Nanobeams,
Proton Drivers, and
Free Electron Lasers

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Interaction Meeting on
Linear Colliders and Neutrinos
Indian National Science Academy
November 10, 2003
New Delhi, India

Topics

- Nanobeam Technologies for Linear Colliders

- Technologies for High Current Proton Drivers

  and Free Electron Lasers

Nanobeam Technologies for Linear Colliders

- High brightness electron and positron sources
- Fabrication of precision microwave linear accelerator structures on a large scale
- Damping ring components and systems (similar to Synchrotron Radiation Rings)
- Instrumentation for monitoring and control of nanometer size beam collisions
- Control system architecture

LEP

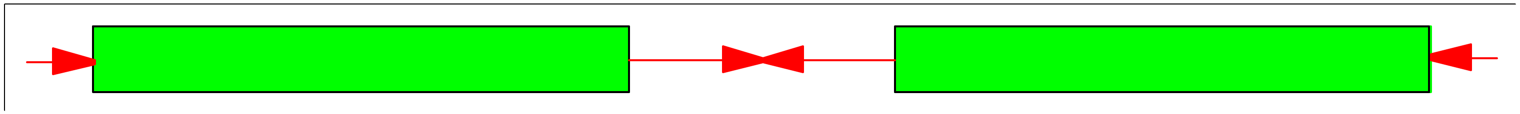
- The largest e+e- collider **LEP** at CERN reached about 200 GeV
- High energy electron on circular orbit looses energy by synchrotron radiation
- The energy loss in one turn is proportional to

$$\frac{(\text{beam energy})^4}{(\text{radius})}$$

- → impossible to build higher energy e+e- ring
- → straight collider

What is Linear Collider?

- Use 2 linear accelerators



- Throwaway beam
- Repeat
  - —beam generation
  - —acceleration
  - —collision

quickly

Luminosity: only few x 10^4 larger than SLC!

$$L = \frac{f_{rep}}{4\pi} \frac{n_b N^2}{\sigma_x \sigma_y} H_D \quad \Rightarrow \quad L = \frac{2P_b}{4\pi\, E_{cms}} \frac{N}{\sigma_x \sigma_y} H_D$$

- Increased beam power from long bunch trains
- Larger beam cross-sectional densities: N / (σ_x σ_y)

Accelerator Physics Issues in ILC

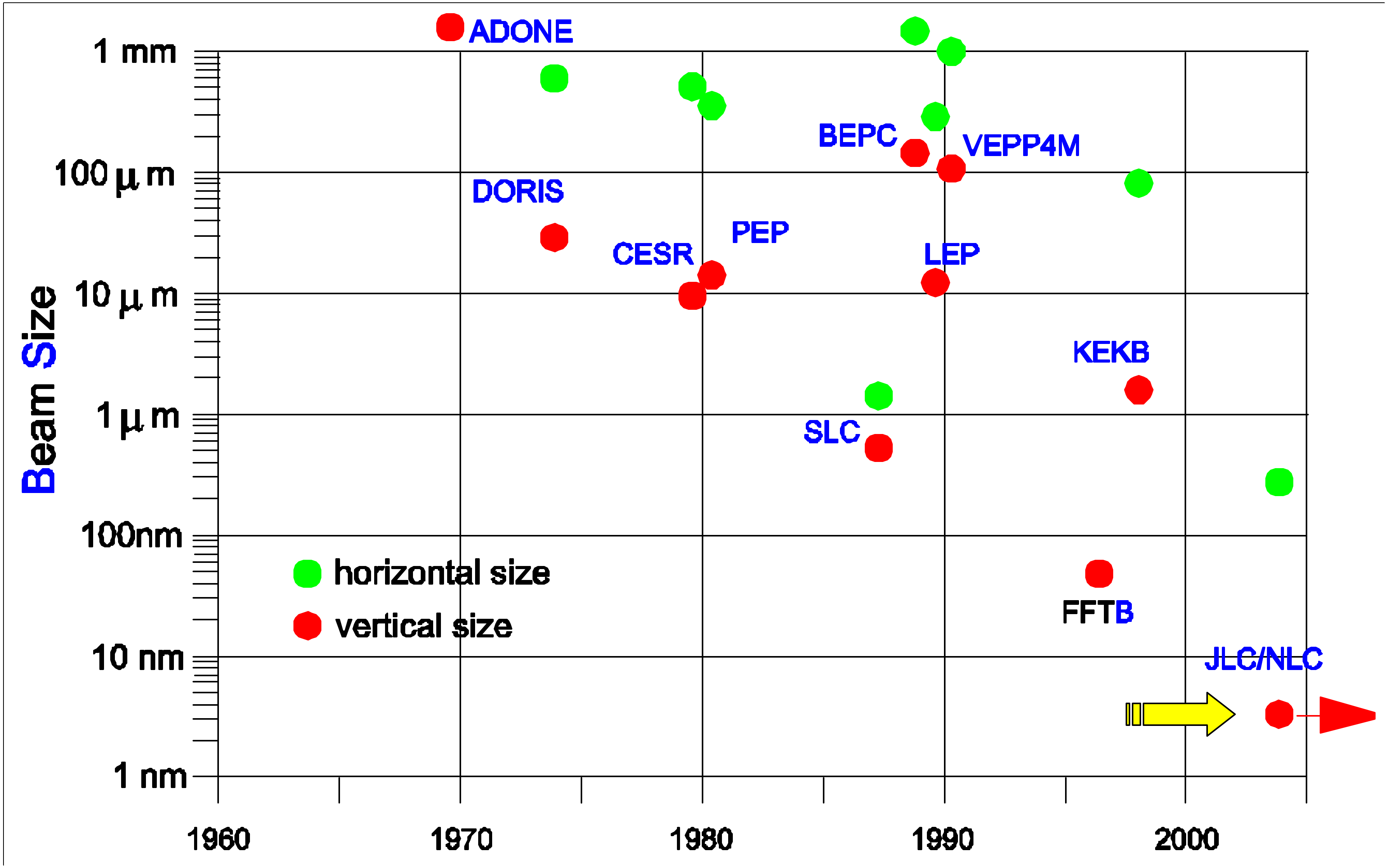
- **Two issues:**
  - **Energy (rf technology)**
  - **Luminosity (small spot and beam power)**

- **Small spot sizes:**
  - **Low emittance damping rings**
  - **Final focus system**
  - **Alignment and jitter tolerances**
  - **Beam-based alignment and feedback**

- **Beam power (long bunch trains):**
  - **Charge from sources**
  - **Long-range wakefields**
  - **Radiation damage**

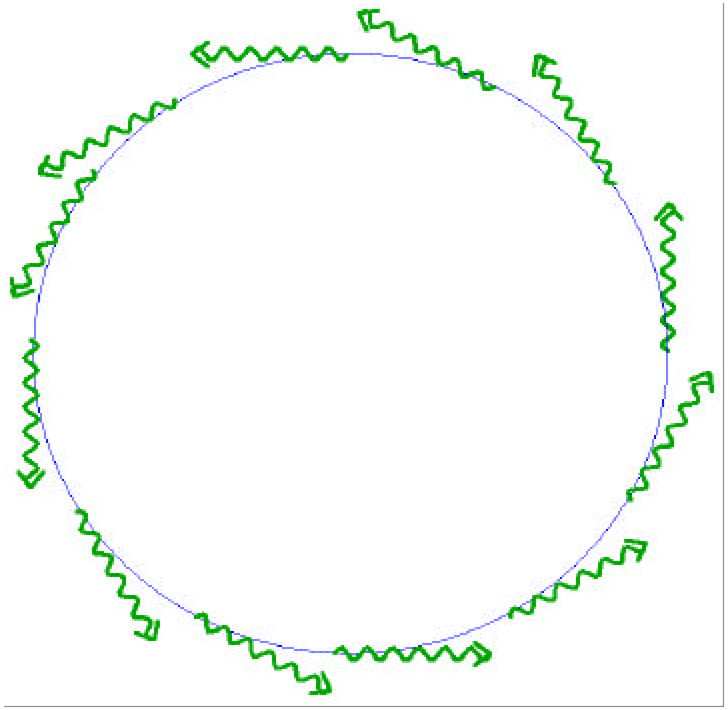
- **Both issues: (very high charge densities)**
  - **Damping ring instabilities**
  - **Beam collimation and machine protection**

History of Beam Size in e^+e^- Colliders



Creating High Quality Beams

- High Brightness Electrons/Positron Source
- Injection into a Damping Ring for "cooling"
- Electrons loose energy by synchrotron radiation in the Damping Ring
- Beam becomes small in this process



Similar to a Synchrotron Radiation Storage Ring (e.g., Indus-II), with 10x better damping.

Synchrotron Radiation

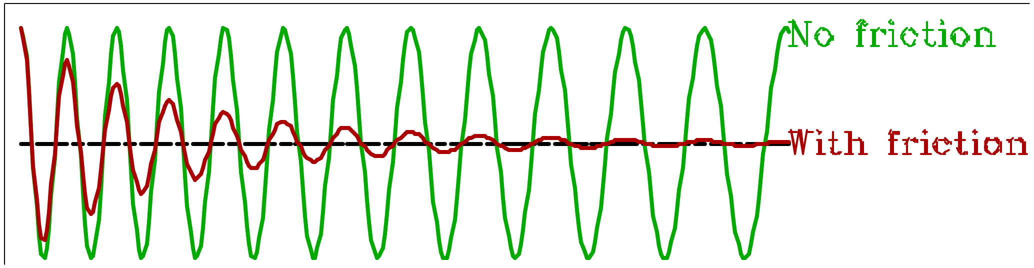
Put a ball in the groove slightly off the center

It falls down along the groove, oscillating

But the oscillation fades away owing to the friction

Synchrotron radiation works as friction

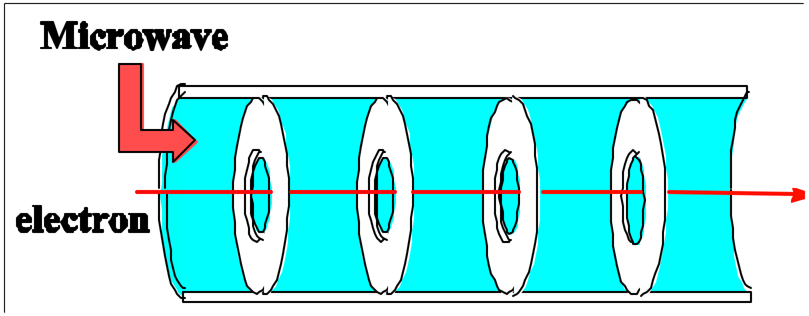
Get a high quality beam in less than a second



Acceleration of High Quality Beams

- Use Linear Accelerator

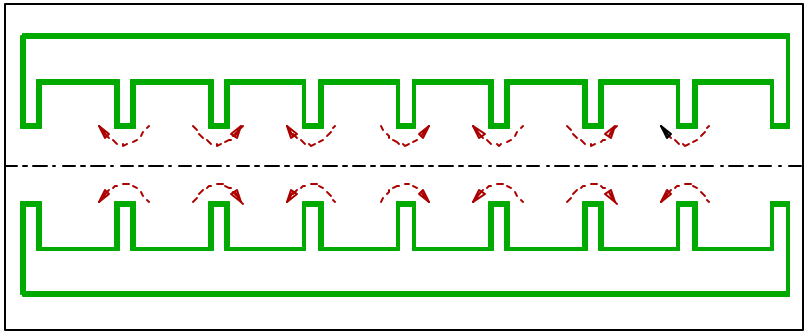
  (Linac)



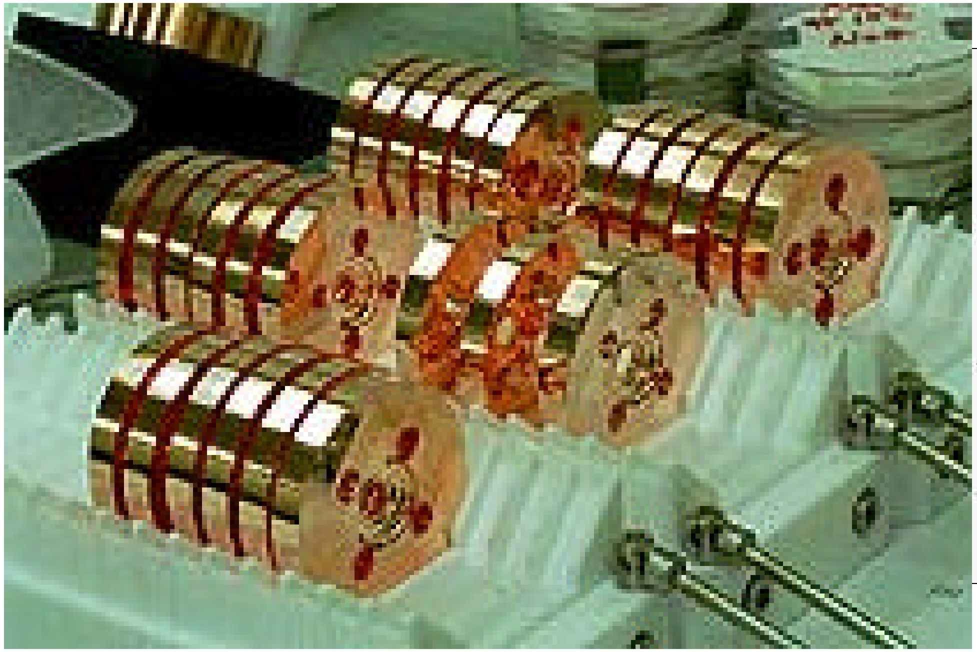
- Accelerate by Microwave

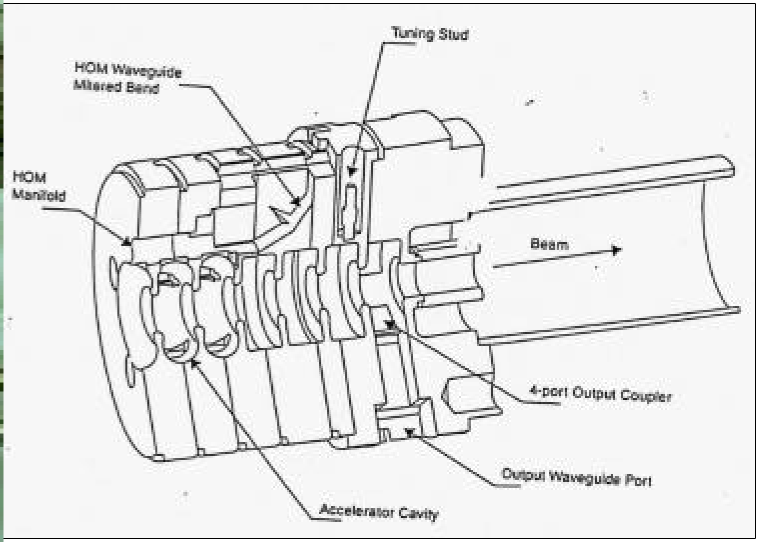
  frequency 11.4 GHz

  wavelength 26 mm



(similar to SLAC with 4x frequency and >10x precision)





Inner surface accurate to 1 µm

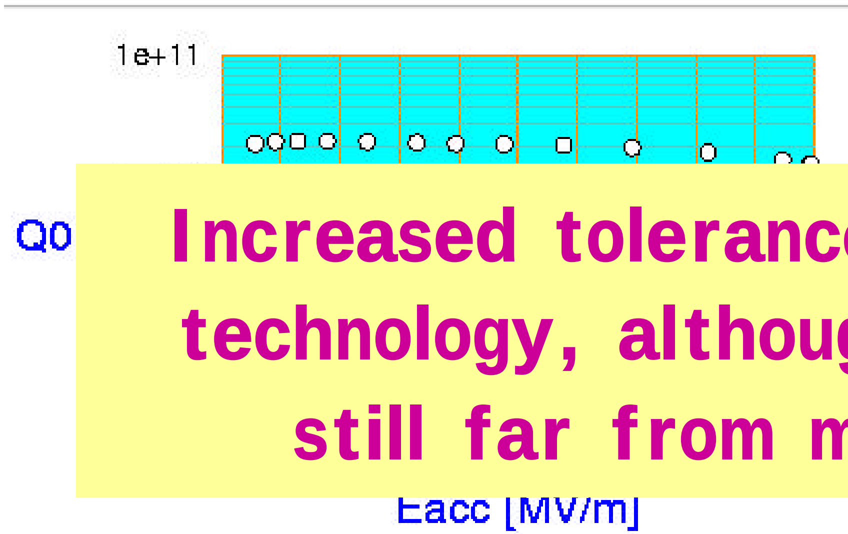
Must be aligned straight within 10 µm

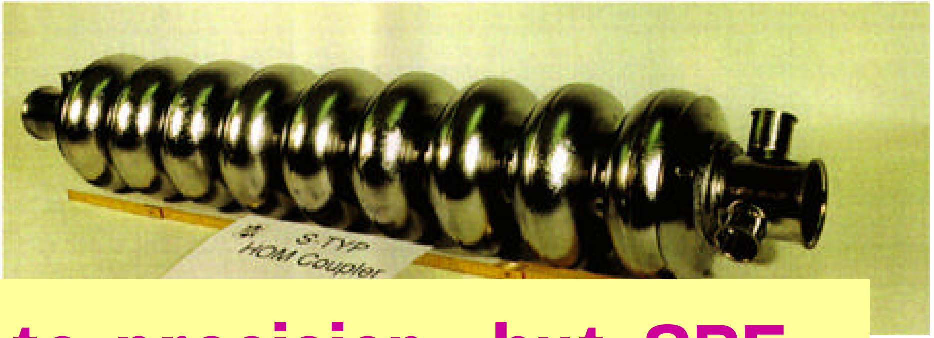
Need efficient large-scale fabrication of high precision accelerator structures.

JLab / DESY/Cornell Technology: Test Result

Cavity Name: S33 Cavity Test: 7

Test Location: V1 Start of test: 06-sep-1999





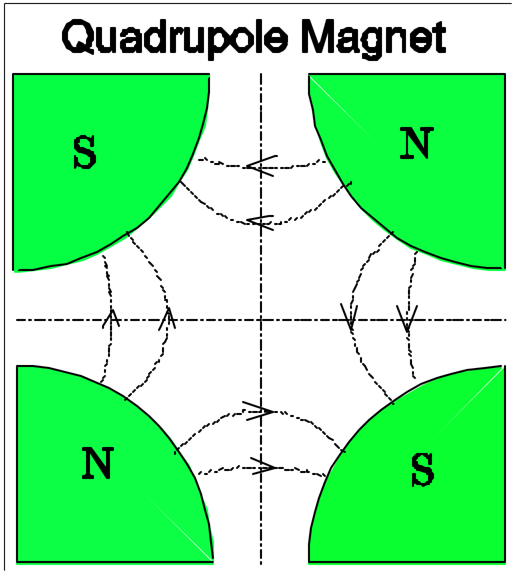
Increased tolerance to precision, but SRF technology, although fully "developed", is still far from maturing – need R&D

-2000

Max field reached in individual cells		
Cell-Pair	**Emax [MV/m]**	**Limitation**
1&9	25.80	Quench
2&8	27.52	Quench
3&7	26.65	Quench
4&6	25.53	Quench
5	28.35	Quench

200	1449.00	35.32	none
300	770.50	35.72	Quench
400	580.80	36.60	Quench
500	556.60	37.64	Quench
600	321.20	35.20	Quench
700	287.10	35.50	Quench
800	256.20	35.41	Quench
900	248.10	35.61	Quench
1000	231.60	35.58	Quench
1100	226.10	35.14	Quench
1200	224.90	34.37	Quench
1300	205.30	33.67	Quench

Guiding the Beam



- Use magnet: Well-known technology since many, many years ago
- But
  - 10 nm vibration can cause miss-collision
  - 500 nm shift can make the beam fat
  - Ground is moving

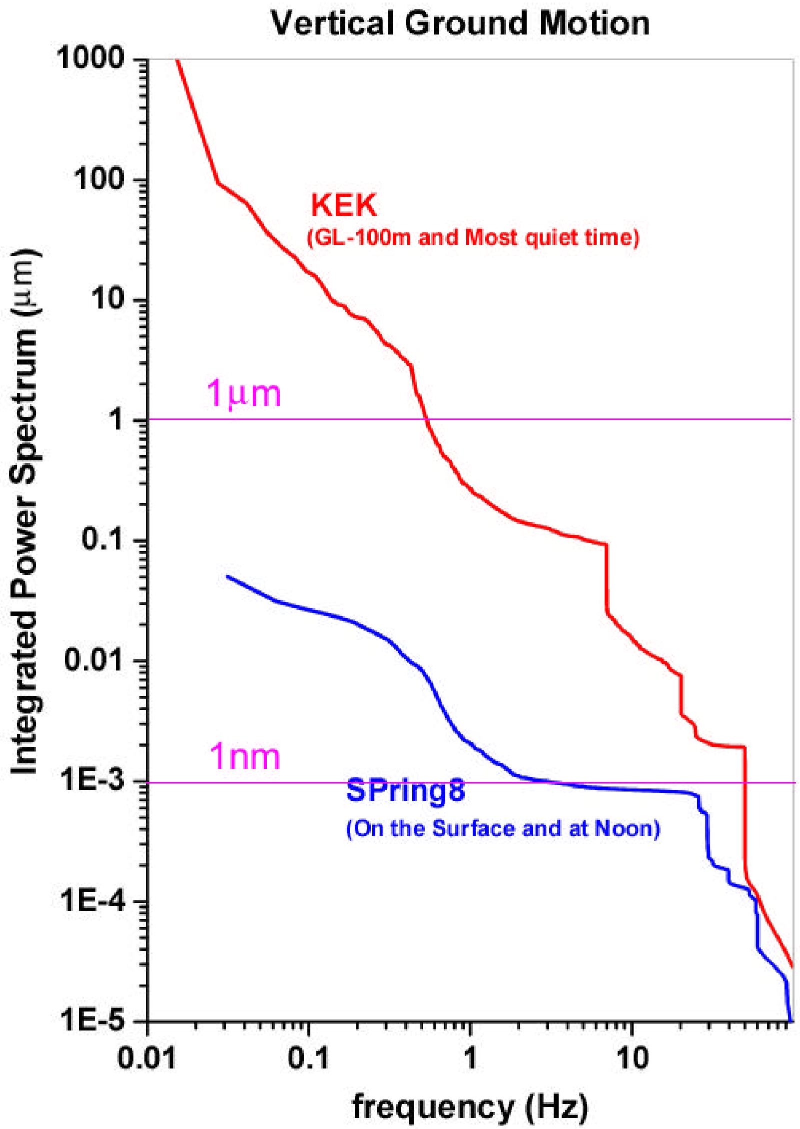
→ Computer control of magnet position

Integrated Magnet and Control System

Ground Motion

Ground is moving

- We cannot stop the ground
- But instead we can steer the beam
- Faster ground motion is harder to correct



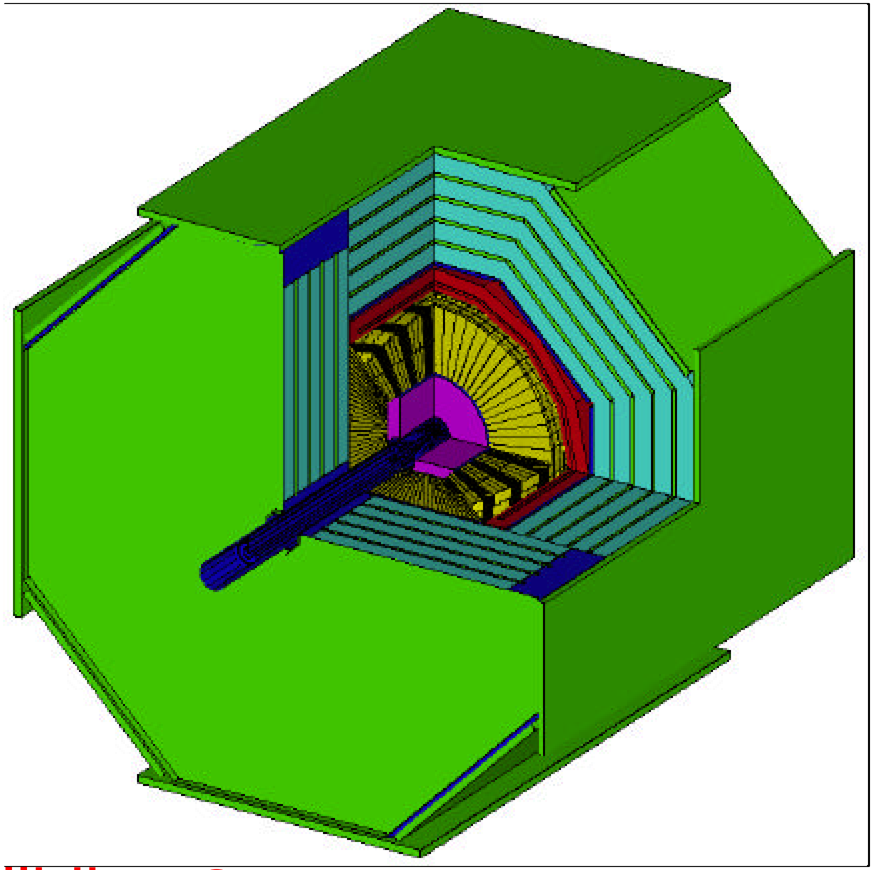
S.Takeda, H.Matsumoto, S.Matsui, K.Togawa and H.Yoshioka

Collide Tiny Beams

Beam size at collision point

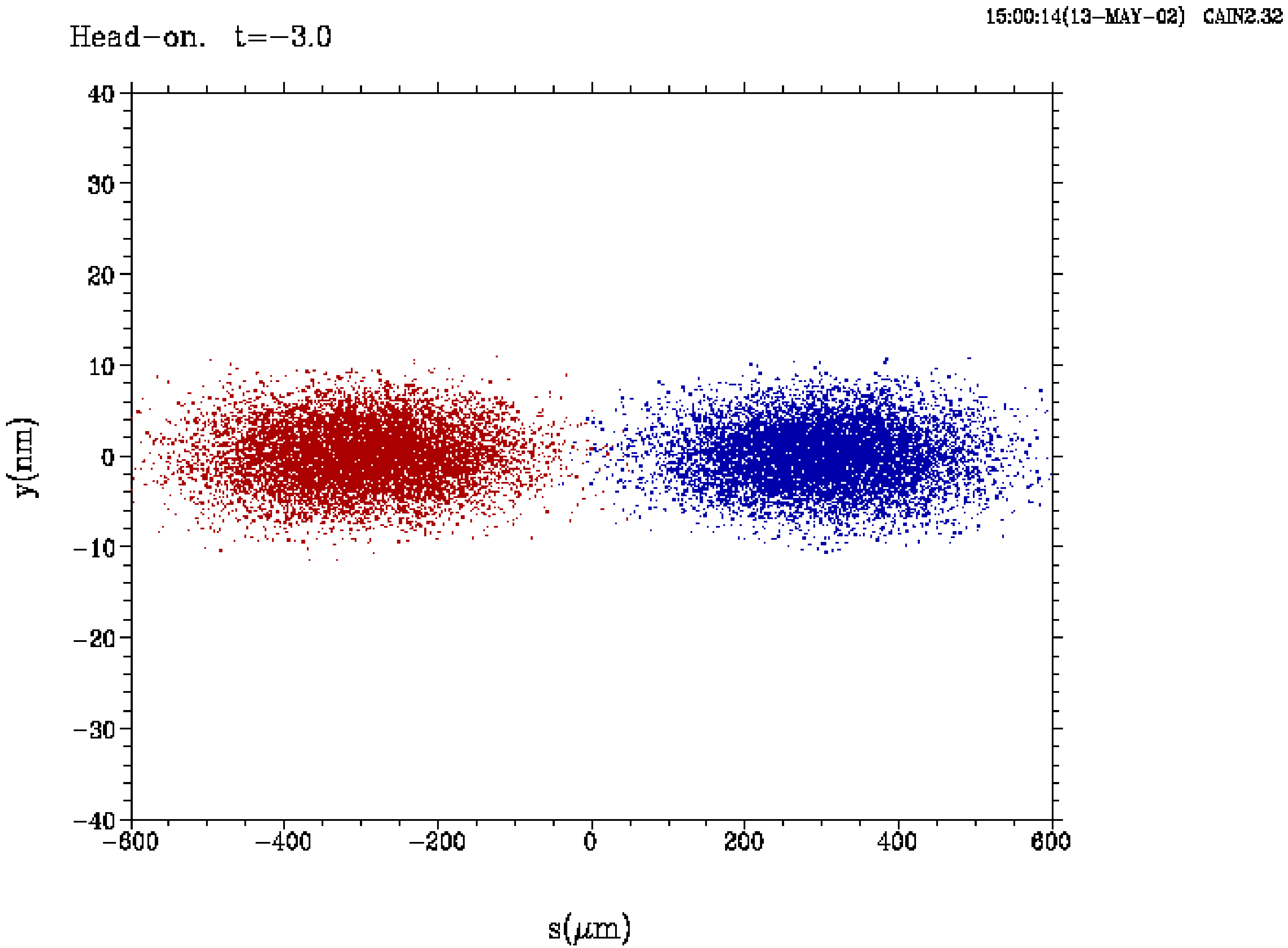
- 100 µm long
- 0.3 µm wide
- 0.003 µm (3 nm) thick

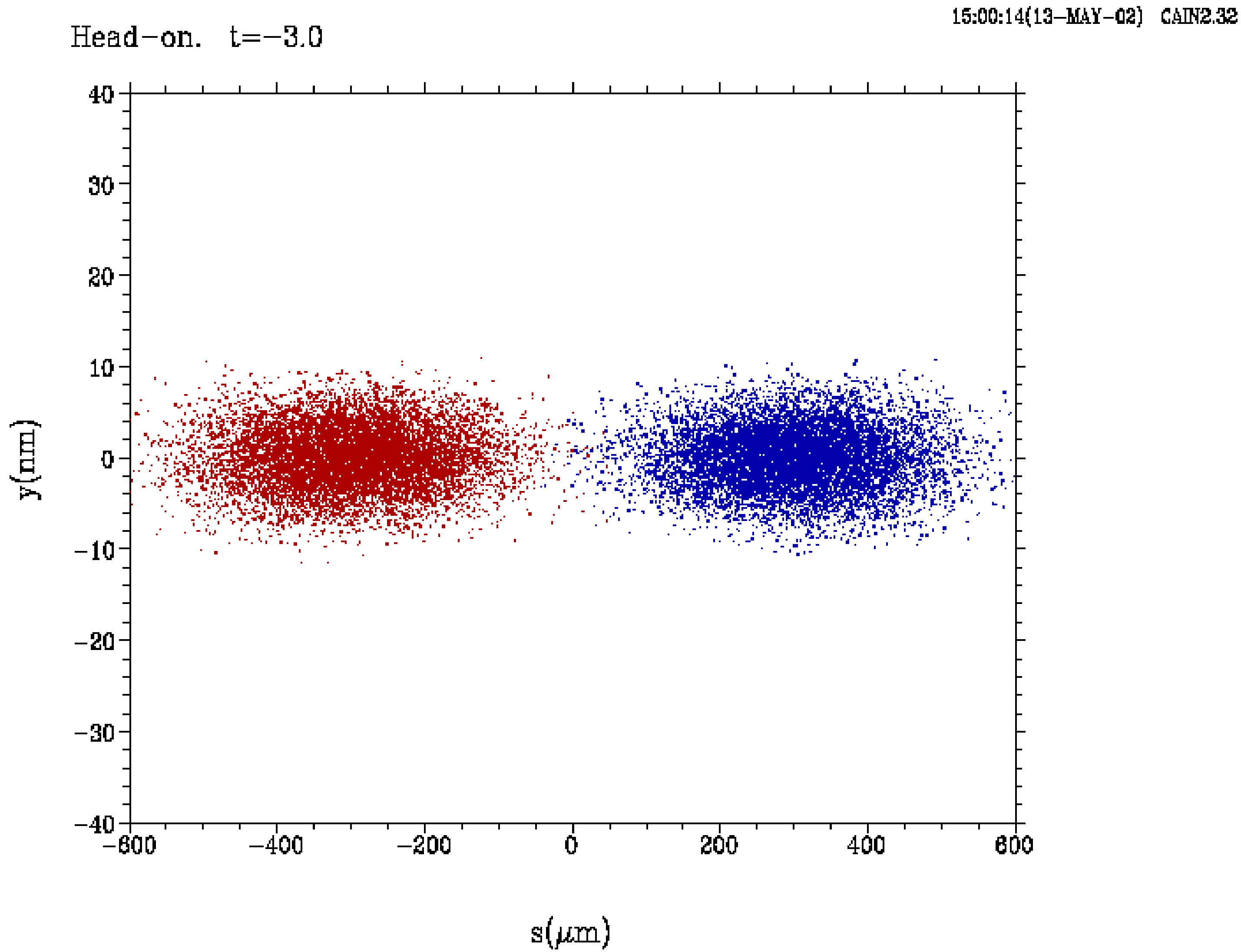
(These are RMS values)



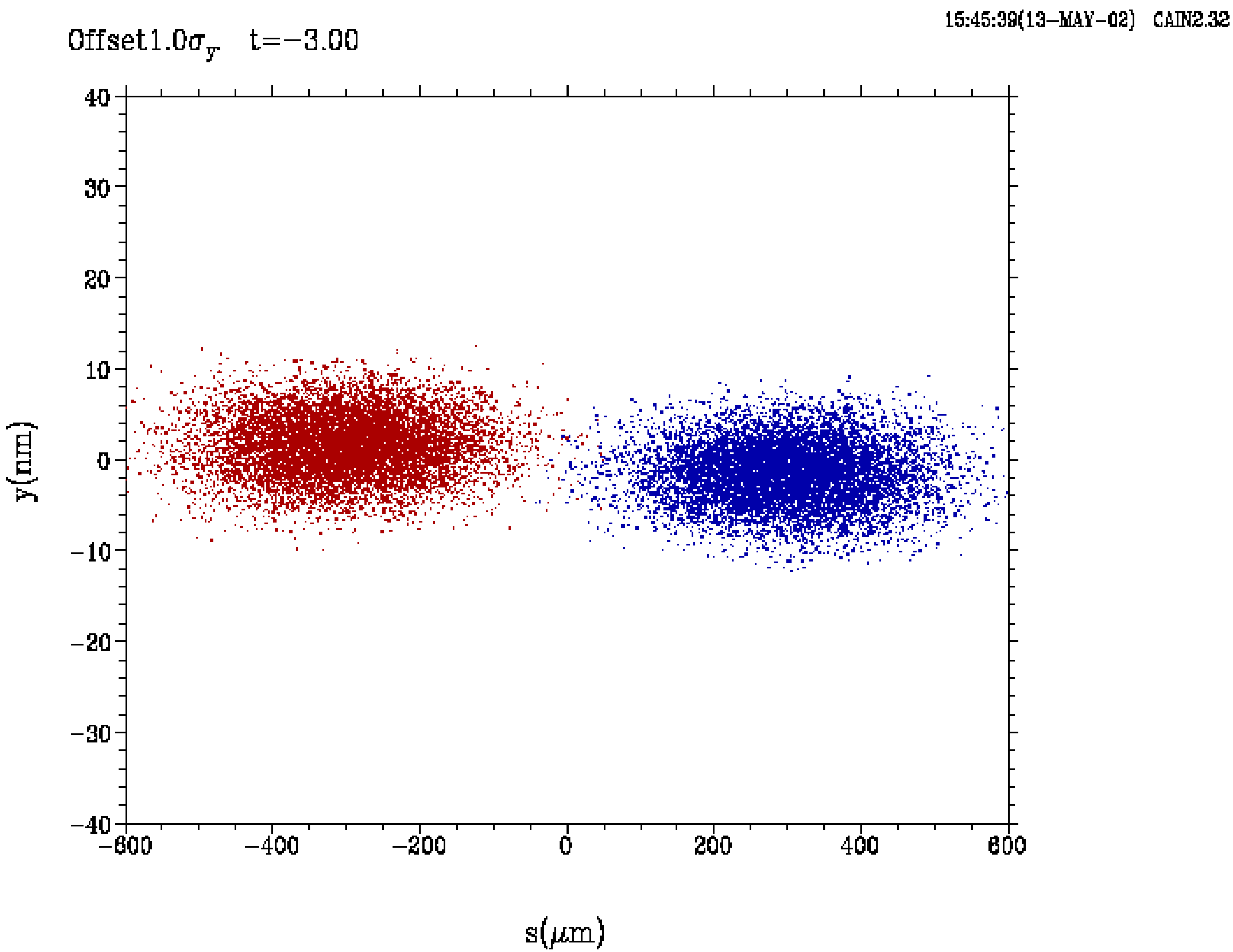
How can you keep them colliding ?

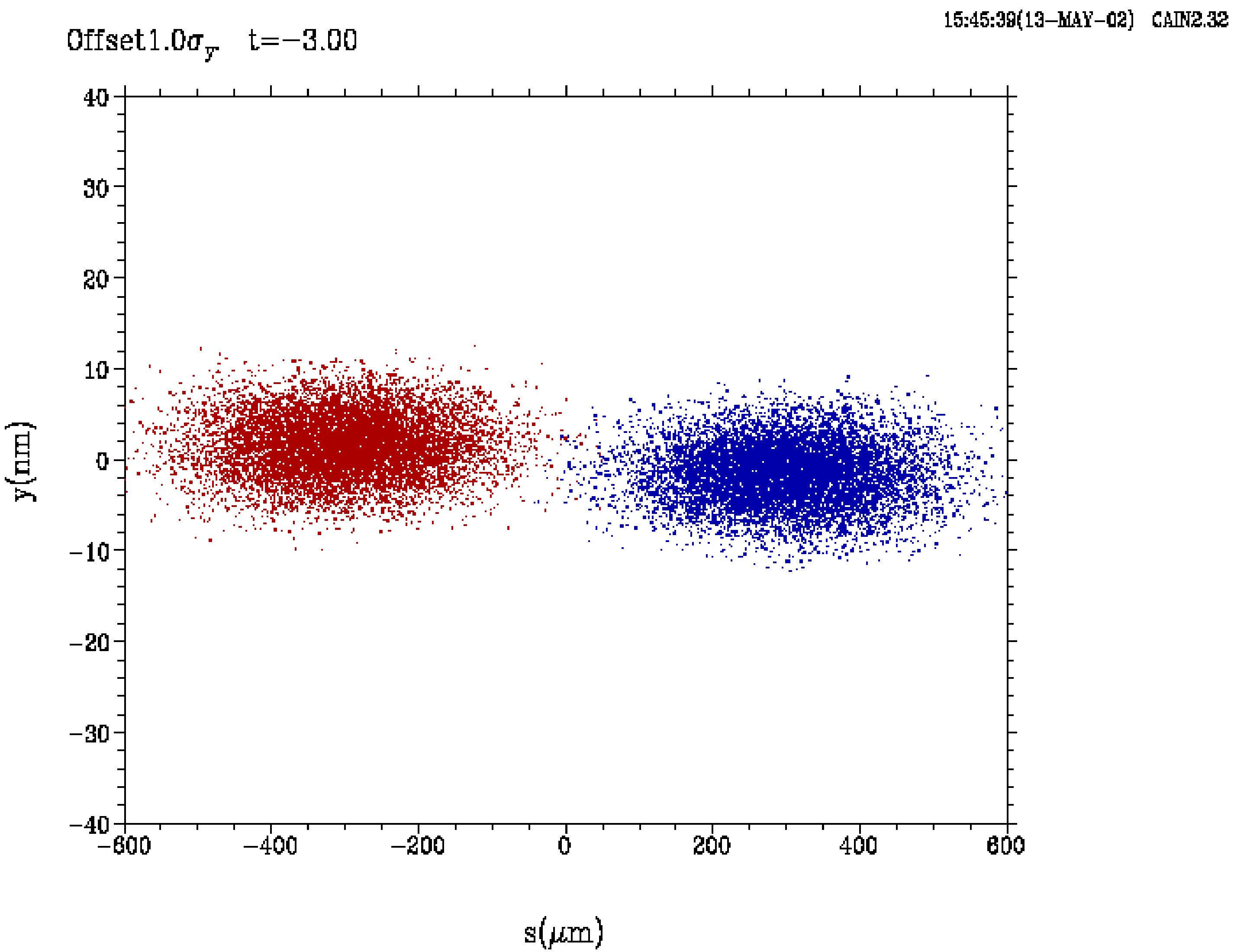
Beam-Beam Simulation



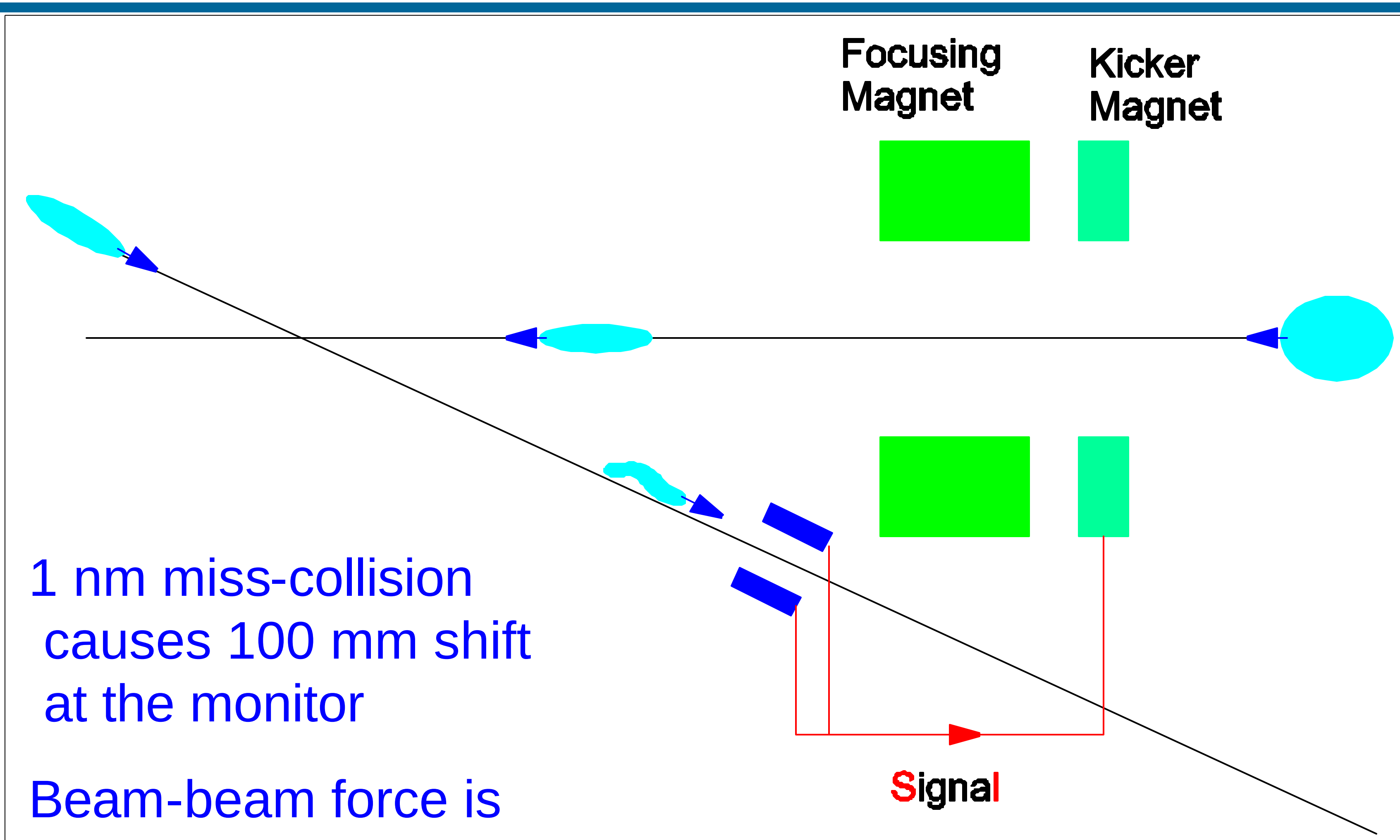


Head-on. t=-3.0
15:00:14(13-MAY-02) CAIN2.32
y(nm)
s(μm)
40
30
20
10
0
-10
-20
-30
-40
-600
-400
-200
0
200
400
600


Offset1.0σ_y t=−3.00
15:45:39(13−MAY−02) CAIN2.32
40
30
20
10
0
−10
−20
−30
−40
y(nm)
−600
−400
−200
0
200
400
600
s(μm)


Offset1.0σ_y t=−3.00
15:45:39(13−MAY−02) CAIN2.32
y(nm)
s(μm)
40
30
20
10
0
−10
−20
−30
−40
−600
−400
−200
0
200
400
600

Feedback System to Control nm-scale Collisions



- 1 nm miss-collision causes 100 mm shift at the monitor
- Beam-beam force is a 100,000 amplifier

Challenges for All

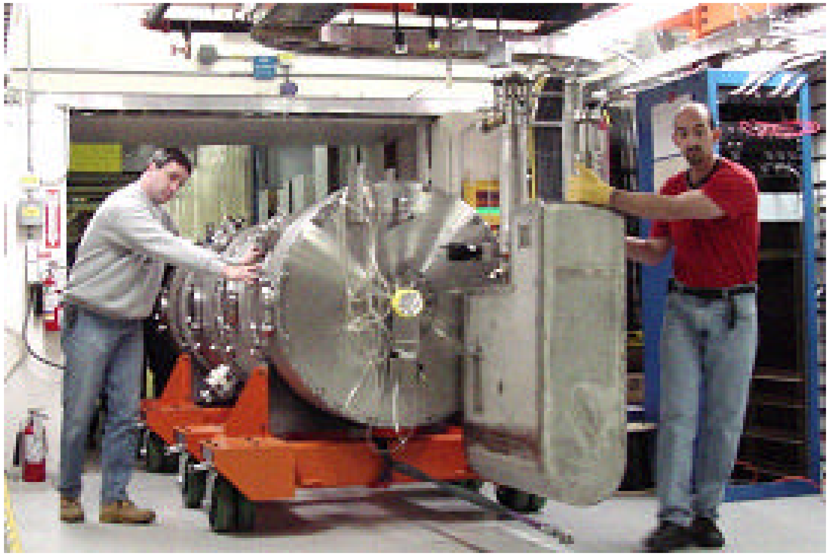
- Technical
  - Simplify design further
  - Reduce cost
- Socio-economic and Political:
  - Reduce ambition: energy and luminosity
  - If ~$1B – one country can host
  - If ~several B$ – international collaboration with several countries
  - Learn how to collaborate globally

Technologies for High Current Proton Drivers and Free Electron Lasers

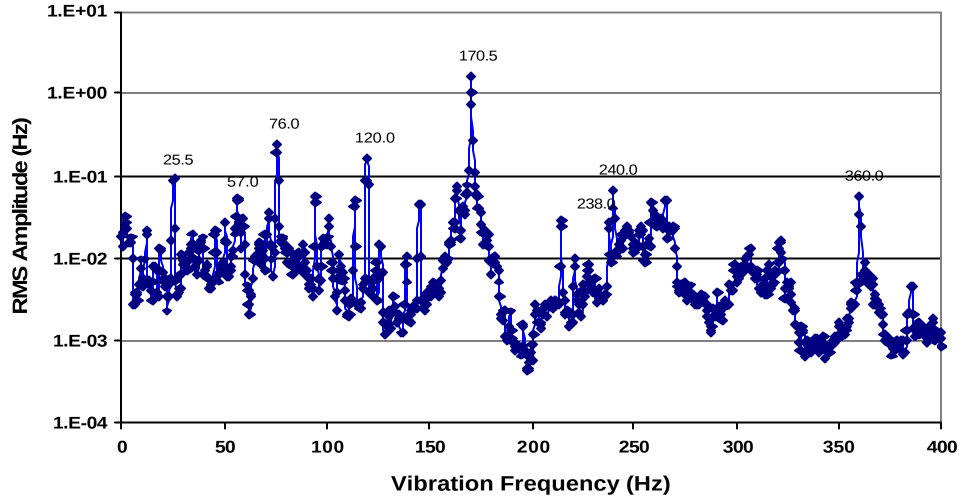
- Superconducting Radiofrequency Science and Technology
    - Spallation Neutron Source
    - Proposed 8 GeV Linac at FNAL
    - Free Electron Laser at Jefferson Lab
- High Current Guns
- High Power Optics / Laser Particle Beam Interactions

The Spallation Neutron Source Partnership

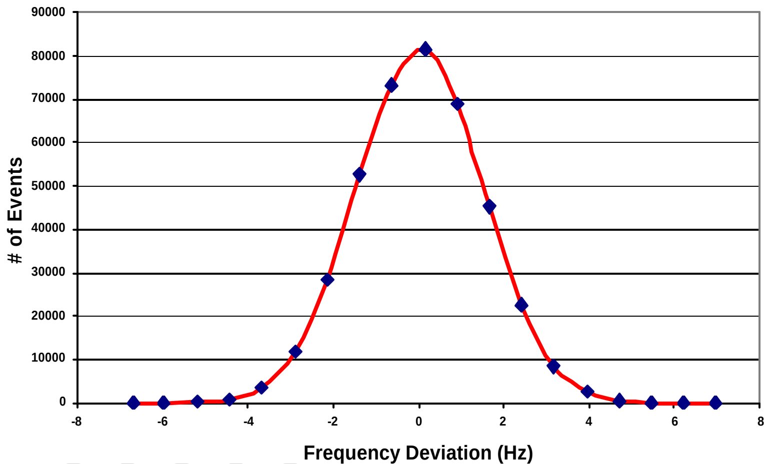
SNS

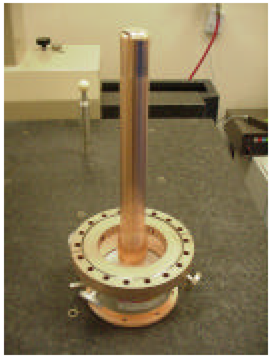


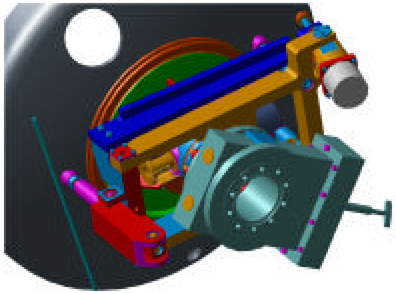
Background Microphonics, Med B Cryomodule Prototype,
Cavity Position 2 @ 1MV/m CW



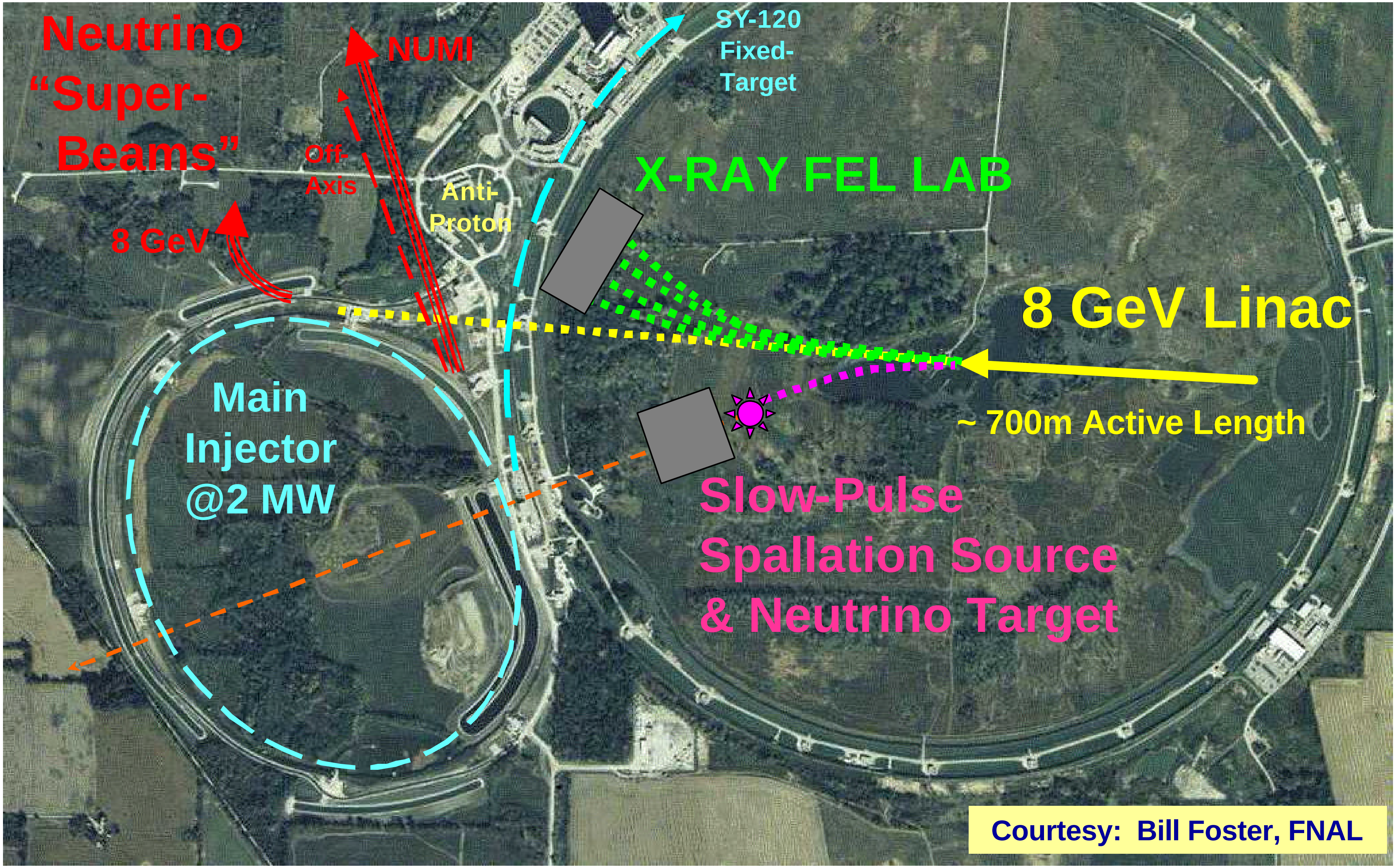
Background Microphonics Histogram
Med B CM Prototype, Cavity #2, CW @ 6MV/m



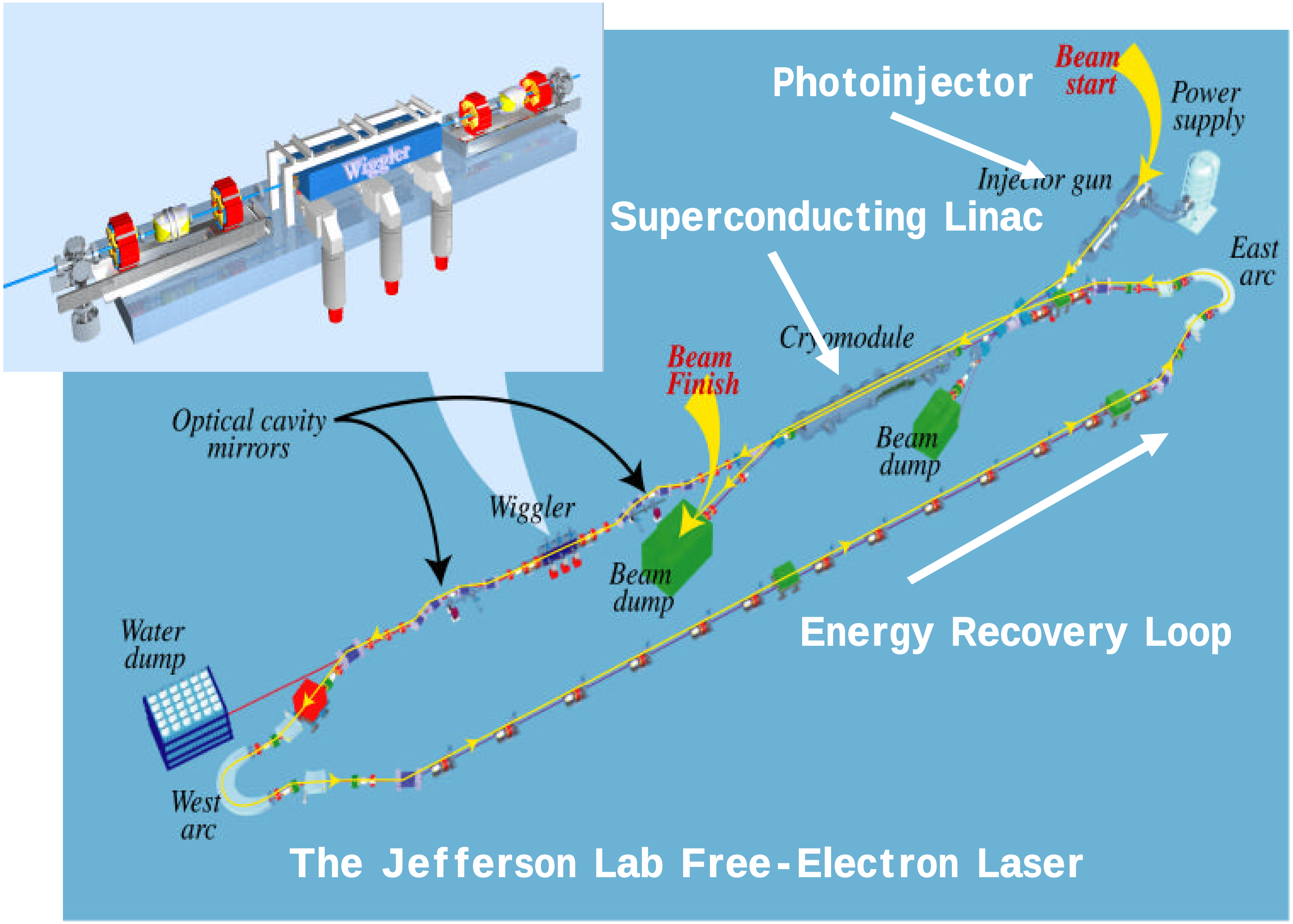




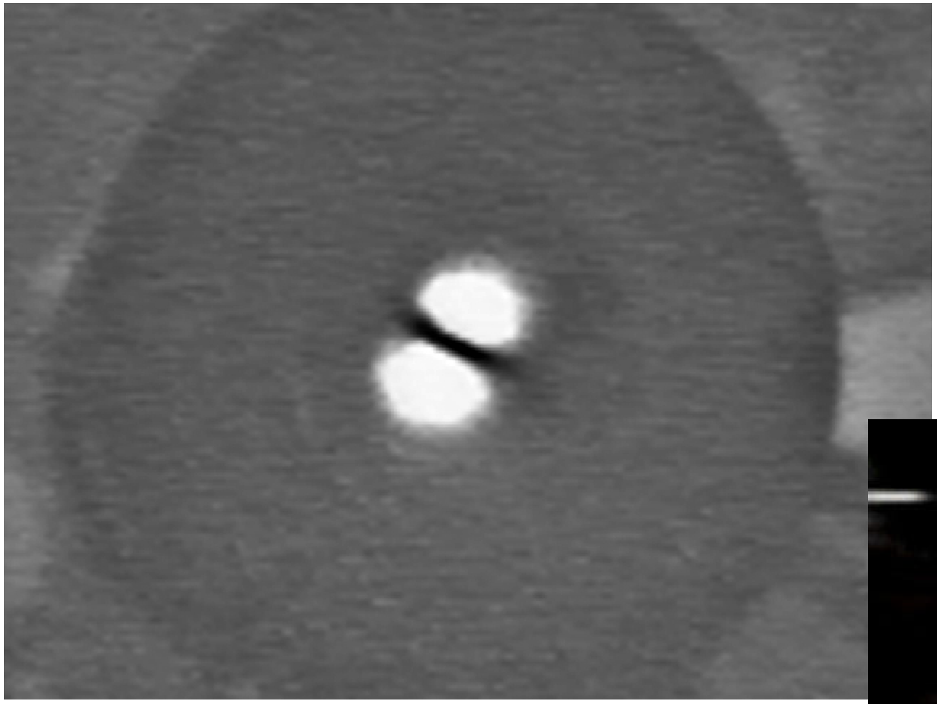
FNAL
8 GeV Superconducting Linac
With X-Ray FEL and 8 GeV Spallation & Neutrino Source



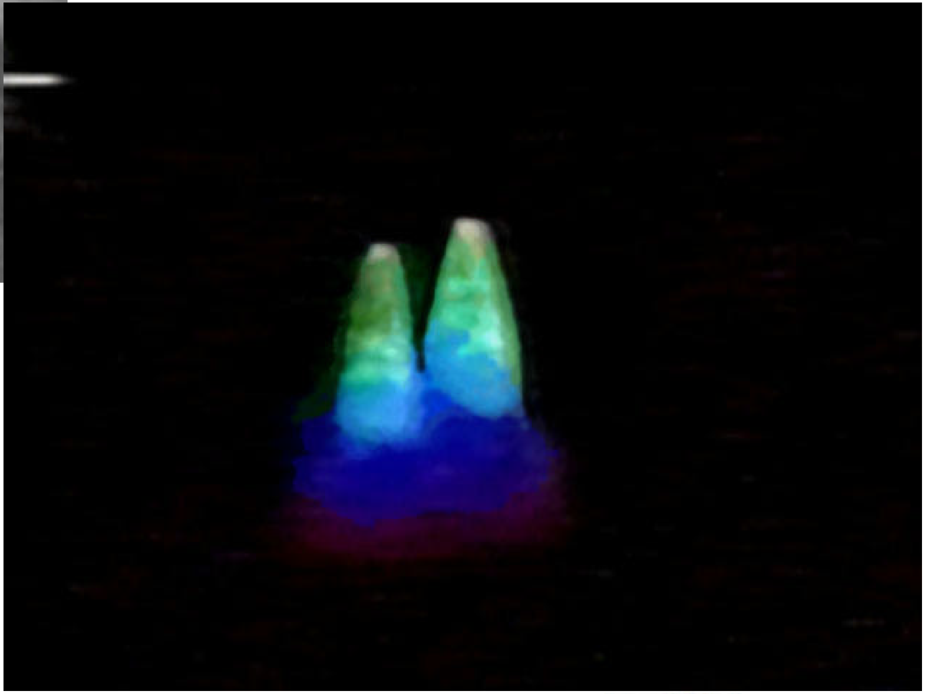
Harmonic Generation in Free Electron Lasers - IR Demo FEL at Jefferson Lab



Second Harmonic Lasing



- 2.925 microns, 0.6 micron detuning width
- 4.5 W average power
- TM01 or higher mode



$$t \approx 300\,\mathrm{fs}$$

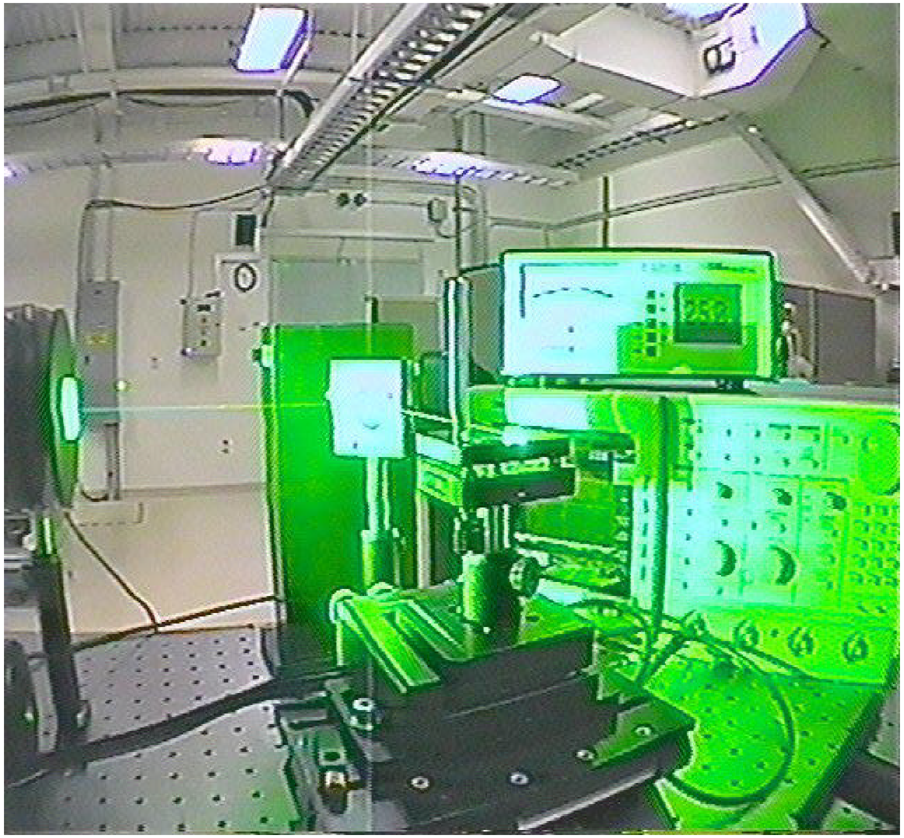
- Gain of 1.35% per pass

Submitted to PRL

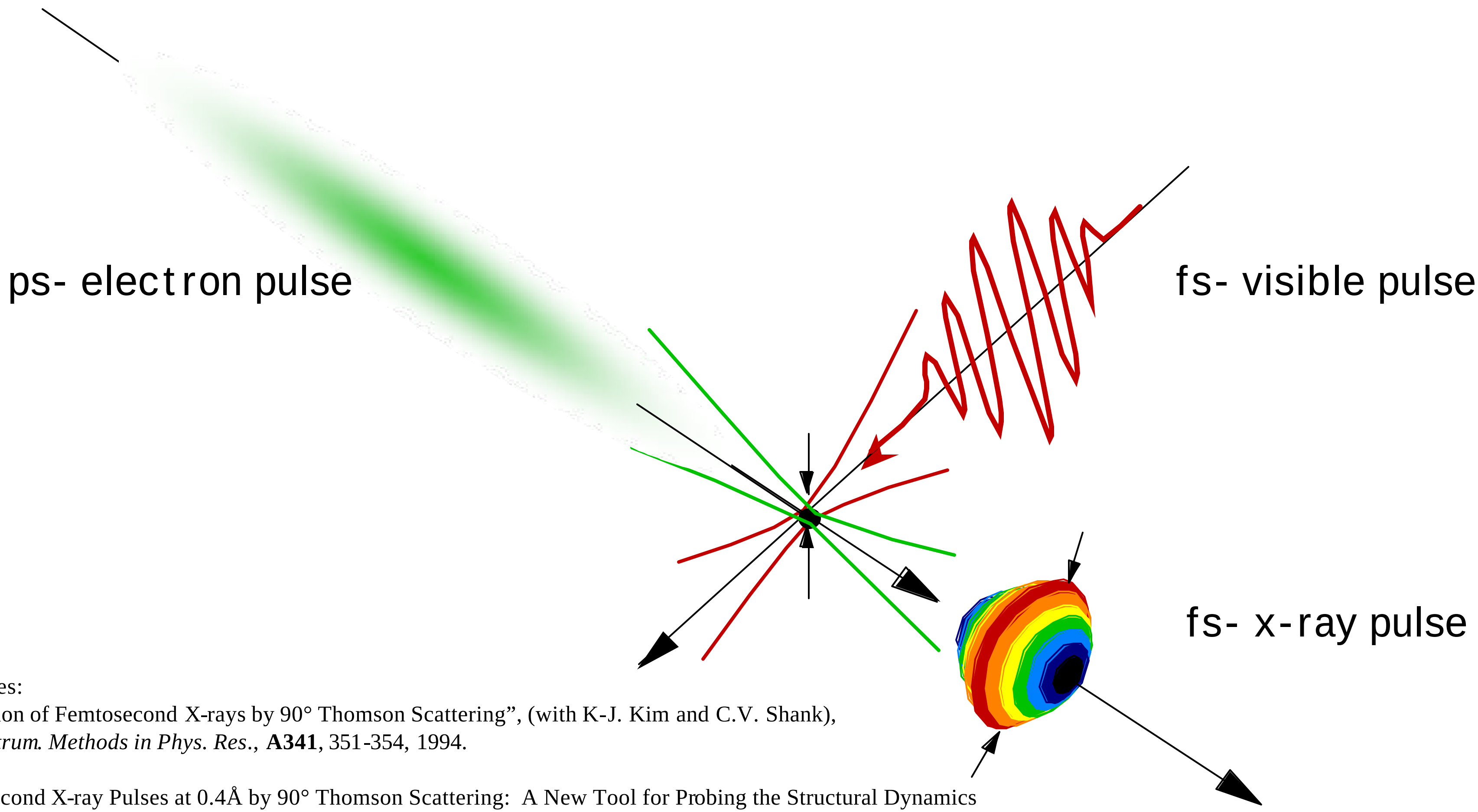
JLab FEL Harmonic Generation

Wavelength	Conversion efficiency	CW Power (Watts average)
Fundamental 3.165 μm	1.6% (ebeam:light)	1700*
Lasing 3rd Harmonic 1.055 μm	0.7% (ebeam:light)	350*
2x 528 nm	40%	56*
3x 352 nm	9%	12*
4x 264 nm	8%	17 (pulsed)

*World record for picosecond laser



Thomson Scattering for Femtosecond X-rays



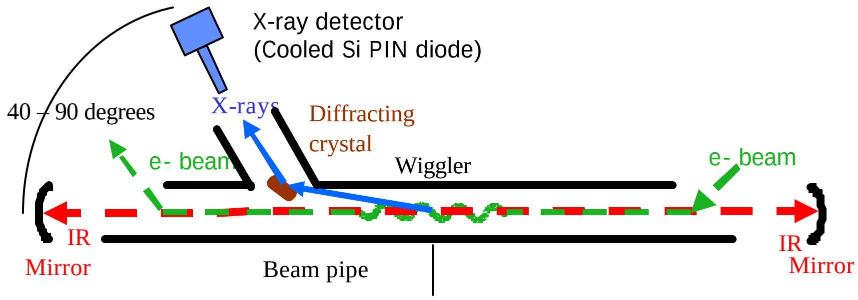
References:

"Generation of Femtosecond X-rays by 90° Thomson Scattering", (with K-J. Kim and C.V. Shank), *Nucl. Instrum. Methods in Phys. Res.*, **A341**, 351-354, 1994.

"Femtosecond X-ray Pulses at 0.4Å by 90° Thomson Scattering: A New Tool for Probing the Structural Dynamics of Materials", (with R. Schoenlein, et. al), *Science*, **274**, 11 Oct. 1996, p. 236.

"X-ray based Sub-Picosecond Electron Bunch Characterization using 90° Thomson Scattering", (with W. Leemans, et al), *PRL*, Vol. **77**, page 4182, 1996.

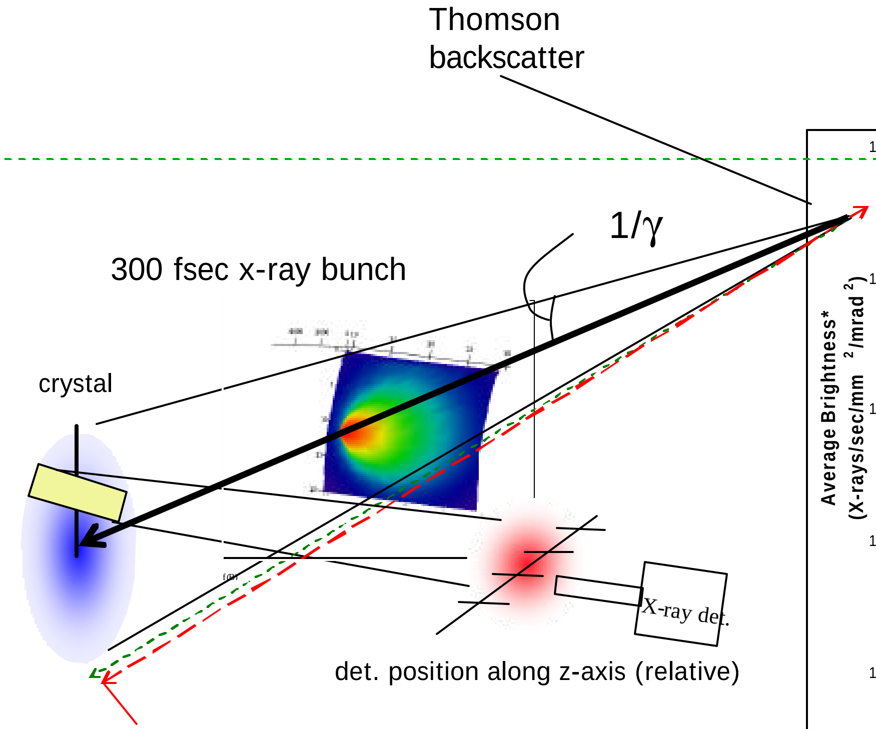
X-rays from IR DEMO at Jefferson Lab

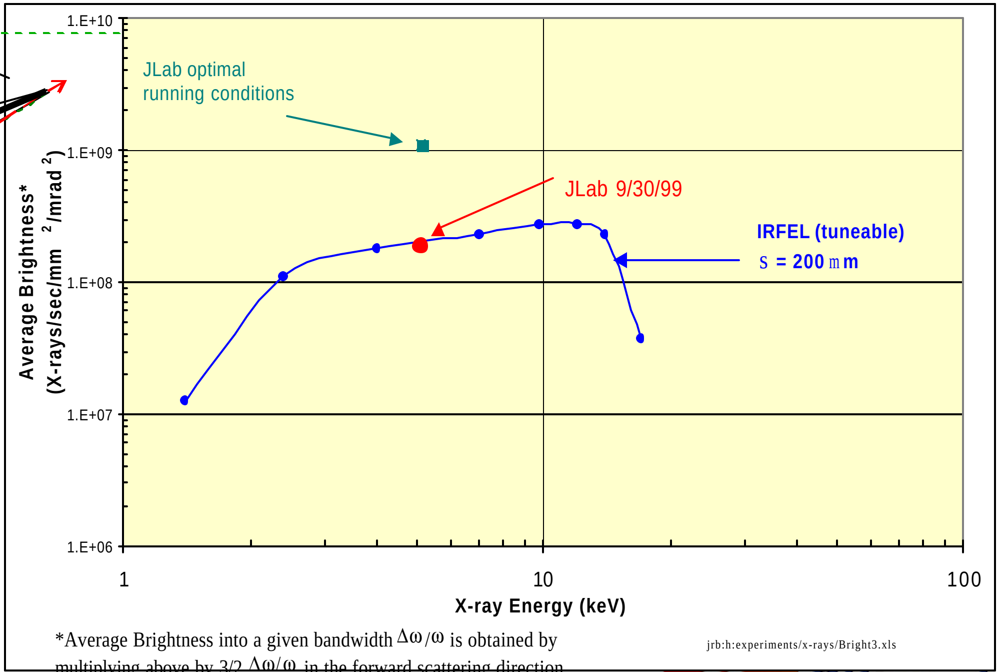


Potential Fields of Research

Femtosecond X-ray probe for:

- **Solid State Physics/Material Science**
  - **Temporal dynamics of condensed matter phase transitions.**
  - **Monitoring structural changes in materials with ultra-fast time resolution.**
  - **Heat propagation at sub-micron dimensions.**
- **Biology & Chemistry**
  - **Short-range order changes in chemical reactions.**

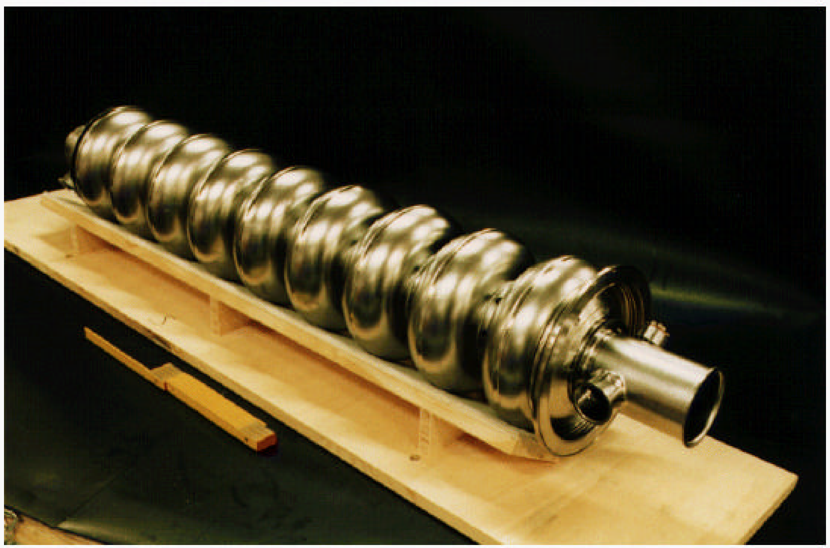




Two Pivotal Technologies for ERL/FEL

Superconducting RF cavities

(Q ~ 10^{10} @ 20 MV/m)



TTF 9-cell 1.3 GHz cavity

(courtesy of DESY)

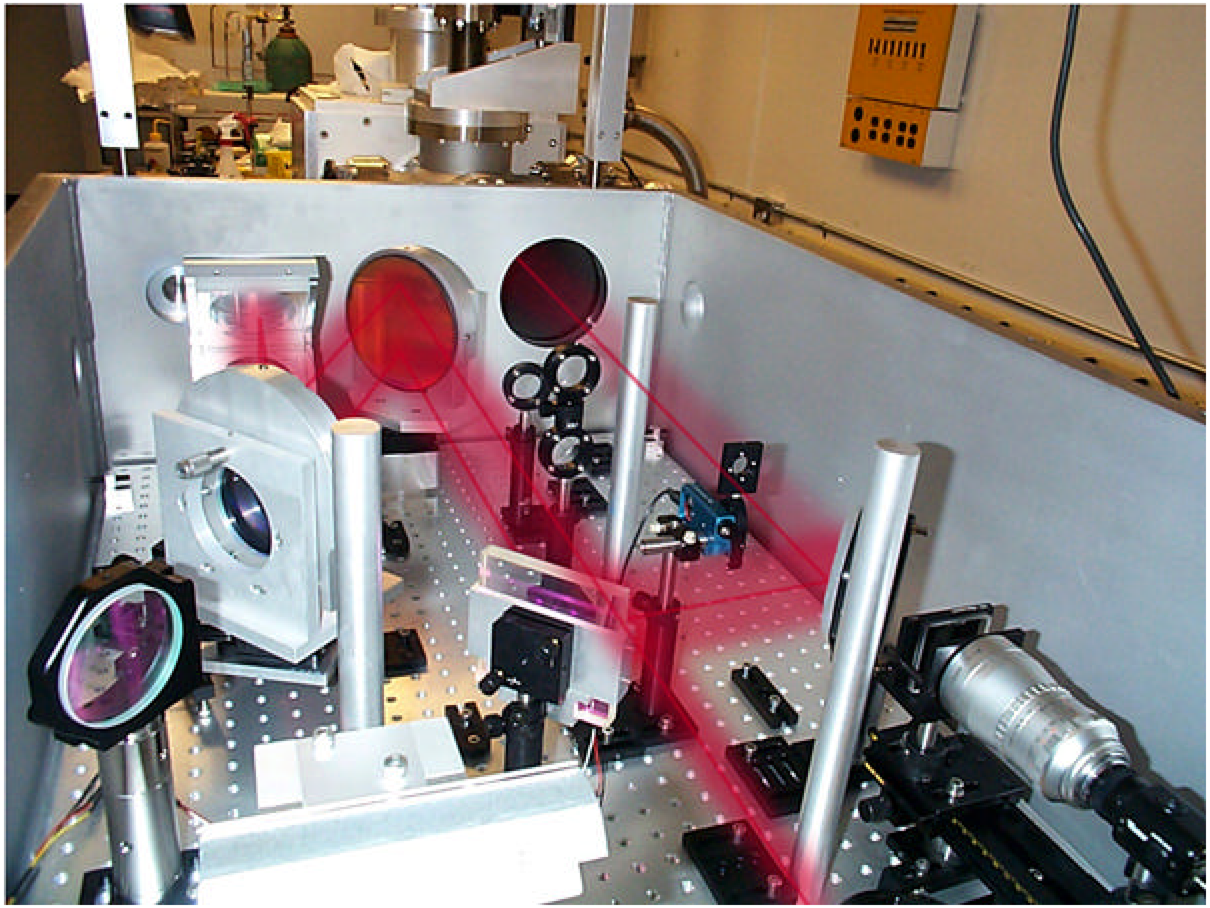
Laser-driven photoinjector

(ε_n ~ μm @ 100 mA)

DC photogun at JLAB IR FEL

(courtesy of JLAB)

Femtosecond Laser System



Pulse energy: 500 mJ

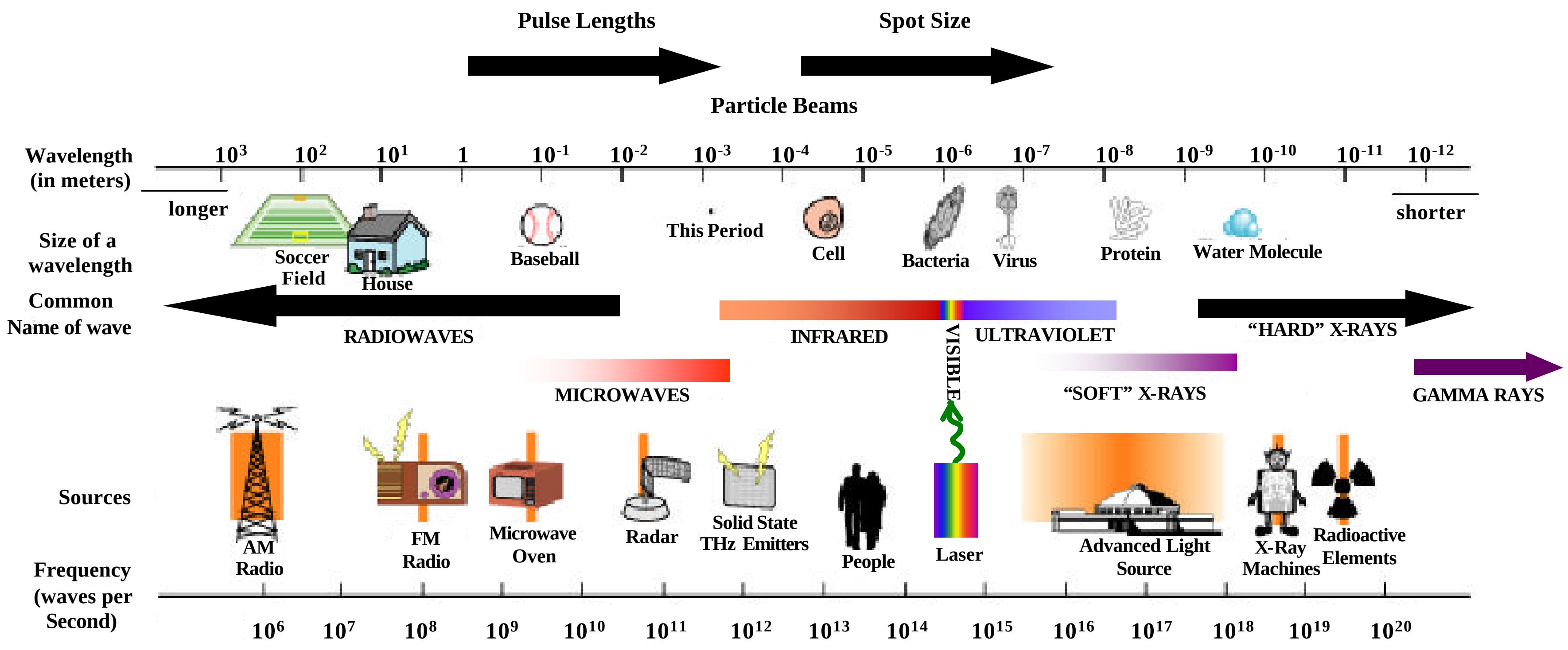
Pulse length: >50 fs

$\Rightarrow$ Power ~ 10 TW

Manipulation of Particle Beams for all these applications needs to take full advantage of

THE ELECTROMAGNETIC SPECTRUM

from the microwave to the visible via various technologies: normal conducting and superconducting microwave cavities, short pulse, high power lasers and sophisticated feedback/control systems.



We invite scientists from institutions across India to collaborate globally in advancing the R&D frontier and participate in possible future international facilities.