Energy savings at the European XFEL

2nd workshop on efficient RF sources

24.09.2024

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Energy savings at the XFEL

Overview

1. Overview

1.1 General overview of the XFEL

1.2 Setup and function of RF station

2. Energy saving measures

2.1 Reducing HV

2.2 Shortening pulses - use of rise and fall time

2.3 Adjusting a slope to the HV pulse

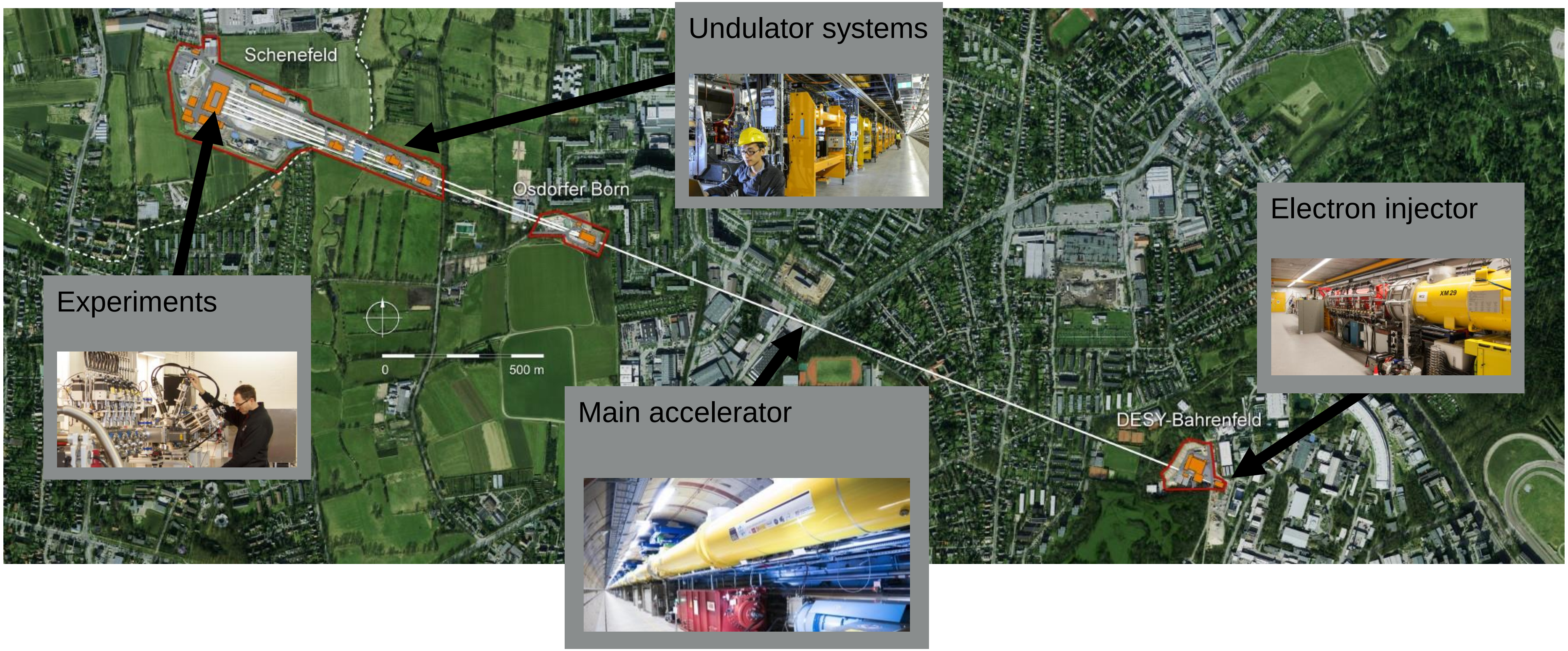
3. Summary

Energy savings at the XFEL

Overview XFEL

Purpose of the XFEL: Generating X-Rays for biological sciences, material sciences, solid state physics and medical sciences

injector part: 100m, main LINAC: 2km, undulator and experiment area/tunnels: ~1.2km → in total: 3.3km



Energy savings at the XFEL

Overview XFEL

Working principle of an FEL (Free Electron Laser):

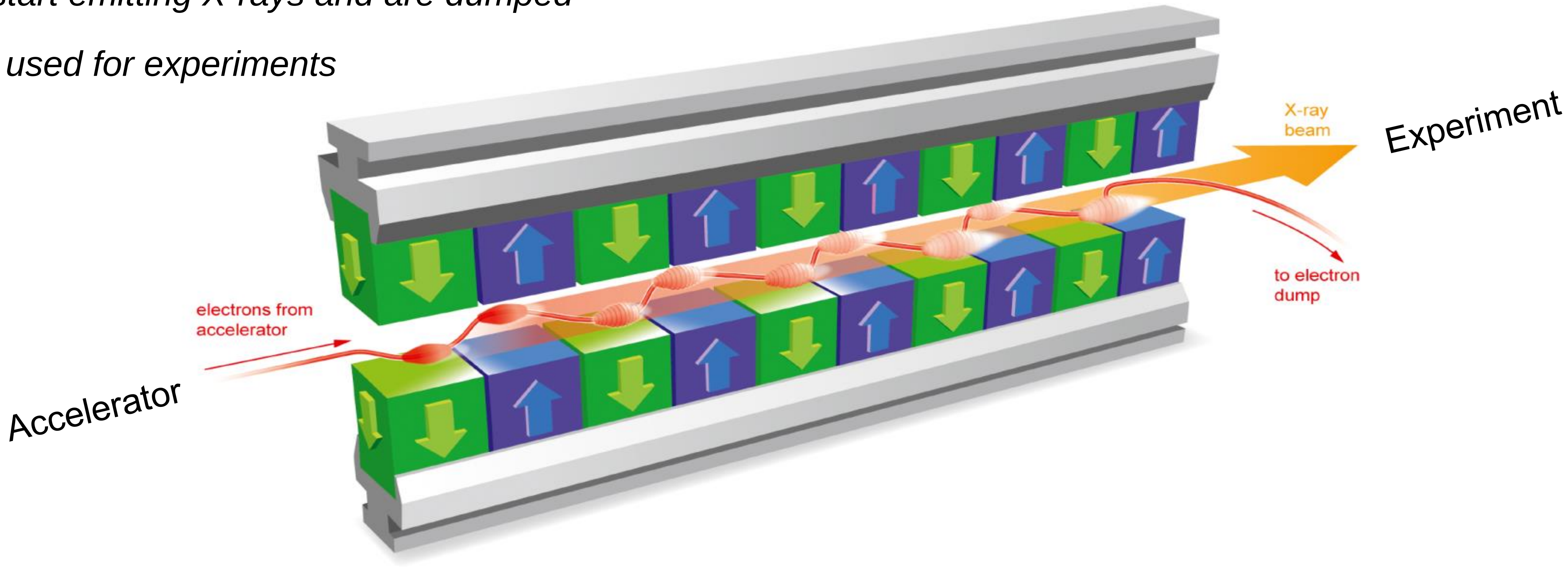
Series of strong alternating permanent magnets put the electrons on a slalom course:

→ *Electrons start emitting X-rays and are dumped*

→ *X-rays are used for experiments*

XFEL parameters:

- Electron Beam energy up to 16.5 GeV
- X-rays with wavelengths from 0.05nm to 4.7nm
- Brilliance up to: $5 \cdot 10^{33}$ photons / (s mm^2 $mrad^2$ 0.1% BW)



Energy savings at the XFEL

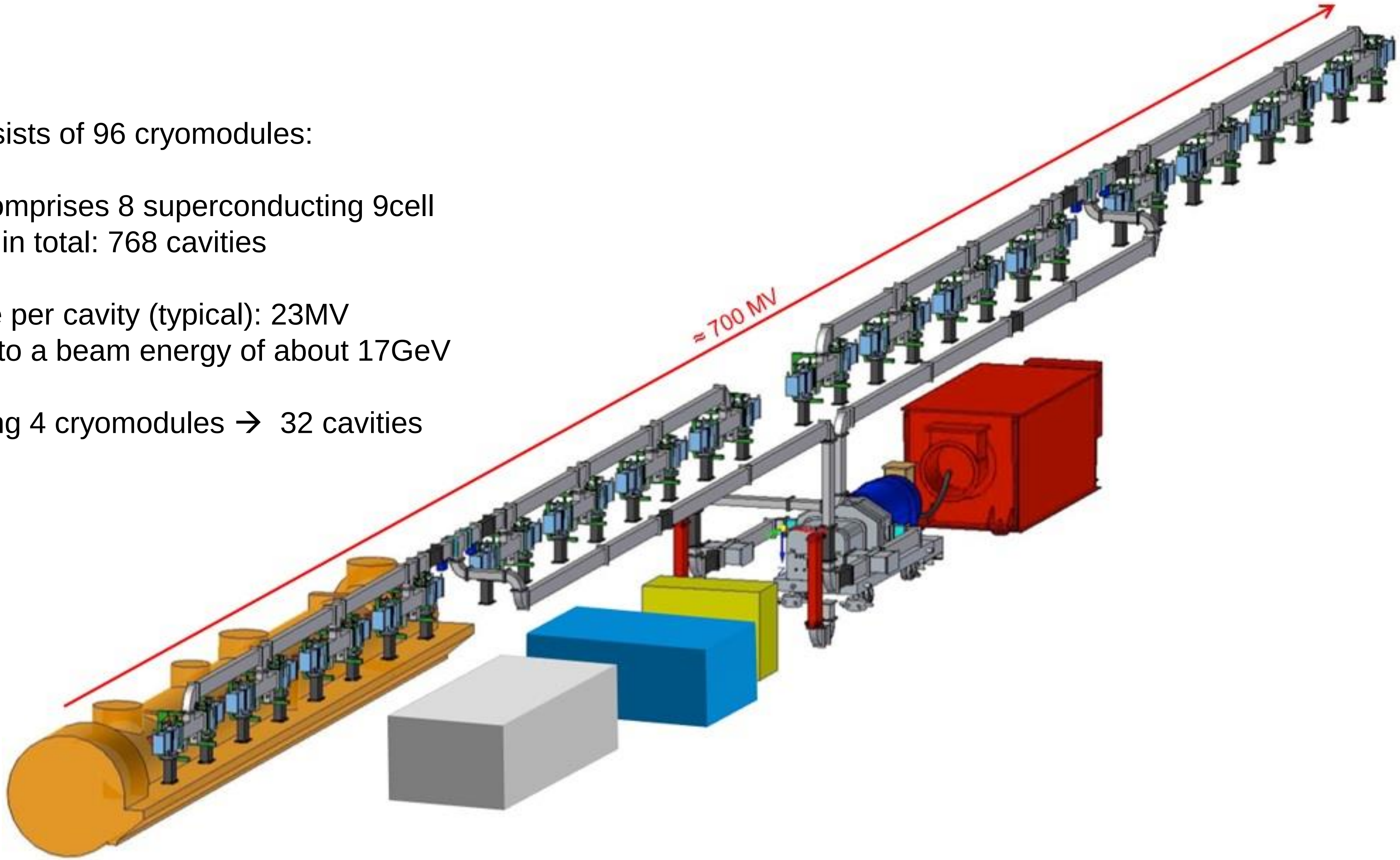
RF station setup

XFEL main LINAC consists of 96 cryomodules:

- Each cryomodule comprises 8 superconducting 9cell “TESLA” cavities → in total: 768 cavities

- Acceleration voltage per cavity (typical): 23MV
  → resulting in total to a beam energy of about 17GeV

- one klystron is driving 4 cryomodules → 32 cavities



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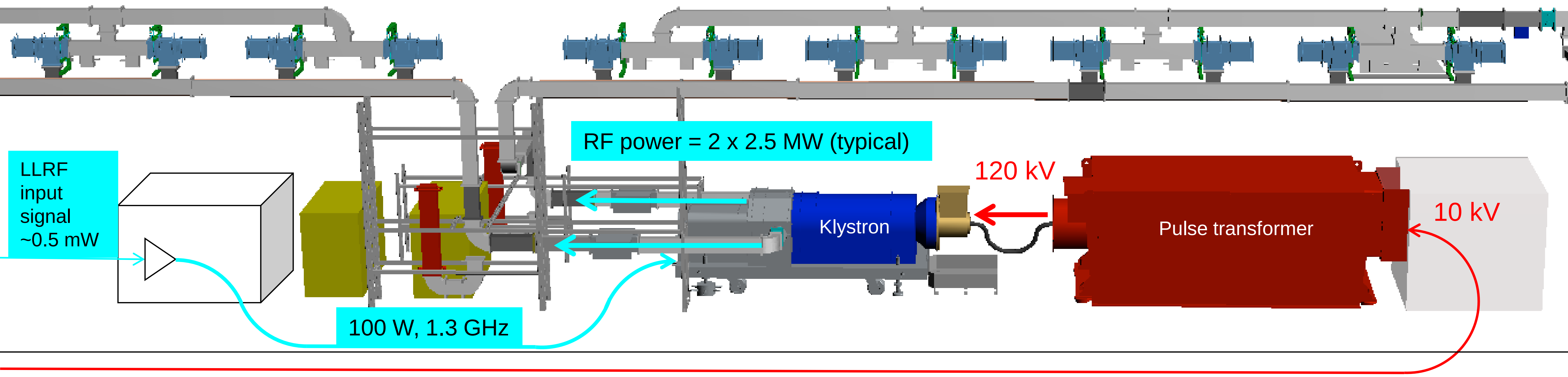
RF station setup

24 RF stations within the main LINAC and 2 RF stations within the injector:

- 7 to 10kV pulses are generated by HV modulators and transmitted to the pulse transformer



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RF station setup

26 klystrons with following parameters (E3736 and TH1802) :

- Frequency: 1.3 GHz
- Repetition rate: 10 Hz
- Maximum RF power of klystron: 10MW

High Voltage (typical):

Pulse width	Modulator	Klystron
1700 μs	8.8 kV	106 kV
	1470 A	124 A

RF (typical):

Pulse width	Pulse power	Average power
1400 μs	5 MW	70 KW

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RF pulse setup

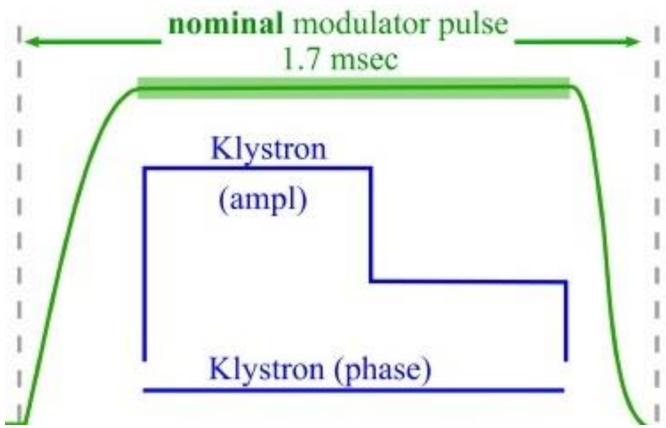
Timing of RF pulse consist of two parts:

1. 0µs to 750µs = „fill time“ – establishing the E-field within SC cavity/ no beam

   → requires max. RF power

2. 750µs to 1400µs = „beam flattop“ -- beam acceleration

   → requires typically 1/4 of RF power of filling intervall



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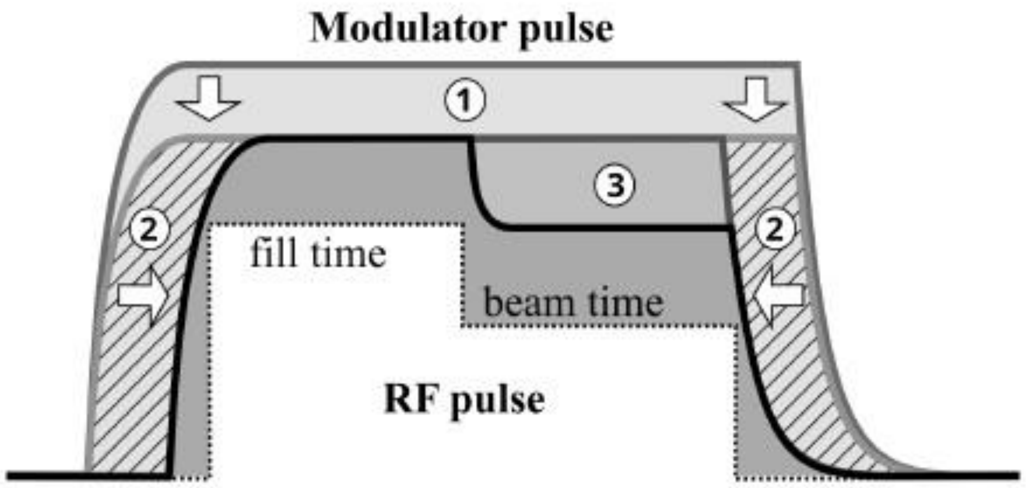
Ideas for energy saving

0. Implementation of beam user dependent RF operation
   → switch off RF station
1. Reducing HV for the klystron – First adjustement (2017/18) was done with a very conservative overhead → HV is now adjusted according to user operation requirements
2. Shortening the HV pulse - Make use of the rising and falling edges of HV pulse. RF pulse length stays with original length!
3. Introduce a step to the HV pulse - usage of the low RF power requirement during „beam flattop".



Courtesy to J. Branlard

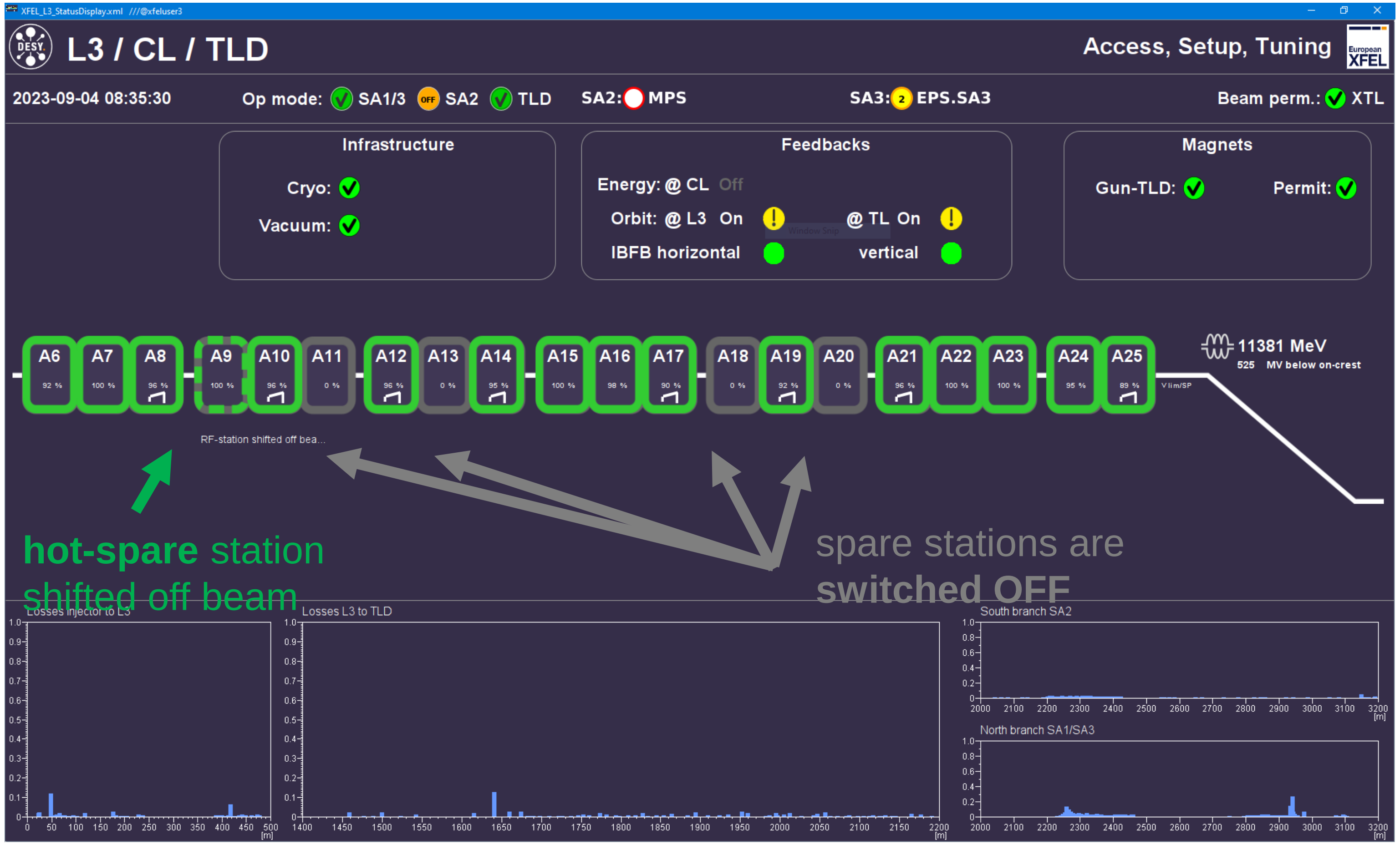
Energy savings at the XFEL

0. Simplest solution = switch RF station off

- For “**reduced**” energy user runs
  < 14.5 GeV
  - only keep **one hot-spare** station
  - other spares (up to 4) are **off**
  - they can be switched back on within 45min (klystron filament warm-up)
- For “**high**” energy user runs
  > 14.5 GeV
  - all stations on – one station as hot spare

→ switching between runs is done typically 4 or 5 times per year

→ Switch time ~1 hour



Courtesy to J. Branlard and N. Walker

Energy savings at the XFEL

1. Reducing the HV working point

- Implementation of two HV working points for the klystron:

Depending on user run: ***"reduced"*** energy run < 14.5 GeV or ***"high"*** energy run 14.5 GeV – 16.3 GeV

Calculation for modulator voltage to modulator power dependency :

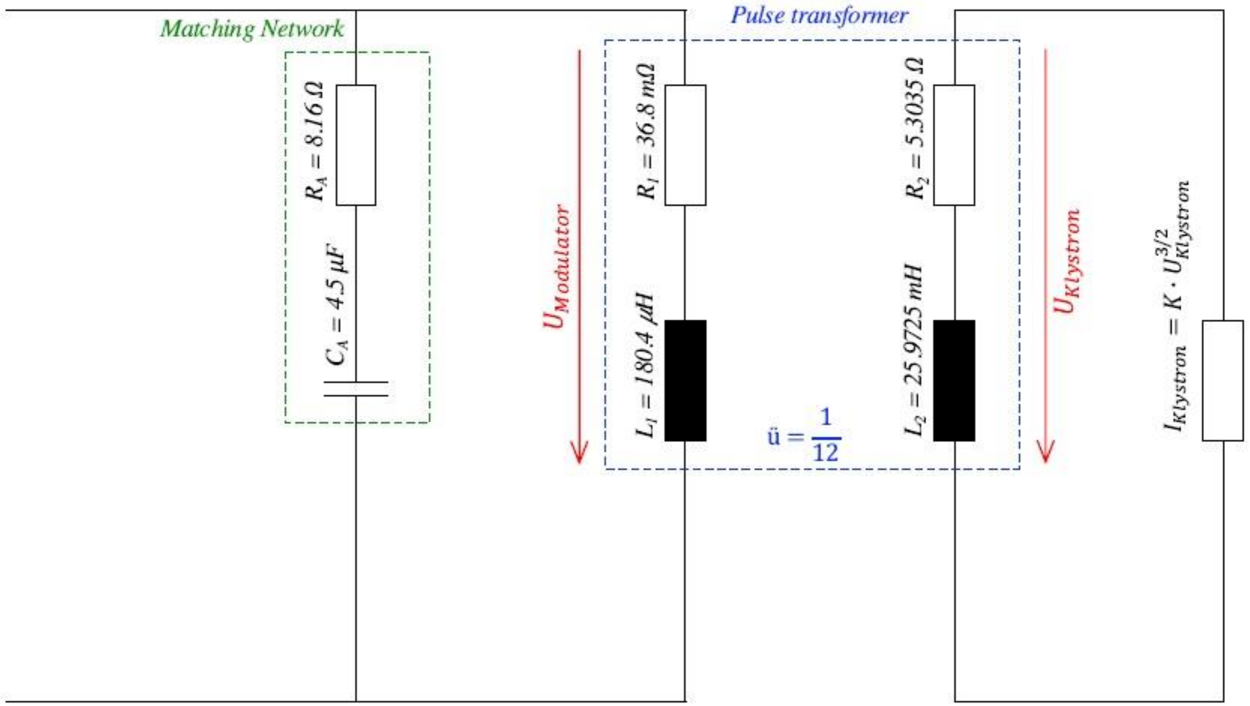
$$\hat{P}_{Klystron} = U_{Klystron} \cdot I_{Klystron}$$

$$\hat{P}_{Modulator} = \hat{P}_{Klystron}$$

$$= \frac{U_{Modulator}}{ü} \cdot K \cdot U_{Klystron}^{3/2}$$

$$= \frac{U_{Modulator}}{ü} \cdot K \left(\frac{U_{Modulator}}{ü}\right)^{\frac{3}{2}}$$

$$= K \left(\frac{U_{Modulator}}{ü}\right)^{\frac{5}{2}}$$



Courtesy to V. Kroeger

Energy savings at the XFEL

1. Reducing the HV working point

Modulator power to voltage dependency:

$$P_{Modulator} = \frac{D}{\eta} K \left(\frac{U_{Modulator}}{\ddot{u}}\right)^{\frac{5}{2}}$$

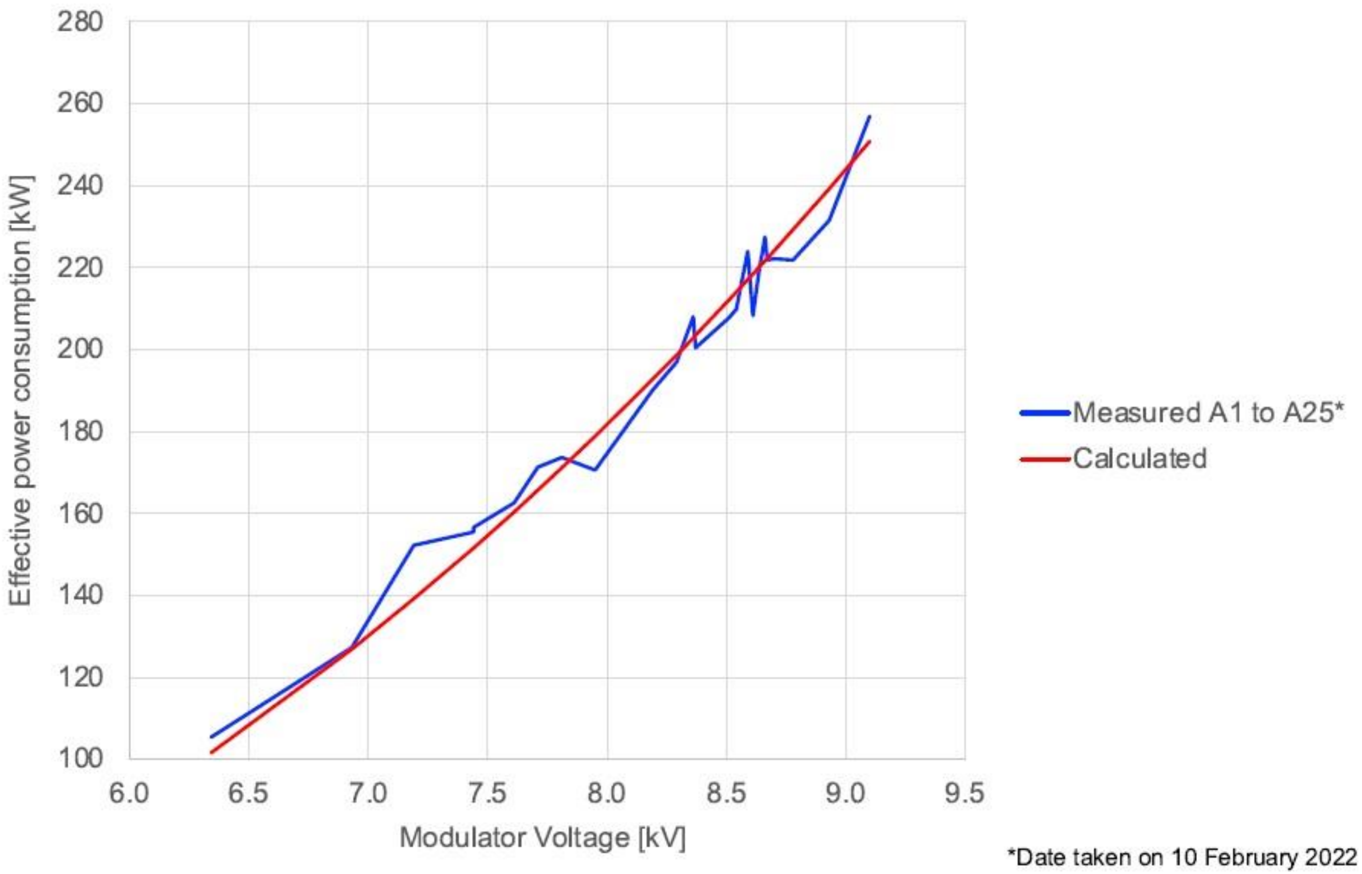
$D = 10Hz \cdot 1.7ms = 0.017$ → Duty cycle

$\eta = 0.935$ → efficiency of HV system

$K = 3.5 \cdot 10^{-6} \frac{A}{V^{3/2}}$ → perveance of klystron

$\ddot{u} = \frac{1}{12}$ → transformer ration

(typical values)



*Date taken on 10 February 2022

Courtesy to M. Bousonville and V. Kroeger

Energy savings at the XFEL

2. & 3. HV pulse shortening and sloping

2. Shortening HV pulse:

→ Make use of rising and falling edge of the HV pulse

- Shorten HV pulse : 1700 µs → 1580 µs
- RF pulse length stays 1400µs

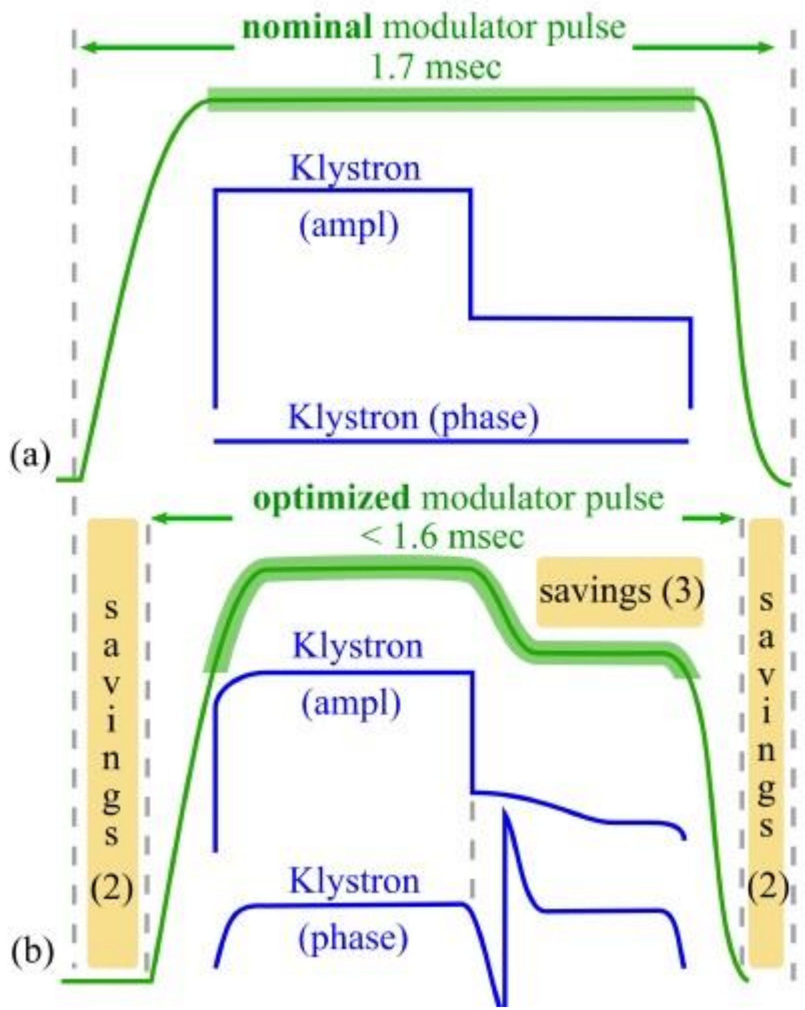
3. Implementation of a slope for the HV pulse:

→ Make use of the two different RF power requirements during “filling” time and “beam” time (1 over 4 in RF power)

- requires a PSM based HV modulator

Use of the non flattop area of the HV pulse requires the LLRF system to compensate on the gain and phase change:

→ *Development of Dynamic Output Vector Correction*



Courtesy to J. Branlard

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HV slope creation

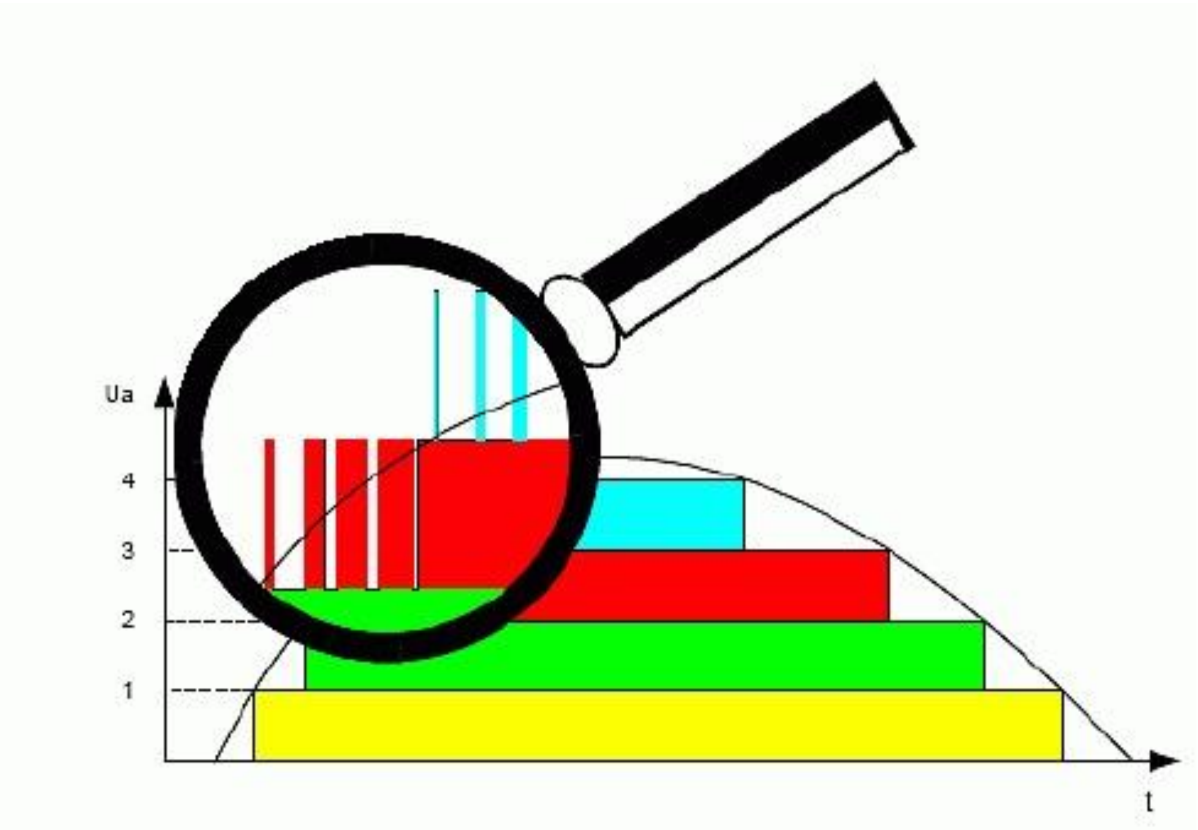
PSM based HV modulators *(Pulse Step Modulation) :*

Based on 24 isolated HV modules, which supply 700V each

→ Voltage of modules is stacked to the desired output voltage

Modules are controlled via PWM principle *(Pulse Width Modulation)*

→Allows to form/ shape the HV pulse according to needs.



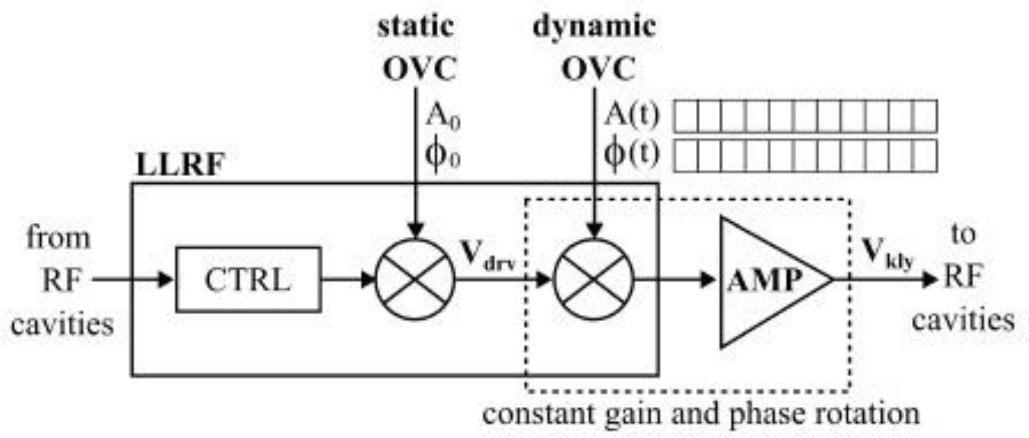
Energy savings at the XFEL

RF pulse compensation

LLRF system is based on MicroTCA using a vector-sum-based algorithm.

Dynamic Output Vector Correction (OVC)

- Static OVC was already in place -- compensation of long term drifts
- Development of a Dynamic OVC:
  - Creating a lookup table by measuring the LLRF drive signal and the klystron output.
  - Each sample point of the LLRF drive can be rotated in phase and scaled in amplitude based on the lookup table



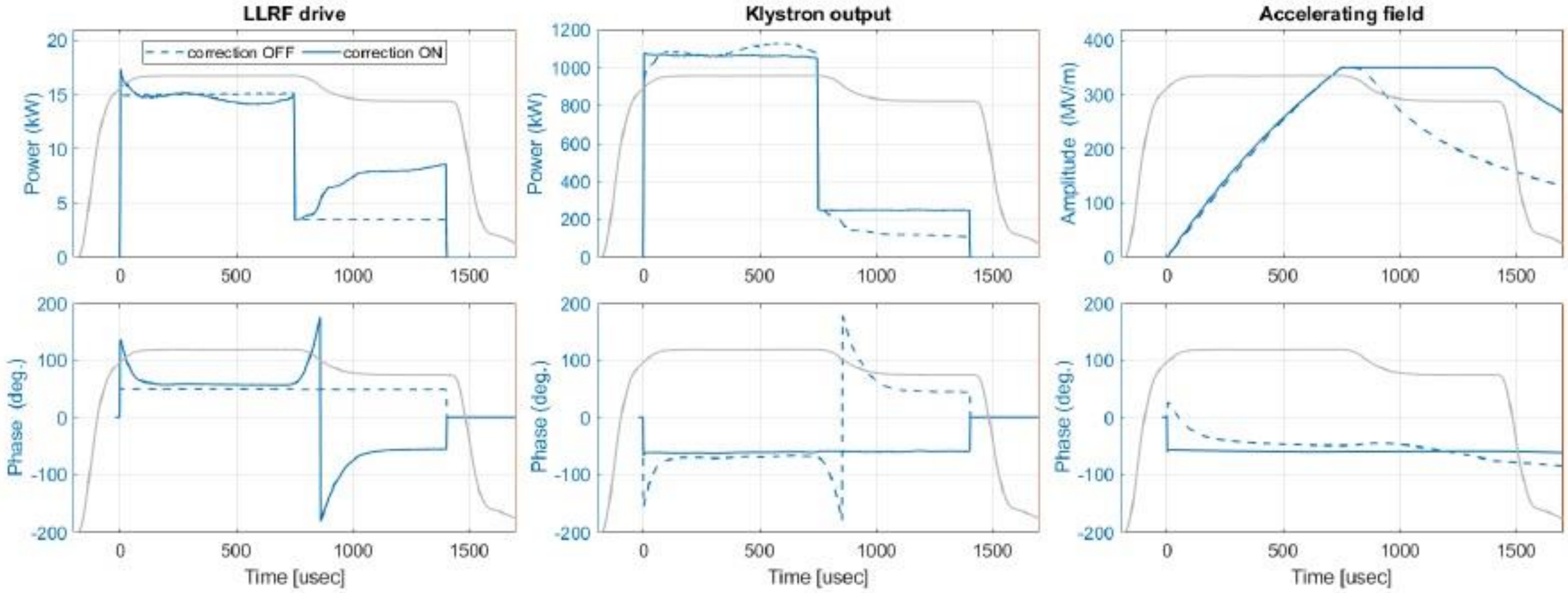
Courtesy to J. Branlard and A. Bellandi

Energy savings at the XFEL

RF pulse compensation

HV reduction is 15% to 20% → Ukly is reduced by up to 20kV → phase change of up to 300° (rate: 15°/kV)

Results of the Dynamic Output Vector Correction:



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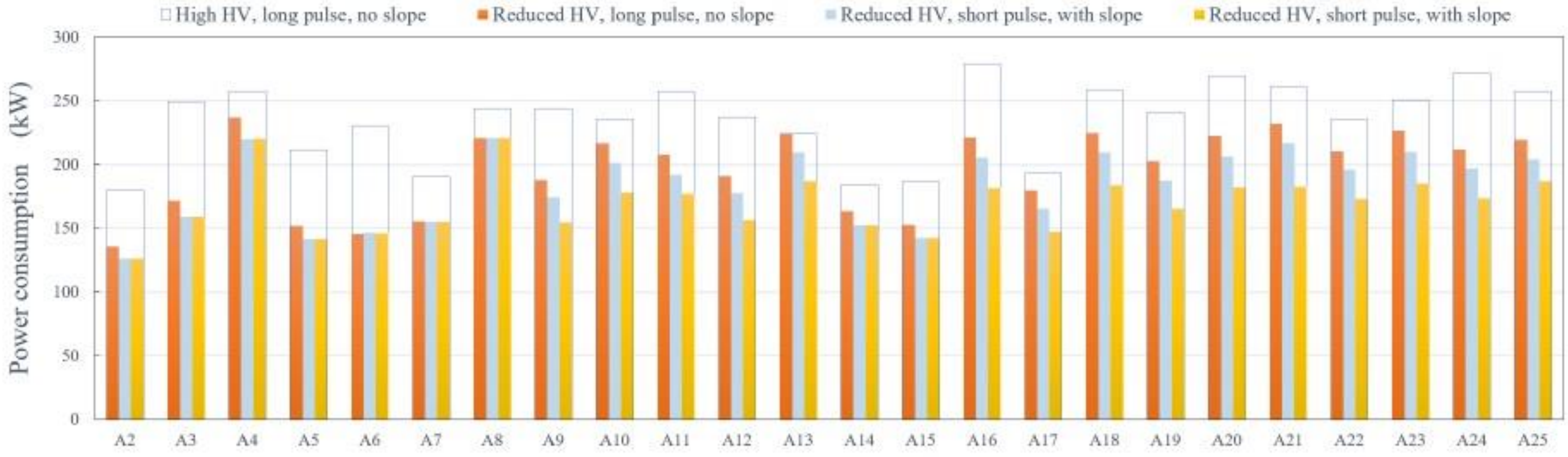
Energy savings at the XFEL

AC power savings in numbers

Power savings per RF Station:



Courtesy to J. Branlard

Energy savings at the XFEL

AC power savings in numbers

Total saving compared to initial setup from 2017/18:

“Reduced” energy user runs (< 14.5 GeV):

3.3MW instead of 5.6MW

→ Saving of 42%

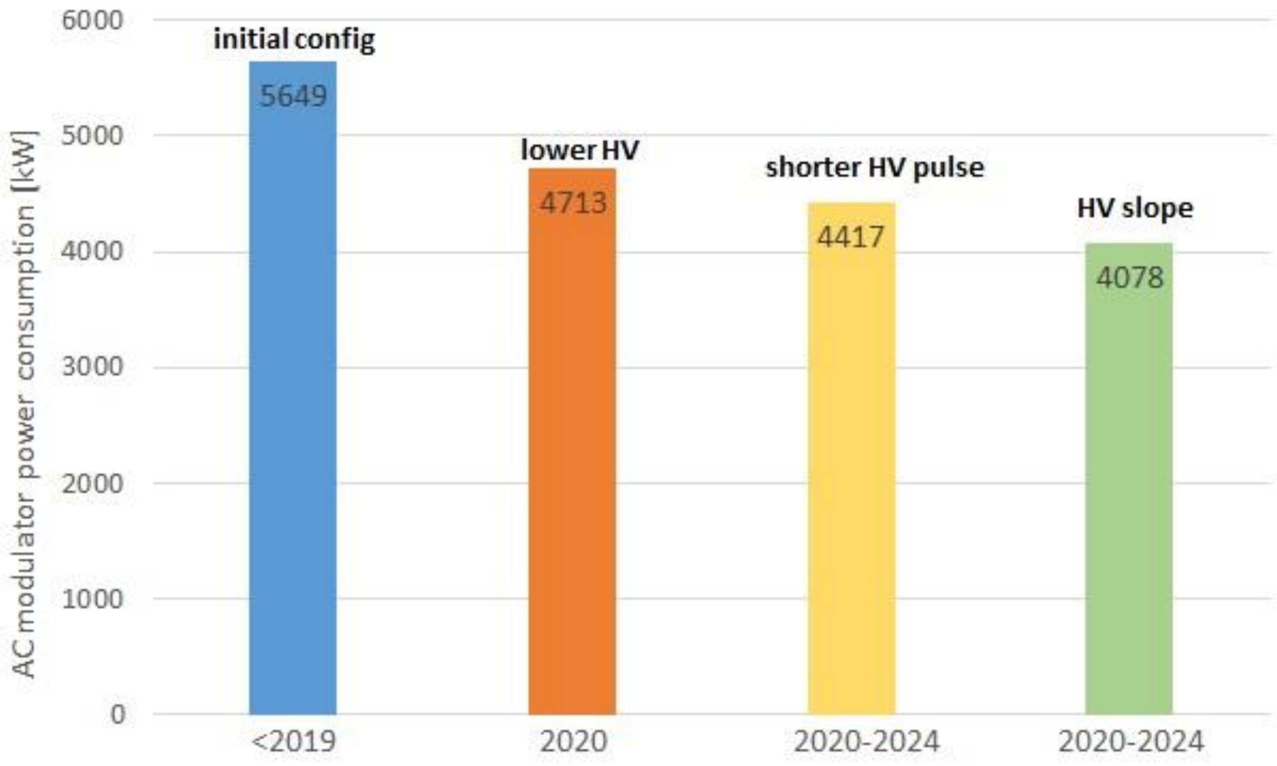
“High” energy user runs (14.5GeV - 16.5GeV):

4.1MW instead of 5.6MW

→ Saving of 27%

AC to RF efficiency of LINAC RF station with those setups ranges between 30% and 45%.

→Klystrons are not operated at most efficient point, due to lower HV.



AC consumption of RF stations in kW

Energy savings at the XFEL

Summary

Power saving concepts have implemented for the XFEL main LINAC in between 2020 and 2024:

- Adjusting HV according to required beam energy/ user run
- Lowering HV compared to original config – no big margin/ overhead for LLRF is left
- Shortening HV pulse, while not changing the RF pulse
- Implementing a HV slope

The reliability for 24h/7d operation and stability of the LINAC is not affected! → There is always one hot spare RF station available.

No change of user related beam properties is required for these power saving concepts.

Positive side effect: Lifetime of the klystron is most likely increased, due to moderate HV operation.

Thank you for your attention!

Most plots are referring to the LINAC 24 Paper: *“RF-based Energy Savings at the FLASH and European XFEL LINACS” by J. Branlard*

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