Recent beam measurements and new instrumentation at the Advanced Light Source

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Credits

K. Baptiste, W. Barry, M. Chin, J. Jilian, S. Kwiatkowski R. Low, D. Plate, G. Portmann, D. Robin, F. Sannibale, T. Scarvie, J. Weber, M. Zolotorev
(LBNL).

D. Filippetto (INFN-LNF),
G. Stupakov (SLAC),
L. Jaegerhofer (Technical University of Vienna).

...

Contents

1- ALS Introduction

2 - Instrumentation upgrades by "commercial" technology

3 - Home developed beam diagnostics and instrumentation

- **Absolute bunch length from radiation fluctuation**

- **Pseudo single-bunch**

- **Bunch cleaning**

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The Advanced Light Source

Normal Sector

Modified Sector

- **First 3rd generation light source. In operation since 1993**

Parameter	Value
Circumference	196.8 m
Beam particle	electron
Beam energy	1.9 GeV
Beam current	400 mA
Emittance	6.3 nm
Energy spread	0.1% rms
Radio frequency	499.642 MHz
Harmonic number	328
Bucket spacing	2 ns
Cell type	Triple bend achrom.
Number of cells	12

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ALS Science Production
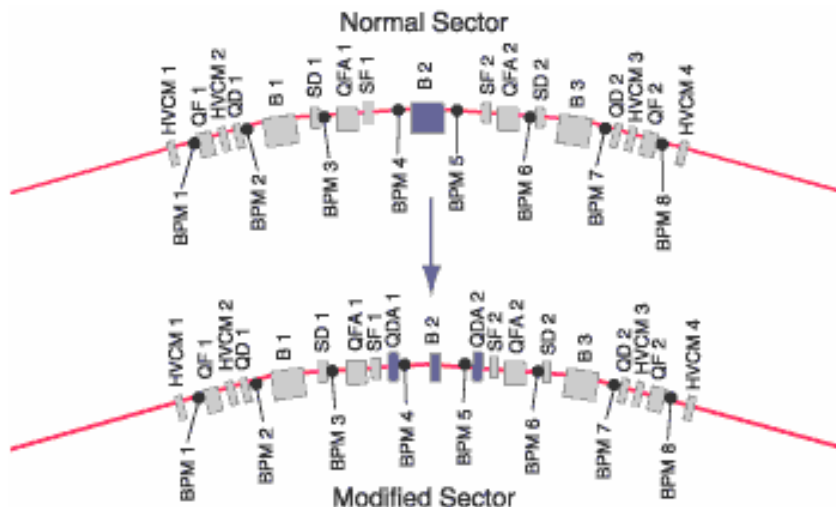
Almost 40 beamlines serving more than 2000 experiments per year using IR to hard x-ray photons.
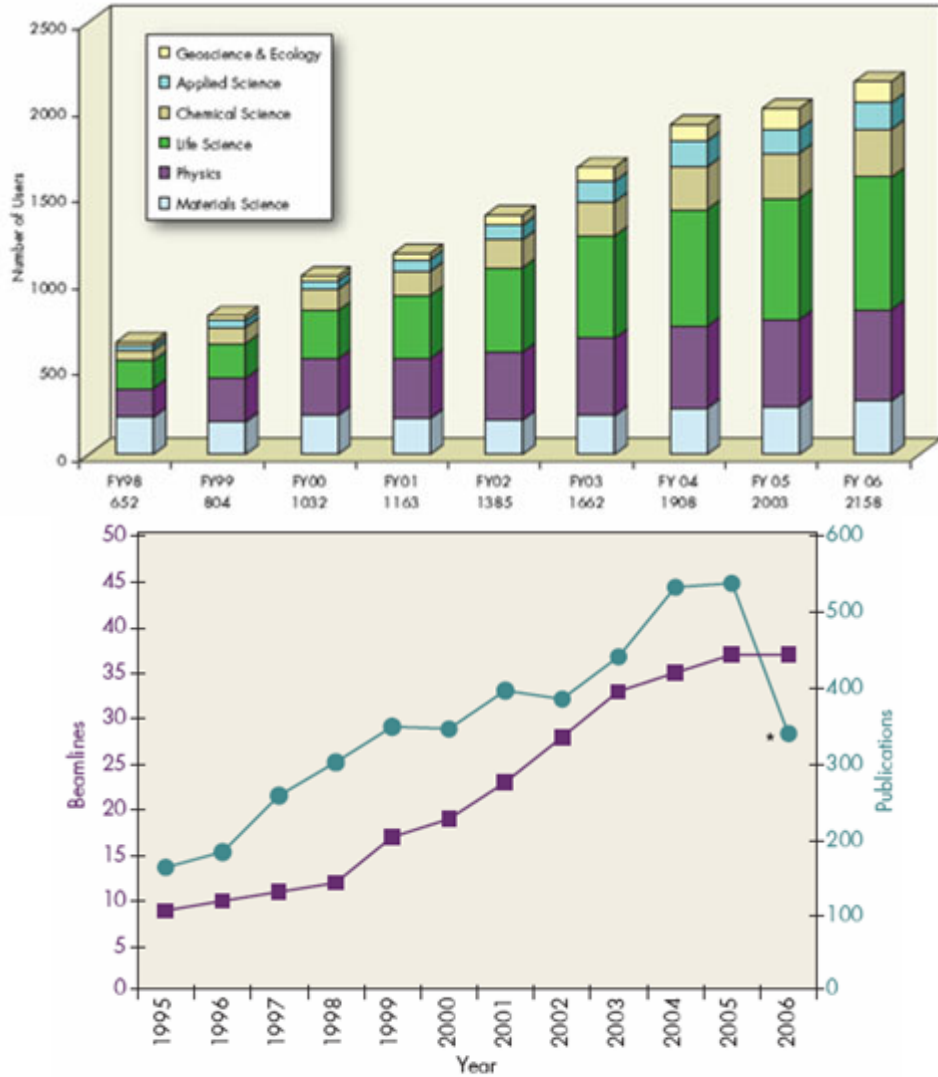
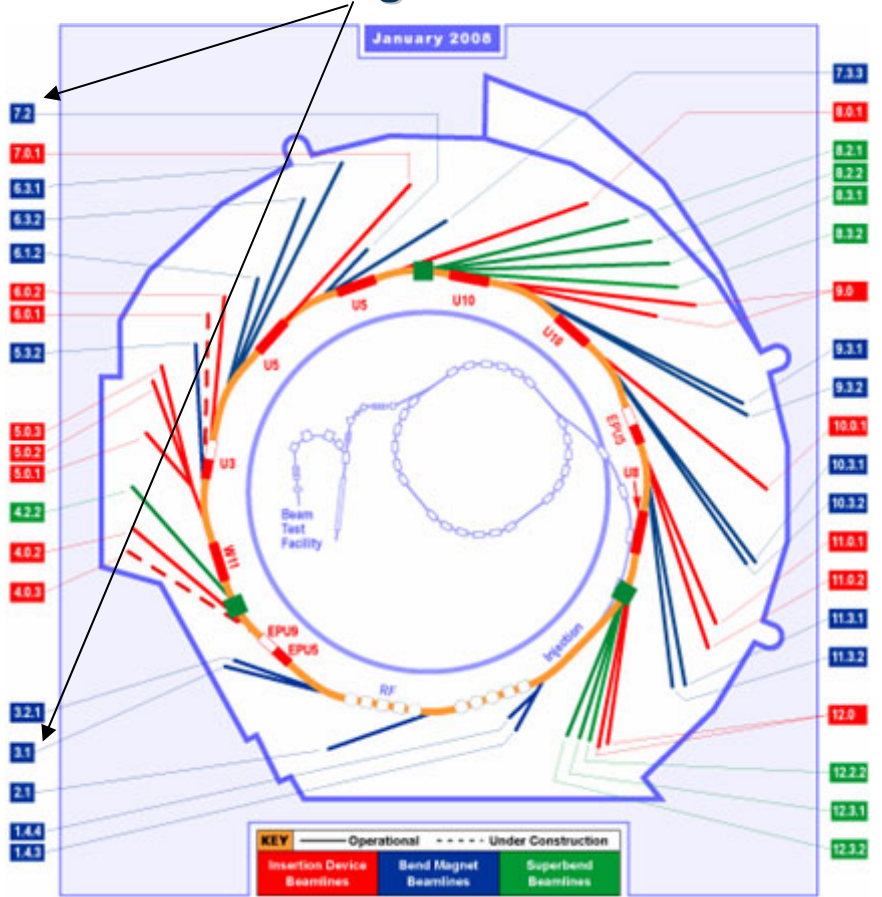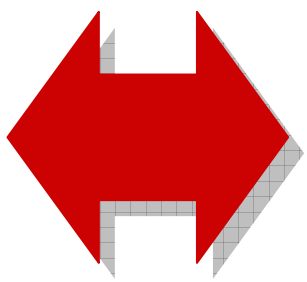**Two beam diagnostic beamlines**

FIGURE 8. Graph of growth in beamlines (pink) and publications (blue). *Note that publications for 2006 were still being collected at the time this section was being written.
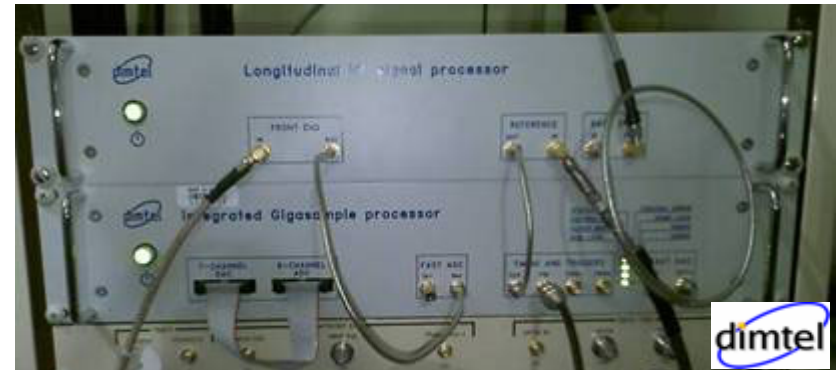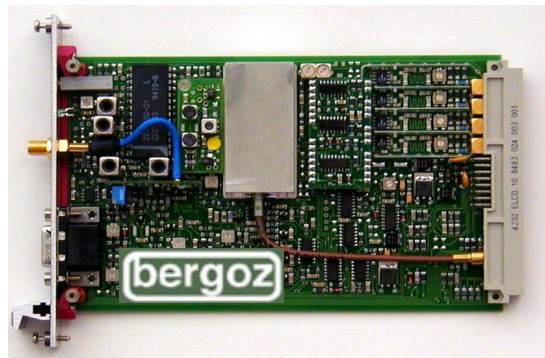
ALS Complex Beam Diagnostics and Instrumentation

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Monitor	Quantity
Synch. Light Monitor	2
Beam pos. Mon. (electr., x-ray)	~140
DCCT	2
Beam Loss Monitor	~24
Streak Camera	1
Fluorescent Screens	12
Integ. Curr. Monitor	4
Fast Curr. Transf	1
Pinger System	1
Slow and Fast Orbit Feedbacks	2
Longitudinal Feedback	1
Transverse Feedback	2
Network Analyzer	1
Real Time Spectrum Analizer	1

Measurable Quantity

Beam Position
Beam Current
Tunes and Chromaticities
Beam Profile
Emittance
Energy Spread
Lifetime
Bunch Length
Instabilities
Beam Losses
Beam Impedance
Frequency Maps
...

Complete set of diagnostics and instrumentation

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A Continuous Evolution

Since 1993, ALS underwent through several upgrades and its present performances compare well with those of newer light sources.

The same situation happened to its beam diagnostics and nowadays the ALS instrumentation does not differs very much from the ones of last generation storage rings.

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Absolute Bunch Length by Radiation Fluctuation Analysis

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**Based on the method described in
M. Zolotorev, G. Stupakov, SLAC-PUB 7132 (1996)**

An absolute bunch length measurement technique based on the analysis of the intensity fluctuations in the incoherent part of the radiation emitted by a particle beam.

The scheme is non-destructive, is remarkably simple and can be used in both circular and linear accelerators including those cases where the very short length of the bunches makes difficult the use of other techniques.

(ALS measurements by D. Filippetto, L. Jaegerhofer, F.Sannibale, M. Zolotorev)

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Incoherent Radiation from Charged Particles

Moving charged particles can radiate photons by synchrotron radiation, Cerenkov radiation, transition radiation, etc. For all such processes, the incoherent component of the radiation is the result of the <u>random distribution</u> of the particles along the beam.

Example: "Ideal" coasting beam moving on a circular trajectory with the particles equally separated by a longitudinal distance d :
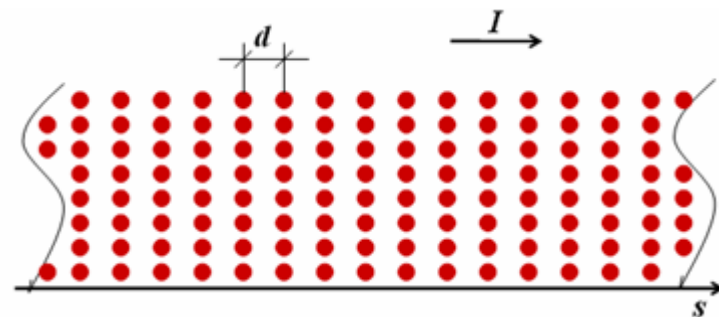
coherent synchrotron radiation emission only for wavelengths with $\lambda = n\,d$ (n integer). For all other wavelengths, the interference between the radiation emitted by the evenly distributed electrons produces a vanishing net electric field.

In a more realistic coasting beam, the particles are randomly distributed causing a small modulation of the beam current. The interference is not fully destructive anymore and the beam radiates also at the other wavelengths.
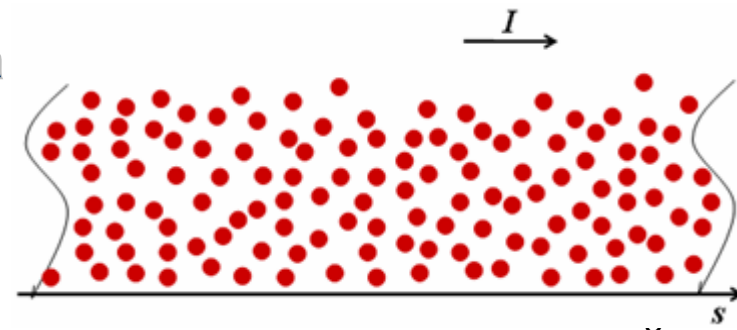
Radiation Fluctuations

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If the particle turn by turn position along the beam changes (longitudinal dispersion, path length dependence on transverse position), the current modulation changes and the radiated energy and its spectrum _fluctuate_ turn by turn.

By averaging over multiple passages, the measured spectrum converges to the characteristic incoherent spectrum of the radiation process under observation. (synchrotron radiation in the example).
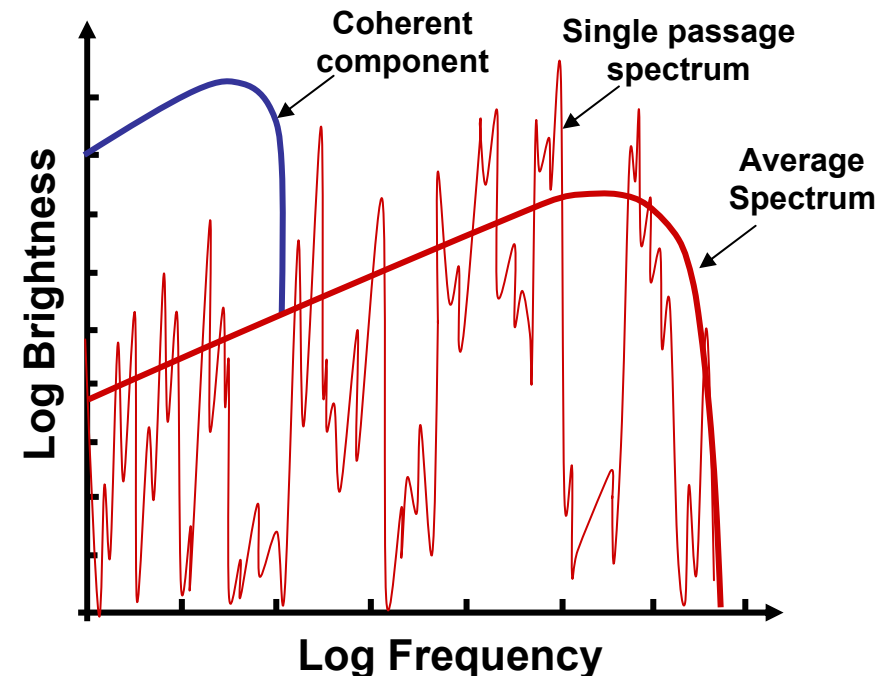
In the case of bunched beams, a strong coherent component at those wavelengths comparable or longer than the bunch length shows up But the higher frequency part of the spectrum remains unmodified.

The electric field associated with the radiation emitted by the beam at the time *t* is:

$$E(t) = \sum_{k=1}^{N} e(t - t_k)$$

where *e* is the electric field of the electromagnetic pulse radiated by a single particle and t_k is the randomly distributed arrival time of the particle (Poisson process).

In the frequency domain:

$$\hat{E}(\omega) = \int_{-\infty}^{\infty} E(t) e^{i\omega t} dt = \hat{e}(\omega) \sum_{k=1}^{N} e^{i\omega t_k}$$

And for the radiated power per passage:

$$P(\omega) \propto \left| \hat{E}(\omega) \right|^2 = \left| \hat{e}(\omega) \right|^2 \sum_{k,l=1}^{N} e^{i\omega(t_k - t_l)}$$

The previous quantity fluctuates passage to passage, and the average radiated power from a beam with normalized distribution $f(t)$ is:

$$\langle P(\omega) \rangle \propto \left| \hat{e}(\omega) \right|^2 \sum_{k,l=1}^{N} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dt_k dt_l \, f(t_k) f(t_l) e^{i\omega(t_k - t_l)} = \left| \hat{e}(\omega) \right|^2 \left[N + N(N-1) \left| \hat{f}(\omega) \right|^2 \right]$$

Incoherent term   **Coherent term**

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More Quantitatively...

The **energy W radiated per passage by incoherent radiation** can be obtained by integrating P over ω neglecting the coherent contribution. It can be shown that the relative **variance** for W is given by:

$$\delta^2 = \frac{\sigma_W^2}{\langle W \rangle^2} = \frac{\int\limits_{-\infty}^{\infty}\int\limits_{-\infty}^{\infty} |\hat{e}(\omega)|^2 |\hat{e}(\omega')|^2 |\hat{f}(\omega-\omega')|^2 \, d\omega \, d\omega'}{\left(\int\limits_{-\infty}^{\infty} |\hat{e}(\omega)|^2 \, d\omega\right)^2}$$

The shape of $e(\omega)$ is defined by the radiation mechanism properties or by the frequency acceptance of the system used for the measure of δ.

If we use a **bandpass filter with gaussian** transmission curve with rms bandwidth σ_ω and the **bunch is gaussian** with rms length in time units σ_τ, we can integrate the above expression and obtain:

$$\delta^2 = 1 \Big/ \sqrt{1 + 4\sigma_\tau^2 \sigma_\omega^2}$$

Possibility of absolute bunch length measurements !

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For $\sigma_\tau \gg 1/2\sigma_\omega$

$$\delta^2 \cong \frac{1}{2\sigma_\tau \sigma_\omega}$$

**When the bandwidth σ_ω, is fixed, the uncertainty principle defines the coherence length σ_{tc}. For the gaussian case:**

$$\sigma_{t_C}\sigma_\omega = \frac{1}{2}$$

The electric field of photons radiated within the coherence length σ_{tc} and within the bandwidth σ_ω adds coherently. σ_{tc} defines a radiation "mode".

$$\delta^2 \cong \frac{\sigma_{t_C}}{\sigma_\tau} = \frac{1}{M}$$

The previous equation shows that in a bunch of length σ_τ, there are $M = \sigma_\tau / \sigma_{tc}$ independent modes radiating simultaneously within the bandwidth σ_ω.

$M \sim 10$

E(t) (arbitrary units) vs t/τ_p
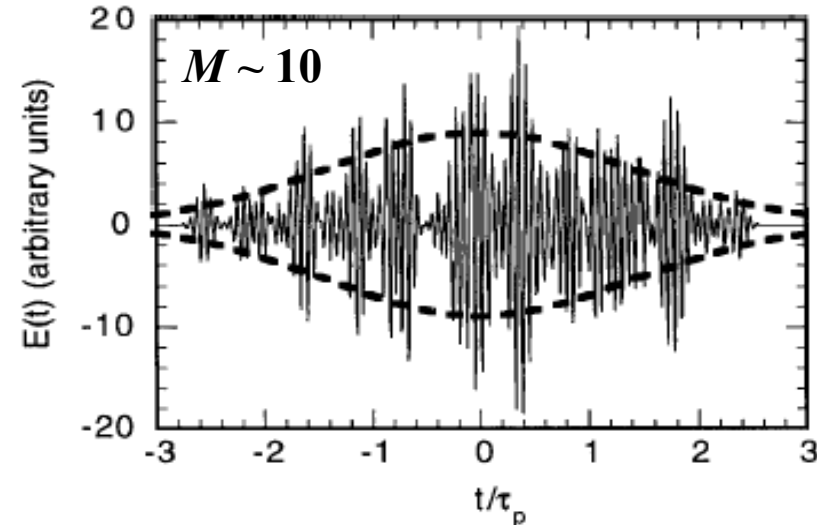
Each mode shows 100% intensity fluctuation, and the variance of the combined intensity scales as $1/M$ (M combined Poisson processes).

Dependence on Longitudinal Distribution

The previous expressions have been obtained for gaussian beams. In the general case:

$$\sigma_\tau = F_{Filter} \frac{F_{Dist.}}{\delta^2}$$

The filter form factor can be measured but the bunch longitudinal distribution is generally unknown.
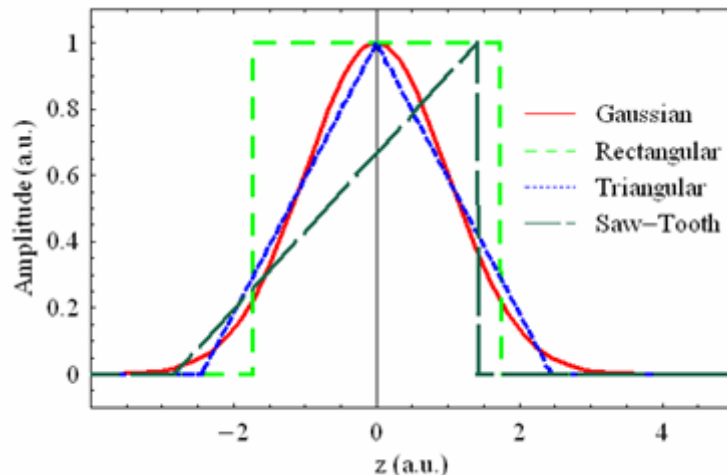
Distribution	Form Factor ($F_{Dist.}$)	Error Assuming Gaussian
Gaussian	$\frac{1}{2\sqrt{\pi}} \cong 0.2821$	0.0 %
Rectangular	$\frac{1}{2\sqrt{3}} \cong 0.2887$	-2.3 %
Triangular	$\sqrt{\frac{2}{27}} \cong 0.2722$	+3.6 %
Saw-Tooth	$\frac{4}{3\sqrt{18}} \cong 0.3143$	-10.2 %

Gaussian
Rectangular
Triangular
Saw-Tooth

The table shows that by using the expression for gaussian beams for different distributions, the consequent error is at the few % level for most cases, as long as the distributions are represented by their rms length and do not include microstructures with characteristic length << σ_τ.

In the previous derivation, a beam with no transverse size was assumed.

Analogously to the longitudinal case, the finite transverse size introduces additional independently radiating **transverse modes (M_x, M_y)**. The resulting intensity fluctuation variance becomes:

$$\delta^2 \approx \frac{1}{M} \times \frac{1}{M_x} \times \frac{1}{M_y}$$

For example, for the full gaussian case one obtains (with σ_x and σ_y the rms transverse beam sizes):

$$\delta^2 = \left(1 + \sigma_\tau^2 / \sigma_{tc}^2\right)^{-\frac{1}{2}} \left(1 + \sigma_x^2 / \sigma_{xc}^2\right)^{-\frac{1}{2}} \left(1 + \sigma_y^2 / \sigma_{yc}^2\right)^{-\frac{1}{2}}$$

The **transverse coherence lengths σ_{xc} and σ_{yc}** are defined by the radiation mechanism and include diffraction effects introduced by any limiting apertures.
σ_{xc} and σ_{yc} can be analytically calculated in the simpler cases or numerically evaluated (SRW, ...)

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The Tests at BL7.2 of the ALS

BL7.2 collects the synchrotron radiation from a dipole magnet.

The limiting apertures were defined by the beamline acceptance 5.5/2.8 mrad (H/V)

BP filter: gaussian filter 632.8 nm, 1nm FWHM

The signal from the avalanche photo-diode (APD) was amplified and sent to a digital scope for data acquisition and analysis. (LeCroy Wavepro 7300 A)

The setup allowed for comparison with streak camera measurements.

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The scope was set to measure the areas of the signal between the points A and B (S_{AB}) and between C and D (S_{CD}), and their statistical moments.

APD Signal

Area S_{AB} histogram

V. Scale: 50 mV/div   H. Scale: 500 ps/div
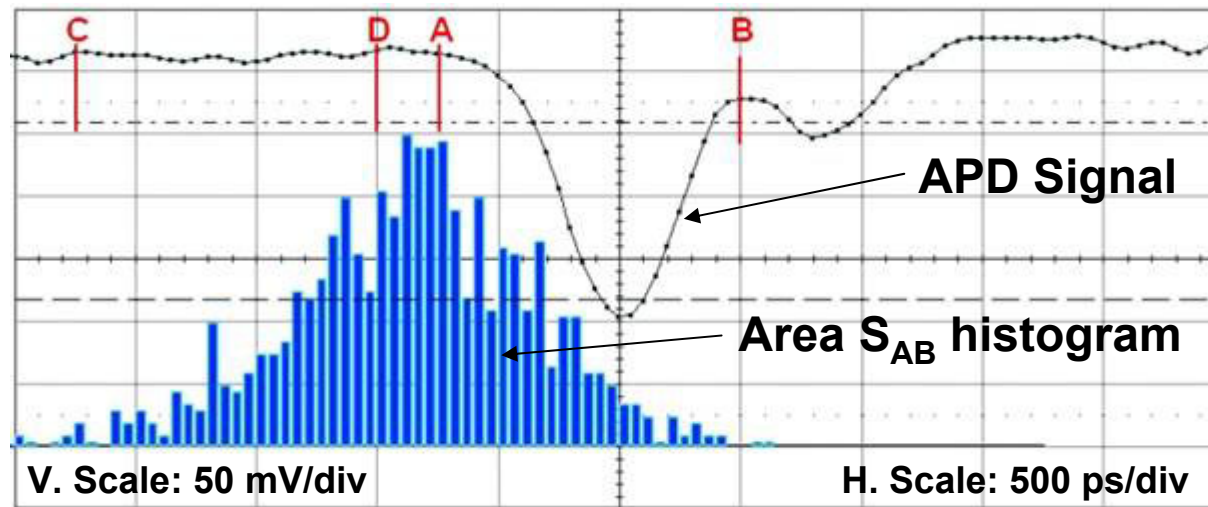
S_{AB} is proportional to the pulse energy convoluted with some electronic noise. S_{CD} is a measure of such a noise.

$$\Rightarrow \delta_M^2 = \frac{\sigma_{S_{AB}}^2 - \sigma_{S_{CD}}^2}{\left(\langle S_{AB} \rangle - \langle S_{CD} \rangle\right)^2}$$

A complete 5 ksample measurement required ~ 1 minute

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Quantum Noise Effects

The number of photons impinging on the APD is finite. Additionally, APDs exploit stochastic processes for the photon-to-electron conversion and for the amplification.

All this effects generate extra-fluctuations (shot noise) that need to be accounted.

$$\sigma_\tau^2 = \frac{1}{4\sigma_\omega^2}\left[\left(\delta_M^2 - \kappa^2\right)^{-2}\left(1 + \frac{\sigma_x^2}{\sigma_{xc}^2}\right)^{-1}\left(1 + \frac{\sigma_y^2}{\sigma_{yc}^2}\right)^{-1} - 1\right]$$

The term κ represents the total photon shot noise and accounts for all the terms above mentioned.

κ needs to be measured once forever, and this can be easily done by performing 2 or more measurements of δ_M^2 for the same bunch length for different number of photons impinging on the APD (using neutral density filters for instance).

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A Sample of the ALS Results

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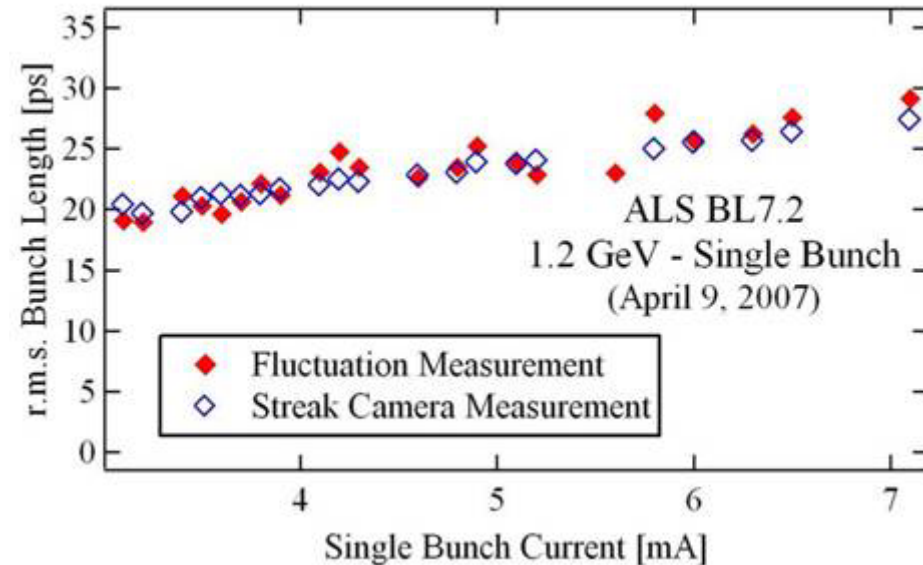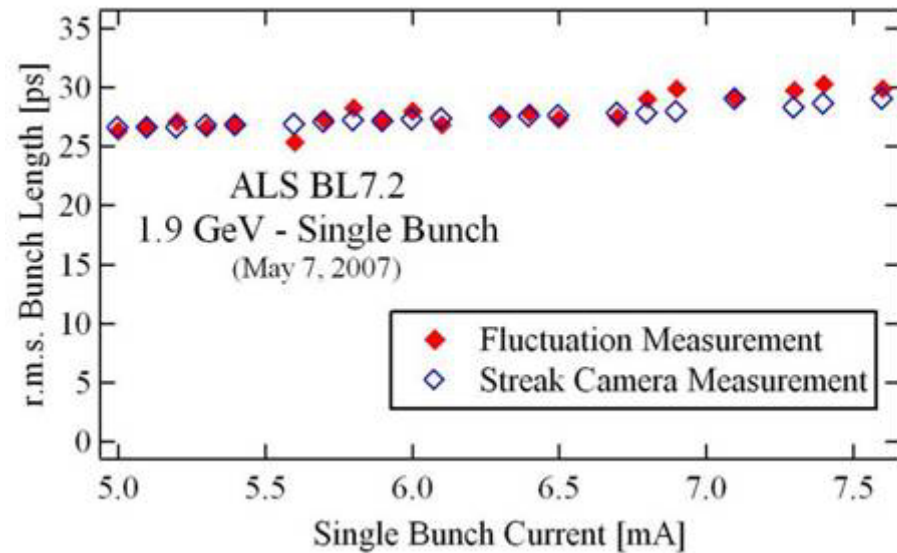
Remarkably good agreement with streak-camera data.
No parameter has been adjusted to fit the data.

**It can be shown that the statistical contribution to the error is given by (~ 2% with 5 ksamples):**

$$\frac{\Delta\sigma_\tau}{\sigma_\tau} = \sqrt{\frac{2}{N_{Samples}}}$$

The typical rms difference between the streak camera and the fluctuation data was ~ 4 %. The extra error is probably associated with the shot noise term that in our measurements was comparable to δ^2.

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Frequency Domain Applications

Frequency domain versions (derived by the 1996 method by Zolotorev, Stupakov) have been already successfully used.

They require a more complex scheme with a photon spectrometer, but potentially allow for single shot measurements.
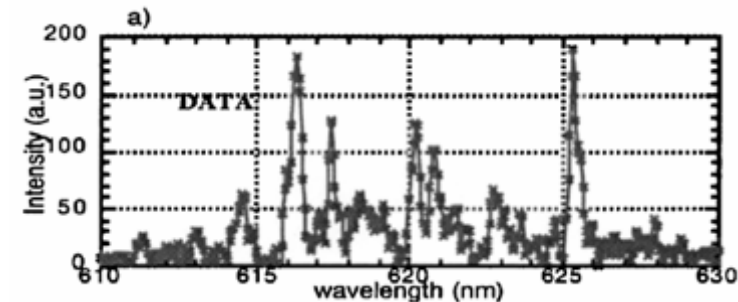
Catravas. ATF measurement

P. Catravas et al., PRL 82, Number 26, June 99

First measurement using the spectrometer technique with undulator radiation at ATF.

V. Sajaev, EPAC 2000, p. 1806

V. Sajaev, BIW 04 p. 74

**Measurements using the spectrometer technique with undulator radiation at LEUTL, Argonne.
Phase retrieval techniques.**

Saldin et al, Opt. Commun. 148, 383 (1998)

M. Yabashi et al., PRL 97, 084802 (2006)

Measurement of the X-rays pulses in SASE FELs.

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Pseudo Single Bunch

ALS (and other light sources as well) dedicates 4 weeks/year to a mode of operation where two high current bunches are stored diametrically opposed .

~ 30 mA/bunch

This special mode allow users to perform experiments requiring a long relaxation time.

The photons from the main bunches excite their samples and the gap between the two bunches (~ 330 ns) permits data taking during the sample relaxation without the contaminating radiation from other bunches.

**"Camshaft" bunch
10 mA in ~ 100 ns gap**

**276 bunches
~ 1.4 mA / bunch
2 ns spacing**
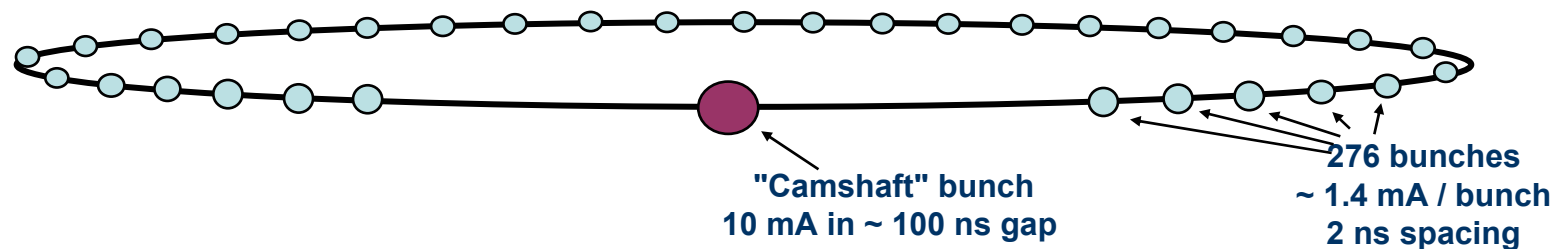
Such experiments <u>cannot</u> run during standard multibunch operation because the gap is to small (~ 100 ns)

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A New Operational Mode: Pseudo Single Bunch

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Electrical Engineering: Slawomir Kwiatkowski and Jim Julian
Physics: Greg Portmann
Mechanical Engineering: Dave Plate and Ray Low
Beamlines: Bob Schoenlein, Marcus Hertlein
Advisors: Walter Barry, Dave Robin, John Byrd, Derun Li, Stefano De Santis, Ken Baptiste, Christoph Steier, Fernando Sannibale, Janos Kirz
**(Poster TUPTPF047)**

Now

10 mAmps

276 Bunches
1.4 mAmps / Bunch
2 nsec spacing
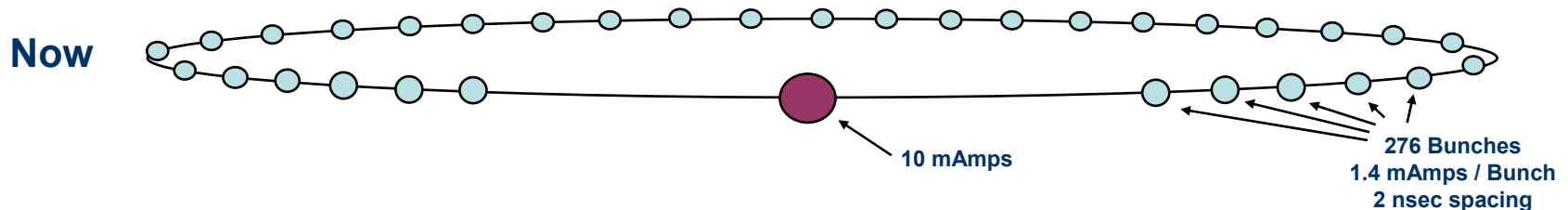
**By vertically kicking only the camshaft bunch,
and collimating out the light from the other bunches,
a pseudo single bunch operation could be obtained.**

Pseudo single bunch

Courtesy of G. Portmann

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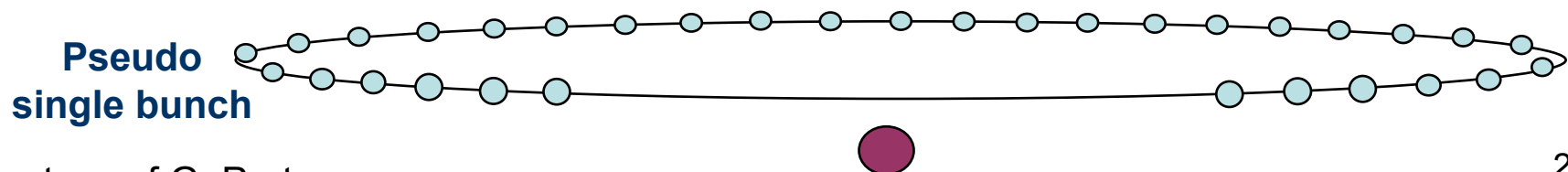
One Kicker, Kick a Single Bunch Every Turn

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Single Kicker Magnet – 1.5 MHz Single Bunch Frequency (60 µrad kick)
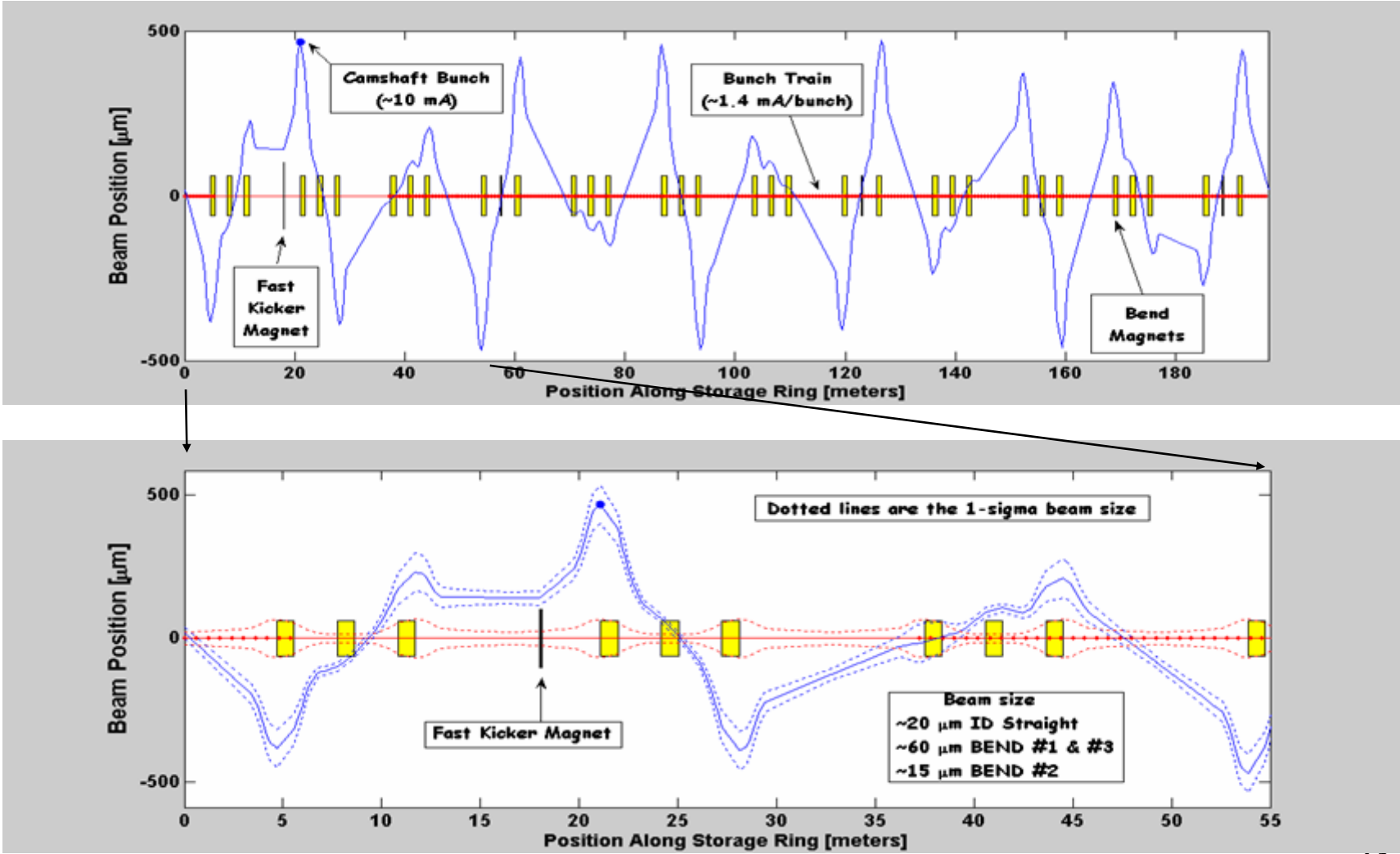
Courtesy of G. Portmann

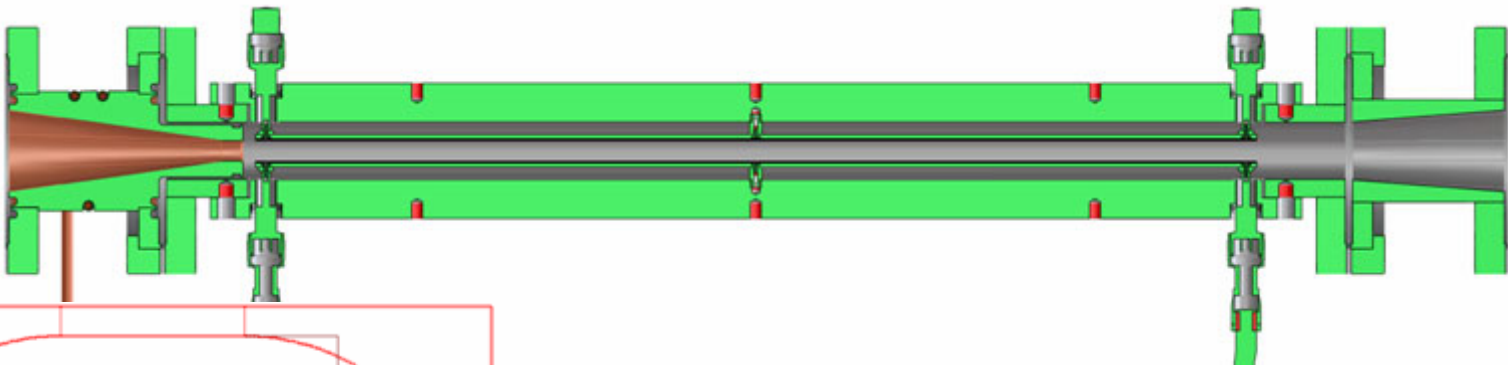# 3 Kicker Sector Bump, Kick Whenever You Want

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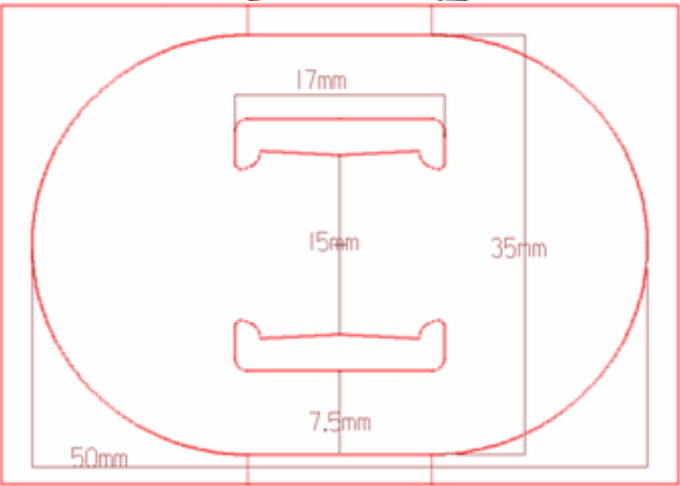## Local Bump using 3 Kicker Magnets – Variable Single Bunch Frequency
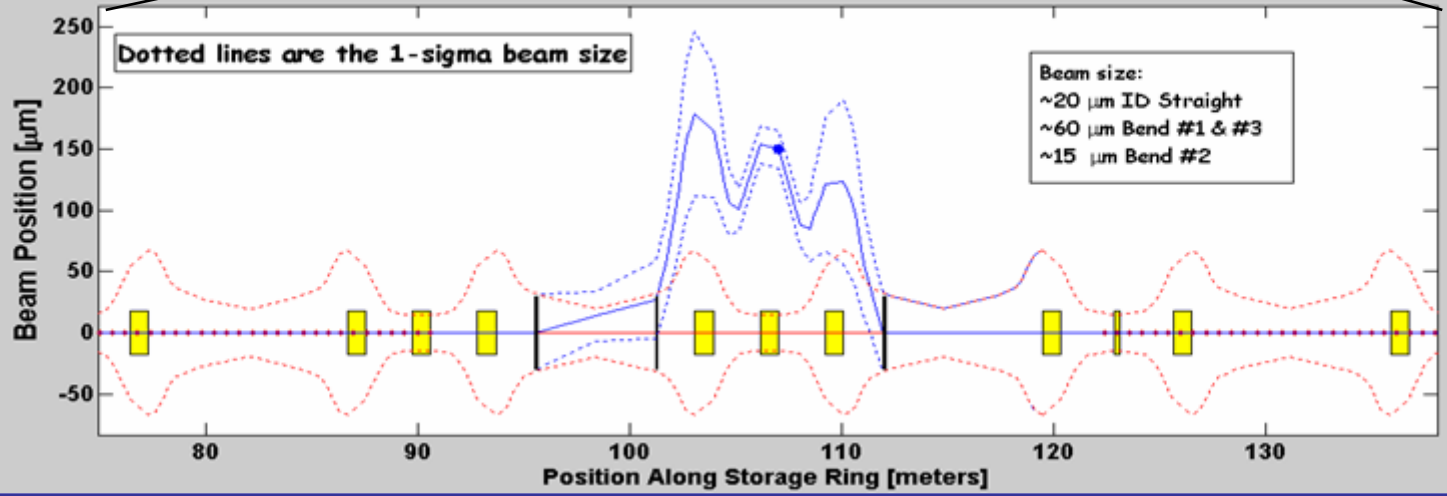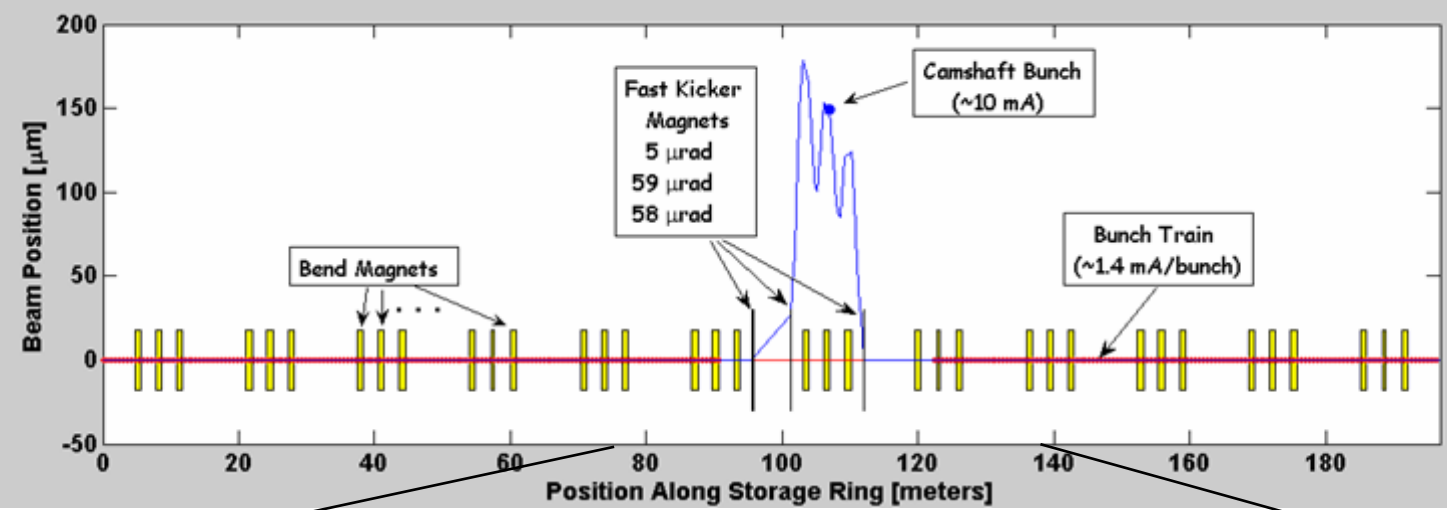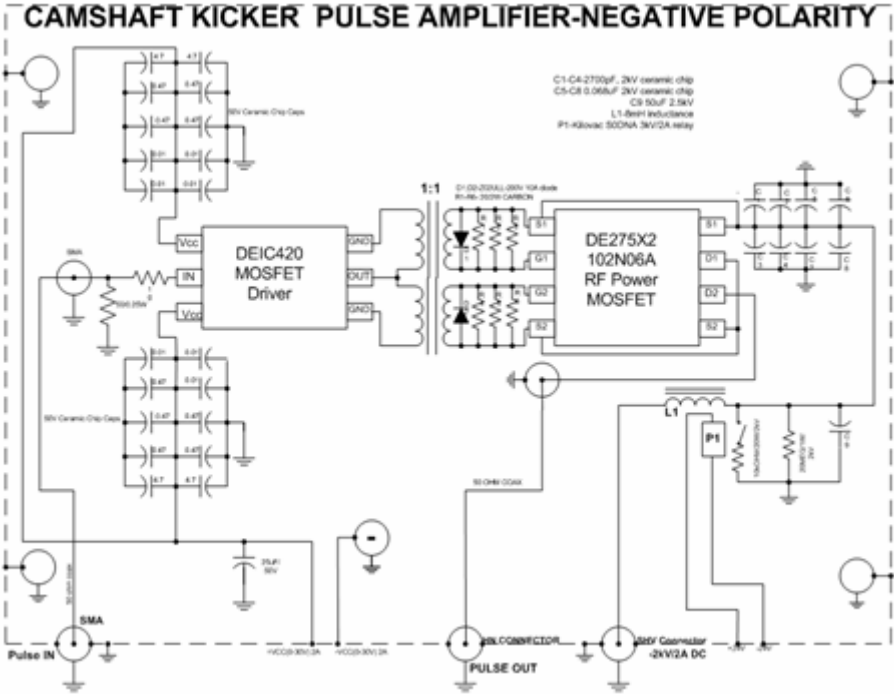

Courtesy of G. Portmann

Kicker Structure

0.6 meters, 50 Ohm Stripline kicker
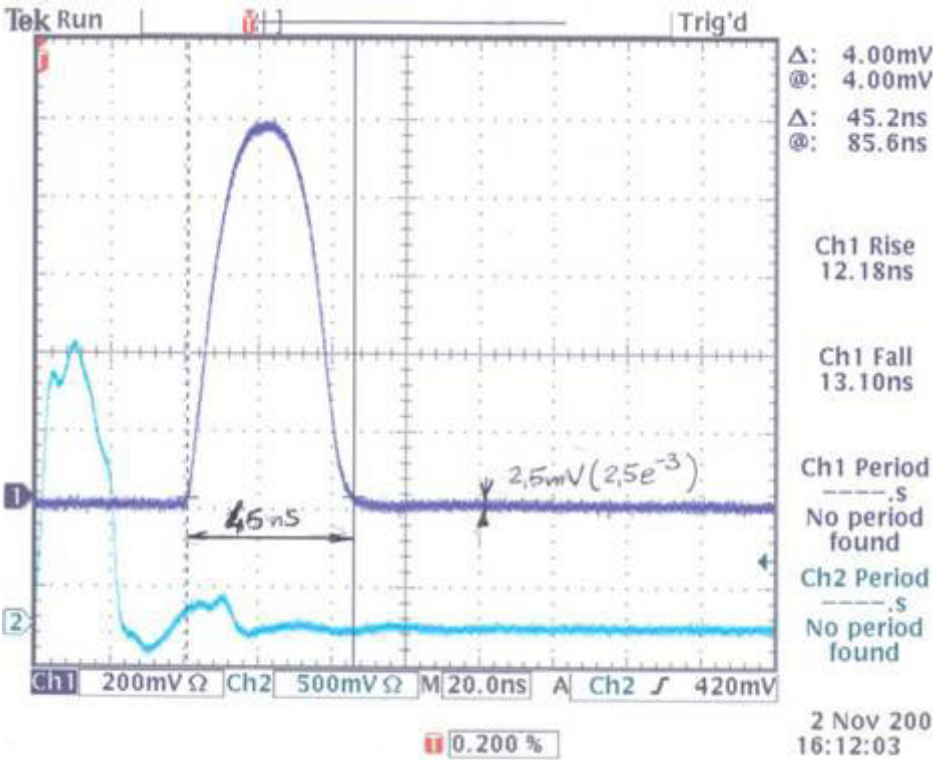**Deflection Angle: 73 μrad/kV**

17mm

15mm   35mm

7.5mm

50mm

Courtesy of G. Portmann

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Kicker Pulser

CAMSHAFT KICKER PULSE AMPLIFIER-NEGATIVE POLARITY

1 kV/electrode @ 1.5 MHz
1 kW average power
~ 10 kW peak power

Two fast MOSFET in push-pull configuration.

2 Nov 2006
16:12:03

First Results
(Kicker installed on January 3, 2008)
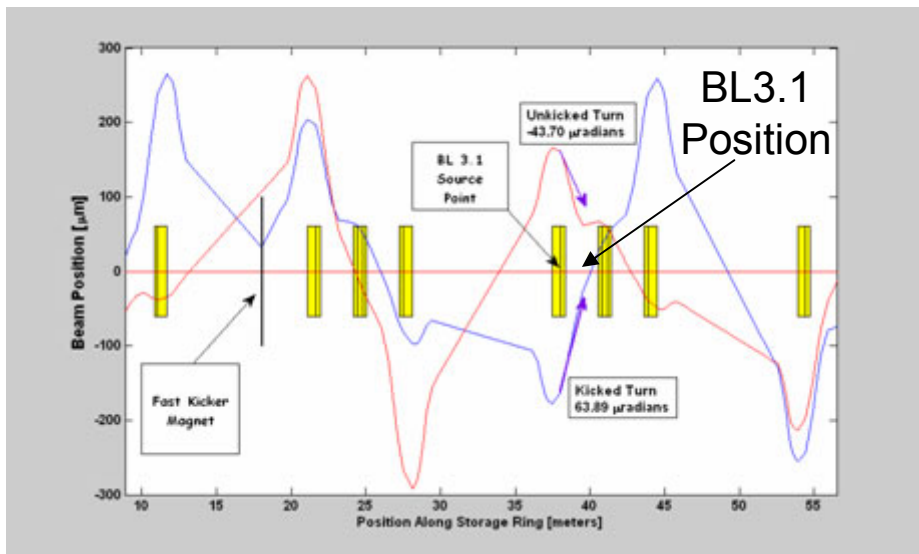
Measured orbit (dots) compared with model (solid line)
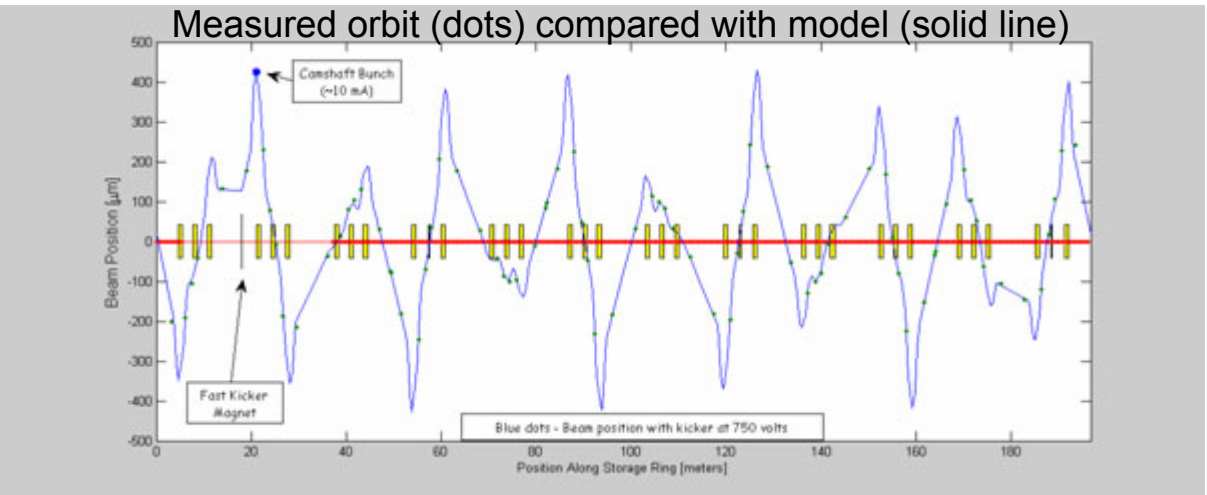
Courtesy of G. Portmann

750 volts on the kicker at 1.52 MHz (kicking every turn), 55 μrad kick (model).
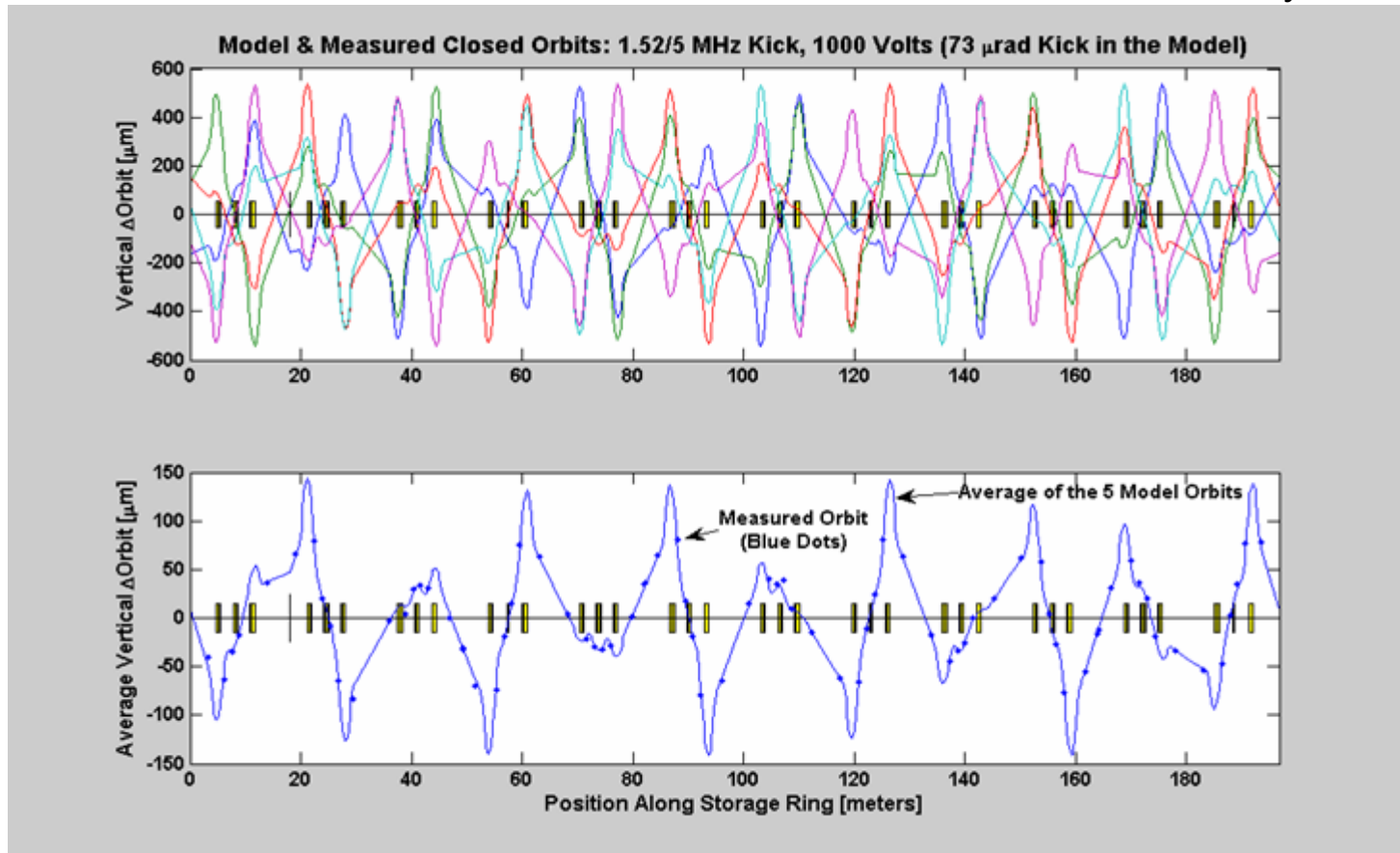
Image on the synchrotron light monitor (BL 3.1) when kicking every other turn

Model orbits when kicking every other turn
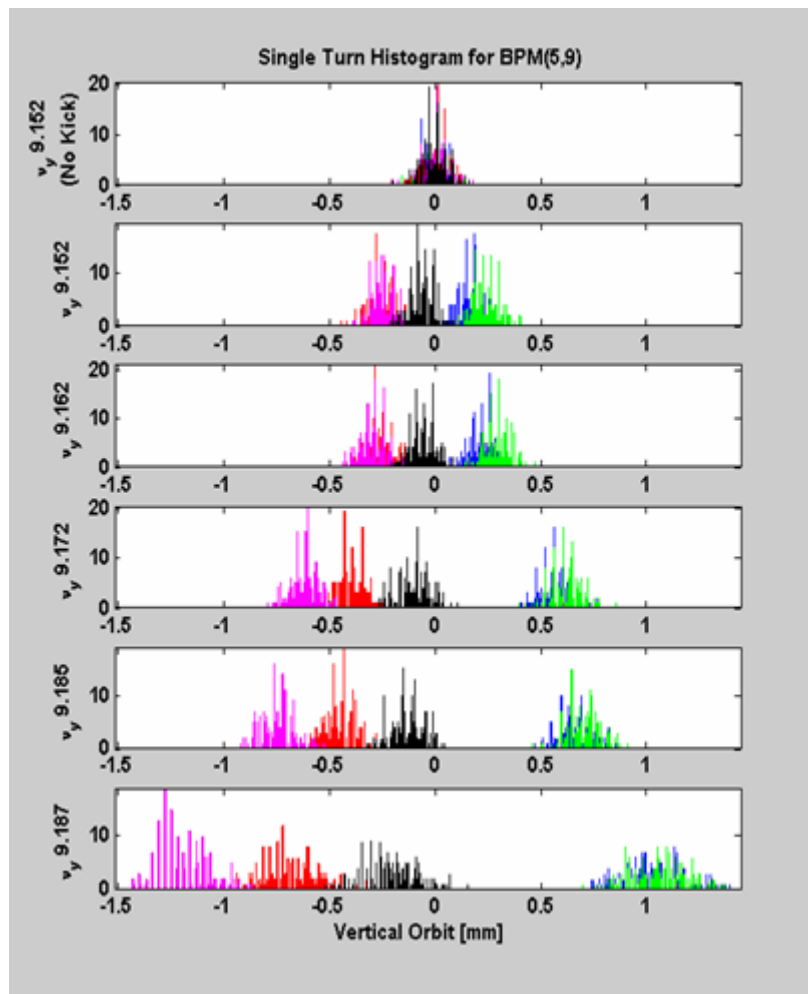
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Kicking Every n-th Turn

Courtesy of G. Portmann

Model & Measured Closed Orbits: 1.52/5 MHz Kick, 1000 Volts (73 μrad Kick in the Model)

- **The slow BPMs measure the center of charge (average of the 5 Orbits). The measured data shows very good agreement to the average of the 5 model orbits.**

- **By kicking every n-turn one can control the "repetition rate" of the pseudo single bunch and also create the displacement in all beamlines.**
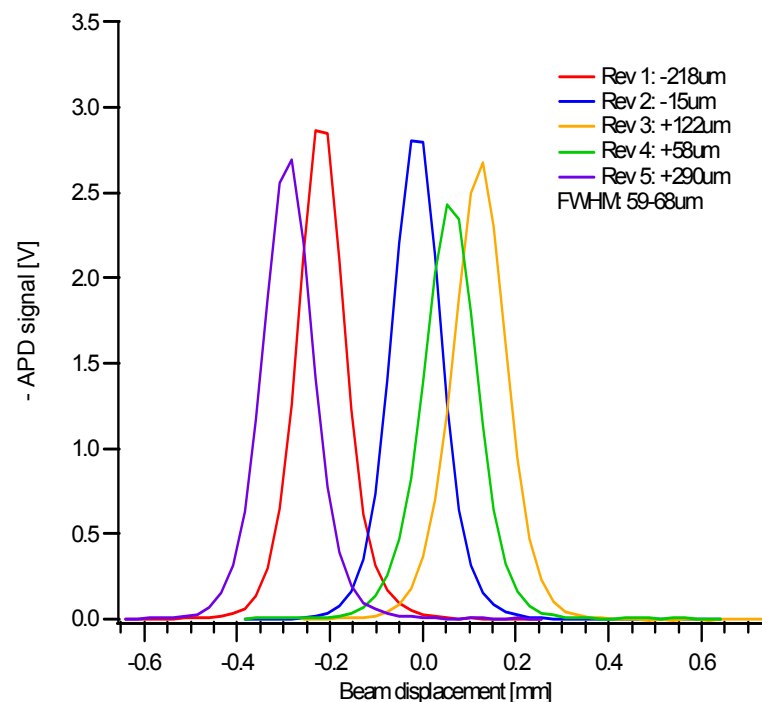
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New ALS Diagnostics and Instrumentation F.Sannibale

BERKELEY LAB

Courtesy of G. Portmann

Single Turn Histogram for BPM(5,9)

Orbit Amplitude α 1/sin(πν)

- Rev 1: -218um
- Rev 2: -15um
- Rev 3: +122um
- Rev 4: +58um
- Rev 5: +290um

FWHM: 59-68um

Histogram of 1024 Turns at a BPM Just Upstream of BL 6.0 for Different Vertical Tunes.

5 Beam Profile Measures at BL 6.0 using a avalanche photon diode (M. Hertlein).

**Very promising results! Additional characterization in progress.**

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Bunch Cleaning

During the 4 weeks of "two-bunch" operation dedicated to experiments requiring a long relaxation time (with two high current equally spaced bunches), the gap between the two bunches must be free of electrons to avoid data contamination by the photons radiated by this undesired electrons.

At the ALS, because of imperfect injection, some of the "empty" buckets are usually populated with undesired electrons at a level of the order of 0.1% respect to main bunches.
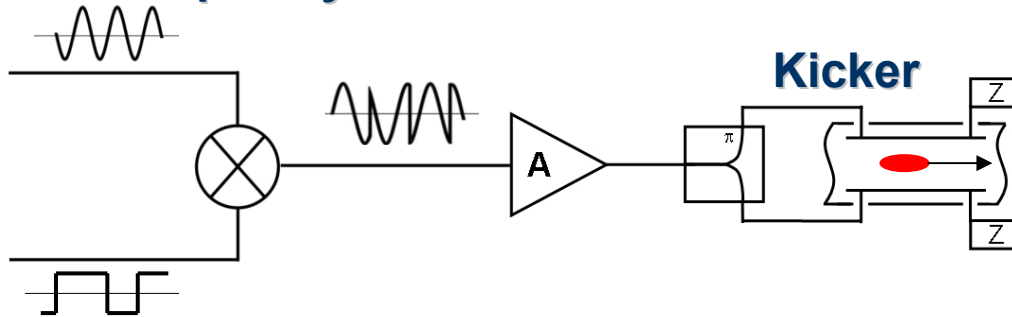
This is a severe limitation for a number of users that require bunch "purity" of 10^{-4} or better.
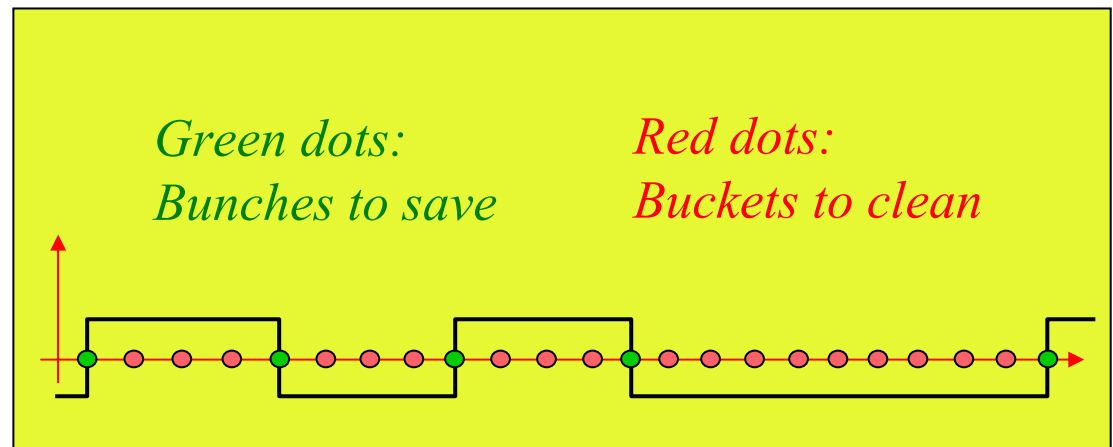
"Bunch cleaning" is required!
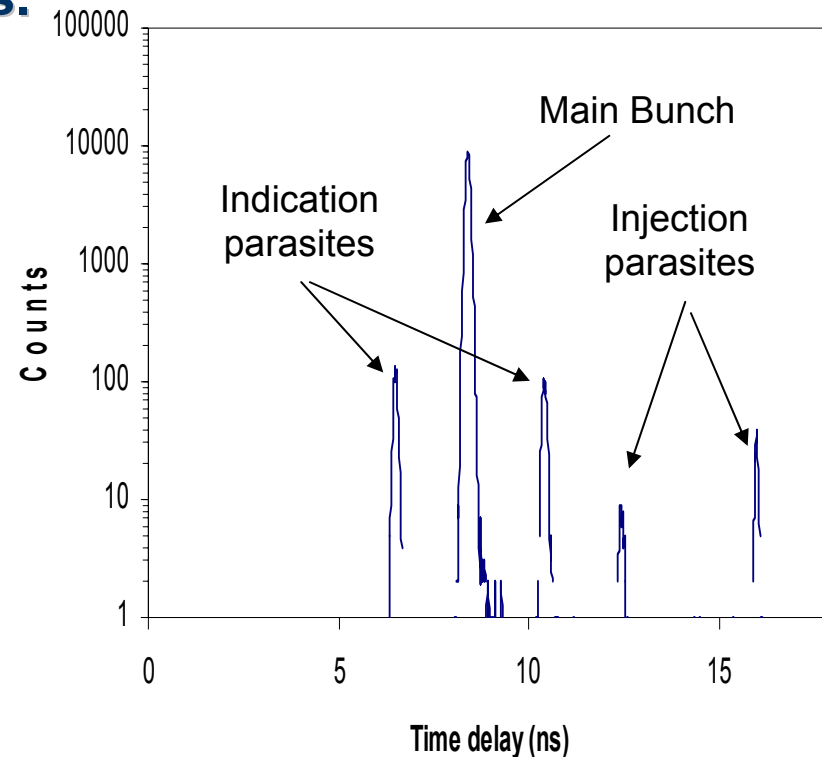
Bunch Cleaning Scheme
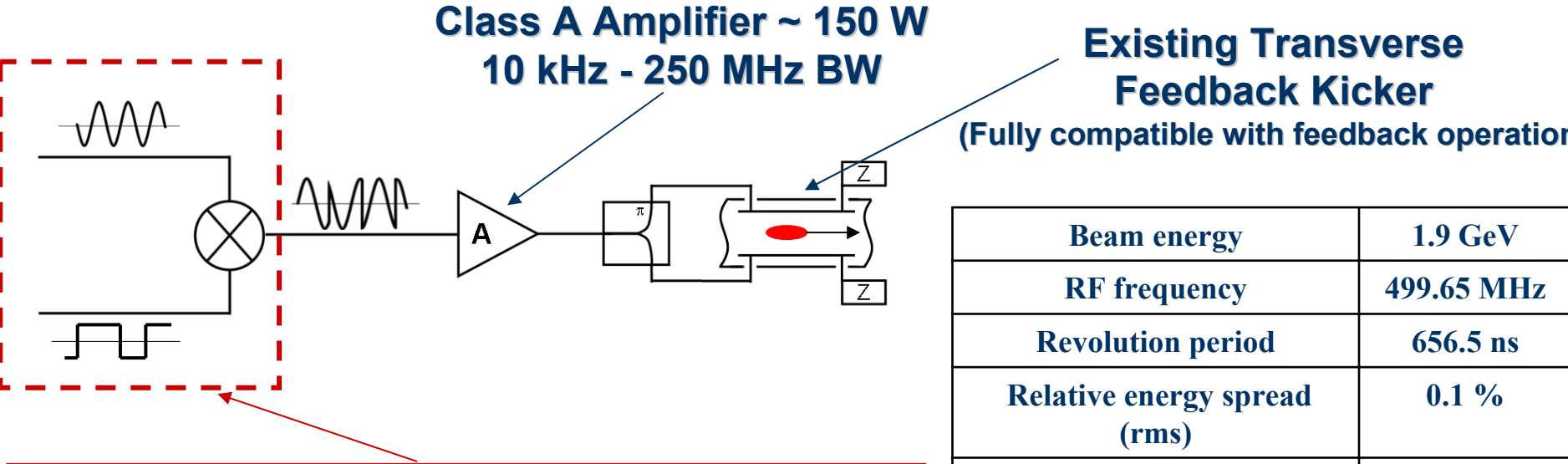
Sinusoid at Vertical
Betatron Frequency

Kicker

Pseudo-square wave

Green dots:
Bunches to save

Red dots:
Buckets to clean

H. Suzuki, *et al*., NIM A **444** (2000) 515-533.

Tested also at ESRF (E. Plouviez)

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The ALS Implementation

Class A Amplifier ~ 150 W 10 kHz - 250 MHz BW

Existing Transverse Feedback Kicker
**(Fully compatible with feedback operation)**

Low cost Xilinx demo-board (HW-V4-ML403-USA) with a DAC and with a 4VFX12 Virtex-4 FPGA clocked at the ALS 500 MHz RF. Imbedded Power-PC allows network control .

Beam energy	1.9 GeV
RF frequency	499.65 MHz
Revolution period	656.5 ns
Relative energy spread (rms)	0.1 %
Vertical Tune	8.20
Vertical chromaticity	1.4
Vert. excitation frequency	1.22 MHz
Excitation bandwidth	4 kHz
Kicker type	stripline
Kicker transv. shunt imped.	~ 9000 Ω
Amplifier operation power	~ 150 W
Amplifier bandwidth	~ 250 MHz

M. Chin, W. Barry, F. Sannibale, J. Weber (Poster TUPTPF074)

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Signal Examples
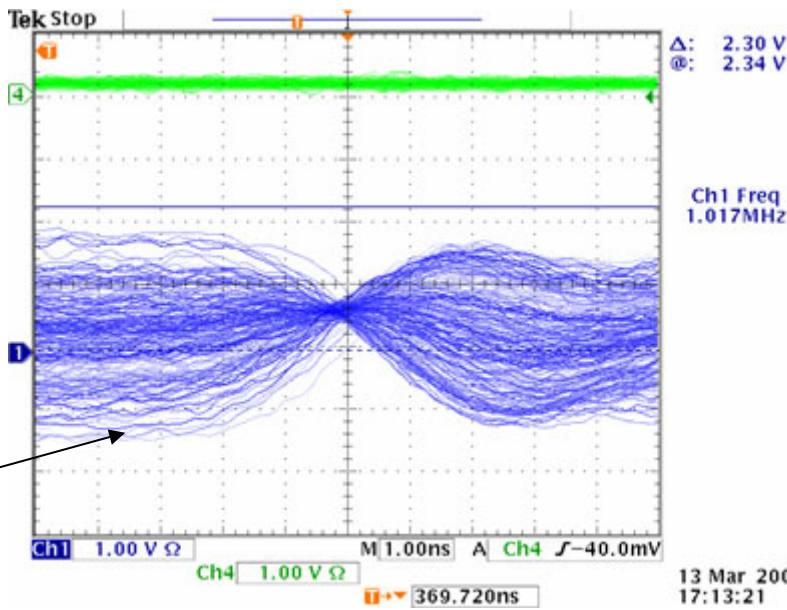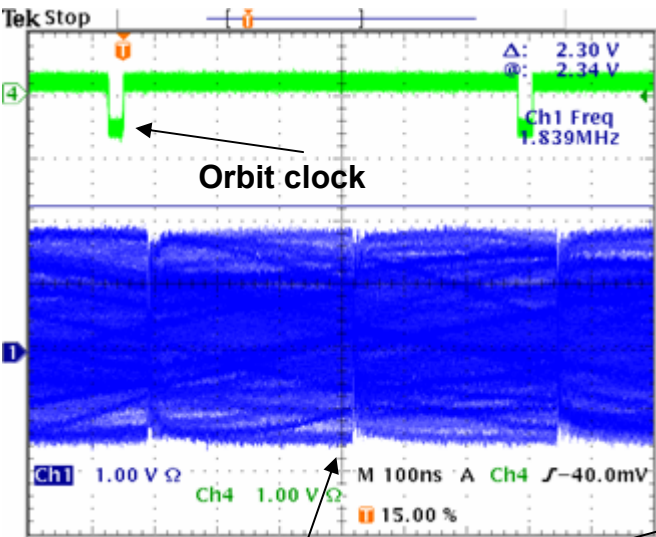
Signal at the kicker

**Arbitrary cleaning patterns
easily programmable.**
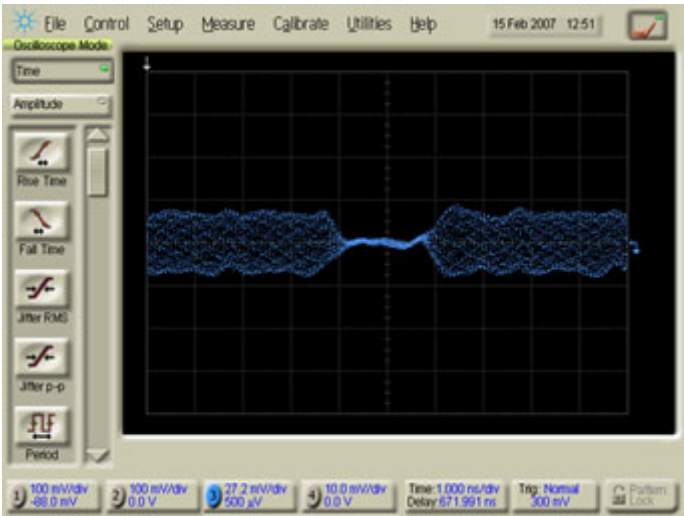
Purity and Cleaning Speed

Before Cleaning

Main Bunch

Indication parasites

Injection parasites

Counts

Time delav (ns)

After Cleaning

Counts

BL 7.2
Anton Trensim
Jinghua Guo

Time delay (ns)

Excitation Signal [V]

BPM Sum Signal [mV]

ALS - 2 bunch lattice
2 mA single bunch current
~150 W excitation at 1.22 MHz
(vertical tune side band), 4 kHz BW

Time [s]
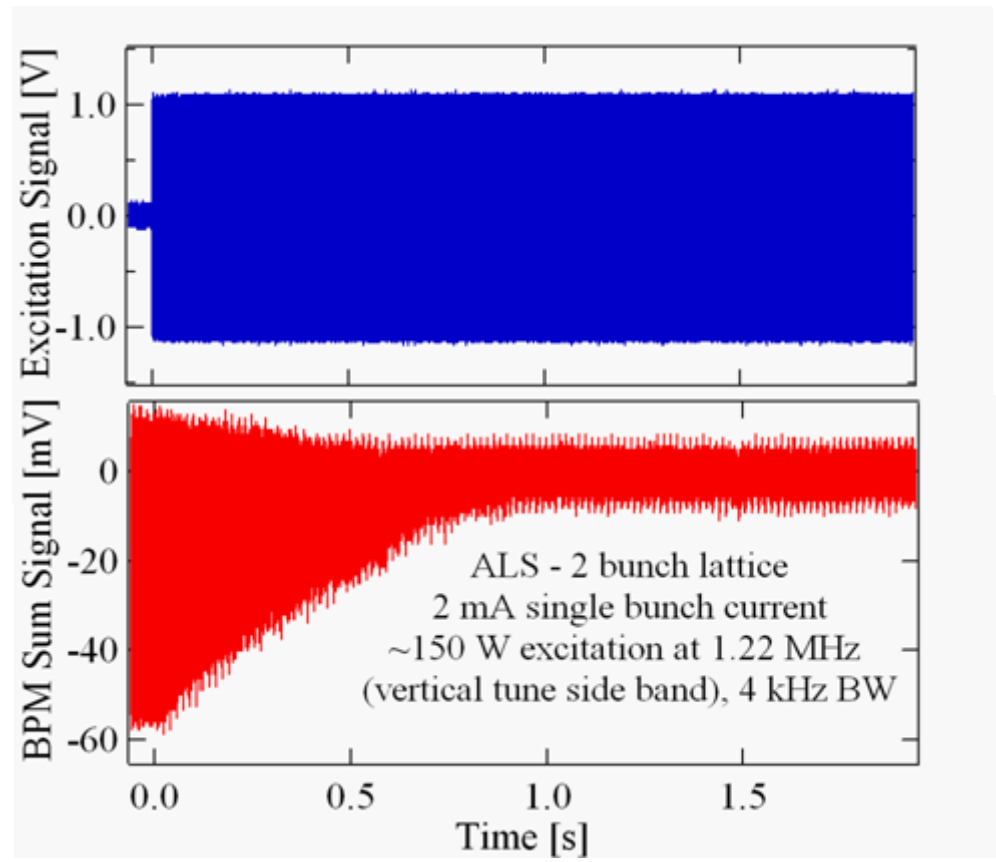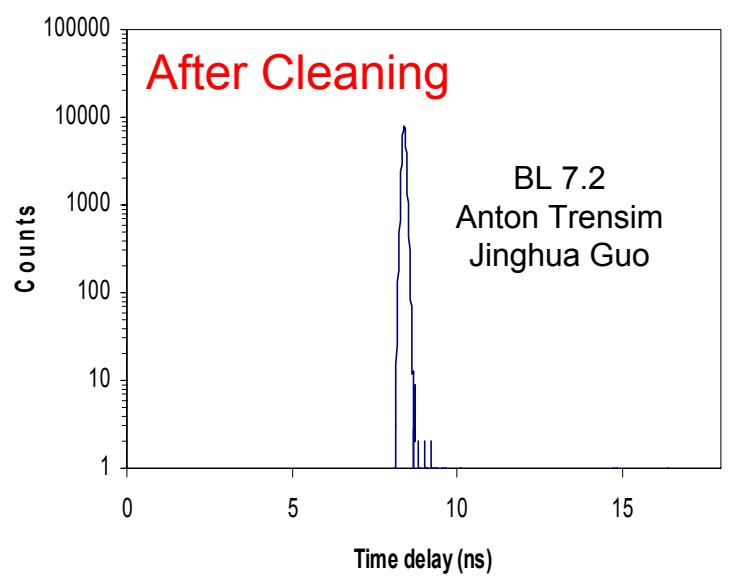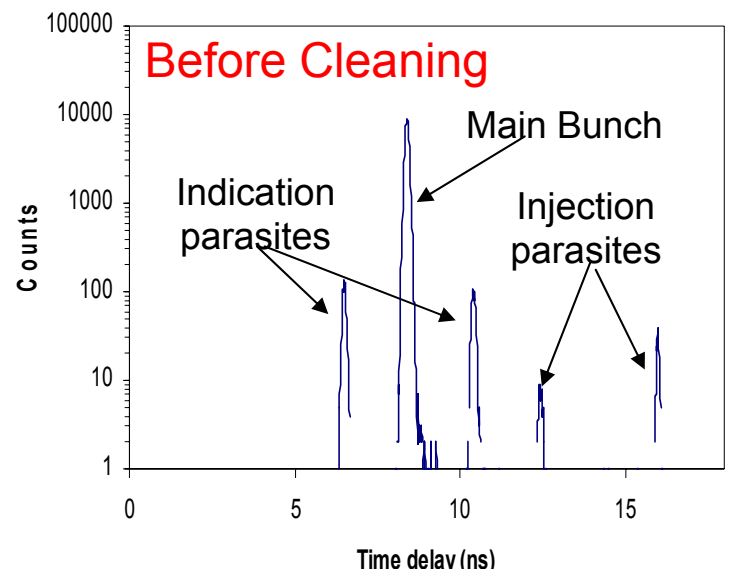
Purity is extremely good.

Cleaning time constant ~ 0.4 s.
(cleaning system not optimised)

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