Laser Pulse Shaping for Electron Injectors

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Agenda

Introduction

Laser pulse shaping at PITZ

- 3D: Ellipsoidal pulses
- 3D: Other shapes
- Transverse: Truncated Gaussian

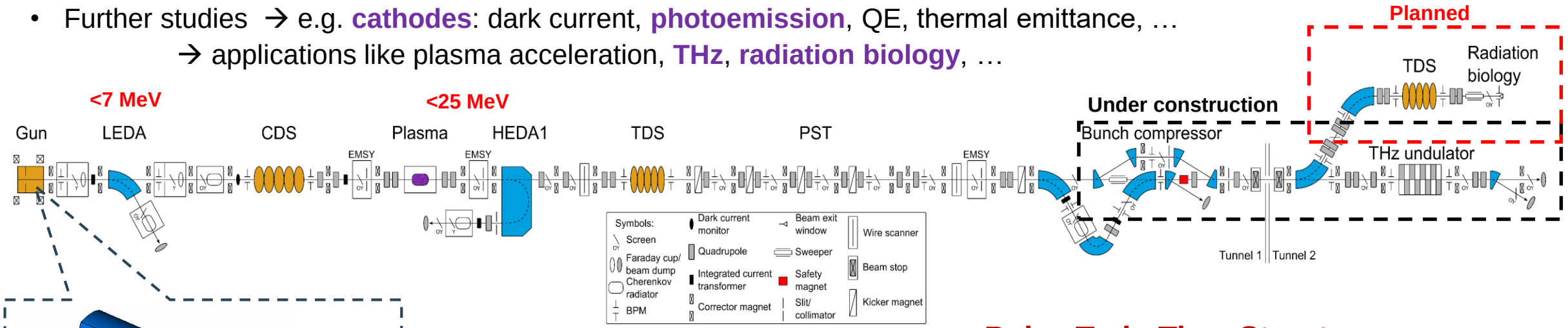
PITZ strategy

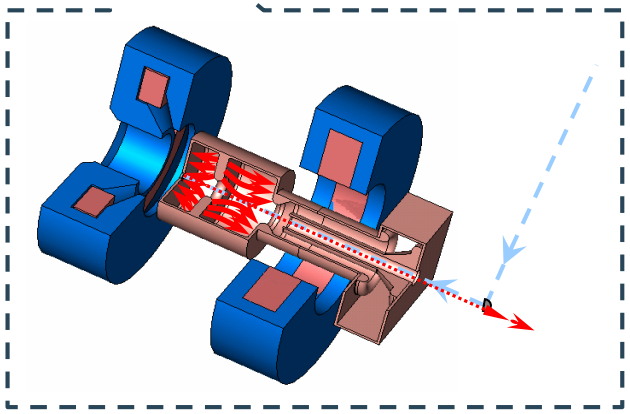
Summary

Photo Injector Test facility at DESY, Zeuthen site (PITZ)

Development, test and optimization of high brightness electron sources for SC linac driven FELs + applications:

- Test-bed for FEL injectors, e.g. **FLASH** and **European XFEL** (**gun cavities** and photo injector subsystems → e.g. **lasers**)
- **High brightness → small** ε_{tr} (projected and slice), **lots of beam diagnostics**
- Further studies → e.g. **cathodes**: dark current, **photoemission**, QE, thermal emittance, …
  → applications like plasma acceleration, **THz**, **radiation biology**, …



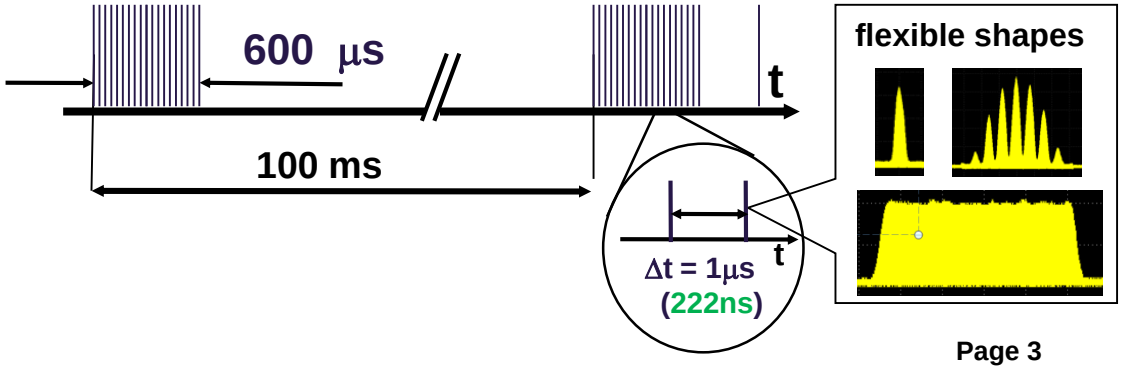


RF gun

- L-band (1.3 GHz) 1.6-cell copper cavity
- Ecath **>~60MV/m** → 7MeV/c e-beams
- 650us x 10Hz → up to **45 kW** av. RF power
- Cs_2Te PC (QE~5-10%) → up to 5nC/bunch
- LLRF control for amp & phase stability
- Solenoids for emittance compensation

Pulse Train Time Structure:

PITZ and **EXFEL** run bunch trains with up to 600 (**2700**) laser pulses



Introduction: Why Laser Pulse Shaping?

Main application for PITZ photoinjector studies: x-ray FEL (FLASH, EuXFEL)

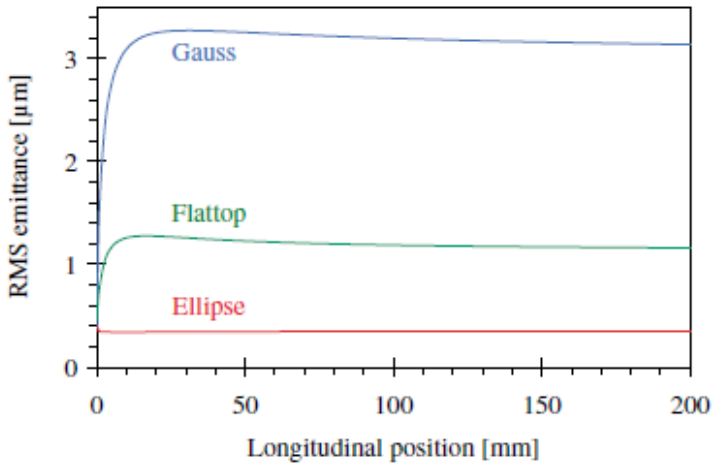
- Important for x-ray FELs:

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

Ideal Solution: Ellipsoidal Pulse Shape

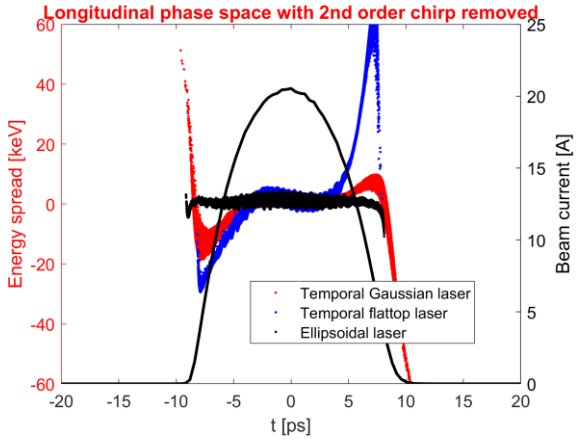
Uniformly filled ellipsoid: I.M. Kapchinskii and V.V. Vladimirskii, in *Proceedings of the International Conference on High Energy Accelerators, CERN, Geneva* (Scientific Information Service CERN, Geneva, 1959), p. 274

Low transverse emittance



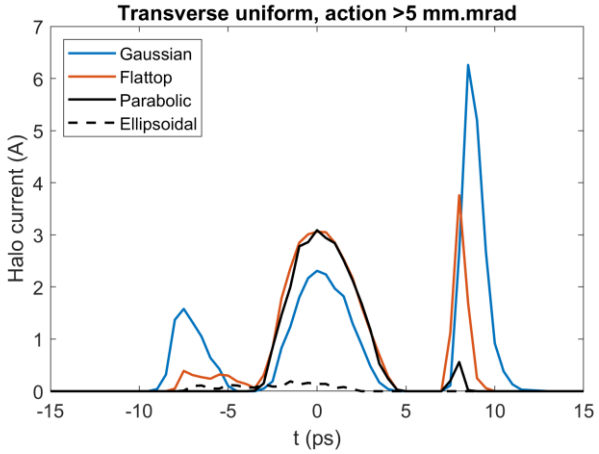
O. J. Luiten, S. B. van der Geer, M. J. de Loos, F. B. Kiewiet, and M. J. van der Wiel, Phys. Rev. Lett. 93, 094802 (2004)

Linear longitudinal phase space



Courtesy: Houjun Qian

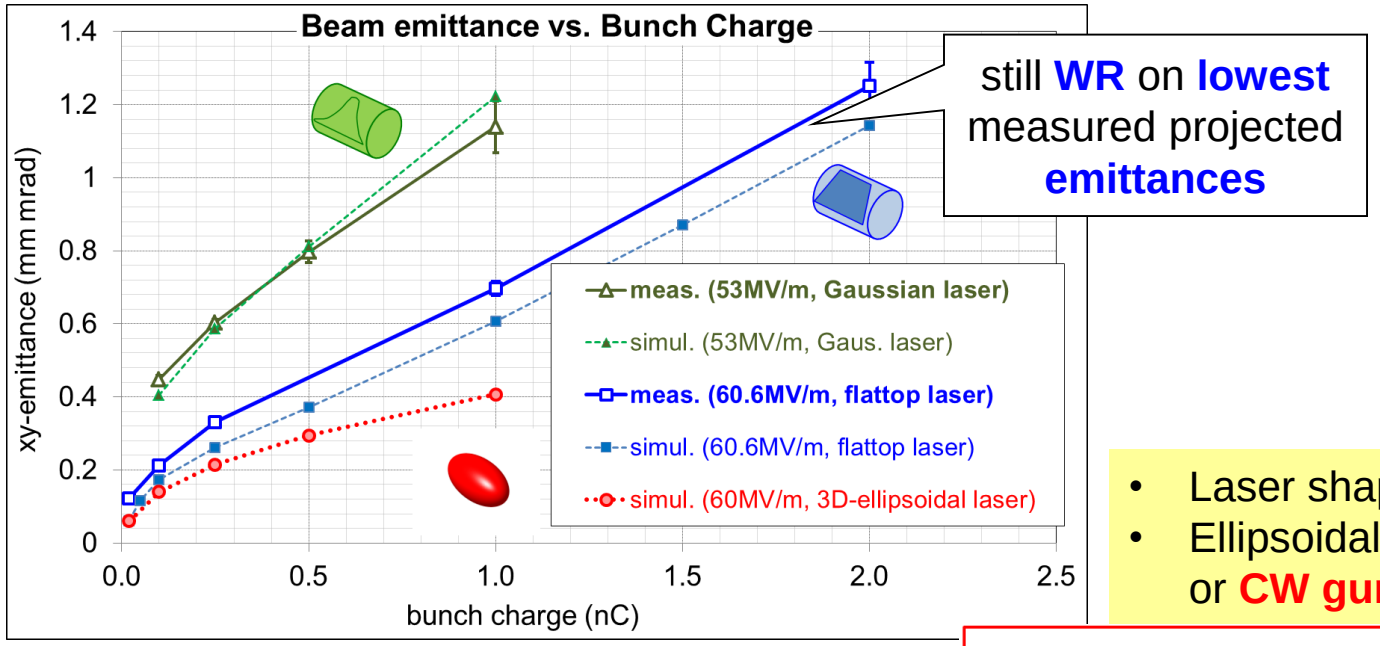
Minimize beam halo



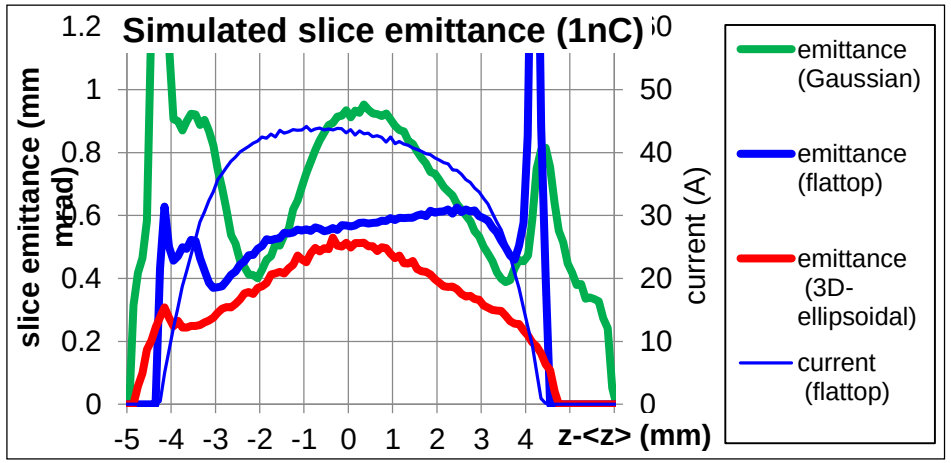
Courtesy: Houjun Qian

Generating Ellipsoidal Pulses at PITZ

Beam dynamics simulations and collaboration with Khazanov group at RAS IAP since 2010



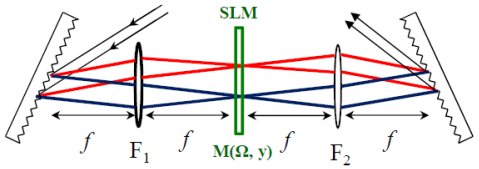
still **WR** on **lowest** measured projected **emittances**



- Laser shaping → **key** for optimizing photoinjector **brightness**.
- Ellipsoidal laser shaping benefits **high bunch charge** beams or **CW guns** (lower gun gradients).

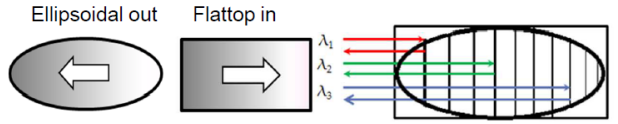
- Two methods to generate 3D ellipsoidal photo cathode laser pulses are under study:
  - Mironov et al., *Appl. Opt*. **55**, p. 1630 (2016)
  - Mironov et al., *Laser Phys. Lett.* **13**, p. 055003 (2016)

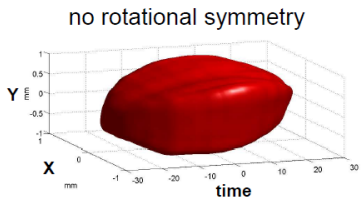
Spatial Light Modulator (SLM) shaper



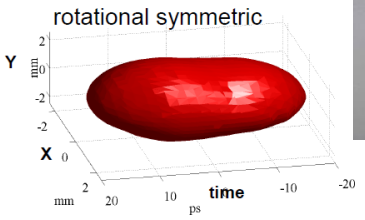
Collaboration with IAP, JINR

3D Volume chirp Bragg grating

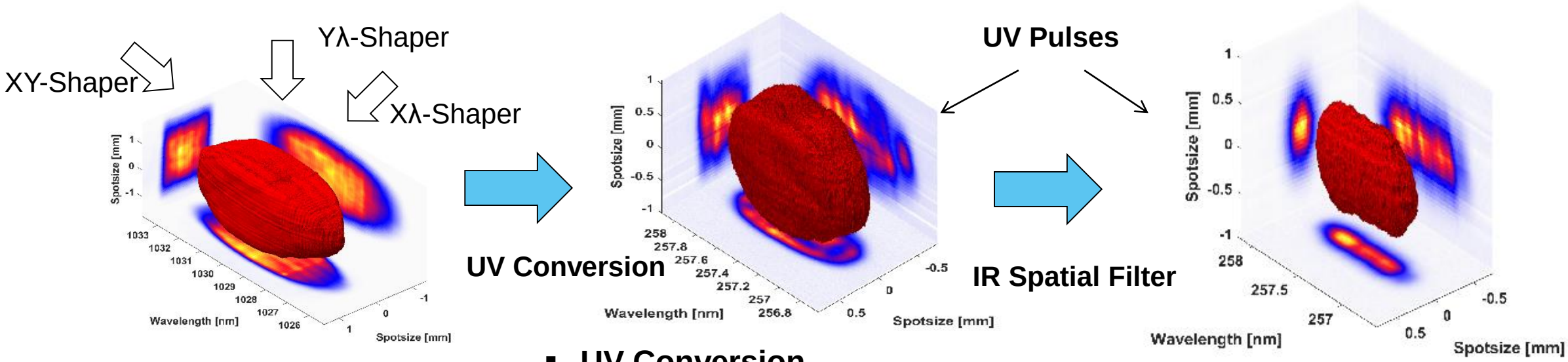




IR cross correlation measurements



Latest Experimental Results at PITZ

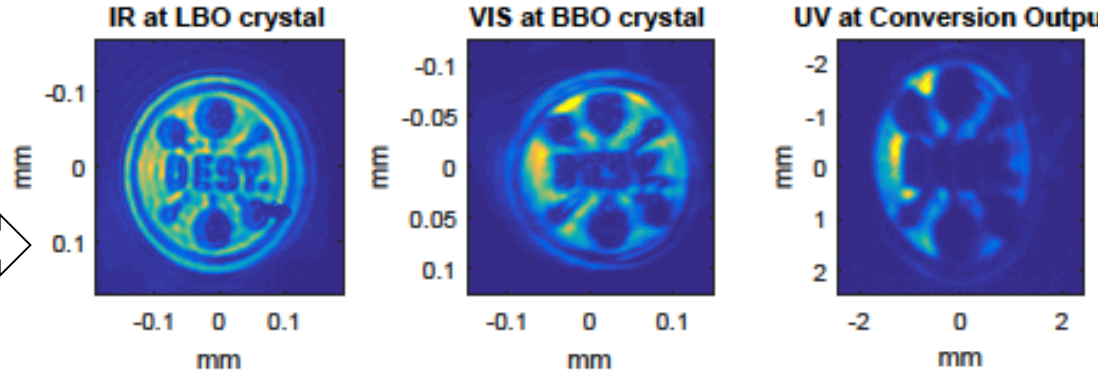


- **IR Shaping**
  - 3 SLM Shapers allow for shaping of all 3 projections
  - Direct feedback loops with IR-Spectrograph allow high quality shaping

- **UV Conversion**
  - 4th harmonic nonlinear conversion heavily exaggerates small non-uniformities
  - Possibly insufficient optical resolution

- **Spatial Filtering**
  - With spatial filtering non-uniformities are removed
  - Temporal/spectral shaping still possible. Some emittance reduction possible in this mode.

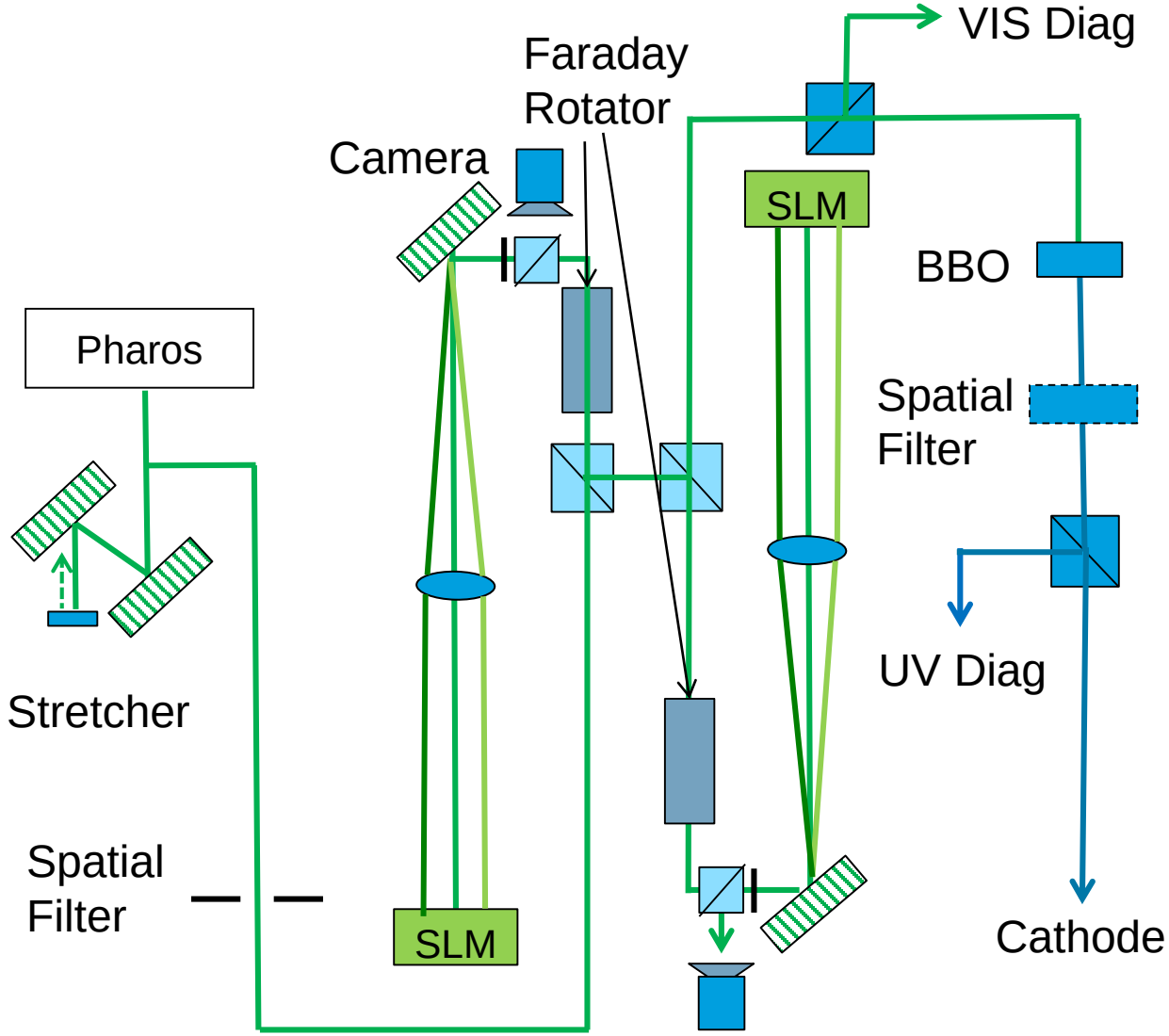
Transverse Shaping through conversion



Next steps

- Biggest problem: conversion from IR to UV (2x SHG)
- New approach: do SLM shaping in the green wavelength region
  - Only one SHG conversion step → improved pulse homogeneity

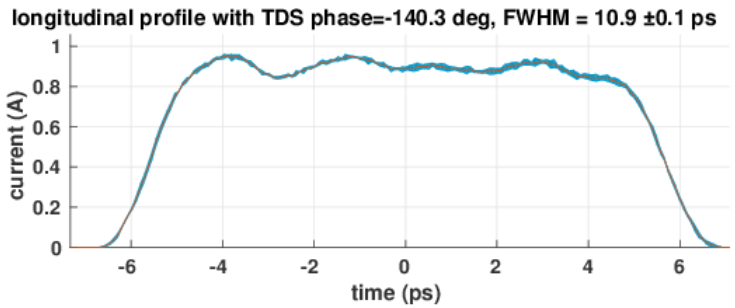
First results are expected this year



Other SLM Pulse Shaping Possibilities

Utilizing the flexibility of SLM shaping

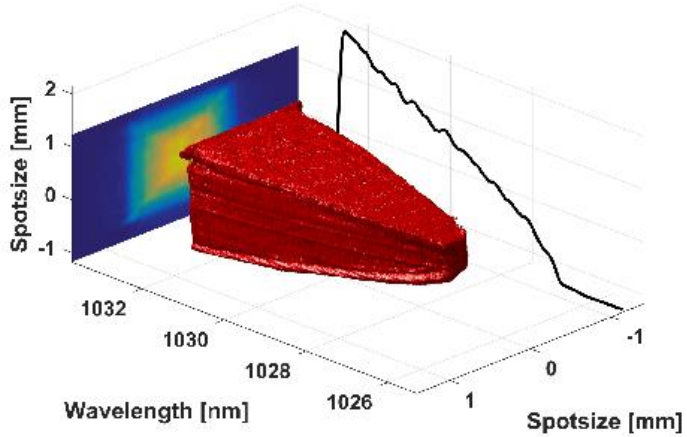
- Longitudinal flat top



- Emittance reduction for photoinjectors
  - Pulse length can be extended to 20 ps or more – restricted in this experiment by seed laser pulse length

See e.g.: M. Krasilnikov et al., *PRST-AB* **15**, 100701 (2012)

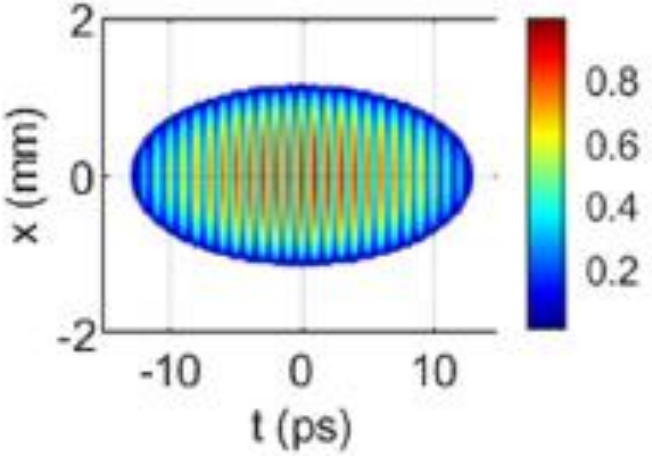
- Cone



- Application: high transformer ratio plasma wakefield acceleration
  - Idea: keep charge density constant for varying beam diameter

See e.g.: G. Loisch et al., *PRL* **121**, 064801 (2018)

- Modulated pulse



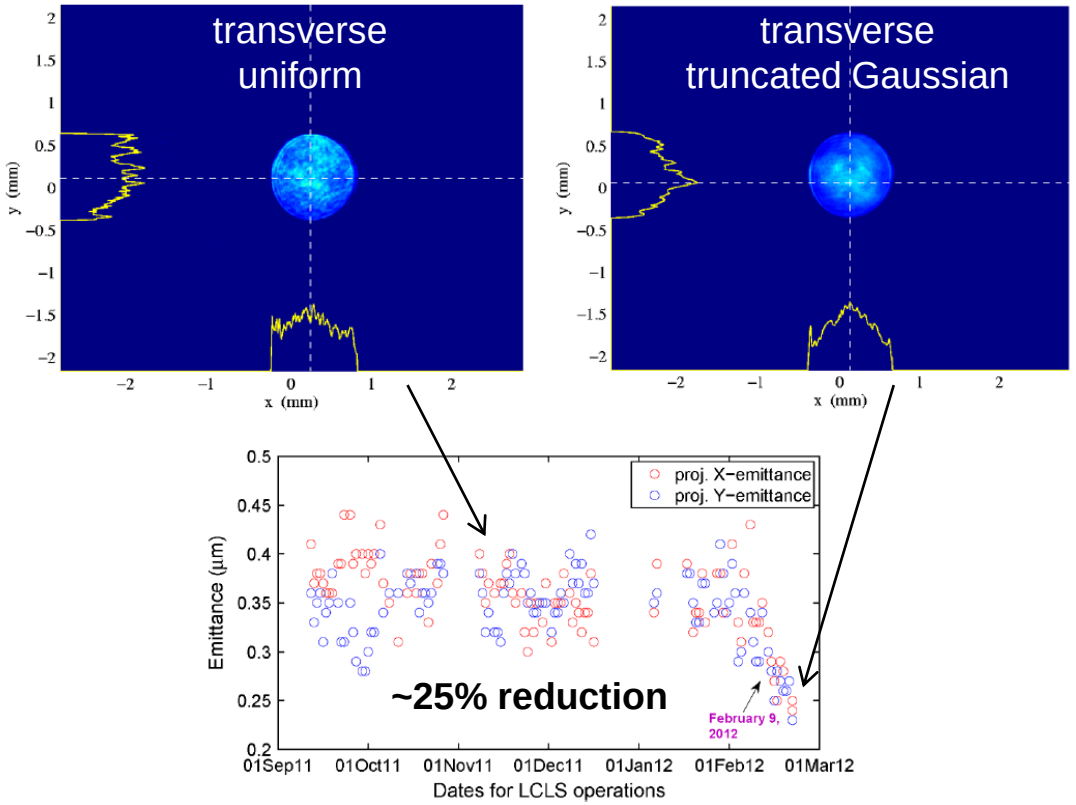
- Application: Seeding of THz SASE FEL

From: I. Kuzmin et al., „Shaping picosecond ellipsoidal laser pulses with periodic intensity modulation for electron photoinjectors", *Applied Optics* **59**, 2776 (2020)

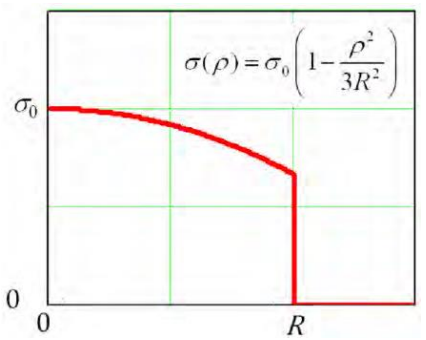
Alternative: Approximation with Gaussian truncation

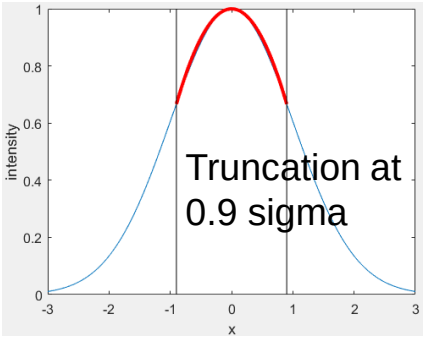
Much simpler setup compared to 3D shaping

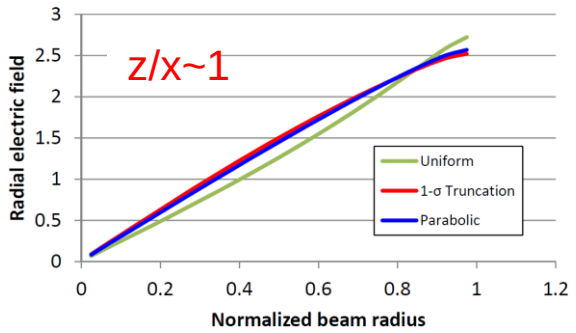
- **2012**, LCLS experience: (*PRST-AB* **15**, 090701)
  - 150 pC, ~1.3 ps (rms) laser
  - Uniform → 1.1-σ Gaussian truncation



- Why '1-σ' Gaussian truncation?
  - Analytical prediction (***2013***, *T. Rao and D. Dowell, An engineering guide to photo injectors*):
  - A special parabolic radial distribution can linearize transverse space charge to the 3rd order

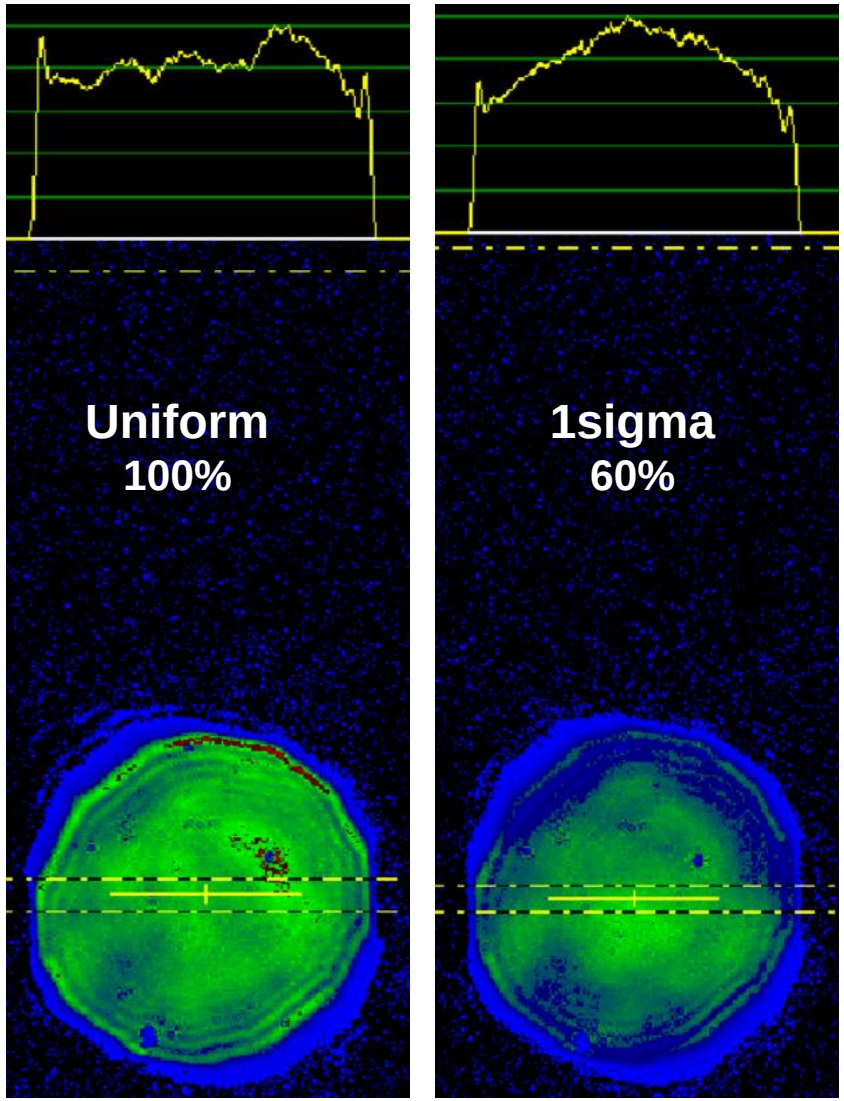


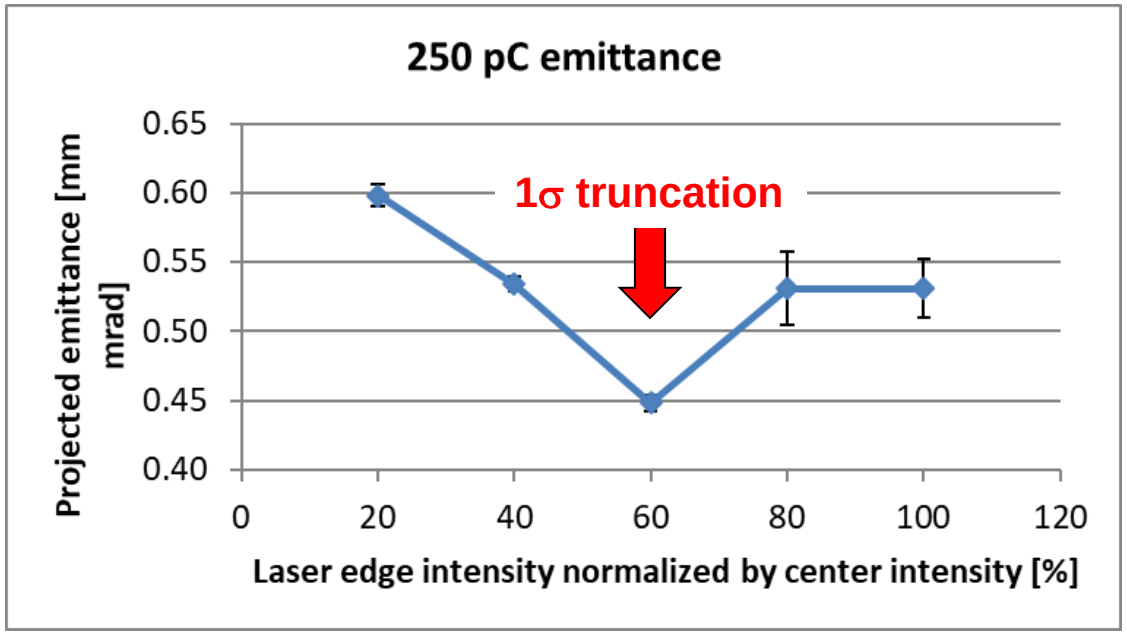




Experimental Results at PITZ

Thorough investigation of effect by transverse truncation



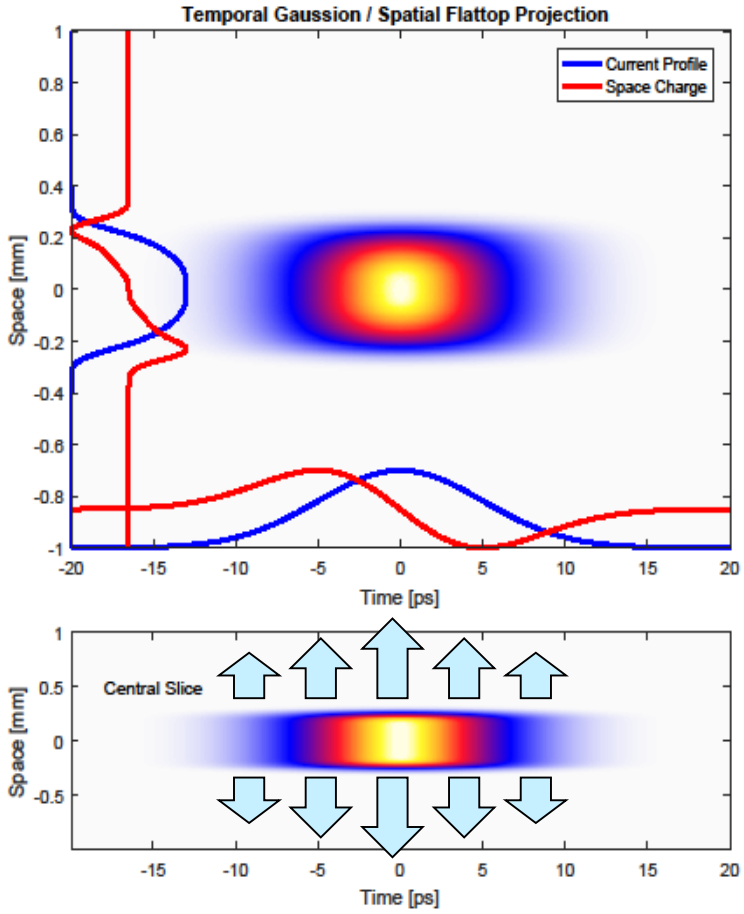


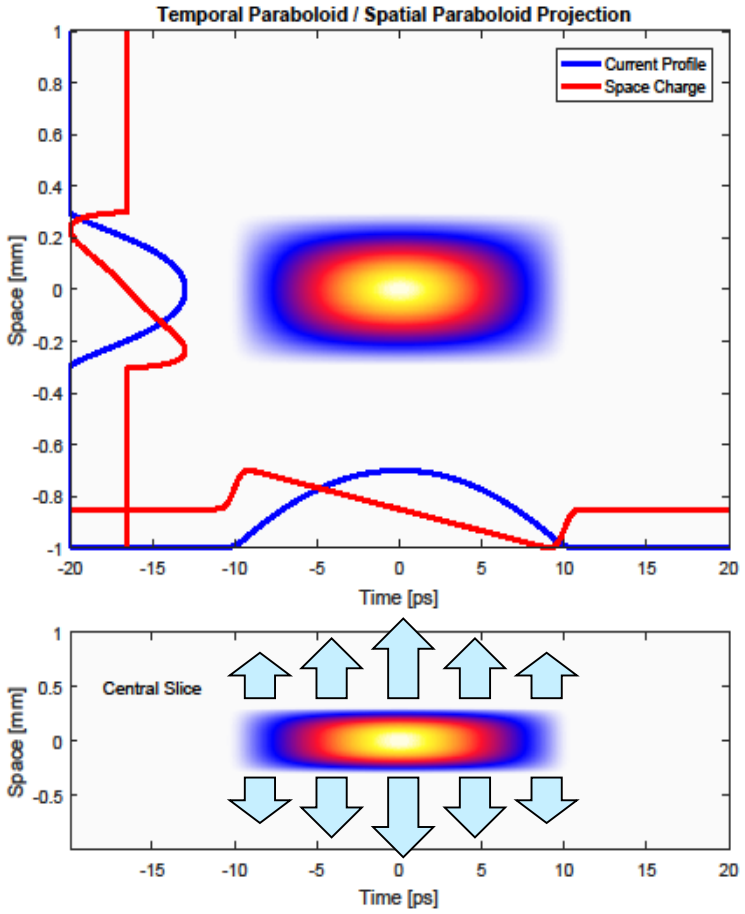
- The emittance reduction from flat-top to optimal case (1σ-truncation): 15%
- Pulse energy is increased by 4.8x

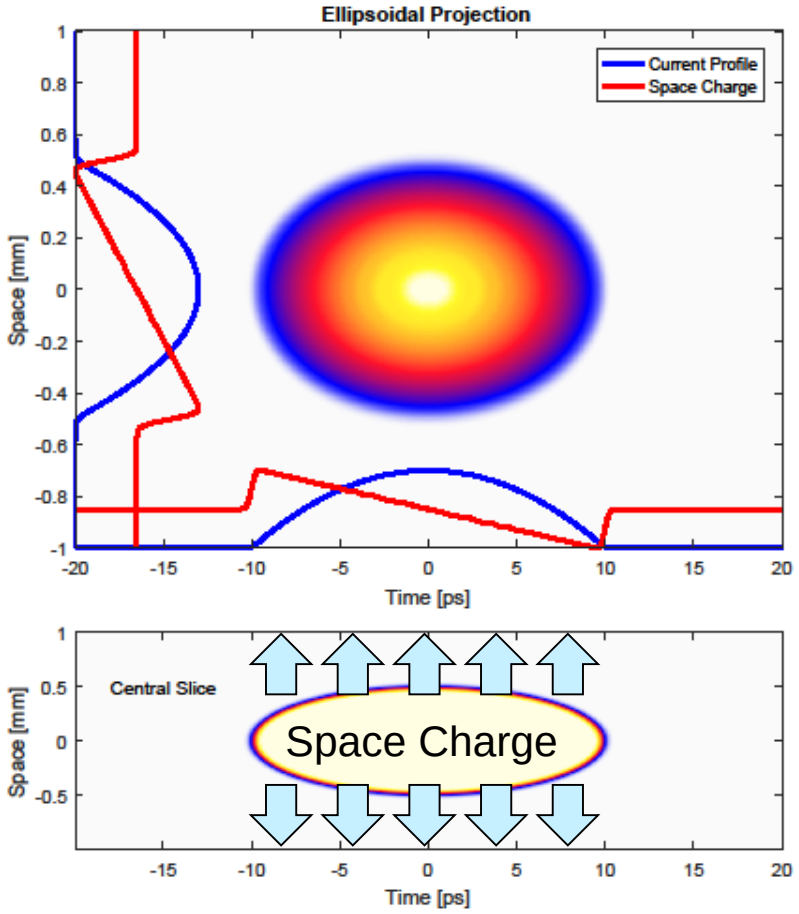
From: M. Gross et al., „Characterization of low emittance electron beams generated by transverse laser beam shaping", Proc. of IPAC 2021

Next Possible Step: “Quasi 3D Shaping”

Combining spatial and temporal 1D shaping



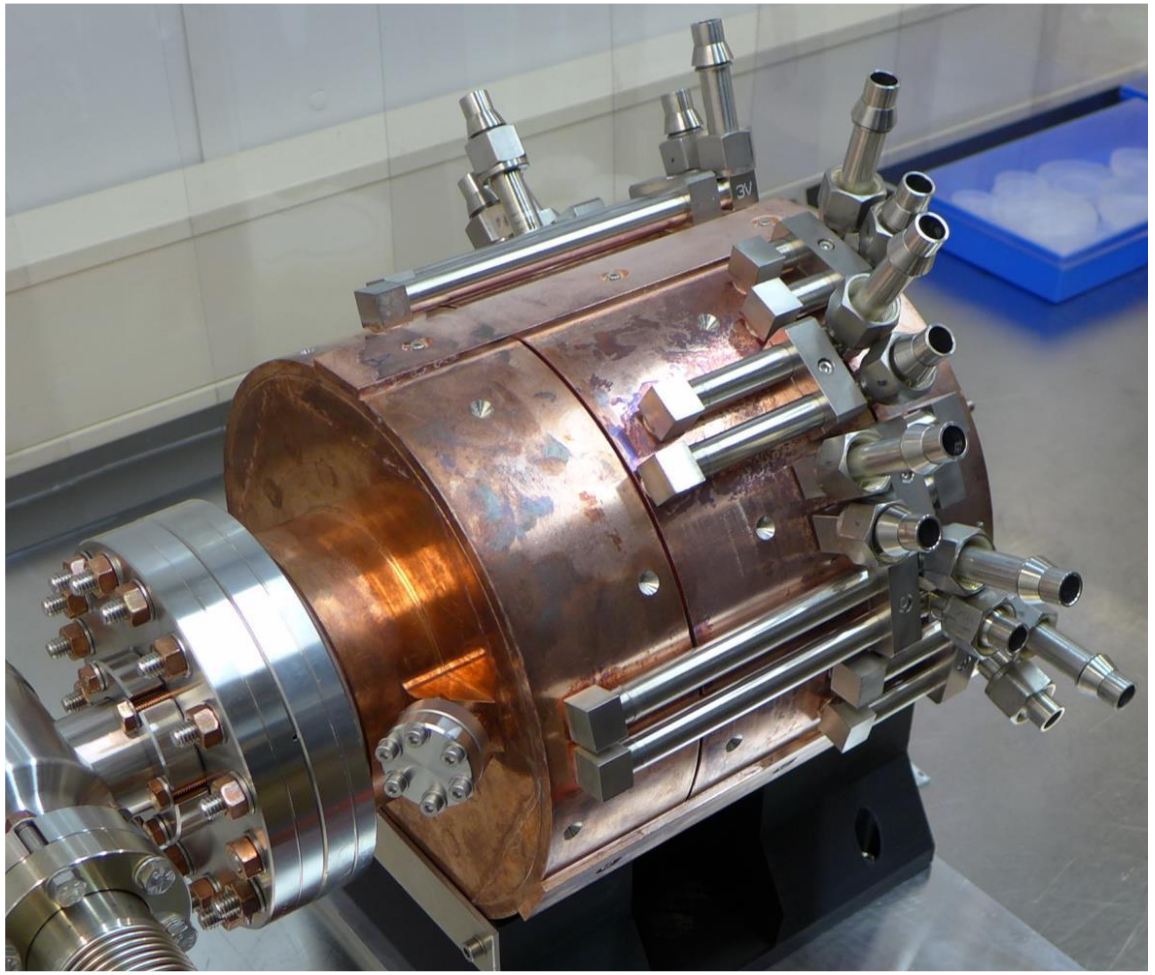




PITZ Strategy

Laser needs

- Latest gun development: 5th generation with some new features:
  - Optimization of inner surface contours
    - → Reduce dark current
  - RF pickup in gun body
    - → Better RF amplitude and phase stability
  - Optimization of water cooling channels
    - → Can afford higher average power. Goal: 6.5MW peak power at 1 ms RF pulse length



Together with

- Laser that can produce long trains of shaped pulses
- Low emittance green photocathode

→ Further peak and average brightness improvement

Summary

- Laser pulse shaping is advantageous for seeding photoinjector of x-ray FEL
  - High intensity
  - Short pulses
  - Protect machine
- Optimal laser pulse shape: ellipsoid
- Approximation: truncated Gauss / quasi 3D shaping
  - Advantage: much simpler setup
- PITZ is running an R&D program to advance laser pulse shaping for photoinjectors

Thank you

Contact

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