Coherent Synchrotron Radiation Studies at the ALS

John Byrd
Lawrence Berkeley National Laboratory

A Team Work

AFRD (CBP and ALS Acc. Physics) : J.M. Byrd, D.S. Robin, F. Sannibale, A. Zholents, M. Zolotorev.

ALS: Z. Hao, M. C. Martin.

MSD: R. W. Schoenlein.

Collaborations: BESSY, DLR (Berlin), SLAC

Important contributions:

M. Abo-Bakr, J. Feikes, E. Forest, S. Heifets, K. Holldack, H. W. Hubers, P. Kuske, W. Leemans, A. Loftsdottir, B. Marcelis, J. Murphy, T. Scarvie, C. Steier, G. Stupakov, M. Venturini, R. Warnock, G. Wustefeld, ...

A Multi-year Effort

2002: The microbunching instability (MBI): First experimental proof.
(J.M.Byrd *et al*., PRL **89**, 224801, 2002.)

2003-2004: Stable CSR in storage rings: Development of a model accounting for experimental observations.
(F. Sannibale *et al*., PRL **93**, 094801, 2004.)

2004-2005: CSR from "femtoslicing" experiment: First experimental data and characterization.
(J.M.Byrd *et al*., PRL **96**, 164801, 2006.)

2004-2006: Laser seeding of the MBI: First experimental observation and model for the phenomenon.
(Submitted for publication.)

Significantly funded by LDRD.

Why Studying CSR?

• **Coherent Synchrotron Radiation (CSR) has been matter of great interest and study in the last years:**

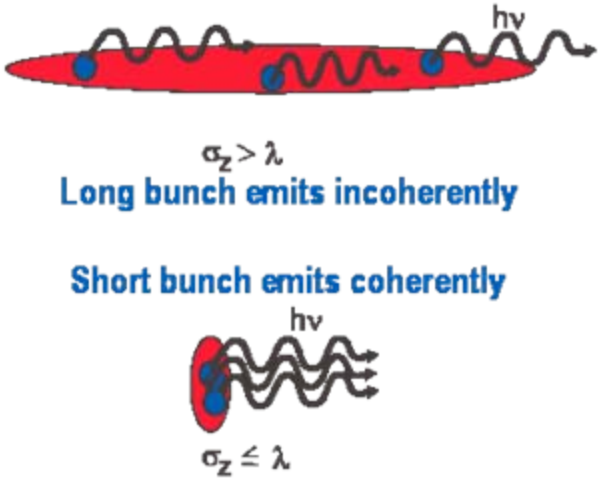
as a 'nightmare' for every short bunch high charge accelerator where CSR can jeopardize the performances (linear colliders, short pulses synchrotron radiation sources, damping rings, ...);

as a powerful diagnostic for bunch compressors (potential collaborations with LCLS, FERMI, ILC, …);

but also as a 'dream' for potential revolutionary synchrotron radiation (SR) source in the THz frequency range;

Our group wants to built such a source at the LBNL!

CSR as a Powerful Radiation Source



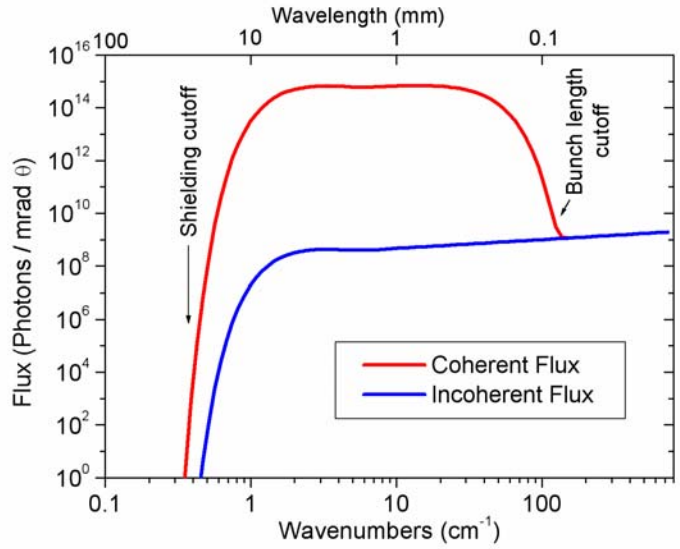
$$\frac{dP}{d\omega} = \frac{dp}{d\omega}\left[N + N(N-1)g(\omega)\right]$$

Nodvick & Saxon, Phys. Rev. **96**, 180 (1954).
G. Williams et al., PRL **62**, 261 (1989).

$$P_{SR} \propto N \qquad P_{CSR} \propto g(\omega)N^2$$

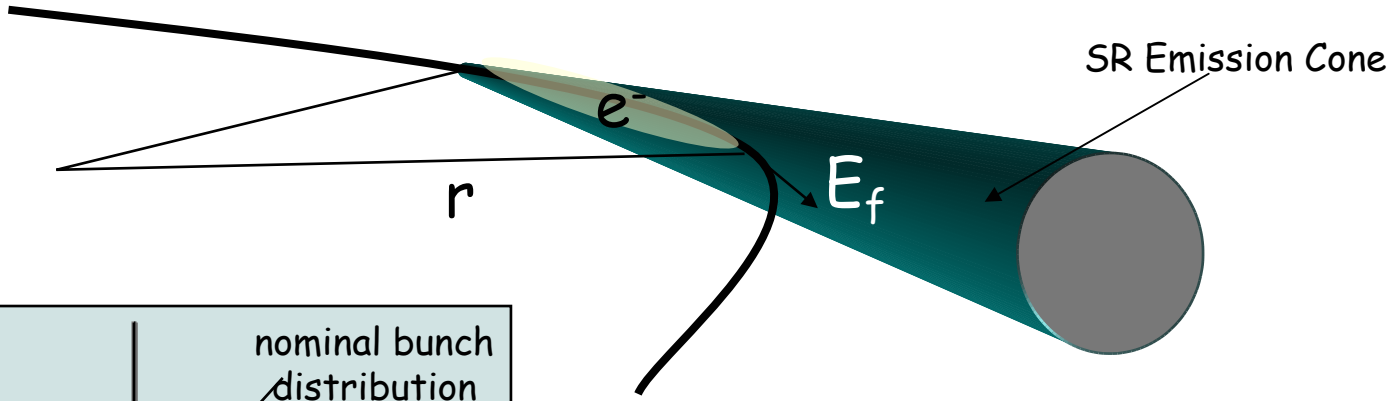
$$g(\omega) = \left| \int_{-\infty}^{\infty} dz\, S(z) e^{i\omega\cos(\theta)z/c} \right|^2$$

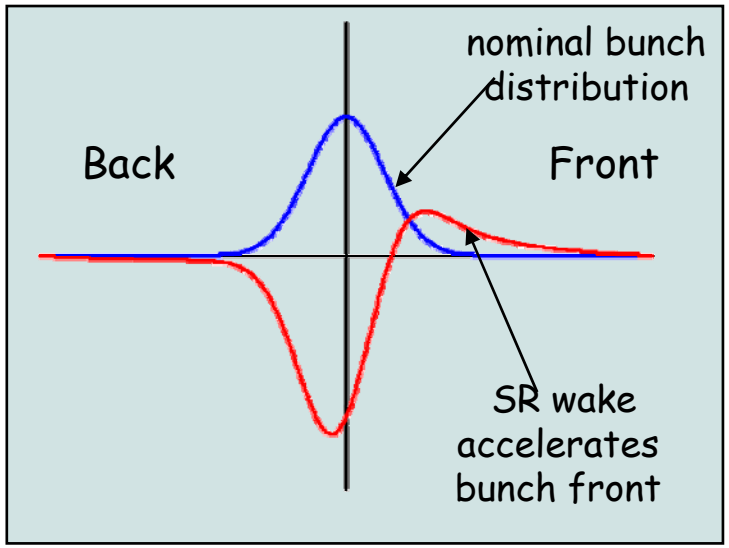
Normalized Bunch Longitudinal Distribution



High potential as an extremely powerful source in the THz frequency range.
"Ideal" match for filling the "THz Gap"

The Synchrotron Radiation Wake





The SR wake can have very significant effects on the longitudinal dynamics of the beam.

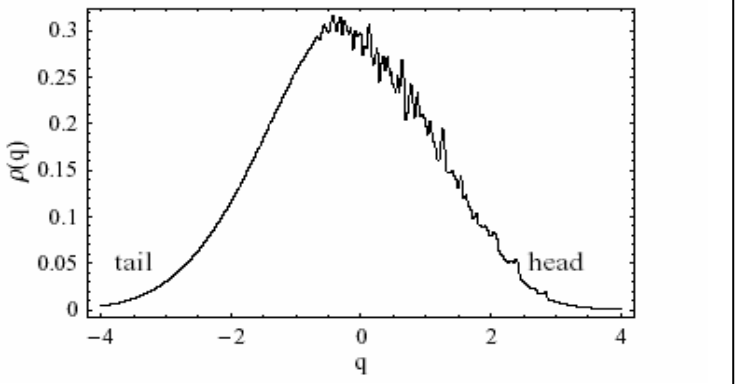
An analytical expression for the SR wake has been derived and can be used for a quantitative calculation of these effects.

J.B. Murphy, S. Krinsky, R. Gluckstern , *Particle Accelerators* **57**, 9 (1997)

The MBI

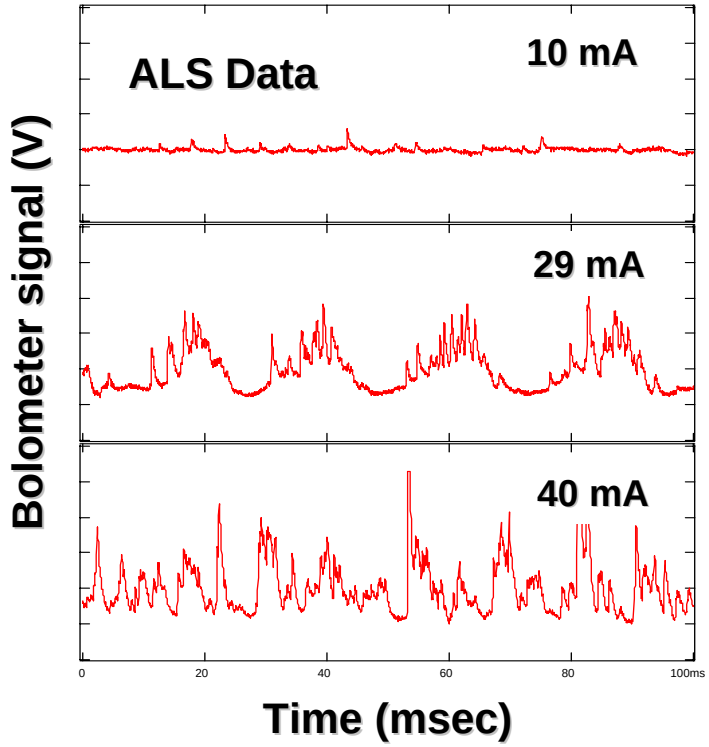
Above a current/bunch threshold the SR wake can drive a microbunching instability in the electron bunch generating bursts of THz CSR and resulting in a noisy source.

S. Heifets, G.Stupakov, PR STAB **5**, 054402, (2002).



Simulated instability showing the microbunching.
Venturini, WarnocK SLAC

M. Venturini, R. Warnock, PRL **89**, 224802, (2002).



A. Anderson et al.:, Opt. Eng. **39**, 3099, (2000).

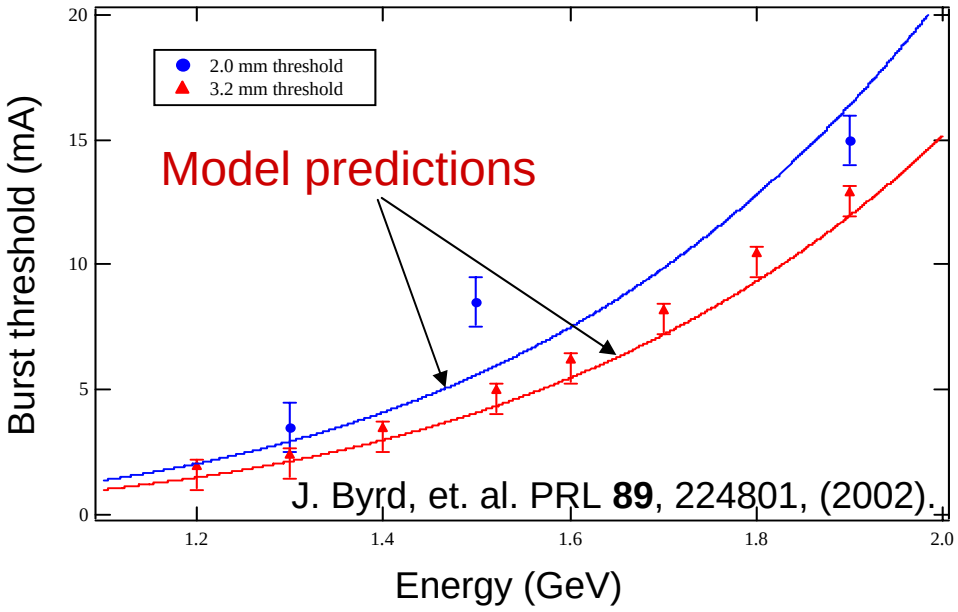
G.L. Carr et al.:, NIMA **463**, 387, (2001).

M. Abo-Bakr et al.:, EPAC2000 Proceedings.

…

CSR Instability Experimental Verification

ALS studies show first experimental confirmation of the Heifets-Stupakov model for the microbunching instability



Instability thresholds understood:
- agreement with observations also at other storage rings

Heifets-Stupakov instability model allows the design of a <u>stable</u> Ring Based CSR Source

$$I_b > A \frac{1}{h^{1/2} f_0 \left(\hat{V}_{RF} \cos\varphi_s\right)^{1/2}} \frac{\alpha_C^{3/2}}{\rho^{11/6} J_s^{3/2}} \frac{\gamma^{9/2}}{\lambda^{2/3}}$$

$$A = \left(m_0^{1/2} e^{1/2} c^3 C_q^{3/2}\right) \Big/ \left(2\pi^{1/3} r_0\right) \quad [MKS\ Units]$$

Ring Based CSR Source

- 1994, First idea of a storage ring based CSR source (1994)

Murphy & Krinsky, NIM A **346**, 571 (1994).

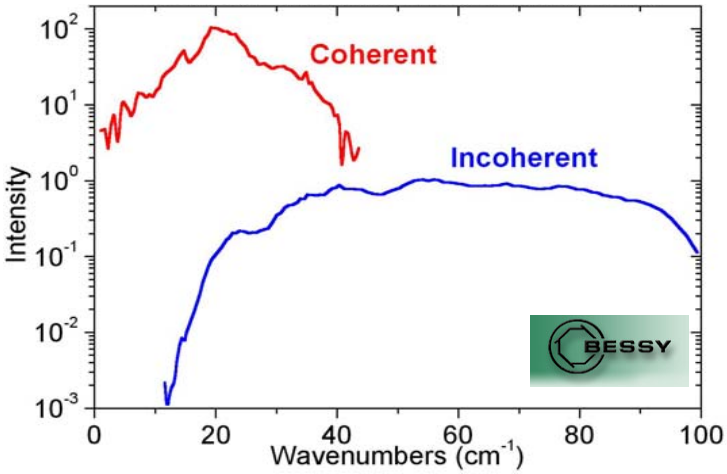
- Spring 2000, CIRCE (Coherent InfraRed CEnter) Idea Conceived

Presented at the Far-IR Workshop at the ALS Users' Meeting, October 2000

- 2002, First demonstration of stable CSR at BESSY-II Ring

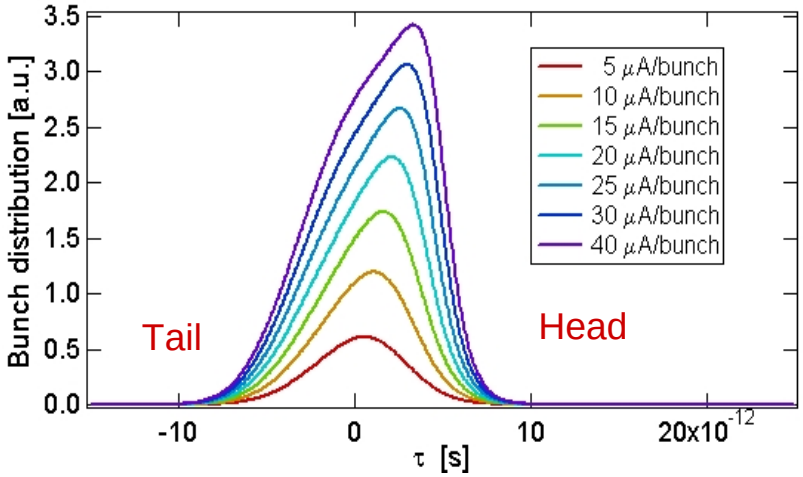
Abo-Bakr *et al.*, PRL **88**, 254801 (2002)
M. Abo-Bakr *et al*., Phys. Rev. Lett. **90**, 094801 (2003)

The BESSY-II Storage Ring



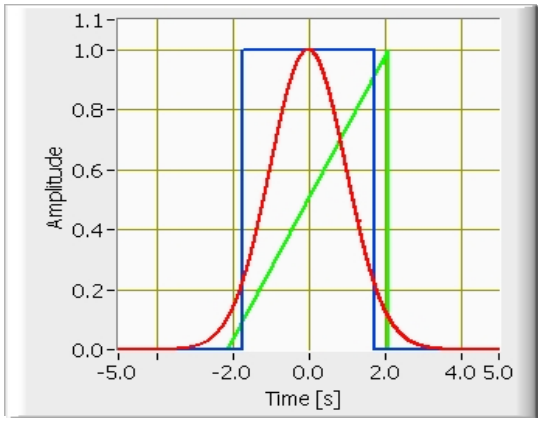
Very interesting characteristics of the BESSY results were the very stable CSR power and a spectrum in the THz significantly broader than the one expected for their bunch length.

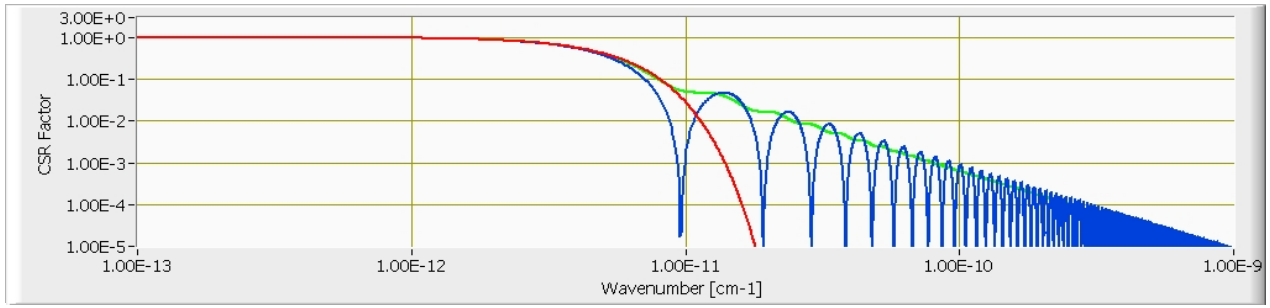
Understanding the BESSY Results



In the short bunch regime (few ps), the SR wake becomes dominant and induces non-gaussian <u>equilibrium</u> distributions with leading edges much sharper than trailing ones.

(Bane, Krinsky and Murphy AIP Proc. **367**)



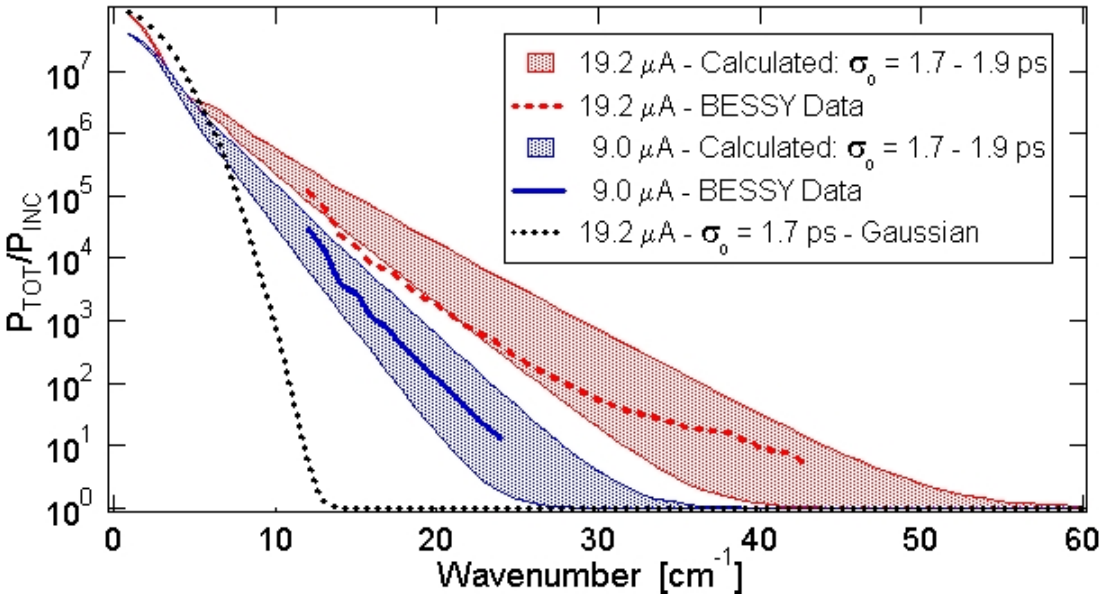


Non-gaussian distributions extends the CSR spectrum towards higher frequencies:

the ‘saw-tooth’ distribution seems to be the best. Mother nature is helping us!

Understanding the BESSY Results

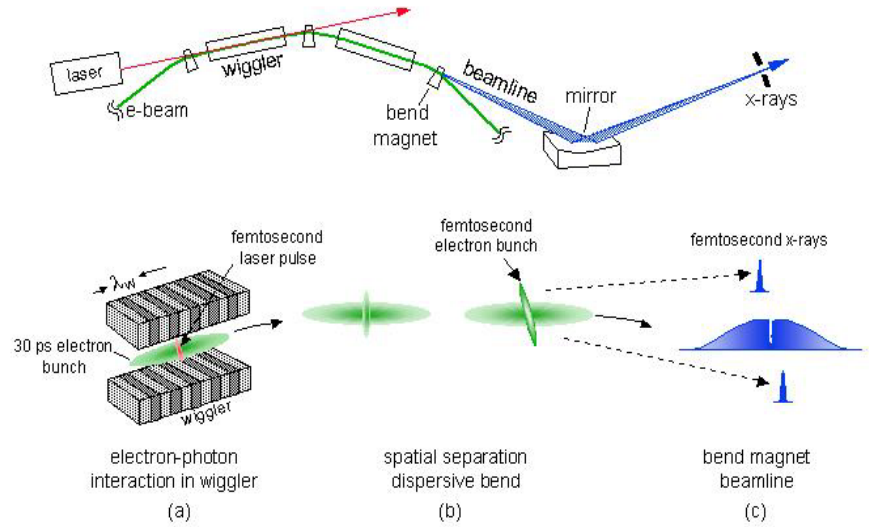
(F. Sannibale *et al.*, PRL **93**, 094801, 2004.)



The understanding of the physics behind the BESSY results allowed to develop a model for optimizing a storage ring as a source of THz CSR.

Such a model has been used for calculating the CSR performance of a number of existing storage rings (DAΦNE, Bates, Spear, …) and also for designing a storage ring completely optimized for the generation of CSR in the THz frequency range (CIRCE).

The `Femtoslicing' Experiment

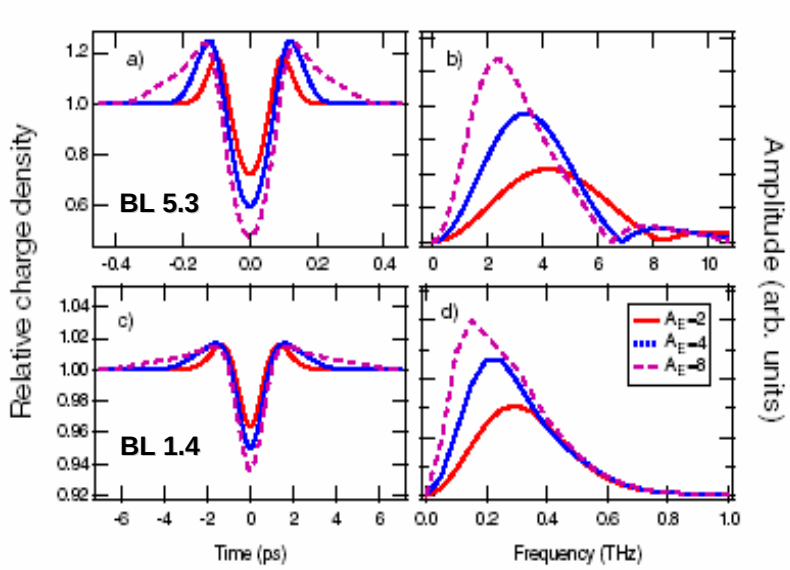


• A. A. Zholents, M. S. Zolotorev, Phys. Rev. Lett. **76**, 912, (1996)

Femtosecond x-ray pulses

In operation at the ALS since 1999, at BESSY II since 2004 and soon at the SLS, …

After the energy modulation, the ring longitudinal dispersion generates a perturbation on the bunch distribution:

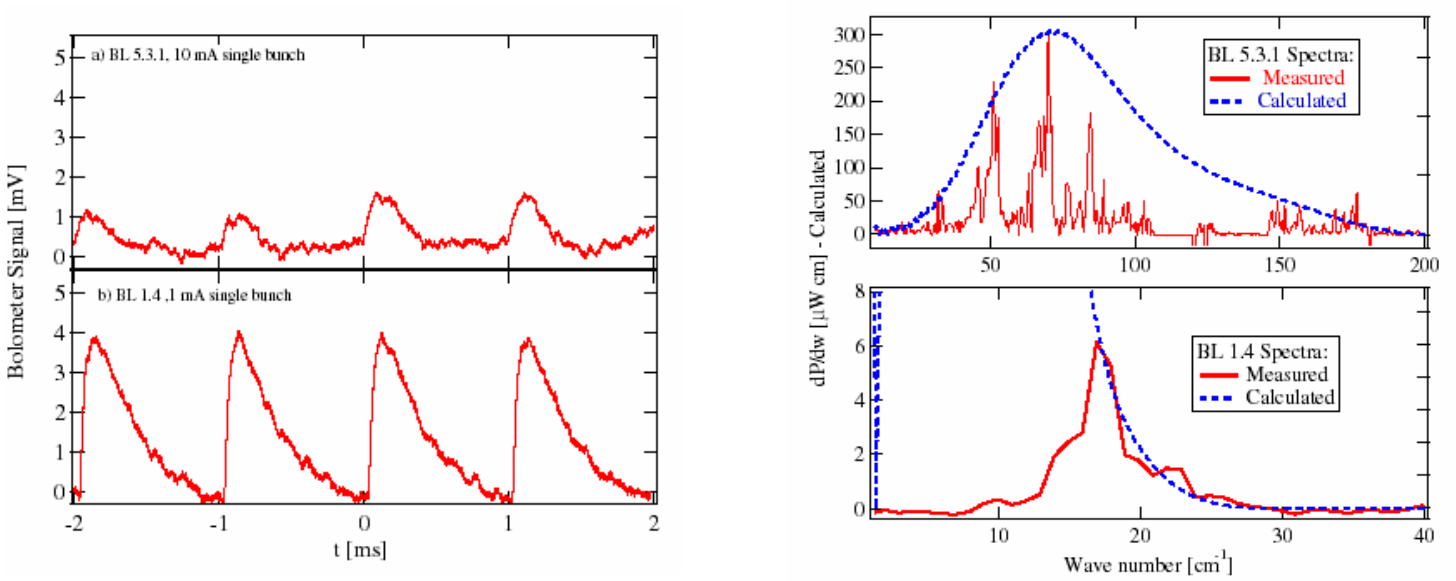


'These density modulations should radiate CSR in the THz frequency range'

•R. W. Schoenlein, *et al*., Appl. Phys. B **71**, 1-10, 2000.

THz CSR From Femtoslicing

Our group at the ALS did the first experimental observation and characterization of the CSR from the femtoslicing experiment:



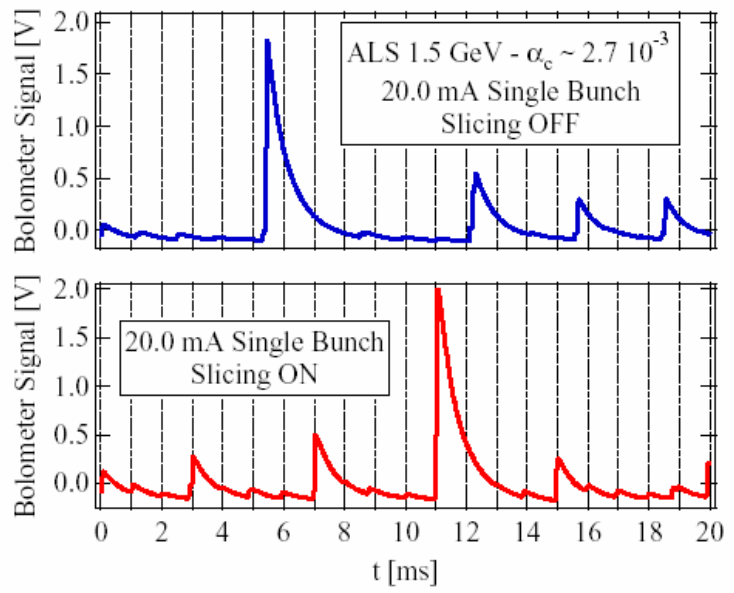
(J.M.Byrd *et al.*, PRL **96**, 164801, 2006.)

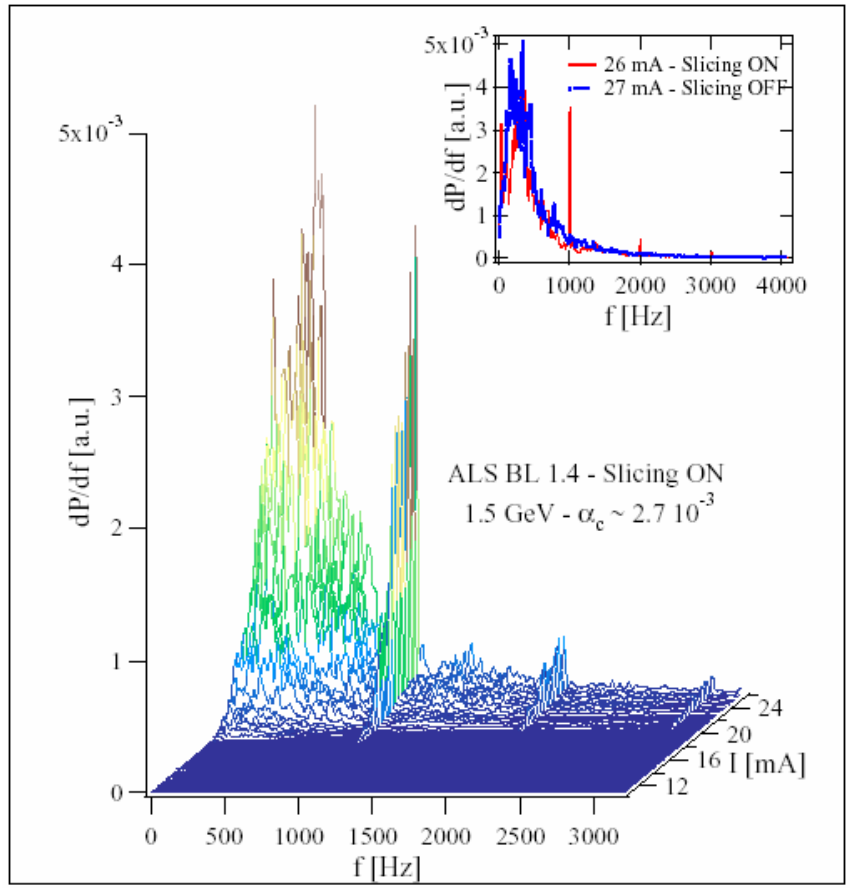
The CSR signal is now one of the main diagnostics for the tune-up for the slicing experiment.

The femtoslicing scheme can also be used as a source of high energy per pulse THz radiation (~ 10 μJ) for pump and probe experiments.

Laser Seeding of the MBI

During the experiments for characterizing the CSR from femtoslicing, we discovered that if the beam is sliced above the MBI threshold the instability can be seeded.





The MBI CSR bursts become synchronous with the slicing laser and the radiated THz power increases exponentially with the current per bunch.

Stimulated bursts

Above microbunching threshold, bursts are observed to be synchronous with slicing.

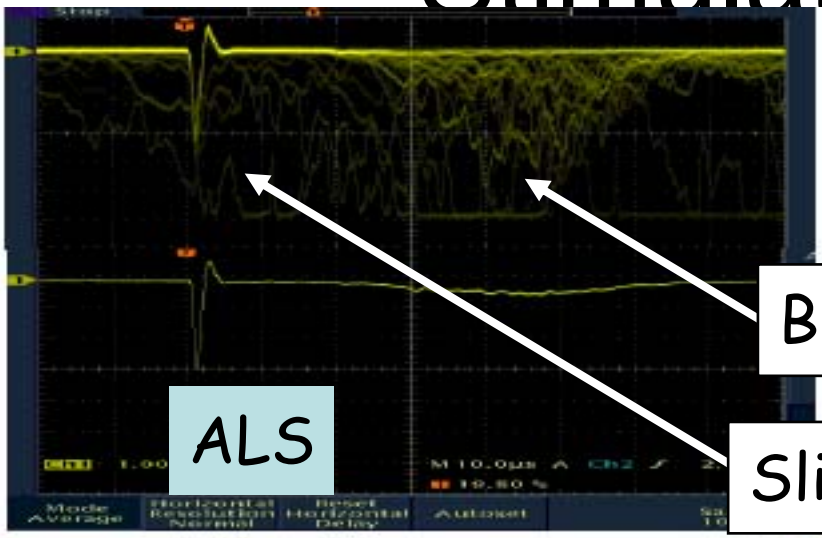
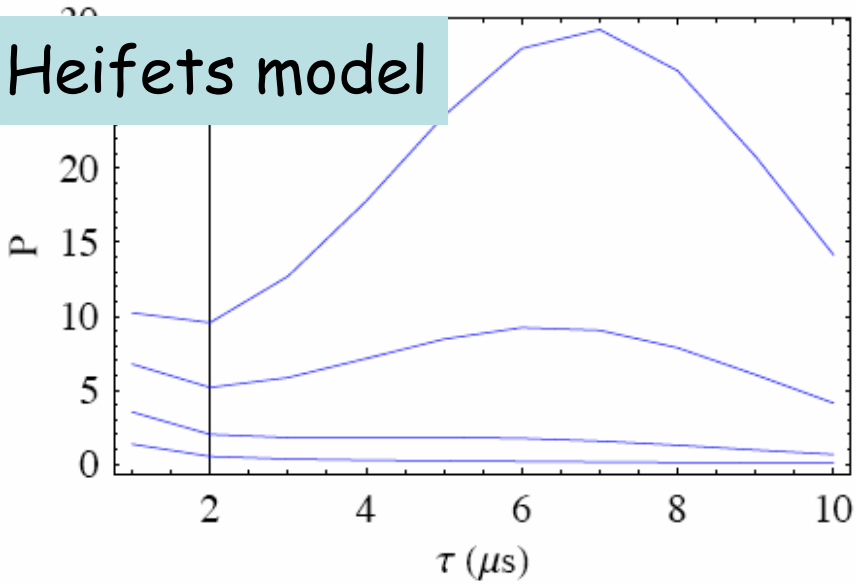
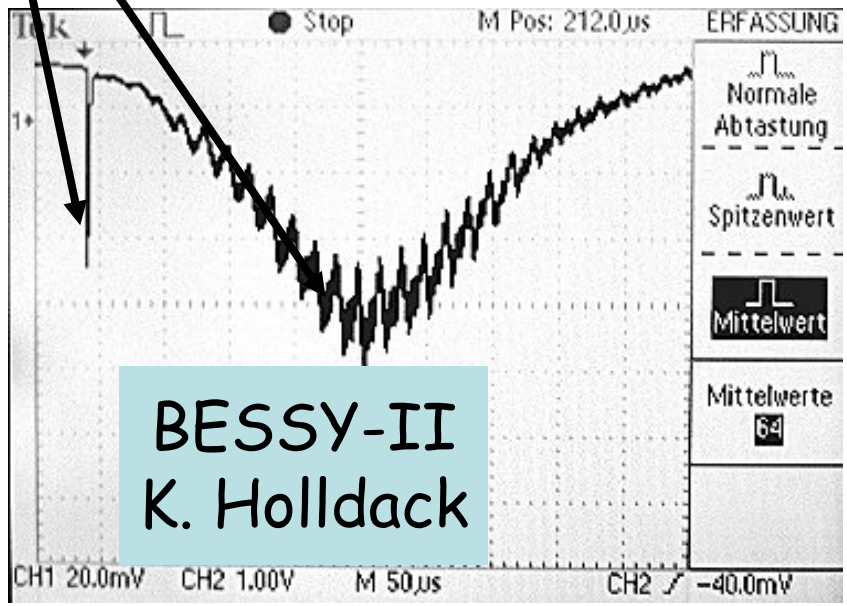


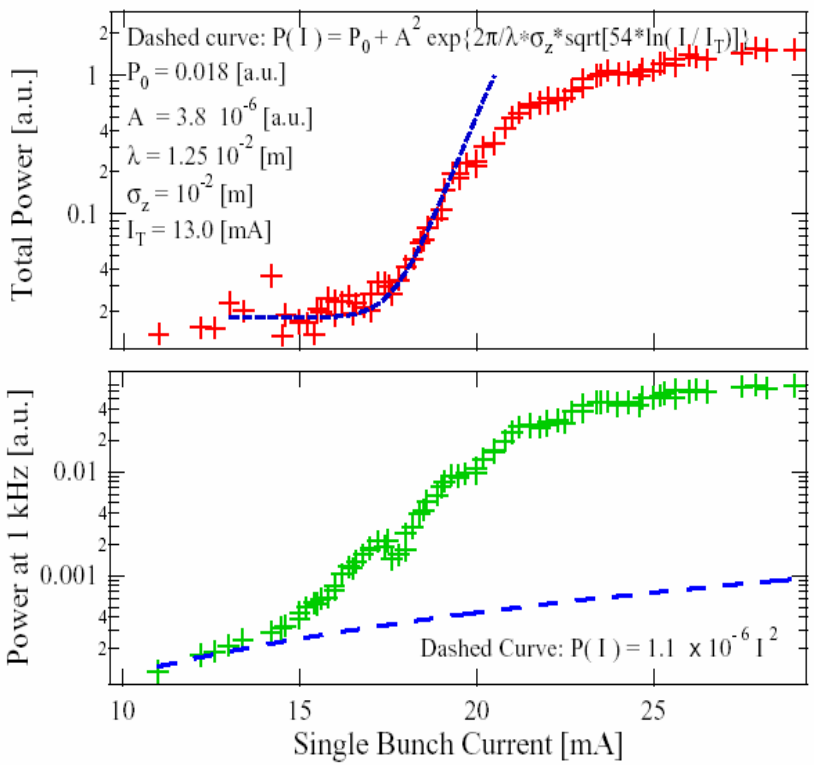
Figure 7: Scope tracks of the seeded burst signal at the fast detector. Scales: 10 μs/div and 1V/div

Heifets model





Laser Seeding of the MBI



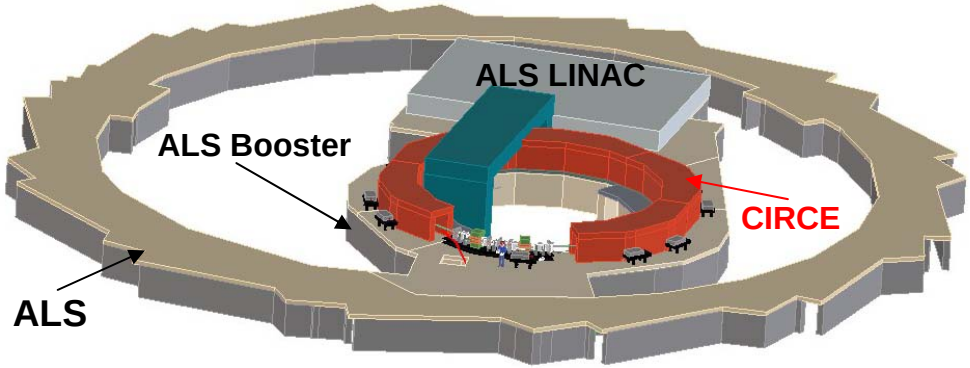
The observations can be explained in the framework of the MBI theory from Stupakov and Heifets.

Submitted for publication.

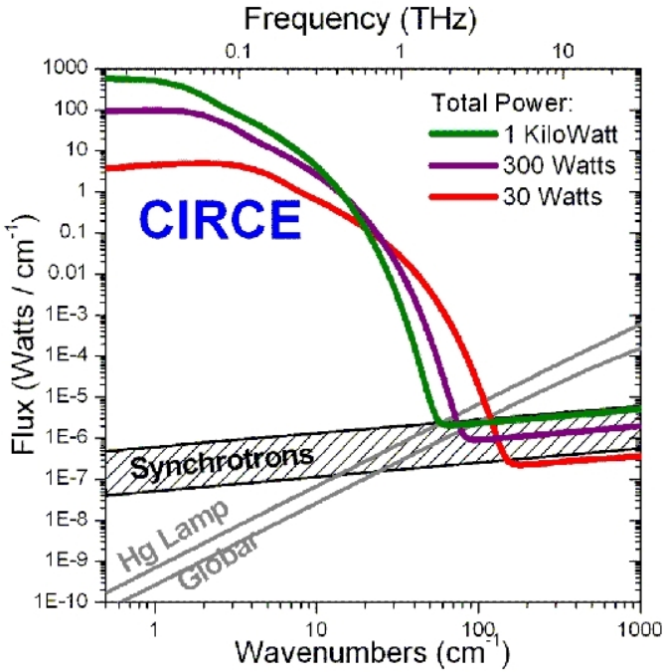
The average power of the seeded CSR burst is about two orders of magnitude larger than for the "conventional" slicing case, but shows very large power fluctuations.

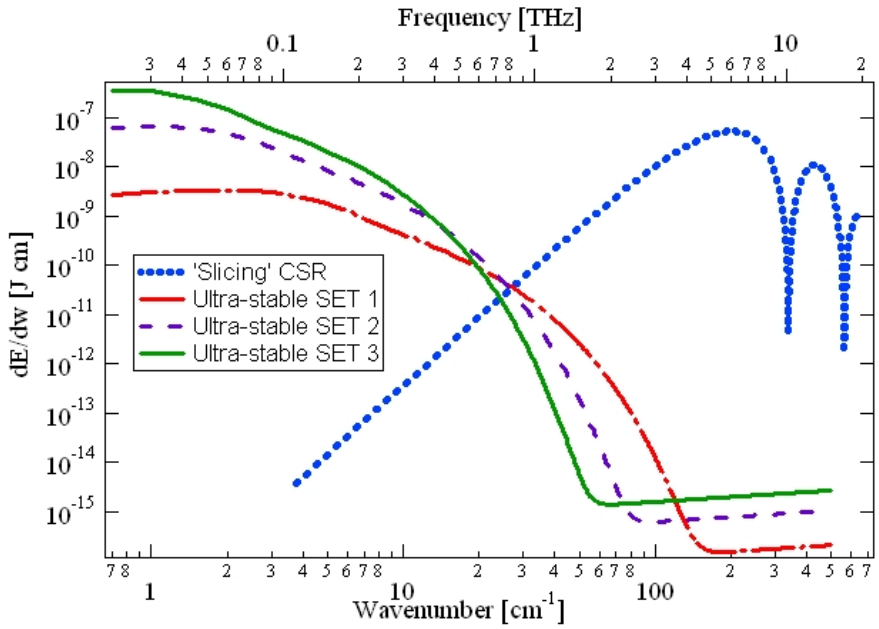
In a more speculative scenario the CSR from the seeded bursts, could be brought back inside the vacuum chamber for interacting again with the electron beam in a FEL oscillator scheme.

CIRCE: the Coherent InfraRed CEnter



CIRCE is completely optimized for the THz CSR production and exploits all the described techniques for generating extremely powerful radiation on a very broad spectrum.





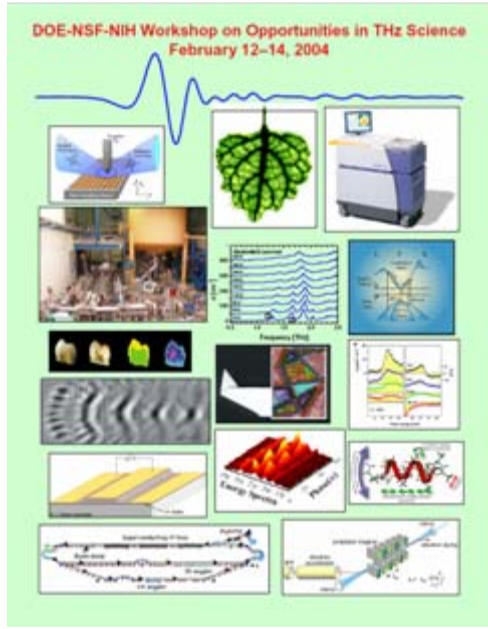
Status of CIRCE

CIRCE
Coherent InfraRed CEnter
Advanced Light Source

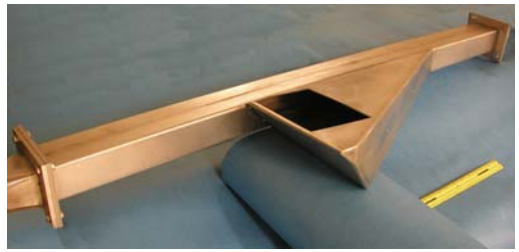
BERKELEY LAB

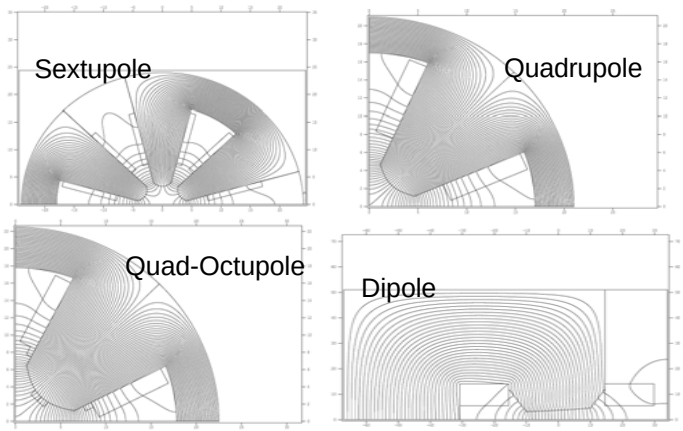
"DOE-NSF-NIH Workshop on Opportunities in THz Science", February 12-14, 2004:

http://www.science.doe.gov/bes/reports/abstracts.html#THz



Perfect Scientific Case (~ 120 pages of THz science) and a very good matching for CIRCE performances.





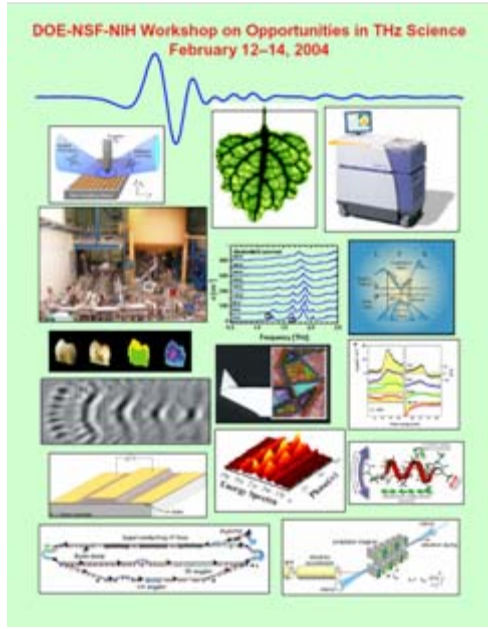
- **All accelerator physics issues addressed**
- **All magnets designed**
- **3D layout updated**
- **Evaluated compatibility & impact on the ALS**
- **Refined cost estimate**

Ready for the check!

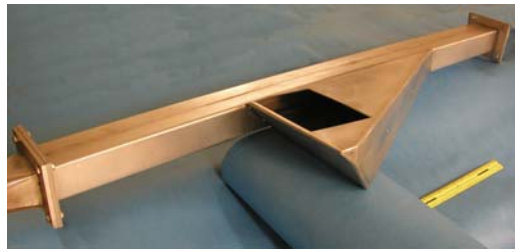
Status of CIRCE

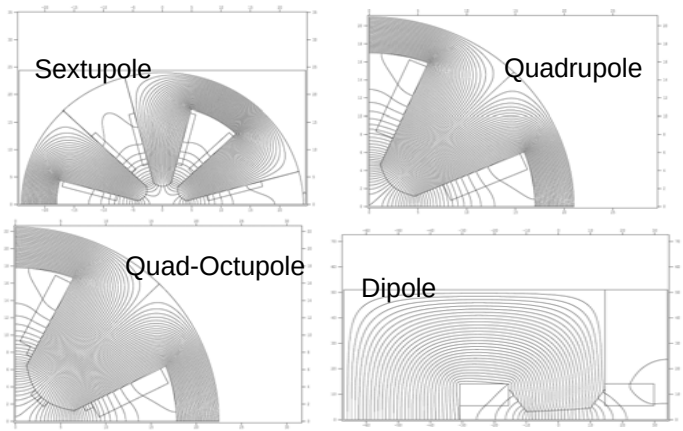
"DOE-NSF-NIH Workshop on Opportunities in THz Science", February 12-14, 2004:

http://www.science.doe.gov/bes/reports/abstracts.html#THz



Perfect Scientific Case (~ 120 pages of THz science) and a very good matching for CIRCE performances.





- **All accelerator physics issues addressed**
- **All magnets designed**
- **3D layout updated**
- **Evaluated compatibility & impact on the ALS**
- **Refined cost estimate**

Ready for CDR!