深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

Cycle of Seminars by Carlo Pagani

Seminar # 8

From the TESLA Pulsed Technology to the new CW FELs

Shenzhen, 10 March 2023 / INFN LASA, 5 February 2025

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INFN LASA

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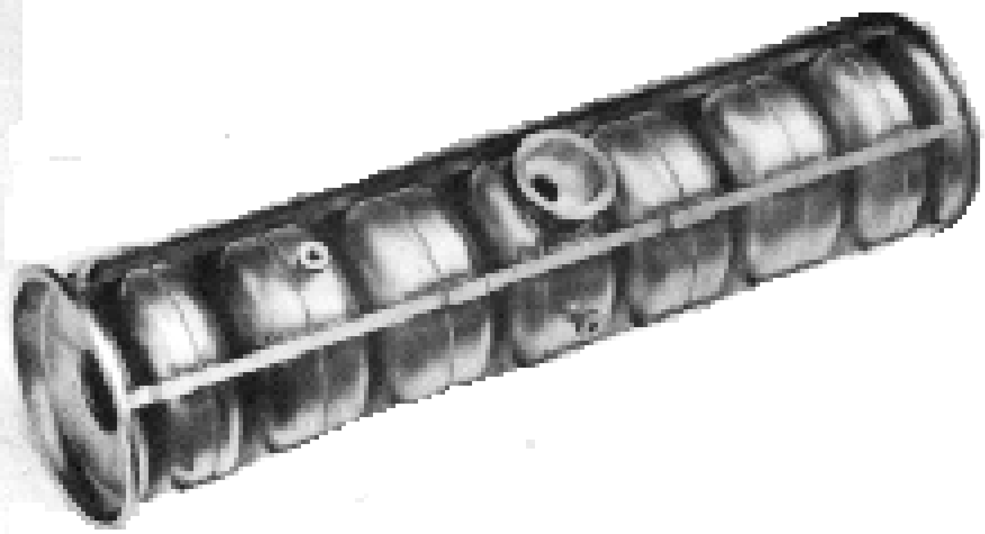
3. What's needed to go back to CW
4. CW interpretation of the TESLA Technology

SRF Conceived for CW Operation



Stanford University

HEPL: Electron Linac for FEL

- First multicell electron cavity: $\beta = 1$

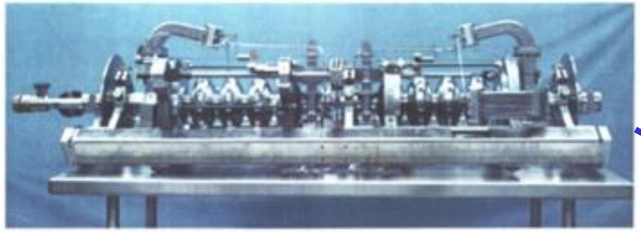
Argonne National Labs

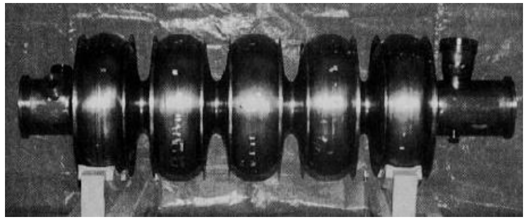
ATLAS: Heavy-ion Linac

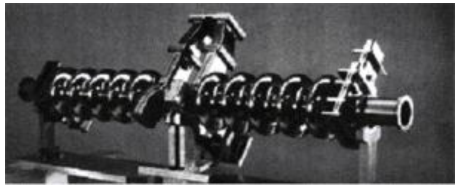
- Originated at Caltech for $\beta \sim 0.1$

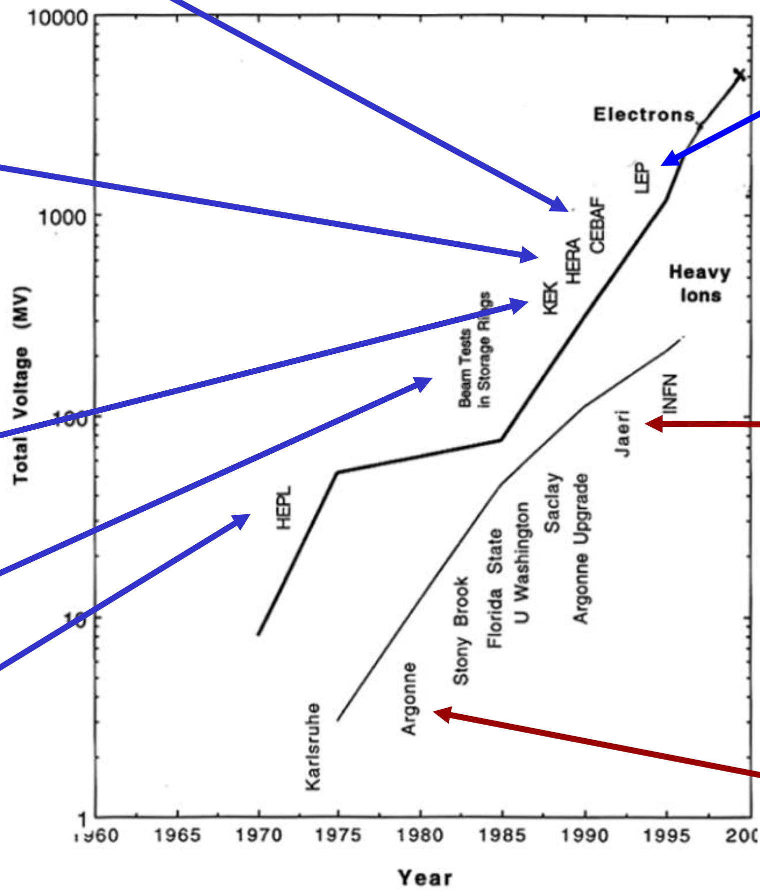
Before TESLA all Project asked for CW

“Livingston Plot” by Hasan Padamsee









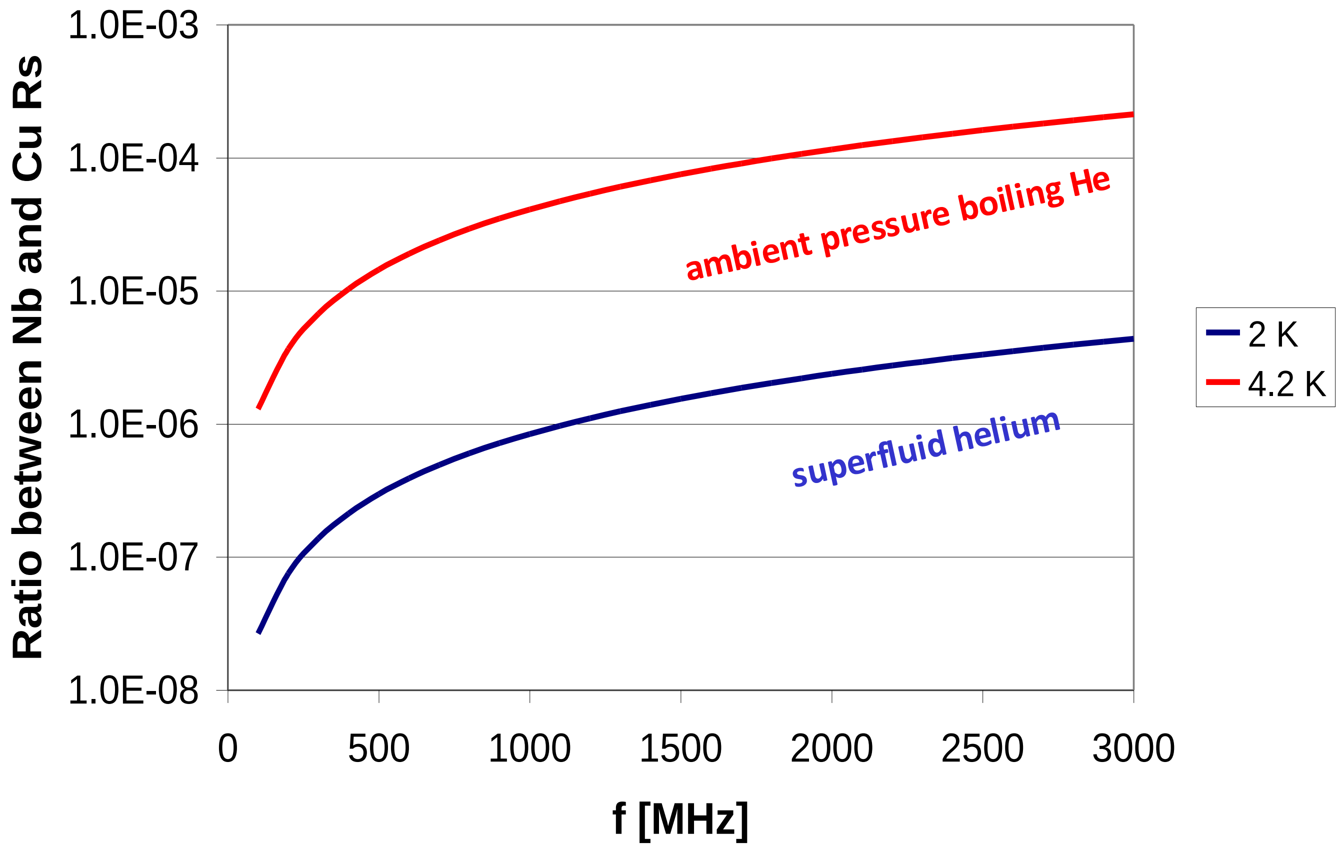
Superconducting RF vs NC-RF

Power dissipated on the cavity walls to sustain the field is:

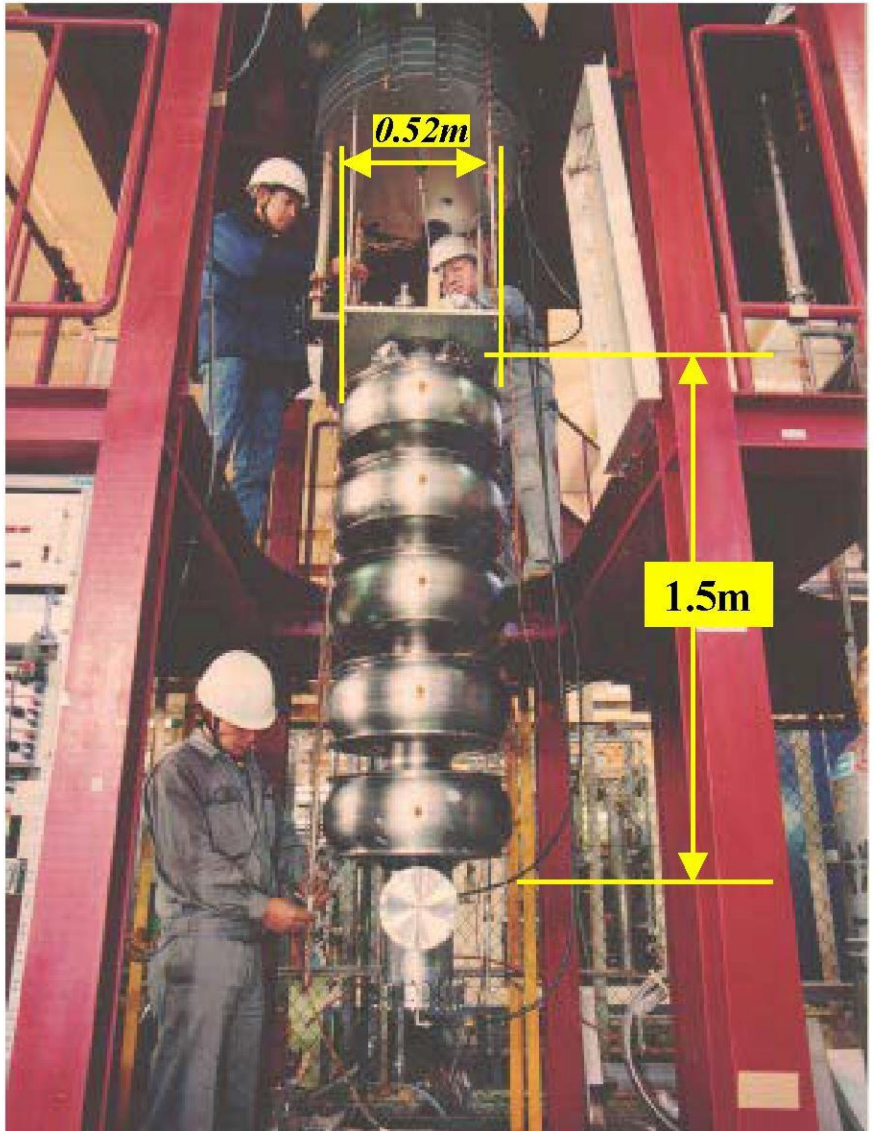
$$P_{diss} = \frac{R_s}{2} \int_S H^2 dS$$

Good, but the gain of up to 6 order of magnitudes is not guaranted and it's not for free:

- Cryogenics
- Material & Surface Science
- Clean Technology
- ……



First Industrial Production in Japan *(1988 – 1995)*

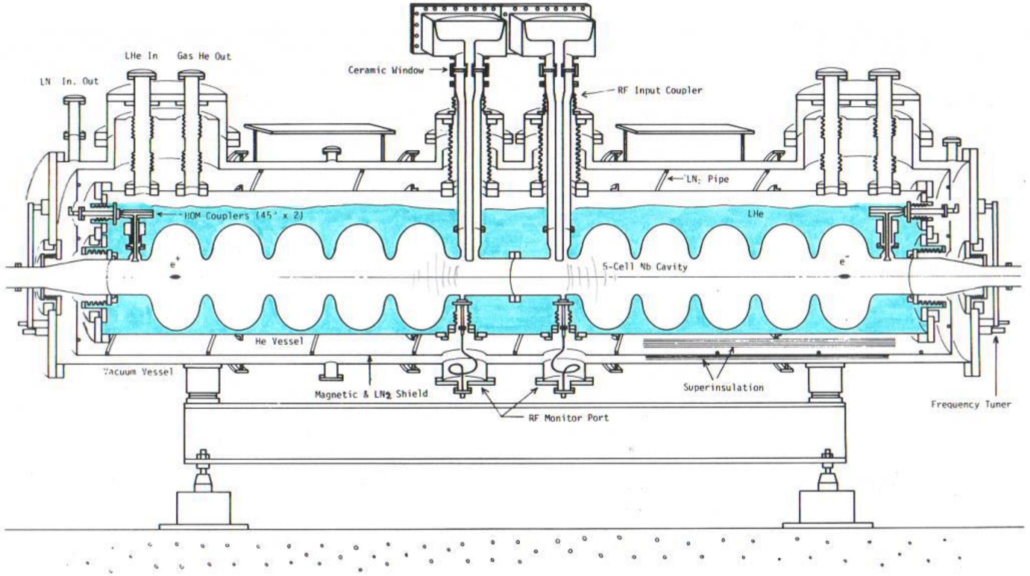


The **first mass-production** of SRF Cavities in the world

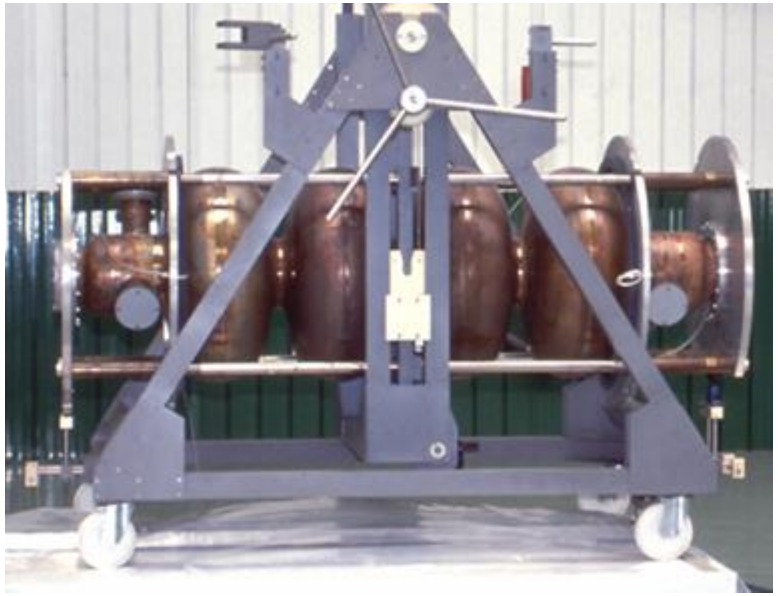
SRF Cavity **for TRISTAN** at **KEK**

Bulk-Nb - 508MHz - 5-Cell Cavity

32 SRF cavities were fabricated by Mitsubishi and operated in TRISTAN



LEP-2 Cavities for CERN in Industry



Installed Cryomodules at TESLA time

Contents

First Pulsing in 1983 by Campisi & Farcas

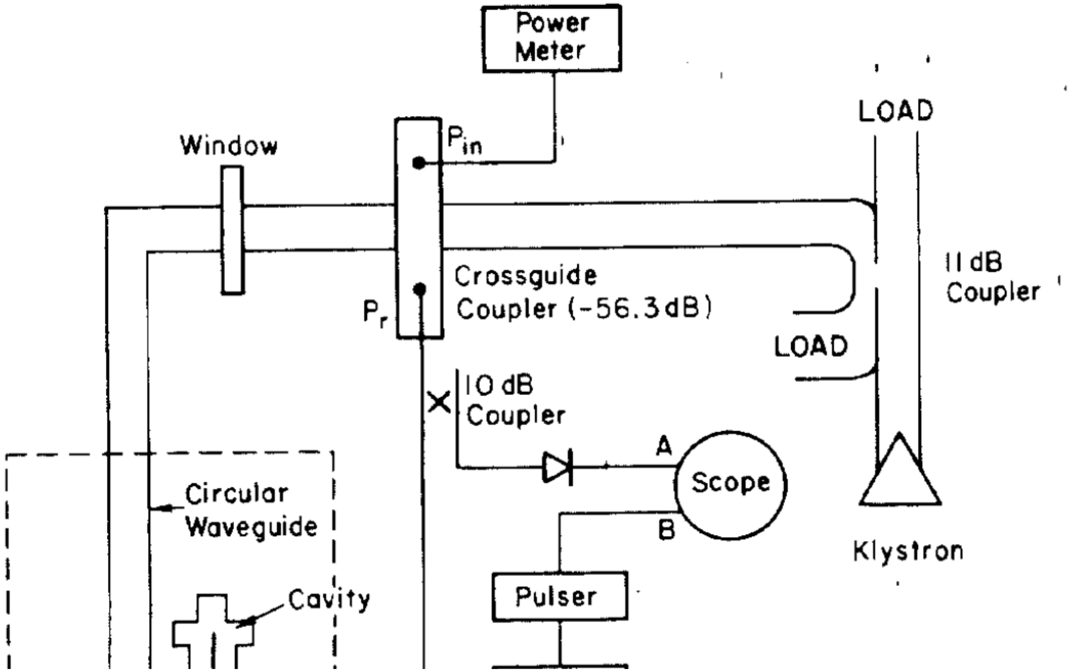
3366 IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

TRANSIENT HIGH-FIELD BEHAVIOR OF NIOBIUM SUPERCONDUCTING CAVITIES*

I. E. CAMPISI, Z. D. FARKAS, H. DERUYTER, AND H. A. HOGG
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

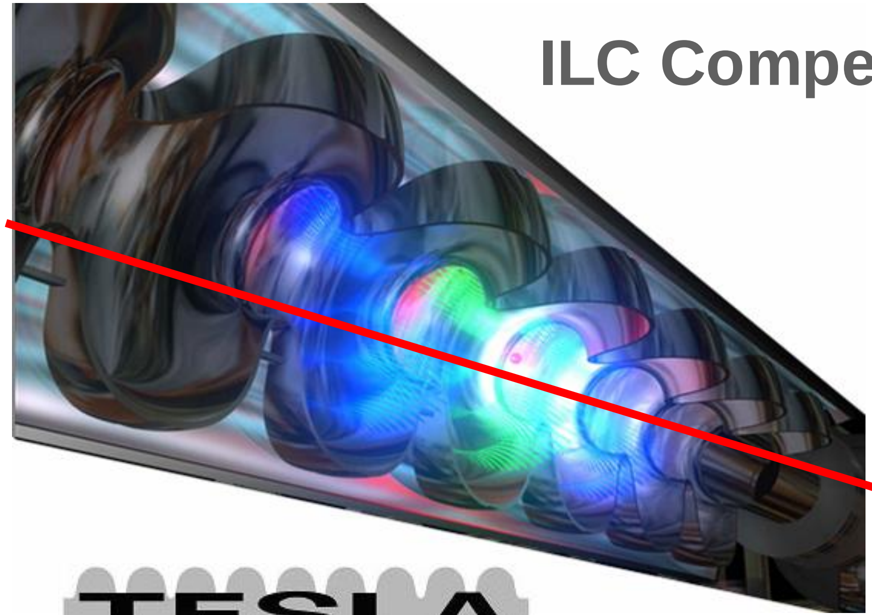
Summary

Tests have been performed on the breakdown behavior of a TM_{010} mode, S-band niobium cavity at low temperatures. Unloaded Q's of 9×10^7 at 4.2 K and of 7×10^9 at 1.35 K were measured during several tests performed using pulses long enough for the cavity to reach steady state. The breakdown field at 1.35 K was increased from 15 to 20 MV/m by processing the cavity at room temperature using 1 MW, 2.5 μs pulses. The response of the cavity at 4.2 K to 1 MW, 2.5μs pulses was also tested in several cool-downs. In these tests the cavity was heavily overcoupled to lower its time constant to a value of 0.80 times the RF pulse length of 2.5 μs. This condition maximizes the energy transfer from the klystron source to the cavity. Measurements made during these experiments clearly indicated that fields of about 50 MV/m were being reached in the cavity without breakdown.



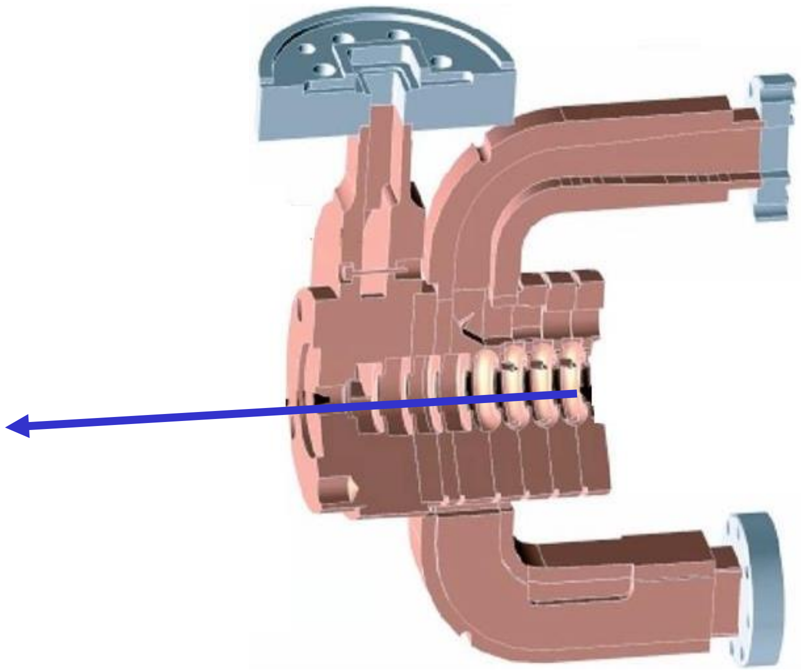
In spite of technology ILC Linacs are pulsed

ILC Competing Technologies in the nineties

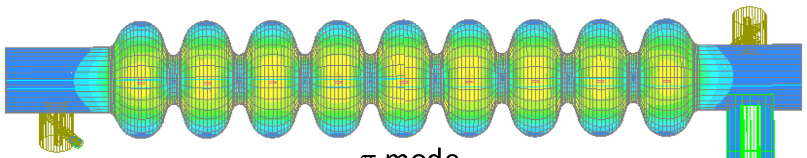


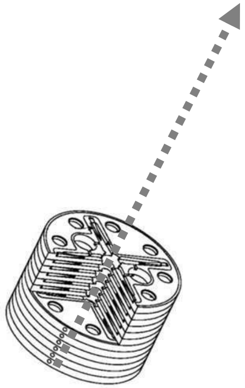
TESLA

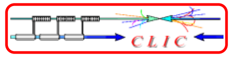
1.3 GHz - Cold



SC Standing wave

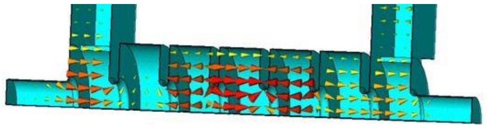






30 GHz-Warm

NC Traveling wave



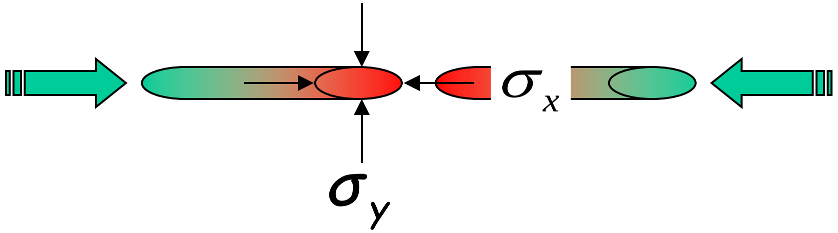
NLC

JLC

11.4 GHz - Warm

Luminosity is Proportional to Beam Power

$$L \propto \frac{N_e^2}{\sigma_x \sigma_y}$$



$$L \propto n_b \times f_{rep}$$

L = Luminosity
N_e = # of electron per bunch
$\sigma_{x,y.}$ = beam sizes at IP
IP = interaction point

$$L \propto \frac{P_b}{E_{c.m.}} \times \frac{N_e}{\sigma_x \sigma_y}$$

n_b = # of bunches per pulse
f_{rep} = pulse repetition rate
P_b = beam power
$E_{c.m.}$ = center of mass energy

Parameters to play with

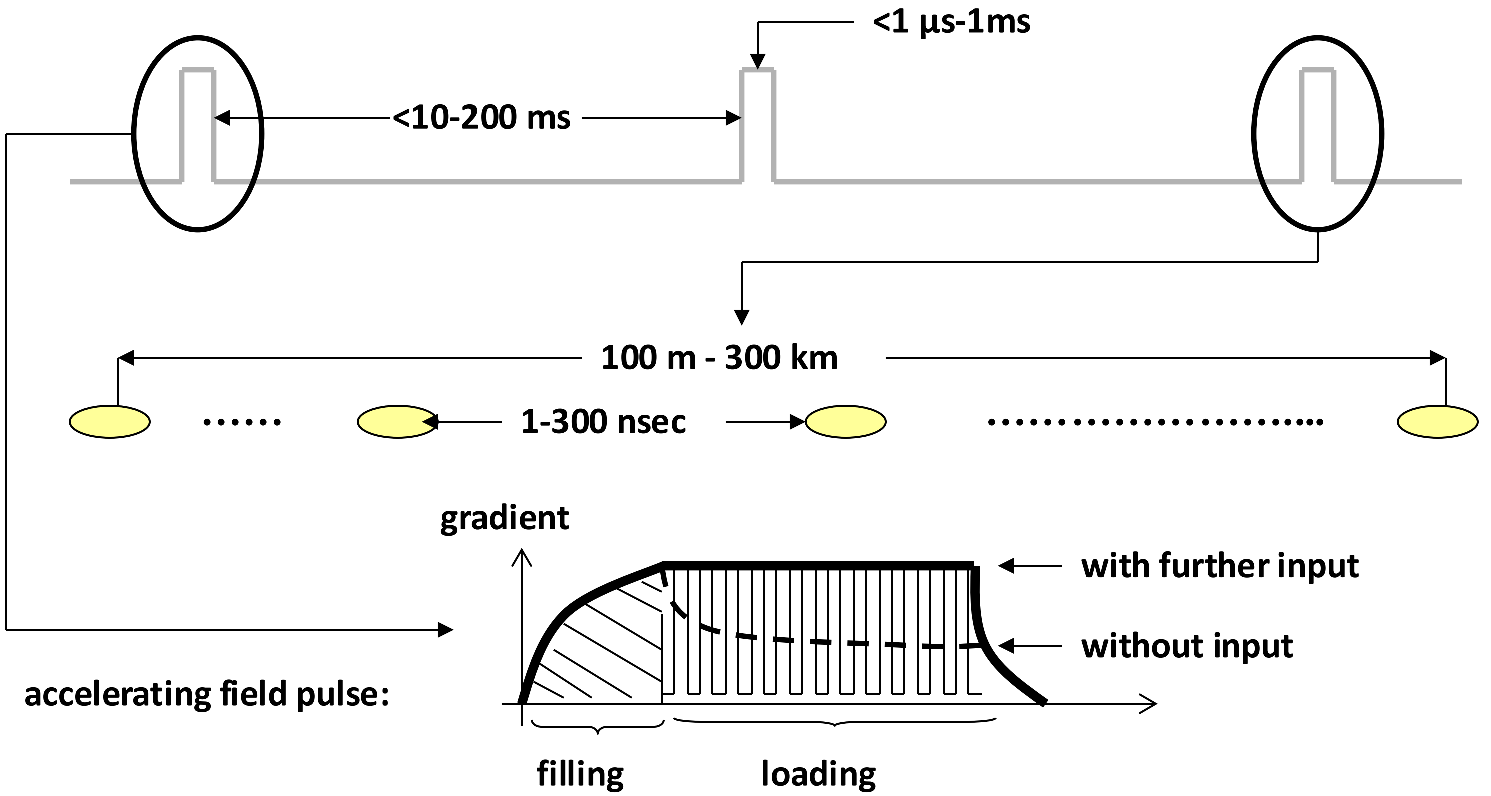
- ↓ **Reduce beam emittance ($\varepsilon_x \cdot \varepsilon_y$)** for **smaller beam size ($\sigma_x \cdot \sigma_y$)**
- ↑ **Increase bunch population (N_e)**
- ↑ **Increase beam power** $\left(P_b \propto N_e \times n_b \times f_{rep}\right)$
- ↑ **Increase beam to-plug power efficiency for cost**

Pulsed Operation for Conversion Efficiency

All the LCs must be pulsed machines to improve Plug Power to Beam Power conversion efficiency. As a result:

- duty factors are small
- pulse peak powers can be very large

C. Pagani - ISLC08 - Lecture 1
Oak Brook, October 20, 2008



TESLA Collaboration: Origin and Mission

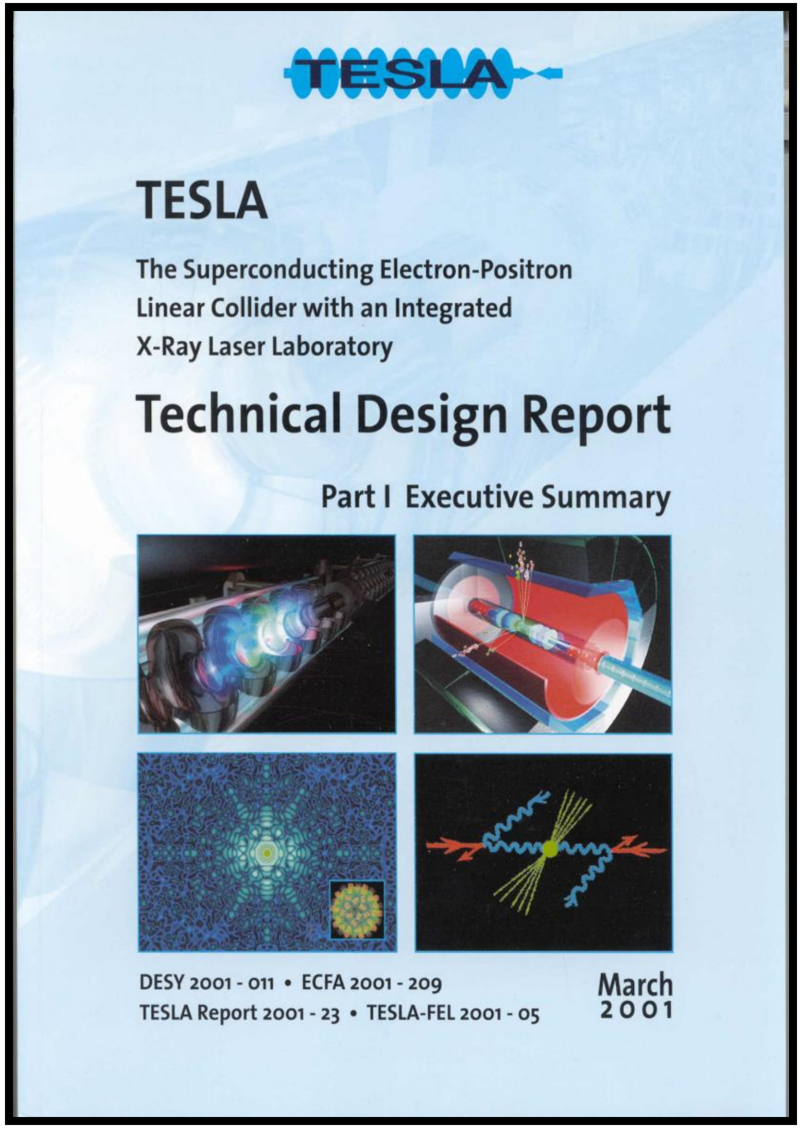
Develop SRF for a TeV Linear Collider

- **Increase gradient** by a factor of 5
- **Reduce cost per MV** by a factor 20 (New cryomodule concept and Industrialization)
- **Make possible pulsed operation**

Major advantages vs NC Technology

- **Higher conversion efficiency**: more beam power for less plug power consumption
- **Lower RF frequency**: relaxed tolerances and smaller emittance dilution

TESLA Technical Design Report: March 2001


TESLA

TESLA

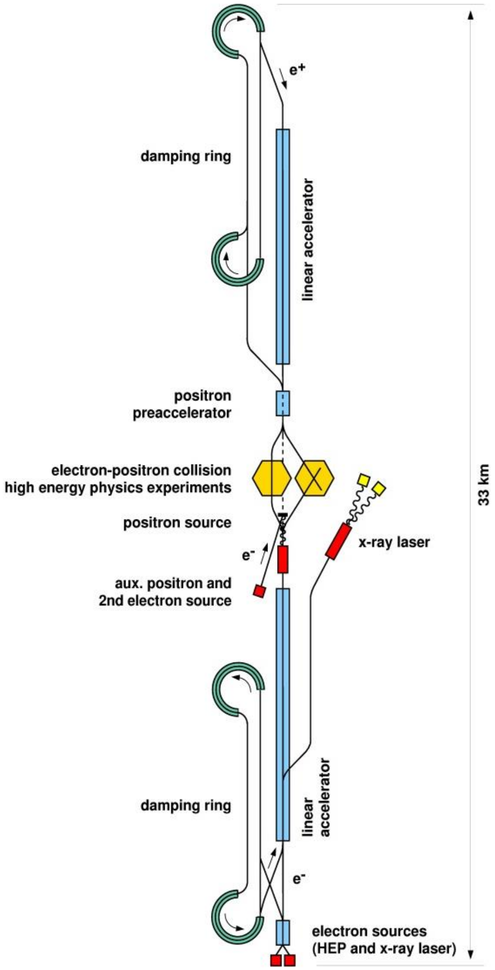
The Superconducting Electron-Positron
Linear Collider with an Integrated
X-Ray Laser Laboratory

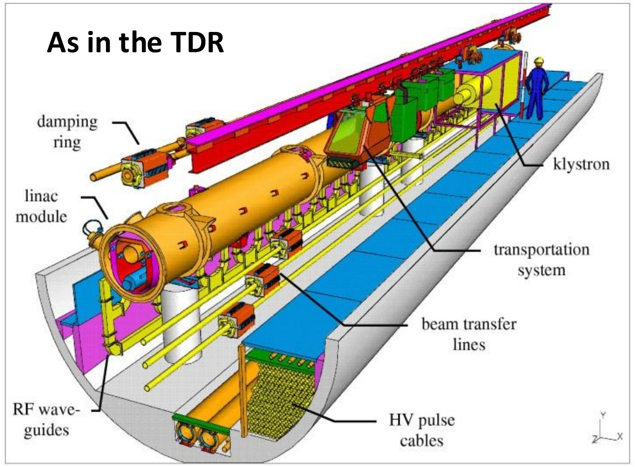
Technical Design Report

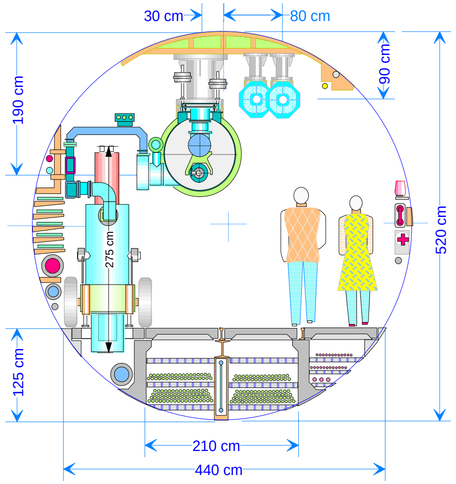
Part I Executive Summary

DESY 2001 - 011 • ECFA 2001 - 209
TESLA Report 2001 - 23 • TESLA-FEL 2001 - 05

March
2001

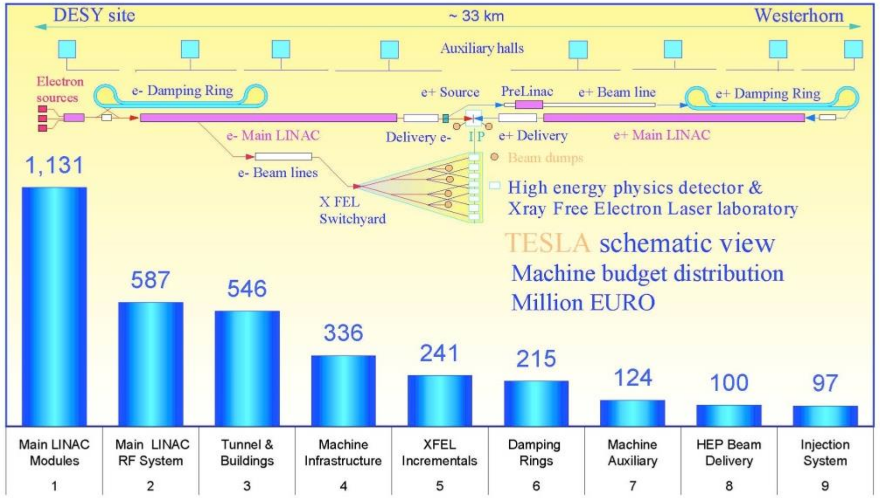


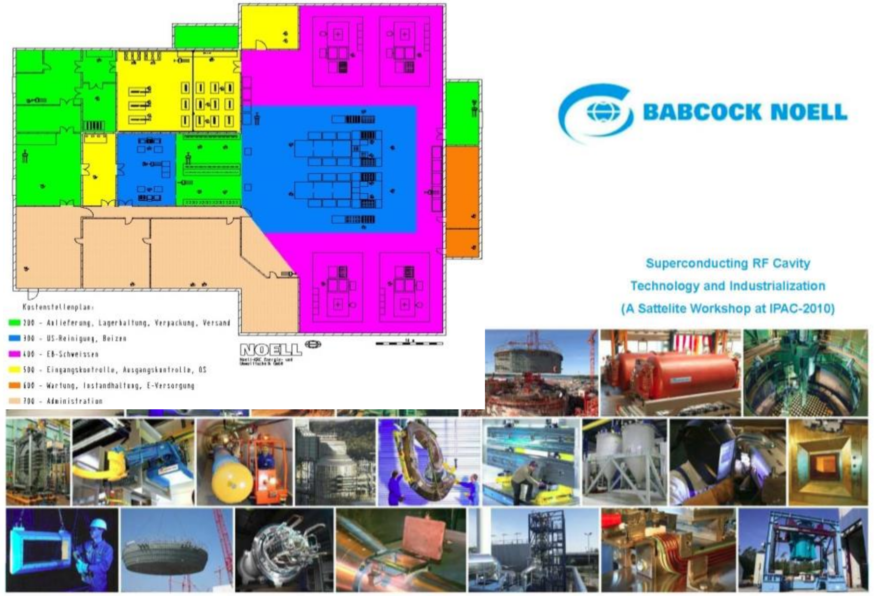


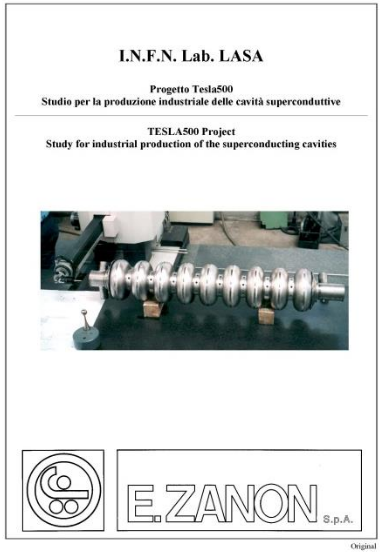


Updated tunnel cross section

Industrial Studies for TESLA TDR & E-XFEL







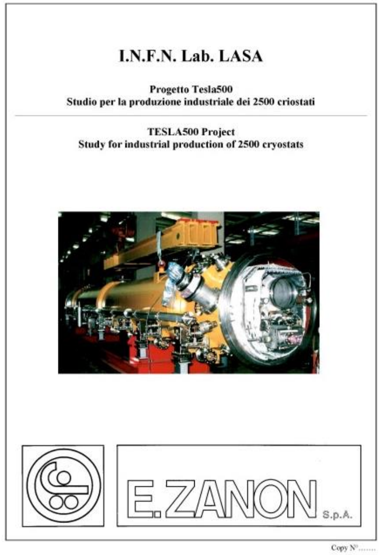
I.N.F.N. Lab. LASA

Progetto Tesla500
Studio per la produzione industriale delle cavità superconduttive

TESLA500 Project
Study for industrial production of the superconducting cavities

E.ZANON S.p.A.

Original



I.N.F.N. Lab. LASA

Progetto Tesla500
Studio per la produzione industriale dei 2500 criostati

TESLA500 Project
Study for industrial production of 2500 cryostats

E.ZANON S.p.A.

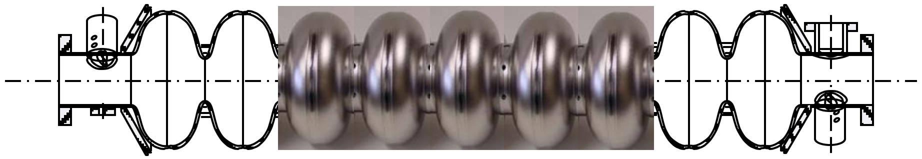
Copy N°.......

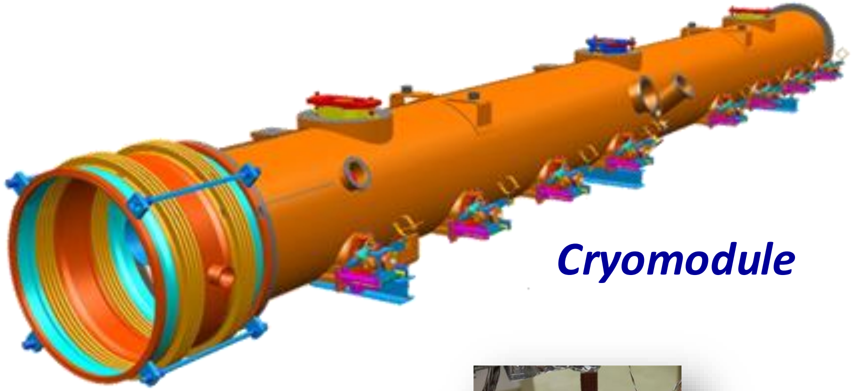
Overview on industrial studies for superconducting linacs (TESLA, XFEL, CARE), status dec.05, D.Proch

#	Subject	main issues	design	fabrication	cost	Contract	Status
1	Nb RRR 300	500 to of Nb sheet production		X	X	DESY	finished
2	Cavity fabrication	20000 cavities, welding		X	X	DESY	finished
3	Cavity fabrication	1000 cavities, welding		X	X	DESY	finished
4	Cavity fabrication	20000 cavities, hydroforming		X	X	DESY	finished
5	Cavity processing	20000 cavities, VT test, 1400°C, BCP		X	X	DESY	finished
6	Module assembly I	Assembly of 20000 cavities		X	X	DESY	finished
7	Cavity processing	Substitute BCP by EP, 1000 cavities		X	X	XFEL	in preparation
8	Module assembly II	Improvements to study 6, 1000 cavities	X	X	X	XFEL	started
9	Input coupler	improvement to TTF3 design, 1000 couplers	X	X	X	XFEL	in preparation
10	EP	Industrial aspects of EP		X	X	CARE	in preparation
11	Improvement of components	Reliability aspects of critical components	X	X		CARE	in preparation
12	Squid scanner	Principle layout, prototype	X	X		CARE	finished

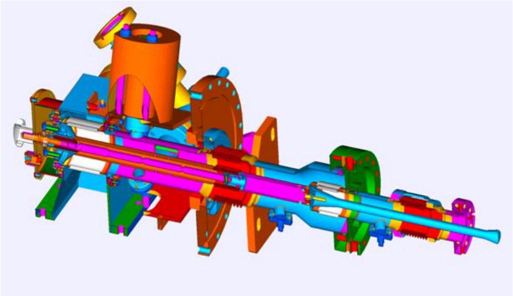
TESLA/XFEL Accelerator Components

cavities



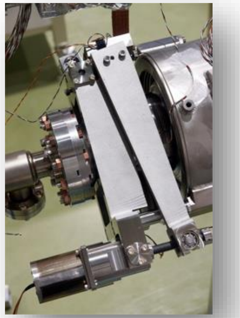


Cryomodule



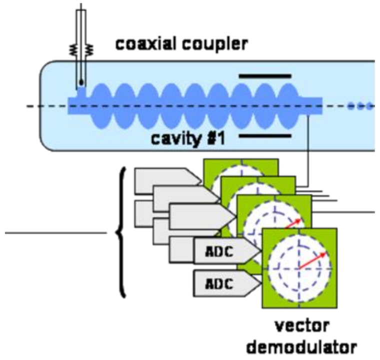
coupler

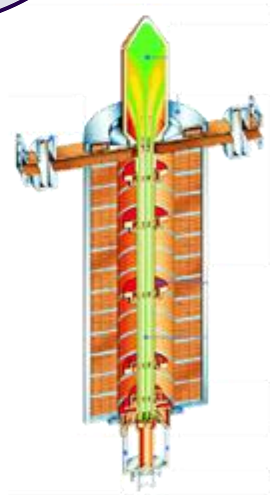
TESLA Technology



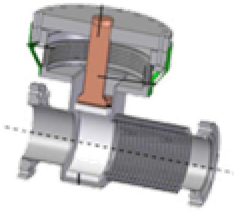
Tuners

LLRF



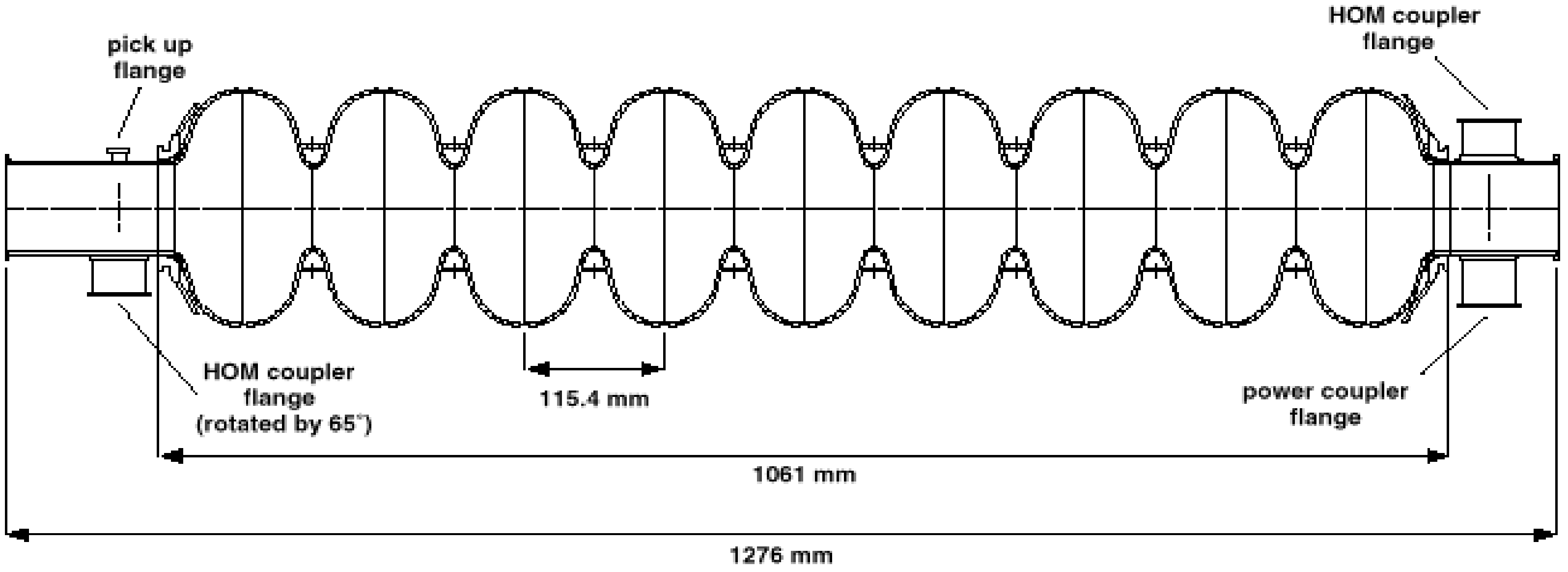


RF



HOMs

The TESLA SRF Cavity, 1.3 GHz, 9-cell



Large number of cells with minimum reasonable bore radius for FF and tuning
Odd number of cells with sligthly different end groups for trap modes

Large wall angle and round equator for surface treatments and multipatoring

2 HOM coupler to extract dangerous modes excited by the beam (1% DF)

Stiffening rings for Lorentz Forces, mechanical rigidity and eigen modes

New fabrication strategy required

Contents

1. SRF Concieved for CW Operation
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4. CW interpretation of the TESLA Technology

From Pulsed EuXFEL back to CW

Duty Factor, DF is goin from 1% to 100%

Dynamic Cryo-losses follow DF if cavity parameters stay unchanged

But dynamic cryo-losses are also:

- proportional to E_{acc}^2
- inversely proportional to Q_0

The reducttion of peak current and bunch charge require different RF sources but they are not affecting the cryo-power

- Beam current: from several mA peak to < 0.2 mA
- Buch charge, N_e : from several nC to < 0.2 nC

A new set of working parameters is needed for CW, but utilising as much as possible all the **technology already developped and qualified** in the framework of the TESLA Collaboration.

Operating EuXFEL in CW

Just changing the pulsed Klystrons with CW RF Sources and adapting coupling and control electronics, the existing EuXFEL design, based on the TESLA pulsed machine, would be modest because of a few bottle neck:

- Limited installed cryo-power
- Cryo-strings of 12 cryomodules served by a JT valve (240 W limit)
- Insufficient HOM cooling

Eacc < 7 MV/m   < 6 GeV with ca. 100 Cryomodules

Building a new machine with a larger cryo-plant, the TESLA design can perform much better thank to a few simple adjustment addressed to overcome the major bottle neck while mantaining all the key technologies.

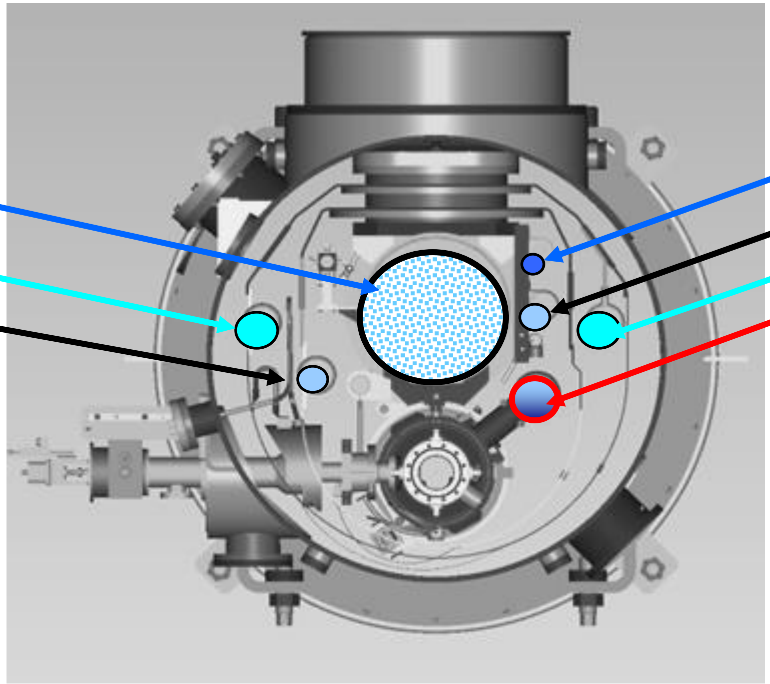
Eacc > 16 MV/m   > 8 GeV with ca. 70 Cryomodules

Limitations of the actual XFEL Module - 1

The XFEL main linac consists out of 7 cryo strings,

every string includes 12 cryo modules,

every cryo module contains 8 cavities.



2-phase tube:
240 W (20 W/cryomodule) is the estimated limit for one cryo string.

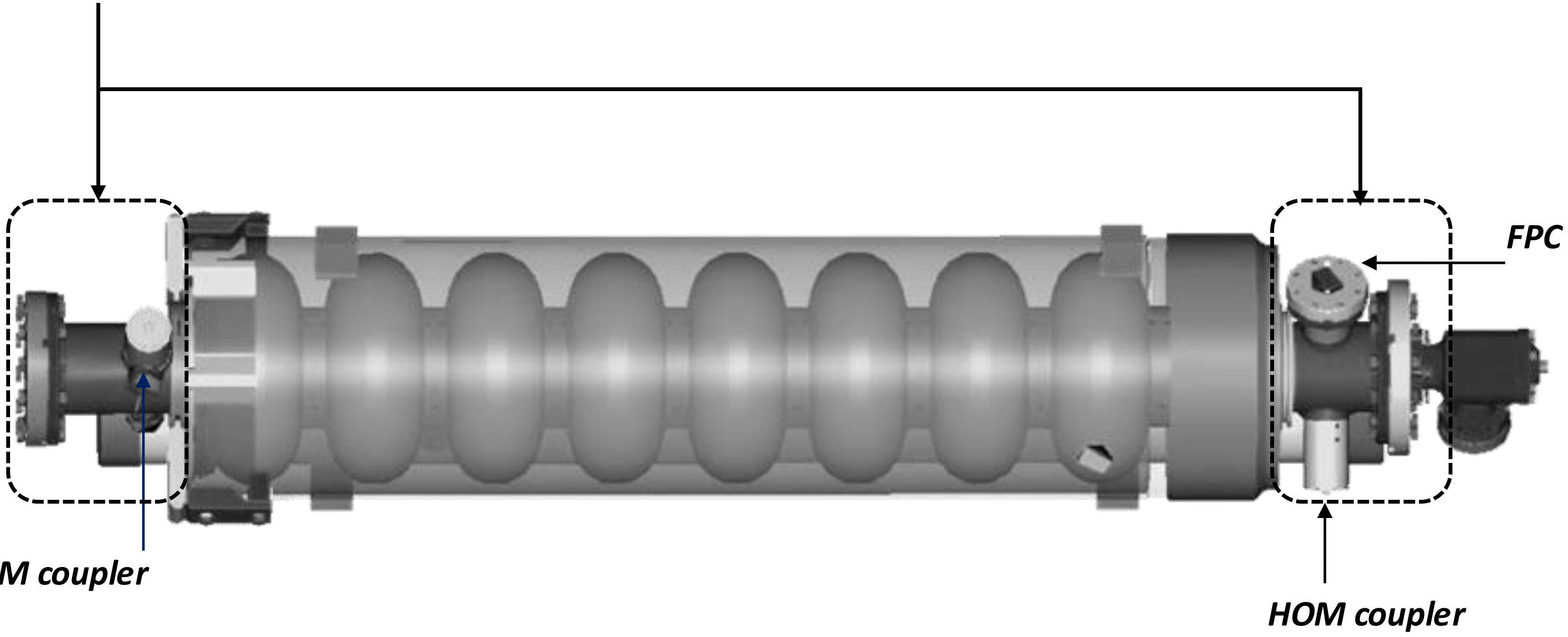
Heat load at 2K for each cryomodule must not exceed 20 W.

W.- D. Möller, J. Sekutowicz|

Limitations of the actual XFEL Module - 2

Each cryomodule houses 8 cavities

- Cavity was designed for ca. **1% DF.**
- End groups (FPC and HOM couplers) are **cooled by means of heat conduction.**

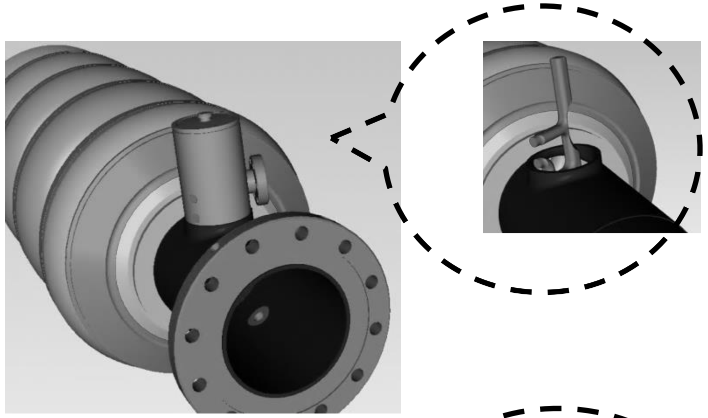


Dissipation on the HOM coupler antennas is the main sources of the heat for the end groups.

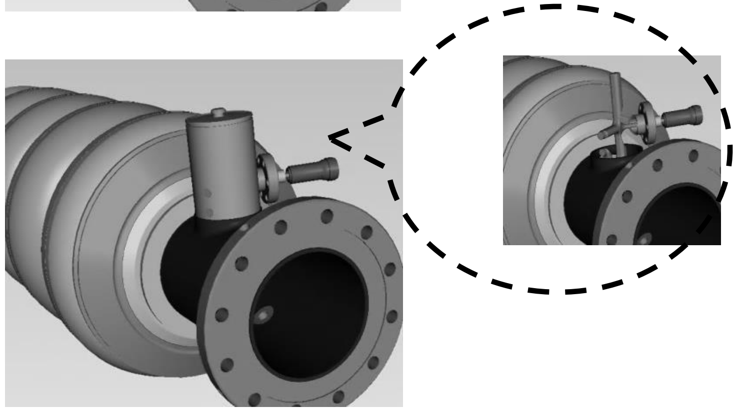
W.- D. Möller, J. Sekutowicz|

Limitations of the actual XFEL Module - 3

Experience with vertical tests (cavities immersed in the superfluid bath):



Without HOM antennae:
E_{acc} up to 45 MV/m in the CW mode



With HOM antennae:
E_{acc} up to 13 MV/m in the CW mode

Heating of the HOM couplers must not lead to quenching of the end-cells.

W.- D. Möller, J. Sekutowicz|

A few guidelines for TESLA based CW XFELs

- **Don't tuch the cavity design** and fabrication metodology
- Improve surface treatment for **higher Q_0** (lower surface resisstance, R_s)
- **Mantain the ancillaries** (power couipler, tuner, etc) whenever possiblle
- **Re-design cryogenic distribution** to allow higher heat load at 2 K.
  - 1 JT valve per module, i.e. up to > 20 W/cavity
  - Slightly increase the size of the 2 phase pipes accordingly
- **Implement touls needed for high Q_0**:
  - Implement magnetic hygiene around the cavities
  - Improuve 2 K distribution for fast cool-down
- **Suppress the lower part of the 5 K schield** not needed for CW operation
- Remember that a **50% marging** is normally added in all cryogenic plants

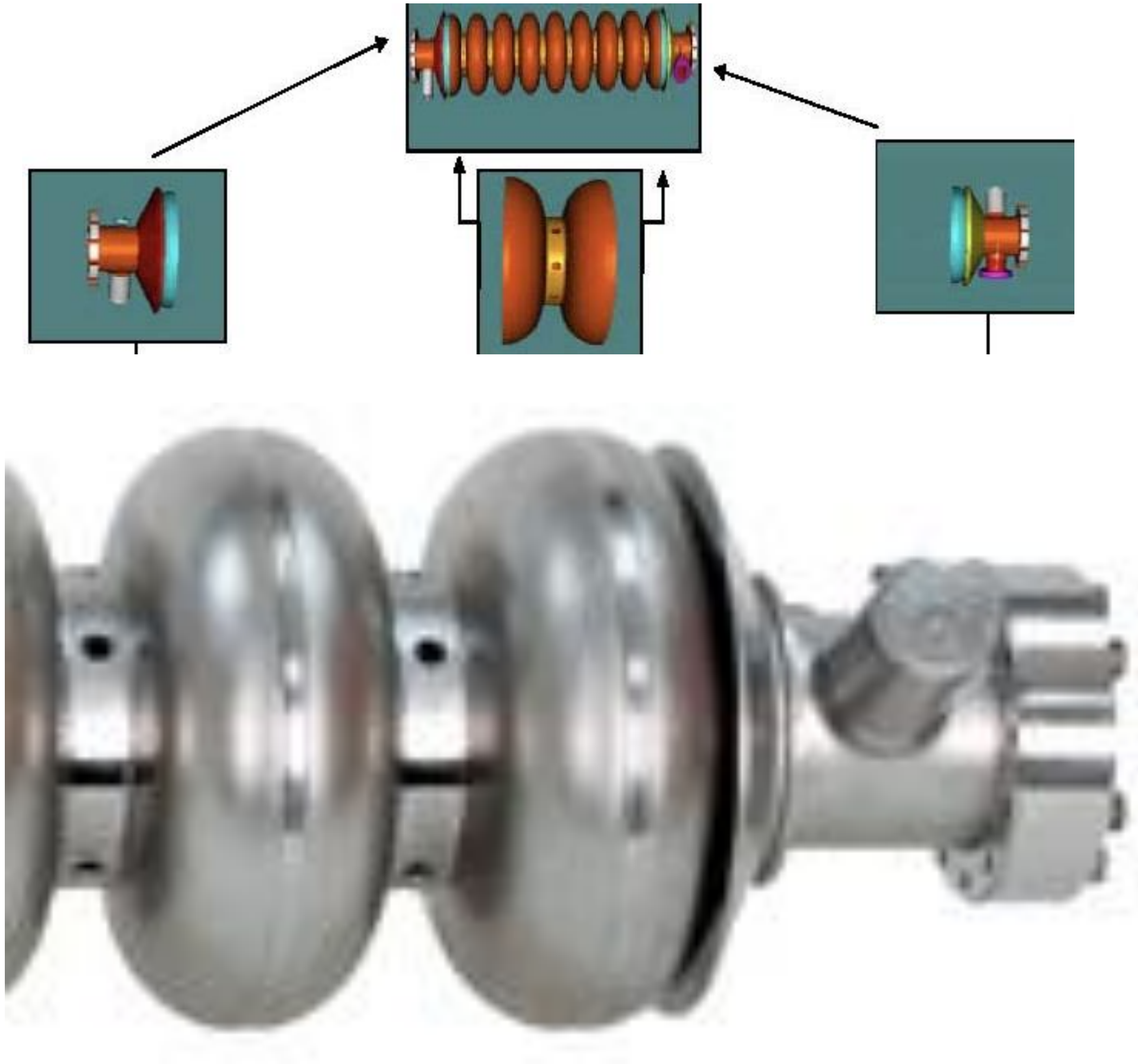
Contents

TESLA / E-XFEL 1.3 GHz cavity

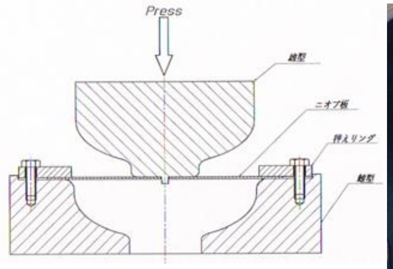
- Pulsed RF up to 10 Hz repetition rate.
  - 1.4 ms RF pulse length
- Longitudinal stiffness at about 3 kN/mm
- Required coarse tuner sensitivity at 1 Hz/step level
- Long piezo stacks required to provide LFD compensation.
  - 500-600 Hz detuning expected
  - About 2 μm stroke at the cavity

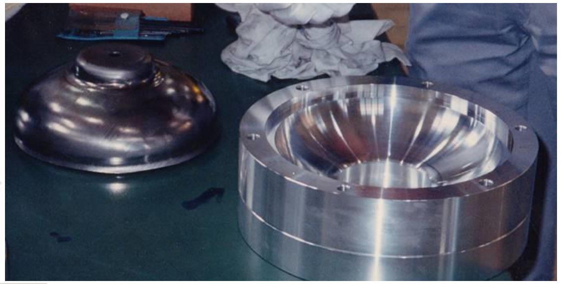
		XFEL
Type of accelerating structure		standing wave
Accelerating mode		TM010, π-mode
Fundamental frequency	f_{RF} [MHz]	1300
Nominal gradient	E_{acc} [MV/m]	23.6
Quality factor	Q_0	> 10^{10}
Active length	L [m]	1.038
Cell-to-cell coupling	k_{cc} [%]	1.87
Iris diameter	[mm]	70
R/Q	[Ω]	1036
E_{peak}/E_{acc}		2.0
B_{peak}/E_{acc}	[mT/MV/m]	4.26
Tuning range	[kHz]	± 300
$\Delta f/\Delta L$	[kHz/mm]	315
Lorentz-force detuning constant	K_{Lor} [Hz/(MV/m)^2]	1
Q_{ext} of input coupler		4.6×10^6
Cavity bandwidth f/Q_{ext}	[Hz] FWHM	283
Fill time	[μs]	780
Number of HOM couplers		2

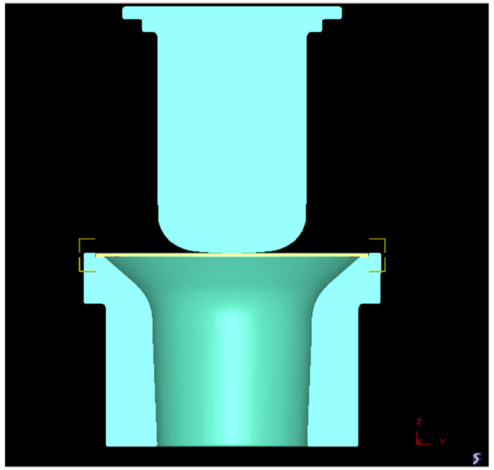
Dumb-bells & Stiffening Rings



Cavity Fabrication Steps

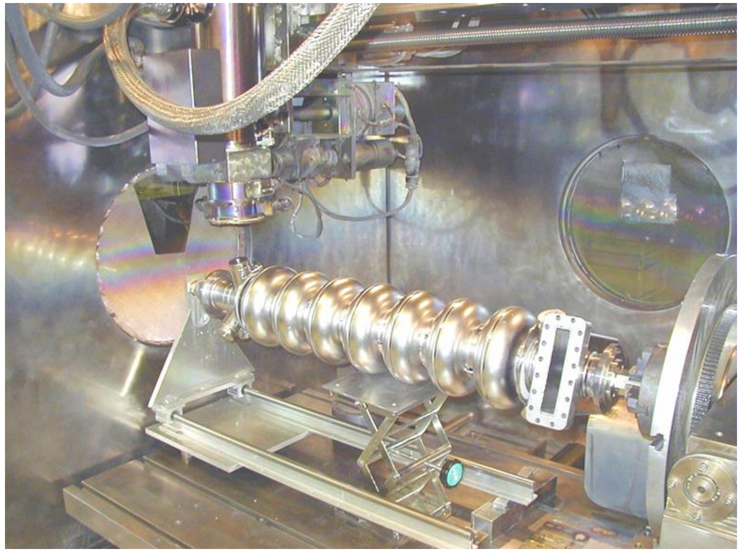






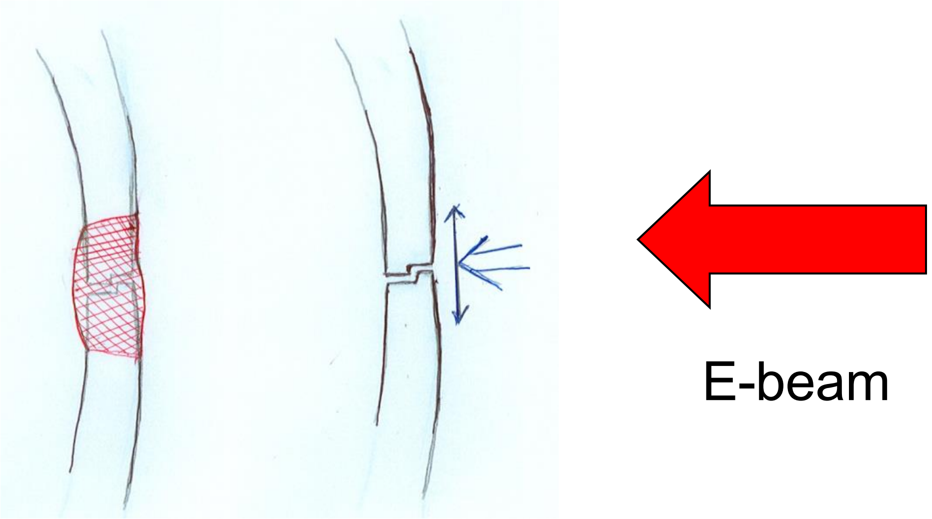
Half cells are shaped by **deep drawing**.

Dumb bells are assemled **by EB welding.**

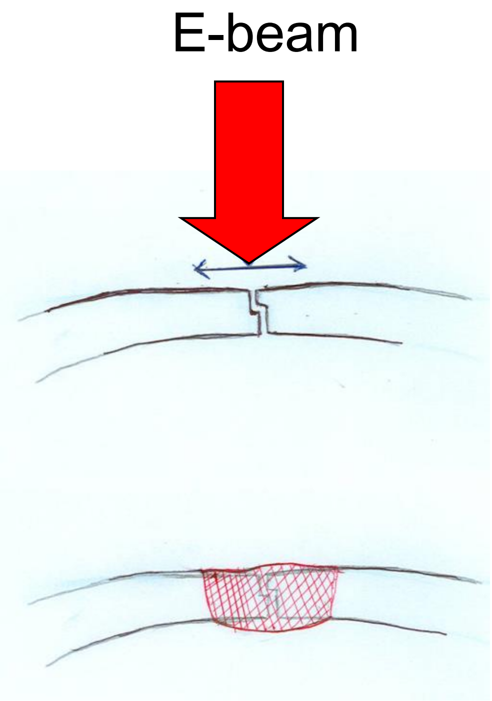


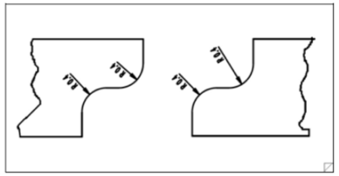
After proper cleaning eight dumb bells and two end group sections welded by EBW together

Different EBW Strategies

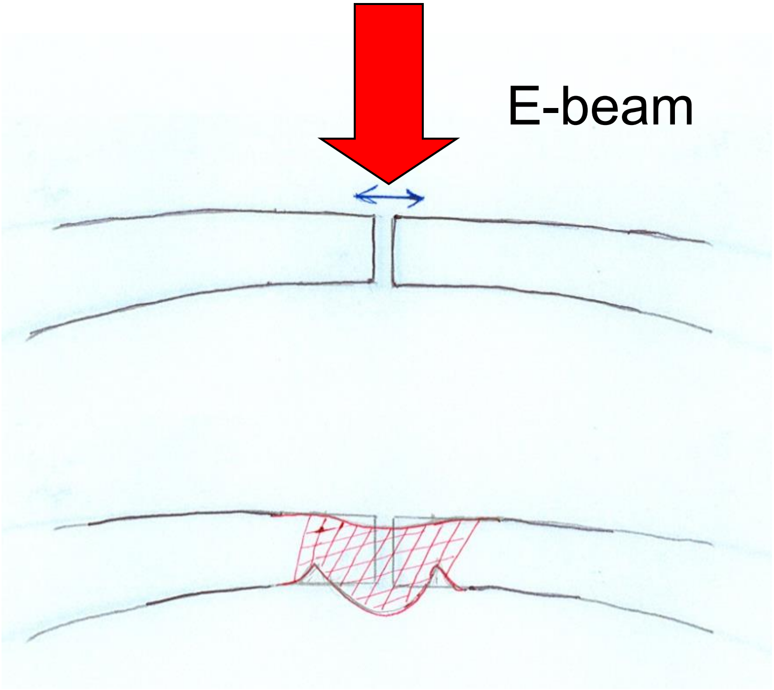


Vert. Pos. EBW: lap joint (recess)
e.g. RI, CERCA, Sciaky





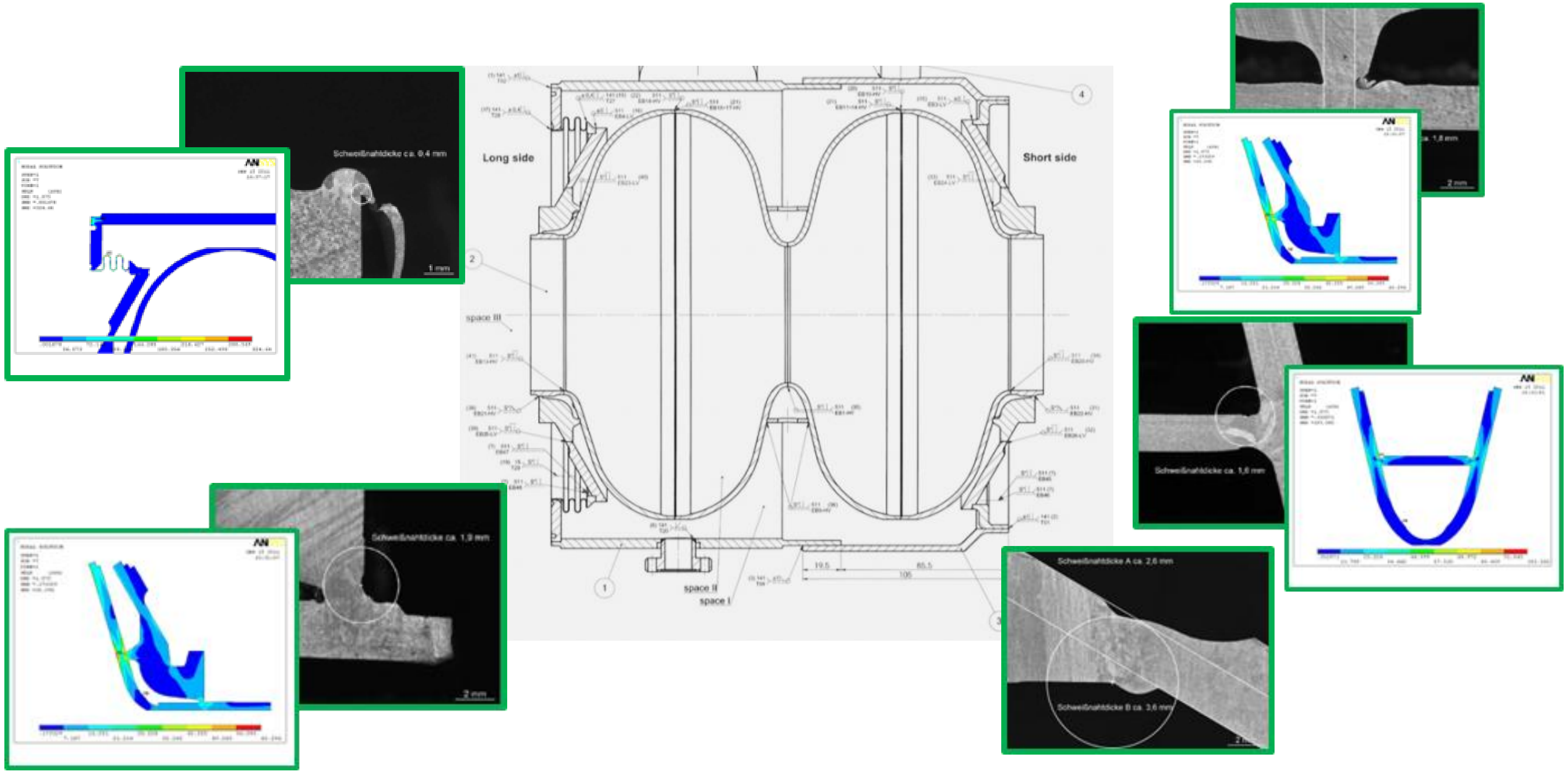
Horiz. Pos. EBW: lap joint (recess) DESY, AES, E.Zanon



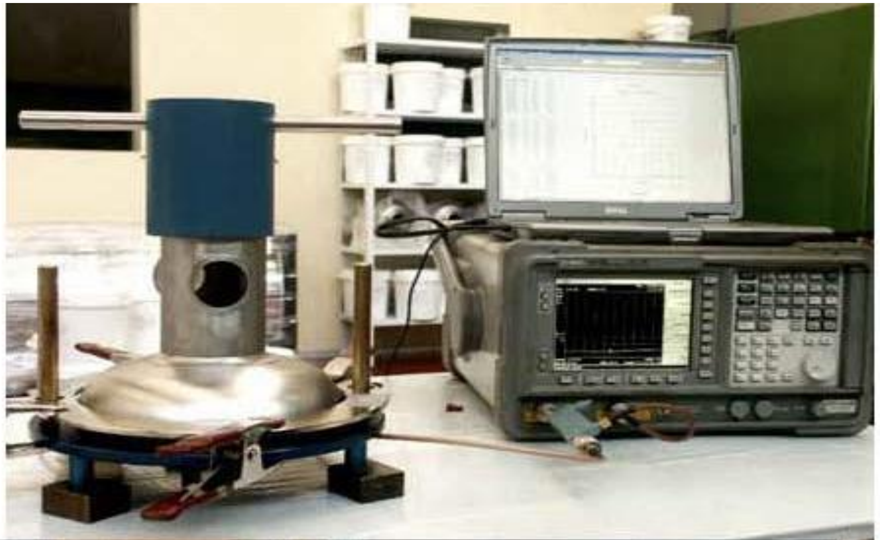
EBW: butt joint (e.g. JLab, PAVAC)

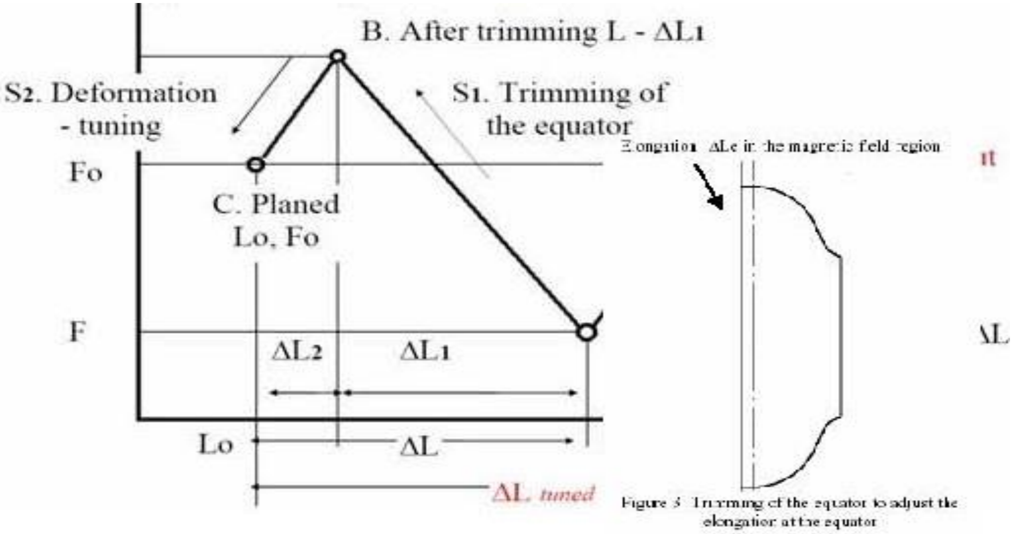
Test Pieces for PAD Qualification

Test piece (TP) is composed by 2 cell with helium vessel, representing all pressure bearing parts and welding seams. It is built using the same welding parameters that will be used in the series production. Two EBW machines/company. Consequently, two test pieces had been built per company.

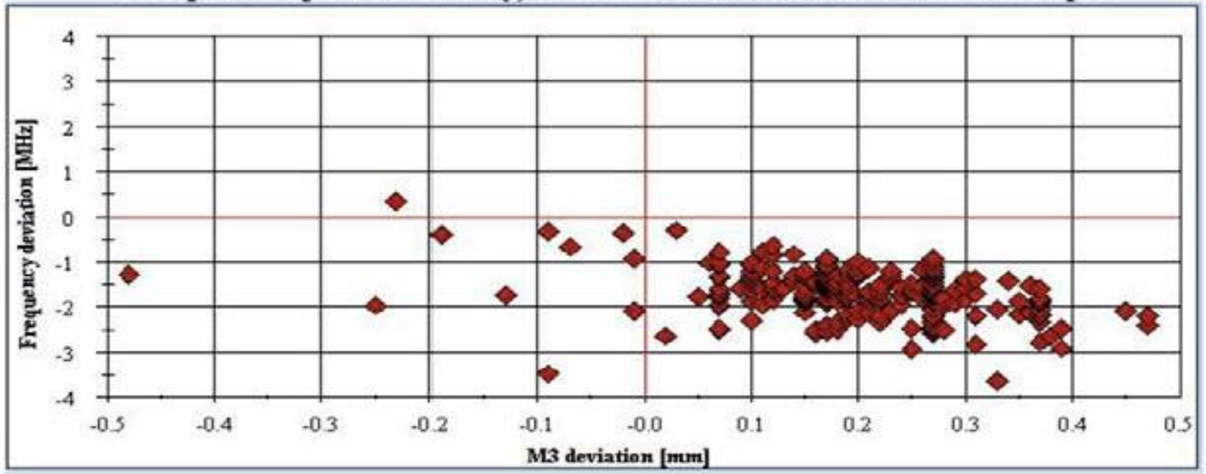


Intermediate Steps for Frequency and Length





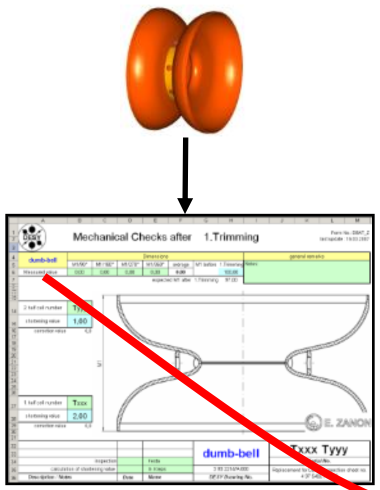
Frequency and length deviation of middle cups



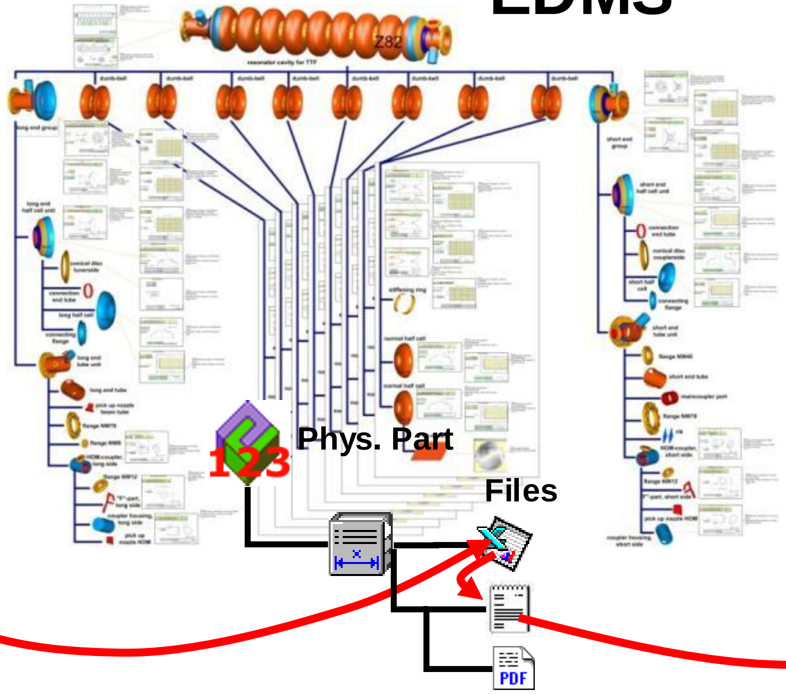
Wah Chang (EDMS-DB)

EDMS for Storing Data and Communication

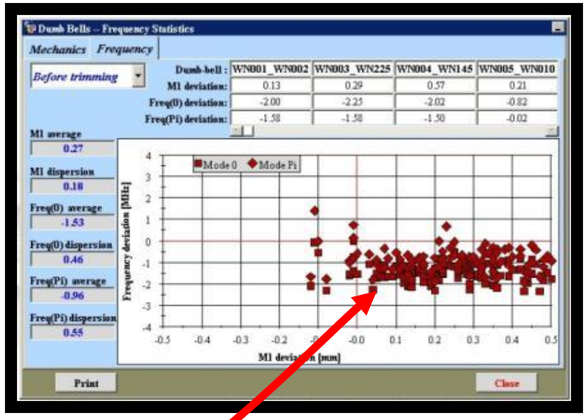
Fabrication



EDMS



Cavity-DB



Inspection sheets for quality management

Fabrication structure.
Subassembly parts related.
Procedure related

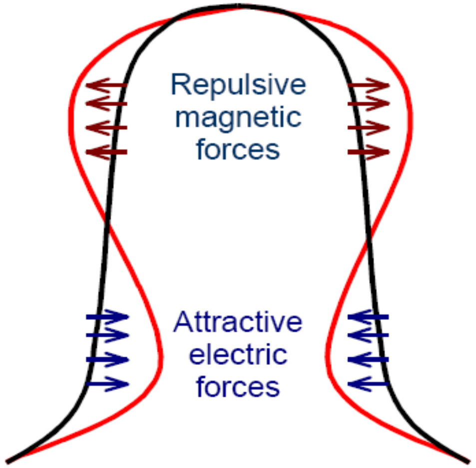
Statistical analysis

All XFEL SC cavity documents (specifications, protocols, PED data etc.) recorded in EDMS. RI and E. Zanon have an access (to relevant data only)

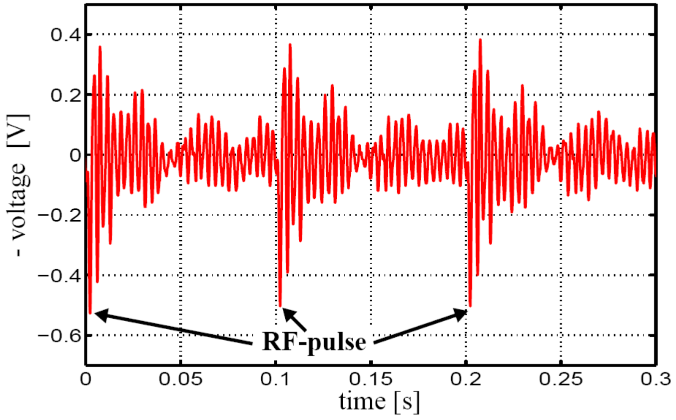
Sources of dynamic detuning, Pulsed & CW

The Lorentz force detuning, LFD

- **Lorentz force** on shielding currents on cavity walls induced by electromagnetic fields, equivalent to **EM radiation pressure**.
- **μm level** complex deformation of the cavity shape
- Detuning amplitude **scales as E_{acc}^2**, forward power instead as E_{acc}^4!
- Depends on both cavity stiffness and on external stiffness
- **Time-varying** for pulsed operations
- **Repetitive**, synchronous to RF pulses

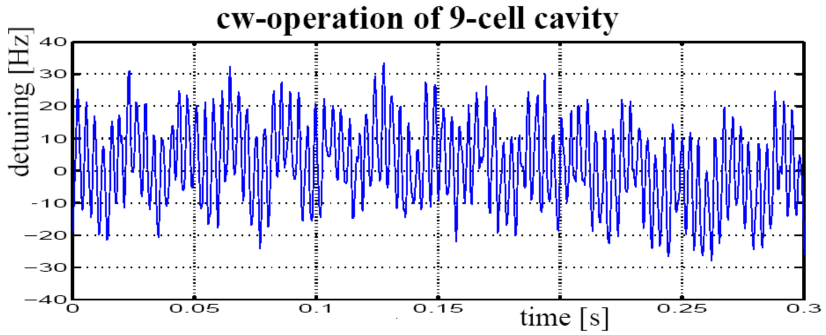


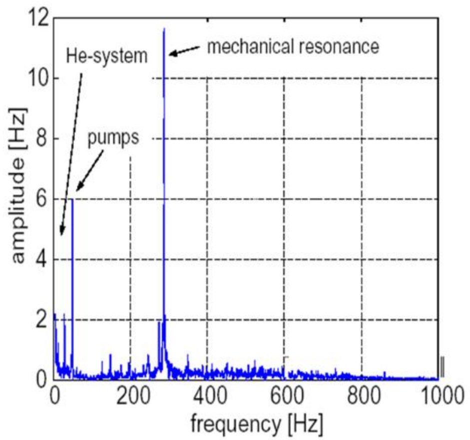
$$P_R = \frac{1}{4}(\mu_0|\mathbf{H}|^2 - \varepsilon_0|\mathbf{E}|^2)$$



Microphonics, MP – Crucial for CW

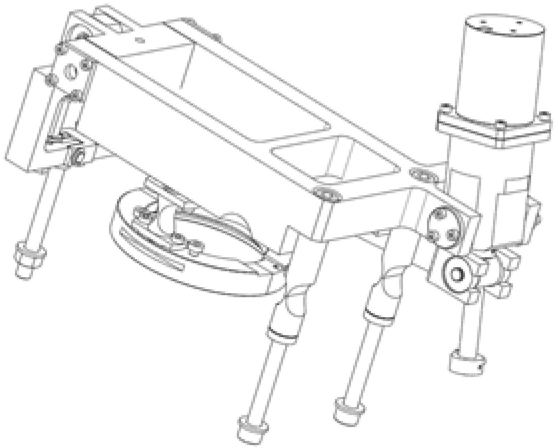
- **Stochastic**, strongly correlated to He bath pressure fluctuations
- **Low amplitude**, about 30 Hz rms
- Main harmonics coming from the **cryomodule environment** are contributing:, typically pumps and any other vibrating element

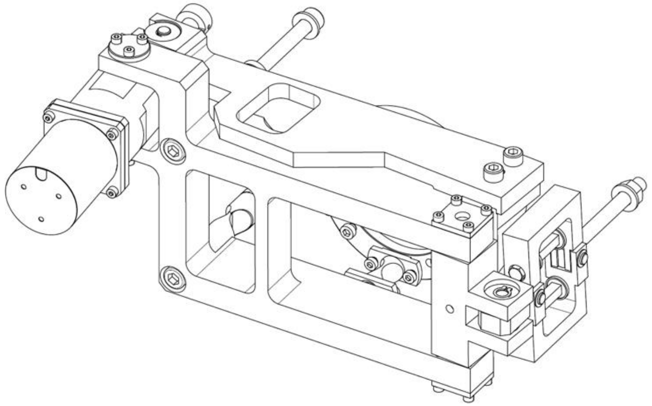


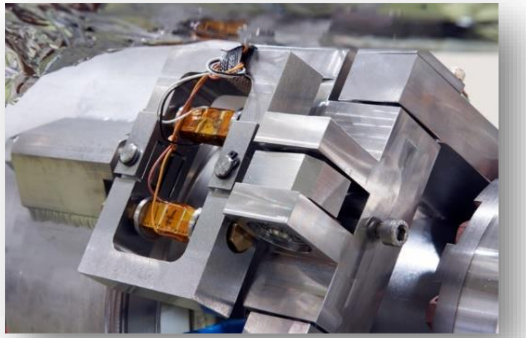


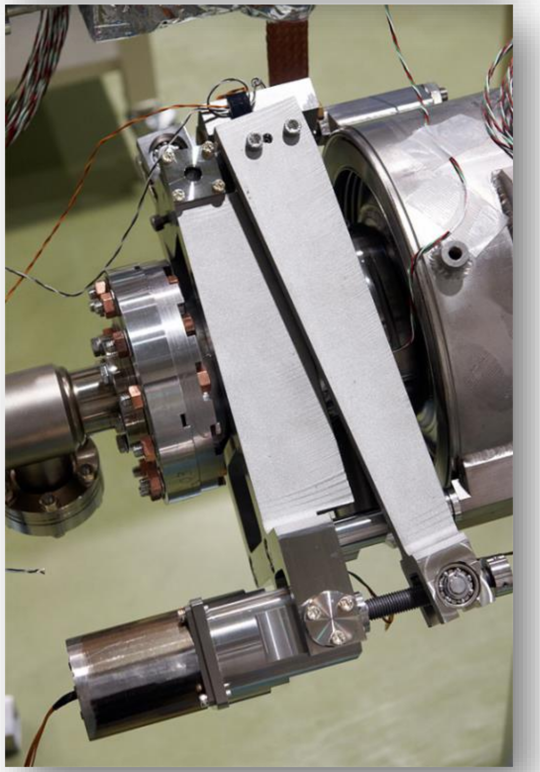
E-XFEL Piezo assisted Tuner, OK for CW

- Double asymmetric leverage
  - lateral on the tank, on pick-up side
  - Modified at DESY from the original CEA Saclay design
  - Modified after TTF at DESY, now cavity is stretched by the tuner: cavity spring force is added to piezo preload
- Cold stepper motor drive unit
  - Harmonic Drive reduction gear
  - Screw-nut coupling to generate the linear motion
- Cold piezo actuators
  - Two stacks in a single preloading frame, to gain redundancy and also to profit of the spare one as a mechanical sensor





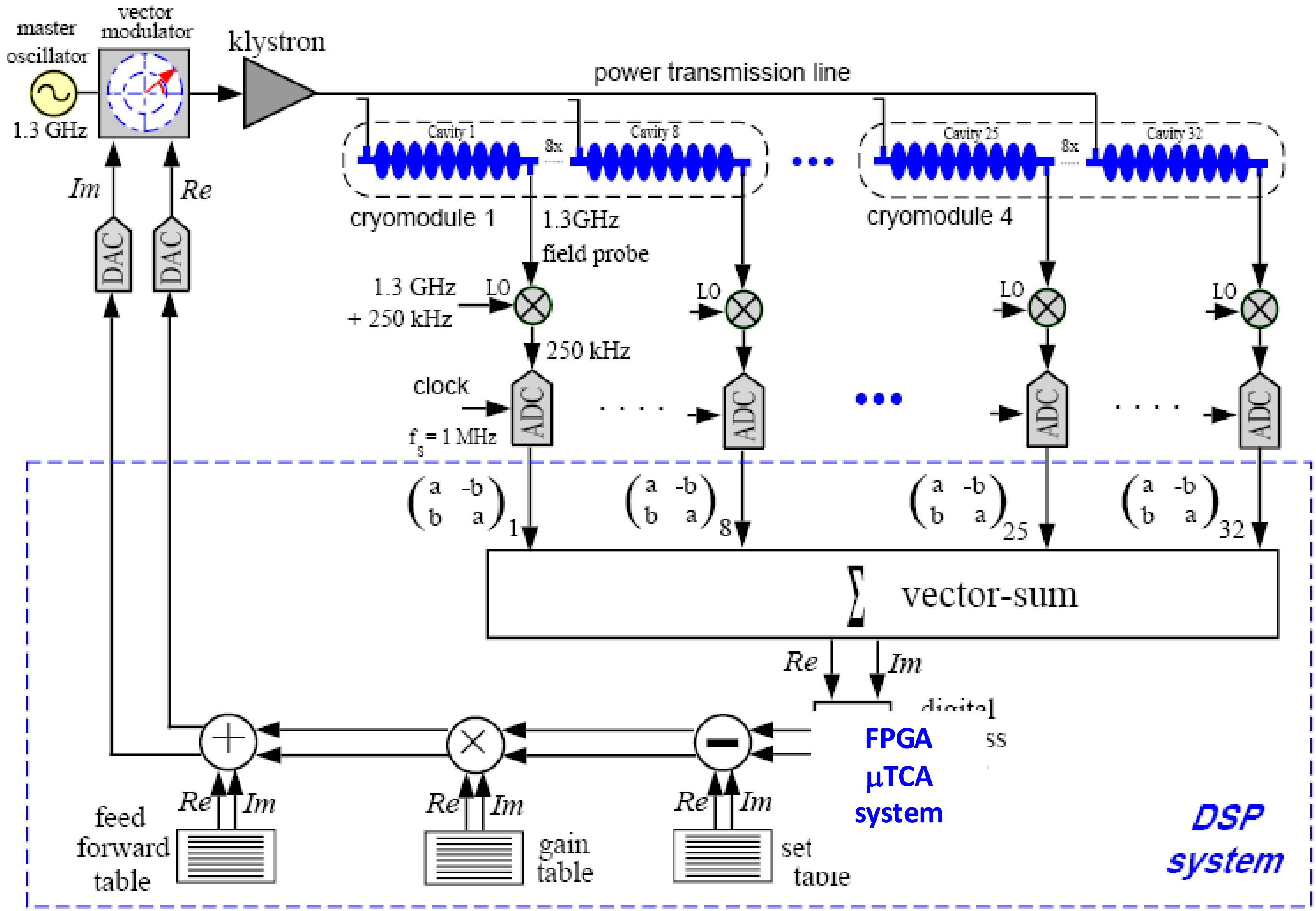




LLRF Based on Vector-sum not for CW

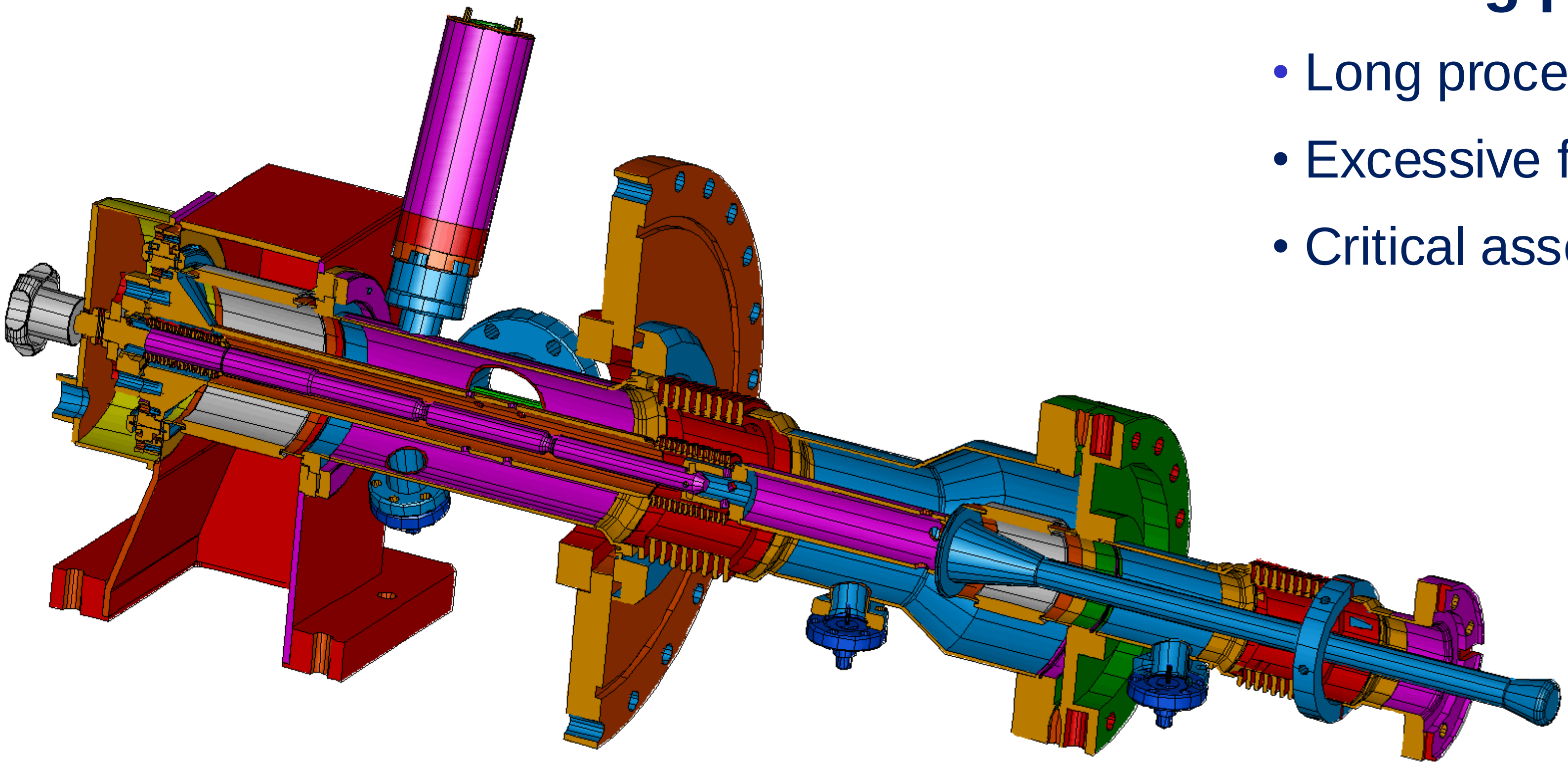
A single RF sorce feeding multiple cavities is possible also for CW, but because of the moderate power of few kW required for each cavity, **independent SSA sources are usually preferred**

Conversely
The possible E-XFEL upgrade to CW would use **the vector-sum scheme with one IOT per module**



Power Coupler is OK but can be simplified

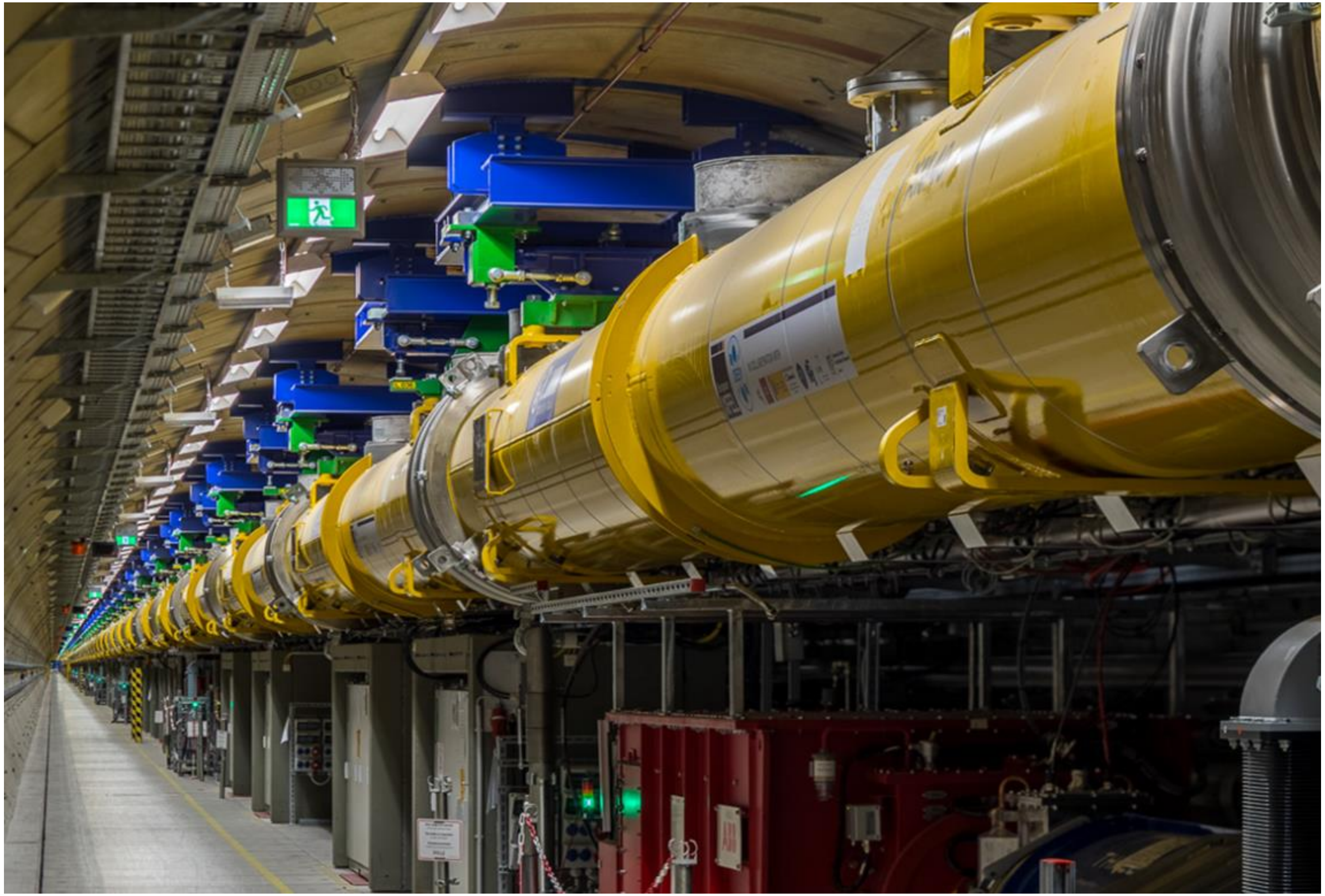
- TTF III Coupler has a robust and reliable design
- Succesfully installed in the European XFEL



Pending problems

- Long processing time: ~ 100 h
- Excessive flexibility and High cost
- Critical assembly procedure

Very Robust Cryomodule Design



TESLA →XFEL→ILC module design criteria

High filling factor

- maximize real estate gradient/cavity gradient
  - long cryomodules/cryo-units, short connections

Moderate cost per unit length

- simple design, based on reliable technologies
- low static heat losses in operation

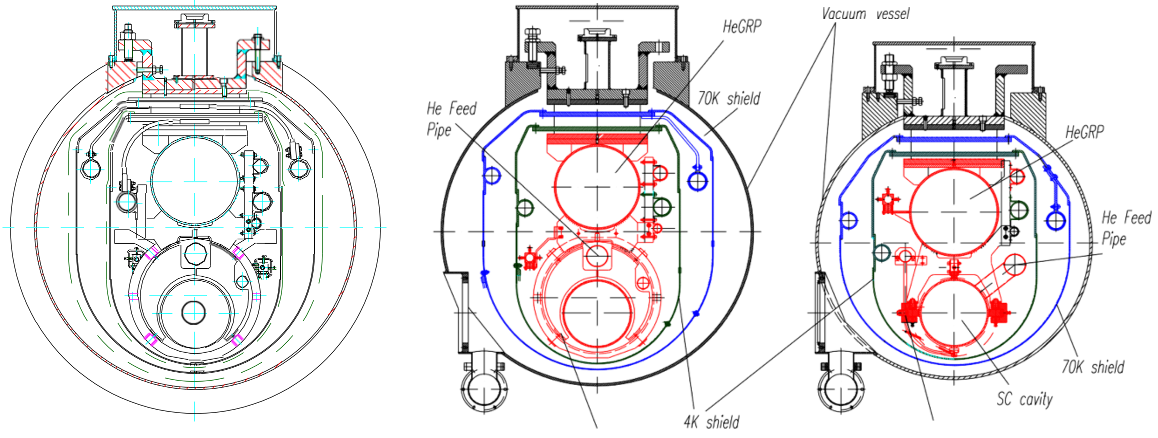
Effective cold mass alignment strategy

- room temperature alignment preserved at cold

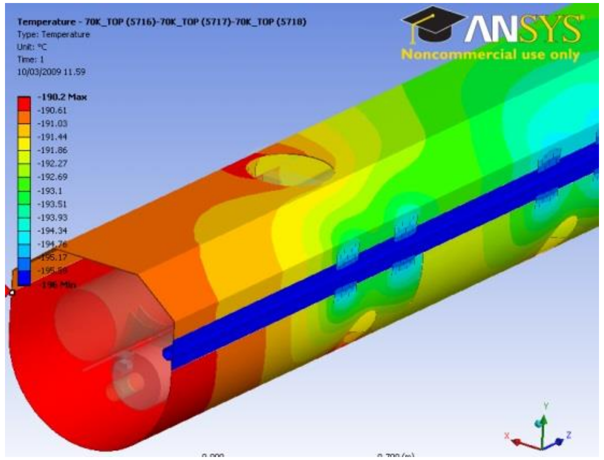
Effective/reproducible assembling procedure

- clean room assembly just for the cavity string
- minimize time consuming operations (cost /reliability)

Cry 1 | Cry 2 | Cry 3



1st Module in TTF I | Module 1 & 2 in TTF I, Module 1, 2 & 3 in TTF II | Module 4 & 5 in TTF II

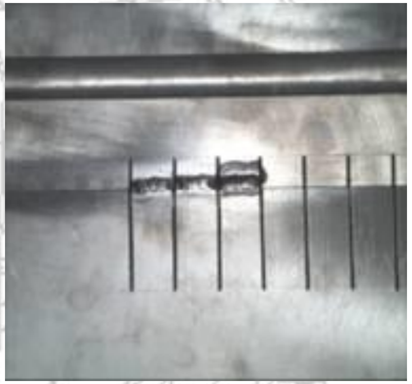


Cryomodule & Assembly as Crucial as Cavity

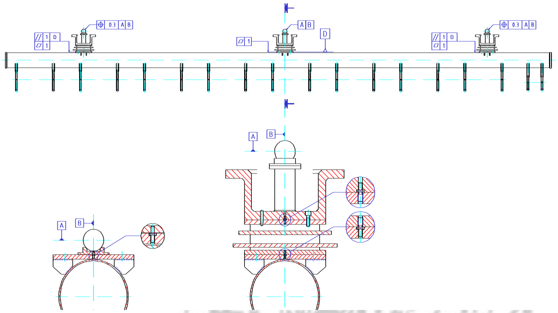
Three cryomodule generations to:

- improve simplicity and performances
- ensure precise alignment
- minimize the cost

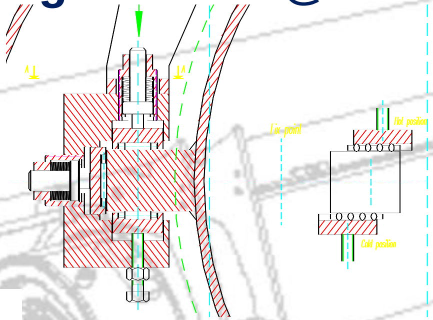
"Finger Welded" Shields



Reliable Alignment Strategy

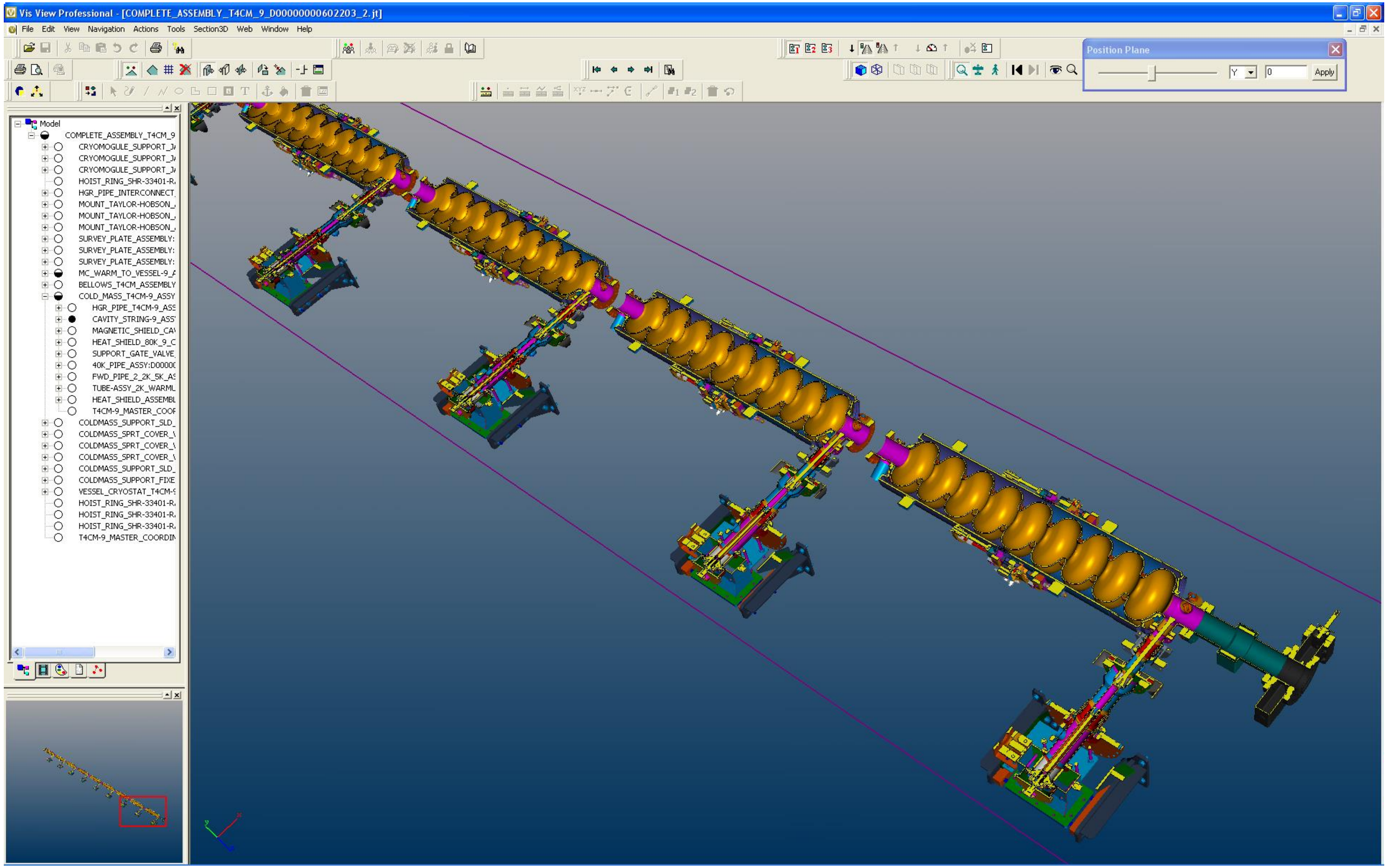


Sliding Fixtures @ 2 K



Required plug power for static losses < 5 kW / (12 m module)

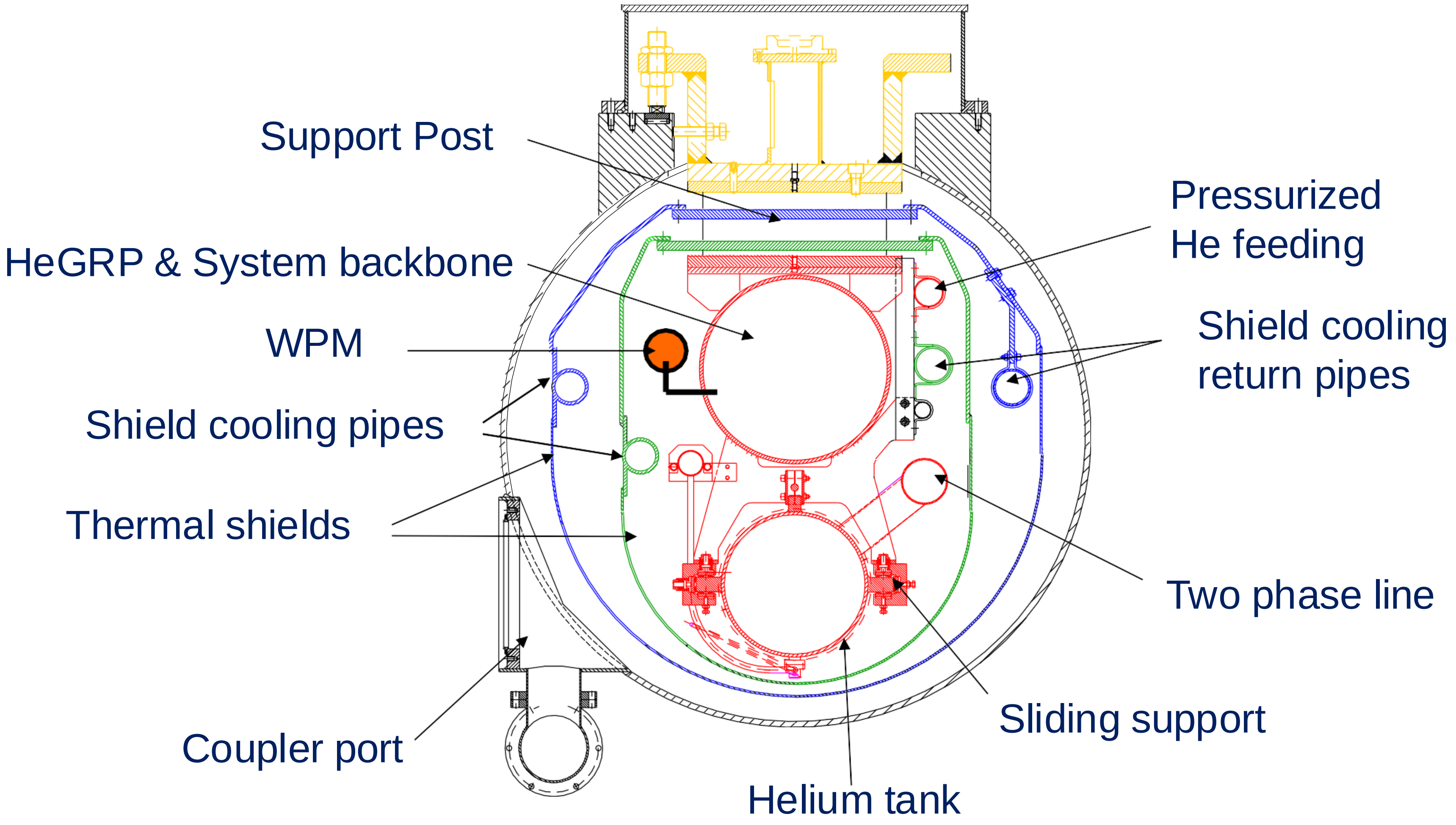
The INFN Cryomodule for XFEL & ILC



TTF Cryomodule Performances

						Status:15-Sep-04 R.Lange -MKS1-				
Designed, estimated and measured static Cryo-Loads TTF-Modules in TTF-Linac										
Module	40/80 K [W]			4.3K [W]			2 K [W]			Notes
Name/Type	Design	Estim.	Meas.	Design	Estim.	Meas.	Design	Estim.	Meas.	
Capture			46,8			3,9			5,5	Special
Module 1 I	115.0	76.8	90.0 *	21.0	13,9	23.0 *	4,2	2,8	6,0 *	Open holes in isolation
Modul1 rep. I	115.0	76.8	81,5	21.0	13,9	15,9	4,2	2,8	5,0	2 end-caps
Modul 2 II	115.0	76.8	77,9	21.0	13,9	13.0	4,2	2,8	4,0	2 end-caps
Module 3 II	115.0	76.8	72.0 **	21.0	13,9	48.0 **	4,2	2,8	5,0 *	Iso-vac 1E-04 mb, 2e-caps
Module 1* II	115.0	76.8	73.0	21.0	13,9	13.0	4,2	2,8	<3.5	1 end-cap
Module 4 III	115.0	76.8	74	21.0	13,9	13.5	4,2	2,8	<3.5	1 end-cap
Module 5 III	115.0	76.8	74	21.0	13,9	13.0	4,2	2,8	<3.5	1 end-cap
Module SS	115.0	~76.8	72.0	~21.0	~13.9	12.0	~4.2	>2,8	4,5	Special, 2 end-caps
Module 3* II	115.0	76.8	75	21.0	13,9	14	4,2	2,8	<3.5	1 end-cap
Module 2* II	115.0	76.8	74	21.0	13,9	14,5	4,2	2,8	<4,5	2 end-caps
Module 6 EP	Type III, EP-Cavities Goal:Solution close to XFEL Modules									(Assembly End-04??)
	Design and estimated values by Tom Petersen 1995 -Fermilab-							Modules under Test in TTF2-Linac		

EuXFEL Cross Section - Pulsed



Some of the TESLA/XFEL specific features

Pulsed operation

- High field dominant wrt minimum losses
- Lorentz force detuning impact the cavity design
- Active fast tuner required for high field
- High peak power coupler for high current

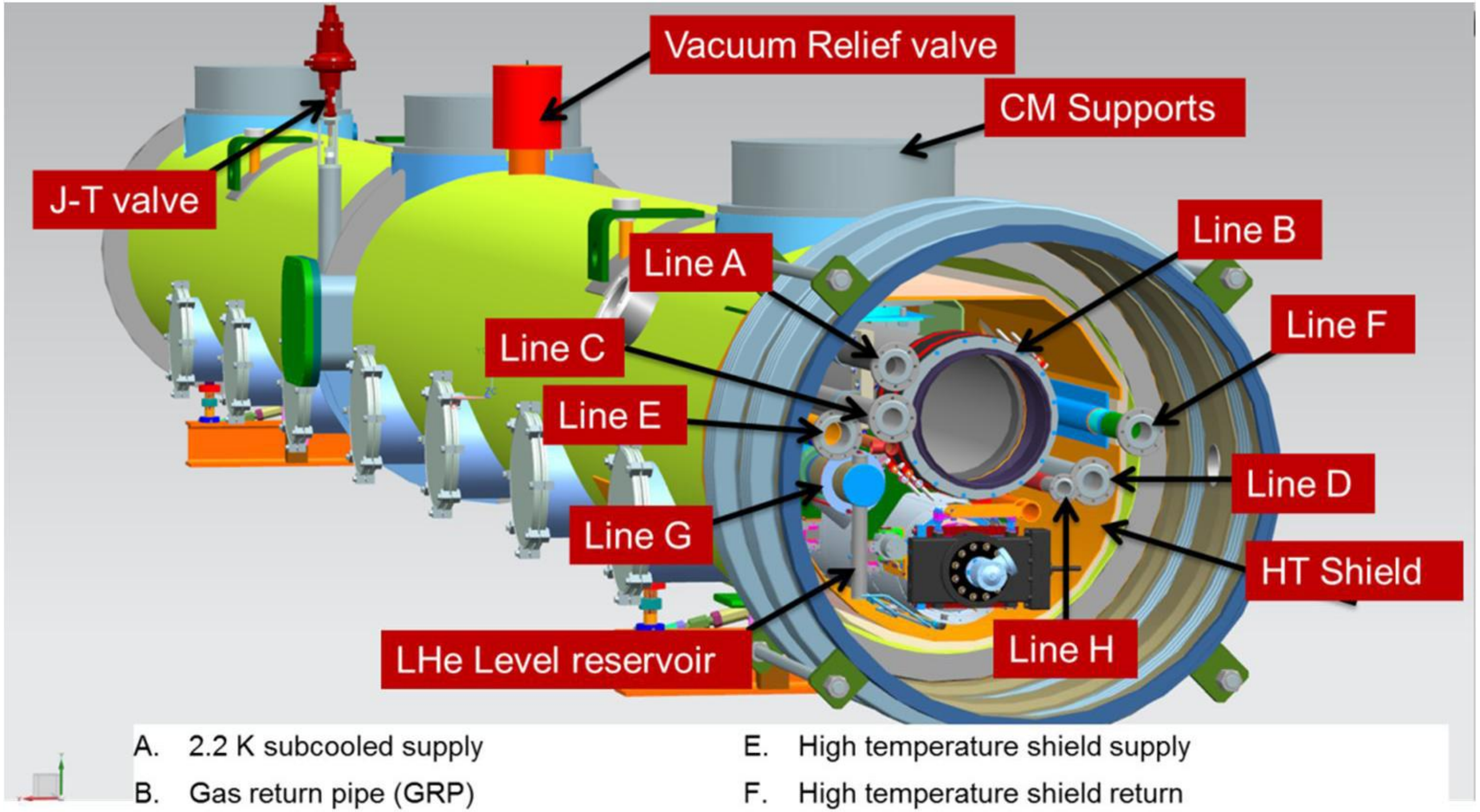
CW operation for XFELs (low average current)

- High Q, low losses, dominant wrt maximum field
- Microphonics can be crucial
- Active fast tuner considered for low current
- High average power coupler for high current

Other TESLA/ILC dependent features

- Very high filling factor : interconnections, tuner, magnets, etc
- Very low static losses : long cryo-strings

LCLS-II: TESLA Cryomodule adapted to CW



A. 2.2 K subcooled supply
B. Gas return pipe (GRP)
C. Low temperature intercept supply
D. Low temperature intercept return
E. High temperature shield supply
F. High temperature shield return
G. 2-phase pipe
H. Warm-up/cool-down line

LCLS-II Director's Review, August 19-21, 2014

J.N. Galayda @ Linac2014

LCLS-II Cavity in its titanum He Vessel

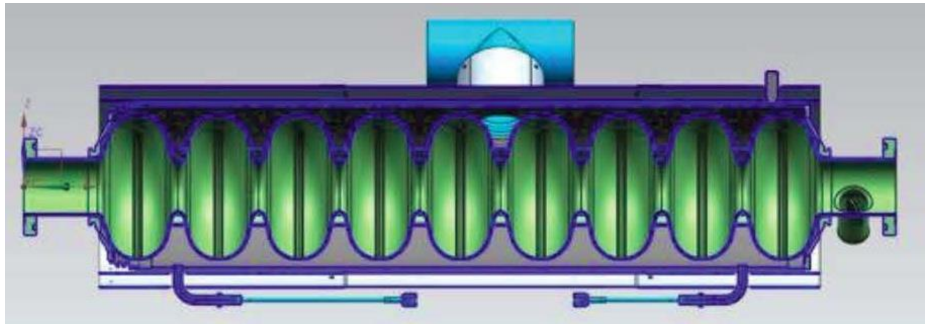
- 27 LHe liters @ 2.0K/0.029 bar

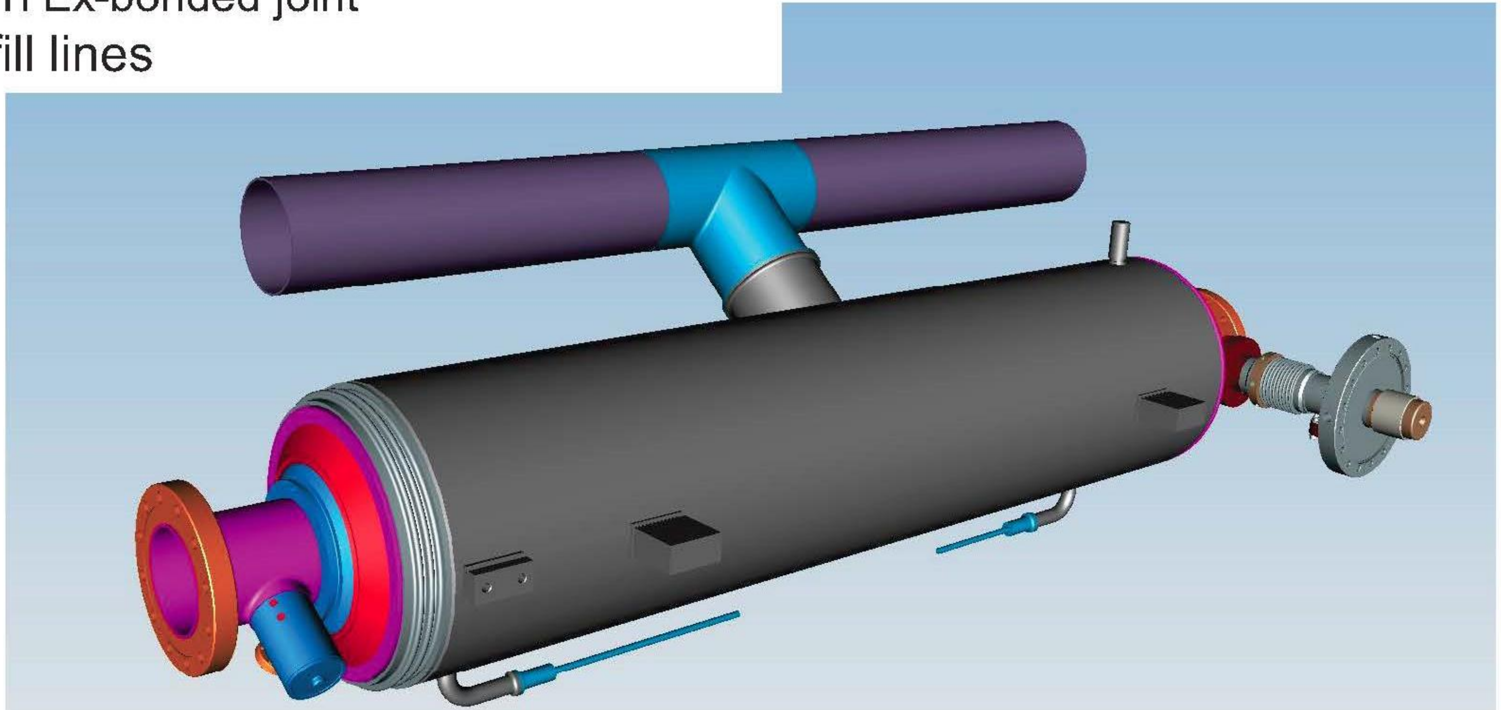
10x greater heat load than XFEL/ILC

95 mm 'chimney'

- ~centrally located
- SS-Ti Ex-bonded joint

Two fill lines





Marc Ross @ SRF 2015

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LCLS-II Cryomodule and TESLA/Eu-XFEL

Table 1: Major Features of the LCLS-II Cryomodules

Key Requirement	Major Features
Series configuration	Continuous insulating vacuum; no external parallel transfer line; cold beam pipe through the interconnect
0.5% longitudinal tunnel slope	One 2 K supply valve in each module for individual steady-state management of helium liquid level
Retention of high Q0 cavity performance	Active external magnetic field cancellation coils provide magnetic shielding and residual field of ≤5 mG at the cavities; a cool-down/warm-up cryogenic valve in the closed-ended cool-down circuit in each module provide high thermal gradient during cool-down through 9.2 K transition temperature to minimize flux trapping; using non-magnetic materials in the module
Seismic safety	Comply with SLAC seismic loading requirements under various accelerations and oscillatory modes
Removal of high heat loads in CW operation	Increased size and closed-ended 2-phase pipe allows sufficient conduction of the heat from the cavities through the superfluid helium; copper plating on beamline components; improved thermal intercepts at 5 K and 45 K

MECHANICAL DESIGN

The overall structural design of the LCLS-II cryomodule is similar to that of the TESLA-style module, shown in Fig. 3. The 5 K radiation shield is omitted not only for cost saving, but also due to the large dynamic heat at 2 K making such a thermal shield of a marginal value.

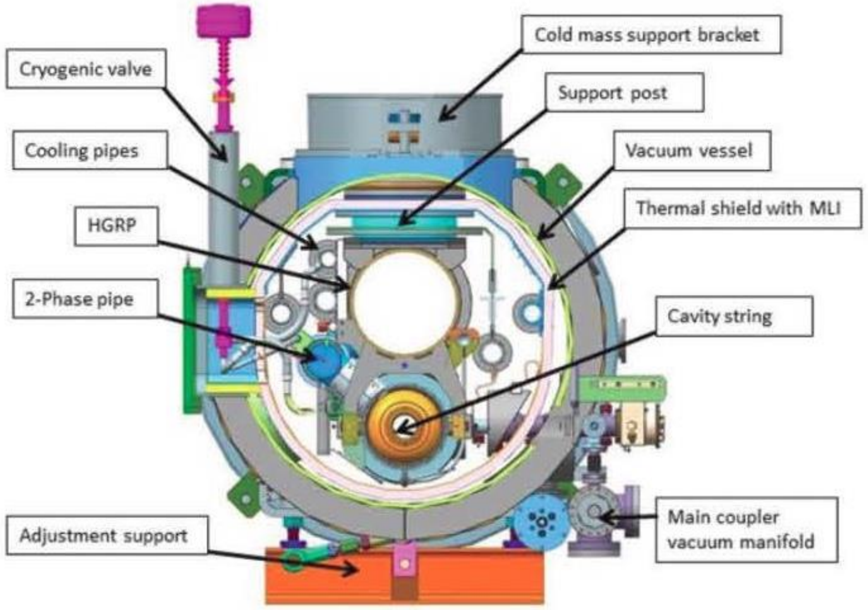


Figure 3: Cross-section of the cryomodule showing its major sub-assemblies.

T. Peterson et al. @ SRF 2015

Cavity Beamline String and Supports

Cavity Beamline String

The beamline string in each cryomodule consists of eight RF cavities. At the downstream end are combined focusing and steering magnets and a beam position monitor (BPM). The beamline terminates at each end with an all-metal gate valve. Between these two gate valves is a Beam line higher-order-mode (HOM) absorber. Active control of the cavity resonant frequency is provided by an end-lever tuner with motor and piezo-driven components. Each RF cavity is independently powered through a fundamental power coupler. The beamline components are shown in Fig. 4. Table 2 gives the descriptions of these components.

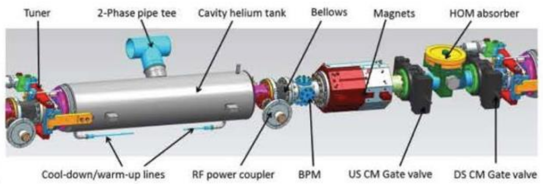


Figure 4: Components in dressed RF cavity and beamline string.

Cold Mass Support and Alignment System

The beam-line string is suspended under the helium gas return pipe (HGRP), which acts as the beamline backbone and is supported by three support posts to the vacuum vessel, shown in Fig. 5.

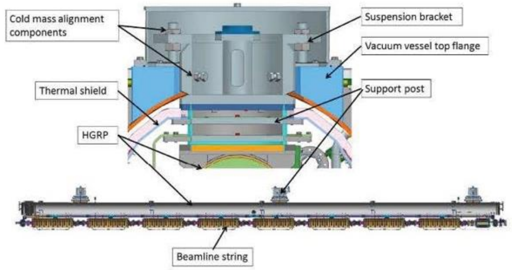


Figure 5: Cold mass support and alignment system.

Differential Thermal Contractions and Expansions

RF cavities are supported through four lugs on the helium vessel to the HGRP bottom hangers with C-shaped needle clamps, shown in Fig. 6. The cavities are anchored in position longitudinally via a clamp to an invar rod. The C-shaped needle clamps with bearing structure for the cavity, magnet package and gate valve mounts allow beamline frictionless movement with respect to the HGRP during thermal cycling.

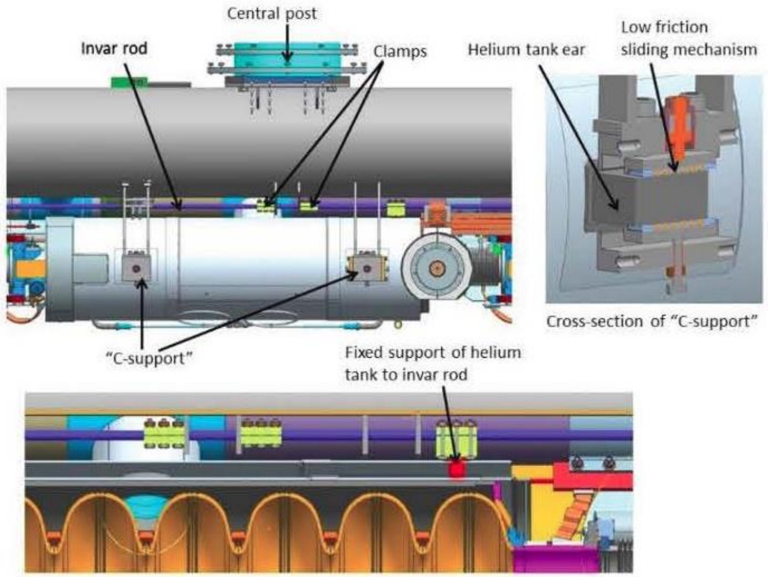


Figure 6: Support system of cavity helium tank to the HGRP and invar rod.

T. Peterson et al. @ SRF 2015

Cryogenic Circuits in the Cryomodule

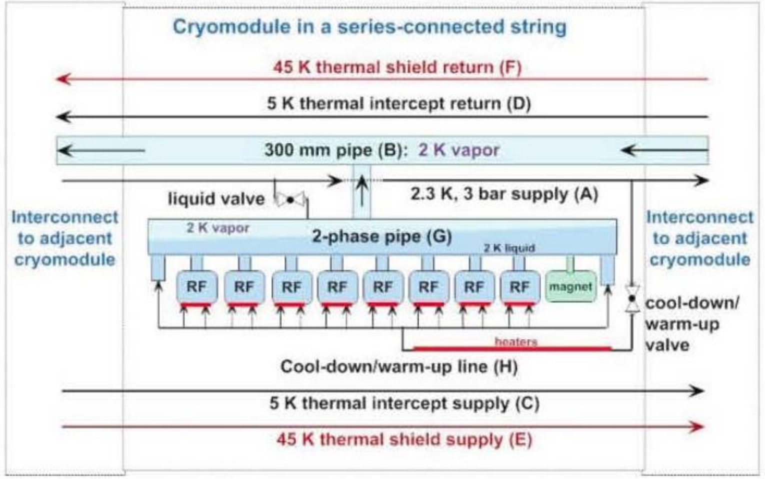


Figure 7: Scheme of cryogenic flow in the module.

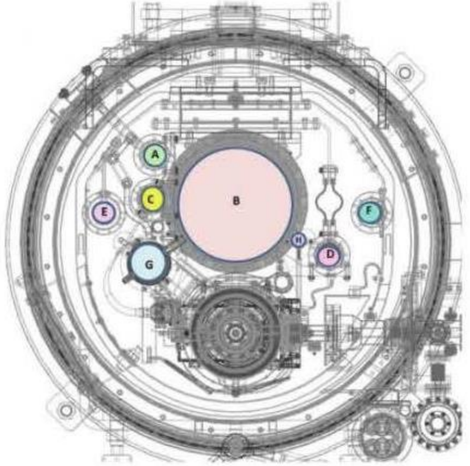


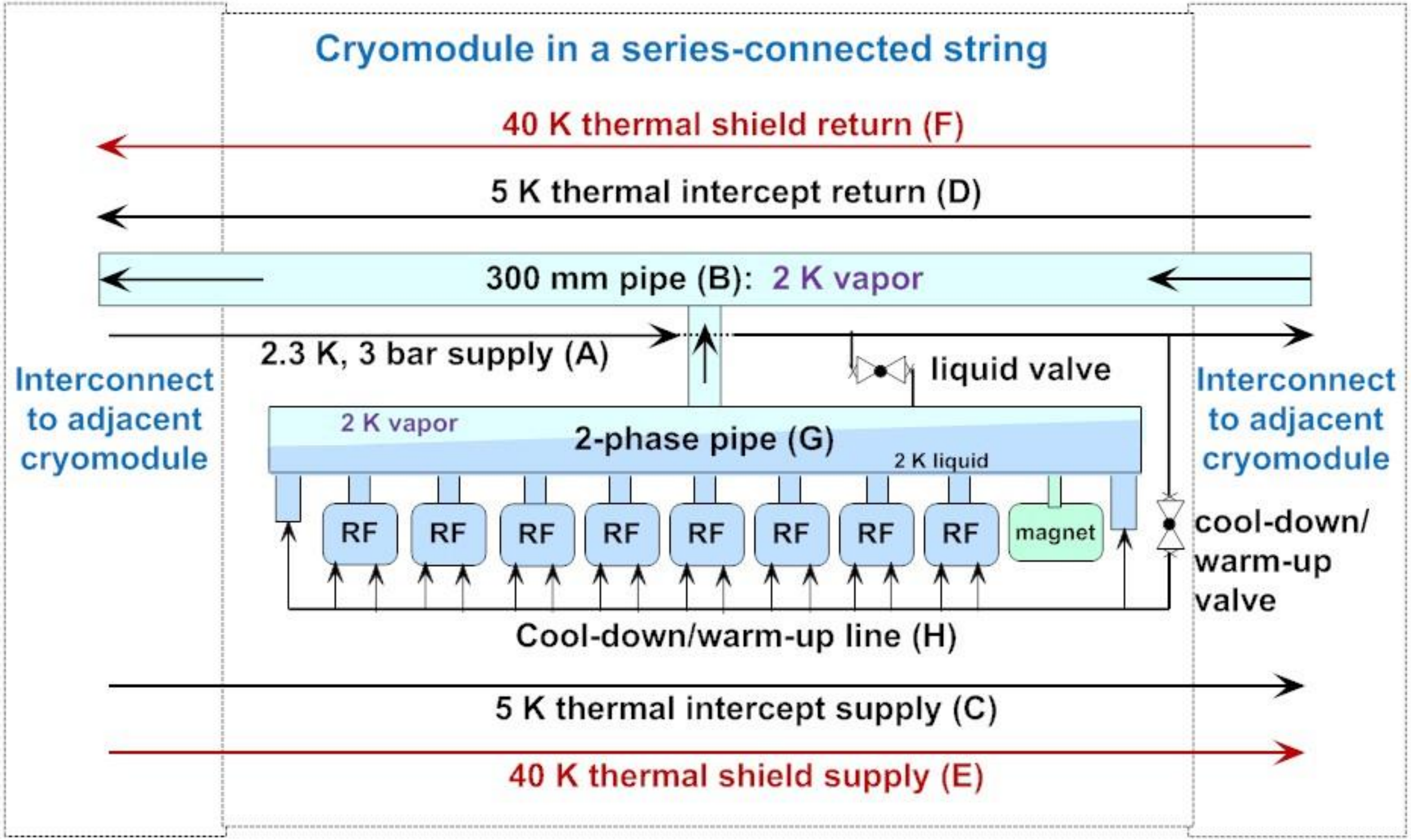
Figure 8: Cryogenic pipe positions and labels.

T. Peterson et al. @ SRF 2015

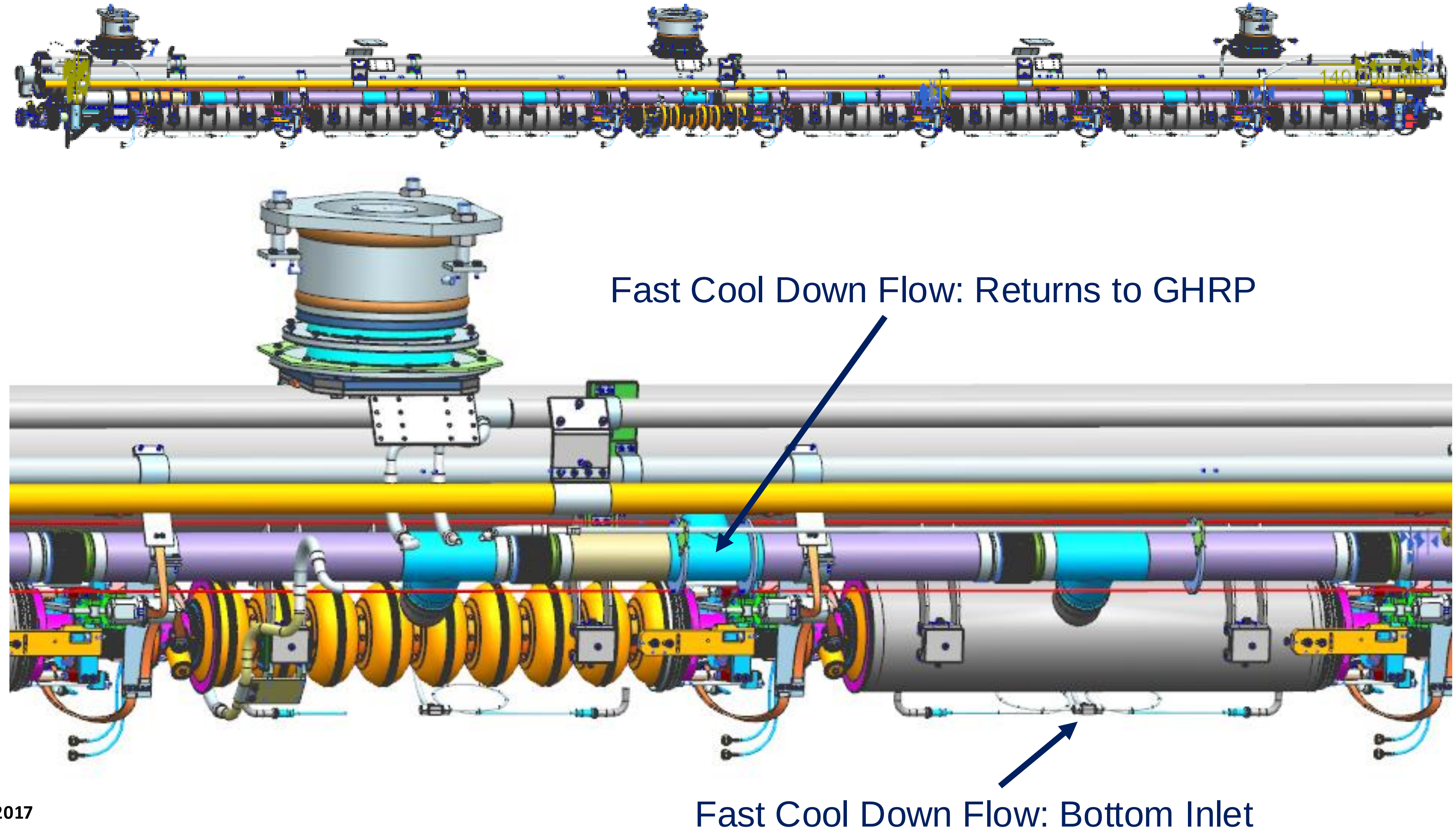
Table 3: Cryogenic Circuits in the Cryomodule

Circuit	Description
2K	Provides 2K liquid helium to the cavities with a valve for liquid supply in each module. The RF cavities are maintained within 1.8 K to 2.1 K range by means of a stagnant bath of saturated liquid helium
Cool-down /warm-up	A cool-down/warm-up valve and closed-ended piping for cool-down /warm-up of individual module, to provide high thermal gradient during cool-down through 9.2 K transition temperature to minimize flux trapping
5 K	A helium circuit in the temperature range of 5 K to 8 K, provides a low temperature thermal intercept for the support posts, magnet current leads, RF power coupler, and instrumentation wires
45 K	A helium circuit in the temperature range of 35 K to 55 K, provides conductive thermal intercepts to the thermal radiation shield, and to tuner piezo actuator wires and housing, RF power coupler, HOM absorbers, cryogenic valves, and instrumentation wires

LCLS-II Cryomodule Flow Scheme

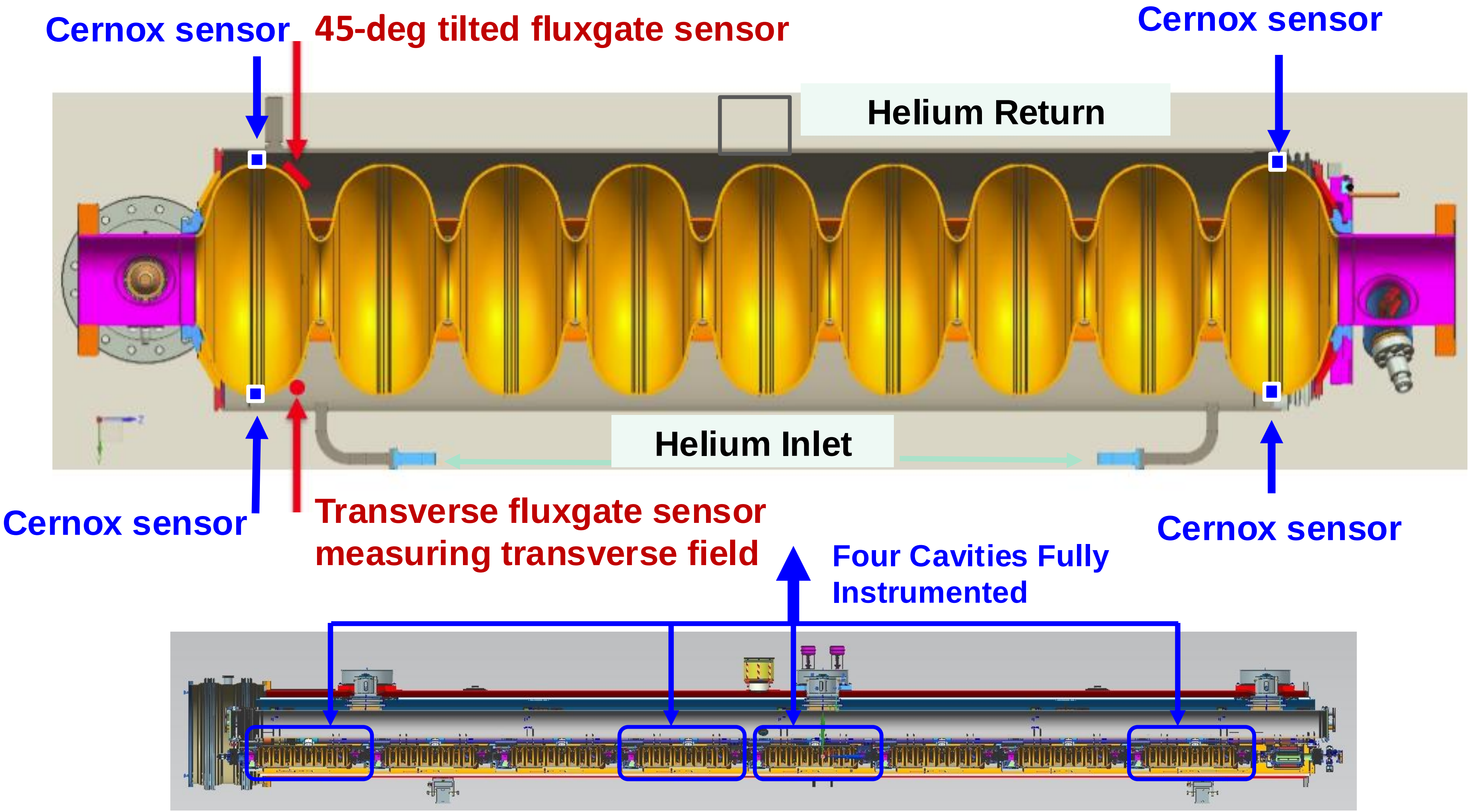


LCLS-II adapted for Fast Cooldown



G. Wu et al | SRF 2017

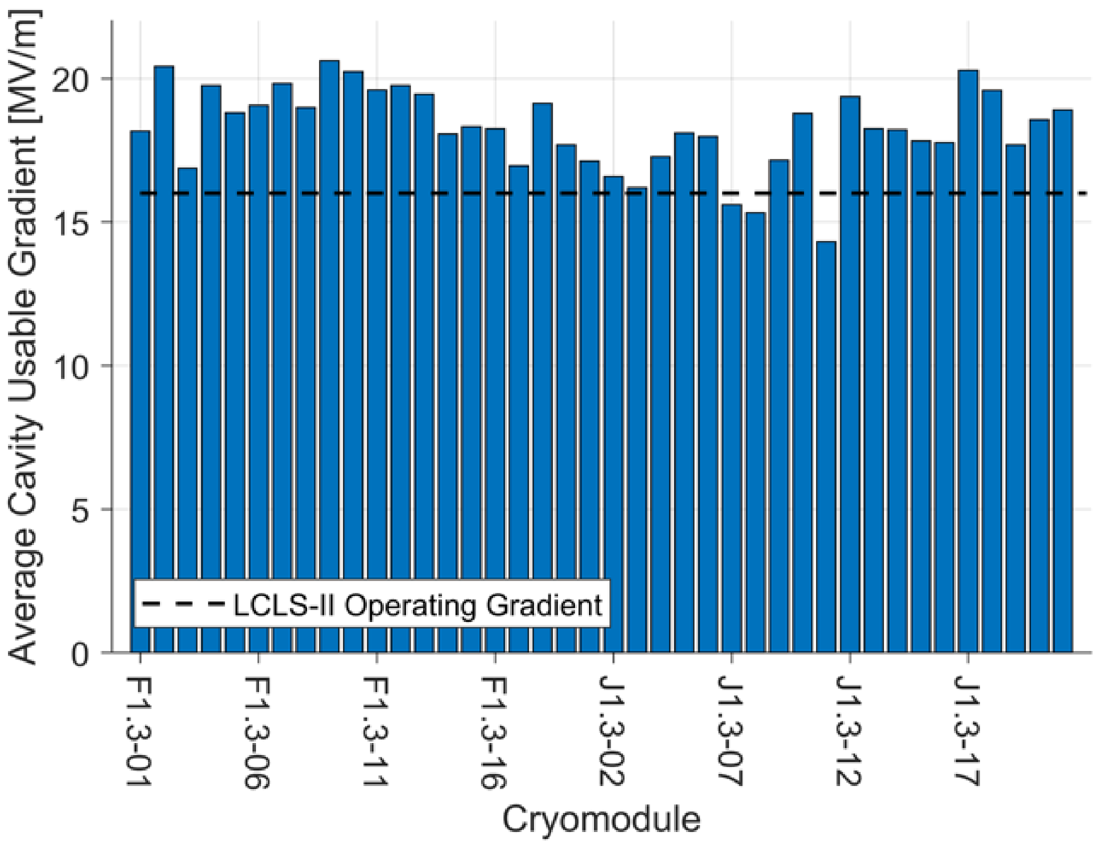
LCLS-II Sensors on Prototypes

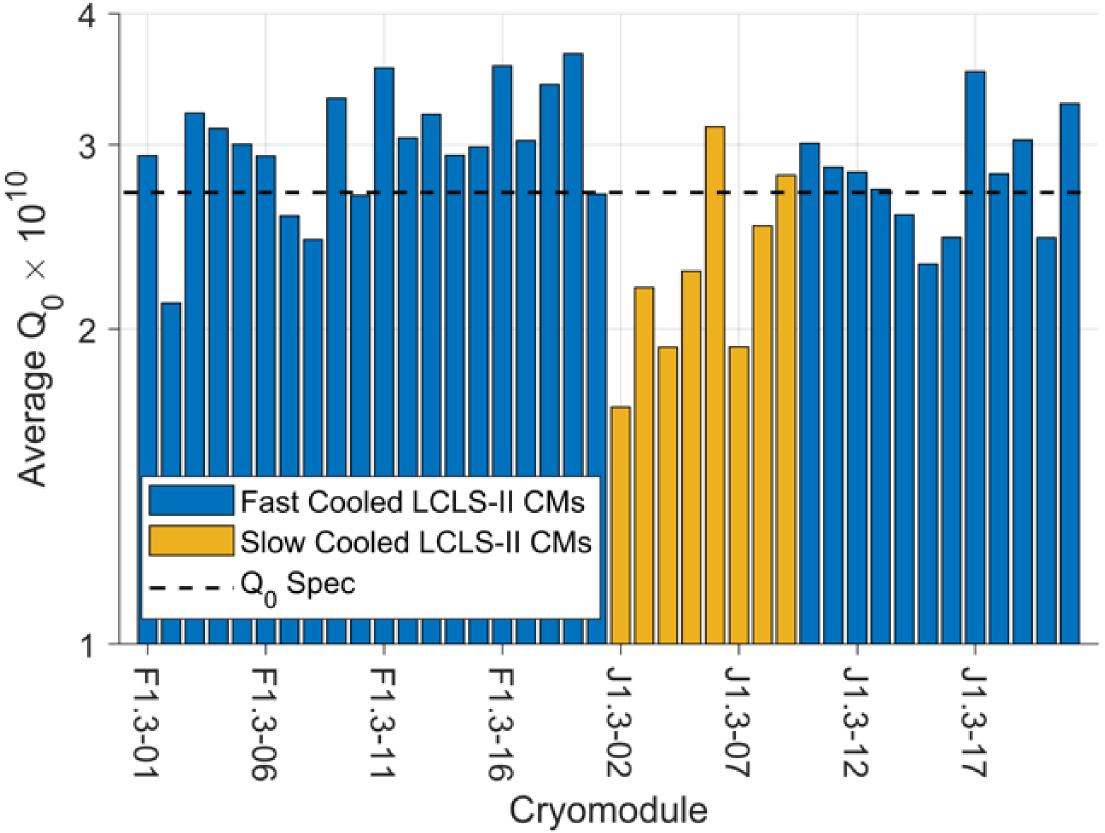


LCLS-II: Overall Cryomodule Performance

Successful demonstration of the first large scale nitrogen doped SRF cavity production by Industry

Demontration of the beneficial effect of fast cooldown for rising Q_0 by flux expulsion





Dan Gonnella at TTC 2020

Single Thermal Shield for large 2-Phase pipe

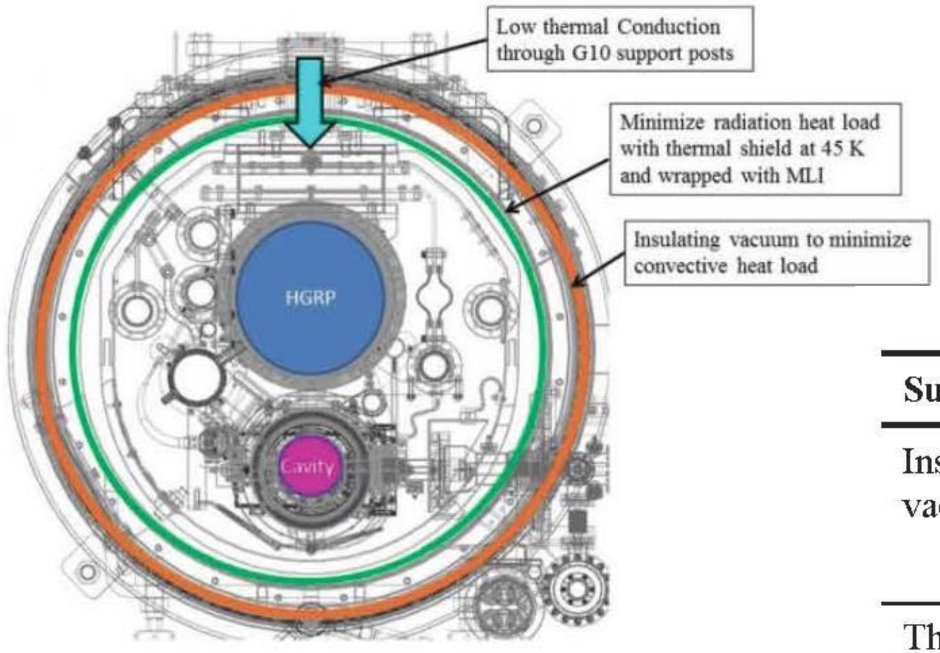


Figure 10: Cryomodule thermal insulation.

Table 5: Module Thermal Insulation Design

Sub-system	Description
Insulating vacuum	Vacuum vessel provides an insulating vacuum in the range of 1.0 x 10 $^{-4}$ Pa to minimize convective heat loads to the cold mass
Thermal shield and MLI	The radiation heat loads are reduced by operating the shield at 45 K and wrapping it with 30 layer multilayer insulation (MLI) blankets; 10 layers of MLI are used on colder piping and helium vessels
Support with low thermal conduction	Thermal conduction is minimized by employing a low thermal conduction composite material G10 tube in the support posts

T. Peterson et al. @ SRF 2015

Connection Details close to E-XFEL

Module Interconnects

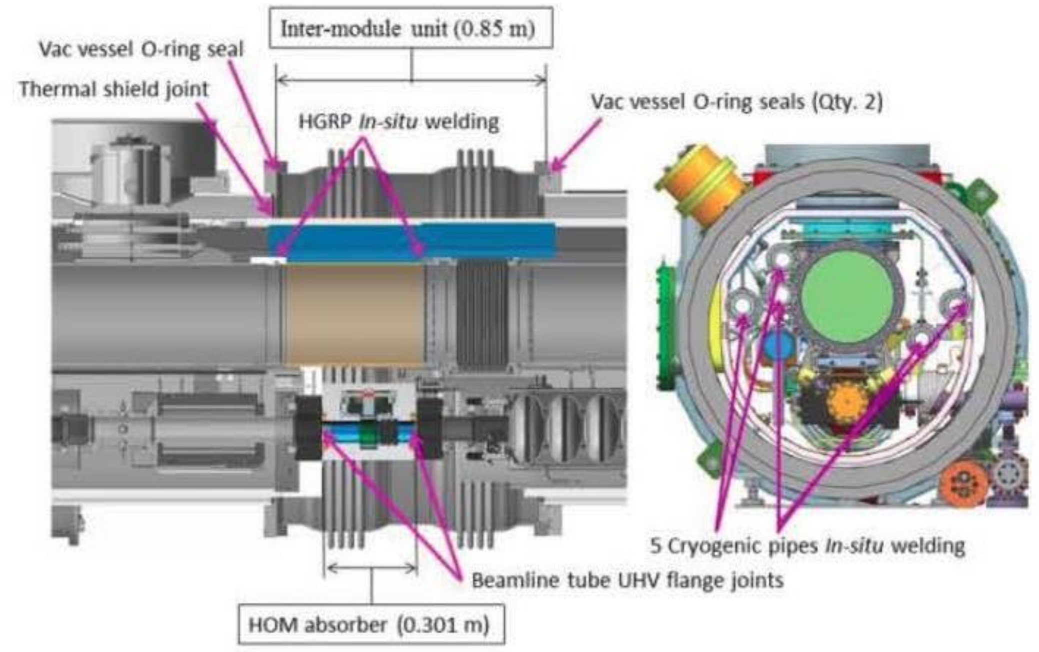


Figure 11: Cross-sectional views showing inter-module connections.

Table 7: Requirements of each Sub-system Inter-connect

Sub-system	Type of Joint
HGRP	Welding, pressure piping code compliance
Cryogenic pipes (5 lines)	Welding, pressure piping code compliance
Beamline tube	Particle free ultrahigh vacuum flange joints
Thermal shield	Connection with fasteners, good thermal conduction
Vacuum vessel	O-ring flange joints, vacuum seal

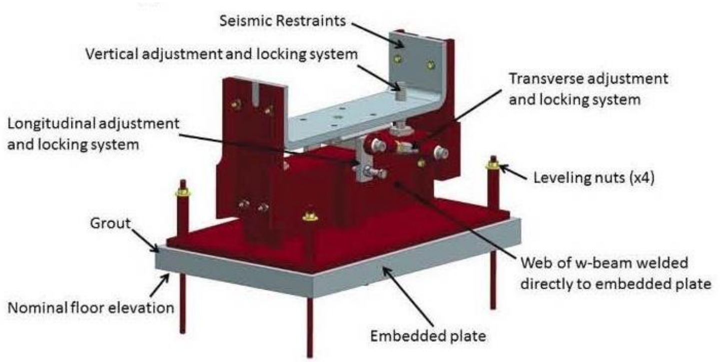
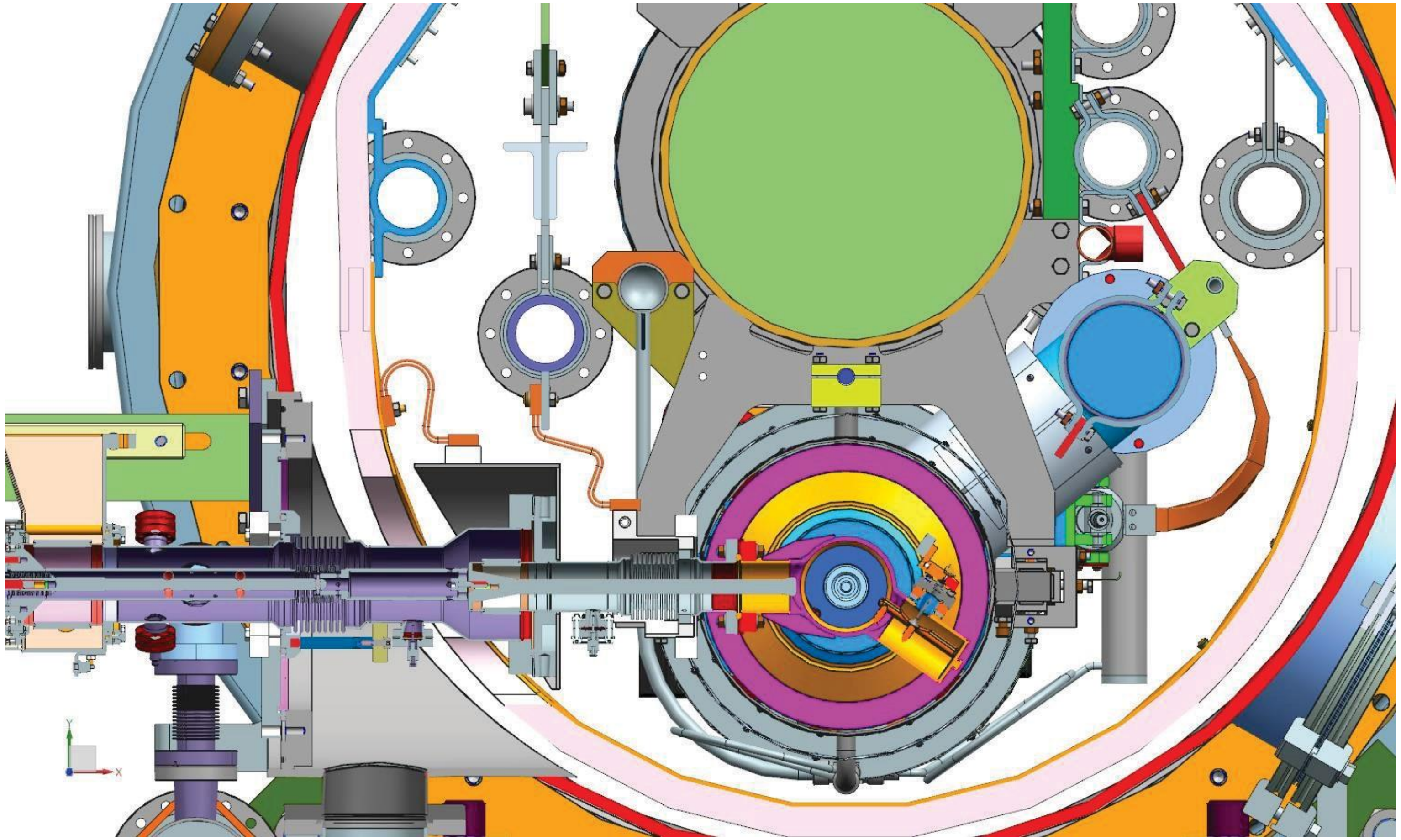


Figure 12: Cryomodule adjustable support stand and its attachment to the tunnel floor.

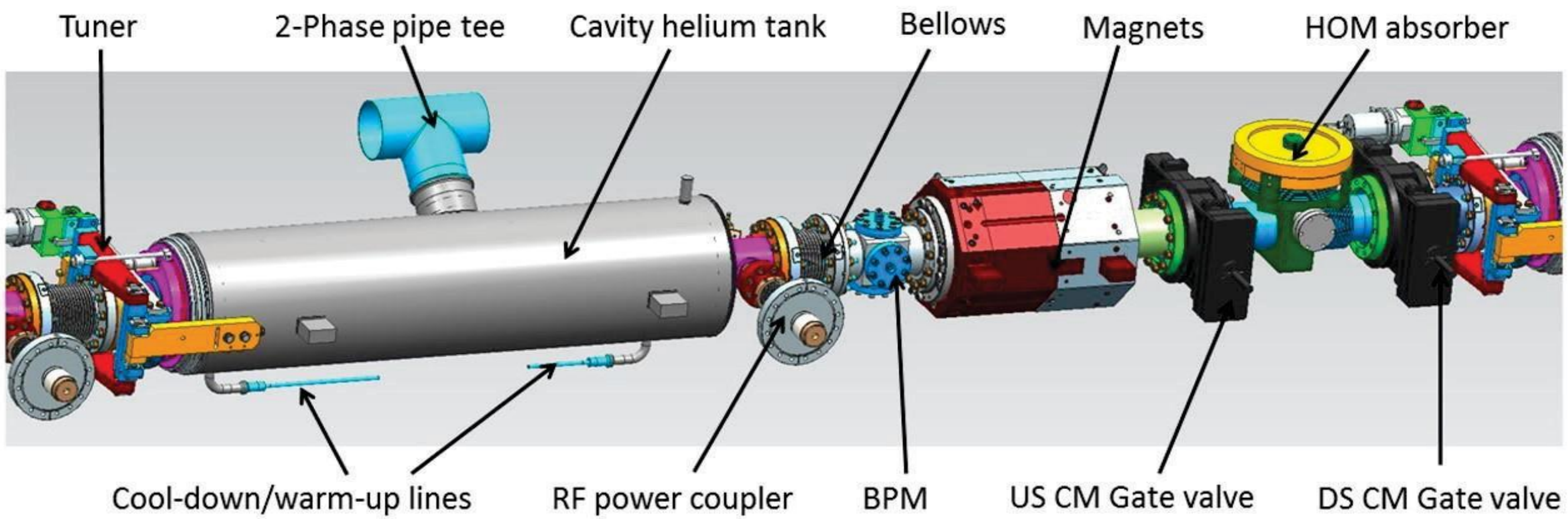
T. Peterson et al. @ SRF 2015

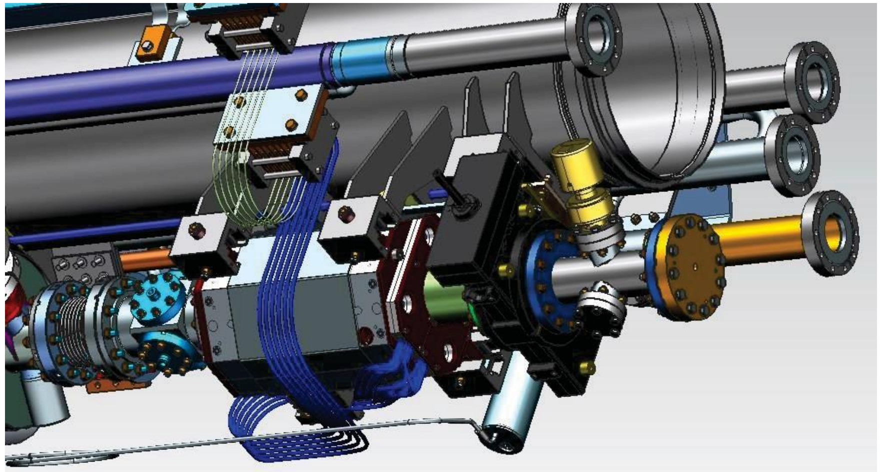
Power Coupler Design and Integration

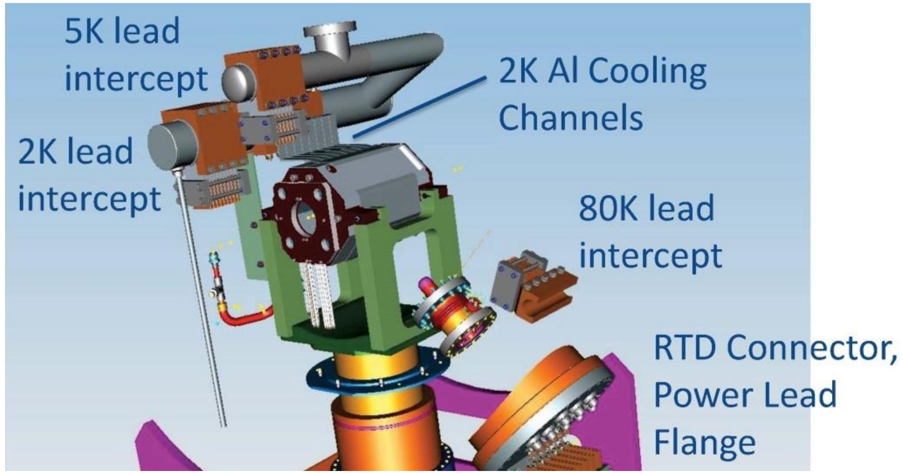


Marc Ross @ SRF 2015

New Split Quad Conduction Cooled







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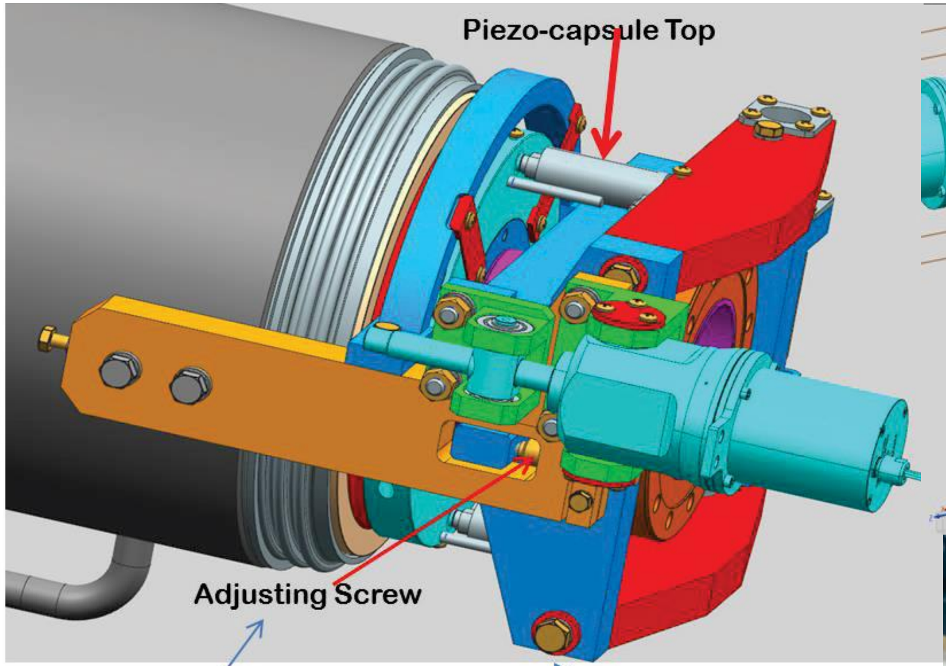
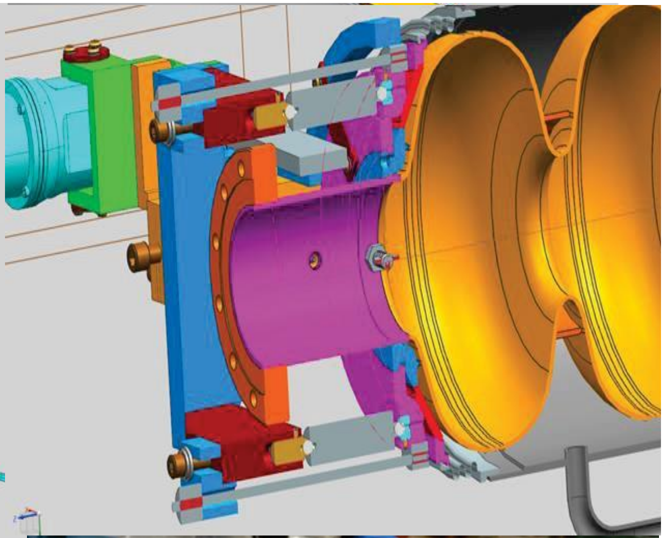
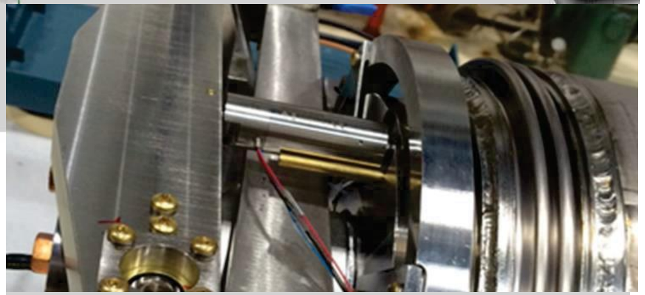
Reviewed Piezo.assisted Tuner







Adjusting Screw to unload piezo-capsule for replacement (in case of failure)… capsule can be replaced through special port

Tuning mechanism to uniformly preload piezo-capsule during initial assembly.

Piez

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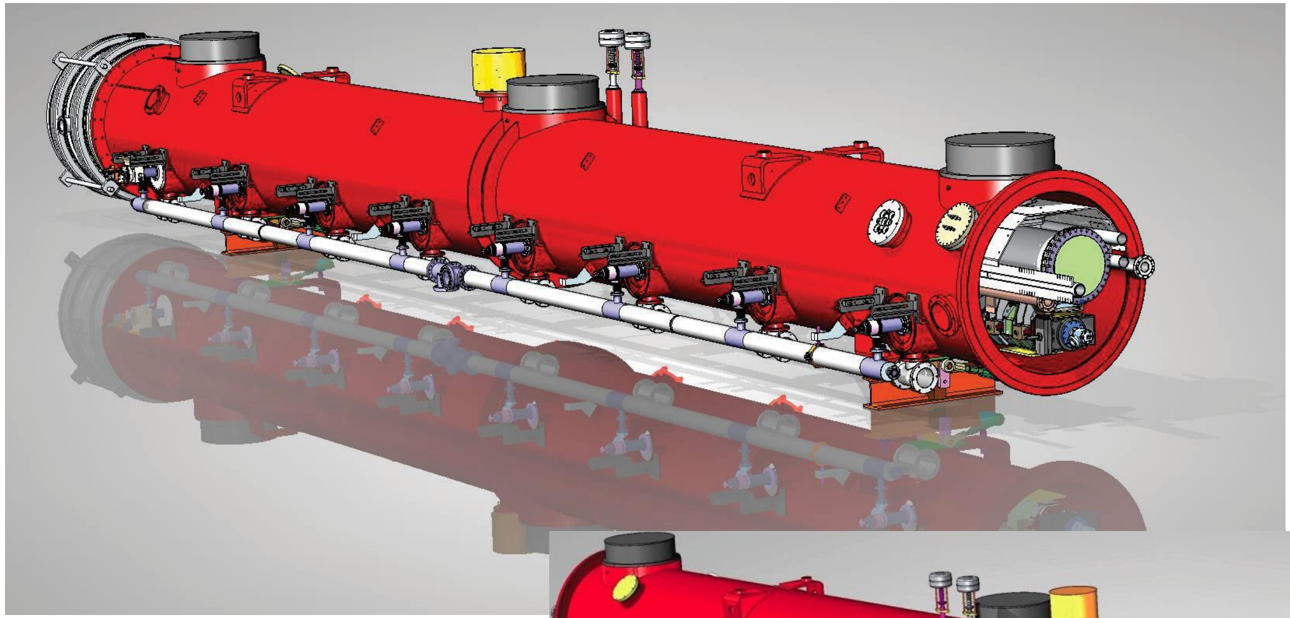
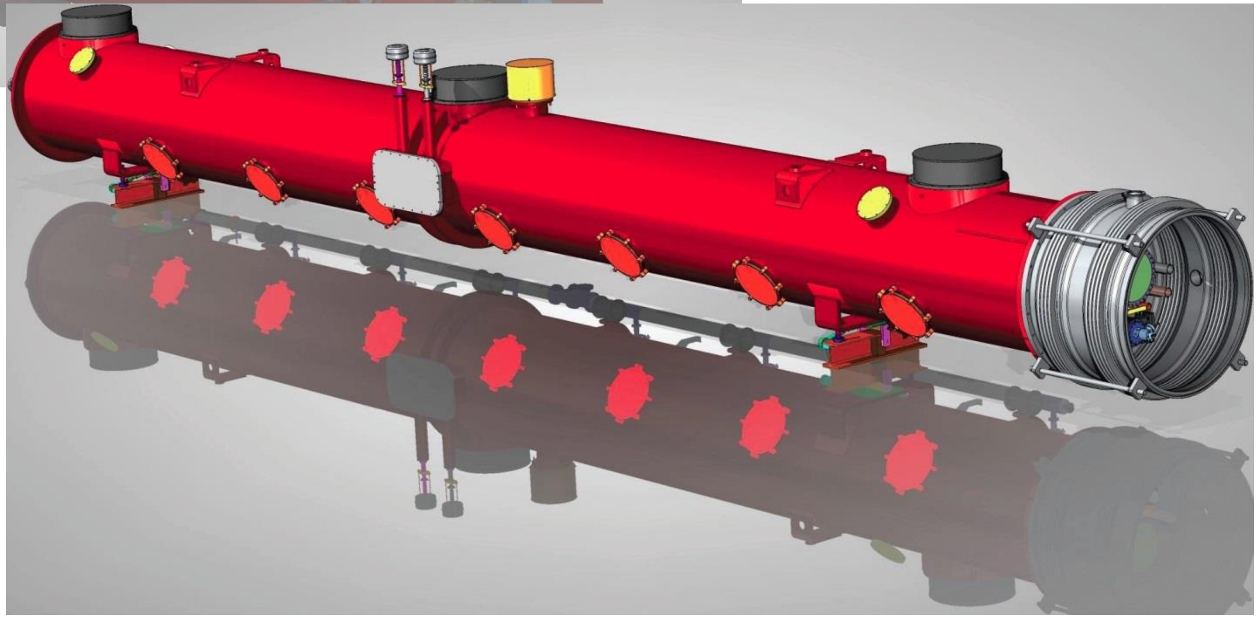
The LCLS-II Cryomodule – Tuner Ports





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Thank you for your attention