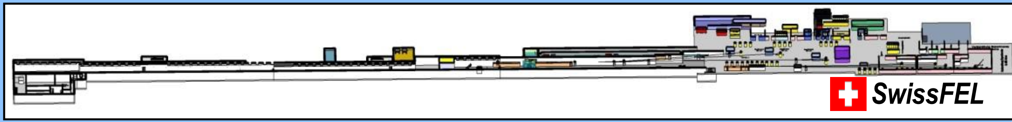



M.Divall

# Beam shaping

LA3NET school

15/10/2012

# Outline

- Introduction to laser applications in FEL
- Laser beam transport
  - basic optics/ rays/ transfer matrix
  - Image relay
  - Gaussian beam
  - Ray-tracing softwares
  - Waves vs. rays, physical optics
- Why is shaping important?
  - Gaussian vs. real beams
  - Emittance optimization
- Transverse shaping
  - Spatial filters
  - Refractive beam-shapers optics
  - Adaptive optics
  - Hard aperture
- Longitudinal shaping
  - Time domain methods
  - Frequency domain methods
- Safety

# Lasers for FEL

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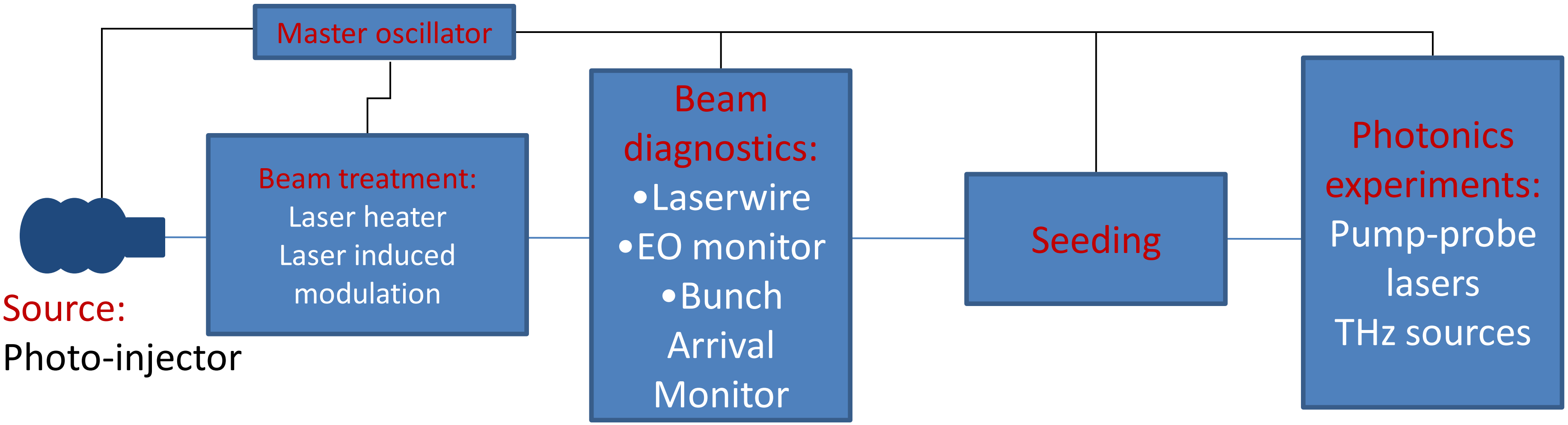
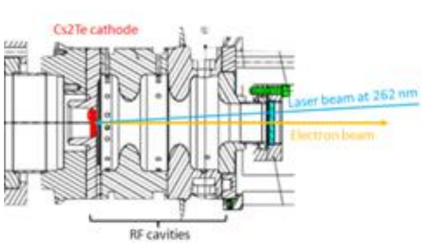
SwissFEL




**Wavelengths range from X-UV to THz**
**Pulse energies from pJ to multi-mJ**
**Pulse length from single cycle to many ps**

**The lecture will not cover all the aspects, it will point to where to find things and what to consider**

**Most examples will be related to photo-injectors**



# Photo-injector

## ADVANTAGES

Capability to synchronize to external RF source with very high accuracy

Flexibility for timing structure, single pulse operation

Size, shape, pulselength, energy can be optimized for machine

Can produce polarized electrons

Gives smaller transverse emittance

No energy tails

No satellites

Thermionic gun

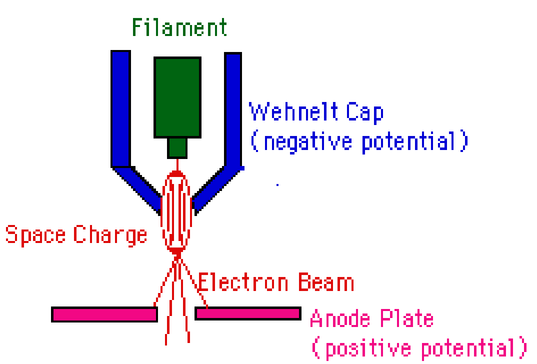
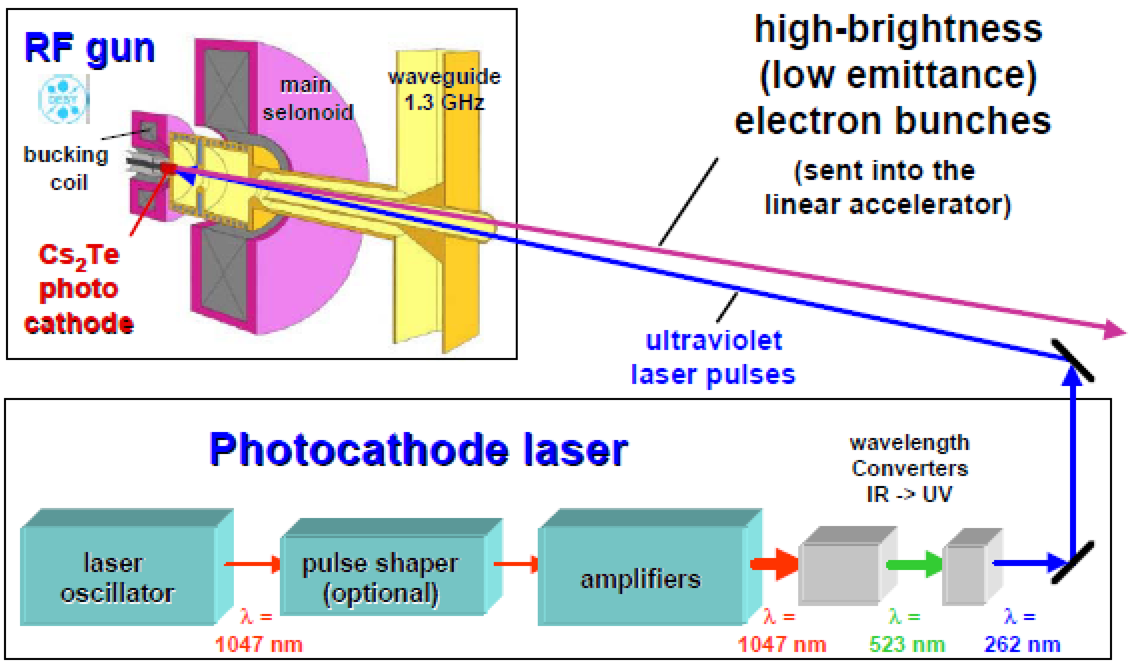



Photo-injector




*K. Floettman DESY*

# The ideal laser system

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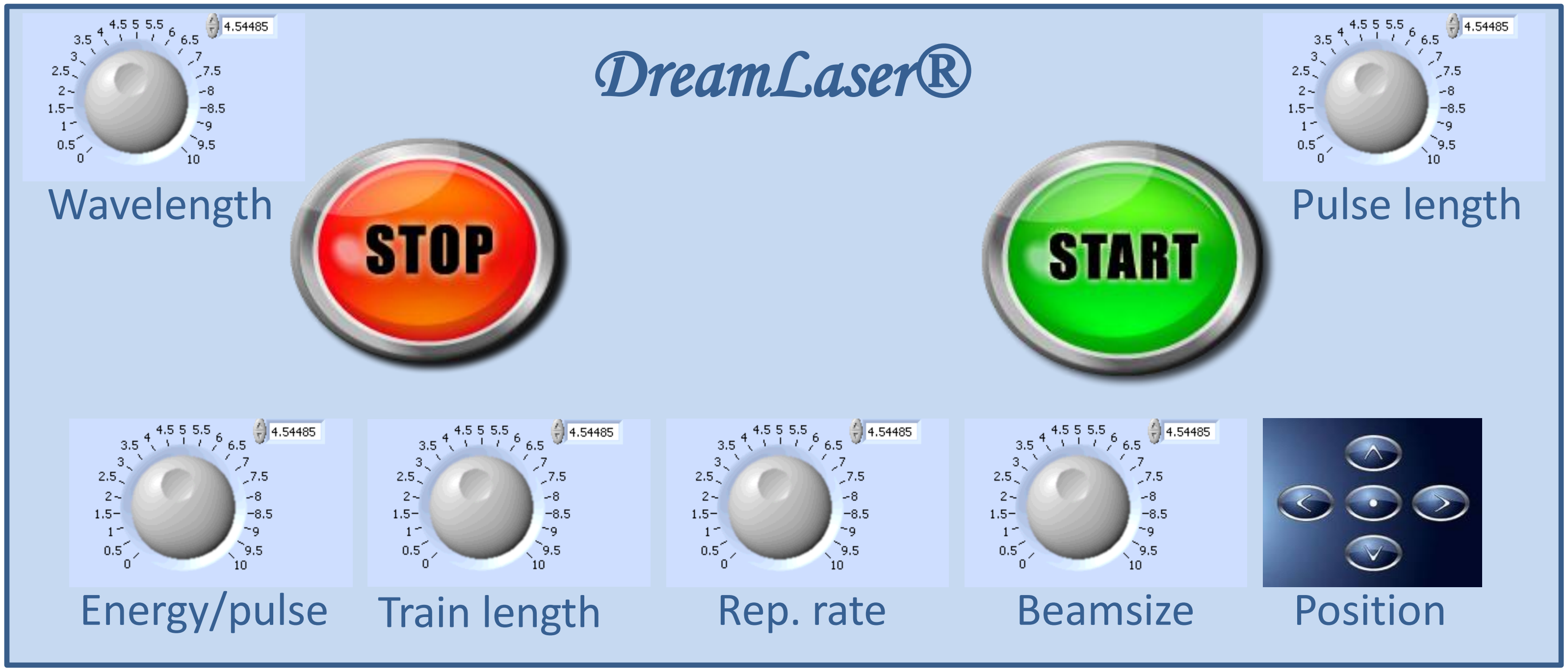


# Flexible Stable

# What to consider when transporting light

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SwissFEL

## You will have it in the specifications

What are the parameter requirements on target?
Wavelength/ Bandwidth
Pulselength/ shape
Beamsize/ shape
Pulse energy
Number of pulses
Average power

Also important
Beam homogeneity
Energy stability
Pulse length stability
Timing stability
Pointing stability

How do we get to the 'target' without loosing on specs? →

## You have to specify accordingly

Environment
Controls and stability
Transition between areas
Air flow
Safety

Control
Remote (limited access)
User friendly
Tuneability
Control system compatibility

Diagnostics/Feedback
What?
Where to measure?
Resolution and dynamic range
Speed

Optics
Distance
Aberrations
Surface quality
Coatings
Losses
Dispersion

# Outline

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  - Frequency domain methods
- Safety

# Recipe

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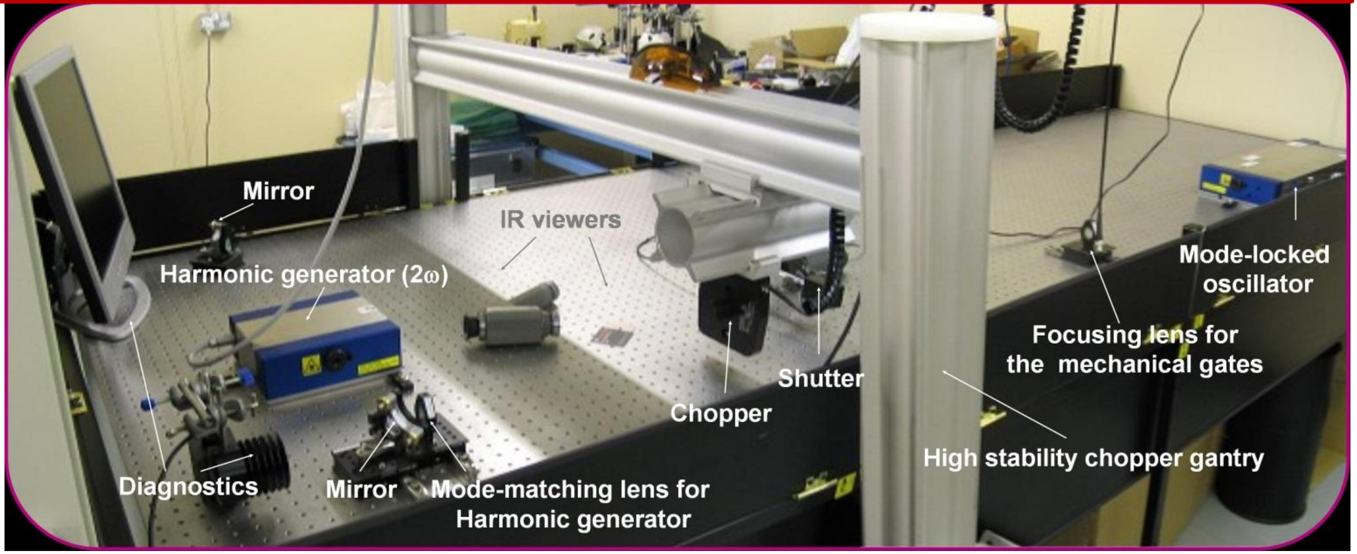
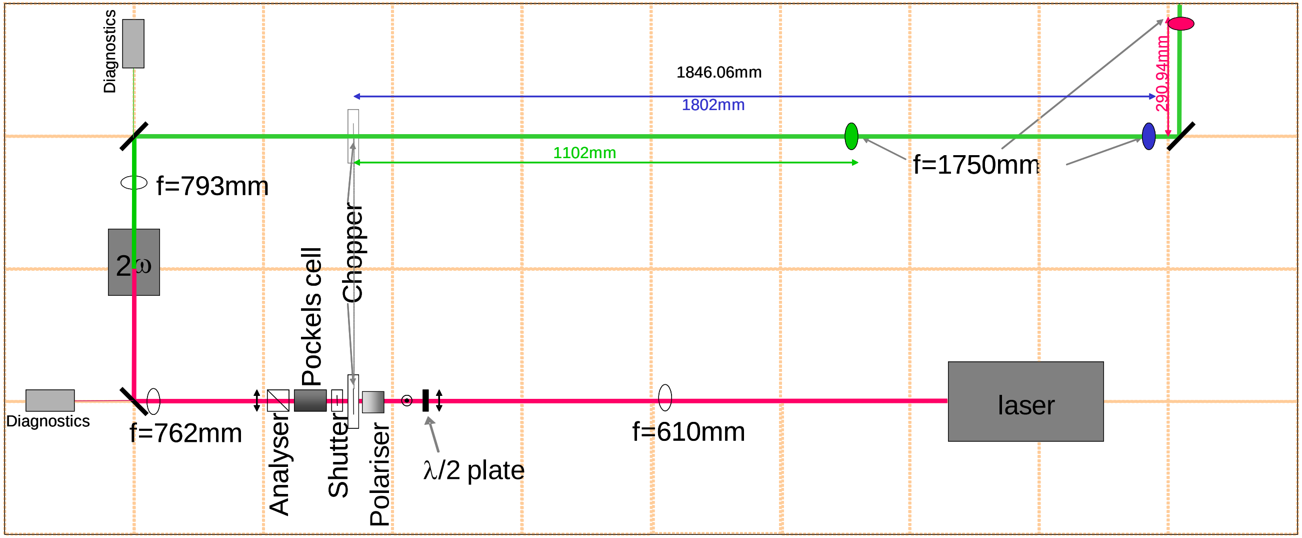
- Check you total distance, beamsize at source and at target
- Look at restrictions for placing optics
- Think of image relay!
- Take a back of an envelo xial approximation and lens equations
- Calculate the dispersion i ven bandwidth (transmissive or reflective optics?)
- Measure your beam (prof
- Put your system into a m your initial results (ZEMAX, OSLO, RAYTRACE…)
- Check tolerances and ab orget apertures/stops and diffraction
- Specify your optics: Size, nce, antireflection, absorption, achromats, da
- Specify optics mounts: R ity, robustness against vibration, motorized
- Decide on diagnostics an the way!
- Do you need transport pipes, vacuum?
- Don't forget safety and interlocks!

# 4GLS photo-injector laser

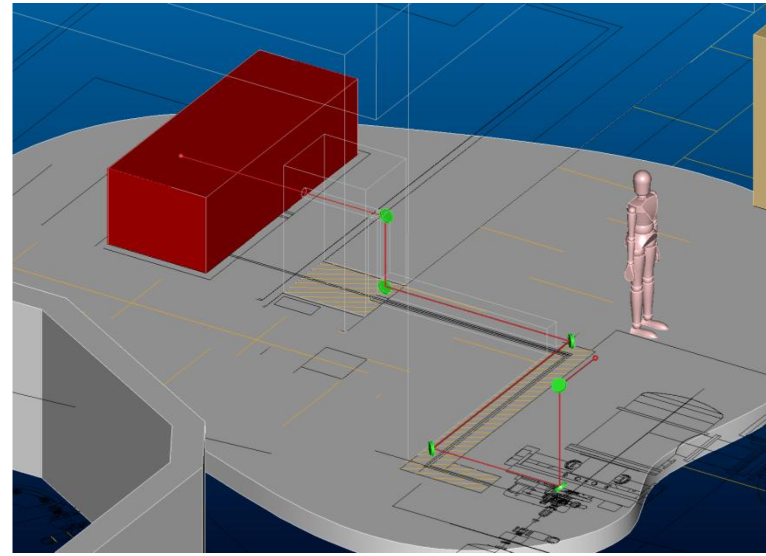
Nd:YVO$_4$ oscillator 10W
81.25MHz
532nm at 2$^{nd}$ harmonic
100μs pulsetrains
100Hz

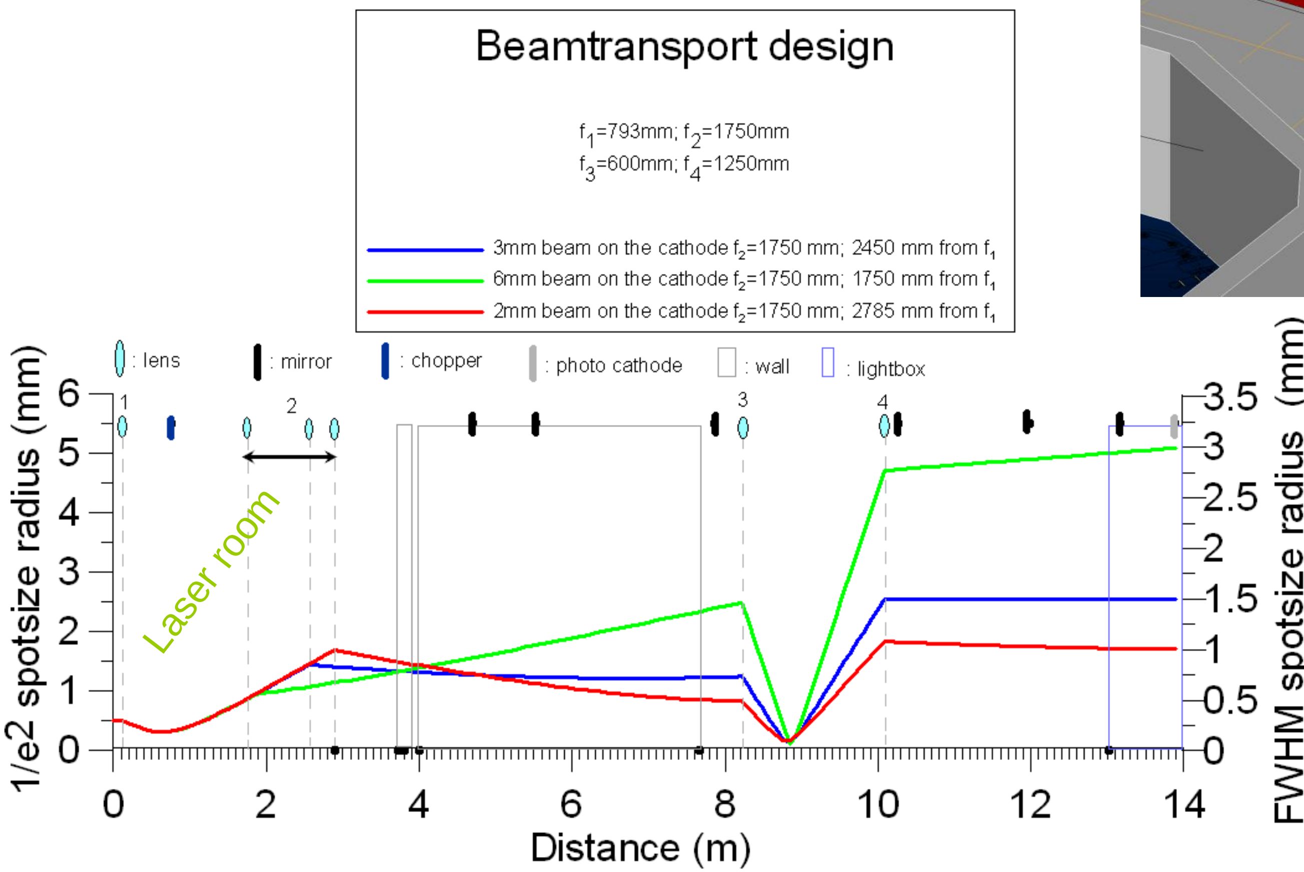


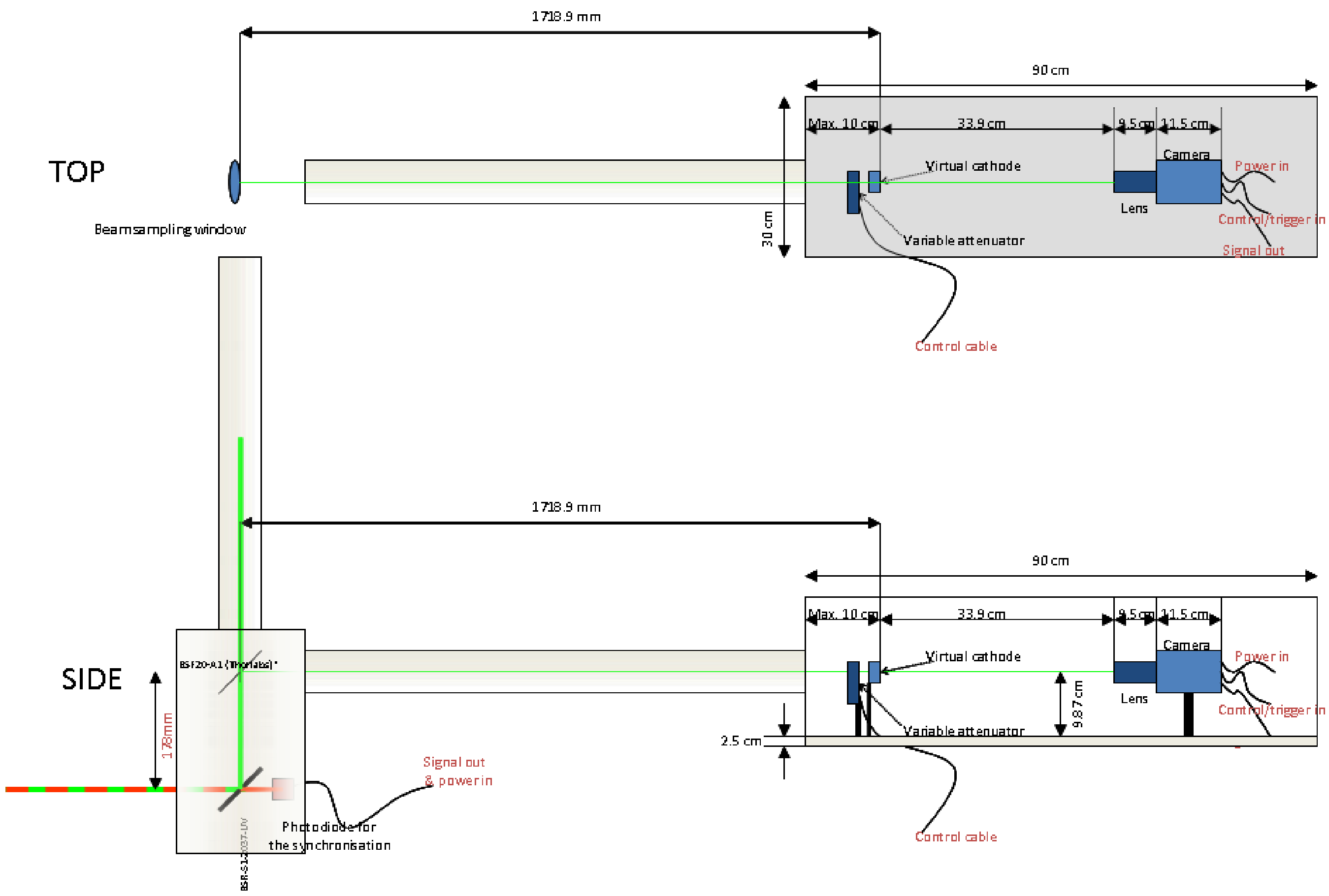
# Transport to cathode

2-6 mm beam size on the cathode
Gaussian beam
523nm





# Diagnotics

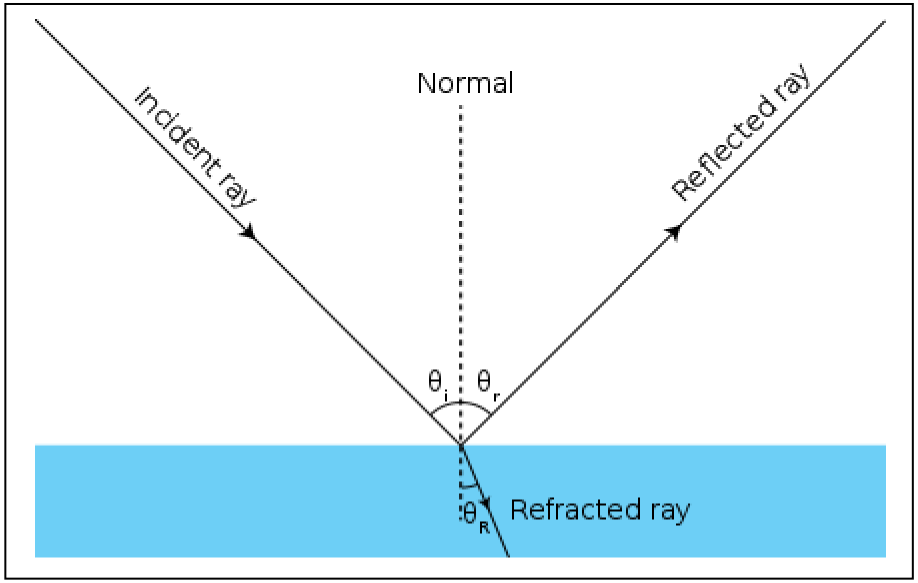


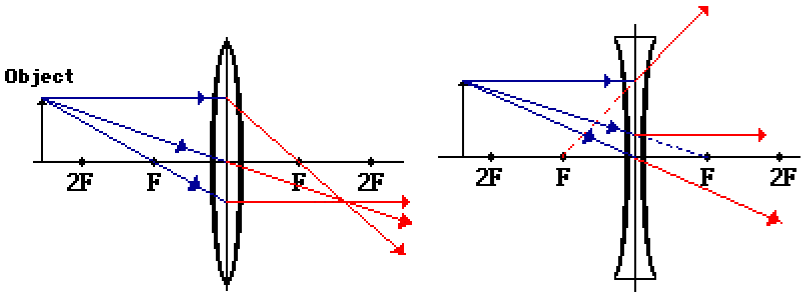

Laser energy on the cathode
Beam position and profile

# Light rays/ paraxial approximation

**Ray:** narrow beam of monochromatic light (ones you used to draw on paper in school)
**Ray tracing:** divides the real light field up into discrete monochromatic rays that can be propagated through the system
**Paraxial rays :** The distance of the ray from the optical axis is small compared to the focal length of each optical element of the system. The angle between the optical axis and the ray is small
Only approximate solutions to Maxwell's equations !!
Objects are much larger, then the wavelength!
Rays follow Snell's law of refraction and energy conservation

Ray theory does not describe interference and diffraction, where wave theory, including phase has to be added!



# You need to know basic geometrical optics

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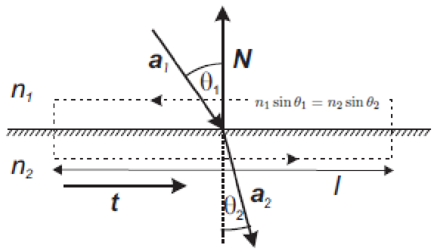
## Snell's law of refraction




## Laws of reflection

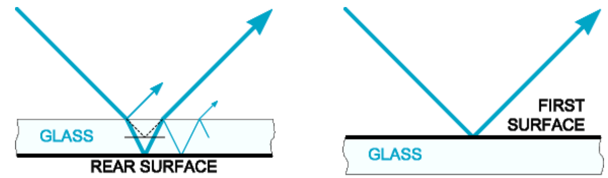



Fig. 4.5 Reflection from a second surface and first surface mirror.

## Lens equations

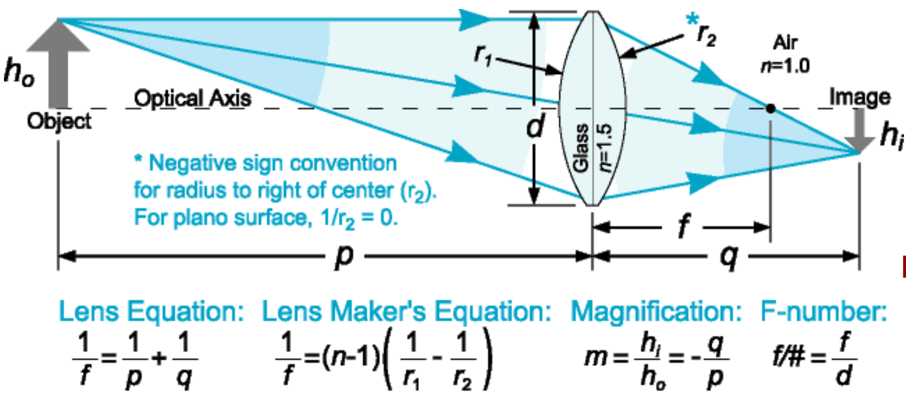



Fig. 4.4 Some useful lens equations.

## Curved mirrors

Homework clue!

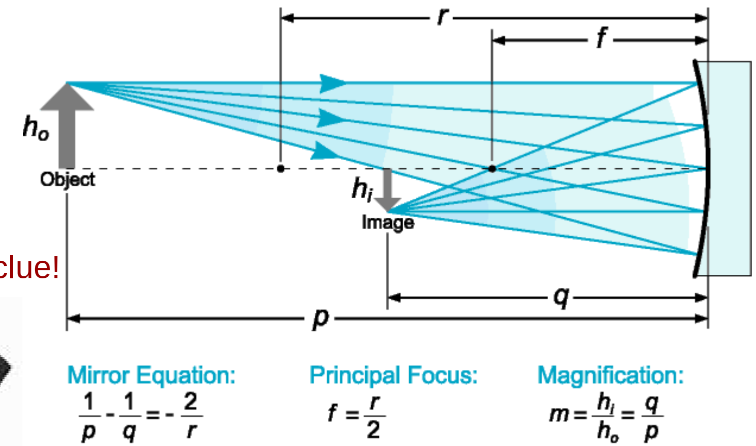



Fig. 4.6 Reflection from a spherical concave mirror.


•*R.Guenter: Modern Optics, John Wiley and Sons, 1990.*

•*E.Hecht, A.Zajac: Optics, Addison Wesley, 1980.*

•*Max Born, Emil Wolf, A. B. Bhatia and P. C. Clemmow :Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light, Cambrisge University Press 1999*

[www.intl-light.com/customer/handbook/handbook](www.intl-light.com/customer/handbook/handbook)

# Matrix optics



Rays can be described by:
r: Distance of the ray at a certain plane from the optical axis
Θ: angle of the ray relative to the optical axis

Optics can also be described by their transfer matrix

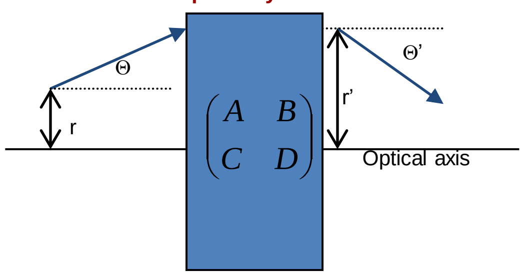
$$\begin{pmatrix} r' \\ \theta' \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} r \\ \theta \end{pmatrix}$$

For a thin lens

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}$$

For free space (drift space)

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix}$$




For a concave mirror R>0

$$\begin{pmatrix} 1 & 0 \\ -2/R & 1 \end{pmatrix}$$

At a flat surface

$$\begin{pmatrix} 1 & 0 \\ 0 & n_1/n_2 \end{pmatrix}$$

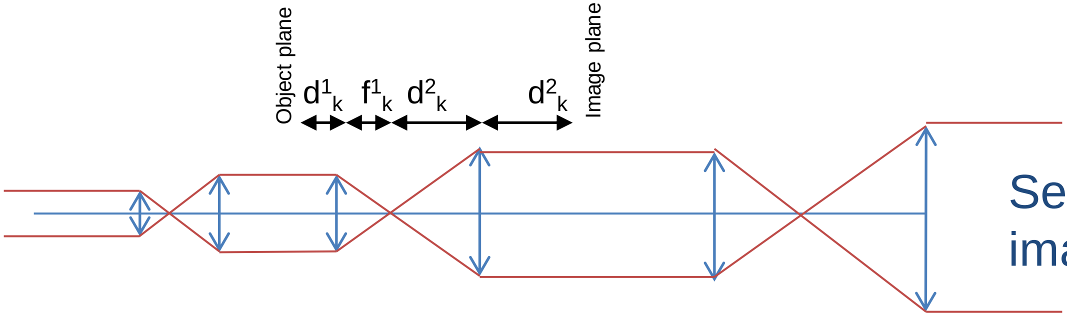
For think lens

$$\begin{pmatrix} 1 - \frac{n_L - n}{n_L R_1} d & \frac{n}{n_L} d \\ \underbrace{-\frac{n_L - n}{n}\left[\left(\frac{1}{R_1} - \frac{1}{R_2}\right) + \frac{n_L - n}{n_L}\frac{d}{R_1 R_2}\right]}_{=-1/f'} & 1 + \frac{n_L - n}{n_L R_2} d \end{pmatrix}$$

**To include wavelength dependence you need to go 3X3**

*Gerrad, A.; Burch, J.M. Introduction to Matrix Method in Optics; John Wiley and Sons: New York, 1975.*
*Wang, S.; Zhao, D. Matrix Optics; Springer-Verlag:Berlin, 2000.*

# Image relay




Series of lens pairs creating an image some distance away

$$t_k = \begin{bmatrix} -m_k & -m_k d_k{}^1 - (m_k)^{-1} d_k{}^2 + f_k{}^1 + f_k{}^2 \\ 0 & -1/m_k \end{bmatrix},$$

Transfer matrix of a lens pair

$$m_k = (f_k{}^2)/(f_k{}^1)$$

Magnification of a lens pair

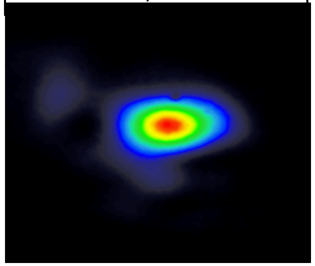
$$T_N = \prod_{k=1}^{N} t_k.$$

Full transfer matrix

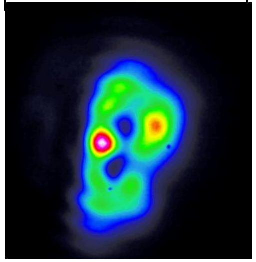
$$m_k d_k{}^1 + (m_k)^{-1} d_k{}^2 - f_k{}^1 - f_k{}^2 = 0.$$

Equation to satisfy imaging

Imaging the 4th harmonic crystal



Imaging an arbitrary plane behind the crystal



Can make a huge difference to the beam quality on target!

*Hunt et al. Suppression of self-focusing through low-pass spatial filtering and relay imaging Applied Optics, Vol. 17, Issue 13, pp. 2053-2057 (1978)*

# Work with Gaussian beams

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- Gaussian distribution is the solution of paraxial Helmholtz equation
- TM00 mode

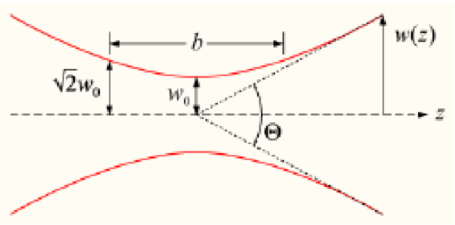
$$E(r,z) = E_0 \frac{w_0}{w(z)} \exp\left(-\frac{r^2}{w^2(z)}\right),$$

$$w(z) = w_0 \sqrt{1+\left(\frac{z}{z_0}\right)^2},$$

$$z_0 = \frac{\pi w_0^2}{\lambda},$$

$$w_0 = \frac{2\lambda}{\pi\Theta},$$

$$b = 2z_0.$$




$w_0$: beam waist
$z_0$: Rayleigh range
b: confocal parameter

These equations, with input values for *w* and $z_0$, allow the tracing of a Gaussian beam through any optical system
BUT
Optical surfaces need to be spherical
Only works for lenses with not-too-short focal lengths –similar to paraxial restrictions for geometric propagation

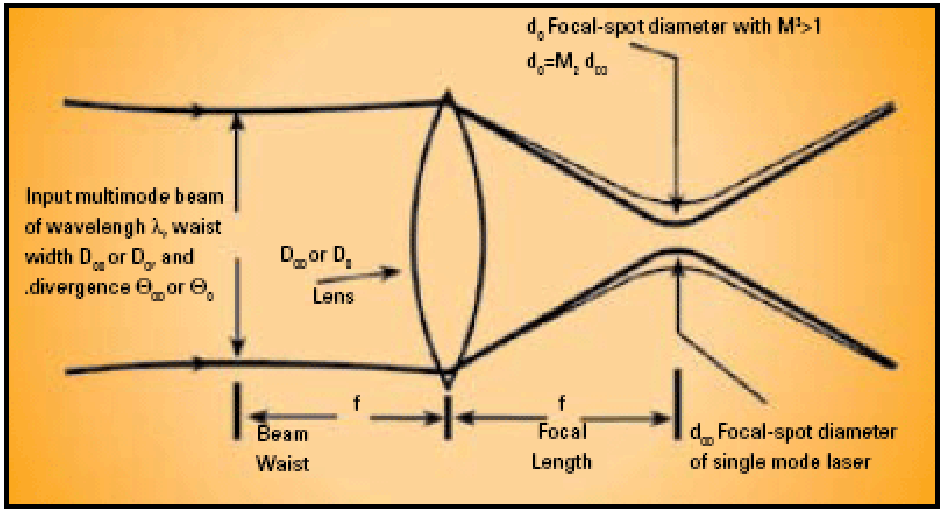
ABCD matrices also work $\frac{1}{q_2} = \frac{C + D/q_1}{A + B/q_1}$
BUT
We need to use the a complex beam parameter q (composite of *w* and $z_0$) $q(z) = iz_0 + z$

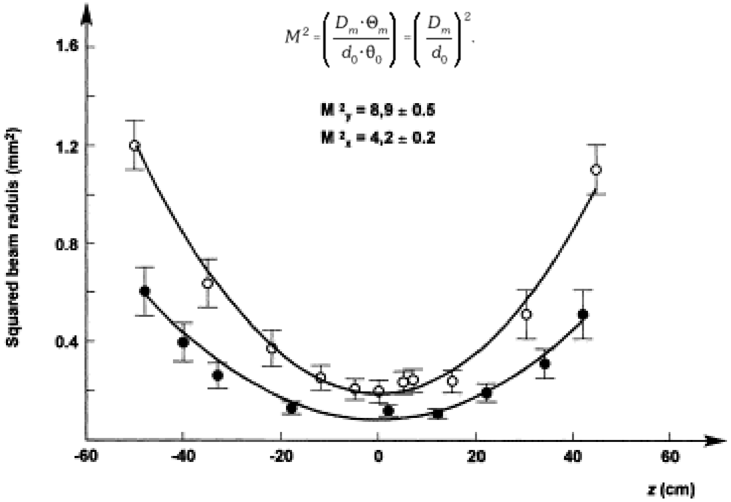
Find the waist, where *q* is purely imaginary and calculate *q* anywhere else using bilinear ABCD
From q one can determine the size and wavefront curvature

*See chapter 17 of Siegman's book, Lasers*
*Encyclopedia of optical Engineering Javier Alda Laser and Gaussian Beam Propagation and Transformation*

# Work with REAL Gaussian beams

M-square measurement is like a solenoid scan. M-square is a bit like emittance.



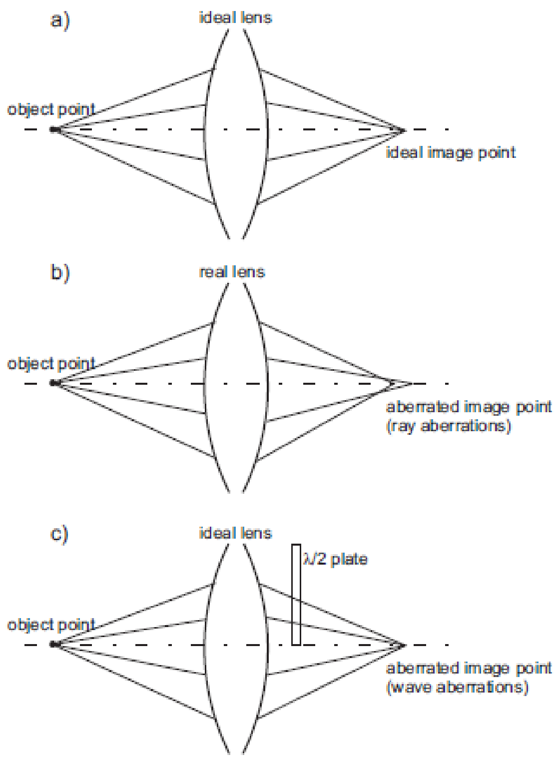

$M^2$ remains invariant through ABCD optical systems.
Commercial systems are available to perform measurement and fit.

Homework clue!

*Example in MathCad.*
.\Marta_CERNPC\PHIN\beamtransportfullPHINMay_2010M2definition_changed.xmcd

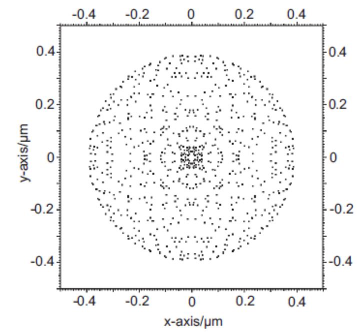
*Siegman, A.E. Defining the effective radius of curvature for a nonideal optical beam. IEEE J. Quantum Electron. 1991, 27, 1146–1148.*

# Quick word on aberrations

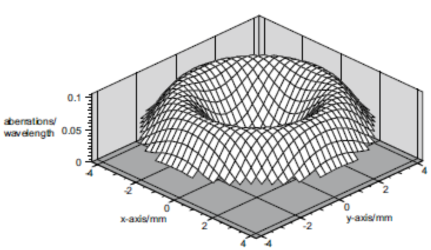



Paraxial ray tracing give a single point image

Full ray tracing will model ray aberrations




Full ray tracing + physical optics will also model interference and diffraction



# You need to get familiar with ray-tracing software

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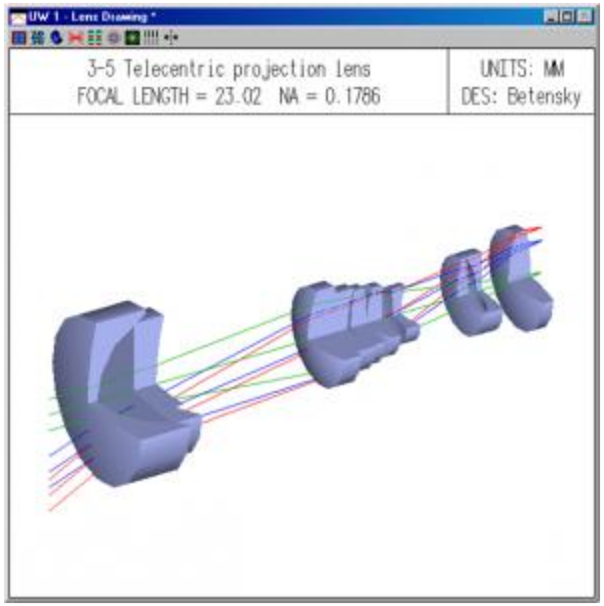
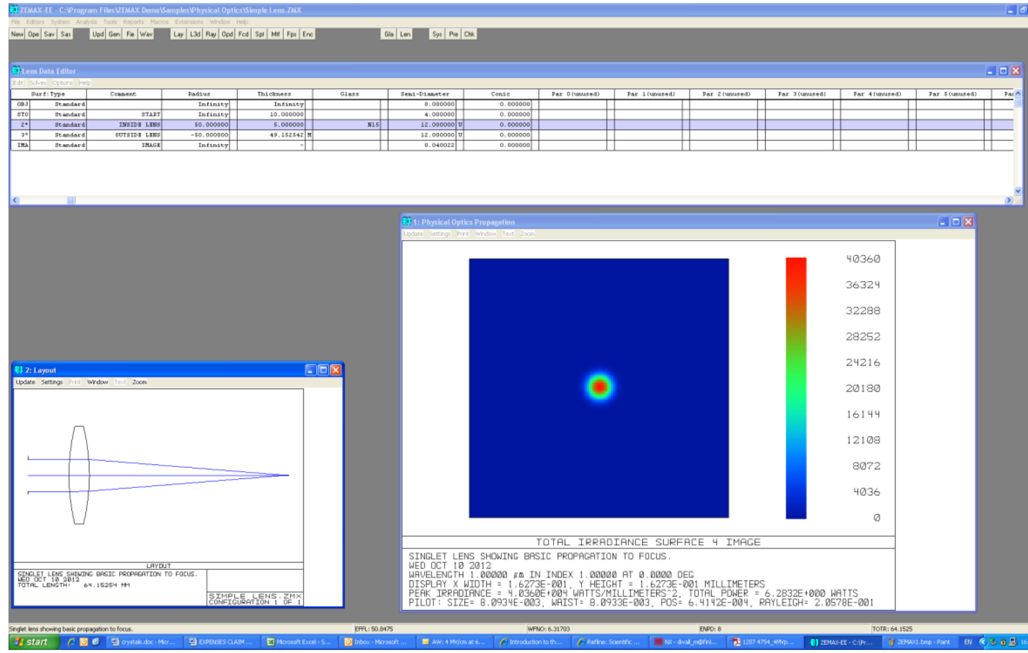
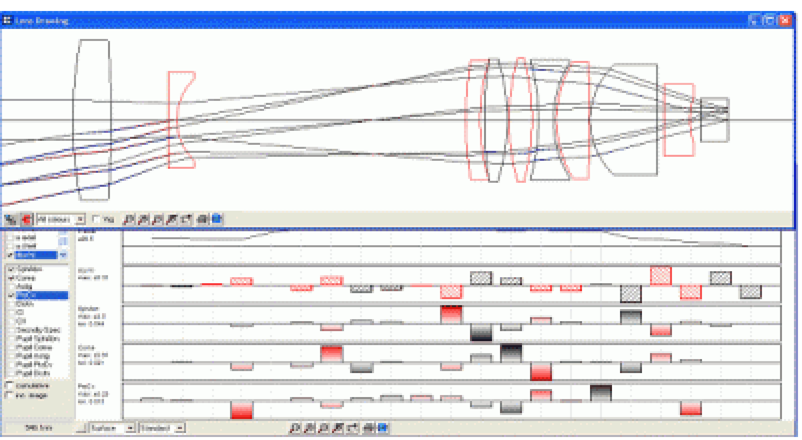



http://lambdares.com/software_products/oslo/




http://www.radiantzemax.com/en/zemax/



http://www.opticalsoftware.net/index.php/how_to/lens_design_software/winlens3d/

INPUTS:

- Input beam parameters discussed above (uploading real profile is possible for some)
- Type of the surface like e.g. plane, spherical, parabolic, cylindrical…
- Characteristic data of the surface itself like e.g. the radius of curvature in the case of a spherical surface or the aspheric coefficients in the case of an aspheric surface.
- Shape and size of the boundary of the surface like e.g. circular with a certain radius, rectangular with two side lengths or annular with an interior and an outer radius.
- Position and orientation of the surface in all three directions of space.
- Refractive indices of all materials in dependence on the wavelength.

# Don't forget to include physical optics

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A general solution to the homogeneous electromagnetic wave equation in rectangular coordinates may be formed as a weighted superposition of all possible elementary plane wave solutions:

$$E_u(x, y, z) = \iint E_u(k_x, k_y)\, e^{j(k_x x + k_y y)}\, e^{\pm jz\sqrt{k^2 - k_x^2 - k_y^2}}\, dk_x dk_y$$

Fourier optics will decompose complicated linear systems into single elements and apply a weighing factor.

**Enables:**
Describing image formation
Full modeling the aberrations of an optical system (also wave aberrations)
Studying the performance of a lens
It allows to calculate diffraction and interference, which simple ray-tracing does not do
Modeling diffraction patterns and light propagation

Don't worry a good software will do this for you!

*Introduction to Fourier Optics by Joseph W. Goodman*

# Checklist

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- Check you total distance, beamsize at source and at target
- Look at restrictions for placing optics
- Think of image relay!
- Take a back of an envelope calculation using simple paraxial approximation and lens equations
- Calculate the dispersion induced by the optics for your given bandwidth (transmissive or reflective optics?) LATER!!
- Measure your beam (profile and M-square)
- Put your system into a more advanced code starting with your initial results (ZEMAX, OSLO, RAYTRACE…)
- Check tolerances and aberrations with real optics, don't forget apertures/stops and diffraction
- Specify your optics: Size, surface quality, spectral reflectance, antireflection, absorption, achromats, damage threshold
- Specify optics mounts: Resolution, precision, reproducibility, robustness against vibration, motorized
- Decide on diagnostics and feedbacks and get controls on the way!
- Do you need transport pipes, vacuum?
- Don't forget safety and interlocks!

# Outline

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SwissFEL

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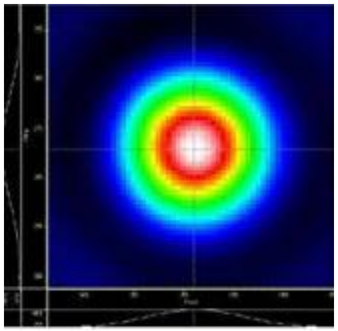
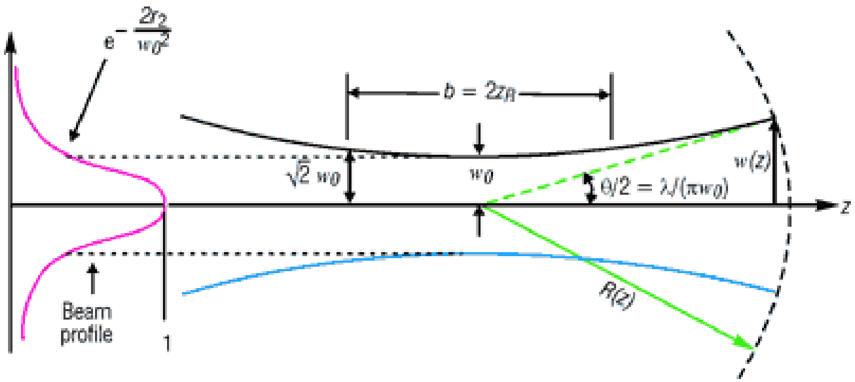
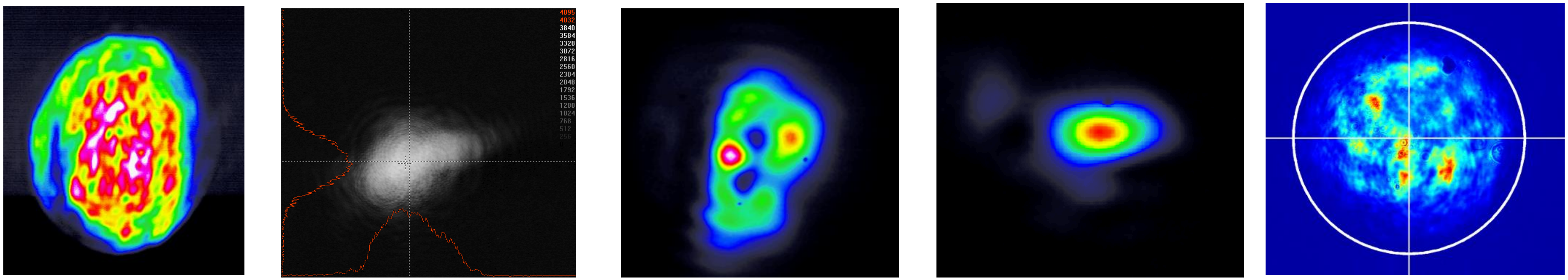
# Gaussian vs. real beam





**Pumping uniformity**
**Surface damage/ quality of optics**
**Thermal lensing**
**Non-linear effects/ self-focusing**

**Material inhomogeneity**
**Dust**
**Depolarization**

# A little bit on nonlinear effects

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Intensity of a typical focused laser beam can be 10's GW/ $cm^2$
compared to sun light on earth ~ 10 $W / cm^2$

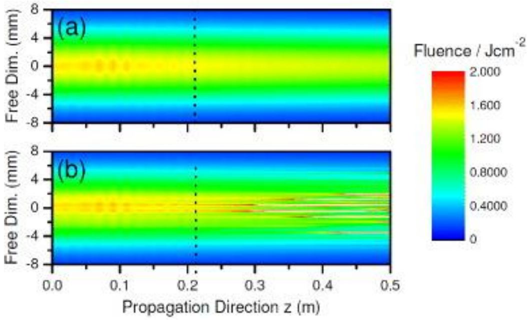
Electric field of the laser beam triggers nonlinear phenomena
Self-focusing, filamenation, non-linear absorption..

Vacuum for the beamtransport is sometimes necessary. ( It is recommended for UV even in the case of linear absorption in air.)

$$P_{crit} = \frac{0.148 \cdot \lambda^2}{n \cdot n_2}$$

~5MW for 1µm

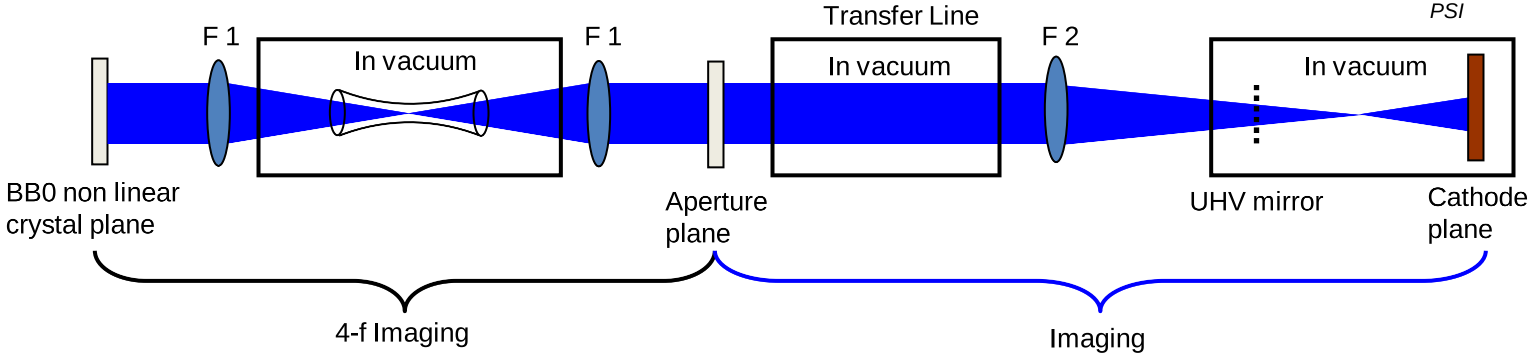
Critical power for self-focusing
$n_2$: non-linear refractive index ($m^2$/W)




*Hunt et al. Suppression of self-focusing through low-pass spatial filtering and relay imaging*
*Applied Optics, Vol. 17, Issue 13, pp. 2053-2057 (1978)*

# High intensity beam transport

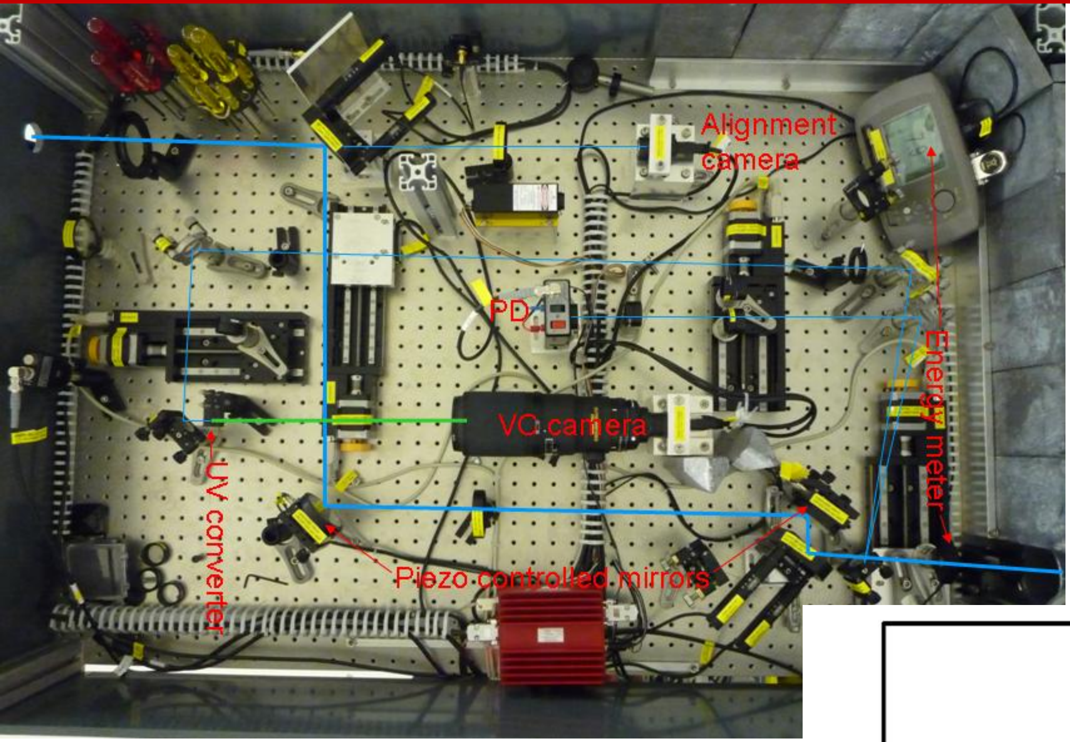
Courtesy A. Trisorio, C. Vicario PSI




- With fs pulse capillary spatial filter must be operated under primary vacuum pressure (<10 mbar) to avoid spectral broadening.
- Laser damage of the UHV mirror needs to be considered → Imaging optics adapted to have lower fluence on the UHV mirror: 0.7 $GW/cm^2$
- Transfer line windows darkening → better vacuum in transfer line (1E-6 mbar) with a dedicated automated pumping unit.
- Choose optics size to avoid clipping induced diffration patterns
- Damage of the UV camera monitoring online the UV profile → better solution with a scintillator screen + imaging onto a camera

SwissFEL gun laser beam transport

# Diagnostics/ controls




- Laser energy
- Laser profile/ size/shape

?Timing

?Pulse length

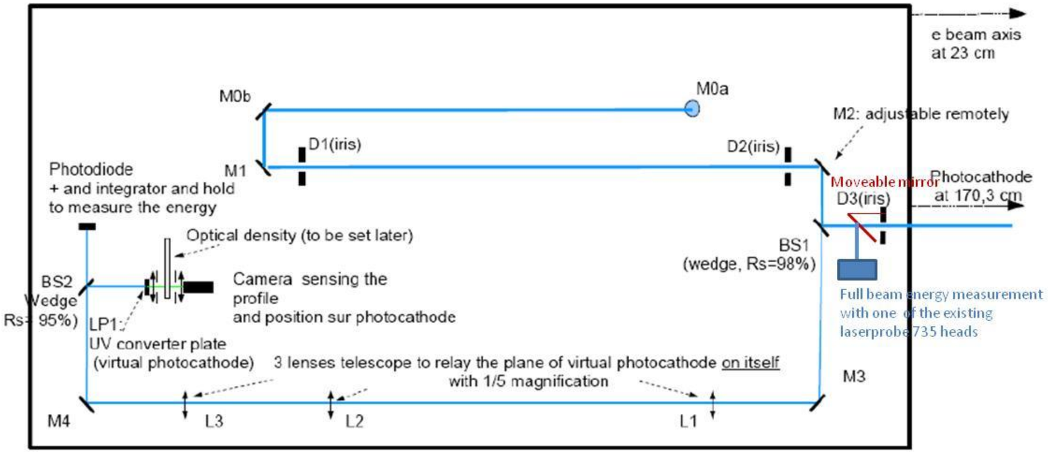
- Preferably online single shot

- Beam position
- Beam size
- Energy

? Pulse length

? Beam shape

- Safety shutter




- The imaging lenses removed and UV converter changed to a 30mm diameter one.
- Install remote flip mirror for full energy measurement

# Timing!

$$\Sigma_t^2 \approx \left(\frac{R_{56}}{c_0}\frac{\sigma_A}{A}\right)^2 + \left(\frac{C-1}{C}\right)^2\left(\frac{\sigma_\phi}{2\pi f_{\mathrm{RF}}}\right)^2 + \left(\frac{1}{C}\right)^2\Sigma_{i,t}^2$$

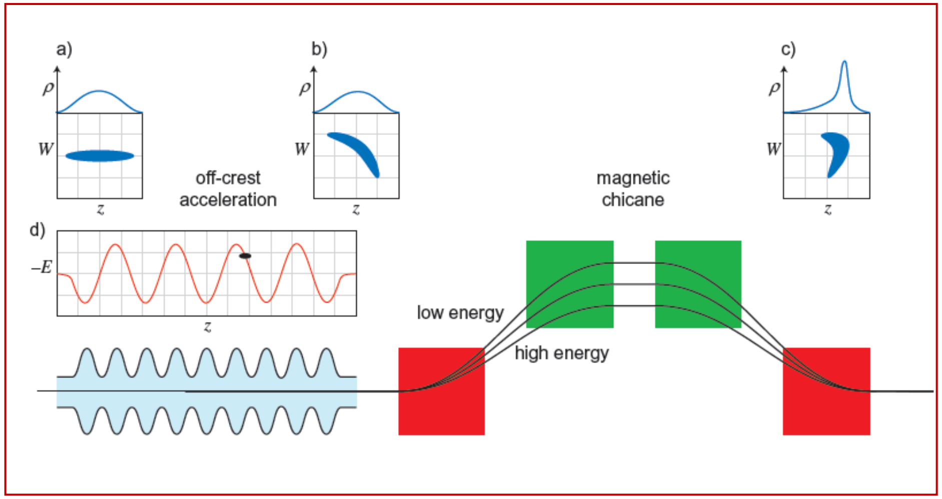
- $\Sigma_t^2$: timing jitter after compressor
- $\sigma_A / A$: cavity field amplitude jitter
- $\sigma_\phi$: cavity phase jitter
- $\Sigma_{i,t}^2$: injector timing jitter

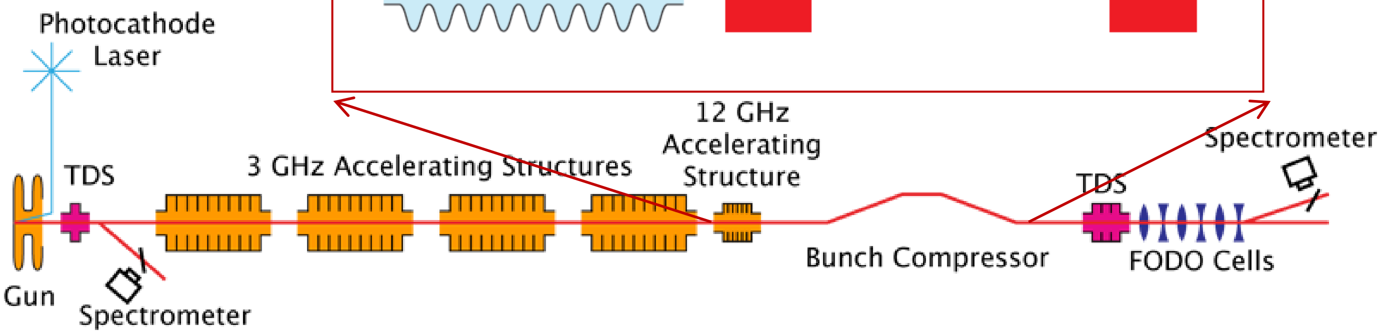
Arrival time and bunch energy at compressor chicane entry is crucial for good compression

↓

Laser arrival at gun is important

**40fs for SwissFEL**




**Think about pointing, humidity, temperature and pressure change over long path!**

TDS: Transversely Deflecting Structure

FODO: Focusing – Drift – Defocusing – Drift

# Outline

- Introduction to laser applications in accelerators
- Laser beam transport
  - basic optics/ rays/ transfer matrix
  - Image relay
  - Gaussian beam
  - Ray-tracing softwares
  - Waves vs. rays, physical optics
- Why is shaping important?
  - Gaussian vs. real beams
  - Emittance optimization
- Transverse shaping
  - Spatial filters
  - Refractive beam-shapers optics
  - Adaptive optics
  - Hard aperture
- Longitudinal shaping
  - Time domain methods
  - Frequency domain methods
- Safety

# Emittance optimization

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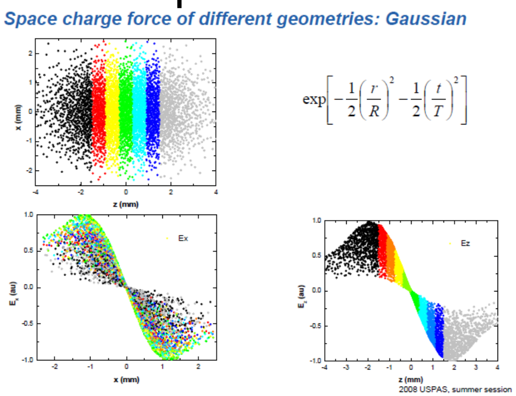
SwissFEL

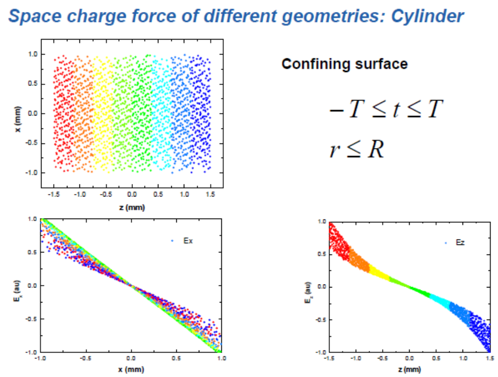
*I don't like you*

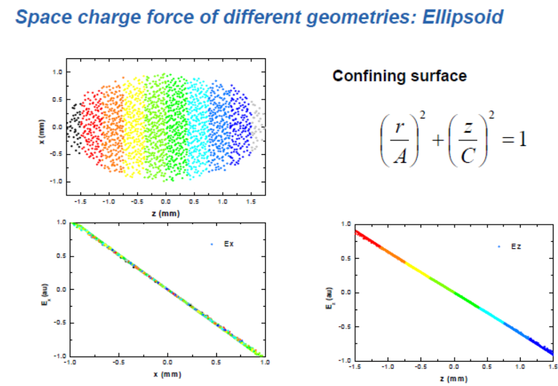
$$\sigma = \sqrt{\sigma_{spacecharge}^2 + \sigma_{thermal}^2 + \sigma_{RF}^2}$$

emittance

With proper focusing, emittance due to linear space charge force can always be compensated.



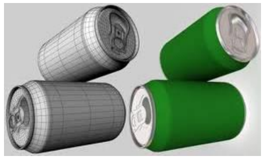




Traditionally for high charge machines, like CLIC drive beam injector

For running FEL's LCLS, FLASH, SPARC, PITZ, SwissFEL

On paper

Beer vs. rugby



# Outline

PAUL SCHERRER INSTITUT PSI

SwissFEL

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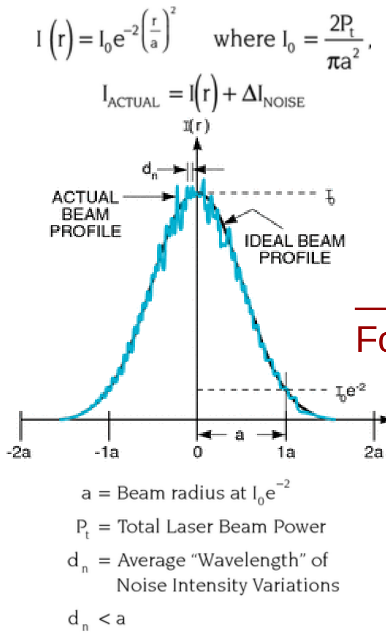
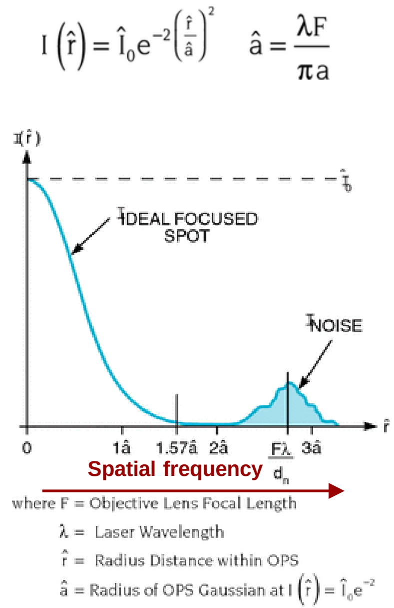
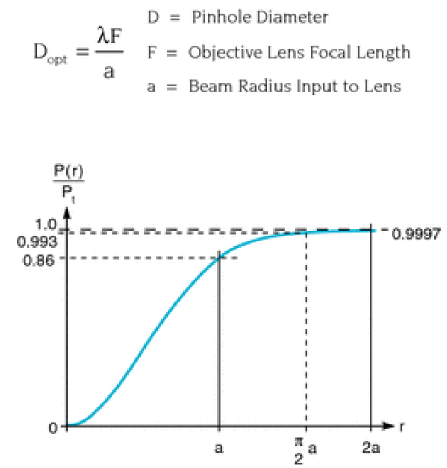
# Spatial filters





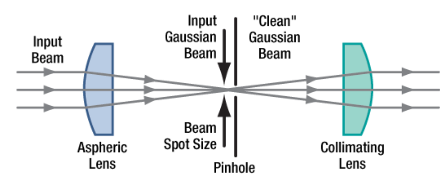

Focus



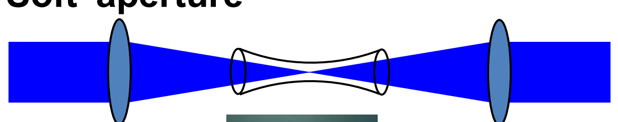

*http://www.newport.com/Spatial-Filters/144910/1033/content.aspx*

## Pinhole




- The focus of the lens (far field) give the Fourier-transform of the object mask (near-field pattern)
- Light in the very center of the transform pattern corresponds to a perfect plane wave
- Light further from the central spot corresponding to structure with higher spatial frequency

## 'Soft' aperture



Rule of thumb:

Pinhole diameter=8·Wavelength · Focal length/($\pi$ ·Beam diameter before lens)

This is to clean up your beam

# Main techniques for shaping

- Refractive shaping
  - Sherical aberration
  - Commercial lens systems
  - Wedge system
  - Matrix of micro-lenses
- Reflective optics
  - Curved mirror systems
  - Adaptive optics
- Diffractive shapers
  - Holographic
  - Random
- Spatial light modulators

**Few examples to follow**

*Fred M. Dickey, Scott C. Holswade:Laser Beam Shaping,Theory and Techniques Published July 11th 2000 by CRC Press*

# Refractive shaping

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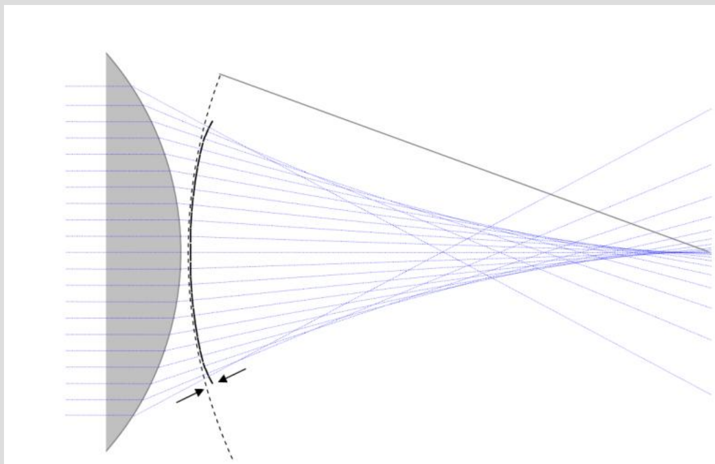
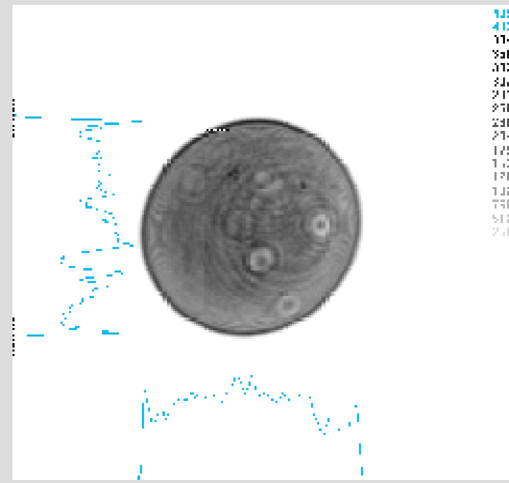
PSI
SwissFEL

Rearrange the rays, so the ones from the wing of the Gaussian come closer to the centre, while the centre itself remains the same



Using spherical aberration



STFC, UK

- Some rays are very divergent
- Not possible to propagate.
- Short focal length lens is required, cannot get close enough to the cathode
- **BUT** ~100% efficient!

Could we use a lens system to help the situation?

# Beam shaper

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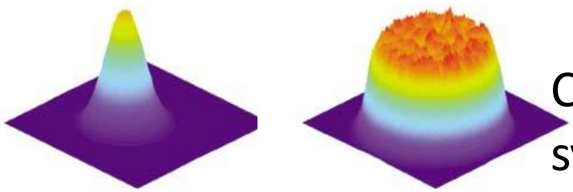
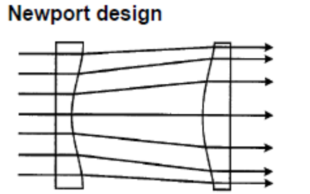
SwissFEL

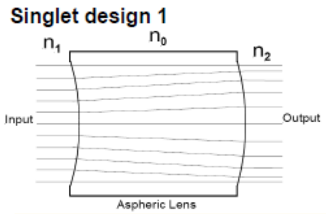
*B. R. Frieden, "Lossless conversion of a plane laser wave to a plane wave of uniform irradiance," Appl. Opt.* ***4****, 1400-1403 (1965).*

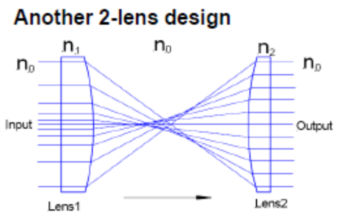
Commercial shaper using aspheric lens system converts Gaussian to "flat top"



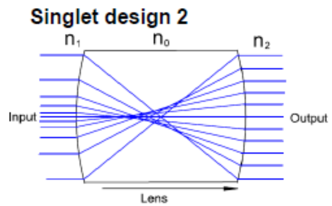

Hoffnagle et al, Apll. Opt. 39, 6488 (2000).



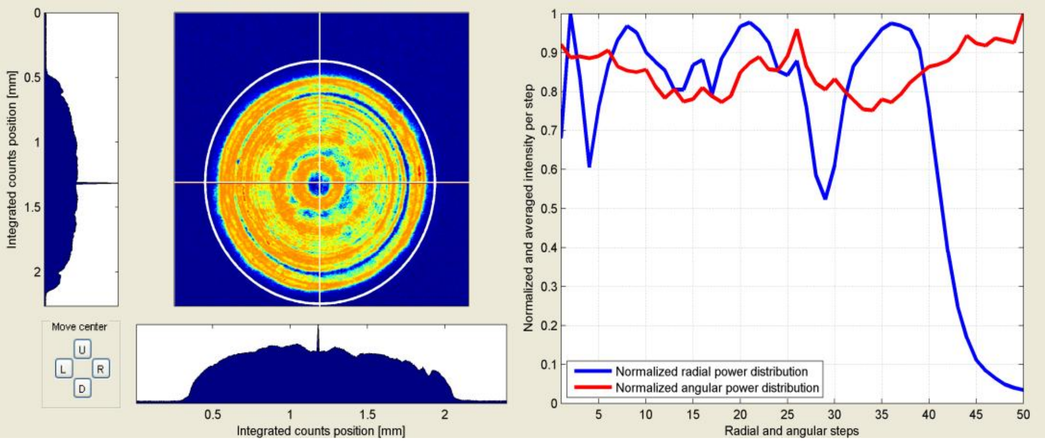

Zhang et al., Opt Express 11, 1942 (2003).




Liu and Zhang et al., Opt. Express 16, 6675 (2008).




Zhang et al., J. Opt. A9, 945 (2007).




*Test at PSI, courtesy A; Trisorio, C. Vicario*

- Good efficiency (~75%)
- Very sensitive to alignement
- Needs a perfect Gaussian input
- If you skilled lens designer you can design one for a specific beamshape

# Microlens

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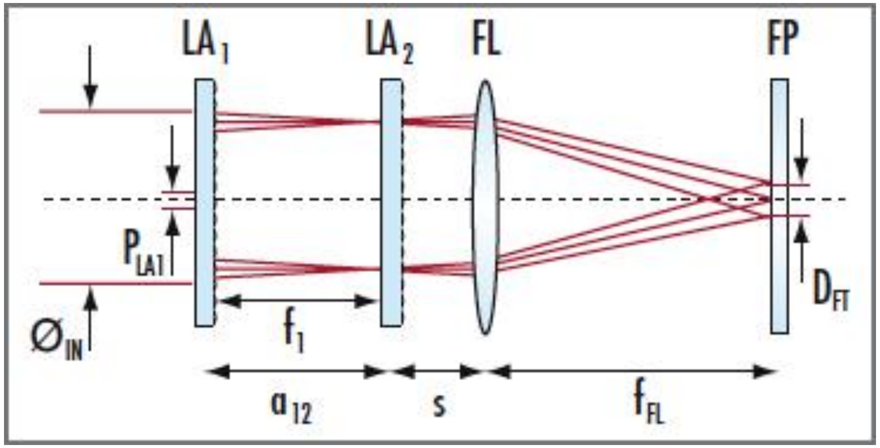
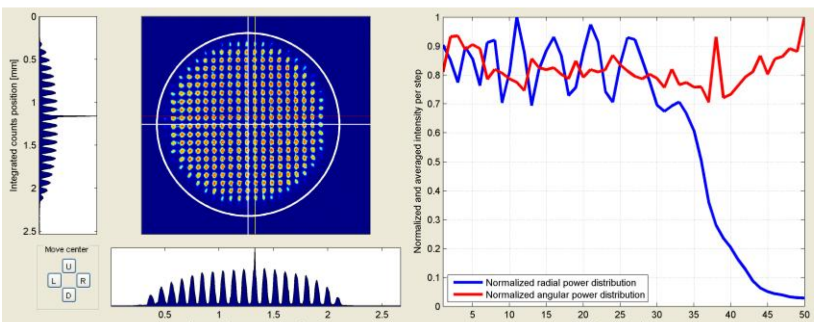
SwissFEL



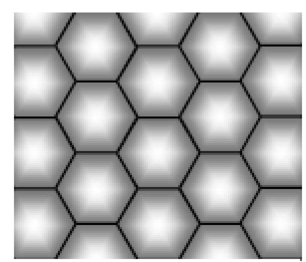




- Relies on the partial coherence properties of the source
- The periodic nature of the array limits its beam shaping capabilities
- Fabrication errors that lead to lens-to-lens variations result in non-uniformity in the scatter intensity profile.

- High transmission (> 90 %)
- Poor beam quality:
  - Rms angular=0.82
  - Rms radial=0.69
- **BUT** Alignment insensitive

*Test at PSI, courtesy A; Trisorio, C. Vicario*

- Need to completely cover the plane of the array with the desired boundary type!
- Need for structured arrays



*Proceedings of SPIE Vol. 5175 Laser Beam Shaping IV, edited by Fred M. Dickey, David L. Shealy (SPIE, Bellingham, WA, 2003)*

# Adaptive optics

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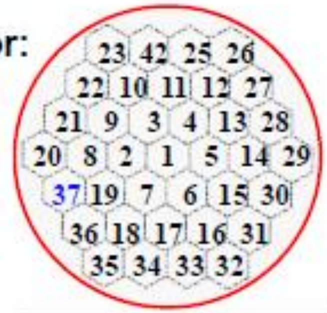
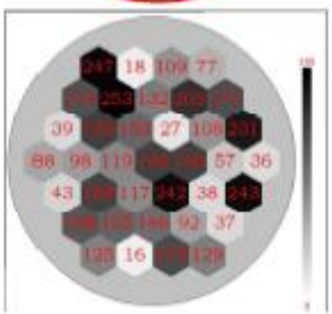
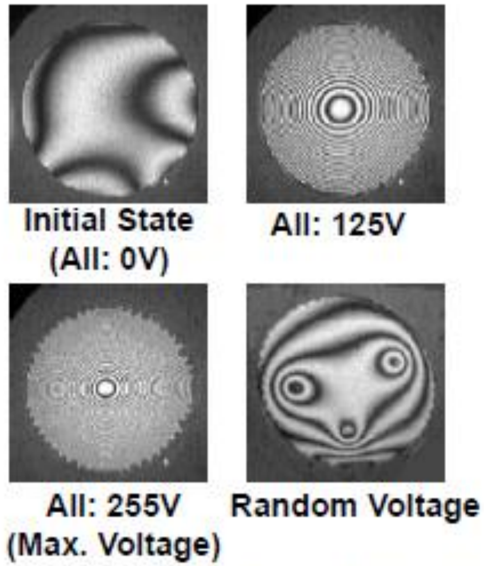
SwissFEL

Actuator:



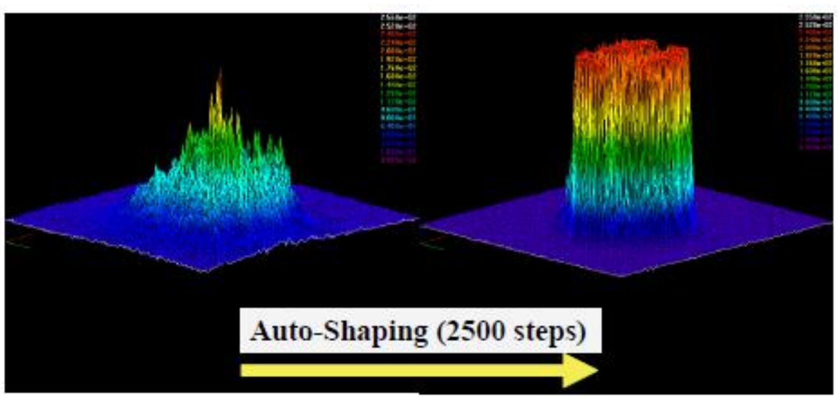





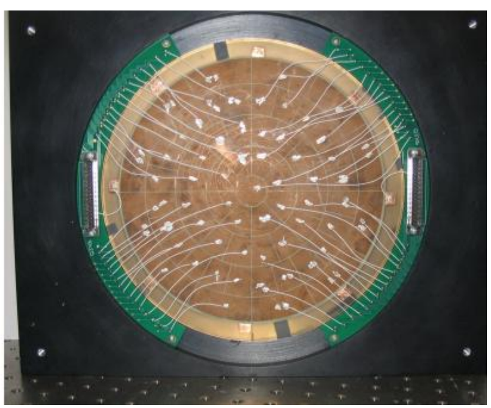

http://www.okotech.com/

Electromagnetic / Electrostatic Mirror
2mm x 2mm to 10mm x 10 mm
3 to 50 µm stroke
36 to >100 actuators
>kHz update
Al or Au coatings

Large piezo Mirror
>10 cm diameter
>100 actuators
>few Hz refresh rate

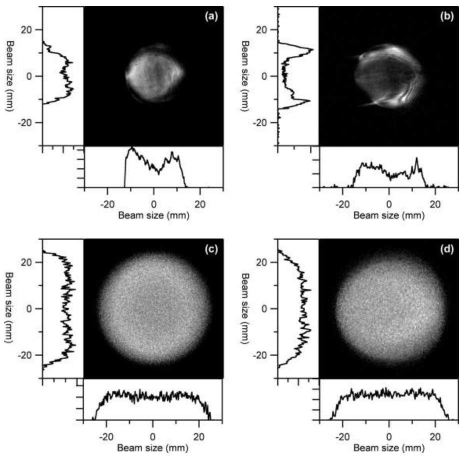



*STFC UK spin-off*



# Diffractive shaping

**Takes advantage of the coherence of the beam (interference)**

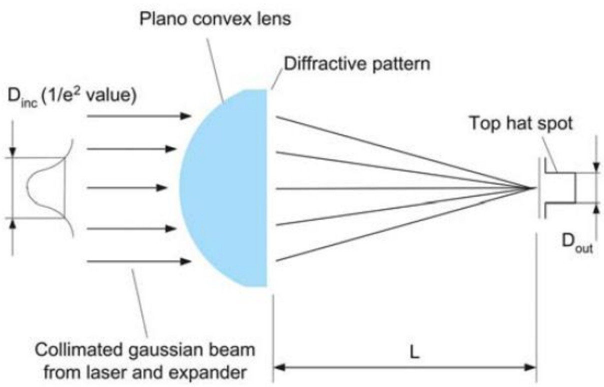



*M.Tanaka et al. Optics Communications, Volume 282, Issue 22, 15 November 2009, Pages 4401-4403*

- Random diffusers (not characteristic aperture shape), but homogenising effect
- Holographic diffusers enable asymmetric scatter, generally in an elliptical fashion
- Specifically designed diffractive elements provide more flexibility in attaining arbitrary scatter distribution

# Diffractive shaping

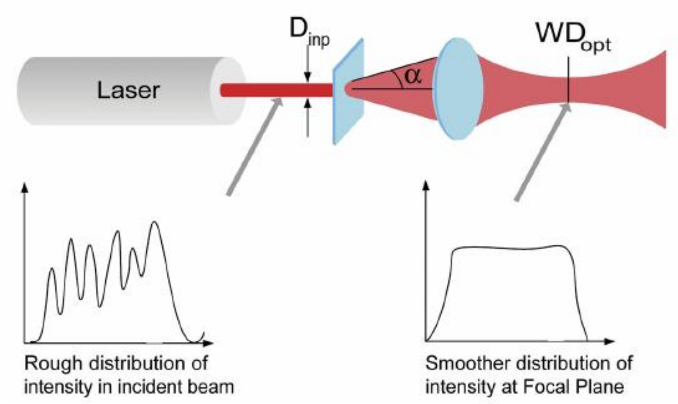
## Top hat beam shaper




*LaserComponernts*

- Only gives good profile in one plane
- Specific size input Gaussian profile with M2 <1.3 is needed
- Very sensitive to positioning and divergence
- Ripples can be 20%
- **BUT** high transmission (75-95%)
- Broad wavelength range

## Beam homogenizer




- Takes out hot spots
- Not sensitive to input shape
- Beam is divergent after
- Further you are the better the homogeneity; but larger the spot
- ~80% transmission

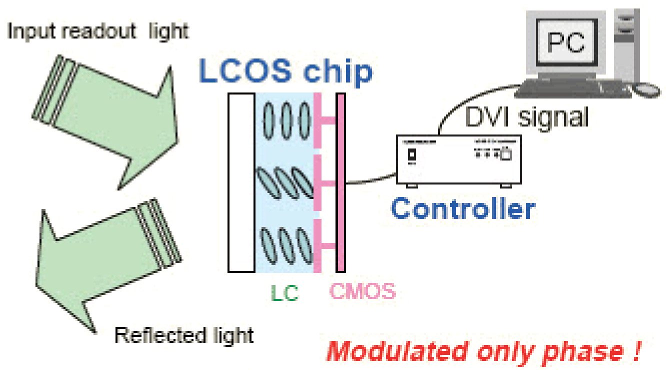
**Most diffractive shapers will give you a speckle pattern**

# Spatial light modulator

- 1D or 2D light modulator
- Usually based on LCD pixel technology (eg 512X512 pixels) i.e. CCD sized
- Control intensity (1000:1) or phase (0 to >2 π)
- Computer control, DVI input

**BUT**

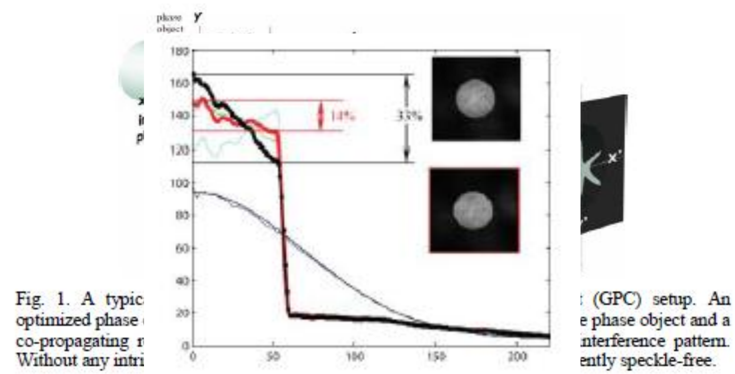
- Wavelengthspecific (532, 633, 1064, 1550 std)
- Limited fluence 500W/cm^2 CW:300mJ/cm^2 in 10n pulses
- Limited refresh rate 60-180 Hz; response time in ms
- Possible diffraction issues from pixels




*Hamamatsu*

*HOLOEYE Spatial Light Modulator*

**Some promising steps towards high power and self-referenced measurement**



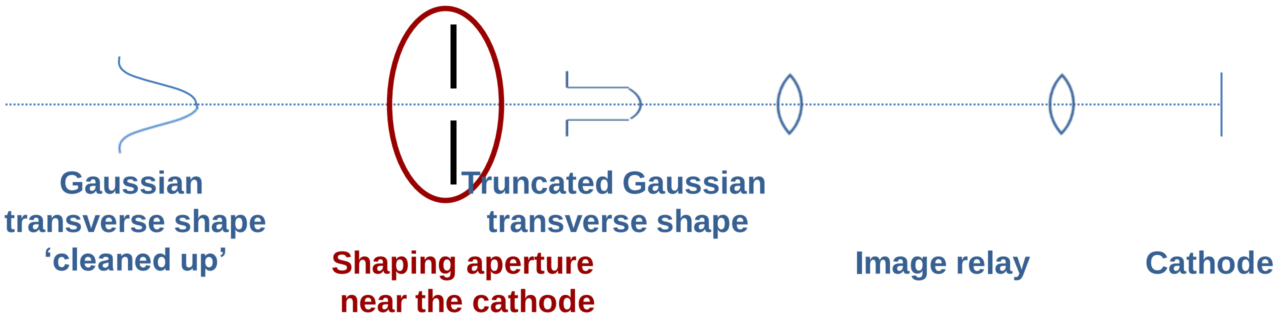

**Experimental demonstration of Generalized Phase Contrast based Gaussian beam-shaper**
Sandeep Tauro
*April 2011 / Vol. 19, No. 8 / OPTICS EXPRESS 7106*

# Conclusion

- So far refractive and diffractive solutions not worked for accelerators (LCLS, SPARC, PITZ, PSI)
- Most needs very accurate fabrication, difficult to make
- Most are either sensitive to alignment or don't give good homogeneity
- The beam tends not to propagate well (needs image relay)
- Dispersion can be a problem for short pulses
- Reflective design possible as an alternative for refractive optics

**Relay imaging and good spatial filtering is always necessary**

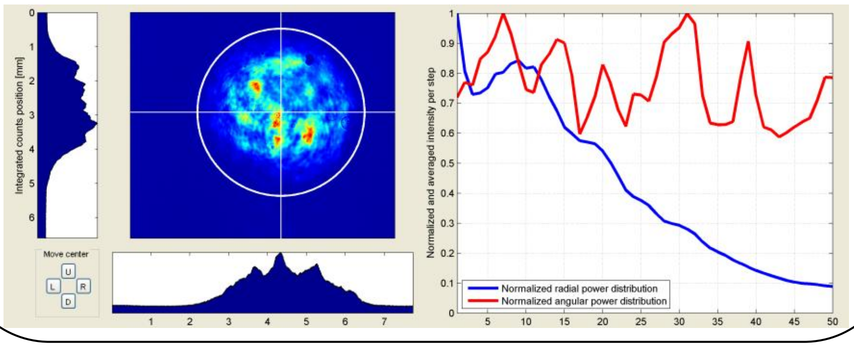
# Hard aperture



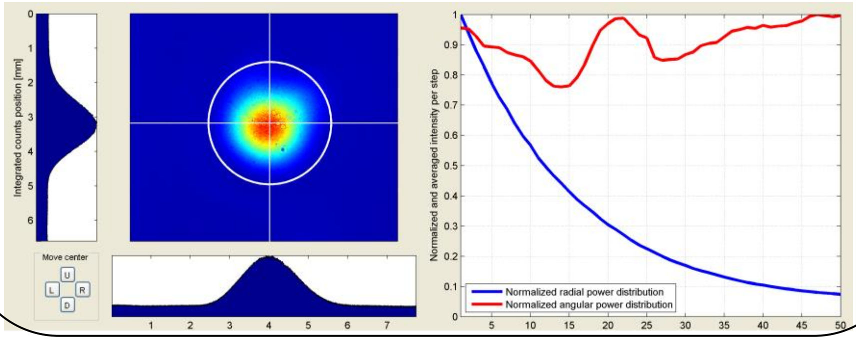

- Can be placed near to the cathode
- Cathode always sees the aperture position and not the beam position
- Transverse movement translates to amplitude instabilities→
- Aperture size/beamsize has to be small →
- Need X10 more laser energy

# PSI gun laser transport

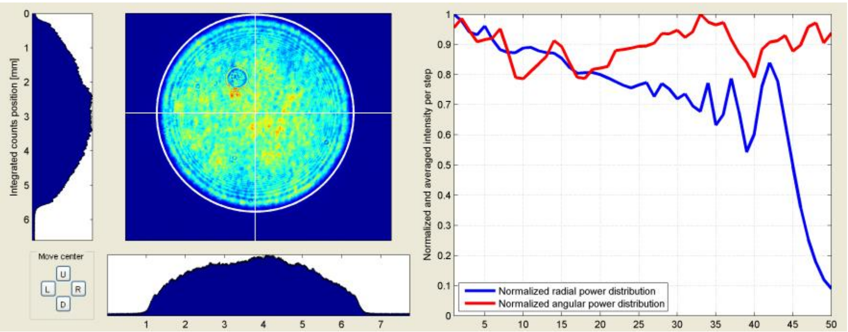
**After TH crystal**
E=250 uJ
Beam ellipticity= 0.91
Angular RMS=0.77
Radial RMS= 0.50



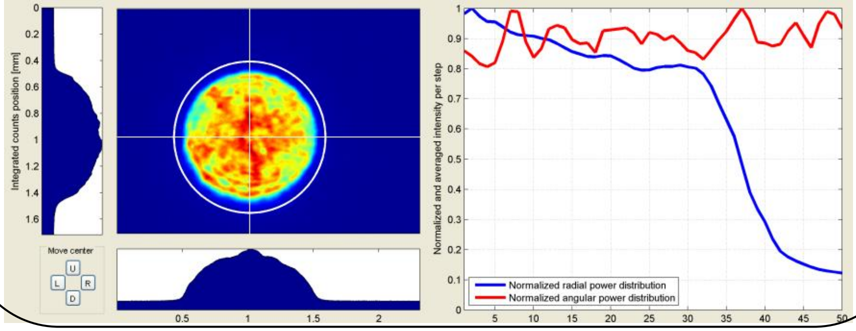

**After the conical capillary**
E=190 uJ
Beam ellipticity= 1.02
Angular RMS=0.91
Radial RMS= 0.41




**After 4 mm diameter aperture**
E=63 uJ
Beam ellipticity= 1
Angular RMS=0.90
Radial RMS= 0.76




**On the cathode**
E=32 uJ
Beam ellipticity= 0.98
Angular RMS=0.90
Radial RMS= 0.73



# PITZ beamline

- Relay imaging with spatial filtering
- Hard edge aperture after diode pumped amplifiers
- Aperture imaged to → amplifier heads → doubling crystals → cathode

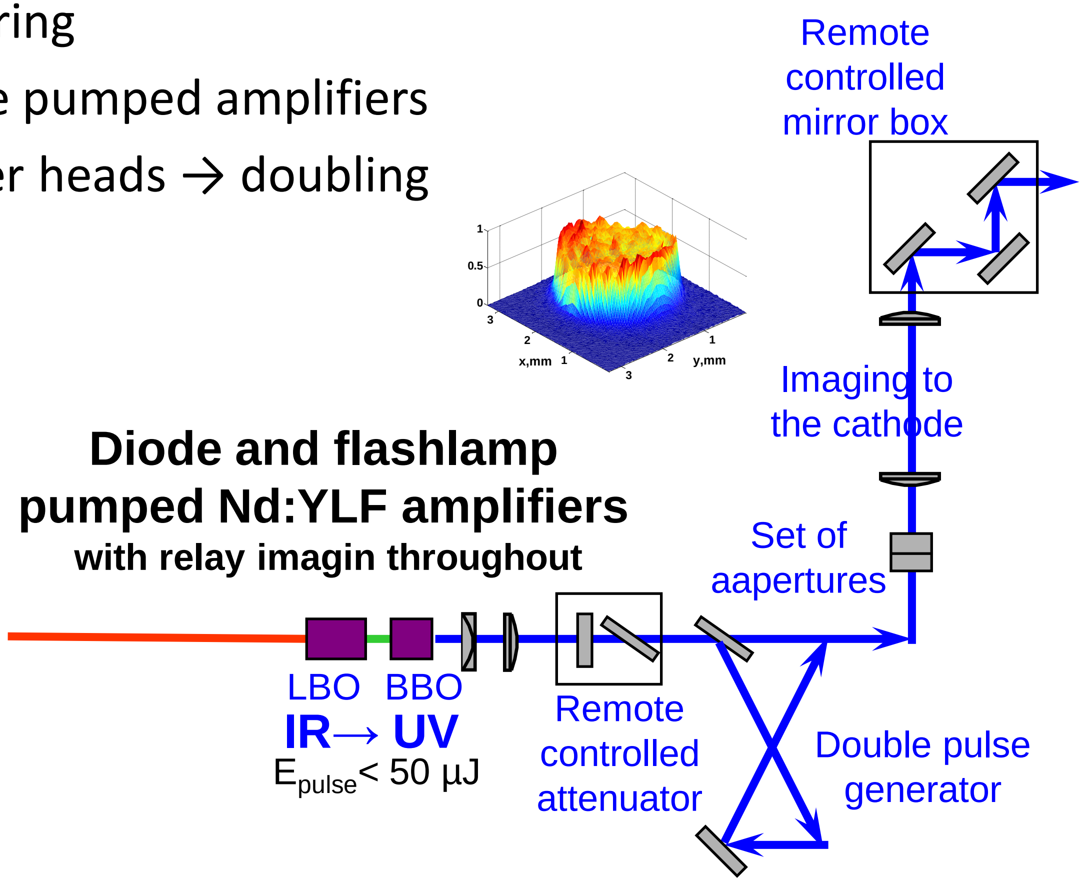
Transverse profile not really flat hat

Still noticeable pointing jitter (~10 % of spot size)

Achieved good pointing stability with an additional iris in front of vacuum window (70 cm from cathode)

Paid with interference fringes (20 % modulation)

For the present FLASH running scheme: stability is more important than perfect beam shape




Siegfried Schreiber, DESY * LCLS Injector Commissioning Workshop (ICW) * 9/11-Okt-2006

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  - Time domain methods
  - Frequency domain methods
- Safety

# Laser types

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- Picosecond Neodymium-doped lasers (Nd:YLF, Nd:YVO4, Nd:YAG) generating both single pulses and pulse trains (macropulses)

- Femtosecond Titanium Sapphire (Ti:Sa) lasers For shorter pulses and for generation of shaped pulses, but for long trains it is not suitable

- Lasers based on Ytterbium-doped materials (Yb:YAG, Yb:KGW, Yb:glass Fibre lasers) directly diode pumped sub-ps; in between the two above

- Fibre lasers, a new emerging technology which promises reliable compact systems, but are presently restricted to low pulse-energy applications. Part fo the system could be in fiber to improve the beam profile

**Shaping will depend on the available bandwidth**

*I.Will : **DRIVE LASERS FOR PHOTOINJECTORS***

# Pulse shaping techniques

- Time domain pulse shaping (pulse stacking)
  - Add up delayed short pulses
  - Simple, good efficiency, poor flexibility

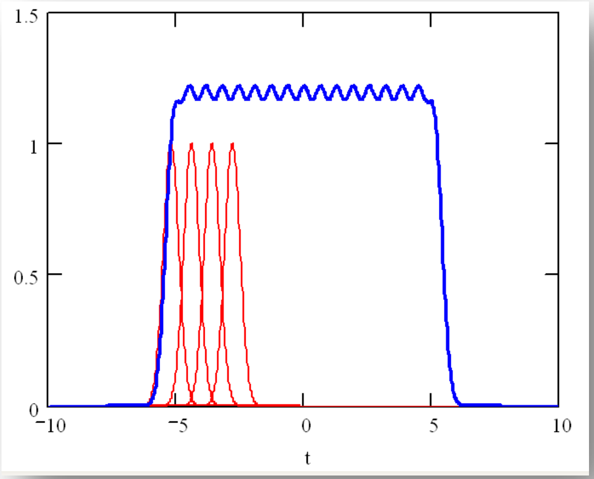
- Spectral domain pulse shaping ( Dazzler AOM, SLM)
  - Spectral amplitude and phase manipulation for a specific profile in time
  - Large bandwidth laser source is needed ->Ti: Sapphire
  - Programmable shaper available in the IR
  - Shaper in the DUV **BUT** low efficiency, lower resolution due to reduced available bandwidth

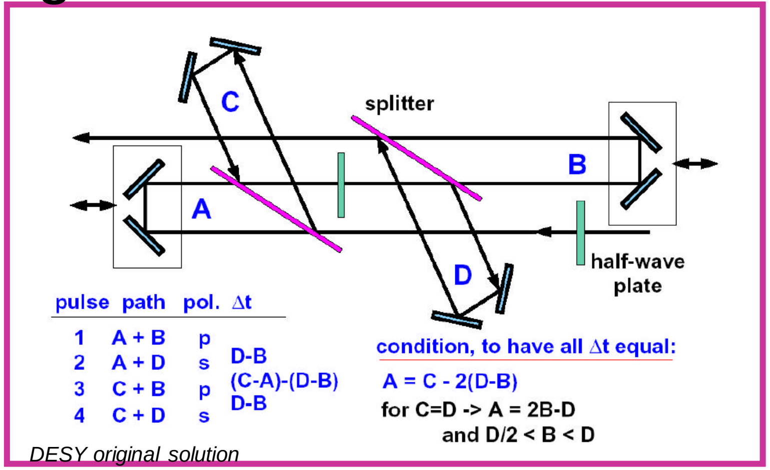
**Should be providing transverse uniformity, allow for high energy per pulse and give good short and long term stability**

# Temporal shaping shaping techniques

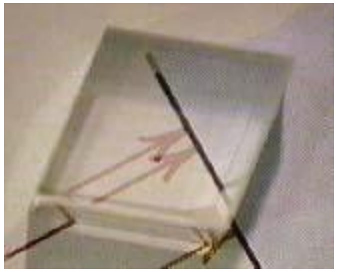
- The flat top pulse can be synthesized with a series of short pulses
- The rise time and ripples depends on the initial pulse duration
- The final length is set by the number of replicas
- Interference is avoided by alternating polarization between sub-sequent pulses

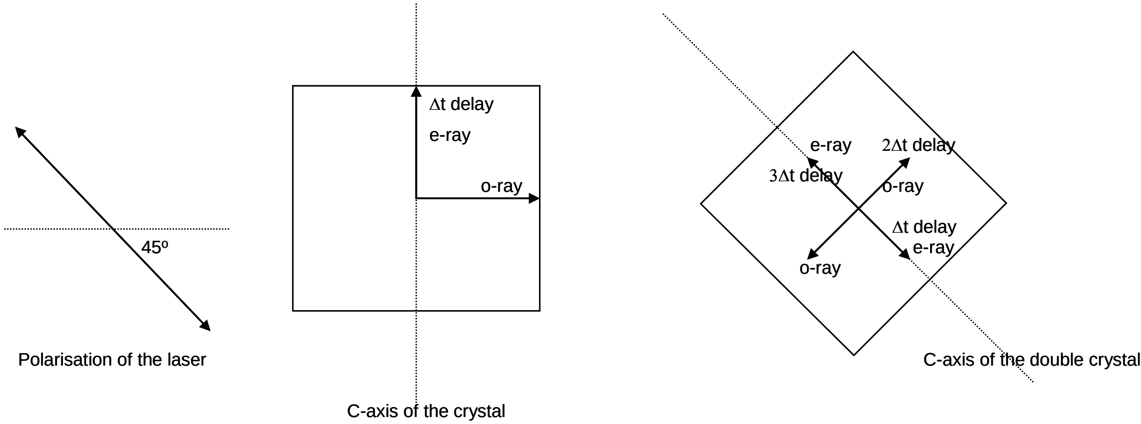
**Starts to become complicated when more pulses are stacked**



# Double refraction






Birefringence, or double refraction , is the division of a ray of light into the ordinary ray and the extraordinary ray

Homework clue!

The birefringence is quantified by:

$$\Delta n = n_e - n_o$$

$n_o$: refractive index for the ordinary ray

$n_e$ : is the refractive index for the extraordinary ray

The optical delay between the extraordinary and ordinary rays can be defined for a z-cut crystal as:

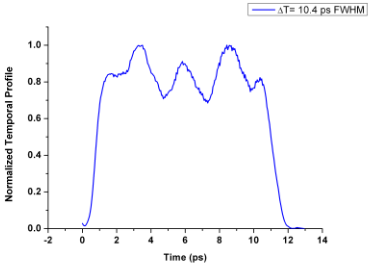
$$\Delta t = \Delta n * l/c,$$

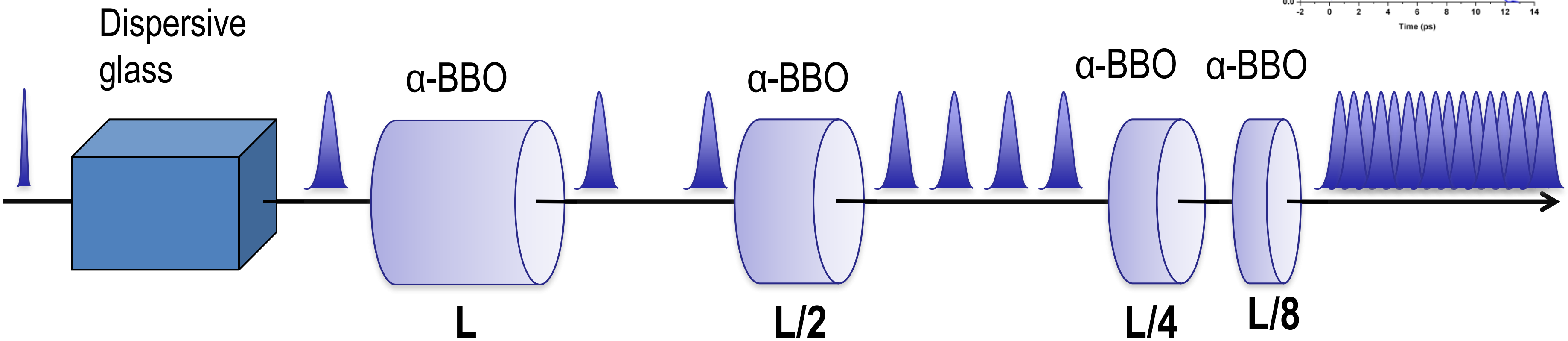
l: is the length of the crystal.

# For 3rd harmonic of Ti:Saph

PSI, courtesy to c. Vicario

- AR coated z-cut BBO for λ>190 nm with relative low losses
- 5 z-cut BBO's are used to overlap 32 pulses, each 0.6 ps long. Total efficiency >70%.
- The alternating polarization makes polarization sensitive pulse length measurements difficult
- Polarization dependence of reflectivity needs to be taken into account when designing the transport optics
- Poor flexibility for shapes
- N crystals with the right orientation make $2^N$ pulses



# SPRING8 system

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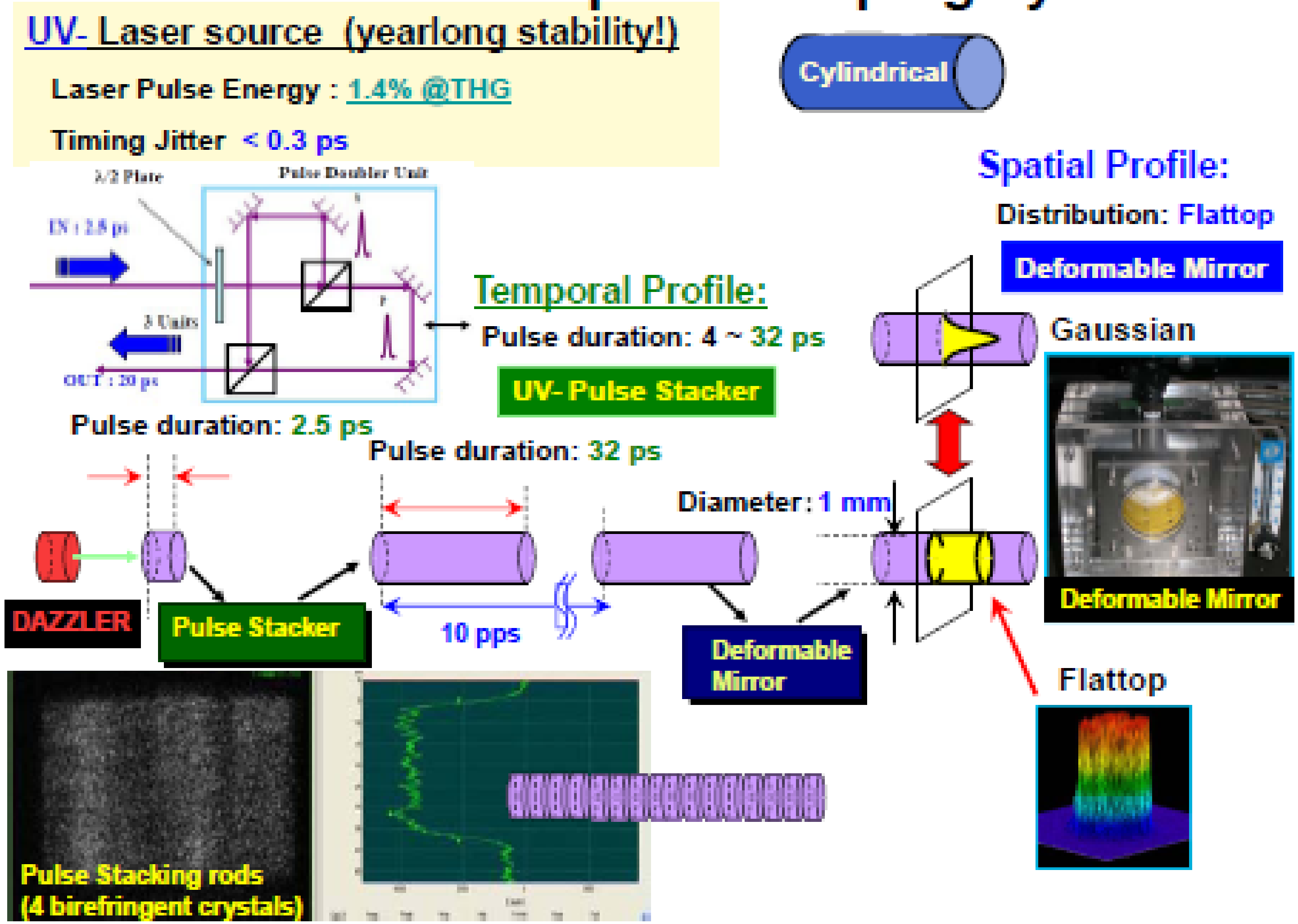
SwissFEL

## “ Beer can” UV-laser pulse shaping system



# Time-bandwidth

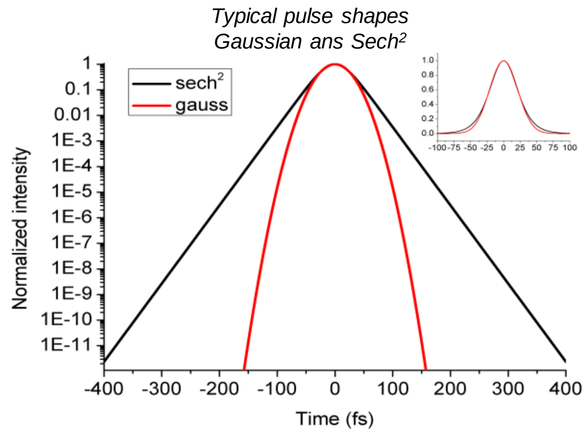
$$E(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{E}(\omega)\cdot e^{i\omega t} d\omega$$

$$\tilde{E}(\omega) = \int_{-\infty}^{\infty} E(t)\cdot e^{-i\omega t} dt,$$

- Temporal shape and spectrum of a pulse are related through Fourier transform
- The spectral bandwidth will determine the shortest pulse achievable (Fourier/ or transform limited)

$$E^{+}(\omega) = \left|\tilde{E}^{+}(\omega)\right| \exp(-i\Phi(\omega)) = \sqrt{\frac{\pi}{\varepsilon_0 c n} I(\omega)} \exp(-i\Phi(\omega))$$

spectral intensity — spectral phase




The 2nd order spectral phase will apply linear 'delay ' between the spectral contents and it's control allows for stretching/ compression of the pulse

$$\tau_p = \tau_0 \sqrt{1 + \left(4 \ln 2 \frac{\phi_2}{\tau_0^2}\right)}$$

**CHIRP**

**Remember from beam transport Make sure you lenses and other transmissive optics don't stretch your pulse before you get to the target**

# Time-domain techniques

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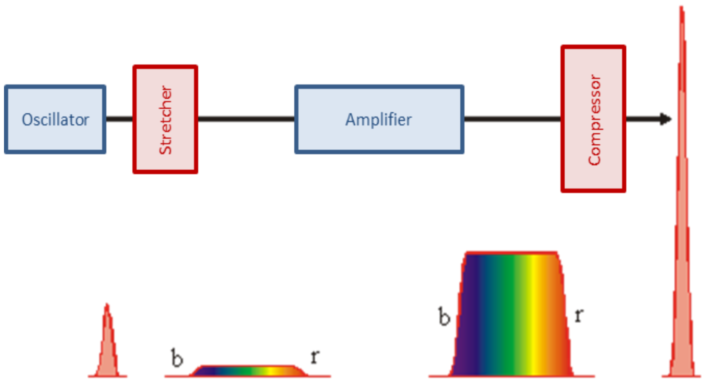
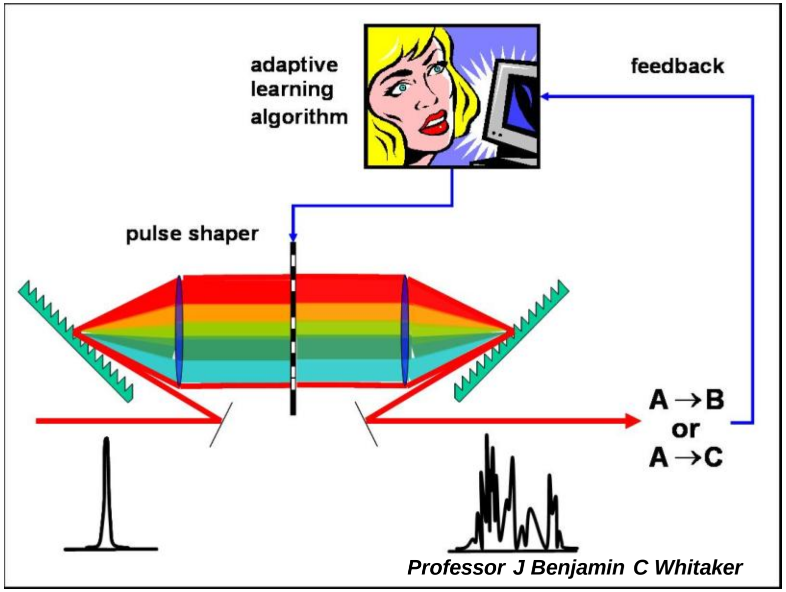
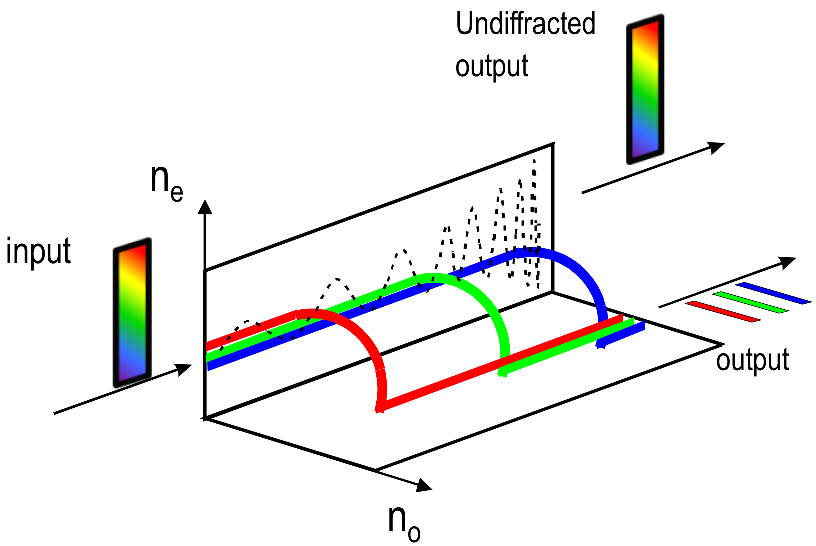



- Stretching with grating or prism based stretcher.
- Applying modulation to the spectrum
  - Acousto-optic modulator (e.g. DAZZLER)
  - Spatial light modulator in Fourier plane
- Compress (transform back) and get the specific pulse shape for the corresponding programmed spectrum




**Can also compensate for dispersion in the system**

# DAZZLER

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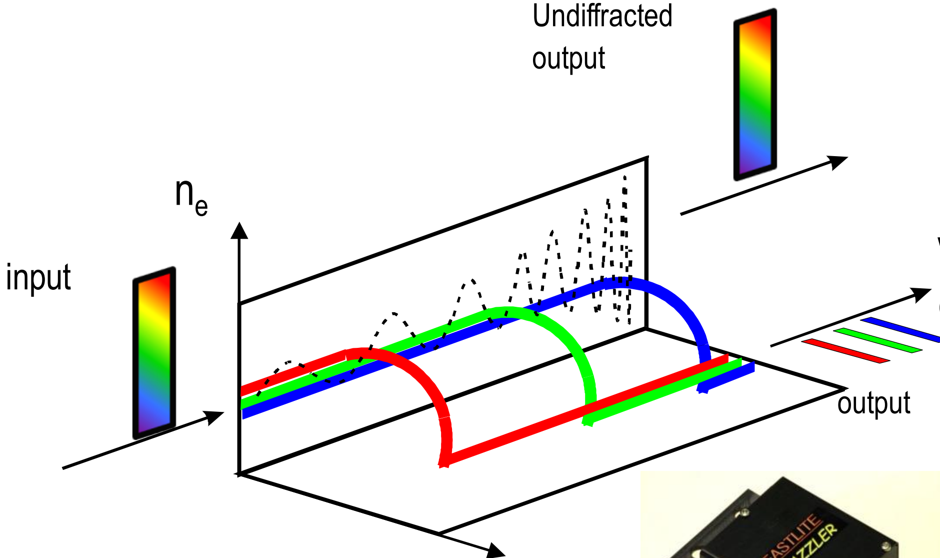
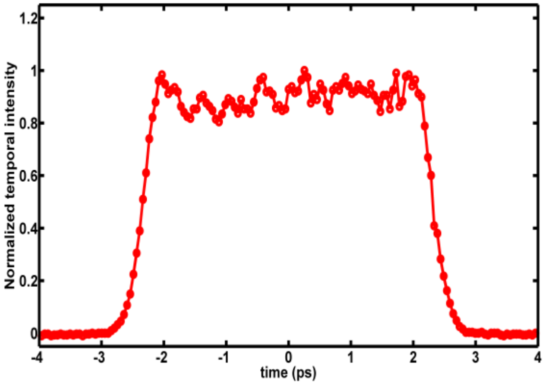



*C. Vicario, "Laser temporal pulse shaping experiment for SPARC photoinjector", EPAC'04, Lucerne, July 2004, p. 1300, http://www.jacow.org.*


•Dazzler is a commercial Acousto Optic Filter.
•Programmable acoustic wave interacts with the optical wave in a birefringent crystal
•Available for specific wavelengths

The optical wavelengths are selectively
- •retarded (spectral phase shaping)
- •diffracted (spectral amplitude shaping)

*A. Trisorio et al. Appl. Phys B, 105, 255 (2011).*



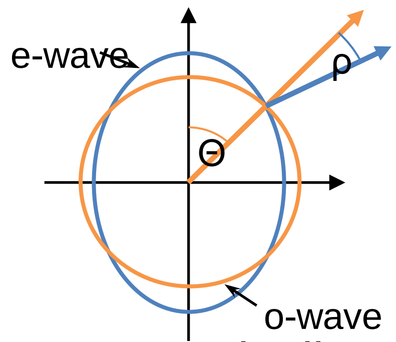

## PSI application directly in UV
- Versatile

**BUT**
- Limited damage threshold and absorption losses (max output ~25uJ in few ps's)
- Need to pre-stretch for longer pulses (>4ps)

# Chirp mathcing

**Refractive index depends on**

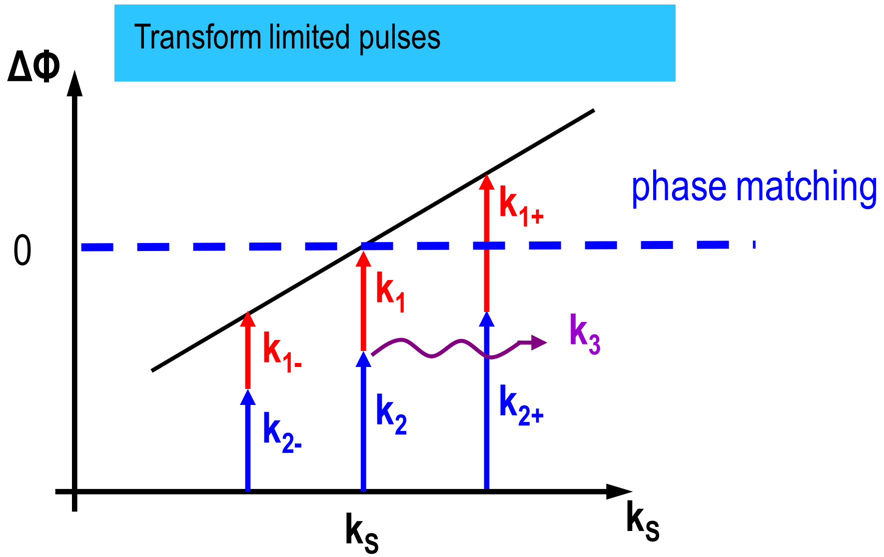
- Temperature
- Angle of the beam
- Wavelength
- Polarization



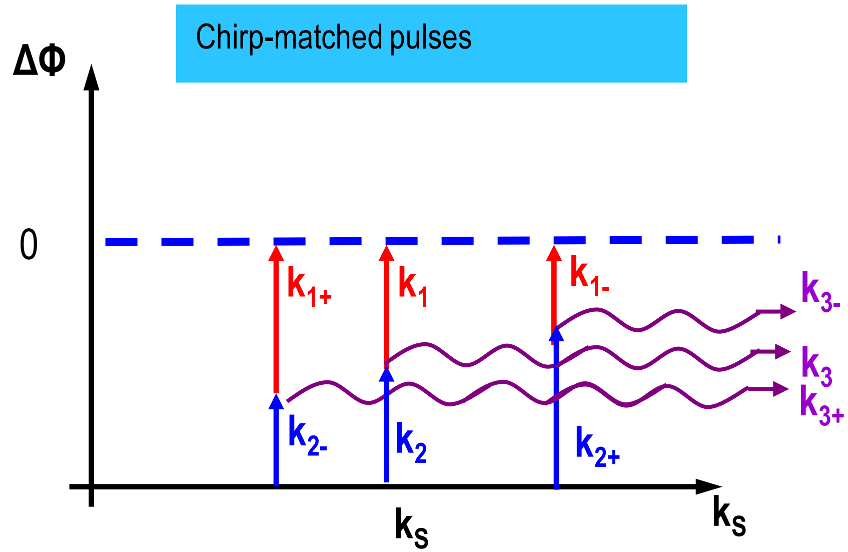

**Conversion efficiency depends on**

- Temperature
- Angle and divergence of the beam
- Wavelength and spectral bandwidth
- Intensity
- Crystal length
- Polarization

For broadband pulses the spectrum is distroted and limited after conversion.




Single short pulse




Mixing oppositely chirped pulses from two compressors

[1]K. Osvay, I.N. Ross, J. Opt. Soc. Am. B Vol. 13, No. 7 p 1431 (1996)

# Chirp matching at PSI

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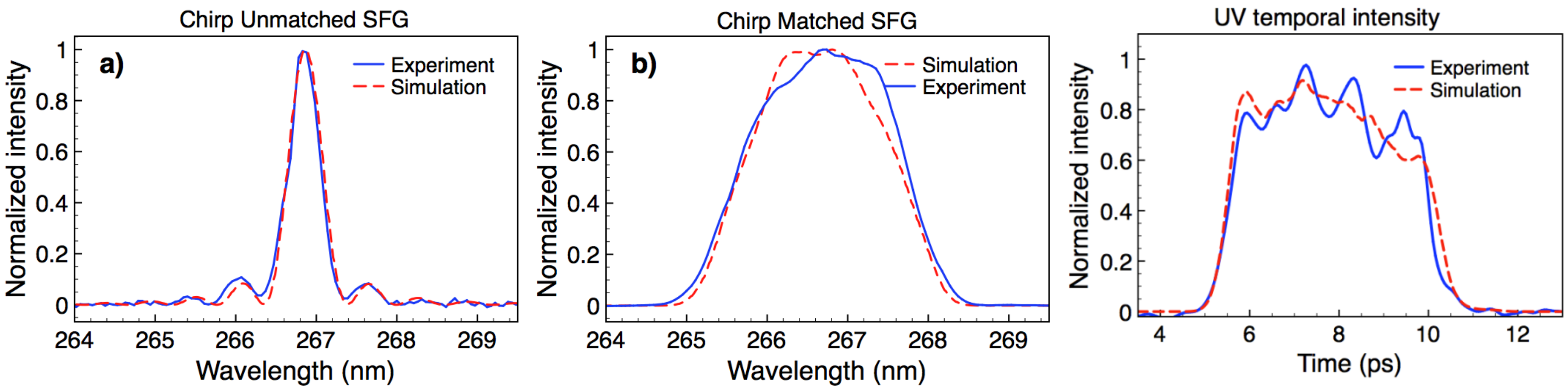
- The output pulse is linearly chirped, and there is a direct correspondence between spectral and temporal shape
- The compressors are set to satisfy the chirp matched condition
- The chirp matching SFG permit to efficiently transfer the spectral shape in the DUV without distortions
- The IR shaper can be used to have top hat IR spectrum in both compressors
- The use of chirp matched SFG can be applied to the generation of flat top pulse




*C. Vicarion et al. Optics Letters*

# Conclusions

- Pulse stacking is most robust for high charge operation
  - For fast rise times broadband source Yb based or Ti:Saph is needed
  - Efficient and simple approach to generate the flat top pulse
  - Measurements indicate a reduction of beam emittance respect to the Gaussian shape

- UV dazzler
  - The technique can be used for the low charge emittance optimization

- The use of chirp-matched SFG allows efficient generation of broadband pulses potentially applicable to RF gun, but need to improve the amplitude stability

# No Shaping!

*No Pulse shaping optics!!*: Luiten scheme

**<u>If it works, we can generate ultra-low emittance.</u>**

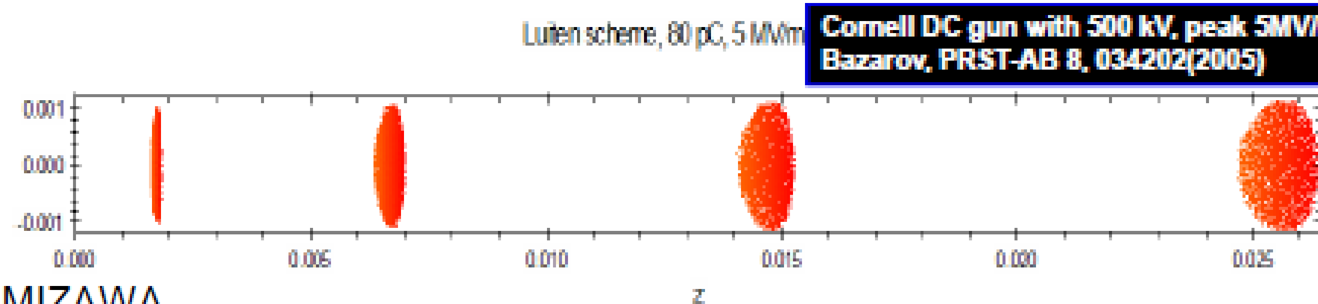
**Idea: Use "pancake" laser pulse, allow beam to self-evolve to ideal ellipse**
**Proposed by Serafiniin 1997; again by Luitenin 2004.**

We can start from femtosecond pulse at the cathode.


**Luiten, "How to realize uniform 3-dimensional ellipsoidal electron bunches", Phys. Rev. Letters 93, 094802 (2004)**

**Laser: 100 fs with parabolic transverse distribution with 1 mm radius**

**Cornell DC gun with 500 kV, peak 5MV/m**
**Bazarov, PRST-AB 8, 034202(2005)**




Hiromitsu TOMIZAWA
JASRI/SPring-8

# Outline

- Introduction to laser applications in accelerators
- Laser beam transport
  - basic optics/ rays/ transfer matrix
  - Image relay
  - Gaussian beam
  - Ray-tracing softwares
  - Waves vs. rays, physical optics
- Why is shaping important?
  - Gaussian vs. real beams
  - Emittance optimization
- Transverse shaping
  - Spatial filters
  - Refractive beam-shapers optics
  - Adaptive optics
  - Hard aperture
- Longitudinal shaping
  - Time domain methods
  - Frequency domain methods
- Safety

# Let people know

DO NOT ENTER!

Laser alignment in progress

Class 3R laser in use at 532nm


For access call C. Hessler 169018 or M Csatari 160282

# Danger and difficulties

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- Power levels/ eye and skin damage
- Picosecond/femtosecond pulse structure
- Tunability (range of wavelengths)
- High voltage power supplies
- Vacuum

# Procedures

Laser Standard Operating Procedure (LSOP)

Author: LSS (the person, who works in the lab)

Approvals: Management, LSO

How are changes to the system applied by whom and under what circumstances?

# Qualification

- General laser safety orientation
- Laser Specific safety training
- Medical Approval

# Requirements

**Class 4 Required Controls**

- Smoke detector interlock to laser power
- Entrance door interlock to shutter or power
- Yellow beacon inline with power
- Crash button inside and outside the laser area
- Emission time delay 10 second minimum
- Approved schematic of safety interlock system

**Class 3b Required Controls**

Same as Class 4 with two exceptions:

1. interlocked smoke detector not required
2. crash button not required

# Calculations for specific laser system

**REAL PARAMETERS**

| Laser beam | Wavelength nm | Beam | Pulse rate | Pulse | Burst rate | Burst | Pulse | Burst energy J | Average power W |
|---|---|---|---|---|---|---|---|---|---|
| Oscillator | 1047 | | | | | | | NA | 0.3 |
| Preamplifier | 1047 | | | | | | | NA | 10 |
| Amplifier 1 | 1047 | | | | | | | 6.00E-01 | 1.30E+01 |
| Amplifier 2 | 1047 | | | | | | | 2.00E+00 | 1.50E+01 |
| Sliced by PC1 | 1047 | | | | | | | 1.54E-02 | 7.70E-02 |
| Green 1 | 523 | | | | | | | 2.90E-03 | 1.45E-02 |
| UV 1 | 262 | | | | | | | 1.50E-03 | 7.50E-03 |
| Sliced by PC2 | 1047 | | | | | | | 8.21E-05 | 4.11E-04 |
| Green 2 | 523 | | | | | | | 1.93E-05 | 9.65E-05 |
| UV 2 | 262 | 2 | 1.50E+09 | 8.00E-12 | 5 | 1.00E-08 | 5.33E-07 | 8.00E-06 | 4.00E-05 |

Note: The burst duration refers to the pumping time. The actual burst is somehwat shorter beacause of the amplifier build up time.
The pulse energy in this row is the average over the pulsetain. To see peak values please see PC1 sliced pulse energy.

**Beams transported from laser setup:**

| CLASS 3B | | Units | CTF3 | CLEX |
|---|---|---|---|---|
| T, s | AEL 262 nm | | UV 1 | UV 2 |
| < 1e-9 | 3.80E+05 | W | 1.88E+05 | 2.50E+05 |
| 0.25 | 3.80E-04 | J | 3.57E-03 | 7.50E-05 |
| >0.25 | 1.50E-03 | W | 1.43E-02 | 3.00E-04 |
| **CLASS** | | | 4 | 3B |

| CLASS 3B | | Units | Oscillator | Preamplifier | Amplifier 1 | Amplifier 2 |
|---|---|---|---|---|---|---|
| T, s | AEL 1047 nm | | | | | |
| < 1e-9 | 1.48E+08 | W | 2.50E+01 | 8.33E+02 | 2.50E+05 | 1.25E+06 |
| < 0.06 | 1.48E-01 | J | | | 6.00E-01 | 3.15E+00 |
| 2.50E-01 | 5.00E-01 | W | 3.00E-01 | 1.00E+01 | 1.30E+01 | 2.08E+01 |
| >0.25 | 5.00E-01 | W | 3.00E-01 | 1.00E+01 | 1.30E+01 | 2.08E+01 |
| **CLASS** | | | 3B | 4 | 4 | 4 |

| CLASS 3B | | Units | Green 1 | Green 2 |
|---|---|---|---|---|
| T, s | AEL 523 nm | | | |
| < 1e-9 | 3.00E+07 | W | 6.25E+05 | 6.25E+05 |
| < 0.06 | 3.00E-02 | J | 9.53E-03 | 1.50E-04 |
| 2.50E-01 | 5.00E-01 | W | 4.76E-02 | 7.50E-04 |
| >0.25 | 5.00E-01 | W | 4.76E-02 | 7.50E-04 |
| **CLASS** | | | 3B | 3B |

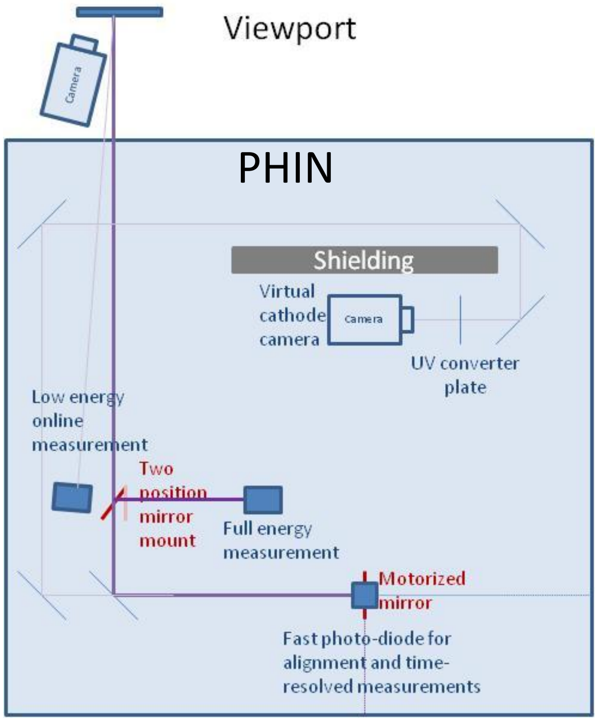
# No clues

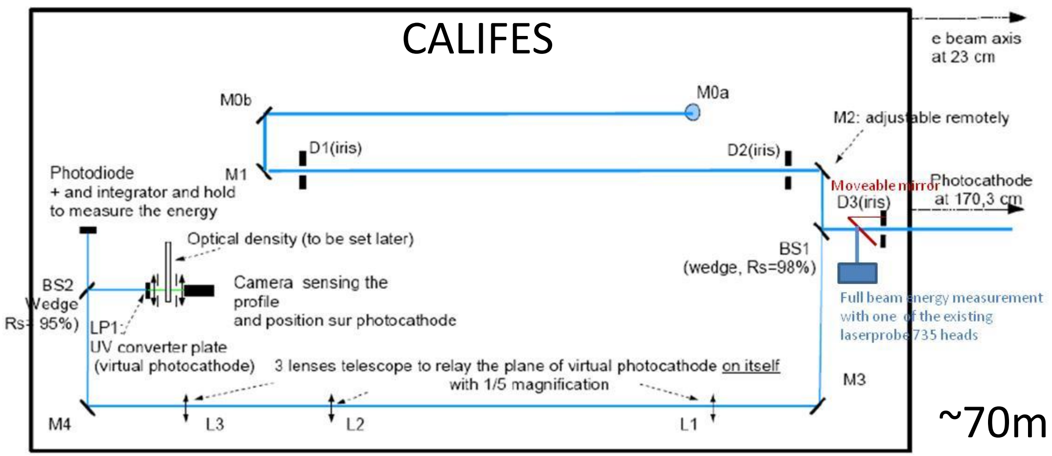
Homework clue!


THINK ABOUT IT! WHERE DOES THE BEAM GO?
DO YOU HAVE GOSTS?
TAKE CARE OF OTHERS YOU WORK WITH!
MOST ACCIDENTS HAPPEN DURING ALIGNMENT!


# Thank you for your attention!!

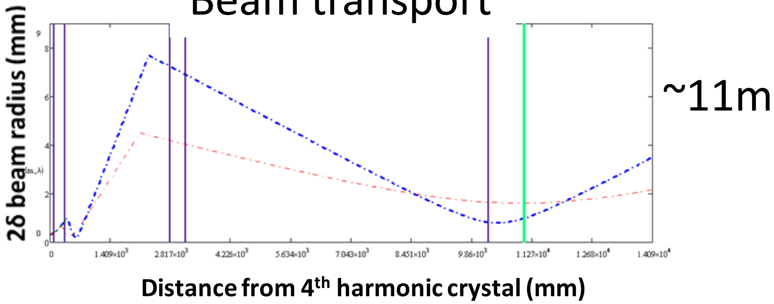
# Laser diagnostics



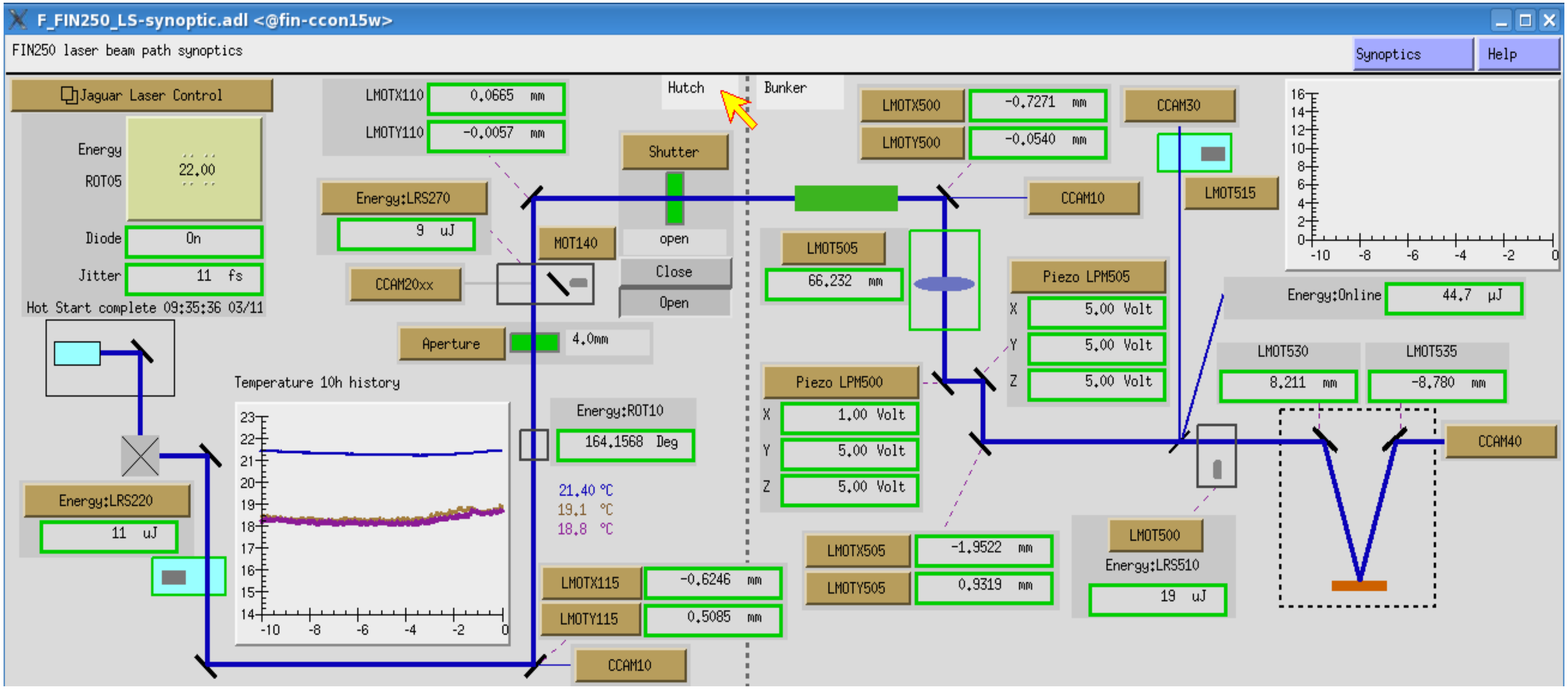

•The imaging lenses removed and UV converter changed to a 30mm diameter one.
• Install remote flip mirror for full energy measurement

Beam transport




- Transmission is low for CALIFES line
- Pointing instabilities are high due to long distances
- Automated measurement system needed

# General control interface




- Complete remote control of the Laser system turn ON/OFF procedure
- Measurement of the laser energy at several critical positions + active feedback to maintain laser energy constant
- Display of essential information (jitter, aperture position etc…) for operators
- Dynamic laser beam path display
- Further update for remote control of the Ti:Sa laser
- Recorded and archived parameters: oscillator power and jitter, chillers temperature, temperature and humidity inside amplifier and in hutch, position of energy feedback rotation stage, laser energy on cathode.
- Foreseen archived parameters: beam profile/position before aperture and on cathode, aperture position.