Topics in Coherent Synchrotron Radiation (CSR) Workshop: Experimental Consequences of Radiation Impedance

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Nov. 1-2 2010, CLS

Details on the topic of the workshop

This workshop will discuss the experimental and theoretical consequences of radiation impedance as it arises when a charged particle moves along a circular path, such as in a bending magnet in a synchrotron lattice. It derives from a forward-propagating wakefield, and is distinct from the familiar "machine" impedance that derives from the backward-propagating wakefields associated with both linear and curved motion. We are particularly interested in **how the longitudinal radiation impedance impacts on the spectral structure of coherent synchrotron radiation (CSR)**. It is well known that the impedance is determined by the geometry of the bending-magnet vacuum chamber, and most CSR studies have employed a simple model of two parallel plates (of infinite extent) representing the upper and lower chamber surfaces. The resulting impedance is a featureless curve with a local maximum and an effective cutoff at long wavelengths. However, in **1990 Warnock el al. [Part. Acc. 25, (1990), 113] showed that the chamber side-walls should modify the impedance by introducing a series of narrow resonant-like features, and these in turn should be reflected in the CSR spectra as a series of narrow peaks, a sort of spectral "picket fence".** A few years ago, a high-resolution CSR study at the CLS exhibited a picket-fence frequency spectrum, and subsequent studies showed that this structure remained unchanged under varying CSR modes. It is premature to claim evidence of the **Warnock "whispering-gallery" modes**, but in view of the **impact these modes might have on future high-resolution CSR spectroscopy** both here and elsewhere, it seemed timely to convene a workshop to discuss how to search for, and identify, them. Indeed, others may also have unexplained features in their CSR spectra, and they are encouraged to present their data for general comment and discussion. Once the modes are identified, the vacuum chambers can be designed specifically to minimize their impact on high-resolution FIR studies.

most contributions can be found at:
http://exshare.lightsource.ca/farir/Topics%20in%20Coherent%20Synchrotron%20Radiation%20CSR%20Works/Forms/AllItems.aspx

List of Invitees:

Bob Warnock – SLAC
Steve Kramer – BNL
John Byrd – LBL
Peter Kuske – Bessy
Markus Ries – Bessy
Anke-Susanne Müller – Anka
Gennady Stupakov – SLAC
Marco Venturini – LBL
James Ellison – New Mexico
Joseph Bisognano – SRC
Tomonori Agoh
Rui Li – JLAB
James Safranek – SLAC
Lia Merminga – TRIUMF
Ward Wurtz – CLS
Les Dallins – CLS
Tim May – CLS
Mark de Jong – CLS
Thomas Ellis – CLS

List of Attendees:

Bob Warnock – SLAC
Steve Kramer – BNL
John Byrd – LBL – via skype
Peter Kuske – Bessy
Markus Ries – Bessy
Anke-Susanne Müller – Anka
Gennady Stupakov – SLAC
Marco Venturini – LBL
James Ellison – New Mexico
Joseph Bisognano – SRC
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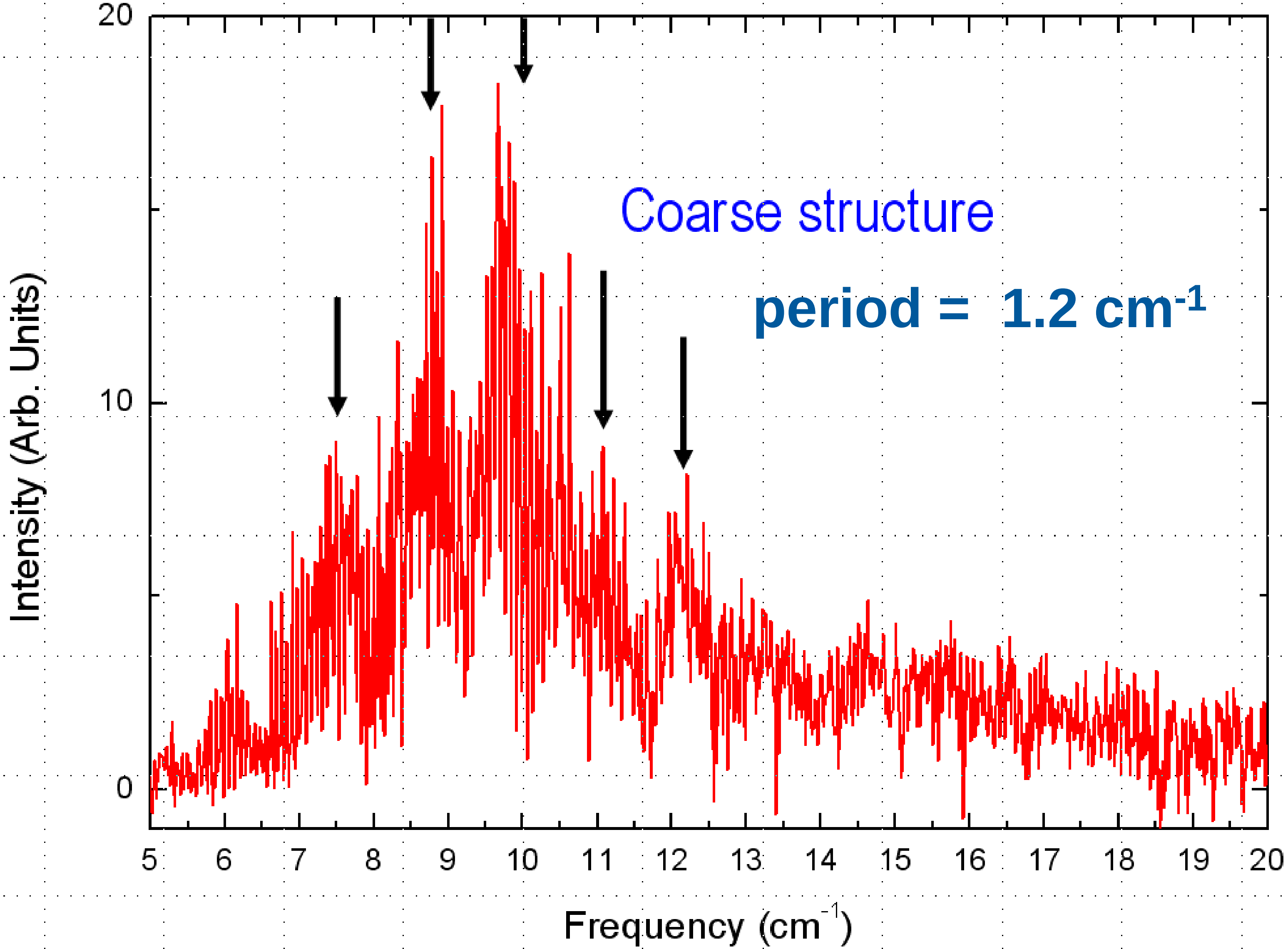
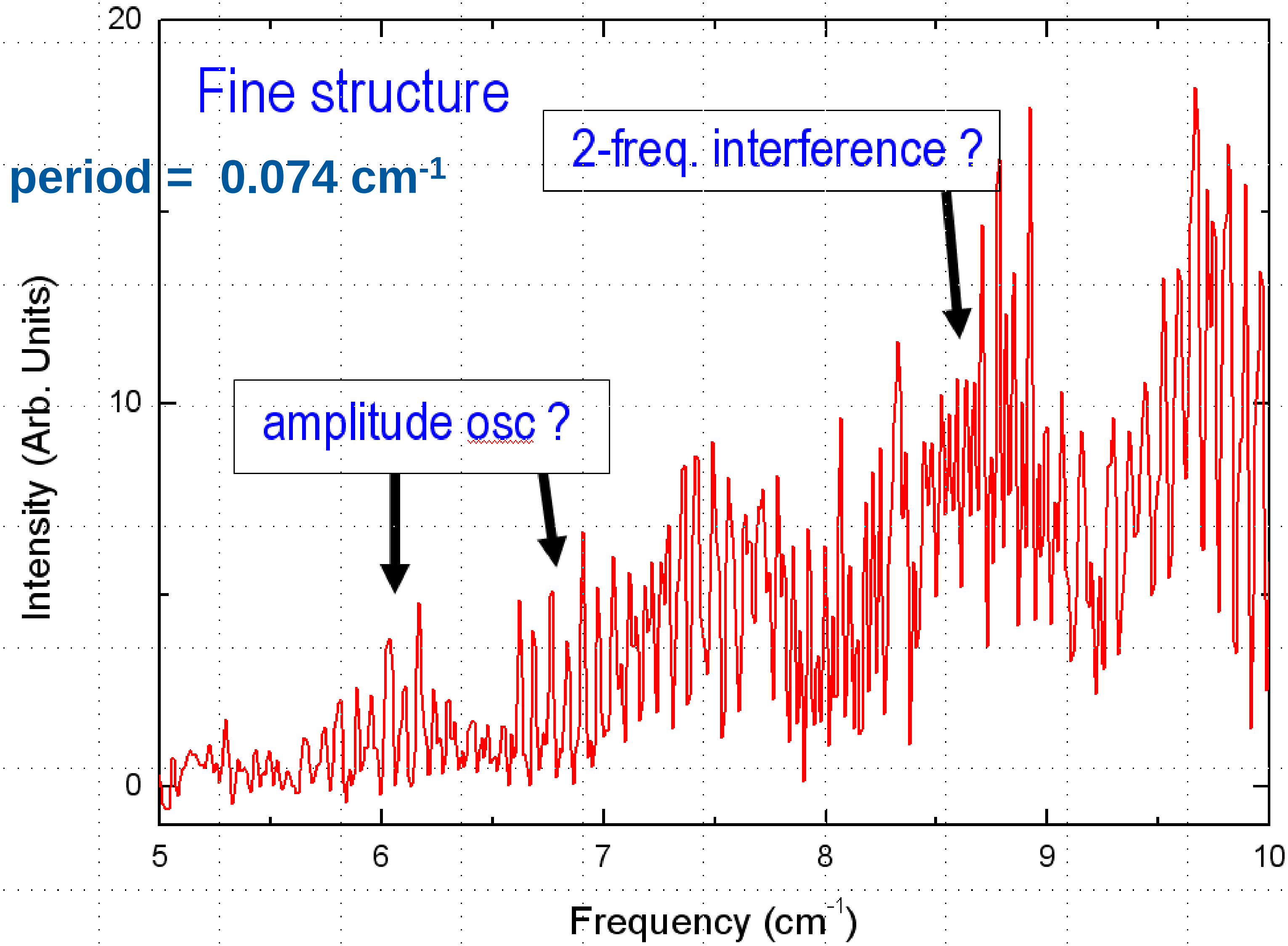
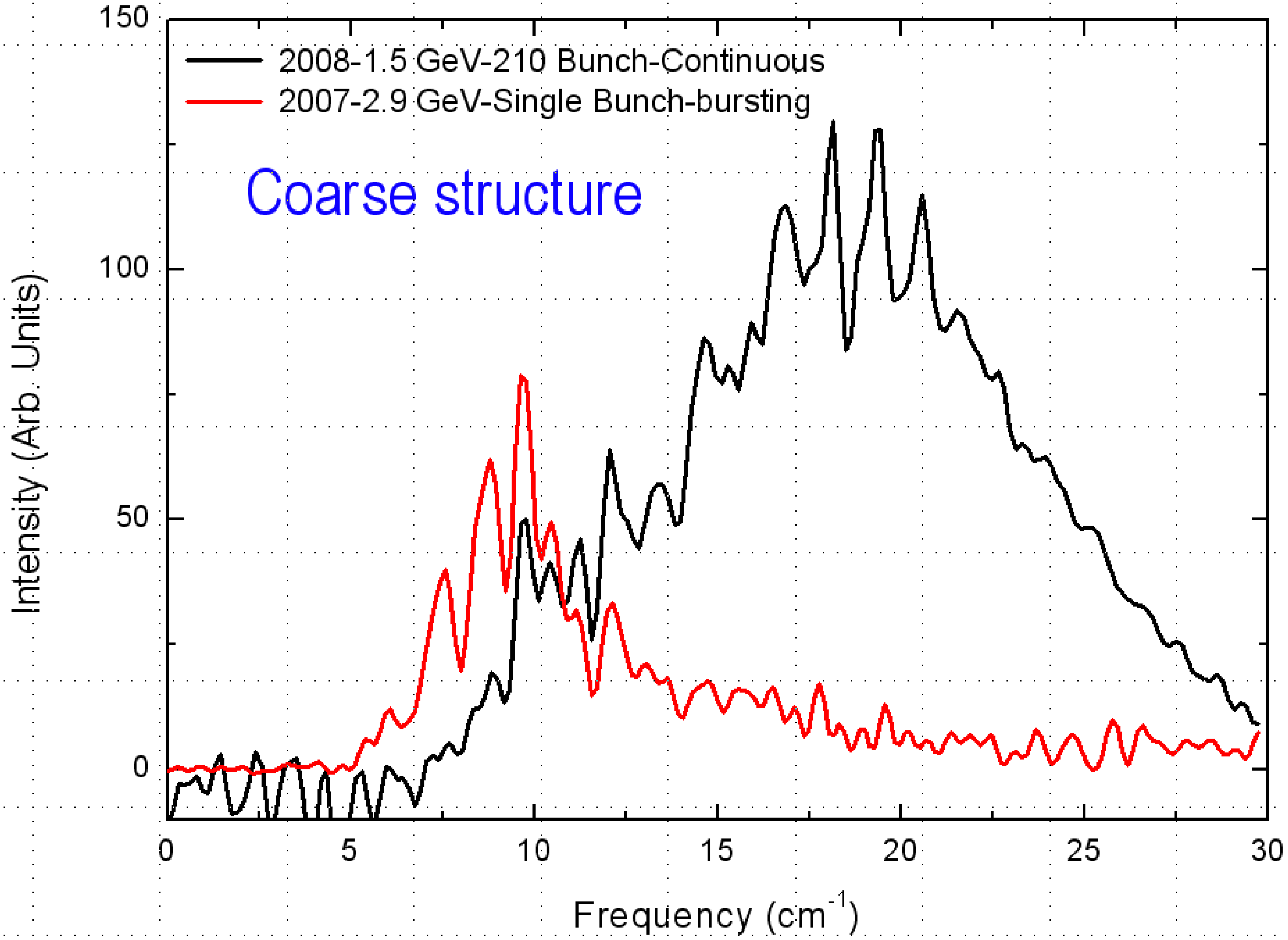
Les Dallins – CLS
Tim May – CLS
Mark de Jong – CLS
Thomas Ellis – CLS
Shane Koscielniak – TRIUMF

2.9 GeV Single-Bunch "Bursting" mode

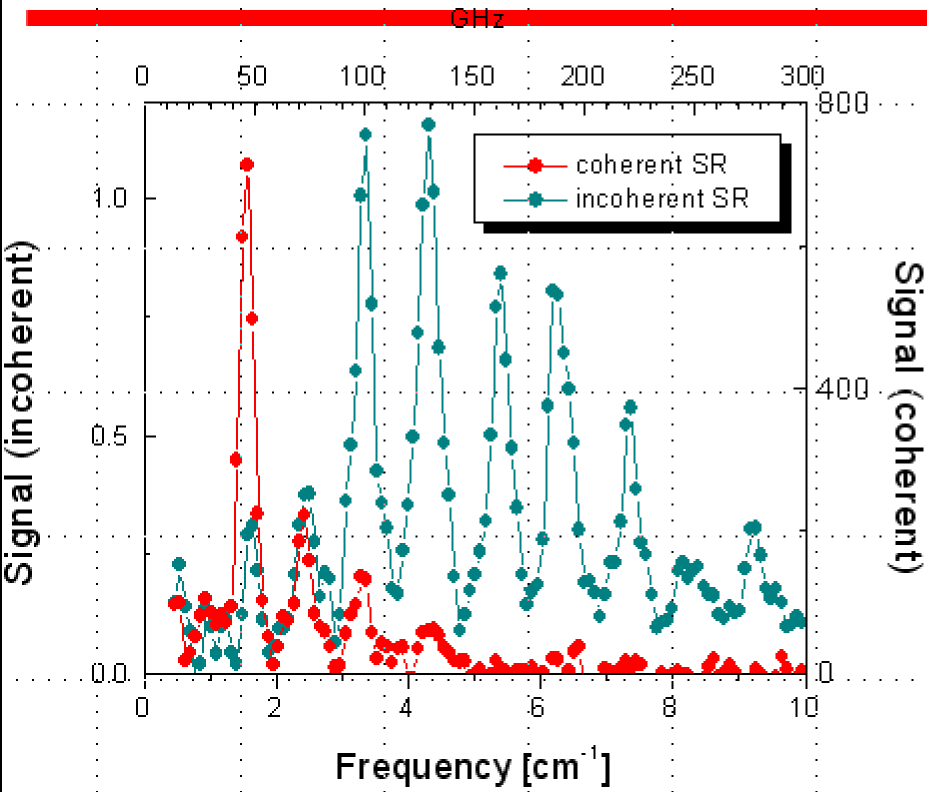


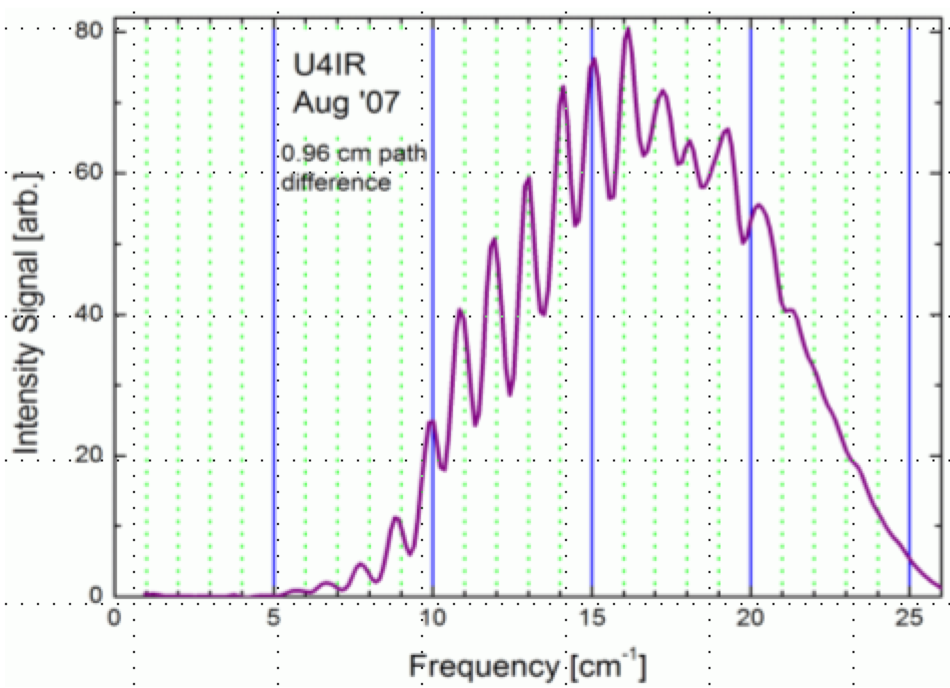
2.9 GeV Single-Bunch "Bursting" mode




2008-1.5 GeV-210 Bunch-Continuous
2007-2.9 GeV-Single Bunch-bursting
Coarse structure
Intensity (Arb. Units)
Frequency (cm^{-1})
150
100
50
0
0
5
10
15
20
25
30

FIR Measurements of Spectra in 2-FIR





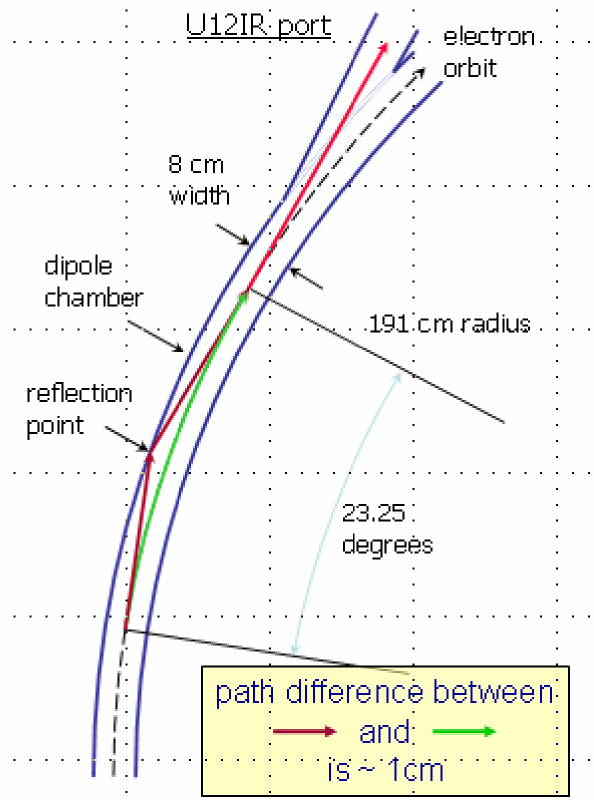
Interference model for line structure in both ISR and CSR pattern with $\Delta f \sim 1 cm^{-1}$ spacing in two similar beamlines with different spectra ranges

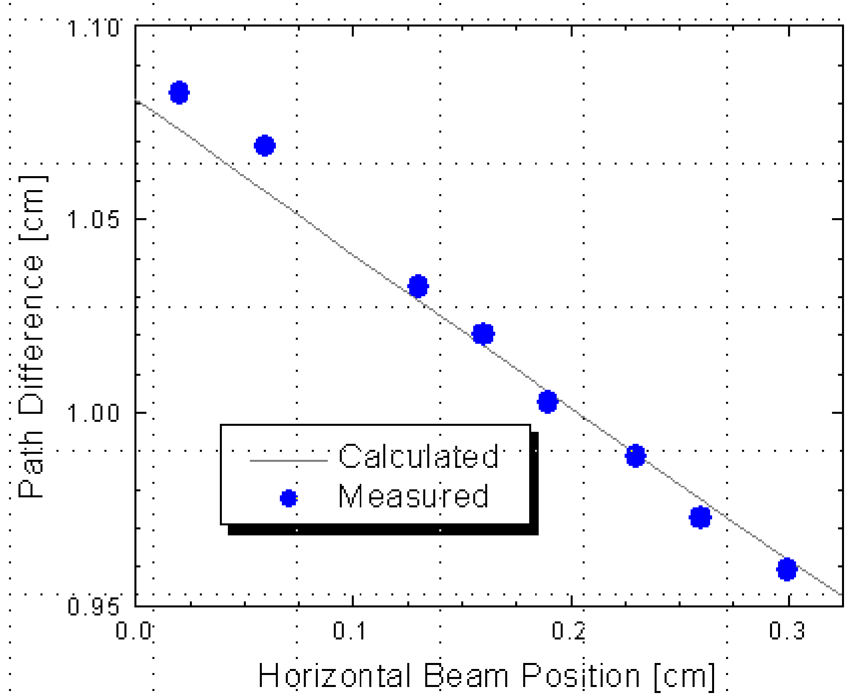
Reflection from Dipole Chamber Outer Wall

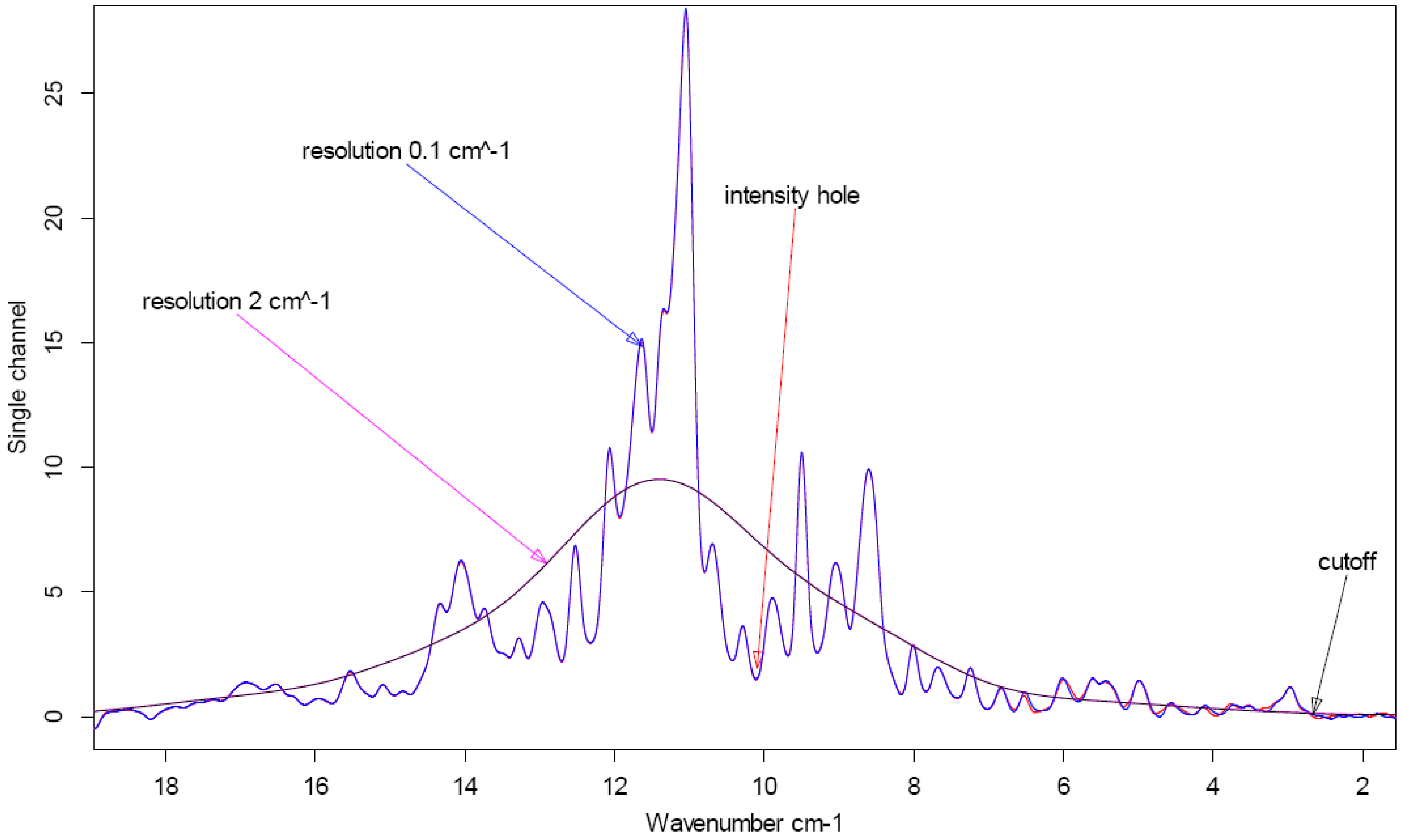
Could give a $\sin^2(2\pi f \Delta t)$ modulation to broadband ISR and CSR spectra
$\Delta L \sim 1$cm or frequency spacing ~ 30 GHz

Slope $= 2*\sin(\theta/2) \sim 0.4$

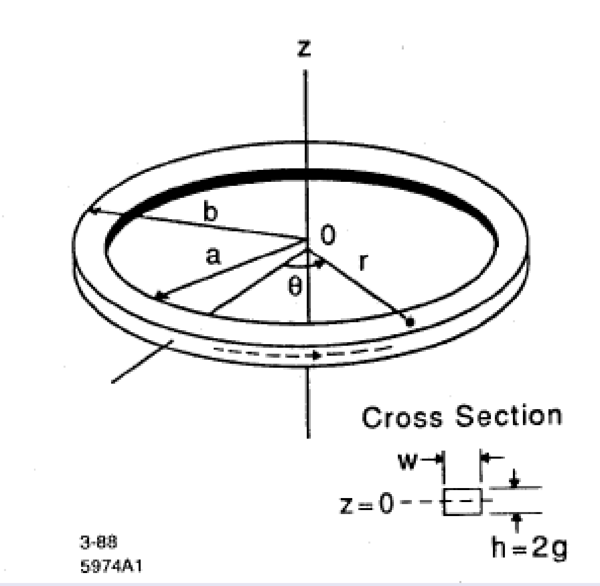
Zero at ~30 GHz due to 180 degree phase shift at metal boundary






resolution 0.1 cm^-1
intensity hole
resolution 2 cm^-1
cutoff
Single channel
0
5
10
15
20
25
18
16
14
12
10
8
6
4
2
Wavenumber cm-1

CSR in Storage Rings - Toroidal Vacuum Chamber



Solve for longitudinal electric field $E_\theta(r,\theta,z,t)$ produced by the beam at the position of beam $(r = R\ , z = 0)$, the Wake Field, which determines the dynamics of the bunch. The work done by the wake field per unit time is the negative of the Radiated Power.

Since the field is concentrated near $r = b$, the result is nearly the same for a "pillbox" chamber with $a = 0$. Let's give equations for pillbox.

Solution in terms of Bessel functions - 3
Longitudinal field

$$
\begin{aligned}
&\hat{E}_\theta(r,n,p,\omega) = -\frac{q\beta c Z_0 \lambda_n}{4(\omega - n\omega_0)} \\
&\cdot\left[\frac{\omega}{c}\left(\frac{J_n'(\gamma_p r)}{J_n'(\gamma_p b)} s_n(\gamma_p b, \gamma_p R) + \theta(r-R) s_n(\gamma_p r, \gamma_p R)\right)\right. \\
&\left. + \frac{n}{\beta R}\left(\frac{\alpha_p}{\gamma_p}\right)^2 \left(\frac{J_n(\gamma_p r)}{J_n(\gamma_p b)} p_n(\gamma_p b, \gamma_p R) + \theta(r-R) p_n(\gamma_p r, \gamma_p R)\right)\right] \\
&\gamma_p^2 = (\omega/c)^2 - \alpha_p^2 \ , \quad \alpha_p = \pi p/h \ , \\
&p_n(x,y) = J_n(x)Y_n(y) - Y_n(x)J_n(y) \ , \\
&s_n(x,y) = J_n'(x)Y_n'(y) - Y_n'(x)J_n'(y)
\end{aligned}
\tag{14}
$$

Whispering Gallery Resonances

Resonances result from boundary conditions, as in Rayleigh theory, and give poles in the ω-plane:

$$J'_n(\gamma_p b) = 0 \quad (TE) \ , \quad J_n(\gamma_p b) = 0 \quad (TM) \ ,$$
$$\gamma_p^2 = (\omega/c)^2 - (\pi p/h)^2 \ . \tag{15}$$

Unusual nomenclature: TE and TM fields transverse to z-axis (vertical)

But infinitely many of these resonances do not affect the beam. By the principles of plasma physics, only waves with phase velocity close to the particle velocity influence the beam appreciably; i.e., Synchronous Modes.

With $E_\theta \sim e^{i(n\theta - \omega t)}$ phase velocity determined by $nd\theta/dt - \omega = 0$, so synchronism means $\omega = n\omega_0$. Then a synchronous TE resonance must satisfy

$$J'_n(\ [(n\omega_0/c)^2 - \alpha_p^2]^{1/2} b\ ) = 0 \ , \quad \omega_0 = \beta c/R \ . \tag{16}$$

Whispering Gallery Modes - 2

Synchronous modes:

$$j'_{ns} = (n\beta b/R)^2 - (\alpha_p b)^2 = n^2(1 - a'_s n^{-2/3} + \cdots)^2 \ . \tag{17}$$

If we retain only n^2 on the right hand side, then

$$n \approx = \frac{\alpha_p b}{((\beta b/R)^2 - 1)^{1/2}} \ , \tag{18}$$

which is a roughly correct for the lowest ($s = 1$) synchronous mode with vertical mode number p. Gives $n = 746, k = 0.62 cm^{-1}$ for VUV parameters, and $n = 7400, k = 1.65 cm^{-1}$ for CLS (with b for normal dipole chambers).

Since $a'_s \sim -\kappa s^{2/3}$, solutions for synchronism at large s vary linearly with s: Equal spacing of synchronous lines of one mode type, as function of radial wave number.

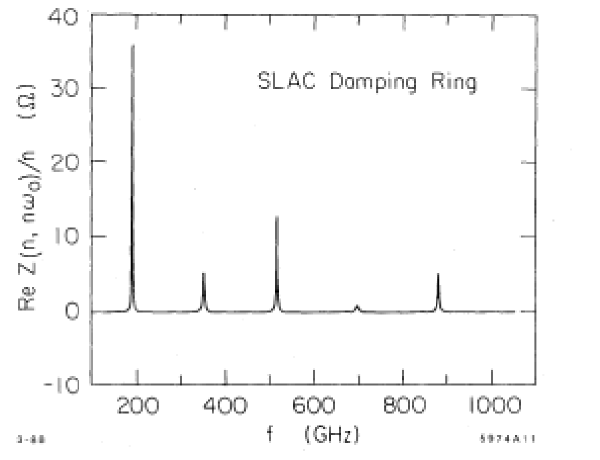
Wake and power at large t with wall resistance

If Z is computed with wall resistance, as was done in W & M, then at large t,

$$V(\theta, t) = q\omega_0 \sum_n \lambda_n Z(n, n\omega_0) e^{in(\theta - \omega_0 t)}$$

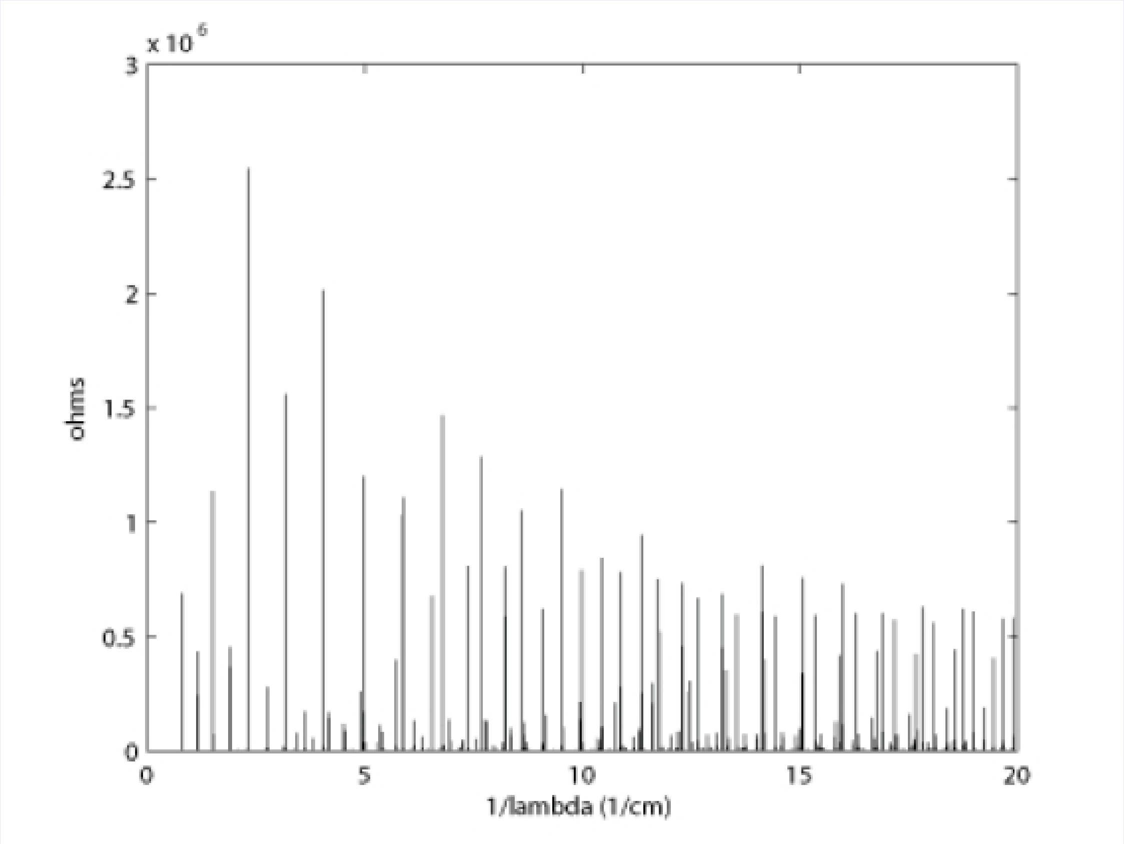
$$P = q\omega_0 \sum_n |\lambda_n|^2 \mathrm{Re}\, Z(n, n\omega_0) \ . \qquad (24)$$

Power spectrum for SLAC damping ring parameters, resistive toroidal chamber: (each peak composed of many n with $n\omega_0 \approx \omega_r$; TE and TM alternate, $n = 23000 - 105000$)



Spectrum from toroidal (or pillbox) model of VUV chamber

Neglecting the straights, the VUV vacuum chamber is well modeled by a smooth torus with $w = 8$cm, $h = 4$cm. The bending radius $R = 1.91$m. I put the beam at $r = R$, and adjust the outer radius to $b = 1.948$m to fit the data; thus beam is 2mm off center.



Dipole Chamber Impedance

Are the CSR features driven by the *Radiation Impedance* of the Dipole Vacuum Chamber ?

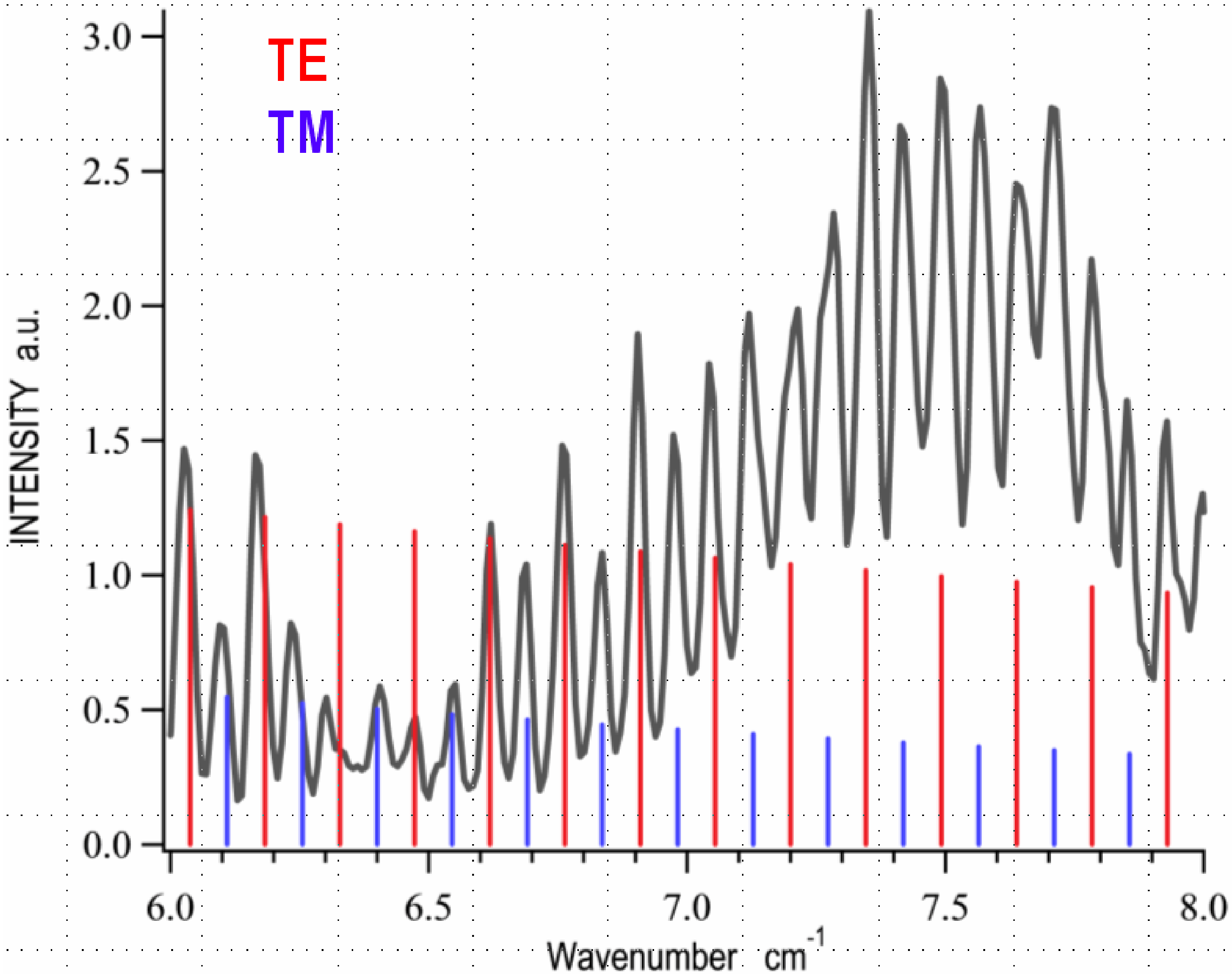
1. **Top and Bottom Plates:**

   Smooth variation of $\mathbf{Z_{rad}(\omega)}$ with ω:

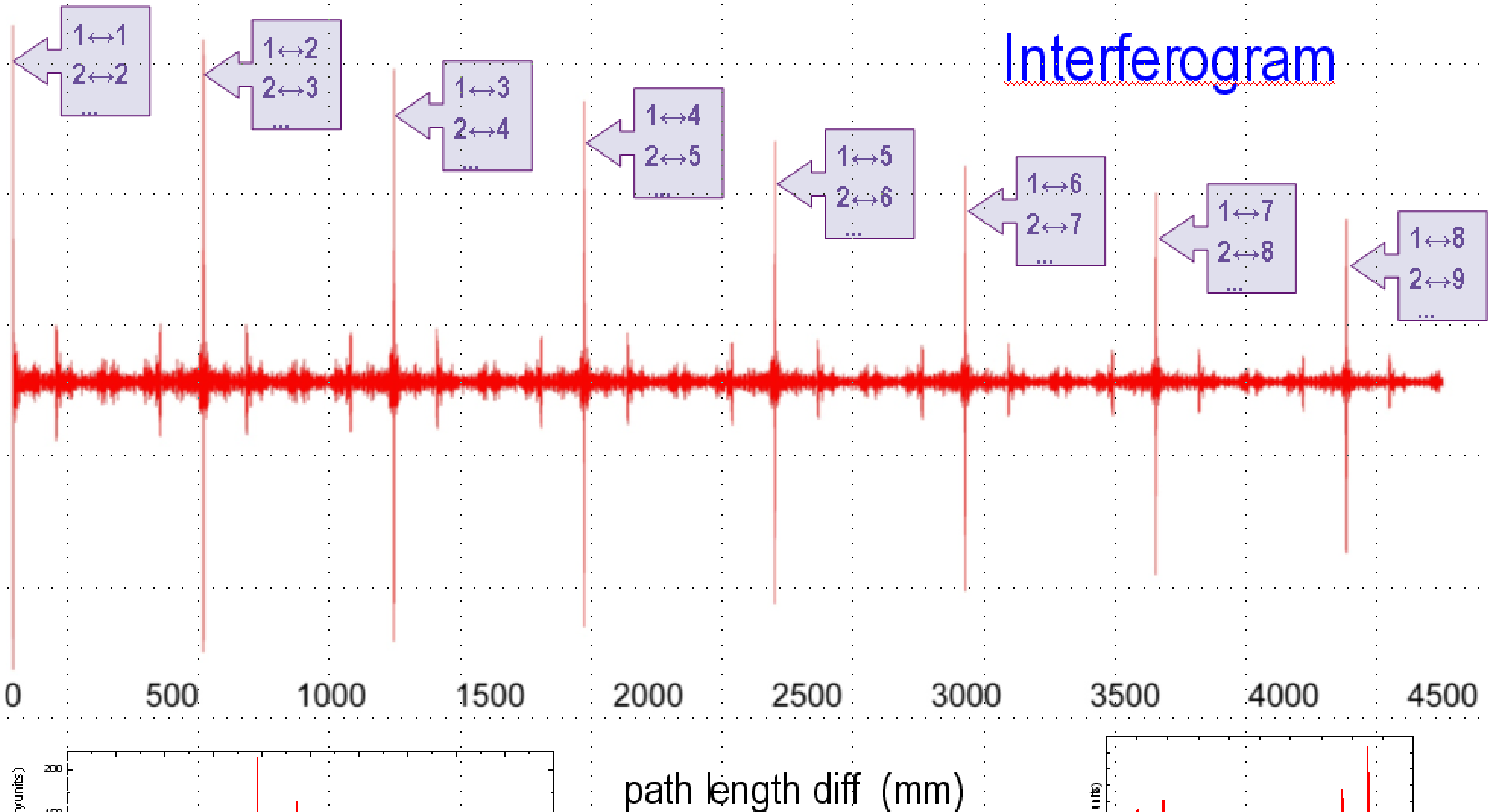
$$P_{CSR}(\omega) = I(\omega)^2 \cdot Z_{rad}(\omega) = \text{featureless}$$

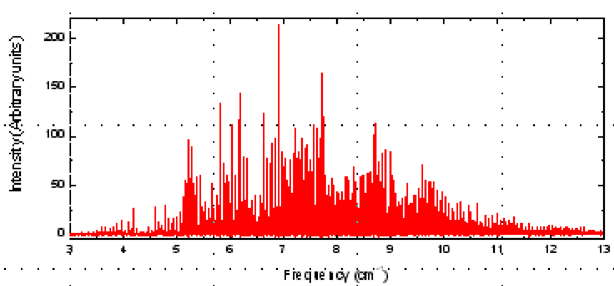
(Nodvick & Saxon P.R. 96 (1954) 180)

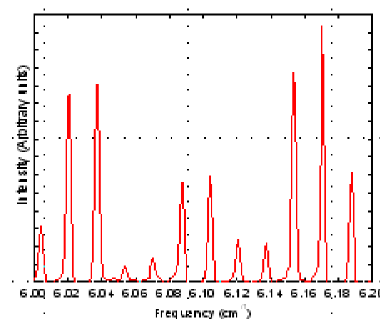
Fit R/Q to observed Periodicity



Bunch to Bunch Interference

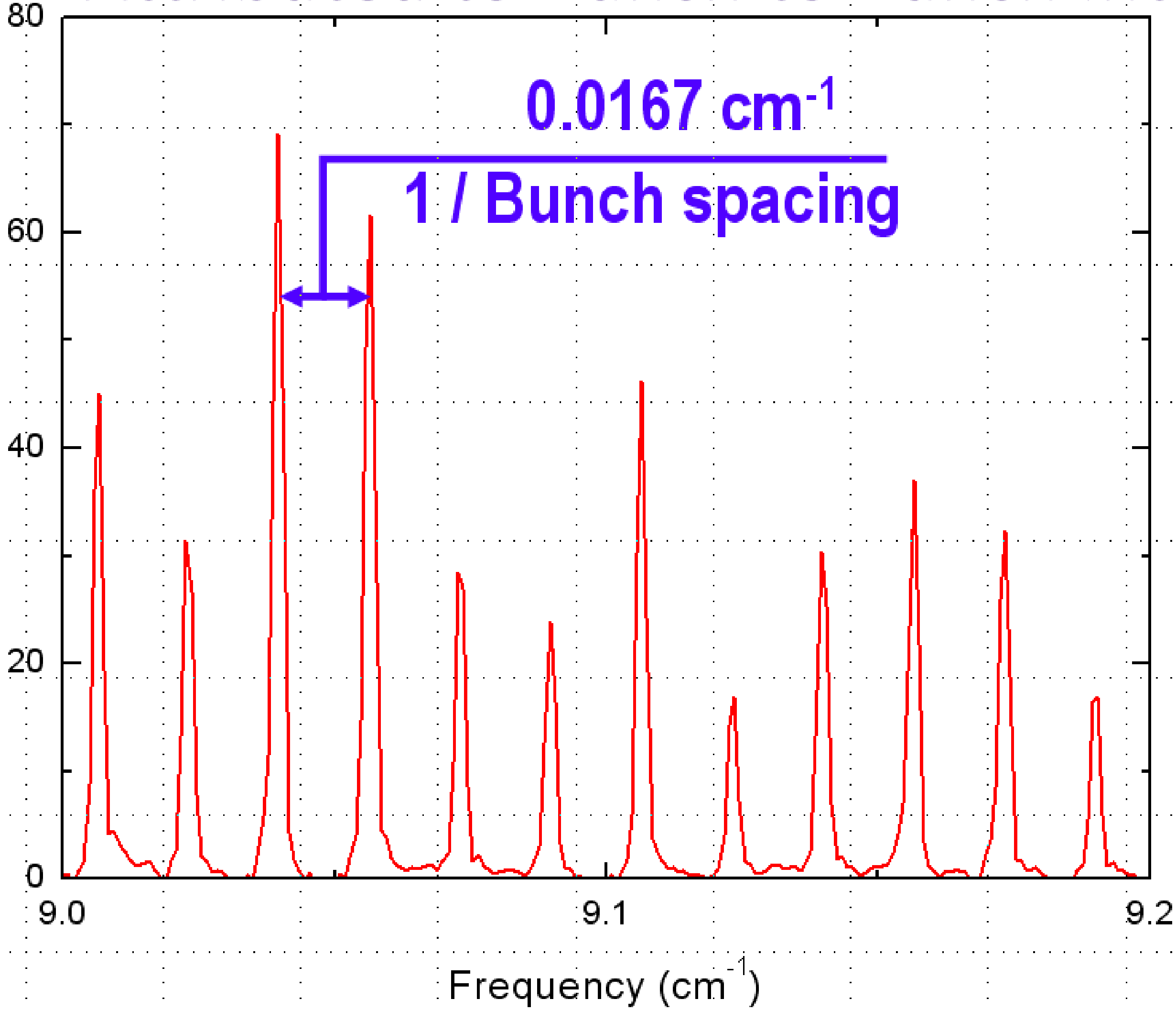






Very Fine Structure

- Attributed to Bunch to Bunch Interference



This is a Multi-bunch effect observed only in the *continuous* CSR mode

In this case the ring was filled with 210 bunches

Summary

No clear understanding of the origins of picket fence type FIR spectra – severe impact for high resolution spectroscopy at long wavelength.

Two explanations have been proposed:

- **„whispering gallery“ modes (R. Warnock, P. Morton, Part. Acc. 25, 1990, 113)**
- **local reflections and interference (L. Carr, et al., PAC 2001, Chicago)**

The spectra of synchrotron radiation at long wavelength depends on the fill pattern and can consist of lines seperated by $1/\lambda_{rf}$

Importance of radiation impedance? – CSR measurements reported by ANKA indicate a backward interaction (like the traditional wakefield)

Many CSR observations at BESSY can be explained with a simple broad band impedance model for the interaction of the bunch with the vacuum chamber

Facilities invest time and money into operating rings with shorter bunches – SPEAR 3 wants to produce short X-ray pulses, the MLS is optimized for CSR, the CIRCE-project at the ALS on ice