ICFA Workshop on Future Light Sources, Hamburg, May 15-19th, 2006

Short Radiation Pulses from Storage Rings

Shaukat Khan, University of Hamburg

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1) Reduction of electron bunch length

- **(a) low momentum-compaction factor**
- **(b) high radiofrequency gradients**

2) Longitudinal-transverse correlation

- **(a) radiofrequency orbit deflection**
- **(b) femtosecond-laser slicing**

1) Reduction of the electron bunch length

random quantum emission ↔ radiation damping

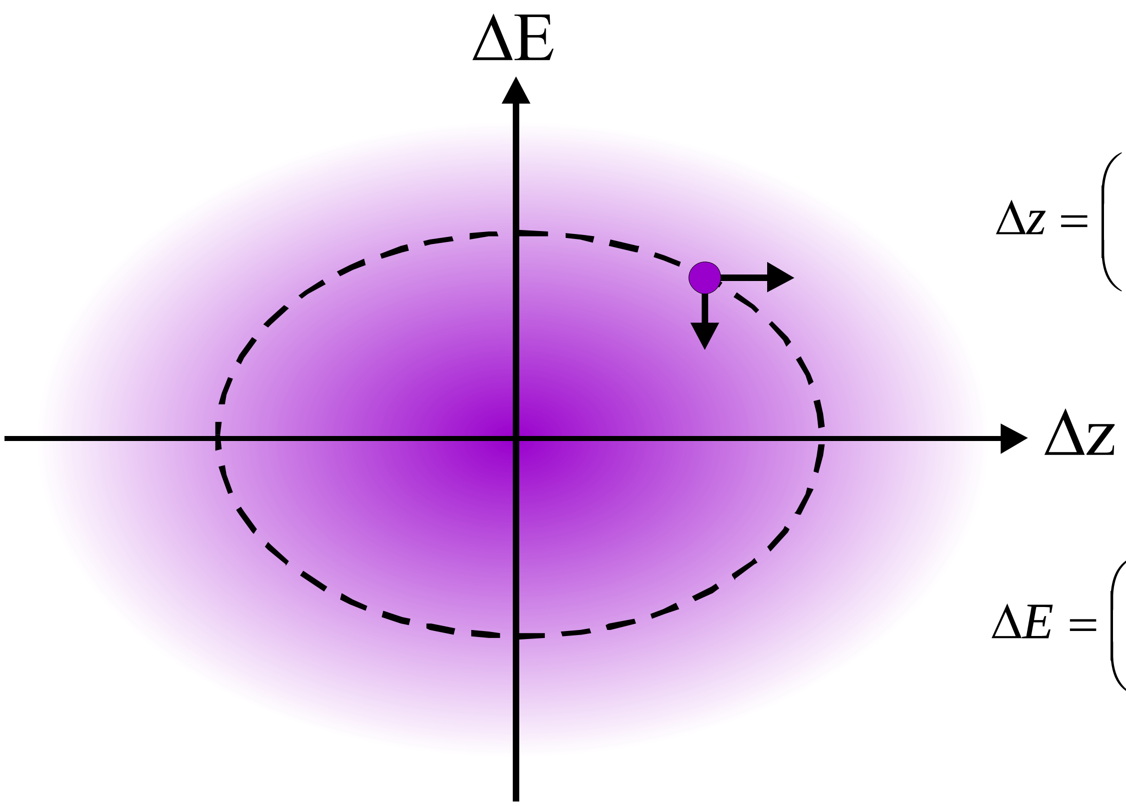
$$\sigma_{\Delta E/E} \sim E_o \sqrt{\frac{\langle 1/R^3 \rangle}{\langle 1/R^2 \rangle}}$$

→ **natural energy spread**

→ **natural bunch length**

→ **current dependent effects** **(i) potential-well distortion**

(ii) bunch-lengthening instability



$$\Delta z = \left(\alpha \frac{L_o}{E_o} \right) \cdot \Delta E$$

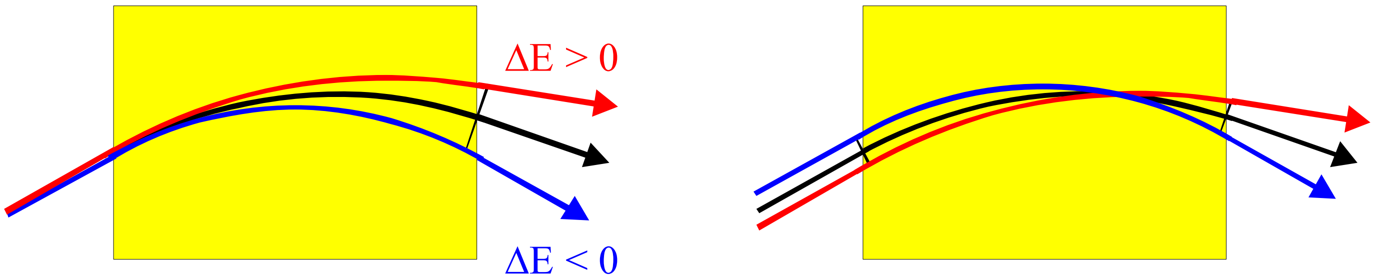
$$\Delta E = \left(e \frac{dV_{rf}}{dt} \right) \cdot \Delta t$$

1) Reduction of the electron bunch length

(given: beam energy, circumference, energy spread)

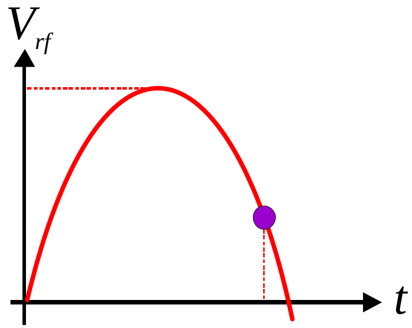
(a) low momentum-compaction factor

$$\alpha \equiv \frac{\Delta L / L_o}{\Delta E / E_o} \approx \frac{1}{L_o} \oint \frac{D(s)}{R(s)} ds$$



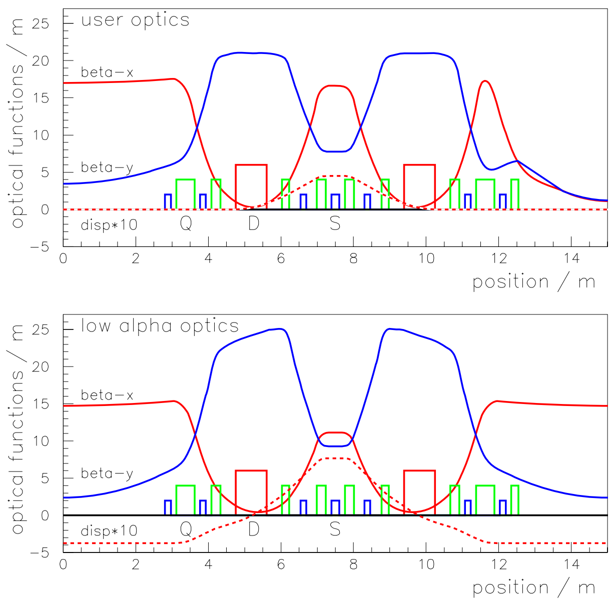
(b) high gradient of the rf voltage

$$\frac{dV_{rf}}{dt} = \hat{V}_{rf}\,\omega_{rf} \cos\phi_s$$



- optimum synchronous phase
- high voltage amplitude
- high frequency
- or: non-sinusoidal shape

the machine optics



main parameters

optics parameter	reg.user optics	low alpha optics
circumference / m	240	240
number of cells	2x8	16
nom. Energy / GeV	1.7	1.7
tunes Qx / Qy	17.8 / 6.7	14.7 / 6.2
nat. chrom ξx / ξy	-53 / -27	-35 / -27
nat. emitt / nmrad	6	30
synchr. freq. / kHz	7.5	7.5 … 0.35
mom. com. factor α	7.2E-4	7E-4 …1E-6 plus & minus
nat. bunch length rms / ps	12	12 … 0.7

4 sextuple families for beam dynamics corrections

short bunches by low α manipulation
$\alpha^2 \sim$ fs = control value

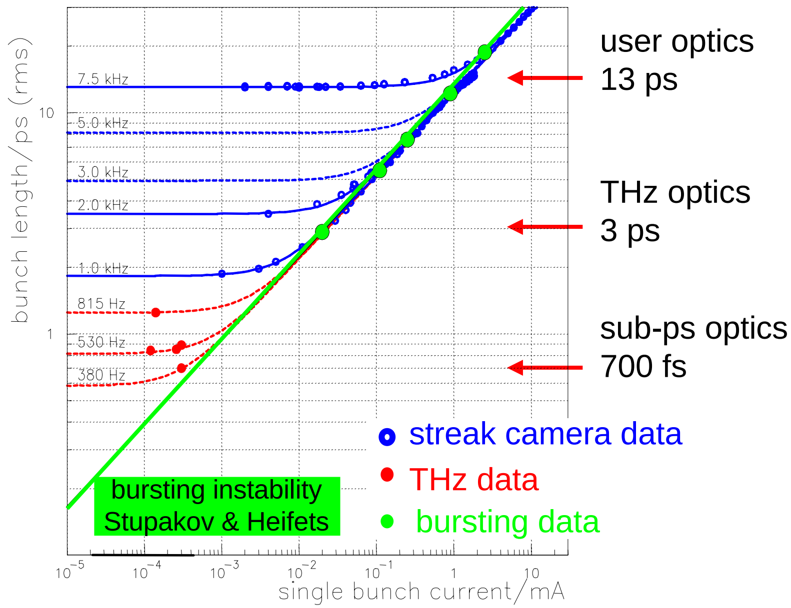
single & multi bunch
1.25 MHz to 500 MHz
10 µA < I< 0.1 mA
(2mA~10^{10}electrons)

very stable machine operation, good life time
20 mA and 20 hours

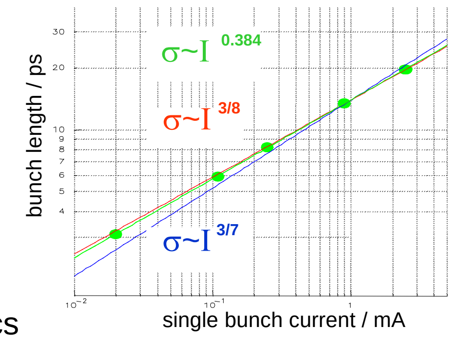
application: coherent THz radiation, ICFA No. 35, article by U. Schade et al.
short x-ray pulses at BESSY, accepted PRL, A. Krasyuk et al., 2005

Bunch length and current relation

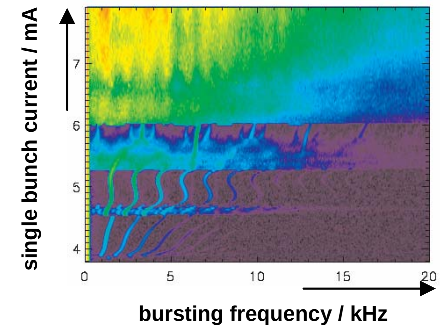
bunch length - current relation



bursting data



temporal emission spectrum of CSR bursts (user optics)



scaling relation between bunch length σ, synchrotron frequency f and current I:

$$(\sigma / \sigma_0)^4 = (f / f_0)^4 + (I / I_0)^{3/2}$$

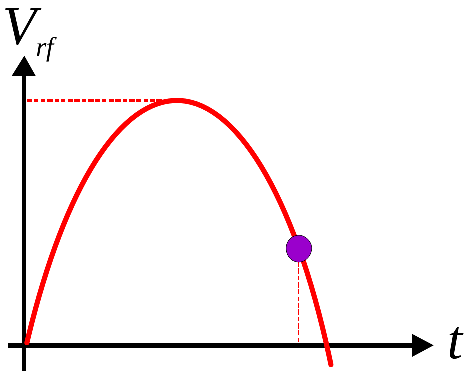
results from bursting threshold:

- eff. / natural bunch length $\sigma/\sigma_0 = 1.5$
- eff. bunch length · unstable mode $\sigma k_i = 2\pi\sigma/\lambda_i = 5$
- bunch length ~ current relation $\sigma \sim I^a$

  a=3/8 from experiments, a=3/7 from theory

(b) High rf voltage gradient

- *optimum synchronous phase*
- *high rf voltage*
- *high frequency*
- *non-sinusoidal rf voltage*



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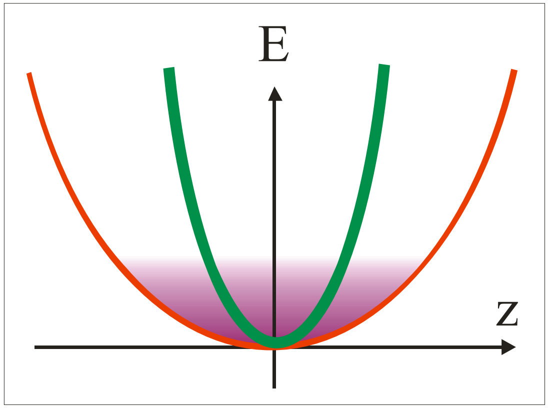

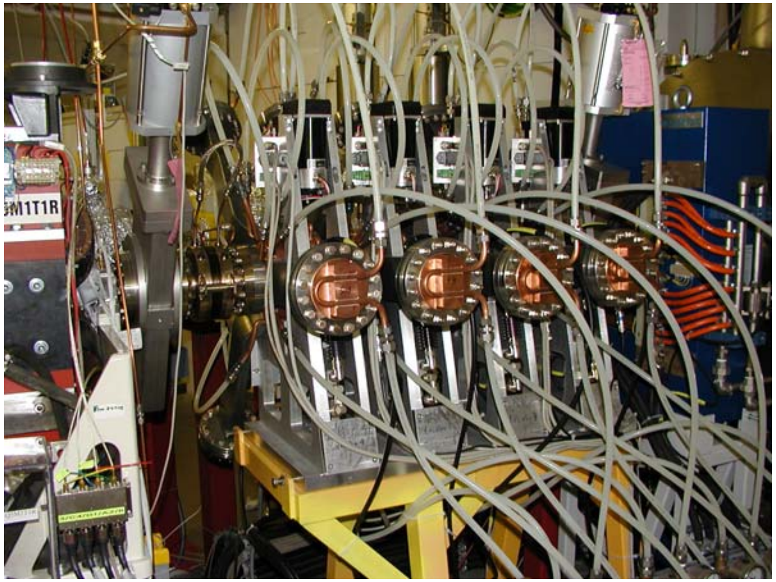

passive 3rd harmonic cavity at BESSY:
W. Anders, P. Kuske, PAC 2003 (Portland), 1186.

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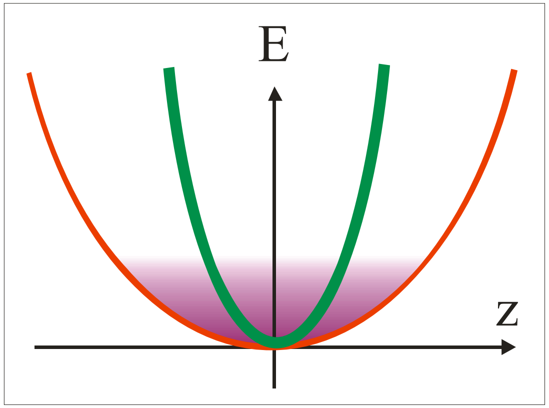
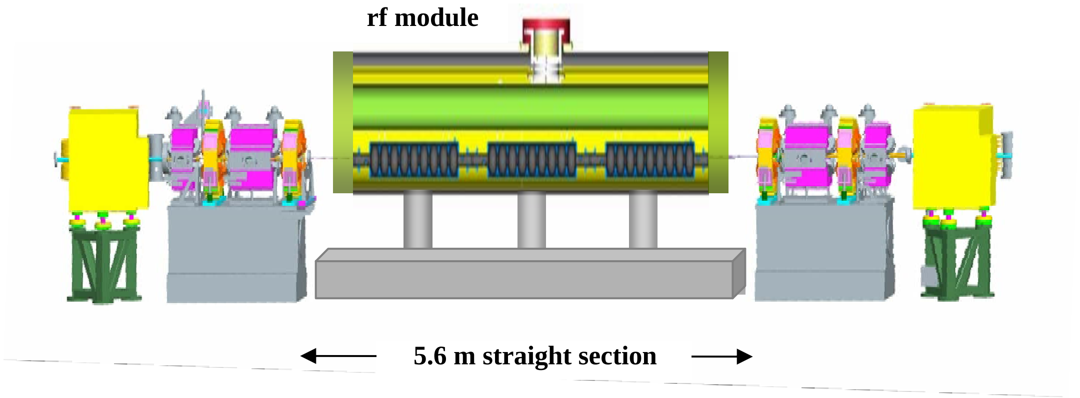




proposed 1.5 GHz superconducting rf structure
G. Wüstefeld, Short-Bunch Workshop, Nov 2005, Frascati

Upgrading of the rf-gradient

option for enhanced THz radiation and short X-ray pulses at BESSY II:

<u>upgrading the rf-gradient</u> by a 1.5 GHz, cw superconducting rf-structure placed into one straight ID-section

upgrading by a factor of 20
1000 x more THz power!

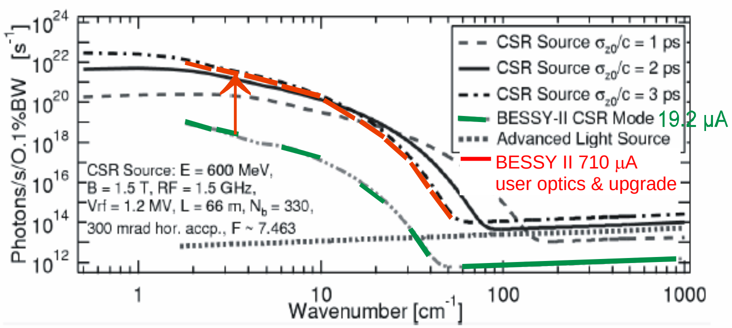
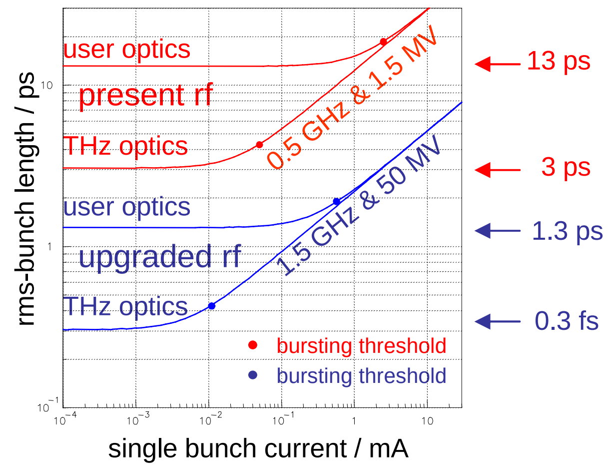


Figure 7. Example of source optimized for the CSR production using the criteria described in this paper. The photon flux is compared with the cases of a conventional SR source (ALS) and of BESSY II CSR mode with 400 bunches, 19.2 µA/bunch, σ_{z0}/c = 1.8 ps and 60 mrad horizontal acceptance..

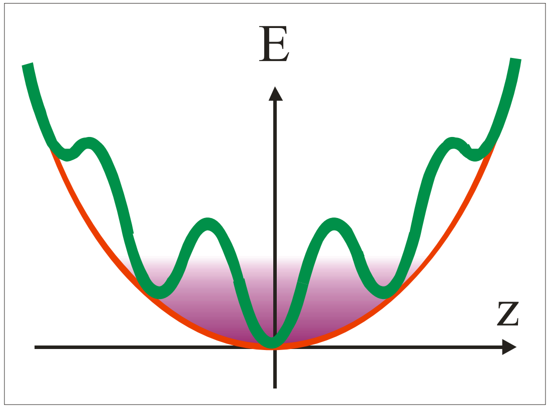
figure copied from F. Sannibale et al, ICFA Newsletter No. 35

upgrading by a factor of 100
sub-ps bunches!



applied scaling law for bursting threshold: $I \propto \sigma_z^{8/3} dV_{rf} / dz$

(b) High rf voltage gradient



- *optimum synchronous phase*
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- *high frequency*
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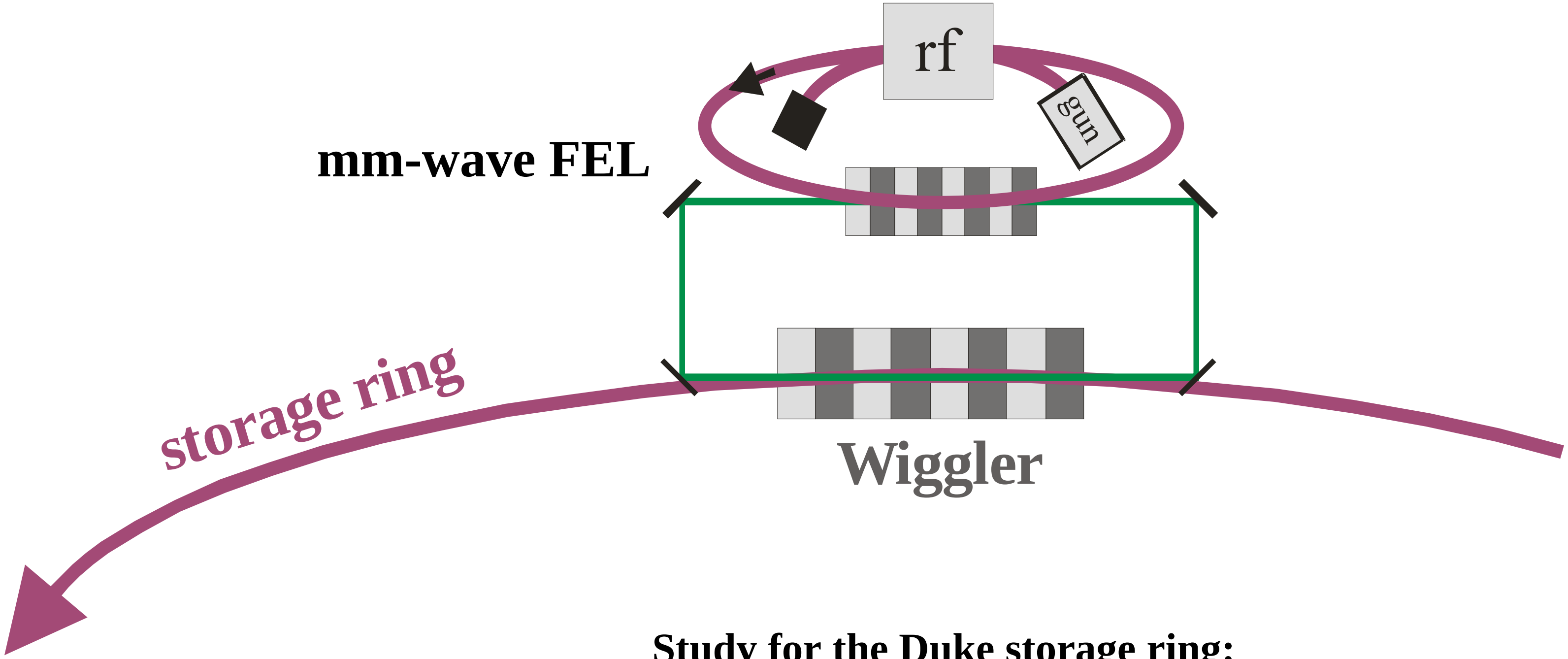
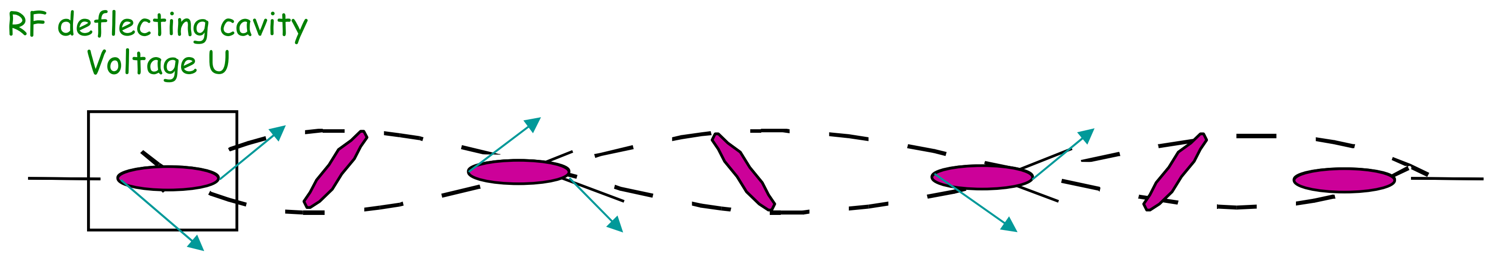


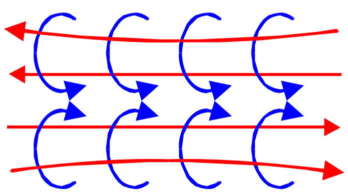
Study for the Duke storage ring:
V. Litvinenko et al., PAC 2001 (Chicago), 2614

2) Longitudinal-transverse correlation

(a) Rf orbit deflection using "crab" cavities [1]



TM_{110}



[1] A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, NIM A 425 (1999), 385

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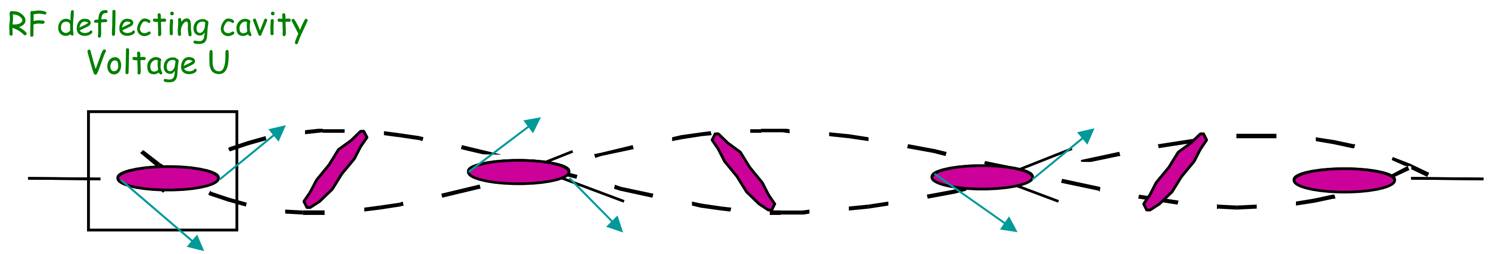
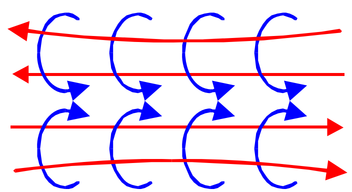
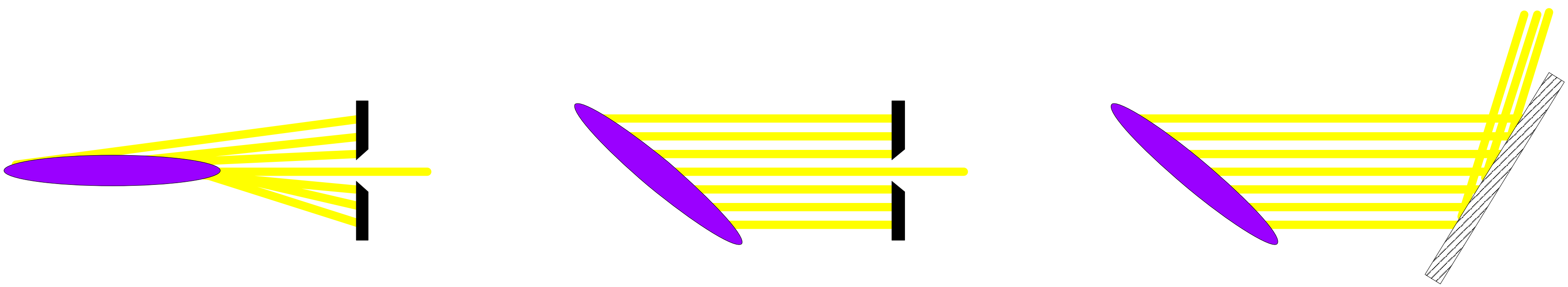


TM$_{110}$





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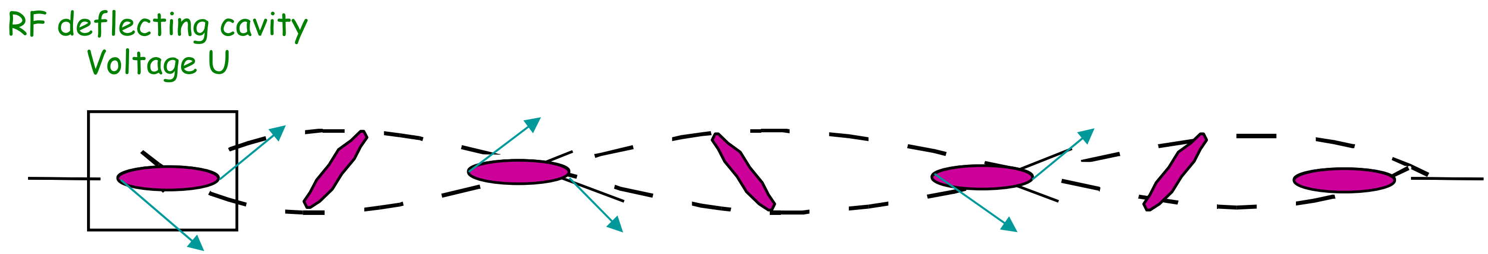

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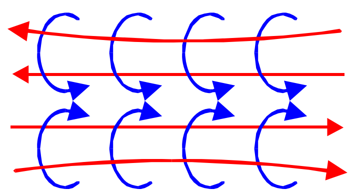


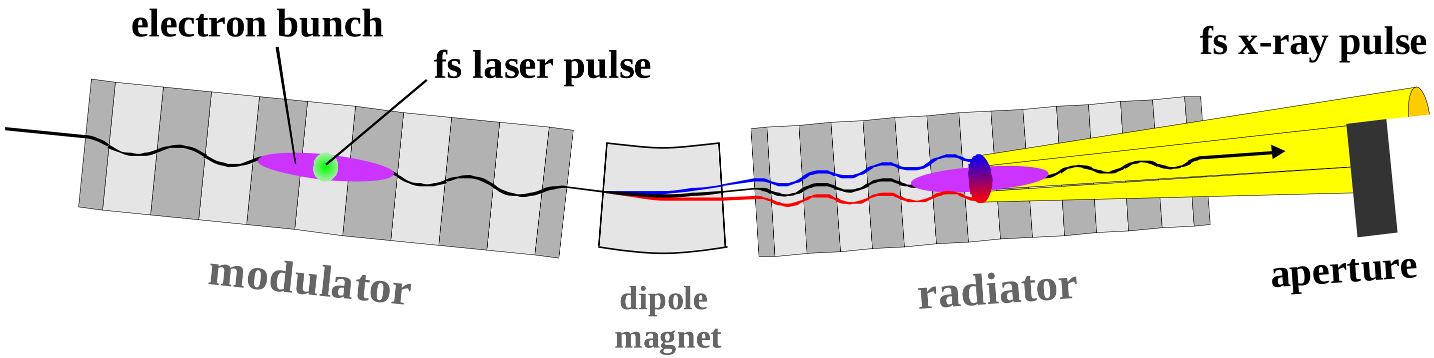
Extensive study for APS/Argonne [2]:

~ 1 ps resolution with 6 MV @ 2.8 GHz (h=8)

[1] A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, NIM A 425 (1999), 385
[2] M. Borland, PRST-AB 8 (2005), 074001

2) Longitudinal-transverse correlation

(b) Femtosecond laser slicing [1]



[1] A. A. Zholents, M. S. Zoloterev, PRL 76 (1996), 912.

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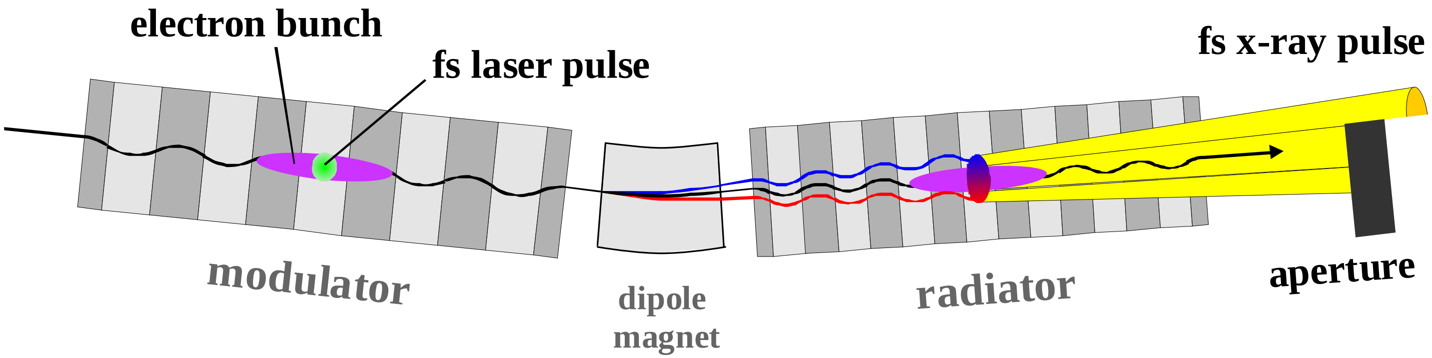

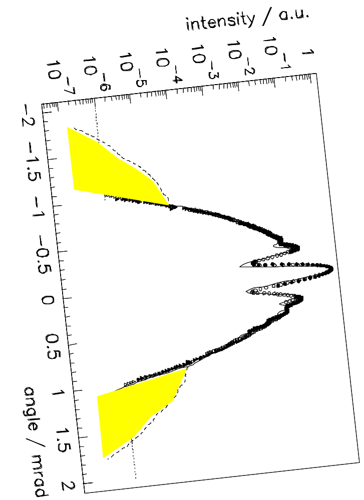

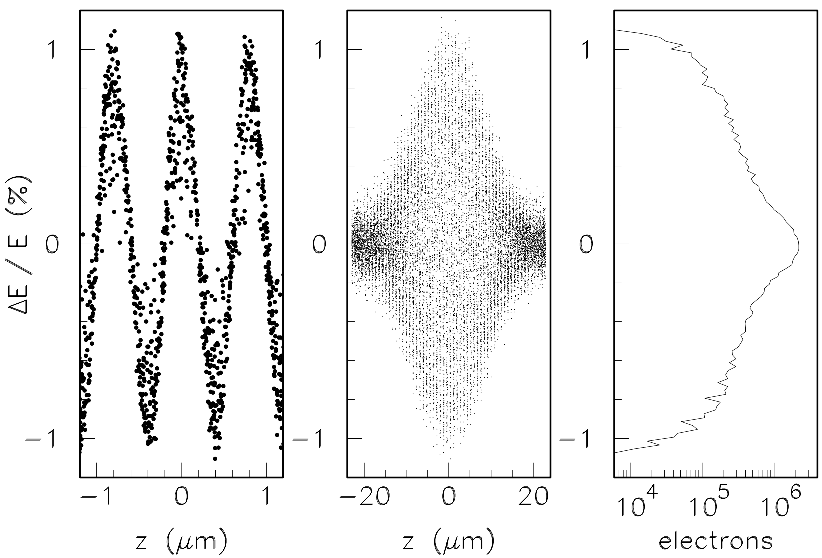

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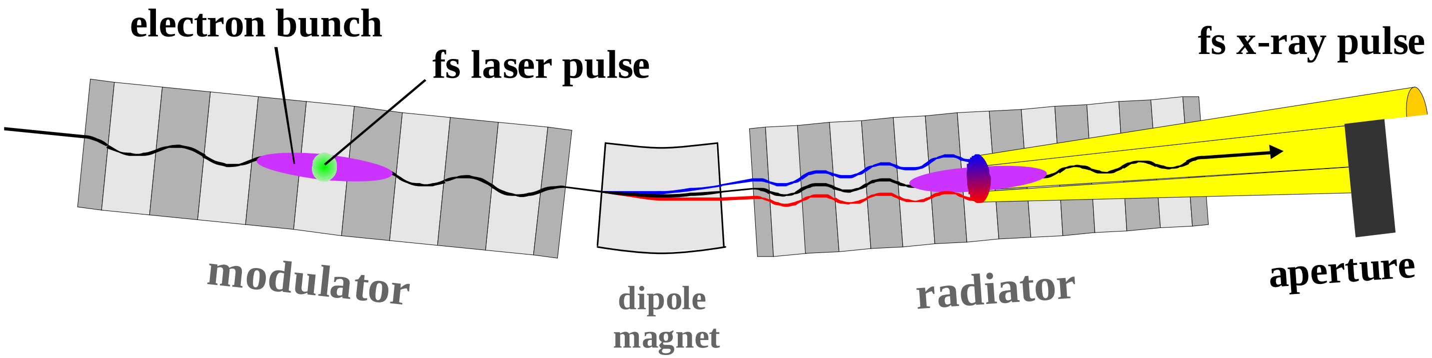
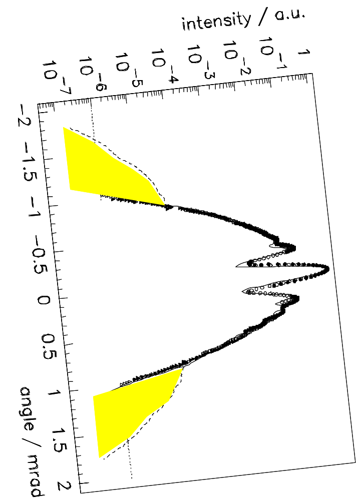
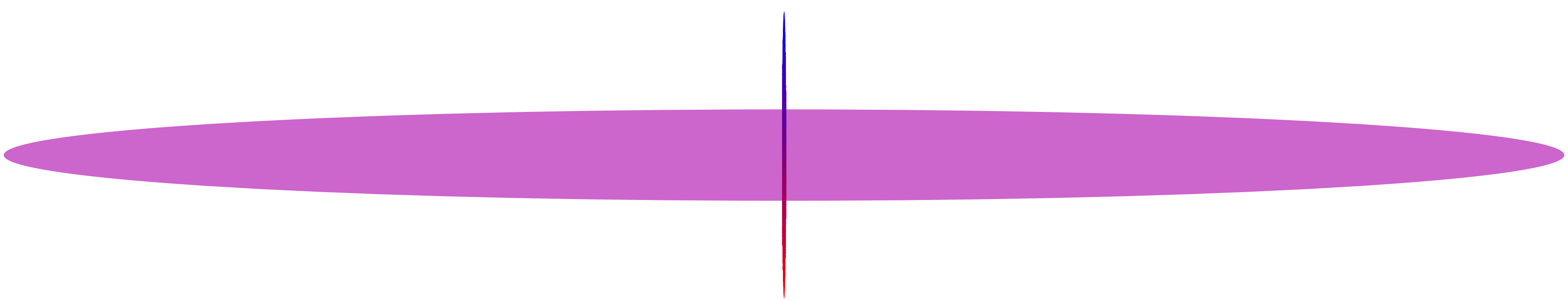
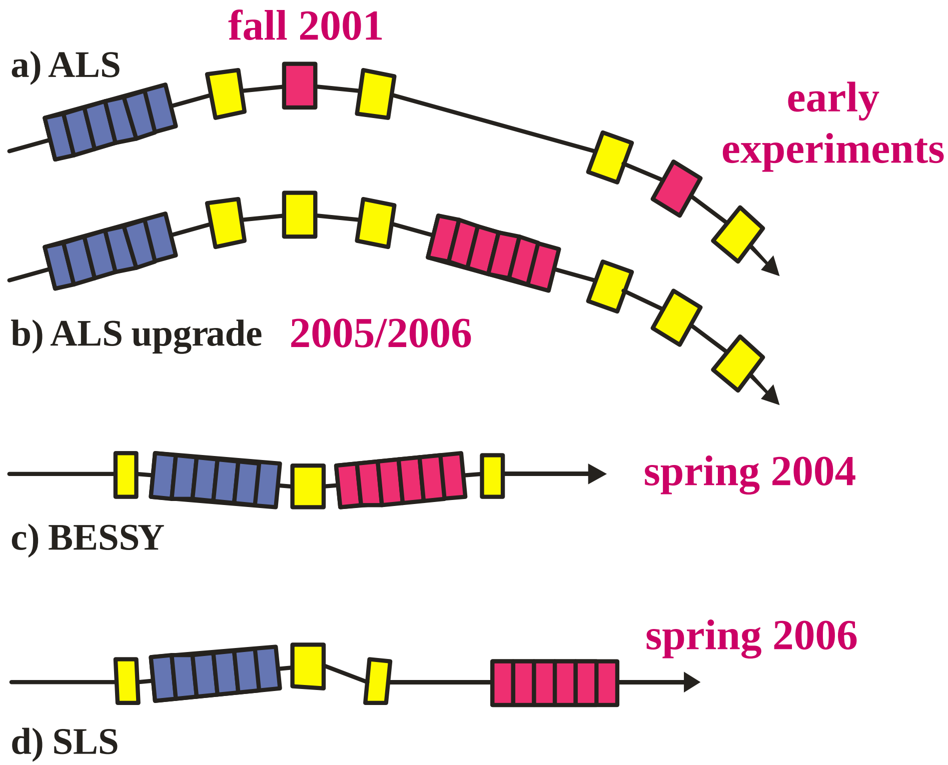






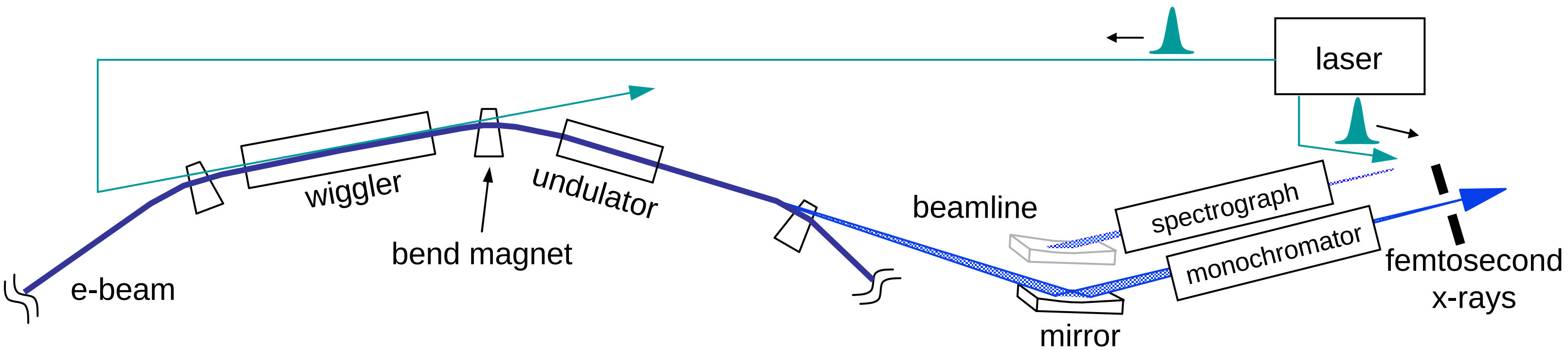
[1] A. A. Zholents, M. S. Zoloterev, PRL 76 (1996), 912.

Femtosecond slicing sources worldwide



	ALS(new)	BESSY	SLS
beam energy (GeV)	1.9	1.7	2.4
photon energy (keV)	0.2-10	0.4-1.4	3-8
photon polarization	linear	lin./circ.	linear
separation scheme	spatial	angular	angular
pulse length (fs, fwhm)	200	100	100
photons/pulse (0.1% bw)	2000	1000	1000
repetition rate (kHz)	20	1	1

Femtosecond Undulator Beamline – Overview



I. Insertion Device

- highest possible flux and brightness 0.2-10 keV
- small-gap undulator/wiggler (1.5 T, 50 x 3cm period)

x10^2 increase in flux, x10^3 increase in brightness

II. Beamlines for Femtosecond X-ray Science

- isolation of femtosecond x-ray, 0.2-2 keV, 2-10 keV

sector 6 - proximity to existing wiggler 200 fs x-rays

III. Laser: average power/repetition rate

- 30 W (1.5 mJ per pulse, 20 kHz)

x10 increase in flux

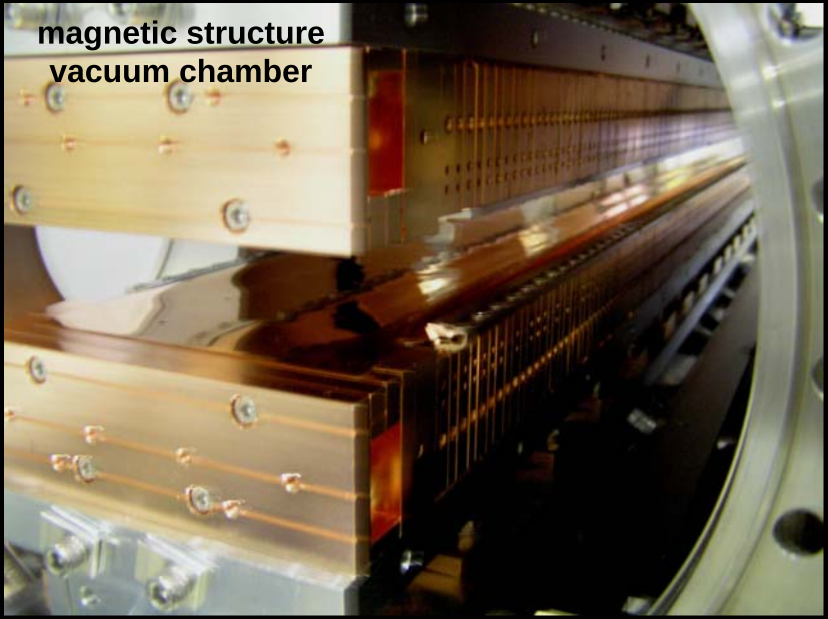
IV. Storage Ring Modifications

- local vertical dispersion bump – sector 6 and/or 5

In-Vacuum Undulator/Wiggler

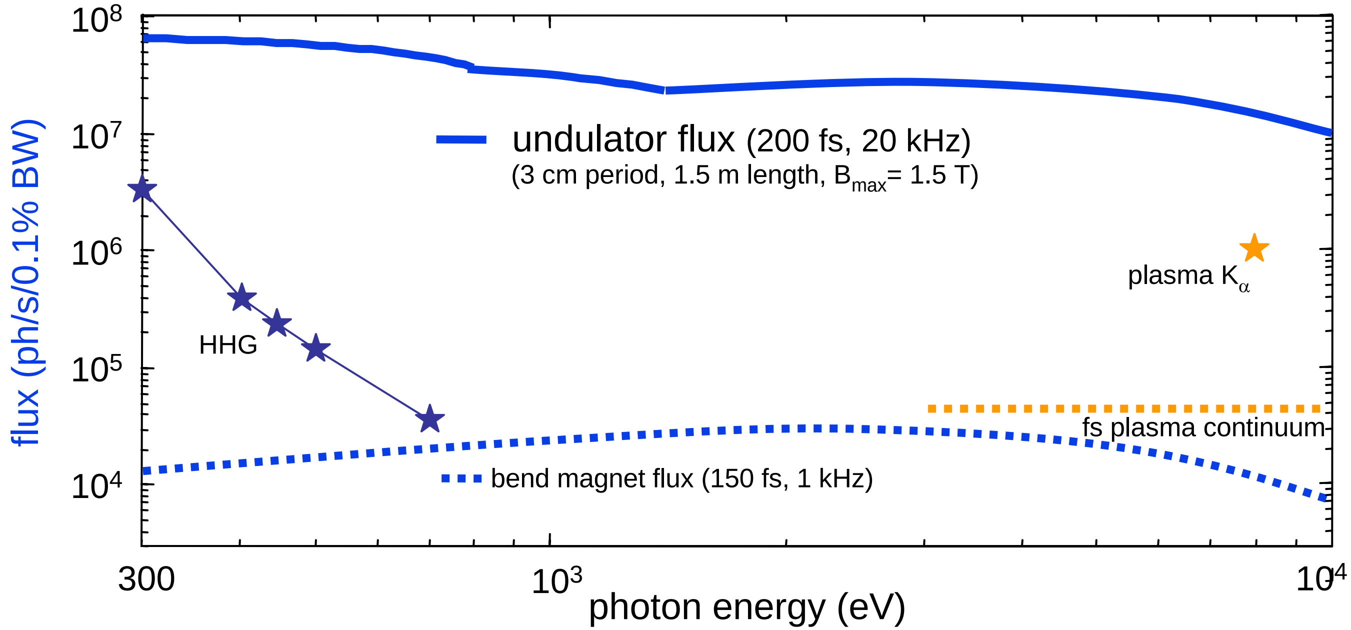
S. Marks et al.

Specifications	
Magnetic gap	5.5 mm
Period	30 mm
No. periods	50
Vacuum gap	>5 mm
B_o	1.45 T



courtesy R.W. Schoenlein

Femtosecond X-ray Flux

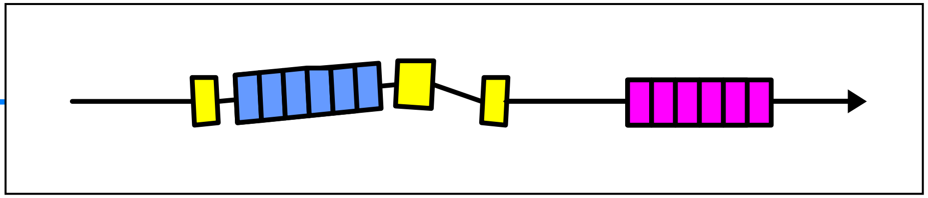


★ HHG flux from F. Krausz, laser: 10 fs, 3 mJ/pulse, 30 W

★ Plasma source flux in mrad² laser: 40 fs, 1 mJ/pulse, 30 W (continuum includes projected 10^5 improvement)

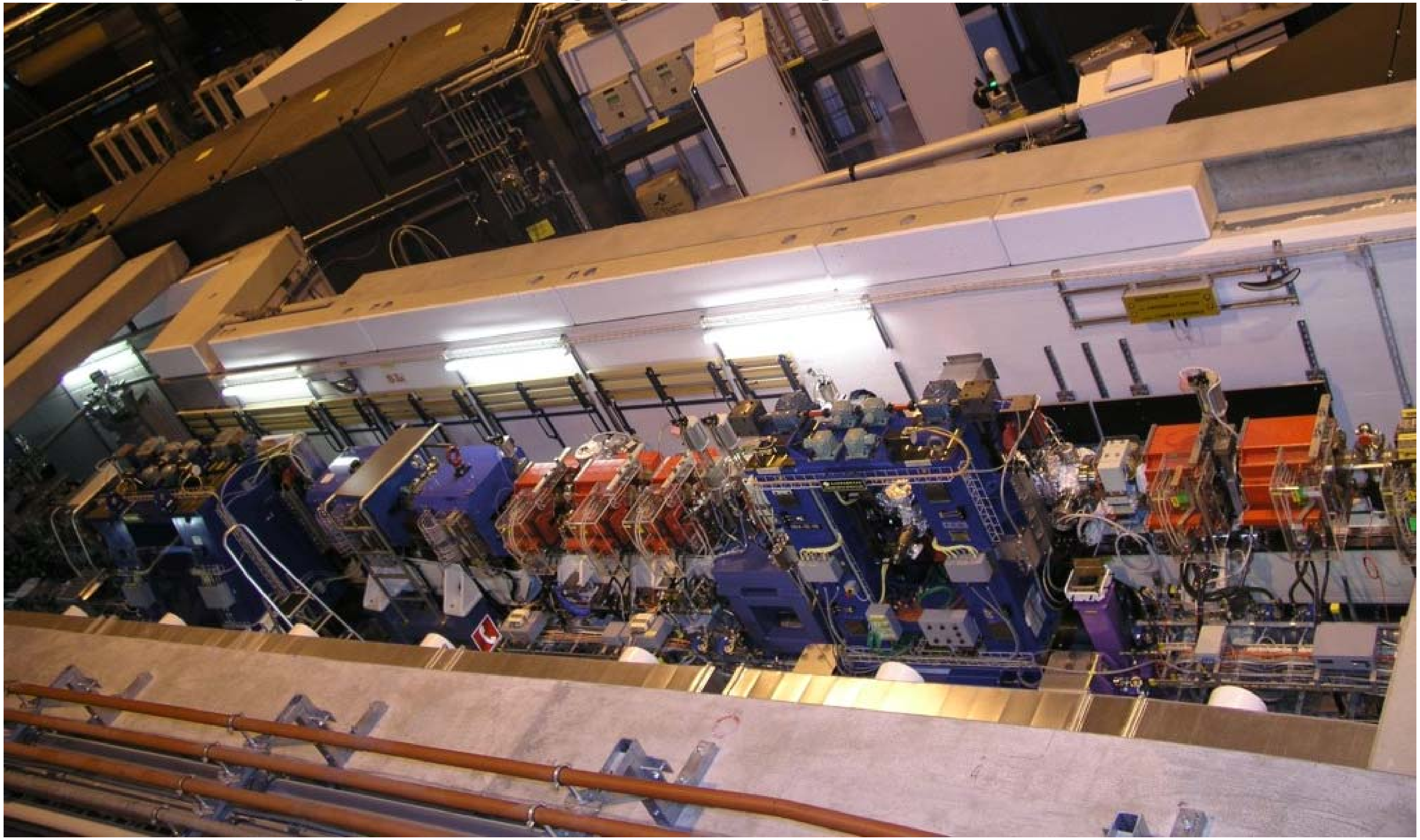
Cu K_α - 10^{10} ph/s/4π (proj. 10^{12} with Hg target)
cont. $6x10^7$ ph/s/4π (integ. from 7-8 keV)

ALS typical average x-ray flux
undulator ~10^{15} ph/s/0.1% BW
bend-magnet ~10^{13} ph/s/0.1% BW



SLS-FEMTO

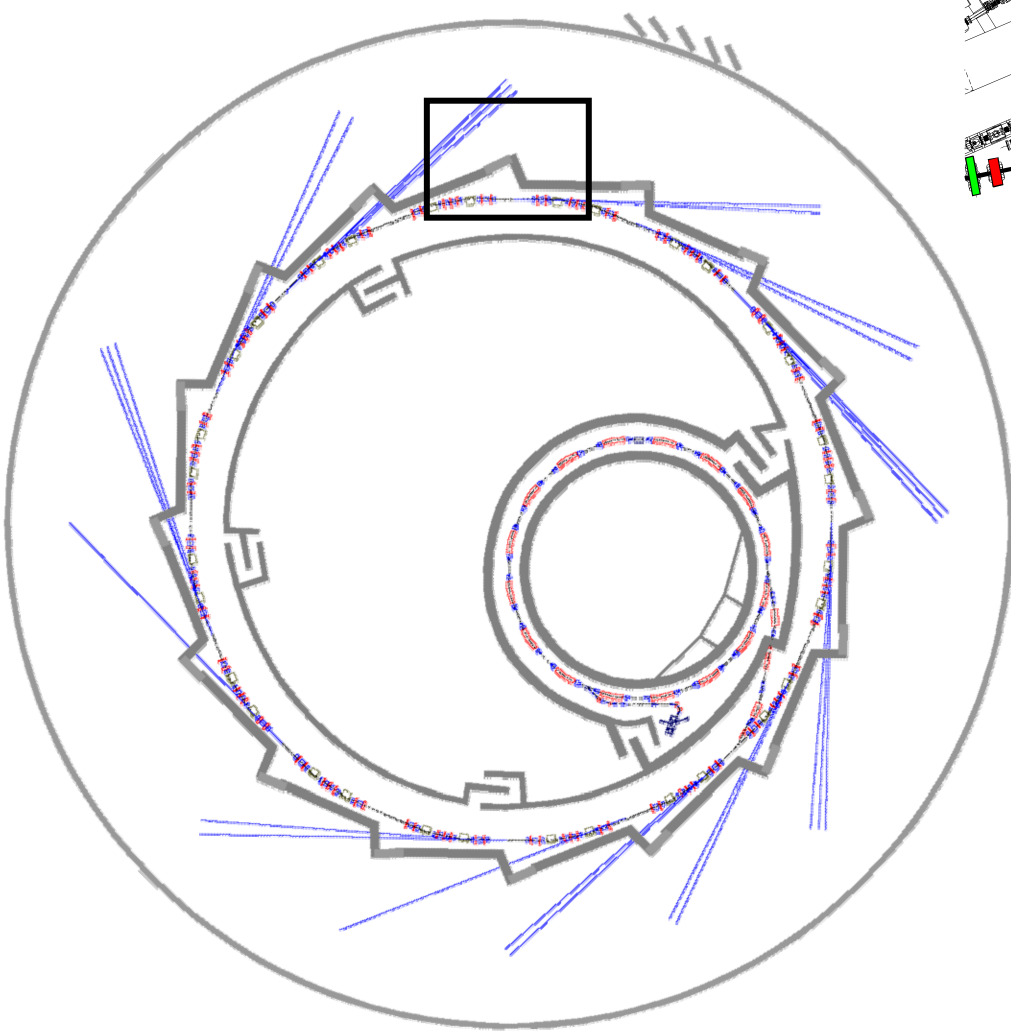
Tunable sub-ps hard X-ray (3-18 keV) source

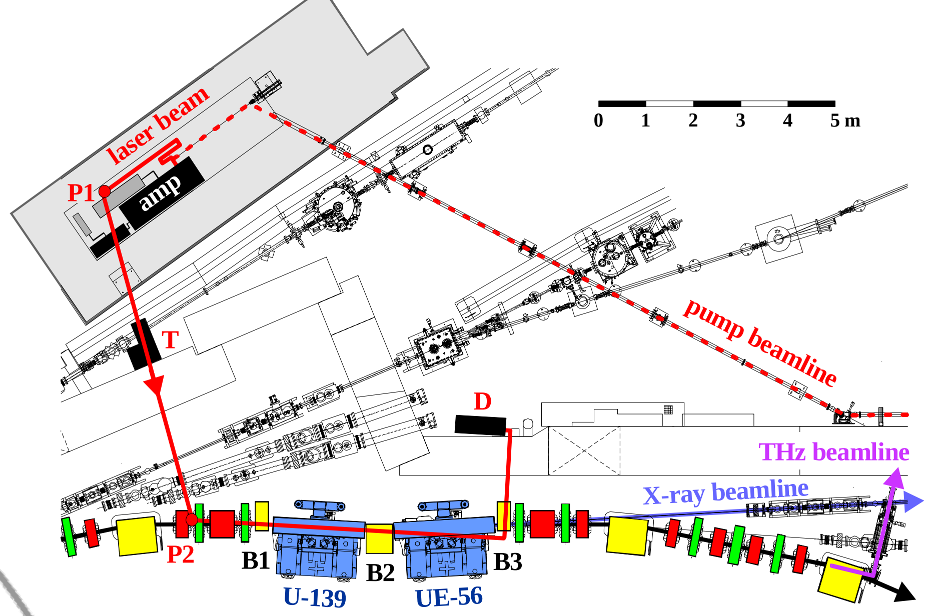


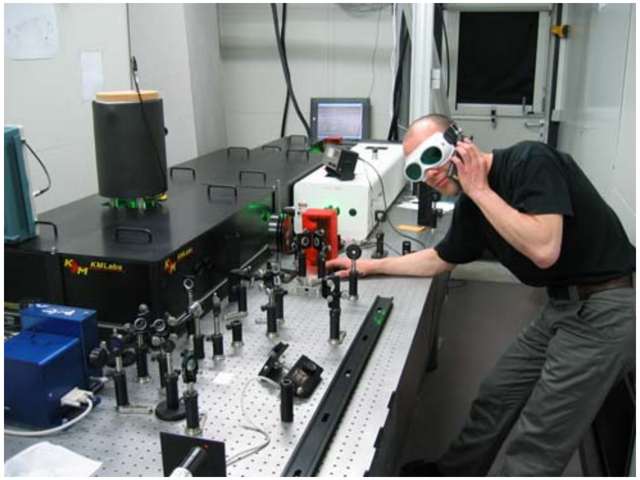
G. Ingold et al., PAC 2001 (Chicago) 2656

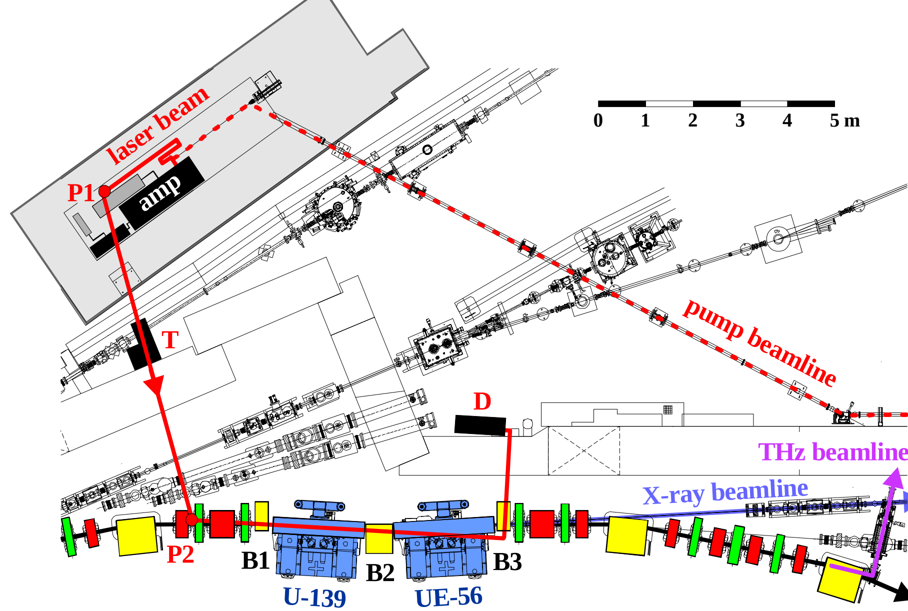
courtesy: G. Ingold, SLS

BESSY Berlin

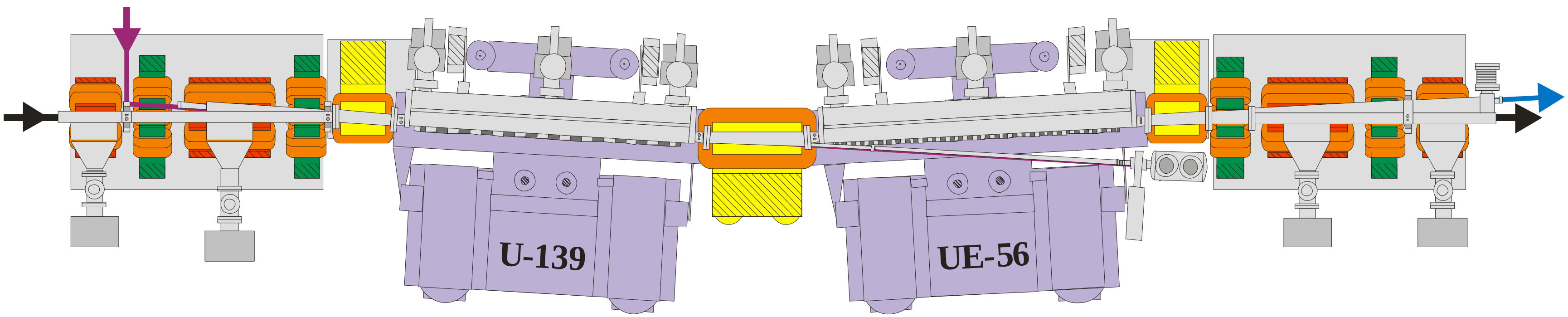








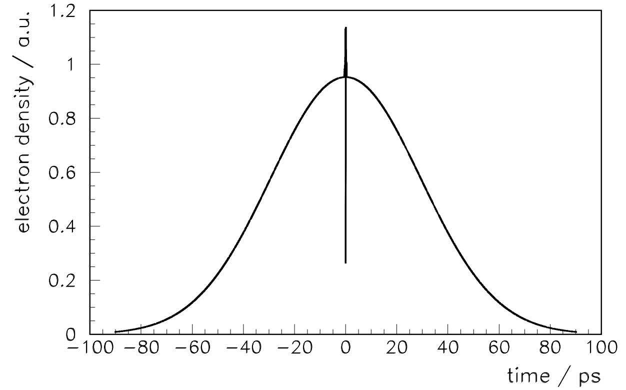
laser beam
P1
amp
T
pump beamline
D
THz beamline
X-ray beamline
P2
B1
B2
B3
U-139
UE-56
0 1 2 3 4 5 m

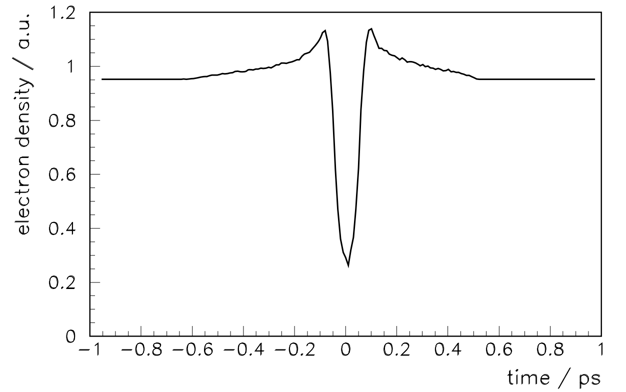


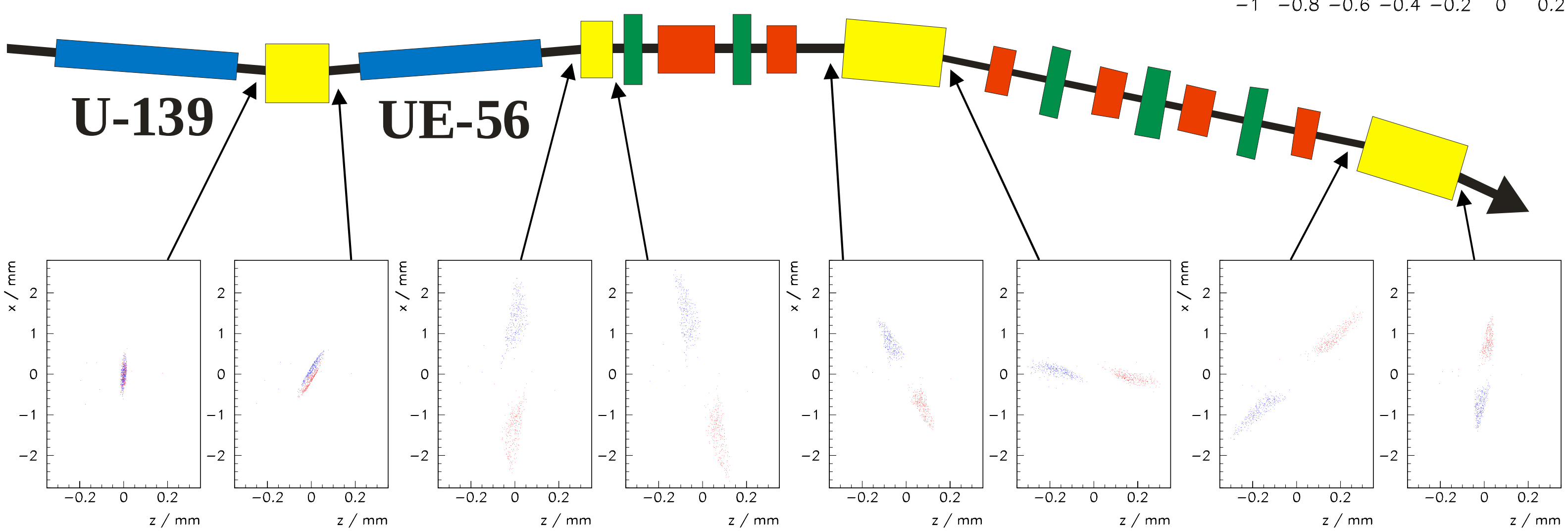
U-139
UE-56

Diagnostics of laser-electron interaction

longitudinal electron distribution
→ coherent THz radiation [1]







[1] K. Holldack et al., Part. Acc. Conf., Knoxville (2005), 2239.

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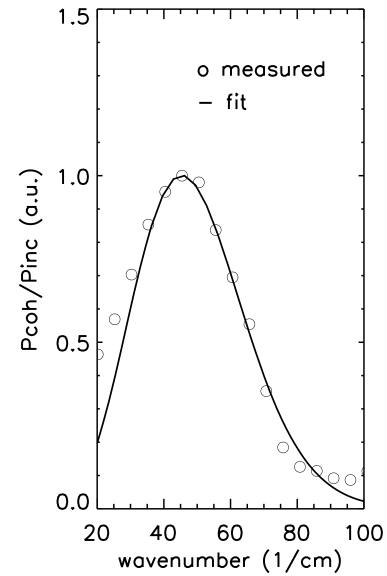

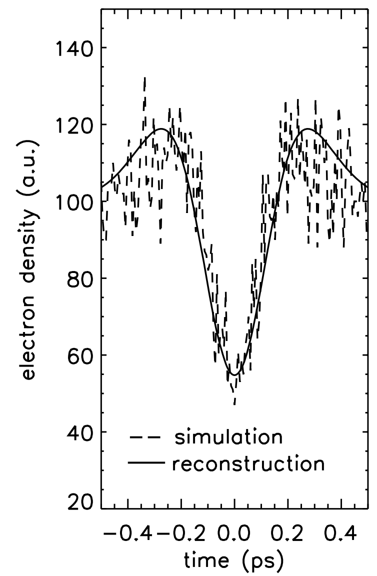

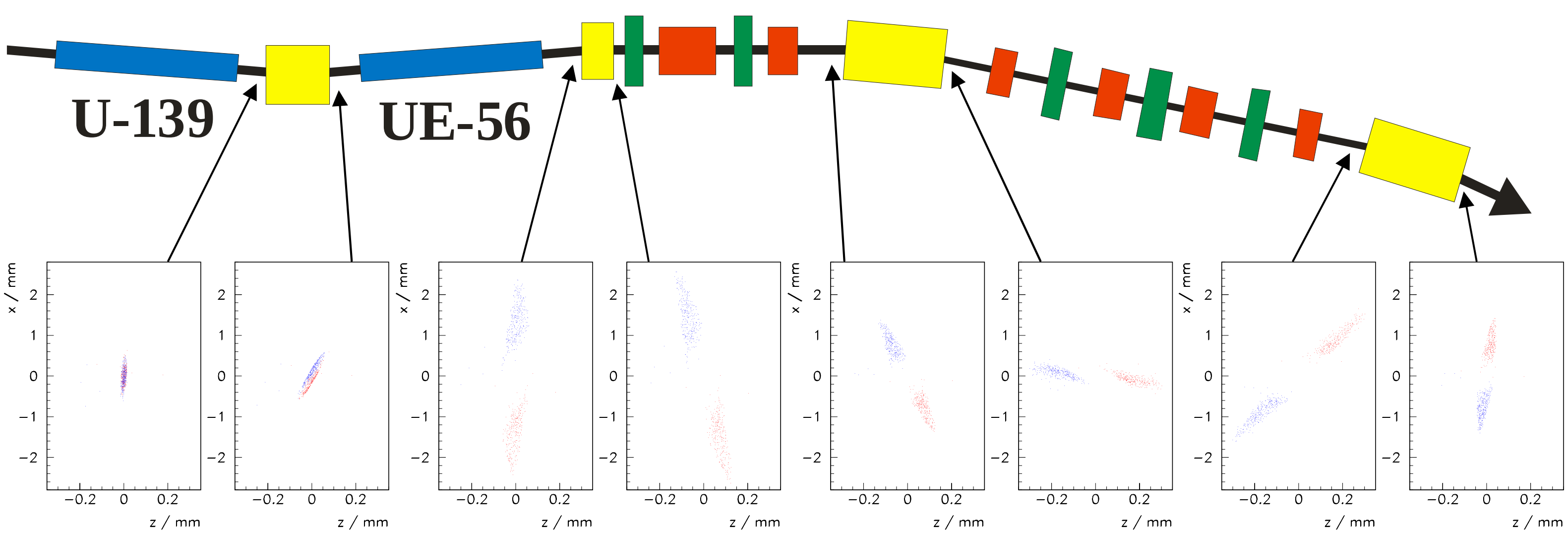

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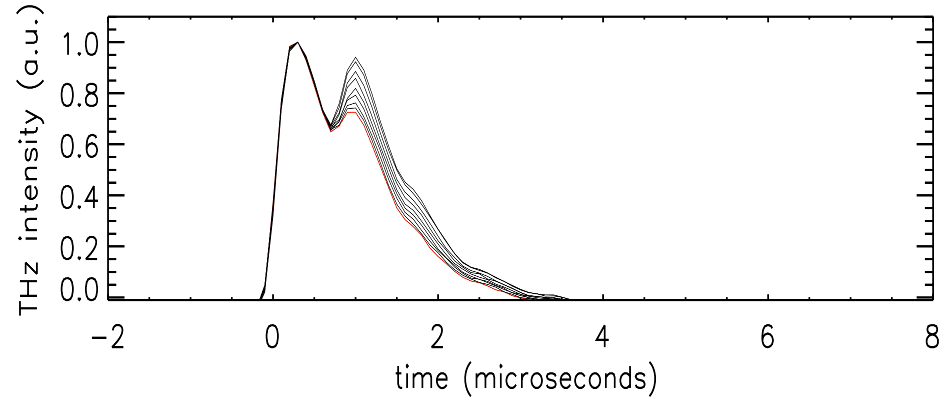
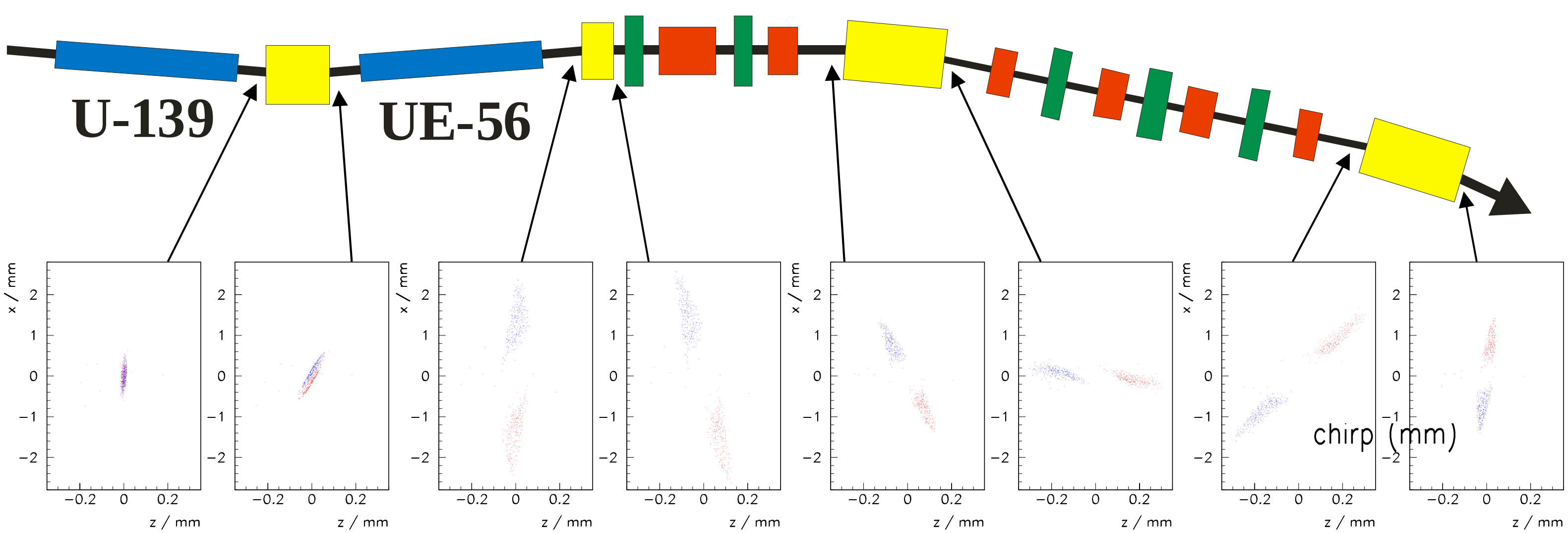




[1] K. Holldack et al., Part. Acc. Conf., Knoxville (2005), 2239.

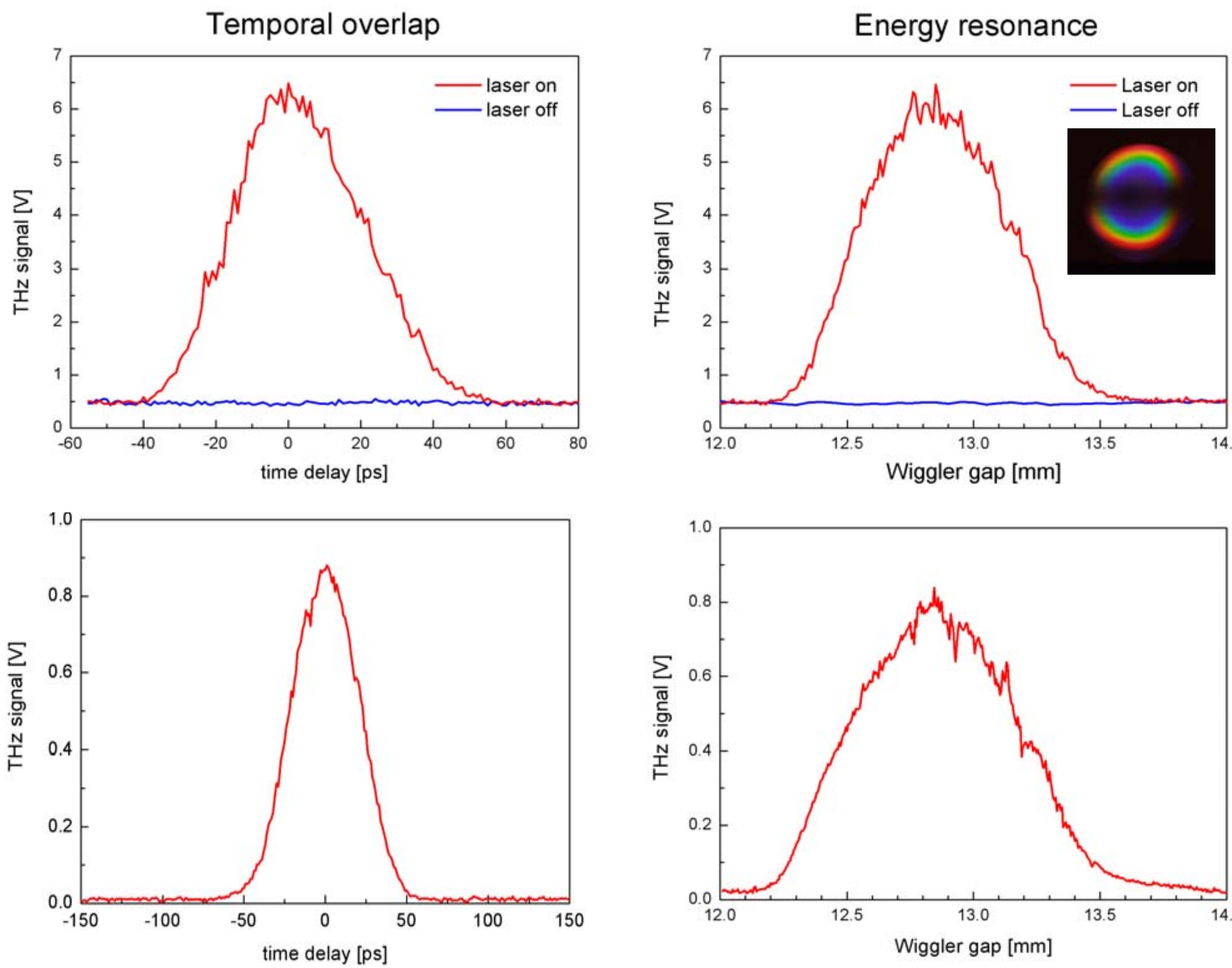
May 9/10, 2006: first sub-picosecond slicing

Alignment mode

- 3mA single bunch
- laser: 1mJ, 50fs

User operation mode

- 300mA multi-bunch
  + 3mA camshaft
- laser: 2.5mJ, 50fs

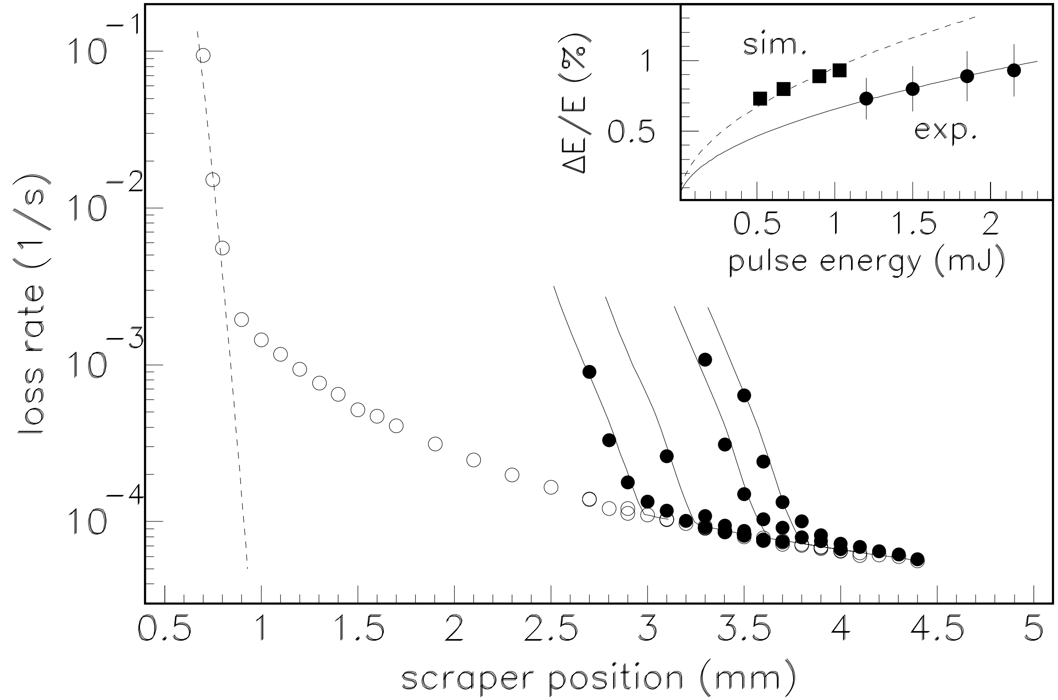


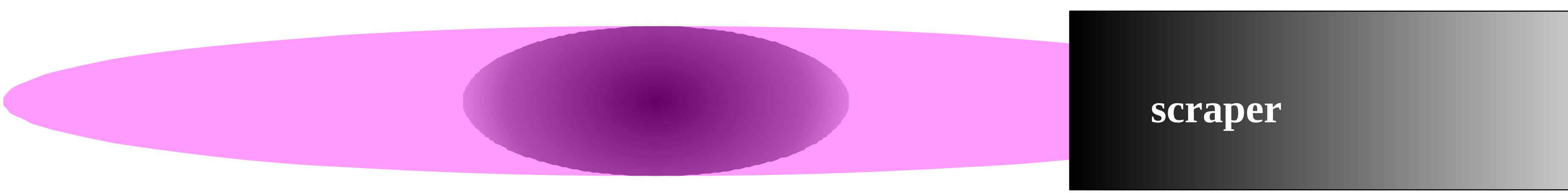
courtesy: G. Ingold, SLS

Diagnostics of laser-electron interaction

transverse electron distribution
→ scraper experiments [1]

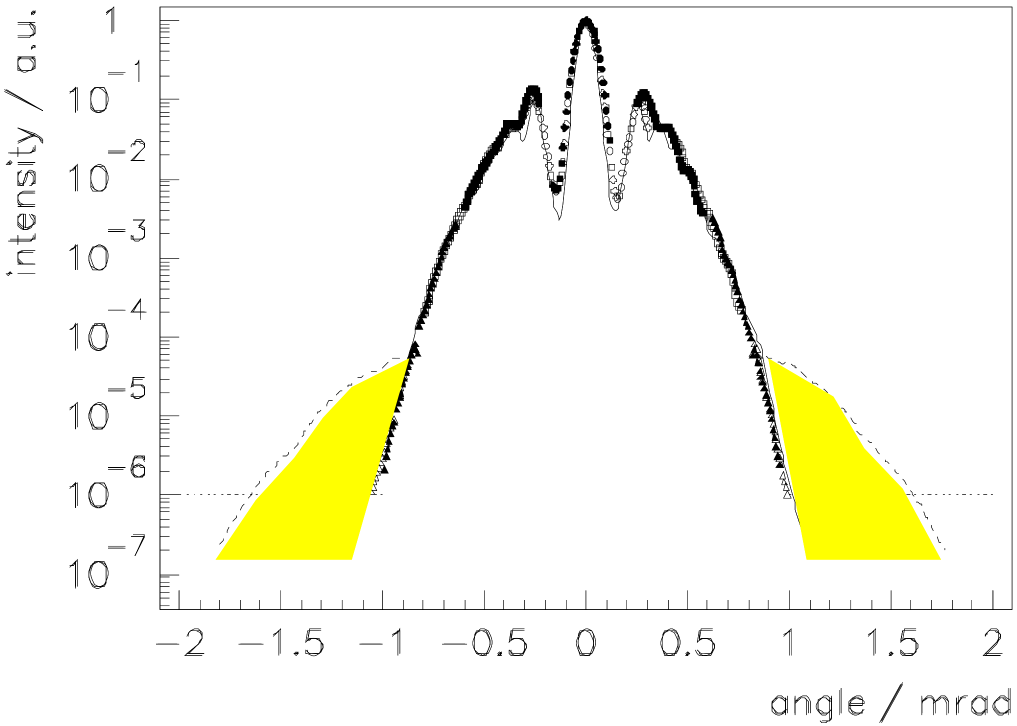
$$\Delta E / E \sim \sqrt{E_{pulse}}$$



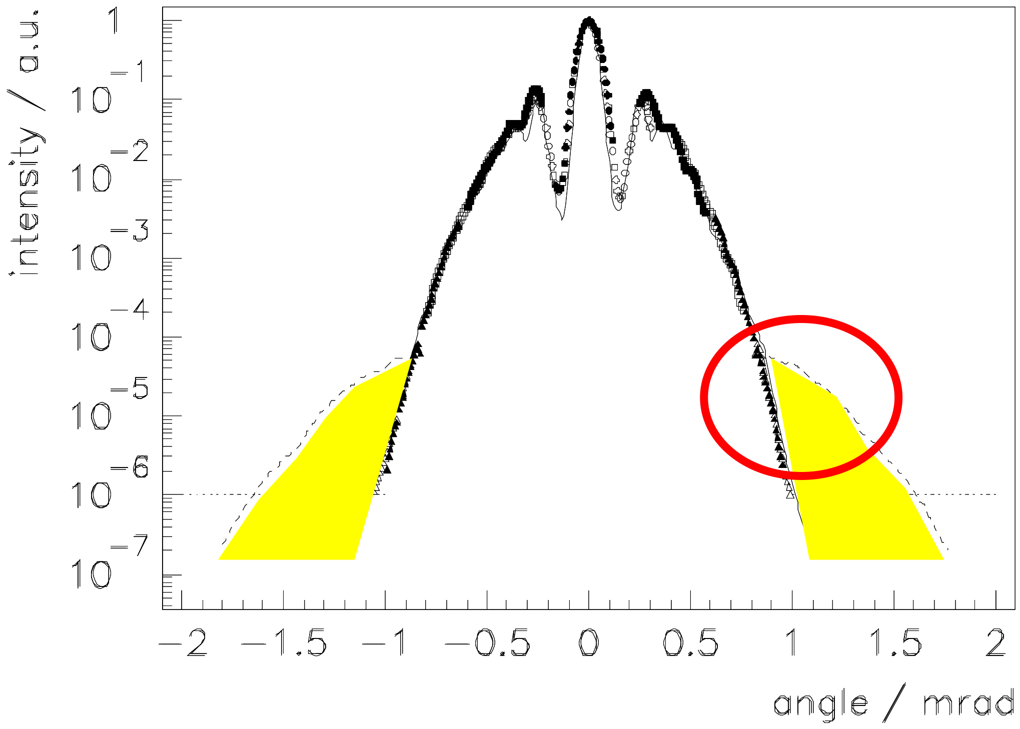


[1] S. Khan et al., PRST-AB 8 (2005), 040704.

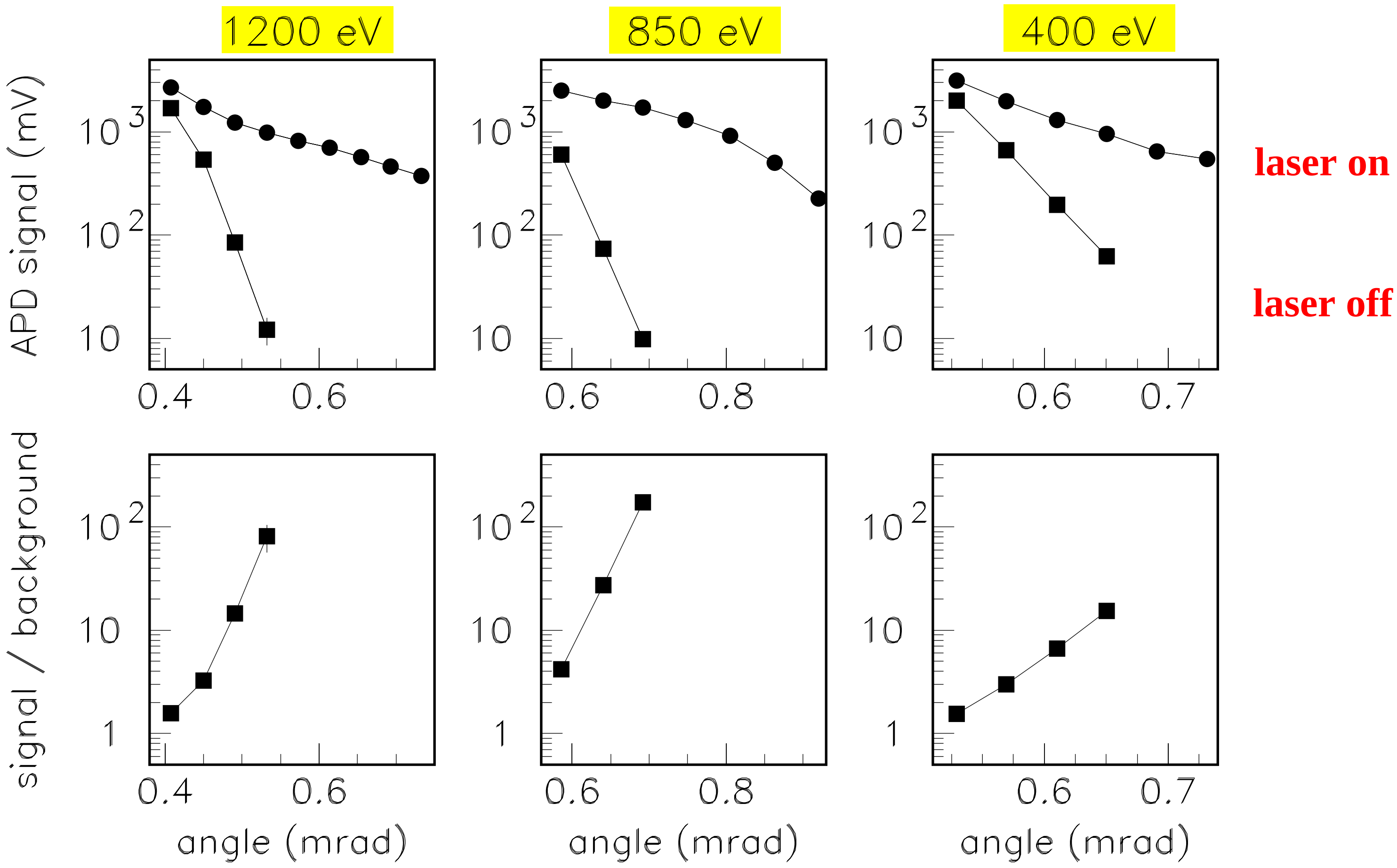
Angular distribution UE56-PGM beamline



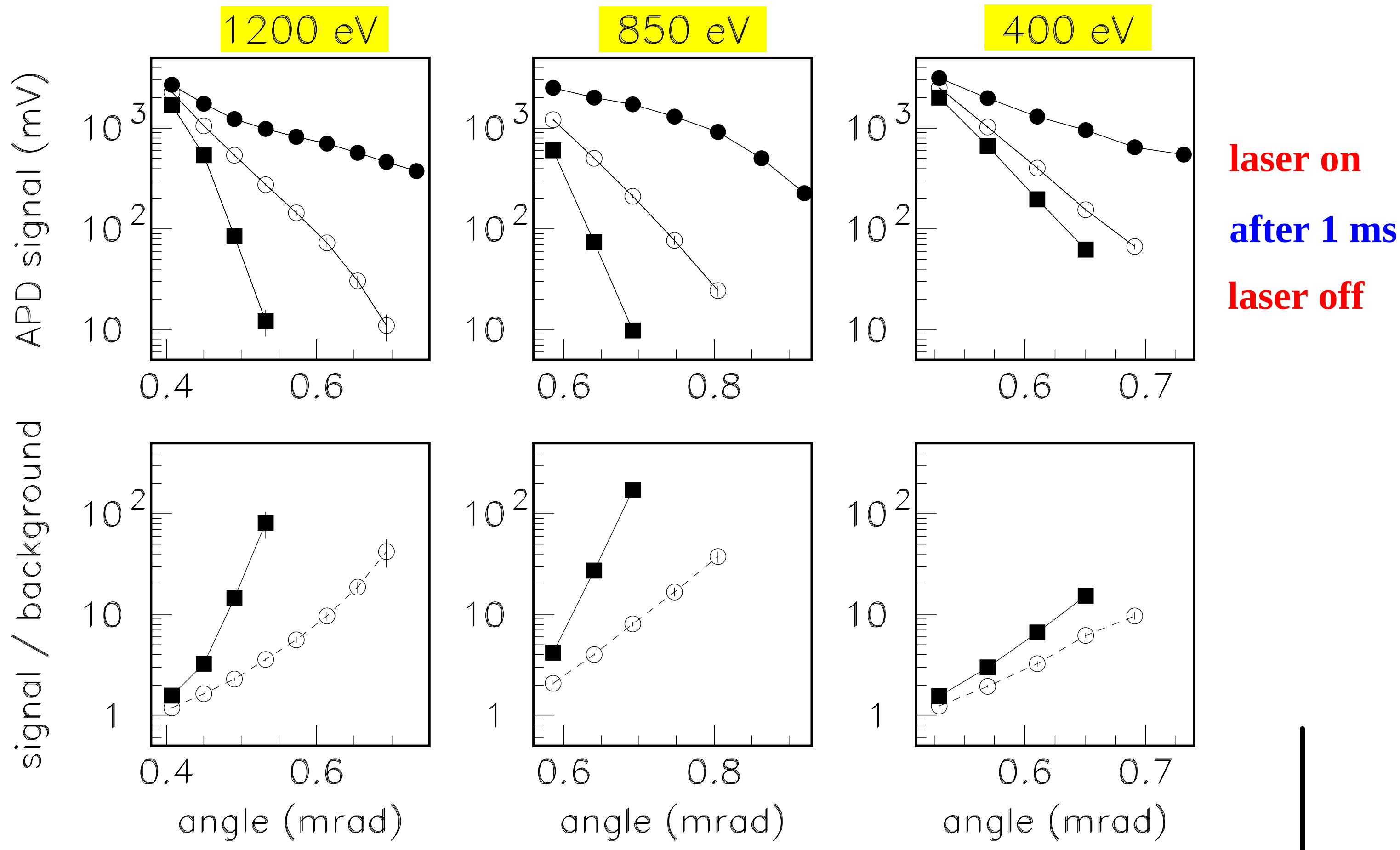
Angular distribution UE56-PGM beamline

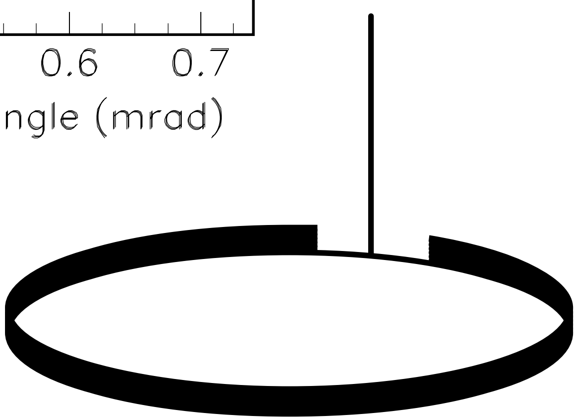


Angular distribution UE56-PGM beamline



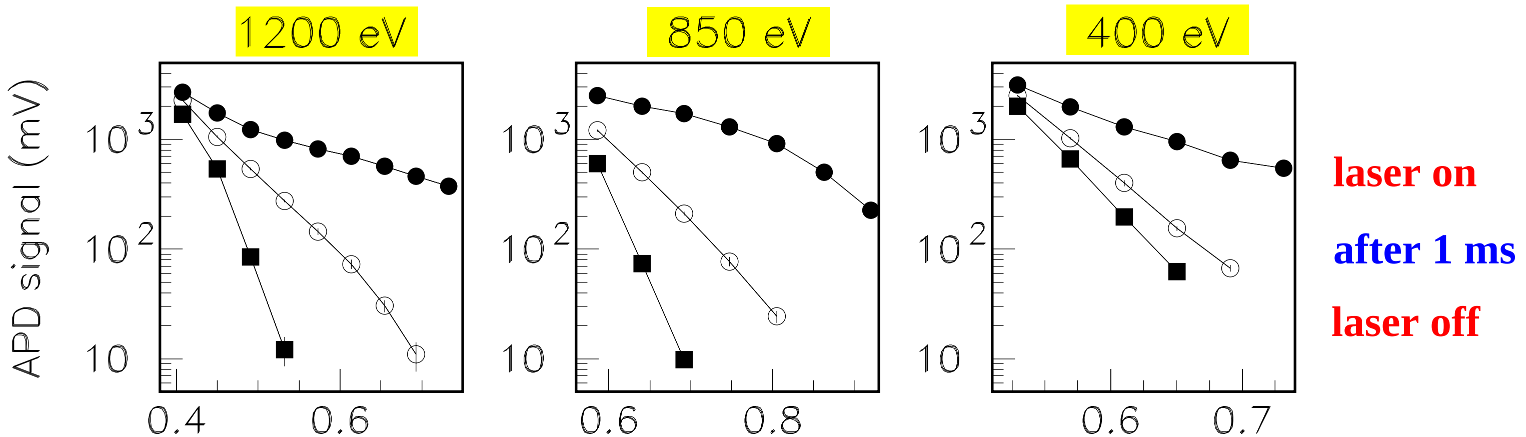
Angular distribution UE56-PGM beamline

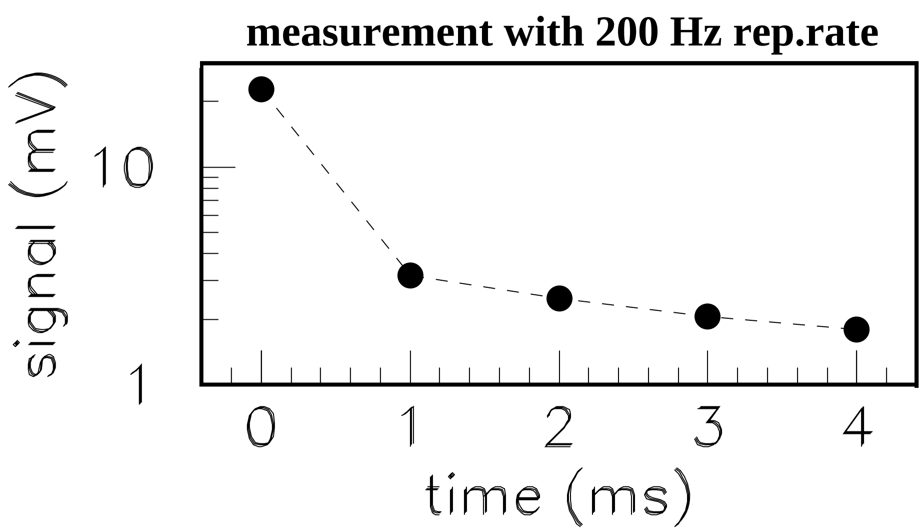


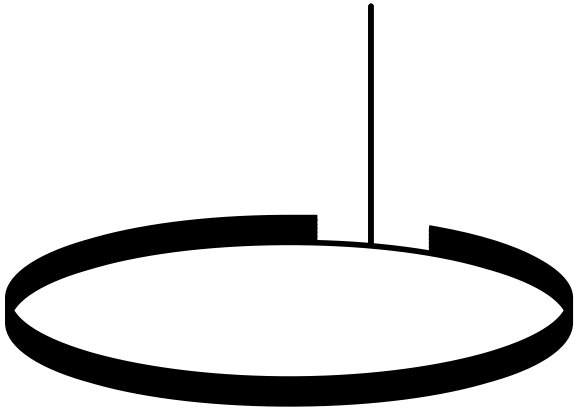


storage ring fill pattern: 350 × 0.7 mA + 7 mA
damping times ~ 10 ms

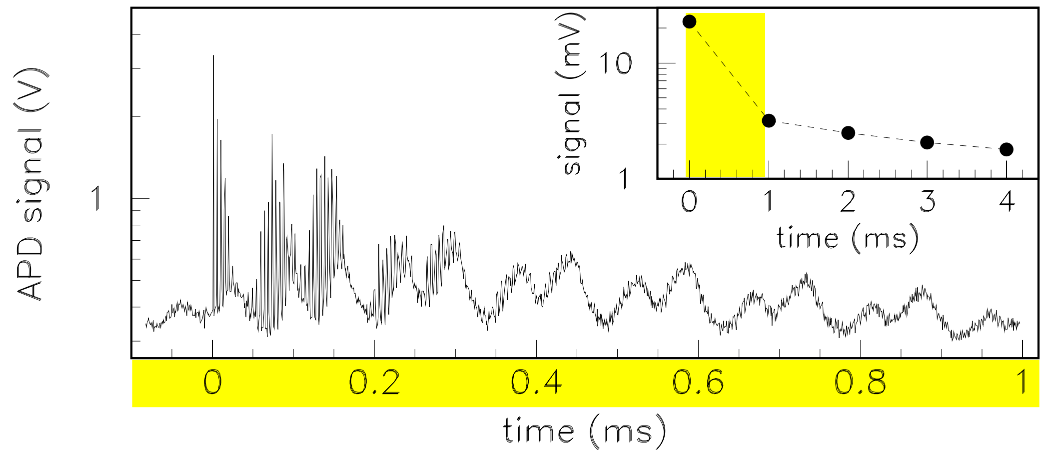
Angular distribution UE56-PGM beamline





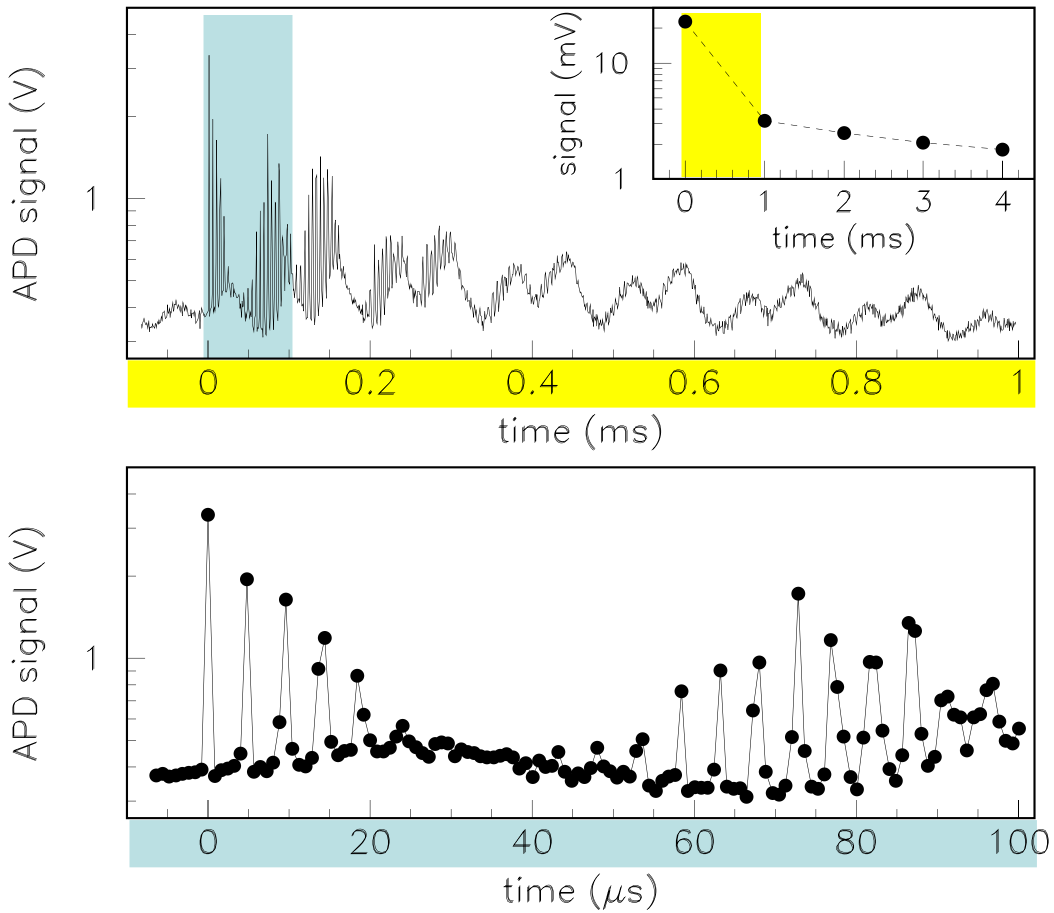


UE56-PGM beamline signal versus time



synchrotron oscillations

UE56-PGM beamline signal versus time

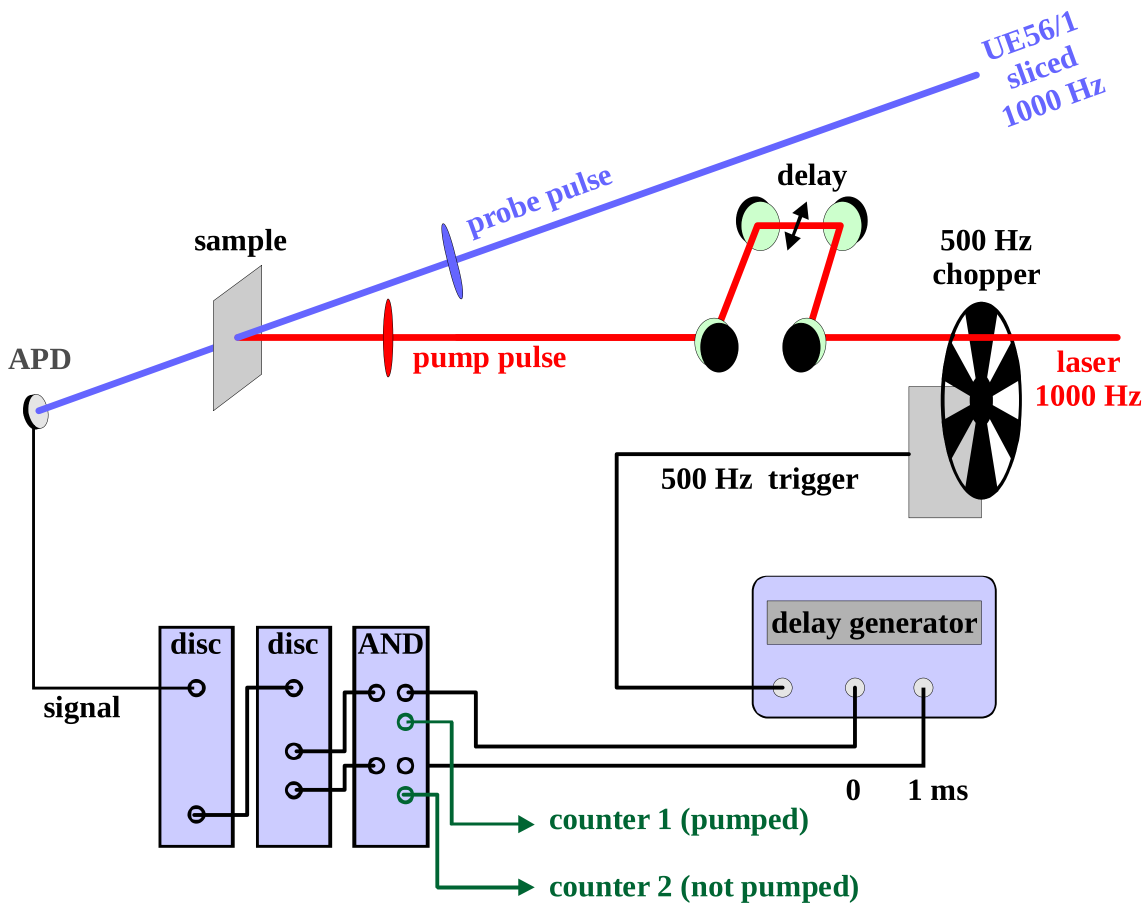


synchrotron oscillations

betatron oscillations

First pump-probe experiments *(preliminary)*

C. Stamm, T. Kachel, N. Pontius, R. Mitzner, T. Quast, K. Holldack, S. Khan, C. Lupulescu, H. Dürr, W. Eberhardt (BESSY)

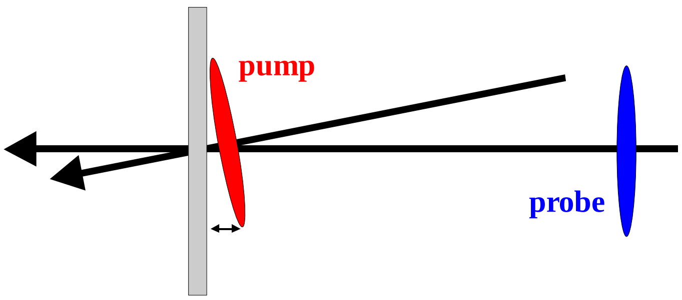


Time resolution ~ 150 fs

Assumed pulse duration 100 fs (FWHM), pulse lengthening:

- monochromator (wavelength K illuminated lines < 30 fs)

- 1º angle between pump and probe pulse



e.g. $$\frac{18\,\text{mrad}\cdot 1\,\text{mm}}{c} = 60\,\text{fs}$$

- path length changes over 8 hrs and 40 m

e.g. $$30\,\mu\text{m}/c = 100\,\text{fs}$$

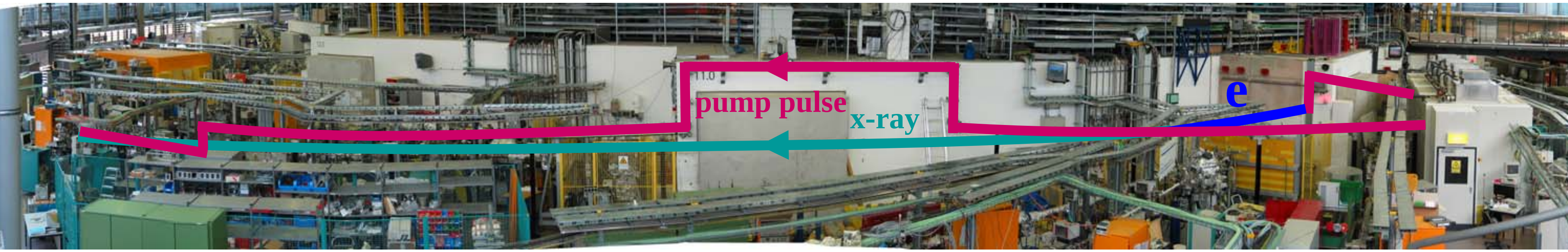


photo: K. Godehusen

Photon flux per s and 0.1% bandwidth

10^6 produced	***(laser repetition rate)***
10^4 on the sample	***(beamline transmission)***
10^3 detected	***(detector efficieny)***

Photon flux per s and 0.1% bandwidth

10^6 produced	K 5-10 laser rep.rate
10^4 on the sample	K 5-10 optimized beamline
10^3 detected	K 2-3 detection efficiency
	K 5 detector array
	1 1000

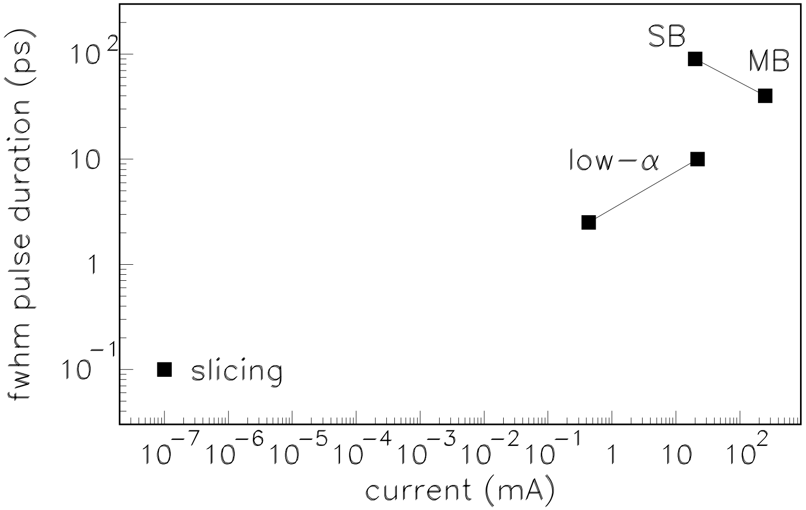
Summary

	resolution	intensity	effort
- low momentum-compaction factor	1 ps	$	--
- high rf gradient	1 ps	+	~ E
- crab-cavity scheme	1 ps	+	~ E
- femtosecond laser slicing	100 fs	$$	~ E^2

Summary

	resolution	intensity	effort
- low momentum-compaction factor	1 ps	$	--
- high rf gradient	1 ps	+	~ E
- crab-cavity scheme	1 ps	+	~ E
- femtosecond laser slicing	100 fs	$$	~ E^2

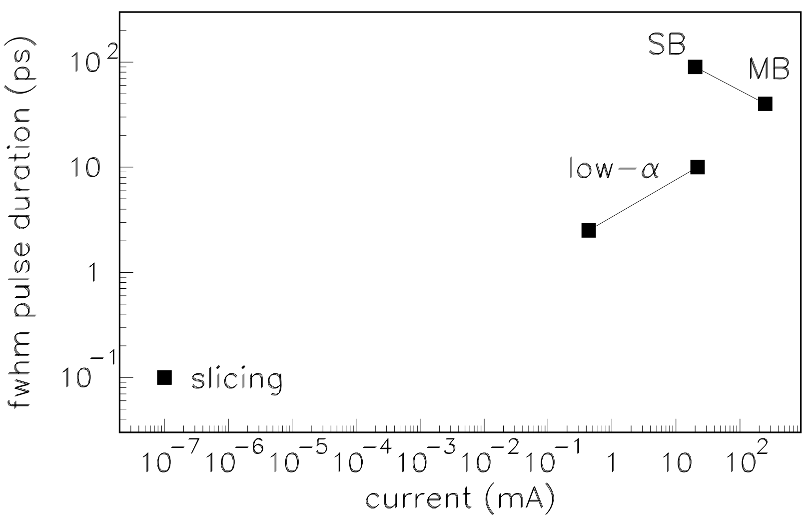
@ full bunch rate (500 MHz)



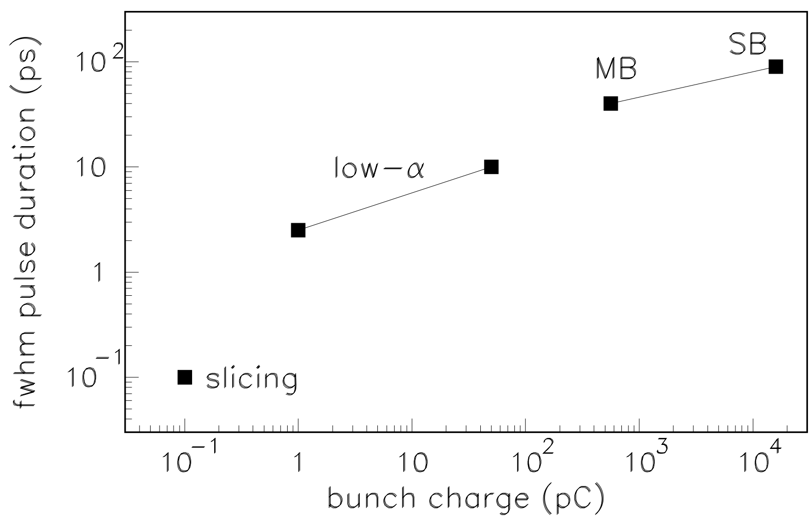
Summary

	resolution	intensity	effort
- low momentum-compaction factor	1 ps	$	--
- high rf gradient	1 ps	+	~ E
- crab-cavity scheme	1 ps	+	~ E
- femtosecond laser slicing	100 fs	$$	$\sim E^2$

@ 500 MHz bunch rate



@ 1 kHz pump-pulse rate



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A. Zholents (LBNL, Berlekey)

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H. Bäcker, J. Bahrdt, H. Dürr, V. Dürr, W. Eberhardt, K. Godehusen, A. Gaupp, K. Holldack*, E. Jaeschke, T. Kachel*, S. Khan*, D. Krämer, C. Lupulescu*, R. Mitzner*, M. Neeb, W. Peatman, N. Pontius*, T. Quast*, G. Reichardt, M. Richter, M. Scheer, O. Schwarzkopf, F. Senf, C. Stamm*, G. Wüstefeld (BESSY, Berlin)
I. Hertel, F. Noack, W. Sandner, I. Will, N. Zhavaronkov (MBI, Berlin)
***) commissioning team**

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