Beyond ellipsoidal laser shaping

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- Simulation comparison between different laser shaping
- Summary

Houjun Qian

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HELMHOLTZ ASSOCIATION

DESY

Motivations

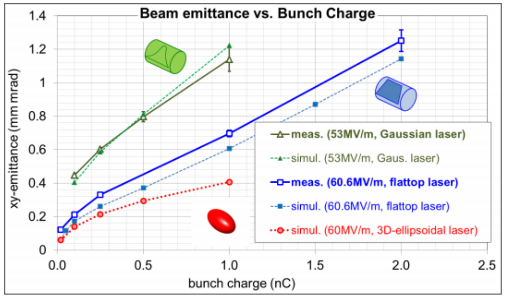
> Ellipsoidal photocathode laser shaping

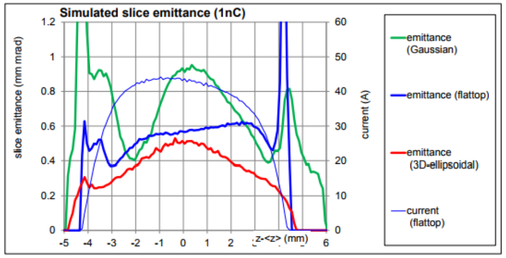
- 3D space charge linearization
- Complicated technology → high maintenance

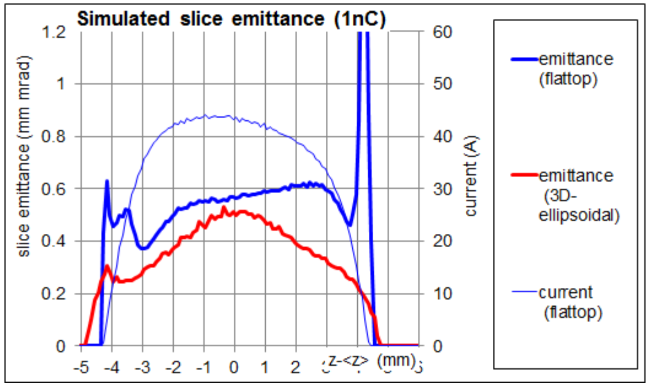
  coupled shaping (r-t), with rotational symmetry
  laser shape conservation through harmonic generation
  low efficiency: Gaussian → flattop → ellipsoidal
  …
- Central slice emittance higher than projected emittance

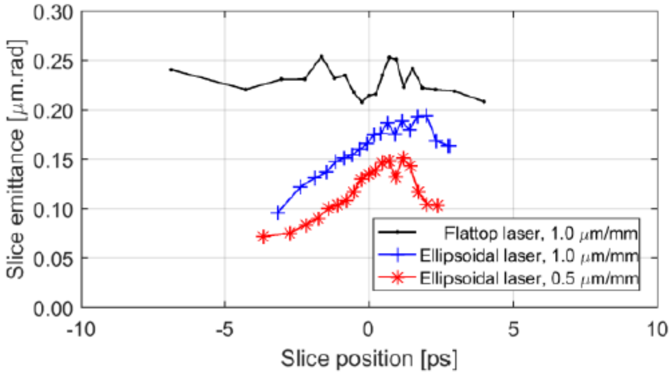
	Core slice emit.	100% Proj. emit.
PITZ - 1 nC (pulsed gun)	0.5	0.4
LCLS2 - 0.1 nC (CW gun)	0.15	0.12

~25% higher









PITZ - 1 nC

Flattop → ellipsoidal: ~10% improvement on core slice emittance

LCLS2 - 0.1 nC

Motivations

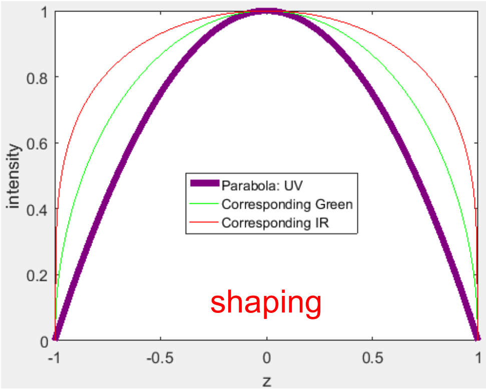
> Ellipsoidal laser shaping simplification

- Decouple t shaping and r shaping

$$\frac{x^2+y^2}{R^2}+\frac{z^2}{z_{\max}^2}=1 \quad \Rightarrow \quad \begin{aligned} &\rho(r)\propto\sqrt{1-\left(\frac{r}{R}\right)^2} && \text{Half circle distribution} \\ &\rho(z)\propto 1-\left(\frac{z}{z_{\max}}\right)^2 && \text{Parabola distribution} \\ &\rho(x)\propto 1-\left(\frac{x}{R}\right)^2 \end{aligned}$$

- Longitudinal shaping: 1D

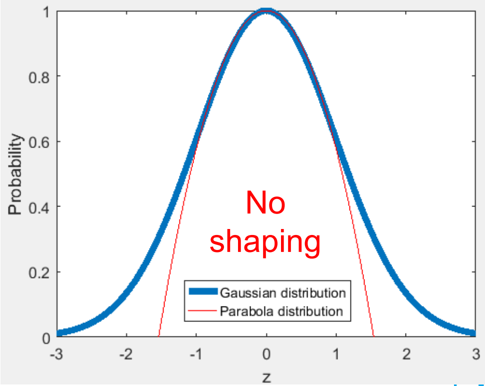
A real parabola shaping by SLM
Or approximate parabola distribution by Gaussian distribution



$$\rho(z)\propto 1-\left(\frac{z}{z_{\max}}\right)^2 \quad \Rightarrow \quad z_{\max}=\sqrt{2}\sigma_z$$

$$\rho(r)\propto e^{-\frac{z^2}{2\sigma_z^2}}\approx 1-\frac{r^2}{2\sigma_z^2}$$

Parabola distribution naturally exists at the core of Gaussian distribution.



Motivations

> Ellipsoidal laser shaping simplification

- Decouple t shaping and r shaping

$$\rho(r) \propto \sqrt{1-\left(\frac{r}{R}\right)^2}$$ Half circle distribution

$$\frac{x^2+y^2}{R^2}+\frac{z^2}{z_{\max}^2}=1 \Rightarrow \rho(z) \propto 1-\left(\frac{z}{z_{\max}}\right)^2$$ Parabola distribution

$$\rho(x) \propto 1-\left(\frac{x}{R}\right)^2$$

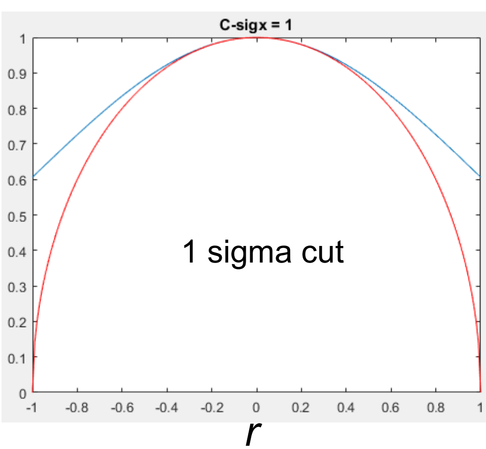
- Transverse shaping: 2D

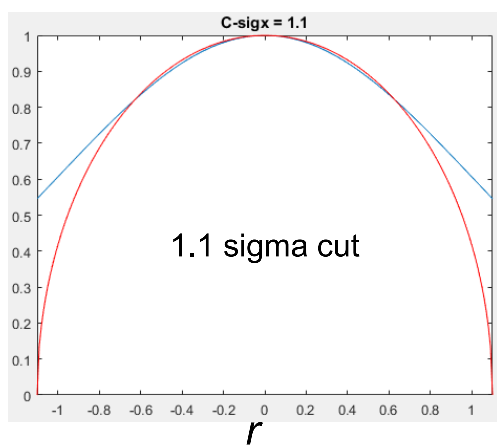
A real half circle shaping
Or cut Gaussian into half circle

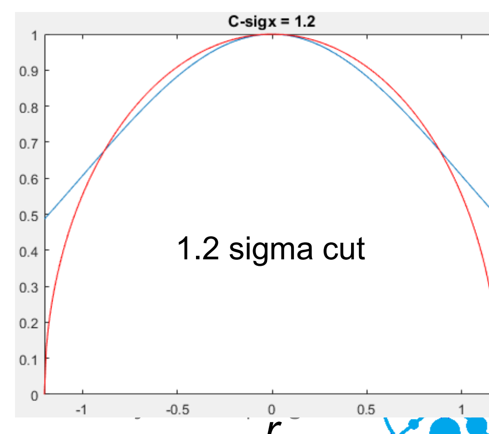
$$\rho(r) \propto \sqrt{1-\left(\frac{r}{R}\right)^2} \approx 1-\frac{r^2}{2R^2}$$

$$\rho(r) \propto e^{-\frac{r^2}{2\sigma_r^2}} \approx 1-\frac{r^2}{2\sigma_r^2}$$

$\Rightarrow$ $R=\sigma_r$
1 sigma cut by BSA







Motivations

> LCLS experience: (prst ab 15, 090701 (2012))

- 115 MV/m, 150 pC, pancake photoemission
- UV laser 1

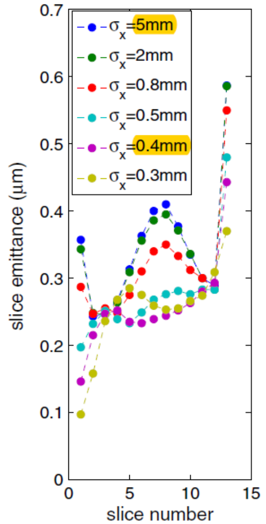
  Longitudinal: 3 ps stacking → 6.5 ps 'flattop'
  Transverse: 1 mm BSA, uniform
- UV laser 2

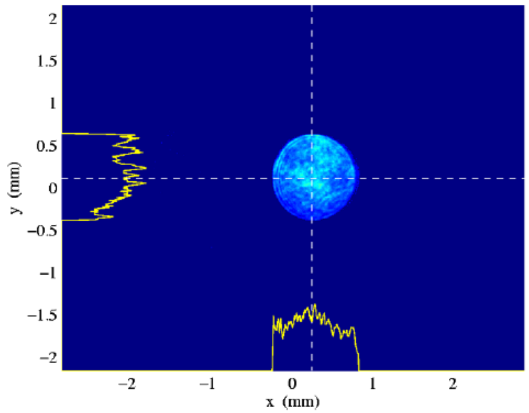
  Longitudinal: remove stacking → 3 ps Gaussian
  Transverse: 1 mm BSA, uniform
- UV laser 3

  Longitudinal: remove stacking → 3 ps Gaussian
  Transverse: 1 mm BSA, truncated Gaussian

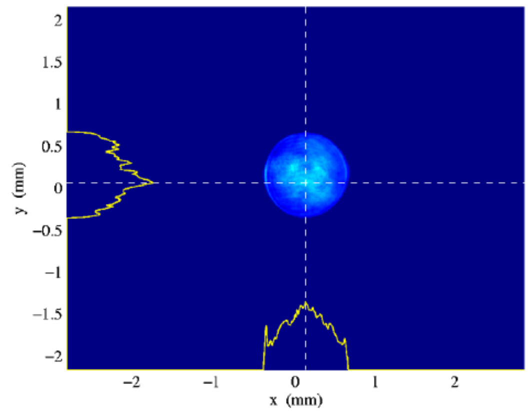
Emittance no obvious change

Emittance reduction by 25%, big UV laser efficiency improvement.

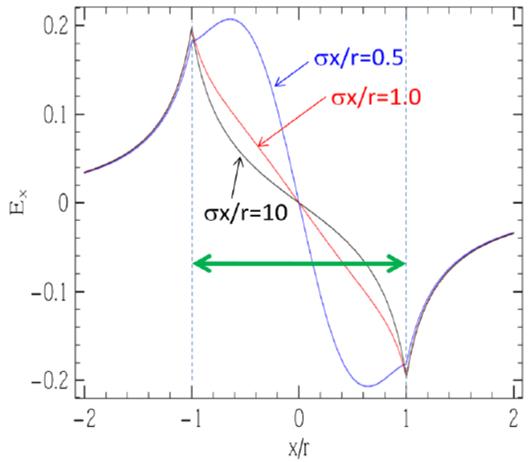




uniform



Truncated Gaussian



Laser shaping comparison

> Different laser shapings

- Ellipsoidal approx. A

  A1: Long. Parabola, Transverse truncated Gaussian
  A2: Long. Parabola, Transverse uniform

- Ellipsoidal approx. B

  B1: Long. Gaussian, Transverse truncated Gaussian
  B2: Long. Gaussian, Transverse uniform

- Flattop C

  C1: Long. Flattop, Transverse truncated Gaussian
  C2: Long. Flattop, Transverse uniform

> Injector setup

- Current PITZ beamline with 60 MV/m gun gradient
- Emittance optimization at EMSY1
- Beam peak current: ~ 45 A

  Ellipsoidal & parabola laser: 6.1 ps rms, 19 ps FWHM
  Gaussian laser: 8 ps rms, 18 ps FWHM
  Flattop laser: 22 ps FWHM, 2 ps edge

- Beam charge: 0.5 & 1 nC
- Optimization parameters

  Laser BSA, Gun phase, booster gradient, solenoid focusing

Laser shaping comparison

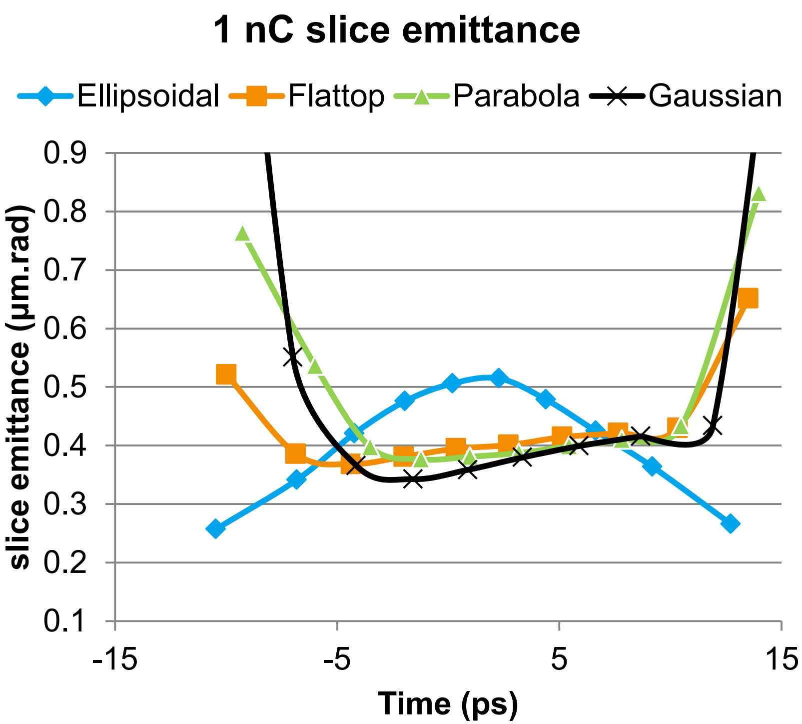
> slice emittance

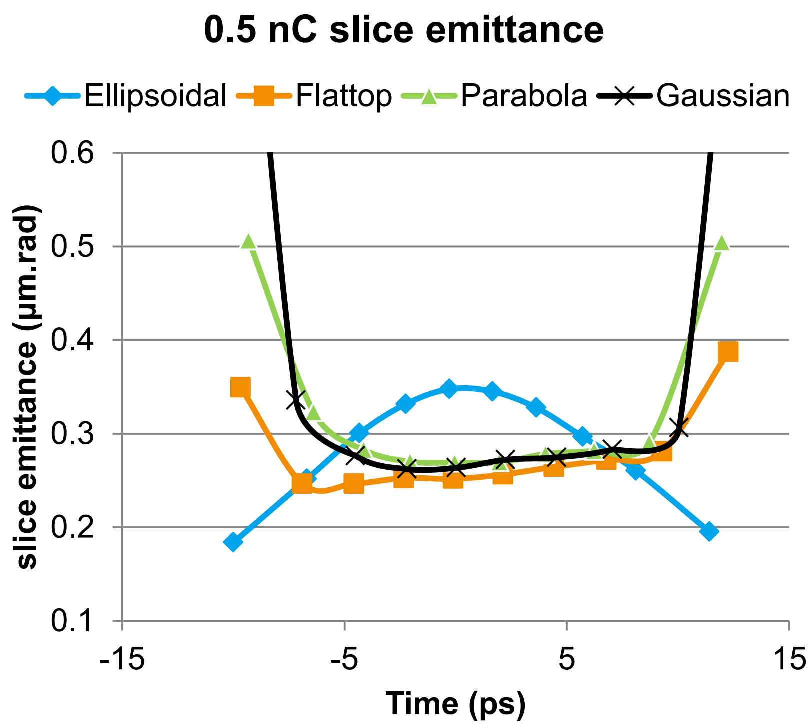
Core slice emittance

	Ellipsoidal	Parabola		Gaussian		Flattop	
		A1	A2	B1	B2	C1	C2
0.5 nC	0.35	0.26	0.42	0.27	0.42	0.26	n/a
1 nC	0.51	0.38	0.73	0.37	0.73	0.4	0.57

Average slice emittance

	0.5 nC	1 nC
ellipsoidal	0.28	0.40
Parabola	0.31	0.47
Gaussian	0.53	0.72
flattop	0.28	0.44



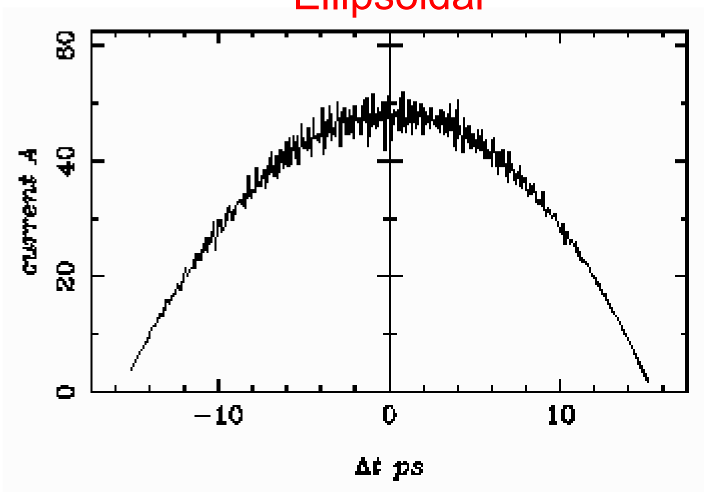


- ✓ Transverse shaping is key for core slice emittance, not longitudinal shaping.
- ✓ Truncated Gaussian Vs Ellipsoidal case, ~25% improvement on core slice emittance.
- ✓ Transversely truncated Gaussian is better than uniform distribution, improving core slice emittance by 30% to 50%.

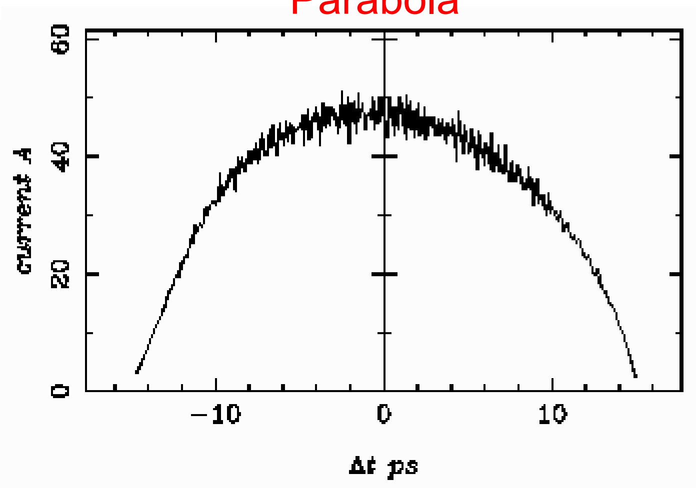
Laser shaping comparison

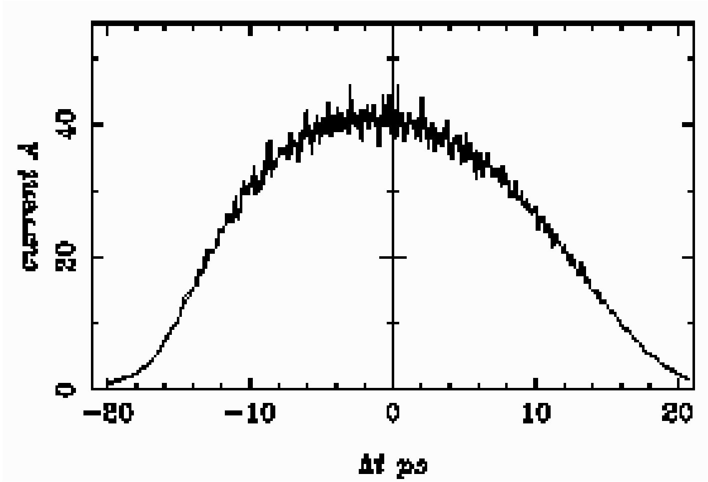
- Peak current (1 nC)

Ellipsoidal

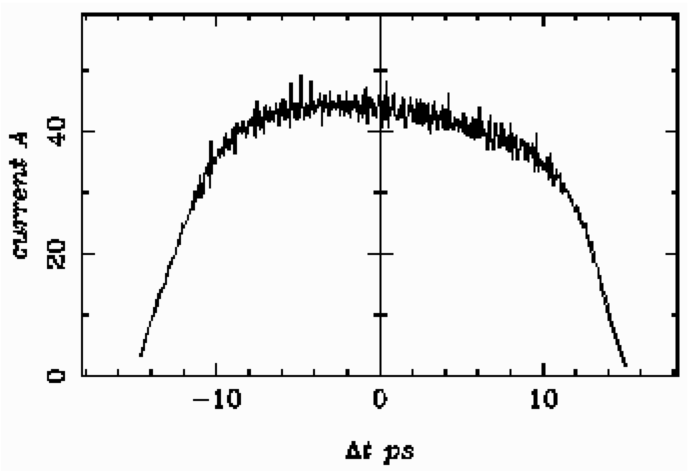


Parabola





Gaussian



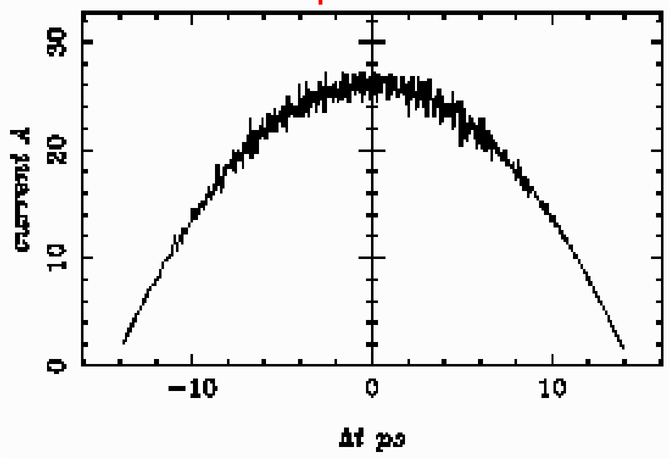
Flattop

	Sigz mm	emit_z mm.keV
Ellipsoidal	2.1	76
Parabola	2.1	68
Gaussian	2.5	118
Flattop	2.2	73

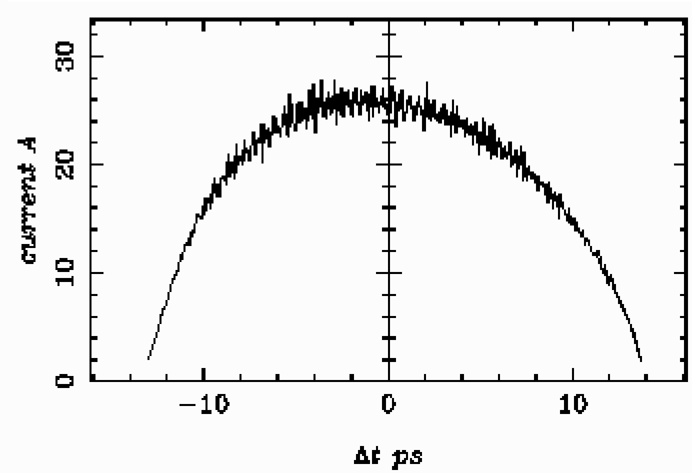
Laser shaping comparison

- Peak current (1 nC)

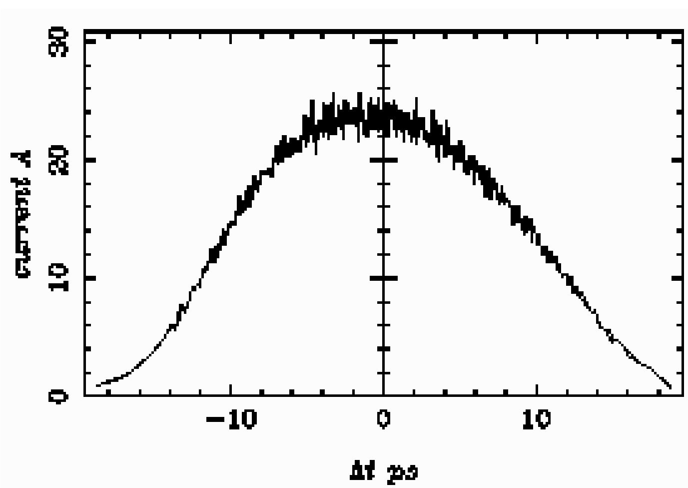
Ellipsoidal



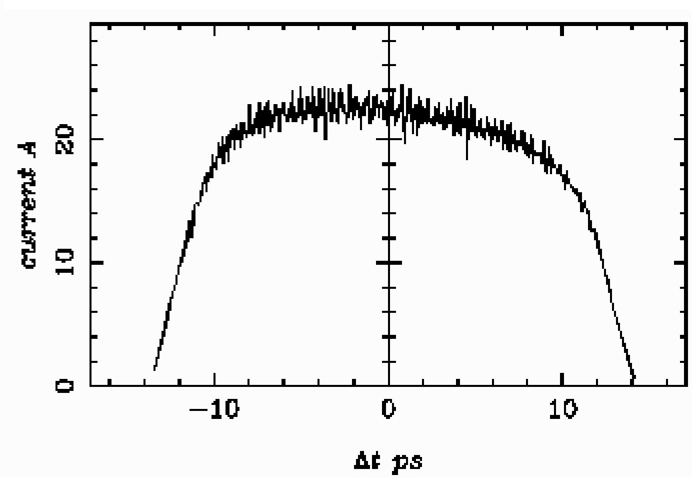
Parabola



	Sigz mm	emit_z mm.keV
Ellipsoidal	1.9	45
Parabola	1.9	46
Gaussian	2.3	92
Flattop	2.0	42



Gaussian



Flattop

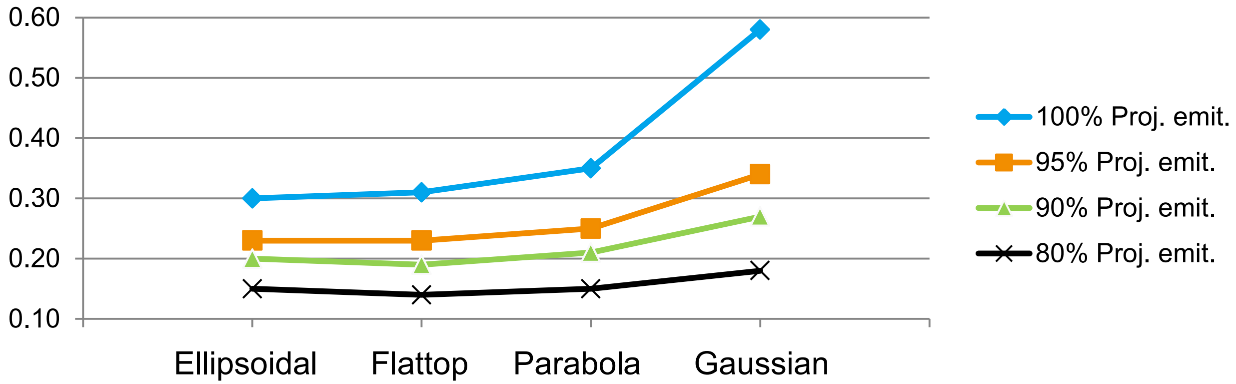
Laser shaping comparison

> Projected emittance for transversely truncated Gaussian laser

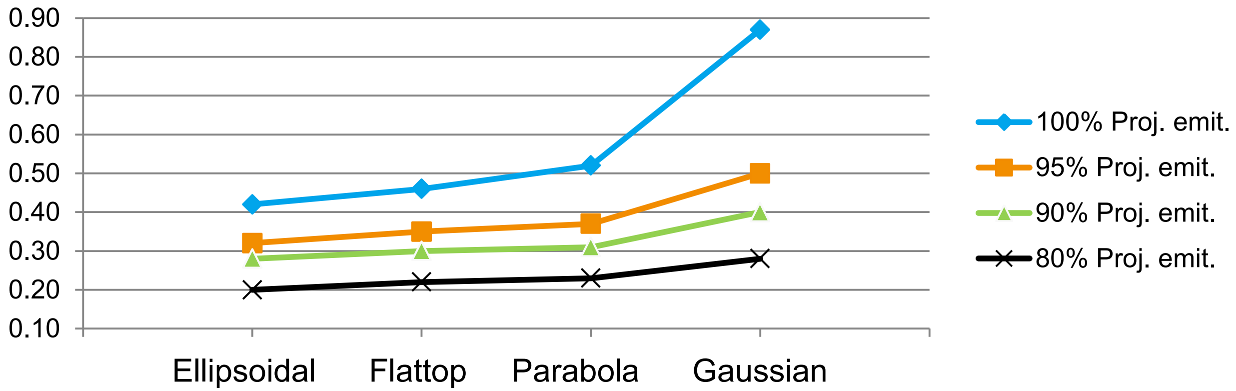
- Flattop (truncated Gaussian) vs Ellipsoidal

0.5 nC: negligible difference
1.0 nC: 10% difference for 100% emittance

0.5 nC



1.0 nC

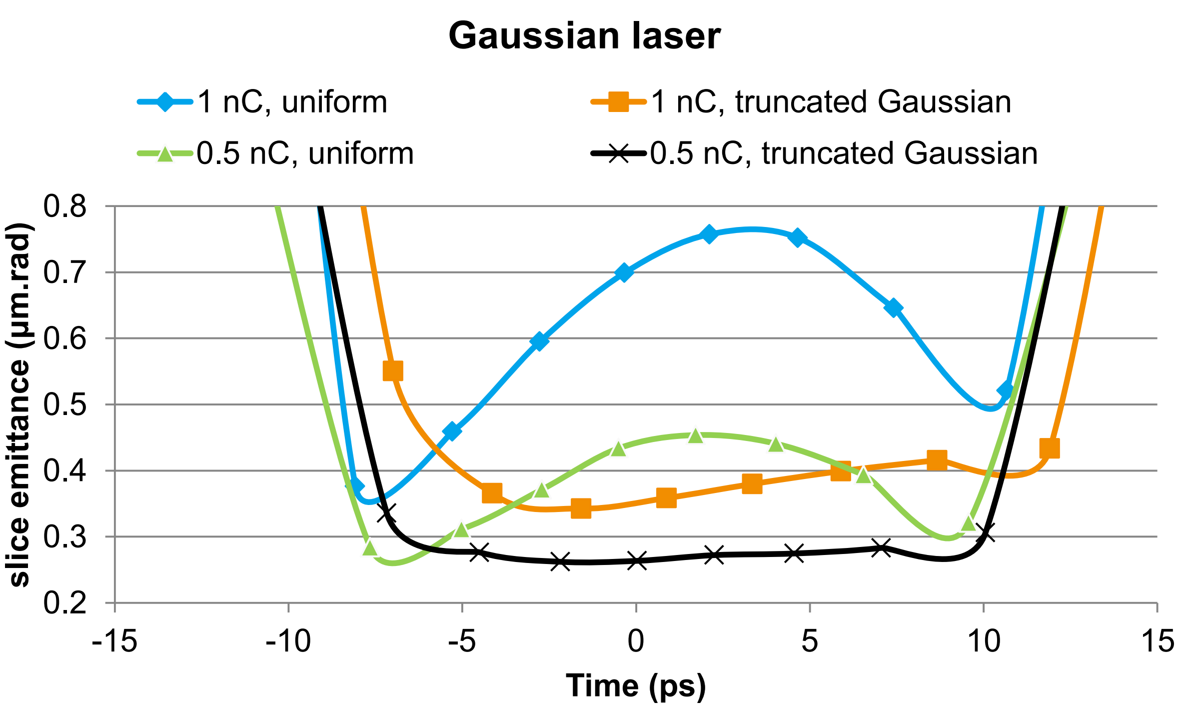


Laser shaping comparison

> XFEL case with Gaussian laser

- 12 ps at XFEL operation
- 18 ps in simulation here

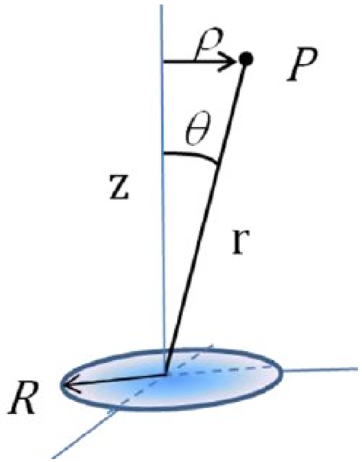
	0.5 nC		1 nC	
	100% proj.	core slice	100% proj.	core slice
uniform	0.68	0.44	1.1	0.73
Truncated Gaussian	0.58	0.27	0.87	0.37
improvement	15%	39%	21%	49%

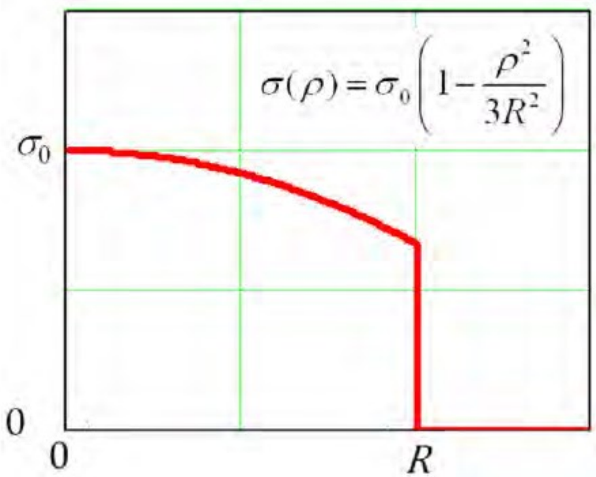


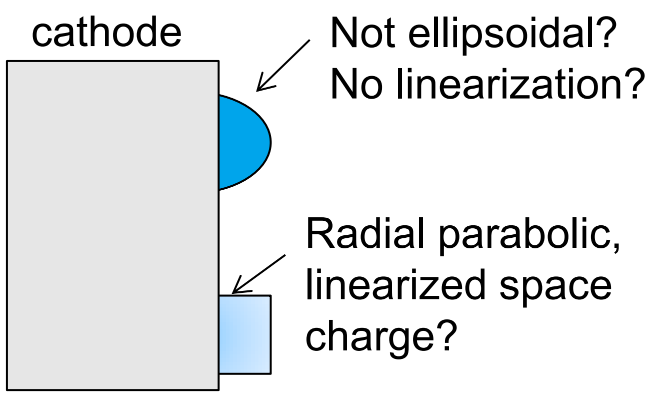
Truncated Gaussian is better than uniform!

Dowell’s distributions

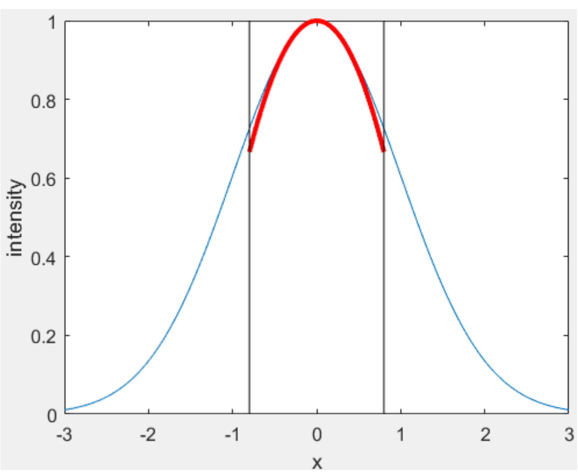
- D. Dowell shows a parabolic radial distribution can linearize transverse space charge



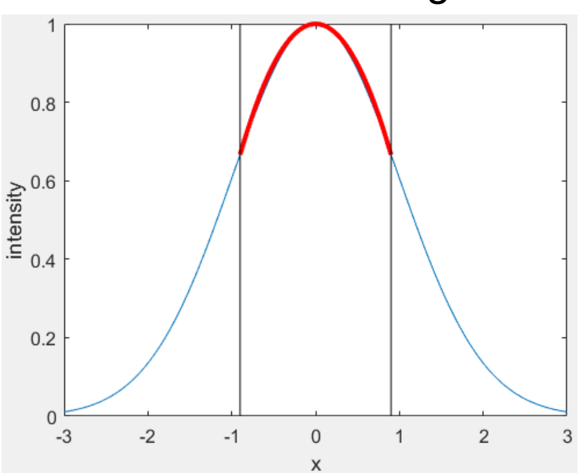




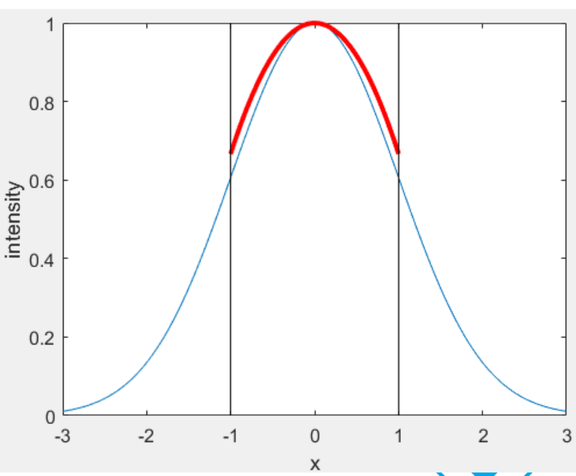
Truncation at 0.8 sigma



Truncation at 0.9 sigma



Truncation at 1.0 sigma



UV laser transverse shaping for truncated Gaussian

- A spatial filter before BSA
  - Clean Gaussian distribution
- A telescope before BSA
  - Tune Gaussian rms size, sigma=BSA/2
- …

Summary

- Simulations show transverse shaping is the key for improving core slice emittance, not longitudinal shaping.
  - Truncated Gaussian vs uniform distribution: 30% - 50% improvement
  - Truncated Gaussian vs Ellipsoidal: 25% improvement
- For 100% projected emittance
  - Truncated Gaussian vs uniform distribution

    1 nC: ~20% improvement
    0.5 nC: ~15% improvement
  - Flattop (Truncated Gaussian) vs Ellipsoidal

    1 nC: ~10% difference
    0.5 nC: negligible difference
- For current XFEL operation with Gaussian laser
  - 12 ps at XFEL, 18 ps in simulation here
  - Truncated Gaussian vs uniform distribution (for 18 ps)

    0.5 nC: ~39% improvement on core slice emittance, ~15% on proj. emittance
    1 nC: ~49% improvement on core slice emittance, ~21% on proj. emittance

Backup slides

- 1 nC

Ellipsoidal

core emittance

	100%	95%	90%	80%
horizontal:	0.4254	0.3230	0.2758	0.2035
vertical:	0.4256	0.3224	0.2752	0.2030
long.:	75.70	54.88	43.02	29.43

Parabola-uniform

core emittance

	100%	95%	90%	80%
horizontal:	0.7333	0.4764	0.3894	0.2741
vertical:	0.7277	0.4745	0.3877	0.2729
long.:	67.33	48.82	39.21	27.13

Parabola-truncated Gaussian

core emittance

	100%	95%	90%	80%
horizontal:	0.5255	0.3733	0.3136	0.2280
vertical:	0.5279	0.3738	0.3142	0.2283
long.:	68.92	51.84	41.44	28.47

Gauss-truncated Gaussian

core emittance

	100%	95%	90%	80%
horizontal:	0.8719	0.5041	0.4023	0.2761
vertical:	0.8638	0.5051	0.4032	0.2763
long.:	118.6	78.53	61.21	41.87

Gauss-uniform

core emittance

	100%	95%	90%	80%
horizontal:	1.108	0.6150	0.4627	0.2984
vertical:	1.109	0.6162	0.4636	0.2987
long.:	116.8	77.38	60.41	41.25

Flattop-truncated Gaussian

core emittance

	100%	95%	90%	80%
horizontal:	0.4644	0.3467	0.2950	0.2171
vertical:	0.4624	0.3461	0.2948	0.2172
long.:	73.21	54.06	45.67	33.04

Backup slides

- 0.5 nC

Ellipsoidal

core emittance

	100%	95%	90%	80%
horizontal:	0.2989	0.2356	0.2016	0.1485
vertical:	0.3008	0.2372	0.2028	0.1495
long.:	45.18	32.97	25.87	17.67

Parabola-uniform

core emittance

	100%	95%	90%	80%
horizontal:	0.4639	0.3090	0.2532	0.1809
vertical:	0.4669	0.3090	0.2529	0.1808
long.:	46.19	34.05	27.07	18.64

Parabola-truncated Gaussian

core emittance

	100%	95%	90%	80%
horizontal:	0.3514	0.2523	0.2103	0.1519
vertical:	0.3517	0.2522	0.2101	0.1516
long.:	50.12	37.23	29.48	20.35

Gauss-truncated Gaussian

core emittance

	100%	95%	90%	80%
horizontal:	0.5840	0.3385	0.2682	0.1842
vertical:	0.5840	0.3397	0.2695	0.1852
long.:	92.80	58.64	45.87	31.40

Gauss-uniform

core emittance

	100%	95%	90%	80%
horizontal:	0.6766	0.3898	0.2892	0.1882
vertical:	0.6796	0.3907	0.2891	0.1876
long.:	93.18	59.02	46.11	31.53

Flattop-truncated Gaussian

core emittance

	100%	95%	90%	80%
horizontal:	0.3077	0.2261	0.1917	0.1412
vertical:	0.3064	0.2250	0.1907	0.1402
long.:	52.60	38.18	32.22	23.03