Compact long-wavelength free-electron lasers

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25 June 2007

Thanks to:
- Charles Brau
- Jonathan Jarvis
- Chase Boulware (PITZ)

Outline

- Motivation and definitions
  - Comparison of existing long wavelength sources
  - What do I mean by “compact” ?
- What is a Smith-Purcell free-electron laser (SP-FEL)?
- 2-D and 3-D theoretical results
- Status of the Vanderbilt experiment
- Comparison with simulations and experiments

WANTED: a compact narrowband terahertz (THz) source

Problem

- Want to do frequency domain spectroscopy at THz frequencies
- No existing narrowband source provides good power over THz range
- Short pulse sources - good for time-domain spectroscopy

Solution Requirements

- Want a source which will produce
  - 300-1000 micron radiation (0.3-1 THz)
  - ~ 1 Watt peak power
  - ~ 5 nanosecond pulses
  - Narrowband

Narrowband terahertz source can be used for spectroscopy and imaging

- Protein spectroscopy
  - Identify specific structures
  - Investigate conformational changes
- Substance Identification
  - Biological or chemical agents
- Imaging
  - Surveillance
  - Industrial inspections

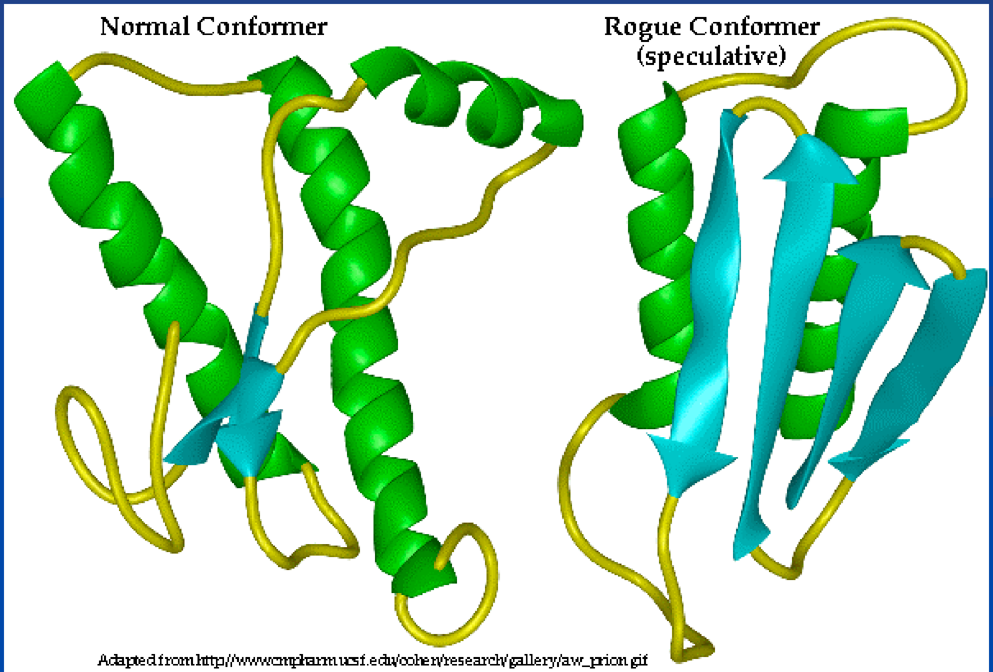
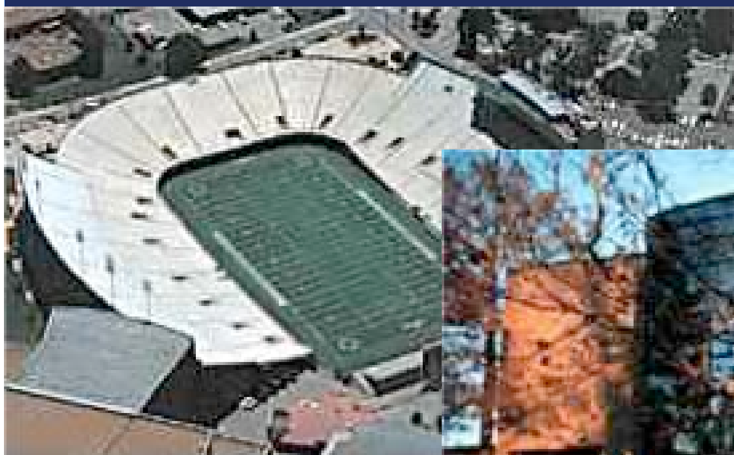


Image adapted from http://www.cmpharm.ucsf.edu/cohen

Existing THz sources don't meet our needs

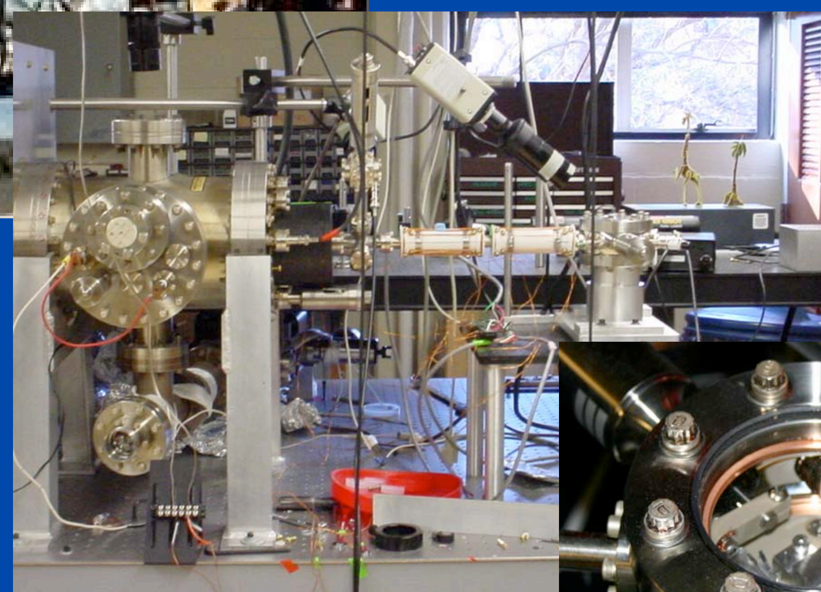
THz Source	Comparison to requirements
UCSB FEL	Longer pulses (microsecond as opposed to nanosecond), higher power, large facility
Synchrotron sources	Lower spectral brightness, much shorter pulses, broadband
Optically pumped FIR lasers	Not tunable
Optical rectification techniques	Very short pulses, low power, broadband
Backward Wave Oscillators (BWO)	Low power, longer wavelengths, very similar operating mechanism

What do I mean by "compact"?

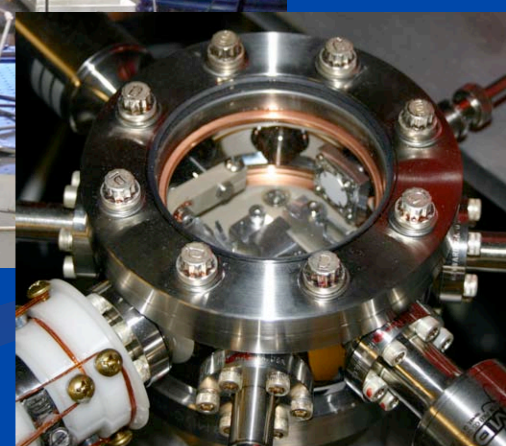


Vanderbilt Stadium
Dudley Field

Vanderbilt FEL Center



Vanderbilt SP-FEL on
a standard optics table



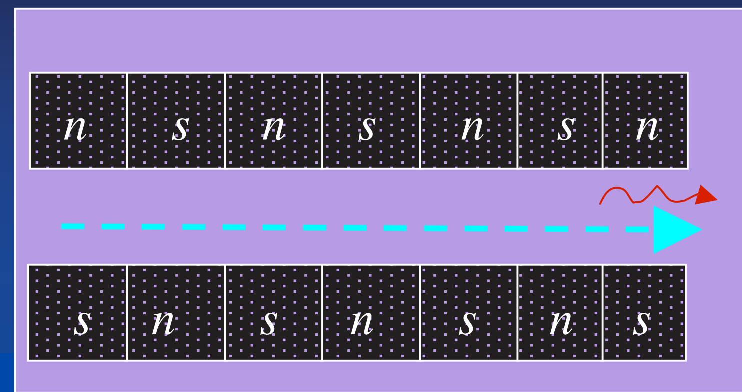
4" vacuum
chamber

3 types of energy transfer

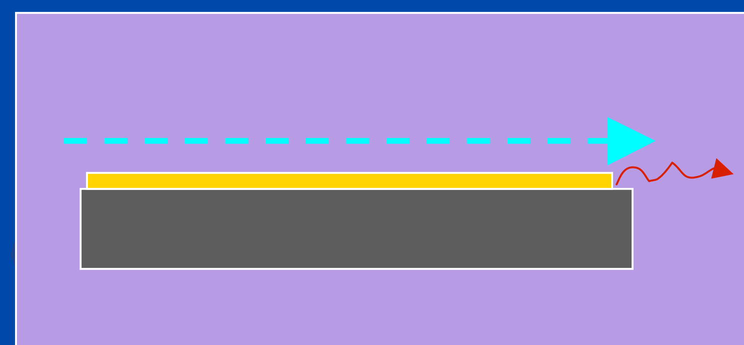
Dashed arrow = electron beam

Squiggly arrow = photons

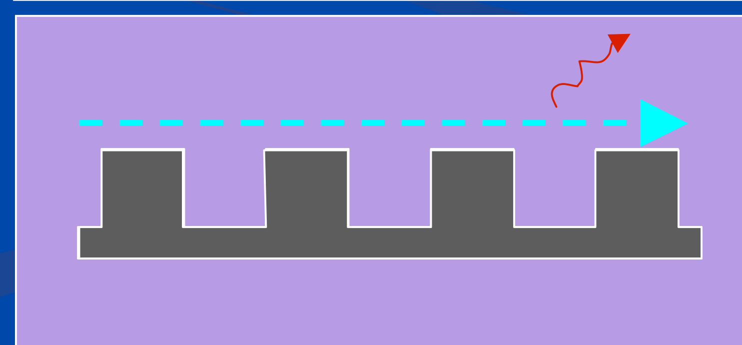
Wiggler Magnets



Dielectric Slab



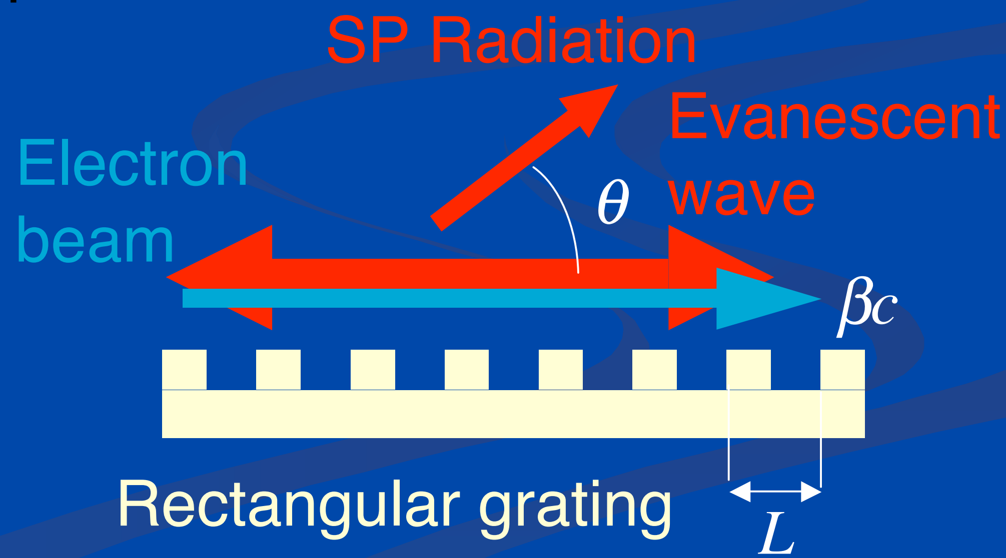
Grating or Slow Wave Structure



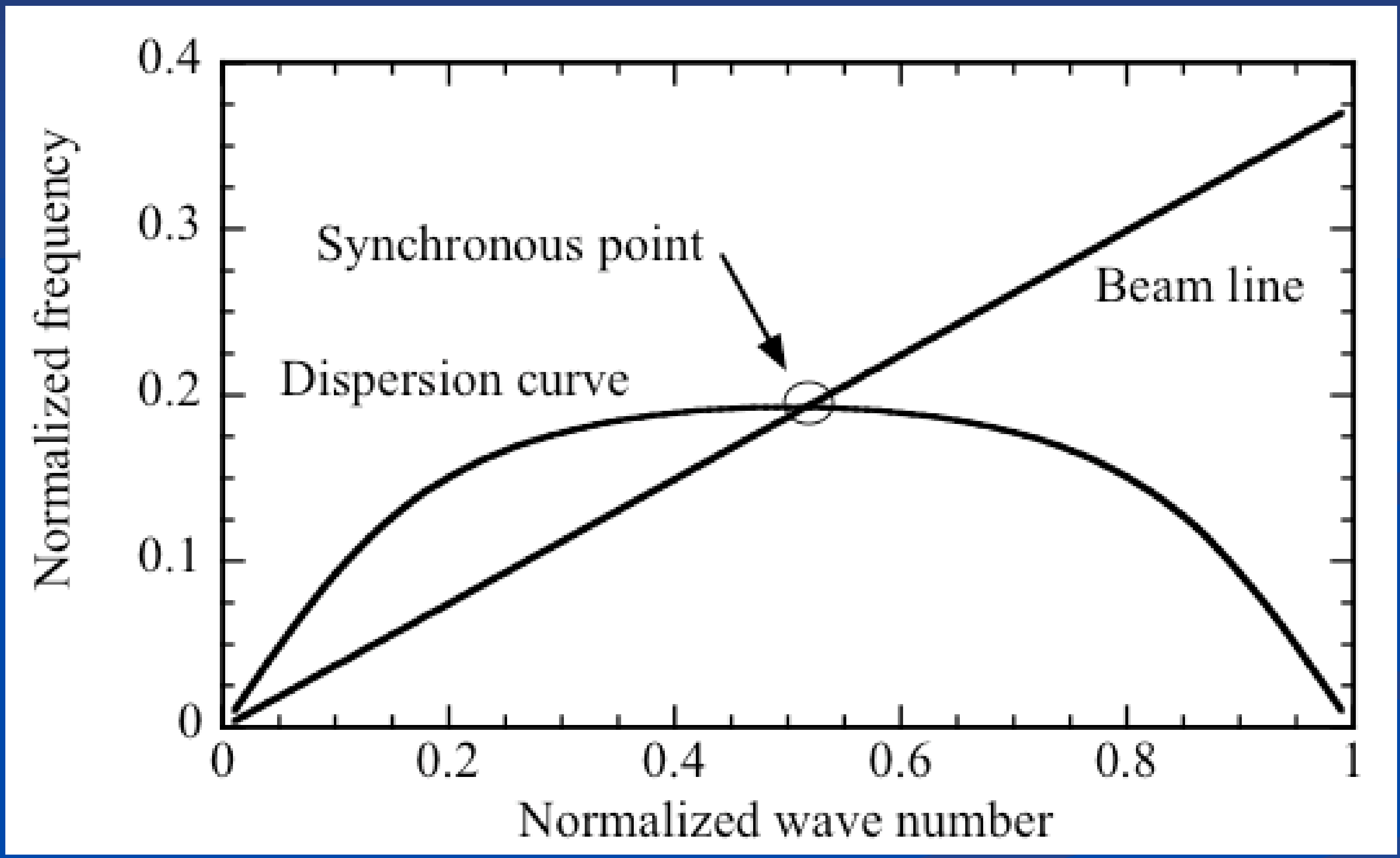
An electron passing over a metal grating produces Smith-Purcell radiation and an evanescent wave

- Smith-Purcell radiation
  - radiates
  - wavelength and angle coupled by Smith-Purcell relation
- Evanescent wave
  - does not radiate
  - scatters off ends of grating
  - has wavelength longer than SP radiation

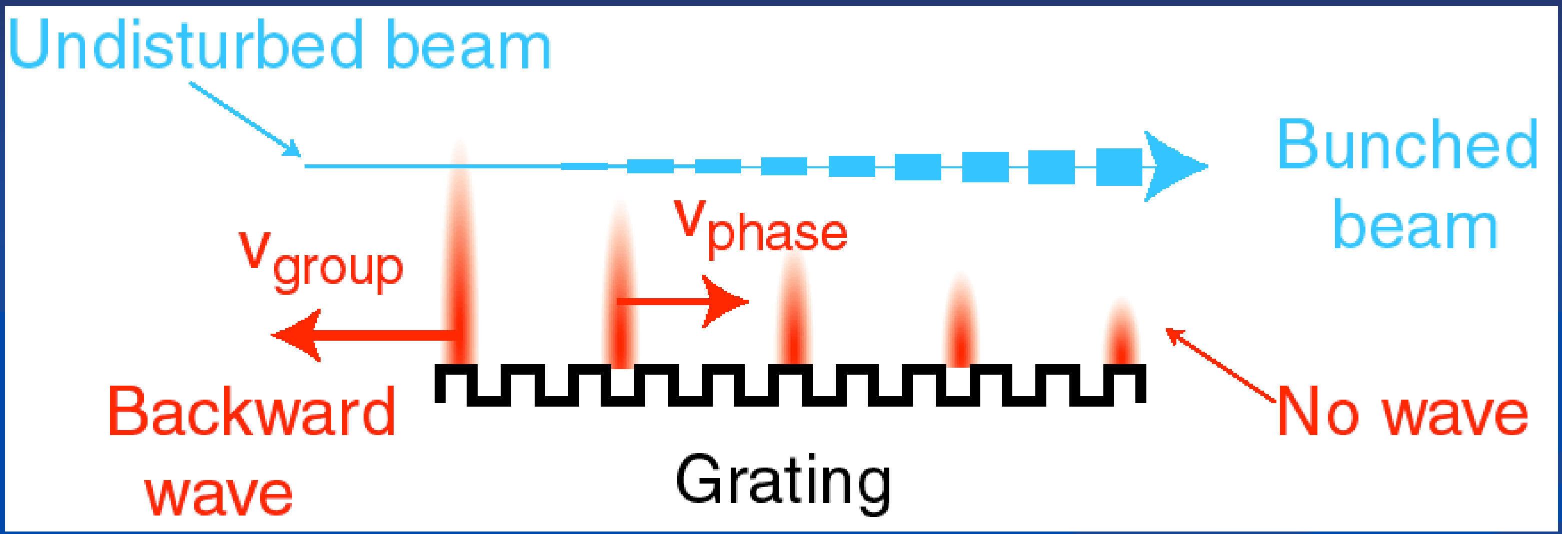
$$\lambda = \frac{L}{|n|}\left(\frac{1}{\beta} - \cos\theta\right)$$



Dispersion relation determines operating parameters



Evanescent wave is key to SP-FEL operation



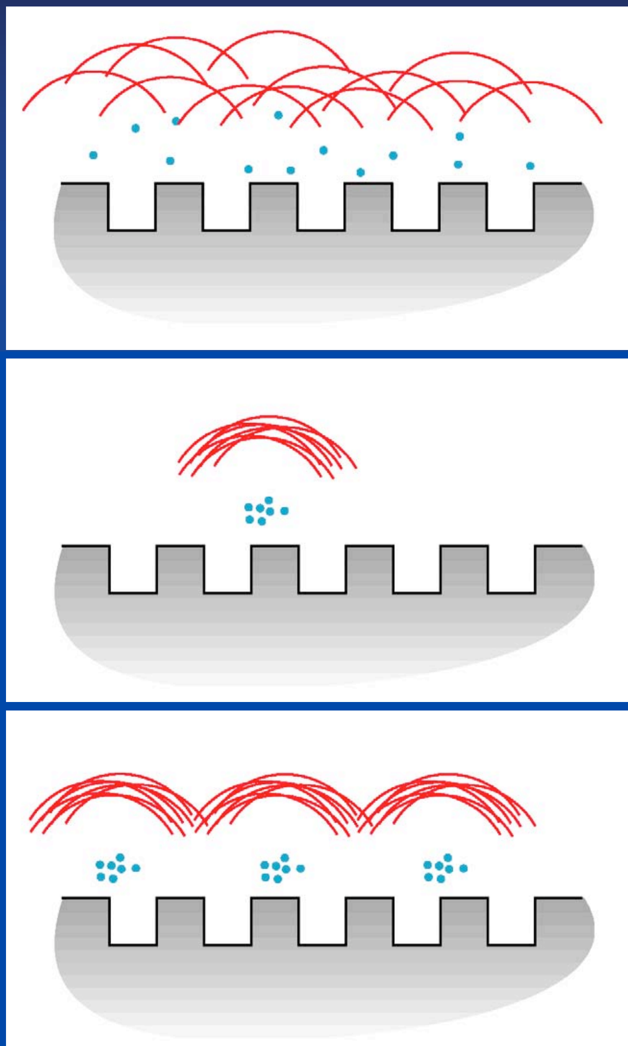
Evanescent wave
- Provides feedback
- Bunches beam

Spontaneous oscillation occurs for e-beam current above "start current"

Below start current spontaneous SP dominates

Small beam-wave interaction region
- Beam must have high current density
- High brightness cathode meets this need

Bunching makes SP radiation superradiant

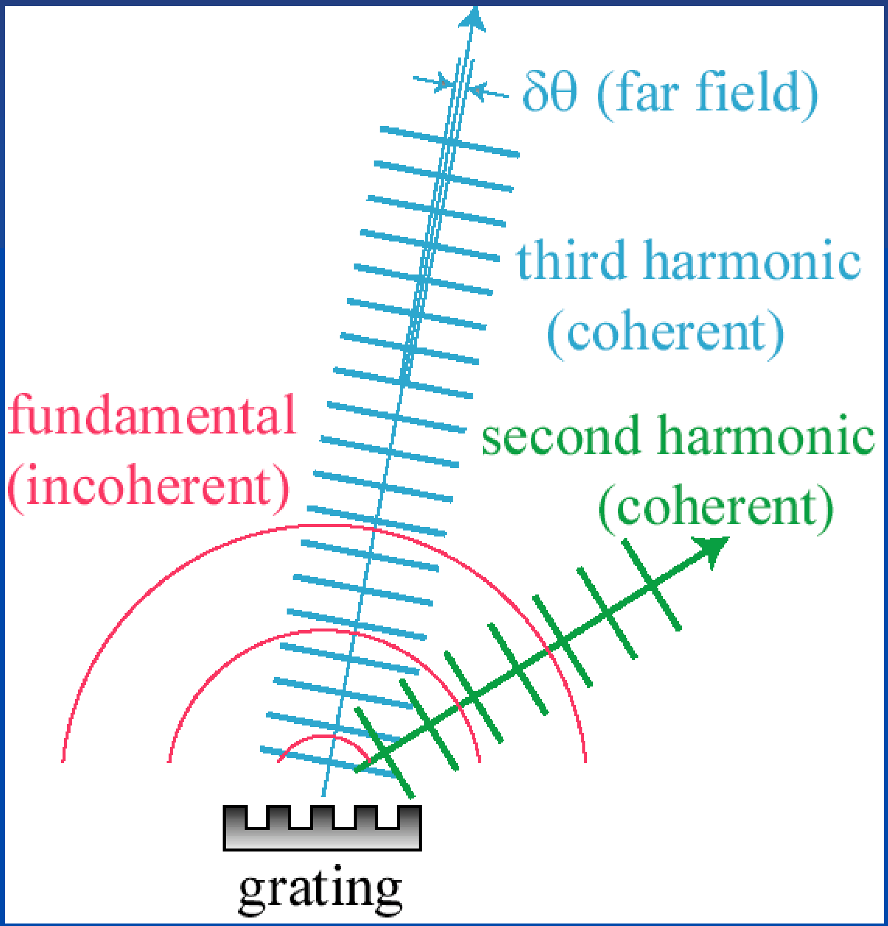


No bunches:
- Incoherent emission
- Intensity ~ N_e
- Normal SP spectrum

Single bunch:
- Coherent emission
- Intensity ~ N_e^2
- Spectrum unchanged

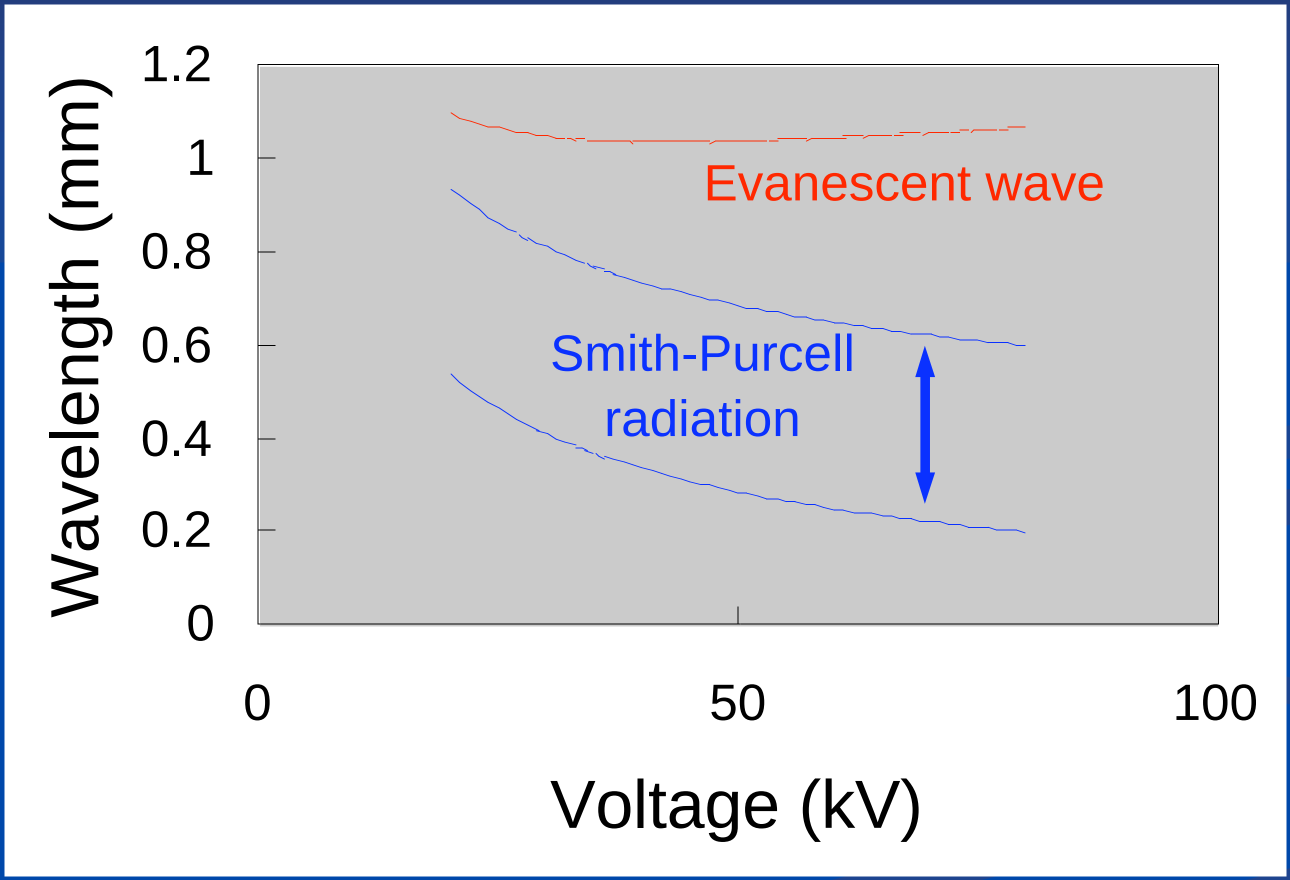
Periodic bunches:
- Superradiant emission
- Intensity ~ N_e^2
- Spectrum peaked at harmonics

SP radiation is enhanced at harmonics of evanescent wave

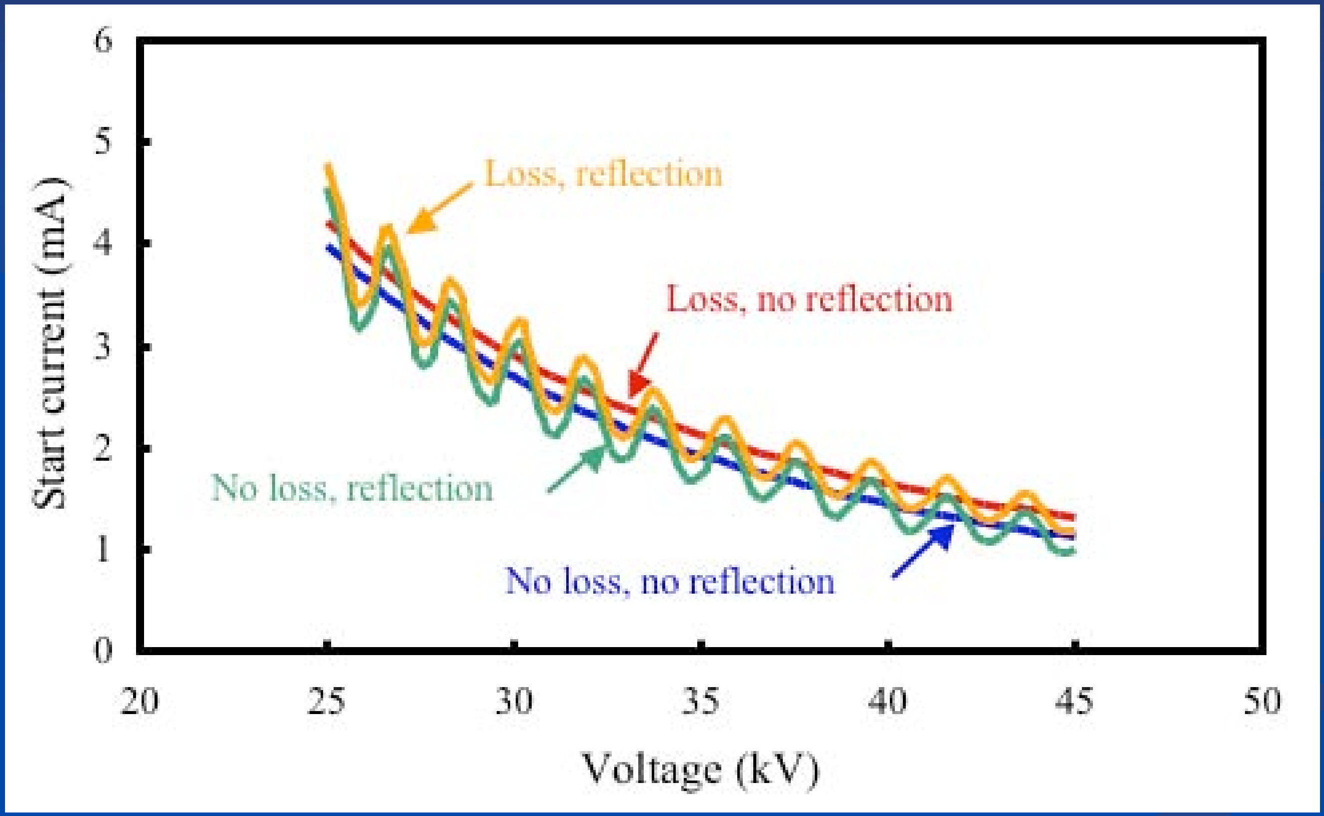


- Evanescent wave scatters off ends of grating
- Harmonics of evanescent wave appear as narrow peaks in the angular power spectrum
- The angle at which harmonics radiate is determined by the Smith-Purcell relation

Harmonics of evanescent wave fall in SP band

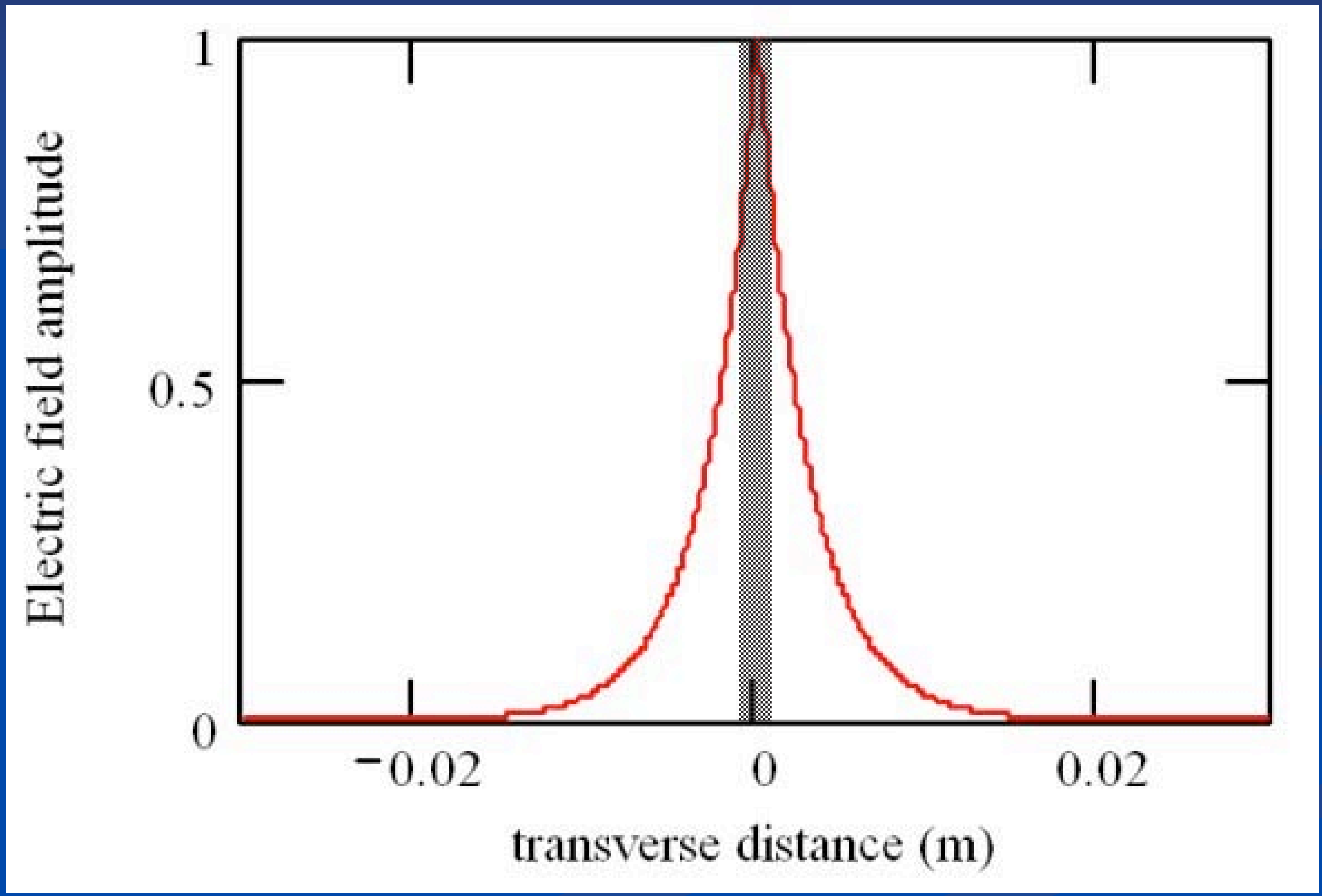


Reflections and losses have small effect on start current for range considered

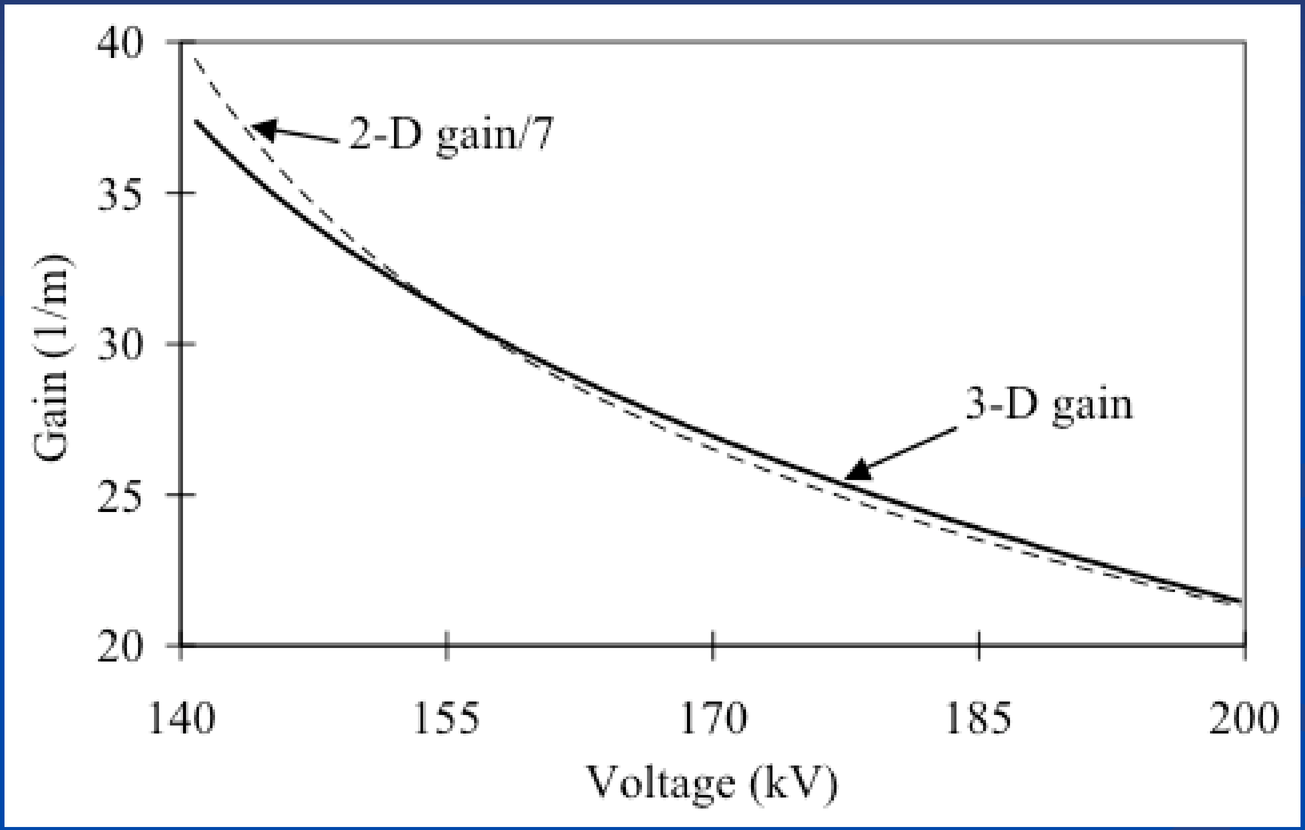


Losses ARE an important consideration for different parameters

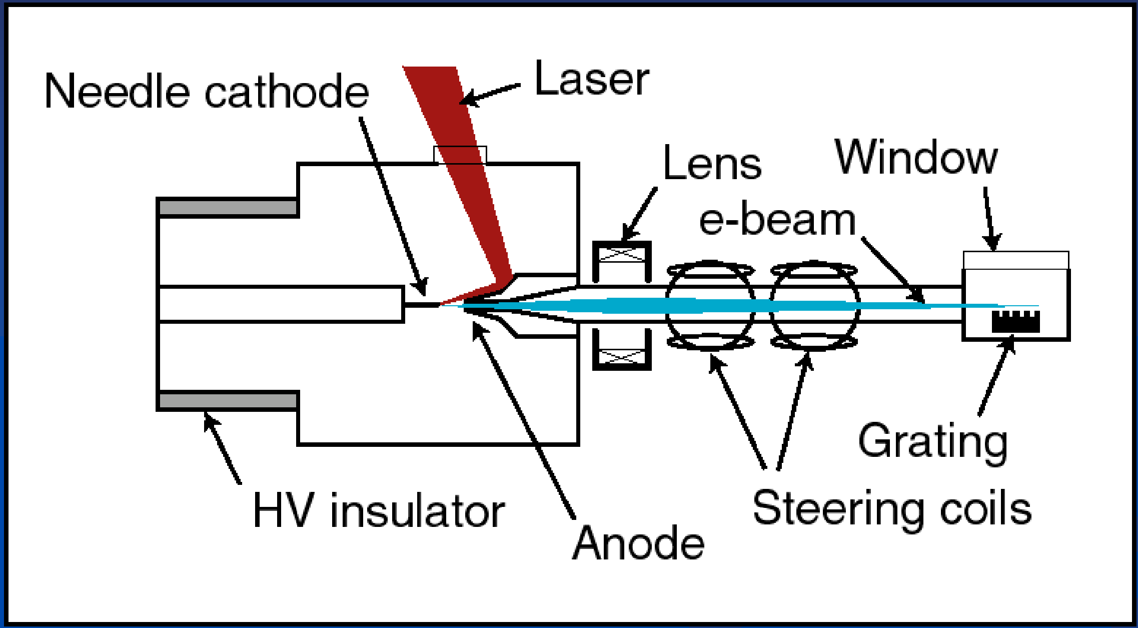
In 3-D theory, mode width is larger than beam width



3-D diffraction effects reduce gain



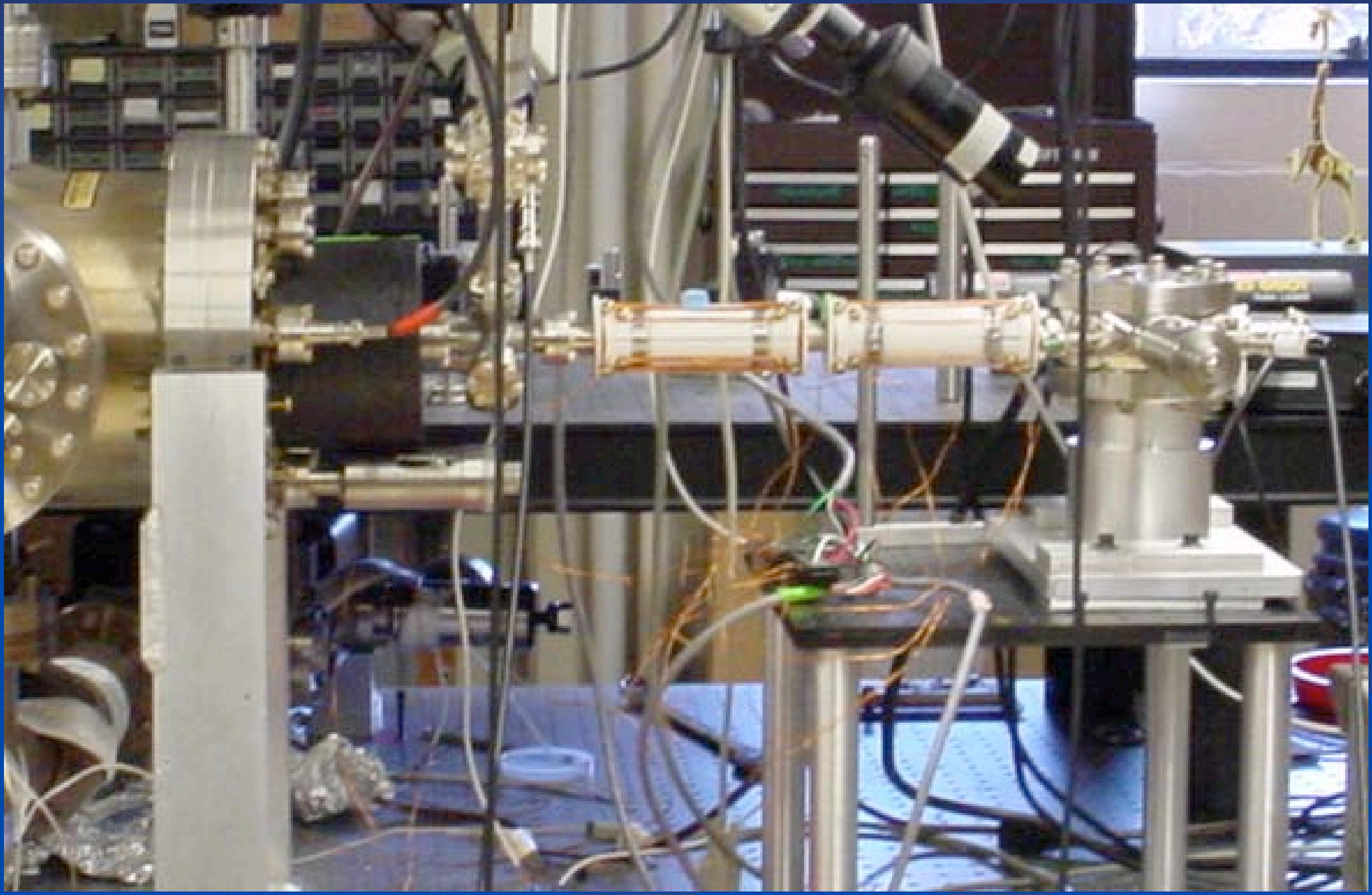
Experiment was developed to test theory and produce THz radiation



Parameters:
- Current = 6 mA
- Voltage = 45 kV
- Pulse = 5 ns
- Length = 1.2 cm
- Period = 250 µm

Desired performance
- Wavelength ~ 1 mm
- Growth rate ~ 10^{10} /s
- Incoherent ~ 10^{-7} W
- Superradiant ~ 10^{-3} W

Experimental Apparatus



Experimental efforts have been limited by cathode performance

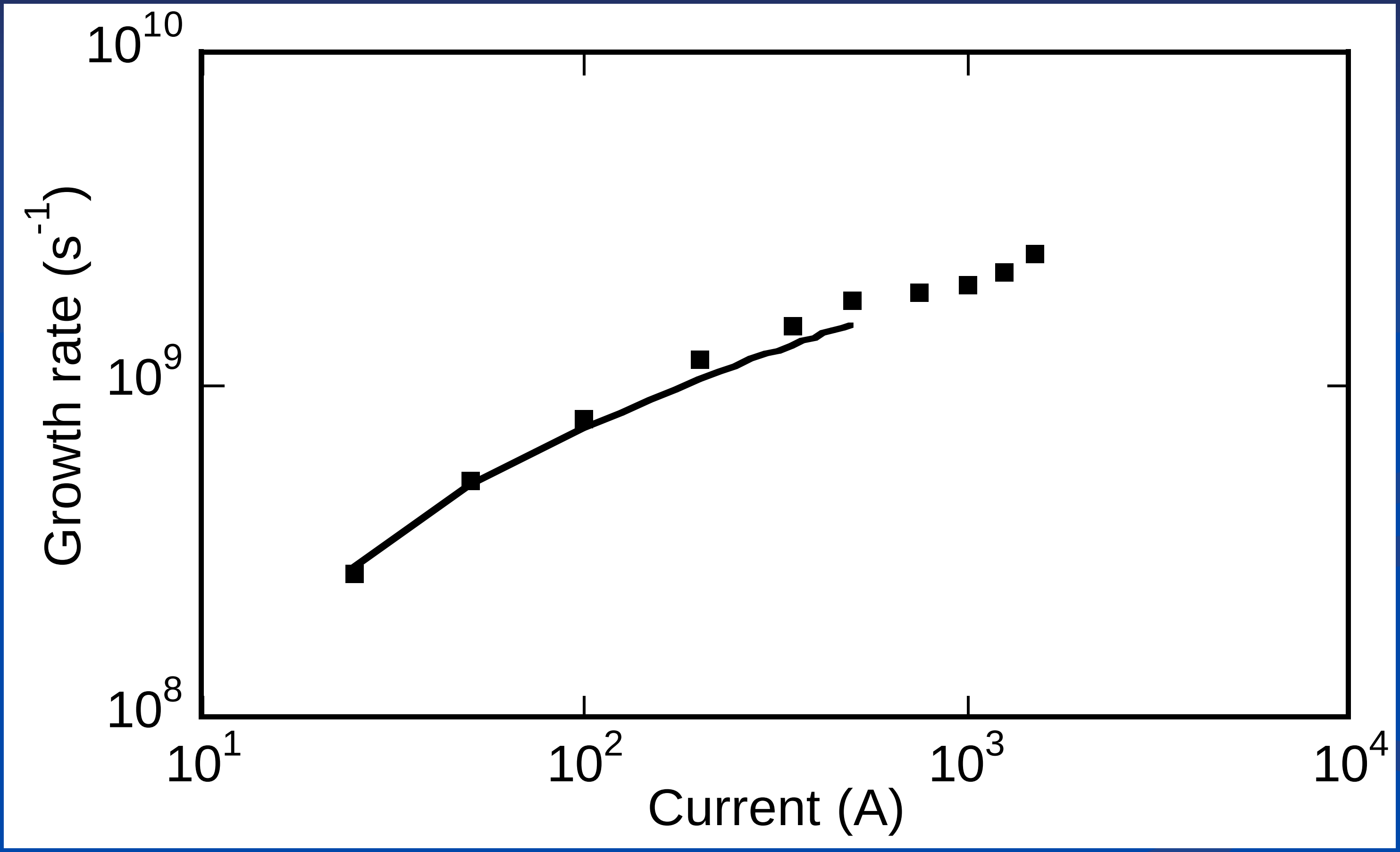
We can reliably produce an electron beam, however it is:

- too low in current
- too large

Spontaneous radiation we produce is 10 - 100 times too small to detect

Efforts have shifted to collaborations with Vermont Photonics

2-D theory agrees well with simulations*



3-D theory and simulations are still under investigation

*Donohue and Gardelle, Phys. Rev. ST-AB **8**, 060702 (2005)

Theory and simulations disagree with experimental results

Experiments at Dartmouth College:

- Observed superradiant emission at a current much lower than any possible predicted start current
- Observed enhancement at wavelengths not predicted
- Never observed an evanescent wave

Experiments at University of Chicago

- Only observed enhanced emission of blackbody radiation from grating heating

These suggest fundamentally different mechanisms than what the theory describes

Conclusions

- We have developed 2-D and 3-D theories describing the operation of a Smith-Purcell free-electron laser
- Particle-in-cell simulations corroborate our theoretical results
- Experiments at Vanderbilt have been hindered by cathode problems
- Other experiments do not agree with our theoretical results