Klystron

Possible RF Sources

- Klystron today

Frequency Range:		~350MHz to ~17GHz
Output Power:	CW:	up to ~1.3MW
		Pulsed: up to ~200MW at ~1μs
		up to ~10MW at ~1ms
Klystron Gun Voltage:	DC:	~100kV
		Pulsed: ~600kV at ~1ms
		~130kV at ~1ms

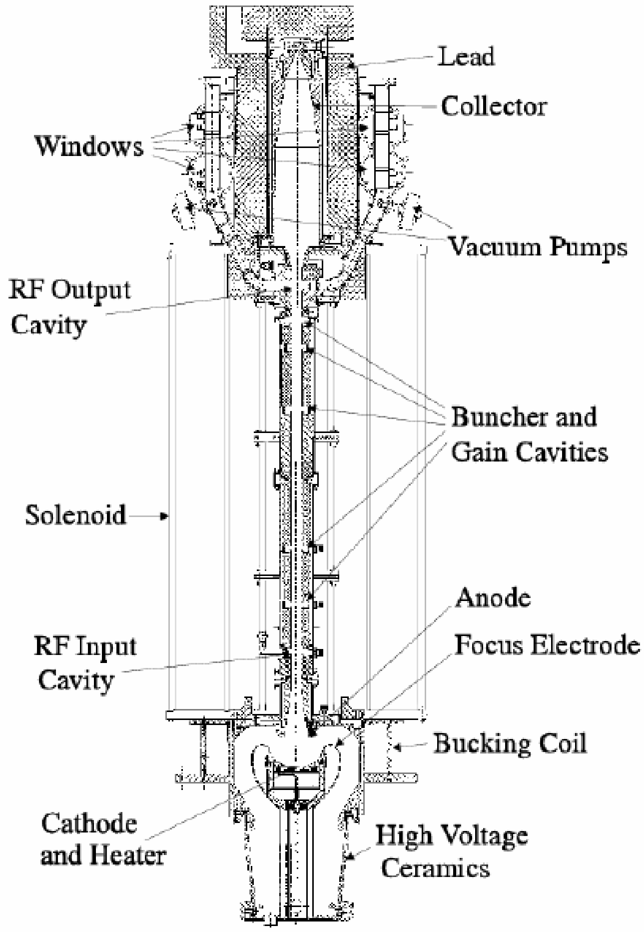
- Tetrode, Triode: Frequency up to ~200-300MHz, ~10kW
- IOT: Frequency up to ~1.3GHz, Power: ~30kW, HOM IOT maybe 5MW in the future
- Gyroklystron: Frequency above ~20GHz, ~10MW
- Gyrotron: Frequency typical 100GHz, ~1MW
- Magnetron: Oscillator, ~10MW
- Travelling Wave Tube, Magnicon, Orbitron, Amplicon etc.

Not for ILC

Klystron Theory

- The klystron principle will be explained
- A basic and simplified theory can be found in the appendix
- Today klystrons or subcomponents of klystrons are designed and calculated making use of different computer codes (Egun, FCI, Mafia, Microwave Studio, Ansys, Magic, special codes developed by klystron manufacturers …)
- PIC codes have been developed recently

Klystron Principle



Example: 150MW, 3GHz S-Band Klystron

- The cathode is heated by the heater to ~1000°C.
- The cathode is then charged (pulsed or DC) to several 100kV.
- Electrons are accelerated form the cathode towards the anode at ground, which is isolated from the cathode by the high voltage ceramics.
- The electron beam passes the anode hole and drifts in the drift tube to the collector.
- The beam is focussed by a bucking coil and a solenoid.
- By applying RF power to the RF input cavity the beam is velocity modulated.
- On its way to the output cavity the velocity modulation converts to a density modulation. This effect is reinforced by additional buncher and gain cavities.
- The density modulation in the output cavity excites a strong RF oscillation in the output cavity.
- RF power is coupled out via the output waveguides and the windows.
- Vacuum pumps sustain the high vacuum in the klystron envelope.
- The beam is finally dumped in the collector, where it generates X-rays which must be shielded by lead.

Klystron Perveance

- Perveance $p = I / U^{3/2}$ (I = klystron current, U = Klystron voltage) is a parameter of the klystron gun determined by the gun geometry (Theory see Appendix)

- Example: THALES TH2104C 5MW, 1.3GHz Klystron U=128kV I=89A $p=1.94*10^{-6} A/V^{3/2}$ (μperveance=1.94)

Klystron Output Power

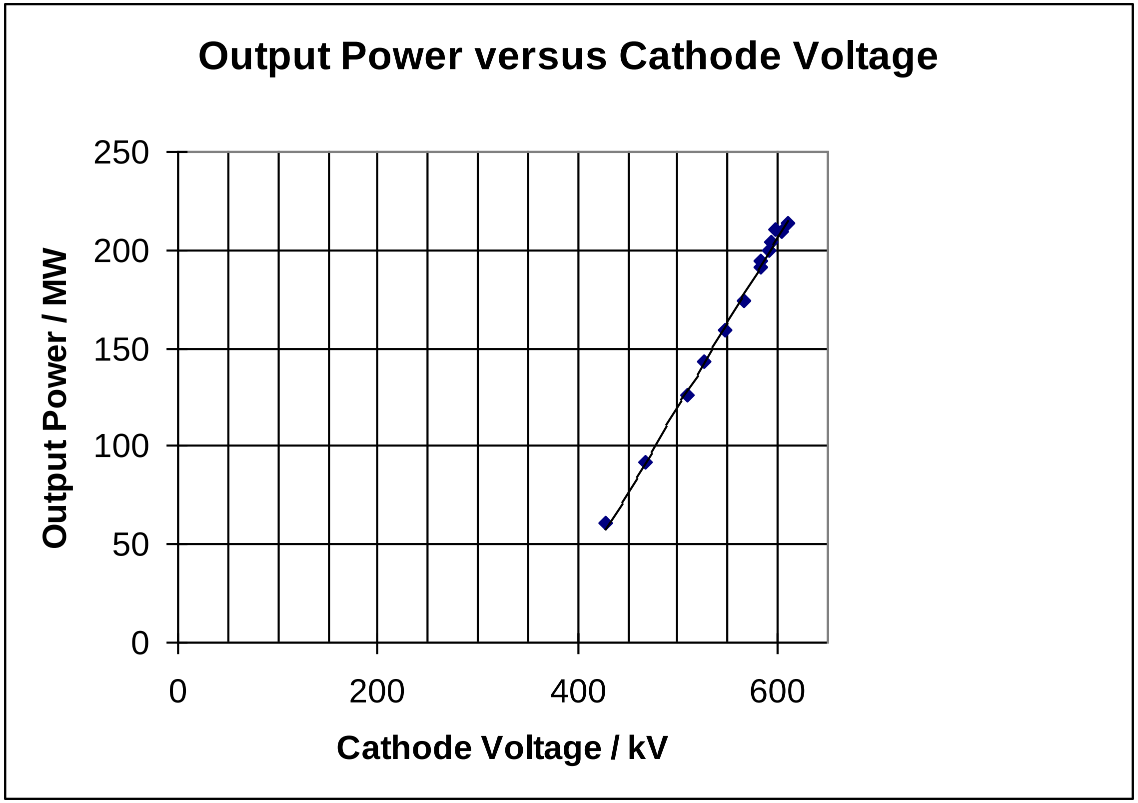
$$P_{RF} = \eta P_{Beam}$$

$$P_{Beam} = UI$$

$$P_{Beam} = pU^{5/2}$$

$$\eta = \eta(U) \propto U^{>0}$$

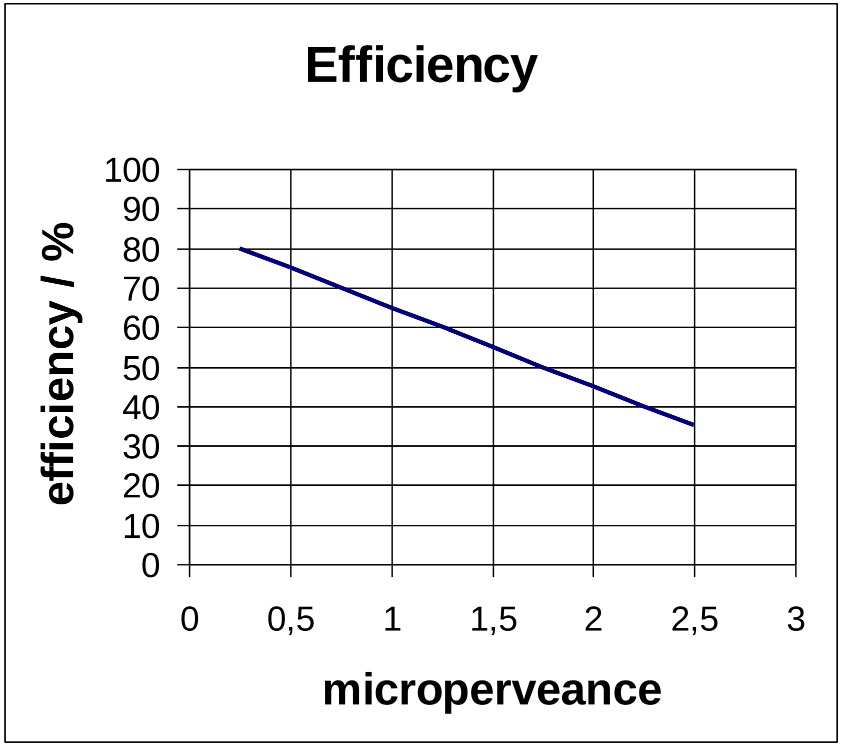
$$P_{RF} \propto U^{>5/2}$$



Example: RF output power of a 3GHz (S-band) klystron as function of the voltage

Klystron Efficiency

- Efficiency of a klystron depends on bunching and therefore on space charge forces
- Lower space forces allow for easier bunching and more efficiency
- Decreasing the charge density (current) and increasing the stiffness (voltage) of the beam increase the efficiency
- Higher voltage and lower current, thus lower perveance would lead to higher efficiency

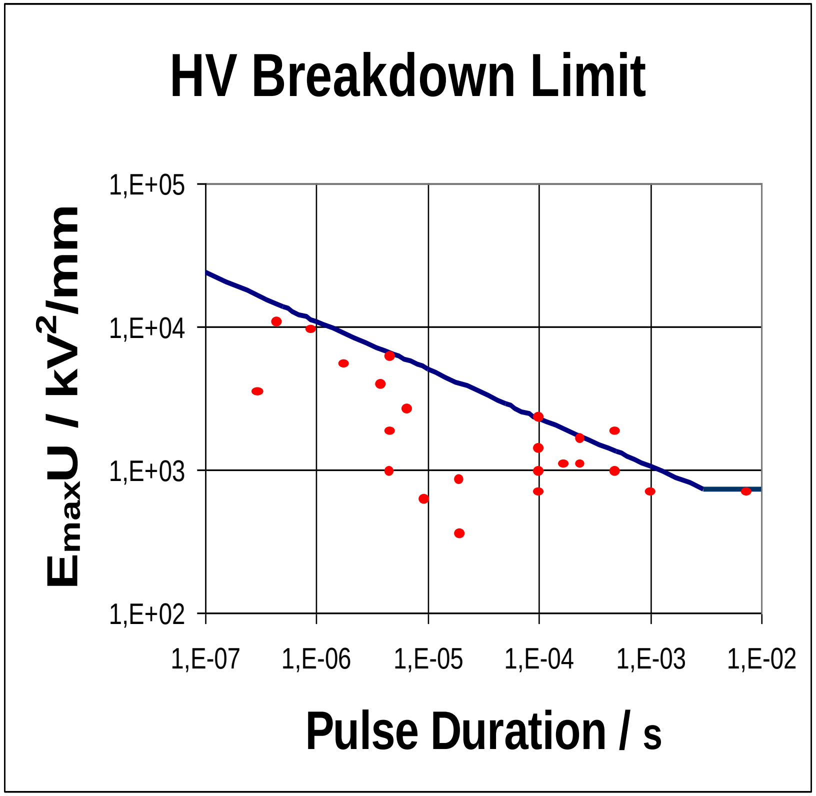


Rule of thumb formula from fit to experimental data

$$\eta = 0.85 - 2 \times 10^{5} \times p$$

Klystron Gun Breakdown Limit

- Disadvantage: higher voltage increase the probability of breakdown
- The breakdown limit EU depend on the pulse duration



$$E_{max} \times U = 100 \times \tau^{-0.34} \left(kV \right)^2 / mm$$

Multibeam Klystron

Idea

Klystron with low perveance:
=> High efficiency but high voltage
Klystron with low perveance and low high voltage
$\Rightarrow$ low high voltage but low power

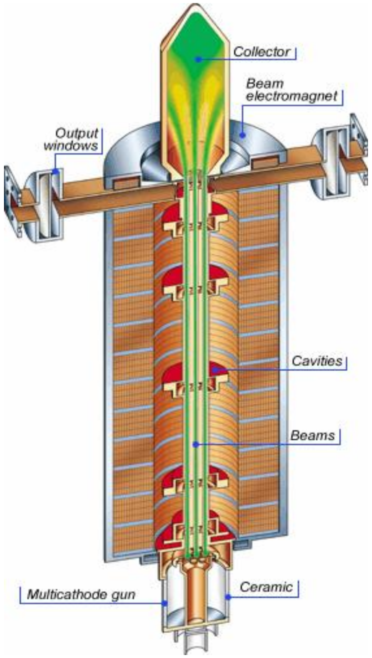
Solution

Klystron with many low perveance beams:
=> low perveance per beam thus high efficiency
low voltage compared to klystron with single low perveance beam

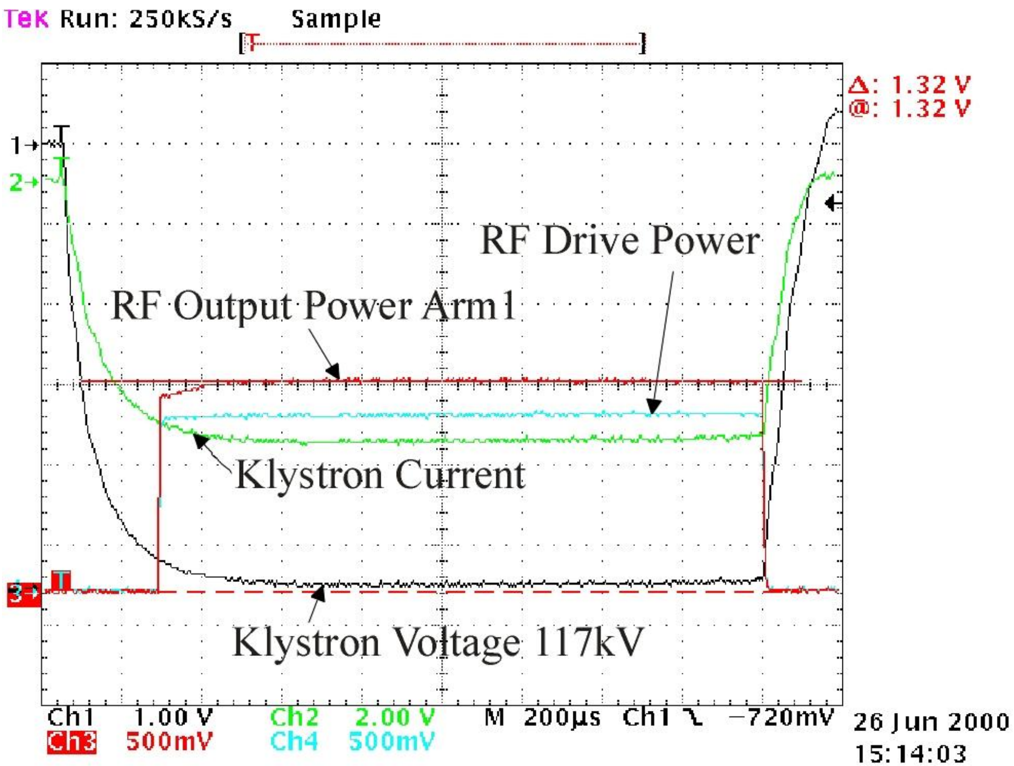
Multi Beam Klystron THALES TH1801 (1)

Measured performance

Operation Frequency:	1.3GHz
Cathode Voltage:	117kV
Beam Current:	131A
mperveance:	3.27
Number of Beams:	7
Cathode loading:	5.5A/cm^2
Max. RF Peak Power:	10MW
RF Pulse Duration:	1.5ms
Repetition Rate:	10Hz
RF Average Power:	150kW
Efficiency:	65%
Gain:	48.2dB
Solenoid Power:	6kW
Length:	2.5m
Lifetime (goal):	~40000h

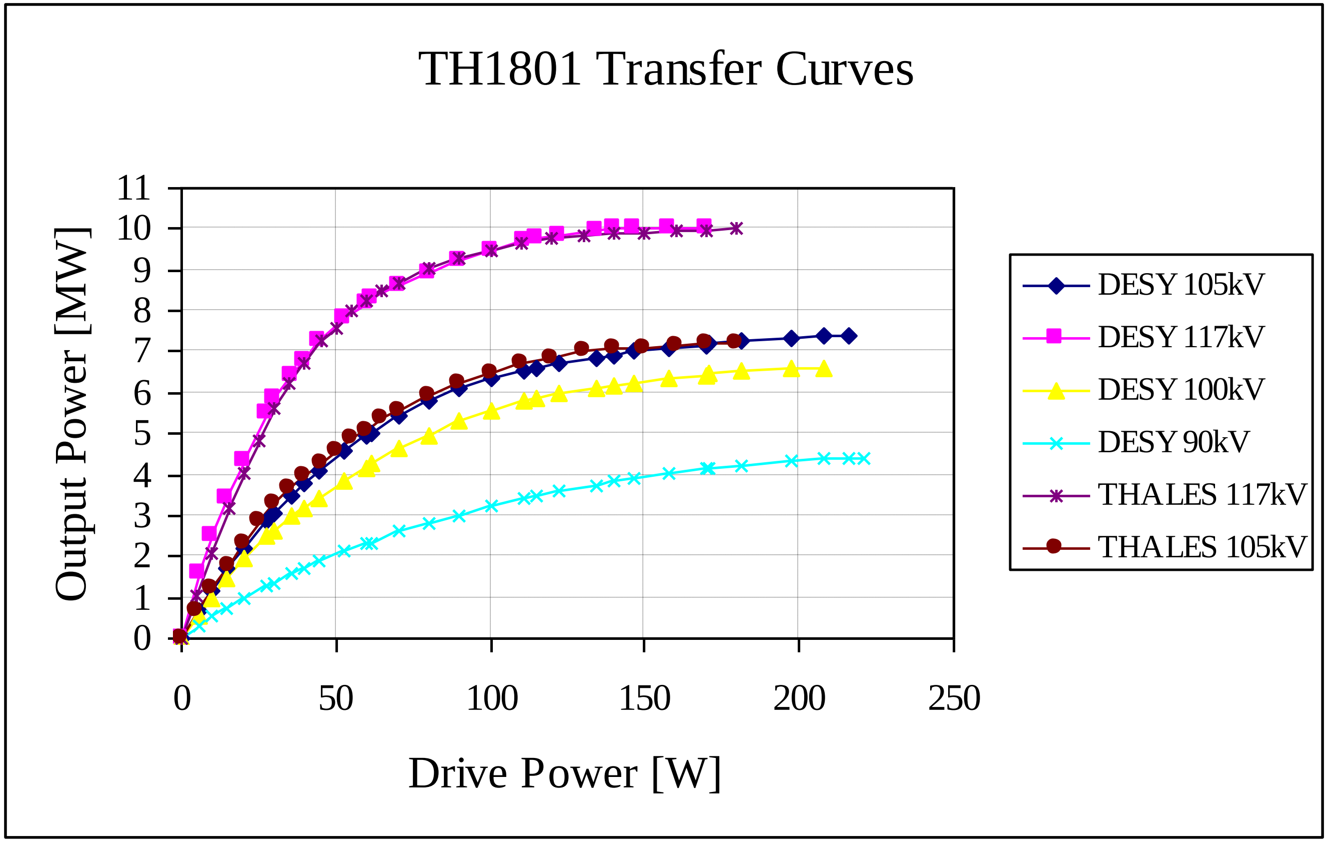


Multi Beam Klystron THALES TH1801 (2)



Pulse Waveforms of a Klystron (Voltage, Current, RF Drive Power, RF Output Power)

Multi Beam Klystron THALES TH1801 (3)

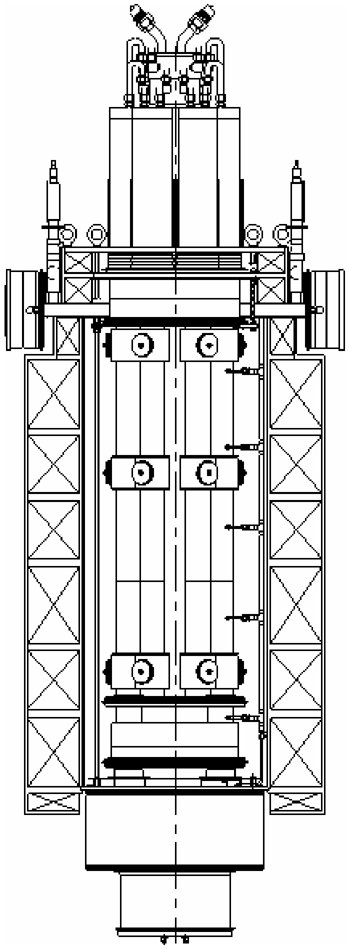


Transfer Curves: RF output as function of RF drive power with klystron voltage as parameter

Multi Beam Klystron CPI VKL-8301(1)

Design Features:

- 6 beams
- HOM input and output cavity
- Individual intermediate FM cavities
- Cathode loading: <2.5A/cm^2 lifetime prediction: >100000h



Drawing of the Klystron

Multi Beam Klystron CPI VKL-8301 (2)

Specified Operating Parameters

Peak Power Output		10	MW (min)
Ave. Power Output		150	kW (min)
Beam Voltage		114	kV (nom)
Beam Current		131	A (nom)
mperveance		3.40	
Frequency		1300	MHz
Gain		47	dB (min)
Efficiency		67	% (nom)
Cathode Loading		2.0	A/cm^2
Dimensions	**H,Ø:**	2.3 by	1.0 meters
Weight		2000	lbs

Electromagnet

Solenoid Power	4	kW (max)
Coil Voltage	200	V (max)
Weight	2800	lbs

Klystron during construction

Multi Beam Klystron CPI VKL-8301 (3)

Measured Operating Parameters at CPI at 500ms pulsewidth

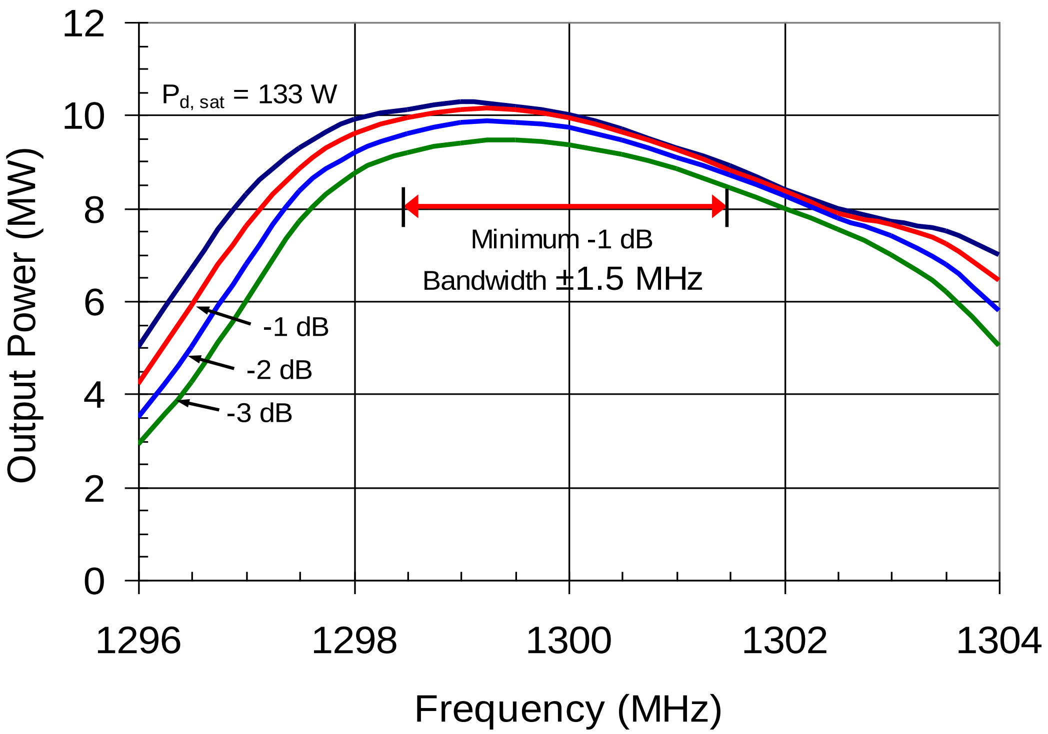
Peak Power Output	10	MW
Ave. Power Output	150	kW
Beam Voltage	120	kV
Beam Current	139	A
mperveance	3.34	
Frequency	1300	MHz
Gain (saturated)	49	dB
Efficiency	60	%

Beam Transmission

DC, no RF	99.5	%
at Saturation	98.5	%

Klystron ready for shipment

Klystron CPI

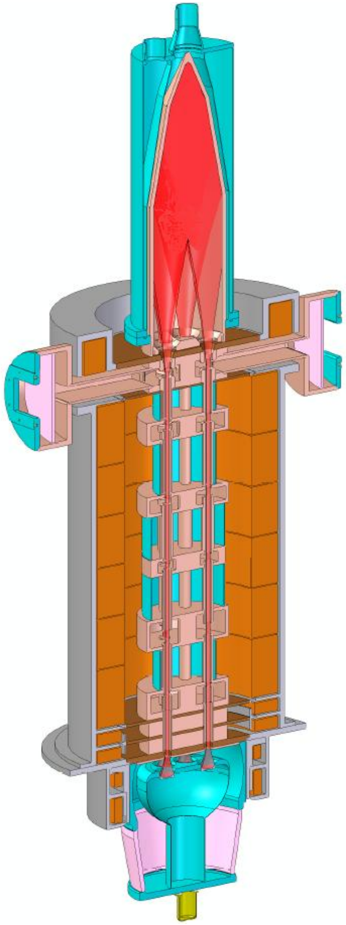


Output power as function of frequency

The TOSHIBA E3736 MBK (1)

Design Features:

- 6 beams
- Ring shaped cavities
- Cathode loading: <2.1 A/cm^2

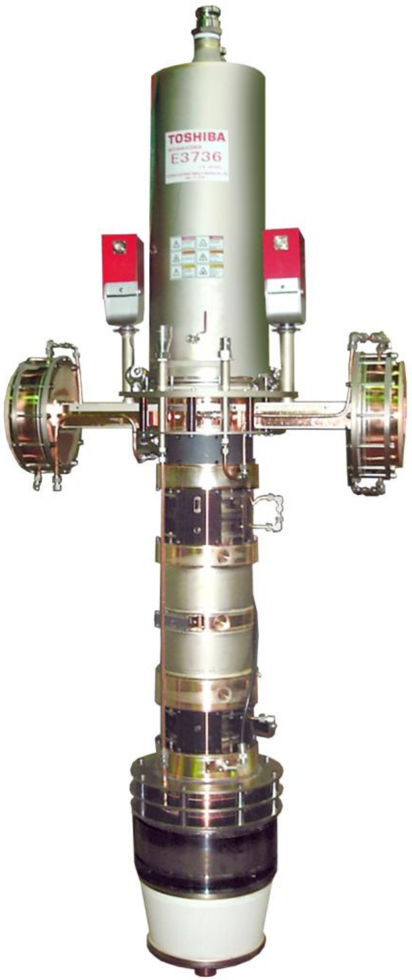


Design Layout

The TOSHIBA E3736 MBK (2)

Measured performance

Voltage: 115kV
Current: 135A
μperveance: 3.46
Output Power: 10.4MW
Efficiency: 67%
Pulse duration: 1.5ms
Rep. Rate: 10Hz



Klystron ready for shipment

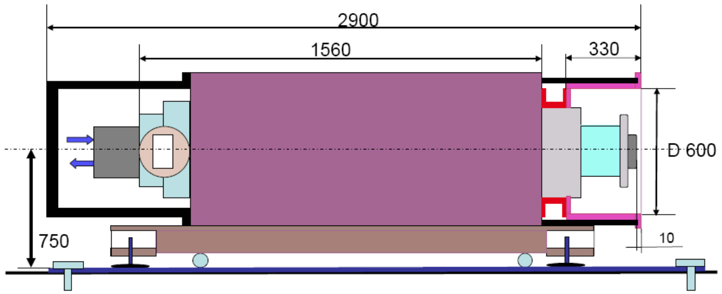
Horizontal Klystron

- Horizontal klystrons are already in use e.g. the LEP klystrons at CERN or the B-factory klystrons at SLAC

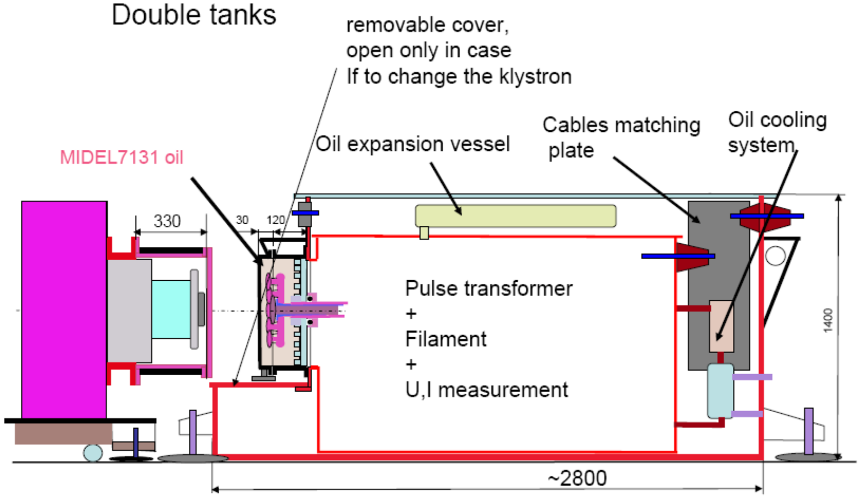
Aspects

- Space in tunnel
- Transportation of klystron and pulse transformer in the tunnel
- Exchange of the klystrons
- Ease of interchange of different types of klystrons to pulse transformer tank and to waveguide distribution system
- X-ray shielding
- Oil leakage

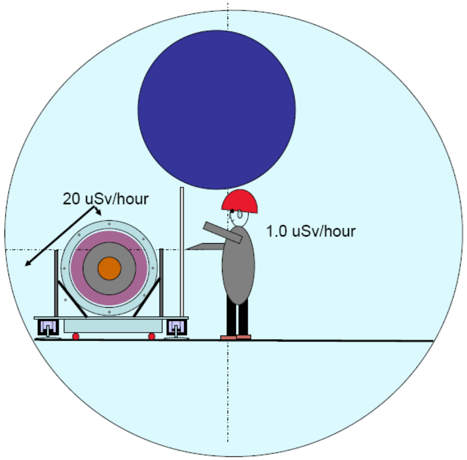
Horizontal MBK



Horizontal MBK



MBK gun and pulse transformer



X-Ray shielding

European XFEL Klystrons

- 27 klystrons
- delivery and installation between spring 2012 and summer 2014
- Toshiba and Thales

Klystron Replacement for the TESLA Linear Collider

- The klystron lifetime will be determined most likely by the cathode lifetime since other klystron components are operated at a moderate level
- With a klystron lifetime of 40000h and an operation time of 5000h per year 8 klystrons must be replaced during a monthly access day
- An overhead of 12 klystrons will be installed, therefore no degradation of accelerator performance is expected between two access days
- Teams of 3-4 people will exchange a klystron within a few hours; klystrons will be equipped with connectors (HV, controls, cooling, waveguides) which allow fast exchange of a klystron in the tunnel

Nr.	Vorgangsname	Dauer
1	**Klystron Exchange Main LINAC**	**0,2 Tage**
2	Transportation to tunnel position	60 Min.
3	Local breakers to change mode	10 Min.
4	Disconnect HV coax cable	20 Min.
5	Disconnect local controls	20 Min.
6	Disconnect water cooling system	30 Min.
7	Disconnect two waveguides	30 Min.
8	Unexpected events	30 Min.
9	Remove klystron	15 Min.
10	Put klystron into positon	15 Min.
11	Connect two waveguides	30 Min.
12	Connect the water cooling system	30 Min.
13	Connect local control	10 Min.
14	Connect HV coax cable	30 Min.
15	Check all above again	20 Min.
16	Unexpected events	15 Min.
17	Local breakers to operation	5 Min.
18	Transportation out of the tunnel	60 Min.