Lasers for External FEL Seeding (Experience and critical aspects of external laser seeding at FERMI)

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OUTLINE

- Introduction
- HGHG, EEHG, Direct seeding: brief comparison and ideal laser source parameters
- HGHG seeding
- Present solution at FERMI: system evolution and critical aspects
- Single cascade
- Double cascade
- Seed Laser Layout
- Synchronization aspects
- Beam transport and Dispersion Compensation aspects
- EEHG
- Layout used at FERMI
- Possible layout for implementation on FEL1
- Alternative laser sources for HGHG/EEHG
- Yb-based systems (DESY and X-FEL approach)
- Stretched Hollow-fibre based seed
- Conclusions

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INTRODUCTION

MAIN REQUESTS TO AN EXTERNALLY SEEDED EUV/SOFT X-RAY FEL

Wavelength range: 2-120 nm (~620-10 eV)
Continuous 'push-button' tunability 1-20% around the wavelength of interest
Energy Per pulse : 10-500 μJ

STABILITY

- **Wavelength stability: ~10^{-4}**
- **Pulse energy stability : <20% RMS acceptable, <10% RMS often requested and typically available, <5% RMS ideal**

SPATIAL QUALITY : close to Gaussian TEM_{00}

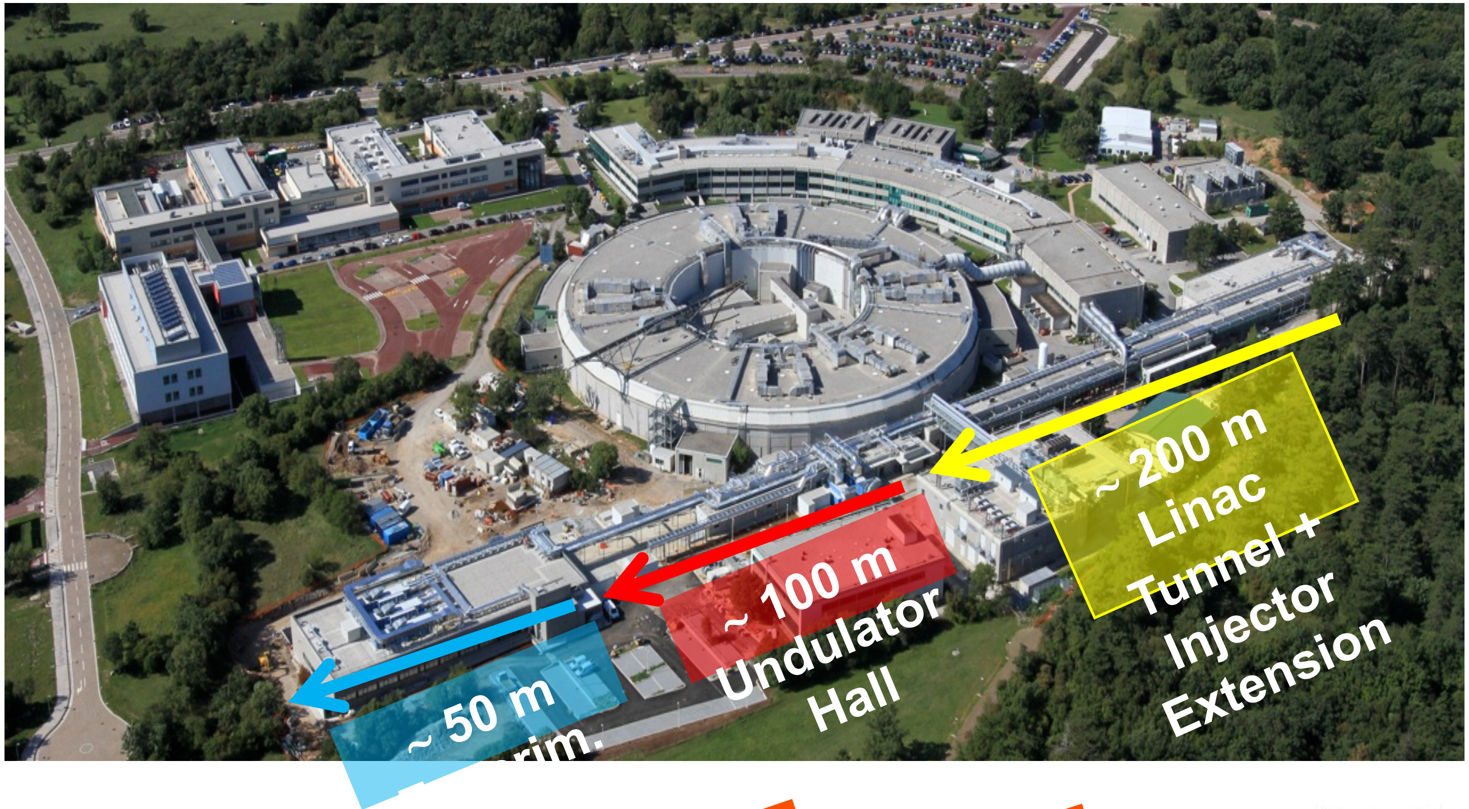
HIGH FLEXIBILITY

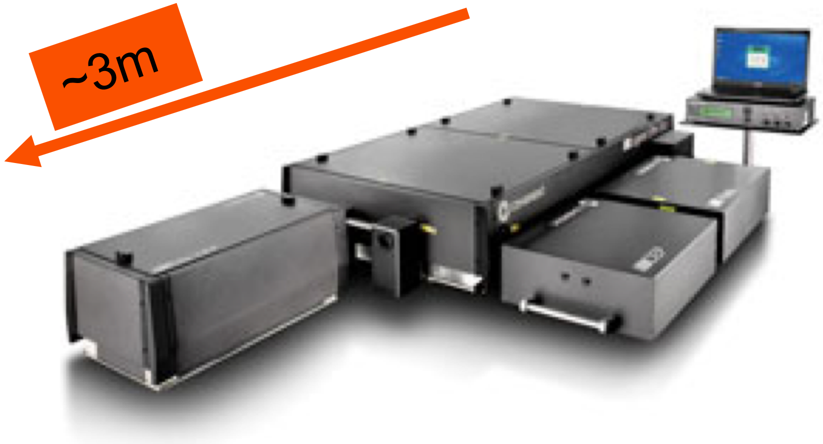
- **Pulse duration: few fs-1 ps**
- **Bandwidth: few meV-0.2 eV**
- **Bandwidth/pulse duration may be adjustable to user needs**
- **Possibility for double X-ray pulse generation with variable delay/wavelength**
- **Simultanous harmonics with fine-tunable phase relation**
- **Variable polarization**

ENABLING HIGH ACCURACY PUMP-PROBE EXPERIMENTS

- **Timing jitter with respect to a synchronized optical laser: <10 fs**

Seeded FEL



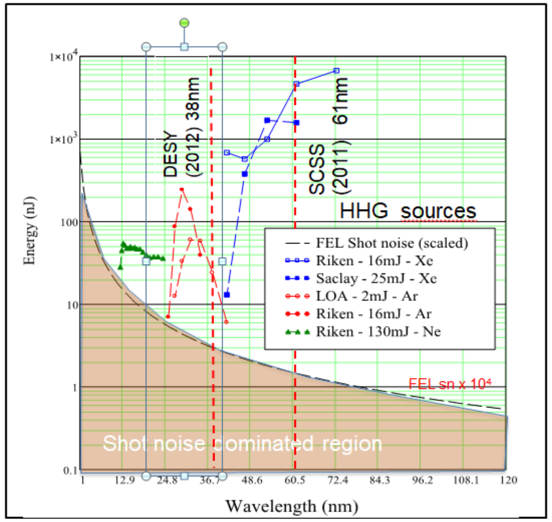


Femtosecond OPA

MAIN EXTERNAL SEEDING SCHEMES

❑ Direct (Injection) Seeding
$\lambda_{FEL} = \lambda_{seed}$
Pseed≥100xPspont
A TW-level pump laser is needed

Courtesy Luca Giannesy



- *data from B. Carré, Colloque AEC - Slicing, Paris 2004*
- *Shot noise estimate includes transport and matching to e-beam – Seeded FELs Workshop, Frascati 10-12 (2008)*

1-W. Boutu M. Ducousso, J.-F. Hergott and H. Merdji on HHG and 2-M.E. Couprie and L. G, on Seeded FELs, both in Springer Series in Optical Sciences 197 (2015) ISBN 978-3-662-47442-6 DOI 10.1007/978-3-662-47443-3

❑ **High Gain Harmonic Generation (**Yu, L. H., *Phys. Rev. A* **44** (1991)**)**
FERMI (4-110 nm), DALIAN (50-180 nm)
- **Seeding in the Deep UV range, P_{DUV}~200-500 MW -> 50-100 GW IR Pump laser**
- Seeding a cascade in the VUV-EUV , P ~400 kW ->TW level IR pump laser

(Dunning et al, *Journal of Mod.Optics* **16** (2011))

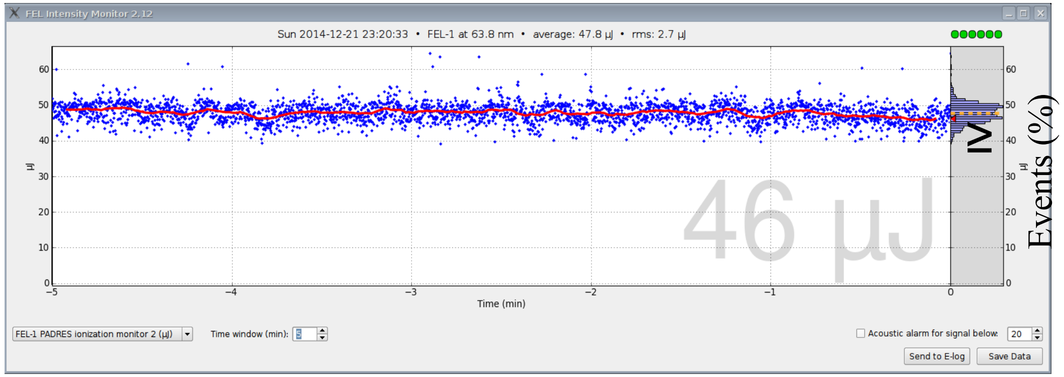
❑ **Echo Enabled Harmonic Generation (**G.Stupakov , Phys. Rev. Lett. **102**, 074801 (2009)**)**
- Seed 1 UV, Seed 2 Deep UV, P_{DUV}~200-500 MW -> 50-100 GW IR Pump laser

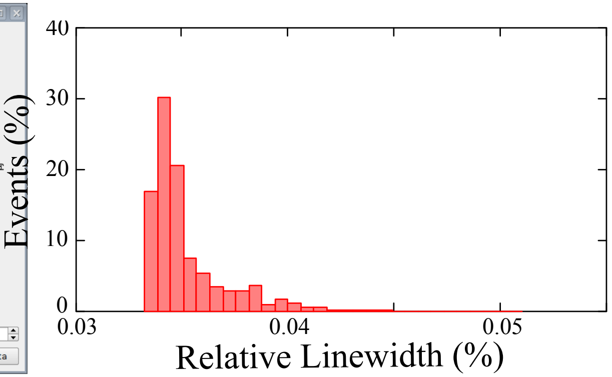
❑ Enhanced SASE , Slicing, …

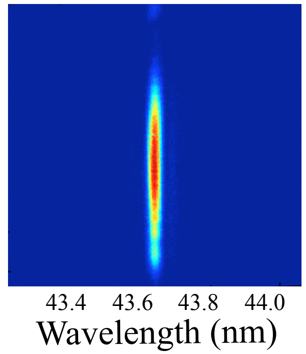
HGHG EXTERNAL SEEDING

SINGLE STAGE (e.g. FERMI FEL1)

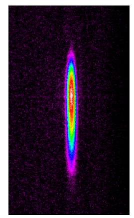
-Wavelength range 15-120 nm , H=3-15, typical energy per pulse 25-500 uJ (up to 1.2mJ)

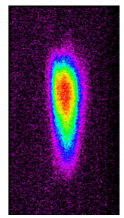


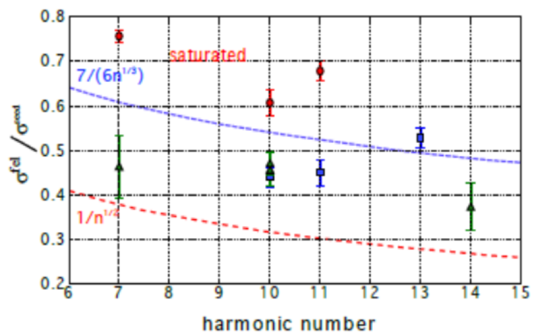


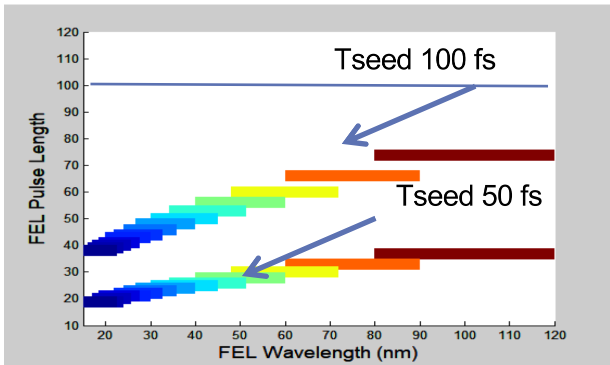


-FEL Pulse duration $T_{SEED}*n^{-1/2} < T_{FEL} < (7/6)\, T_{SEED}*n^{-1/3}$









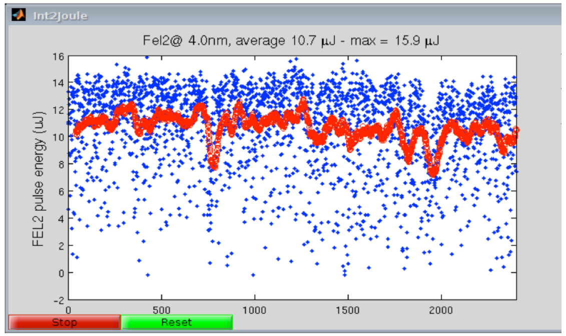
IDEAL SEED

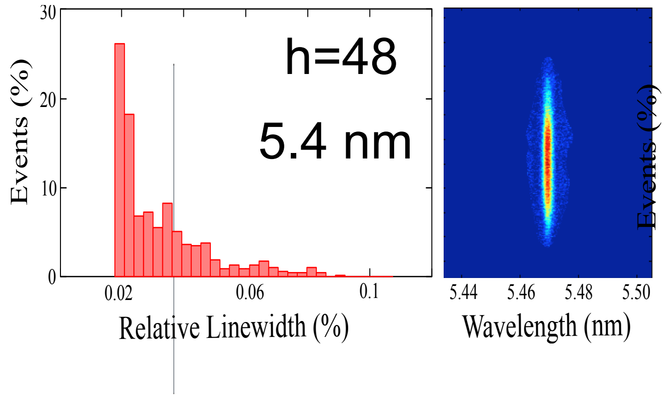
- λ=240-360 nm
- P≥150 MW in Modulator (i.e. ≥ 300 MW at the souce)
- $\Delta\lambda/\lambda \sim 10^{-4}$
- $\Delta P/P \leq 1\text{-}2\times10^{-2}$
- 2-3 different nearly TL pulse duration and chirp options

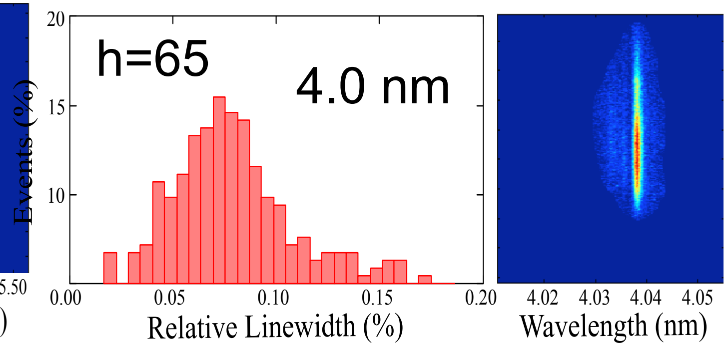
HGHG EXTERNAL SEEDING

DOUBLE CASCADE FRESH-BUNCH (e.g. FERMI FEL2)

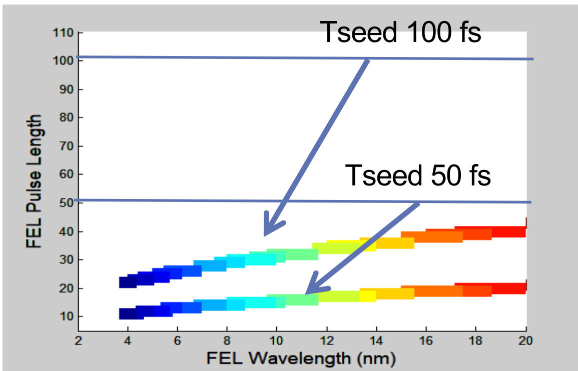
-Wavelength range 4-20 nm , H=12-65 (excluding prime numbers) , typical energy per pulse 10-100 uJ







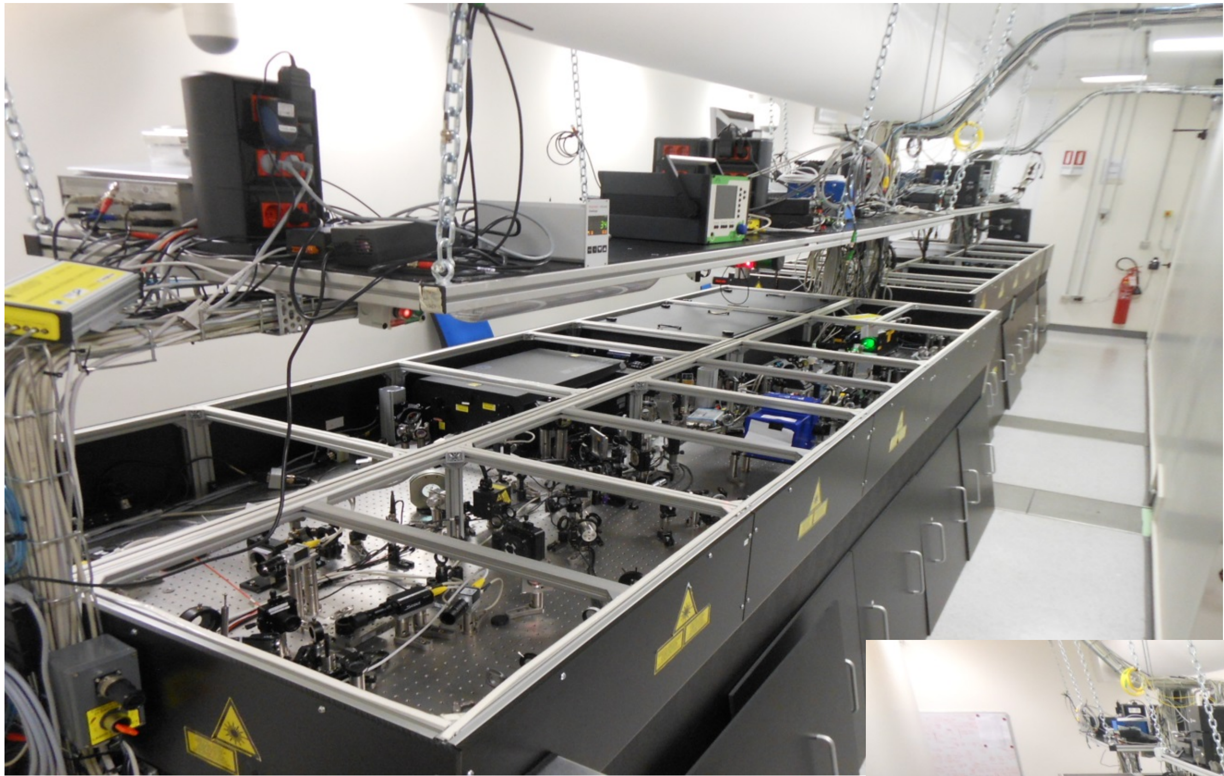
-FEL Pulse duration **$TSEED*(nxm)-1/2 < T_{FEL} < (7/6)\ T_{SEED}*(nxm)^{-1/3}$**

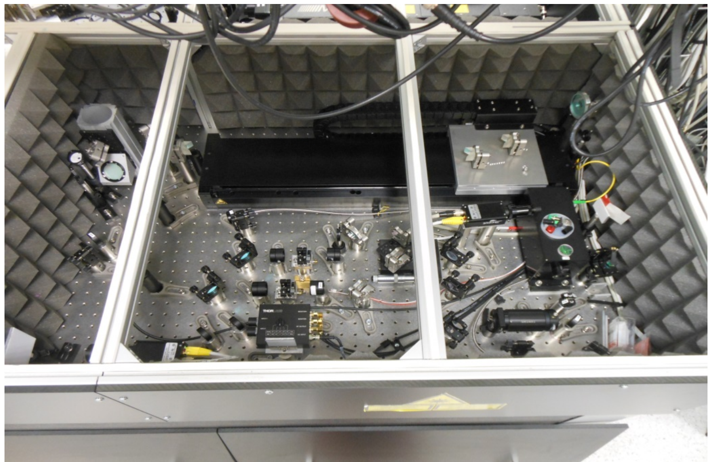


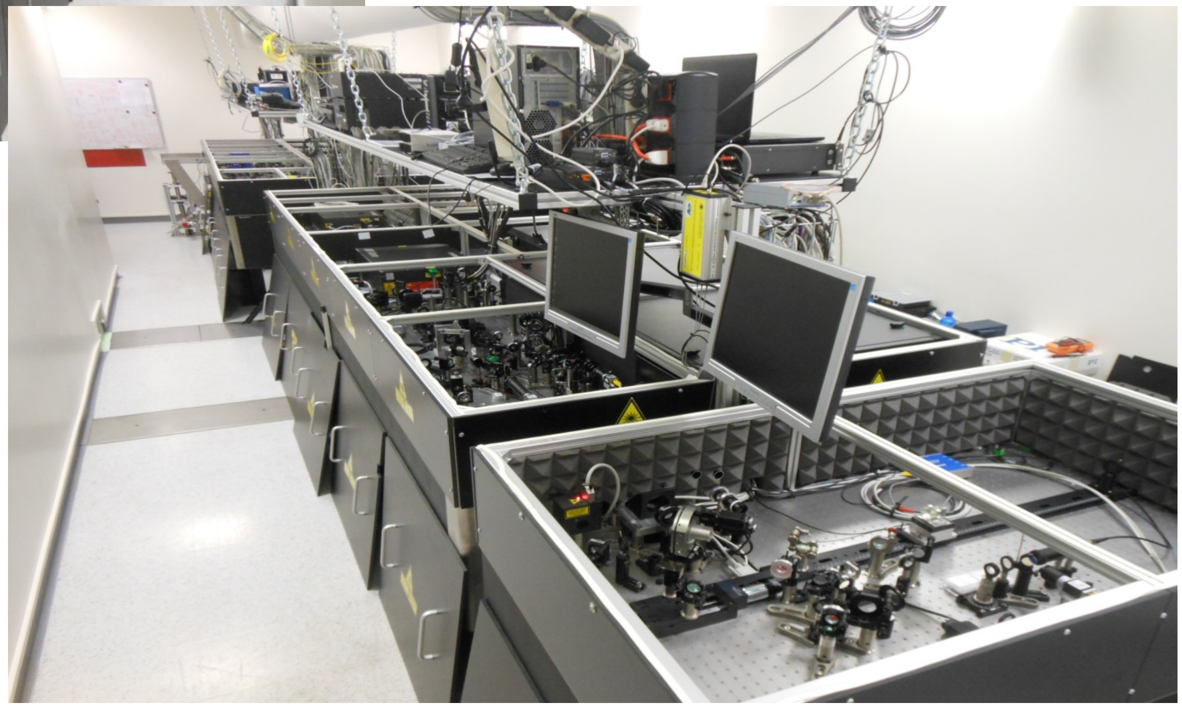
'IDEAL' SEED

- λ=240-280 nm
- P≥300 MW in MOD1
- i.e. ≥ 600 MW at the source
- $\Delta\lambda/\lambda \sim 10^{-4}$
- $\Delta P/P \leq 1\text{-}2\times10^{-2}$
- Low spectral phase distortions: pulse as close as possible to TL

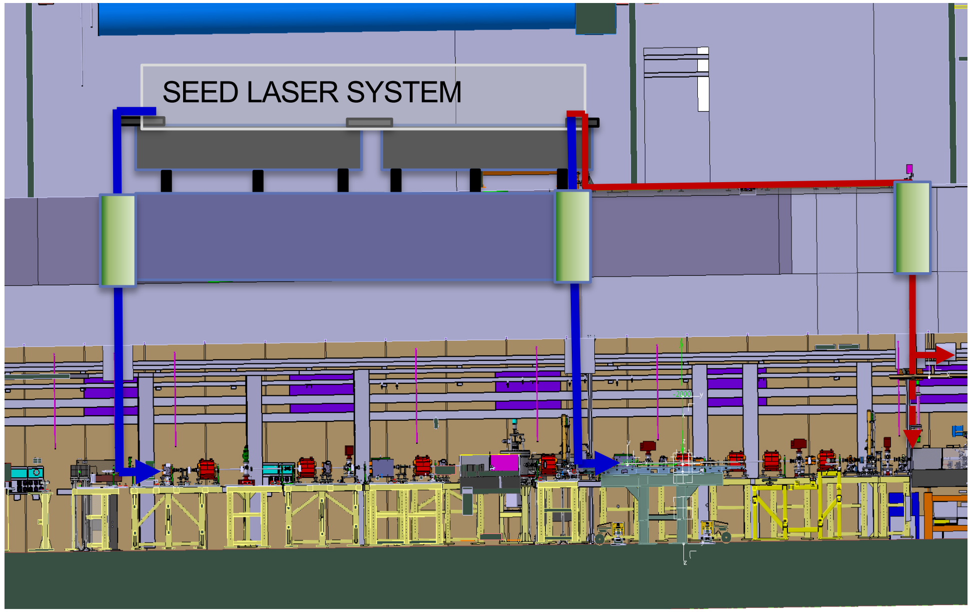
THE FERMI SEED LASER







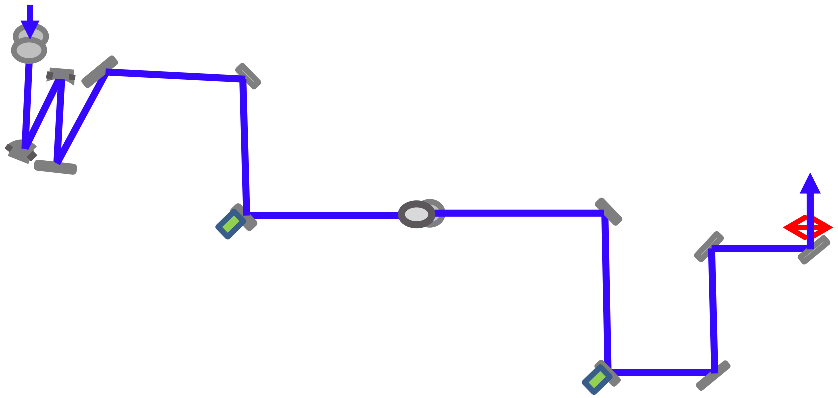
THE FERMI SEED LASER

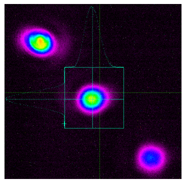


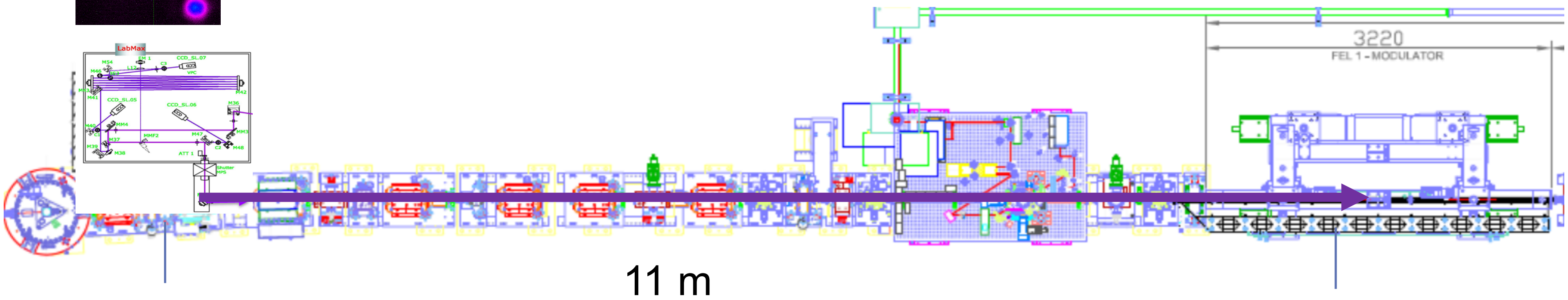
Boundary conditions :

- Distance from laser telescope to modulator centre: ~ 25 m
- Distance from last window to modulator center: ~ 11 m
- Input polarization horizontal
- No access to the used seed beam

-BT contains 14-15 mirrors, including 45P and 0 deg
- Beam pointing feedback a 'must'
'-Virtual' undulator is not common path





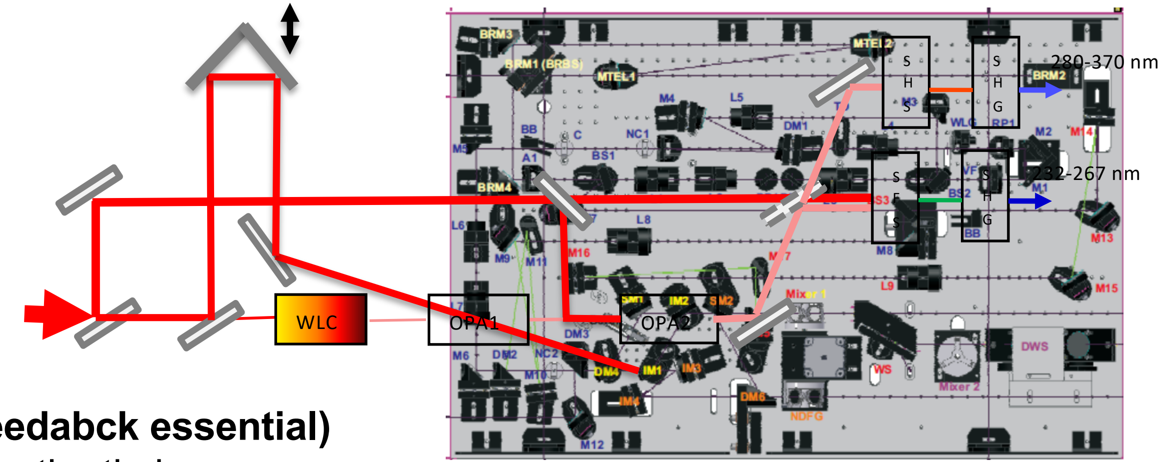


THE FERMI SEED LASER

FEL1

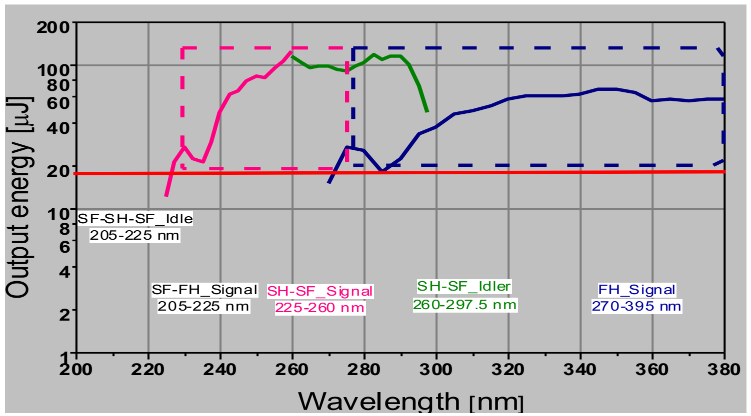
Main seed option: IR OPA with up-conversion to UV (modified OPERA-SOLO) mode:

Main range R1: 232-267 nm,
Second range R2:300-360 nm
Peak power **> 150 MW**
Pulse duration **R1~110-120 fs and R2~** 90-100 fs
(with precompression for the BT)
Wavelength stability: **<10^{-4}**
Pulse energy stability: **<1.5% RMS**
Position stability: **<20 µm RMS (**piezo **tip-tilt feedabck essential)**
Timing jitter UV pulse: <7 fs RMS with respect to the timing



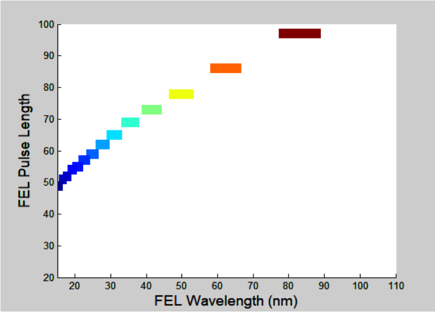
THG based fixed wavelength mode:

Wavelength : 261-265 nm (tunability **± 1 nm),**
UV peak power ≥ **800 MW** (energy per pulse >80 µJ)
Energy stability **<0.8% RMS**
Pulse duration (FWHM): **100**-350 fs range
(negative or positive linear chirp of up to can be added)
Typical bandwidth 0.75 nm
Mostly used in machine studies, FEL2 , Chirped Pulse
Seeding or twin-seed mode

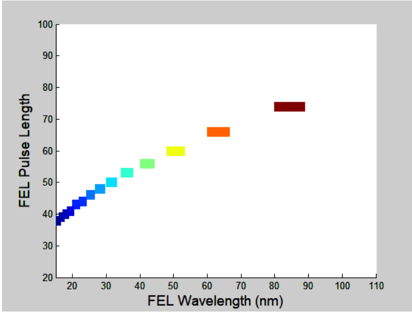


FEL1 SEEDING OPTIONS

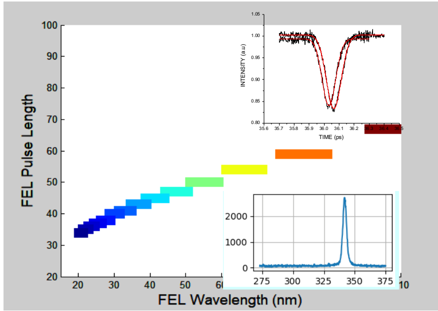
Main Seed Wavelength ranges for FEL1



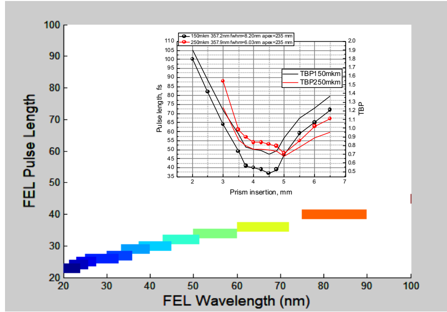
SeedR1: 232-267 nm, 130 fs, H=3-16



SeedR1m: 240-267 nm, 110 fs, H=3-16



SeedR2:300-360 nm, 90 fs; H=3-16



SeedR2SP 300-360 nm, 60 fs H=3-16, (under development)

Beam transport issues:

- Minimum amount of material (vacuum windows, bea

Solution: Transmission grating compressor

pensation

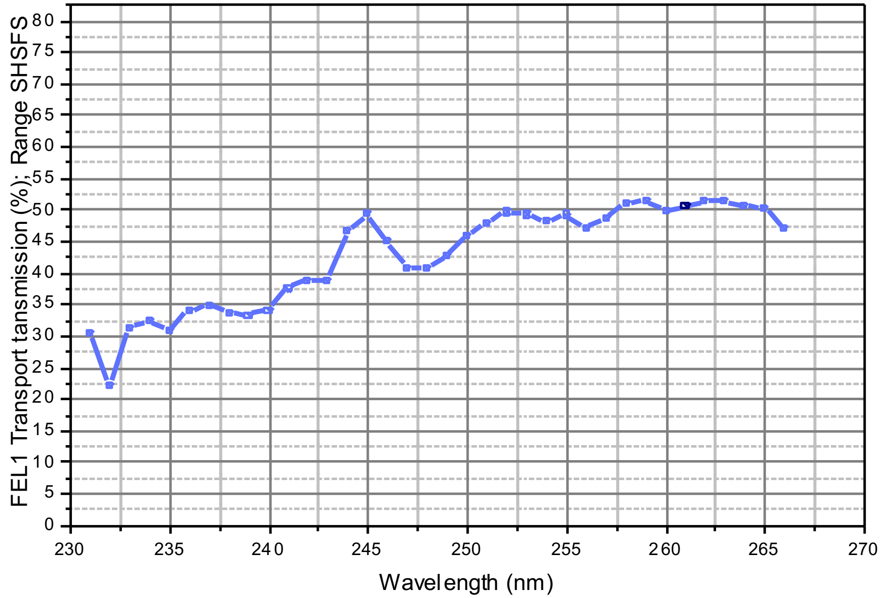
on with WL

$z)I_{laser}(z)dz$

- BT transmission ≤50% : mirrors, grating comp
- Beam pointing stabilization : virtual undulator

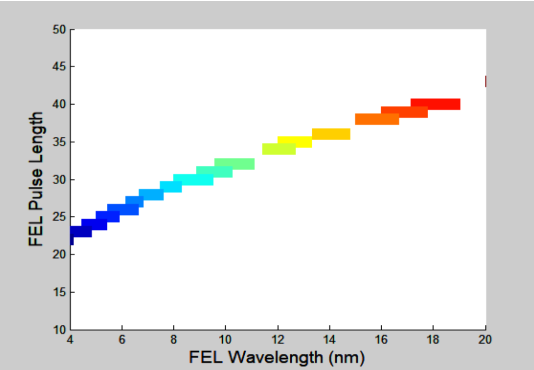
Solution:

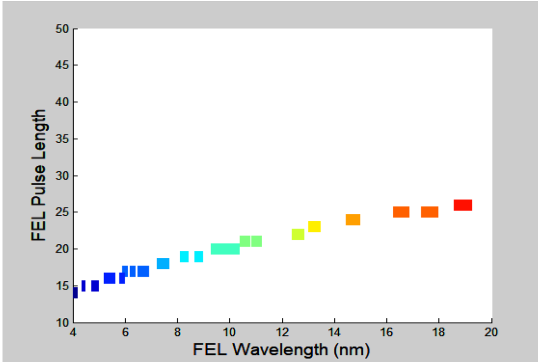
- Holed screen inside FEL : installed, under tes
- Beam sampling grating
- Enlarge 1st Disp Section for inserting an out-
  May be allowed by the redesign for the EEH

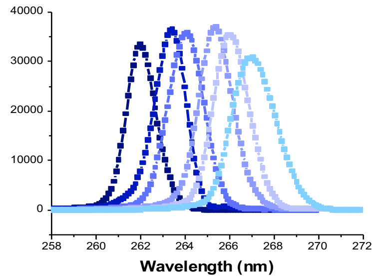


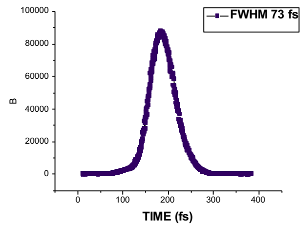
FEL2 SEEDING

Seed Options





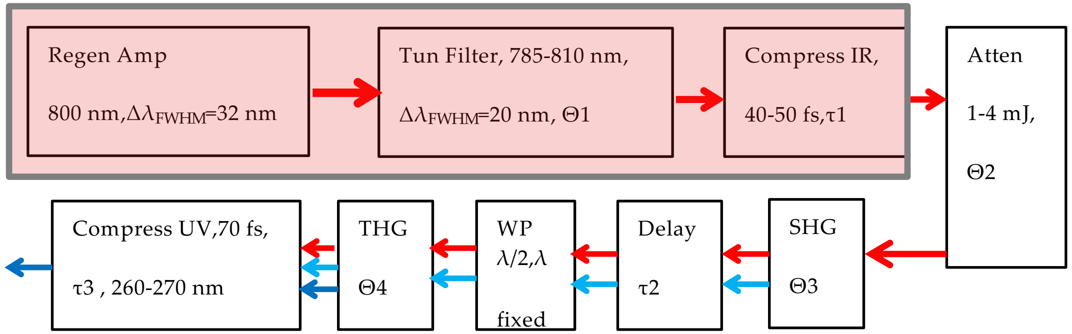




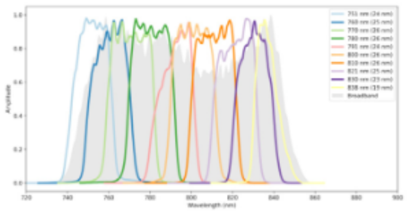
OPA Seed: 240-267 nm, 100 fs,
H1=3-13, H2=2-7
(Present OPA seed Range FEL2)

a.260-270 nm, 70 fs,
H1=3-13, H2=2-7
(THG seed Range FEL2 under development)

Scheme: fixed wavelength BB

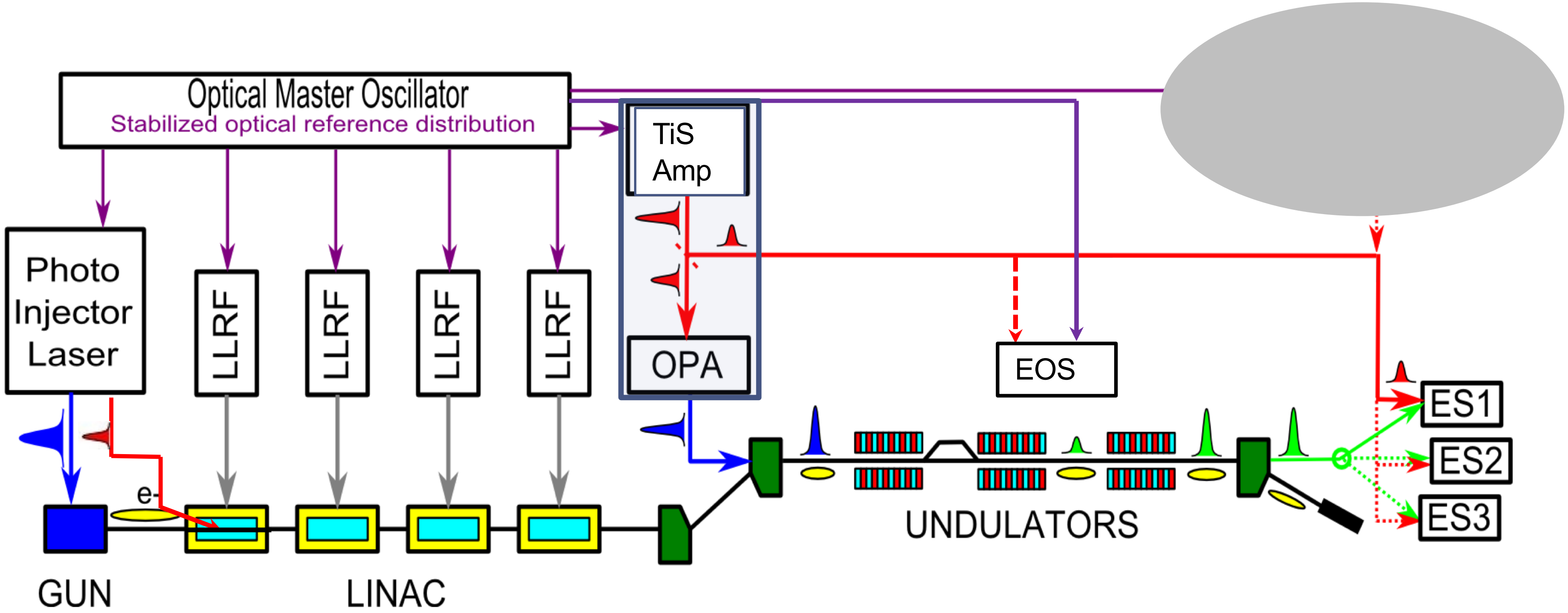


Possible alternative approach:
Tunable RG , e.g. with intracavity wavelength selection , e.g. ARCO (Amplitude)
Main concern: reproducible WL tuning and WL stability



For < 20 fs duration
tunability over 100 nm with Mazzler

SYNCHRONIZATION ASPECTS



MUST HAVE

- Low phase noise Timing Ref distribution with drift compensation: stabilized fibre link based
- Seed Laser&Pump-probe laser:
- Low phase noise mode-locked oscillator(s) with optical locking (BOCC based) to the timing Ref
- Timing drift stabilization of Regen Amplifiers

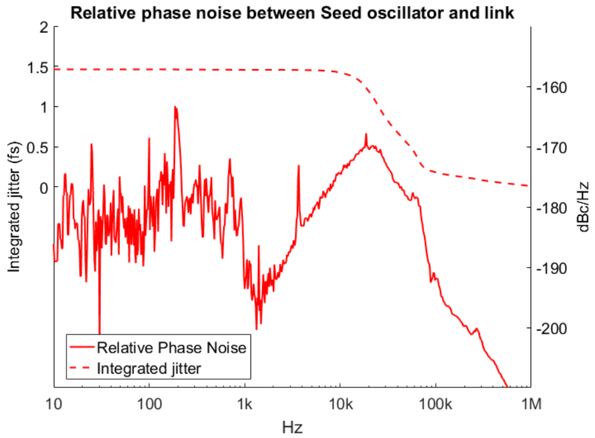
GOOD TO HAVE

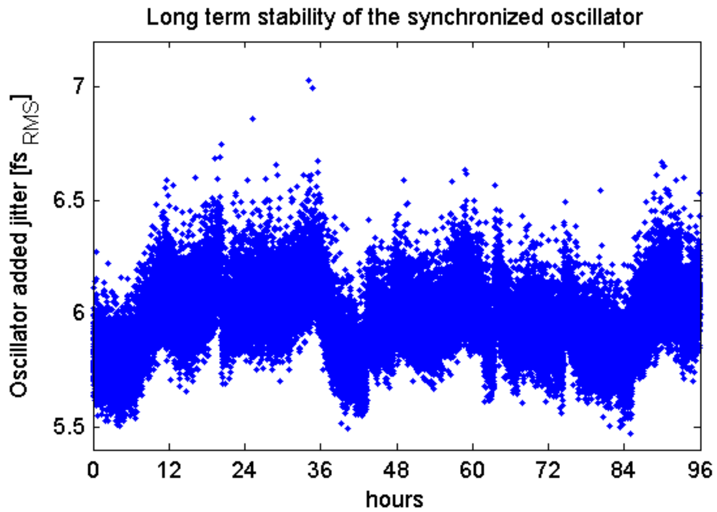
- Seed Beam transport drift stabilization
- Timing tool at experimental stations in case of sub-5 fs Pump-Probe resolution request

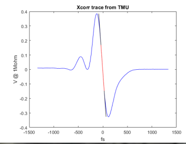
SYNCHRONIZATION ASPECTS

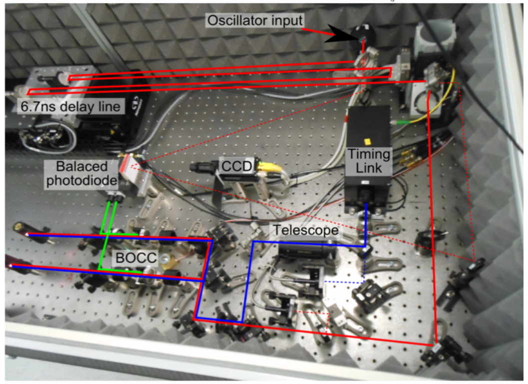
Mode Locked Oscillator Timing stabilization

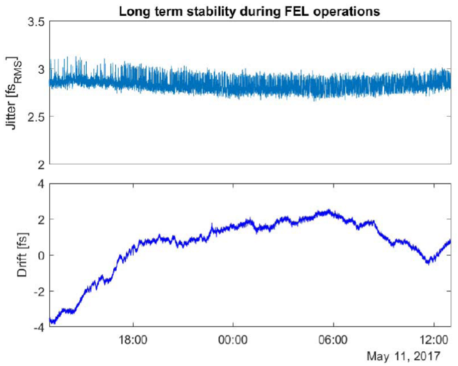
Ti:Sapphire oscillator: a custom version of the Coherent Vitara and a home-developed BOCC

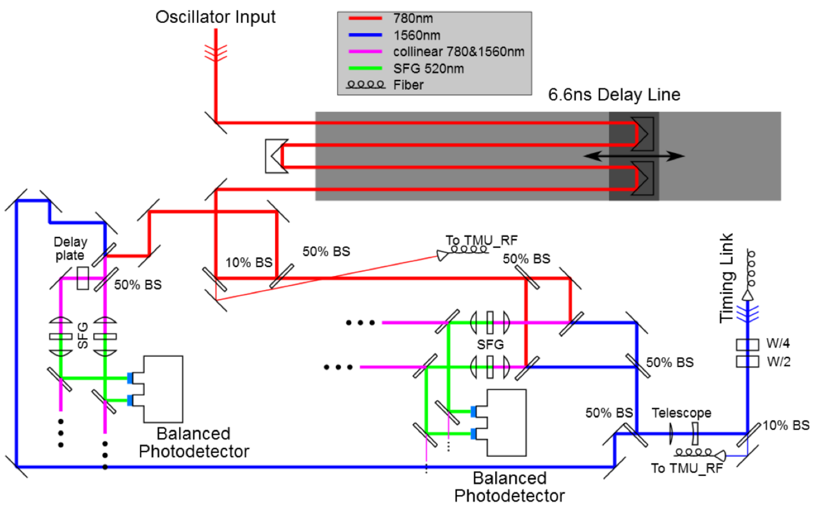


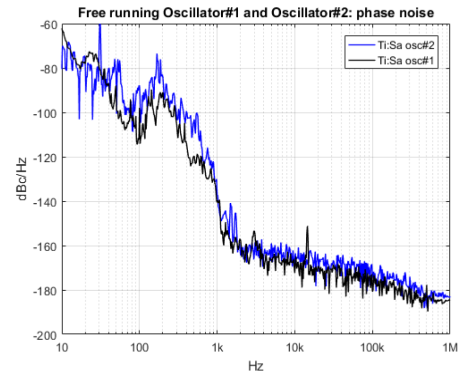






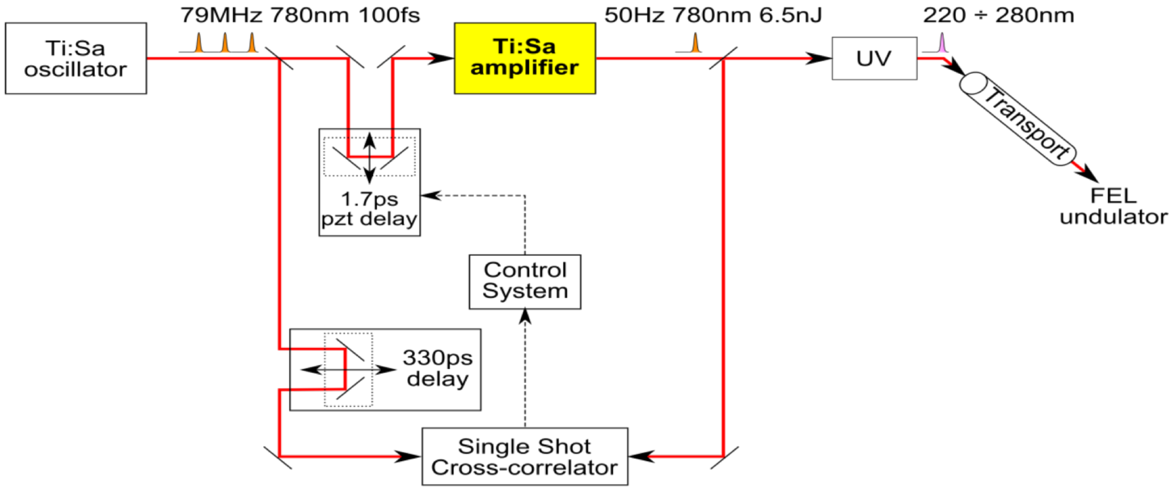


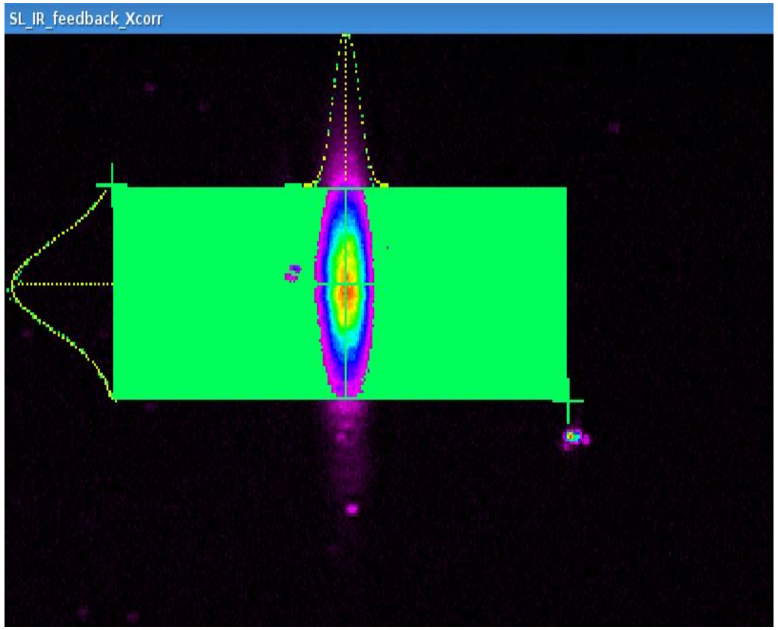


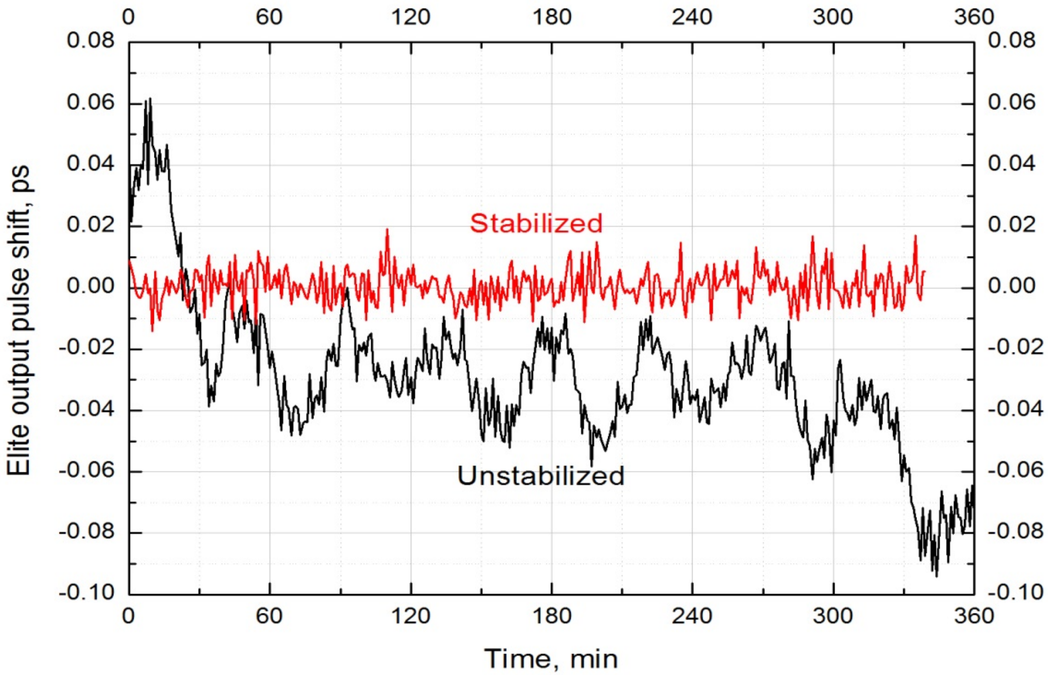


SYNCHRONIZATION ASPECTS

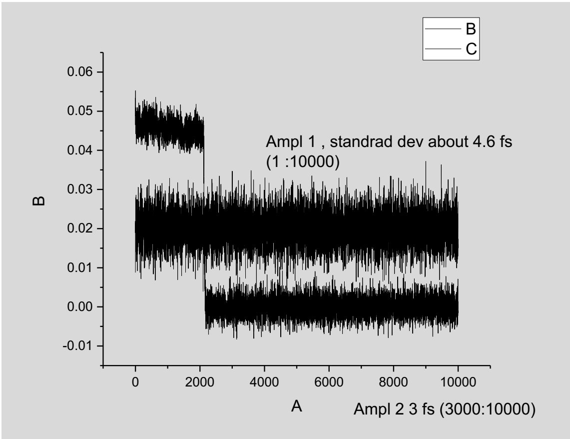
Timing Stabilization Regenerative Amplifiers

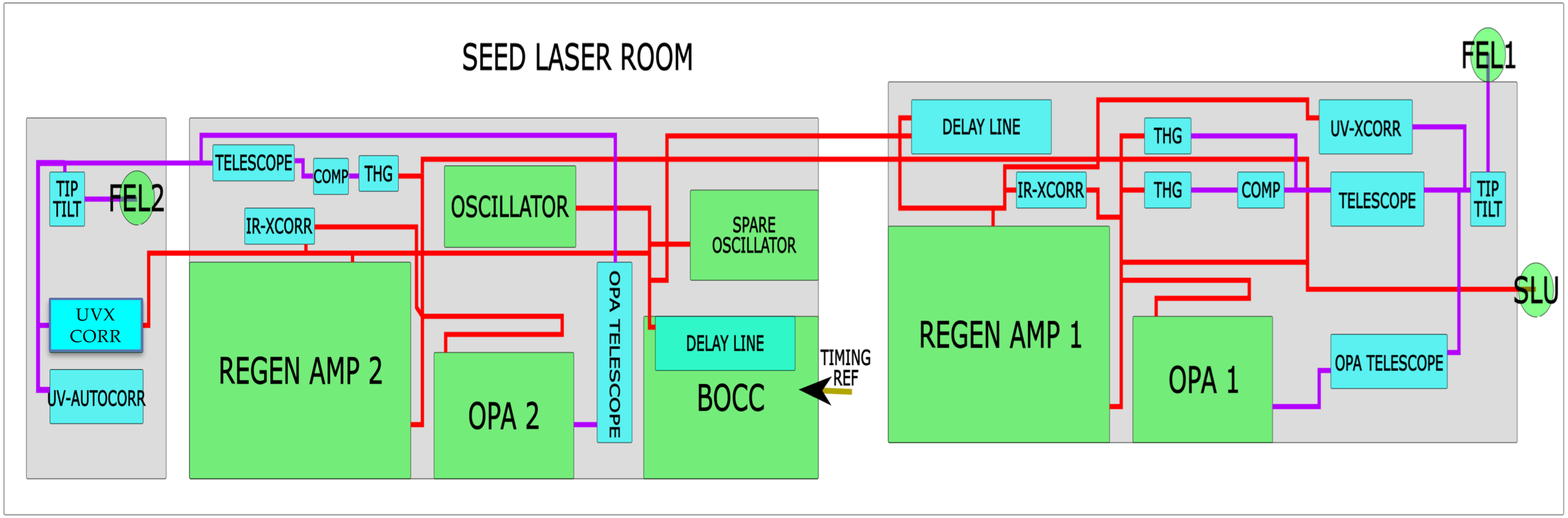




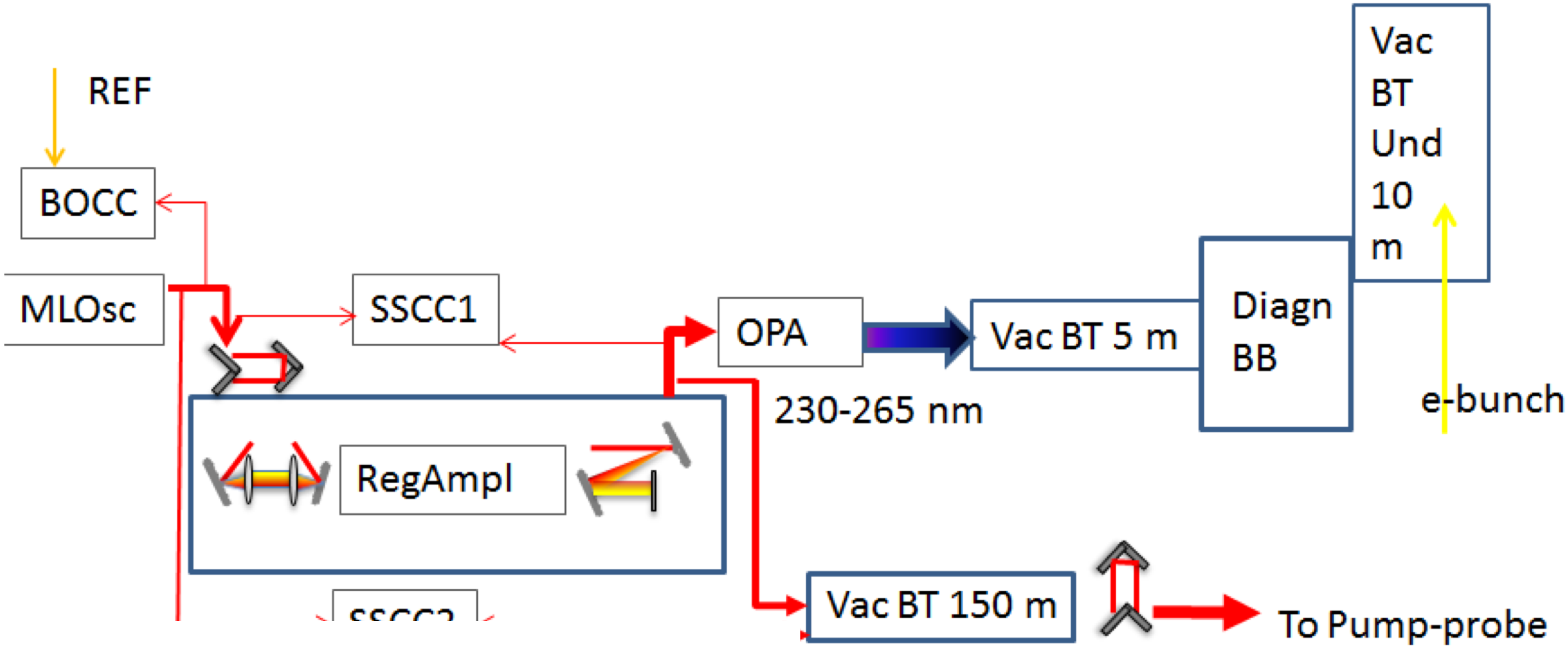


Time drift of the Ti:Sa amplifier is fully compensated, the short term jitter is below 6fs RMS

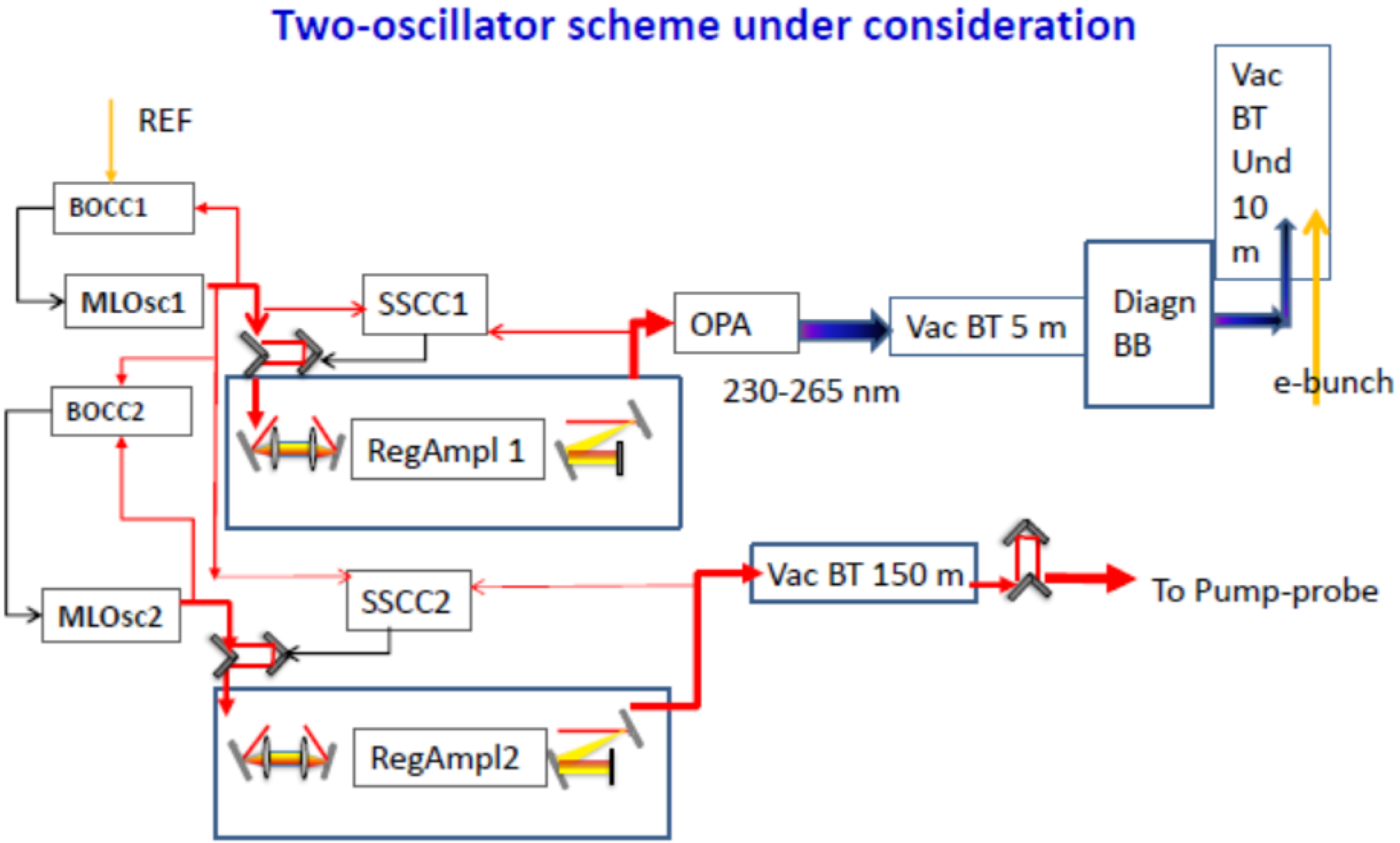



SEED LASER ROOM
FEL1
DELAY LINE
THG
UV-XCORR
IR-XCORR
THG
COMP
TELESCOPE
TIP
TILT
SLU
REGEN AMP 1
OPA 1
OPA TELESCOPE
TIMING
REF
BOCC
DELAY LINE
SPARE
OSCILLATOR
OSCILLATOR
OPA TELESCOPE
OPA 2
REGEN AMP 2
TELESCOPE
COMP
THG
IR-XCORR
TIP
TILT
FEL2
UVX
CORR
UV-AUTOCORR

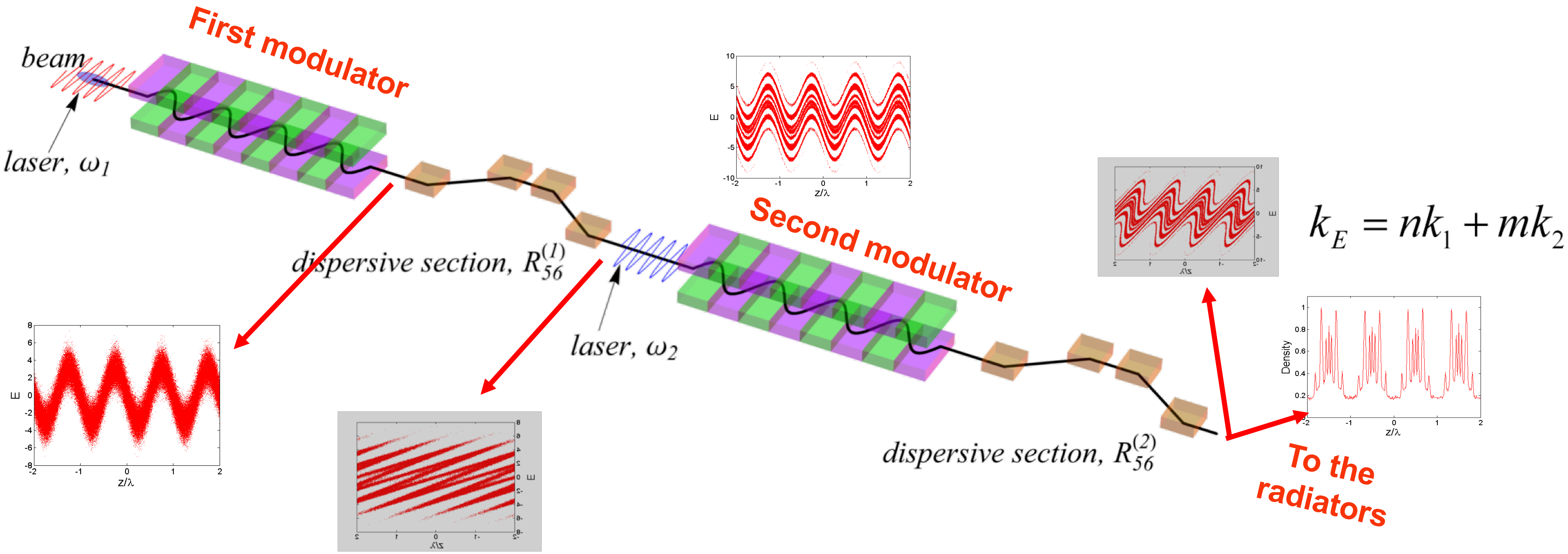
SEED LASER TIMING LAYOUT



FUTURE SEED LASER TIMING LAYOUT?



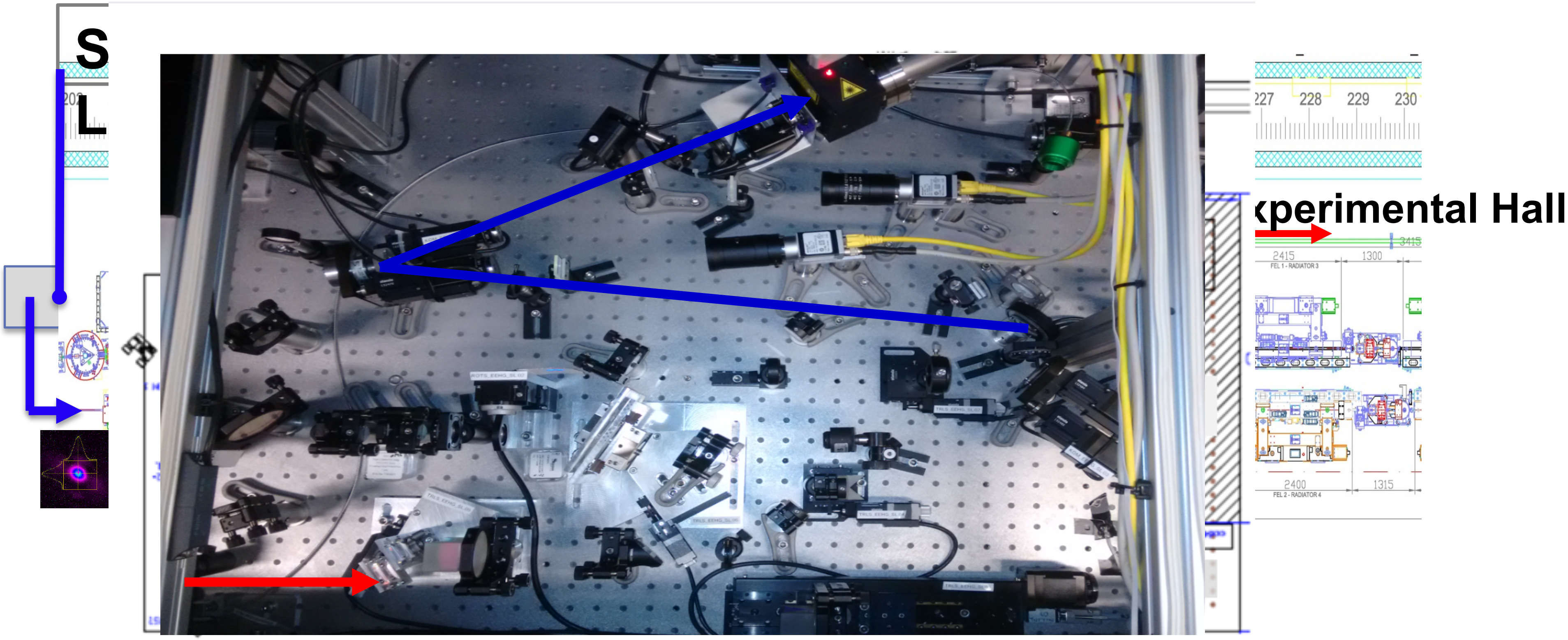
ECHO ENABLED HARMONIC GENERATION



The single stage seeded FEL range can be extended to higher harmonics by EEHG (G.Stupakov , Phys. Rev. Lett. **102**, 074801)

- A first laser generates energy modulation in electron beam.
- A strong chicane creates stripes in the longitudinal phase space.
- A second laser imprints energy modulation.
- The second chicane converts energy modulation into harmonic density modulation.

EEHG IMPLEMENTATION AT FERMI 2018



First seed pulse: 120 fs range, 264 nm , with possibility for chirp variation
Second Seed Pulse: 80-100 fs range, **nearly FT limited,**
Timing: no carrier phase stability required, timing jitter <10 fs,
Feedback on pointing stability and remote control on pulse parameters, including UV compressor for fine chirp adjustment

FUTURE EEHG IMPLEMENTATION AT FEL1

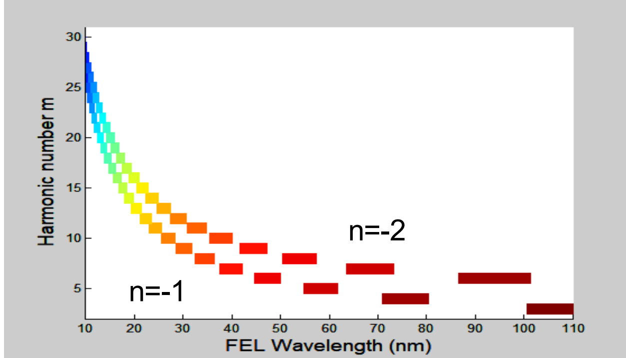
Main motivation: extend FEL1 range to 10 nm and below

➢ Additional advantages:

- Less sensitive to microbunching, narrower bandwidth
- Single Seed2 OPA range can cover 10-110 nm
- Easier twin-pulse implementation compared to double-cascade

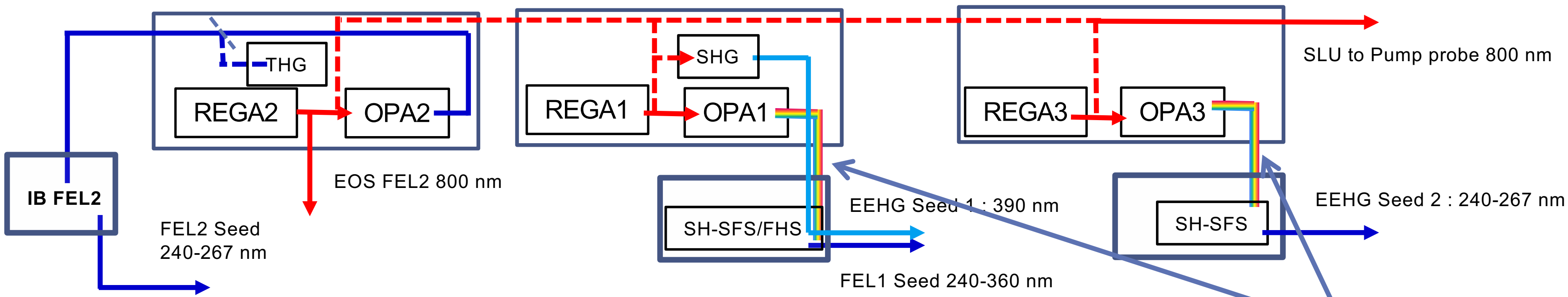
➢ Boundary conditions :

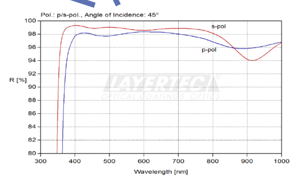
- Coexistence with standard FEL1 operation
- FEL2 operation unaffected
- SLU operation unaffected
- EEHG Seed 2 pulse beam highest quality
- If possible single BT optics



λ_{seed1}=390 nm
λ_{seed2}=240-267 nm

A new laser has to be added





Layout under consideration:

- Last up-conversion process at the insertion breadboard in UH
- BT and dispersion management of pulses in the visible (SFS, SHS,SHF)

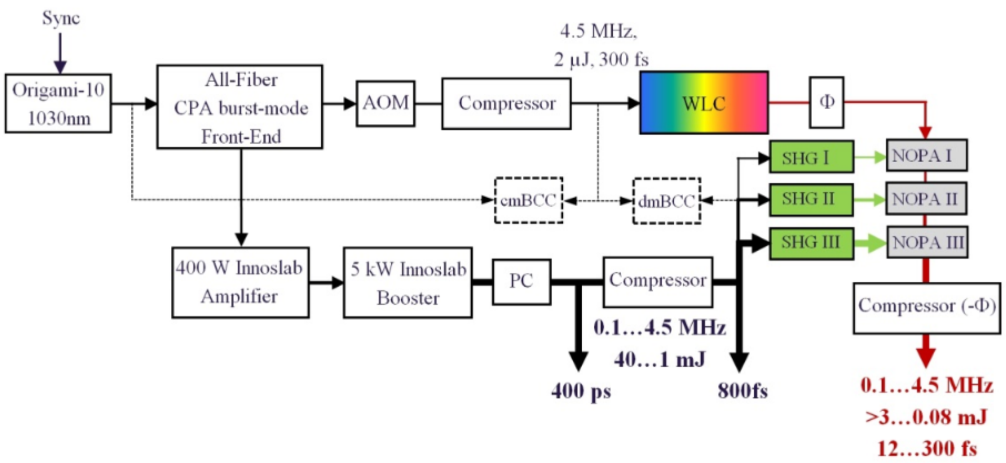
ALTERNATIVE SEED LASER TECHNOLOGIES

Motivation: High-Repetition rate Burst mode needs very high average power (a few kW) pump laser, not within reach by Ti:Sapphire technology

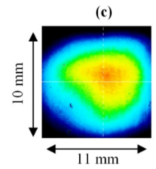
Solution: **Yb-based** technology (1030 nm) for pumping OPCPA/NOPA systems

Example: Systems developed at X-FEL and DESY for the pump-probe laser

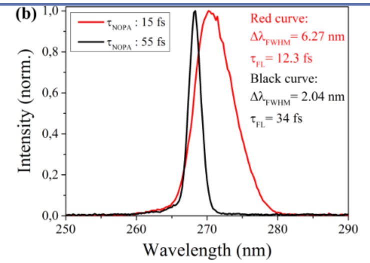
(a similar approach is also under development at LCLS)



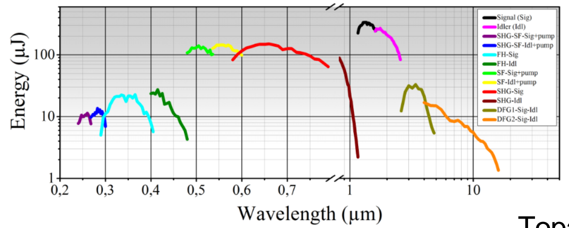
M. Pergament et al, *Opt.Express* **24** 29349-29359 (2016)



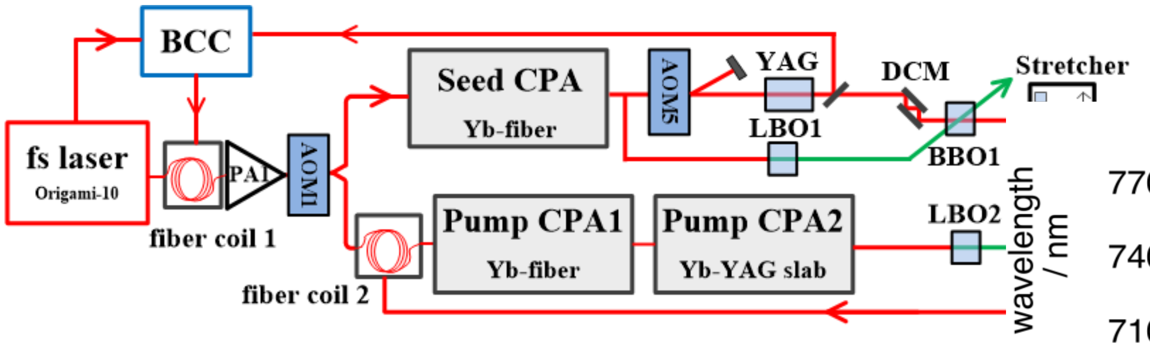
M2≤1.2



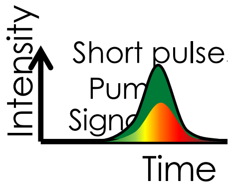
THG
at fixed λ



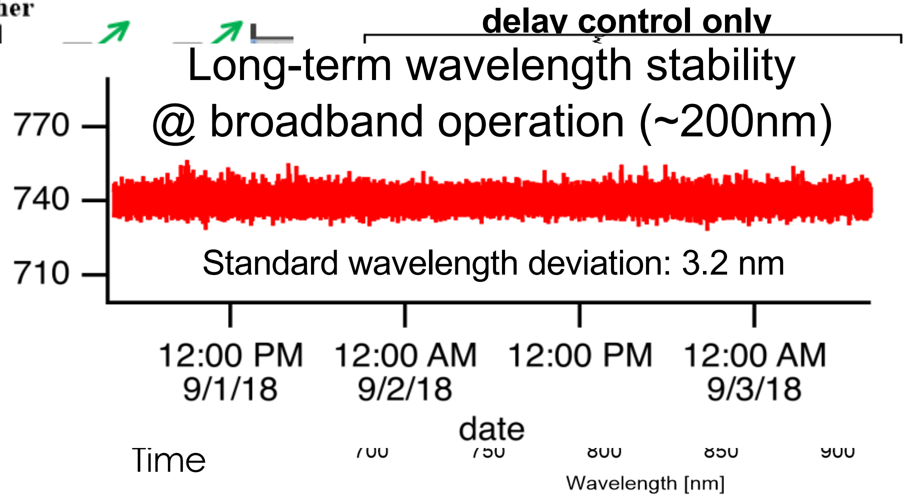
Topas pumped
By NOPAIII



FLASH Pump-probe laser (Courtesy T.Lang)
see poster at this workshop



Tunability by pump-seed delay control only



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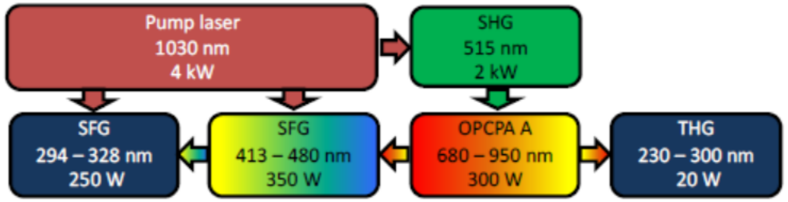
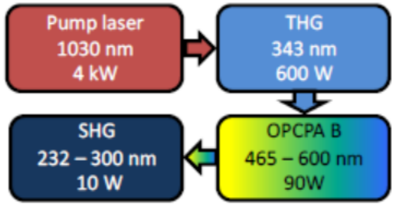
ALTERNATIVE SEED LASER TECHNOLOGIES



SHG pumped OPCPA + cascaded SFG

SHG pumped OPCPA + THG



SHG pumped OPCPA + THG

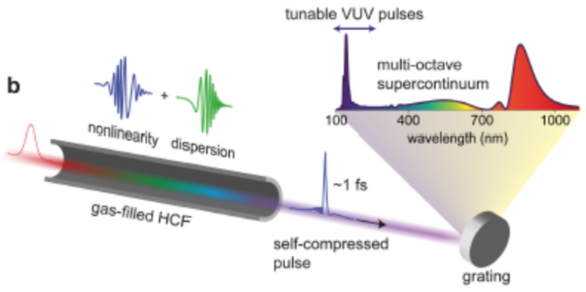
	Average power in 1ms burst (compressed before beam transport) (W)	Compressed pulse energy @ 100 kHz before beam transport (mJ)	Compressed pulse energy @ 1 MHz before beam transport (mJ)	Tunability (nm)
Pump laser as reported in (Pergament et al., 2016).	4000	40.0	4.00	1030
OPCPA A (515nm pump, as reported in (Pergament et al., 2016)	300	3.0	0.30	690 – 900
OPCPA B (343nm pump, alternate concept, simulation)	90	0.9	0.09	465 – 600
Visible output OPCPA A (sum frequency simulation)	350	3.5	0.35	413 – 480
UV output – OPCPA A (cascaded sum frequency, simulation)	250	2.5	0.25	294 – 328
UV output – OPCPA A (THG, simulation)	20	0.2	0.02	230 – 300
UV output – OPCPA B (SHG, estimation)	10	0.1	0.01	232 – 300

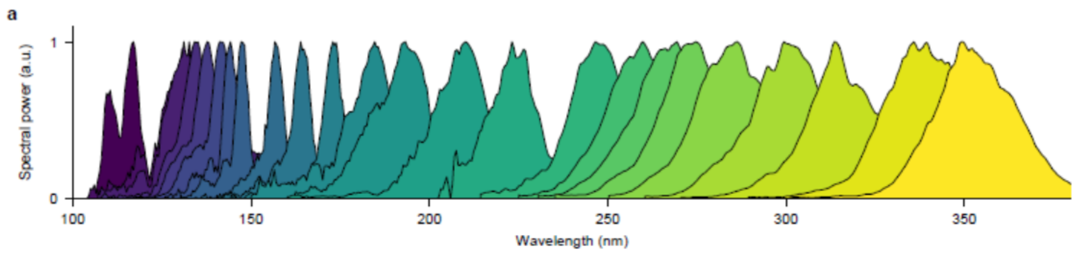
Schemes under investigation for FLASH 2020+ seeding , expected power and efficiency
Courtesy T.Lang, see poster for details

ALTERNATIVE SEED LASER TECHNOLOGIES

DUV/VUV generation and wavelength tuning without OPA : Soliton self-compression and dispersive wave emission in gas-filled hollow core fibre

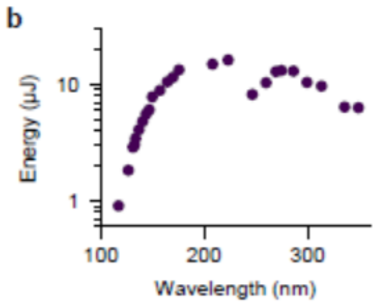
J.Travers et all, *Nature Photonics* **13**, 547-554 (2019)





Advantages:

- Ultrabroadband-tunability by only gas pressure change
- Simple setup
- Sufficiently high peak power also in the VUV
- Pulse duration down to few fs
- High spatial quality
- Energy scaling possible by increasing diameter/length of the fibre



Aspects to be studied:

- Pulse spectrum/structure long-term stability and reproducibility
- Narrow-band long-pulse option may not be feasible:

May be extremely suitable as a complementary seed source and pump-probe laser

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CONCLUSIONS

FEL SEEDING ALLOWS VERY GOOD PERFORMANCE IN TERMS OF

STABILITY

SPECTRAL AND SPATIAL QUALITY

FLEXIBILITY

PUMP-PROBE EXPERIMENTS ACCURACY

THERE ARE REALISTIC ROOTS FOR FURTHER IMPROVEMENTS BASED ALSO ON FURTHER SEED LASER DEVELOPMENTS

ACKNOWLEDGEMENTS

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Alexander Demidovich

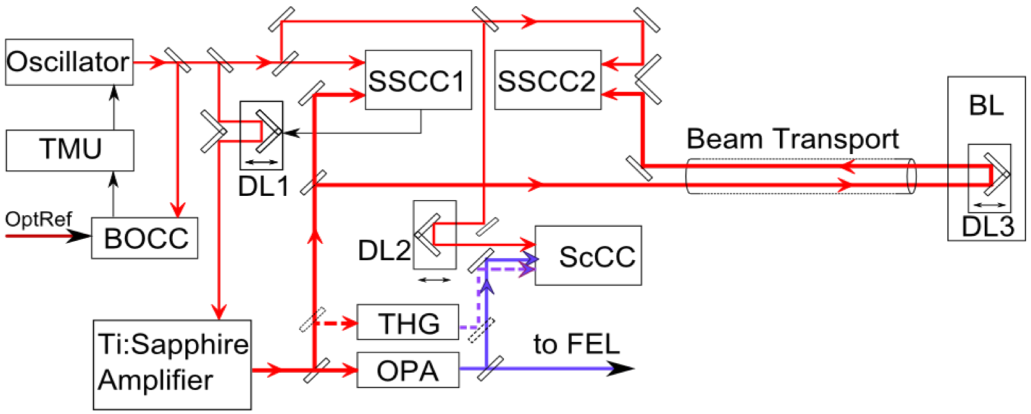
Gabor Kurdi

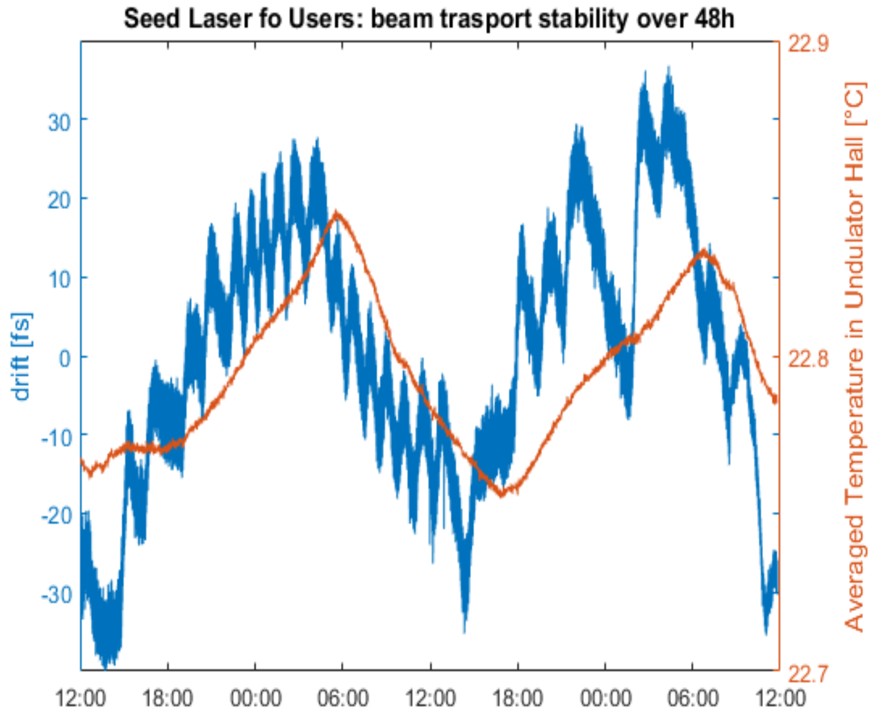
Paolo Cinquegrana

and to the FERMI Team

•BACKUP SLIDE1

LONG BEAM TRANSPORT TIMING DRIFTS





Cross-correlator measurement of the optical beam transport timing drift BOCC stands for balanced cross-correlator, ScCC- a scanning cross-correlator, SSCC1 and SSCC2 – single shot cross-correlators; BL- beamline chamber; DL1,DL2 and DL3 – delay lines.