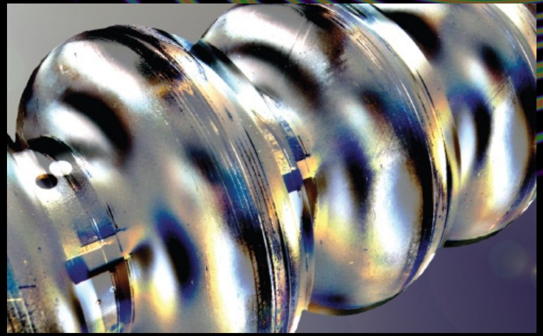
Progress towards Continuous Wave Operation of the SRF LINAC at DESY



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Superconductivity & Particle AcceleratorS, SPAS'2018, IFJ PAN, Krakow, Poland, November 29th 2018

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Outline

1 Introduction CW SRF
- E-XFEL LINAC
- CW Options and Limits
- CW Operation
- Operating E-XFEL in CW Mode
- CW Summary

2 RF Coupler Issues
- E-XFEL FPC
- CW Modifications
- Coupler R&D

3 Cavity / Cryostat
- E-XFEL Cavity CW issues

4 LCLS-II and E-XFEL
- Differences between LCLS-II and E-XFEL

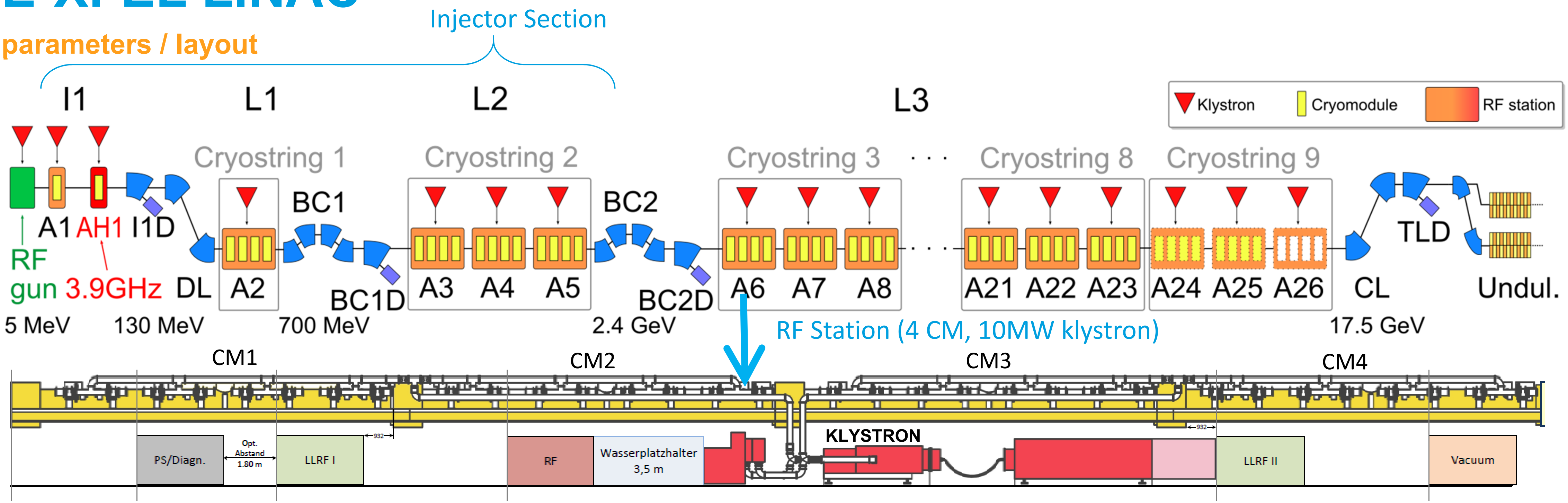
5 LLRF CW operation at CMTB
- CW Module Test
- XM-3 on CMTB
- Pulsed Test Data
- CW Test Summary

6 Conclusion
- Summary

Introduction CW SRF

E-XFEL LINAC

parameters / layout



101 Cryo Modules (97 installed now)

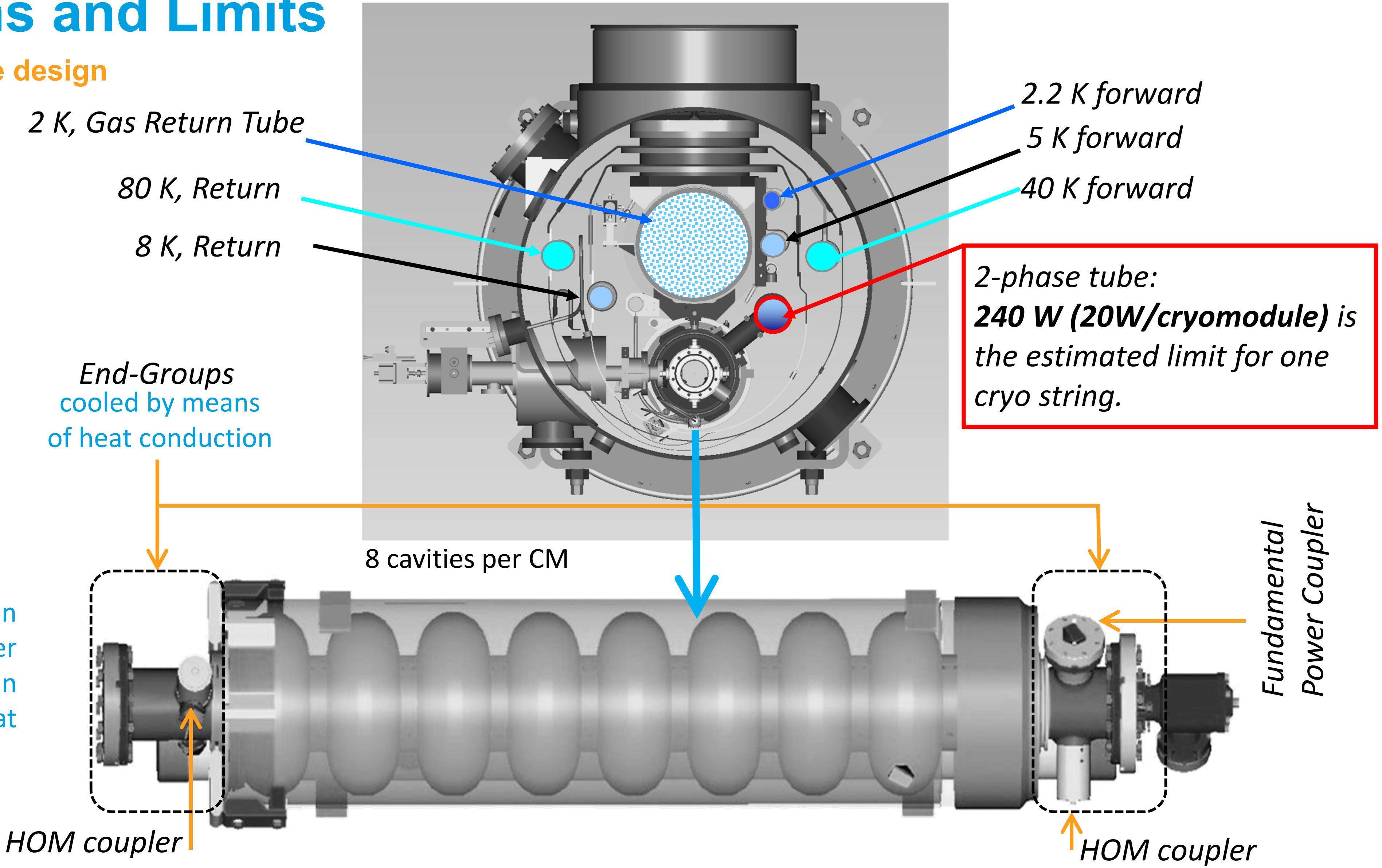
Injector Section: 17 (4×4+1) CMs

8 SRF 9-cell cavities per CM

Beam pulse length	ms	**0.65**
Repetition rate	Hz	**10**
Max. # of bunches per pulse		**2700**
Min. bunch spacing	ns	**240**
Bunch charge	nC	**≤ 1**
Beam current	mA	**5.0**
Nominal beam DF	%	**0.65**
Average Gradient	MV/m	**23.6**

CW Options and Limits

accelerating module design



RF power dissipation on the HOM coupler antennae is the main sources of the heat for the end groups

CW Operation

operating temperature and power

Operation of L0, L1, L2 and L3 at 2K

Max. microphonics has been assumed to be peak-to-peak ±15Hz

		at 2K	at 2K	at 2K	at 2K	at 2K	at 2K	at 2K		
		L0	L1	L2	L3 CW	L3 LP	L0+L1+L2	L3	Total CW	Total LP
Eacc in L0-L3	[MV/m]	20.00	20.00	20.00	7.20	12.50				
Total Energy/Linac	[GeV]	0.166	0.7	2.0	5.7	10.0			8.6	12.8
P_{cryo} / CM	[W]	194	194	194	20	58				
P_{cryo} / Linac	[W]	194	777	2331	1893	5590	3303	1893	5196	
2-phase limit / CM	[W]	new design	new design	new design	20	20				
DF	[%]						100			28

Operation of L0, L1, L2 at 1.8K and L3 at 2K

		at 1.8K	at 1.8K	at 1.8K	at 2K	at 2K	at 1.8K	at 2K		
		L0	L1	L2	L3 CW	L3 LP	L0+L1+L2	L3	Total CW	Total LP
Eacc in L0-L3	[MV/m]	20.00	20.00	20.00	7.20	12.50				
Total Energy/Linac	[GeV]	0.166	0.7	2.0	5.7	10.0			8.6	12.8
P_{cryo} / CM	[W]	119	119	119	20	58				
P_{cryo} / Linac	[W]	119	474	1423	1893	5590	2016	1893	3909	
2-phase limit / CM	[W]	new design	new design	new design	20	20				
DF	[%]						100			28

Operating the XFEL in CW

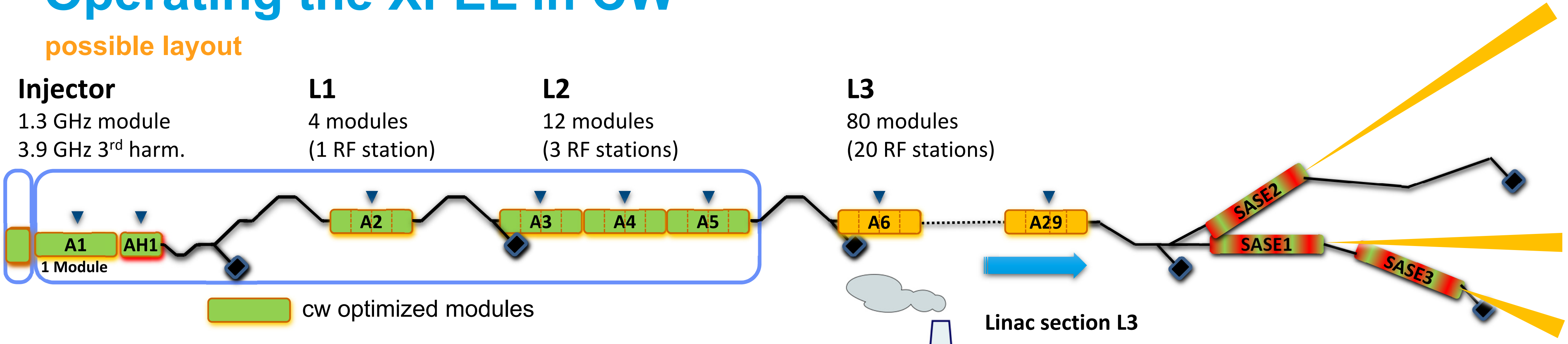
possible layout

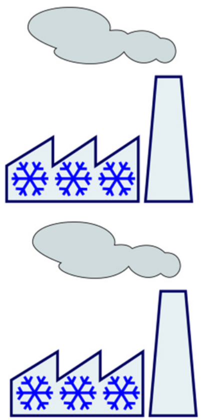
Injector
1.3 GHz module
3.9 GHz 3rd harm.

L1
4 modules
(1 RF station)

L2
12 modules
(3 RF stations)

L3
80 modules
(20 RF stations)





Linac section L3

- operated at moderate CW gradients
- lengthened by former A2 … A5
  80 + 12 modules
  24 RF stations

Expected energy 8 GeV !

1 – Replace the front-end cryomodules (17x)

- Larger cooling capability
- CW optimized cavities

2 – Install CW capable RF sources

- 1× **IOT** per RF station

3 – Double the cryo plant (cost driver)

- 2.5 → 5kW

4 – CW electron gun (preferred option: SRF gun)

- **The former front-end cryomodules can be installed at the end of the linac to lengthen L3 (+4 RF stations)**
- **No further action required in L3 (>1km)**
- **The upgraded XFEL would be capable of short pulse long pulse <u>AND</u> continuous wave operation**

CW Summary

known limits

1. Heat load at 2K for each cryomodule must not exceed 20W (Limit in L3 is 20W/CM at 2K and 10W/CM at 1.8K);
2. Assumed average static load at 2K (1.8K) is 5W/CM;
3. Heating of the HOM couplers must not lead to quenching of the end-cells;
4. The main XFEL linac will not be rebuilt for the new operation modes;
5. An upgrade of the cryogenic plant should be “doable”;
6. New RF-sources will be added to the klystrons used for the nominal operation – the new sources should fit in the tunnel: a single RF-source per CM;
7. Bunch quality as high as for the nominal short pulse operation;
8. Gradient in the injector sections is 20MV/m for all 136 cavities (may still change – R&D ongoing).

CW beam: 25µA (100pC and 250kHz)

Before upgrade: 101 CMs in total, 17 in the IS and 84 in L3

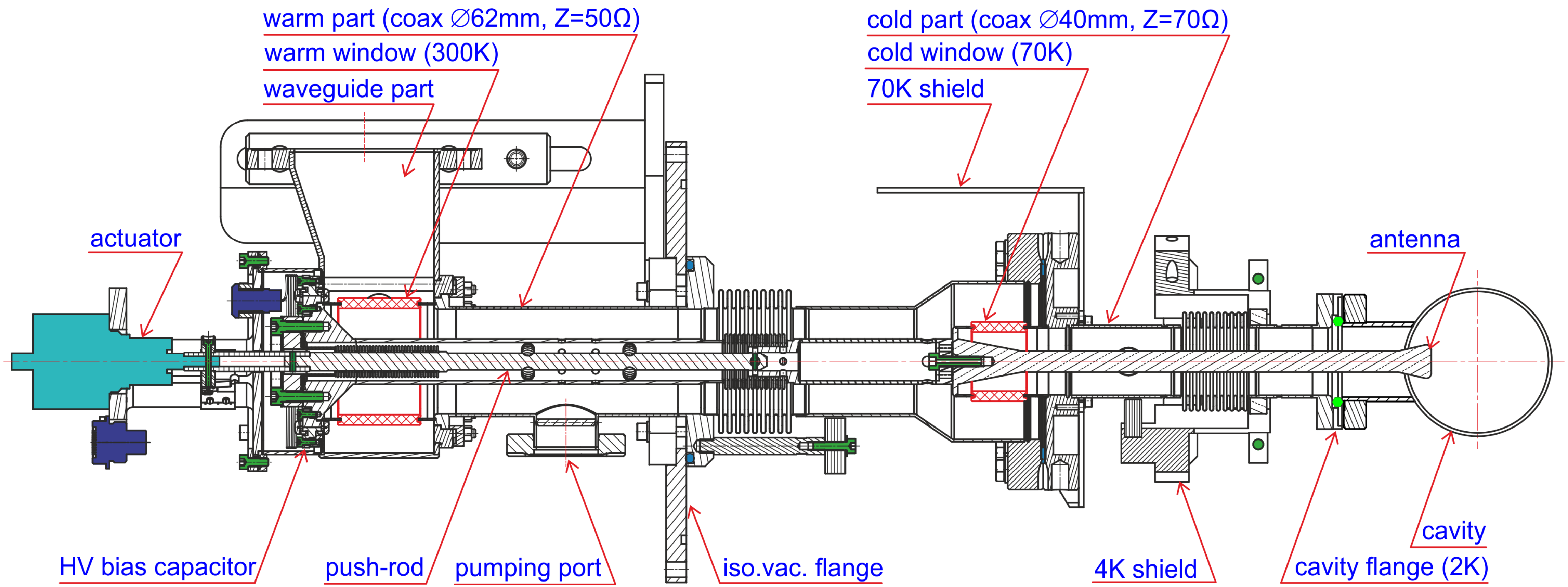
After upgrade: New 17 CMs modified for CW will be installed in the IS
113 CMs in total, 17 in the IS and 96 in L3
12 present CMs from the IS will be re-installed at the end of L3

Capacity of present cryo-plant is ~2.4 kW.
We will need additional one for the IS

RF Coupler Issues

E-XFEL Fundamental Power Coupler

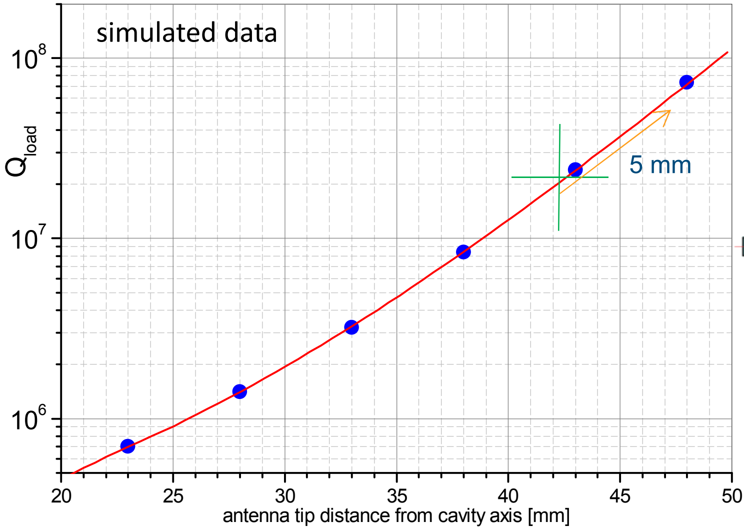
design and main parameters

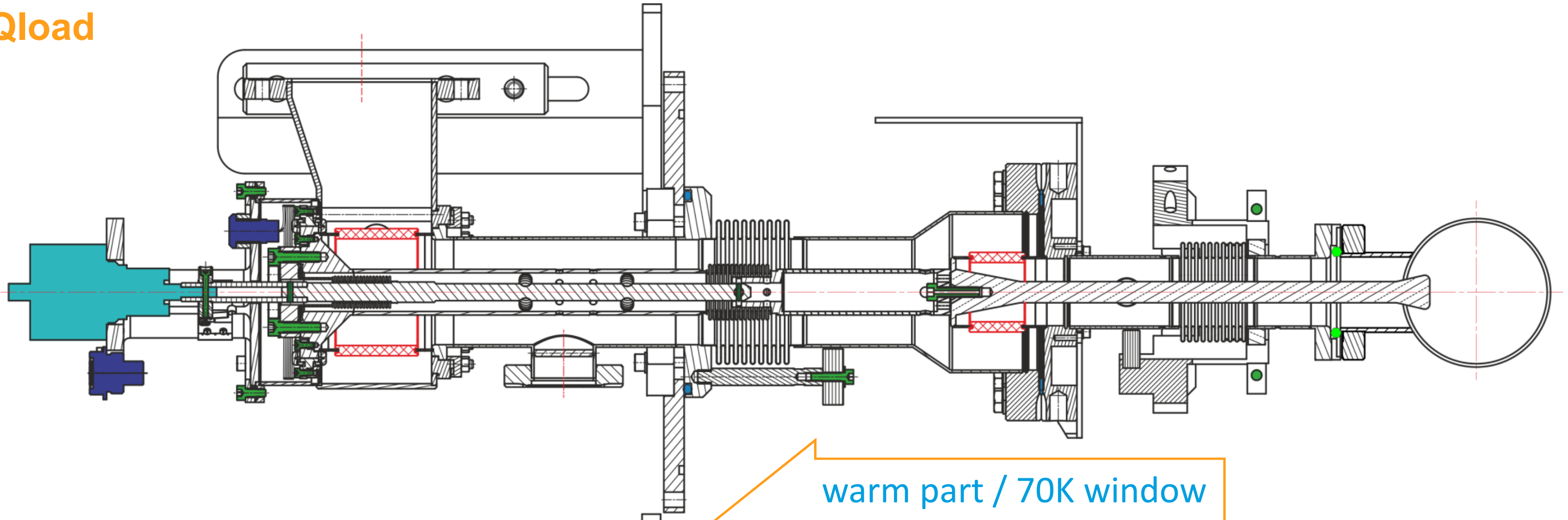


E-XFEL Input RF power coupler consists of warm, cold and waveguide main parts. Coaxial coupler is made of copper and copper plated (10/30µm) stainless steel with alumina TiN coated ceramic windows. Motorized antenna tuning (±10mm) allows for Q_{ext} adjustment ($10^6..10^7$).

CW Modifications [1]

Warm Part shift to achieve higher Qload

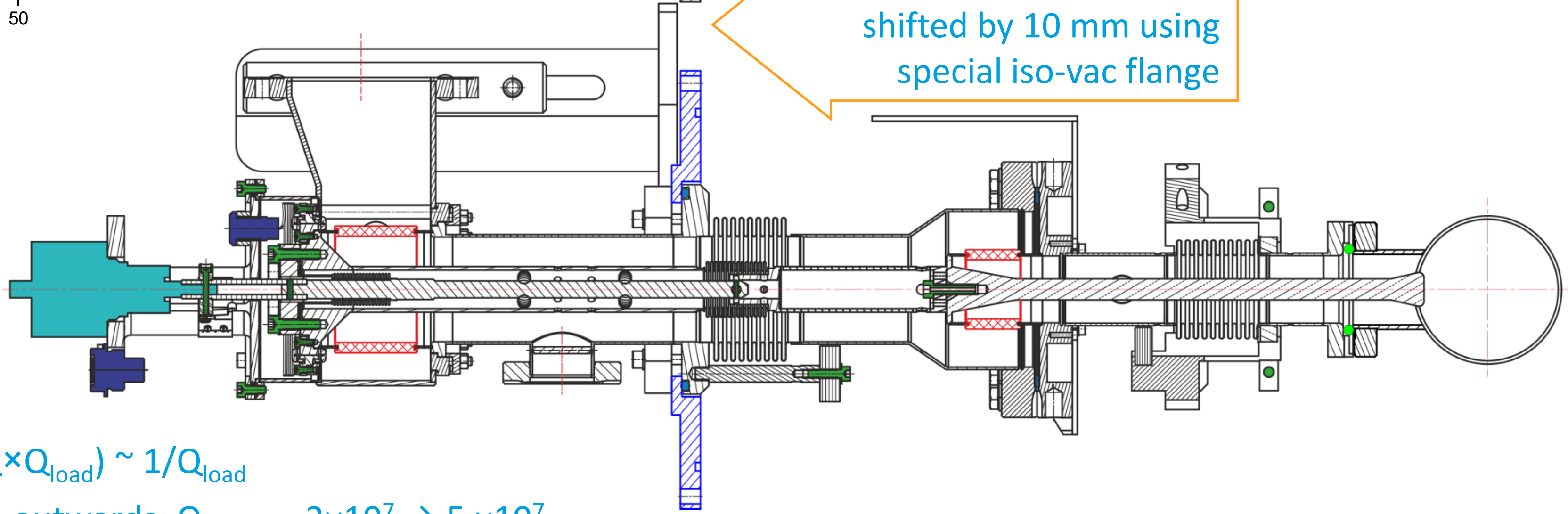




1	**8.4×10⁷**
2	**6.8×10⁷**
3	**1.1×10⁸**
4	**9.1×10⁷**
5	**7.5×10⁷**
6	**6.6×10⁷**
7	**2.6×10⁷**
8	**2.6×10⁷**

warm part / 70K window shifted by 10 mm using special iso-vac flange

XM-3 achieved $Q_{load.max}$



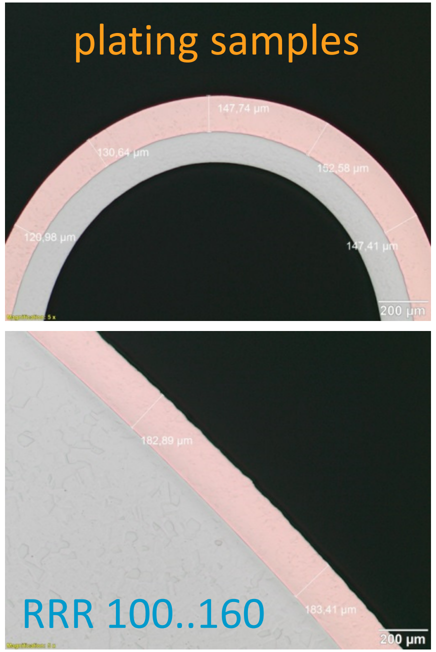
$P_{for} = (E_{acc} \times L)^2/(4 \times R_{sh}/Q \times Q_{load}) \sim 1/Q_{load}$

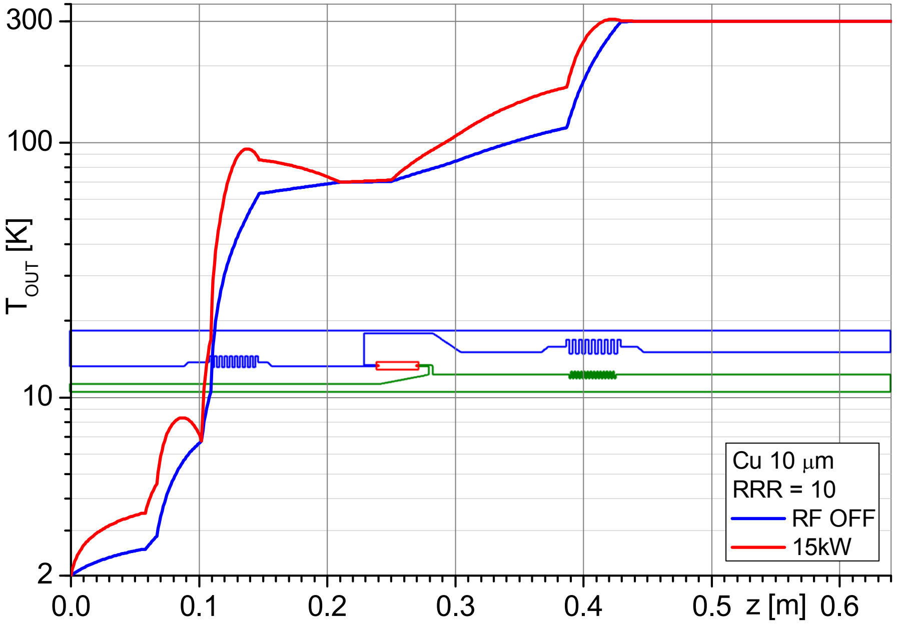
shift antenna by +5 mm outwards: $Q_{load.max}$ $2 \times 10^7 \rightarrow 5 \times 10^7$

CW Modifications [2]

Copper Plating with increased average RF power

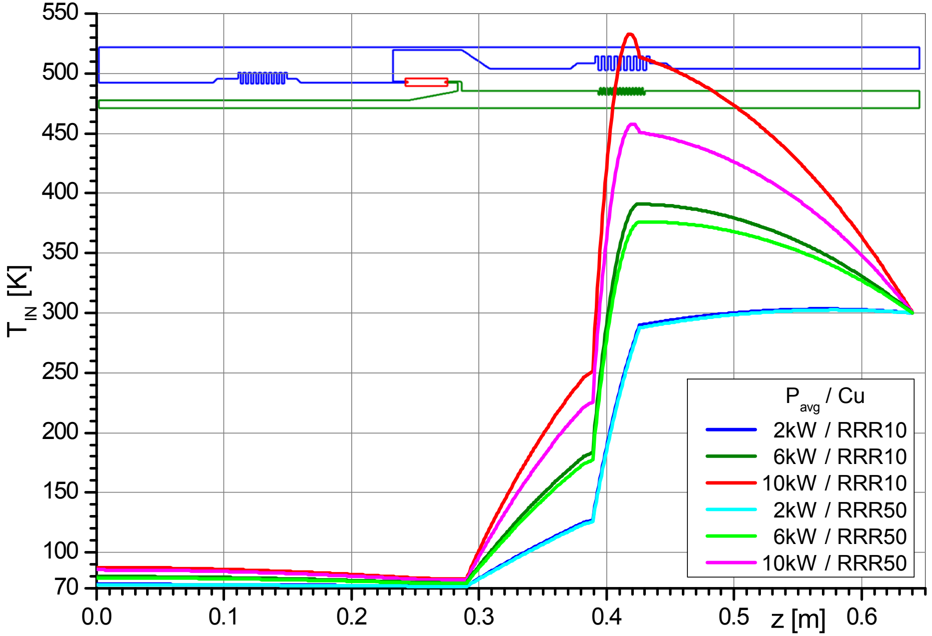
- With the CW RF power in a range of 10..15 kW inner conductor overheating will be an issue, with a maximum temperature on the warm inner conductor bellow;
- To decrease the inner conductor temperature it must be gas cooled from inside or copper-plated with increased layer thickness (≥150µm) and RRR (>50, 100..160 achieved on last 150µm plating samples);
- Coupler tests with warm parts having 150µm copper re-plated inner conductor are in preparation – 10 warm parts are being re-plated.

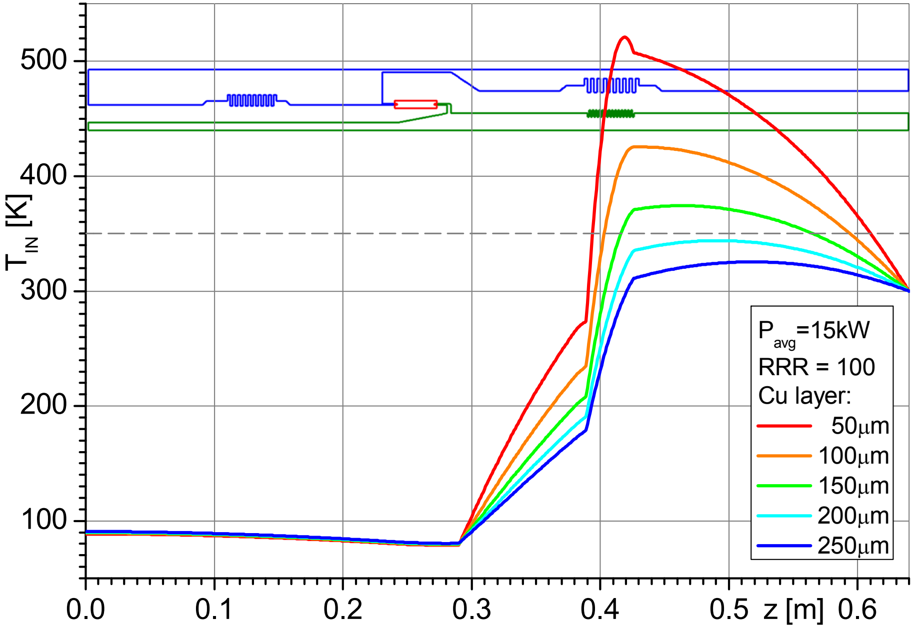




outer conductor

inner conductor

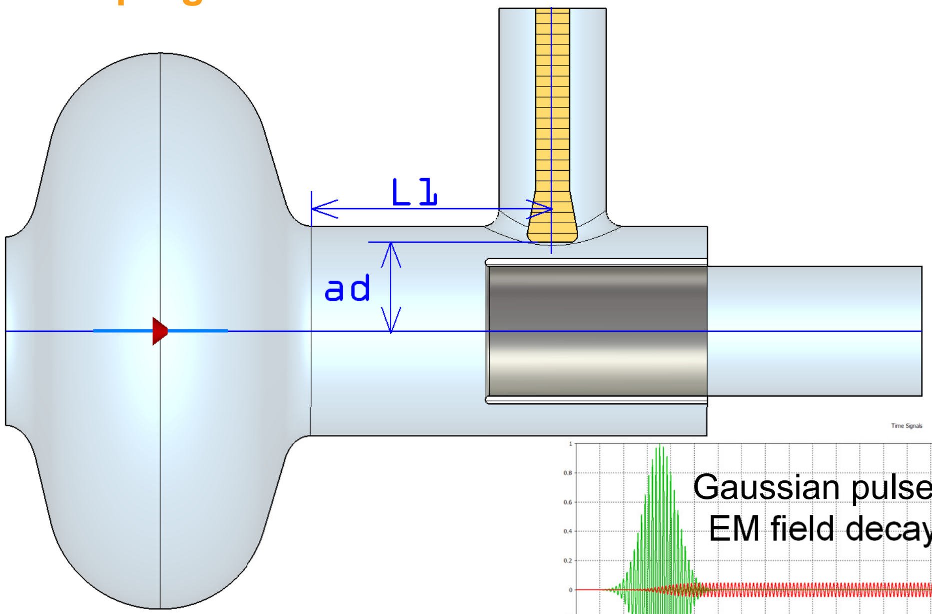


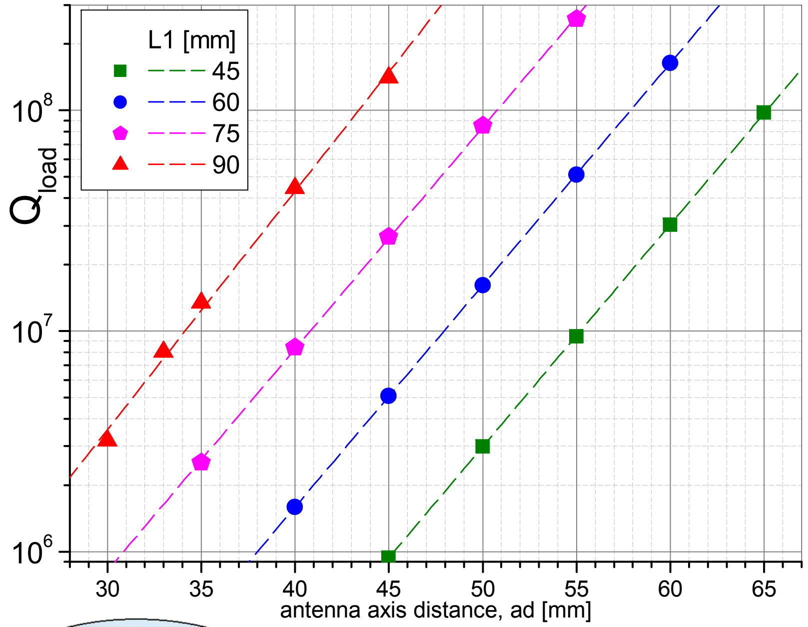


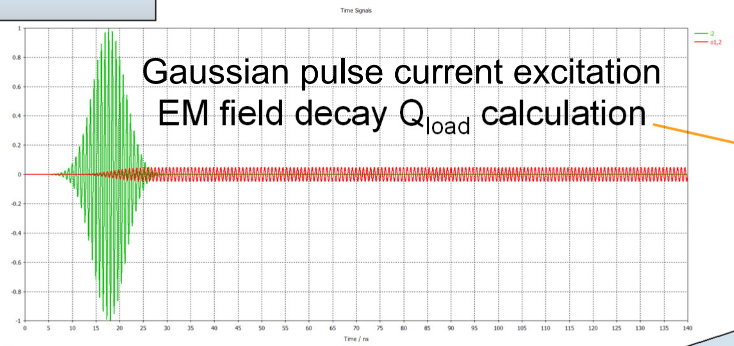
inner conductor

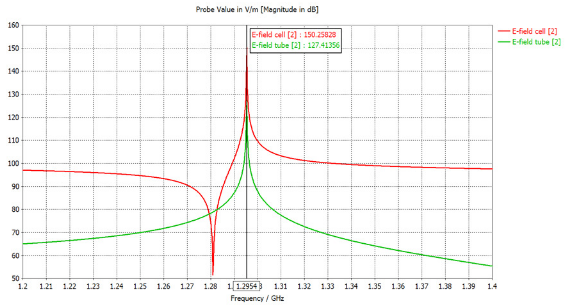
CW SRF Injector Coupler Development

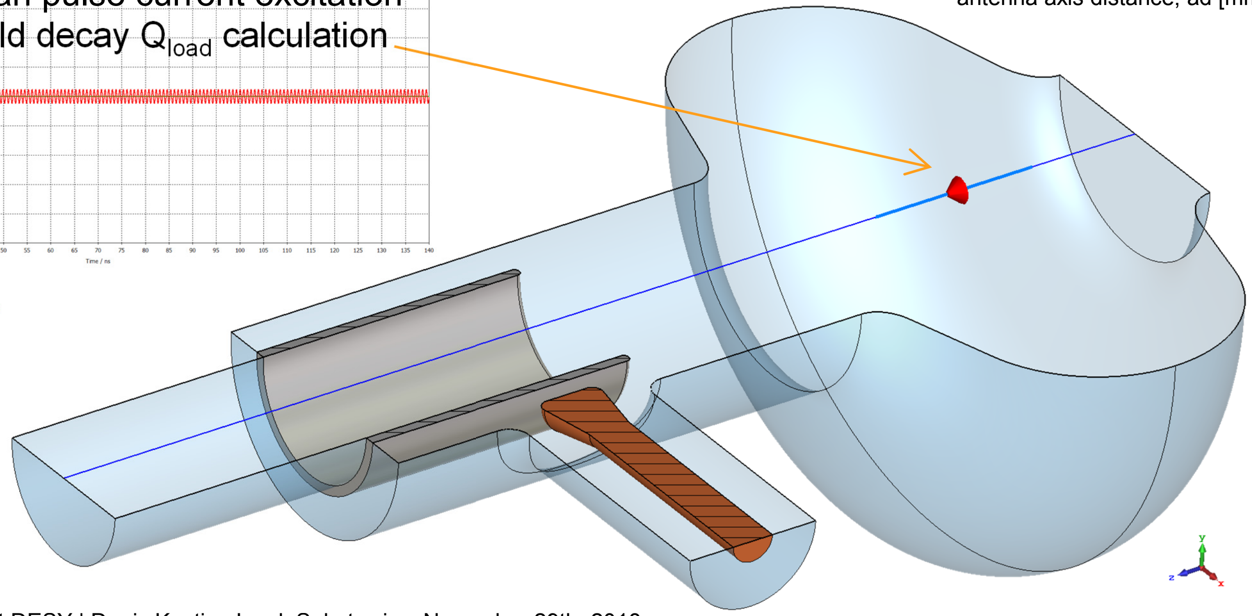
R&D program started









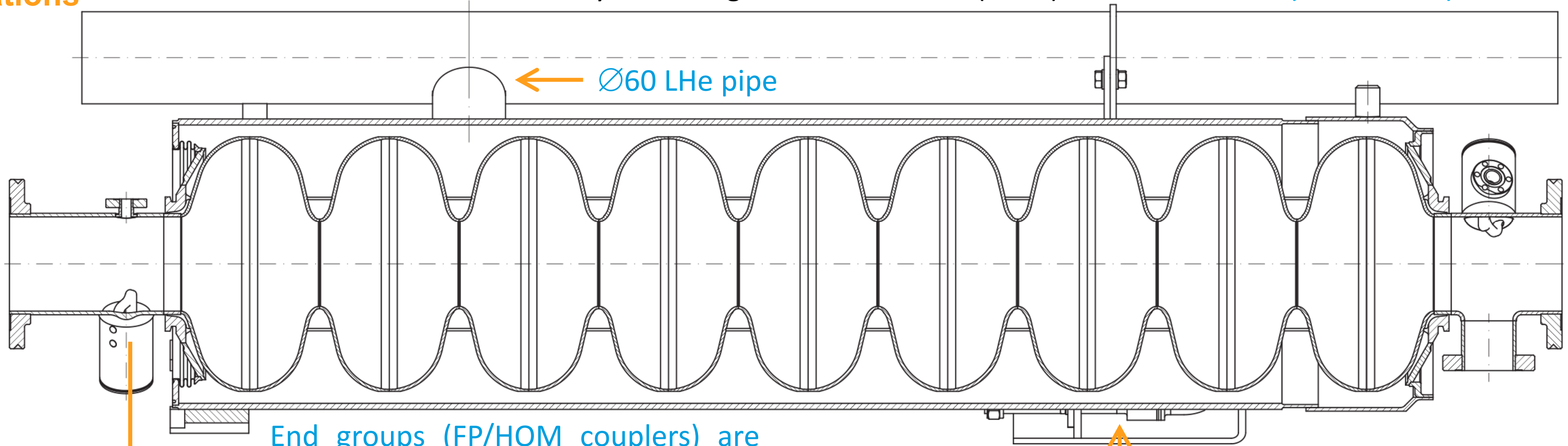


Cavity / Cryostat

E-XFEL Cavity CW issues

possible modifications

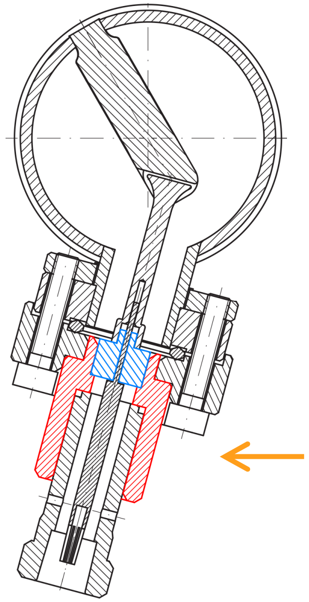
TESLA cavity was designed for ca. 1% DF (1992) → some CW optimization possible



∅60 LHe pipe

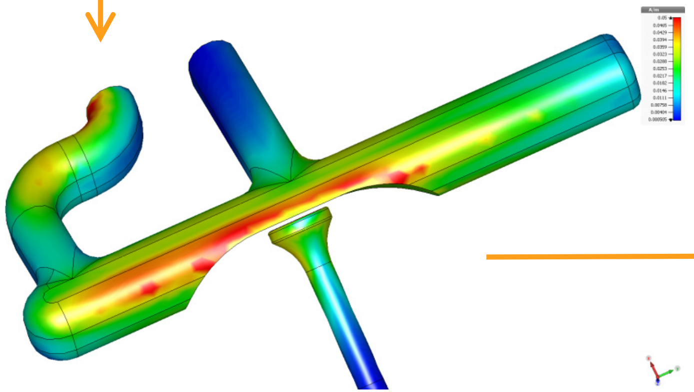
End groups (FP/HOM couplers) are cooled by means of heat conduction

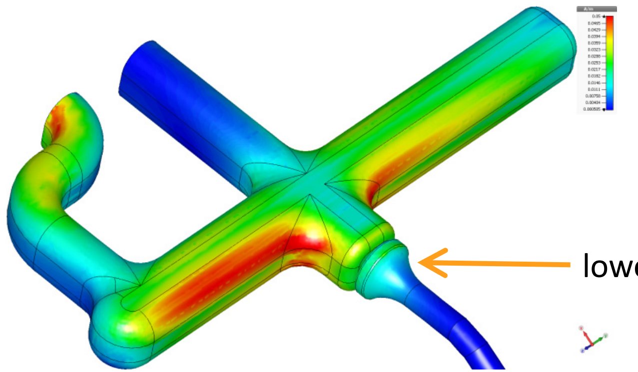
one LHe supply line



sapphire/copper HOM feedthrough

E-XFEL standard





lower H-field (~50%) at antenna tip

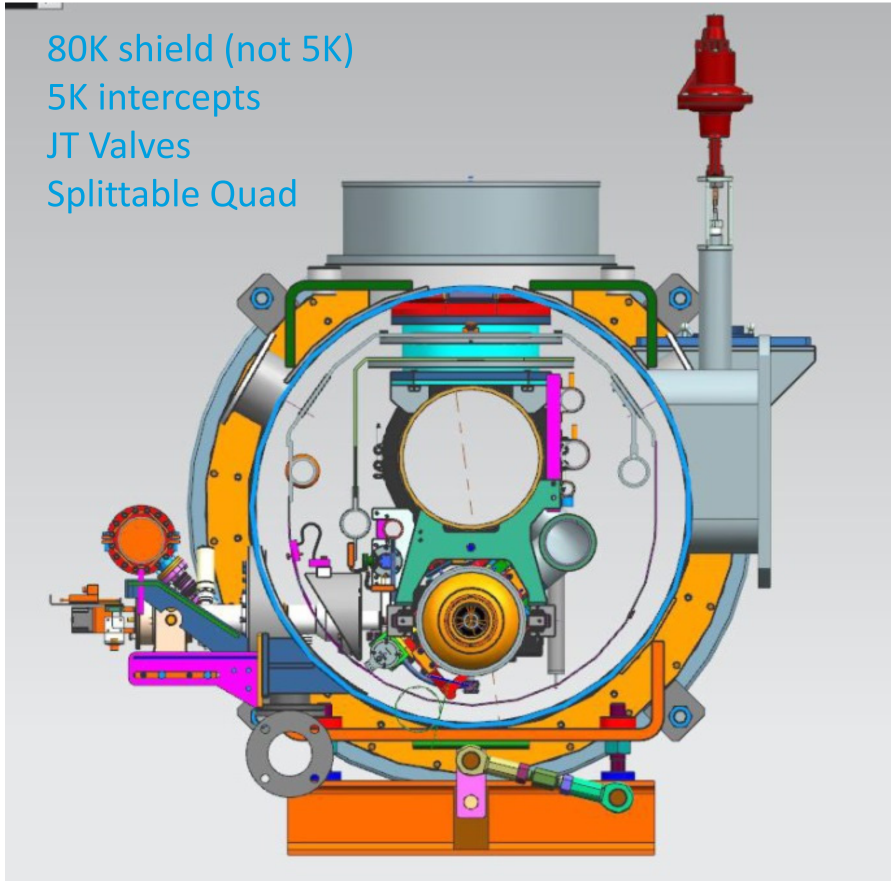
HOM antenna is exposed to the residual magnetic field of the FM

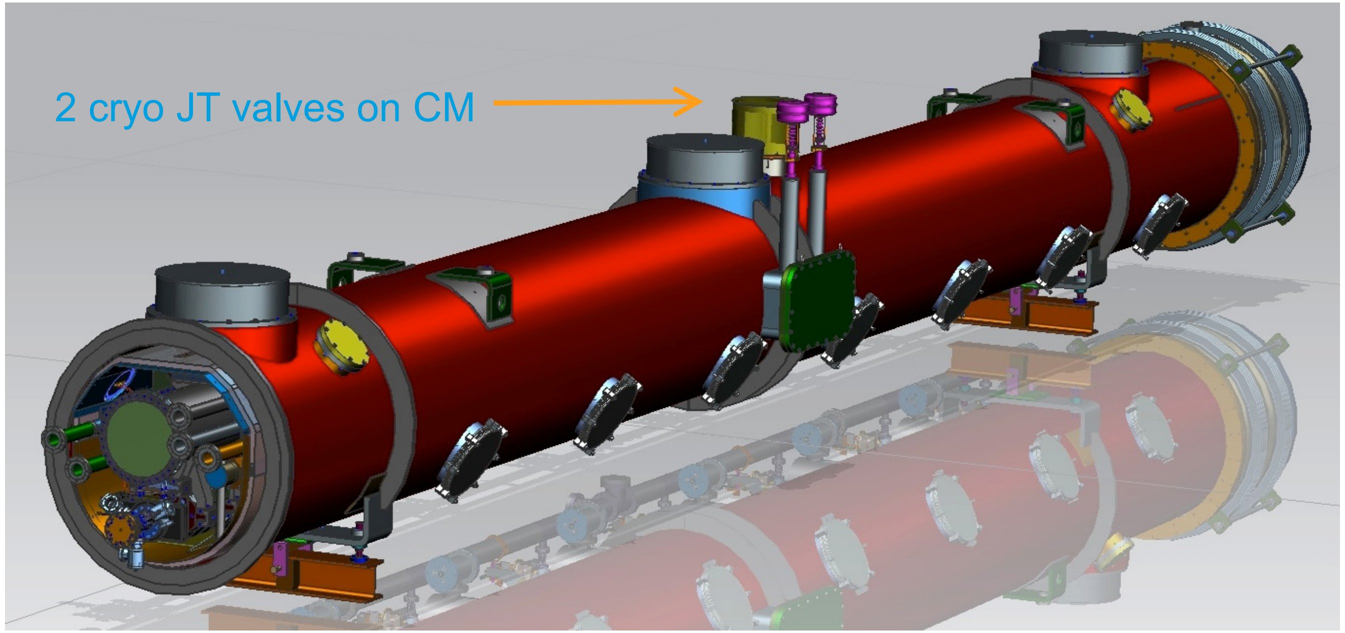
LCLS-II and E-XFEL

Differences between LCLS-II and E-XFEL [1]

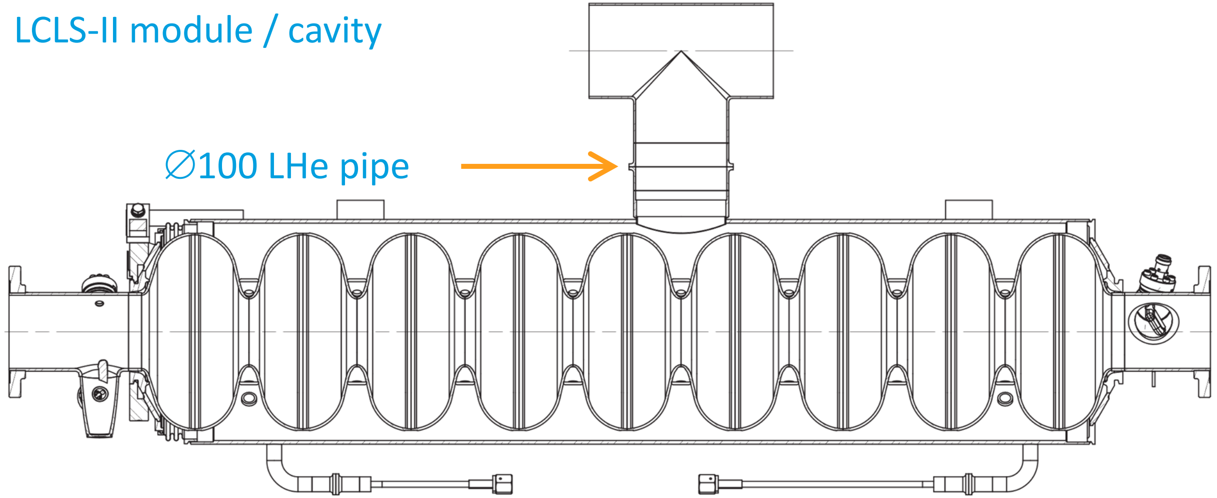
LCLS-II design parameters

4 GeV up to 300 µA CW SRF linac based on TESLA / ILC / E-XFEL 1.3 GHz technology with 110W at 2K per CM (or better) based on high-Q_0 cavity.





LCLS-II module / cavity



Differences between LCLS-II and E-XFEL [2]

LCLS-II linac parameters

component	count	parameters
linac	4 cold segments	35 8 cavity Cryomodules (1.3 GHz) 3 4 cavity Cryomodules (3.9 GHz)
1.3 GHz Cryomodule	8 cavities / CM	13 m long. Cavities + SC Magnet package + BPM
1.3 GHz 9-cell cavity	280	E_{ACC} ~ 16 MV/m; Q_0 ~ 2.7×10^{10} (avg) at 2K; Q_{load} ~ 4×10^7 bulk niobium fine-grain sheet-metal
Cavity Auxiliary	per cavity	Coaxial Input Coupler (7kW CW mode); 2 HOM couplers; lever-type cavity tuner
Injector	1	1 special cryomodule

Close to E-XFEL design, but higher Q_0 cavities specified

LCLS-II cryogenics

CM heat loads	40K	5K	2K
predicted static heat load per CM [W]	**100**	**12**	**6**
predicted dynamic heat load per powered CM [W]	**88**	**10**	**85**
predicted total linac heat load [kW]	**9.4**	**0.9**	**3.1**

For helium vessel and cryomodule thermal design, a 50% margin for heat load is taken

Differences between LCLS-II and E-XFEL [3]

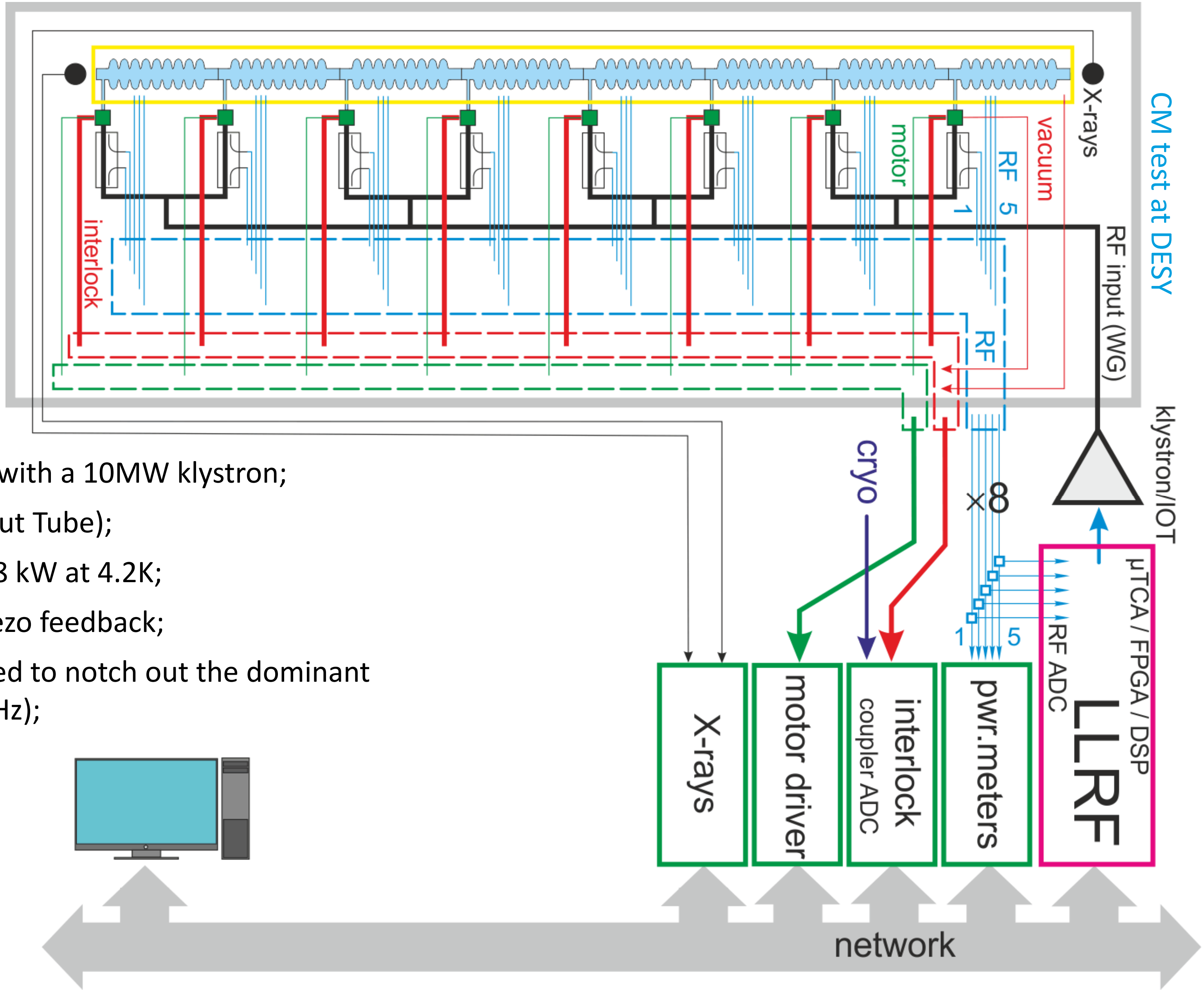
LCLS-II modifications summary

1. Origin: the TESLA Type 3+, E-XFEL, and Type 4 designs;
2. Modifications for high heat loads:
   - Larger chimney pipe from helium vessel to 2-phase pipe;
   - Larger 2-phase pipe ($\varnothing$100);
3. Closed-ended 2-phase pipe:
   - Separate 2 K liquid levels in each cryomodule;
   - 2 K JT valve on each cryomodule;
4. End lever tuner and helium vessel design for minimal df/dP;
5. Two cool-down ports in each helium vessel for uniform cool-down of bimetal joints;
6. No 5 K thermal shield:
   - But retain 5 K intercepts on input coupler;
7. Input coupler design for 7 kW CW plus some margin.

LLRF CW operation at CMTB

CW Module Test

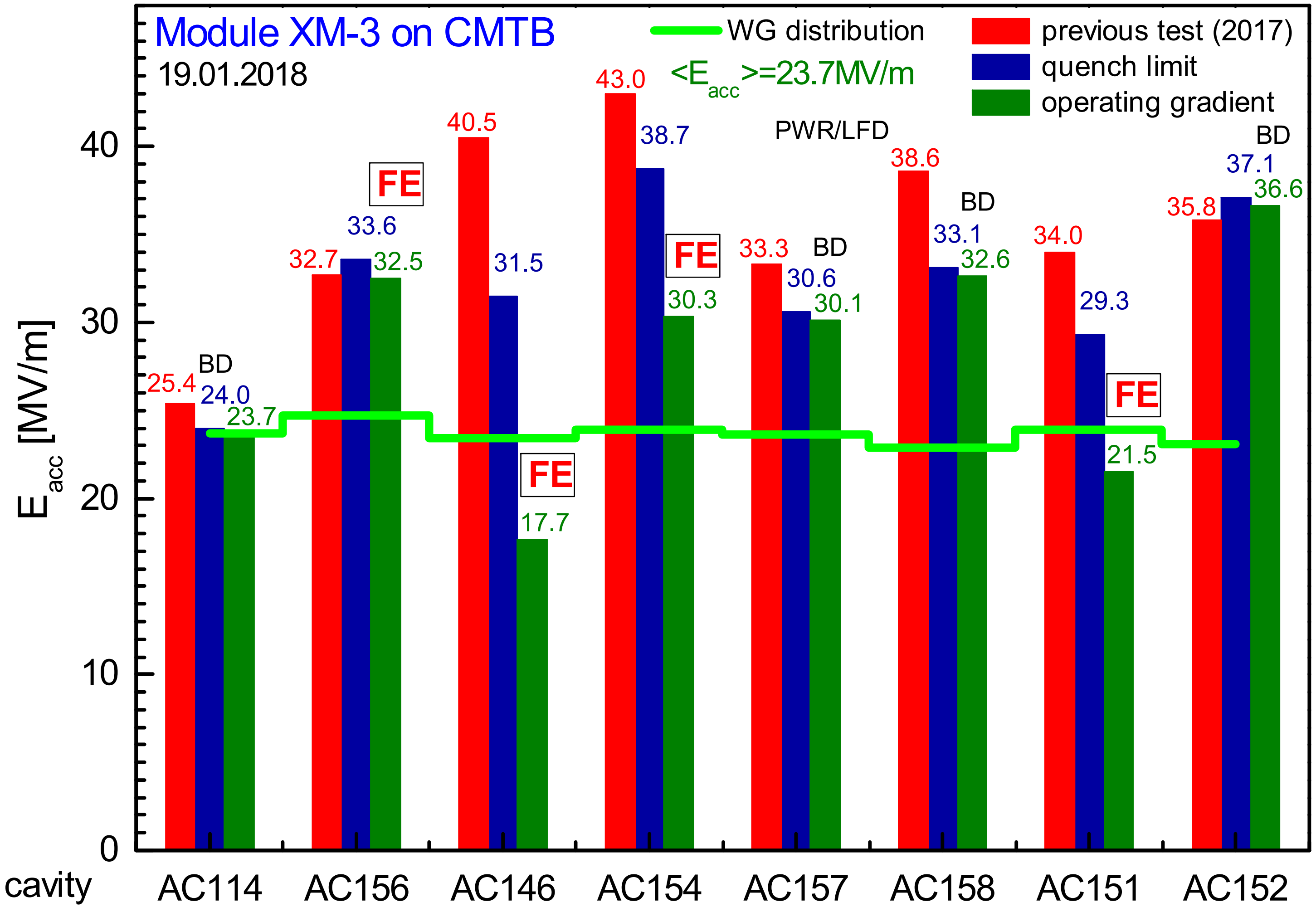
parameters, infrastructure

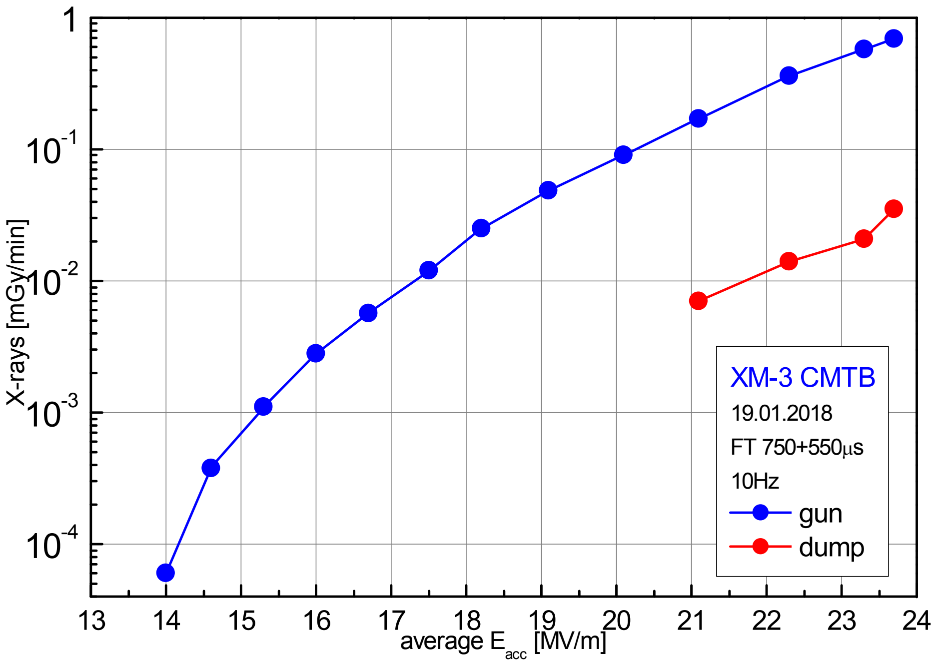


- Standard CMTB pulsed module test is done with a 10MW klystron;
- CW / LP test uses 80kW IOT (Inductive Output Tube);
- CMTB cryoplant has a cooling capacity of 6.8 kW at 4.2K;
- CW LLRF system has the RF field and fast piezo feedback;
- Active noise cancellation (ANC) is also applied to notch out the dominant microphonics frequencies (typ. ~30 and 49 Hz);

XM-3 on CMTB

pulsed test data





	BD	Eacc
1	23.7	23.73
2	33.6	24.72
3	31.5	23.41
4	38.7	23.85
5	30.6	23.63
6	33.1	22.86
7	29.3	23.94
8	37.1	23.11
	MV/m	MV/m

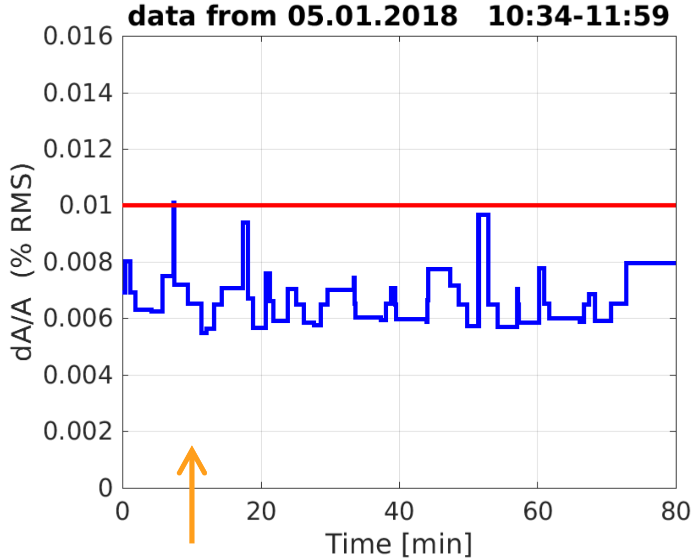
Eacc.avg 23.66 MV/m

Xray.gun 6.90E-1

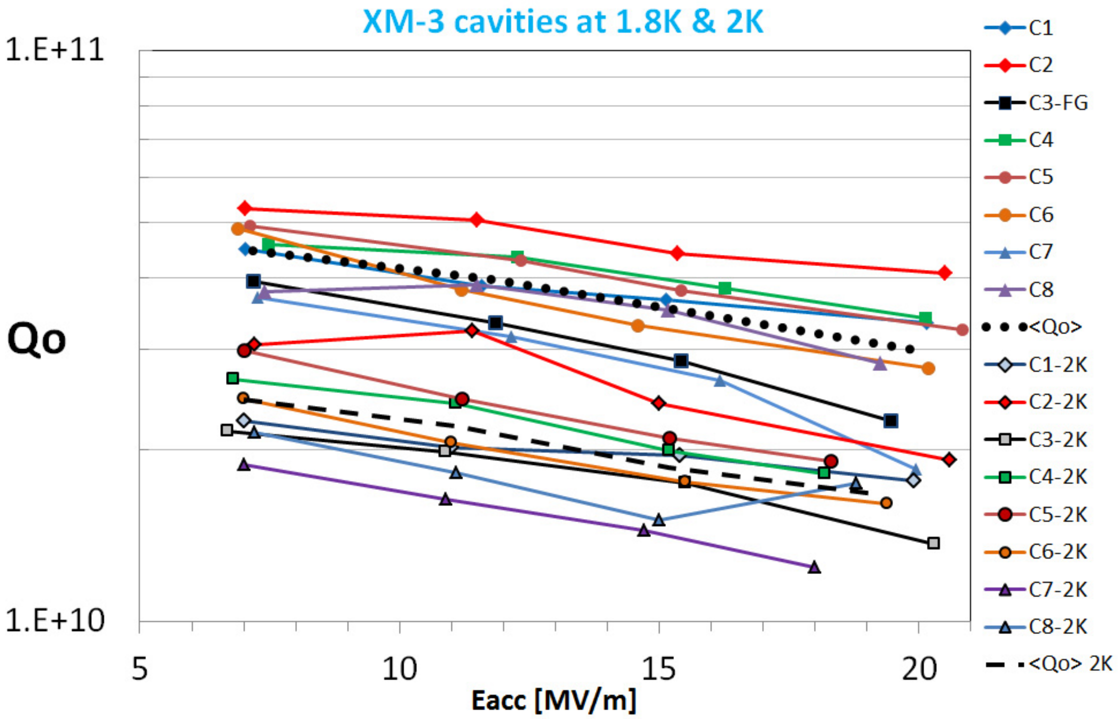
Xray.dump 3.50E-2 mGy/min

XM-3 on CMTB

CW test data

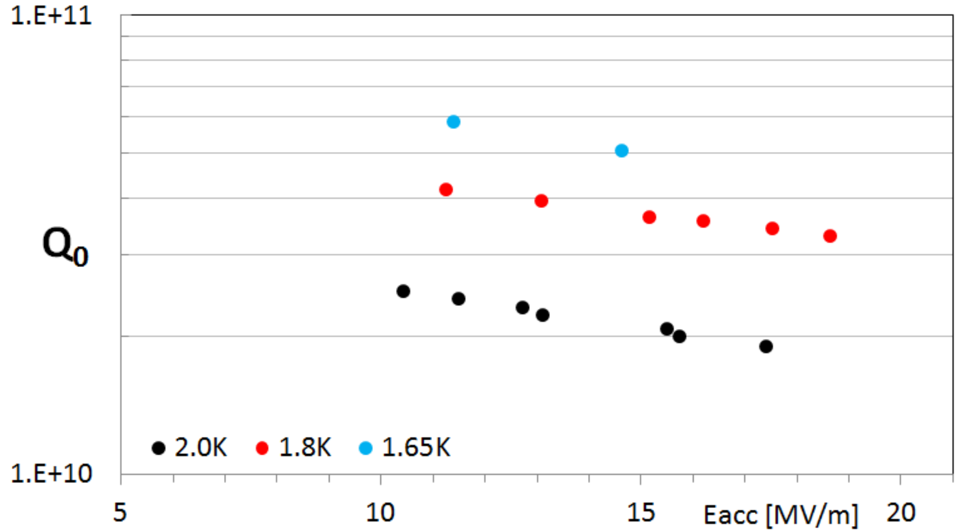


The amplitude and phase regulation level met the XFEL specifications of 0.01% and 0.01°.



XM-3 individual cavity settings for the VS test

	C1	C2	C3	C4	C5	C6	C7	C8
E_{ACC} [MV/m]	16	16	8	16	16	16	11	11
Q_L [$x10^7$]	6	6	**1.4**	6	6	6	**2.5**	**2.5**
BW [Hz]	22	22	93	22	22	22	52	52



CW Test Summary

results and outlook

1. Some very encouraging results have been obtained at CMTB during continuous wave (CW) and long pulse (LP) tests of XFEL prototype cryomodules;
2. The high Q_0 observed on large grain (LG) cavities might be an indication to pursue this approach when upgrading the front end cryomodules in the XFEL CW upgrade scenario;
3. RF stability compliant with the XFEL specifications (10^{-4}) could be achieved in amplitude and phase at an optimal CW RF operation $Q_L \sim 4\times10^7$ with 16..20 MV/m;
4. An amplitude and phase regulation of dA/A = 0.019% and dP = 0.014° respectively was achieved for a maximum gradient of 23.5 MV/m in CW mode;
5. Fast cooldown (FCD) increases Q_0 by 45% at 1.8K and 33% at 2K: magnetic flux expulsion for FCD takes place;
6. With the next 2 cryomodules to be investigated in CW mode (XM46.1 and XM50.1), we will see how these results translate to series XFEL cryomodules;
7. More work is required on the LLRF system, to improve the robustness of the piezo feedback and automate the optimization of ANC parameters (frequency detection, learning rate…), a more sophisticated controller (MIMO-based) is in preparation.

Conclusion

Summary

1. Continuous Wave (CW) mode is the origin of the SRF accelerator technology. European XFEL project was based on the Linear Collider (LC) technology (TESLA) operating in the pulsed RF power mode (10Hz / 650µs beam pulse). Many FEL user experiments will get an advantage (or become possible) with CW mode operation;
2. European XFEL SRF accelerator recently reached its project goal of 17.5 GeV electron beam energy. Possible CW mode linac operation scenario with 17 modified injector section cryo-modules (CM) may reach ~50% of that energy with 25µA (100pC and 250kHz) CW beam in European XFEL. A Long Pulse (LP) mode (duty factor < 100%) may provide even higher beam energies and still long enough FEL radiation pulses;
3. The SLAC LCLS-II project progressing to CW mode SRF linac based XFEL presents a few changes and optimizations of LC TESLA/E-XFEL technology for CW mode;
4. Some very encouraging results have been obtained at DESY on Cryo Module Test Bench (CMTB) during CW/LP tests of XFEL prototype CMs. The possibility to run an E-XFEL accelerating module in CW/LP mode was clearly shown together with reaching higher unloaded Q-factor (Q_0) of the cavities in the CM.

Acknowledgements

We want to express our gratitude to all Colleagues contributing to and supporting the experiments and R&D programs towards CW/LP SRF cavities operation modes:

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Thank you

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