Emittance measurements and beam optimization using Laser Wire Scanners

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ABP/CLIC meeting

LWS as CLIC diagnostic

Beam emittance diagnostics:

- needed by physics experiments
- evaluate performance
- commissioning lattice – “emittance bumps”

LWS is non-destructive (small total cross section)

- relative number of electrons intersecting laser beam
- transverse density scan if small enough laser width
- does not directly measure beam angles

Concerns about background and statistical noise

Thomson scatter

In electron rest frame, photon is upshifted by γ_0, so $\nu' \approx \gamma_0\, \nu_0$

(or $2\, \gamma_0$ if originally antiparallel)

If photon energy is still less than electron rest mass, nearly elastic collision, with scattering angle distribution (in rest frame)

$$d\sigma/d\Omega \propto 1 + \cos^2\theta$$

Photons which are nearly backscattered then get upshifted by another factor of $2\, \gamma_0$ when go back to lab frame

Scattered frequencies as high as $2\, \gamma_0^{\,2} \times$ initial frequency

- with angles $< 1 / \gamma_0$ (much smaller deflection for electrons)
- still a small fraction of electron energy

Compton Scatter

Define $\xi = h\nu'/m_ec^2$, where ν' is the laser frequency in the electron rest frame – key parameter for behavior

When $\xi > 1$, can't ignore energy exchange in electron rest frame.

Net result:

the photon can acquire most of the electron's energy

final electron energy is at least $m_e^2c^4 / 2\, h\nu_0$, so final $\gamma > \gamma_0 / 2\,\xi$

typical angle of photon, maximum angle of electron

$$\sim \xi / \gamma_0 \approx h\nu_0 / m_ec^2$$

electrons with largest angle have energy $\sim \gamma_0\, m_ec^2 / \ \xi$

Scaling for LWS signal

Main demands for LWS: large signal, good resolution

electron beam params: ε_X, ε_Y, σ_X, σ_Y, σ_Z, charge -- only control size

laser: peak power P_L, σ_{L0}, τ_L, λ

look at measuring Y profile:

need $\lambda < \sigma_{L0} < \sigma_Y$ and $\sigma_Y / \sigma_X > M^2 \lambda / 2 \pi \sigma_{L0}$ = angle of laser cone

number of scatters $\propto N_e P_L (\lambda / \sigma_Y) [c\tau_L / (c^2\tau_L{}^2 + \sigma_Z{}^2)^{1/2}] \underbrace{(\lambda / E_B)}_{\text{Compton regime only}}$

take as large λ, τ_L as acceptable

want large $\xi = h\nu'/m_e c^2 = 5\, E_B[\mathrm{TeV}] / \lambda[\mu\mathrm{m}]$

For higher energies, need more laser power for same signal.

CLIC parameters:

electrons: 0.67 nC per bunch

~10 μ spot size, 10 x 680 nm normalized emittance

energy 1.5 TeV, typical angle 10 nrad

laser: 0.4 μ wavelength, 4 μ waist, 1 mJ per pulse

0.12 ps matches 35 μm bunch length

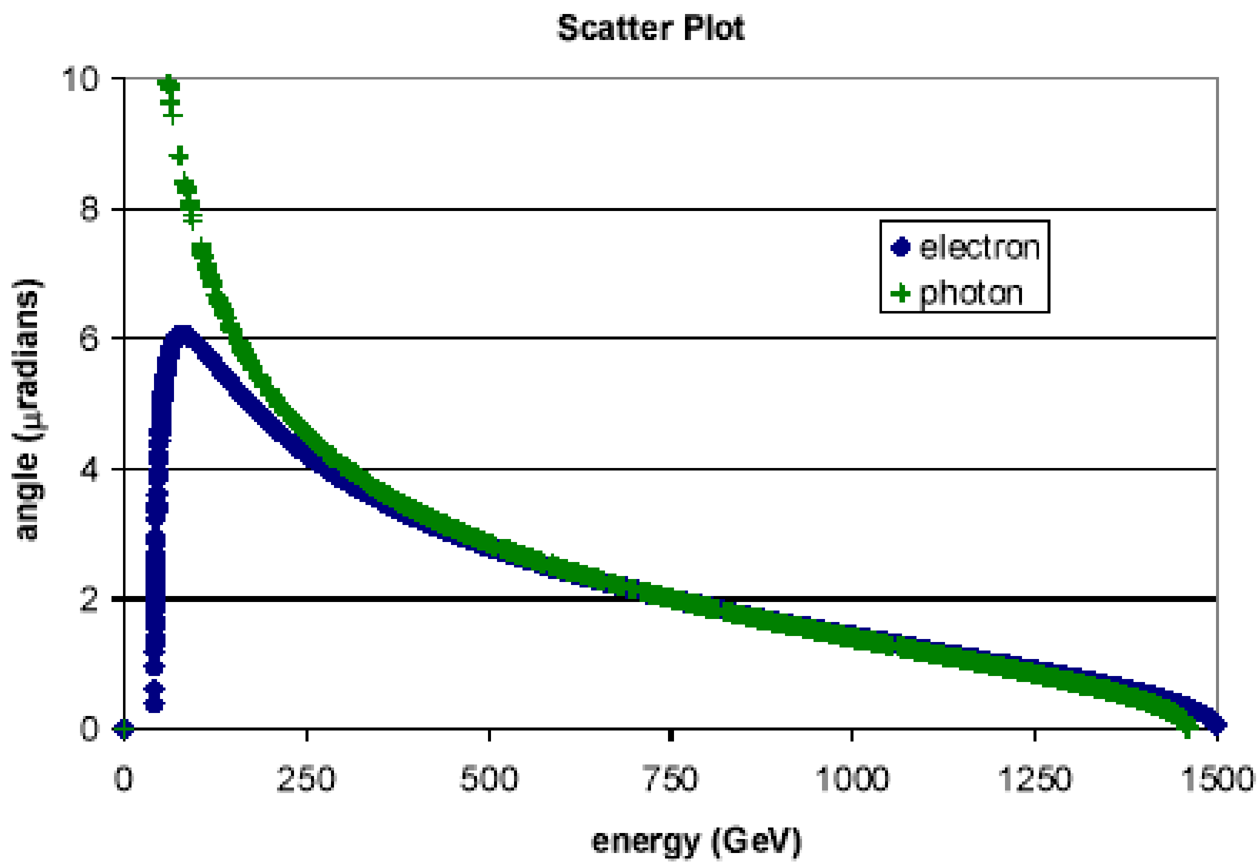
scatter params: $h\nu_0 / m_e c^2 \approx 6 \times 10^{-6}$ $\xi_0 \approx 20$

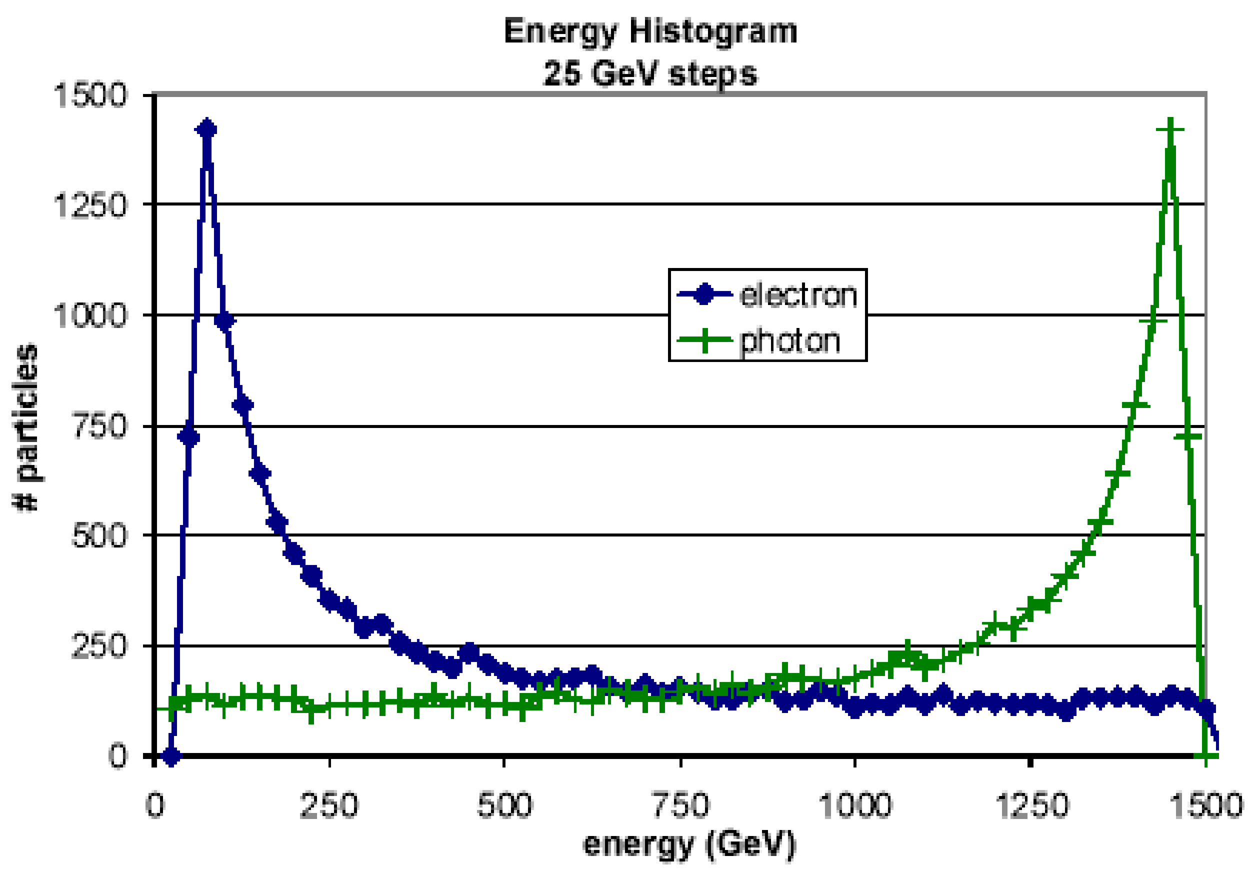
diagnostics: gas detector, signal is from low energy electrons

diverted using uniform dipole field, 50 or 100 gauss

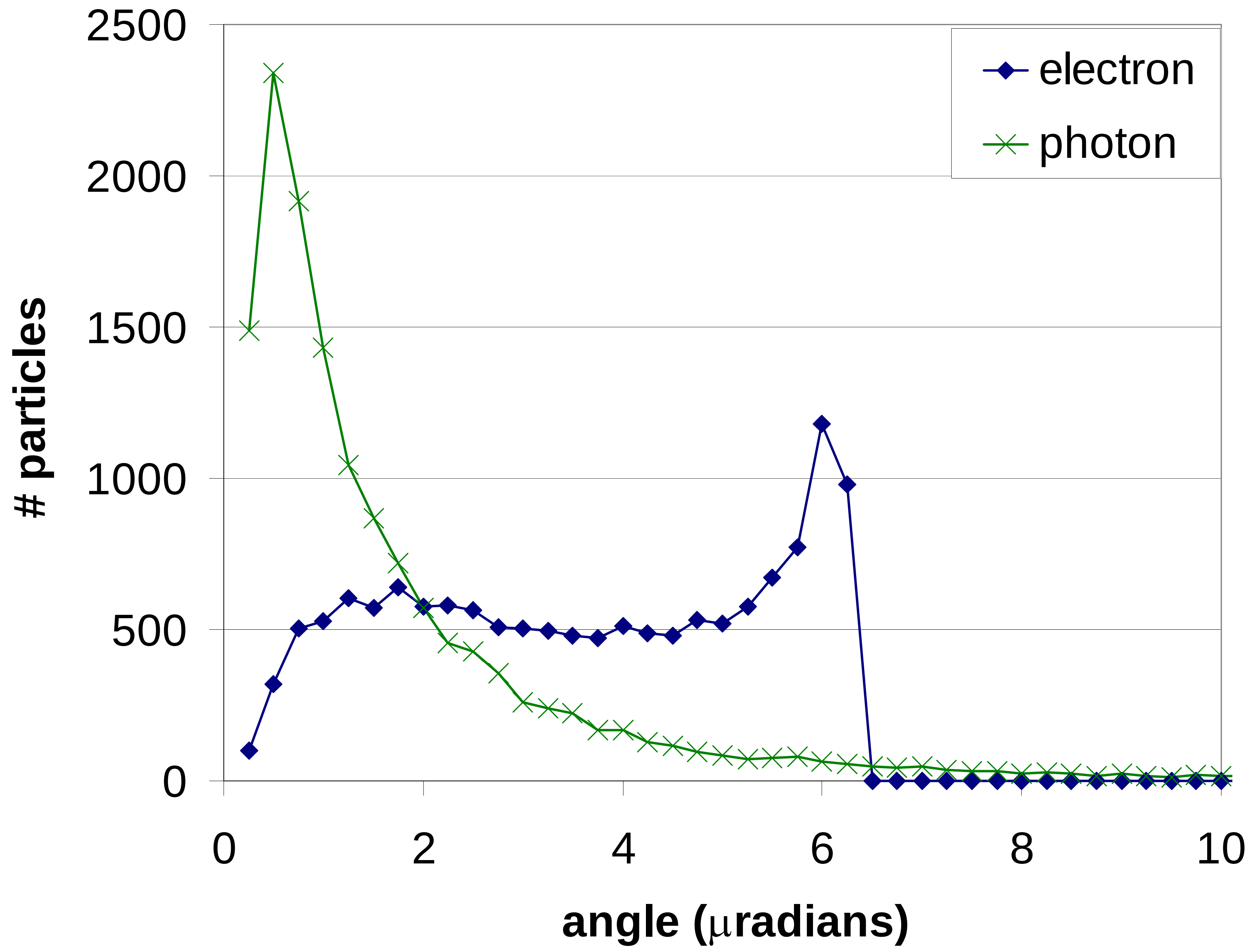
roughly **14000** scattering events per pulse

CLIC parameters 1.5 TeV no emittance





Distribution of Scattering Angles



GEANT Simulations

GEANT4 results, for GeV deposited in detector

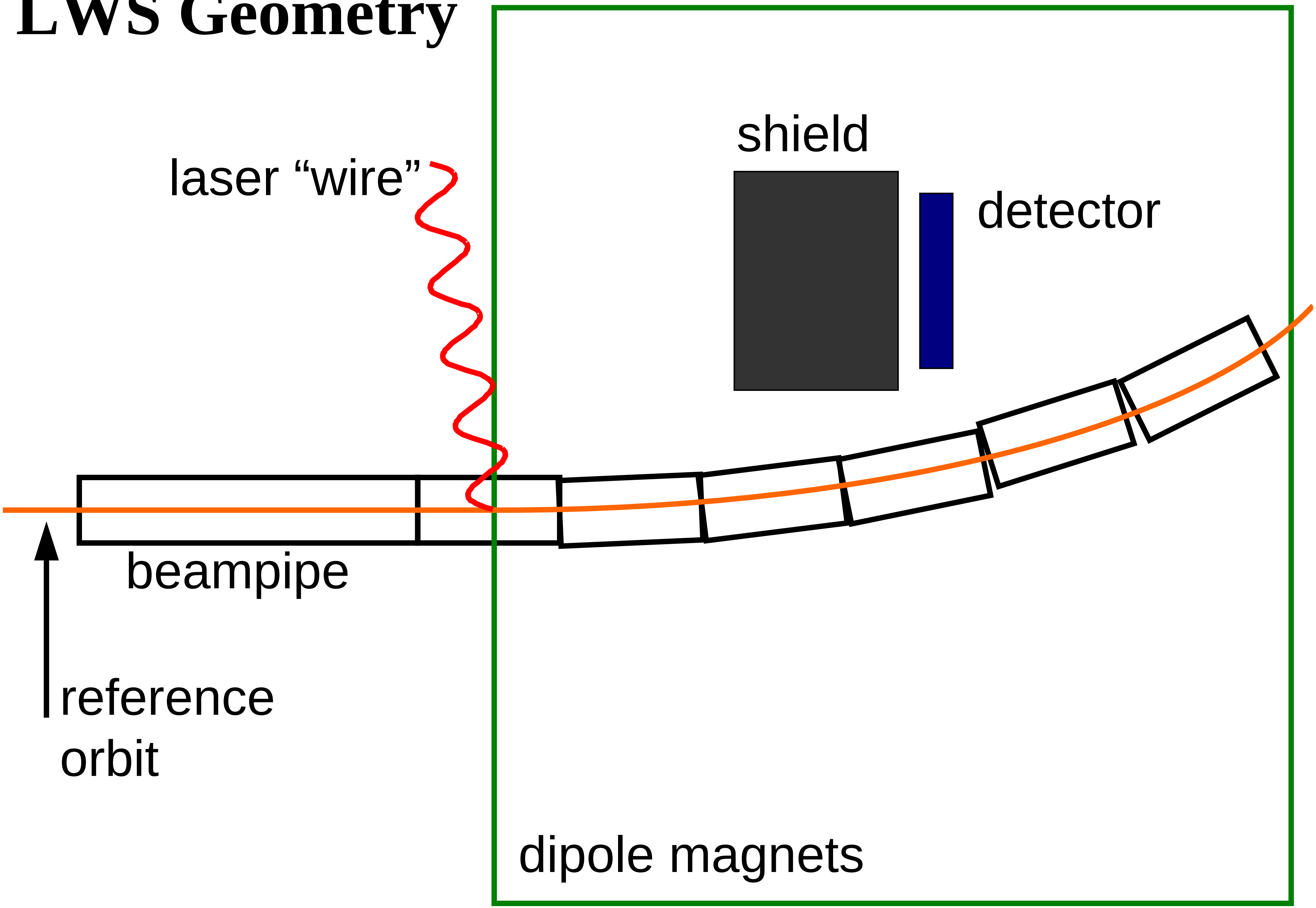
- with 1 halo electron hitting beampipe / meter / bunch (very clean).
- corr to time-average of 3.7 mW per meter, for CLIC timing

Design case is 400 nm laser, 100 gauss dipole field, gas detector, 1 shield

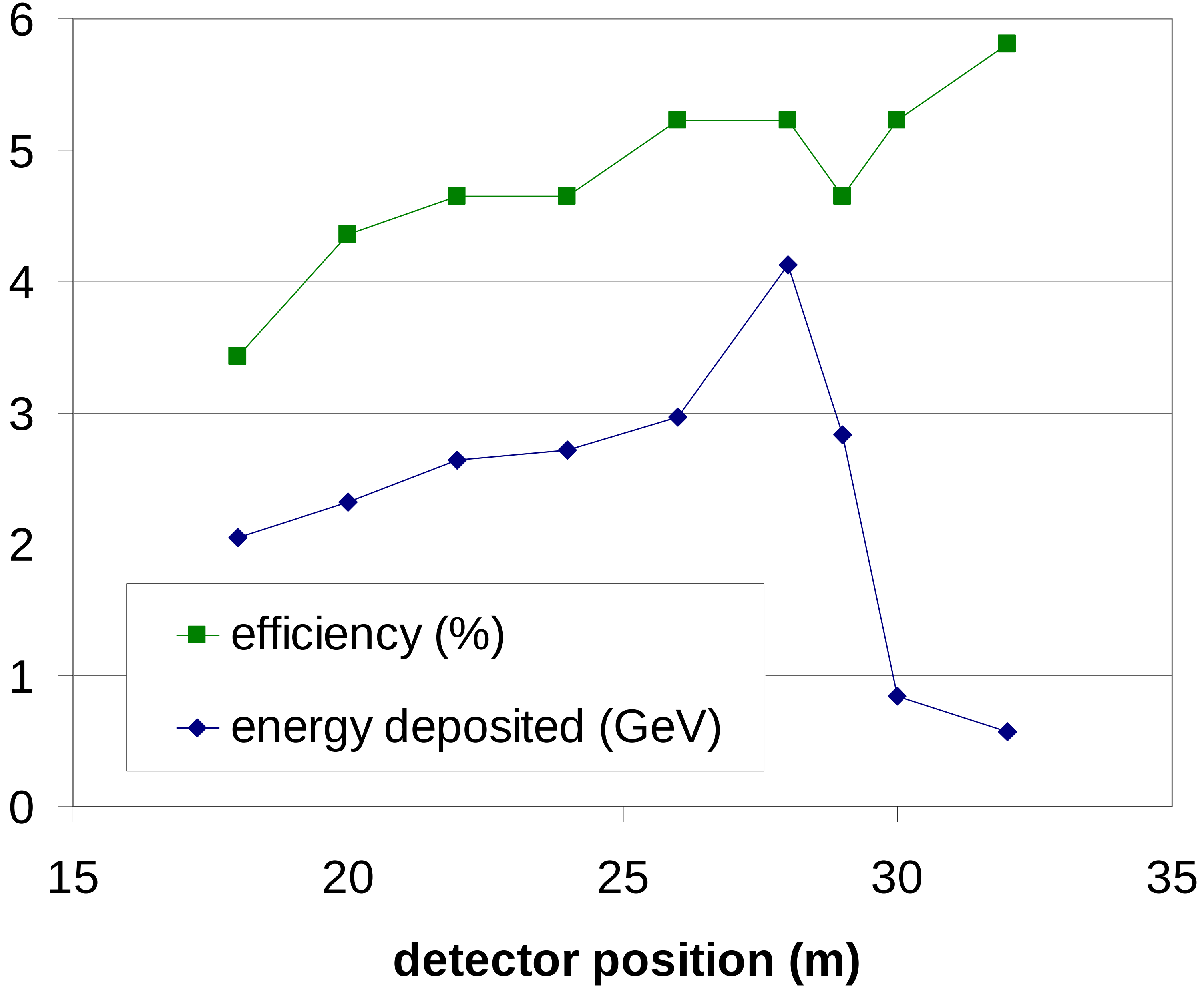
System	Signal	Background (x4)
design	**3.3**	**0.4**
unshielded	**0.78**	**0.6**
solid detector (Pb)	**4800**	**600**
267 nm laser	**2.7**	**0.4**
50 gauss	**2.0**	**0.4**
500 GeV beam	**7.0**	**0.2**

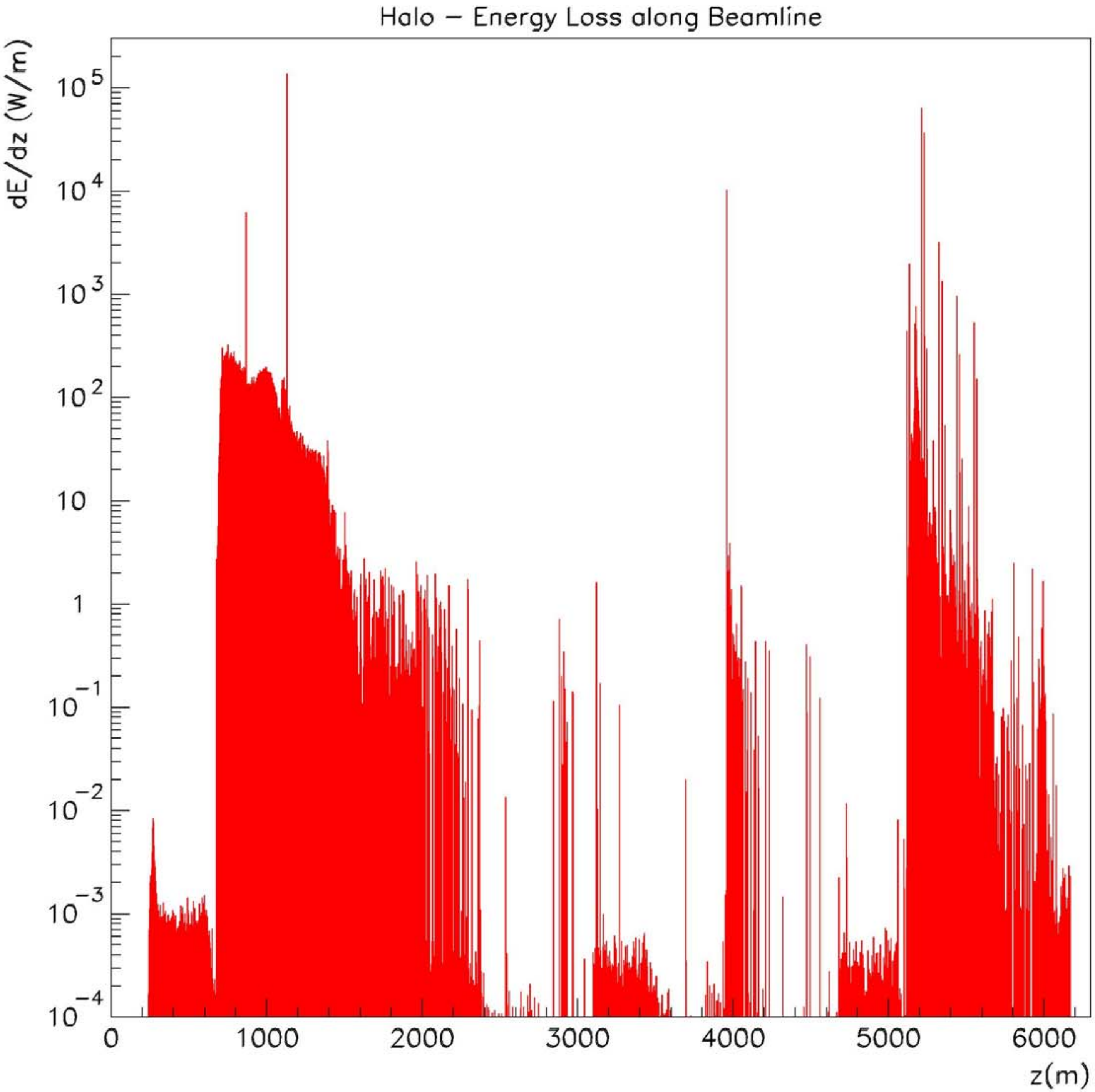
Detector sees losses from 4 bunches due to time resolution

LWS Geometry



Performance vs. Position of Detector





graph obtained
from G. Blair

Laser Parameters

Design parameters compared with currently available lasers:

	Design	Nd:YAG	Ti:Sapphire
wavelength	**800 nm**	**1064 nm**	**800 nm**
pulse (FWHM)	**150 fs**	**3 ns**	**50 fs**
energy per pulse	**2 mJ**	**2200 mJ**	**0.7 mJ**
rep rate	**100 Hz**	**10 Hz**	**1 kHz**
energy fluct	**?**	**8 %**	**1 %**
peak power at 400 nm	**5 GW**	**0.35 GW**	**5 GW**
effective energy	**1 mJ (by def)**	**0.1 mJ***	**0.5 mJ**

*enhanced by overlap with multiple bunches in pulse train

Emittance Measurement

The measured beam size will satisfy

$$\sigma_{meas}^2 \approx \sigma_Y^2 + \sigma_{L0}^2 + \sigma_R^2, \text{ when } \sigma_R = \lambda\, M^2\, \sigma_X / 2\,\pi\, \sigma_{L0} \ll \sigma_Y$$

For the given parameters and a signal to noise ratio of 10:1,

the beam size can be found with an accuracy of 2.6% after 10 scans;

low statistics in the detector is more important than the background.

The emittance can be obtained by measuring σ_Y at 3 positions at once:

if each position is separated by $\pi/4$ phase advance, then

$$\varepsilon_Y^2 = (P_Z/mc)^2\,[\sigma_1^2\sigma_3^2/\beta_1\beta_3 - (\sigma_2^2/\beta_2 - \sigma_1^2/2\beta_1 - \sigma_3^2/2\beta_3)^2]$$

The second term vanishes for matched beams (if total phase adv is $\pi/2$).

Emittance Bumps

"Emittance bumps" prevent beam distortion due to misalignment

- requires using a noisy measurement to correct a changing error
- balance between rapidity and accuracy of measurement
- the emittance can be optimized more precisely than accuracy of a
  - single measurement

Envision using 10 emittance bumps, each bump is a pair of cavities

- sep by 72° in phase
- both can be displaced on the order of 100 microns

Optimization using LWS

Noisy emittance measurement used to choose emittance bump settings

Method:

- take 1D scans, varying one parameter at a time
    - emittance is increased by 10%, to locate minimum
    - half of the time $\Delta\varepsilon/\varepsilon < 2.5\%$
- match to quadratic dependence; failing that, get linear fit
- number of measurements per scan is self-adjusting
- predicted settings are fitted to a linear dependence on time

Emittance Results

Assumed 10% accurate emittance measurement, at a rate of 10 Hz

With no ground motion, can find minimum to within 1%

Ground motion is fast enough that is hard to stay optimized

Use ground motion model with slow stabilization:

- w/o bumps, emittance growth is about 10%
- about 2% cannot be corrected using emittance bumps
- best case so far, $\Delta\varepsilon/\varepsilon \sim 5\%$; 5 emittance bumps seems sufficient

Optimization Strategies

So far, used one “knob” at a time

Better to find linearly independent basis vectors

    need to know how changing knob A affects

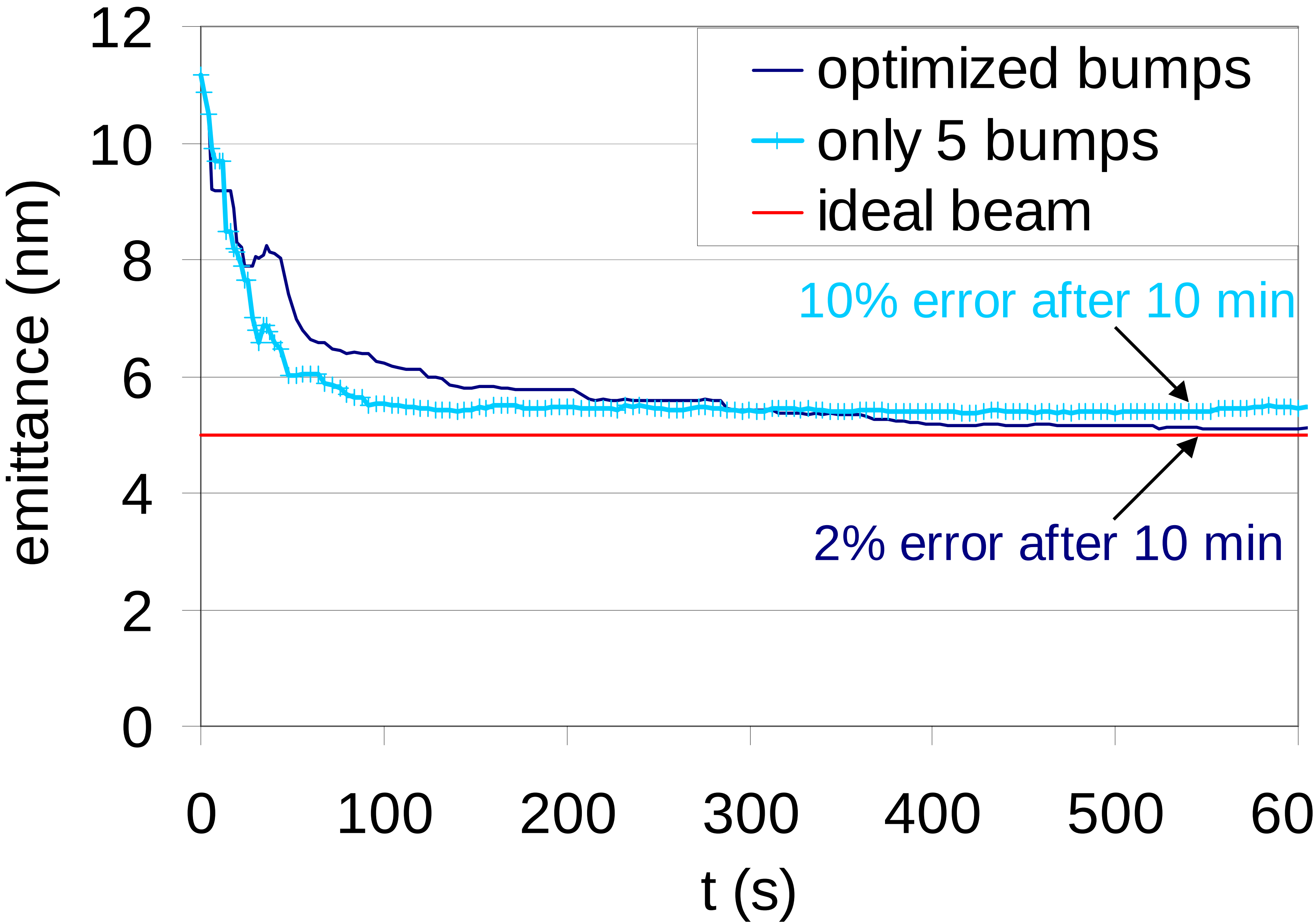
    optimum setting of knob B

Can try using simple correlations, but ground motion interferes

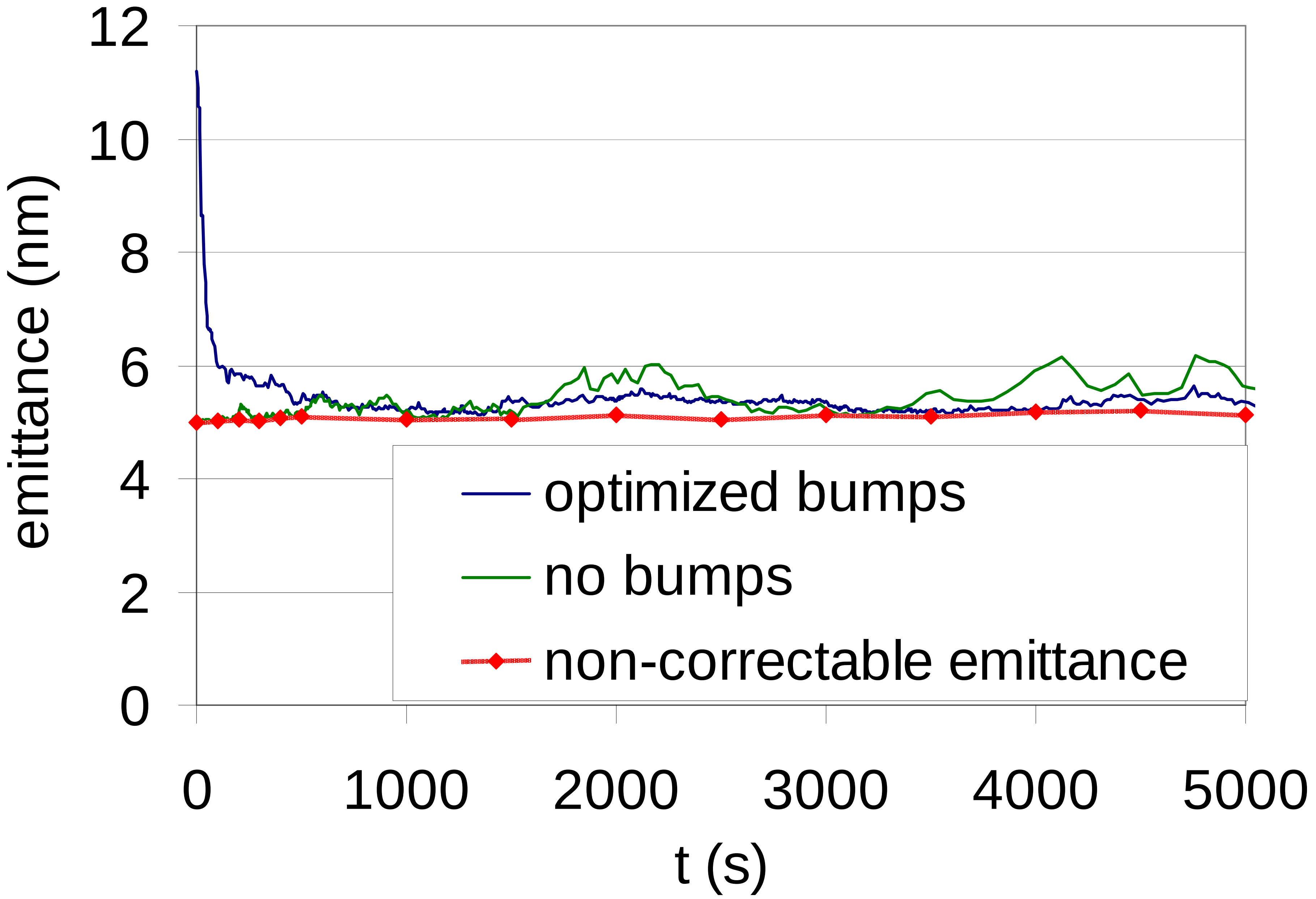
Calculating derivatives is slow but results should not change over time

“Dithering” option better when already close to minimum?

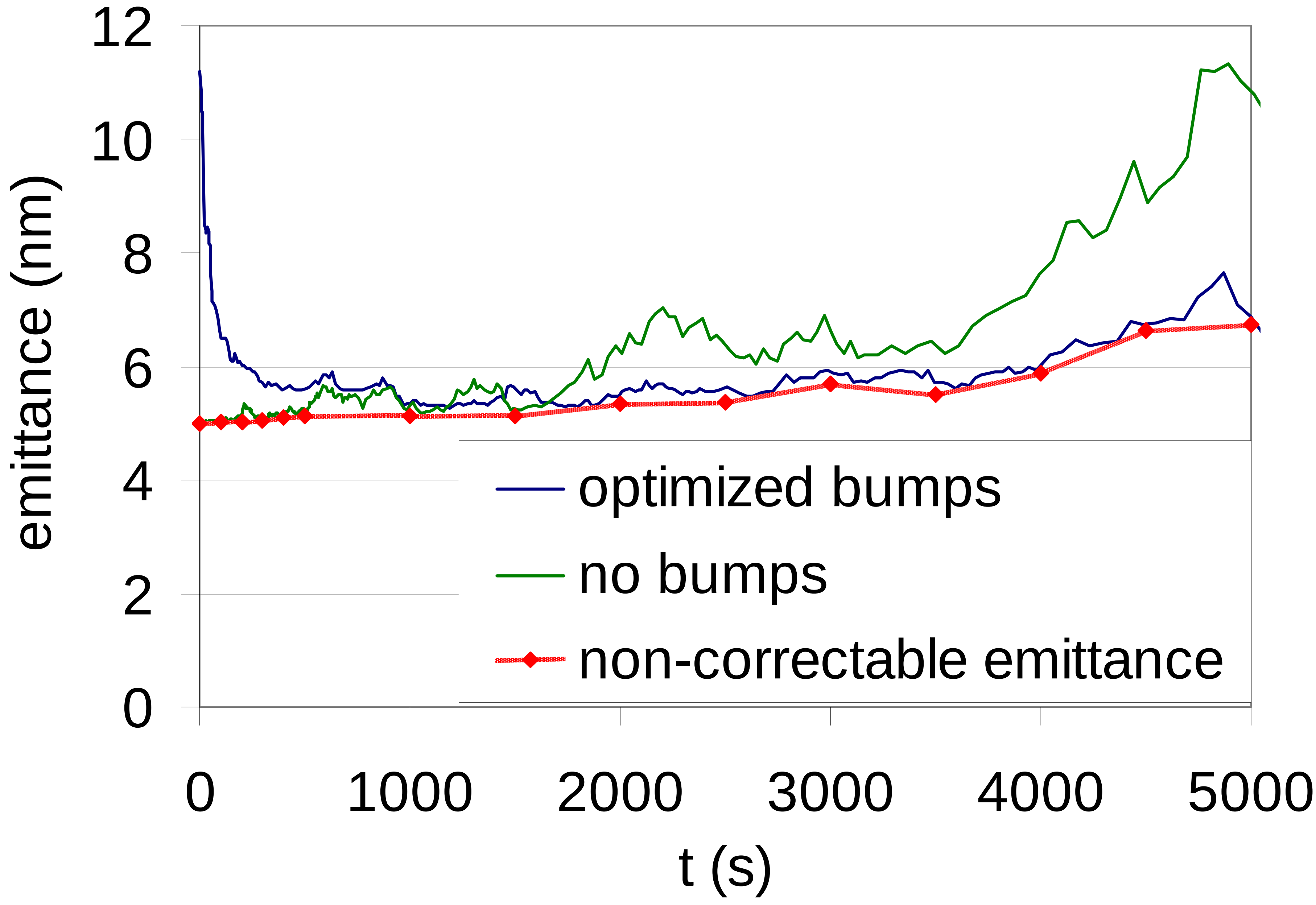
Emittance Bumps w/o Ground Motion



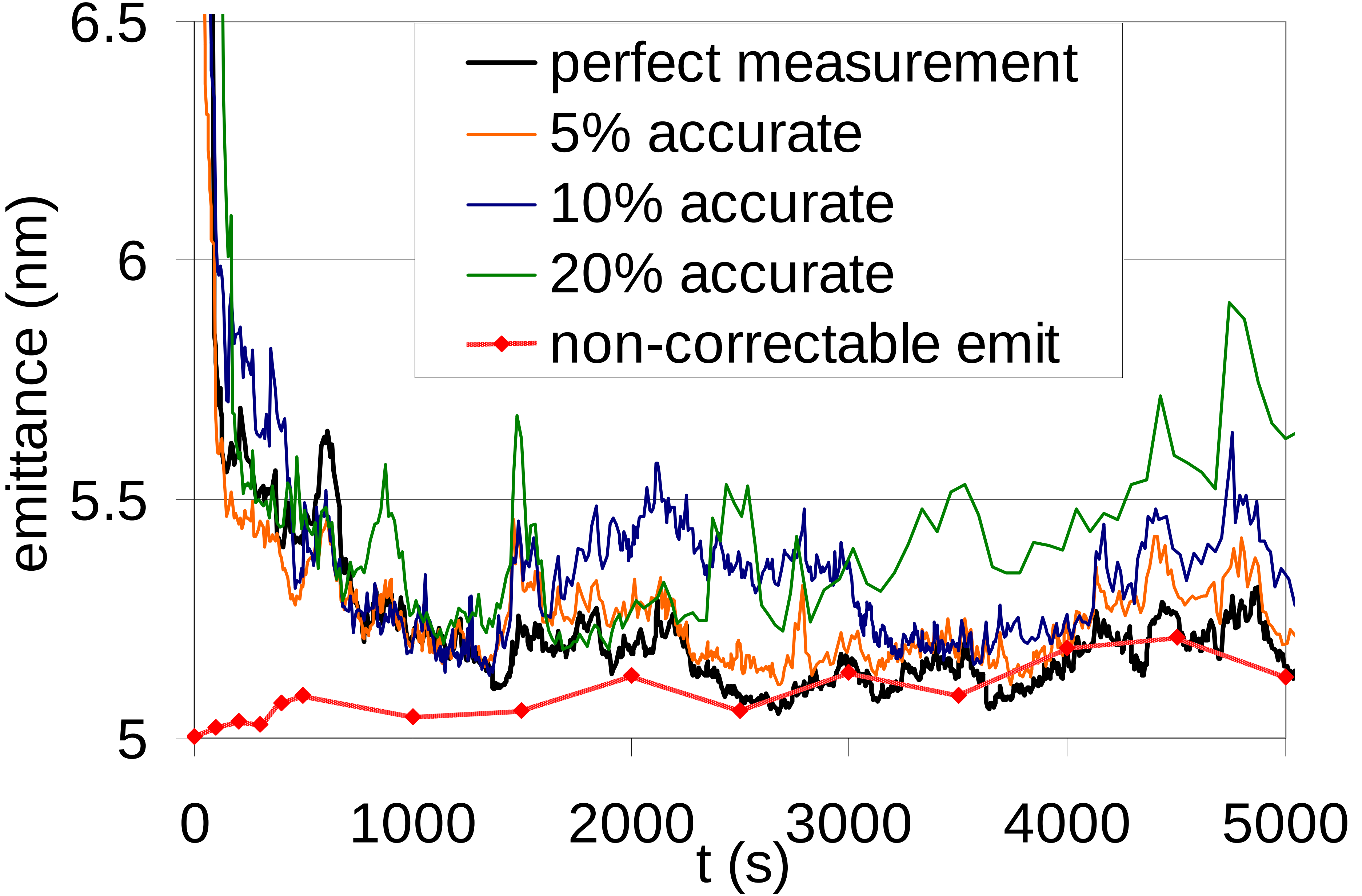
Ground Motion with Feedback



Ground Motion without Feedback



Effect of Accuracy of LWS Measurement



Example Input File for Optimizer

	feed.out	! output file name
	beam.bump.	! bump file name
	beam.gr.	! ground motion file name
	0.1	! interval between scans
	0.	! starting time
	-1	! random number seed (<0)
Order of magnitude,	3.	! size of initial offset
for faster initial corr.	0.0002	! guess for quadratic dependence
	1.0	! overall scale factor for ground motion
If too small, “jumpy” results	20 40 50000	! nvector, minimum nscan, nmeasure
	3	! fit method
Hard to keep	0.1	! relative increase in emittance (minimum)
below 10%	2.0 0.01	! max shift, min interval
	0.1	! noise
Strongly Affects	0.001	! decay with time
Accuracy	0	! skip emittance bumps