Report on FEL07 Novosibirsk, Russia August 26-31, 2007

Alex H. Lumpkin

Instrumentation Group Seminar

October 31, 2007

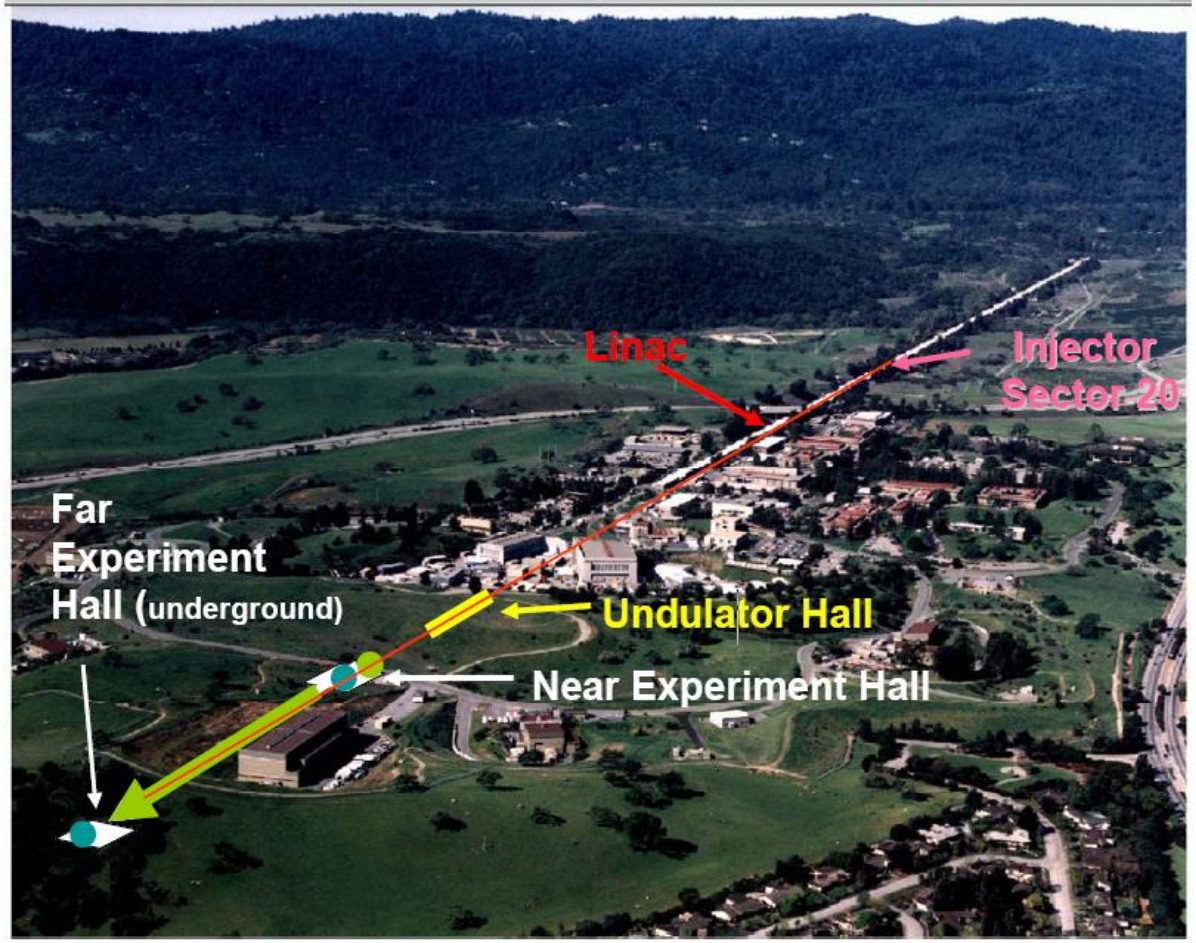
FEL07 Scientific Program Diverse

- FEL07 had 10 sessions covering New lasing, FEL Projects, FEL Technology (2), High power FELs, SR FELs, X-ray FELs, FEL theory, Operation, and Applications
- I will focus mostly on the FEL technology aspects which were dominated by photoinjectors and electron-beam measurements. About 1/3 of the 180 total papers were submitted in this overall category.
- Our program subcommittee sorted 64 abstracts and selected the ones for invited and contributed oral presentation for two technology sessions.
- Brief comments on laser wakefield accelerators (LWFA).
- FEL landscape comments.

Ongoing X-ray FELs at SLAC and DESY are Two Dominant Projects

- LCLS injector has just been commissioned this year.
- 1.5 to 15 Angstrom target with 14 to 4.5 GeV electron beam from last km of SLAC normal conducting rf linac.
- DOE mandate to build what has already been proven.
- XFEL project in Europe was viewed as a technology driver for SC rf linacs, synchronization, e-beam diagnostics, and photon diagnostics.
- TTF1 and then FLASH have been used as test beds.
- FLASH is oversubscribed by a factor of three for users of photon beam and studies time for diagnostics and machine development seem to be scheduled 6 months in advance.
- XFEL construction at DESY will start soon.

The LCLS will use the last 1/3 of the SLAC linac to create an x-ray FEL



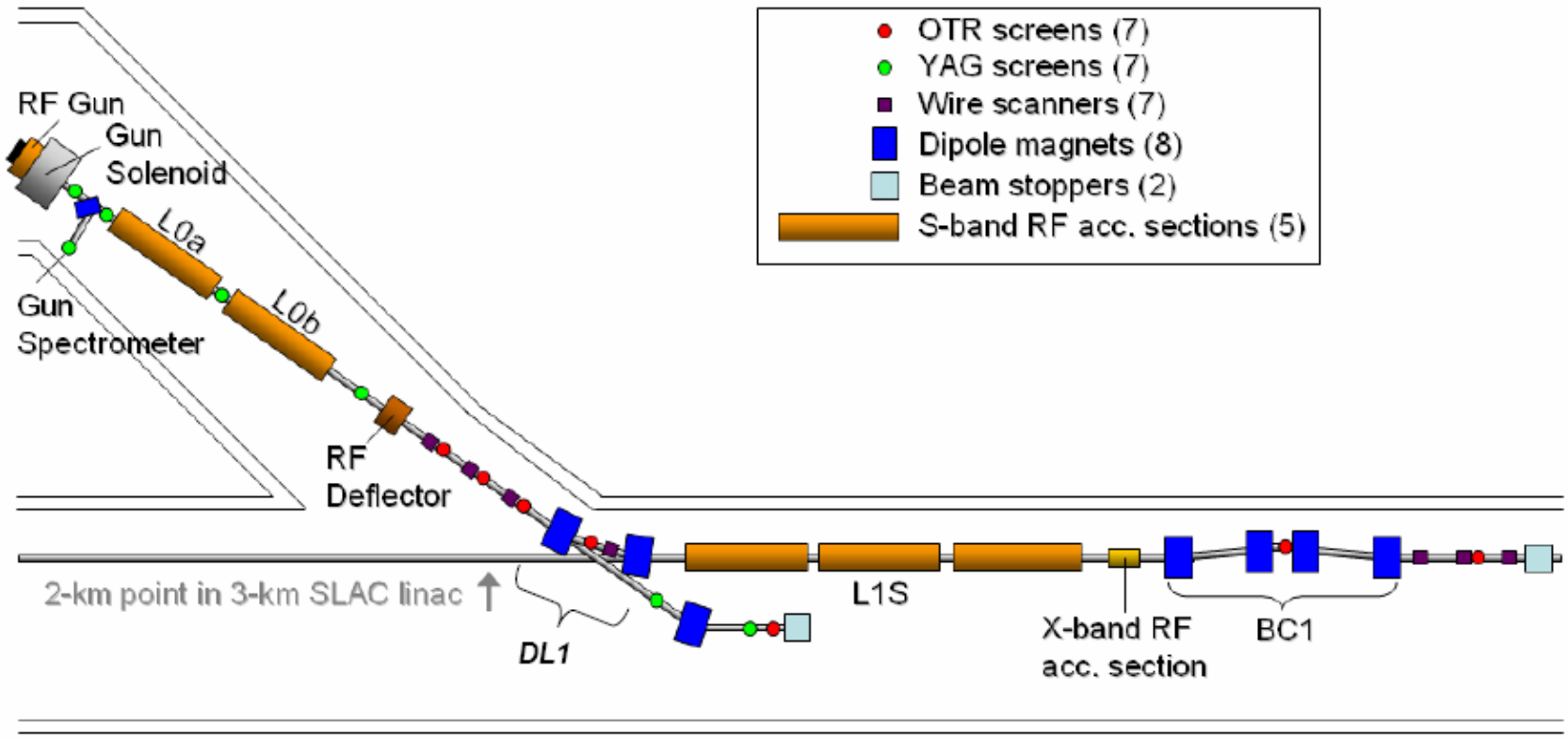
LCLS Design Parameters

Fundamental FEL Wavelength	1.5	15	Å
Electron Beam Energy	13.6	4.3	GeV
Normalized Slice Emittance (rms)	1.2	1.2	mm-mrad
Peak Current	3.4	3.4	kA
Energy Spread (slice rms)	0.01	0.03	%
Bunch/Pulse Length (FWHM)	≤ 200	≤ 200	fs
Saturation Length	87	25	m
FEL Fundamental Power @ Saturation	8	17	GW
FEL Photons per Pulse	1	29	10^{12}
Peak Brightness @ Undulator Exit	0.8	0.06	10^{33} *

* photons/sec/mm^2/mrad^2/ 0.1%-BW

David H. Dowell et al.
dowell@slac.stanford.edu

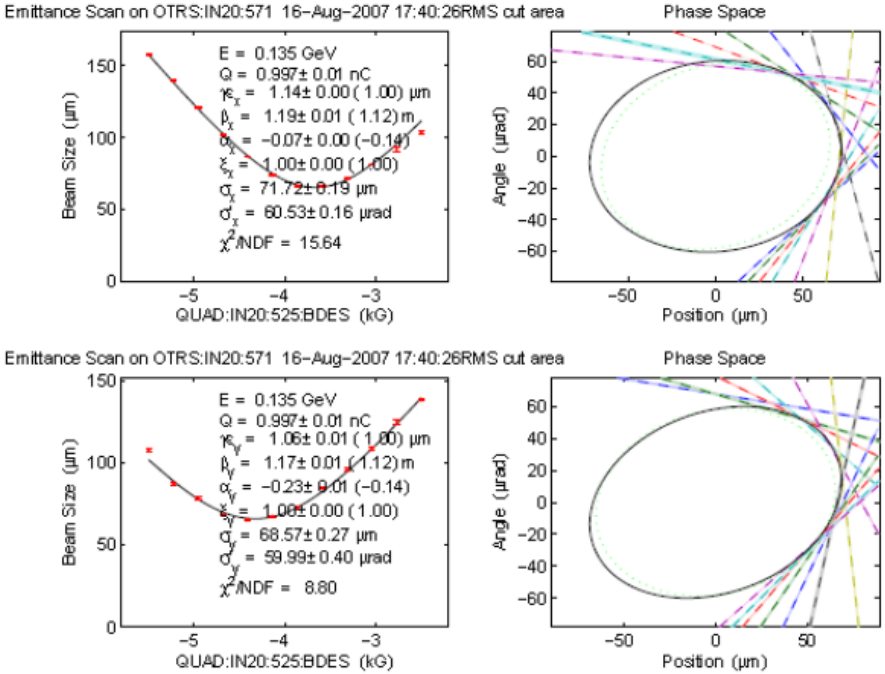
Injector and Bunch Compressor 1 Commissioned from April to September 2007 ~5 Months

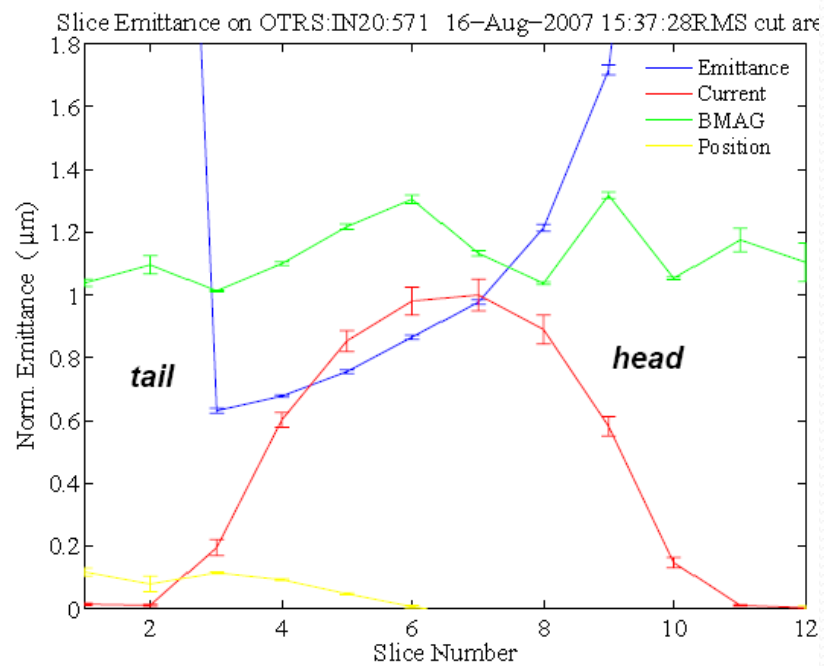


Projected & Slice Emittances at 1nC

Projected Emittance (rms) at 1nC (95% of the beam):
ε_x = 1.14 microns
ε_y = 1.06 microns

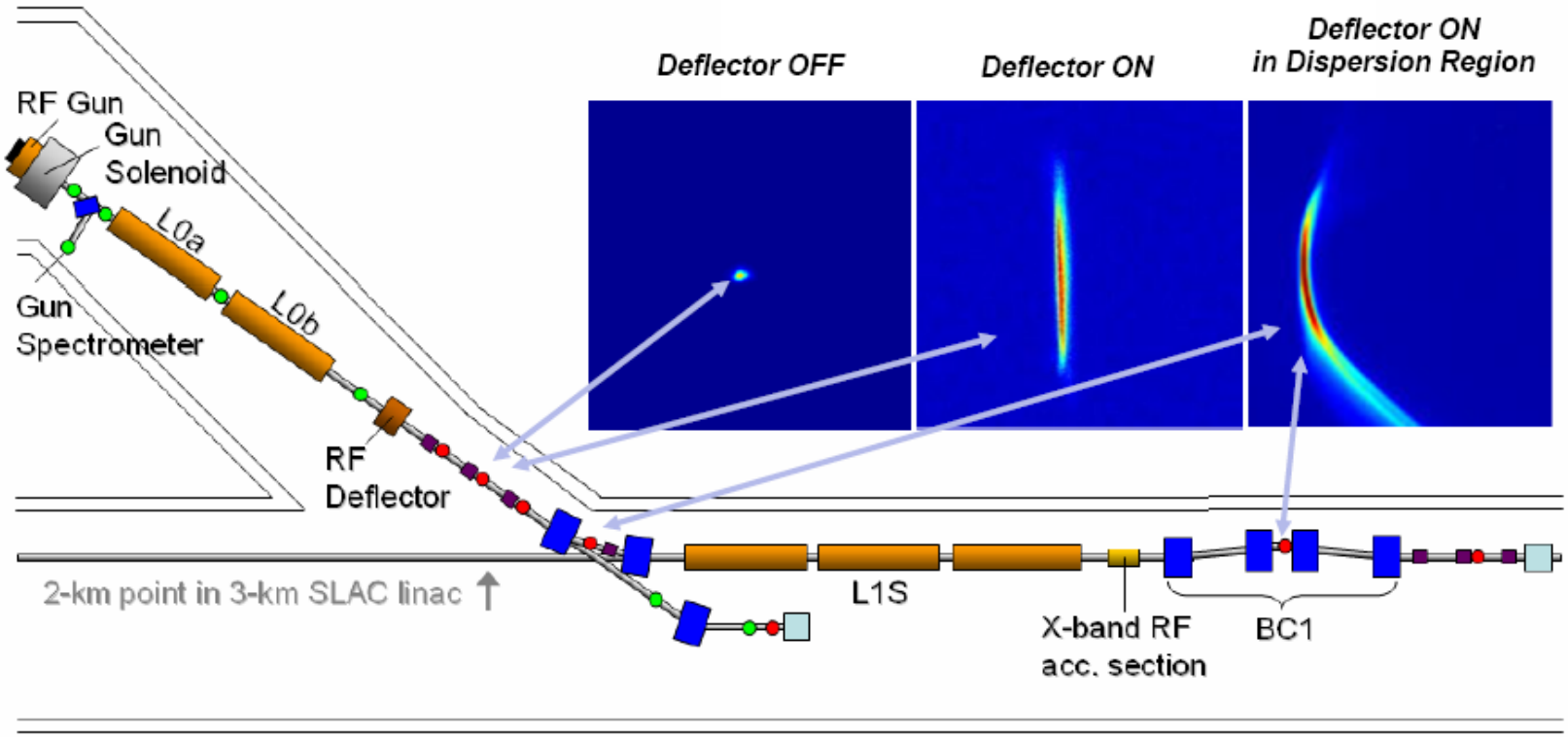
Slice Emittance, Current & Matching:
Slices 3 to 7 (tail) are all below 1 micron.
Head slices (8-10) are > 1 micron.
Peak Current is 100 amps.





On-line analysis tools by H. Loos

Transverse Cavity (RF-Deflector) Measurements of Bunch Length



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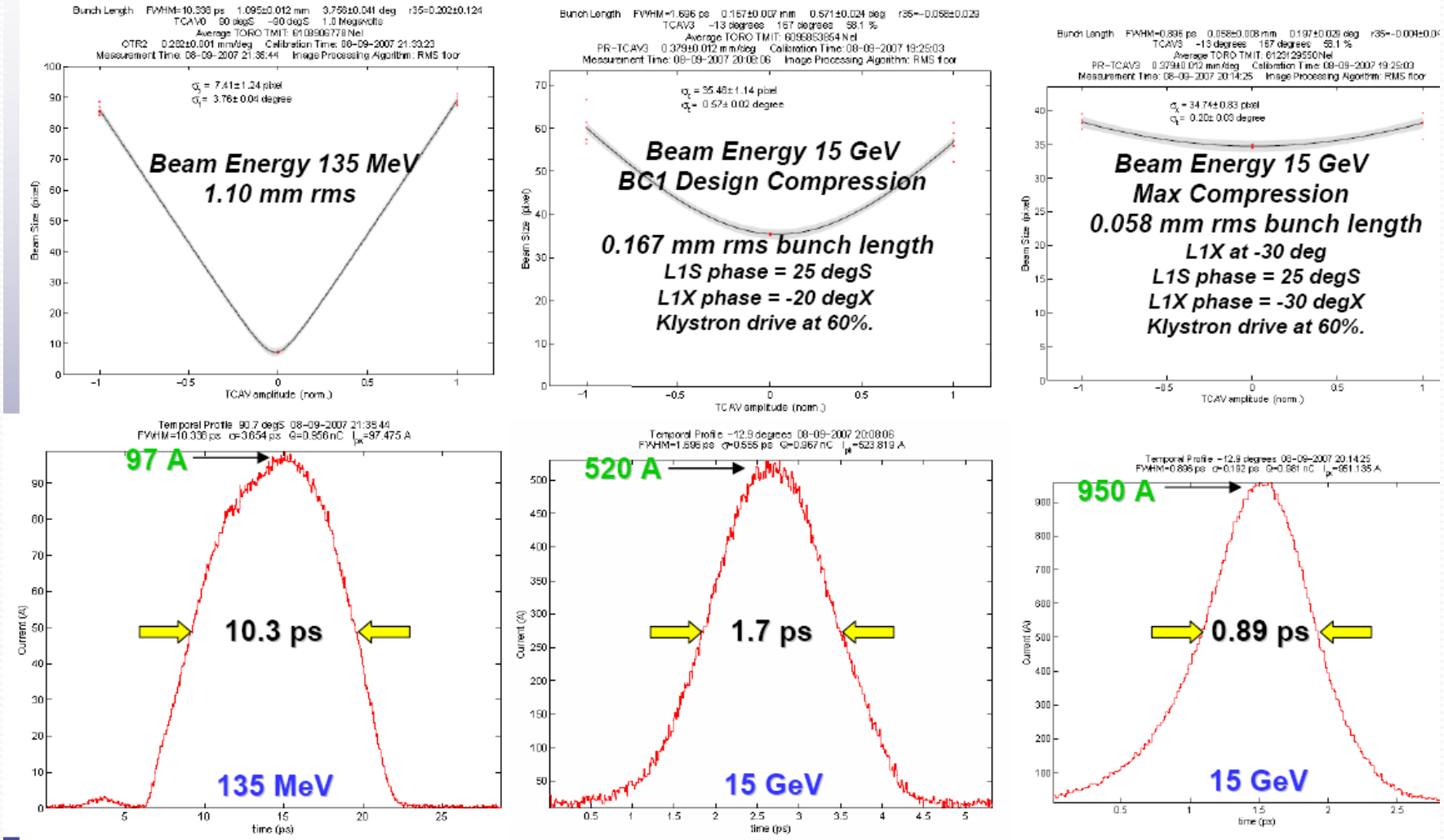
dowell@slac.stanford.edu

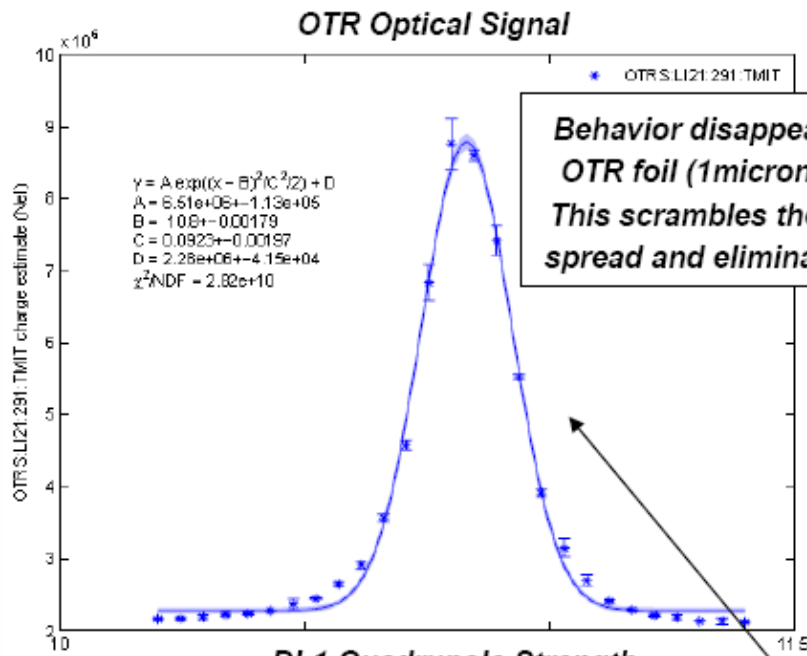
Bunch Length Measurements at 135MeV & 15GeV



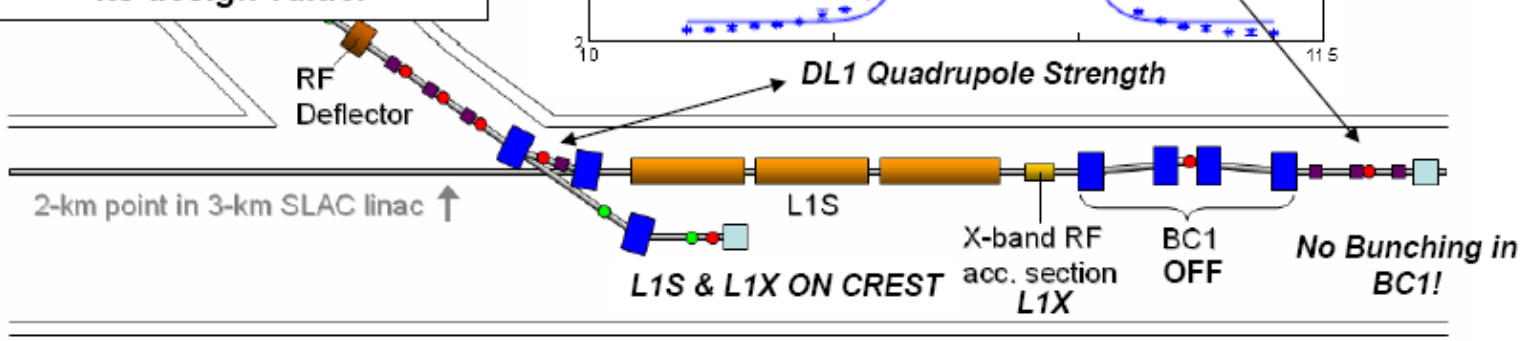
Unexpected Physics!
Coherent Optical Transition Radiation after DL1 Bend Even With No BC1 Compression

Evidence for Optical Microbunching:

Optical Signal from OTR screen with BC1 OFF is strongly dependent upon bend quad. Signal largest when quad is adjusted to make bend dispersionless, its design value.



Behavior disappears when upstream OTR foil (1micron thick) is inserted: This scrambles the correlated energy spread and eliminates microbunching



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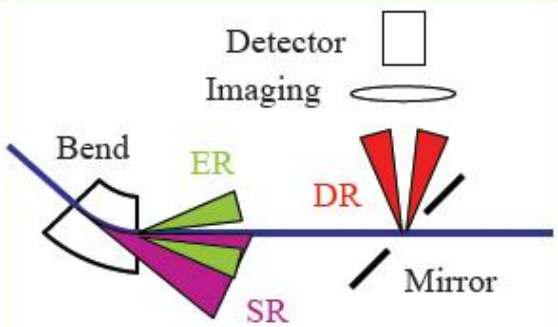
BC1 Edge Radiation Bunch Length Monitor

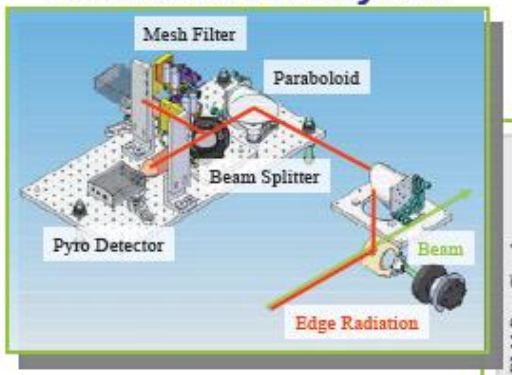
Coherent Radiation Sources from Bend



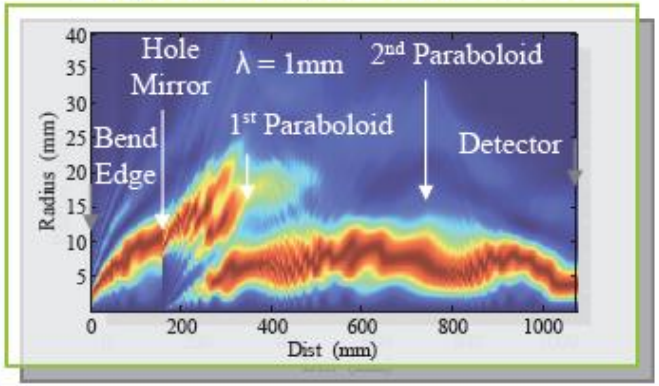
ER dominates at λ ~ 1mm

Bunch length after BC1: 60 – 200 μm
Wavelength range to determine bunch length: 0.3 – 1 mm
Measure integrated coherent power and use frequency filters

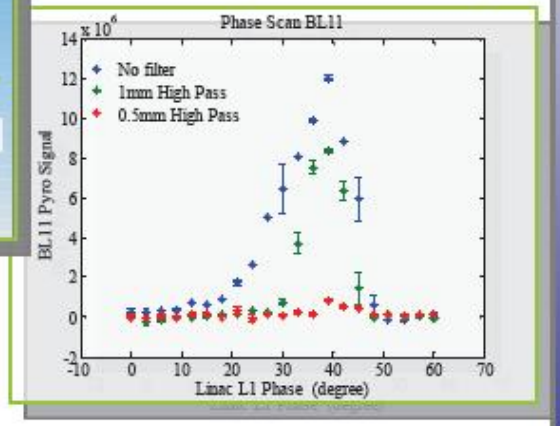
Measurement Layout



Edge Radiation Simulation



First Signals from Pyro



Slide and data compliments H. Loos

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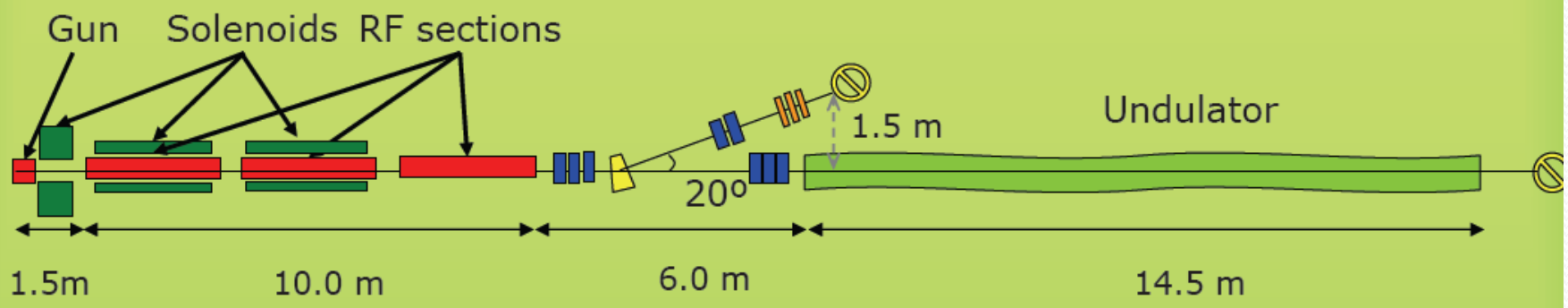
Comparison of Required and Demonstrated Beam Properties

Parameter	Sym	dsgn	meas.	unit
Final e^- energy	γmc^2	15	15	GeV
Bunch charge	Q	1000	1000	pC
Init. bunch length (fwhm)	Δt_0	10	10	ps
Fin. bunch length (fwhm)	Δt_f	2.3	1.5	ps
Initial peak current	I_{pk0}	100	100	A
Projected norm emittance	$\gamma\varepsilon_{x,y}$	1.2	1.1 to 1.3	μm
Slice norm. emittance	$\gamma\varepsilon^s_{x,y}$	1.0	0.8 to 1.0	μm
Single bunch rep. rate	f	120	10-30	Hz
RF gun field at cathode	$E_{cathode}$	120	115	MV/m
Laser energy on cathode	U_l	250	450	μJ
Laser wavelength	λ_l	255	255	nm
Laser diameter on cathode	2R	1.5	1.3	mm
Cathode material	-	Cu	Cu	
Cathode quantum eff.	QE	6	3	10^{-5}
Commissioning duration	-	8	5	mo

The SPARC Injector Project

MAIN GOAL: the promotion of an R&D activity oriented to the development of a high brightness photoinjector to drive SASE FEL experiments



GUN PARAMETERS		LINAC PARAMETERS		FEL PARAMETERS
Frequency	2856 MHz	Frequency	2856 MHz	Wavelength 530 nm
Peak Field	120 MV/m	Accelerating Field	25 MV/m	Undulator period 2.8 cm
Beam Energy	5.6 MeV	Beam Energy	155 MeV	
Charge	1 nC	Energy Spread	10^{-3}	
Emittance	< 2 mm-mrad	Peak Current	100 A	
Laser	10 ps (Flat Top with <2 ps rise time)			

Novosibirsk
August 26-31, 2007

E. Chiadroni LNF - INFN
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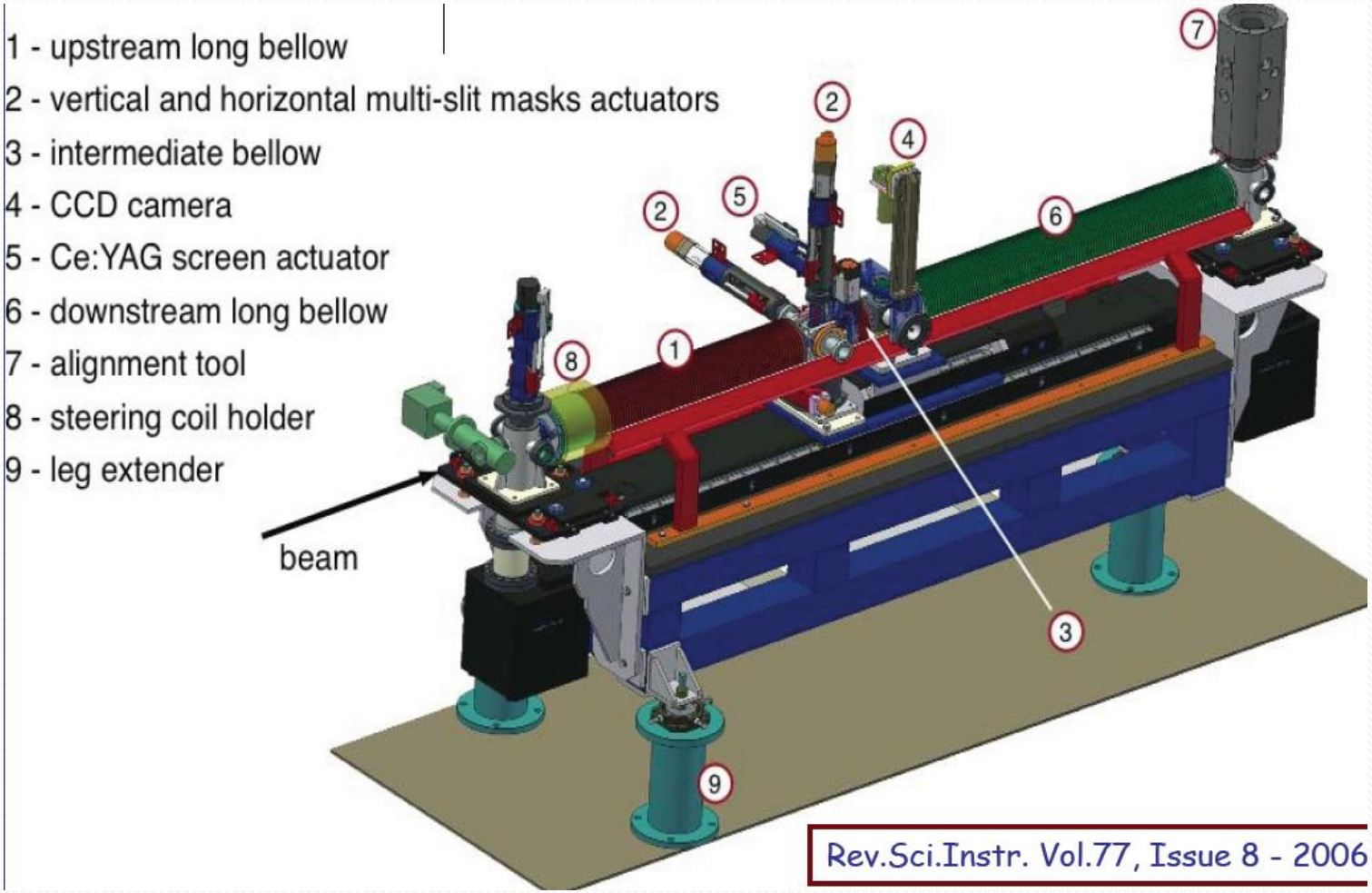
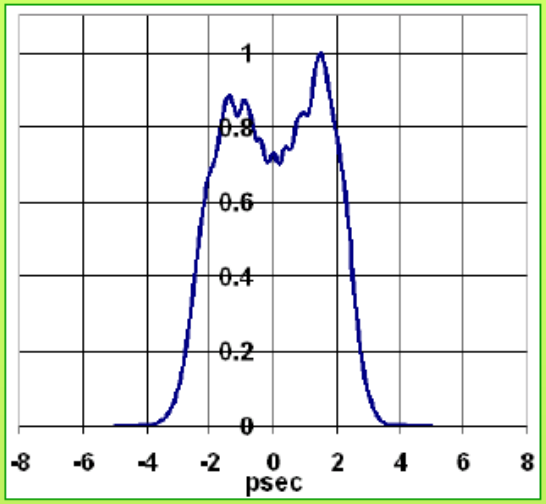
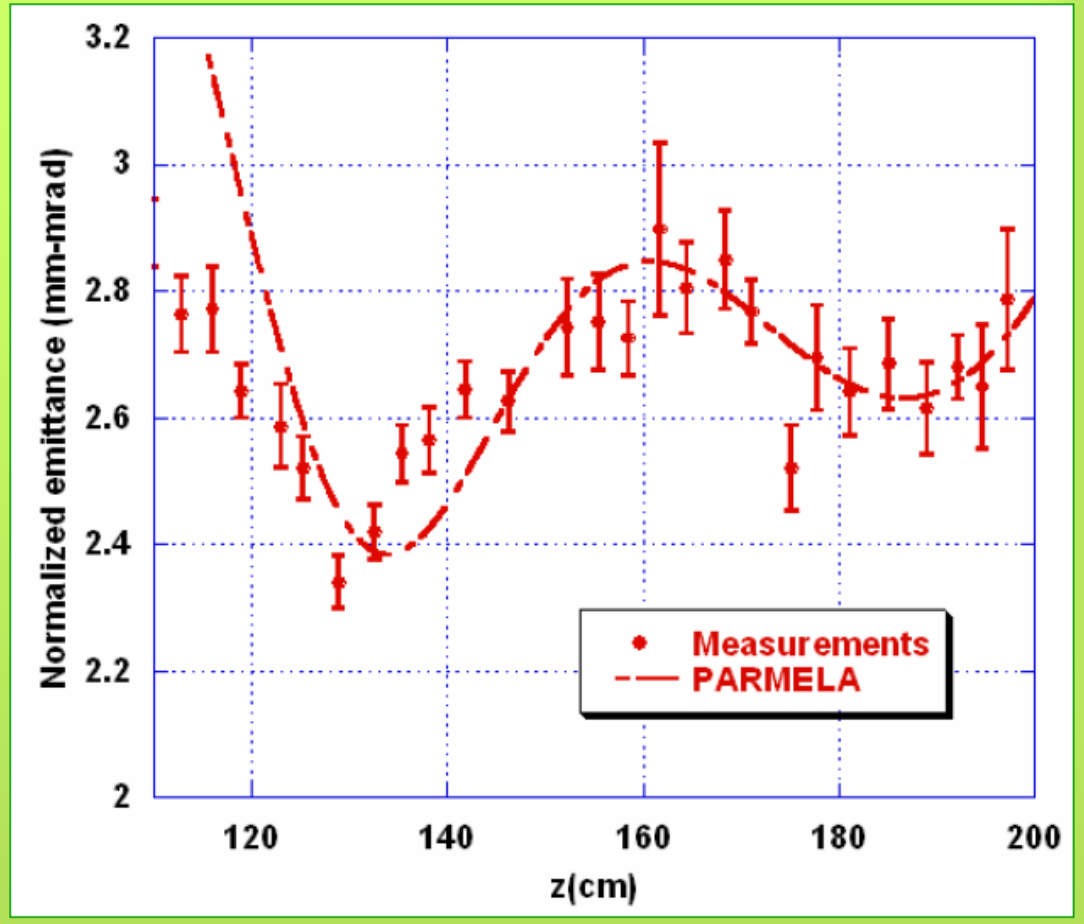
The SPARC Emittance Meter



Double Minimum Signature



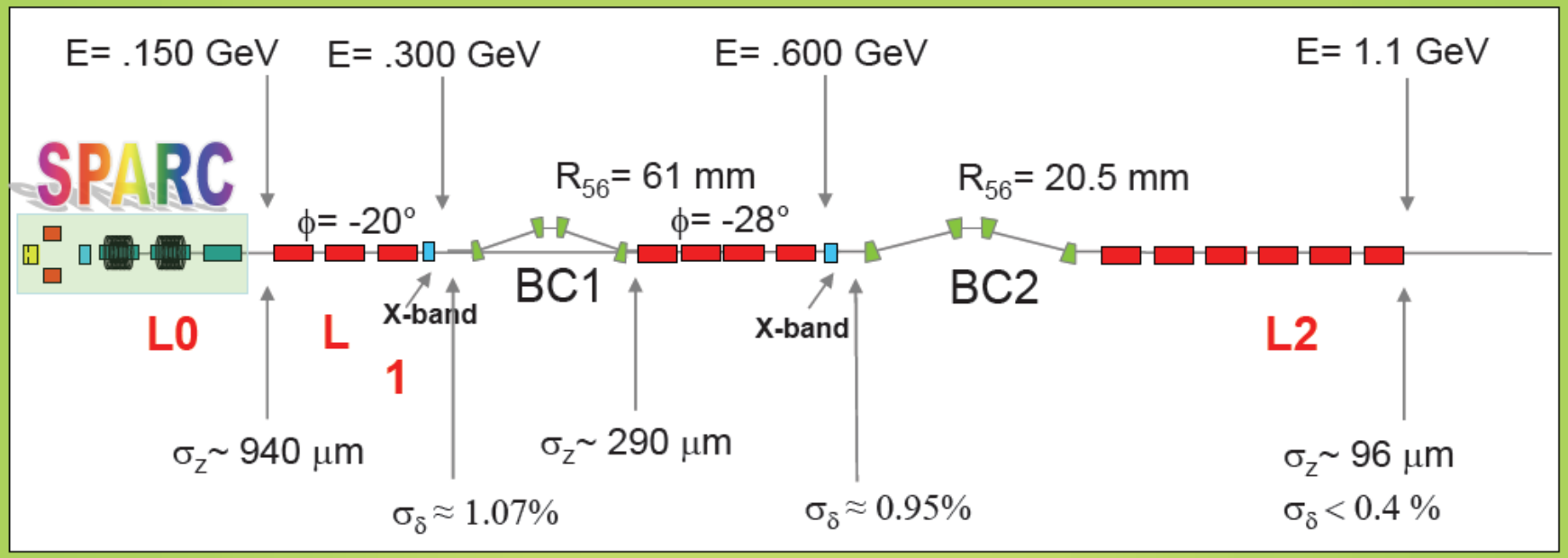
charge	0.5 nC
pulse length (FWHM)	5 ps
rise time	1.5 ps
rms spot size	0.45 mm
RF phase (φ-φ_{max})	+12°



M. Ferrario et al.,
"*Direct measurement of double emittance minimum in the SPARC high brightness photoinjector*",
submitted to Physical Review Letters

SPARX Project Recently Approved

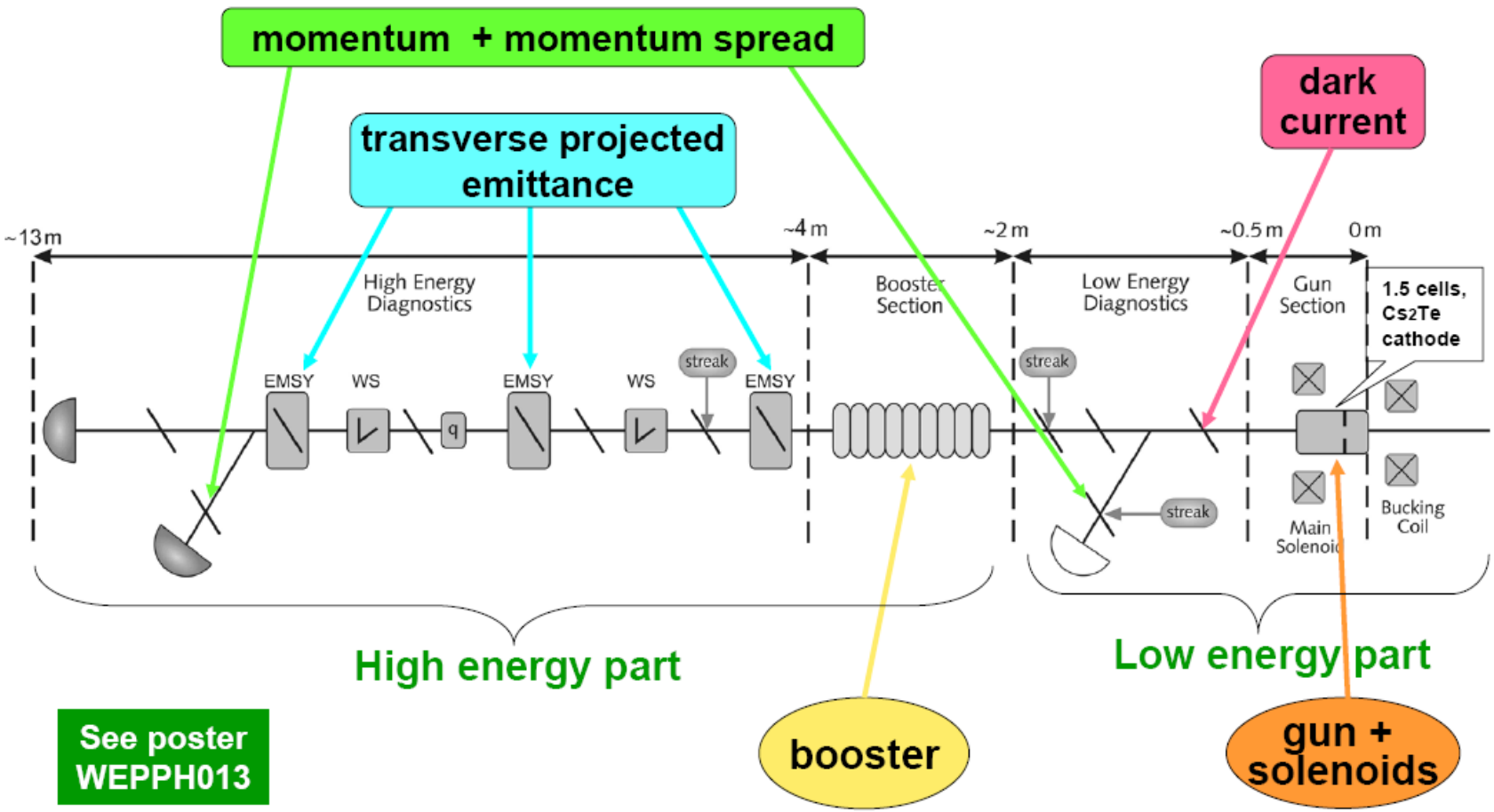
1 - 2 GeV → 10 - 1 nm FEL



2007	TDR, Tunnel & buildings project
2008	Procurement of long term devices, Start tunnel construction
2009	Construction, Procurement, Installation
2010	Installation
2011	Installation & Commissioning
2012	Operation

Present layout of PITZ

This setup was used for the measurements to be presented:



Projected Emittance Measurements: → Slit Scan Technique

$$\varepsilon_{x,n} = \beta\gamma \cdot X_{rms} \cdot X'_{rms}$$

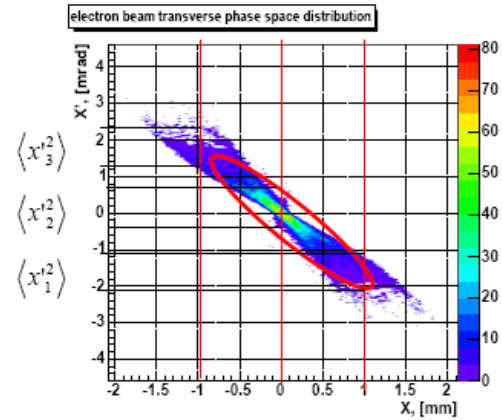
X_{rms} - RMS size of full beam at EMSY station (e.g. z = 4.3m)

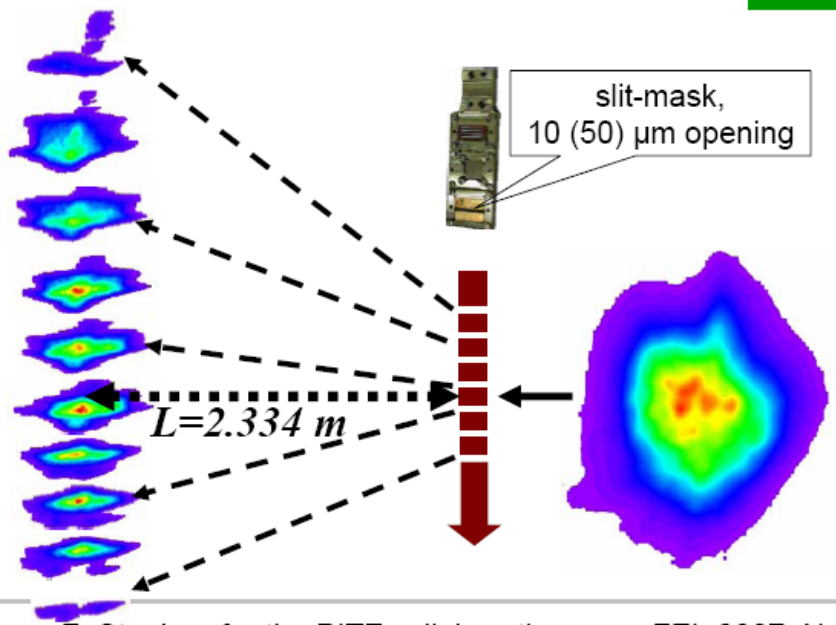
$X'_{rms} = \frac{1}{L}\sqrt{\sum_{i=1}^{n} w_i \cdot \left(X_{rms}^{beamlet}\right)_i^2 \Big/ \sum_{i=1}^{n} w_i}$ - uncorrelated local divergence

$X_{rms}^{beamlet}$ - RMS size of the beamlet image

L - distance from slit location to screen for beamlets

See poster MOPPH055





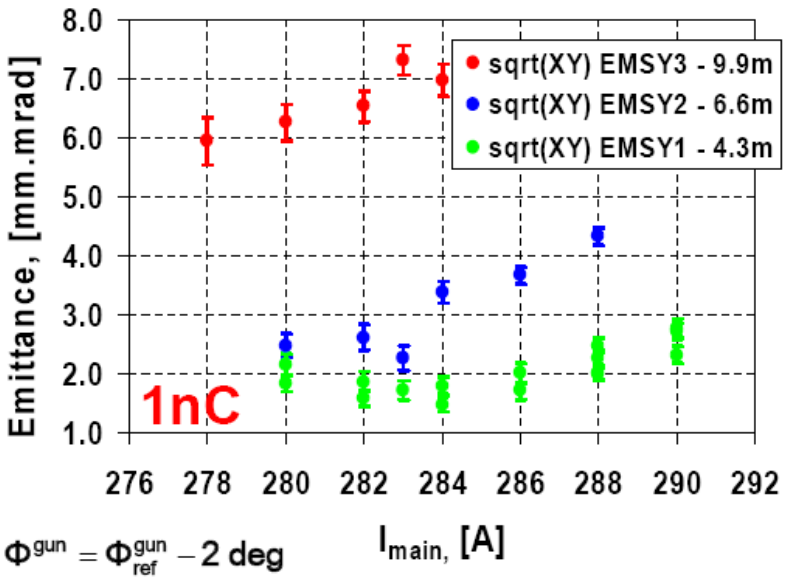
- **Current standard procedure:**
  - take 11 equidistant beamlets over the full beam size
  - use 10 µm slit opening
- ultimate resolution (current setup): → 36µm x 15.4 µrad
- use camera with 12 bit signal depth for beamlet measurements

F. Stephan for the PITZ collaboration FEL 2007, Novosibirsk August 29th, 2007 9

Emittance results October 2006

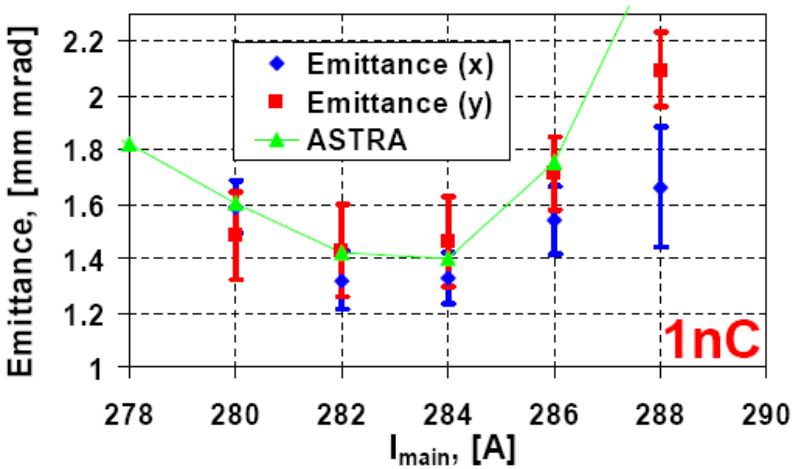
Gun gradient: ~ 43MV/m
Gun phase: $\Phi^{gun} = \Phi^{gun}_{ref} - 2\ deg$
Momentum from gun: ~ 5.0 MeV/c

Booster phase: $\Phi^{booster} = \Phi^{booster}_{ref} - 5\ deg$
Total beam momentum: 12.8 MeV/c



$\Phi^{gun} = \Phi^{gun}_{ref} - 2\ deg$

$\Phi^{booster} = \Phi^{booster}_{ref} - 15\ deg$



➔ for 43 MV/m we obtained

$\varepsilon_{x,n} = 1.32 \pm 0.11$ mm mrad
$\varepsilon_{y,n} = 1.43 \pm 0.17$ mm mrad
@1nC

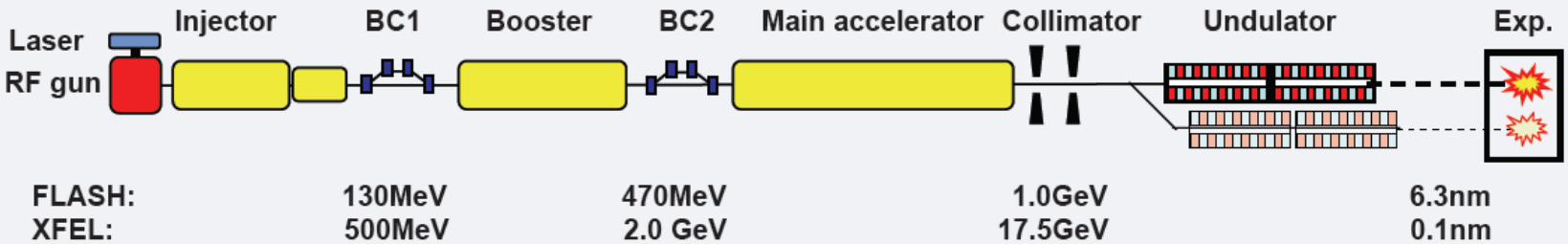
➔ emittance strongly increases with distance from booster

See poster MOPPH055

F. Stephan for the PITZ collaboration FEL 2007, Novosibirsk August 29th, 2007 10

Technology Push From the XFEL Project in Europe

FLASH and European XFEL are on the fundamental level very similar machines



Based on same SRF technology
Only small differences in beam parameter (except E)

⇒ High level RF & RF controls
⇒ Beam dynamics issue
⇒ Diagnostics development
⇒ Test of utility systems

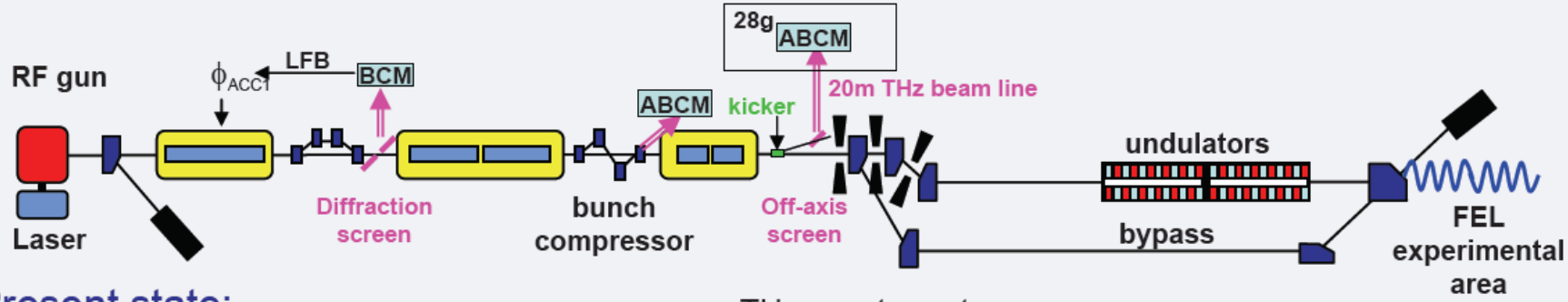
Can almost all be carried out at FLASH!

Para.	FLASH	XFEL
$\varepsilon_{x,y}$	2 μm	1.4 μm
I_{peak}	2.5 kA	5 kA
f_{rep}	1 (9)MHz	5 MHz
Q	1 nC	1 nC
E	1 GeV	17.5 GeV
RF	1.3/3.9GHz	1.3/3.9GHz
Δt	800μs	650μs
Δx/Δy	5μm	3μm

H.Schlarb (DESY) talk

Diagnostics developments –frequency domain-

Coherent radiation: bunch compression monitoring (BCM) and long. FB!



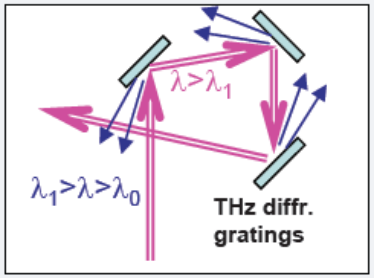
Present state:

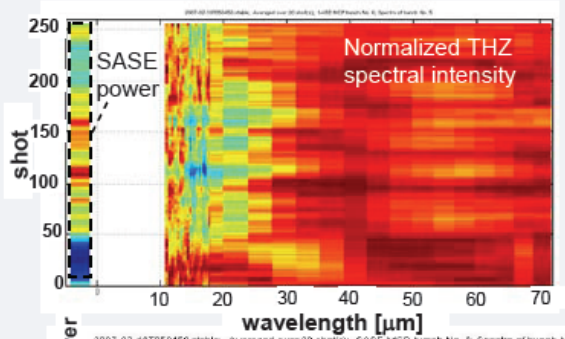
- Integrated THz signal (>λ_0) used to stabilize ACC1 phase
- Development of single shot spectrometer (ABCM)
- Reveals importance of spectral information for FEL operation

Next steps:

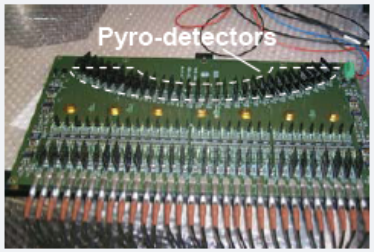
- Investigation of online, suited for macro-pulse operation using CSR
- Compact THz spectrometer (next generation)
- Electronics allowing for readout + processing > 1 MHz for long. feedback systems

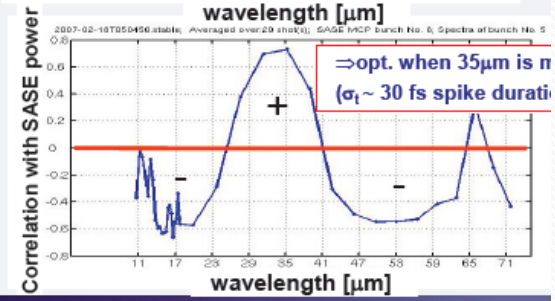
THz spectrometer





Readout system





Holger Schlarb, DESY
FEL2007, August 28, 2007

Courtesy: H. Delsim-Hashemi, B. Schmidt

Diagnostics developments – time domain –

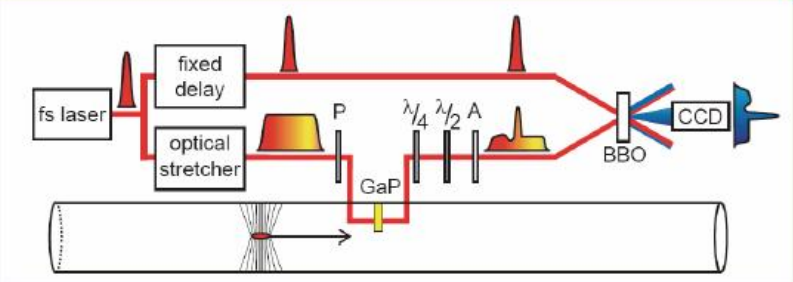
Time domain longitudinal bunch profiling:

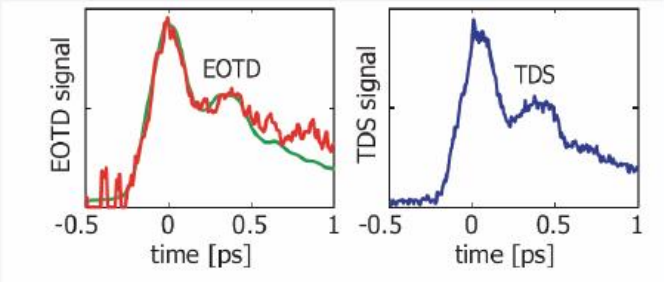
- Electro-optical technique (birefringence crystal)
- Time domain approach with stretched laser pulse + cross-correlation in BBO for encoding (EOTD)
- Bench marked with transverse deflecting structure

⇒ Good agreement with expectation

⇒ Resolution 55fs rms (65 μm GaP crystal)

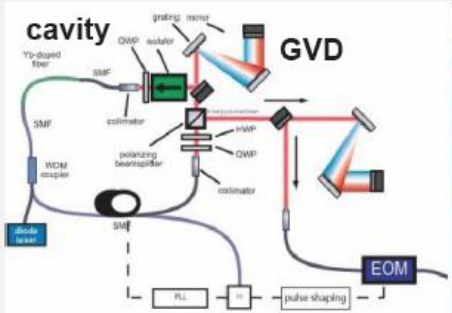
Collaboration: Abertey & Dundee Uni., Daresbury Lab., FELIX / FOM and DESY (See talk WEBAU04)





Next development steps:

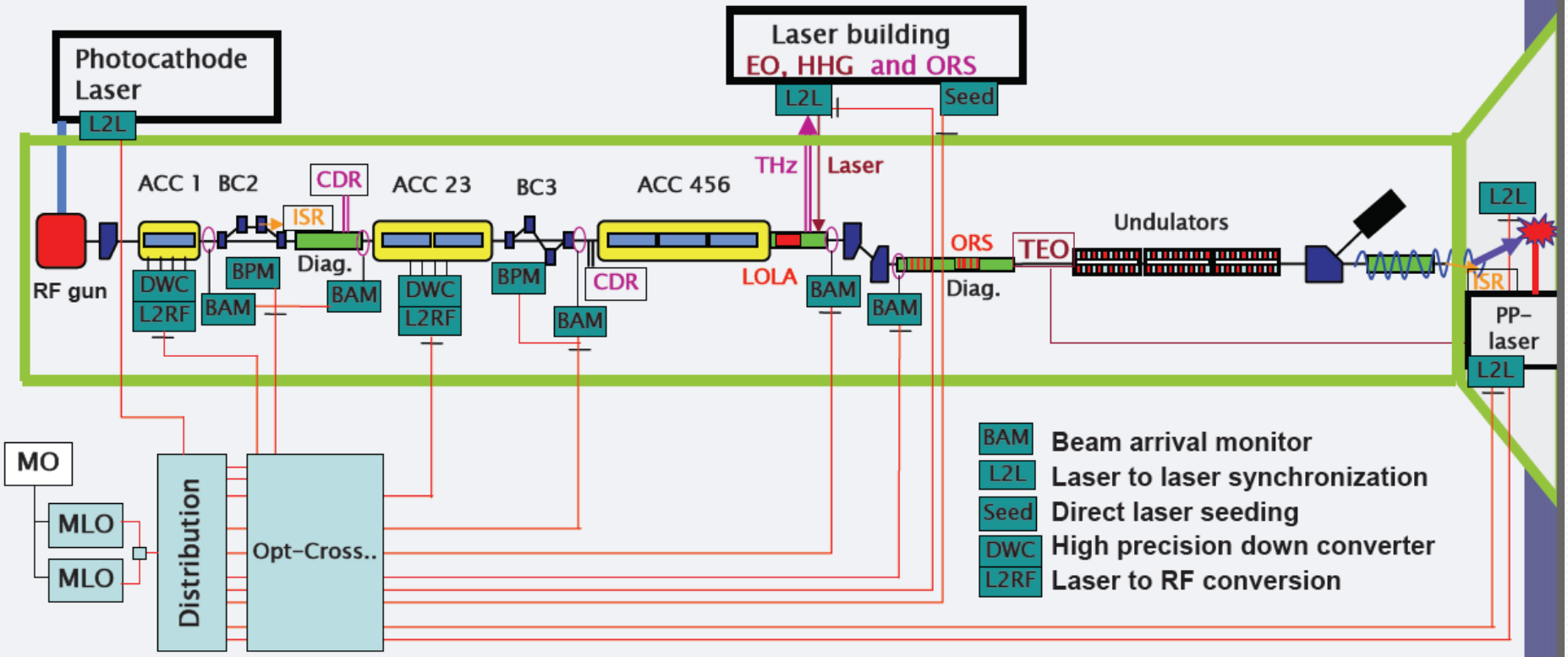
- Robust source: mode-locked Yb-fiber laser Δt_{FWHM}<100fs (30fs has been achieved)
- Suitable for operation in acc. tunnel
- Packaging of laser: IRUVX-FP7 proposal in collaboration with BESSY (T. Quast)
- Fast line camera readout (1030nm, >1MHz)
- Technique: EO spectral or spatial



Courtesy: A. Winter, DESY
Ö. Ilday, Bilkent Uni. Ankara
DIPAC07:WEPB03

Synchronization system – FLASH –

Implementation of complete system 2008/2009



- Synchronization of all timing critical devices (~ 12 points)
- Point-to-point synchronization ~ 10fs rms
- Permanent operation and long term stability /availability investigation

Holger Schlarb, DESY
FEL2007, August 28, 2007

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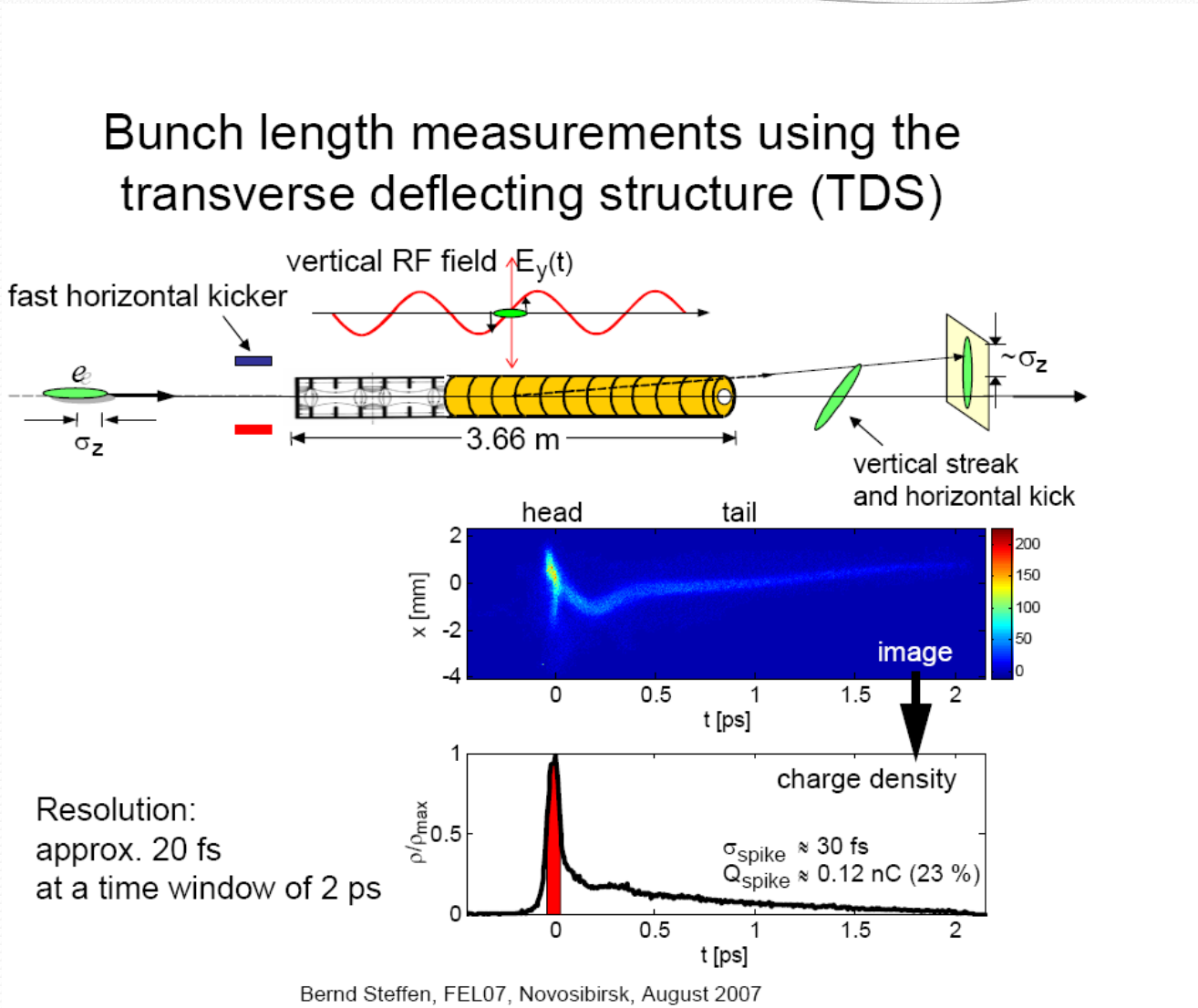
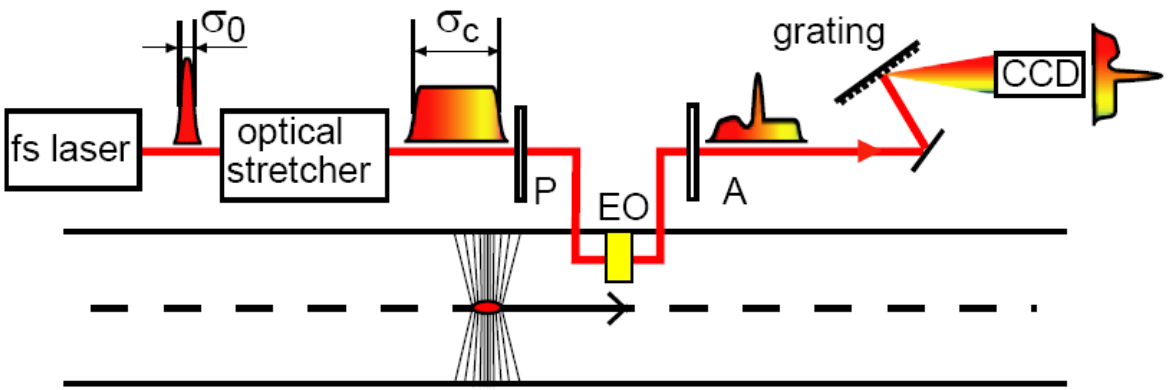
Time Domain



B. Steffen (FLASH) talk

Time Domain

EO Spectral Detection



- Linear relationship between wavelength and long. position in laser pulse ("linear chirp")
- Bunch profile is transferred to spectral profile of the laser pulse
  - Problem: Frequency mixing with Coulomb field creates new frequency components:

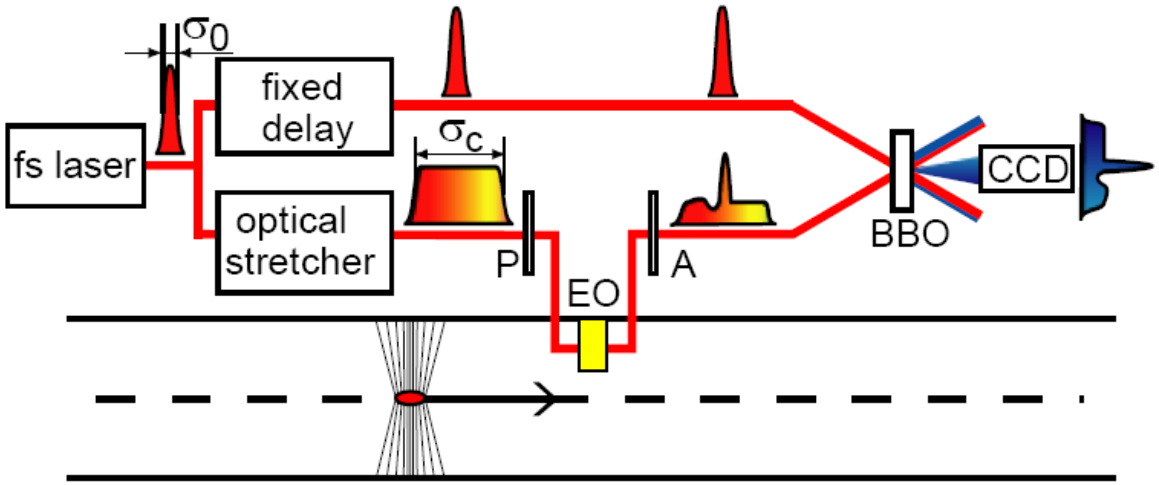
    $\Rightarrow$ Distortions at large chirp $\alpha \approx 1/\sqrt{\sigma_0 \sigma_c}$

$$\sigma_{\min} \approx 2.6\sqrt{\sigma_0 \sigma_c} \approx 200 \text{ fs}$$ (for Gaussian pulses!)

Bernd Steffen, FEL 07, Novosibirsk, August 2007

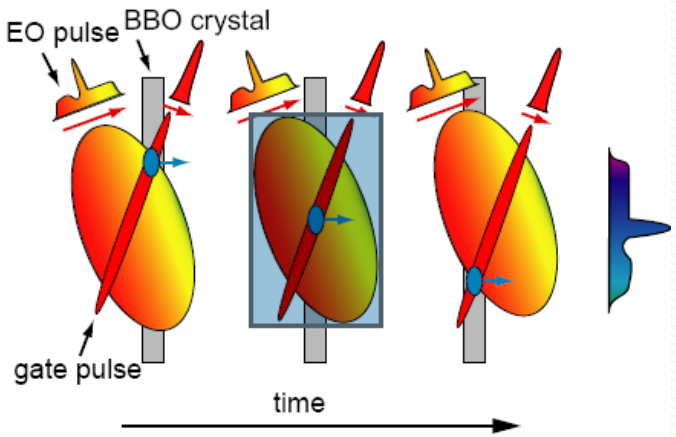
Time Domain

EO Temporal Detection



- Single shot cross-correlation with fs pulse in a frequency doubling crystal (BBO)

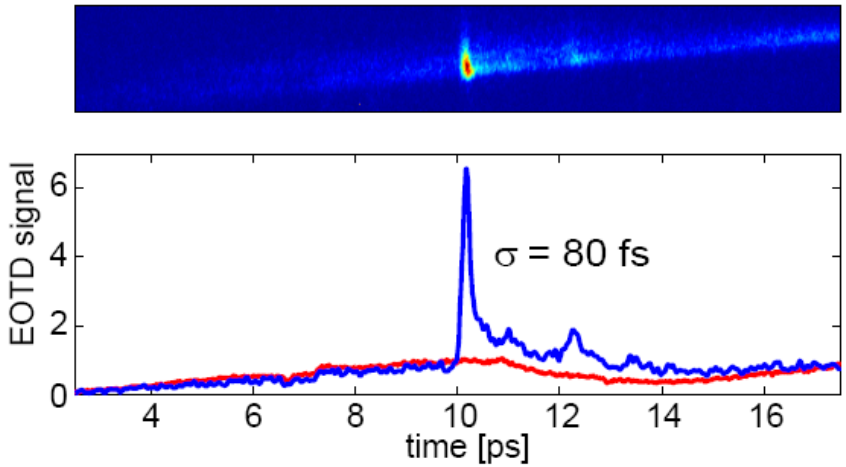
- approx. 100 μJ pulse energy necessary for 10 ps time window



Bernd Steffen, FEL 07, Novosibirsk, August 2007

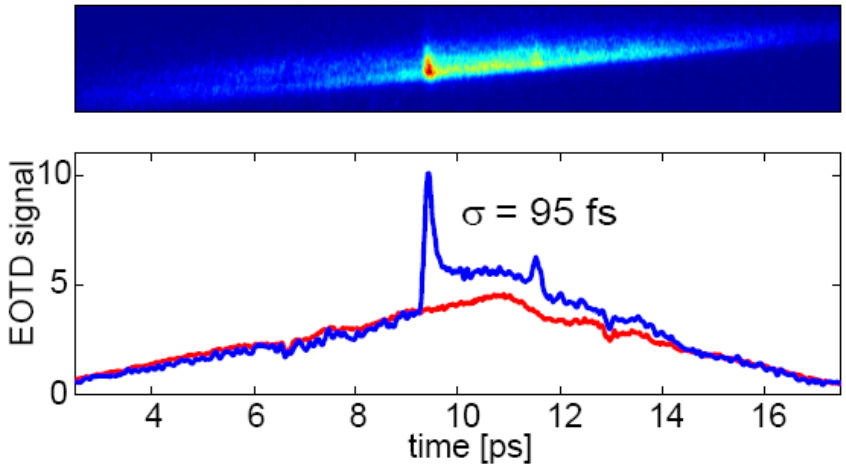
Time Domain

EO Temporal Detection



$\theta = 0$

EO signal $\propto \mathbf{E}^2_{\mathbf{Coul}}$



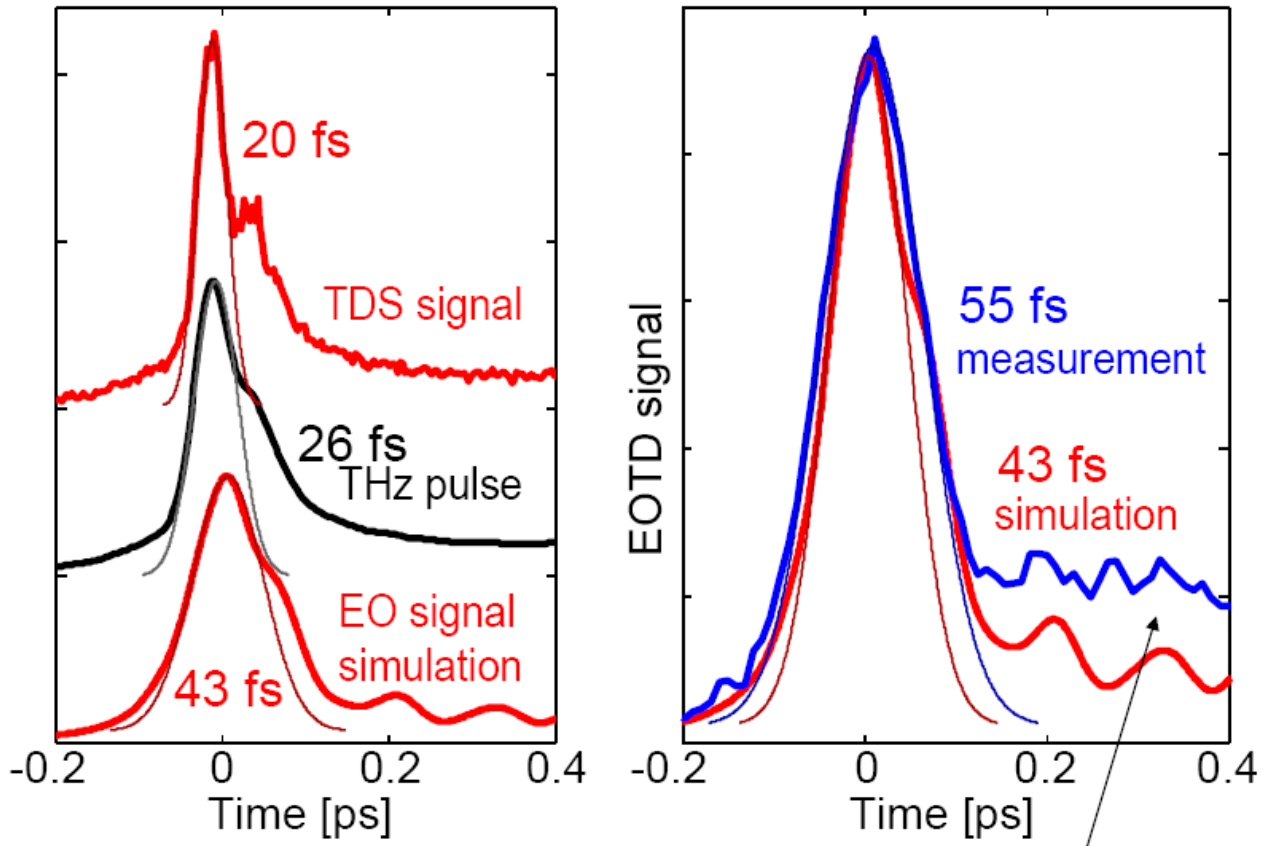
$\theta = 1°$

EO signal $\propto \mathbf{E}_{\mathbf{Coul}}$

Bernd Steffen, FEL07, Novosibirsk, August 2007

Time Domain

Comparison of EOTD vs. TDS measurements



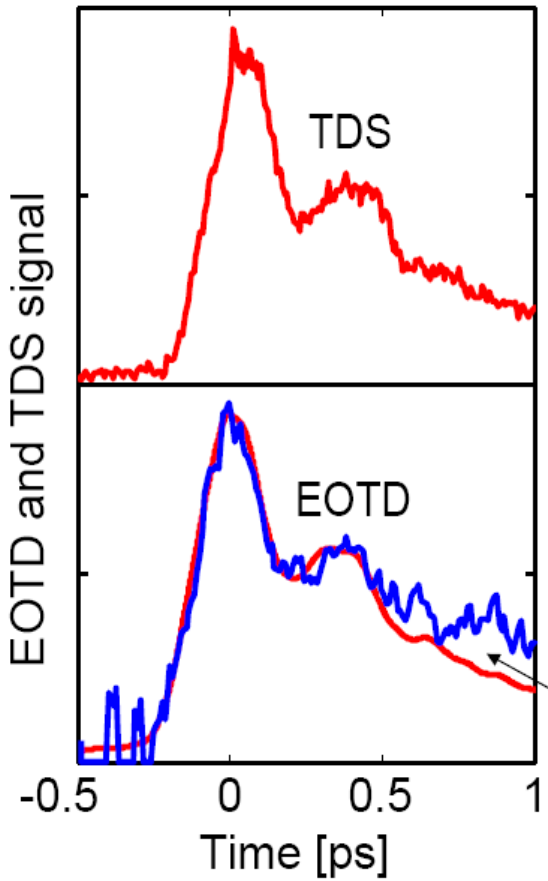
Signal due to wake fields

- **Good agreement between measurement and simulation**
- **close to the resolution limit of GaP**

Bernd Steffen, FEL07, Novosibirsk, August 2007

Time Domain

TDS and EOTD measurement of overcompressed bunches



In good agreement with the electron bunch shape

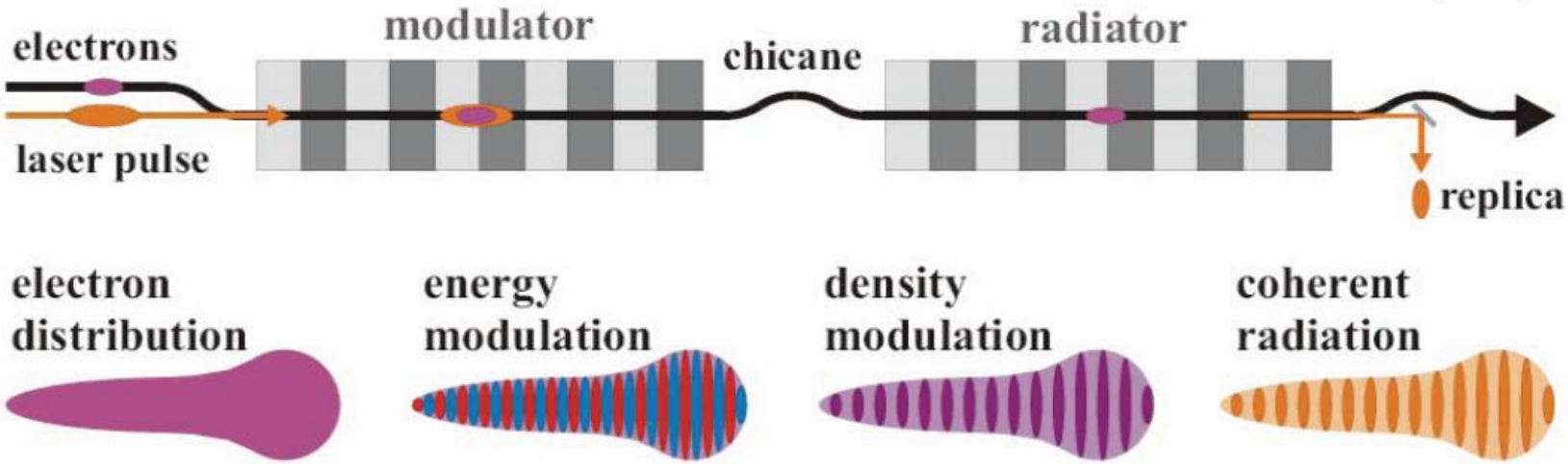
Signal due to wake fields?

Bernd Steffen, FEL07, Novosibirsk, August 2007

Diagnostics developments – time domain –

Optical replica synthesizer

SSY: Nucl. Inst. and Methods A 539 (2005) 499.



→ Parasitic, high resolution (10fs), single shot, longitudinal bunch profiling
→ Valuable experience for laser heater design

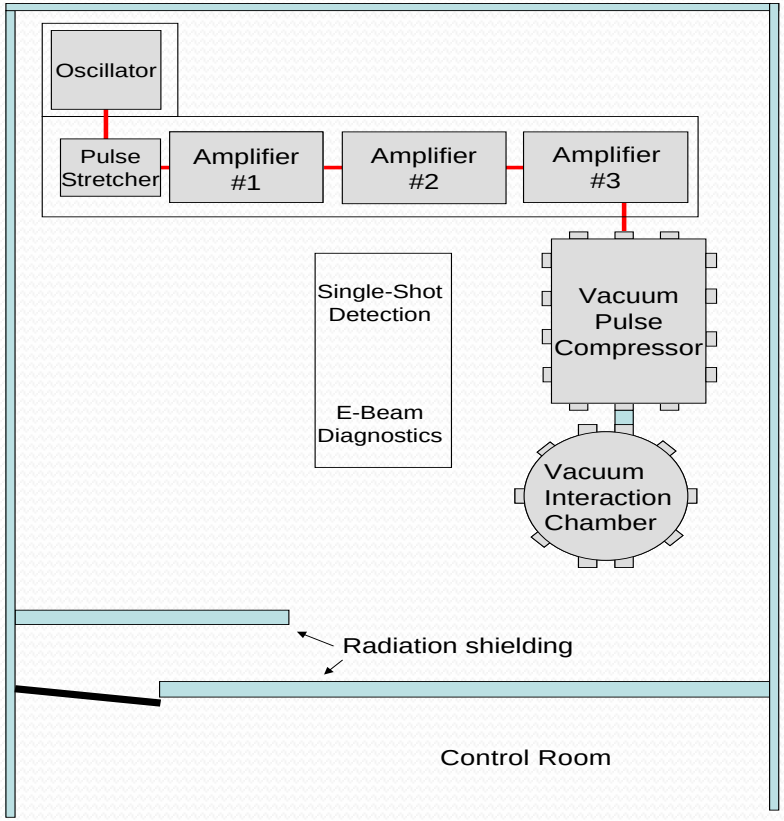
G. Angelova, V. Ziemann,
M. Hamberg, P. Salén, P. van der Meulen, M. Larsson,
S. Khan, J. Bödewadt, A. Winter,
A. Meseck,
E. Saldin, H. Schlarb, B. Schmidt, E. Schneidmiller, M. Yurkov,

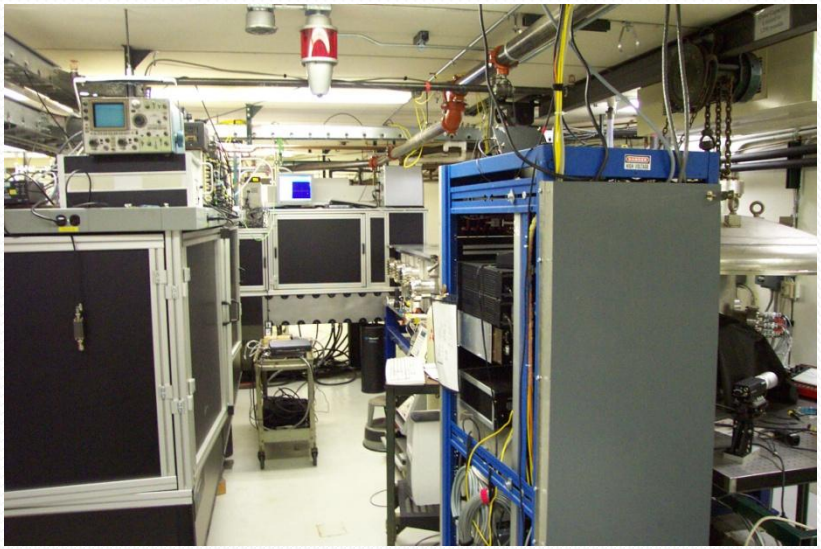
Uppsala Uni.,
Stockholm Uni.
Uni. Hamburg
BESSY
@DESY

H. Schlarb (DESY) talk

Terawatt Ultrafast High Field Facility (TUHFF)

- Ti:Sapphire oscillator with three amplifiers used.





TUHFF Laser Output

30fs, 0.6 J (20 TW) @ 10 Hz

Acknowledgments (Rob Crowell)

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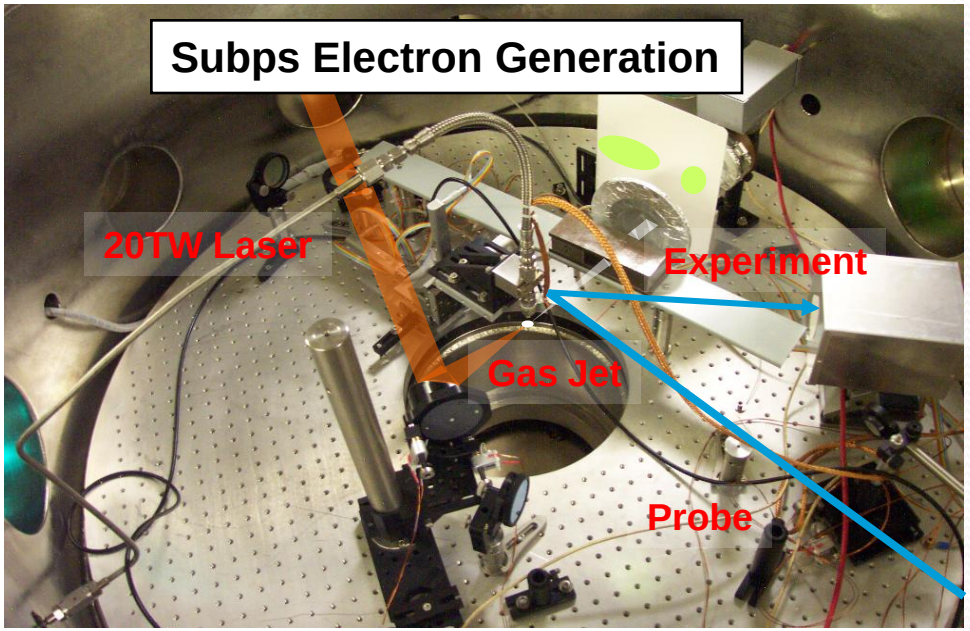
Chuck Jonah
Bob Lowers
Chris Elles
Tim Marin
Alex Lumpkin
Oleg Korovanko - Coherent
Roberto Rey-Castro - Princeton
Rui Lian – Coherent
Dmitri Oulianov - Spectra



Collaborators

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Dave Bartels (NDRL)
Prof. Steve Bradforth (USC)
Prof. Don Umstadter (U. Mich./Nebraska)
Prof. Christoph Rose-Petruck (Brown)
Prof. John Cary (U. Colorado, Tech-X)
Stanislas Pommeret (CEA/Saclay)

Towards sub-ps Electron Beams

Nature 431, Sept. 2004

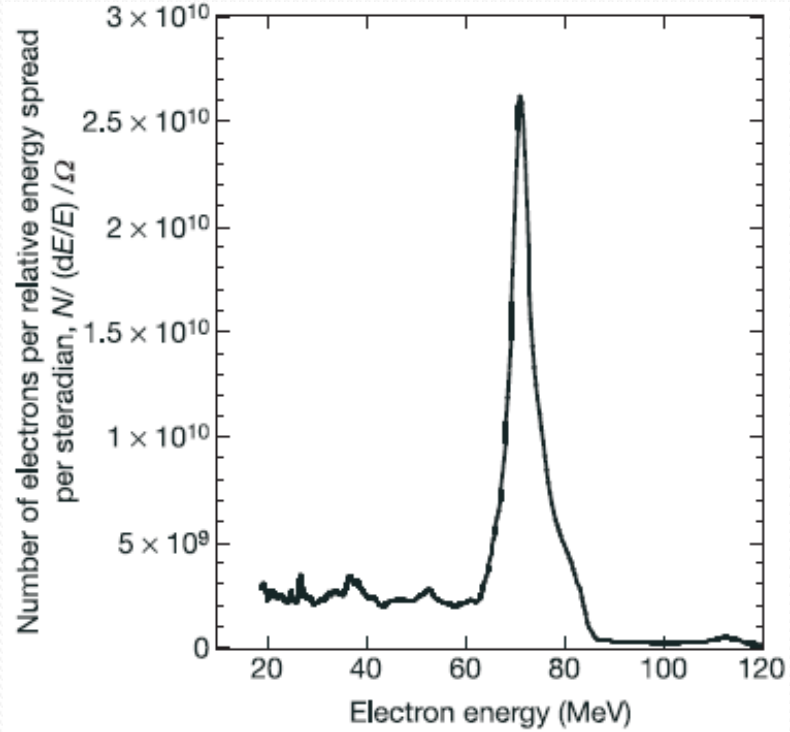
news and views

Electrons hang ten on laser wake

Thomas Katsouleas

Electrons can be accelerated by making them surf a laser-driven plasma wave. High acceleration rates, and now the production of well-populated, high-quality beams, signal the potential of this table-top technology.

TIME LIFE PICTURES/GETTY IMAGES

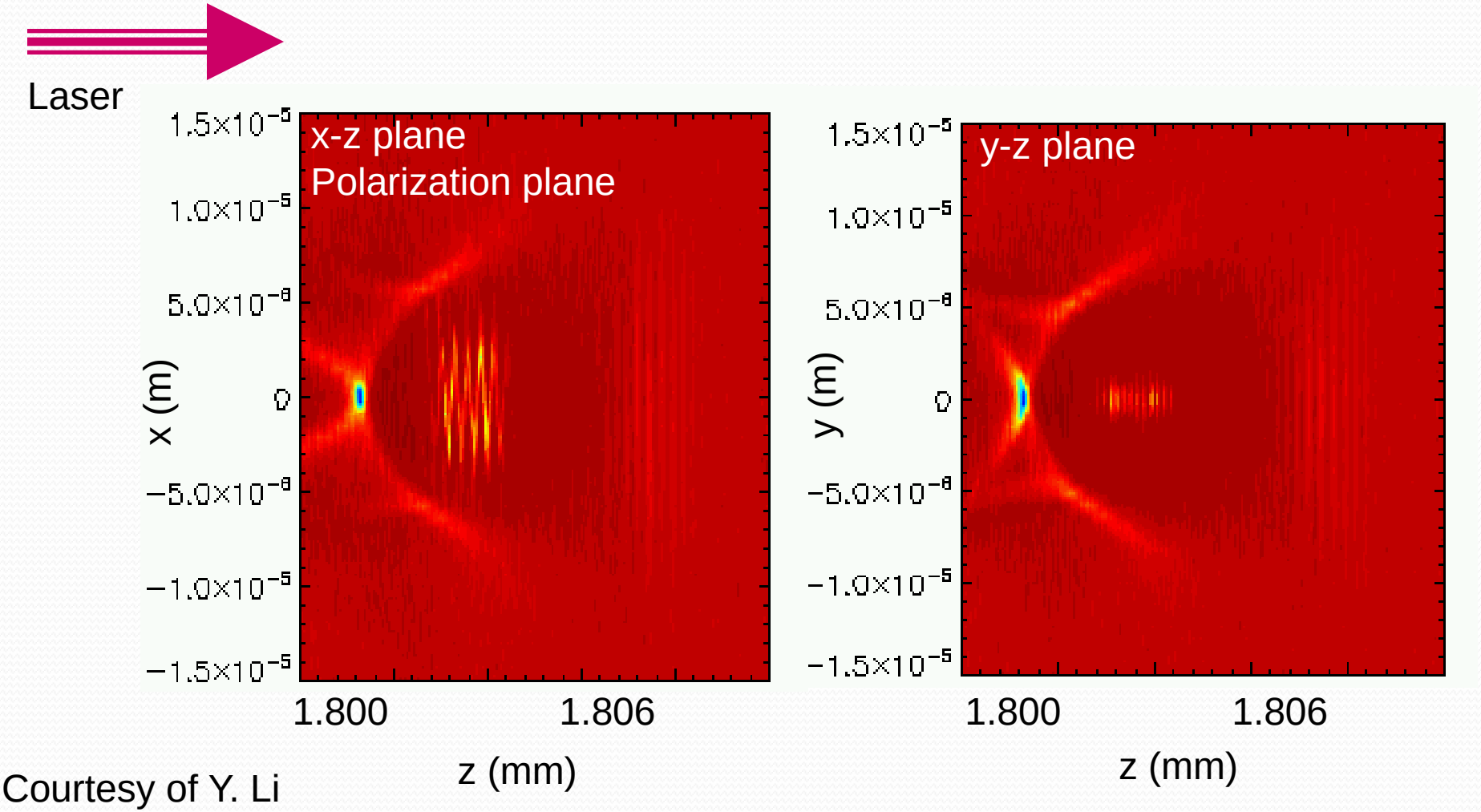


S.P.D. Mangles et al. Nature 431, 535 (2004) Strath.
C.G.R. Geddes et al. Nature 431, 538 (2004) LBNL
J. Faure et al. Nature 431, 541 (2004) LOA

Estimated τ~ 10 fs
Low divergence

Physics is very complicated and must be understood to optimize LWA
For reliable quasimonochromatic electron beam generation

Laser Modulation of the Beam Structure in the Bubble



Courtesy of Y. Li

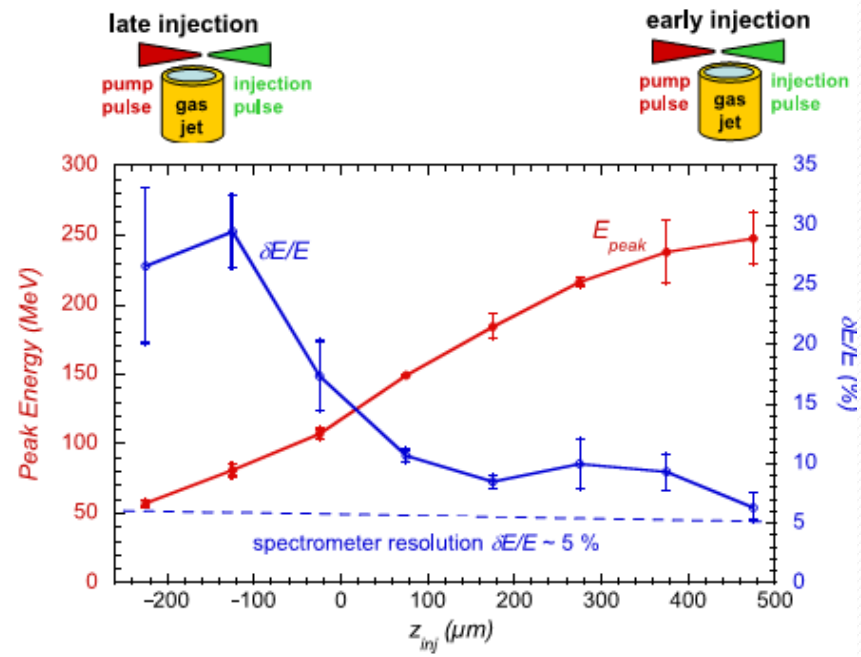
Injection Technique Provides More Reproducible Performance and Energy Tuning

- 20-shot statistics tabulated.
- Energy tuning by adjustment of injection timing.

Table 1: Statistics of the electron beam parameters over 20 shots.

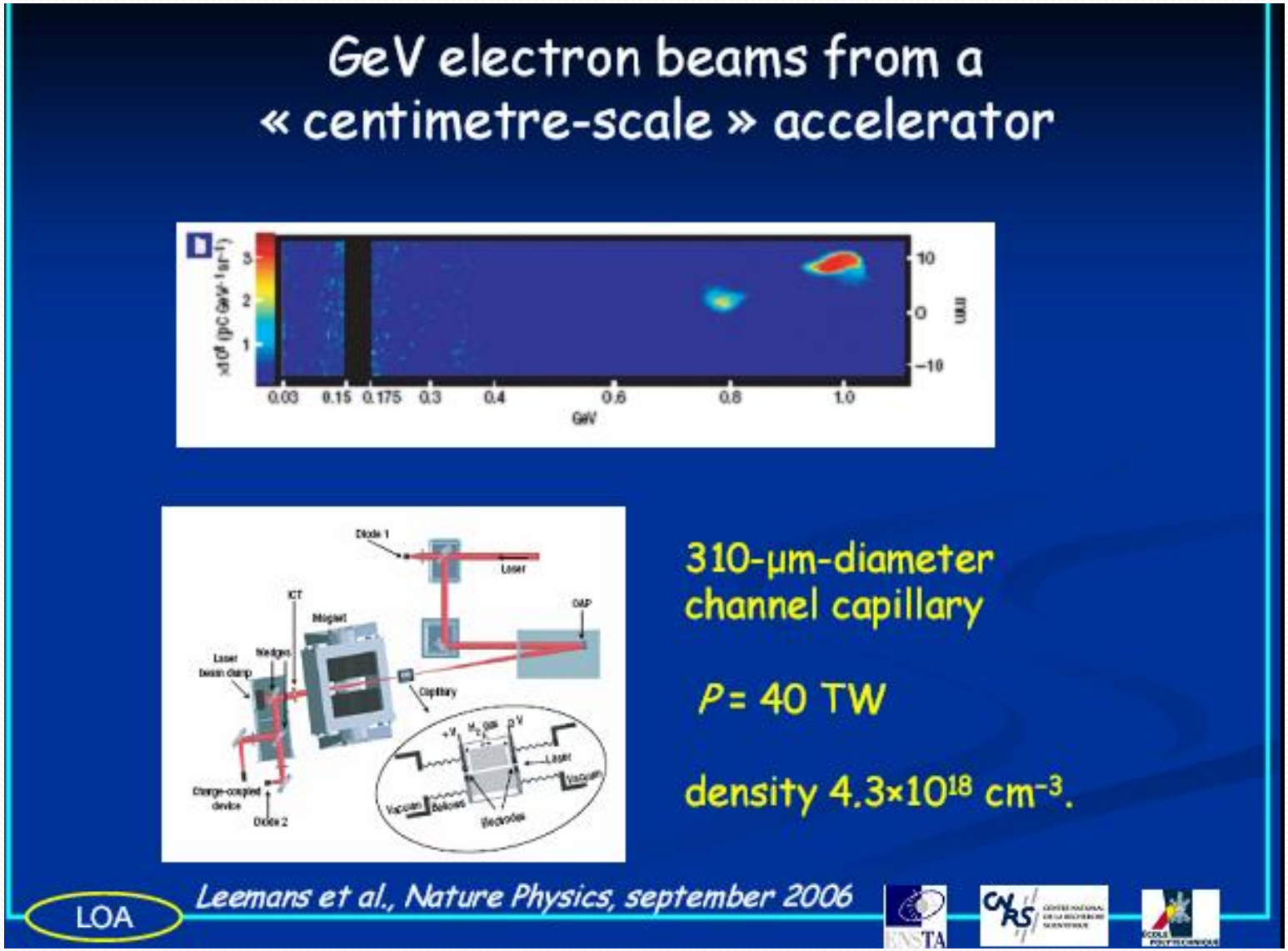
<Peak energy>*	$\sigma_{Peak energy}$	<Energy spread>	$\sigma_{Energy spread}$
117 MeV	7 MeV	11 % (FWHM)	2 %
<Charge>	σ_{Charge}	<Divergence FWHM>	$\sigma_{Beam pointing}$
19 pC	6.8 pC	5.8 mrad	1.8 mrad

*<X> refers to the mean value of X and σ_X to the standard deviation of X.



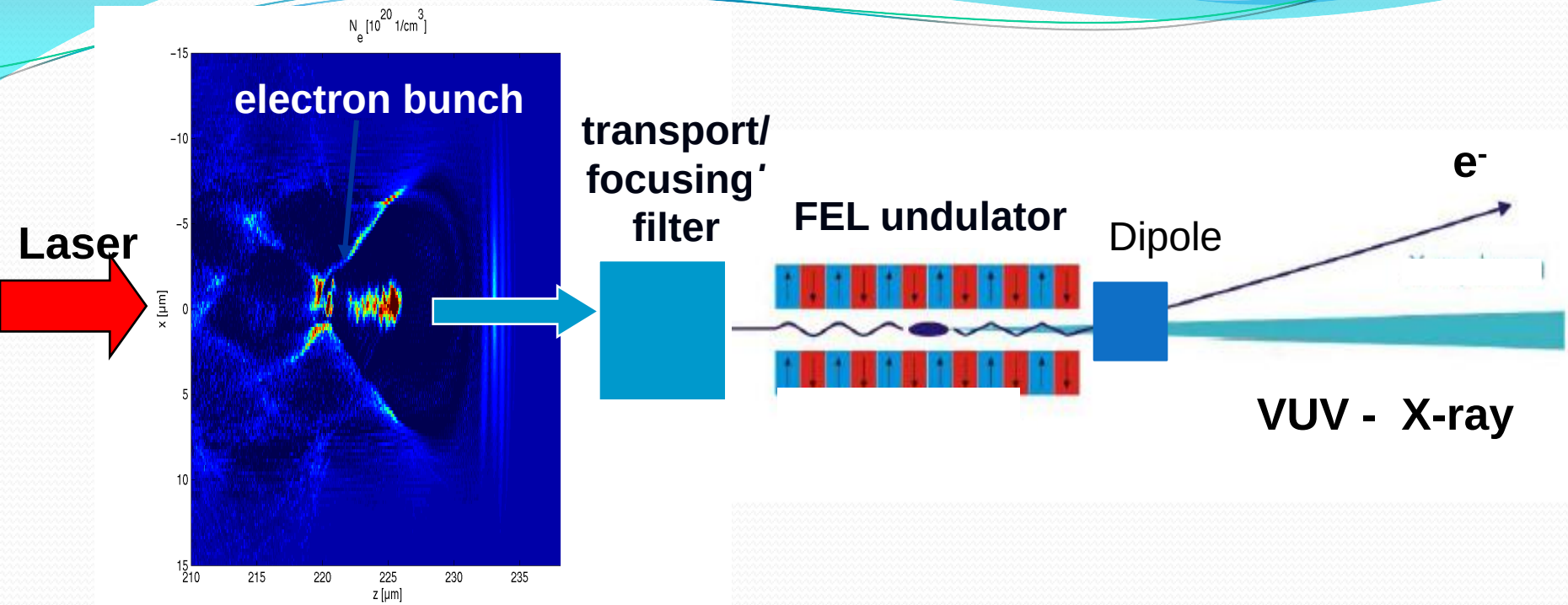
J.Faure et al., Nature, 2006

- LBNL LOASIS Experiments Attain 1 GeV



Courtesy of V. Malka

TUHFF as an Ultrafast x-ray/VUV Source



- **X-ray absorption, scattering studies of solvent structure and dynamics**
- **VUV (1-photon) probing of excited states**

Several New SASE FEL Projects were Reported at Conference

- SPARX in Frascati, 1-2 GeV linac Italy
- FERMI at Elettra, seeded, 2 GeV linac Italy
- PSI 1-10 Angst., with more compact accelerator proposed,250-MeV Injector test funded Switzerland
- XFEL with 8-GeV linac at Spring-8 after SCSS success at 130 nm. Japan
- EUV SASE at Max Lab in Uppsala, Sweden
- PAL XFEL, injector linac, Korea
- BESSY, HGHG demo first Germany
- 4GLS at Daresbury, injector prototype, ERL England
- Arc-en-Ciel, SC linac SASE proposal France

PSI Strategy for Low Cost XFEL

7

Project Realization Strategy

Development of the critical technology

- low emittance electron source
- high voltage generation and high gradient acceleration
- two-frequency cavity for bunch compression

→ ongoing

Experimental verification of this technology

- Construction of a high voltage and high gradient facility
- Construction of a 250 MeV injector facility

→ 2008-2011

Construction of an X-FEL

- FEL-3 / 10 nm - 1 nm
- FEL-2 / 1 nm - 0.3 nm
- FEL-1 / 0.3 - 0.1 nm

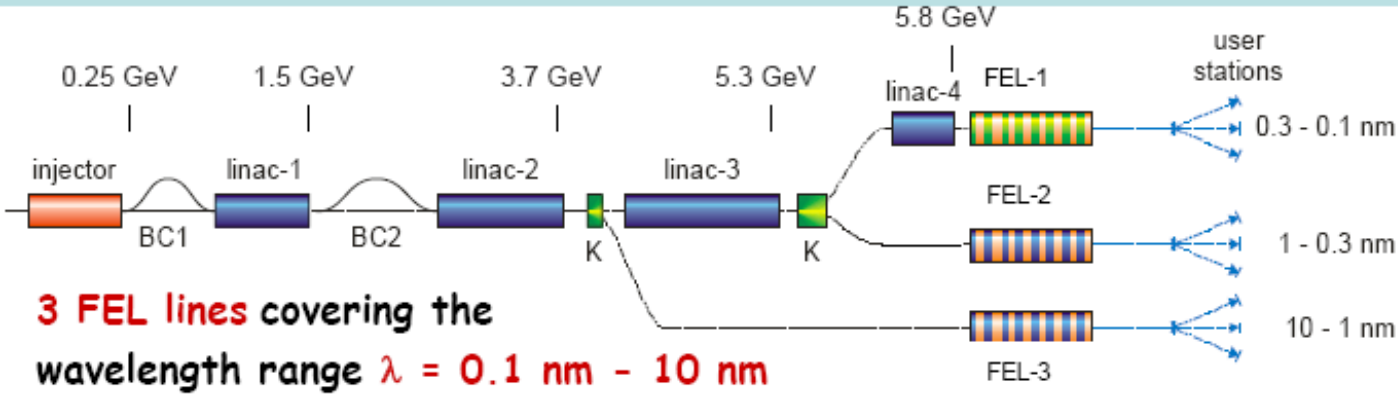
→ development after successful demonstration of the low emittance accelerator concept (2011-2016)

A. Oppelt (PSI) talk

Innovations to Reduce Cost of XFEL

3

Proposed layout of the PSI-XFEL



3 FEL lines covering the wavelength range λ = 0.1 nm - 10 nm

XFEL Parameters:

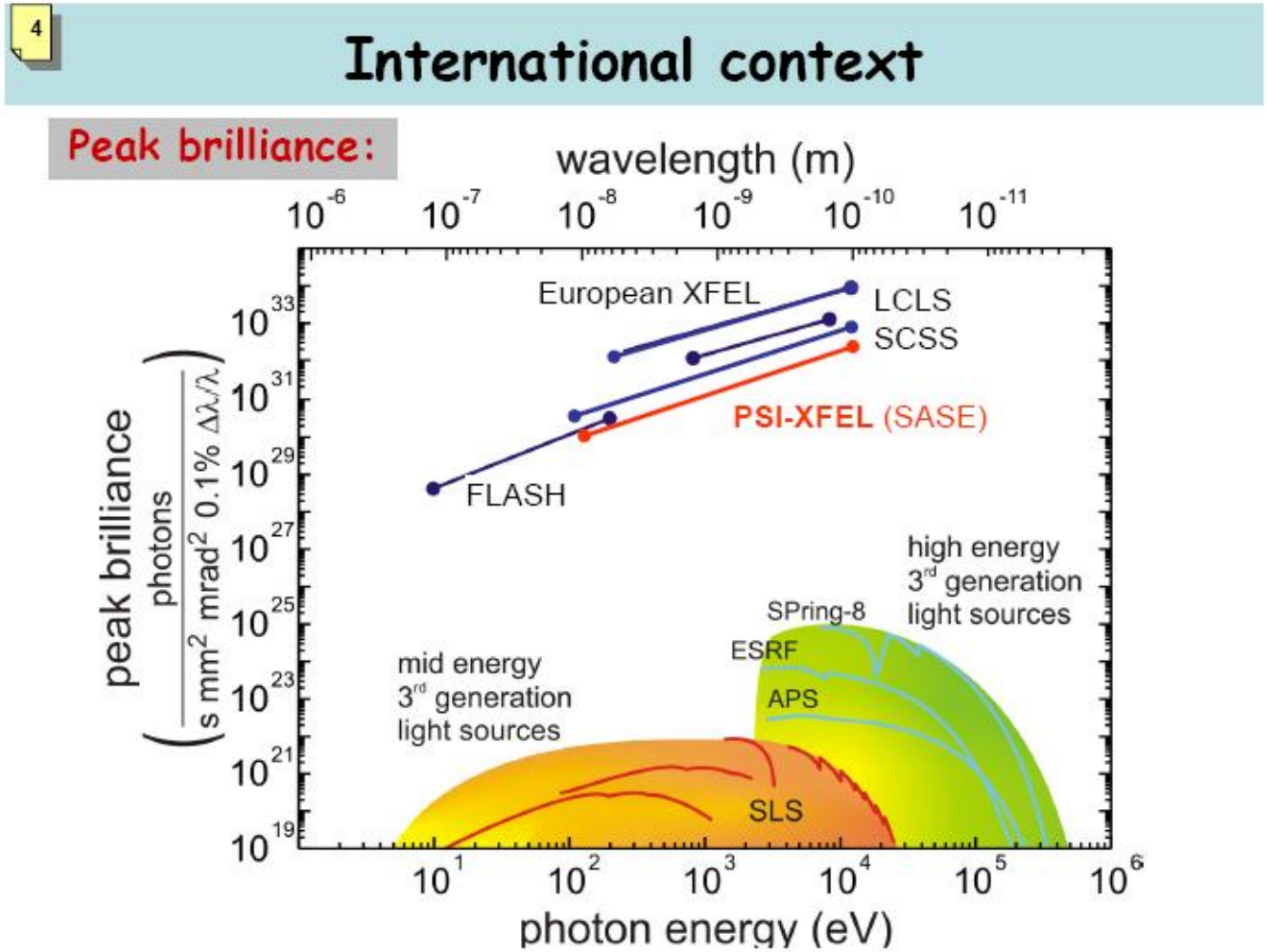
Target values @ undulator entrance (5.8 GeV, Q= 200 pC)

peak current	1.5 kA
slice emittance	0.2 mm mrad (rms)*
energy spread	10^{-4}
undulator length	30 m
undulator period	15 mm

* 1pC slice

A.Oppelt (PSI) talk

Worldwide Interest in Ultrafast Light Sources Growing



A. Oppelt (PSI) talk

EUV and Soft x-ray Regime Attainable with GeV-Class Linac

- Estimate with APS SASE FEL Undulator Parameters

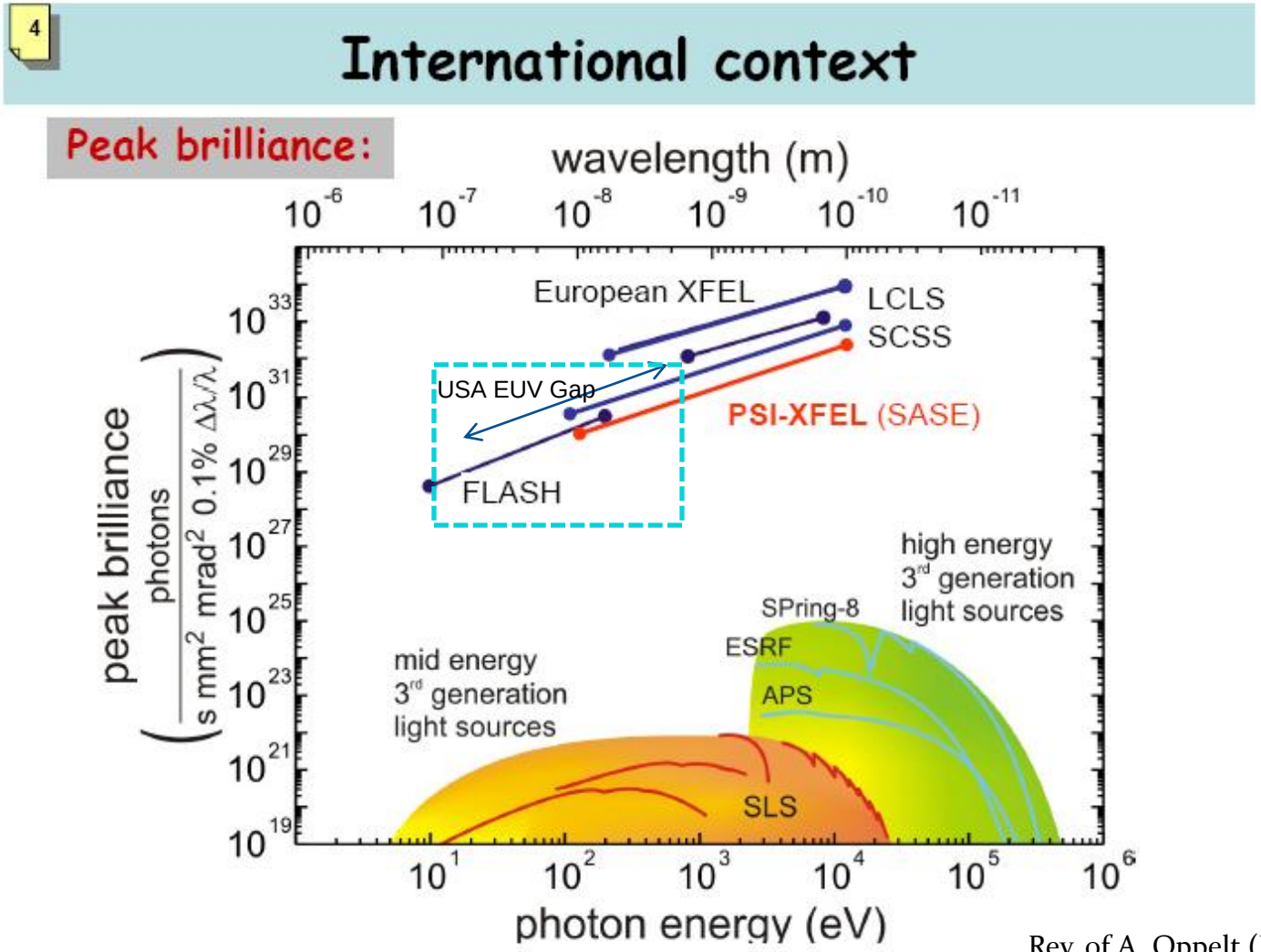
Energy (GeV)	Facility	Harmonic No.	Wavelength (nm)
0.220	APS	1	540
0.408	APS	1	157
0.570	NML	1	80
0.750	NML	1	46
1.000	NML	1	26
1.500	NML	1	12
1.500	NML	3	4

FEL Performance Estimates Done with Ming Xie Formulas (Proc. of PAC'95)

- Base case: ε=2 π mm mrad, I_{pk} =1 kA, β = 5m
- *Extra case: ε=1.5 π mm mrad, I_{pk} =2 kA, β = 5m

Gamma	Lambda (nm)	3D Gain Length(m)	Saturated Length(m)	Natural Beta (m)	Saturated Power(GW)
430	540	0.29	6.8	1.00	1.4
798	157	0.45	10.0	1.86	1.6
1115	80	0.58	12.8	2.60	1.7
1467	46	0.71	15.7	3.44	1.7
1957	26	0.95	20.0	4.58	1.6
2935	12	1.46	29.6	6.71	1.3
2935*	12	0.83	17.6	6.7	5.9

USA Needs EUV-Soft x-ray Source



Rev. of A. Oppelt (PSI) VG

ILC is the Next Technology Driver for Diagnostics after XFEL

- XFELs have served as technology driver over last 4-5 years. Significant progress on photoinjectors, SC rf, EO sampling, and facility-wide synchronization has occurred.
- The ultra short bunches of XFELs are not in ILC, but the NI aspect is common and synchronization specs are tight.
- It would be hoped that ILC can be a technology driver for synchronization of rf or diagnostics over km scale, monitoring of high-power beam position (cavity BPM) and size (ODR) in a nonintercepting manner, EO bunch length/phase monitors, beam parameters at the IP, beam dynamics in damping rings, etc. as well as SC rf.

EUV/Soft X-ray FEL Provides a Complementary Technology Push

- Need to preserve emittance in chicanes.
- Requires high peak currents and much shorter pulses (100 fs or shorter).
- Synchronization specs are tighter than ILC if seeding.
- Photon diagnostics need development, z-dependent.
- Diagnostics undulator for divergence, optical replica synthesizer for bunch length.
- Z-dependent intra-undulator diagnostics of SASE-induced microbunching (challenge).