PSI Center for Accelerator Science
and Engineering

Next Generation High Brightness Electron Sources

with Intrabeam Scattering

Thomas Geoffrey Lucas and Paolo Craievich (Paul Scherrer Institut)

Erion Gjonaj (TU Darmstadt)

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Beam Brightness and Cathode Electric Field

- Higher brightness electron sources are key to the improvement of XFELs.
- Extensive investigations have demonstrated that brightness increases with the electric field gradient on the surface of the cathode, for a given electron source [1] (this doesn’t translate between different electron sources).

$$B_{5D} \propto E_0^n \text{ where } 1.5 < n < 2$$

- For pulsed facilities, the state-of-the-art S-band room temperature normal conducting guns have proven a robust solution to FEL injectors. However, they have began to reach their performance limit with gradients up to 120 MV/m.
- How do we go beyond this cathode field?

1) J. B. Rosenzweig, Next generation high brightness electron beams from ultrahigh field cryogenic rf photocathode sources

How to achieve higher surface electric field gradients?

- The physical mechanism driving RF breakdown still illudes the community. However, there's much we've learnt in the generation of higher gradients.
- These are some factors that well demonstrated evidence to allow higher gradients.
  - ***Higher Frequencies [8]***
  - ***Shorter RF pulse lengths [4,5,6]***
  - ***Low Group Velocity [2,3,4]***
- More recently developing evidence
  - *New materials (CuAg) [6]*
  - *Cryogenic Copper [7]*
- In this work we will exploit the first three techniques. However, this work could also be combined with these newly developing concepts if further evidence demonstrates their high gradient abilities.

A non-exhaustive list of references:

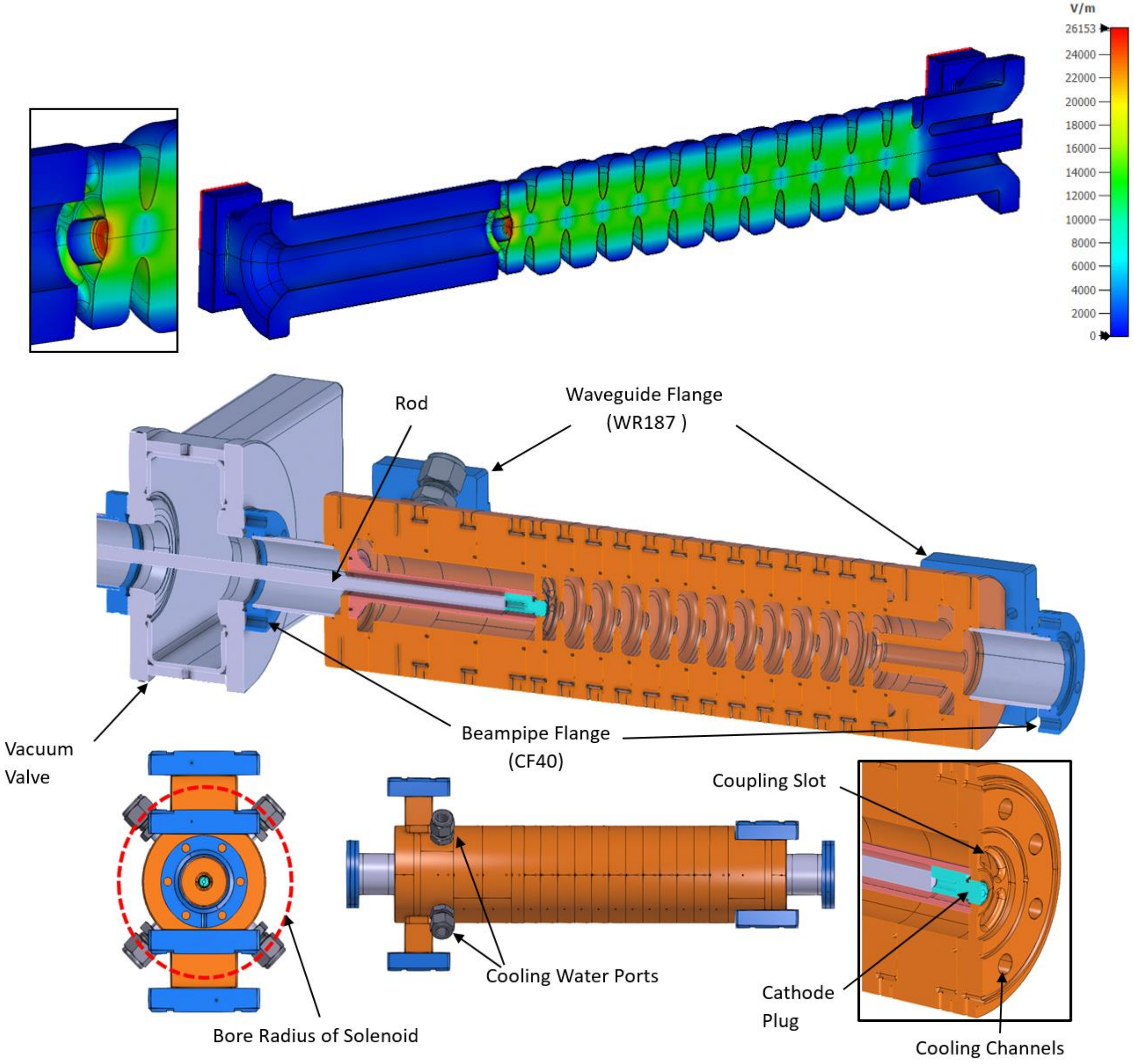
1. **V. A. Dolgashev, *Design Criteria for High-Gradient Radio-Frequency Linacs. Appl. Sci.* 2023, *13*(19), 10849**
2. Dolgashev, V.; Tantawi, S. Effect of RF Parameters on Breakdown Limits in High-Vacuum X-Band Structures. In AIP Conference Proceedings; American Institute of Physics: College Park, MD, USA, 2003; Volume 691, pp. 151–165.
3. Wuensch, W. The Scaling of the Traveling-Wave RF Breakdown Limit; Technical Report; CERN: Geneva, Switzerland, 2006.
4. Grudiev, A.; Calatroni, S.; Wuensch, W. New local field quantity describing the high gradient limit of accelerating structures. Phys. Rev. Spec.-Top.-Accel. Beams 2009, 12, 102001.
5. Dolgashev, V.A.; Tantawi, S.G.; Nantista, C.D.; Higashi, Y.; Higo, T. High Power Tests of Normal Conducting Single Cell Structures. In Proceedings of the IEEE PAC 2007, Albuquerque, NM, USA, 25–29 June 2007; pp. 2430–2432.
6. Dolgashev, V.; Tantawi, S.; Yeremian, A.; Higashi, Y.; Spataro, B. Status of High Power Tests of Normal Conducting Single-Cell Standing Wave Structures. In Proceedings of the IPAC 2010, Kyoto, Japan, 23–28 May 2010; pp. 3810–3812.
7. Cahill, A.D.; Rosenzweig, J.B.; Dolgashev, V.A.; Tantawi, S.G.; Weathersby, S. High gradient experiments with X-band cryogenic copper accelerating cavities. Phys. Rev. Accel. Beams 2018, 21, 102002.
8. Kilpatrick,W.D. Criterion for vacuum sparking designed to include both rf and dc. Rev. Sci. Instrum. 1957, 28, 824–826.

The ‘Classic’ Recipe to designing an RF Photogun

and its application to a TW photogun

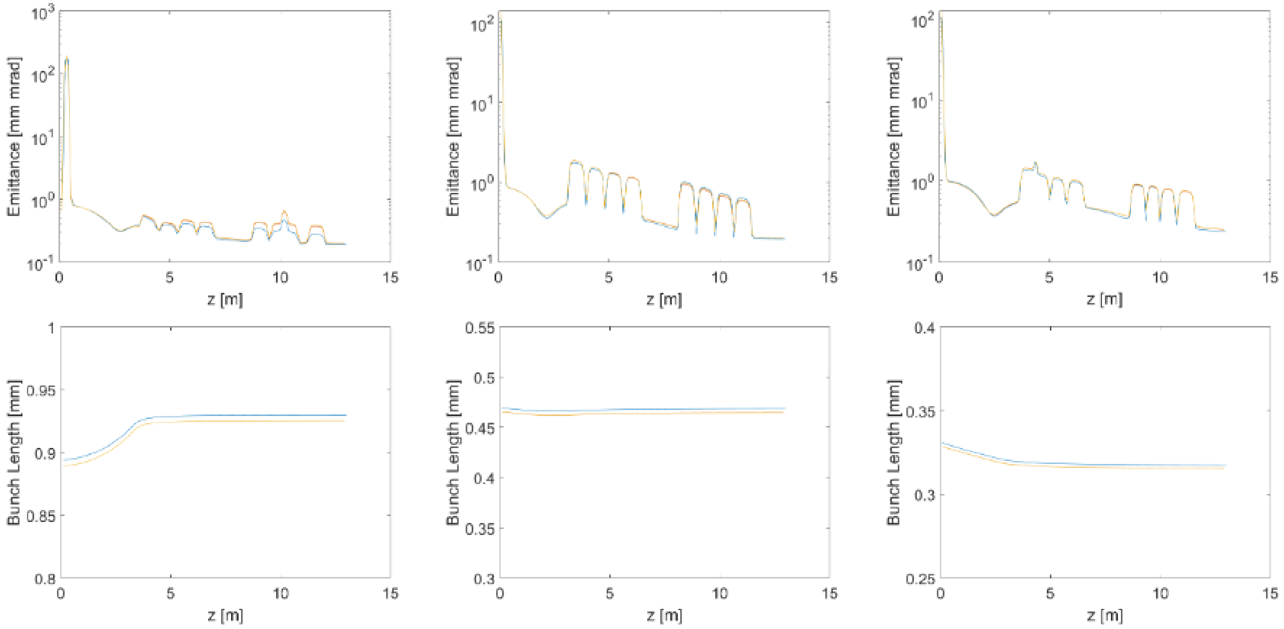
TW Photogun: Design

- An 11.5-cell Travelling-Wave RF Photogun with coaxial input and output couplers.
- Designed with an exchangable cathode capability.
- RF Design and mechanical design by PSI.
- Published here: https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.26.103401



Beam dynamics performance

- Beam dynamics simulations performed in ASTRA and REPTIL.
- Initial simulations using normal space-charge model.
- Both codes demonstrate extremely similar results.

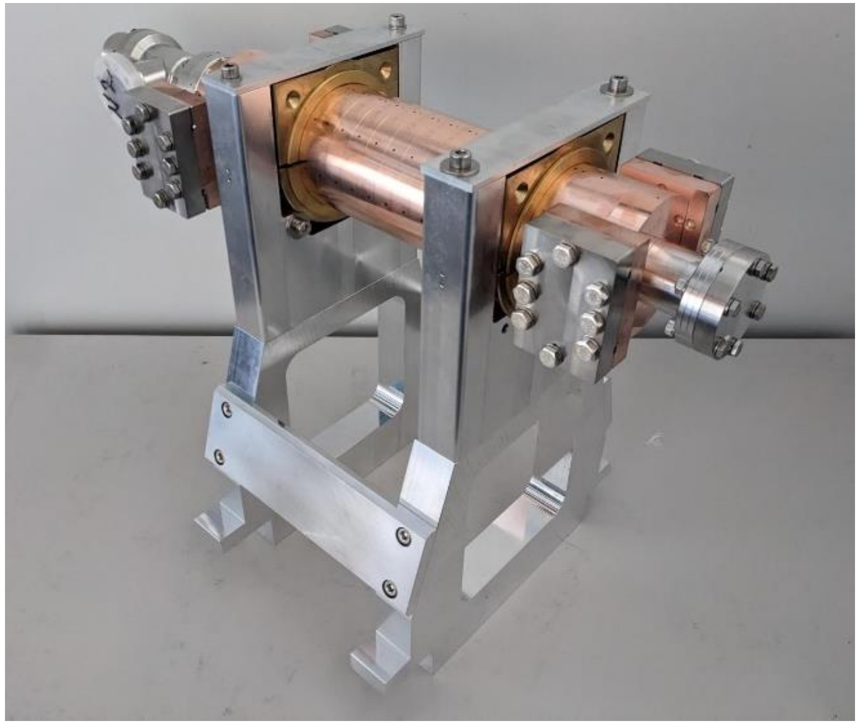


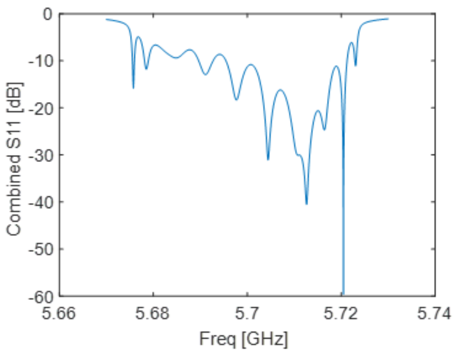
Parameter	SF Gun	TW Gun	TW Gun
Charge [pC]	200	200	200
Cathode Gradient [MV/m]	100	135	200
Energy [MeV]	130	128	144
Energy Spread [keV]	265	334	353
Peak current [A]	18.6	36.9	54.1
Sliced Emittance [mm mrad]	0.141	0.136	0.130
5D Brightness [A/(mm mrad)^2]	936	1992	3195
Sliced energy spread [keV] (Space-Charge Model)	0.24	0.5	0.8
6D Brightness [A/ (keV (mm mrad)^2)]	3900	3984	3994

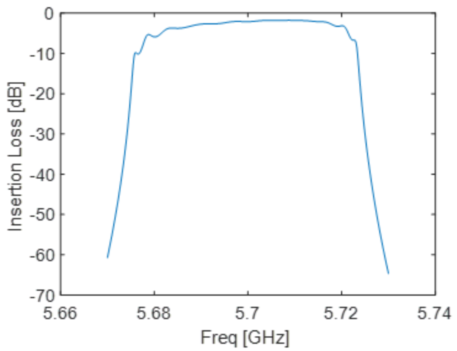
Hmmm…. Luckily we know this number is wrong. More on this later.

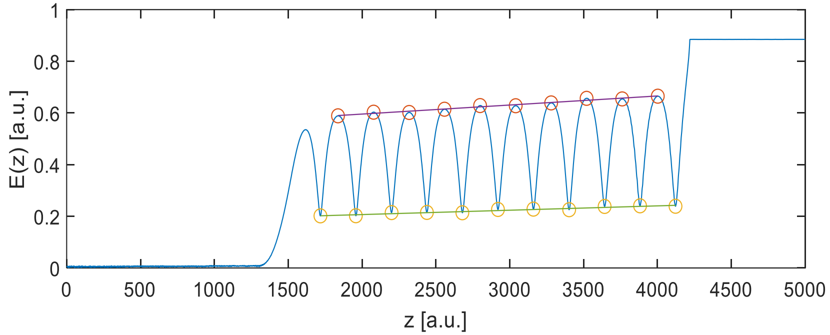
TW RF Photogun: Realisation and Testing

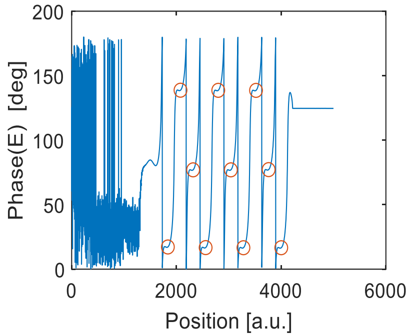
- Low power testing performed demonstrated a well-tuned and coupled RF photogun.

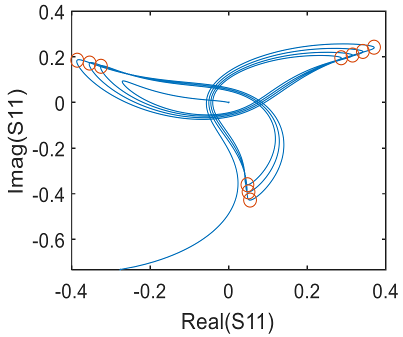












Next steps

- The TW RF Photogun will be installed in the high power test stand at PSI that was developed for the testing of the two rf photoguns realised under the IFAST collaboration.
- The TW RF Photogun will then be characterised at high power including:
  - High gradient RF conditioning and performance assessment
  - Dark current meausrement and mapping
  - Testing of semiconductor cathodes
  - Beam measurements
- This is a classic approach to designing an RF Photogun.

But … There’s a missing step in this classic formula:

But … There’s a missing step in this classic formula:

Modelling of Intrabeam Scattering

SwissFEL Measurements

Intrabeam-Scattering contribution

$$\sigma^2_{\gamma_{j+1}} = \sigma^2_{\gamma_j} + \alpha \frac{2r_e^2 N_e}{\epsilon_n \sigma_j \sigma_s}\Delta z_j$$

Microbunching instabilities contribution

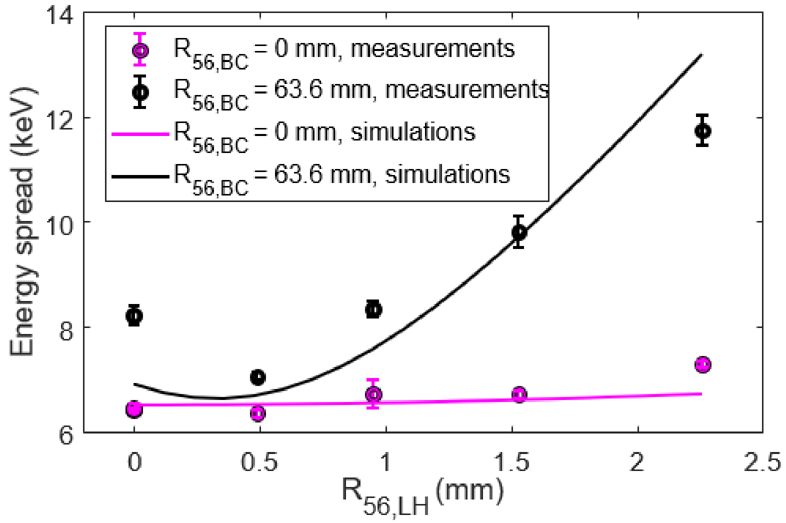
$$\delta\gamma_{j+1}(k) = \delta\gamma_j(k) - \frac{I}{e\pi I_A}\frac{Z_j(k)}{Z_0}\Delta s_j b_j(k).$$

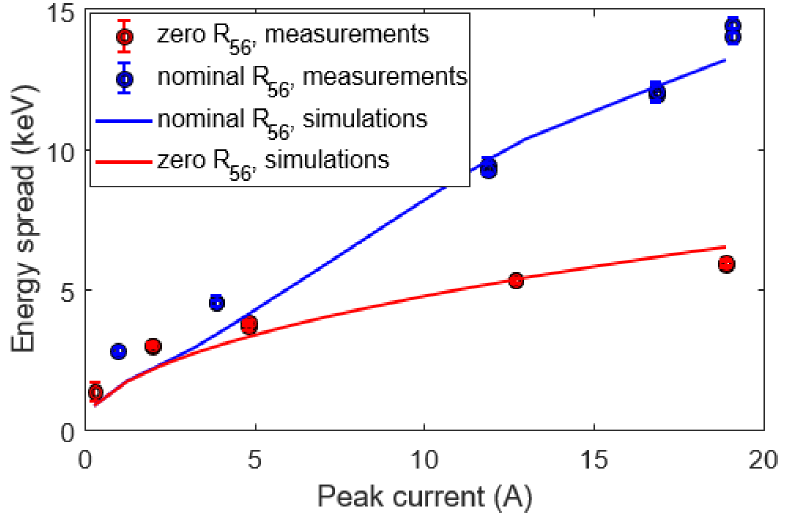
$$b_{j+1}(k) = \left[b_j(k) - i\frac{kR_{56,j}}{\gamma_j}\delta\gamma_j(k)\right] e^{-\frac{1}{2}\left(kR_{56,j}\frac{\sigma_{\gamma,j}}{\gamma_j}\right)^2}$$

$$Z_j(k) = i\frac{Z_0}{\pi k\sigma_j^2}\left[1-2I_1\left(\frac{k\sigma_j}{\gamma_j}\right)K_1\left(\frac{k\sigma_j}{\gamma_j}\right)\right]$$

$$R_{56,j} = \frac{\Delta s_j}{\gamma_j^2} + \hat{R}_{56}(s_j)$$

$$\tilde{\sigma}_\gamma = \sqrt{\sigma_\gamma^2 + \frac{1}{2}\sum_{i=M_k}^{N_k}\delta\gamma^2(k_i)}$$



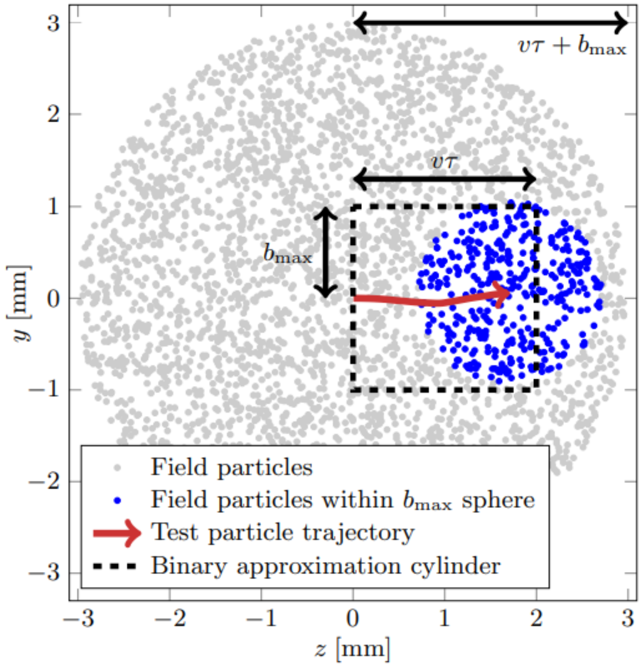


Reference: E. Prat, et al. Energy spread blowup by intrabeam scattering and microbunching at the SwissFEL injector. PHYSICAL REVIEW ACCELERATORS AND BEAMS 25, 104401 (2022)

How does intrabeam scattering affect the electron source brightness?

- A TU Darmstadt and PSI collaboration on modelling IBS in SwissFEL and the new electron source.
- The modelling is performed in the REPTIL code of TU Darmstadt with the inclusion of the scattering.
- The REPTIL code uses a scattering model from Chap and Sedwick to describe the scattering of the macroparticles in a stochastic manner.
- IBS is also modelled using the Piwinski equation:

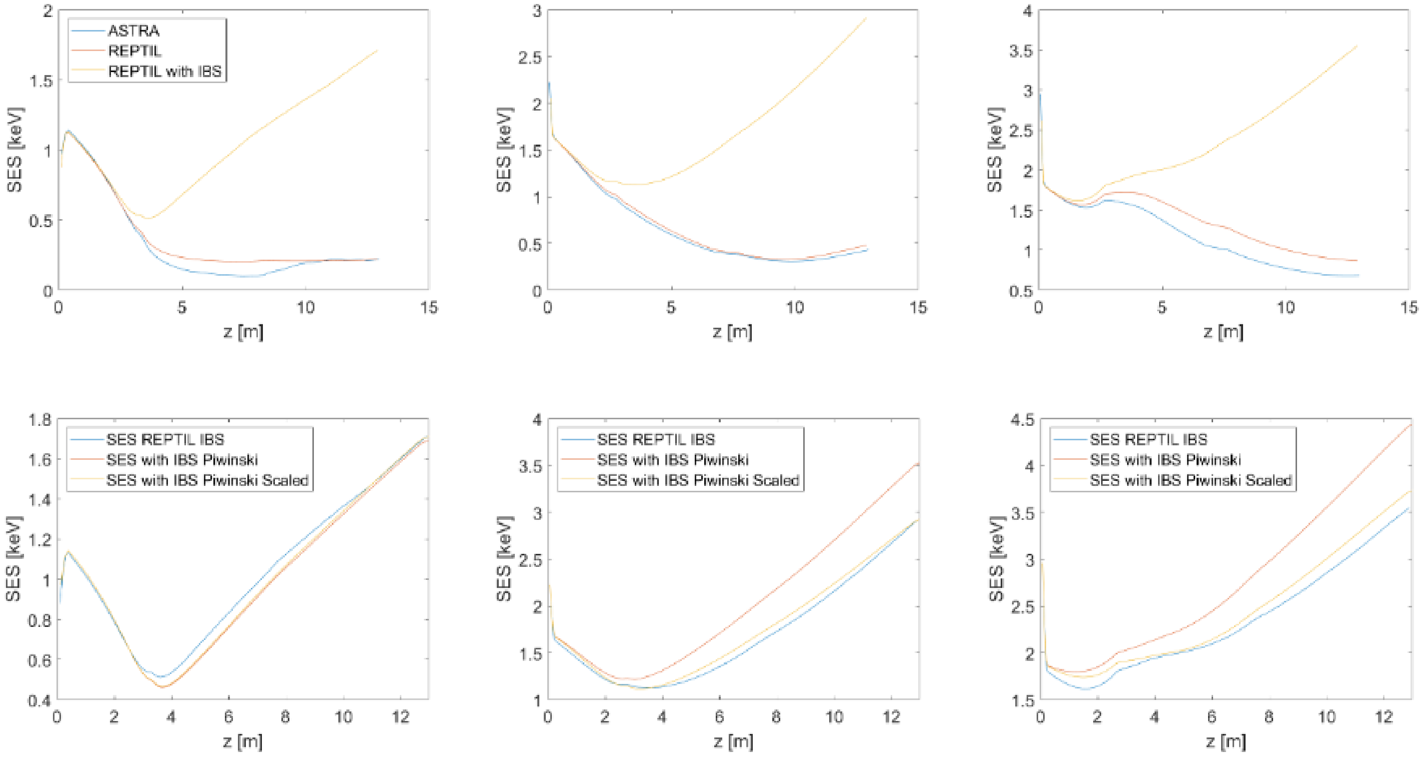
$$\sigma_{\gamma_{j+1}}^2 = \sigma_{\gamma_j}^2 + \alpha \frac{2 r_e^2 N_e}{\epsilon_n \sigma_j \sigma_s} \Delta z_j$$



Coulomb collision model for use in nonthermal plasma Simulation, Andrew M. Chap and Raymond J. Sedwick Phys. Rev. E 95, 063209 — Published 29 June 2017. DOI: 10.1103/PhysRevE.95.063209

Intrabeam Scattering in TW Gun

- Sliced energy spread calculated up to 13 metres.



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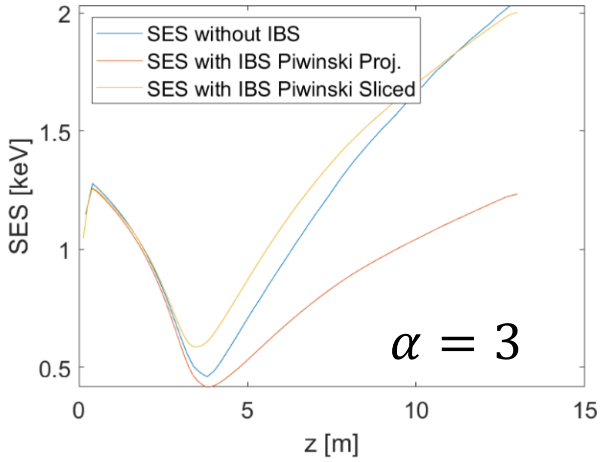
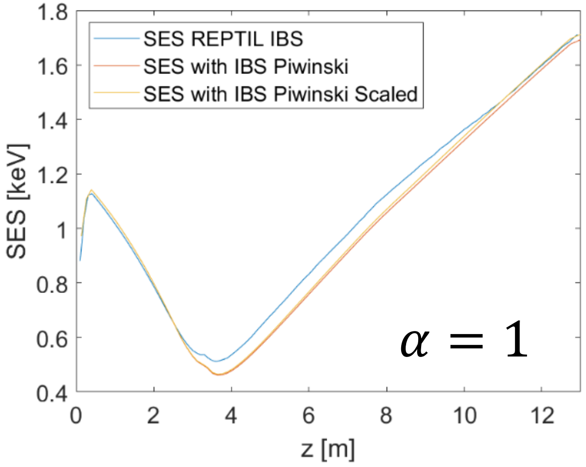
6D Brightness [A/ (keV (mm mrad)^2)]	3900	3984	3994
Sliced energy spread (Scattering and Space-Charge Model)	1.7	2.95	3.5
6D Brightness with IBS [A/ (keV (mm mrad)^2)]	**550**	**675**	**1423**

Gaussian vs Uniform Longitudinal Distribution

- Modelling the IBS for a longitudinally gaussian initial distribution compared to a longitudinally uniform distribution produces stark differences.
- For the gaussian distribution it is significantly greater $\alpha = 3$
- This result fits with that of SwissFEL which has $\alpha = 2.4$.
- **Causation is unknown but may be linked to the definition of the the impact parameter.**





$$\sigma^2_{\gamma_{j+1}} = \sigma^2_{\gamma_j} + \alpha \frac{2 r_e^2 N_e}{\epsilon_n \sigma_j \sigma_s} \Delta z_j$$

The Next Generation TW Photogun

Next Generation Design Requirements (and those for our SwissFEL)

Next Generation should:

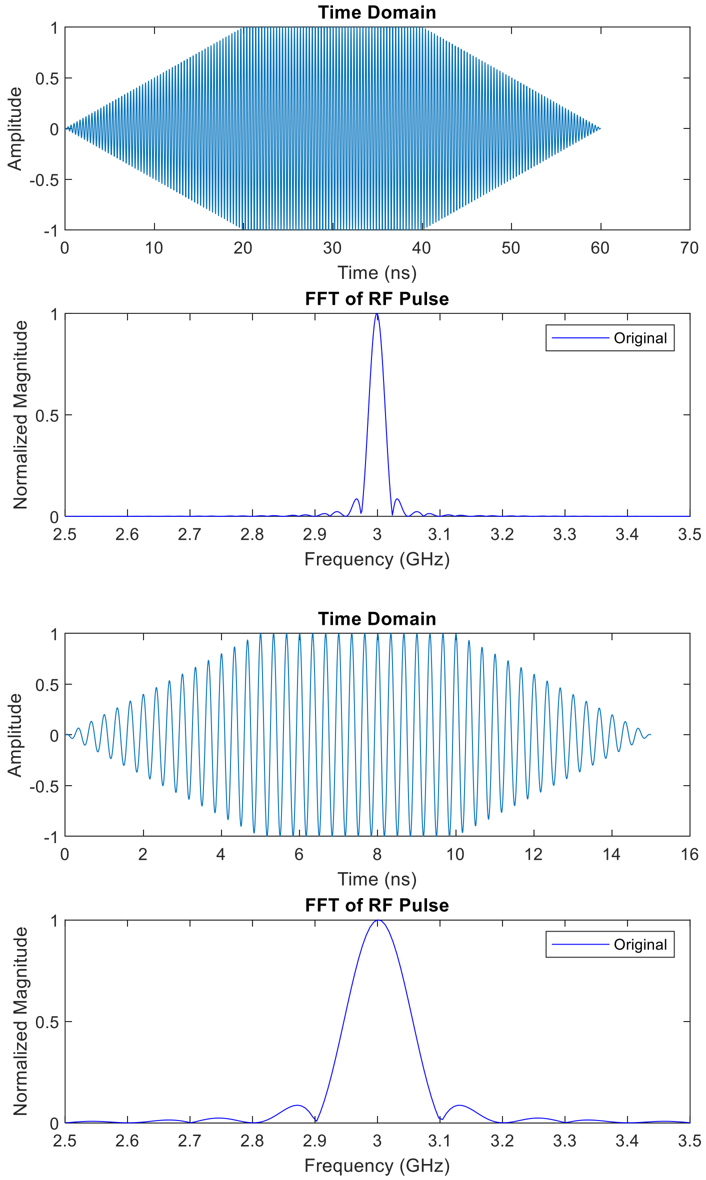
1. Fill time should be reduced to allow for use of short RF pulses higher gradients. Even using non-flat pulses for single bunch operation.
2. Use of short RF pulses and pulse shaping shouldn’t induce issues with nearest modes (common problem with short RF pulse systems).
3. Solenoid around the gun to maintain high brightness.

Also for our purposes in SwissFEL:

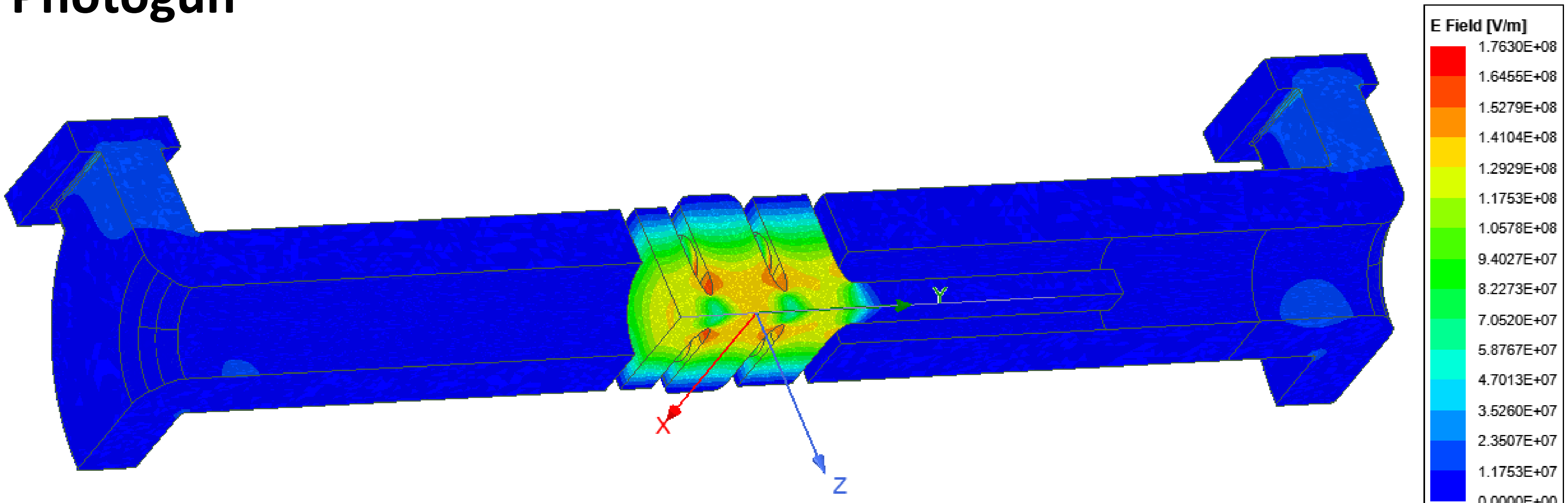
1. The RF Photogun should be S-band to fit with the current power amplifier.
2. Possible to use the same load-lock system as in SwissFEL.

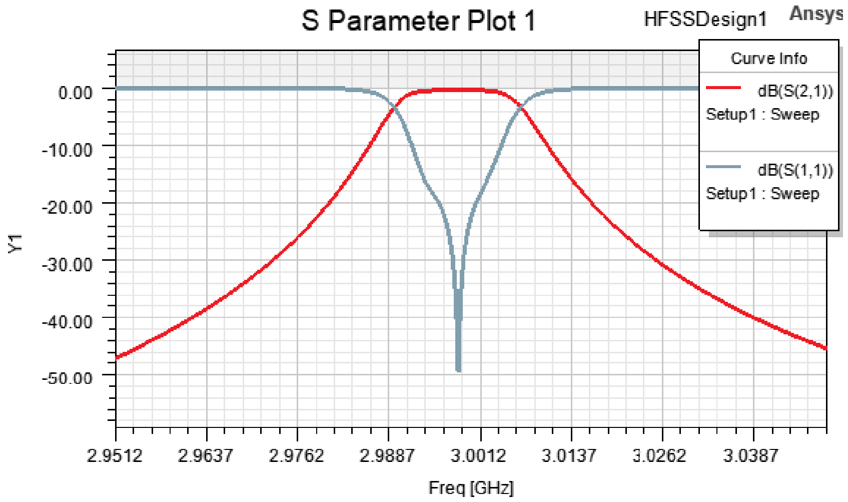
The Issue with Very Short RF pulses

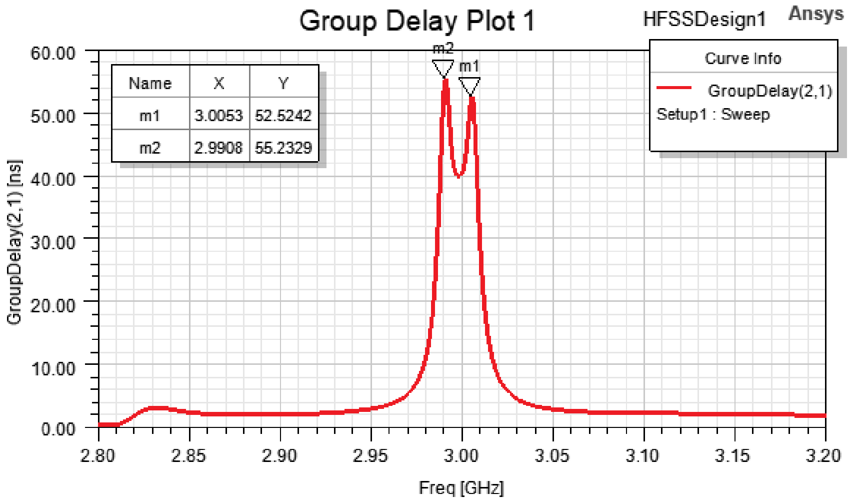
- Short RF pulses have a broad range of frequencies.
- Unlike for RF pulses of 100s of ns, inputting short RF pulses into a system one must be care about symmetric responses to the frequencies and the linearity of the of combining the frequencies.
- Furthermore, such pulses can only be generated by a system with enough bandwidth. This is a problem for the klystrons we used in accelerators.



RF Design of a Highly Symmetric and Linear BTW RF Photogun



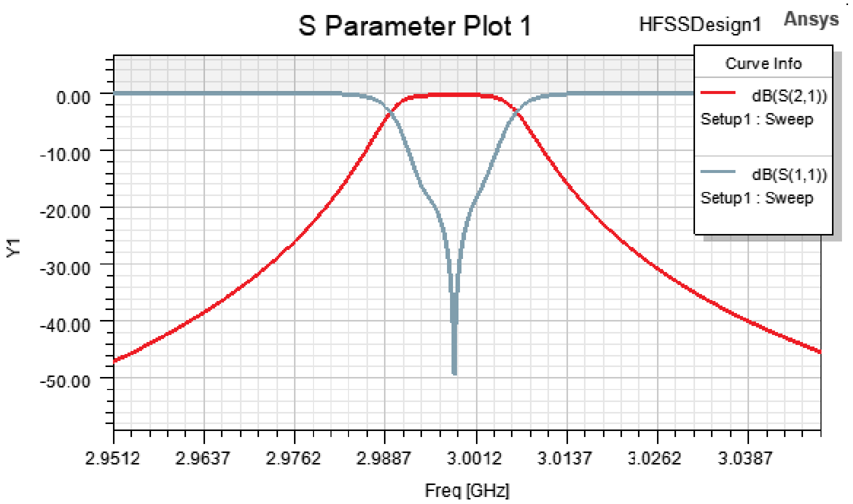


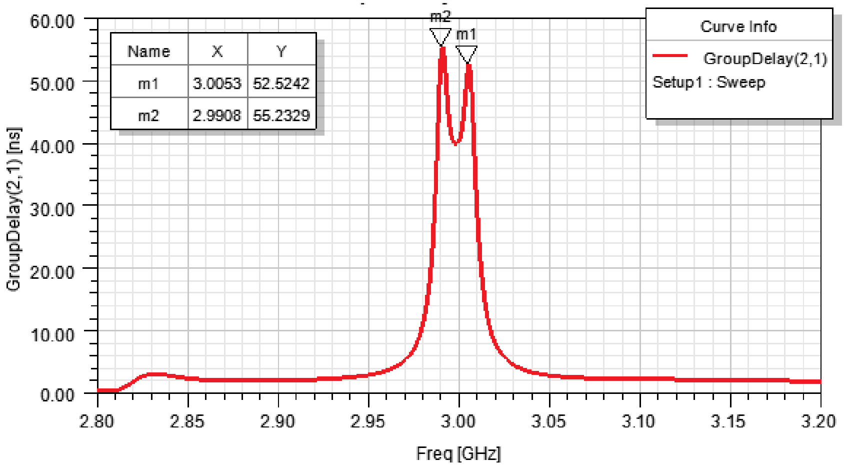


Name	X	Y
m1	3.0053	52.5242
m2	2.9908	55.2329

Symmetry and Linearity

Symmetry





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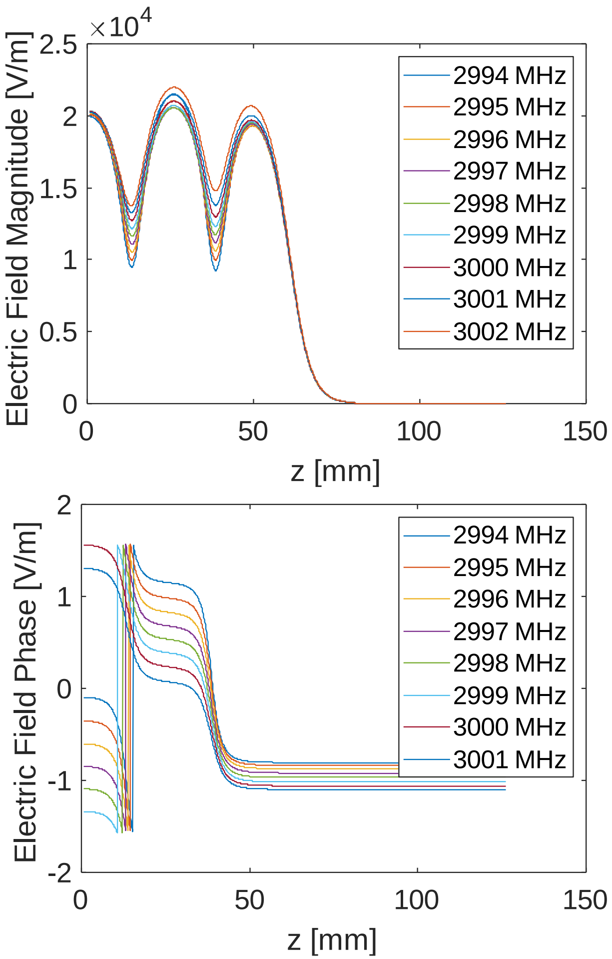
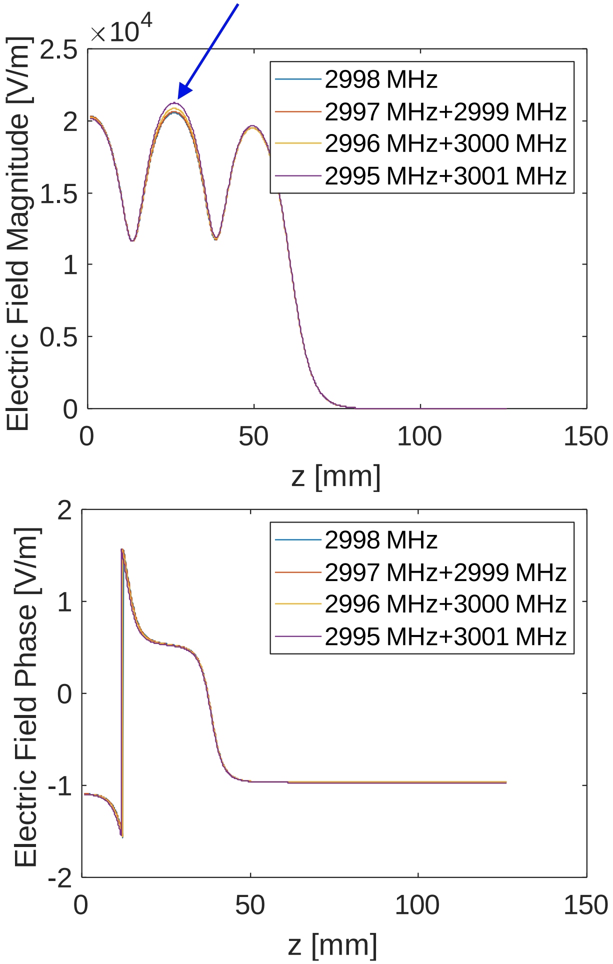
Linearity

Minor SW component





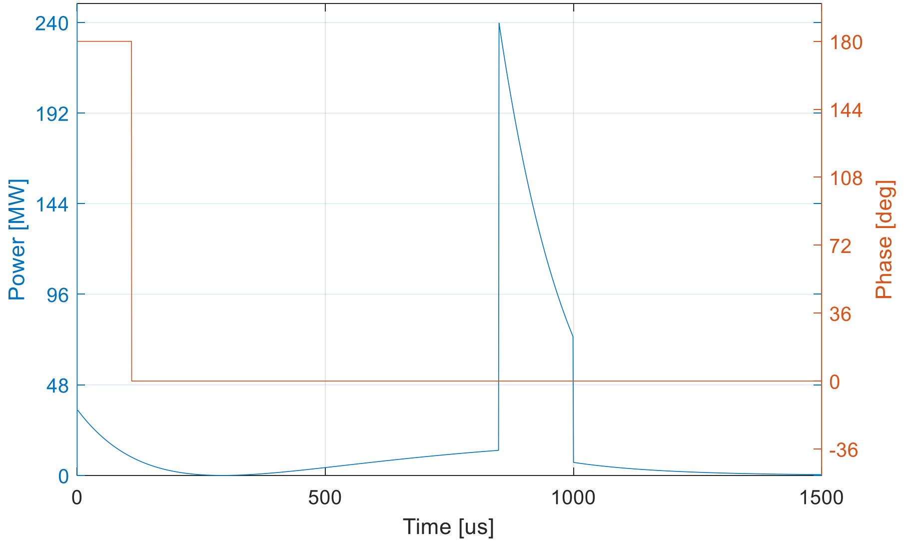
RF Feeding Schemes

Regular Flat-top

- For multi-bunches operation.
- At least 50 ns flat top for three bunches separated by 25 ns.
- Tough power requirements without a SLED but question on how to make a flat pulse from a pulse compressor.

SLED Pulse

- Single bunch operation
- SLED pulse shape
- Use of an S-band pulse compressor with a reduced Q (~30000) for fast filling and fall.

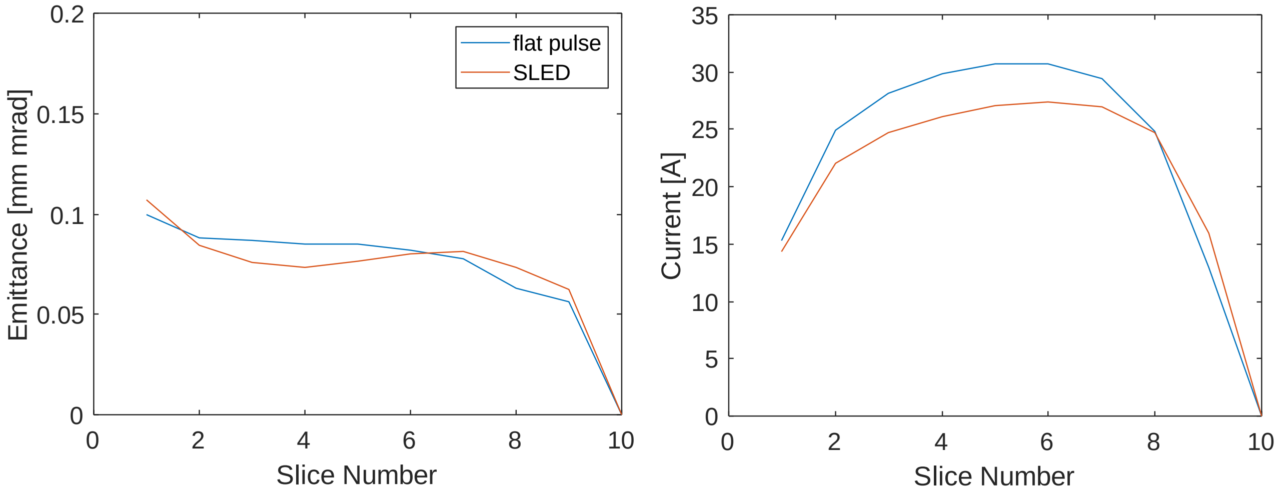


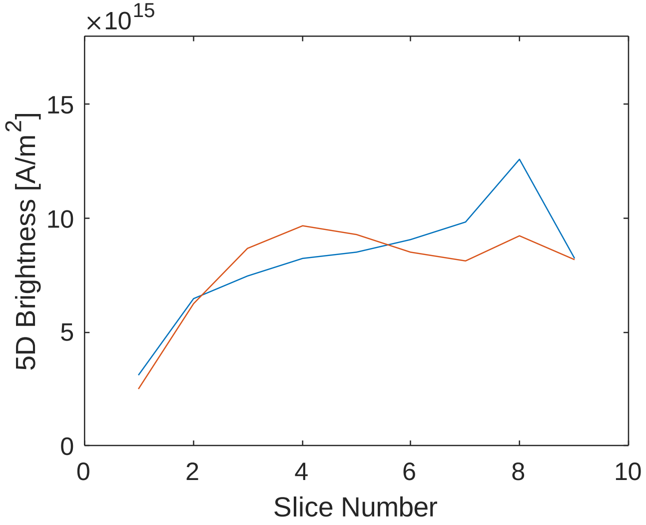
Beam Dynamics Performance

- Initial beam dynamics calculation demonstrate a good performance desite lower cathode gradient.

Parameter	Value
Charge	200 pC
Cathode Gradient	140 MV/m
Energy	60 MeV
Energy Spread	0.15 MeV
Peak current	30 A
Sliced Emittance	0.09 mm mrad
5D Brightness	3703 A/(mm mrad)^2

- Next step is the IBS contribution!





Summary

- First ever TW gun to be realised. Low power testing has been performed and shows good field flatness and low reflected power.
- TW gun was design and realised through the use of the 'classic' recipe. This classic design model requires an additional step in the future which is the calculation of the contribution of IBS to the sliced energy spread.
- High power testing of the TW gun will soon come.
- In the meantime, we continue to look towards the future in how the design can be further improved. The use of a backward travelling-wave enables the possibility of using a SLED RF pulse to drive the gun.
- New design has been made for a BTW RF Photogun whose design aims to cancel the effects of adjacent modes through a highly symmetric and linear design.