

# Layout and design of positron and electron linacs up to 20 GeV

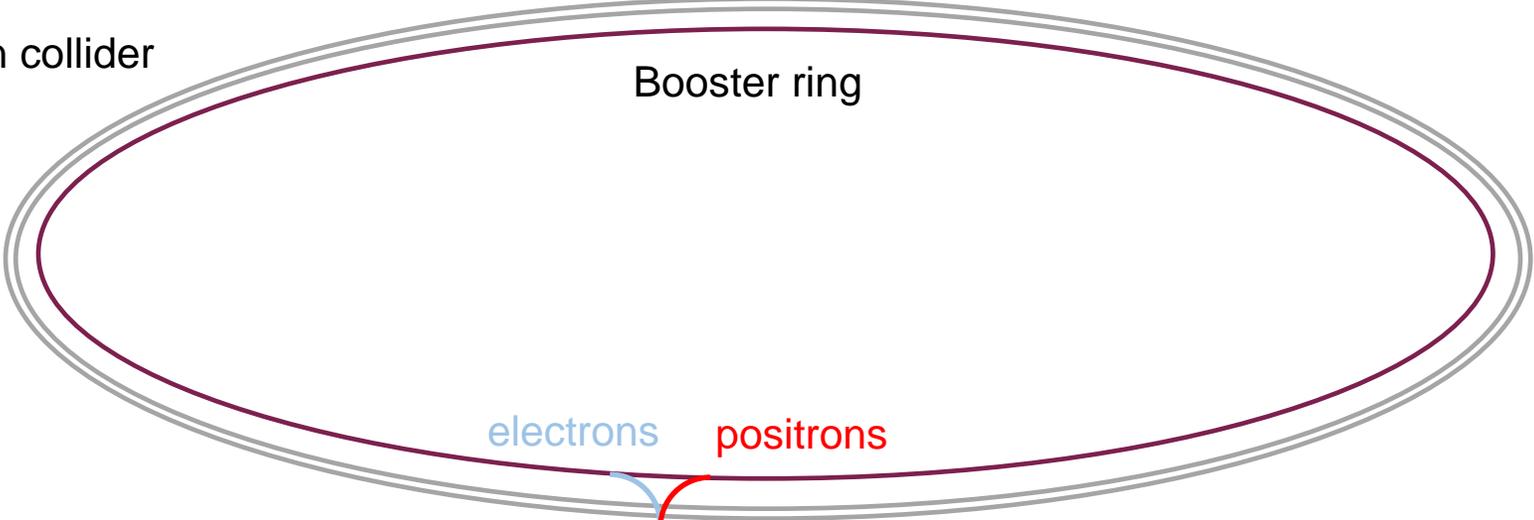
Alexej Grudiev (CERN) and Jean-Yves Raguin (PSI)  
on behalf of FCC-ee Pre-Injector CHART Collaboration  
FCC week, London, June 5-9, 2023

# Outline

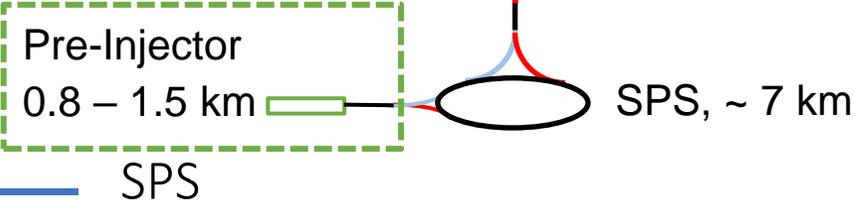
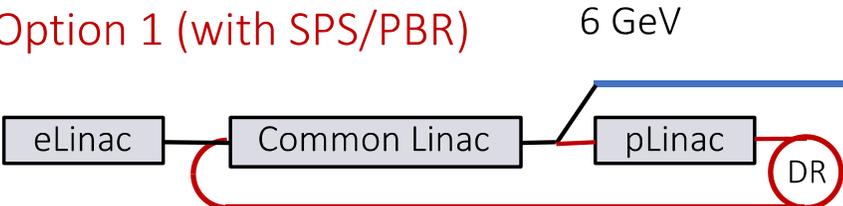
- Introduction
- RF module and linac layout
- Relative cost and power comparison
- High power RF components: SwissFEL – State-of-the-Art technology demonstrator
- Conclusions

# Options for the FCCee Pre-Injector complex

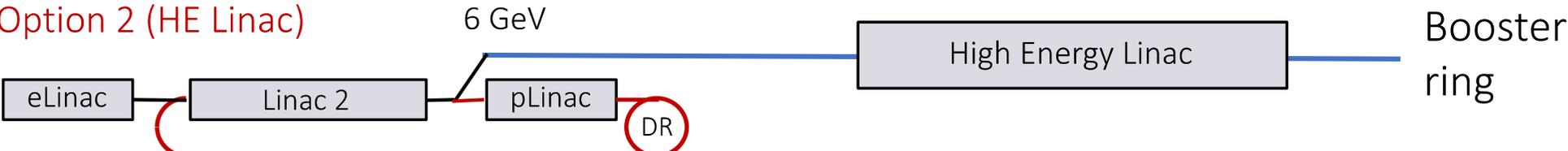
Electron-Positron collider  
~91 km



Option 1 (with SPS/PBR)



Option 2 (HE Linac)



# Injector parameters (Z-mode)

FCC Accelerator Pillar meeting #07, 01.11.22

	SPS	HE Linac	Unit
Injection energy	6	20	GeV
<b>Bunch charge both species</b>	<b>4.4</b>	<b>4.4</b>	<b>nC</b>
Repetition rate	200	200	Hz
Number of bunches	2	2	
Bunch spacing	25	25	ns
Normalized emittance (x, y) (rms)	10,10	10,10	mm mrad
Bunch length (rms)	~1	~1	mm
Energy spread (rms)	~0.1	~0.1	%

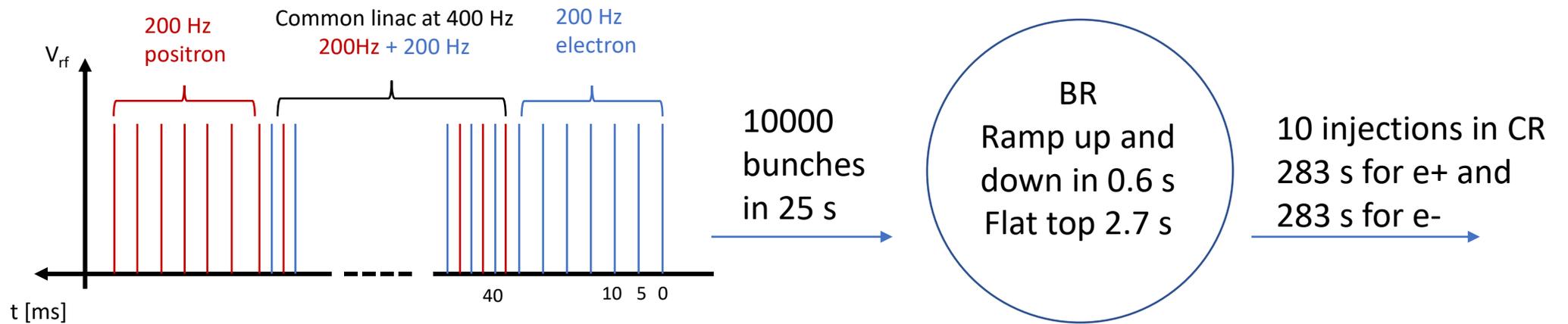
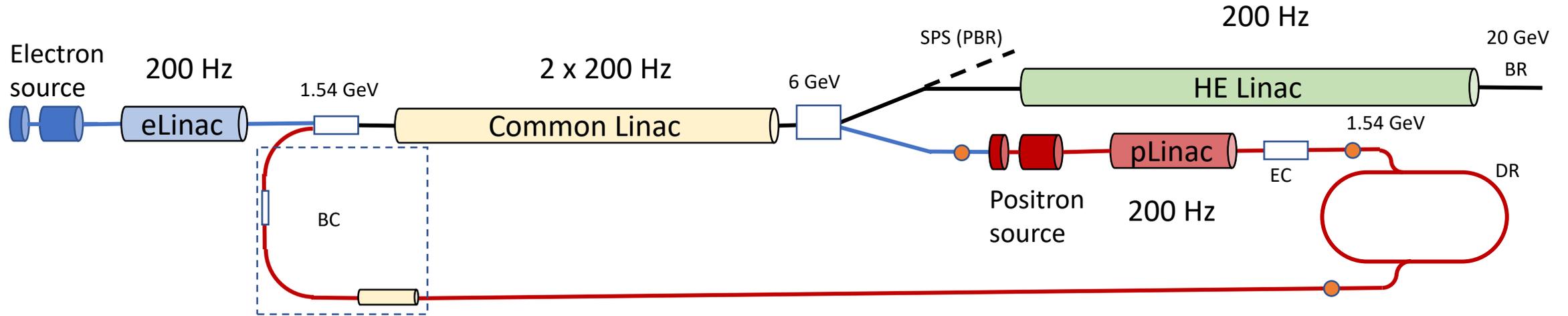
← Specification for the charge at the linac end. Charge to be injected into the collider rings is 3.84 nC (bunch population  $2.4 \times 10^{10}$  particles)

← Target bunch length and energy spread at the linac end, TL from HE linac to booster will include an energy compression (and bunch decompression)

Other important requests:

- The bunch by bunch intensity will **arbitrarily vary 0 to 100%**, depending on the intensity balance between the collider rings
- **Bunch-by-bunch injection intensity fluctuation: 3%**
- **Bucket selection/filling pattern**

# Schematic layout and injection to BR, Z-mode



# Linac design steps

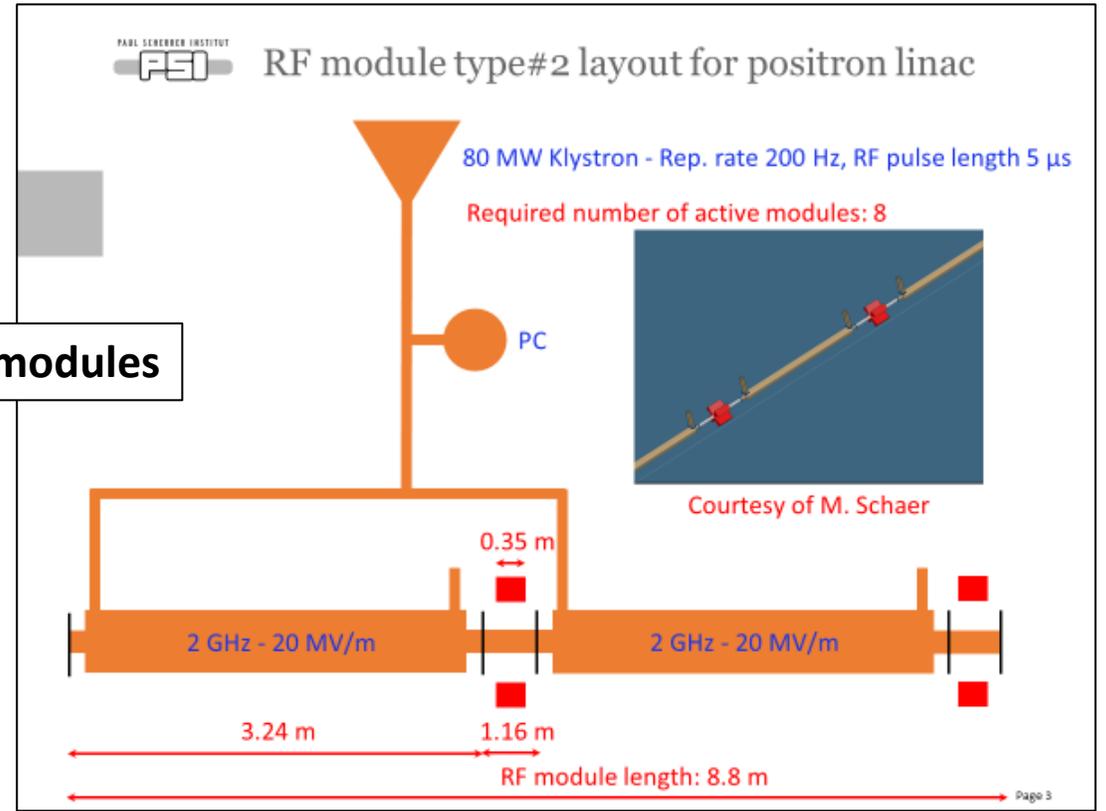
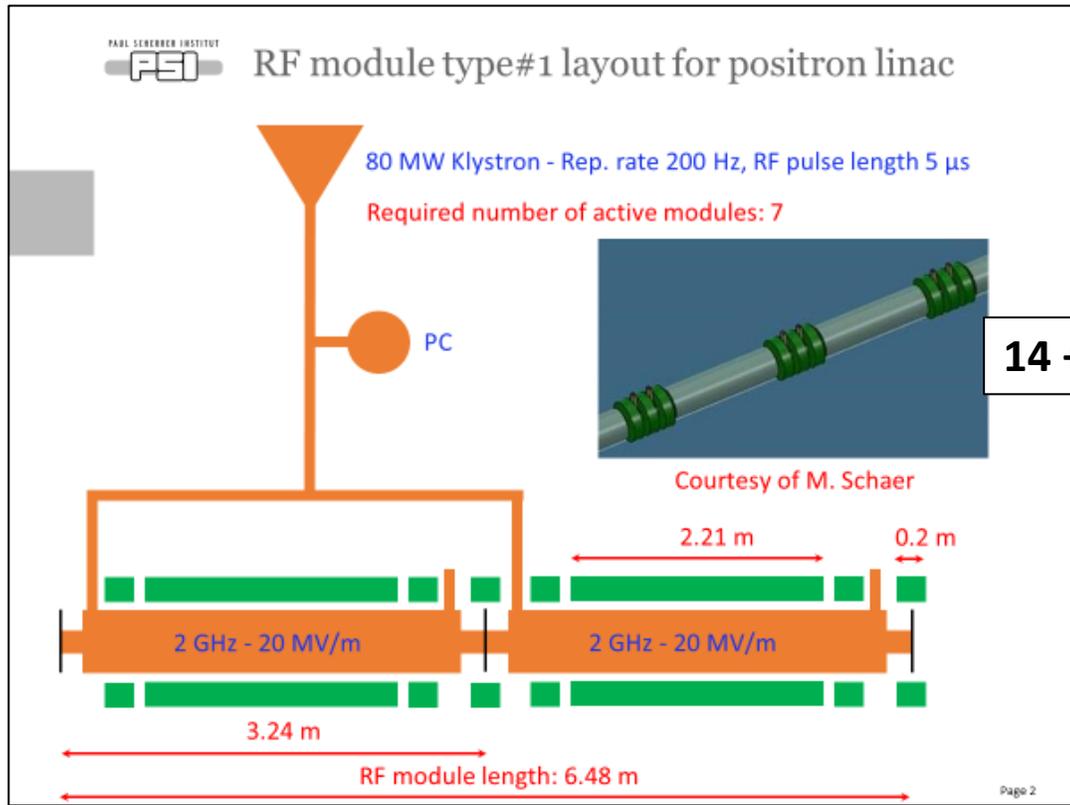
1. Beam dynamics design provides specification for accelerating structure design: aperture, RF frequency, structure length, gradient, etc. (covered in the previous talk by Simona Bettoni)
2. RF design of accelerating structures (to some extent) covered by Hermann Pommerenke in previous FCC week talk (FCCweek2022)
3. **RF module layout and parameters are put together based on the above input and the parameters of the RF power sources. (presented below)**



# RF power source parameters

Klystron abbreviation	Linac	Frequency [MHz]	Peak power specification [MW]	Rep. Rate [Hz]	RF pulse length [ $\mu$ s]	Duty factor [1e-3]	Average power [kW]	Required numbers
Kly_p	p-linac	2004	80	200	5	1	80	16 + 1
Kly_e	e-linac HE-linac S-band	2806	80	200	3	0.6	48	10 + 1 82
Kly_c	c-linac	2806	50	400	3	1.2	60	35
Kly_HE_C	HE-linac C-band	5611	50	200	3	0.6	30	86

# Layout of positron linac



14 + 1 RF modules

e-/e+

separation

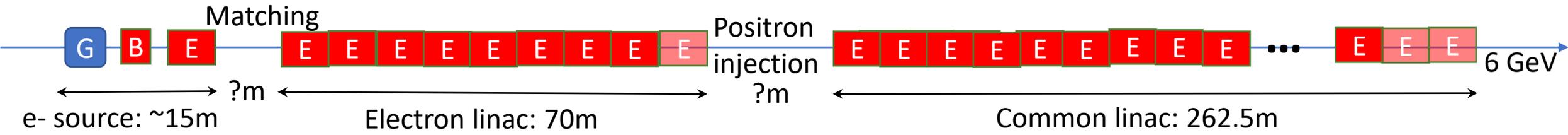
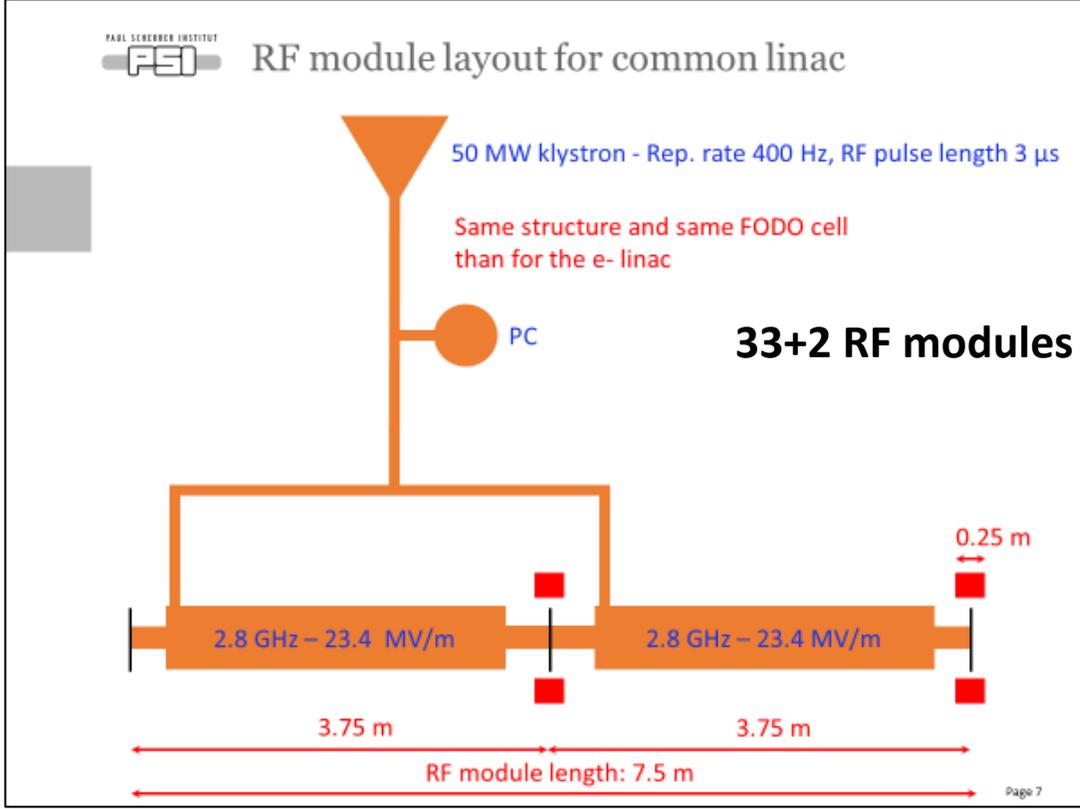
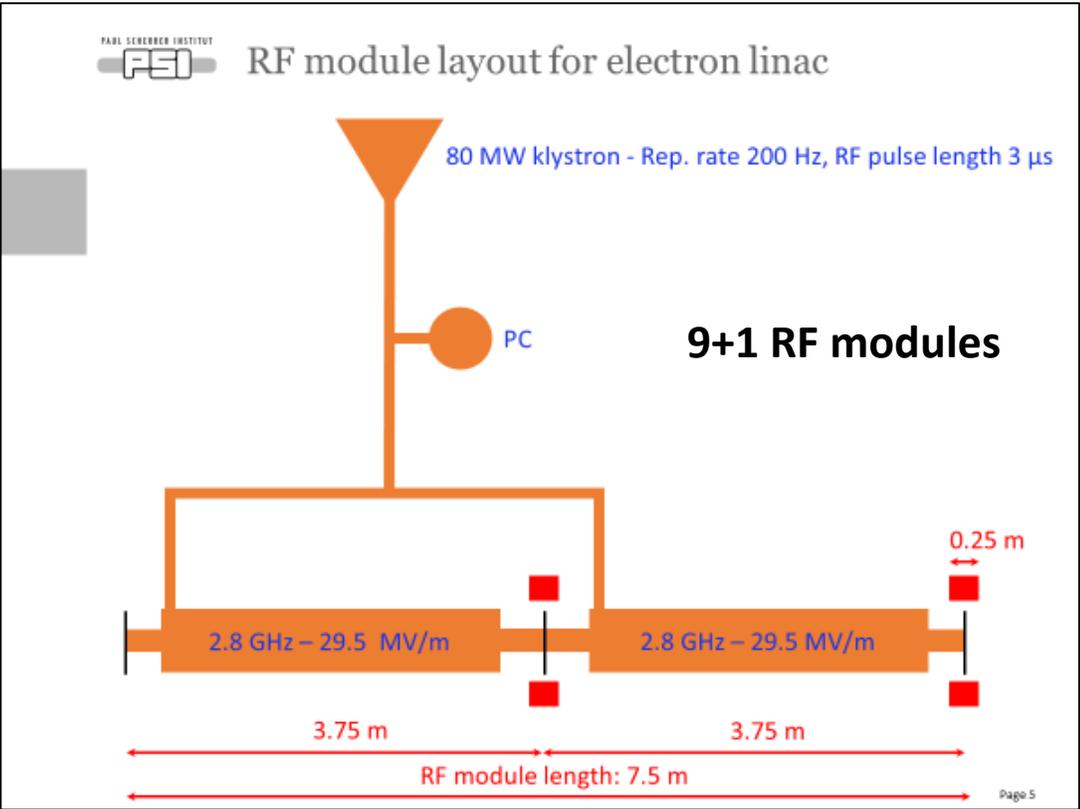
Matching

Energy

compressor



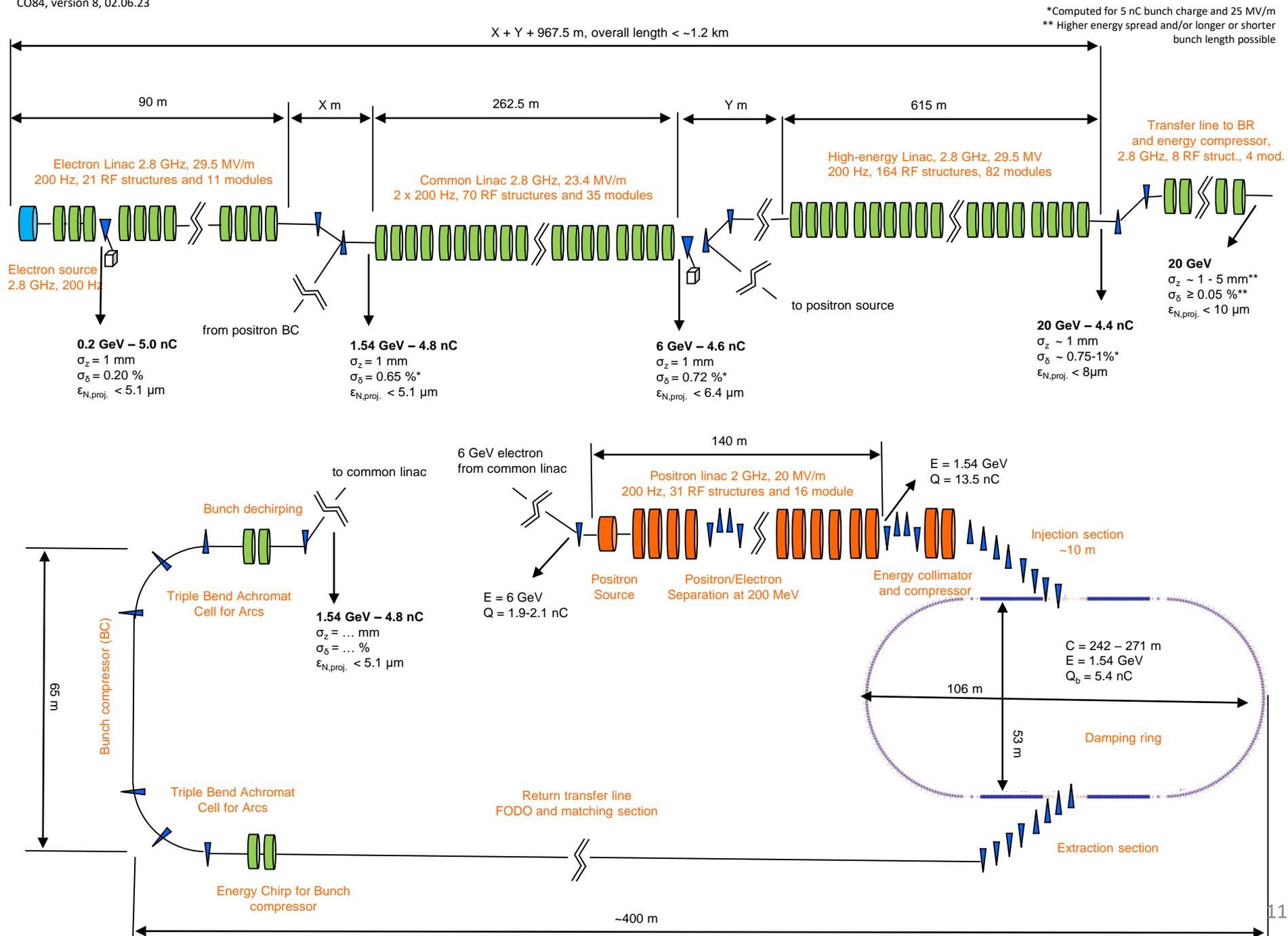
# Layout of electron and common linacs



# RF module summary table for all linacs

	p-linac	e-linac	c-linac	HE-linac (S)	HE-linac (C)	
Frequency [GHz]	2	2.8	2.8	2.8	5.6	
Accelerating structure	F3	$a/\lambda=0.15$	$a/\lambda=0.15$	$a/\lambda=0.15$	$a/\lambda=0.19$	
Repetition rate [Hz]	200	200	400	200	200	
Aperture radius [mm]	30	16.1	16.1	16.1	10.2	
Length [m]	3	3	3	3	3	
Filling time [ns]	447	486	486	486	334	
SLED coupling	17	15	15	15	10	
Klystron RF pulse length [ $\mu$ s]	5	3	3	3	3	
Average gradient [MV/m]	<b>20</b>	<b>29.5</b>	<b>23.4</b>	<b>29.5</b>	<b>28.8</b>	
Energy gain per structure [MeV]	60	88.5	70.2	88.5	86.4	
Klystron power per structure [MW]	31	30	18.9	30	18.2	
Klystron output power specification [MW]	<b>80</b>	<b>80</b>	<b>50</b>	<b>80</b>	<b>50</b>	Inc. WG loss and 90% margin
Number of structures per klystron	<b>2</b>	<b>2</b>	<b>2</b>	<b>2</b>	<b>2</b>	
Number of structures total	<b>1 + 30</b>	<b>1+20</b>	<b>70</b>	<b>164</b>	<b>172</b>	Same for quads, corrs. and BPMs
Number of modules total	<b>1 + 15</b>	<b>1+10</b>	<b>35</b>	<b>82</b>	<b>86</b>	
Total length of all modules [m]	<b>140</b>	<b>90</b>	<b>262.5</b>	<b>615</b>	<b>645</b>	

# Schematic layout of Pre-injector complex



# RF module summary table for bunch length and energy compressors

	Positron energy compressor before DR	Positron bunch compressor after DR	Energy compressor after HE-linac (S)	Energy compressor after HE-linac (C)
Frequency [GHz]	2	2.8	2.8	5.6
Accelerating structure	F3	$a/\lambda=0.15$	$a/\lambda=0.15$	$a/\lambda=0.19$
Repetition rate [Hz]	200	200	200	200
RF voltage per structure [MV]	60	88.5	88.5	86.4
Required voltage [MV]	100	60 + 150	680	500
Number of structures total	2	1 + 2	8	6
Number of modules total	1	1 + 1	4	3
Total length of all modules [m]	6.5	7.5 + 7.5	30	22.5

# Comparison of relative cost of linacs in a.u.

Linac	Klystron cost [a.u.]	Modulator cost [a.u.]	Cost estimation [a.u.]
p-linac	0.27	0.9	32.5
e-linac	0.18	0.82	20.5
c-linac	0.19	0.85	66.5
Total p-,e-,c-linacs			<b>119.5</b>
HE-linac – S-band option	0.18	0.82	<b>152.5</b>
HE-linac – C-band option	0.16	0.8	<b>155</b>

Cost estimate includes:

- RF
- LLRF
- Vacuum
- Magnets
- BI

- Cost of HE linac is comparable to the cost of all other linacs
- Cost of HE linac S-band (baseline) and C-band options is similar

# Power consumption of linacs comparison

Linac	Plug-Power [MW]	
Klystron Efficiency [%]	42	65
p-linac	6.1	4.0
e-linac	3.2	2.1
c-linac	12.5	8.3
Total p-,e-,c-linacs	<b>21.8</b>	<b>14.5</b>
HE-linac – S-band option	<b>23.6</b>	<b>16.0</b>
HE-linac – C-band option	<b>15.2</b>	<b>11.1</b>

Power estimate includes:

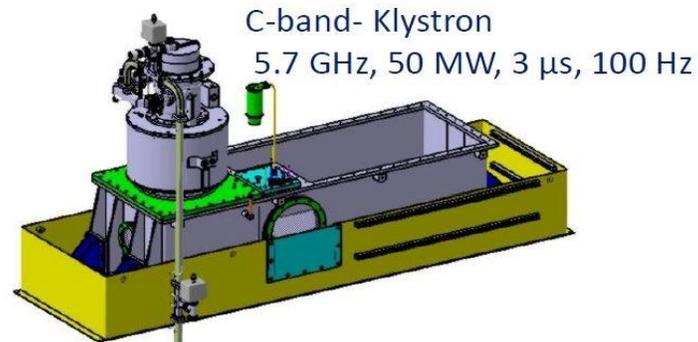
- High power RF

- Power of HE linac is comparable to the power of all other linacs
- Power of HE linac C-band option is 30% lower than for S-band options
- Power is 30% lower if the high efficiency klystrons are used

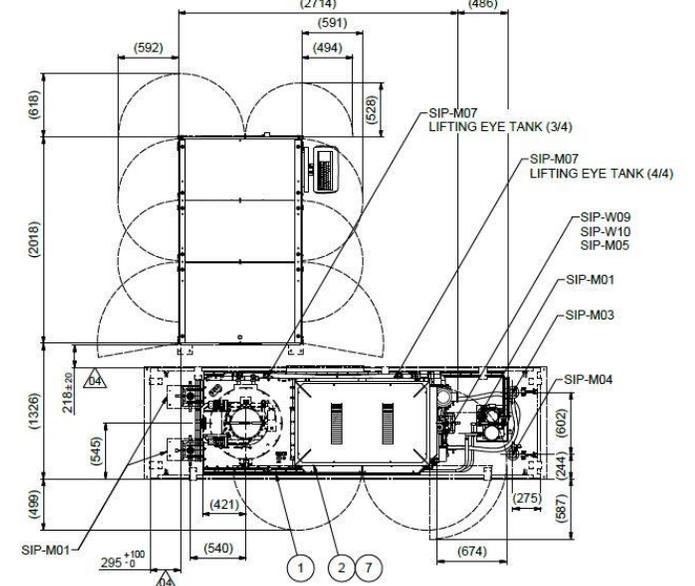
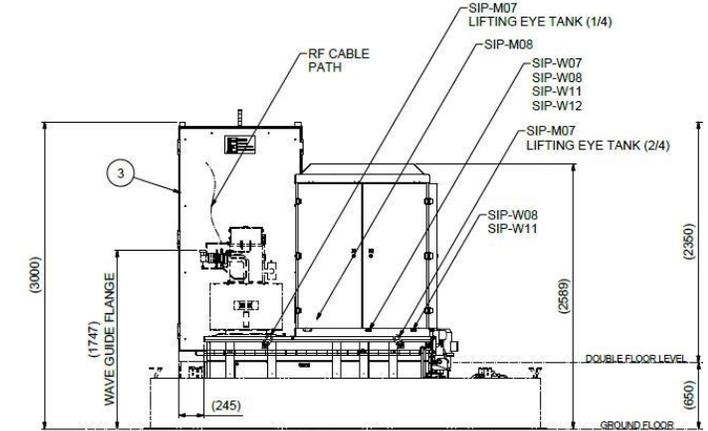
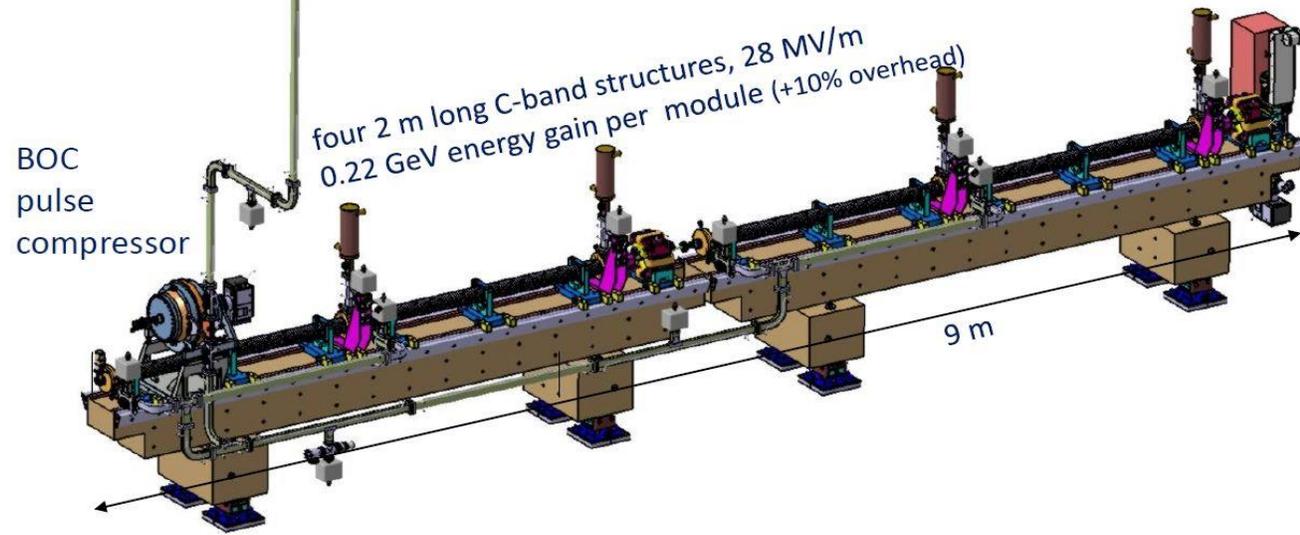
# HE-linac: S- and C-band comparison

- S-band (baseline)
  - It uses the same RF module as for the e-linac, same spares, etc
  - Better for the beam: Larger aperture, smaller “RF curvature”
  - Similar cost as C-band (a bit less actually)
  - S-band is more commercially available and more mature
- C-band
  - 30% (~10MW) lower power consumption. Although it is significant, but it is negligible compared to FCC overall power consumption

# SwissFEL RF module layout and modulator



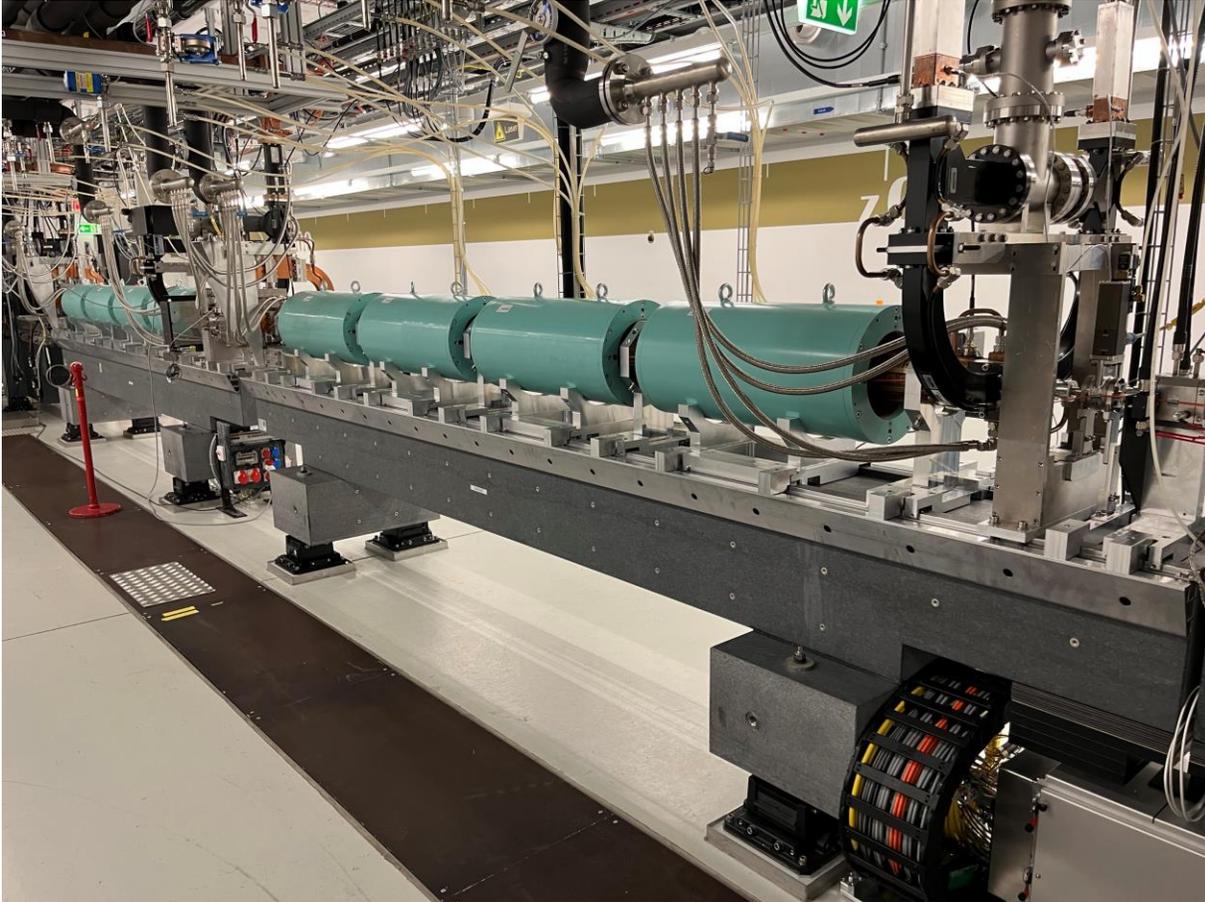
Main LINAC	#
LINAC modules	26
Modulator	26
Klystron	26
Pulse compressor	26
Accelerating structures	104
Waveguide splitter	78
Waveguide loads	104



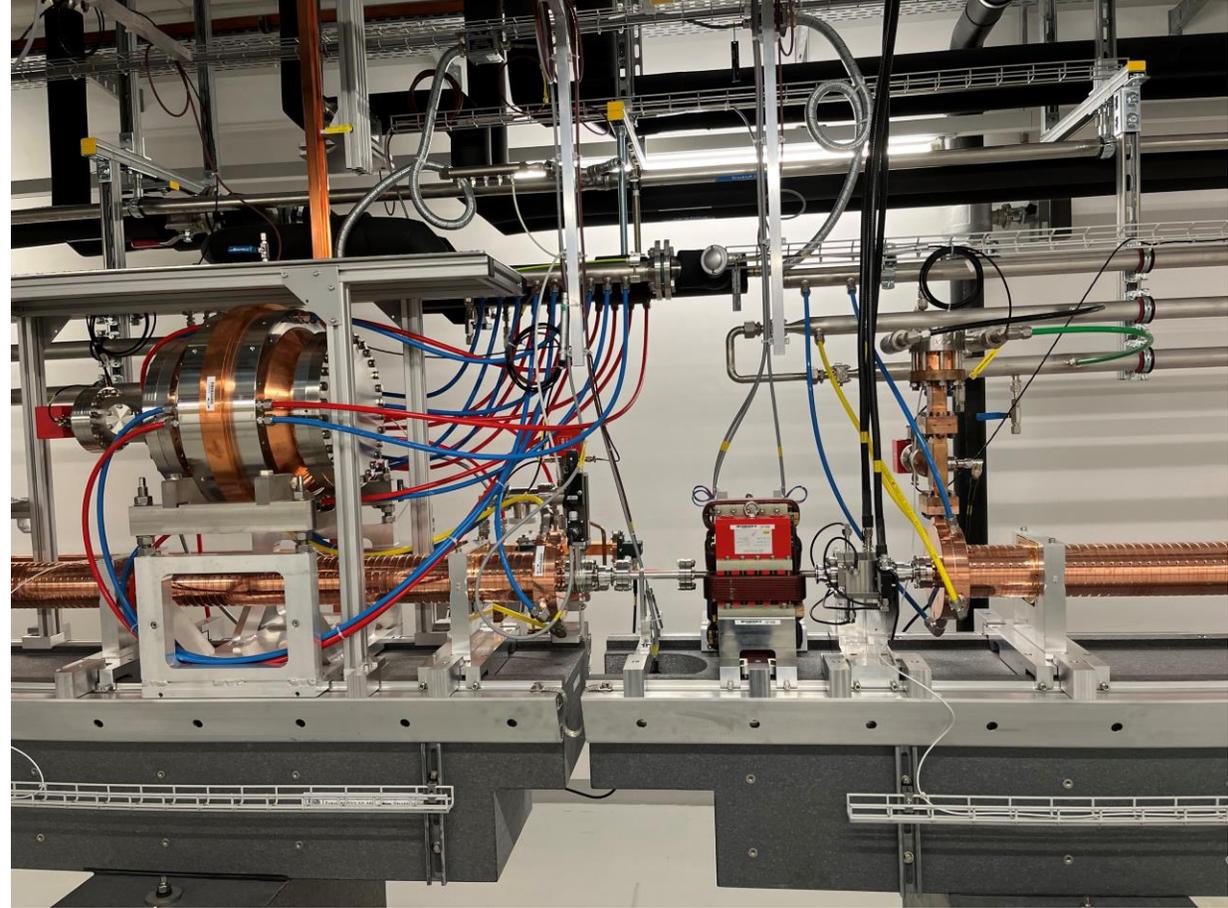
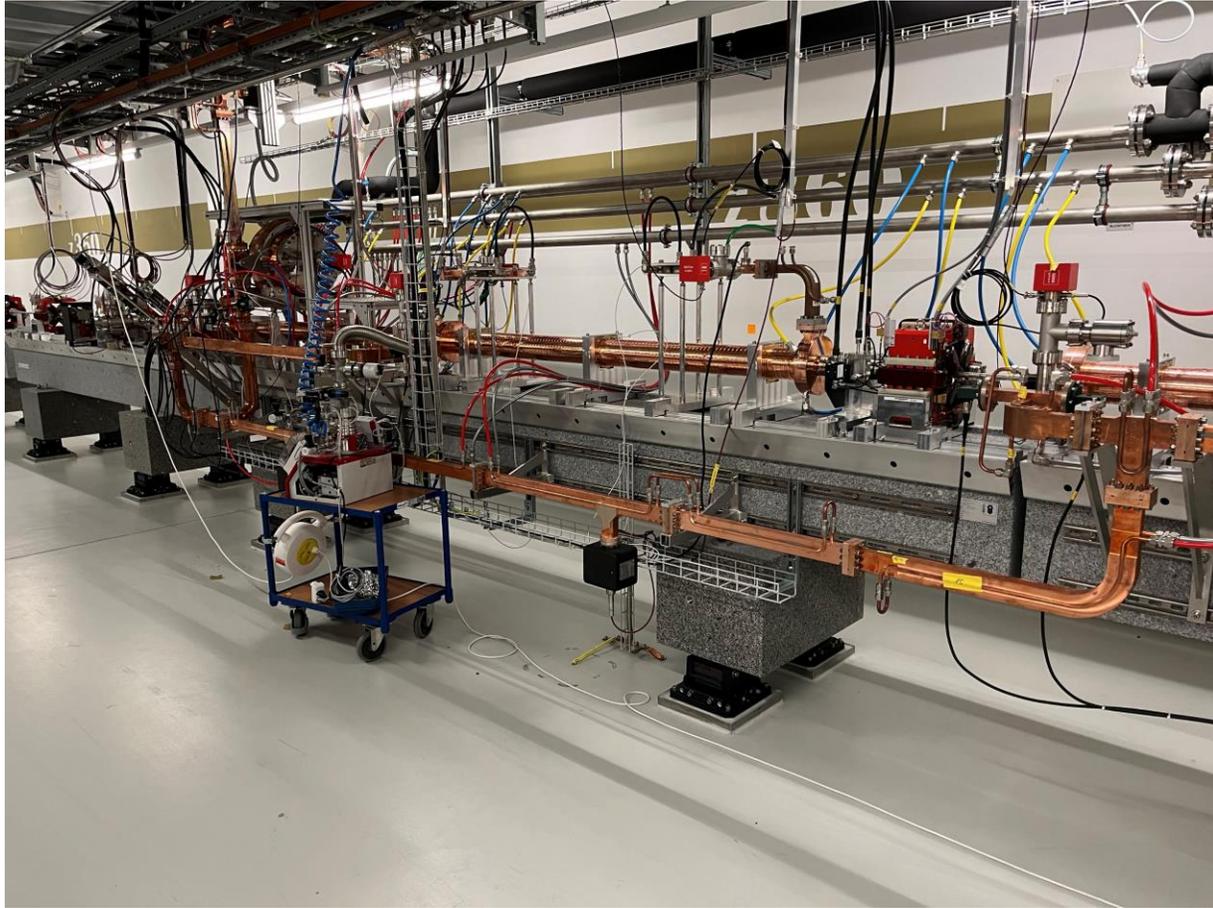
# SwissFEL RF modules: klystron, modulator



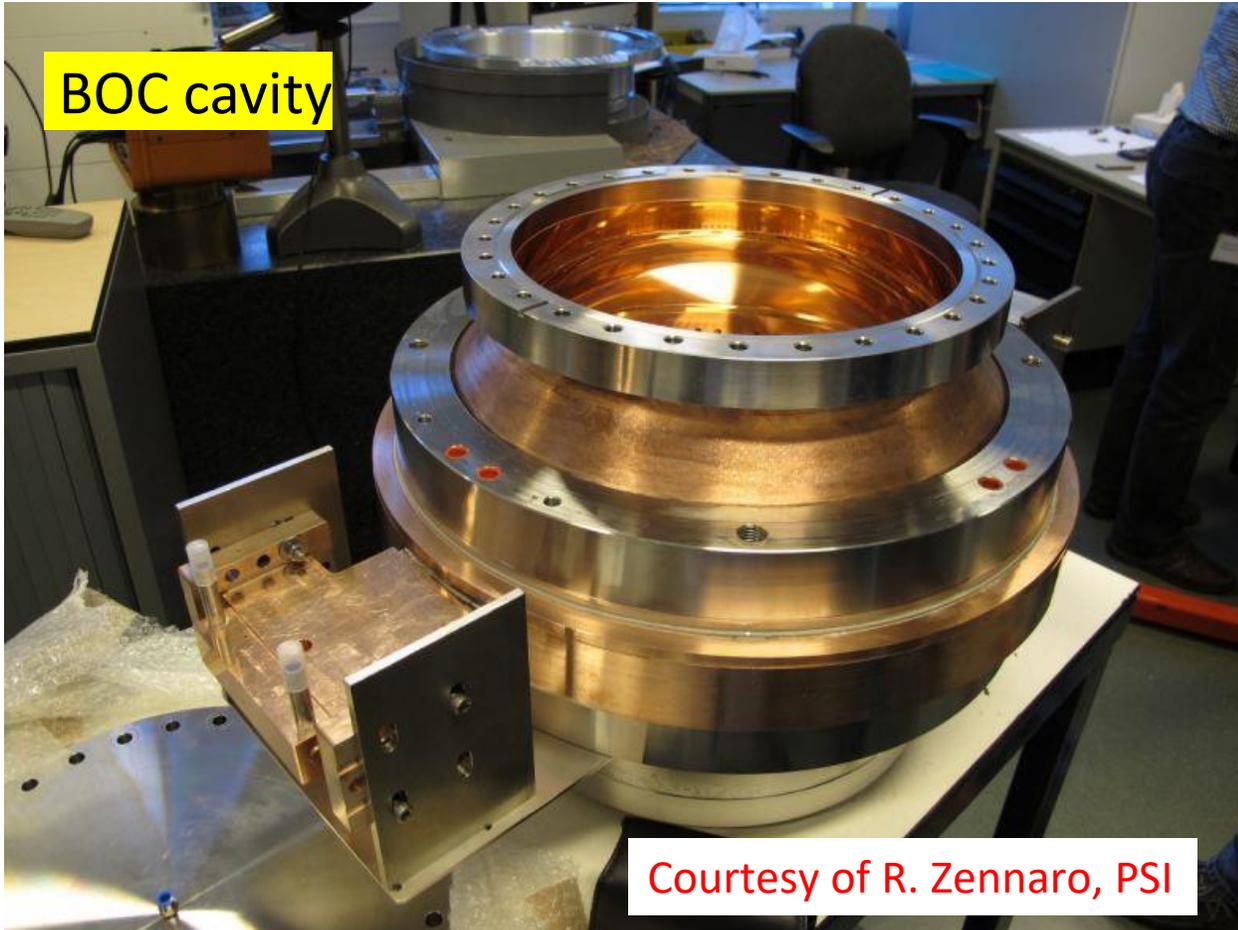
# SwissFEL linac S-band RF modules



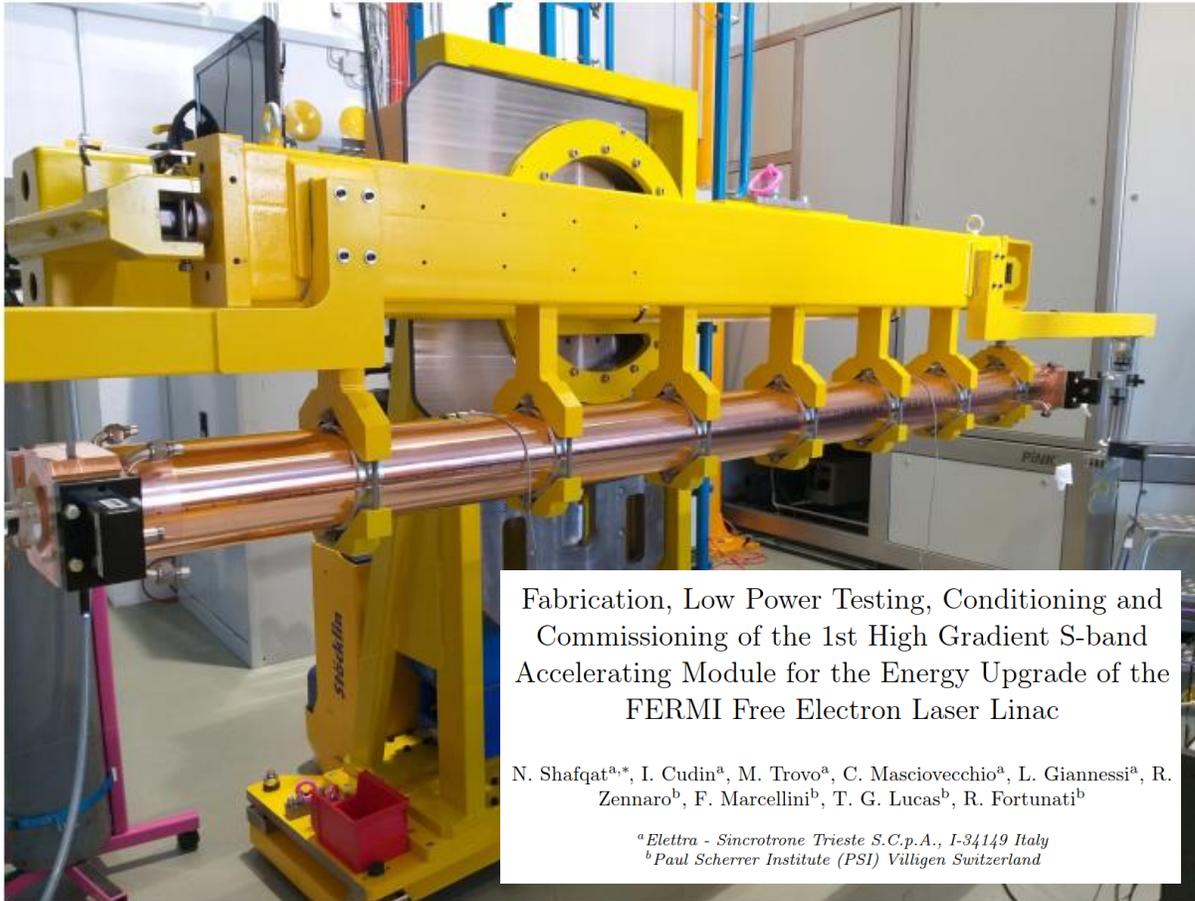
# SwissFEL linac C-band RF modules



# Spherical cavity rotating mode RF pulse compressor



# State-of-the-art manufacturing of accelerating structure 'on tune' using UHP turning at PSI



## 3m-long S-band structure brazed in one piece

Figure 6: Measured S-parameter for HG2 structure at 34.6 °C

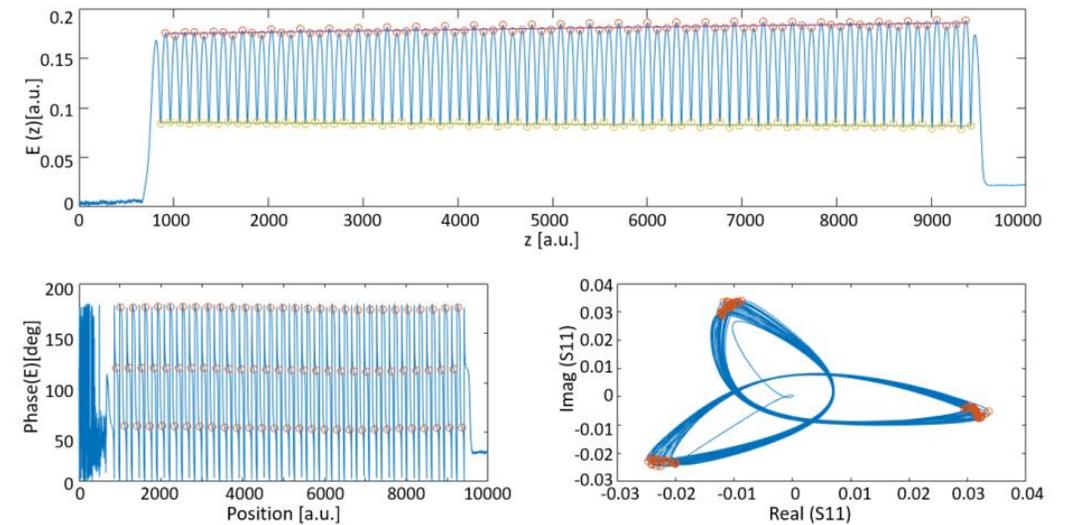


Figure 7: Measured field profile along the beam axis and phase advance for HG2 structure at 34.6 °C

# Conclusions

- RF module and overall linac layout has been developed based on the beam dynamics, RF requirements
- Positron, electron and common linacs bring the beam energy up to 6 GeV
- High energy linac accelerates nominal beams further up to 20 GeV.
- The cost and power of the p-,e- and c-linacs is comparable to the one of the HE-linac.
- For HE-linac, baseline is based on the S-band (same module as in e-linac)
- C-band option has been studied in detail. It is a bit more expensive but offer 30% less power consumption.

# Acknowledgements

- WP1 - linac design
- Task 1.1: electron source and Pre-Pre-injector design
  - Steffen Doebert, Zdenek Vostrel (CERN)
- Task 1.2: RF design of linacs
  - Alexej Grudiev, Hermann Pommerenke (CERN)
- Task 1.3: Beam dynamic design of the linacs
  - Simona Bettoni, Mattia Schaer (PSI)
- Task 1.4: RF module design and cost
  - Jean-Yves Raguin (PSI)
- Great Support from
  - Riccardo Zennaro and Paolo Craievich (PSI), Andrea Latina and Yongke Zhao (CERN), Iryna Chaikovska (IJCLab)



This work was done under the auspices of CHART (Swiss Accelerator Research and Technology) Collaboration, <https://chart.ch> - **CHART Scientific Report 2022:** <https://chart.ch/reports/>



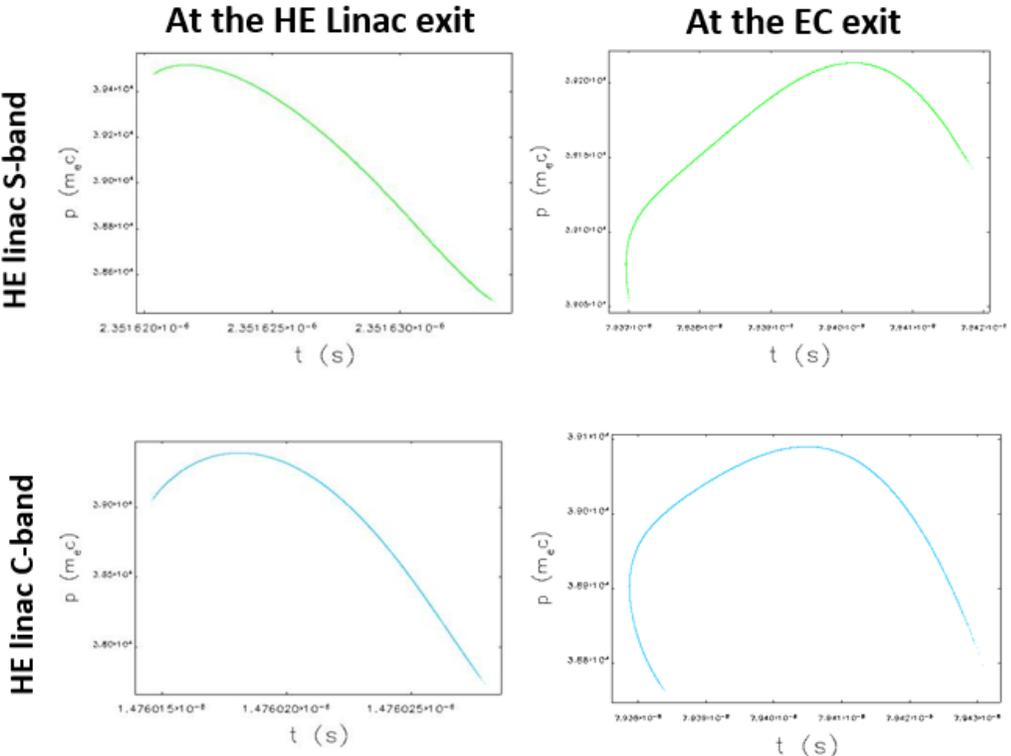
FCCIS: 'This project has received funding from the European Union's Horizon 2020 research and innovation programme under the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.'

# Back up

# Peak gradient and Average power

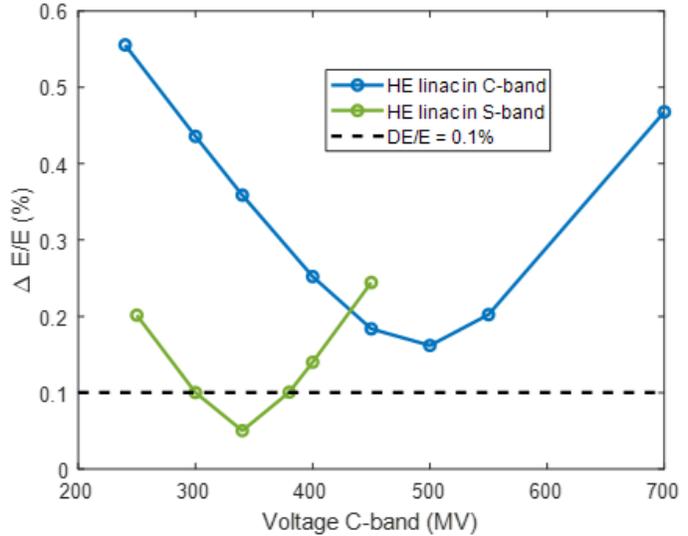
Linac	Frequency [GHz]	Peak gradient [MV/m]	Average power <Pin> [kW/structure]	Structure length [m]	Average power [kW/m] <Pin>/L*3/4	Outer wall radius [mm]	Power density on outer wall radius [kW/m <sup>2</sup> ]
p-linac	2.0	20	31	3	7.5	60	125
e-linac HE-linac S-band	2.8	29.5	18	3	4.5	~40	112.5
c-linac	2.8	23.4	22.5	3	5.6	~40	141
HE-linac C-band	5.6	28.8	11	3	2.8	~20	140
SwissFEL C-band	5.7	30	5	2	1.9	~20	95

# Energy compressor after HE linac



$$V_2 = \frac{\lambda_2 E}{2q\pi R_{56}}$$

	HE linac S-band	HE linac C-band
Initial HE linac $\delta E/E$ (%)	0.74	1.1
$R_{56}$ (m)	0.41	0.28



**S-band HE linac:** target bunch length (4 mm considered) and  $\delta E/E = 0.05\%$  achievable with a reasonable voltage in C-band

**C-band HE linac:** minimum of  $\delta E/E$  limited to 0.15% and higher voltage necessary to reach it