How to make intense, coherent far infrared light from a ring

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Overview

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- What is CSR?
- Challenges for generating CSR
- Experimental results
  - First observations of CSR at Bessy-II
  - analysis of Bessy-II results
  - "inductive" radiation impedance
- Source stability
  - CSR microbunching instability
- CIRCE: A dedicated ring for coherent far-IR
- Summary and Plans

Coherent Synchrotron Radiation

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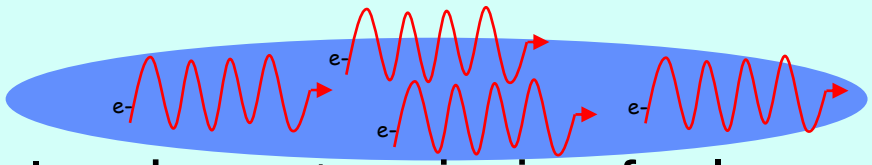
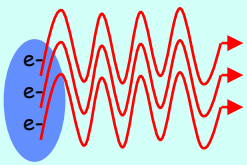
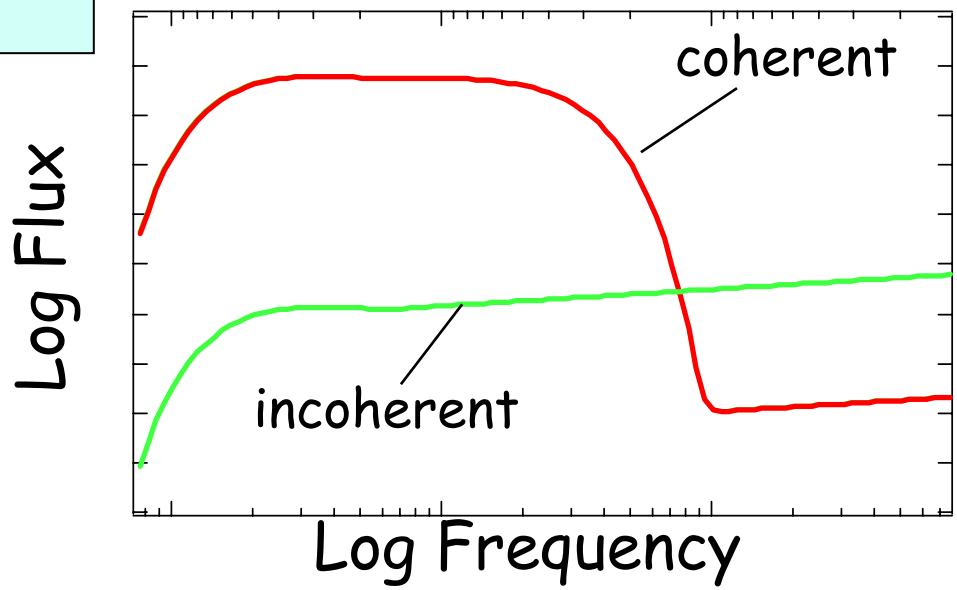


Incoherent emission for long bunches, P~N



Coherent emission for short bunches
$P \sim N^2$

Light is emitted coherently when bunch length is shorter than the wavelength. Increase can be huge for modest currents (10^7-10^8 e^-) for short bunches.



Challenges for generating CSR

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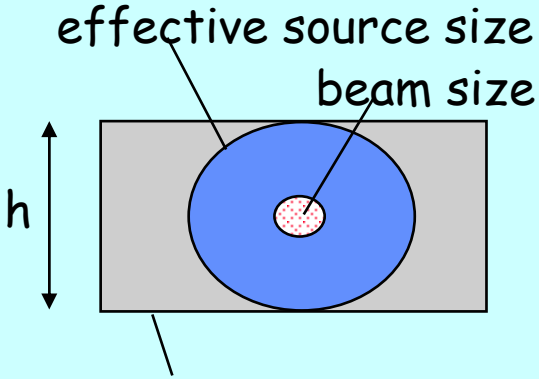
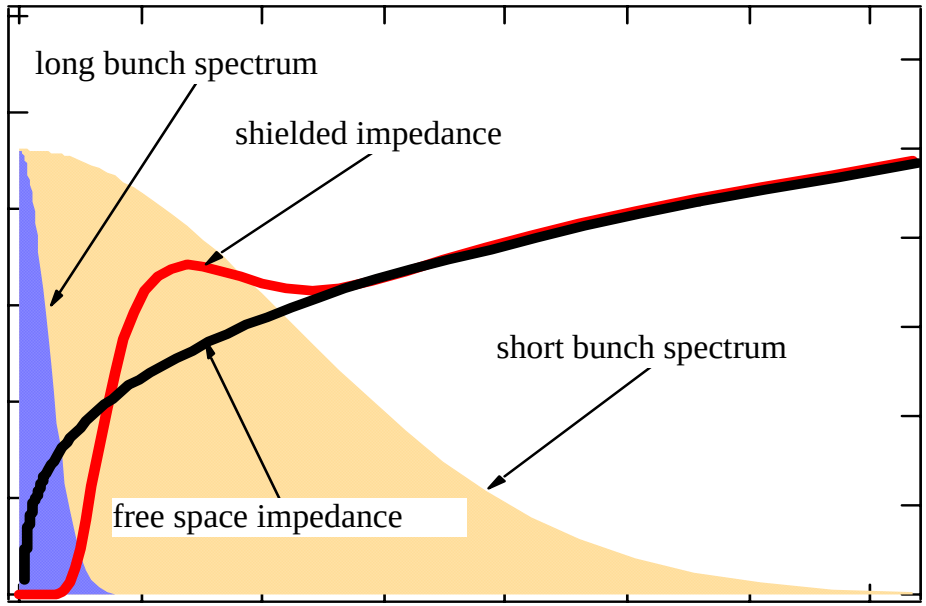
Vacuum Chamber acts as a High Pass Filter



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

Most rings can not make short enough bunches to generate stable CSR!



Nodvick, Saxon, Phys. Rev. **96**, 1, p. 180 (1954)

Shielding by the vacuum chamber limits the SR emission to wavelengths above the waveguide cutoff condition

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

General approach

- Apply "standard model" of single bunch collective effects using radiation impedance as input.
  - potential well distortion results in 'steady' pulses generated by the impedance
  - 'microwave' instability occurs above a current threshold resulting in higher frequency bursts. Threshold given by straightforward Vlasov analysis.

First CSR at Bessy-II

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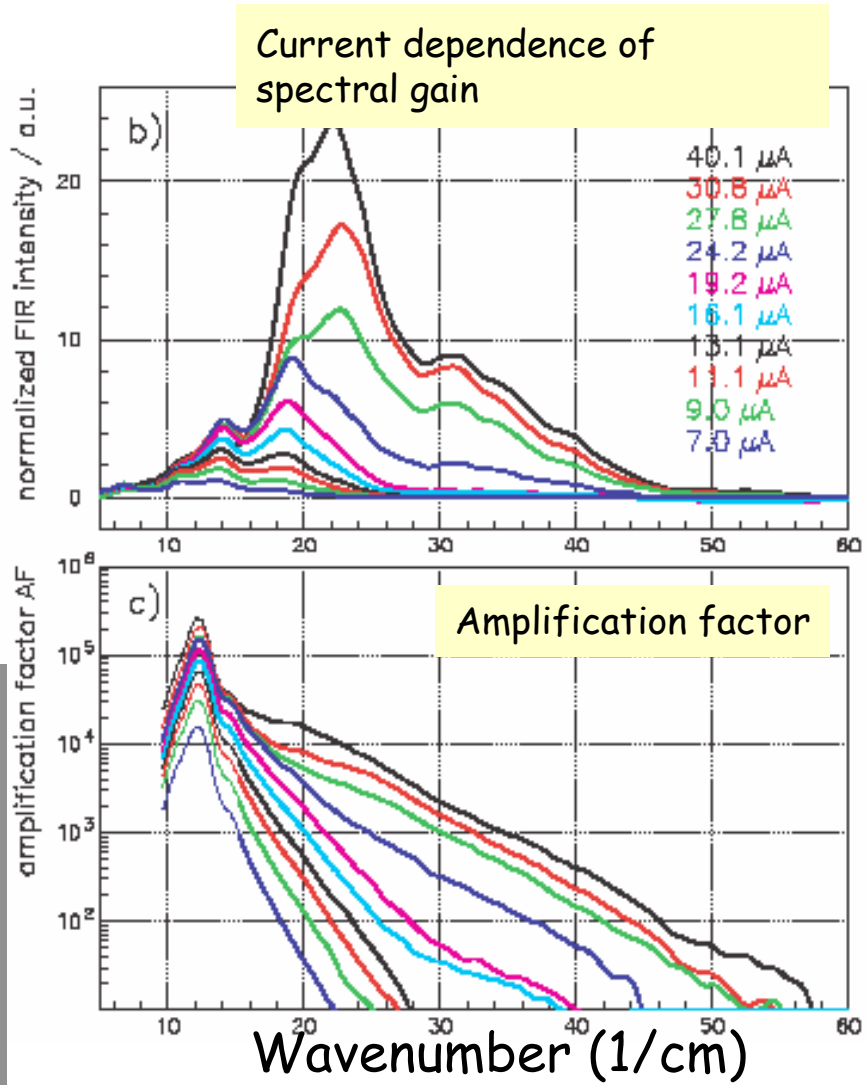
Bessy-II observed the first steady CSR in late 2001. They observed several unusual features:

- -coherent emission much shorter than the bunch length
- -bunch shape distortion
- -greater than N^2 dependence
- -factor 30000 max. enhancement
- -bursting behavior at higher current

Bessy results can be explained using standard model of single bunch instabilities. We have used this model to optimize a new source of CSR.



M. Abo-bakr, et. al. PRL **88**, 254801, (2002).
M. Abo-bakr, et. al PRL **90**, 094801 (2003).

Radiation Force

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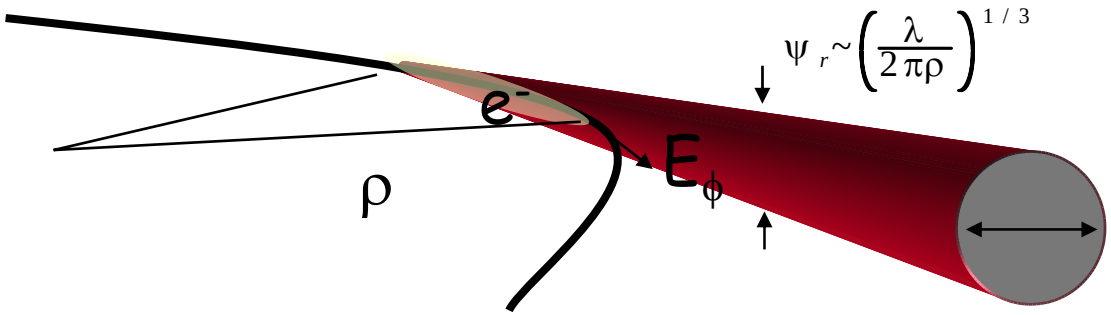
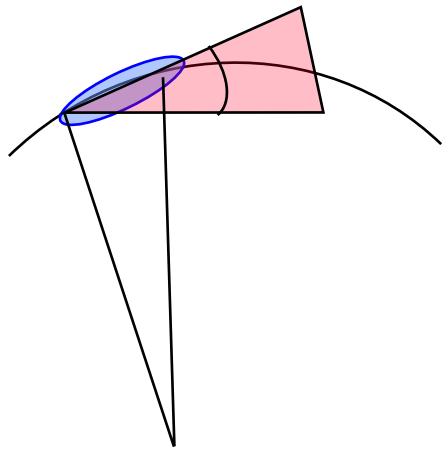




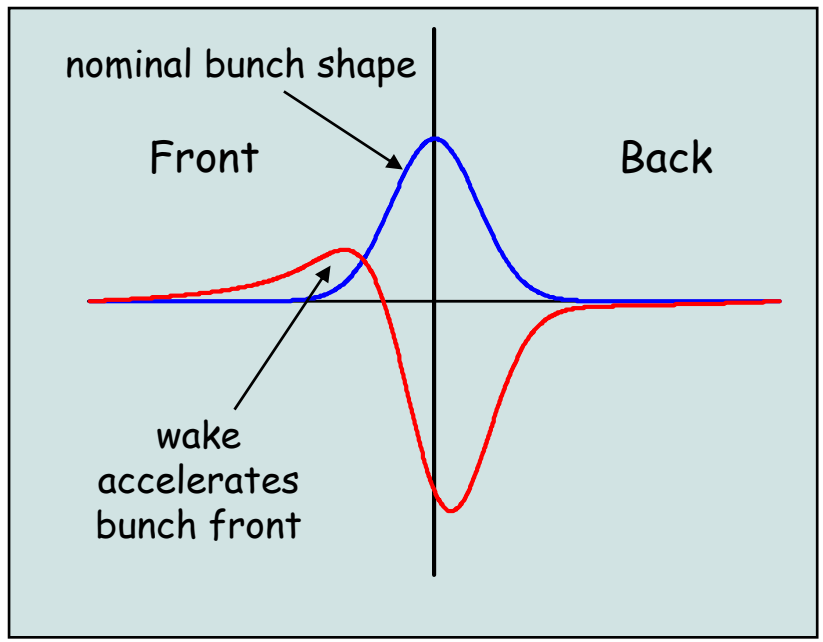
In free space

$$E_\phi = \frac{Z_0 c}{4\pi} \frac{2e}{\left(3^4 \rho^2\right)^{1/3}} \frac{1}{s^{4/3}}$$

for s>0

Total voltage on a bunch

$$V(s) = 2\pi\rho \int_{-\infty}^{s} ds' E_\phi(s - s') I(s')$$



Bunch distortion from radiation

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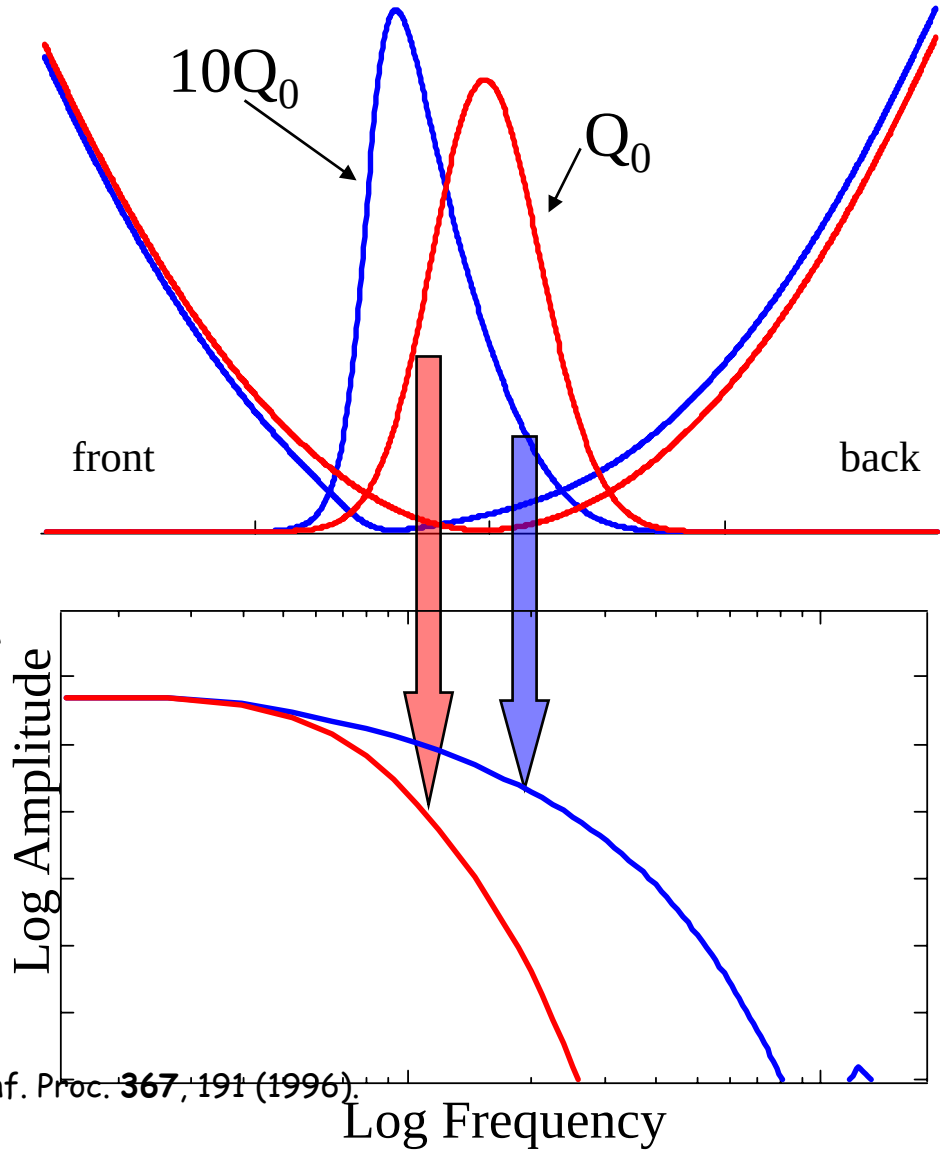
Nominal distribution for thermalized electron bunch is determined from harmonic potential given by RF focussing. The radiation force additionally focusses the front of the bunch. Limit reached when back of bunch is defocussed.



Steep leading bunch edge extends coherent emission spectrum to shorter wavelengths. Coherent spectrum can be tuned by adjusting ring parameters.

Bane, Krinsky, & Murphy, Microbunches Workshop,AIP Conf. Proc. **367**, 191 (1996).
Murphy, Krinsky, & Gluckstern, Part. Accel. **57**, 9 (1997).

Bessy Analysis

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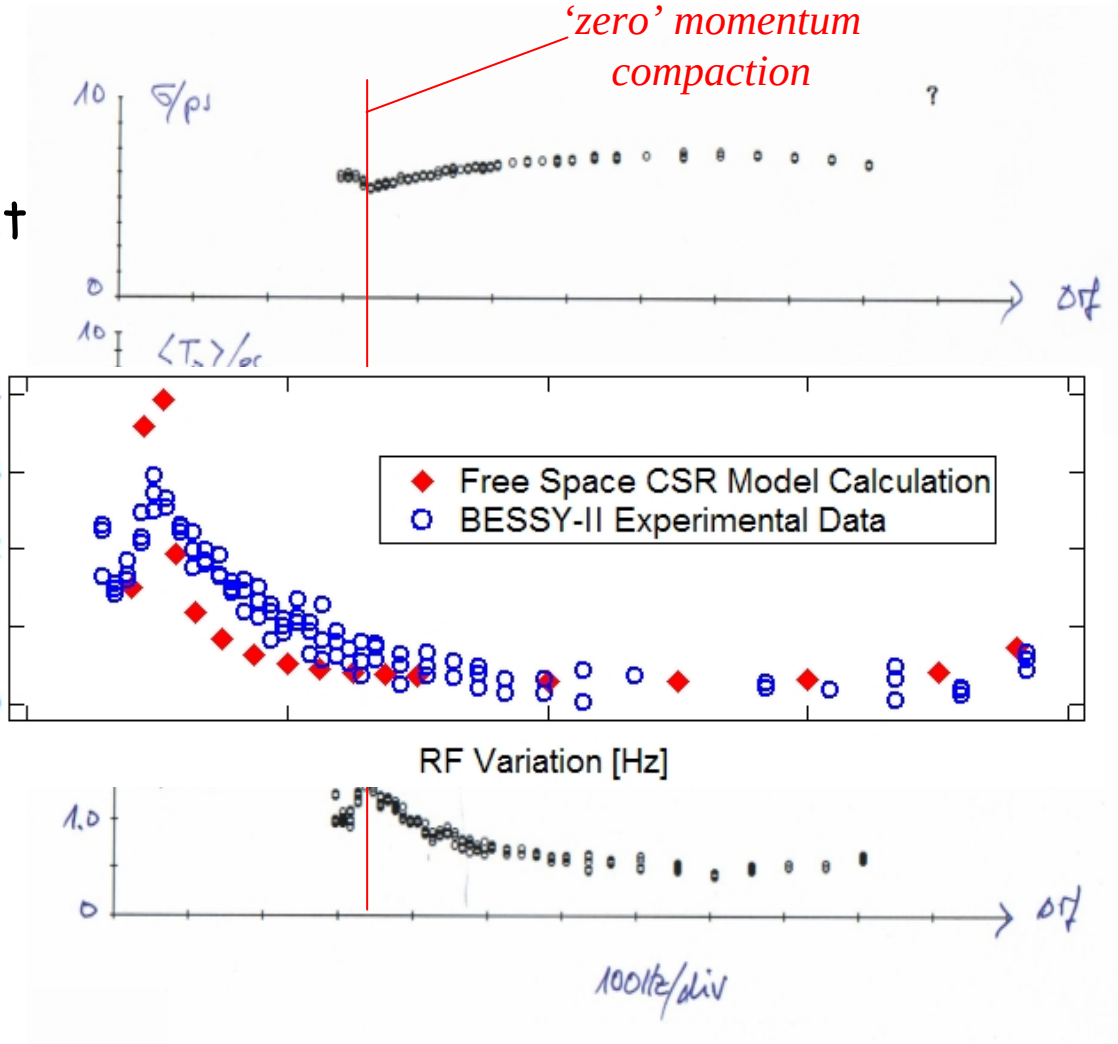
BESSY streak camera measurements unable to direct resolve bunch distribution. However, distortion from a gaussian is clearly visible



Apply Haissinski equation to calculate bunch distribution in the presence of SR wake

$$I(\tau) = K\, e^{-\frac{(c\tau)^2}{2\sigma_z^2} - \frac{c^2}{\sigma_z^2 \dot{V}_{RF}} \int_0^\infty I(\tau - t) S(t)\, dt}$$

Bessy Analysis (cont.)

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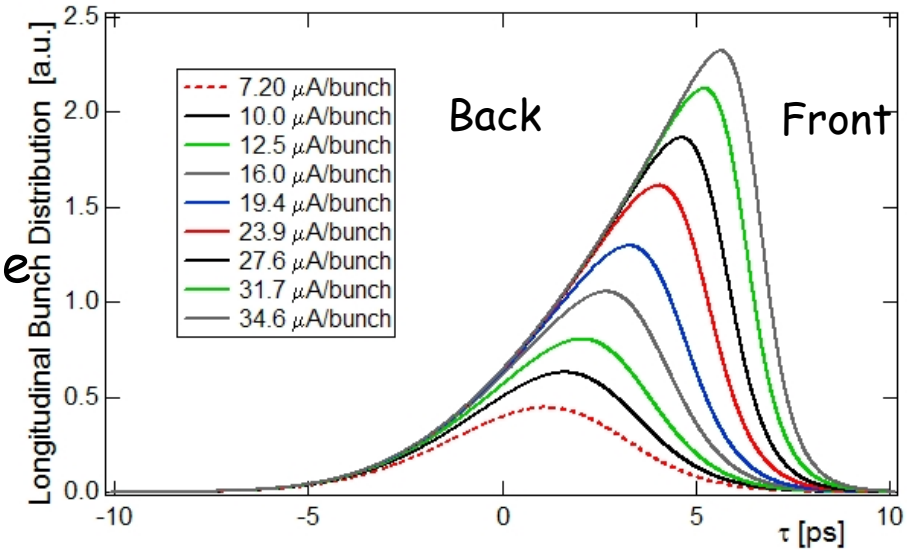
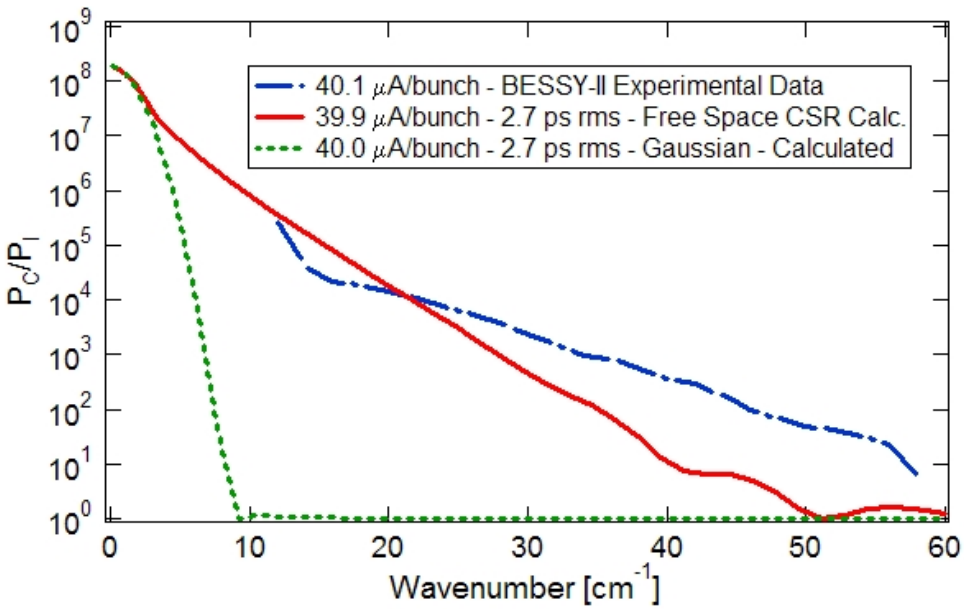
Using this, we can calculate
- bunch distortion vs. current
- spectral power
- dependence on energy, alpha, RF voltage

We cannot calculate
- instability thresholds
- nonlinear effects





Calculated power spectrum agrees well with measured spectrum

Bessy Analysis (cont.)

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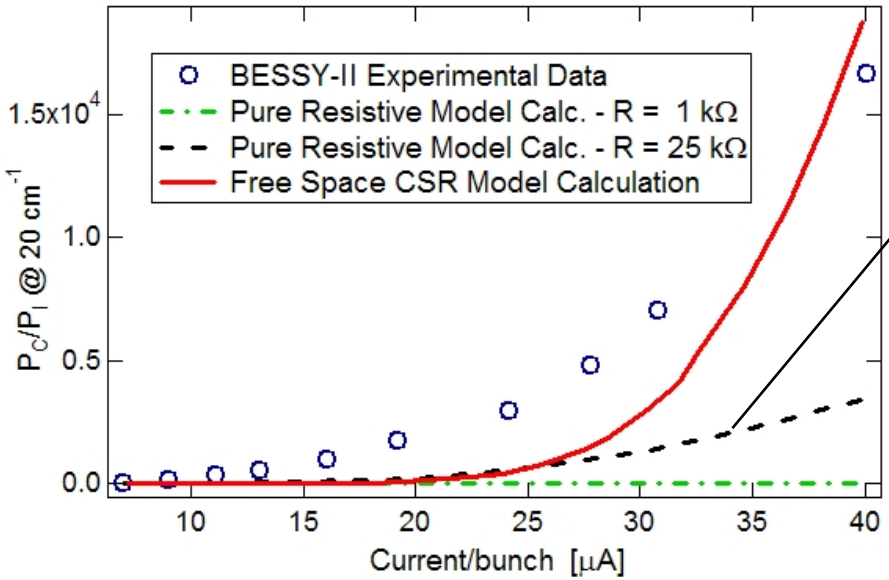
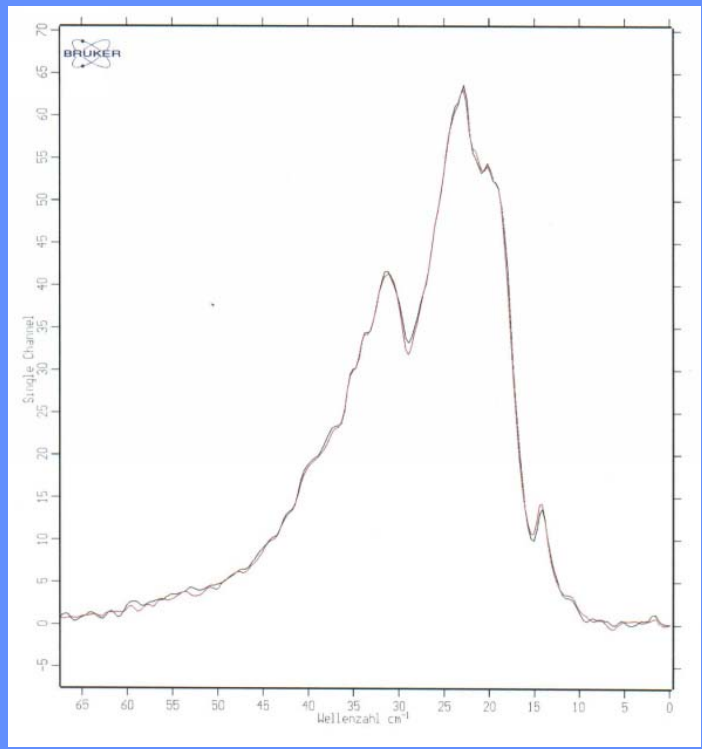


Results inconsistent with pure resistance

Calculation of coherent power enhancement shows good agreement with measurement

The spectra are clean and repeatable

Comparison of subsequent raw spectra



CSR Time structure

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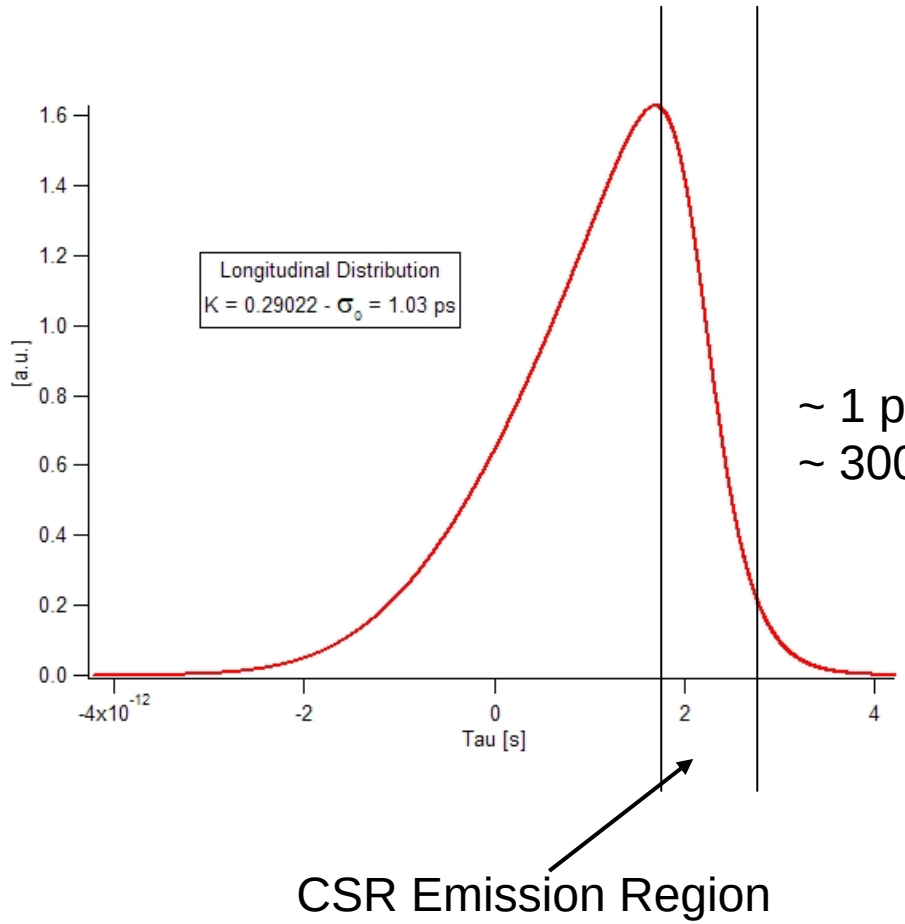
Pulse front edge radiates coherently

- CSR pulse can be shorter than the electron pulse
- pulse is repetitive and fluctuations arise only from variation in bunch current



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Source stability

A "clean" source is critical for FTIR measurement techniques. The primary noise is amplitude modulation of the light.

Noise sources include:

- electron beam motion
- modulation of the electron beam current
- modulation of the electron bunch distribution
  - "beam breakup"-like instabilities of the bunch driven by the CSR itself.

CSR Instabilities

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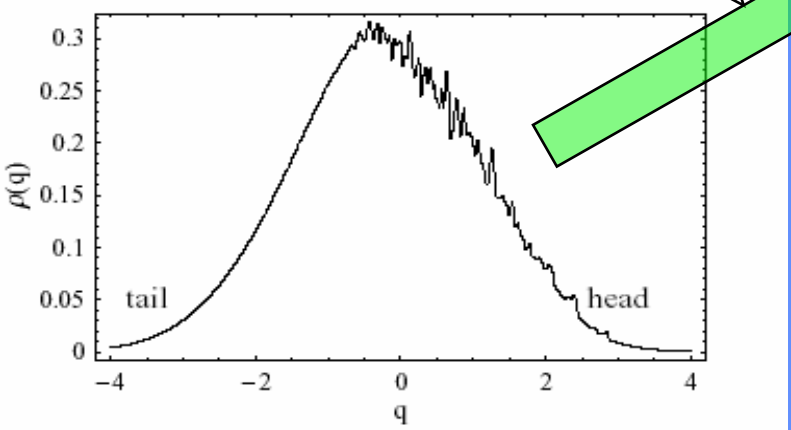
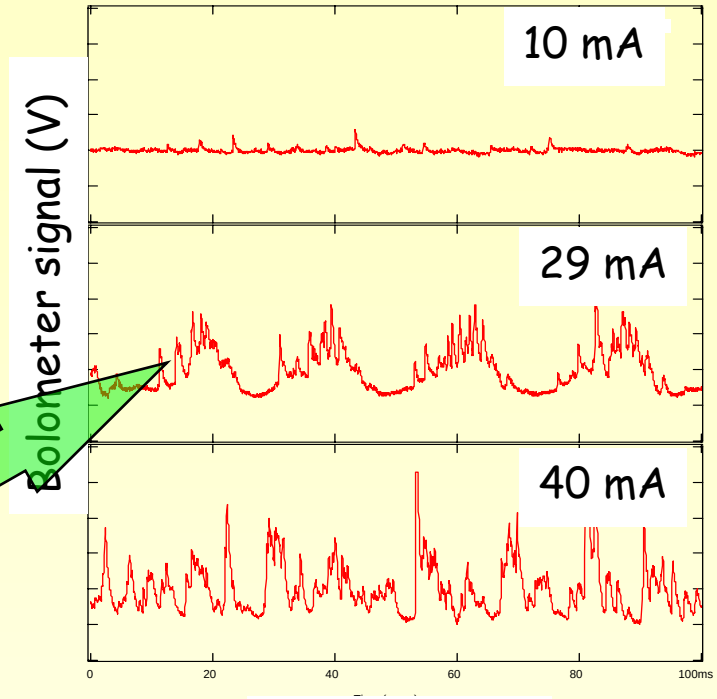
CSR can drive a microbunching instability in the electron bunch, resulting in a periodic bursts of terahertz synchrotron radiation, resulting in a noisy source.



Simulated instability showing bunch shape



Bursts of far-IR CSR observed on a bolometer. Threshold depends on beam energy, bunch length, energy spread, and wavelength.

Microbunching Model

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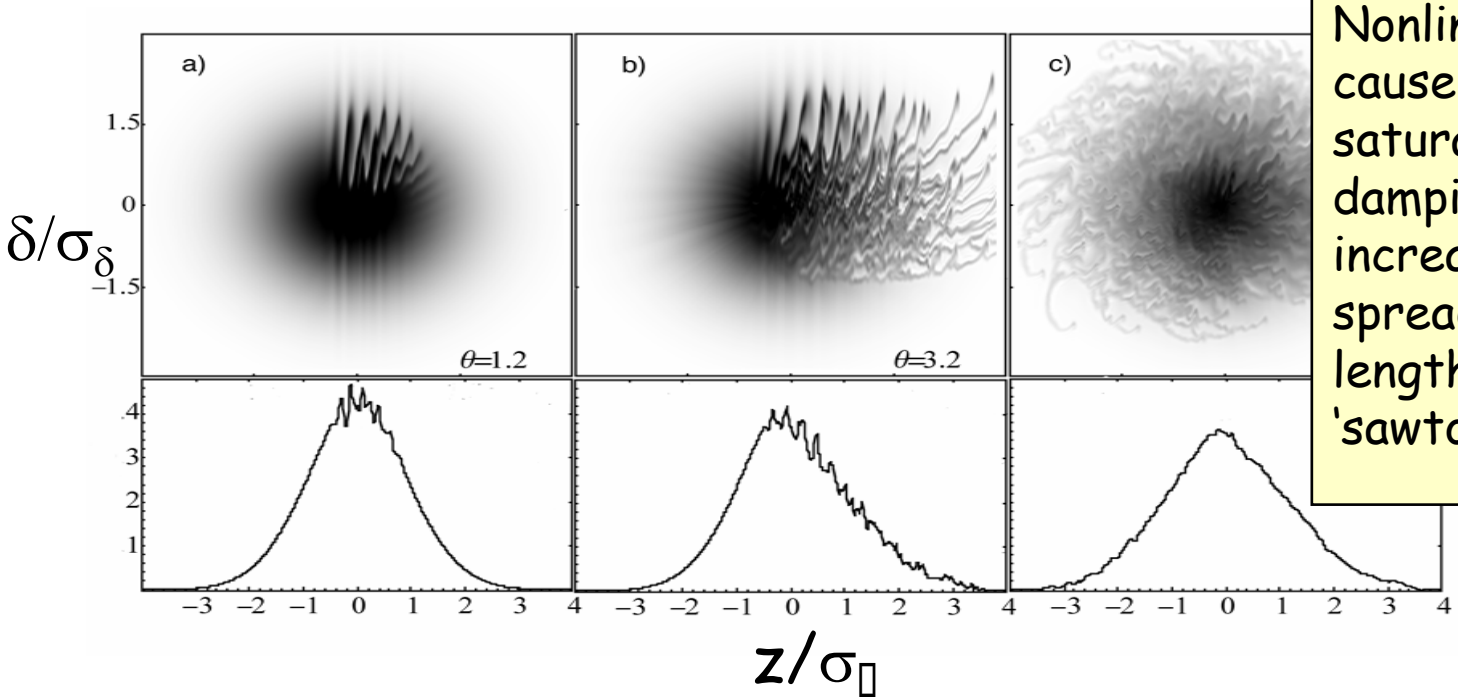
Small perturbations to the bunch density can be amplified by the interaction with the radiation. Instability occurs if growth rate is faster than decoherence from bunch energy spread.



Nonlinear effects cause the instability to saturate. Radiation damping damps the increased energy spread and bunch length, resulting in a 'sawtooth' instability.

S. Heifets and G. Stupakov, PRST-AB **5**, 054402 (2002).
M. Venturini and R. Warnock, PRL **89**, 224802 (2002).

ALS microbunching results

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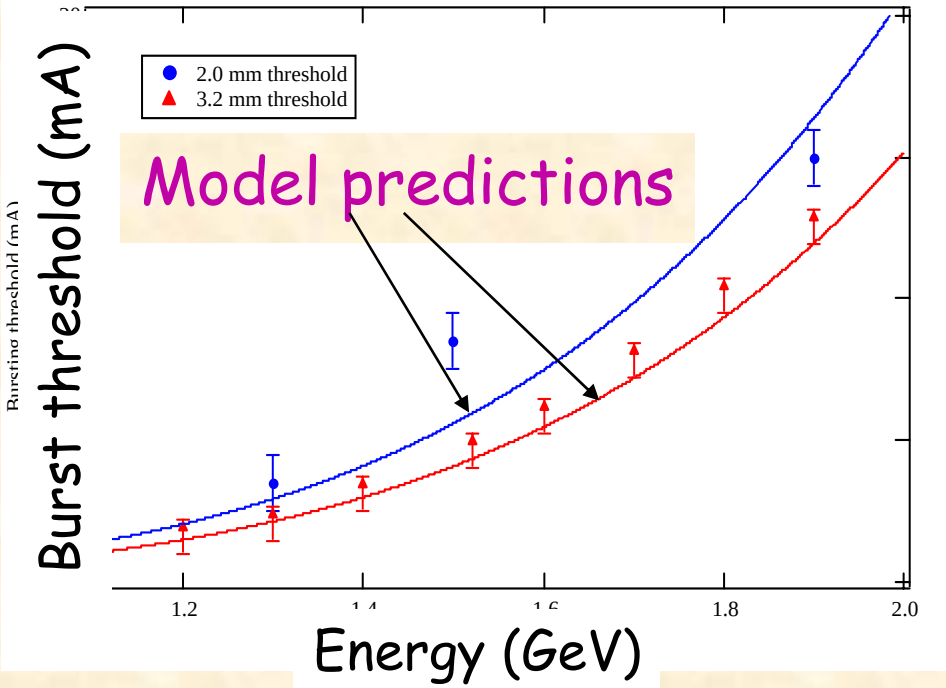
ALS studies show first confirmation of CSR driven sub-microwave instability



Instability thresholds understood:

- -agreement w/observations at other sources
- -coherent power enhanced w/lower S/N
- -possibility of raising threshold using nonlinear momentum compaction

Standard FTIR techniques require "clean" sources. A CSR source must be below the instability threshold.

J. Byrd, et. al. PRL 89, 224801, Nov 2002.

Bessy-II Microbunching

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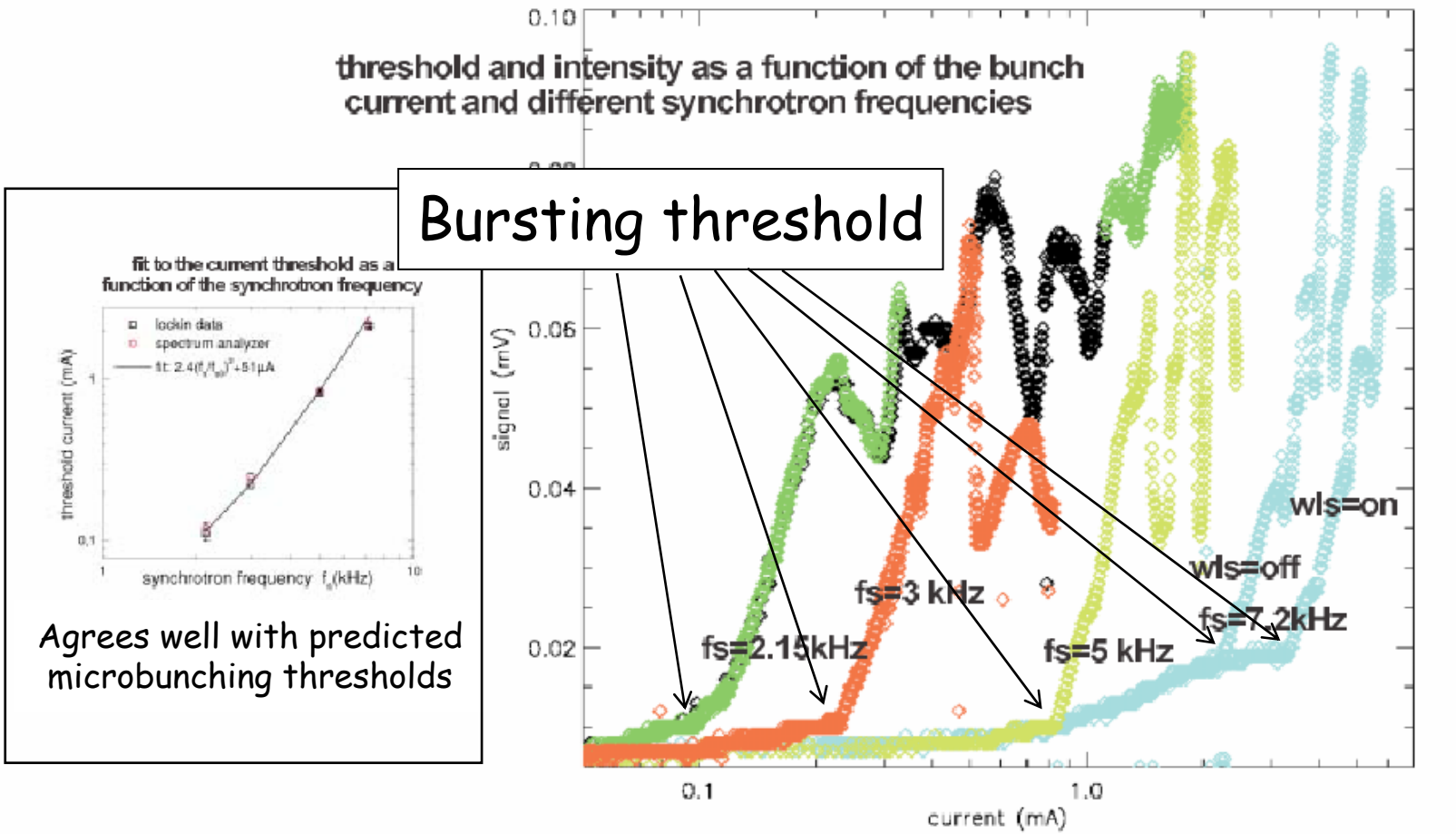
Single bunch CSR-signal at 1.25 MHz and ~5Hz bandwidth



G. Wuestefeld, Napa CSR Workshop, Oct. 2002

-CIRCE: A dedicated source of CSR

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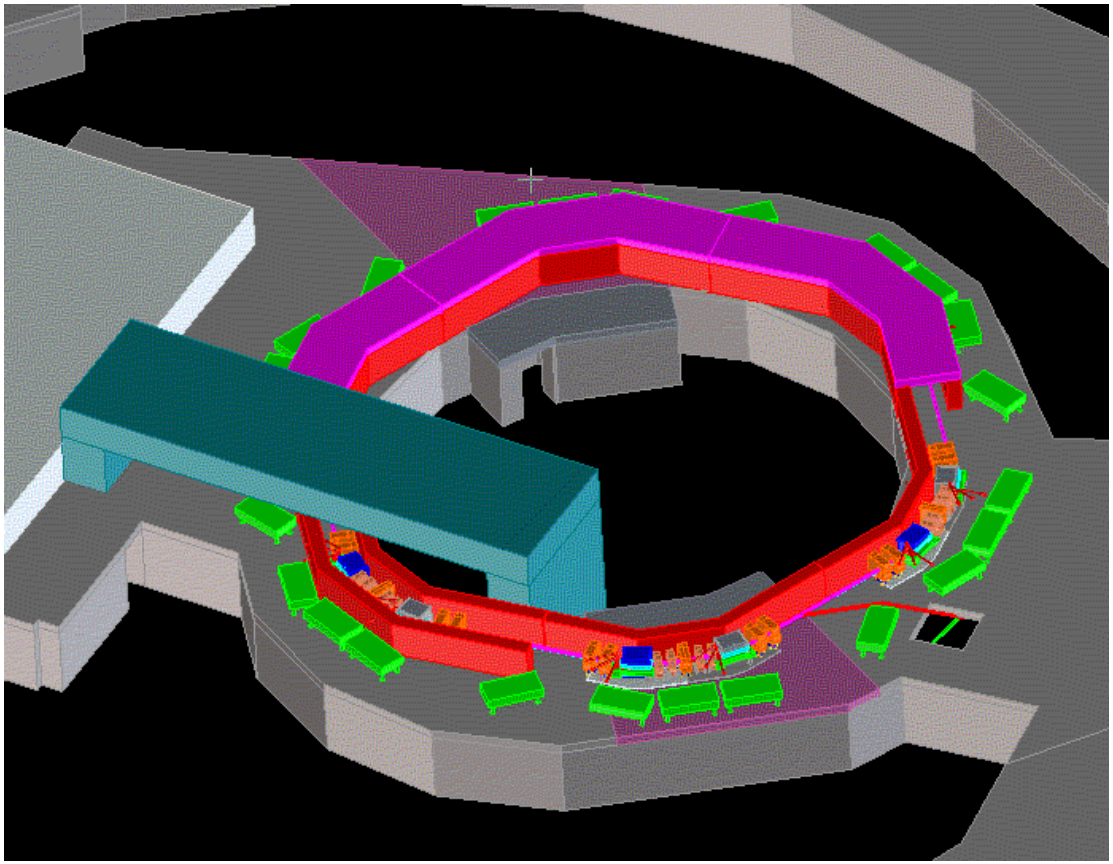

Beam Line Experiments Located on Top of the Booster Shielding

-"Free" full energy (600 MeV) injector-Compatible with ALS topoff operation.

-Adequate floor space for IR beamline experiments.

-Stable surface supporting ring and beamline.

-SR vacuum chamber and collection optics optimized for IR

CIRCE Overview

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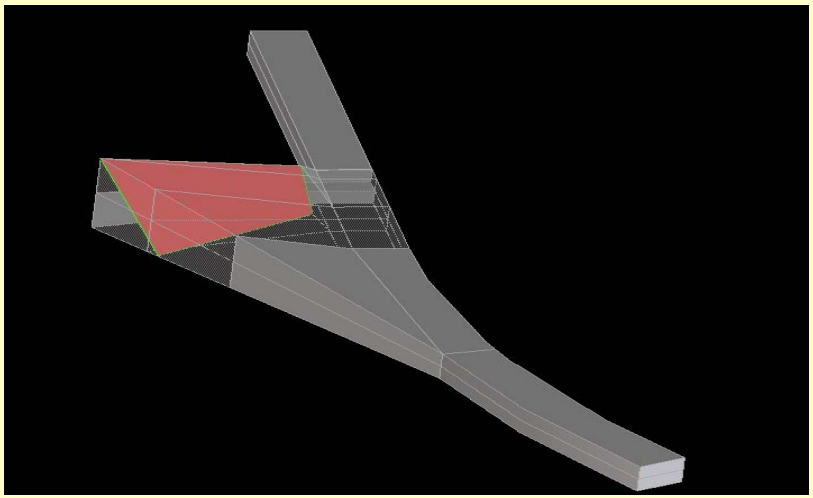
CIRCE Parameters

E=600 MeV	f_{rf}=1.5 GHz
V_{rf}=0.6 MV	U_0=8.62 kV
I_{total}=30-90 mA	I_{bunch}=90-230 μA
C=66 m	h=330
σ_τ=1-3 psec	σ_δ=4.5e-4
α=2e-3 - 2e-6 (?)	

QuickTime™ and a Photo - JPEG decompressor are needed to see this picture.

Large Vertical acceptance dipole chamber for long wavelengths



- DBA lattice 50 nm-rad emittance (diffraction limited in far-infrared)
- variable momentum compaction with 4th order correction
- magnets pre-aligned on girders
- shielding fits directly over magnets (i.e. no tunnel access)

CIRCE capabilities

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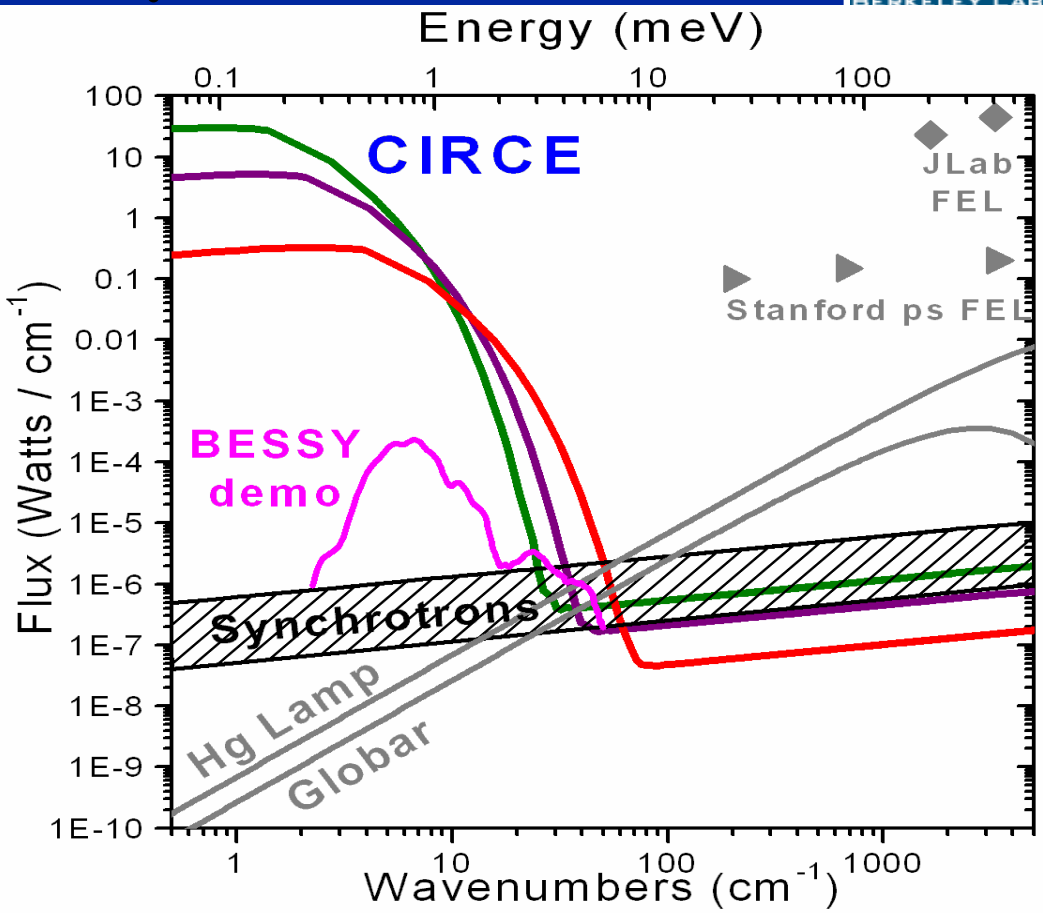
In the far-IR, the CSR source has an enhancemer of 6-10 orders of magnitude over conventional sources.



The nature of coherent pulses may enable new techniques:

- fast detector technologies
- coherent pulse adding for ultrahigh power
- multi-color SR pump probe (i.e. far-IR/x-ray)

Performance optimized by varying natural bunch length and charge while staying below threshold.

Novel techniques for using CSR

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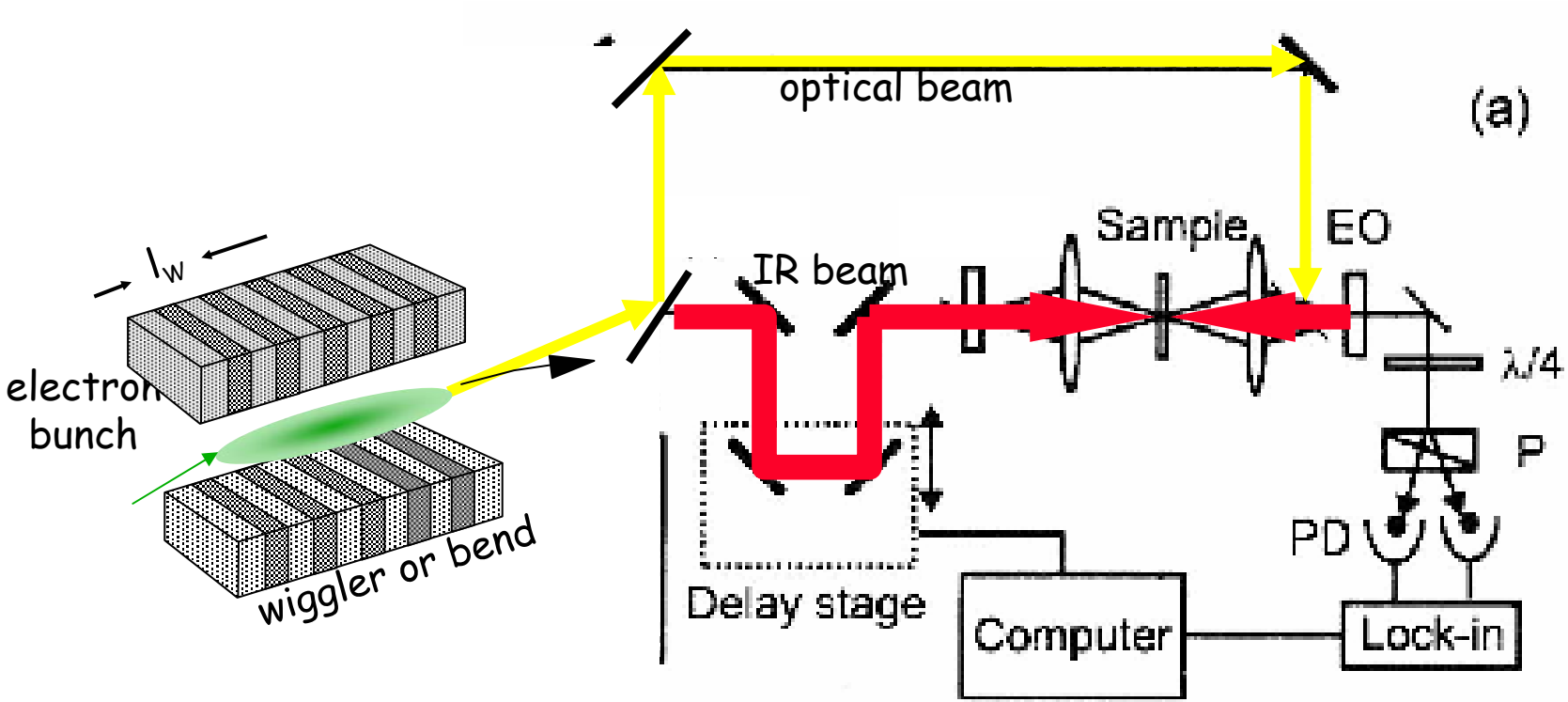
Self-synchronized Electro-optic sampling

- provides functionality of benchtop setup w/1.5 GHz rep-rate
- use inherent synchronization of optical and THz beams
- optical source can be dipole (very weak) or undulator
- self-mixing techniques also possible.



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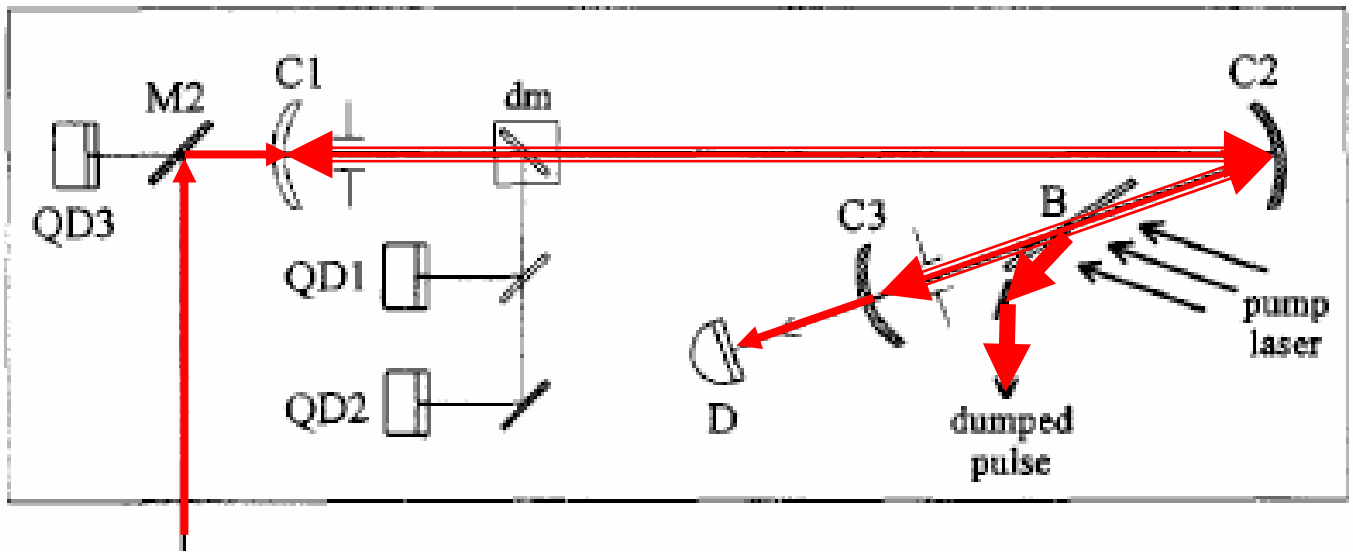
Pulse stacking

Because input pulses are coherent, it is possible to resonate the signals to gain high pulse power levels.



Peak power limited by cavity Q and phase stability of pulses

T. Smith, et al., NIMA 393 (1997) 245-251.

CIRCE status

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- Physics of stable CSR emission understood
  - bunch distortion effects increase emission at shorter wavelengths
  - limits for stable operation from instabilities predicted
- Optimized IR Ring conceptual design complete
  - ring lattice, injection, RF system
  - prelim. engineering design of magnets, supports, shielding
  - request for budgetary quotes almost complete
  - positive reception at BESAC Review in Feb. 2003
  - No technical showstoppers. We are ready to build.

Summary and Plans

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- Standard model of single bunch instabilities explains most of the experimental observations to date.
- First CSR science experiment completed and submitted to PRL (Singley, Martin, et al.)
- Upcoming experiments to look for steady CSR in ALS at "low"ish momentum compaction and low energy (1.0 GeV).
- Current studies evaluating effect of geometric impedance.
- Survey of existing rings to search for future experiments.
- Satellite meeting at 2003 PAC on Storage Ring CSR planned for Wed. from 2-6 PM.
- DOE is organizing a national workshop to determine the needs for high power THz sources. Possible in Fall 2003.

The CIRCE Team

Science Opportunities: **Michael C. Martin, Wayne R. McKinney**, Dimitri Bas ov, Daniel Chemla, Ben Feinberg, Robert Kaindl, Jim Krupnick, Laszlo Mihaly, Joe Orenstein, Al Sievers, Jason Singley, Neville Smith

Accelerator Physics: **John Byrd, Fernando Sannibale,** David Robin, Hiroshi Nishimura, Weishi Wan, Christoph Steier, Warren Byrne, Tom Scarvie, Agusta Loftsdottir

Engineering: **Ross Schlueter, Jin-Young Jung, Dawn Munson,** Ken Baptiste, Walter Barry, R.J Benjegerdes, Alan Biocca, Daniela Cambie, Mike Chin, John Corlett, Stefano De Santis, Rick Donahue, Mike Fahmie, Slawomir Kwiatkowski, Derun Li, Steve Marks, David Plate, J.A. Paterson, Greg Stover, Will Thur, J.P. Zbasnik

Collaborations: Marco Venturini - LBNL, Etienne Forest - KEK, Gennady Stupakov - SLAC, Jim Murphy - NSLS-BNL - Larry Carr, NSLS-BNL, Wim Leemans - LBNL, Bout Marcelis - LBNL/Eindhoven, Bob Warnock - SLAC, Rui Li - JLab, Gode Wustefeld - BESSY, Peter Kuske - BESSY, ...

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