XFEL Accelerator R&D Status
RP-216: Development and test of advanced photo cathode laser shaping at PITZ

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HELMHOLTZ

Scope of the R&D activity

- Important for x-ray FELs:

1) Future possible CW operation regimes at EuXFEL: lower accelerating gradient at the photo cathode and in the linac
2) Even shorter radiation wavelength with the existing pulsed EuXFEL

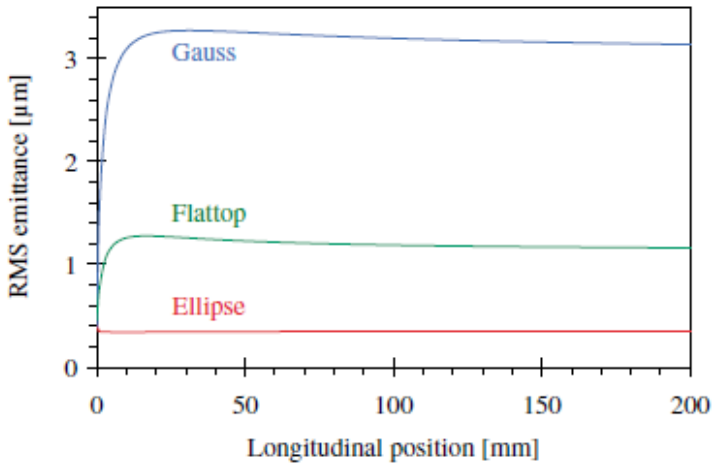
➢ To reach the required beam quality: laser beam shaping towards ellipsoidal pulses - and lower thermal emittance cathodes for 2) – can provide a path

1. High intensity → Reach saturation in undulator → Low transverse emittance
2. Short pulses (high time resolution) → Strong bunch compression → Linear longitudinal phase space
3. Protect machine → Minimal radiation damage of undulators → Minimize beam halo

Scope of the R&D activity

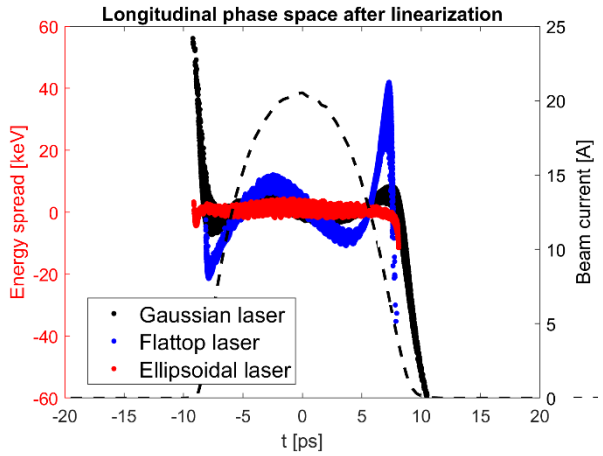
- Uniformly filled ellipsoid: I.M. Kapchinskii and V.V. Vladimirskii, in *Proceedings of the International Conference on High Energy Accelerators, CERN, Geneva* (Scientific Information Service CERN, Geneva, 1959), p. 274

Low transverse emittance



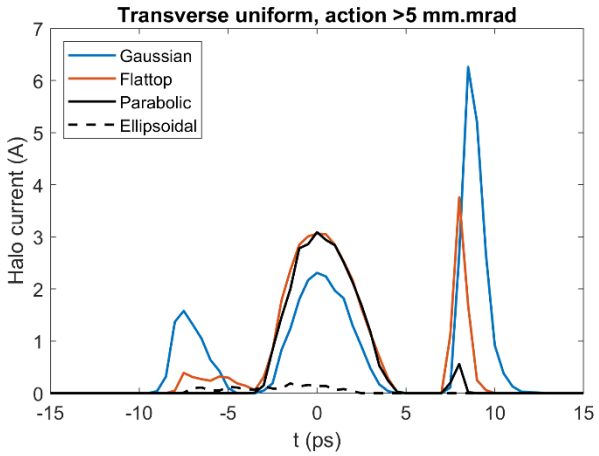
O. J. Luiten, S. B. van der Geer, M. J. de Loos, F. B. Kiewiet, and M. J. van der Wiel, Phys. Rev. Lett. 93, 094802 (2004)

Linear longitudinal phase space



Courtesy: Houjun Qian

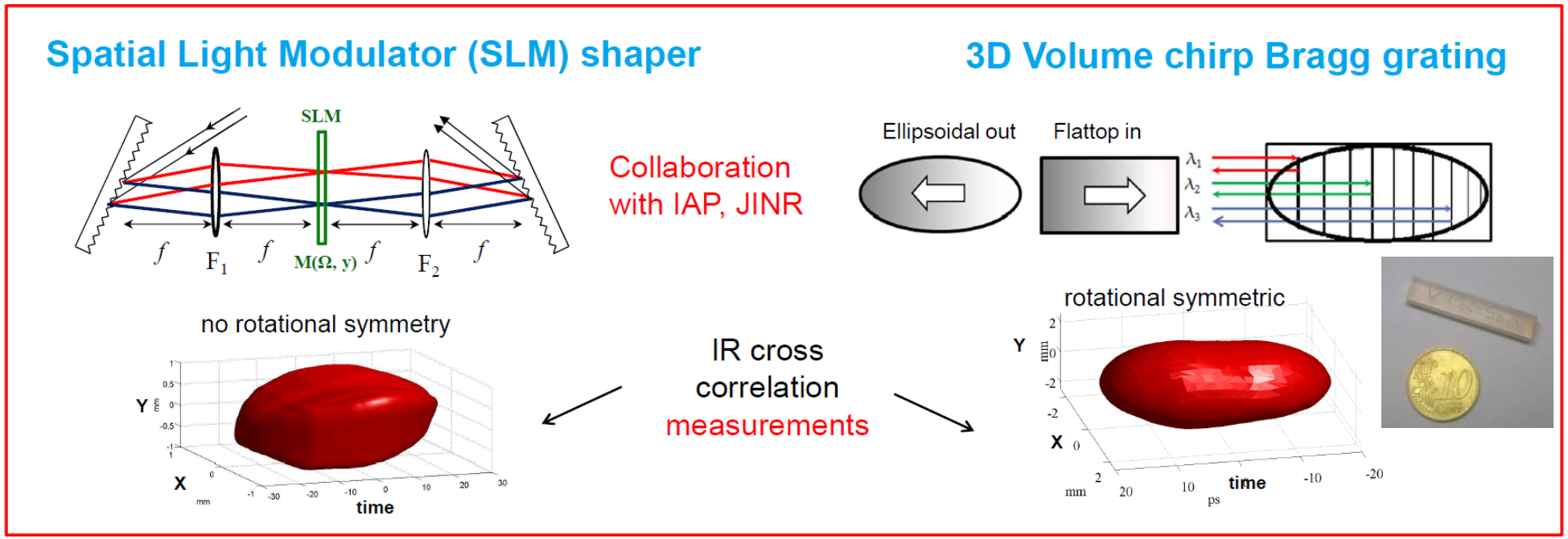
Minimize beam halo



Courtesy: Houjun Qian

Scope of the R&D activity

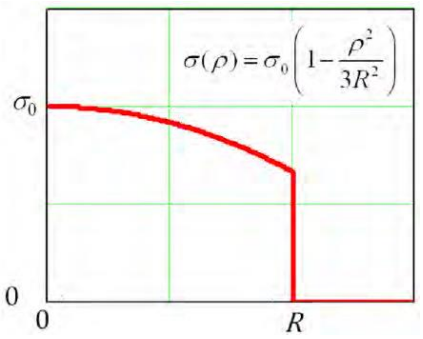
- Basic principle:

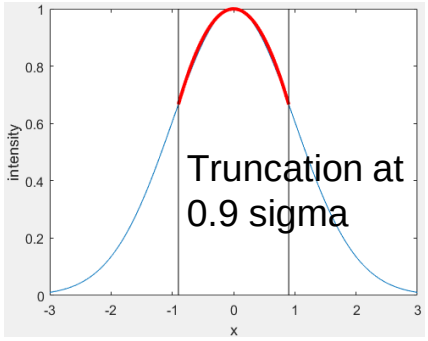


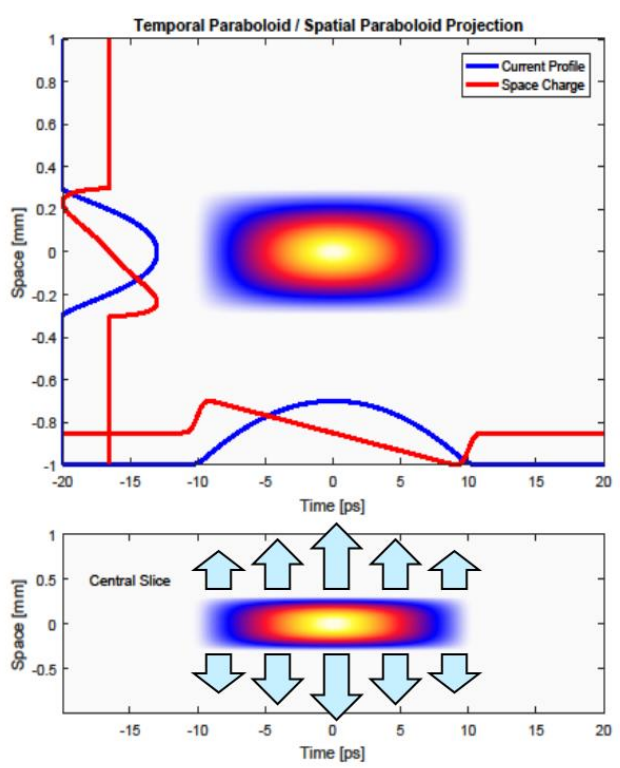
- Interface with other XFEL R&D or operation activities: XFEL-RP-214 Basic CW gun Research → photocathodes with high quantum efficiency in the green wavelength range

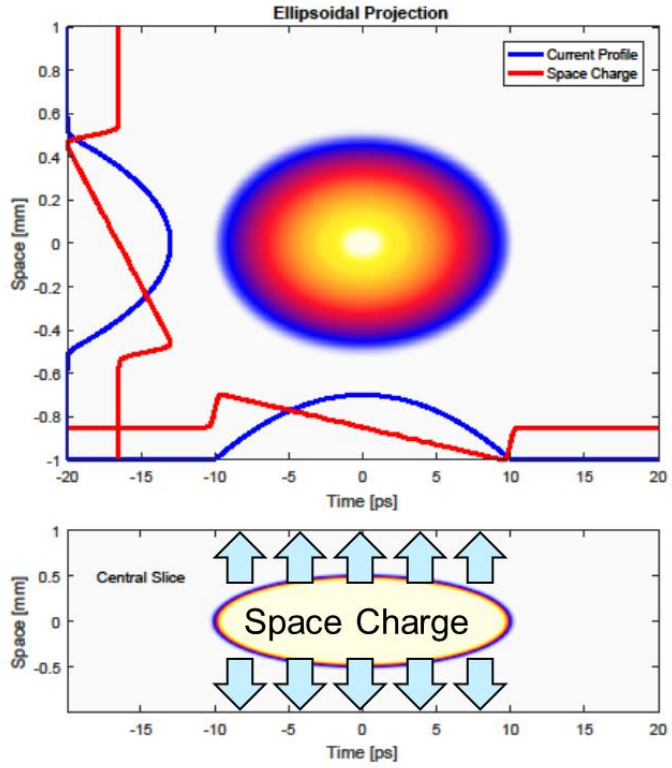
Achievements in the past year

- Looked into alternative: Approximation with Gaussian truncation
  - Much simpler setup compared to 3D shaping
- Why ‘1-σ’ Gaussian truncation?
  - Analytical prediction (***2013***, *T. Rao and D. Dowell, An engineering guide to photo injectors*):
  - A spatial parabolic radial distribution (= projection of ellipsoid) can linearize transverse space charge to the 3rd order









- “Quasi 3D Shaping”
  - Combining spatial and temporal 1D shaping

Achievements in the past year

$$B_{5D} = \sum_{sl=0}^{23} \frac{2 \cdot I_{sl}(t)}{\epsilon_{sl,x}(t) \cdot \epsilon_{sl,y}(t)}$$

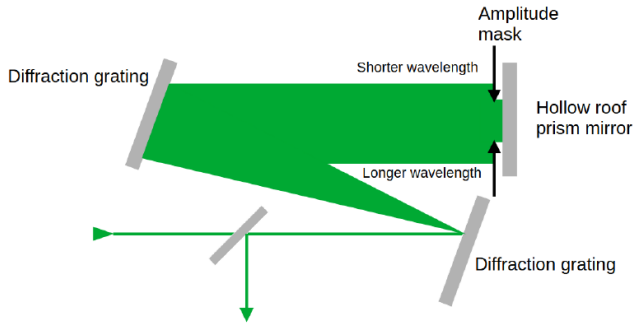
- Beam dynamics simulation at PITZ for different pulse shapes.

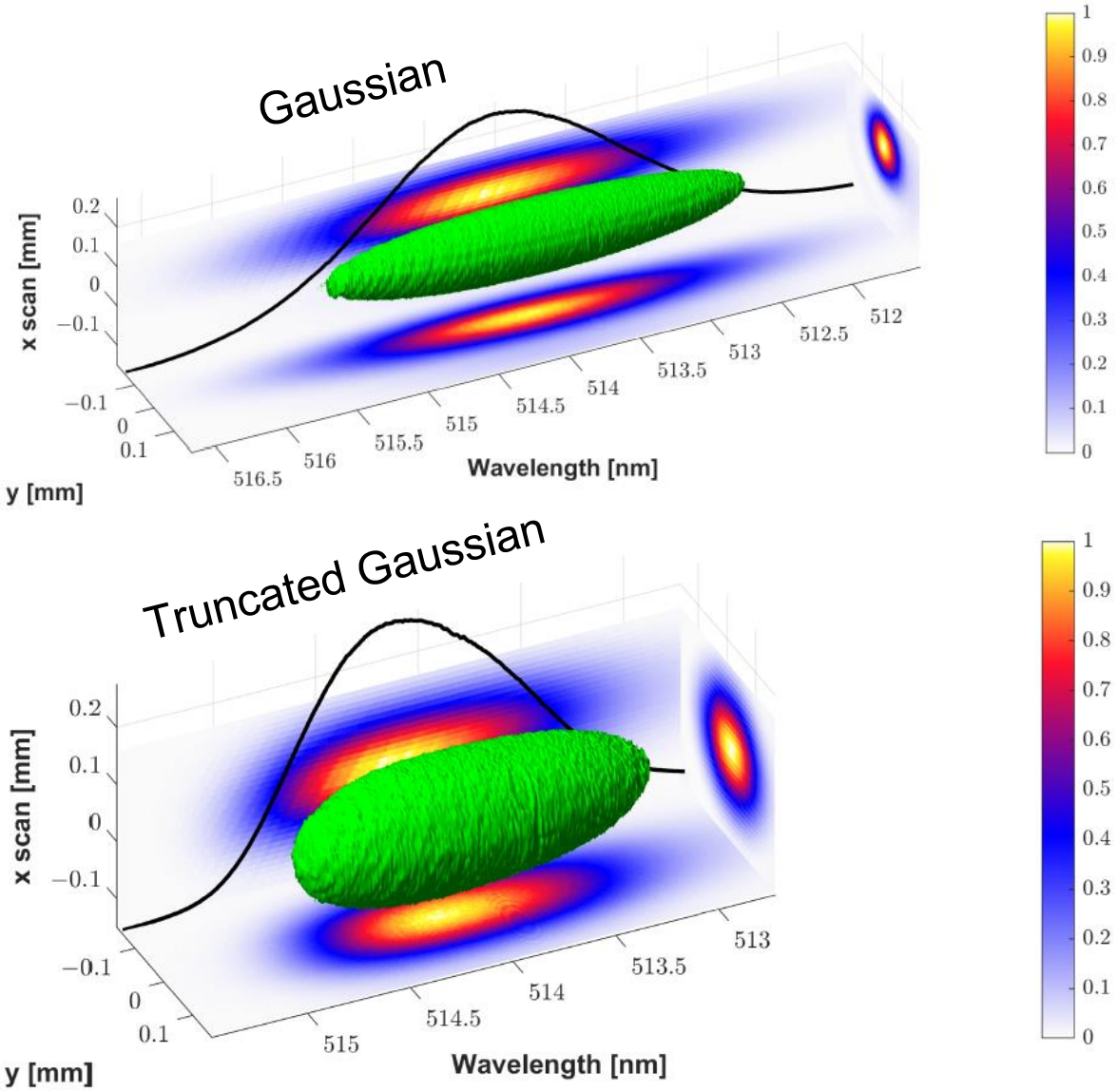
Longitudinal Shape	Transversal Shape	BSA [mm]	I_{Main} [A]	$\epsilon_{n,x}$ [mm · mrad]	σ_z [ps]	ϵ_z [keV · mm]	B_{5D} $[\frac{A}{\mu m^2}]$	Relative $\epsilon_{n,x}$ Reduction	B_{5D} Improvement
Gaussian	Radial uniform	1.1	373	0.535	5.09	32.3	3447	100%	1
Super-Gaussian	Truncated Gaussian (0.9σ)	1.3	374	0.439	4.78	25.6	4995	−18%	1.4
Flattop	Truncated Gaussian (0.9σ)	1.3	374	0.339	4.17	17.5	7162	−37%	2.1
Parabolic	Truncated Gaussian (0.9σ)	1.3	374	0.318	4.26	16.9	8909	−41%	2.6
Truncated Gaussian (1.5σ)	Truncated Gaussian (0.9σ)	1.1	374	0.297	4.25	17.4	9647	−45%	2.8
Ellipsoidal	Truncated Gaussian (0.9σ)	1.1	376	0.242	4.29	13.7	12,775	−55%	3.7

- Beam properties of truncated Gaussian bunches approaches those of ellipsoids

Achievements in the past year

- Generation of a truncated Gaussian laser pulse and characterization with an imaging spectrograph





- Outlook: Better quality with NEPAL (Finisar waveshaper). Then: electron beam characterization (emittance …)

Deviations from plan

- 2024 milestones not reached:
- 1) Improvements in laser shaping system to allow 24/7 operation at a user facility (Long-term stability of pulse-shaping units)
  - Delays due to, mostly, lack of manpower. Proposal: finish work in Q4/2025
- 2) Technology for optimized ellipsoidal laser shaping at UV and green wavelength is ready to be copied at European XFEL user facility
  - Practical approach based on results found in 2024/2025: replace full 3D-ellipsoid with temporal and transverse truncated Gaussian, which is a good approach to reach similar beam quality with much simpler system (can be done in IR with NEPAL, e.g. for XFEL and PITZ, and can be done with PHAROS, e.g. for TS4i).
  - Proposal: Change to 'Technology for practical laser shaping at European XFEL user facility is ready as a concept' - finish work in Q4/2025
- No consequences for further work since project ends in 2025

Timeline of this R&D activity

Proposed Date	Milestone Description	Updated Date
Q2/2023	First beam characterization and emission study for ellipsoidal laser pulses in the green wavelength range at reduced gun gradients Extension: Emittance studies of ellipsoidal electron bunches generated in the “blow-out-regime”	Done: Q3/2024, but not yet conclusive Q2/2024
Q4/2023	Further improvement of ellipsoidal shaping technique by modulating the 3D density distribution	Done with flat top: Q3/2023
Q2/2024	Improvements in laser shaping system to allow 24/7 operation at a user facility (this includes the green wavelength range) Done: Laser, green stretcher, UV Conversion, transport beamline to cathode Open: Long-term stability of pulse-shaping units	Q2/2024 Proposal: Q4/2025
Q4/2024	Technology for optimized ellipsoidal laser shaping at UV and green wavelength is ready to be copied at European XFEL user facility* Proposal: Technology for practical laser shaping at European XFEL user facility is ready as a concept	 Proposal: Q4/2025

* Practical approach based on results found in 2024/2025: replace full 3D-ellipsoid with temporal and transverse truncated Gaussian. Improvement in emittance and brightness is almost as high and no special laser system is needed (can be done in IR with NEPAL, e.g. for XFEL and PITZ, and can be done with PHAROS, e.g. for TS4i). The concept could be developed into a final product in future R&D for the EuXFEL.

Risks to R&D Project

- No risks anticipated in the last 4 months of the project

Outlook / Summary

- Planned activities for this year: finish project with the following:
  - Test long-term stability of pulse-shaping units (Ellipsoidal)
  - Work on technology for practical laser shaping concept (Truncated Gaussian)

- Plan for a **follow-up proposal**:
  - Optimizing laser pulse shapes: truncated Gaussian, in cooperation with OPAL-FEL
  - Projected and slice emittance measurements with shaped electron bunches / simulations at PITZ
  - Simulation of EuXFEL injector and start-to-end to set up measurements with shaped pulses at the EuXFEL
  - Comparison with 3D shaped laser pulses

- **List of publications** / conference proceedings connected to this activity
  - A. Hoffmann, J. Good, M. Gross, M. Krasilnikov, and F. Stephan, “Towards Implementation of 3D Amplitude Shaping at 515 nm and First Pulse shaping Experiments at PITZ”, *Photonics* **11** (2023), p. 6 (15 pages)
  - A. Hoffmann, S. Zeeshan, J. Good, M. Gross, M. Krasilnikov, F. Stephan, “Efficient Generation of Transversely and Longitudinally Truncated Chirped Gaussian Laser Pulses for Application in High-Brightness Photoinjectors”, *Photonics* **12** (2025), p. 460 (19 pages)