High Power RF: from TESLA to XFEL and ILC

RF Power Generation and Distribution

Stefan Choroba, DESY
High Power RF:
from TESLA to XFEL and ILC
DESY, ILC Seminar 14.02.2014

HELMHOLTZ
ASSOCIATION

TESLA, XFEL, ILC and superconducting cavities

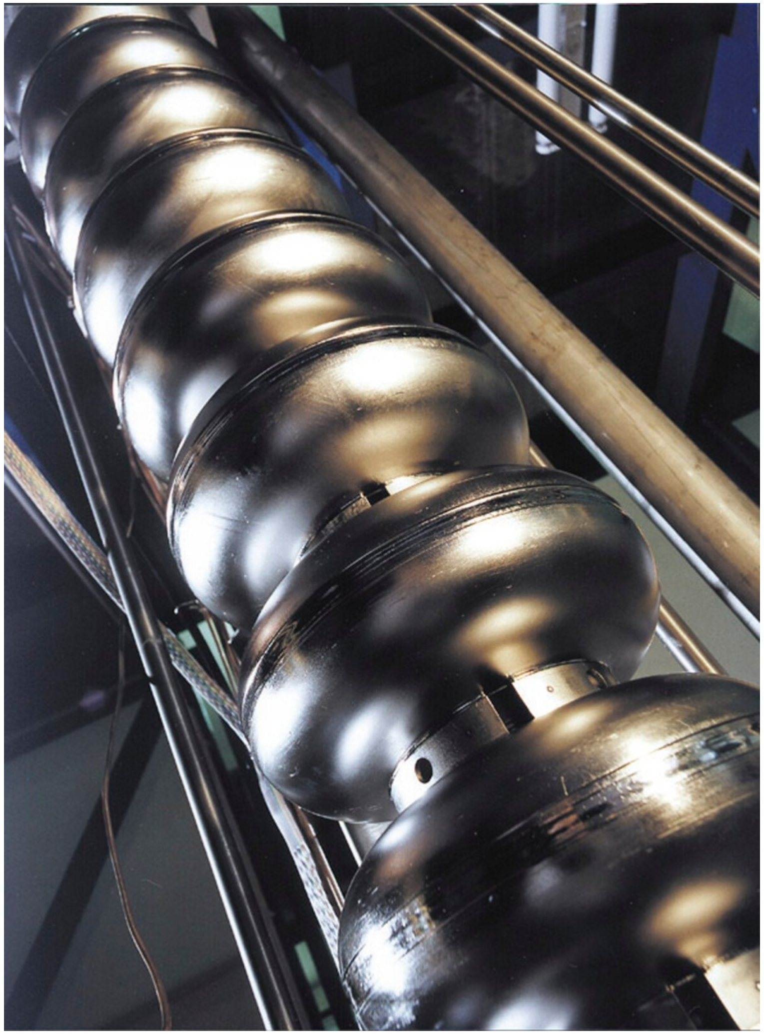
- Early 1990s start of the TESLA Collaboration
- In 1990s Tesla Test Facility (TTF) setup at DESY
- 2001 TESLA TDR of a Linear Collider with integrated XFEL
- 2002 Supplement to the TDR on a dedicated linac for the XFEL, negotiations started to build the XFEL as European project at DESY
- 2006 TDR of 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
- Many of the developments for TESLA and the XFEL might be used for the ILC
- Many other projects use 1.3GHz Tesla type cavities too

Overview

- Introduction TESLA, European XFEL, ILC
- Superconducting cavities
- RF system requirements
- RF sources
- HV power generation
- Power distribution

1.3GHz superconducting cavities

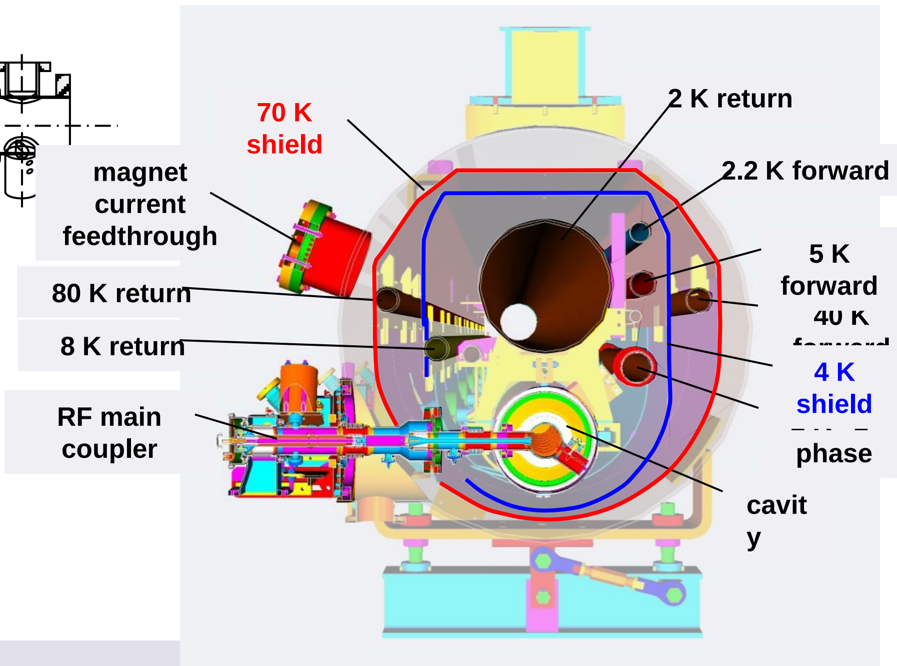
- 1.3GHz 9-cell Tesla type
- Max. gradient 46MV/m
- Typical achieved today 25-35MV/m
- Coaxial input coupler
- Assembled in modules



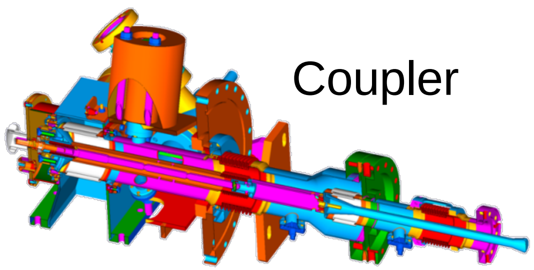
1.3GHz accelerator modules

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

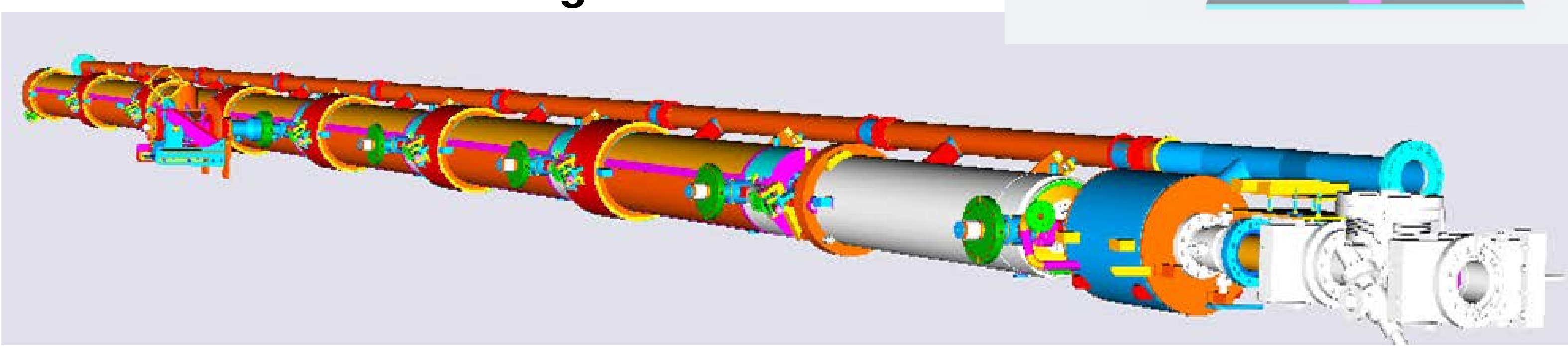
Cryo Module



Coupler

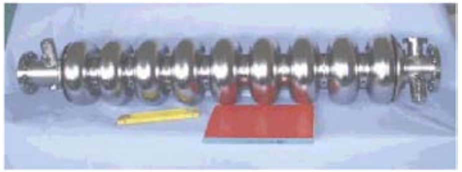


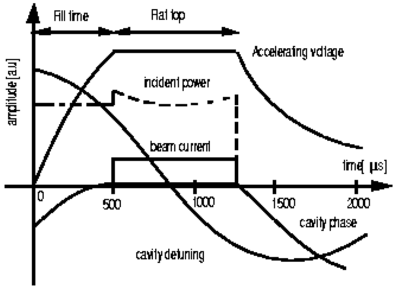
Module String



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**

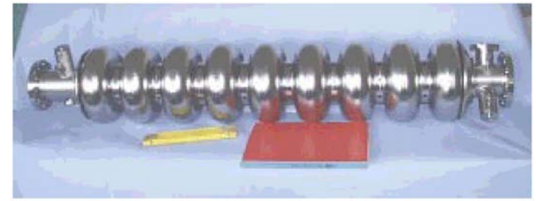


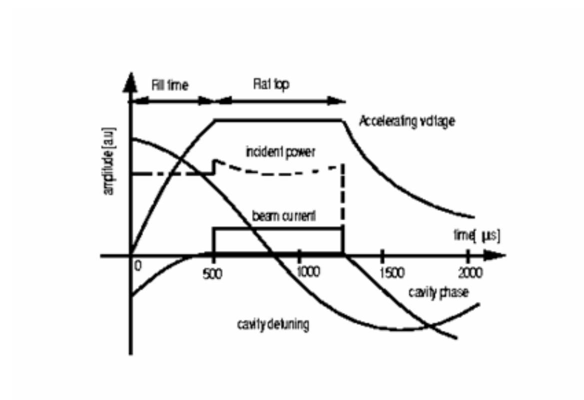


For TESLA 800 the number of stations must be doubled.
The gradient is 35MV/m.

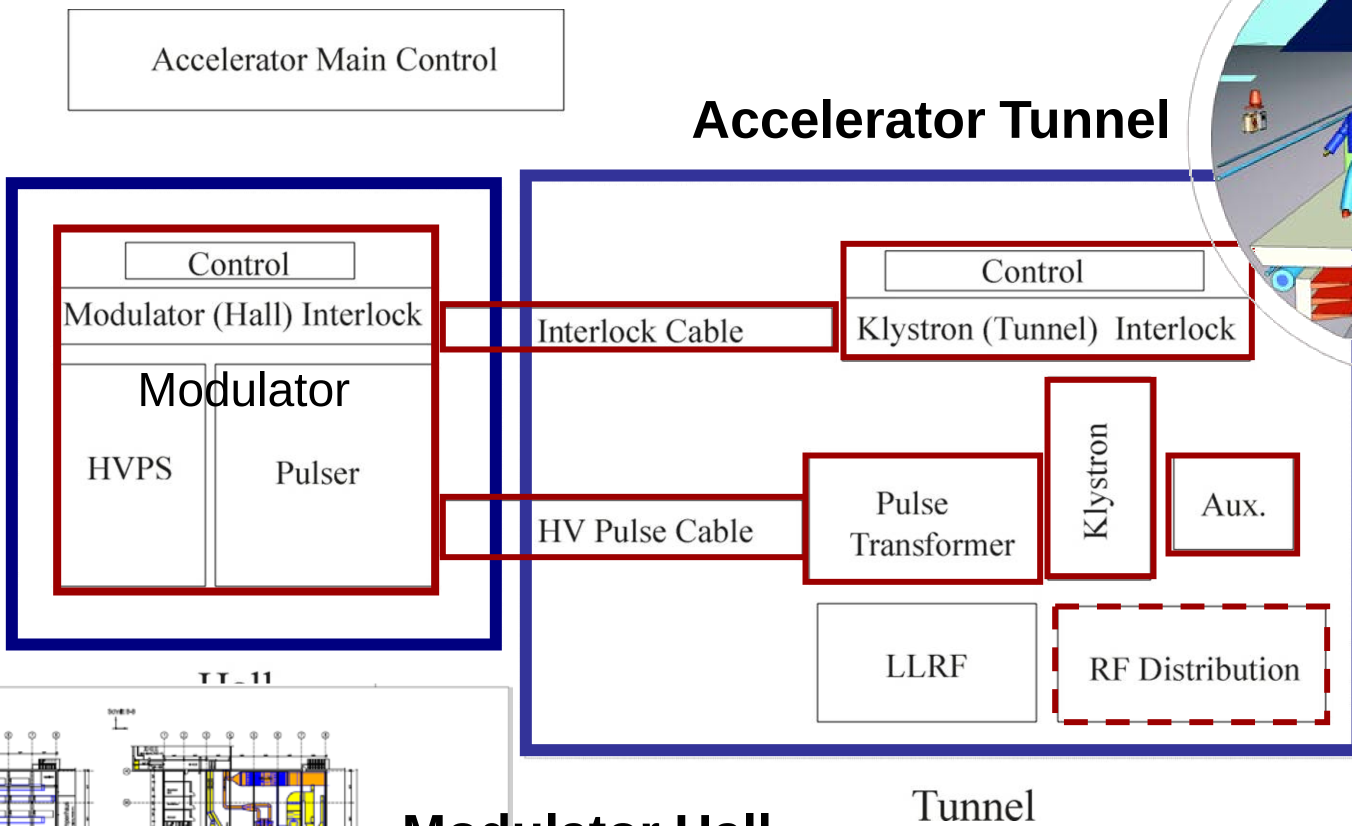
XFEL RF System Requirements

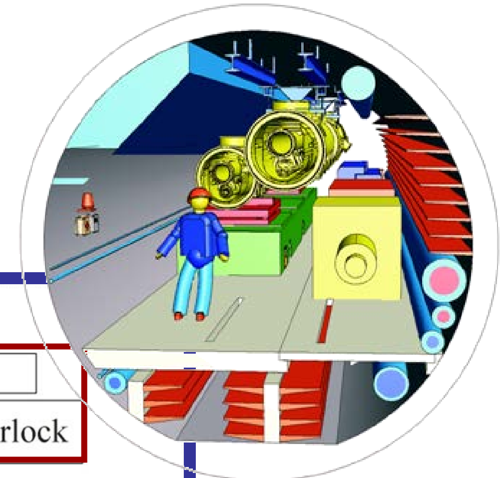
Number of sc cavities:	800 total for 17.5GeV
Power per cavity:	122 kW
Gradient at 20GeV:	23.6 MV/m
Power per 32 cavities (4 cryo modules):	3.9MW
Power per RF station:	**5.2MW** (including 10% losses in waveguides and circulators and a regulation reserve of 15%)
Number of RF stations:	**25** (27), active **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)**

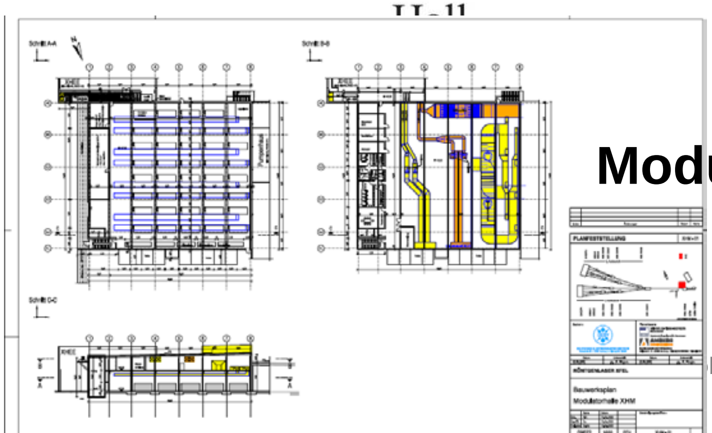




Layout of a RF Station for TESLA and the European XFEL







Modulator Hall

RF Power Source for TESLA and XFEL

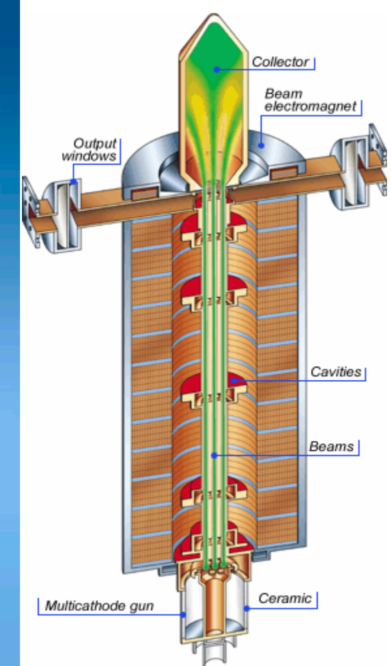
> Operation Frequency:	1.3GHz
> Cathode Voltage:	< 120 kV
> Beam Current:	< 140 A
> Max. RF Peak Power:	10MW
> RF Pulse Duration:	1.5ms
> Repetition Rate:	10Hz
> RF Average Power:	150kW
> Efficiency:	63%
> Solenoid Power:	< 5.5kW
> Length:	2.5m

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

Multi Beam Klystron THALES TH1801

Measured performance

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



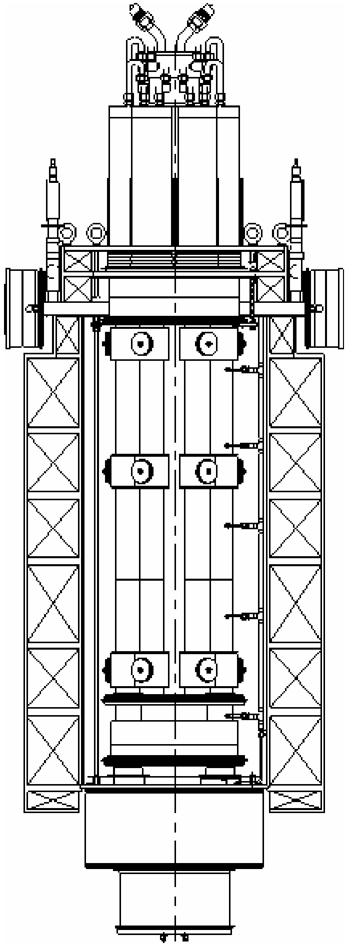
Multi Beam Klystron CPI VKL-8301

Design Features:

•6 beams

•HOM input and output cavity

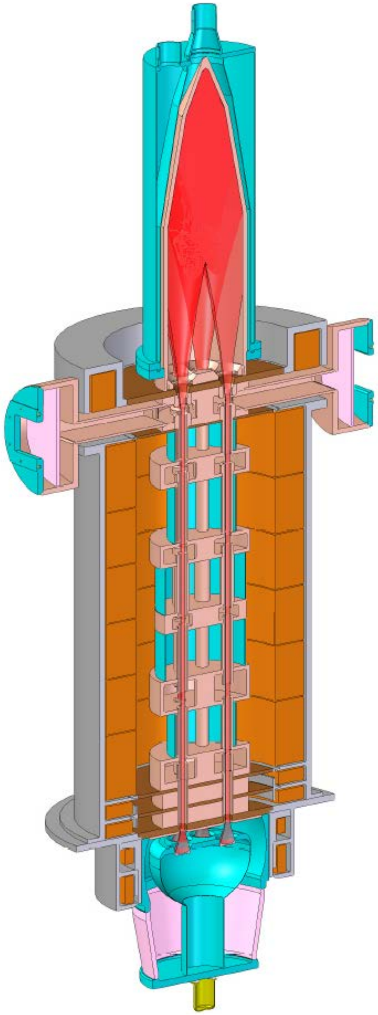
•Cathode loading: <2.5A/cm^2 lifetime prediction: >100000h



The TOSHIBA E3736 MBK

Design Features:

- •6 beams
- •Ring shaped cavities

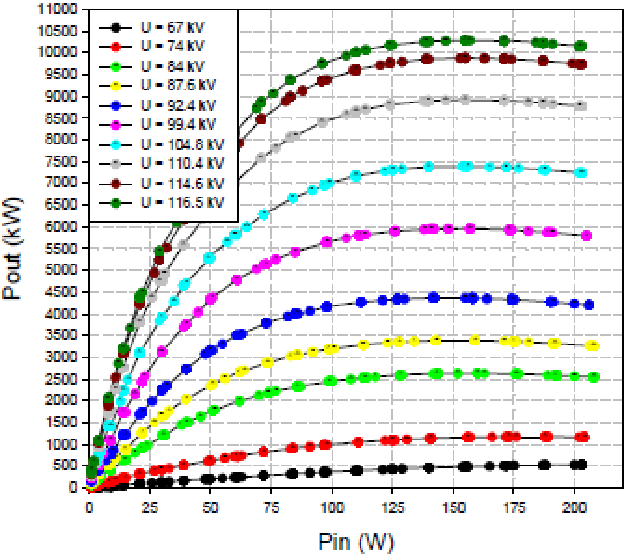


Horizontal MBKs

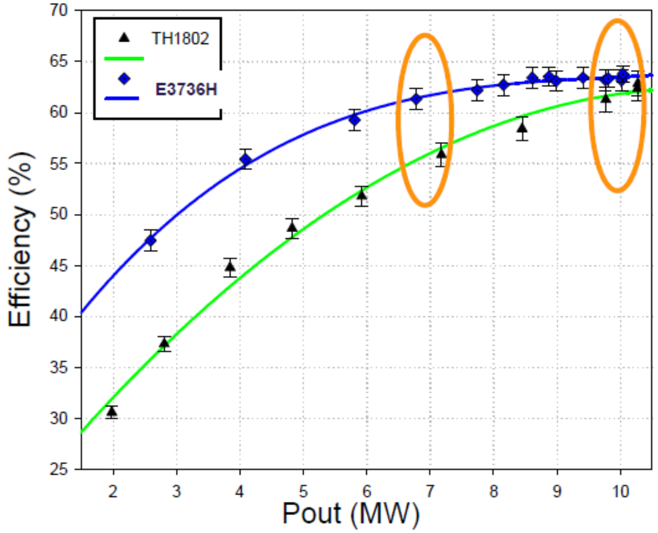
- Since vertical MBKs do not fit in the accelerator tunnel horizontal version have been developed.
- All three vendors of MBKs have developed and manufactured horizontal versions of their MBK.
- These klystrons have been successfully tested at the klystron test facility at DESY.
- Finally two vendors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

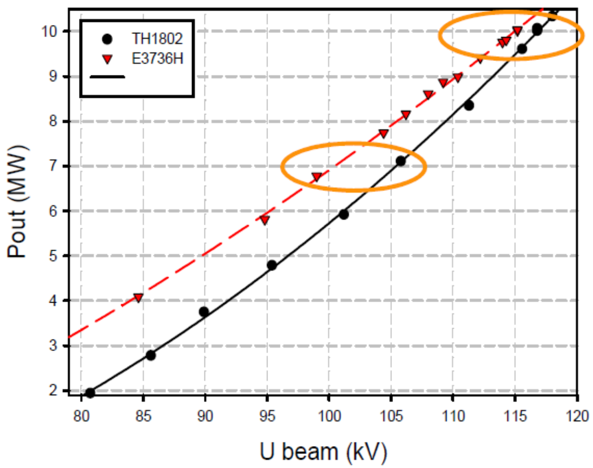
Horizontal multibeam klystron prototypes at the klystron test facility (KTF)

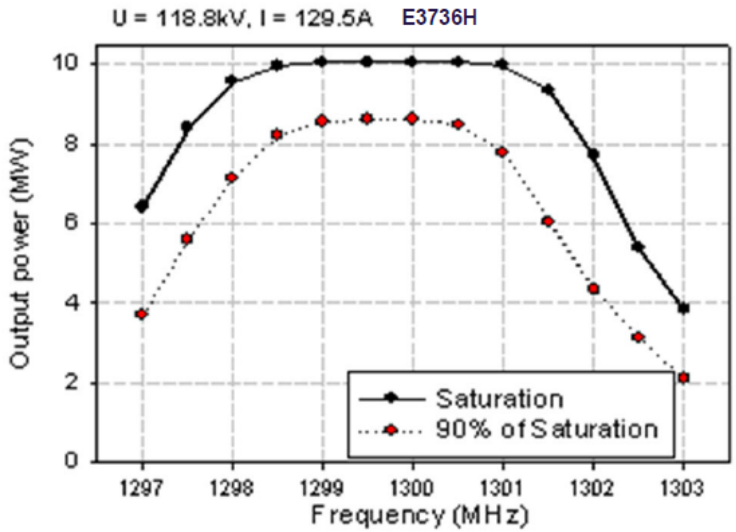
Some Test Results

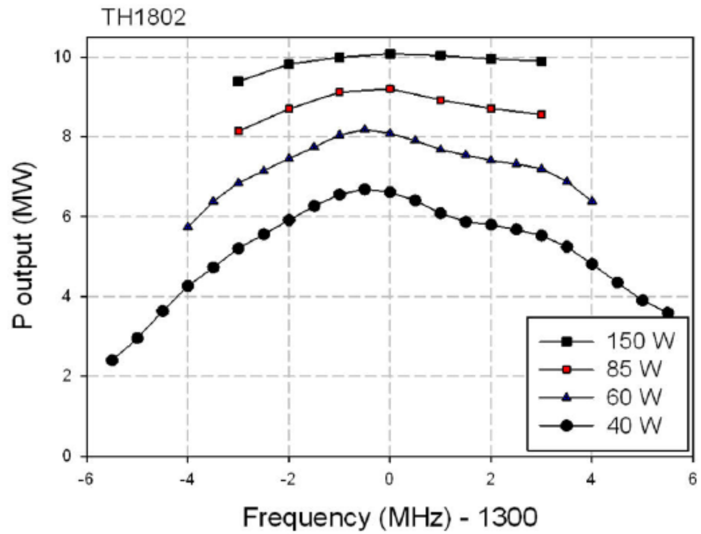


TH1802 prototype gain curves







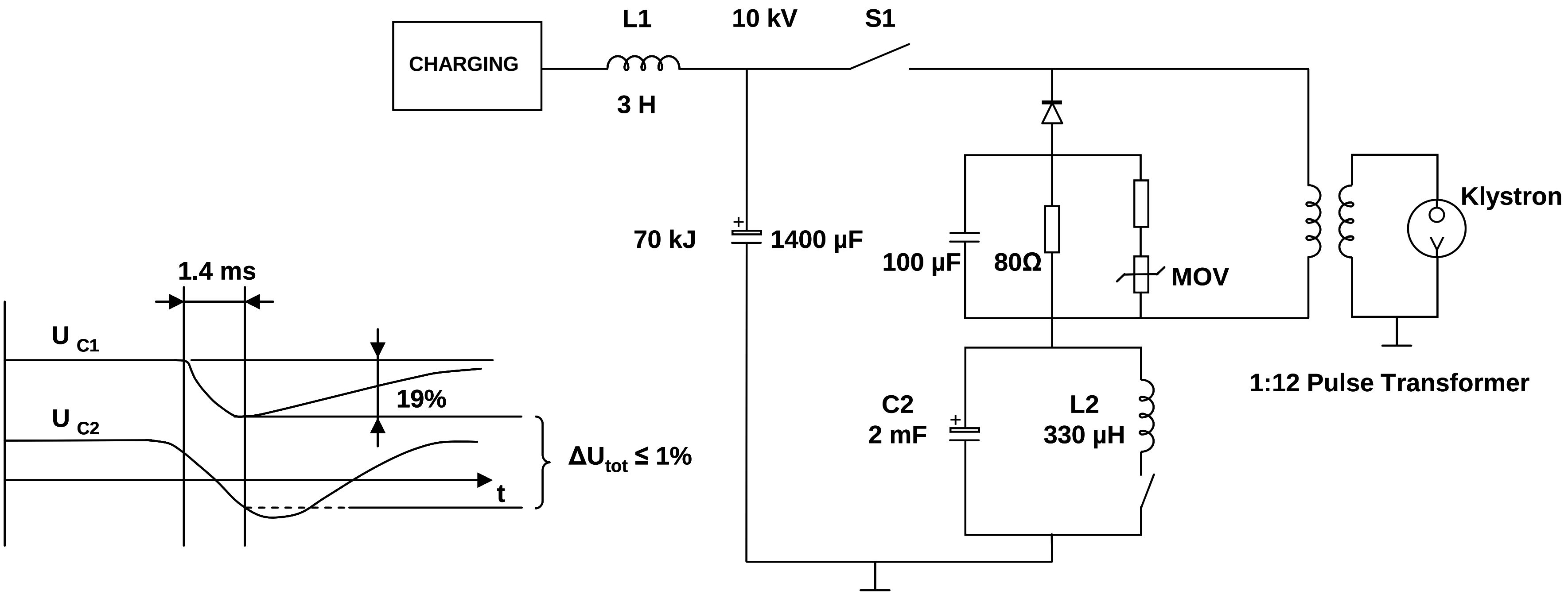


Modulator Requirements

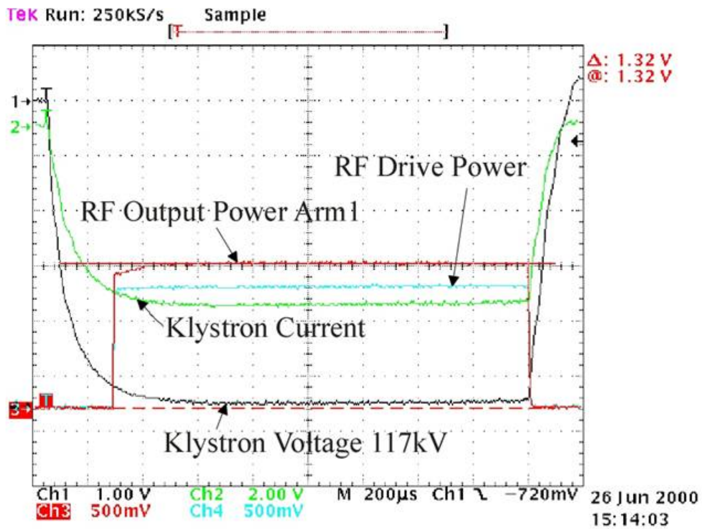
	typical	max.
Modulator Pulse Voltage/ Pulse Transformer Primary Voltage	9.6kV	12kV
Modulator Pulse Current Voltage/ Pulse Transformer Primary Current	1.62kA	1.8kA
Pulse Transformer Secondary Voltage / Klystron Gun Voltage	**115kV**	**132kV**
Pulse Transformer Secondary Current / Klystron Gun Current	**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.



Bouncer Modulators by FNAL

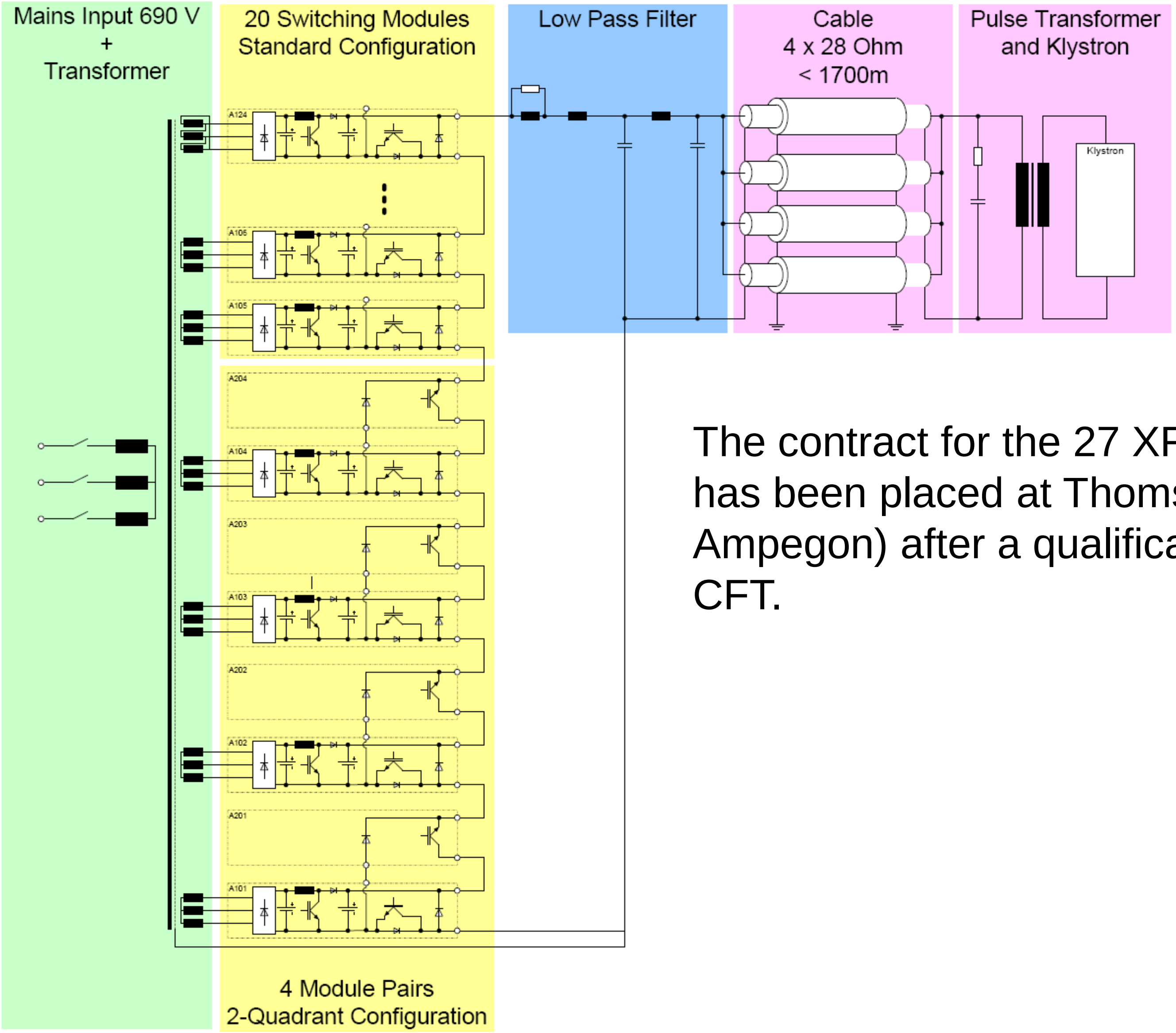


- 3 modulators have been developed, built and delivered to TTF by FNAL since 1994
- 1 modulator is still in use, 2 others have been united and modified to 1 new modulator

Industry made bouncer modulator

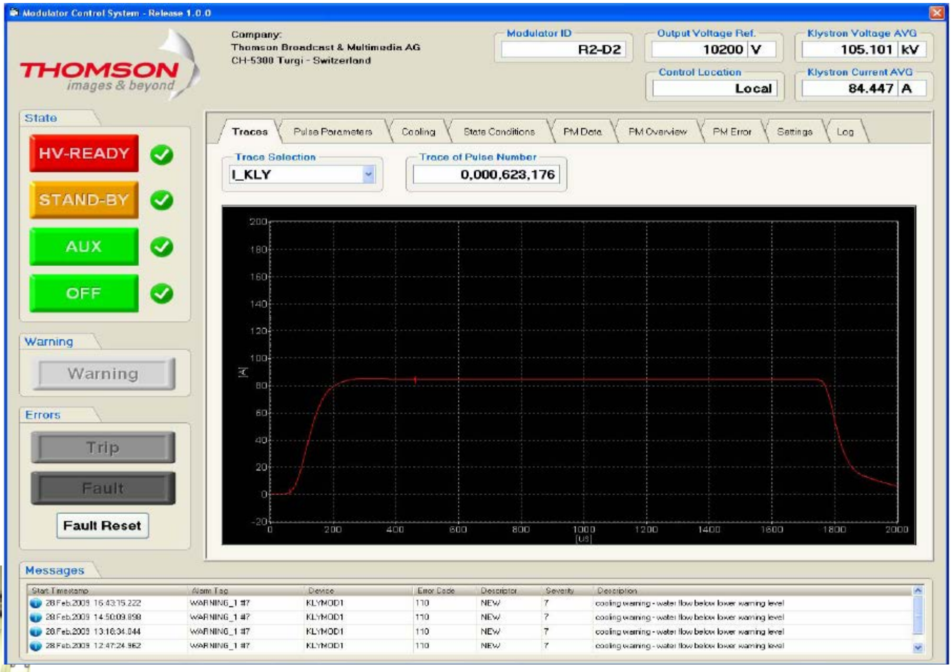
- Industry made subunits (PPT, ABB, FUG, Poynting)
- Constant power power supply for suppression of 10Hz repetition rate disturbances in the mains
- Compact storage capacitor bank with self healing capacitors
- IGCT Stack (ABB); 7 IGCTs in series, 2 are redundant
- Low leakage inductance pulse transformer (ABB) L<200μH resulting in shorter HV pulse rise time of <200μs
- Light Triggered Thyristor crowbar avoiding mercury of ignitrons

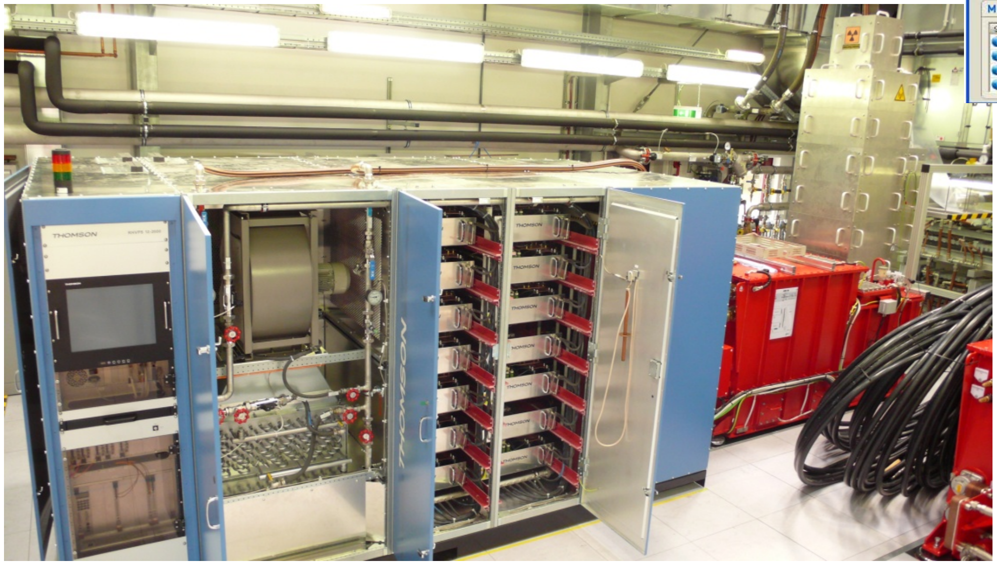
The Pulse Step Modulator for XFEL



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

The Pulse Step Modulator





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

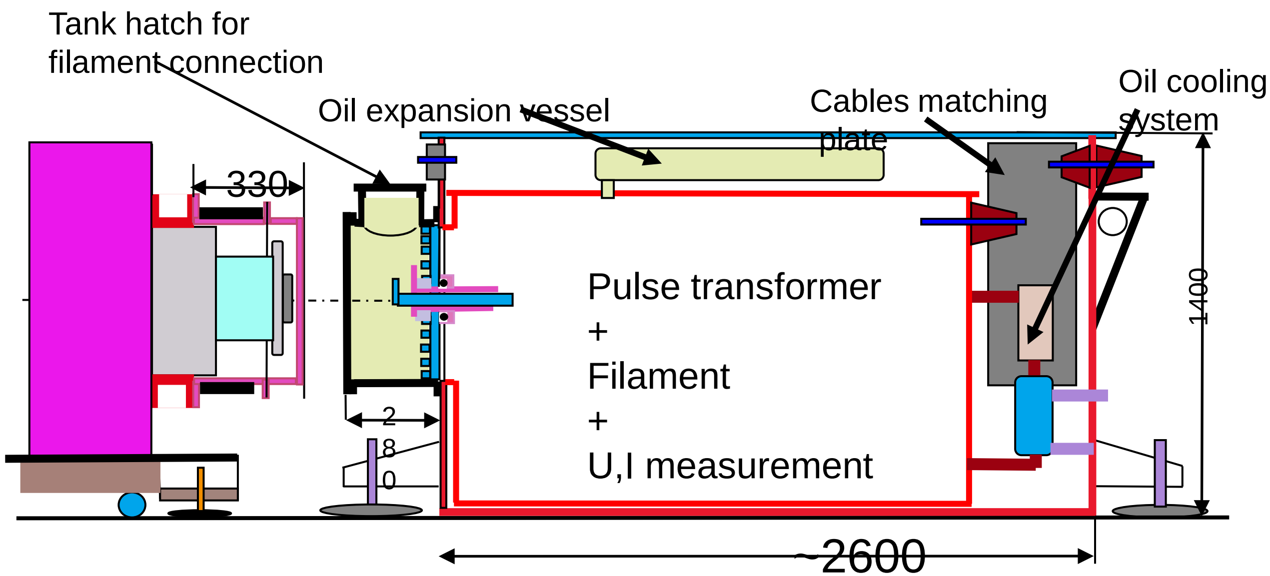
DESY

MBK to Pulse Transformer Connection

Base line:

direct connection

Klystron/PT

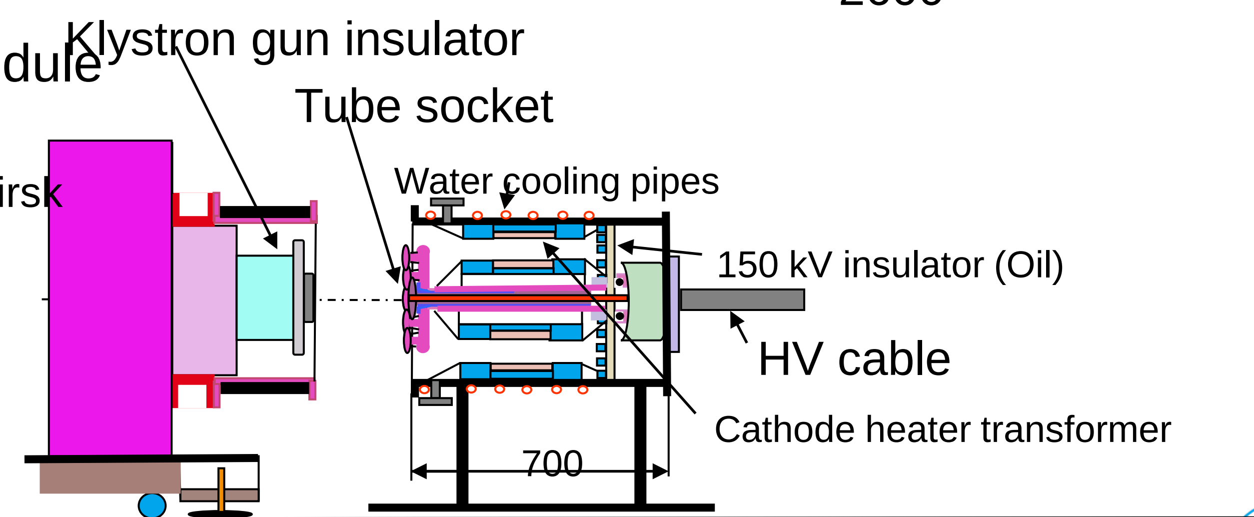


Alternative:

Connection module

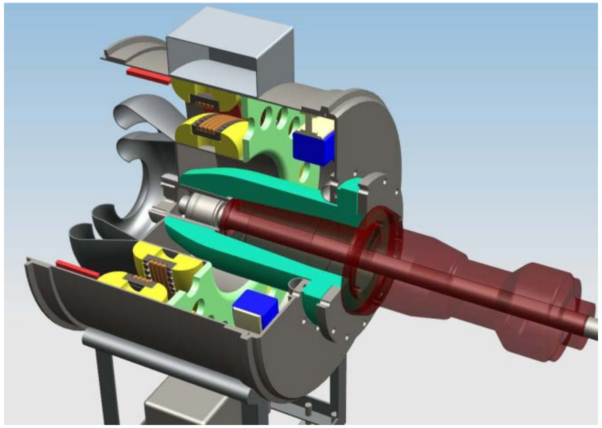
being investigated

with BINP/Novosibirsk



Pulse Transformer and Connection Module for XFEL

Double wall pulse transformer



Connection module

Marx Modulator for ILC

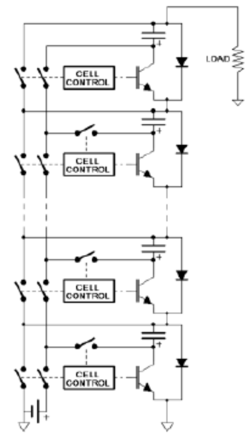
> Performance requirements

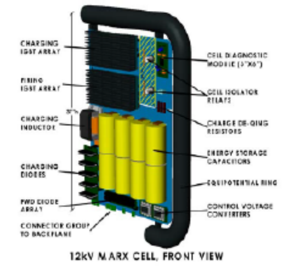
Parameter	Unit	Specification
Output voltage	kV	120
Output current	A	140
Pulse width	ms	1.65
Pulse repetition frequency	Hz	5 (10)
Max. average power	kW	139
Output pulse flat-top	%	±0.5
Pulse-to-pulse voltage fluctuation	%	±0.5
Energy deposited into klystron during a gun spark	J	< 20

Power efficiency and heat loads of Marx

Parameter	Unit	Specification
SLAC P2 Marx DC to pulse flattop efficiency	%	95 ± 1
Assumed charging supply AC to DC efficiency	%	95
Usable power delivered to klystron	kW	138.6
Power delivered to collector during pulse rise and fall	kW	0.5
Power dissipated to air inside of modulator enclosure	kW	7.1
Power dissipated in the DC chargers	kW	7.4

Marx Generator Modulator





12 kV Marx Cell (1 of 16)

- IGBT switched
- No magnetic core
- Air cooled (no oil)

Pulse Transformer-less
Fast Rise and Falling Time
No pulse transformer

Information from GDE PAC Review (S. Fukuda, KEK) 2012-12-13

Marx modulator variants

	SLAC P1	DTI	ISA Corp.	SLAC P2
Cell voltage	11 kV	6 kV	3.5 kV	3.75 kV
Number of cells	16	20	42 (7 delay)	32
Redundancy	Vernier (16) 1.2 kV + delay	Correction cells (16) 0.9 kV	Vernier (16) 0.5 kV + delay	Regulated cell (PWM correction)
Regulation	N+1	N+3	N+1	N+2
Status	full test completed	SLAC/KEK for MTBF test	Voltage test completed	full test completed

(a) DTI Marx modulator (b) SLAC P1 Marx modulator (c) SLAC P2 Marx modulator

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P2 Marx Modulator at SLAC

Table 1. ILC klystron modulator parameters.

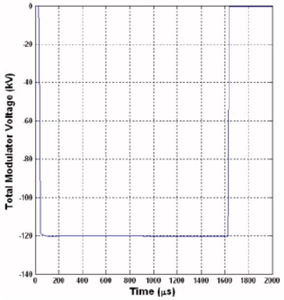
Output Voltage	120 kV
Output Current	140 A
Pulse Width	1.6 ms
Pulse Repetition Frequency	5 Hz
Average Power	134 kW
Output Pulse Flat-top	±0.5%
Energy Deposited into Klystron During a Gun Spark	<20 J

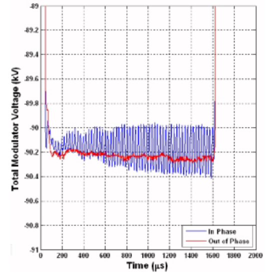
Table 2. P2 Marx cell and modulator parameters.

Cell Weight	< 50 lb
Cell Dimensions (inc. shield) (WxDxH)	13.75"x29.5"x8"
Cells Per Modulator	32
Minimum Cells for Full Output	30
Modulator Dimensions (WxDxH)	9'x5'x8'

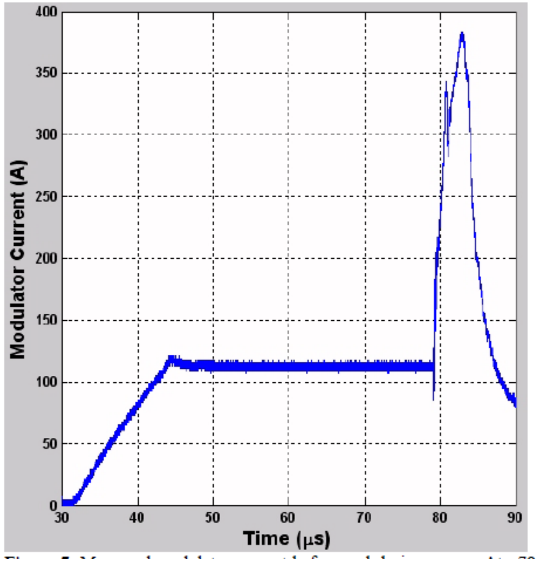
P2 Marx celld are plug-in module types and high availability.

Fast rise and falling time





Flatness of the pulse



Fast recovery after arc

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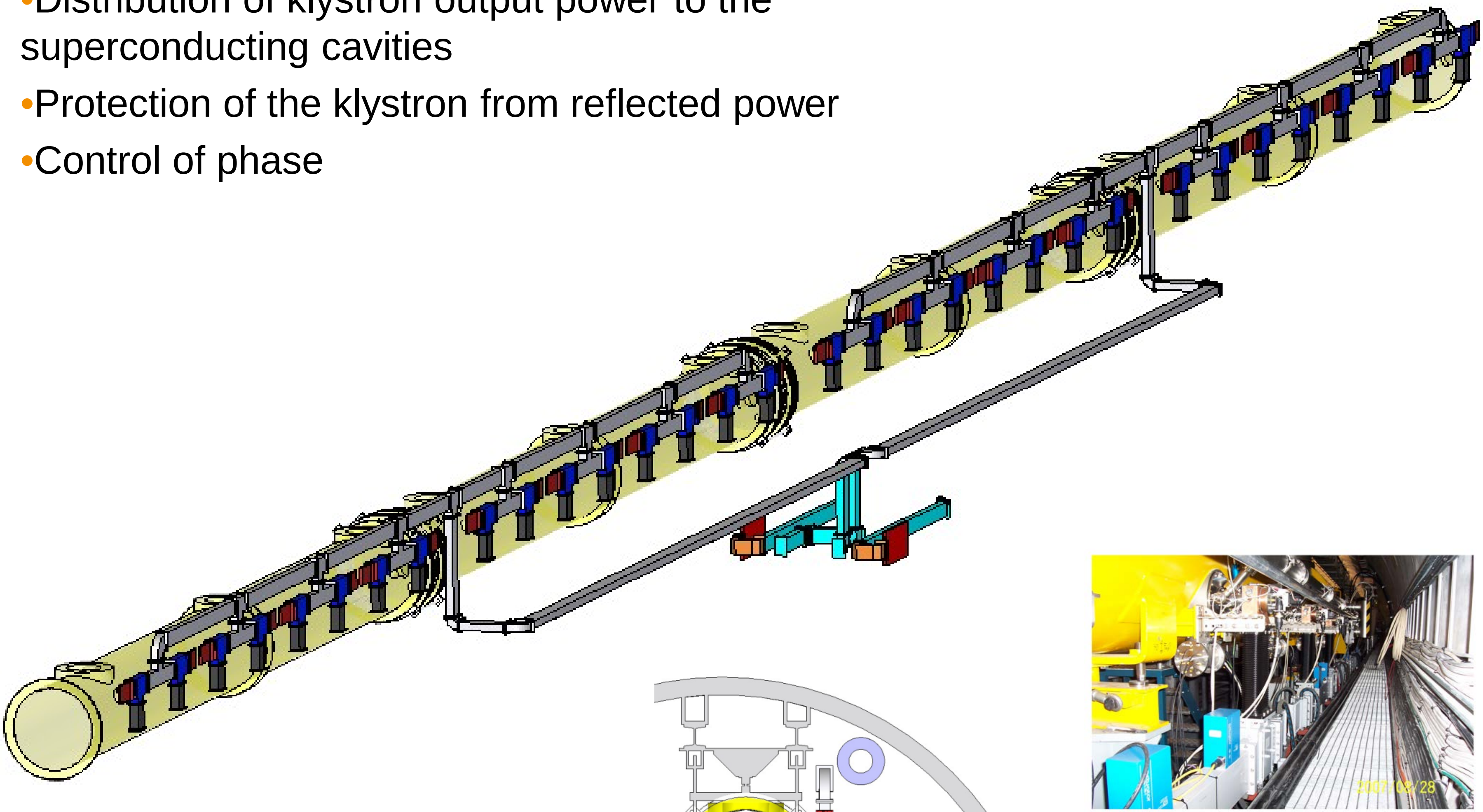
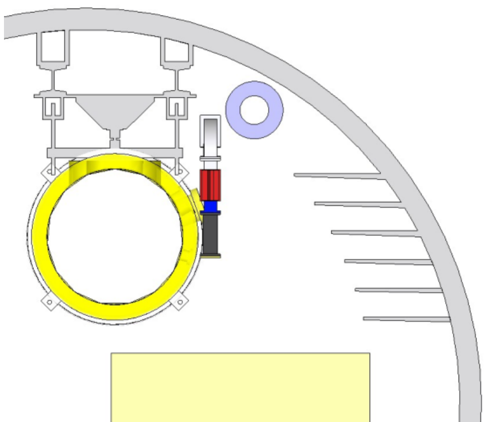
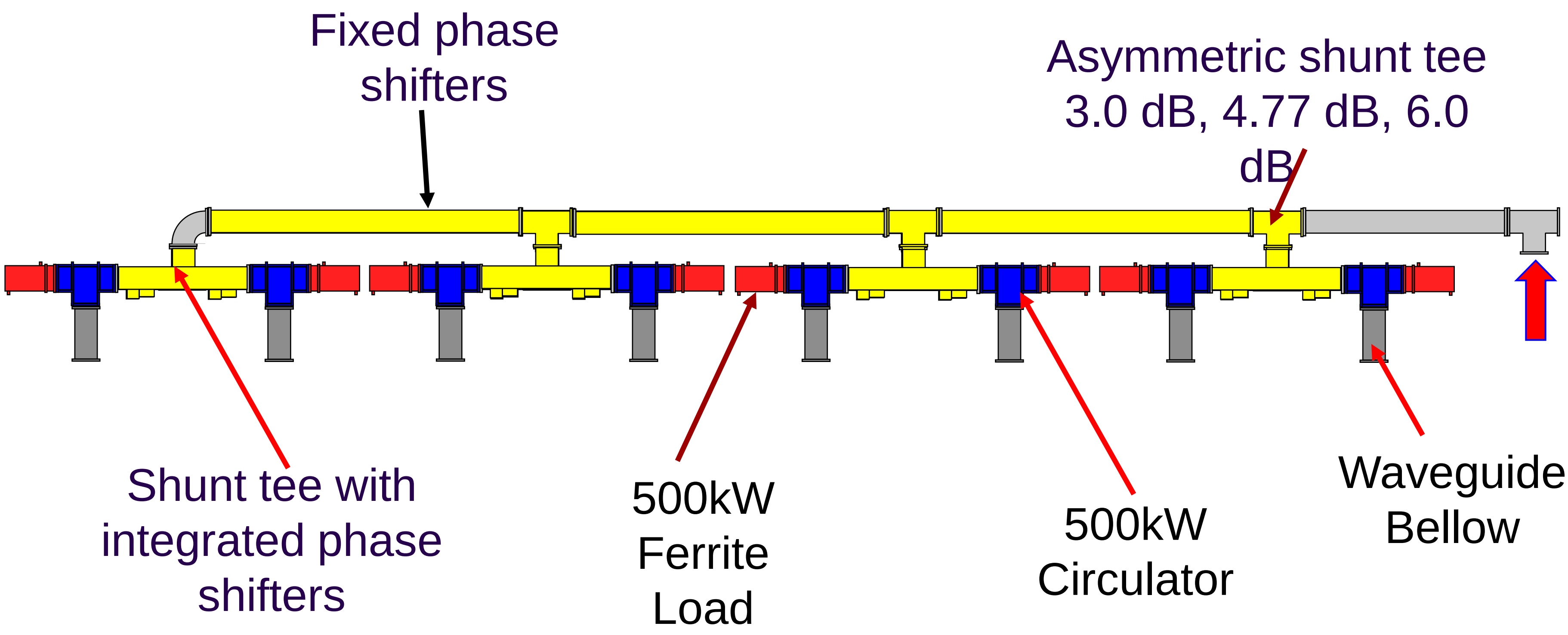
RF Power Distribution

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



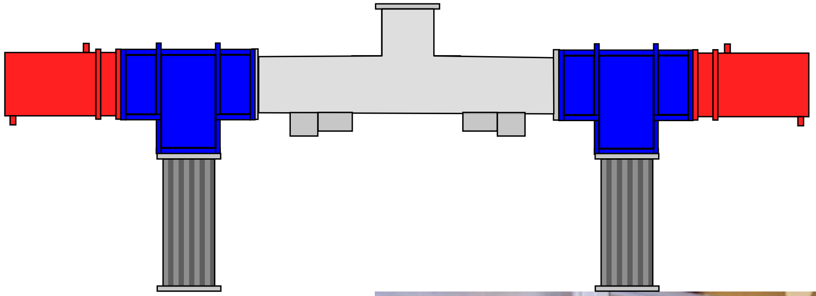


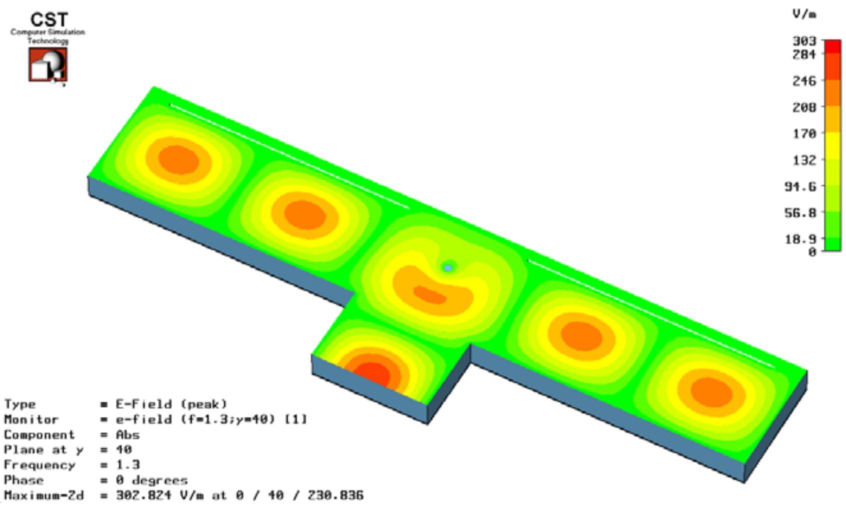
Module Waveguide Distribution

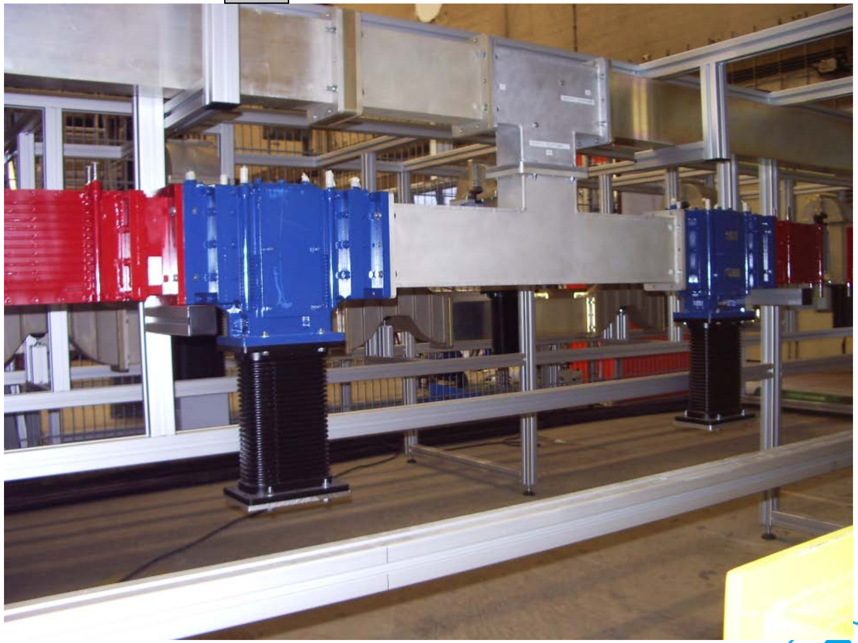


Waveguide Distribution

Binary cell with shunt tee with integrated phase shifter



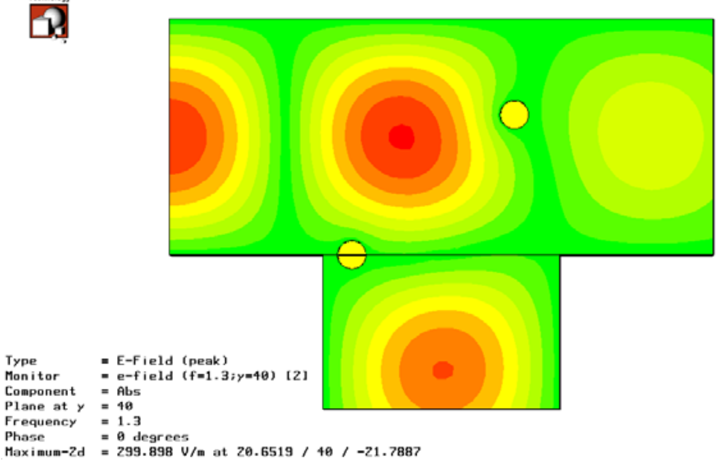


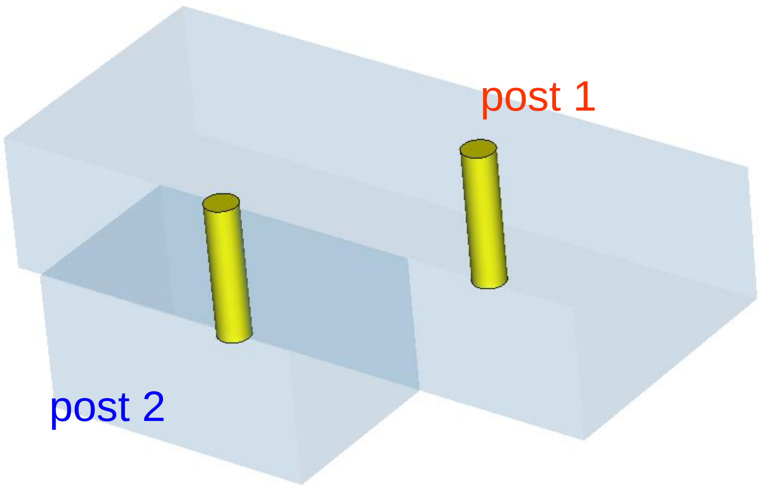


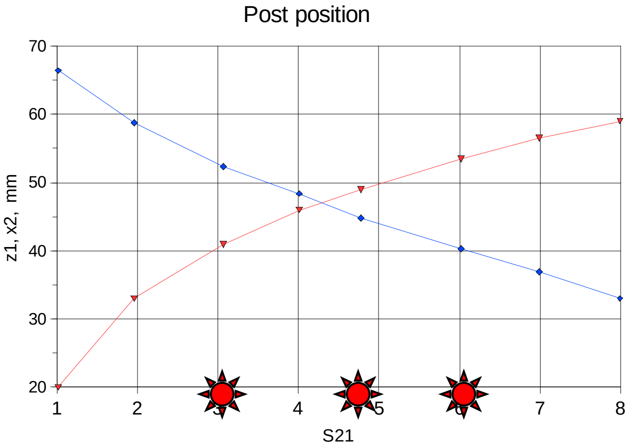
Waveguide Distribution

Asymmetric shunt tee

Coupling ratio 6dB







Examples for waveguide distribution

Waveguides at girder during installation test

Waveguides with cooling tubes at module during installation test

WATF with girders for waveguide assembly

Waveguides at AMTF

Local PDS Layout of KCS / DKS

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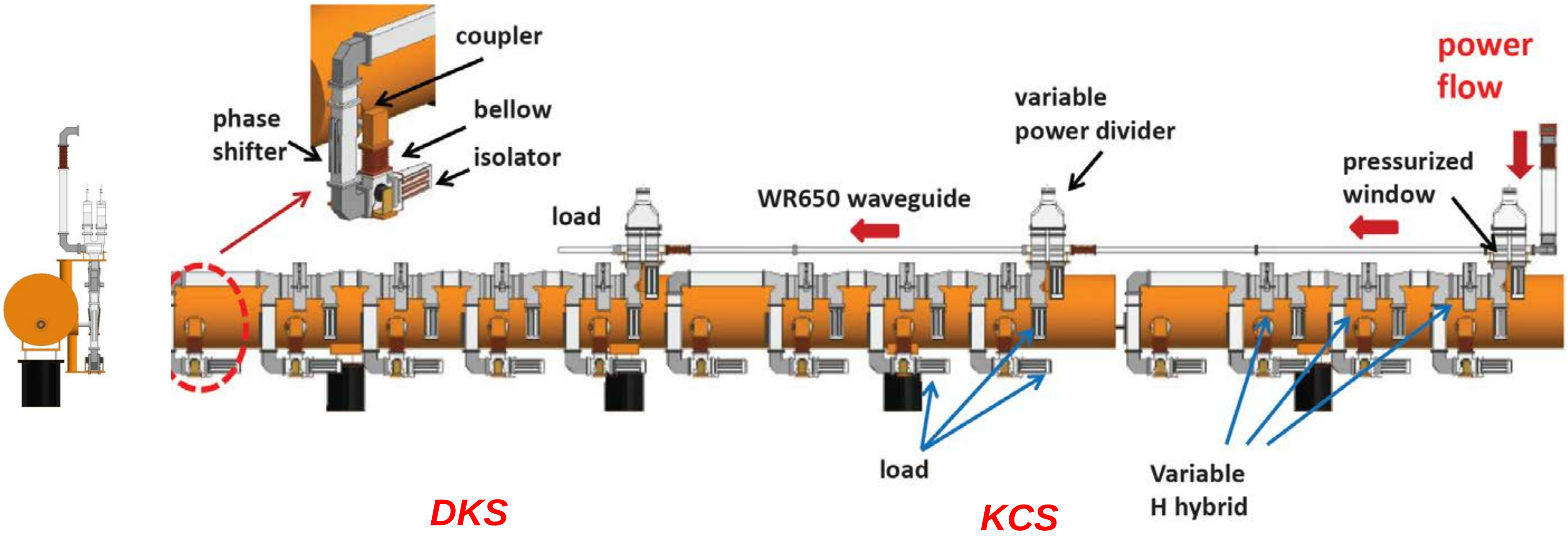
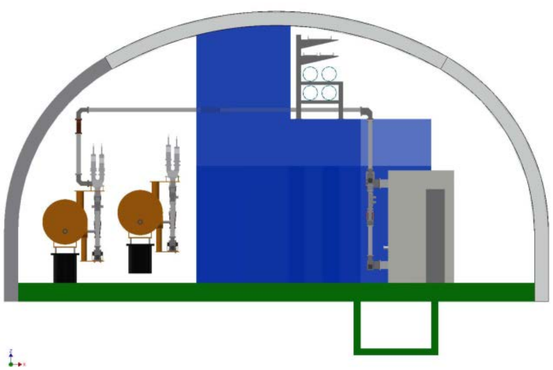
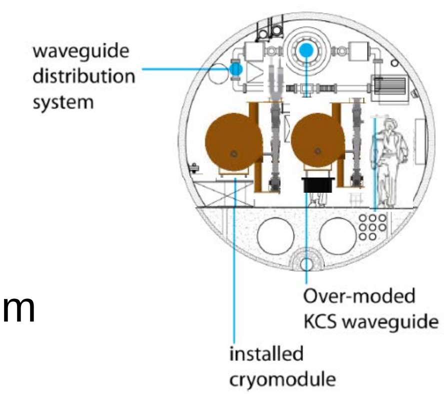




Cross section view of tunnel and installation concept of local power distribution system



Power Delivery
in the Distributed Klystron System

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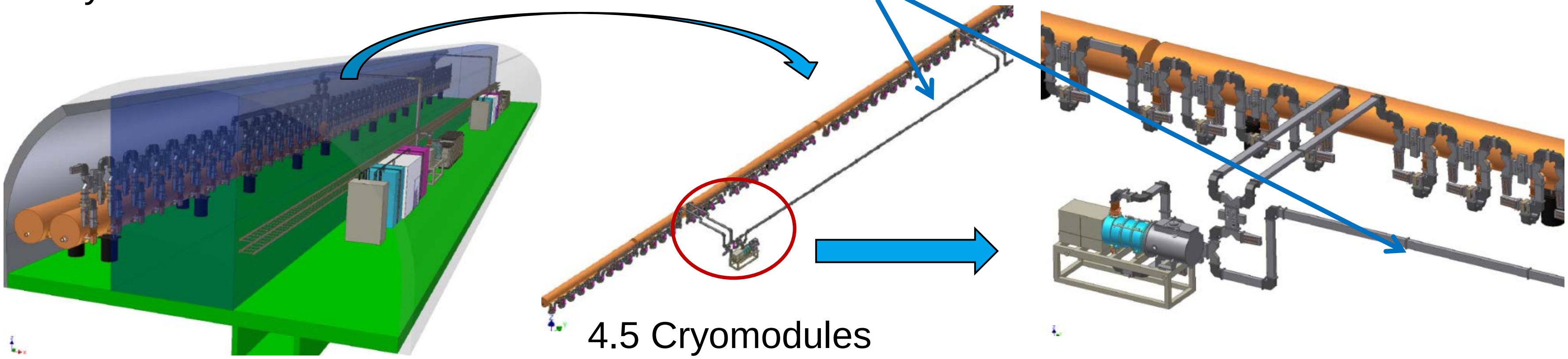
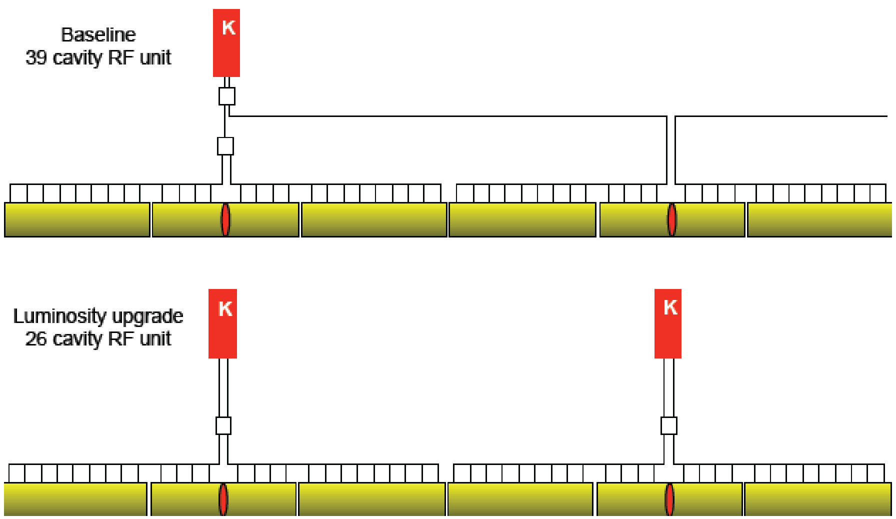
Layout of Kamaboko Tunnel

33m long WR770 WG aiming for lower loss



Horizontal multi-beam klystron and power delivering system

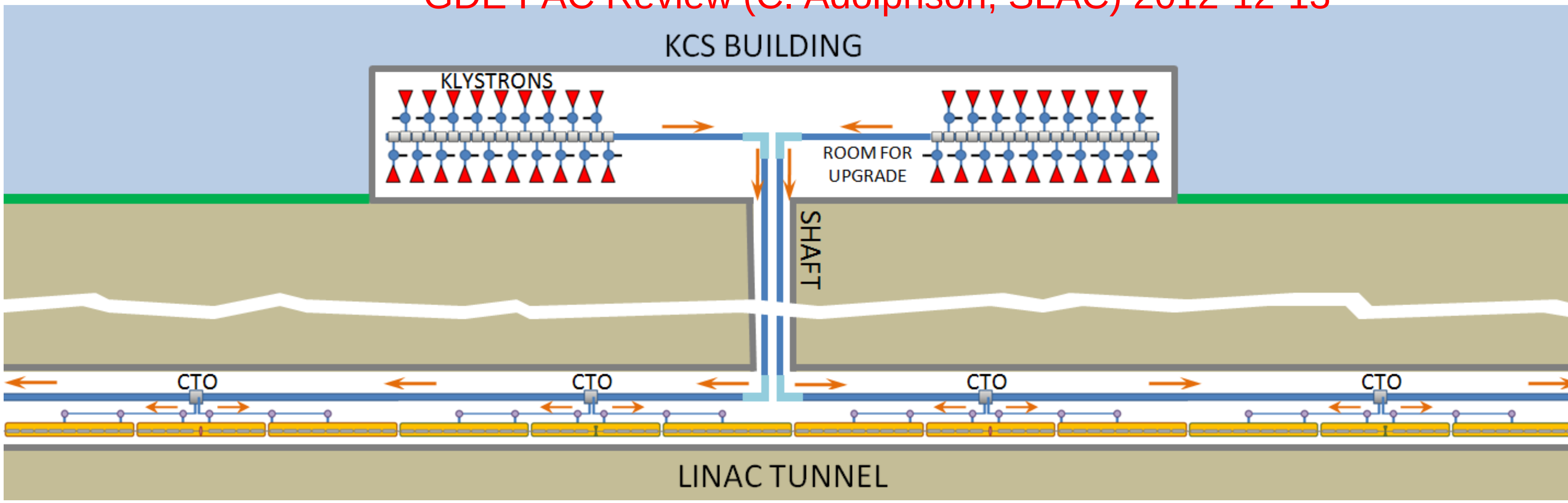
Baseline RF Unit of DKS



For the lumi upgrade, the layout of the cryomodule corridor remains same and only the service corridor configuration is redone.

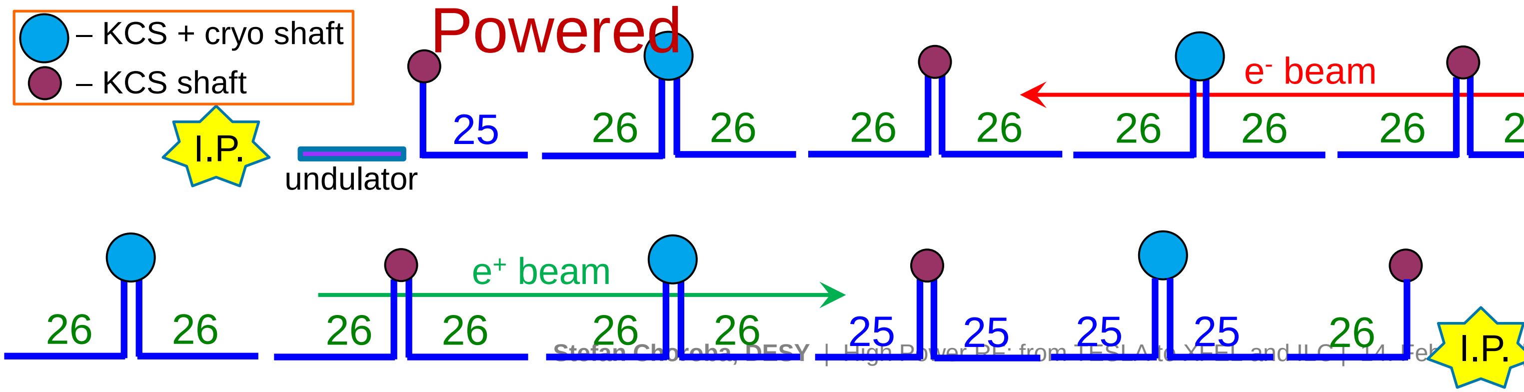
Klystron Cluster Scheme

GDE PAC Review (C. Adolphson, SLAC) 2012-12-13



- RF power sources clustered in surface buildings.
- Power combined, transported through overmoded waveguide, and tapped off locally at each ML Unit.
- Two KCS systems per building/shaft feed upstream and downstream, ~1 km each.

Shaft Layout and ML Units Powered



main linac totals:
12 shafts
22 KCS systems
567 rf units (285+282)
1,701 cryomodules
14,742 cavities

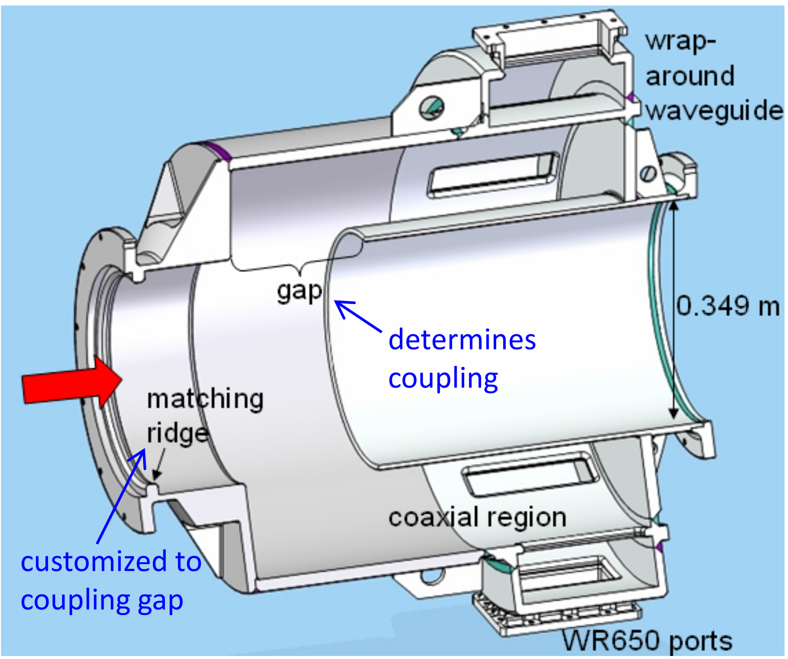
Coupling into the Circular Waveguide

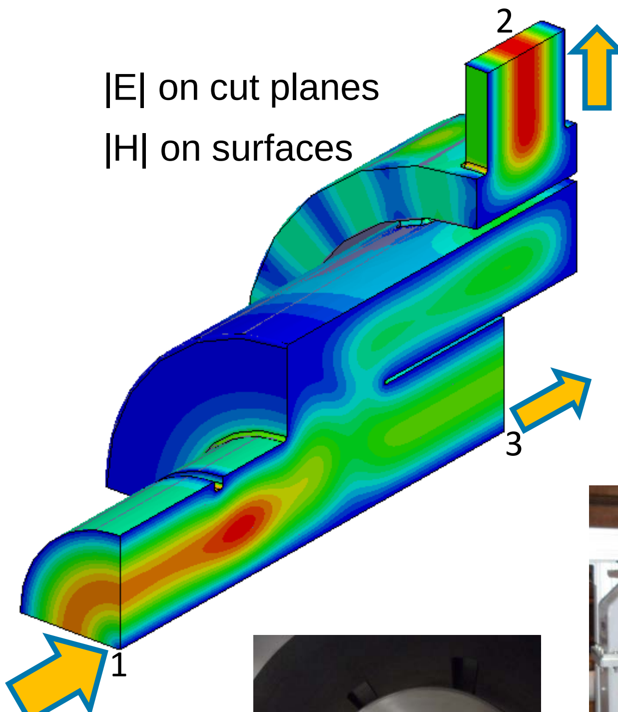
GDE PAC Review (C. Adolphson, SLAC) 2012-12-13

To couple power to the pipe, developed a "coaxial (wrap-around) tap-off", or CTO

Couplings range from -3 dB to ~-14 dB are needed, controlled by gap width

CTO (Coaxial Tap-Off)

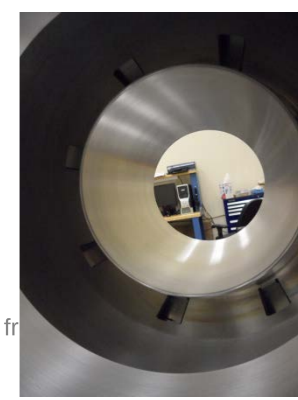




3 dB design

Coupling due to beating with TE_{02}

Prototype CTO's built for R&D program.



Thank you for your attention