New Developments on RF Power Sources

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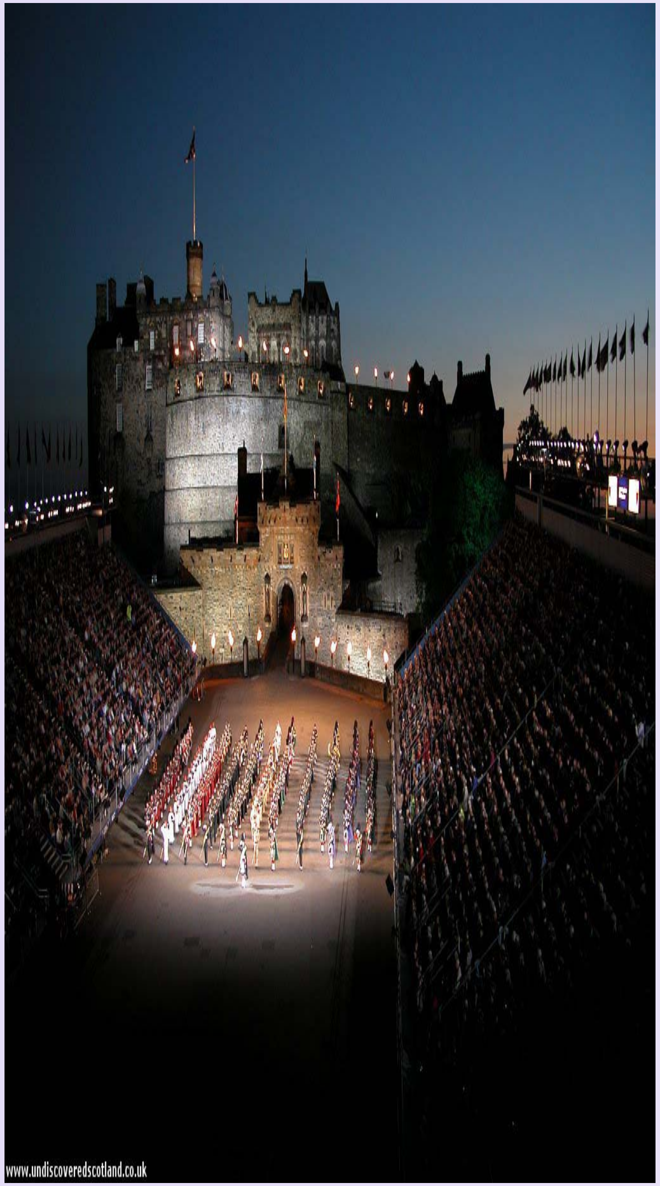
EPAC’06 – Edinburgh, June 2006



Outlook

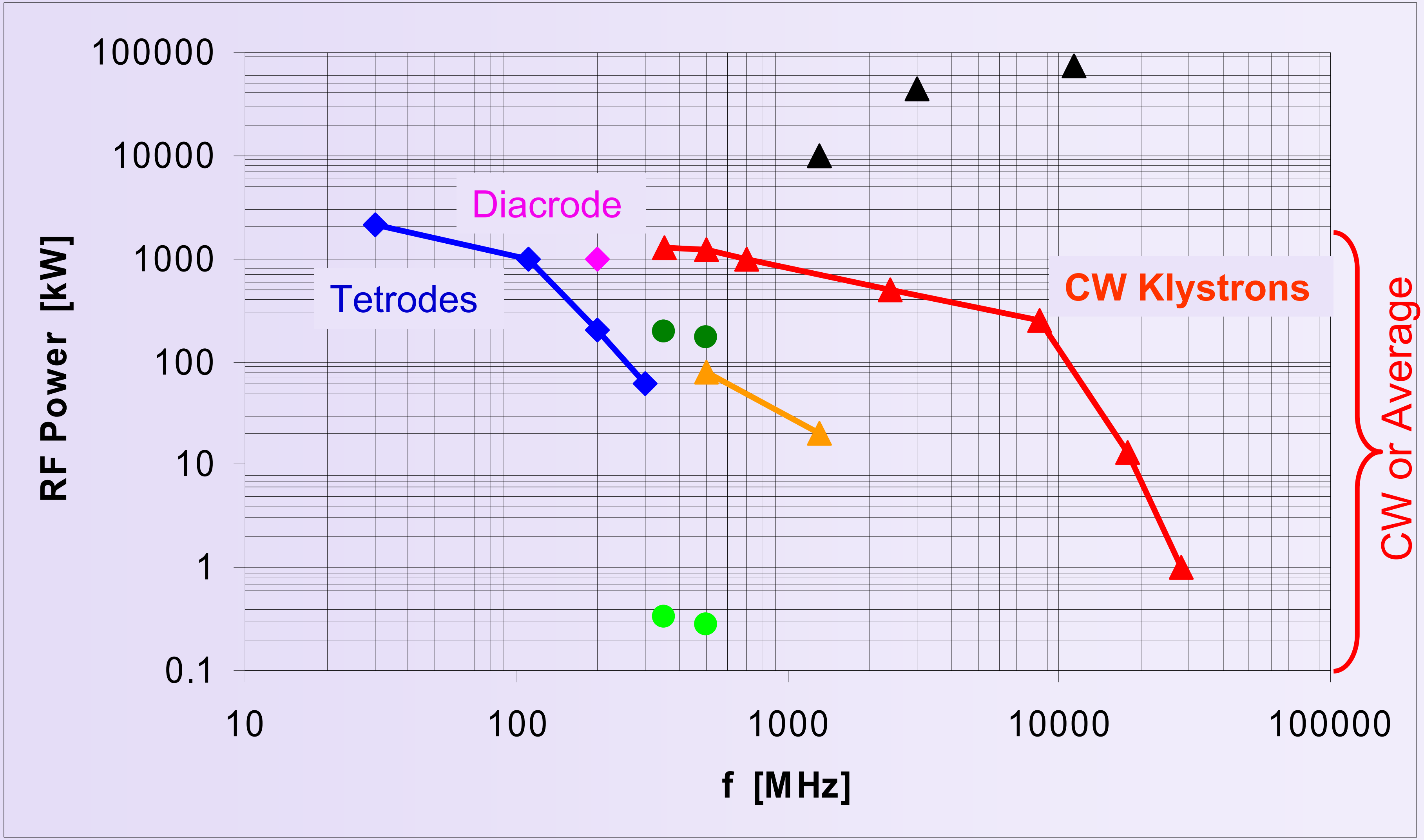
RF power sources for accelerators

- Brief review

350 MHz -1.3 GHz transmitters for recent Storage Rings & Linacs

- Examples using
  - ◊ Klystrons
  - ◊ IOTs
  - ◊ Solid state amplifiers

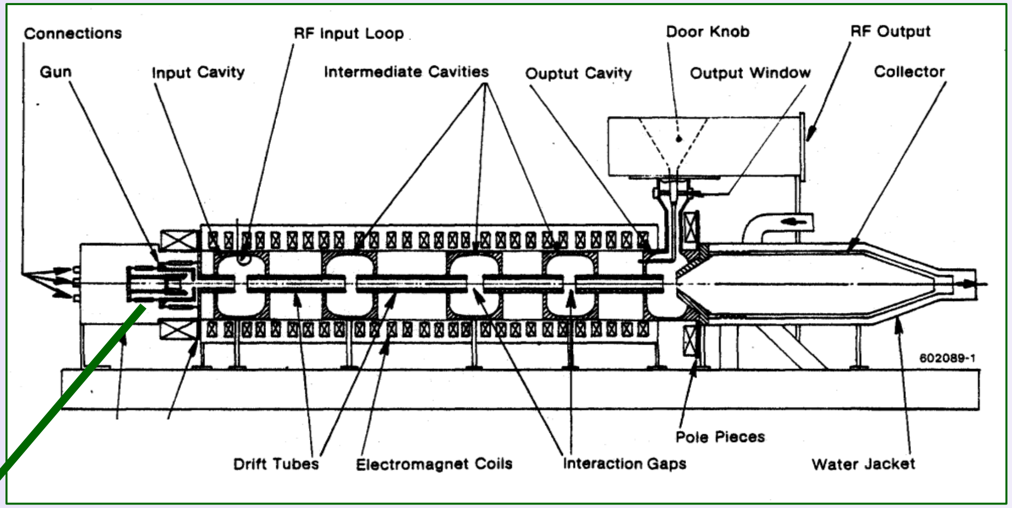
RF power sources for accelerators



CW klystrons

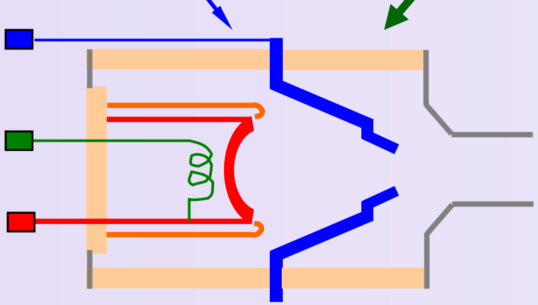
Typical CW klystrons:

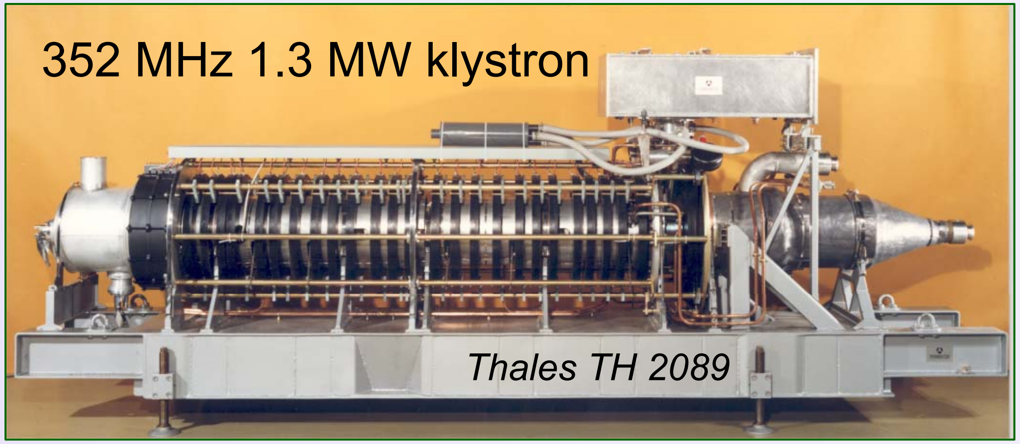
- Smaller accelerators: TV klystrons
  - → *60 kW / 500 MHz*
- Larger Machines: Superklystrons
  - → *1…1.3 MW / 352, 500, 700 MHz*
  - → $\eta_{typ} = 62\ \%$
  - → $G_{typ} = 42\ dB \Rightarrow P_{in} \leq 100\ W$



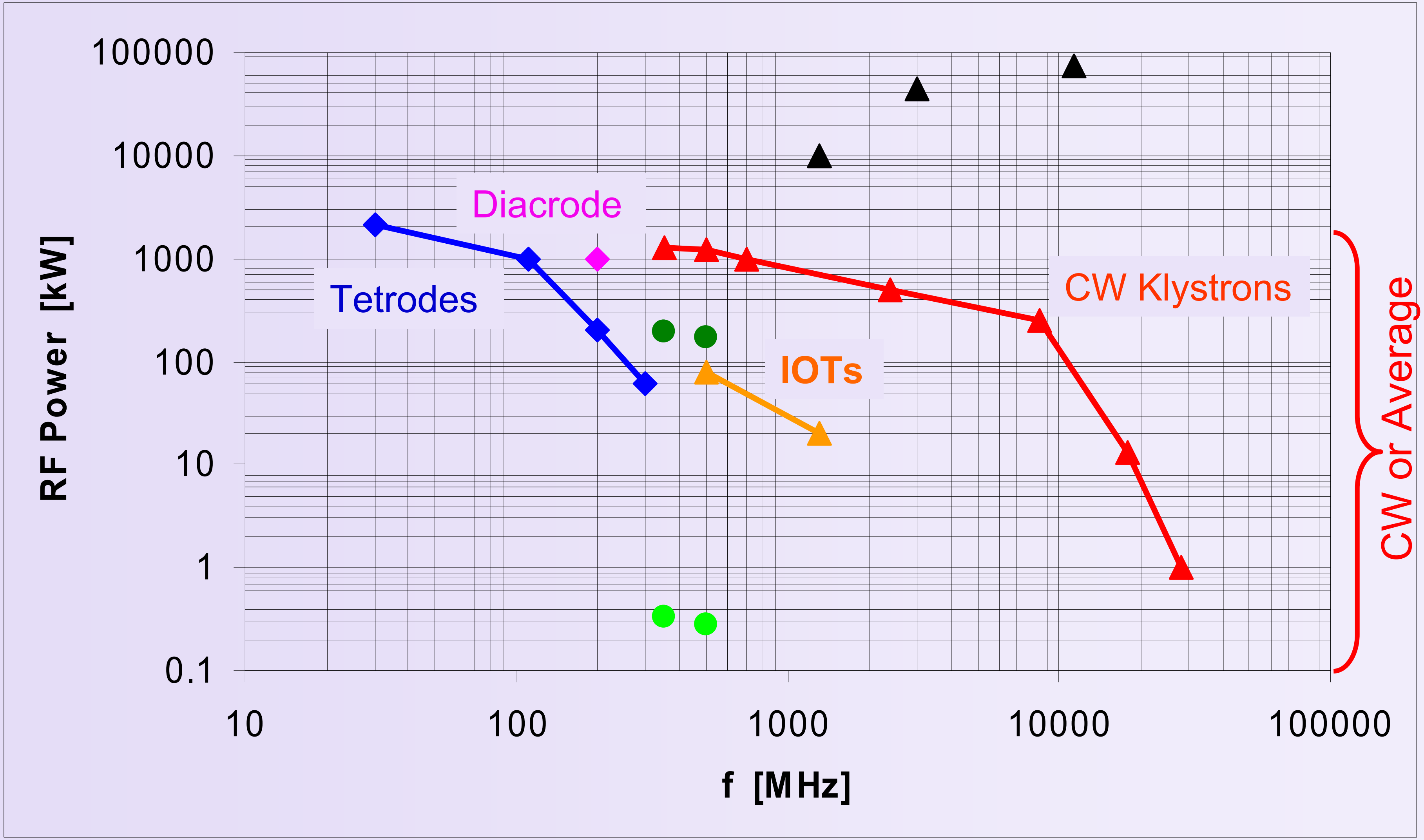
Modulating Anode for good η at lower Power

Gun

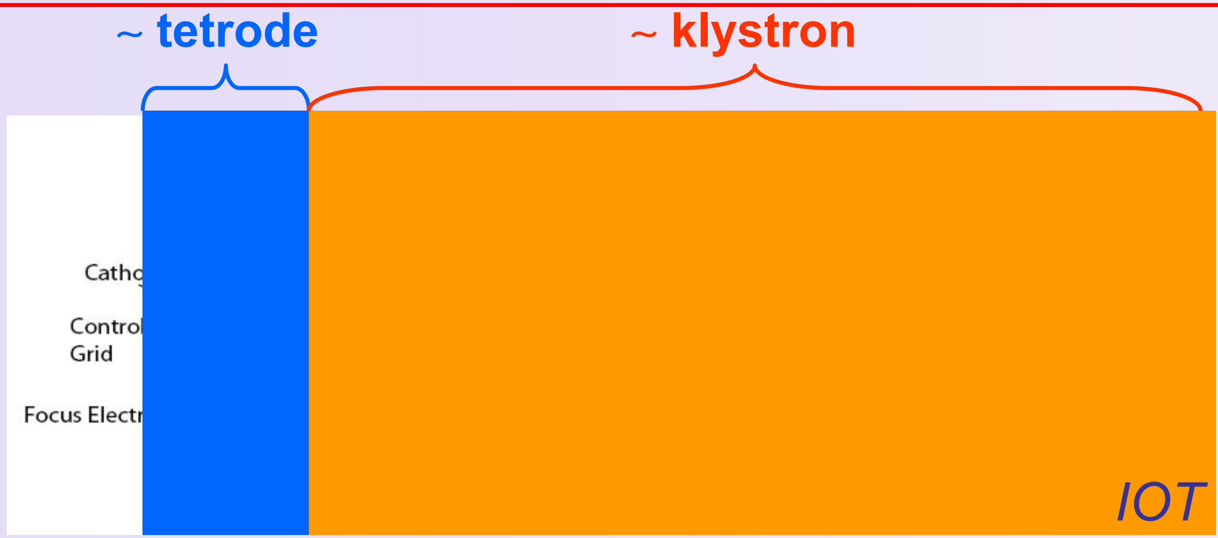




RF power sources for accelerators



IOTs - Inductive Output Tubes or klystrodes



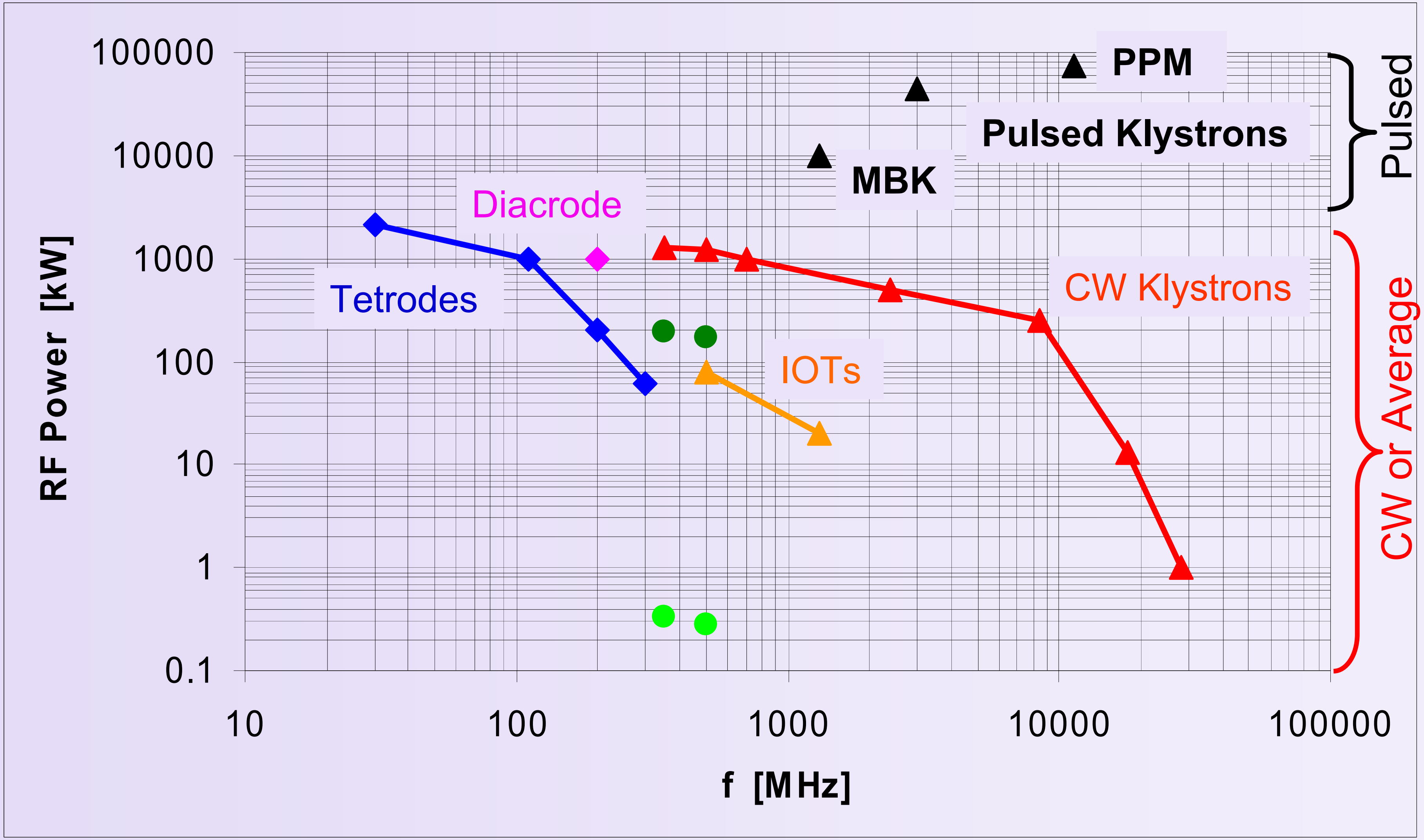
[www.cpii.com/eimac/PDF/Theory.PDF]

- TV IOT: typ. 60 kW at 460 – 860 MHz
- IOT developed for accelerators [Thales, CPI, E2V]:
  - 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]


TV –IOT from CPI


TV-IOT from E2V

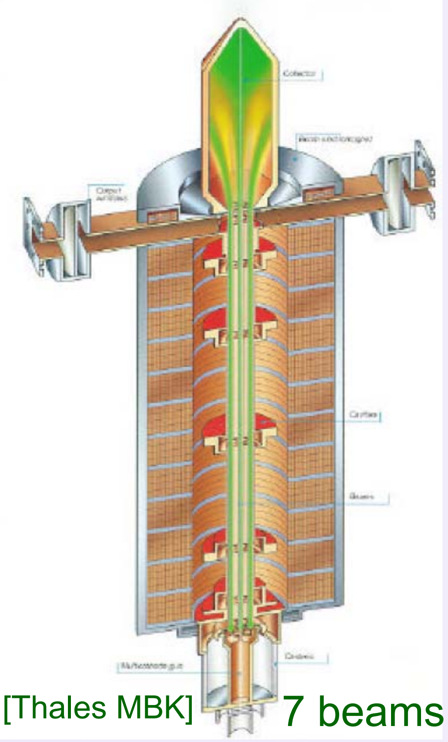
RF power sources for accelerators



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
    - ◊ ILC, X-FEL,…
  - ➢ Periodic Permanent Magnet – PPM klystrons
    - ◊ Example: 75 MW / 11.4 GHz for NLC: saving 80 MW of focus supply !



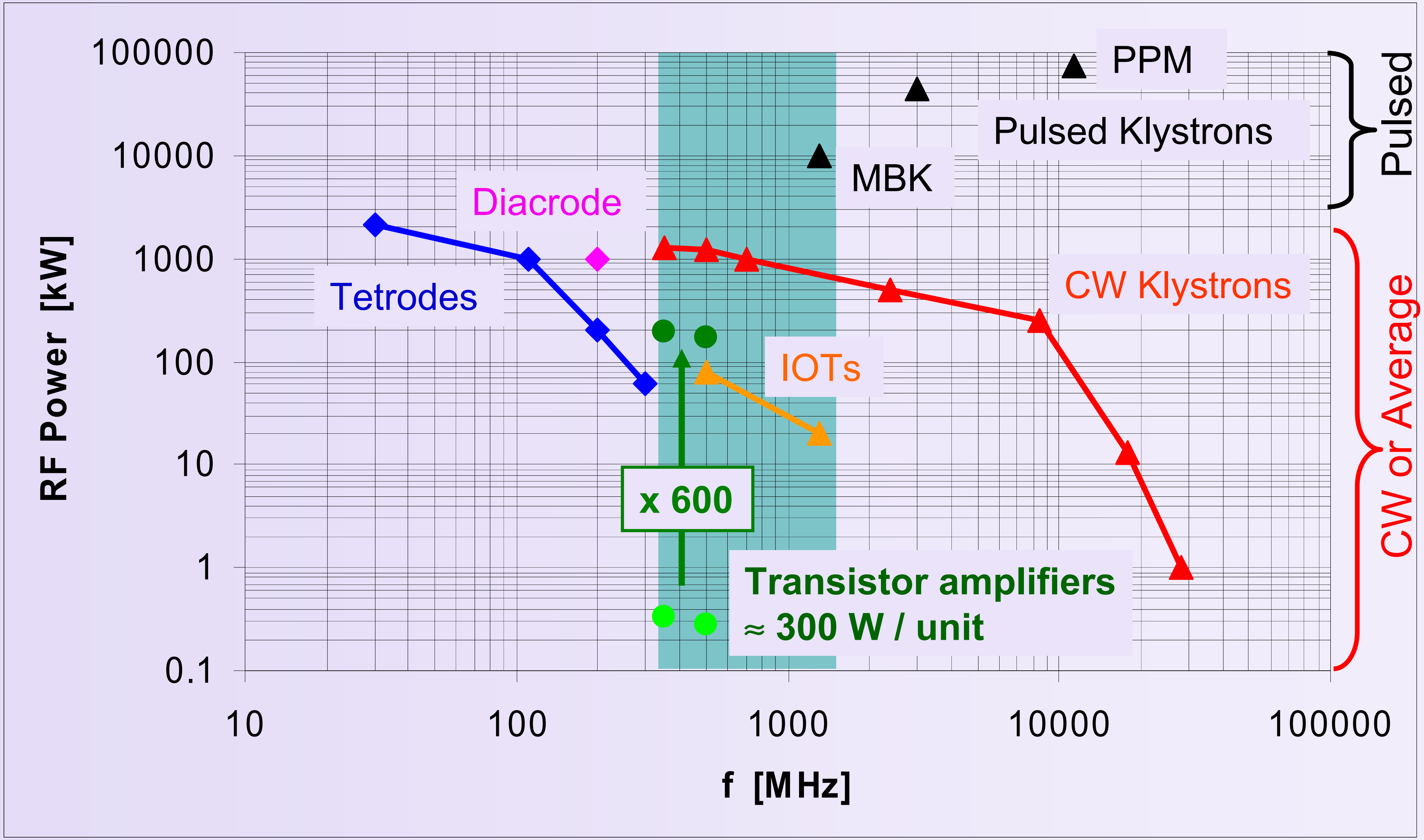
[Thales MBK] 7 beams

- Future: CLIC concept = very dedicated RF source
  - ◊ 3 GHz / 937 MHz (CTF3/CLIC) high intensity drive beam

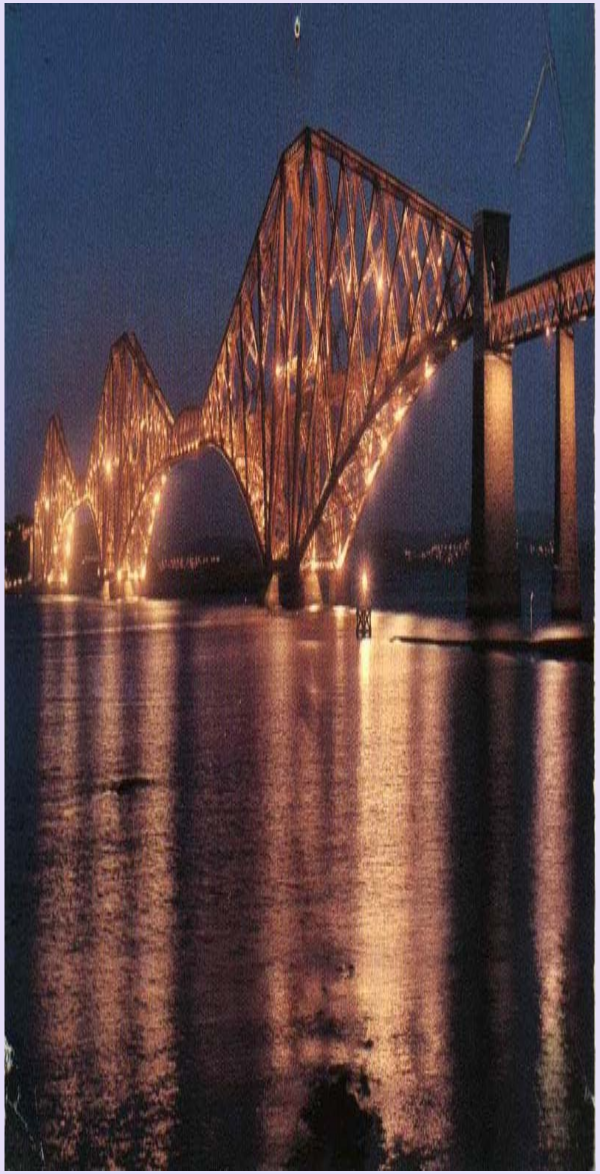
    →PETS: transfer ≈ 10 MW/cm at 30 GHz to high energy Linac

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

RF power sources for accelerators



Recent projects for 350 MHz – 1.3 GHz



What are the criteria of choice between

- Classical klystron transmitters
- IOTs & power combiners
- Solid state amplifiers & power combiners

for various recent examples of

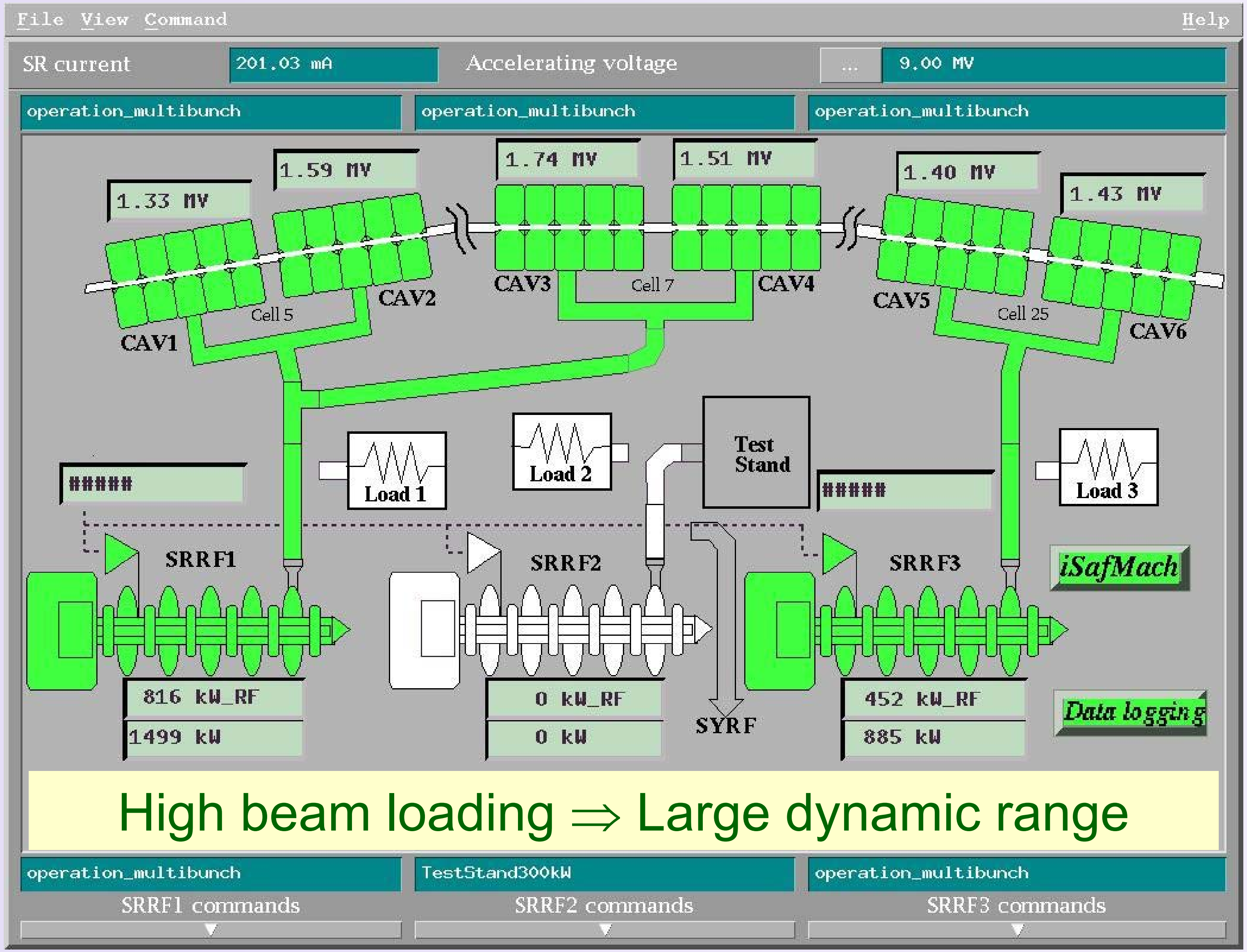
- Storage Rings at 352 or 500 MHz
- SC Linacs & ERLs at 1.3 GHz

?

1) High Power Klystrons at ESRF

- 1980's: 1.3 MW - 352.2 MHz klystrons developed for LEP
- 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

ESRF Storage Ring: RF system in operation



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 > 40 h, 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

→ possible obsolescence ?

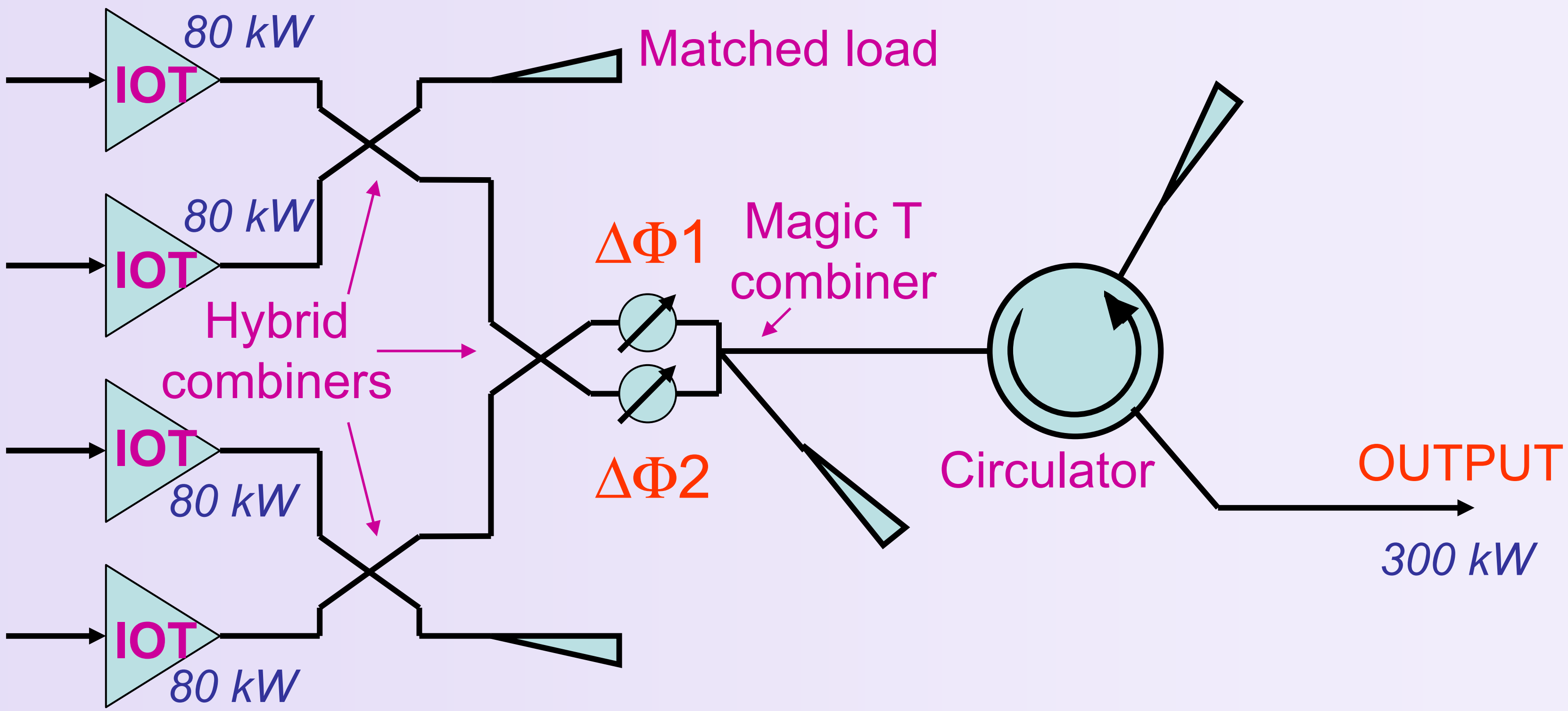
Klystron transmitter / Australian light source

Recent light source

- Turn key transmitters
- 500 MHz 150 kW klystron from Toshiba
- η = 65 %

2) IOT transmitters for 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



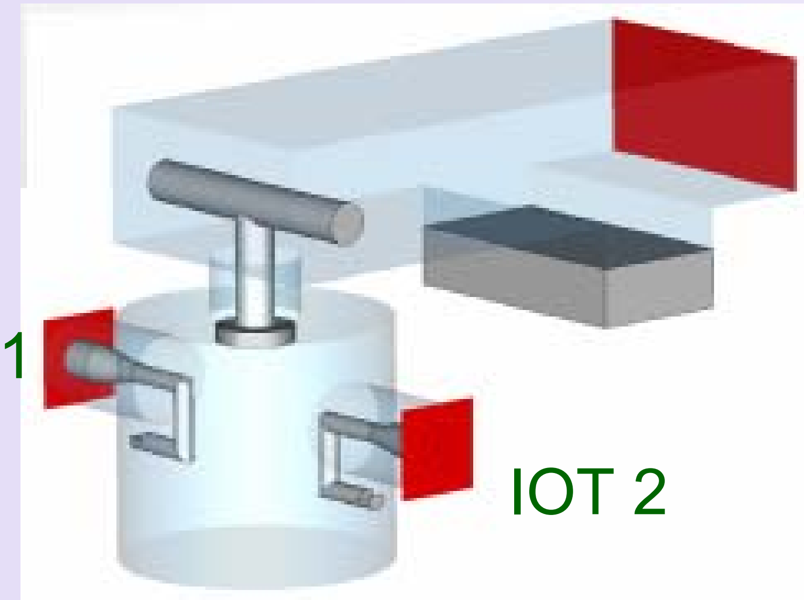
IOT transmitters for DIAMOND, continued…

- 300 kW demonstrated
- Some arcing on IOT and inside output cavity
- Low sidebands: -70 dBc at 50 kHz (crowbarless switched PS)
- DIAMOND commissioning just started: 2 mA stored
  - ➢ Waiting for operation experience before comparing with single klystron transmitter:
    - ◊ Reliability ?
    - ◊ Availability ?
    - ◊ Ease of operation follow up and maintenance by small crew ?

[see poster TUPCH157]

3) IOTs with cavity combiners for ALBA

- 150 kW / NC cavity *(6 cavities)*
- Compact **Cavity type** power combiner 2 x 80 kW
- Prototype by 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)

[see posters TUPCH141 & THPCH179]

4) IOT transmitters for ELETTRA

- Initially:
  - Turn key **60 kW TV-klystron** transmitters operated at 500 MHz
  - Efficient solution in terms of resources and costs for a smaller machine
  - 12 years very reliable operation
- Major machine upgrade
  - Again turn key, 150 kW transmitters from 13 dBm input
  - Finally also combination of 2 x 80 kW IOTs TH793
  - Also one IOT operation possible by phase switching
  - Spec: $\eta \geq 65$ %
  - Crowbarless switched PS: switching frequency adjustable within 16 to 21 kHz

Thales IOT TH793

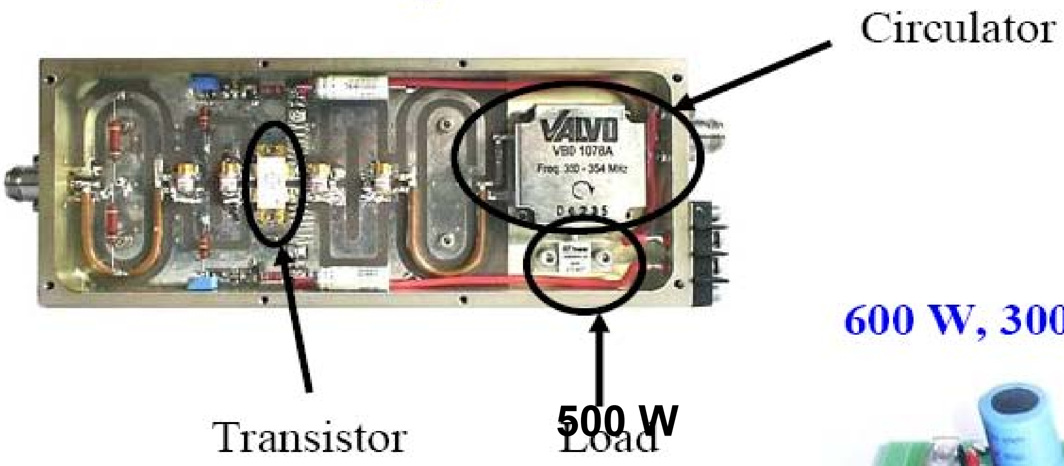
Important argument: availability of IOT amplifiers on TV transmitter market

[A. Fabris, 4th CWHAP, APS, 2006]

5) 190 kW solid state amplifiers for SOLEIL

- Basis = **352 MHz - 35 kW** amplifiers of SOLEIL booster
  - ➢ Combination of 147 amplifier modules:

330 W solid state amplifier module



600 W, 300 Vdc / 30 Vdc converter

C. Thomas-Madec / SOLEIL , 4th CWHAP, APS, 2006

190 kW solid state amplifiers for SOLEIL, continued…

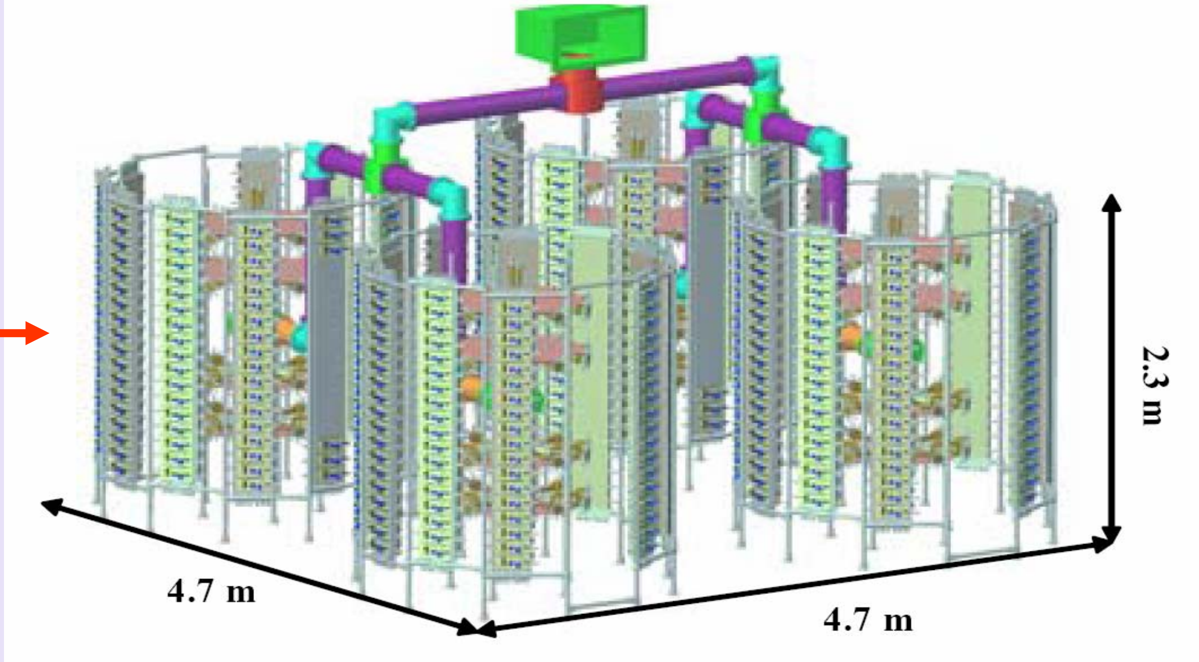
SOLEIL storage ring: no IOT at 352 MHz, no klystron for 190 kW / SC cavity

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

☞ Further development of modules

- LDMOS FET LR301 developed in collab. SOLEIL / POLYFET
- 315 W, 12 dB gain, η = 50 %

50 kW tower



- **352 MHz - 190 kW** Storage Ring amplifier
- 682 modules + 42 in standby

- Claimed features of solid state amplifiers
  - Extreme modularity
  - High redundancy: no interruption if some modules fail
  - No need for HV
  - No high power circulator
  - Simple start up procedures
  - Easy operation and maintenance
- Good experience so far
  - 1000 hours run test with 50 kW tower: only 5 transistors damaged
  - April 2006: 180 kW reached
  - May 2006: Startup on SOLEIL SR: ≈ 60 … 80 mA stored beam

[see poster MOPCH142]

6) 500 MHz 60 kW solid state amplifier for SLS

- At 500 MHz, slightly lower power: 250 W / module
- Low sideband level
- Harmonic 2 is 44 dB below fundamental
- Expected lower costs as compared with Klystron
- Starting investigations of transistors for 300 W up to 1 GHz

[M. Gaspar, 4th CWHAP, APS, 2006]

7) 1.3 GHz IOTs for CW SC Linacs / ERLs

- For future X-FELs operated in CW:
  - MIT, BESSY, 4GLS, … → TESLA type SC Cavities
  - Special development of 1.3 GHz, 16 to 20 kW IOTs [Thales, CPI, E2V]

- Why IOT?
  - ☞ Higher efficiency
  - ☞ Less amplitude & phase sensitivity to HV ripples
  - ☞ No collector overheating after loss of drive
  - ☞ Expected lower costs

[see e.g. A. Zolfghari et al., EPAC 2004]

Conclusion (1)

1. Clear trend towards compact and modular RF transmitters for frequencies ≤ 1.3 GHz

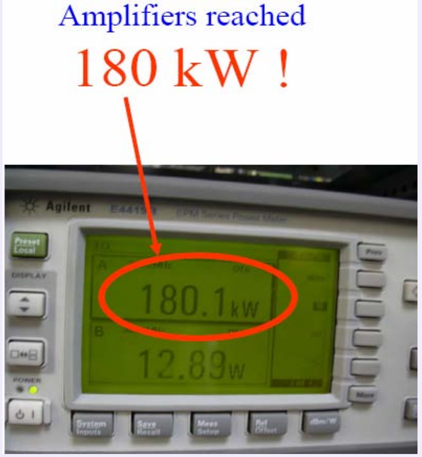
2. As for recent TV transmitters, IOTs are increasingly selected for accelerators:

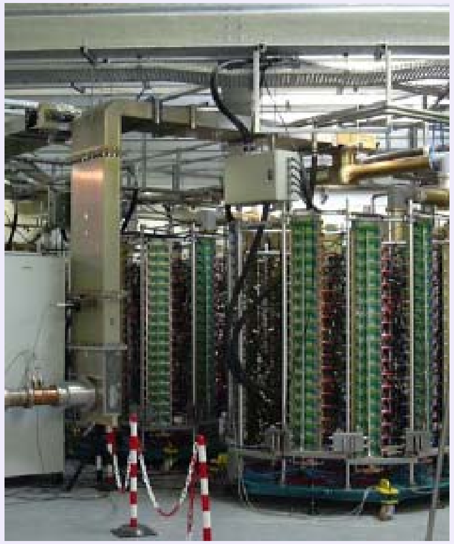
   - High η = 65 … 70 %
   - Up to 300 kW at 500 MHz by power combining schemes
   - Combiners designed to sustain operation if 1 IOT fails
   - Modularity, ease of manipulation: attractive features for modern user facilities, which must achieve high up time with limited manpower
   - Intrinsically lower phase noise and high efficiency = major advantage of IOTs over Klystrons for 1.3 GHz SC Linacs & ERL

Conclusion (2)

3. Solid state amplifiers entered field of high power RF generation:
   - Highly inovative approach → next trend for accelerator applications ?
   - Combining 1000's of 315 W modules

     ⇒ Total of nearly 1 MW at 352 MHz available at SOLEIL
   - 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 well established
     - ☞ Good procurement strategy in place





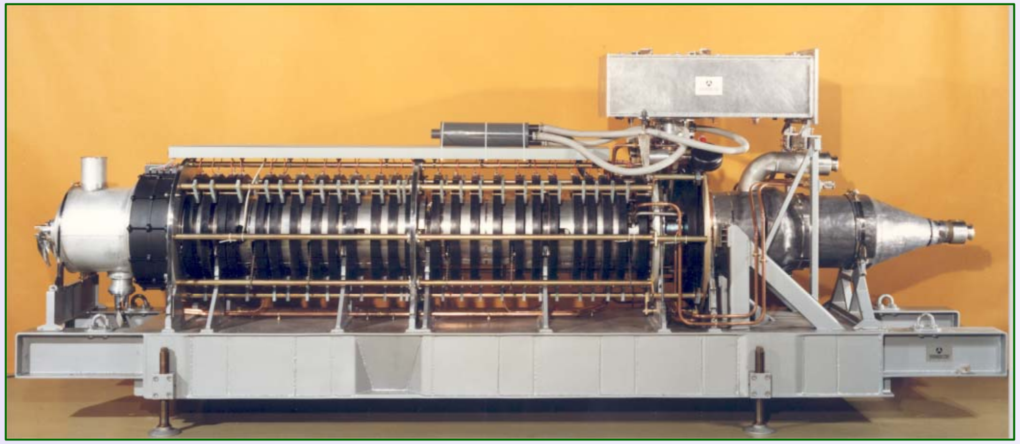
Conclusion (3)

4. Accelerator applications requiring multi-MW level (or 100's kW at 1.3 GHz)

    - Replacement of klystrons with the combined power of tens of IOT's needs to be checked in terms of complexity, reliability and costs.

    - Today, still need for classical klystron transmitters

5. Today no alternative to high power klystrons at frequencies above 1.3 GHz



Summary

1. Clear trend towards compact and modular RF transmitters for frequencies below 1.3 GHz
2. As for recent TV transmitters, IOTs are increasingly selected for accelerators
3. Solid state amplifiers entered field of high power RF generation: future trend ?
4. Still klystrons for accelerator applications requiring multi-MW level (or 100’s kW at 1.3 GHz)
5. Today no alternative to high power klystrons at frequencies above 1.3 GHz