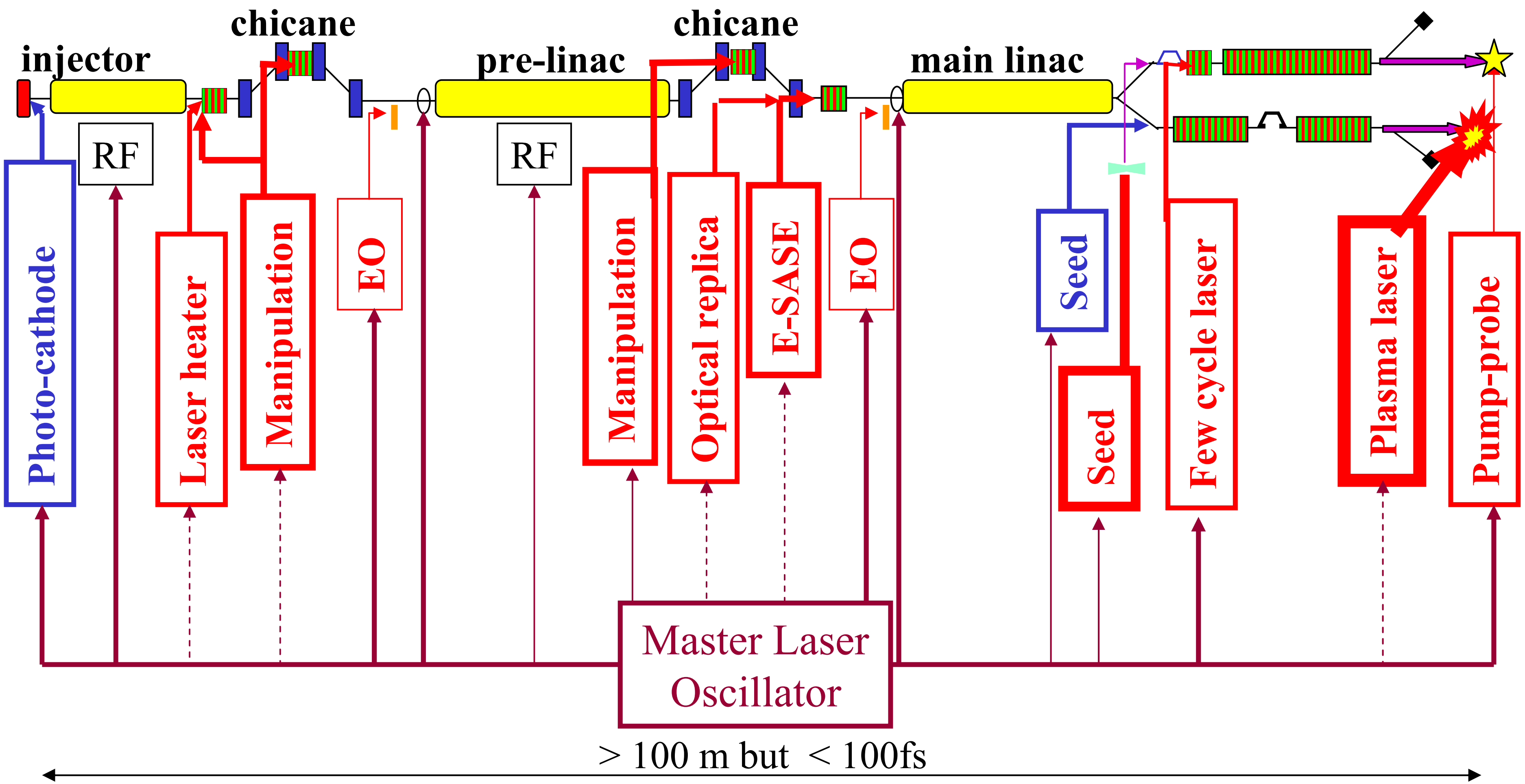
Laser and accelerators

Holger Schlarb
DESY, Hamburg

- Photoinjector lasers
- Laser heater
- ESASE /Attosecond generation
- HHG
- Synchronization

Lasers for FELs

Generic layout of single pass FELs



Parameters for classification

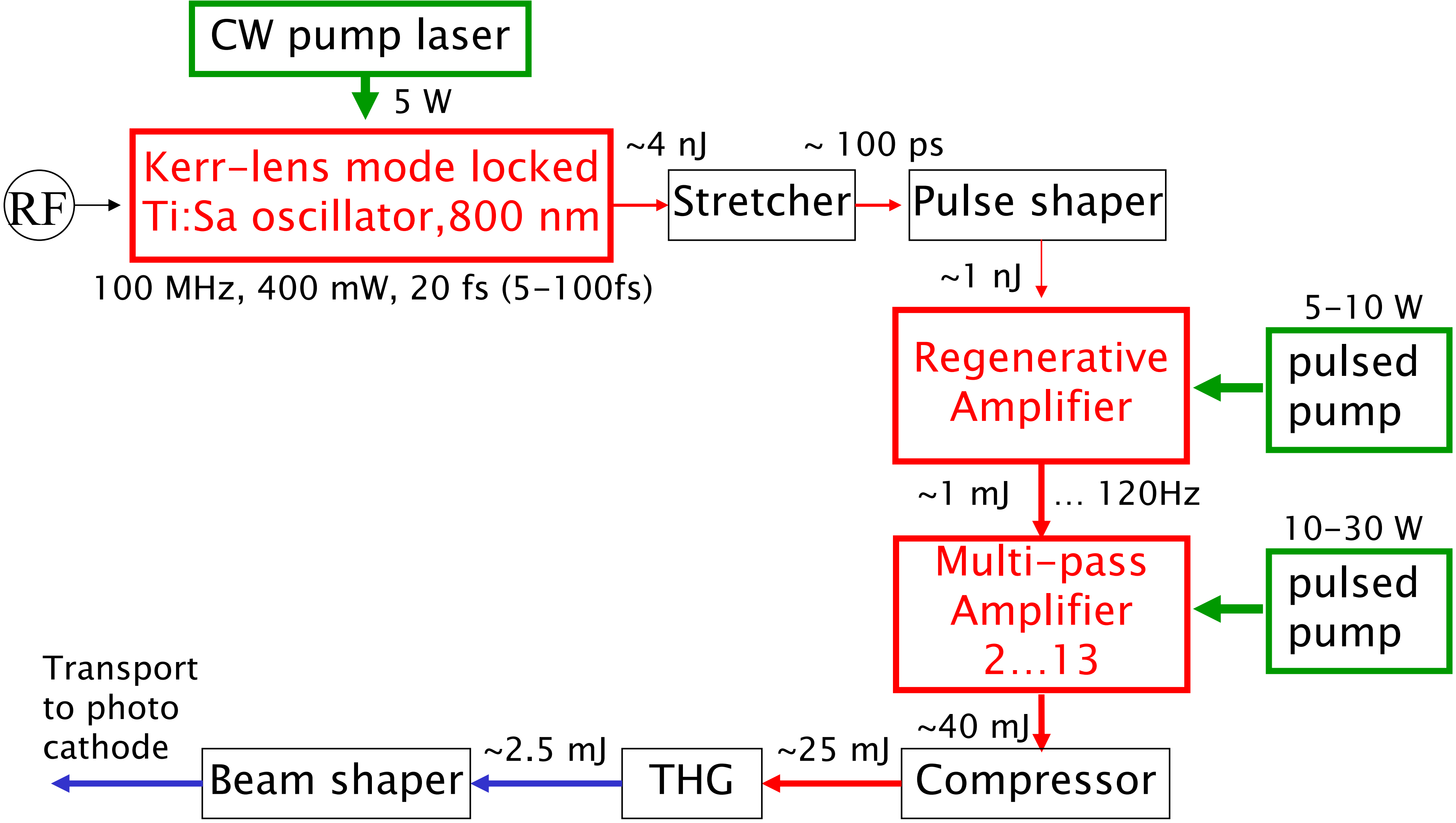
• wavelength λ	2 µm …. 266nm (HHG 30 nm)
• bunch repetition	1 Hz … 1 kHz (continuous) 10 kHz … 9 MHz (burst pulse)
• pulse duration	5 fs … 30 ps
• pulse energy	1 nJ … 40 mJ (30J)
• pulse shaping	yes or no?
• beam shaping	yes or no?
• synchronization	10 ps … < 1fs
• stability	single point of failure? dedicated experiment!

Photo-injector laser
- photo cathode -

Type	Metal cathode	Semi-conductor
Example	Cu	Cs_2Te
QE (UV)	10^{-4} …10^{-5}	0.5% … 10%
	Drops dramatically towards longer wavelength	
$\varepsilon^N_{Thermal}$ (σ_x=0.5mm)	~ 0.6 µm (ok) (120MV/m)	~ 0.6–0.7 µm (ok) (40MV/m)
E_{laser} UV @1nC	~ 150 µJ	0.8 µJ

D.H Dowell et al., NIM A 507 (2003) p. 327–330
V. Miltchev et al., Proc. of the 27th FEL conf., p. 560–563
J.H. Han et al., Proc PAC05, p. 856–858

Photo-injector laser
- low repetition rate high energy -



Adapted from: B. White (SLAC)

Photo-injector laser
- beam shaper, transport, launch -

- aspheric Galilei type shaper
- variable telescope (r=0.6-1.5mm)
- relay imaging to cathode (20m)
- diagnostics + FB control

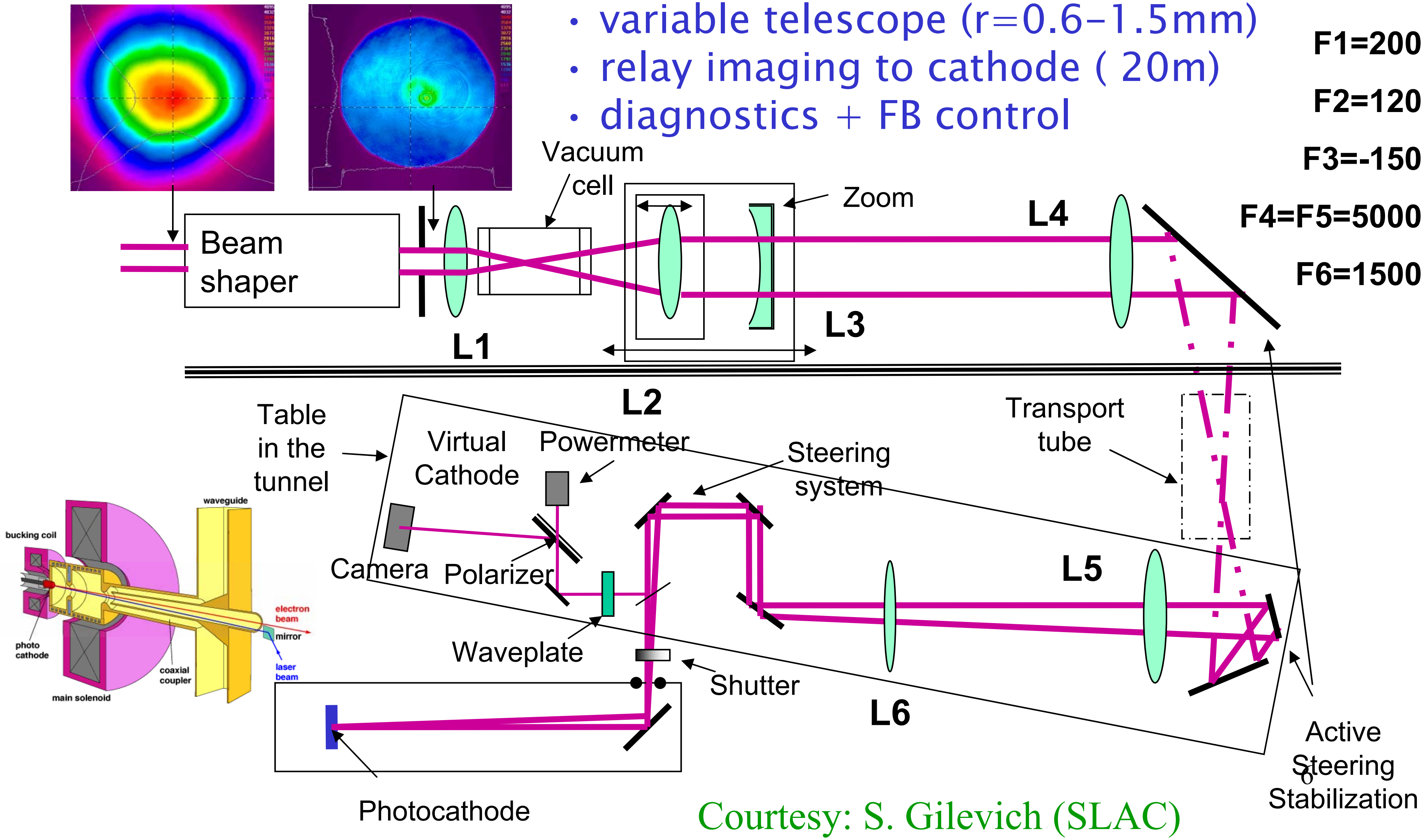
F1=200

F2=120

F3=-150

F4=F5=5000

F6=1500



Courtesy: S. Gilevich (SLAC)

Photo-injector laser
- beam shaper, transport, launch -

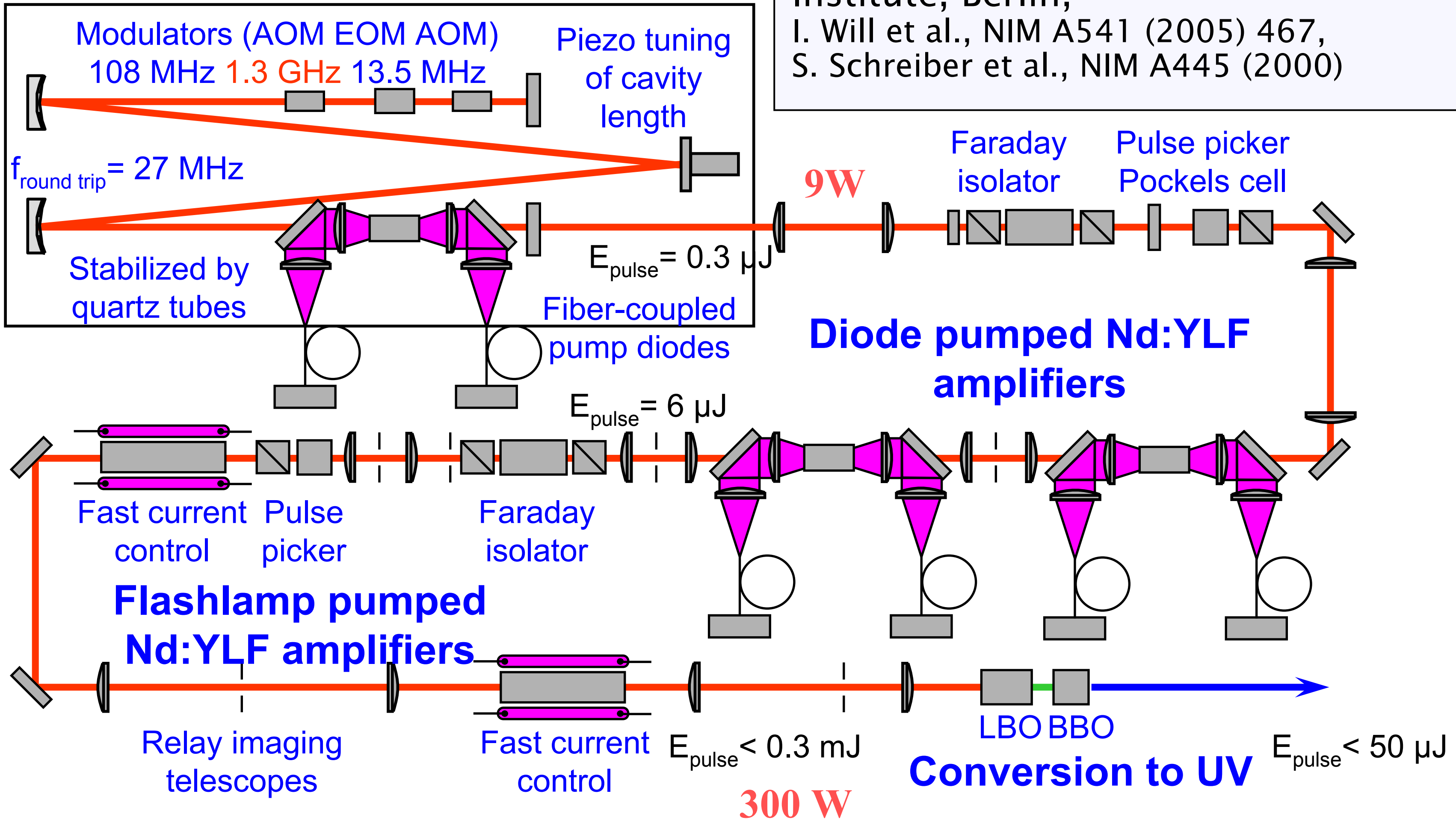
	Component		Surf.	Losses per surface	Transmission
1	Adjustment of the shaper input	2 lenses	4	1%	0.961
2	Transport Tube windows	2 windows	4	2%	0.922
3	Imaging system	6 lenses	12	1%	0.886
4	Launch system Mirrors upstairs	8 mirrors	8	2%	0.851
5	Launch system Mirrors, vault	4 mirrors	4	2%	0.922
6	Vacuum mirror	1	1	10%	0.900
7	Vacuum Window	1	2	2%	0.960
8	2 Beamsplitters	2	4	4% and 1%	0.903
9	Waveplate	1	2		0.950
10	Energy Control				0.800
11	Beamshaper	3 lenses	6	2%	0.886
12	Aperture			10%	0.900
	Total				29.2 %

Courtesy: S. Gilevich (SLAC)

Photo-injector laser
- high repetition rate (burst) -

In cooperation of DESY and Max-Born-Institute, Berlin,
I. Will et al., NIM A541 (2005) 467,
S. Schreiber et al., NIM A445 (2000)

Diode-pumped Nd:YLF Oscillator



Modulators (AOM EOM AOM)
108 MHz 1.3 GHz 13.5 MHz

Piezo tuning of cavity length

$f_{\text{round trip}}$ = 27 MHz

Stabilized by quartz tubes

Fiber-coupled pump diodes

E_{pulse} = 0.3 μJ

9W

Faraday isolator

Pulse picker Pockels cell

Diode pumped Nd:YLF amplifiers

E_{pulse} = 6 μJ

Fast current control

Pulse picker

Faraday isolator

Flashlamp pumped Nd:YLF amplifiers

Relay imaging telescopes

Fast current control

E_{pulse} < 0.3 mJ

300 W

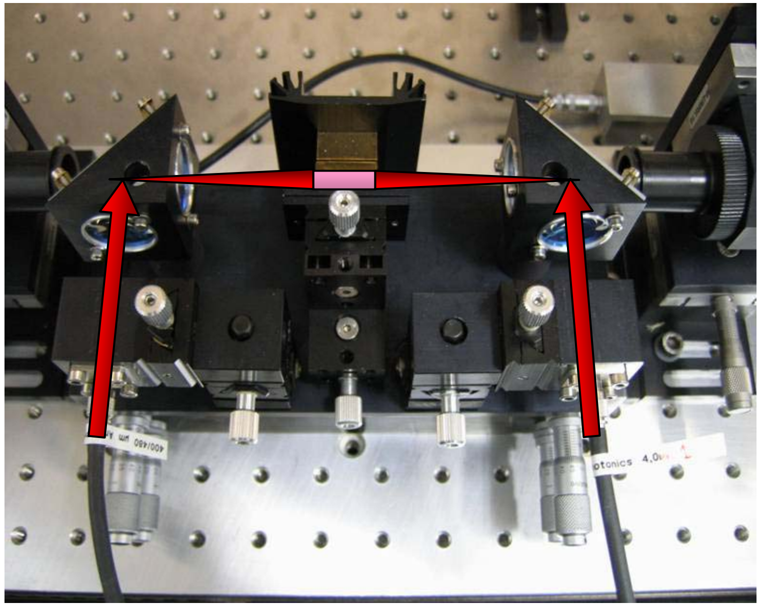
LBO BBO

Conversion to UV

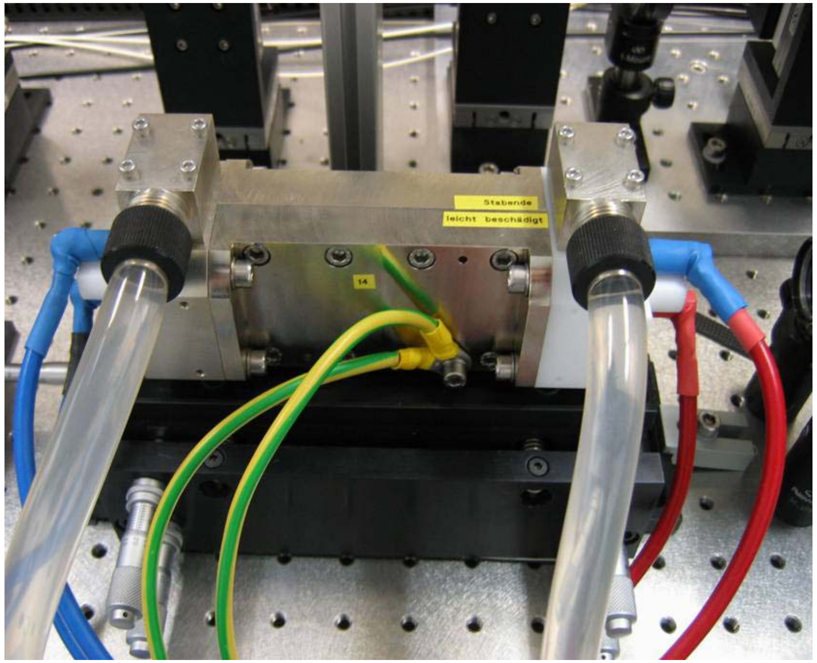
E_{pulse} < 50 μJ

Chain of Linear Amplifiers

- 2 diode pumped and 2 flashlamp pumped single pass amplifiers
- Fully diode pumped version is being tested now at PITZ, DESY Zeuthen



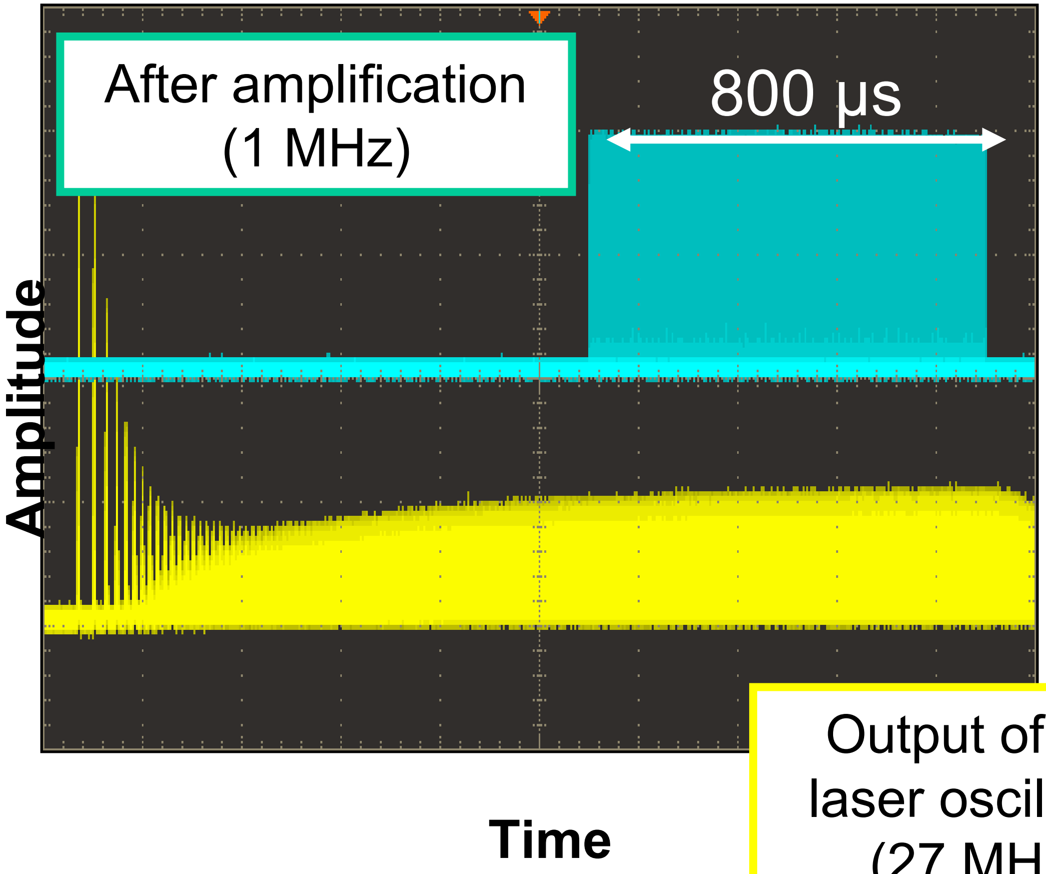
- Laser diodes:
  → 32 W pulsed, 805 nm
  → end pumped through fibers
  → energy from 0.3 μJ to 6 μJ/pulse



- Flashlamps:
  → cheap, powerful (pulsed, 50 kW electrical/head)
  → current control with IGPT switches
  → allows flat pulse trains
  → energy up to 300 μJ (1 MHz), 140 μJ (3 MHz)

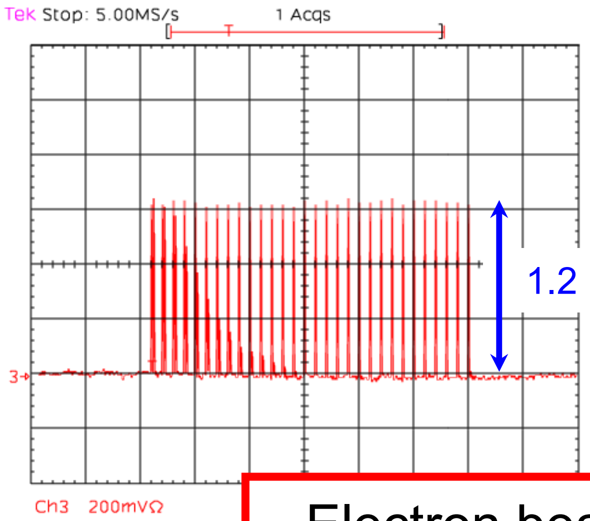
Burst-pulse trains

- Amplified laser pulse train – now up to 3 MHz possible, 9 MHz in preparation



After amplification (1 MHz)

Output of the laser oscillator (27 MHz)



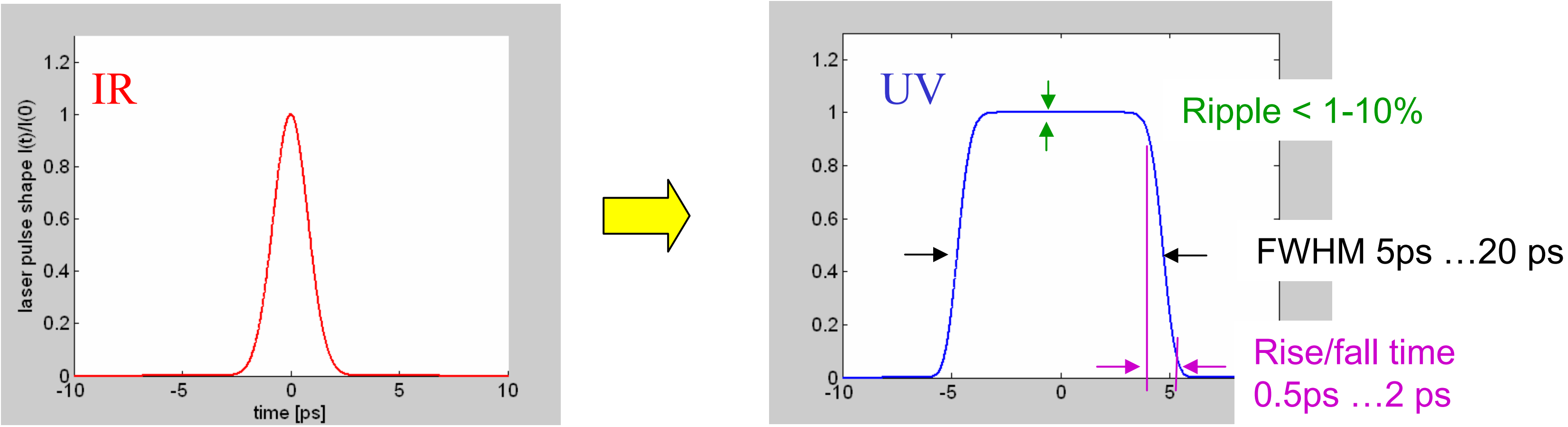
Electron beam pulse train (30 bunches, 1 MHz)

Temporal pulse shaping

Motivation:

space-charge force distributed evenly across the bunch

⇒ decrease projected emittance



Ripple < 1-10%

FWHM 5ps …20 ps

Rise/fall time 0.5ps …2 ps

Spectral filtering:

$$\left.\begin{aligned} E_{in}(t) &= \sqrt{I(t)}\cdot e^{-i\omega_0 t+i\phi(t)} \\ E(t) &= [H * E_{in}](t) \end{aligned}\right\} \quad E(\omega) = \boxed{T(\omega)}\sqrt{I(\omega)}\cdot e^{-i[\boxed{\psi(\omega)}+i\phi(\omega)]}$$

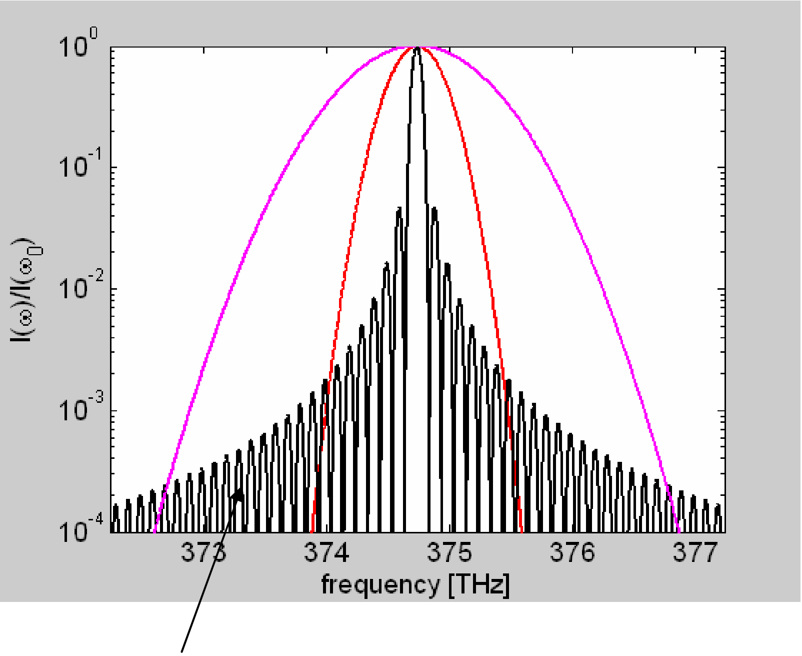
Amplitude modulation

Phase modulation

Temporal pulse shaping
- bandwidth issue … -

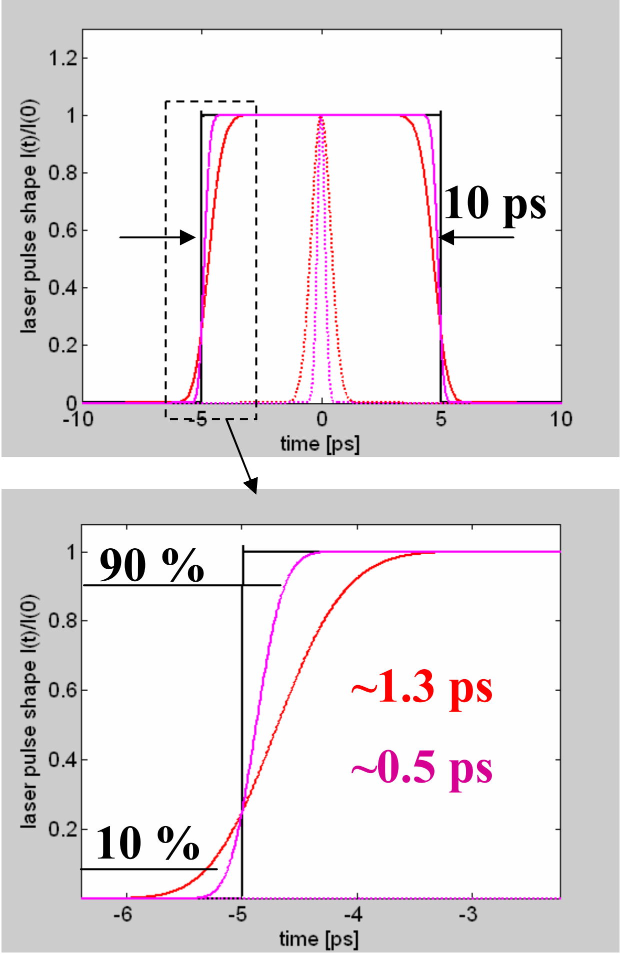
$\Delta\lambda_{FWHM} = 2\ \text{nm} \Rightarrow \Delta\tau = 940\ \text{fs}$

$\Delta\lambda_{FWHM} = 5\ \text{nm} \Rightarrow \Delta\tau = 370\ \text{fs}$



Filter function: sinc

After frequency filter

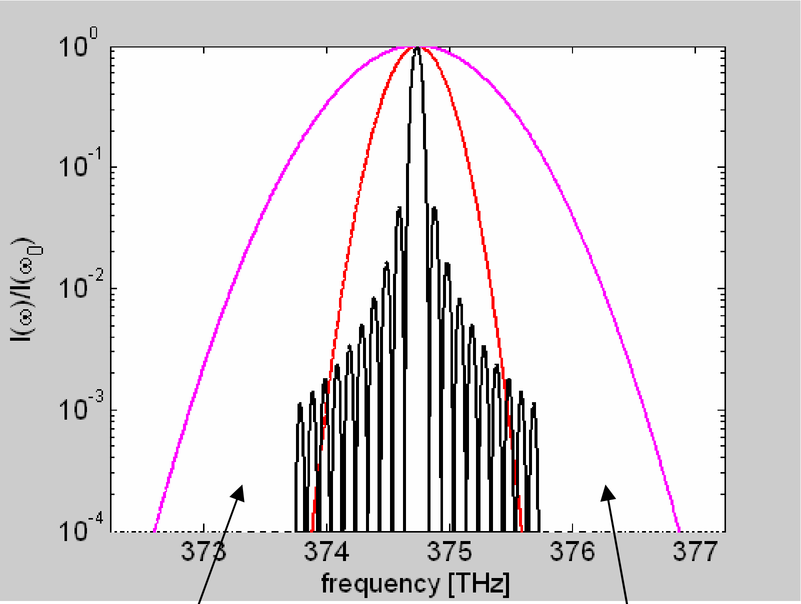


See also C. Limborg & P. Bolton LCLS-TN-04-16

Temporal pulse shaping
- bandwidth issue … -

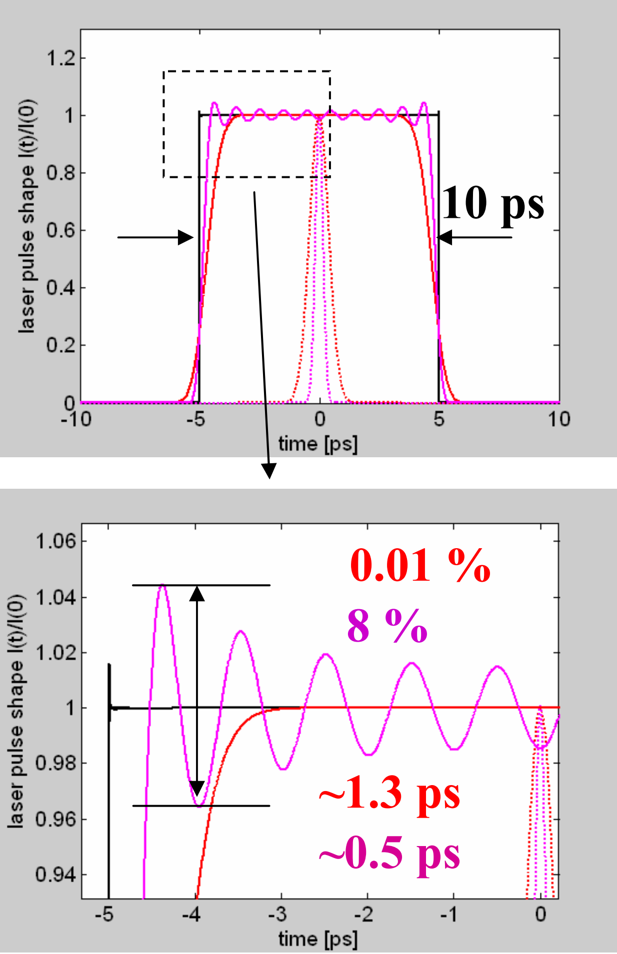
$\Delta\lambda_{FWHM} = 2\text{ nm} \Rightarrow \Delta\tau = 940\text{ fs}$

$\Delta\lambda_{FWHM} = 5\text{ nm} \Rightarrow \Delta\tau = 370\text{ fs}$



Imperfection of filter
e.g. truncation of sinc

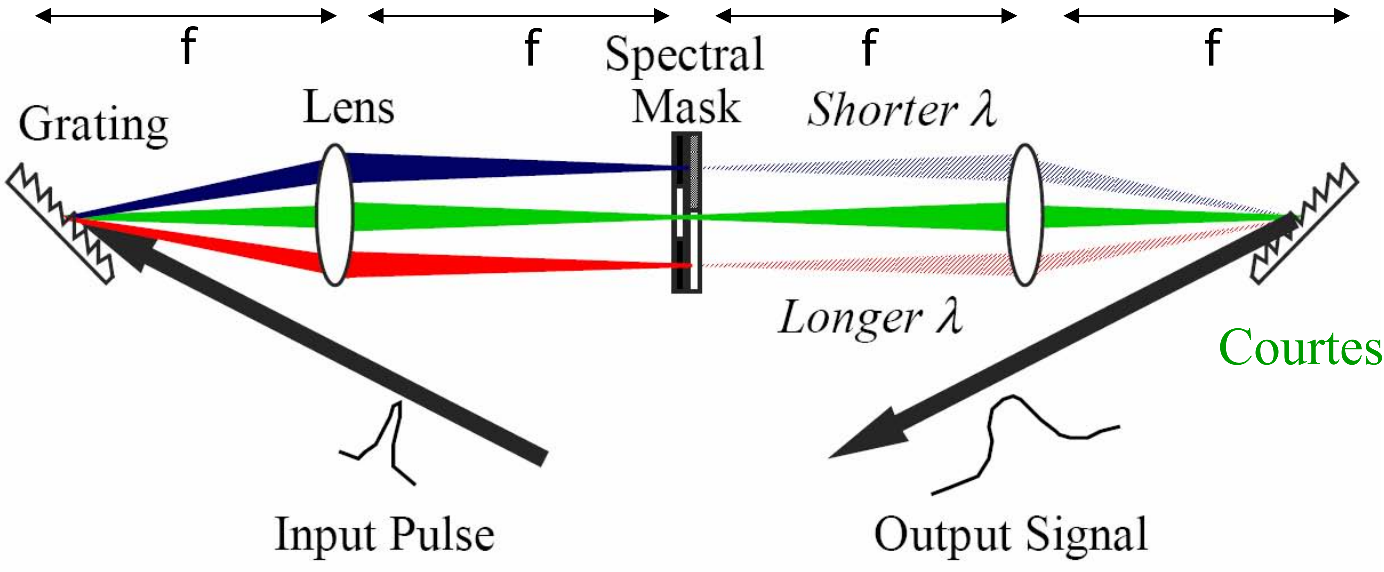
After frequency filter



Bandwidth critical impact on frequency Tripler! P. Bolton LCLS-TN-05-29

Temporal pulse shaping
- 4f LCP-SLM shaper -

- Grating maps frequency spectrum into spatial coordinates
- 4f configuration: dispersion-free shaper + beam spot is focused on mask
- spectral mask (Liquid crystal programmable spatial light modulator w/o wave plates)



Courtesy: X.J.Wang

Used also to compensate fiber transport (see A. Azima MOPCH011)

Optical express, Vol 14 No.3, 1314, 6 Feb. 2006
A.M. Weiner, Rev. Scientific Instr., Vol. 71 No.5, 2000, p.1929
S. Cialdi, I. Boscolo, NIM A 526 (2004) 239-248)

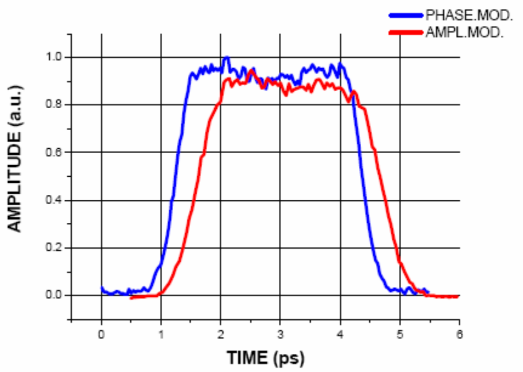
Acousto-optic programmable dispersive filter (AOPDS)

- collinear acousto-optical modulation in birefringent crystal
- input polarization propagates along the fast axis
- traveling chirped acoustic wave is launched by transducer
- acoustic wave diffracts light at z(ω) to slow axis ($k_2=k_1+K$, $\omega_2=\omega_1+\Omega$)

⇒ Group delay depends upon diffraction position

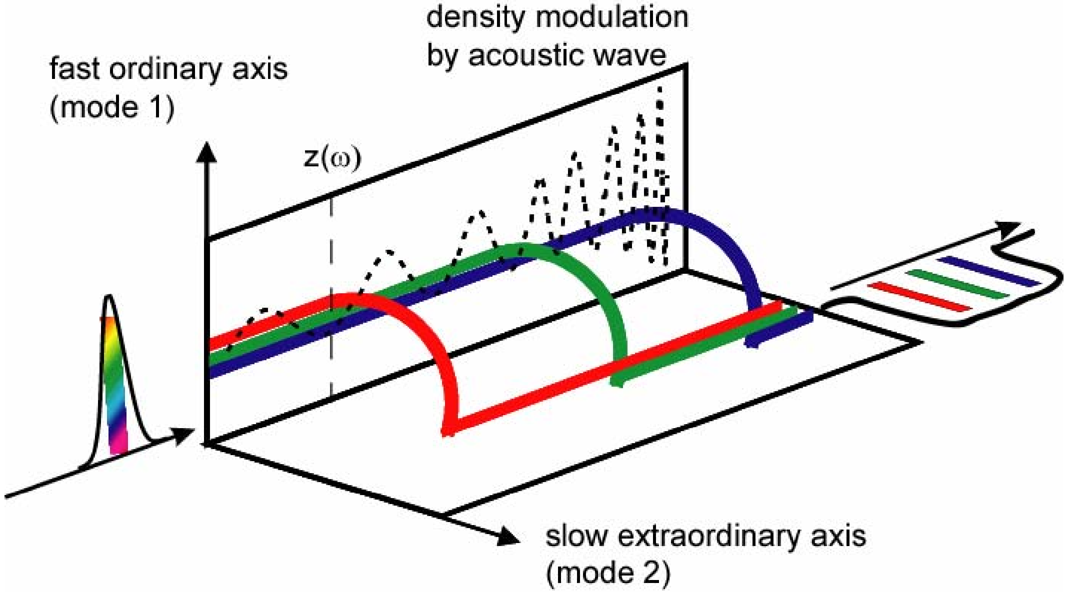
⇒ Amplitude modulation depends on acoustic wave intensity

- output wave selected with polarizer



First results with purely amplitude (red)
And purely phase (modulation)

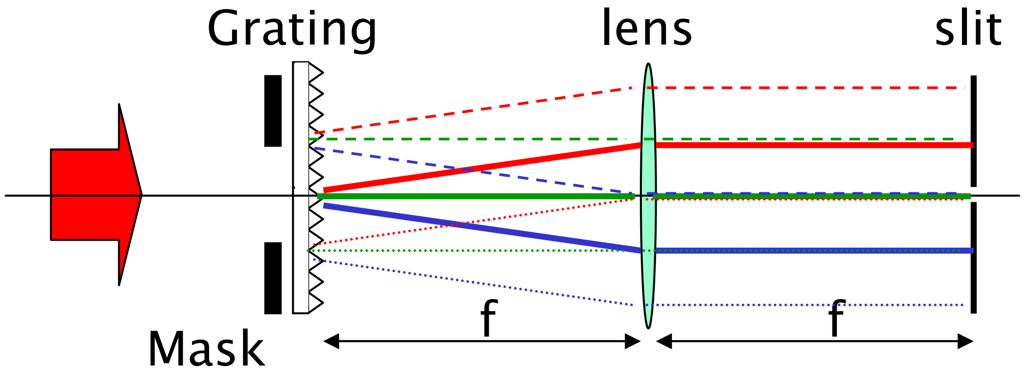
Courtesy: M.B. Danailov (Fermi)



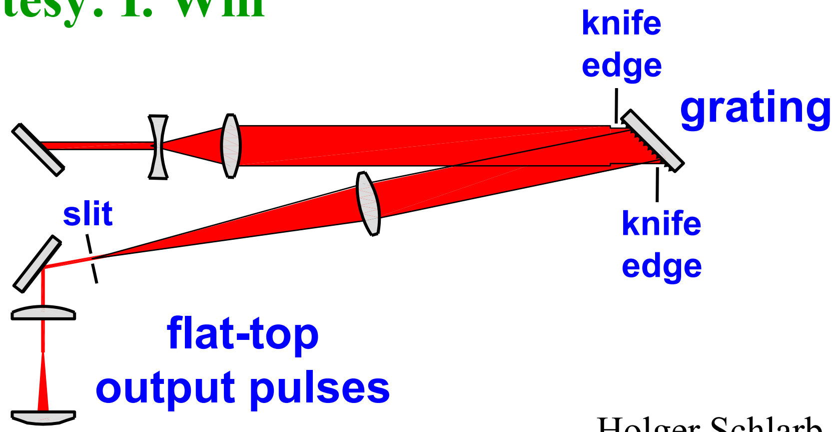
P. Tournois, Opt. Comm. **140**, 245 (1997)
F. Verluise et al., J. Opt. Soc. Am. B **17**, 138 (2000)

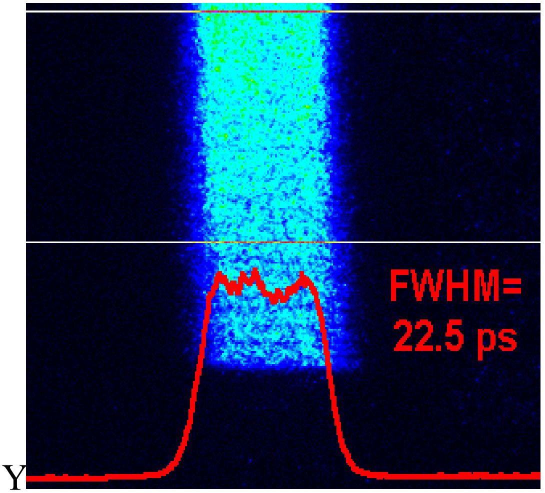
Temporal pulse shaping
- direct space to time (DST) -

- Laser beam passes spatial mask
- Diffraction grating disperses the spatial pattern
- Lens performance a spatial Fourier transform



Courtesy: I. Will





Edges
5-6ps
R&D
towards
2ps

A.M. Weiner, Optical and Quantum Electronics 32: 473-487, 2000

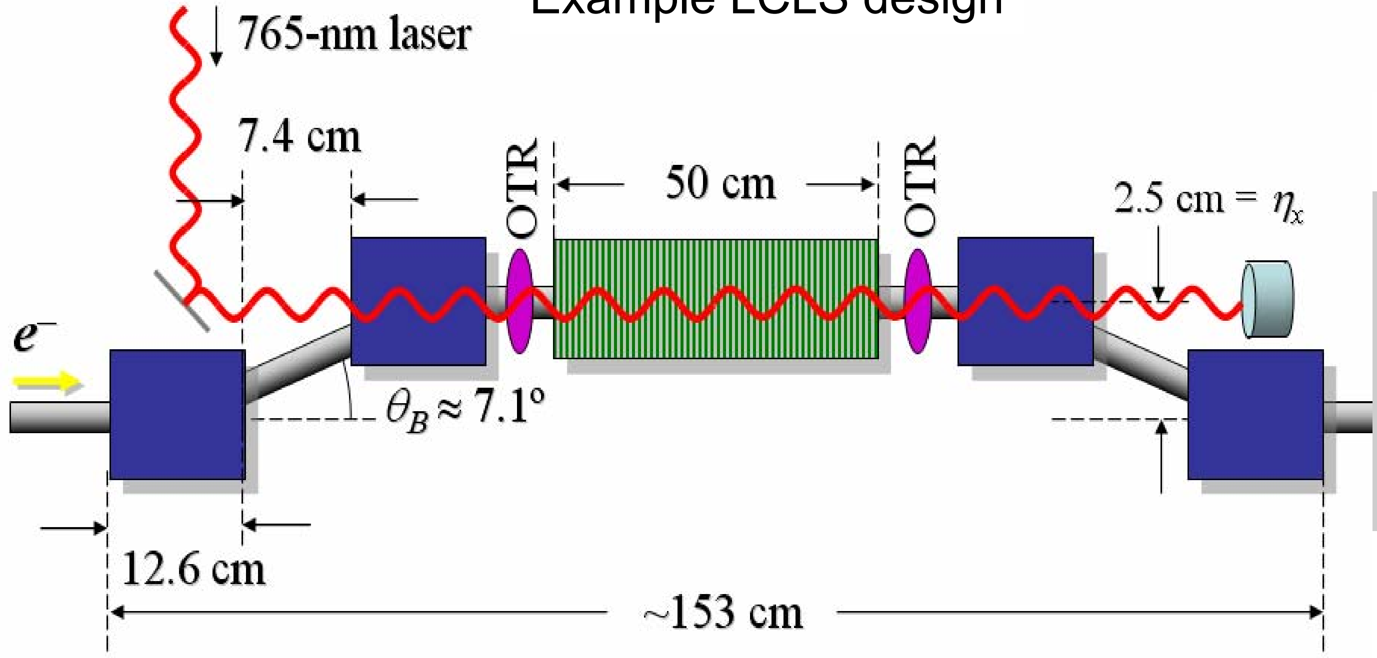
Laser heater

Motivation:

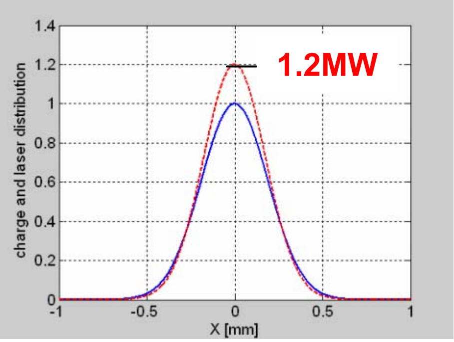
- Collective effect: SP/CSR drive micro-bunch instabilities
- Residual energy-spread ~ 1–3keV ⇒ No Landau damping
- Energy-spread can be larger for FELs ($\sigma_E/E < \rho \sim 5e{-}4$)

⇒ increase $\varepsilon_E \rightarrow$10–50 keV (compression factor C!)

Example LCLS design



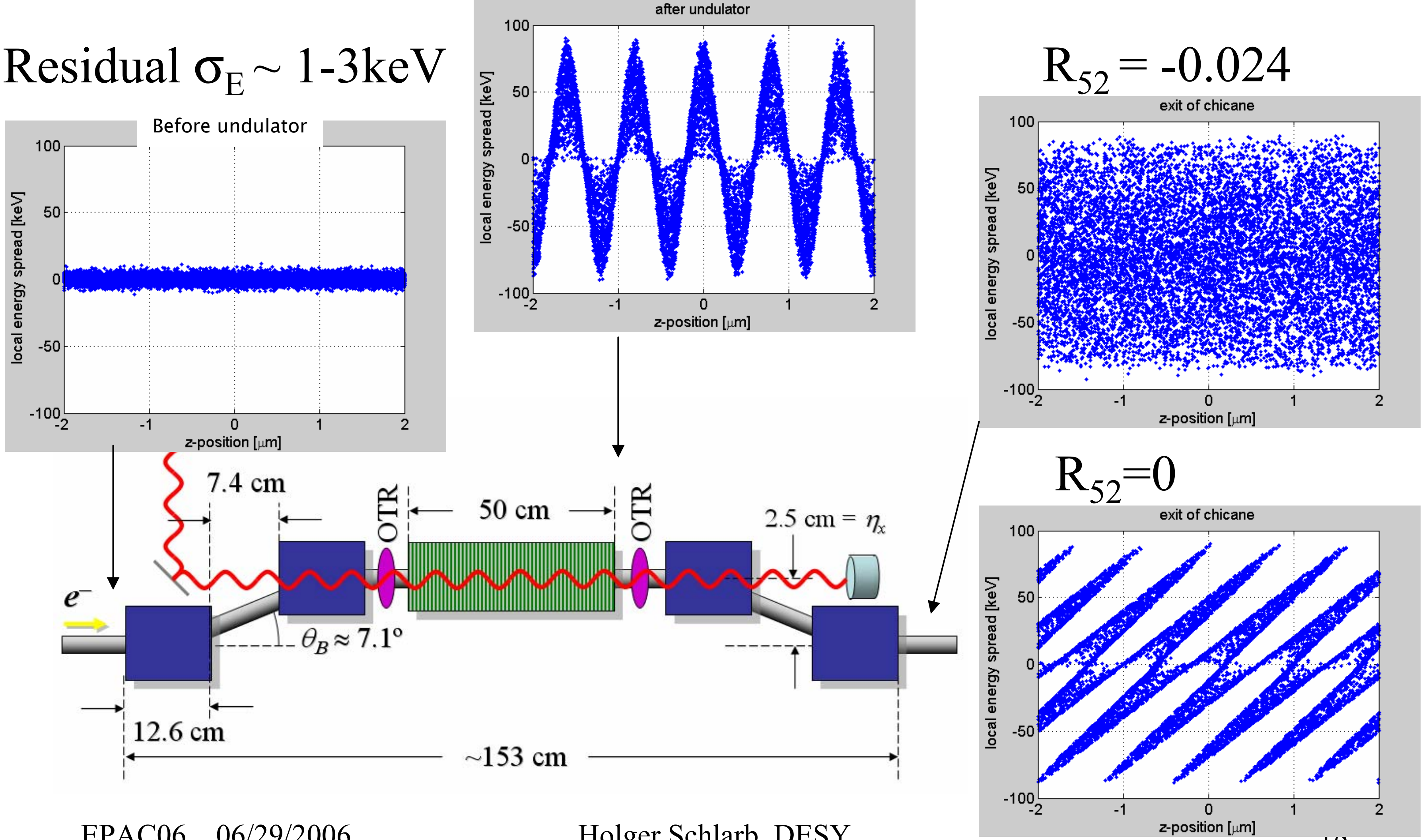
Laser spot size approx. equal to electron spot size



⇒ Energy modulation amplitude is radial position of the electron

Z. Huang et al., Phys. Rev. STAB 7, 074401 (2004)
J. Wu et al., SLAC-PUB-10430

Laser heater



heating $\sigma_L \sim 40$keV

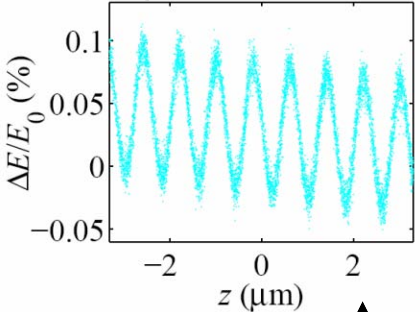
Residual $\sigma_E \sim 1$-3keV

$R_{52} = -0.024$

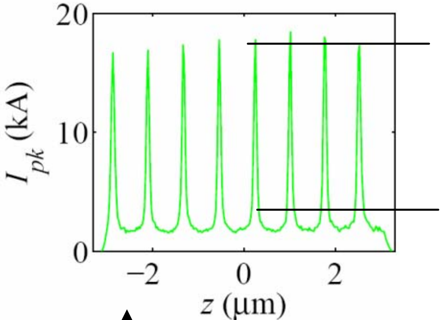
$R_{52}=0$

Current enhanced SASE
- ESASE -

Energy modulation



Peak current modulation



I > 15 kA for ESASE

I = 3.4 kA

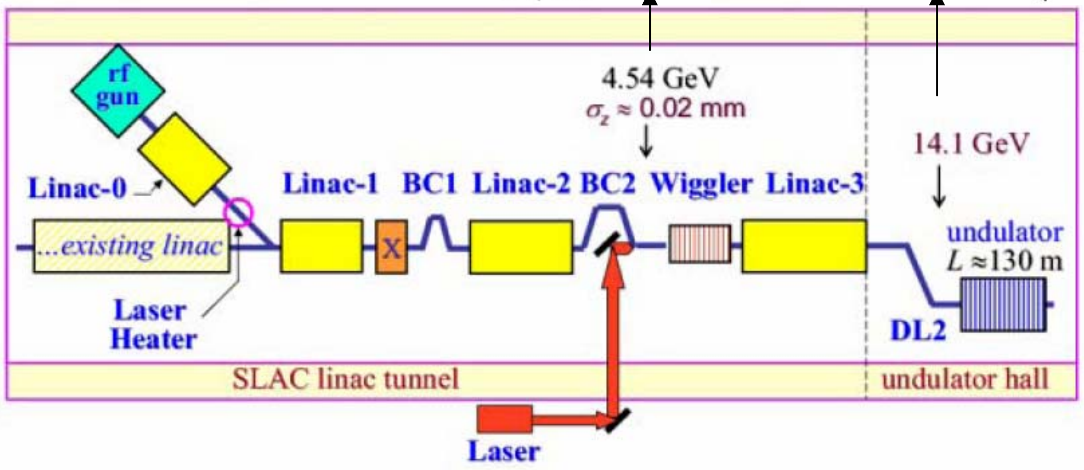
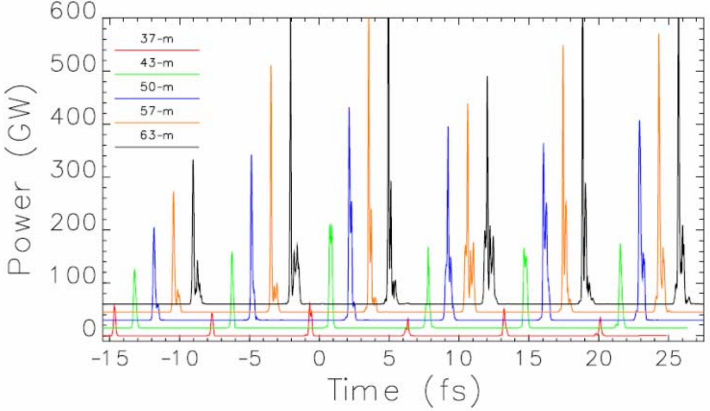


Figure 1: A schematic of ESASE as applied to the LCLS.

Xray spikes (~300as)

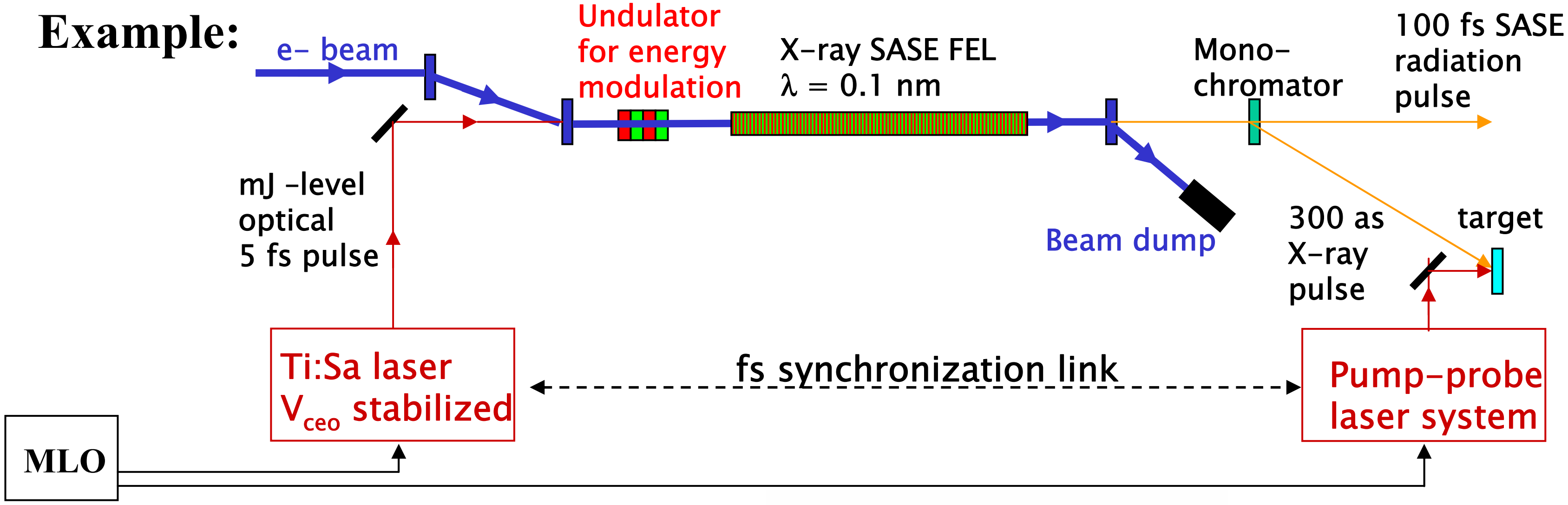


significantly reduces gain length of SASE

A.A. Zholents, Proc. 27th FEL conf., 582-585

Attosecond pulse generation

Example:



e- beam

Undulator for energy modulation

X-ray SASE FEL $\lambda = 0.1$ nm

Mono-chromator

100 fs SASE radiation pulse

mJ -level optical 5 fs pulse

Beam dump

300 as X-ray pulse

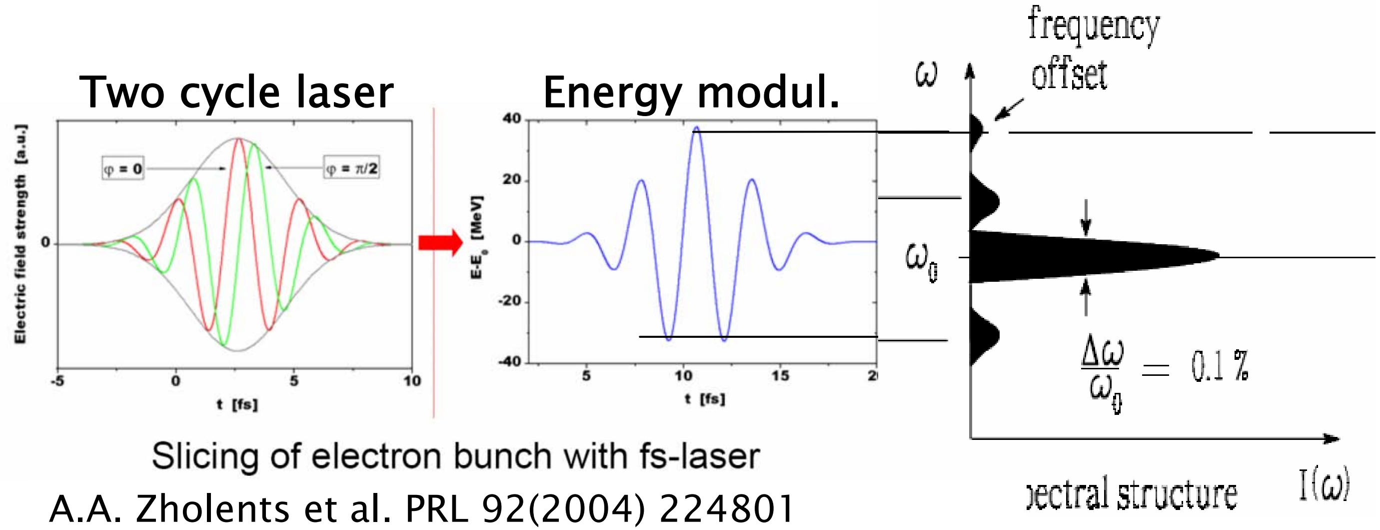
target

Ti:Sa laser V_{ceo} stabilized

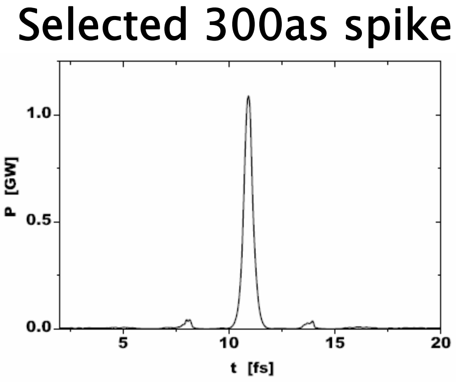
fs synchronization link

Pump-probe laser system

MLO



Slicing of electron bunch with fs-laser

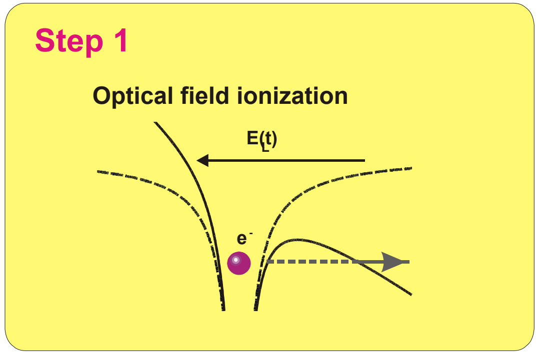


A.A. Zholents et al. PRL 92(2004) 224801
Saldin et al., Opt. Comm., 237 (2004) 153
Saldin et al., Opt. Comm., 239 (2004) 161
A.A. Zholents et al. Phys. Rev. STAB 8 (2005) 050704
Saldin et al. Phys. Rev. STAB (2006)= 050702

Higher Harmonic Generation

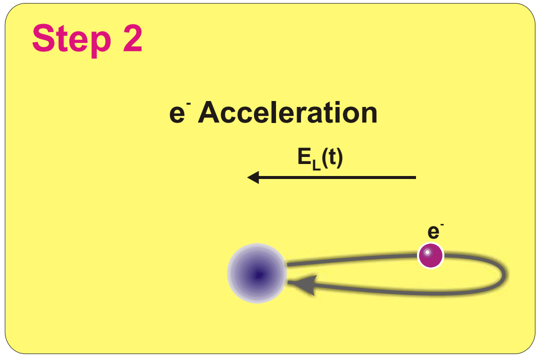
XUV pulse generation

Courtesy: R. Kienberger MPQ



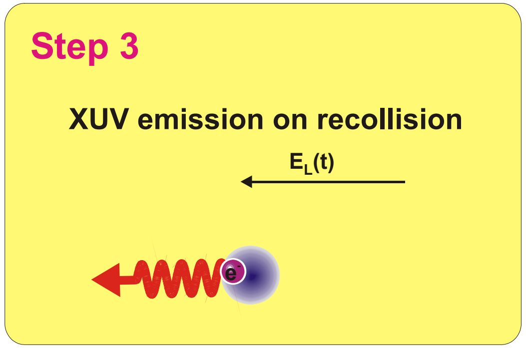
Step 1

Optical field ionization



Step 2

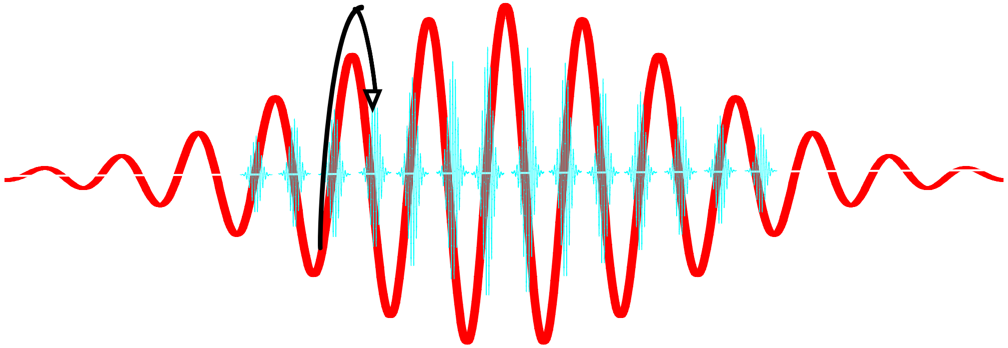
e^- Acceleration



Step 3

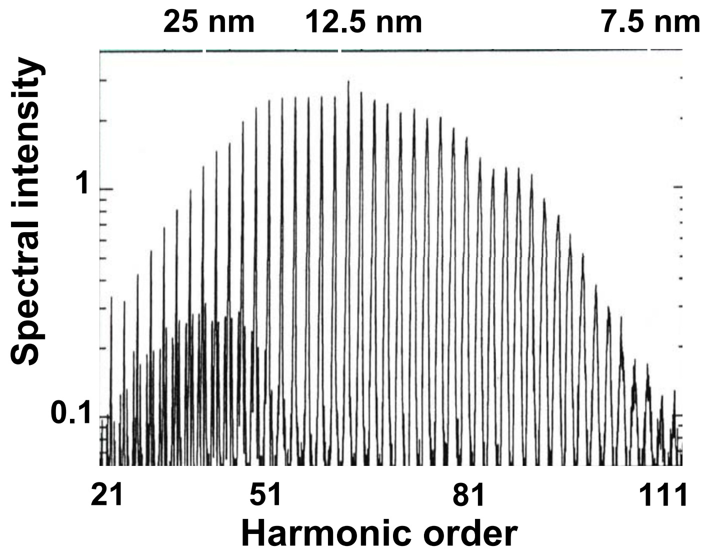
XUV emission on recollision

P.B. Corkum PRL **71**, 1994 (1993)



Cut-off harmonics: train of attosecond bursts

Paul *et al*, Science 292, 1689 (2001)
Tsakiris, Charalambidis *et al*, 2003

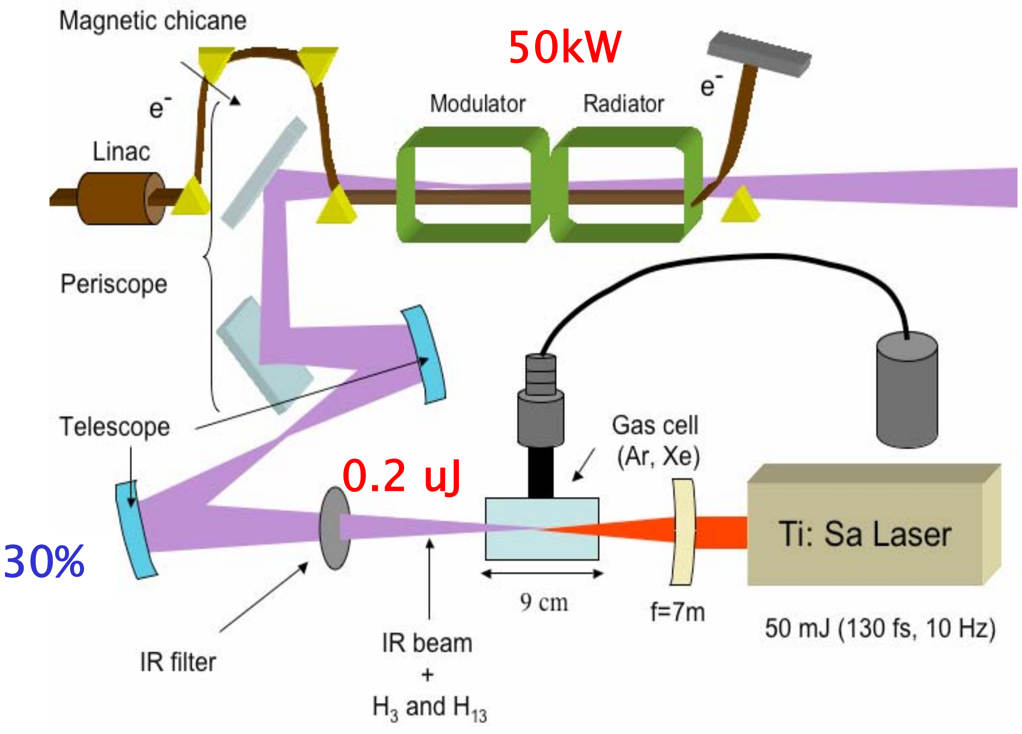


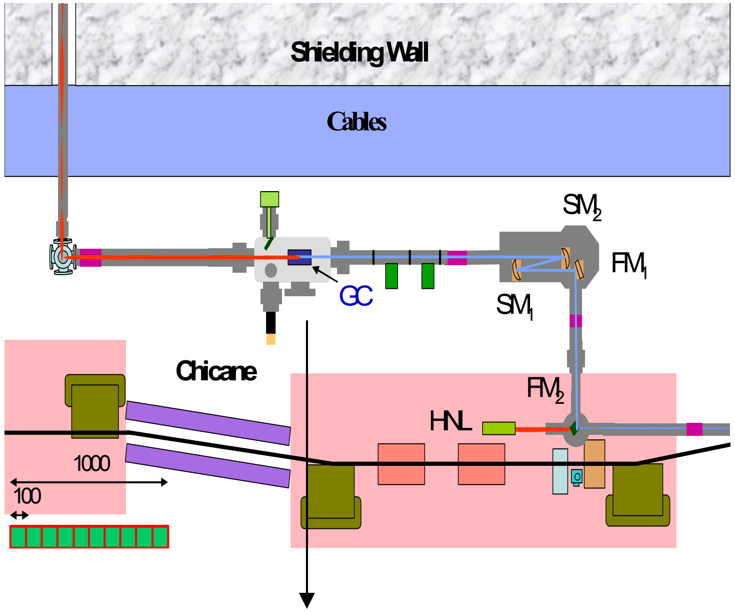
L'Huillier, Balcou, 1993, *PRL* 70, 774
Macklin *et al*, 1993, *PRL* 70, 766

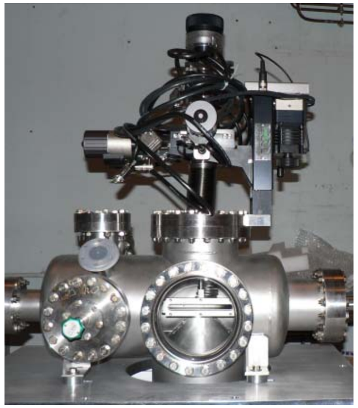
CEA / Service des Photons Atomes et Molécules

Higher Harmonic Generation
- 3rd/13th harmonic -

Scheme of experiment at SCSS





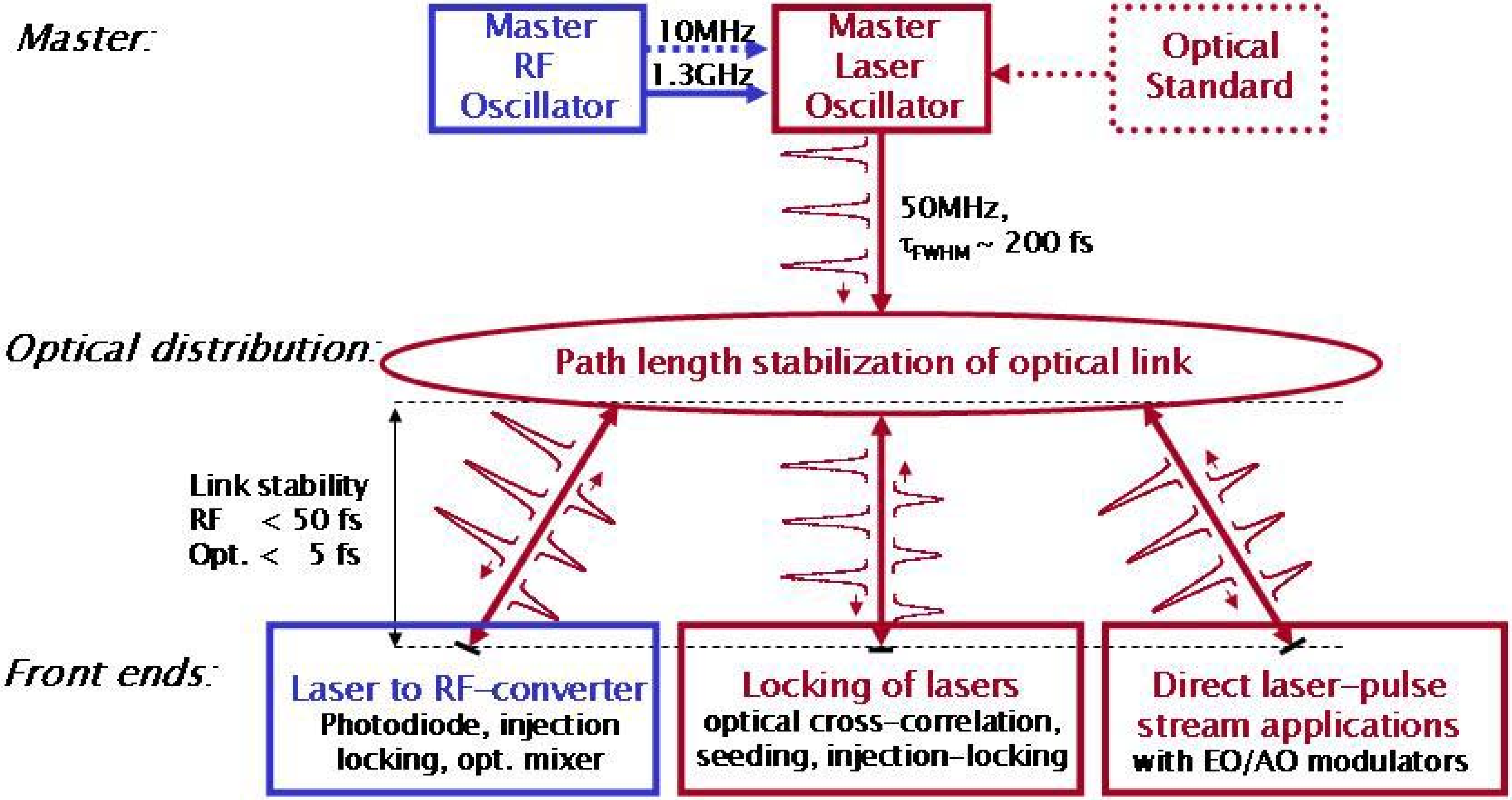


- Characterization of 3th/13th harm.
  photon energy/beam profile/waist position

See also: M. Labat et al. ,MOPCH002/MOPCH003

Courtesy: M. Labat

Layout of laser based synchronization



Master:

Master RF Oscillator

10MHz

1.3GHz

Master Laser Oscillator

Optical Standard

50MHz,
$\tau_{FWHM} \sim 200$ fs

Optical distribution:

Path length stabilization of optical link

Link stability
RF < 50 fs
Opt. < 5 fs

Front ends:

Laser to RF–converter
Photodiode, injection locking, opt. mixer

Locking of lasers
optical cross–correlation, seeding, injection–locking

Direct laser–pulse stream applications
with EO/AO modulators

Applications:

LO generation
-down converter LLRF
-PPL for synchronization
-RF signals for diagnostics

Lasers for
- photo–injector
- pump–probe experiment
- e–beam diagnostics
- e–beam manipulation

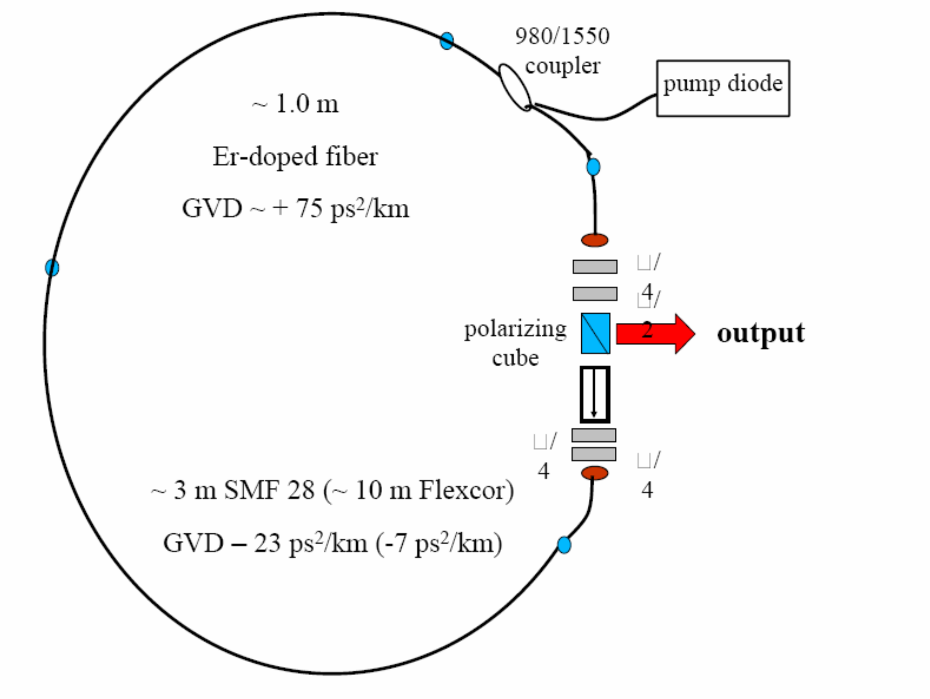
High precision appl.
-Beam phase monitor
-Laser phase monitor
-Optical down converter
-Chicane BPM

See also: A. Winter TUPCH028/TUPCH029, talks: Kim THOPA03, F.Löhl THOBFI01

Synchronization laser

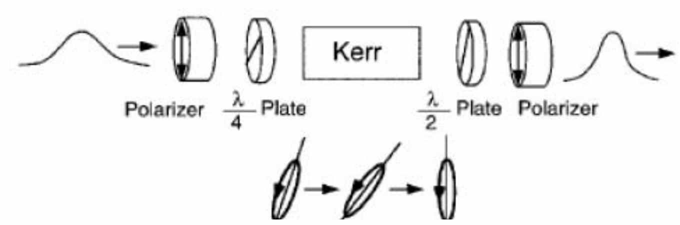
Dispersion managed soliton fiber-laser with artificial saturable absorber

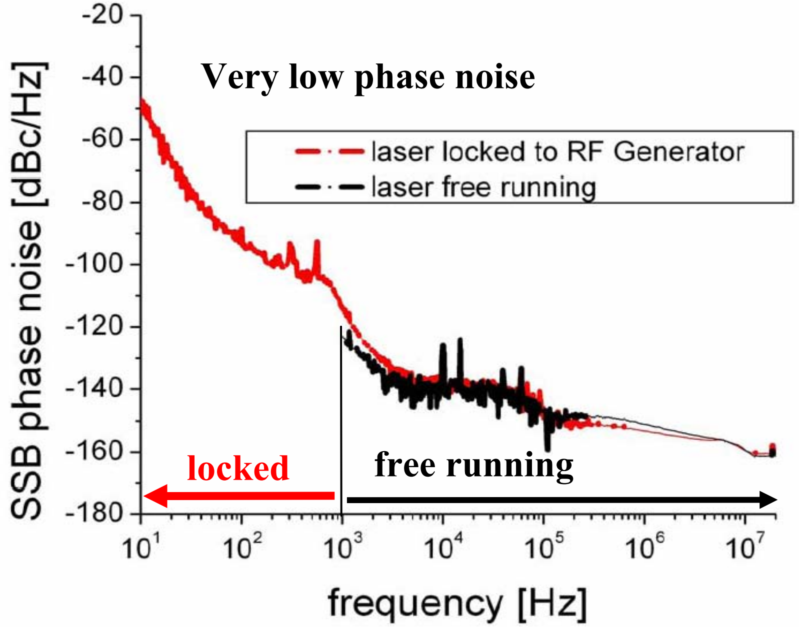
- Fiber stretcher for passive mode locking to RF generator
- Gain medium Erbium, 1550 nm wavelength
- High output power up to ~ 1 nJ (50 mW average)
- Pulse duration ~ 100 fs FWHM
- Repetition rate ~ 50 MHz



www.bilkent.edu.tr/~ilday

Polarization control for mode locking





Summary

- **Laser systems have become key components of FELs**
- **Lasers substantially extend the capabilities of FELs**
- **The applications range from electron generation, beam conditioning, seeding and two color pump-probe experiments**
- **For user facilities ⇒ stability of laser system is the most critical item, especially for advanced systems**
- **New schemes and combinations for laser usage are expected in future**