Dr Marta Divall:: Laser scientist :: Paul Scherrer Institut

Lasers in FEL facilities

CAS CERN Accelerator School , 31st May-10th June 2016
DESY, Hamburg

Aim

- Give a quick introduction to lasers and necessary terminology
- Give an overview of where lasers are used in FEL's (timing, injector, experiments, beam diagnostics)
- Show the most important parameters for each of these applications
- Give examples of laser systems from existing FEL facilities
- Give an outlook of how lasers could be used in the future for compact FEL's
- Keep everyone awake!

Outline

- Small introduction to lasers (laser vs FEL)
- Lasers used in FEL's
- Requirements/parameters/examples
  - Photo-injector lasers
  - Laser heater
  - Experimental lasers
  - Seeding laser
  - Diagnostics lasers
- The future of lasers in FEL's

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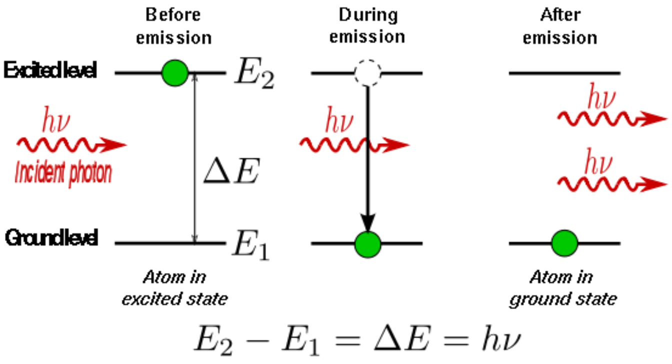
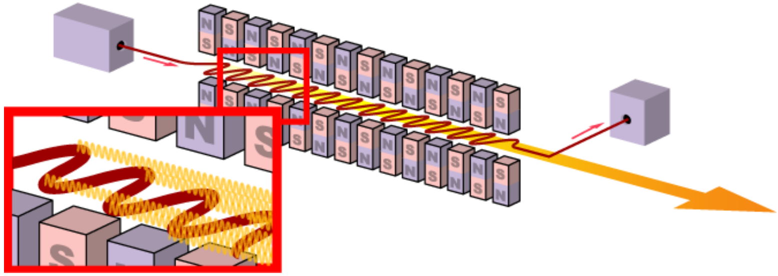
Laser vs FEL

A **laser** is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The term "laser" originated as an acronym for "**light amplification by stimulated emission of radiation**".



A **free-electron laser** (FEL), is a type of laser whose lasing medium consists of very-high-speed electrons moving freely through a magnetic structure, hence the term *free electron*.

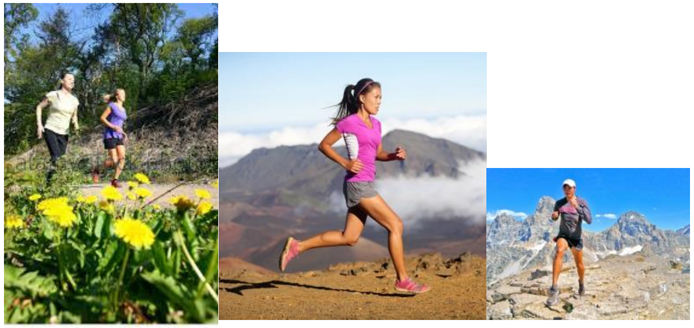


en.wikipedia.org

We could call lasers 'bound-electron' lasers!

Lasers/ stimulated emission

Einstein postulated that **photons prefer to travel together** in the same state. If one has a large collection of atoms containing a great deal of excess energy, they will be ready to emit a photon randomly. However, if a stray photon of the correct wavelength passes by (or, in the case of a laser, is fired at an atom already in an excited state), its presence will stimulate the atoms to release their photons early– and those photons **will travel in the same direction with the identical frequency and phase as the original stray photon**. A cascading effect ensues: as the crowd of identical photons moves through the rest of the atoms, ever more photons will be emitted from their atoms to join them.



Spontaneous emission

Stimulated emission

Essentials/ amplifier material

The choice of material is determined by many different parameters:

- the available pump sources for the given absorption band will determine the efficiency of the pumping
- the pulse shape and length and rise time are important for low emittance machines for FEL, thus broadband laser materials are needed for spectral manipulation or stacking of several short pulses
- the fluorescence lifetime of the material will set the limit of the longest extractable macropulse, although pre-pumping techniques could slightly extend beyond this timescale
- stimulated emission cross-section and small signal gain for given a pump will determine the number of stages required for the laser amplifier chain
- the thermal properties of the crystal will determine the scalability of the system to high average powers and ultimately the complexity of the final system as well as the quality of the beam
- the available oscillators with high repetition rate and their power level will also have a net effect on the complexity of the system.
- saturation fluence together with available crystal sizes and their thermal fracture limit will determine the maximum fluence which can be extracted efficiently from a single amplification stage
- the difference between the pump and the emission band determines the proportion of the power converted into thermal losses and will limit the average power or complicate the cooling required

Essentials/ amplifier material

- **Picosecond** Neodymium-doped lasers (Nd:YLF, Nd:YVO4, Nd:YAG)

generating both single pulses and pulse trains (macropulses), can be pumped by diodes

- **Femtosecond** Titanium Sapphire (Ti:Sa) lasers

For shorter pulses and for generation of shaped pulses, but for long trains it is not suitable, needs pump laser

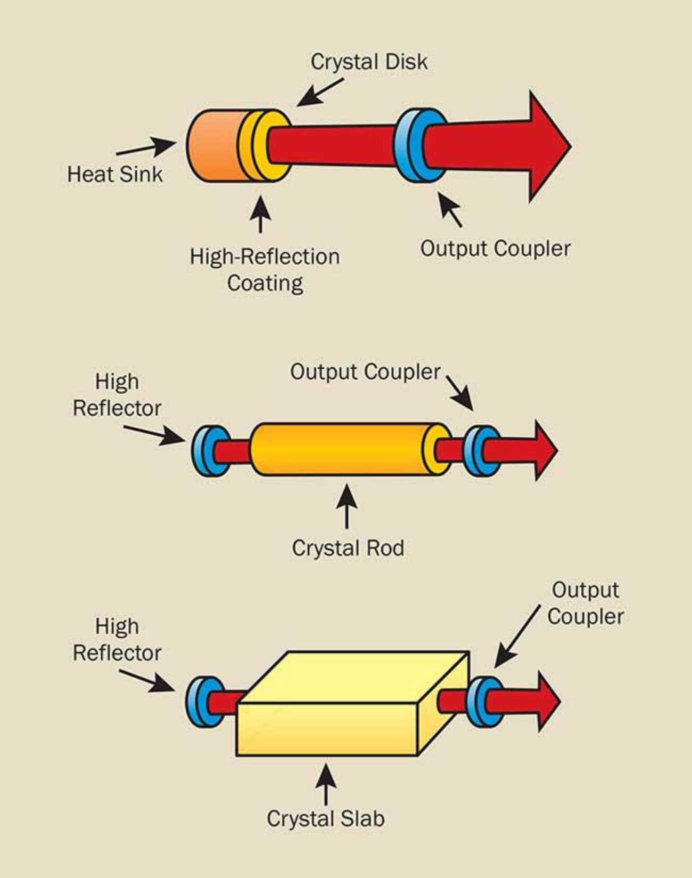
- Lasers based on **Ytterbium-doped materials**

(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 for the system could be in fiber to improve the beam profile.

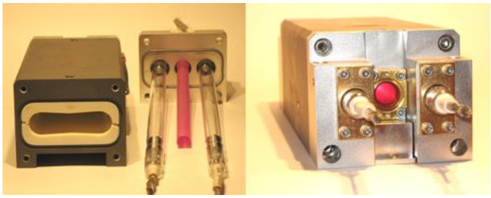
crystals	Nd:YAG	Yb:YAG	Ti:Sapphire
fluorescence lifetime(ms)	0.23	0.96	0.0032
stimulated-emission cross section($\times 10^{-20}$ cm^{-1})	20 to 30	2.1	30
luorescence wavelengths(nm)	1064	1030	660-1100
absorption wavelengths(nm)	808	941	514 to 532
fluorescence bands(full width at half maximum) (nm)	0.67	to 10	440
absorption bands(full width at half maximum) (nm)	1.9	>10	200
pumping quantum efficiency	0.76	0.91	0.55
saturation fluence(J/cm^2)	0.67	9.2	0.9

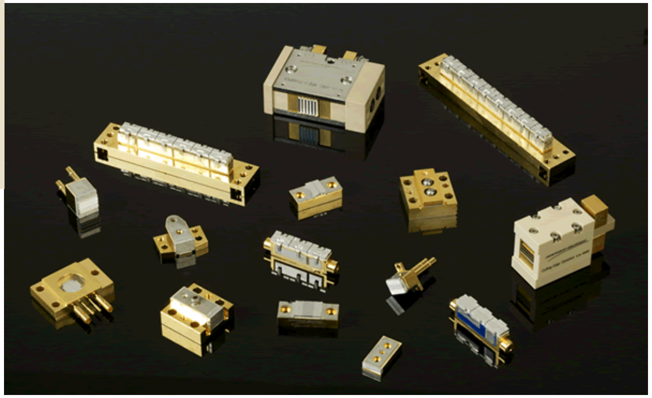
Essentials/ Excited amplifier material

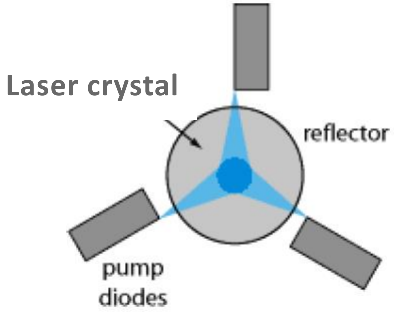


Pumped by

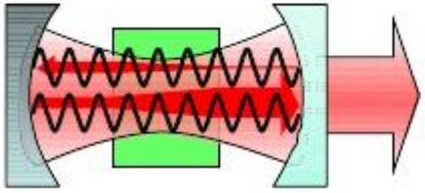
- Diodes
- Flash-lamps
- Other lasers





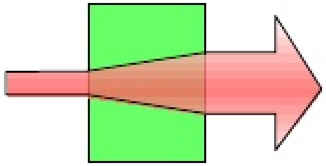


Essentials/ Laser system

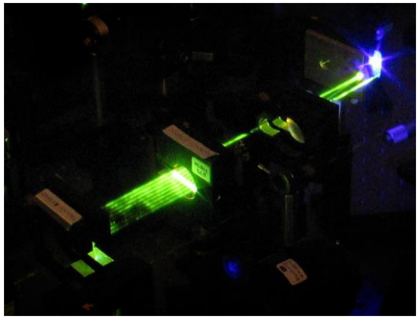
1\. 

Put a cavity with the right length to make an oscillator to produce a train of short pulses synchronized to the machine

2\. Throw away unwanted pulses, create the right pulse structure, using acousto- or electro-optical switches

3\. 

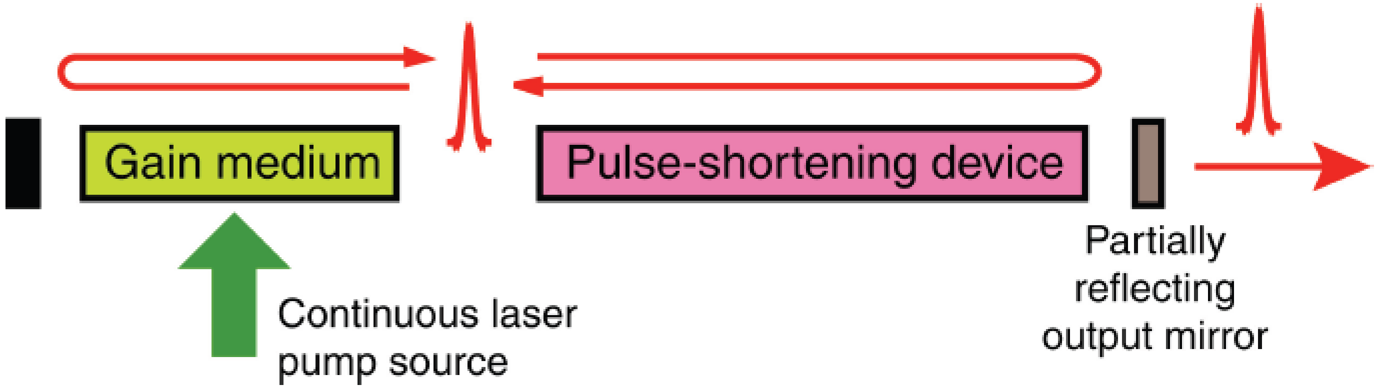
Amplify the pulses further to reach required energy

4\. 

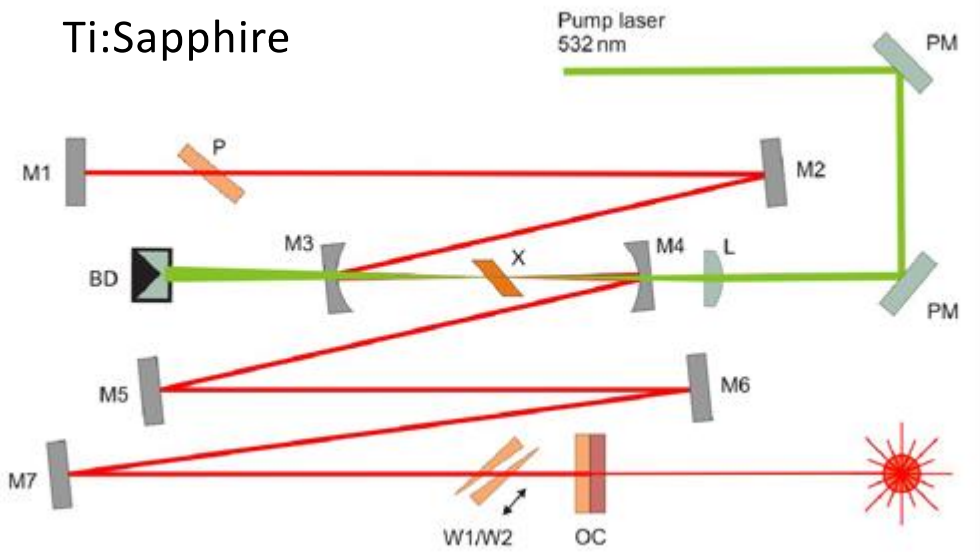
Convert the wavelength to the desired one, using birefringent nonlinear crystals or gas

Harmonic generation or optical parametric amplification

Essentials/ Oscillators

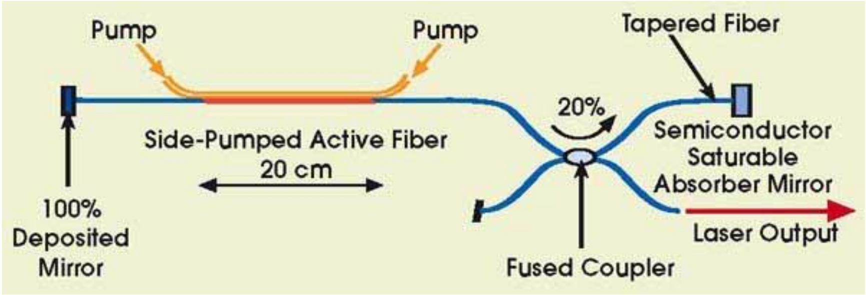


Ti:Sapphire



http://www.iqo.uni-hannover.de/591.html, 4fs octave-spanning oscillator

Yb fiber oscillator



Breck Hitz Optics Letters, March 1, 2006, pp. 592-594 W's of power 10ps.

- Cavity length to match sub-harmonics of the RF
- Low noise architecture for low jitter
- Wavelength and bandwidth to match application

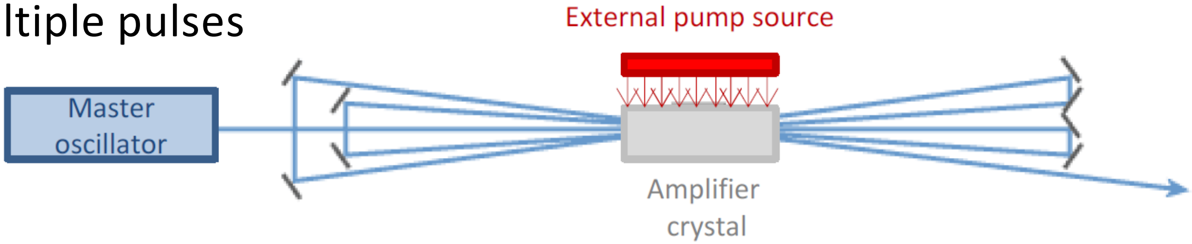
Amplifiers

- Multipass amplifiers for :

    high gain materials

    final low gain amplification

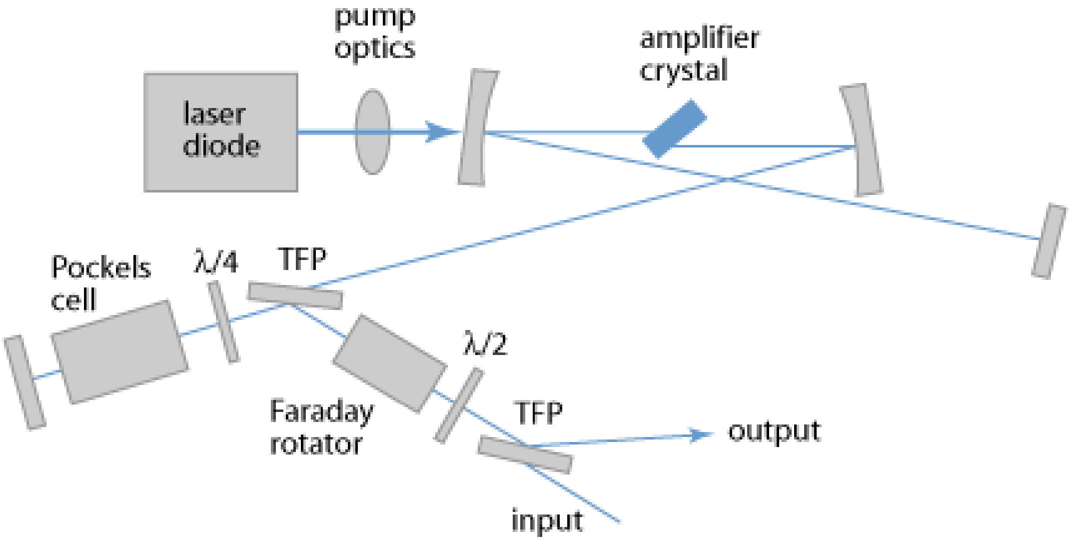
    amplifying multiple pulses



- Regenerative amplifier for:

    amplifying single pulses

    to obtain high gain from a single stage of amplification



Ultrashort pulse amplifiers (<ps)

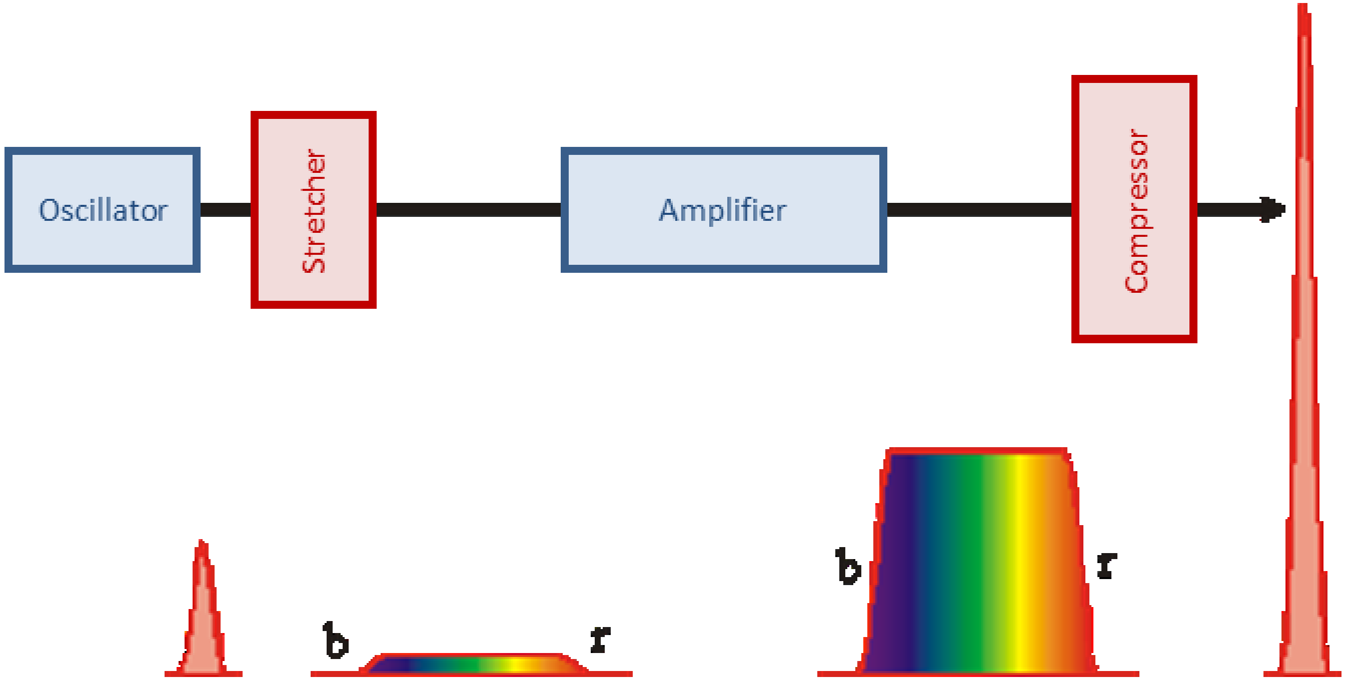
Amplifying single pulse at high energy

Chirped Pulse Amplification

At high intensities the refractive index becomes function of the intensity

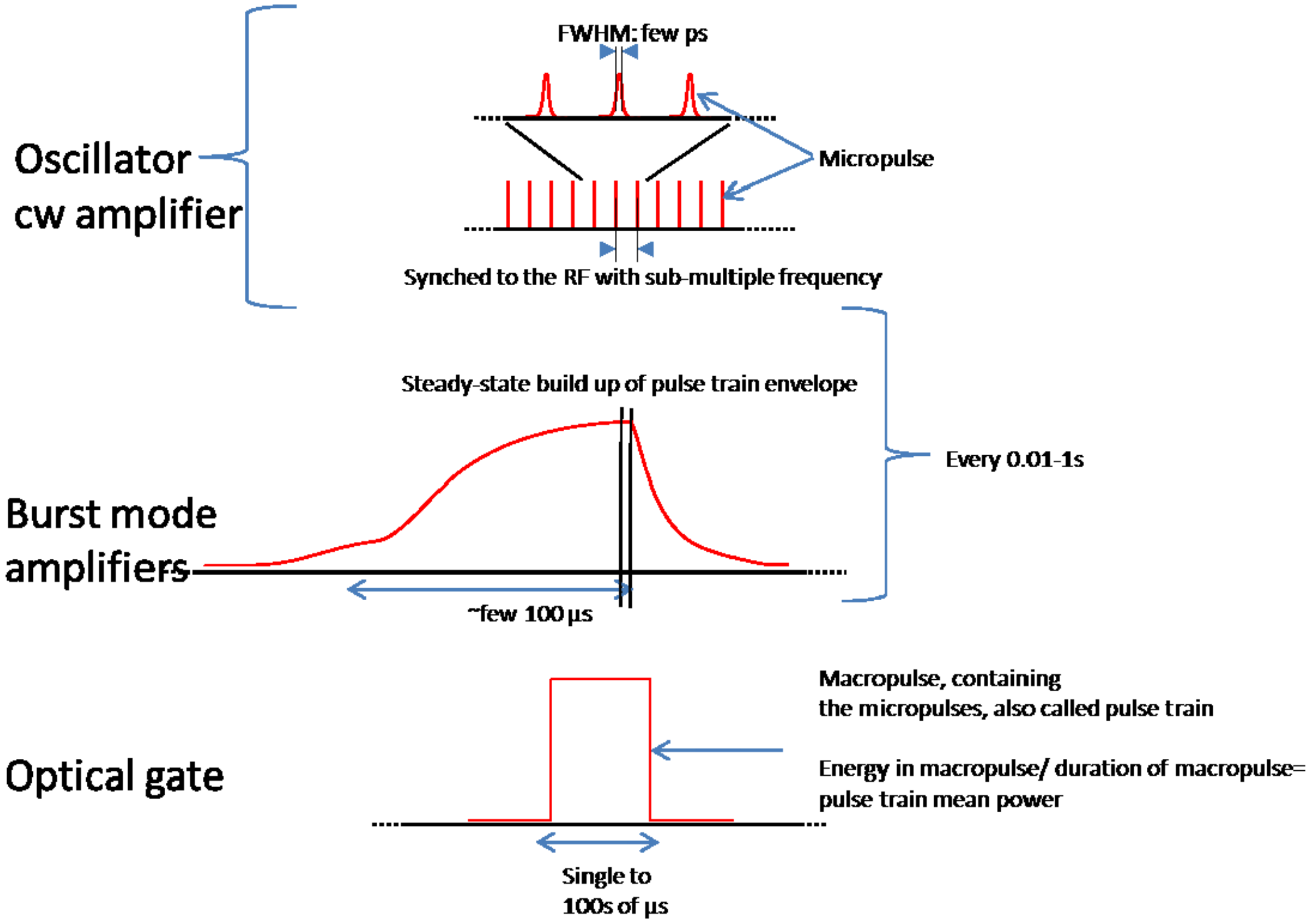
Nonlinearities will cause self-focusing and damage

To reduce the intensity in the amplifier we stretch the pulse



Master oscillator power amplifiers

Burst mode operation



Oscillator
cw amplifier

FWHM: few ps

Micropulse

Synched to the RF with sub-multiple frequency

Steady-state build up of pulse train envelope

Every 0.01-1s

Burst mode
amplifiers

~few 100 µs

Optical gate

Macropulse, containing
the micropulses, also called pulse train

Energy in macropulse/ duration of macropulse=
pulse train mean power

Single to
100s of µs

Optical parametric amplifiers (OPA)

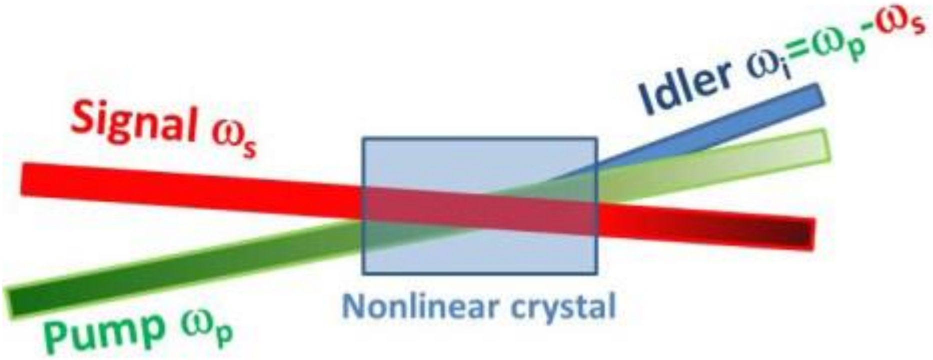
Amplify in a nonlinear optical material using a parametric process

Transfer the pump light of a laser working at a shorter wavelength into the signal beam. The transfer is instantaneous, there is no energy storage.

Chirped pulse used to:

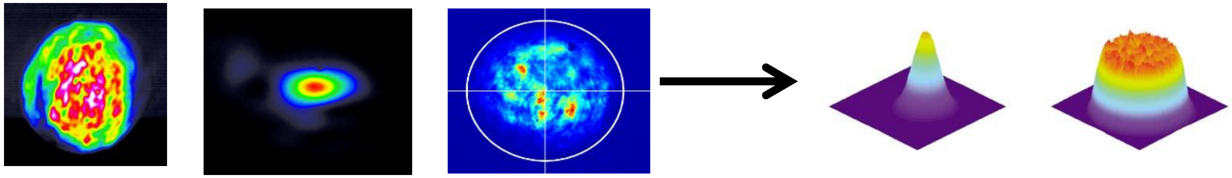
- avoid damage and unwanted non-linear effects
- efficiently match and overlap with the length of the pump pulse

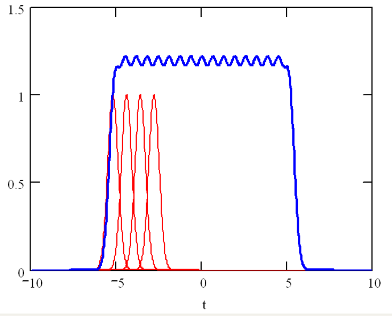
OPA's can cover a wide range of wavelengths from 300nm-4µm. Most of the commercially available tunable wavelength sources are based on parametric oscillators or amplifiers.



Extras

- 4-D pulse shaping

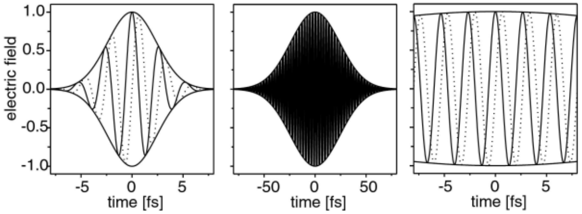




- Pulse-shortening techniques

to reach pulse-lengths below 20fs

- Carrier-envelope stabilization



- Programmable pulse-trains

https://indico.cern.ch/event/177701/contributions/1441170/attachments/232573/325458/beam_shaping_Marta_Divall.pdf

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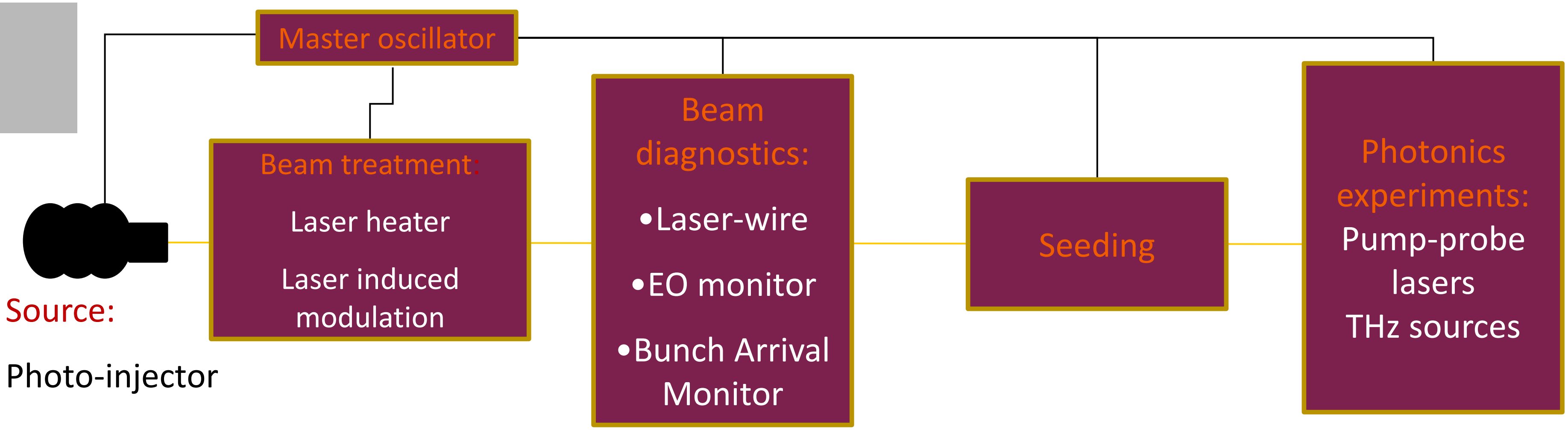
- Small introduction to lasers (laser vs FEL)
- **Lasers used in FEL's/ general requirements**
  - Photo-injector lasers
  - Laser heater
  - Experimental lasers
  - Seeding laser
  - Diagnostics lasers
- The future of lasers in FEL's

Lasers in FEL’s



Master oscillator

Source:

Photo-injector

Beam treatment:

Laser heater

Laser induced modulation

Beam diagnostics:

- Laser-wire
- EO monitor
- Bunch Arrival Monitor

Seeding

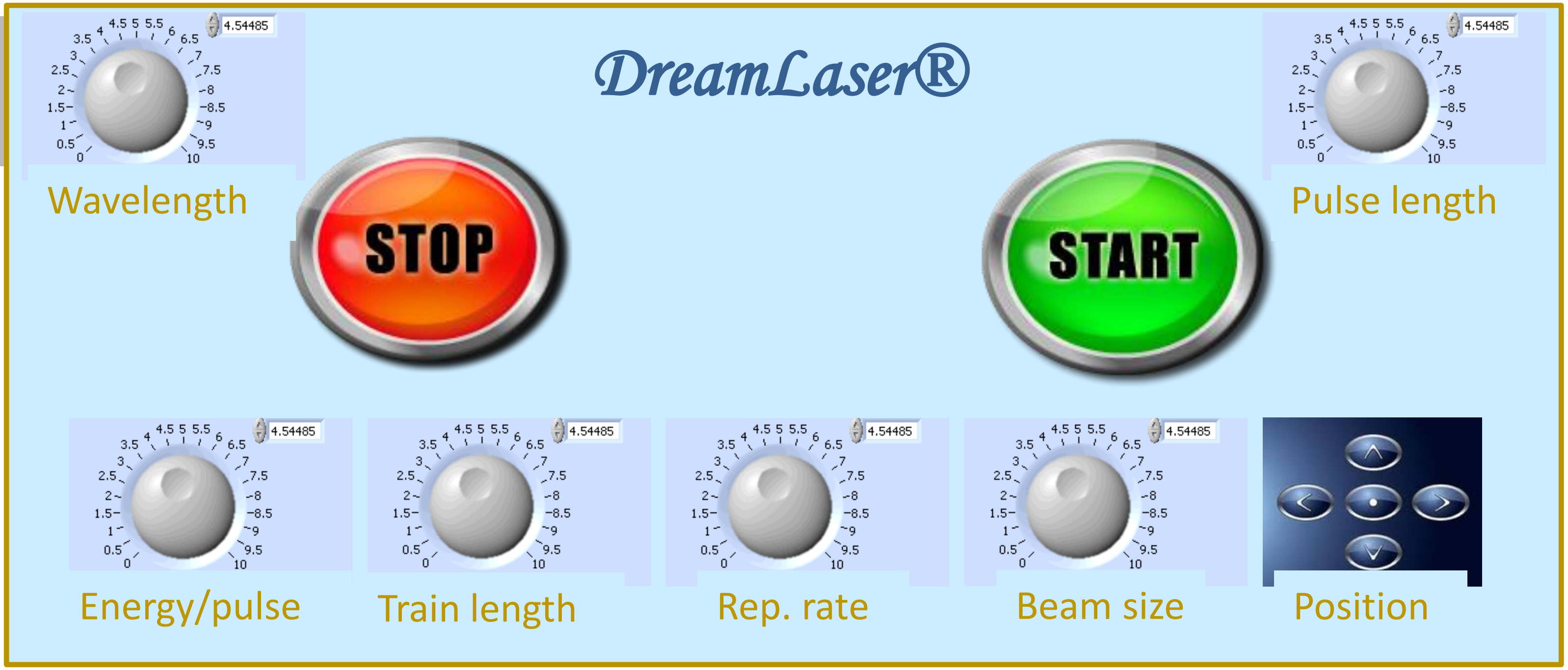
Photonics experiments:

Pump-probe lasers

THz sources

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

Requirements in general



Flexible Tunable Stable

Requirements in general/ Timing-gun-LINAC

Timing of laser → timing of the released electrons

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

↓

Directly related to FEL performance

- Reference distribution
- Laser
- RF at the gun

↓

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

↑ timing jitter after compressor

↑ cavity field amplitude jitter

↑ cavity phase jitter

↑ injector timing jitter

B. Beutner, S. Reiche Sensitivity and tolerance study for the SwissFEL Proc FEL2010 WEPB17, Malmö, Sweden (2010)

Requirements in general/ Timing-experiment

Ultimate goal: Arrival-time stability between x-ray pulses and pump-probe laser pulses to be fraction of pulse duration

$$\Delta t = \sqrt{\Delta t_{\mathrm{laser}}^2 + \Delta t_{\mathrm{XUV}}^2 + \Delta t_{\mathrm{jitter}}^2}.$$

Only measure timing → sort data after by binning

Measure and correct timing → fs scans online

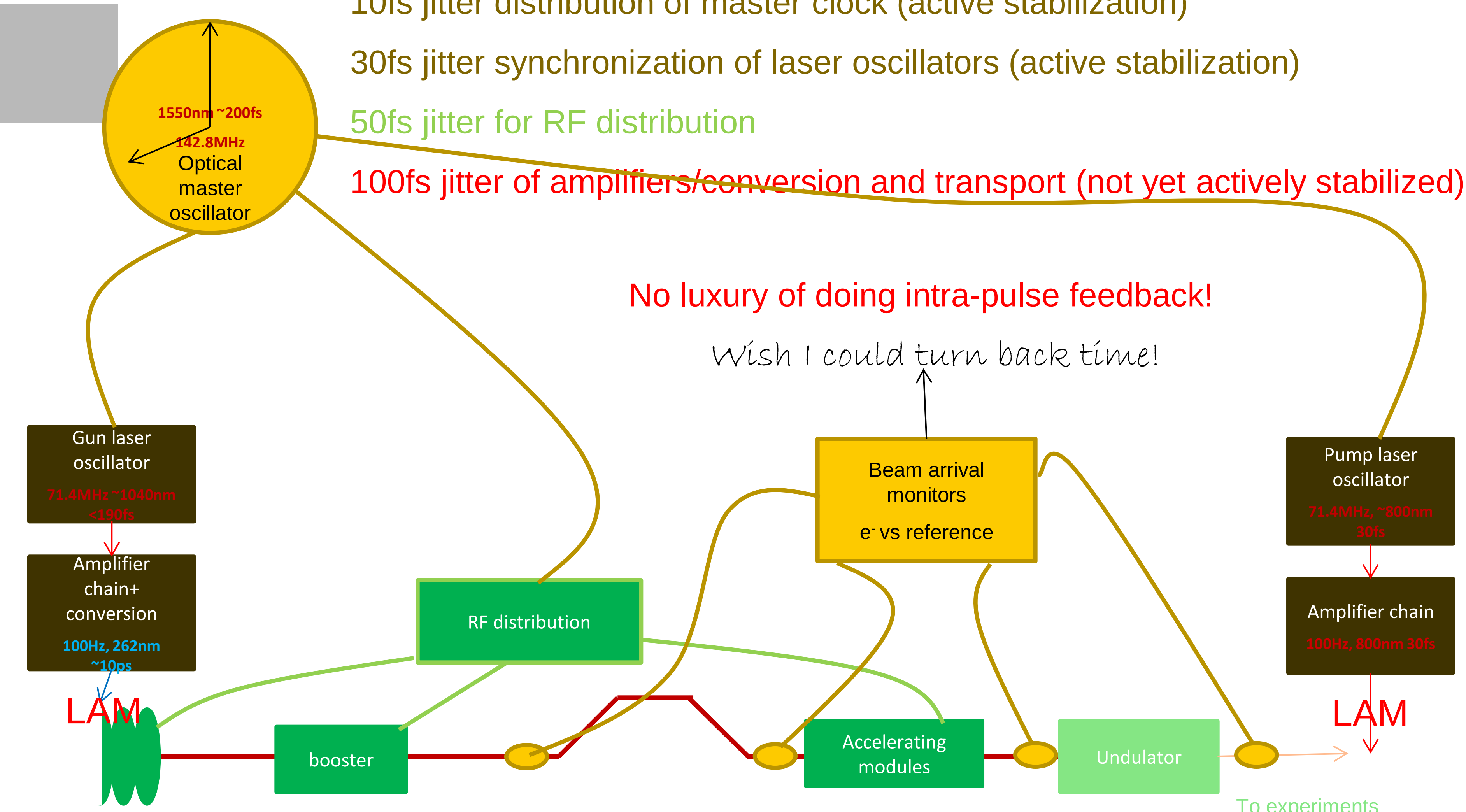
Timing and synchronization

10fs jitter distribution of master clock (active stabilization)

30fs jitter synchronization of laser oscillators (active stabilization)

50fs jitter for RF distribution

100fs jitter of amplifiers/conversion and transport (not yet actively stabilized)



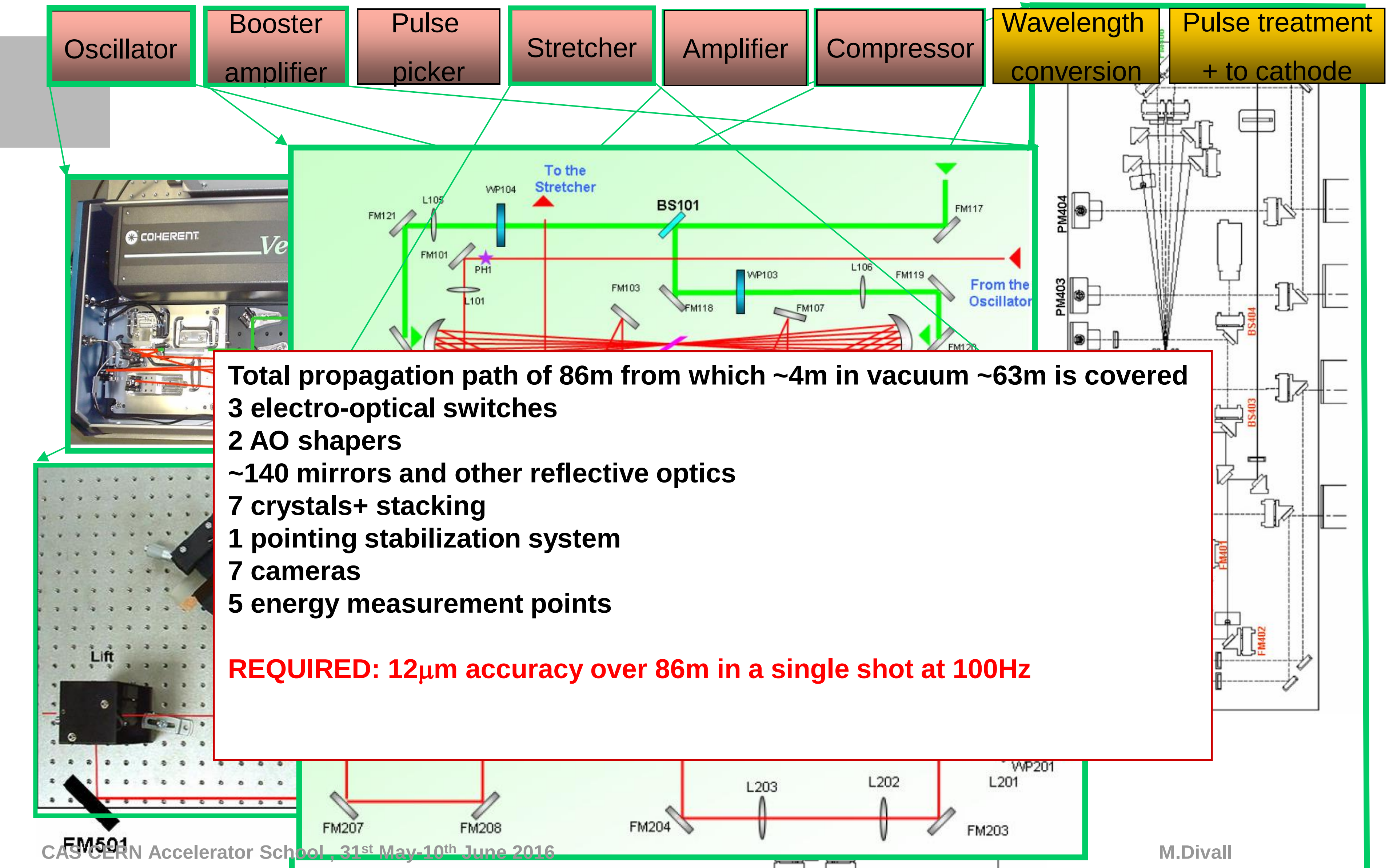
No luxury of doing intra-pulse feedback!

Wish I could turn back time!

Requirment: 40fs rms

Requirement:10fs rms

Architecture



Oscillator

Booster amplifier

Pulse picker

Stretcher

Amplifier

Compressor

Wavelength conversion

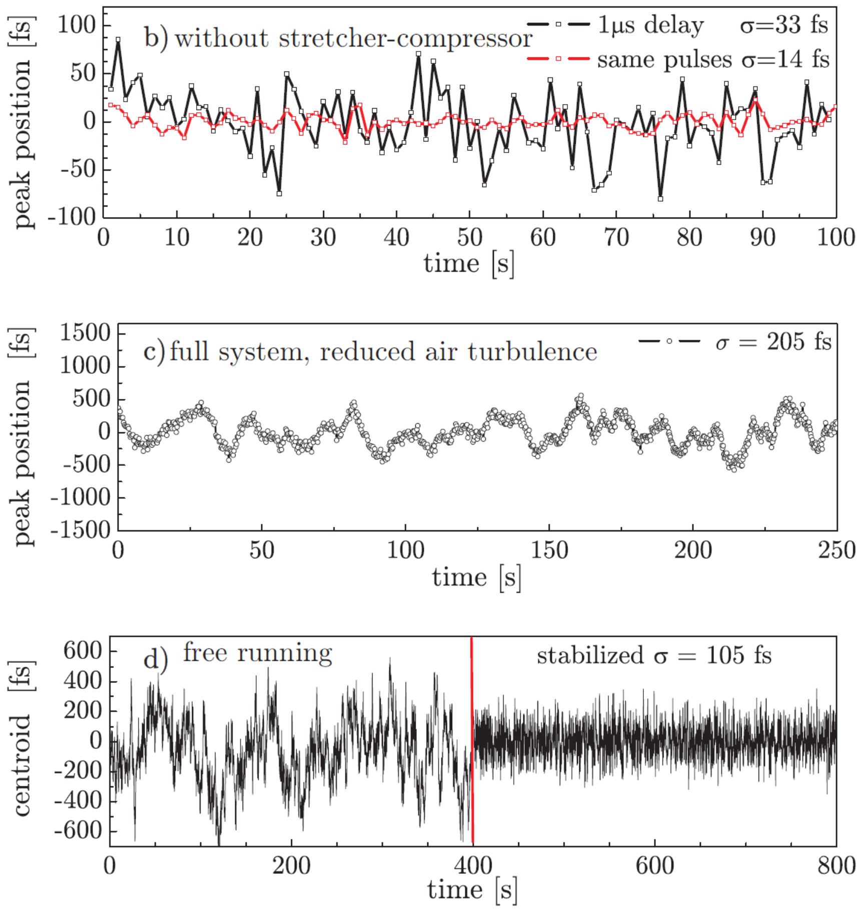
Pulse treatment + to cathode

Total propagation path of 86m from which ~4m in vacuum ~63m is covered
3 electro-optical switches
2 AO shapers
~140 mirrors and other reflective optics
7 crystals+ stacking
1 pointing stabilization system
7 cameras
5 energy measurement points

REQUIRED: 12μm accuracy over 86m in a single shot at 100Hz

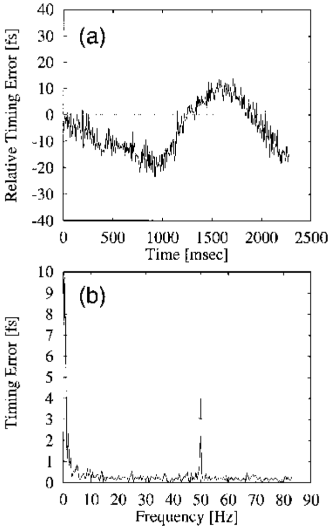
Timing of the whole laser

Stretcher and compressor



S. Lingebiel et al.: Experimental and theoretical investigation of timing jitter inside a stretcher-compressor setup Opt. Exp. Vol. 20, No. 4 p3444 (2012)

Regenerative amplifier

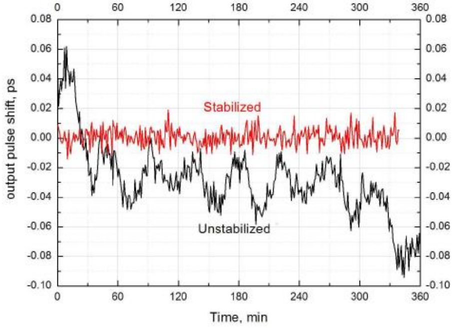


The thermal expansion:
1-m-long standard stainless-steel base plate is approximately 15um/^{o}C
0.1^{o}CWith 20 round trips this gives 100fs drift.

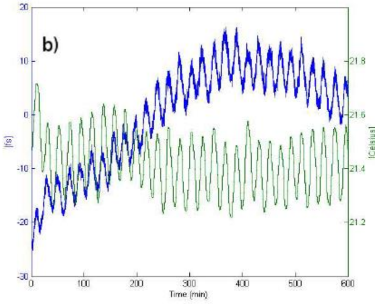
+ vibration of the mirrors

T. Miura et al. Timing jitter in a kilohertz regenerative amplifier of a femtosecond-pulse Ti:Al2O3 laser Opt. Lett. Vol. 25, No. 24 (2000)

Beam transport



Ti:saphire amplifier
Main contribution is temperature
7ps/^{o}C drift



Transfer line 10m air 10m vacuum

30fs/^{o}C drift

P.Singalotti et al.: Ultrafast Laser Synchronization at the FERMI@Elettra FEL Proc. SPIE Vol. 8778 87780Q (2013)

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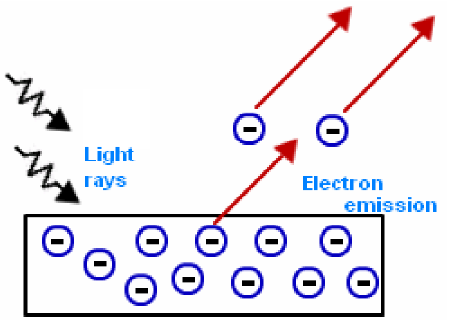
- Lasers used in FEL’s/ general requirements
- **Requirements/parameters/examples**
  - ➢ **Photo-injector/gun lasers**
  - –Experimental lasers
  - –Laser heater
  - –Seeding laser
  - –Diagnostics lasers
- The future of lasers in FEL’s

Parameters for gun lasers

- Electrons produced through photo-emission have the 'imprint' of the laser pulse structure from which they are produced and hence allow for great flexibility

- Short laser pulses with **4D shaping** have the potential to deliver ultra-bright electron beams



- The electron bandgap of the photo-cathode material will define the laser wavelength

- The quantum efficiency of the cathode will determine the energy per pulse required from the laser;

- The application will determine the average current and pulse structure, having a direct effect on the laser average power requirements and its architecture.

Parameters for gun lasers

- Wavelength (tuned close to the work-function of the material)
  - Cs$_2$Te and Cu require UV ~260nm,
  - GaAs IR (also polarized)
  - New type of alkaline cathodes, requiring visible light
- **Timing**
  - Synchronized to external reference/sub-harmonic of the RF
  - Noise of the oscillator architecture, active elements
- Single pulse/burst mode to match machine operation
  - Determines the chosen laser architecture (regenerative amplifier or multipass)
- **3D shaping to reduce emittance**
  - Beer-can/ truncated Gaussian/ ellipsoidal
- Pulse length
  - To mitigate space-charge effects at the gun
  - To allow for shaping techniques
- Pulse energy
  - Dependent on cathode choice/QE and operational charge + transport losses
- Reliability/reproducibility/stability
  - Used architecture
- Running cost/service support

Cathodes

Photo cathode	Advantage	Disadvantage
Cs_3Sb, CsK_2Sb	✓ High quantum efficiency ✓ 500 nm laser	• Difficult to prepare • Short lifetime • Not sustain very high fields • Expensive preparation chamber • Expensive transport system • Need very good vacuum
Cs_2Te	✓ High quantum efficiency ✓ Long lifetime ✓ Sustains high fields	• Needs UV • Expensive preparation chamber • Expensive transport system • Questionable response to pulsetrain
Cu, Y, Mg	✓ No preparation chamber needed ✓ Long lifetime (> 1 year) ✓ Fast response ✓ Sustain very high fields ✓ Sustain bad vacuum	• Needs UV • Low quantum efficiency (Mg better 0.3%)
LaB_6, WcaOBaO	✓ No preparation chamber needed ✓ Long lifetime	• Needs UV • Low quantum efficiency • Need to be heated prior to operation

***C**: charge to be produced*

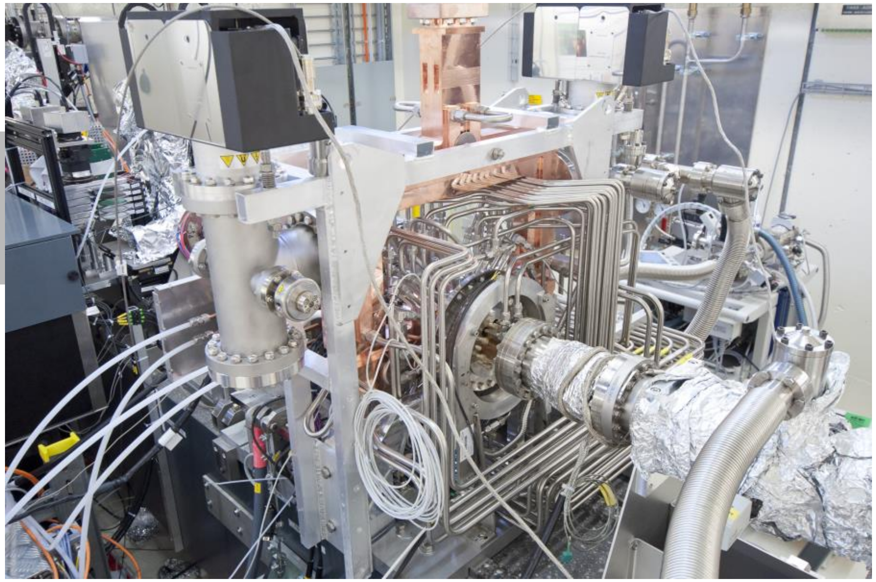
η: quantum efficiency

***W**: laser energy on the cathode*

λ: laser wavelength

$$C[nC] = 8 \cdot \eta[\%] \cdot W[\mu J] \cdot \lambda[nm]$$

Example SwissFEL

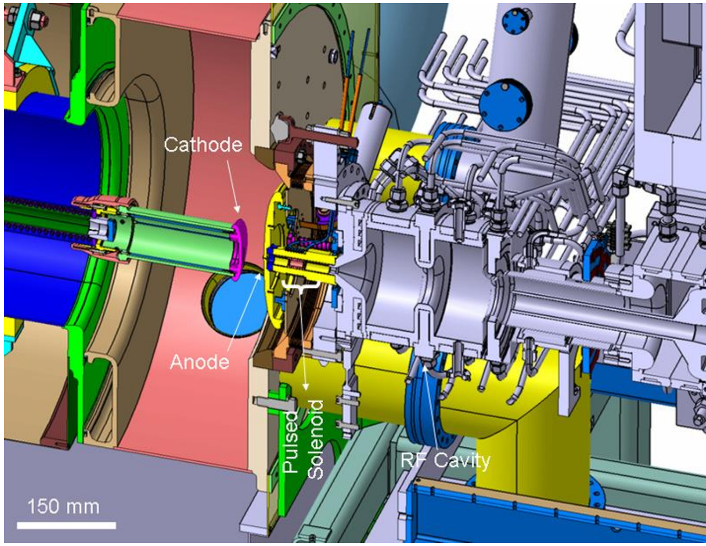


GUN 2.5 cells

RF:	2998.8 MHz
Repetition rate	100 Hz.
Cavity peak acceleration:	120 MV/m
Maximum charge:	200 pC
Peak current:	20A
Cathode:	Copper
Pr. norm.emittance (200pC/10pC):	0.275/0.114 μm
Thermal emittance (200pC/10pC):	195/92 nm

LASER

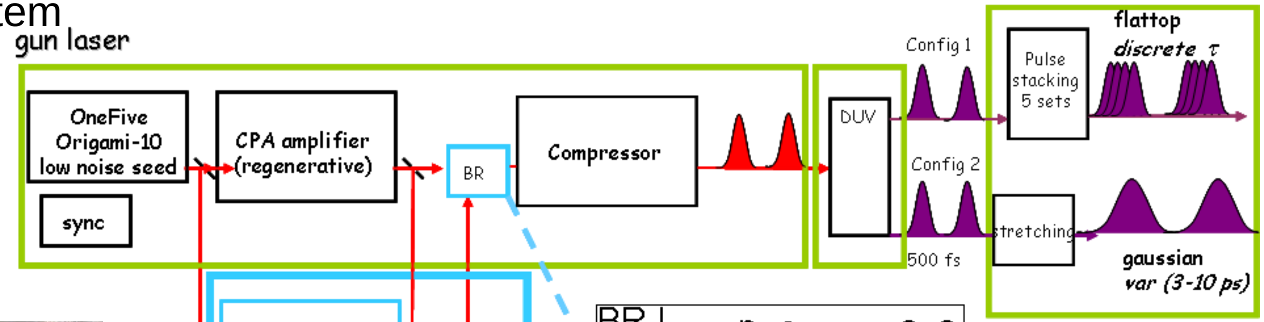
Wavelength:	~260nm
Energy on the cathode:	up to 60μJ
Pulse length:	4-10ps with risetime <700fs
Repetition rate:	100 Hz, double pulse (28nsec)
Spot size:	Variable flattop 0.1-0.27mm
Energy stability :	<0.5%rms
Pointing stability/size:	<1%rms
Timing jitter vs RF ref.:	<40fs rms (<10fs*)

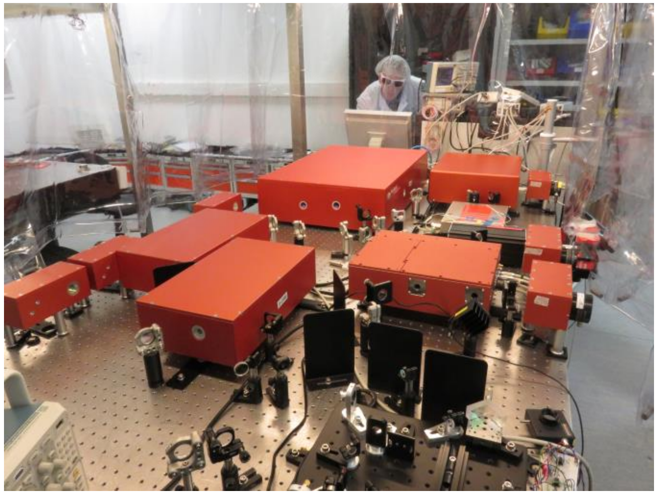


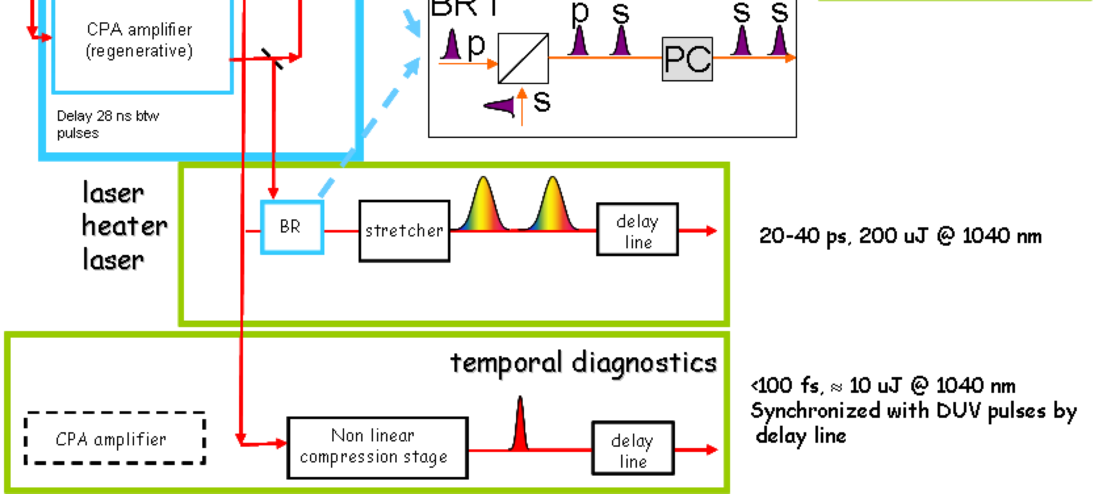
SwissFEL gun laser

Directly diode pumped compact laser system:

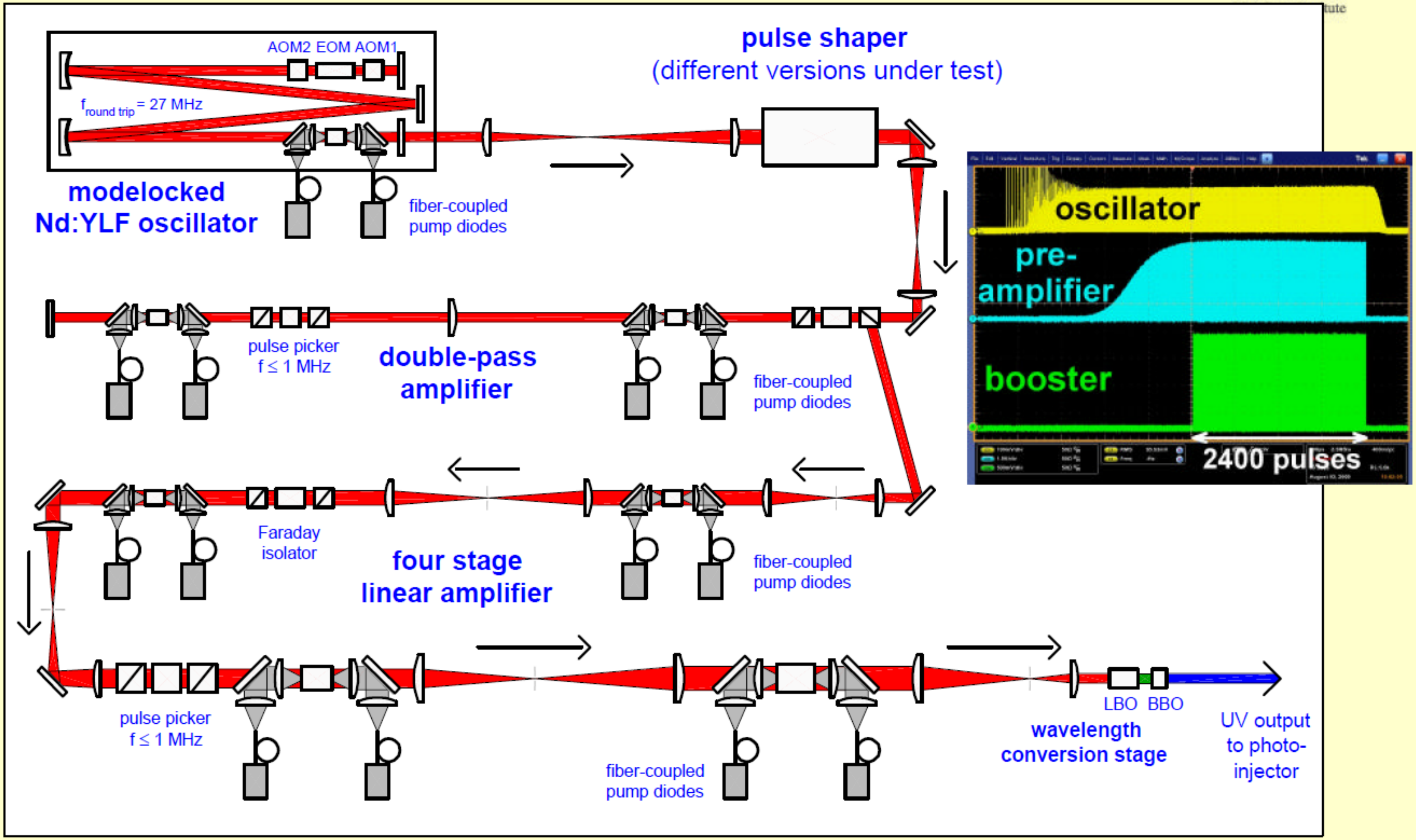
- Low noise fiber seed (same as our optical reference laser)
- Fiber preamplifier
- Yb:CaF$_2$ high power amplifiers
- Compact sub-ps system







Nd:YLF system for FLASH



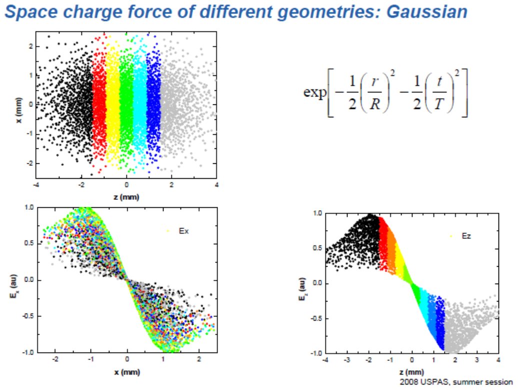
Emittance optimization

I don't like you

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

emittance

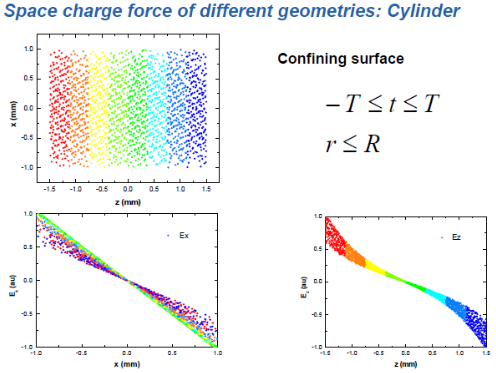
With proper focusing, emittance due to linear space charge force can always be compensated.



Space charge force of different geometries: Gaussian

$\exp\left[-\frac{1}{2}\left(\frac{r}{R}\right)^2 - \frac{1}{2}\left(\frac{t}{T}\right)^2\right]$

2008 USPAS, summer session

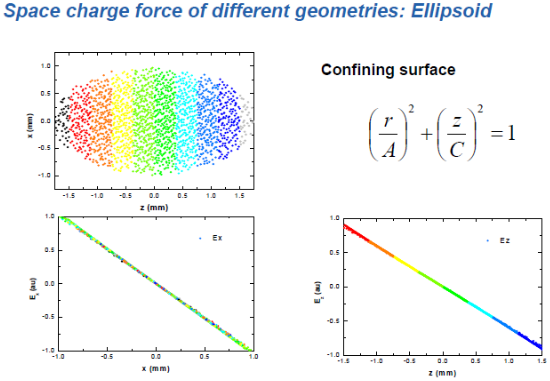


Space charge force of different geometries: Cylinder

Confining surface

$-T \le t \le T$

$r \le R$



Space charge force of different geometries: Ellipsoid

Confining surface

$\left(\frac{r}{A}\right)^2 + \left(\frac{z}{C}\right)^2 = 1$

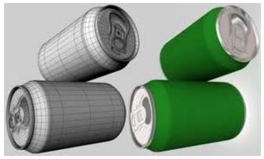
Traditionally for high charge machines, like CLIC drive beam injector

For running FEL's

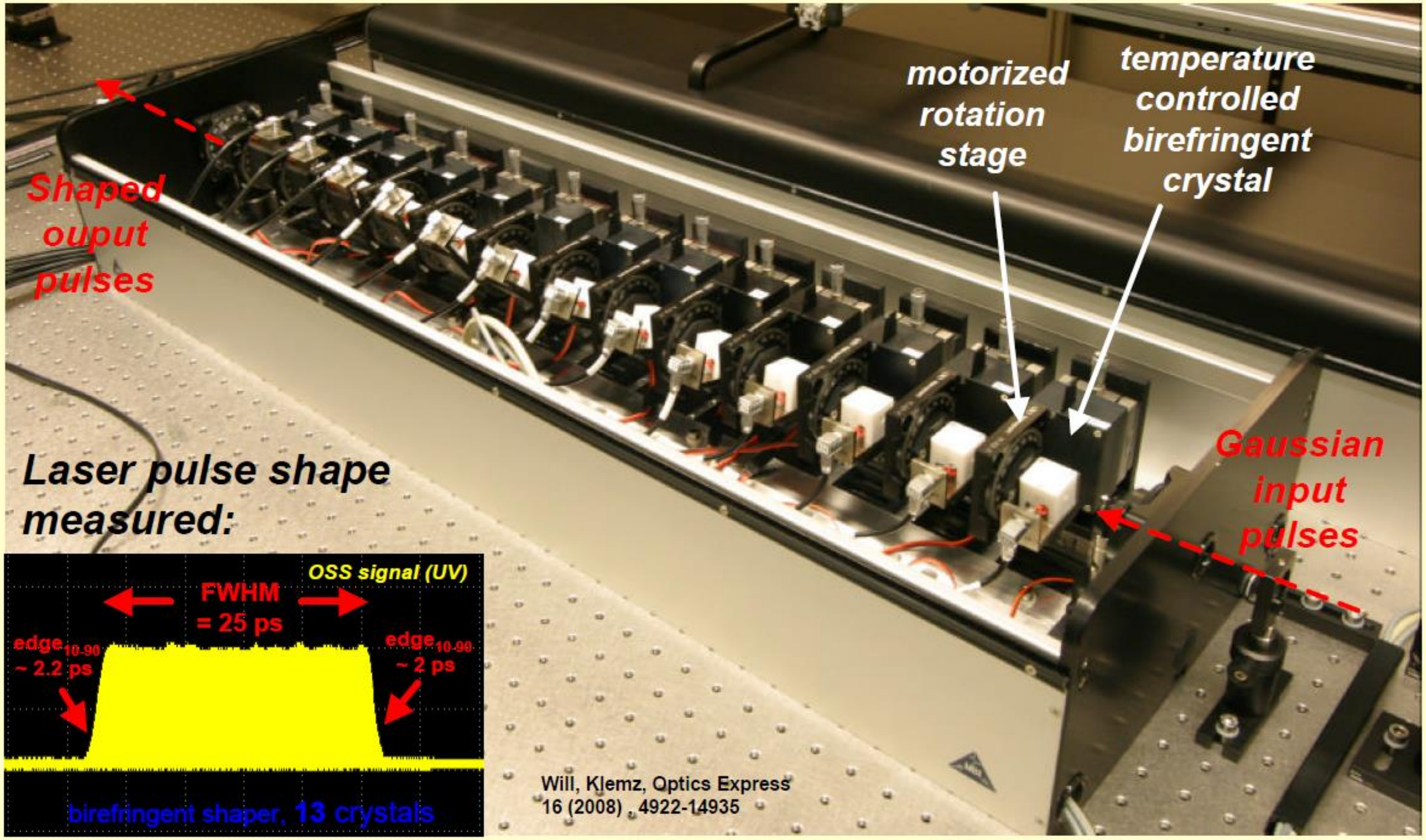
LCLS, FLASH, SPARC, PITZ, SwissFEL

On paper

Beer vs. rugby



Pulse shaping for emittance optimization



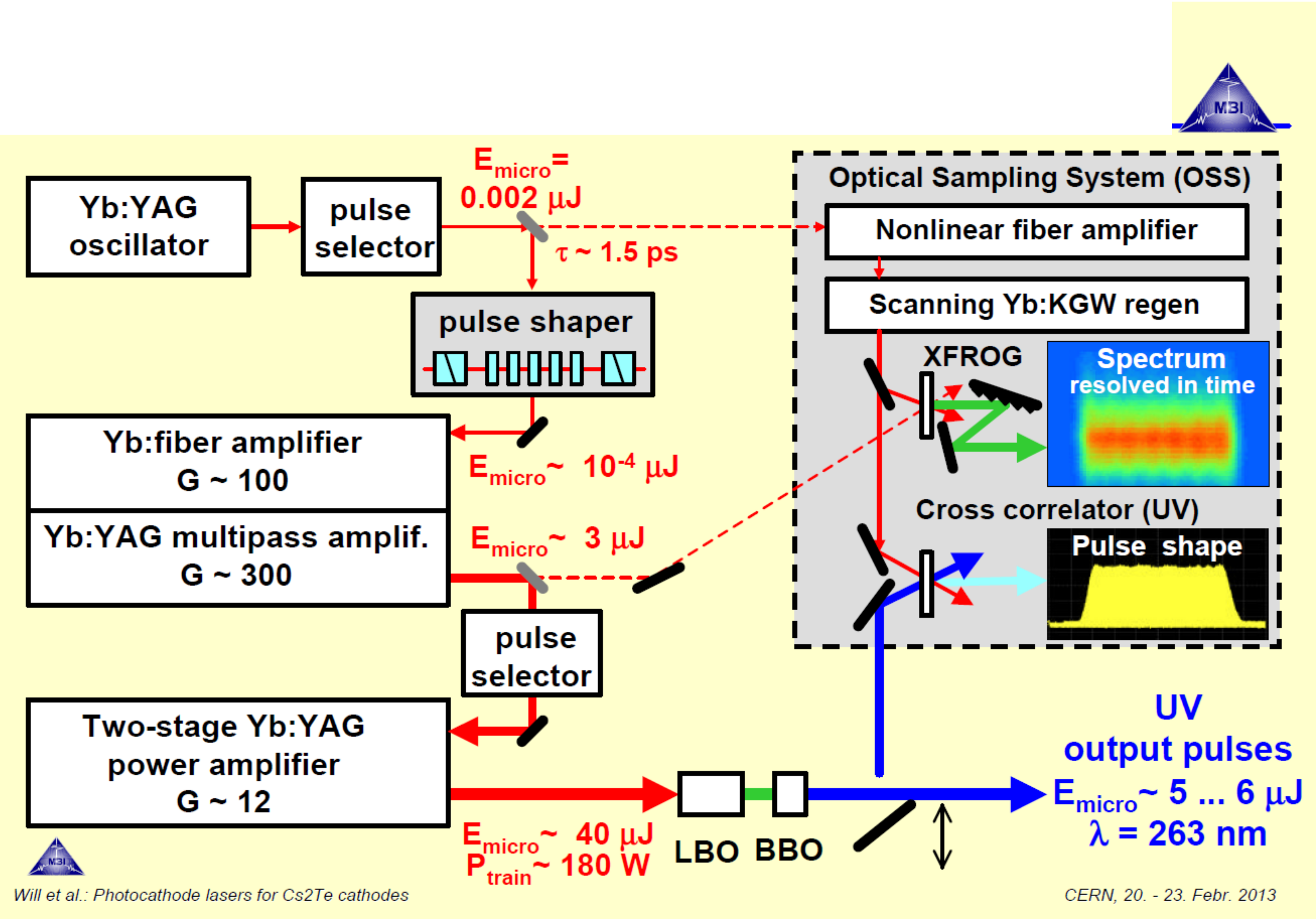
Laser pulse shape measured:

Will, Klemz, Optics Express 16 (2008), 4922-14935

Will et al.: Photocathode lasers for Cs2Te cathodes

CERN, 20. - 23. Febr. 2013

European XFEL gun drive laser



Will et al.: Photocathode lasers for Cs2Te cathodes

CERN, 20. - 23. Febr. 2013

Thermal emittance

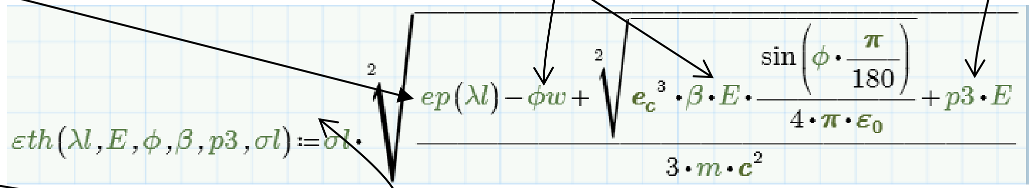
For X-FEL ultralow emittance is required for high brilliance:

Emittance/ Charge	Core slice	Projected
10pC	0.18mm.mrad	0.25mm.mrad
200pC	0.43mm.mrad	0.65mm.mrad

Thermal emittance from the gun becomes significant

Contributions to thermal emittance:

- Cathode workfunction (material property)
- Cathode surface quality (varies from cathode to cathode)
- Schottky-effect (can be determined at fixed wavelength by changing gun phase or gun field or by keeping gun parameters and scanning the well known photo energy)
- Laser wavelength/photon energy
- Laser beamsize



$$\varepsilon th(\lambda l, E, \phi, \beta, p3, \sigma l) := \sigma l \cdot \sqrt[2]{\frac{ep(\lambda l) - \phi w + \sqrt[2]{\mathbf{e_c}^3 \cdot \beta \cdot E \cdot \frac{\sin\left(\phi \cdot \frac{\boldsymbol{\pi}}{180}\right)}{4 \cdot \boldsymbol{\pi} \cdot \boldsymbol{\varepsilon_0}}} + p3 \cdot E}{3 \cdot m \cdot \mathbf{c}^2}}$$

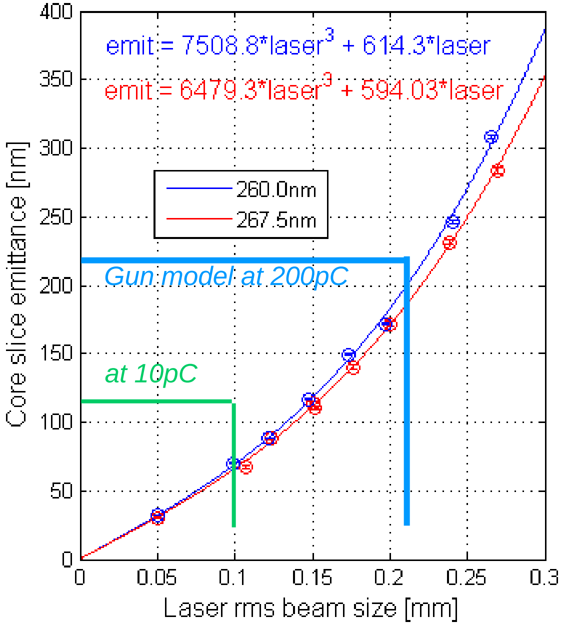
One can scale photon energy to get lower intrinsic emittance at the cost of lower QE

PAUL SCHERRER INSTITUT

Wavelength tuning at SwissFEL Test Injector

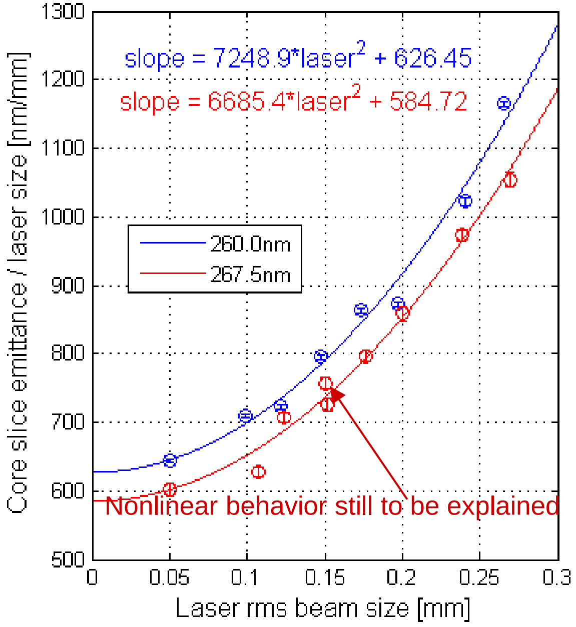
Measure core-slice emittance at different wavelengths as a function of laser spot-size

Ti:Sapphire tunable laser system, 10 ps flattop (stacked)
10 pC @ σ=0.15 mm;

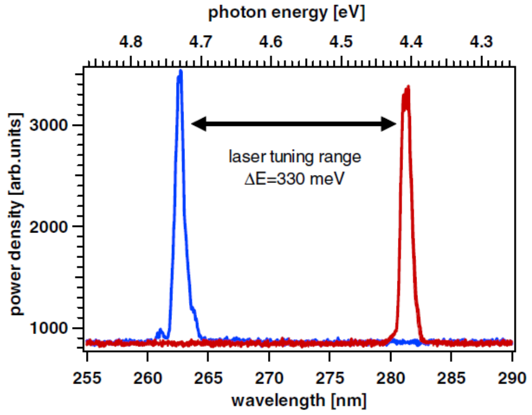


Gun model at 200pC

at 10pC



Nonlinear behavior still to be explained



laser tuning range
ΔE=330 meV

	QE	Emittance/beamsize
267.5nm	1.04e-4	584 nm/mm
260nm	1.62e-4	626 nm/mm

4th harmonic of Nd and Yb based materials

or

3rd harmonic of Ti:Saph

List of lasers for FEL injectors

	ELSA	FLASH (FEL)	TESLA	LCLS	ELETTRA	EuropeanXFEL	SwissFEL
Cathode	K_2CSSb	Cs_2Te	Cs_2Te	Copper	Copper	Cs_2Te	Cs_2Te/Copper
Wavelength on cathode	532nm	262 nm	263nm	253nm	261nm	262nm	260nm
Pulse length on cathode	30ps	4.4ps	20ps square	3-20ps Flat top	6-15ps	6ps	4-10ps Flat top
Material	Nd:YAG	Nd:YLF	Nd:YLF Nd:Glass	Ti:Saph	Ti:Saph	Nd:YLF	Yb:CaF2
Harmonic	2nd	4th	3rd and mixing	3rd	3rd	4th	4th
Macropulse reprate	1Hz	Up to 10Hz	10 Hz	30-12Hz	Up to 50Hz	1-5 Hz	100Hz
Micropulse reprate	14.44MHz	27 MHz	1 MHz	NA		1.5 GHz	Na (28ns multi-bunch)
Pulse train length	150µs	1 pulse-800 µs	800 µs			1.3 µs	2 pulses
Pumping (FL:flashlamp; D:diode; L: laser)	FL	D, FL	FL	L	L	L	D
Energy/pulse IR	10 µJ	300 µJ	200 µJ	25mJ	15mJ	5 µJ	2mJ
Macrop. stability	3%	?	3% (<10%)		0.8%	1.5-3% (<0.5% in IR)	Na
Microp. stability	?	1-2%	? (<5%)			?	0.7%

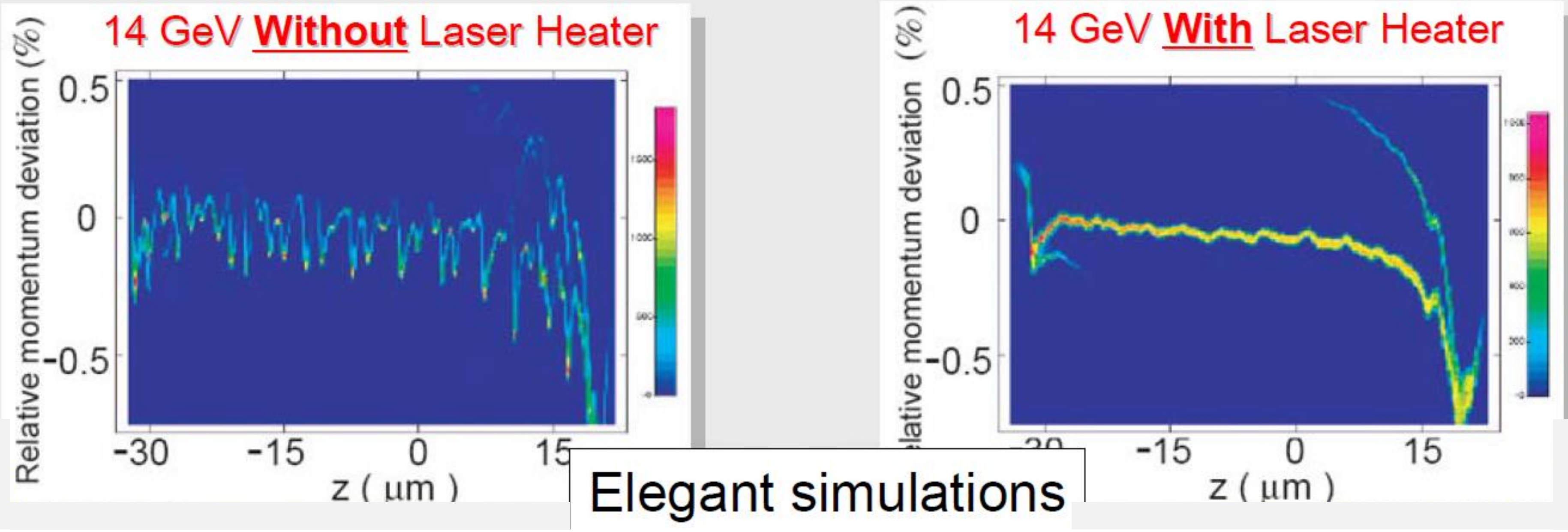
Outline

- Laser vs FEL
- **Lasers used in FEL's**
- **Requirements/parameters/examples**
  - Photo-injector/gun lasers
  - ➢ **Laser heater**
  - Experimental lasers
  - Seeding laser
  - Diagnostics lasers
- The future of lasers in FEL's

Why laser heater?

'Laser heater' suggested by Saldin et al., NIMA, 2004; independently by J. Galayda

LCLS design study: Z. Huang et al., PRST 2004 (chicane suggested by T. Smith)



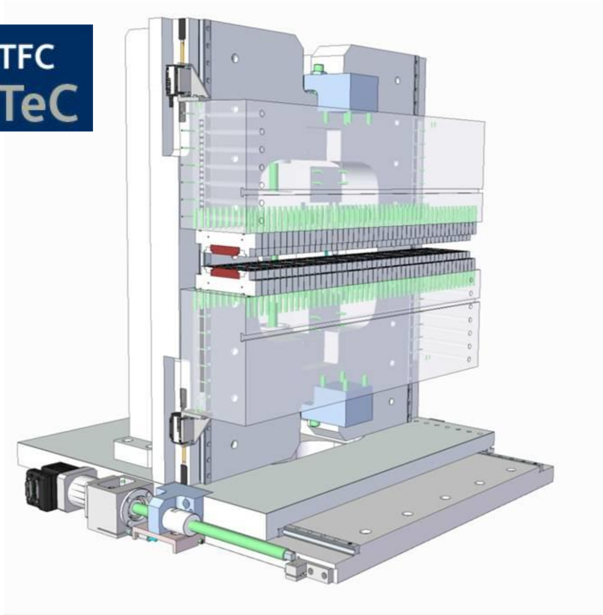
The laser heater increases the uncorrelated momentum spread of the electron beam from photocathode RF guns→ reduces micro-bunching instabilities

Laser heater/ requirements

- long 10’s of ps FWHM gaussian pulses
- beam-size to match electron beam
- wavelength to match undulator and noise to be eliminated (800nm to 1000nm)
- up to 100µJ/pulse at the undulator

- pulse structure to match electron beam structure

STFC ASTeC



Usually they can rely on the residual IR (fundamental) radiation from the photocathode drive laser

Outline

- Laser vs FEL
- **Lasers used in FEL's**
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  - Photo-injector/gun lasers
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Requirements

- Biological studies: visible and UV
- fs-chemistry: 800nm
- Study molecules: Mid-IR
- Surface-magnetization: THz
- Pump-probe crystallography

Need to be able to synchronize the laser to the X-rays

Needs to match pulse structure of the FEL

Need to be able to perform high resolution scans

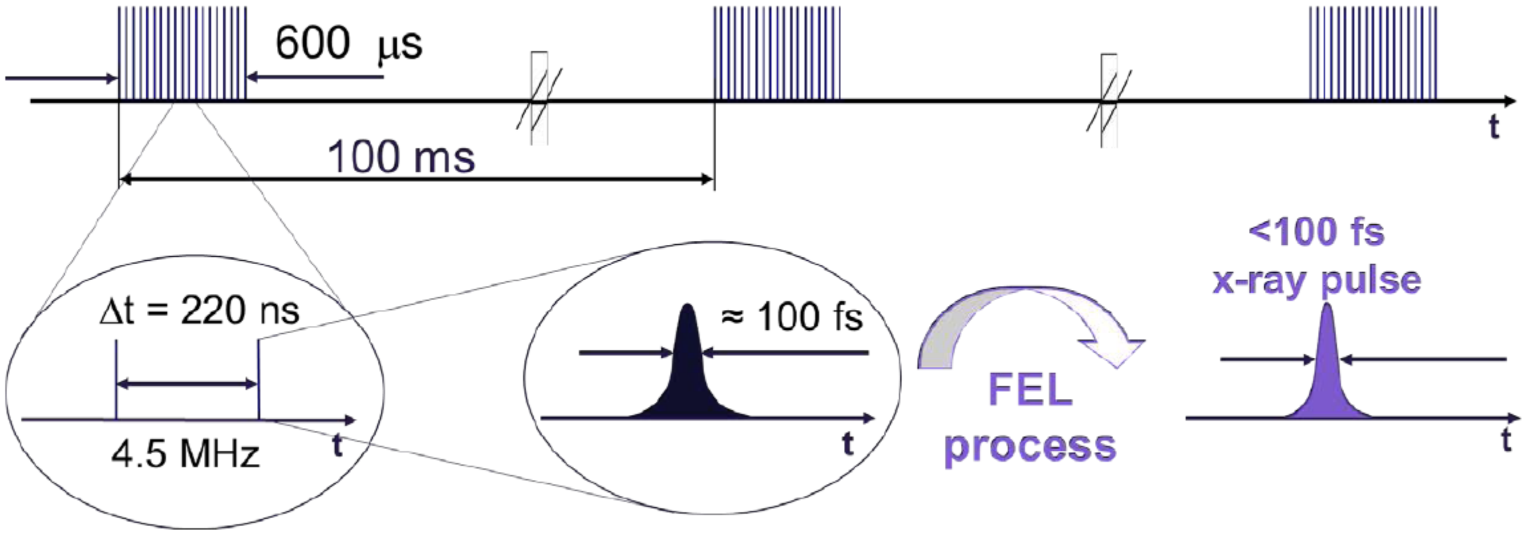
Pulse-length to match X-ray pulse length

Some resonant experiments require tunable source and longer pulses

European XFEL

The European XFEL mode of operation: 10Hz Burst

up to 2700 „e^- bunches“ à 0.1…1 nC => eff. rep-rate: 27000 Hz



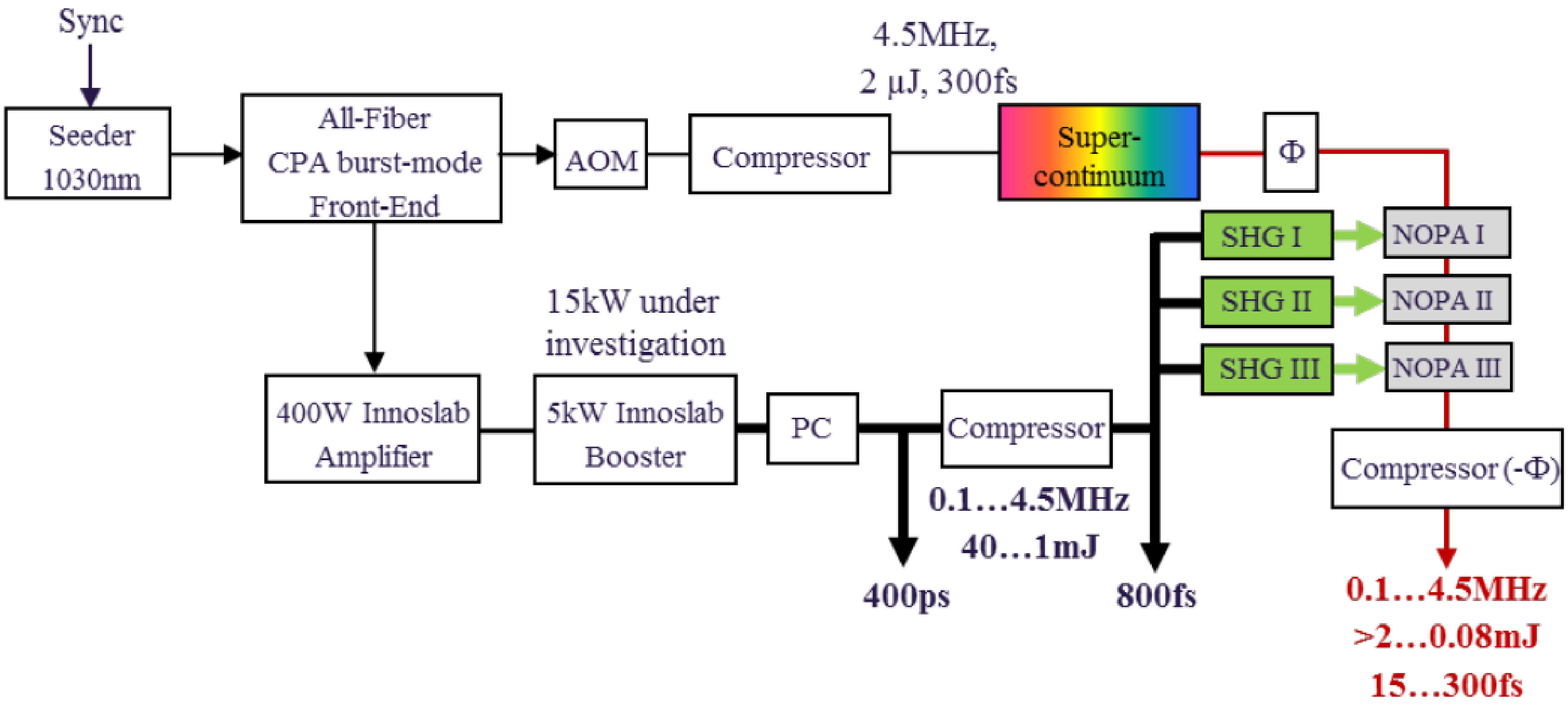
Pump-probe laser goals

⇨ **Match XFEL:**	**10Hz burst, 0 – 4.5MHz**
⇨ **800nm:**	**15 - 300fs, mJ**

- ⇨ **Arbitrary pulse pattern selection**
- ⇨ **Frequency conversion**

Talk: “Laser systems for science instruments”
M. J. Lederer, Laser Group WP78, European XFEL GmbH

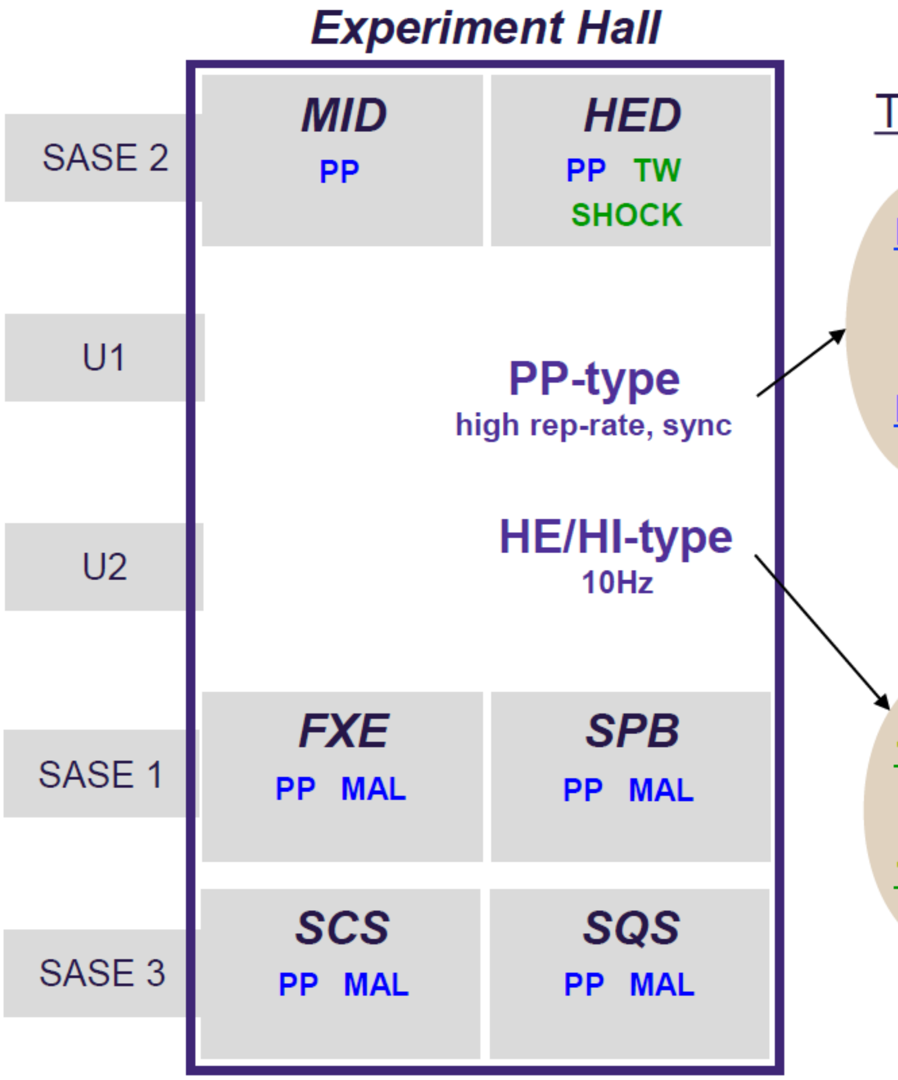
European XFEL experimental laser scheme



European XFEL experimental laser scheme

- **800nm** burst-mode NOPA:
  - burst average power of >300W
  - up to >2mJ single pulse energy
  - <15fs … 300fs, close to transform limited
  - nearly diffraction limited beam quality
  - 4.5MHz, 1.1MHz, 200kHz, 100kHz, arbitrary pulse sequences
- **1030nm** burst-mode:
  - Burst average power of >4kW
  - up to 40mJ single pulse energy
  - 800fs or 400ps
  - $M^2 < 1.5$
  - 4.5MHz, 1.1MHz, 200kHz, 100kHz, arbitrary pulse sequences

European X-FEL



Types of experimental lasers:

PP **pump-probe:**

- ➔ sub-15…300fs, mJ-class, 0…4.5MHz, 800nm
- ➔ UV…mid-IR, THz

MAL **molecular alignment:**

- ➔ sub-20fs, 1…10mJ, 800nm („kick“)

or

- ➔ 1J-class, 10Hz ns („adiabatic“)

In-house R&D

100TW **high intensity (HI):**

- ➔ <30fs, 10Hz, 100 TW–class laser, Tisa

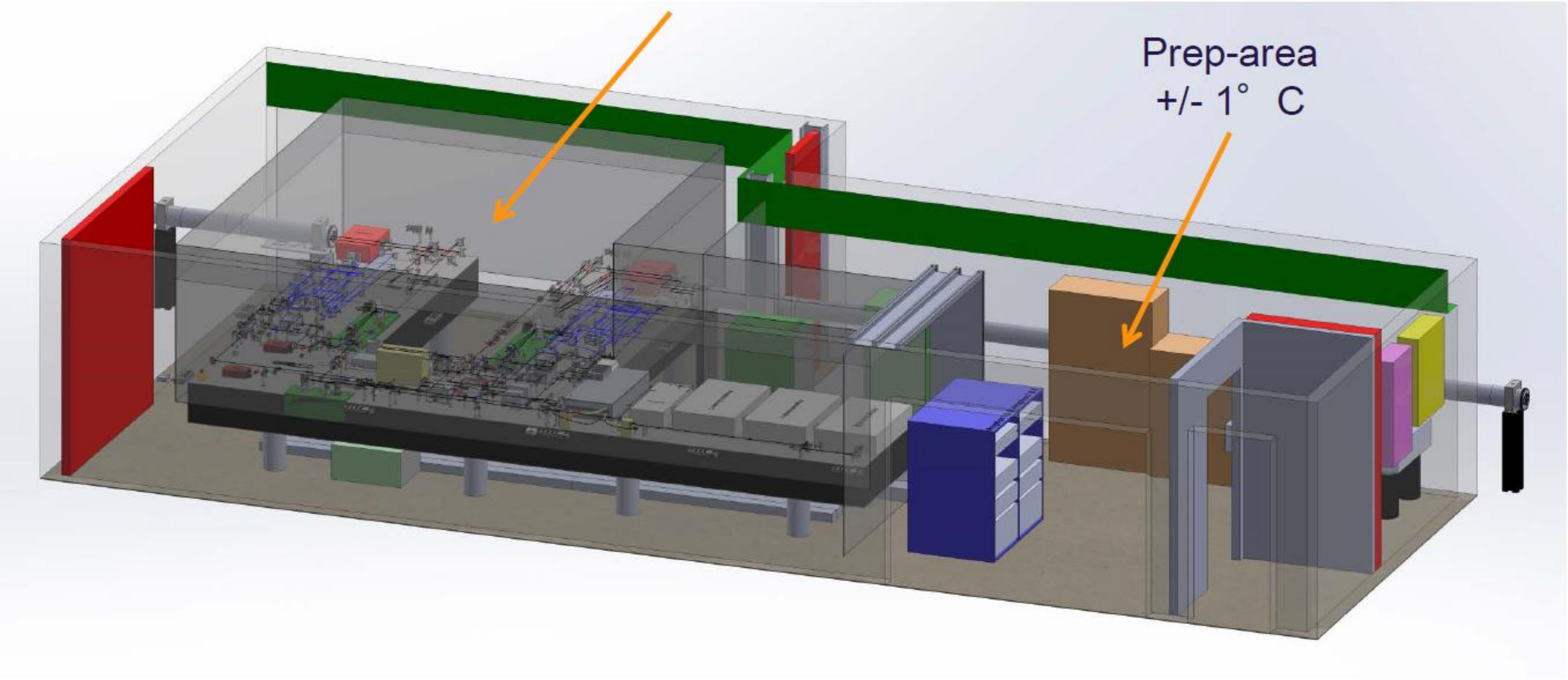
100J **high energy (HE):**

- ➔ 100J … kJ-class ns-laser, 10Hz, green, exp. ramp

UC „HiBEF“

Talk: “Laser systems for science instruments”
M. J. Lederer, Laser Group WP78, European XFEL GmbH

European X-FEL



Clean room,
+/- 0.1° C

Prep-area
+/- 1° C

SwissFEL experimental laser

Core laser system:

- Commercial Ti:Sa System
- > 20 mJ compressed
- < 30 fs
- 100 Hz
- Redundant layout for reliability

Local installation in experimental station:

OPA:

- 1100 nm - <15’000 nm
  ca. 1 mJ - ca. 10 µJ
  ca. 40 fs - < 100 fs

THz[3]:

- 1 – 10 THz
  > 1 MV/cm, ca. 10 µJ
  single cycle

Short pulse[4]:

- < 10 fs @ 800 nm
  ca. 500 µJ

Pulse diagnostics

User accessible space ca. 1m^2

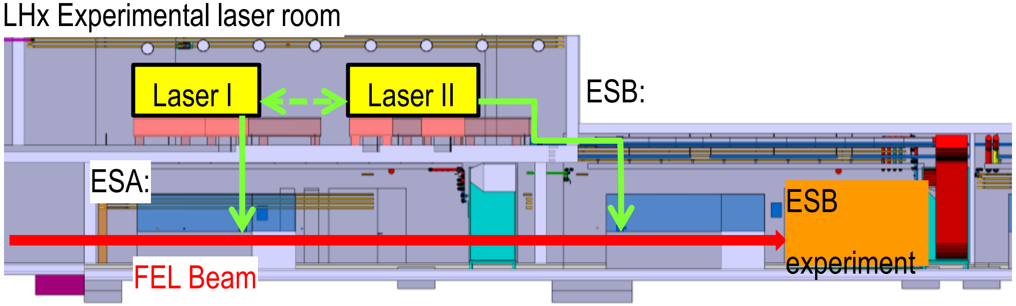
[1]: Hebling et al. Appl. Phys. B, 78, 593, 2004

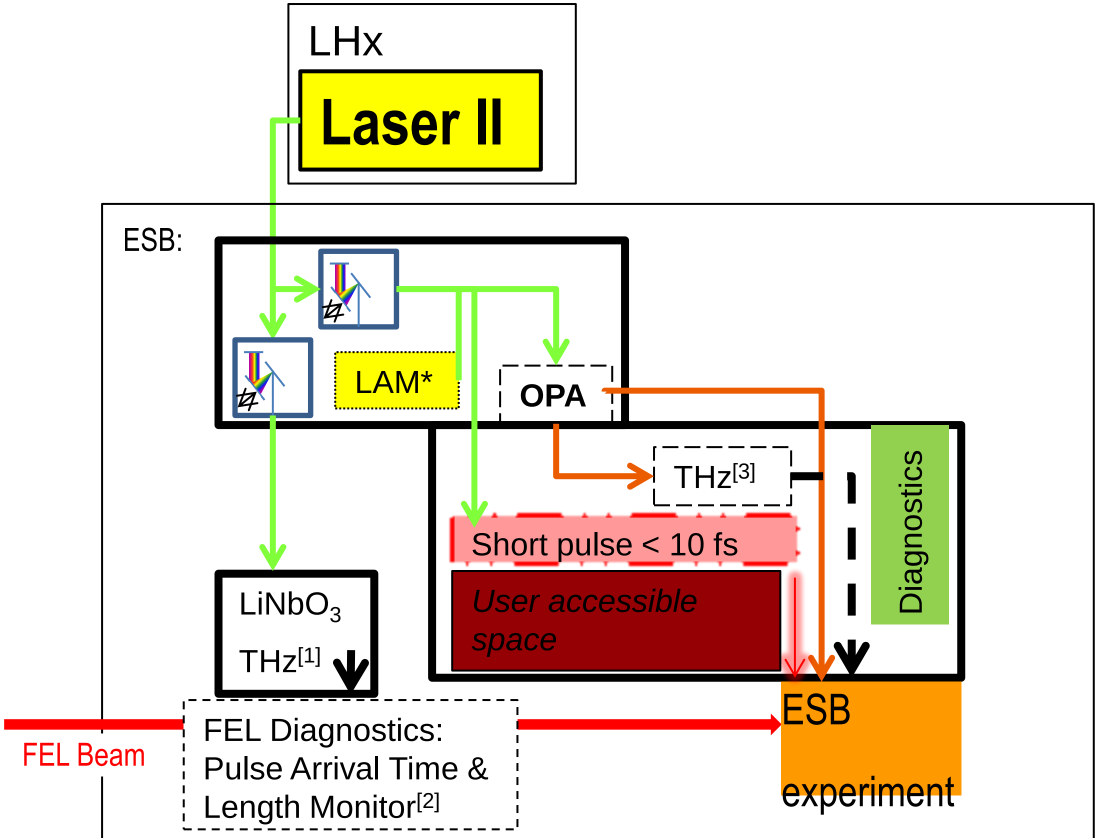
[2]: Juranic et al. JINST 9, P03006, 2014

[3]: Ruchert et al. PRL 110, 123902, 2013

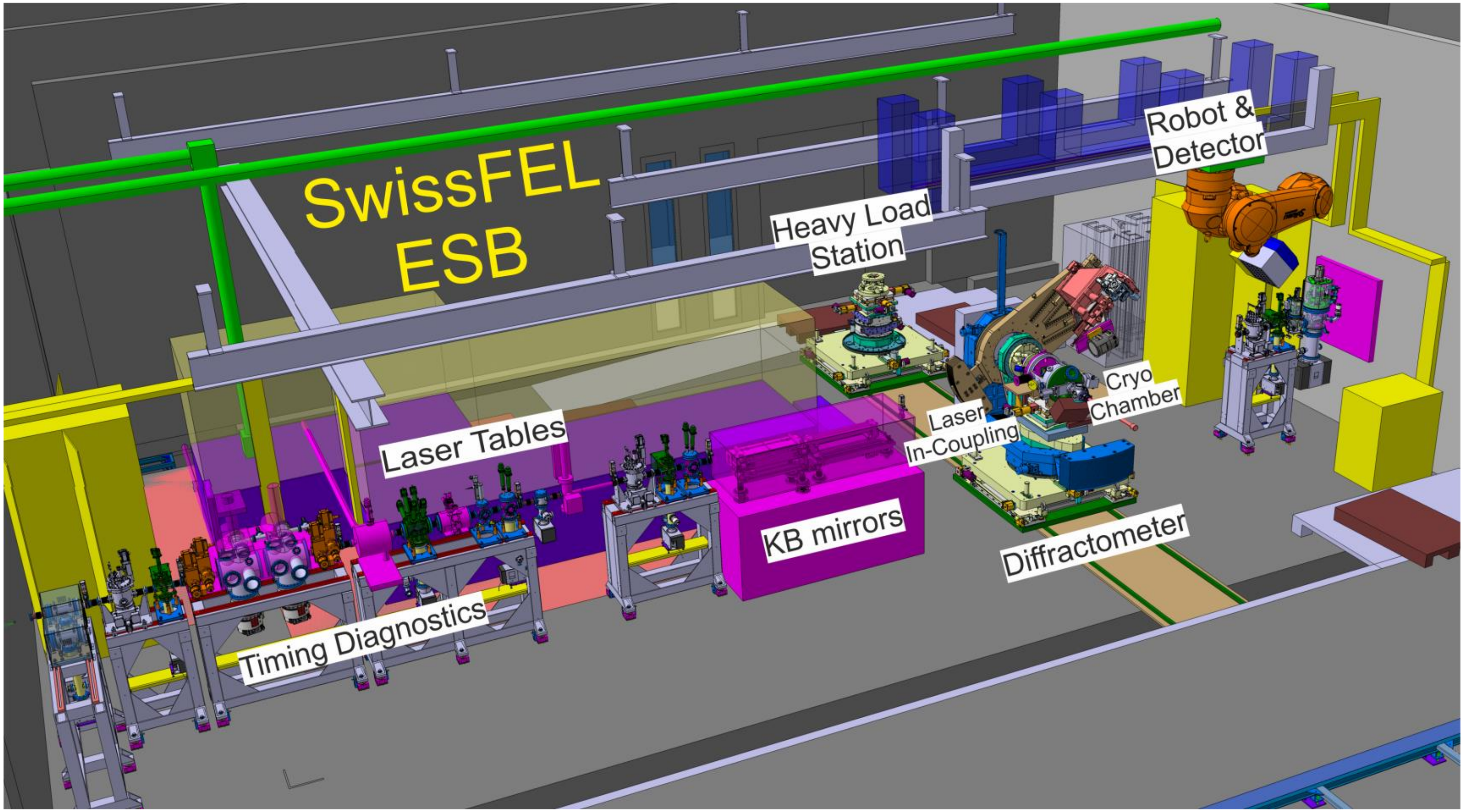
[4]: Nisoli et al. Appl. Phys. Lett. 68, 2763, 1996

**: Laser Arrival Time Monitor*





SwissFEL experimental laser



IR FEL’s

Table-top laser systems installed in the FELBE user labs

Table-top laser systems installed in the FELBE user labs

Laser system	Pulse duration	Energy per pulse	Repetition rate	Wavelength range
Femtosecond Ti-sapphire laser with optical parametric oscillator	80 fs	10 nJ	78 MHz	730 – 870 nm
	200 fs	1 nJ		1.1 – 3.2 µm
Picosecond Ti-sapphire laser	2 ps	30 nJ	78 MHz	730 – 980 nm
Femtosecond Ti-sapphire laser with regenerative amplifier, optical parametric amplifier, and difference frequency mixer	40 fs	5 µJ	100 – 250 kHz	800 nm
	50 fs	160 nJ		1.2 – 2.4 µm
	100 fs	10 nJ		2.6 - 10 µm
	35 fs	30 nJ	78 MHz	800 nm
Femtosecond Ti-sapphire laser with amplifier, dual optical parametric amplifier, and difference frequency mixer	< 35 fs	6 mJ	1 kHz	800 nm
	< 100 fs	> 200 µJ		1.15 - 2.6 µm
	< 100 fs	> 40 µJ		470 nm - 1.15 µm
	15 fs	4 nJ	78 MHz	800 nm

All lasers can be synchronized to the FEL.

In addition, the fs laser systems are suitable for generating broad-band THz pulses, which can be used for probing the dynamics excited with FEL pulses (FEL-pump - broadband THz-probe).

Outline

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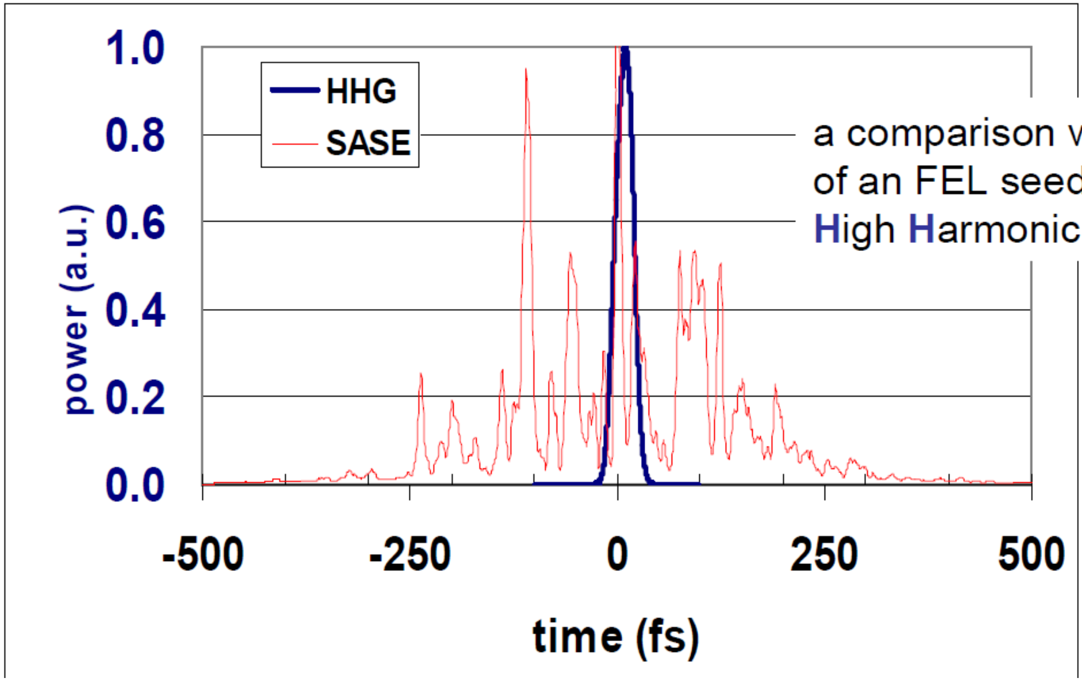
Laser Seeding vs SASE

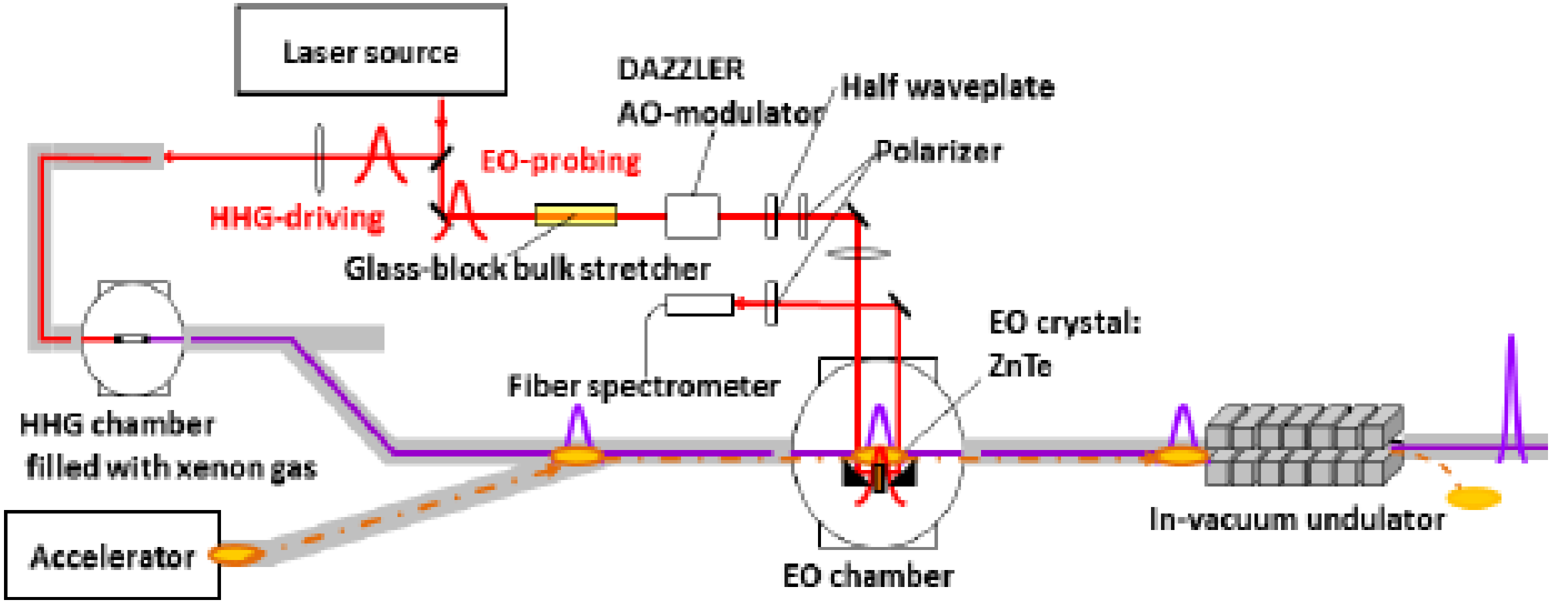


a comparison with the output of an FEL seeded using **H**igh **H**armonic **G**eneration (**HHG**)

- Very **high peak flux** and higher 6D brightness than SASE
- **Temporal and transverse coherence** of the FEL pulse.
- **Control** of the time duration, polarization, wavelength and bandwidth of the FEL pulse.
- Close to **transform-limit pulses** provide excellent resolving power
- **Inherent synchronization** of the FEL pulse to the seed laser.
- Reduction in **undulator length** needed to achieve saturation as compared to starting from noise as in SASE FELs..

Important requirements

- **spatial overlap** between electron bunch and laser pulse → good pointing stability of optical laser
- **stable harmonic parameter** (pulse energy, chirp, frequency …) from the laser
- good **temporal overlap** between electron bunch and laser pulse
- time jitter between the laser and the electron bunch should be much smaller than << σ_t for reliable operation



Tomizawa ***The first demonstration of EOS 3D-BCD monitor to maximize 3d-overlapping for HHG-seeded FEL***

30eV to 0.25keV laser needs for seeding

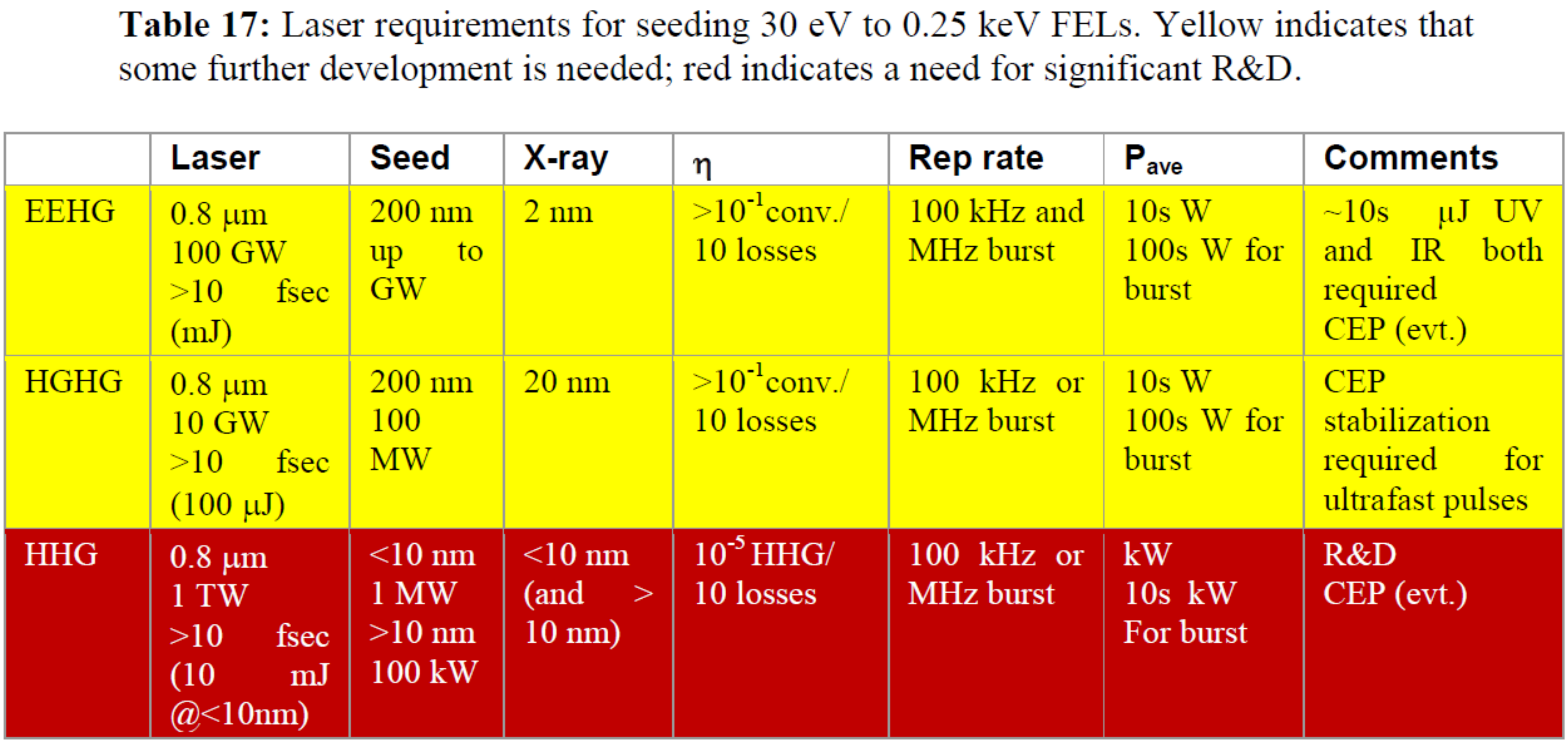


Table 17: Laser requirements for seeding 30 eV to 0.25 keV FELs. Yellow indicates that some further development is needed; red indicates a need for significant R&D.

	Laser	**Seed**	**X-ray**	η	**Rep rate**	P_{ave}	**Comments**
EEHG	0.8 μm 100 GW >10 fsec (mJ)	200 nm up to GW	2 nm	$>10^{-1}$conv./ 10 losses	100 kHz and MHz burst	10s W 100s W for burst	~10s μJ UV and IR both required CEP (evt.)
HGHG	0.8 μm 10 GW >10 fsec (100 μJ)	200 nm 100 MW	20 nm	$>10^{-1}$conv./ 10 losses	100 kHz or MHz burst	10s W 100s W for burst	CEP stabilization required for ultrafast pulses
HHG	0.8 μm 1 TW >10 fsec (10 mJ @<10nm)	<10 nm 1 MW >10 nm 100 kW	<10 nm (and > 10 nm)	10^{-5} HHG/ 10 losses	100 kHz or MHz burst	kW 10s kW For burst	R&D CEP (evt.)

0.25keV to 50 keV laser needs for seeding

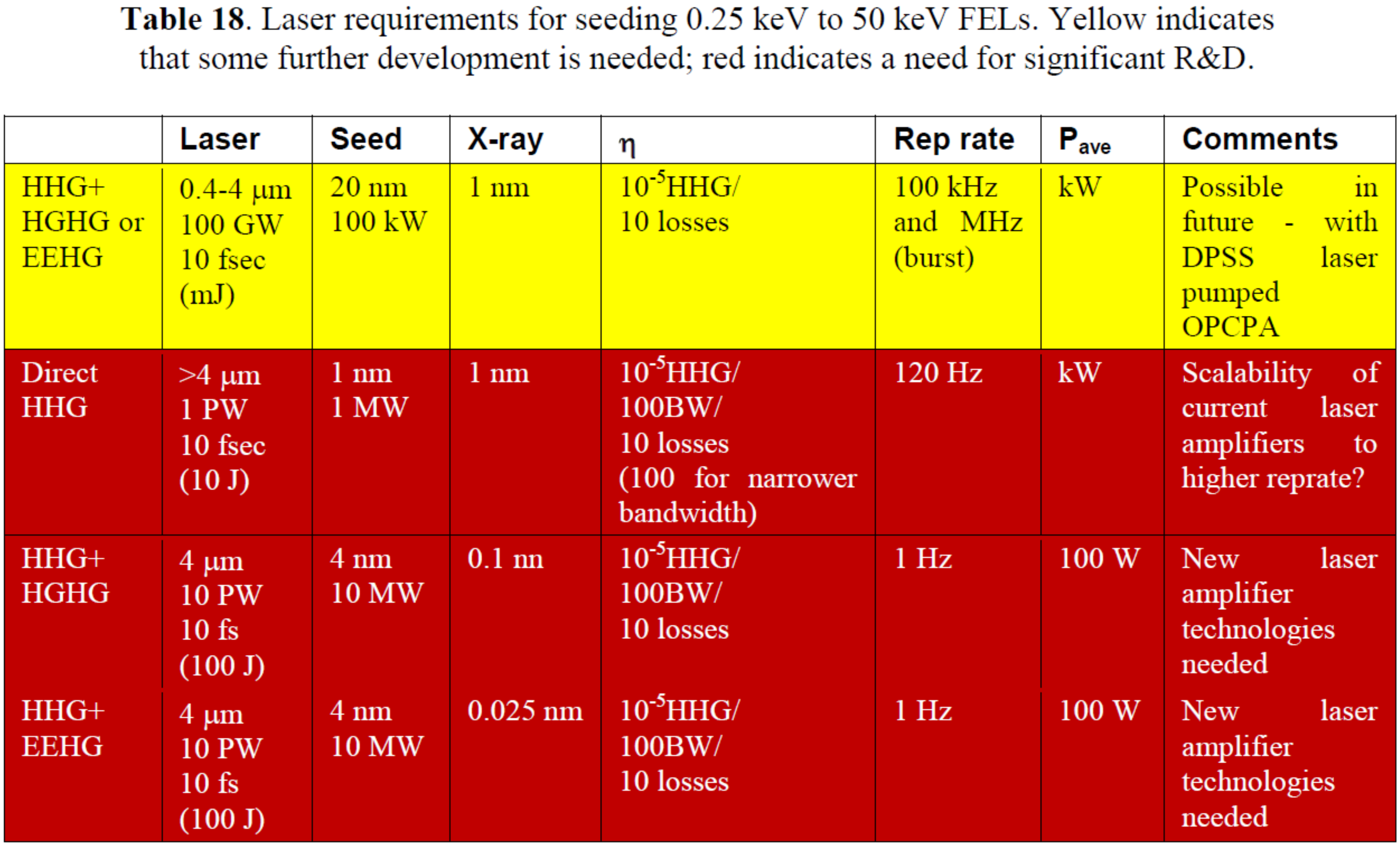
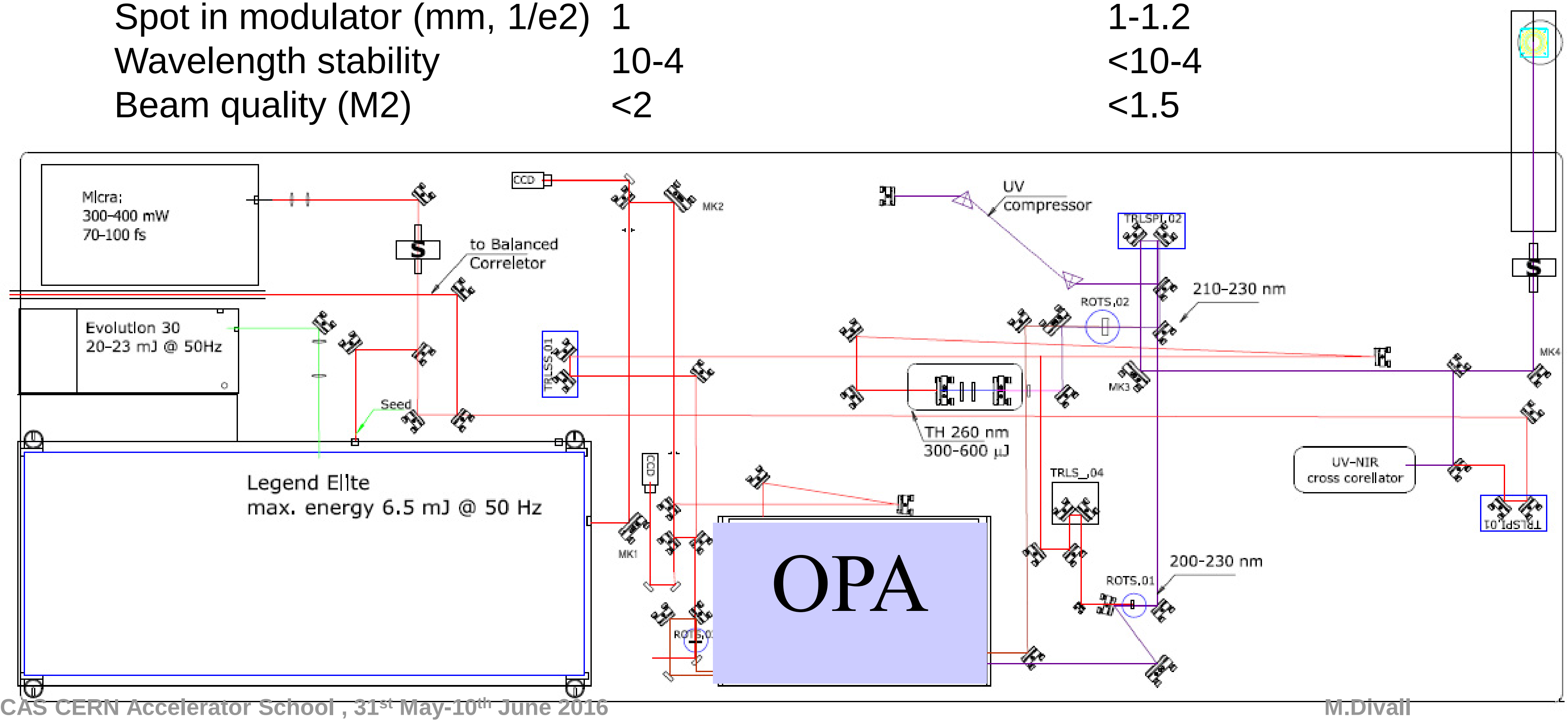


Table 18. Laser requirements for seeding 0.25 keV to 50 keV FELs. Yellow indicates that some further development is needed; red indicates a need for significant R&D.

	Laser	**Seed**	**X-ray**	η	**Rep rate**	**P$_{ave}$**	**Comments**
HHG+ HGHG or EEHG	0.4-4 μm 100 GW 10 fsec (mJ)	20 nm 100 kW	1 nm	10^{-5}HHG/ 10 losses	100 kHz and MHz (burst)	kW	Possible in future - with DPSS laser pumped OPCPA
Direct HHG	>4 μm 1 PW 10 fsec (10 J)	1 nm 1 MW	1 nm	10^{-5}HHG/ 100BW/ 10 losses (100 for narrower bandwidth)	120 Hz	kW	Scalability of current laser amplifiers to higher reprate?
HHG+ HGHG	4 μm 10 PW 10 fs (100 J)	4 nm 10 MW	0.1 nn	10^{-5}HHG/ 100BW/ 10 losses	1 Hz	100 W	New laser amplifier technologies needed
HHG+ EEHG	4 μm 10 PW 10 fs (100 J)	4 nm 10 MW	0.025 nm	10^{-5}HHG/ 100BW/ 10 losses	1 Hz	100 W	New laser amplifier technologies needed

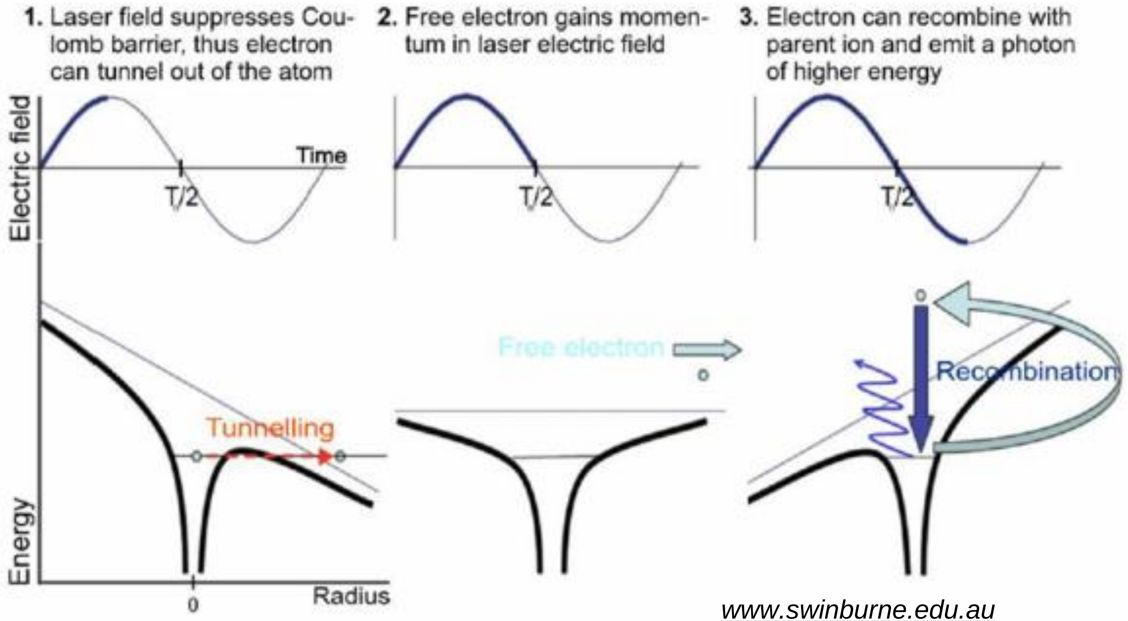
Fermi ELETTRA HGHG

Parameter	Tunable UV	Fixed UV
Tunability range (nm)	210-280 (230-260)	261, 197 (261)
Peak power (MW)	100	>400
Pulse duration (fs)	100 (180)	<150 (150-500)
Pulse Energy Stability RMS 5000 shots	<4%	<2%
Timing jitter (fs RMS)	<50 (100)	<50 (100)
Spot in modulator (mm, 1/e2)	1	1-1.2
Wavelength stability	10-4	<10-4
Beam quality (M2)	<2	<1.5



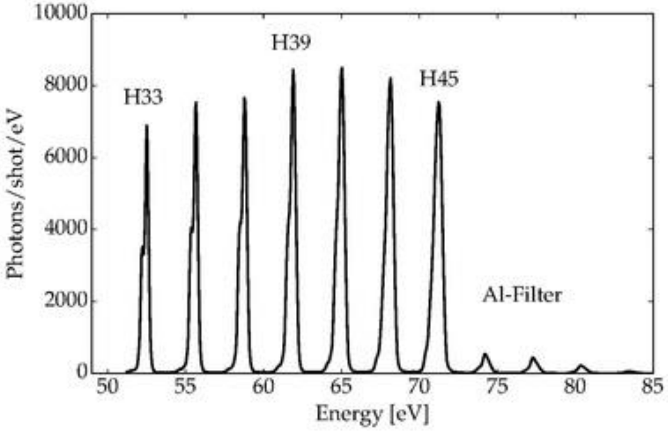
HHG

- Higher-odd harmonics of the driving laser frequency (HHG)
- The HHG radiation forms ‘*combs*’ in frequency and time domains, resulting in *as* pulse
- Structures separated by half driving laser period

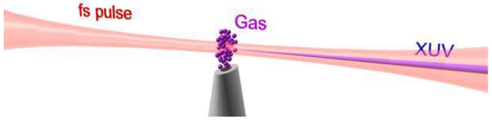


1. Laser field suppresses Coulomb barrier, thus electron can tunnel out of the atom
2. Free electron gains momentum in laser electric field
3. Electron can recombine with parent ion and emit a photon of higher energy

www.swinburne.edu.au



sFLASH 800 nm, 20mJ, 35 fs (off shelf system)



Achievements with HHG

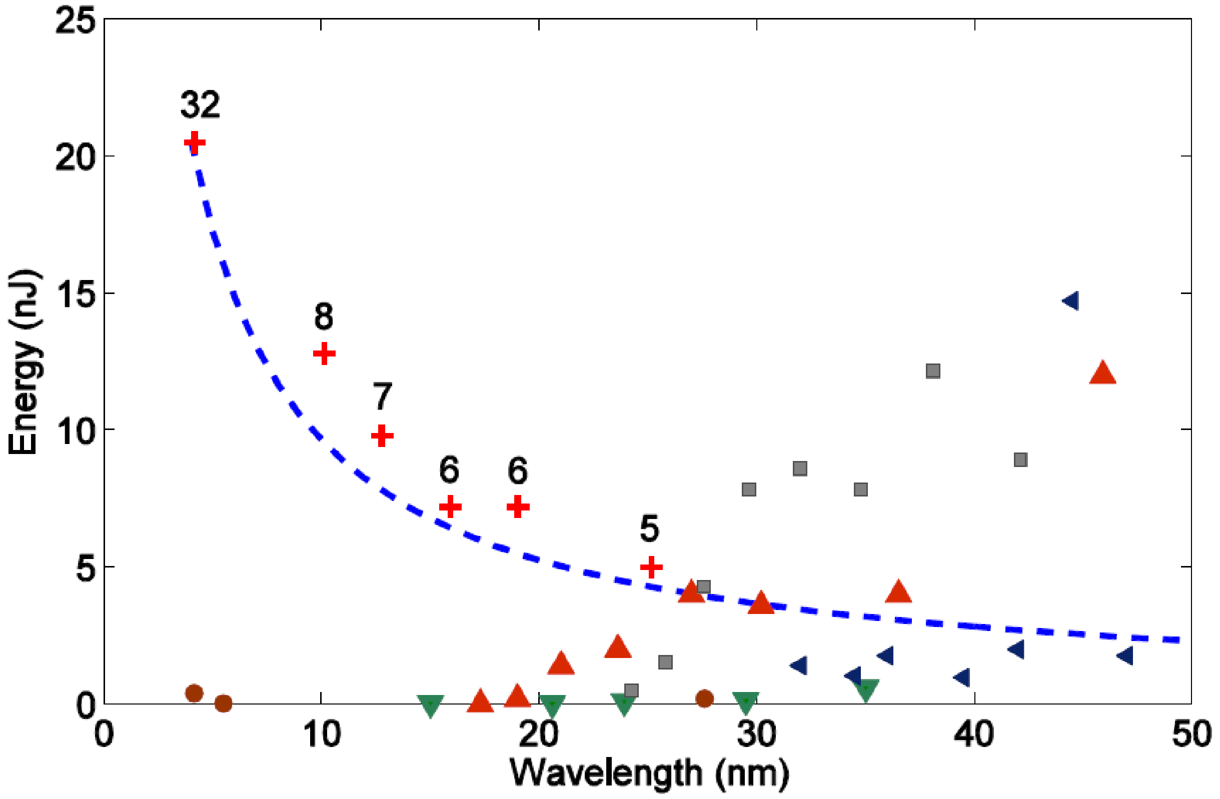


Figure 12: HHG state-of-the art, with the blue dashed line indicating 100 times the shot noise at that wavelength. The number by the crosses indicate the number of QPM jets needed. The triangles refer to HHG in Ar and Xe and the circles to QPM in capillaries. The squares are achieved with two-colour mixing.

Wim Leemans, LBNL : White Paper of the ICFA-ICUIL Joint Task Force – High Power Laser Technology for Accelerators

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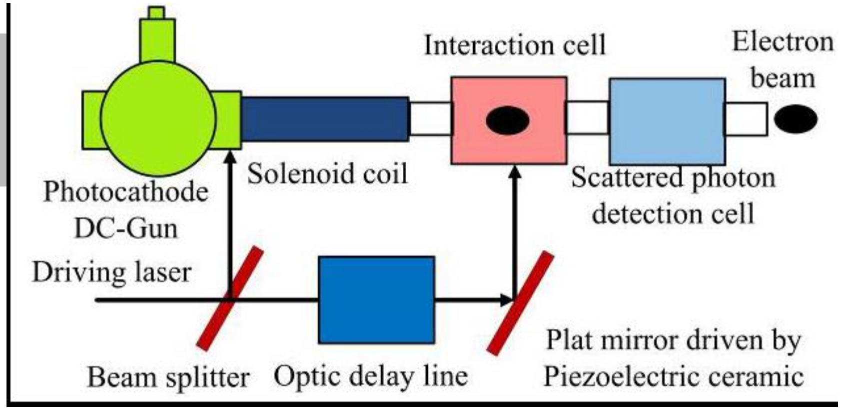
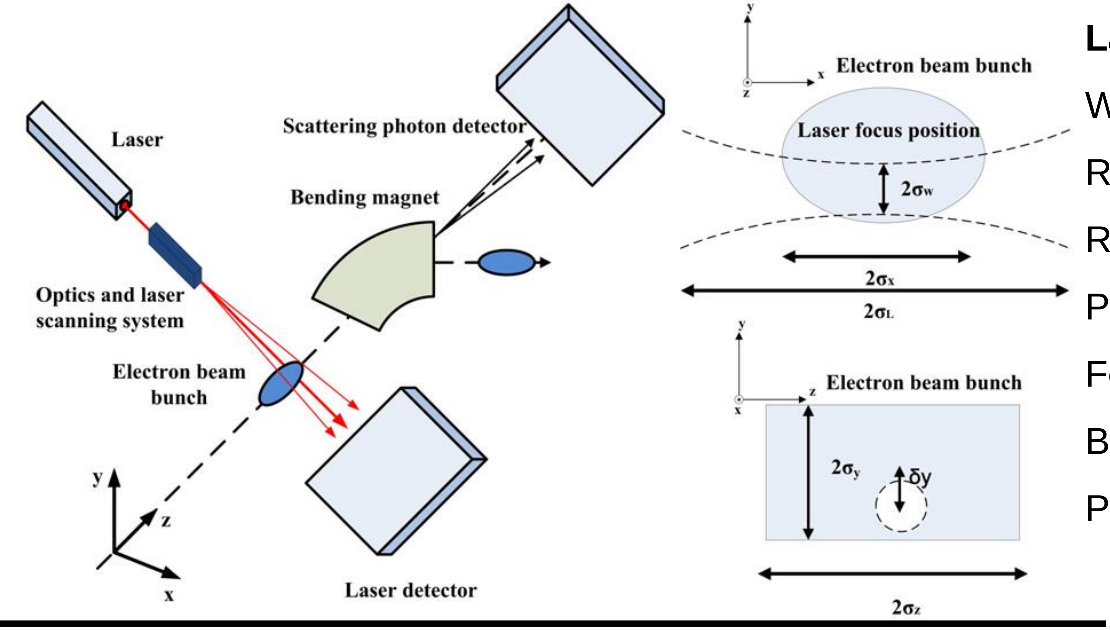
Laser wire scanner at CAEP FEL





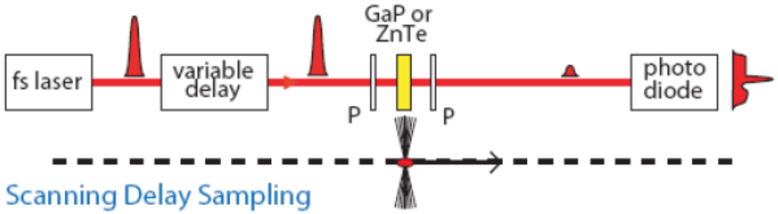
Electron Beam

Beam energy (*Ek*)	250 keV
Beam repetition rate (*f*)	54.167 MHz
RMS bunch length (σz)	15 ps
Charge per bunch (Q)	100 pC
Tr.e Emittance (*εx, εy*)	1.5 mm.mrad
Transverse beam size (σx, σy)	1000 μm

Laser Beam

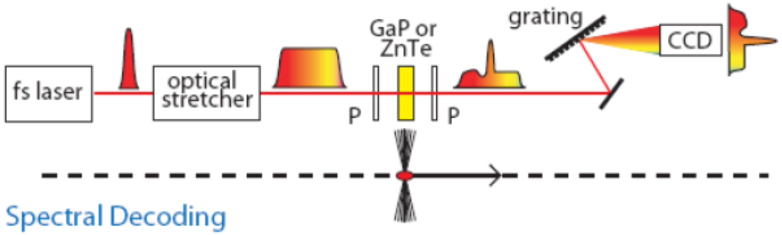
Wavelength (*λL*)	532 nm
RMS waist size (σw)	50 μm
Repetition rate (*f*)	54.167 MHz
Pulsed energy at interaction point (*W*)	55.4 nJ
Focal length (*fL*)	1000mm
Beam quality (*M2*)	1.4
Pulse duration (σL)	5 ps

EOM based bunch length measurements



Scanning Delay Sampling

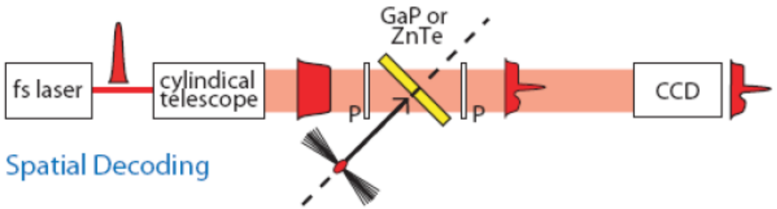
1. Sampling:
   - multi–shot method
   - arbitrary time window possible



Spectral Decoding

2. Chirp laser method, spectral encoding):
   - laser bandwidth limited~ 250fs

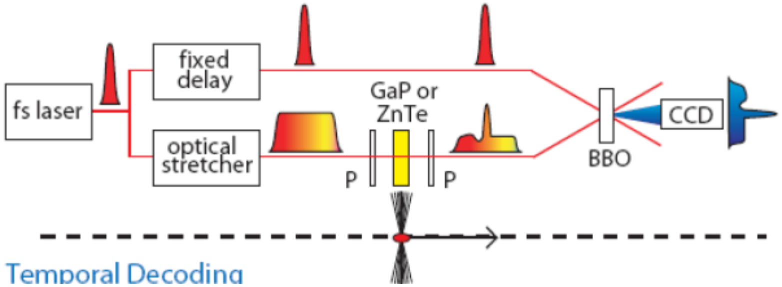
   I. Wilke et.al., PRL Vol.88, No.12



Spatial Decoding

3. Spatial encoding:
   - imaging limitation ~ 30–50 fs

   A. Cavalieri, et. al., PRL. 94, 114801



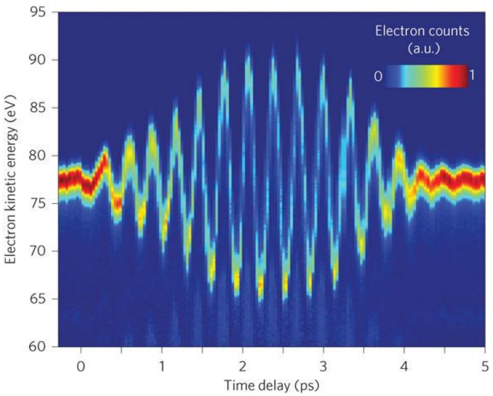
Temporal Decoding

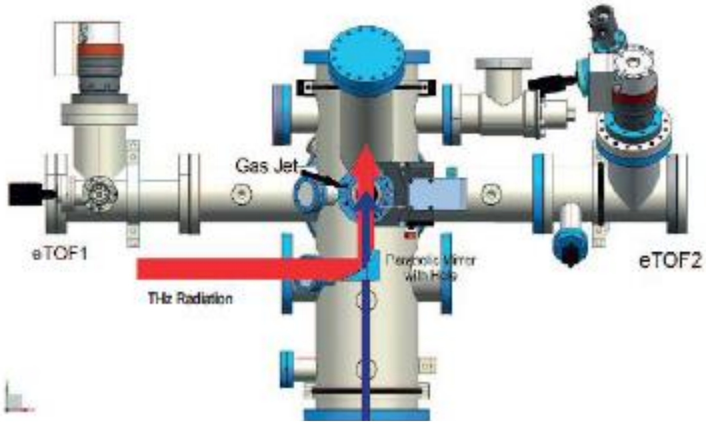
4. Temporal decoding:
   - laser pulse length limited ~ 30fs

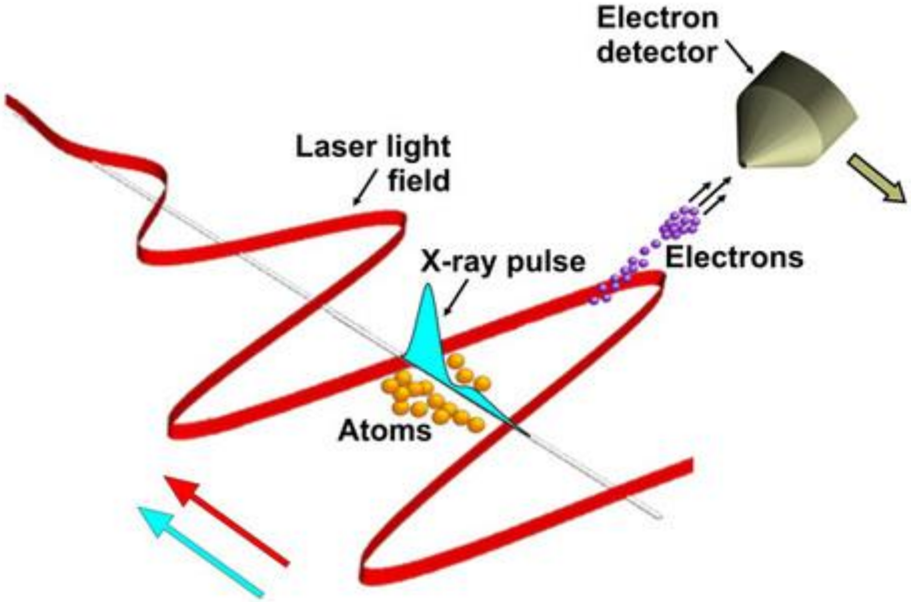
   S.P. Jamison, et.al., PRL Vol.93, No.11

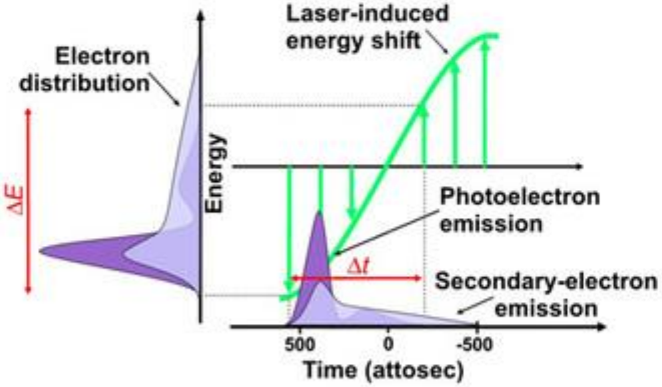
T Lefevre CERN

THz streak camera





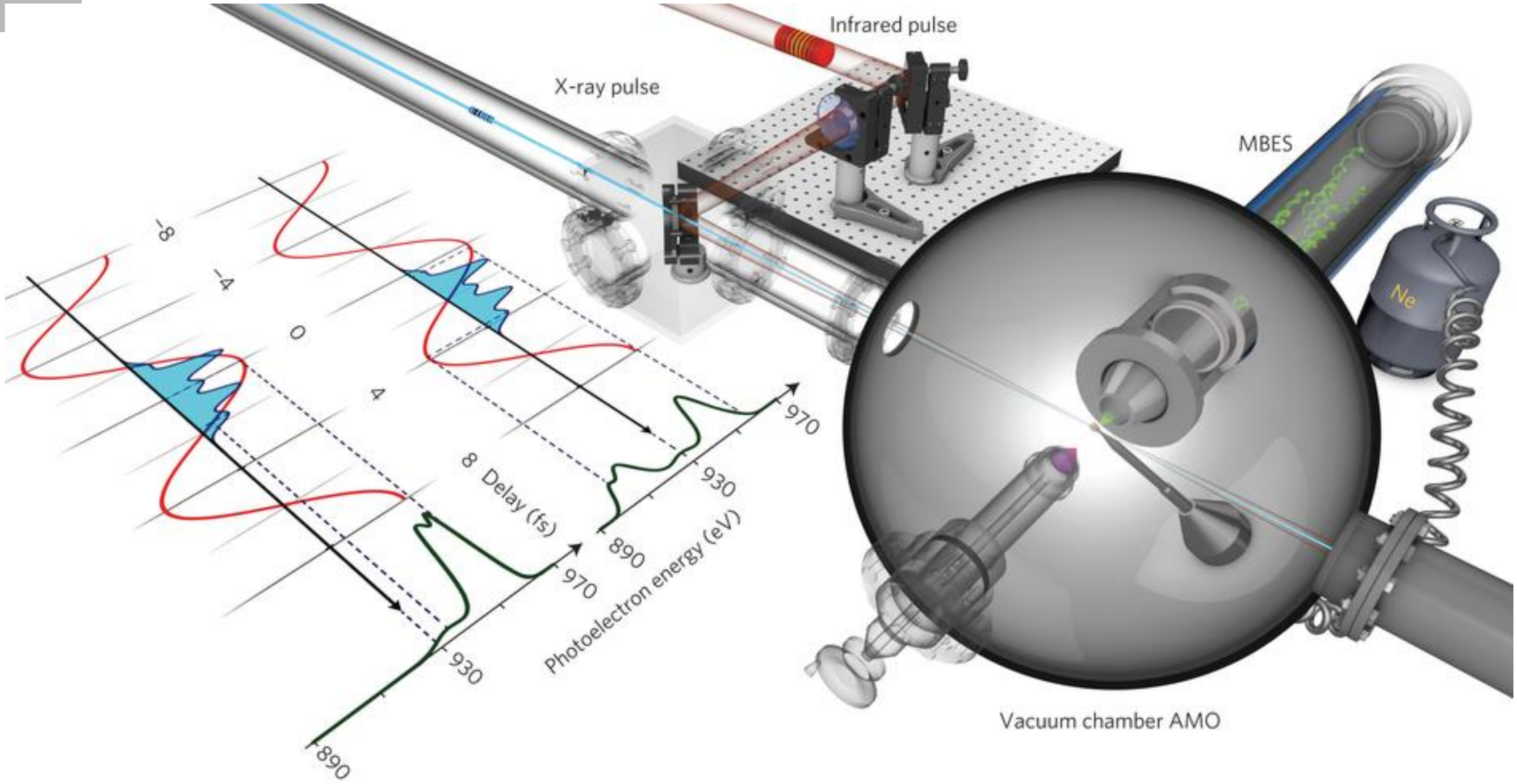




- The linear part of the electric field from the laser has to match the bunchlength
- The field has to be strong enough to deviate the electrons

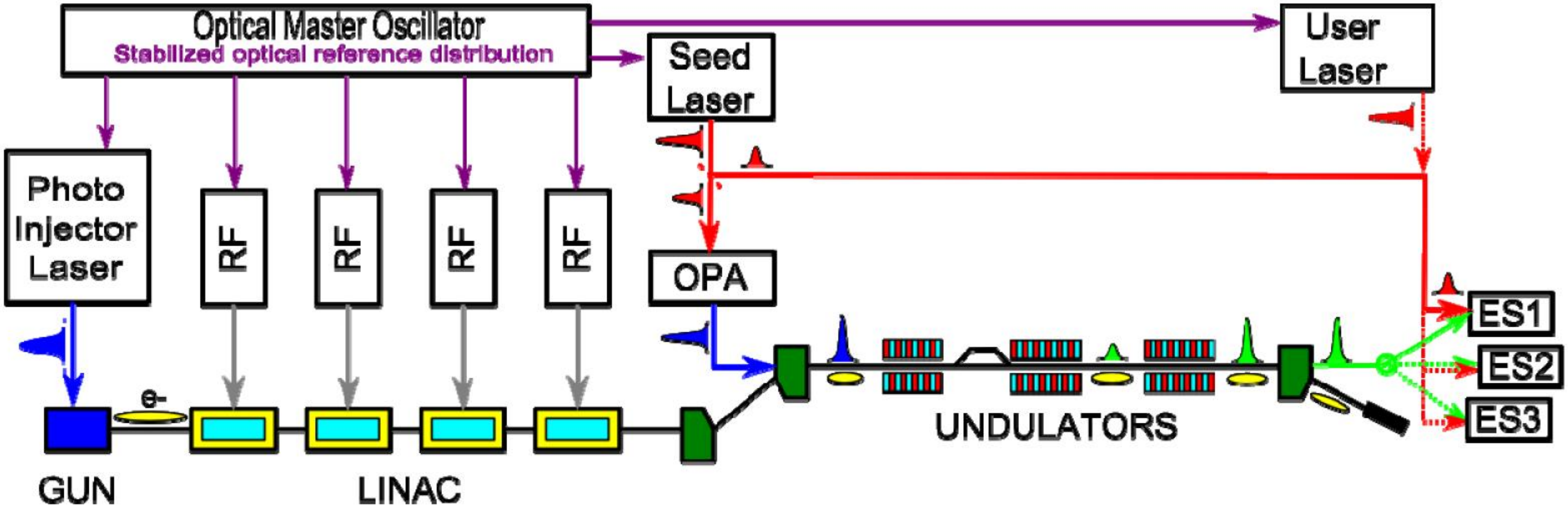
"Single-shot Terahertz field driven X-ray streak-camera", Nature Photonics doi: 10.1038/NPHOTON.2009.160.

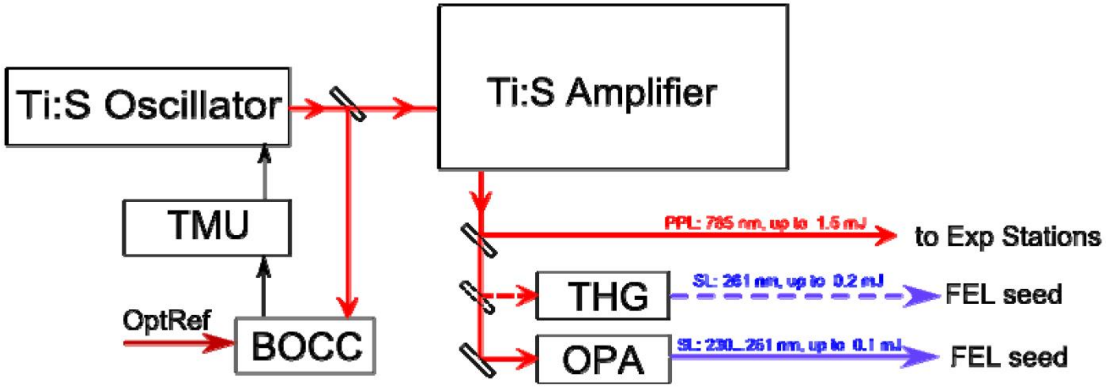
AMO at LCLS



Helml et al. Nature Photonics Volume: 8, Pages:950–957 Year published:(2014) DOI:doi:10.1038/nphoton.2014.278

FERMI all in one





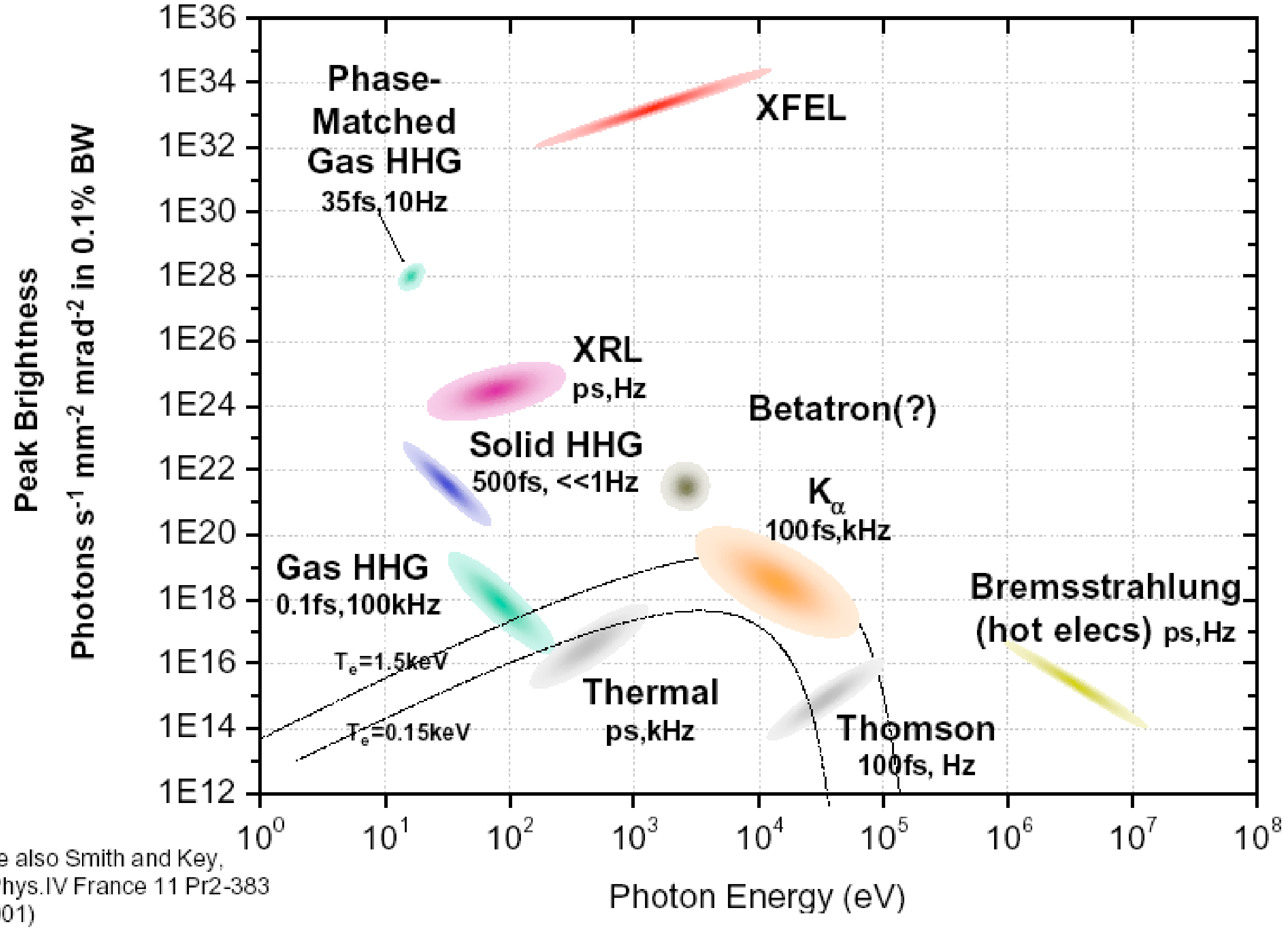
NFFA Workshop Dec 2014 Miltcho Danailov

Outline

- Laser vs FEL
- **Lasers used in FEL's**
- **Requirements/parameters/examples**
  - Photo-injector/gun lasers
  - Laser heater
  - Experimental lasers
  - Seeding laser
  - Diagnostics lasers

➢ **The future of lasers in FEL's**

Performance



See also Smith and Key, J.Phys.IV France 11 Pr2-383 (2001)

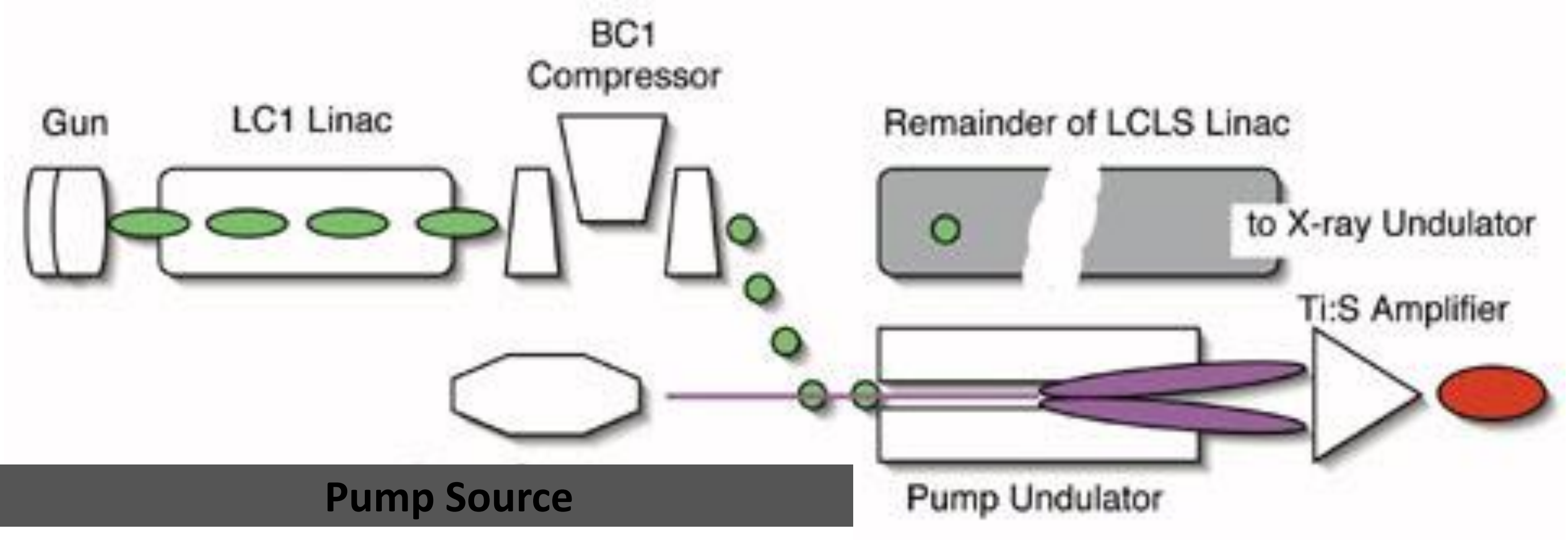
Future challenges for the laser:

Higher repetition rates (enabled by RF)

Eventually J's of energy to drive laser plasma accelerators

FEL’s at laser facilities ☺

- http://pbpl.physics.ucla.edu/Research/Theory/High_Power_FEL/Laser_Pumping/



Pump Source				
	Flashlamp	**Diode**	**Laser**	**FEL**
Avg. Energy	Very high	High	Low	High
Peak Energy	Medium	Low	High	Very High
Heat Load	High	Low	Low	Very Low
Wavelength	VIS	IR - NIR	IR-UV	IR - UV

Thank you for your attention

Are you a-wake? What do you see?