Spontaneous coherent microwave emission and the sawtooth instability at SURF

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Outline

- Experimental observations
  - o Frequency domain
  - o Time domain
- Instability simulations
  - o Agreement with observations
  - o Disagreement with observations
- What is missing?

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SURF Storage Ring Parameters

Energy, E_0	10 – 380 MeV
Circumference	5.267 m
rf frequency, f_{rf}	113.845 MHz
Harmonic no.	2
rf voltage, V_{rf}	8 – 14 kV
U_{rad}, loss/turn	0.456 keV
Long. damping time	12.8 ms
Transv. damping time	13.9 ms
Bunch length , FWHM	1 ns
Tunes, ν_x, ν_y	0.64, 0.768
Dispersion, η_x	2.065 m
Momentum compaction, α	2.463
Synchrotron frequency, f_s	~ 330 kHz

This is a weak-focusing ring whose vacuum chamber is entirely within a single dipole magnet.

Experimental Observations – Chronology

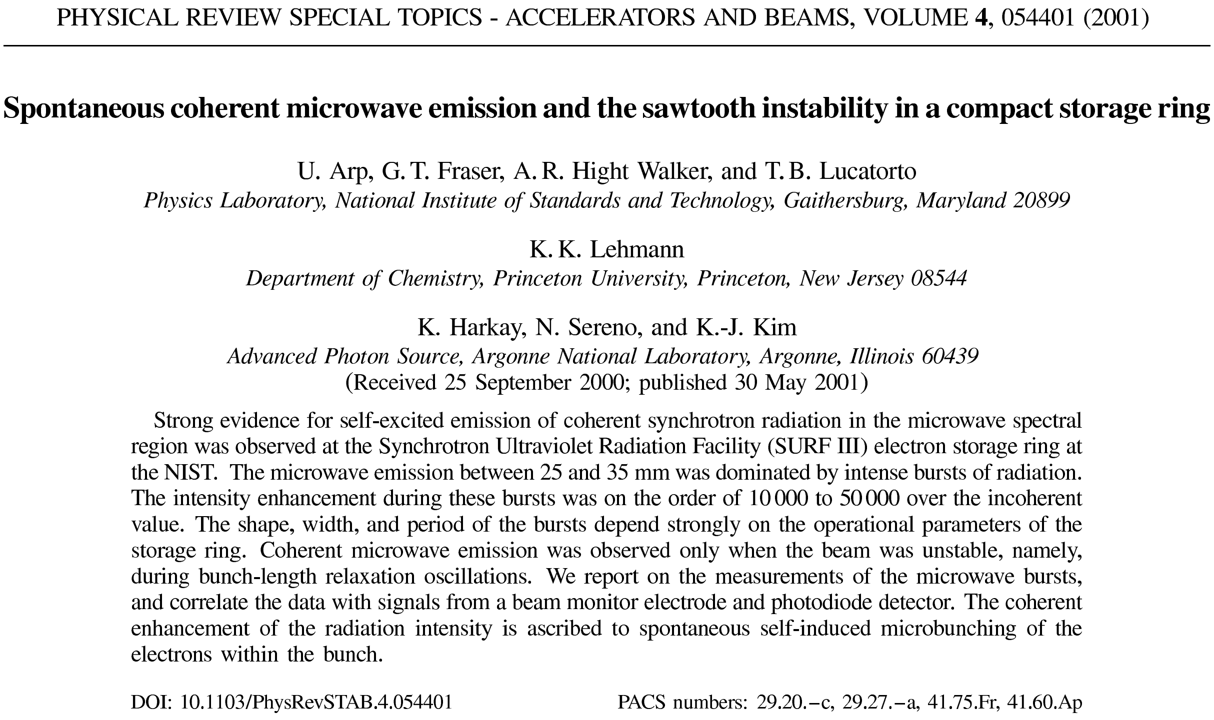
- Longitudinal sawtooth instability long observed
  [G. Rakowsky and L.R. Hughey, *IEEE Trans. Nucl. Sci.* **26**, 3845 (1979); G. Rakowsky, *IEEE Trans. Nucl. Sci.* **32**, 2377(1985)]
- Coherent microwave radiation observed (~10 GHz)
  [G.T. Fraser et al., *AIP Conf. Proc. No*. 417 (1997); A.R. Hight-Walker et al., *SPIE Proc. No.* 3153 (1997)]
- Correlate sawtooth instability with microwave emission
  [U. Arp et al., *Phys. Rev. ST Accel. Beams* **4**, 054401, 2001]
- Simulations studies of HOM-induced Robinson instability at SURF [Harkay et al., *Proc. 2001 PAC*, 1918 (2001)]
- Implementing HOM damping and control of rf low level eliminates instability [E. Hagley et al., unpublished (2001-2002)]
- Time-domain streak camera data show microbunching
  [M. Bergher, *Nucl. Instrum. Meth. A* **492**, 464 (2002)]

Data on following pages excerpted from:

K. Harkay and N. Sereno, ANL Internal Light Source Note No. LS-268, (1998)

(http://www.aps.anl.gov/techpub/lsnotes/ls268/ls268.pdf)

AND



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME **4**, 054401 (2001)

Spontaneous coherent microwave emission and the sawtooth instability in a compact storage ring

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Strong evidence for self-excited emission of coherent synchrotron radiation in the microwave spectral region was observed at the Synchrotron Ultraviolet Radiation Facility (SURF III) electron storage ring at the NIST. The microwave emission between 25 and 35 mm was dominated by intense bursts of radiation. The intensity enhancement during these bursts was on the order of 10 000 to 50 000 over the incoherent value. The shape, width, and period of the bursts depend strongly on the operational parameters of the storage ring. Coherent microwave emission was observed only when the beam was unstable, namely, during bunch-length relaxation oscillations. We report on the measurements of the microwave bursts, and correlate the data with signals from a beam monitor electrode and photodiode detector. The coherent enhancement of the radiation intensity is ascribed to spontaneous self-induced microbunching of the electrons within the bunch.

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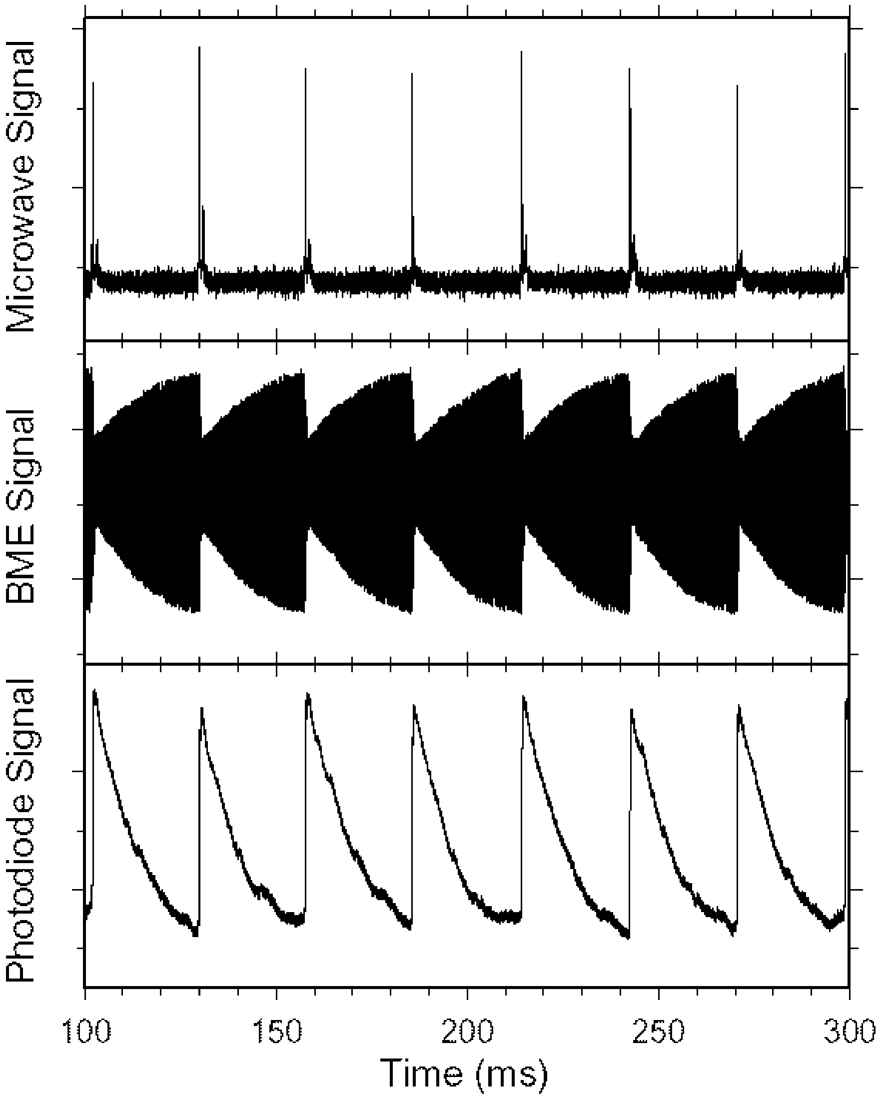
The time correlation between the different signals is very clearly exhibited.



7 – 12 GHz (integrated); bursts occur exactly as beam blows up.

BME (beam monitor electrode) pickup is capacitive up to 2 GHz; envelope approx. inverse of bunch length.

Iris overfilled: intensity varies with beam size, itself a function of bunch length or beam energy spread due to the dispersion.

E_0 = 255.9 MeV, I_b = 87.6 mA, V_{rf} = 10.7 kV, and φ_{rf} = 32.4°

The period of the microwave bursts is 28 ms. The FWHM of the main burst is 0.13 ms. A second, much smaller peak follows with 1 ms delay and FWHM 0.34 ms.

The rf phase φ_{rf} is the value of the phase shifter in the transmission line between the rf source and the rf cavity. I_b is the total beam current.

Measuring the BME signal with a spectrum analyzer, we obtain the synchrotron sidebands as well as the bunch length from the rf harmonics.

Typical synchrotron line spectra during bursts

Figure 2 shows typical spectra at the third rf harmonic (341.5 MHz) observed when the instability cycles through maximum amplitude. As many as five synchrotron harmonics can be seen. The horizontal scale is frequency relative to the third rf harmonic and the snapshot times are relative to the start of data acquisition. The machine parameters for these data were 83 mA, 9.7 kV rf voltage, and 89.6 degrees rf phase (machine condition 5). A synchrotron frequency of 330 kHz is obtained from these data.

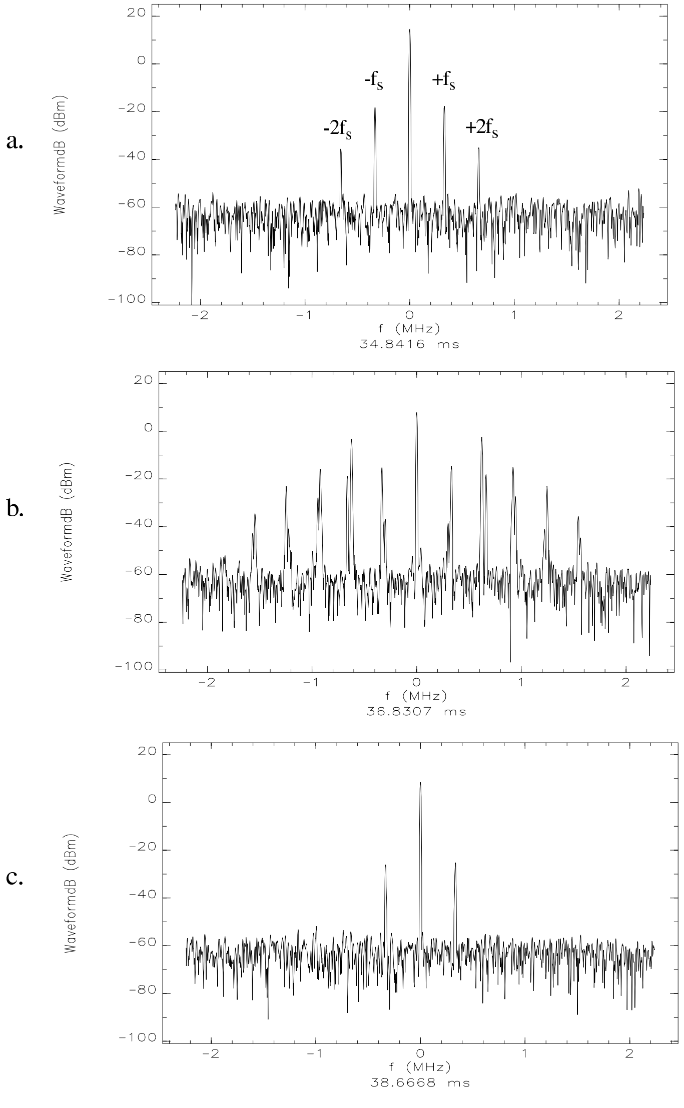
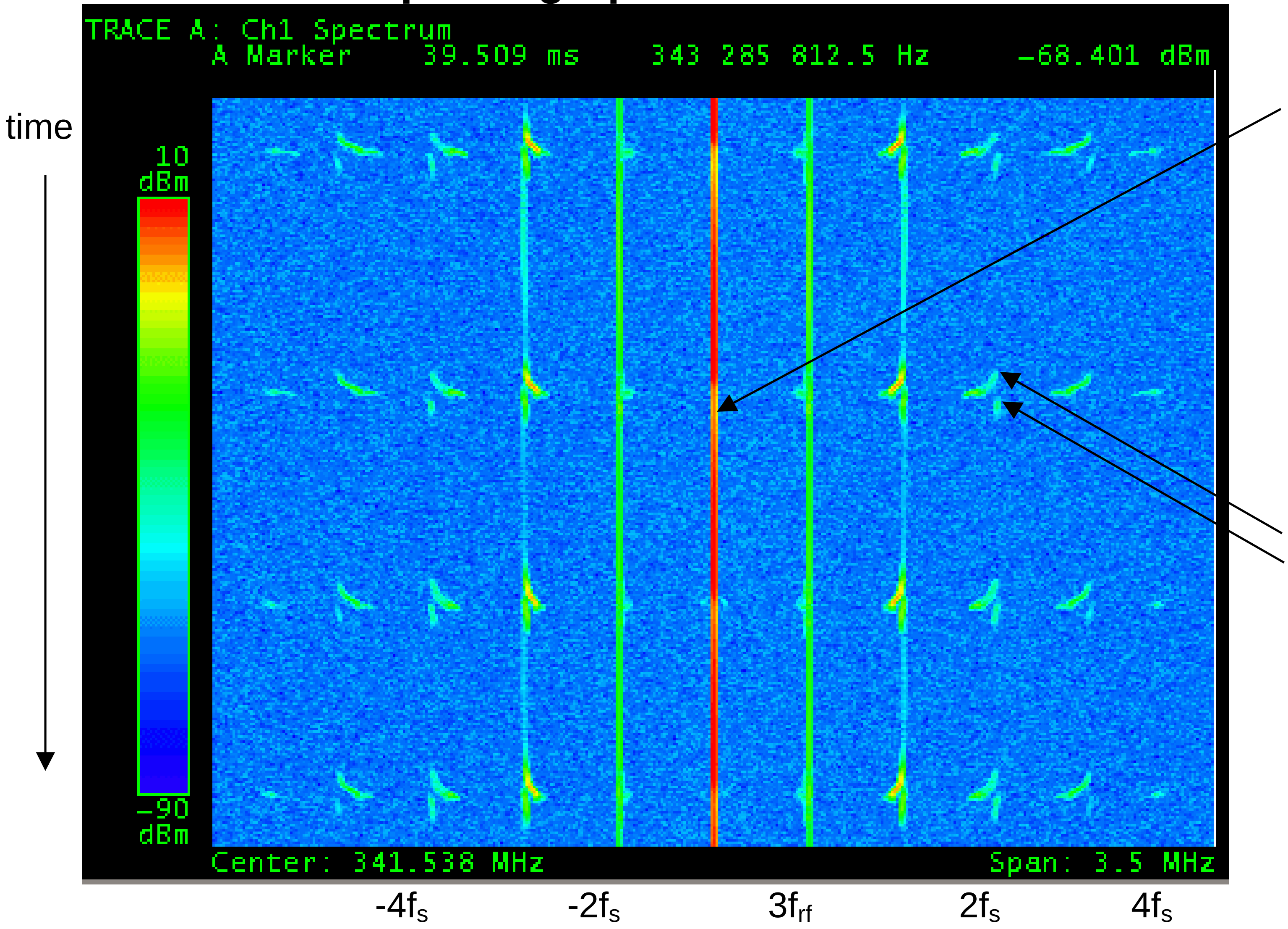


FIGURE 2. Typical synchrotron line spectra around the 3rd rf harmonic during an instability cycle. The spectra are shown at intervals of ~2 ms, where the instability (a) begins (bunch length, τ_L, min), (b) maximum amplitude (τ_L increasing), and (c) ends ($\tau_L$max). (machine condition 5)

The dominant quadrupole mode appears to be split; the signal associated with the first blow-up has shifted in frequency after growing in amplitude, while the signal associated with the second blow-up begins to rise.

Spectrograph over several bursts

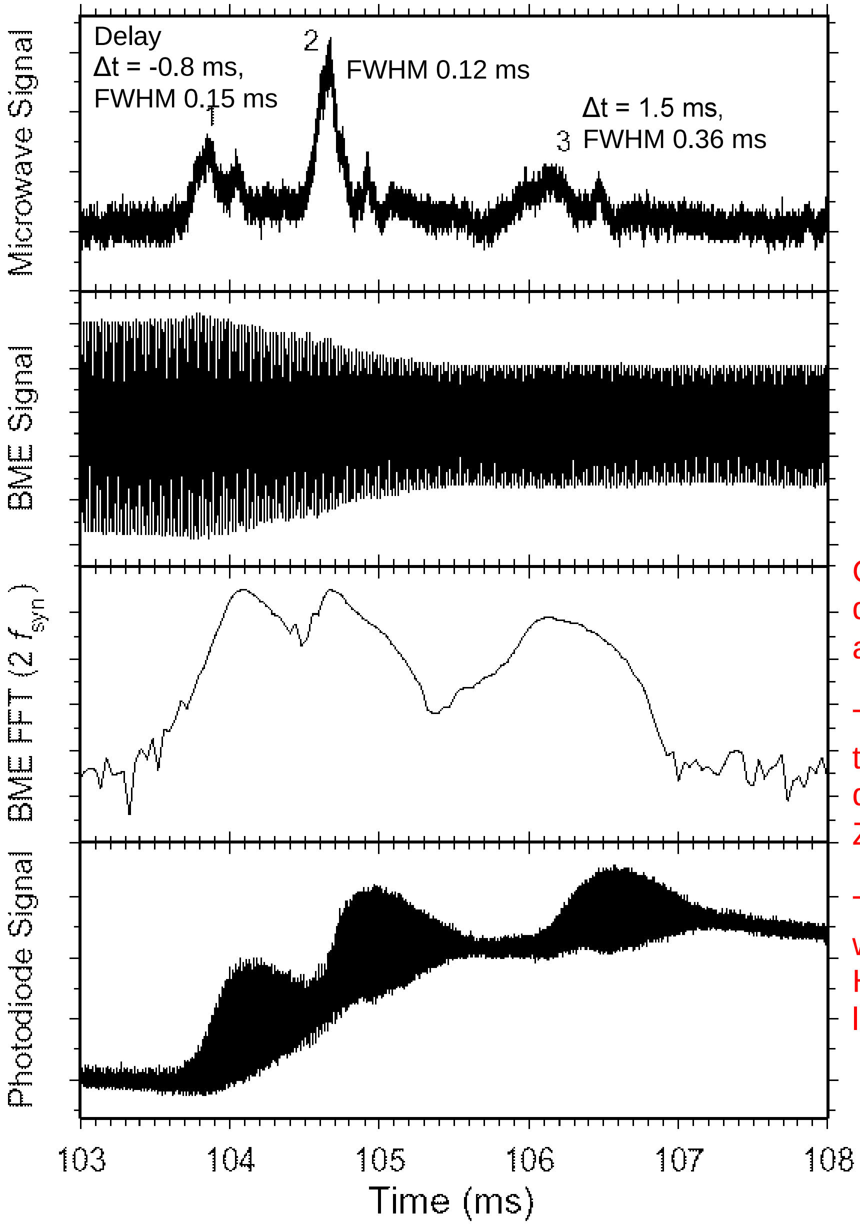


Amplitude of $3f_{rf}$ harmonic drops when bunch length blows up at end of bursts.

Note multiple f_s sidebands appearing during each major burst cycle: sideband associated with first mini-burst shifts in frequency as amplitude grows; later the same sideband, associated with the second mini-burst, re-appears at the unshifted frequency.

(same data and conditions as previous page, E_0 = 256 MeV)

Time-structure details of the bursts are correlated with the amplitude of the quadrupole synchrotron sideband in the BME spectrum and features in the photodiode signal.



Growth rate of quadrupole mode at $2f_s$ is $(70\ \mu s)^{-1}$.

This corresponds to an effective driving impedance $Z_{eff} = 2\ k\Omega$.

This is consistent with an rf cavity HOM as the most likely source.

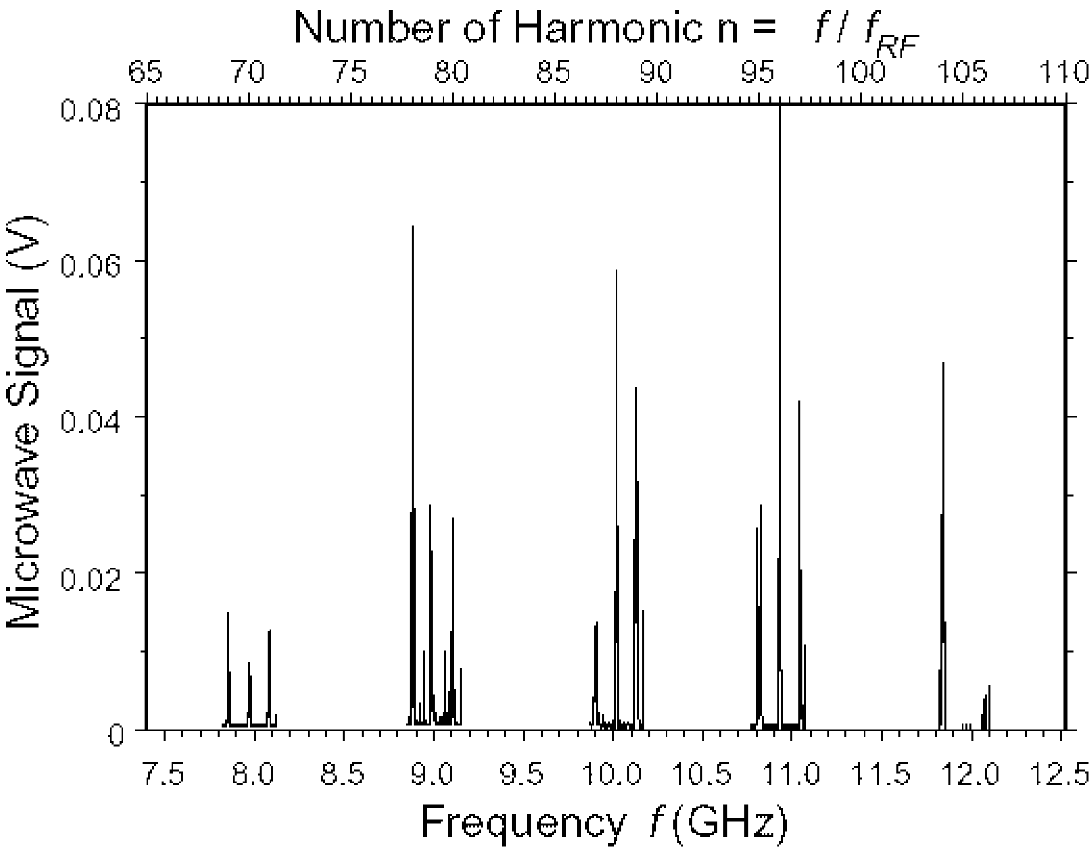
$E_0 = 255.9$ MeV, $I_b = 90$ mA, $V_{rf} = 10.8$ kV, and $\varphi_{rf} = 34.5°$

In this example, there is a main microwave burst and two smaller peaks.

During the third mini-burst, the envelope of the BME signal doesn’t change; however, the $2f_s$ sidebands indirectly indicates internal bunch structure.

Microwave Emissions Spectrally Resolved

The coherent signal enhancement is estimated to be **10^4** over incoherent synchrotron radiation (measured with a Schottky diode, comparing signals during bursts and between bursts).

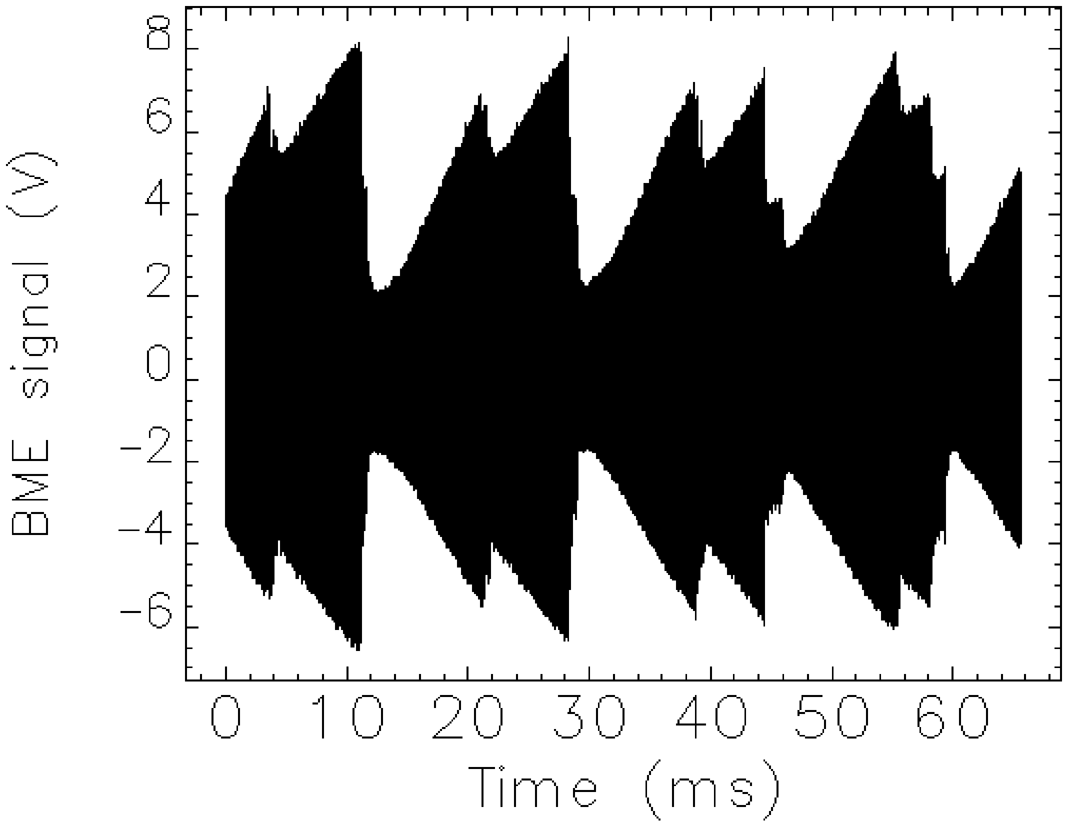


Heterodyne spectra of the microwave emission from SURF III between 7.8 GHz and 12 GHz. All spectra were recorded at E_0 = 255.9 MeV with beam currents between I_b = 98.7 mA to 121 mA. Not all harmonics were recorded.

Each spectrum corresponds to the average of approximately 1000 sweeps of the local microwave oscillator. The oscillator is continuously swept over a 300 MHz interval at a rate of ~10 Hz and the resulting spectra are added using a digital oscilloscope.

All spectra were recorded using a preamplifier except for the three peaks at the lowest frequency.

Sawtooth instability can be made very non-periodic by adjusting φ_{rf}

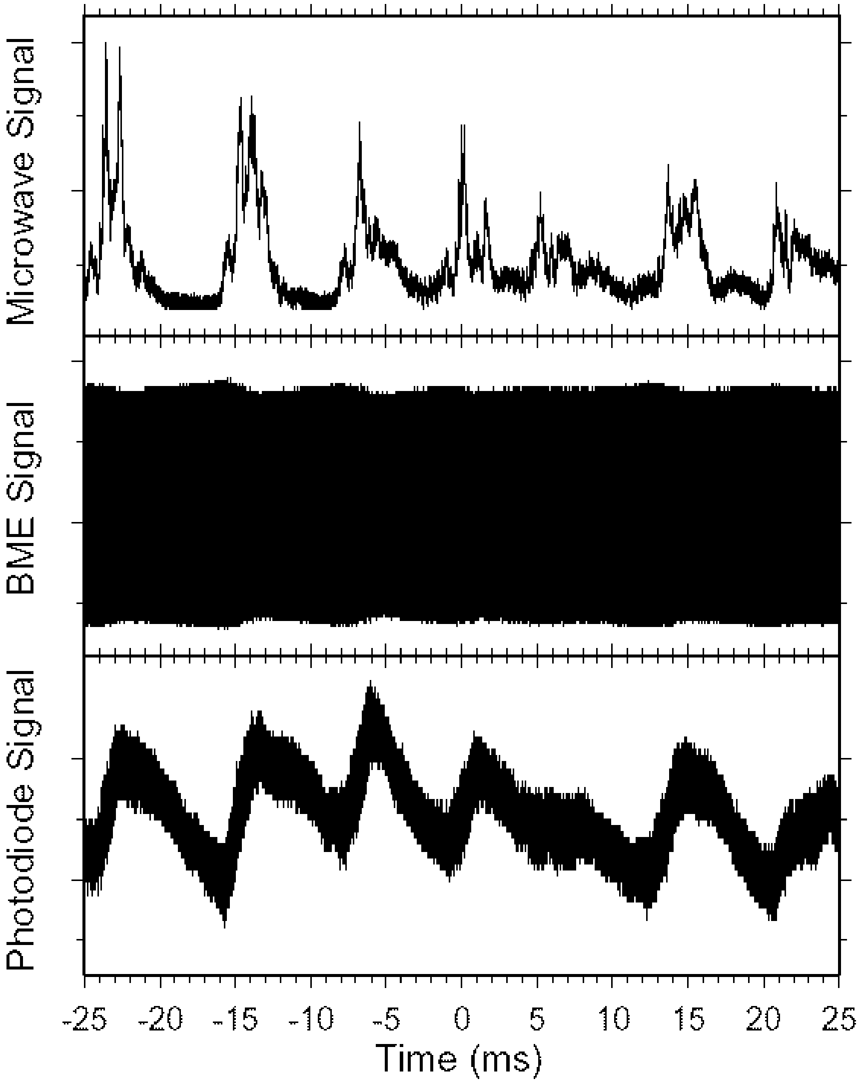


E_0 = 256 MeV, I_b = 114 mA, V_{rf} = 10 kV, and φ_{rf} = 54°

The beam can be made unstable at as low as 7 mA by adjusting φ_{rf} (131° for these conditions). The sawtooth instability is not a simple case of HOMs driving the beam with a fixed intensity threshold.

The transmission line is phase-matched at the fundamental frequency only, and changing the rf phase alters the matching condition between the rf source and the cavity; this results in detuning the cavity for unmatched phase angles. Also, HOMs that couple out into the line can be reflected back and add constructively at the gap, depending on the phase.

Microwave bursts at a lower beam energy



E_0 = 183.1 MeV, I_b = 105.5 mA, V_{rf} = 10.9 kV, and φ_{rf} = 67.0°.

At this lower energy the microwave bursts are not as regular in time and shape. Their behavior is rather chaotic. The bursts do not seem to be connected with strong changes in bunch length; however, they are correlated with dipole and quadrupole modes in the BME spectrum (not shown).

Simulations with *elegant*

Used R, Q of rf cavity HOMs up to 1.5 GHz as measured on bench, assuming no other impedance.

Simulation details: two bunches, 10^4 macroparticles each, representing 100 mA total; 256 MeV; 3×10^6 turns to cover a few sawtooth periods (transmission line and rf phase φ_{rf} not modeled).

The sawtooth instability may be characterized as a Robinson instability driven by an HOM; the HOM near $3f_{rf}$ has a shunt impedance 25% that of the fundamental.

Physics virtually same as beam in a higher-harmonic cavity:

> [R. Bosch et al., Phys. Rev. ST Accel. Beams **4**, 074401 (2001)]
>
> [J. Byrd et al., Phys. Rev. ST Accel. Beams **5**, 092001 (2002)]

Agreement with observations:

- Sawtooth period and bunch length relaxation
- Details of multiple bursts when all HOMs included (only single bursts when only first HOM included)
- Effect of detuning cavity reproduced
- Damping HOMs in transmission line cures instability

Disagreement with observations:

- Mainly dipole, some quadrupole mode in simulation; quadrupole mode typically dominates in experiments
- Bunches oscillating in phase in simulaiton: streak camera shows bunches sometimes out of phase
- Density modulation only up to 3 GHz, not 10 GHz observed, and modulation smaller in amplitude than streak camera

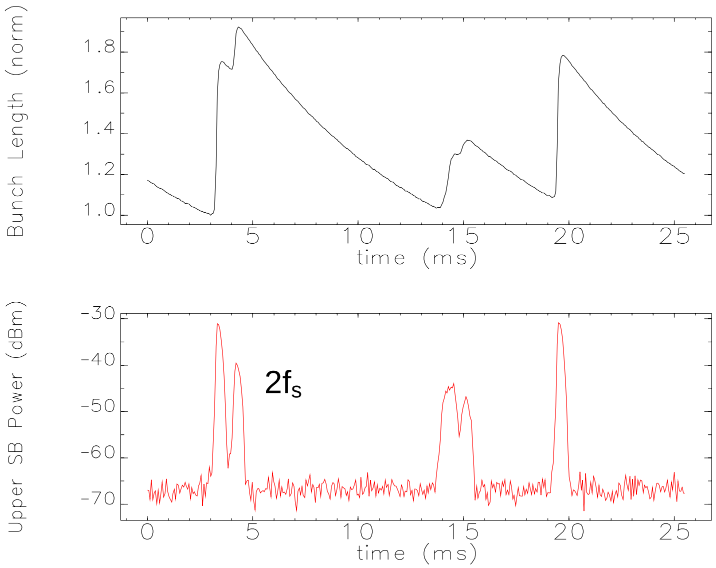
Bench measurements of the SURF rf cavity fundamental and HOM parameters

Frequency (MHz)	Q_L	R_L (kΩ)	Detuning (rad)
113.8	680	12	–
342.0	540	3.1	0.97
571.8	190	0.7	1.0
797.5	230	0.6	0.32
1027	143	0.3	0.59
1257	193	0.4	0.97

Right: rf cavity from the top, showing its curve to follow vacuum chamber

Below: Inside cavity end showing accelerating gap (note also discontinuities introduced by cooling loops and step)

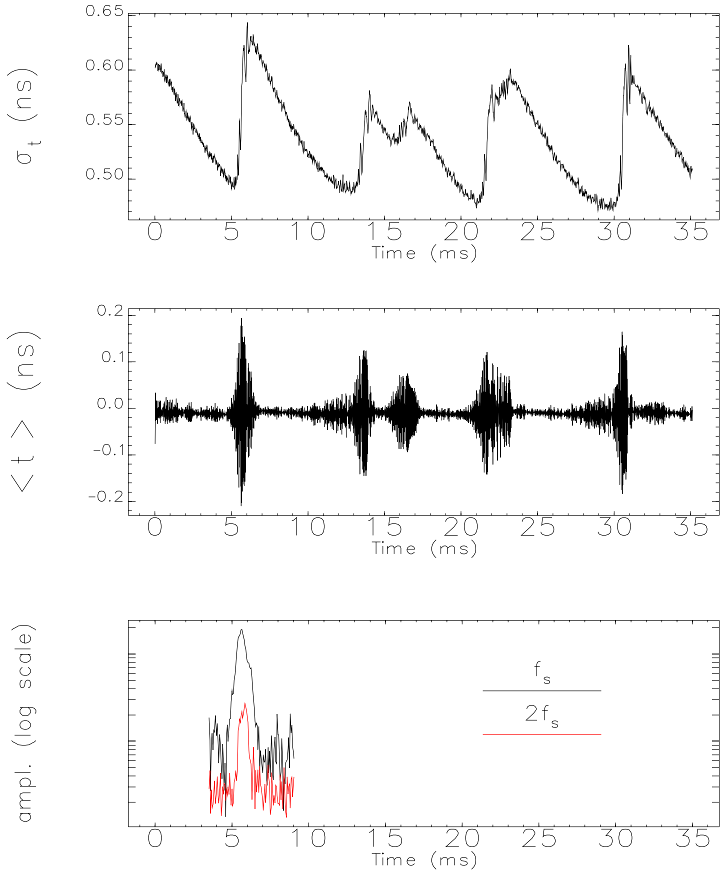
EXPERIMENTAL DATA



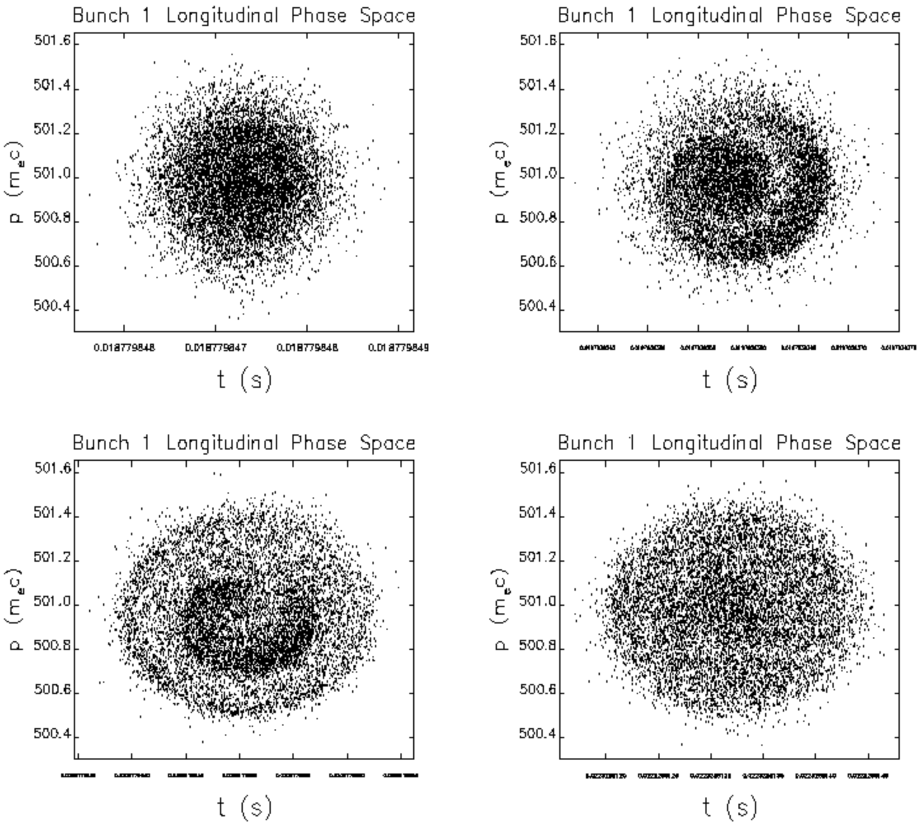
Sawtooth period very similar, but observed bunch length fluctuates by a factor of two (as calculated from rf harmonics in spectrograph), wheras in the simulation, it varies by 30%.

Also, quadrupole mode dominates in the experiment, whereas dipole mode dominates in the simulation.

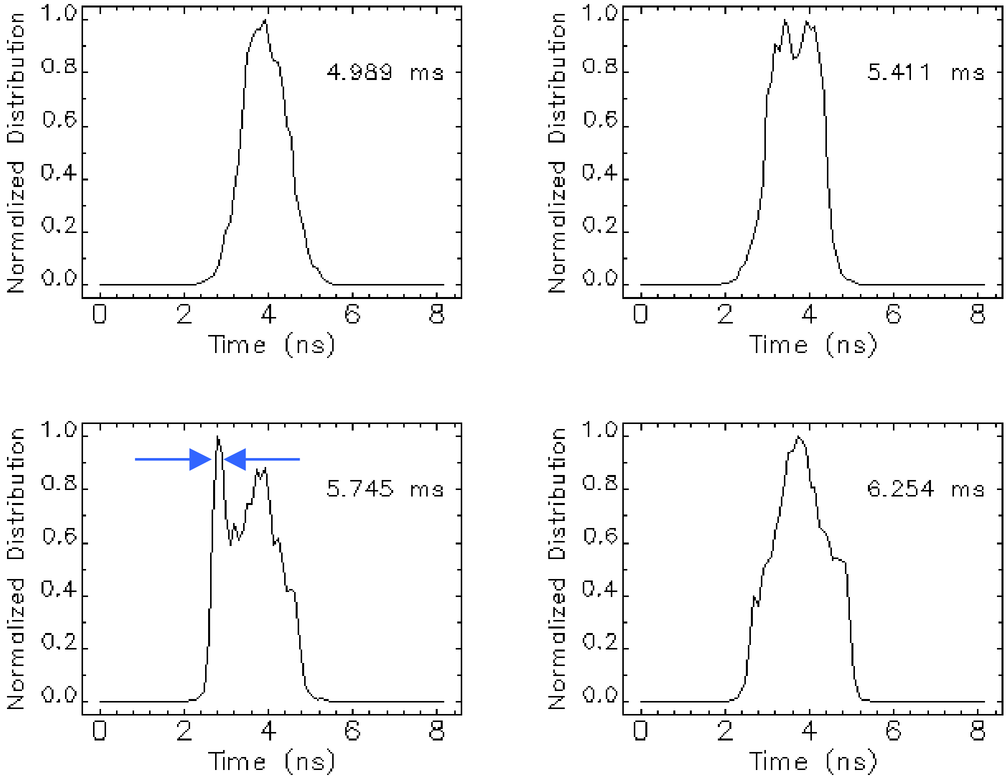
SIMULATION RESULTS



Simulation results – details



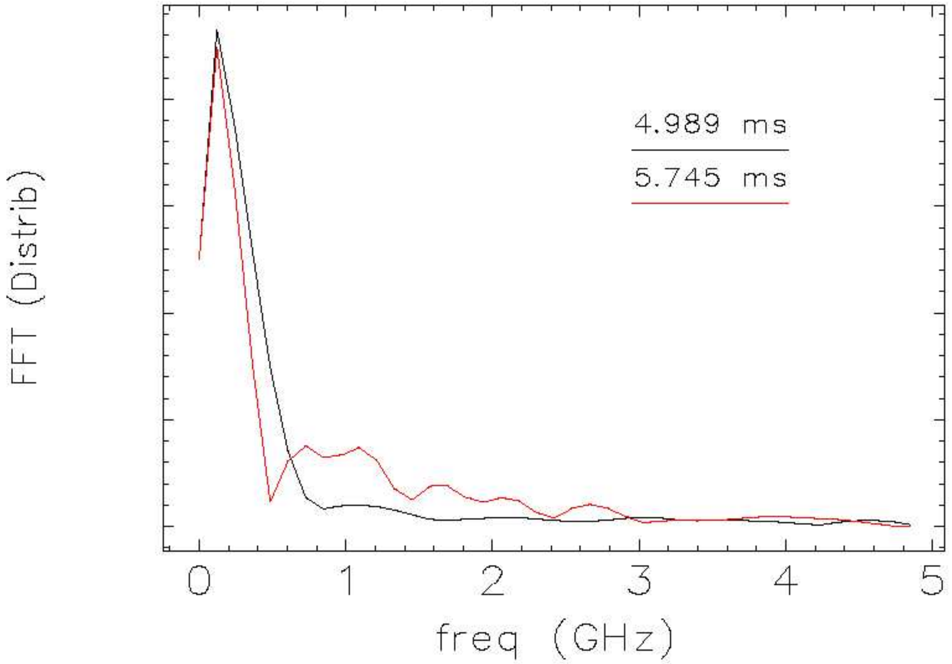
Simulation phase space plots show that bunch core becomes unstable and blows up twice before entire bunch stabilizes and decoheres.



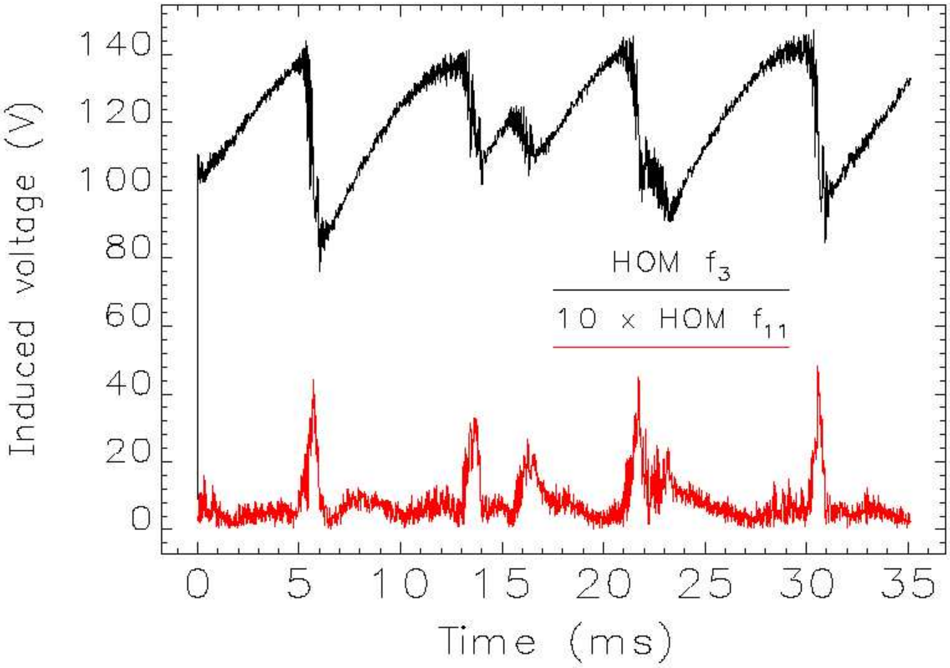
Projection shows density peak whose width is 0.3 ns (3 GHz) (plot at lower left).

More simulation results – details

FFT of histograms show maximum 3 GHz spectral width:

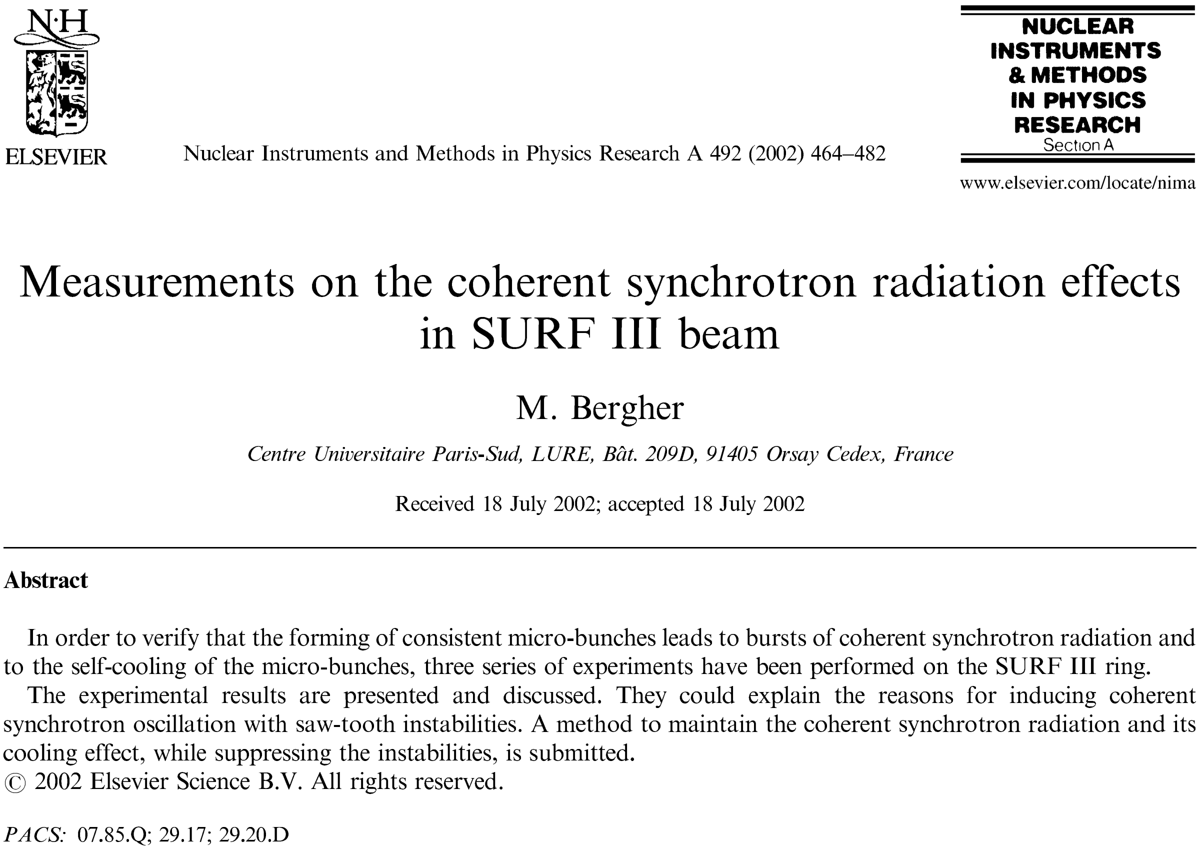


Induced voltage at HOMs near $3f_{rf}$ and $11f_{rf}$:



Experiments recorded the bunch evolution in the time domain using a streak camera and array of fast photodiodes (at end of 2001)

Time-domain streak camera measurements excerpted from
(courtesy M. Bergher):



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Measurements on the coherent synchrotron radiation effects in SURF III beam

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Abstract

In order to verify that the forming of consistent micro-bunches leads to bursts of coherent synchrotron radiation and to the self-cooling of the micro-bunches, three series of experiments have been performed on the SURF III ring.

The experimental results are presented and discussed. They could explain the reasons for inducing coherent synchrotron oscillation with saw-tooth instabilities. A method to maintain the coherent synchrotron radiation and its cooling effect, while suppressing the instabilities, is submitted.

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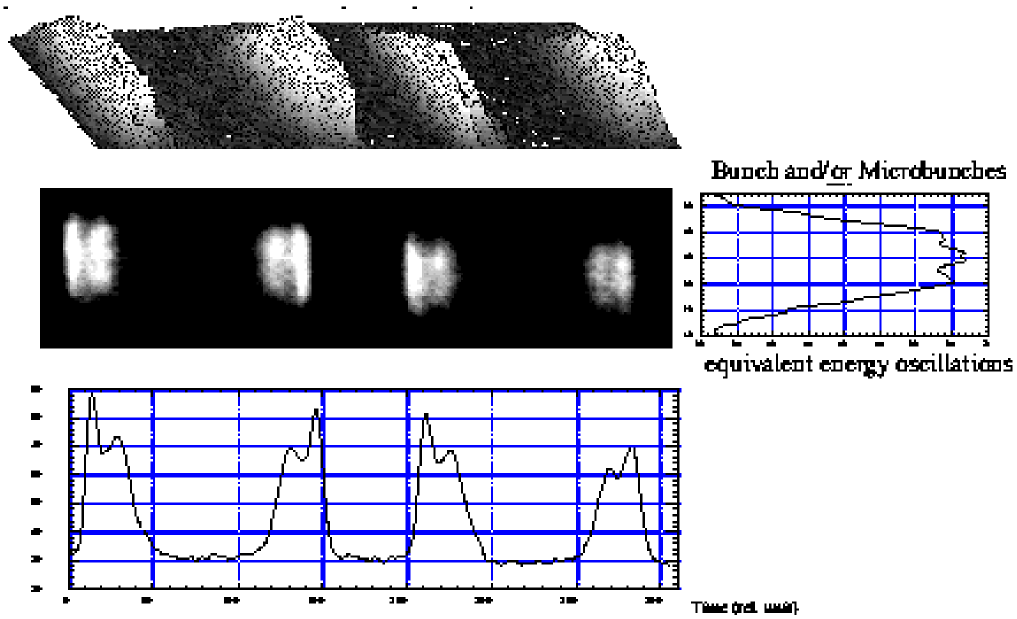
PACS: 07.85.Q; 29.17; 29.20.D

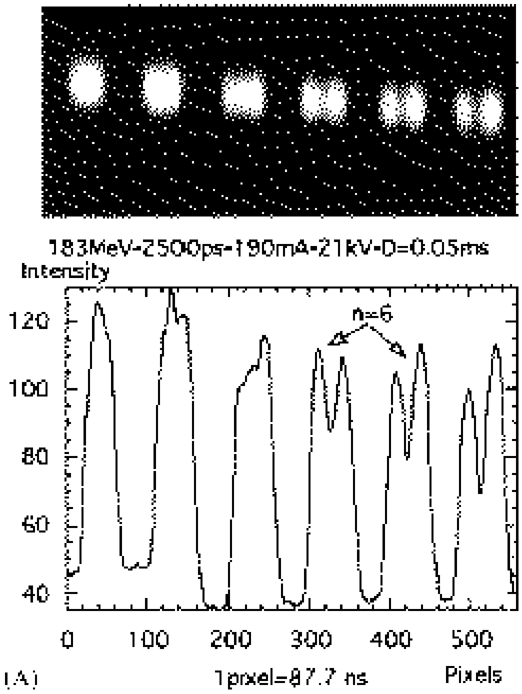
These data show some disagreement with previous assumptions based on the modeling of HOM-induced Robinson instability leading to high-frequency structure on bunch.

Bunches sometimes oscillate out-of-phase:

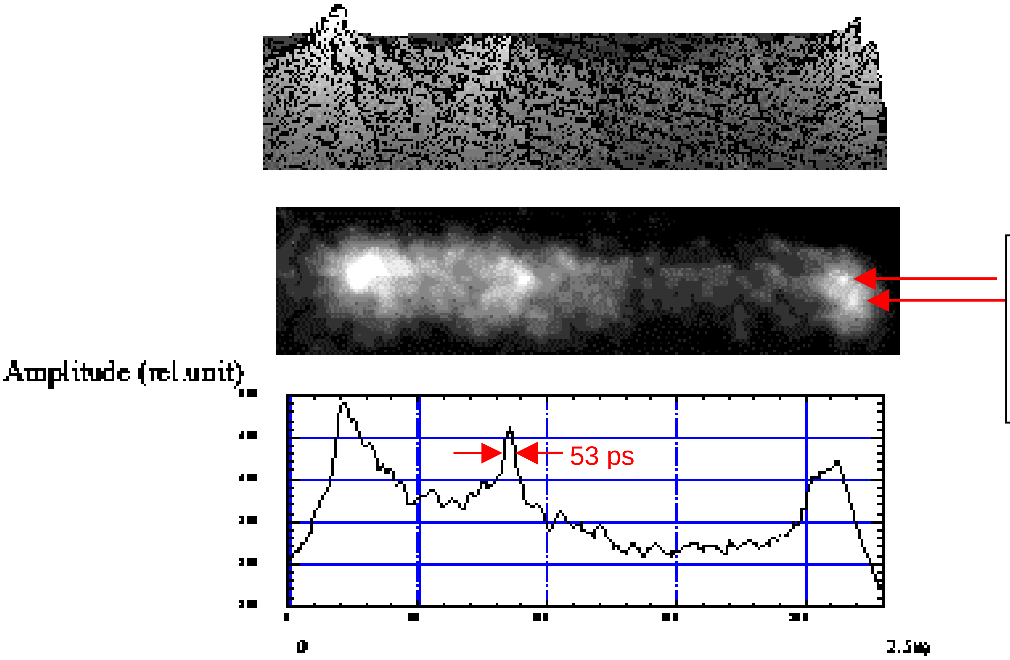


Phase oscillations > +/- 50°, Bunch $\sigma_{t\,RMS}$ = 2.5ns, Microbunch $\sigma_{t\,RMS}$ = 0.42ns, H_{RF} = 7

Bunch density modulation grows faster, about a few turns (~30-50 ns) than measured rise time of quadrupole mode (~70 µs):

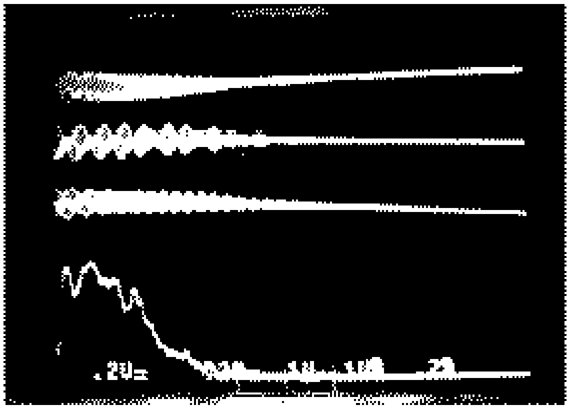


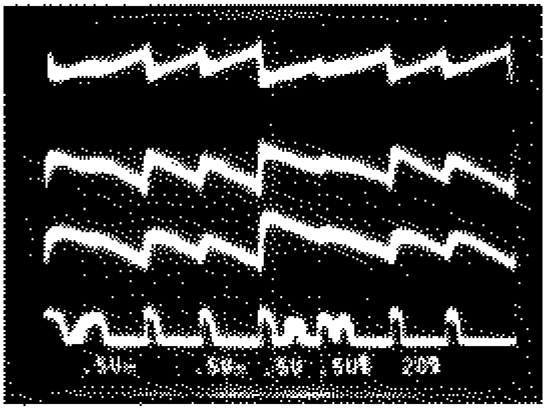
Bunch density shows features with 53 ps time structure:

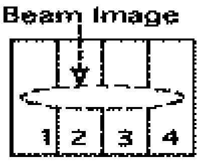


Transverse density modulation (per M. Bergher)

Photodiode array signals 1-3 shows varying transverse structure (left) and bunch size shrinking (right) on CSR emission (bottom trace is CSR pickup) (per M. Bergher):







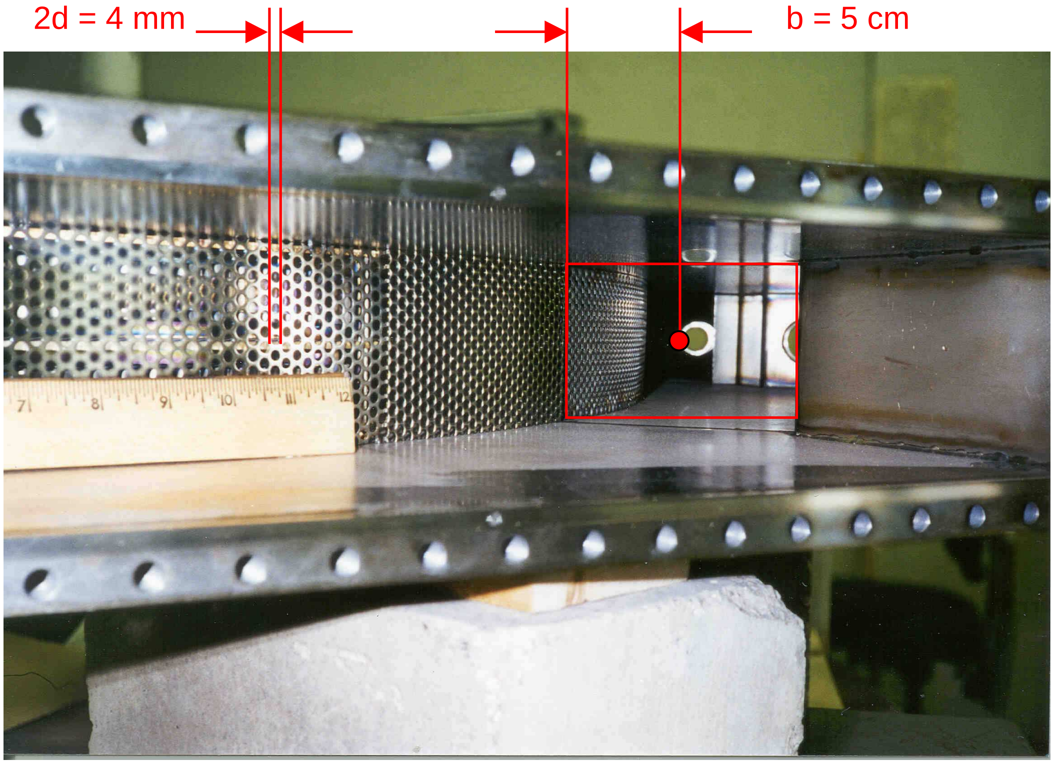
Photodiode Array

Position of Photo-diode signals and CSR

What’s missing?

- Other geometric impedance: Preliminary modeling of vacuum pumping holes show no effect (N. Sereno)
- Direct observation of energy loss when CSR emitted
- Modeling to include both geometric and CSR wakes (N. Sereno)
- Modeling to include effect of transmission line

Other sources of geometric impedance in SURF ring



$Z_{||}$ (holes): BBR model: $\omega_r = 1.35\ c/d$; $Q = 1.8$; $R_s = 0.2\ Z_0\ (d/b)^2$;

Total is linear sum of N holes (high-precision machining required to sum like N^2)

[Y.C. Chae, Proc. 1995 PAC, 2997 (1995)]

One hole: f_r 30 GHz, $R_s \sim 0.1\ \Omega$; ~500 holes/turn; $R_{tot} \sim 50\ \Omega \rightarrow$ very small!

Speculation: What drives CSR at SURF?

CSR wake?

- Heifets-Stupakov criterion not satisfied at bunch length, σ_z, but maybe applies after HOM-induced time structure develops
- CSR shielded at σ_z by vacuum chamber, but *can* propagate at microbunching of the order of $\sigma_z/10$

rf cavity HOMs clearly involved

- Passive damping of HOMs in transmission line cures instability and microwave emission
- For certain rf phase angles, HOMs drive beam and produce bunch density modulation
- Two-step process?
  - o CSR emission from microbunches
  - o Microbunches couple to CSR wake or other impedance
  - o Microbunches grow until dissipated by CSR energy loss