Optical Replica Synthesizer and EuXFEL Laser Heater

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Theme

- Uppsala University is involved in activities to manipulate bright electron bunches with an external laser
  - for diagnostic purposes
    - Optical Replica Synthsizer
  - for beam stability
    - Laser Heater
- Other systems in a similar spirit are (that you already do) are EO or slicing

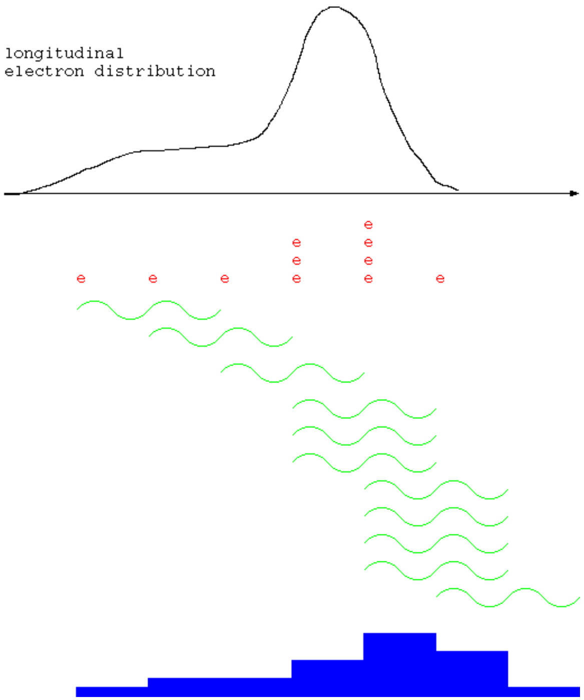
Optical Replica Synthesizer in FLASH

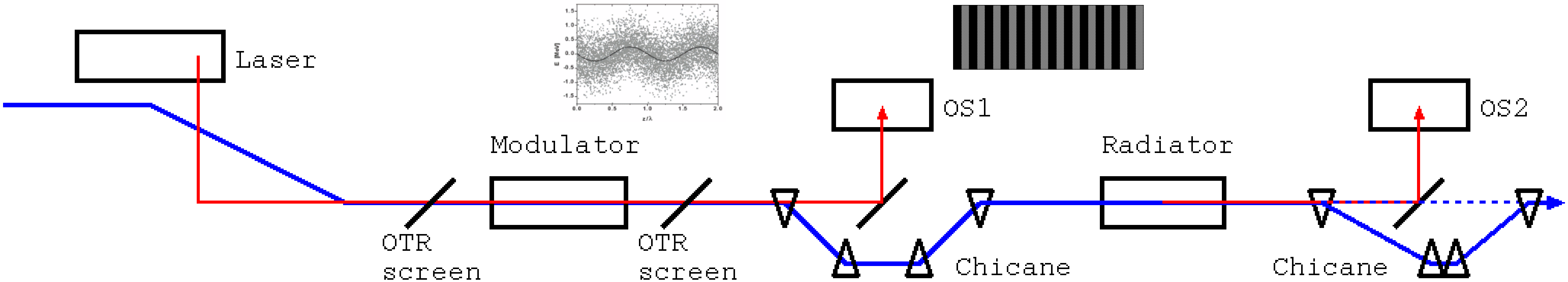
The original ORS collaboration:

G. Angelova, VZ, *Uppsala University*
P. van der Meulen, P. Salén, M. Larsson, *Stockholm University*
H. Schlarb, J. Bödewadt,E. Saldin, E. Schneidmiller,
M. Yurkov, F. Löhl, A. Winter, DESY
S. Khan, *DELTA, TU Dortmund*
A. Meseck, *BESSY*

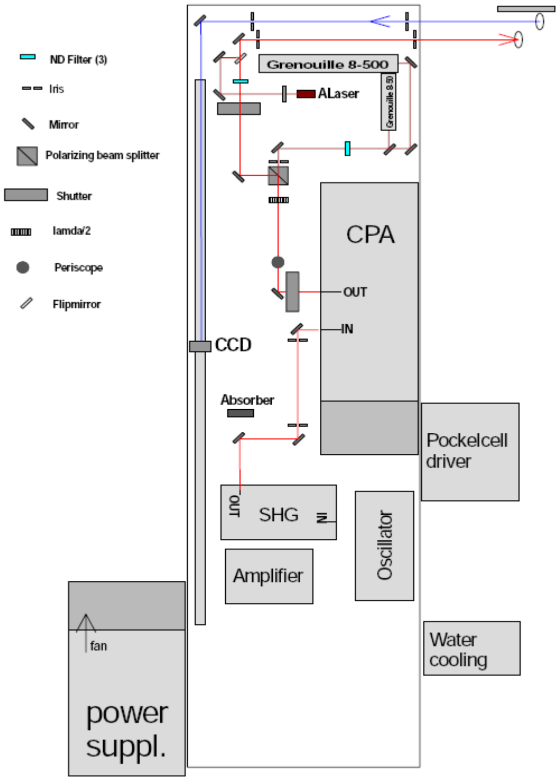
The Idea behind the ORS

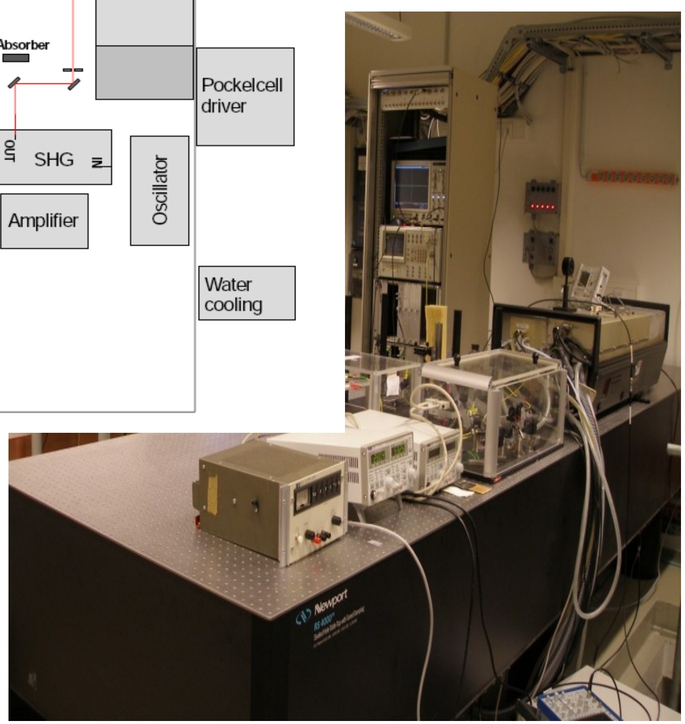
- Problem: measure ultra-short bunches in the 10s of fs range: EOS, TEO, LOLA, ORS
  - too fast for electronics (10 Gs/s, 100 ps)
  - but laser folks know (autocorrelation, FROG)
- Solution: make an optical copy of the electron bunch and analyze that with laser methods.



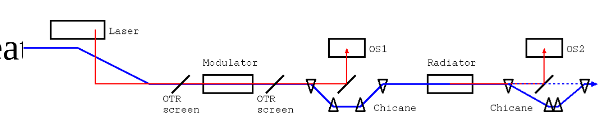


The Seed Laser

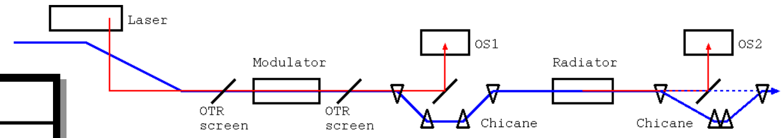


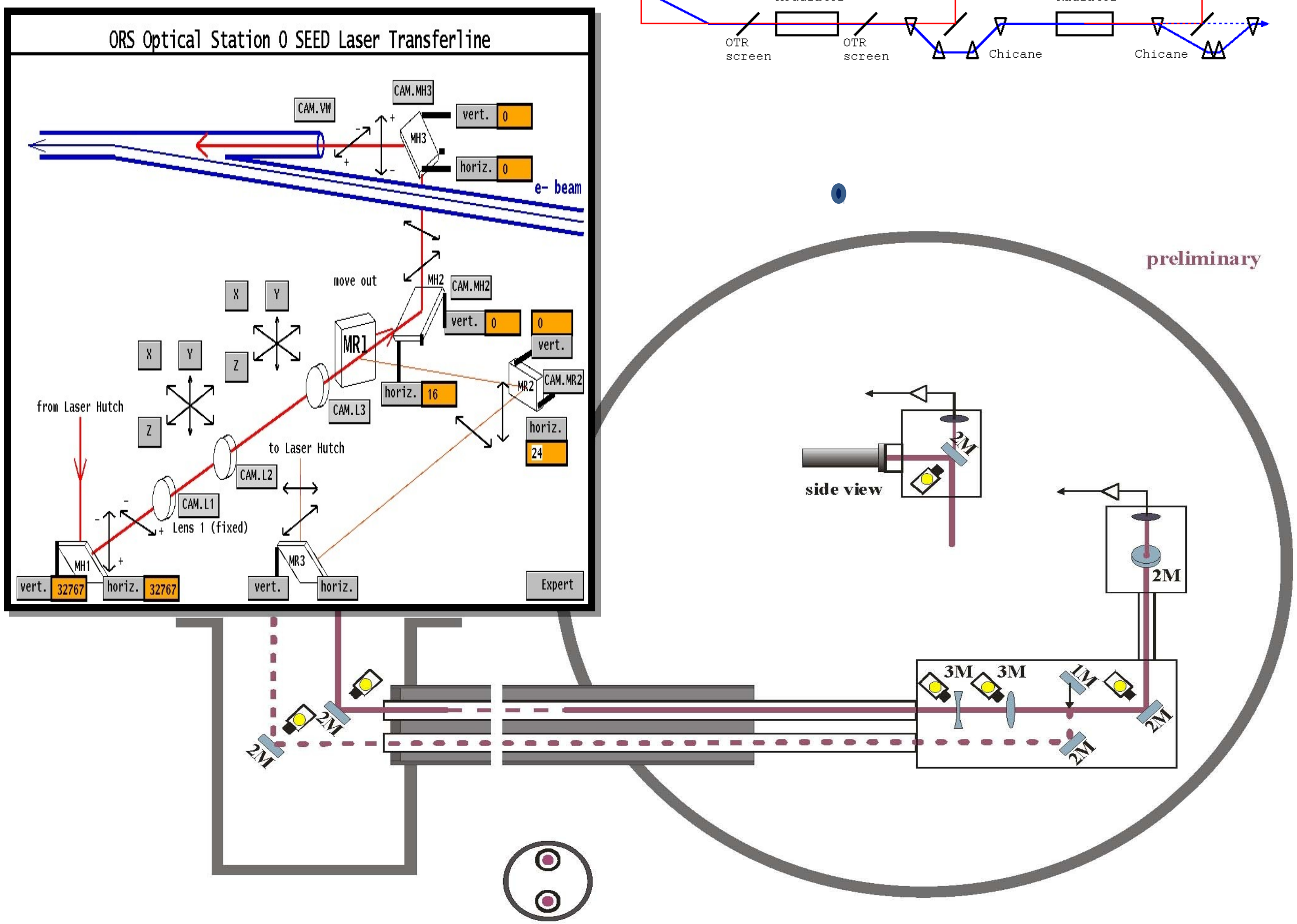


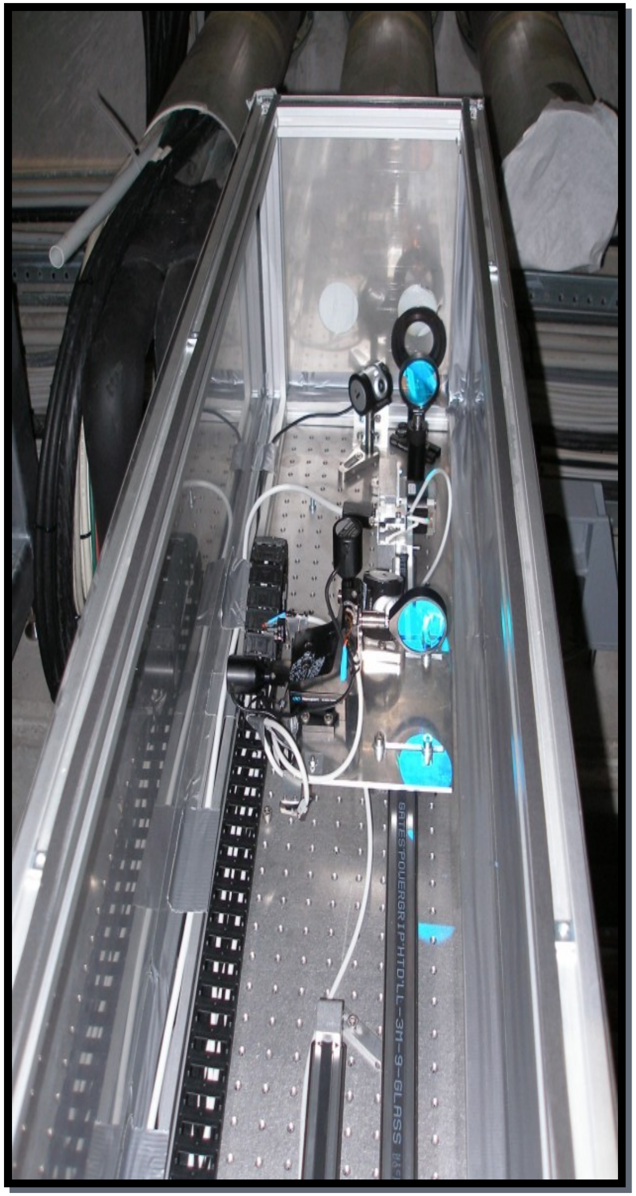
- Er-fiber ring-oscillator (~1550 nm) phase locked to RF (micro-timing)
- Booster amplifier
- 2nd harmonic generation to 772 nm
- CPA 2001 regenerative amplifier on loan from Stockholm
- Pockels cell fire to let the light pulse out (macro-timing)
- 0.7 mJ/pulse, 150 fs to 2 ps
- Safety shutters (ND and other)
- Diagnostics: Frog, virtual waist



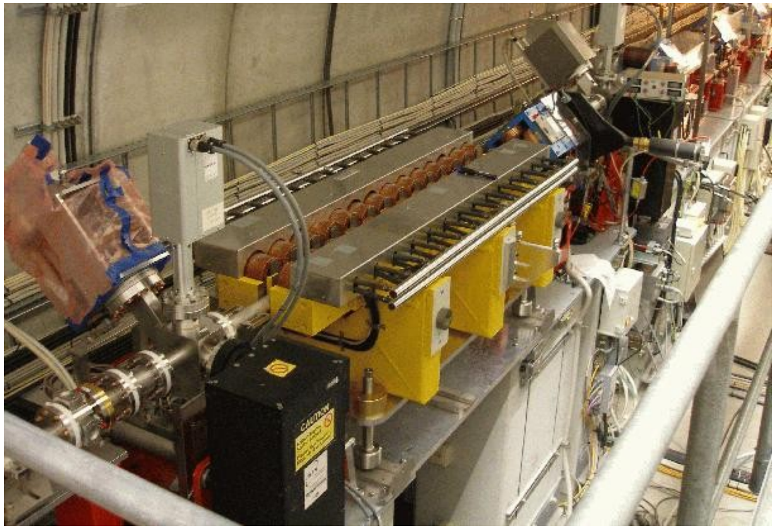
Laser Transfer Line and OS0



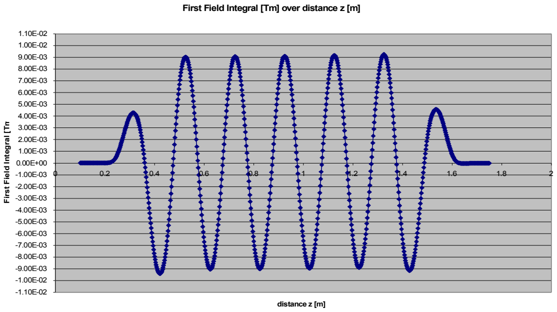


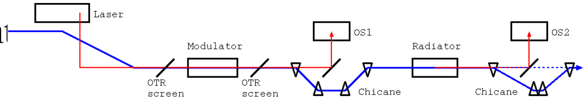


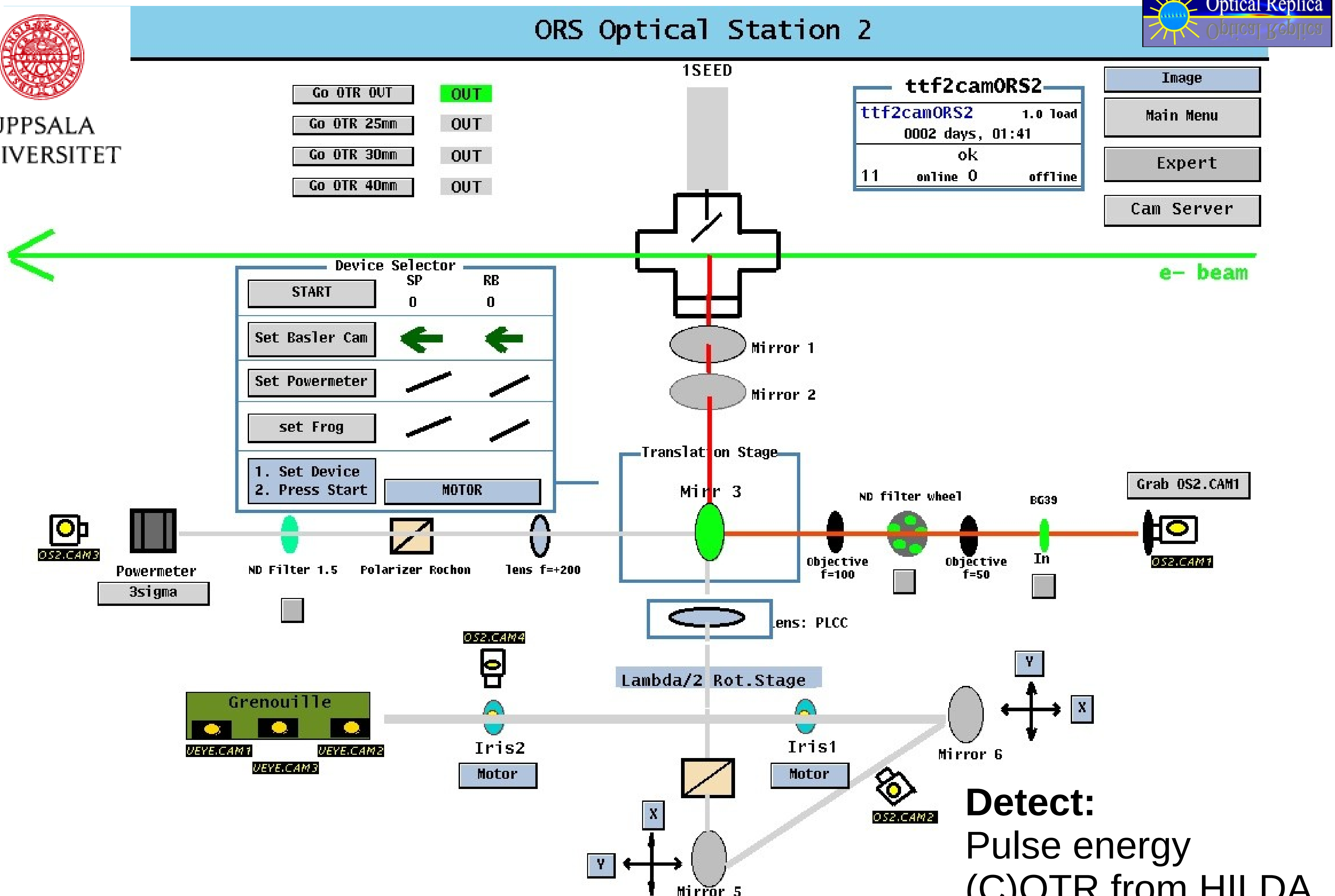
The Undulators



- Electromagnets
- Designed and built by Scanditronix, Vislanda, Sweden
- Period 20 cm
- 5+2 periods
- 4 power supplies per magnet
- Modulator=(V)eronica
- Radiator=(H)ilda







Detect:

Pulse energy

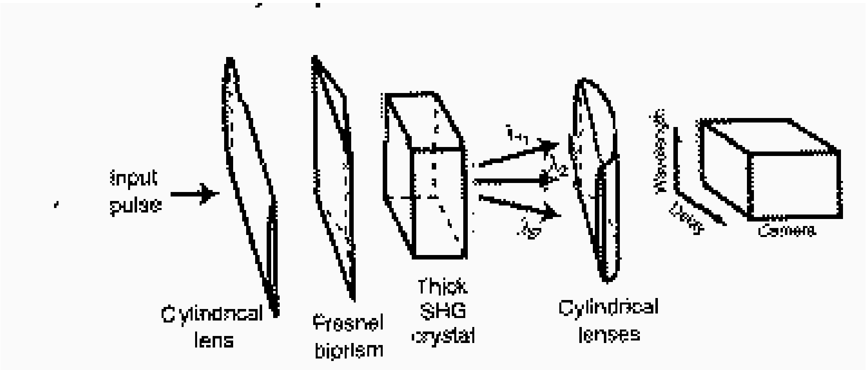
(C)OTR from HILDA

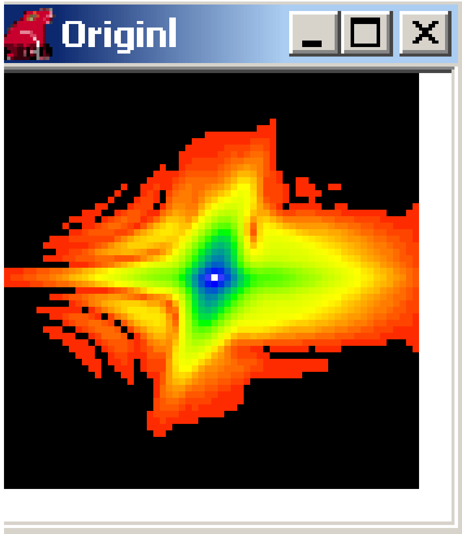
FROG

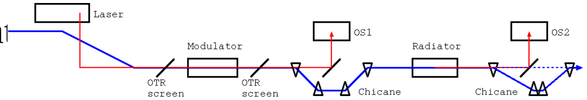
GRENOUILLE

- *Cyclidrical lens* makes horizontal strip
- *Fresnel biprism* creates crossing wavefronts in thick *SHG crystal* → auto-correlator
- Effective thickness of SHG crystal varies with viewing angle → Spectrally resolved
- Second double cylidrical lens images onto camera
- Horizontally → time
- Vertically → spectrum
- GRENOUILLE USB 8-50 controlled by VideoFROG software

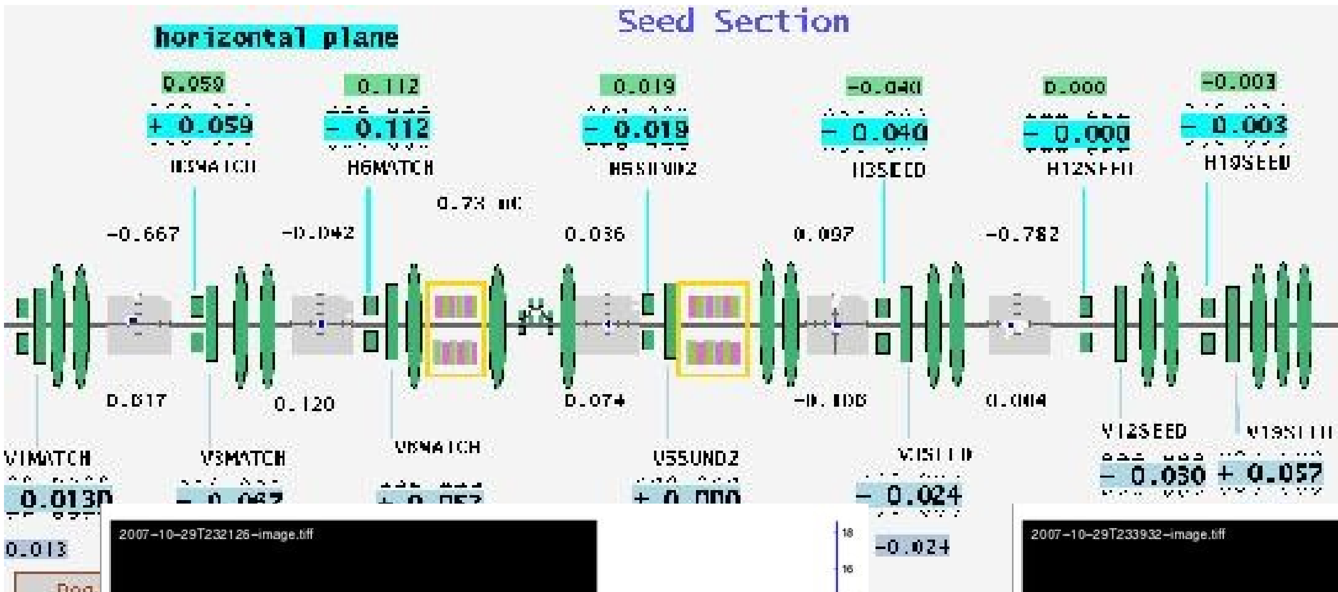
- Picture from Trebino's book





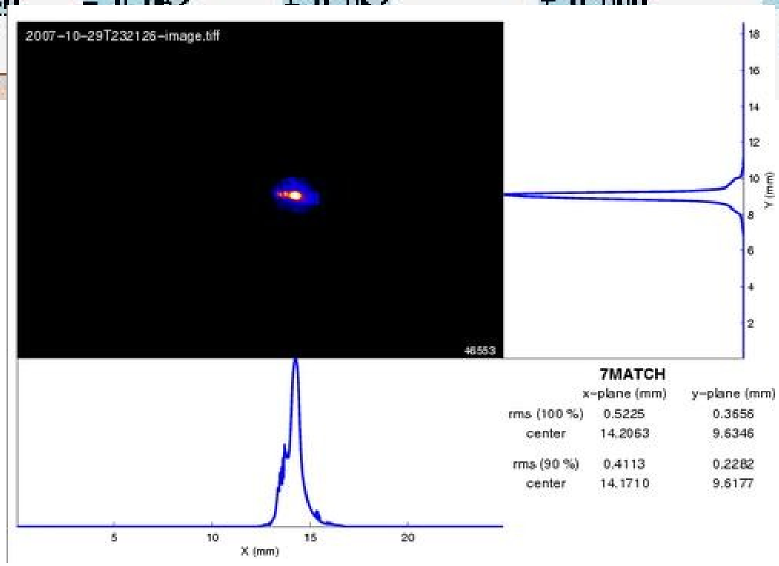


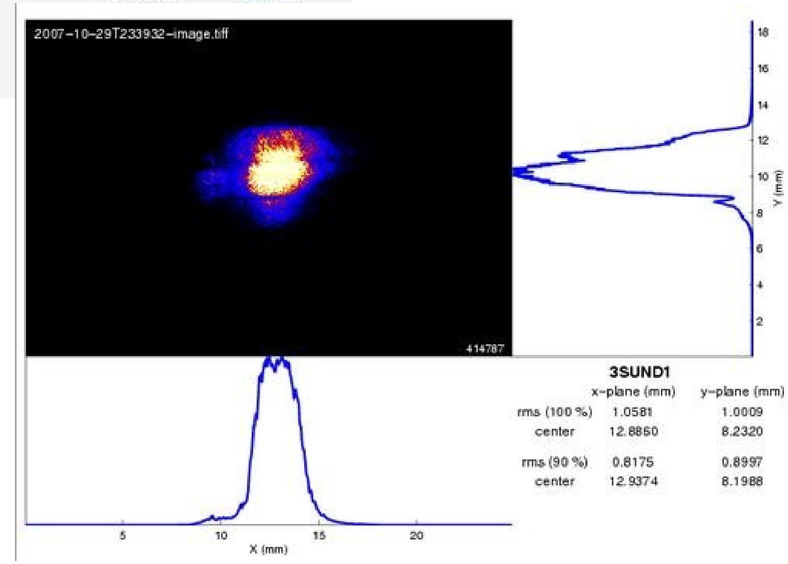
Experiment Preparation: Transverse Overlap

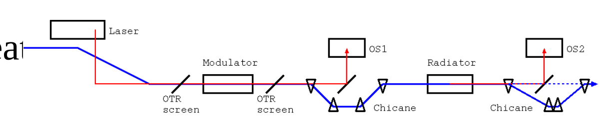


Electron orbit < 0.1 mm

Electron and Laser-position on OTR equal before and after modulator

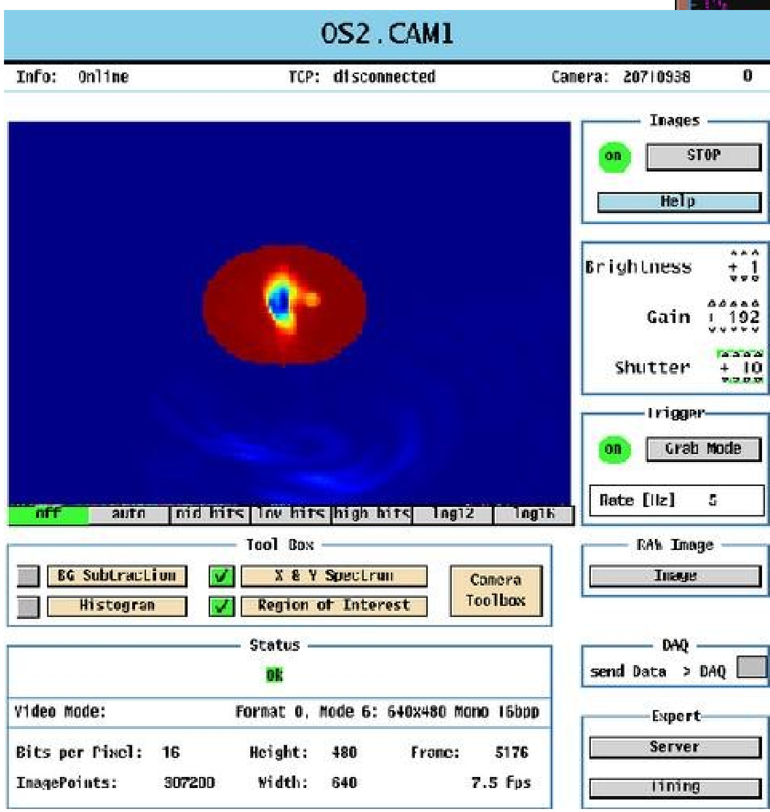






Temporal Overlap of sub-ps Electron bunch und Laser pulse

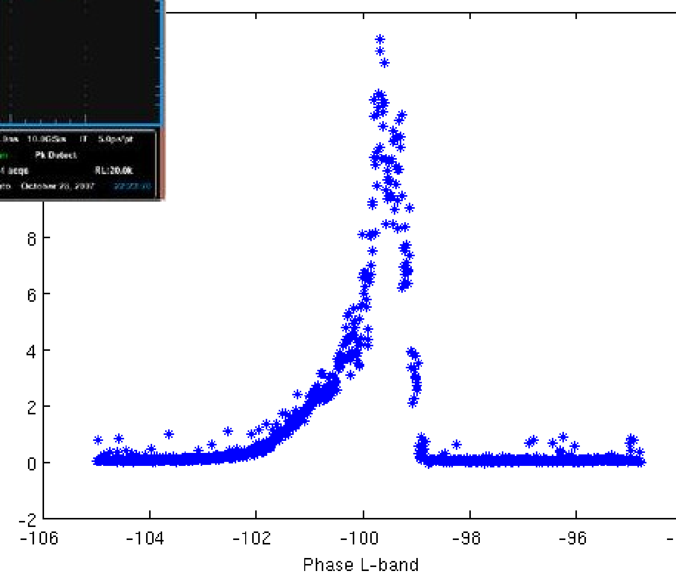
Rough adjustment on photo diode on OS1 per synchrotron radiation and laser ~ 100 ps

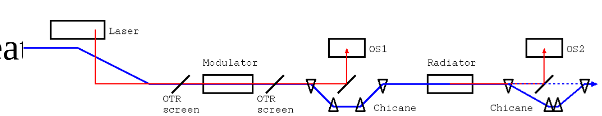


Fine-tuning on OS2 by observing cohrrent OTR of modulated electrons

* 2nd harmonic (BG39)
* Intensity in R.O.I

Adjust laser-timing in ~100 fs steps





OTR on OS2-camera while 200 fs laserpulse passes through electron bunch

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **11**, 070702 (2008)

Observation of two-dimensional longitudinal-transverse correlations in an electron beam by laser-electron interactions

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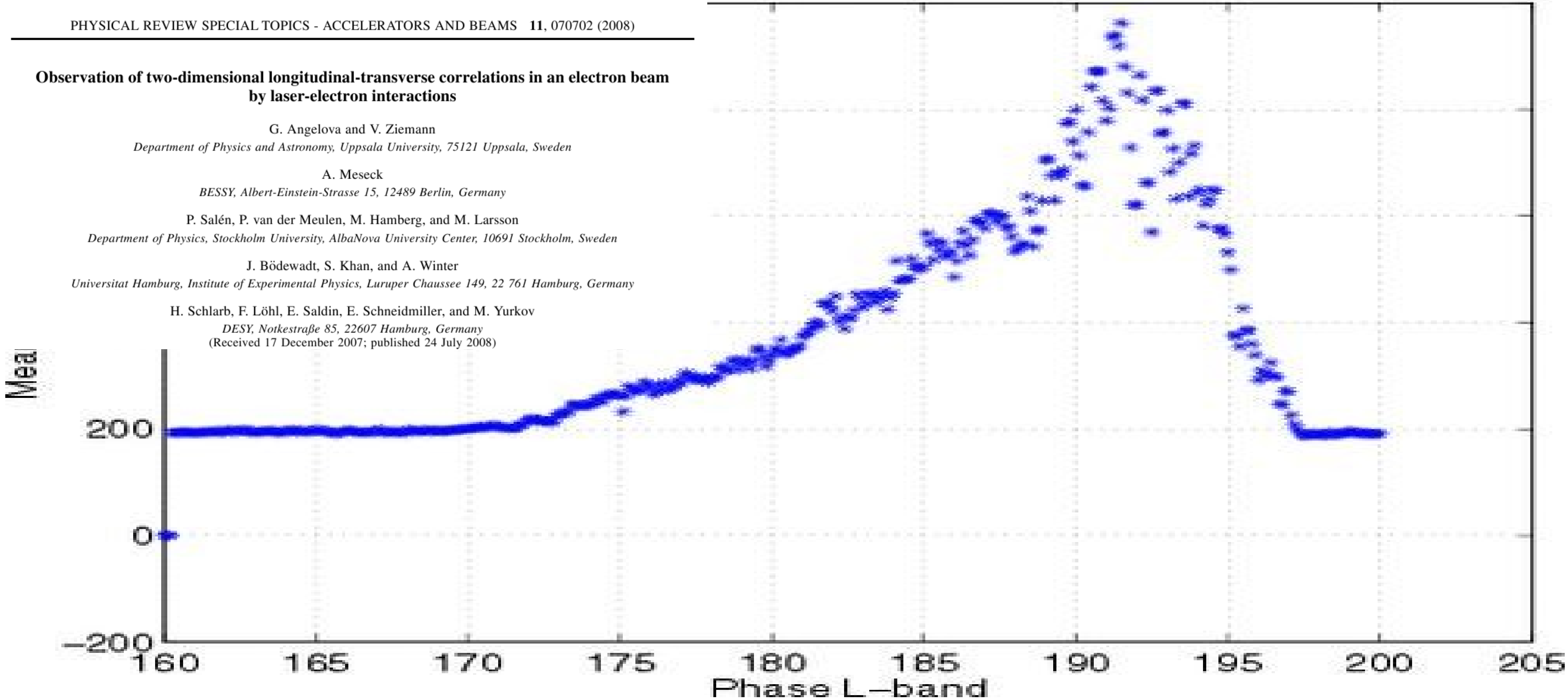
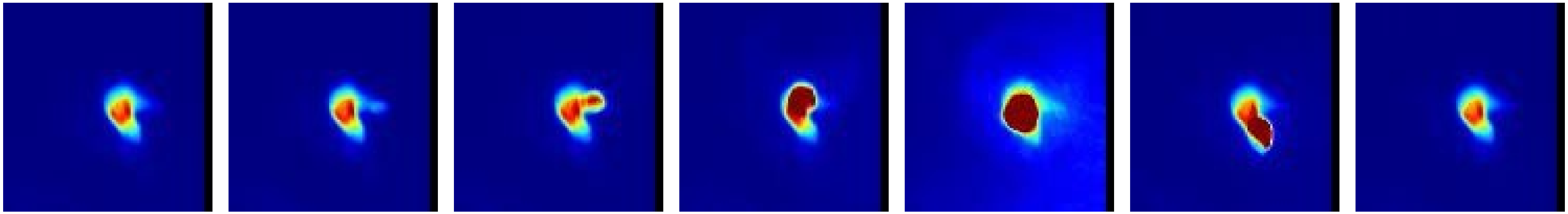
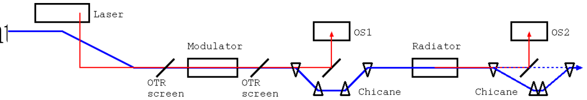
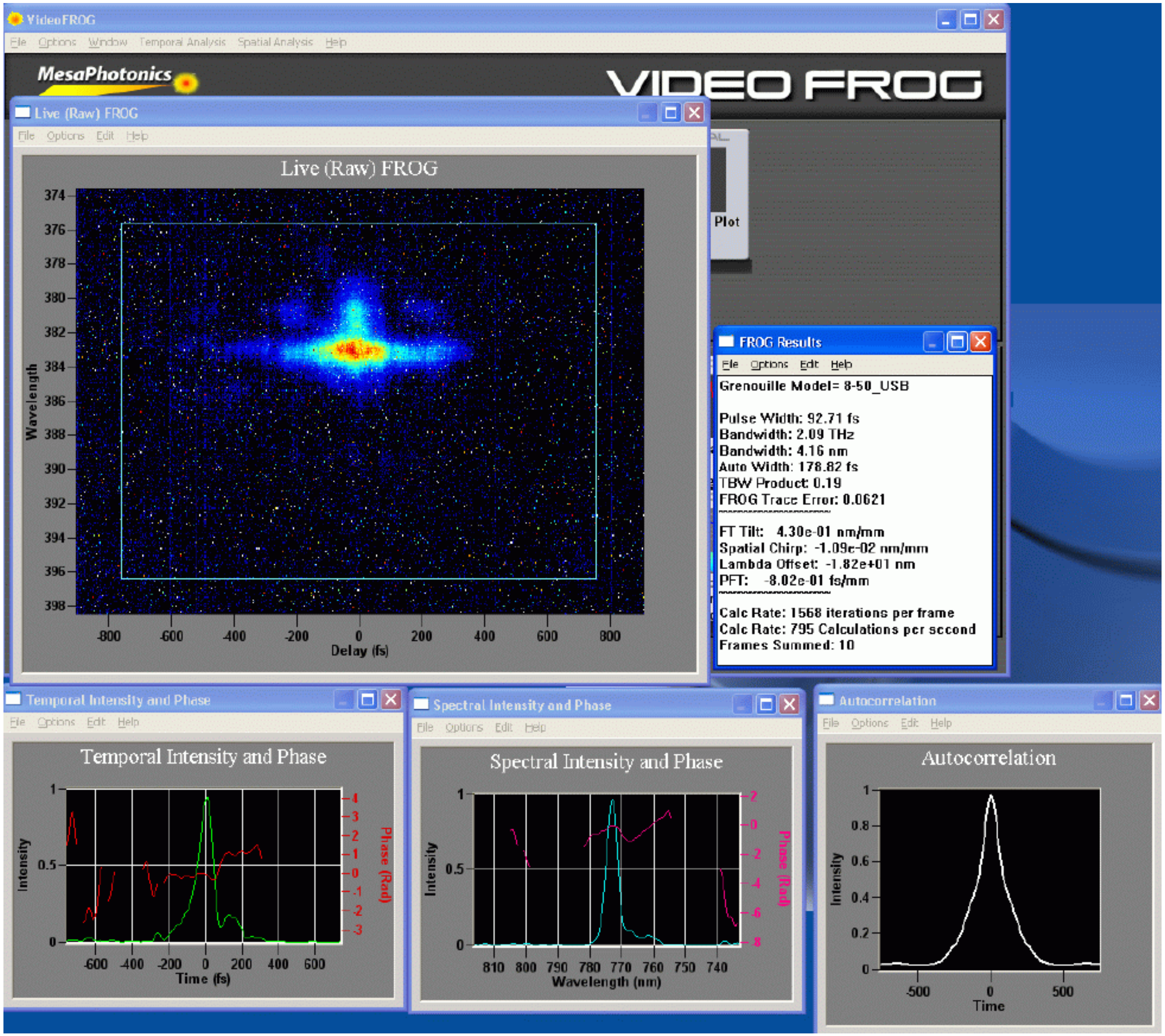


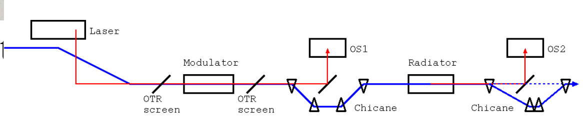




...finally: Single-shot FROGs



- From radiator (HILDA)
- Significant tuning with OS2 Setup
- long/short Grenouille
- First shortE/shortL because of intensity
- Here shortE/longL during SASE conditions at 700 MeV (13 nm)
- Unfortunately no simultaneous LOLA measurement
- Parasitic operation



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Optical Replica

What's next?

- ORS undulators are installed in the sFLASH beam line.
- sFLASH HHG laser can deliver 30 mJ in IR, but presently mirrors are optimized for harmonics around 30 nm.
- New laser beamline for 800 and 270 nm (tripler) will be installed this fall...
- ...for EEHG experiments (hopefully) in conjunction with Replica experiments early 2012 (stiff competition for beam time in FLASH)

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Optical Replica

ORS Conclusions

- Installed and commissioned the optical replica synthesizer in FLASH since fall 2007
- We managed to hit the electron bunch with laser
  - can be used to measure longitudinal-transverse correlations in long (few ps) bunches
- Eventually recorded online FROG traces from the short-pulse GRENOUILLE
  - unfortunately no simultaneous LOLA measurements
- Undulators were reinstalled in the sFLASH beam line and using the HHG laser and new laser beam line they will be used for EEHG and hopefully ORS experiments.

EuXFEL Laser Heater

- Call by the Swedish Research Council for EuXFEL contributions in March 2008
- We were triggered by the electron-laser theme
- Succesful bid, approved May 2008, but money was only released in October 2010!
- Swedish in-kind contribution to the EuXFEL
  - UU: Gergana Angelova-Hamberg, Mathias Hamberg, Vitaliy Goryashko (from September)
- So why does EuXFEL need one and what is it?

Why ...

- Electrons are born in the photo cathode with a very small momentum spread (~3 keV)
  - makes them susceptible to microbunching instability on their travel through the linear accelerator and bunching chicanes
- Add Landau damping (decoherence) in a well-controlled way to increase momentum spread
  - induce moderate momentum modulation by passing a laser over the electrons in an undulator
  - and smear out by coupling some of the angular spread into the longitudinal plane

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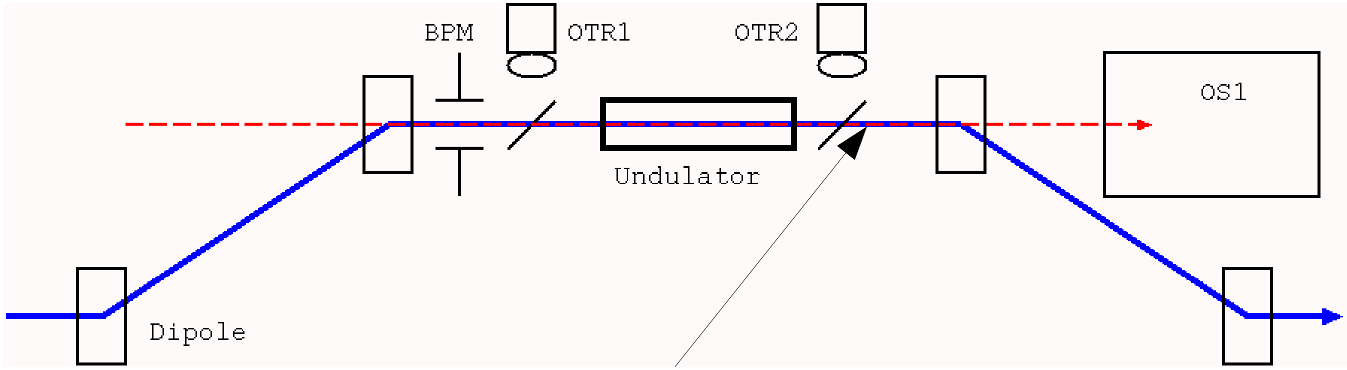
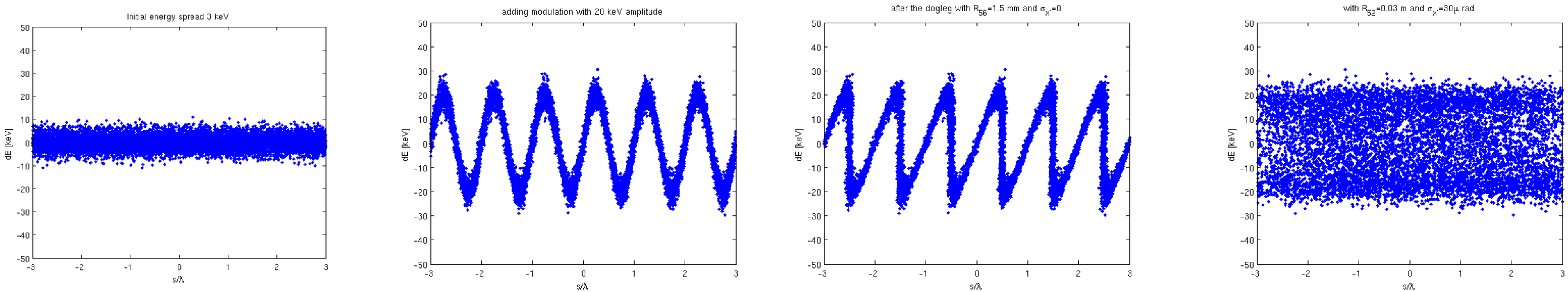
European XFEL

How ...

- Pass IR laser over beam in undulator → modulate dE
- R_{52} of 2nd leg of chicane couples 'transverse heat' into the longitudinal plane and smears out the modulation



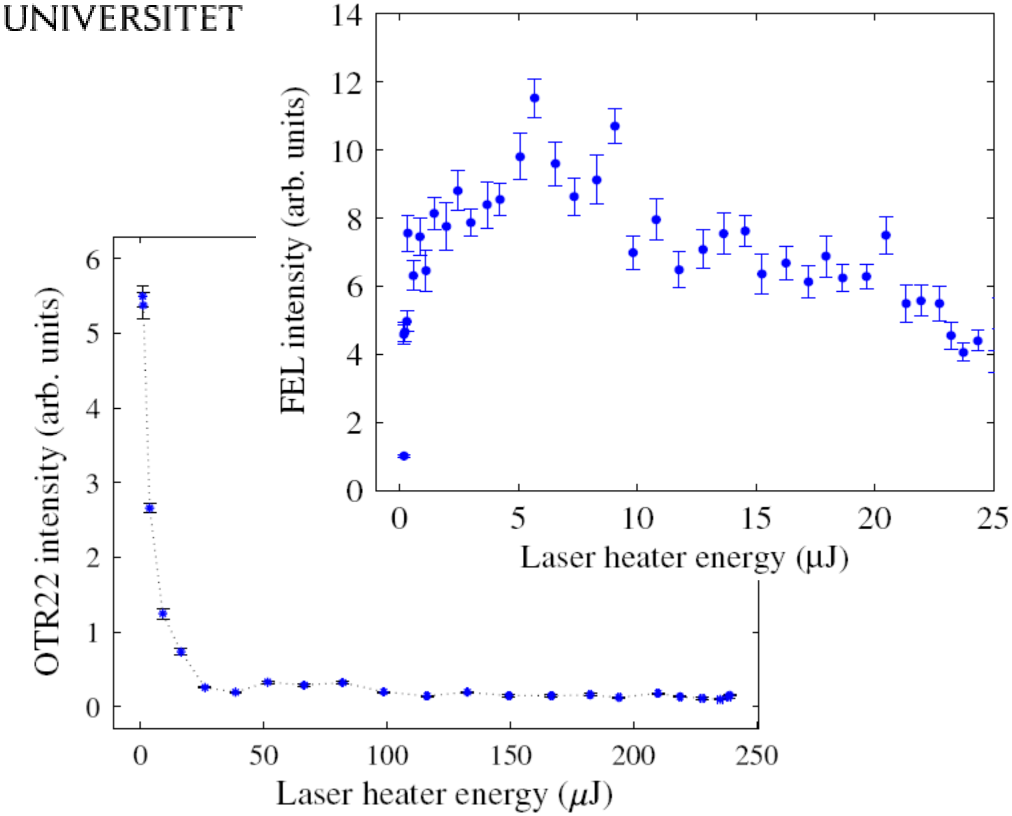


Parameters

- Will use 1030 nm photons
- Operate between 110 and 160 MeV
- Permanent undulator with variable gap
- 8+2 periods of l=74 mm
- Chicane offset 30 mm
- Second half has R_{56}=0.003/2 m, R_{52}=0.030 m
- Pulse energy up to 50 uJ (2.5 MW, 20ps)
- Beta functions 9 and 12 m, σ ~ 0.2 mm

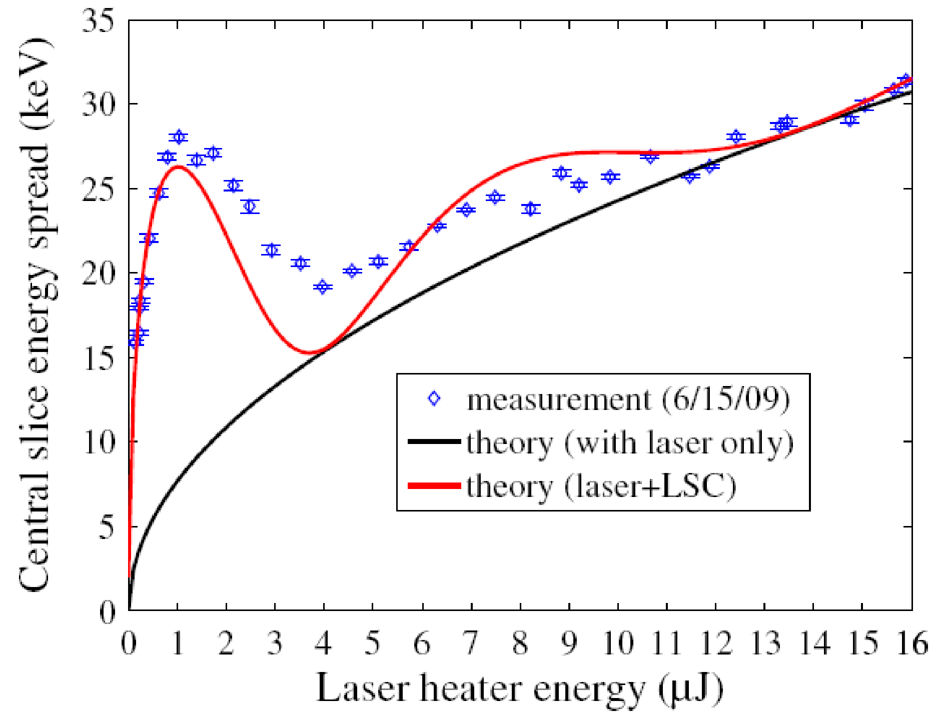
Experience from LCLS

Z. HUANG *et al.* Phys. Rev. ST Accel. Beams **13**, 020703 (2010)



- ...but, sign of 'anomalously' strong heating
- trickle heating

$$\delta_{LSC} \propto \int ds \exp\left[-\frac{\varepsilon}{2\beta}(k_0 R_{52} R_{11})^2\right] \frac{\varepsilon\bar{\beta}}{\sigma_r^2} \frac{1}{1+\gamma^2 R^2}$$



- FEL intensity increases
- Coherent OTR (sign of μ-bunching) is reduced

What does it mean for XFEL?

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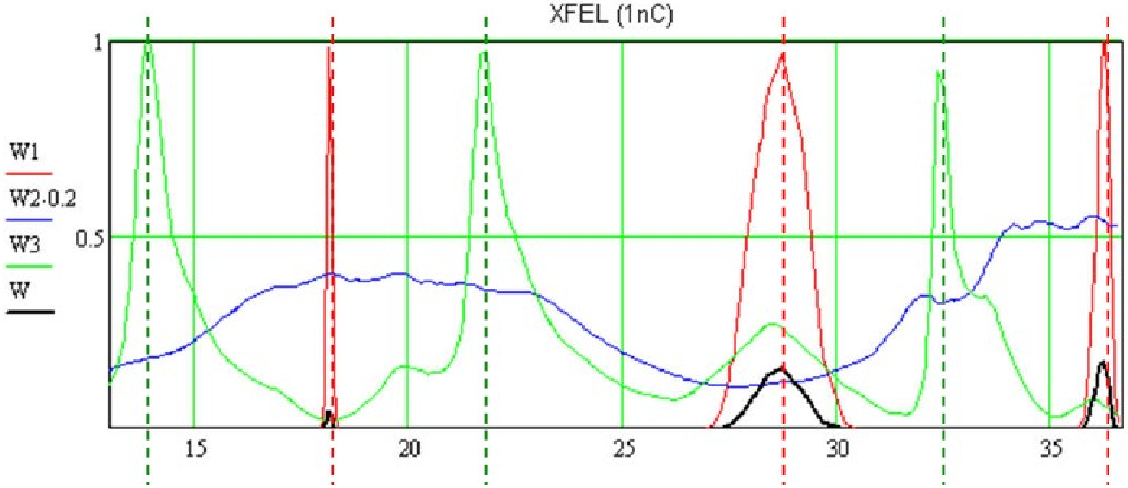
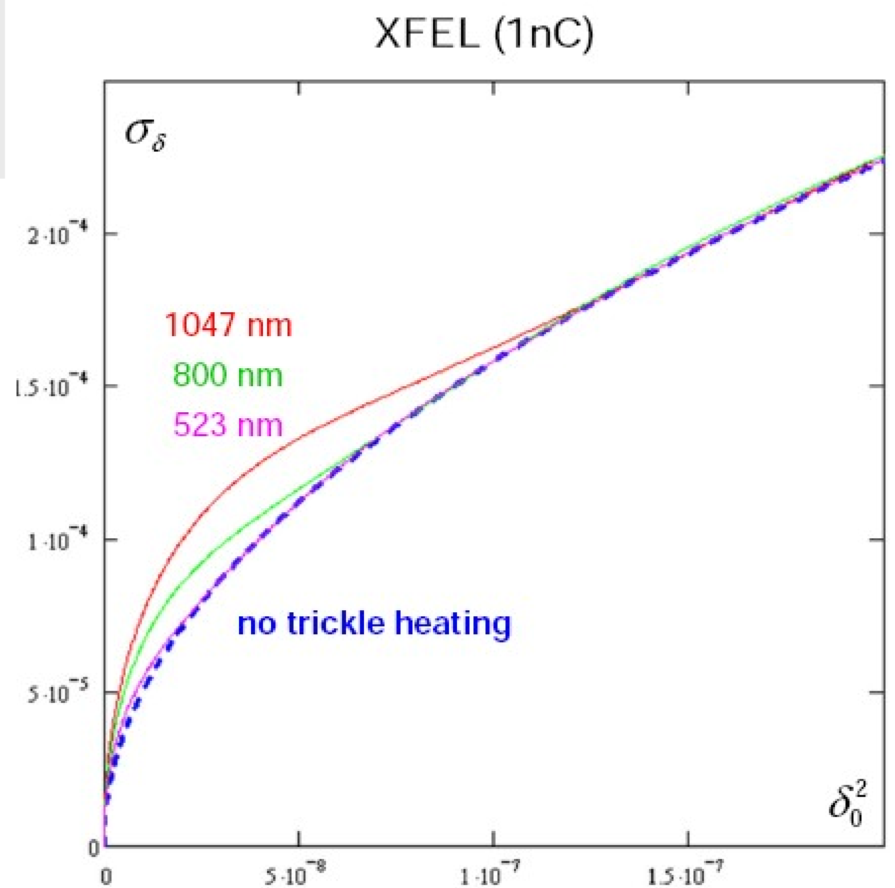
European XFEL

analysis done by Martin Dohlus 

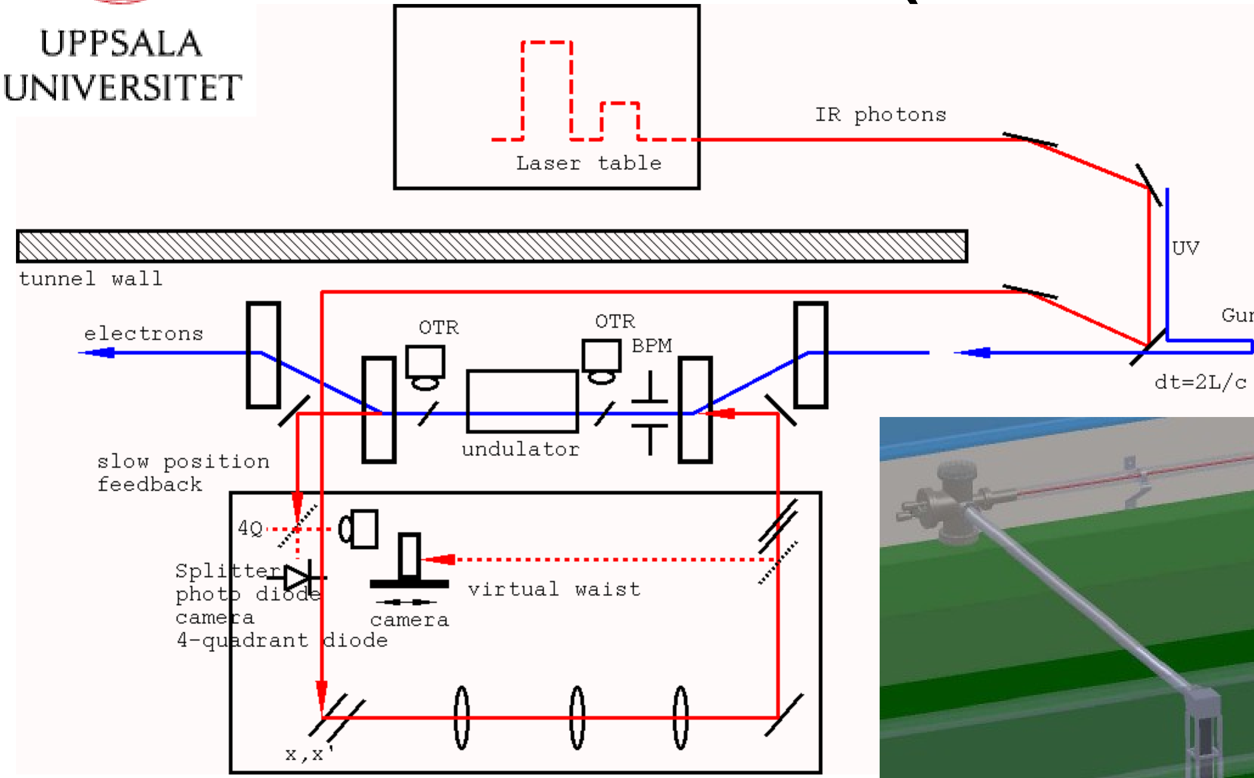
$$\int dz \times \exp\left(-\frac{\varepsilon}{2\beta}\left(k_0 R_{52} R_{11}\right)^2\right) \frac{\varepsilon\bar{\beta}}{\sigma_r^2} \frac{1}{1+\gamma^2 R^2}$$

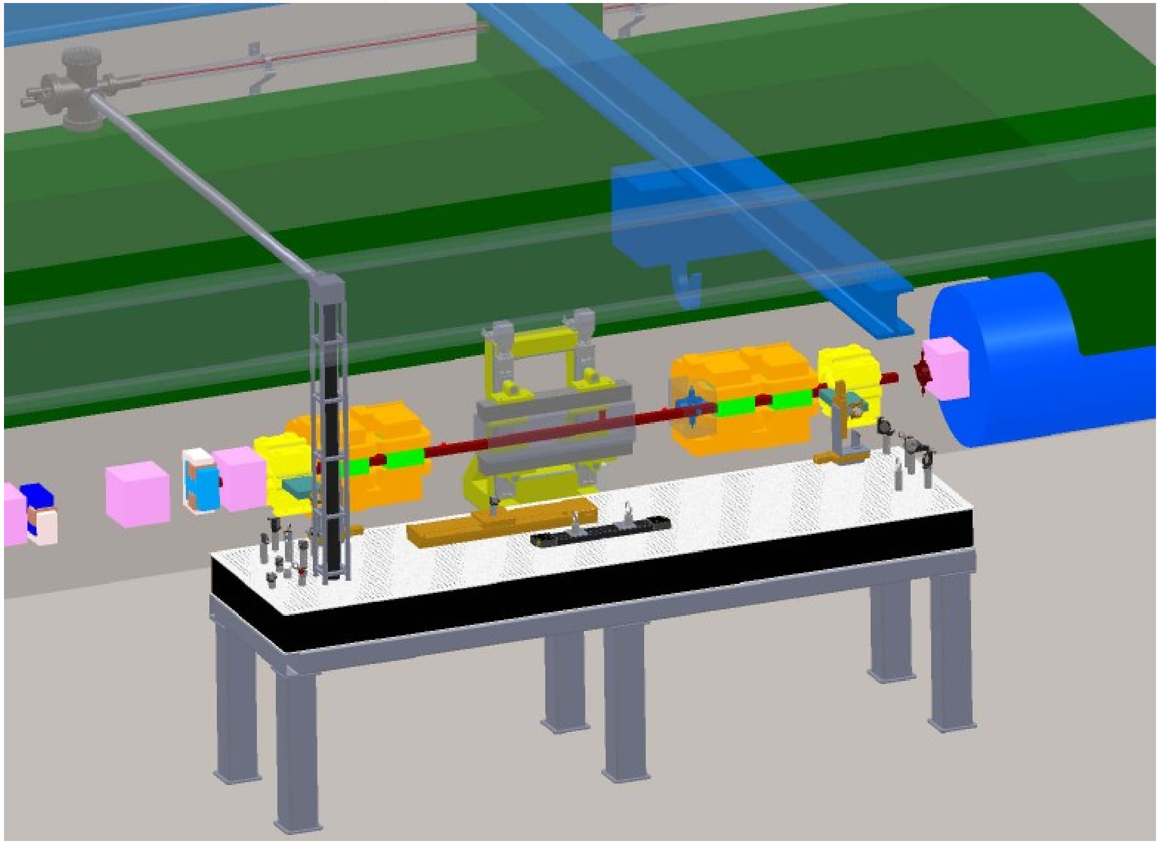




- Make R large when R_{11} is zero
- XFEL is doing ok

'Our' task (schematic)





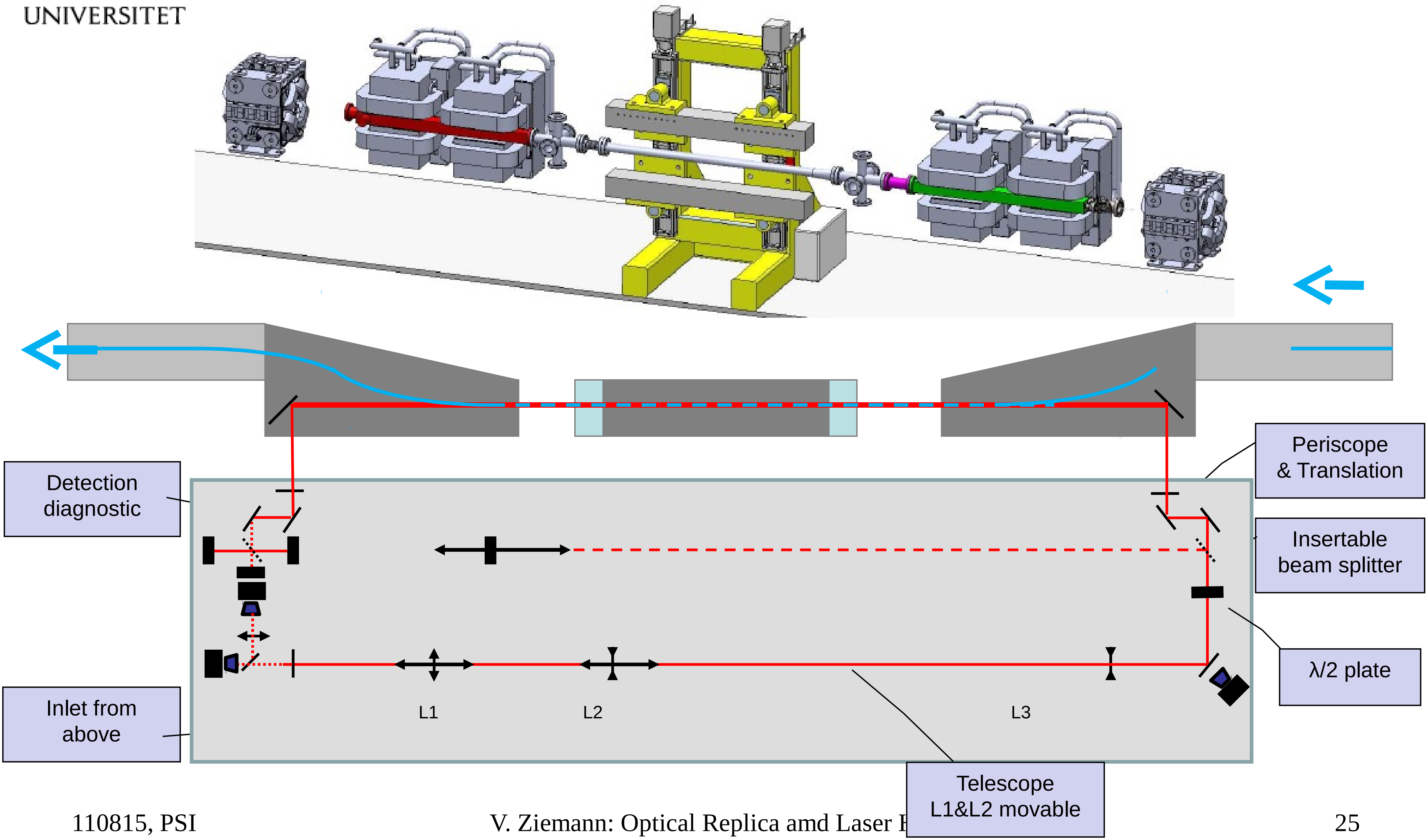
Obtaining 1030 nm Photons

- Use the non-converted "red" photons from the first frequency doubling (red2green) stage
  - Inherently locked in timing to the parent UV photons for the entire pulse train
  - Bandpass filter to separate
  - Intensity according to Ingo Will is 30 to max 50 μJ depending on the pulse flattening scheme. This is adequate for routine operation, but for start-up and commissioning more is desirable (LCLS has 200 μJ available).
- Plan: study stability of photons (intensity, pointing, M2)
- Critical issue: **additional laser amplifier stage** (~100 kEuro according to Ingo Will, not in our budget, but MAC ok'ed it)
  - we need to follow the gun laser development

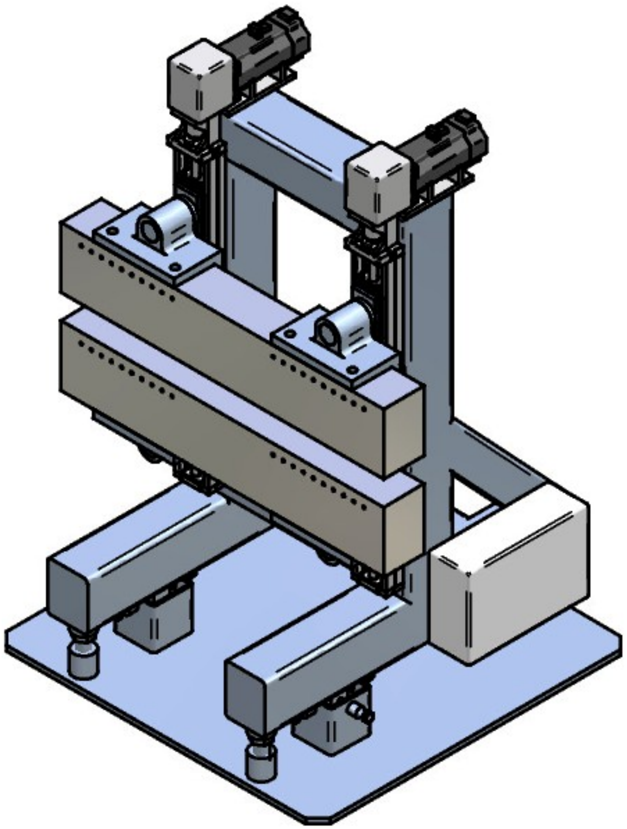
Transporting the photons

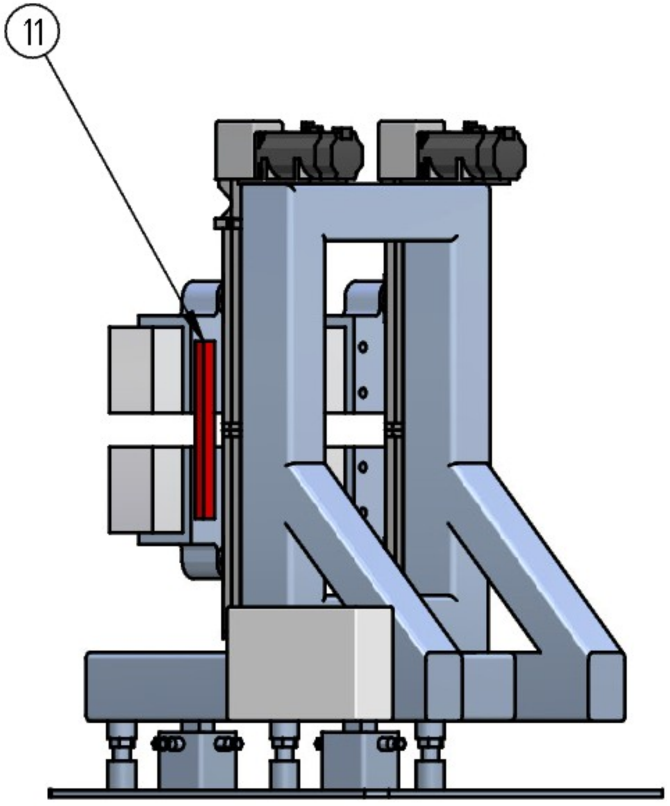
- Long (~50 m) transport path through 'hostile' environment such as the vertical shaft
- Evacuated pipe to avoid dn/dT-wandering
  - actually need moderate vacuum but will use ion pumps to avoid mechanical noise
- Mirror mounts and pointing stability
  - passive stability to counteract fast jitter
  - slow feedback near undulator to counteract drifts
- Dielectric mirrors, use "spill" for target practice

Chicane Layout



Undulator Magnet

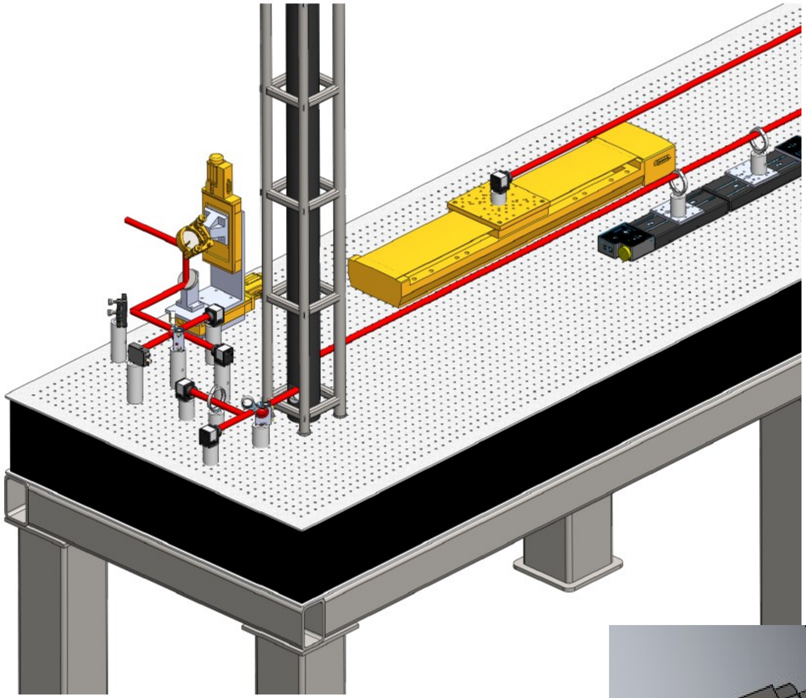


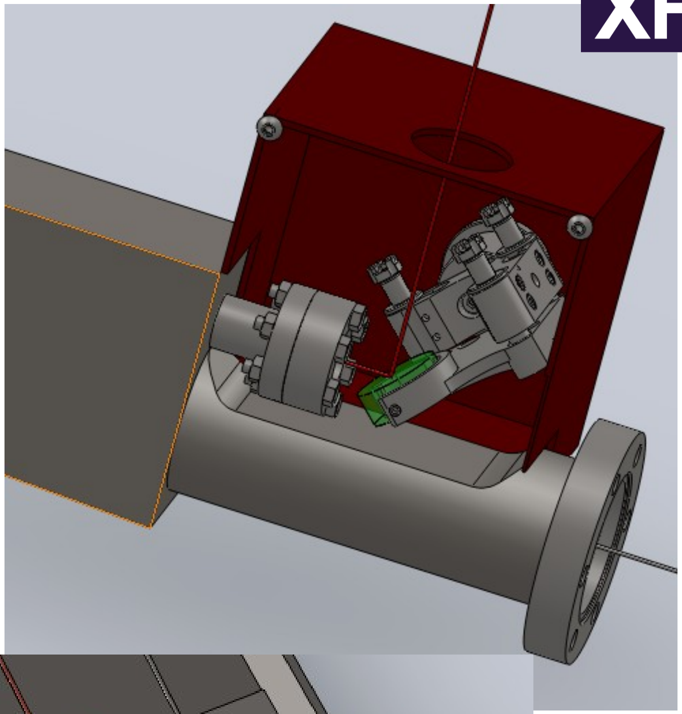


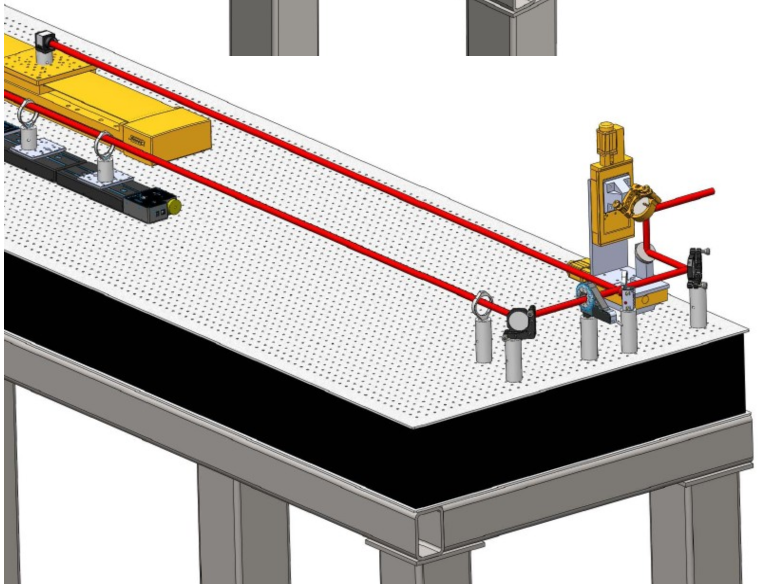
- Variable gap
- Gap > 30 mm
- 110..160 MeV
- L_0=74 mm
- 8+2 periods
- B_0=0.11..0.27 T

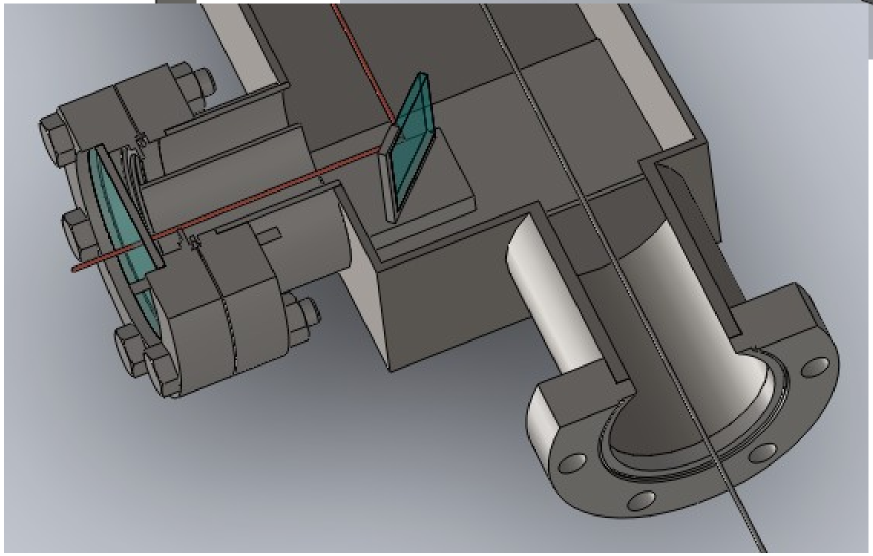
Courtesy of SCANDITRONIX Magnet

Hardware



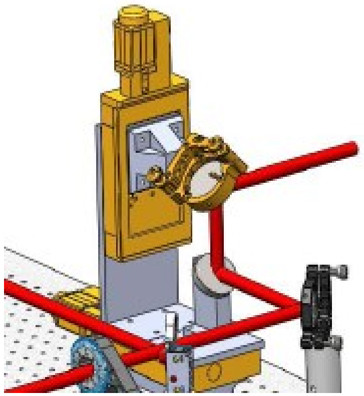




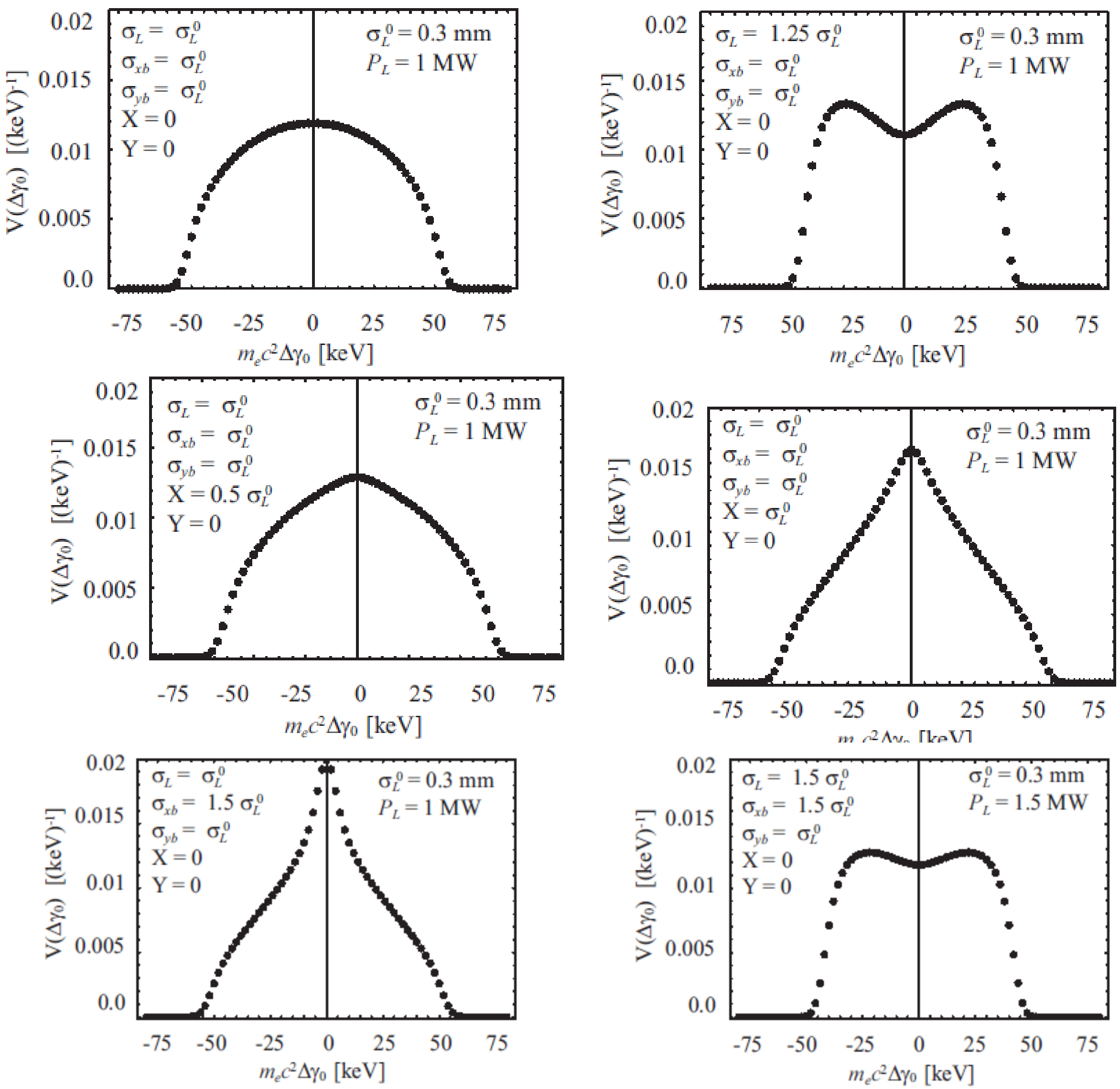


Chicane and Photon Overlap

- Transverse
  - Screen before and after the undulator
  - Diagnostic: OTR for electrons and diffuse for laser
  - Control: in periscope
- Longitudinal
  - Diagnostic: fast photo-diode and oscilloscope (20 ps pulses) laser and synchrotron light
  - Control: delay stage in laser hut

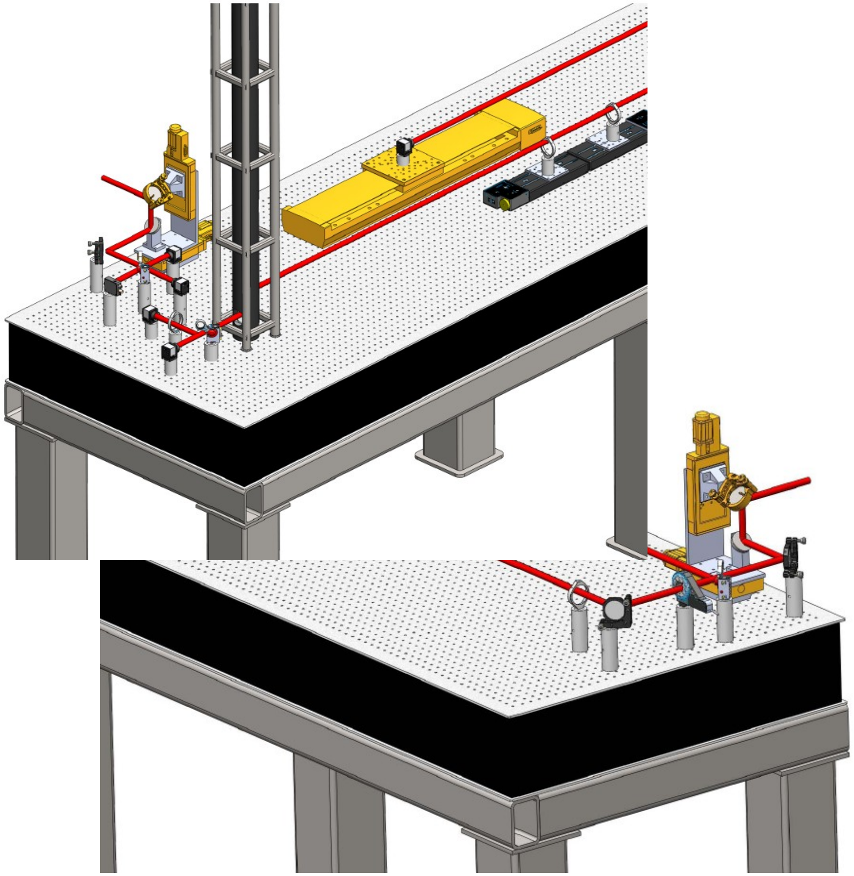


Tolerances



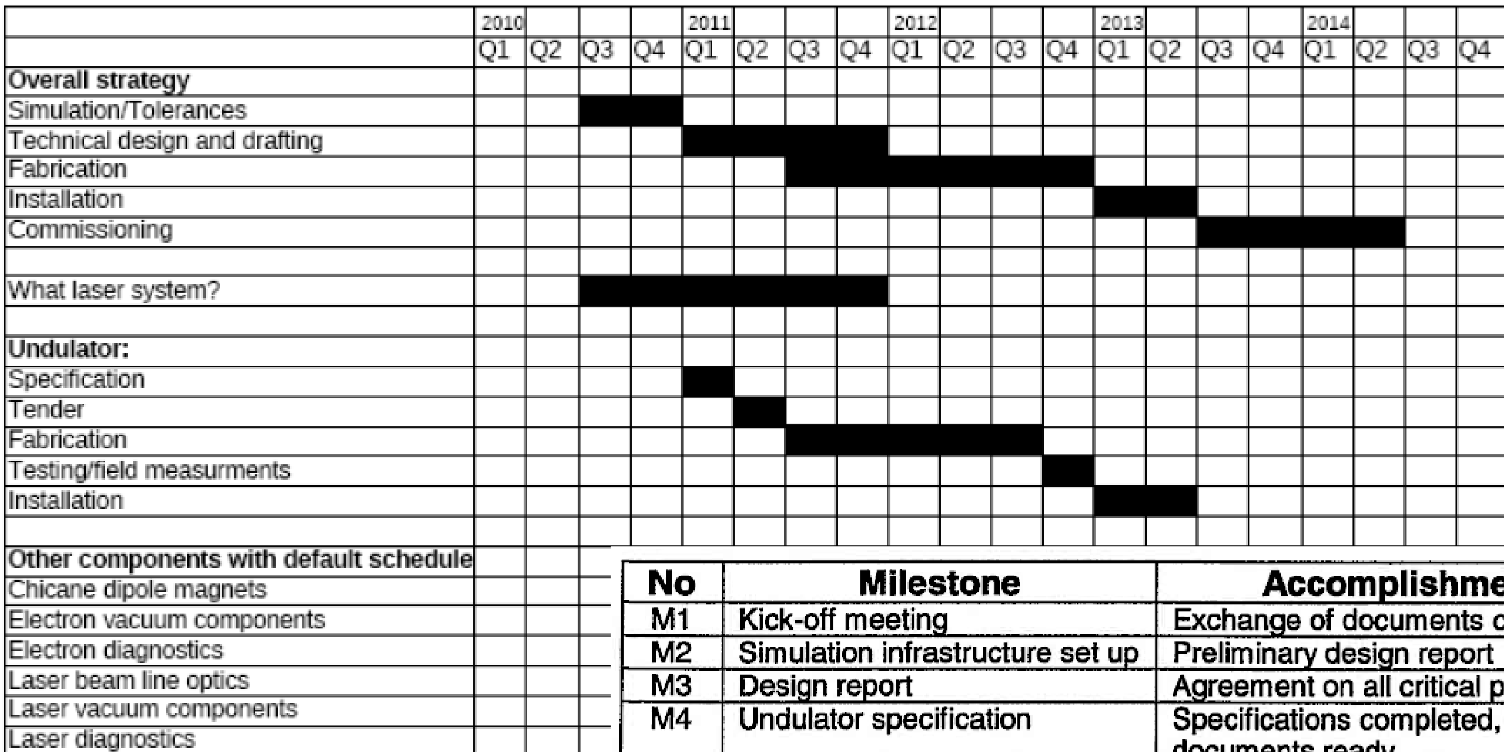
- Size ~20%
- Offset ~σ/2
- Elliptic, ok, if we increase laser size
- Angle < ~σ/L

Diagnostics on Laser Tables



- Initial Setup
  - photon waist size and position
  - control transverse position
- Online Monitoring
  - photon beam position (4Q)
  - photon beam size (camera)
  - Timing (diode)
- Stabilization
  - Use signals from near-farfield, x,x' cameras after dielectric mirrors to compensate drifts with 2 upstream mirrors.

Timeline



No	Milestone	Accomplishment criteria	Date
M1	Kick-off meeting	Exchange of documents completed	Q3-10
M2	Simulation infrastructure set up	Preliminary design report	Q4-10
M3	Design report	Agreement on all critical parameters	Q3-11
M4	Undulator specification	Specifications completed, tendering documents ready	Q3-11
M5	Undulator contract	Contract award after tendering	Q4-11
M6	Laser system concept	Conceptual design agreed	Q4-11
M7	Laser system design	Final design completed, TDR	Q1-12
M8	Undulator	Delivery of undulator	Q2-12
M9	Vacuum chambers	Delivery of vacuum chambers and support structures	Q3-12
M10	Optical components	Delivery of all optical components	Q3-12
M11	Field measurements	Undulator field measurements completed	Q4-12
M12	Installation and integration	Installation & integration completed	Q2-13
M13	Commissioning	Commissioning completed	Q3-13

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Laser Heater Conclusions

European XFEL

- Laser heater is a Swedish in-kind contribution to the EuXFEL project done by Uppsala University.
- Started for real early 2011.
- Simulations and tolerance calculations are in progress. (Martin Dohlus and Vitaliy Goryashko)
- We are working on engineering solutions (Mathias Hamberg, Niklas Johansson, Masih Noor)
- Undulator parameters are fixed and draft of tender is in the works.

Backup slides

Scheme of the ORS synchronization & trigger system

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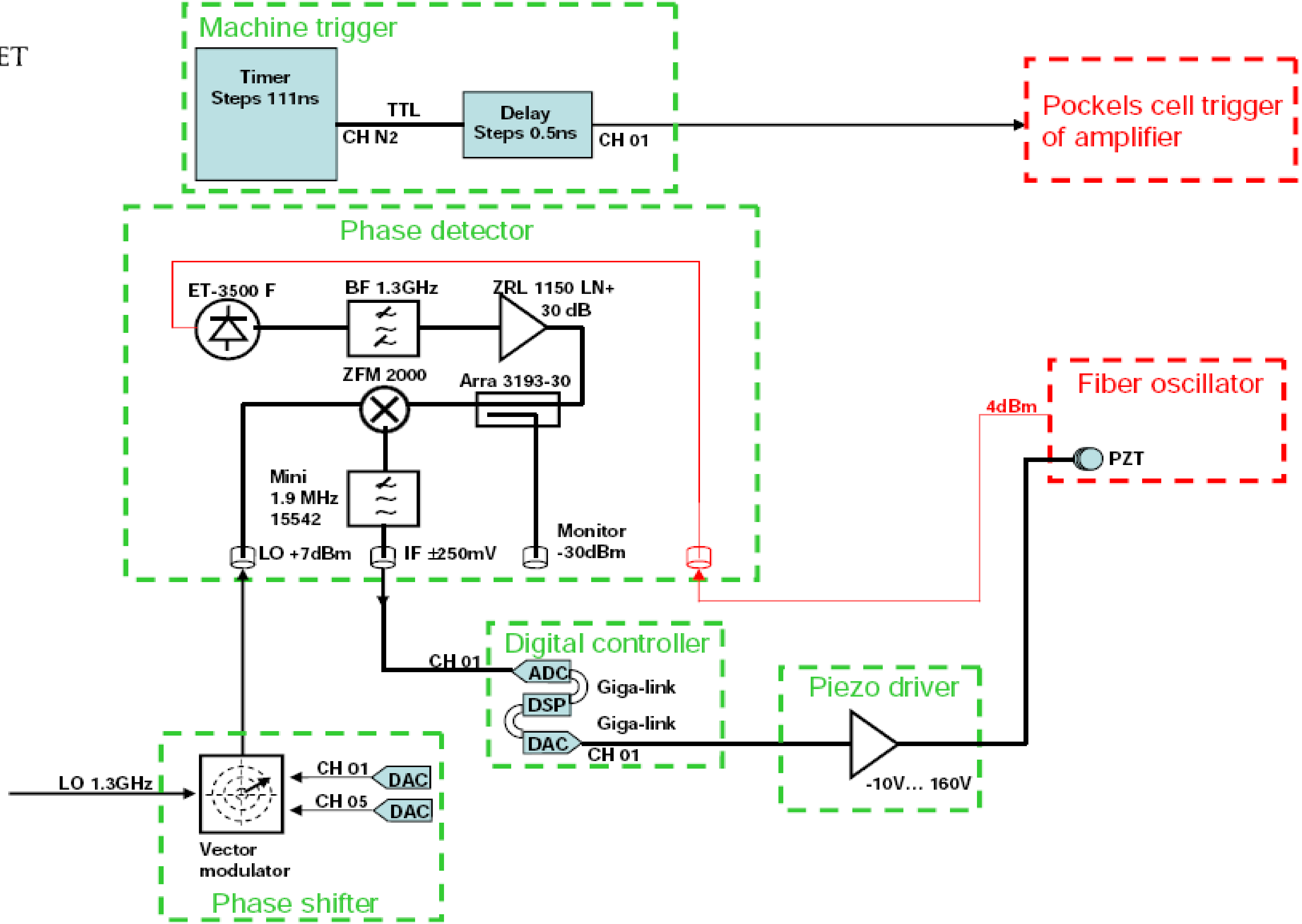
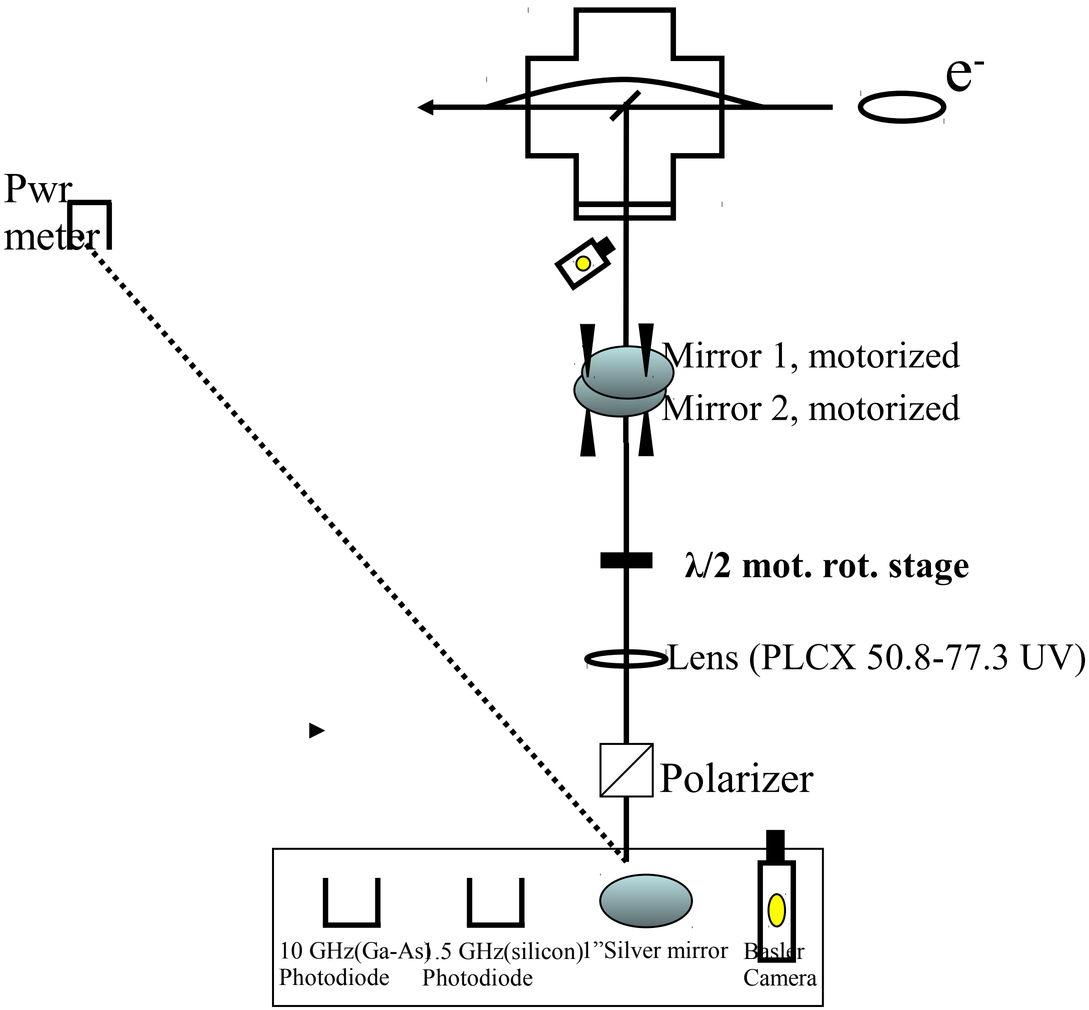
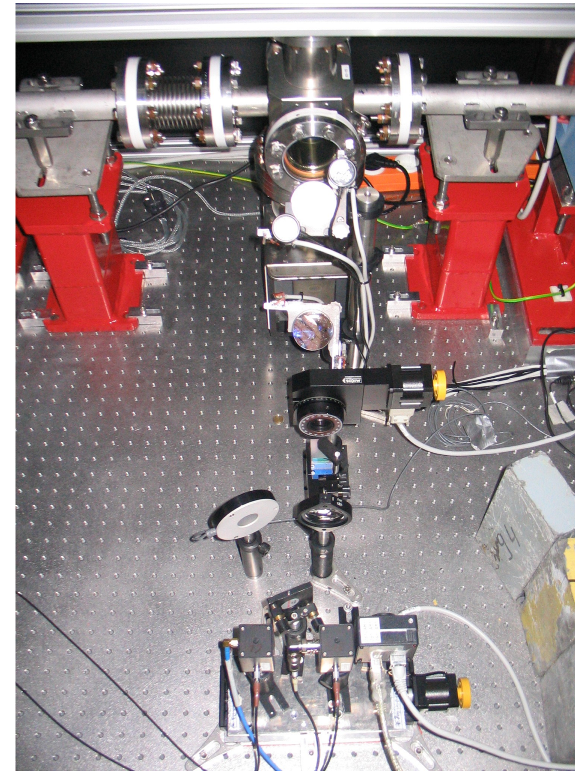
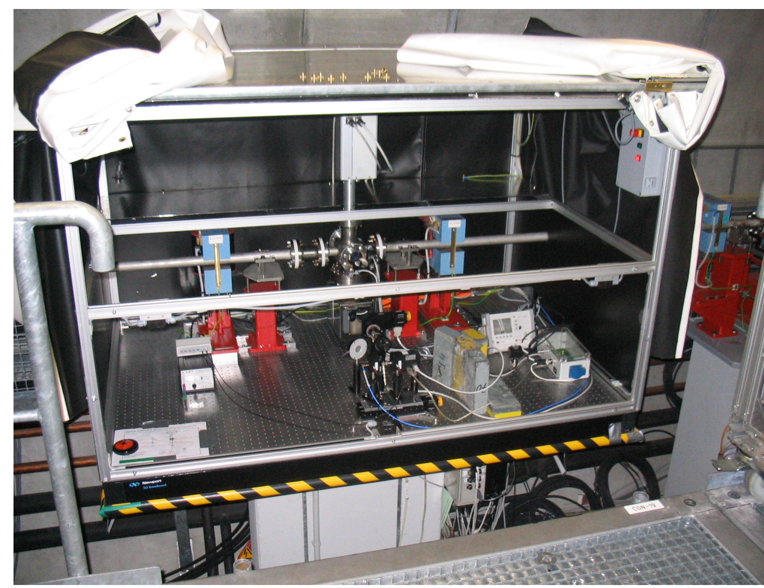


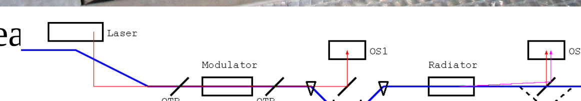
Optical Station 1

Essential for timing: Laser + Synchrotron radiation







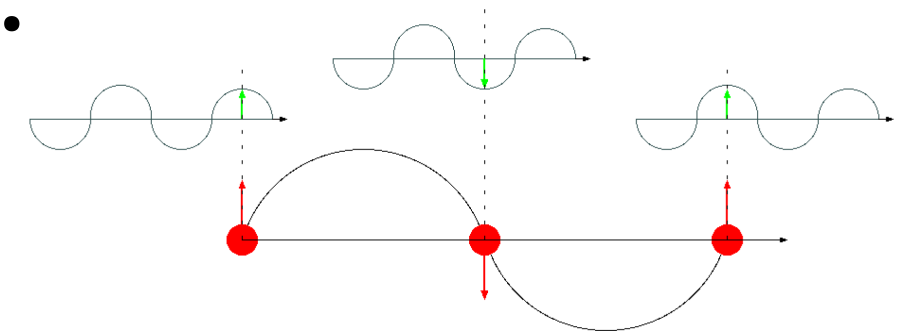


Seed Laser and Modulator

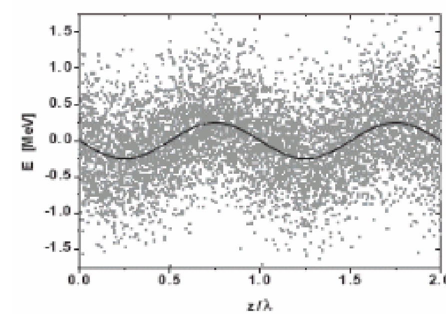
- Seed laser must overlap electron bunch and provide sufficient strength to modulate the energy
- probably Ti:Sapphire
- Length: a few ps, say 10 ps
- Synchronization to bunch RF and electron gun
- Power: 100 MW, 1 mJ/pulse, 5 Hz
- modulation amplitude: dp/p $\sim 10^{-3}$
- Need dog-leg to shine laser onto electron trajectory
- Undulator with about 5 periods

- Coupling between laser and electrons

$$\Delta U = e\int(\vec{E}.d\vec{s}) = e\int E_x v_x dt$$

- 

- Some gain, some loose, depending on initial phase



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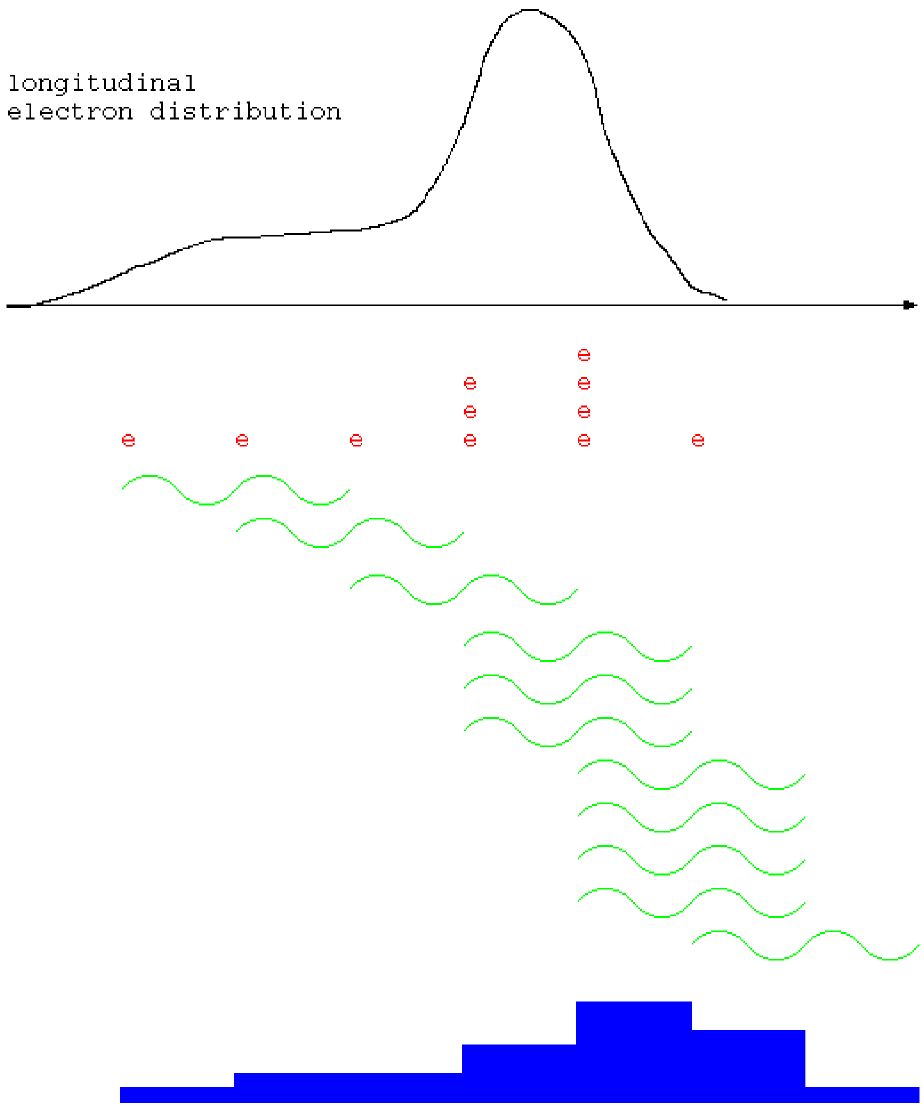
Radiator Undulator



- Electrons have longitudinal density modulation and can radiate coherently.
- Each electron slice oscillates in undulator (like an antenna) and all contributions are added in phase.
- Number of periods *N* determines the length of the light pulse that an electron emits → short undulator
- Need to propagate replica pulse to diagnostic section

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Resolution

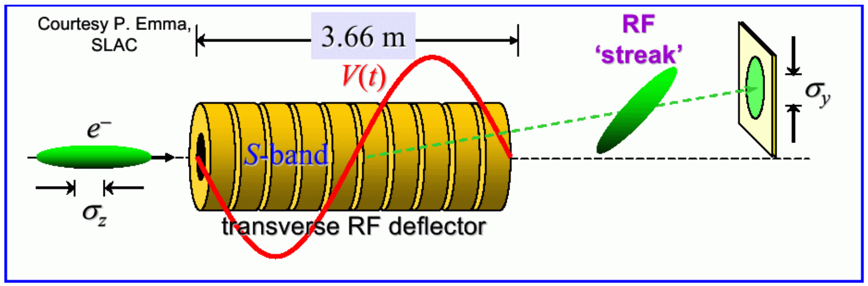
- 8-50: 17 fs
- 5 Periods
  - 4 µm/13 fs
- Wavefront tilt
- Dispersion in optics on OS2
- Bent(?) mirrors
- Plasma-oscillations(?)

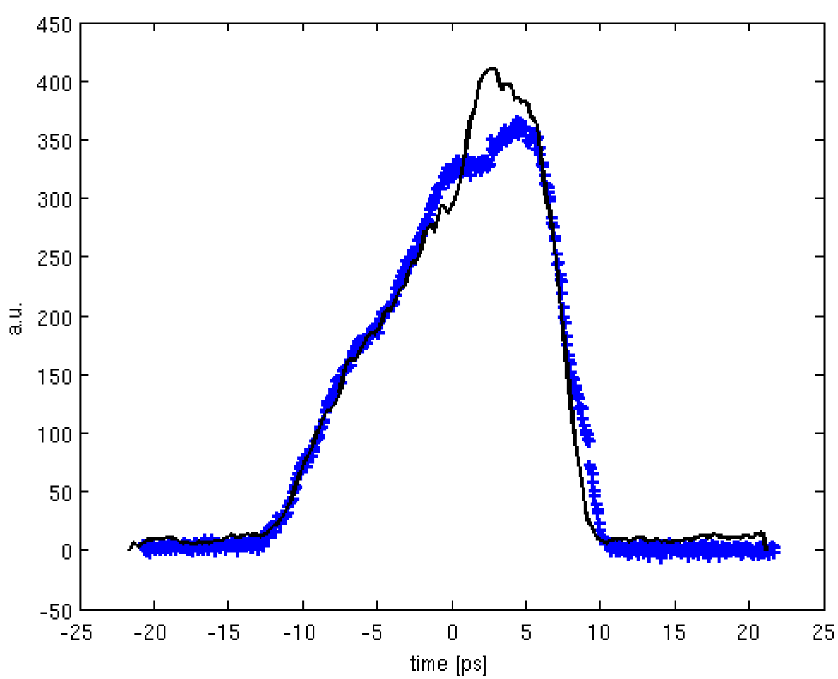
- Grenouille: Datenblatt von Swamp Optics

GRENOUILLE model:	8-9USB	8-20USB	8-50USB	8-300USB	8-500USB
Wavelength range:	700 – 1100 nm				700 – 900 nm
Pulse-length range @ 800 nm:	~10 – ~100 fs	~20 – ~200 fs	~50 – ~500 fs	~0.3 – ~2 ps	~0.5 – ~5 ps
Pulse-length range @ 1050 nm:	~8 – ~80 fs	~15 – ~80 fs	~30 – ~100 fs	~0.1 – ~1 ps	na
Temporal resolution @ 800 nm:	3.7 fs	12 fs	17 fs	50 fs	90 fs
Temporal resolution @1050 nm:	2 fs	9 fs	13 fs	41 fs	na
Delay increment[1]:	0.95 fs/pixel	0.85 fs/pixel	1.145 fs/pixel	11.5 fs/pixel	11.5 fs/pixel
Temporal range[3]:	336 fs	480 fs	1.9 ps	19 ps	19 ps
Spectral resolution @ 800 nm:	5 nm	4 nm	2 nm	0.23 nm	0.05 nm
Spectral resolution @1050 nm:	6.5 nm	15 nm	7 nm	0.8 nm	na
Spectral range @ 800 nm[3]:	300 nm	160 nm	50 nm	8 nm	10 nm
Spectral range @1050 nm[3]:	400 nm	400 nm	125 nm	20 nm	na
Pulse complexity:	Time-bandwidth product < ~10				
Intensity accuracy:	2%				
Phase accuracy:	0.01 rad (intensity-weighted phase error)				
Single-shot possible?	Call us.[2]	Yes; both free-running mode & triggered single-shot are now standard.			
Sensitivity (single-shot):	Call us.[2]	1 µJ			
Sensitivity (at 10^3 pps):	500 µW (500 nJ)	100 µW (100 nJ)			
Sensitivity (at 10^8 pps):	50 mW (500 pJ)	10 mW (100 pJ)			
Spatial profile accuracy:	< 0.2 % (Camera has true 8 bits and 480 x 640 pixels)				
Spatial chirp accuracy (dx/dλ):	1 µm/nm				
Pulse-front tilt accuracy (dt/dx):	0.05 fs/mm				
Required input polarization:	Any (just rotate GRENOUILLE!)				
Required input-beam diameter:	2 – 4 mm (collimated)				
Input-beam lateral-displacement tolerance:	> 1 mm				
Number of alignment knobs:	Zero				
Time to set up:	~ 10 minutes				
Dimensions (L x W x H) w/camera:	33 cm x 7.5 cm x 16.5 cm	33 cm x 7.5 cm x 16.5 cm	33 cm x 4.5 cm x 11.5 cm	45 cm x 7.5 cm x 16.5 cm	61 cm x 7.5 cm x 16.5 cm
Weight:	3 kg	3 kg	1.2 kg	3 kg	6 kg

1. At full camera resolution.
2. The Model 8-9 can be modified to allow single-shot measurement, but at a reduction in sensitivity.
3. Temporal and spectral "ranges" are the full-scale ranges, not the pulse FWHM (which is typically a factor of 2 to 3 smaller).

Comparison with LOLA (long several ps bunches)

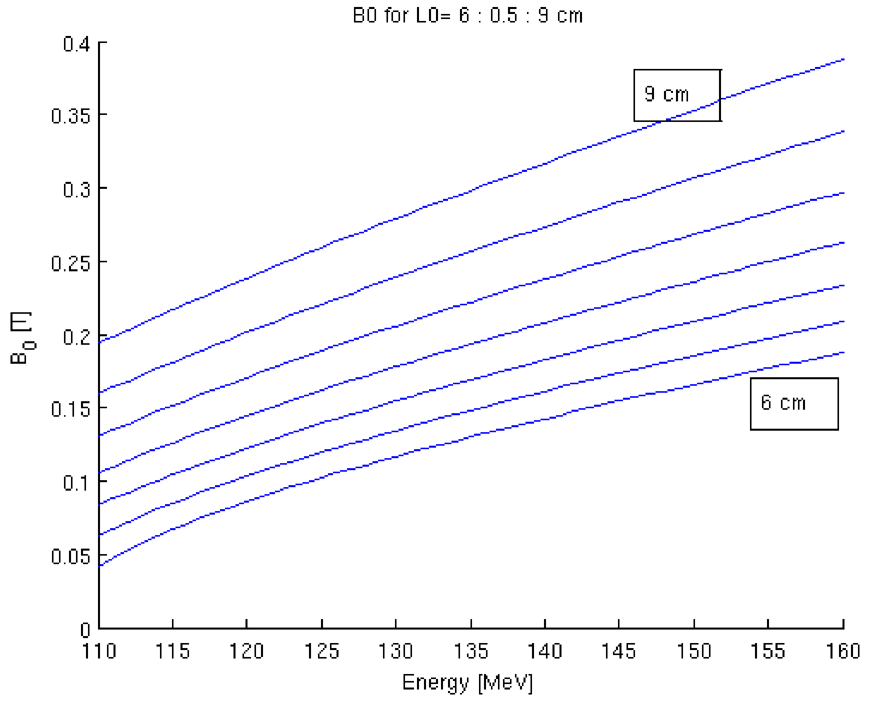




- Simultaneous (almost, 30 min) measurement of bunch profile with transversely deflecting cavity LOLA (blue) and ORS (black).
- Initially the time calibration of LOLA was off by 20 %, now fixed.
- OD2 Neutral density filter before the Basler camera to prevent saturation
- smoothing and sqrt(ORS)
- Very good agreement of the recorded bunch length

Undulator period

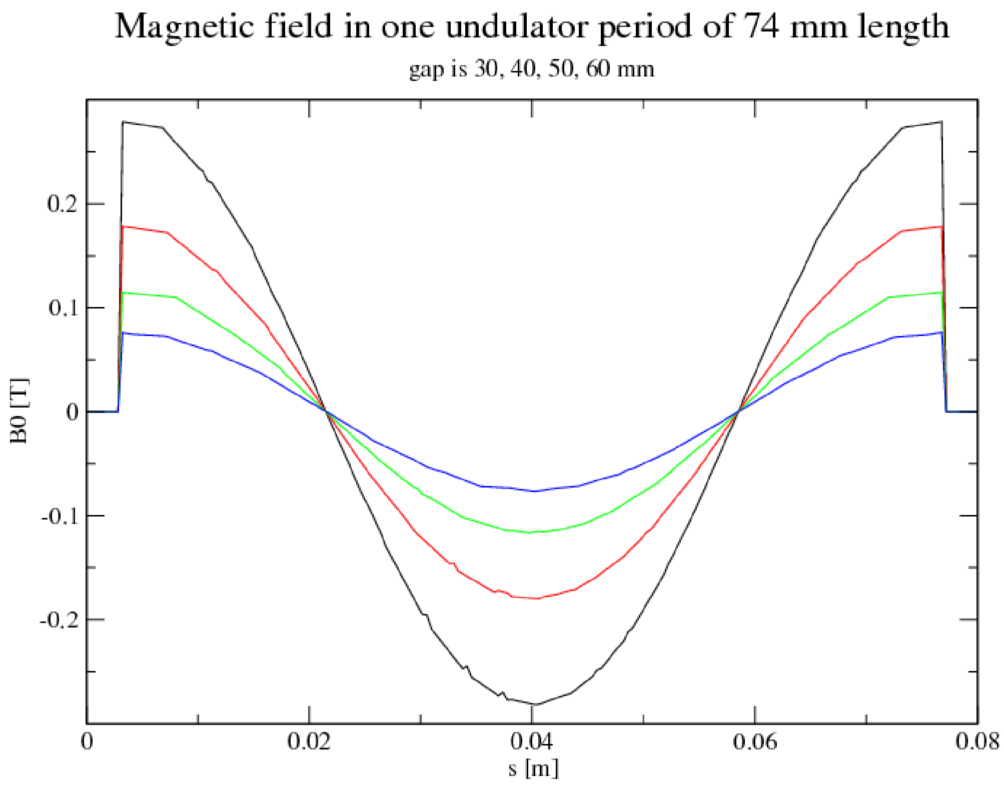
- Parameters
- Laser at 1130 nm
- Resonant between 110 and 160 MeV
- If period too short, filed is very low and hardly any wiggeling
- If too large, the field gets too large

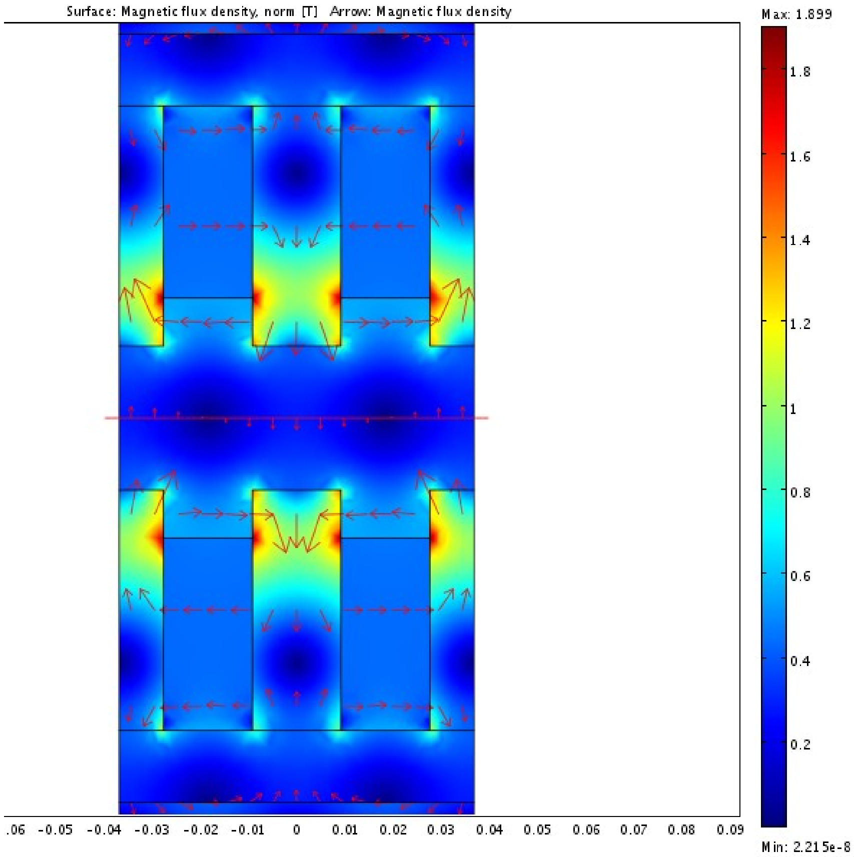


- 7.4 cm was chosen as a decent compromise

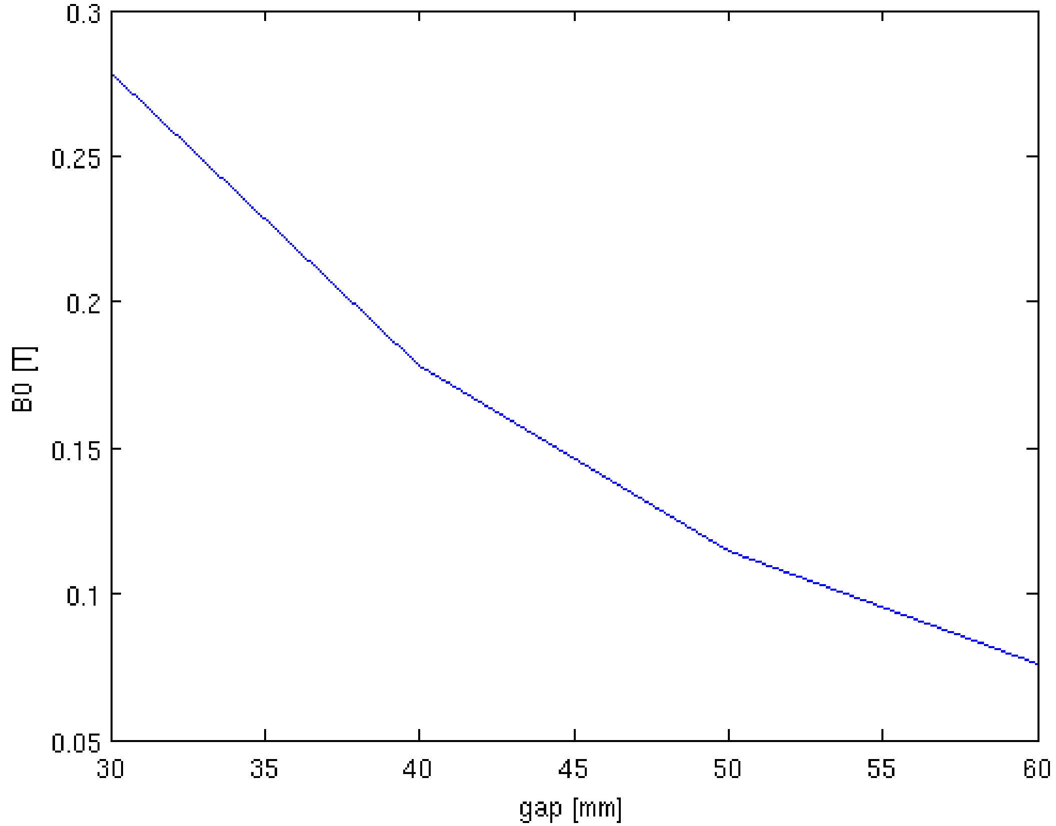
FEMLAB 2D simulation

- Field pattern and field on axis, here choose B_r=1T
- Gap between 30 and 50 mm suffices





Field vs gap



- Maximum gap to minimize effect on beam?
  - $B \sim B_{max}$ exp(-gap/period)

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Parameter list

Energy		110	120	130	140	150	160
B0	T	0.1102	0.1497	0.1832	0.2136	0.2420	0.2691
K		0.7615	1.0346	1.2662	1.4762	1.6725	1.8597
A	micron	42	52	59	63	67	70
gap(est.)	mm	51.0	45.0	39.5	36.5	33.7	30.9

Synchronization

- Delay stages on laser table (Level 5)
    - crude: ~ns scale, mm-screw
    - delicate: ~ps scale, µm-screw
    - can we also delay the UV photons in case 'we' are too slow?
    - implications for photon routing in tunnel
- Lens to collimate photon beam
- Pulse stretcher to lengthen photon pulse
    - simplify the longitudinal overlap

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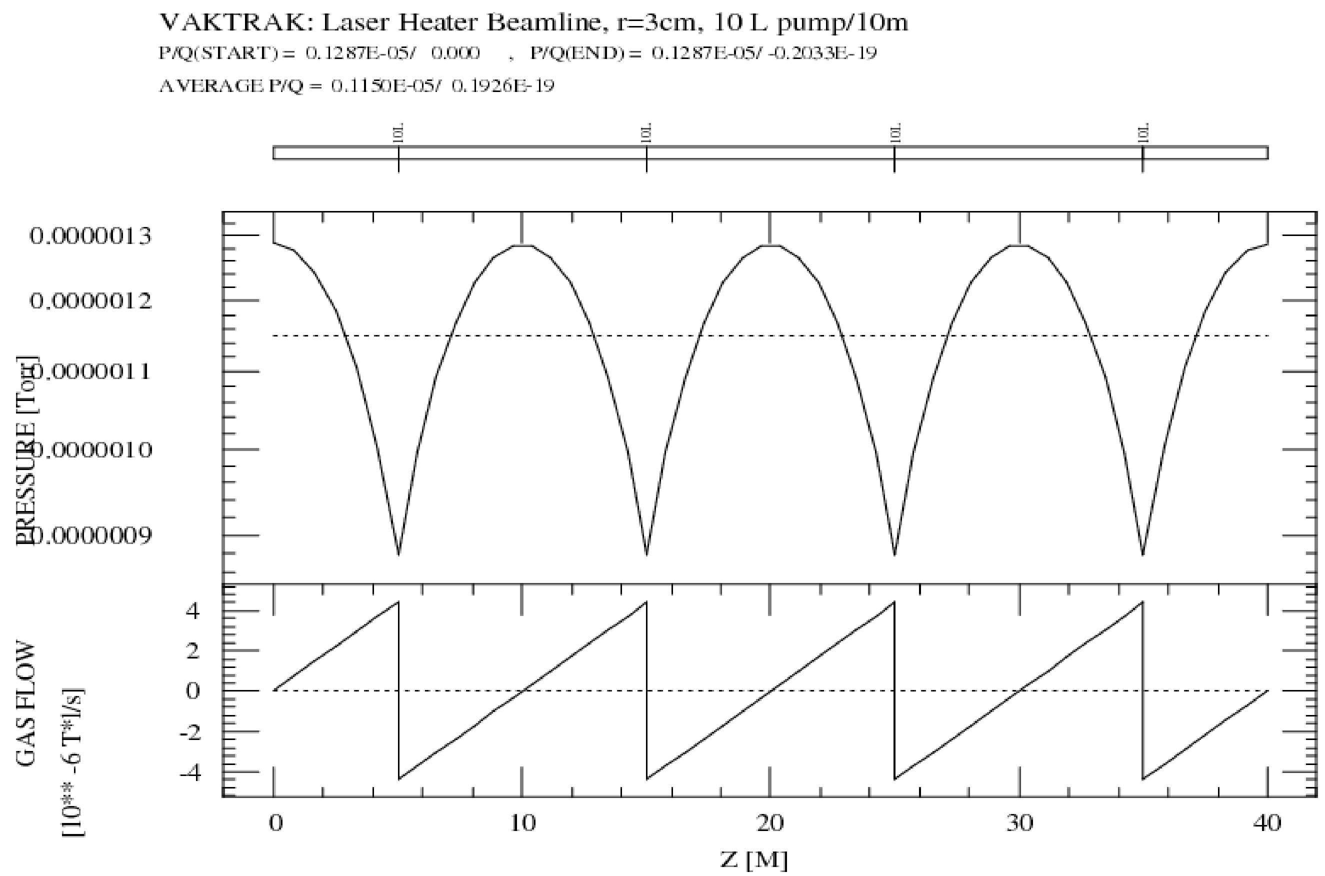
Laser Vacuum System

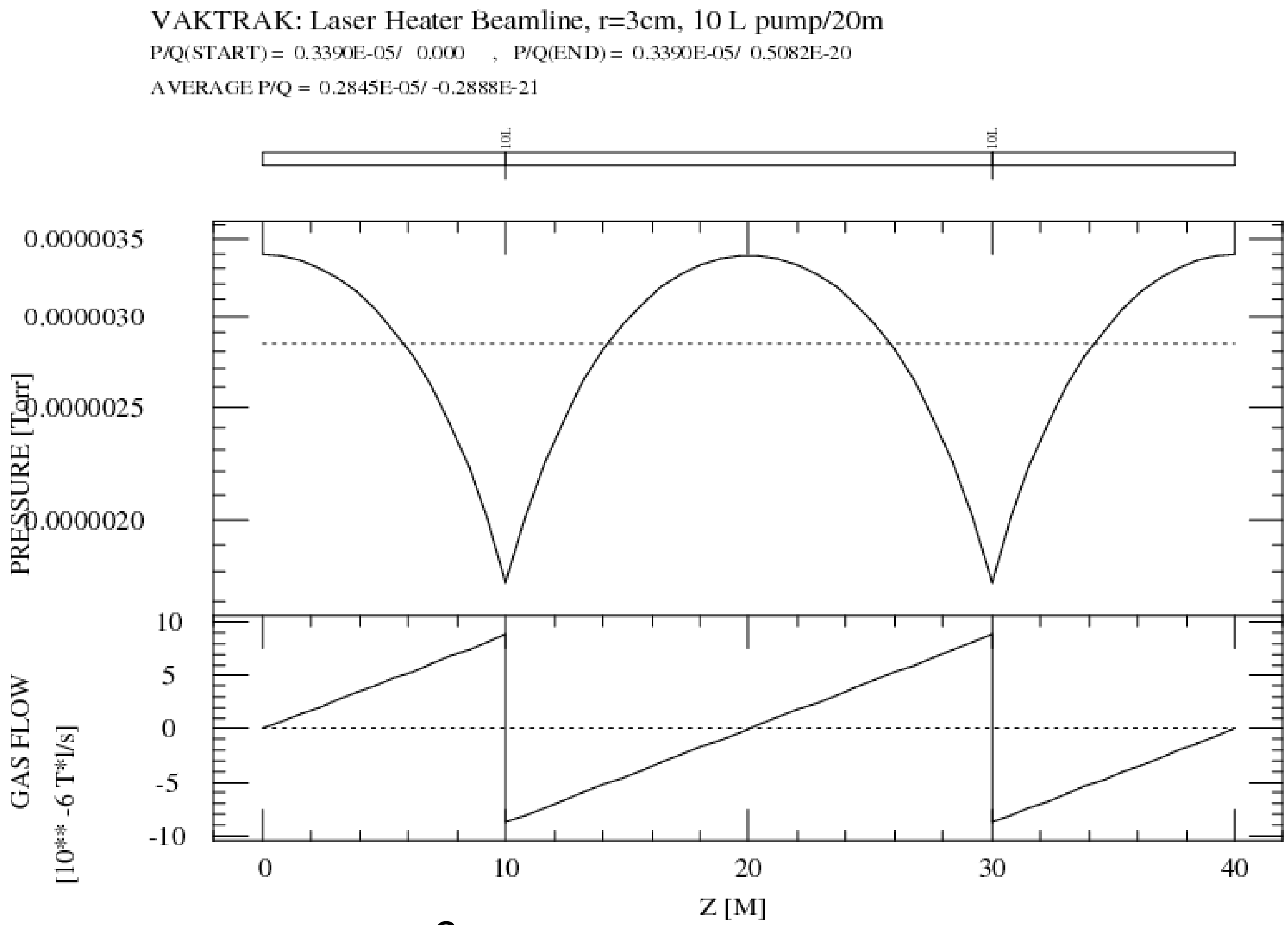
- Enter vacuum system on the table in laser room (window)
- Need only moderate vacuum to avoid
  - Convection, Schlieren effect
- Roughing pumps would suffice
  - easier, 'gadgets' need not be UHV compatible
- But ion pumps are preferred because they have no moving parts and avoid vibrations
- No baking foreseen
- Ion pums have an expected lifetime of minutes in rough vacuum
- Can we mechanically decouple the pumps from the mirror holders?
- Resonance frequency of long pipe?

Vacuum, 10L pump every 10 m



- Assume outgassing 14e-10 torr l/s/cm^2 (Stainless steel after 10 h pumping)
  - R. Elsey, Outgassing II, Vacuum 25, 347, 1975
- Moderate pumping every 10m OK for 10^{-6} torr

Vacuum 10 L pump every 20 m



- Enough for 3 10^{-6} torr average pressure
- Looks like 10L pumps are ok

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Mirror Holders

- Must be stable (jitter and drift)
  - solidly bolted to the wall without extended support structure
- Mechanically decouple from long vacuum pipe
  - long bellow on either side
- Pointing capability to direct laser to next mirror
  - piezo- or stepper-motor driven mirror mounts
- Need capability to determine whether the laser hits the mirror
  - pin diode array with BPW34F probably works

BPW34F sensitivity