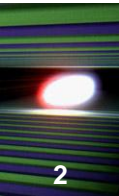




# Superconducting Linear Accelerator for the European XFEL

J. Sekutowicz  
DESY





## ■ 1st-stage; pulse operation

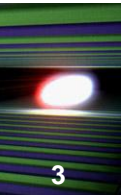
- Beam parameters for the nominal operation
- Electron source
- Superconducting accelerator
- RF- and cryogenic system

## ■ 2nd-stage (after several years of the pulse operation); near-cw operation

- Beam parameters for the near-cw operation
- Cryogenic plant
- RF-power sources
- Electron source

## ■ Final remarks

# 1st-stage; Photon beam parameters



Spec for the photon beam:

## X-ray FEL radiation (0.2 -12.4 keV)

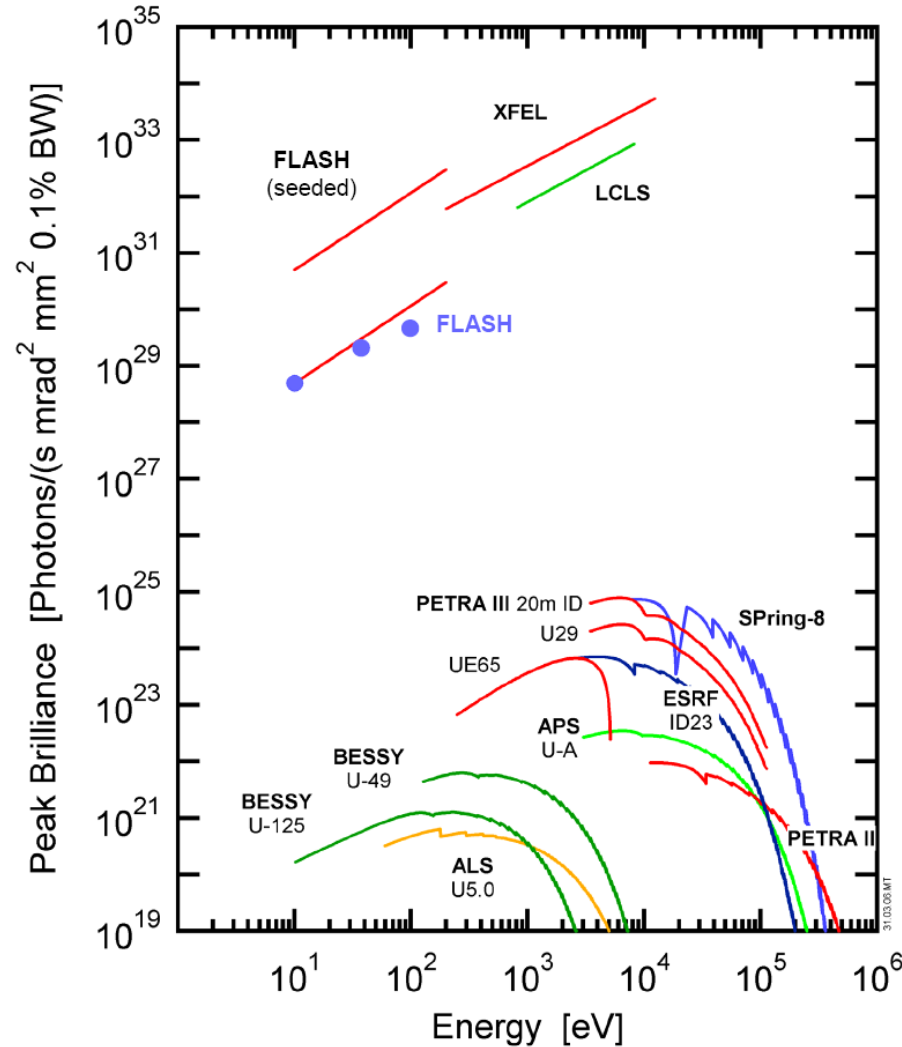
- ultrashort pulse duration <100 fs (rms)
- many photons/pulse  $10^{12}$ - $10^{14}$
- high peak/average power 20GW/65W (1Å)
- high peak/average brilliance  $5E33/1.6E25$  (\*)

## Spontaneous radiation (20-90 keV)

- ultrashort pulse duration <100 fs (rms)
- high peak/average brilliance  $2E27/2E19$  (\*\*)

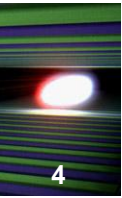
(\*) at 12.4 keV, units: photons/0.1%bw/s/mm<sup>2</sup>/mrad<sup>2</sup>

(\*\*) at 90 keV, units: photons/0.1%bw/s/mm<sup>2</sup>/mrad<sup>2</sup>



Peak FEL brilliance vs. photon energy

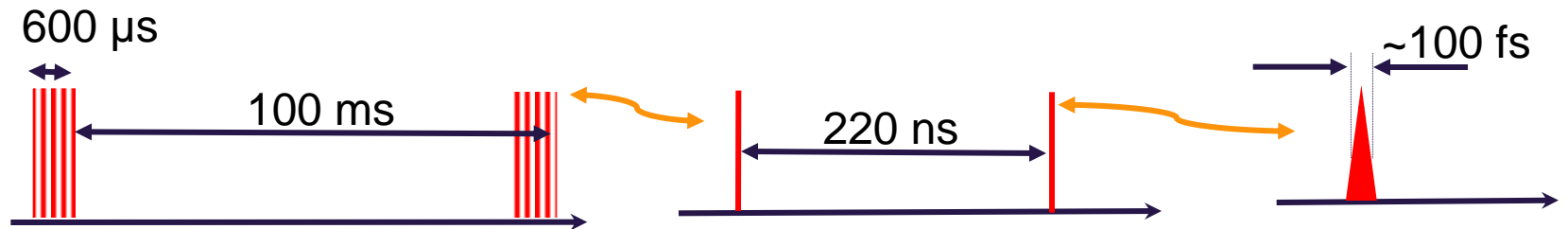
# 1st-stage; Beam parameters for the nominal operation



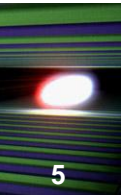
Our goal is to produce reliably the bunched beam, with following parameters:

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	220
Bunch charge	nC	1
Bunch length, $\sigma_z$	$\mu\text{m}$	< 20
Emittance (slice) at undulator	$\mu\text{rad}$	< 1.4
Energy spread (slice) at undulator	MeV	1

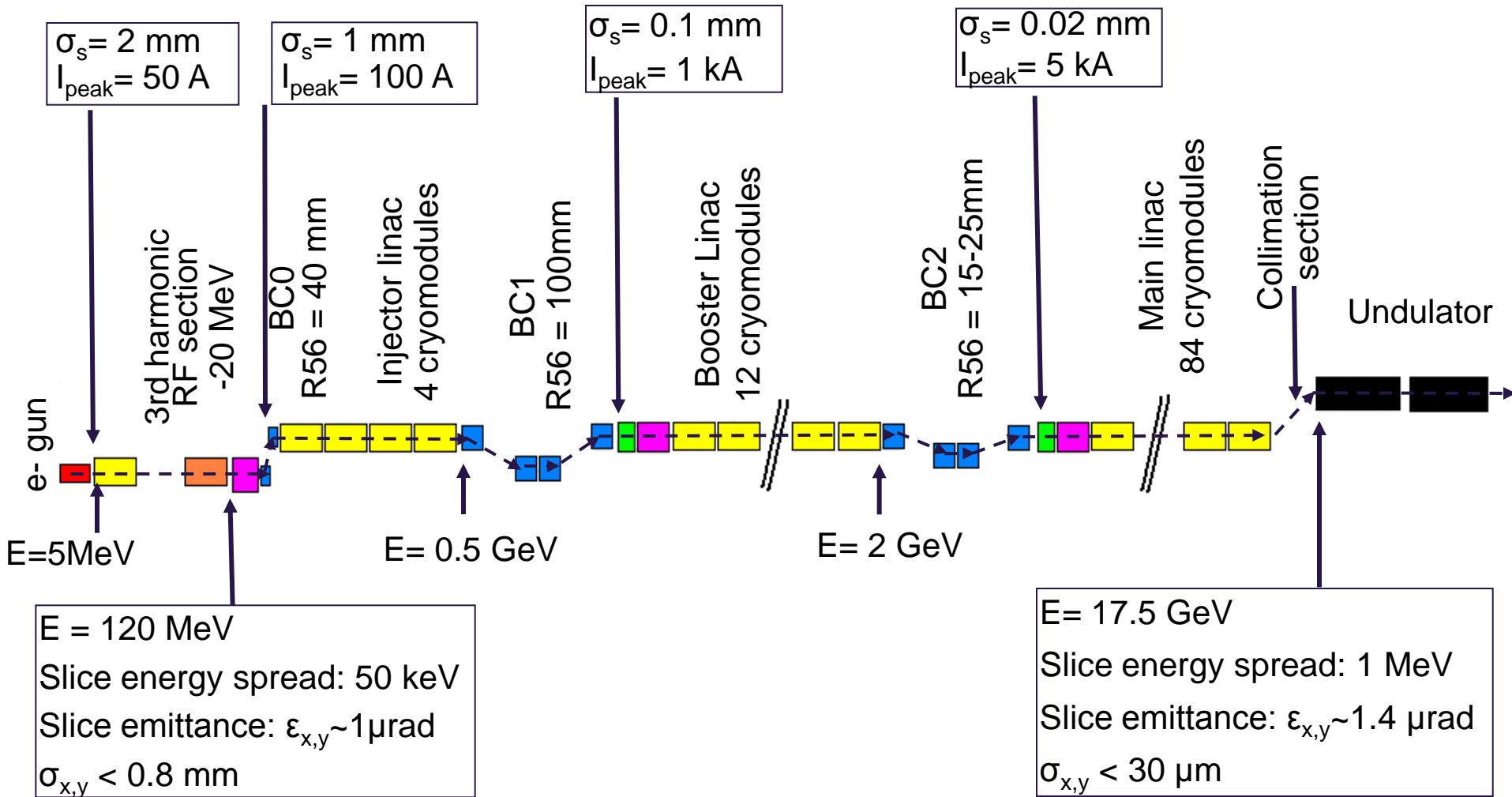
The time structure of the beam:



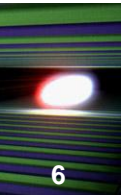
# 1st-stage; Beam parameters for the nominal operation



## Bunch properties along the linac



# 1st-stage; Electron source



RF-gun: Cu, 1.3GHz, 1.6-cell

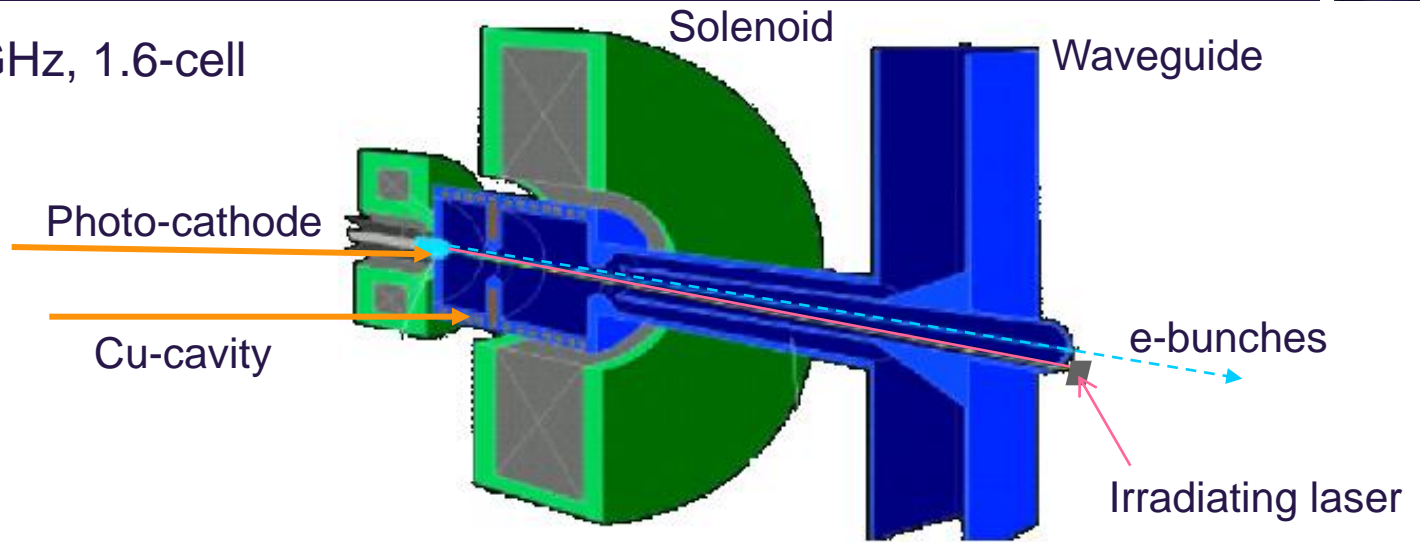
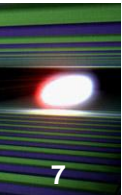
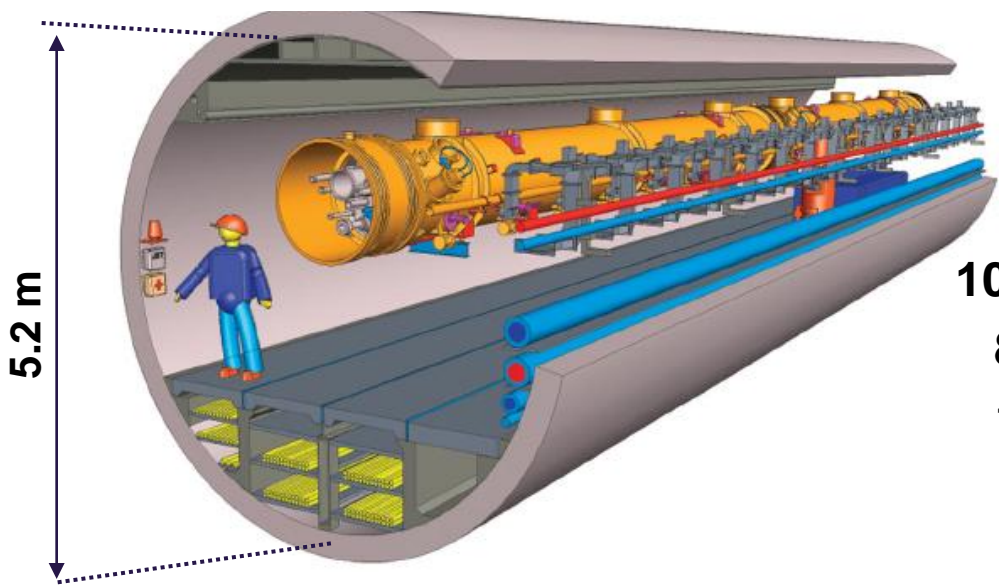
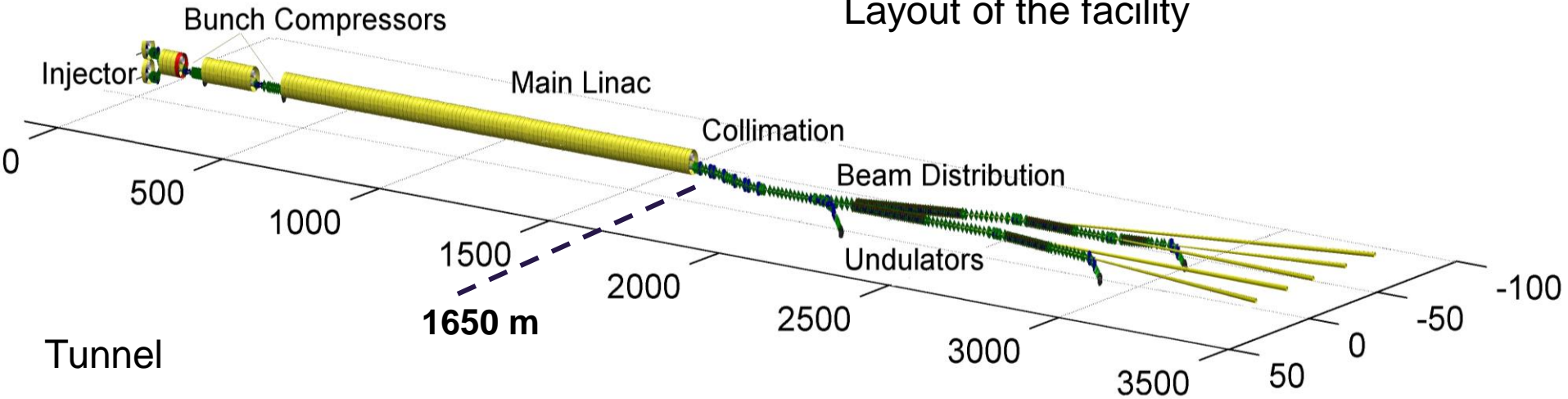


Photo-emitter	-	Cs <sub>2</sub> Te
Laser Pulse length (total)	[ps]	20
Laser Pulse rise/fall time	[ps]	2
Laser Spot radius	[mm]	1.1
Quantum Efficiency (QE) @ 262 nm	[%]	~1+
Peak electric field on the cathode	[MV/m]	60
<b>Peak power / Power dissipated</b>	<b>[kW]</b>	<b>5000 / 50</b>
<b>DF</b>	<b>[%]</b>	<b>~ 1</b>

# 1st-stage; Superconducting accelerator

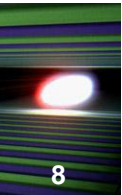


Layout of the facility

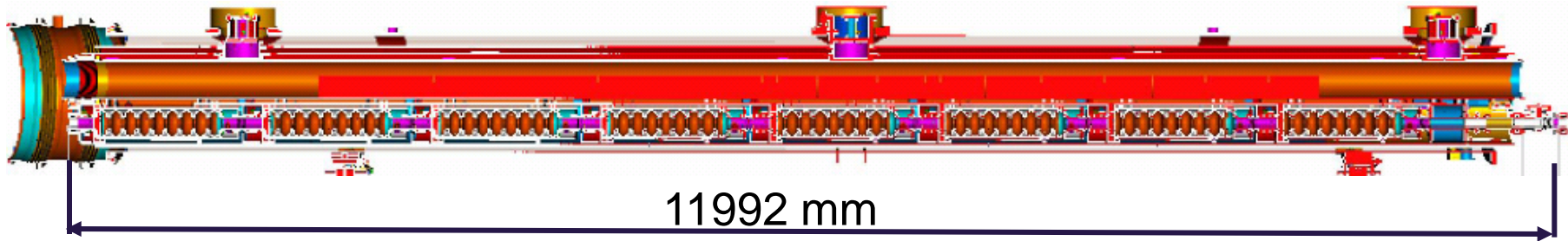


- 101 cryomodules in total**
- 84 in the main linac
- 12 between two bunch compressors
- 4 between injector and BC1
- 1 in the injector

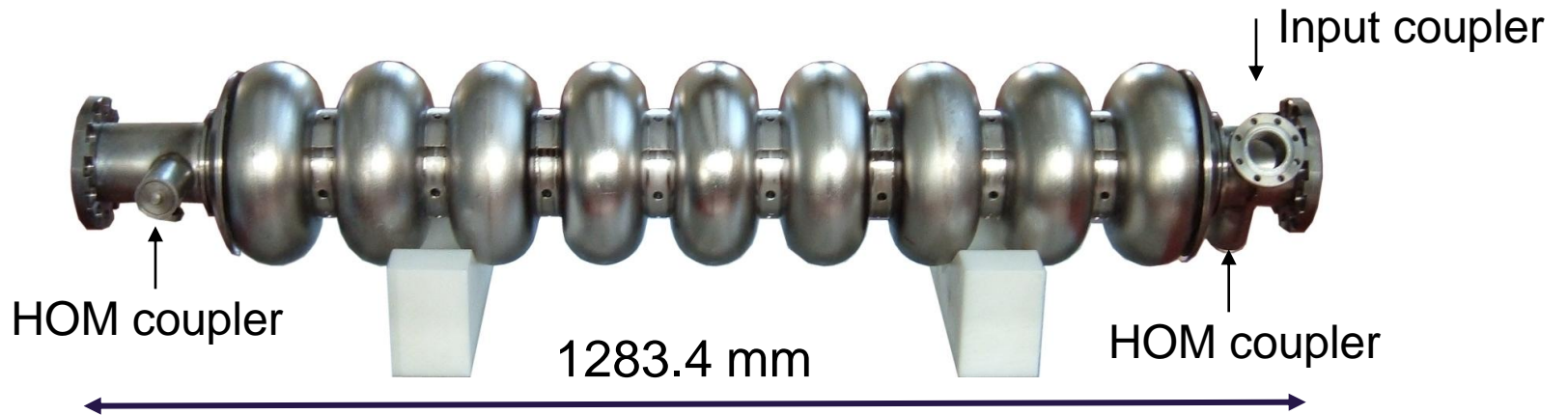
1st-stage; Superconducting accelerator



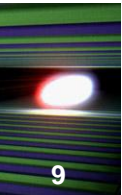
Cryomodule housing: 8 cavities, quadrupole and BPM



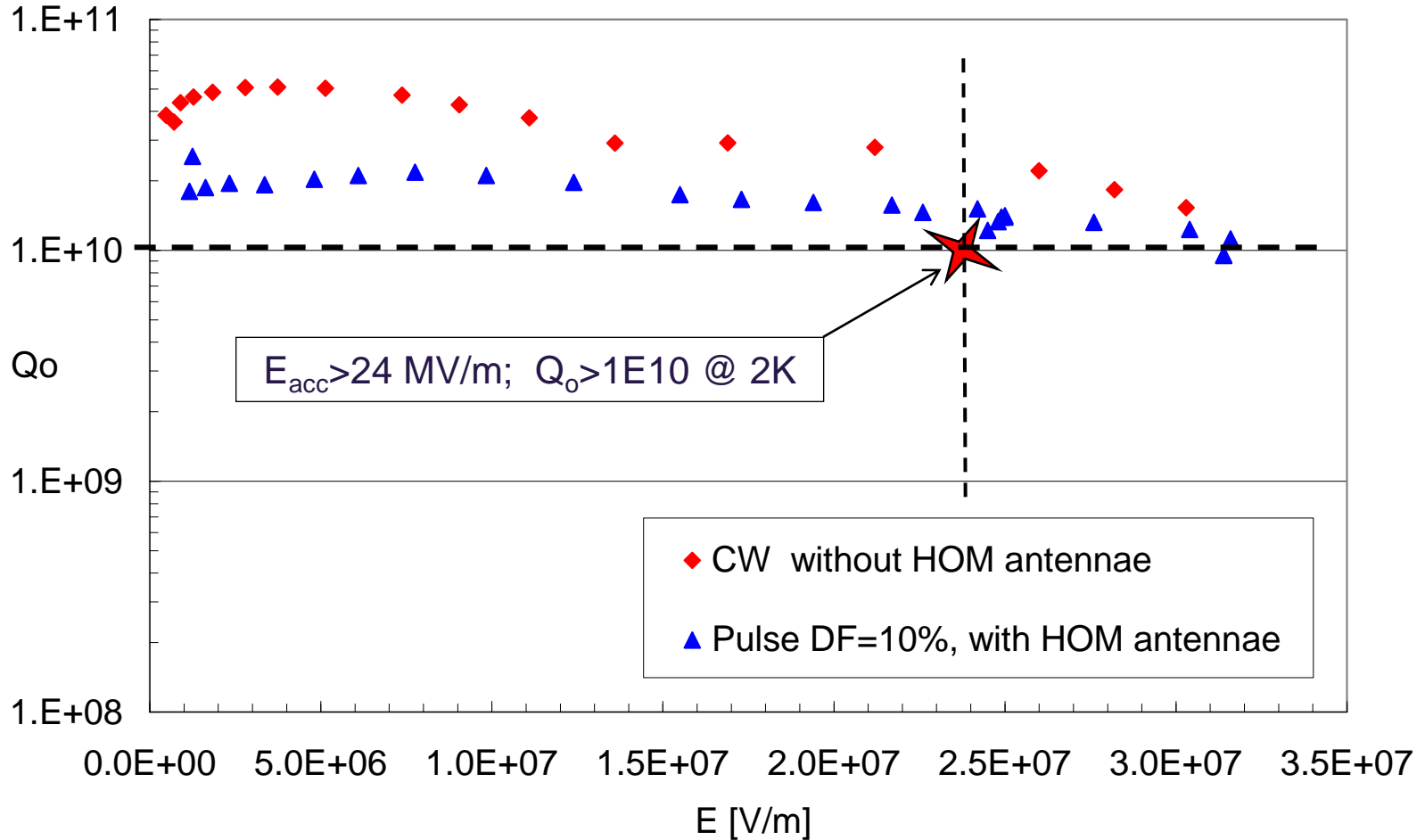
1.3 GHz, standing wave, 9-cell superconducting cavity, made of pure Nb



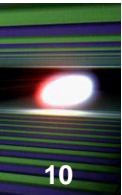
1st-stage; Superconducting accelerator



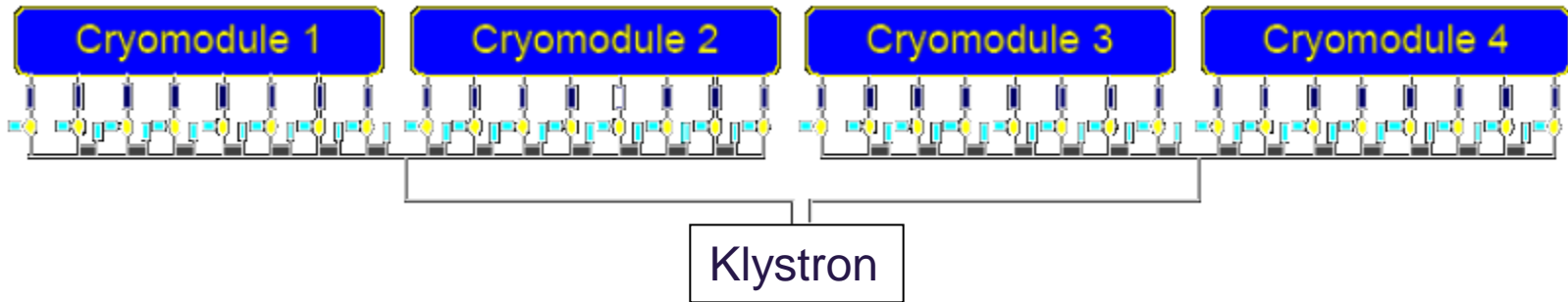
Spec for the superconducting cavities with assembled HOM antennae:  
 $E_{acc} > 24 \text{ MV/m}$ ;  $Q_o > 1E+10$  at 2K and  $DF=0.1$



# 1st-stage; RF- and cryogenic system

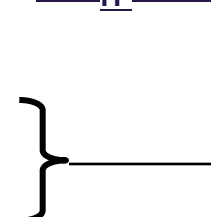


RF- system: 25 RF units. The unit = 4 cryomodules + RF-power source (klystron)

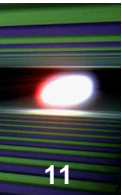


It is pulse RF- system with the nominal duty factor  $DF_{rf} = 1.4\%$

Frequency	[GHz]	1.3
RF Pulse Duration	[ms]	1.38
Repetition Rate	[Hz]	10
Cathode Voltage	[kV]	95
Beam Current	[A]	103
HV Pulse Duration	[ms]	1.57
Microperveance		3.5
RF Peak Power	[MW]	5.2



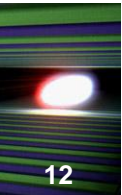
# 1st-stage; RF- and cryogenic system



Three klystrons produced at Thales, CPI and Toshiba.



## 1st-stage; RF- and cryogenic system



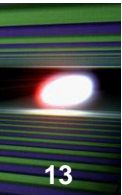
## Cryogenic plant capacity and loads for the pulse operation (101 cryomodules)

T range	Capacity Heat Load [W]	Heat Load (101 CM) [W]	Capacity Mass flow [g/s]	Mass flow [g/s]
<b>2 K</b>	<b>2450</b>	<b>1468</b>	<b>117</b>	<b>70</b>
5-8 K	4000	2264	142	81
40-80 K	30000	15307	142	73

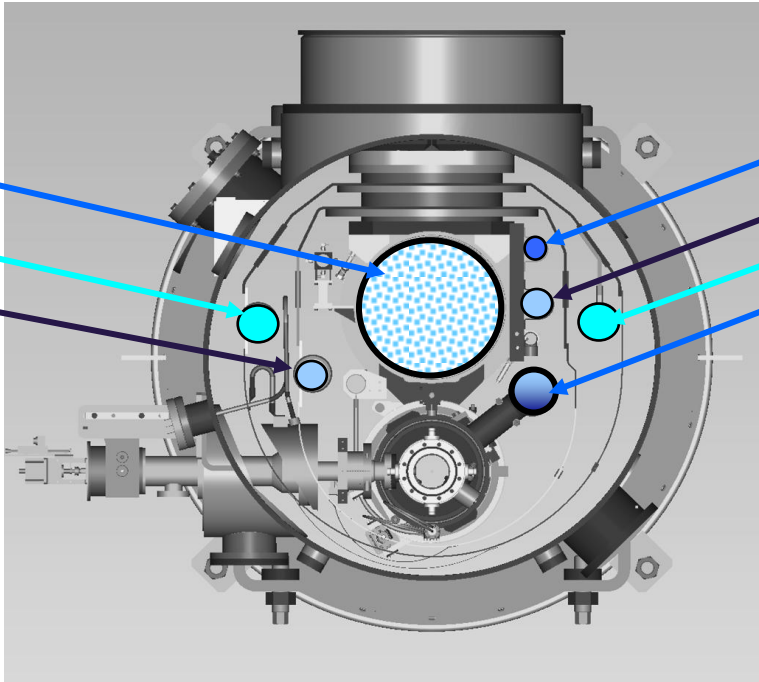
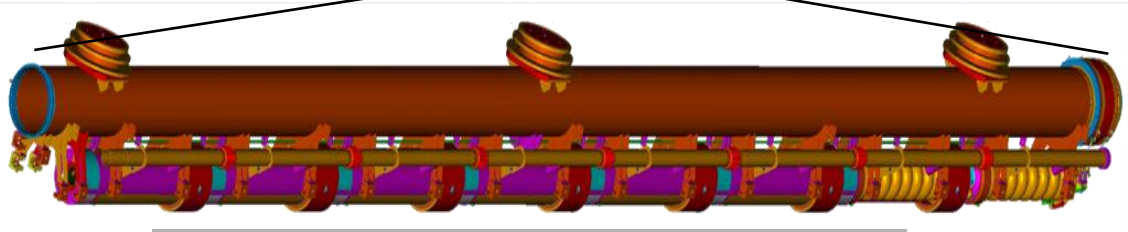
## Cryogenic plant power consumption (full capacity)

T range	Ratio: (AC power) / (1W load) [W/W]	AC Power [MW]	Percentage [%]
2 K	870	2.13	59
5-8 K	220	0.88	24
40-80 K	20	0.60	17
<b>Total</b>		<b>3.61</b>	<b>100</b>

# 1st-stage; RF- and cryogenic system

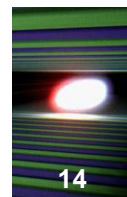


Linac has been split in 8 cryogenic-strings (CS) + 1+4 cryomodules;  
 CS = 12 cryomodules supplied with LHe (2.2 K, 1 Bar) via Joule-Thomson valve.



2 K, Gas Return Tube  
 80 K, Return  
 8 K, Return

2.2 K forward  
 5 K forward  
 40 K forward  
 2-phase tube:  
**240 W (20W/cryomodule)**  
 is the estimated limit for one CS. The limit was not yet experimentally proven.  
*(B. Petersen, DESY)*



- The linac design for the 1st stage should enable the 2nd stage.
- The present investment cost must not be increase due to the present modifications for the second stage
- The near-cw operation will be “implemented” if and when the Community will ask for. No schedule has been proposed yet.
- The 2nd stage operation we propose seems to have high probability, but the future may show that other operation mode is more attractive.
- The new operation mode should guarantee the beam quality not worse than that for the pulse operation; requirements mainly for the injector section and LLRF electronic.

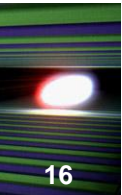
## 2nd-stage: Beam parameters for the near-cw operation

In following, we will discuss an example of the parameter set for near-cw operation allowing for the beam energy up to **17.5 GeV**

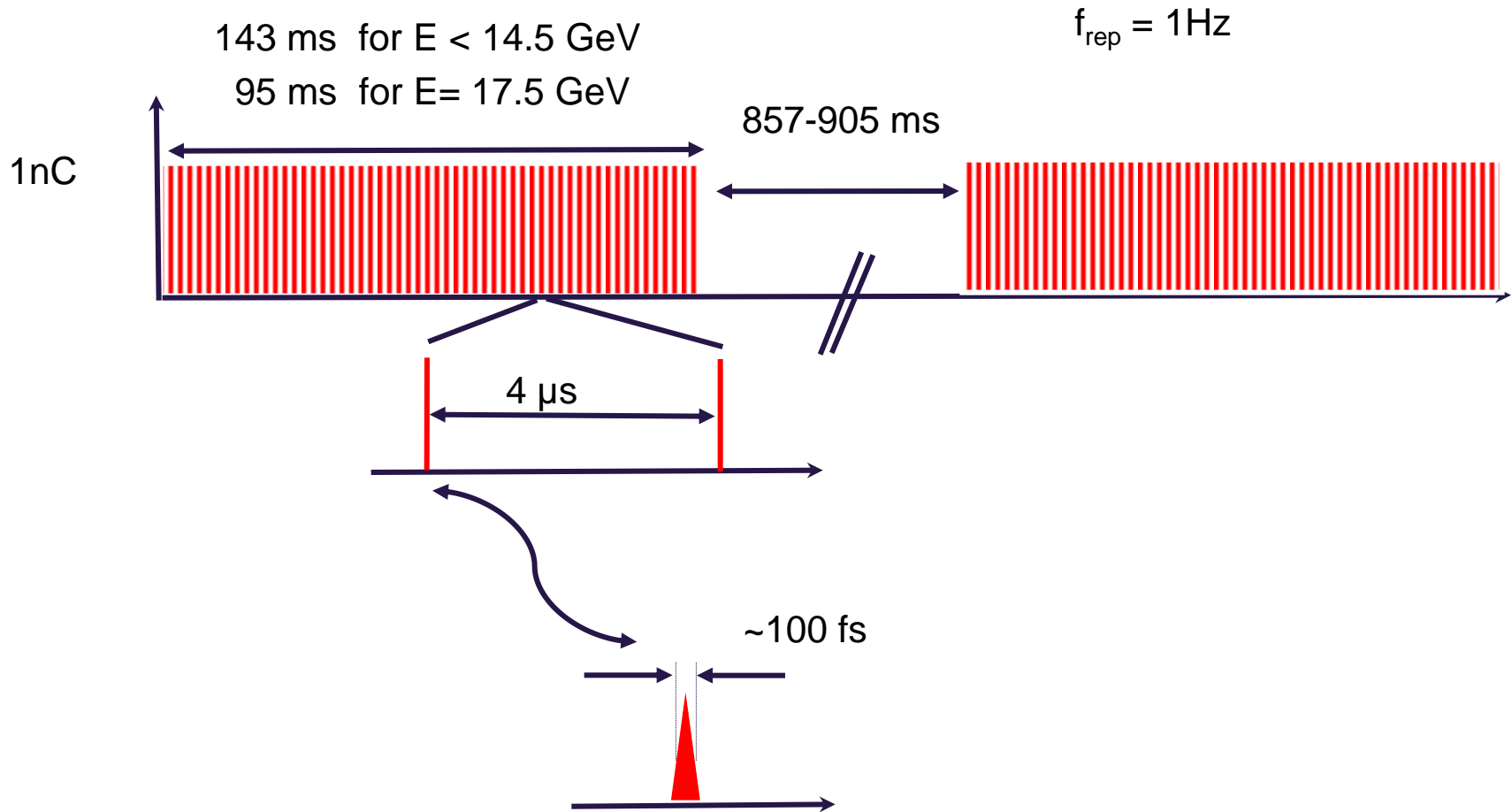
## Assumptions:

1. Cryogenic losses  $\leq$  **20W** /cryomodule (32 W in the injector cryomodule)
2. Operational T for the LHe is **1.8 K**
3. RF power  $\sim$ **15 kW** /cavity
4. Microphonics  $<$  **24 (30) Hz** peak-to-peak
5. All **84** cryomodules in the main linac are in operation
6. Charge of **1 nC/bunch** has been chosen to simplify the “scaling”

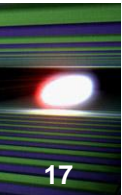
## 2nd-stage: Beam parameters for the near-cw operation



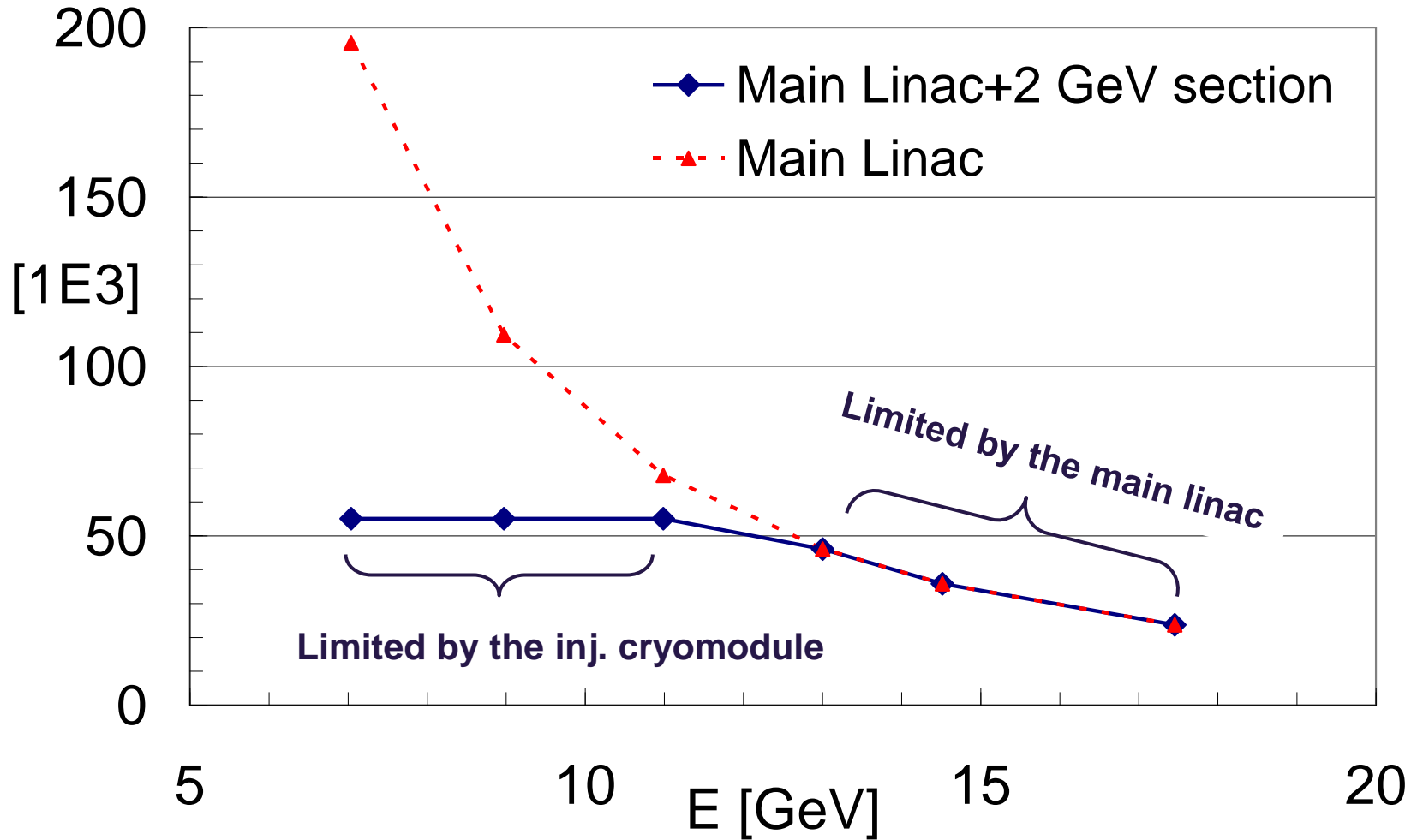
Time structure of the electron beam (1 nC bunches):

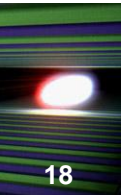


# 2nd-stage: Beam parameters for the near-cw operation

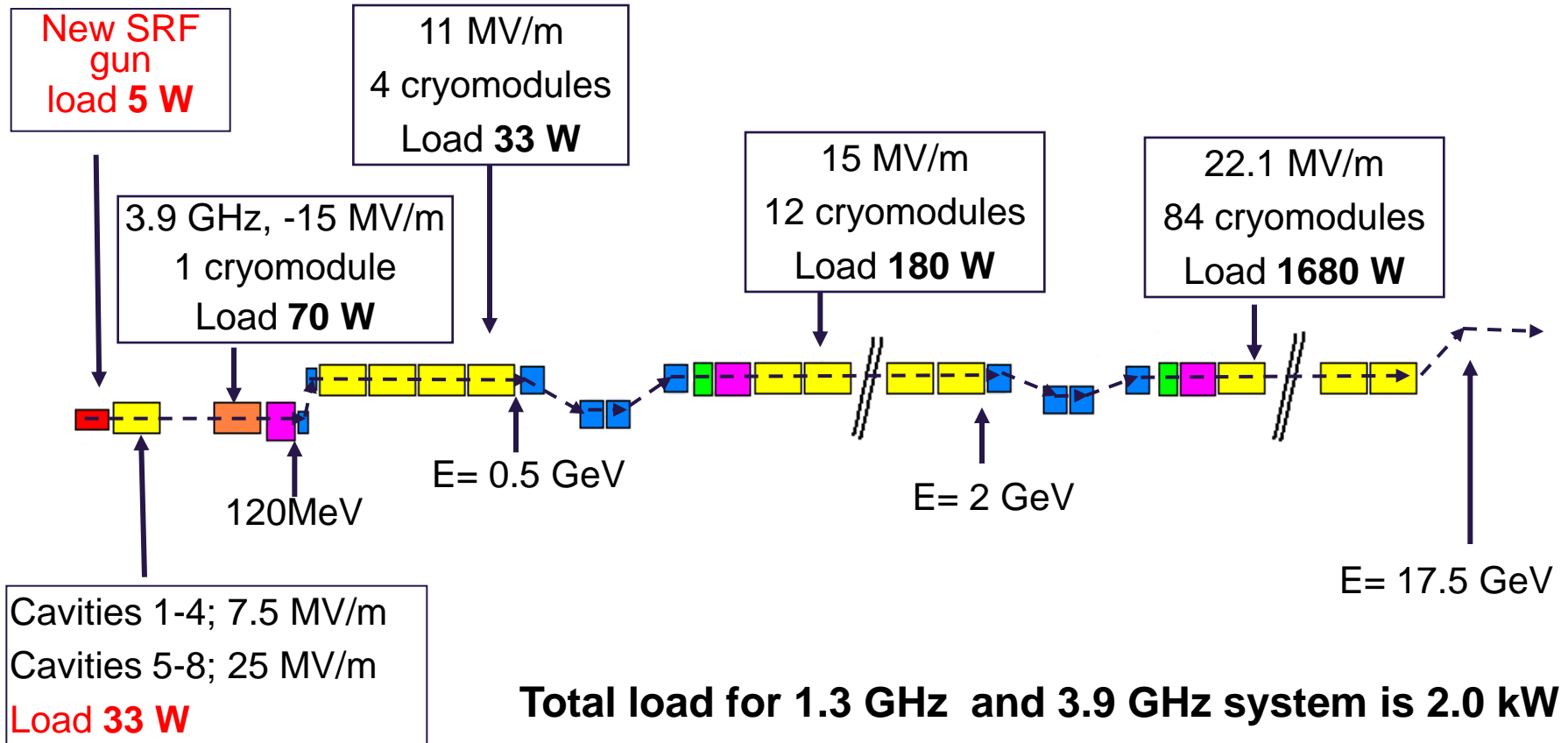


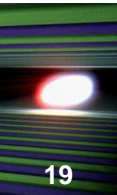
Number of 1 nC bunches/s





Cryogenic loads for the near-cw operation





## Cryogenic plant capacity for the 2nd stage

T range	Pulse operation (2K)		Near-cw operation (1.8K)	
	Capacity (116 CM) [W]	Heat Load (101 CM) [W]	Capacity (101 CM) [W]	Heat Load (101 CM) [W]
<b>2 K (1.8)</b>	<b>2450</b>	<b>1468</b>	<b>3825</b>	<b>2550</b>
5-8 K	4000	2264	6240	4160
40-80 K	30000	15307	46800	31200

This is the a rough estimation. It needs both more precise analysis and experiments verifying the 20 W/cryomodule limit for 12-cryomodule long CS.

With 20W/cryomodule we probably can keep the LHe distribution system (length of the CS) as for the stage 1, but we will need to **increase capacity of the cryo-plant at least by 60% and to operate it at 1.8 K.**

The near-cw operation will need a new RF-system, which should be based on the power sources, which do not “consume” AC power between the pulses.

- cw operating klystrons, pulsed with the input power are not an option, because they take the energy continuously, even when the input power is off (85% of time)
- Inductive Output Tubes (IOT) seem to be a good option, maybe in the future solid-state amplifiers will be an option too.

IOT is a tetrode, which negative polarized grid breaks the current flow when the input power is off. It can operate in cw and pulse mode without modulator, but has relatively small gain ~23 dB (klystrons >40 dB)

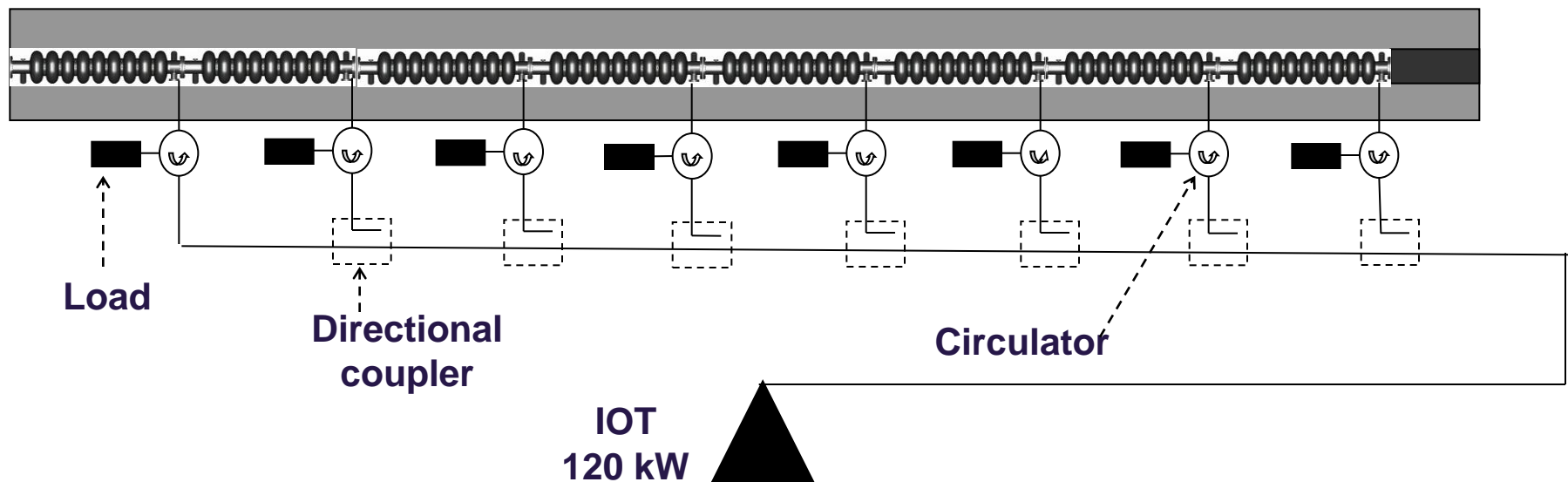
These amplifiers operating at lower frequencies (500-800 MHz) work very reliably since many years in broadcasting (TV).

CPI Company in US offers 32 kW IOT at 1.3 GHz, two other vendors offer 16 kW.

In frame of the first EUROFEL program (2005-2007, <http://www.eurofel.org/e693/e1009>) we pushed for the R&D on 120 kW IOT at 1.3 GHz.

The motivation for the 120 kW IOT was two-fold:

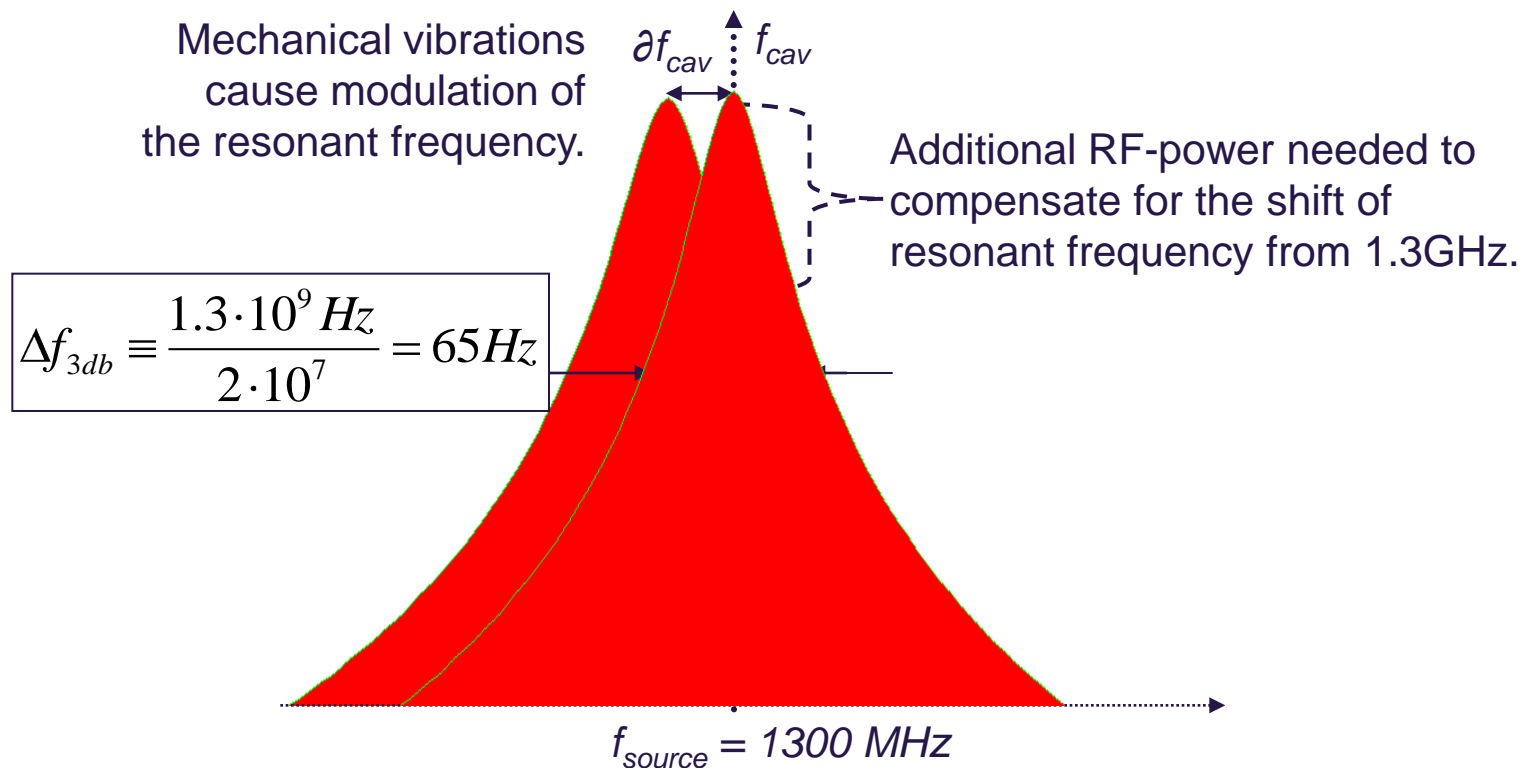
- Cost reduction of the RF-system
- Supply the RF-power to 8 cavities of one cryomodule by one microwave source (modular structure of a linac)



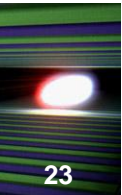
$$120 \text{ kW}/8 \Rightarrow 15 \text{ kW/cavity}$$

The RF power supplied to a cavity during operation:

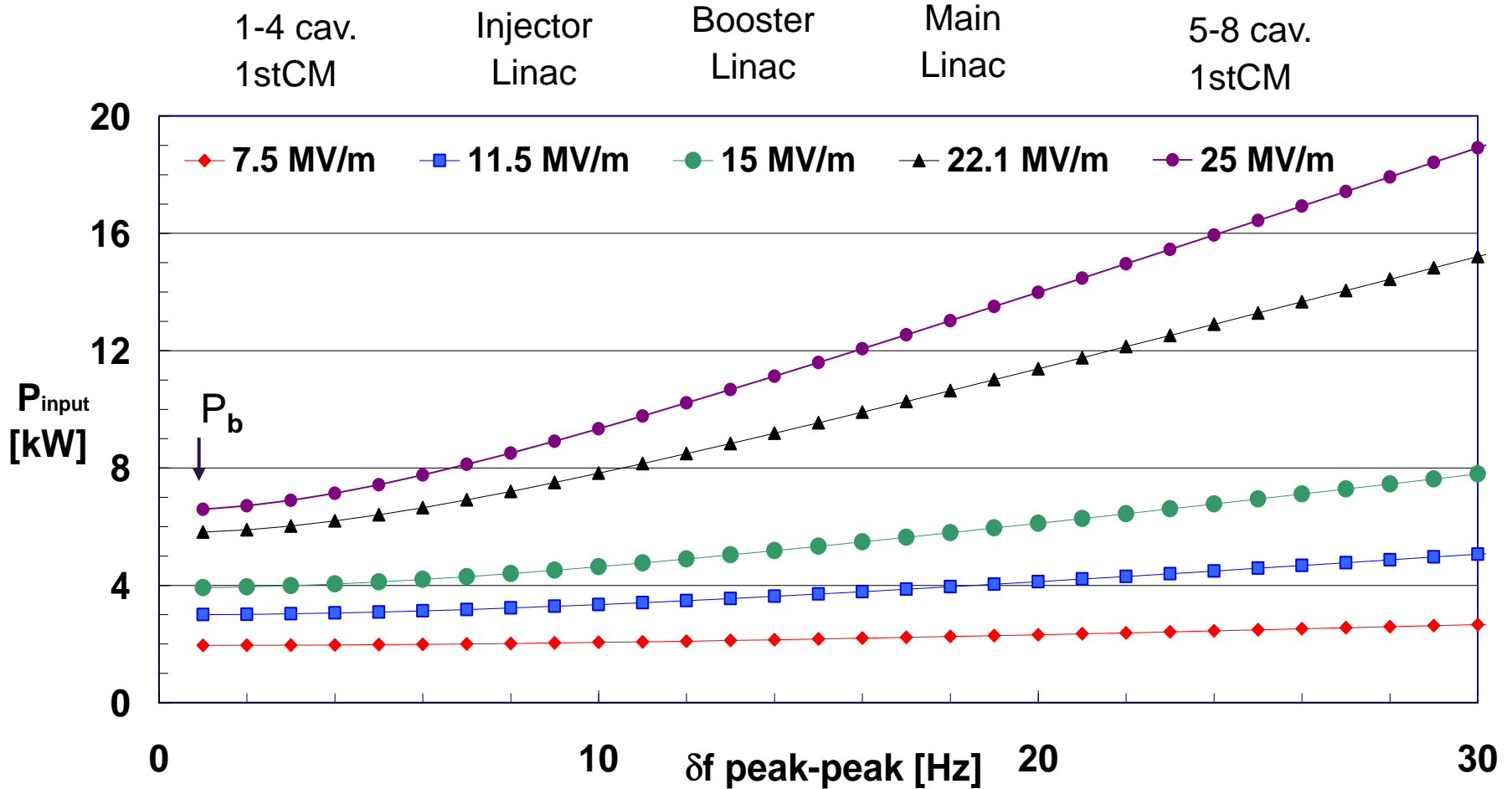
- refills portion of the stored energy, which is transferred to the beam:  $P_b$
- refills portion of the stored energy lost in the cavity wall:  $P_{\text{wall}}$
- compensates for the detuning of cavity caused by Lorentz force and mechanical vibrations (microphonics):  $P_{\text{overhead}}$



## 2nd-stage: RF-system



The RF-power required for stable operation of TESLA cavities at 5 gradients in the XFEL linac vs. microphonics.



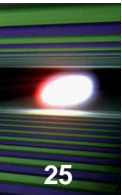
## 2nd-stage: RF-system

The prototype of 120 kW IOT was built by CPI, tested and delivered to DESY in 2009.



Parameter	Unit	Spec	Measured at CPI
F	[MHz]	1300	1300
Output P	[kW]	60-120	85
Gain	[dB]	>21	22.3
Efficiency	[%]	>60	54
Voltage	[kV]	36-50	45-48

The tube is currently tested at DESY



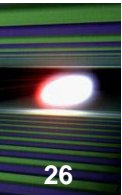
The present e-guns made of copper dissipate 50 kW at 1 % DF. At 10-15 % DF dissipation will increase to ~750 kW. The cooling and temperature stabilization would be technically very impractical.

For the 2nd stage we need **superconducting (SRF) electron source**.

Two approaches:

Cathode	Main advantage	Main disadvantage	Application
NC	High QE	Integration of the cathode in the SC environment	$\geq 100$ mA cw class injectors
<b>SC (*)</b>	<b>Simpler integration of the cathode in the SC cavity</b>	<b>Low -&gt; moderate QE</b>	<b><math>\leq 1</math> mA</b> <b>cw class injectors</b>

BNL, JLab, INS, SLAC, DESY (\*)



We think that the Pb cathode is a good choice (\*):

- Pb is metallic superconductor ( $T_c = 7.2$  K)
- Pb is very insensitive to exposure to air
- Pb is very durable
- Pb has “reasonable” Quantum Efficiency

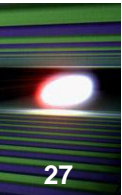
QE of the best arc-deposited Pb cathodes, manufactured at INS Świerk

Wavelength	QE
213 nm	2.7E-03
258 nm	4.8E-04

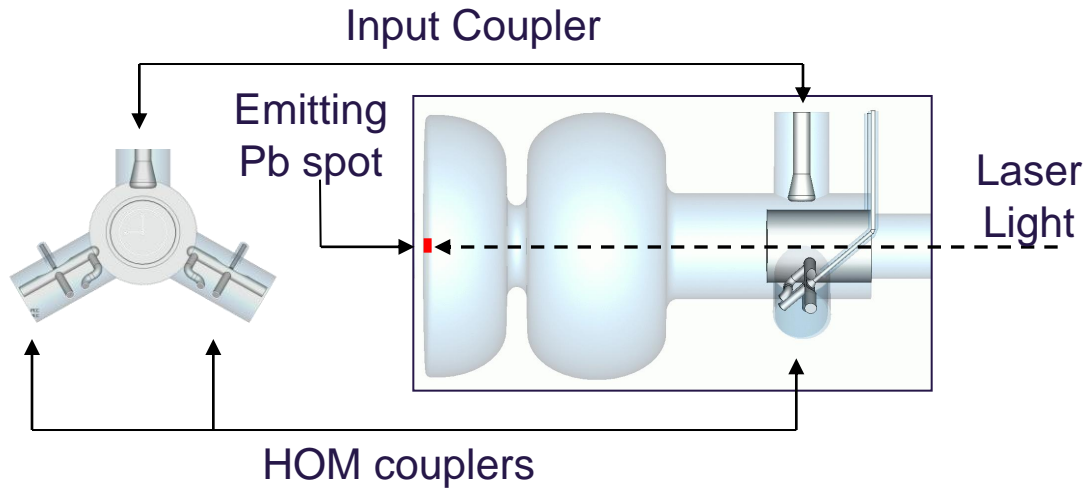
Parameters of the irradiating laser for 50000 bunches with 1 nC charge

Wavelength	Pulse energy [ $\mu$ J]	Power [W]	Comments
213 nm	2.1	0.11	Less power dissipated in the sc spot
258 nm	10.0	0.5	Lower thermal emittance

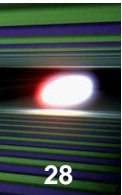
(\* ) J. S. et al., Phys. Rev. ST-AB, vol. 8, January 2005 and J. Smedley et al., Phys. Rev. ST-AB vol. 11, 2008



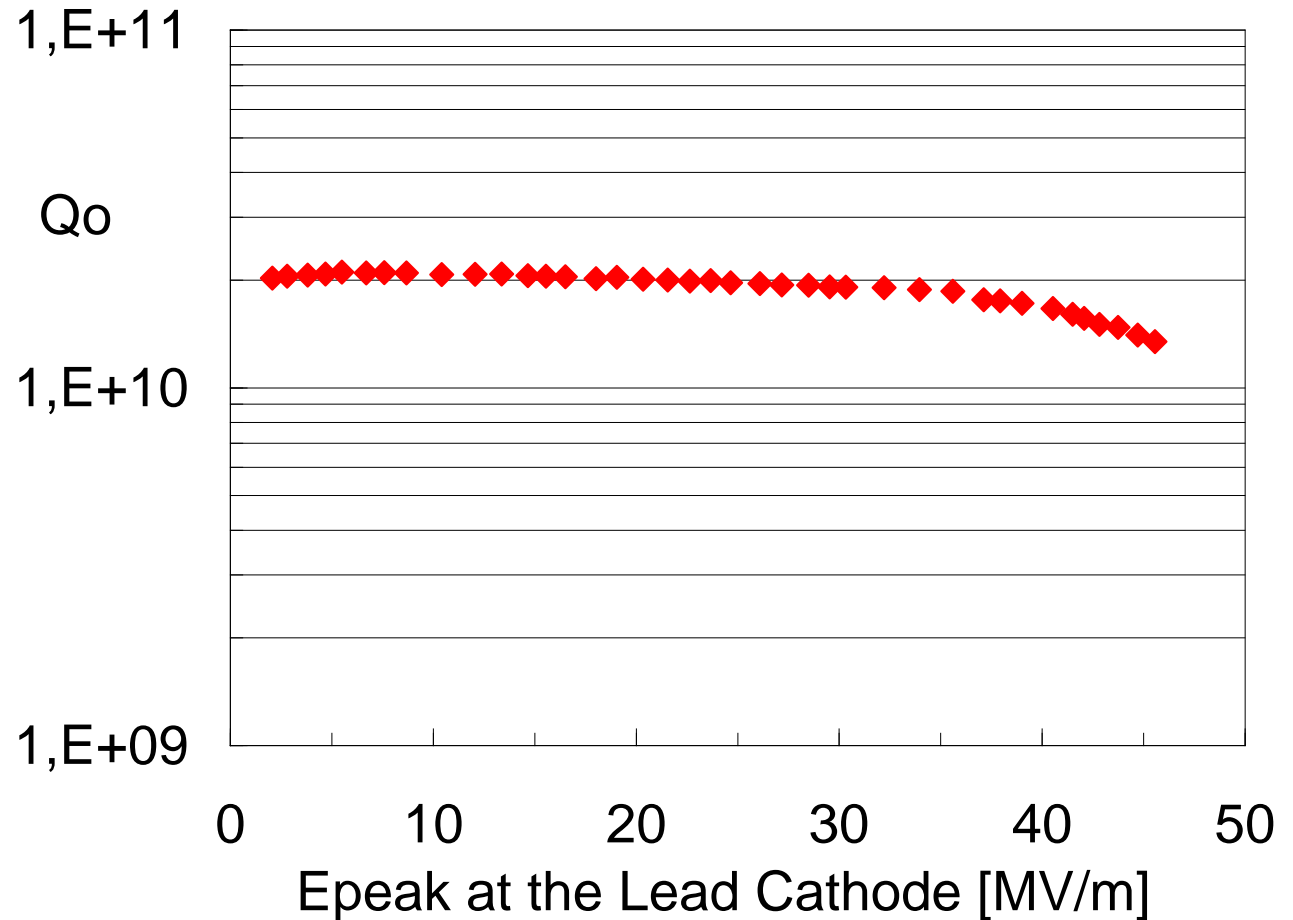
RF-design



Parameter	Unit	Value
$\pi$ -mode frequency	[MHz]	1300
Spot radius	[mm]	1.5
Nominal $E_{cath}$ at cathode	[MV/m]	~50
Energy stored at nominal $E_{cath}$	[J]	20
Nominal beam energy	[MeV]	~5



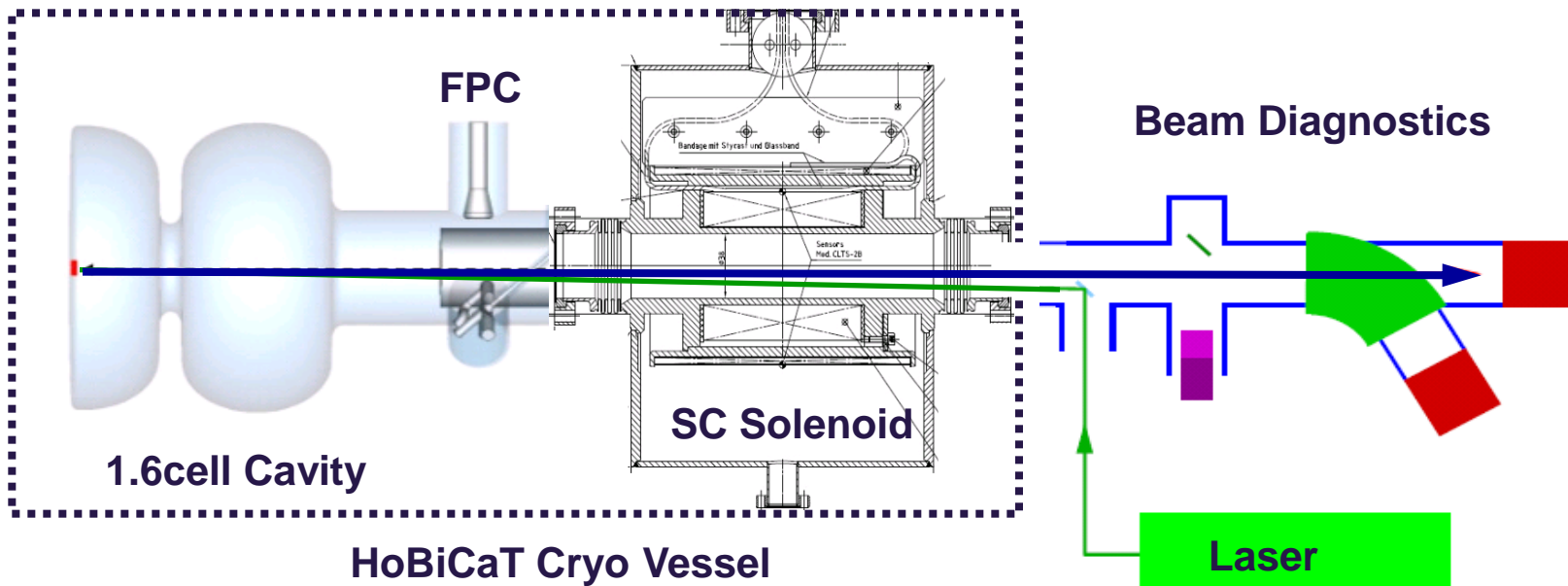
Cryogenic test at JLab of the RF-gun cavity with Pb spot, coated at INS.

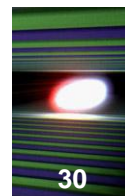


## 2nd-stage: SRF electron source

HZB (BESSY), JLab, INS and DESY prepare horizontal test of the new Nb-Pb e-gun.

- New 1.6-cell cavity with LHe vessel will be shipped to Swierk in April for coating.
- Max Born Institute builds new laser at (HZB) BESSY
- This time we will learn about the beam quality.
- The test is scheduled for Fall 2010.





## ad. 1st stage

- The technical spec for cavities ( $E_{\text{acc}}=24\text{MV/m}$ ,  $Q_0=1\text{E}10$ ), is very close to that of the TESLA collider (TDR 2001), which was demonstrate many times at DESY since late 90`s.
- Our main goal now is to transfer the technology to Industry and support International Partners with our know-how in their in-kind contributions.
- Some “fine tuning” making the production of superconducting cavities and other components more efficient and less expensive is in progress.
- We are developing and testing few minor components enabling better performance of the accelerator in the 1st- and 2nd stage.

## ad. 2nd stage

- The components for the 2nd stage are in the R&D phase and need still time to be ready for the implementation.
- We received a lot of support from BNL, JLab, INS-Swierk, SLAC and Stony Brook Uni. for proposed Nb-Pb electron injector.
- Recently HZB (BESSY) joint the collaboration and offered to conduct the test of the QE and beam quality diagnostics.
- The first prototype of 120kW IOT amplifier was build (EU funds) and the 2-nd test will be accomplished by the end of June 2010. There is no fund to build the second tube with better performance.
- The test of XFEL cryomodule with IOT, demonstrating the amplitude and phase stability of the accelerating field for cavities with loaded  $Q = 2E+7$ , will be of great importance for the upgrade of XFEL.

ad. 2nd stage cont.

- I think, that the sc electron source and cryomodule(s) supplied with RF-power by IOT(s) should be tested extensively, before we will make decision to implement them in the XFEL accelerator.
- My final conclusion is that we need a cw-able test facility, which could be a useful coherent radiation source (similar to ELBE at the Forschung Zentrum Rossendorf) to prove the concept presented in this talk.

From my point of view, POLFEL would be of great benefit for both the research with long pulses and for the upgrade of XFEL.