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A Discussion of Key Concepts for the Next Generation of High Brightness Injectors

International Linear Accelerator Conference 2022

LINAC2022 LIVERPOOL

Introduction

Numerous injectors for Free-Electron Lasers (FELs) around the world have demonstrated high reliability and performance in feeding these machines.

Future FELs aim for performance requirements beyond that possible using current standard FEL injectors.

The aim of this talk is to describe and stimulate discussion of the ways in which we proceed with injector development, outlining some key technologies and ideas which are worth pursuing in order to achieve this performance increase.

I'll focus on **pulsed and compact FELs** for this talk due to time constraint.

Classic Approach to High Brightness Photoguns

In 1D FEL theory the FEL gain length is determined by the Pierce parameter (1):

$$P_\gamma = \alpha P_n e^{\frac{s}{L_g}} < P_{sat}$$

Two crucial conditions are that:

$$\sigma_\delta < \rho$$

$$\epsilon_\perp \leq \frac{\lambda}{4\,\pi}$$

We can describe the beam in terms of the 5D brightness parameter defined as:

$$B_{5D} = \frac{2 I_{peak}}{\epsilon_n^2}$$

It can be shown that the Pierce parameter is related to the brightness

$$\rho \propto \left(\frac{B_{5D}}{\gamma_0}\right)^{\frac{1}{3}}$$

M. Schaer, RF travel-wave electron gun for high brightness photoinjectors, PhD Thesis (2016).

Some Injectors from around the world

	SwissFEL	LCLS	FERMI	SPARC	PAL	SACLA	EUROXFEL	FLASH	PITZ
Rep Rate (Hz)	100	120	50	10	60	60	10-27000 (10Hz bursts)	10	1-10 (1MHz trains)
Bunch Charge (pC)	200	250	500	20 - 250	250	300	50-1000	1-2000	1-5000
Gun frequency (GHz)	2.998	2.856	2.998	2.856	2.856	DC	1.3	1.3	1.3
E cath (MV/m)	100	115	120	115	120	500 kV	54-58	50	60
E kin end of gun (MeV)	7.1	5.5	5.3	6	6	0.5	6.1-6.5	5.63	5.8-6.0
Emittance (mm mrad)	0.28	<0.5	1	0.3 - 1.5	0.35 - 0.45	1.1	0.35	0.4	0.4
Sliced Emittance (mm mrad)	0.2	0.4	0.7	0.2-0.7	<0.3	0.6	0.3	0.4	0.45 +/- 0.05
Peak current (A)	20	45	50	25 - 65	~80	25	5	20	18
5D Brightness (TA/m^2)	1000	563	204	1250	1780	139	111	250	178

S-band Room Temperature RF Photoguns

L-band Room Temperature RF Photoguns

Values provided by labs, except brightness which was calculated.

Lessons from Past S-band, Normal Conducting, Room temperature Injectors

The first generation of accelerators have in general opted for a very similar design of S-band room-temperature RF photogun and accelerating structures.

Three lessons from past sources for future high brightness source design:

1. To move to higher brightness pulsed compact FELs, higher cathode gradients (>150 MV/m) are generally advantageous.
2. Room temperature cathodes are beginning to limit the achievable emittance from injectors.
3. 5D brightness is not the end of the story. High current densities are leading to unexpected energy spread issues in modern injectors. The next generation of high brightness injectors for FELs should be modelled on 6D brightness.

1. High Gradients RF Photoguns

To move to higher brightness pulsed FELs, higher cathode gradients are generally advantageous.

High cathode gradients are vital to high brightness injectors:

1. The reduction of space-charge (SC) effects scale strongly with the energy (2)

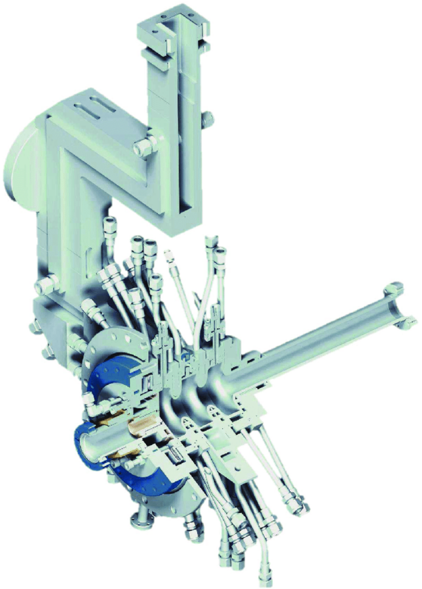
   Transverse SC effects $\propto \frac{1}{\gamma^3 \beta^2}$

   Longitudinal SC effects $\propto \frac{1}{\gamma^5 \beta^2}$

2. Brightness increases with the gradient(1):

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

SwissFEL gun (3)



Reference injector

Parameter	SwissFEL
Rep Rate (Hz)	100
Bunch Charge (pC)	200
Gun frequency (GHz)	2.998
E acc (MV/m)	100
Emittance (mm mrad)	0.28
Sliced Emittance (mm mrad)	<0.2
Peak current	20
5D Brightness (TA/m^2)	1000

1) J. B. Rosenzweig, Next generation high brightness electron beams from ultrahigh field cryogenic rf photocathode sources
2) M. Schaer, RF travel-wave electron gun for high brightness photoinjectors, PhD Thesis (2016).
3) P. Craievich, et al. High Power RF Test and Analysis of Dark Current in the SwissFEL gun, FEL 2014 Basel, Switzerland.

1. High Gradients RF Photoguns

How to achieve higher gradients without sacrificing breakdown rate?

I. The scaling of BDR with electric field and pulse length (1):

$$BDR \propto E^{30}\tau^{5}$$

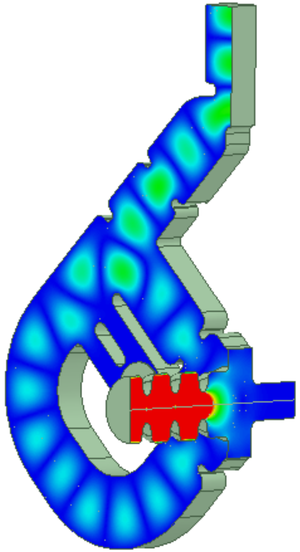
Note this is for **TW accelerating structures**.

II. The other key piece of knowledge has been used for several decades now which is that **higher frequencies correlate with higher gradients (2).**

1) A. Grudiev, S. Calatroni, and W. Wuensch, New local field quantity describing the high gradient limit of accelerating structures, Phys. Rev. ST Accel. Beams **12**, 102001

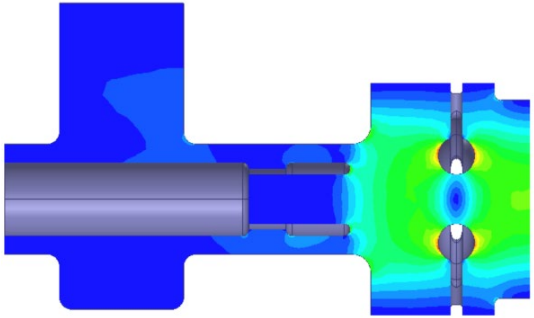
2) RF Linear Accelerators, Wangler.

1. High Gradients RF Photoguns: Example



D. Alesini et al. , "THE NEW C BAND GUN FOR THE NEXT GENERATION RF PHOTO-INJECTORS", Proceedings of IPAC2022, Bangkok, Thailand(2022)

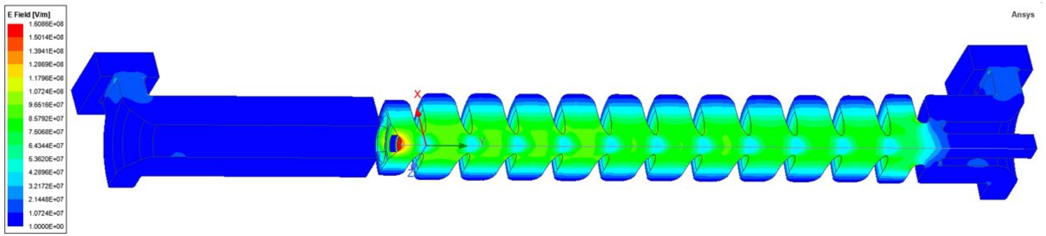
Parameter	C-band SW Gun	Overcoupled X-band SW gun	SwissFEL
Rep Rate (Hz)	1000	100	100
Bunch Charge (pC)	200	100	200
Gun frequency (GHz)	5.712	11.7	2.998
E cathode (MV/m)	160	388	100
Pulse length (ns)	300	<10	1000
Projected Emittance (nm mrad)	210	150	280
Sliced Emittance (nm mrad)	200	100	200
Peak current	40	25	20
5D Brightness (TA/m^2)	2000	5000	1000

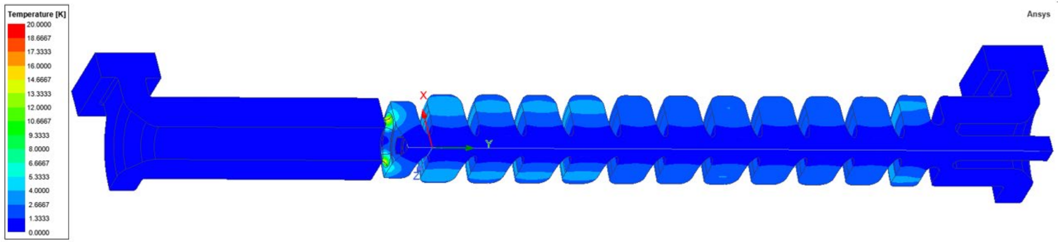


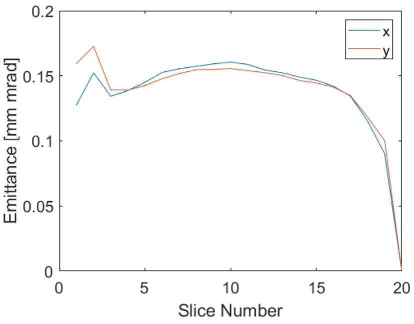
Talk at snowmass21, Chunguang Jing

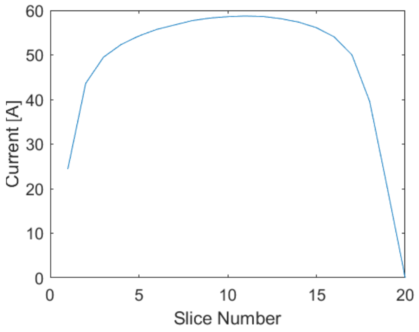
https://indico.fnal.gov/event/46053/contributions/232504/attachments/152209/196934/TWPhotogunJing.pdf

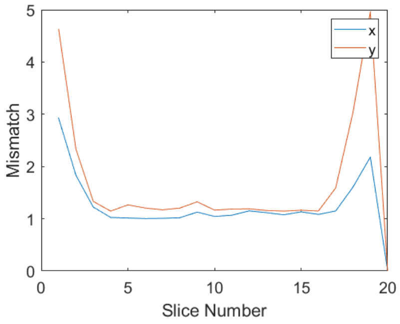
1. High Gradients TW RF Photoguns: Example











Parameter	C-band TW Gun	SwissFEL
Rep Rate (Hz)	400	100
Bunch Charge (pC)	200	200
Gun frequency (GHz)	5.712	2.998
E cathode (MV/m)	135/200	100
Fill Time (ns)	90	1000
Projected Emittance (nm mrad)	210/150	280
Sliced Emittance (nm mrad)	200/150	200
Peak current	40/58	20
5D Brightness	2000/5155	1000

Towards a Brightness Upgrade to SwissFEL with a High Gradient Travelling-Wave RF Photogun

T. G. Lucas, et al. (to be submitted)

2. Cryogenic (Cold) Cathode

Room temperature cathodes are beginning to limit the achievable emittance from injectors.

- Recall 5D brightness is defined as

$$B_{5D} \equiv \frac{2\,I}{\epsilon_{n,x}^2}$$

- The cold-cathode operates on the simple principle that a reduction of the cathode temperature will reduce the mean transverse energy ($\frac{1}{2}\mathrm{m}\langle v_x^2\rangle$) of the electrons at emission.

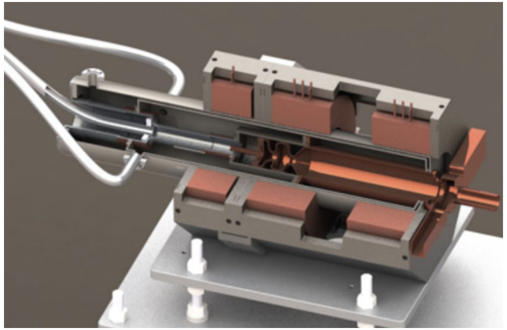
$$\epsilon_{n,x} = \sigma_x \sqrt{\frac{k_B T}{m_e c^2}} \rightarrow k_B T = m\langle v_x^2\rangle$$

- Furthermore a study of a cryogenic high gradient structure has suggest that a cryogenic cathode also offers some possibility to increase the cathode gradient (1).

1) A.D. Cahill et al. High gradient experiments with X-band cryogenic copper accelerating cavities, Phys. Rev. Accel. Beams 21, 102002.

2. Cryogenic Cathode: Example

- A handful of cryogenic RF photoguns have been designed.
- These achieve an intrinsic emittance around four times lower than that available for room temperature RF photoguns without significant changes to the RF design.
- Example: UCLA Cryogenic S-band Gun



Parameter	S-band Cryogenic SW Gun (1)	SwissFEL
Bunch Charge (pC)	100	200
Gun frequency (GHz)	2.856	2.998
E cathode (MV/m)	240	100
Fill Time (us)	0.9	1.0
Sliced Emittance (nm mrad)	50	200
Peak current (A)	20	20
5D Brightness (TA/m^2)	16000	1000

1) J. B. Rosenzweig, Next generation high brightness electron beams from ultrahigh field cryogenic rf photocathode sources Phys. Rev. Acc. and Beams 22, 023403 (2019)

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3. Energy Spread Issues

5D brightness is not the end of the story for FEL design. The next generation of injectors should be modelled on 6D brightness. High charge densities are leading to unexpected energy spread issues in high brightness injectors.

- It can be shown that when optimising the compression in an FEL, the Pierce parameter is influenced by the sliced energy spread (σ_γ):

$$\rho \propto \frac{I}{\epsilon_x \epsilon_y \sigma_\gamma} \rightarrow \rho \propto B_{6D}$$

- **Given the situation where a decrease in emittance or increase in peak current leads to an increase in sliced energy spread. There will be a decrease in FEL performance despite increasing 5D brightness.**

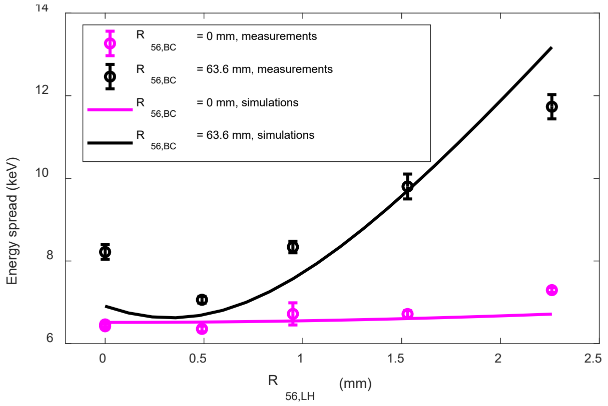
- Therefore to optimise based on 6D brightness it is important to accurately model sliced energy spread.

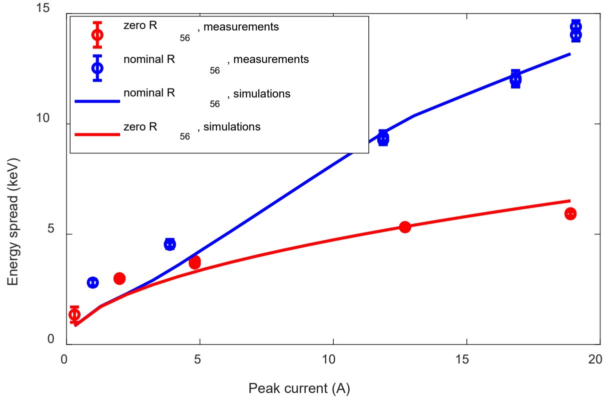
3. Energy Spread Issues

- Codes such as **ASTRA, GPT and OPAL are beginning to grossly underestimate energy spread.**
- Recently, we have measured intrabeam scattering (IBS) in an FEL injector for the first time at PSI.
- **Such codes lose pair-wise interactions which cause IBS due to the use of macro-particles and space-charge meshing.**
- Using the original Piwinski model for IBS

$$\frac{d\sigma_\gamma^2}{dz} = \frac{2r_e^2 N_b}{\langle\sigma_x\rangle\sigma_z\epsilon_{n,x}}$$

the energy spread behaviour was reproduced however **when using an artificial scaling factor of 2.4 on the intrabeam scattering.**





Energy spread blow-up by intra-beam scattering and microbunching at the SwissFEL injector.
E. Prat, et al. (Submitted)

3. Energy Spread Issues

Piwinski model is a highly successful model for IBS in storage rings but it did not accurate predict energy spread in an FEL injector.

Can be reformulated for a waist (top, right) which is more appropriate to an FEL injector. However it has drawbacks:

1. The theory is divergent when applied to a waist
2. Has a singularity for zero emittance.

A numerical model based on pair-wise interactions for small charges was made to consolidate this model and also offers the ability to model regions which are unphysical with Piwinski model.

Piwinski Model for a single waist

$$\sigma_\gamma = \sqrt{\frac{\sqrt{8\pi} r_e^2}{ce} \frac{\gamma I \sigma}{\epsilon_n^2} \int_{-\infty}^{\infty} \frac{d\hat{z}}{\sqrt{1+\hat{z}^2}}}$$

Monte Carlo Particle Tracking Model with Pair-wise Interaction

$$\sigma_\gamma \propto \frac{\gamma^{0.22} I^{0.45} \sigma^{0.32}}{\epsilon_n^{0.63}}$$

1) Z. Huang, Intrabeam Scattering in an X-ray FEL Driver LCLS-TN-02-8

2) A. Piwinski, in Proceedings of the 9th International Conference on High Energy Accelerators, Stanford, CA,USA, 1974, p. 405.

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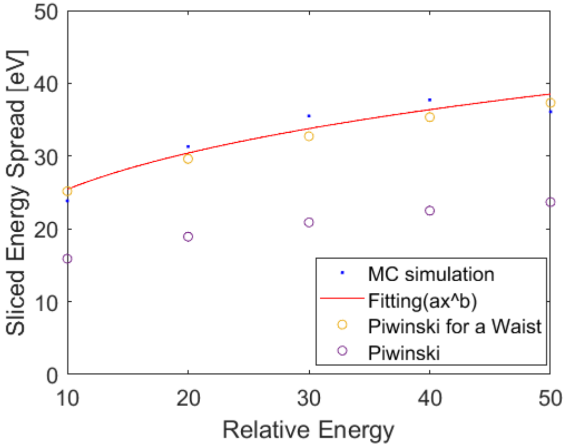
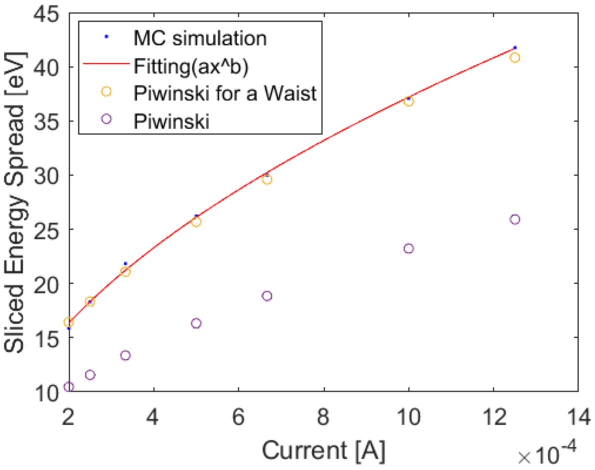
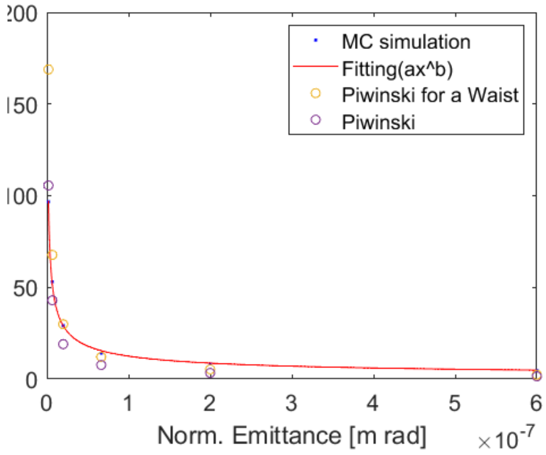
Energy Spread Issues

- Original Piwinski model underestimates the energy spread through a waist.
- The updated model fits much better with particle tracking simulations.
- Clear issue of singularity in Piwinski equation where analytical equation blows up.







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Conclusion

- Moving towards a high brightness future for injectors there will need to be a reformulation on the typical injector development.
- High gradient photogun appear to be the future of RF photoguns with C-band a popular frequency.
- Moving to cryogenic cathode could offer a significant leap forwards in brightness without a significant change in beam dynamics.
- Assuming that the sliced energy spread remains small is no longer applicable and this should be taken into account with future compact injector designs to avoid running into nasty surprises.

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Acknowledgements

Funding:
This work has been performed as part of IFAST W.P 7.4.

This project has received funding from the European Union's Horizon 2020 Research and Innovation program under GA No101004730

Thank you to those who provided the injector performance from other labs:
SLAC: Feng Zhou
FERMI: Mauro Trovo
INFN/LNF: David Alesini
PAL-XFEL: Chang-Ki Min and Jang-Hui Han
MAXIV: Dionis Kumbaro
SPRING8: Hitoshi Tanaka
Argonne/Euclid Labs: Jing Chunguang
EuroXFEL: Frank Brinker
FLASH: Siegfried Schreiber
PITZ: Mikhail Krasilnikov and Frank Stephan

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Thank you!

- Any Questions?