Synchronization and Timing Challenges for Future Light Sources

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Plan

Introduction and coverage

General issues and ways of addressing them

Specific examples

Conclusions

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Timescales

Slow - minimum bunch rate of machine

Orbit period in a storage ring ~ microseconds

Macrobunch spacing in a linac ~ milliseconds to seconds

Fast - minimum inter-bunch period

Depends on RF ~ nanoseconds

Fastest - comparable with bunch length or photon pulse length

Can be ~ picoseconds to femtoseconds

Slowest - set by length of experiment or period between re-tunes

Can be ~ hours (or days ?)

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Applications

What drives the need for timing management on the shortest timescales ?

User experiments:

Multiphoton, nonlinear optics (need synchronism)

Pump-probe (needs delay)

Coherent control* (e.g. pump-dump, needs delay and pulse shaping)

Machine requirements:

Control of energy variation (RF, lasers)

Operation of diagnostics (EO sensors)

FEL seeding, electron bunch modulation (conventional lasers)

Compton scattering (particularly with optical storage cavities)

*See e.g. M Shapiro and P Brumer, Rep Prog Phys **66** (6) 859 (2003)

Measurement and control

Measurement:

Timing can be managed by measurement and data binning e.g.

using timing jitter to map out a decay curve in pump-probe

rejecting asynchronous data in multiphoton experiments

Control:

Timing stabilisation may be called for

when data rejection or process failure is too inefficient

when jitter distribution is inappropriate

when a nonlinear response needs to be strongly averaged

Active control depends on measurement, but passive control does not (so can be used e.g. to extend stability in gravitational wave detectors)

Intermediate approaches exist (e.g. controlled frequency offset to allow "automatic" time scanning between consecutive pulses*)

*X Yan et al, Phys Rev Letts **85** (16) 3404 (2000)

Timing control - passive

- Photons and electrons travel at or near c, so their speed is ~fixed and their arrival times depend predominantly on PATH LENGTH
- 10fs corresponds to 3μm in vacuum

Subsystem	Path length (m)	Notes
Laser cavities	0.2 - 40	Perhaps 10km, given recirculation
LLRF distribution	10 - 3000	X1.5 correction factor for signal speed
Electron BTS	200 - 2000	Also depends on e^- energy and EM fields
Photon BTS	2 - 1000	X1.5 if in fibre

- The above can be affected by:
  - Temperature (~10 ppm/K unless invar/Zerodur/PS cable and fibre used)
  - Vibration, ground stability and materials creep
  - Machine tuning (e.g. in multi-user operation)
- Maximum passive stability forms the best basis for active control, but will ultimately be limited by cost

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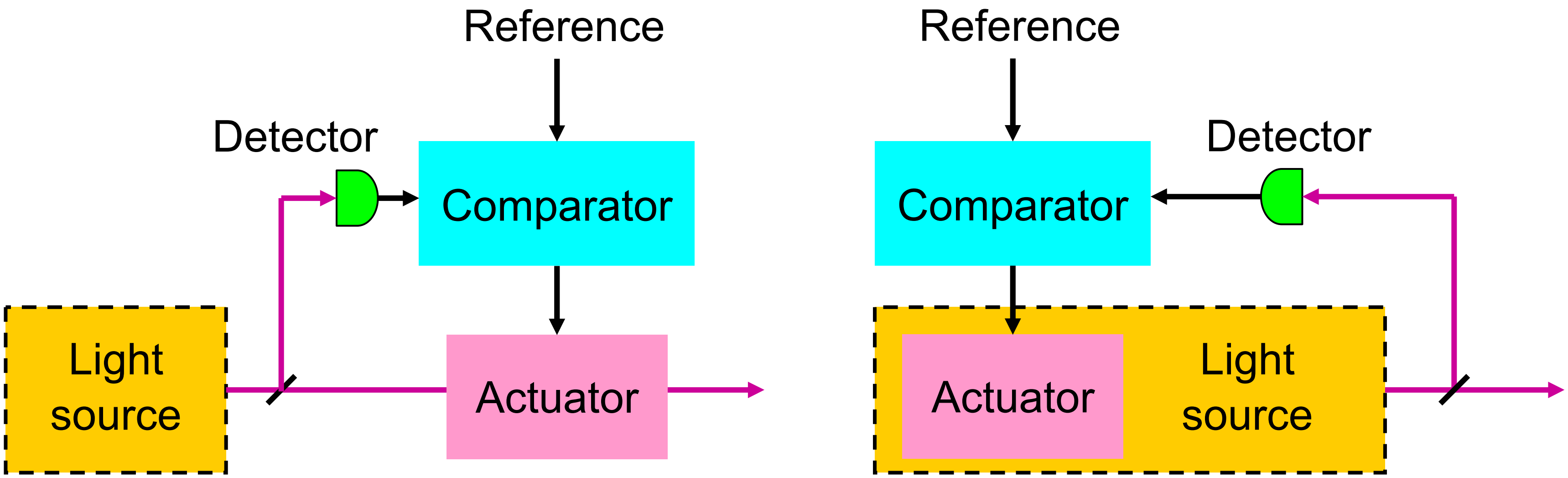
Timing control - active



- Active synchronisation involves DETECTING the timing, generating an error signal based on COMPARISON with a reference and correcting the error with one or more ACTUATORS, ideally in a closed feedback loop
- Detectors must be optimised for stability, linearity and signal-to-noise near the zero-error position and should be sited as near as possible to the point of use
- The speed, range and linearity of actuators commonly limit the rate at which timing noise can be corrected – above this limit stabilisation must be passive
- An optimised, closed-loop feedback control system can suppress noise by many orders of magnitude

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Timing detection - sensors

PHOTONS

Photodiodes	<100 ps resolution, issues with signal vs speed, saturation, sensitivity at low photon energy and thermal effects
Streak cameras	<500 fs resolution, 20 ps window, issues with dynamic range, readout speed, triggering (use timing fiducial), sensitivity at low photon energy and cost

Hamamatsu
FESCA 200

200 fs resolution

20 ps window

1.4eV – 4.5eV

100 Hz sweep rate

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Timing detection - sensors

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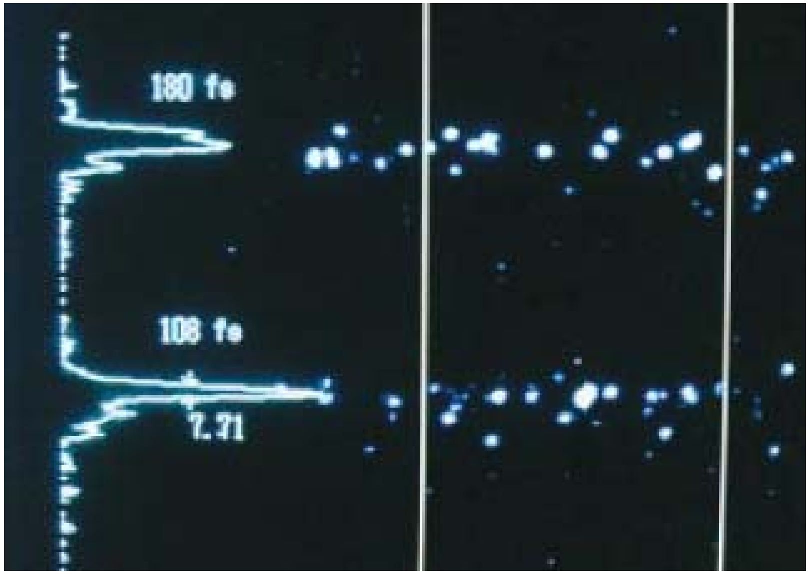

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Timing detection - sensors

PHOTONS	
Photodiodes	<100 ps resolution, issues with signal vs speed, saturation, sensitivity at low photon energy and thermal effects
Streak cameras	<500 fs resolution, 20 ps window, issues with dynamic range, readout speed, triggering (use timing fiducial), sensitivity at low photon energy and cost
Correlators	<30 fs resolution, window ~ pulse duration, issues with sensitivity*, stability, spectral range† and readout speed
"Amphibians" (FROG, TOAD SPIDER …)	<10 fs resolution, issues as with correlators (maybe worse) plus signal deconvolution, mainly used for pulse profiling
ELECTRONS	<30 fs (Florian Löhl, WG5 paper)
Pickups	~~<1 ps~~ resolution (zero crossing)
SR correlators	see correlators above
EO sensors	<100 fs resolution (30 fs ?), few ps window

*V Tenishev et al, Meas Sci Tech **15** (9) 1762 (2005)

†B W Adams Rev Sci instr **73** (3) 1632 (2002)

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Time and frequency domains

Timing sensor outputs can have (at least) two uses:

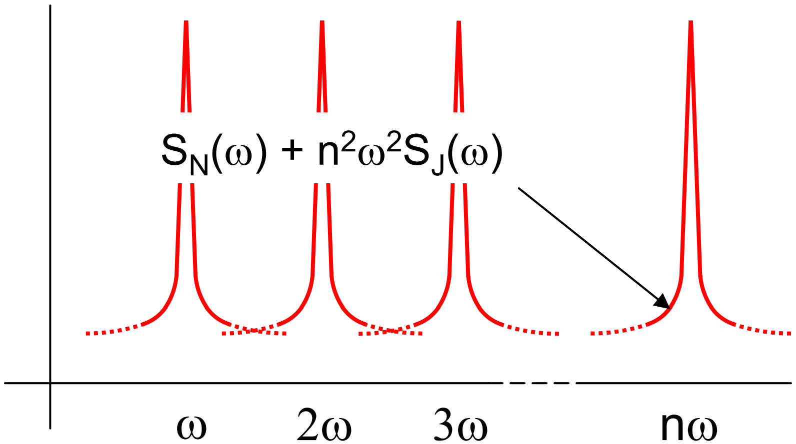
As the signal source for a full timing jitter measurement

As the input to a timing control system

Low noise, high resolution spectrum analysers allow the best jitter measurements to be made in the **frequency domain**, whereas rapid timing control takes place in the **time domain**

In each case it is necessary to separate timing (phase) information from the effects of amplitude variation

The spectrum of the sensor signal consists of the fundamental and its harmonics whose sidebands reflect amplitude noise, $S_N(\omega)$, and phase noise, $S_J(\omega)$. Phase noise dominates at high harmonic number*



Phase noise derivation at high n has significantly improved timing control†

*M J W Rodwell et al, IEEE JQE **25** (4) 817 (1989)

†R K Shelton et al, Opt Letts **27** (5) 312 (2002)

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Time and frequency domains

Jitter measurements can also be carried out using high harmonics to isolate phase noise, but an alternative approach may be more accurate

It can be shown* that if a timing sensor signal is filtered and mixed with a reference oscillator, both at the fundamental, the mixer output will reflect only the phase noise if the signal and reference are kept in quadrature

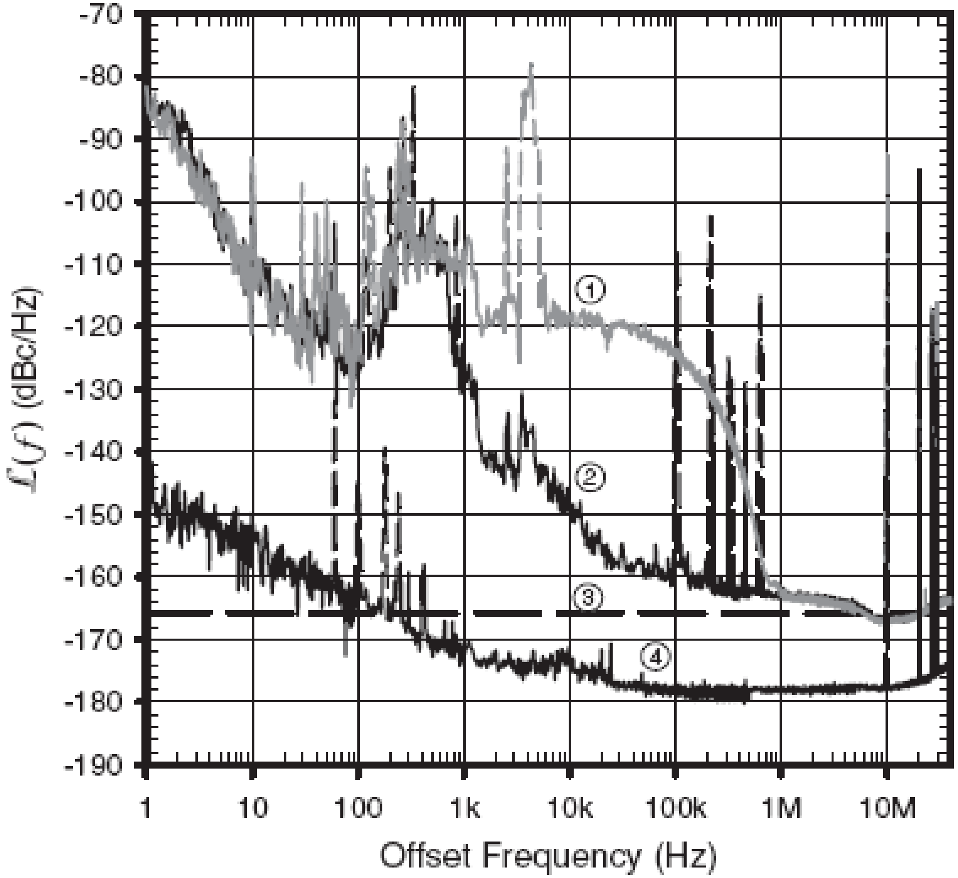
① TiS laser pumped by Ar^+

② TiS laser pumped by DPSS

③ Detector shot noise limit

④ Analyser system noise floor

$$\Delta t_{RMS} = \frac{1}{n\omega_0}\sqrt{2\int_{f_1}^{f_2}\mathcal{L}(f)df}$$



*R P Scott, C Langrock and B H Kolner, IEEE J Select Topics in QE **7** (4) 641 (2001)

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Sampling

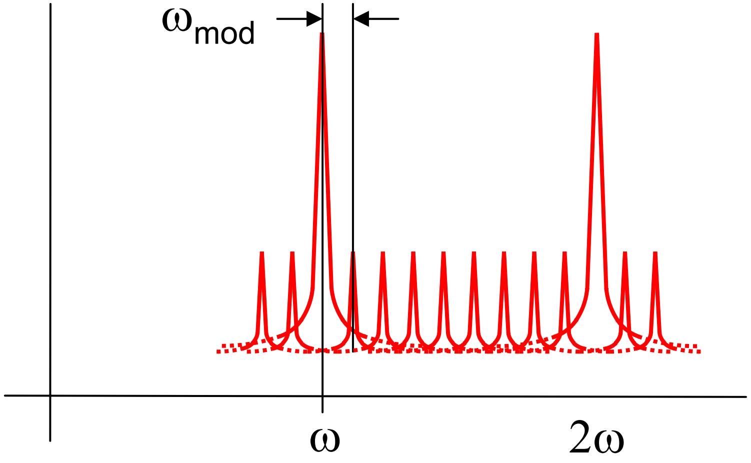
Nyquist sets an upper limit of ~ω/2 to the noise frequency which can be sampled by a probe pulsed at ω

Electron bunches and photon pulses are commonly used as probes of their own timing noise spectra, which may well have components above ~ω/2

Noise probed this way will appear to be random jitter in the time domain

The Nyquist limit is a special case of a more general result concerning modulated pulse trains

The impact of simple modulation on frequency domain phase noise measurement has been analysed elsewhere*



*Agilent application note AN 386 (2000)

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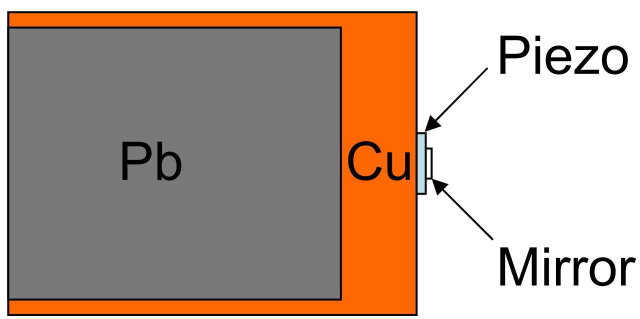
Timing actuators

Issues - Range, Speed, Linearity (resonances) and stability

PHOTONS — R S L

Moving mirrors: piezo-mounted

Implemented in L Matos' lab at MIT
>60 kHz f_{res}



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Timing actuators

Issues - Range, Speed, Linearity (resonances) and stability

PHOTONS R S L

Moving mirrors: piezo-mounted

motorised

New Focus
Picomotor

30 nm resolution

20 μm/sec

Model 8302 1" Picomotor Actuator

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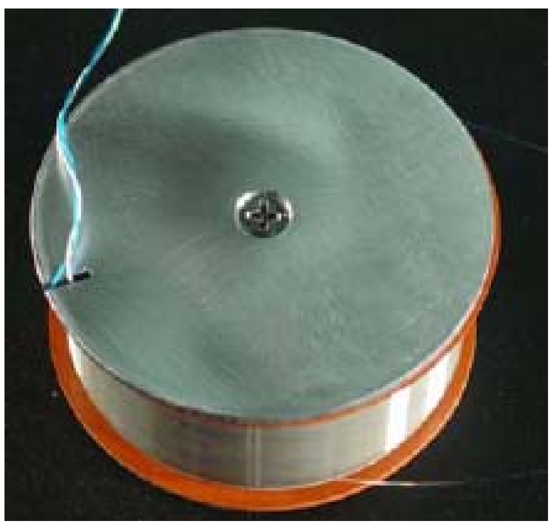
Timing actuators

Issues - Range, Speed, Linearity (resonances) and stability

PHOTONS		R	S	L
Moving mirrors:	piezo-mounted	🟠	🟢	🔴
	motorised	🟢	🟠	🟢
Fibre stretchers:	piezo-drum	🟢	🟢	🔴

Optiphase
PZ2-HE
5.6 μm/V
200 ns delay
18 kHz f_{res}



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Timing actuators

Issues - Range, Speed, Linearity (resonances) and stability

PHOTONS		R	S	L
Moving mirrors:	piezo-mounted	● (amber)	● (green)	● (red)
	motorised	● (green)	● (amber)	● (green)
Fibre stretchers:	piezo-drum	● (green)	● (green)	● (red)
	oven	● (green)	● (red)	● (green)
EO materials:	Pockels cell	● (red)	● (green)	● (amber)

Actuators can be placed inside an optical cavity to control frequency

ELECTRONS

Convention is to take RF as the master clock and to adjust photon timing

But in some cases (e.g. compensating for ID gap changes in a multi-user system) it may be easier to delay the electrons

Options include adjustable chicanes or, for global changes, varying the RF phase and (on linacs) injector timing

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A “typical” future light source

There is no such thing as a typical light source !

STORAGE RINGS

Repeated use of “the same electrons” leads to a degree of reproducibility

But the bunch charge does decay and top-up may leave some noise

Natural bunch length is 10-100 ps

But crab cavities may cut this to 1 ps and pulse slicing to 100 fs

LINACS

Fresh electrons avoid decay and allow time-structure flexibility

But bunch properties can vary and dumping limits the current and duty cycle

Bunch lengths can be <100 fs

ERLS

The best of both worlds !

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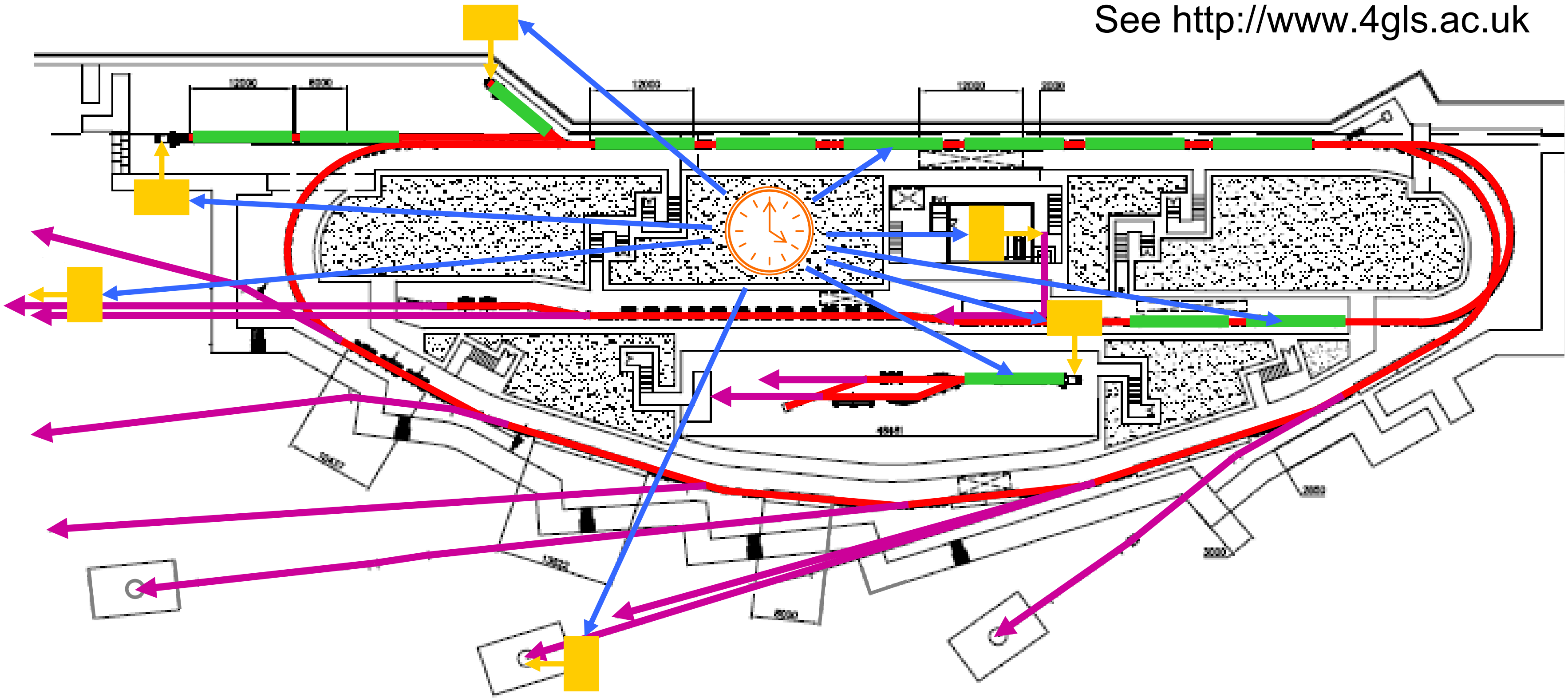
A “typical” future light source

See http://www.4gls.ac.uk



- Master clock
- Stabilised LLRF link
- Conventional laser
- RF acceleration
- Electron beam transport
- Photon beam transport

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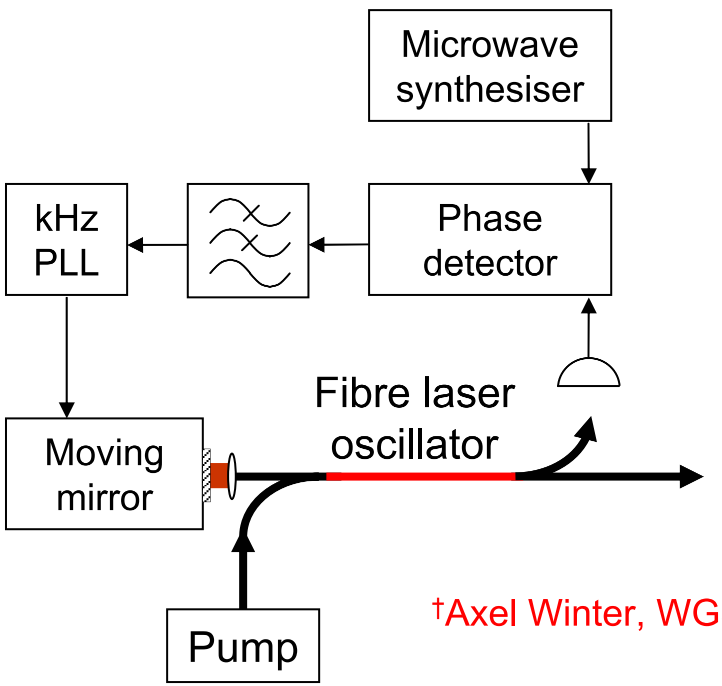
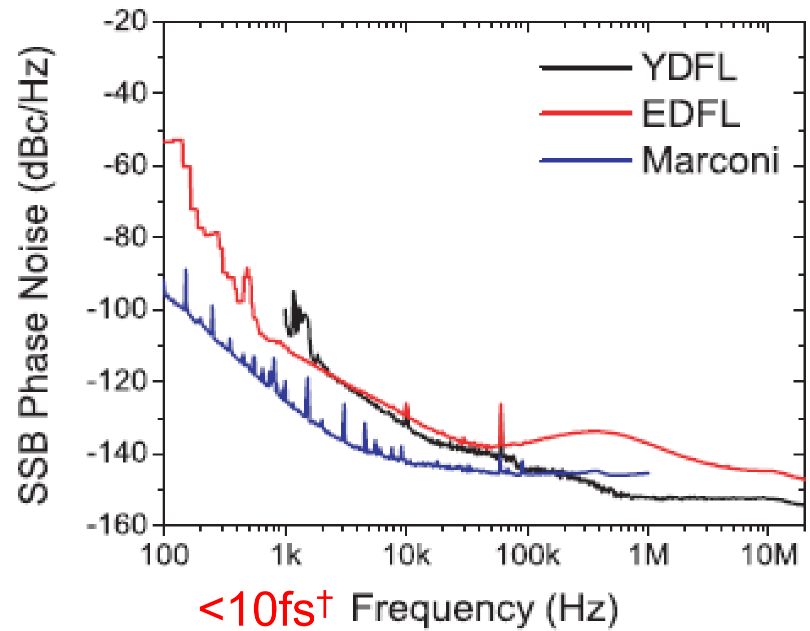
Master clock

- Minimum clock noise is required
  - a) for the SCRF,
  - b) to minimise the workload on the active synchronisation systems and
  - c) to minimise jitter above the active systems' cutoff frequencies
- Fibre laser oscillators have the lowest HF noise and can be locked to a microwave synthesiser for LF stability





<10fs†

The YDFL has ~~18fs~~ jitter above 10kHz without correction for AM to PM effects

†Axel Winter, WG5 paper

Data from Winter et al Paper RPPT038, PAC05

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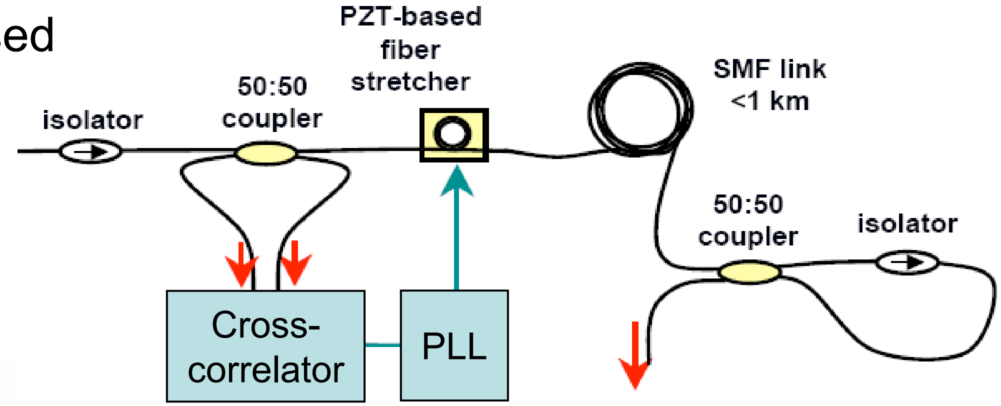
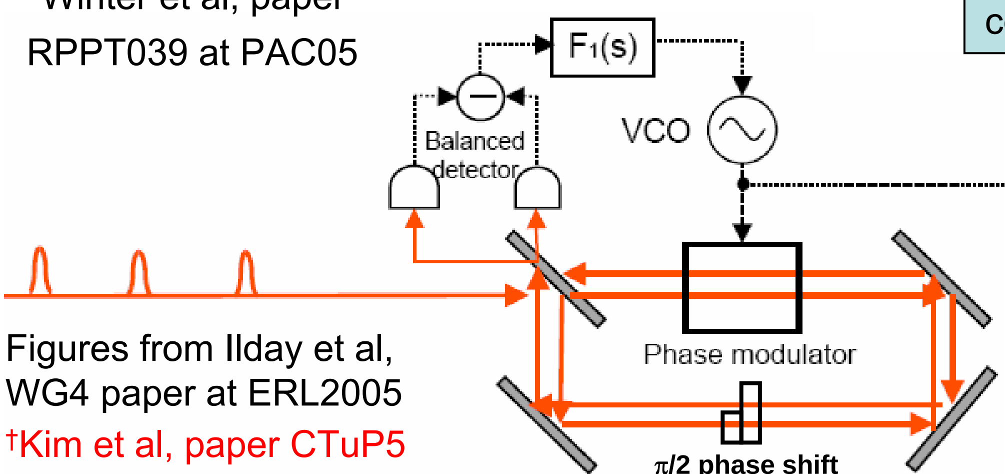
LLRF distribution

- The options for LLRF distribution are copper and optical fibre. Until recently their best demonstrated performances were similar, but optical fibre is now ahead and offers greater room for improvement
- 1550nm components are commercially available and, with frequency doubling, lasers at this wavelength can directly seed Ti:S amplifiers
- A 50m fibre link has been stabilised with a jitter of 3fs up to 10kHz*. 20fs up to 1MHz seems possible
- Transit times set the 1MHz frequency limit

*Winter et al, paper RPPT039 at PAC05





Figures from Ilday et al, WG4 paper at ERL2005

†Kim et al, paper CTuP5 at CLEO/QELS 2006

- Direct photodiode detection is limited by AM to PM effects
- Optical conversion from phase to intensity allows RF locking with ~~≤60fs~~ jitter
  <10fs†

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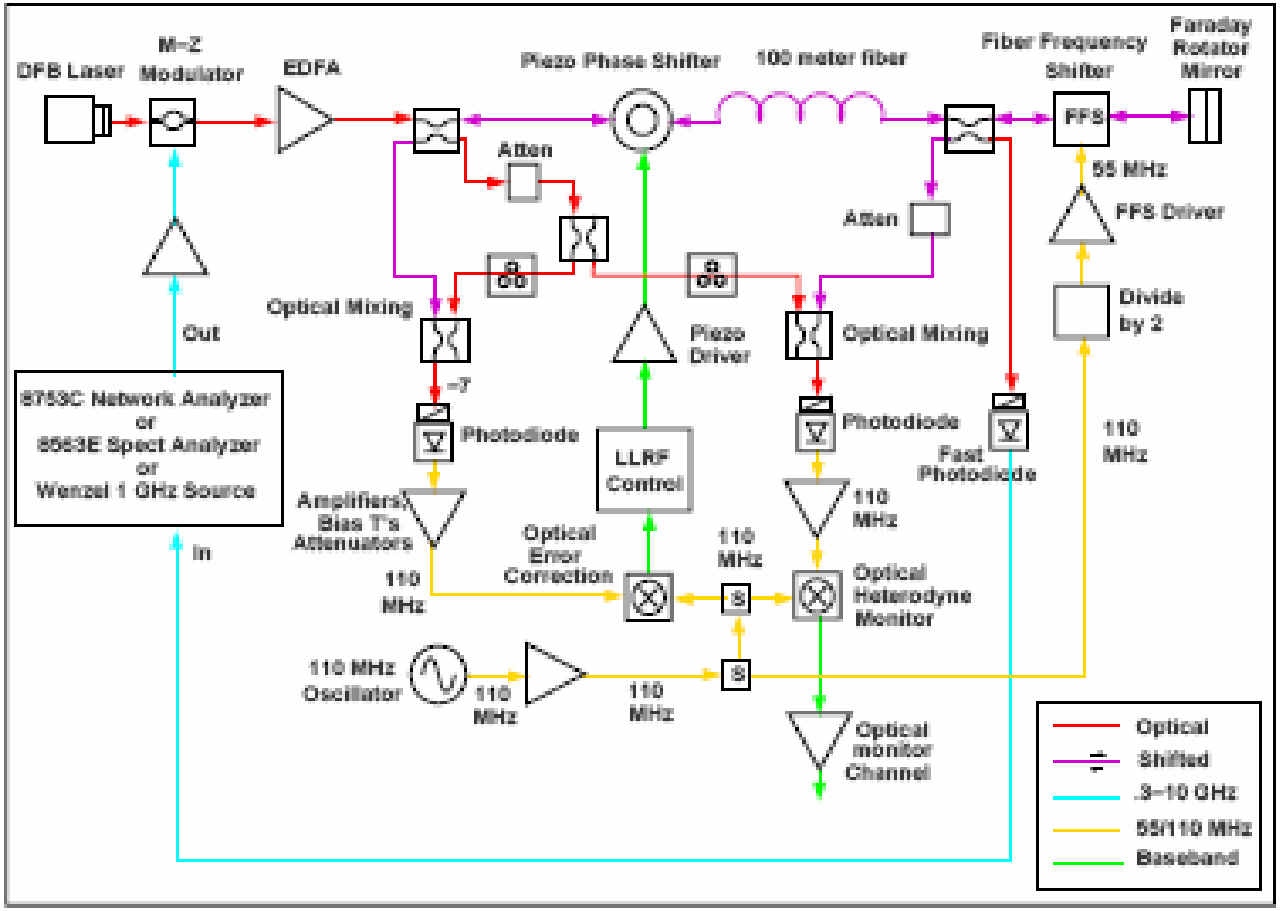
LLRF distribution

More sophisticated fibre distribution schemes have been proposed*

Proof-of-principle experiments have demonstrated cw optical length stabilisation of <1fs over kHz BW

Use of optical frequency combs promises locking of remote lasers to a master oscillator with ~1fs fidelity



*R Wilcox, J W Staples and R Holzwarth, Proc PAC05, p3958 (2005)

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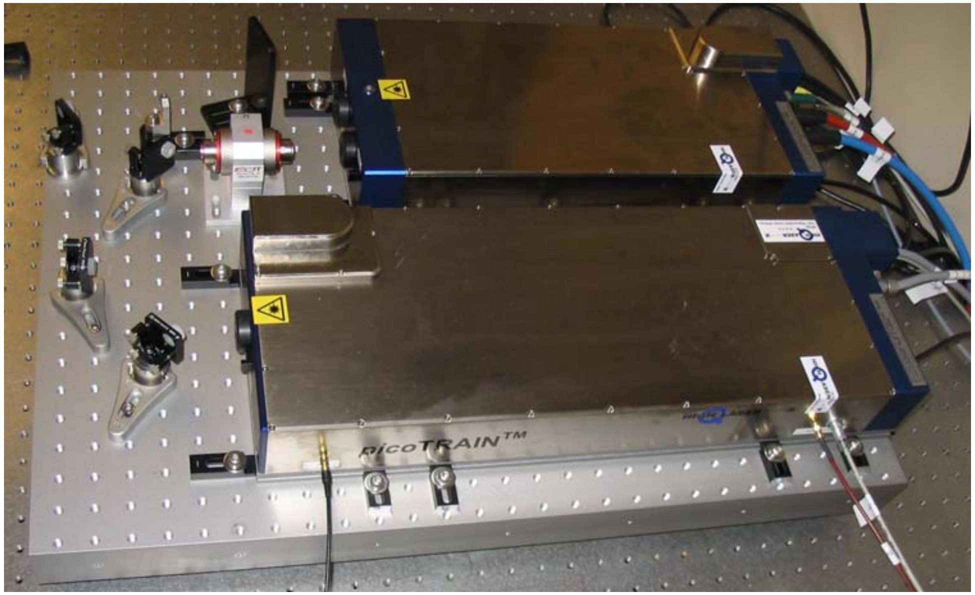
Conventional lasers

- Synchronisation of conventional lasers to RF is a mature subject. Sub-100fs jitter is commercially available (in a low-noise environment), sub-20fs has been delivered to users*, ~1fs has been achieved in several labs.
- Optical-to-optical coupling has recently achieved ~0.1fs jitter between two separate lasers over the frequency range 10mHz-1MHz (i.e. for >100s)†.
- 1.5GHz commercial laser which achieved ~120fs jitter in factory tests and <100fs after delivery to CCLRC laboratory

  (Jitter measured both electronically and by cross-correlation with a second laser.)



*D J Jones et al, Rev Sci Instr **73** (8) 2843 (2002)

†D Yoshitomi et al, Opt Letts **30** (11) 1408 (2005)

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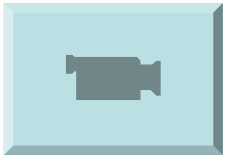
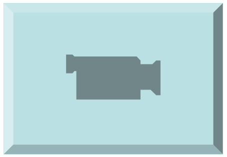
Laser synchronisation

High Q IC-532-5000 modelocked Nd:YVO_4 laser beating with Wenzel ultra low noise 81.25 MHz oven-controlled crystal oscillator



High Q laser synchronised to Wenzel oscillator showing ~100 fs rms jitter (predominantly between 150 Hz and 1kHz) and environmental effects



Issues include:

- stability and resonances in optical mounts and casings,
- relaxation oscillations in the laser medium,
- index modulation reflecting pump diode power fluctuations,
- frequency limits in PLL control system

Fibre laser oscillators are inherently quieter than bulk-media systems

Yb-doped fibre amplifiers have delivered 320 W average power in 20 ps pulses at 1 GHz* and have enough bandwidth for ~200 fs pulses†

*P Dupriez et al, Paper PD3 in OFC2005 (2005)

†F Röser et al, Opt Letts **30** (20) 2754 (2005)

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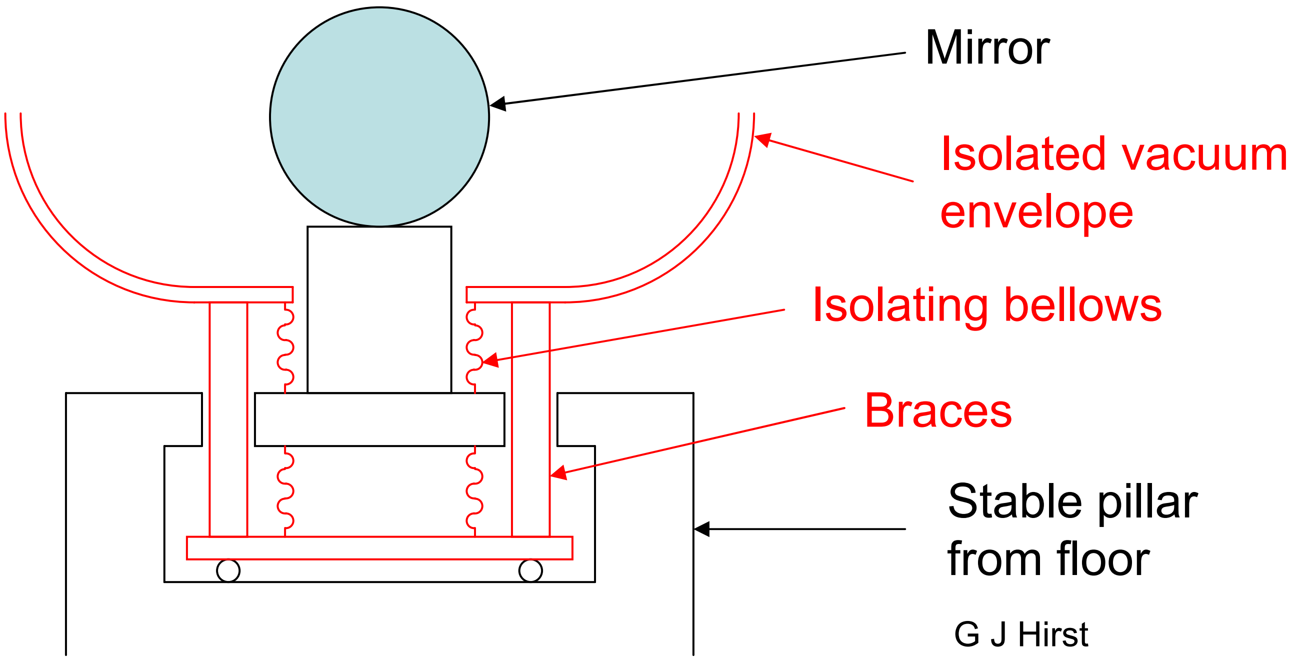
Photon beam transport

- Propagation is generally in vacuum, so timing depends on positional stability of the mirrors
- Floor-mounted components can, with no special stabilisation, be used for visible interferometry over >10m, provided simple passive steps are taken to avoid vibration. This corresponds to <300nm movement over 10m.
- Issues include floor stability (must either be sufficiently thick or well-bonded to bedrock) and control of vibration transmitted through vacuum envelope
- Scaling suggests 3μm over 100m should be practical
- Interferometry can be used to monitor slow movements
- Dynamic heat loading may need to be compensated



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Electron acceleration & transport

Once electrons are relativistic timing depends “only” on path length

But path length depends on:

Component positions
Which depend on vibration, thermal expansion, floor stability, phase of the moon* …

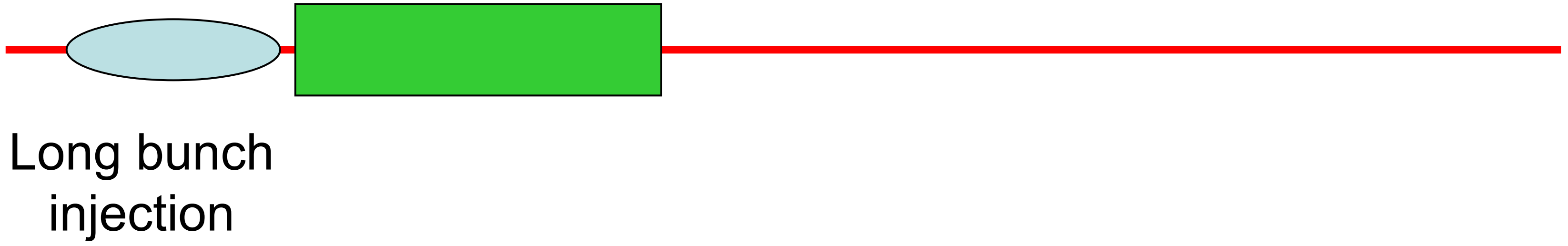
Field strengths
Which depend on power supply stability, undulator gaps, stray fields ...

Bunch compression†
Which depends on ...

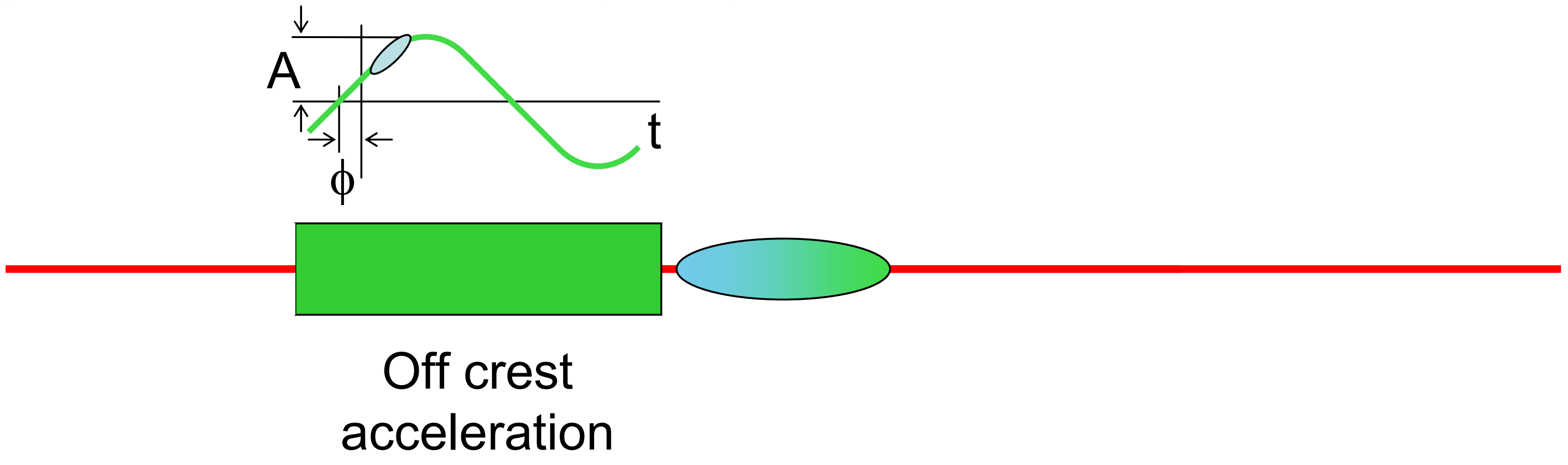
† P Emma, WG2 paper at 17th ICFA ABD Workshop on Future Light Sources (1999)
http://www.aps.anl.gov/conferences/FLSworkshop/proceedings/papers/wg2-03.pdf

* R O Hettel, Rev Sci Instr **73** (3) 1396 (2002)

Bunch compression



Bunch compression



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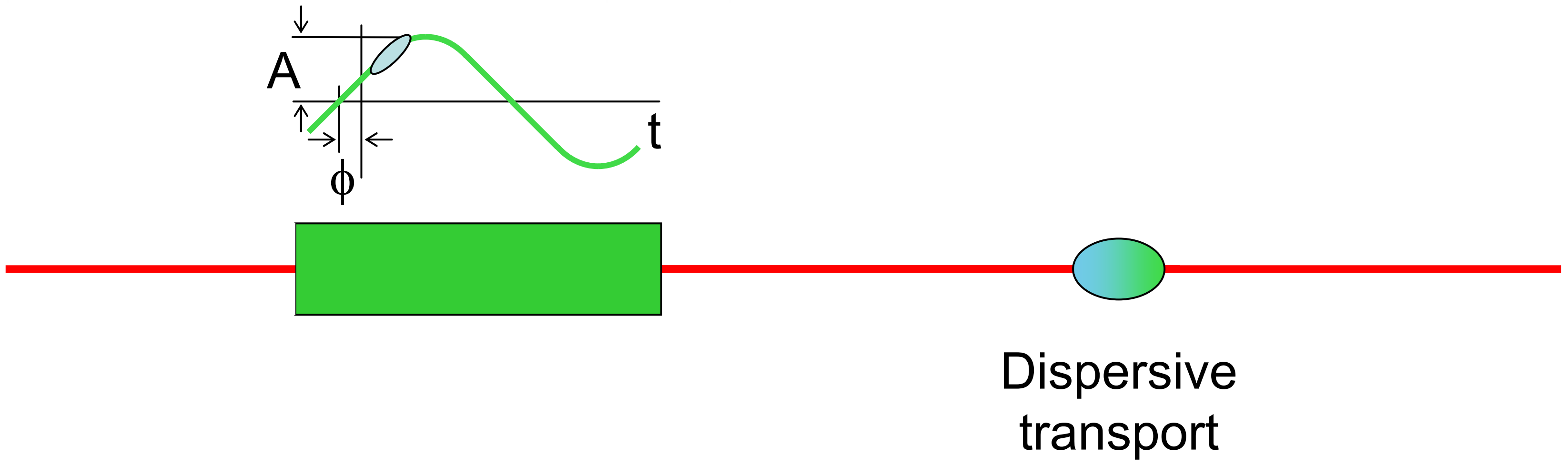
Bunch compression



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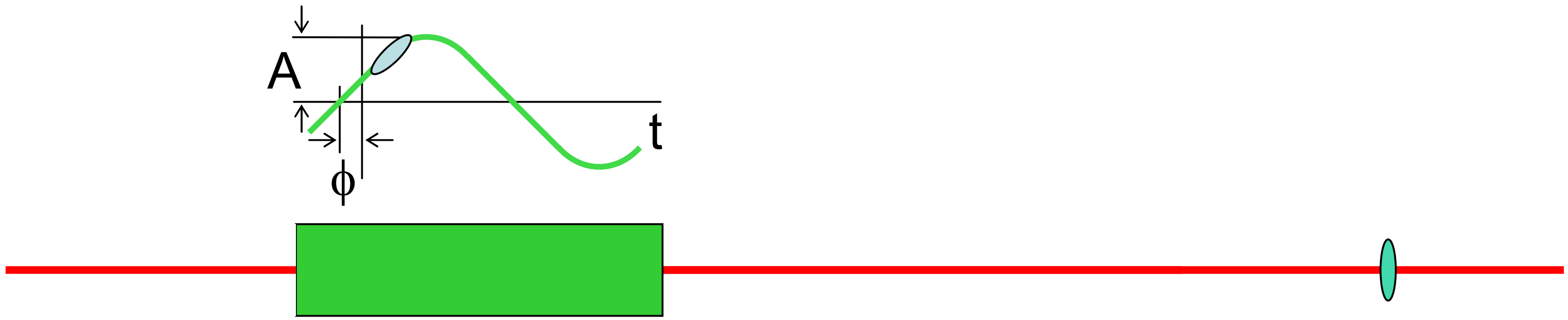
Bunch compression



Basic analysis:

$$\Sigma_t^2 = (1/C)^2.\Sigma_{in}^2 + (R_{56}.\sigma_A/c.A)^2 + (1-1/C)^2.(\sigma_\phi/\omega_{RF})^2$$

Injection jitter	RF amplitude noise	RF phase noise
1 fs	50 fs	21 fs

f_{RF} = 1.3 GHz
C = 100
Σ_{in} = 100 fs
R_{56} = 0.15 m
$\sigma_A/A = 10^{-4}$
$\sigma_\phi = 0.01°$

Σ_t^2 = 54 fs

} SCRF noise has low cutoff frequency

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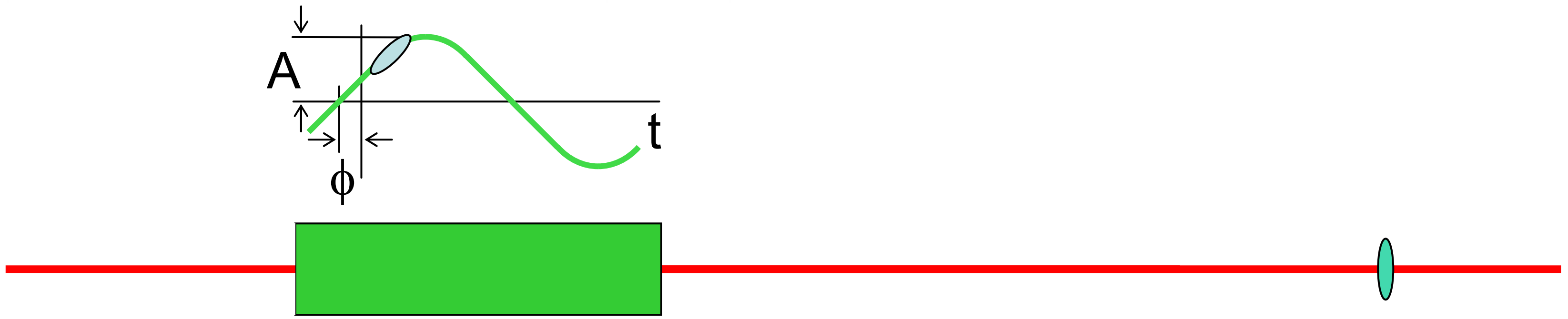
Bunch compression



Basic analysis:

Or maybe not … (P Krejcik WG5 talk)

$$\Sigma_t^2 = \cancel{(1/C)^2}.\Sigma_{in}^2 + (R_{56}.\sigma_A/c.A)^2 + (1-1/C)^2.(\sigma_\phi/\omega_{RF})^2$$

	Injection jitter	RF amplitude noise	RF phase noise
f_{RF} = 1.3 GHz C = 100 Σ_{in} = 100 fs	1 fs	50 fs	21 fs

R_{56} = 0.15 m

Σ_t^2 = **54 fs**

$\sigma_A/A = 10^{-4}$
$\sigma_\phi = 0.01°$ } SCRF noise has low cutoff frequency

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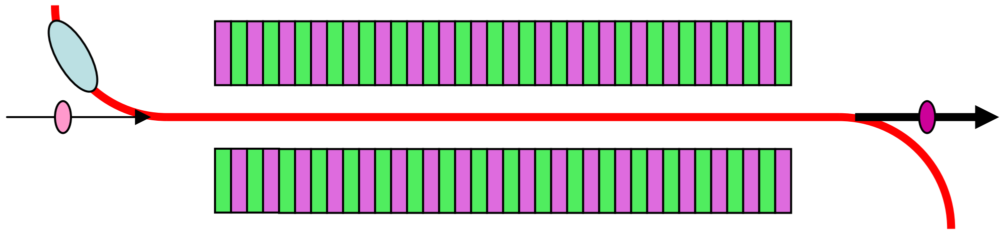
FELs

FEL pulse timing depends on electron bunch timing but other factors can improve control:

SEEDING

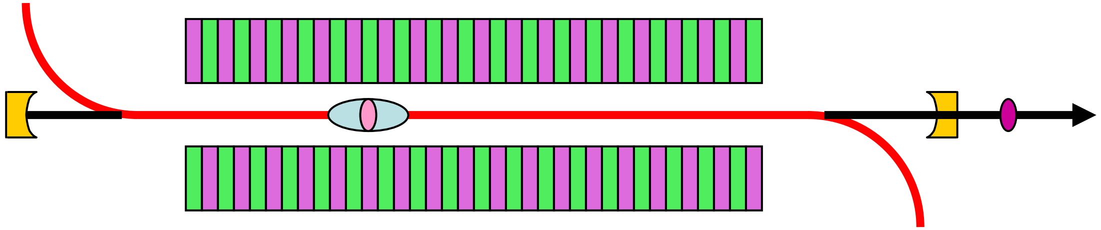


HHG sources based on conventional lasers can deliver femtosecond seed pulses up to several hundred eV at kHz pulse rates

Pulse timing is now dominated by the seed laser

Similar effects occur with HGHG* or direct laser modulation of electrons†

CAVITY EFFECTS



The recirculating photon pulse in an optical cavity stabilises HF timing, the more so as the cavity Q increases

However there is a corresponding requirement for electron bunch timing stability

*L H Yu, Phys Rev A 44 (8) 5178 (1991)
†E L Saldin et al, DESY report 04-13 (2004)

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Jitter summary

- **Master clock** ✓
  fibre lasers locked to RF synthesisers have <10 fs jitter and promise better, perhaps via optical frequency combs and DROs
- **RF distribution** ✓
  fibre links and optical-to-RF converters also have <10 fs jitter and quieter, more robust systems are under active development
- **Stand-alone lasers** ✓
  ~100 fs is achievable with commercial systems, 10-20 fs has been demonstrated regularly, sophisticated techniques can deliver ~1 fs …
- **Photon transport** ?
  component stability is acceptable, but timing adjustment gets tougher as photon energy gets higher
- **FELs** ?
  Laser control (seeding, HGHG, electron modulation) shows promise
- **Electron acceleration and transport** ?
  Compression schemes can relax the injector requirements but present serious difficulties below ~50 fs

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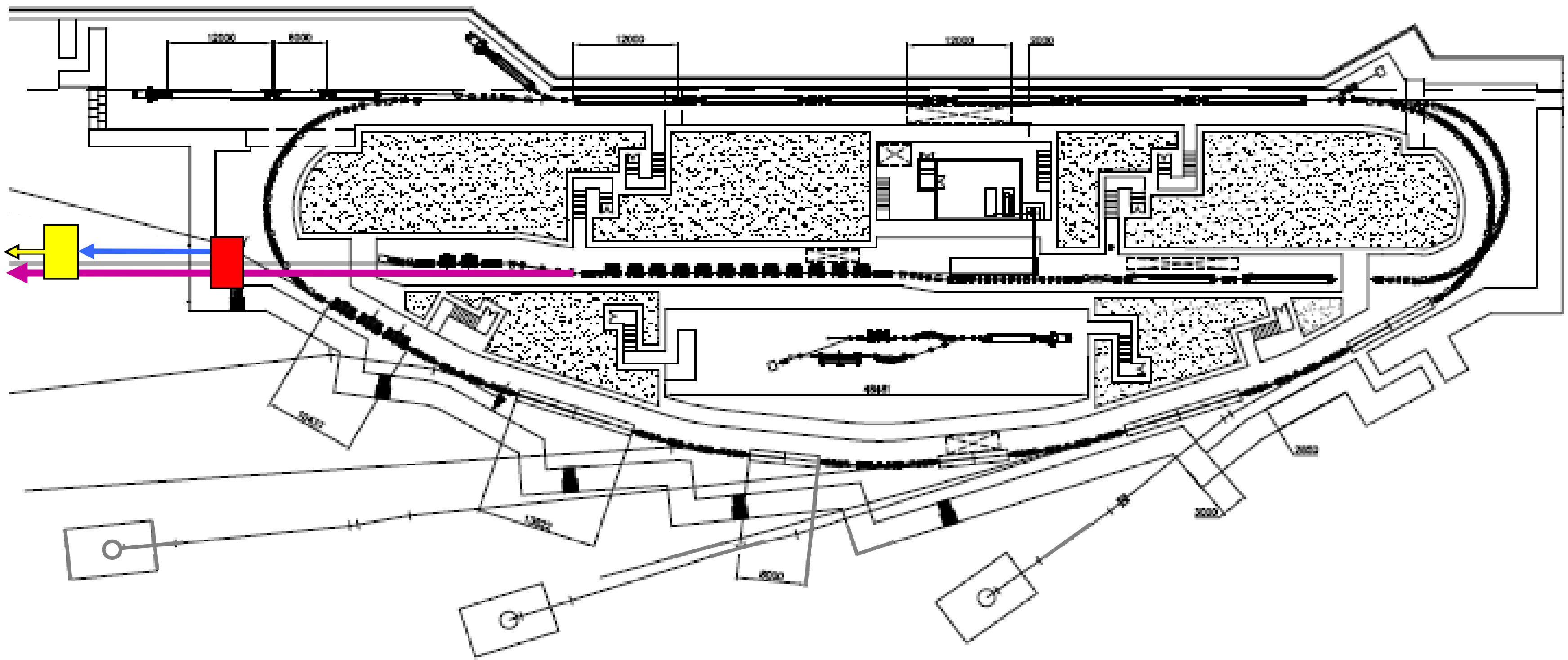
Local sensing



Local beam sensor

Stabilised LLRF link

Conventional laser

Photon beam transport

- A compact system with few components may deliver the very lowest jitter
- Issues include the beam's time structure, the performance of the sensor and the availability of actuators for most beams

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Conclusions

Huge demand

Jitter receiving a lot of attention

~100fs looks possible

~10fs looks much tougher

Long-term drifts still a big issue

History

JOURNAL OF APPLIED PHYSICS VOLUME 24, NUMBER 7 JULY, 1953

Experiments on Radiation by Fast Electron Beams*

H. MOTZ, W. THON, AND R. N. WHITEHURST
Microwave Laboratory, Stanford University, Palo Alto, California
(Received October 27, 1952)

The results of some experiments on millimeter wave and light generation by means of an undulator are described. After a brief survey of the theoretical background the design of a magnet system is discussed. An experiment is described in which a 100-Mev electron beam from the Stanford linear accelerator passed through the undulator. Light radiated by the beam was observed and the plane of polarization determined. A small linear accelerator with good bunching action was used for an experiment on millimeter wave generation. At a beam energy of 3 Mev, radiation in a wavelength band below 1.9 millimeters was observed. A peak power output of the order of one watt was obtained. Millimeter waves generated in the accelerator tube were also observed.

I. INTRODUCTION

THEORETICAL investigations have shown[1–4] that under certain conditions radiation ranging from millimeter waves to visible light is emitted by electrons in accelerated motion in the energy range of a few Mev to, say, 100 Mev. In particular, sinusoidal orbits were investigated in detail,[3] and the power level obtainable in the millimeter range from electrons with an energy of a few Mev seemed promising. In this paper the results of some preliminary experiments on millimeter wave and light generation are presented.

While the light generation experiments are of purely academic interest, the millimeter wave experiments may have some practical importance. In this case it is possible to bunch the electron beam so that groups of electrons radiate coherently. It was shown[3] that the power level may be higher by a factor of the order of a million as compared to noncoherent radiation and that a peak power of the order of kilowatts may be obtainable in practice.

path, describe a periodic orbit in a plane perpendicular to that of the field. We call the arrangement a magnetic undulator (Fig. 1). It was shown[3] that electrons moving in a sinusoidal orbit radiate electromagnetic waves of angular frequency,

$$\omega = 2\pi v/l_0[1-(v\cos\theta)/c], \quad (1)$$

depending on the angle θ which the wave normal makes with the axis of the undulator. Here l_0 is the space period of the magnetic flux distribution and v the axial electron velocity. This formula is valid as long as $evBl_0/m_0c^2$ is small compared to unity. For larger values of this quantity harmonics of the fundamental frequency (1) will appear with increasing intensity. The foregoing formula applies to an infinitely long undulator and to radiation in free space. If the electron beam is confined by a wave guide of transverse dimensions comparable with the wavelength of the radiation the various modes of wave-guide propagation have to be considered.

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History

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Experiments on Radiation by Fast Electron Beams*

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The results of some experi
described. After a brief sur
experiment is described in
through the undulator. Lig
A small linear accelerator v
tion. At a beam energy of
peak power output of the o
were also observed.

In this paper the results of some preliminary experiments on millimeter wave and light generation are presented.

While the light generation experiments are of purely academic interest, the millimeter wave experiments may have some practical importance.

I. INTRODUCTI

THEORETICAL investigation
under certain conditions ra
millimeter waves to visible light is e
in accelerated motion in the energy range of a few Mev to, say, 100 Mev. In particular, sinusoidal orbits were investigated in detail,[3] and the power level obtainable in the millimeter range from electrons with an energy of a few Mev seemed promising. In this paper the results of some preliminary experiments on millimeter wave and light generation are presented.

While the light generation experiments are of purely academic interest, the millimeter wave experiments may have some practical importance. In this case it is possible to bunch the electron beam so that groups of electrons radiate coherently. It was shown[3] that the power level may be higher by a factor of the order of a million as compared to noncoherent radiation and that a peak power of the order of kilowatts may be obtainable in practice.

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