Feasibility of CW and LP Operation of the XFEL Linac

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1. Introduction and motivation
    a. XFELs and their technologies
    b. Continuous wave (cw) and long pulse (lp) operation modes
    c. Limitations of DF for the XFEL linac
2. Cw and lp operation; 2 experiments
    a. Dynamic heat load vs. DF
    b. Dynamic heat load vs. Eacc
3. Final remarks and conclusion
    a. Possible upgrade scenario
    b. Conclusion

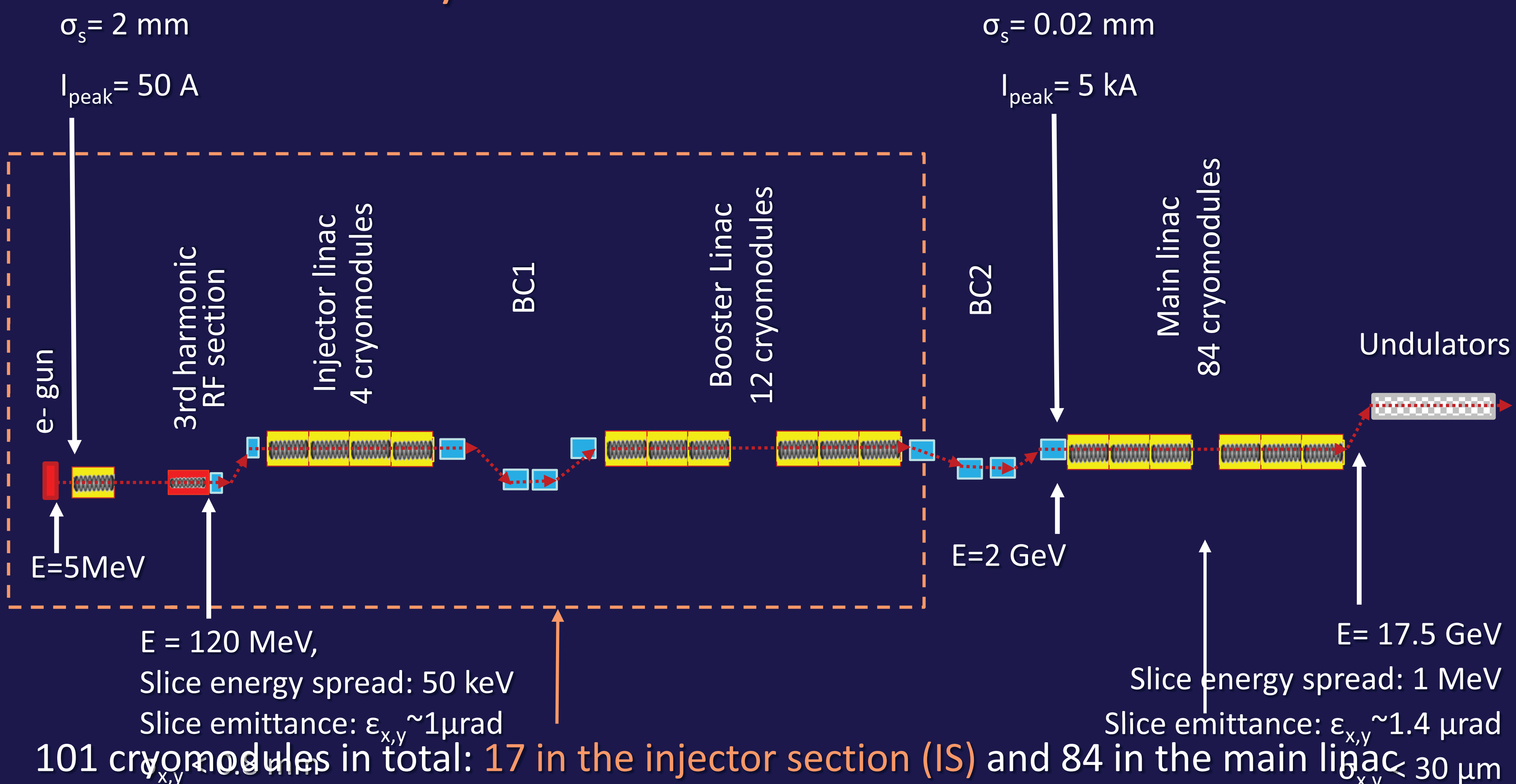
XFELs are based on LC technologies and because of this they have low Duty Factors (DF) and thus limited flexibility in time structure of the electron and photon beam

Facility	LC-project & technology	f [GHz]	Energy [GeV]	RF-pulses Length [μs]	RF-pulses Rep. Rate [Hz]	Max DF [%]
LCLS	SLC nc	2.856	14.7	3	120	<0.04
SACLA	JLC nc	5.7	8	3	60	<0.02
Swiss-FEL	JLC nc	5.7	5.8	3	100	<0.03
XFEL	TESLA sc	1.3	17.5	1380	10	1.38

(see H. Braun at IPAC12)

The European XFEL facility, because it is driven by the sc linac, has a potential for substantially larger than 1.38% DFs.

Layout of the XFEL sc linac

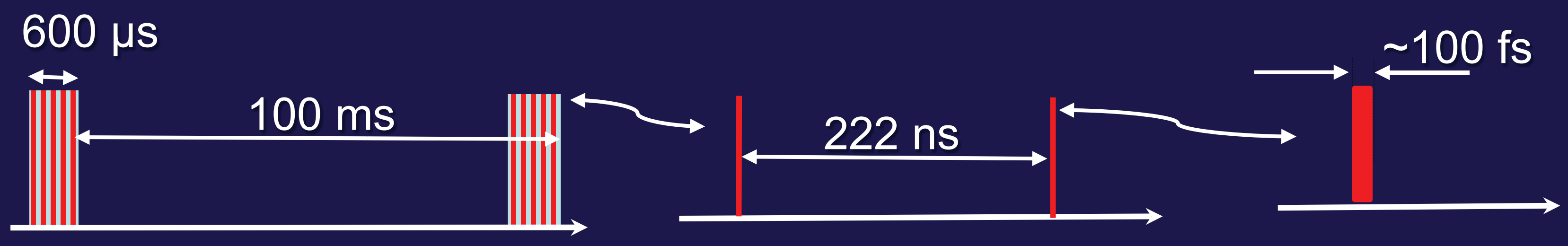


101 cryomodules in total: 17 in the injector section (IS) and 84 in the main linac

Each cryomodule houses eight 1.3 GHz 9-cell sc TESLA cavities.

Time structure of the XFEL nominal electron beam (sp, short pulse operation)

Nominal Energy	GeV	17.5
Beam pulse length	ms	0.60
Repetition rate	Hz	10
Max. # of bunches per pulse		2700
Min. bunch spacing	ns	222
Bunch charge	nC	≤ 1



XFEL will generate high average brilliance photon beam at very short λ:

$1.6 \cdot 10^{25}$ photons/0.1%bw/s/mm^2/mrad^2 @ 1 Å

Two additional features could make the XFEL photon beam even more attractive

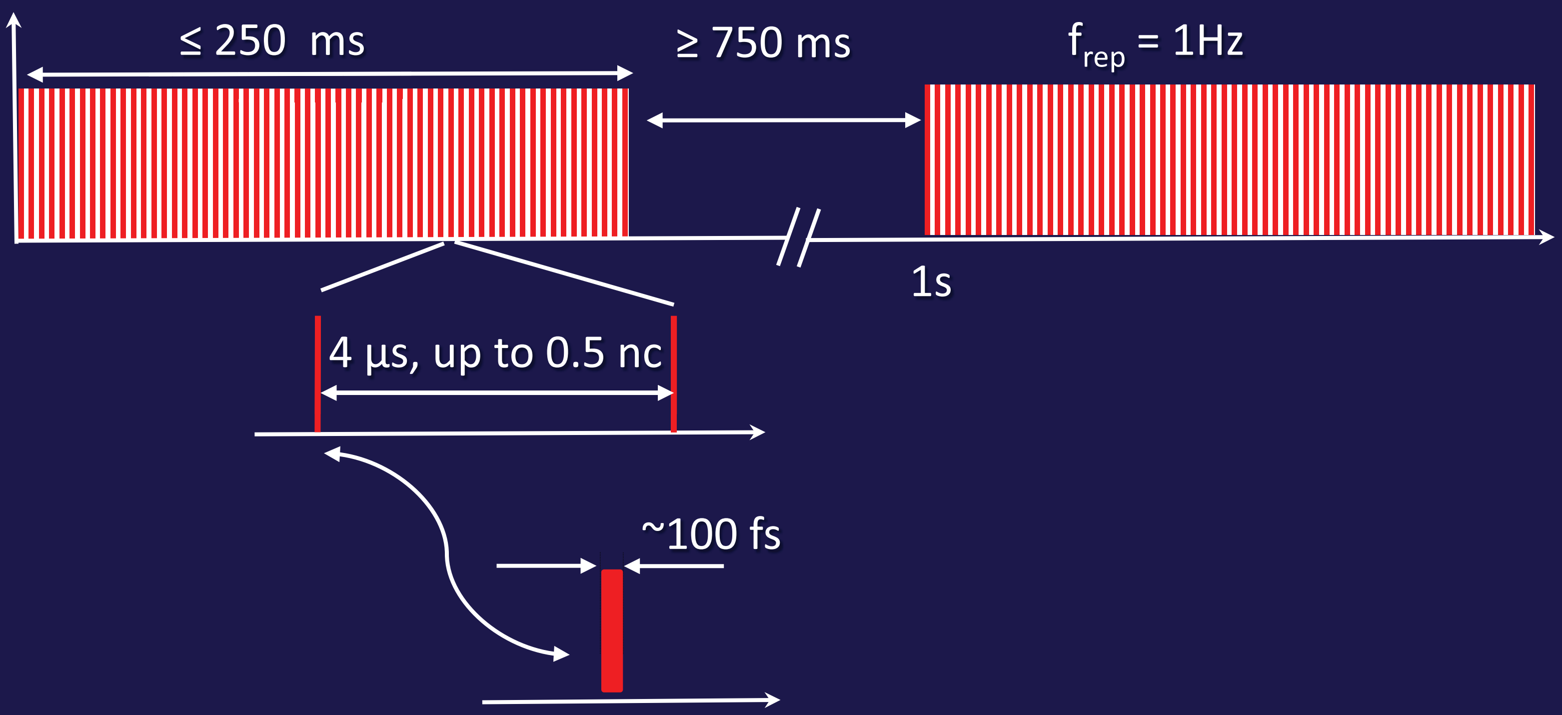
- An increased, to several μ-seconds, intra pulse distance between bunches, which will allow for less technically demanding detectors
- A few kHz photon burst repetition rate, which will allow to use less expensive optical lasers (few kHz rep.-rate) for pump-and-probe experiments

For the nominal beam, these features will lead to substantially reduced number of bunches/s and significantly lower average brilliance.

We proposed (several years ago) additional operation modes;

- Continuous wave (cw) operation for $E_{acc} \leq 7$ MV/m
- Long pulse (lp) operation at $E_{acc} > 7$ MV/m with $DF \leq (7/E_{acc})^2$
- The bunch quality should be as high as for the nominal sp operation

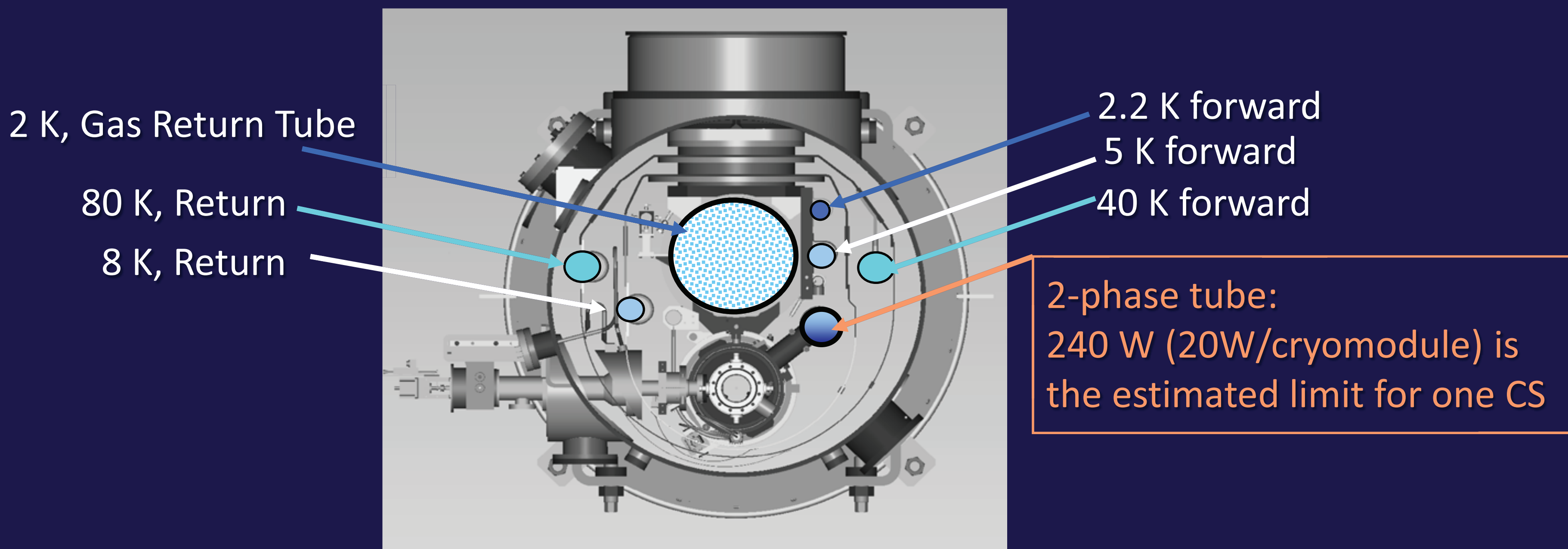
Example of lp operation at $E_{acc} = 14$ MV/m



What are the technical and "practical" limits for DF ?

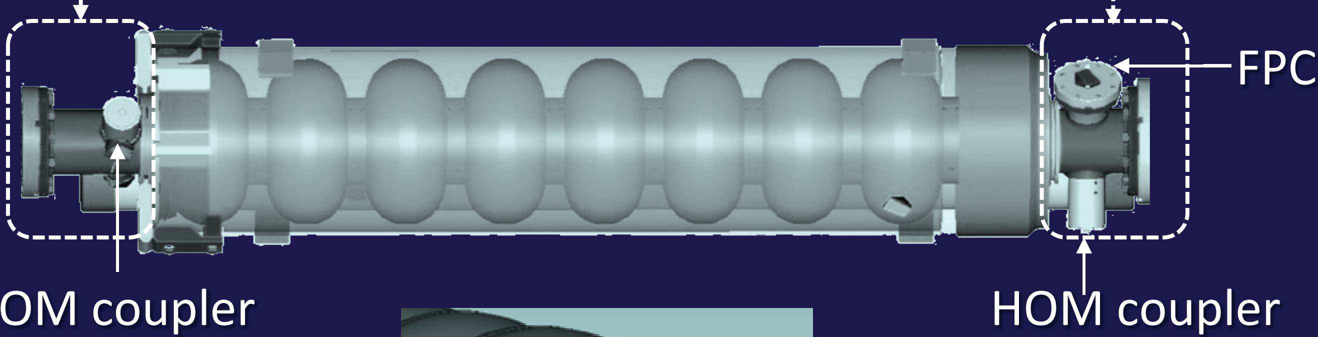
1st limit: Heat load at 2K for each cryomodule should not exceed ca. 20 W

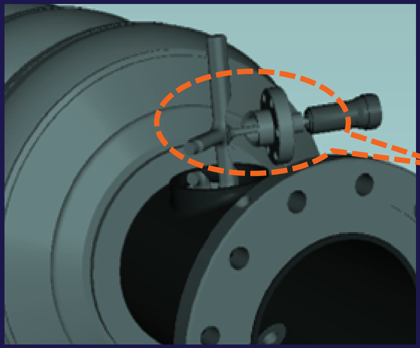
The main XFEL linac will be split in 7 cryogenic-strings (CS = 12 cryomodules)



2nd limit: Heating of the HOM couplers must not cause quenching of the end-groups

- TESLA cavity was designed for ca. 1% DF (1992)
- End groups (FPC and HOM couplers) are cooled by means of heat conduction





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

Other, "practical" limits

3th limit: An upgrade of the cryogenic plant should be "doable"

	Existing Cryo-Plant	High Duty Factor Operation
Capacity	2450 [W] (T=2K)	4980 [W] (T=1.8K)

Upgraded cryo-plant will have capacity of one unit at JLab

4th limit: New RF-sources will be added to klystrons used for the sp operation

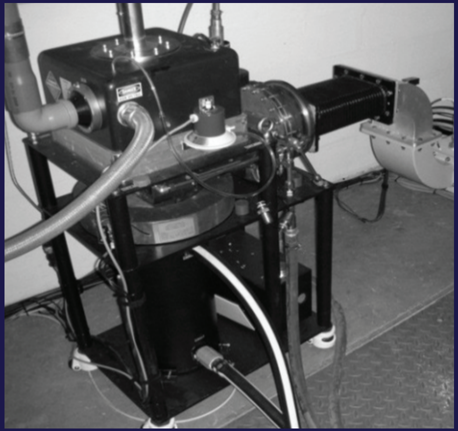
They should fit in the XFEL tunnel. We plan to have one RF-source/CM

IOT seems to be the best choice (at present):

- It is very compact, what makes it superior to solid-state amplifiers
- It takes energy from the mains only when it generates RF-power. This makes IOT more efficient for the lp operation than a cw klystron

Other, “practical” limits, cont.

The first prototype of the IOT was built by CPI and delivered to DESY in 2009.



Parameter	Unit	Spec	Measured (1stprototype)
Output P	[kW]	120	85
Gain	[dB]	>21	22.3
Efficiency	[%]	>60	54

The second prototype will be delivered in fall 2013.

Experiments with **pre-series** Cryomodules at 2K (2 examples)

We equipped in 2011 Cryo-Module Test Bed at DESY with the IOT prototype

I. Example of the cw/lp run (cryomodule PXFEL3_1)

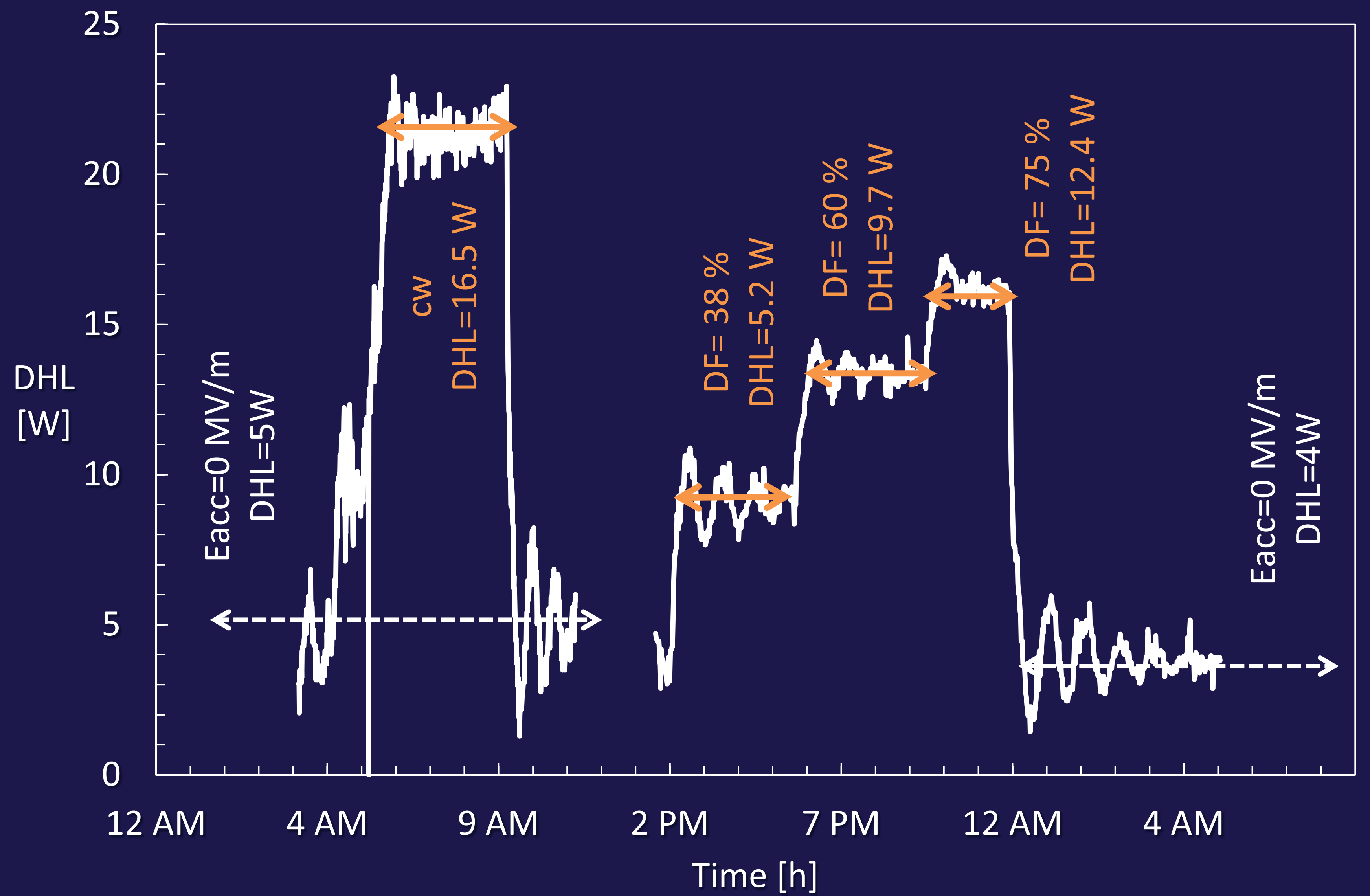
Goal: Measurement of dynamic heat load (**DHL**) vs. DF

Technical conditions:

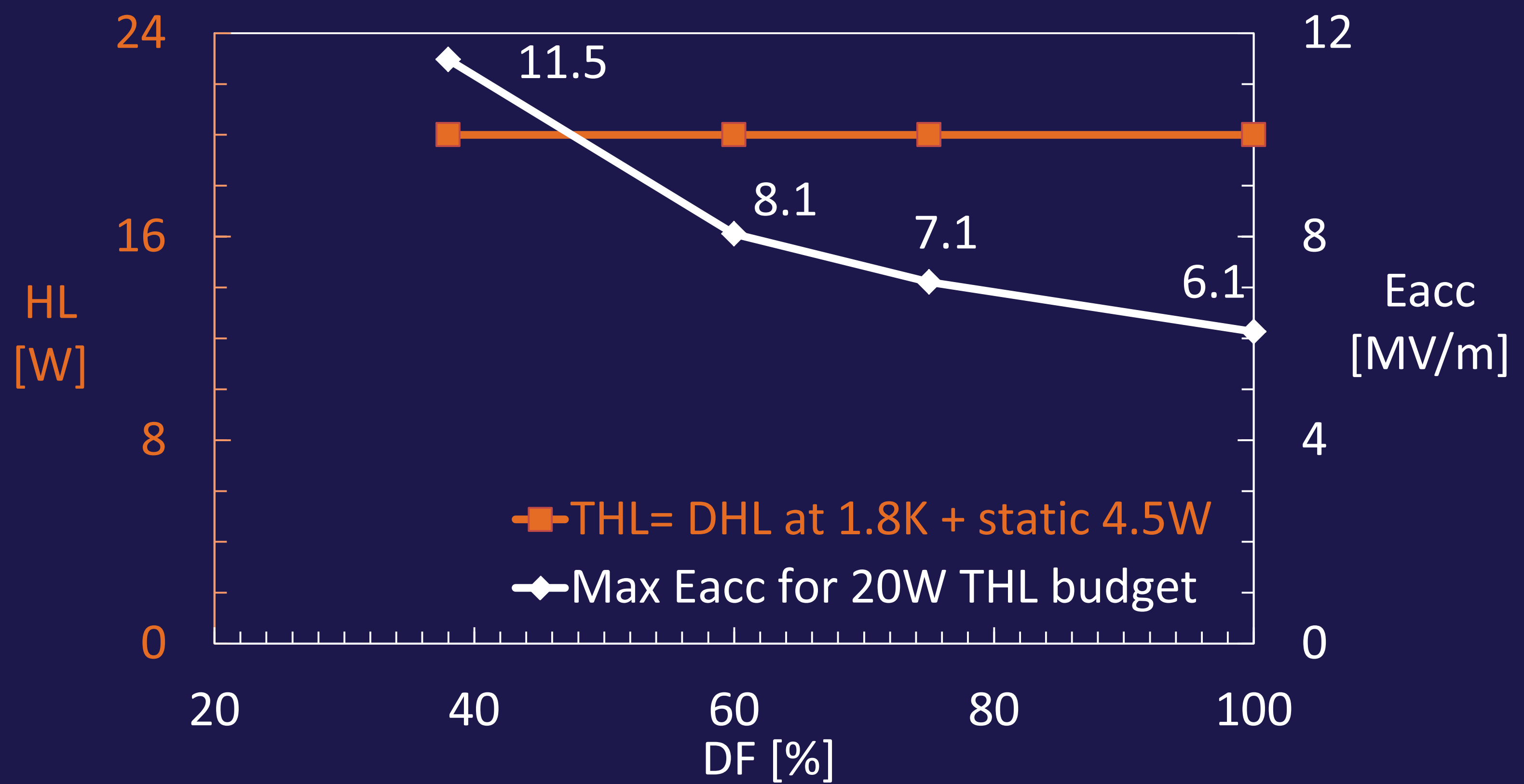
1. $< Q_{load} >$ = 1.5E7, 3 dB resonance width 87 Hz
2. E_{acc}= 5.6 MV/m
3. Only 3 cavities had new feedthroughs and new thermal connections
4. The measurements were done for DF = 38, 60, 75 and 100% (cw)
5. No abnormal behavior was observed during the test (no quench….)

Measured dynamic heat load

⇩


25
20
15
10
5
0
DHL [W]
Eacc=0 MV/m
DHL=5W
cw
DHL=16.5 W
DF= 38 %
DHL=5.2 W
DF= 60 %
DHL=9.7 W
DF= 75 %
DHL=12.4 W
Eacc=0 MV/m
DHL=4W
12 AM
4 AM
9 AM
2 PM
7 PM
12 AM
4 AM
Time [h]

Eacc vs. DF at 1.8 K (scaled from the presented test I)



Conclusion: Following operations of the XFEL linac should be possible

- cw operation at Eacc = 6.1 MV/m
- ....
- lp with DFs of ca. 38% at Eacc = 11.5 MV/m

II. Example of the cw/lp run (cryomodule PXFEL2_3)

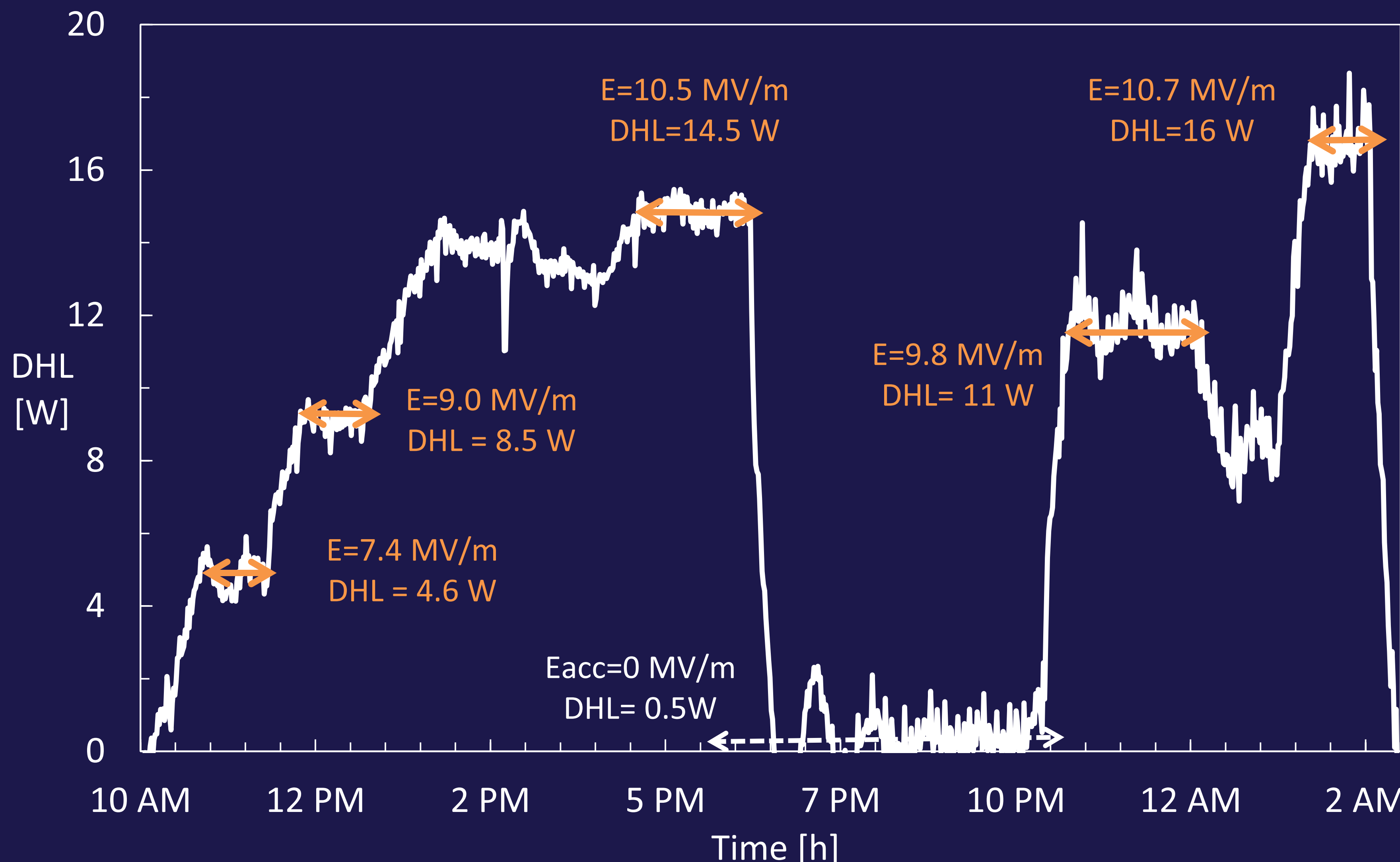
Goal: Measurement of the 2K DHL vs. Eacc

Technical conditions:

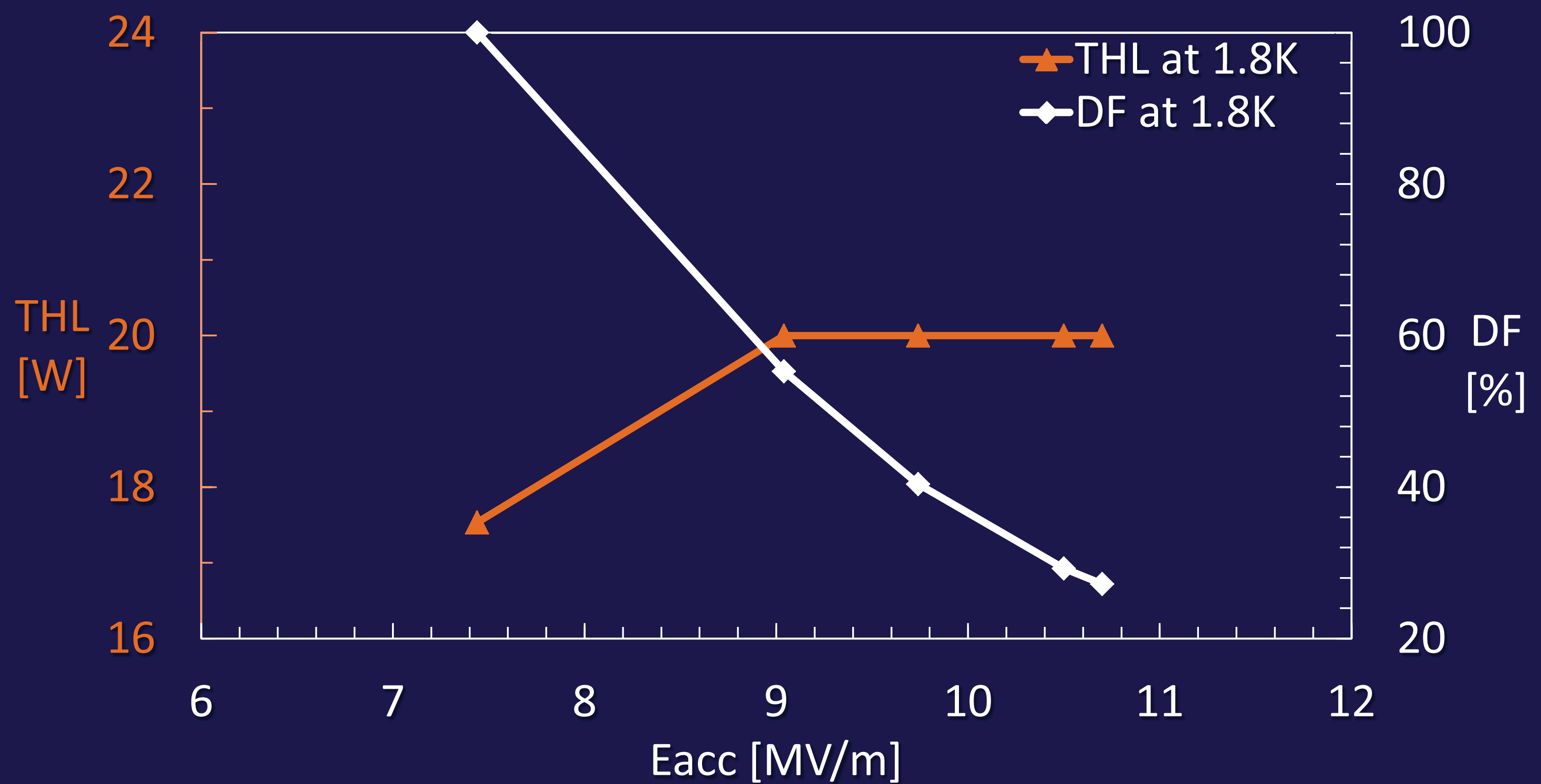
1. $< Q_{load} >$ = 1.5E7, 3 dB resonance width 87 Hz
2. Only 2 cavities had new feedthroughs and new thermal connections
3. The measurements were done for DF = 20%
4. Eacc = 7.4, 9.0, 9.8, 10.5 and 10.7 MV/m
5. No abnormal behavior was observed during the test (no quench….)

Measured dynamic heat load

⇩


20
16
12
8
4
0
DHL
[W]
E=10.5 MV/m
DHL=14.5 W
E=10.7 MV/m
DHL=16 W
E=9.8 MV/m
DHL= 11 W
E=9.0 MV/m
DHL = 8.5 W
E=7.4 MV/m
DHL = 4.6 W
Eacc=0 MV/m
DHL= 0.5W
10 AM
12 PM
2 PM
5 PM
7 PM
10 PM
12 AM
2 AM
Time [h]

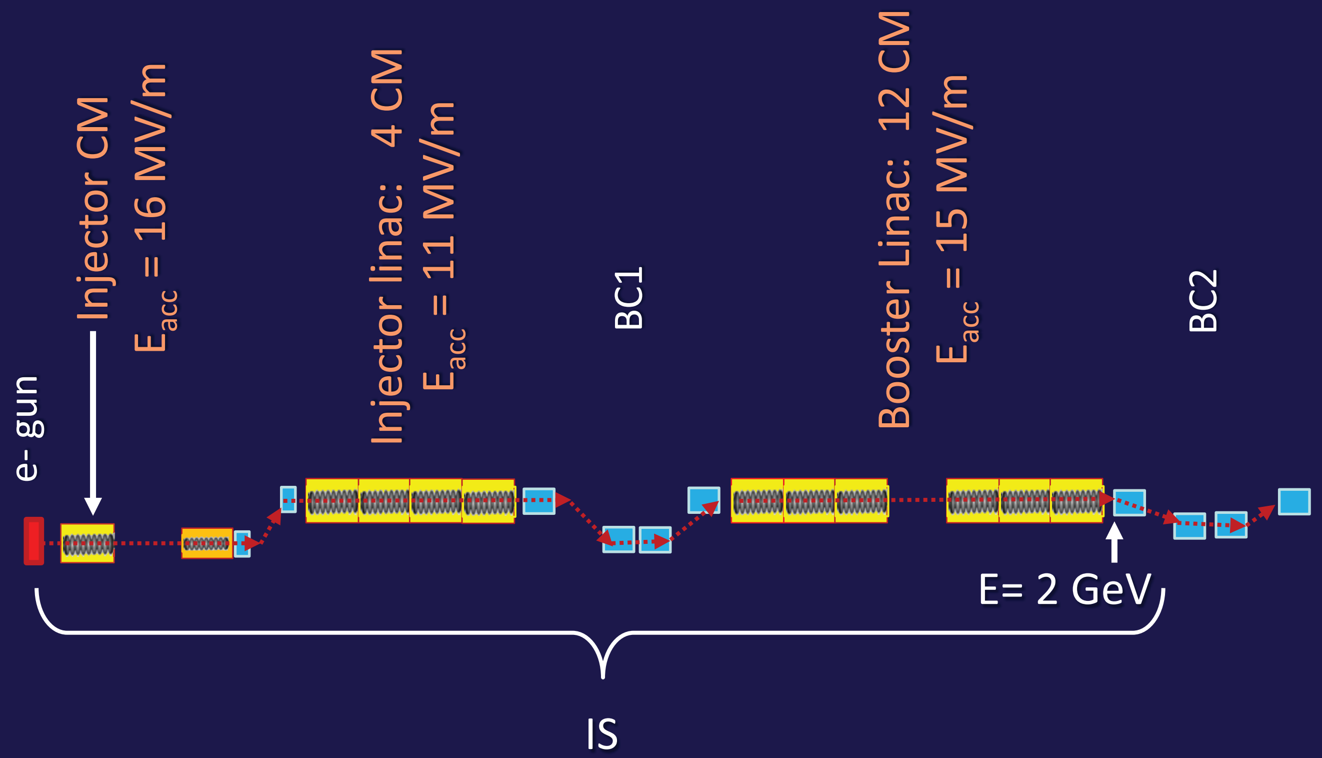
DF vs. Eacc at 1.8 K (scaled from the presented test II)



Conclusion: Following operations of the XFEL linac should be possible

- cw operation at Eacc = 7.4 MV/m
- ……….
- lp with DFs of ca. 24 % at Eacc = 11 MV/m.

To ensure the bunch quality we need the same gradients in the injector section (IS) as for the nominal sp operation



- Gradients in the IS are > 7 MV/m
- We need: low current cw-operating 9-cell TESLA-like cavities
- R&D program is in progress.

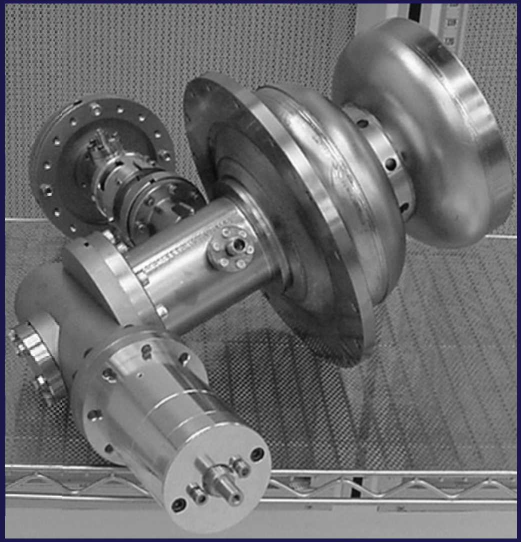
Assuming, the IS will be equipped with 136 new cw-cavities and 12 out of 17 present CMs will be relocated to the end of ML

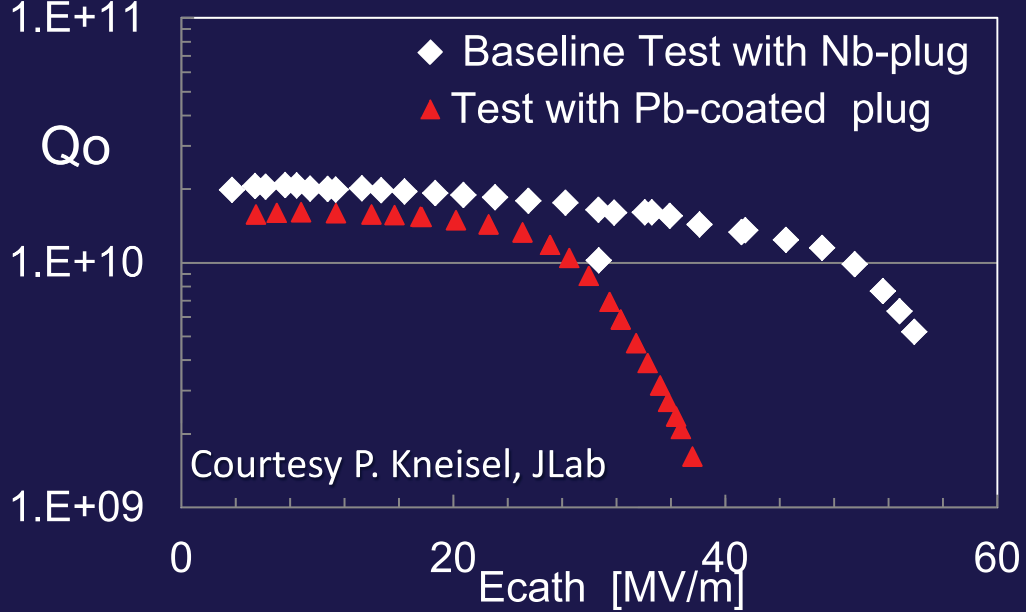
Energy and DFs for the scenario with new IS

Operation mode	Energy [GeV]	Eacc ML [MV/m]	RF-pulses Length [ms]	RF-pulses Rep. Rate [Hz]	Max DF [%]
sp	17.5		1.380	10	1.38
cw	7.2	6.5	-	-	100
lp	10	10	350	1	-> 35
lp	14	15	150	1	-> 15

Recently presented modeling by Evgeny Schneidmiller and Mikhail Yurkov showed that lasing at 1 Å with 0.5 nC and 0.7 mm·mrad emittance seems possible at 10 GeV (more tomorrow by Evgeny)

1. The experiments showed feasibility of more flexible operations for the XFEL
2. Following must be demonstrated in near future with coming XFEL CMs
   - Benefit of operation at 1.8 K
   - Higher gradients than 10.7 MV/m in lp operation
3. All superconducting electron gun still needs more R&D (program in progress)





4. R&D programs for cw-cavities should give an answer by the end of 2015/16 at what gradients we can operate reliable IS of the linac.

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DESY: V. Ayvazyan, J. Branlard, M. Ebert, J. Eschke, T. Feldmann, A. Gössel, D. Kostin, M. Kudla, F. Mittag, W. Merz, C. Müller, R. Onken, I. Sandvoss, E. Schneidmiller, A. Sulimov, M. Yurkov

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Thank you for your attention