Short-pulse Driven Photogun for Very Hard X-ray Free-electron-laser

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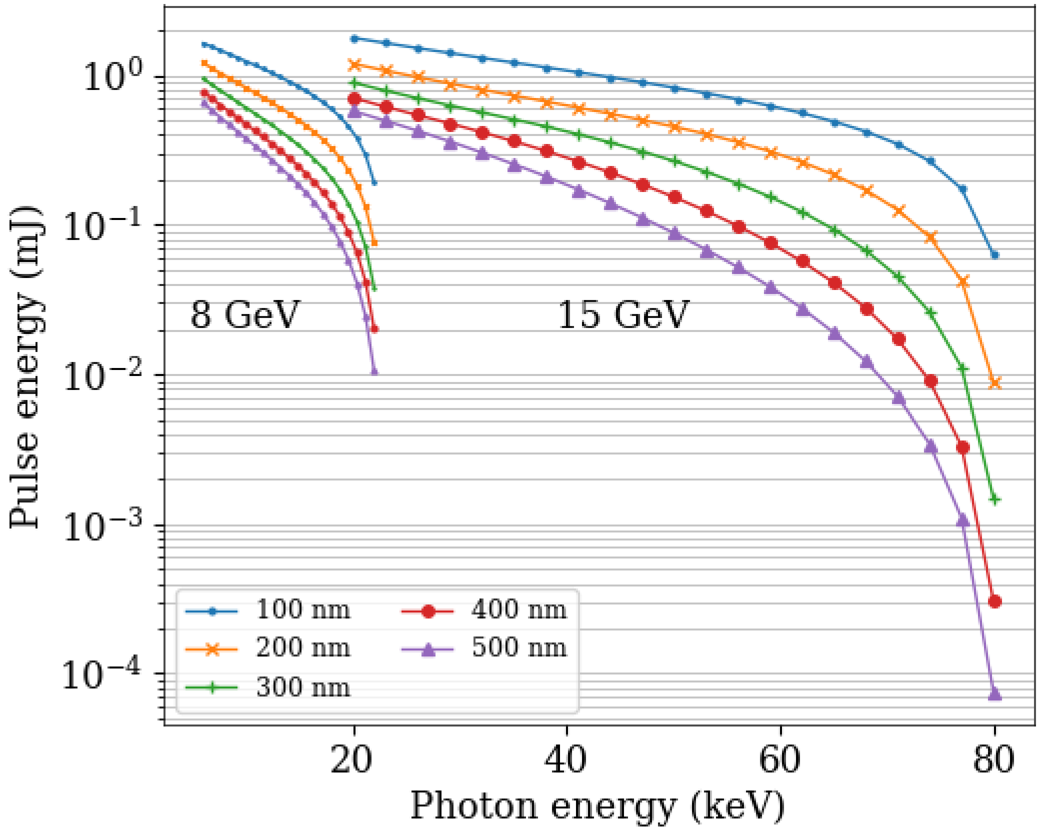
Motivation: Low emittance beams for better FELs

- Lower emittance beams result in better free-electron-laser (FEL) performance for the same beam energy
- Figure here shows the increase of pulse energy for beams with different emittances

$$\rho \propto \mathcal{B}_{6\mathrm{D}} = \frac{2I}{\varepsilon_n^2 \sigma_\gamma}$$

$$\frac{\varepsilon_n}{\gamma\beta} \approx \frac{\lambda}{4\pi}$$

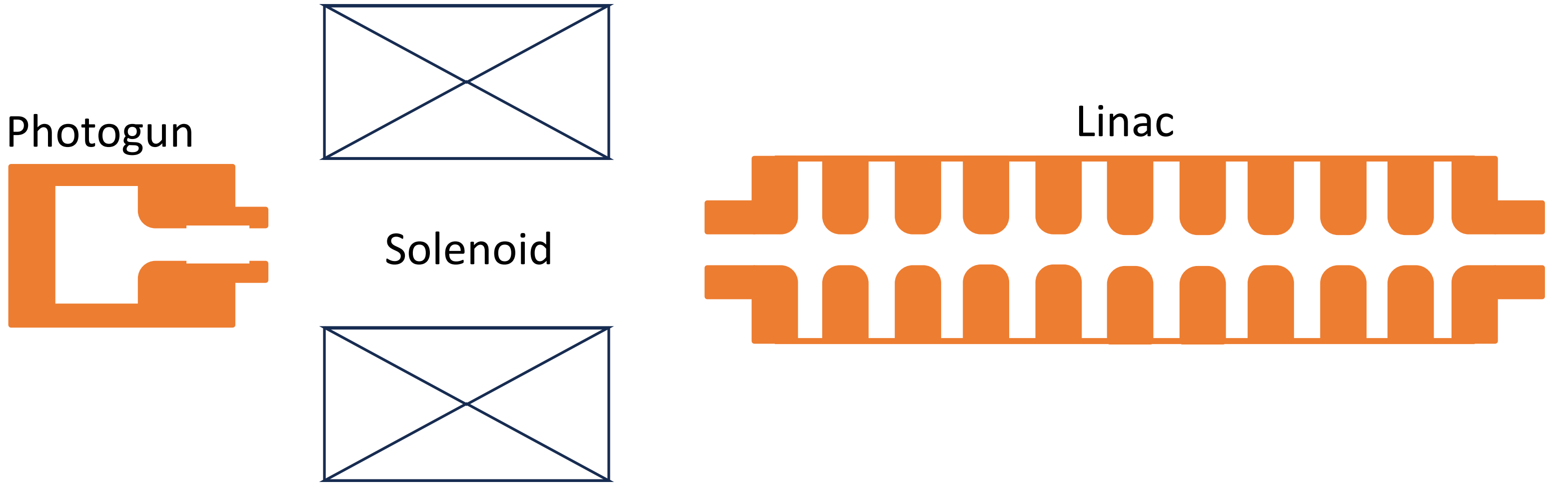


Assuming 100pC 3.5 kA beam, Ming-Xie parameterization, parameters taken from Future Electron Source report 2016

Motivation: High gradient field for low emittances

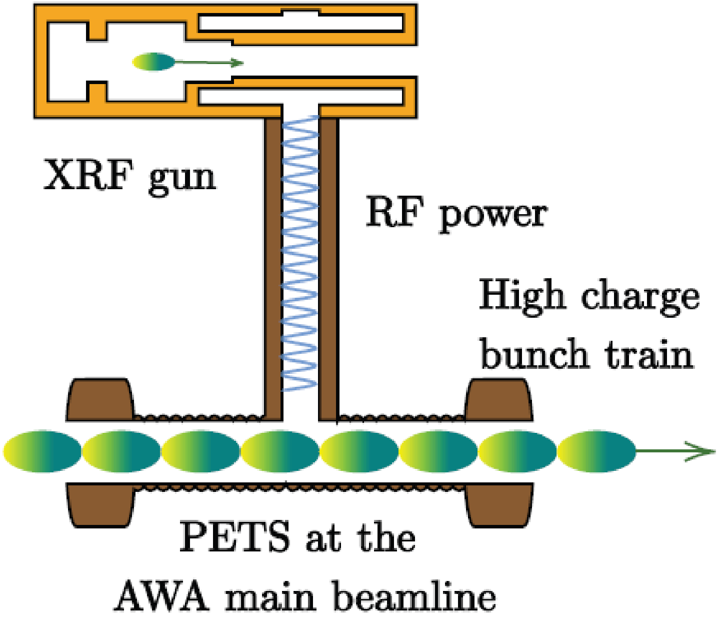
- Beam's emittance is inversely proportional to the square of field
- Breakdown rate is proportional to field gradient & input rf pulse duration

$$\rho \propto \mathcal{B}_{6\mathrm{D}} = \frac{2I}{\varepsilon_n^2 \sigma_\gamma} \propto |E|^2$$



Motivation: High gradient gun driven by short rf pulses

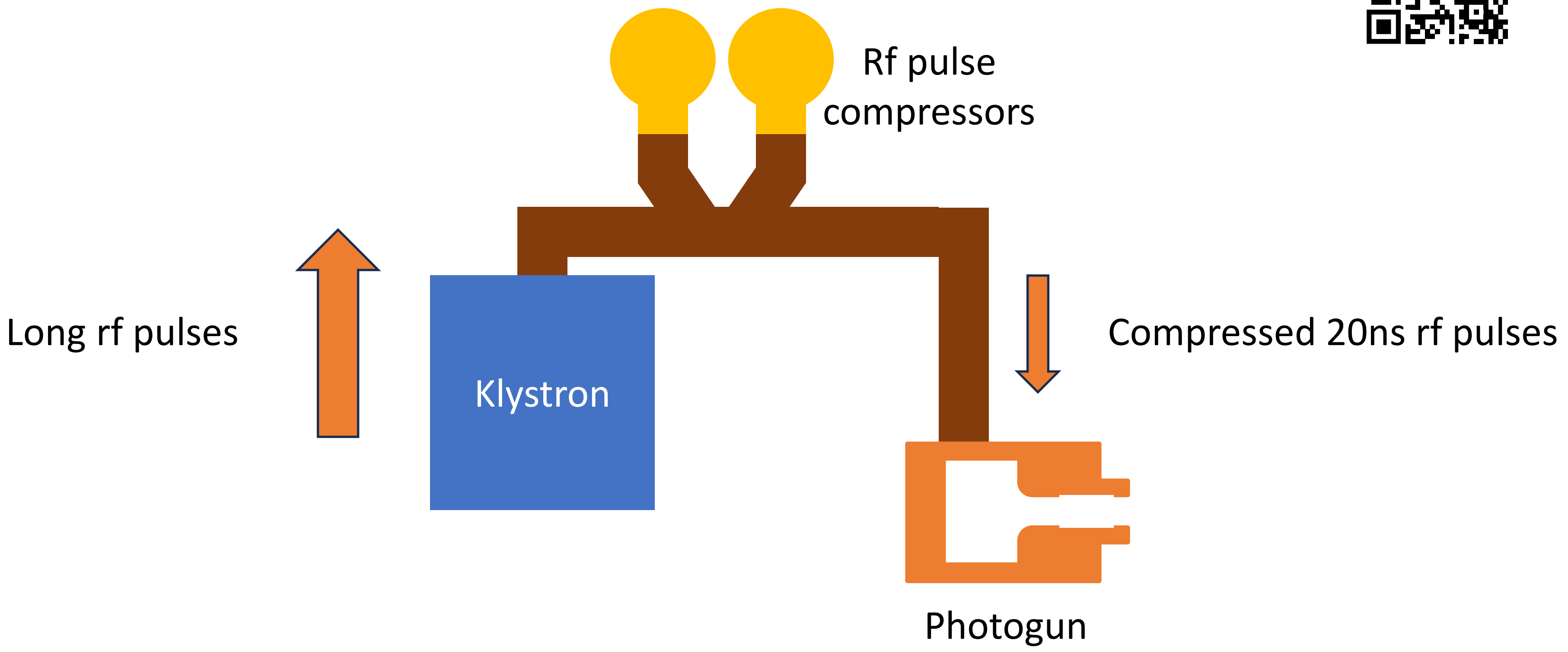
- Argonne Wakefield Accelerator (AWA) demonstrate a high gradient photogun (~400 MV/m)
- Short rf pulses generated from another accelerator



from Tan et al 2022

Compressed Ultrashort Pulse Injector Demonstrator (CUPID)

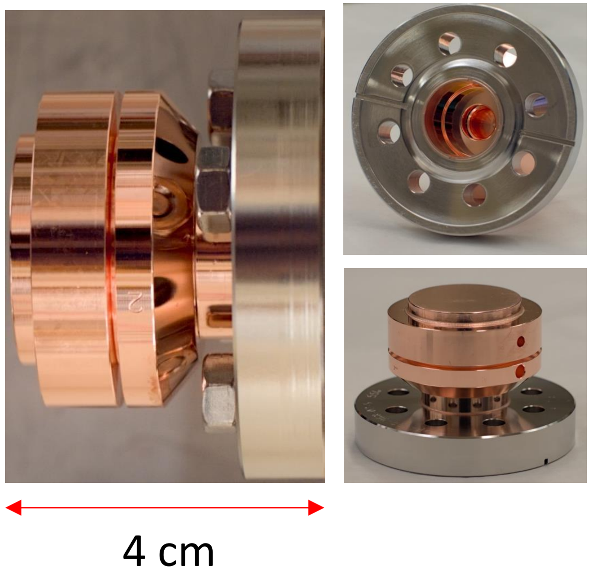
- Short-pulse X-band photogun driven by high power compressed pulses from klystron and pulse compressors
- Demonstrated 317 MW from recently commissioned pulse compressors

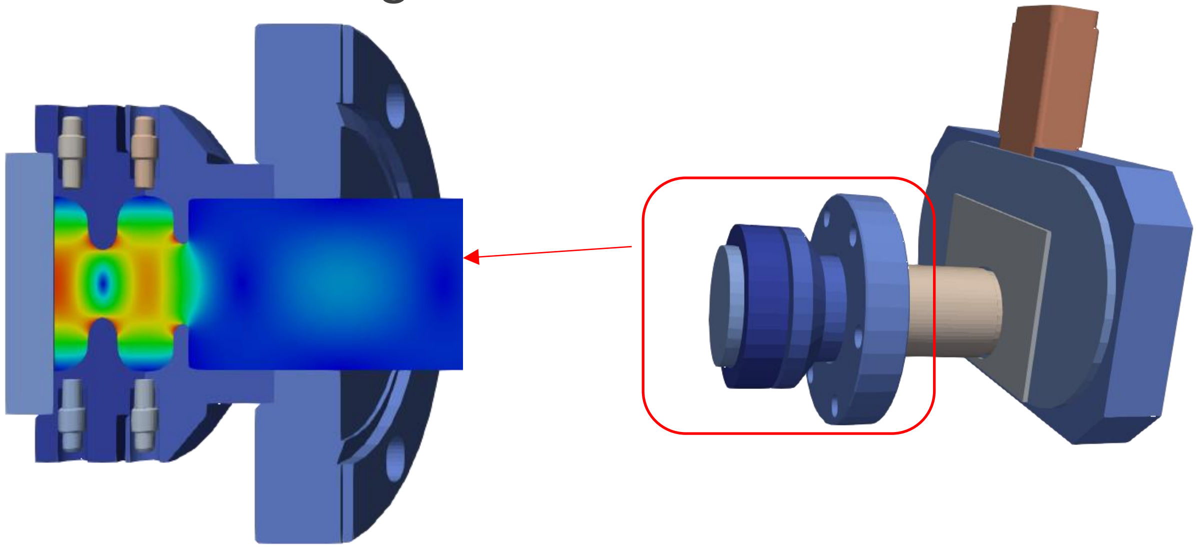


Photogun design

Photogun design

- Operates at X-band (11.424 GHz)
- Over-coupled (allow RF pulses to rapidly fill in the photogun)
  - Low external quality factor
- Low iris-to-cathode field ratio for high gradient operation
- Connected to a waveguide to make use of the existing X-band TM01 mode launcher



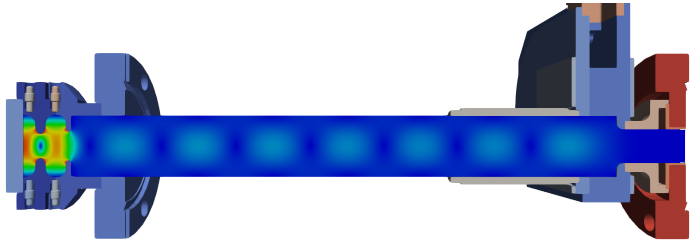


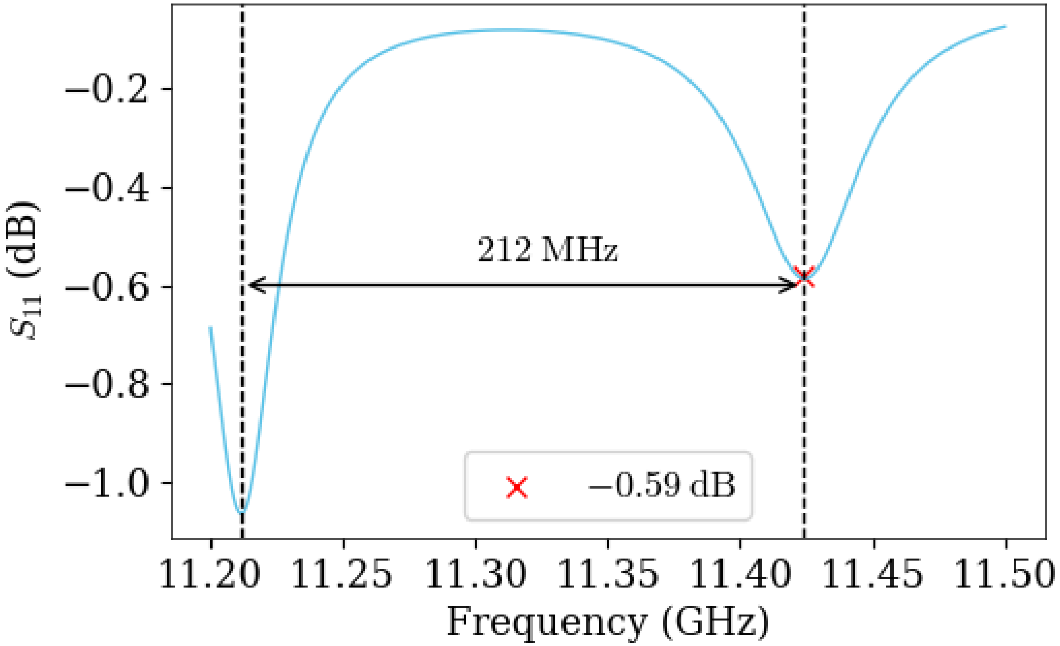
Photogun design

- 1.5 cell photogun
- Large aperture to have lower quality factor

$$Q_{\text{total}} = \frac{f}{\Delta f} \propto \frac{1}{t_{\text{fill}}}$$

Parameters	Value
frequency	11.424 GHz
Q total	215
Q intrinsic	6585
S-parameter	-0.59 dB
Short pulse bandwidth	100 MHz

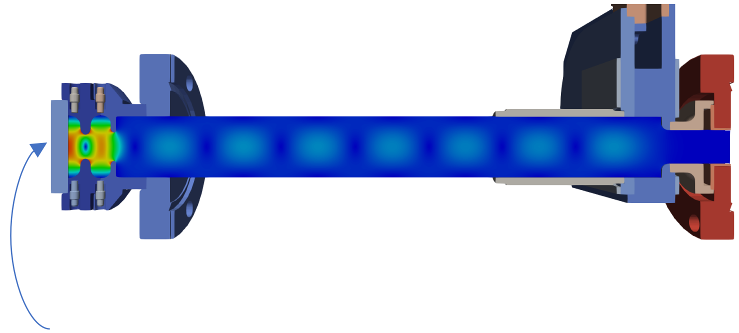




Photogun design

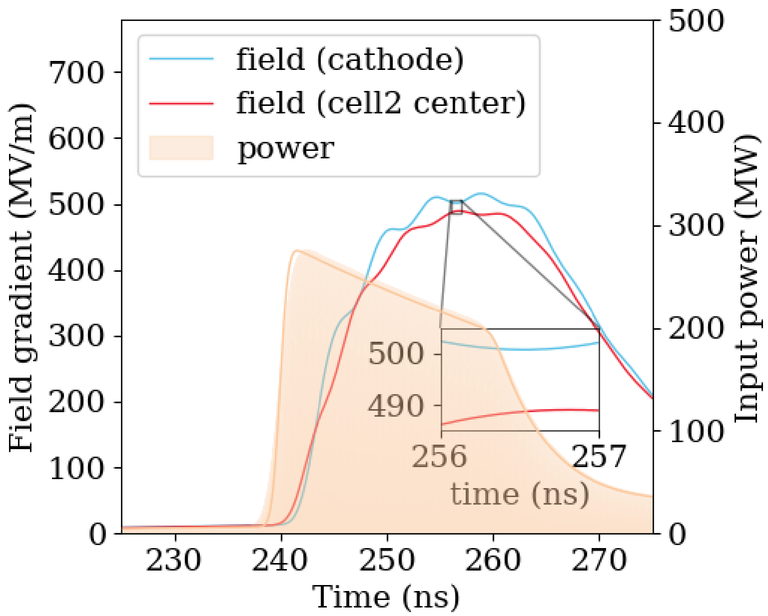
- Time domain simulation using ACE3p
- 500 MV/m at cathode needs 275 MW peak power

Parameters	Value
frequency	11.424 GHz
Q total	215
Q intrinsic	6585
field at cathode	500 MV/m
Peak input power (500 MV/m peak field)	275 MW
S-parameter	-0.59 dB
Short pulse bandwidth	100 MHz



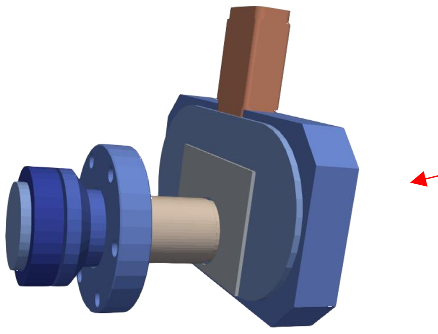
500 MV/m at the cathode

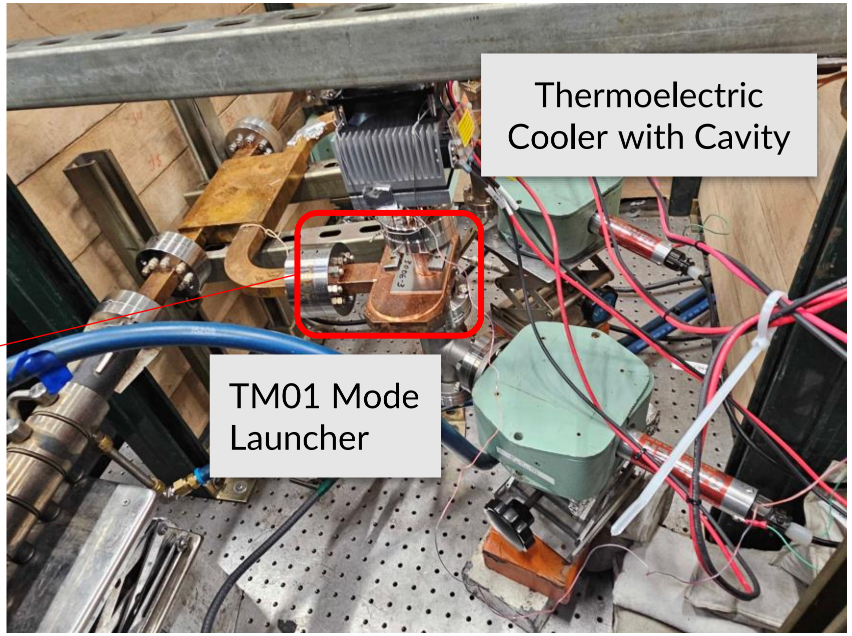
Time-domain simulation using ACE3p

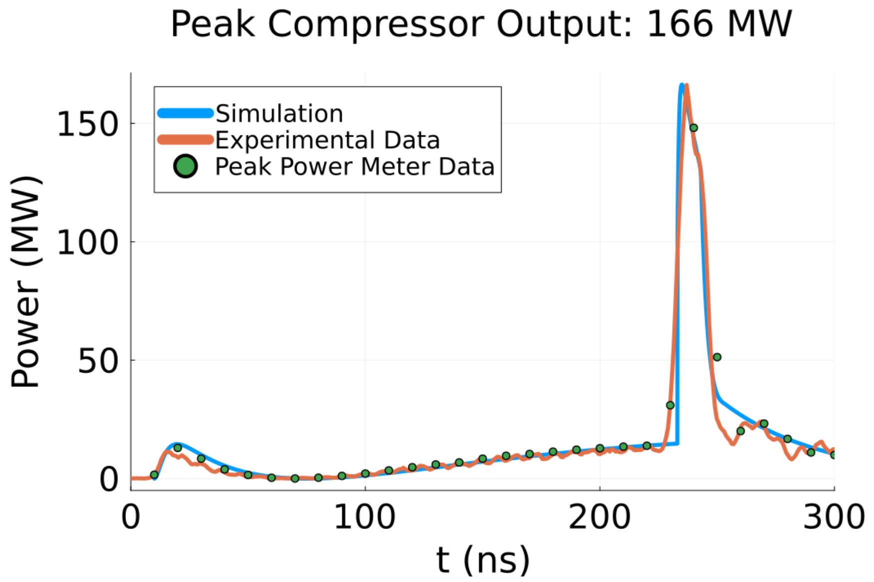


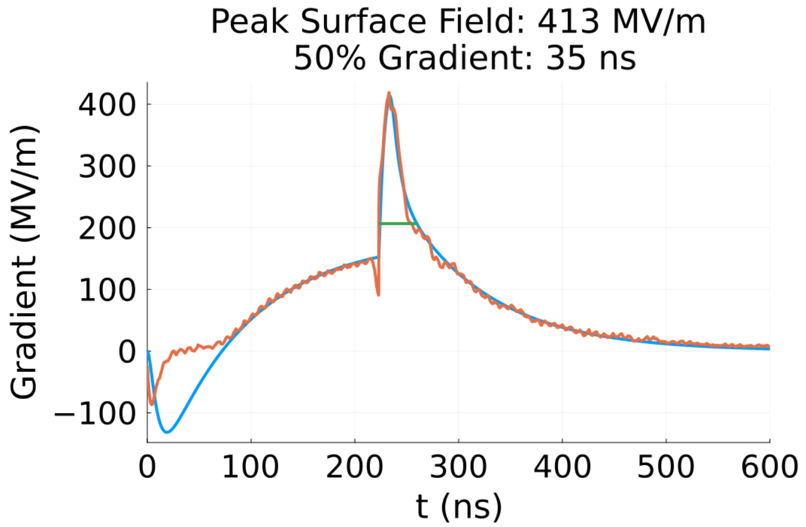
Preliminary high power testing results

- Demonstrated 166 MW peak power to a single photogun prototype
- Corresponds to 413 MV/m peak field
- Testing and analysis are ongoing (stay tuned!)



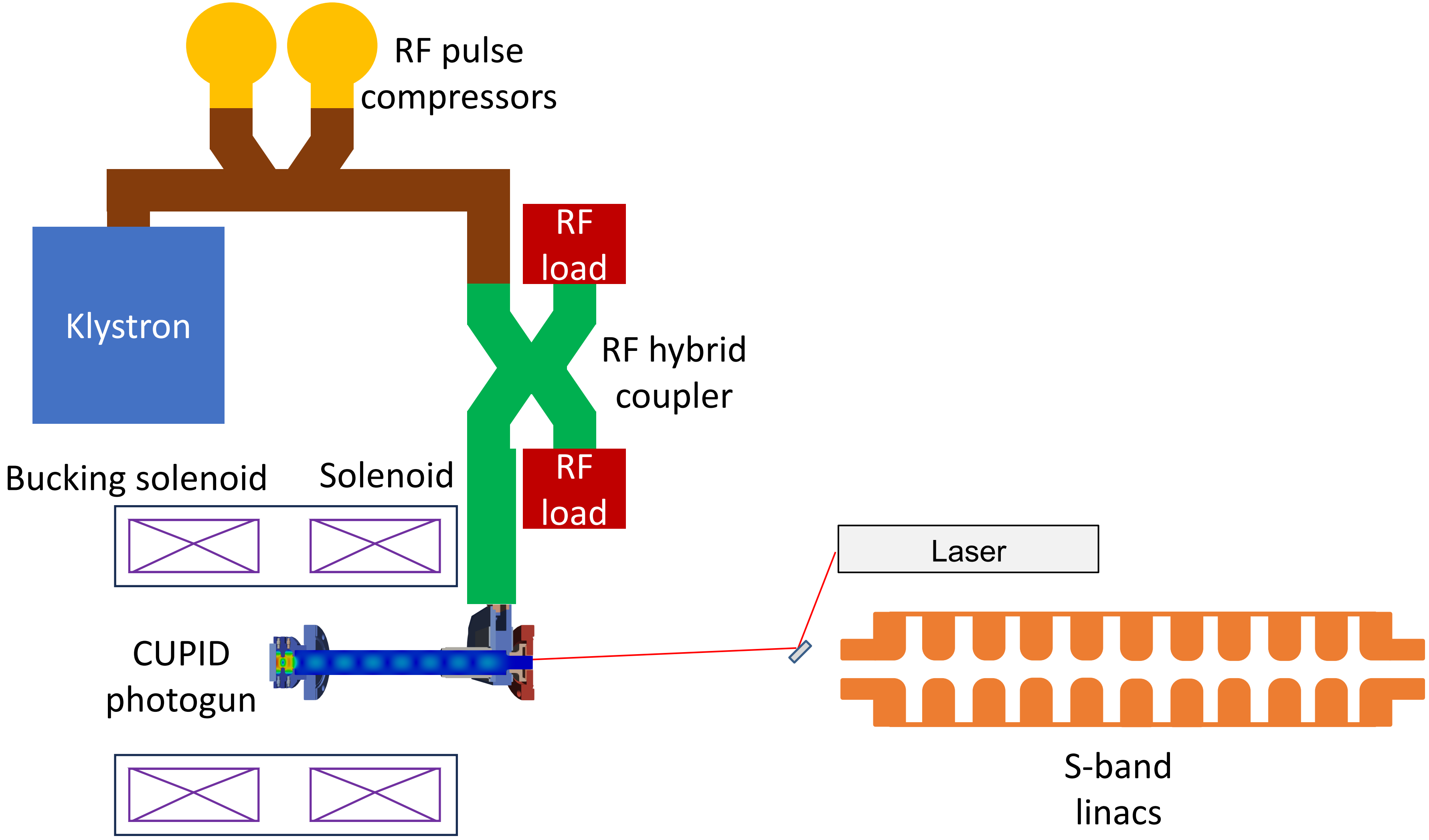






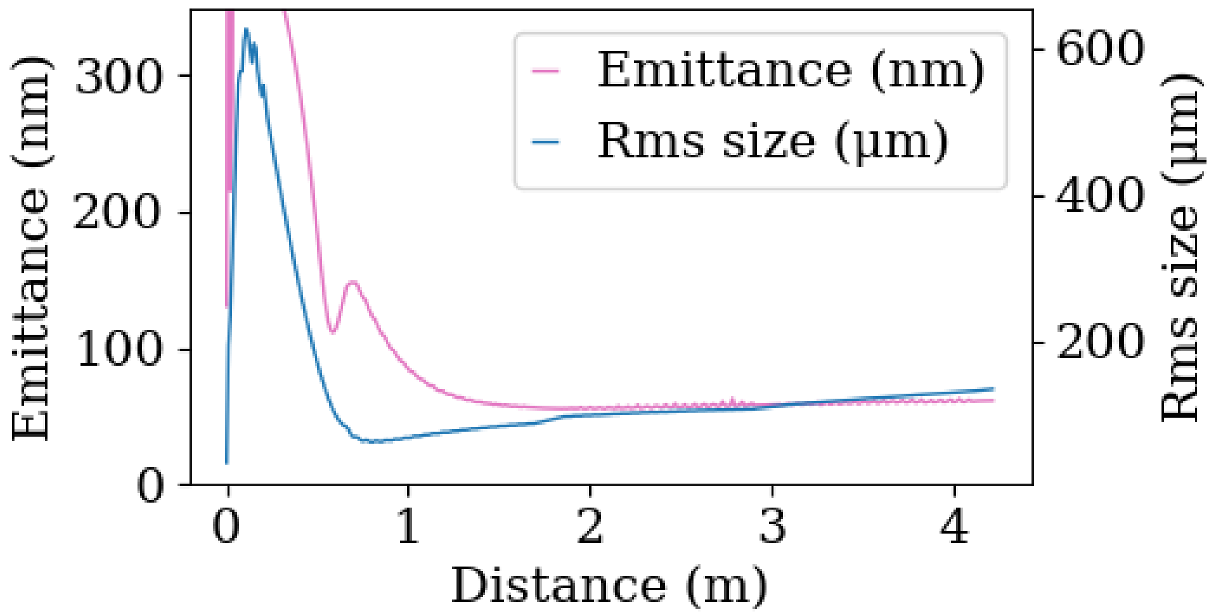
Photoinjector beam dynamics

Photoinjector beam dynamics studies



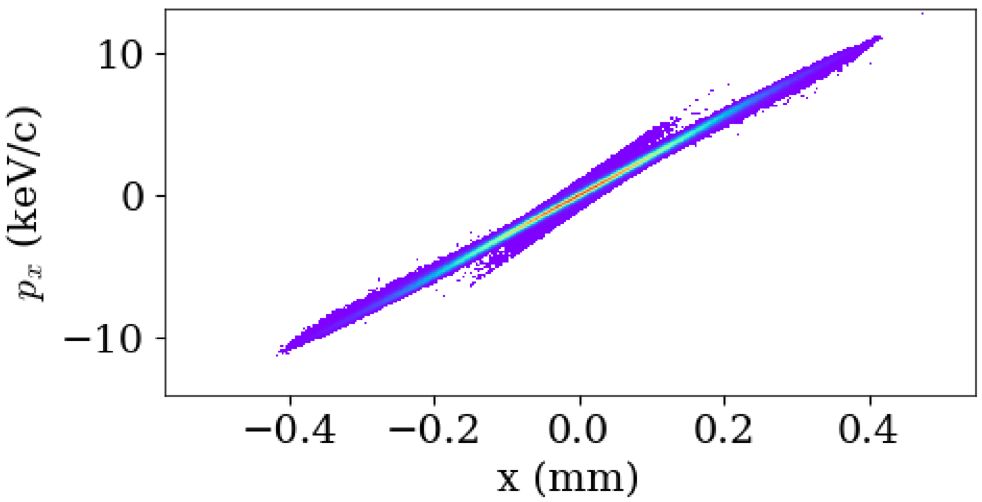
Photoinjector beam dynamics result

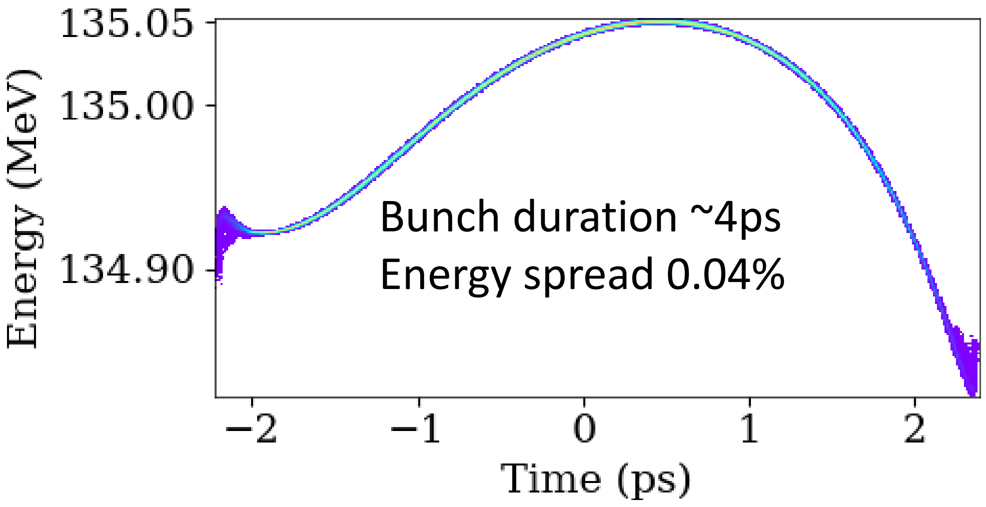
- Simulations using General Particle Tracer (GPT)
- Final beam emittance at 63 nm

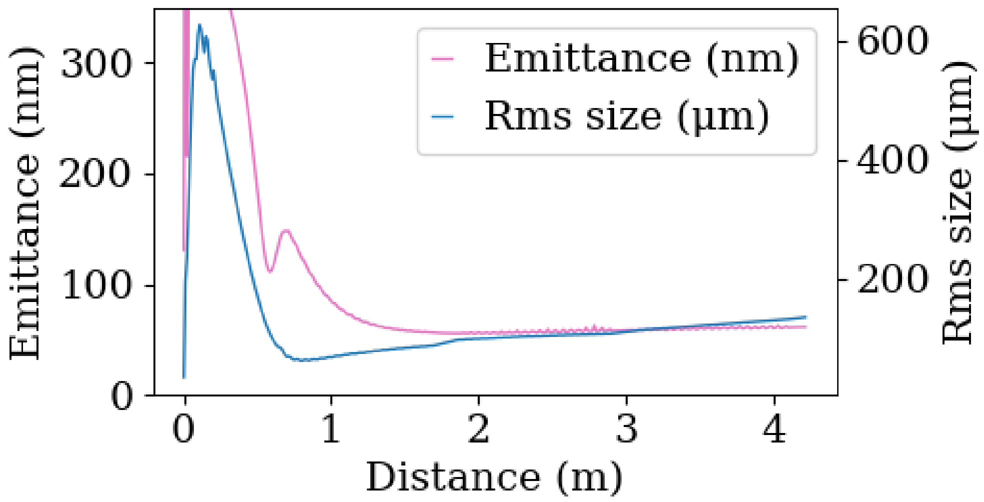


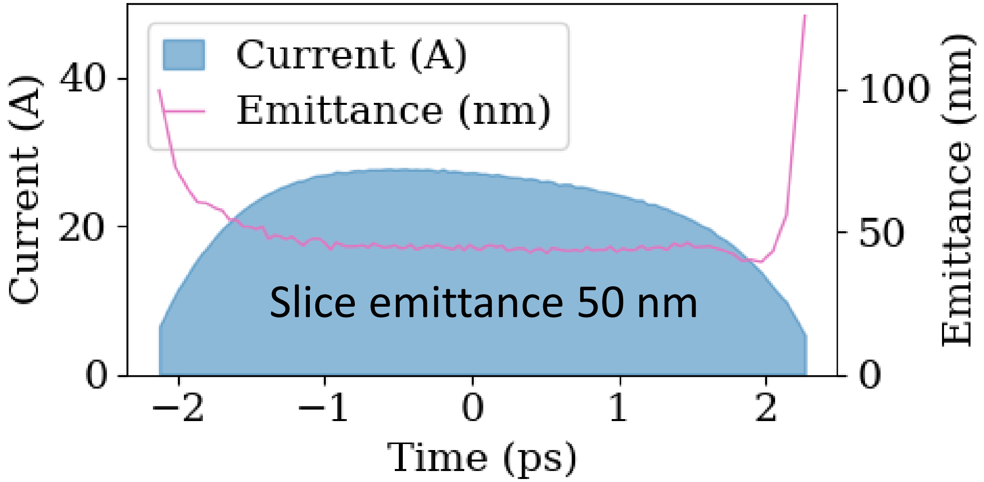
Parameters	Value	Unit
Frequency	11.424	GHz
Field at cathode	500	MV/m
Linac peak field	100	MV/m
Gun phase	70	deg
Linac 1 phase (from on-crest)	-3.3	deg
Linac distance from the cathode	0.6	meter
Solenoid strength	0.62	T
Linacs 2 and 3 phases	0	deg
Beam spot size (radial uniform)	70	µm
Beam rms duration (flattop)	4.5	ps
Beam mean transverse energy	414	meV

Photoinjector beam dynamics result









LCLS with CUPID photoinjector

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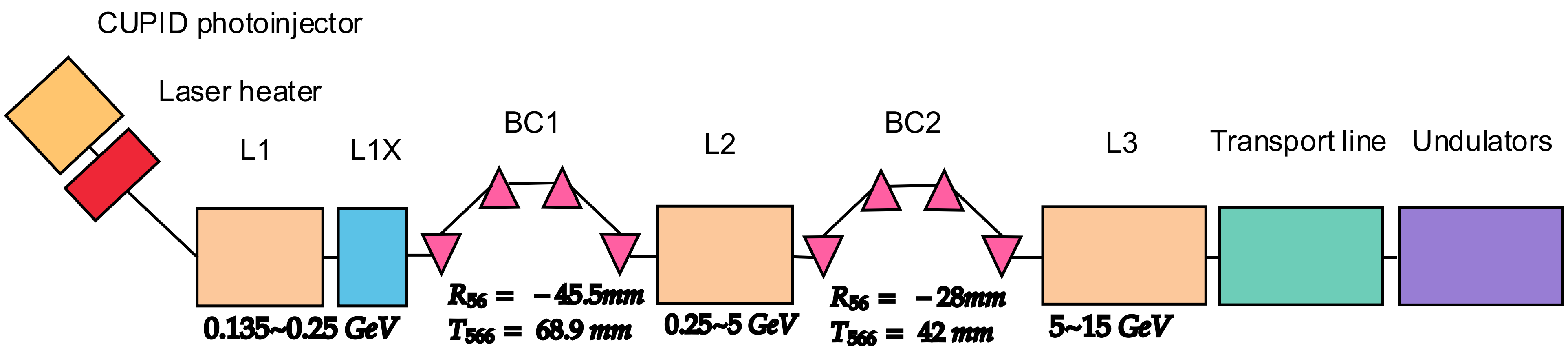

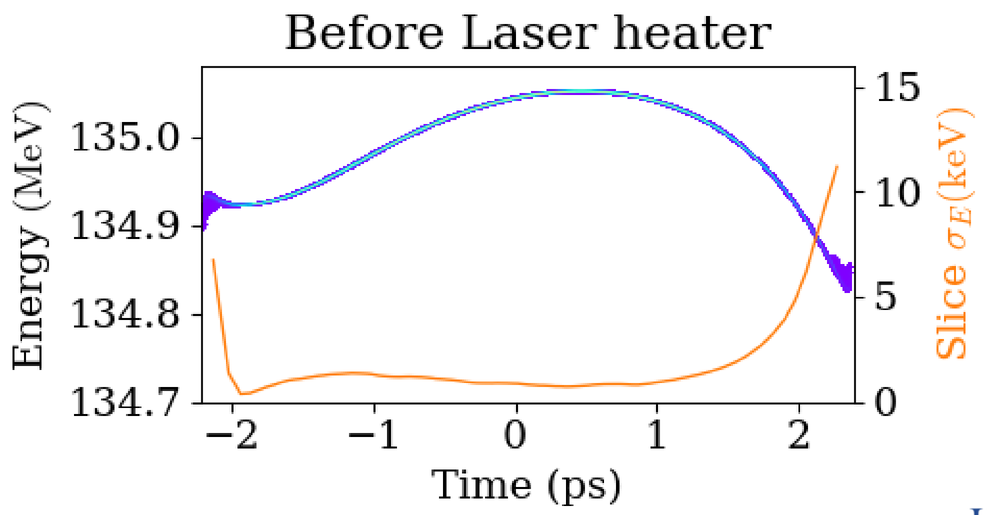

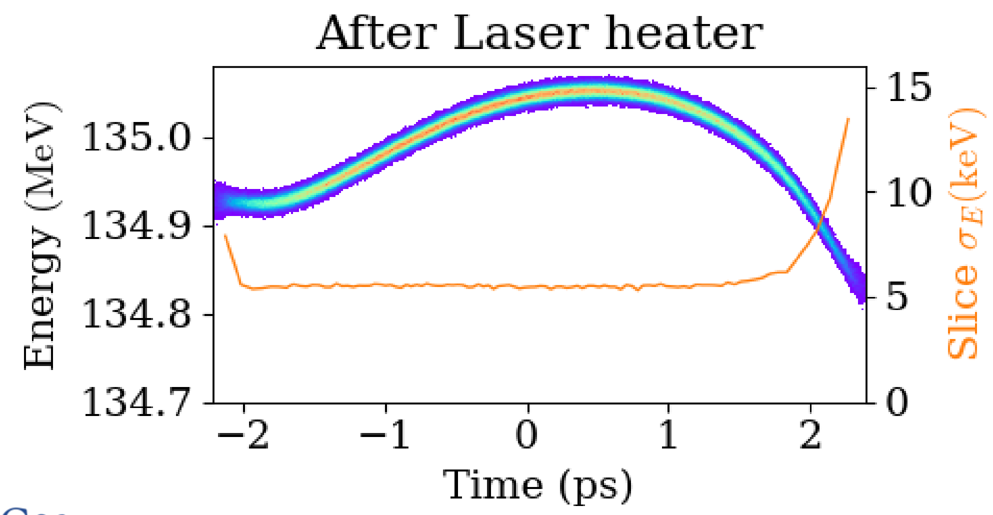

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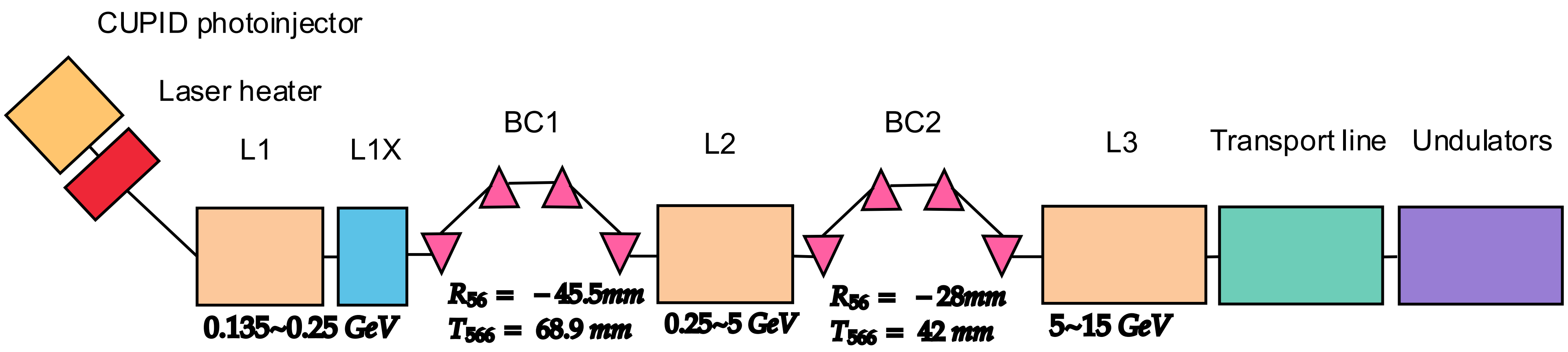

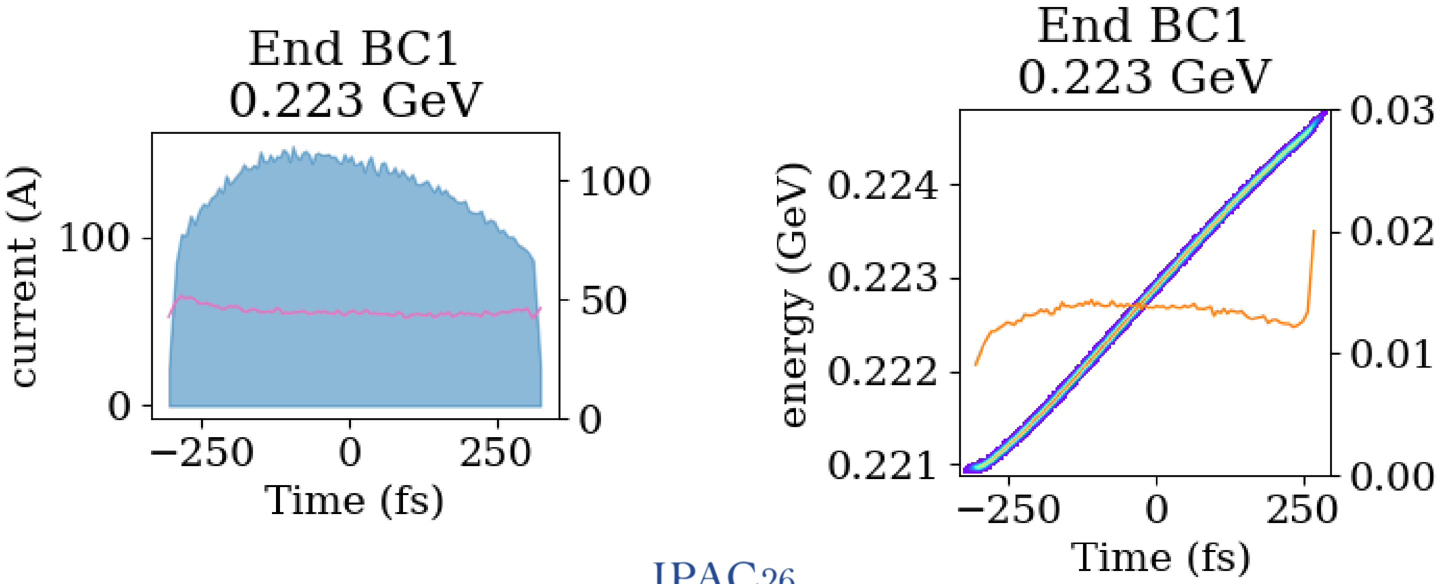

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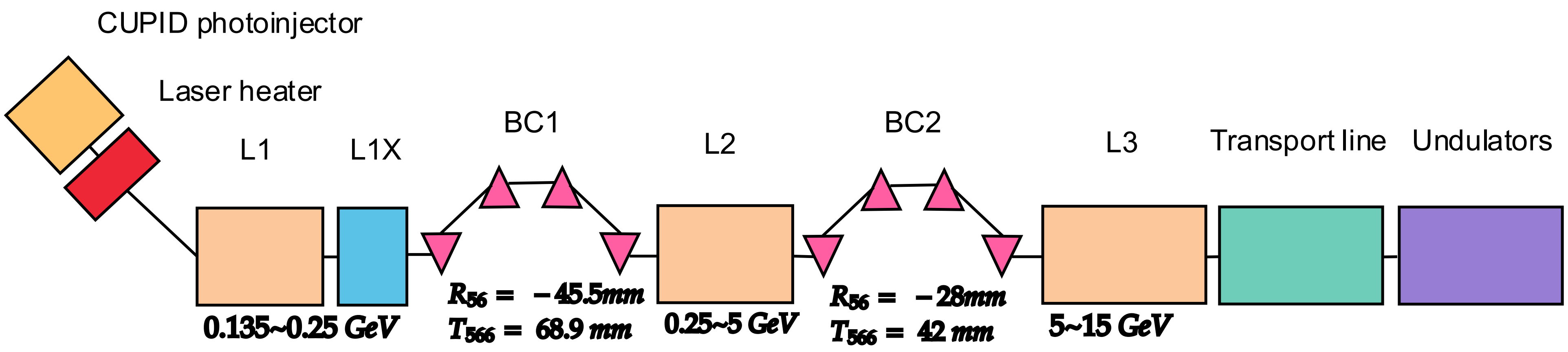

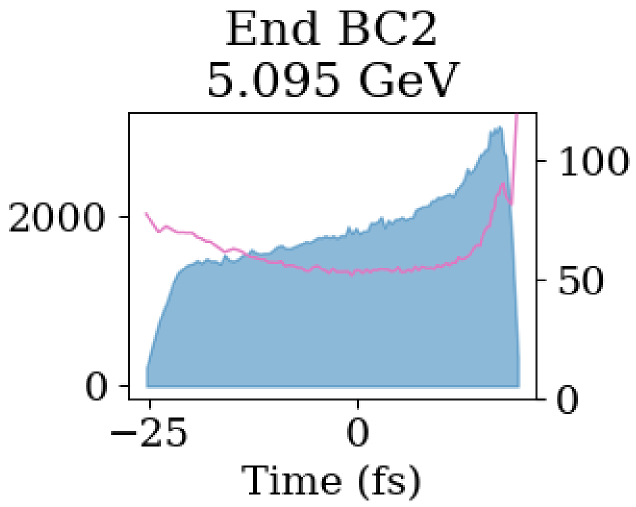

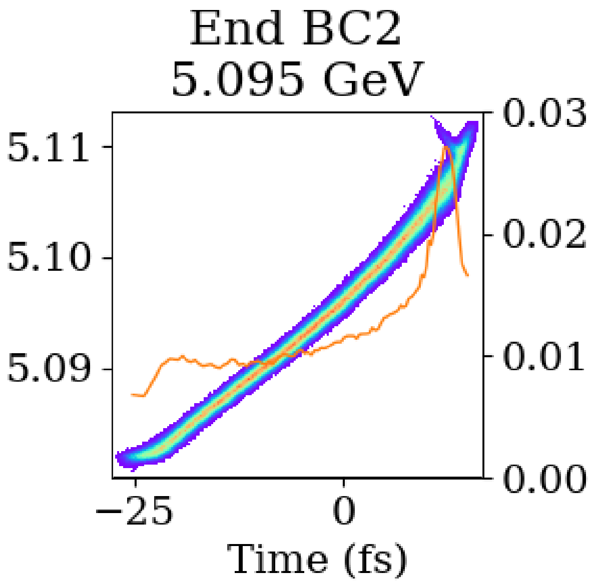

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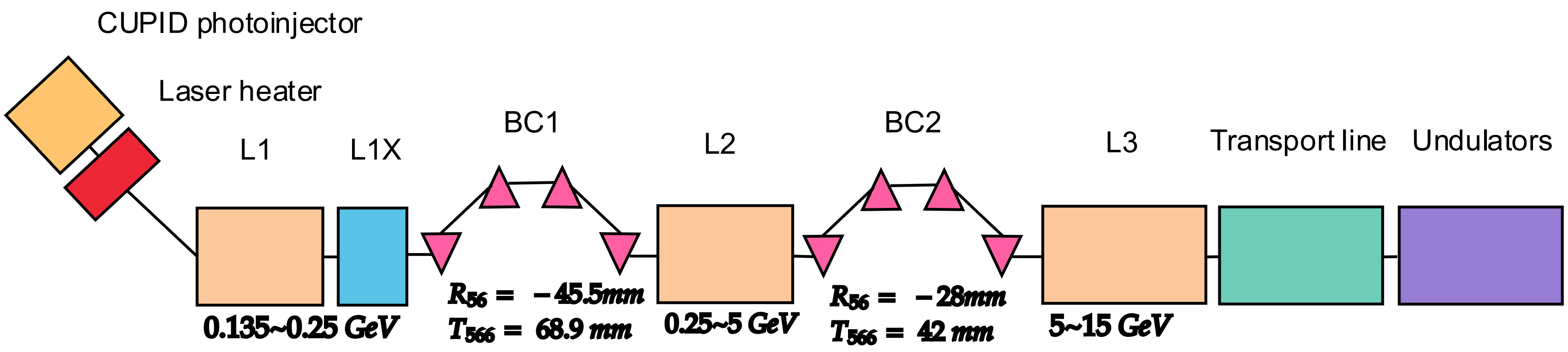
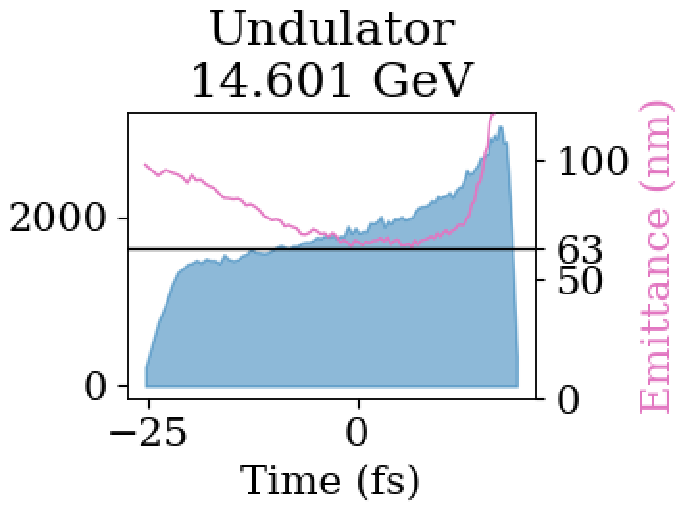
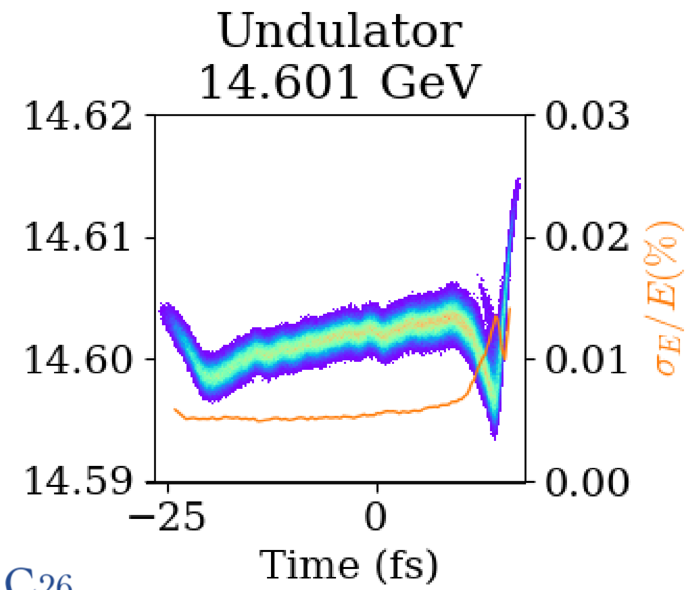
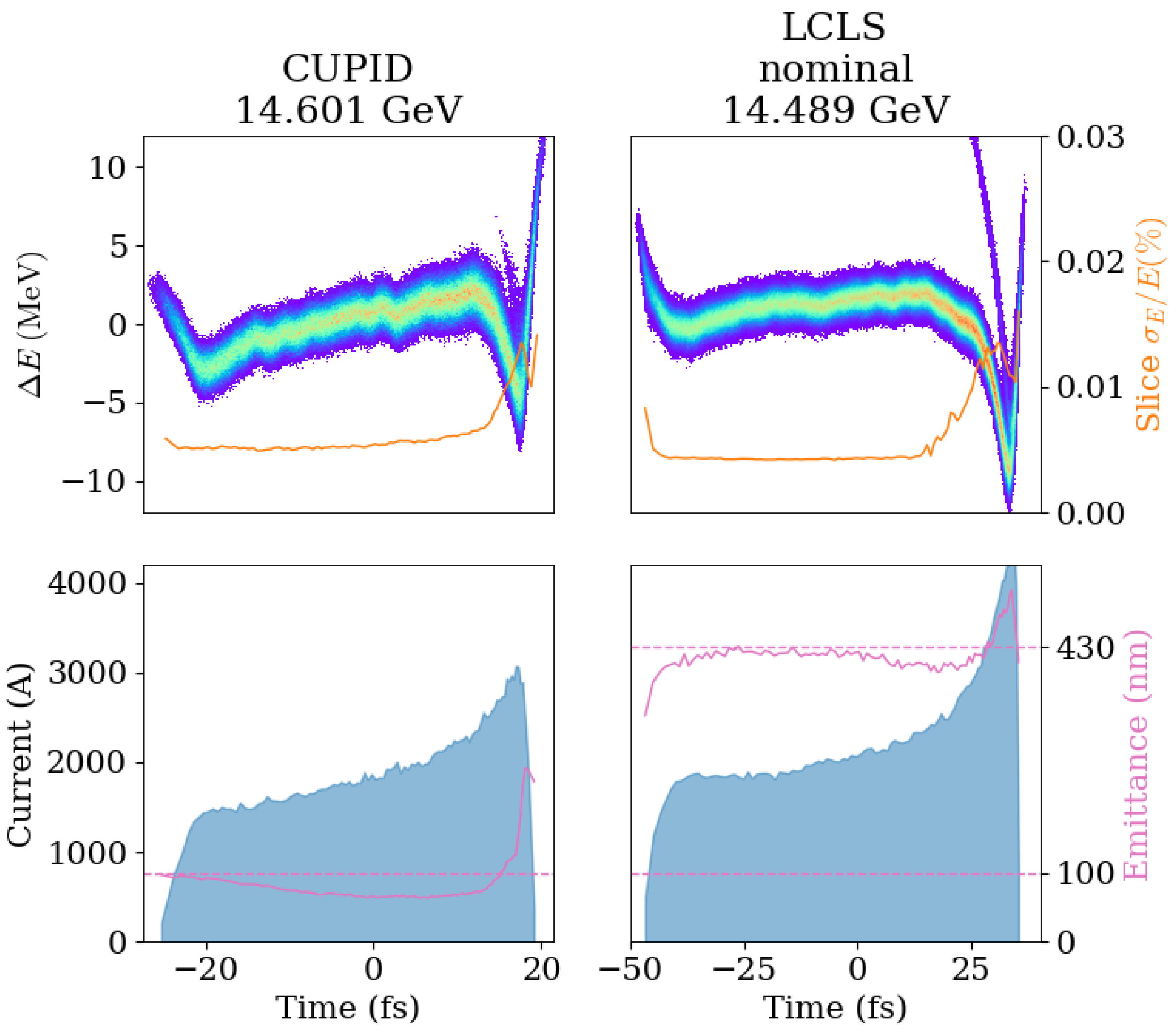






Comparison between LCLS nominal and CUPID

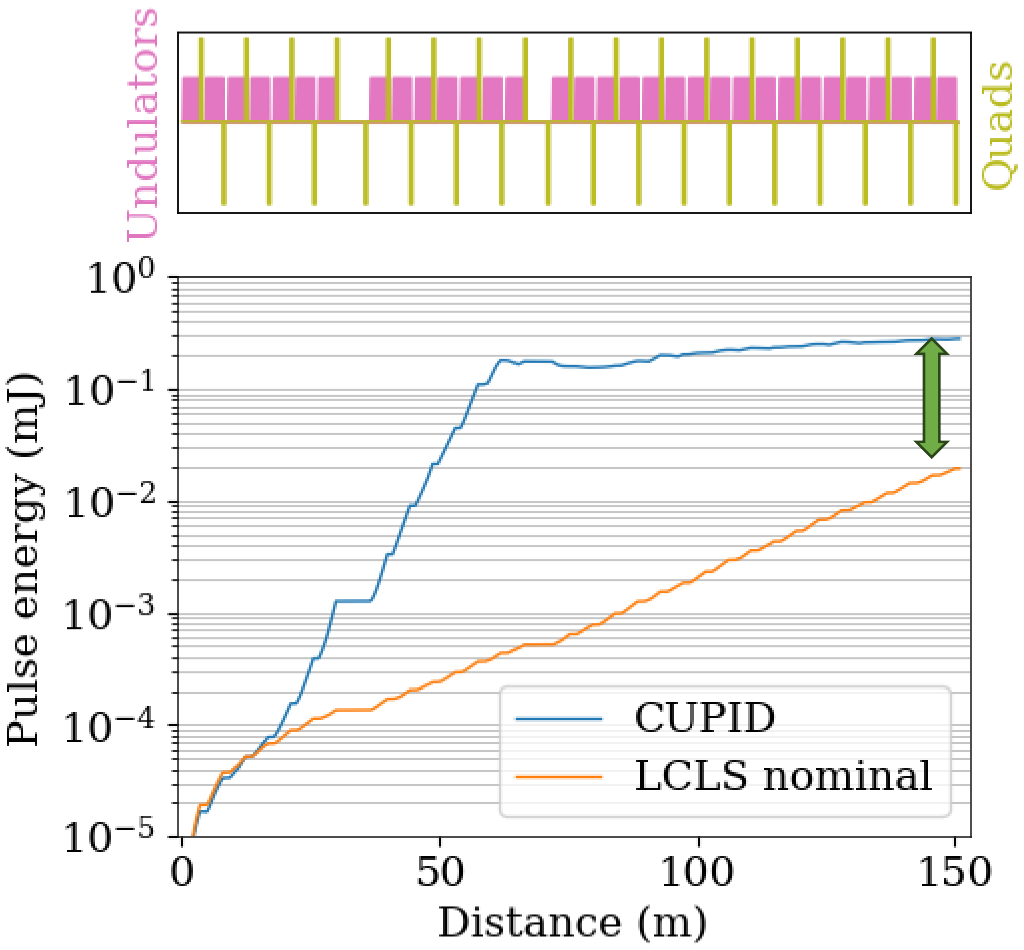
Parameters	CUPID	LCLS nominal	Unit
Charge (beginning)	100	250	pC
Charge (ending)	81	184	pC
Final energy	14.601	14.489	GeV
Final core emittance	<100	430	nm
Core current	1600	2000	A



40 keV FEL output for LCLS nominal and CUPID

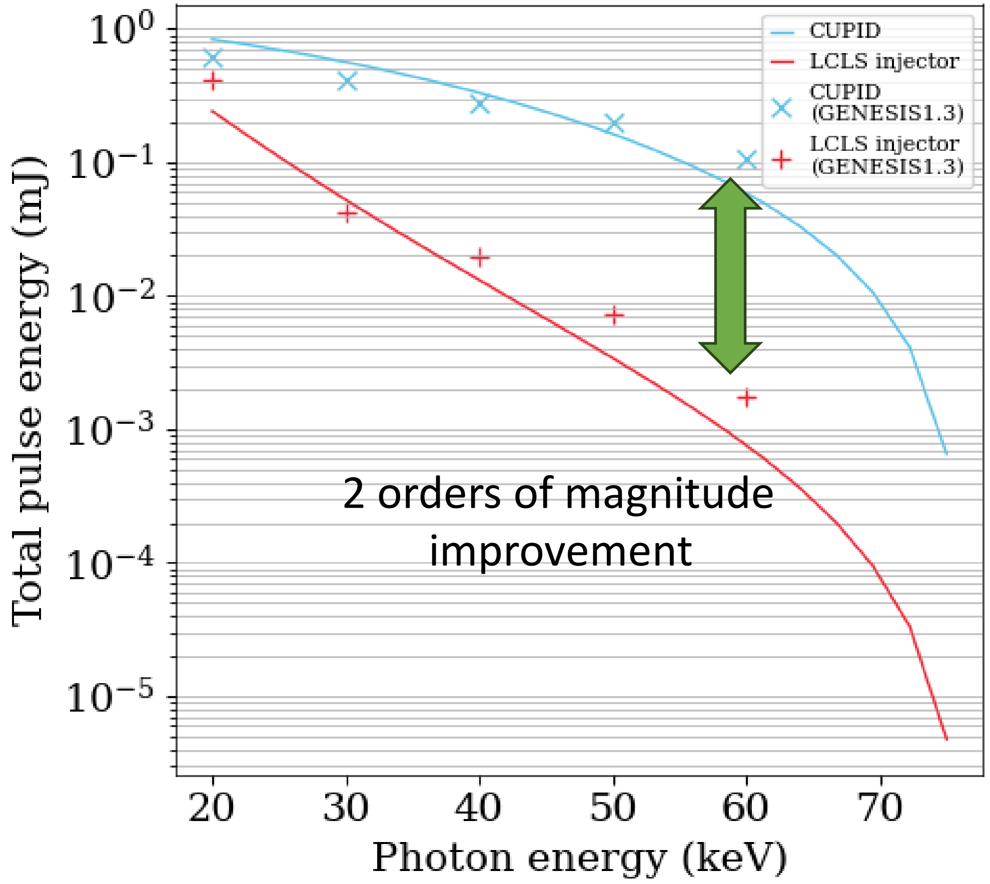
Parameters	CUPID	LCLS nominal	Unit
Charge (beginning)	100	250	pC
Charge (ending)	81	184	pC
Final energy	14.601	14.489	GeV
Final core emittance	<100	430	Nm
Core current	1600	2000	A
40 keV pulse energy	0.28	0.02	mJ

10x improvement
Pulse energy



Comparison between LCLS nominal and CUPID

- FEL performance analysis using Ming-Xie parameterization and GENESIS1.3 simulations
- Up to 2 orders of magnitude improvement for 60 keV photons



Summary and outlook

- We present CUPID, a photogun designed to run at 500 MV/m peak field with high power short rf pulses
- Beam dynamics studies of CUPID photoinjector show low emittances beams, down to 63nm
- Using LCLS with CUPID, we show that very hard x-ray FEL (>40 keV) generation with ~0.1 mJ pulse energy
- These results open a pathway for newer FEL science such as mesoscale probing with hard x-rays
- High power testing reaches 166 MW, corresponding to 413 MV/m
- Detailed studies are here

Acknowledgements

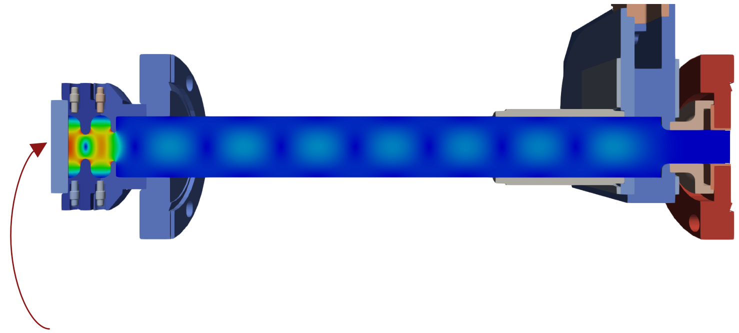
- SLAC: Zenghai Li, Valery Dolgashev, River Robles, David Cesar, Emma Snively, Juan E Hernandez Jr, Emilio Nanni, Ankur Dhar
- Argonne Wakefield Accelerator group for useful discussions
- Robert Soliday (ANL), Ji Qiang (LBNL), Andrea Latina (CERN) for help on simulations
- SLAC S3DF and NERSC computing facilities

Photogun design

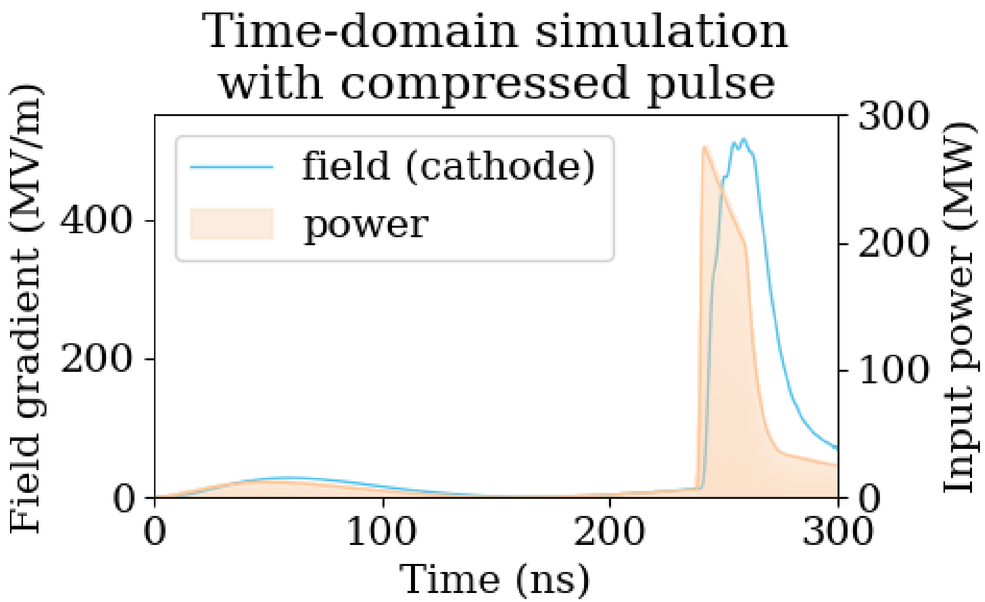
- One and half cell electron gun
- Large aperture to have lower quality factor

$$Q = \frac{f}{\Delta f} \propto \frac{1}{T}$$

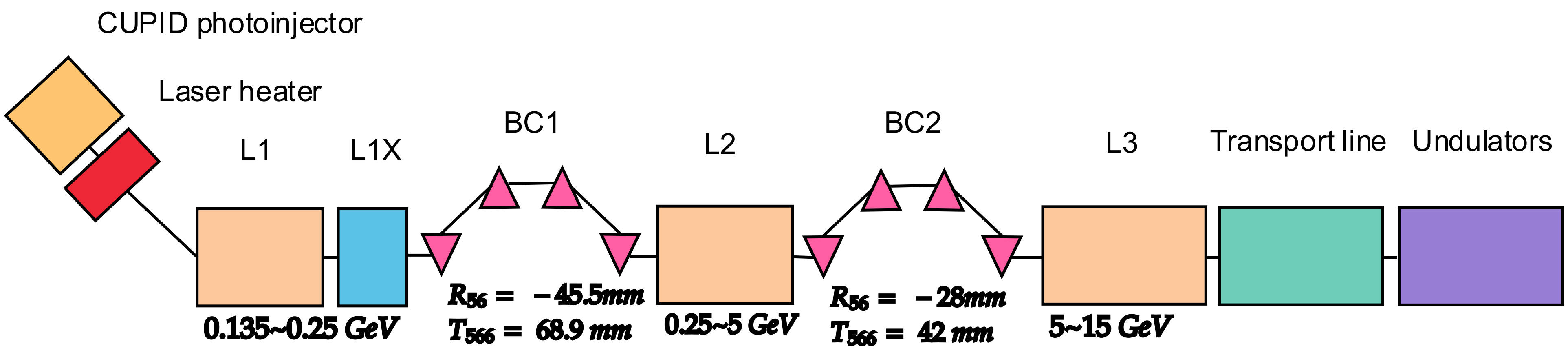
Parameters	Value
frequency	11.424 GHz
Q total	215
Q intrinsic	6585
field balance	1.07
peak-to-cathode ratio	1.22
Peak input power (500 MV/m peak field)	275 MW
S-parameter	-0.59
Short pulse bandwidth	100 MHz

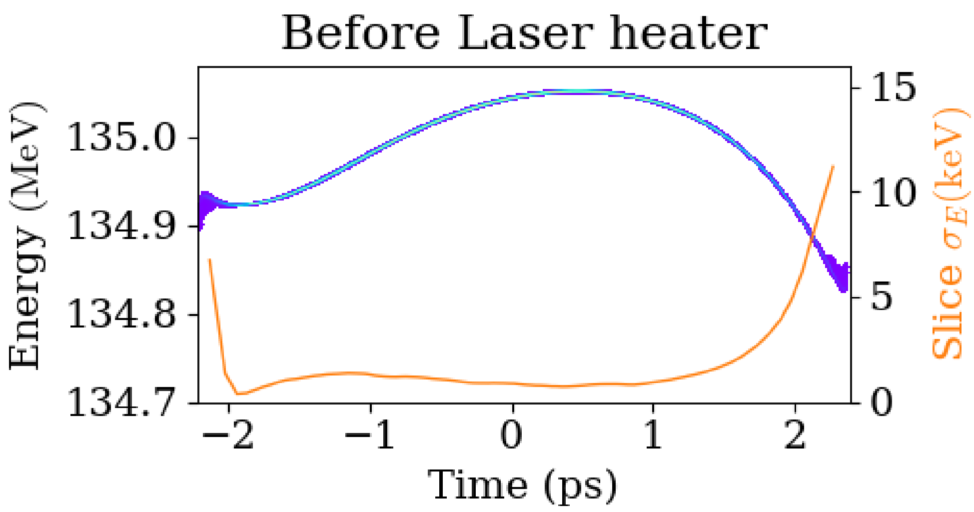


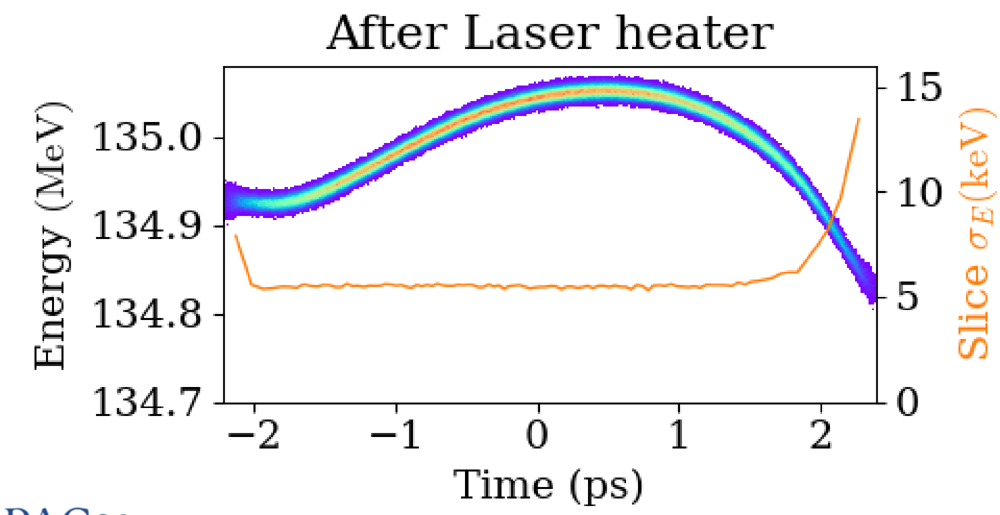
500 MV/m at the cathode



LCLS with CUPID photoinjector







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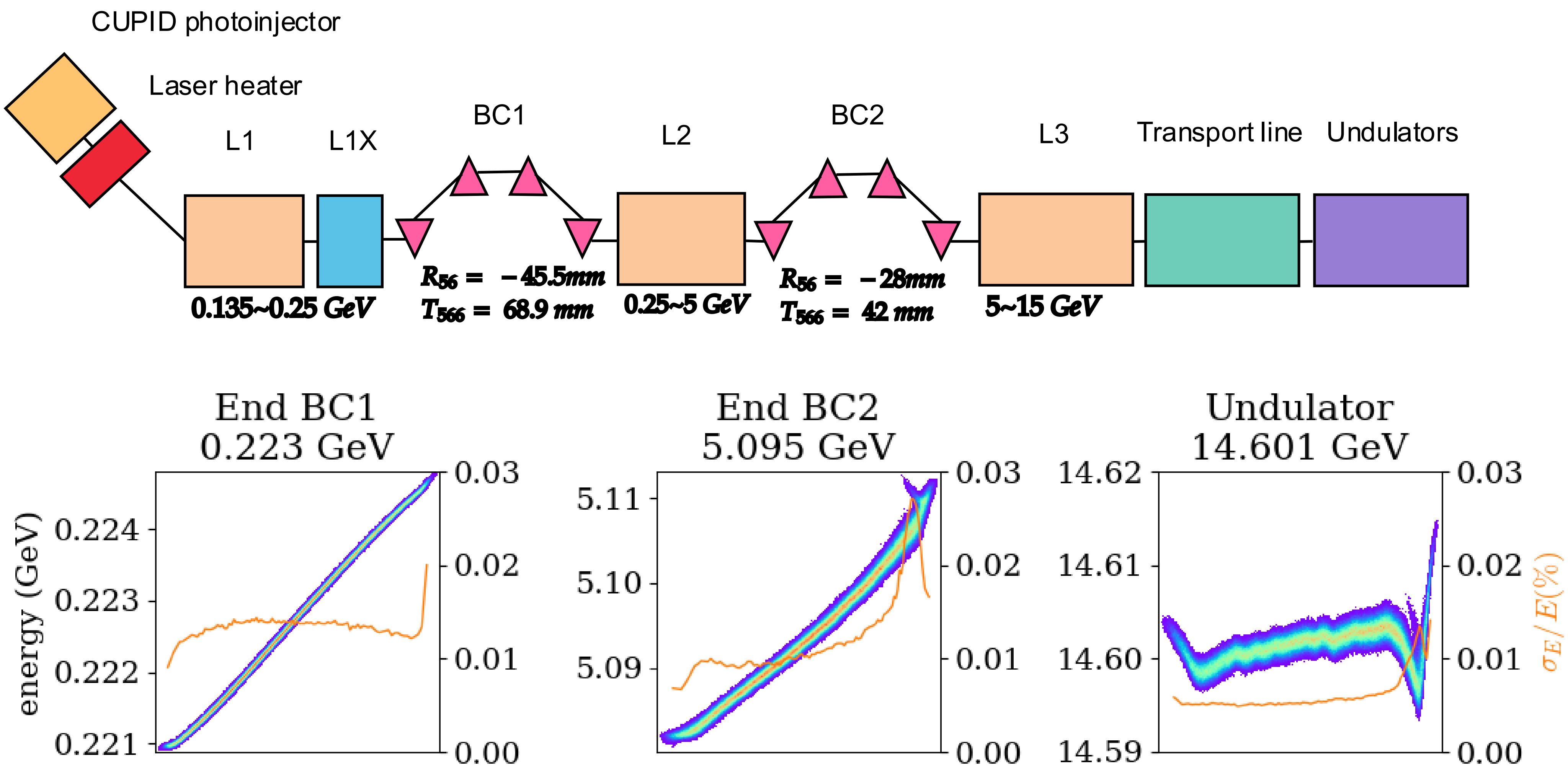

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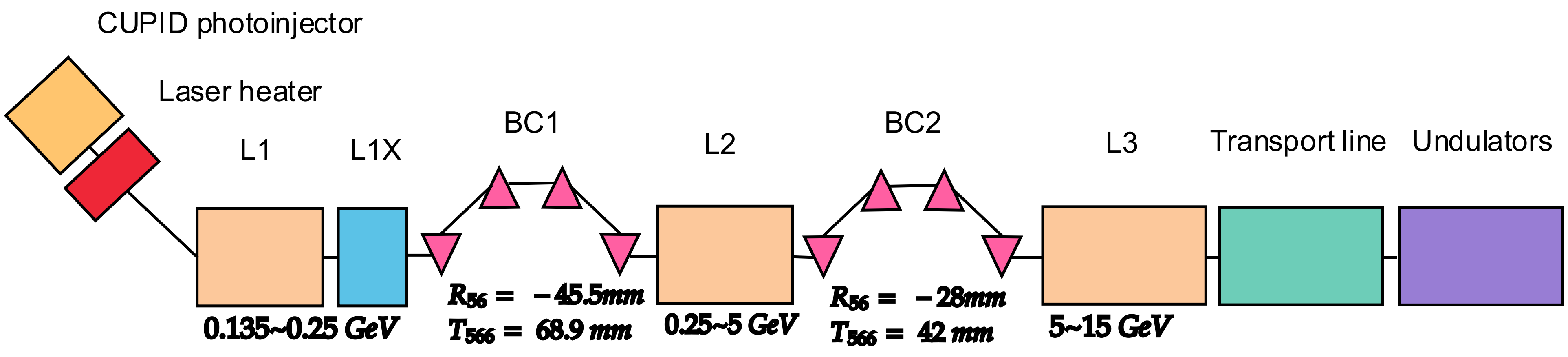
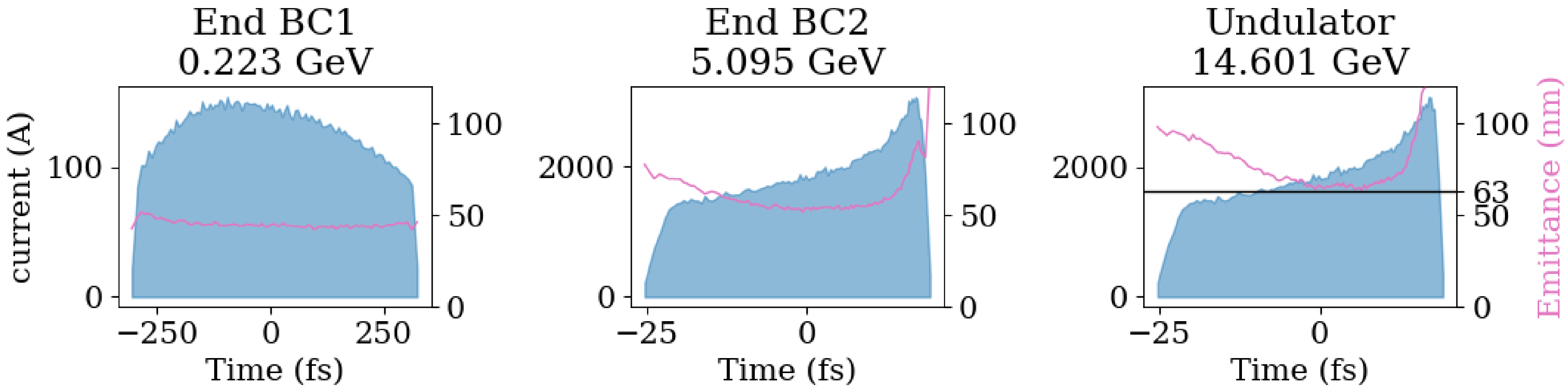
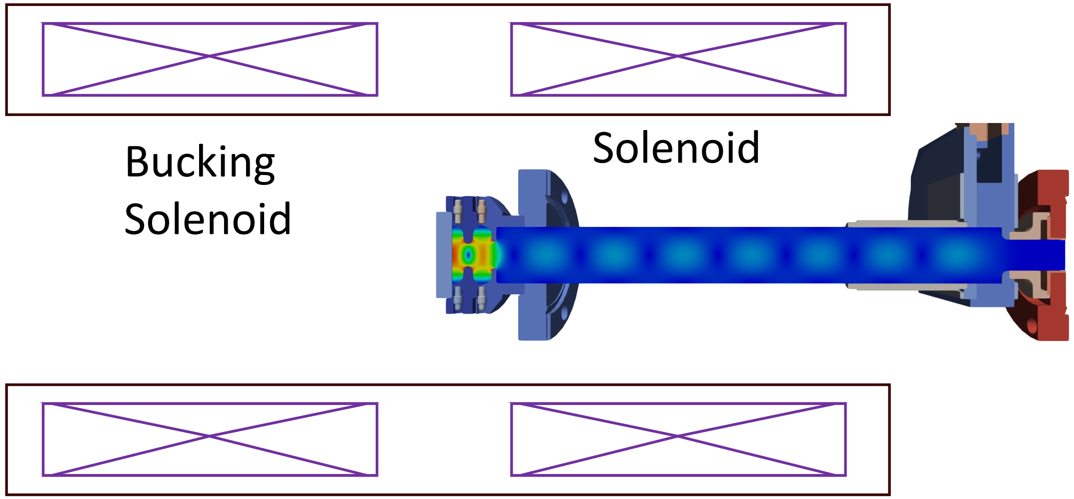
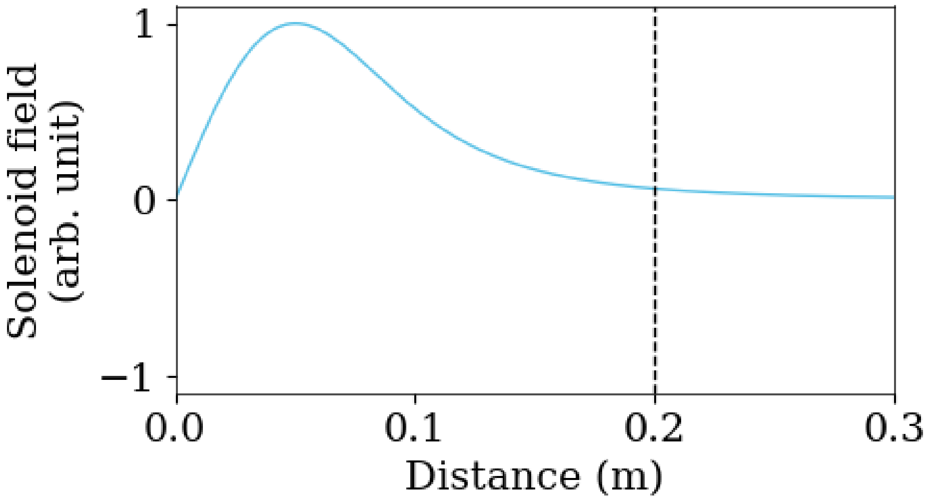




Solenoid

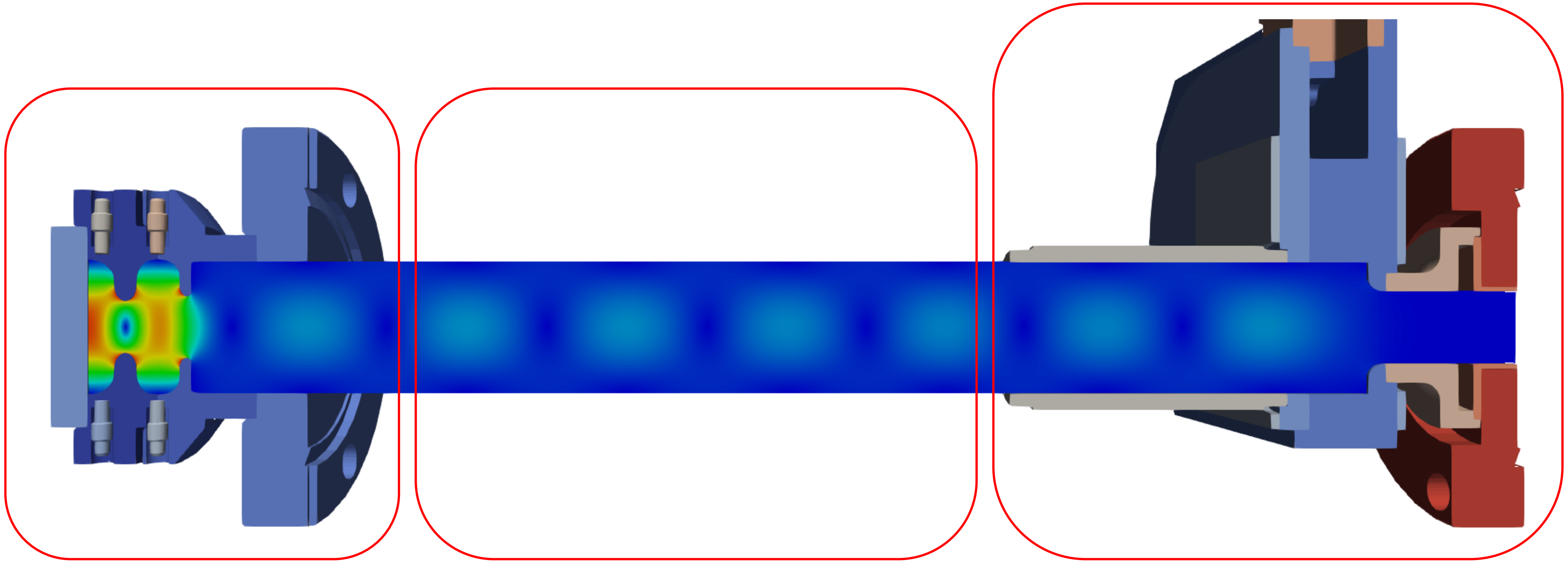
- A superconducting solenoid was designed for CUPID photoinjector
- A long beam pipe is needed to accommodate the solenoid
- Solenoid was designed by Cryomagnetics, Inc





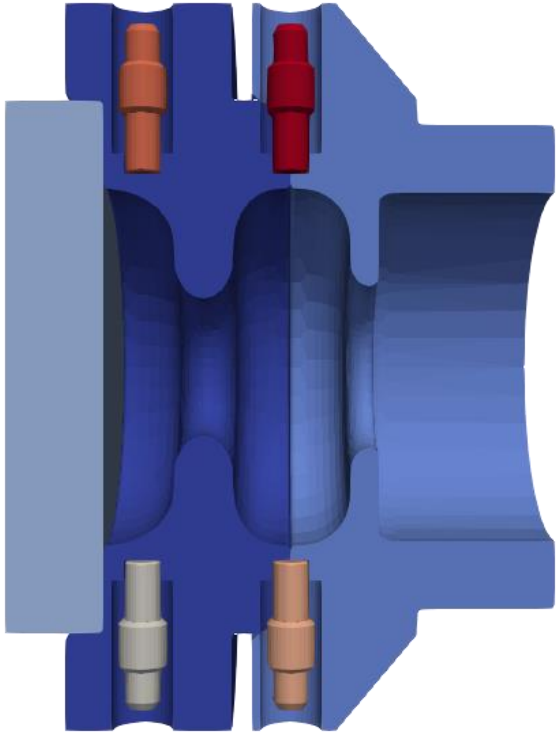
Mechanical design

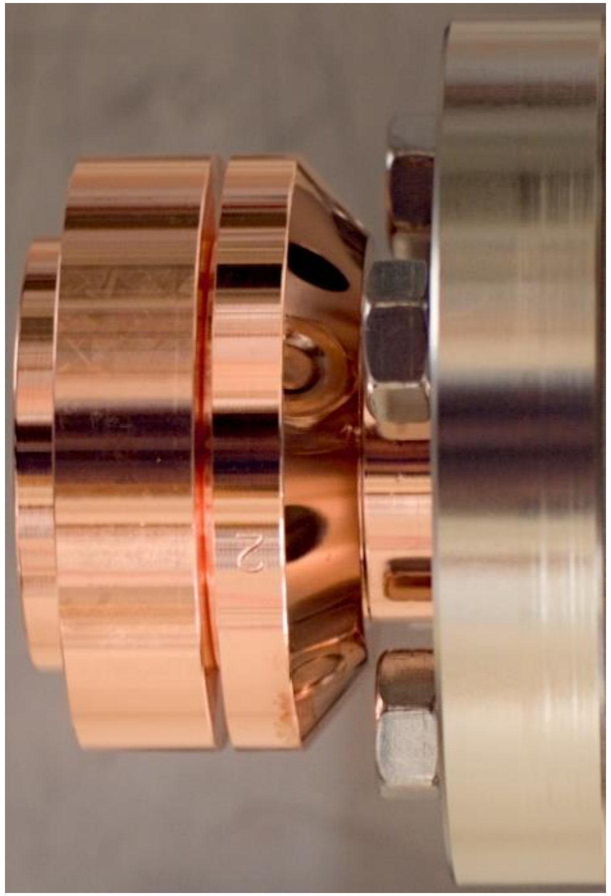
- A long beam pipe is used to connect the CUPID photogun to TM01 mode launcher
- It is needed to accommodate the solenoid

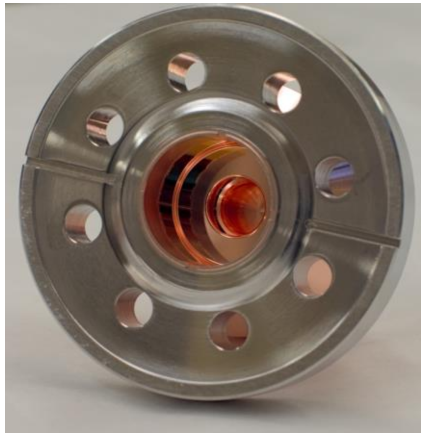


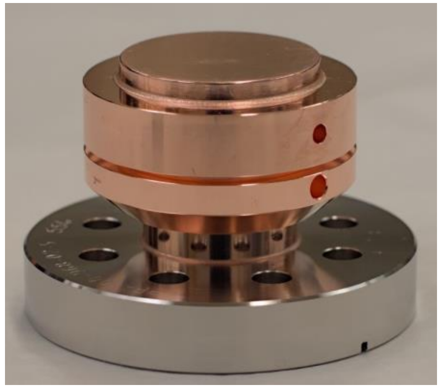
CUPID photogun Beam pipe TM01 mode launcher

Mechanical design









CUPID photogun beam dynamics

- Beam experiences oscillation it tis energy because of residual traveling waves inside the waveguide
- This is the consequence of our design choice to use TM10 mode launcher and long beam pipe