longitudinal Coupled Bunch Instabilities by Cavity Temperature regulation

Current upgrade to 300 mA

- No transmitter redundancy
- Need LFB to stabilize HOM driven instabilities
- Increased voltage to master Robinson Instability

Long term

- Only 1 klystron manufacturer left, possible obsolescence
- That particular design: stability issues

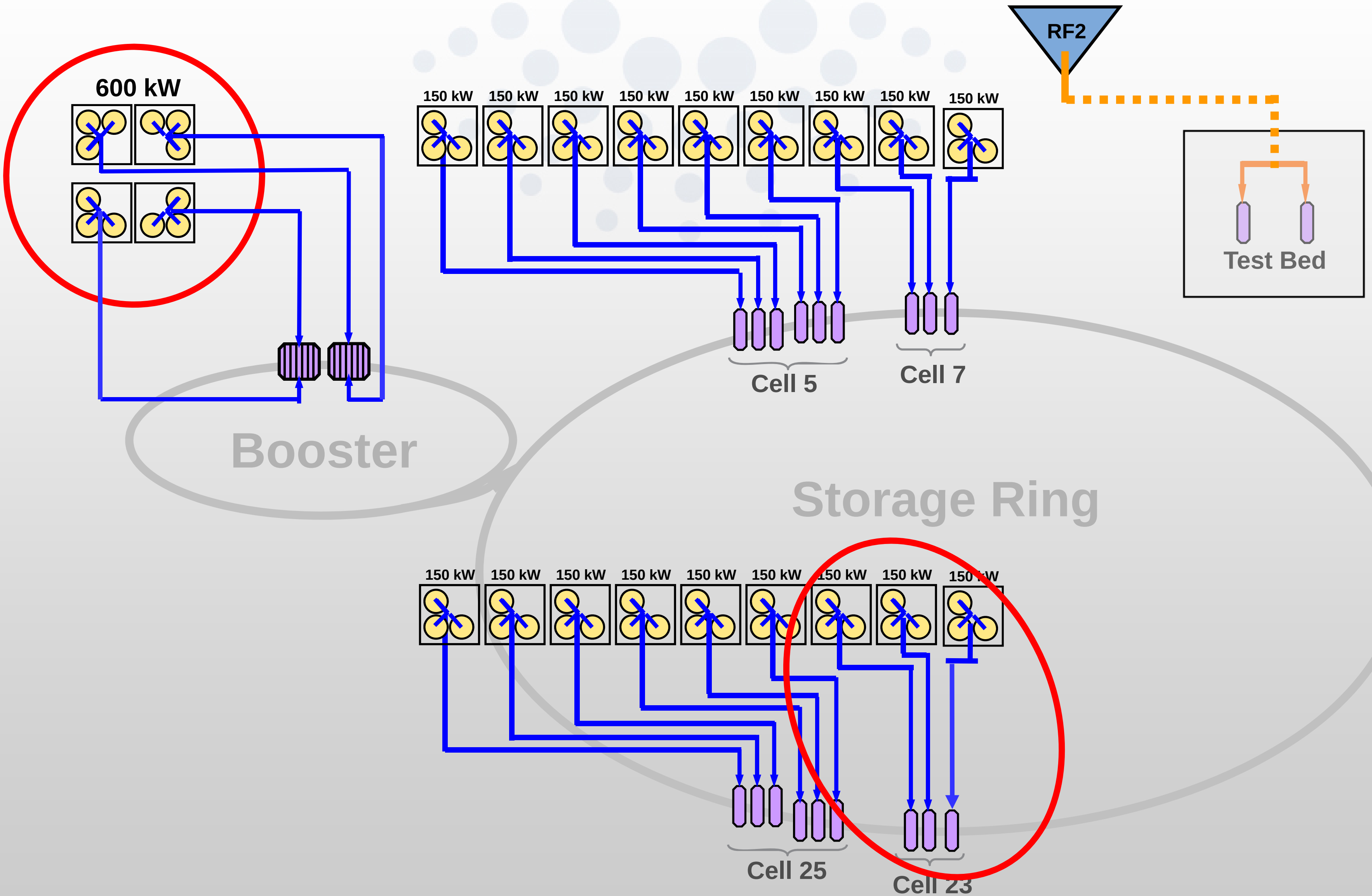


ESRF RF upgrade

- Replacement of 6 five-cell cavities with 18 new HOM damped Cavities for the Storage Ring
- Transmitter upgrade with 150 kW Solid State Amplifiers (SSA):
  - SSA highly modular ⇒ redundant ⇒ intrinsically reliable
  - Good experience at SOLEIL
  - 20 dB less phase noise
  - No HV
  - No X rays
  - Easy maintenance
  - Likely to become the new standard for high power CW RF applications

- Phase 1 has started: procurement of 7 x 150 kW SSA:
  - 4 x 150 kW for the booster RF
  - 3 x 150 kW for the new RF in cell 23
- Similar layout as for SOLEIL, but with
  - Next - 6th generation LDMOS transistors
  - 500…700 W, i.e. almost doubled RF power per module
  - 2 x 75 kW towers, also almost doubled RF power per tower
  - Reduced space requirement
- Status: Order for phase 1 about to be placed

Overview of ESRF RF upgrade

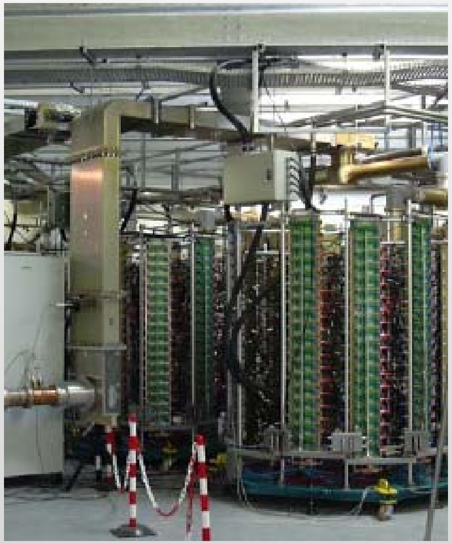


Summary (1)

1. Clear trend towards compact and modular RF transmitters for frequencies ≤ 1.3 GHz
2. As for recent TV transmitters, IOTs are increasingly selected for accelerators:
   - High η = 65 … 70 %
   - Up to 300 kW at 500 MHz by power combining schemes
   - Combiners designed to sustain operation if 1 IOT fails
   - Modularity, ease of manipulation: attractive features for modern user facilities, which must achieve high up time with limited manpower
   - Intrinsically lower phase noise and high efficiency = major advantage of IOTs over Klystrons for 1.3 GHz cw SC Linacs & ERLs

Summary (2)

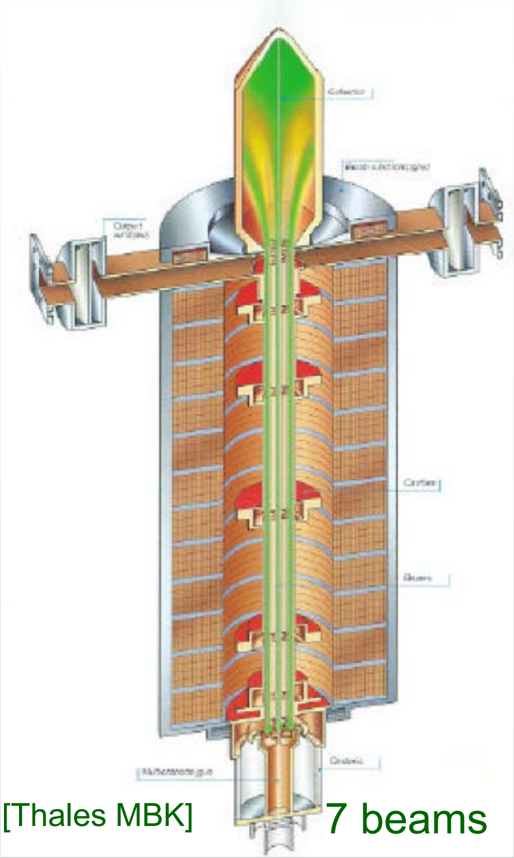
3. Solid state amplifiers entered field of high power RF generation:



- Highly innovative approach → next trend for accelerator applications ?
- Combining 100’s of 300 to 1000 W RF modules to obtain 100’s of kW total RF power
- Could open the door to highly industrialised mass production of RF power modules
- Extremely modular: probably easy to operate and maintain even for small crews
- Overall reliability and availability could approach 100 %, provided:
  - ☞ Intervention and replacement procedures are well established
  - ☞ Good procurement strategy in place

Summary (3)

4. Accelerator applications requiring multi-MW level (mostly the case for pulsed systems)
   - Replacement of klystrons with the combined power of tens of IOT's does not seem attractive in terms of complexity, reliability and costs.
   - Still need for classical klystron transmitters
5. Today no alternative to high power klystrons at frequencies above 1.3 GHz



[Thales MBK] 7 beams

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… See also other references either as indicated on the slides as well as more recent publications from the authors and labs cited above…