Massachusetts Institute of Technology
Bates Linear Accelerator Center

Storage ring-based Coherent THz Synchrotron Radiation Source Research at MIT-Bates

Fuhua Wang

MIT-Bates Linear Accelerator Center

Thanks

MIT-Bates: D. Cheever, W. Franklin, M. Farkhondeh , E. Ihloff, J. van der Laan, B. McAllister , R. Milner, C. Tschalaer, D. Wang, D.F. Wang, F. Wang, A. Zolfghari, T. Zwart

BNL/NSLS: L. Carr, B. Podobedov, J. Murphy

LBNL/ALS: F. Sannibale

JLab : G. Williams

BESSY : U. Schade, K. Holldack

Topics

1. Storage ring-based Coherent Terahertz Synchrotron Radiation Source: introduction, potential and source comparison.

2. Unique THz source research opportunities at MIT-Bates South Hall Ring
   Initial tests : results and analysis

3. Bates THz source R & D plan

Coherent Synchrotron Radiation (CSR)

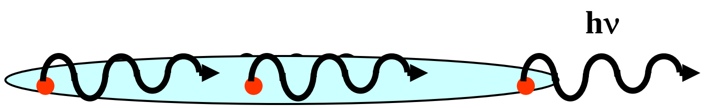
$$\frac{dP}{d\omega} = \frac{dp}{d\omega}\left[N + N(N-1)g\left(\sigma_l\right)\right]$$

Incoherent

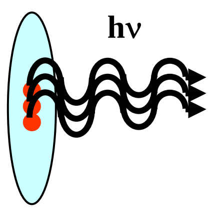
Coherent

Form factor: FT of bunch long. density

$\sigma_s > \lambda$ incoherent emission



$\sigma_s < \lambda$ coherent emission



Wave length limits:

- Bunch length and distribution--

  Short wave length cut off

- Vacuum Chamber shielding --
  Long wavelength cut off

For Gaussian bunches and parallel plates mode:

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

h: Vaccum Chamber total height,

ρ: bending radius

Accelerater Based Broadband THz CSR Sources: history

Accelerator CSR: E.M. McMillan (PR '1945), J. Schwinger (PR '1946), L.L. Schiff (RSI '1946)

……

Linac

1989 Observation

Nakazato et al. (PRL '89)

1994-97 **Sunshine Stanford ~100pC,σ~120fs, RF gun, 30 MeV. 1μs,10-30 Hz,TR, CDR**

H. Wiedemann J. Nucl. Mat. 1997

2004 BNL SDL

CSR 80 μJ/pulse

10 Hz

Suoerconducting Energy Recover Linac

2002 JLab, 20 W avr. Power. L. Carr et al., Nature 420, 153 2002.

2005 JLab, 800 W avr. Power.

Storage Ring

1981,89,94 **predications, proposal.** Curtis Michel, Williams, Murphy.

1997-2002 "bursting" observations (NIST, BNL,…)

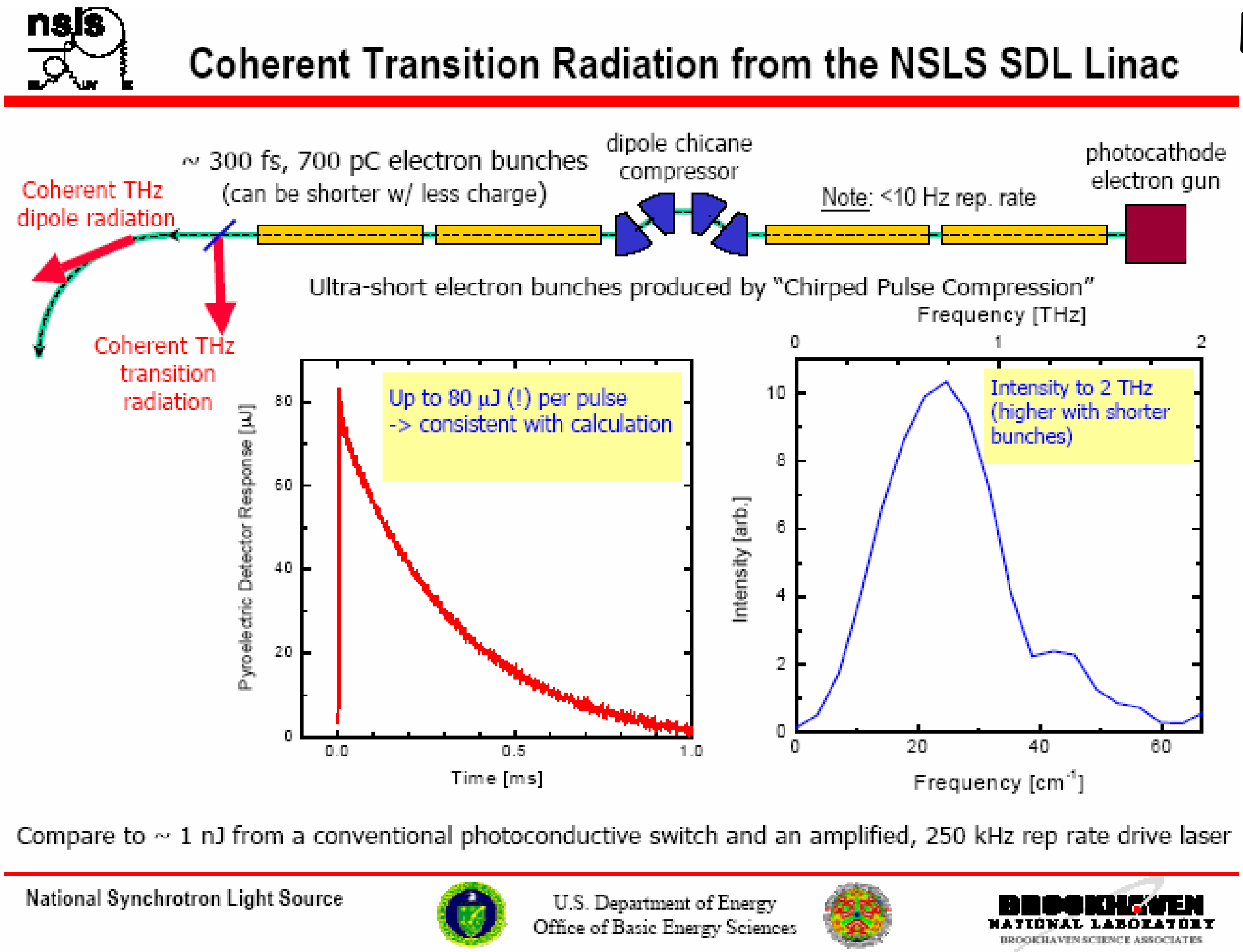
2002 BESSY II,Steady state CSR M.Abo-bakr et al. (PRL 2002)

2004 Application:

J. Singley et al. (Phys. Rev. B, 2004)

High Field normal linac based CSR source: Status

L. Carr



100 µJ/pulse June 2005.

Ring CSR (1): Spectrum - CSR wake distortion dependent

The equilibrium longitudinal current distribution with the free space synchrotron radiation wake.

K. Bane , S. Krinsky, and J.B. Murphy , AIP 367, p.191-198, 1996

$$y(x) = K\exp\left[-\frac{x^2}{2} \pm \int_0^\infty \frac{y(x-x')}{x'^{1/3}}dx'\right], \qquad F = \int_{-\infty}^{\infty} y(x)dx$$

$$where \qquad x \equiv \frac{s}{\sigma_0}, \qquad y(x) \equiv \frac{Z_0}{V_{RF}^{'}\sigma_0}\left(\frac{\rho}{3\sigma_0}\right)^{1/3}, \sigma_0 = \frac{\alpha c \sigma_e}{\Omega_s}$$

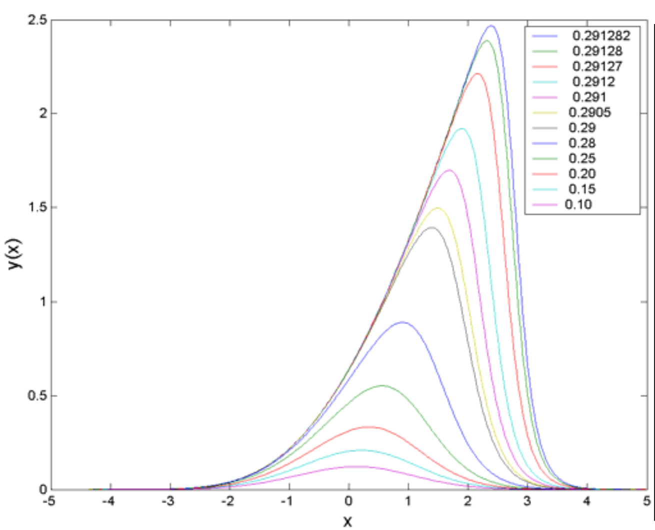
Haïssinski Equation J. Haïssinski, IL Nuovo Cimento 1973

CSR wake Distortion of bunch shape

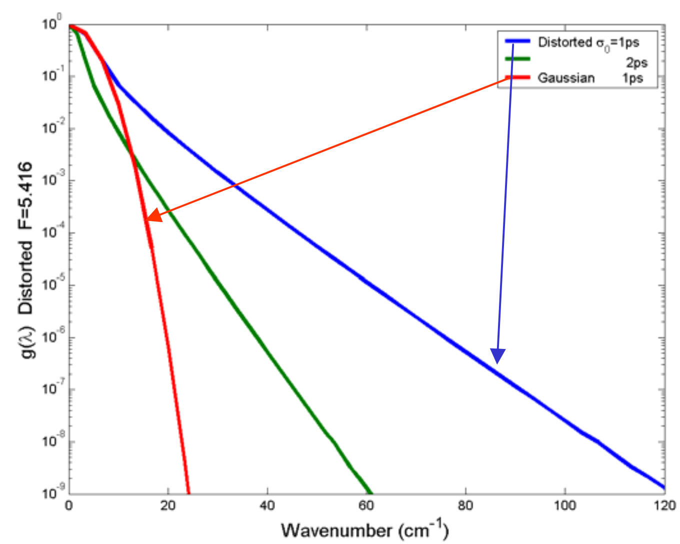
(Intensity dependent - F) => high frequency :

Gaussian: 0.6THz => 3 THz distorted

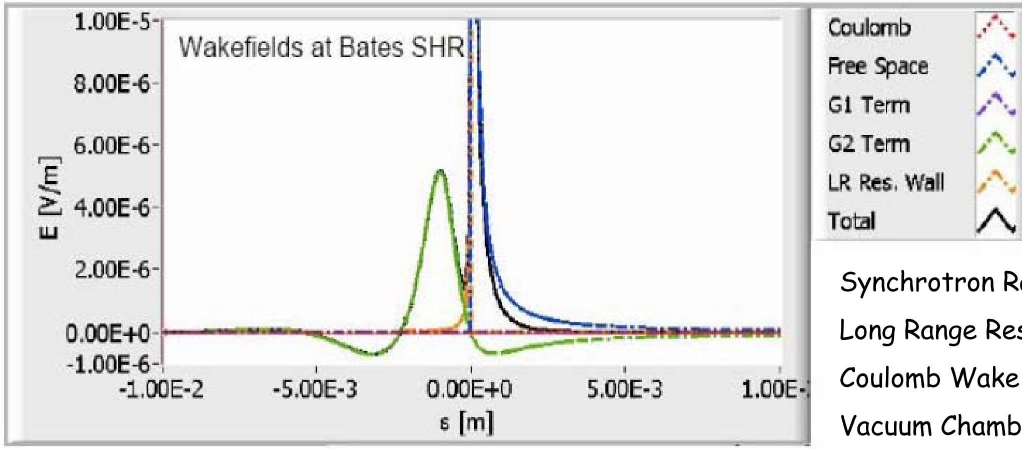
Show coherency for 1ps rms bunch.



K	F
0.1	0.2991
0.15	0.5051
0.2	0.7891
0.25	1.2692
0.28	1.8732
0.29	3.0004
0.2905	3.2156
0.291	3.6430
0.2912	4.1318
0.291282	5.4159



SHR CSR (present) : Simulations by F. Sannibale (all fields)



Synchrotron Radiation Wakes Included (Free space and Shield G1 and G2)

Long Range Resistive Wall Included

Coulomb Wake not included (negligible)

Vacuum Chamber Geometric Wakes not included (usually negligible)

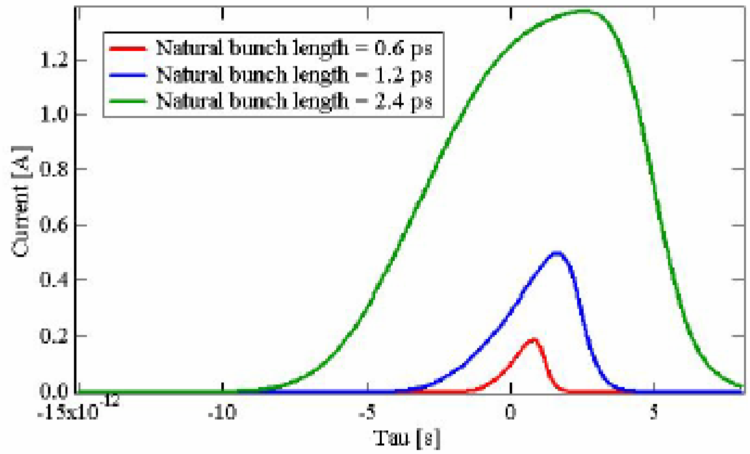
Energy	0.6 GeV
RF frequency	2856 MHz
Harmonic Number	1812
RF Voltage	140 kV
Ring Circumference	190m
Bending Radius	9.144m (9.44m in simulation)
Vacuum Chamber material	Stainless steel
Dipole total gap	4 cm
Horizontal acceptance	50 mrad

Simulation parameters

All modes are stable, no CSR bursts

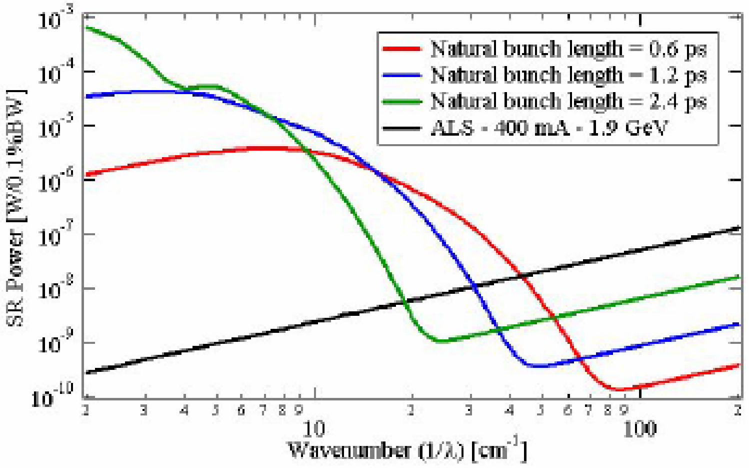
Natural bunch length (ps)	Momentum compaction	Electrons per bunch	Current per bunch (mA)	Total current (mA)	CSR power (W) Integrated from $2 cm^{-1}$ to $60 cm^{-1}$
0.6	8.0e-5	1.64e+6	4.16 e-4	0.753	0.00596
1.2	3.2e-4	9.56e+6	2.41e-3	4.374	0.0510
2.4	1.35e-3	7.13e+7	1.60e-2	32.64	0.227

Simulations Results



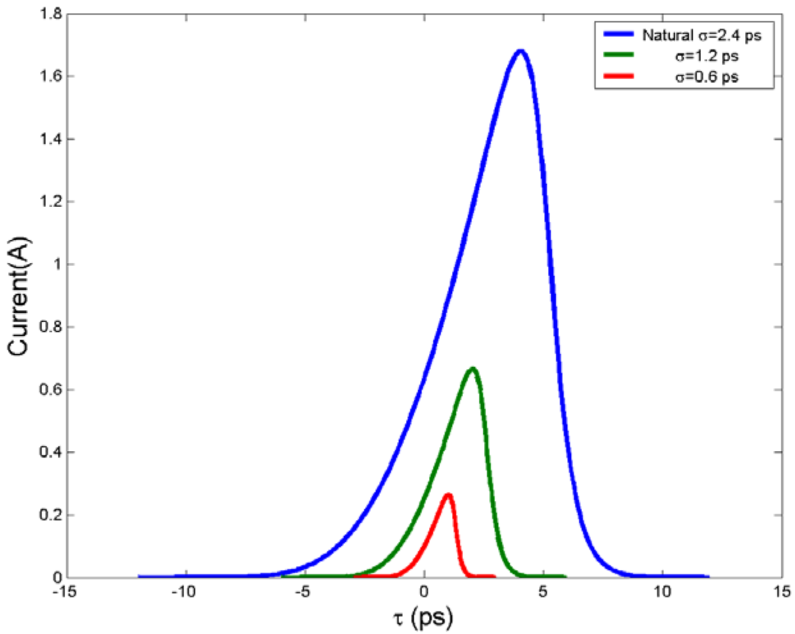
Longitudinal equilibrium distributions (Haissinski equation solutions) and relative spectra for three different modes. Stable solutions, no IR bursts present (SR driven instability).

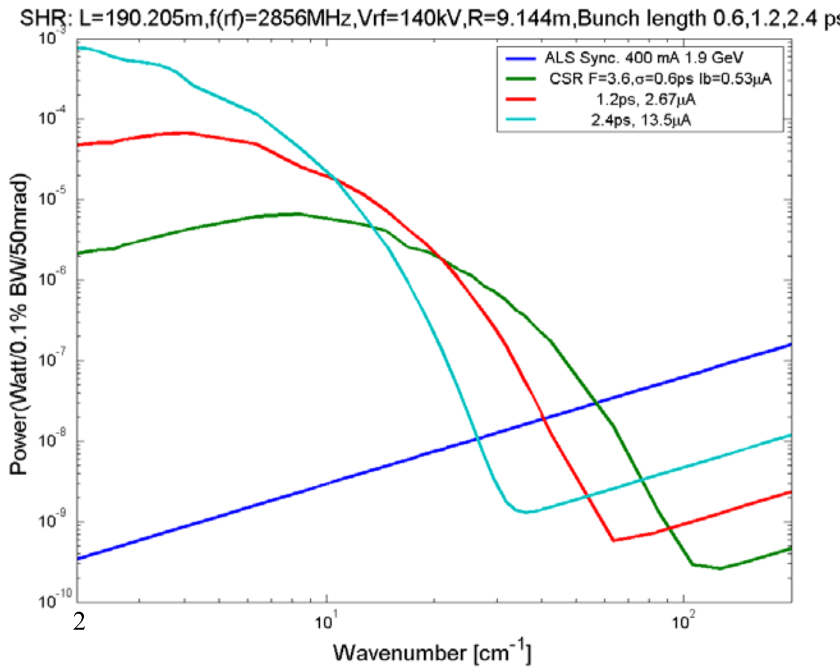
The different modes trade between bandwidth and power. The hump-like shape on the 2.4 ps distribution indicates significant shielding from the vacuum chamber. There is no convenience in going towards larger natural bunch lengths.



F. Sannibale - September 2004

SHR CSR : Simplified simulations





Universal equilibrium long. distribution for different bunch length with F=3.64.

Free Space wake

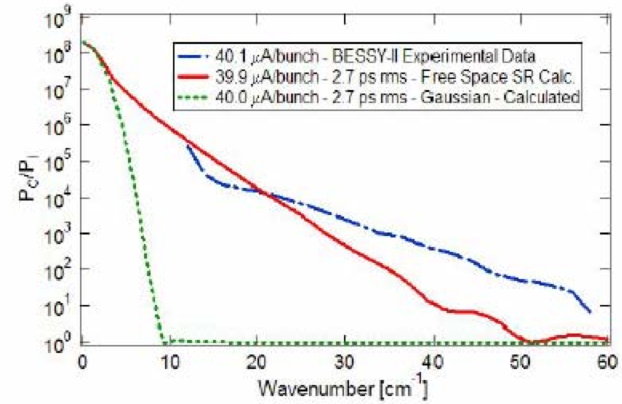
(Numerical solution of Haïssinski equation).

Bates SHR CSR power spectrum. Two plates shielding cutoff.

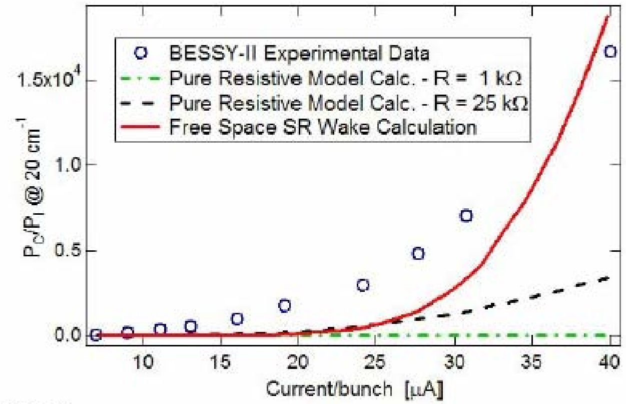
Kheifets and Zotter CERN SL-95-92(AP)

Simulation of the BESSY-II Results

Calculations using the model are in good agreement with the published BESSY-II experimental results.



Collaboration with BESSY Group for refining the model (including vacuum chamber shielding, minimize the experimental error, ...)



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

Ring CSR(2): Stability

- Bunch intensity threshold, Steady-state CSR Power limit.

CSR driven microbunching instability can generate chaotic IR bursts resulting in a noisy source :

S. Heifets and G. Stupakov, Phys. Rev. Lett. 89, 224802 (2002)

F. sannibale, Phys. Rev. lett. 93, 0948012 (2004)

Exp. : J. M. Byrd et al., Phys. Rev. lett. 89 224801(2002), …

$$N < 8.34 \left(\frac{B}{E} \right)^{1/3} \frac{V_{rf} f_{rf} \sigma^3}{\lambda^{2/3}}$$ λ: wave length of perturbation , $\lambda \sim 2\sigma$

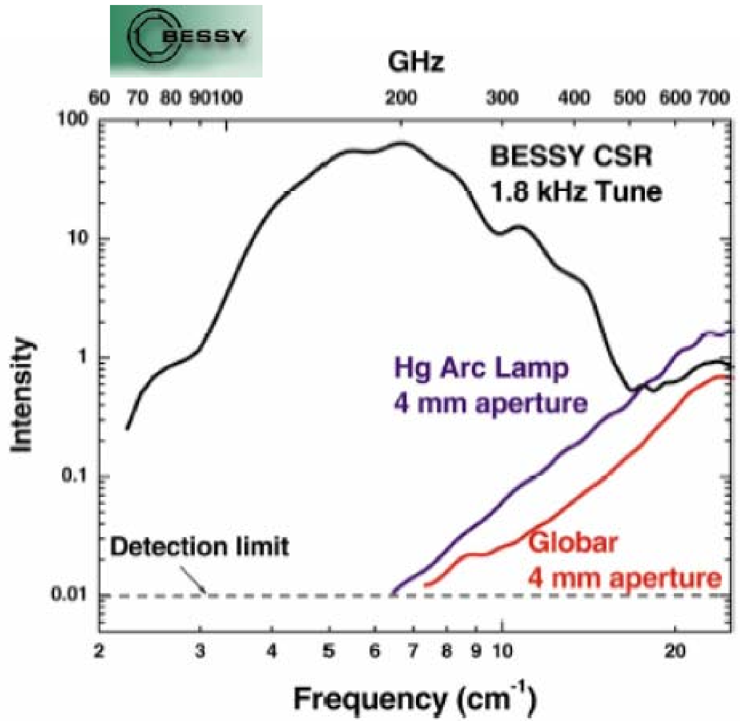
$$N \le 1.669 \frac{f_{rf} V_{rf} \sigma_{z0}^{7/3}}{\rho^{1/3}} F_{max} \quad \text{(MKS units)} \qquad F_{max} \sim 5.$$

Higher RF frequency & RF Voltage are advantageous to attain high power stable CSR from storage ring source.

Any technical challenges for using higher RF frequency System ?

Status of Ring & ERL Based CSR sources

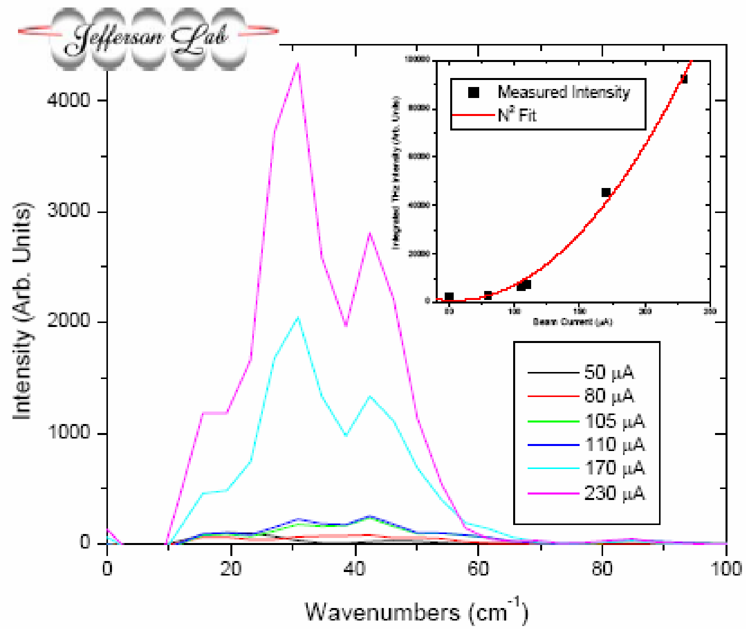
Storage Ring



M. Abo-Bakr et al., Phys. Rev. Lett. 88,254801(2002)

E.J. Singley et al., Physics Review B 69, 092512 (2004)

Energy Recovery Linac



L. Carr et. al., Nature 420, 153(2002)

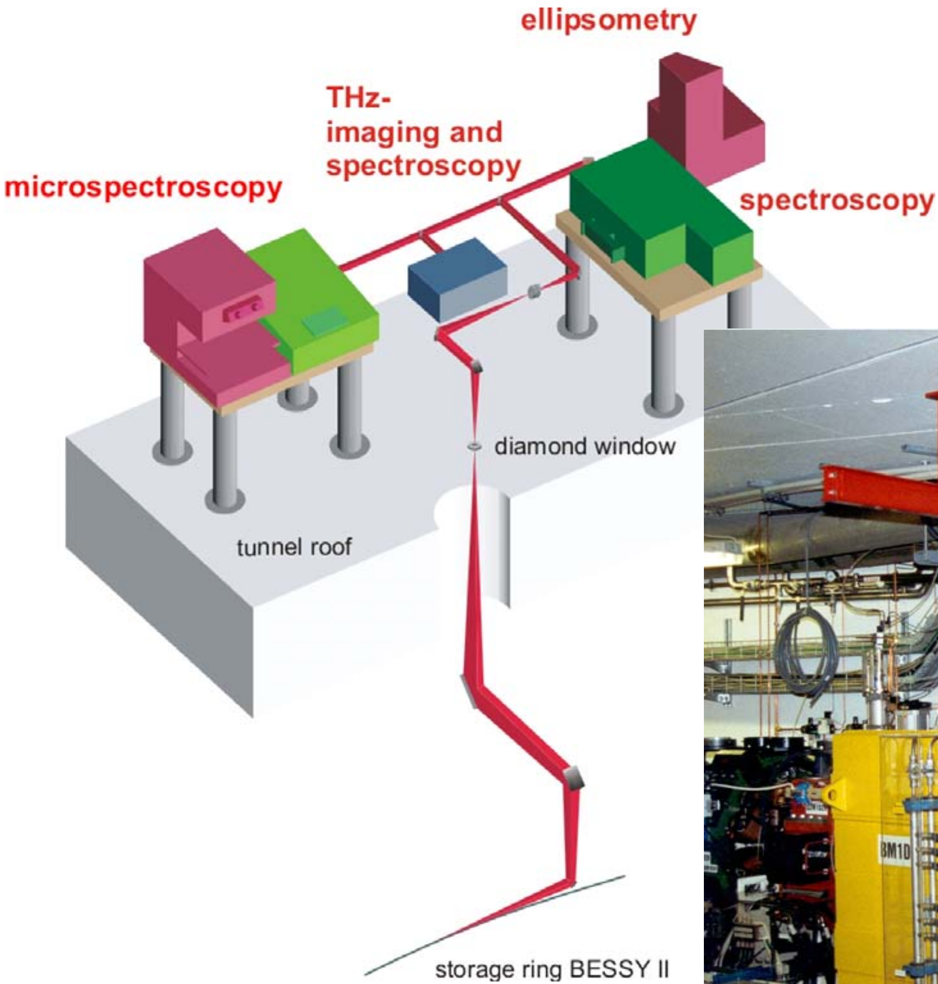
G. R. Neil, G.P. williams, Infrared Physics& Technology 45(2004) 389

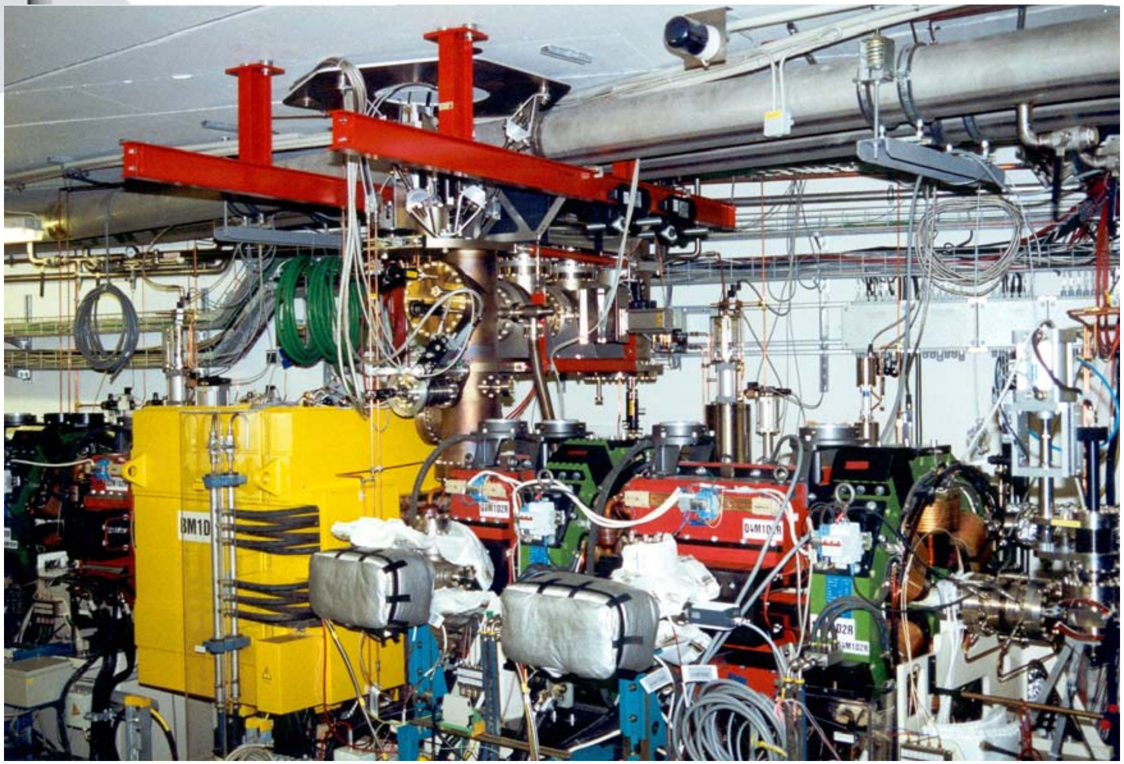
800 W average ! 2005 IRMMW-THz 2005.

More ring THz CSR run: ANKA Germany, NewSUBARU Japan, …

& ***Planning***: CIRCE/LBNL, Metrology Light Source(MLS) Germany, SOLEIL France, DAΦNE Italy,…

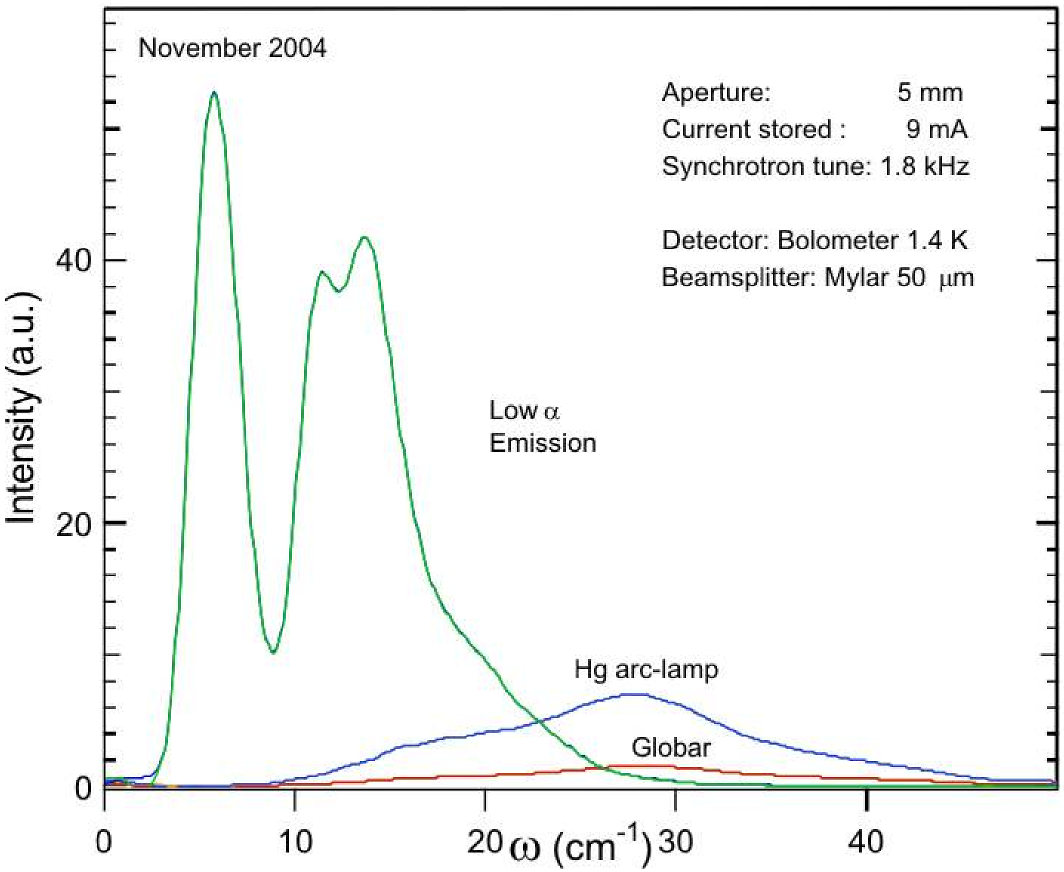
IRIS - Infrared Beamline at BESSY

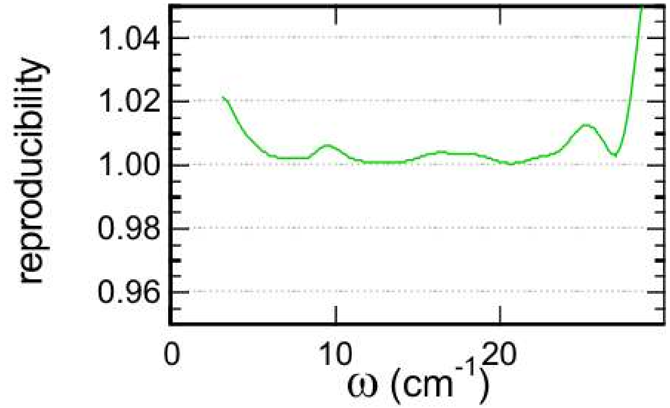




Workshop to explore Terahertz opportunities at MIT-Bates, October 11-12, 2005 **Ulrich Schade**

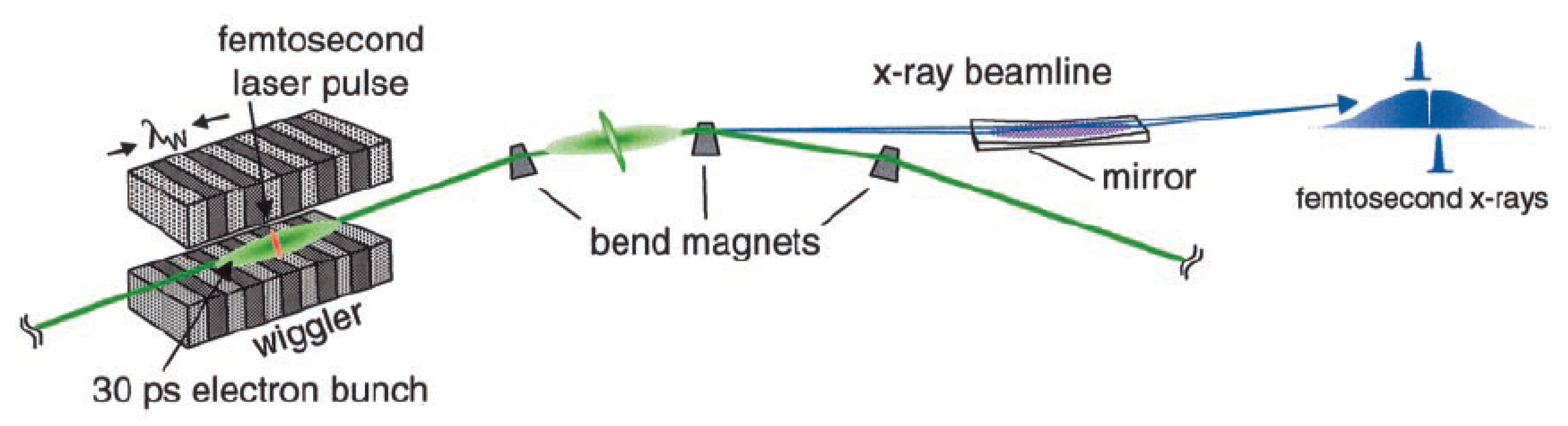
Coherent Synchrotron Radiation in the low-a mode





- long life time of the beam (>20 h)
- gain of 10^3 below 10 cm^{-1} (0.3 THz)
- highly reproducible

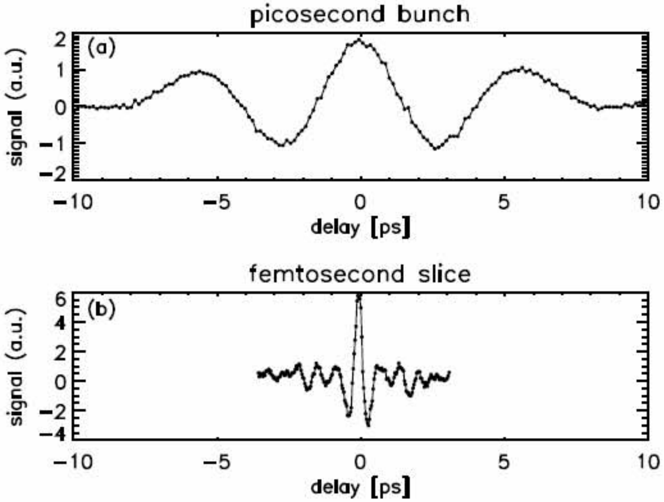
Ring CSR (3): Femotosecond laser slicing (LBNL 2000)



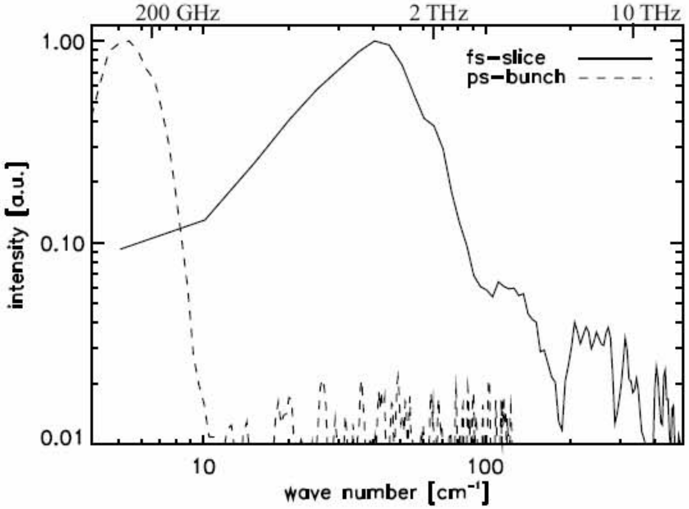
R. W. Schoenlein et. al, Science 287, 2237(2000)

Femotosecond laser slicing results at BESSY II

FIR-Interferograms of a 1.2 ps rms bunch
in low alpha vs. femtoslice



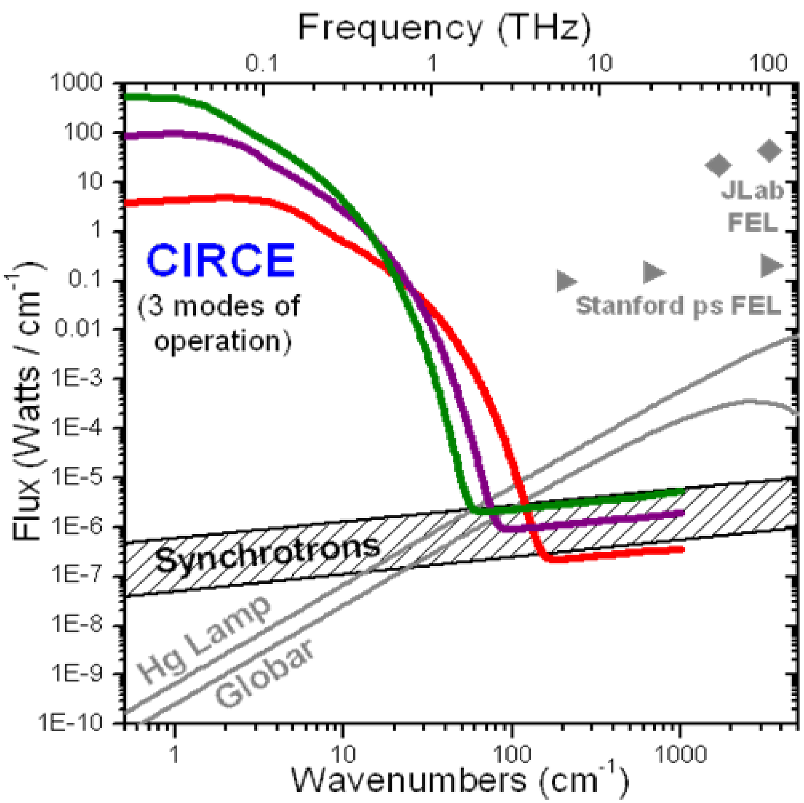
FIR spectra picosecond bunch vs. femtoslice



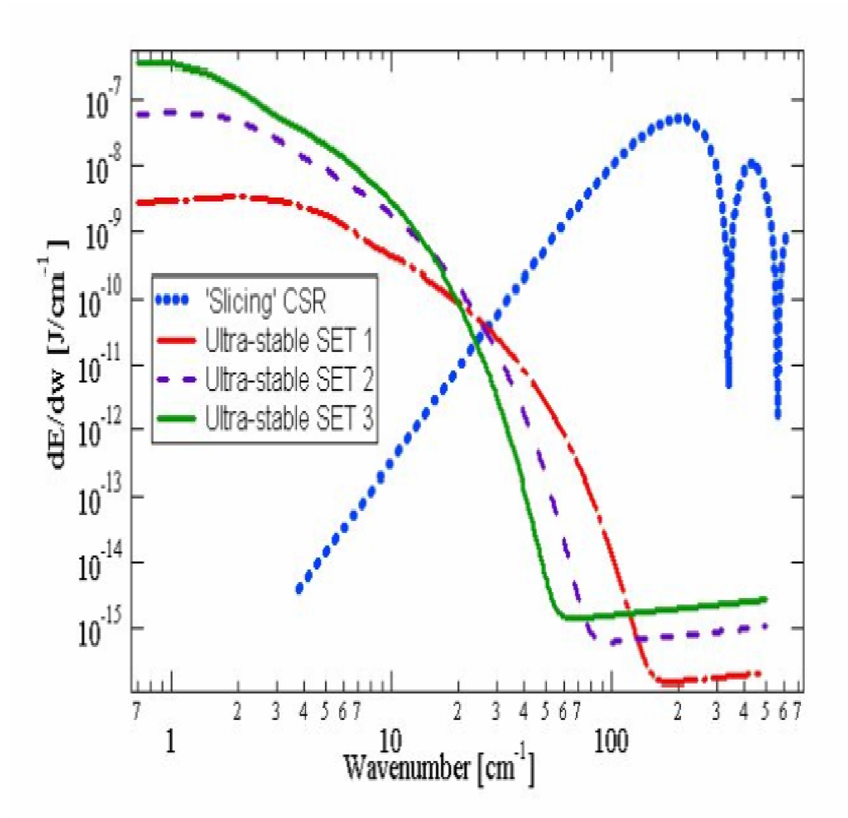
we really see a fs-modulation:
max. pulse energy seen: 0.7 nJ
peak power estimate: > 2 kW
conversion efficiency at 1mJ laser power: ~10^{-6}

Compares to fs-laser based sources (optical rectification)
Is there any advantage of an accelerator source ?

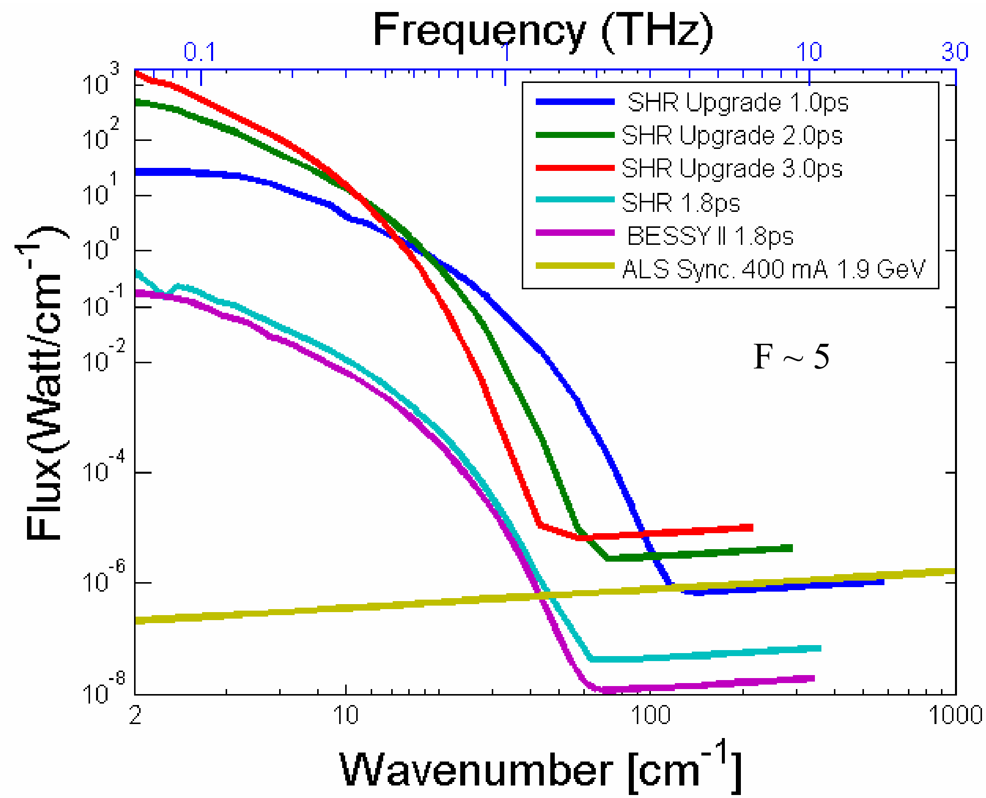
Future Ring THz Source : CIRCE, SHR upgrade



Stable CSR



Femotosecond slicing



SHR

Stable CSR

Upgrades:

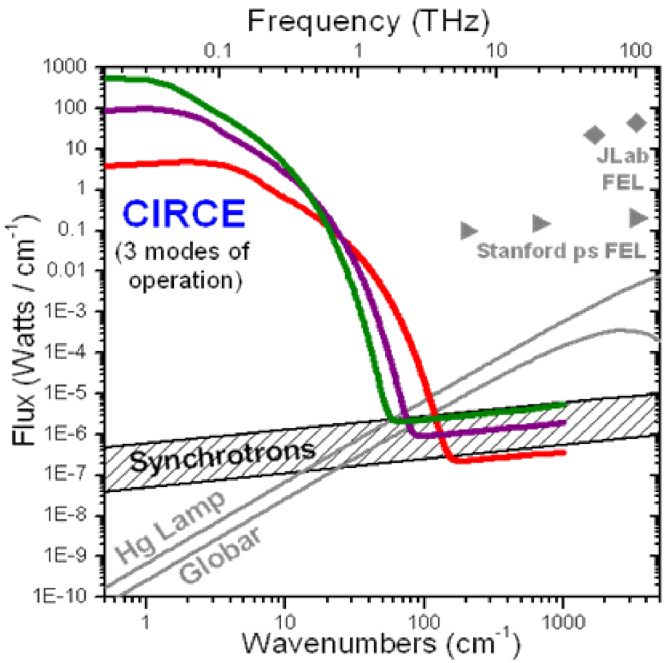
- RF: high gap voltage.
- source dipole, small ρ.
- Larger radiation extraction port.

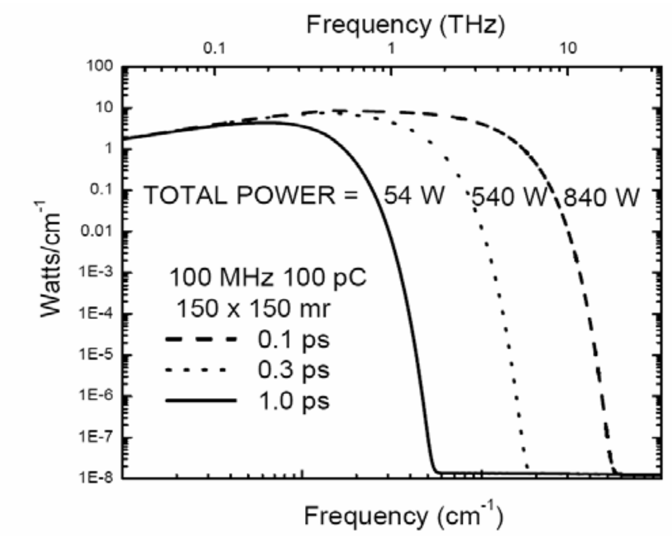
Ring	E (GeV)	R (m)	F_{rf} (MHz)	V_{rf} (kV)	L(m)	Hor. Accept. (mrad/port)	Bunch length σ(ps)
SHR	0.6	9.144	2856	140	190.205	60	1.8
SHR-upgrade	0.6	1.335	**2856**	**1500**	190.205	300	1,2
CIRCE	0.6	1.335	**1500**	**1300**	66	300	1,2,3
BESSY II	1.19	4.361	500	1300	240	60	1.8
ALS	1.9	4.957	476	400	196.8	60	

High average power, Broad band sources

Ring based source

ERL based source *G. Williams*





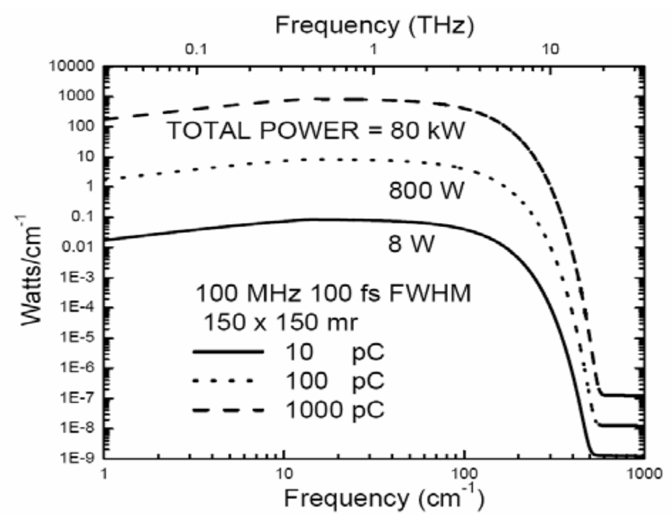
1.5 GHz 140×300 mr

20 pC (30mA), 1ps, 30 W

100 pC (150 mA), 2ps, 277 W

253 pC (380mA), 3ps, 973W

Charge/bunch of stable operation limited by microbunching instability.



Possible ring and ERL based Broadband, THz source features

Source features	**Storage Ring**	**ERL linac**
High average power, Band width Time structure	~kWatts, 1.4 THz *0.03-1 THz very high power density, ~ps.*	~1-10 kWatts, *10 THz* *~100 fs.*
High field, Bandwidth	~1MV/cm , ~1THz (stacking) 20THz(Low rep. rate)	~1-10 MV/cm, 10 THz
Reproducibility	*~10^{-3}* *Required for some applications.*	~ 10^{-2}
Serve users with different special needs simultaneously	*Multi-ports. Using different methods for different applications at same time*	possible
Source development	New , *Exist ring upgrade, SR Light source co-use*	SC linac, FEL co-use

Unique THz source research opportunities at MIT-Bates South Hall Ring

Nuclear physics operation end 2005, 2006 (MIT owned facility)
=> open to researches in all scientific fields

- Energy: 0.3-1.0 GeV with injection at beam energy.
- Circumference 190.2m, long straights, flexible lattice structure,
  16 Bends, ρ=9.144m, gap: 7.62 cm .
- Ample floor space available for IR beam lines.
- A Unique 2856 MHz RF system, single cavity, 50 kW, CW klystron.
  Routine operation: 200-300 mA (long bunch).

The advantages of using higher rf frequency:

$$\sigma_L \propto \left(\frac{\alpha}{f_{rf} V_{rf}}\right)^{1/2} \gamma^{3/2}$$

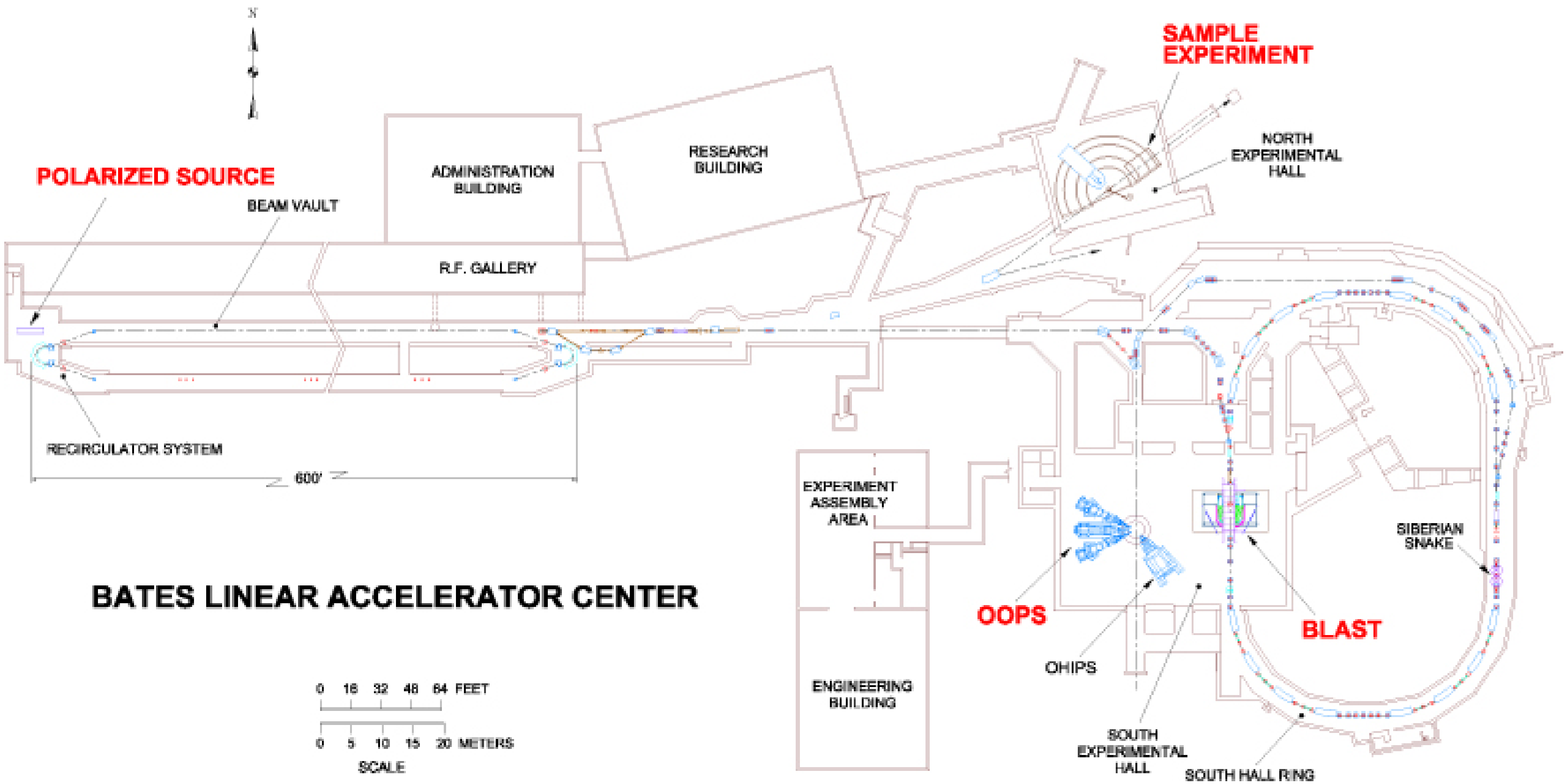
With Higher f_{rf} and $V_{rf,}$ short σ can be attained with moderate α. Larger α is favorable for stable operation.

$$N_{b,\max} \propto f_{rf} V_{rf} \sigma_0^{7/2} / \rho^{1/3}$$

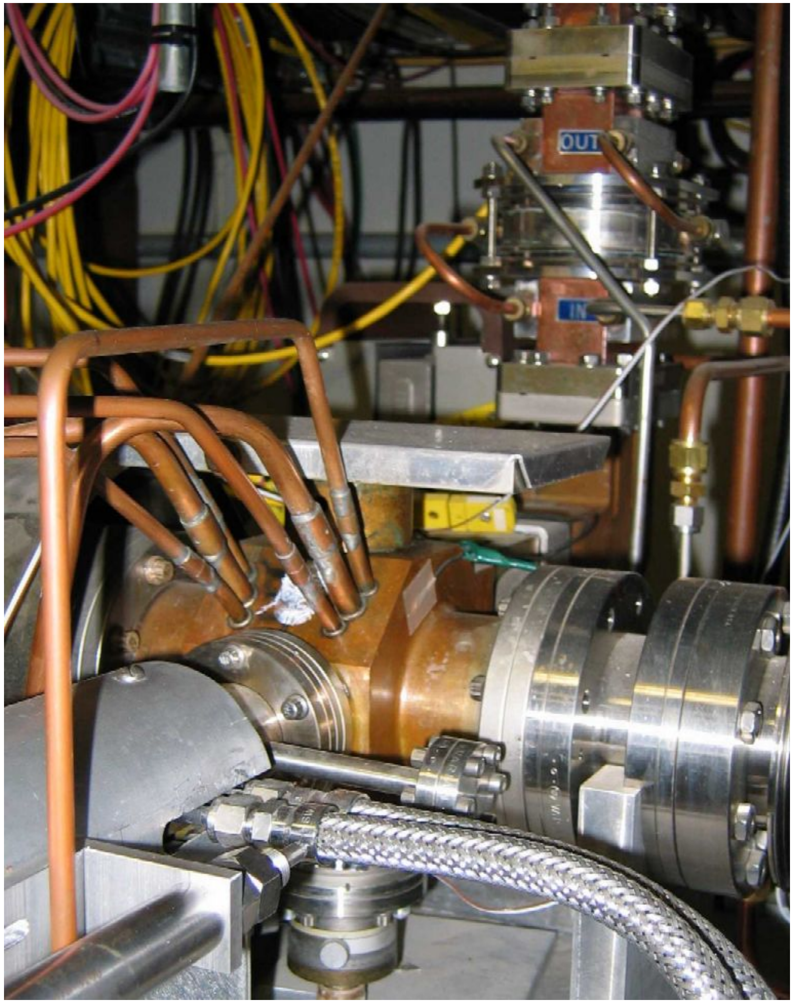
Higher bunch intensity threshold for stable CSR:

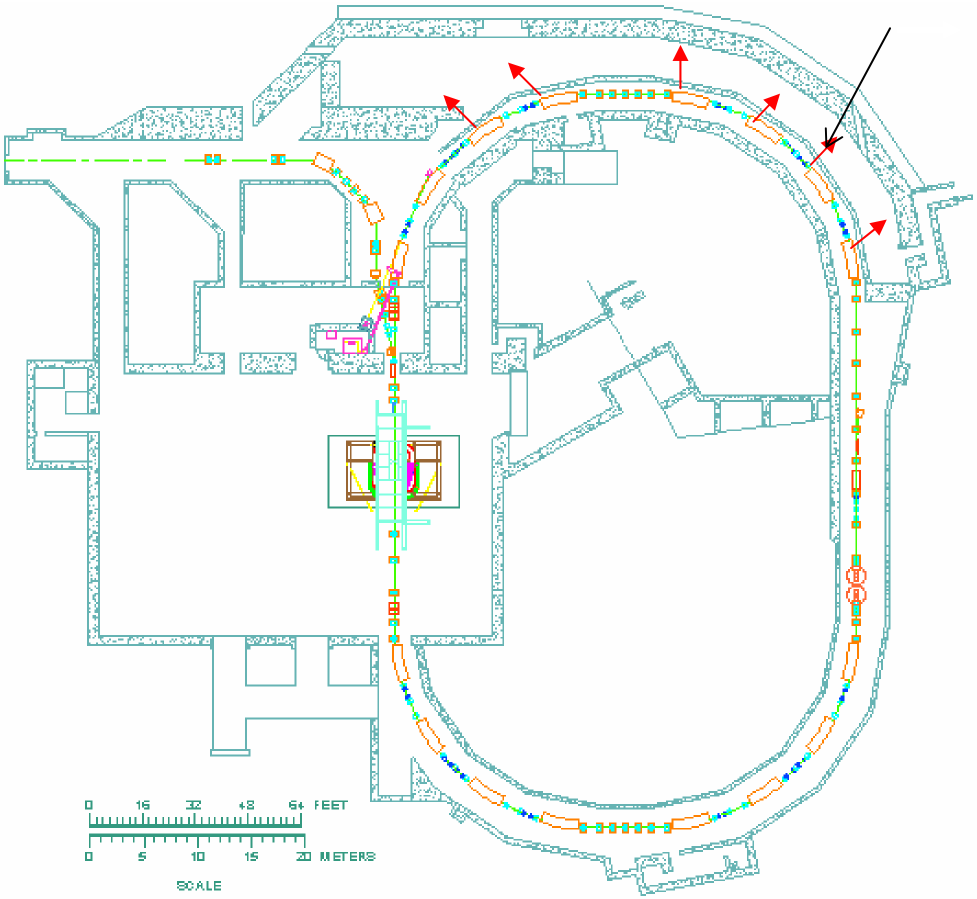
- Larger distortion -> higher freq.
- Higher CSR Power

The MIT-Bates Accelerator Complex



The 2.856 GHz RF Cavity & SHR Floor Space for IR Beam lines

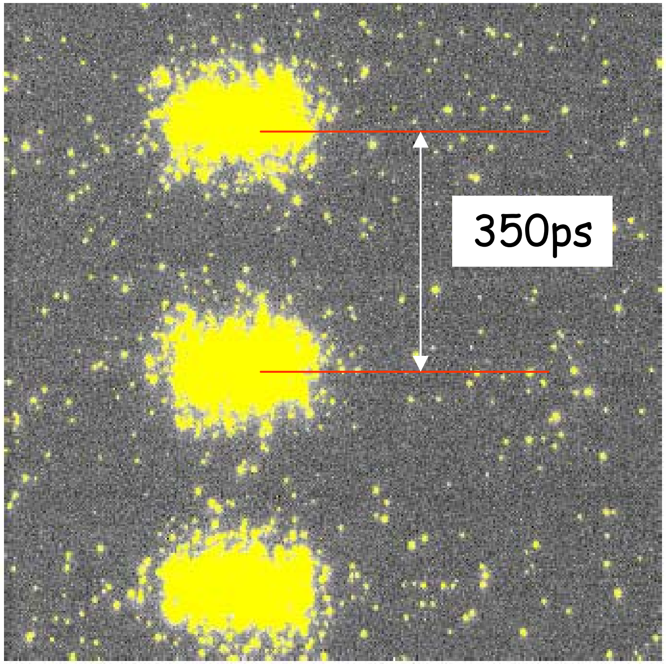




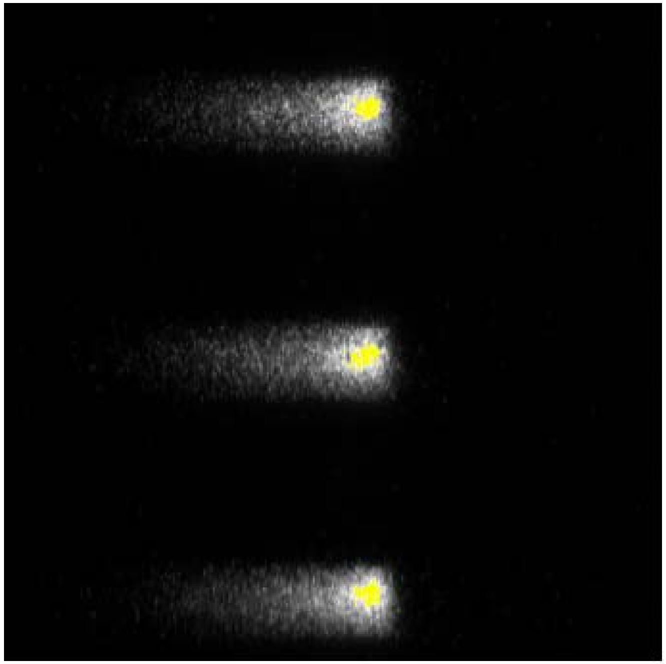
Initial tests: First-Short Electron bunch

SHR Low momentum compaction Lattice operation (Dec. 2004)

Bunch Longitudinal profile from Streak Camera (C6860) B. Podobedov



"BLAST" (original)



"LMC-4"

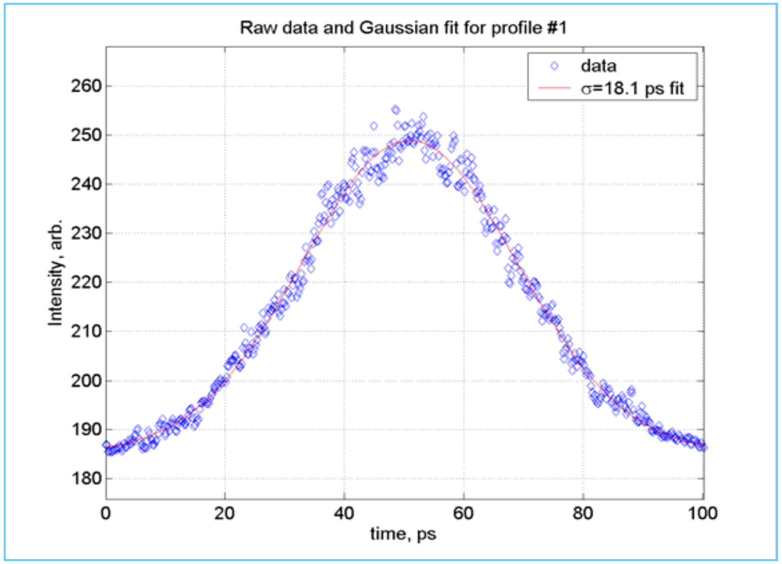
Synchroscan f: 81.6 MHz (2856/35), integration time ~ 100ms

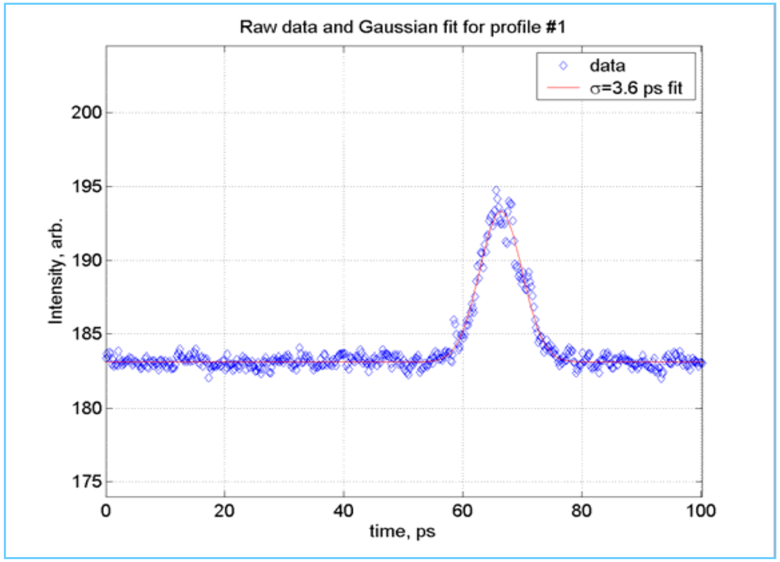
Bunch length (V_{rf}=134kV)

B. Podobedov

"BLAST", rms 18 ps

"LMC-4", rms 3.6 ps





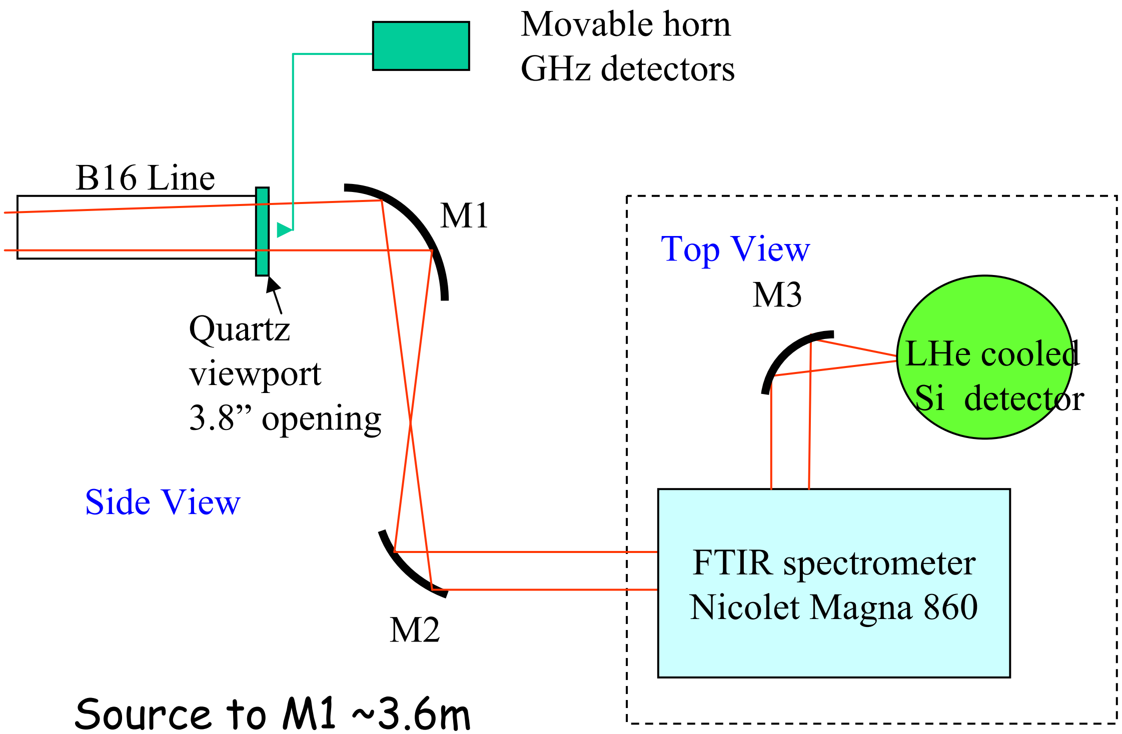
Preparations for the first test:

Low α Lattice : Quadrupole regroup and polarity switches.
LB9 SR Visible light transport (to Steak camera).

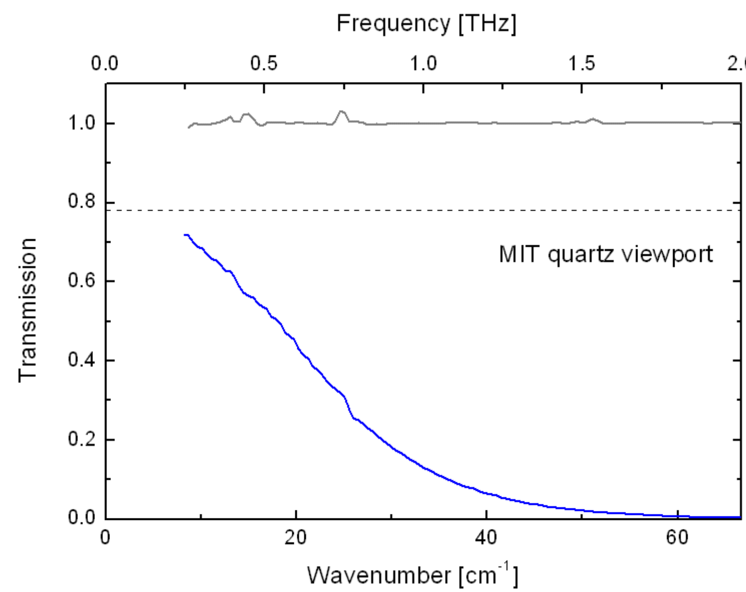
Second test: CSR Power, spectrum measurement & lattice study
June 5-7, 2005

CSR detector system

L. Carr

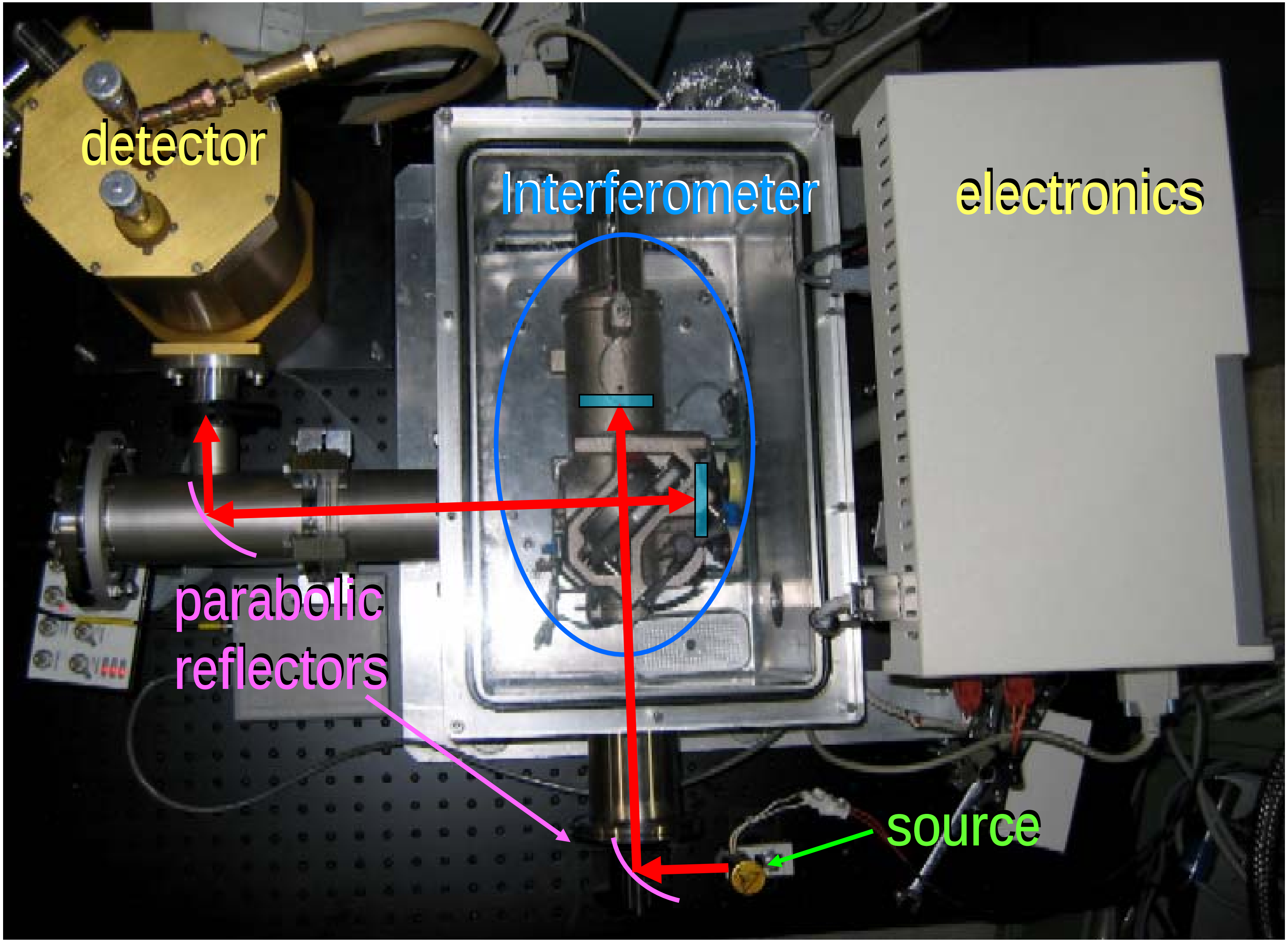


Quartz view port (6 mm) transmission



Source to M1 ~3.6m

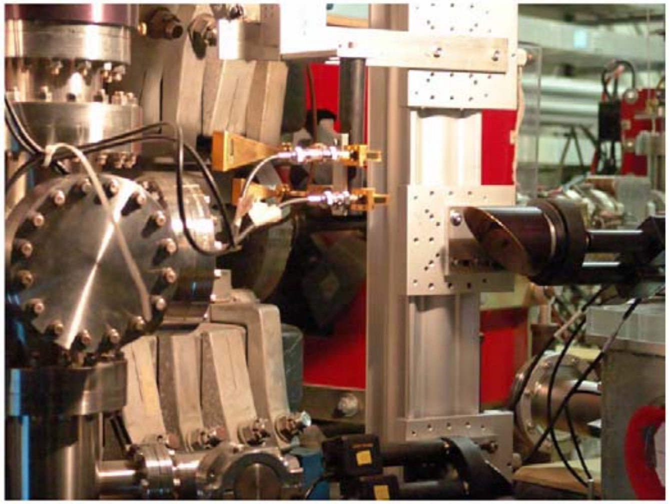
M1,2: parabolic mirrors


detector
Interferometer
electronics
parabolic
reflectors
source

Setup for THz run: second test

- Remote RF frequency control: Electron path length adjustment for thermal closed orbit changes.
- B16 line & instrumentation for CSR measurement.

Final interferometer and bolometer assembly



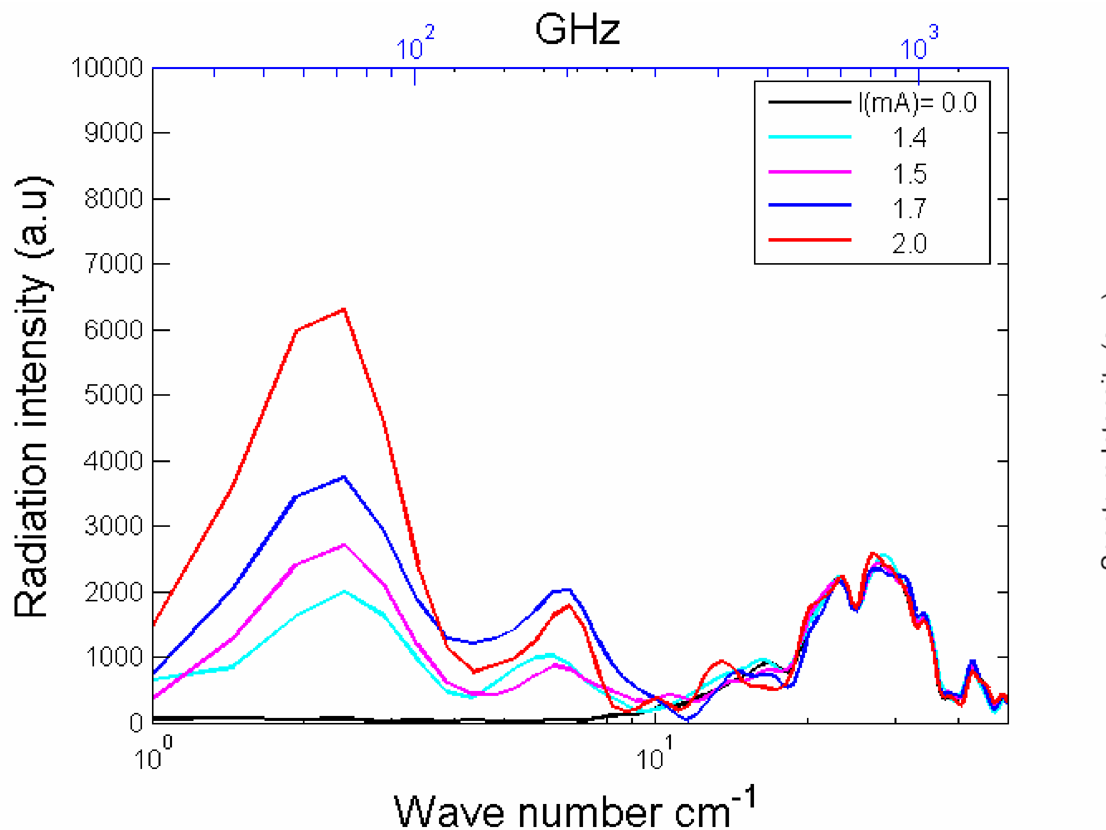
Microwave detector

for CSR in time domain

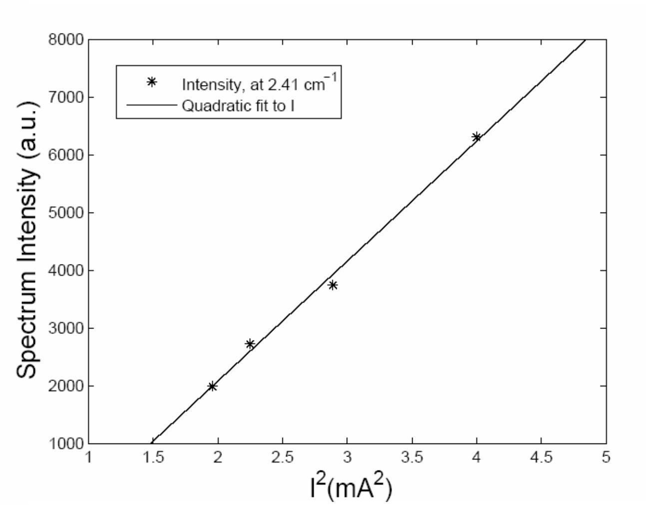
B. Podobedov

Coherent Synchrotron Radiation from SHR June 5, 2005

Poor alignment , Filter gain 1000, 10.

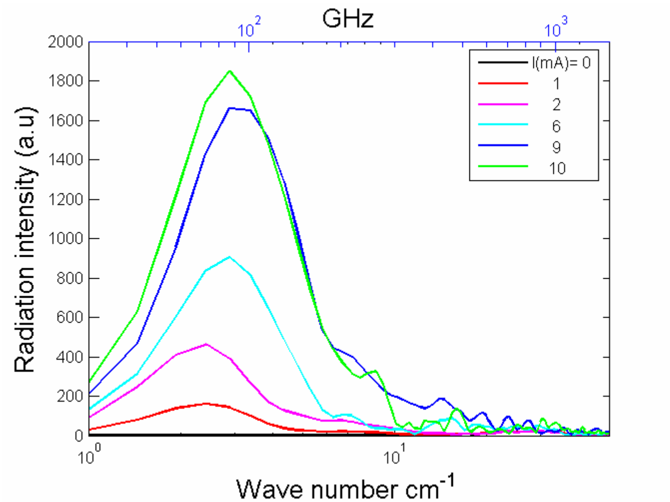


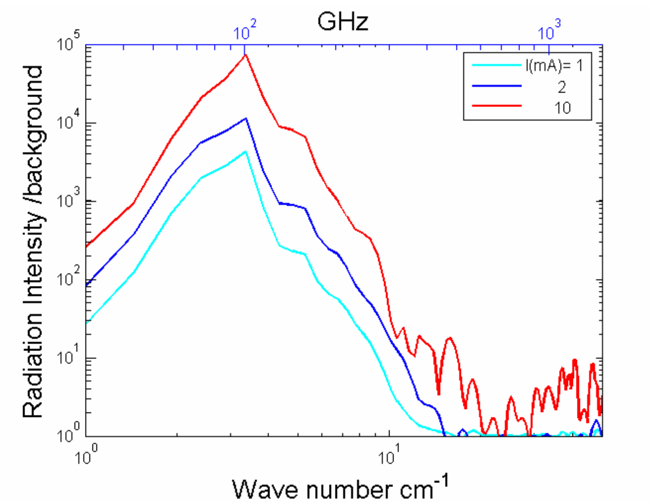
The radiation intensity is proportional to I^2 :
Coherency test



Coherent Synchrotron Radiation from SHR June 6th, 2005

Good alignment , Filter gain 316.2, 1, : High Gain





< 2mA, Intensity$\propto I^2$

At 2 mA (sig./bg.)max~ 10000.
At 10 mA, 50-110 GHz
Signal/background ~ 2000-80000.

Observations: beam instability.

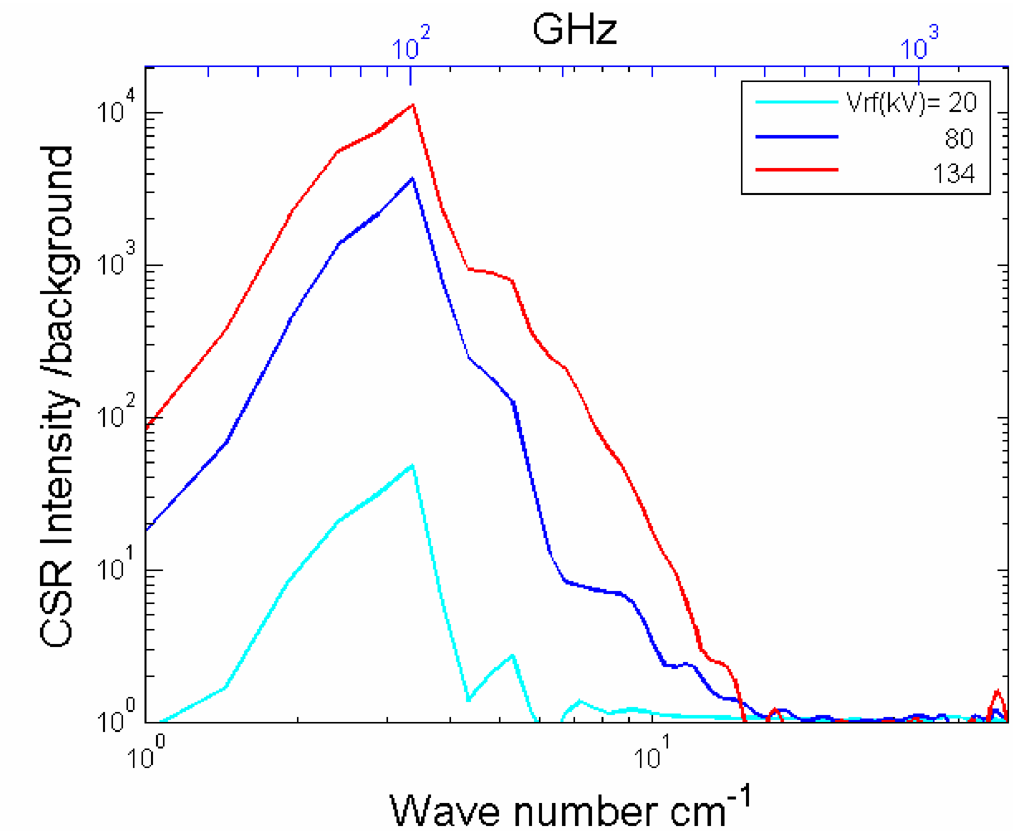
Questions: a. Frequency low.

b. Not total coherent at higher bunch intensity.

CSR from SHR June 6th, 2005

CSR Intensity/background vs. bunch length (Vrf) : **Coherency test**

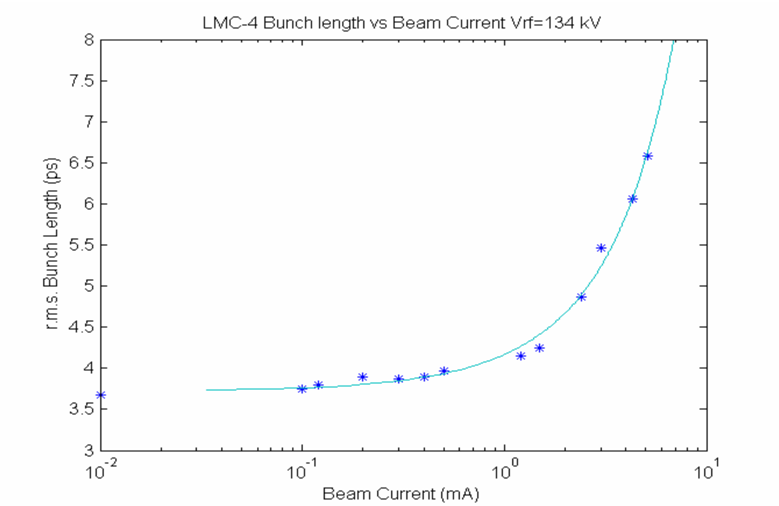
I=2mA

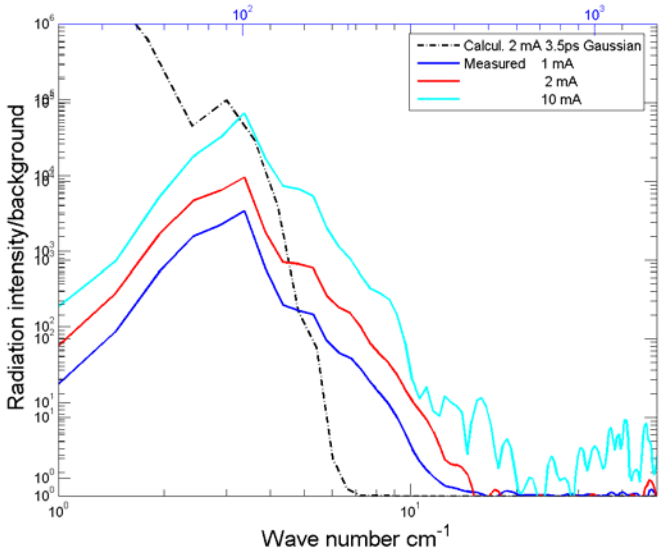


V_{rf} (kV)	σ_s (ps)
20	~ 7.6
80	~ 4.4
134	~ 4.0

Bunch length (Streak Camera) vs. bunch current & Spectrum comparison to Gaussian beam (3.5ps rms)

Significant lengthening when $I_b > 1.1\mu A$ (I=2 mA)





Notice:

The bunch length is measured over 100 ms integration time. (over ~1.57×10^5 turns and 2.85×10^8 bunches)

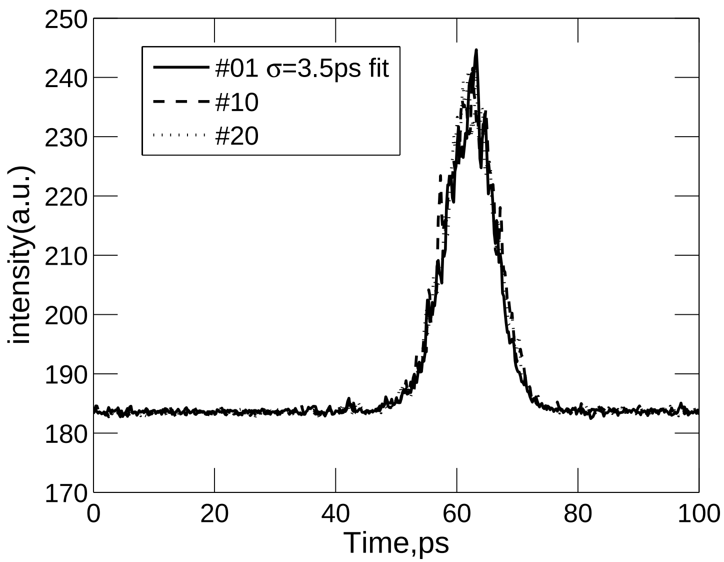
Distinguish of bunch "lengthening" caused by instabilities and other mechanisms is not possible.

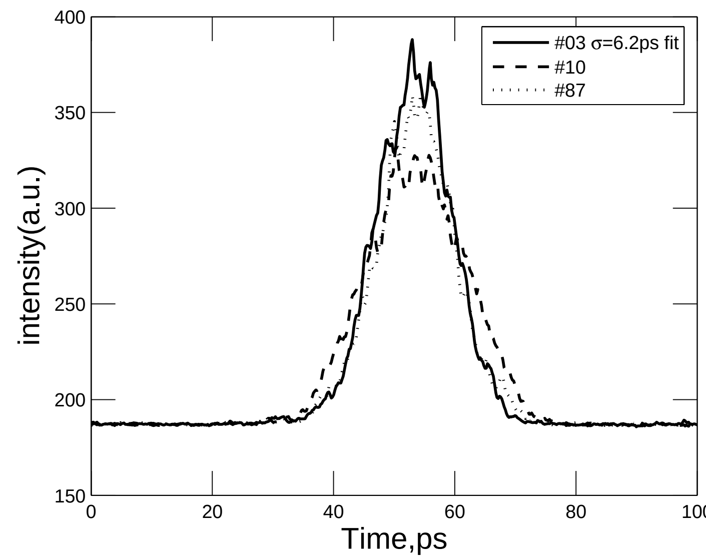
Low spectrum frequency, similar to Gaussian beam.

Low bunch intensity & insignificant bunch distortion

Bunch profile / beam current

Three bunch profiles from streak camera.
Each profile was average of many bunches over ~105 turns.



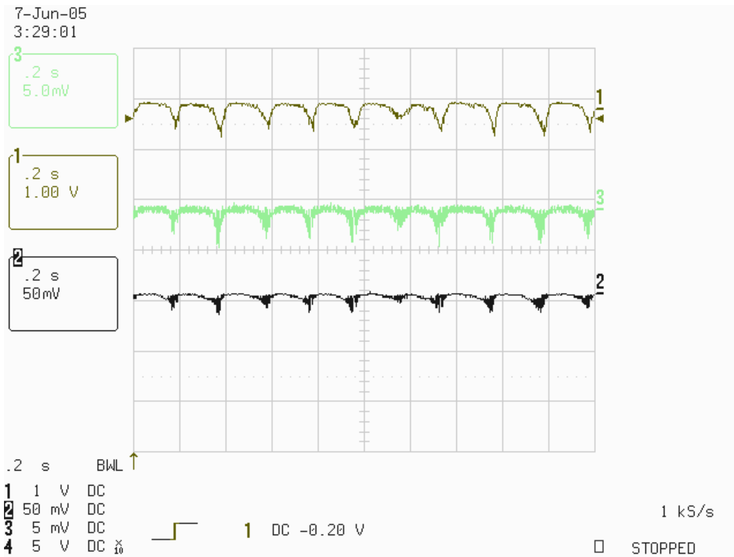


I=0.09mA

I=5.1mA

“Bunch lenthening” including longitudinal instability. Short high intensity peak exist.

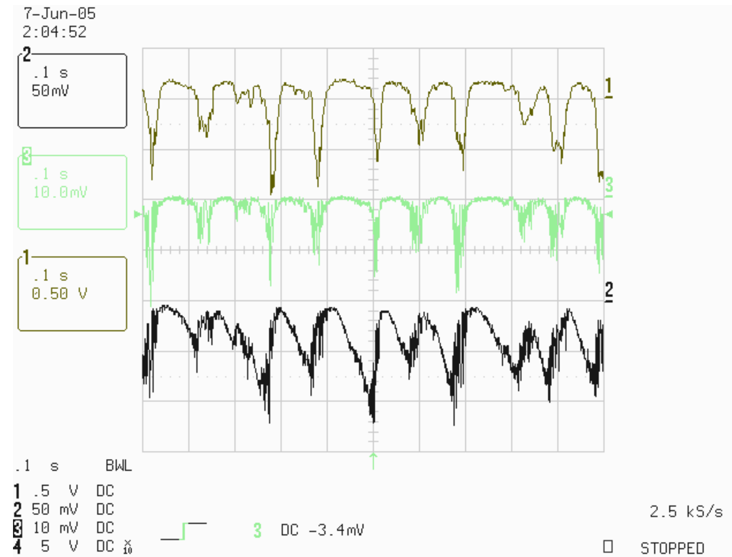
Sub-THz signal in time domain (Microwave detector)



Bolometer

75-110 GHz detector

50-75 GHz detector



At low current, only **transverse** beam instability

I=2 mA, transverse damping

τ_x=200 ms

Longitudinal beam instability at higher current

I= 10 mA, longitudinal damping

τ_s= 100 ms

What do we learned from the tests

- Need to suppress bunch intensity dependent beam instabilities.

(dominate: multi-bunch instabilities at present)

Plan:

Controlled bunch-bunch filling to allow single bunch operation or larger bunch separations.

RF cavity HOM damping (Ferrite-loaded HOM absorber ready).

Ring impedance check (single & multi-bunch instabilities).

Increase of synchrotron radiation damping?

- Need to store beam for lower α (<~10^{-4}) lattices.

Low α lattice study, path length control (orbit ? Rf frequency)

3. MIT-Bates SHR THz source R & D plan: **Goals**

- Address technical challenges to storage ring based CSR THz sources for high stability, high average and peak power, and desired time structures. Our research could benefit future dedicated source development or existing ring upgrades.

  The research will take full advantages of the unique high frequency rf system of the MIT-Bates South Hall Ring, the capacities of the Bates accelerator complex.

  Research collaboration: NSLS, ALS, Jlab, MIT community,…

- Provide a test source for the scientific communities to explore applications with this broadband, stable, high power THz source.

BESAC Subcommittee Workshop Report on 20-Year Basic Energy Science Facilities Roadmap (2003)

Far Infrared (Terahertz) Light Source Facilities

……

Further the BESAC Subcommittee notes that some of the parameters of these coherent synchrotron machines are only comparable to available table-top sources: the energy per pulse, full dc to terahertz coherence, and pulse durations are not much different. **However, there are opportunities for significantly higher stability and average power in these machine. Some significant technical hurdles need to be explored more fully.** The BESAC Subcommittee noted that trials at BESSY have explored coherent synchrotron radiation (CSR) instabilities in storage rings, but have not yet addressed the issue fully. Research to resolve this issue, as well as to develop the energy recovery technology needed for linac-based sources, must precede any full-scale commitment to a new facility.

MIT-Bates SHR THz source potential

- High average power, stable CSR: 1.5MV, 2.856 GHz,SC RF cavity.
- High field (~ MV/cm): THz pulse stacking cavity.
- Short pulse: femtosecond laser slicing (higher frequency).

SHR	Band Width	Pulse width	Rep Rate	Average Power	Pulse Energy	Peak E-field
Present lattice	-	~18 ps	-	-	-	
LMC lattice	~1 THz	~1-2ps	2.86 GHz	~Watts	~nJoules	~ 1-10kV/cm
Ultra-stable Anticipated	~1THz	~1-2ps	2.86 GHz	100W to kW	~100nJoules	~100kV/cm
High Peak Power (With Stacking cavity) Anticipated	~1THz	~1-2ps	~MHz	100W to kW	~10μJoules	~MV/cm
High field, short pulse (Slicing) Anticipated*	~20THz	~50 fs	~100kHz	~Watts	~ μJoules	~MV/cm

* 10mA/bunch, $\sigma \approx 10$ ps.

The R & D plan

A. Establish ultra-stable CSR operation condition with the 2.856 GHz RF system.

(moderate accelerator R & D,)

B. Explore full potentials of ring based CSR source to meet multi-user needs (high average power, high field, time structure,…).

C. Provide test source for scientific applications at early stage.

A. Establish ultra-stable CSR operation condition with the 2.856 GHz RF system.

- Controlled bunch-bunch filling:
  - ➢ Study single bunch phenomenon.
  - ➢ Optimal bunch filling pattern.
  - ➢ Multi-bunch instability study and suppressing.
  - ➢ Uniform bunch charge distribution
  - o Special Challenge: 2.856 GHz bunch chain filling.
- Machine Physics and other ring adjustment
  - ➢ Low α lattices, high order α control.
  - ➢ Better orbit, rf frequency control – stability.
  - ➢ Beam instability.
  - ➢ Impedance, RF cavity HOM absorber.
  - ➢ Long beam life time > 10 hours
- Test beam line
  - – For machine study and source test.

Ferrite-loaded HOM absorber for the 2.856 GHz RF cavity

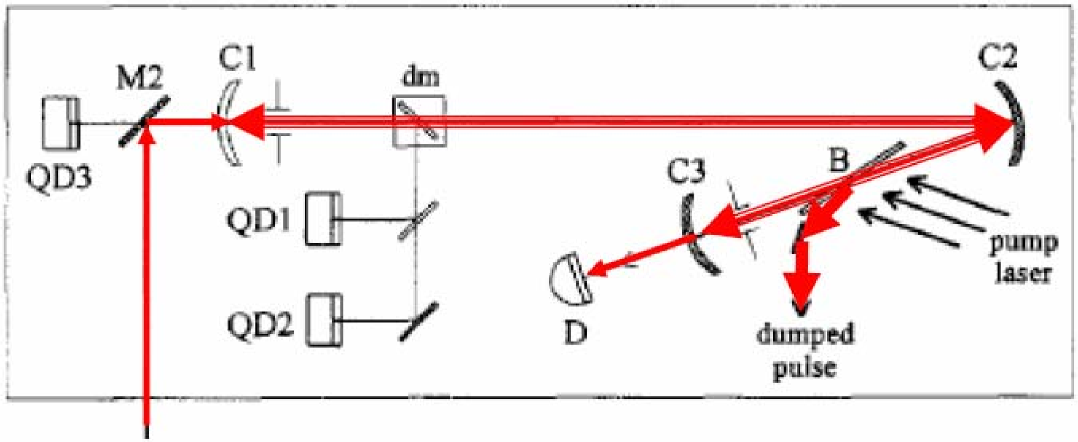
A. Zolfaghari

B . Explore full potential of ring based CSR source

- Superconducting 2.856 GHz RF cavity
  - Higher RF cavity gap voltage => 1.5MV.
  - existing CW 50 kW RF power source
    - SC RF cavity & cryo module – proposing, SBIR.
- External pulse stacking cavity
  - High average power => high peak power, higher field (MV/cm), pump-probe…
    - Initial discussion with
      Optics & Quantum Electronics Group, MIT/EECS (F. X. Kaertner).
- Femtosecond Laser slicing
  - The Electron Beam for slicing is available. Potential ?
- Modular dipole for large aperture and increase SR damping
  - Low energy operation and beamline optimization.
    one dipole 3.59m => three ~ 0.6m dipoles. Center one for THz.

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.

Recommendations from the IAC (G. Williams chair) at MIT-THZ workshop (Oct. 11-12, 2005)

http://bpc.ins.mit.edu/THz/workshop2005.htm

1. Accelerator:
   - Steady CSR operation.
   - Potential of 1 nC 600 Hz source.
   - Potential of femto-slicing as a source.

2. Define unique properties of potential sources comparison to existing sources.

3. Establish working group of local potential users.

4. THz spectroscopist: co-ordinate activities with other facilities in the USA, guide the evolution at Bates and speed up implementation.

Initial Scientific Applications

CSR THz experiments at BESSY

Between fall 2002 and 2005:

- ~ 22 days at BESSY dedicated for THz users
- shared by over 10 groups!

User group	Project
H.-W. Hübers et al.	- detector technology for space applications
M. Martin et al.	- High-T_c BSCCO
P. Calvani et al.	- High-T_c cuprates
P. Calvani et al.	- B-doped diamond
P. Calvani et al.	- MgB_2
D. Fried et al.	- spectral imaging on human teeth
K. Kamaras et al.	- carbon nano-tubes
B. Lendl et al.	- structuring effects in water
G. Loupia et al.	- CaC_6
BESSY	- detection schemes - spectroscopic near-field techniques - ellipsometry

Workshop to explore Terahertz opportunities at MIT-Bates, October 11-12, 2005 Ulrich Schade

Possible applications at MIT-Bates THz source (MIT THz workshop discussion)

Potential source: THz range 0.03-1.5 THz, ~ps, W-kW, reproducibility ~10^{-3}.

- THz Resonance Transmission and Time Domain spectroscopy : Biological Polymers and Others. **T. Globus** (UV)
- Oxidative Damages to Human and Microbial Genomes. **H. Holman** (LBNL)
- Condensed Matter Physics and Materials Science
  - Unconventional superconductivity.
  - Intrinsic magnetoelectric and Multiferroic materials.
  - Photovoltaic and Fuel Cells.

  P. Guptasarma (UWM)