Optical laser requirements, developments and simulations at the European XFEL

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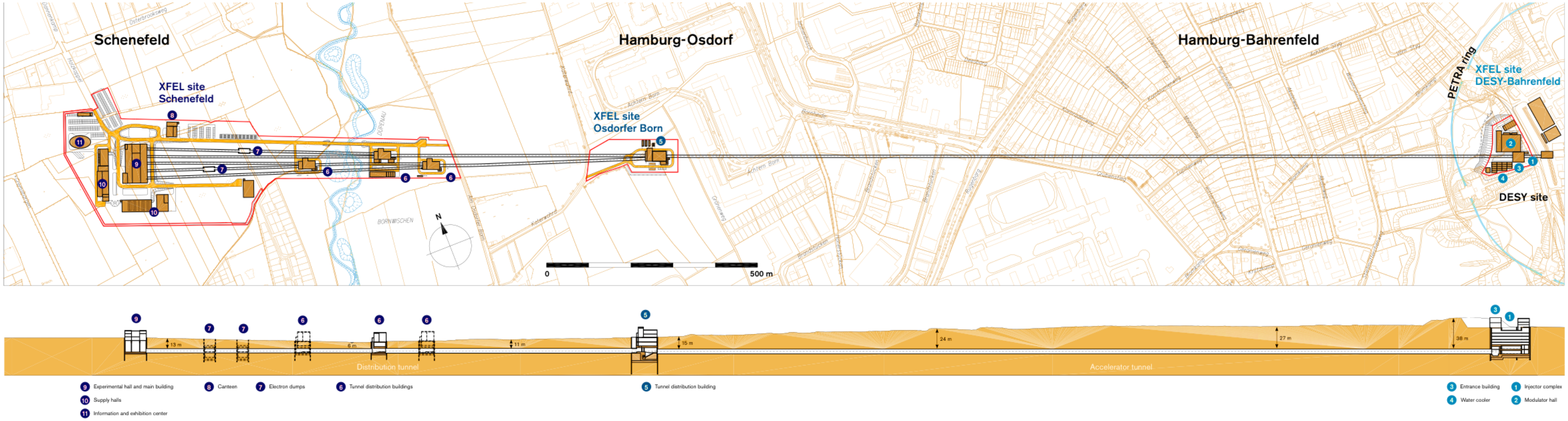


Overview

A. The European XFEL project

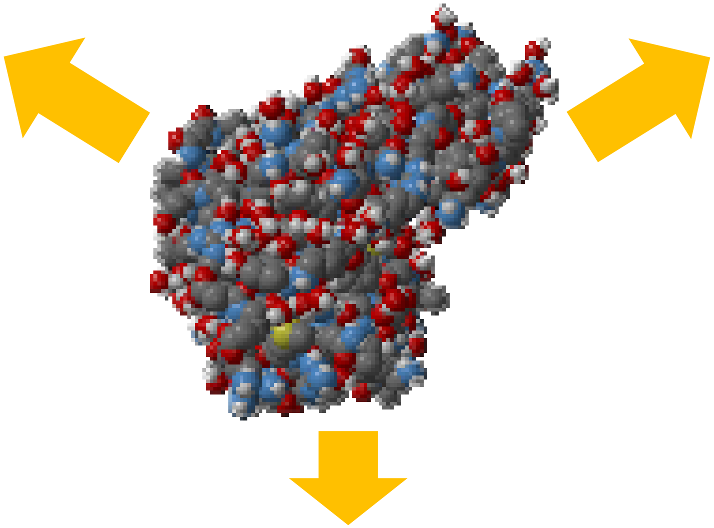
B. Experimental laser requirements at XFEL

C. Pump-probe laser development and supporting simulations

A. The European XFEL project

Why X-Ray Free-Electron Lasers?

Investigation of nano-scale ultrafast dynamic processes and highly excited states of matter require a „different kind of microscope“.



Observation wavelength /
Diffraction limit < desired resolution

Shutter speed /
Pulse duration < vibration period

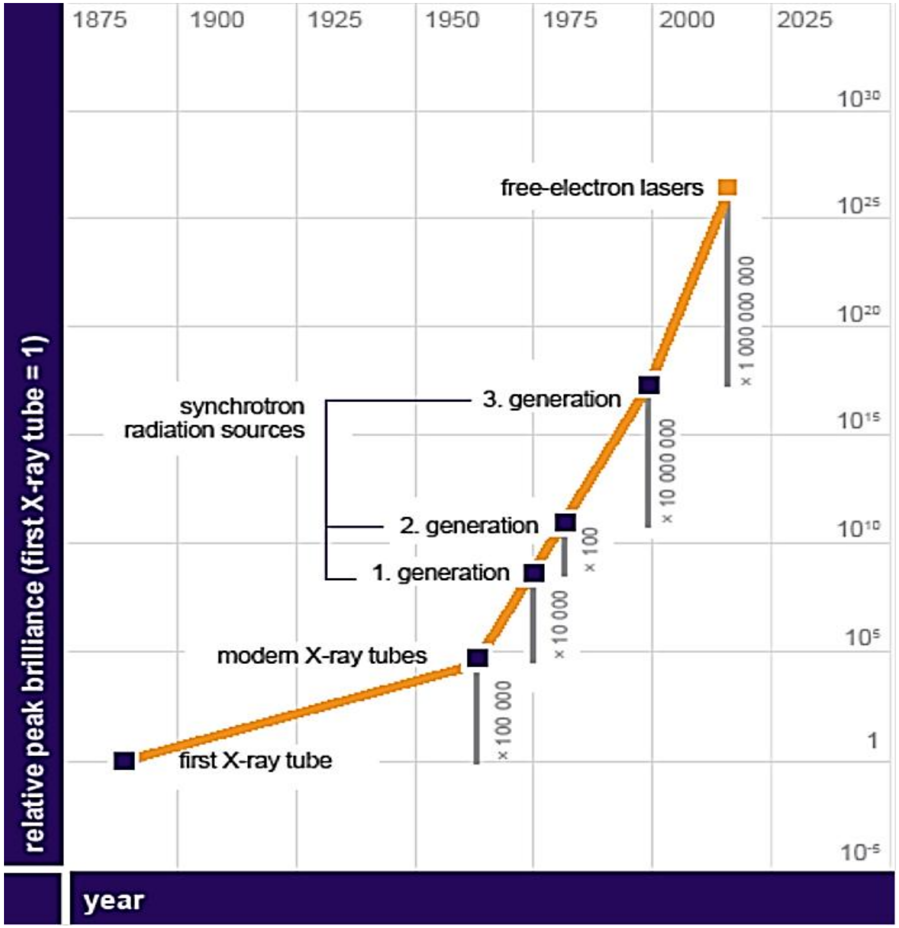
Scattering power /
Single pulse intensity > noise

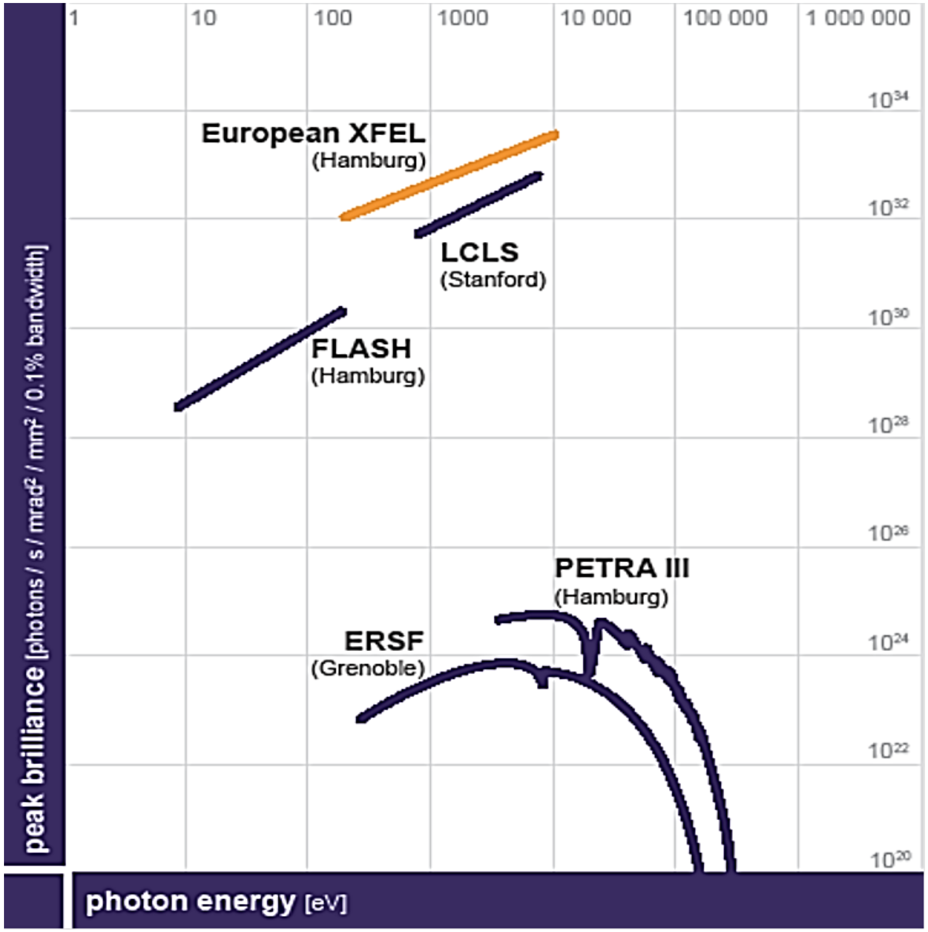
⇒ X-Ray Free-Electron Laser sources open new scientific possibilities

Courtesy T. Tschentscher

Peak brilliance

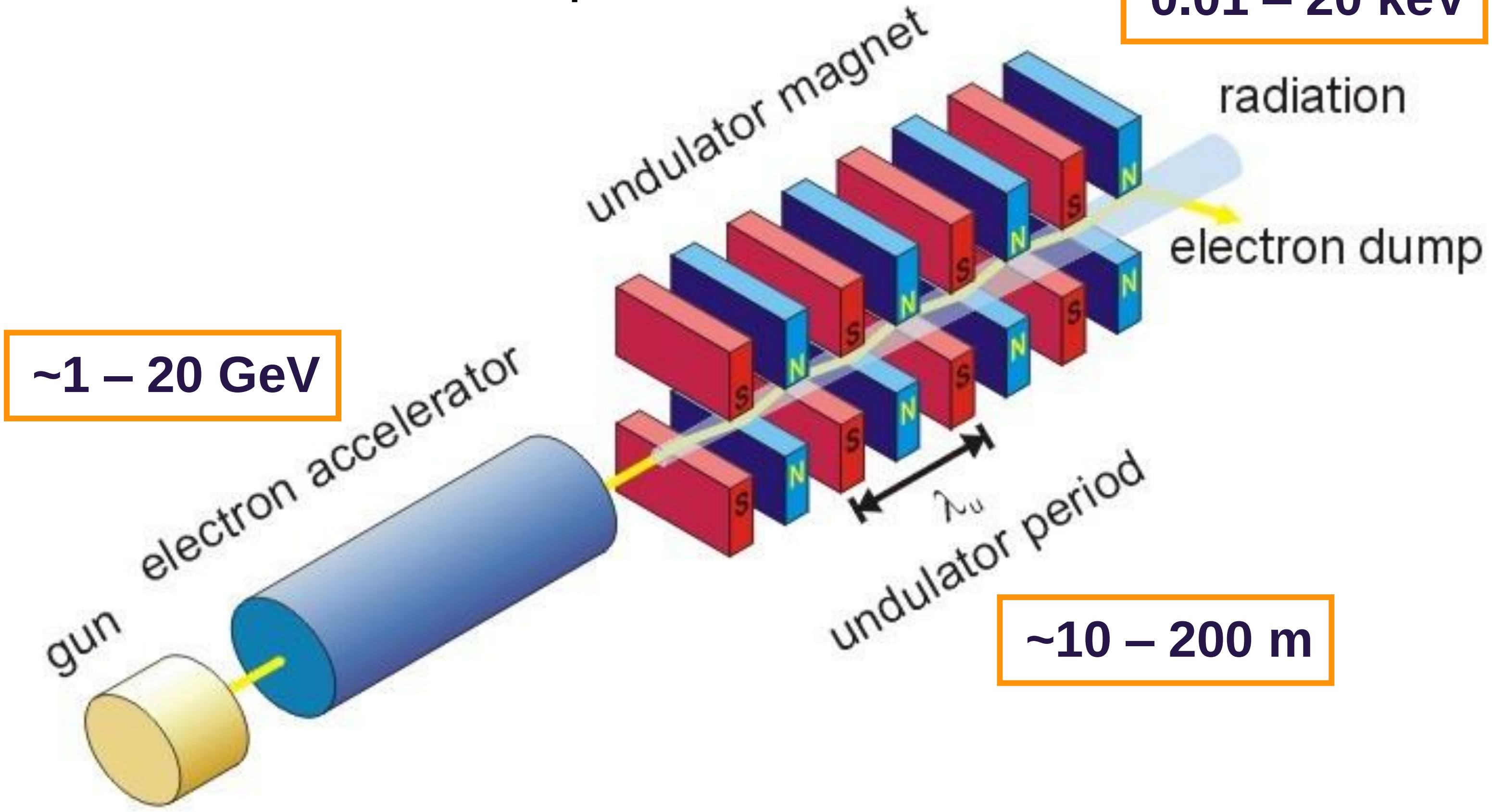
$$\text{Peak brilliance} = \frac{\mathit{Number\ of\ photons}}{\Delta x \Delta x' \times \Delta y \Delta y' \times \Delta \dfrac{\omega}{\omega_0} \times \Delta \tau}$$





An X-Ray Free-Electron Laser

- low emittance high energy linac.
- SASE or seeded FEL process



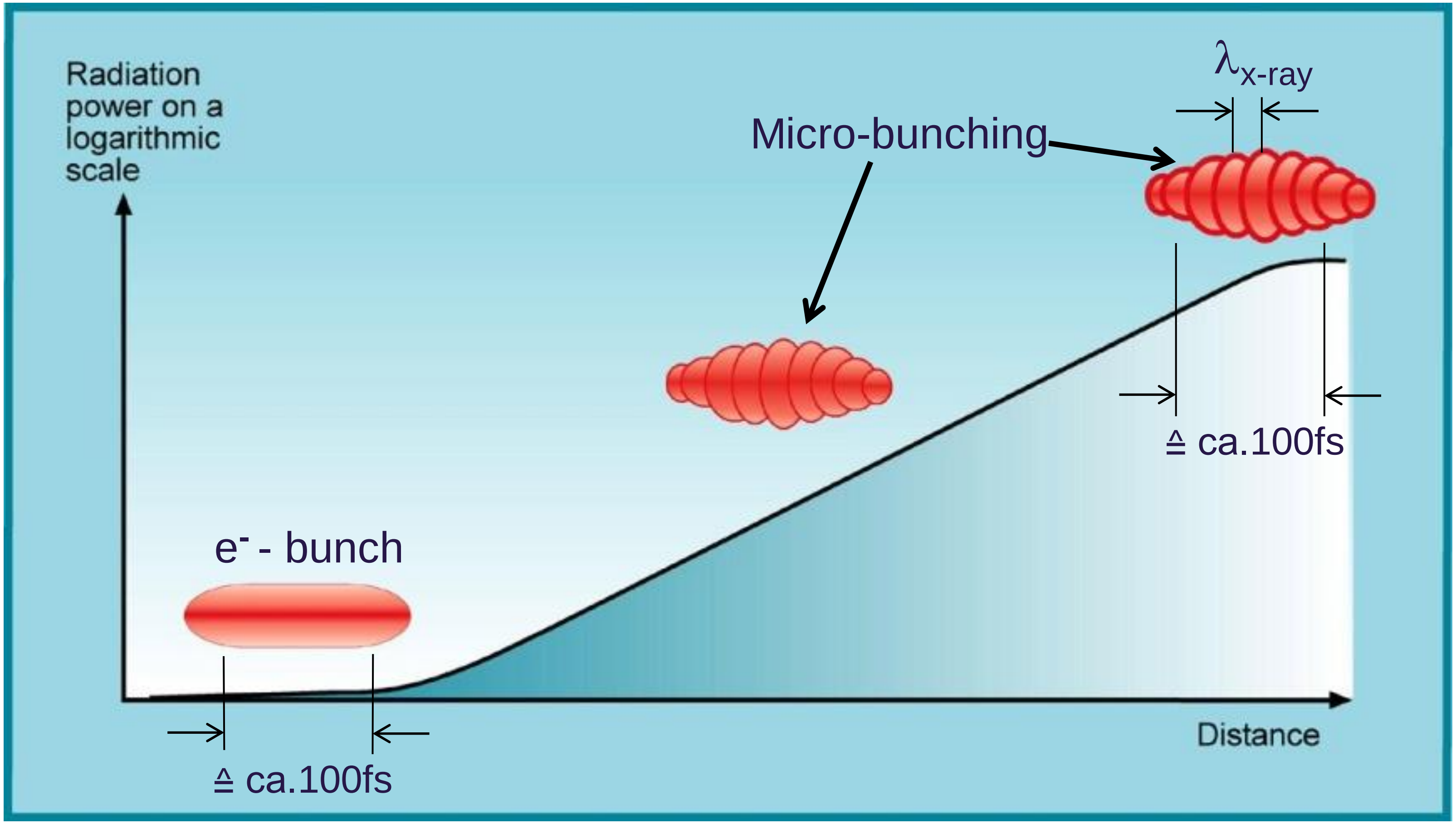
0.01 – 20 keV

~1 – 20 GeV

~10 – 200 m

Courtesy T. Tschentscher

SASE-process



Light generation in the undulator:

SASE - Self-Amplified Spontaneous Emission

April 10, 2009 LCLS: First Operative X-ray FEL

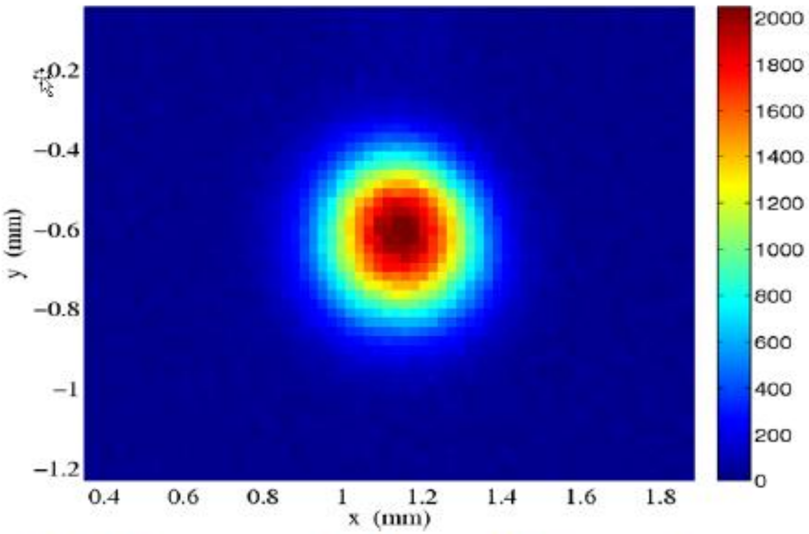
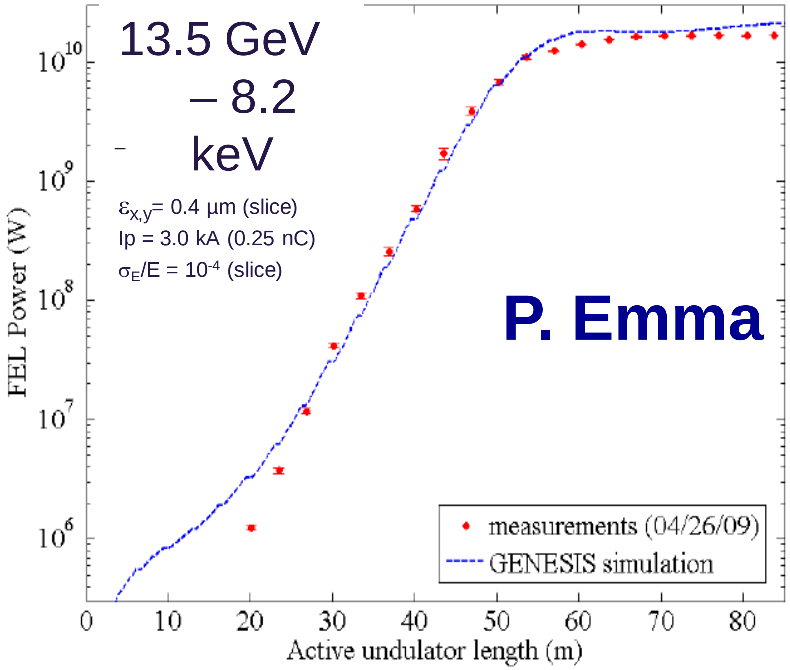


Figure 10: FEL x-rays at 1.5 Å on a YAG screen 50 m after the last inserted undulator (see Table 1 for measured parameters).

SASE process very robust at x-ray wavelengths.



13.5 GeV – 8.2 keV

$\varepsilon_{x,y}$= 0.4 μm (slice)
Ip = 3.0 kA (0.25 nC)
$\sigma_E/E = 10^{-4}$ (slice)

P. Emma

- New short-wavelength SASE record
- First spatially coherent hard x-rays
- ***Rep-rate: 60-120Hz***

X-ray FELs worldwide

Soft / Hard

MAX-IV
Lund, SWE

FLASH
Hamburg, GER

European XFEL
Hamburg, GER

SXR NGLS
Berkeley, CA

LCLS
SLAC, Stanford, CA

PSI-FEL
Villigen, SUI

FERMI@ELETTRA
Trieste, ITA

SACLA
SCSS Test
Spring-8
Harima, JAP

PAL XFEL
Pohang, KOR

Courtesy T. Tschentscher

European XFEL Features

What is the European XFEL adding in 2016?

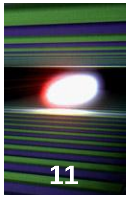
up to 5 beam lines (3 in base line)

simultaneous operation

0.25 ... 24keV photon energy

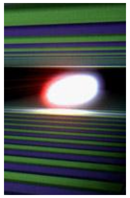
much higher pulse rate: up to 27000 pulses / sec

Some facts about the European XFEL Project

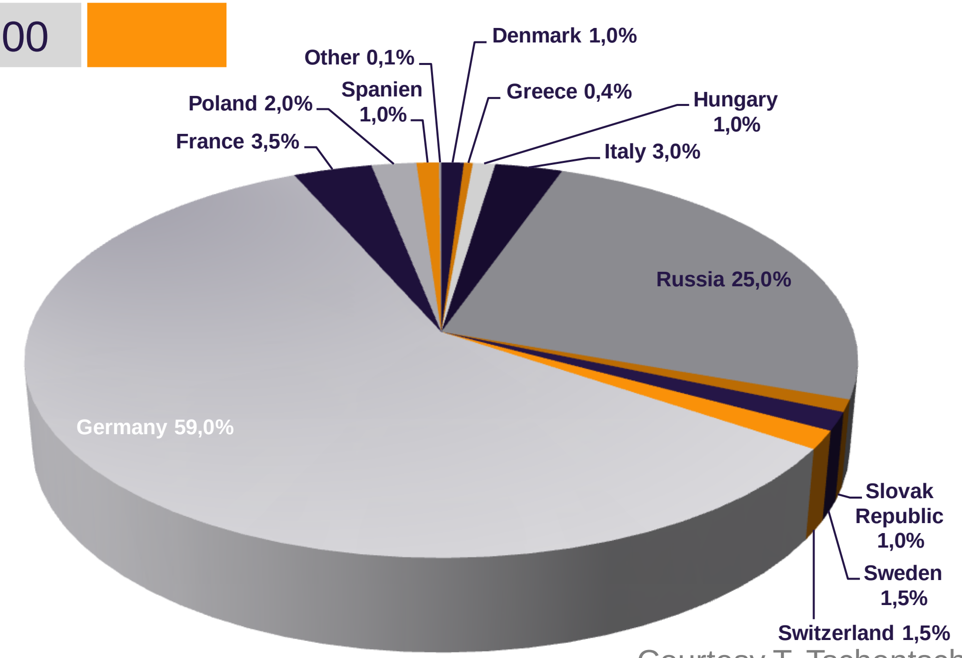


- 12 participating countries
- DESY, Hamburg
  - ➔ is host laboratory for the project team
  - ➔ responsible for injector and linac
- XFEL GmbH established in fall 2009
  - ➔ Currently ca. 150 international staff, final staffing 230
  - ➔ responsible for photon beam lines and experiments
- First beam: end of 2015
- XFEL Laser Group established in Nov. 2010
  - ➔ currently 6 members, final staffing ca. 10 - 15

Key figures



Total construction cost	1147	M€*
In-Kind contributions	~500	M€*
External funding (up to 2011)	~6	M€
Staff European XFEL GmbH	~230	
Total staff (incl. DESY staff)	~400	
Start of user operation	2016	
Science users per year	~1000	



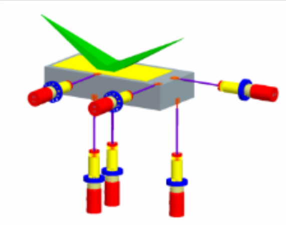
Courtesy T. Tschentscher

Technological challenges at European XFEL

Scientific instruments & ancillary instrumentation

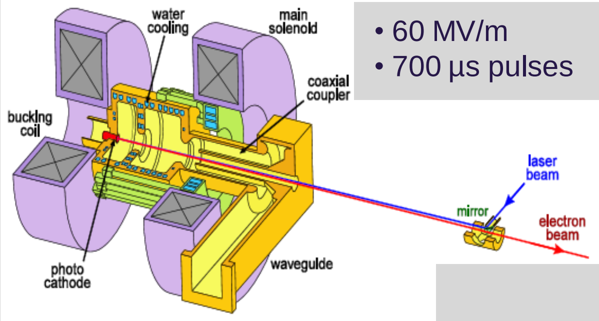
- 6 stations

X-ray optics & beam transport



- 3 systems
- ~2000 m
- 1m mirrors

Low emittance electron injector



- 60 MV/m
- 700 µs pulses

Schenefeld

Hamburg - Bahrenfeld

Undulator systems

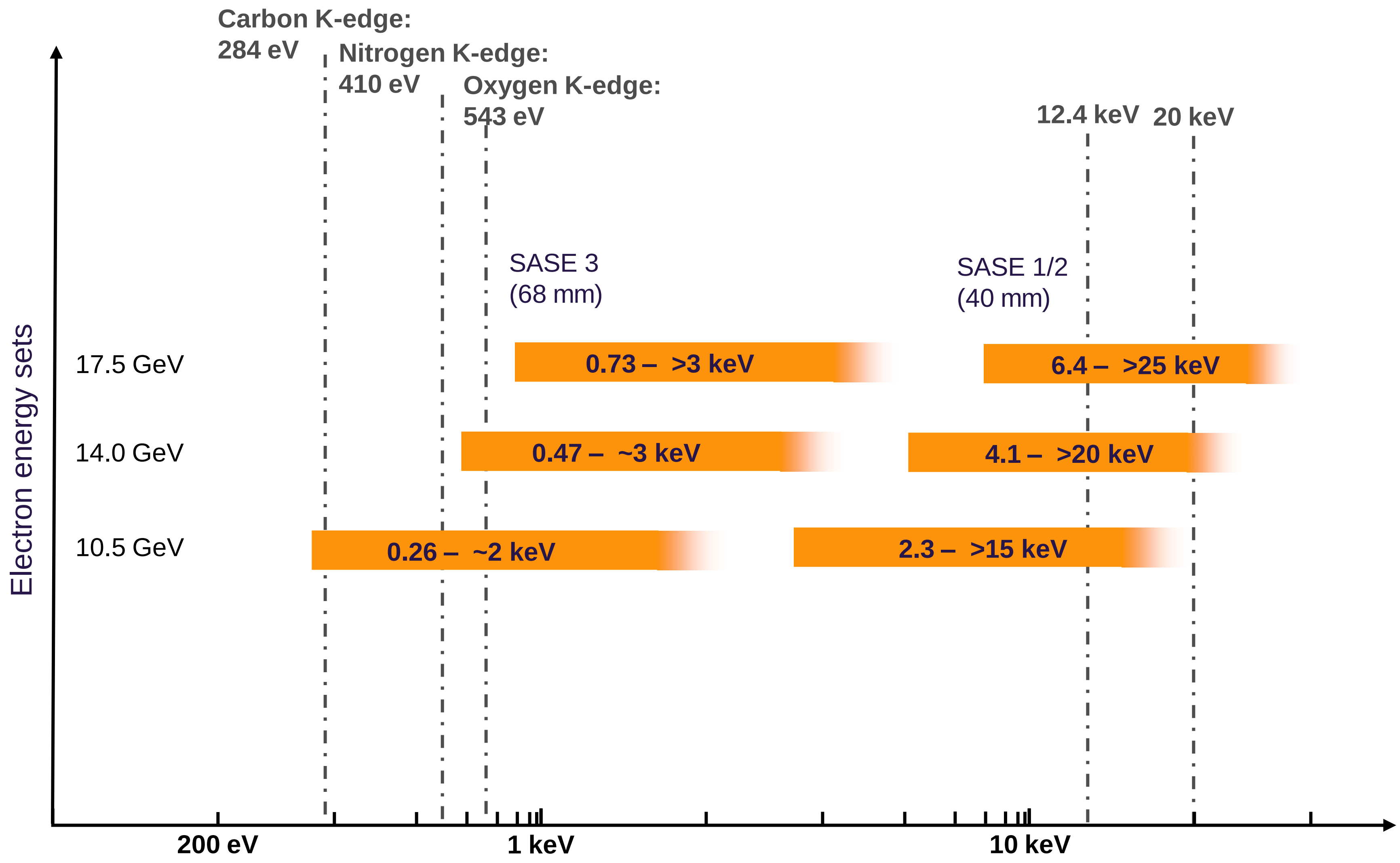
- 3 systems
- >450 m

Superconducting electron accelerator

- 23 MV/m
- 800 cavities
- 17.5 GeV

Courtesy T. Tschentscher

Undulator ħω ranges

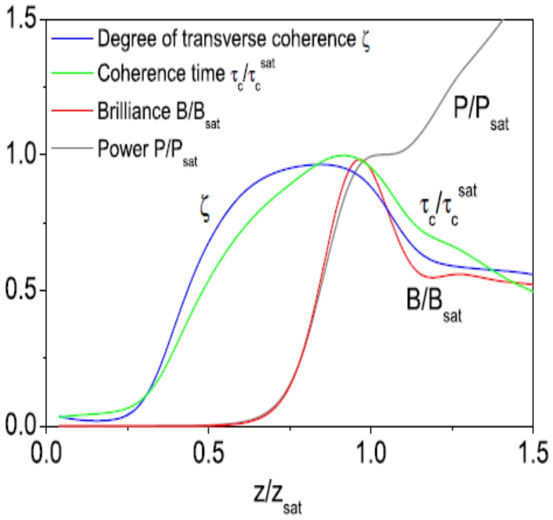


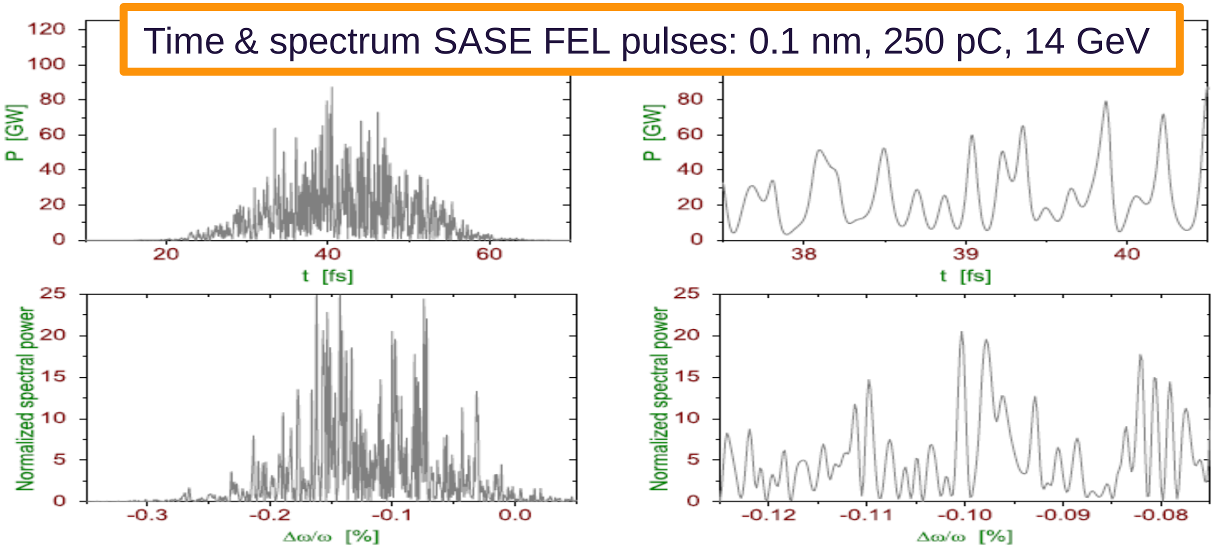
updated layout, Feb 2011

Courtesy T. Tschentscher

European XFEL beam parameters

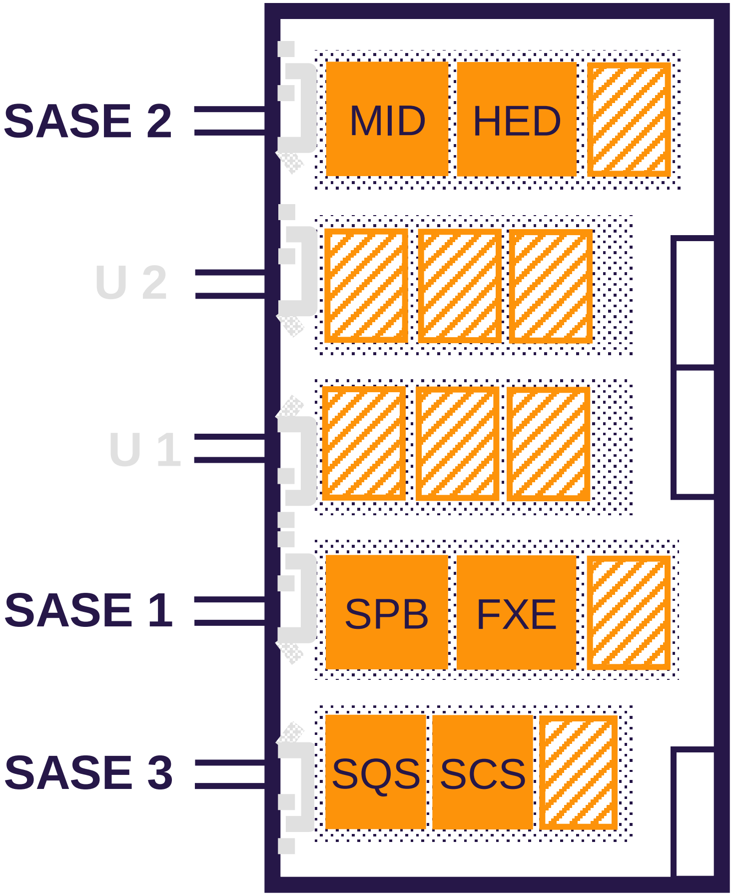
Parameter	Unit	
Photon energy	keV	**0.27 – 24**
Pulse energies (@saturation)	µJ	**0.2 - ~4000**
Pulse duration	fs	**2 - 107**
Power density	W/cm^2	**~10^{13} - 10^{18}**
Spectral bandwidth		**~ 10^{-3}**
Source size	µm	**30 - 60 (100)**
Coherence degree		**0.4 - 0.96**

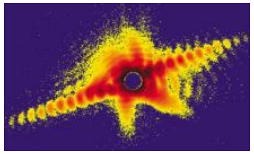



Time & spectrum SASE FEL pulses: 0.1 nm, 250 pC, 14 GeV

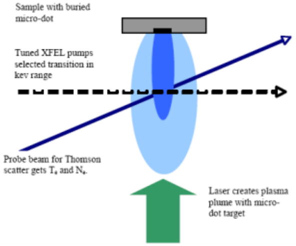
Courtesy T. Tschentscher

The suite of instruments

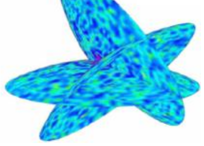




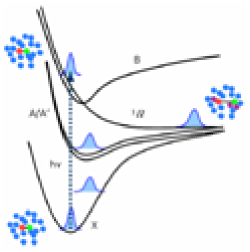
MID Materials Imaging & Dynamics



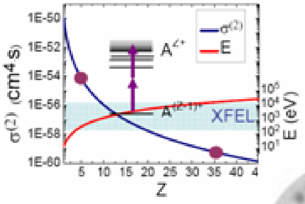
HED High Energy Density Science



SPB Single Particle & Biomolecules



FXE Femtosecond X-ray Experiments



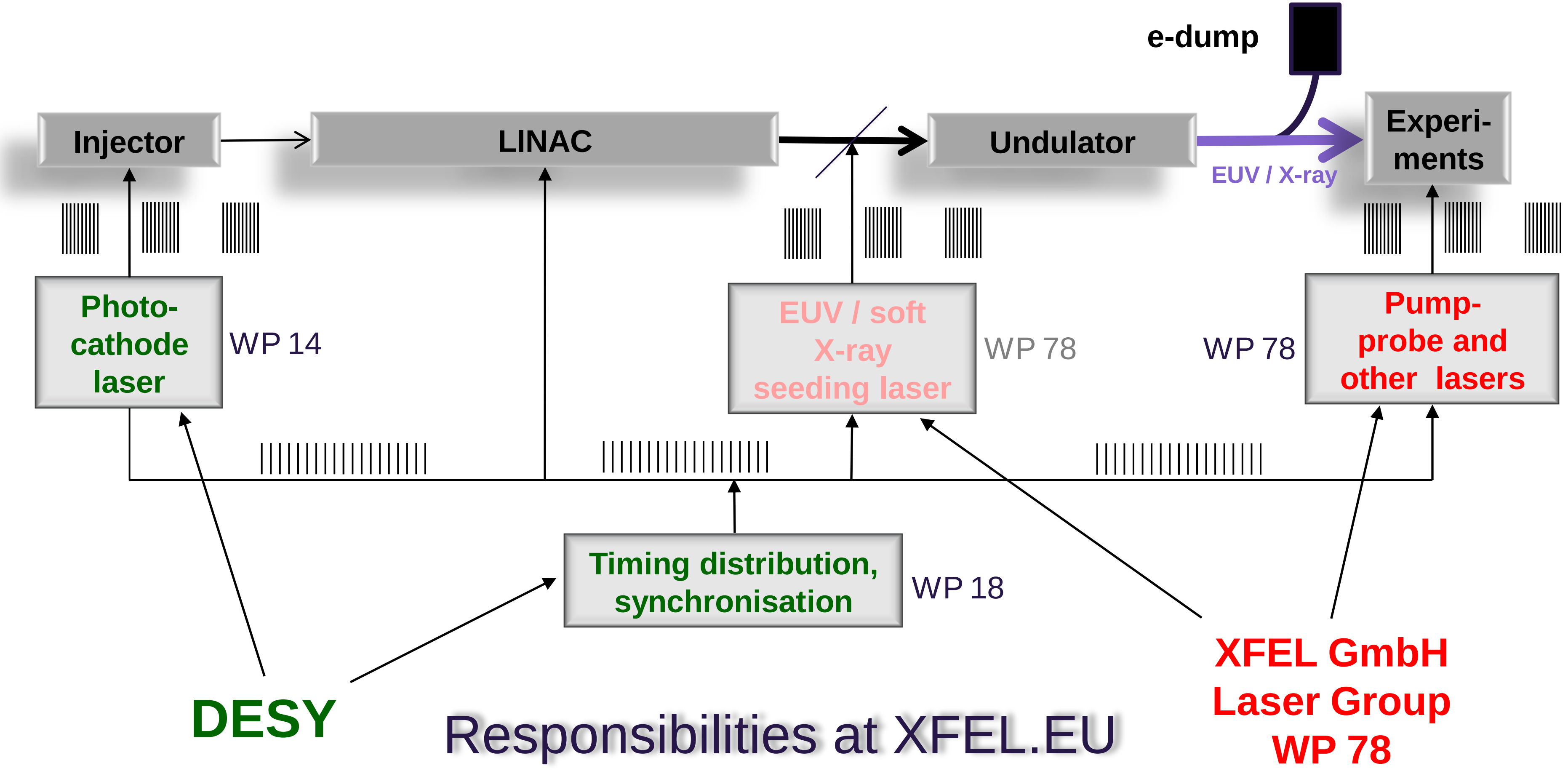
SQS Small Quantum Systems

SCS Spectroscopy & Coherent Scattering

Courtesy T. Tschentscher

B. Experimental laser requirements at XFEL

Simplified schematic of a SASE Free-Electron Laser:



e-dump

Injector

LINAC

Undulator

EUV / X-ray

Experi-ments

Photo-cathode laser

WP 14

EUV / soft X-ray seeding laser

WP 78

WP 78

Pump-probe and other lasers

Timing distribution, synchronisation

WP 18

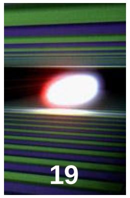
DESY

XFEL GmbH Laser Group WP 78

Responsibilities at XFEL.EU

European XFEL

Experimental laser requirements analysis



Experiment Hall

SASE 2 — ***HED + MID + NNN***

Types of lasers

PP **TUNE** **TW** **SHOCK** **PW**

U1

U2

currently not in use.

SASE 1 — ***SPB + FXE + NNN***

Types of lasers:

PP **MAL** **TUNE**

SASE 3 — ***SQS + SCS + NNN***

Types of lasers:

PP **MAL** **TUNE**

Types of lasers - *a wish list*:

PP (pump-probe):

➔ sub-15…100fs, 0.2mJ, 10Hz ***burst***, 0…4.5MHz, 800nm

MAL (molecular alignment):

➔ sub-20fs, 3…10mJ, 800nm („kick“)

or

➔ 1J, 10Hz, ns („adiabatic“)

TUNE (tunability, freq. conversion):

➔ UV…mid-IR, THz (not in hutch, in coll. with instr. sci.)

TW (Terawatt):

➔ <30fs, 5-10Hz, 100 Terawatt–class laser, Ti:sapphire

SHOCK (high energy):

➔ kJ-class ns-laser

PW (Petawatt):

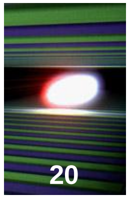
➔ 30fs, 1Hz, Ti:sapphire

or

➔ 150fs, 1Hz, diode-pumped Yb:CaF$_2$

- Fixed
- Future (potential User Consortium)

Some remarks on laser requirements



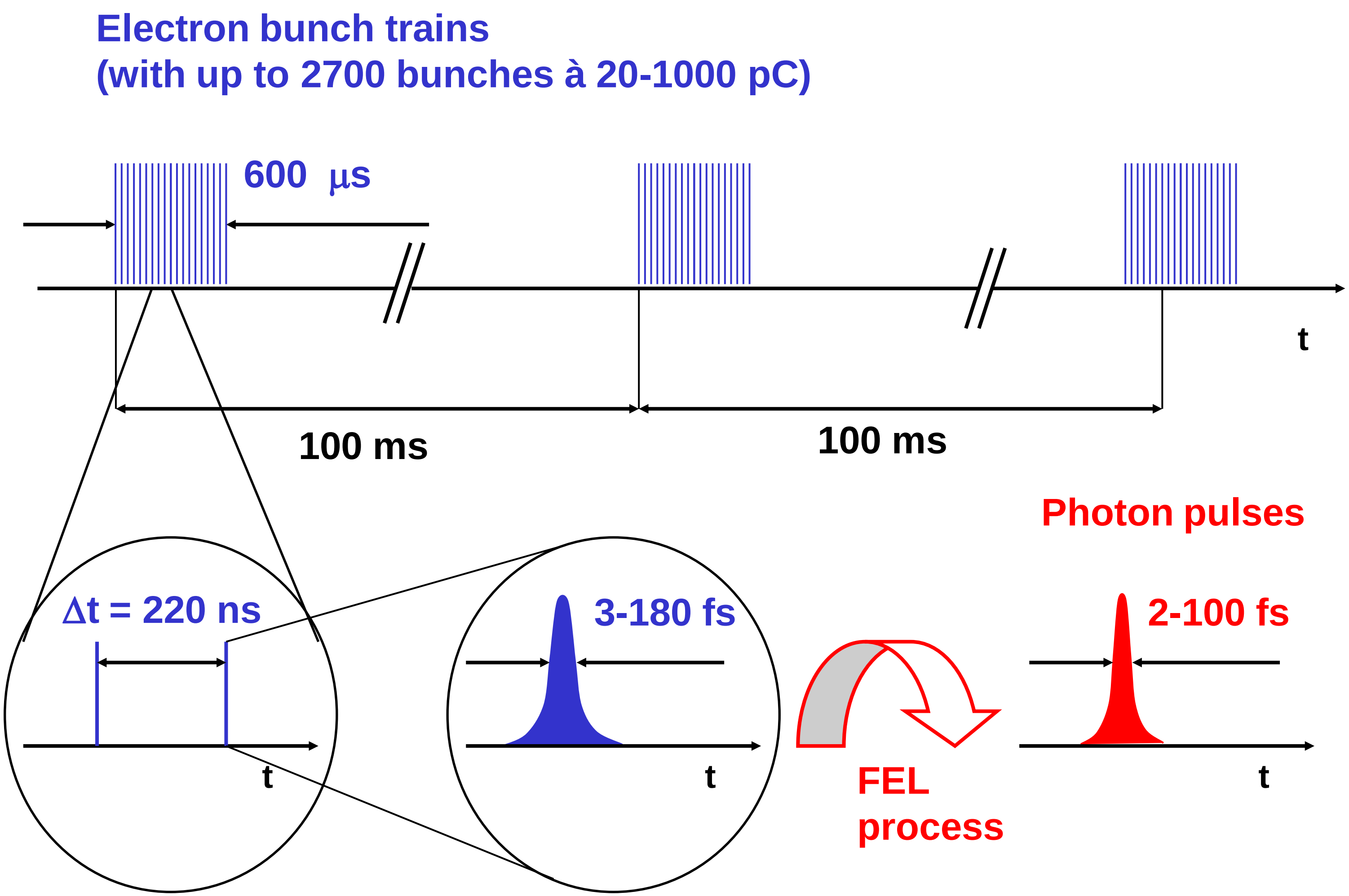
- **100TW-class** laser technology is mature and commercially available from several vendors**.**
  - ➔ Plan for installation in time with start of operation phase of the XFEL.EU.
- **PW- and kJ-class** lasers are also becoming commercially available and are being installed (e. g. BELLA Ti:sapphire 1.3PW).
  - ➔ Future of these efforts at XFEL.EU depends on external user consortium.
  - ➔ Due to the size of these lasers, an additional external building will be required.
- **PP-laser will require major development effort, no commercial system is available.**
  - ➔ 10Hz burst operation with up to 4.5MHz intra-burst rep-rates.
  - ➔ mJ-class pulse energies, shorter and longer pulses.
  - ➔ Attempt to also achieve specs useful for MAL.

high flexibility
AND
high uptime

- **Tunability** will have to be derived from PP-laser and adapted to needs of instruments and users.
  - ➔ In cooperation with instruments scientists.

C. Pump-probe laser development and supporting simulations

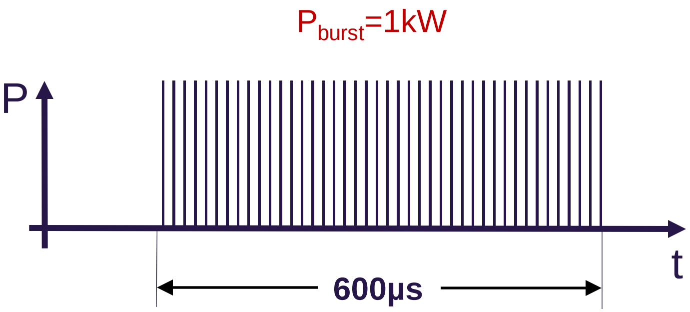
European XFEL pulse timing



Pump-Probe laser goals

High-rep-rate operation (PP-mode):

- ➔ 10Hz ***burst***, 0.6% duty cycle,
- ➔ 15 … 100fs,
- ➔ 1 … 4.5MHz intra-burst, „PoD“,
- ➔ 1…0.2mJ per pulse, ca. 800nm

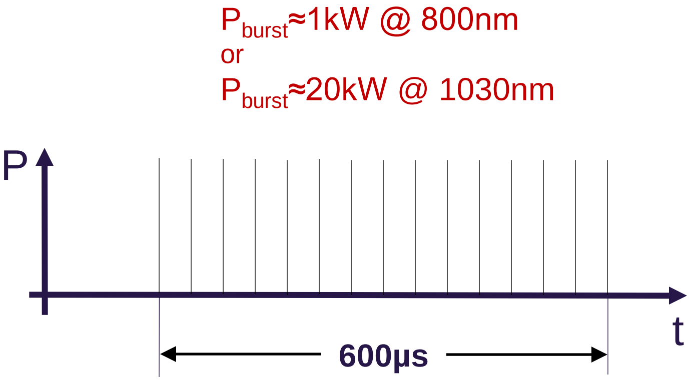


Low-rep-rate operation (MAL-mode):

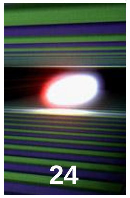
- ➔ 10Hz ***burst***, 0.6% duty cycle,
- ➔ 200kHz intra-burst, „PoD“
- ➔ sub-20fs, >3mJ per pulse, 800nm.

or

- ➔ ps or ns, ≈ 0.1J per pulse, 1030nm.



Options for high burst power ultrashort pulse generation



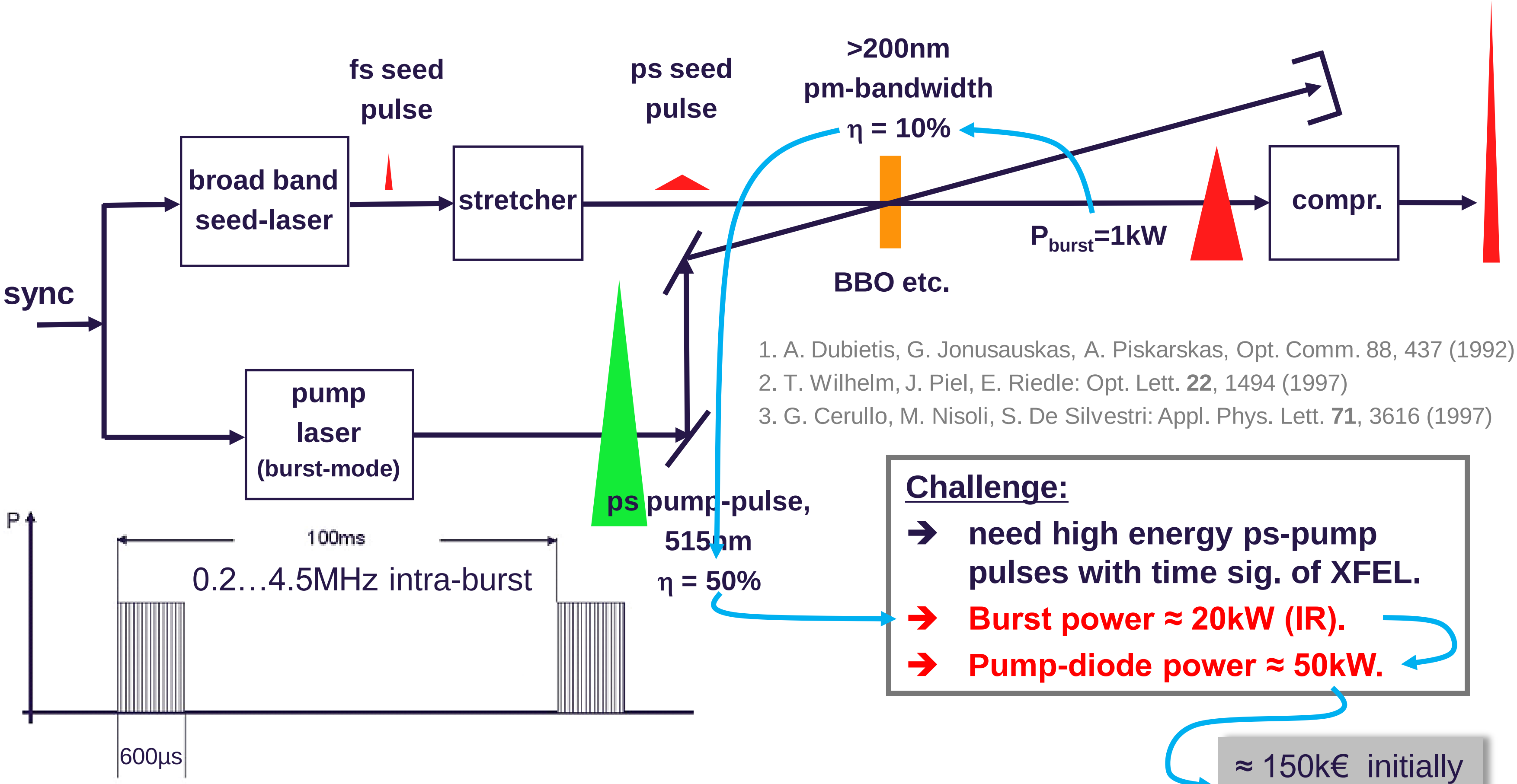
	Ti:Sapphire		OPCPA	
Operation mode	Cryo, staged multi-pass amps, ns-sync-pumped, burst		Non-collinear, staged single pass amps, ps-sync-pumped, burst	
Average power scaling	XFEL duty cycle is 1%, i. e. 10W, therefore no problem	☺	No problem	☺
15fs capable	borderline	😐	yes	☺
Gain per length	low	☹	high	☺
Thermal transients	Cryo-management	😐	negligible	☺
Pump efficiency	≈ 20%	😐	≈ 20%	😐
Flexibility	low	☹	high	☺
Misalignment sensitivity	medium	😐	High angular and temporal	☹

➔ **Require 5-10kW burst-power green ns/ps pump lasers for synchronous pumping in both cases.**

Choose OPCPA in non-collinear configuration: NOPA

NOPA principle

NOPA ⇨Non-collinear Optical Parametric Amplifier



sync

broad band seed-laser

fs seed pulse

stretcher

ps seed pulse

>200nm pm-bandwidth

η = 10%

BBO etc.

P_{burst}=1kW

compr.

pump laser (burst-mode)

ps pump-pulse, 515nm

η = 50%

P

100ms

0.2…4.5MHz intra-burst

600µs

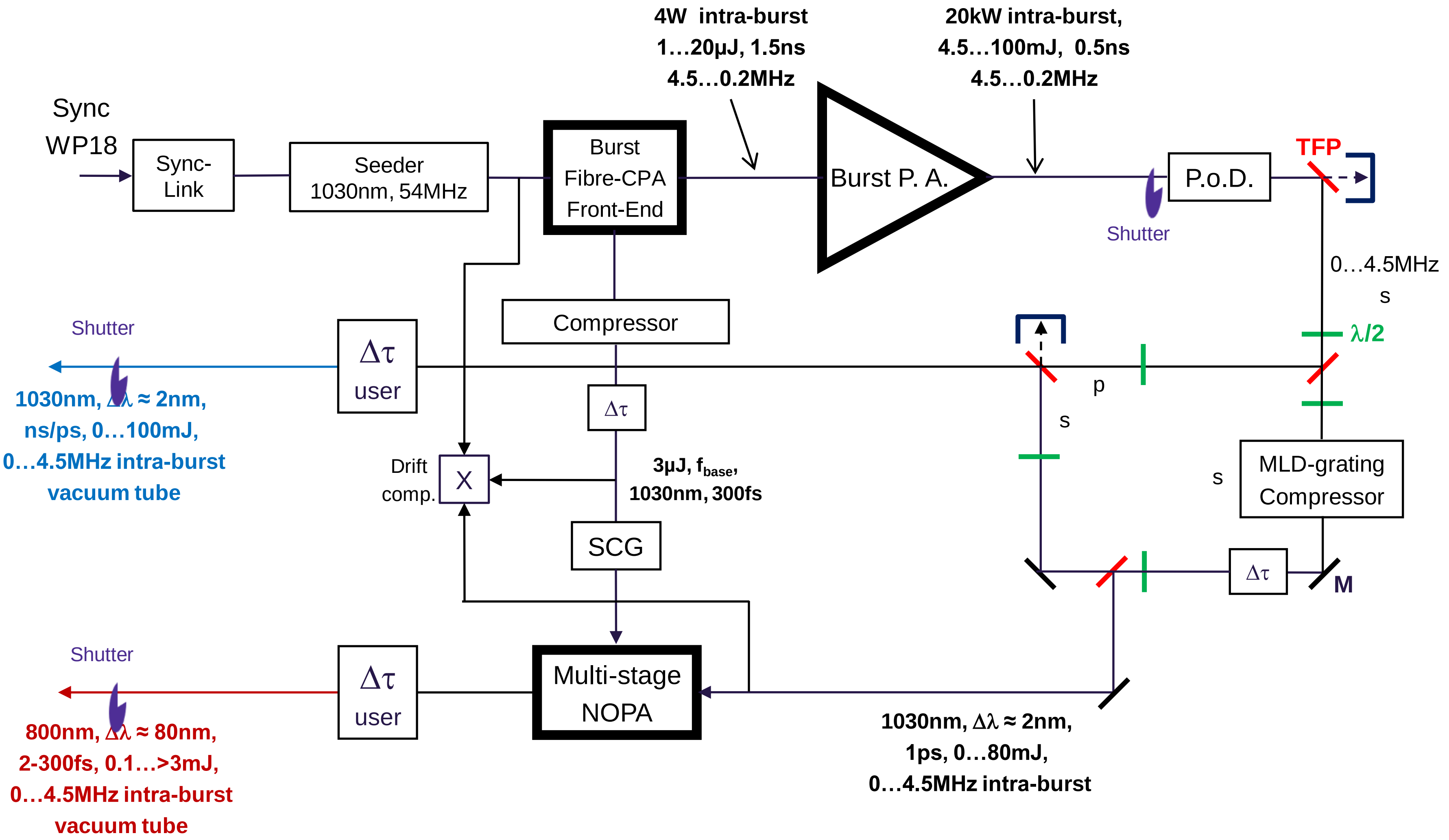
1. A. Dubietis, G. Jonusauskas, A. Piskarskas, Opt. Comm. 88, 437 (1992)
2. T. Wilhelm, J. Piel, E. Riedle: Opt. Lett. **22**, 1494 (1997)
3. G. Cerullo, M. Nisoli, S. De Silvestri: Appl. Phys. Lett. **71**, 3616 (1997)

Challenge:

- ➔ **need high energy ps-pump pulses with time sig. of XFEL.**
- ➔ **Burst power ≈ 20kW (IR).**
- ➔ **Pump-diode power ≈ 50kW.**

≈ 150k€ initially
≈ 50k€ p. a.

Pump-Probe laser conceptual layout



Sync WP18

Sync-Link

Seeder 1030nm, 54MHz

Burst Fibre-CPA Front-End

4W intra-burst
1…20µJ, 1.5ns
4.5…0.2MHz

Burst P. A.

20kW intra-burst,
4.5…100mJ, 0.5ns
4.5…0.2MHz

Shutter

P.o.D.

TFP

0…4.5MHz

s

λ/2

p

s

MLD-grating Compressor

s

Δτ

M

Compressor

Δτ

3µJ, f_{base},
1030nm, 300fs

Drift comp.

X

SCG

Multi-stage NOPA

1030nm, Δλ ≈ 2nm,
1ps, 0…80mJ,
0…4.5MHz intra-burst

Shutter

Δτ user

1030nm, Δλ ≈ 2nm,
ns/ps, 0…100mJ,
0…4.5MHz intra-burst
vacuum tube

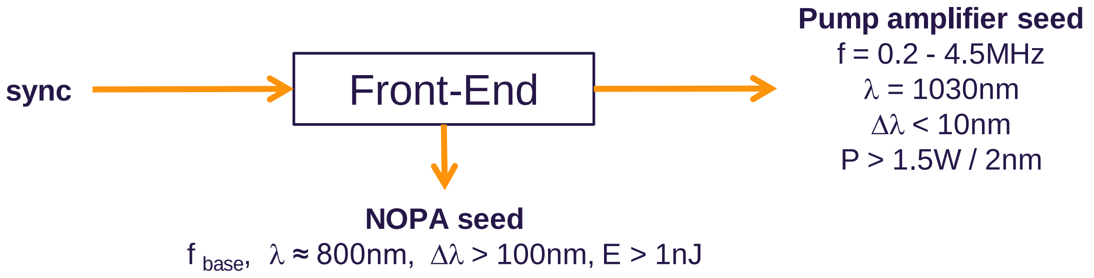
Shutter

Δτ user

800nm, Δλ ≈ 80nm,
2-300fs, 0.1…>3mJ,
0…4.5MHz intra-burst
vacuum tube

Burst-mode 1030nm CPA fibre front end

Requirements and options for a NOPA front-end



sync

Front-End

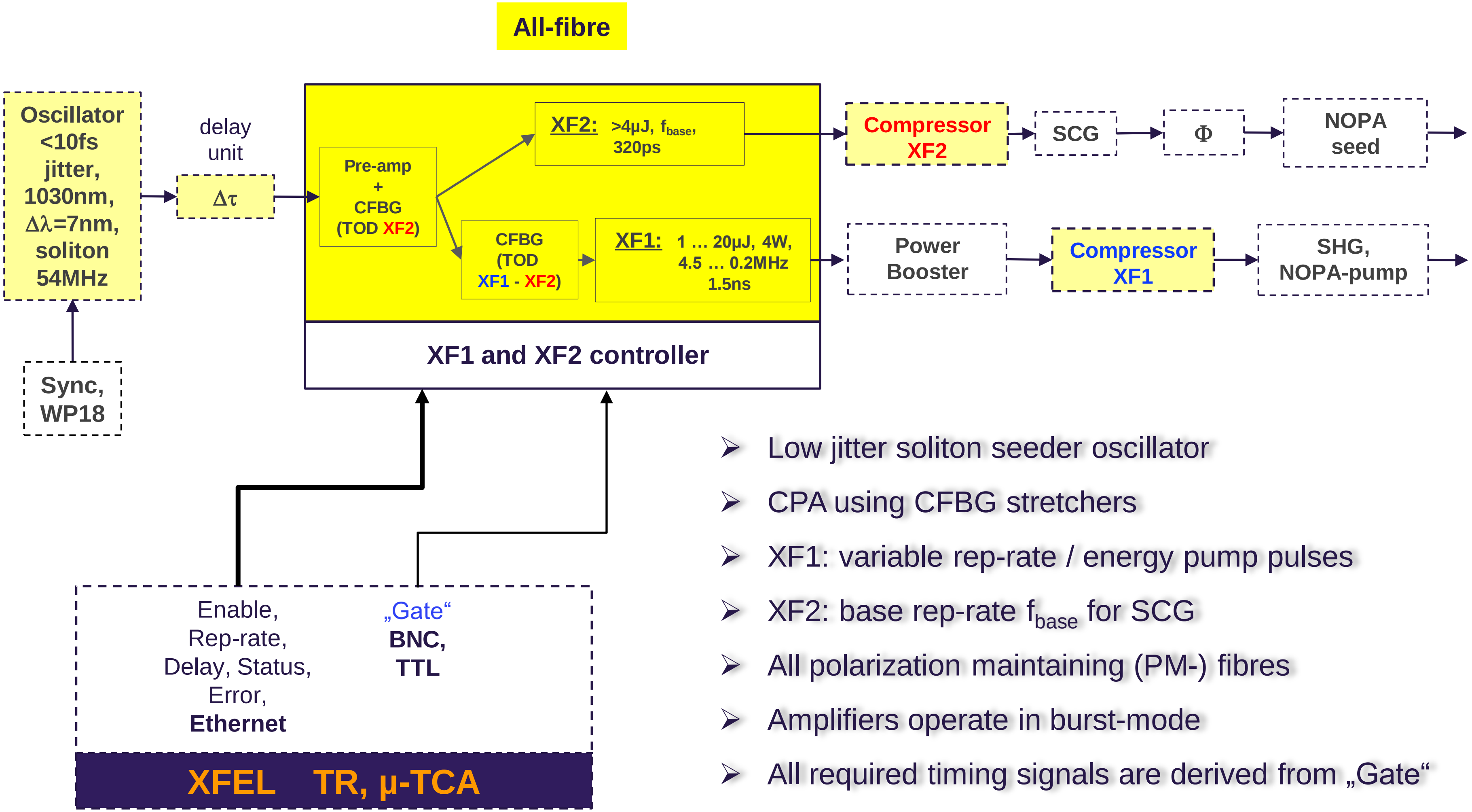
Pump amplifier seed
f = 0.2 - 4.5MHz
λ = 1030nm
$\Delta\lambda$ < 10nm
P > 1.5W / 2nm

NOPA seed
f_{base}, $\lambda \approx$ 800nm, $\Delta\lambda$ > 100nm, E > 1nJ

NOPA seed	Pros	Cons
Ultra-broadband TiSa oscillator, $\Delta\lambda \approx$ 300nm for 800nm and 1030nm	- „all-in-one“ oscillator	- poor long-term stability
Standard TiSa oscillator, $\Delta\lambda \approx$ 100nm + fibre amp and Raman-Soliton in PCF for 1030nm	- only one oscillator	- complexity of Raman-Soliton setup
Yb-oscillator, 1030nm, $\Delta\lambda$ < 10nm + Standard TiSa, $\Delta\lambda \approx$ 100nm	- jitter only depends on TiSa	- uneconomical
Yb-oscillator, 1030nm, $\Delta\lambda$ < 10nm + supercontinuum in YAG, $\Delta\lambda \approx$ 100nm	- one oscillator with proven longterm stability and low jitter - efficient and economic	- unknown, if jitter of compressed supercontinuum is worse than that of oscillator.

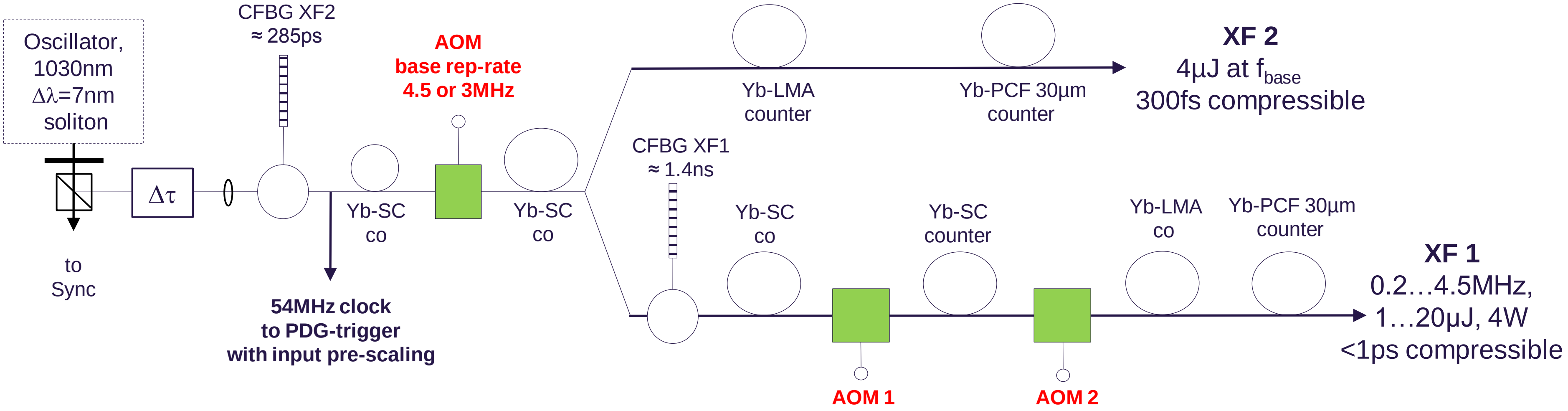
Pump amplifier seed	Pros	cons
Yb regenerative amplifier	- energy scaling at constant power is easy, moderate CPA	- drift due to long length - 4.5MHz switching …
Yb rod-type-fibre amplifier	- envisaged energy scaling at constant power is easy - no rep-rate limitation	- bulk-like, not all-in-fibre - need substantial CPA
Yb all-fibre amplifier	- high thermomechanical stability - no rep-rate limitation	- energy scaling at constant power is not straight forward, need substantial CPA.

Burst-mode fibre front-end conceptual design



- Low jitter soliton seeder oscillator
- CPA using CFBG stretchers
- XF1: variable rep-rate / energy pump pulses
- XF2: base rep-rate f_{base} for SCG
- All polarization maintaining (PM-) fibres
- Amplifiers operate in burst-mode
- All required timing signals are derived from „Gate“

Burst-mode 1030nm CPA fibre front-end



Oscillator,
1030nm
$\Delta\lambda$=7nm
soliton

$\Delta\tau$

to
Sync

CFBG XF2
≈ 285ps

54MHz clock
to PDG-trigger
with input pre-scaling

Yb-SC
co

AOM
base rep-rate
4.5 or 3MHz

Yb-SC
co

Yb-LMA
counter

Yb-PCF 30µm
counter

XF 2
4µJ at f_{base}
300fs compressible

CFBG XF1
≈ 1.4ns

Yb-SC
co

AOM 1

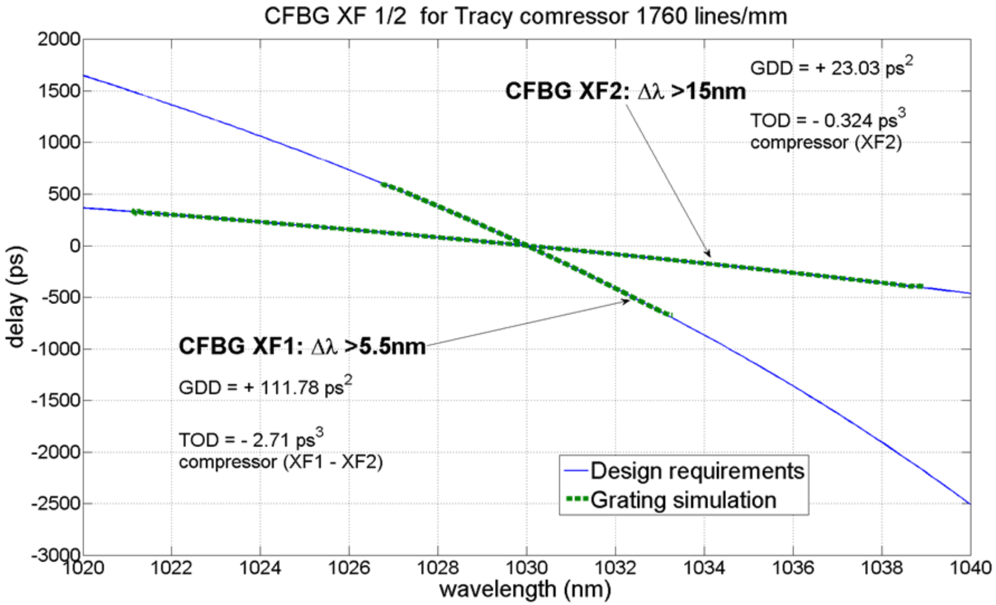
Yb-SC
counter

AOM 2

Yb-LMA
co

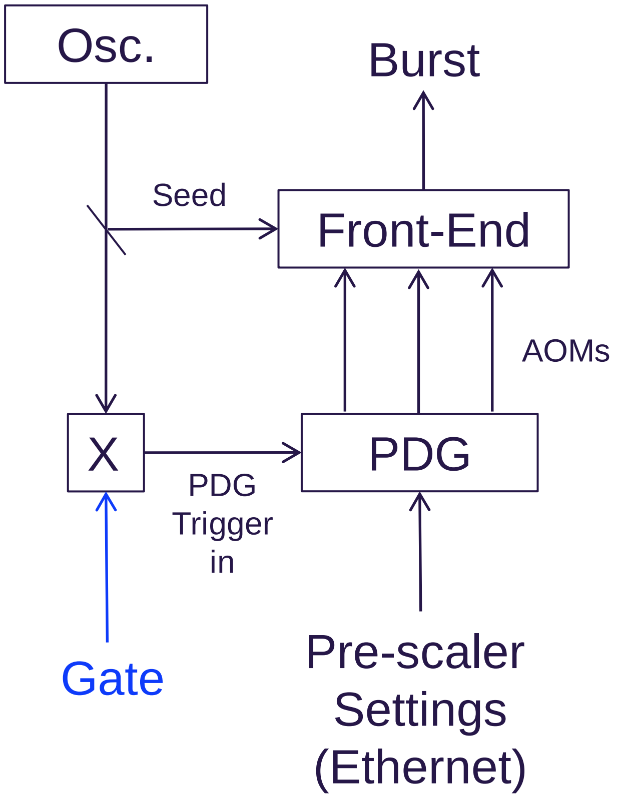
Yb-PCF 30µm
counter

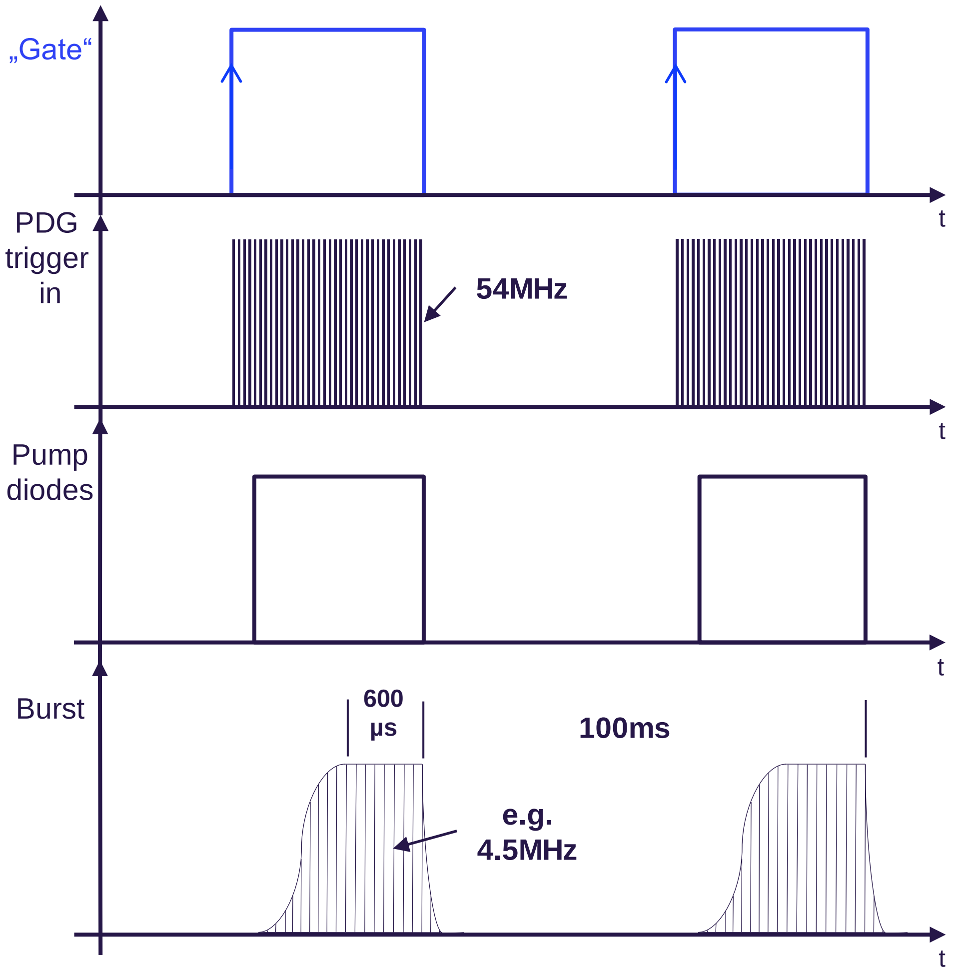
XF 1
0.2…4.5MHz,
1…20µJ, 4W
<1ps compressible



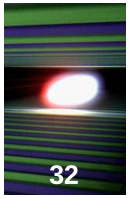
- XF2 base rep-rate of 4.5 and 3MHz possible.
- Various XF1 rep-rates through AOM1 and AOM2 plus gain adjustments.
- Apodized PM-CFBGs with GD conjugate to compressors.

Burst-mode 1030nm CPA fibre front-end timing





Simulation of 1030nm CPA fibre front-end



Model: Generalized Nonlinear Schrödinger Equation

(e. g.: G. P. Agrawal, „Nonlinear fiber optics“, (2007), AP)

gain and losses

Dispersion
(GDD, TOD, FOD, etc.)

SPM

Raman

Shock

$$\frac{\partial A(z,t)}{\partial z} = \left(\frac{g(z)-\alpha(z)}{2}\right)A + \left(\sum_{n=2}\frac{(i)^n}{n!}\cdot\delta(z)_n\cdot\frac{\partial^n A}{\partial t^n}\right) + i\cdot\left(\sum_{n=2}\frac{(i)^n}{n!}\cdot\beta(z)_n\cdot\frac{\partial^n A}{\partial t^n}\right) + i\gamma(z)\left(|A|^2 A - T_R\frac{\partial |A|^2}{\partial t}A + \frac{2i}{\omega_0}\frac{\partial}{\partial t}\left(|A|^2 A\right)\right)$$

A(z,t) is scalar field
envelope, slowly
varying along z.

gain filter and
passive filters
(CFBGs, etc.)

$$\gamma = \frac{\omega_0 n_2}{cA_{eff}}$$

γ : nonlinear refractive coefficient
A_{eff} : fiber effective area.

Assumption: Optical field maintains its polarization

Numerical method: split-step FFT

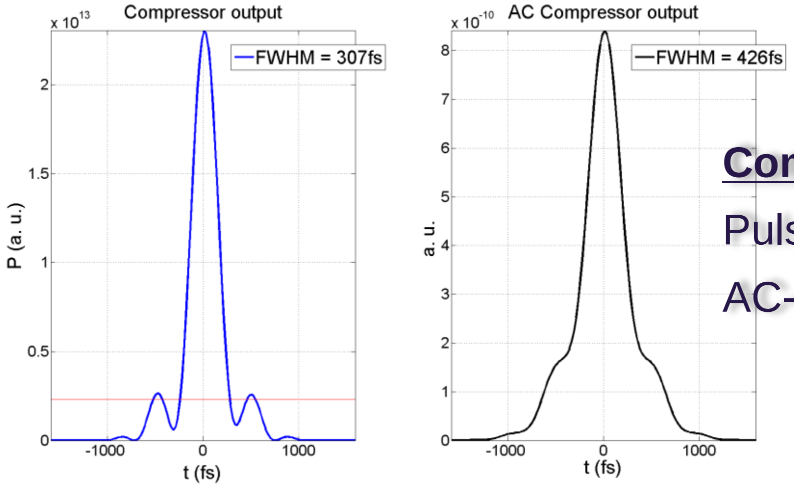
For front-end simulations: Raman, shock are negligible, exponential gain distributions along fibres.

Purpose: assist in system design (e. g. CFBG chirp/bandwidth, permissible fibre lengths and types, etc. for compressibility).

Some fibre-CPA simulation results: XF2

Typical case (long PCF, some gain narrowing):

Pulse energy:	3.3µJ
Bandwidth:	6nm
Rep-rate:	4.5MHz
B-integral:	3.5



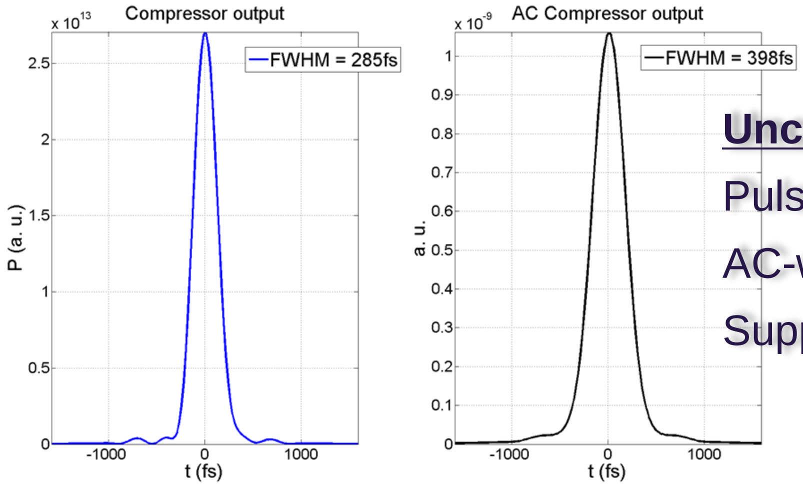
Compensated FOD:

Pulsewidth: 307fs

AC-width: 426fs

Limiting factors:

- SPM
- Gain narrowing
- Poor FOD control



Uncompensated FOD:

Pulsewidth: 285fs

AC-width: 398fs

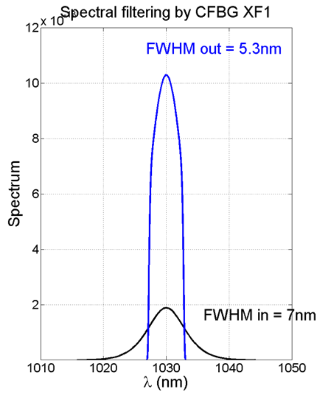
Suppr. SPM-satellites.

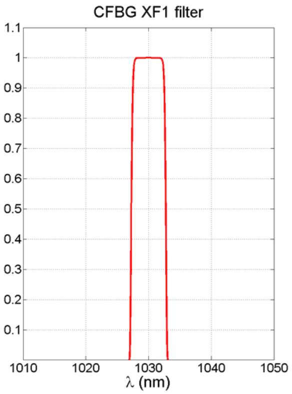
Similar to TOD:
S. Zhou et al,
Opt. Expr. 13, 4869, (2005).

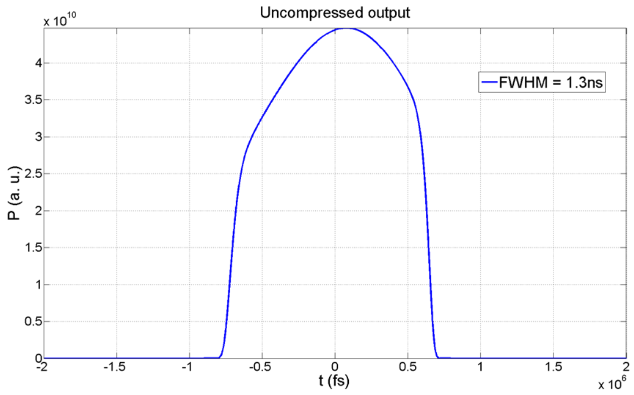
Some fibre-CPA simulation results: XF1

Typical worst case (highest pulse energy):

Pulse energy:	20µJ
Bandwidth:	5nm
Rep-rate:	200kHz
B-integral:	11.8

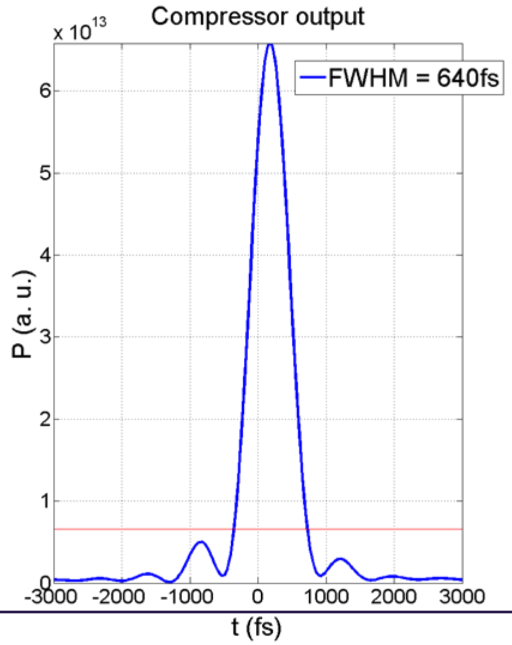


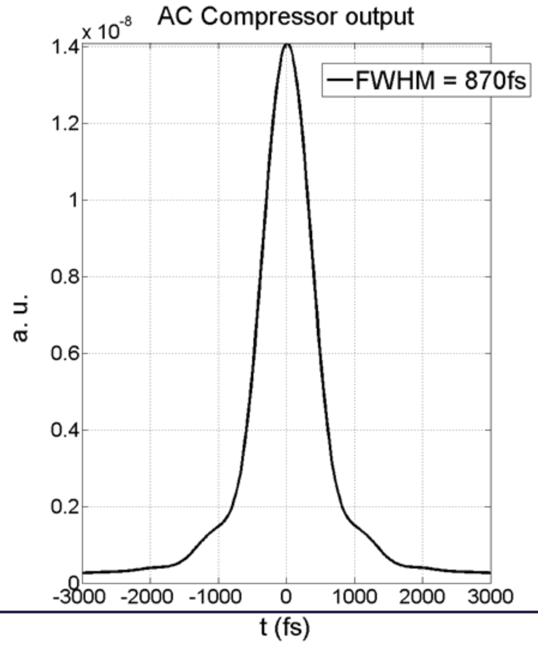




Limiting factors:

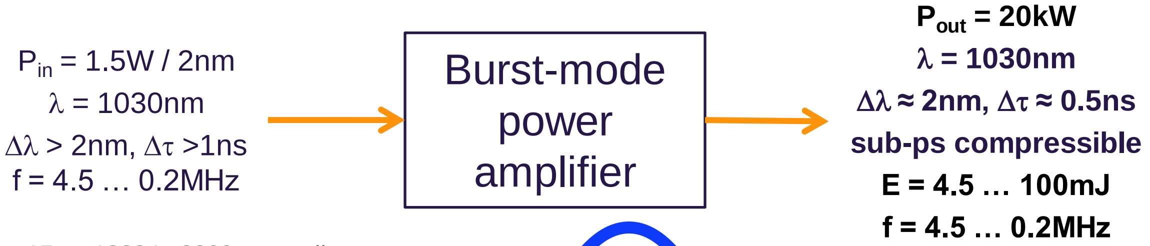
- SPM
- CFBG bandwidth





Burst-mode 1030nm CPA power amplifier

Requirements and options for a burst-mode power amplifier



P_{in} = 1.5W / 2nm
λ = 1030nm
$\Delta\lambda$ > 2nm, $\Delta\tau$ >1ns
f = 4.5 … 0.2MHz

Burst-mode power amplifier

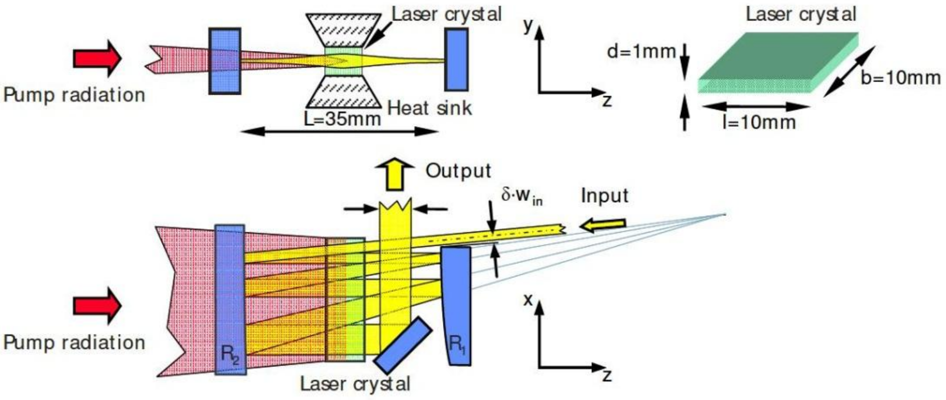
P_{out} = 20kW
λ = 1030nm
$\Delta\lambda \approx$ 2nm, $\Delta\tau \approx$ 0.5ns
sub-ps compressible
E = 4.5 … 100mJ
f = 4.5 … 0.2MHz

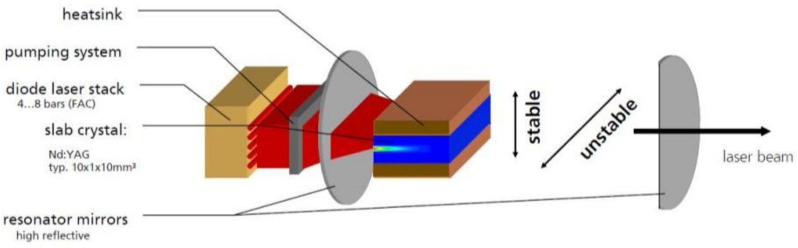
OPTICS EXPRESS, Vol. 17, No. 15, p. 12234, 2009 as well as own.

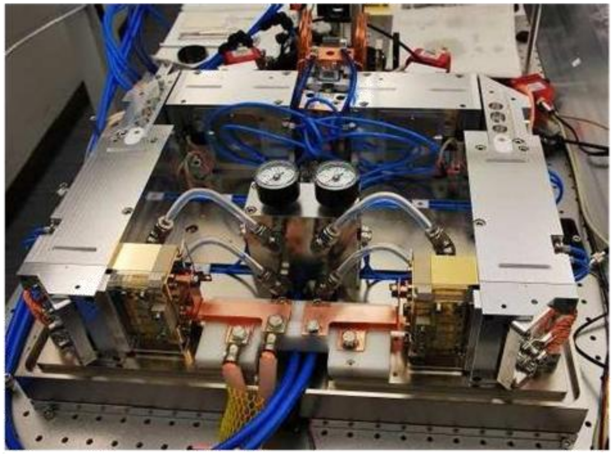
Amp. Technology / Property	Yb-Fibre	Yb-Fibre + coherent combining	Yb:YAG InnoSlab	Yb:XXX Thin-Disk		Cryo-XXX
				Regen	Multi-pass	
TEM$_{00}$ av. power	++	++	+	+	+	+
CPA pulse energy	– –	??	+	+	+	+
Sub-ps capable	+	+	+	**+**	+	– –
MHz rep-rate	++	++	++	– –	++	++
Gain / amp-length	++	++	++	– –	– –	++
Thermal transients	++	++	0	0	0	0
Complexity	+	– –	0	–	–	LN$_2$
Availability (near term)	+	– –	+	+	+	–

The InnoSlab concept

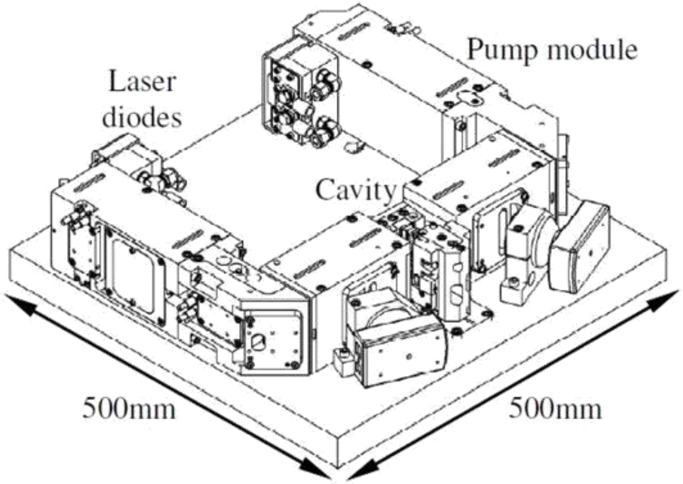
- Multi-pass stabilized by therm. lens in fast axis.
  - ➔ constant beam size.
- No thermal lens in slow axis.
  - ➔ increasing beam size.
- Intensity always around saturation.
  - ➔ Efficient extraction.







2009 Prototype setup at ILT



Yb:YAG InnoSlab amplifiers: state of the art

- First 50W Nd:YVO$_4$ amplifier in 2000 by Fraunhofer ILT, Aachen [1].
- First Yb:YAG picosecond amplifiers in 2007 by Fraunhofer ILT, Aachen [2].
- **Current state of the art Yb:YAG InnoSlab amplifiers :**
  - ✓ >600W, ~600fs, 20MHz from a single amplifier module with multi-passes.
  - ✓ 1100W total power or >500W power extraction (~600fs, 20MHz) from a booster amplifier with a single pass [3]
  - ✓ 20mJ @ 2.25ns with 250W average power [4]
  - ✓ non-saturated single pass gain >10 shown [5]
  - ✓ Saturated gain approaching a value of 2 with a single pass power extraction of >40%
  - ✓ damage threshold of the optics used exceeds 5J/cm^2 (@ 2,25ns)

[1] J. Giesekus et al, "High power diode end pumped slab MOPA system," CLEO, paper CThI3, (2001)
[2] P. Rußbüldt et al, "High Power Yb:YAG Innoslab fs-Amplifier", CLEO, paper CTuK5, (2008)
[3] P. Rußbüldt et al, "Compact diode-pumped 1.1 kW Yb:YAG Innoslab femtosecond amplifier," Opt. Lett. **35**, 4169-4171 (2010)
[4] M. Schulz et al, "Yb:YAG Innoslab amplifier: efficient high repetition rate subpicosecond pumping system for optical parametric chirped pulse amplification," Opt. Lett. **36**, 2456-2458 (2011)
[5] P. Russbueldt et al, "400W Yb:YAG Innoslab fs-Amplifier," Opt. Express **17**, 12230-12245 (2009)

InnoSlab 20kW Burst-mode booster feasibility study

- AMPHOS GmbH (ILT spin-off) was commissioned to show feasibility of an Yb:YAG InnoSlab amplifier system with these core parameters:

Burst-rate:	10Hz
Burst length:	200µs … 1ms
Burst av. Power:	>20kW
Intra-burst:	100kHz or higher
Pulse energy:	200mJ or lower
P_{in}	1.5W / 2nm
Pulse duration:	500ps
M^2	<1.5, round, smooth

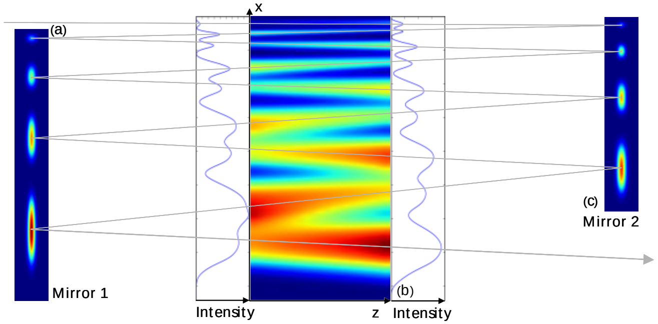
- **Calculated effects include:**
  - Amplification (3D gain model)
  - Thermally induced stress (3D thermo-mechanical FE-simulations)
  - Thermal lensing (bulging and refractive), calculated and compared with known standard.
  - Dynamic thermal lensing and path length variation during burst.
  - B-Integral

- **Design constraints:**
  - Beam quality limitations of the pump source
  - ASE and parasitic lasing
  - Cost and lifetime of pump diodes
  - Complexity and cost of pumping optics
  - Exchangeability of pump diodes
  - Handling, availability and cost of laser crystals

- **Output:**
  - System design
  - Cost estimation and time-line.
  - Risk analysis

Gain simulations

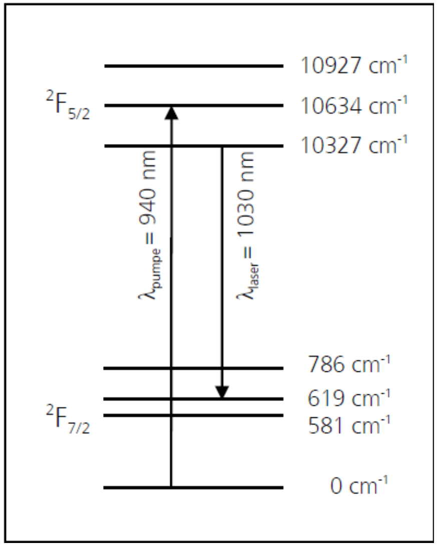
- 3d intensity distribution (laser/pump) inside crystal
- in good areement with standard Amphos400



- recursive calculation of steady state solution (quasi-three-level-scheme*):

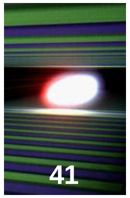
$$\frac{1}{\alpha_p L}\frac{I_p}{I_p^{Sat}}\left(1-\exp\left(\alpha_p\left(\beta-f_p\right)L\right)\right)+\frac{1}{\alpha_l L}\frac{I_l}{I_l^{Sat}}\left(1-\exp\left(\alpha_l\left(\beta-f_l\right)L\right)\right)-\beta=0$$

λ_{Pump}	λ_{Laser}	σ_{Abs}(940nm; 300K)	σ_{Ems}(940nm;300K)	σ_{Abs}(1030nm;300K)	σ_{Ems}(1030nm;300K)
940nm	1030nm	$0.7*10^{-20}cm^2$	$0.2*10^{-20}cm^2$	$0.15*10^{-20}cm^2$	$2.0*10^{-20}cm^2$
τ	n_{YAG}	$n_{2\,YAG}$	dn_{YAG}/dT	ρ_{Yb3+}(1%)	
951µs	1.82	$9.34*10^{-16}cm^2/W$	$7.3*10^{-6}\ K^{-1}$	$1.38*10^{20}cm^{-3}$	



*Gilbert L. Bourdet "Theoretical investigation of quasi-three-level longitudinally pumped continuous wave lasers", Applied Optics (2000)

Thermo-mechanical simulations



- ANSYS Workbench Simulation
- Standard (Material-)Parameters:

Density	Thermal Expansion Coefficient @22°C	Youngs Modulus	Thermal Conductivity[8]
4,56g/cm³	7,8*10⁻⁶K⁻¹	3*10¹¹Pa	10W/(m*K)@-23°C 8,6W/(m*K)@27°C
Specific Heat[8]	**Poisson Ratio**	**Heating Ratio**	**Heat Sink Temperature**
574J/kg*K	0.3	15%	22°C

- (transient) Temperature-Gradient for
  - ➔ thermal lens

$$f_{th} = \frac{r_{pump}^{2}}{2\frac{dn_{YAG}}{dT}L_{crystal}}\frac{1}{\Delta T}$$

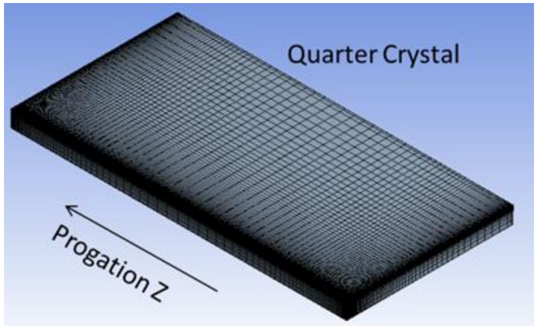
  - ➔ Optical path length

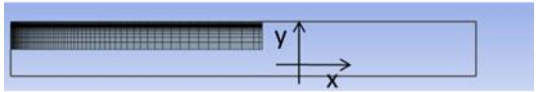
$$\Delta L_{opt\_total} = n_{YAG}\cdot\Delta z_{mech} + \frac{dn_{YAG}}{dT}\cdot\Delta T_{avg}\cdot L_{crystal}$$

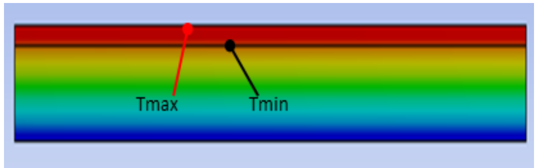
- Thermally induced stress for
  - ➔ Mechanically induced lens (bulging)

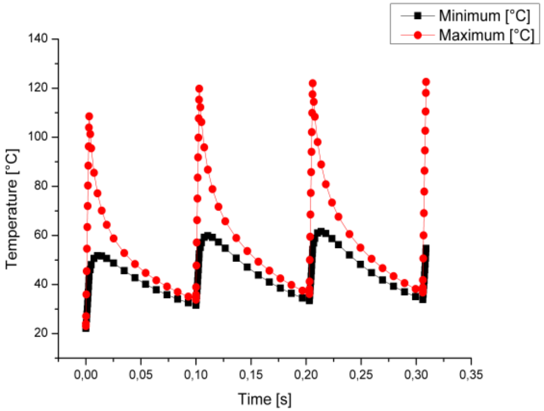
$$f_{mech} = \frac{r_{crystal}^{2}}{2(n_{YAG}-1)\Delta z_{mech}}$$

  - ➔ Fracture limit
    (Tensile Stress for thermal fracture of YAG-rod: 120MPa-240MPa*)



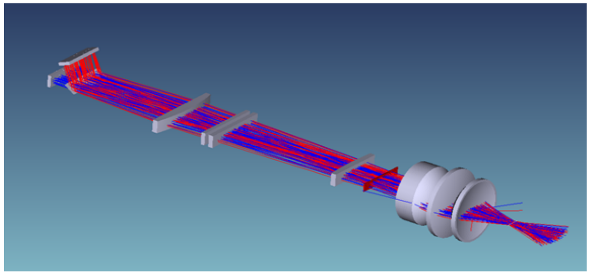


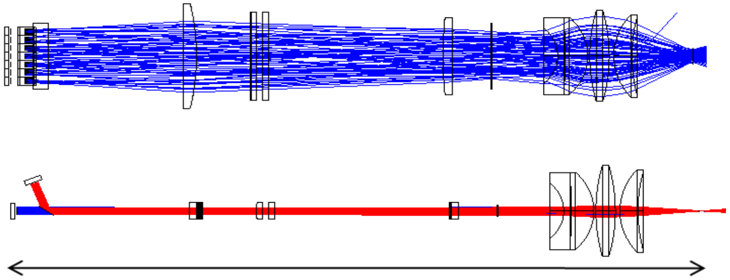




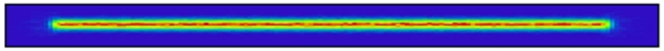
*R. Weber, B. Neuenschwander, H. P. Weber, Thermal effects in solid-state laser materials, Optical Materials, Volume 11, Issues 2-3, January 1999, Pages 245-254

Pump diodes and optics

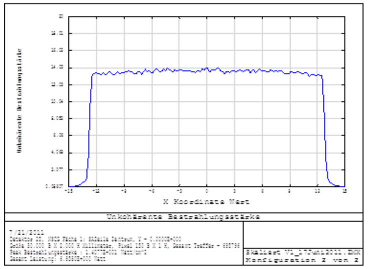




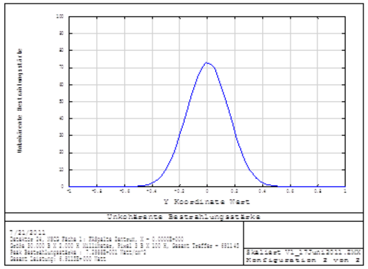
Total length app. 1m



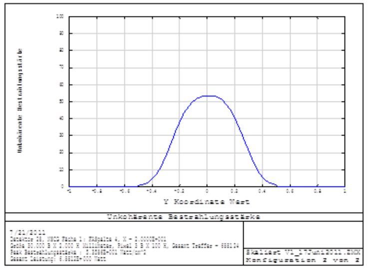
Intensity profile slab entrance



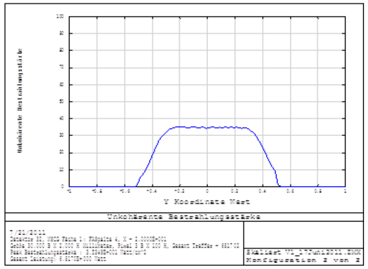
Slow-axis



Fast-axis entrance

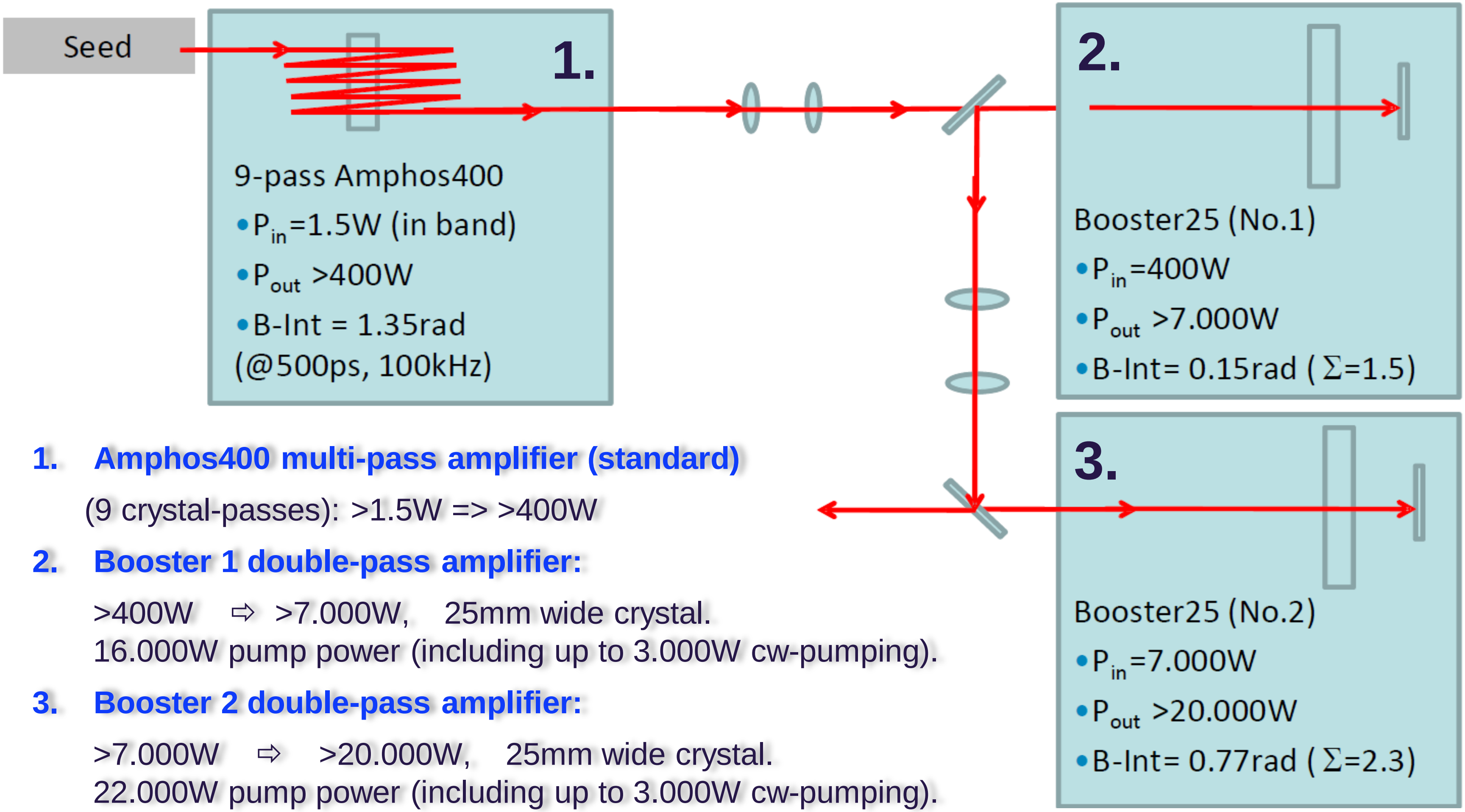


FA 5mm



FA 10mm

InnoSlab 20kW Burst-mode booster conceptual design



9-pass Amphos400
- P_{in}=1.5W (in band)
- P_{out} >400W
- B-Int = 1.35rad (@500ps, 100kHz)

Booster25 (No.1)
- P_{in}=400W
- P_{out} >7.000W
- B-Int= 0.15rad (Σ=1.5)

Booster25 (No.2)
- P_{in}=7.000W
- P_{out} >20.000W
- B-Int= 0.77rad (Σ=2.3)

1. **Amphos400 multi-pass amplifier (standard)**

   (9 crystal-passes): >1.5W => >400W
2. **Booster 1 double-pass amplifier:**

   >400W ⇨ >7.000W, 25mm wide crystal.
   16.000W pump power (including up to 3.000W cw-pumping).
3. **Booster 2 double-pass amplifier:**

   >7.000W ⇨ >20.000W, 25mm wide crystal.
   22.000W pump power (including up to 3.000W cw-pumping).

➔ **Variation in total optical path length is below 5µm (~17fs) for the last 1ms of the pump pulse.**

➔ **Variation of the length of the thermal lens can be kept below 10% during this time window.**

Simulation of booster output pulse shape

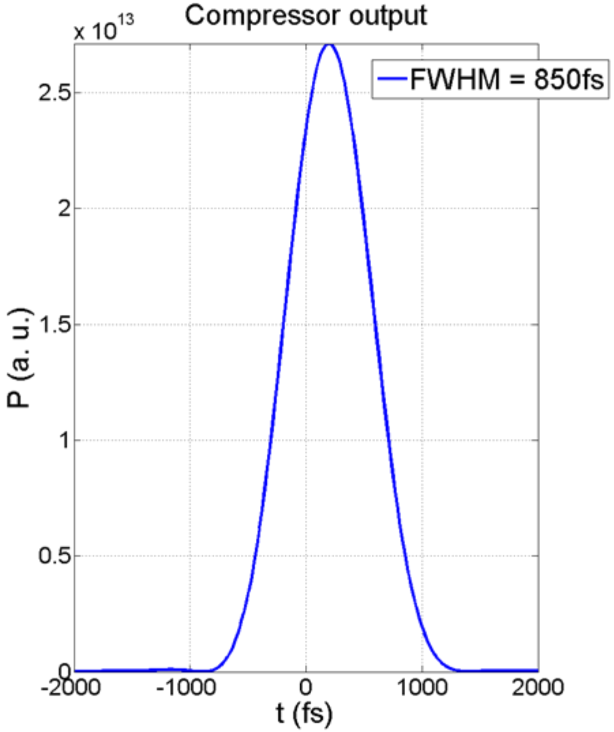
Output of XF1:

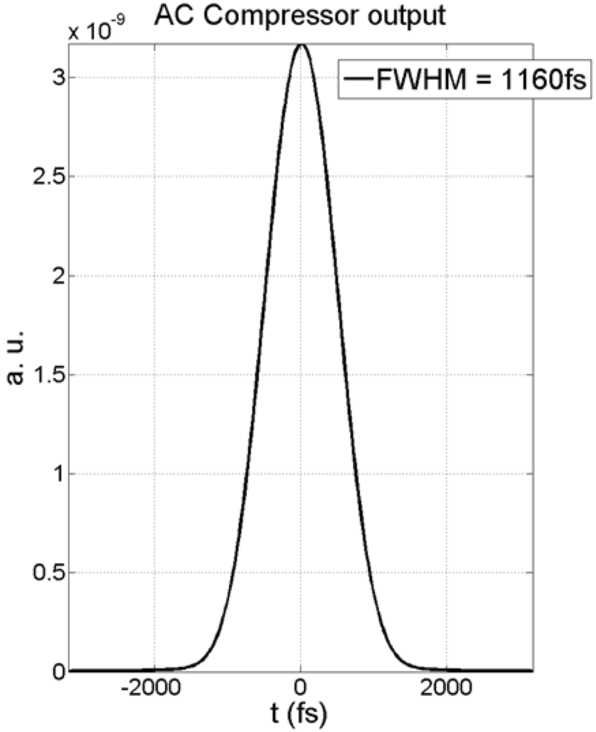
Inulse energy:	20µJ
Rep-rate:	200kHz
B-integral:	11.8
Bandwidth:	5nm
Pulsewidth:	1.3ns

↓

Gain-filter

↓

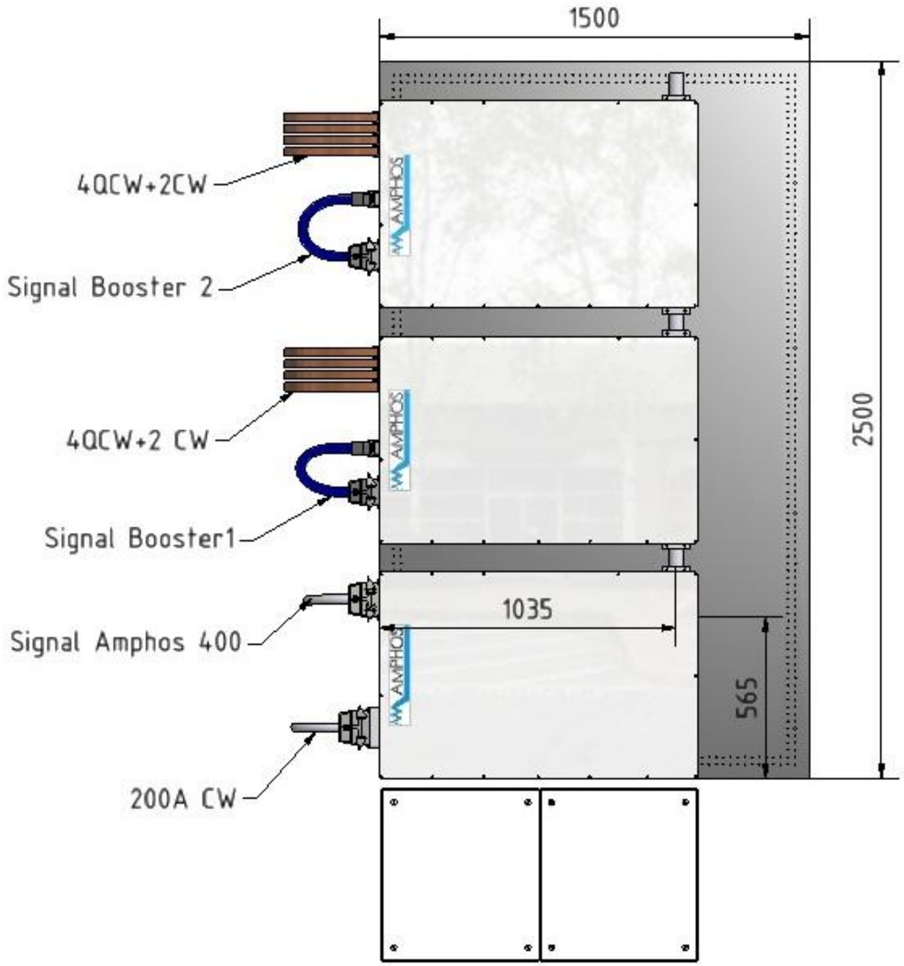




Output pulse:

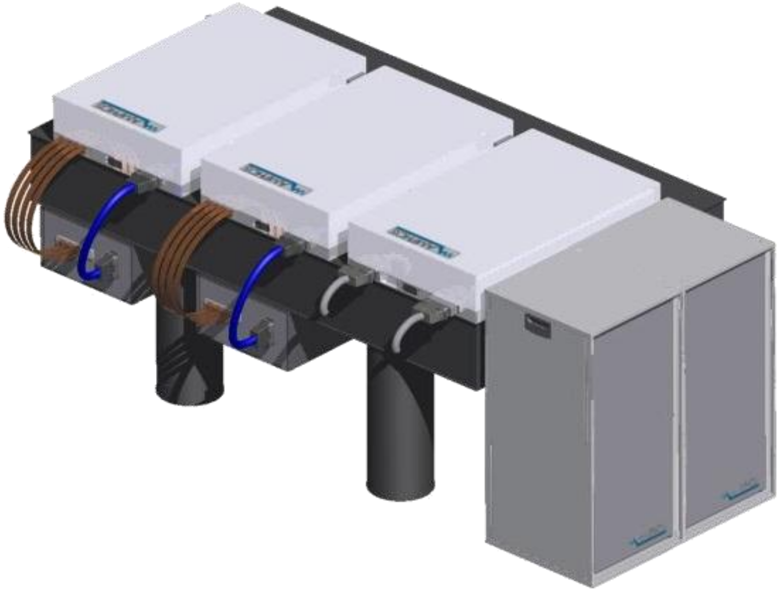
Bandwidth:	2nm	Compressed pulsewidth:	850fs
Uncompressed pulsewidth:	0.5ns	AC-width:	1160fs

InnoSlab 20kW Burst-mode booster CAD



Shutter-box at output will include:

- Potential-free shutter: „Guillotine“
- Water-cooled beam dump
- Motorized attenuator
- Fast PD
- Average power
- Port for beam pointing measurement



Multi-stage NOPA

NOPA basics

- Use non-collinearity with angle α between pump and signal to match the group velocity of signal and idler over larger bandwidth.
- Typical nonlinear materials: BBO, BIBO, LBO, KD*P

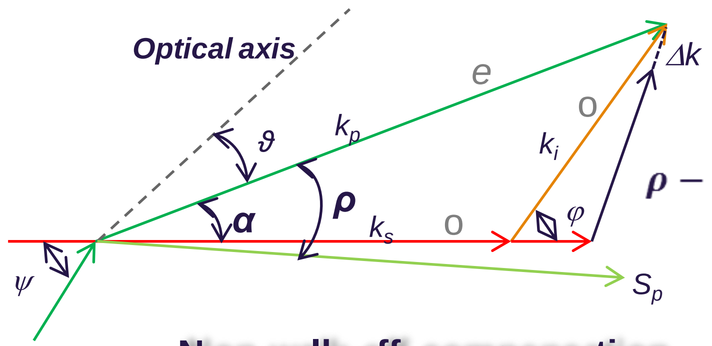
1. A. Dubietis, G. Jonusauskas, A. Piskarskas, Opt. Comm. 88, 437 (1992)
2. T. Wilhelm, J. Piel, E. Riedle: Opt. Lett. **22**, 1494 (1997)
3. G. Cerullo, M. Nisoli, S. De Silvestri: Appl. Phys. Lett. **71**, 3616 (1997)

$$\Delta\vec{k} = \vec{k}_p - \vec{k}_s - \vec{k}_i$$

phase-matching:

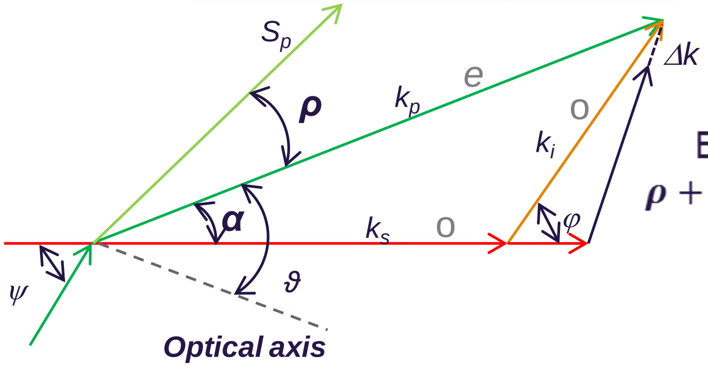
$\Delta k = 0$

Walk-off compensation

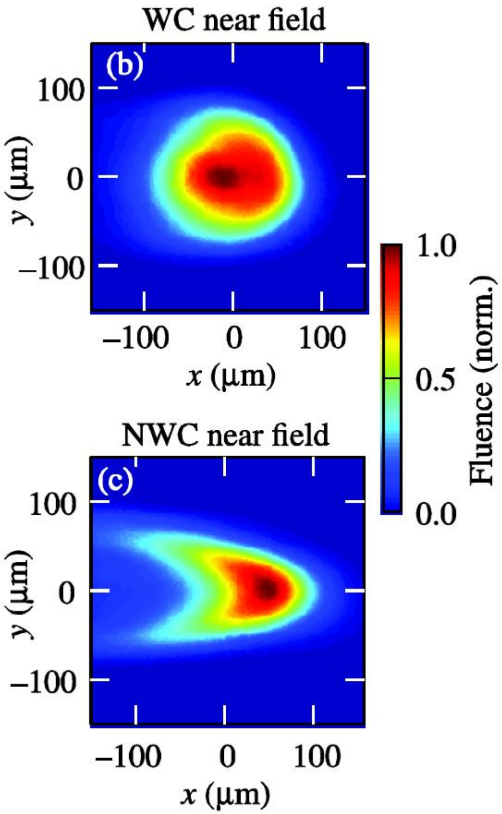


BBO
$\rho - \alpha$ = 0.75°

Non-walk-off compensation

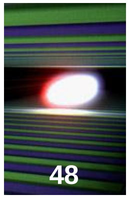


BBO
$\rho + \alpha$ = 6°



J. Bromage et al, Vol. 19, Opt. Expr., 16797, (2011)

Multi-stage NOPA: choice of crystal



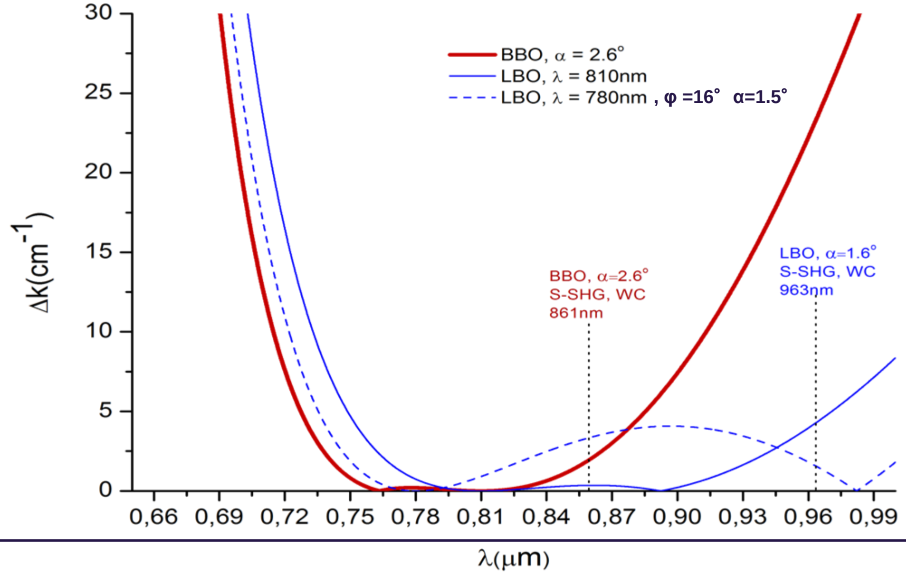
NOPA crystal	Pros	Cons
BBO **1st stage in WC** **2nd stage**	- Large bandwidth - High damage threshold - High gain - Medium apertures - Medium residual absorption	- Large walk-off - Parasitic SHG of signal and idler in WC
BiBO	- High gain	- Somewhat restricted bandwidth - Material quality is questionable
LBO **3rd + 4th stage**	- Large bandwidth - No parasitic SHG of signal and idler in WC - Medium to large apertures - Very low residual absorption - Small walk-off	- Low gain - Somewhat lower damage threshold
KD*P	- Very large apertures - Economical	- Low gain - High residual absorption

BBO

Optimised for 810nm,
θ = 24.7º (pump internal angle), φ= 90º
α=2.6º

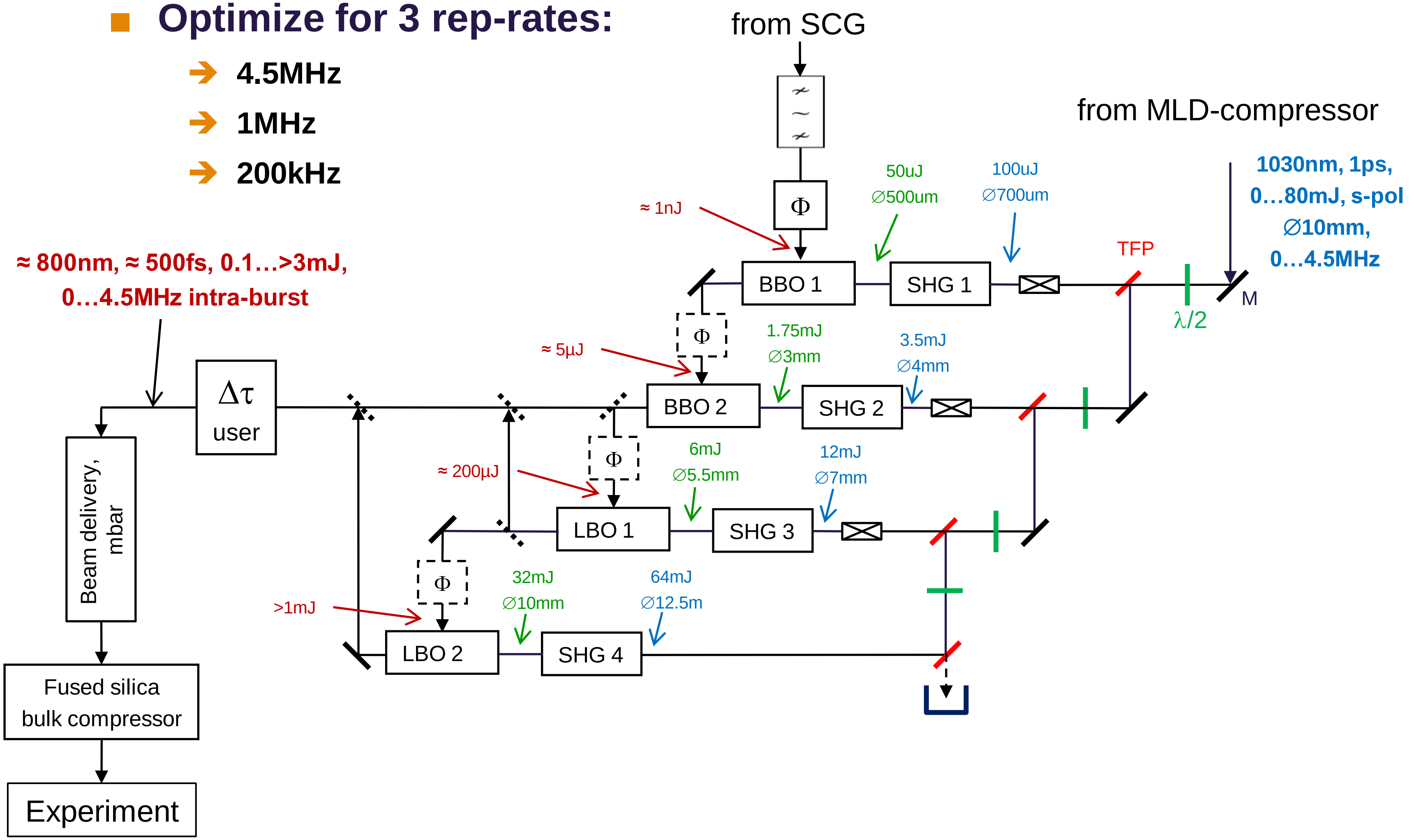
LBO

Optimised for 810nm
φ = 16.5º (pump internal angle), θ = 90º
α=1.6º



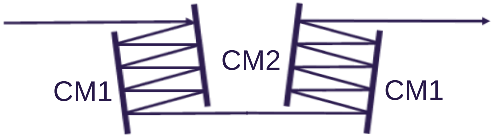
Multi-stage NOPA conceptual design

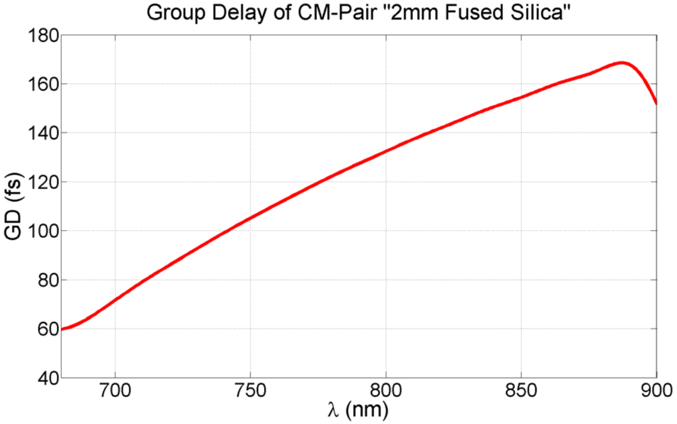
- **Optimize for 3 rep-rates:**
  - → **4.5MHz**
  - → **1MHz**
  - → **200kHz**



Dispersion and bandwidth management

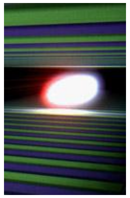
- Use passive dispersion management : chirped mirrors (CMs)
- Limit amplified signal bandwidth to 15fs (transform limited)
- Pre-chirp continuum before amplification
  - ➔ **Stretcher is made from compensated CM-pair.**
  - ➔ Amount of chirp is chosen to amplify ≈ 80nm by the ≈ 800fs pump pulse.
- Compressor: bulk fused silica at experiment.
  - ➔ **Fused silica is dominating element.**
  - ➔ **GDD / TOD ratio of BBO is similar to that of fused silica.**
  - ➔ **Use CM-design optimised for GDD and TOD to be conjugate to fused silica.**





- Flexibility of scheme:
  - ➔ **Bandwidth of CM-pair might support shorter pulses ⇨ reduce input chirp.**
  - ➔ For longer pulses ⇨ **increase input chirp** (≈ 15nm, i. e. 50fs compressed) .

Theoretical model of three wave mixing.



Time domain:

$$E(r,t) = \frac{1}{2}\sum\{\boldsymbol{e_m} A_m(r,t)\exp[i(\omega_{n0}t - \boldsymbol{k}_m r)] + c.c.\}$$

With m replaced by **s, p, i, ssh, ish**, the coupled equations in (r, t) space are :

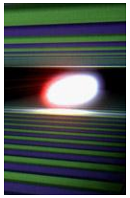
$$\begin{cases} \widehat{M_s} A_s = i\sigma_s A_i^* A_p \exp(i\Delta kz) - i\sigma_s A_s^* A_{ssh} \exp(-i\Delta k_{ssh} z) \\ \widehat{M_i} A_i = i\sigma_i A_s^* A_p \exp(i\Delta kz) - i\sigma_i A_i^* A_{ish} \exp(-i\Delta k_{ish} z) \\ \widehat{M_p} A_p = -i\sigma_p A_s A_i exp(-i\Delta kz) \\ \widehat{M_{ssh}} A_{ssh} = i\sigma_{ssh} A_s^2 \exp(i\Delta k_{ssh} z) \\ \widehat{M_{ish}} A_{ish} = i\sigma_{ish} A_i^2 \exp(i\Delta k_{ish} z) \end{cases}$$

Where

$$\widehat{M_m} = \frac{\partial}{\partial z} + \frac{\alpha_m}{2} + \rho_m \frac{\partial}{\partial x} + \frac{i}{2k_m}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) + \frac{1}{v_m}\frac{\partial}{\partial t} + \frac{i}{2}\beta_{2_m}\frac{\partial^2}{\partial t^2} + \cdots$$

α_m	absorption	$\rho_m = -1/n(\vartheta)*dn(\vartheta)/d\vartheta$	walk-off angle extra-ordinary wave,
v_m	goup velocity,	β_{2_m}	group velocity dispersion
$\sigma_n = \frac{\omega_n d_{eff}}{n_n c}$		Δk	phase mismatch at carrier frequencies

e. g. Dmitriev V.G., Gurzadyan G.G., Nikogosyan D.N. “Handbook of Nonlinear Optical Crystals”. Springer, Berlin, 1997.



Theoretical model of three wave mixing.

Frequency domain:

$$E(r,\omega) = \frac{1}{2}\sum\{E_m(r,\omega) + c.c\}$$

With m replaced by ***s, p, i, ssh, ish***, the coupled equations in (r, ω) space are:

$$\frac{\partial}{\partial z}E_s + \frac{\alpha_s}{2}E_s + \frac{i}{2k_I}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)E_s + ik_sE_s = i\sigma_s\mathcal{F}\{E_I^*E_P\} - i\sigma_S\mathcal{F}\{E_S^*E_{SSH}\}$$

$$\frac{\partial}{\partial z}E_I + \frac{\alpha_I}{2}E_I + \frac{i}{2k_I}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)E_I + ik_IE_I = i\sigma_I\mathcal{F}\{E_S^*E_P\} - i\sigma_I\mathcal{F}\{E_I^*E_{ISH}\}$$

$$\frac{\partial}{\partial z}E_P + \frac{\alpha_P}{2}E_P + \rho_P\frac{\partial}{\partial x}E_P + \frac{i}{2k_P}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)E_P + ik_PE_P = -i\sigma_P\mathcal{F}\{E_SE_I\}$$

$$\frac{\partial}{\partial z}E_{SSH} + \frac{\alpha_{SSH}}{2}E_{SSH} + \rho_{SSH}\frac{\partial}{\partial x}E_{SSH} + \frac{i}{2k_{SSH}}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)E_{SSH} + ik_{SSH}E_{SSH} = i\sigma_{SSH}\mathcal{F}\{E_SE_S\}$$

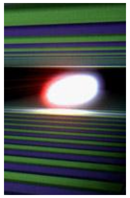
$$\frac{\partial}{\partial z}E_{ISH} + \frac{\alpha_{ISH}}{2}E_{ISH} + \rho_{ISH}\frac{\partial}{\partial x}E_{ISH} + \frac{i}{2k_{ISH}}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)E_{ISH} + ik_{ISH}E_{ISH} = i\sigma_{ISH}\mathcal{F}\{E_IE_I\}$$

Where

α_m	absorption	$\rho_m = -1/n(\vartheta)*dn(\vartheta)/d\vartheta$	walk-off angle extra-ordinary wave
$\sigma_m = \frac{\omega_m d_{eff}}{n_m c}$	nonlinear coefficient	$k_m = \frac{\omega_m n_m(\omega)}{c}$	propagation constant

e. g. J. Zheng, H. Zacharias, Appl. Phys. B 97, 765–779, (2009) European XFEL

Numerical Methods



Fourier space Method

- Calculations:
  - linear and nonlinear parts in $\{\omega, k_n\}$ space by Runge Kutta 4th order

☺ Standard solving technique like 4-order Runge Kutta

☹ Calculations of all equation components at the same time (time consuming).

☺ Error scales with power ~5 with the step size

1. S. C. Sheng and A. E. Siegman, “Nonlinear-optical calculations using fast-transform methods: second-harmonic generation with depletion and diffraction,”’Phys. Rev. A 21, 599–606 (1980)

Split Step Method

- Calculations:
  - linear parts analytical solution in $\{\omega, k_n\}$ space
  - nonlinear parts by Runge Kutta 4th order in time domain

☺ Standard solving technique like 4-order Runge Kutta

☺ Evaluation of linear propagation with FFT

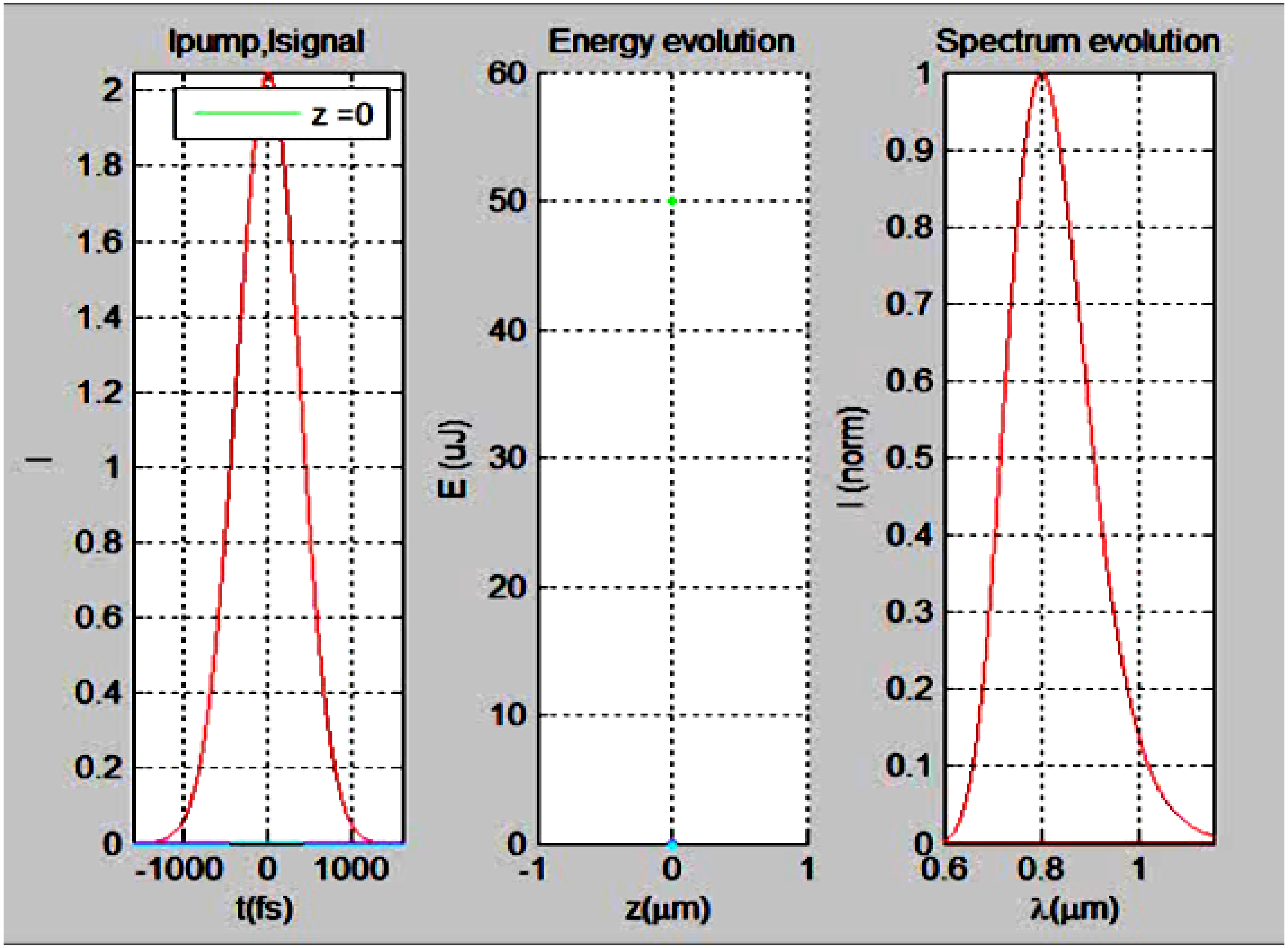
☺ Nonlinear differential for each spatial element independent

☹ Error scales with power ~2 with the step size

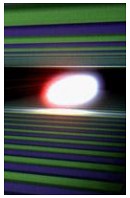
2. G. P. Agrawal, “Nonlinear Fiber Optics (3rd ed.) Academic Press, San Diego (2001).

3. G. Arisholm, “General numerical methods for simulating second-order nonlinear interactions in birefringent media,” **14**, J. Opt. Soc. Am. B, 2543, (1997)

Split-step Method (1D + time)

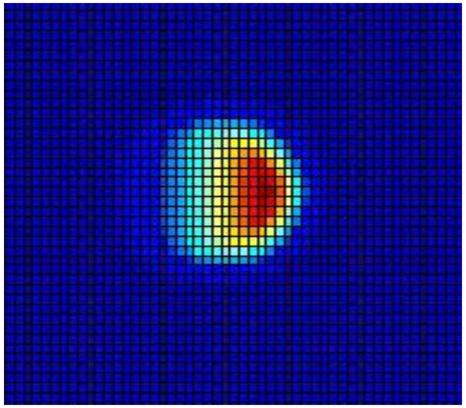


- BBO
- Walk-off compensation scheme
- Energy
- Temporal
- Spectral

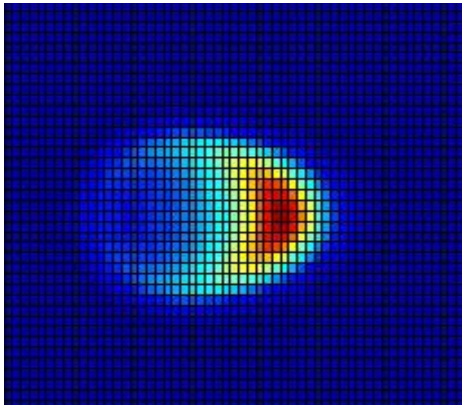


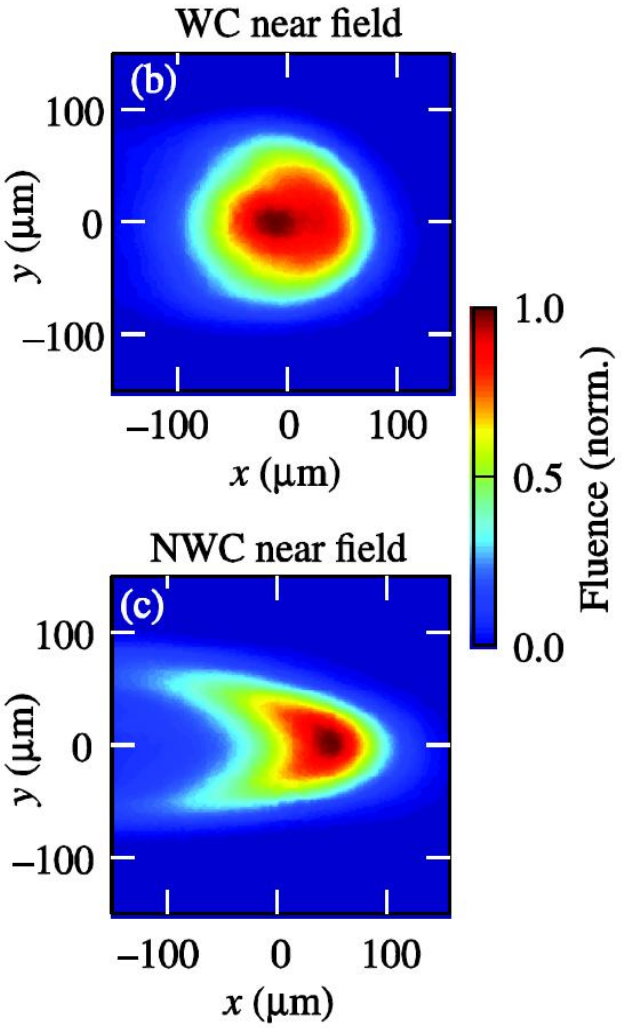
Fourier space method (3D+time)

WC near field



NWC near field





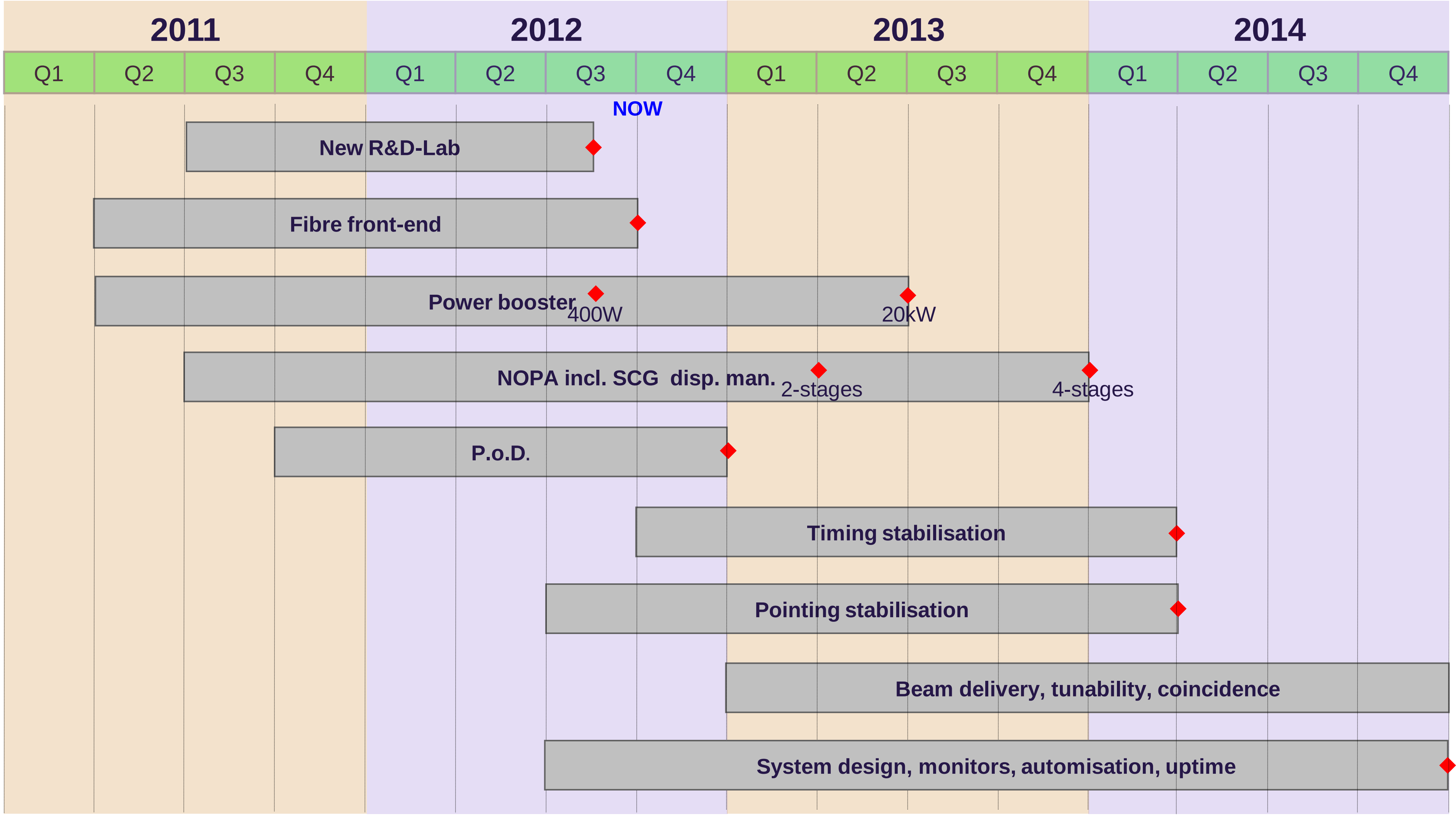
Simulations: nonlinear propagation code "Sisyfos", developed at Forsvarets ForskningsInstitutt:

G. Arisholm, "General numerical methods for simulating second-order nonlinear interactions in birefringent media," **14**, J. Opt. Soc. Am. B, 2543, (1997)

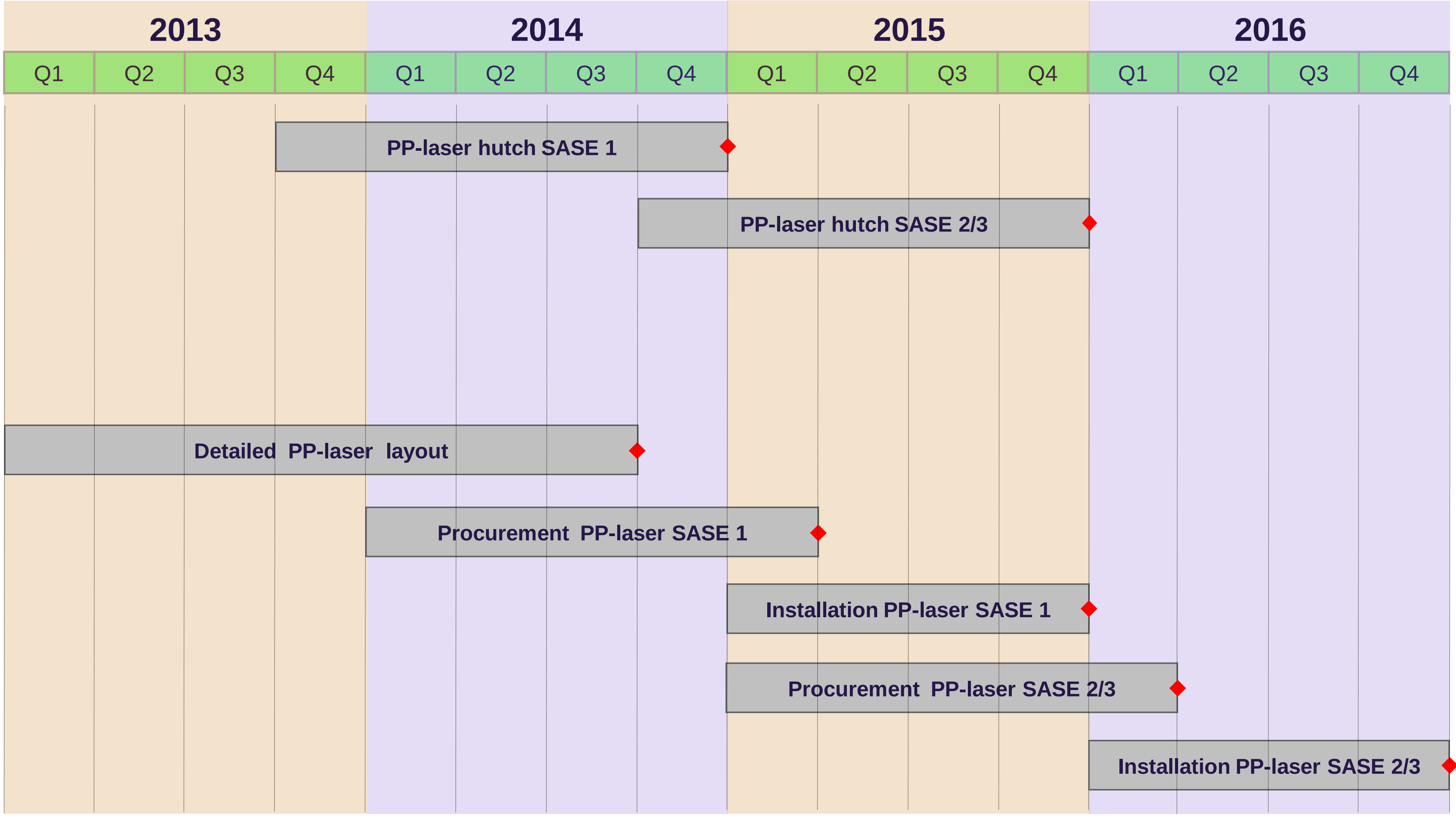
Experiment: "Analysis and suppression of parasitic processes in noncollinear optical parametric amplifiers" J. Bromage et al, Vol. 19, Opt. Expr., 16797, (2011)

Planning

Major mile stones in pump-probe laser R&D



Pump-probe laser installation plan



2013 2014 2015 2016

Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4

PP-laser hutch SASE 1

PP-laser hutch SASE 2/3

Detailed PP-laser layout

Procurement PP-laser SASE 1

Installation PP-laser SASE 1

Procurement PP-laser SASE 2/3

Installation PP-laser SASE 2/3

Conclusions

X-ray FELs for the soft and hard regimes have proven to show excellent beam properties. The European XFEL has started constructions and early experiments are scheduled for 2016.

◆

FEL science has only just started. Experiments have exploratory character and fields have to be established. In the soft x-ray regime this process is in full swing. Hard x-ray experiments only started in 2010. Coming years will enable to establish new fields.

◆

We are facing an exciting period of R&D at the highest level, including high power ultrafast laser development.

◆

Due to the burst-mode emission pattern of the European XFEL and the pulse requirements, the pump-probe laser development faces unique challenges, both technological as well as time line.

Thank You!