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PSI

Dr. Thomas Lucas :: Research Fellow :: Paul Scherrer Institute

Analysis of the Commissioning and Operation of the SwissFEL Linac (and Other High Gradient Activities at PSI)

High Gradient Workshop 2022

Overview

- Brief Overview of SwissFEL
- SwissFEL Conditioning Analysis
  – Overview of SwissFEL's C-band Linacs
  – Initial Conditioning Structures
  – Long Term Operation of Structures
- High Gradient Travelling-Wave Photogun
  – Overview of SwissFEL's S-band Injector
  – Electromagnetic Design
  – Dark Current and Multipacting Simulations
  – Beam Dynamics Simulations

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SwissFEL Overview

- SwissFEL is a Free-Electron Laser based at the Paul Scherrer Institute in Villigen, Switzerland.
- It consists of an S-band Injector and C-band main linac with X-band linearisers and deflector.
- The linac feeds two separate X-ray beamlines (Hard and Soft X-ray) simultaneously with two colour operation where a two bunches are separated by 28 ns.

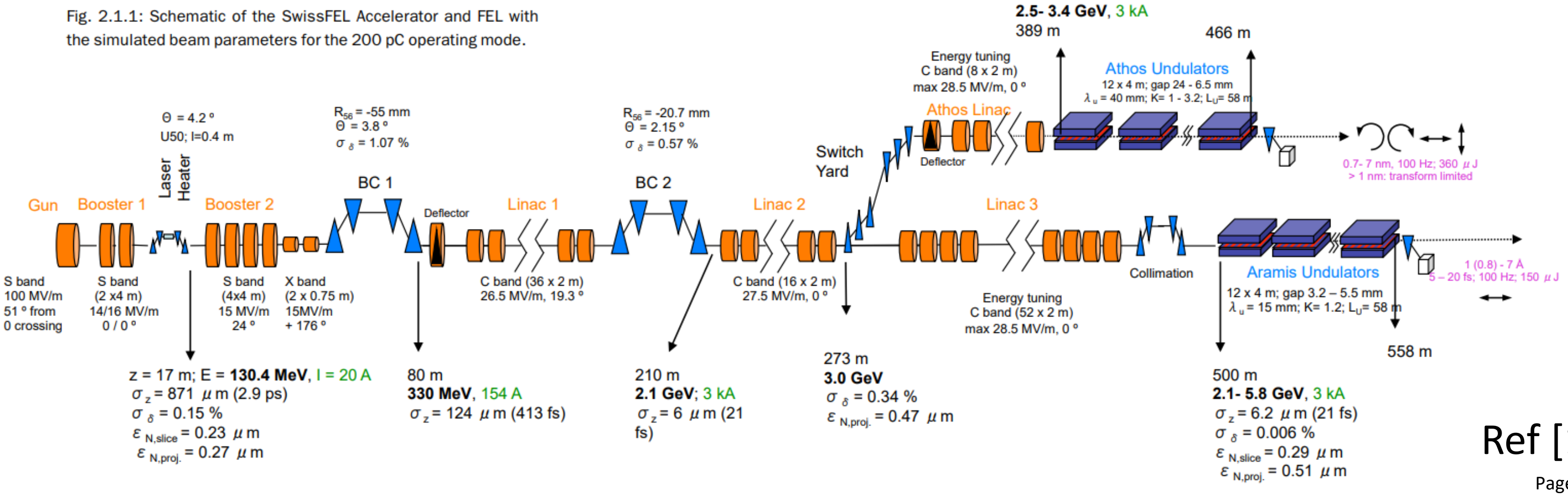

Fig. 2.1.1: Schematic of the SwissFEL Accelerator and FEL with the simulated beam parameters for the 200 pC operating mode.

Ref [1]

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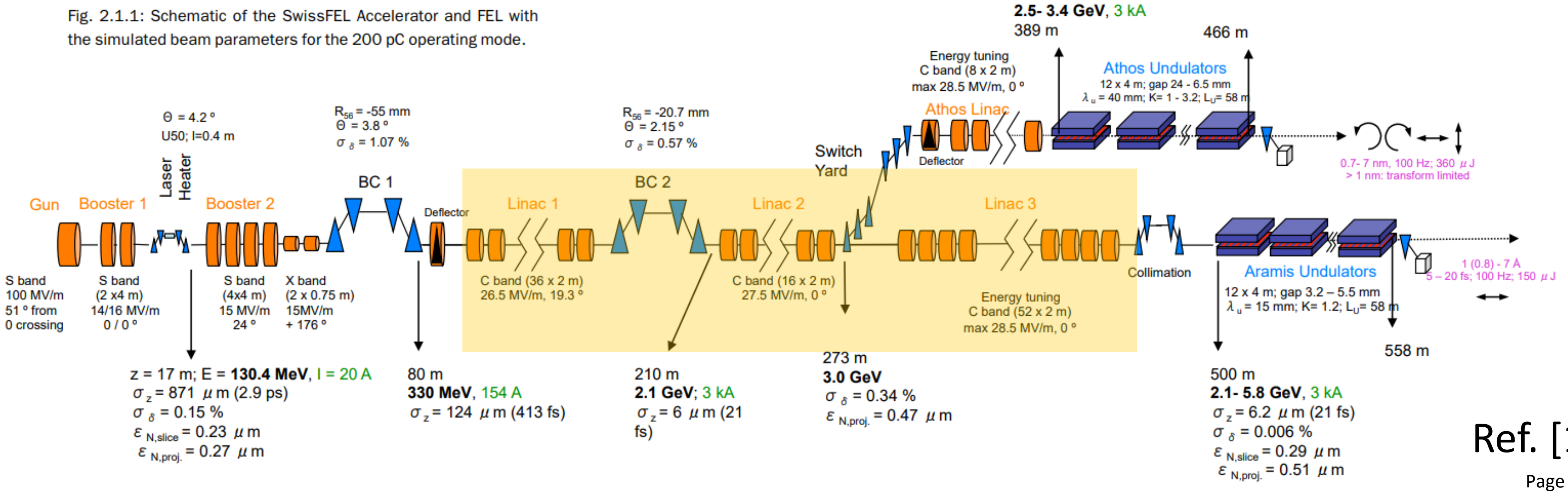
SwissFEL Overview: C-band Linac

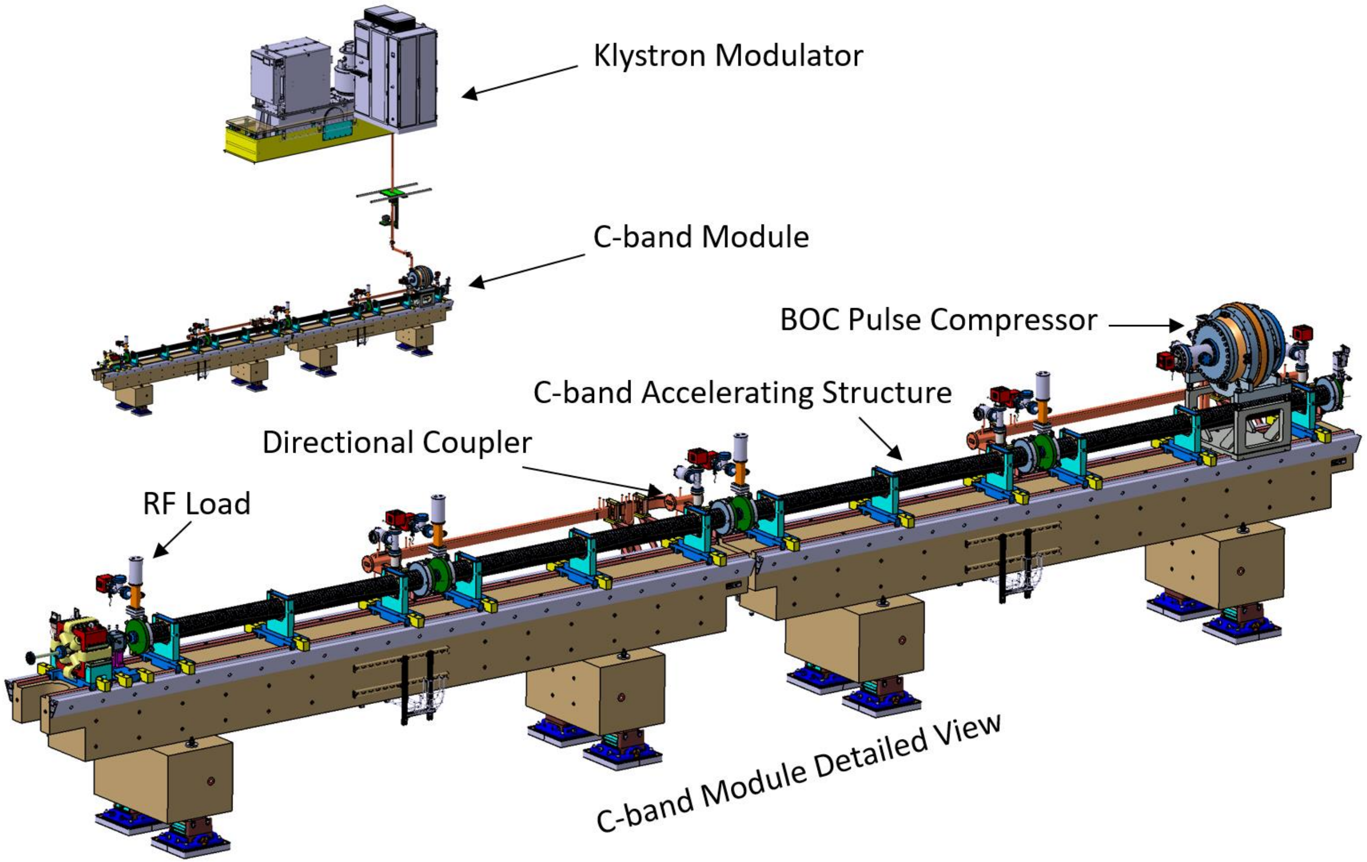
- Three linacs consisting which consist of 26 C-band modules in total (no including soft X-ray line).
- Each C-band module has four accelerating structures each two metres in length.
- Each module is powered by a 50 MW, 3 µs Modulator and Klystron feeding a BOC style pulse compressor.

Fig. 2.1.1: Schematic of the SwissFEL Accelerator and FEL with the simulated beam parameters for the 200 pC operating mode.



Ref. [1]

C-band Module



Parameter	Value	Unit
Frequency	5.712	GHz
Length	2	m
Phase Advance	$2\pi/3$	
Number of Cells	113	
Power	28	MW
Gradient	28	MV/m
Peak surface field	60.5	MV/m
Group Velocity	3.1-1.19	%c
Fill time	330	ns
Pulsed surface heating (350 ns)	4	K

Ref. [2]

Conditioning of Structures

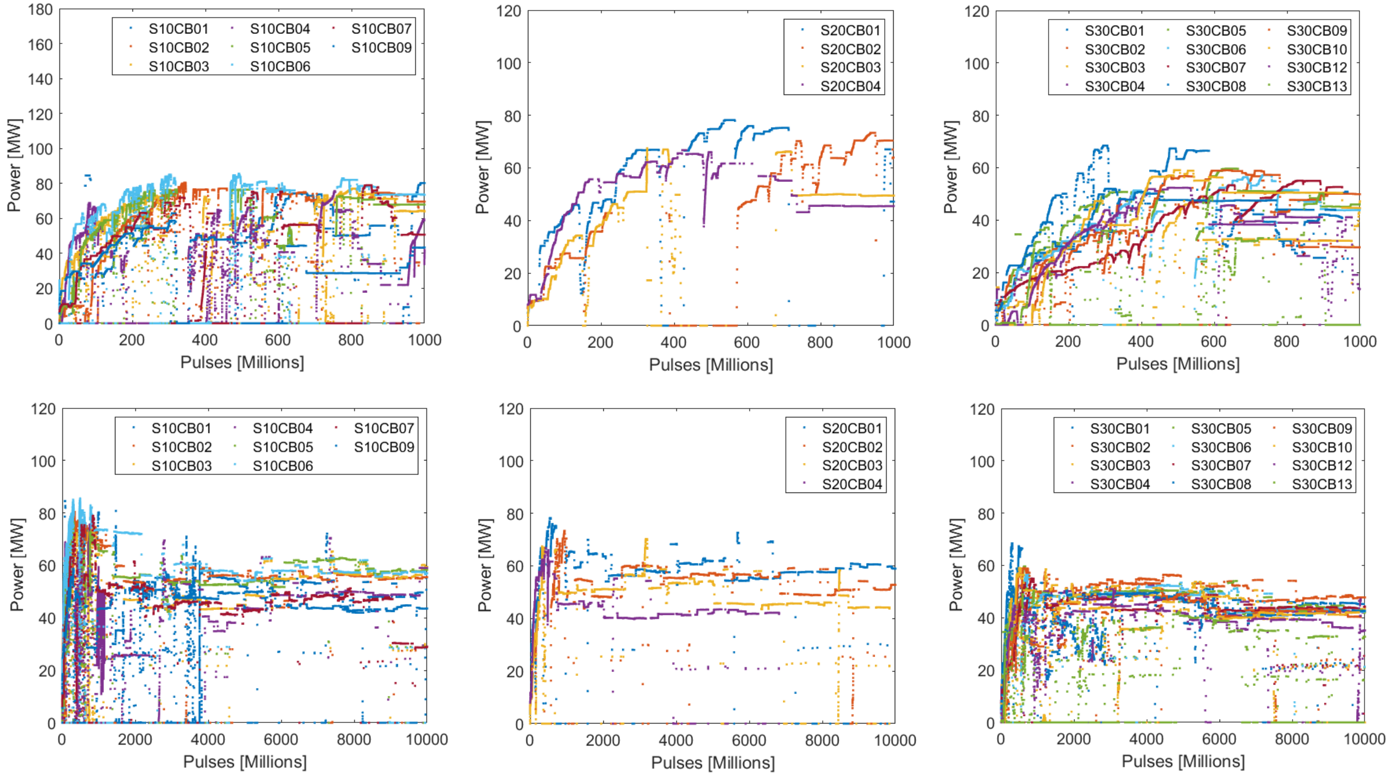
Conditioning Overview:

- Conditioning between August 2016 and October 2018 for all 26 modules.
- Required gradient approximately 30 MV/m.

Conditioning Parameters:

- Conditioning predominantly at 100 Hz.
- All structures in module powered with same power with only difference from waveguide losses.
- Pulse length varied between 100 ns and 400 ns.
- RF pulse compressor used in decay mode.
- Interlocked with reflected power and vacuum.

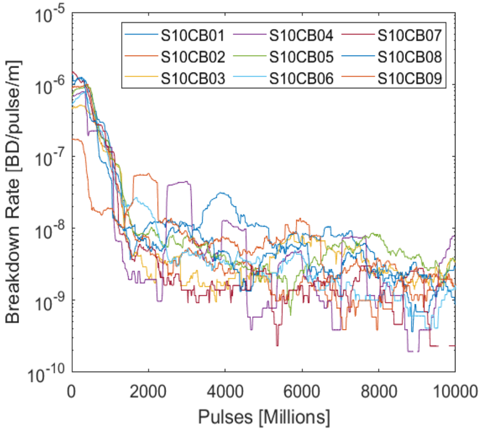
Conditioning and Nominal Operation

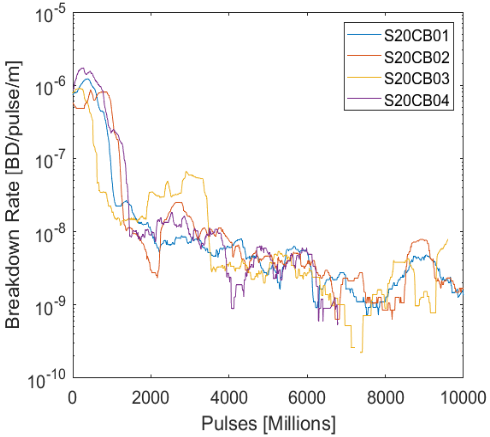


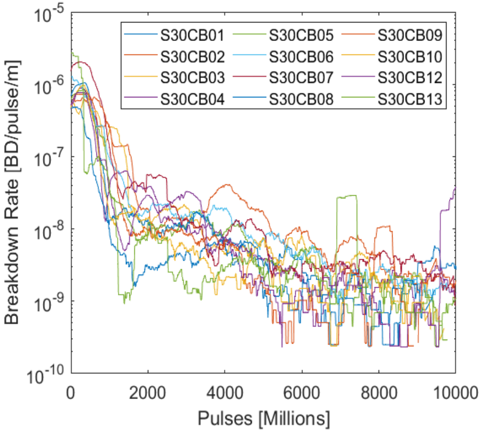
Notes:

- 28 MW = 28 MV/m
- 100 Hz operation = 3150 million pulses/year.
- Two modules (S10CB08 and S30CB11) not included as data quality was too poor.

Conditioning during Nominal Operation







Comments and Observations

1. Conditioning to full power took between 300 and 600 million pulses for all structures.
2. Some had clear evidence of conditioning algorithm impeding progress which made them condition slower.
3. All 104 structures surpassed the required 30 MV/m gradient (32 MW) for SwissFEL.
4. Breakdown rate during high power ramp was set to 10^{-6} BD/Pulse/m.
5. All structures demonstrate extremely similar breakdown behaviour.

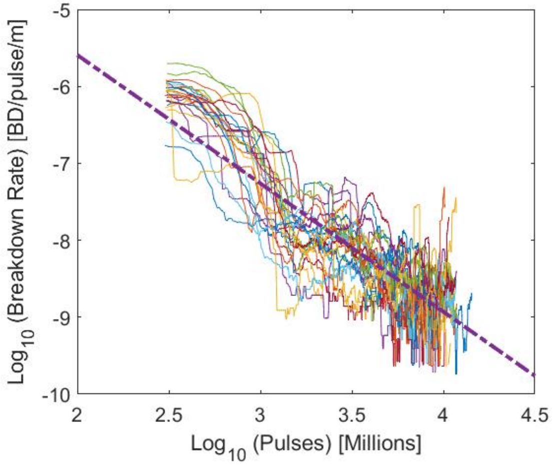
Conditioning Rate

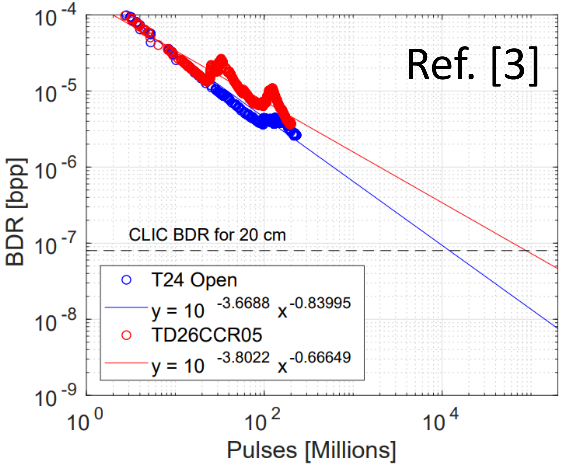
- Conditioning of the structures continued for over 10 billion pulses.
- Reduction in breakdown rate followed an inverse power law with no evidence of a breakdown rate floor.
- Reduction of 50 times for every decade.
- A fit of the form:

$$\log 10(BDR) = a\log 10(N_p) + b$$

gives a value $a = -1.67 \pm 0.347$.

- Similar behaviour as observed in tests at CLIC structures over 200 million pulses at constant power.





Ref. [3]

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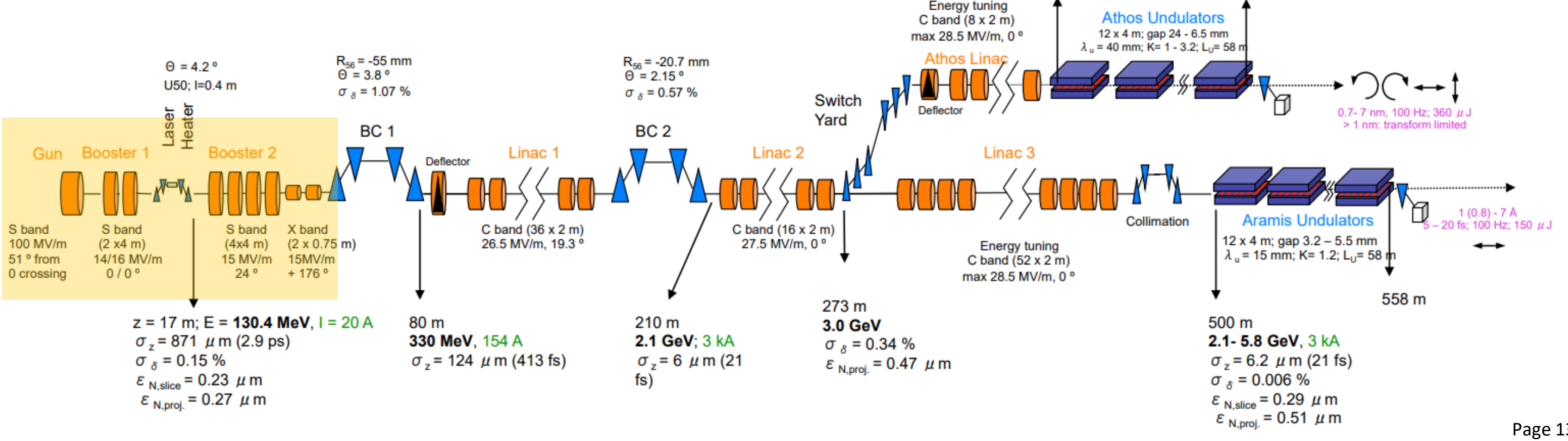
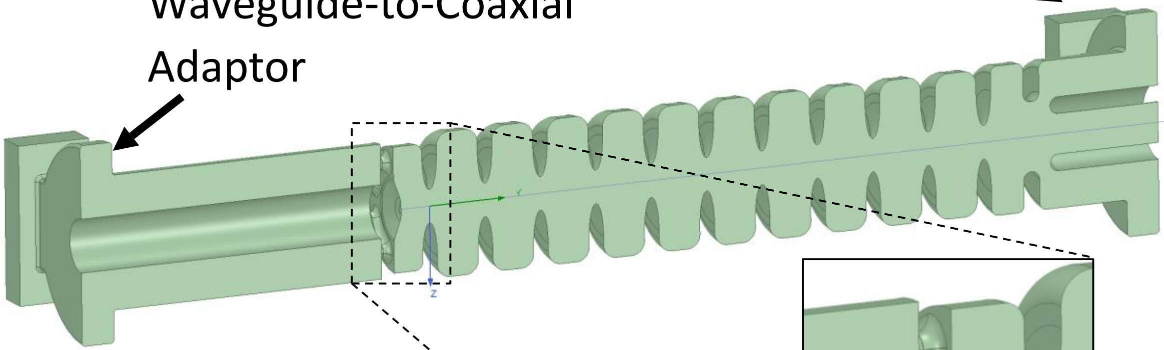
SwissFEL Overview: S-band Injector

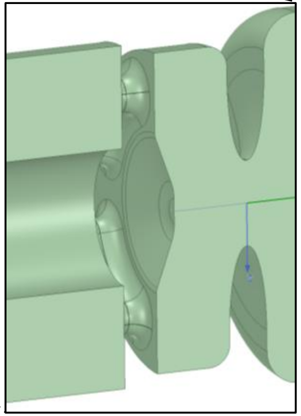
- The S-band Standing Wave RF Photogun with a nominal peak cathode field of 100 MV/m.
- The nominal bunch parameters are a 200 pC bunch charge with a normalised emittance of 0.23 um rad and 20 A bunch current.

Fig. 2.1.1: Schematic of the SwissFEL Accelerator and FEL with the simulated beam parameters for the 200 pC operating mode.



C-band TW Photogun: RF Design





New Magnetically Coupled Input Coupler With Cathode

Parameter	Value	Units
Accelerating Cells	10 (+2 coupling cells)	
Cell Length	17.495	mm
Total RF Length	229	mm
Phase Advance	120	degs
Attenuation	1.4	dB
Group velocity	0.0079	c
Fill Time	90	ns
Power	37.5	MW
Cathode Field	138	MV/m
Extracted Field	95	MV/m
Energy	13.1	MeV
Pulsed Surface Heating	14	K

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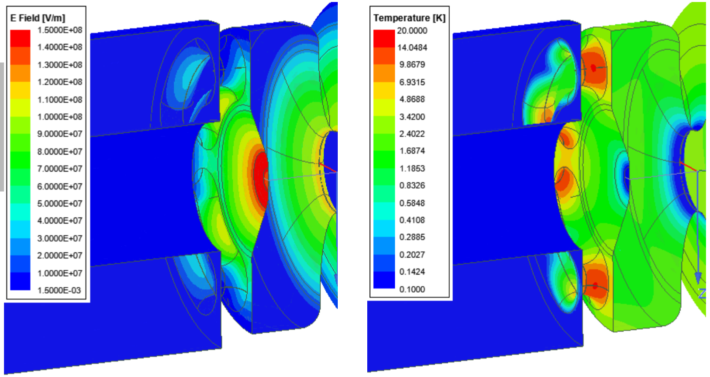
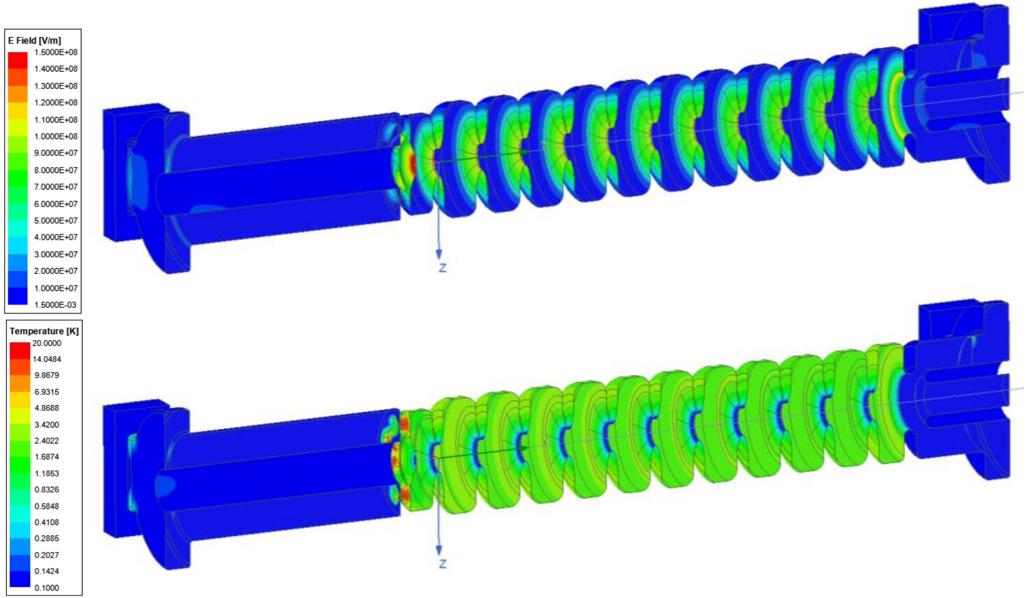
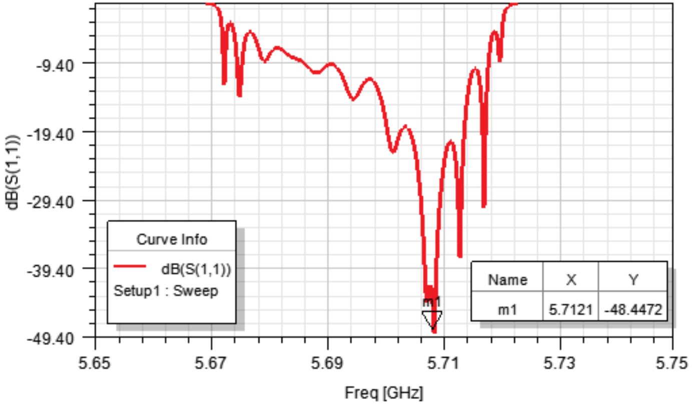
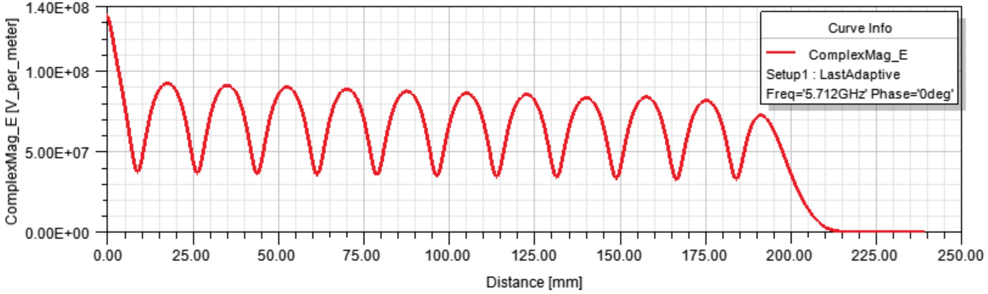
Electromagnetic Field Distributions





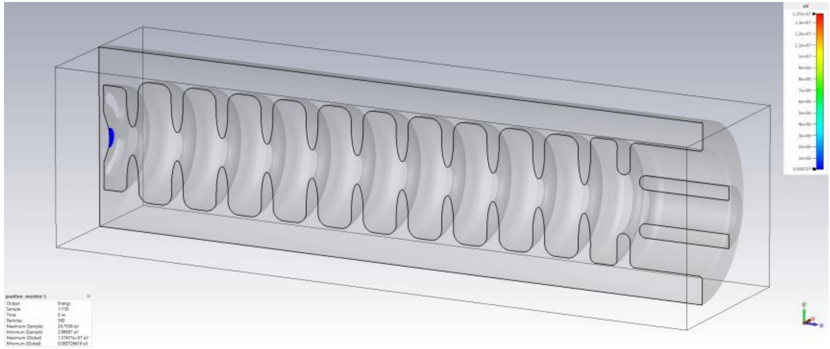




PIC simulations of Performance Limiting Phenomena

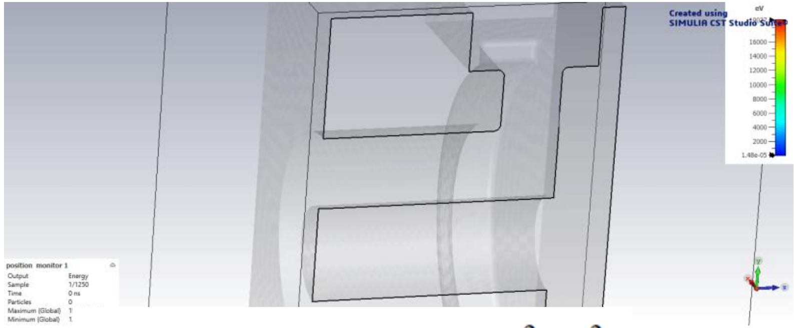
Dark Current

- Simulations technique described in: T. G. Lucas, *Dependency of the capture of field emitted electron on the phase velocity of a high-frequency accelerating structure Nucl. Instrum. Meth. A 914 (2019) 46-52*

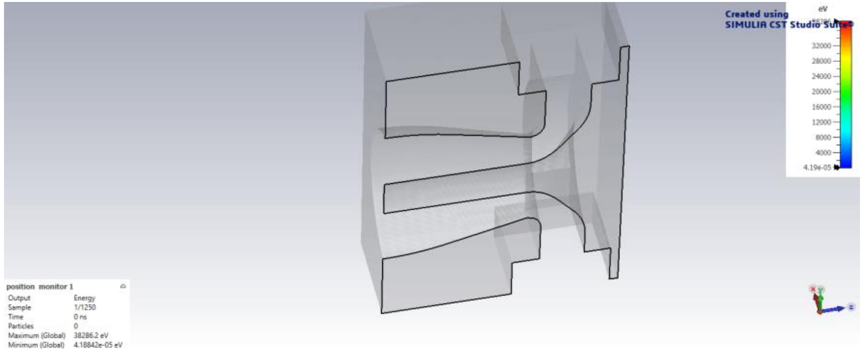


Field Enhancement Factor (β)	Effective area (A_e) [um^2]	Cathode Gradient [MV/m]	Charge arriving downstream (per 90ns RF pulse) [pC]	Capture Ratio	Total Field emitted charge (per RF pulse) [pC]	Peak Energy [MeV]
70	0.01	135	5.9	0.31	19.0	13.0
70	0.01	200	160.3	0.29	552.8	19.2

Multipacting



$$\ddot{\mathbf{r}}_0 = -\nabla\Phi, \ \ \Phi = (\eta/2\omega)^2|\mathbf{E}|^2,$$



Ref: A.V. Gaponov, M.A. Miller, Potential wells for charged particles in a high-frequency electromagnetic field. Sov. Phys. JETP 7, 168 (1958)

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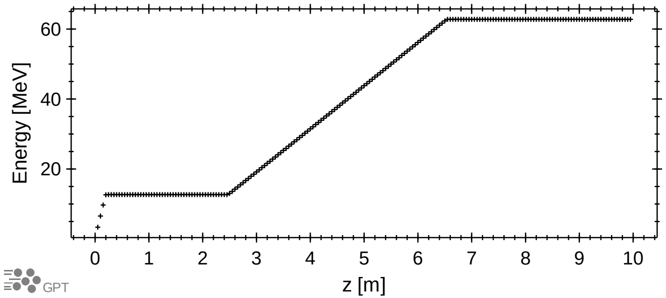
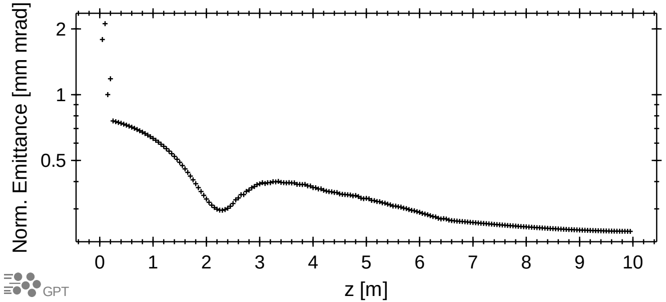
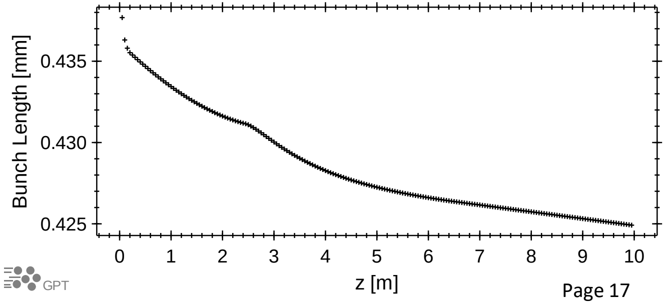
Beam Dynamics

- Simulations performed in GPT with Mesh Space-charge.
- Increase in brightness achieved through increase in peak current.
- Ongoing investigations on increasing 6D brightness.

Parameter	TW RF Photogun		SwissFEL Nominal	Units
Peak Cathode Field	135	200	100	MV/m
Bunch Charge	200	200	200	pC
Energy	13.1	18.8	6.6	MeV
Projected Emittance	0.23	0.155	0.21	mm mrad
Bunch Length	0.425	308	0.933	mm
Peak Current $(Q/\sqrt{12}t)$	41	56	19	A

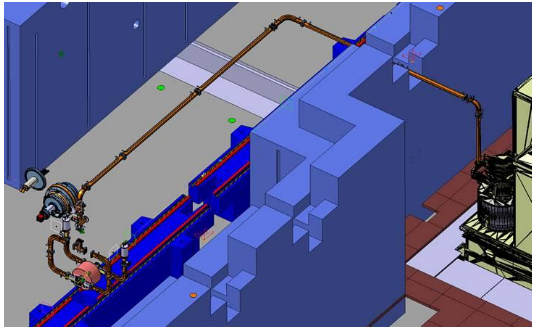






Bunker preparation

- **Waveguide network** drawn with some small WG sections to fabricate.
- **Radiation simulations** started and will determine shielding requirements particularly thickness of new wall.
- Waveguide from klystron extended in preparation for IFAST.
- **Setup ready for isolator testing** (SW gun).
- Once we have the radiation simulations done we'll proceed with the **BAG application**.



Conclusion

SwissFEL Conditioning Analysis

- Conditioning Analysis of SwissFEL has demonstrated that consist performance for all 104 structures operating at 30 MV/m for a 400 ns with a breakdown rate of 6×10^{-10} BD/pulse/m.
- Long term operation has demonstrated that the breakdown rate continues to drop following an inverse power law fashion with a reduction 50 times per decade.

Travelling Wave Gun

- New RF design for TW gun has been finished.
- Dark current simulations performed for nominal and high gradient operation.
- Beam dynamics demonstrates that the gun can generate a peak current which is three times that of SwissFEL with a 25% reduction in emittance.

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3. Initial Testing of Techniques for Large Scale Rf Conditioning for the Compact Linear Collider, T.G. Lucas, et al. 9th International Particle Accelerator Conference, Vancouver, Canada, 29 Apr - 4 May 2018, pp.THPMK103

Thank you!

- Any Questions?