Experience with the development and operation of high efficiency MBKs

MBKS for TESLA, TTF, ILC and European XFEL

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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
> MBKs
> Other important RF system components
> HV power generation
> Power distribution

Preliminary Remark

> DESY is a user of multi beam klystrons

> DESY triggers the development of accelerator components, e.g. multi beam klystrons

> 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 presentaion is about how the development of MBKs started and continued. Some problems occured during this time until finally klystrons meeting DESYs demands have been available. This may or may not be an example for the development of other high efficient RF system components.

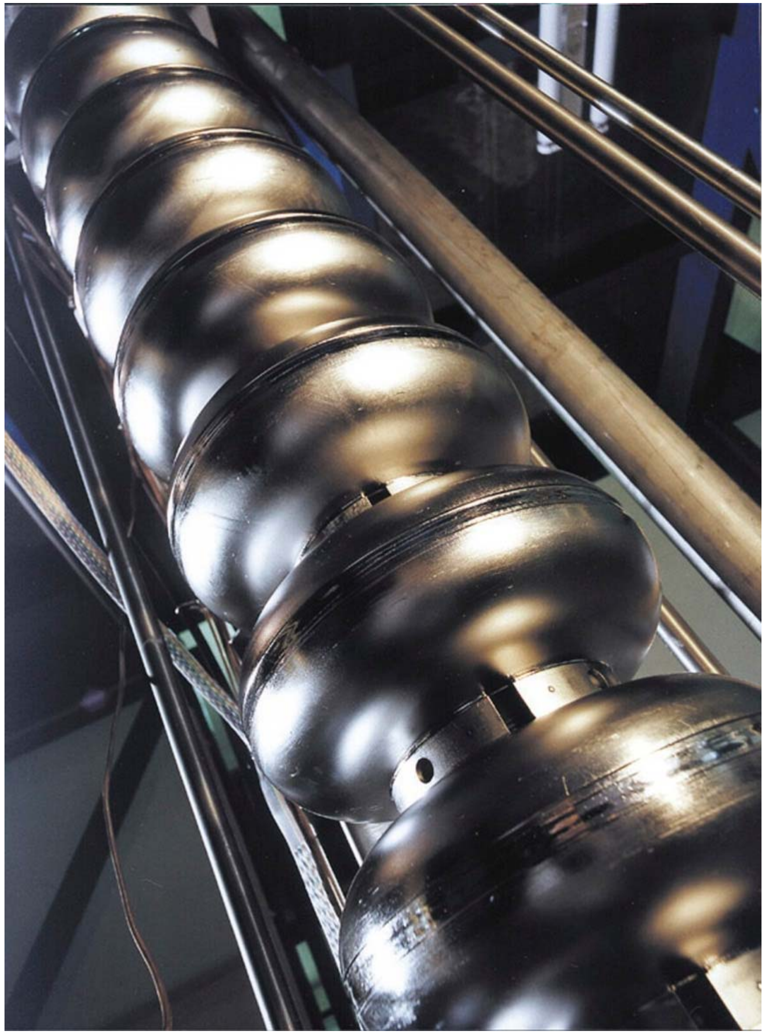
TESLA and its descendants

- 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
- TTF is in use as FEL user facility under the new name FLASH
- Many other projects use 1.3GHz Tesla type cavities too

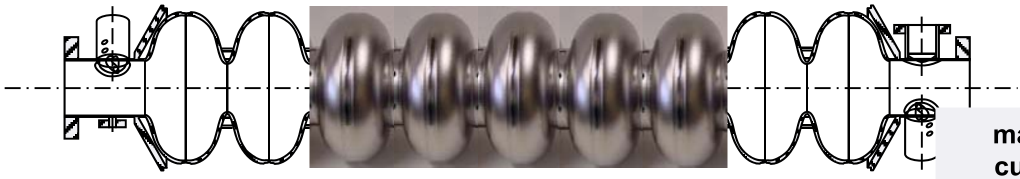
1.3GHz superconducting cavities

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

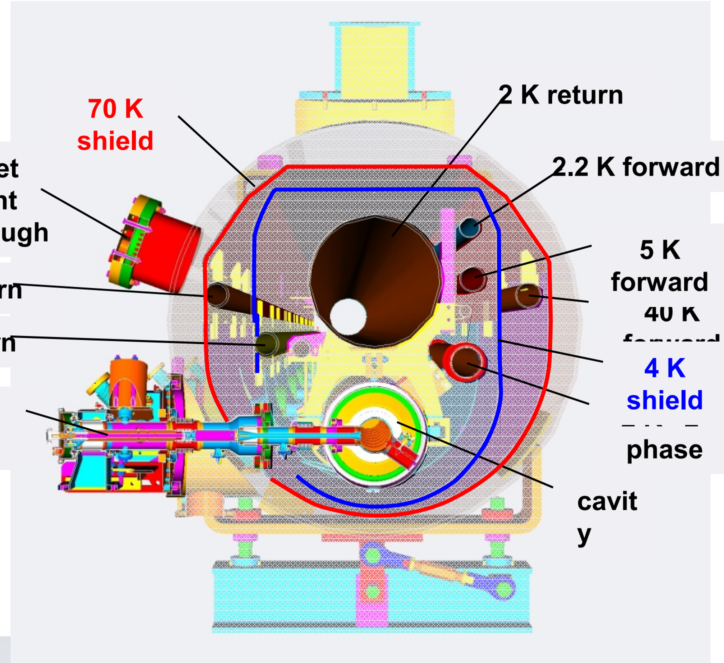


1.3GHz accelerator modules

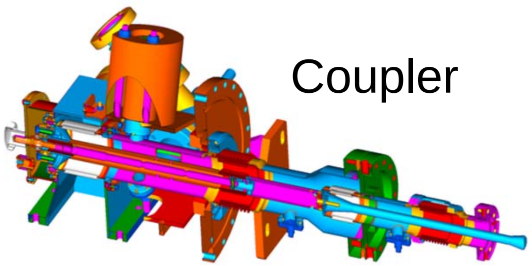
Cavity made of niobium, operated at 2K,
gradient >23MV/m Q=10^{10} and 1.3GHz



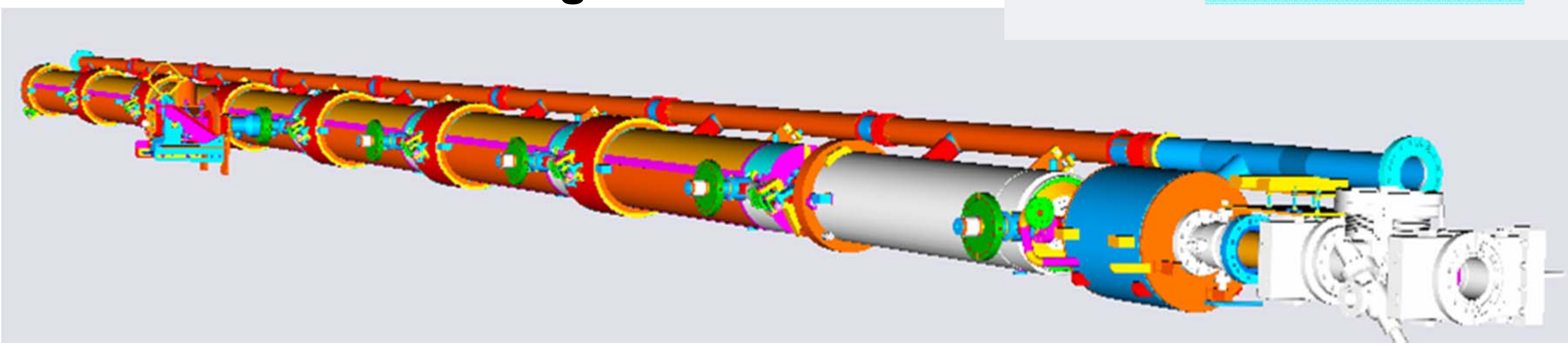
Cryo Module



Coupler

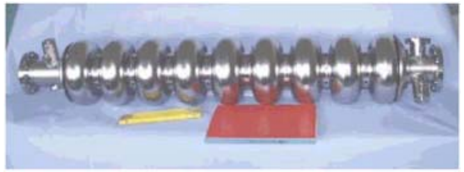


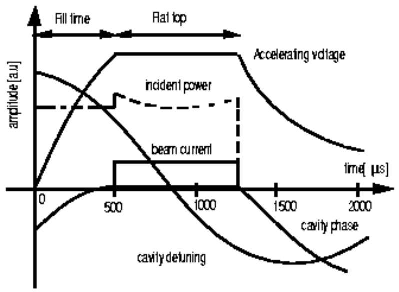
Module String



TESLA 500 RF System Requirements

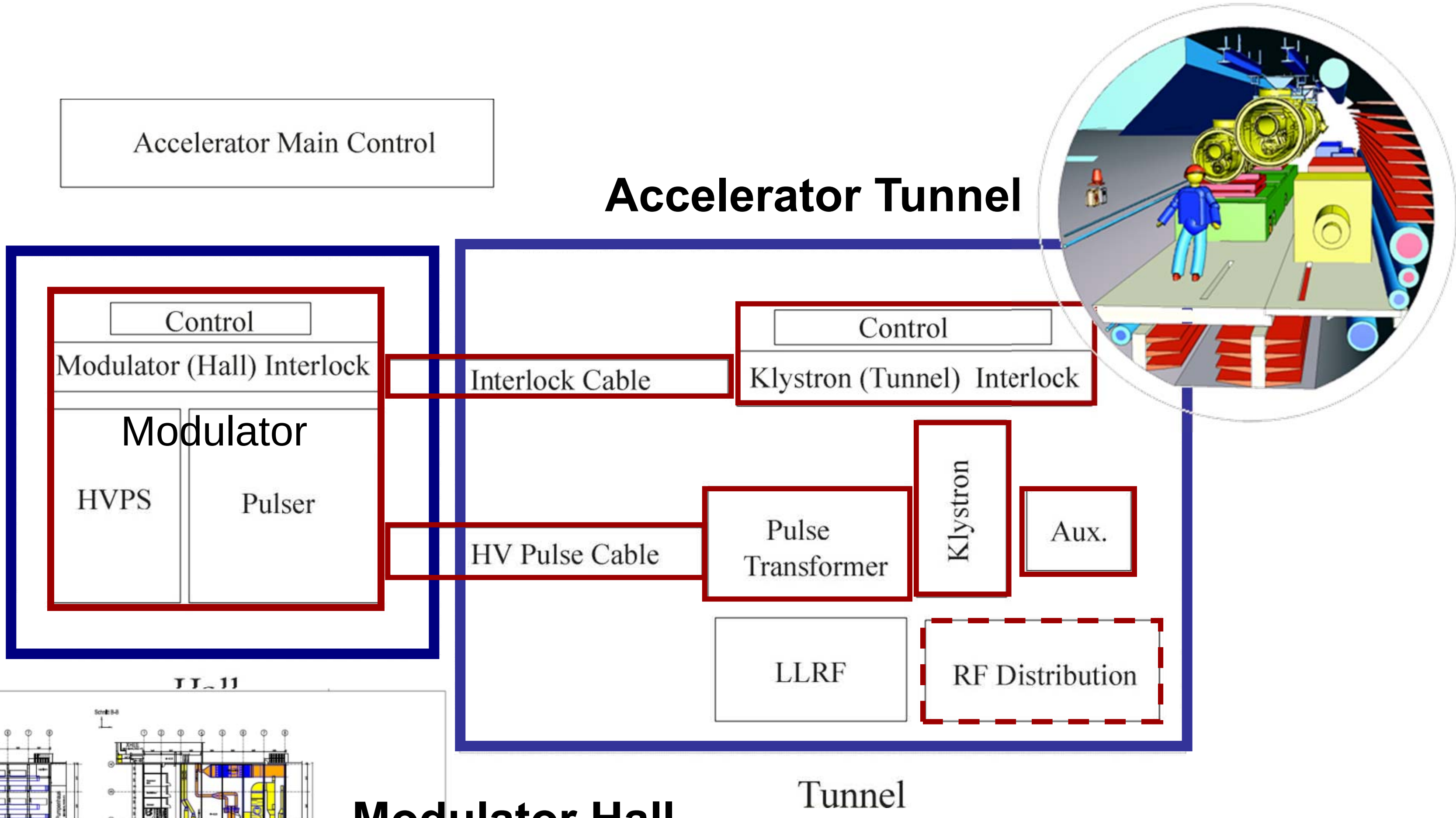
Number of sc cavities:	21024 total
Power per cavity:	231kW
Gradient at 500GeV:	23.4MV/m
Power per 36 cavities (3 cryo modules):	8.3MW
Power per RF station:	**9.7MW** (including 6% losses in waveguides and circulators and a regulation reserve of 10%)
Number of RF stations:	**572**
Macro beam pulse duration: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

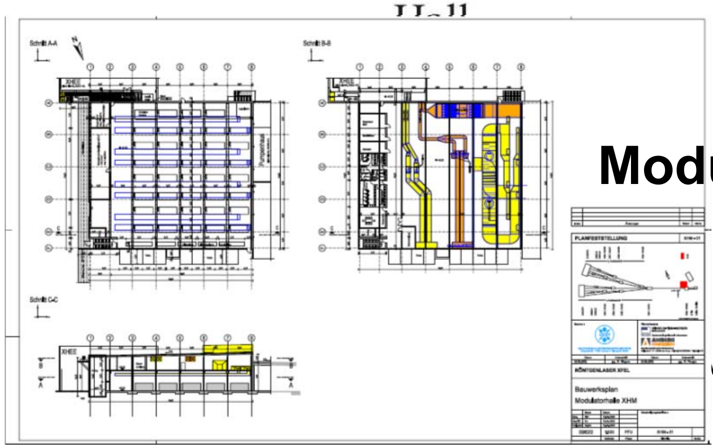




For TESLA 800 the number of stations must be doubled.
The gradient is 35MV/m.

Layout of a RF Station for TESLA and the European XFEL





Modulator Hall

DESY

Single Beam L-Band Klystron

- TH2104C 5MW, 128kV, 89A, 500μs 30Hz
- In use for TTF 5MW, 128kV, 89A, 1,5ms 10Hz
- 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

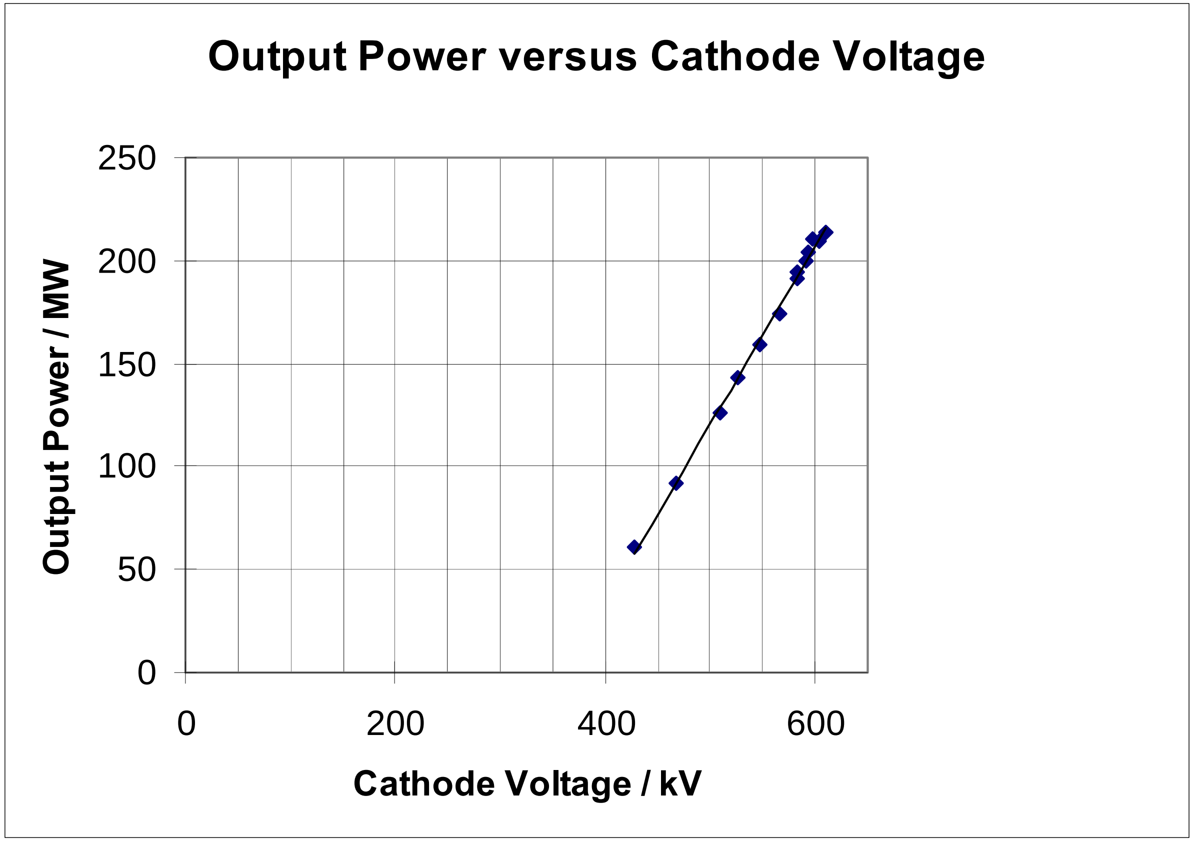
$$P_{RF} = \eta P_{Beam}$$

$$P_{Beam} = UI$$

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

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

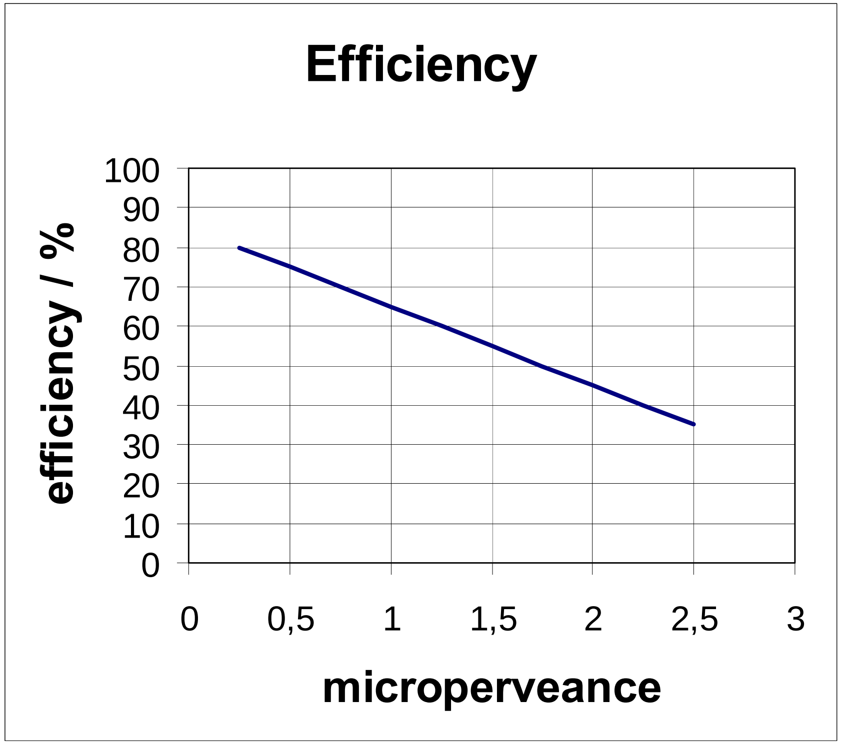
$$P_{RF} \propto U^{>5/2}$$



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

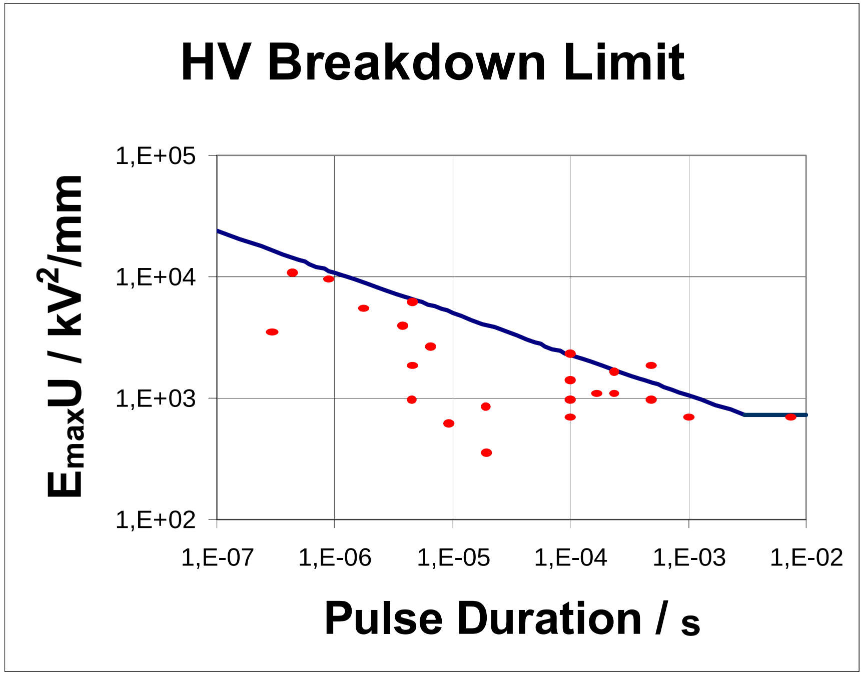


Rule of thumb formula from fit to experimental data

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

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

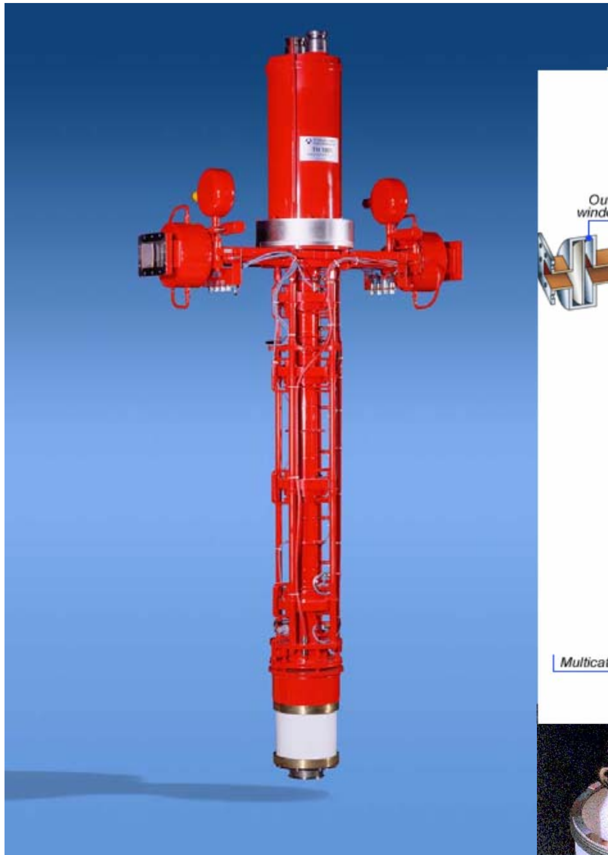
> Operation Frequency:	1.3GHz
> Cathode Voltage:	< 120 kV
> Beam Current:	< 140 A
> Max. RF Peak Power:	10MW
> RF Pulse Duration:	1.5ms
> Repetition Rate:	10Hz
> RF Average Power:	150kW
> Efficiency:	> 65%
> Solenoid Power:	< 5.5kW
> Length:	2.5m

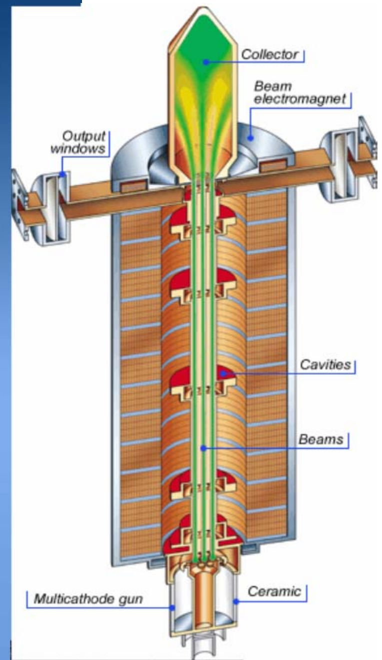
Multi Beam Klystrons (MBK) have been chosen.

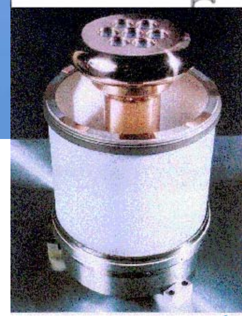
Multi Beam Klystron THALES TH1801 (1)

First Prototype 2000

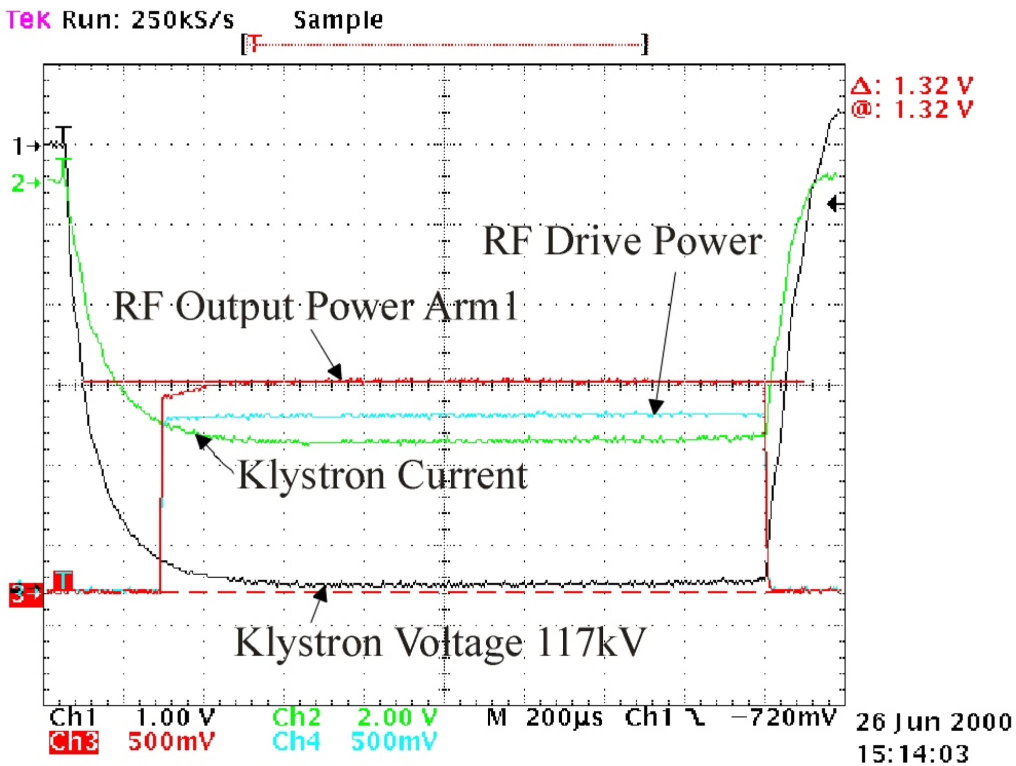
Operation Frequency:	1.3GHz
Cathode Voltage:	117kV
Beam Current:	131A
μperveance:	3.27
Number of Beams:	7
Cathode loading:	5.5A/cm^2
Max. RF Peak Power:	10MW
RF Pulse Duration:	1.5ms
Repetition Rate:	10Hz
RF Average Power:	150kW
Efficiency:	65%
Gain:	48.2dB
Solenoid Power:	6kW
Length:	2.5m
Lifetime (goal):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





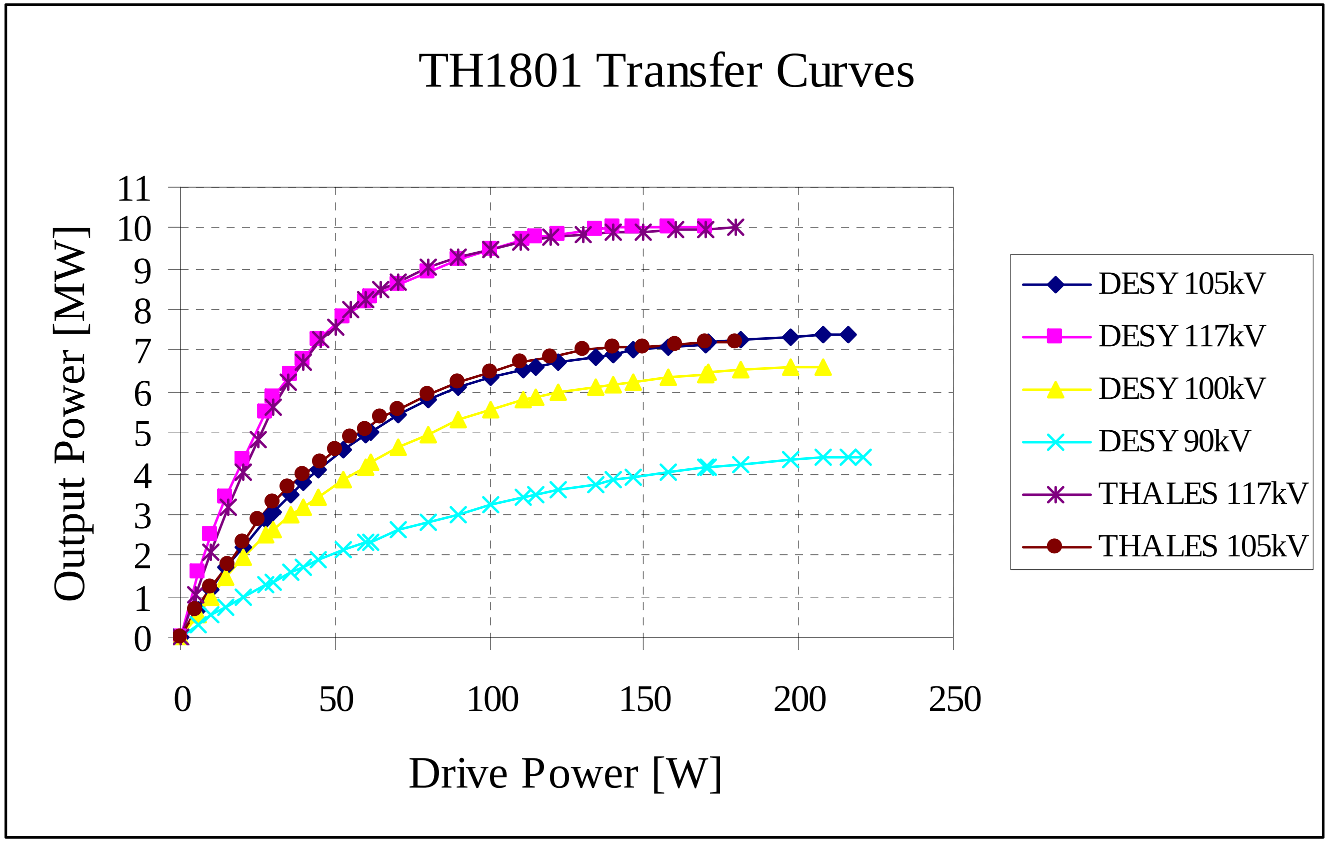


Multi Beam Klystron THALES TH1801 (2)



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

Multi Beam Klystron THALES TH1801 (3)

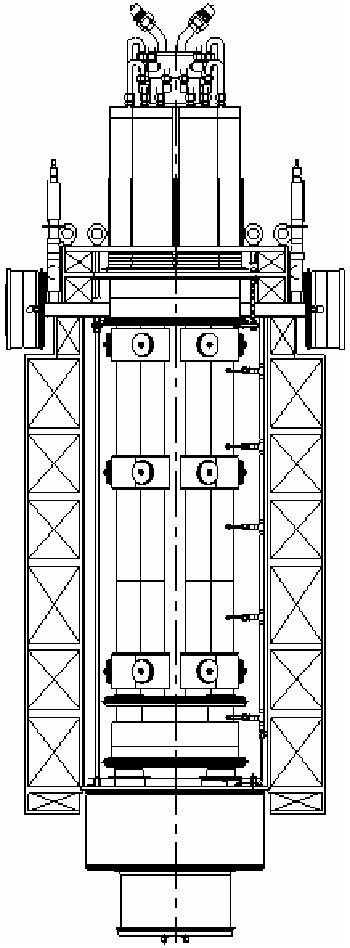


Transfer Curves: RF output as function of RF drive power with klystron voltage as parameter

Multi Beam Klystron CPI VKL-8301(1)

Proposal 2001 (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

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)

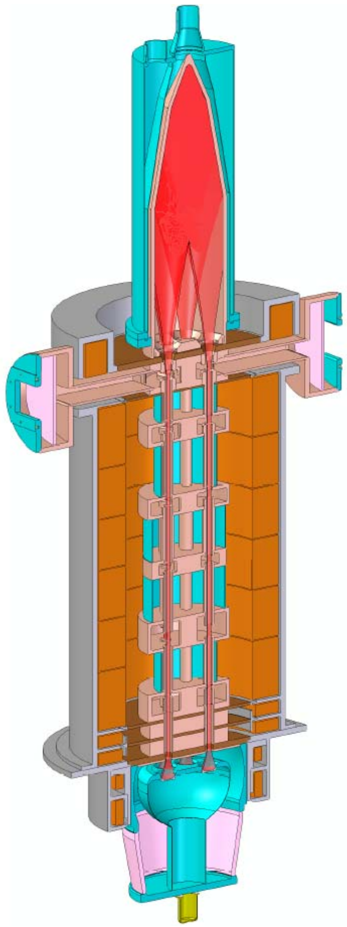
Peak Power Output	10	MW
Ave. Power Output	150	kW
Beam Voltage	120	kV
Beam Current	139	A
μperveance	3.34	
Frequency	1300	MHz
Gain (saturated)	49	dB
Efficiency	60	%
Beam Transmission		
DC, no RF	99.5	%
at Saturation	98.5	%

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

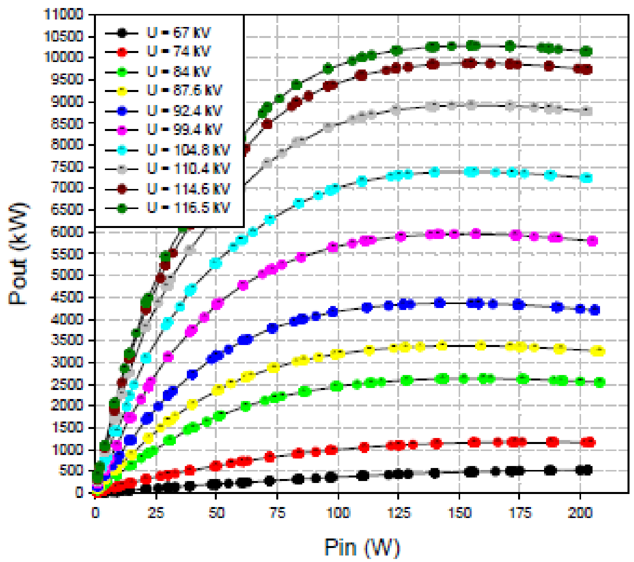
Klystron ready for shipment

Horizontal MBKs for XFEL

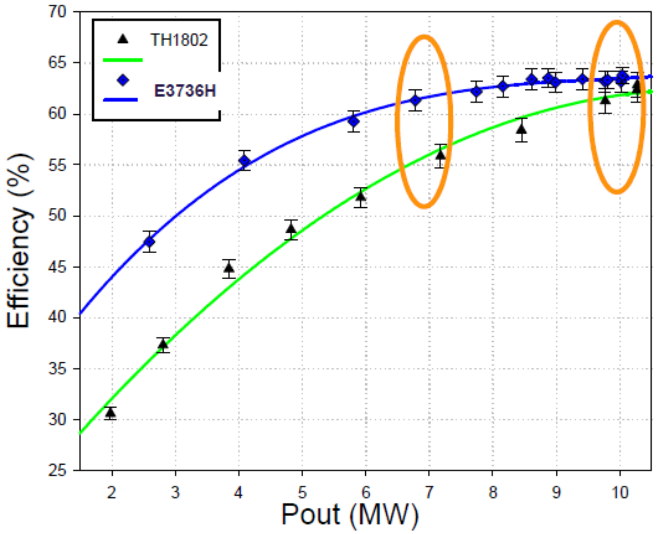
- Since vertical MBKs do not fit in the XFEL tunnel horizontal version have been developed.
- All three vendors of MBKs have developed and manufactured horizontal versions of their MBK (start 2006-2010).
- These klystrons have been successfully tested at the klystron test facility at DESY.
- Finally two vendors are producing MBKs for the XFEL.

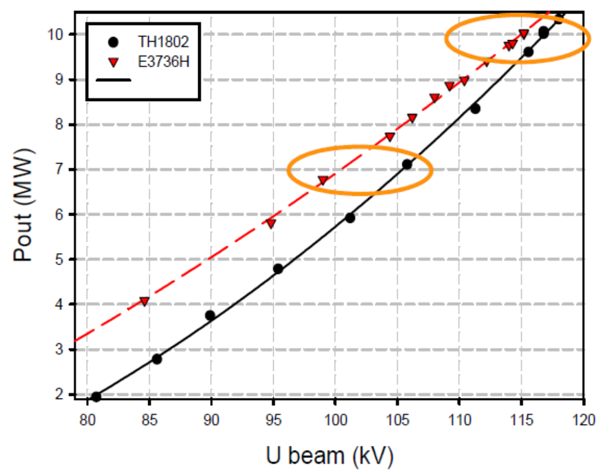
Horizontal multibeam klystron prototypes at the klystron test facility (KTF)

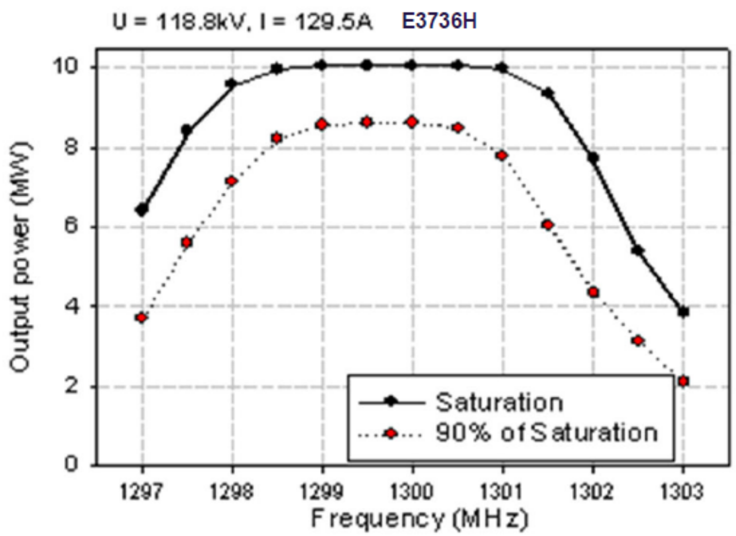
Some Test Results

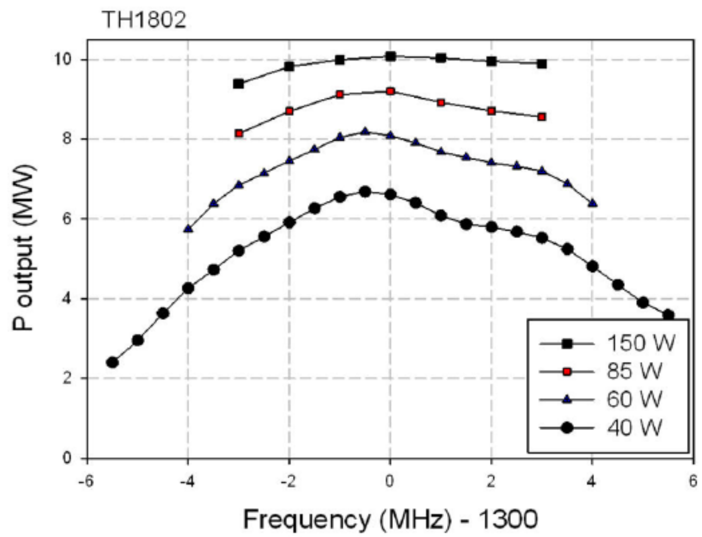


TH1802 prototype gain curves









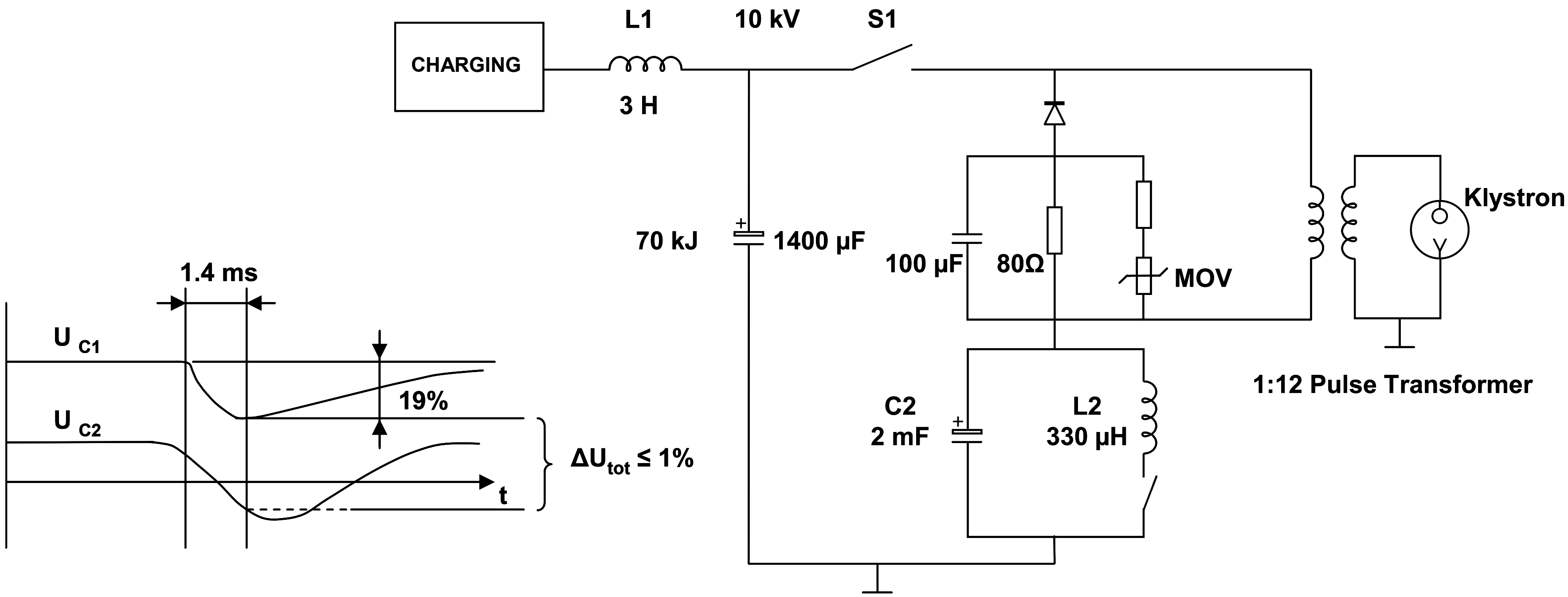
Thank you for your attention

Modulator Requirements

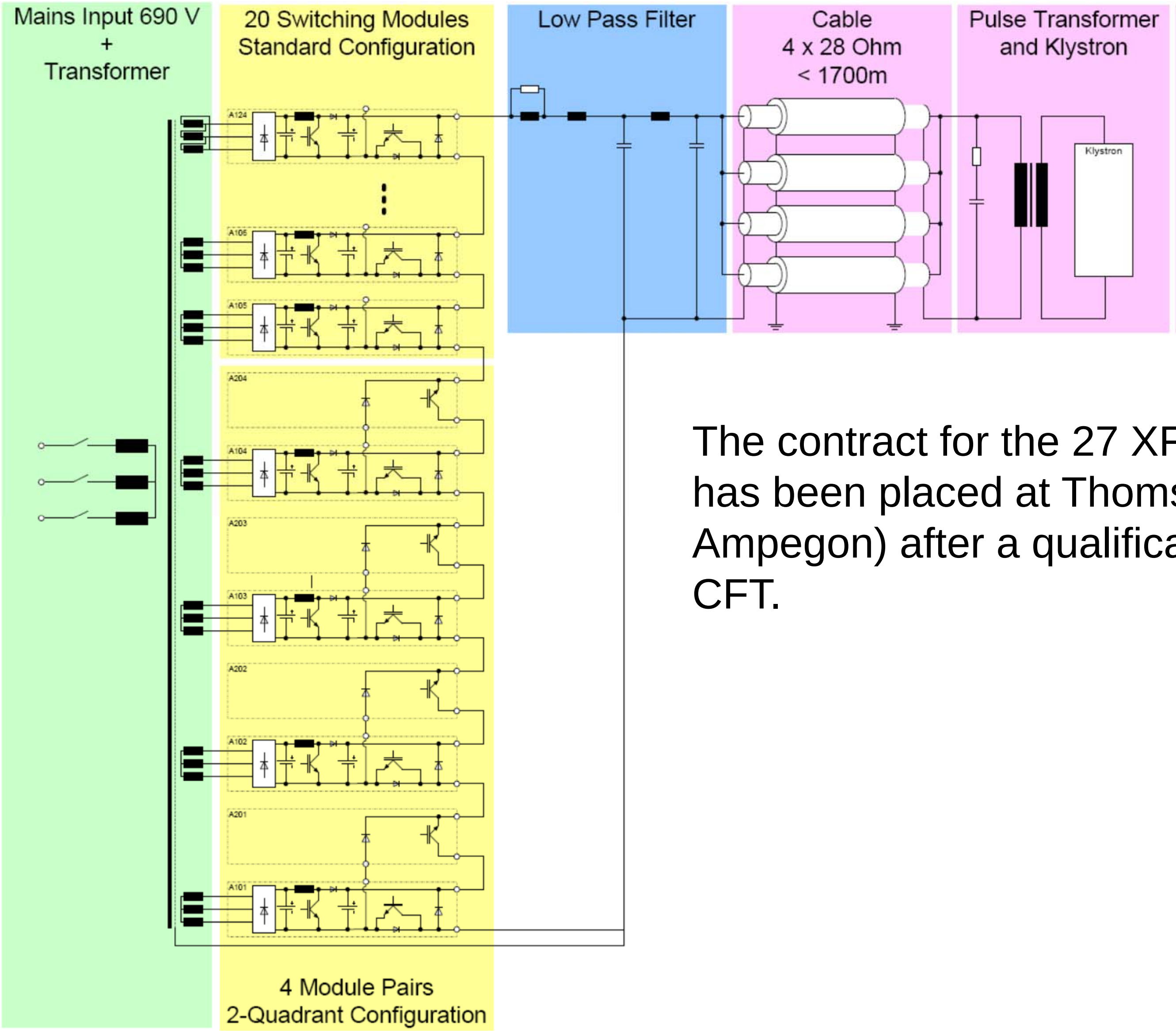
	typical	max.
Modulator Pulse Voltage/ Pulse Transformer Primary Voltage	9.6kV	12kV
Modulator Pulse Current Voltage/ Pulse Transformer Primary Current	1.62kA	1.8kA
Pulse Transformer Secondary Voltage / Klystron Gun Voltage	**115kV**	**132kV**
Pulse Transformer Secondary Current / Klystron Gun Current	**135A**	**150A**
High Voltage Pulse Duration (70% to 70%)	**1.57ms**	**1.7ms**
High Voltage Rise and Fall Time (0 to 99%)	0.15ms	0.2ms
High Voltage Flat Top (99% to 99%)	1.37ms	1.5ms
Pulse Flatness during Flat Top	±0.2%	±0.3%
Pulse-to-Pulse Voltage fluctuation	±0.1%	±0.1%
Energy Deposit in Klystron in Case of Gun Spark	<20J	20J
Pulse Repetition Rate	**10Hz**	**10Hz (30Hz)**
Pulse Transformer Ratio	1 :12	NA

Bouncer Modulator

•Bouncer modulators have been proposed for TESLA and are in use at FLASH and at the XFEL test facilities.

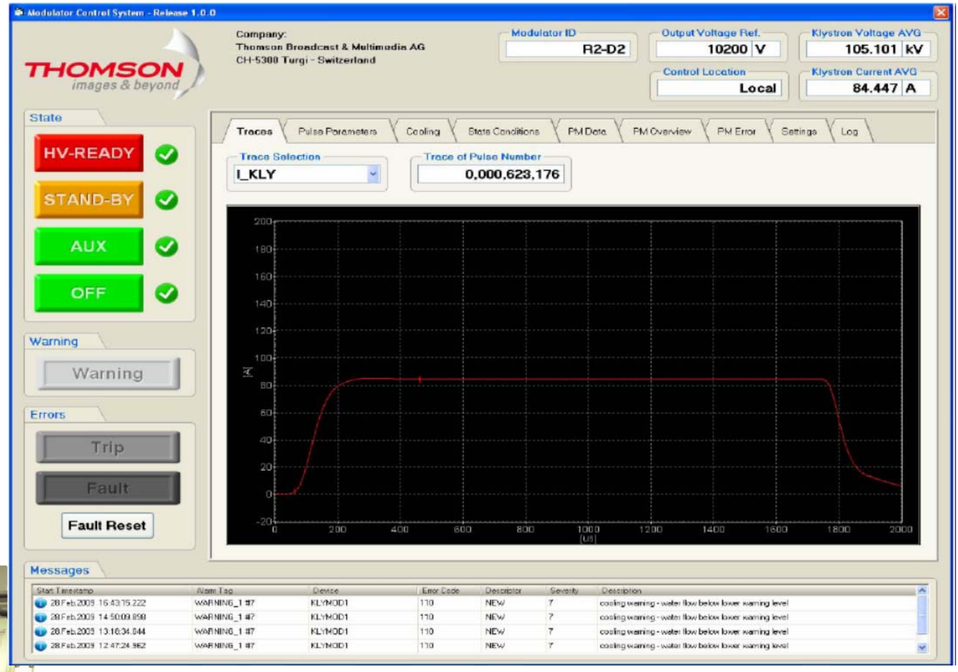


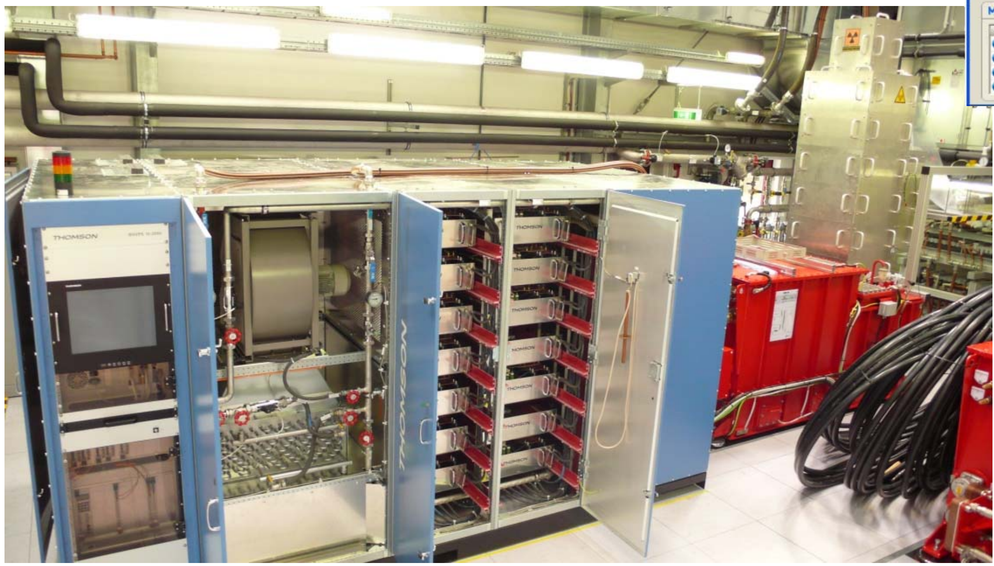
The Pulse Step Modulator for XFEL



The contract for the 27 XFEL modulators has been placed at Thomson (now Ampegon) after a qualification phase and CFT.

The Pulse Step Modulator at DESY Zeuthen





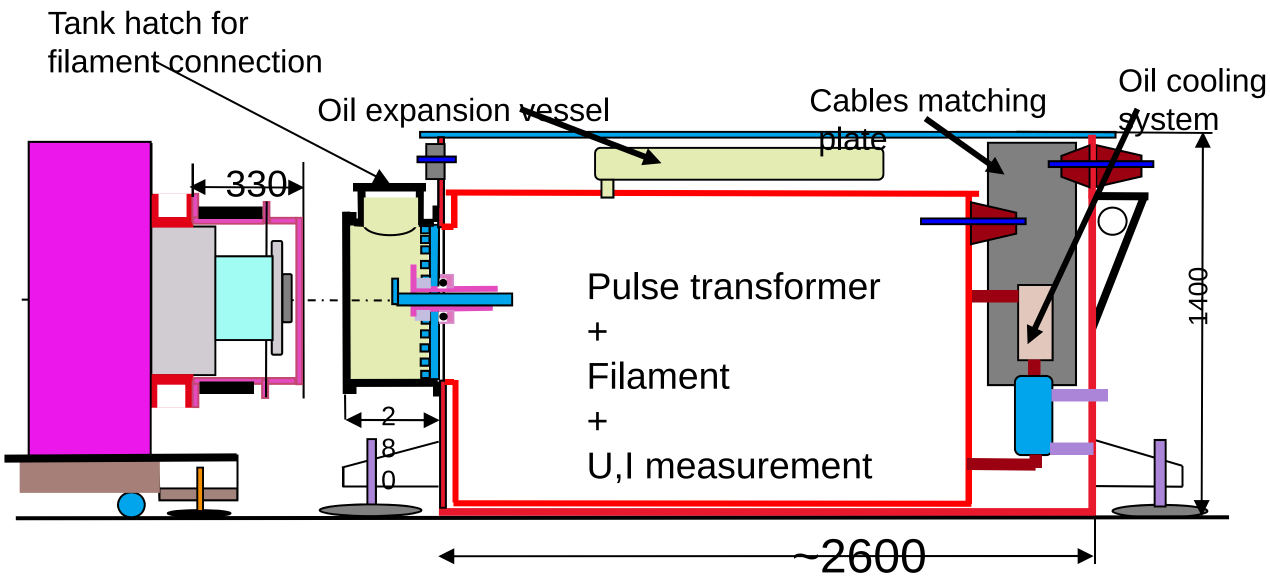
- PSM meets XFEL requirements
- Operation time: several 1000h
- Efficiency: 87% (wallplug to 10kV modulator output)

MBK to Pulse Transformer Connection

Base line:

direct connection

Klystron/PT

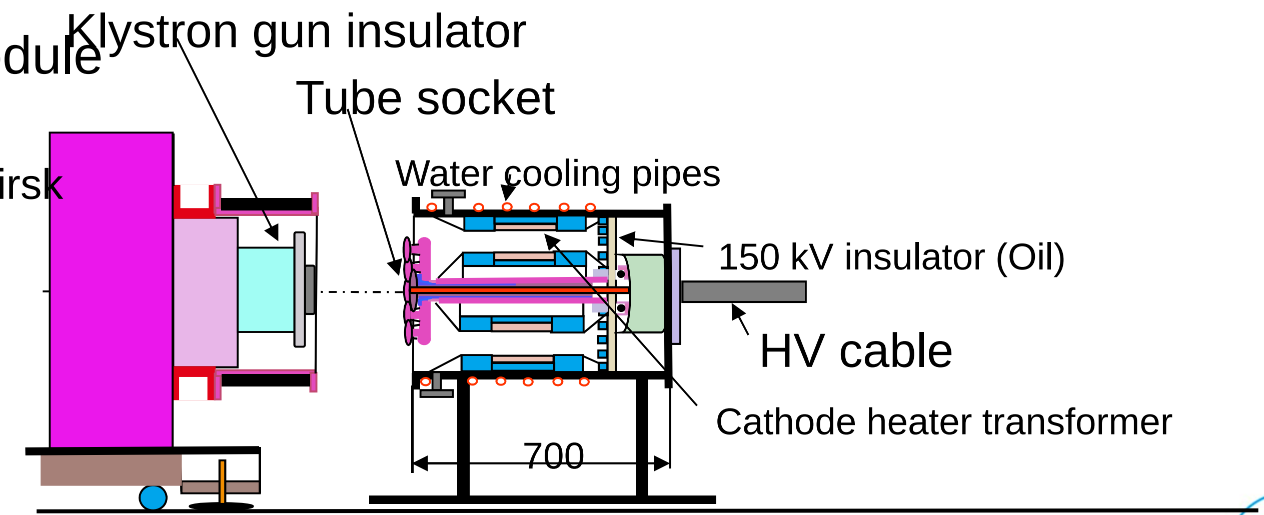


Alternative:

Connection module

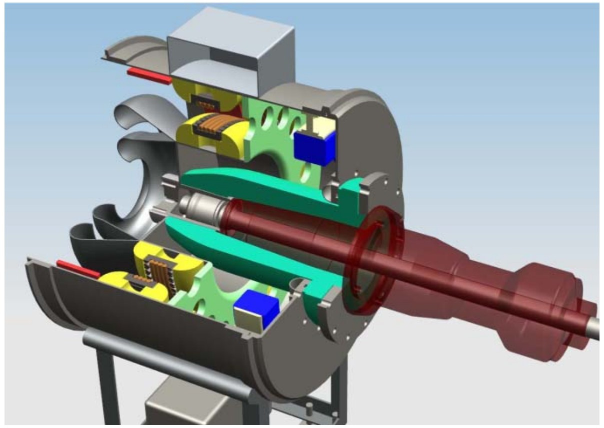
being investigated

with BINP/Novosibirsk



Pulse Transformer and Connection Module for XFEL

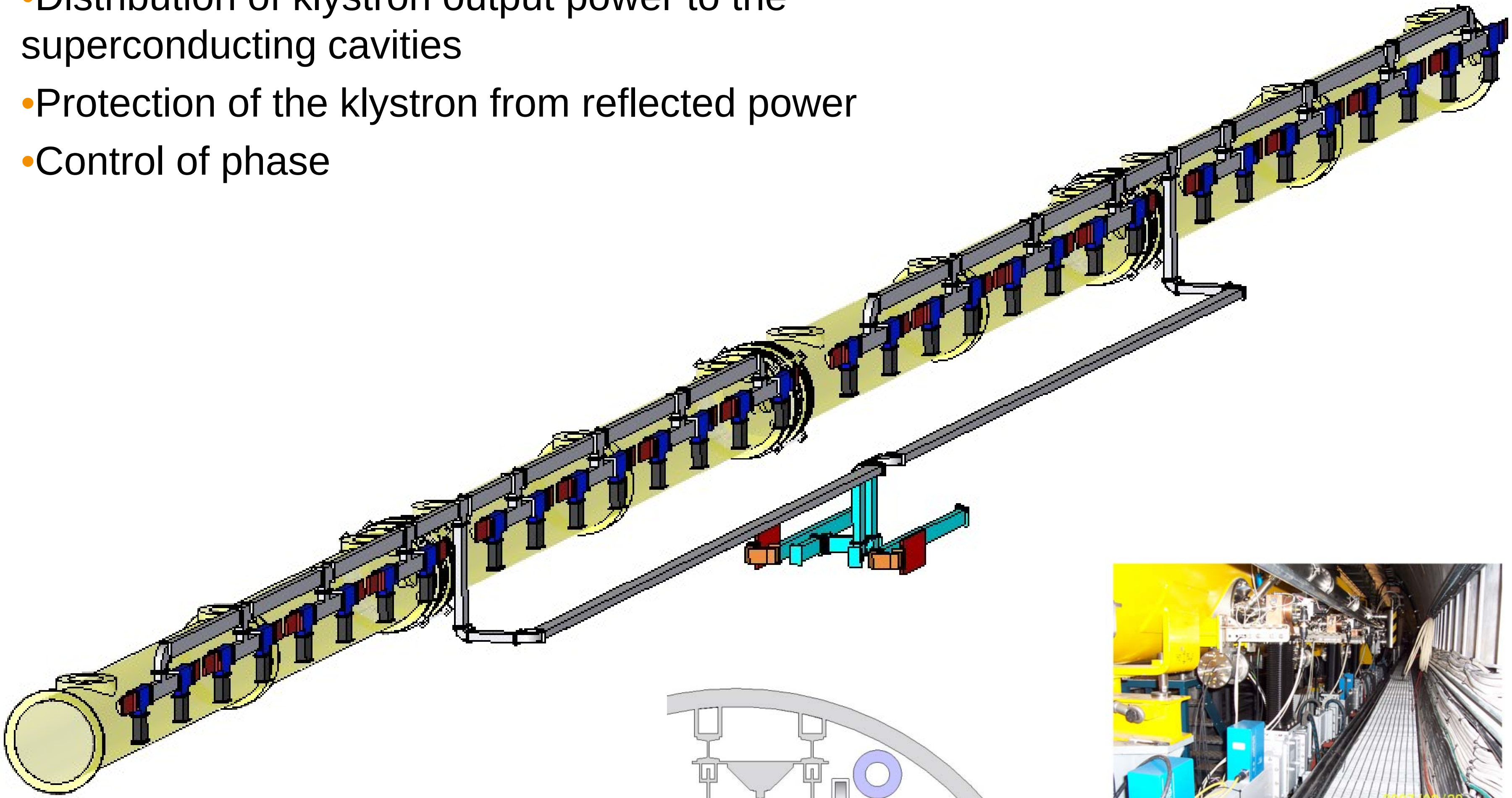
Double wall pulse transformer

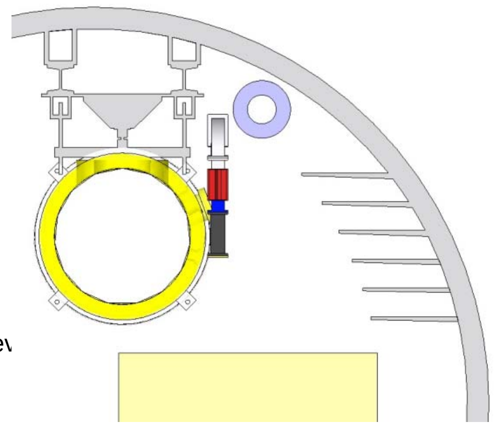


Connection module

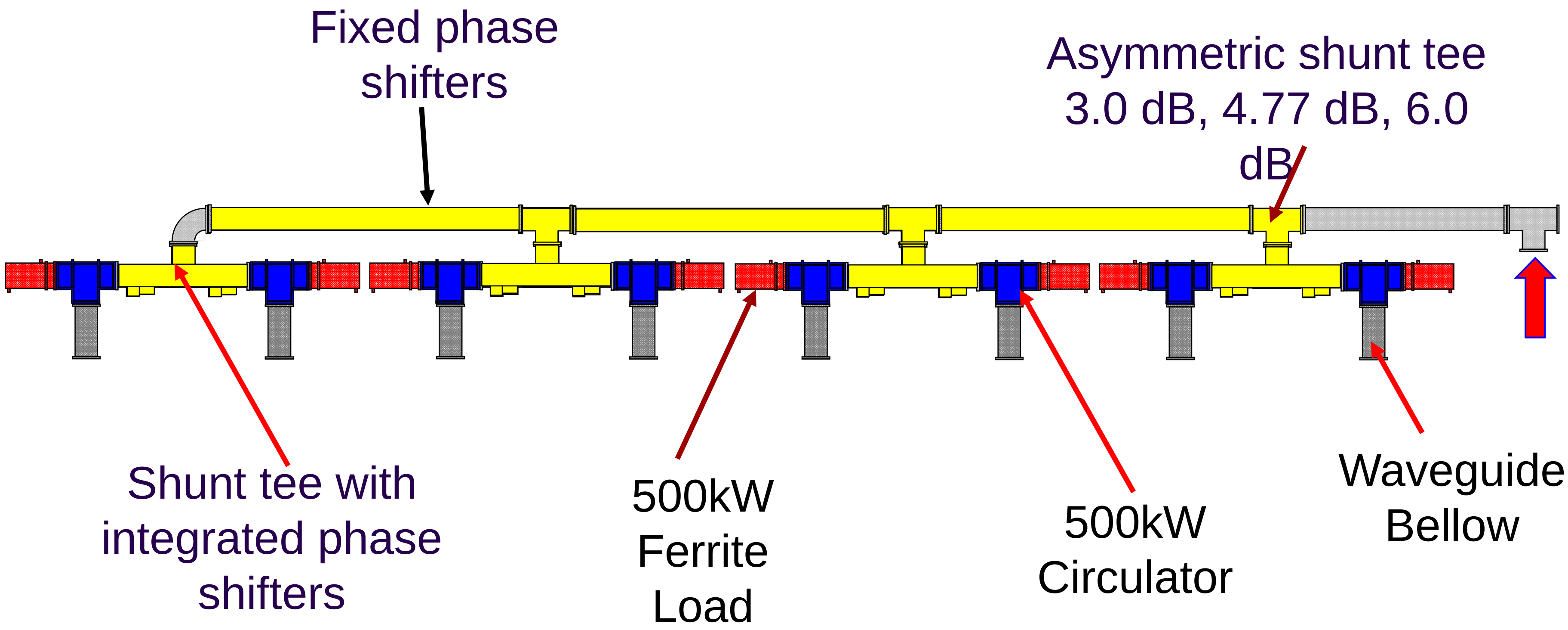
RF Power Distribution

- Distribution of klystron output power to the superconducting cavities
- Protection of the klystron from reflected power
- Control of phase

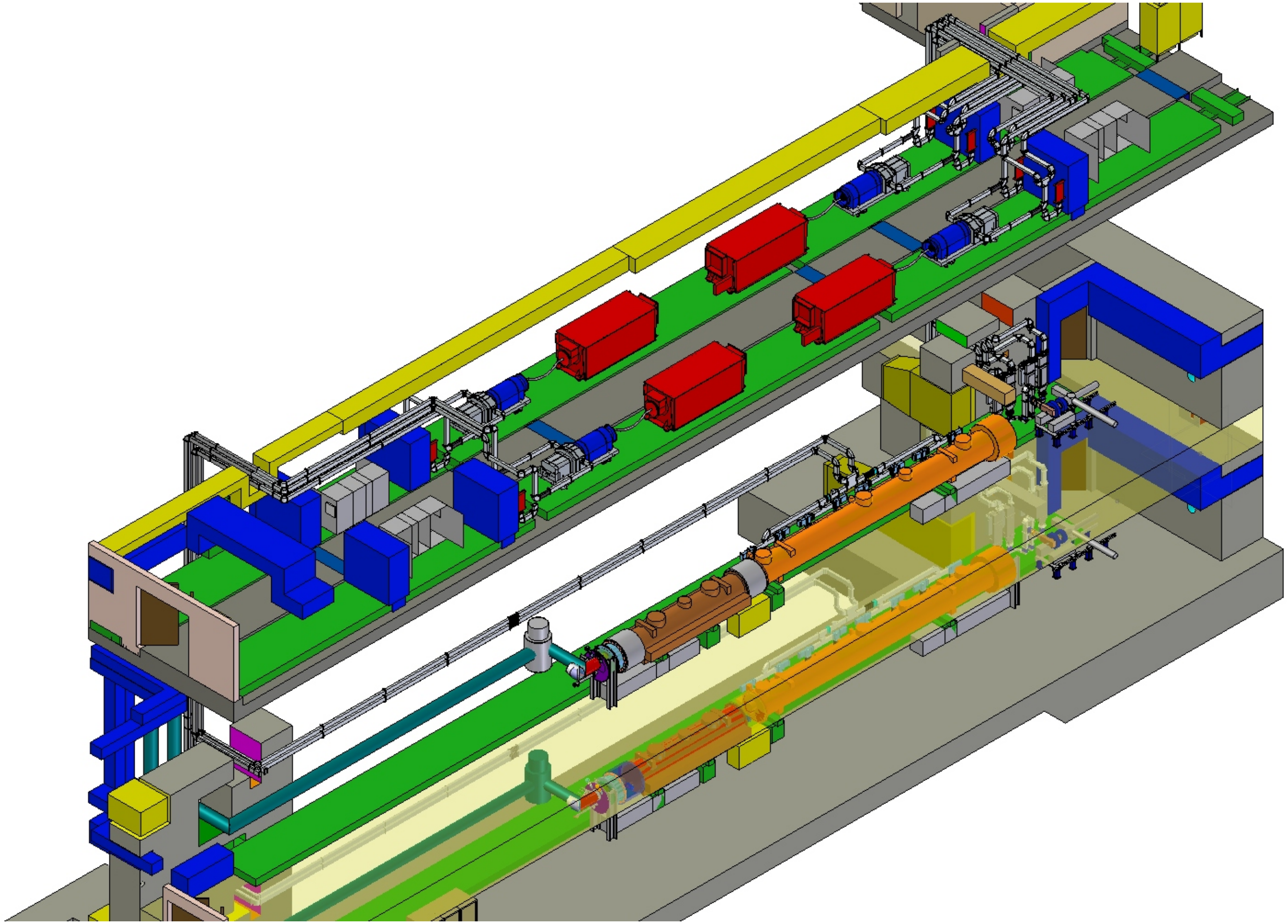




Module Waveguide Distribution



XFEL Injector Complex



Multi Beam Klystrons

Multi Beam Klystrons (MBK) have been chosen.
Three vendors have developed and manufactured MBKs, meeting the XFEL/TESLA requirements. Several years of development.

THALES TH1801

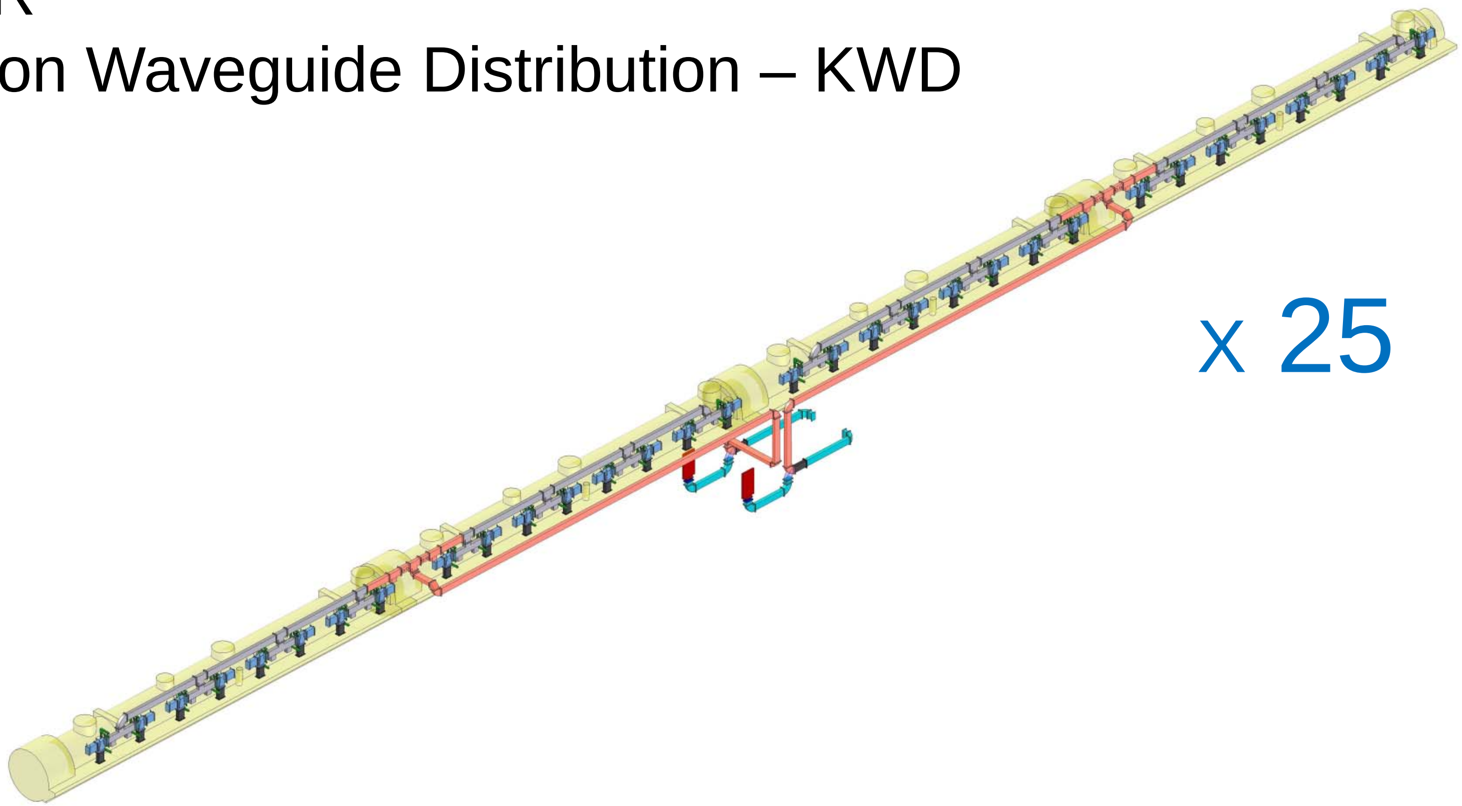
CPI VKL8301

TOSHIBA E3736

Linac Waveguide Distribution System

Linac Waveguide Distribution System consists of:

- Waveguide Distribution for cryomodule (Left & Right) – WDL & WDR
- Connecting Waveguide Distribution Left & Right) – CWDL & CWDR
- Klystron Waveguide Distribution – KWD



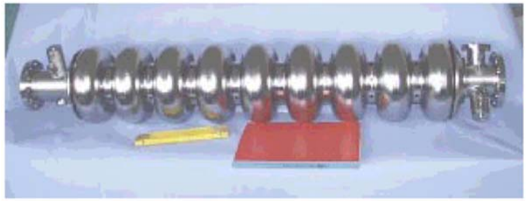
x 25

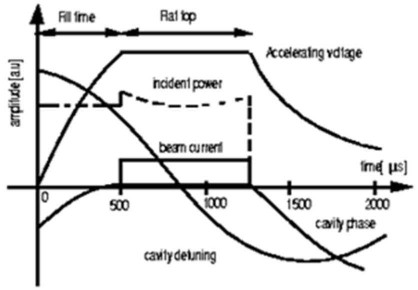
Status Bouncer Modulator

- 17 bouncer modulators have been built, 3 by FNAL and 14 together with industry
- 13 modulators are in operation at present (FLASH, PITZ, XFEL test stands)
- Almost 20 years of operation experience
- The actual internal layout of the bouncer modulators has been modified over the years (e.g. EMI reduction, regulation improvement, new (more reliable or smaller) components)
- Some downtime was caused by failure of components due to mechanical stress (e.g. broken transformer, loose cables, broken crow bar resistors)
- FLASH downtime during user run between Nov. 07 and Sep. 08 6%, 31% of these 6% were caused by 1.3GHz RF stations
- FLASH downtime during user run between Sep. 10 and July 11 4%, 9% of these 4% were caused by 1.3GHz RF stations

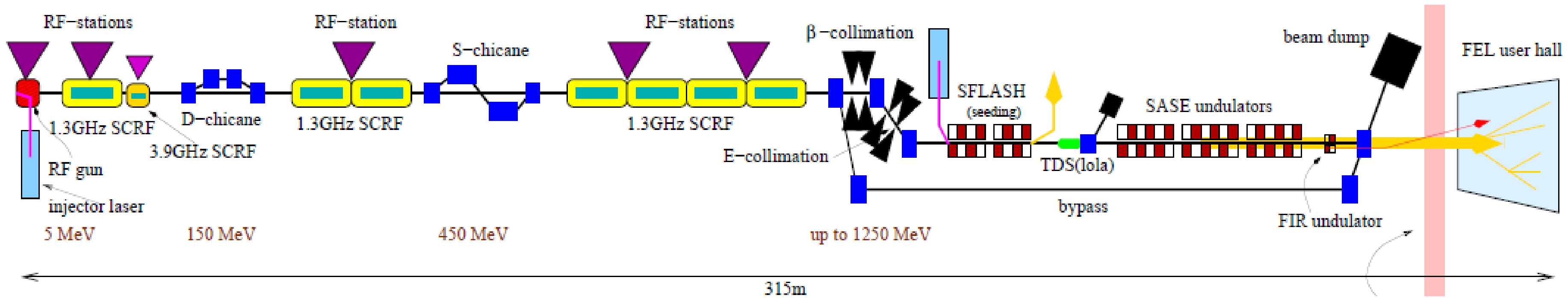
XFEL RF System Requirements

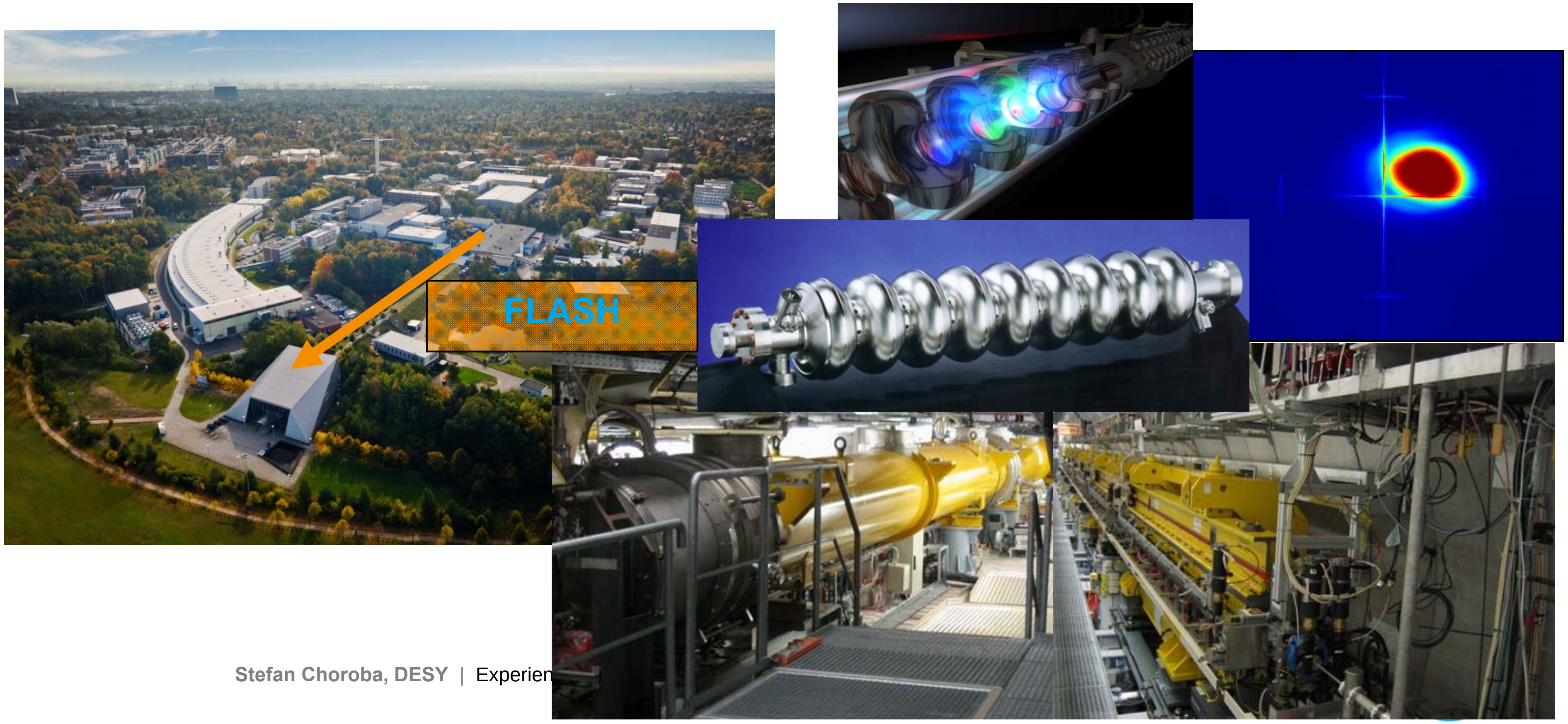
Number of sc cavities:	800 total for 17.5GeV
Power per cavity:	122 kW
Gradient at 20GeV:	23.6 MV/m
Power per 32 cavities (4 cryo modules):	3.9MW
Power per RF station:	**5.2MW** (including 10% losses in waveguides and circulators and a regulation reserve of 15%)
Number of RF stations:	**25** (27), active **23** (25)
Number of RF stations for injectors:	**2**
Macro beam pulse duration:	650μs
RF pulse duration:	**1.38ms**
Repetition rate:	**10Hz (30Hz)**
Average RF power per station:	**72kW (150kW)**



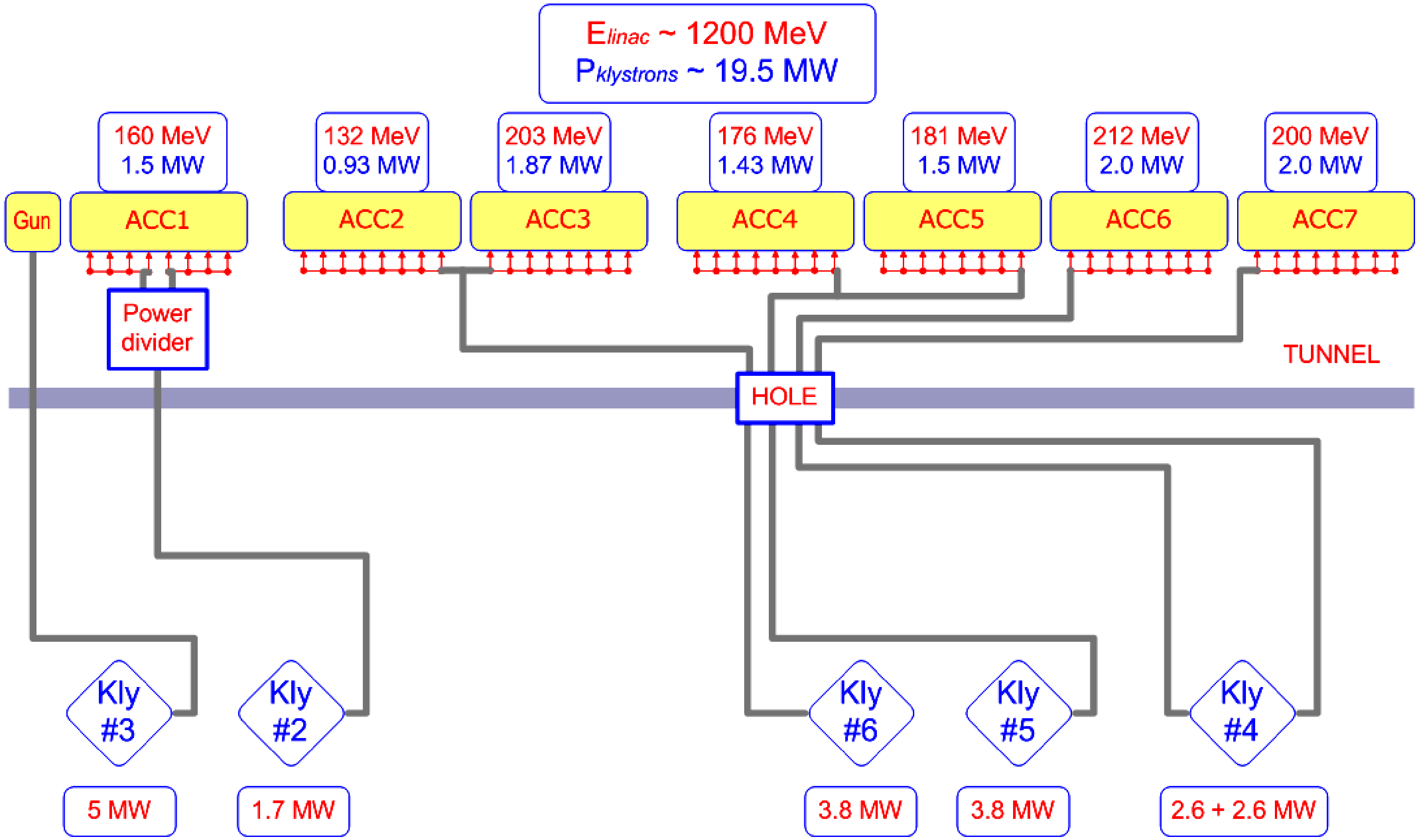


TTF/FLASH


RF−stations
RF−station
S−chicane
RF−stations
β −collimation
beam dump
FEL user hall
SFLASH
(seeding)
SASE undulators
1.3GHz SCRF
D−chicane
1.3GHz SCRF
1.3GHz SCRF
3.9GHz SCRF
RF gun
injector laser
E−collimation
TDS(lola)
bypass
FIR undulator
5 MeV
150 MeV
450 MeV
up to 1250 MeV
315m


FLASH

FLASH RF System 2011



Additional 8 RF stations in operation for test of XFEL RF system components and cavities at DESY Hamburg and for RF gun development at DESY Zeuthen plus 3 in construction for XFEL module test at DESY Hamburg.