Novel Cathode plug development for Dark Current Mitigation in LCLS-II photo-injector

Tianhuan Luo (LBNL), Dave Dowell (SLAC),
With contributions from Feng Zhou, Theo Vecchione, Fuhao Ji, Zhen Zhang, Gowri Adhikari, Liling Xiao

Frontiers in Ultrafast Scattering of Electrons
SLAC, Aug 28th, 2025

LCLS-II Injector Gun

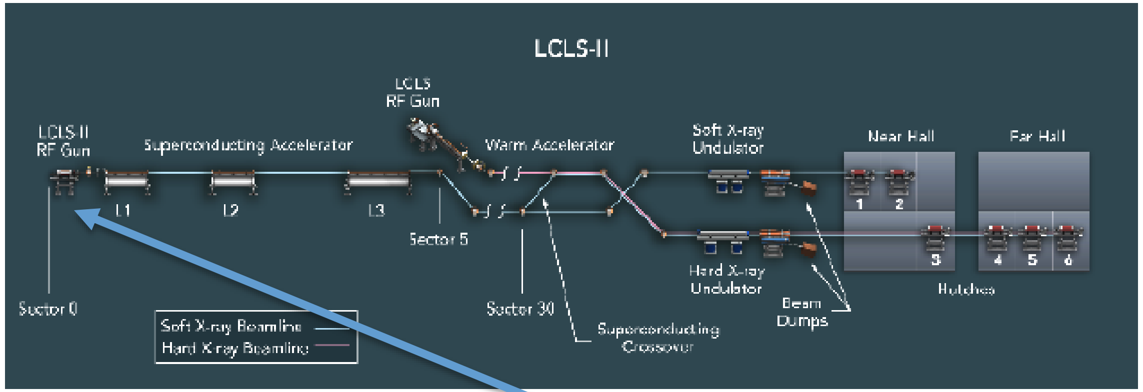
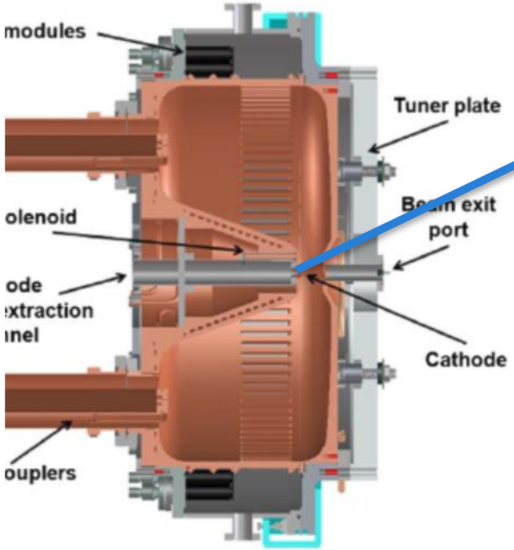
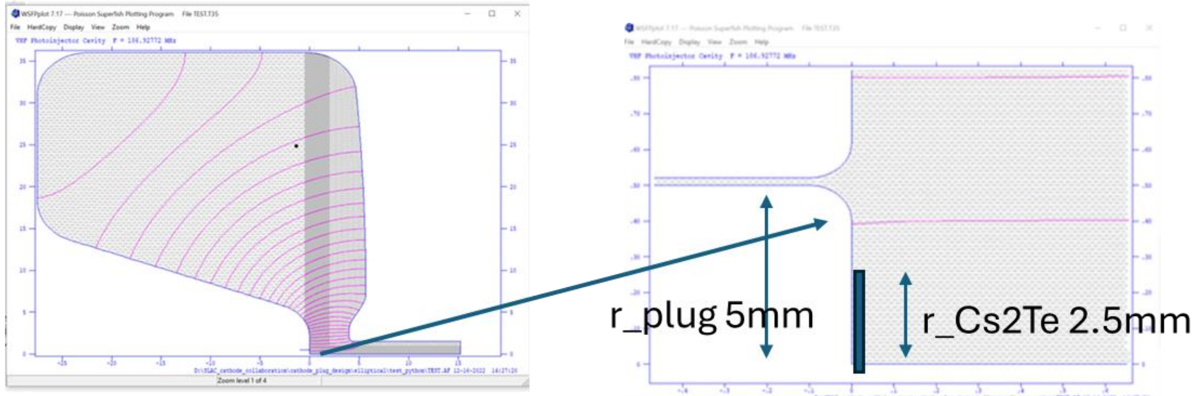


Figure 1: Schematic of the LCLS-II facility.

Frequency	187 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.47 MV/m
Q_0	30887
Shunt impedance	6.5 MΩ
RF Power	87.5 kW
Stored energy	2.3 J
Peak surface field	24.1 MV/m
Peak wall power density	25.0 W/cm²
Accelerating gap	4 cm
Diameter	69.4 cm
Total length	35.0 cm

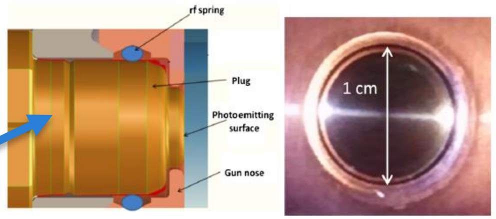


F. Sannibale et al., PRAB 15:103501 (2012)



2D SUPERFISH RF model

LCLS-II gun cathode



LCLS-II gun delivered by LBNL in early 2018, successfully commissioned at SLAC, and has been operating since then.

TABLE 1 LCLS-II gun and injector parameters.

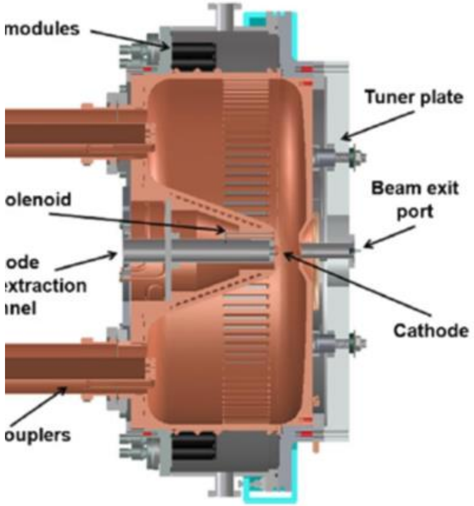
Parameters	Nominal
Gun energy (keV)	650–750
Gun gradient on the photocathode (MV/m)	17.5–19.5
Cs_2Te photocathode QE (%)	>0.5
Drive laser pulse: Gaussian shape, FWHM (ps)	15–20
Maximum bunch repetition rate (MHz)	0.93
Bunch charge (pC)	20–100
Maximum average beam current (μA)	30
Injector final energy (MeV)	>90
Normalized emittance (μm, rms) @ 50–100 pC	<0.5
RMS bunch length (mm)	<1

F. Zhou et al., Front. Phys. 11:1150809

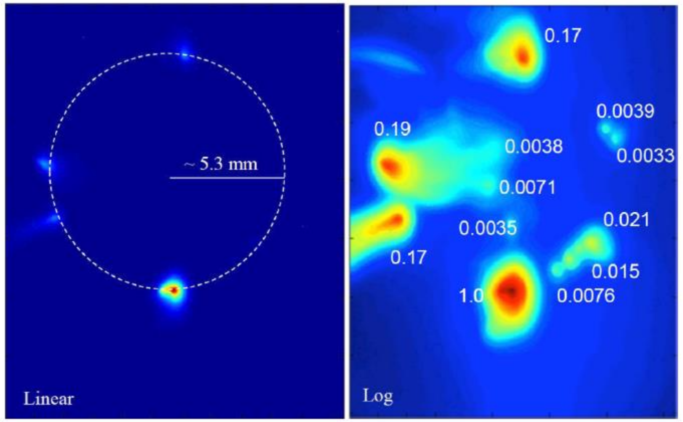
The dark current challenge for the electron source for the high-rep-rate FEL

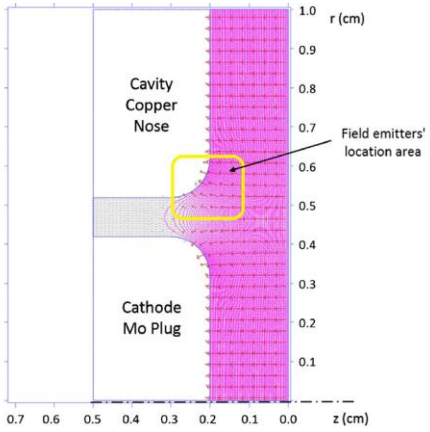
- Dark current: electrons generated by the field emission, accelerated and transmitted to the downstream beamline at a proper RF phase.
- A major challenge for the high-repetition-rate FEL facility, leading to SRF cryomodules heating, beam radiation damage, undulator magnet degradation, etc. LCLS-II injector requires dark current < 400nA.
- Dark current mitigation:
  - Lower the surface E field, but may compromise the beam emittance.
  - Smoother surface finishing: polishing and dry-ice cleaning but too invasive for an operating source. (and the dark current usually returns!)
  - RF conditioning, but results can be mixed and potentially produce more emitters.
  - Collimator, kicker, chicane, but can affect the photobeam as well. Need to dump dc before CM01 to reduce dc beam power and energy below neutron threshold.

The dark current in APEX gun

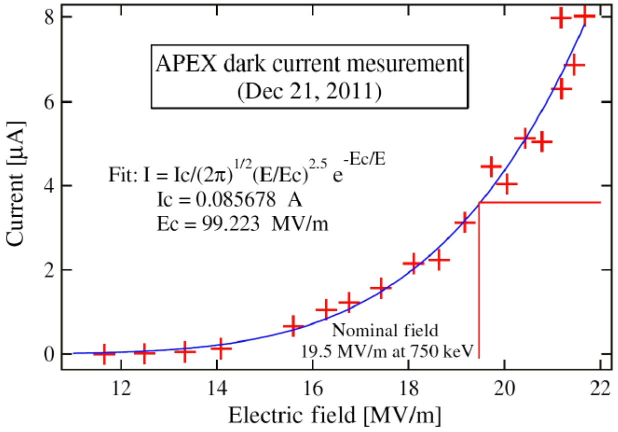


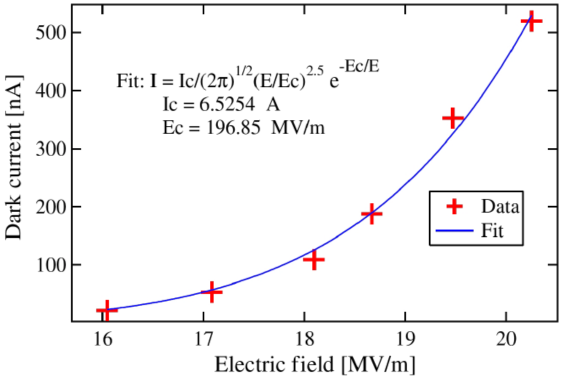
An elder sister of LCLS-II gun, commissioned and operated at LBNL since 2011.





The strongest emitters are located on the cavity nosecone, outside the cathode plug.



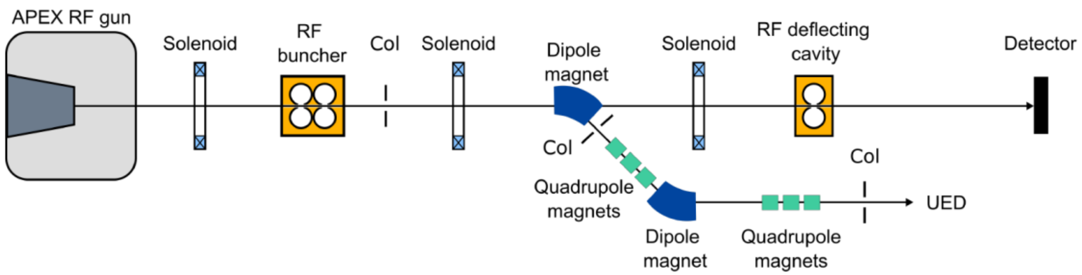


The gun was opened up in late 2014 for cleaning after a vacuum incident due to a cracked RF window.
After the mirror-polishing and dry ice cleaning of the cavity wall, the dark current was reduced from 350 to 0.1 nA.

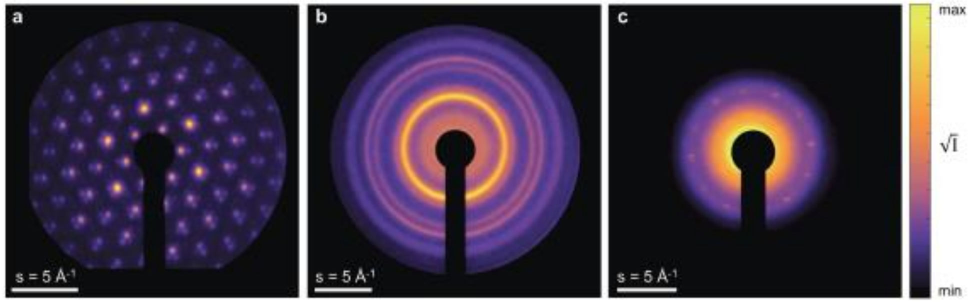
R. Huang et al, PRAB 18, 013401 (2015)

APEX gun serves as the electron source for the High Repetition-rate Electron Scattering (HiRES) UED instrument at LBNL

HiRES beamline layout



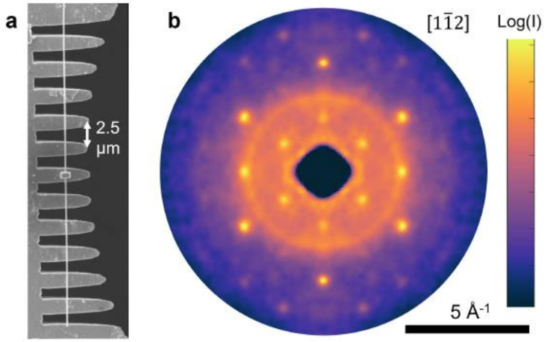
- UED experiment beamline + diagnostics beamline
- Dark current is removed by two collimators and "filtered" by the magnetic focusing system.



Static electron diffraction patterns of (a) TaS2 [001], (b) polycrystalline gold, and (c) bicrystal graphene measured at HiRES using a repetition rate of 250 kHz.

Electron beam parameters

Parameter	Value
Beam energy	750 keV nominal
Bunch charge	1 - 10^8 electrons per pulse
Bunch length*	100 - 10000 fs RMS
Beam emittance*	0.1 - 100 nm
Repetition rate	single shot → 62 MHz



UED pattern from an individual VO_2 nanowire at HiRES. (a) SEM image of the prepared sample on a fabricated Cu microcomb support. (b) Symmetrized diffraction pattern from the monoclinic [112] zone axis.

Laser parameters

Main Laser	
Parameter	**Value**
Central wavelength	1030 nm
Pulse energy	≤100 μJ
Pulse duration	≈ 315 fs FWHM
Repetition rate	single shot → 250 kHz
Beam spot size	250 - 1100 μm FWHM
Accessible fluence range	0.1 - 300 mJ cm^{-2}
OPCPA	
Parameter	**Value**
Central wavelength	800 nm
Pulse energy	≈ 10% of laser input
Pulse duration	≈ 10 fs

- **K. M. Siddiqui, D. Filippetto, et al.;** Relativistic ultrafast electron diffraction at high repetition rates. *Struct. Dyn.* 1 November 2023; 10 (6): 064302.
- **W. Liu et. al.;** An overview of R&D activities at HiRES to advance MeV-UED instruments, poster presentation at this workshop.

The dark current in LCLS-II gun

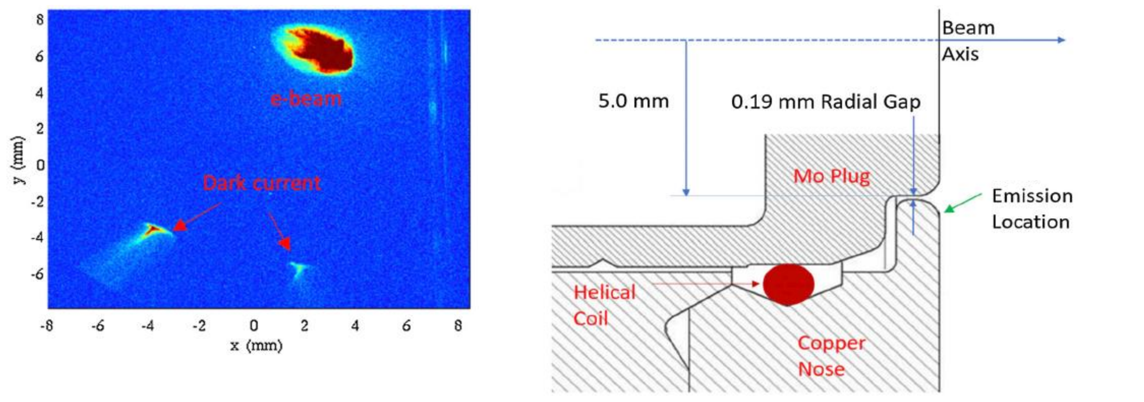


FIG. 12. Left: YAG screen image of a laser-generated electron beam and dark current. Right: geometry of the molybdenum cathode plug when inserted into the copper cathode nose.

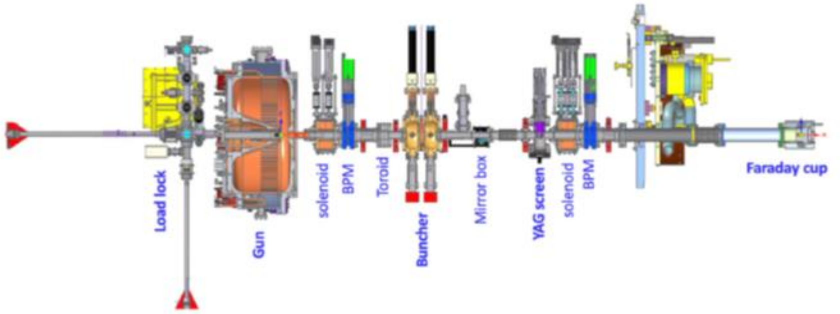


FIG. 1. Schematic of the LCLS-II electron source.

When E_cathode* = 20.0 MV/m, E_max = 24.6 MV/m @ copper nose corner, max E on Mo plug ~24.1 MV/m @ round corner.

F. Zhou et al. PRAB, 24, 073401 (2021)

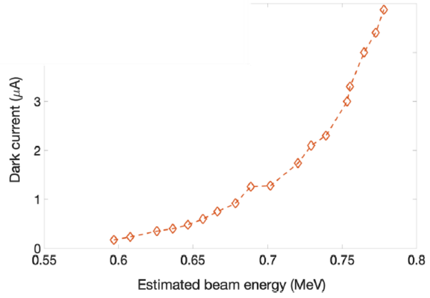
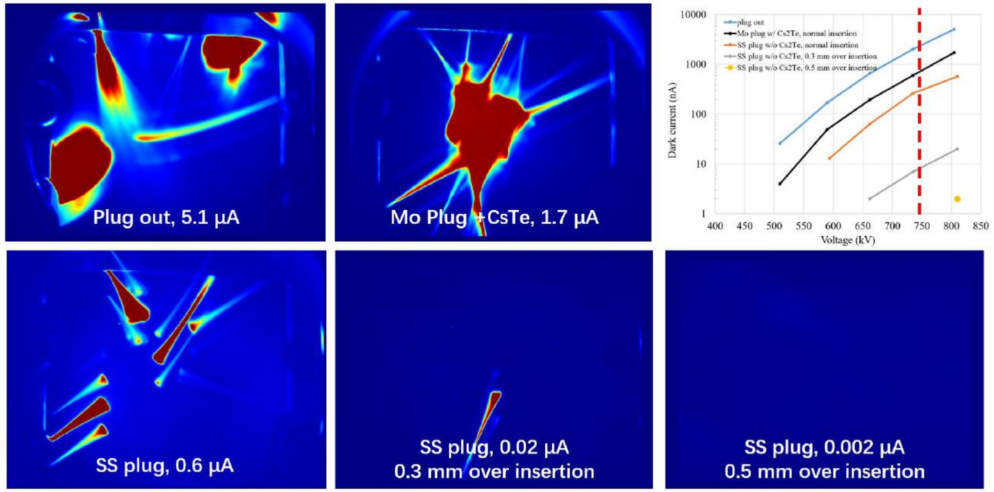


FIG. 13. Measured dark current versus beam energy.

- During the injector commissioning, the dark current gradually grew from 10nA to the μA level.
- The gun voltage was reduced to 650 kV and the dark current was ~3.5 μA.
- Field emission sites are from the rounded opening on the copper cathode nose.
- A collimator was installed in the low energy beamline (<1MeV) and removed ~ 90% dark current.
- Compromising the XFEL performance: 1) lower the gun voltage from 750kV to 650kV; 2) limit the tuning range of the solenoid thus the optimization of the e-beam properties.

Dark current mitigation by over-inserted cathode plugs at SHINE

▪ **Cathode plug insertion impacts on dark current @810kV, 28MV/m, 1%DF**



SHINE

H. Qian, FEL24, Aug 2024

- The SHINE result strongly boosted the confidence of testing an over-inserted cathode plug at LCLS-II.
- The high E field gradient demonstrated by SHINE retires a major concern of RF breakdown for an over-inserted plug.

- SHINE first reported their dark current reduction results by cathode plug insertion at FEL24.
- With a SS plug of 0.5mm over insertion, the dark current was dropped from 1.7 uA to 2 nA.
- Before modifying the SHINE cathode, comprehensive testing has been carried out in a R&D ZJLAB/SARI VHF gun, demonstrating the drastic dark current reduction by the over-inserted plug.

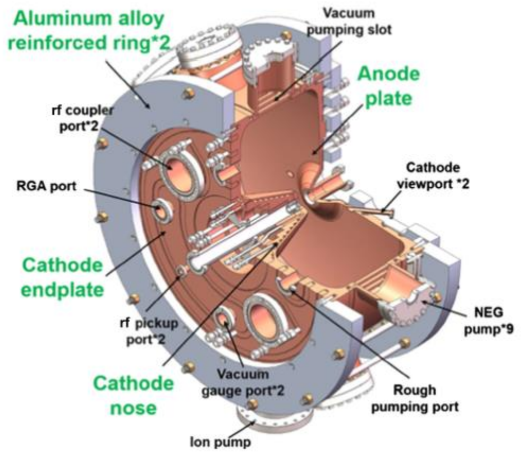


FIG. 1. Mechanical layout of ZJLAB/SARI VHF gun.

TABLE I. Main rf parameters of SHINE and ZJLAB/SARI VHF guns.

Parameter	SHINE gun	ZJLAB/SARI gun
Frequency (MHz)	216.667	
Accelerating gap (mm)	30	40
Unloaded quality factor (Q_0)	33,717	32,426
Power coupling factor	1.0	
Shunt impedance (MΩ)	8.34	7.89
Cathode gradient (MV/m)	26	19.8
Cavity voltage (kV)	750	750
RF power (kW)	68	72
Peak surface (MV/m)	32.0	22.6
Maximum surface loss density (W/cm^2)	21.3	24.5

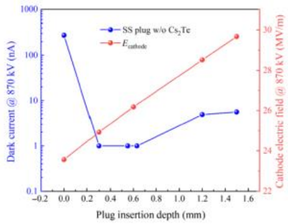
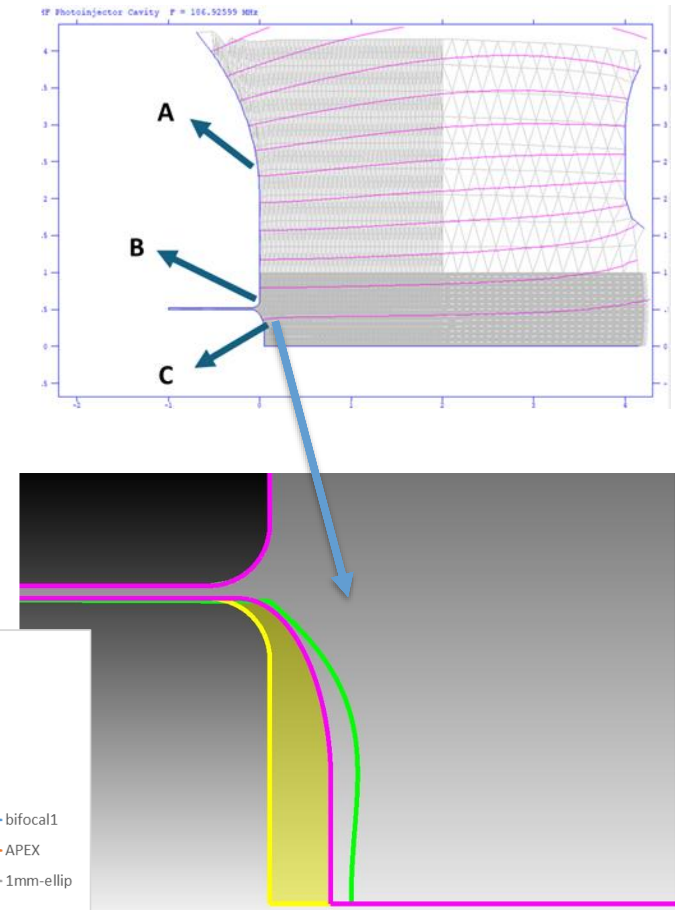


FIG. 15. Dark current measurements (blue dots) and cathode electric field values (red dots) as a function of plug insertion depth at a gun voltage of 870 kV.

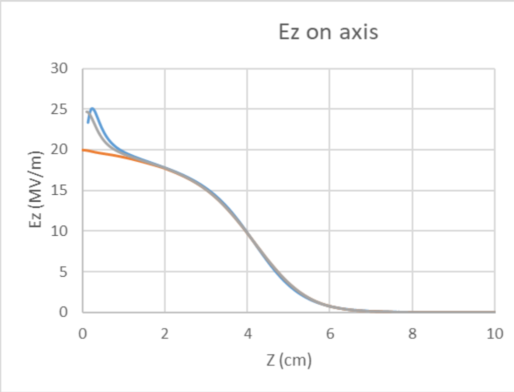
X. Wang et al. PRAB 28, 043401 (2025)

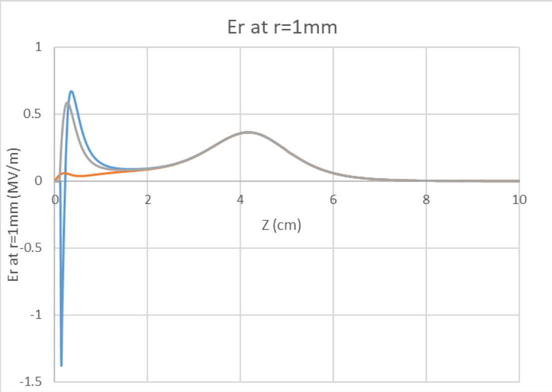
Three cathode plugs have been tested in LCLS-II gun: APEX,1mm-elliptical, and bifocal01

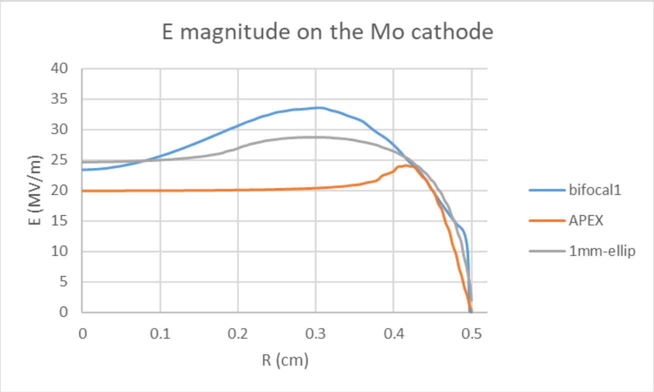
Cathode plug type	APEX	1mm-ellip	bifocal_1
E_cathode (MV/m)	20.0	24.7	23.5
E_max on Cu (MV/m) @ A	24.5	24.5	24.6
E_max on Cu (MV/m) @ B	23.5	19.9	18.0
E_max on Mo (MV/m)@ C	24.1	28.8	33.6
f (MHz)	186.928	186.922	186.880
P (kW)	77.5	77.5	77.6
V (kV) no transient time factor	760	760	760
Cathode center insertion(mm)	0	1	1.33



Plug profiles: Yellow: APEX; Magenta: 1mm-ellip; Green: bifocal_1

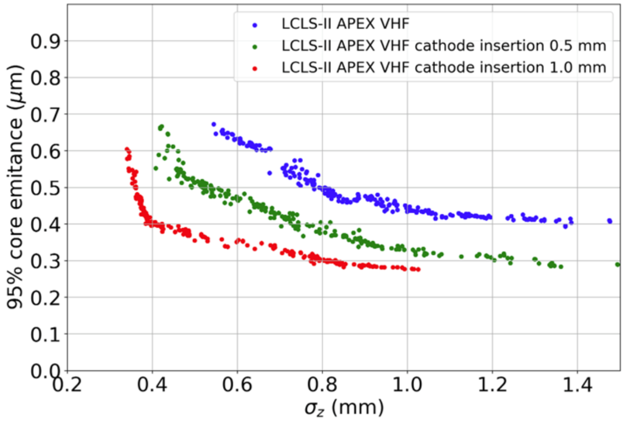




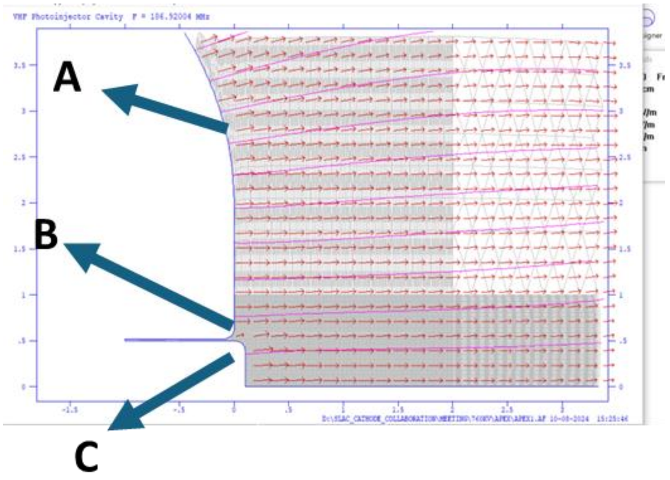


The potential benefits and risks with an over-inserted cathode plug

- Increase the E field at the cathode center E_cathode: emittance
- Increase the maximum E field on the Mo cathode plug @ C: dark current, RF breakdown
  - SHINE testing up to 0.5mm insertion with a 3cm accelerating gap greatly reduce this risk.
- Decrease the E field on the copper nosecone @ B: dark current
- Increase the off-center transverse field near the cathode and the corresponding defocusing effect: emittance, dark current
- Very small effects on the gun resonant frequency and shunt impedance: gun operation
- Comprehensive risk analysis and mitigation planning have been carried out before testing the plugs in the LCLS-II injector gun.



Emittance simulation, by Fuhao Ji

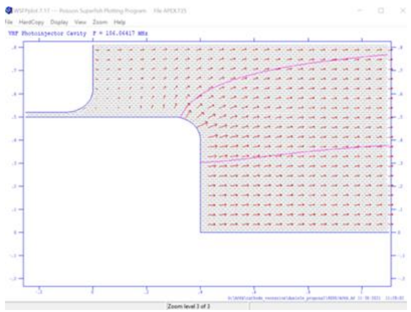


Elliptical cathode plug design

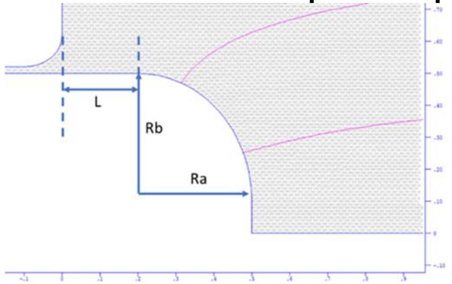
Lowering E field on cathode plug by an elliptical corner

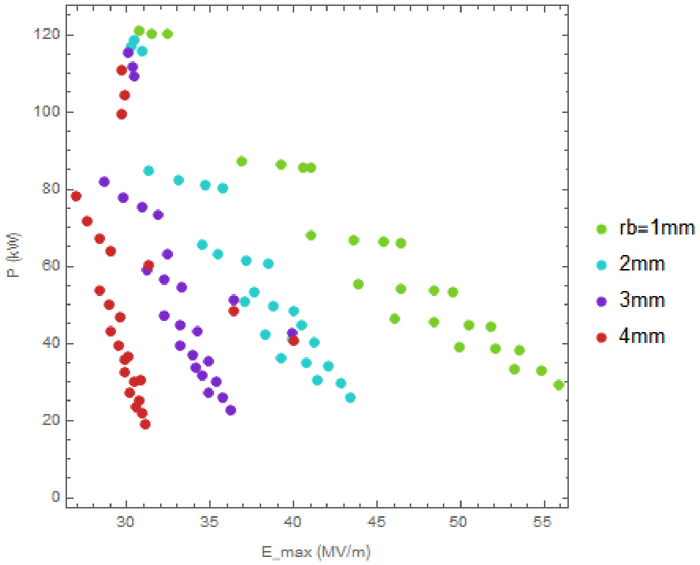
- The elliptical over-inserted plug was originally designed for the cathode testing project for Low-Emittance-Injector, to achieve an E_cathode of +25MV/m in APEX gun at LBL.
- Over-insertion can efficiently increase E_cathode, but E_max at the plug corner increases even faster.
- Changing the plug corner from round r=1mm to upright elliptical shape significantly lower the local E field.
- Comprehensive parameter scan to find the best elliptical profile.

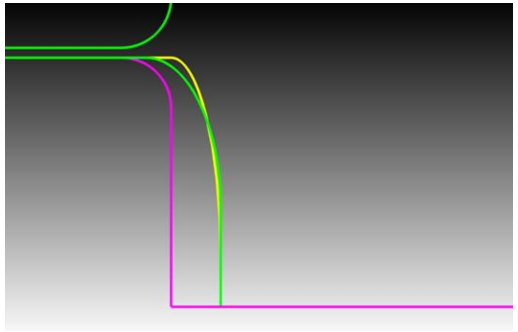
Over-inserted APEX plug



Over-inserted elliptical plug



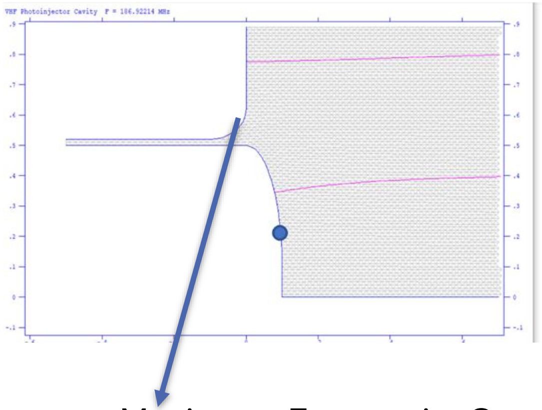




	APEX	Config1	Config3
E_cathode (MV/m)	20	25	25
P (kW)	77.4	78.1	79.5
V (kV)	761	765	772
E_max (MV/m)	24.1	27.0	29.2
PD_max (W/cm^2)	23.6	23.8	24.2
df (kHz)	0	6	6
R_flat (mm)	4	1	2

The over-inserted plug also reduces the E_max on the copper nose cone

A plug design for E_cathode = 25MV/m



E_max = 27.0 MV/m @blue dot

V=765 kV

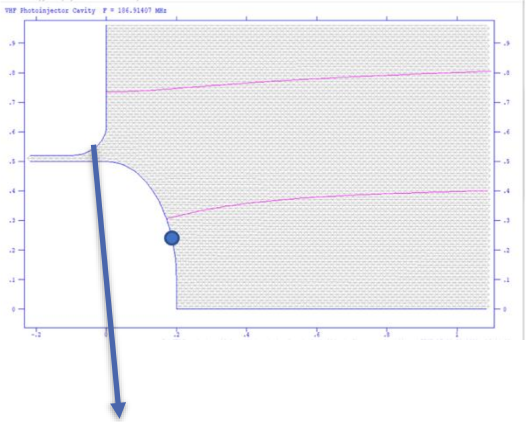
P=78.1 kW

PD_max=23.8 W/cm^2

df = 6 kHz

Maximum E on cavity Cu surface ~ 24.7 MV/m

A plug design for E_cathode = 30MV/m



E_max = 34.0 MV/m @blue dot

V=763 kV

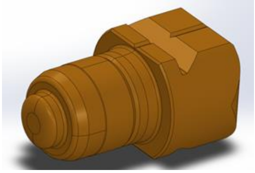
P=77.6 kW

PD_max=23.6 W/cm^2

df = 14 kHz

Maximum E on cavity Cu surface ~ 24.6 MV/m

- The over-inserted plug produce a bonus **"shielding effect"** for the E_max on the copper nose cone, where the LCLS-II gun and APEX gun dark current emits. The further the insertion, the more the E field reduction on the copper nose cone.
- Proposed to test an over-inserted cathode to mitigate LCLS-II injector dark current.
- Elliptical plug designed by LBL, manufactured at SLAC leveraging plug production capacities for LCLS-II injector.

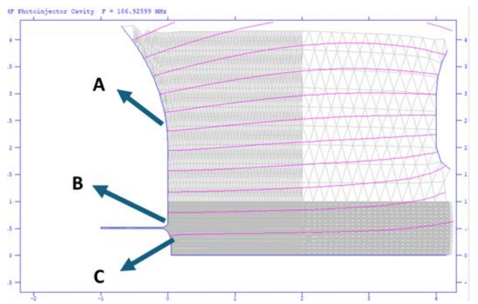


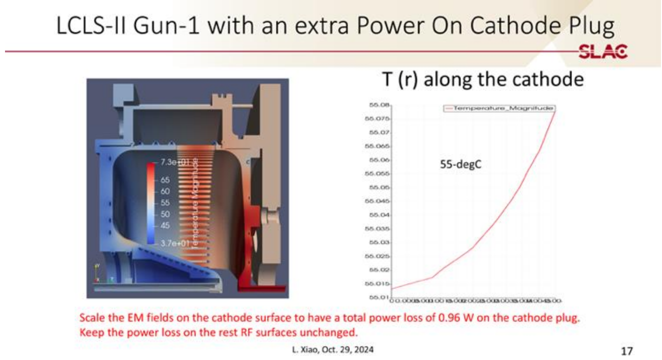
CAD model

SLAC production

Designing an over-inserted elliptical cathode plug for LCLS-II injector

Insertion (mm)	0 (original)	0.5	1	1.5
E_cathode (MV/m)	20.0	22.4	24.7	26.5
E_max on Cu (MV/m) @ A	24.5	24.5	24.5	24.5
E_max on Cu (MV/m) @ B	23.5	21.9	19.9	16.7
E_max on Mo (MV/m)@ C	24.1	24.8	28.8	31.7
f (MHz)	186.928	186.926	186.922	186.917
P (kW)	77.5	77.5	77.5	77.5
V (kV) no transient time factor	760	760	760	760





Plug thermal simulation, by L. Xiao

- Three insertion depths were considered 0.5mm, 1mm and 1.5mm.
- Design goals: sufficient reduction of E_nosecone, E_cathode contained in the safe range.
- No compromise of beam emittance. Least intrusive to gun operation, with minimum impact on resonant frequency, RF power, plug temperature, etc.
- Choosing the 1mm over-insertion plug as a good balance between the benefits and risks.

Bifocal cathode plug design

Bifocal cathode plug design

The new plug designs utilize two effects which reduce the dark current:

- **The “shielding effect”** :
  - The further the insertion, the greater the E field reduction on the copper nose cone.

- **Defocusing the dark current:**
  - The plug is shaped to defocus the dark current and dump it along the beampipe

In the bifocal design, dark current from the plug-nosecone region is more strongly suppressed and deflected compared to the elliptical plug

Bifocal cathode plug design philosophy

- shape the outer part of the plug to radially deflect/defocus the dark current
- shape the inner region to have a high cathode field and to gently focus the photobeam
- therefore, the surface should have a convex curvature near the edge and be concave at the center

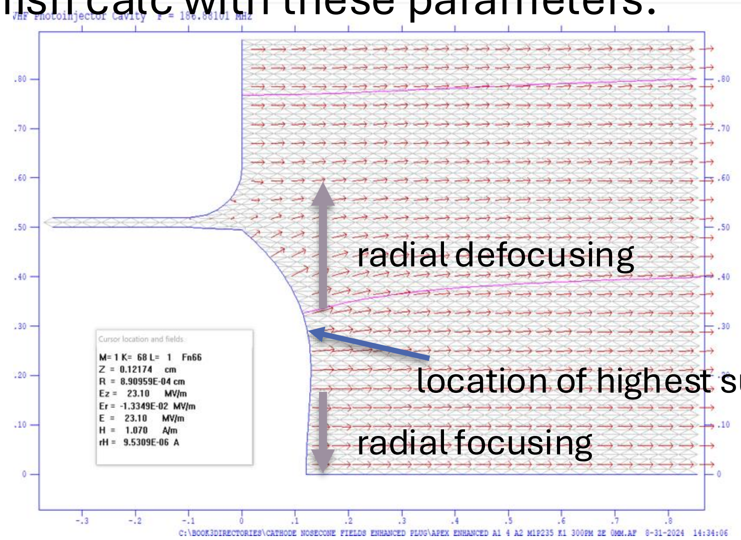
These conditions can be achieved using the following radial function for the plug surface

$$\Delta z(r) = a_1 \cos(k_1 r) + a_2 \cos(2k_1 r) - z_{off}$$

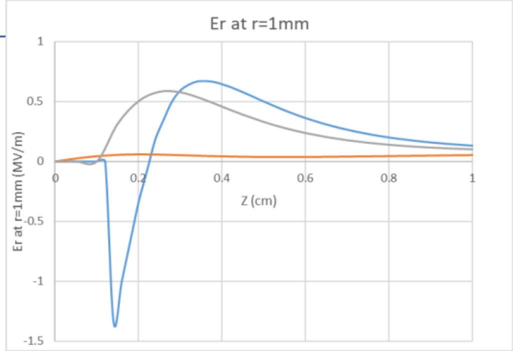
A trial-and-error search meeting these requirements gives (in superfish coordinates)

$$a_1 = 4mm, \qquad a_2 = -1.235mm, \qquad k_1 = \frac{0.3}{mm}, \quad z_{off} = 1.559627mm$$

Superfish calc with these parameters:



- peak field at cathode center=23MV/m
- highest surface field=31.5MV/m at r=2.81mm
- z-extent of negative radial focusing, Er<0, from the cathode surface=0.94mm

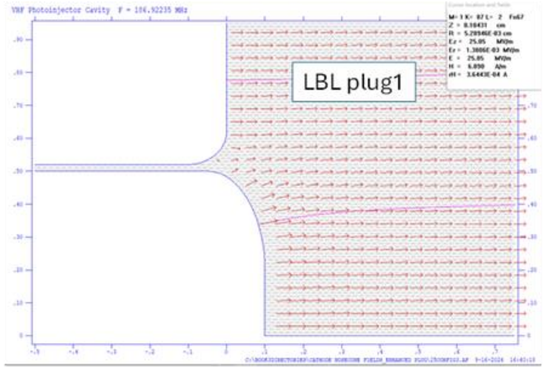


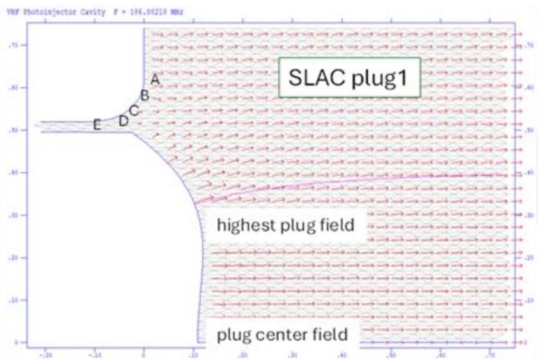
Fowler-Nordheim prediction of the reduction in dark current for the three plug designs, verified by measurements

The dark current by FN:

$$J_{FN} = A_e 1.54 \times 10^{-6} \frac{(\beta F)^2}{\varphi} exp\left(-6.83 \times 10^7 \frac{\varphi^{\frac{3}{2}}}{\beta F} + \frac{9.81}{\sqrt{\varphi}}\right)$$

φ is the work function in eV, F is the applied field in V/cm, the emitter area is A_e, β the field enhancement.





$$\frac{j(F_2)}{j(F_1)} = \left(\frac{F_2}{F_1}\right)^2 exp\left(-6.83 \times 10^7 \frac{\varphi^{3/2}}{\beta}\left(\frac{1}{F_2} - \frac{1}{F_1}\right)\right)$$

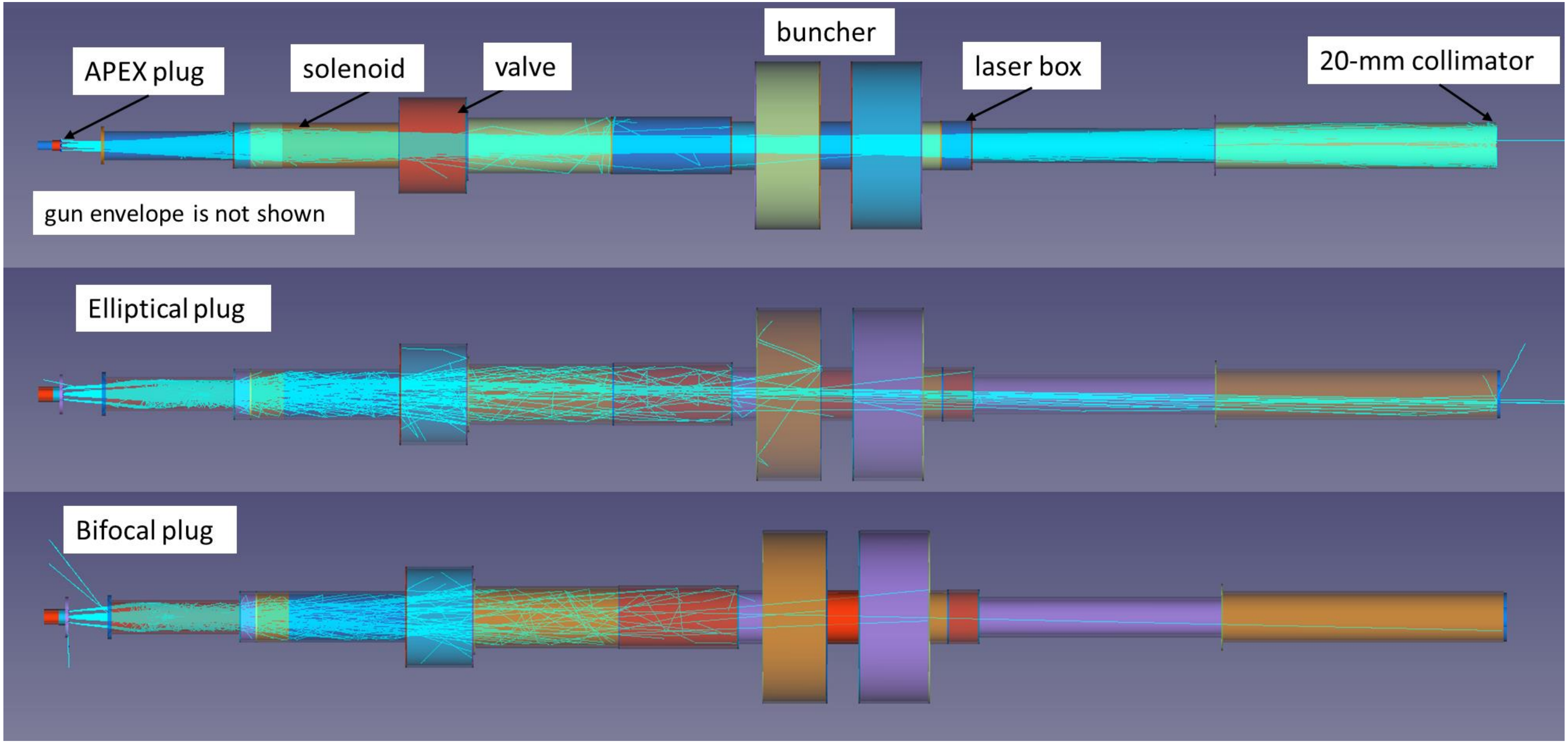
φ =4.6 eV for copper

β estimated from measured LCLS-II gun dark current.

Location	Field enhancement factor,β 3uA/4 per emitter	nominal/APEX field (MV/m)	Elliptical plug field (MV/m)	Elliptical plug reduction in emission wrt APEX	Bifocal plug field (MV/m)	Bifocal plug reduction in emission wrt APEX
A, r=6.1mm	135	23.71	19.68	108	17.61	2.66E+03
B, r=5.68mm	171	18.75	13.77	3.71E+03	11.56	1.25E+06
C, r=5.45mm	290	11.02	6.17	5.00E+07	4.36	6.20E+14
D, r=5.29mm	892	3.59	1.84	1.90E+09	0.79	5.10E+33
highest plug field	-	24.3	29.04	-	32.78	-
center plug field	-	19.97	25.05	-	23.21	-

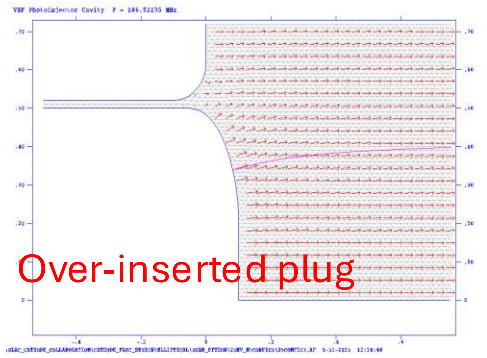
The field emission strongly depends on the surface field along the nosecone. The analytical estimation gives 2 to 3 orders of magnitude dark current reduction in field emission from the nosecone.

Dark current trajectories for the three plug shapes (without FN suppression)
The stronger radial defocus of the bifocal plug dumps essentially all the dark current before the buncher

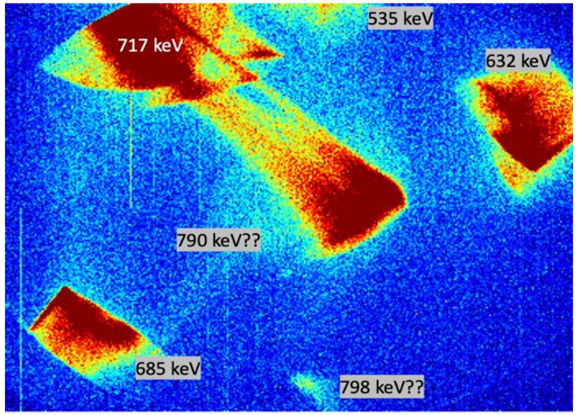


Experimental verification of the dark current reduction with over-inserted plugs

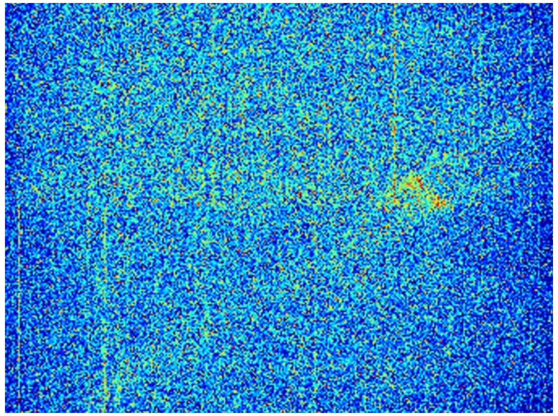
- Measurements shows the dark current is reduced by 500 times and field emitters imaged on the YAG screen are barely seen!
- For both the over-inserted elliptical and bifocal plugs:
  - Significant drop of the radiation level recorded by the radiation monitor.
  - Evolution of quantum efficiency unchanged.
  - Good beam emittance, improving solenoid tunability.
  - No interruption to user program, good example of performing beneficial R&D without interrupting user operations.

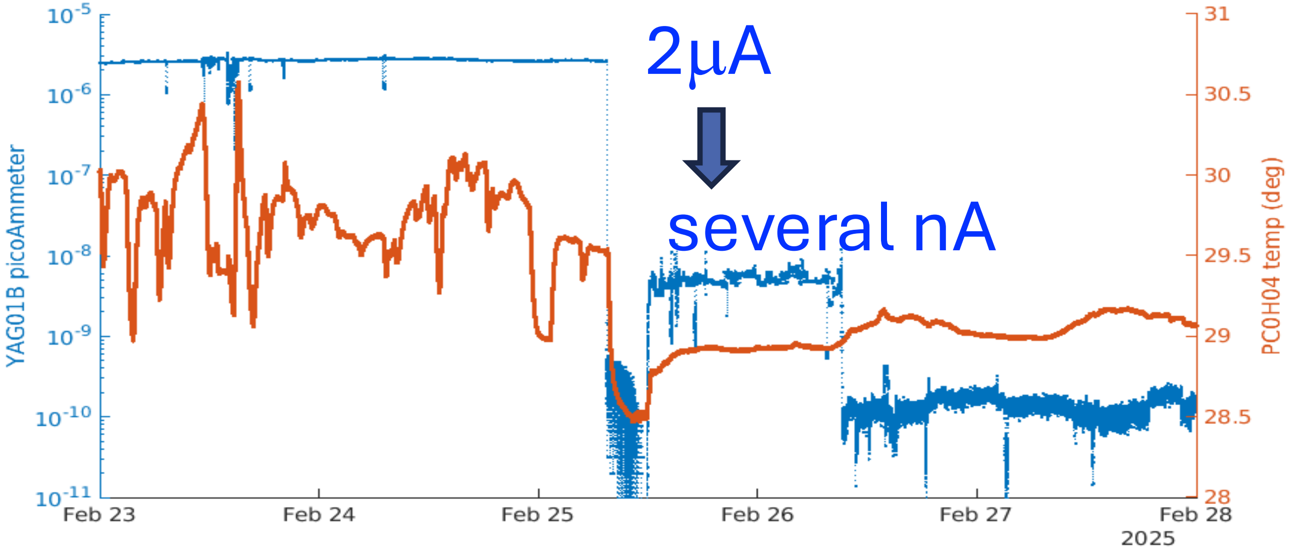


w/ APEX plug

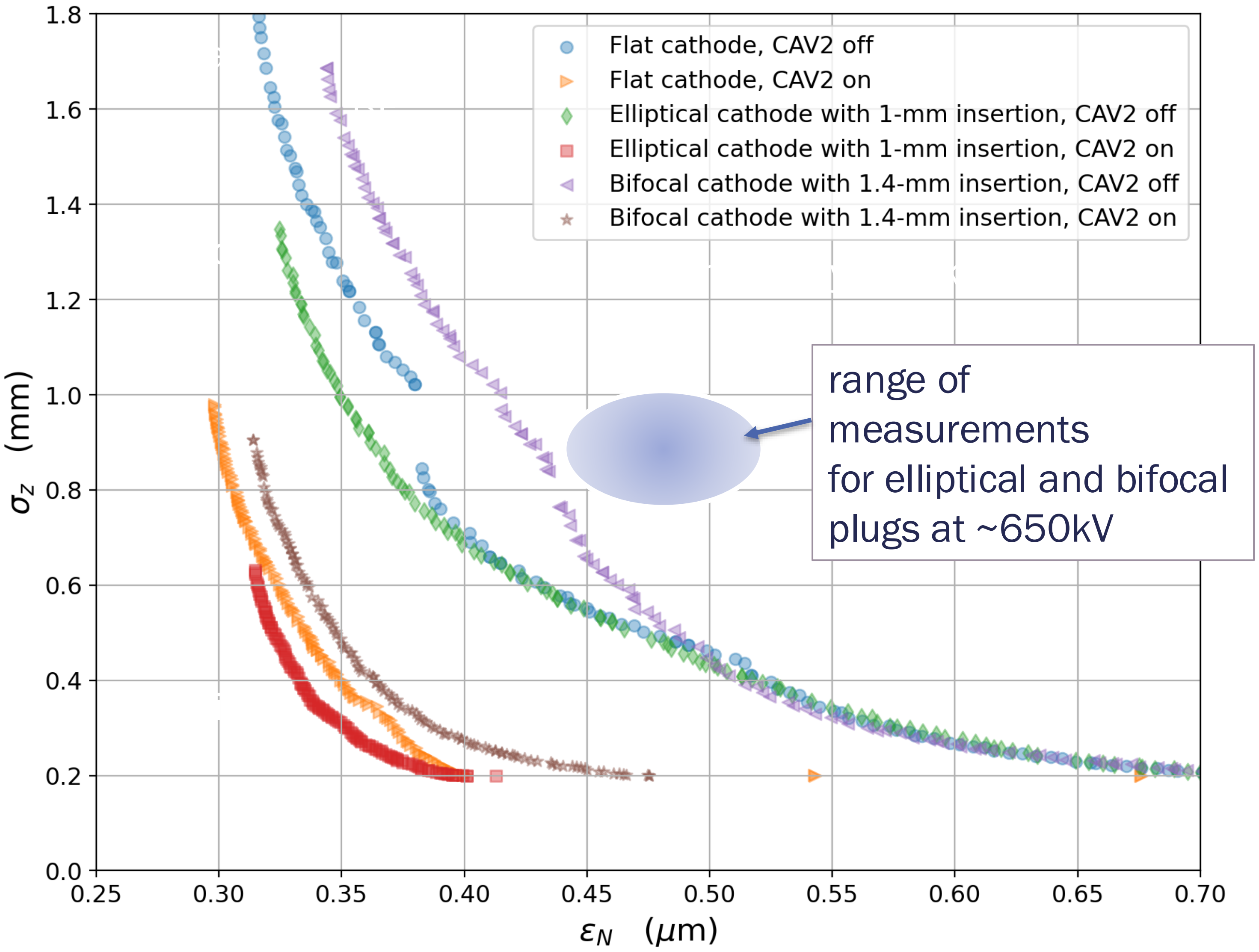


w/ 1mm over-inserted elliptical plug





Injector emittance simulations for the three plugs with two modes of Cav 2 operation (Z. Zhang)



Parameters	Value / Range	Units
Beam Charge	75	pC
MTE/thermal emittance	511/ 1.0	eV / um/mm
Laser transverse profile	1-σ-cut	
Laser spot size σ	0.4	mm
Laser longitudinal profile	Gaussian	
Laser rms length /FWHM	7 / 16	ps
Gun energy	700	keV
Buncher max. energy gain	220	keV
Buncher phase	[-120, 20]	deg
CAV1 peak gradient	[0, 30]	MV/m
CAV1 phase	[-120, 20]	deg
CAV2 peak gradient	0	MV/m

slide compliments of Zhen Zhang
measurement range suggested by Feng Zhou

Summary

- Two types of over-inserted cathode plug have been design, manufactured and commissioned at LCLS-II injector. Both plugs successfully reduce the dark current from uA to nA level, solving a major operation challenge for LCLS-II.
- Elliptical plug
  - Over-insertion suppresses dark current by shielding emitters and weakly defocuses dark current.
  - Higher cathode field
  - Insensitive to alignment
- Bifocal plug
  - Both suppresses and strongly defocuses dark current
  - Sensitivity to alignment
  - Lower cathode field, higher radial focusing field; requires higher applied field
  - Extra focusing of photobeam, but sacrifices the longitudinal field making space charge more dominant
- Besides suppressing the dark current, the over-inserted plugs enhance the cathode E field, and free the tunability of the injector solenoid. This could lead to further improvement of injector beam performance. Further studies are on-going at LCLS-II.