Experience with the development and operation of high efficiency MBKs

MBKS for TESLA, TTF, ILC and European XFEL

Stefan Choroba, Vladimir Vogel, DESY

Experience with the development and operation of high efficiency MBKs
The Cockcroft Institute, Daresbury Laboratory, UK, 03. June 2014

HELMHOLTZ | ASSOCIATION

DESY

Overview

> Introduction TESLA, TTF, ILC and European XFEL

> RF system requirements

> MBK development

> MBK status and lessons learned

Preliminary Remarks

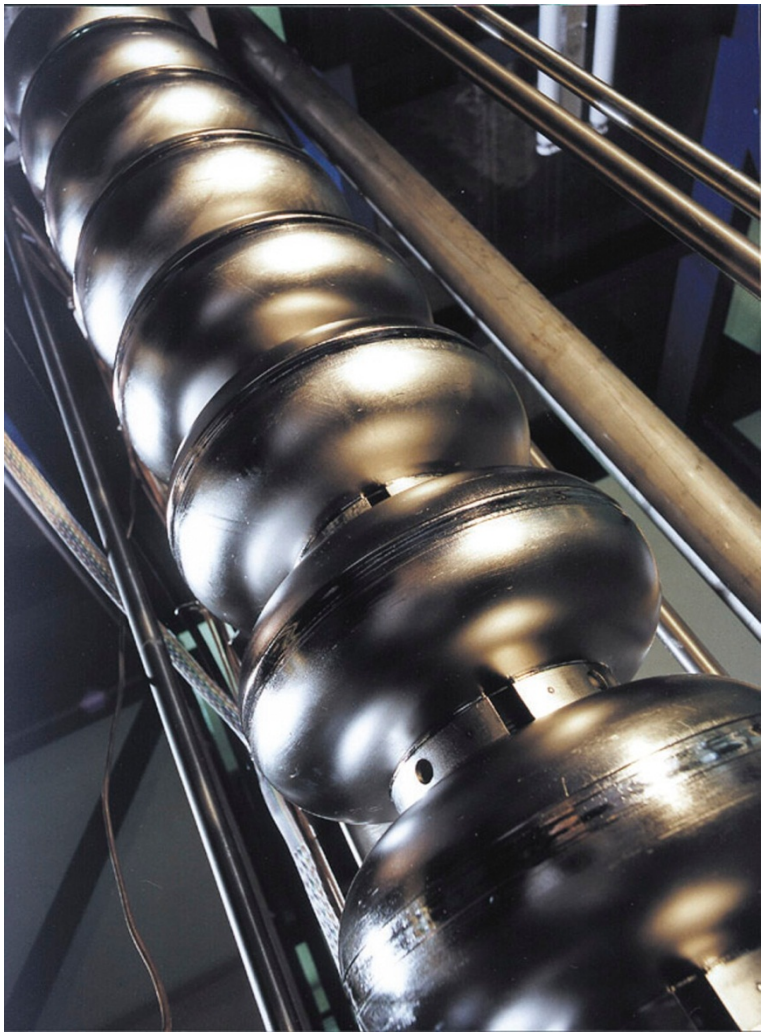
- DESY is a user of multi beam klystrons.
- DESY has triggered the development of multi beam klystron for accelerators.
- DESY supports manufacturers during the development.
- DESY can offer support during discussions, calculations and simulations.
- DESY can also offer sometimes technological support and sometimes the use of test facilities.
- This presentation is about how the development of MBKs started and continued. Some problems occured during this time until finally these klystrons meet DESYs demands. This may or may not be an example for the development of other high efficient RF system components.

TESLA and its descendants

- Early 1990s start of the TESLA Collaboration
- In 1990s Tesla Test Facility (TTF) setup at DESY
- 2001 TESLA TDR of a Linear Collider with integrated XFEL
- 2002 Supplement to the TDR on a dedicated linac for the XFEL, negotiations started to build the XFEL as European project at DESY
- 2006 TDR of the European XFEL
- June 5, 2007 official launch European XFEL
- First beam expected for 2016
- 2004 ITRP recommended superconducting technology for a future Linear Collider
- ILC might be constructed in the future
- TTF is in use as FEL user facility under the new name FLASH
- Many other projects use 1.3GHz Tesla type cavities too

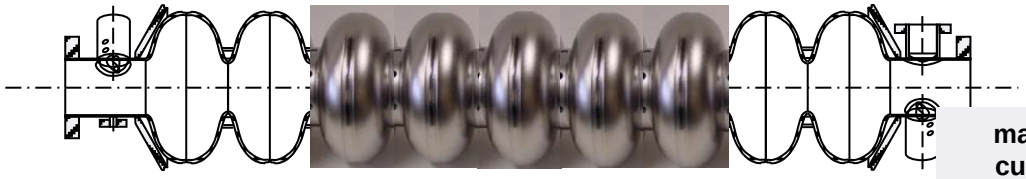
1.3GHz superconducting cavities

- 1.3GHz 9-cell Tesla type
- Max. gradient 46MV/m
- Typical achieved today 25-35MV/m
- Coaxial input coupler
- Assembled in modules

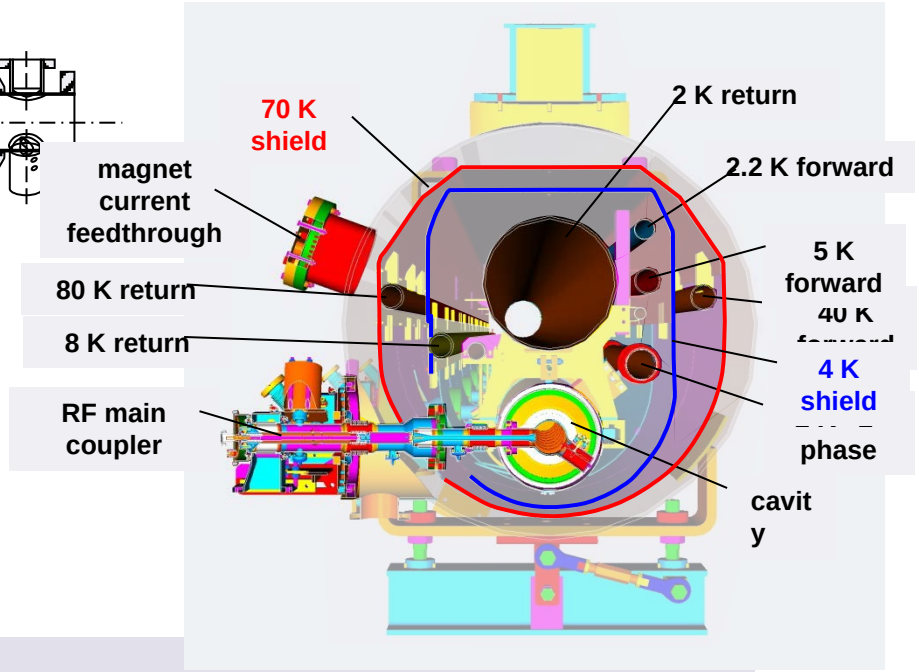


1.3GHz accelerator modules

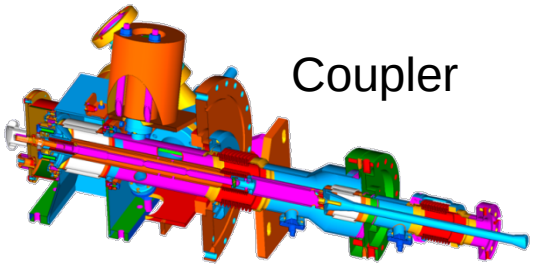
Cavity made of niobium, operated at 2K, gradient >23MV/m Q=10^{10} and 1.3GHz



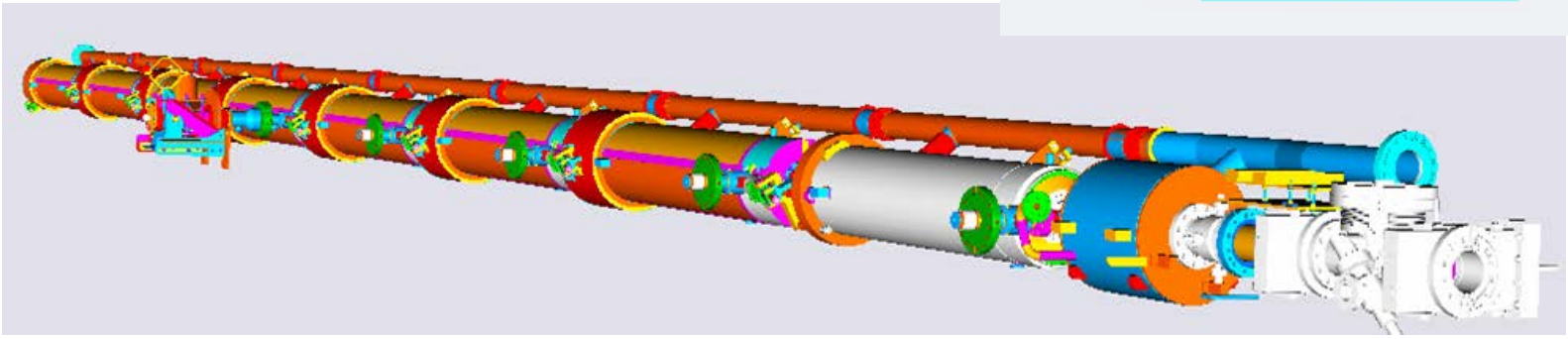
Cryo Module



Coupler

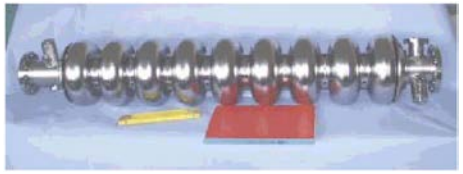


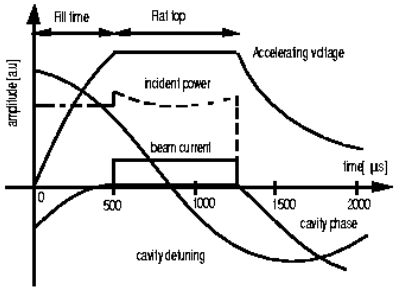
Module String



TESLA 500 RF System Requirements

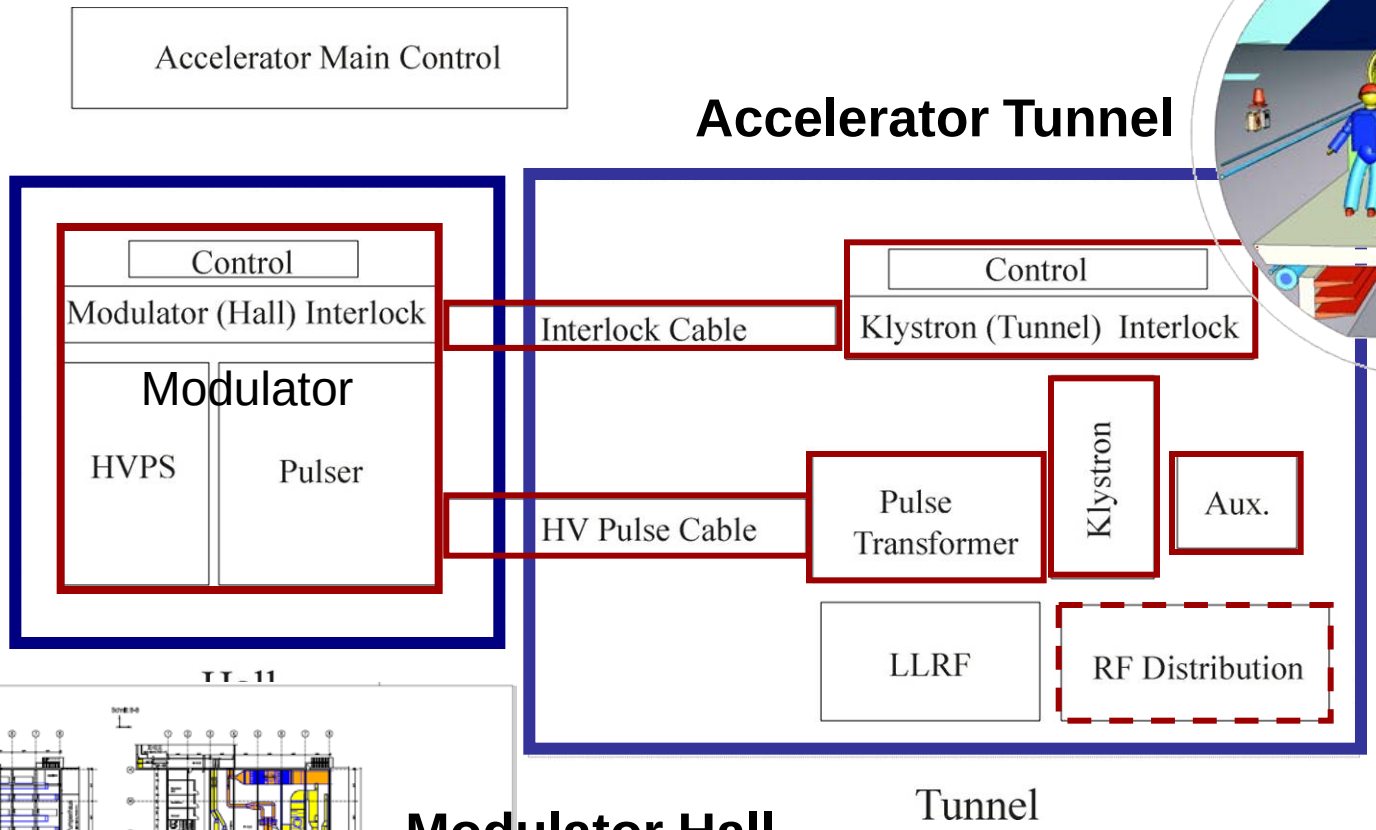
Number of sc cavities:	21024 total
Power per cavity:	231kW
Gradient at 500GeV:	23.4MV/m
Power per 36 cavities (3 cryo modules):	8.3MW
Power per RF station:	**9.7MW** (including 6% losses in waveguides and circulators and a regulation reserve of 10%)
Number of RF stations:	**572**
Macro beam pulse duration:	950µs
RF pulse duration:	**1.37ms**
Repetition rate:	**5Hz**
Average RF power per station:	**66.5kW**

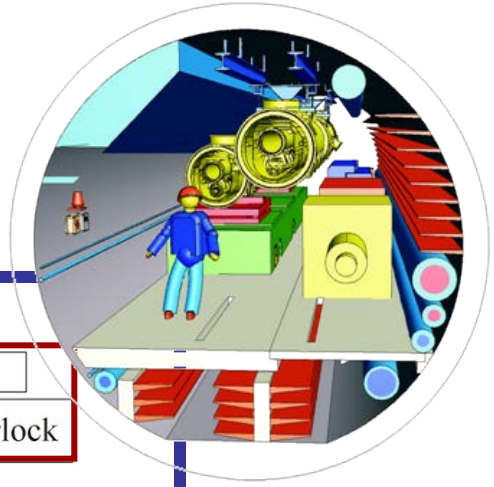


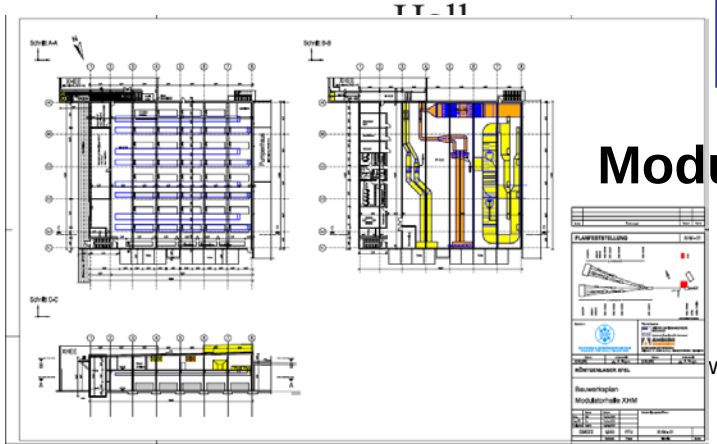


For TESLA 800 the number of stations must be doubled.
The gradient is 35MV/m.

Layout of a RF Station for TESLA and the European XFEL







Modulator Hall

Single Beam L-Band Klystron

- TH2104C 5MW, 128kV, 89A, 500µs 30Hz
- In use for TTF at 5MW, 128kV, 89A, 1,5ms 10Hz
- Developed in the 1980s
- Efficiency ~45%

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

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

Klystron Power

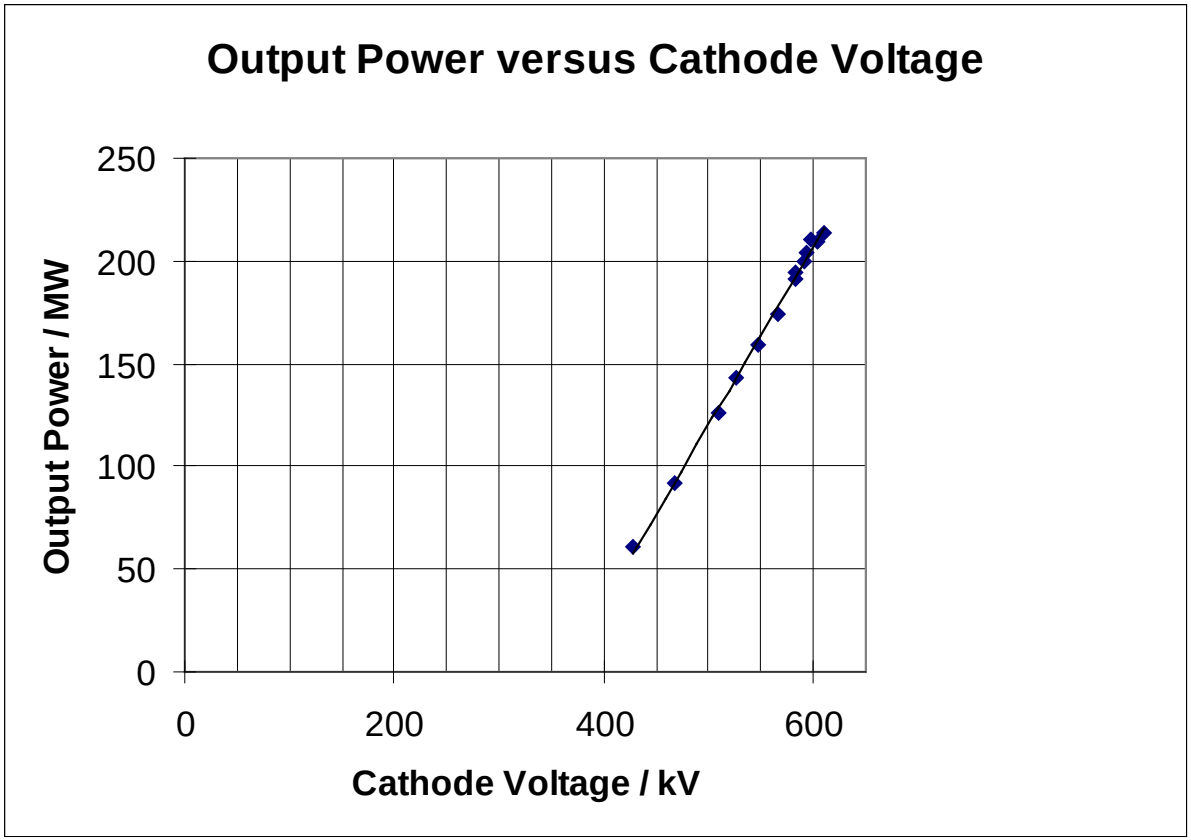
$$P_{RF} = \eta P_{Beam}$$

$$P_{Beam} = UI$$

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

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

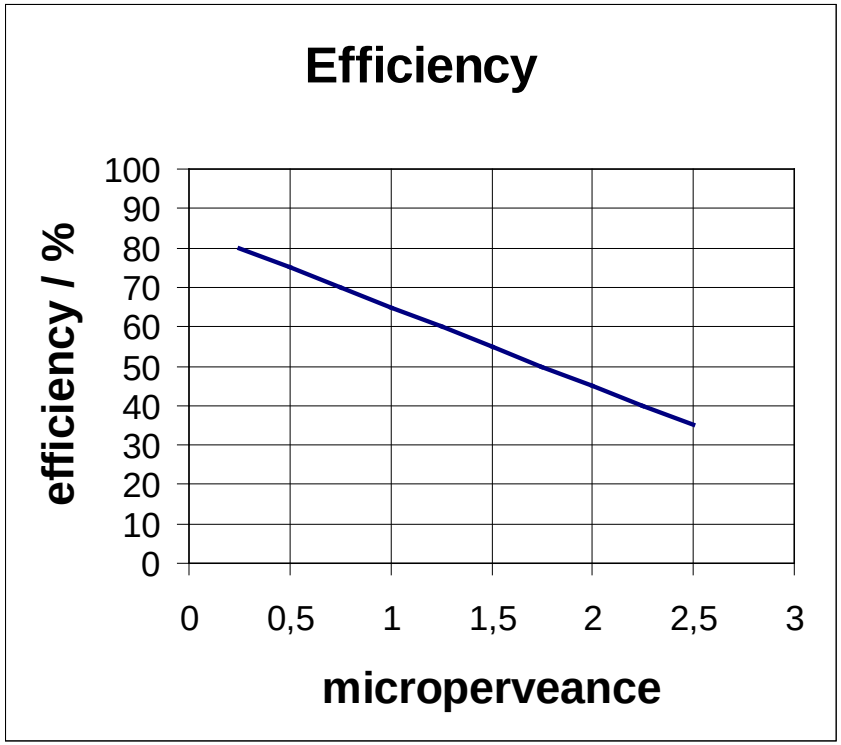
$$P_{RF} \propto U^{>5/2}$$



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

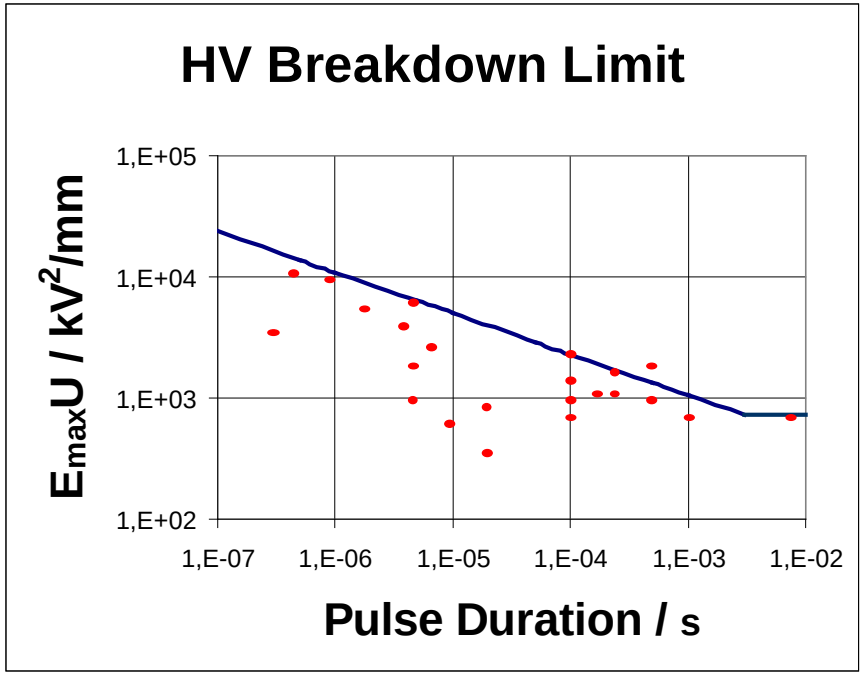


Rule of thumb formula from fit to experimental data

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

Klystron Gun Breakdown Limit

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



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

Multi beam Klystron

Idea

Klystron with low perveance:

=> High efficiency but high voltage

Klystron with low perveance and low high voltage

⇒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

RF Power Source for TESLA

Requirements 1995

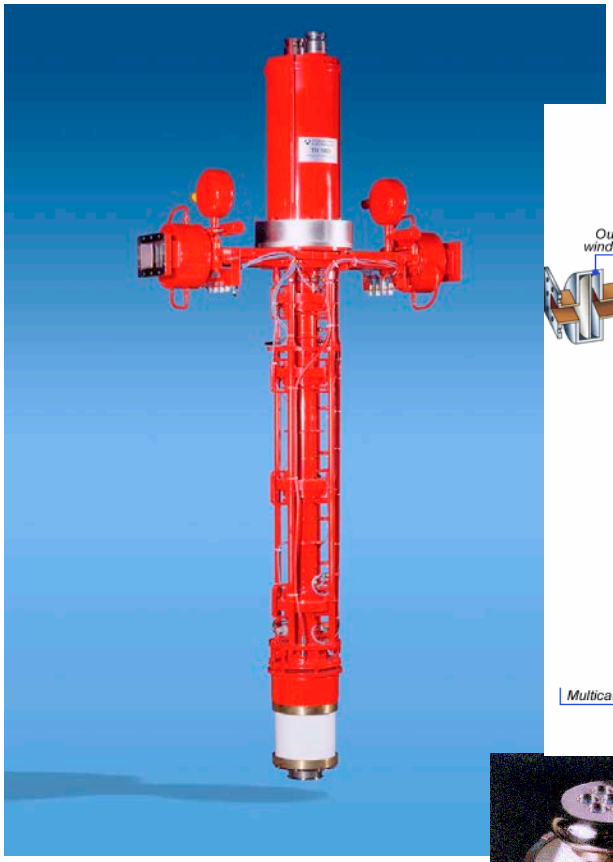
> Operation Frequency:	1.3GHz
> Cathode Voltage:	< 120 kV
> Beam Current:	< 140 A
> Max. RF Peak Power:	10MW
> RF Pulse Duration:	1.5ms
> Repetition Rate:	10Hz
> RF Average Power:	150kW
> Efficiency:	> 65%
> Solenoid Power:	< 5.5kW
> Length:	2.5m

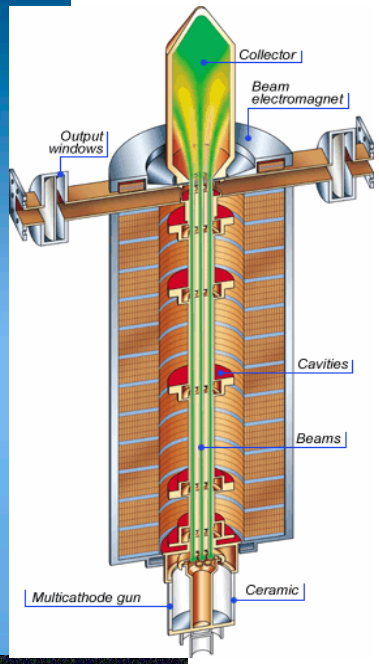
Multi Beam Klystrons (MBK) have been proposed. MBKs have been used in Russia before. Thomson received the contract to develop a MBK for TESLA.

Multi Beam Klystron THALES TH1801 (1)

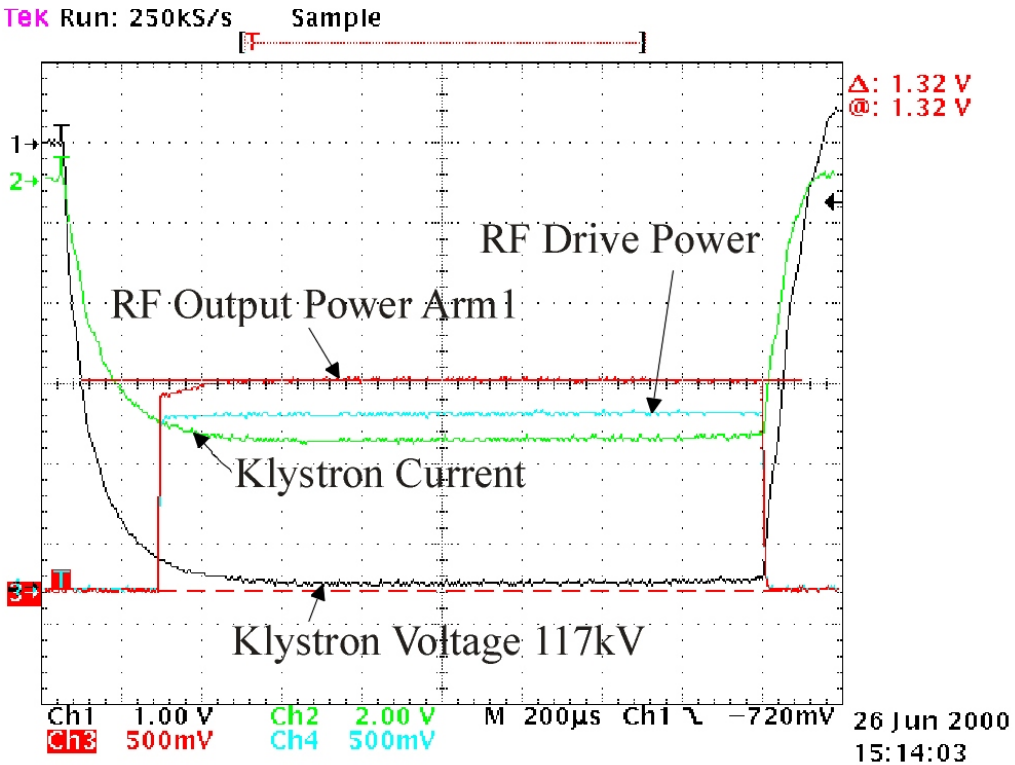
First prototype 2000

Operation Frequency:	1.3GHz
Cathode Voltage:	117kV
Beam Current:	131A
μperveance:	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



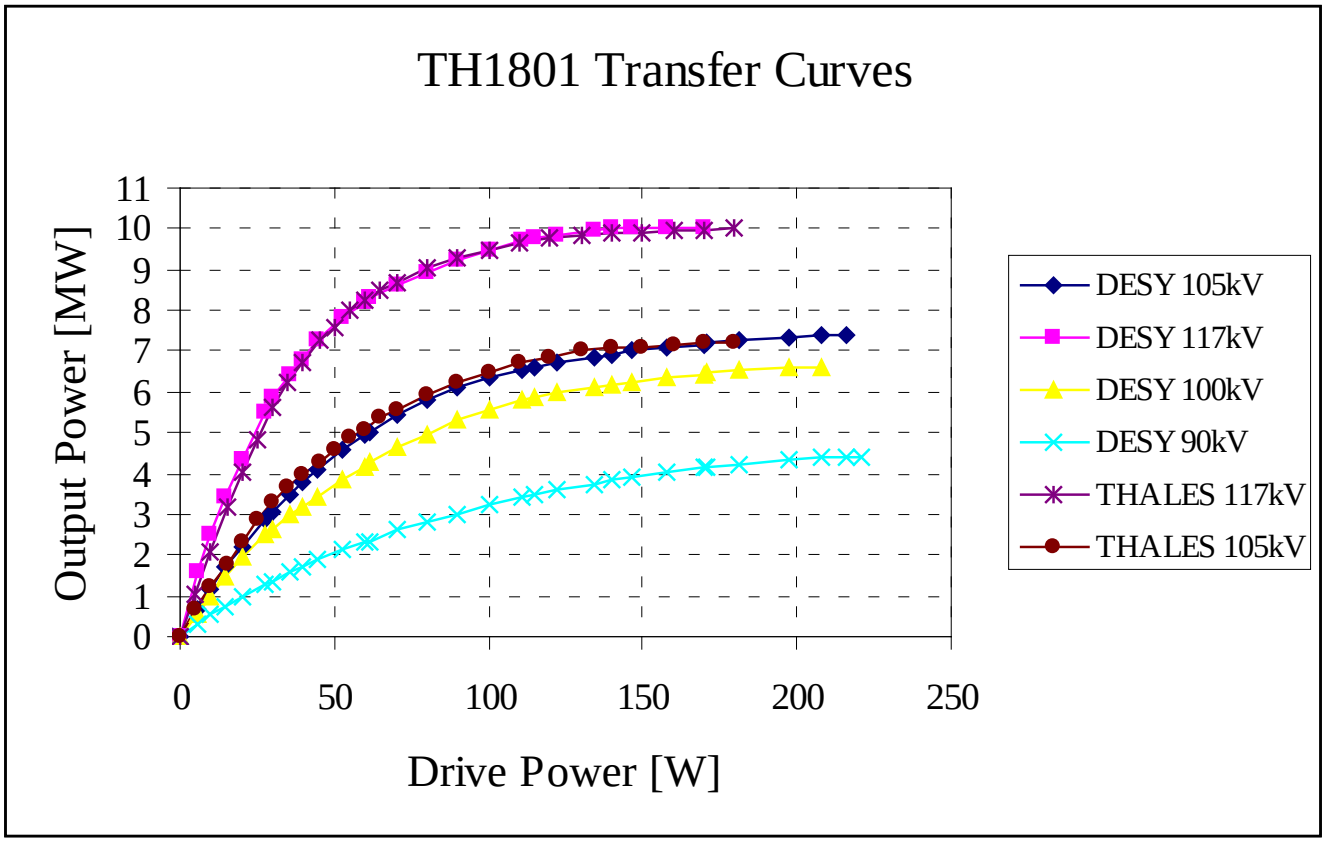


Multi Beam Klystron THALES TH1801 (2)



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

Multi Beam Klystron THALES TH1801 (3)

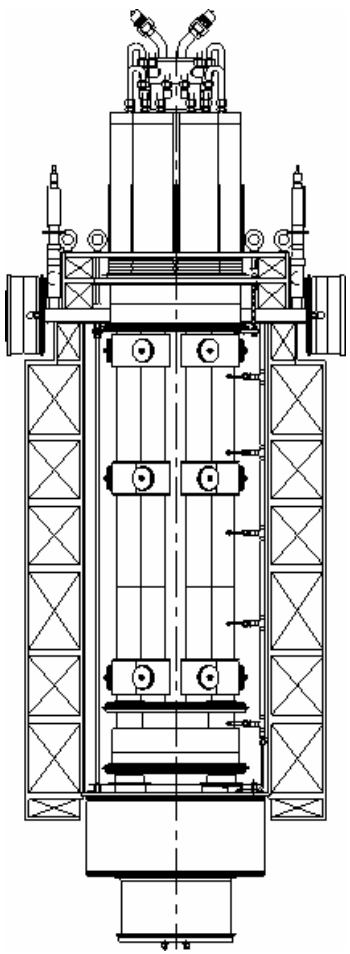


Transfer Curves: RF output as function of RF drive power with klystron voltage as parameter

Multi Beam Klystron CPI VKL-8301(1)

Proposal 2001 after discussions since 1999

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



Multi Beam Klystron CPI VKL-8301 (2)

Specified Operating Parameters 2001

Peak Power Output		10	MW (min)
Ave. Power Output		150	kW (min)
Beam Voltage		114	kV (nom)
Beam Current		131	A (nom)
μperveance		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 500µs pulse width (2005)

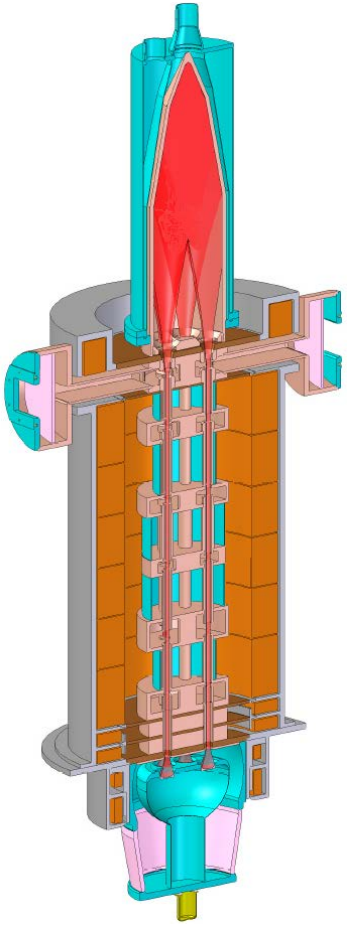
Peak Power Output	10	MW
Ave. Power Output	150	kW
Beam Voltage	120	kV
Beam Current	139	A
µperveance	3.34	
Frequency	1300	MHz
Gain (saturated)	49	dB
Efficiency	60	%
Beam Transmission		
DC, no RF	99.5	%
at Saturation	98.5	%

Klystron ready for shipment

The TOSHIBA E3736 MBK (1)

Development Start 2003

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



Design Layout

The TOSHIBA E3736 MBK (2)

Prototype 2006

Voltage: 115kV

Current: 135A

μperveance: 3.46

Output Power: 10.4MW

Efficiency: 67%

Pulse duration: 1.5ms

Rep. Rate: 10Hz

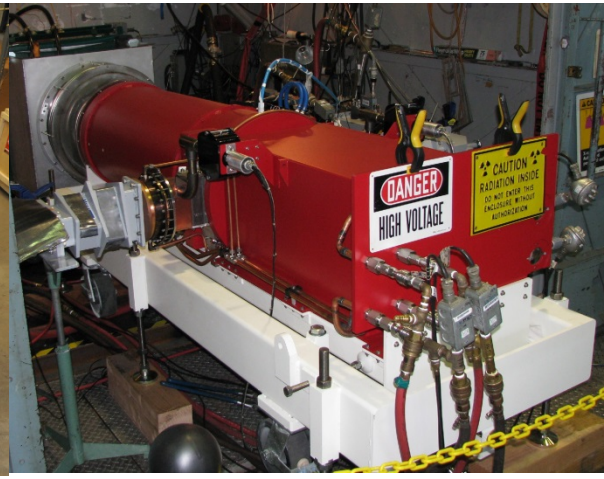
Klystron ready for shipment

Horizontal MBKs for XFEL

- Since vertical MBKs do not fit in the XFEL tunnel horizontal versions have been developed.
- All three vendors of MBKs have developed and manufactured horizontal versions of their MBK (2006-2010). CPI even changed the electronic design.
- All interfaces allow for change klystrons manufactured by different vendors.
- Efficiency requirements reduced to 63%.

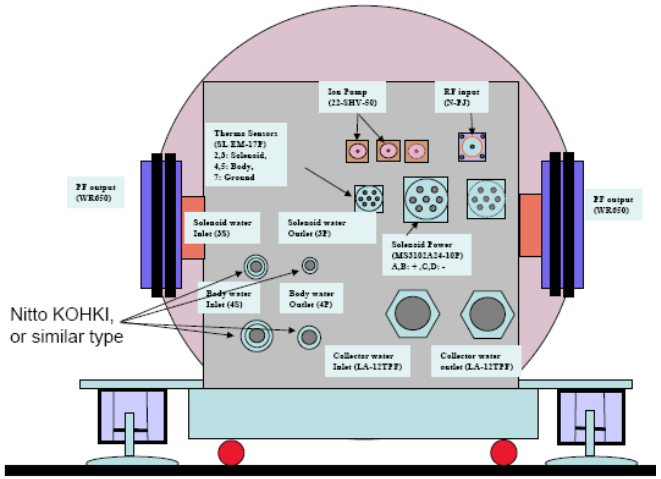
Thales TH1802

Toshiba E3736H

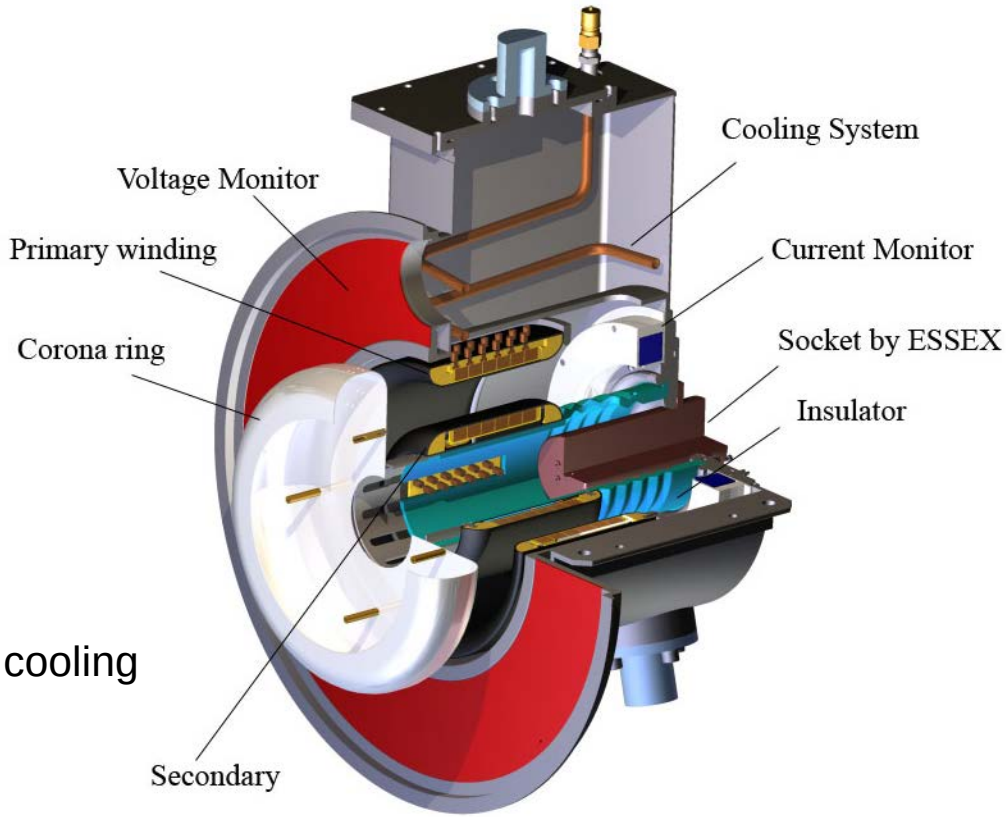


CPI VKL-8301B

Interfaces for MBKs for XFEL



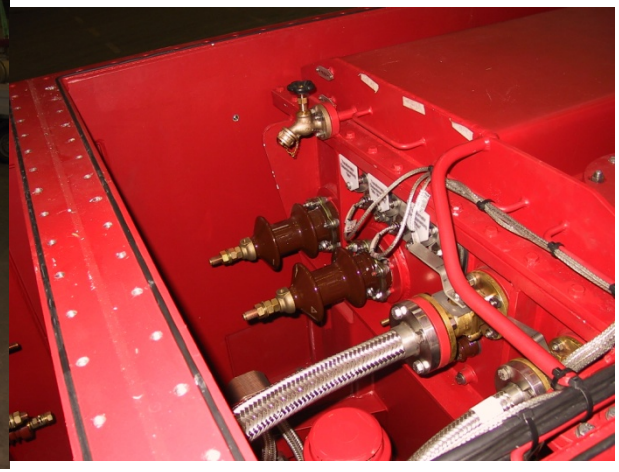
MBK Collector side view



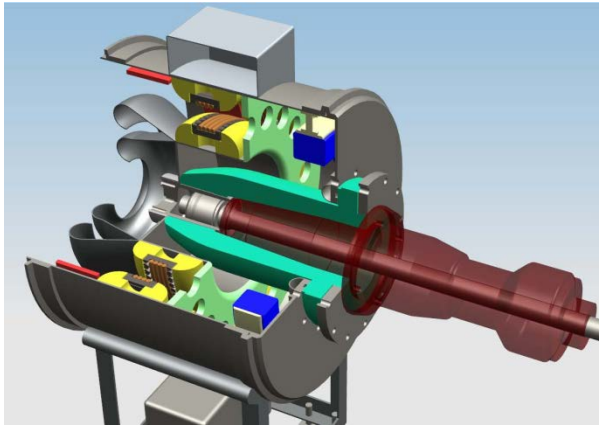
Connectors for axiliary PS, drive and cooling

Connection module for filament PS, HV connector, voltage and current diagnostics

Pulse Transformer and Connection Module for XFEL



Double wall pulse transformer



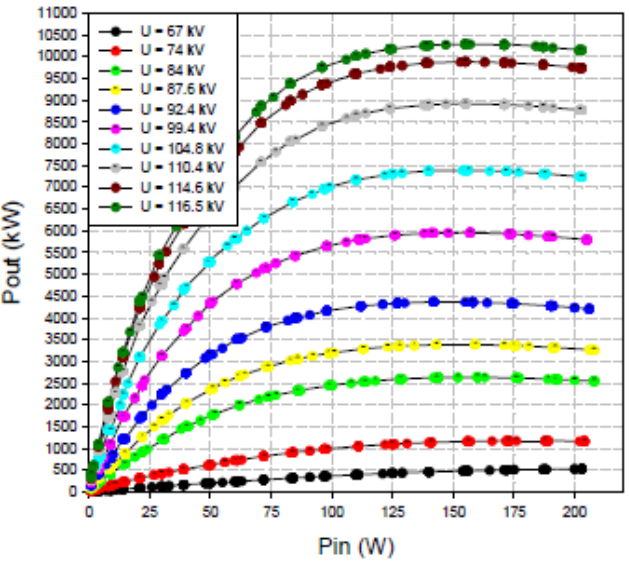
Connection module

Test Stand for Horizontal MBKs

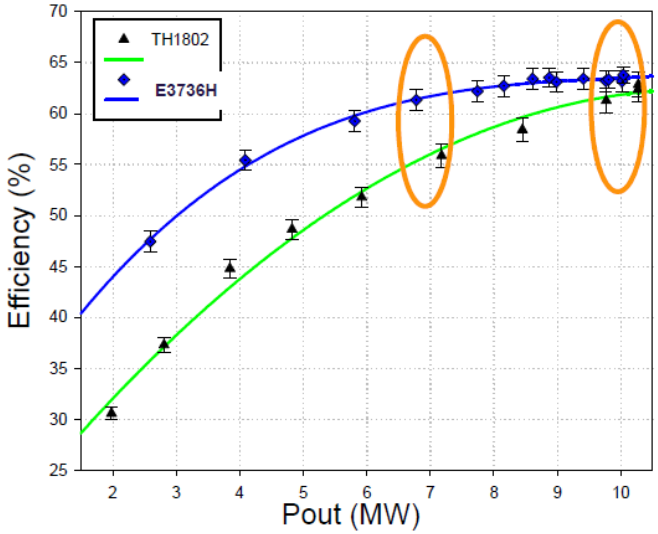
- These klystrons have been successfully tested at the klystron test facility at DESY.
- Finally two vendors are producing MBKs for the XFEL.

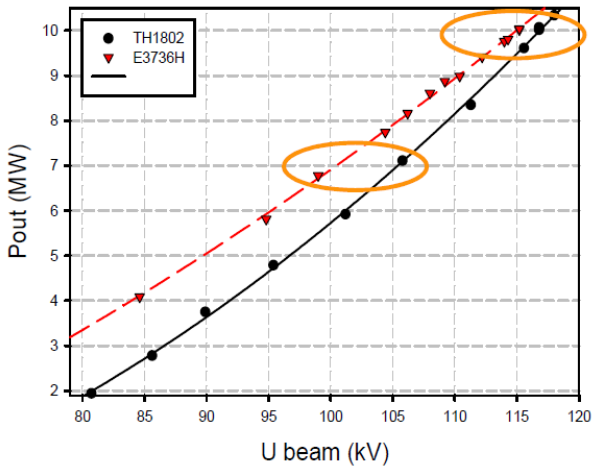
Horizontal multibeam klystron prototypes at the klystron test facility (KTF)

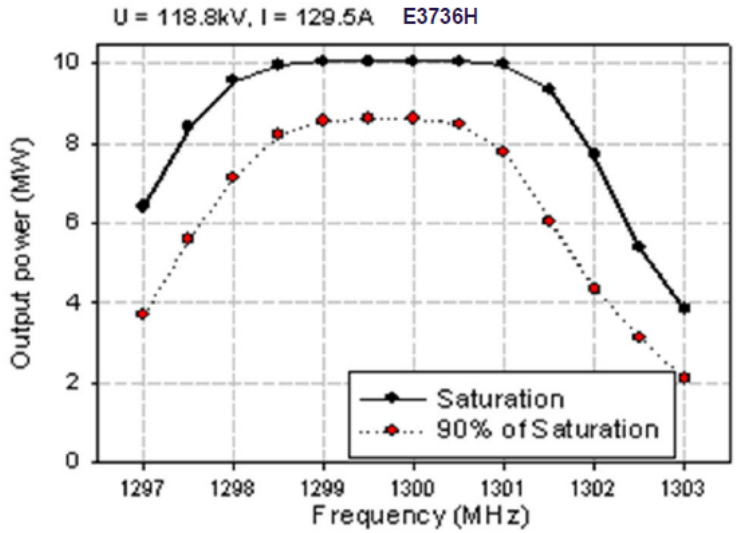
Some Test Results

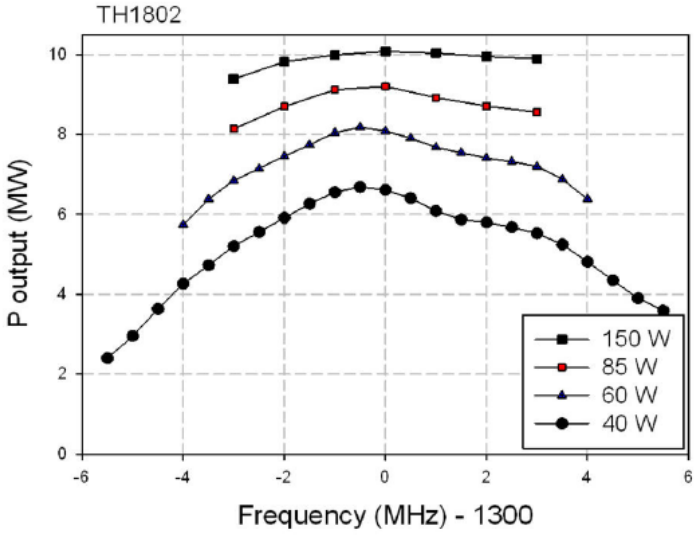


TH1802 prototype gain curves







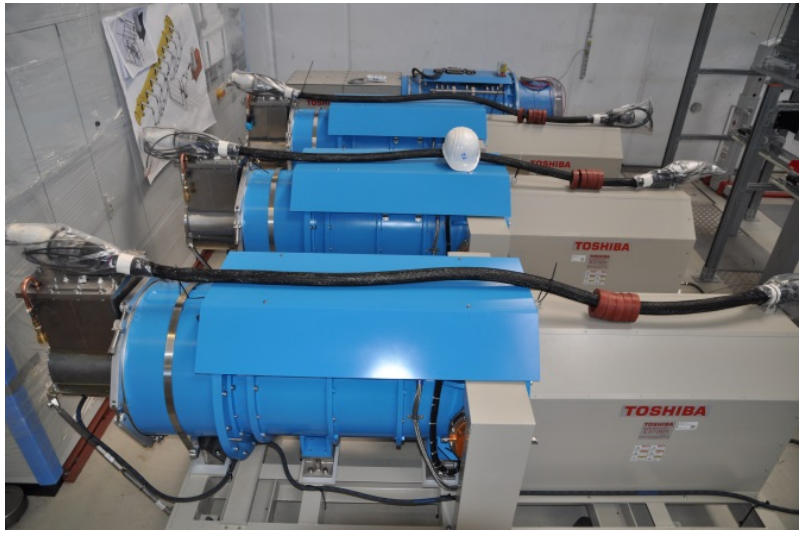


Usage of MBKs at DESY

- Thales TH1801 10 klystrons have been built since 1999, in 4 are use at present at FLASH, PITZ, and XFEL test stands
- Toshiba E3736 1 klystron built and in use at PITZ
- CPI VKL-8301 1 klystron built and in use at XFEL test stand (CMTB)
- Thales TH1802 12 klystrons have been built and have been tested at XFEL test stand
- Toshiba E3736H 7 klystrons have built and have been tested at XFEL test stand
- CPI VKL-8301B 1 klystron built and in use at XFEL test stand

Series MBKs for the XFEL

- 17 of 29 Multibeam Klystrons delivered, 11 of 22 Thales TH1802, 6 of 7 Toshiba E3736H



- All connection modules delivered

Lessons learned

- Development takes much longer than estimated, not 1-1.5years, 3-4 years for a first prototype may be more realistic, several iterations are required, even after that new problems might appear.
- Prototypes may only operate reliable at reduced power or efficiency.
- Even first series tubes may show instabilities or problems, which were not evident in the prototype.
- Sometimes oscilliations at certain operation conditions occur.
- In case the tube design has been developed with tools just sufficient, e.g. computer codes at the edge of the state of the art, the tube design is standing on tippy-toes.
- Aim for high efficiency but do not insist on the last percent in efficiency. 2-3% less (>65% to 63%) can improve reliablity.
- Experienced personell required to understand and able to support vendors and solve problems is mandatory.
- Other System components are important, too (etc. modulators, waveguides) the total efficiency counts.

Thank you for your attention