WG5 Summary: Novel Diagnostics and Stability

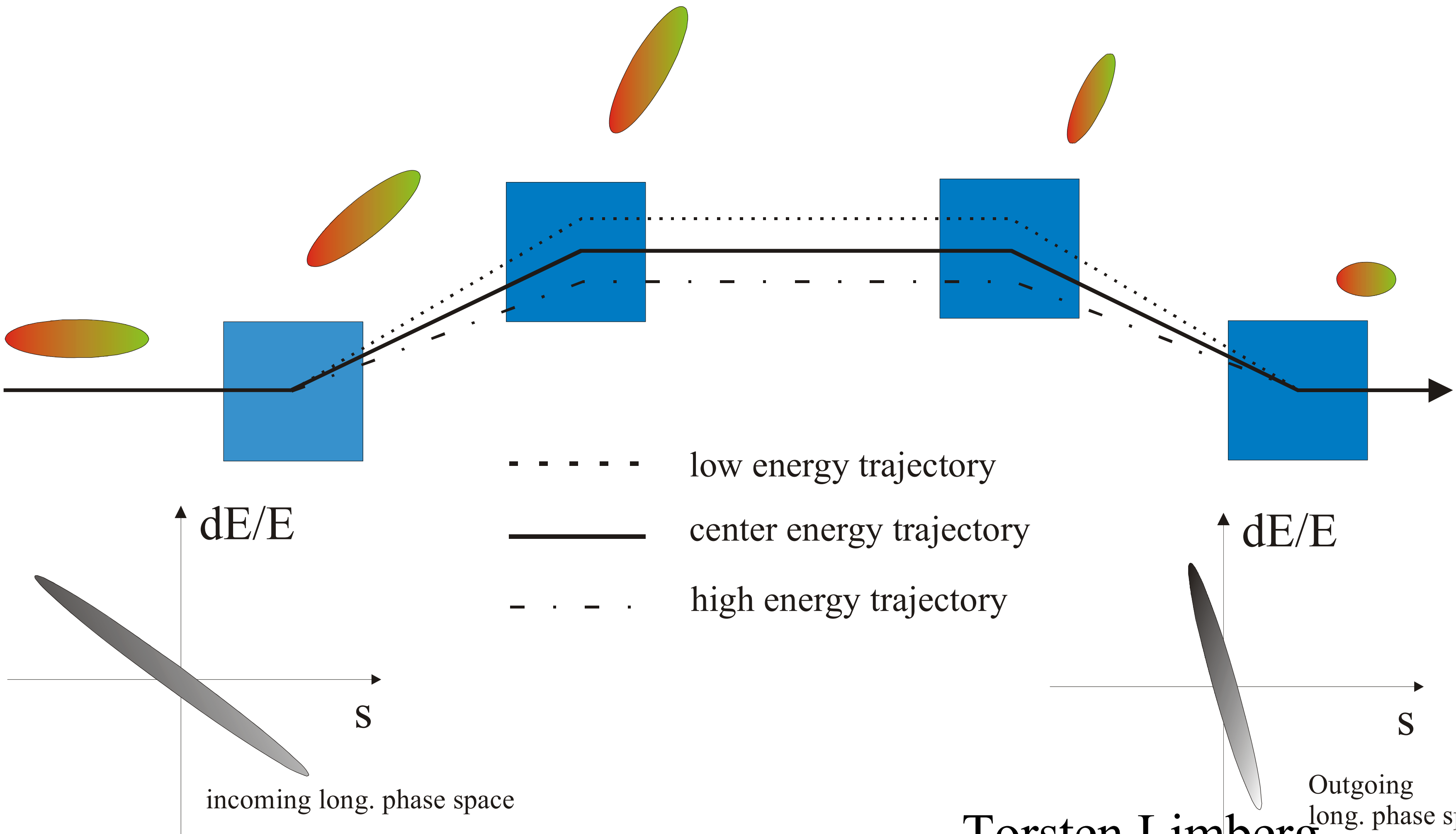
John Byrd and Dirk Noelle

ICFA

FLS 2006

37th ICFA Advanced Beam Dynamics Workshop on Future Light Sources

Sources of jitter



Torsten Limberg

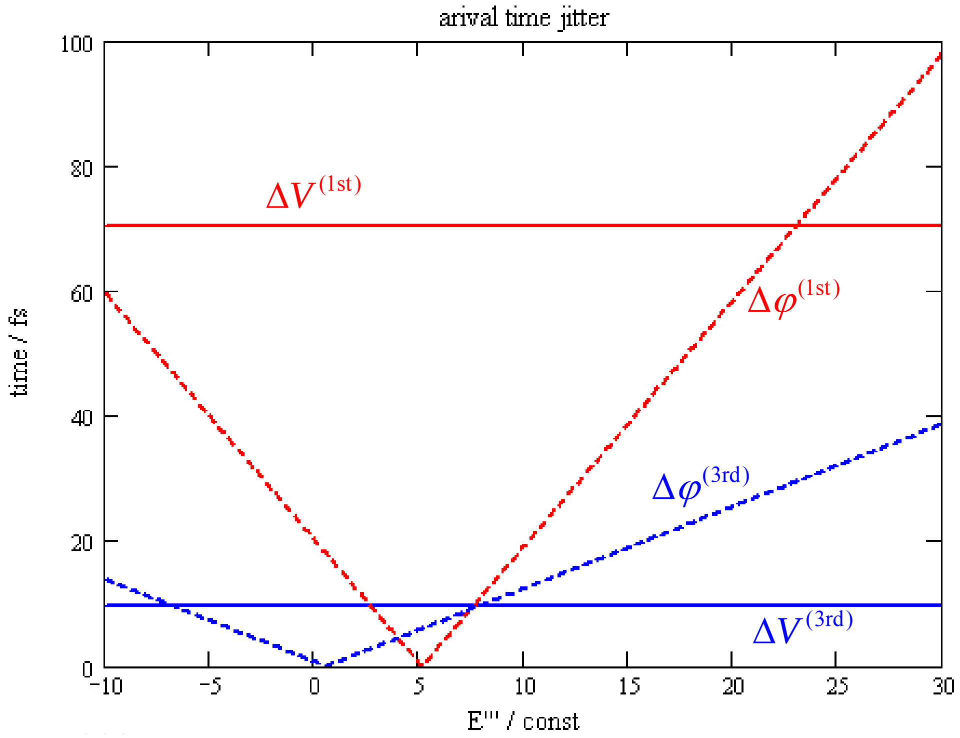
Multi-Knob tuning

$$\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & -k & 0 & -(nk) \\ -k^2 & 0 & -(nk)^2 & 0 \\ 0 & k^3 & 0 & (nk)^3 \end{bmatrix} \cdot \begin{bmatrix} a_1 \cos\varphi_1 \\ a_1 \sin\varphi_1 \\ a_n \cos\varphi_n \\ a_n \sin\varphi_n \end{bmatrix} = \begin{bmatrix} 1 \\ p_0'^{(1)} \\ p_0''^{(1)} \\ p_0'''^{(1)} \end{bmatrix}$$

Beam energy (normalized)

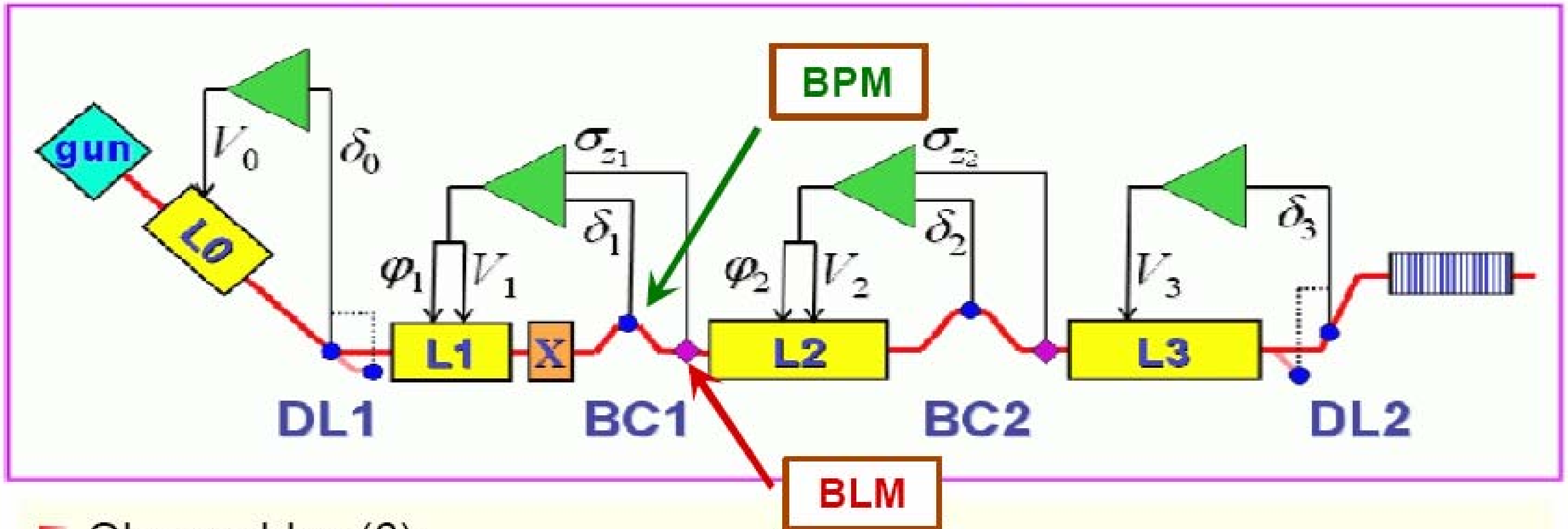
Chirp

2nd and 3rd derivatives of particle momentum deviations



Parameters can be adjusted to redistribute jitter to minimize specific observables such as arrival time jitter. Timing correction will become analogous to orbit correction.

LCLS longitudinal feedback system schematic



- Observables (6):
  - Energy: E_0 (at DL1), E_1 (at BC1), E_2 (at BC2), E_3 (at DL2)
  - Coherent Radiation power → bunch length: $\sigma_{z,1}$ (at BC1), $\sigma_{z,2}$ (at BC2)
- Controllables (6):
  - Voltage: V_0 (in L0), V_1 (in L1), V_2 (effectively, in L2)
  - Phase: φ_1 (in L1), φ_2 (in L2), φ_3 (in L3)

Patrick Krejcik
pkr@slac.stanford.edu

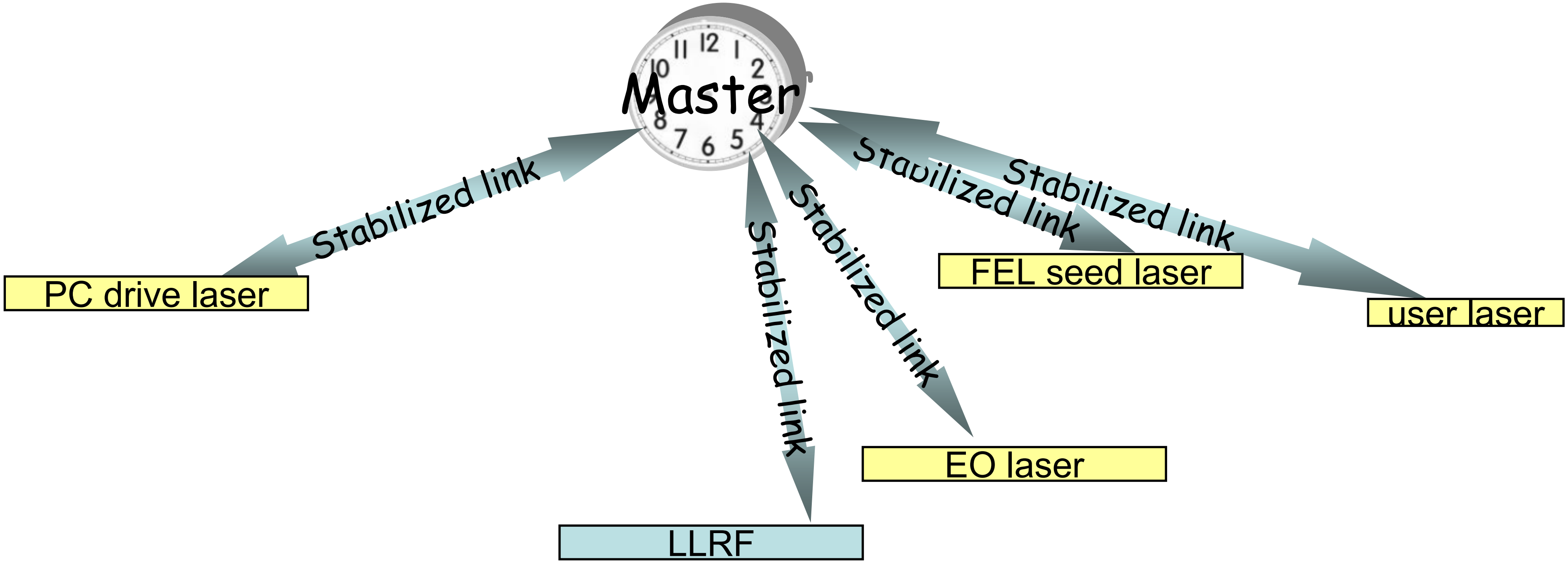
Synchronicity

- Next generation light sources require an unprecedented level of *remote* synchronization between x-rays, lasers, and RF accelerators to allow pump-probe experiments of fsec dynamics.
  - Photocathode laser to gun RF
  - FEL seed laser to user laser
  - Relative klystron phase
  - Electro-optic diagnostic laser to user laser

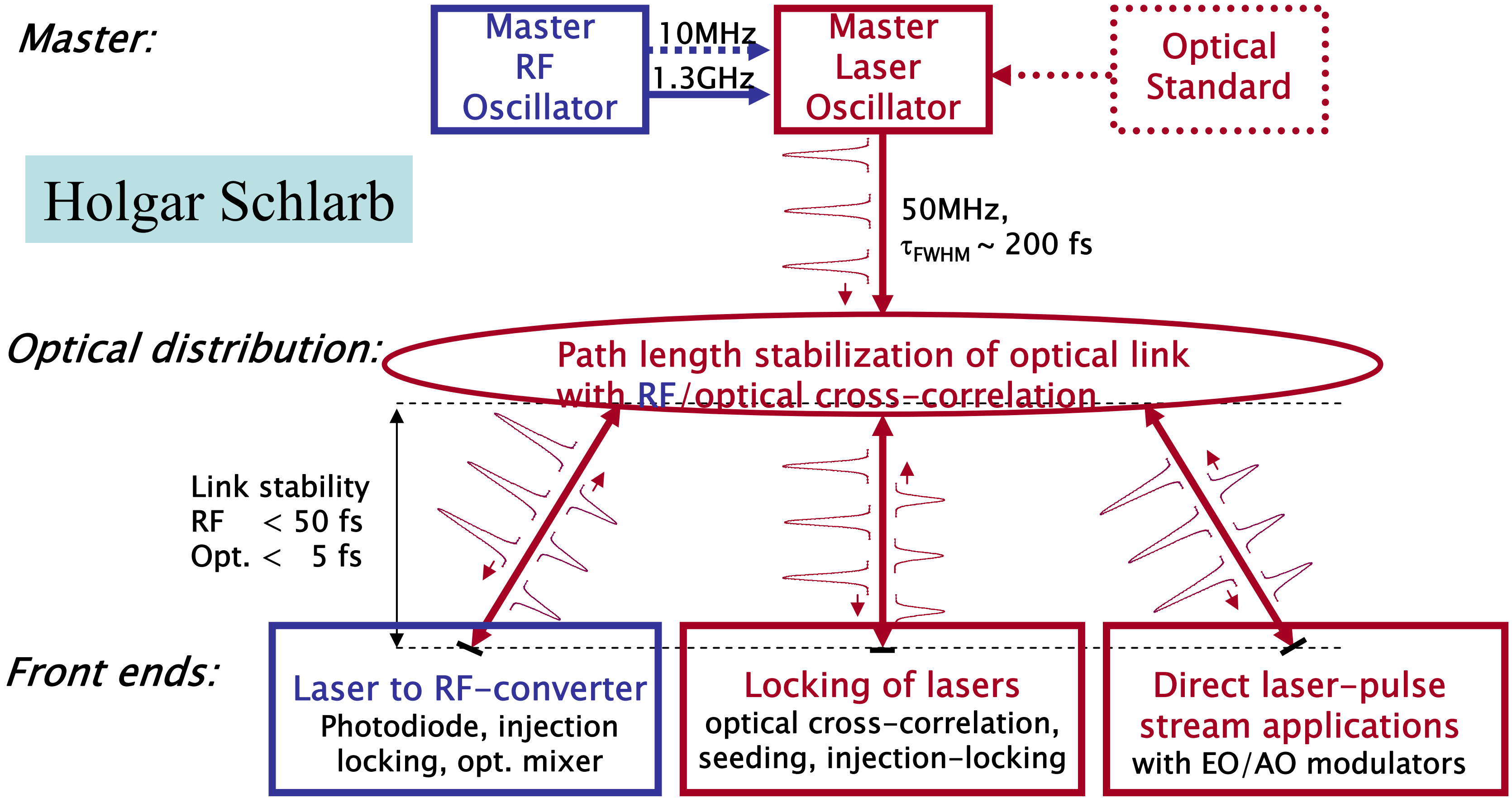
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Synchronicity

- Next generation light sources require an unprecedented level of *remote* synchronization between x-rays, lasers, and RF accelerators to allow pump-probe experiments of fsec dynamics.
  - Photocathode laser to gun RF
  - FEL seed laser to user laser
  - Relative klystron phase
  - Electro-optic diagnostic laser to user laser



Layout of laser based synchronisation



Applications:

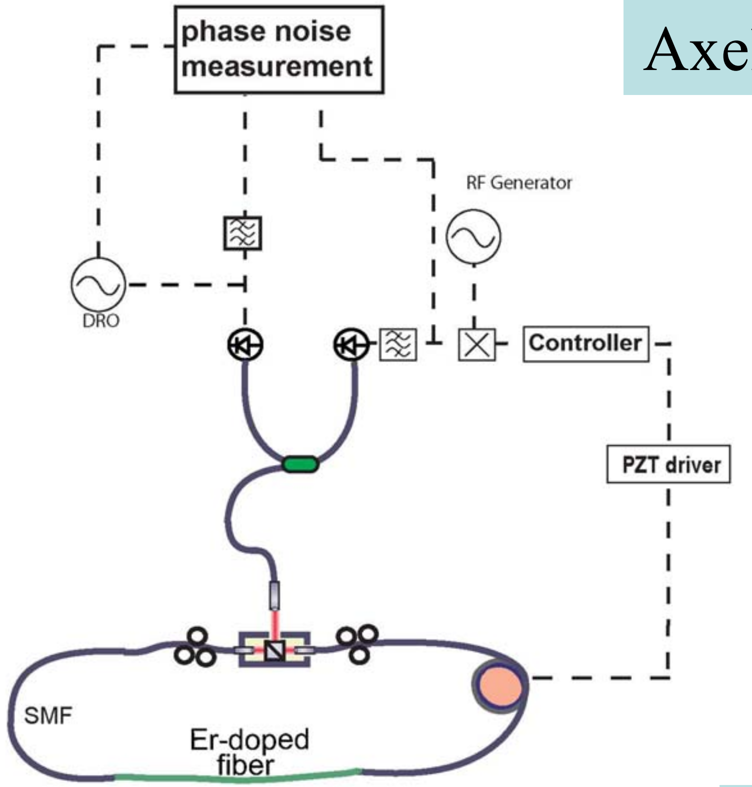
LO generation
-down converter LLRF
-PPL for synchronization
-RF signals for diagnostics

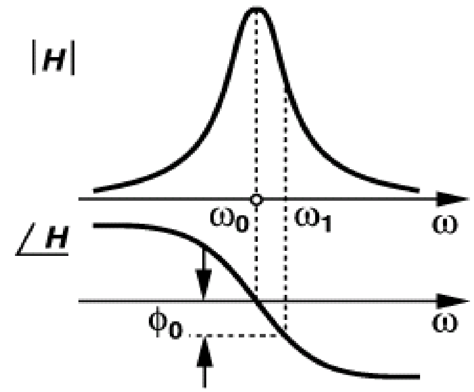
Lasers for
- photo-injector
- pump-probe experiment
- e-beam diagnostics
- e-beam manipulation

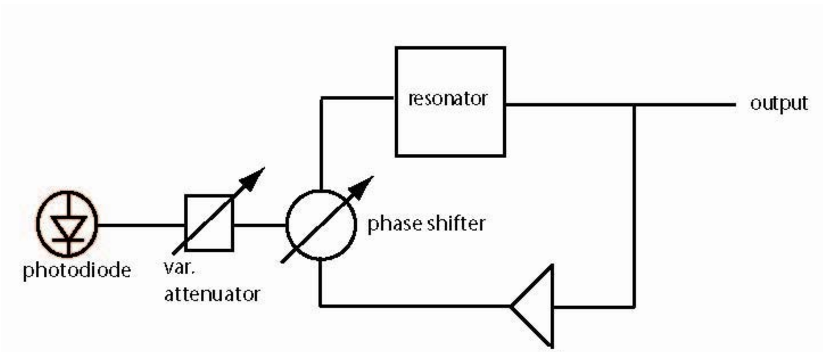
High precision appl.
-Beam phase monitor
-Laser phase monitor
Optical down converter
Chicane BPM

Injection locking of DRO

Axel Winter







- Pulse train is directly fed to VCO input of DRO
- Unity gain is determined by amplitude of pulse train

- Resonant circuit: phase=n*360 deg
- DRO reacts to phase shift by changing center frequency
- If locked: pulses will be at zero-crossing of 1.3 GHz wave
- High bandwidth of photodiode can be fully used

Time domain status

- Present state:
  - Engineering and design effort on first generation master laser oscillator system for the VUV-FEL
- Things accomplished:
  - Lock of Laser to RF source
  - Switching concept to combine redundant MLO's
  - First tests with FPGA-based regulation
  - First tests with injection locking external DRO to MLO

- Things to be done:
  - Evaluate performance of FPGA-based regulation and include second feedback and exception handling
  - Implement suitable set of diagnostics for MLO's to assure reliable operation of system
  - Long-term tests of system
  - Evaluation of injection locking performance

Frequency domain approach

Frequency-offset Optical Interferometry

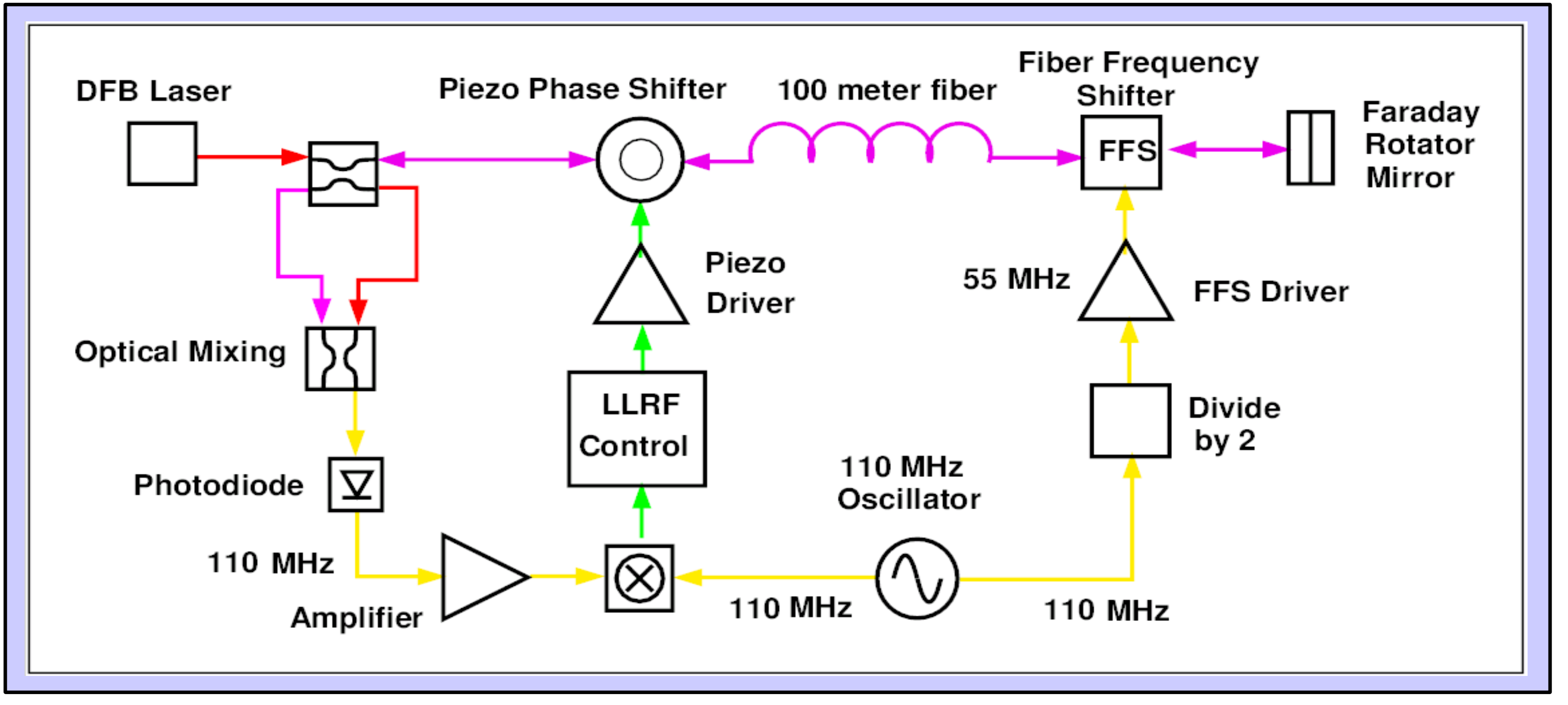
Technique used at ALMA
64 dishes over 25 km footprint, 37 fsec requirement

Principle: Heterodyning preserves phase relationships

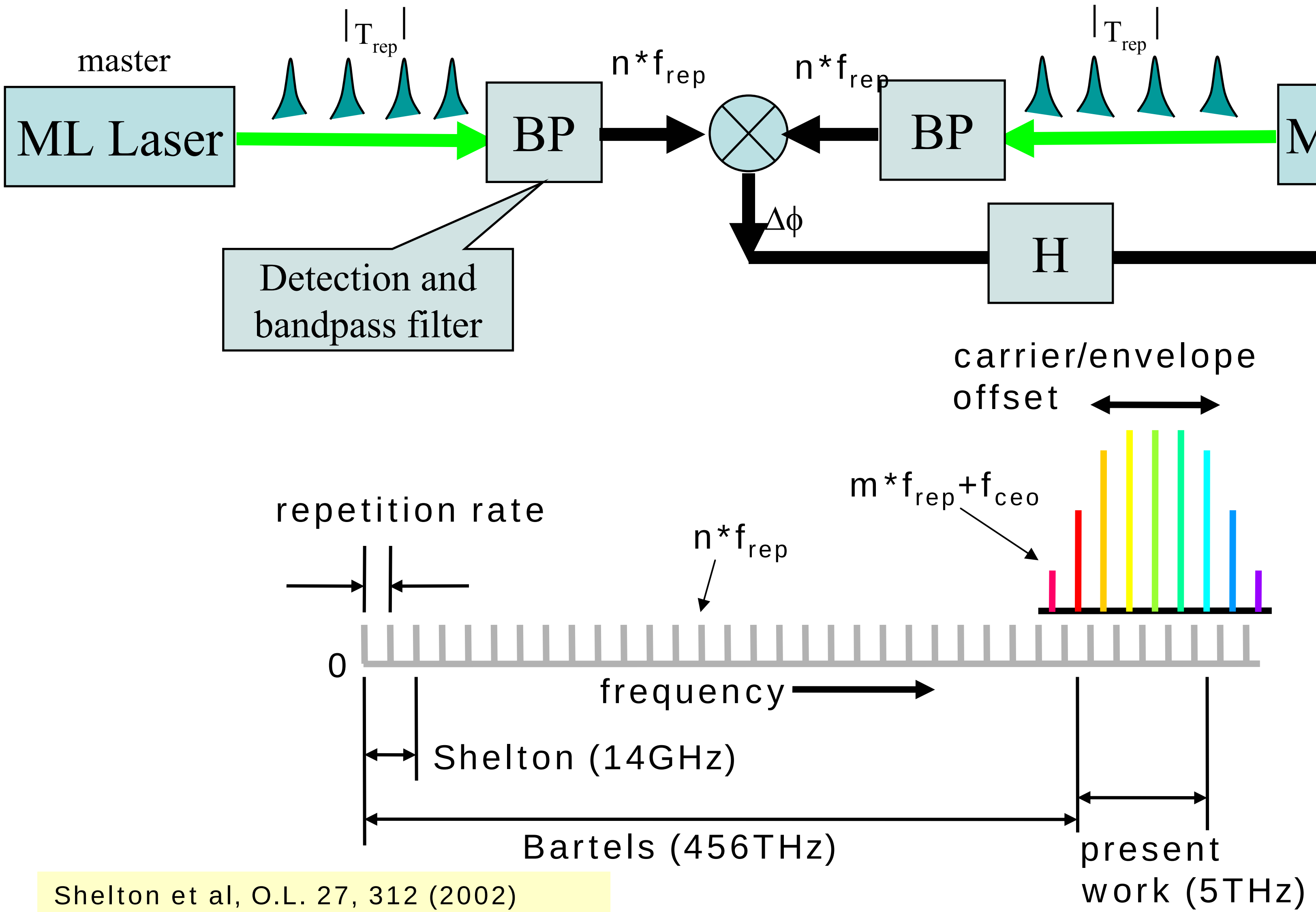
1 degree at optical = 1 degree RF

1 degree at 110 MHz = 0.014 fsec at optical

Gain 10^5 leverage over RF-based systems in phase sensitivity

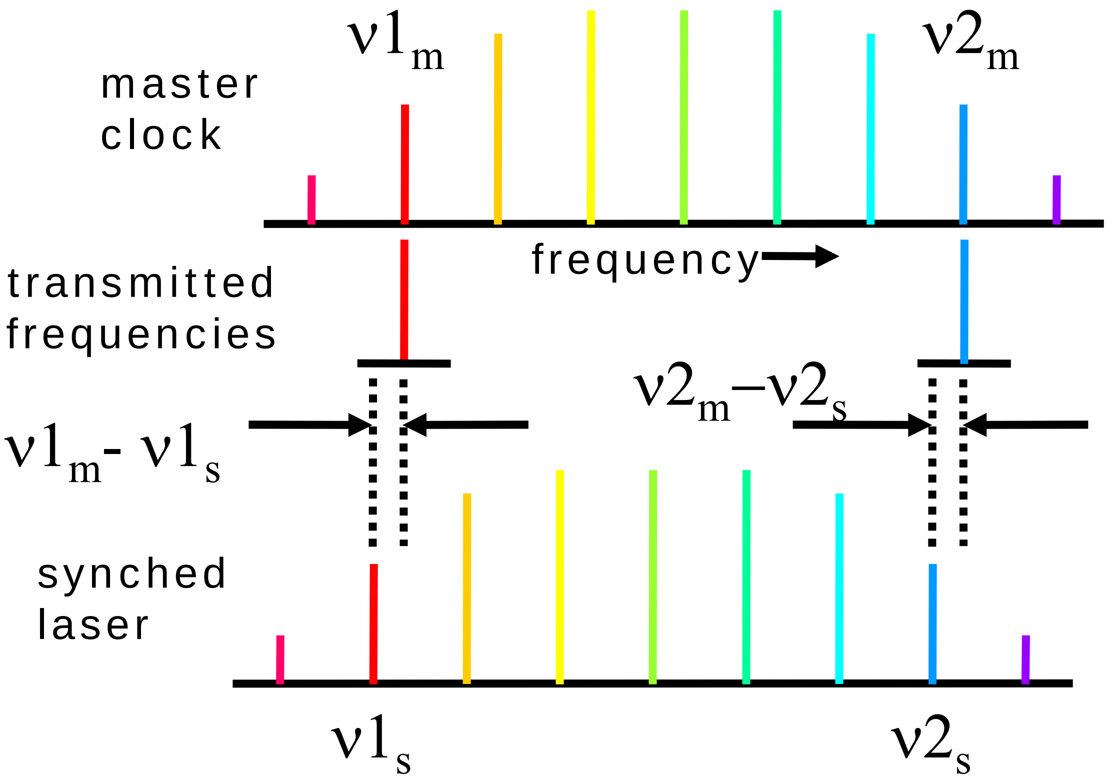


Synching mode-locked lasers



Shelton et al, O.L. 27, 312 (2002)
Bartels et al, O.L. 28, 663 (2003)

Two-frequency synch scheme



Lock two frequencies within the frequency comb separated by 5 THz.

For a 1**degree e**rror in phase detection, temporal error is <0.6 fsec

$$(\nu 1_m - \nu 1_s) - (\nu 2_m - \nu 2_s) = 0$$

$$\underbrace{(\nu 1_m - \nu 2_m)}_{5\text{THz}} - \underbrace{(\nu 1_s - \nu 2_s)}_{5\text{THz}} = 0$$

FD Status

- Stabilized link
  - achieved drift of 0.13 fsec/hour and wideband jitter (55 MHz) of 0.2 fsec rms. Jitter within stabilization bandwidth at attosecond level.
  - dual link ready for ready for RF transmission expt
  - Setup being prepared for test in SLAC tunnel/KG
  - Radiation hardness study in progress
  - FPGA-based feedback developed
- Synchronizing lasers
  - achieved 150 fsec rms lock over 1 hour at 2 GHz
  - present studies aimed at locking under 100 fsec over 24 hours
  - optical beat lock still under development

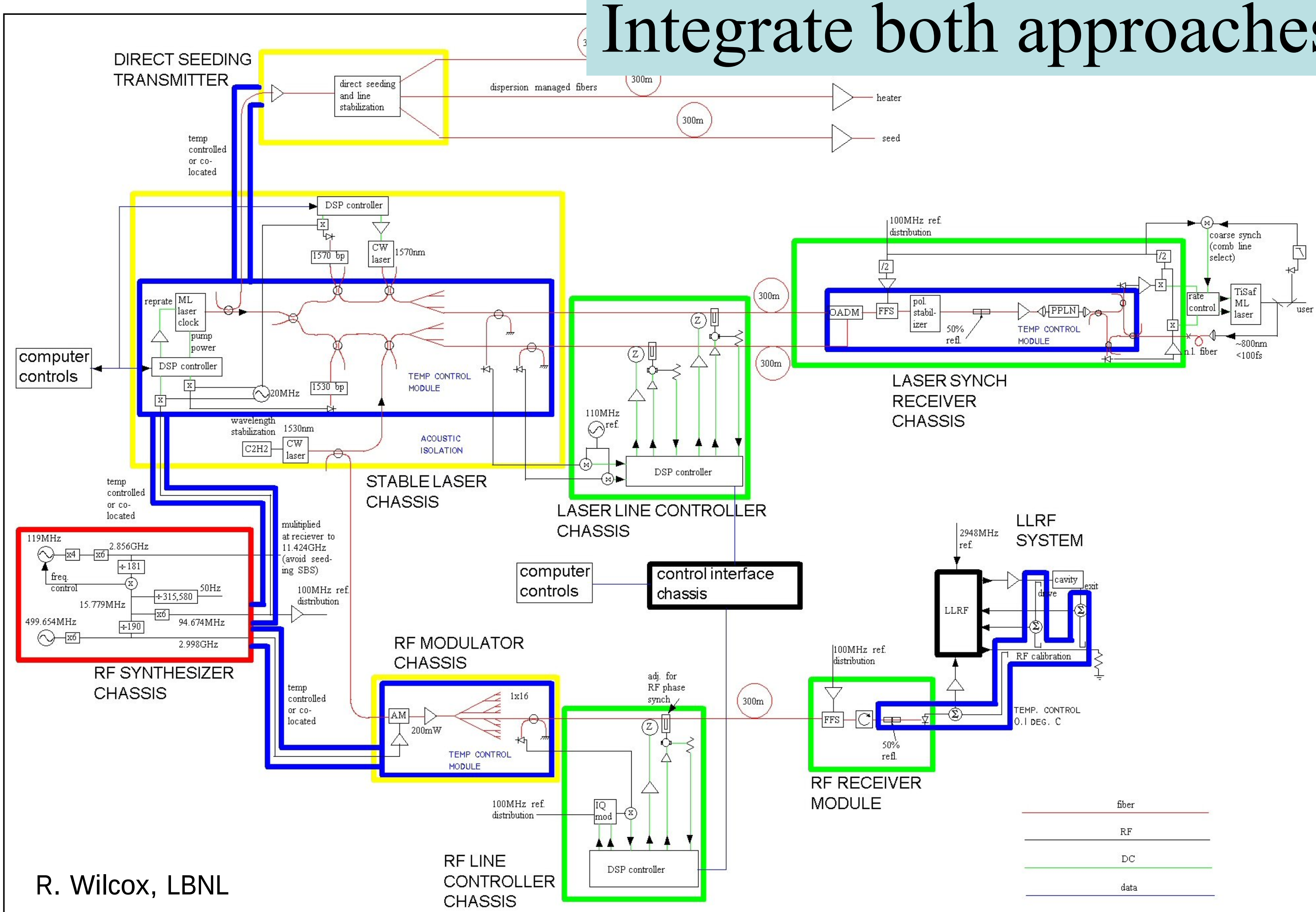
Time and Frequency domain comparison

MIT timing, time domain		LBNL, frequency domain	
PRO	**CON**	**PRO**	**CON**
Group delay compensation	Power limit <30mW	High temporal resolution	Needs group delay compensation
Transmission of fundamental & harmonics	Output pulse shape limited	Direct optical synchronizati on at 5THz carrier	Needs mode locked receiver laser
Possible direct seeding of remote optical amplifier	GVD, SPM, SRS	No non-linear effects <100mW	Brillouin scattering >100mW

Reference: FERMI Technical Review Panel meeting, Nov 2005

FERMI approach

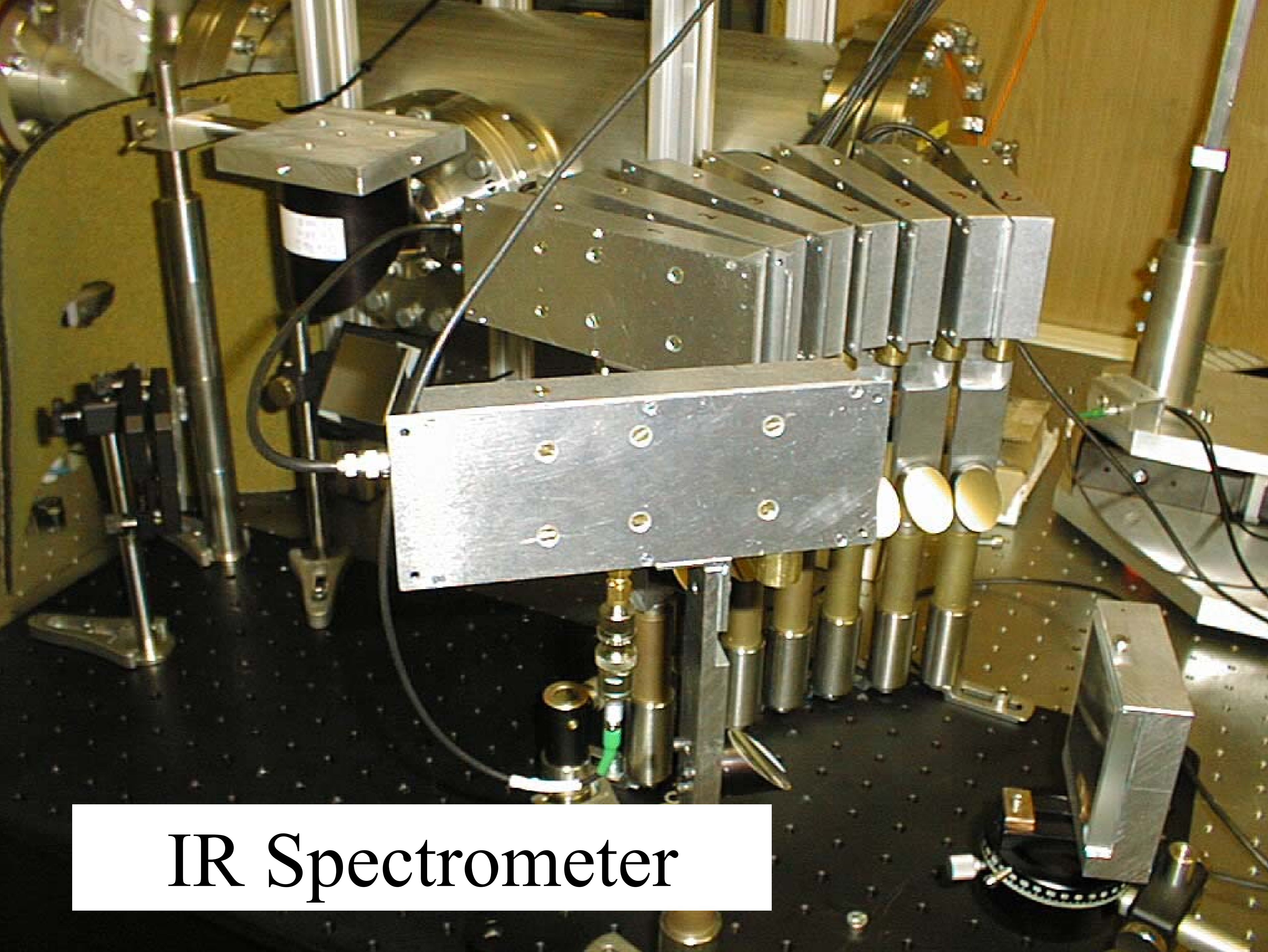
Integrate both approaches



R. Wilcox, LBNL

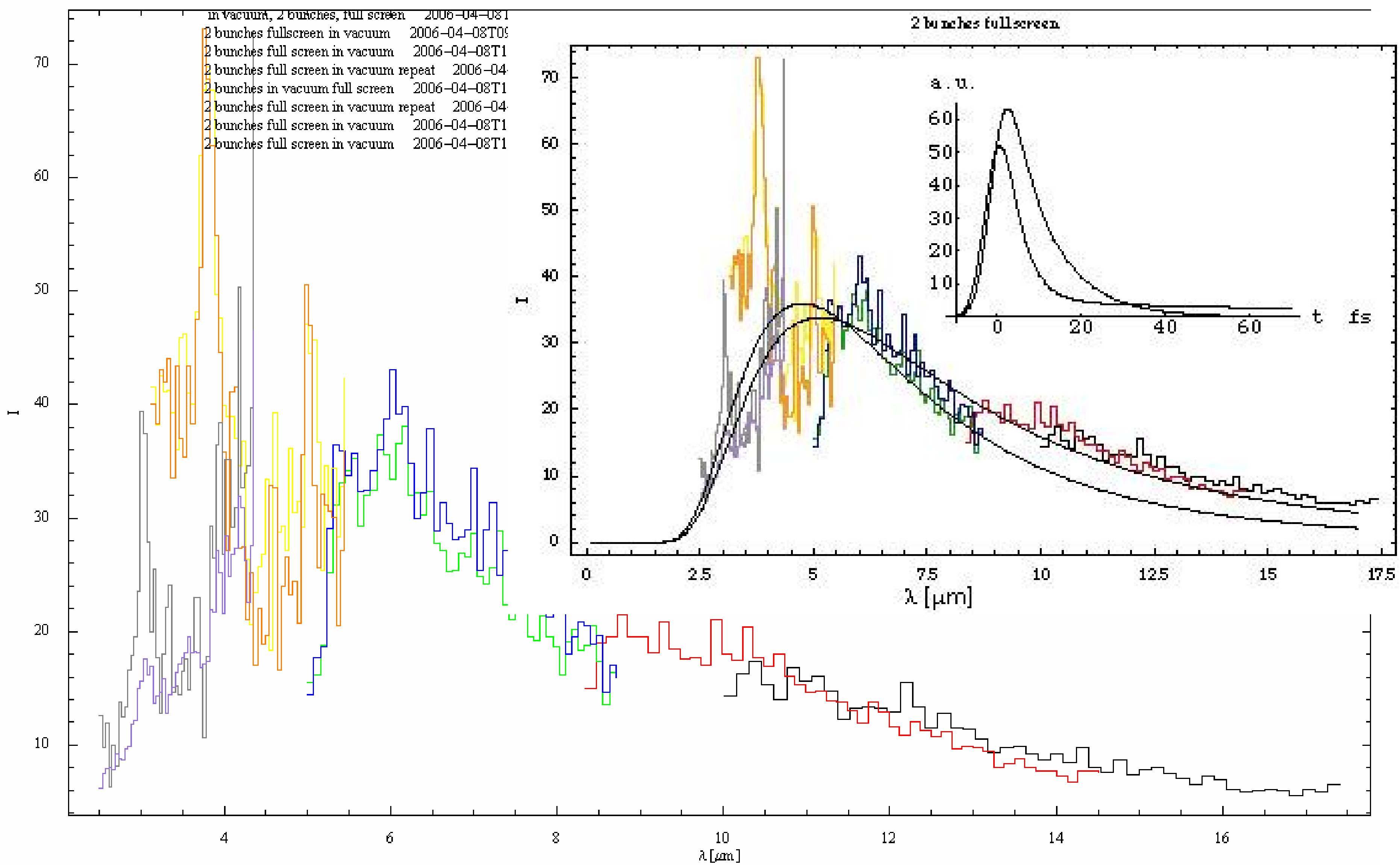
Timing Measurements

- Measure bunch arrival timing and/or bunch shape information
  - CTR spectrum over infrared spectrum (H. Delsim-Hashemi)
  - Deflecting cavity (M. Roehrs)
  - BTM- Beam timing monitor (F. Loehl)
  - Electro-optic sampling (A. Cavalieri, B. Steffen)
  - Optical replicants (V. Ziemann)
  - New ideas-Kerr effect (P. Krejcik)

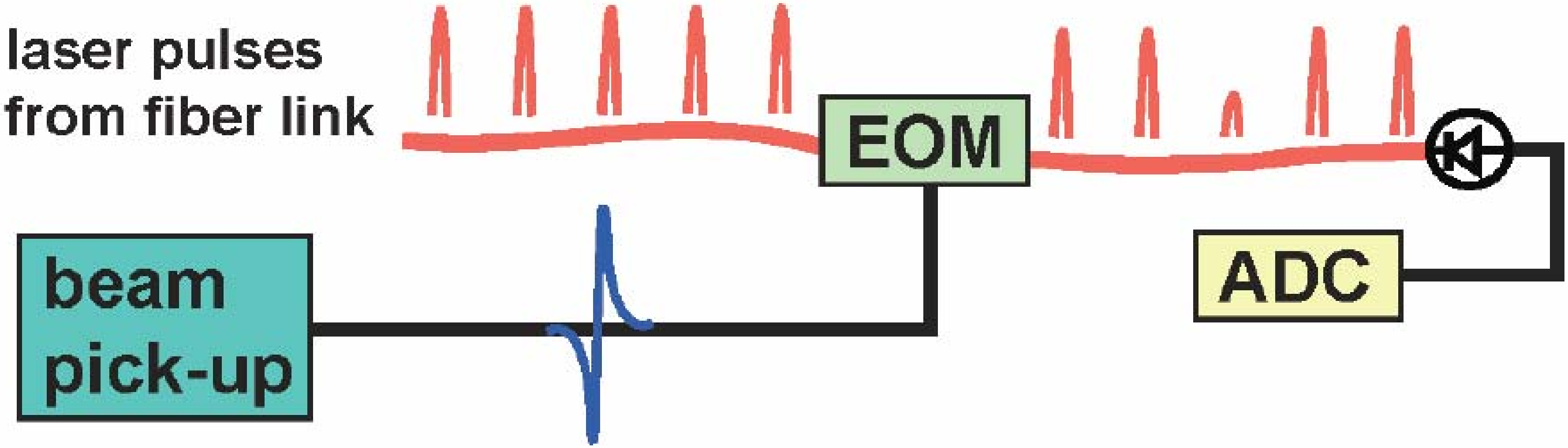


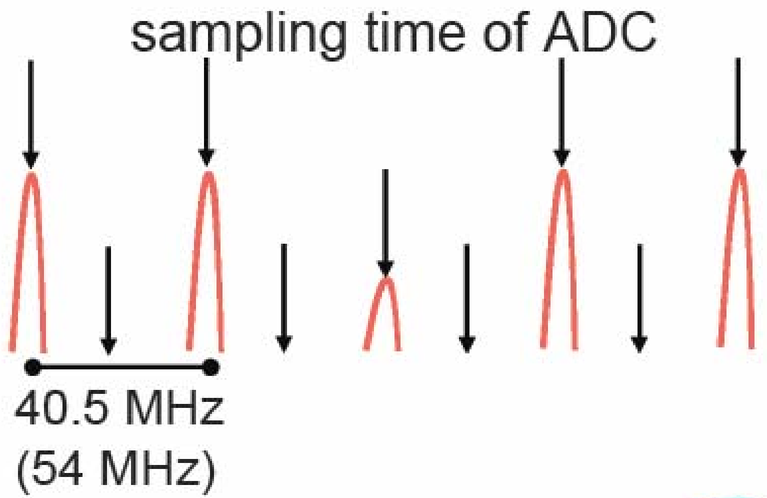
IR Spectrometer

CTR Spectrum



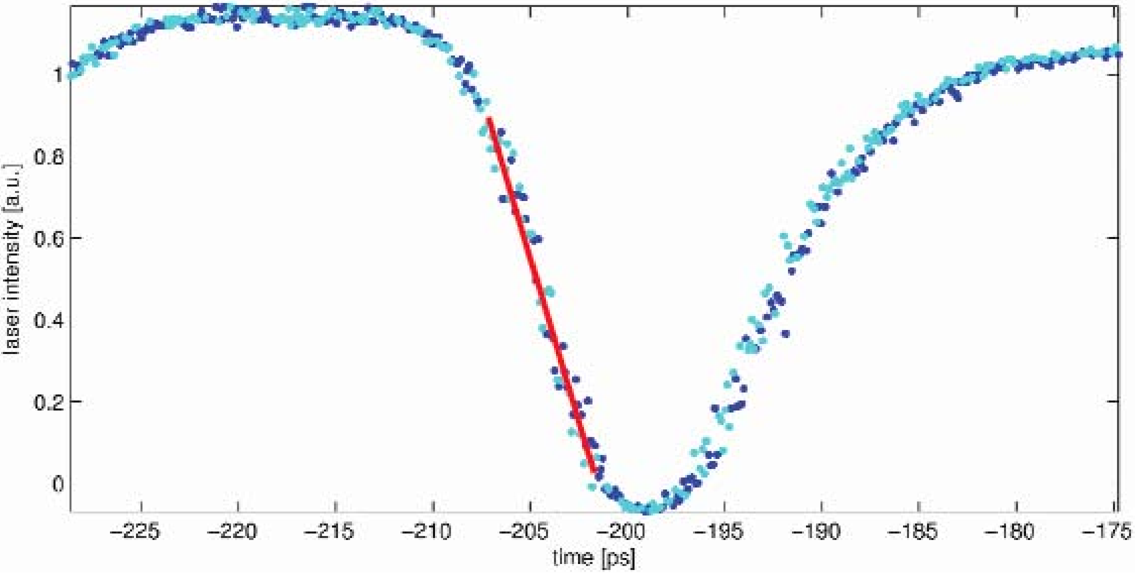
Principle of the Beam Phase Monitor





The timing information of the electron bunch is transferred into an amplitude modulation. This modulation is measured with a photo detector and sampled by a fast ADC.

First Results: Calibration and Resolution of the System



The resolution can be estimated from the slope of the phase monitor signal and the amplitude noise of the unmodulated laser pulses:

Best results:

slope ~ 7.1 ps / unit
rms(laser amplitude) ~ 0.425 %

➢ rms resolution ~ 30 fs

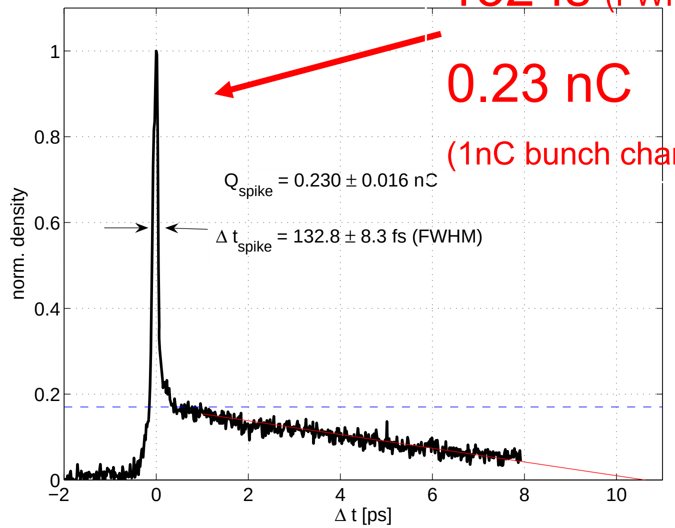
Measurements with LOLA:

Longitudinal density profile

132 fs (FWHM);

0.23 nC

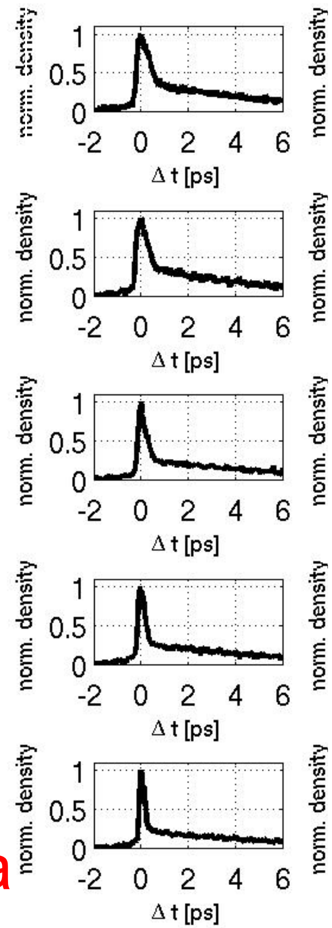
(1nC bunch charge)



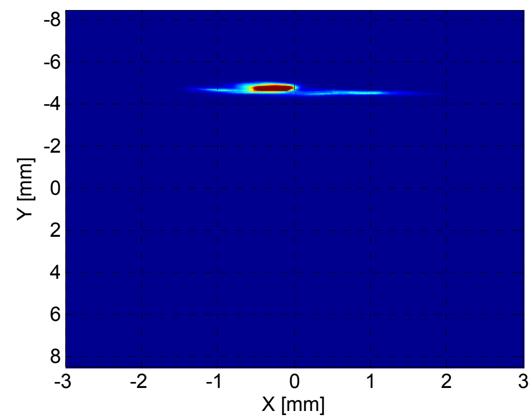
→ Resolution depends on the vertical beam size at the screen

Horizontal slice emittance

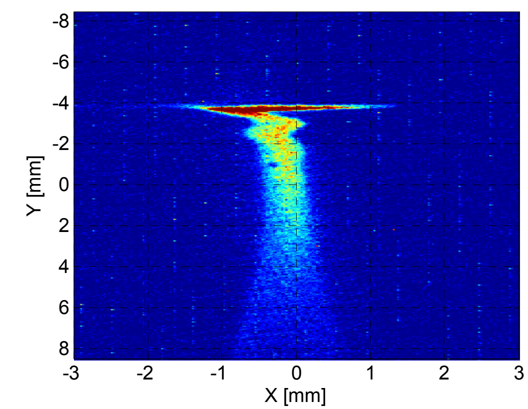
Energy-time correlation (via dispersion)

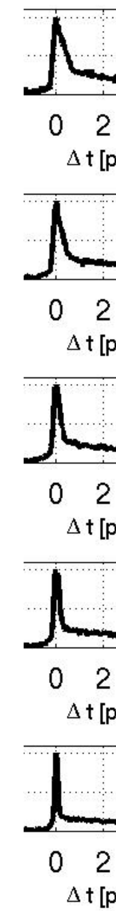


LOLA off:



LOLA on:

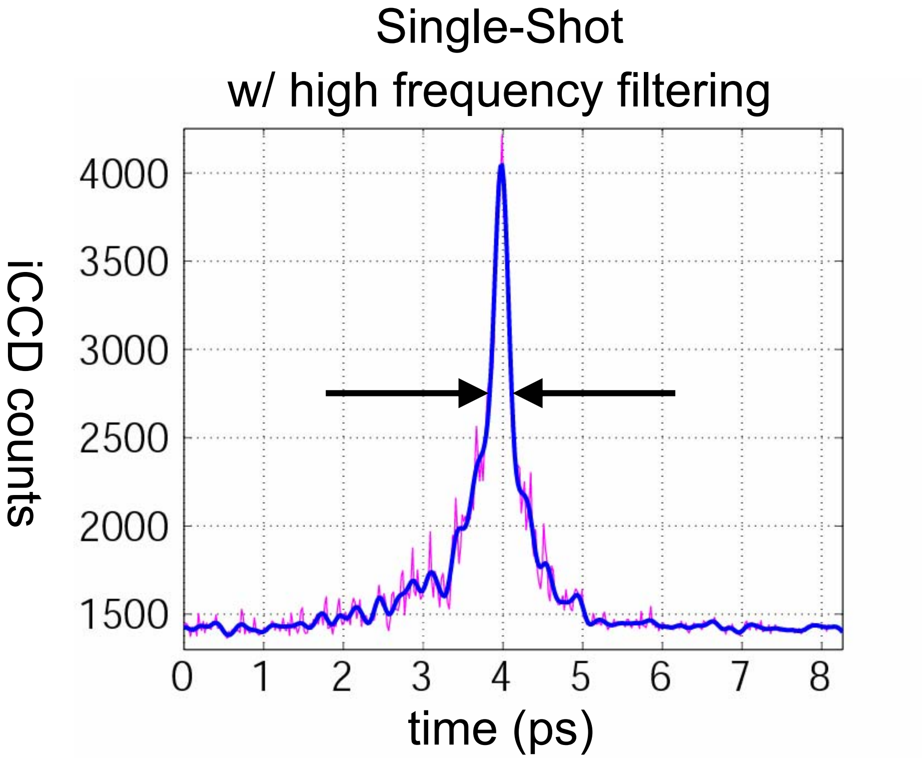


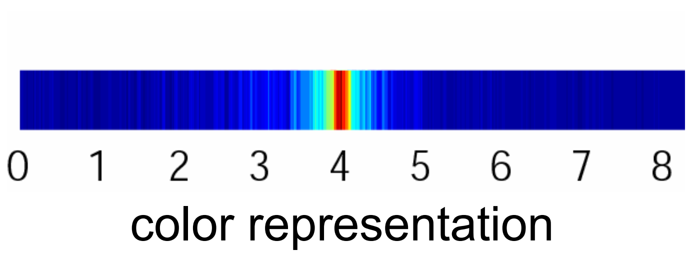


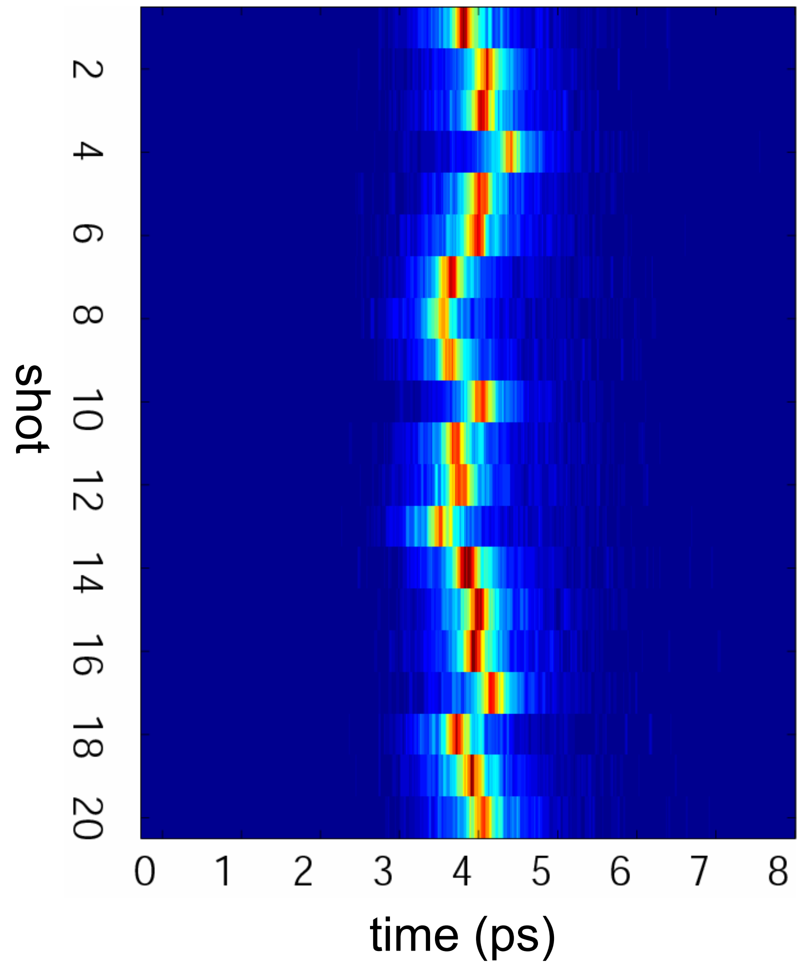
EO Sampling

EOS data from SPPS

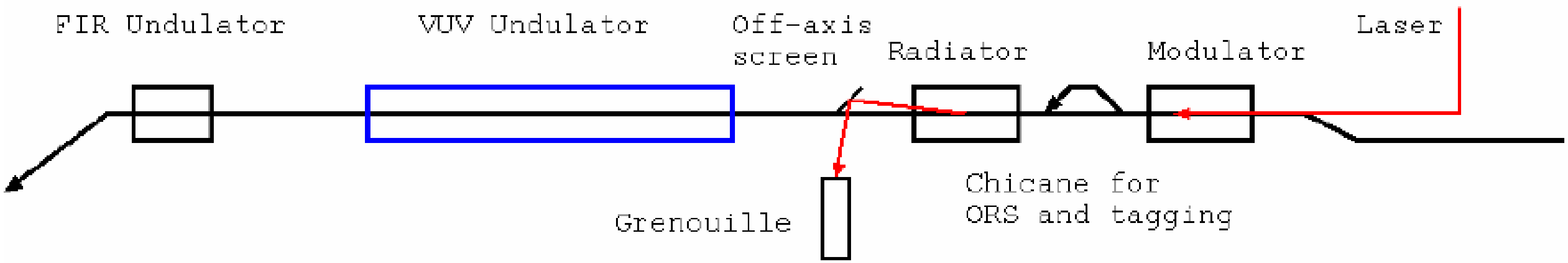
A. Cavalieri





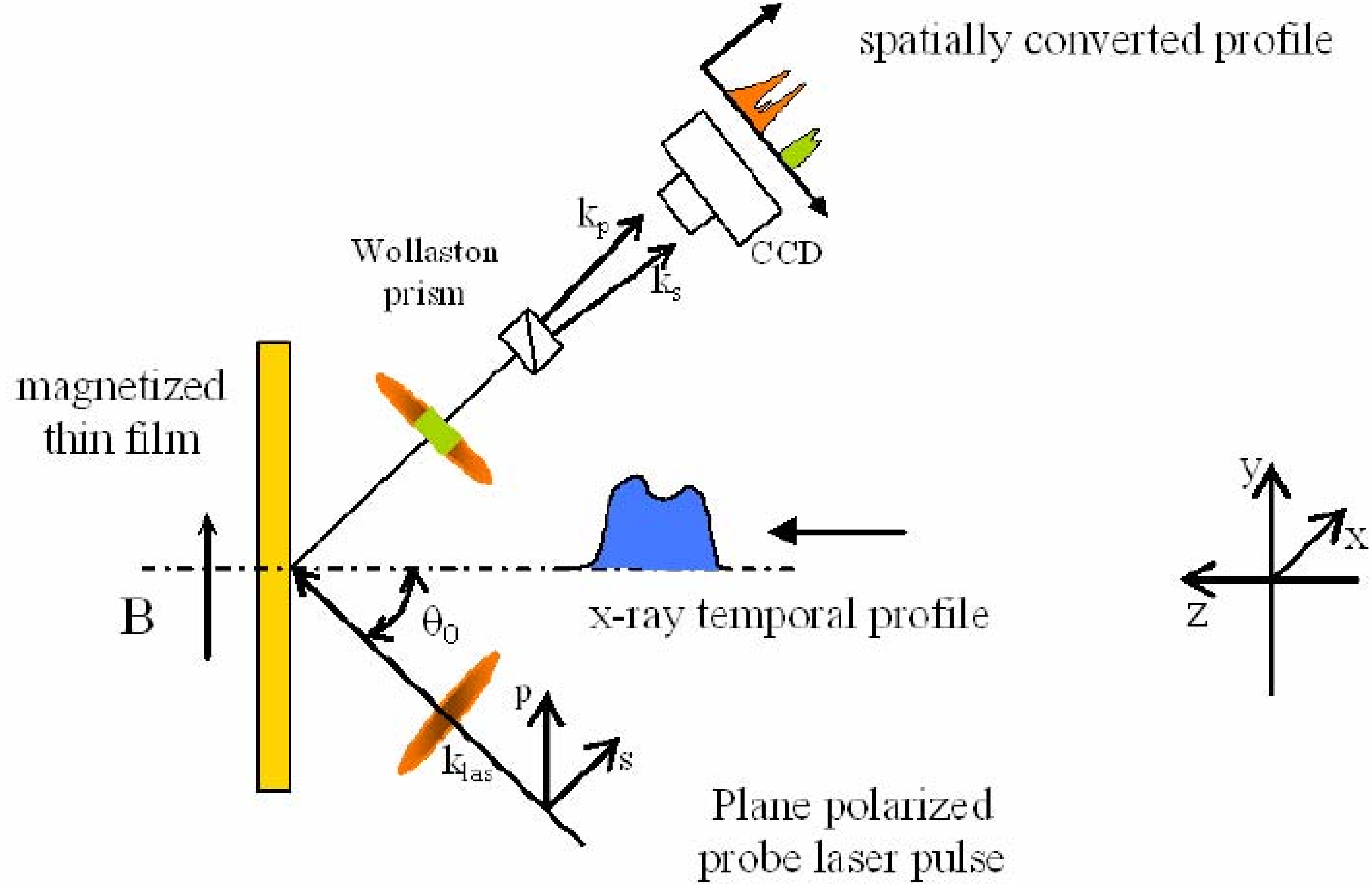


Laser tagging beams



- Measure the longitudinal bunch profile of the femto-second long electron bunches (Saldin, Schneidmiller, Yurkov: NIM A 539 (2005) 499.)
- Energy modulation via (v.E) coupling
- Longitudinal density modulation in chicane
- Cause coherent emission of light pulse in radiator that mimics the longitudinal shape of the electron bunch (optical replica).

SMOKE Pump Probe Geometry



Patrick Krejcik
pkr@slac.stanford.edu

Small things

100 femtoseconds

= 100×10^{-15} sec

= 30 microns

= 0.8 mrad@1.3 GHz

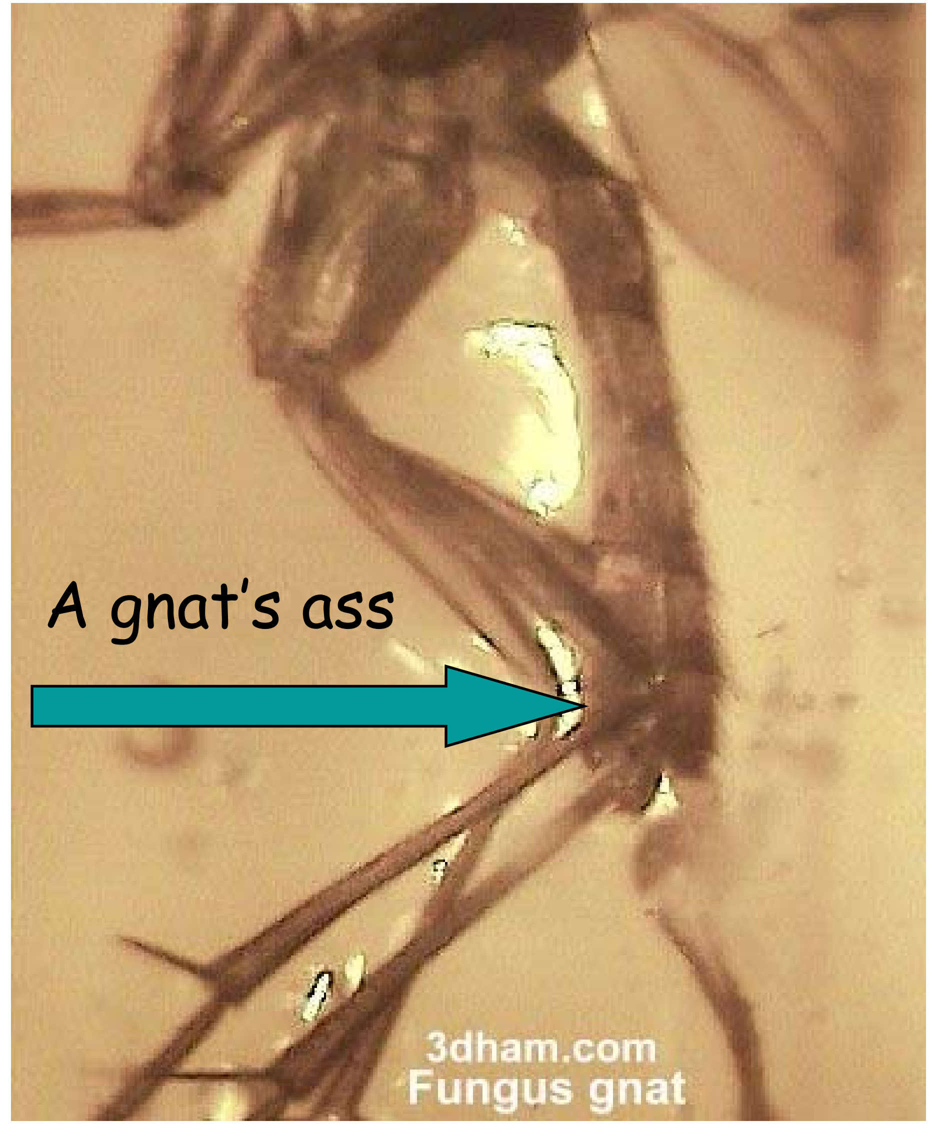
= 0.045 deg@1.3 GHz

= 1.8 mrad@2856 MHz

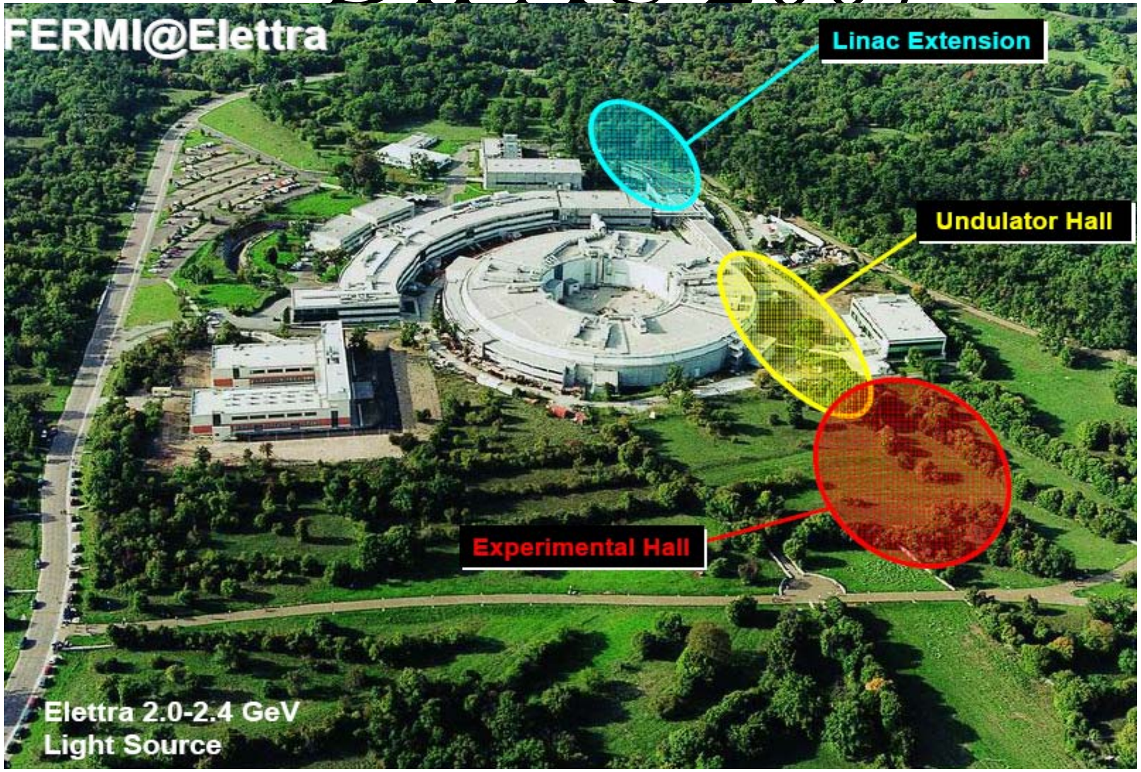
= 0.1 deg@2856 MHz

= $(10 \text{ TeraHertz})^{-1}$

= 20*(1.5 micron)



DIPAC 2007



Let me here remind you that ELETTRA will host

<u>DIPAC in May 2007</u>

the European workshop on

Diagnostics and Instrumentation for Particle Accelerator:

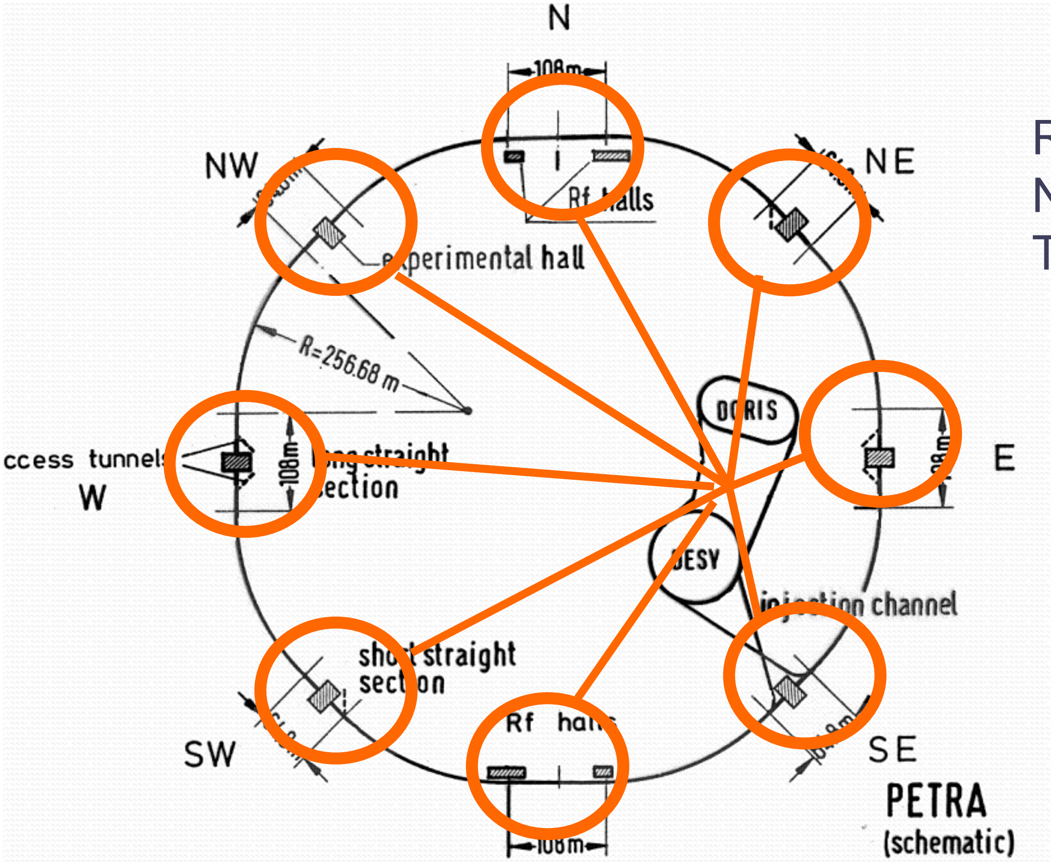
you are all kindly invited!!!

Summary WG 5
Part 2

Transverse Phasespace
&
Protection Systems

Orbit Feedbacks

- Essential and well established Tools in 3rd Generation SR Facilities
- But, also SASE FELs
  - Will use them
  - Pulse to Pulse Basis (LCLS)
  - Pulse to Pulse and Intrabunch (FLASH, XFEL)
- Get to more accurate and faster and Systems

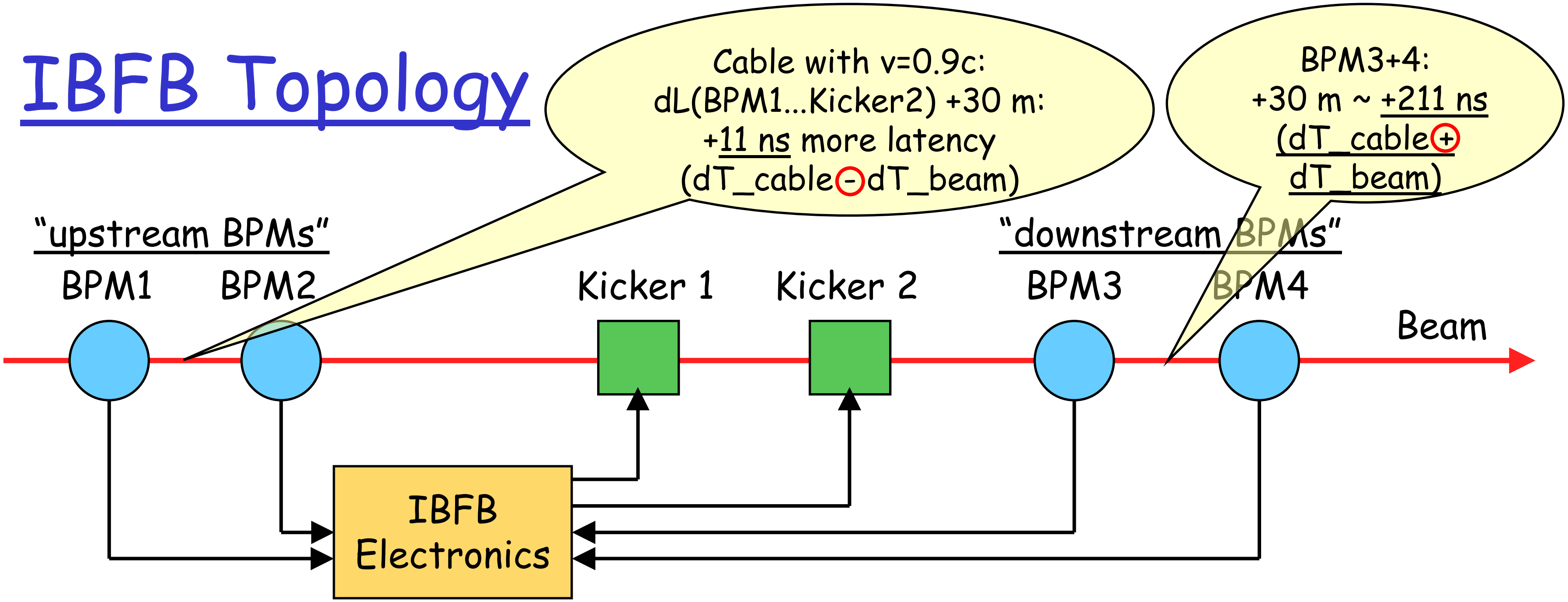


Remember,
No much symmetry in
This Machine

Rate of orbit measurements: ≥4 kHz
Data flow on cables (fiber optics) manageable
Digital controller (SVD & PID) feasible
Power supplies: work in progress
Correctors: air coils similar to ESRF

Gajendra Sahoo, DESY

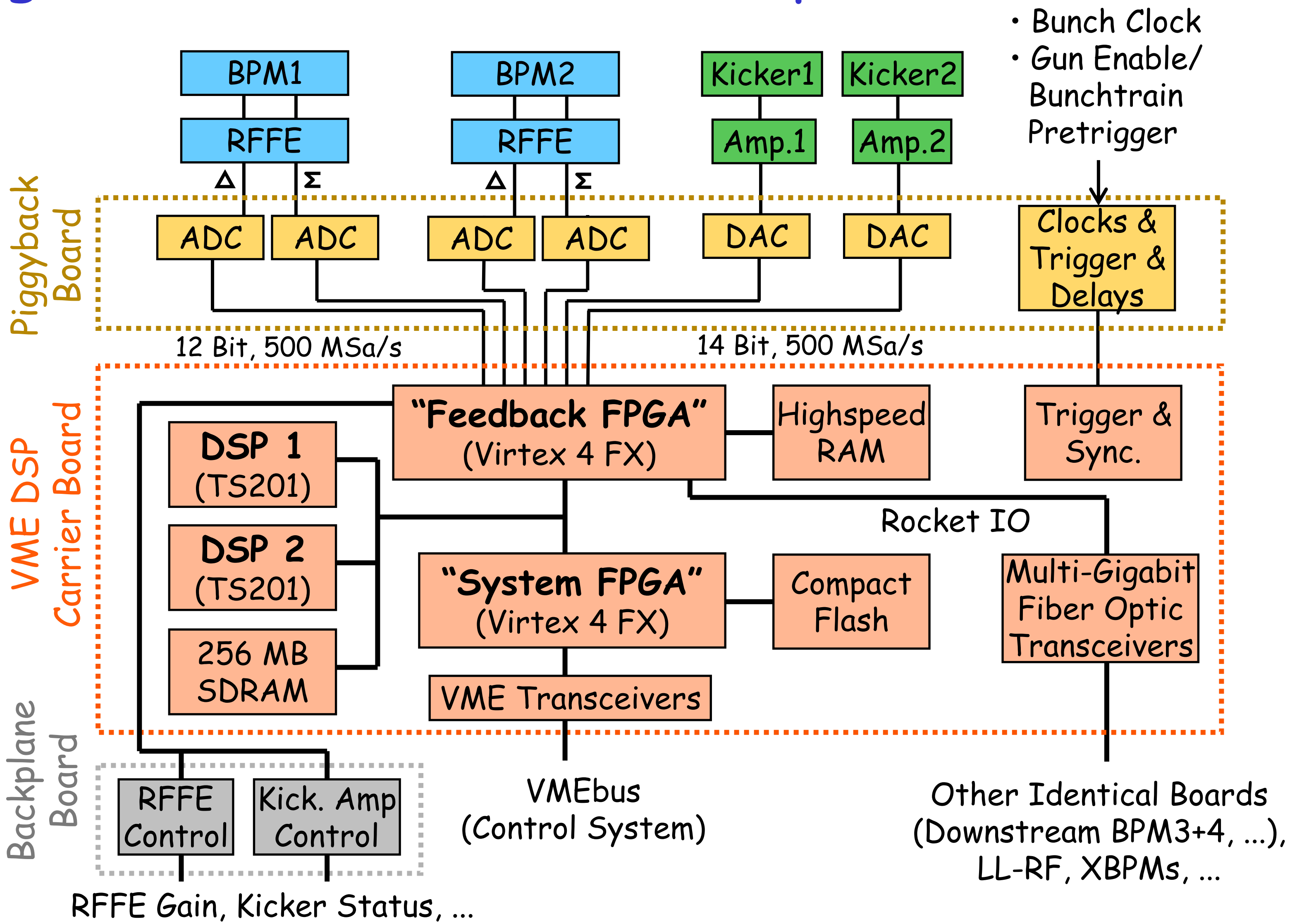
IBFB Topology



- Use beam positions at upstream BPMs of bunch no. N, N-1, N-2, N-3,... to calculate kicks for bunch no. N+1 using a model (200 ns bunch spacing)
- Use downstream BPMs to check & correct model (less fast)
- Why upstream (not downstream) BPMs for fast feedback loop ?
  - Less latency (beam and cable signals travel in parallel)
  - -> Larger distance between BPMs -> better angle resol.
  - BPM1+2 see unkicked beam: IBFB puts less noise onto the beam

B: Keil, PSI

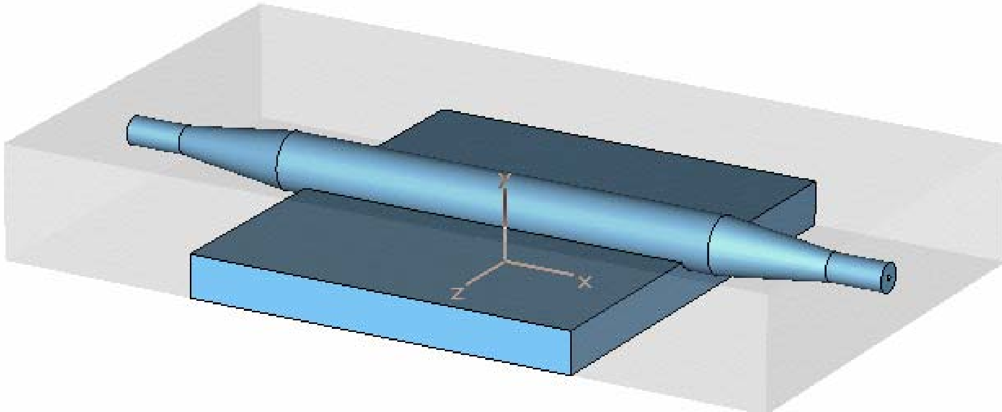
Digital IBFB Hardware Concept



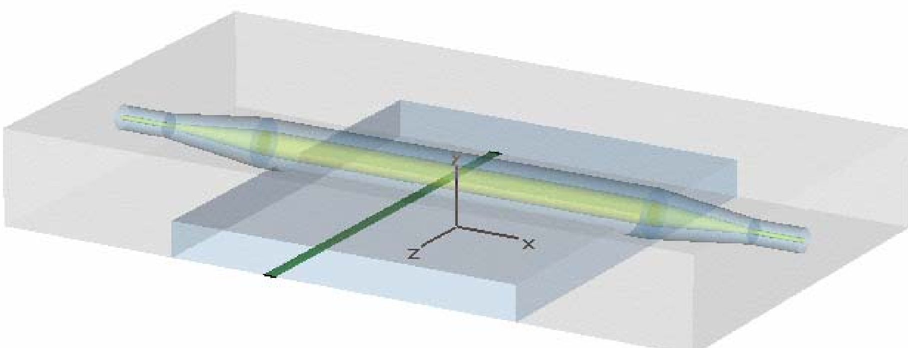
Special Requirements for SASE Machines

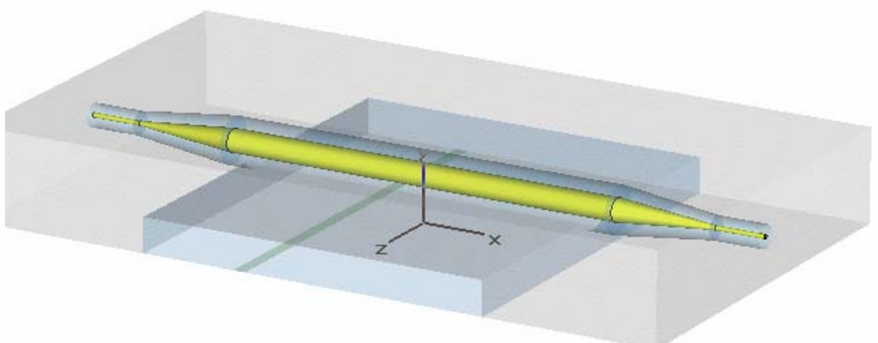
- Precise Energy Measurements in the Bunch Compressors
  - Wide Beampipes
  - Beam Size of several mm
  - Resolution Requirements to resolve „Center of Charge“ of 10 μm
  - Although „Center of Charge“ might not be that relevant for Lasing
- Orbit Control in the FEL Undulator
  - Single Bunch Resolution with μm or sum μm Resolution

MW Studio Simulation



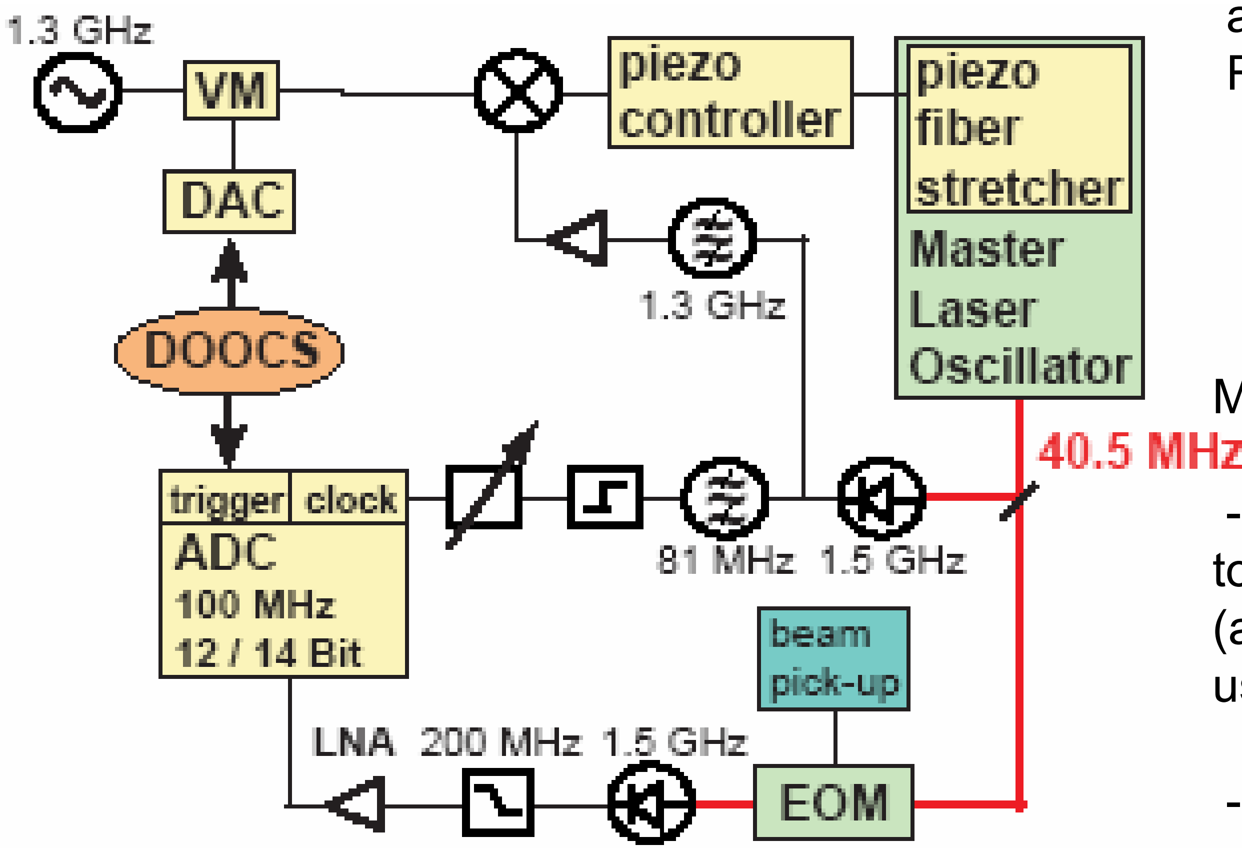
Coaxial cable impedance matching model
Tapered to SMA connector to maximize bandwidth of output





K. Hacker

Test bench



Use electro-optical modulators and a timing laser to sample RF pulses

Measurement is limited by:

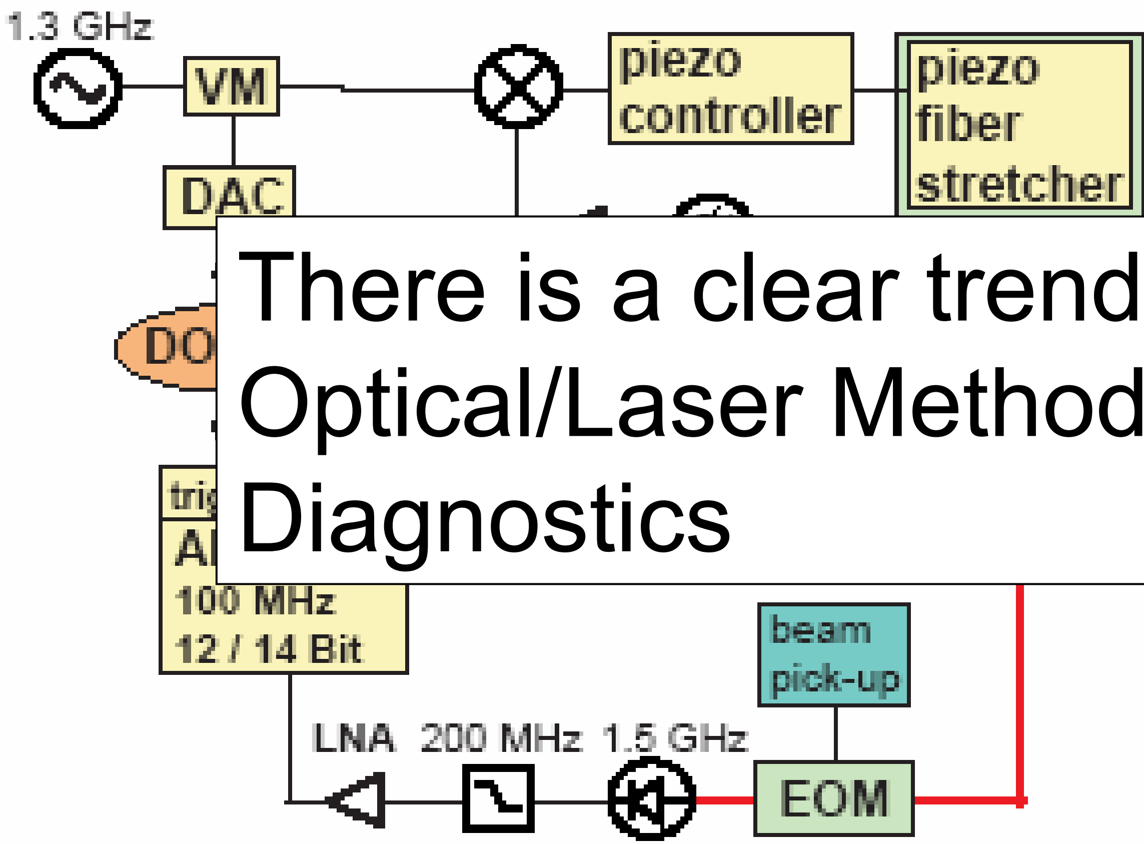
- the electro-optical modulator's tolerance for high voltage (attenuator or limiter must be used)

- slope of RF (BC BPM slope is more than twice as steep as beam phase monitor slope)

Setup developed by Florian Loehl

K. Hacker

Test bench



Use electro-optical modulators and a timing laser to sample RF pulses

There is a clear trend to use Optical/Laser Methods for Diagnostics

tor's

(attenuator or limiter must be used)

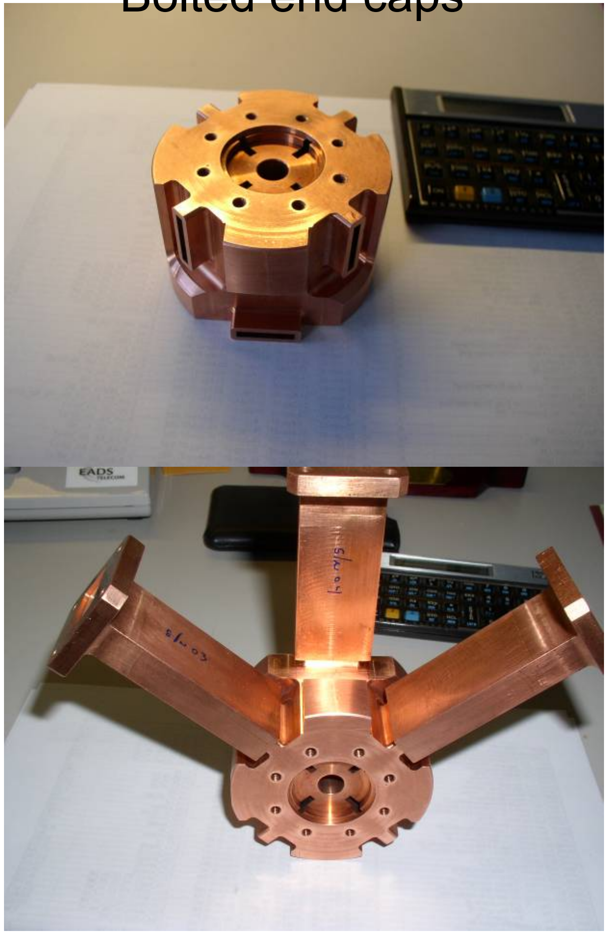
- slope of RF (BC BPM slope is more than twice as steep as beam phase monitor slope)

Setup developed by Florian Loehl

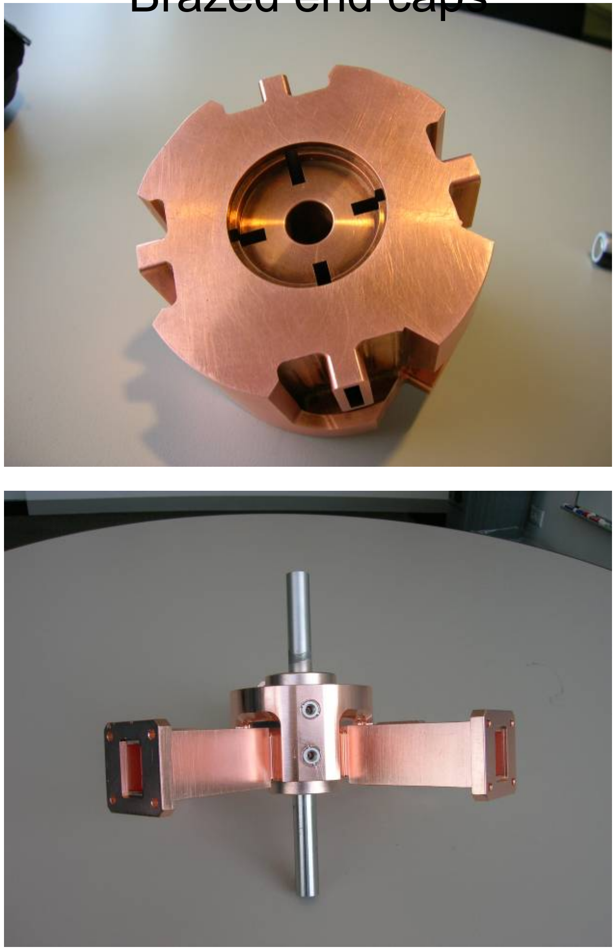
K. Hacker

ANL Prototypes for the LCLS Undulator

Bolted end caps



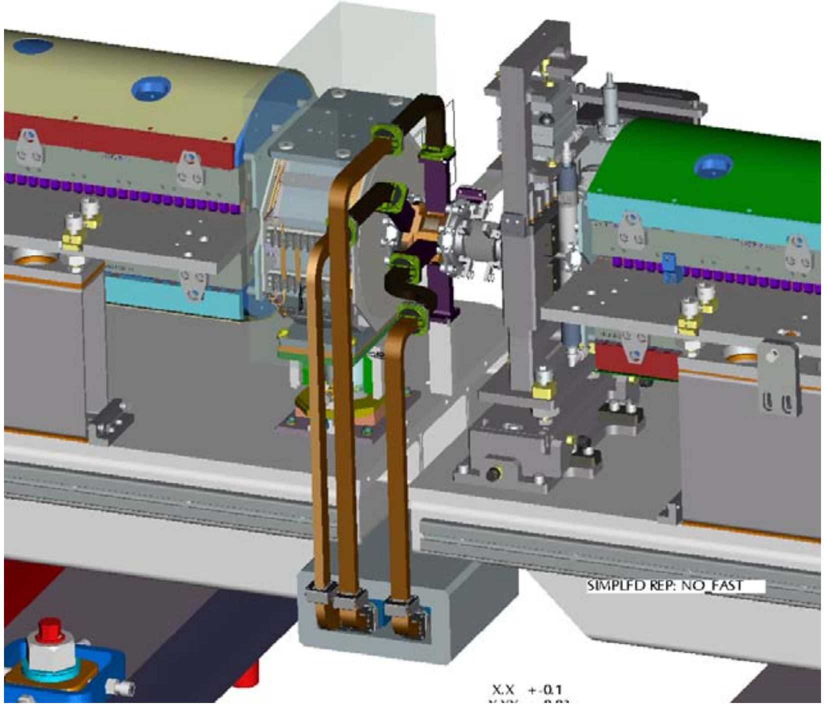
Brazed end caps



Patrick Krejcik
pkr@slac.stanford.edu

LTU and Undulator Planning

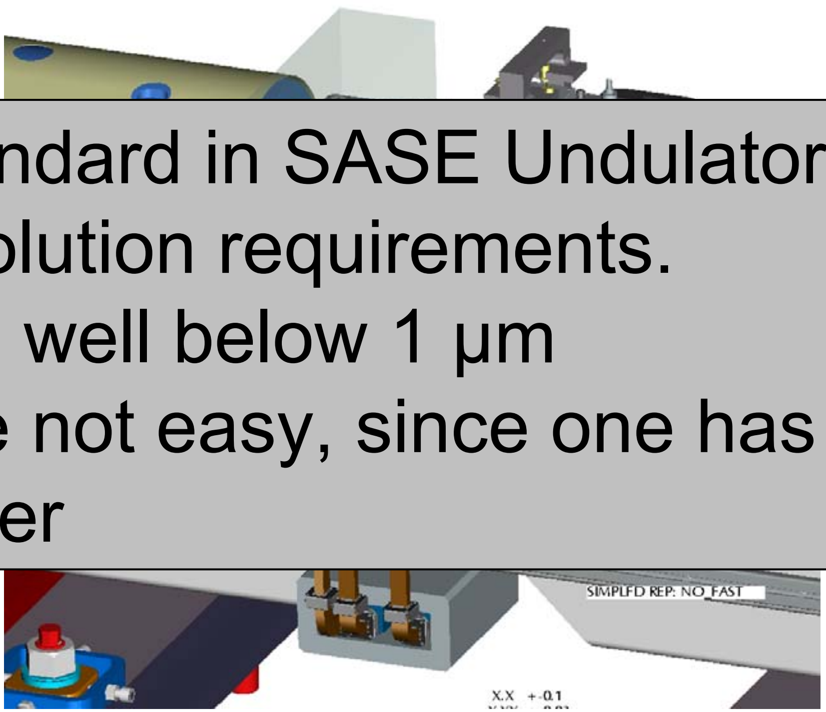
- Receiver and LO housed in shielded enclosure below girder 20 watt power dissipation maximum
- Presently BPM output on wall side
- BPM output flexible waveguide section allows movement for alignment



Patrick Krejcik
pkr@slac.stanford.edu

LTU and Undulator Planning

- Receiver and LO housed in shielded enclosure below girder 20 watt power



Cavity BPMs are getting standard in SASE Undulators
They can meet the high resolution requirements.

- Have the potential to go well below 1 µm
- Alignment Problems are not easy, since one has hit them close to the center

movement for alignment

Patrick Krejcik
pkr@slac.stanford.edu

Protection Systems

- Both Ring Based and LINAC Based Sources need Protections Systems
  - Damage by uncontrolled Beam Loss
  - Heat load of Synchrotron Radiation
- Time Scales
  - Storage Rings: Slow: 100 µs … ms
  - LINAC:
    - Two time scales:
      - Rep Rate (slow)
      - Intra Bunchtrain (fast), depending on cable length

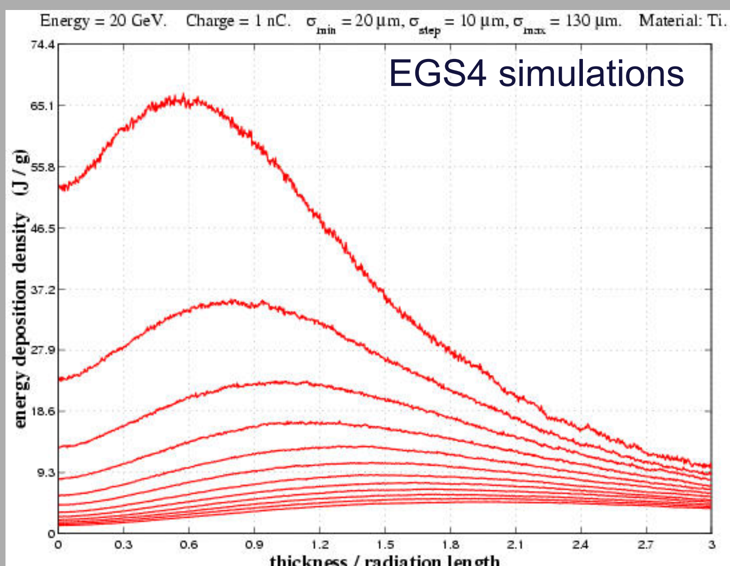
Emergency Scenario:

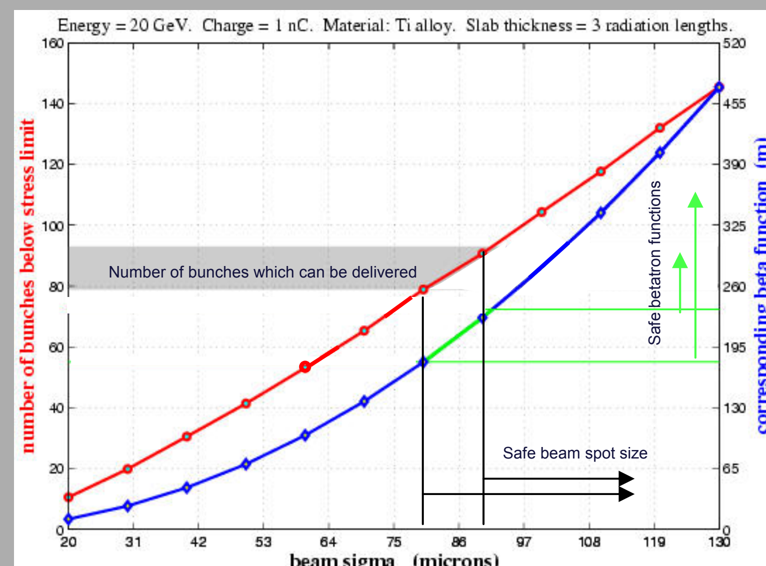
detect a failure and switch the beam production off as quickly as possible

Candidate for Collimator Material: Titanium Alloy

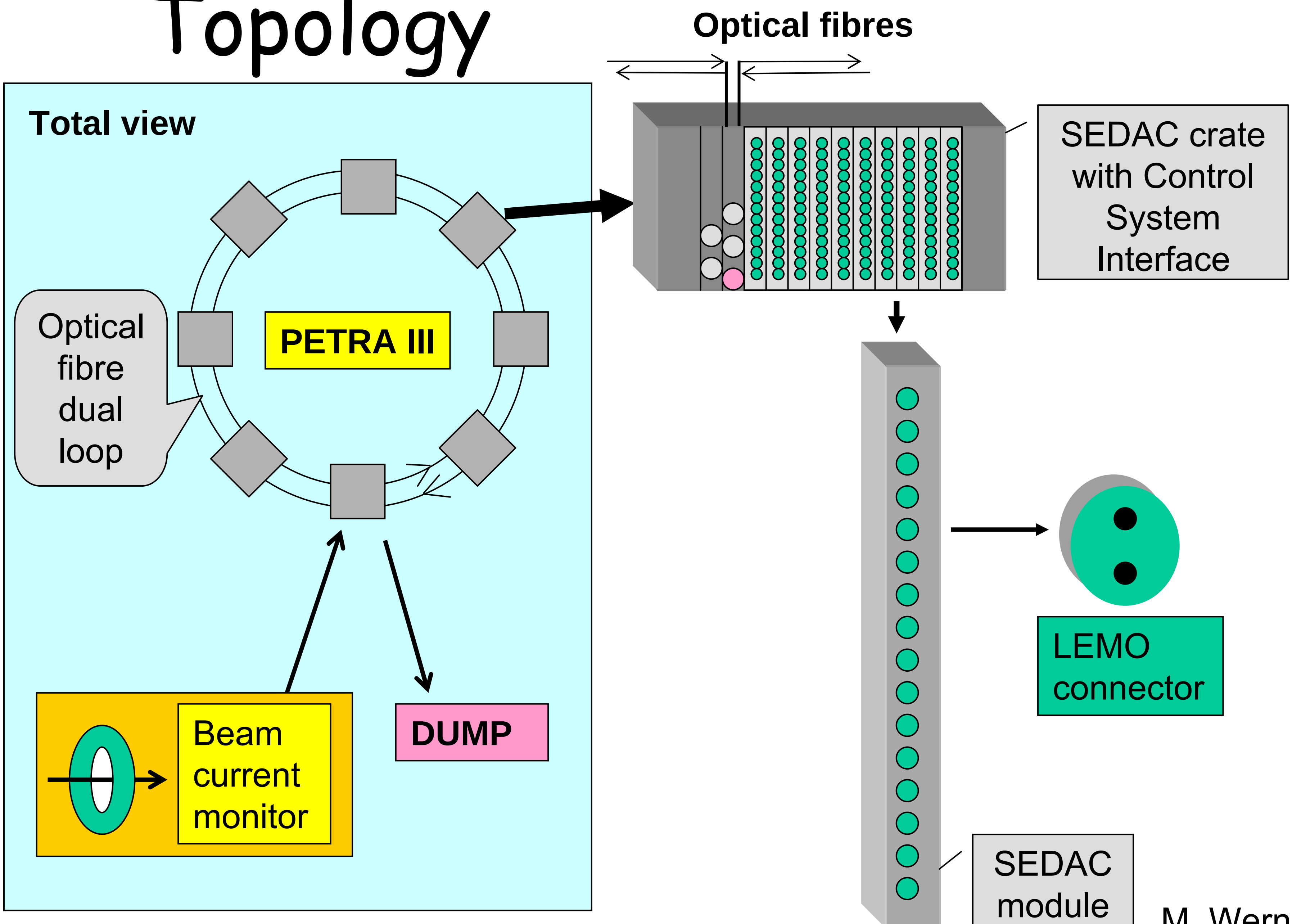
Rough stress analysis shows that to withstand a direct impact of such number of bunches **(~100)** which can be delivered to collimator location until failure will be detected and the beam production will be switched off, the beam spot size should be not smaller than 80-90 microns

(energy: 20GeV, normalized emittance: 1.4 mm·mrad, bunch charge: 1 nC, bunch spacing: 200 ns).



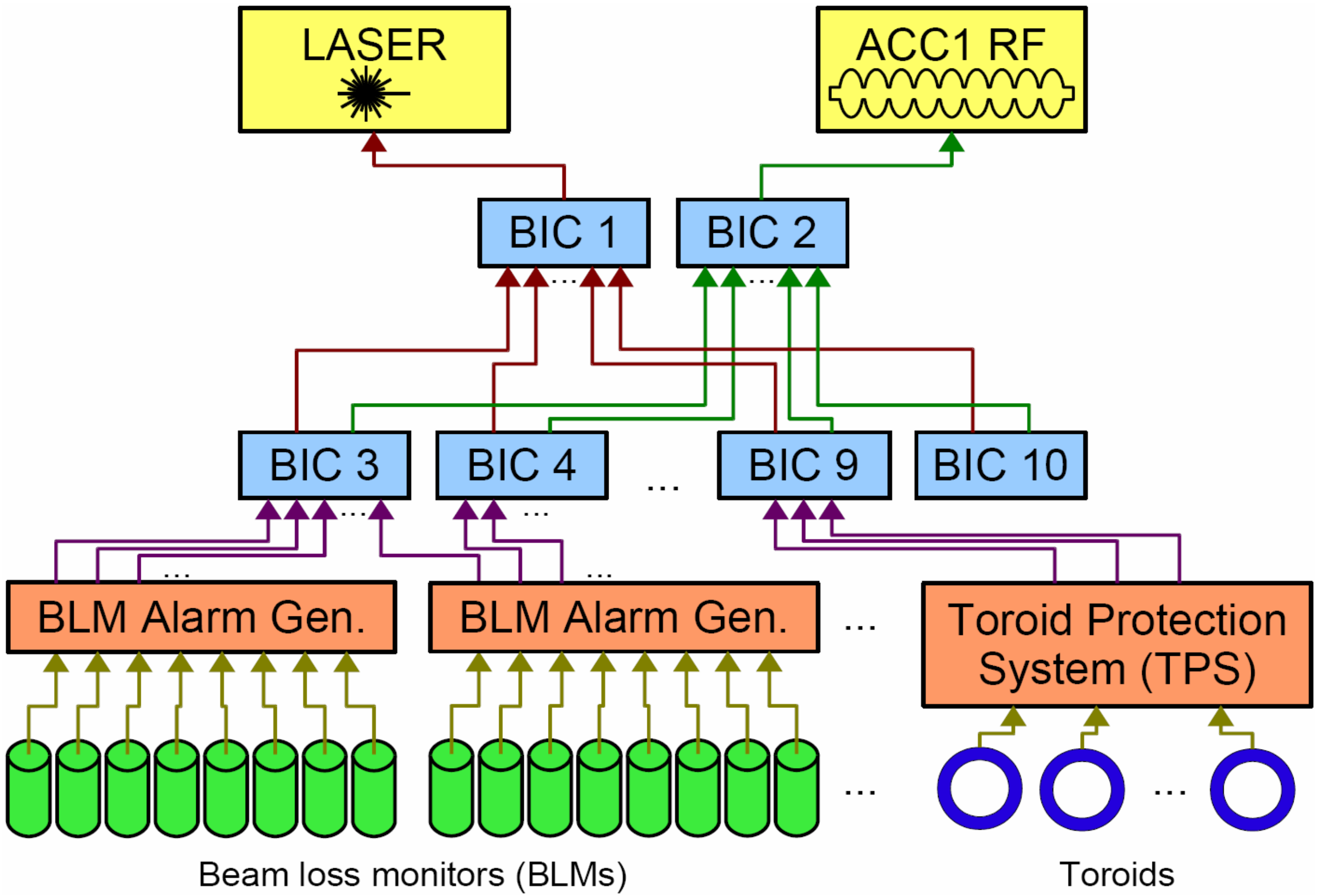


Topology



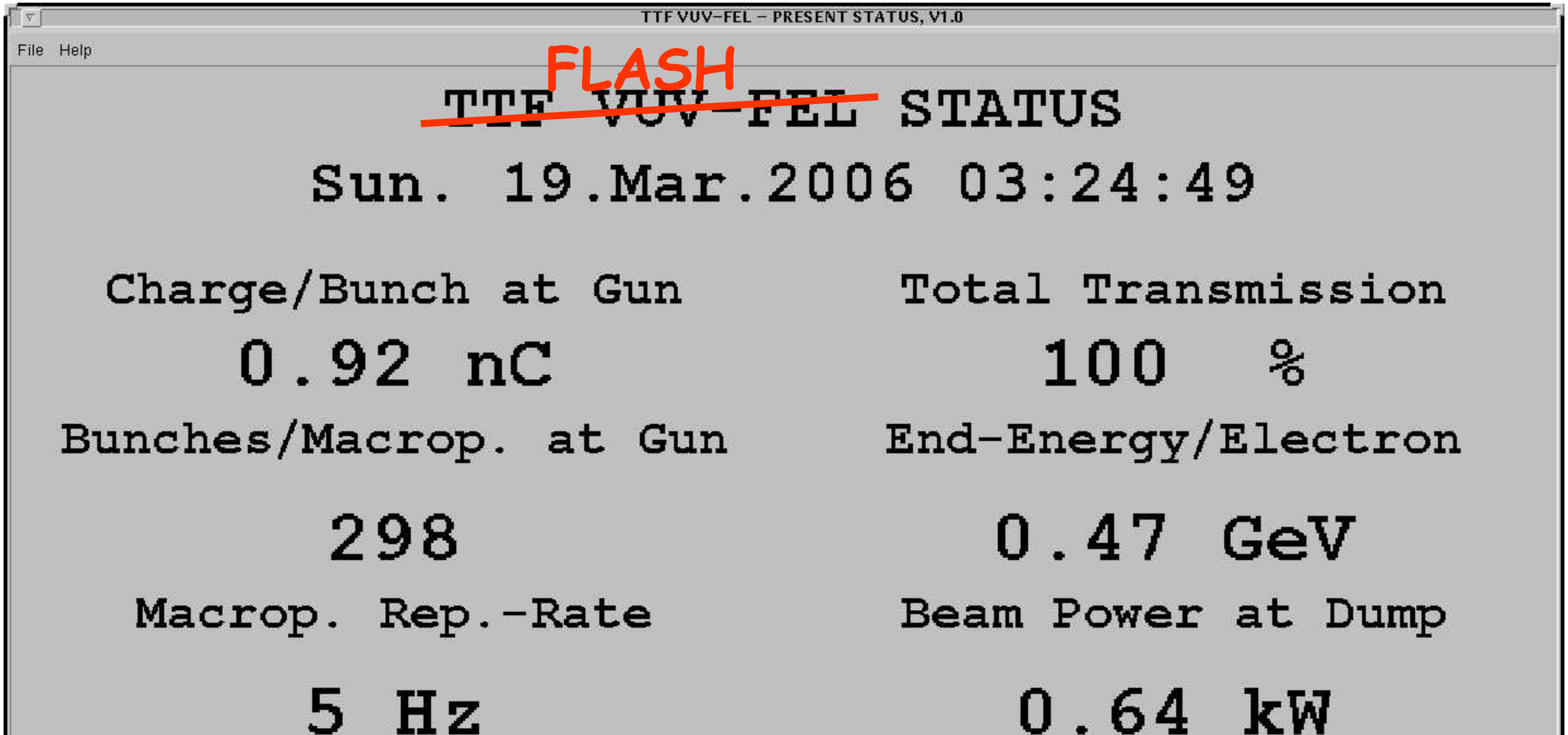
M. Werner

Fast beam interlock



Combination of fast,
And more intelligent Slow System

L. Fröhlich



Prove of Principle of the Protection System of FLASH
There are still some 100 µs to go, and rep rates to increase, but the protection system is prepared.

We have a prototype for the XFEL system.

L. Fröhlich

Concluding the Conclusion

- Very interesting WG
- Forefront Technologies everywhere
  - Optical Systems come in, not only for Synchronization and Timing
  - Proposal for Optical BPM Readout
  - Techniques to work on 100 fs time Scales evolve
  - Sub-microns Resolution in Single Shot BPMs
- Solutions to cope with Challenges of Diagnostics with X-RAY SASE Machines are close to our hands.