Commissioning of the new Injector Laser System for the Short Pulse Project at FLASH

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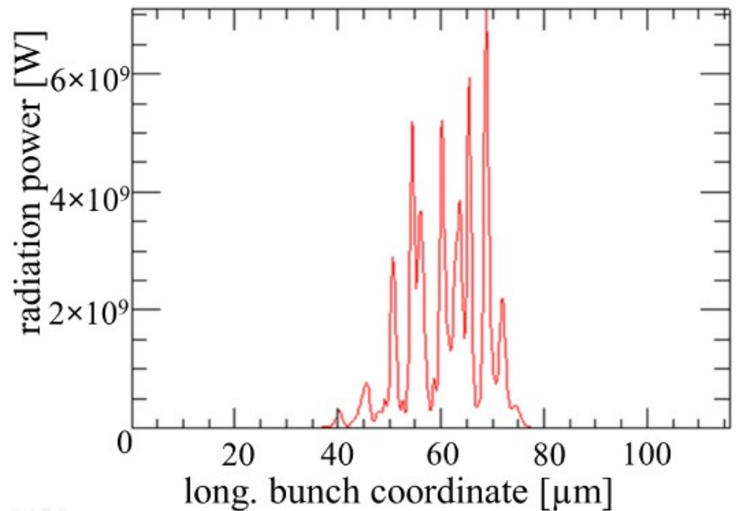
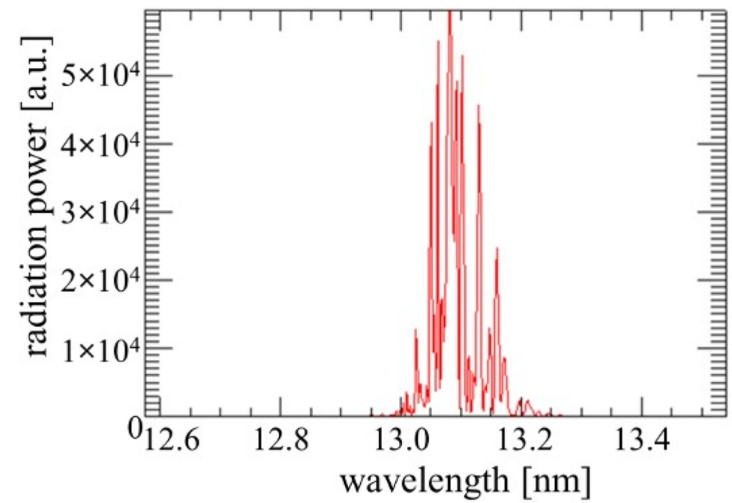
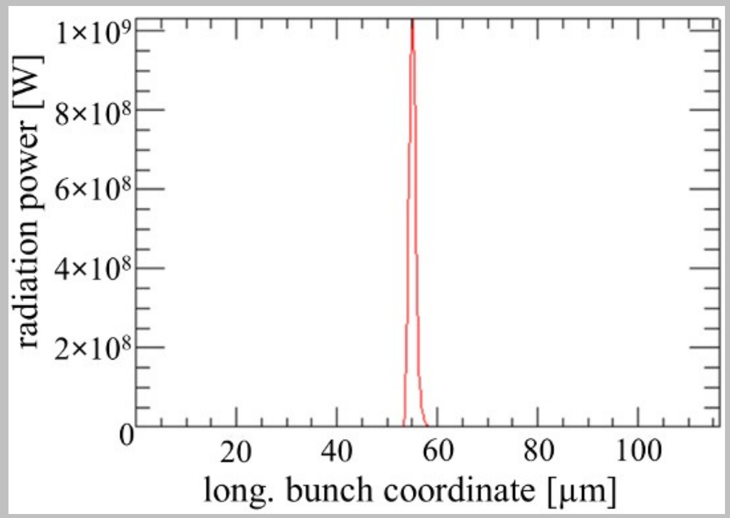
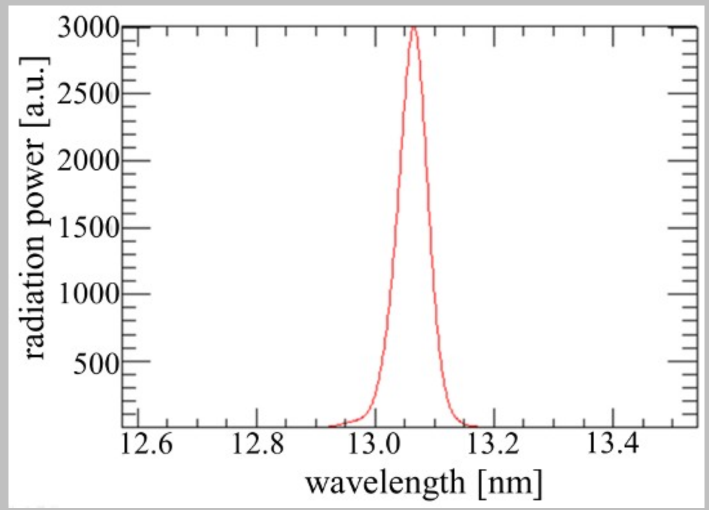
05.11.2013

Supported by BMBF under contract 05K10GU2 & FS FLASH 301

Motivation

- short pulses allow for time-resolved imaging of nanoparticles

Motivation

e⁻ bunch length (Gaussian, rms)	Long. distribution of FEL pulse	FEL pulse spectrum
10 μm (30 fs) 200 pC **standard short pulse operation**		
1 μm (3 fs) 20 pC (single spike) **Our Goal**		

GENESIS 1.3 Simulation

Courtesy of M. Rehders

The Project

The short-pulse project at FLASH

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HELMHOLTZ | ASSOCIATION

TECHNISCHE UNIVERSITÄT DARMSTADT

Supported by BMBF under contract 05K10GU2 & FS FLASH 301

- Beam dynamics calculations
  Start-to-end simulations
- Diagnostic Development
  for Small Charges
- Commissioning of
  the new photo-injector Laser
  - Laser System
  - Diagnostics

Outline

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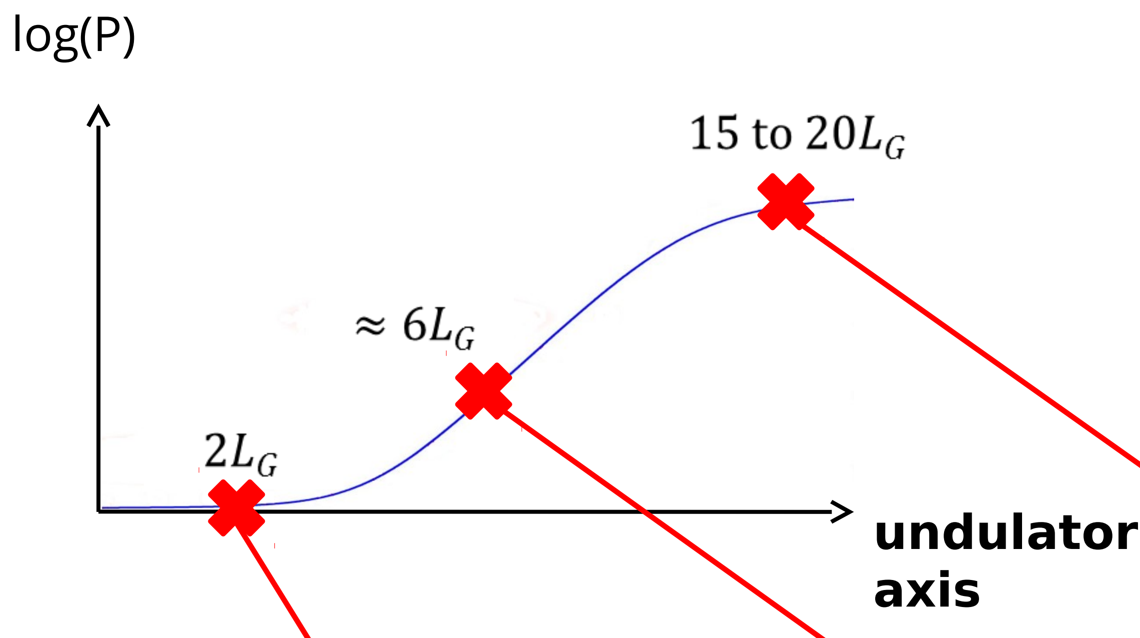
Lasyer System	What are the requirements for a short FEL pulse? How can we shorten the electron bunch? The New Laser System. Optimisation of Laser Parameters for Short Bunch Length and Low Emittance
Diagnostics	Laser Diagnostics
Shifts	First Results and SASE generation

FEL Process

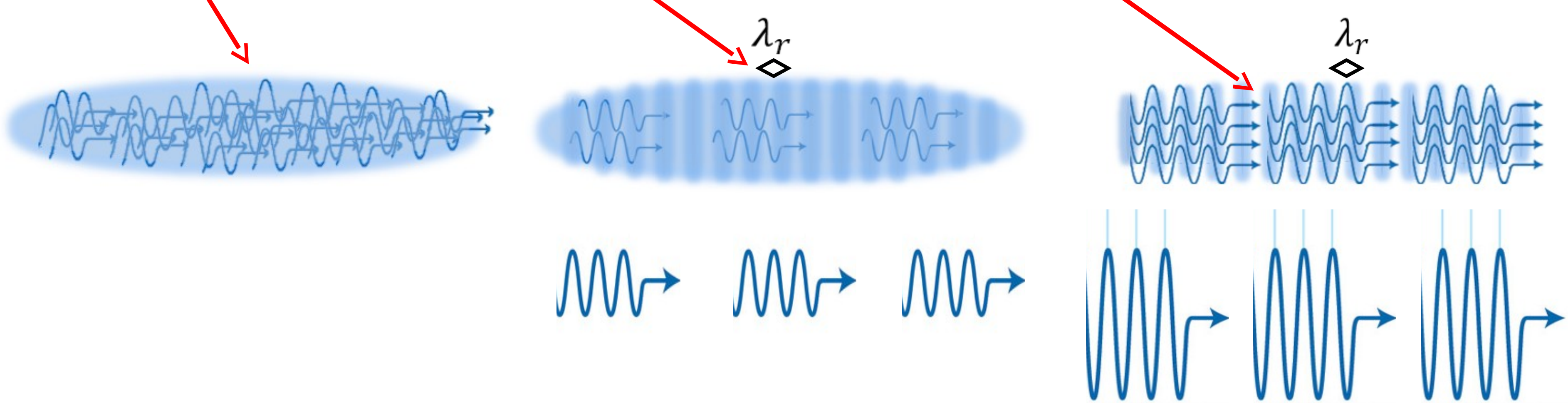


radiation slips forward one L_{coop} every gain length, with $L_{coop} = \frac{\lambda_r}{\lambda_u} * L_G$

L_G (power gain length) : length in which the FEL power grows by a factor e

number of modes in radiation pulse:

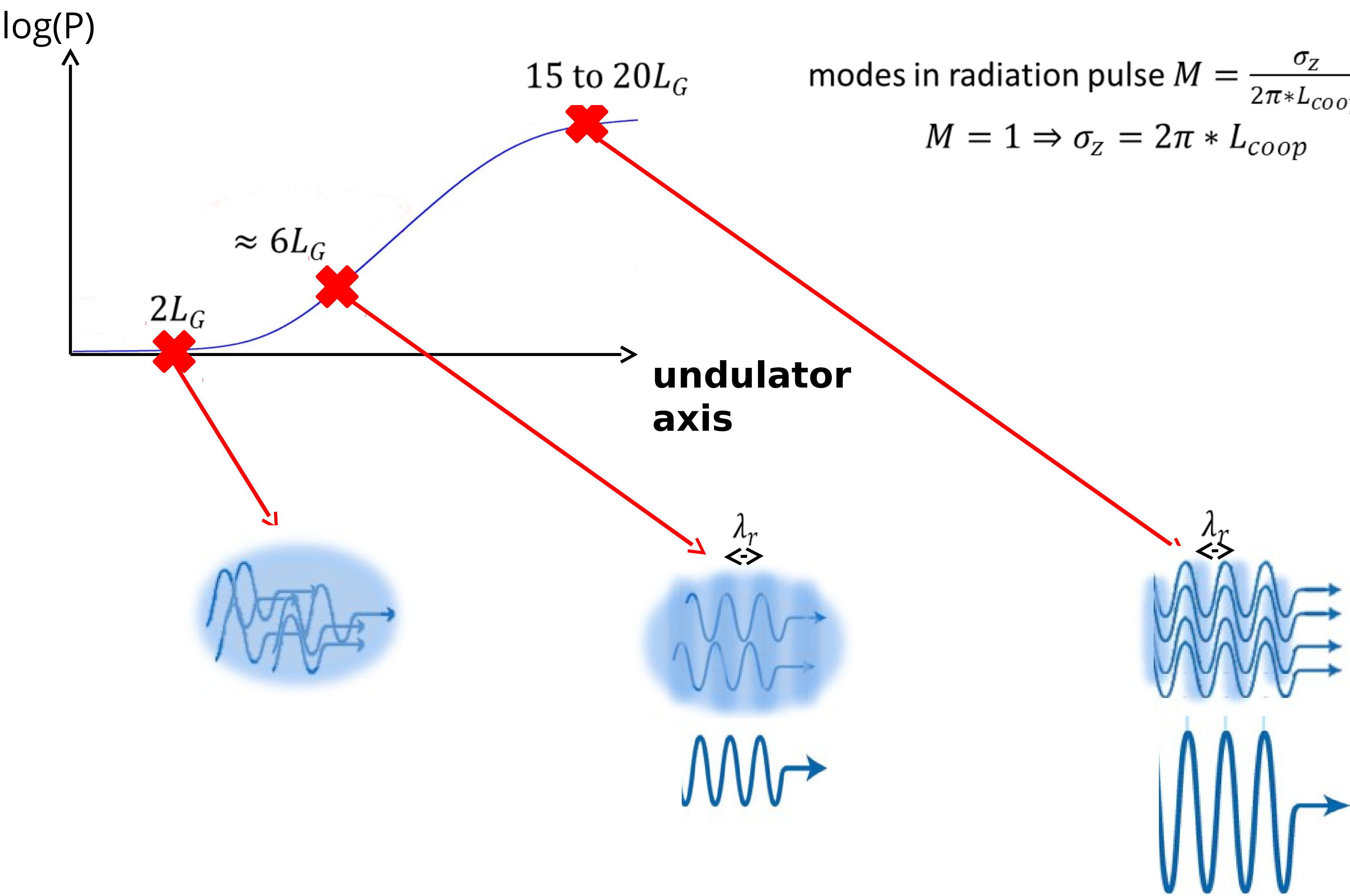
$$M = \frac{\sigma_z}{2\pi * L_{coop}}$$



FEL Process

modes in radiation pulse $M = \frac{\sigma_z}{2\pi * L_{coop}}$

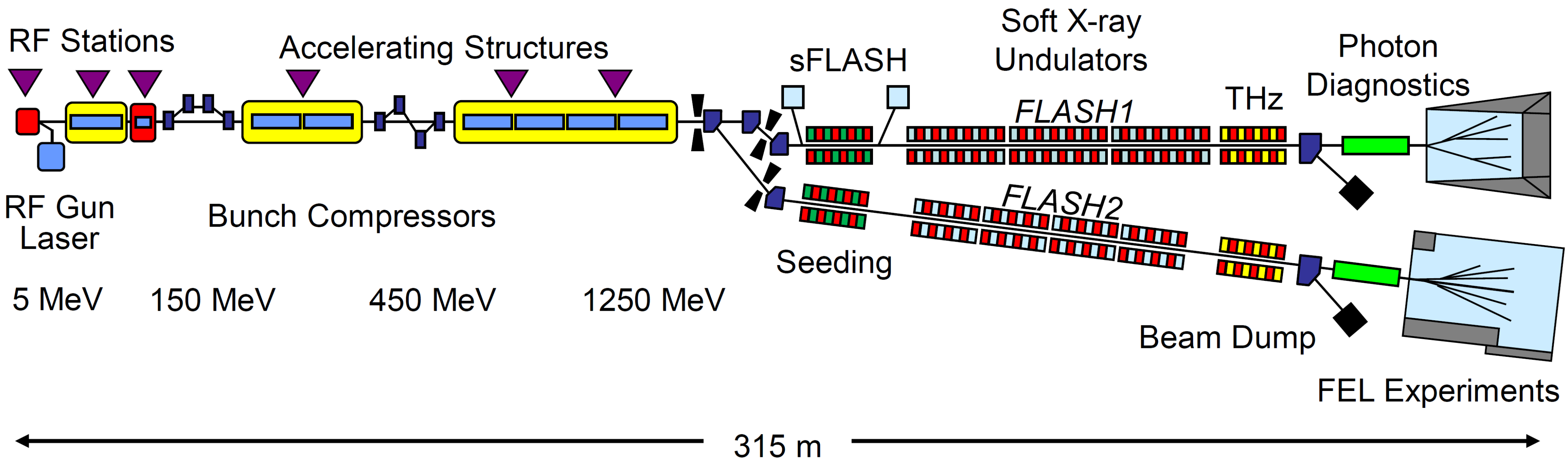
$$M = 1 \Rightarrow \sigma_z = 2\pi * L_{coop}$$



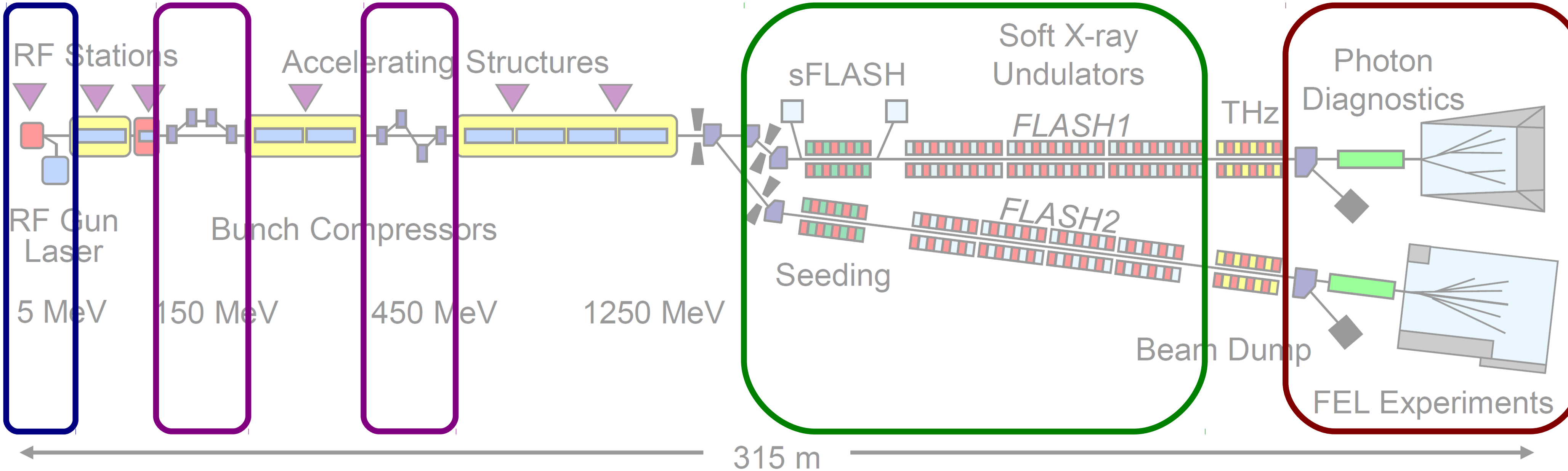
How can we shorten the electron bunch?

Optimizing small bunch length and peak current

FLASH


RF Stations
Accelerating Structures
sFLASH
Soft X-ray
Undulators
Photon
Diagnostics
THz
FLASH1
FLASH2
RF Gun
Laser
Bunch Compressors
Seeding
5 MeV
150 MeV
450 MeV
1250 MeV
Beam Dump
FEL Experiments
315 m

FLASH



laser pulse length (rms) **bunch duration (rms)** **FEL pulse length (FWHM)**

Standard FLASH Operation

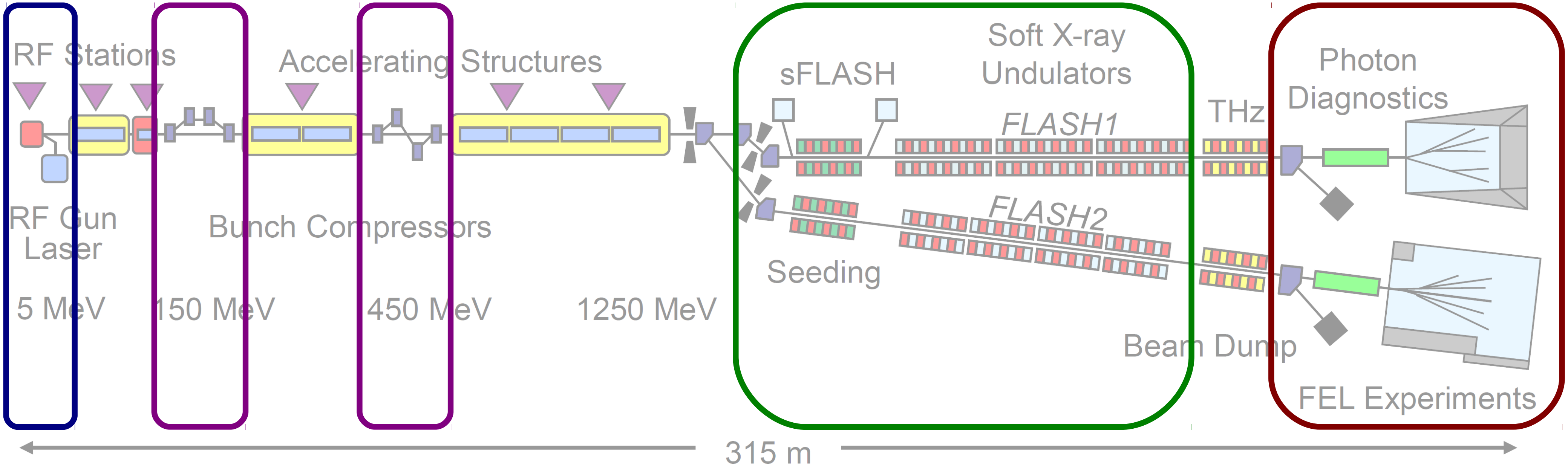
6.4 ps
80 pC – 1 nC

30-200 fs

30-200fs

Compression factor : ~30 - 220

FLASH



laser pulse length (rms) | **bunch duration (rms)** | **FEL pulse length (FWHM)**

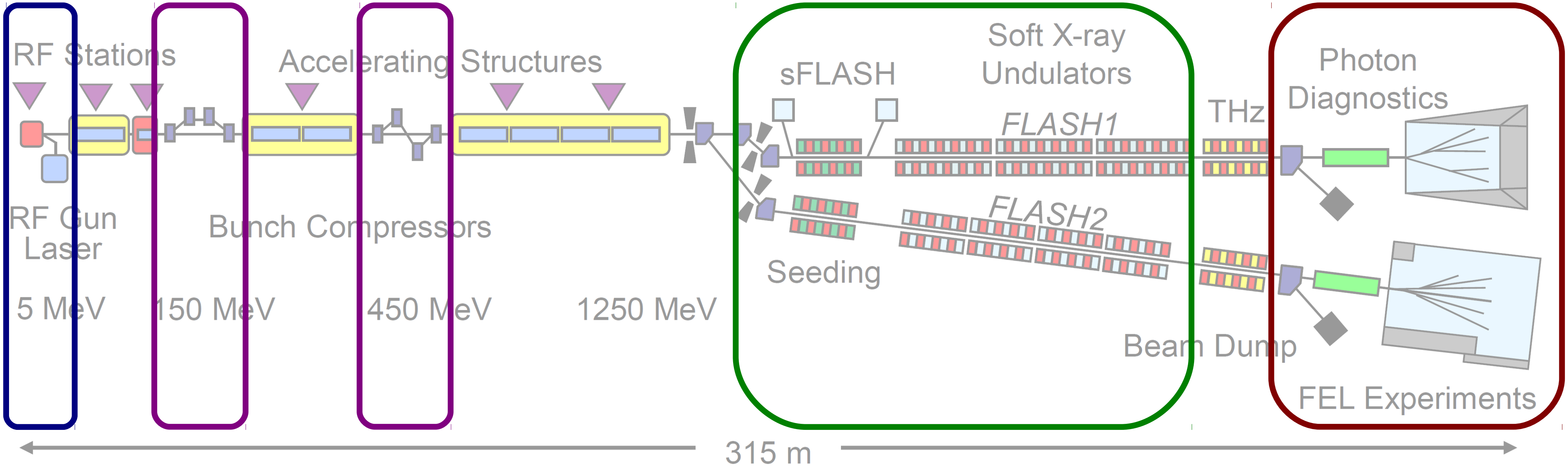
Singe Spike Operation at FLASH

6.4 ps
20pC

~3 fs

~3 fs

Compression factor : ~2000



laser pulse length (rms) | **bunch duration (rms)** | **FEL pulse length (FWHM)**

Singe Spike Operation at FLASH

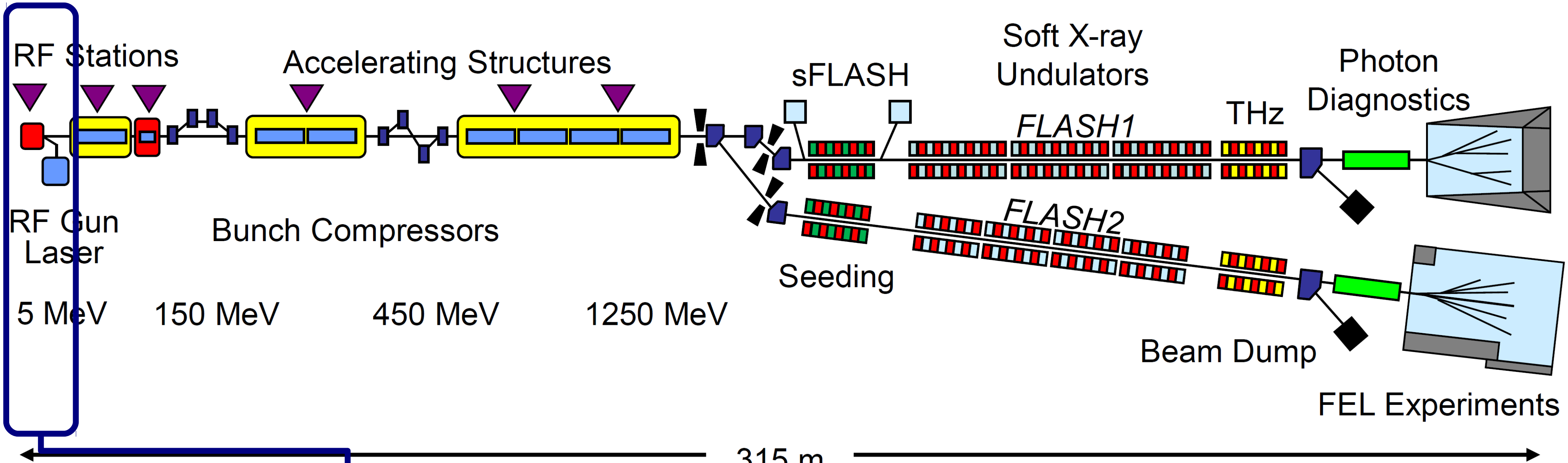
0.4 - 2.0 ps
20pC

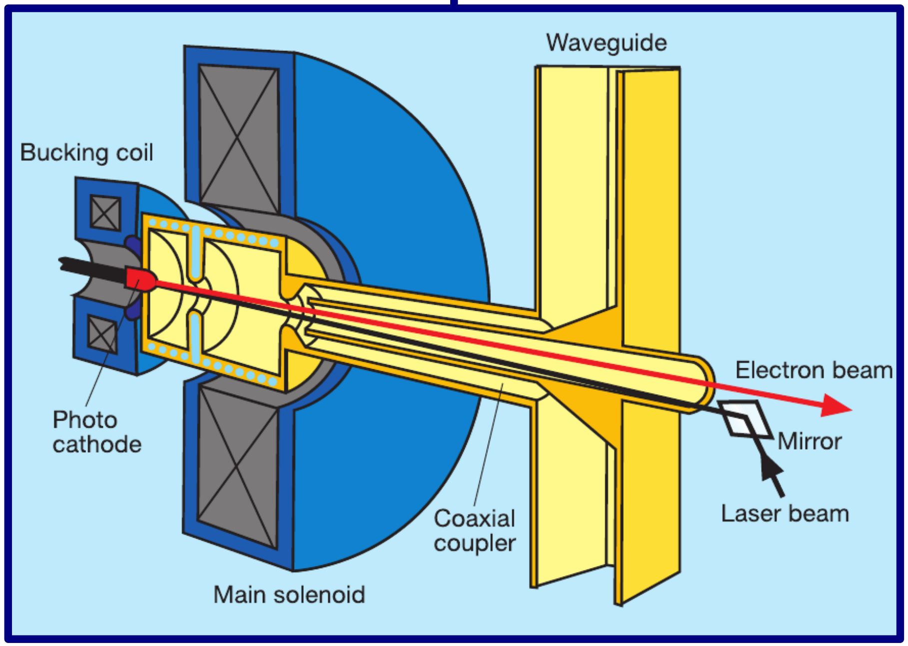
~3 fs

~3 fs

Compression factor : ~130-390

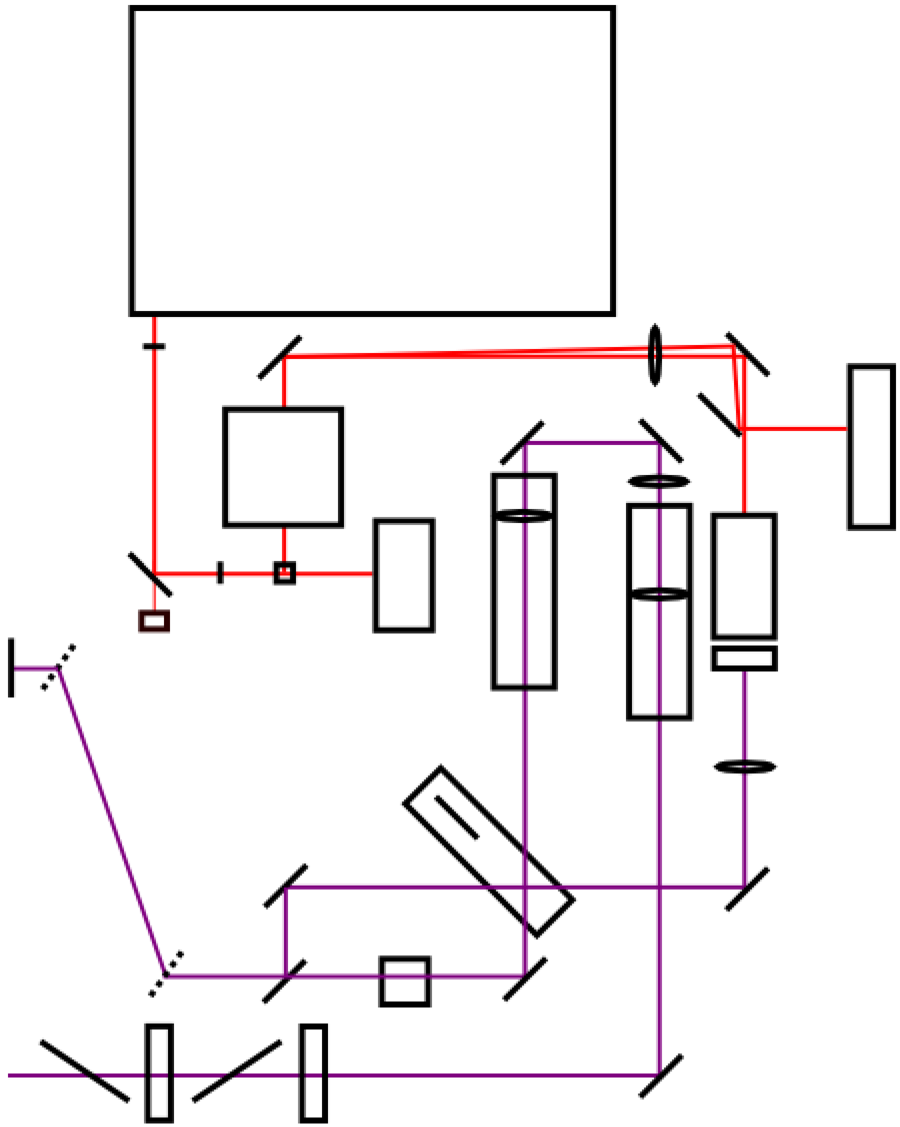
FLASH

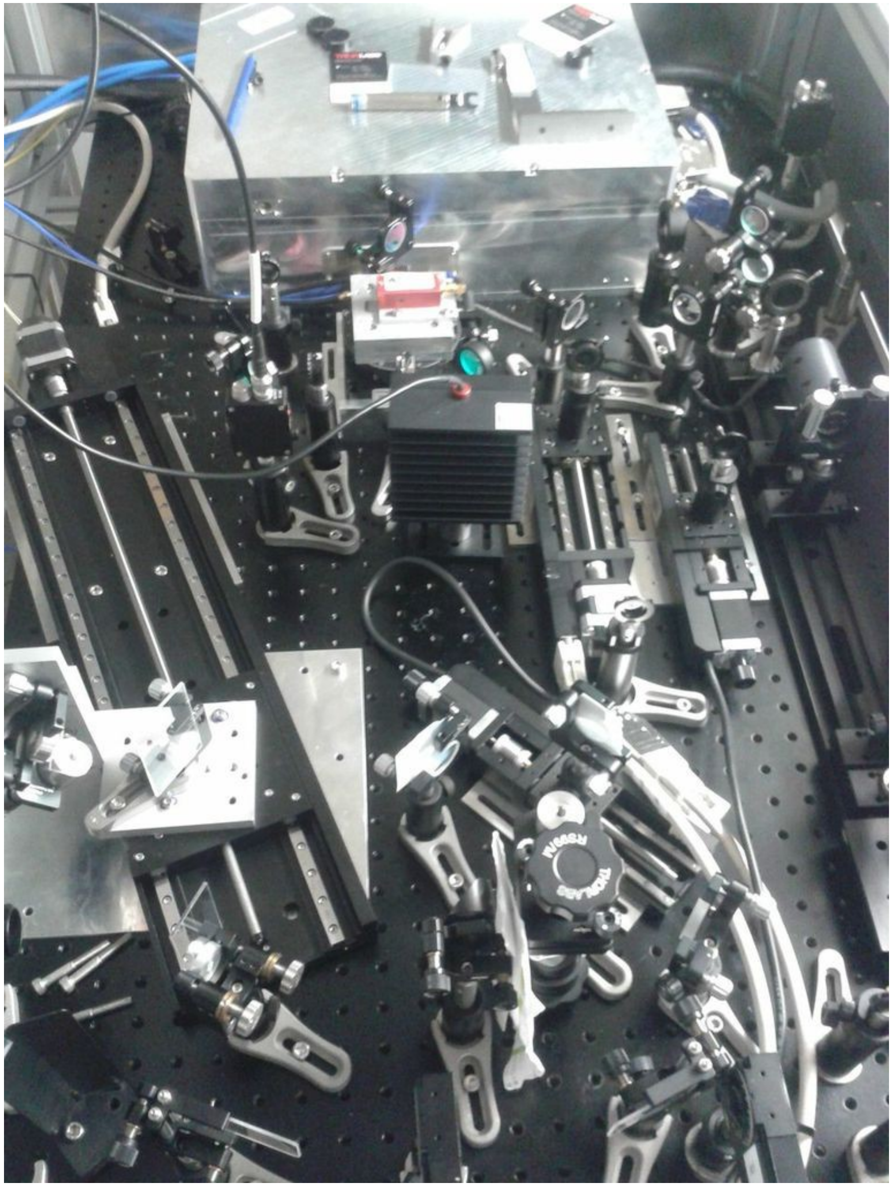




cathode material	Cs_2Te
injector laser wavelength	UV (around 260nm)
laser pulse energy	several nJ
laser pulse length	< 5ps rms
repetition rate	1 MHz // 10 Hz trains
transversal spot size	~ mm

New Laser System





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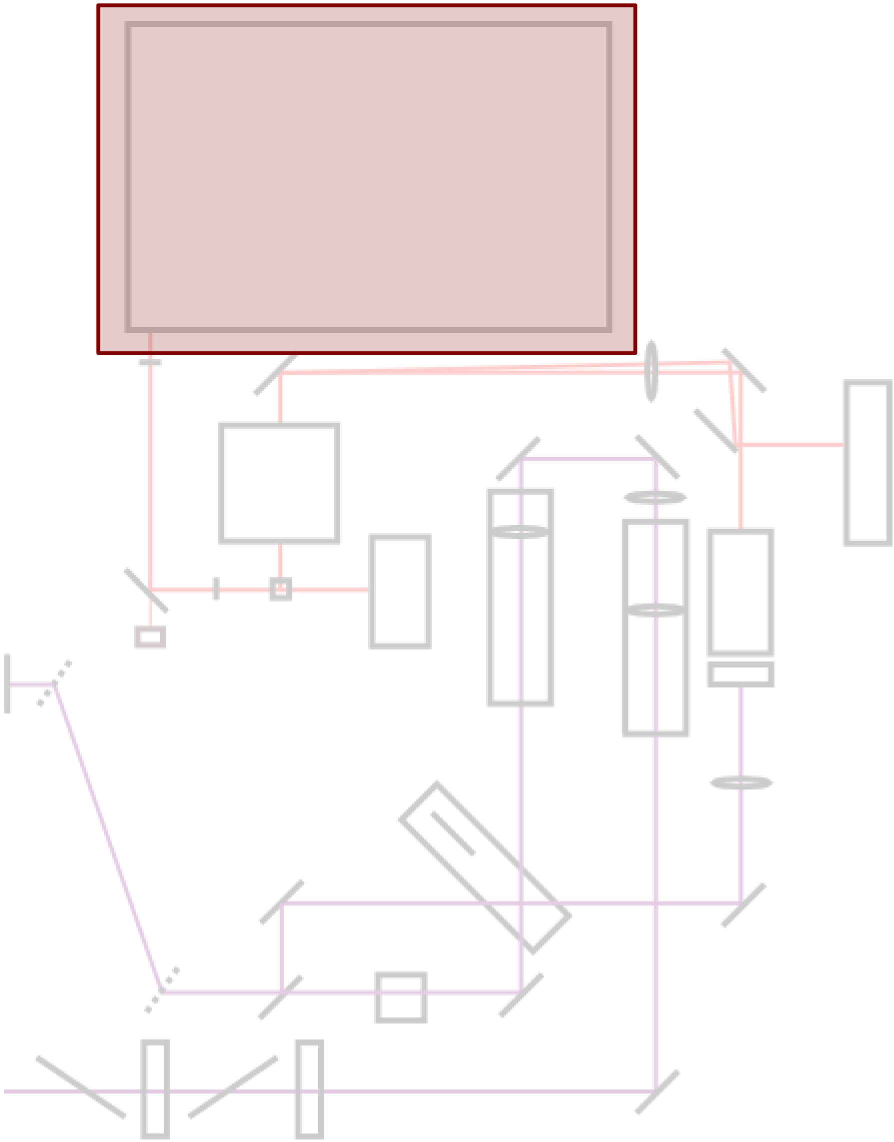
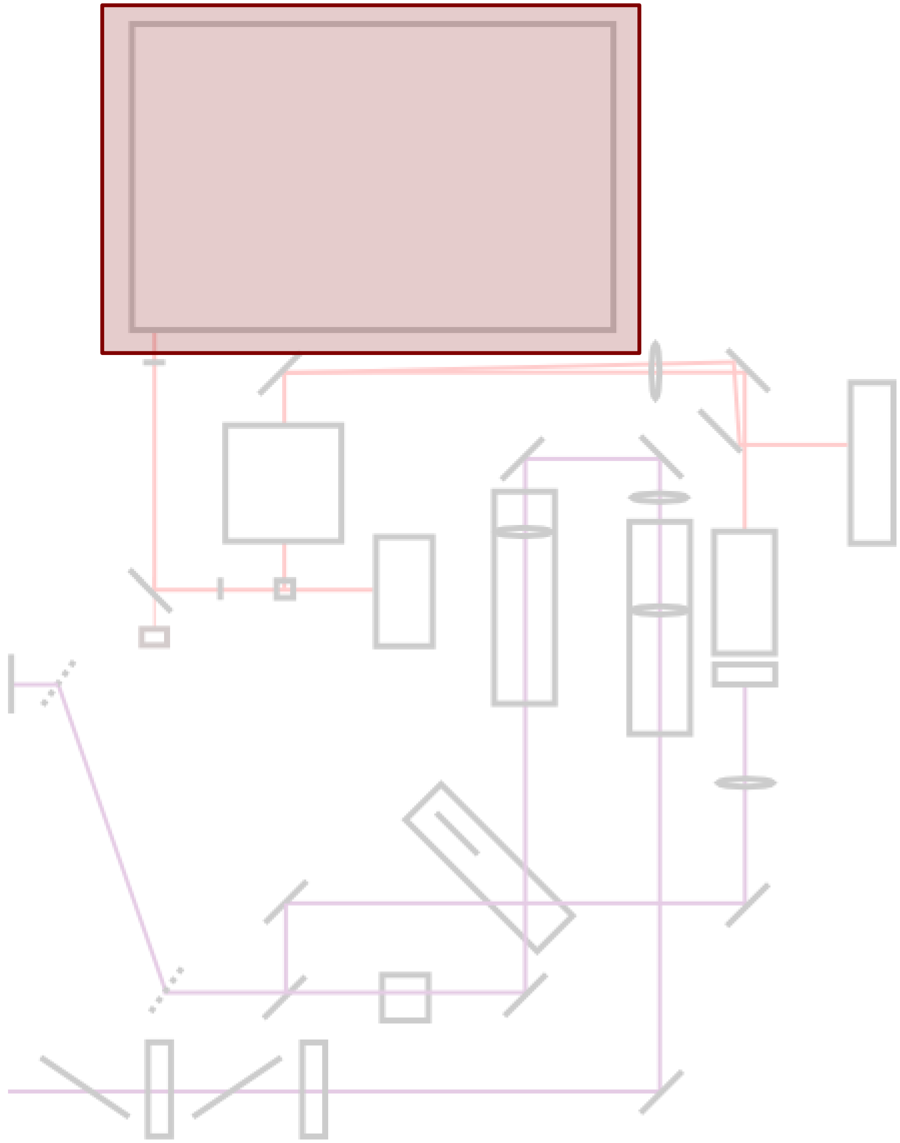


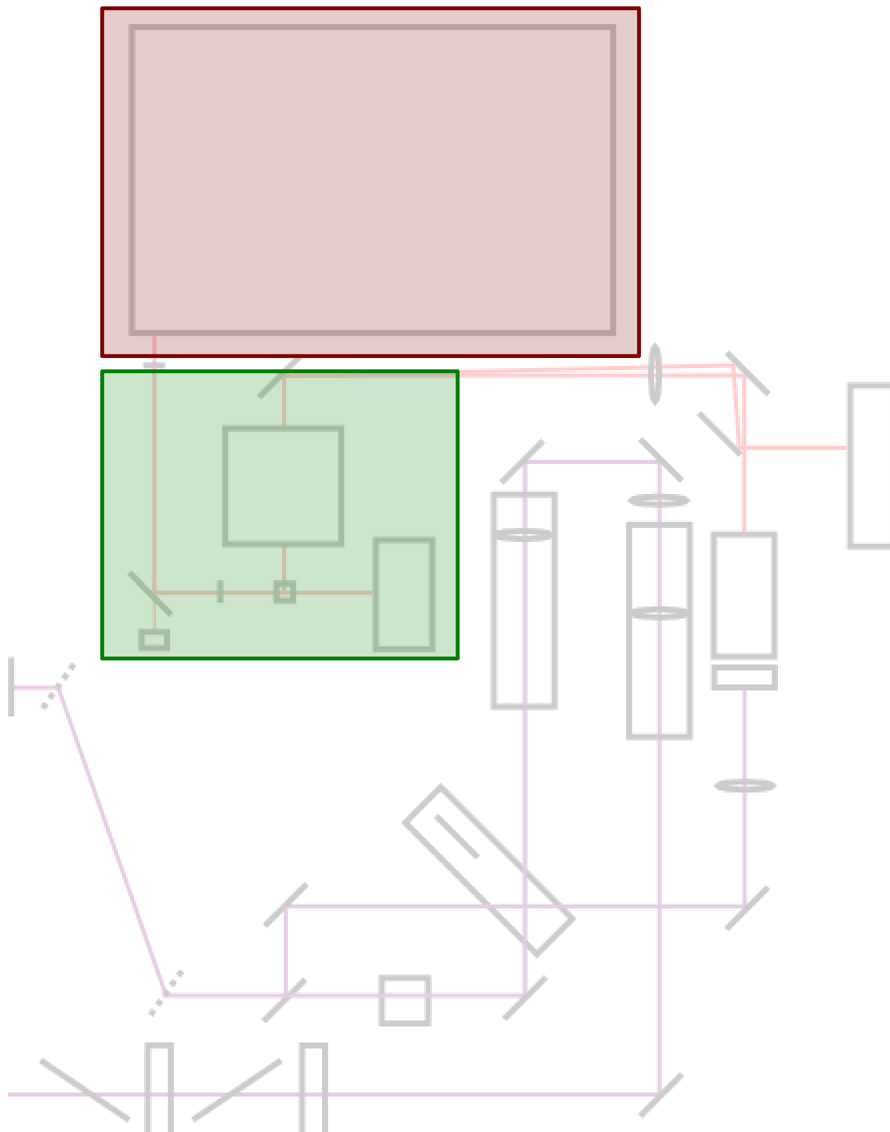
oscillator	Onefive Origami 10
	1030nm, 260mW, 54MHz, 400fs

New Laser System



oscillator	Onefive Origami 10 1030nm, 260mW, 54MHz, 400fs
amplifier	2stage Amphos amplifier 1030nm, 10W, 1MHz, 600fs

New Laser System



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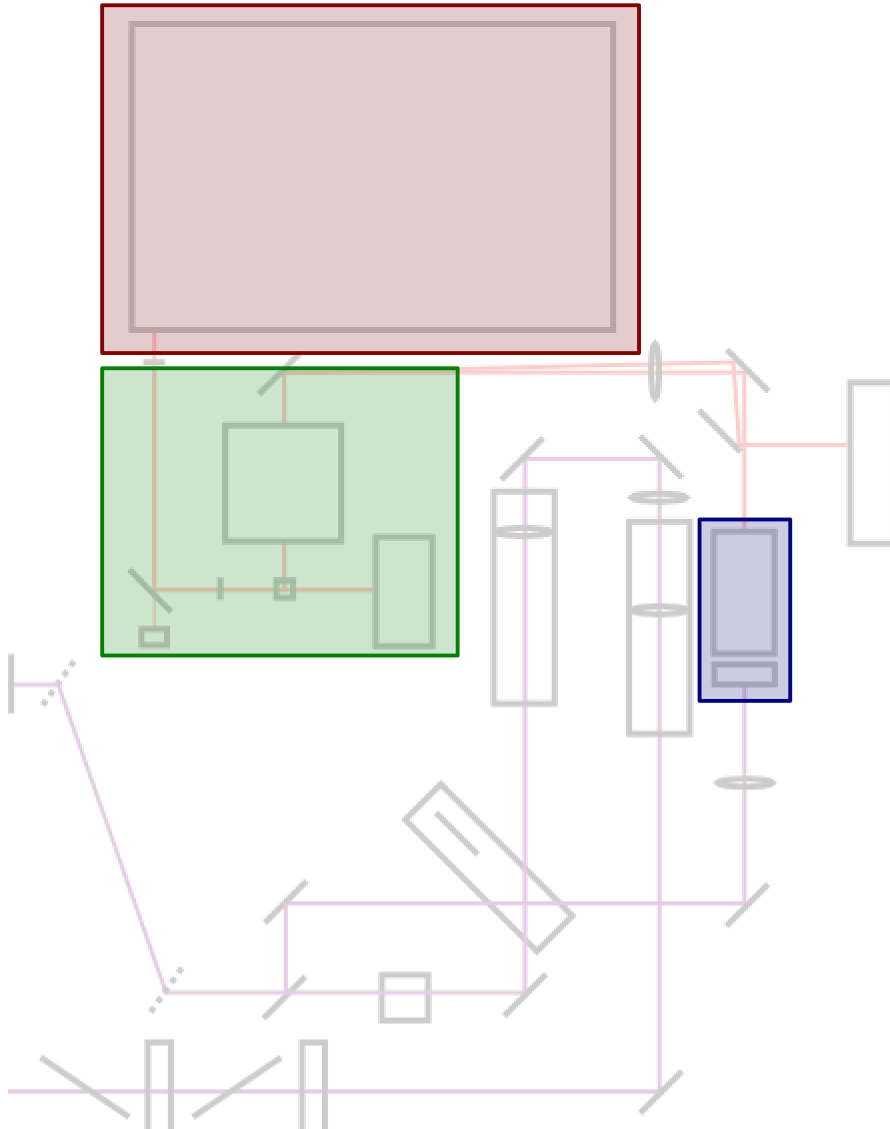
acousto-optic modulator	arbitrary pulse picking → 10Hz pulse trains

New Laser System



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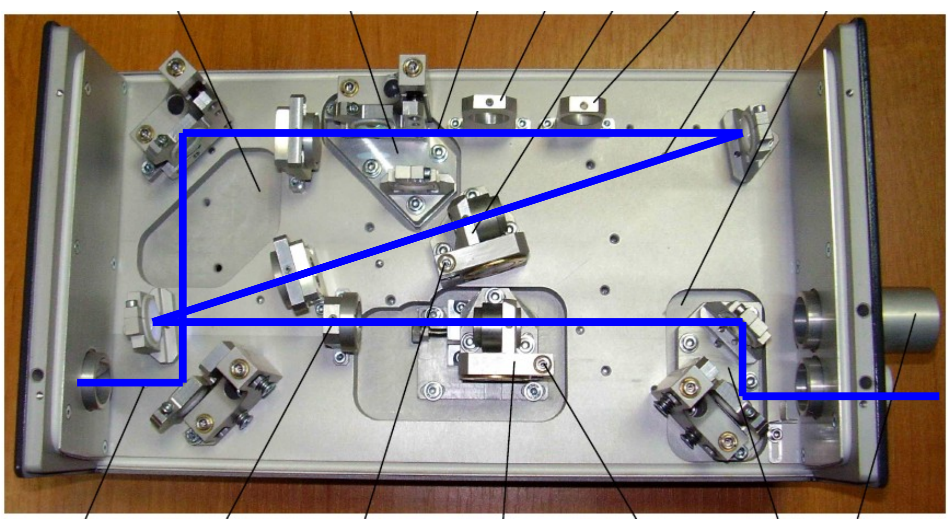
4th harmonic	LBO + BBO / 1030 → 257.5nm @ 10% efficiency → 1µJ

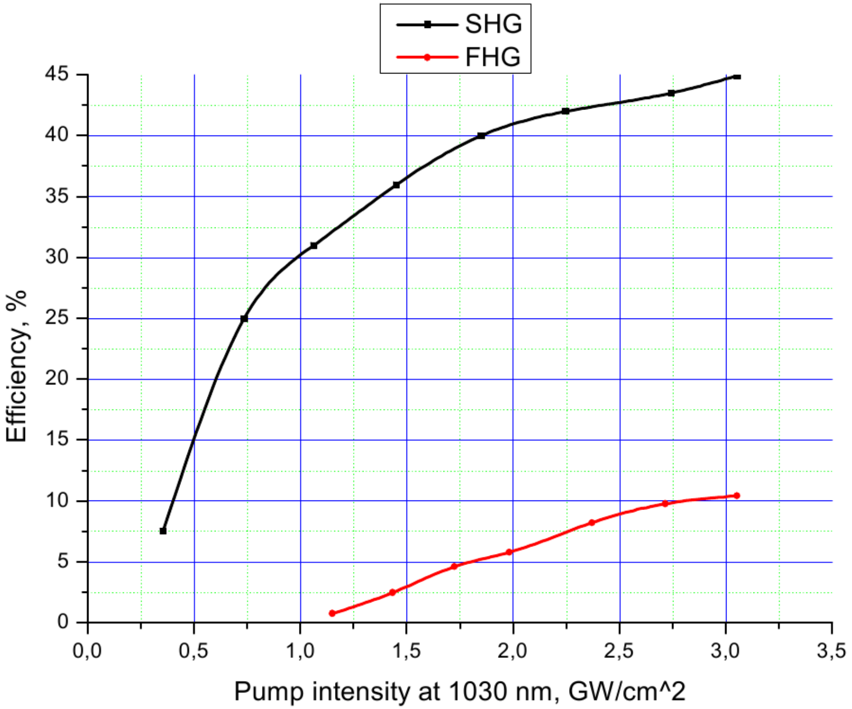
New Laser System – Frequency Conversion

BBO: Beta Barium Borate

Design efficiency: 10% for collimated beam (~800µm beam diameter)

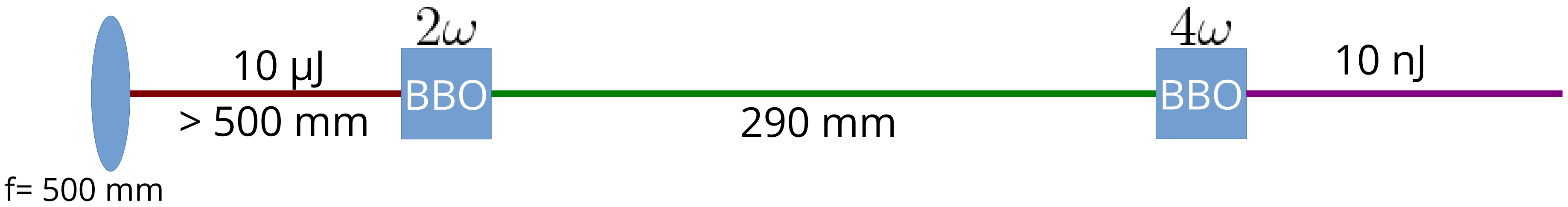
achieved efficiency: 0.1%



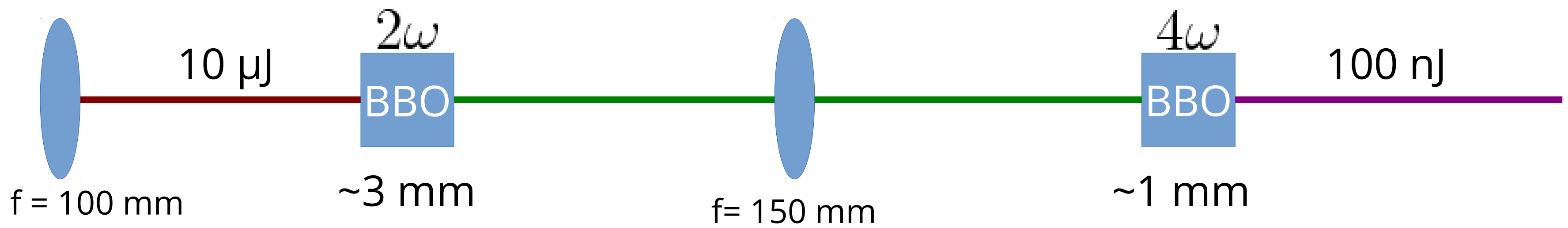


SOLAR Laser Systems Test Curve

New Laser System – Frequency Conversion



January setup (1% achieved efficiency, SASE Setup)



problems with January setup:

- focussing too strong, causes an imperfect wavefront, this affects the transversal profile at cathode
- problems with phase matching

→ less electron charge stability at the gun

New Laser System – Frequency Conversion

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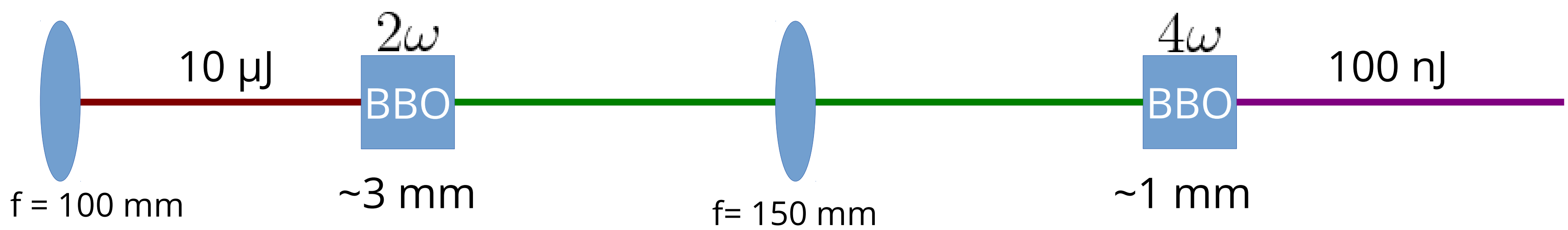
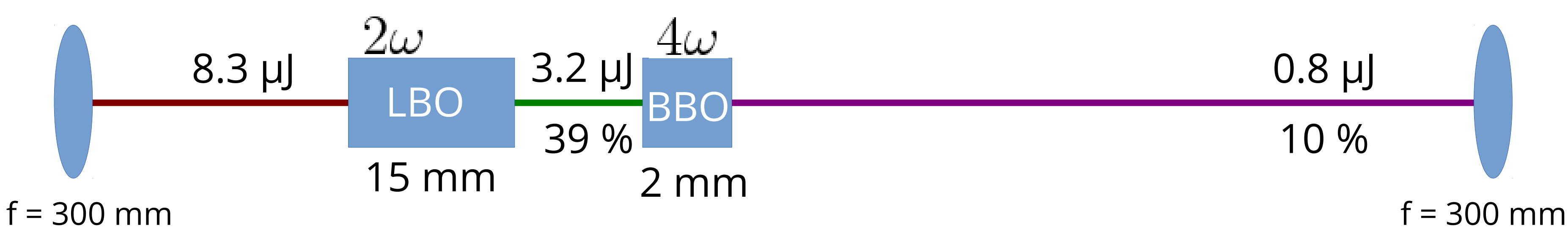
January setup (1% achieved efficiency, SASE setup)

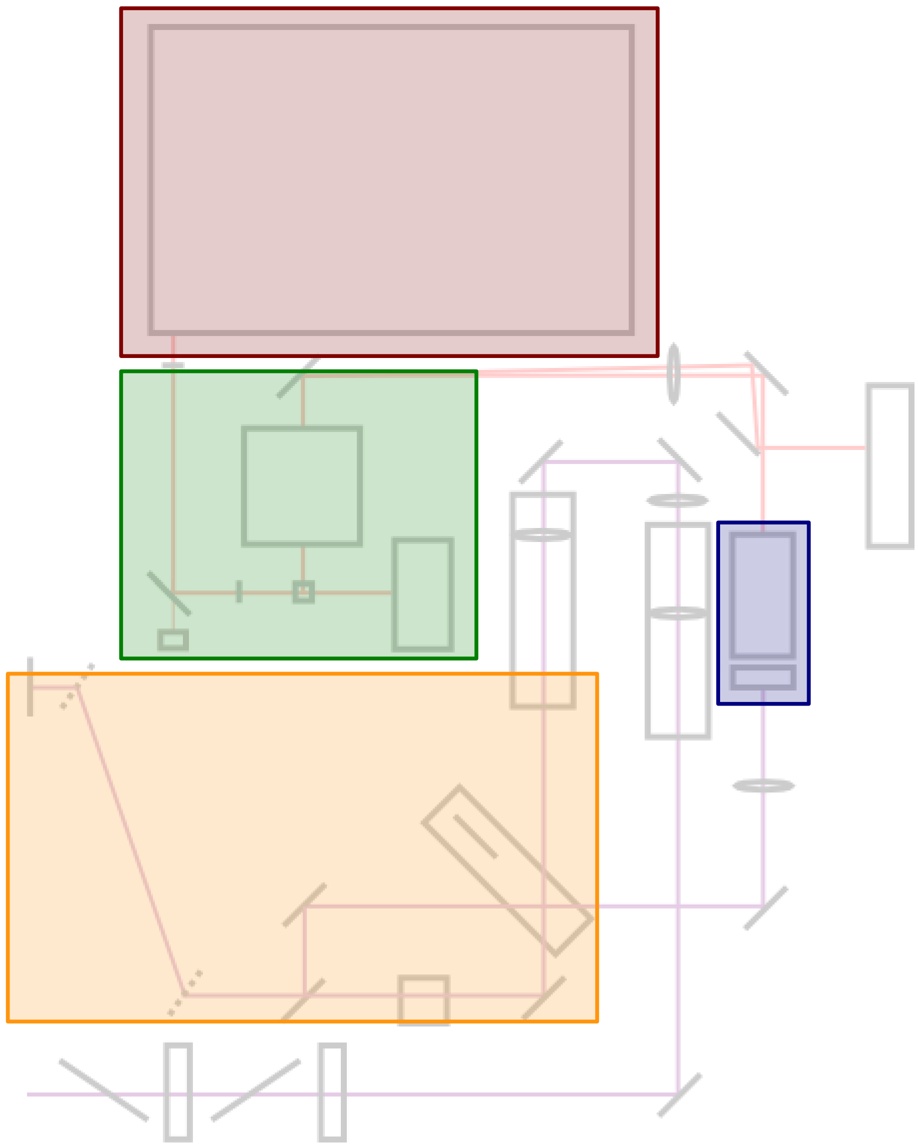


Current setup (~11% efficiency)



LBO: Lithium Triborate

New Laser System



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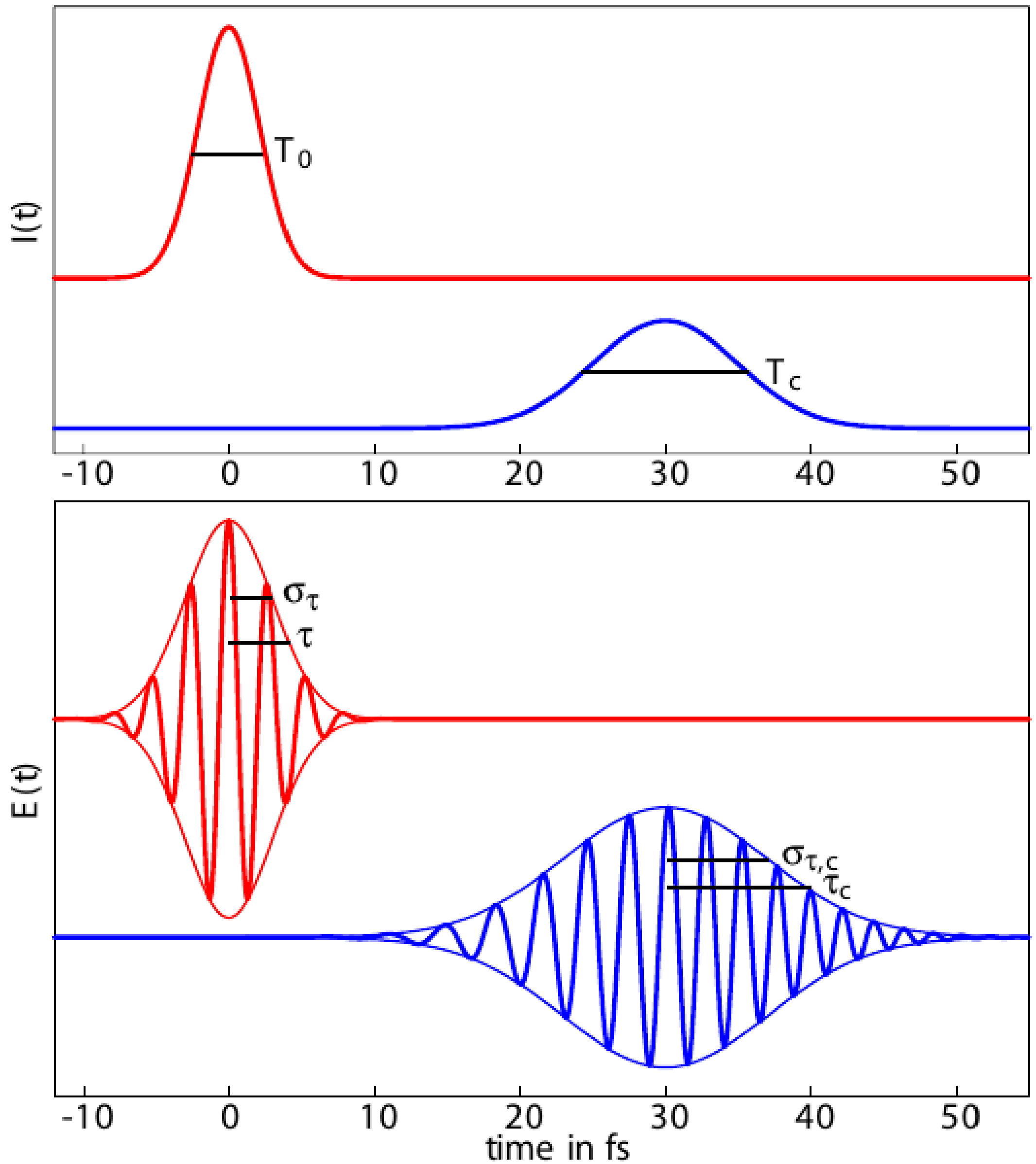
amplifier	2stage Amphos amplifier 1030nm, 10W, 1MHz, 600fs
acousto-optic modulator	arbitrary pulse picking → 10Hz pulse trains
4th harmonic	LBO + BBO / 1030 → 257.5nm @ 10% efficiency → 1µJ
stretcher	Stretching pulse up to 4 ps

Optical Stretcher



B. R. Steffen, „Electro-Optic Methods for Longitudinal Bunch Diagnostics at FLASH", 2007

Fourier-limited laser pulses can be stretched in their duration by introducing a group-delay dispersion (chirp).

$$\beta = \frac{d^2\Phi}{d\omega^2}\Big|_{\omega=\omega_0}$$

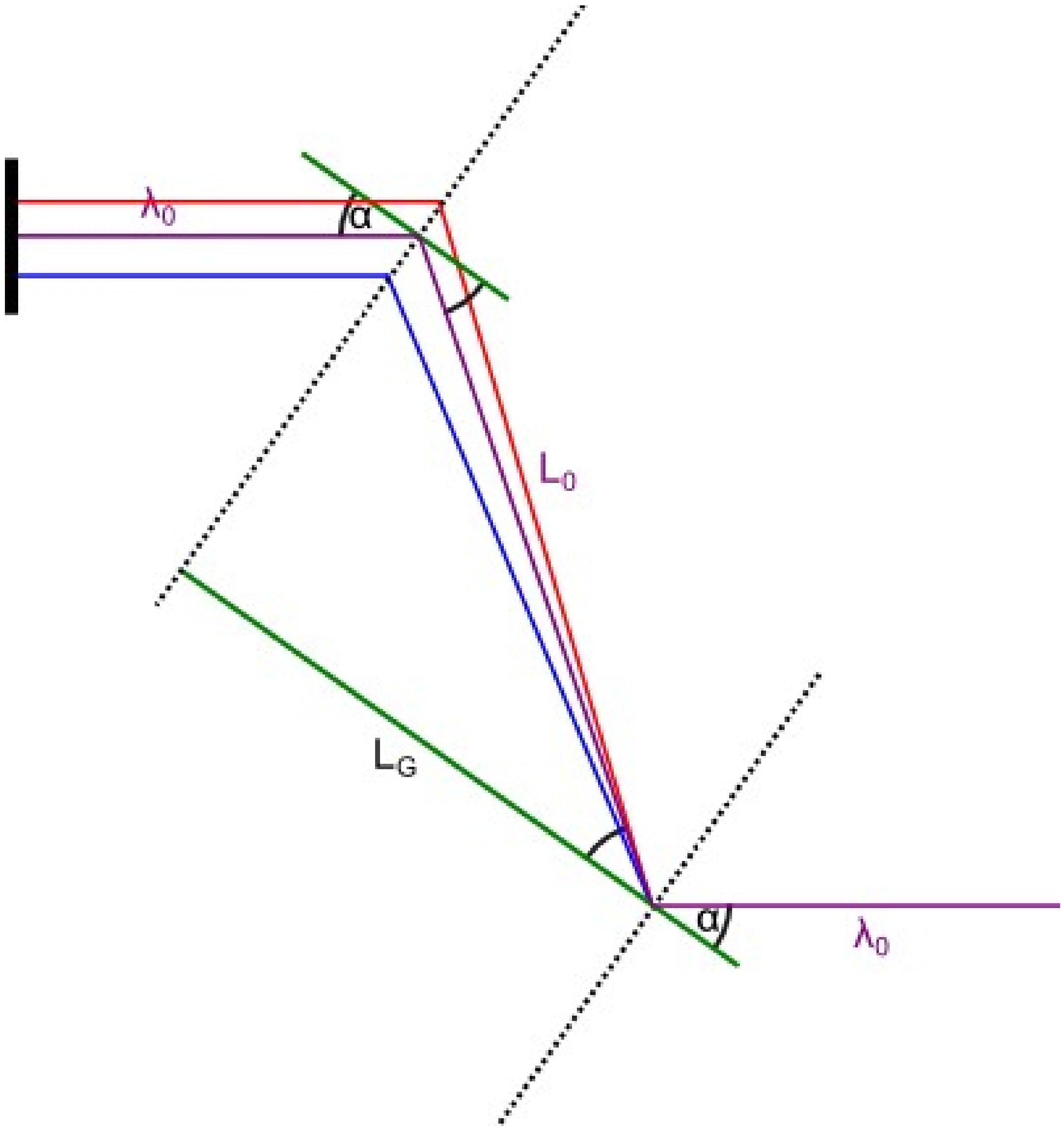
Φ phase advance throughout stretcher

ω_0 central frequency

$$\Phi = \frac{P\omega}{c} \qquad P = \int n(x)dx$$

Optical path length depends on frequency. → Dispersion

Optical Stretcher



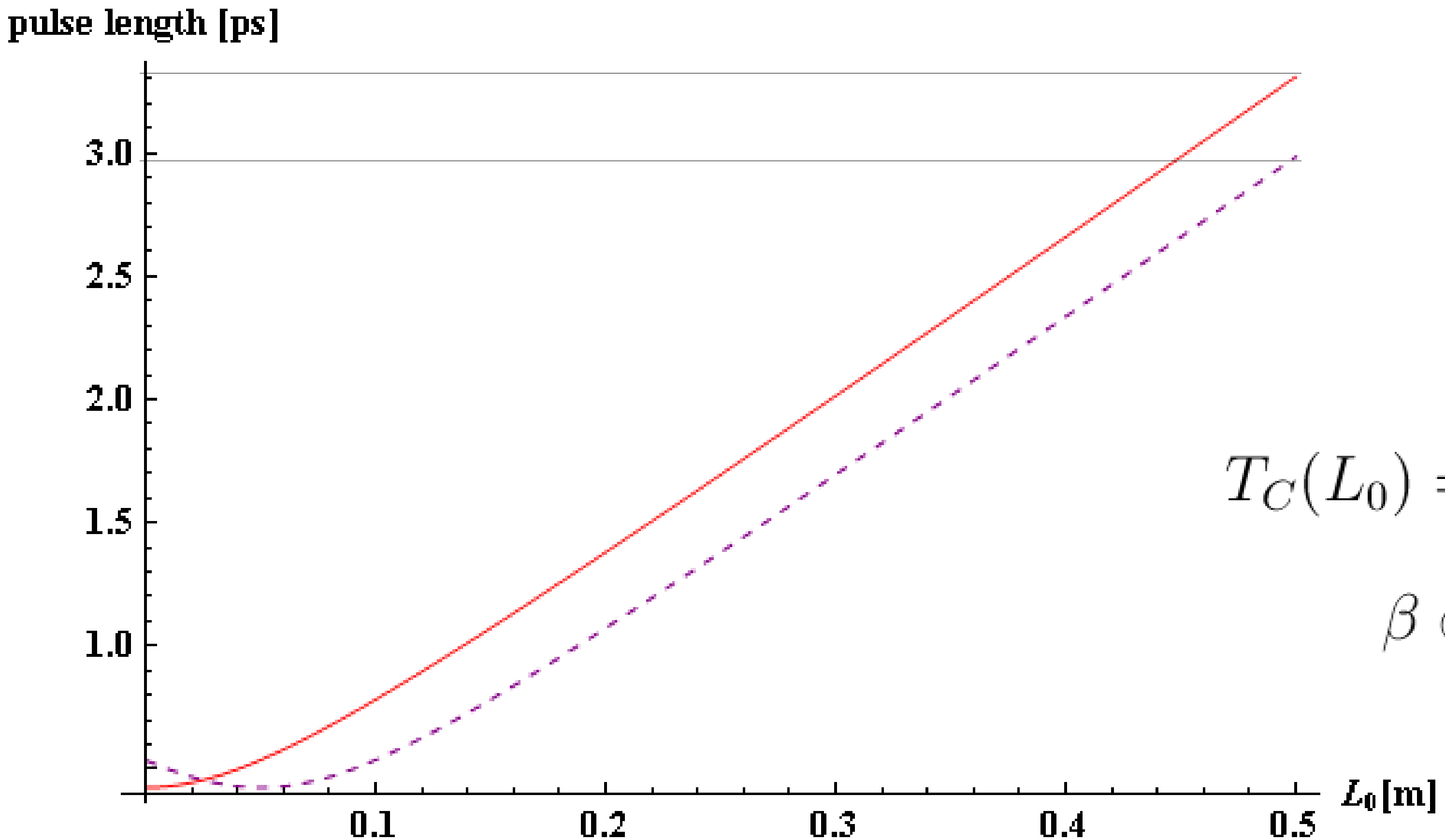
Grating diffraction introduces different path lengths for different wavelength → Dispersion.

Principle very similar to an electron bunch compressor.

- variable grating distance and thus pulse length come with timing differences that have to be corrected
- a calibration curve has to be taken that relates grating distance to pulse length

Optical Stretcher

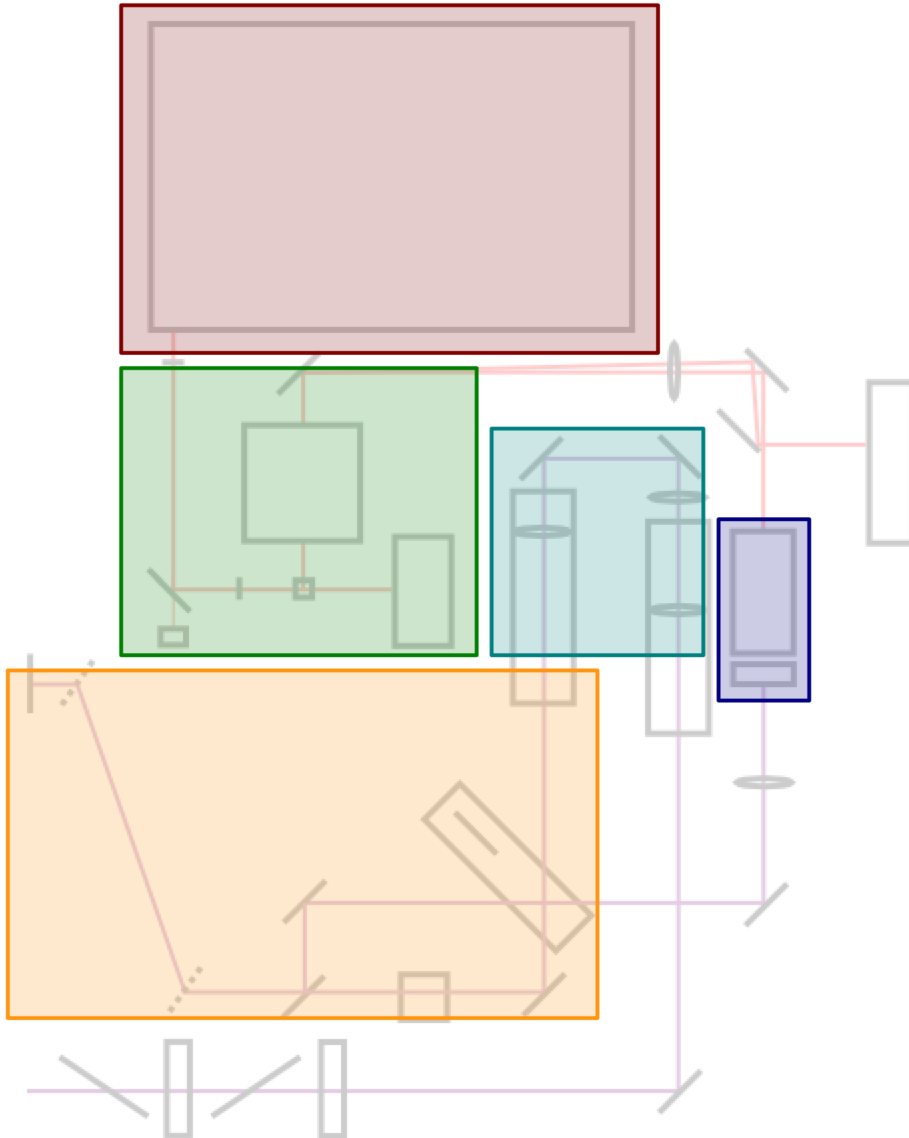
- Approaches linear slope for big L_0
- measured curve will be shifted to the right due to initial chirp, with knowledge of the spectrum (→ spectrometer), chirp before the stretcher can be calculated by finding the stretcher setting of minimal pulse length



$$T_C(L_0) = T_0\sqrt{1+\frac{\beta^2}{T_0^4}}$$

$$\beta \propto L_0$$

New Laser System



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telescope	reducing beam size up to a factor of 5

New Laser System

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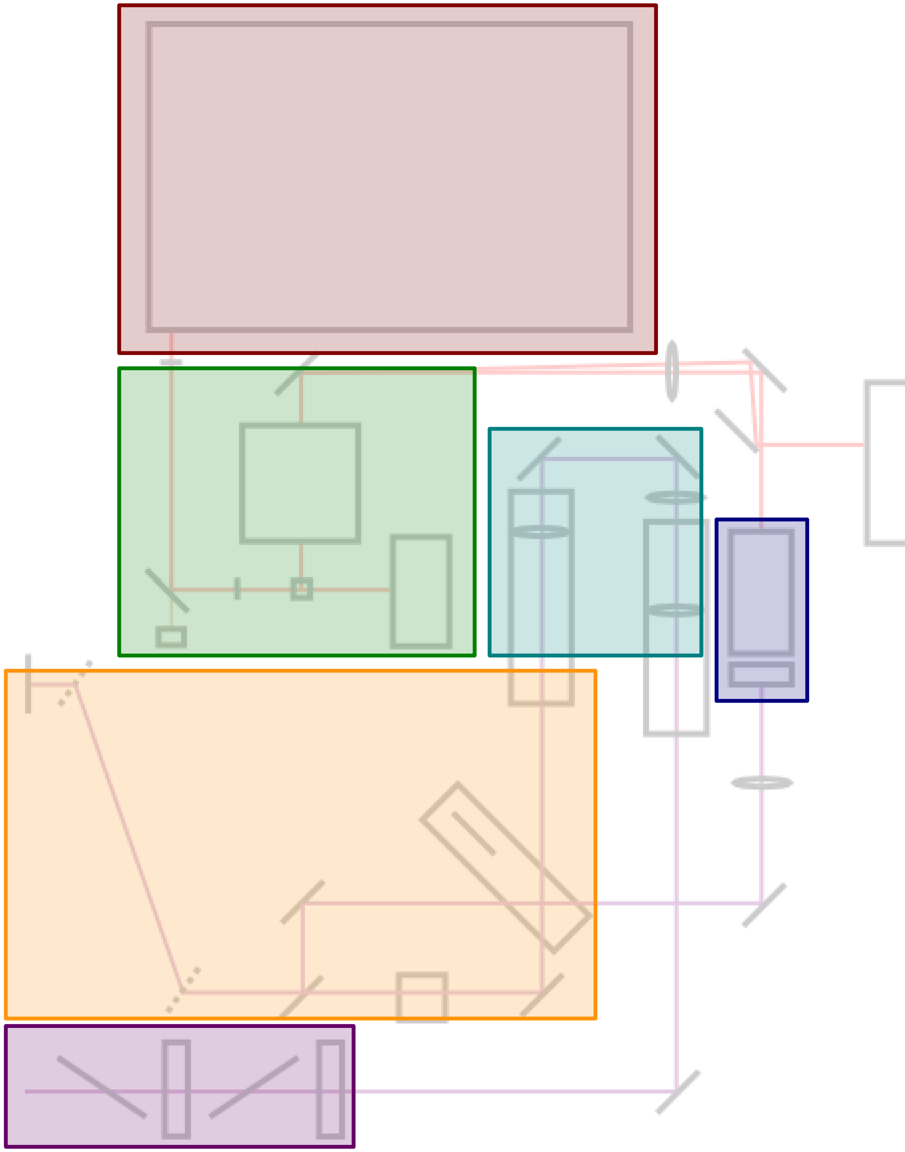

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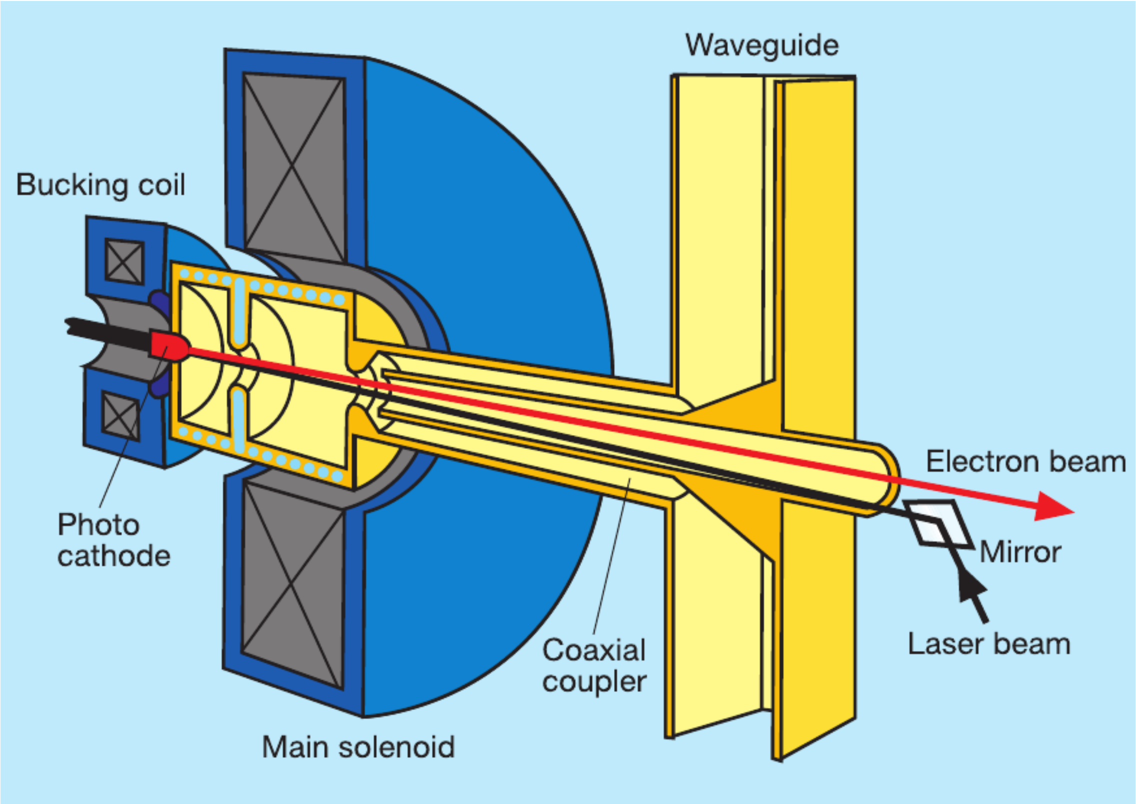
stretcher	Stretching pulse up to 4 ps
telescope	reducing beam size up to a factor of 5
attenuator	2 attenuators (λ/2 plates + polarisers)
aperture (BSA)	aperture with different radii, imaged on cathode

What is the optimum distribution at the cathode?

Optimizing bunch length and emittance

Cathode



P. Schmüser, M. Dohlus und J. Rossbach, Ultraviolet and Soft X-Ray Free-Electron Lasers, Springer-Velrag Berlin Heidelberg, 2008

Normalized emittance is determined by gun and injector laser

emittance at the gun

$$\epsilon = \sqrt{\epsilon_{\rm cath}^2 + \epsilon_{\rm sc}^2 + \epsilon_{\rm RF}^2}$$

$\epsilon_{\rm cath} \propto x_{\rm rms}$

$\epsilon_{\rm sc}$ is a function of laser pulse shape

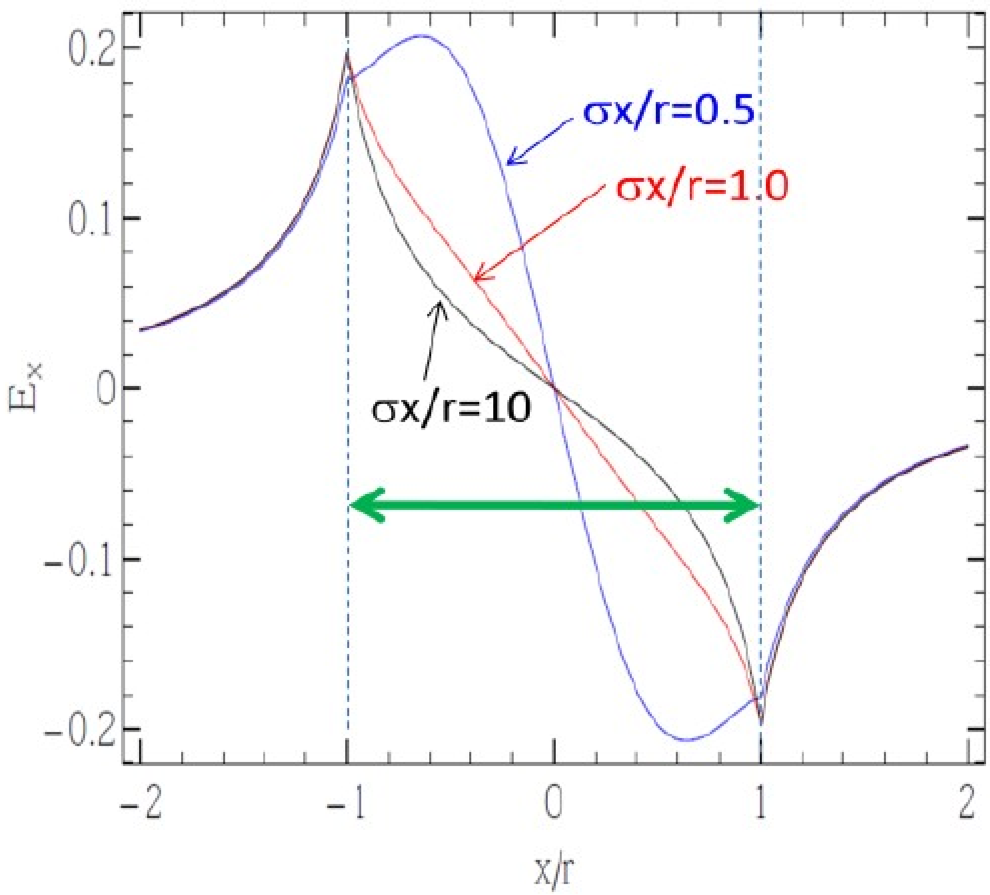
$\epsilon_{\rm RF} \propto \sigma_z^2$

Solenoid magnet focussing forces: $F_{\rm Sol}(r) \propto r$

For stable machine operation, the **electron bunch duration** has to be **small** to allow for small compression factors. **Emittance** should be **small** for high FEL output power.

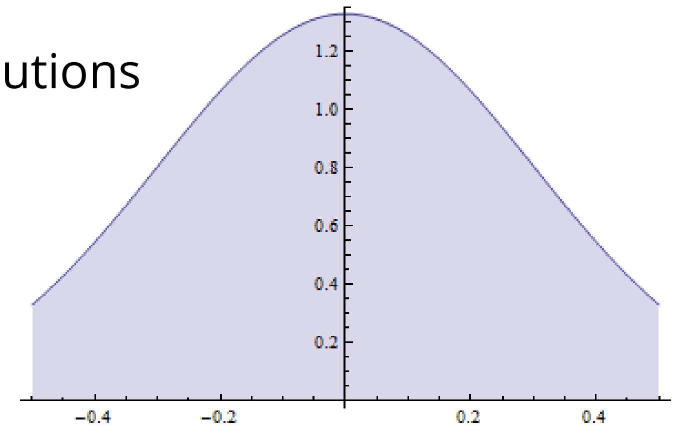
Emittance and Bunch Length Optimisation

space charge forces of different transverse electron distributions

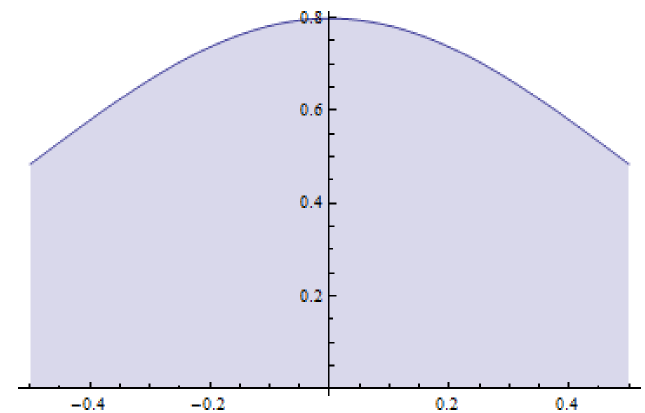


Feng Zhou et al, Impact of the laser spatial distribution on the LCLS photocathode gun operation, PRST-AB 15, 090701, 2012

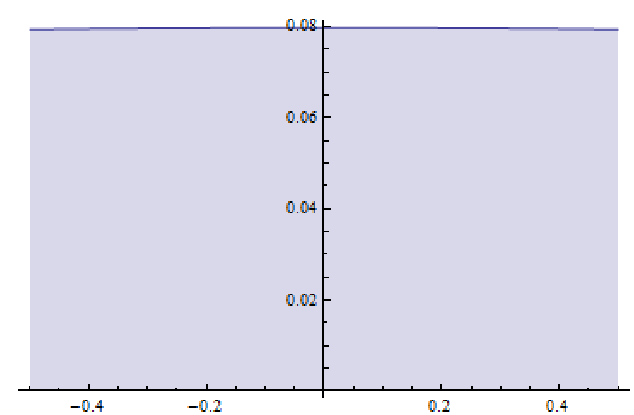
blue



red

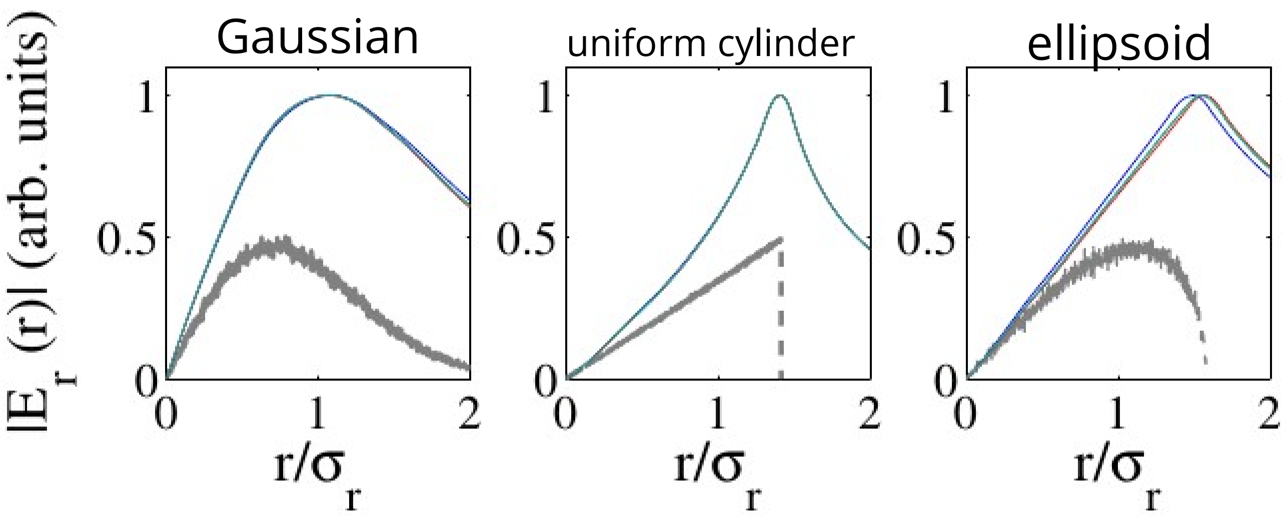


black



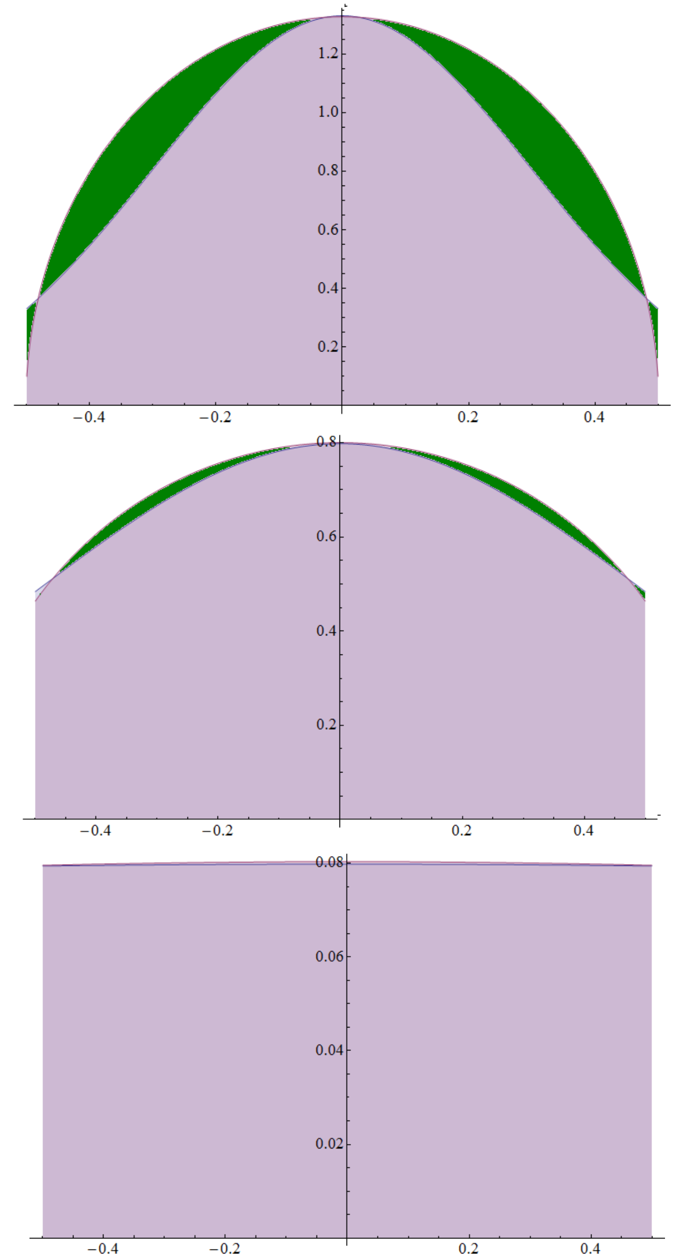
Emittance and Bunch Length Optimisation

- theoretically best distribution is a 3D ellipsoid generating linear space charge forces [7]



- truncated gaussian is very close to ellipsoid (transversally)

- spatial truncated Gaussians reduced emittance by ~25% at LCLS at 150pC [8, Feng Zhou]



Emittance and Bunch Length Optimisation

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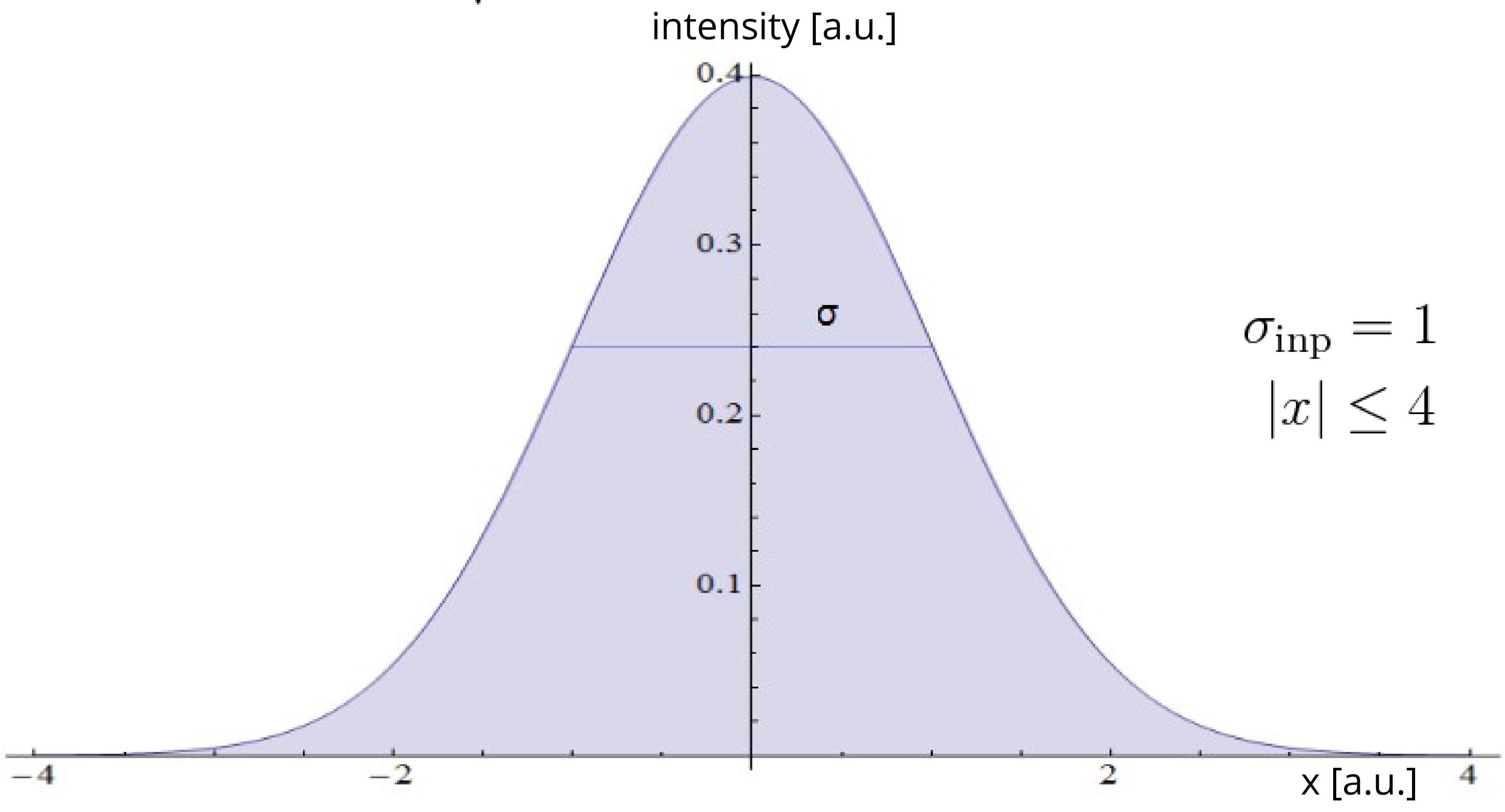
$$f(x) = \frac{1}{\sqrt{2\pi\sigma_{inp}^2}} \exp\left(-\frac{1}{2}\frac{x^2}{\sigma_{inp}^2}\right) \quad \text{for } |x| \le a$$

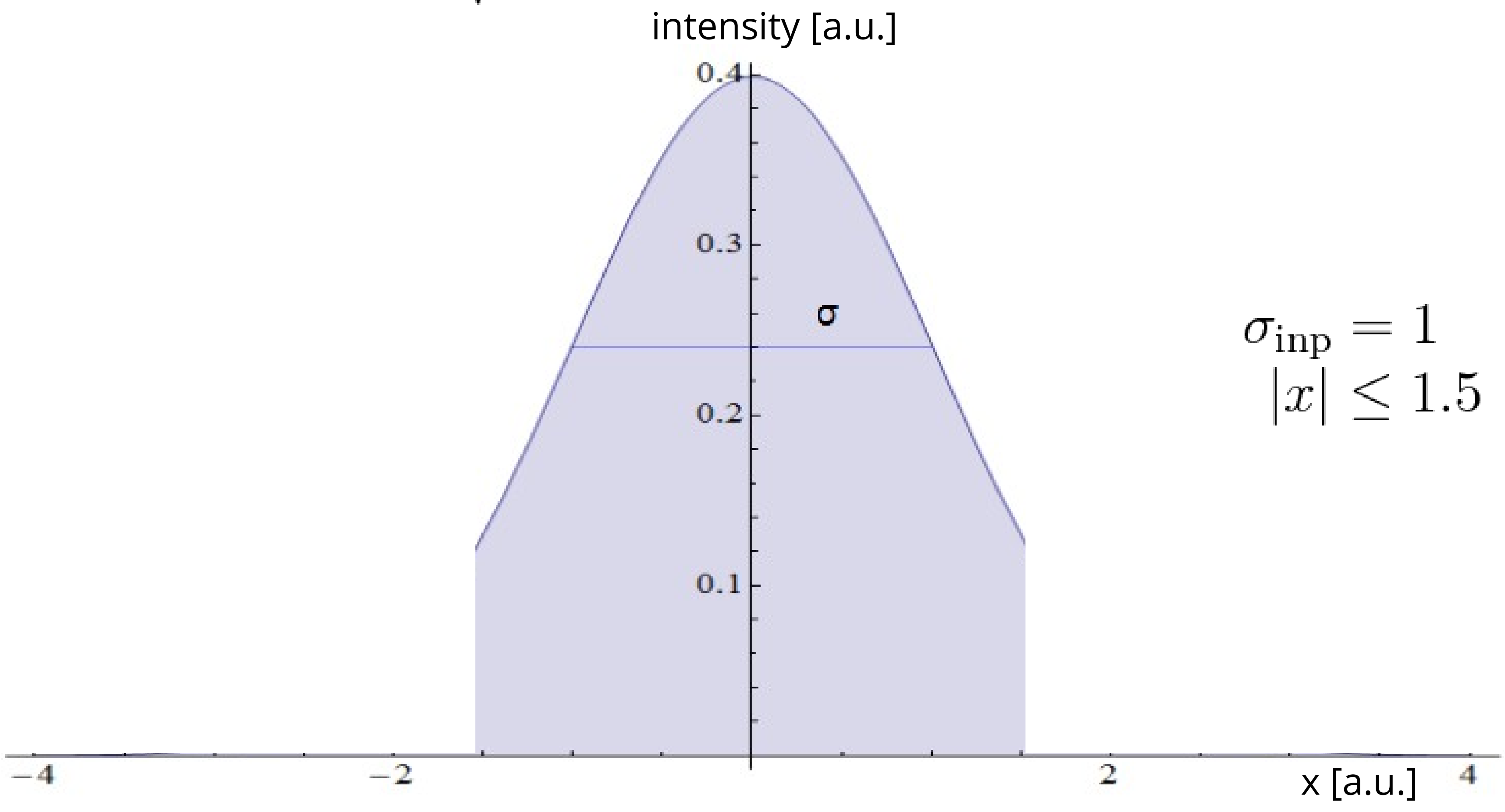


$\sigma_{\text{inp}} = 1$

$|x| \le 4$

Emittance and Bunch Length Optimisation

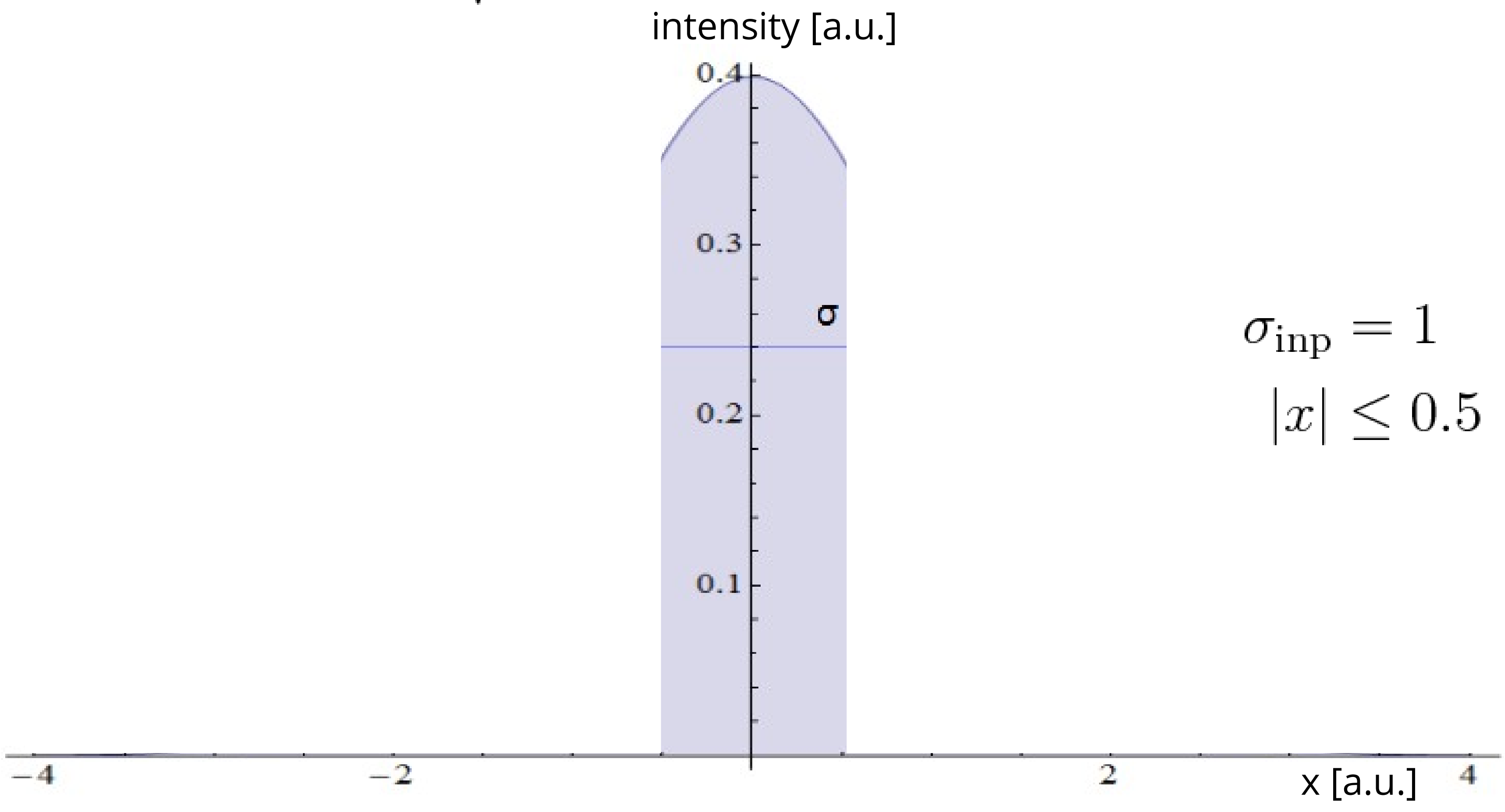
$$f(x) = \frac{1}{\sqrt{2\pi\sigma_{inp}^2}} \exp\left(-\frac{1}{2}\frac{x^2}{\sigma_{inp}^2}\right) \quad \text{for } |x| \leq a$$



$$\sigma_{\text{inp}} = 1$$
$$|x| \leq 1.5$$

Emittance and Bunch Length Optimisation

$$f(x) = \frac{1}{\sqrt{2\pi\sigma_{inp}^2}} \exp\left(-\frac{1}{2}\frac{x^2}{\sigma_{inp}^2}\right) \quad \text{for } |x| \leq a$$

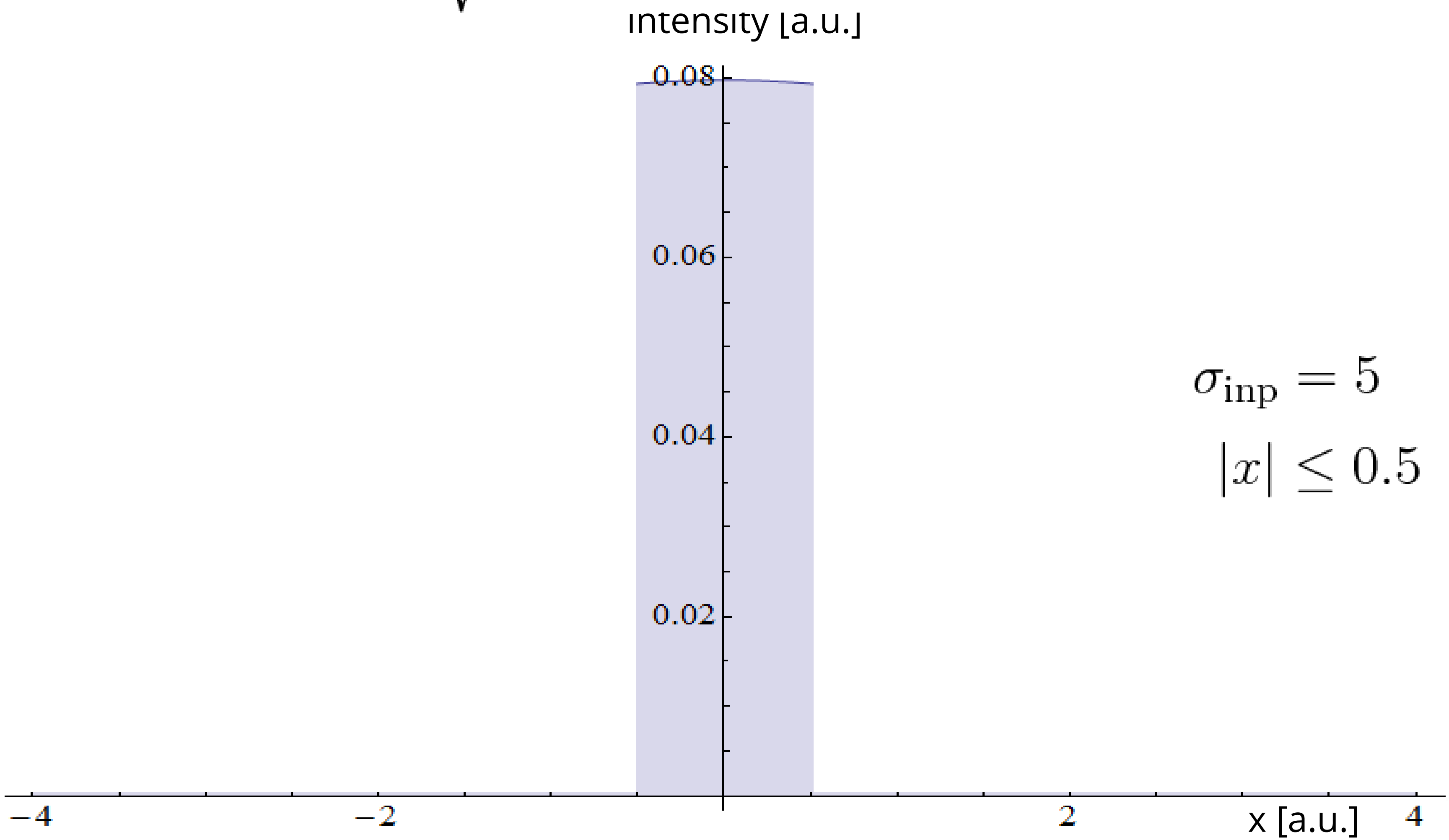


$$\sigma_{\text{inp}} = 1$$

$$|x| \leq 0.5$$

Emittance and Bunch Length Optimisation

$$f(x) = \frac{1}{\sqrt{2\pi\sigma_{inp}^2}} \exp\left(-\frac{1}{2}\frac{x^2}{\sigma_{inp}^2}\right) \quad \text{for } |x| \leq a$$

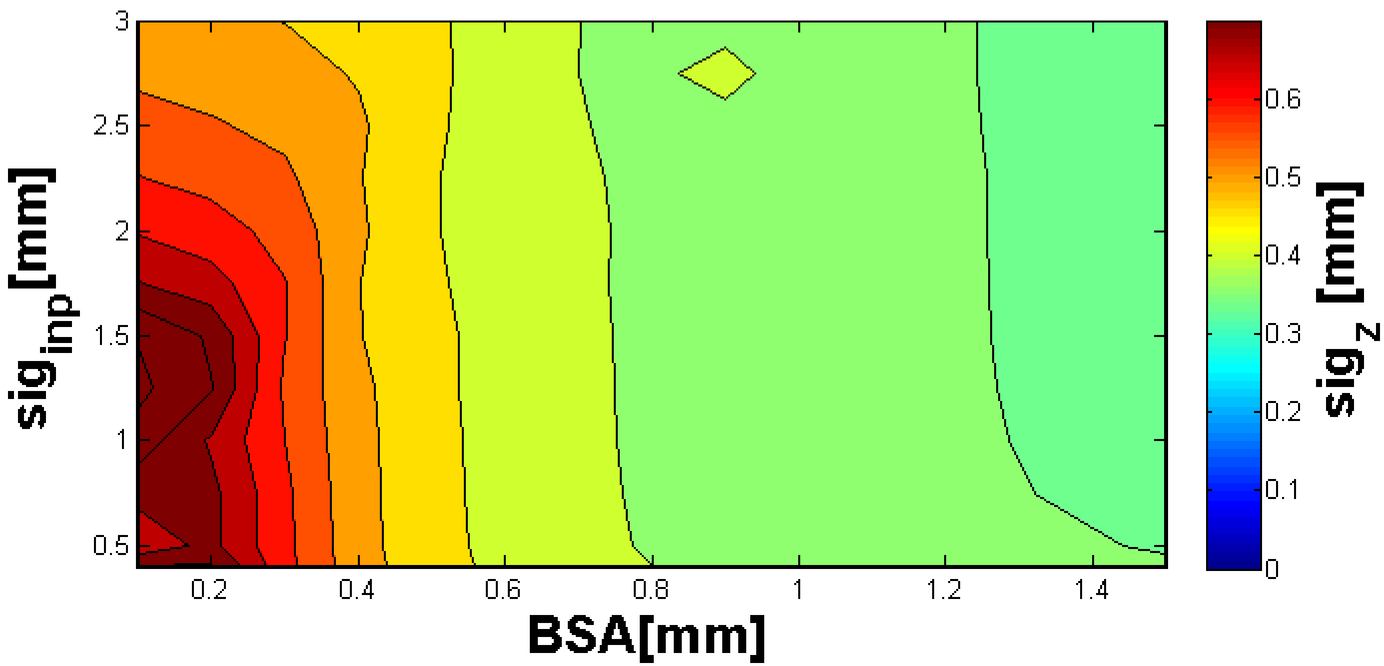


Emittance and Bunch Length Optimisation

- first simulations (1.0 ps laser pulse) to find the parameter set σ_{inp}, a (aperture) for minimum emittance have been made
- for each simulated pair, the solenoid's magnetic field strength has been scanned

parameter	value
laser pulse duration (rms)	1.0 ps
bunch charge	20 pC
macro particles	20 000
gun gradient	50 MV/m
laser spot profile	truncated Gaussian
laser spot size (rms)	0.25 - 3.0 mm
aperture size	0.3 – 3.0 mm

Emittance and Bunch Length Optimisation



Big transverse aperture size for smallest possible bunch length.

With a desired final length about 1µm and a compression factor of <450, the threshold for the bunch length at the end of the injector is about 0.45mm.

Emittance and Bunch Length Optimisation

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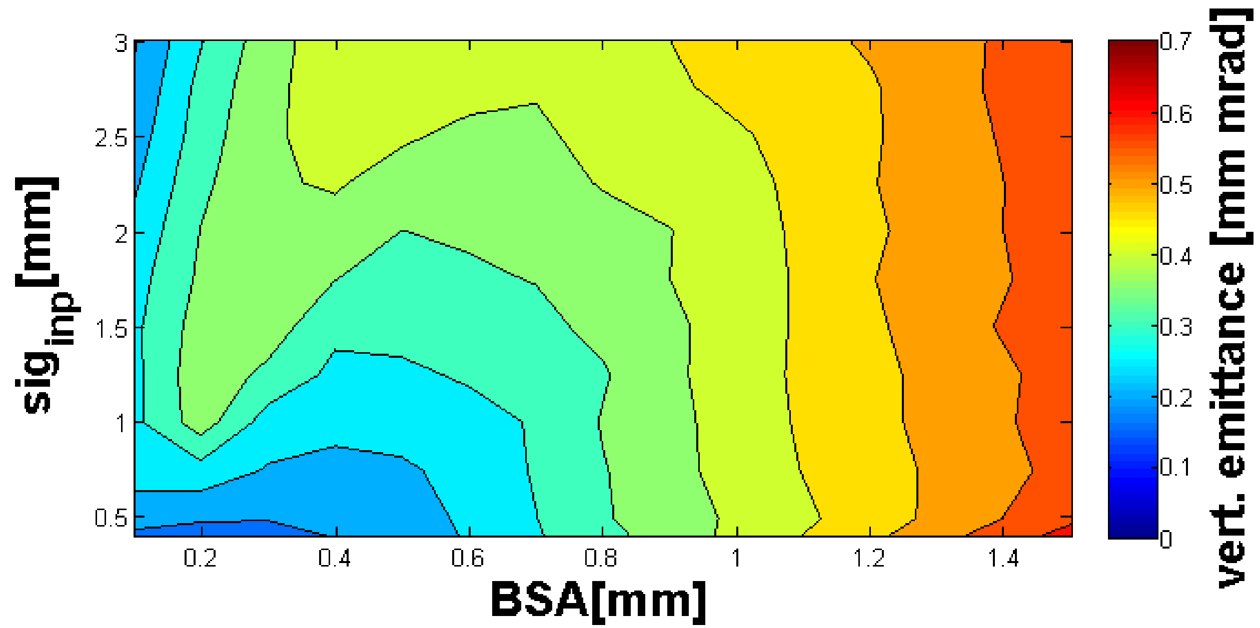
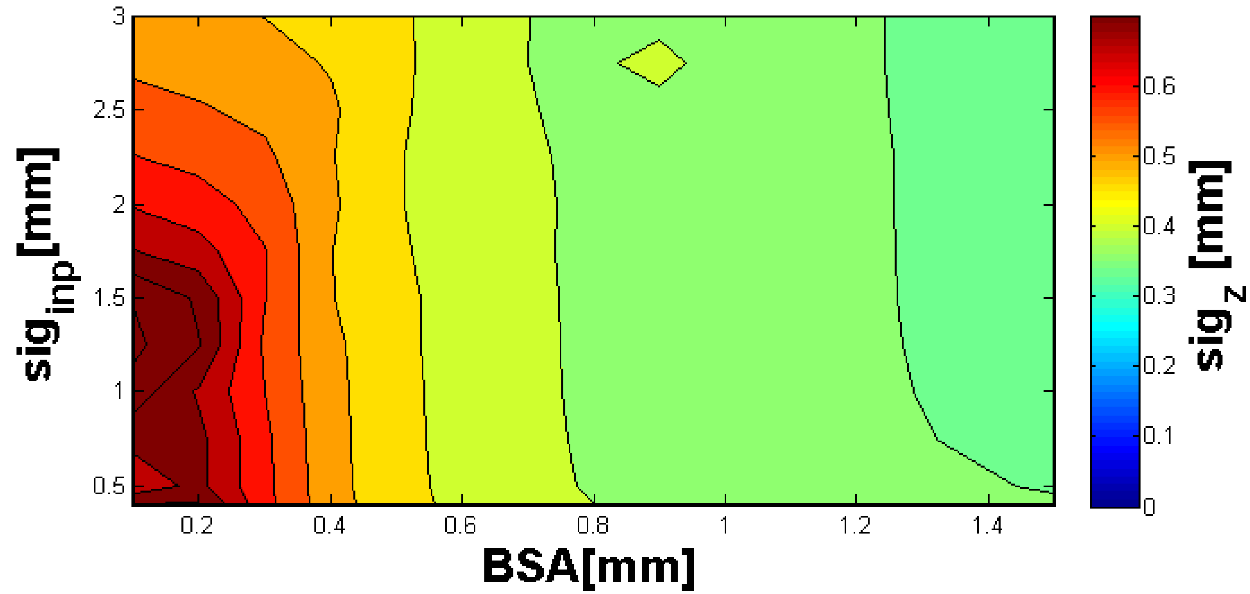
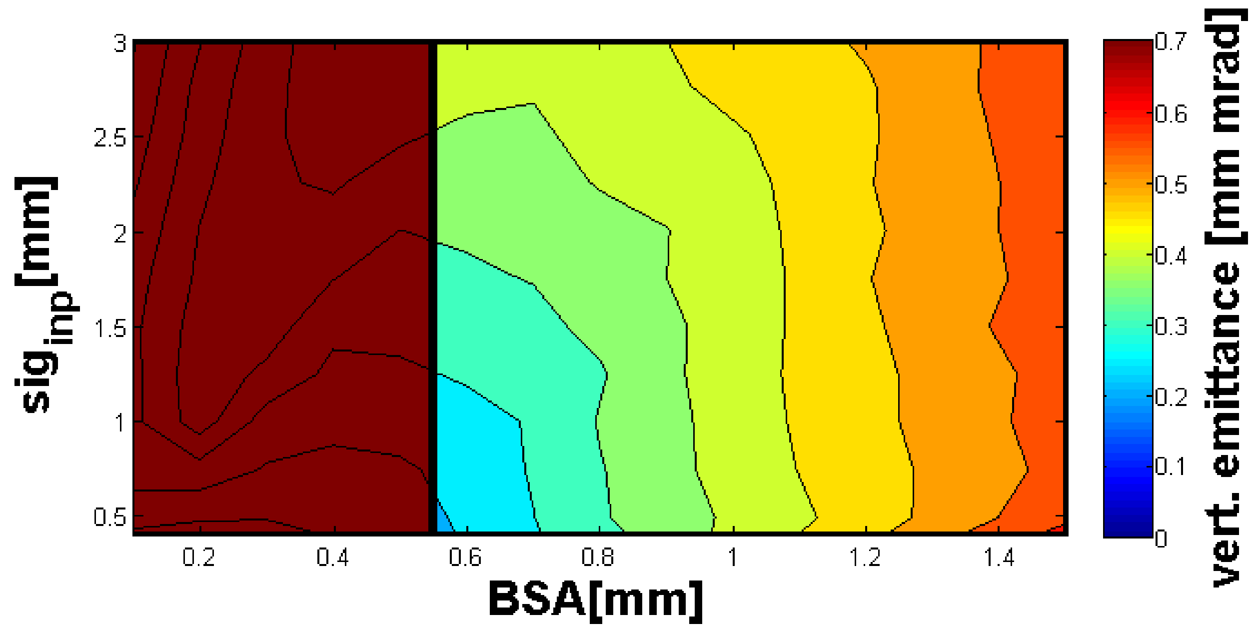
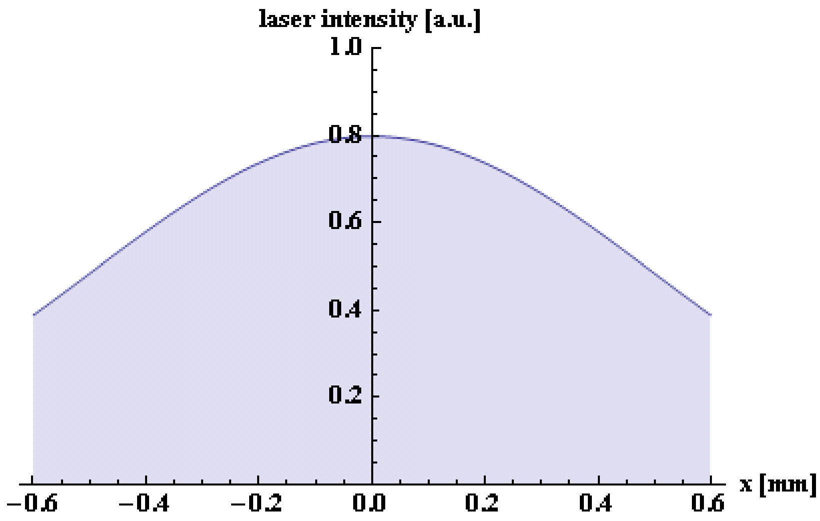




Emittance and Bunch Length Optimisation



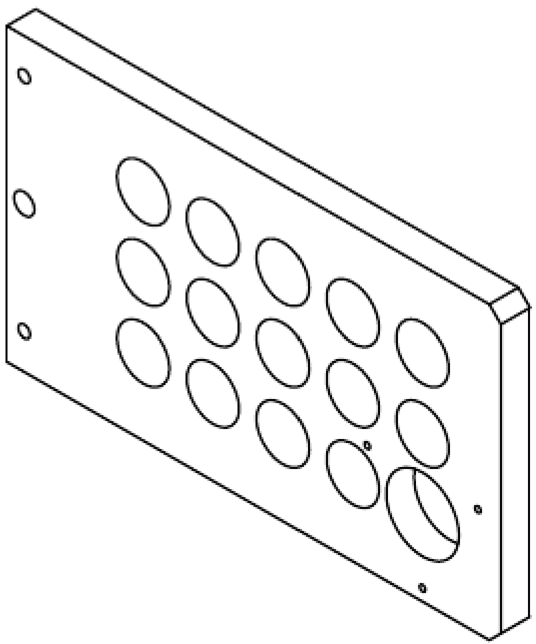


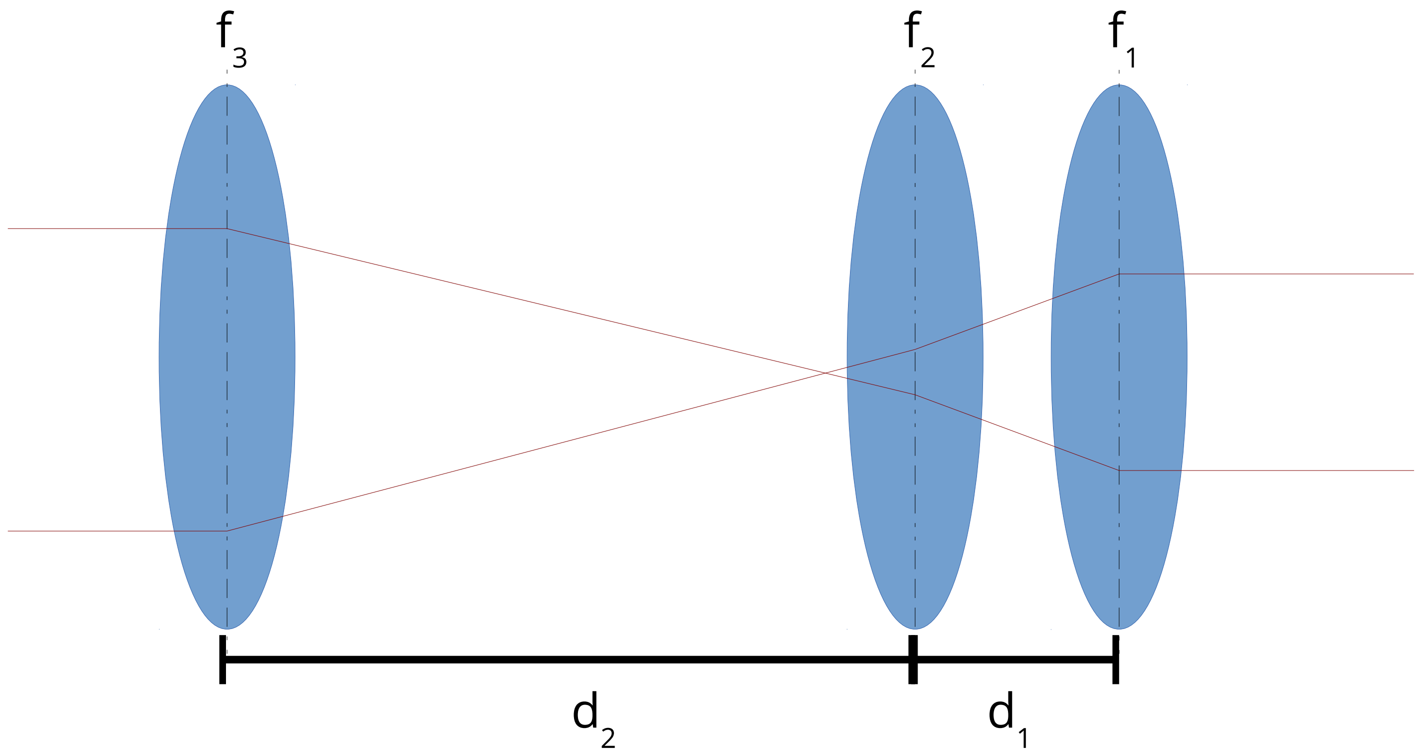
With the prior limit for the compression factor, the optimum transverse distribution would be.

$$\sigma_{inp} = 0.5\,mm$$
$$|x| = 0.6\,mm$$

Telescope & BSA

- round apertures with different diameters from 0.15 mm up to 2.5 mm
- mounted on a movable stage to move in x,y,z direction
- aperture is imaged 1:1 on FLASH cathode
- use variable telescope for stepless spot size selection on aperture





Reduction

$$R = \frac{-f_2 f_3}{f_1(f_3 + f_2 - d_2)}$$

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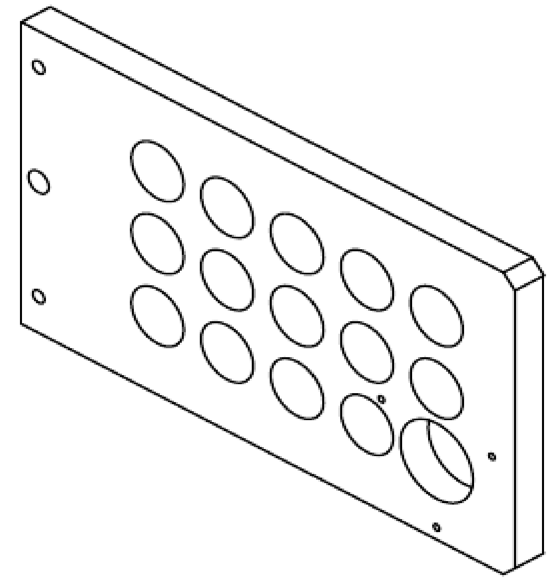
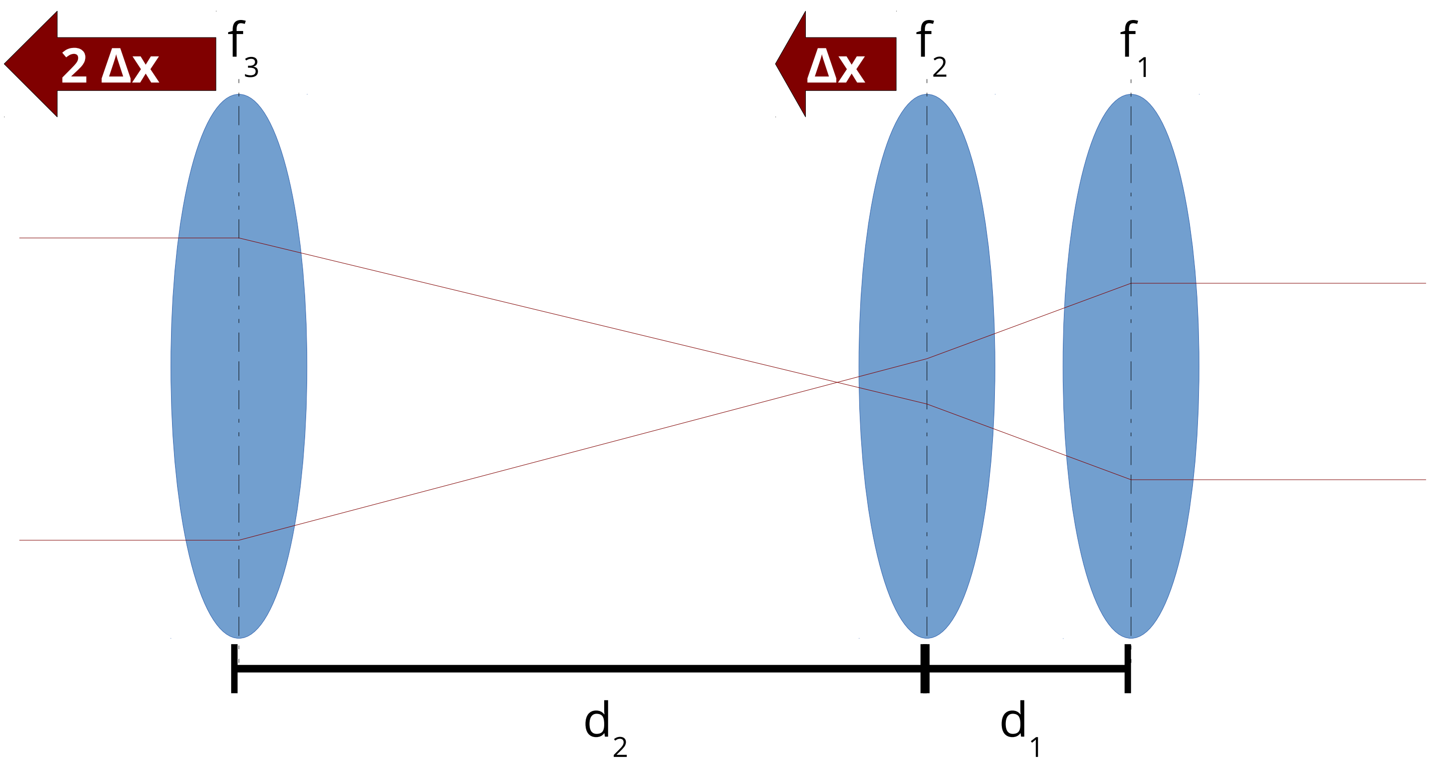




preserves collimated beam

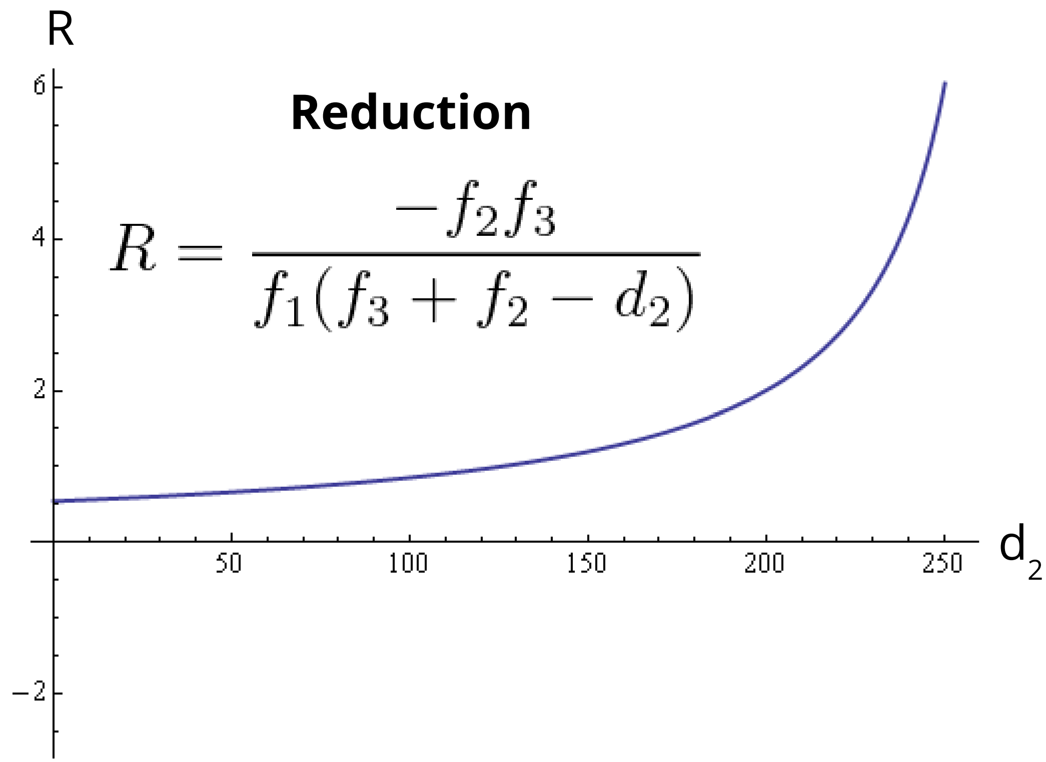
d_2 increased by Δx

Reduction

$$R = \frac{-f_2 f_3}{f_1(f_3 + f_2 - d_2)}$$

Telescope & BSA

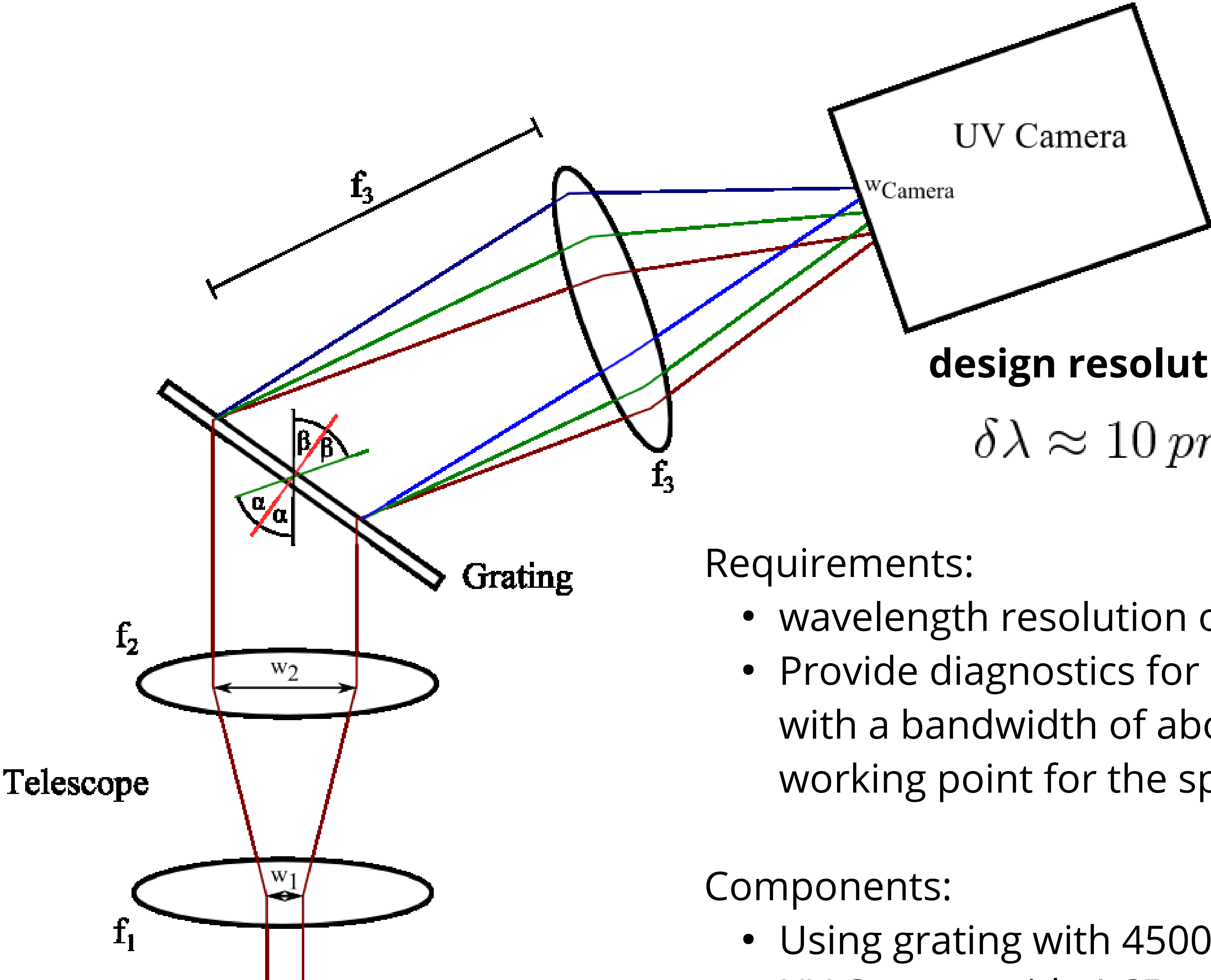
- Depending on magnification needed, the focal lengths of the lenses have to be chosen
- stepless magnification allows for stepless beam shape choosing between Gaussian and flattop
- available displacement allows for reduction of the laser spot size up to a factor of 5.



for values f_1 = 50mm, f_2 = -25mm, f_3 = 300mm

How can we measure laser parameters?

Laser Diagnostics



design resolution

$$\delta\lambda \approx 10\,pm$$

Spectrometer

Measurements:
- What is the UV spectrum?
- Get an idea of spectral stability of the laser

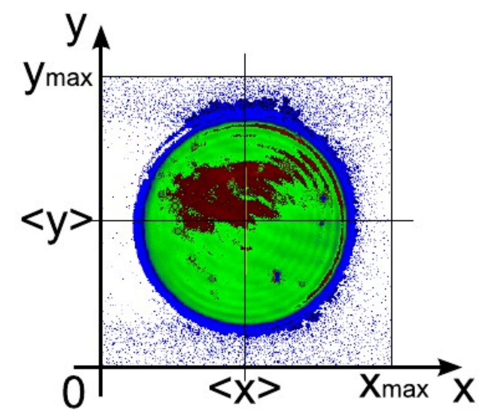
Requirements:
- wavelength resolution of about 10 pm
- Provide diagnostics for all three injector lasers with a bandwidth of about 1nm. This gives a working point for the spectrometer: 256-268nm

Components:
- Using grating with 4500 lines/mm
- UV Camera with 4.65 µm pixel size

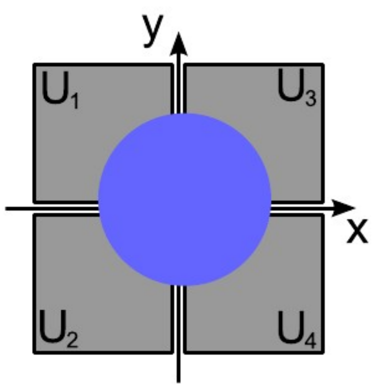
Alignment Camera

- Use spectrometer camera as virtual cathode for laser alignment
- Imaging of 50µm up to 2mm apertures

Quadrant Diode



aus [1]



Measurements:

- Position of the intra train laser pulses
  → stability during pulse train
- Laser pulse energy

Requirements:

- Fast electronics working at least 1MHz (repetition rate of laser pulses)

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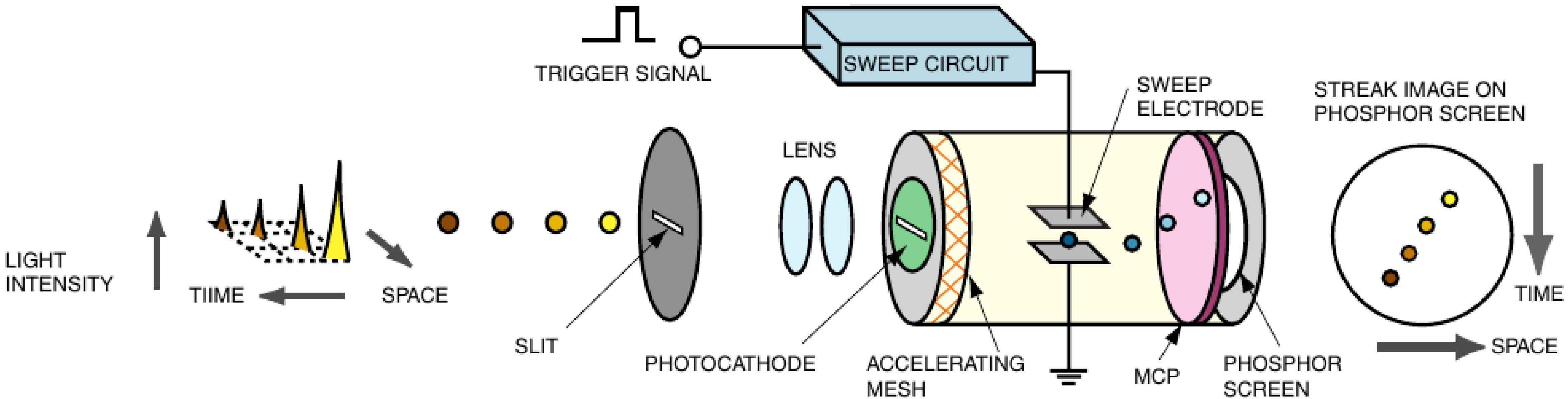
Streak Camera



working principle

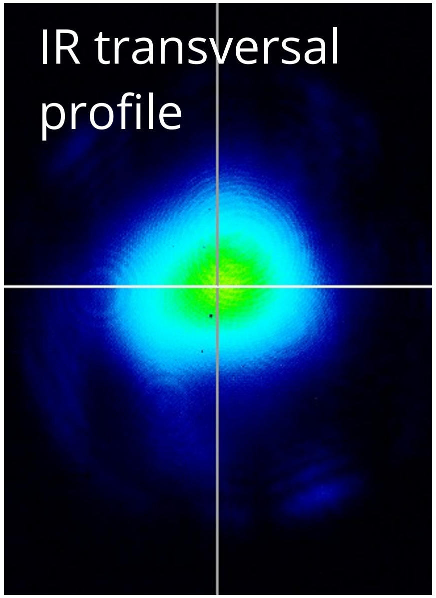
- Electron bunches with a similar temporal distribution are generated in a photo-cathode by a photon pulse
- electrons get accelerated onto fluorescence screen
- electrons get deflected by a fast time varying high voltage
- the flourescence screen translates electrons back to photons which can be detected

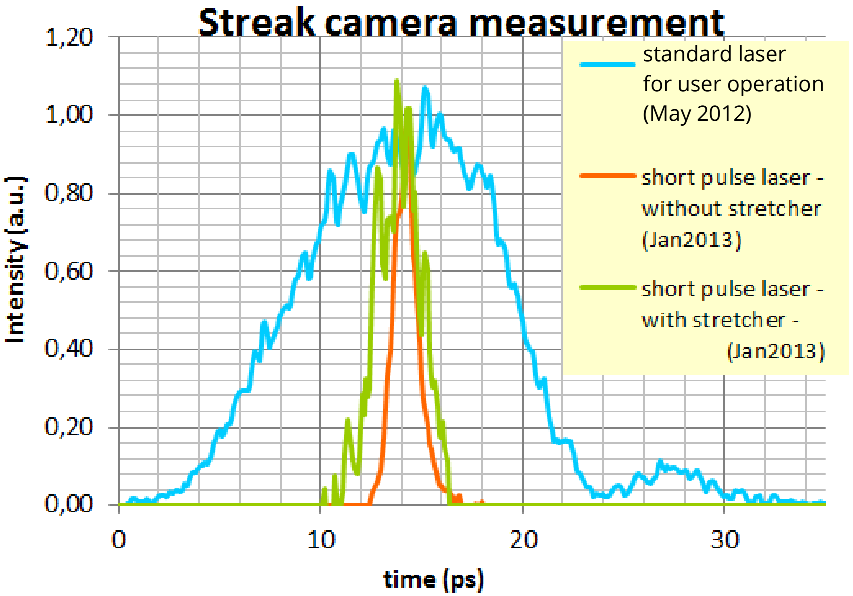
Laser pulse length can be measured down to a limit of about 0.5 ps.

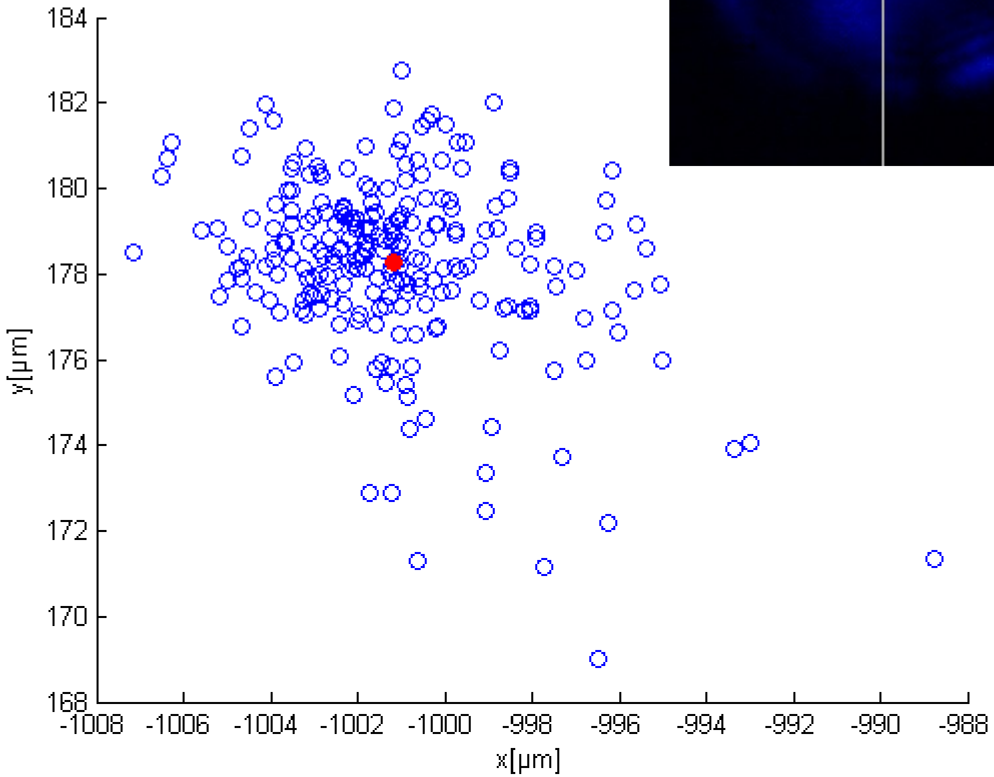
Measurements and Shifts

Laser Beam

Position instability about 3 µm at a total laser pulse width of 1mm. (IR)







Measurements Jan 2013 [FWHM]

- short pulse without stretcher:

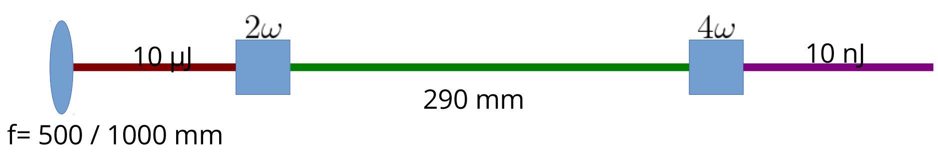
$$\sigma = 1.3 \pm 0.5 \text{ ps}$$

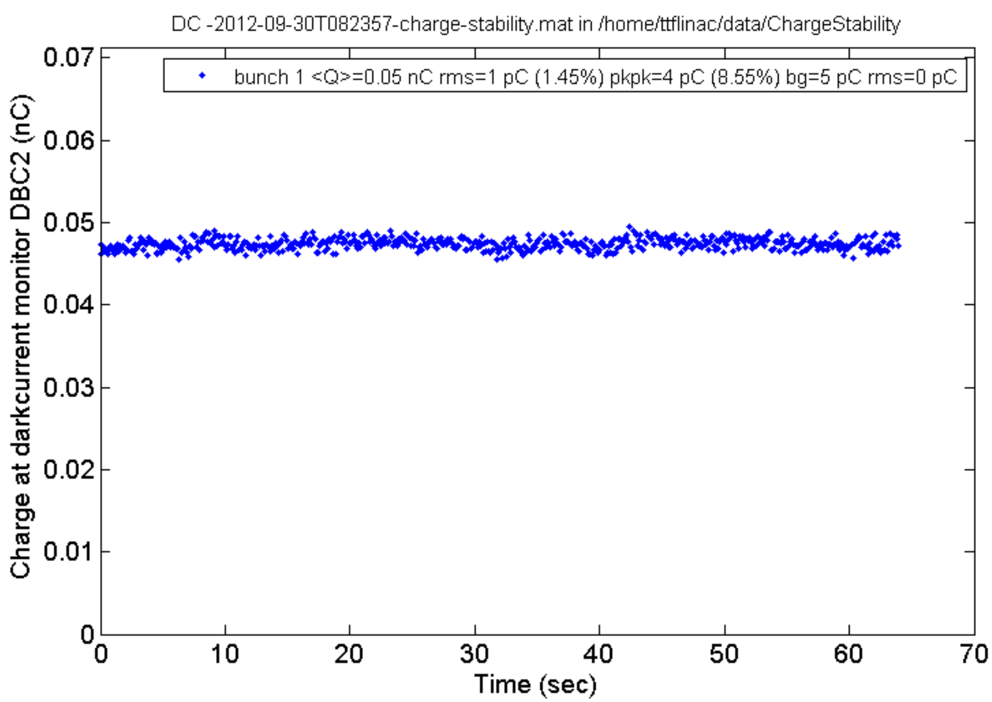
- short pulse with stretcher:

$$\sigma = 2.4 \pm 0.5 \text{ ps}$$

Charge Stability

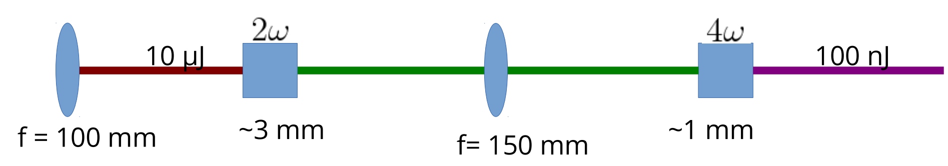
Sep 2012

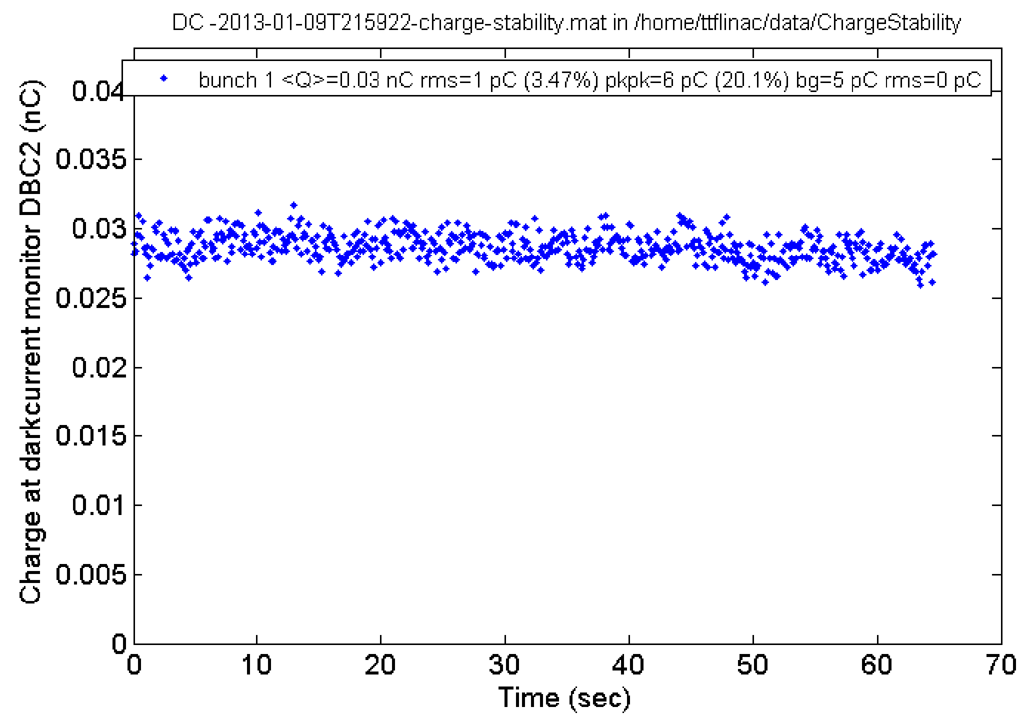




$$\sigma_C = 1.4\%$$

Jan 2013





$$\sigma_C = 3.5\%$$

SASE – Jan 2013

parameters	09.01.13	11.01.13
injector laser pulse duration (rms)	1.0 ps	1.0 ps
bunch chage	35 pC	80 pC
bunch duration (rms) [LOLA]	35 fs	78 fs
wavelength	13.5 nm	13 nm
number of modes in FEL pulse	unknown	~ 5.7
FEL pulse duration (rms)	unknown	~ 50 fs
compression factor	~70	~30
SASE energy	5 µJ	25 µJ
SASE power	unknown	~ 0.5 GW
SASE bandwidth	unknown	0.34 %

Improved SASE stability compared to short pulse runs with standard injector laser due to shorter compression factors and thus more stable electron bunch length and form.

Summary & Goals

- laser beamline with frequency conversion, stretching, transversal pulse shaping has been built and integrated into the control system
- after two shifts in January first SASE was generated with new injectorlaser
- first laser diagnostics have been built to characterise the laser

Goals

Enable routine operation with new short pulse laser this year:

- full control system integration has to be done (laser controls)
- characterise laser with diagnostics
- measure pulse length and emittance for different transversal laser profiles

Thank you for your attention!

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