Observations of coherent synchrotron radiation in electron storage rings

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Acknowledgements

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¥ALS AP and operations group

Overview

¥ What is CSR?

¥ Why CSR is important for storage rings?

¥ ALS observations

¥ Measurements at other rings

¥ Stupakov-Heifets CSR instability model

¥ Application to a new ring at ALS

Coherent Synchrotron Radiation

When the electron bunch is comparable to the SR wavelength, the individual electrons radiate coherently and the intensity scales with N^2.

$$P(\omega) = p(\omega)\left[N + N(N-1)g(\sigma_l)\right]$$

INCOHERENT

COHERENT

For a gaussian bunch distribution, coherent radiation will occur when:

$$\sigma_l \; ? \; \lambda/\pi$$

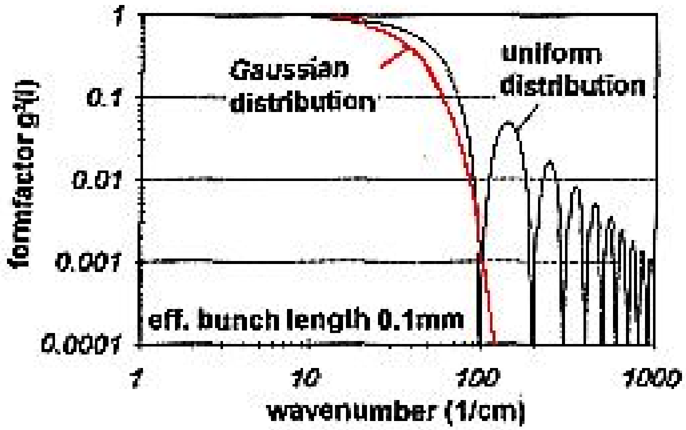


FIGURE 3. Form factor for a Gaussian and rectangular particle distribut

Typical storage rings have bunch lengths greater than 5 mm, so most SR is incoherent.

Since: $N > 10^6$

the potential gain is large.

CSR in electron rings

Why is CSR interesting in electron storage rings?

¥ Instabilities driven by SR impedance cause increase in bunch length and energy spread

¥ Instability bursts present undesirable noise to infrared SR user

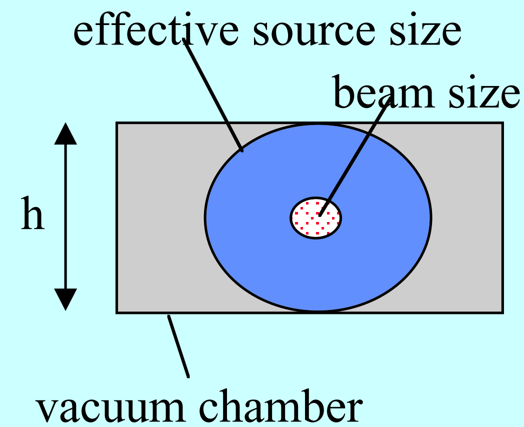
¥ stable CSR may be very useful as an intense source in the far-infrared/THz range.

¥ very generic source of impedance. Effects apply to wide variety of rings.

Vacuum Chamber as a High Pass Filter

The SR spectrum does not extend to DC.
The vacuum chamber acts as a high pass filter in two ways:

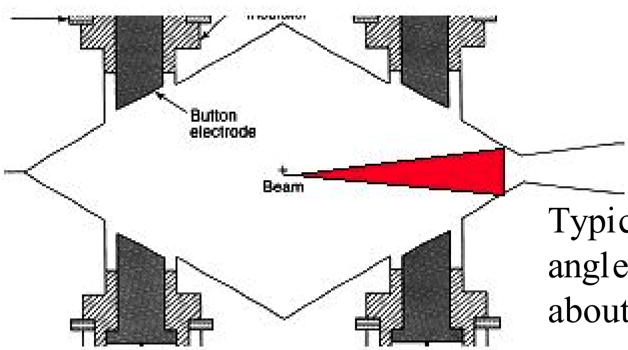
- ¥shielding
- ¥reduced vertical aperture in antechamber design



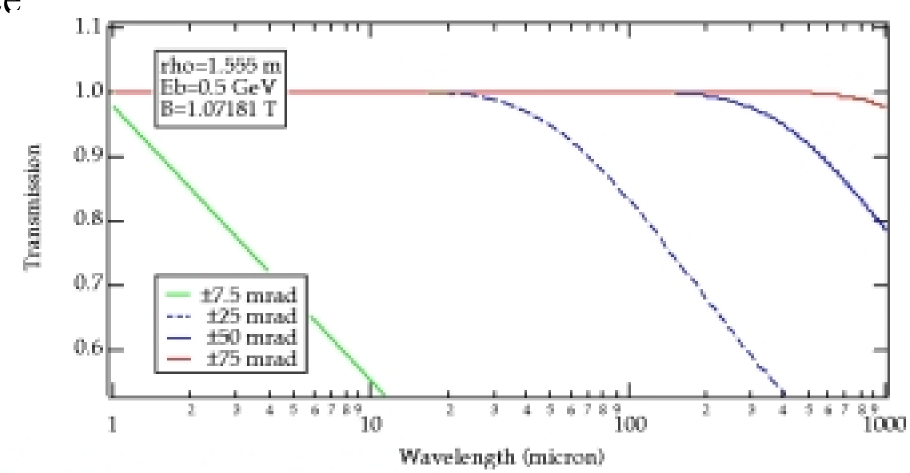
When the effective size of the SR source is equal to the height of the vacuum chamber, SR is suppressed.

$$\theta_{rad} = \left(\frac{\lambda}{\rho}\right)^{1/3}$$ opening angle

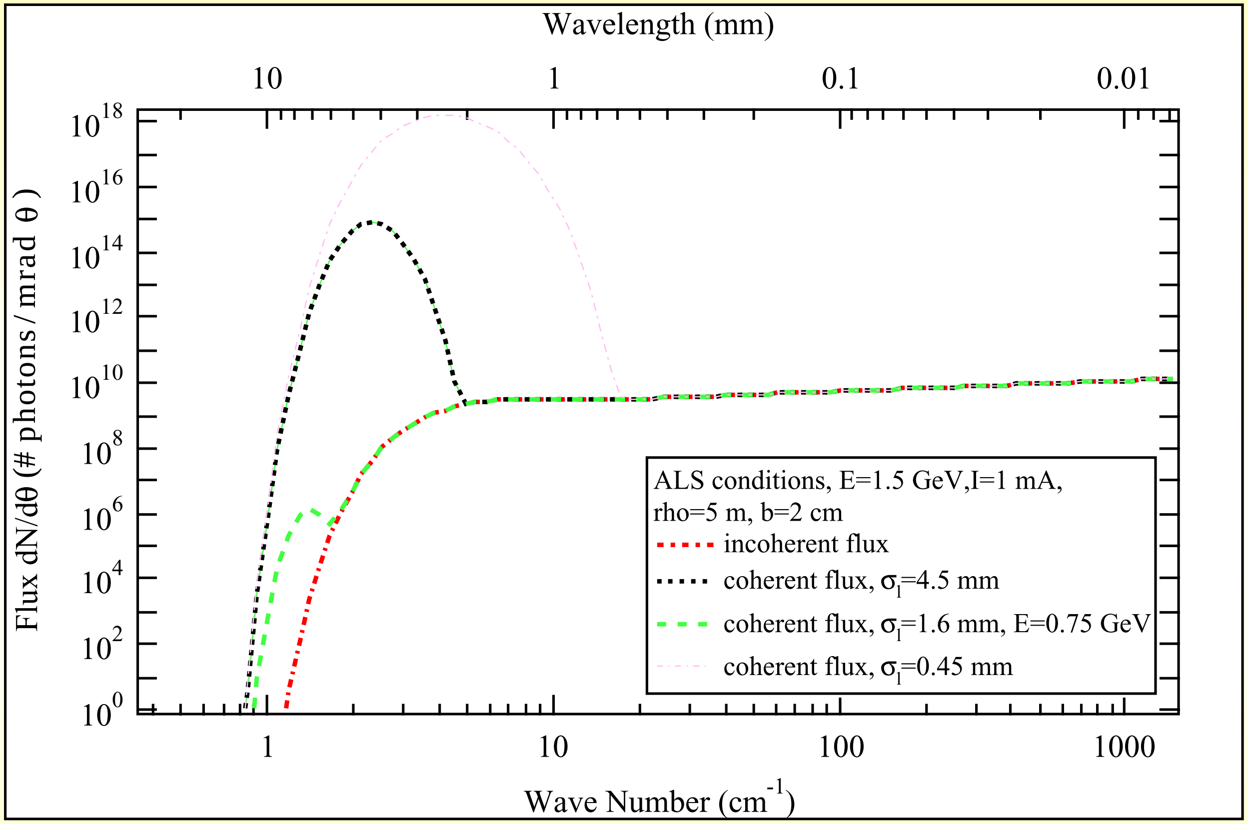
$$\sigma_{source} = \frac{\lambda}{\theta_{rad}} = \lambda^{2/3}\rho^{1/3}$$ diffraction limited source size



Typical opening angles for far-IR about 6 degrees.



CSR Calculations for ALS



Calculated ALS CSR

Steady CSR difficult to observe for nominal ALS conditions due to vacuum chamber cutoff.

Possibilities

¥reduce momentum compaction

    ¥difficult due to TBA lattice structure

¥run at lower energy

    ¥beam much more unstable

¥Increase RF voltage

    ¥very expensive

¥Replace ALS vacuum chamber or decrease bend radius

    ¥very expensive for VC, possible improvement at Superbends

ALS IR Beamline 1.4

The IR beamline is the best existing port on the ALS to observe far-IR SR

¥10 mrad vertical acceptance

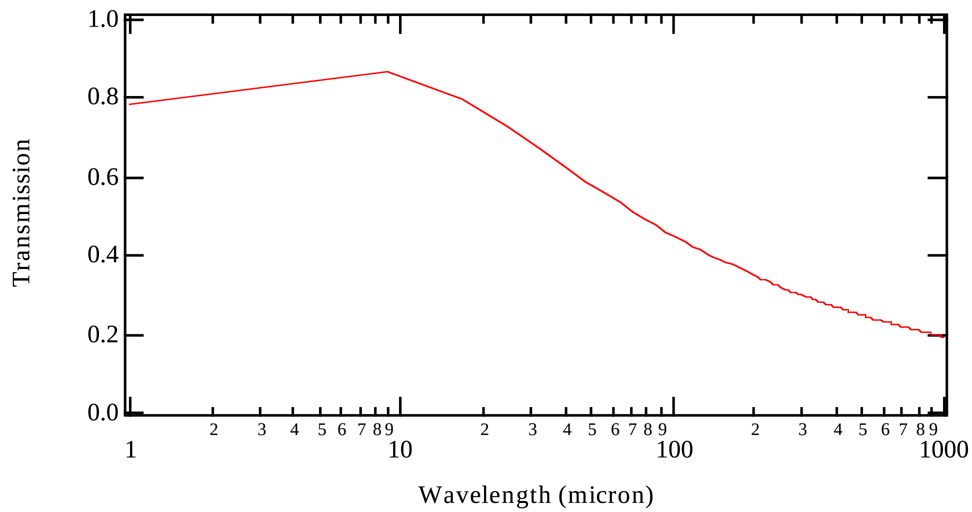
¥7 meter from source

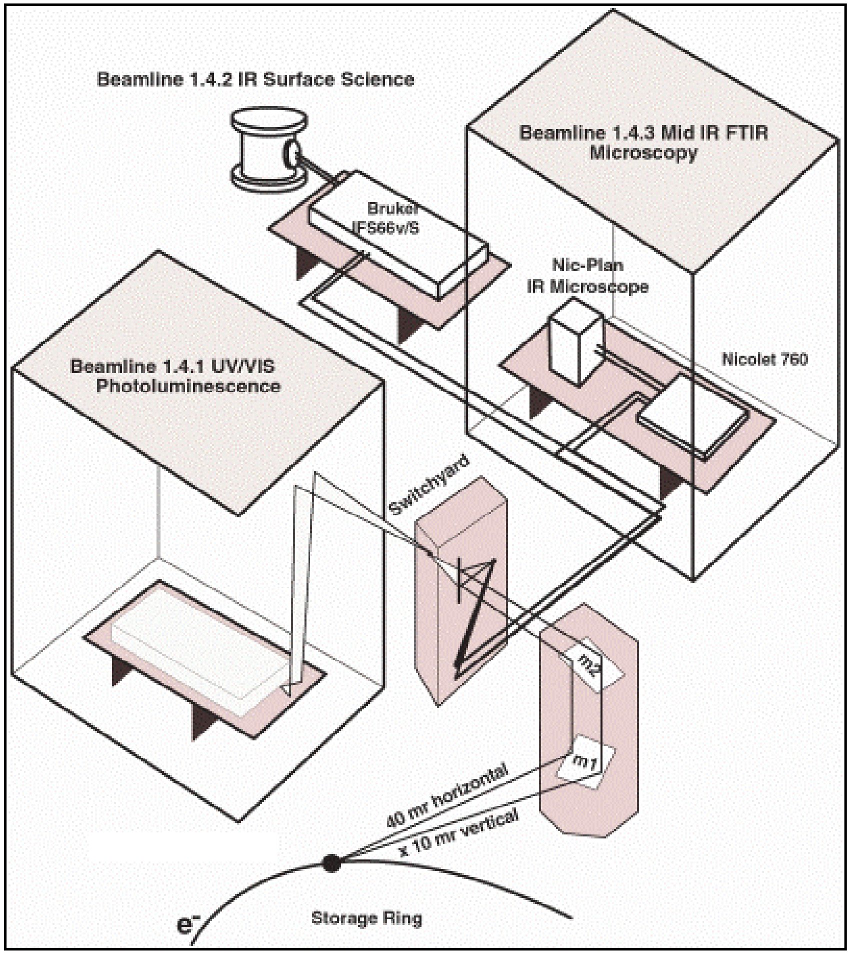
¥diamond vacuum window for mid-IR transmission

¥optical SR beam for alignment

¥existing diagnostic tools (detectors, spectrometers, etc.)

¥20% geometric transmission at 1 mm (not including diffraction effects)

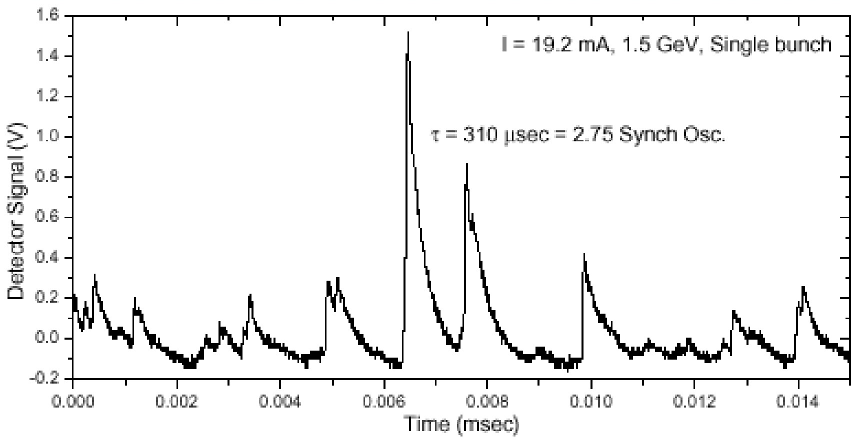




Detectors

- ¥ mm-wave receiver- BW 2.7-4 mm, not able to see incoherent SR, < 1 nsec time response, room temperature
- ¥ LHe cooled silicon bolometer, BW 0.5-2 mm, able to see incoherent SR down to < a few mA of stored beam current, ~10 msec time response, requires 1.6 deg-K operation, spectrometer on order
- ¥ LHe bolometer, BW 0.1-1 mm (?), able to see incoherent SR, time response ~1 msec, 4.2 deg-K operation, spectrometer available up to 0.5 mm

Coherent FIR Bursts at ALS



At currents above 8 mA single bunch, we observe bursts of FIR SR with apparent peak at 400 micron. Coherent enhancement not yet calibrated due to detector response time.

Similar bursts have been observed at SURF, NSLS VUV, MAX-I, Bessy-II with enhancement factors from 10^3-10^4. Nobody yet understands the mechanisms for the effect. Probably due to microbunching instability, possibly driven by radiation impedance.

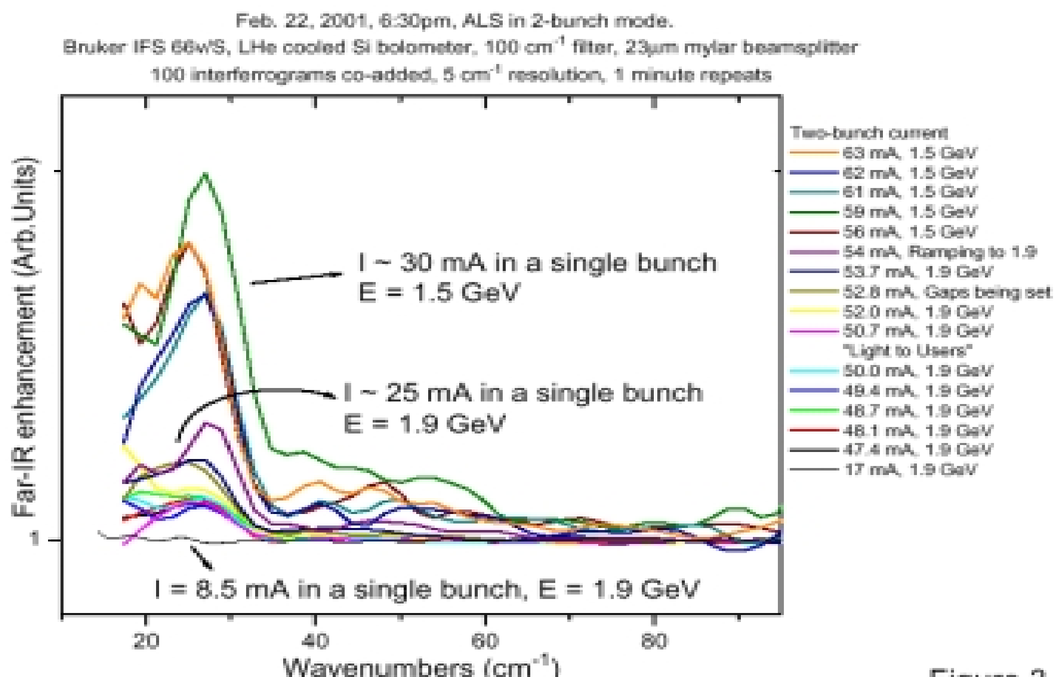


Figure 3

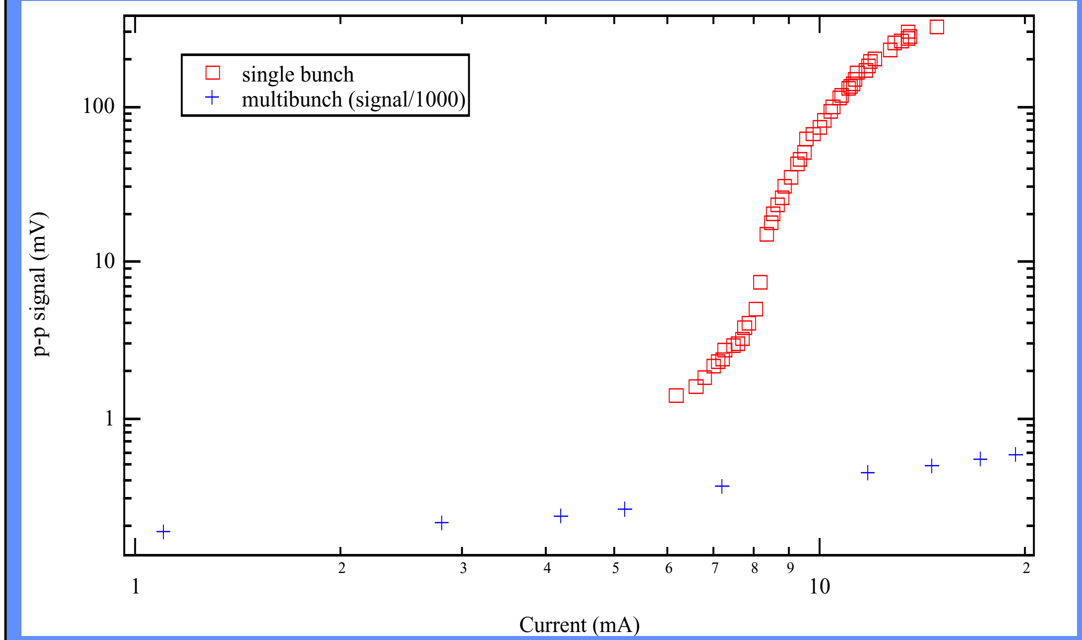
Single bunch vs multibunch

Compare single and multibunch signal to look for coherent enhancement

¥SB signal appears larger than MB at same current. Slope also larger (steady CSR?)

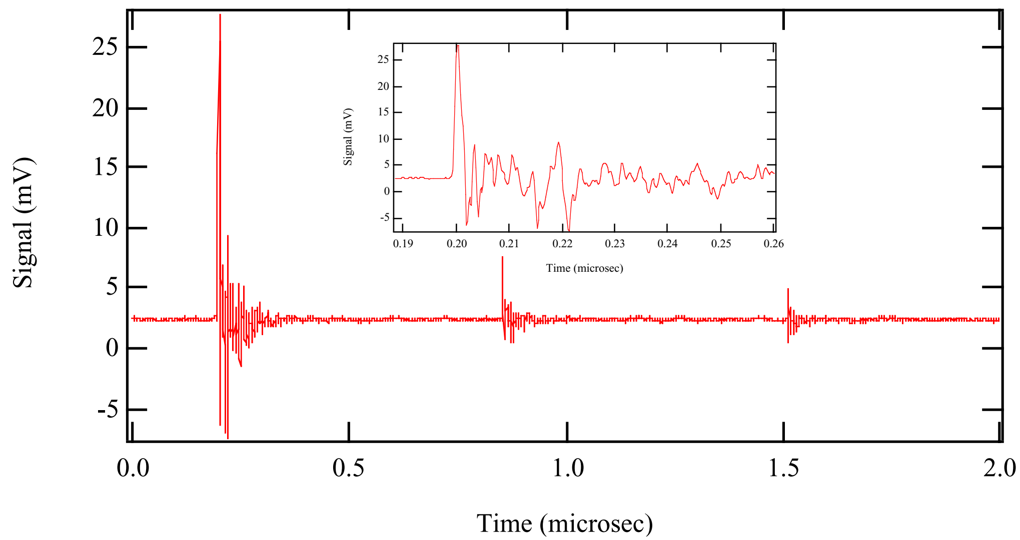
¥SB signal grows rapidly at threshold; possible saturation for larger bursts

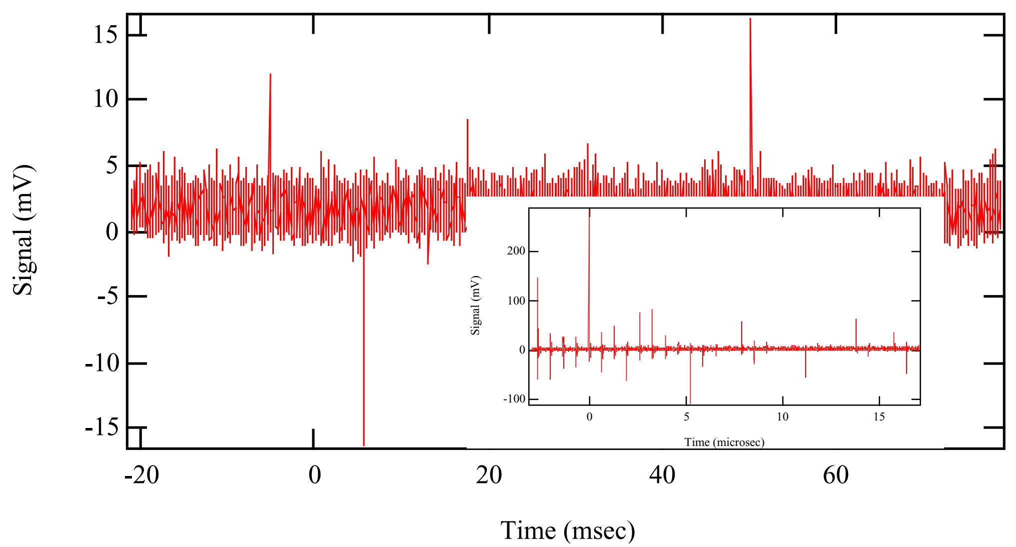
¥threshold at 4.9 mA in mm-wave rcvr, 8.5 mA, and 9.3 mA in bolometers at 1.5 GeV



Average single bunch and multibunch signals vs. current in 0.5-2 mm bolometer. Planning to measure single bunch signal down to < 1 mA.

mm-wave detector





A borrowed mm-wave rcvr allowed us to observe SR from 2.5-4 mm wavelength.

¥sensitive to burst SR only

¥1 nsec width pulses

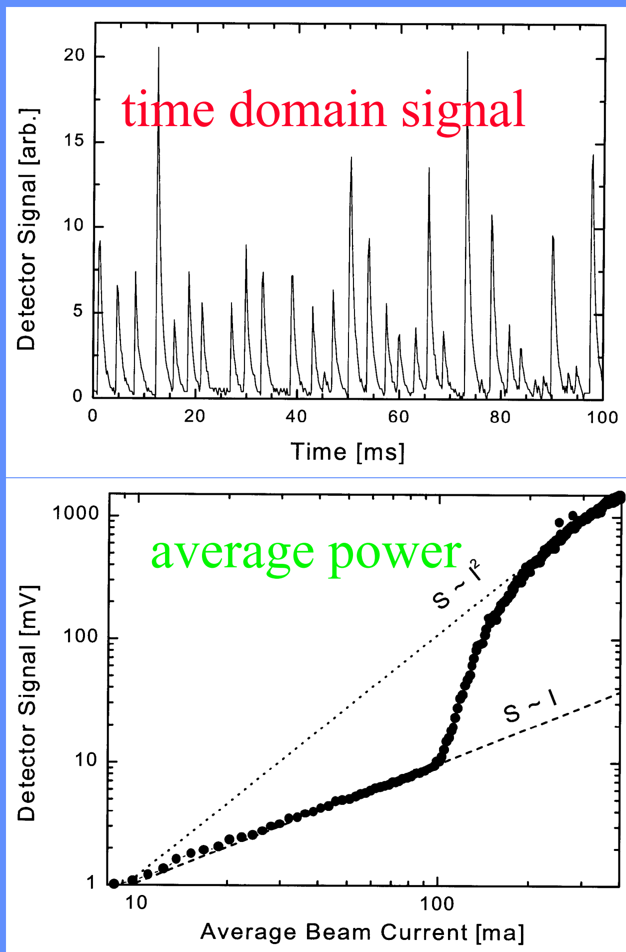
¥able to resolve bunch-bunch bursting

¥signal detection unlocked to beam. Relative turn-by-turn signal levels unreliable.

¥potential ringing of signal

Other observations

NSLS-VUV Ring (G. Carr, et. al., NIMA 463 (2001) 387-392)



E=737 MeV
chamber cutoff=10 GHz

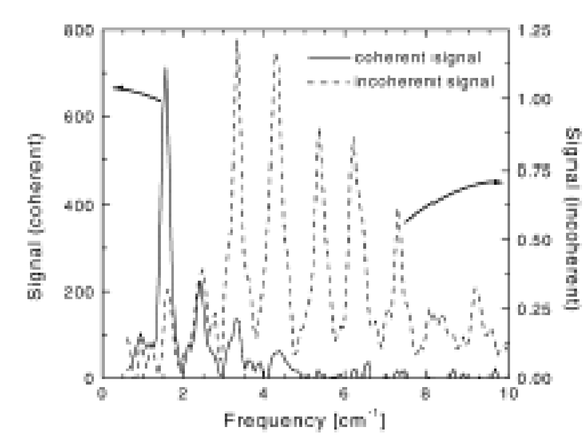
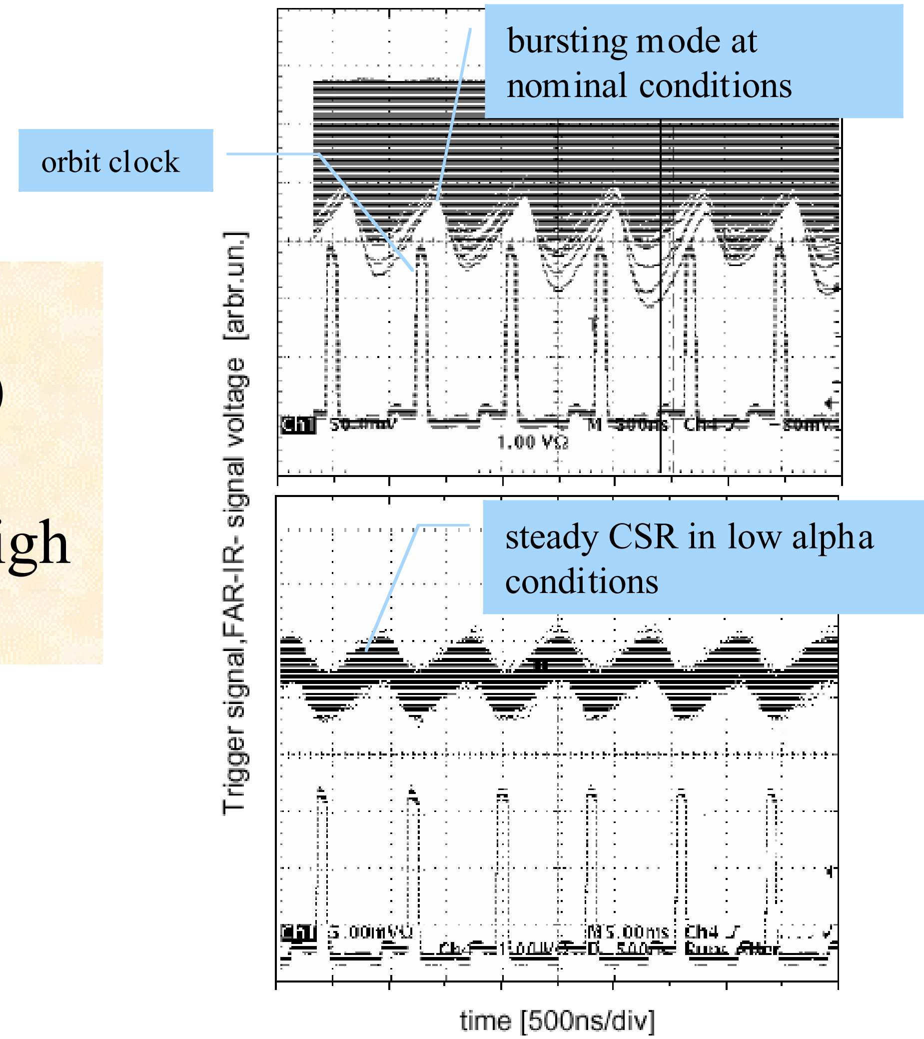


Fig. 3. Spectral signal for both incoherent (dashed line, right axis) and coherent (solid line, left axis) synchrotron radiation emission. The complex structure of both spectra is due to interference between two source points, the second from an upstream tangent point reflected in the outer wall of the storage ring chamber.

Frequency spectrum

Other observations (cont.)

BESSY-II (Abo-Bakr, et. al., preprint, submitted to PRL)



Bessy-II has observed apparent steady-CSR in a low alpha (~-2e-5) lattice. They also observe bursting behavior in the nominal lattice at high bunch current.

SURF-II NIST (U. Arp, et. al.)

MAXLab MAX-I(. Anderssen. et. al.)

Infrared Catastrophe

Use theory developed by Heifets and Stupakov (SLAC-PUB-8761, PAC 2001)

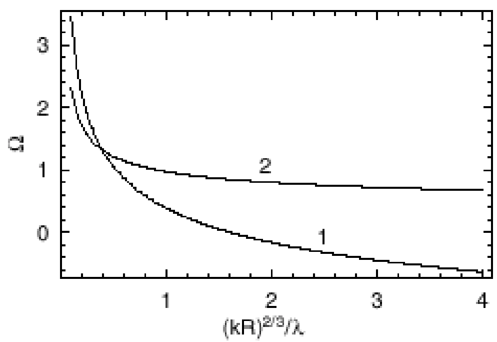
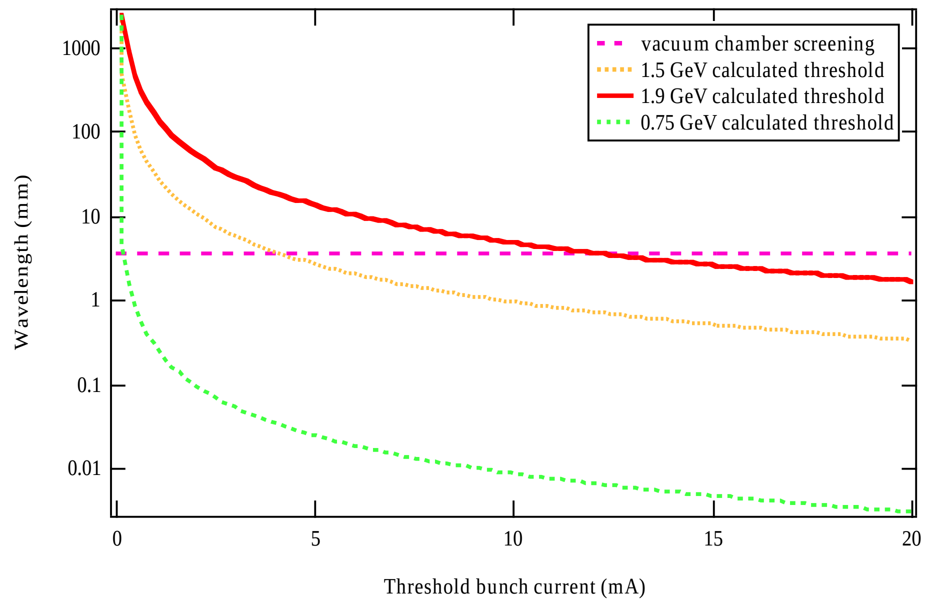


Figure 2: The imaginary (*1*) and real (*2*) parts of Ω as functions of $(kR)^{2/3}/\lambda$.

Questions:
¥Should the shielded wake be used?
¥What is the effect of short mag nets?
¥What is the expected bunch length vs current?
¥What is the distribution of burst amplitudes/times?
¥How long does a burst last?

Solution of Vlasov eqn for free space SR impedance
¥longer wavelengths have lower threshold due to Landau damping
¥Shielding added as an ad hoc cutoff
¥amplitude of modulation growth undetermined



Comparison with ALS data

Data to date shows rough agreement with theory

Questions:

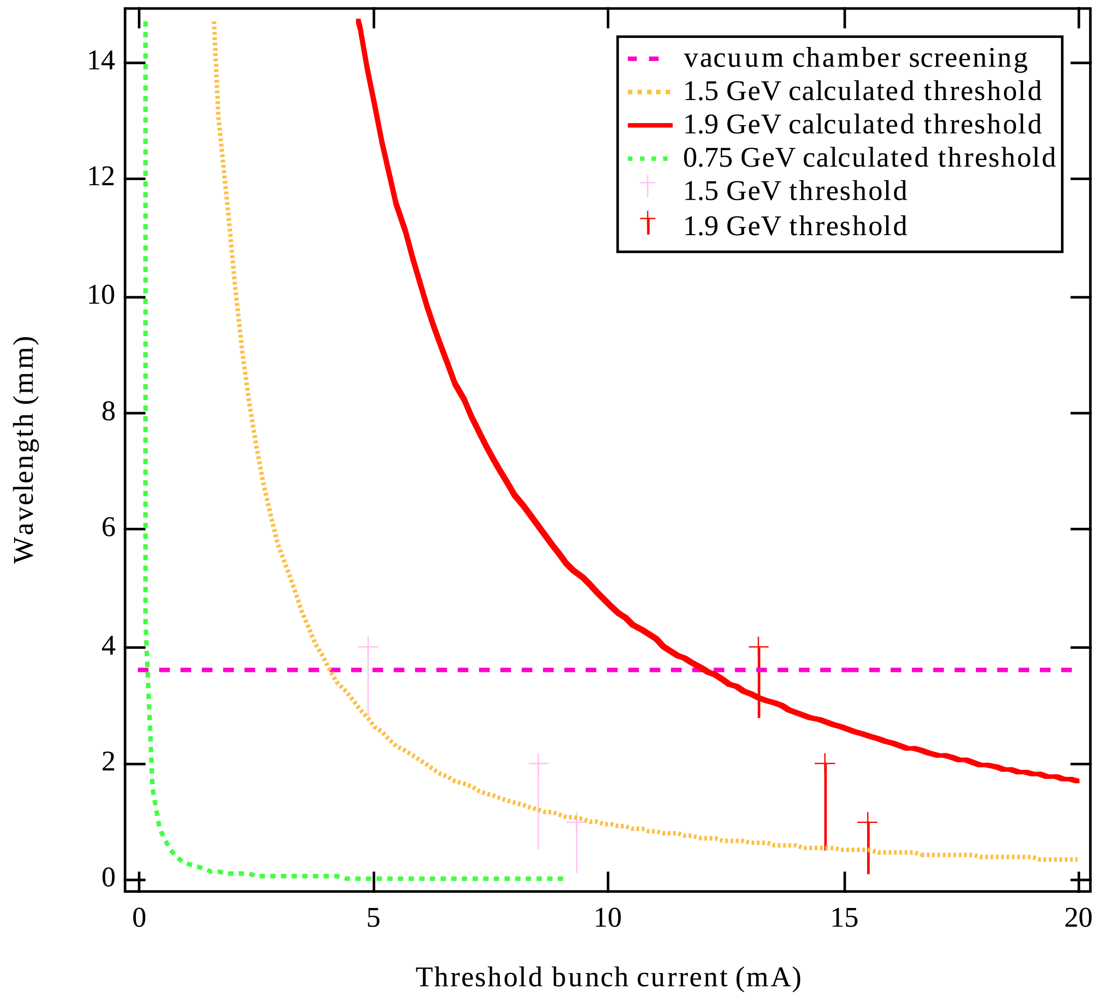
What is actual bandwidth of detectors?

spectral data available only on 0.1-1 mm bolometer

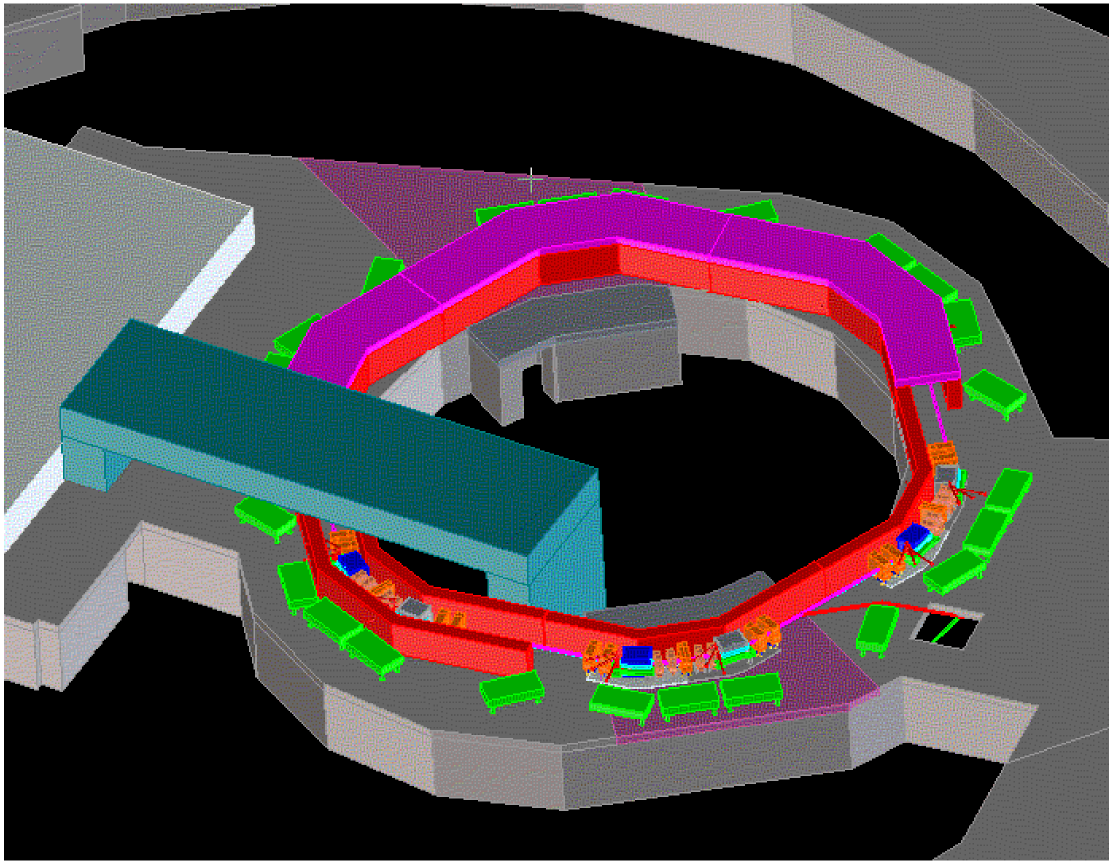
What is actual chamber cutoff?

What is transmission of beamline at long wavelengths?

What is total power emitted?



IR Ring Modes of Operation



Two Operation Modes:

- Conventional
  $\lambda = 1\ \mu m — 1 mm$

- Coherent Far-IR

Beam Line Experiments Located on Top of the Booster Shielding as Well

A Possible Coherent FIR Source

Coherent SR can occur in the wavelength range

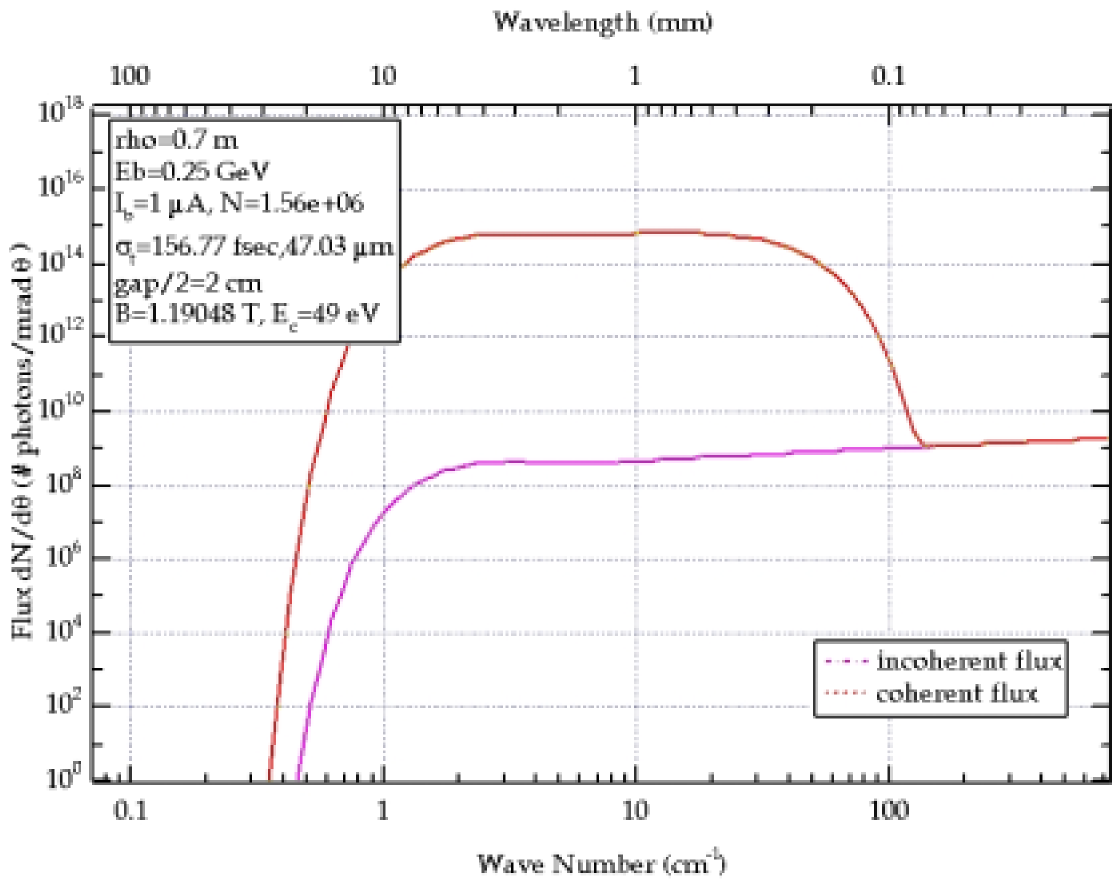
$$\pi\sigma_l < \lambda < 2h\left(\frac{h}{\rho}\right)^{1/2}$$

Bunch Shortening Knobs:

$$\sigma_l \propto \left(\frac{\alpha_C E^3}{V_{RF} f_{RF}}\right)^{\frac{1}{2}}$$

With Reasonable Numbers:

Large enhancement in the 0.1-10 mm range is theoretically possible!



(Originally Inspired by Jim Murphy)

IR Ring in the Coherent Mode

Energy	300 [MeV]
RF (Super Conductive)	1.5 [GHz]
RF Voltage	~ 2 [MV]
Momentum Compaction	~ 3 10^{-4}
rms Bunch Length	200 [fs]
Current/Bunch	10 [μA] (N ~1.4 10^{7})
Max. Number of Bunches	330

Small current/bunch for avoiding microwave instabilities (bunch lengthening)

Very small current: no cavity beam loading

~ 50,000 times higher FIR flux (0.1 — 10 mm) than in the conventional mode with 1 A current

Coherent Mode of Operation Still to Be Demonstrated!

Summary

¥ bursting CSR has been observed in several rings

¥ steady CSR has possibly been observed at Bessy-II

¥ a Heifets/Stupakov microbunching model has rough agreement with ALS results

¥ any help will be appreciated (especially theoretical help!)