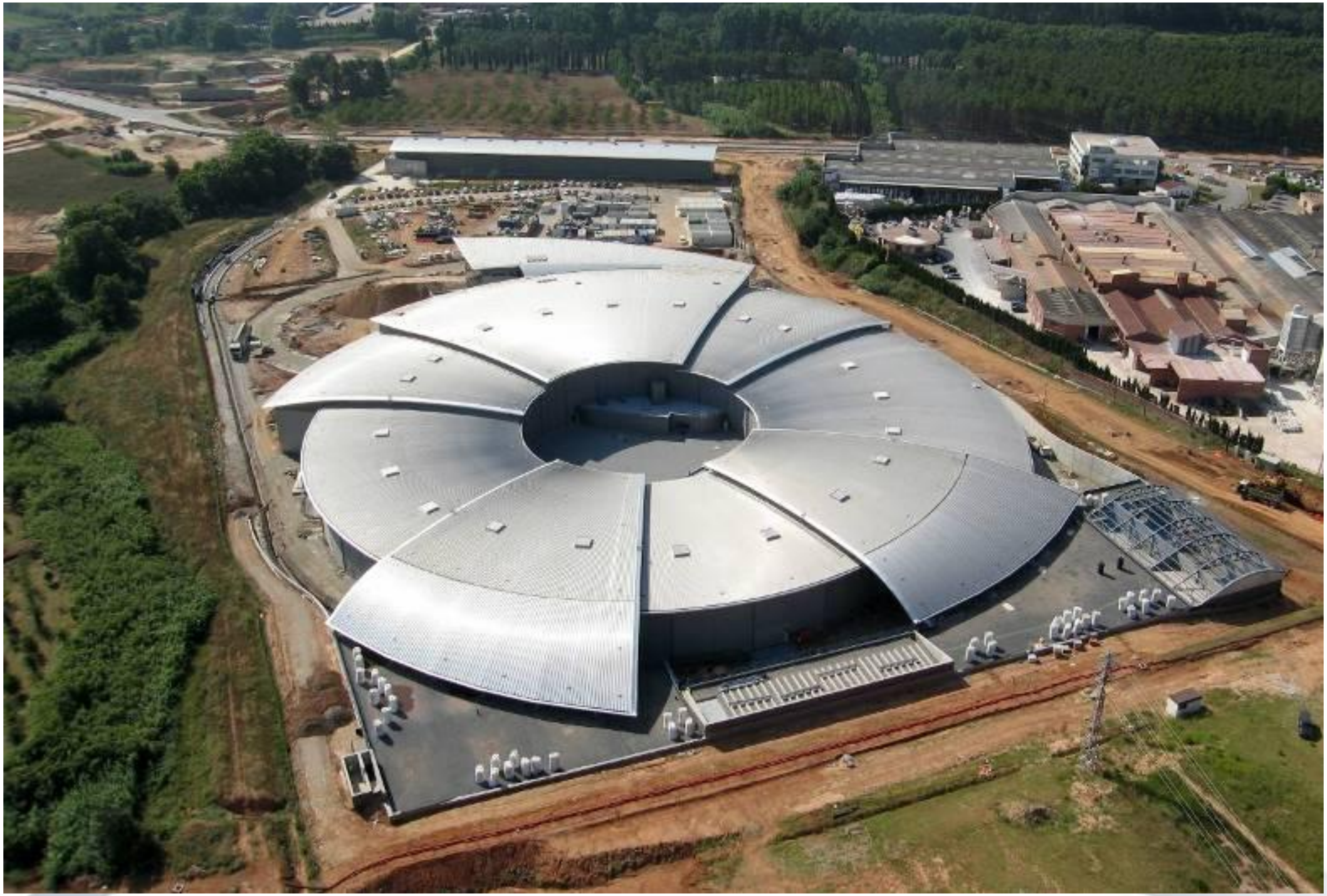
RF Amplifiers: Solid State vs IOTs vs Klystrons



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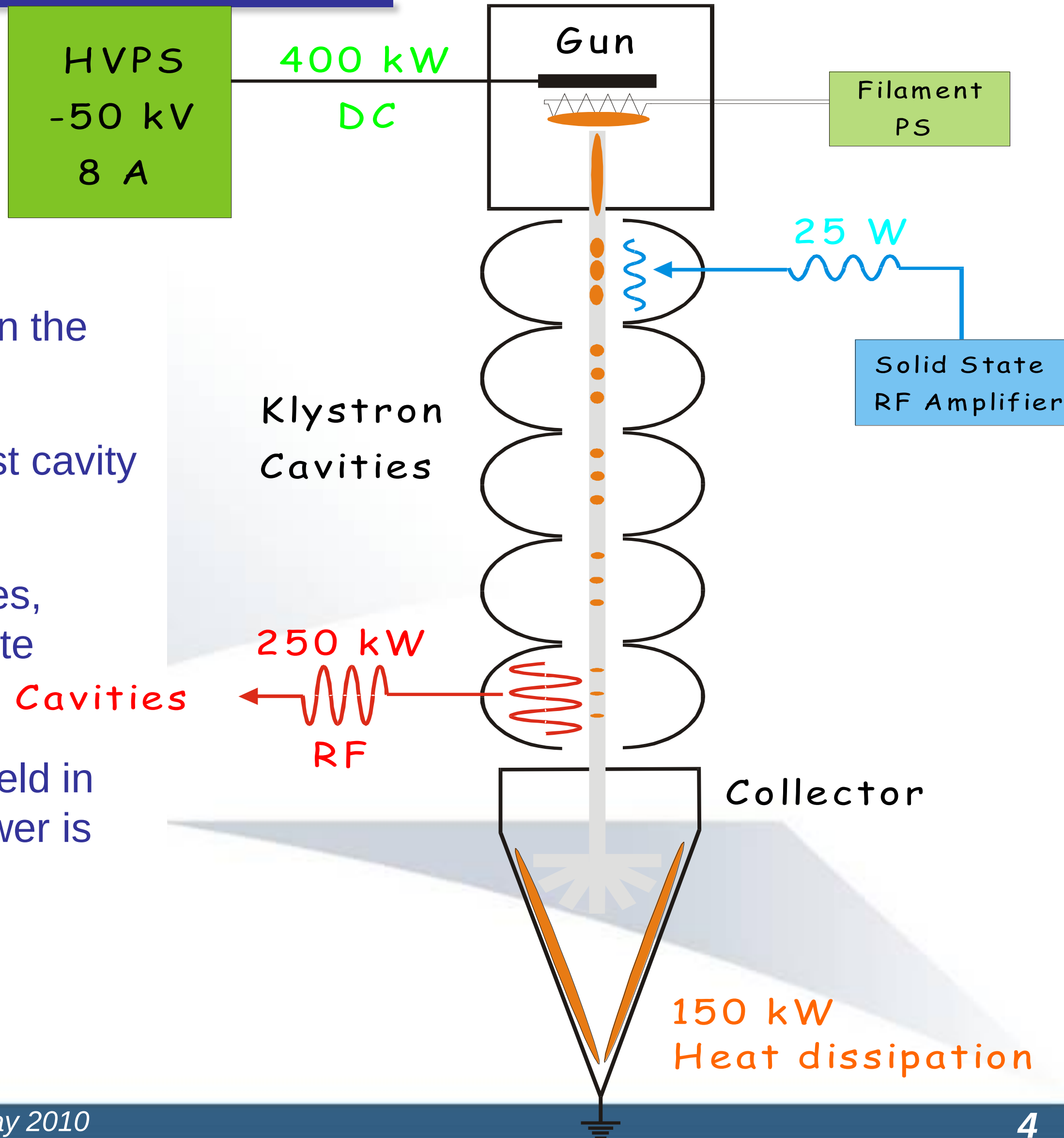
RF Amplifiers

1. RF Amplifiers: Klystrons



Klystron principle:

- High electron DC current produced in the klystron gun.

- Current velocity modulated in the first cavity by the driving power.

- The e-beam is then grouped in pulses, which are enhanced in three intermediate cavities (shorter pulses)

- This pulsed stream induces a high field in the last cavity, out of which the high power is decoupled.

1. RF Amplifiers: Klystrons

Klystron performances:

Freq. (ANKA): 500 MHz

Output Power: 250 kW

Efficiency: 62%

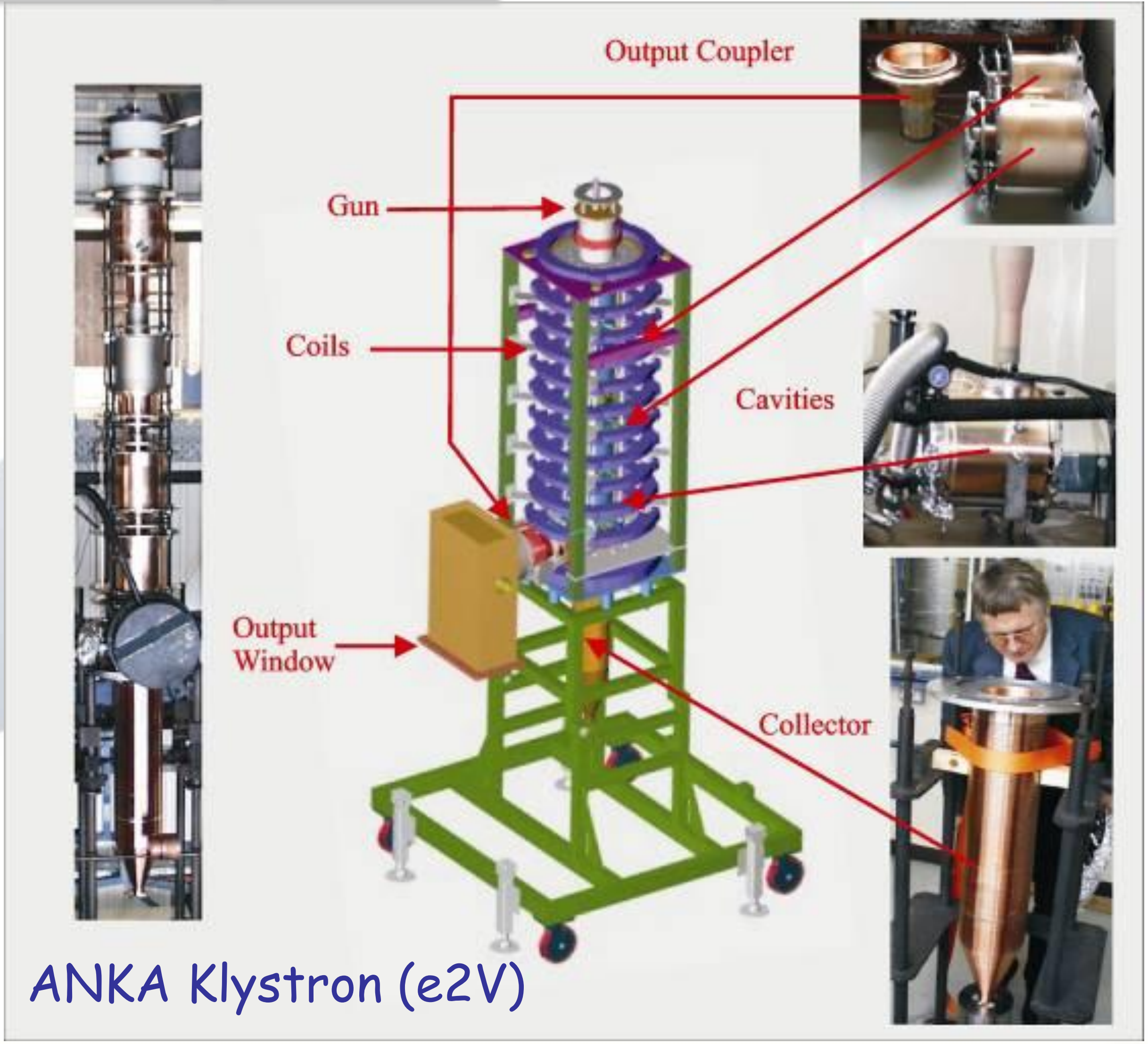
Gain: > 40 dB

Freq. (CERN): 400 MHz

Output Power: 300 kW

Efficiency: 62%

Gain: > 35 dB



ANKA Klystron (e2V)

1. RF Amplifiers: Klystrons

Dimensions:

- Cavity size and drift tube length are related to wavelength
- The size of the interaction structure increases as the frequency decreases

@ 3000 MHz

1,5 m

@ 400 MHz

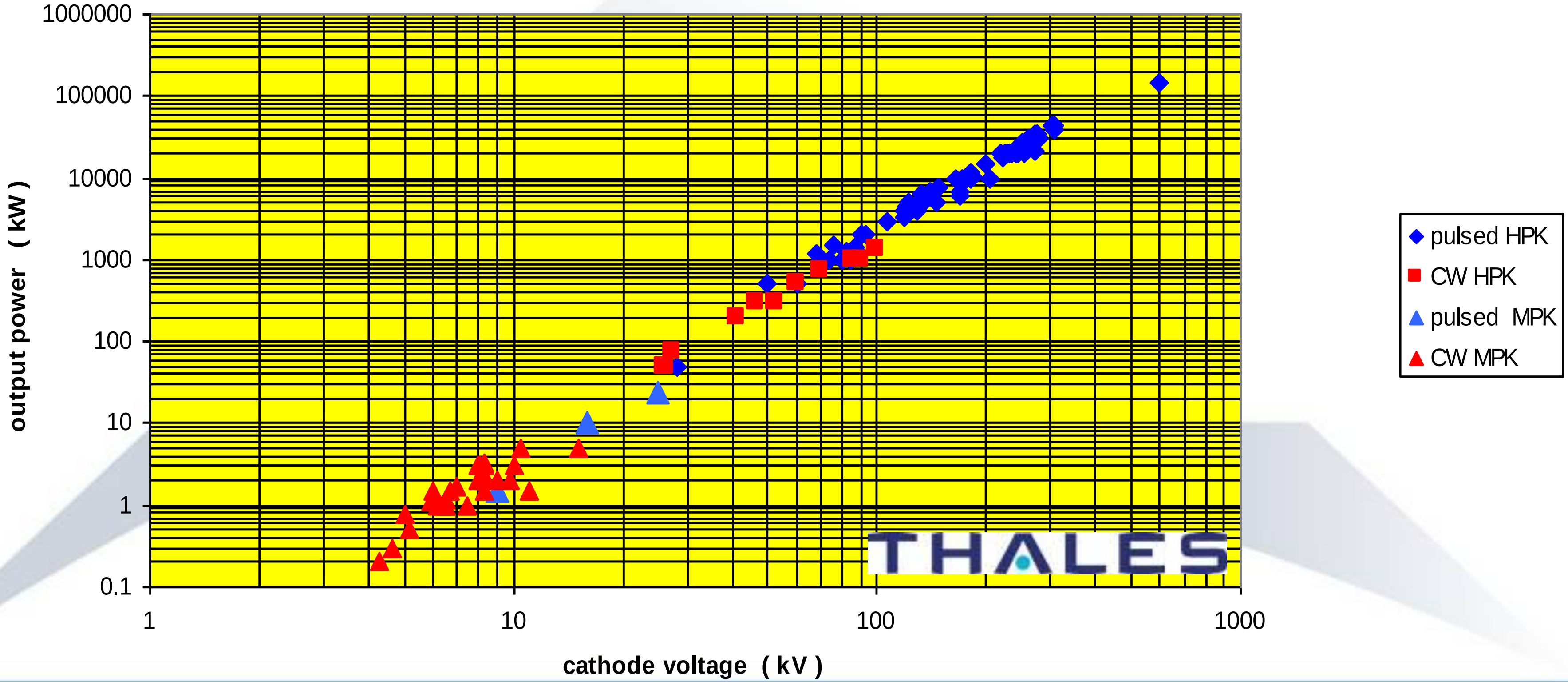
4,5 m

1. RF Amplifiers: Klystrons

Output power and efficiency: Po = η Vk.Ib ,

* As η < 1 , increase of Pout requires increase of both beam power and cathode voltage (both related to space charge).

output power versus cathode voltage for medium and high power klystron



1. RF Amplifiers: Klystrons

Output power and efficiency:

* Pout increases with Vk , but the increase of Vk is limited by breakdown in the gun , i.e. vacuum breakdown

* Breakdown occurs when the electric field in the range 5 x10^3 to 10^4 kV/mm

* High Output Power (up to a few MWcw in the frequency range, required in particle accelerators)

* High Efficiency (up to about 70%, by inserting the intermediate cavities): One tuned to the second harmonic, the others to frequencies well above, ensuring that they are inductive at the operating frequency

* High efficiency is only achieved at rated output power, decreases rapidly at lower power levels.

1. RF Amplifiers: Klystrons

Gain, Lifetime, experience:

* High gain, typically 40 dB are obtained at an output bandwidth of a few percent

* Price per W of output power decreases by increasing the output power per unit.

* Very sturdy, especially when cavities are an integral part of the klystron body. (klystrons with an output power of about 100kW and more)

* TV klystrons (< 60kW) are equipped with external cavities. More fragile due to RF contacts body-cavities, and to the many ceramics in the klystron body

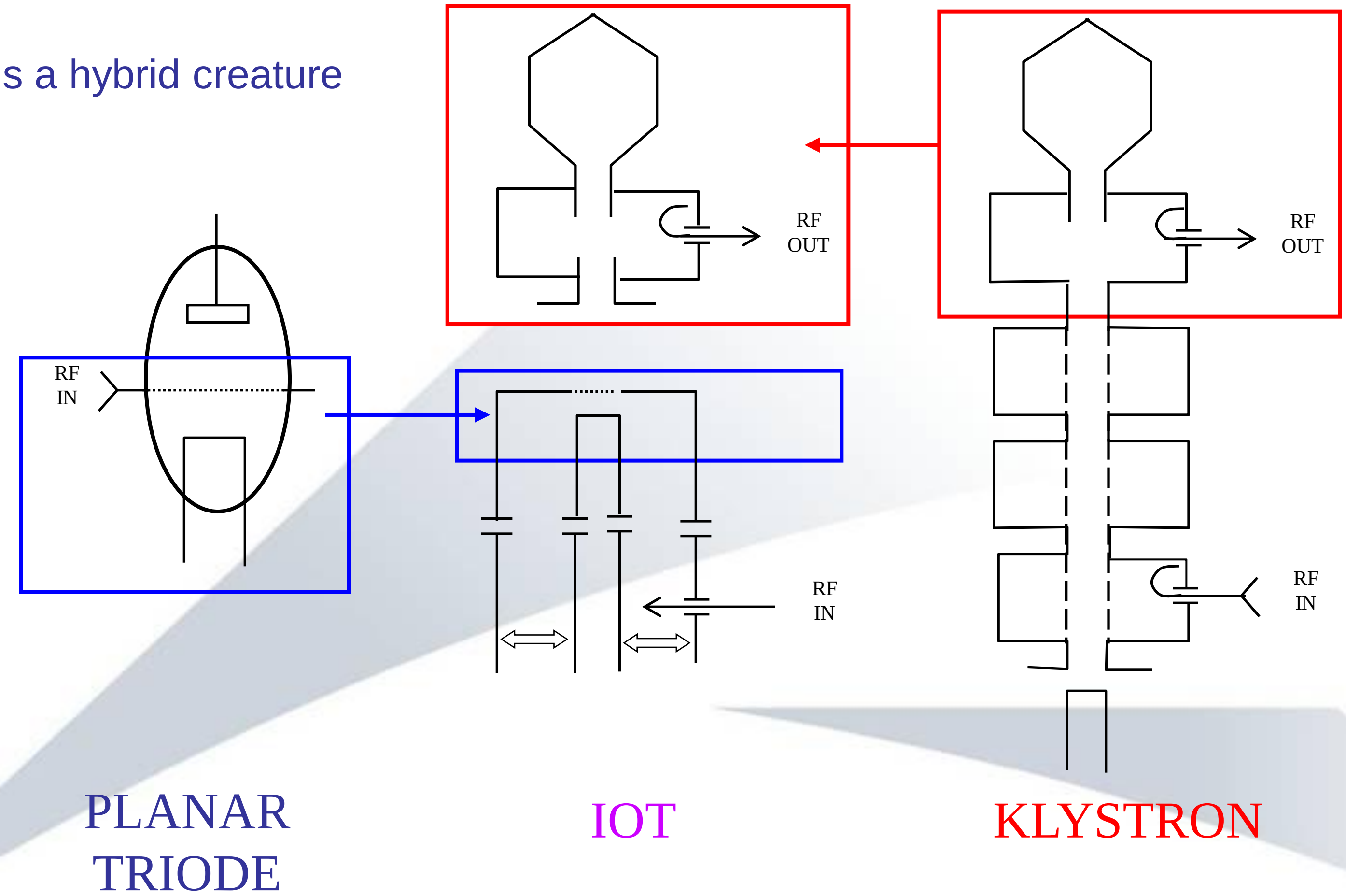
* Experience: most frequently failure is related to the electron gun (heater or HV feedthrough, heater filament interrupt, high voltage arcing, HV ceramic leak)

* For a long cathode life (> 100000h): the emission density should be < 1 A/cm^2.

* In high power klystrons the low cathode loading is achieved by the convergence from cathode to beam cross-section area, i.e. the cathode surface is about 10 to 30 times that of the electron beam.

2. RF Amplifiers: IOTs

An IOT is a hybrid creature



2. RF Amplifiers: IOTs

* From the triode, the IOT inherit a cathode and a grid. Its beam is not velocity modulated, as in a klystron, but density modulated as in a triode.
It means a RF voltage swing must exist between cathode and grid. Contrary to the klystron case, the cathode (and the grid) are included in a RF circuit.

* From the klystron, the IOT gets nearly everything else:

- Linear beam
- Pierce gun
- Hollow anode
- Magnetic field for focussing
- TM_{010} output cavity
- Collector

2. RF Amplifiers: IOTs

In the ALBA case:

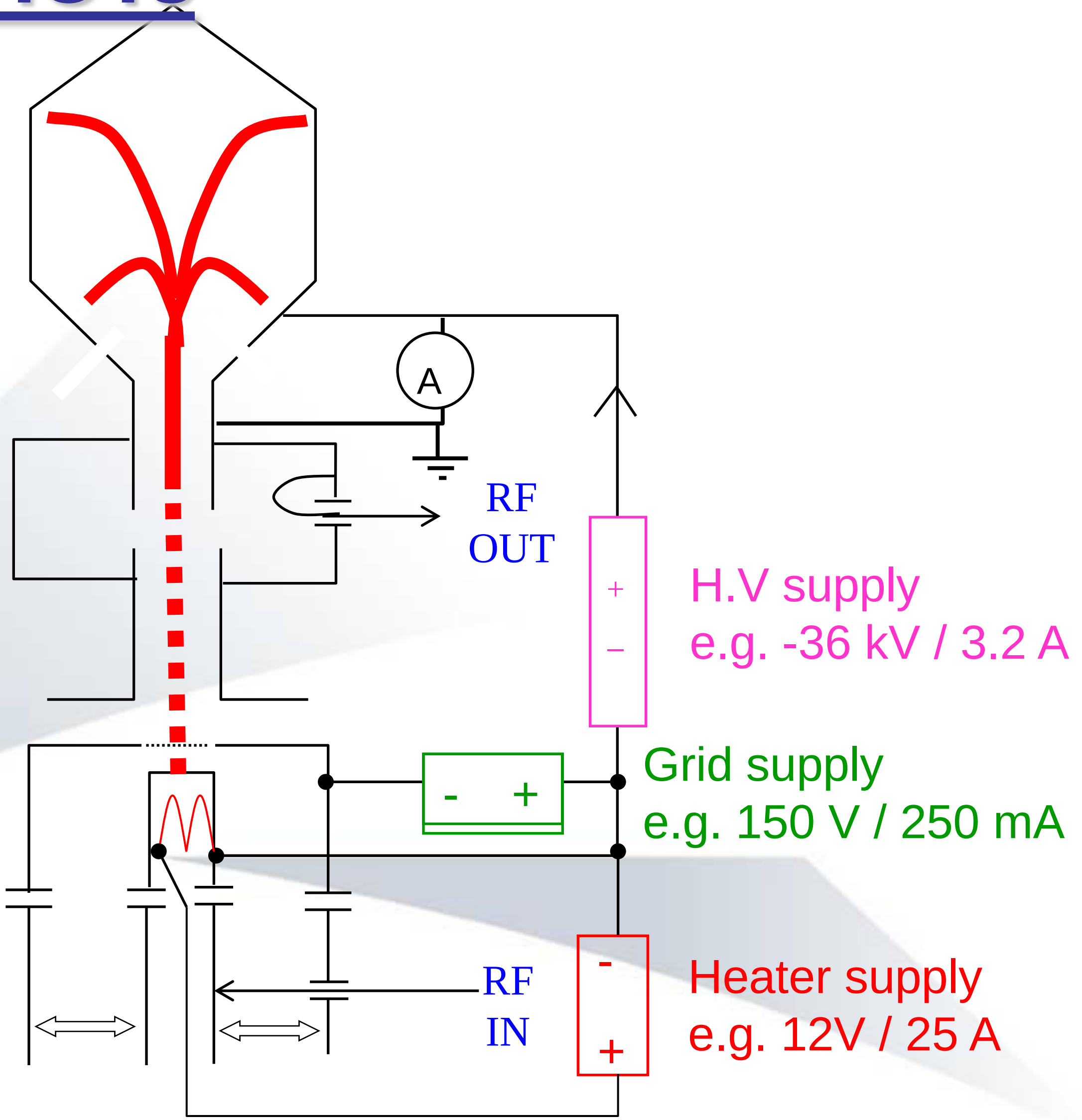
P_{RF} = 80 kW
V_{HV} = - 36 kV
I_{HV} = 3.2 A

η = 71 %

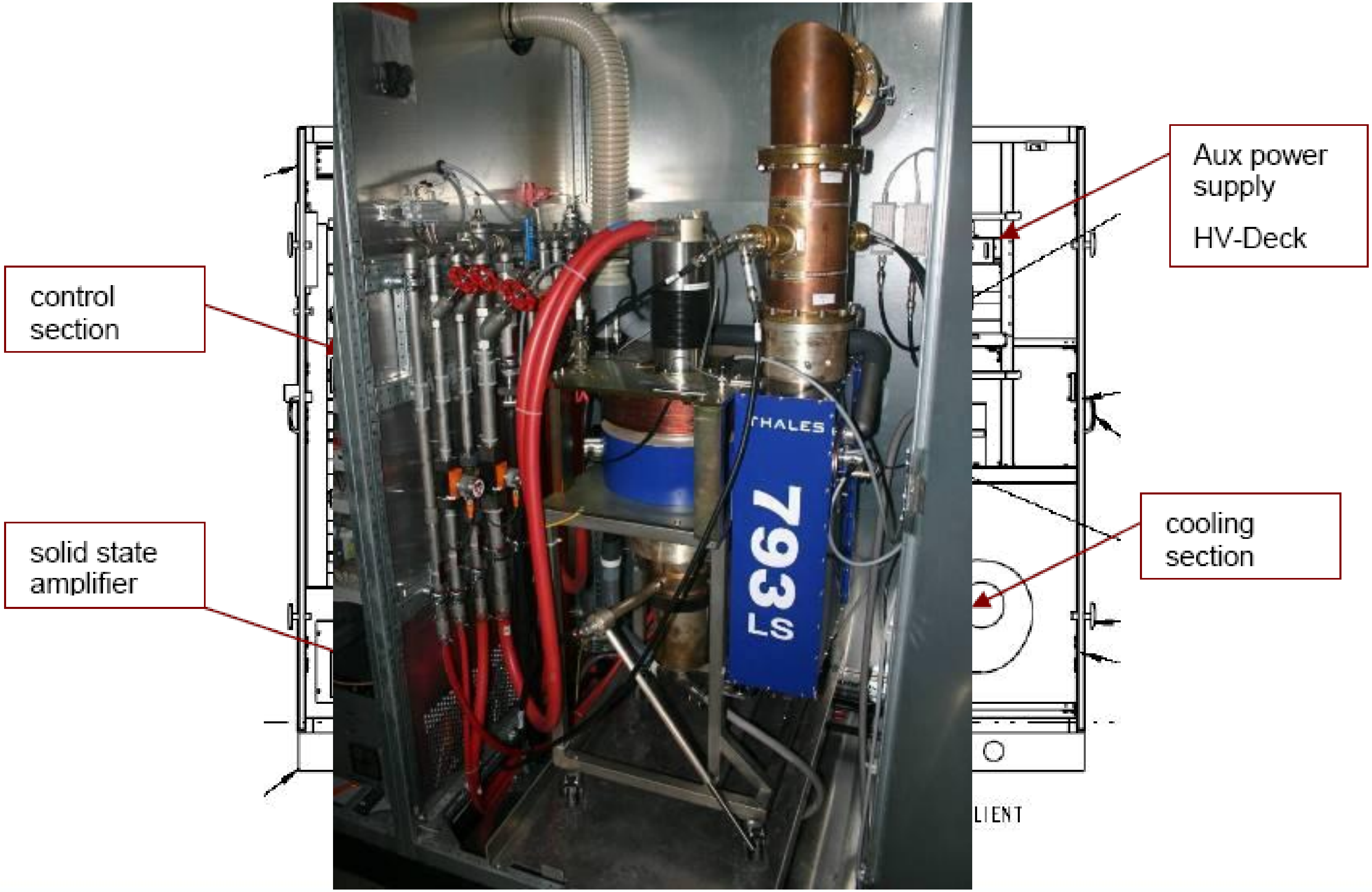
Since:

P_{RFin} = 266 W

Gain = 25 dB



2. RF Amplifiers: IOTs



2. RF Amplifiers: IOTs

- **Tube Modifications (THALES ED):**
  1. **Bigger output window diameter**
  2. **Conical insulator between grid and anode**

- **Advantages**
  1. **Better suited for High Power cw operation**
  2. **Electric Field in the ceramic insulator decreased**
  3. **Losses also decreased**
  4. **Less stray electrons impinge on the tube**

- **Drawback**
  1. **Dedicated product for monofrequency applications**

80 kW version (TV)

90 kW version (LS)

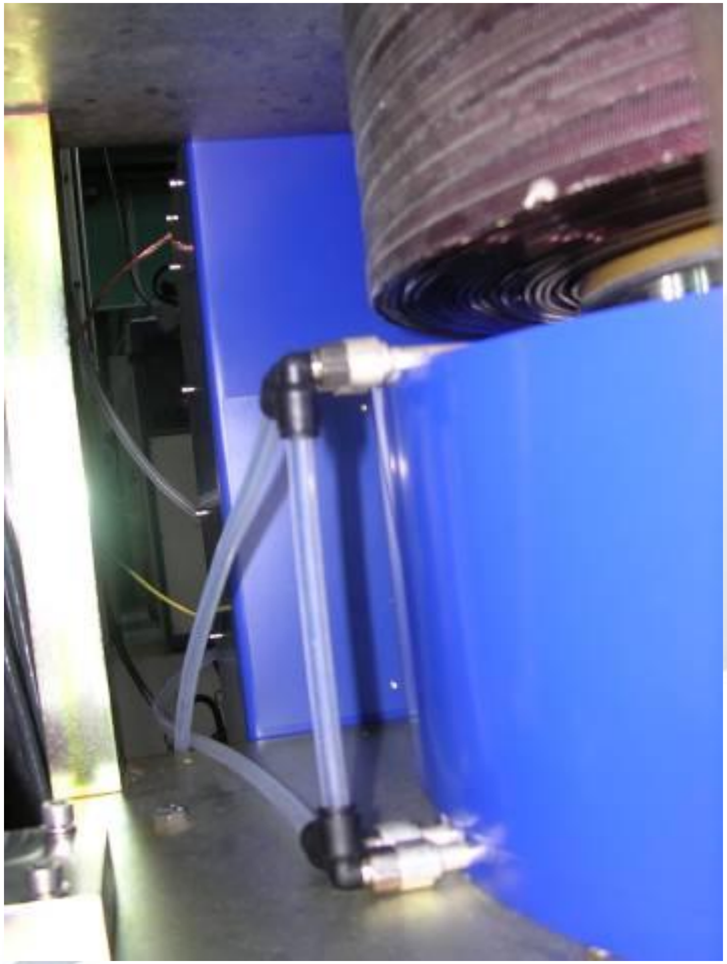
2. RF Amplifiers: IOTs

- **Output Cavities Modifications (TED-CELLS):**
  1. Enlarge coax output coupling from 4-1/16” to 6-1/8”
  2. Redesigned primary cavity to house the new tube 90 kW
  3. Increase the secondary output cavity depth
  4. Add a post (resonance vs. harmonics)
  5. Second arc detector

- **Advantages**
  1. Cope with the higher cw power operation
  2. Simplified tuning devices in primary cavity

- **Drawback**
  1. Dedicated product (500 MHz)

2. RF Amplifiers: IOTs



- **Other Modifications (TED-CELLS):**
  1. **Modify accordingly the cavities coupling loops:**
     - **Output loop**
     - **Prim-sec cavity loop**
  2. **Water cooling added:**
     - **Primary cavity**
     - **Inter-cavity loop**

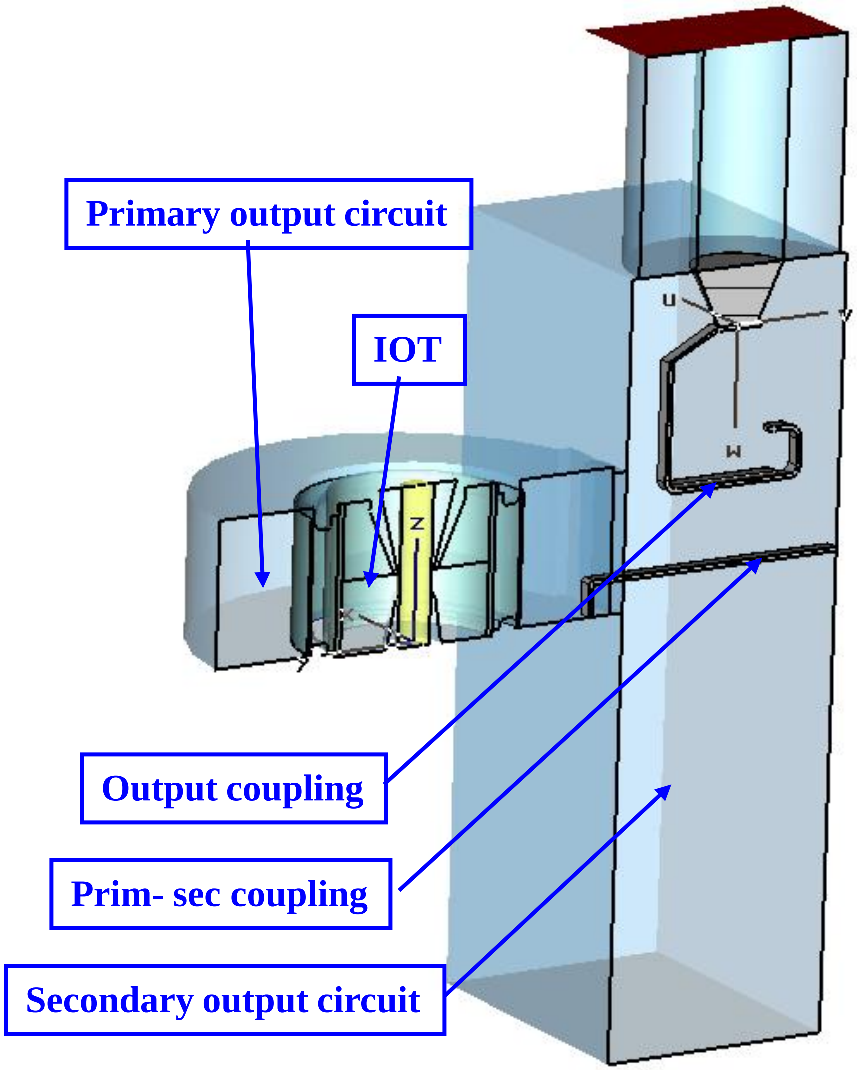
- **Advantage**
  1. **Prevent thermal frequency shifts**

- **Drawback**
  1. **Add water cooling circuits in the RF Tx**

2. RF Amplifiers: IOTs

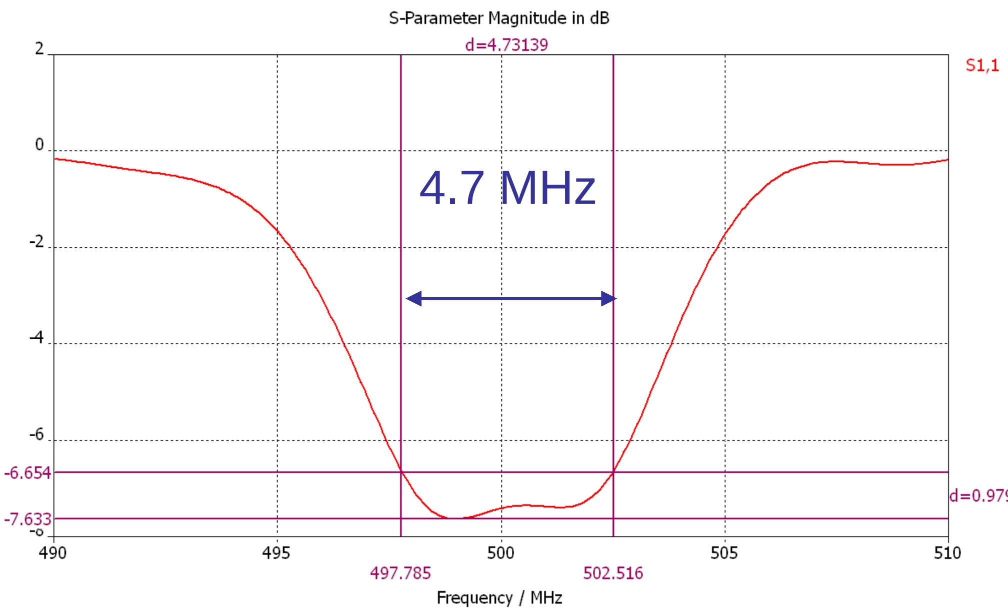
- Cavity Simulations (CELLS):

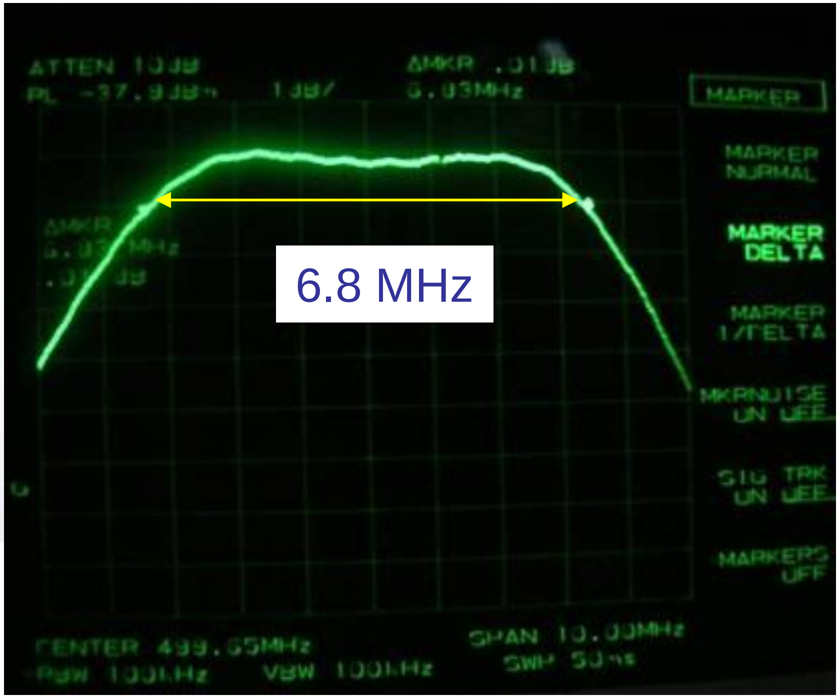
  1. CST-Microwave Stutio ™
  2. Output circuit simulated to obtain the cavities' dimensions and the coupling loops' dimensions
  3. Conductive material in the drift tube gap to simulate the beam
  4. Material conductivity adjusted in order to get the beam voltage at 90 kW
  5. Bandwidth evaluation from the S_{11} parameter



2. RF Amplifiers: IOTs

- **Computed BW compared to the measured one:**





2. RF Amplifiers: IOTs

- Duration test, at 80 kW, during more than 24 h, at THALES premises
- Also tested in factory at 90 kW during ½ hour

HV [kV]	Beam I [A]	Pout [kW]	Eff [%]	Gain [dB]
-36	3.18	80	69.9	23.8
-36	3.31	85	71.3	23.7
-37	3.42	90	71.1	23.9

- Harmonics at Dir-Coupler (6" coax output):

Pout [kW]	H2 [dB]	H3 [dB]	H4 [dB]	H5 [dB]
80	-37.5	-62.7	-52.2	-64.0

- Bandwidth = 6.8 MHz; and Tuning capabilities = ± 5 MHz
- Problems: IOT SN 499413 Ionic Pump ➔ reconditioning in factory
- IOT SN 499443 Poor efficiency ➔ reconditioned on site (FIL on 1 week)
- IOT SN 611024 High Body current ➔ reconditioned on site (FIL on 3 days)

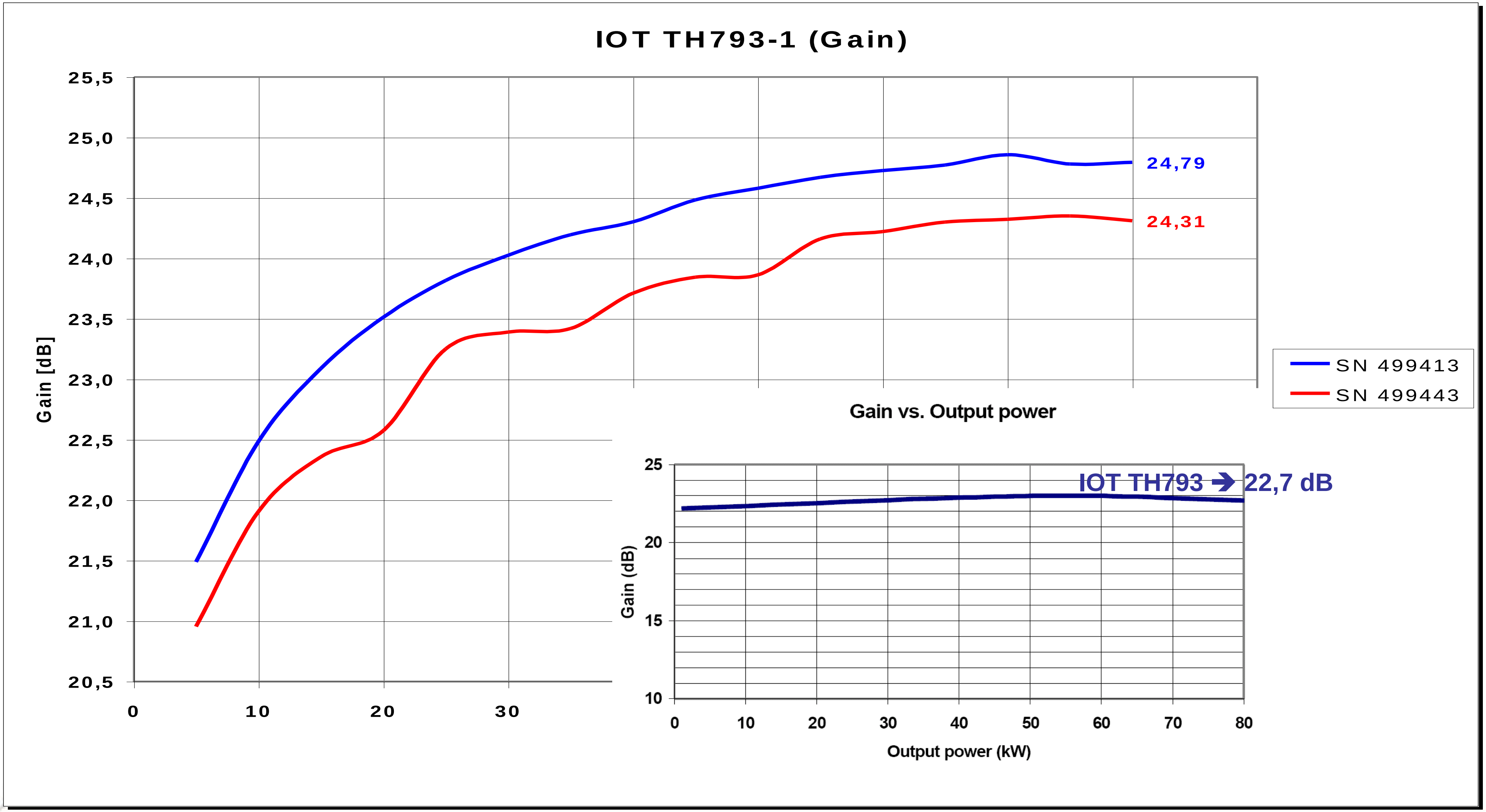
2. RF Amplifiers: IOTs

New problem appeared on May 04, 12h00 (yesterday, during lunchtime)

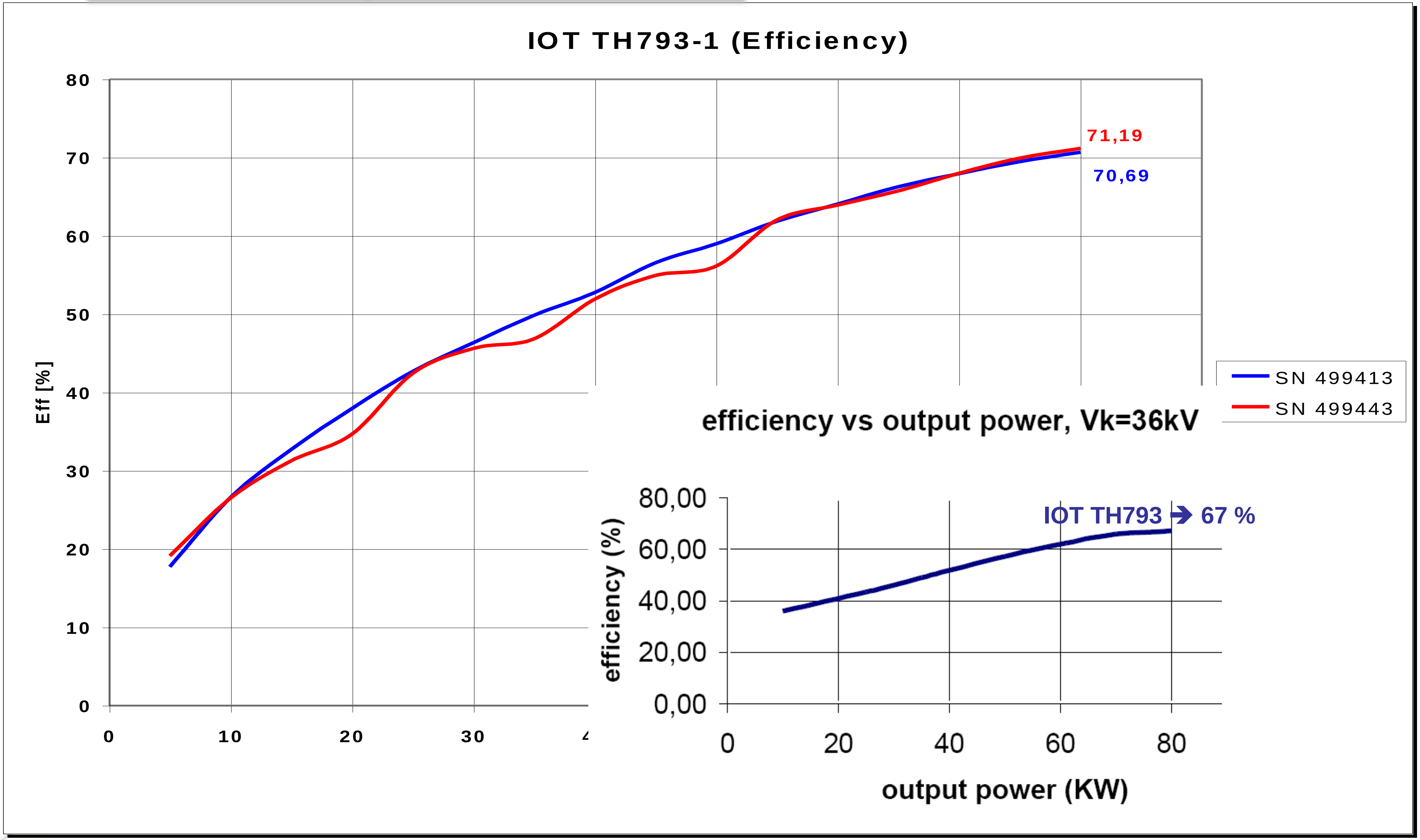
IOT SN 611024 ceramic broke (to be investigated)

2. RF Amplifiers: IOTs

The 2 IOTs already high power tested on site (out of 14 in future operation)



2. RF Amplifiers: IOTs



2. RF Amplifiers: IOTs

Item	Laboratory	Manuf.	Type	IOT S/N	f [MHz]	P average-cw [kW]	η [@ max power, %]	G [@ max power, dB]	LAST UPDATE	Operating FROM	Operating UNTIL	Filament Hours	HV Hours	Death Certificate	*Comments*
IOT_LS001	ALBA	TED	**TH793-1**	499413	500	60	70,7	24,7	09/Feb/2010	17/Dec/2007	09/Feb/2010	**588**	**521**		*RF Lab*
IOT_LS002	ALBA	TED	**TH793-1**	499443	500	80	71,2	24,3	21/Apr/2010	02/Nov/2009	21/Apr/2010	**398**	**166**		*Booster RF Plant*
IOT_LS003	ALS	CPI-Eimac	K2H80W	XBQ-50	500	40 pk AM	64,9	24,0	06/Jul/2009	28/Jul/2006	24/Jun/2009	**17486**	**17222**		*CHK2800W: Pmax reached, 60 kW*
IOT_LS004	BESSY-MLS	CPI	CHK5900W	001	500	80	73,4	22,8	12/Oct/2009	25/Apr/2008	08/Oct/2009	**11260**	**10842**	**OFF-resonance due to overpressure (15 bar) in cooling system**	*Refurbished S/N 000*
IOT_LS005	DIAMOND	TED	TH793	539481	500	80			31/Jan/2010				**18973**	**Replaced**	*Replaced by e2V tube*
IOT_LS006	DIAMOND	TED	TH793	539652	500	80			31/Jan/2010				**14813**	**Replaced**	*Replaced by e2V tube*
IOT_LS007	DIAMOND	TED	TH793	539653	500	80			21/Apr/2010				**12133**		*Failed*
IOT_LS008	DIAMOND	TED	TH793	541272	500	80			21/Apr/2010				**9860**		*Spare offline*
IOT_LS009	DIAMOND	TED	TH793	541273	500	80			21/Apr/2010				**2666**		*Failed*
IOT_LS010	DIAMOND	TED	TH793	541276	500	80			21/Apr/2010				**8252**		*Failed*
IOT_LS011	DIAMOND	TED	TH793	542301	500	80			21/Apr/2010				**1597**		*Failed*
IOT_LS012	DIAMOND	TED	TH793	542789	500	80			21/Apr/2010				**2890**		*Failed*
IOT_LS013	DIAMOND	TED	TH793	576282	500	80			21/Apr/2010				**3982**		*Failed*
IOT_LS014	DIAMOND	TED	TH793	595367	500	80			21/Apr/2010				**2461**		*Failed*
IOT_LS015	DIAMOND	TED	TH793	600663	500	80			21/Apr/2010				**2969**		*Failed*
IOT_LS016	DIAMOND	TED	TH793	600664	500	80			21/Apr/2010				**4314**		*Failed*
IOT_LS017	DIAMOND	TED	TH793	602801	500	80			21/Apr/2010				**4905**		*In use*
IOT_LS018	DIAMOND	TED	TH793	606648	500	80			21/Apr/2010				**2146**		*Failed*
IOT_LS019	DIAMOND	TED	TH793	608801	500	80			31/Jan/2010				**2992**	**Replaced**	*Replaced by e2V tube*
IOT_LS020	DIAMOND	TED	**TH793-1**	615402	500	80			21/Apr/2010				**4052**		*Failed*

2. RF Amplifiers: IOTs

IOT_LS021	DIAMOND	TED	**TH793-1**	628638	500	80			31/Jan/2010				**1373**	**Replaced**	*Replaced by e2V tube*
IOT_LS022	DIAMOND	e2V		205-0639	500	80			21/Apr/2010				**1219**		*Failed initial commissioning*
IOT_LS023	DIAMOND	e2V		273-0907	500	80			31/Mar/2010				**2867**		
IOT_LS024	DIAMOND	e2V		210-0647	500	80			03/May/2010				**15000**		*Under investigation for tripping*
IOT_LS025	DIAMOND	e2V		211-0647	500	80			03/May/2010				**17000**		
IOT_LS026	DIAMOND	e2V		212-0647	500	80			03/May/2010				**17100**		
IOT_LS027	DIAMOND	e2V		223-0710	500	80			03/May/2010				**15300**		
IOT_LS028	DIAMOND	e2V		287-0931	500	80			31/Mar/2010				**1507**		
IOT_LS029	DIAMOND	e2V		288-0935	500	80			31/Mar/2010				**1507**		*Under investigation for tripping*
IOT_LS030	DIAMOND	e2V		289-0938	500	80			31/Mar/2010				**1511**		
IOT_LS031	DIAMOND	e2V		224-0711	500	80			03/May/2010				**600**		
IOT_LS032	DIAMOND	e2V		290-0939	500	80			03/May/2010				**500**		
IOT_LS033	ELETTRA	TED	TH793	559442	500				21/Apr/2010	Jun/2006	Jul/2008		**11364**	**No fil current (HV 4,3 kV)**	*Reconditioned, no success*
IOT_LS034	ELETTRA	TED	TH793	557132	500				21/Apr/2010	Jun/2006	Dec/2006		**2463**	**HV inhibit above 25 kW**	
IOT_LS035	ELETTRA	TED	TH793	574752	500				21/Apr/2010	Dec/2006	Jan/2007		**417**	**Ceramic broken**	
IOT_LS036	ELETTRA	TED	TH793	572382	500				21/Apr/2010	Jan/2007	Dec/2007		**4748**	**Tube broken**	
IOT_LS037	ELETTRA	TED	TH793	557132	500				21/Apr/2010	Dec/2007			**5809**	**Dark spot on ceramic**	*Installed after Refurbishing*
IOT_LS038	ELETTRA	TED	**TH793-1**	617303	500	30			21/Apr/2010	Oct/2008			**2378**		
											Failed x	**17**	**5195**	**AVERAGE LIFE (FAIL)**	
											In use x	**16**	**7234**	**AVERAGE LIFE (in use)**	

2. RF Amplifiers: IOTs

From the previous table:

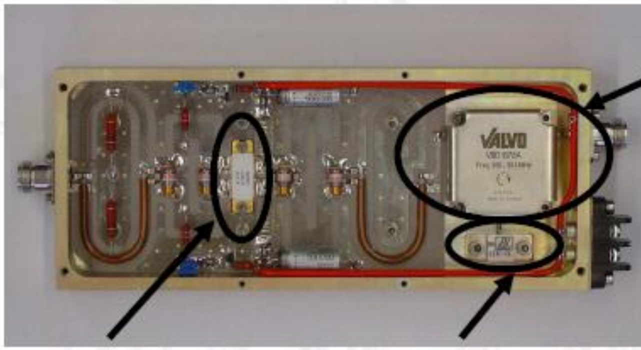
	Average Life (Fail)	Average (In _Use)
CPI (1 / 1) ➔	**10842 h**	17222 h
e2V (1 / 10) ➔	**1219 h**	7289 h
TH793 (14 / 6) ➔	**5834 h**	9559 h
TH793-1 (1 / 4) ➔	**4052 h**	1109 h

3. RF Amplifiers: SSA

Alternative (e.g. SOLEIL): Solid State Technology

352 MHz 330 W Module

Wideband Circulator



Transistor

50 Ohms Termination

Main Specifications
RF power 315 W CW
Frequency 352 MHz
Gain 13 - 14.5 dB
Phase dispersion 15°
Efficiency 63%
Unconditional Stability

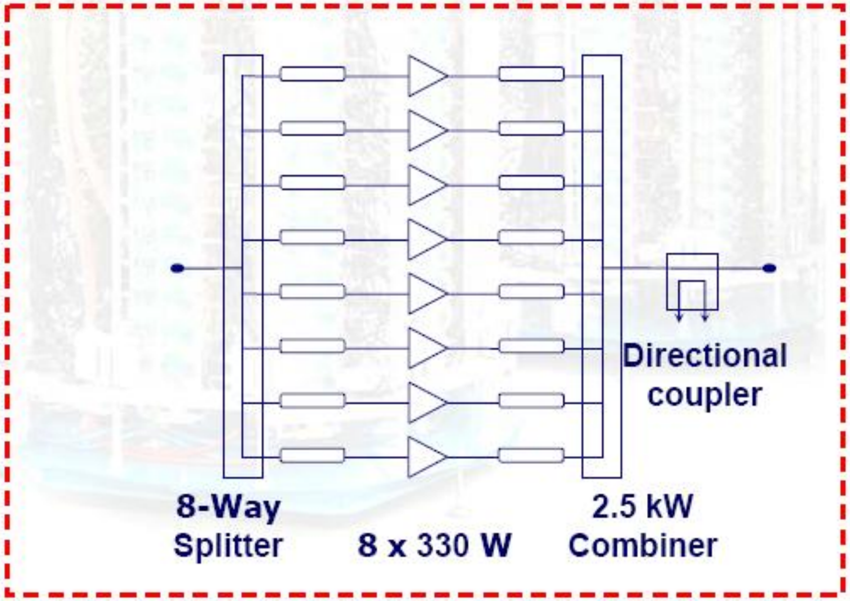
DC/DC Converter

Input 280V DC

Control & Measurement

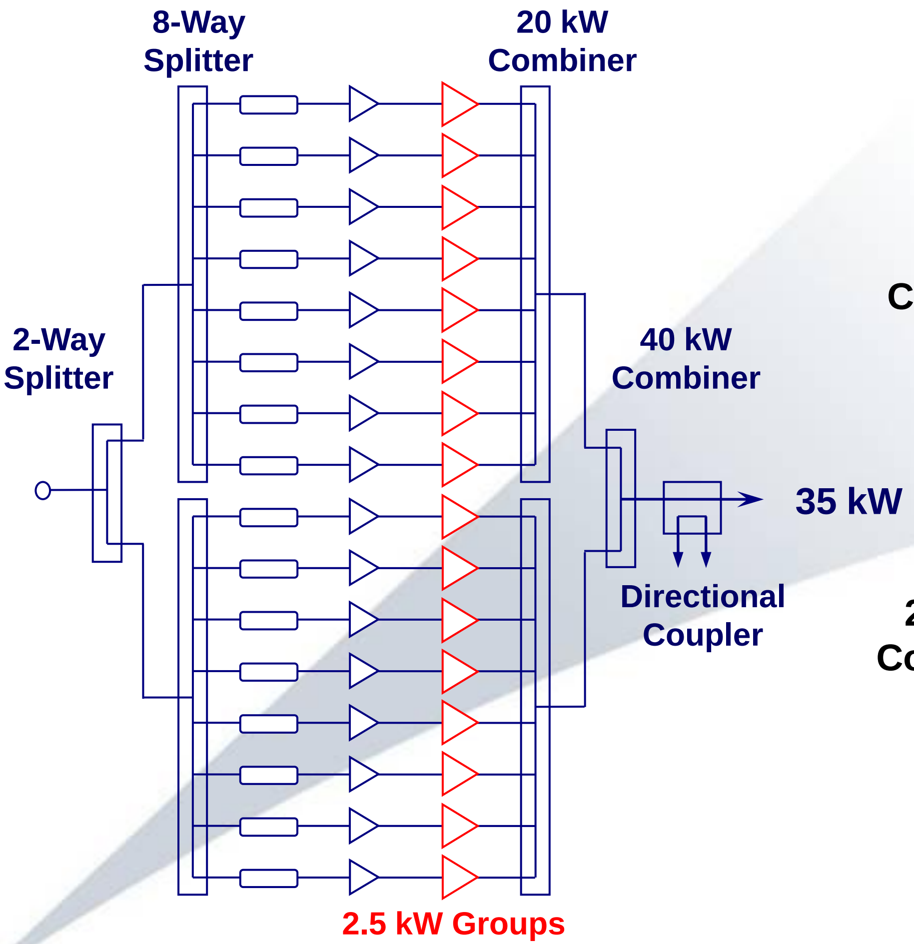
Output 28V DC

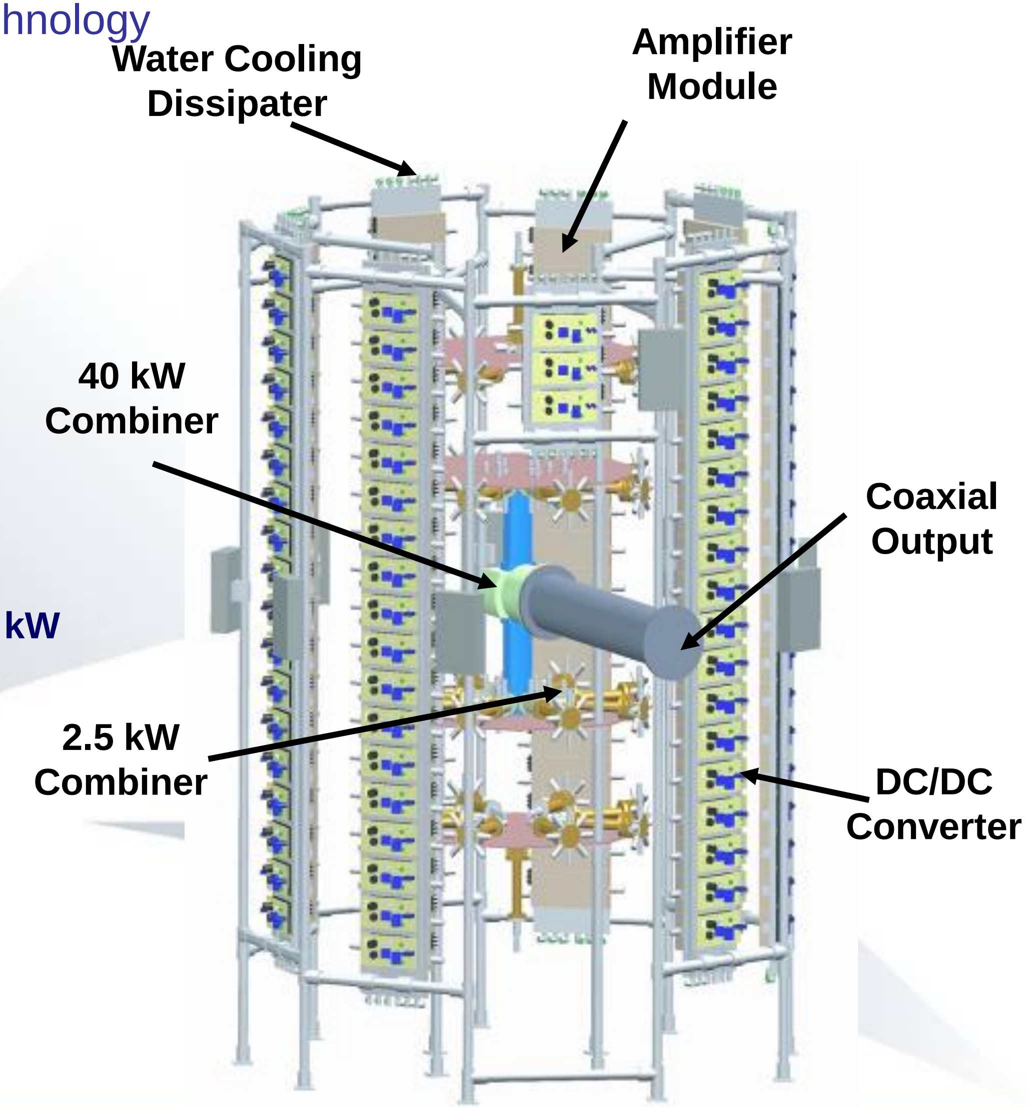
2.5 kW Group



3. RF Amplifiers: SSA

Alternative in some labs: Solid State Technology





3. RF Amplifiers: SSA

3. RF Amplifiers: SSA

In the SOLEIL case:

P_{RF} = 315 W modules
V_{DC} = 50 V
f = 352 MHz

η = 62 %

Gain = 13 dB

P_{RF} = 400 W modules
V_{DC} = 50 V
f = 476 MHz

η ~ 70 %

Gain ~ 20 dB

P_{RF} = 700 W modules
V_{DC} = 50 V
f = 352 MHz

η > 70 %

Gain > 20 dB

P_{RF} = 180 kW "TOWER"

η ~ 60 %

Gain ~ 53 dB

3. RF Amplifiers: SSA

Running hours:

Booster RF: 35 kW SSA, with no trips after 20000 hours

SR RF: 4 towers of 180 kW at 352 MHz, with no impact in the operation.

A1: running time 20.000 h (2006-2009) and around 4% trans. failure
A2: running time 20.000 h (2006-2009) and around 1.2% trans. failure
A3: running time 10.000 h (2008-2009) and around 1.7% trans. failure
A4: running time 10.000 h (2008-2009) and around 1.7% trans. failure

4. RF Amplifiers: Some Criteria

Running Hours:

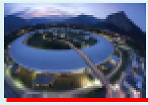
Klystron	IOT	SSA
1 MW (APS) **53000 h** (5 units average)	80 kW (ALBA) **520 h (ups!)**	35 kW, **20000 h** (Booster)
250 kW (CERN) **50000 h**	80 kW (ELETTRA) **5000 h** (5 units TV type) **2500 h** (2 units LS type)	180 kW, **20000 h** (SR x 2 towers) 180 kW, **10000 h** (SR x 2 towers)
60 kW (ELETTRA) **26000 h** (4 units average)	80 kW (DIAMOND) **4300 h** (11 IOT average life on failure) **15000 h & 17000 h** (oldest 2 IOTs)	
	40 kW (ALS) **17500 h** (1 unit, 40 kW pk AM)	
	80 kW (BESSY) **11300 h** (1 unit)	

4. RF Amplifiers: Some Criteria

Output Power, Efficiency and Gain:

Klystron	IOT	SSA	
60 - 1000 kW	80 kW	700 W	180 kW
62 %	71 %	70 %	60 %
40 dB	25 dB	20 dB	53 dB
		(module)	(Tower)

4. RF Amplifiers: Some Criteria



Comparison – Storage Ring Upgrade

3.2M€ for Booster upgrade isn't considered in the Purchase Cost

300mA upgrade	Re-use of existing 1100kW klystron	Klystron 8 x 350kW	IOTs (combined by 2) 32 x 80kW	Solid State Amplifier 16 Amplifiers
Device Availability	Until 2020	To be developed Based on KGP family	To be developed	Yes
Redundancy	Transmitter Yes Cavity under conditions	Yes 300mA possible w/ 7 TX 14 Cav	Yes 300mA possible w/ 30 TX 15 Cav	Yes 300mA possible w/ 15 TX 15 Cav
Modularity	No	Yes	Very good	Excellent
Reliability / MTBF	Average	Probably lower	Probably lower	MTBF → ∞
Maintenance Troubleshooting	Not Easy	Not Easy	Easy	Very Easy
Stability	Bad	Unknown	Unknown	Good
Possible 500mA	Yes (if 200kW/cav OK)	Yes (cost 1.5 M€)	No (add 4 cav)	Yes (cost 6M€)
Efficiency (300mA)	60% P=95%	58% P=75%	72% P=80%	55% P=95%
Elec. cost 10 years 6500h/year @ 82€ / MWh	18.7 M€	19.4 M€	15.6 M€	20.4 M€
Purchase Cost	transfer of TRA0 1.0 M€	8 x 350kW 10.4 M€	32 x 80kW 14.4 M€	16 x 135kW 12.8 M€
Circulator/combiner		8-4 0.6 M€	16-4 1.0 M€	Included
Maintenance Cost Base 10 years @ 6500h/year	1.0 M€ (2 x 1 klys)	2.8 M€ (8 x 1 klys)	3.2 M€ (32 x 1 IOT)	0.5 M€ (transistors + PS DC/DC)
Possession Cost	20.7 M€	33.2 M€	34.2 M€	33.7 M€

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4. RF Amplifiers: Some Criteria

Purchase Cost in kEuro/ kW:

Klystron 400 MHz / 250 kW ➔ ~ 230 k€ ➔ ~ **0.9 k€ / kW**

IOTs 500 MHz / 80 kW ➔ ~ 50 - 70 k€ ➔ ~ **0.6 - 0.9 k€ / kW**

***SSA** 352 MHz / 200 kW ➔ ~ 740 k€ ➔ ~ **3.7 k€/ kW** (300W)

~ **2.8 k€/ kW** (700W)

***N.B:** SSA from SOLEIL data (4 "towers" of 200 kW). The complete transmitter includes transformer + HV rectifier + control system, …), but SOLEIL manpower is not included. All components were built in the industry according to the SOLEIL specifications)

4. RF Amplifiers: Some Criteria

Since SSA include power supplies, we have to add:

ALBA **IOTs** (***HVPS - PSM***) 160 kW ➔ ~ 230 k€ ➔ ~ **1.44 k€/kW**

DESY **Klystron** (***thyristor converter***) 3040 kW ➔ ~ 880 k€ ➔ ~ **0.29 k€/kW**

At 1.3 GHz (SLAC needs 30 kW):

Purchase Cost:

Klystron ➔ ~ 500 k$ ➔ ~ **16.7 k$ / kW** ➔ **~ 12.7 k€ / kW**

IOTs ➔ ~ 300 k$ ➔ ~ **10 k$ / kW** ➔ **~ 7.6 k€ / kW**

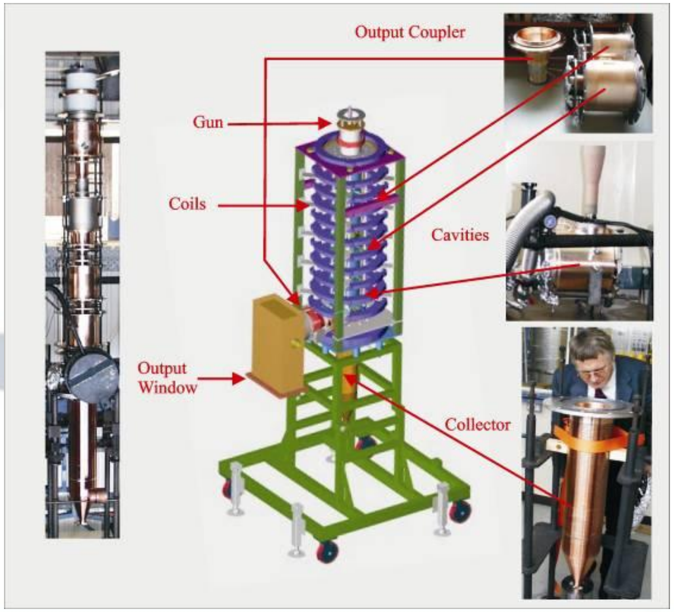
SSA ➔ ~ 480 k$ ➔ ~ **16 k$ / kW** ➔ **~ 12.2 k€ / kW**

5. IMPLEMENTATION

Laboratory	Type	Qty
ANKA	KLY - 250 kW	2
Argonne National Laboratory	KLY - 1 MW	5
BESSY-II	KLY - 60 kW	2
BESSY-PTB	IOT - 80 kW	1
Brookhaven National Lab		
CELLS - ALBA	IOT - 80 kW	14
CERN - LHC	KLY - 300 kW	16
CERN - SPS	IOT 800 MHz ?	
Cornell University	KLY-IOT?	
DESY	KLY	
Diamond	IOT	12
ELETTRA	IOT	2
ESRF	KLY - 1,3 MW	2
ESRF - Update	SSA	
Fermilab		
JASRI - SPring-8	KLY	
Jefferson Lab		
Lawrence Berkeley National Laboratory - ALS	KLY-IOT?	
Oak Ridge National Laboratory - 402 MHz	KLY - SSA	90? - 5
Paul Scherrer Intitute - SLS	KLY - 250 kW	4
Research center Dresden-Rossendorf (FZD) - ELBE	KLY - 10 kW?	4
SLAC - 1,3 GHz	KLY-IOT-SSA?	
SOLEIL - Booster	SSA - 35 kW	1
SOLEIL - SR	SSA - 180 kW	2
TRIUMF		

6. DISCUSSIONS / CONCLUSIONS?

* Hard to collect data for comparison
* Difficulties to get prices
* SSA includes power supplies and development
* IOTs including several modifications but…
* New IOTs without long term data
* Discussion is served!



MANY THANKS again to ALL of YOU