C-band vs S-band: Minimizing Emittance in a High Charge TopGun Photoinjector

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Outline

1. Introduction;
2. Sources of emittance;
3. Space charge emittance compensation 100 pC vs 250 pC in C-band;
4. Space charge emittance compensation of 250 pC bunch in S-band mode;
5. Conclusions.

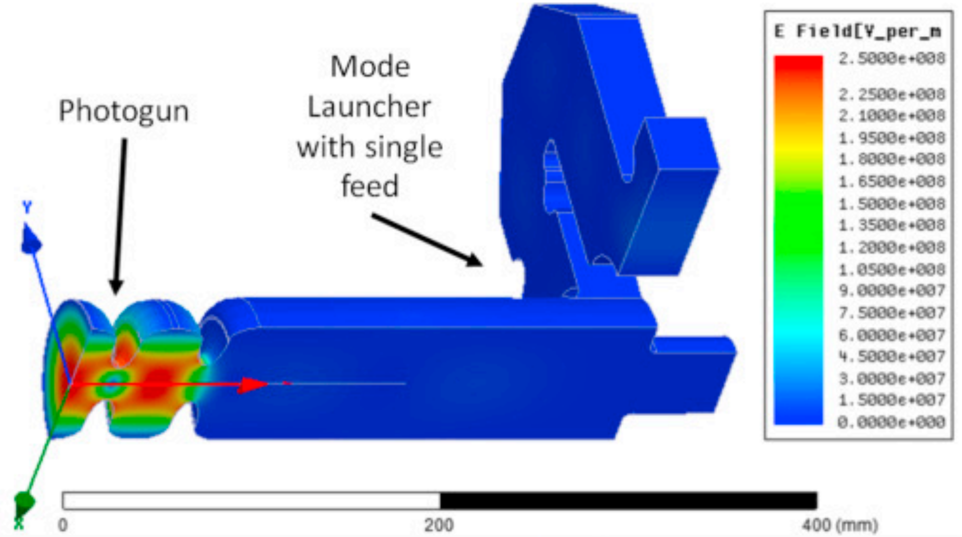
Special thank you to the collaboration with UCLA led by Jamie Rosenzweig!

Further reading:

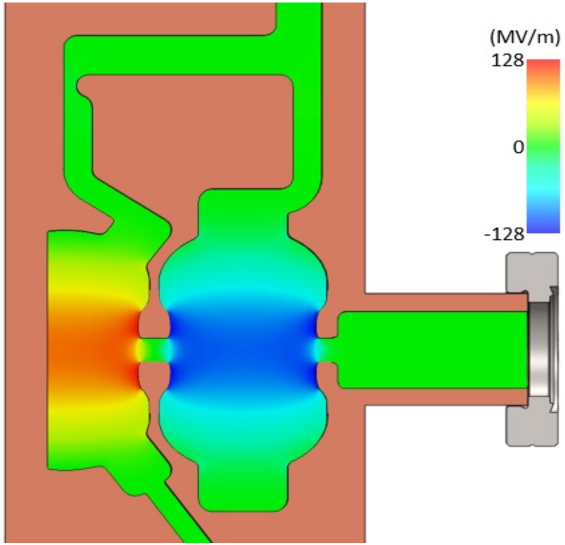
1. L. Serafini and J. B. Rosenzweig, "Envelope analysis of intense relativistic quasilaminar beams in rf photoinjectors: A theory of emittance compensation," Phys. Rev. E v. 55, p. 7565, 1997;
2. S. G. Anderson and J. B. Rosenzweig, "Nonequilibrium transverse motion and emittance growth in ultrarelativistic space-charge dominated beams," Phys. Rev STAB v. 3, 094201, 2000;
3. R. R. Robles *et al.*, "Versatile, high brightness, cryogenic photoinjector electron source," Phys. Rev. AB v. 24, 063401, 2021.

TopGun Designs

The TOPGUN collaboration between UCLA, SLAC, and INF has shown evidence of 250 MV/m accelerating gradients in cryogenically cooled copper structures.



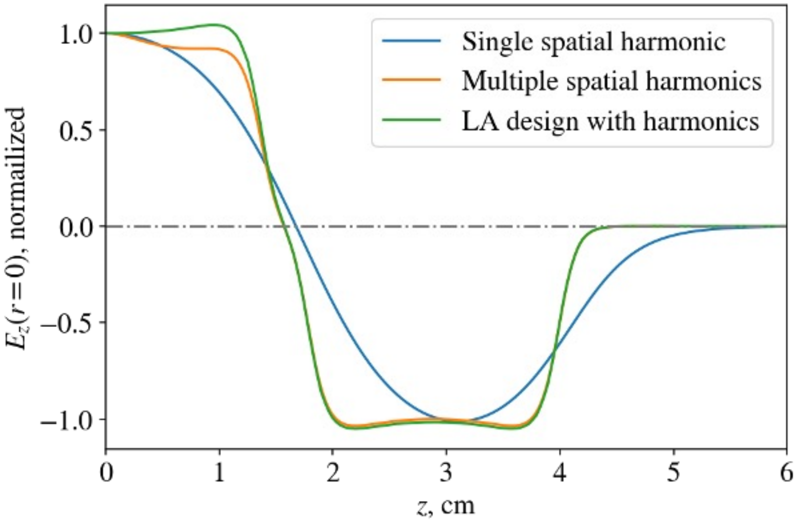
A. D. Cahill *et al.*, “RF design for the TOPGUN photogun: A cryogenic normal conducting copper electron gun”, *NIMA*, v. 865, pp.105-108, 2017. (S-band)



IPAC’23 posters TUPL139 (Xu) and TUPL138 (Simakov) discuss Los Alamos design for C-band work.

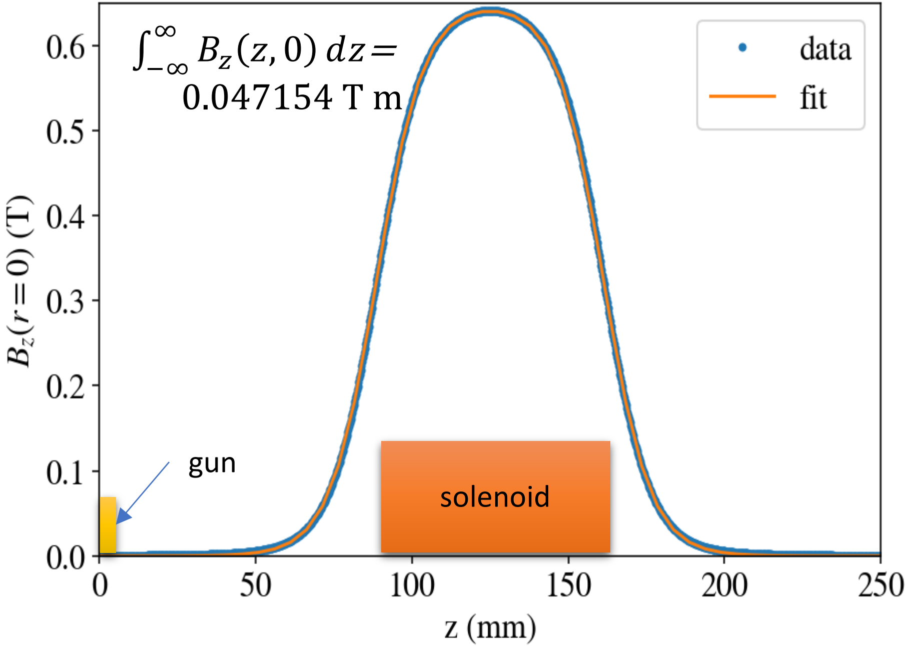
On-axis Field Profiles for C-band designs

- 1.6 cell in a π-mode (blue);
- 0.6 and 1.0 cell individually designed by UCLA and combined in a π-mode (orange):
  - Acceleration of low β-electrons;
  - Additional transverse focusing;
  - Reduced $E_{surf}/E_{cathode}$ ratio;
  - The maximum mean momentum gain (MMMG) is achieved with launching phase 134°; the final energy is then equal to $\gamma = 13.52$.
- 1.6 cell design to be implemented at Los Alamos National Lab (green):
  - The MMMG case of $\gamma = 13.52$ is achieved with 131° launching phase and on the cathode field of 230 MV/m instead of 240 MV/m needed for the UCLA design.



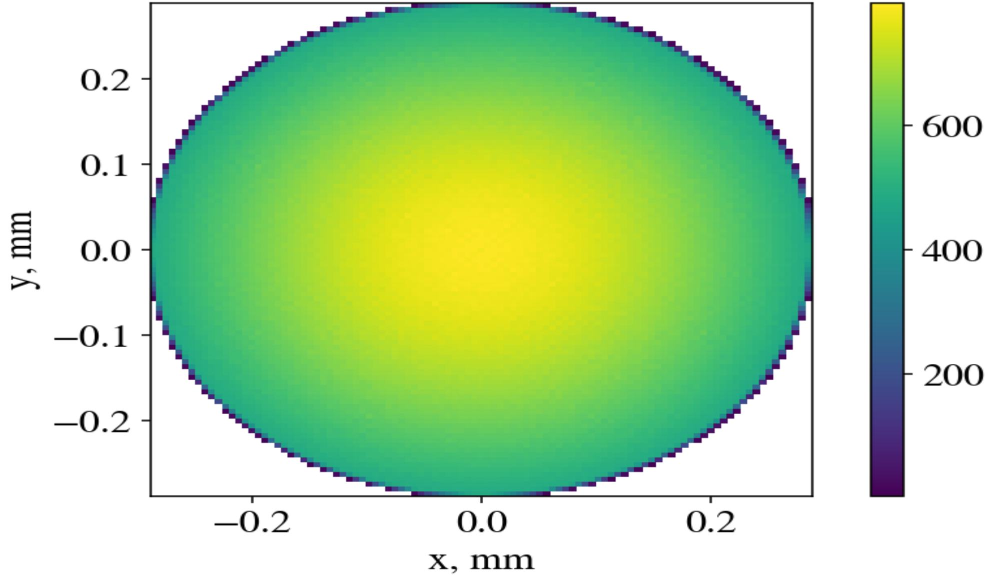
On-axis Field Profile for UCLA Solenoid

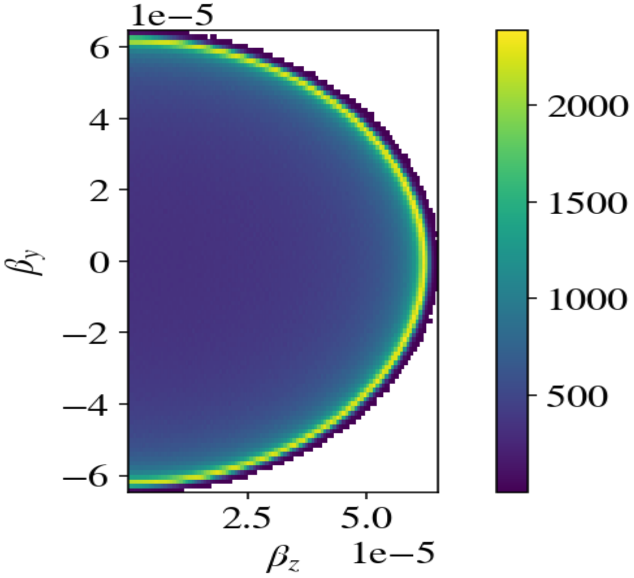
- The axis magnetic field profile of the solenoid is $B_z(r=0) = \frac{B_0}{2}\left[\mathrm{Tanh}\left(\frac{b(d+z-z0)}{2}\right) + \mathrm{Tanh}\left(\frac{b(d-z+z0)}{2}\right)\right]$, which implies that the solenoid is
- $2d = 72.5\ \mathrm{mm}$ long and
- its center is located $z_0 = 125\ \mathrm{mm}$ from the cathode.
- The solenoid has the maximum magnetic field of about $B_0 = 0.6504\ \mathrm{T}$ and
- the bore radius of $\pi/b = 23.5\ \mathrm{mm}$, which determines the region of the fringe field.



Intrinsic Emittance due to Excess Energy

- We follow GPT prescription to describe a metallic cathode with a one-sigma-cut Gaussian distribution.
- The intrinsic emittance in our simulations comes from an excess energy $E_o = 0.01\ \text{eV}$ and a laser spot size $\sigma_{\text{uv}} = 240\ \mu\text{m}$: $\varepsilon_n^{(x)} = \sigma_x\sqrt{\langle p_x^2\rangle}/m_e c$ or $\varepsilon_n^{(x)} = \sigma_x\sqrt{2eE_o/3m_e c^2} = 12\ \text{nm}$.

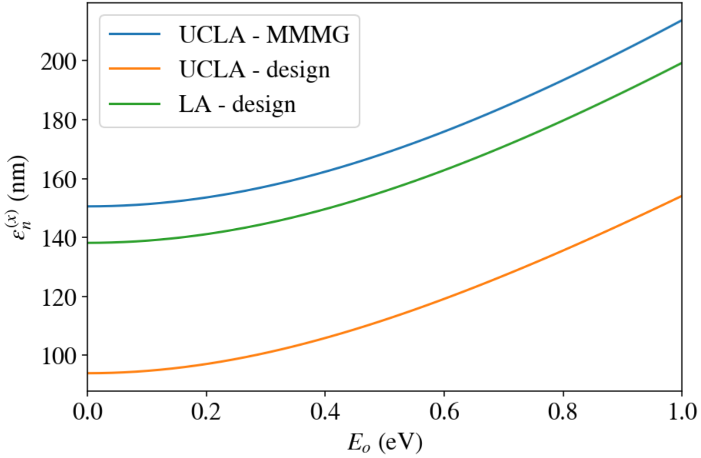


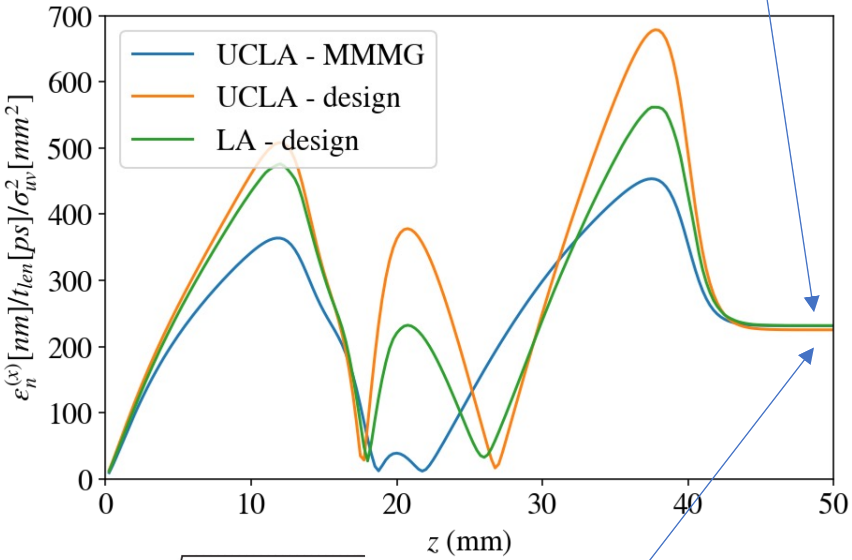


RF Emittance

R. R. Robles *et al.*, ”Versatile, high brightness, cryogenic photoinjector electron source”, *Phys. Rev. Accel. Beams*, v. 24, p. 063401, 2021.

- The scaling of RF emittance in TOPGUN is $\propto \Delta T\ \sigma_x^2$. The behavior without space charge or intrinsic emittance for three designs is shown:
- at the end of the gun, the scaling coefficient becomes [231.3, 225.2, 231.7] $\mathrm{nm\ ps^{-1} mm^{-2}}$ for three designs presented here.





$$\epsilon_x = \epsilon_{x0}\sqrt{1+\frac{5a^2\delta^2\sigma_{x0}^8}{\epsilon_{x0}^2}}.$$

$$\frac{a\delta\sigma_{x0}^4}{\epsilon_{x0}} = \left(\frac{eE_z(0)\sin(\phi)}{mc^2}\right)\frac{\beta_{x0}(k\sigma_{x0})^2}{16\gamma}\left[1+\frac{c^2}{\omega^2}\frac{E_z''(0)}{E_z(0)}\right]$$

Space Charge Emittance Compensation (1st take)

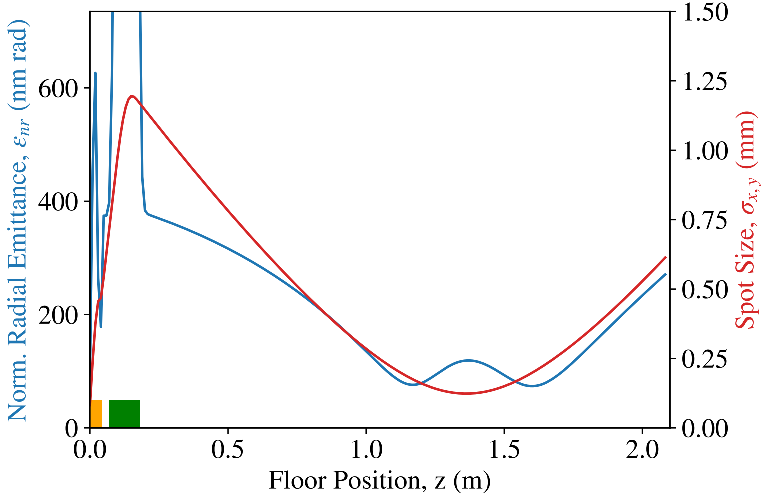
Parameter	Unit			Ratio
Charge	pC	100	250	2.5
Laser RMS spot size, σ	μm	129 (151)	233.5	1.81
Laser aperture size		1σ		
Injection phase		134°	133°	same
Laser length	ps	5.62 (5.8)	6.075	1.08
Peak cathode field	MV/m	240		
Solenoid field	T	0.5665 (0.51)	0.5759	
Solenoid FWHM	cm	7.4		
Solenoid center	cm	12.5		

Values if booster linac is present!?

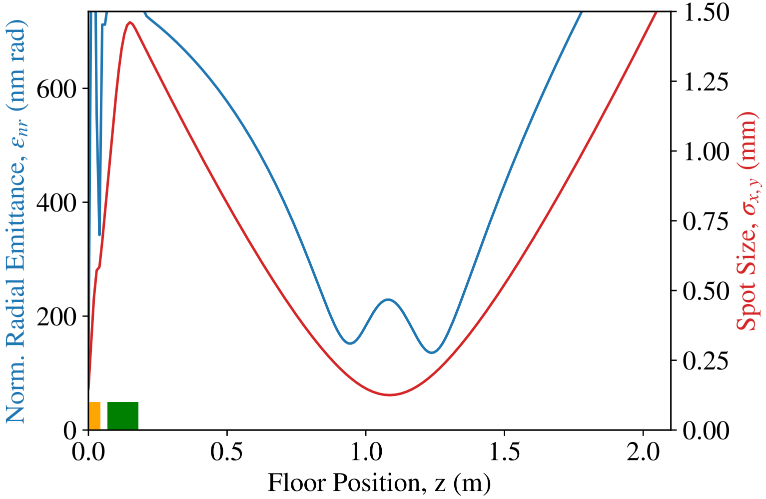
Charge density is reduced by 0.7!

GPT simulations (UCLA Design): beam emittance and spot size

100 pC case

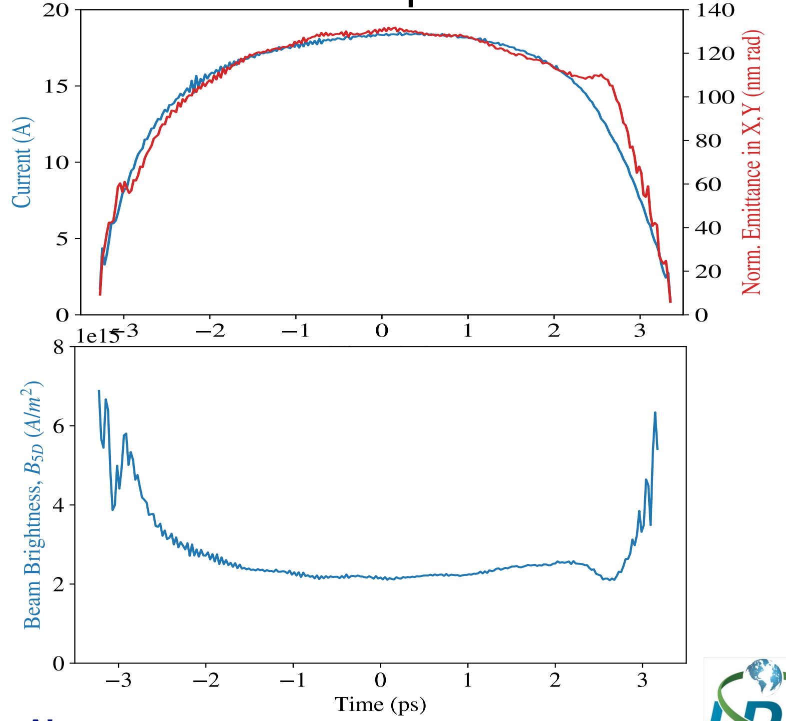


250 pC case

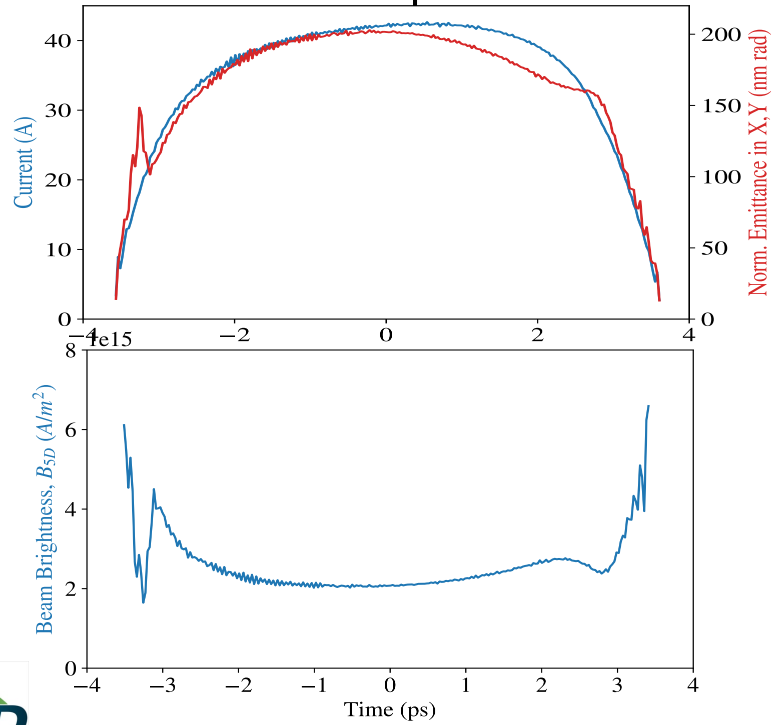


GPT simulations (UCLA Design): beam current, slice emittance and brightness at emittance minimum

100 pC

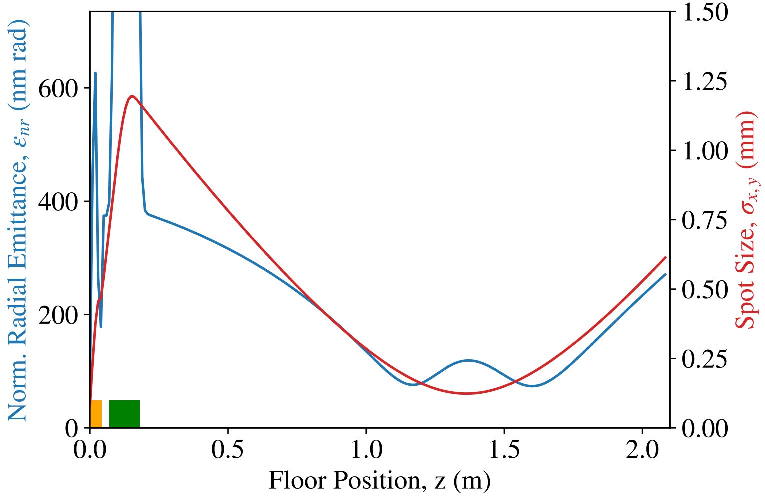


250 pC



GPT simulations (UCLA Design): beam emittance and spot size

100 pC case



PHYS. REV. ACCEL. BEAMS **24,** 063401 (2021)

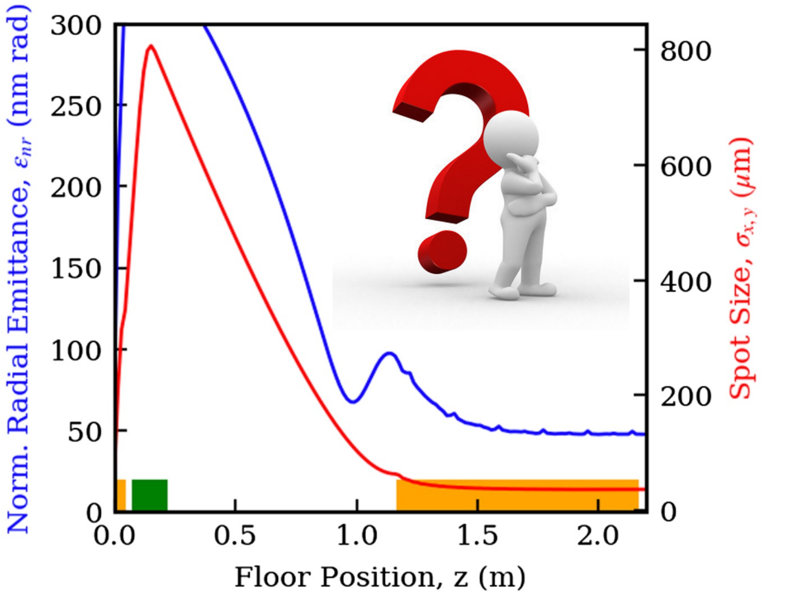


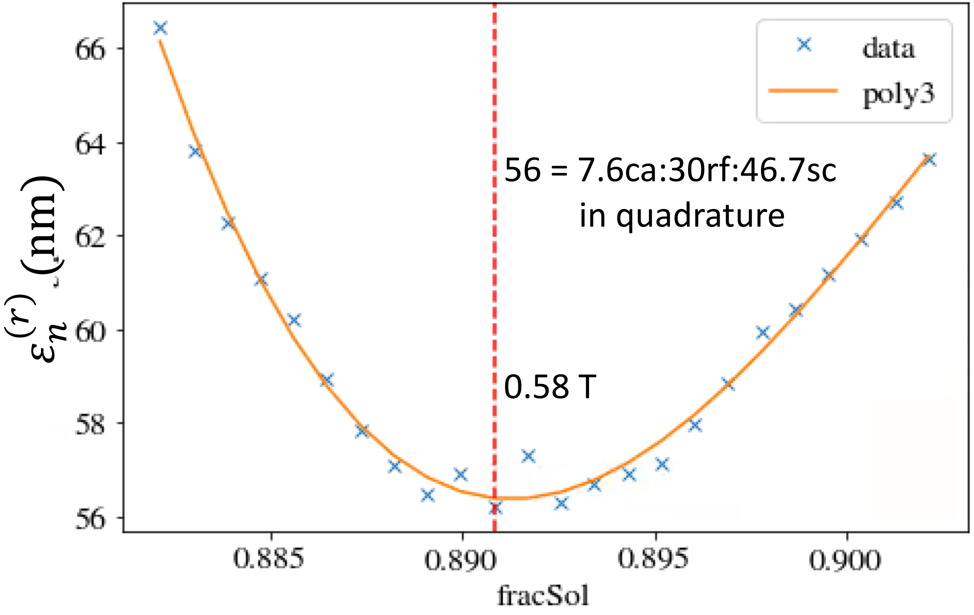
FIG. 8. The emittance and beam size evolution of the ultrahigh brightness operating point are shown through the first booster linac.

Space-Charge Emittance Compensation (UCLA Design): Educated approach

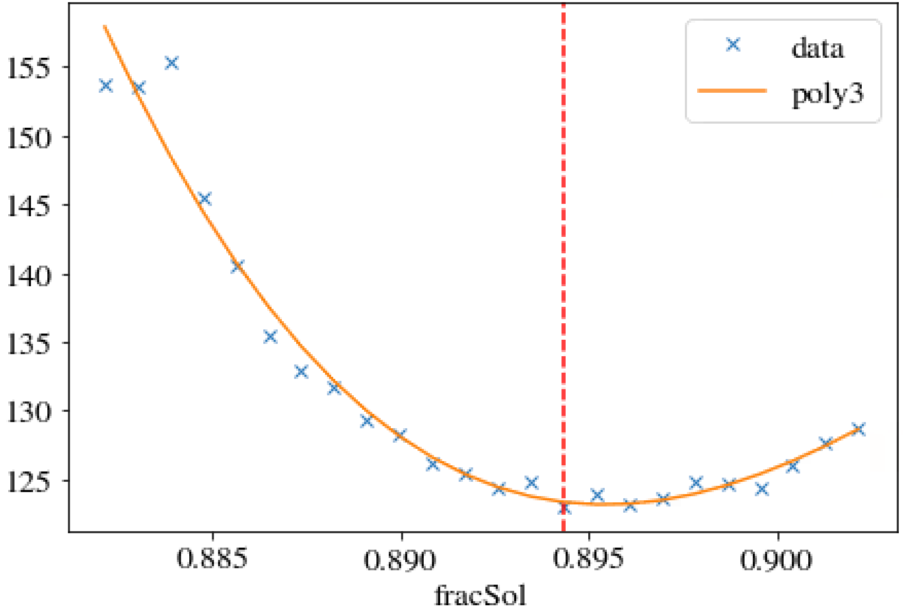
- The emittance compensation scheme developed by the UCLA team aims to eliminate effects of the space charge forces in a needle-shaped bunch, $\sigma_r \ll \sigma_z$, by reversing transverse dynamics with solenoid focusing. The charge density near cathode determines transverse dynamics and thus $\sigma_{r,z} \propto Q^{1/3}$. *J. Rosenzweig and E. Colby, "Charge and Wavelength Scaling of RF Photoinjectors: A Design Tool", in Proc. PAC'95, Dallas, TX, USA, May 1995, paper WPB05, pp. 957-960.*
- The Gaussian profile of the laser beam is cut at $r = \sigma_{\mathrm{uv}}$ in order to linearize transverse space charge forces.
- The laser parameters for 100-pC injector design are $\sigma_{\mathrm{uv}} = 151\ \mu\mathrm{m}$ pre-cut, or $\sigma_{\mathrm{x}} = 68\ \mu\mathrm{m}$ post-cut, and a uniform pulse length $\Delta T = 5.8\ \mathrm{ps}$. The solenoid peak field is 0.58 T, which is 0.892 fraction of the maximum field.
- A 250-pC photoinjector scales to $\sigma_{\mathrm{uv}} = 205\ \mu\mathrm{m}$ and $\Delta T = 7.87\ \mathrm{ps}$ in order to achieve the same level of space charge emittance compensation based on the scaling.
- NOTE: In the case of independent phasing of the cavities, we have found the minimum projected normalized emittance to be $\varepsilon_n^{(r)} = 140\ \mathrm{nm}$ for $\sigma_{\mathrm{uv}} = 298\ \mu\mathrm{m}$ and $\Delta T = 7.33\ \mathrm{ps}$ with 0.914 solenoid field fraction.

UCLA design without booster requires stronger solenoid

100 pC without booster



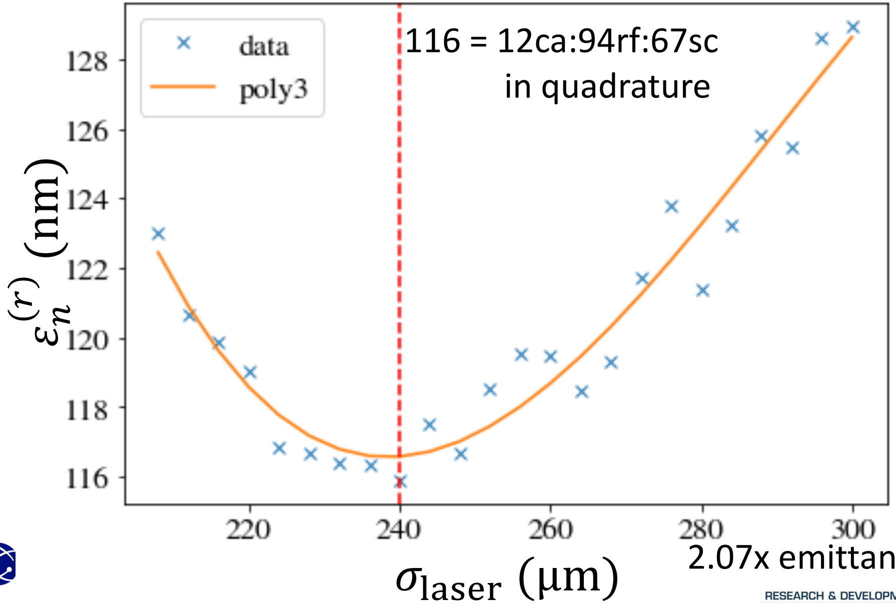
250 pC (scaled) without booster



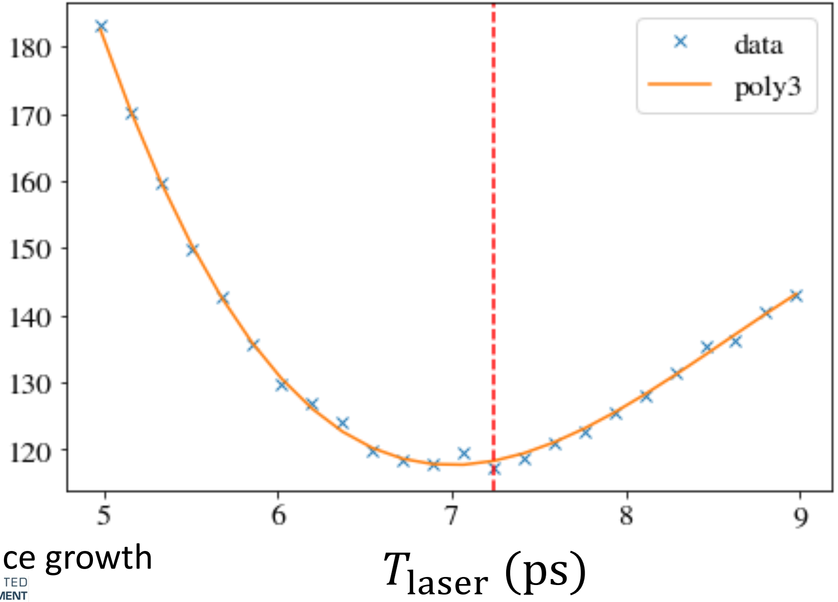
2.23x emittance growth

Space-Charge Emittance Compensation
250 pC optimized

- In π-mode, the minimum projected normalized emittance can be optimized to $\varepsilon_n^{(r)} = 116$ nm for $\sigma_{\mathrm{uv}} = 240$ μm and $\Delta T = 7.24$ ps with 0.58 T solenoid field. This is 1.26x brightness gain.
- These optimized values are slightly different (1.26x volume) from the scaled values (205 μm and 7.87 ps) that produces a slightly larger emittance of $\varepsilon_n^{(r)} = 125$ nm vs. $\varepsilon_n^{(r)} = 116$ nm here.



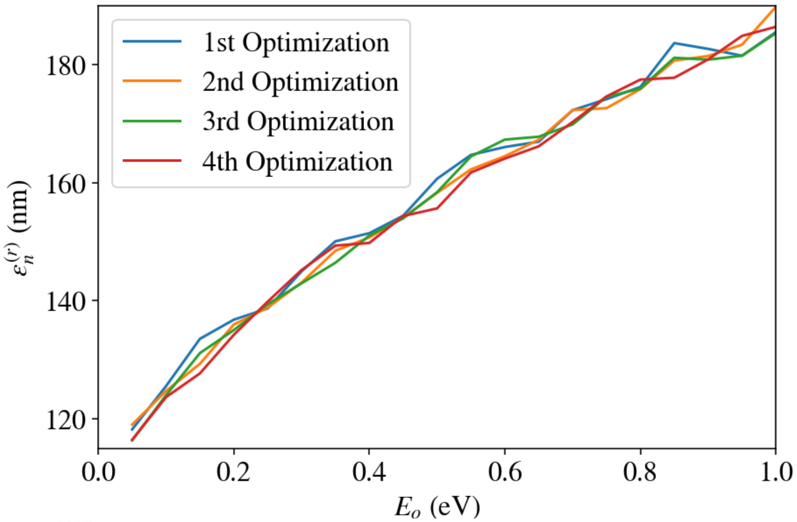
2.07x emittance growth

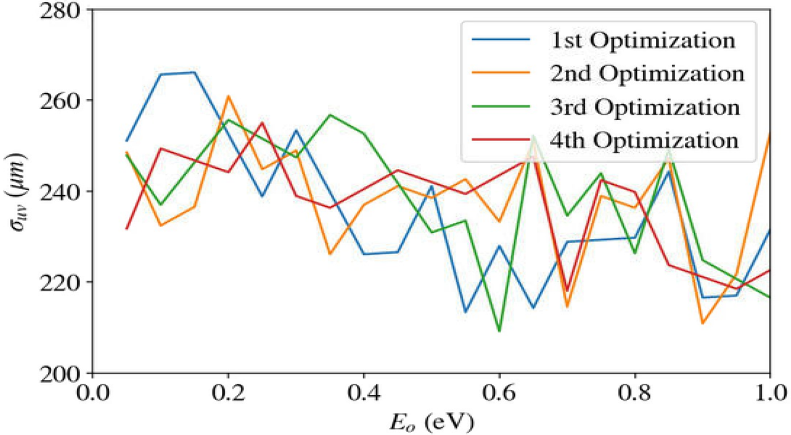


TED
RESEARCH & DEVELOPMENT

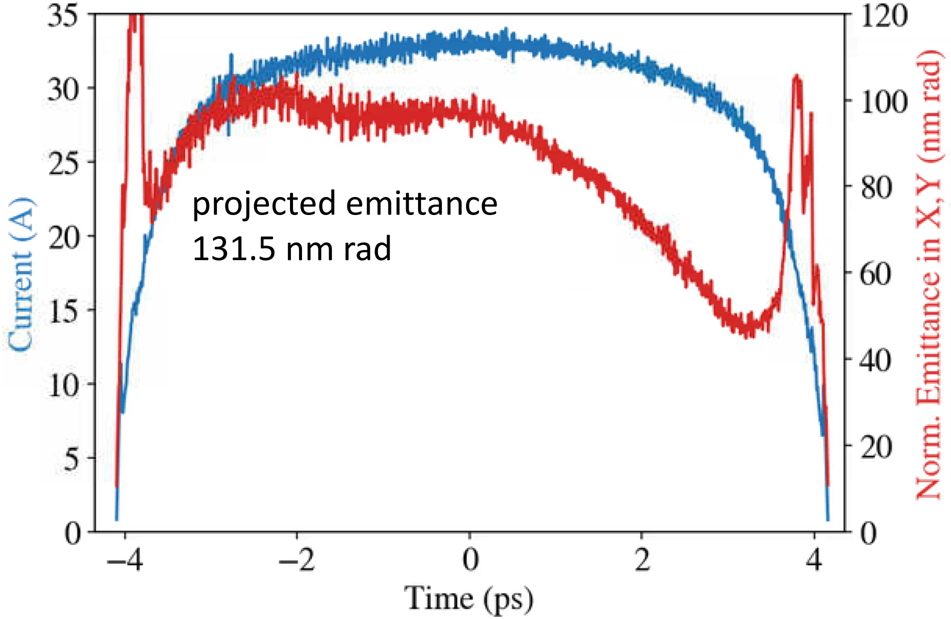
C-band Optimization of LA TopGun

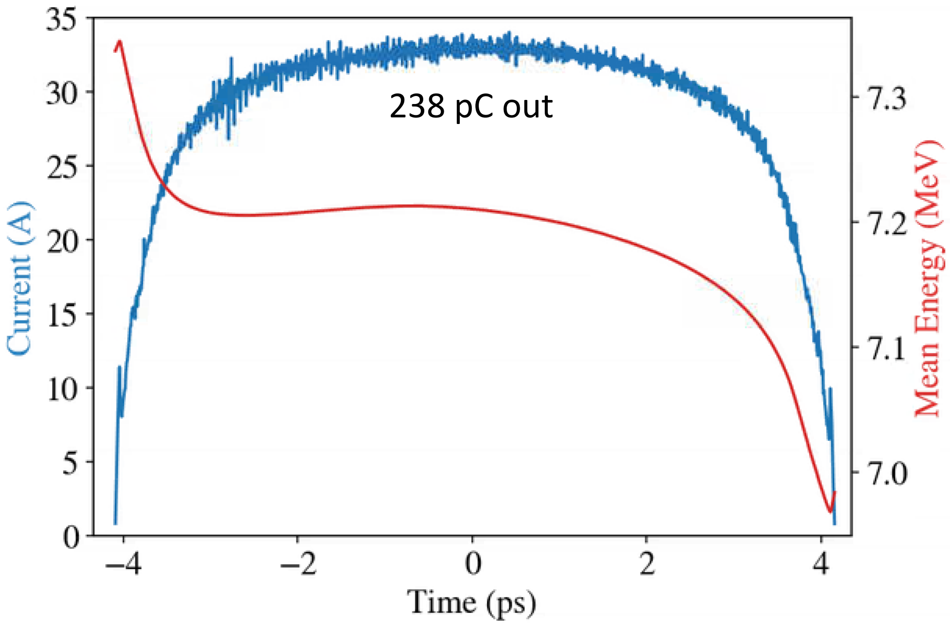
- We have performed multiple optimizations of LA TOPGUN for each value of the excess energy, concluding that for 240 MV/m gradient, 132.8 degree launching phase instead of 131 degree MMMG phase and $\Delta T = 7.34$ ps are the best.
- We had to move the solenoid 7 mm towards the cathode.
- σ_{uv} value however should be reduced from 250 μm to 220 μm in order to counteract the growth of intrinsic emittance.
- This effort leads to a noticeable improvement for $E_o < 0.3$ eV or MTE < 0.1 eV.





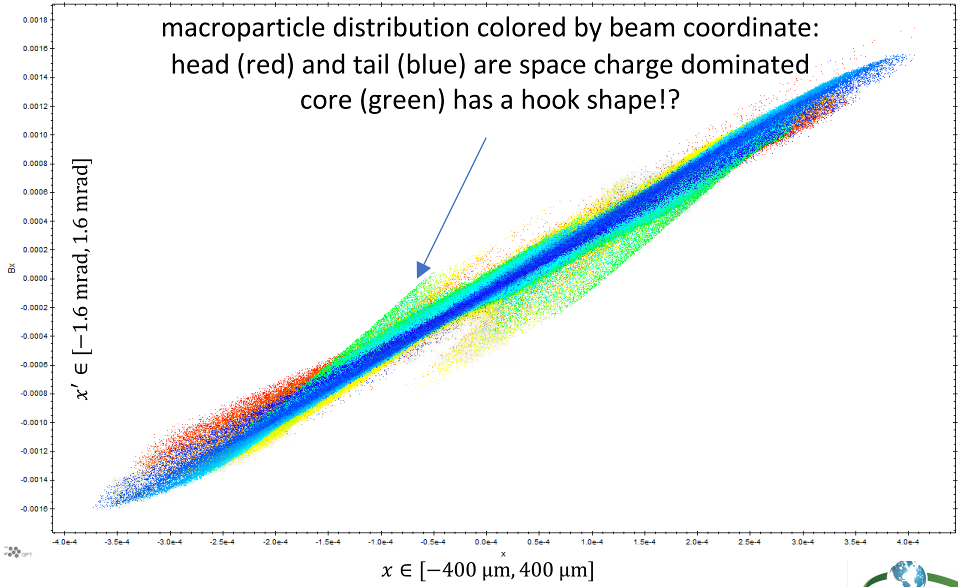
GPT simulations (250 pC LA Design): beam current, slice emittance and brightness at emittance minimum

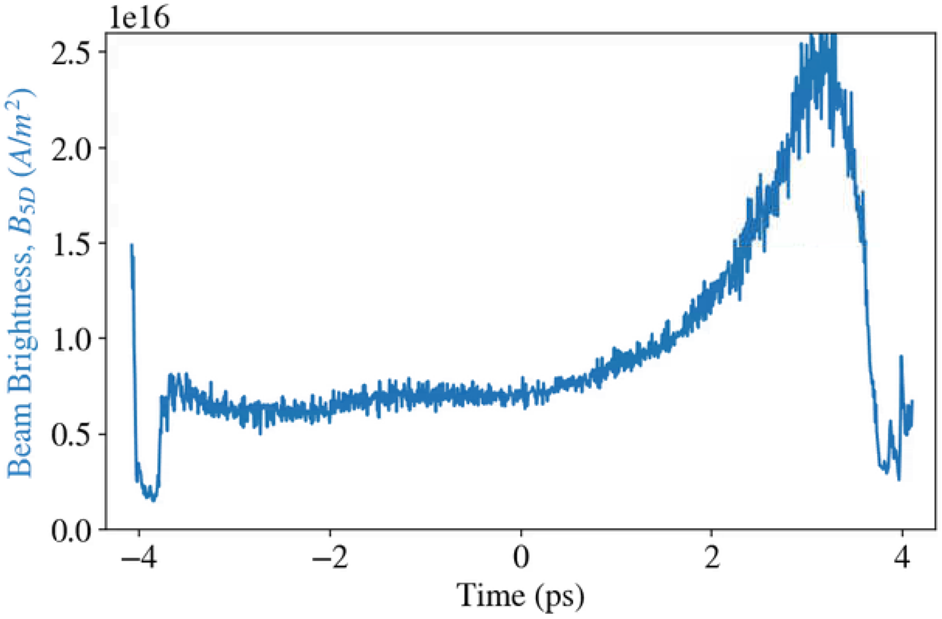




GPT simulations (250 pC LA Design): beam current, slice emittance and brightness at emittance minimum

131 nm rad projected emittance vs
86 nm rad current averaged slice emittance

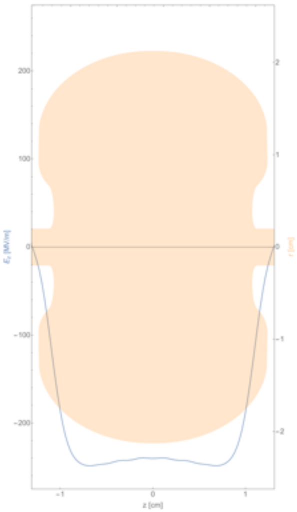




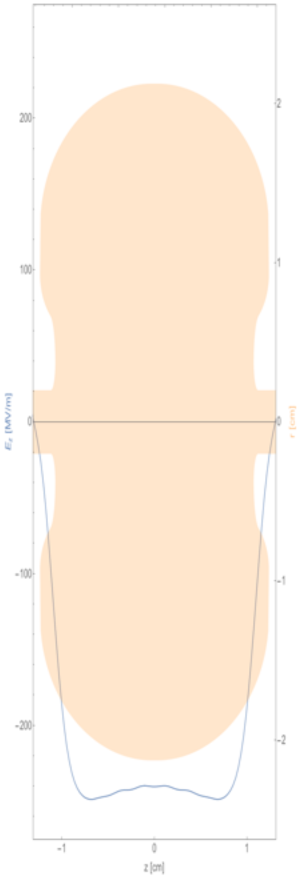
New “TopGun” in S-band

- This analysis has been motivated by Jamie’s suggestion to take $E_z(r = 0)$ profile of the C-band cavity and assume S-band operation.
- We do not do any wavelength scaling and keep $240\ \mathrm{MV/m}$ on the cathode field as well as the solenoid.
- MMMG case corresponds to 150° launching phase and 73° follow-up cavity phase.
- $\pi/2$-case MMMG corresponds to 159° and 69° phases correspondingly.
- Resulting energy for $240\ \mathrm{MV/m}$ accelerating gradient on the cathode is $\gamma = 16.63$ vs. $\gamma = 16.53$.
- C-band had $\gamma = 13.52$ for comparison with 134° launching phase, which is 25° instead of 45° expected.

C-band



S-band



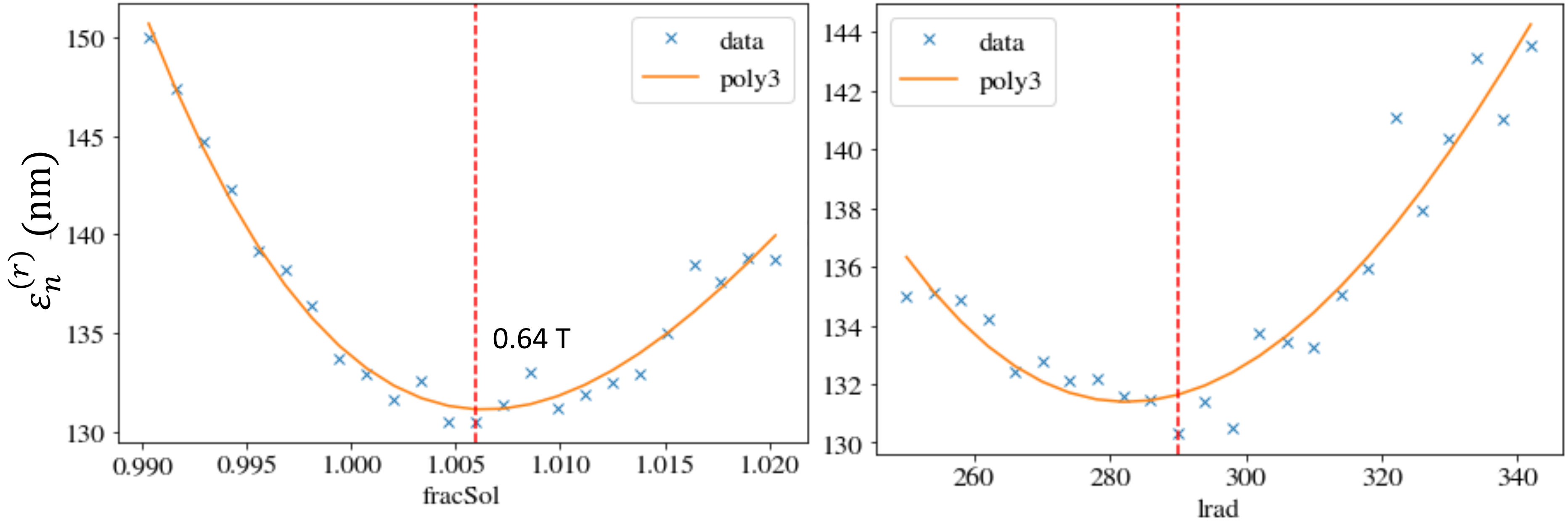
Same length in z, roughly twice the radius for S-band cells.

Space Charge Emittance Optimization in S-band

Parameter	Unit	$\pi/2$-mode	MMMG-mode
Laser RMS spot size, σ	μm	290	318
Laser length	ps	19.3	16.1
Solenoid field	T	0.64	0.65
Emittance	nm rad	123	126
Energy	MeV	7.99	7.94

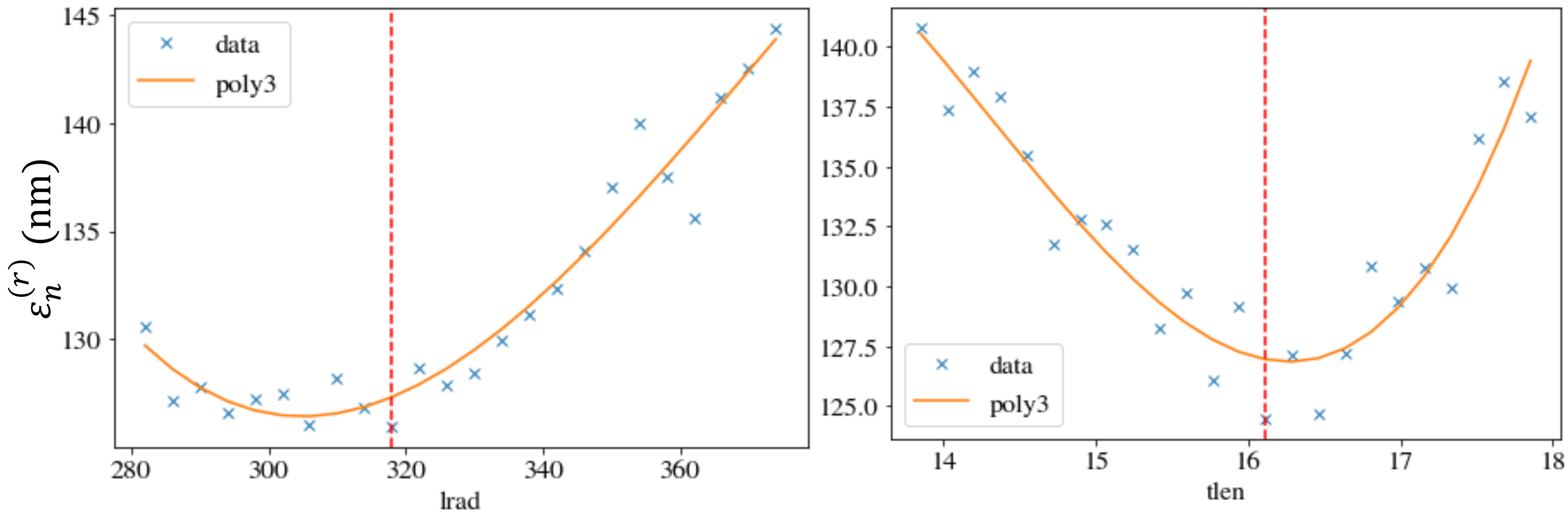
both cases result in comparable brightness.

$\pi/2$-mode emittance for $t_{len} = 19.3$ ps



sensitivity to the solenoid field strength and the laser spot size

MMMG case for $B_0 = 0.65$ T



sensitivity to the laser spot size and to the pulse length

Conclusions

- Space charge emittance compensation in TopGun photon injector has been studied numerically in C-band and S-band;
- 250 pC bunches could be generated with emittance on the order of 100 nm where the major contribution comes from RF emittance;
- $Q^{1/3}$ scaling of the laser spot size and pulse length has been confirmed;
- RF emittance thus is growing as $\sim Q$ such that if 100 pC case has 55 nm emittance then 250 pC case will have 137 nm emittance;
- S-band case performs comparably to C-band case.