CERN SPS TETRODES HIGH EFFICIENT SYSTEM AT THE END

Workshop on efficient RF sources

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Outline

Frequency & Power range of tetrodes & diacrodes

Theoretical and measured efficiency

Availability vs Efficiency, an example with a YL1530 tetrode operated in the CERN SPS

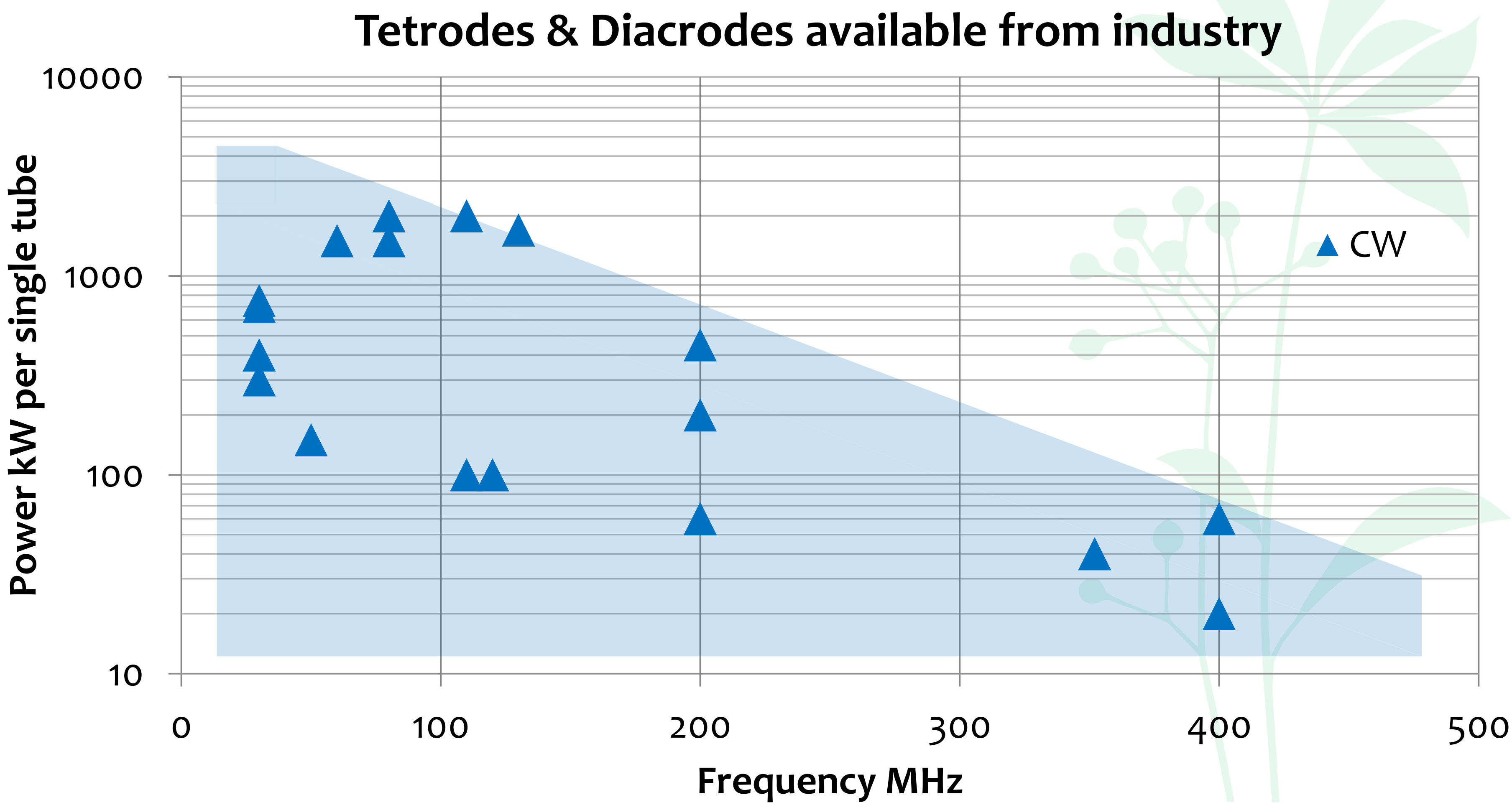
Imposed parameters and their impact to efficiency

- Overhead
- Circulators
- High Voltage Power Supply
- Fundamental Power Coupler

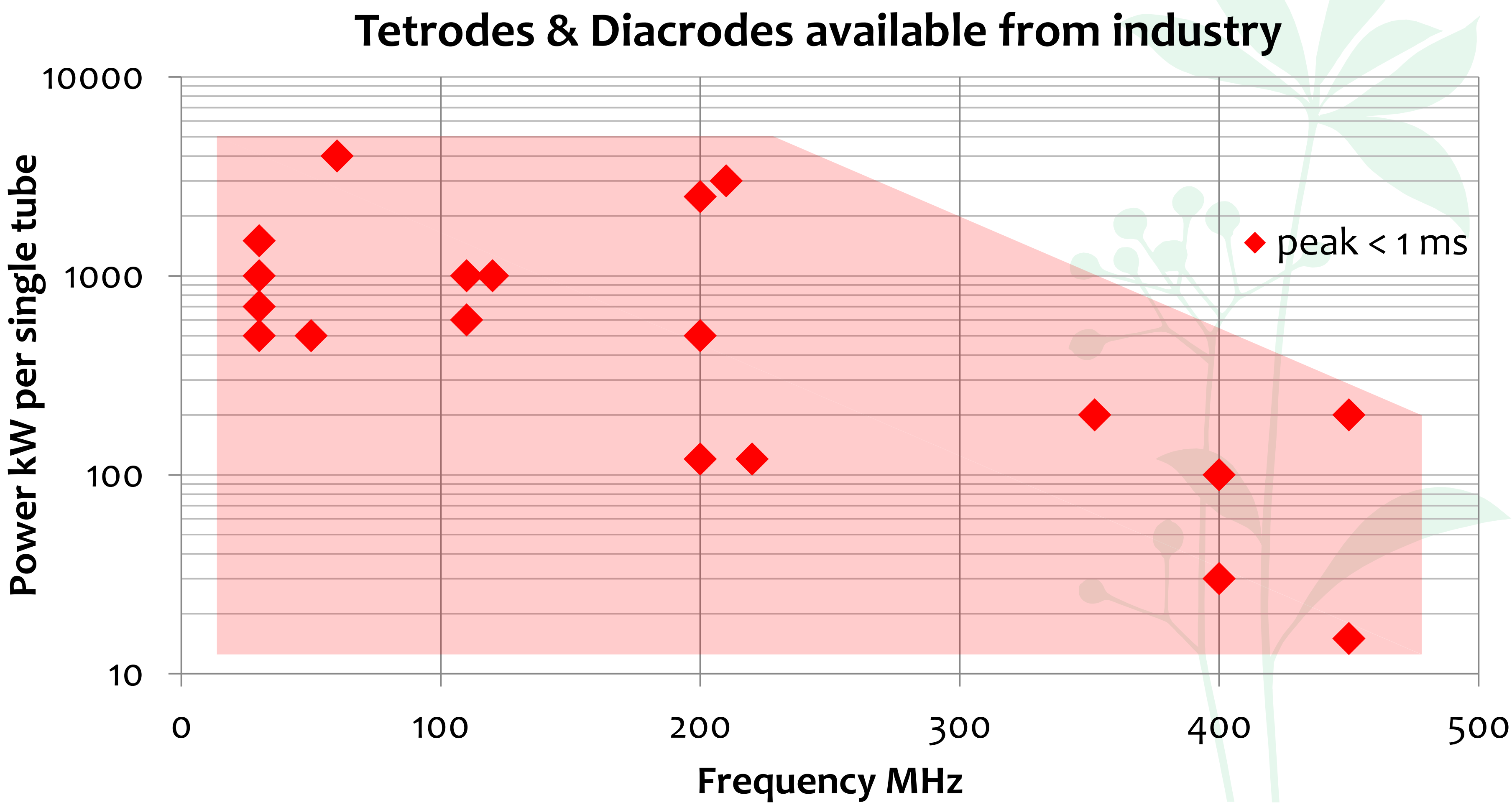
Granularity

Conclusion: Tetrodes are very efficient

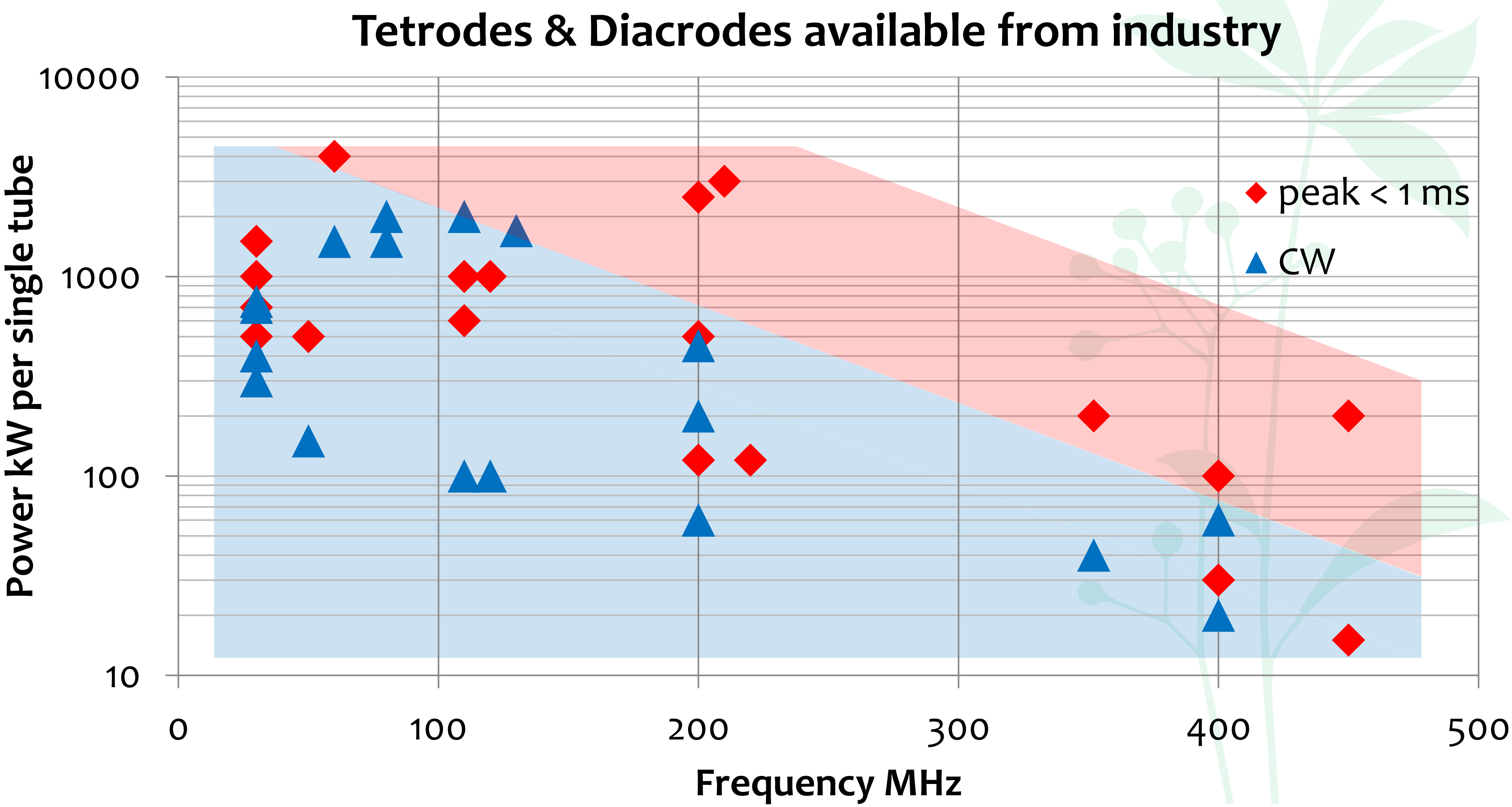
Frequency & Power range of tetrodes



Frequency & Power range of tetrodes



Frequency & Power range of tetrodes



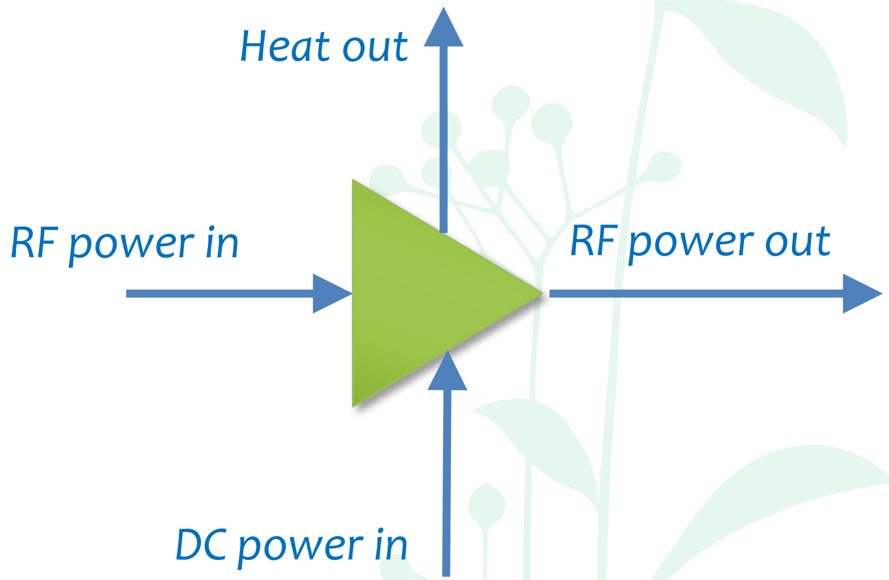
Theoretical efficiency

$$P_{RFin} + P_{DCin} = P_{RFout} + Heat$$

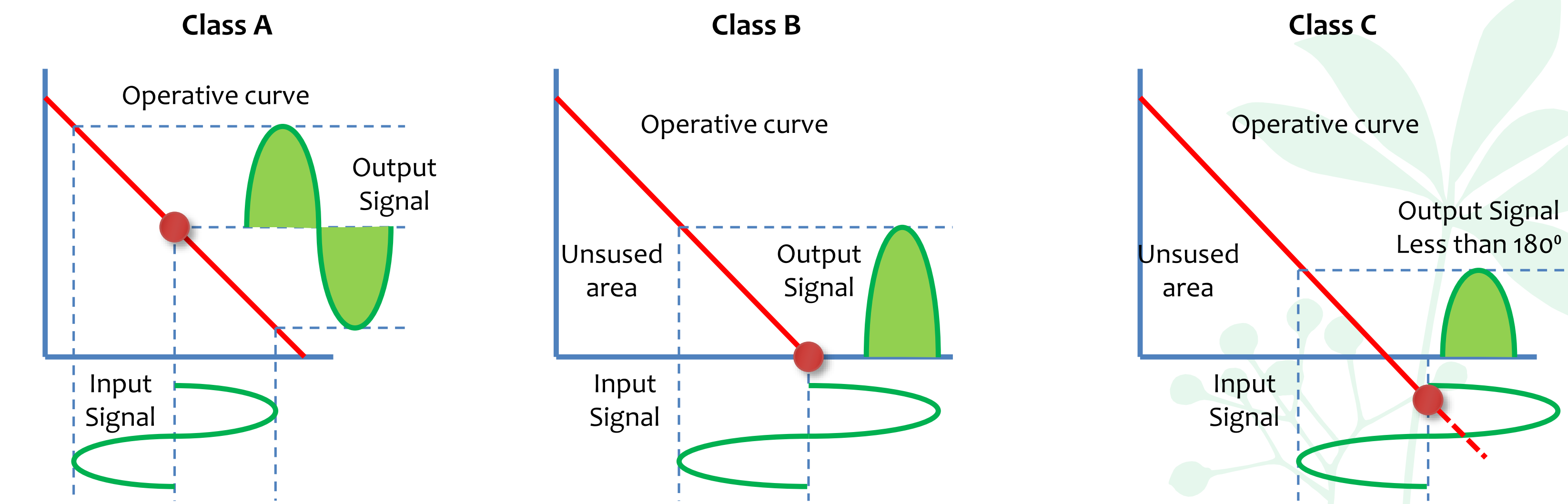
$$Efficiency = \frac{P_{RFout}}{P_{DCin} + PRFin}$$

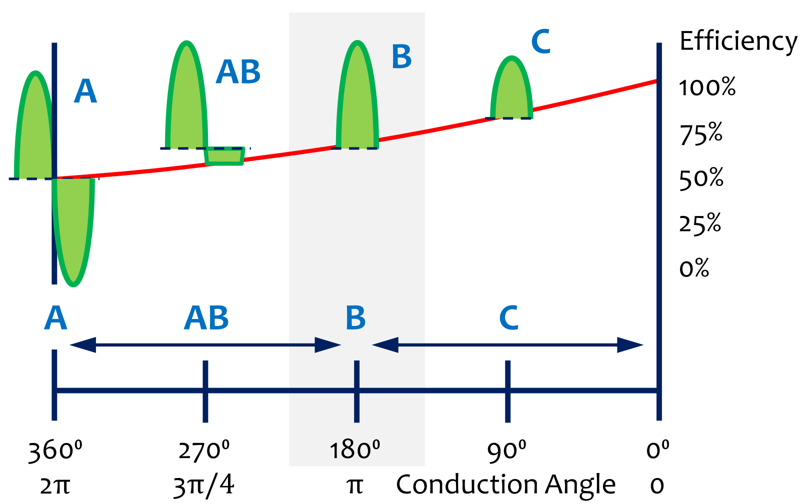
As with tetrodes Gain is usually > 13-16 dB

$$Efficiency \simeq \frac{P_{RFout}}{P_{DCin}}$$



Amplifier class





Amplifier Class	Description
Class-A	Full cycle 360⁰ of conduction
Class-AB	More than 180⁰ of conduction
Class-B	**Half cycle 180⁰ of conduction**
Class-C	Less than 180⁰ of conduction

Theoretical Class B efficiency

DC power is

$P_{dc} = V_{dc} I_{dc}$

Assuming the tube is linear whilst it is conducting, the dc anode current is found by Fourier analysis of the current waveform and is $I_{dc} = I_{pk}/\pi$

$I_{rf} = I_{pk}/2 = I_{dc}\, \pi/2$

And ideal class B, $V_{rf} = V_{dc}$

So, RF power is

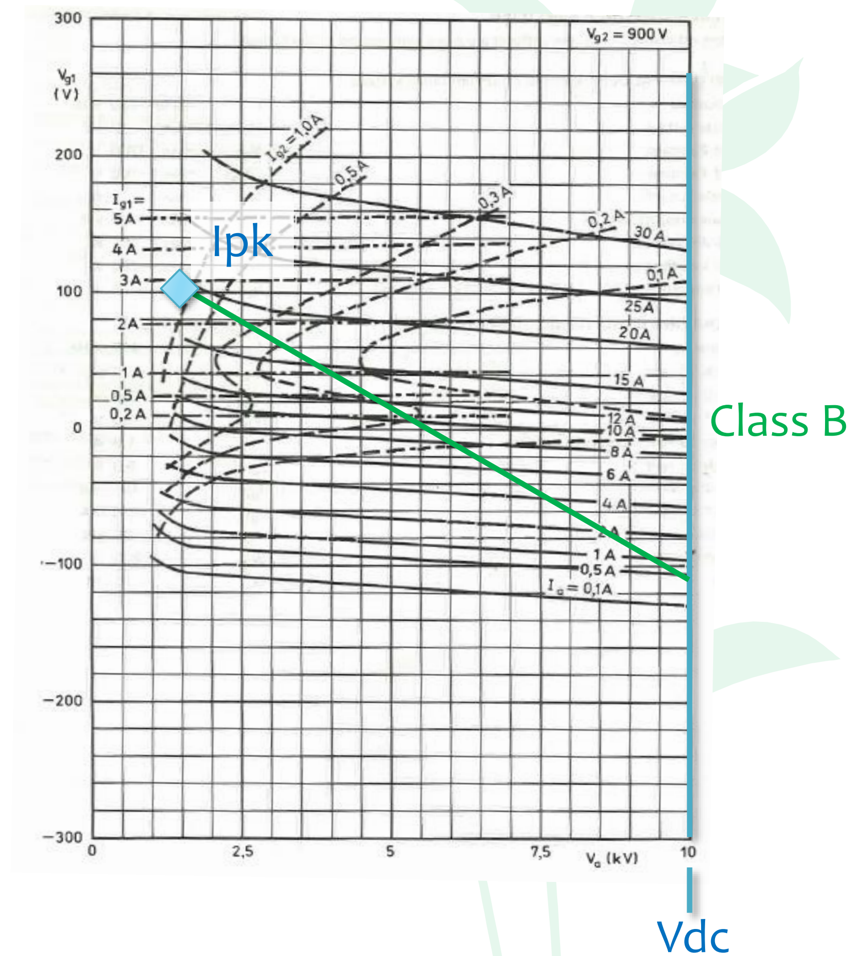
$P_{rf} = ½\, V_{rf} I_{rf}$

$P_{rf} = ½\, V_{dc} I_{dc}\, \pi/2 = \pi/4\, V_{dc} I_{dc}$

Theoretical efficiency

$\eta = P_{rf}/P_{dc} = ¼\, V_{dc} I_{pk} / V_{dc} I_{dc}$

$\eta = 78.5\ \%$



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Class B efficiency in practice

Two reasons for not achieving this impressive number

1. tube is not fully linear whilst it is conducting
2. Anode voltage must be higher than G2 voltage, VG2 being ~ 10% Vdc

This leads into

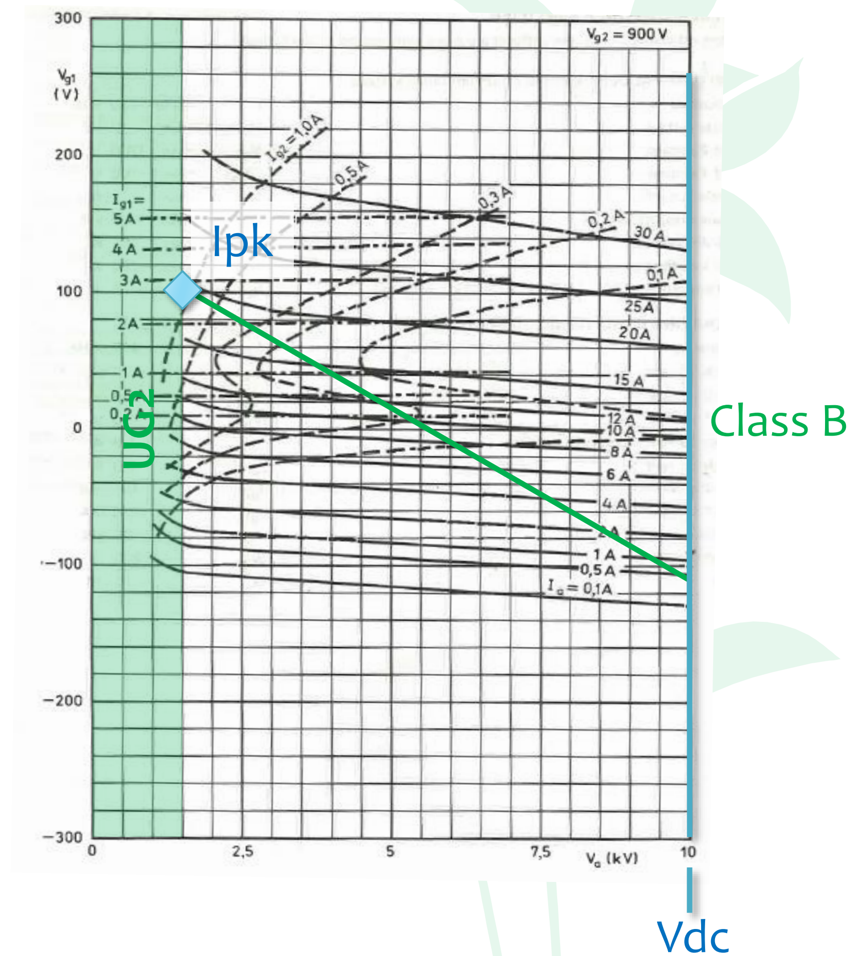
Pdc = Vdc Idc = Vdc 1.05 Ipk/π

Prf = ½ Vrf Irf = ¼ 0.9 Vdc Ipk

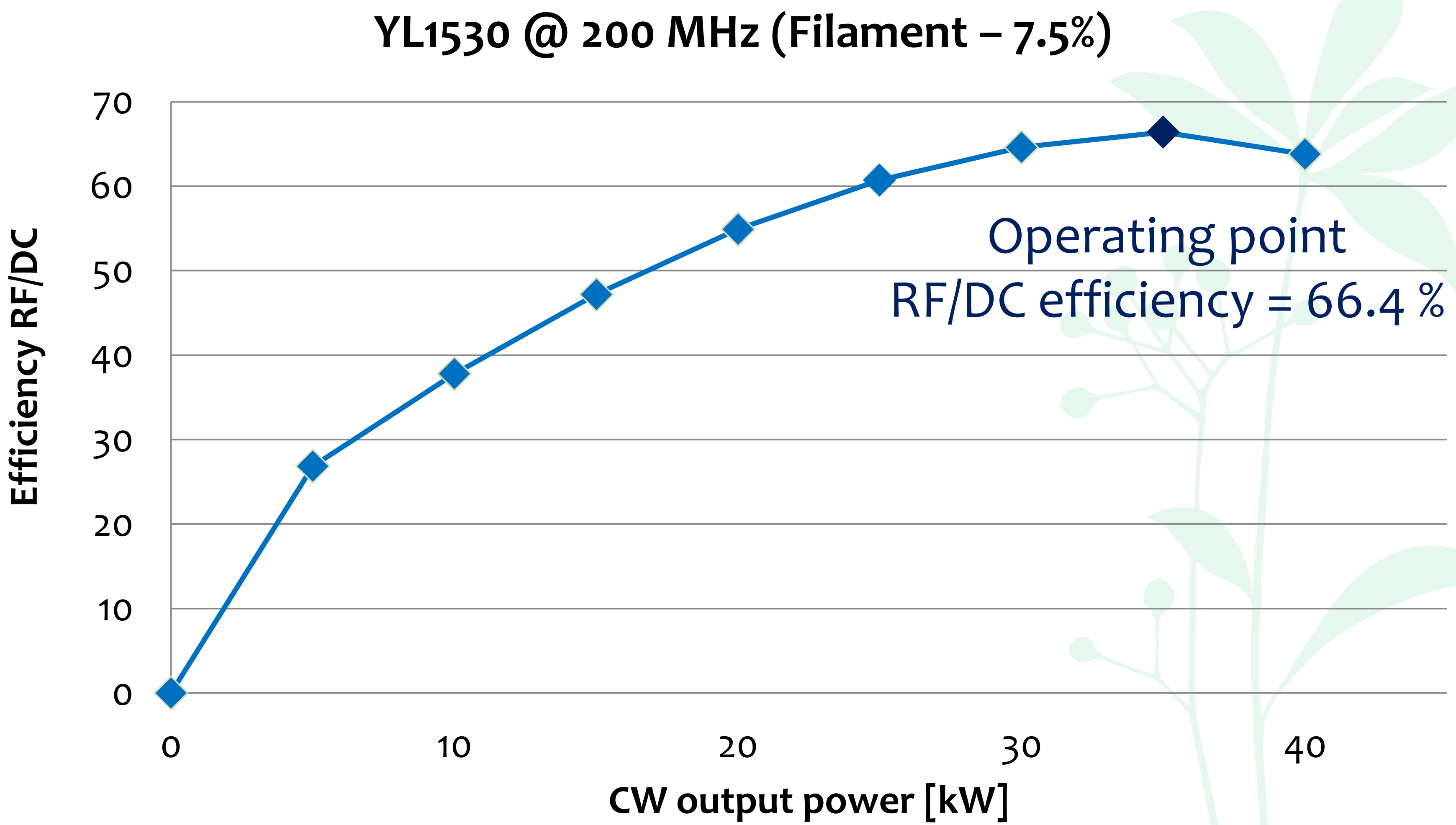
Theoretical efficiency in practice

η = Prf/Pdc = ¼ 0.9 Vdc Ipk / 1.05 Vdc Ipk/π

η = 67 %



Measurement on a YL1530 tube



Overall YL1530 efficiency @ 35 kW

Operating conditions for 35 kW

Gain = 16 dB, P_{RFin} = 0.88 kW

P_{G1} & P_{G2} = 50 W

$P_{filament}$ = 1.3 kW

I_{pk} = 19 A

V_{DC} = 10 kV

$I_{DC} = 1.05\ I_{pk}/\pi$ = 6.4 A

V_{RF} = 8.5 kV

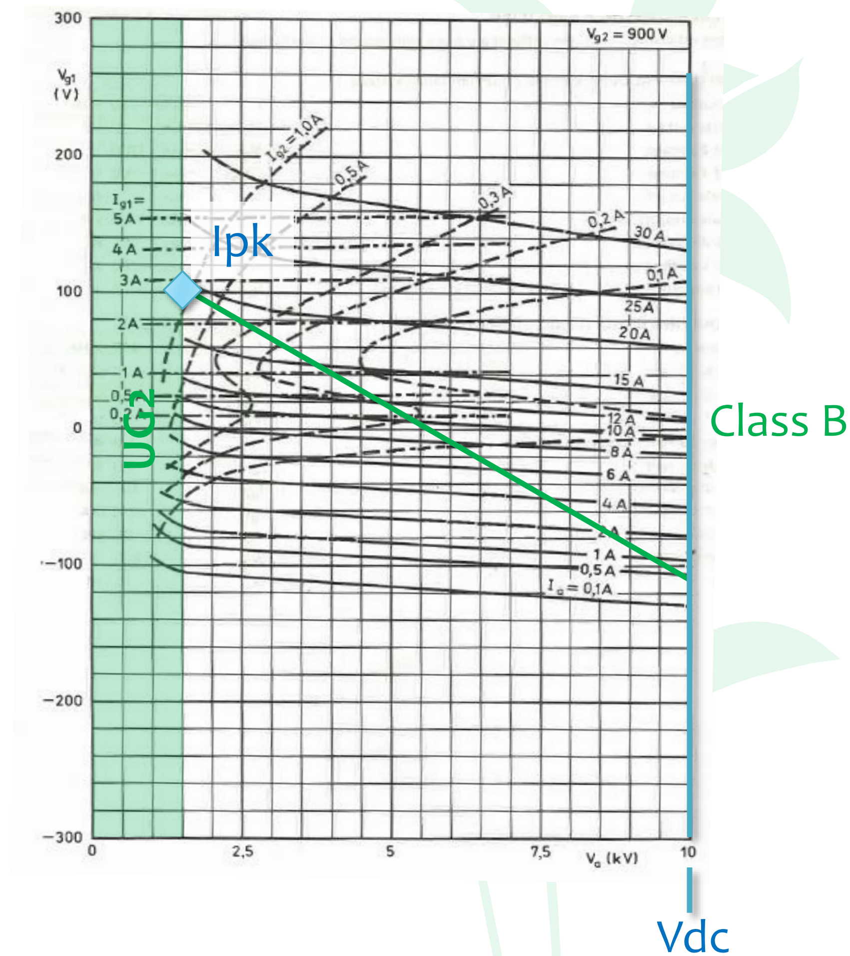
$I_{RF} = I_{pk}/2$ = 9.5 A

$$Efficiency = \frac{P_{RF}}{P_{DCin} + \ PRFin}$$

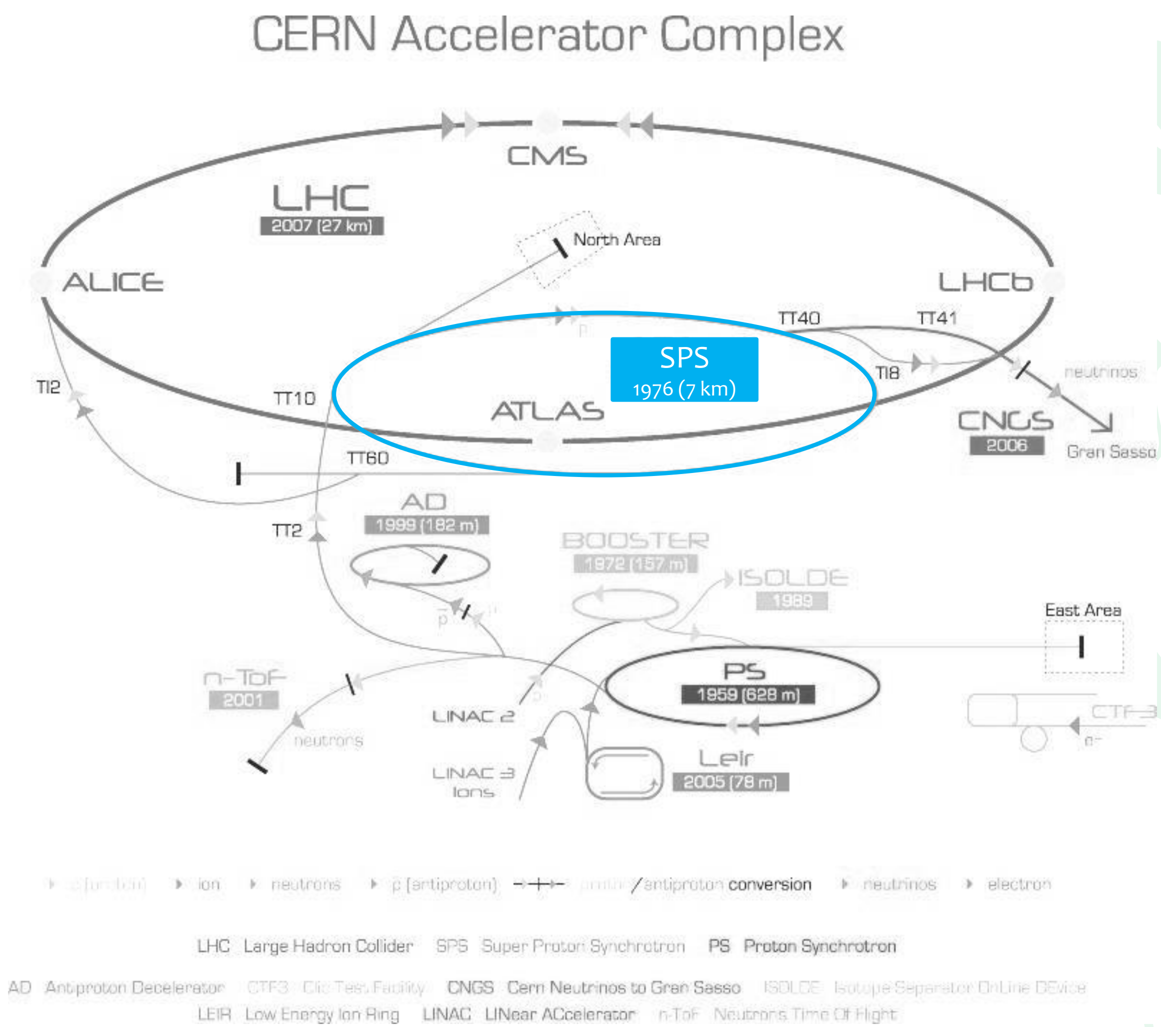
$$Efficiency = \frac{\frac{1}{2}\ 8.5kV\ 9.5A}{10kV\ 6.4A + 0.9kW + 1.3kW}$$

$$Efficiency = \frac{40.4kW}{64kW + 0.9kW + 1.3kW}$$

$$Efficiency = 61\ \%$$



CERN SPS



CERN Accelerator Complex
CMS
LHC
2007 (27 km)
North Area
ALICE
LHCb
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
CNGS
2006
Gran Sasso
TT60
AD
1999 (182 m)
TT2
BOOSTER
ISOLDE
East Area
n-ToF
2001
PS
1959 (628 m)
LINAC 2
LINAC 3
Ions
LEIR
2005 (78 m)
LHC Large Hadron Collider
SPS Super Proton Synchrotron
PS Proton Synchrotron
CNGS Cern Neutrinos to Gran Sasso
LEIR Low Energy Ion Ring
LINAC LINear ACcelerator

CERN SPS YL1530 Power plants

Two amplifiers, 64 YL1530 tubes

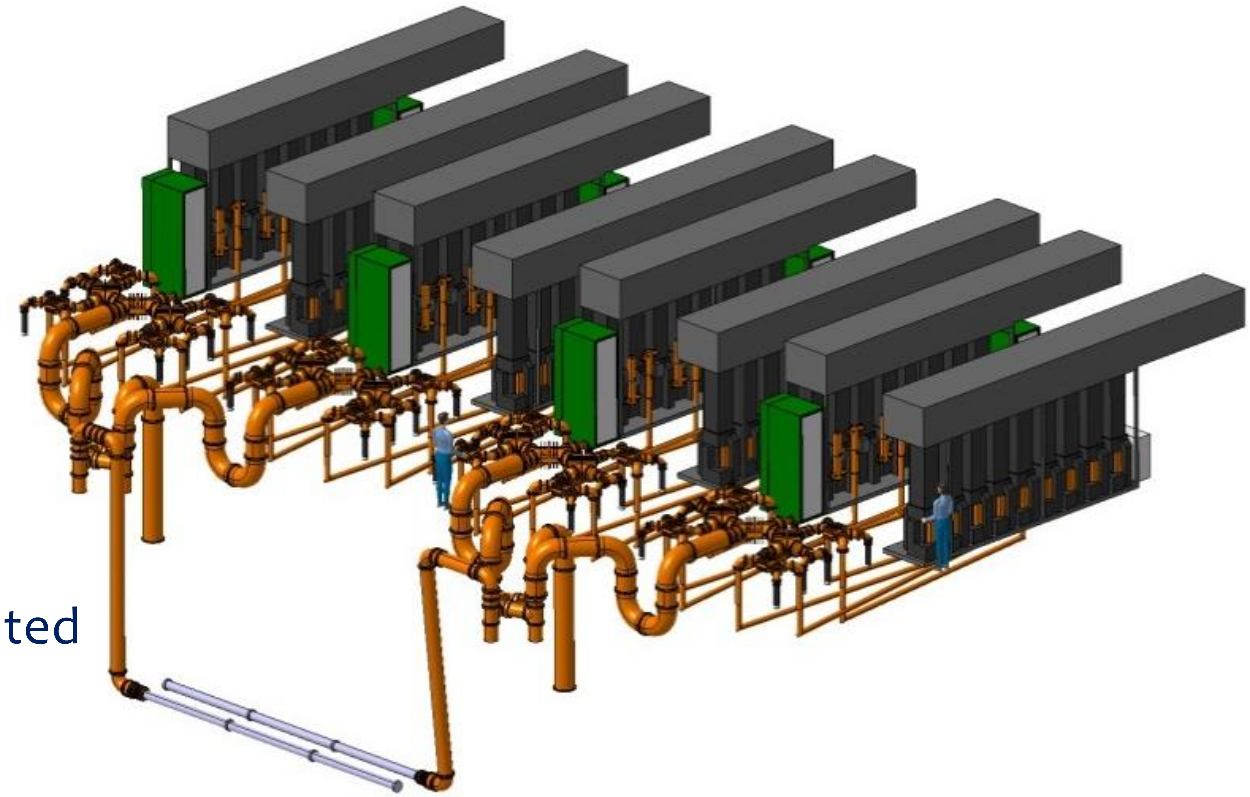
Frequency 200.2 MHz

One amplifier delivers 650 kW with 32 YL1530

-0.2 dB for combining plant (-4.7 % power)

Each single tube is operated 21.2 kW

Overall Efficiency = 48 %



Overall YL1530 efficiency @ 21 kW

Operating conditions for 21 kW with settings for 21 kW

Gain = 16 dB, P_{RFin} = 0.58 kW

P_{G1} & P_{G2} = 50 W

$P_{filament}$ = 1.3 kW de-rated to 1.2 kW

I_{pk} = 13 A

V_{DC} = 10 kV

I_{DC} = 1.03 I_{pk}/π = 4.3 A

V_{RF} = 6.5 kV

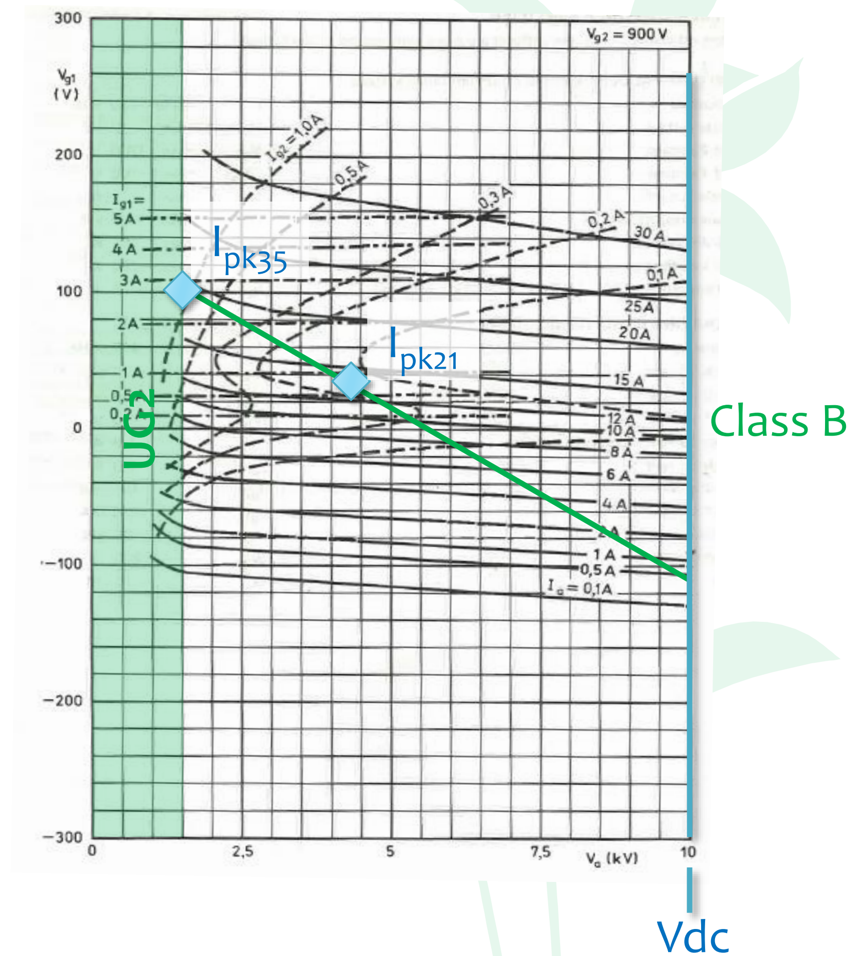
I_{RF} = $I_{pk}/2$ = 6.5 A

$$Efficiency = \frac{P_{RF}}{P_{DCin} + \ PRFin}$$

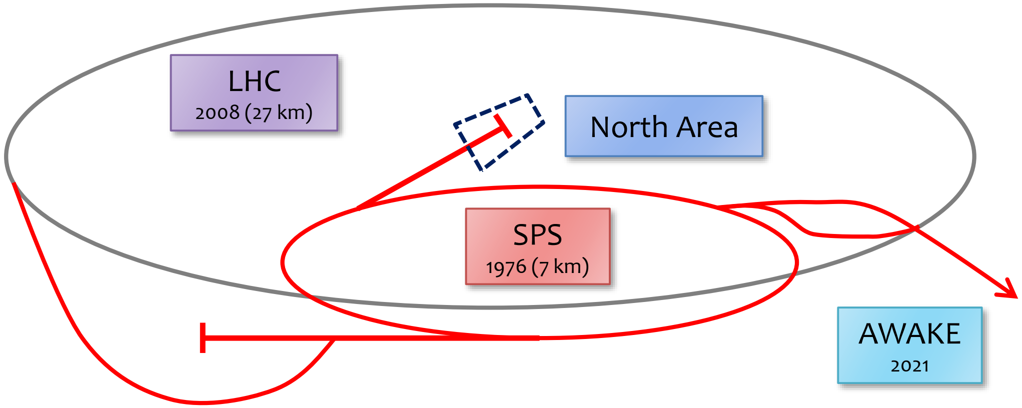
$$Efficiency = \frac{\frac{1}{2}\ 6.5kV\ 6.5A}{10kV4.2A + 0.6kW + 1.2kW}$$

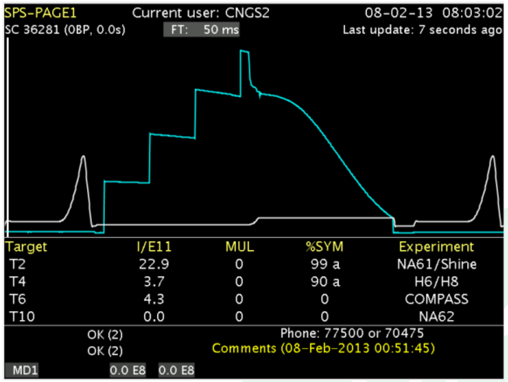
$$Efficiency = \frac{21\ kW}{42kW + 0.6kW + 1.2kW}$$

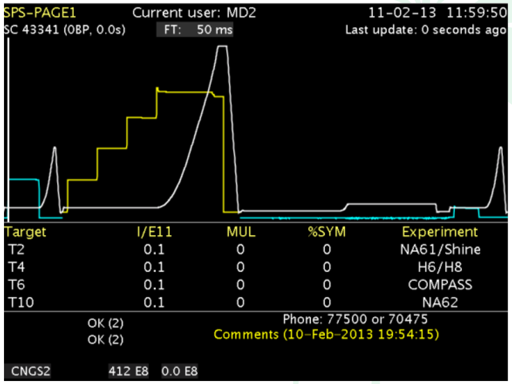
$$Efficiency = 48.2\ \%$$

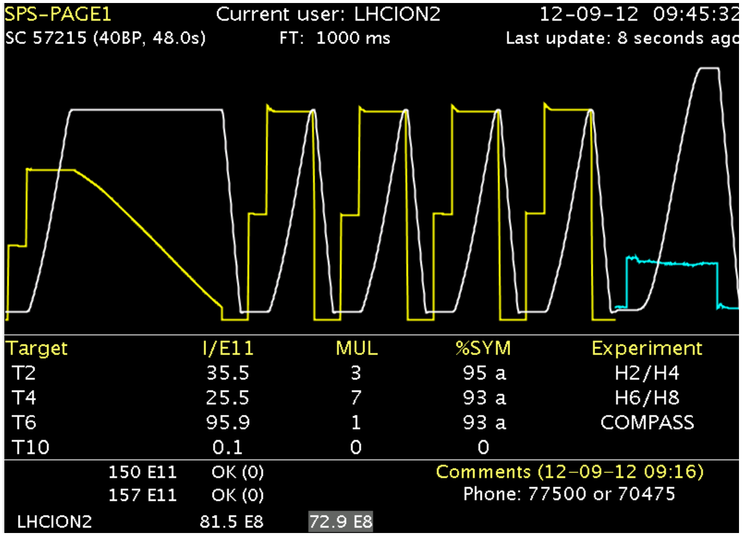


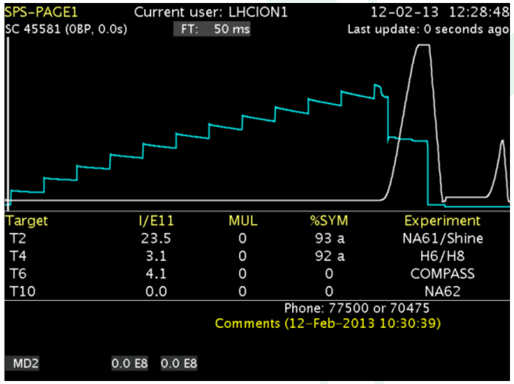
SPS Supercycle



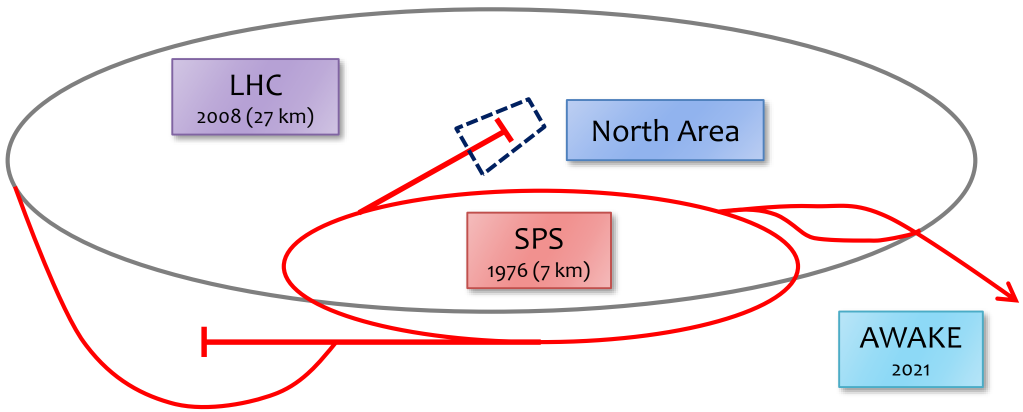


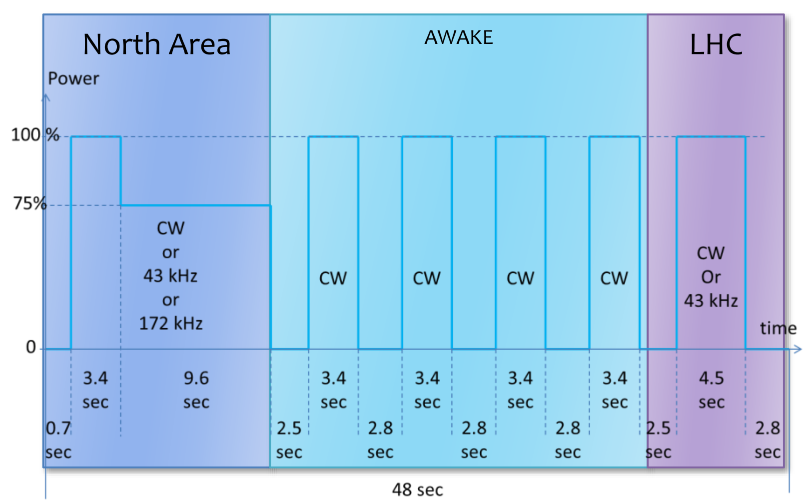






SPS Supercycle





If CW operation, Total average Power : 59.7 % of full power

During 2022

Example of a 48 seconds supercycle (400 kW average)

- 19.25 seconds / 650 kW
- 9.6 seconds / 500 kW
- 19.15 seconds / 80 kW (no RF)

For SPS, with 7’000 hours of operation 3 GWh per year

Please, note that

- LHC is 750 GWh per year
- Total CERN is 1’300 GWh per year
- Geneva 3’000 GWh per year

Operating with 'OFF Line' Tubes

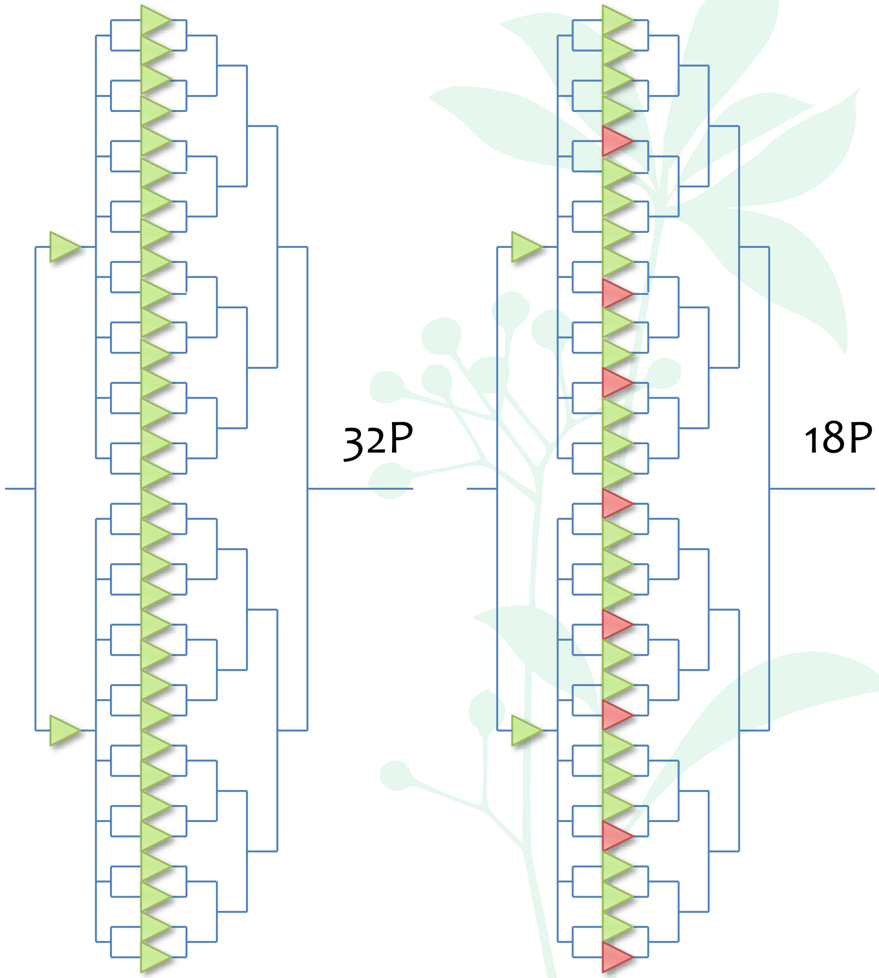
In normal operation, one tube delivers a maximum power of (650 kW + 4.7 %) / 32 = 21.2 kW

Systems have been designed (1980) to deliver full voltage into the cavity *even with only 24/32 tubes*

In case of 8 tubes 'OFF Line', remaining tubes shall deliver 23 kW x (32/24)^2 = 37.8 kW

32 x 21.2 kW = 18 x 37.8 kW = 680 kW

YL1530 tubes are rated 37.5 kW



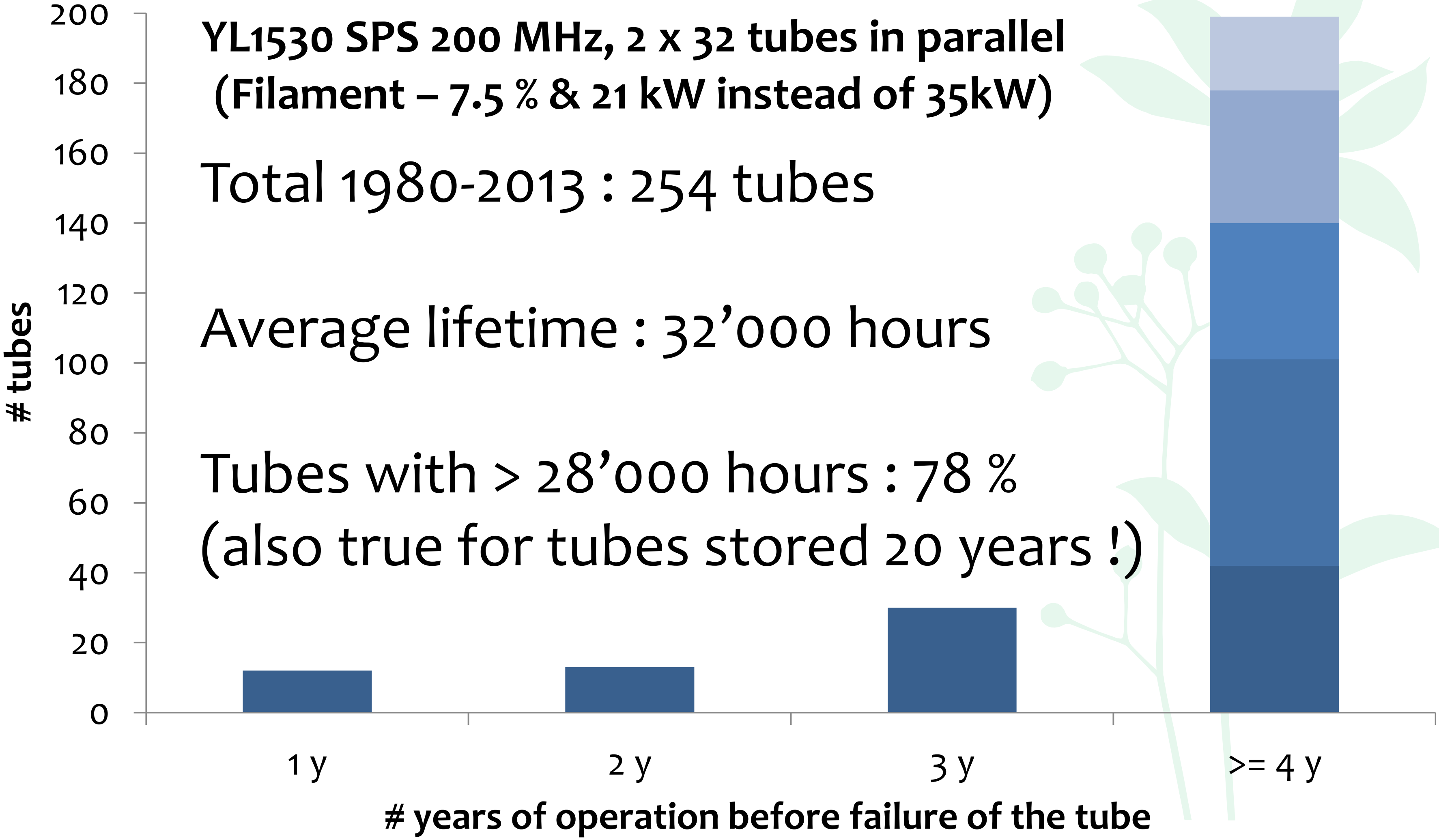
Tubes statistics

YL1530 SPS 200 MHz, 2 x 32 tubes in parallel
(Filament – 7.5 % & 21 kW instead of 35kW)

Total 1980-2013 : 254 tubes

Average lifetime : 32’000 hours

Tubes with > 28’000 hours : 78 %
(also true for tubes stored 20 years !)



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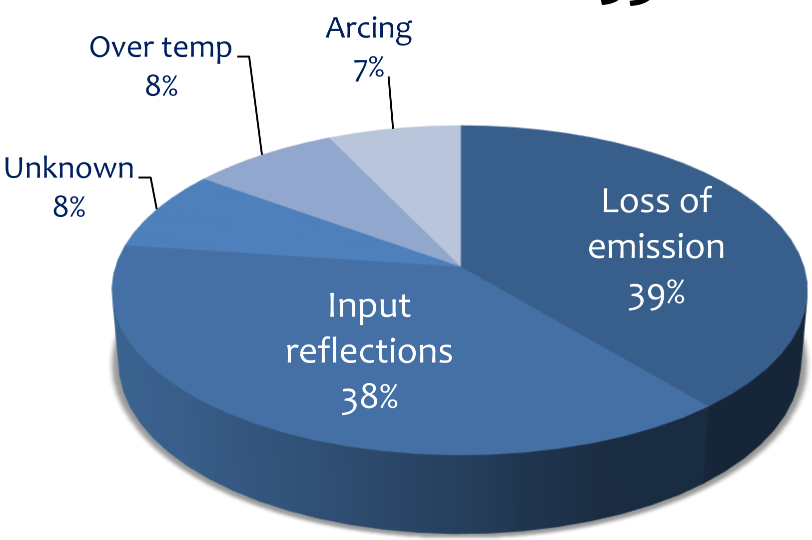
Amplifiers statistics

YL1530 SPS 200 MHz, 2 x 32 tubes in parallel



Reason of fault	# of faults	% of faults
Loss of emission	99	39
Input reflections	97	38
Unknown	20	8
Over Temp	20	8
Arcing	18	7

We lose 14-16 tubes per year,
that we exchange during Technical Stops 3-4 times a year
Unpredictable : 23 % (equivalent to 4 tubes)
Graceful degradation : 77 % (possible to monitor and predict)

Availability of the CERN SPS

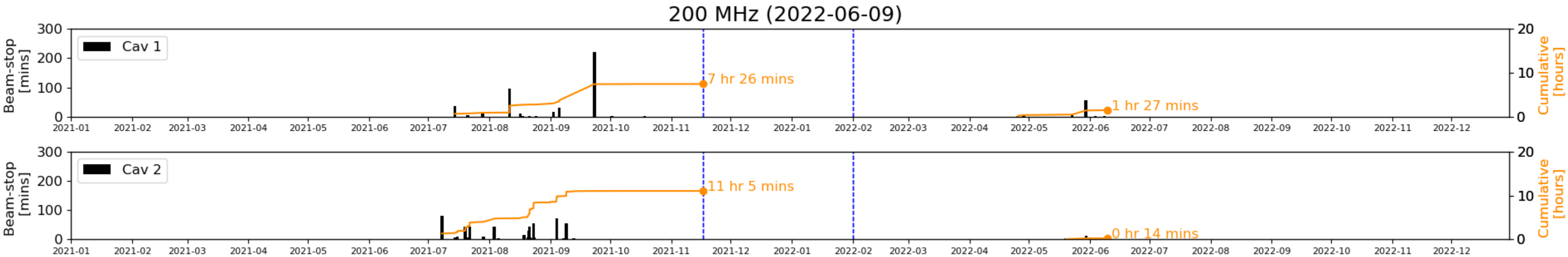
Availability of an Injector is the key parameter

CERN's total annual electricity consumption is 1.3 TWh, for an operation of almost 7'000 hours per year

- 43 % for the LHC (including 13 % for LHC cryogenics + 8 % for the cooling and ventilation)
- 11 % for LHC experiments (ATLAS, CMS, ALICE and LHCb)
- 30 % for the SPS (including 6 to 7% for the North Area experiments)
- 3 % for the PS + Booster + Linac
- 6 % for the Computer Centre (B513)
- 7 % for offices and restaurants, etc.
- (http://cds.cern.ch/record/1324541?ln=en)

When SPS is down, electrical bill costs 7'500 CHF/h (this is a minimum, 52 MCHF / 7'000 hours, this will hugely increase in the coming years)

Availability of the CERN SPS



With these operating conditions

- - 7.5 % $U_{filament}$ → + 37.5 % lifetime
- Off Line tubes for the unpredictable faults
- Overall efficiency 48 % during cavity maximum voltage
- Supercycle average power 400 kW

With stating that, all inclusive, one hour costs

- 200'000 CHF for entire CERN (incl. LHC)
- 100'000 CHF for LHC alone

Over 7'000 hours of operation in 2021, these two RF Power plants have been responsible for only 18,5 hours of down time!

- 18.5 hours x 7'500 CHF/hour [electricity bill] = 140 kCHF
- 18.5 hours x 200'000 CHF/hour [CERN overall cost] = 3.7 MCHF

Availability of the CERN SPS

We can improve the efficiency from **48 % to 61 %** of the RF Power source by

- Increasing the filament to the nominal value (- 37.5% lifetime)
- Reducing the number of tubes in operation
(2 x 20 tubes operated 34 kW,
2 x 7 tubes exchanges per year)
- no additional down time with 'off line' operation **BUT reduced beam intensity**

Savings **77,000 CHF**

Money (electrical bill savings)

2.9 GWh at 60 CHF/MWh with

48 % efficiency costs 362,000 CHF

61 % efficiency costs 285,000 CHF

Availability of the CERN SPS

We can improve the efficiency from **48 % to 61 %** of the RF Power source by

- Increasing the filament to the nominal value (- 37.5% lifetime)
- Reducing the number of tubes in operation
  (2 x 20 tubes operated 34 kW,
  2 x 7 tubes exchanges per year)
- no additional down time with 'off line' operation ~~BUT reduced beam intensity~~ **OR Three hours stop for a tube exchange**

Savings **77,000 CHF**

Money (electrical bill savings)

2.9 GWh at 60 CHF/MWh with

48 % efficiency costs 362,000 CHF

61 % efficiency costs 285,000 CHF

Costs **315,000 CHF**

(*money, not taking into account impact to physics*)

14 additional tube exchanges,
3 x 14 = 42 hours physics lost

electrical bill due to LHC & experiments infrastructure costs (7'500 CHF/h x 42)

Availability of the CERN SPS

With respect to this CERN SPS example, applicable to all RF plants with smaller energy consumption compare to ‘other’ energy consumers in the machine,

being more efficient with RF power plant with an overall efficiency increased from 48 % → 61 %, and no margin in the RF power plant,

for the same beam quality

- Will induce more accelerator stops
- Cost more electricity at the end
- Even worse with the kWh cost increases in the coming years…

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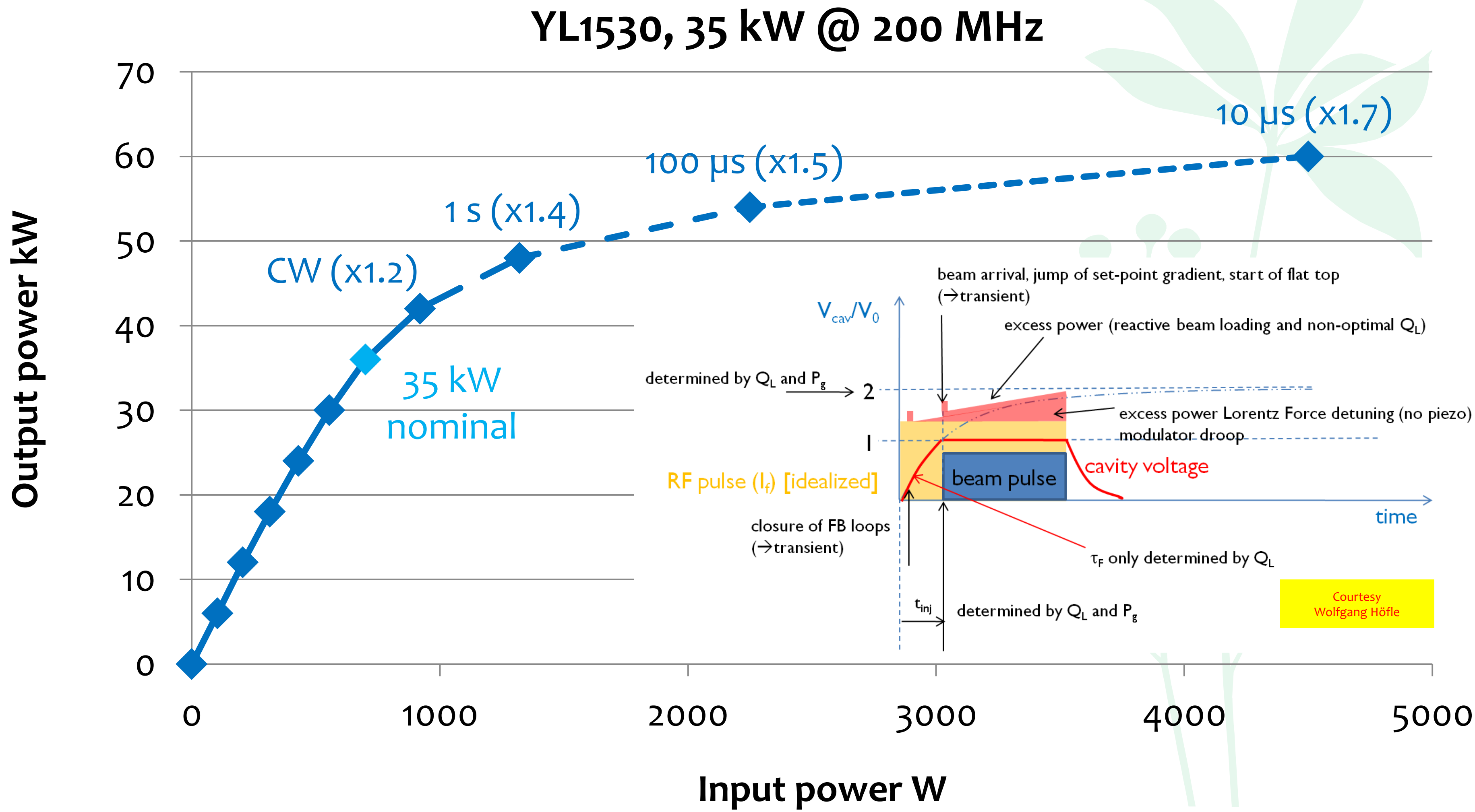
Overhead



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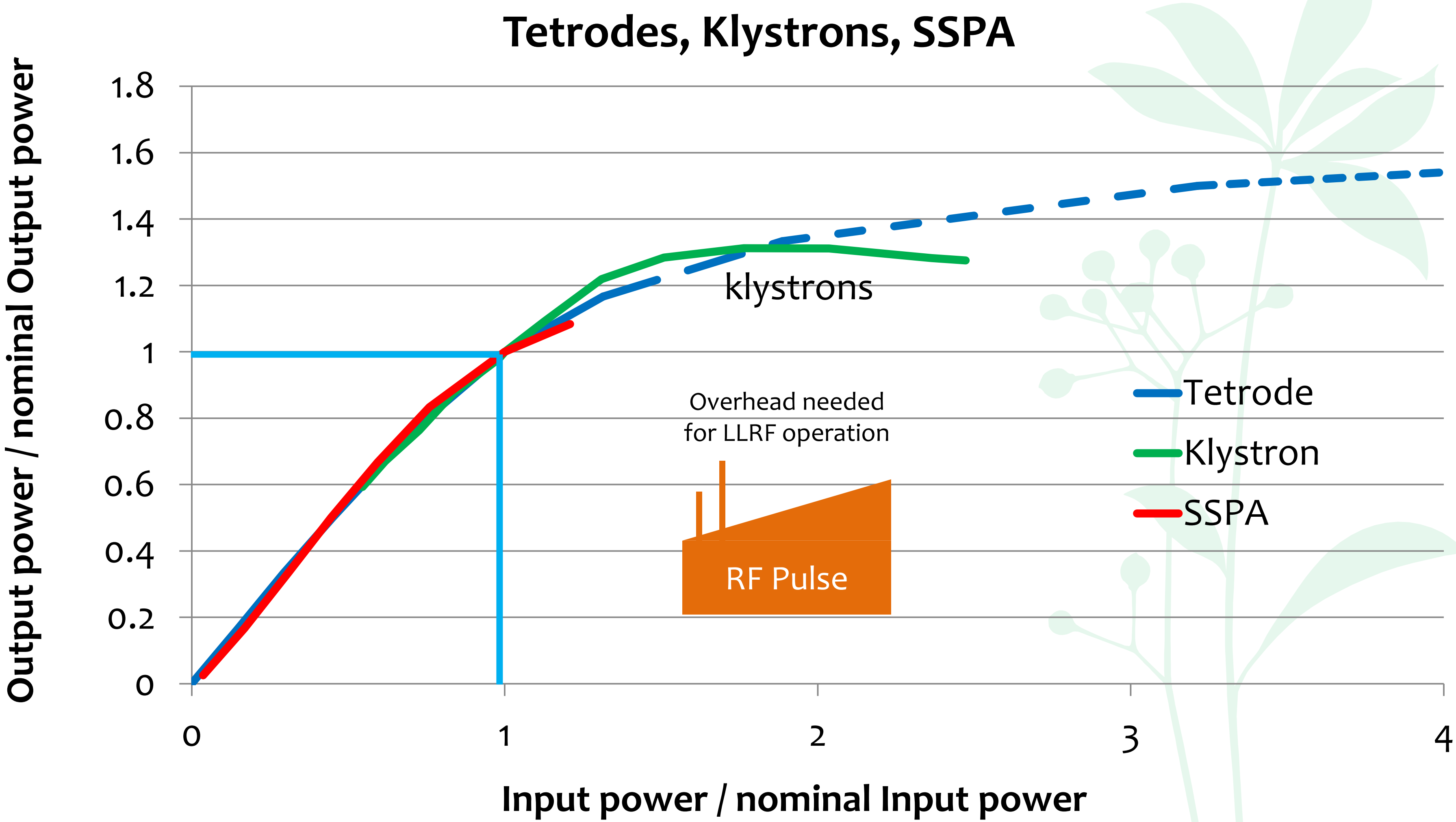
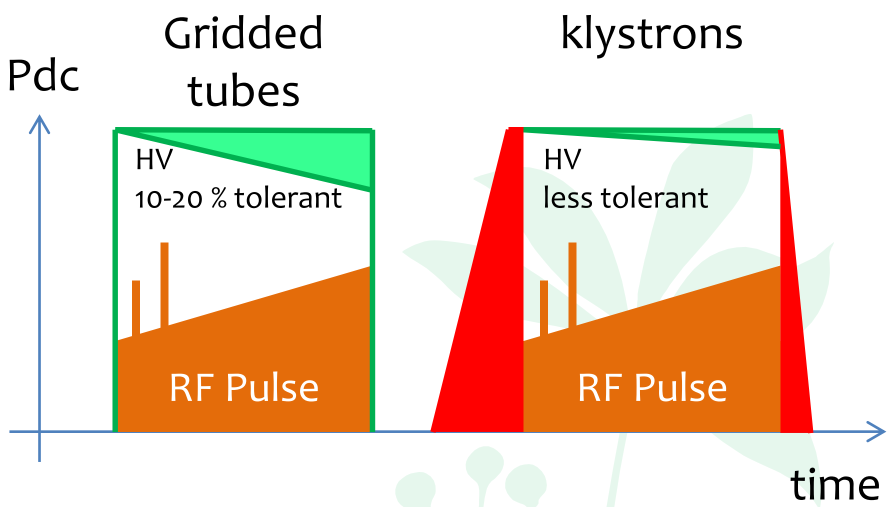

Tetrodes, Klystrons, SSPA
Output power / nominal Output power
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
Input power / nominal Input power
klystrons
Overhead needed
for LLRF operation
RF Pulse
Tetrode
Klystron
SSPA

HVPS

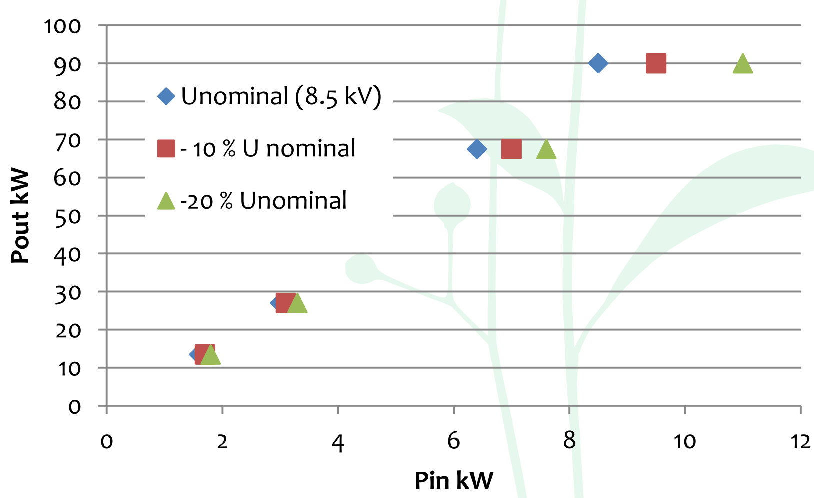


For tetrodes (and gridded tubes more generally) HVPS is very simple

No RF -> idle current (can be zero in class B or class C)

Even if HV is drooping, the LLRF will impose output power, and tetrode remains able to deliver requested Power

RS2004 tetrode



Circulator

If the reflected power is not too long, Tetrodes do NOT need a circulator

With a good reflected power protection, Tetrodes can sustain full reflection

We operate the SPS since 1976-1980 without a single failure due to reflected power

Our protection is made with old relays, few milliseconds

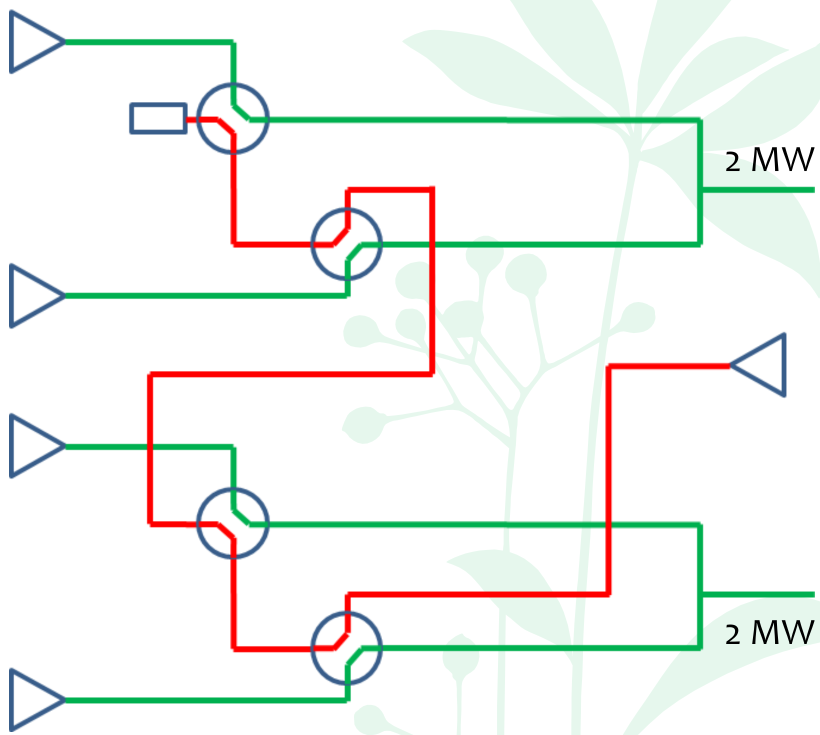
Granularity

‘New’ way of making the storage of spares

One tube is in ‘stand-by’ mode and can possibly replace any faulty tube within few minutes with a ‘OFF line – ON line’ matrix

All four tubes in operation will be operated at their best efficiency point

Still have robustness thanks to the fifth tube



New SPS power plants: 2 x 2 MW @200 MHz
Four + one diacrodes option scheme

Conclusion (I/II)

Regarding the frequency range & regarding the power range

If **AVAILABILITY** of the machine is the key criteria

Tetrodes are a good choice

- Multi tubes solution for redundancy operated at a lower power, lower efficiency with nevertheless a very correct final overall cost

If EFFICIENCY is the key criteria

- Regarding the arrangement choices, Tetrodes can be operated 60-70 % overall efficiency in operation

Conclusion (II/II)

If within the frequency & power range

Never neglect a tetrode (diacrode) option

Carefully look at it, and you will see they are very good!

They did not know it was impossible, so they did it
(Mark Twain, 1835-1910)

The ultimate sophistication is simplification
(Leonardo Da Vinci, 1452-1519)

Theoretical Class B efficiency

DC power is

$P_{dc} = V_{dc} I_{dc}$

Assuming the tube is linear whilst it is conducting, the dc anode current is found by Fourier analysis of the current waveform and is $I_{dc} = I_{pk}/\pi$

$I_{rf} = I_{pk}/2 = I_{dc}\,\pi/2$

And ideal class B, $V_{rf} = V_{dc}$

So, RF power is

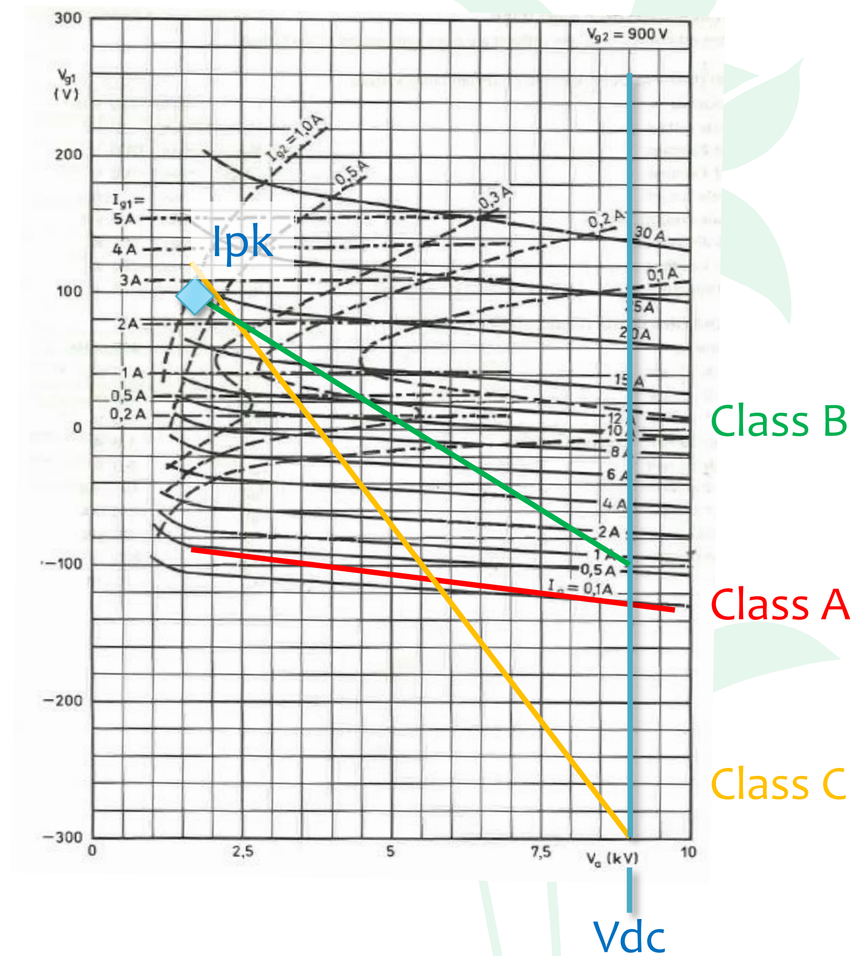
$P_{rf} = ½\, V_{rf} I_{rf}$

$P_{rf} = ½\, V_{dc} I_{dc}\, \pi/2 = \pi/4\, V_{dc} I_{dc}$

Theoretical efficiency

$\eta = P_{rf}/P_{dc} = ¼\, V_{dc} I_{pk} / V_{dc} I_{dc}$

$\eta = 78.5\ \%$



Tubes costs in the CERN SPS
7000 hours operation per year

2 x 32 tubes operation

Filament, nominal -7.5 %

Lifetime 32000 hours

Reduced thermal losses

Broken tubes per year 14

Cost 350,000 CHF

Overall efficiency 48 %

Electricity 2.5 GWh, 0.125 CHF/kWh

Cost = 0.06 2.5/0.48

Cost = 312,000 CHF

2 x 20 tubes operation

Filament, nominal

Lifetime 20000 hours (-37.5%)

Increased Thermal losses

Broken tubes per year 14

Cost 350,000 CHF

Overall efficiency 61 %

Electricity 2.5 GWh, 0.06 CHF/kWh

Cost = 0.06 2.5/0.61

Cost = 246,000 CHF

Pulsed machine

Operating frequency 352 MHz

Pulse duration 3.5 ms

Repetition rate 14 Hz

Number of cavities 26

RF Power 400 kW

Total RF peak power 10.4 MW

Total RF average power 510 kW

Redundancy by number of cavities (operation still possible with one/two cavity OFF)

Operated at maximum power

Same tetrode being driver

Pre-driver SSA ~ 600 W

Tetrodes TH595

Operating conditions for 200 kW

Gain = 15 dB, P_{RFin} = 6.3 kW

P_{G1} & P_{G2} = 500 W

$P_{filament}$ = 1.35 kW

I_{pk} = 56 A

V_{DC} = 16 kV

$I_{DC} = 1.05\, I_{pk}/\pi$ = 18.7 A

V_{RF} = 14.5 kV

$I_{RF} = I_{pk}/2$ = 28 A

$$Overall\ Efficiency = \frac{P_{RF}}{P_{DCin} + PRFin}$$

$$Overall\ Efficiency = \frac{\frac{1}{2}\ 14.5kV\ 28A}{16kV\ 18.7A + 6.3kW + 1.4kW}$$

$$Overall\ Efficiency = \frac{203\ kW}{299kW + 6.3kW + 1.4kW}$$

$$\mathbf{Overall\ Efficiency = 66\ \%}$$

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