X-ray FEL Oscillator (XFEL-O) Injector Beam Dynamics and R&D Program

FLS2010: *WG5: High Brightness Guns, FLS 2010*

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For the

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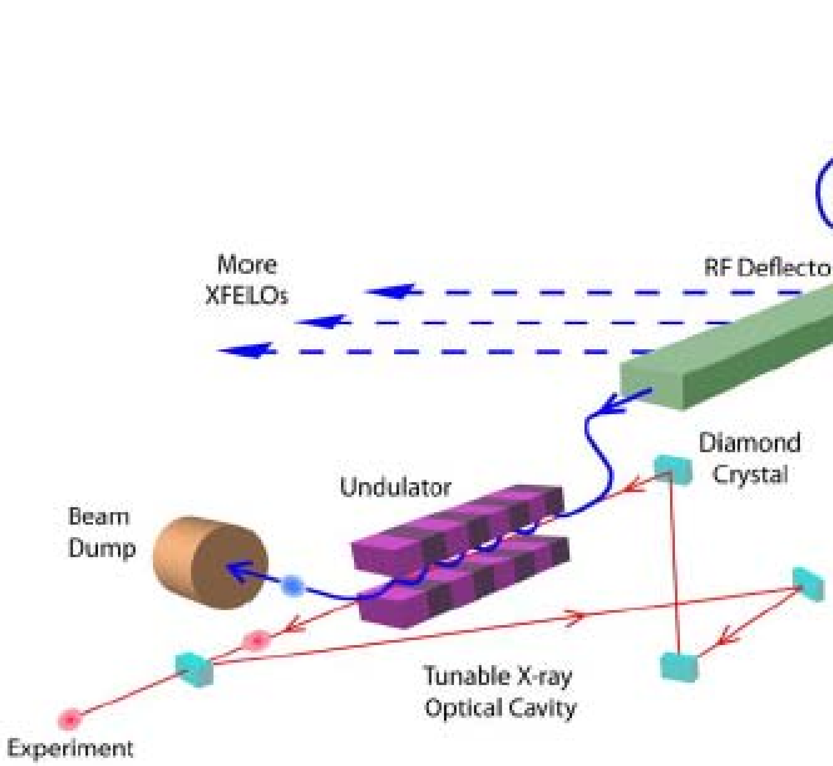
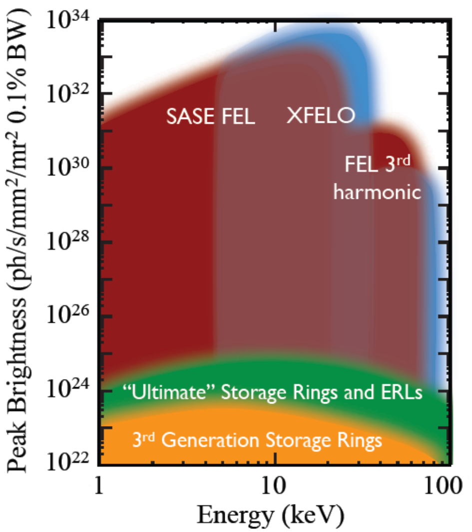
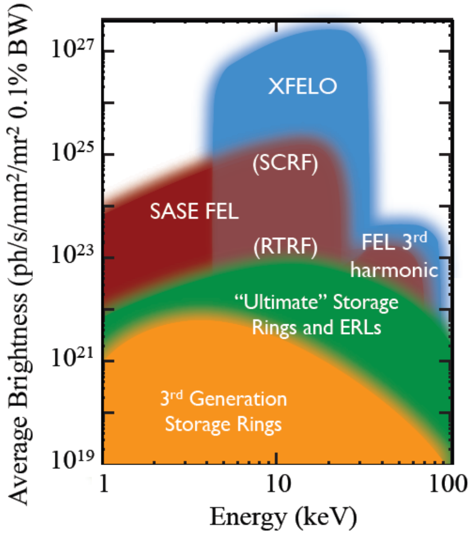
XFEL-O: Would deliver ultra-high spectral purity with high average power



Optical Cavity:
- Proposed by Collela and Luccio, 1984.
- Revisited in 2008, K-J Kim, S. Reiche, Y. Shvyd'k0, PRL 100, 244802.





(XFEL-O) Injector and Linac Requirements (Gun Parameters)

- **Normalized transverse emittance - < 0.2 mm**
- **Bunch Charge – 40 pC**
- Bunch length - < 1 ps
- Peak Current – 10-20 A
- Energy Spread – 2 x 10^{-4}
- **Bunch Repetition rate 1 MHz**
- Average Current – 40 mA
- Beam Energy – 542 MeV
- Linac – 7 GeV (JLAB type recirculating linac)

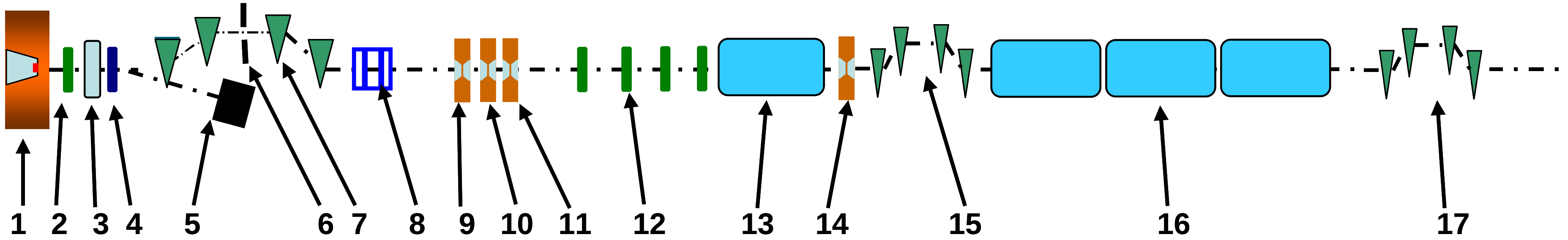
(XFEL-O) Injector Gun Possible Approaches

- **XFEL-0 requires low charge, ultra-low emittance and high repetition rate**
  - LCLS injector has required emittance but low rep – rate (Y. Ding etal. PRL 102, 2009)
  - Cornell gun spec has required rep-rate and achieved 0.43 mm normalized emittance at 20 pC/pulse (I. Bazarov etal PAC 2009)
  - PITZ gun has required emittance could drive a pulsed ~10 Hz XFEL-O (F. Stephan, ICFA HBEB 2009)
- **We explore a different concept using a thermionic cathode in a low frequency 100 MHz, 1 MV gun using CeB_6 cathode (A. Nassiri's talk this working group).**
  - LBNL using this approach for an FEL injector 187 MHz, 750 kV (K. Baptiste, etal. NIM A 599, 9 2009)
  - Inspired by success at SPRING-8 of a pulsed DC gun (K. Togawa, etal PRST-AB 10, 020703 2007).
  - Laser gating of cathode using an IR laser may be a way of achieving 1 MHz
  - First look simulation cathode back-bombardment performed

(XFEL-O) Injector Gun Possible Approaches cont.

- **We are also exploring use of a high rep-rate >~300 kV DC pulsed gun (T. Shintake)**
  - Add a control electrode close to the cathode and pulse the electrode 1 MHz, for 1 ns.
  - Is emittance growth due to the control electrode acceptable?
  - Performed a first look simulation of this idea

(XFEL-O) Injector system layout



1 – RF cavity with thermionic cathode, 100 MHz, 1 MV;

2 – focusing solenoid;

3 - RF (or other) chopper to form bunch rep rate (1 -3 MHz);

4 – quadrupole;

5 – beam dump;

6 – slits;

7 – chicane and slits (6) as an energy filter;

8 – quadrupole triplet;

9 – 100 MHz rf cavity;

10 – monochromator, 600 MHz;

11 –buncher, 300 MHz;

12 – solenoids;

13 – SC linac section, 66 MeV, f=400 MHz.

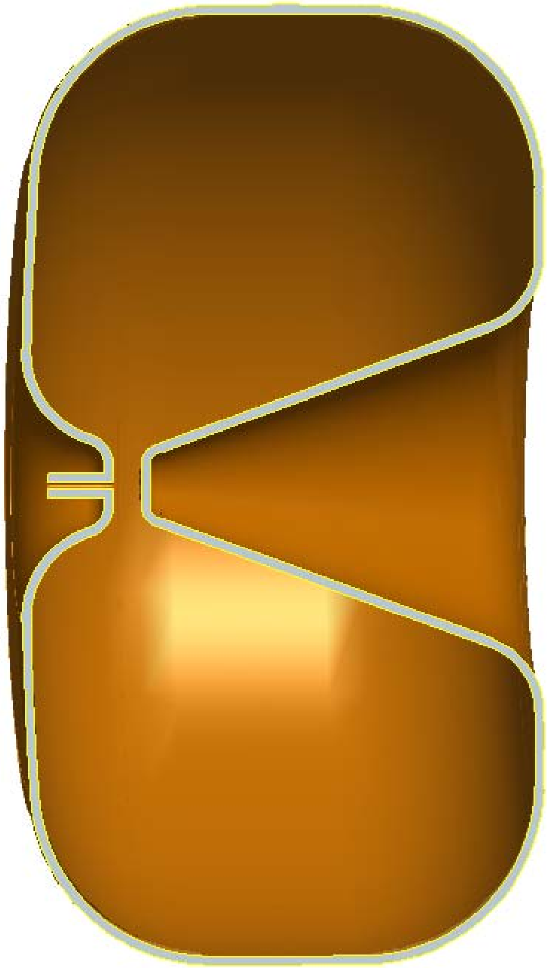
14 – high-harmonic cavity (1300 MHz);

15 – bunch compressor – I;

16 – SC linac section,546 MeV, f=1300 MHz.

17 – bunch compressor – II;

(XFEL-O) Injector system 100 MHz gun

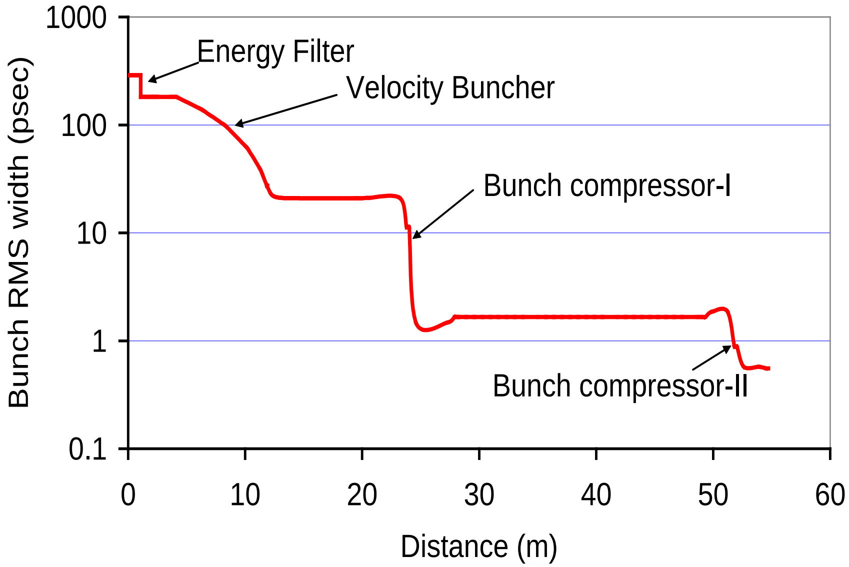


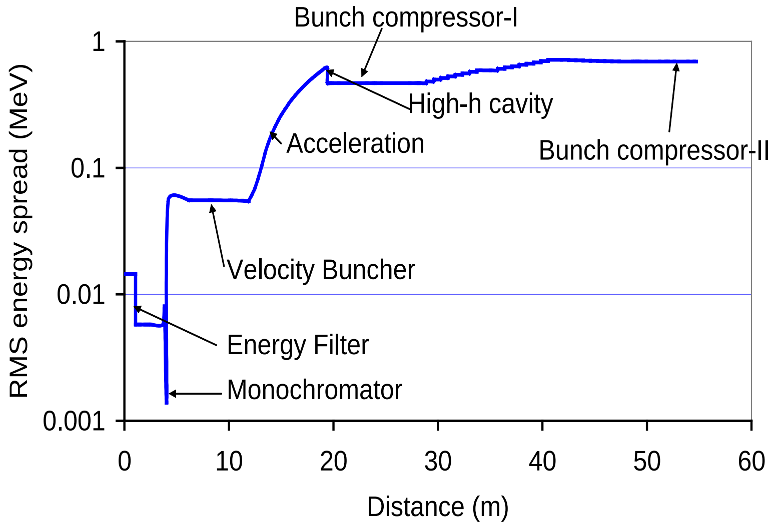
Frequency	100	MHz
Q_U	44,991	
V_{gap}	1.0	MV
Energy	6.06	J
R_s	11.81	Mohm
$E_{cathode}$	25.6	MV/m
Peak E_{surf}	33.8	MV/m
P_{loss}	85	kW
Peak $P_{density}$	12	W/cm^2
Radius	0.68	m
Length	0.73	m

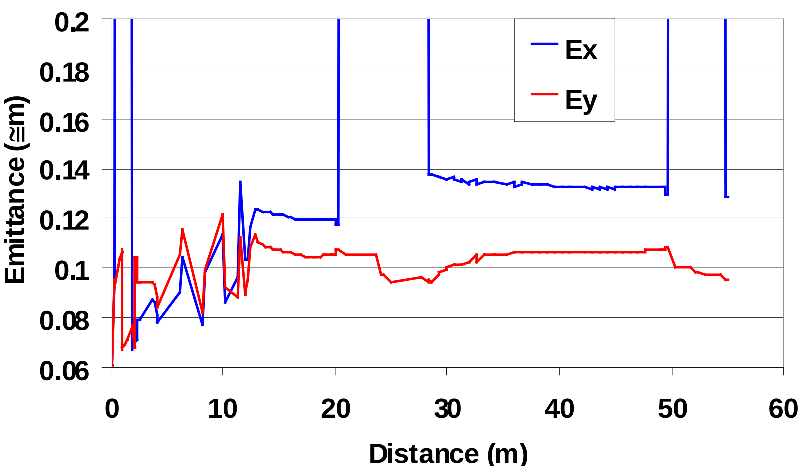
(XFEL-O) Injector system baseline design (B. Mustapha (PHY), P. Ostroumov (PHY))

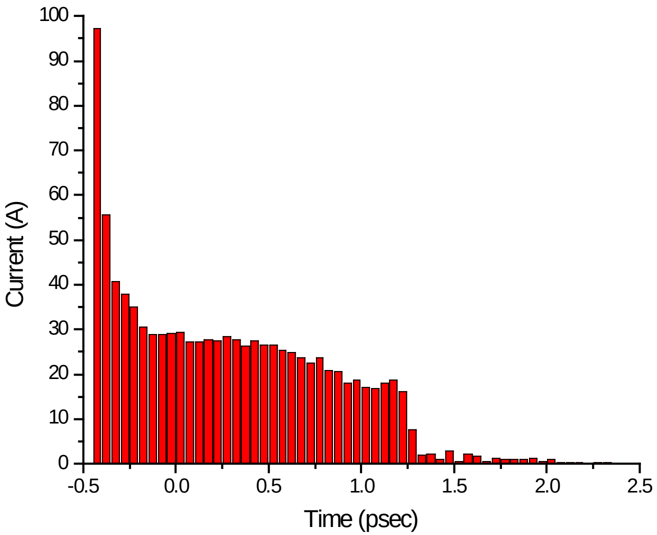
- **100 MHz, 1 MV RF gun with 40 pC at 1 MHz, ~300 ps rms bunch length**
- **After chopping ~40 mA average current**
- **Chicane energy filter gives 0.15 % energy spread**
- **100 MHz + 600 MHz cavities linearize energy spread**
- **300 MHz cavity + drift space velocity bunches beam to ~30 ps rms bunch length**
- **400 MHz booster linac accelerates to 66 MeV at entrance of BC-1**
- **1300 MHz harmonic cavity linearizes energy chirp on the beam before BC – 1**
- **BC-1 takes bunch length down to 2 ps rms**
- **Main SC linac section takes beam to 542 MeV (ILC design 1300 MHz)**
- **BC-2 takes bunch length down to < 1 ps rms.**

(XFEL-O) Injector system beam parameter evolution



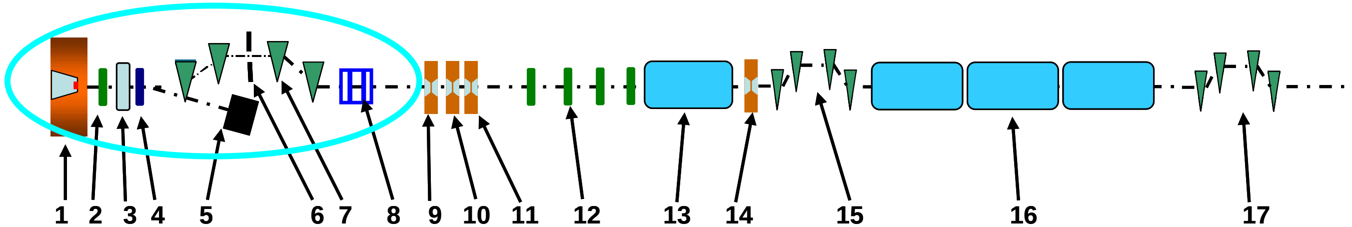






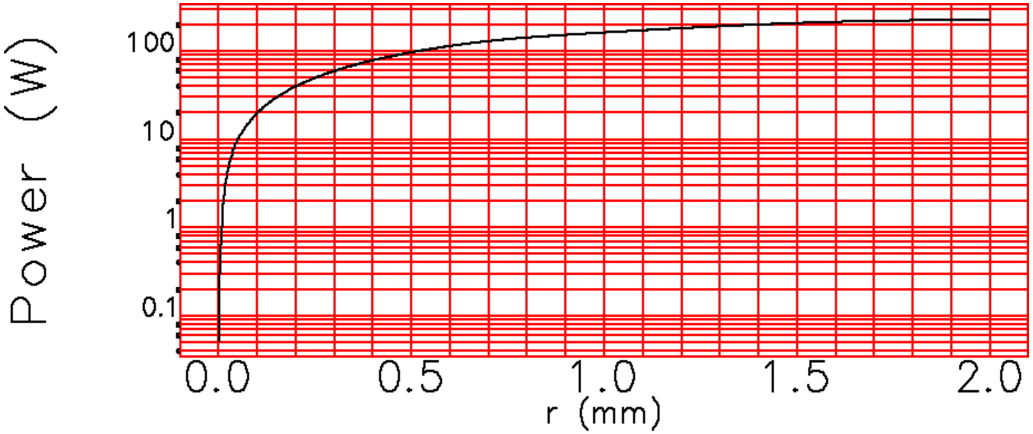
(XFEL-O) Injector system R&D program

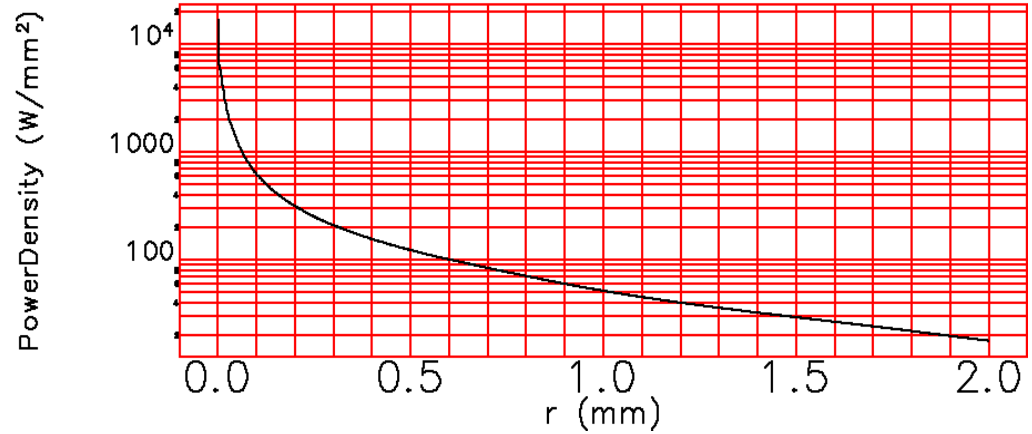
- Performed “manual” simulations using TRACK to verify baseline design and choose gun frequency and voltage (evaluated 50, 100 and 180 MHz)
- Used ASTRA with a genetic optimizer to do emittance optimization at 20 MeV
  - Manually filtered beam (no real chicane in the model) and used charge of 50 pC
  - Used 3rd order off axis field expansion in the accelerator cavities
  - Used 3rd order off-axis field expansion for solenoids (JLAB IR FEL solenoids)
- Investigating use of IMPACT-T to continue start-to-end optimization
- Design 100 MHz, 1 MV rf gun with CeB_6 cathode through end of the chicane
  - Design will include realistic cathode system design based on 300 kV DC gun tests
  - Design will include magnetic system to mitigate back-bombardment on the cathode
- Design and build a 300 kV DC gun cathode “test bench” to test CeB_6 cathodes
- Investigate IR laser gating of a cathode in an experiment at the APS linac injector test stand (ITS) at low rep rate.
- Explore beam dynamics a 300 kV DC “triode” gun as a possible alternative (T. Shintake)



100 MHz gun Back-bombardment mitigation *(M. Borland)*

- All thermionic rf guns suffer from BB
  - Electrons that don't exit cavity before field reversal are back-accelerated into the cathode.
- Using spiffe[1] to simulate the gun, we find
  - ~200W of total BB power
  - ~60W on the cathode itself
  - Power density above 10 kW/mm²

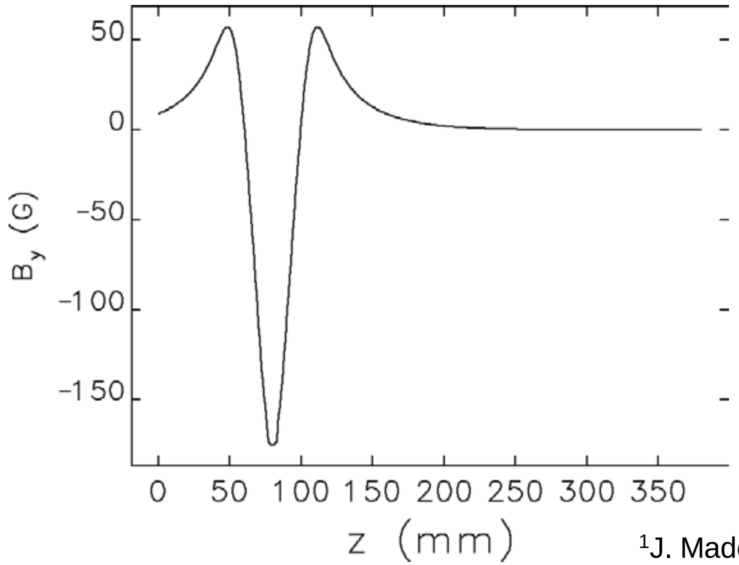


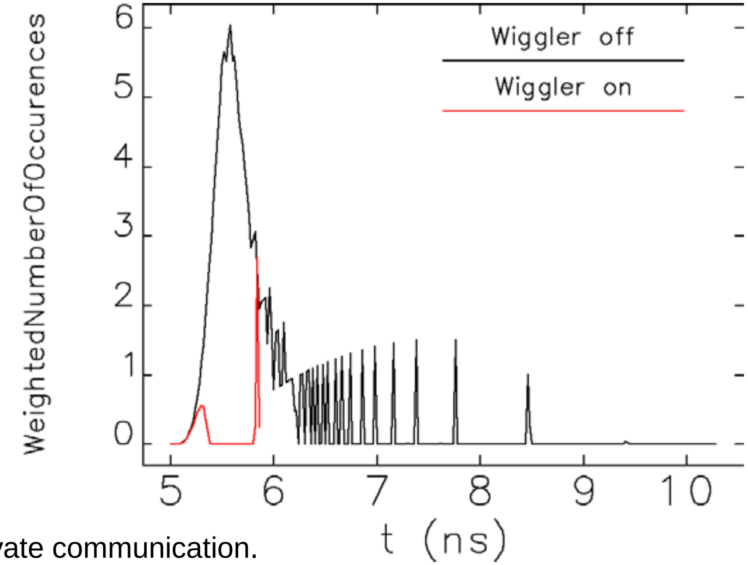


[1] M. Borland, Users Guide for spiffe, www.aps.anl.gov.

Back-bombardment mitigation cont.

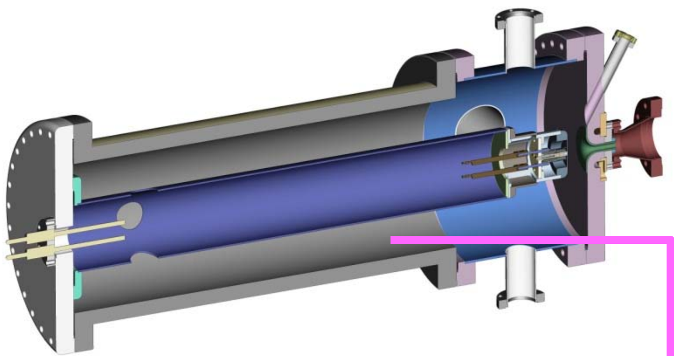
- BB was controlled on the original Stanford rf gun using a deflecting magnet around the gun[1]
- We made a very preliminary simulation
  - POISSON[2] used to design 3-pole wiggler inside the gun body
  - rfgun[3] used to perform beam tracking without space charge
  - BB power reduced 20-fold
  - Emittance and trajectory seem acceptable



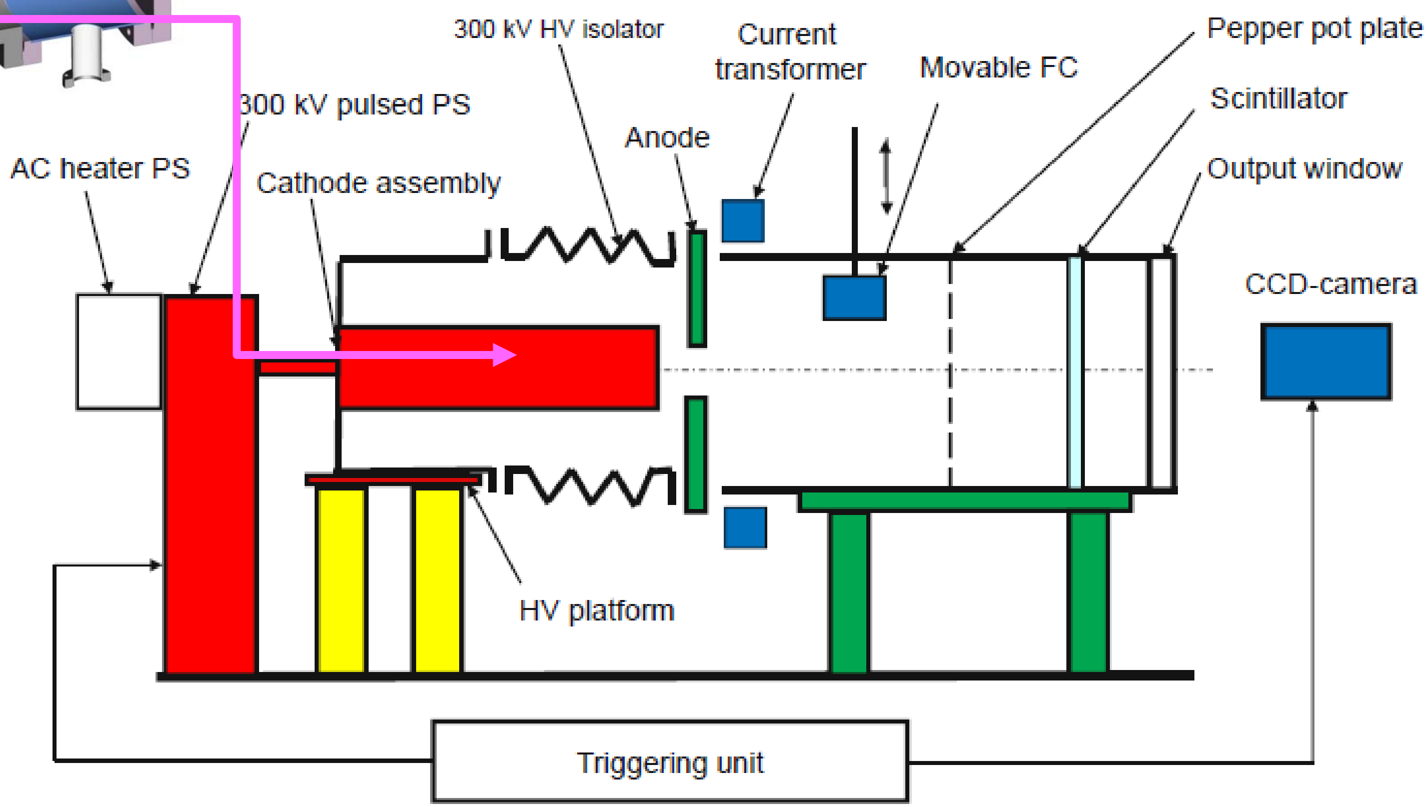


[1]J. Madey, private communication.
[2]R. Hollister *et al.*; LANL code group.
[3]M. Borland, unpublished program.

Pulsed DC Gun "test-bench" for cathodes concept



CeB_6 cathode, diameter 1 mm
300 kV pulsed DC voltage



Pulsed DC Gun cathode “test-bench” R&D

- Based on the Spring 8, 500 kV DC gun approach
- Measure the emittance of beams produced by various diameter CeB_6 cathodes
- Design of emittance measurement diagnostic (pepper pot, slits)
- Other measurements: cathode power, temperature, gun voltage/current pulses, electron beam current pulse

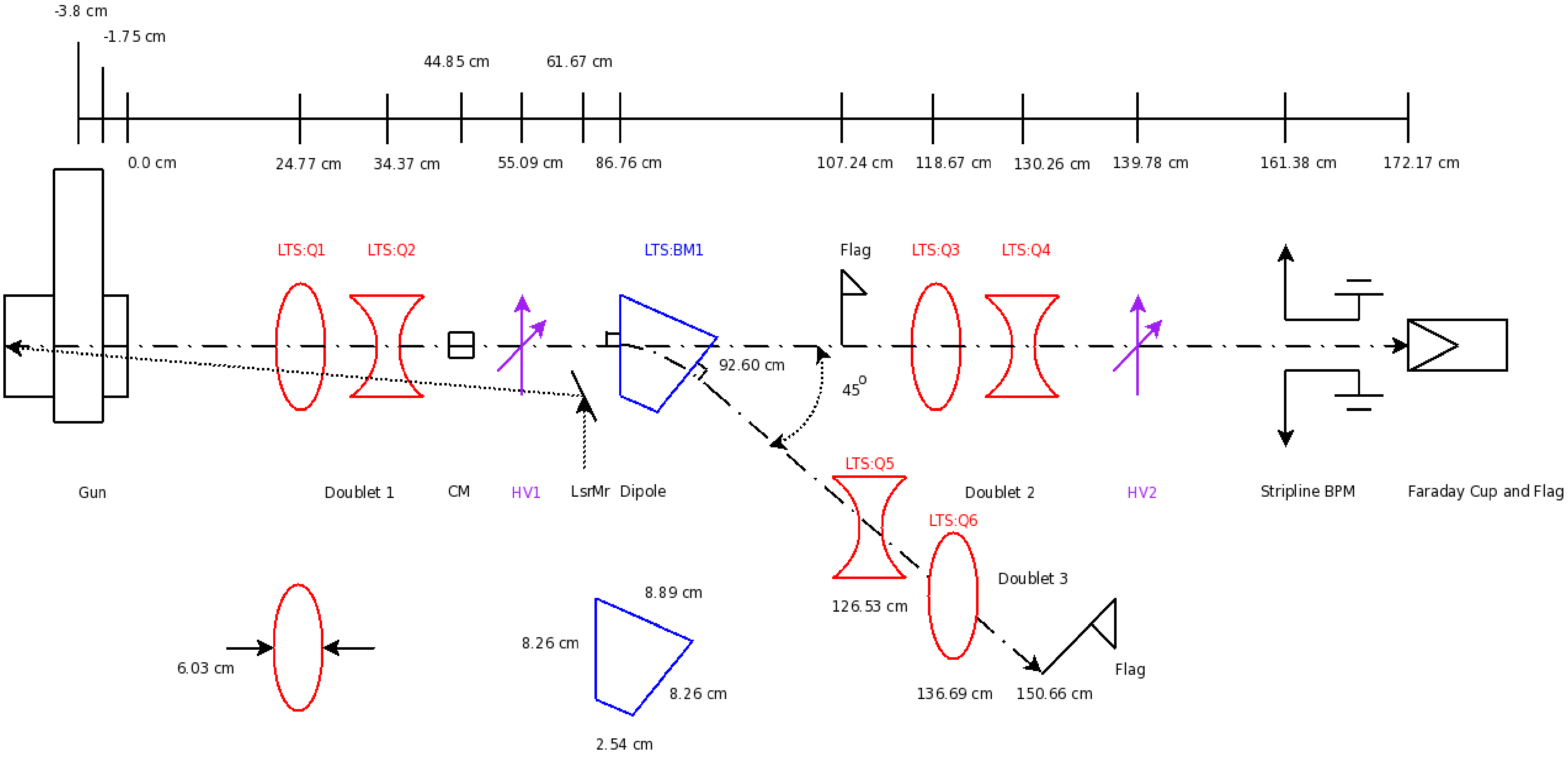
Parameter	Spring8 / RIKEN Achieved	ANL Design
Energy (keV)	500	300
Average Current (mA)	1000	80-100
Pulse Width (ms)	3	2
Rep Rate (Hz)	10	1-10
Normalized Emittance (90 %) mm-mrad	0.6	0.1
Cathode Diameter (mm)	3.0	0.5-3.0

Cathode laser gating experiment in the APS linac ITS[1] *and Simulation* ***(collaborators - K. Harkay, J. Dooling, Y. Li)***

- Use long ~5 ns IR laser to flash heat the tungsten cathode of an APS spare 1.5 cell S-Band thermionic gun (low rep rate 6 Hz)
- Using a linac stripline bpm, measure the resulting S-Band pulse envelope vs gun, cathode and laser parameters and answer:
  - How short a pulse can we get? (~1 ns to a few ns??)
  - What charge can we get at a given pulse length??
- Investigating thermal and mechanical properties of CeB_6 cathode illuminated by the laser via simulation
  - Large laser heat load on the cathode at 1 MHz (~kW)
  - Single pulse simulations indicate thermal diffusion is dominant (compared to radiation and electron cooling)
  - Looking into optimal laser pulse shape to get optimal temperature profile (electron emission for ~< 1 ns)
  - Extend these simulations to include multiple pulses at MHz rep rate
  - Use accurate material properties as a function of temperature and use realistic boundary conditions

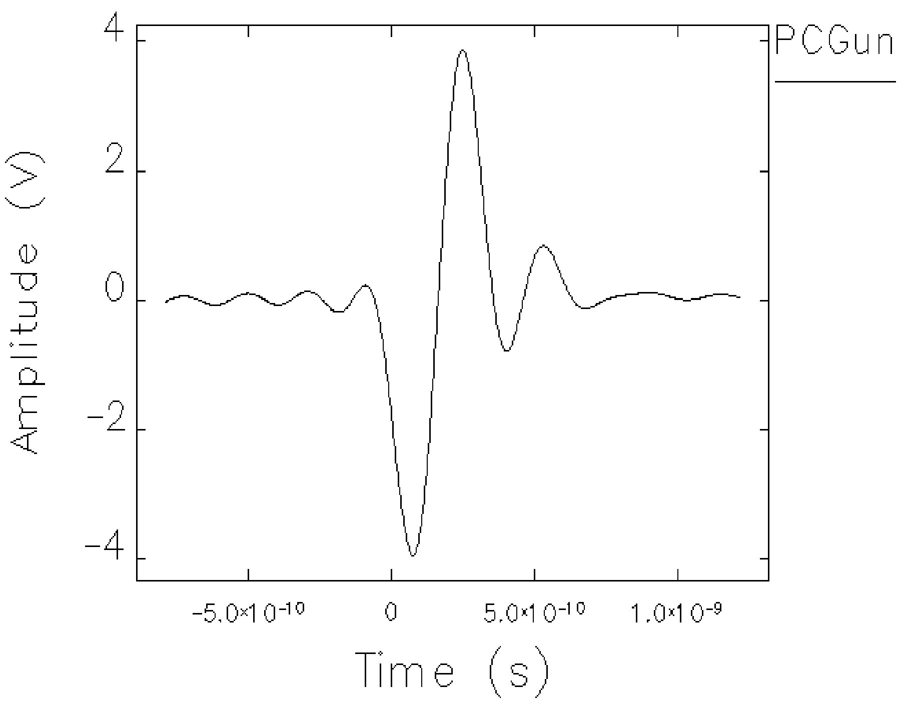
[1] J. Lewellen etal. PAC 2003

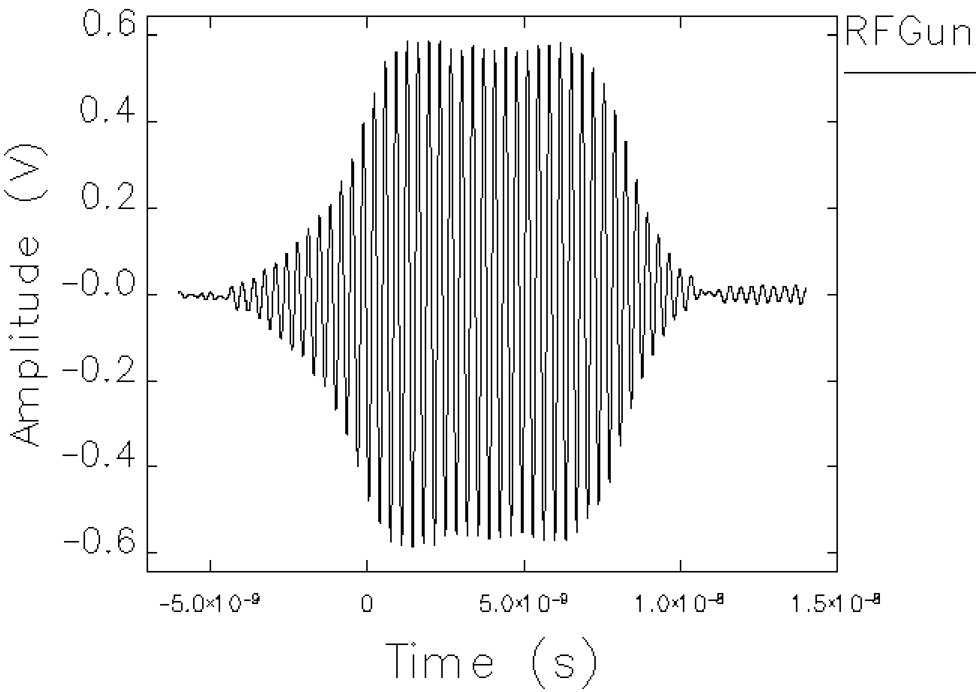
Cathode laser gating experiment in the APS linac ITS cont.



Cathode laser gating experiment in the APS linac ITS cont.

- Stripline response to PC Gun pulse (~2 ps) and rf gun pulse (~10 ns)



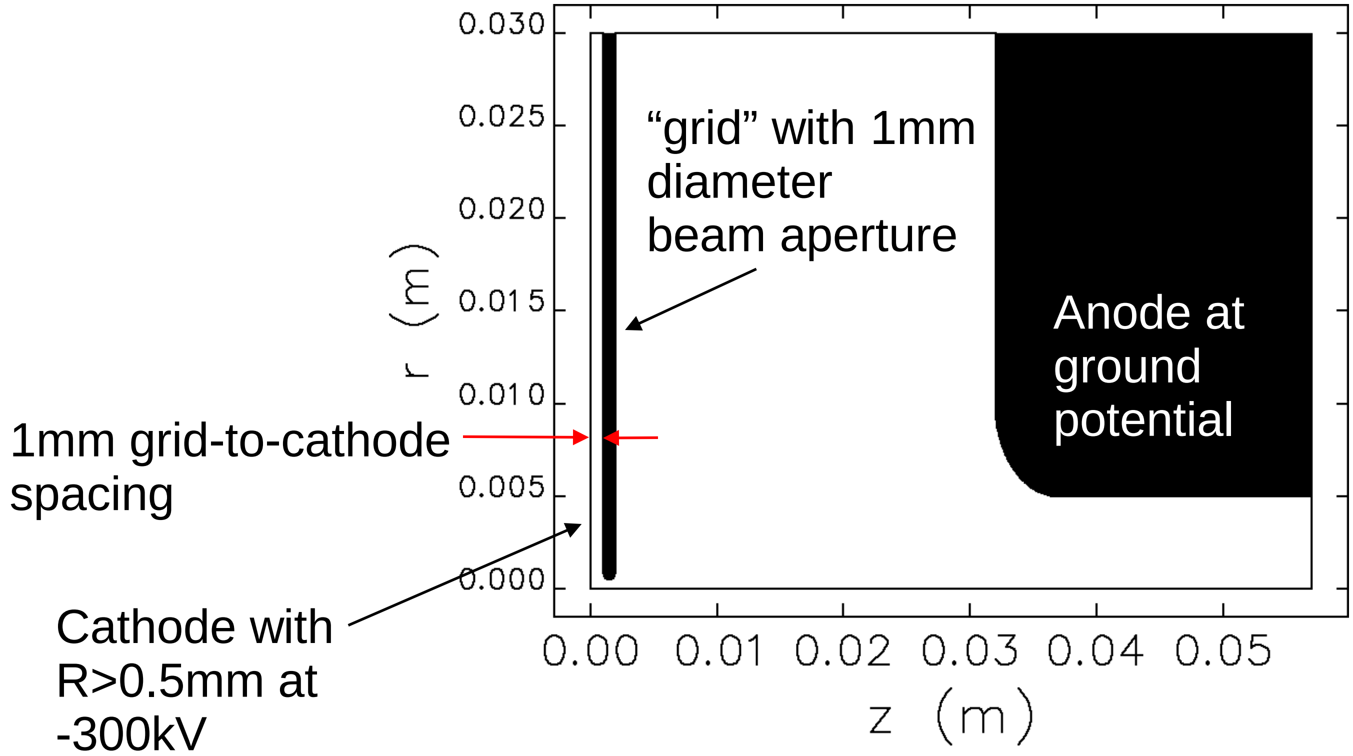


PC Gun pulse ~0.5 ns resolution

Linac RF Gun pulse ~15 ns

First look at 1 MHz 300 kV DC "triode" gun *(M. Borland)*

- T. Shintake proposed a pulsed triode gun for XFEL-O
- We put together a simple model of this idea

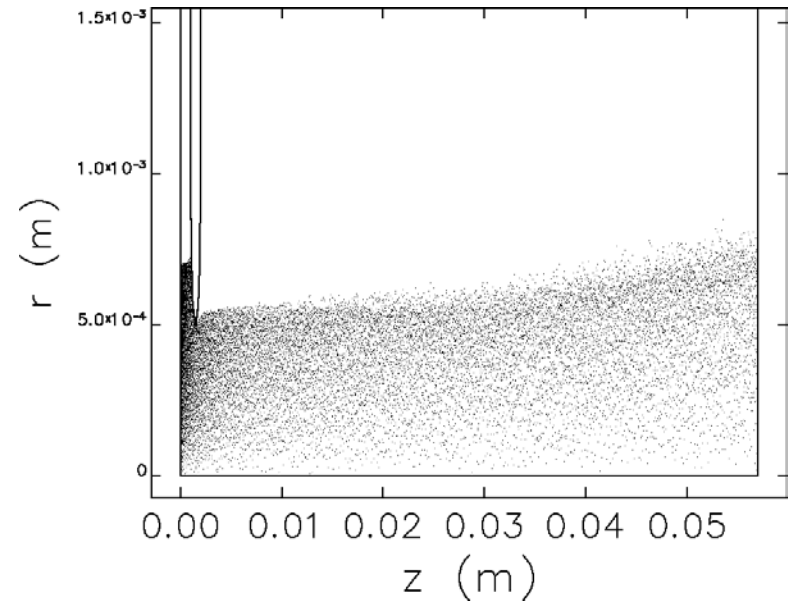


Grid is normally at cathode potential (-300kV) + small bias (-20V) to impede beam.

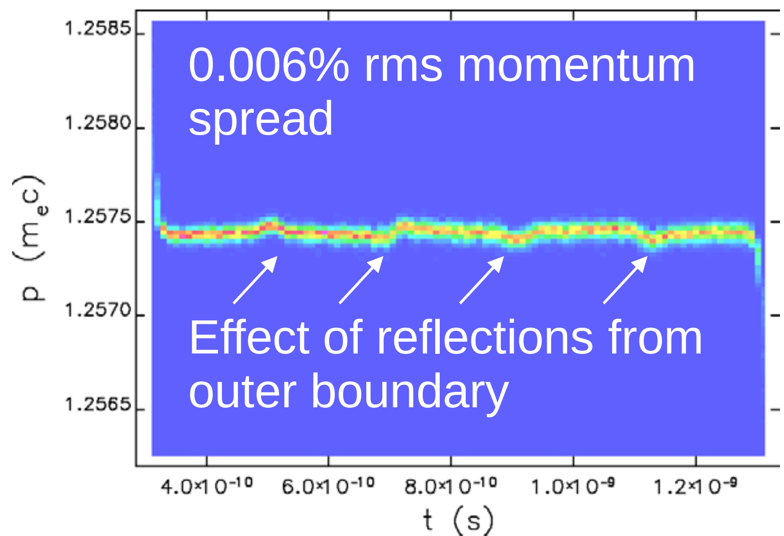
Pulsed to -290kV to allow beam to flow.

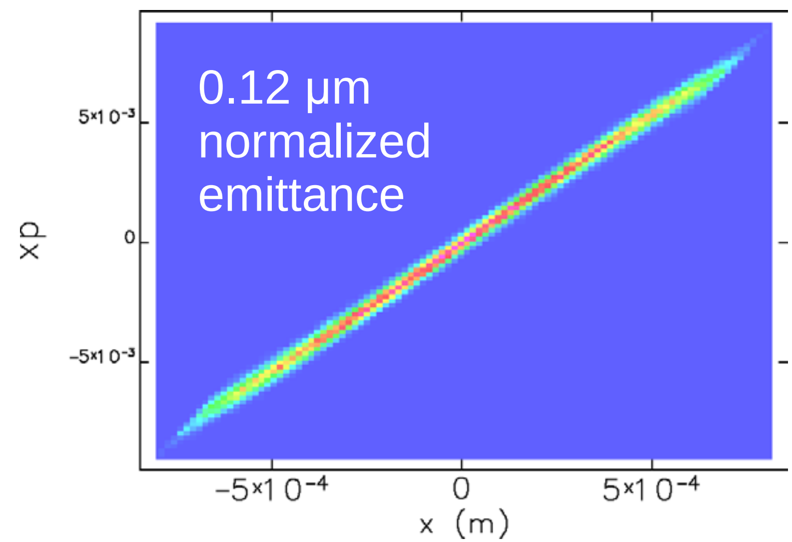
First look at 1 MHz 300 kV DC "triode" gun cont.

- Used SPIFFE[1]
- Modeled the gun with static potentials (not pulsed)
- 0.07 A current through iris for 1 ns gives a 70 pC pulse
- Included thermal velocity spread (1500 K)



[1]M. Borland, Users Guide for spiffe, www.aps.anl.gov.





Summary

- Completed baseline injector design for XFEL-O meeting required parameters
  - We continue design of 100 MHz, 1 MV rf gun using CeB_6 thermionic cathode (A. Nassiri's talk)
  - Requires energy filtering and rf gymnastics to produce the required longitudinal phase space since the gun pulse is quite long (~300 ps rms)
  - Need to continue S2E optimization and evaluation with errors
- R&D program
  - In the process of building a modulaor “Marx” generator for 300 kV DC gun cathode “test bench” to measure emittance of cathodes down to 0.5 mm diameter
  - Need to design emittance measurement system (slits, pepper pot)
  - Investigating IR laser gating of a cathode:
    - At low rep rate using our spare RF gun in the APS linac ITS
    - Via simulation for 1 MHz realization in the 100 MHz gun (both thermal and mechanical properties)
- Took a first look at a “triode” 300 kV DC gun and emittance growth looks tolerable