From Quark Confinement to Protein Dynamics via Nano-beams and Attosecond Pulses

A Theme with Variations on Microwave Superconductivity and Energy Recovery

Swapan Chattopadhyay
Associate Director, Jefferson Lab

Inaugural Lecture
for the
John Adams Institute of Accelerator Science at
Oxford/RHUL

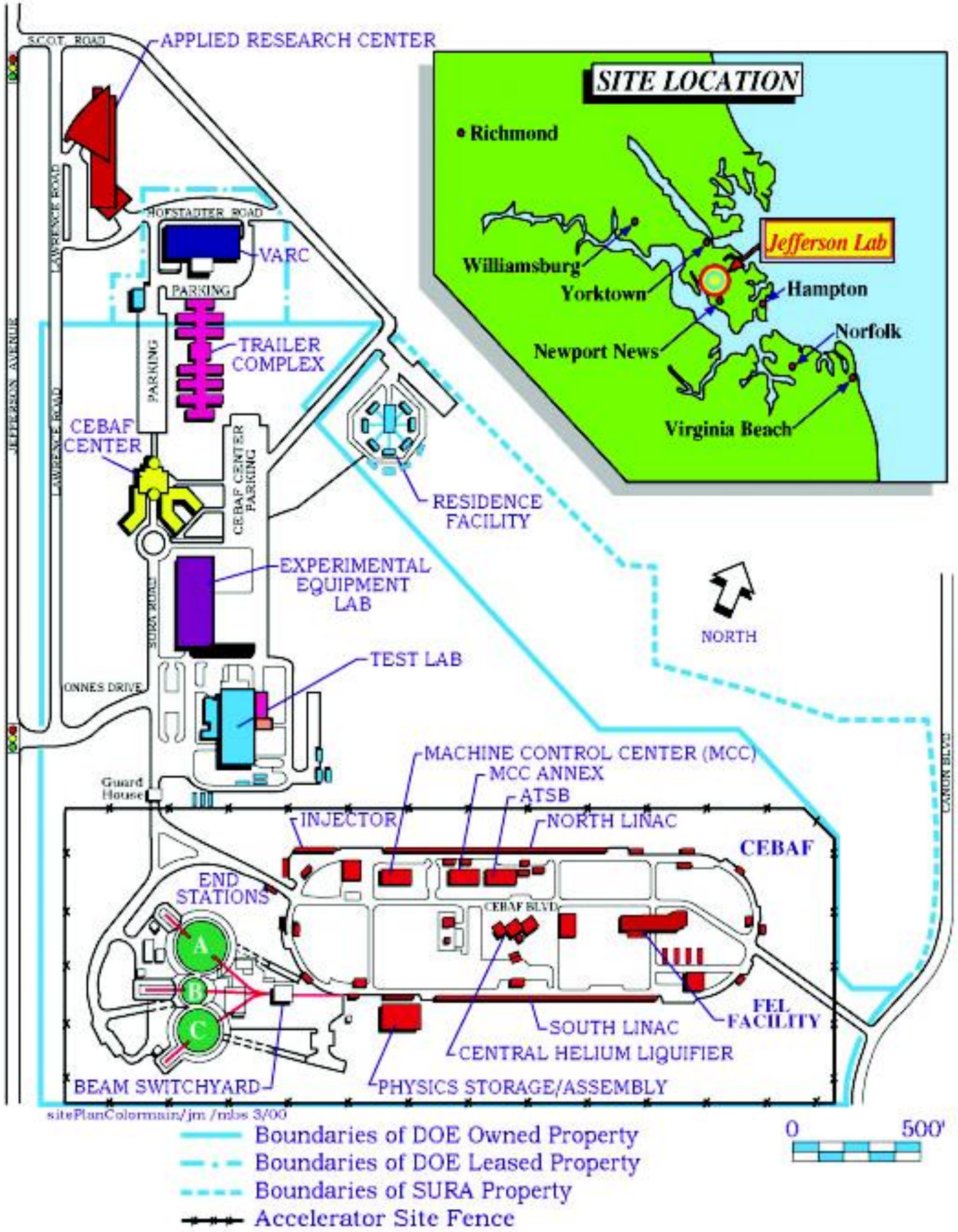
Oxford University
October 25, 2004

OUTLINE

- Introduction to Jefferson Lab and its activities
- Motivation for CEBAF Energy Upgrade 6 GeV → 12 GeV
- Control of Lorentz Detuning in High Gradient SRF linacs:
  12 GeV Upgrade and ILC
- Ultrabright via Energy Recovery
  - Acceleration and Radiation in Vacuum
  - Energy Recovery in JLab FEL and CEBAF
  - Future Prospects with Energy Recovering Linacs
- Ultrashort Probes
  - Science
  - Generation Mechanisms
- Ultracold Beams
  - Microwave and Optical Stochastic Cooling
- Outlook

Facility

Jefferson Lab Site

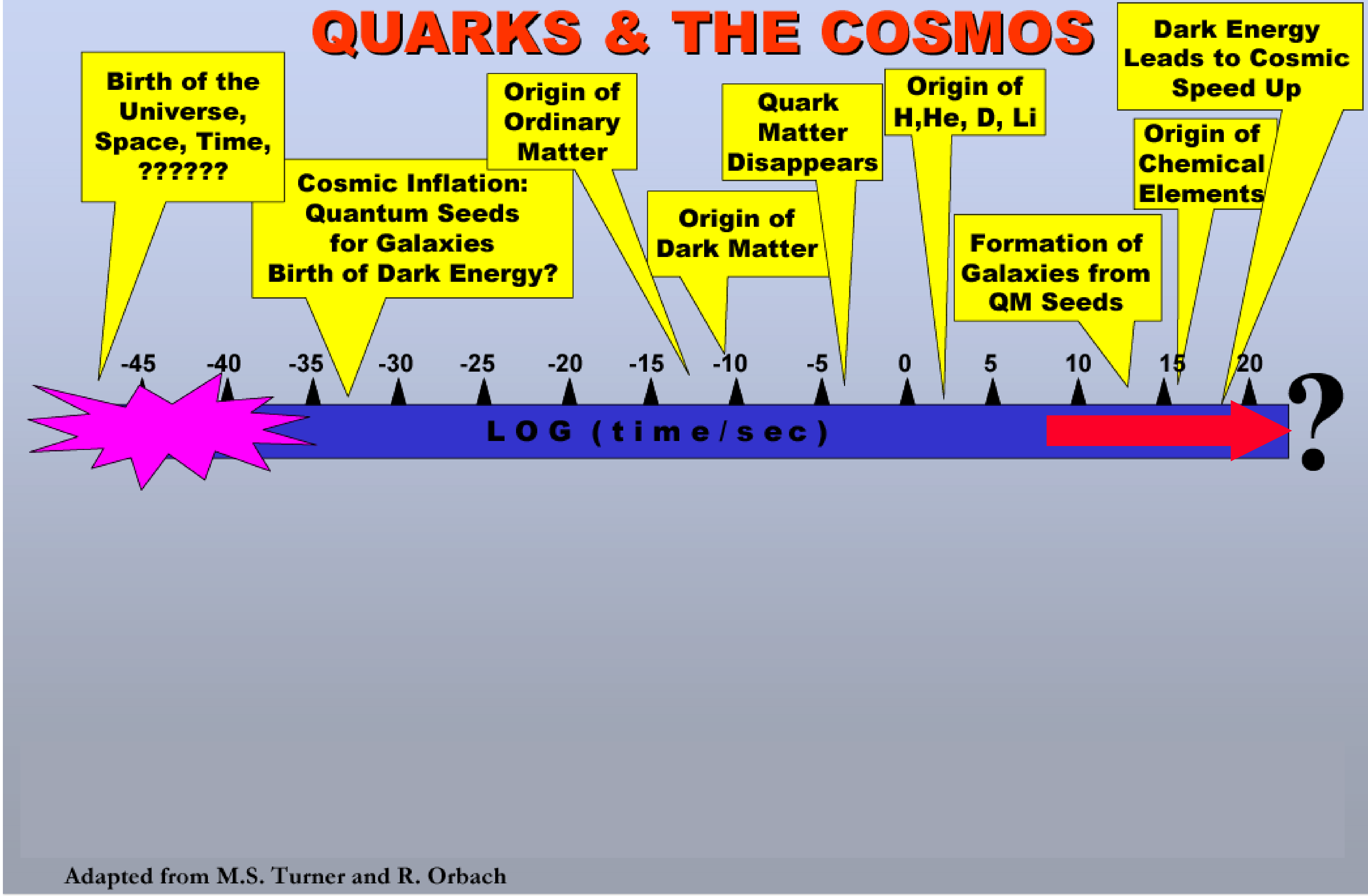


Core Activities

- Nuclear/Particle Physics
- Photon Sciences: synchrotron radiation and FELs
- Microwave Superconductivity: superconducting radiofrequency technology
- Accelerator Physics

(youngest of the 10 national laboratories of pure science in the DOE Office of Science Complex)

DEEP CONNECTIONS:
QUARKS & THE COSMOS



Birth of the Universe, Space, Time, ??????

Cosmic Inflation: Quantum Seeds for Galaxies
Birth of Dark Energy?

Origin of Ordinary Matter

Origin of Dark Matter

Quark Matter Disappears

Origin of H,He, D, Li

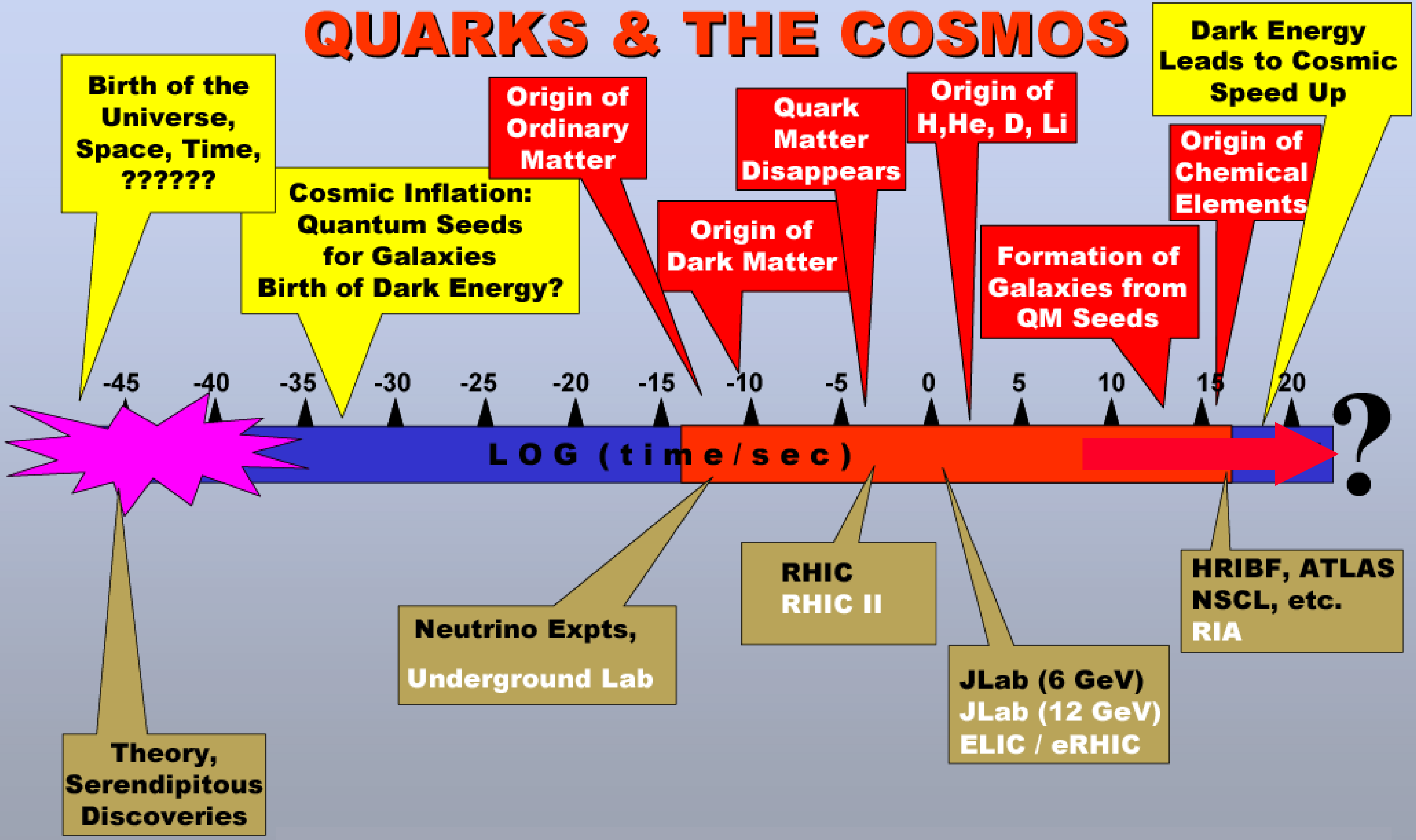
Formation of Galaxies from QM Seeds

Origin of Chemical Elements

Dark Energy Leads to Cosmic Speed Up

Adapted from M.S. Turner and R. Orbach

DEEP CONNECTIONS: QUARKS & THE COSMOS



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Theory, Serendipitous Discoveries

Neutrino Expts,
Underground Lab

RHIC
RHIC II

JLab (6 GeV)
JLab (12 GeV)
ELIC / eRHIC

HRIBF, ATLAS
NSCL, etc.
RIA

Adapted from M.S. Turner and R. Orbach

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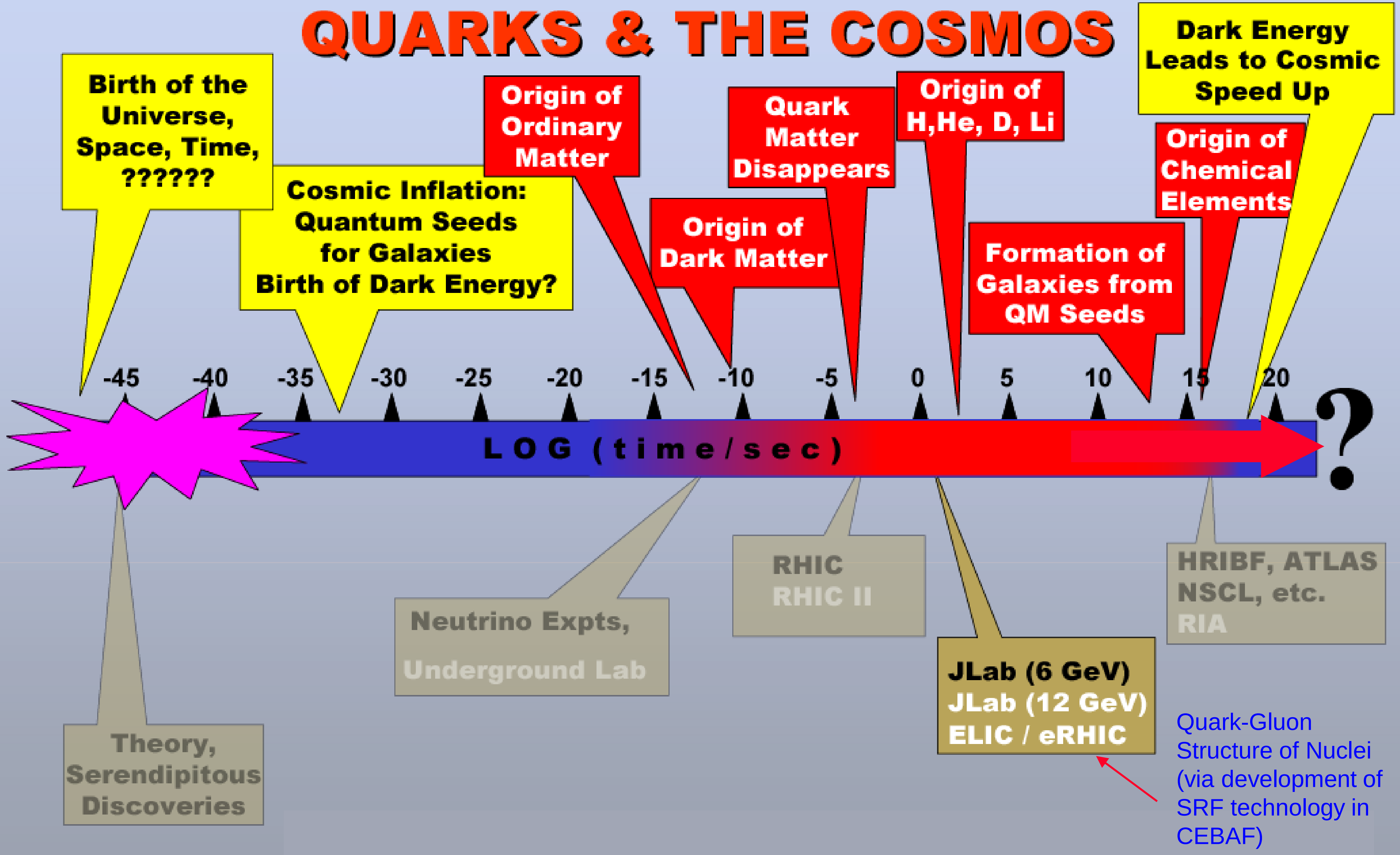

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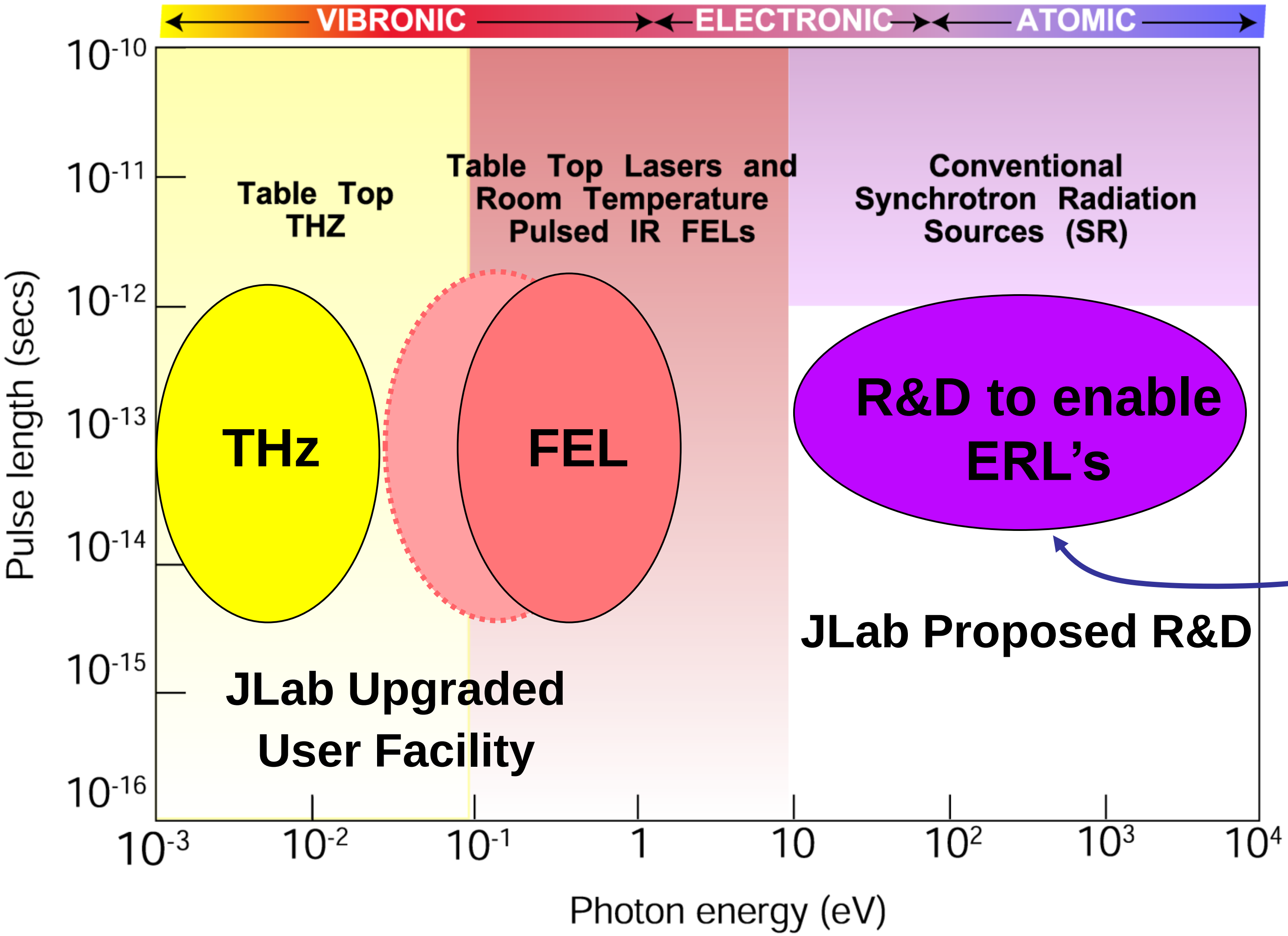
Quark-Gluon Structure of Nuclei (via development of SRF technology in CEBAF)

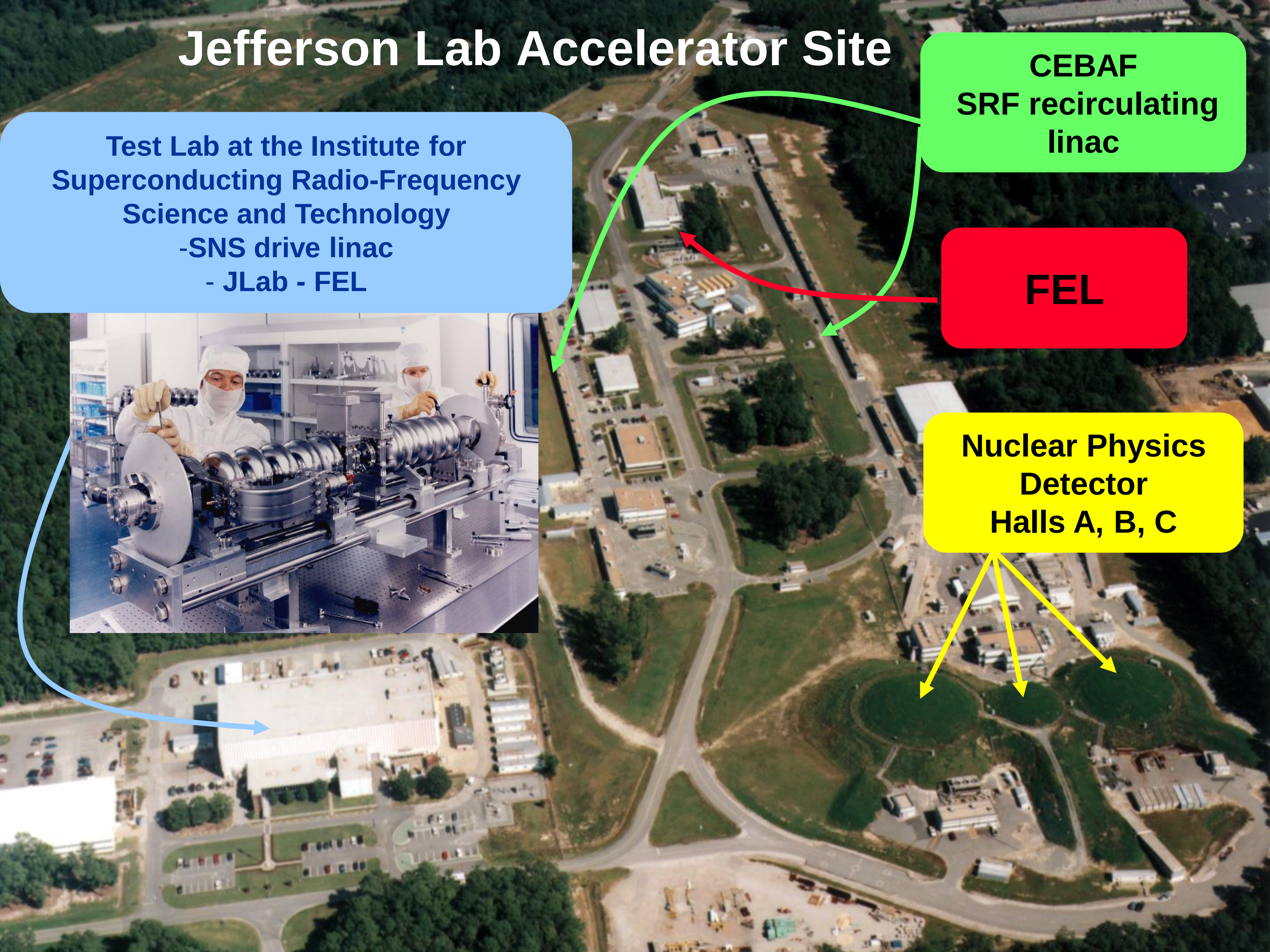
Adapted from M.S. Turner and R. Orbach

Canvas of Photon Sciences



Accelerator Physics and SRF technology

Jefferson Lab Accelerator Site



Test Lab at the Institute for Superconducting Radio-Frequency Science and Technology
-SNS drive linac
- JLab - FEL

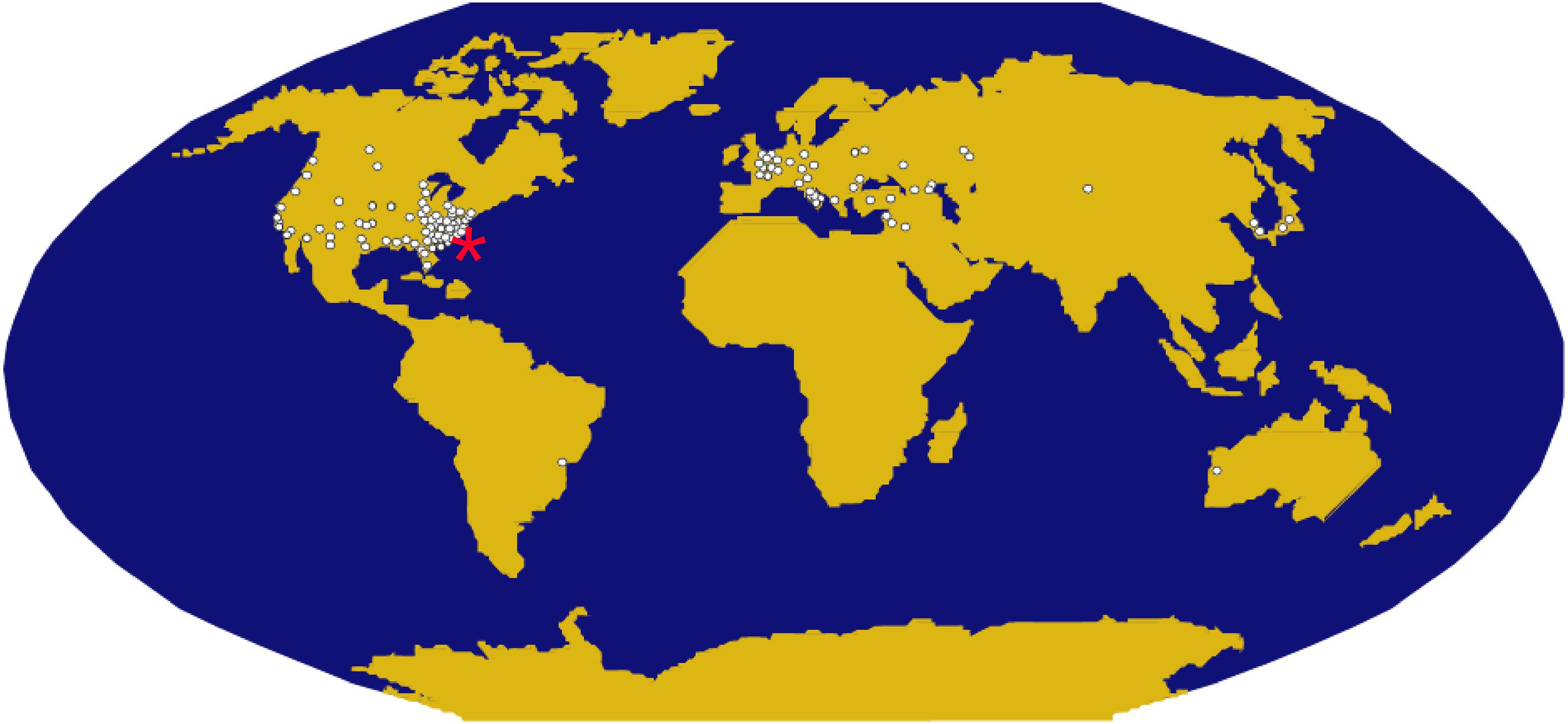
CEBAF
SRF recirculating linac

FEL

Nuclear Physics Detector
Halls A, B, C

Applied Research Center: *A Model Incubation Center for University, Industry, Local Business and National Laboratory*

JLab is the Leading International Facility in Hadronic Physics



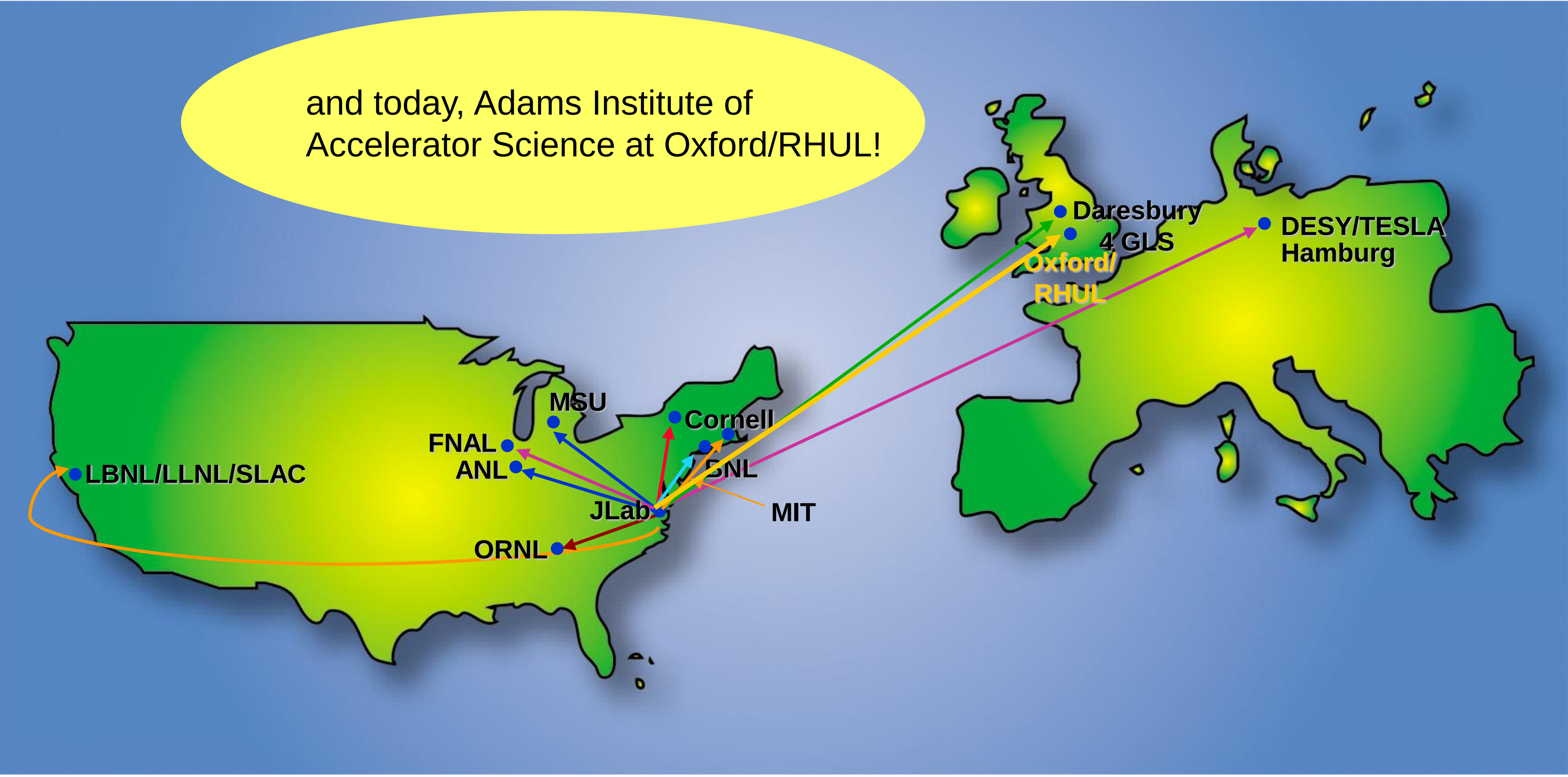
- Our approved research program involves half of our 2100 member user community:

1011 scientists from 167 institutions in 29 countries

US Spallation Neutron Source: A model B$ class collaboration

…JLab has developed the requirements to aggressively pursue a construction plan that meets the original delivery dates…The team, continues to work closely with Oak Ridge National Laboratory, Lawrence Berkeley National Laboratory, Brookhaven National Laboratory, Los Alamos National Laboratory, and Argonne National Lab to pursue construction and testing activities and meet schedule milestones…

Accelerator Physics Collaborations



1 – RIA (MSU, ANL)
2 – TESLA (DESY, FNAL)
3 – ERL Prototype (Cornell)

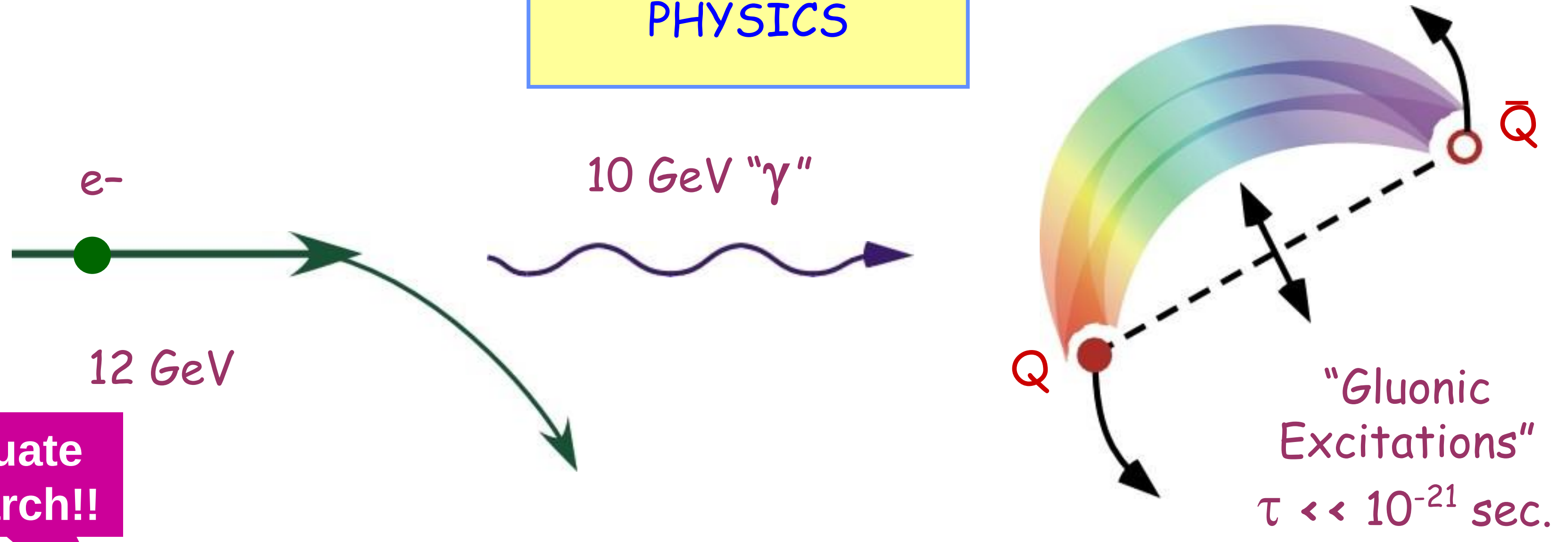
4 – 4 GLS (Daresbury)
5 – RHIC II (BNL)
6 – Femtosource (LBNL, LLNL,MIT)

7 – SNS (ORNL)
8 – ILC (SLAC,FNAL,..)
9 – Adams Inst. of Accel. Science (Oxford/RHUL)

CEBAF Energy Upgrade from 6 GeV to 12 GeV: Approved DOE near-term project: Color Mapping in QCD

NUCLEAR
PARTICLE
PHYSICS

Exotic Meson spectroscopy with "gluon degrees of freedom excited"

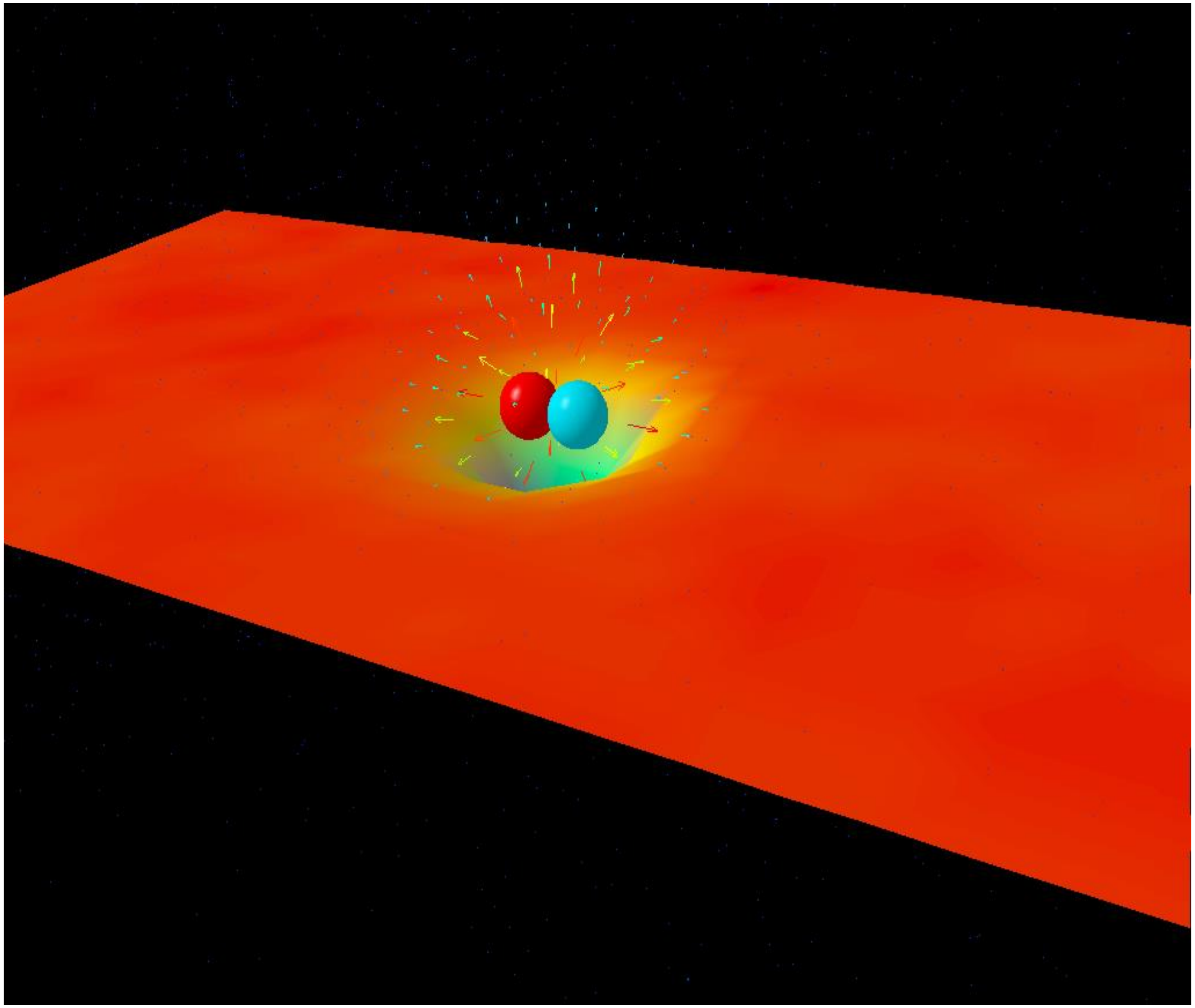


Graduate Research!!

Strategic Simulation: Lattice-gauge QCD Code

Possible at JLab's 12 GeV Upgrade of CEBAF.

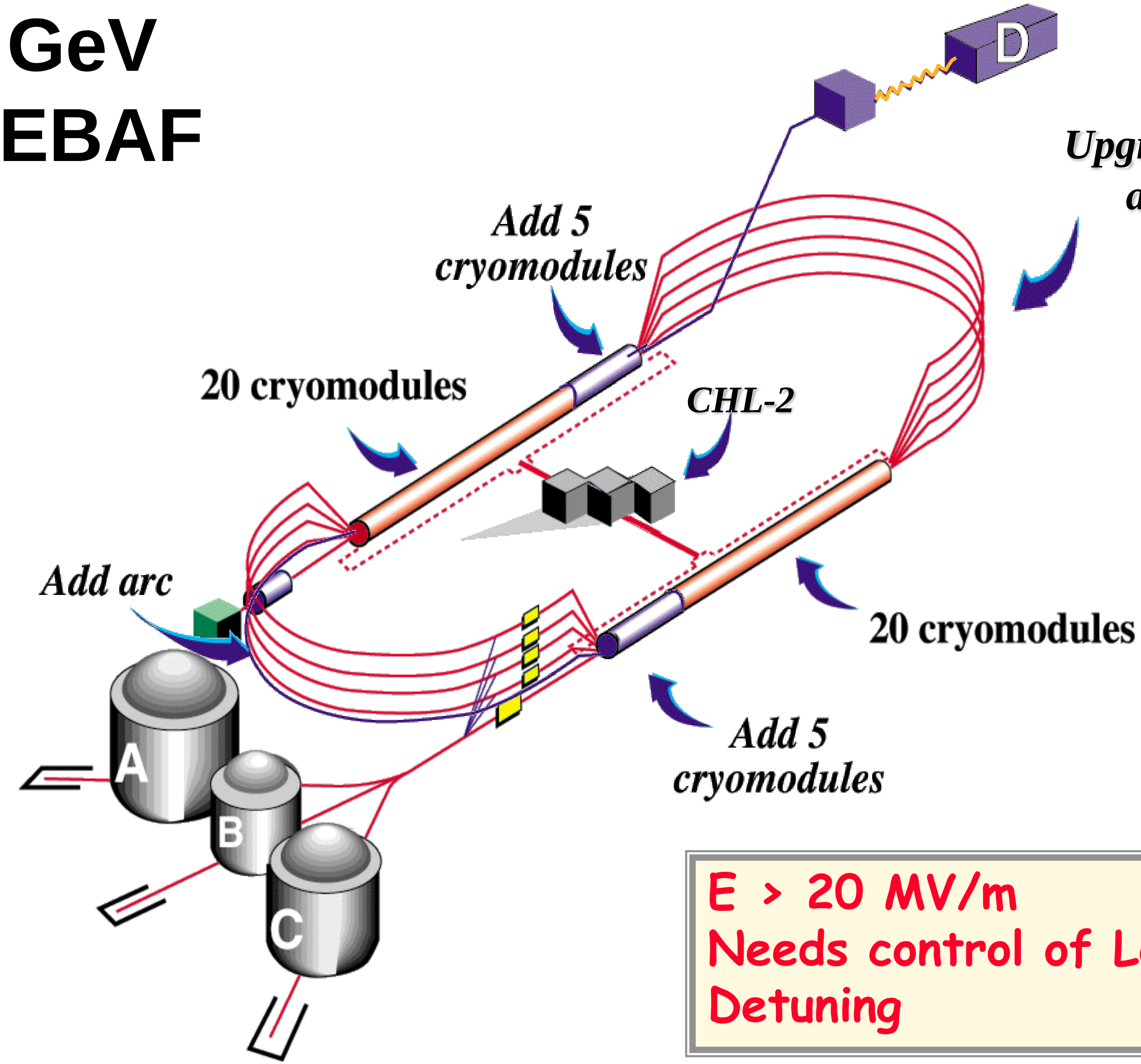
Quark-Anti-Quark Flux Tube: “String”



Experimental Understanding of “Quark Confinement”

Lasscock, Leinweber, Thomas & Williams

12 GeV CEBAF



Upgrade magnets and power supplies

Add 5 cryomodules

20 cryomodules

CHL-2

Add arc

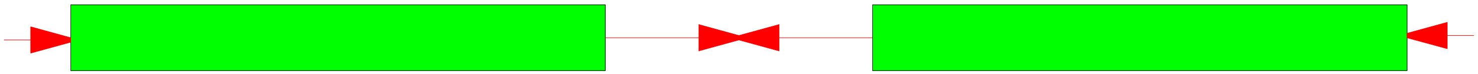
20 cryomodules

Add 5 cryomodules

E > 20 MV/m
Needs control of Lorentz Detuning

Lorentz Detuning Expected in the International Linear Collider

- Use 2 linear accelerators

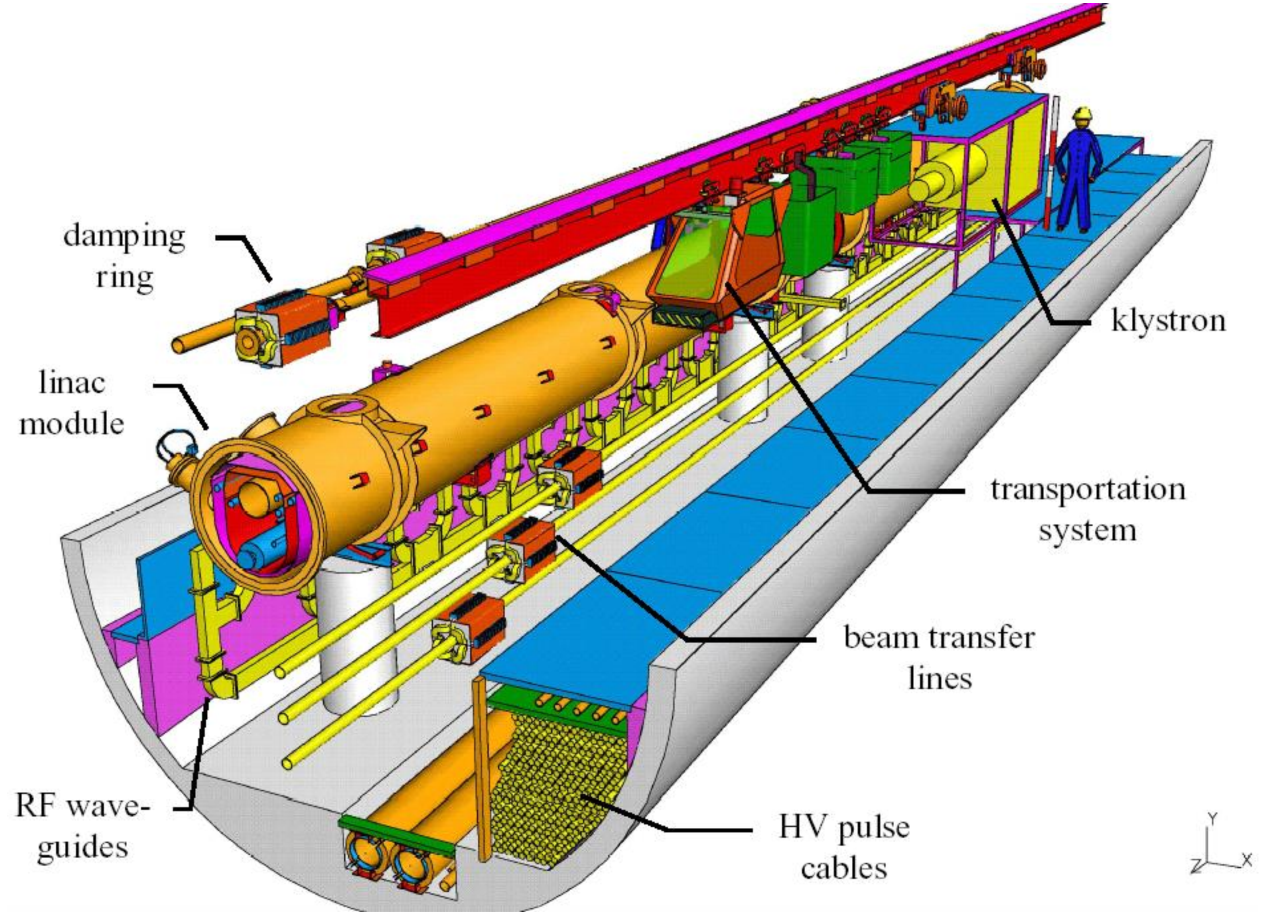


- Throwaway beam
- Repeat
  - beam generation
  - acceleration
  - collision

quickly

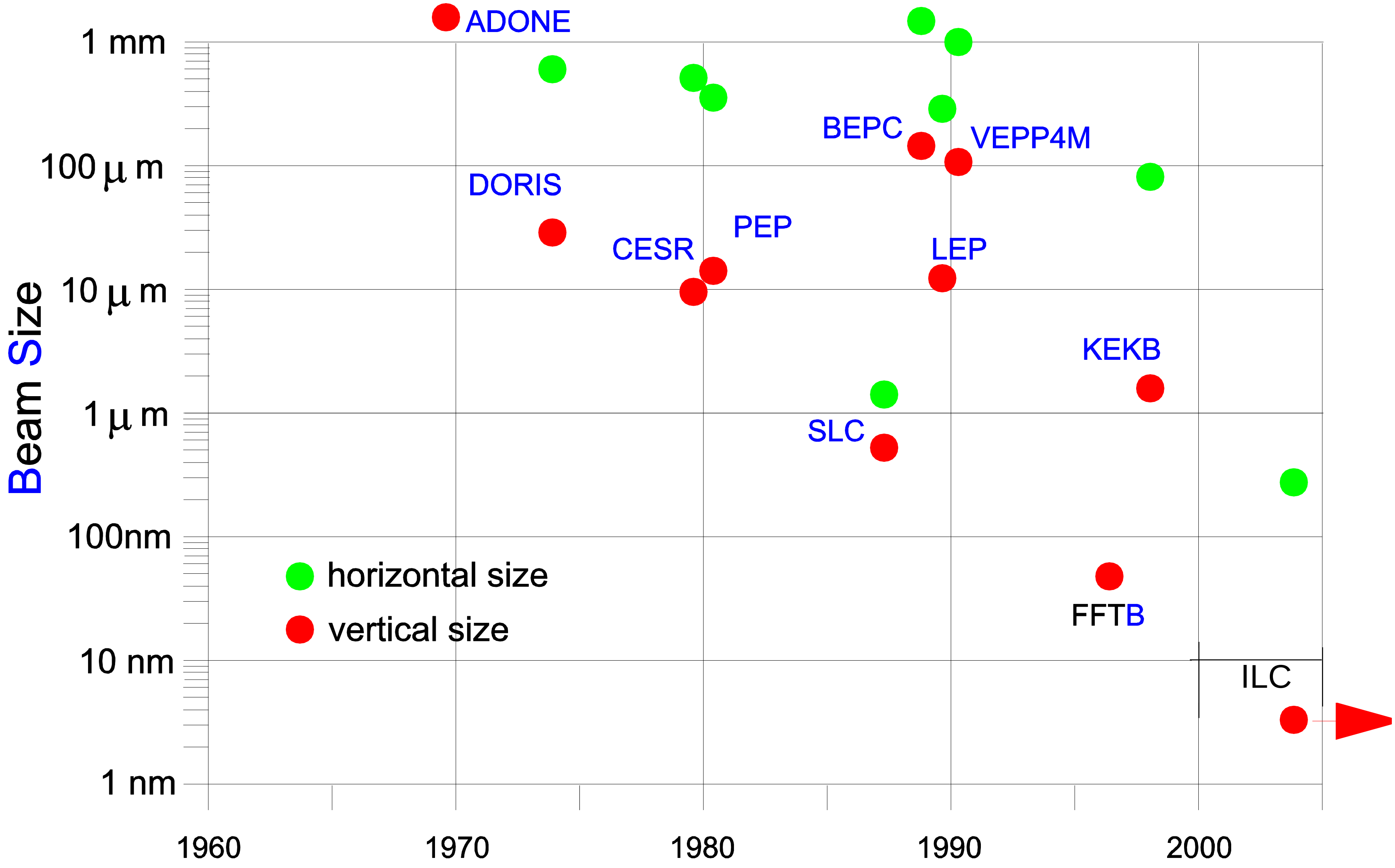
E ~ 35 MV/m will also require control of Lorentz Detuning of SRF cavities, specifically to control transverse offset leading to luminosity loss

A Typical SRF Linac Section

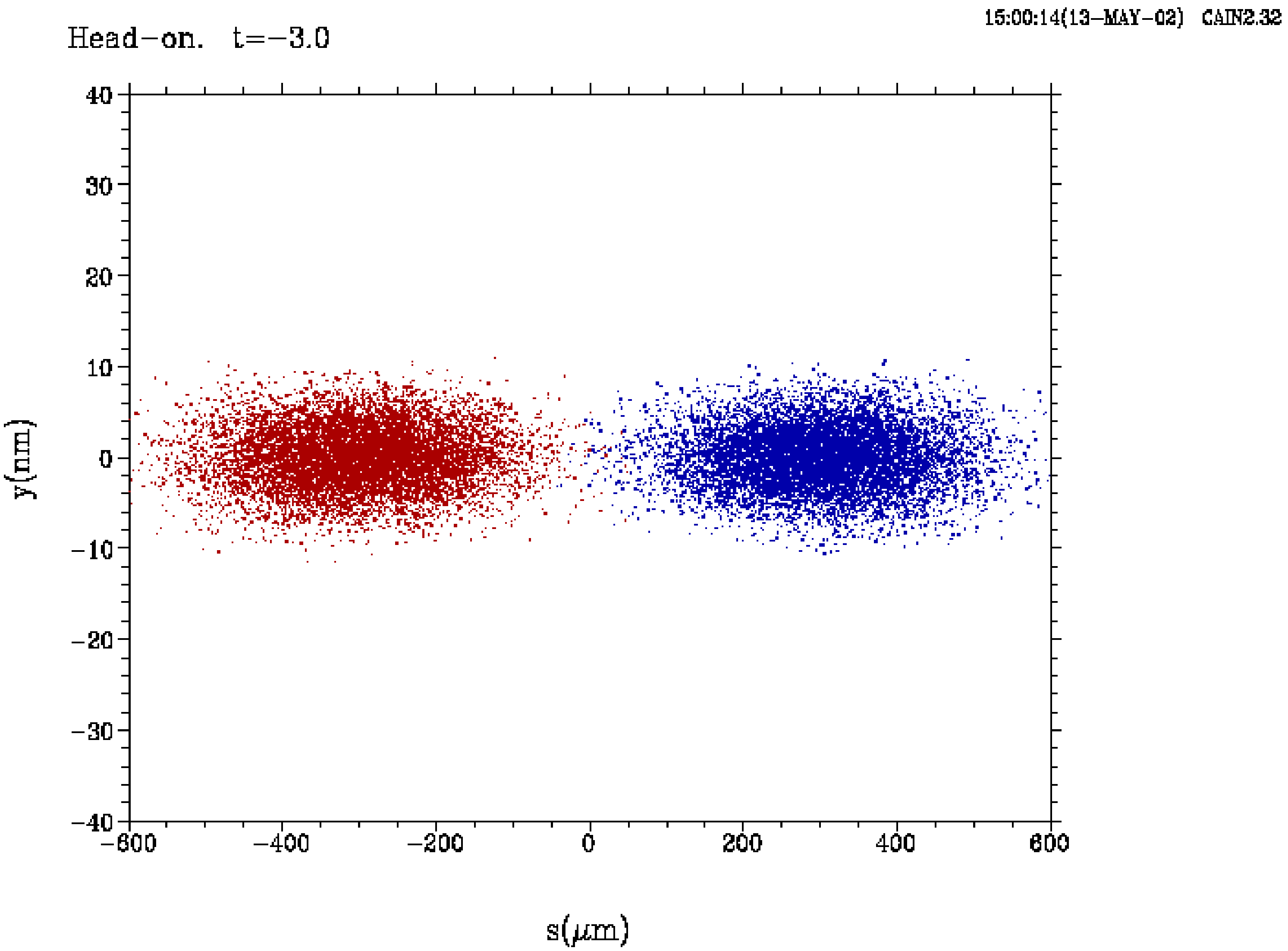


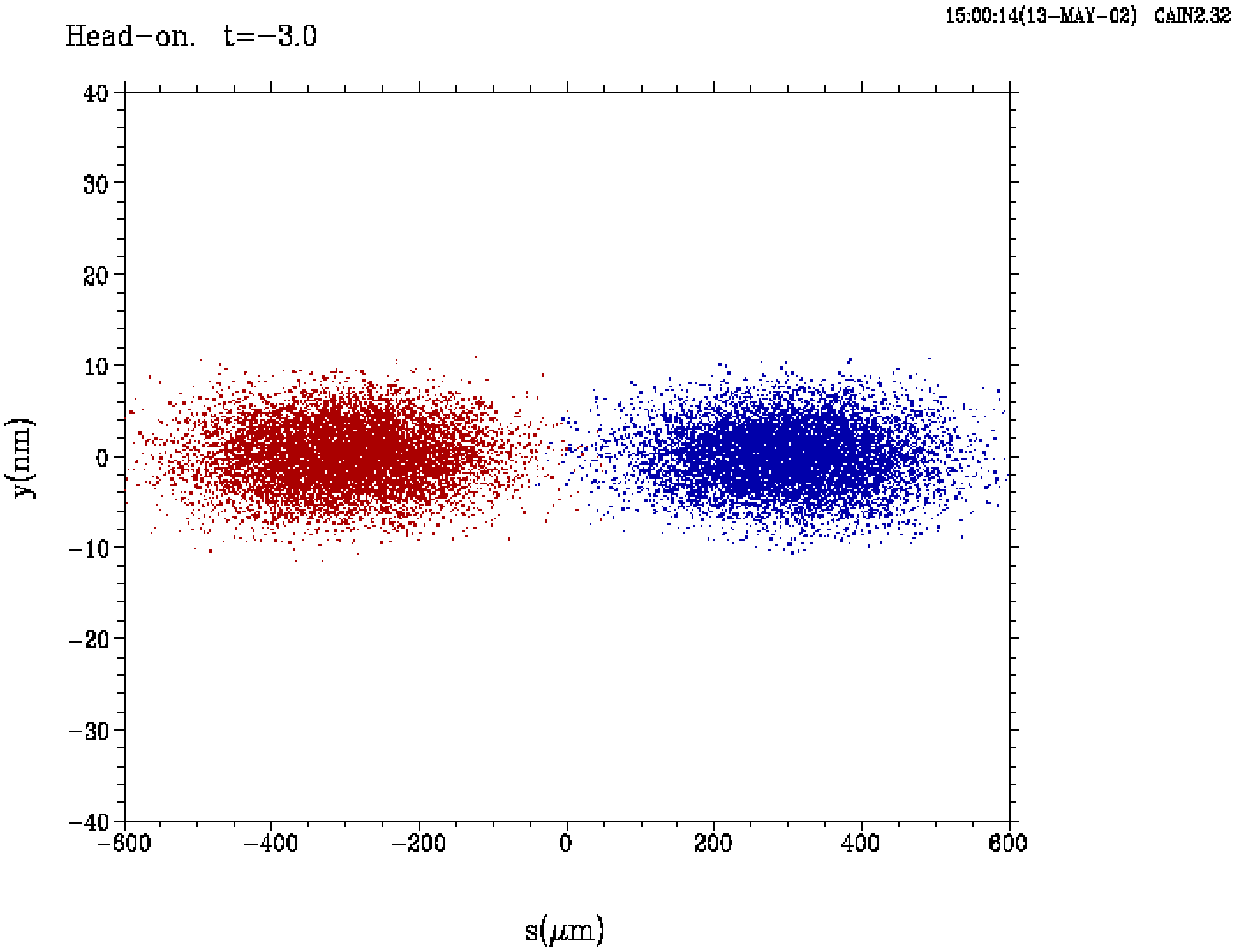
From TESLA Technical Design Report

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

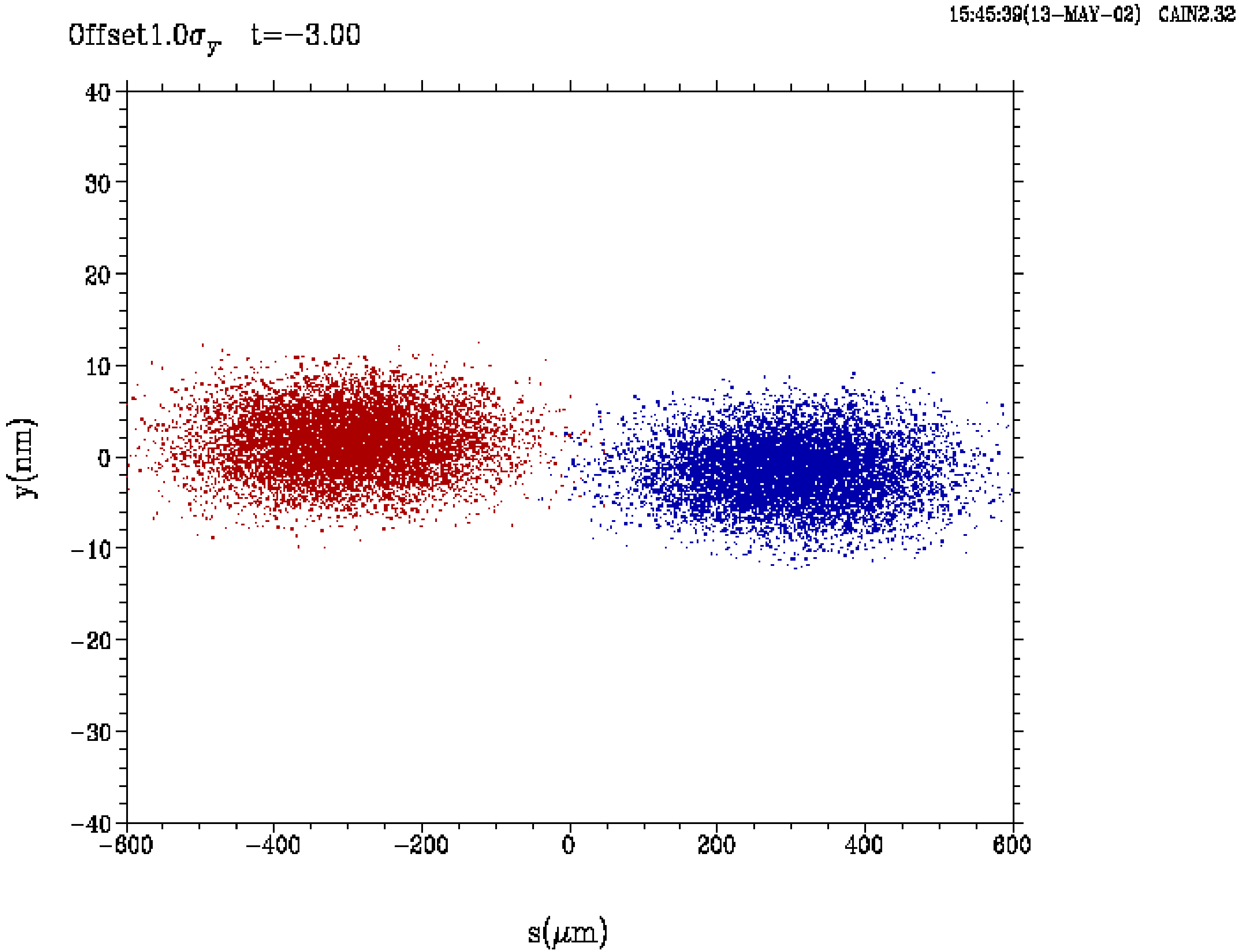


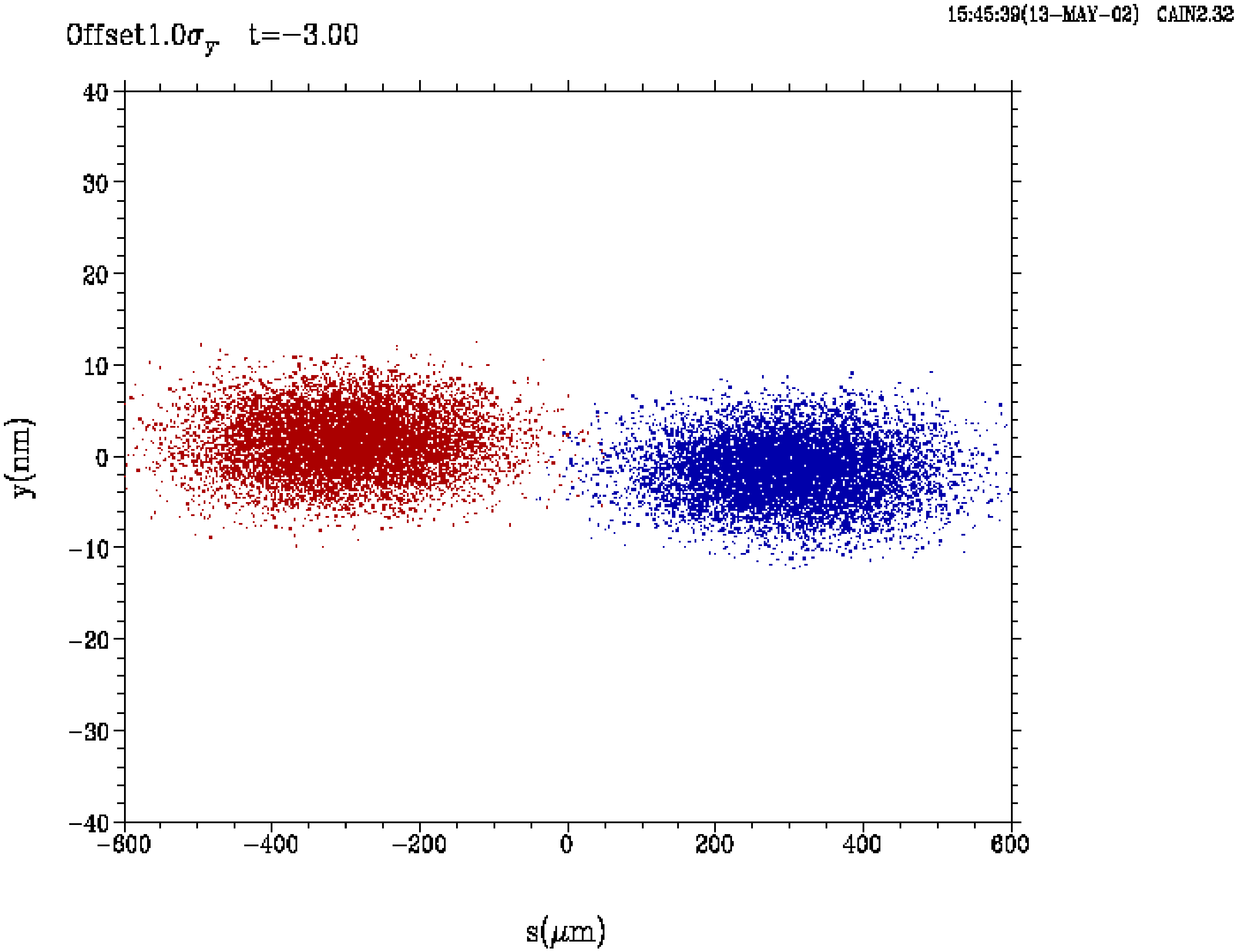
Colliding Nano-Beams in ILC





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

Transverse off-sets can arise from ground motion or RF phase distortion coupled via dispersion in collision magnetic optics

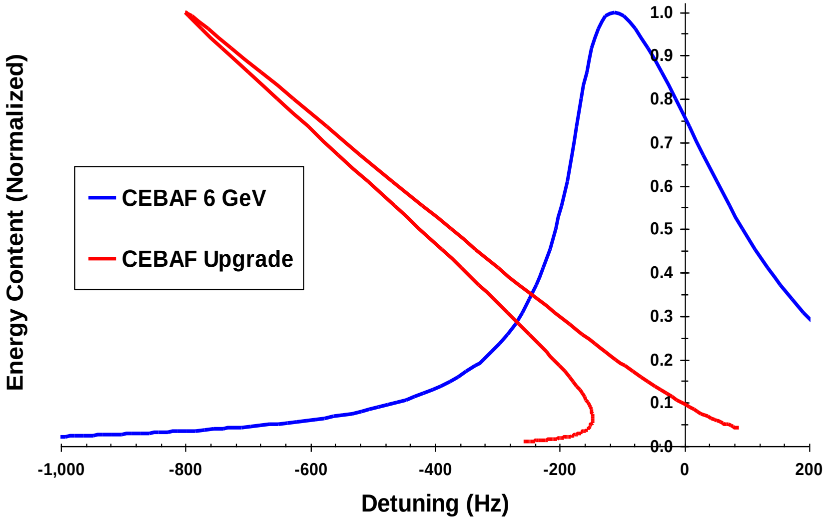
Must control RF Lorentz Detuning

RF Control of Lorentz Detuning

Overall performance requirements:

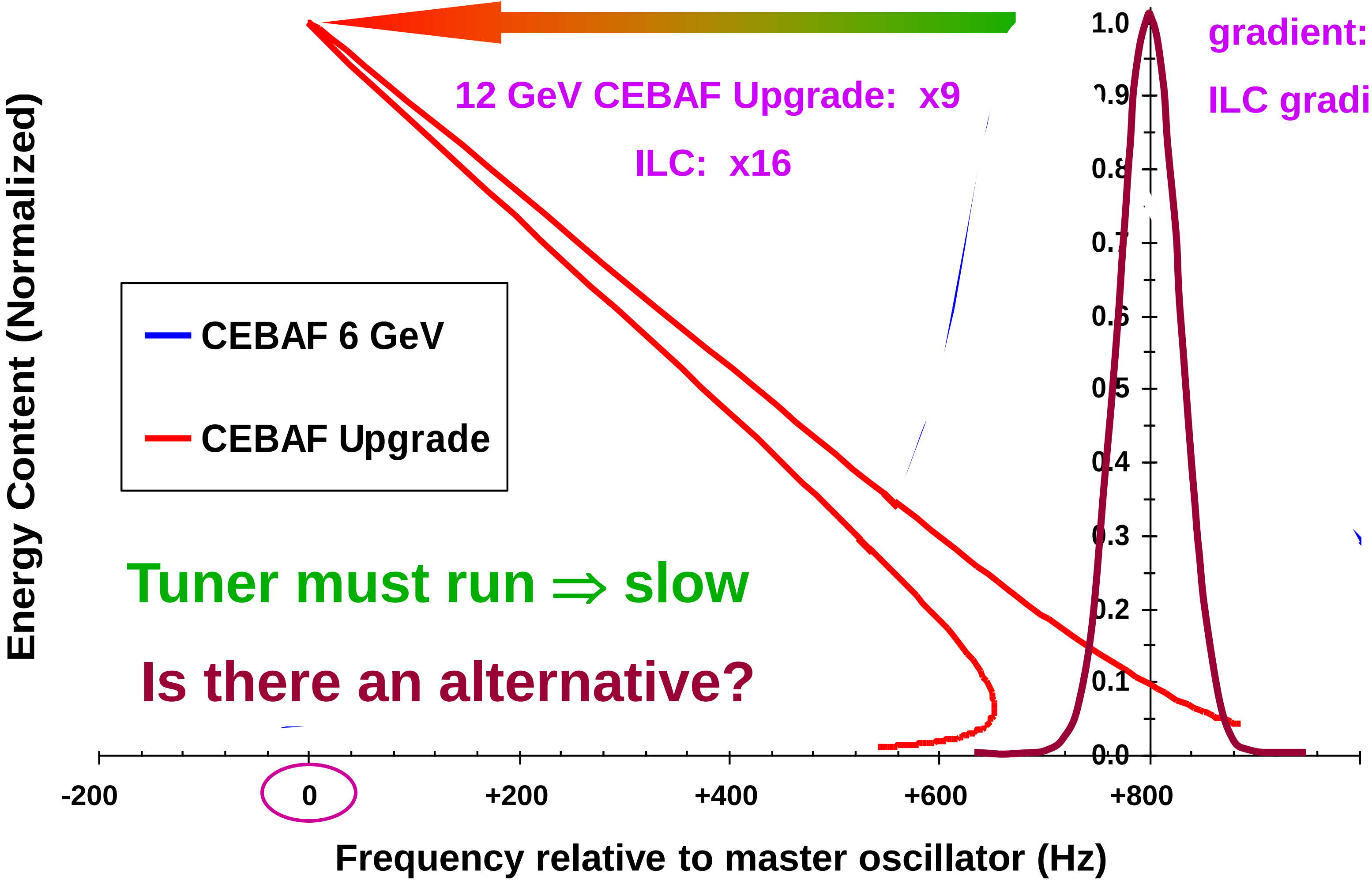
- Amplitude: $1\text{x}10^{-4}$
- Phase: 0.1º

- Algorithm choice
  - Large Lorentz forces
  - Narrow bandwidth
  - ⇒ Detuning curve is VERY different.



Lorentz Detuning Effects

Peak moves as $(\text{gradient})^2$



12 GeV CEBAF Upgrade: x9

ILC: x16

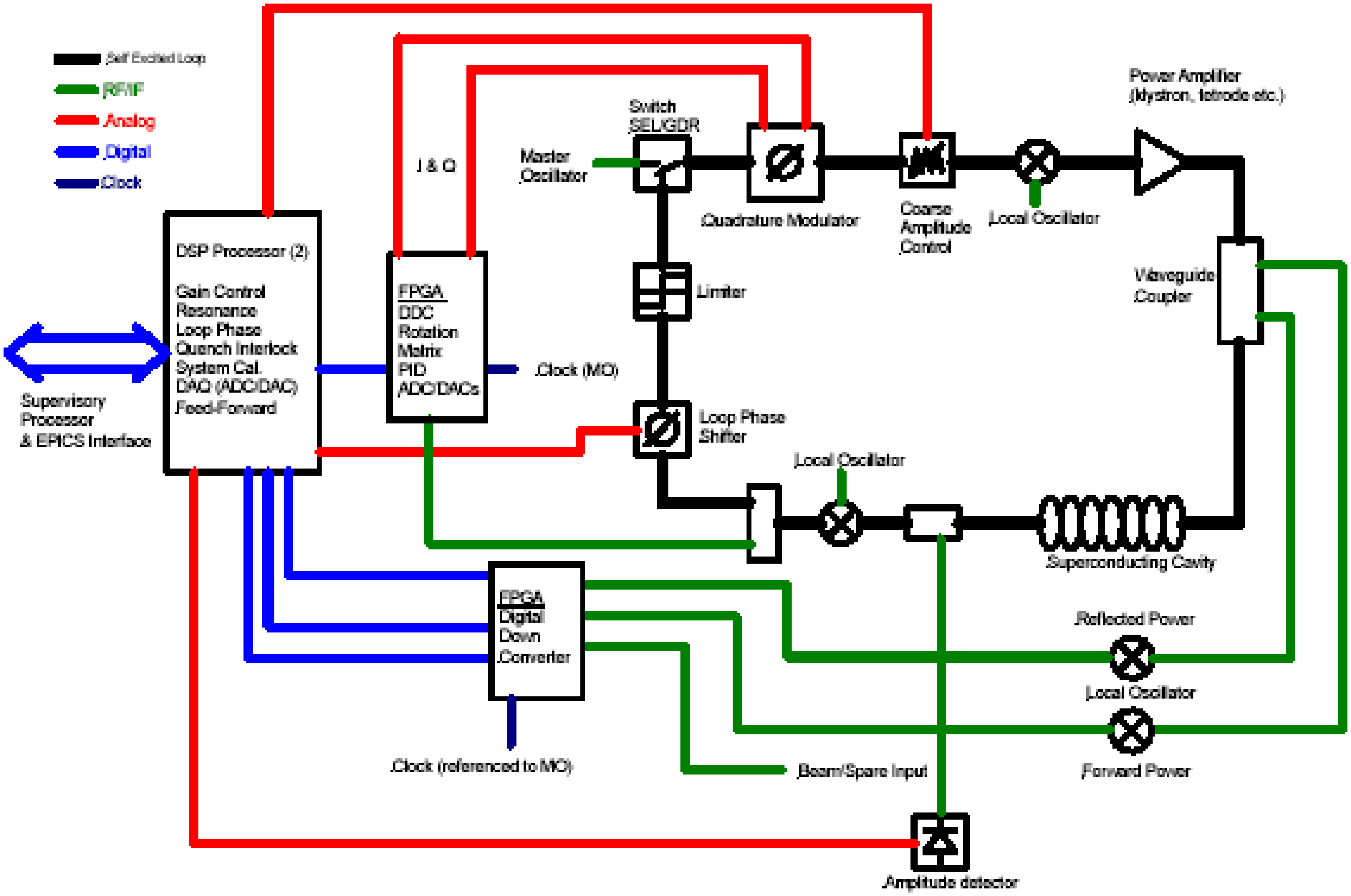
CEBAF Upgrade gradient: x3

ILC gradient: x4

Tuner must run ⇒ slow

Is there an alternative?

RF Control (cont'd)



RF Control (cont'd)

Graduate Research topic!! Applied Math, EE, Nonlinear Dynamics!

- Algorithm for Amplitude and Phase Control.

Nonlinear, dissipative, dispersive map with 'memory':

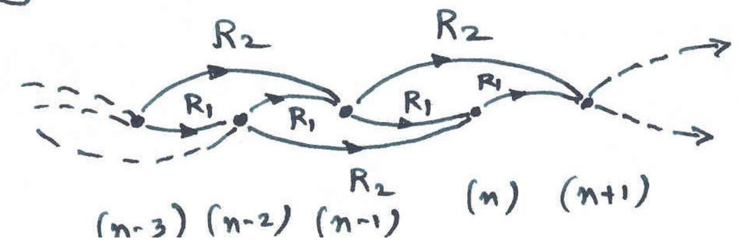
$$A_{n+1} - A_n = -k g(\psi_n) - \lambda A_{n-1}$$

$$\psi_{n+1} - \psi_n = A_{n+1} + \varphi_{n+1} - \varphi_n - \alpha \left[\langle \psi'_{n+1} \rangle - \varphi_{n+1} \right]$$

where: A: Amplitude, ψ: Phase, φ: Microphonic noise of cavity, λ: Damping Coefficient, $g(\psi)$: Nonlinearity and α: gain of RF Control feedback loop, working on the phase centroid:

$$\langle \psi_{n+1} \rangle = \frac{1}{K} \sum_{k=1}^{K} \psi'_{n+1,k}, \quad \psi'_{n+1,k} = \psi_{n,k} + A_{n,k}$$

Memory function: 2-point Markov chain:



$$R_n - a_1 R_{n-1} - a_2 R_{n-2} = 0$$

ULTRABRIGHT BEAMS
via Energy Recovery

→ **Need to appreciate the connection between acceleration and radiation in vacuum in order to understand the mechanism of Energy Recovering Linacs (ERLS)**

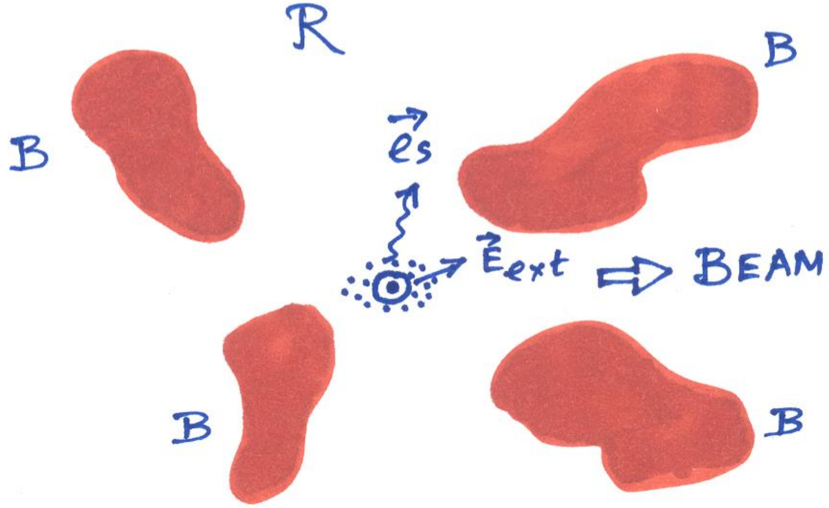
Acceleration and Radiation in Vacuum

and

Energy Recovery

$$\vec{E} = \vec{E}_{ext}(\omega,\vec{r}) + \vec{e}_s(\omega,\vec{r})\,N$$

Total Field in region 'R' bounded by boundaries 'B'



The field energy density:

ENERGY LOSS TO COHERENT SPONTANEOUS RADIATION

$$\mathcal{E} \sim \int |\vec{E}|^2 d^3\vec{r}\, d\omega$$

$$= \int |\vec{E}_{ext}|^2 d^3\vec{r}\, d\omega + N^2 \int |\vec{e}_s(\omega,\vec{r})|^2 d^3\vec{r}\, d\omega$$

$$+ \boxed{2\,\mathrm{Re}\left[N \int \vec{E}_{ext}(\vec{r},\omega)\cdot\vec{e}_s(\vec{r},\omega)\, d^3\vec{r}\, d\omega\right]}$$

EXTERNAL STORED ENERGY

STIMULATED ABSORPTION/RADIATION: EXCHANGE OF ENERGY BETWEEN PARTICLES and WAVES: ENERGY GAIN (DECEL. OF PARTICLES) or LOSS (ACCEL. OF PARTICLES).

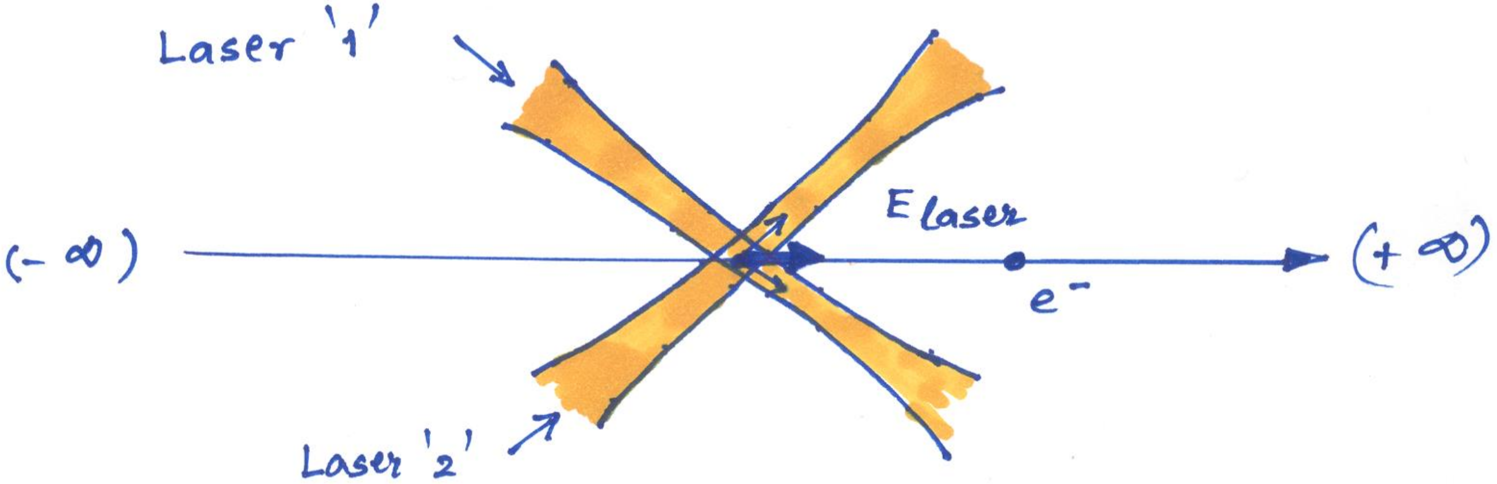
FUNDAMENTAL THEOREM of ACCELERATION and DECELERATION

For optimal acceleration/deceleration, linear *or* otherwise in $\vec{E}_{ext}$, there must be optimal overlap of 'acceleration' mode $\vec{E}_{ext}(\omega, \vec{k})$ with 'radiation' mode $\vec{e}_s(\omega, \vec{k})$. The particles are accelerated if the coherent radiation loss is less than the energy gain, leading to the restriction:

$$\boxed{N \lesssim \left(|\vec{E}_{ext}|/e\right) ƛ^2}$$

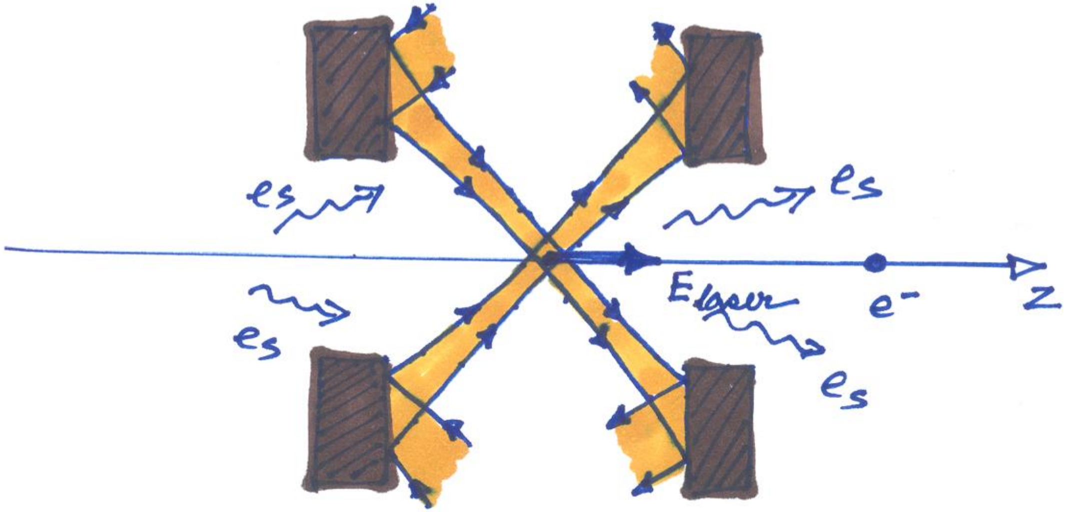
on the number of particles in a bunch that can be effectively accelerated before losses start to dominate, leading to deceleration ($ƛ \equiv \lambda/2\pi$ is the reduced wavelength of accelerating mode).

EXAMPLE : **Open System**



Intersection of two TM Gaussian Laser modes to create a longitudinal accelerating electric field. No spontaneous radiation in open space with no boundaries in linear motion — no cross-term $\vec{E}_{ext} \cdot \vec{e}_s$. No net acceleration as an electron travels from $(-\infty)$ to $(+\infty)$ $\Longrightarrow$ **"Lawson-Woodward Theorem"**.

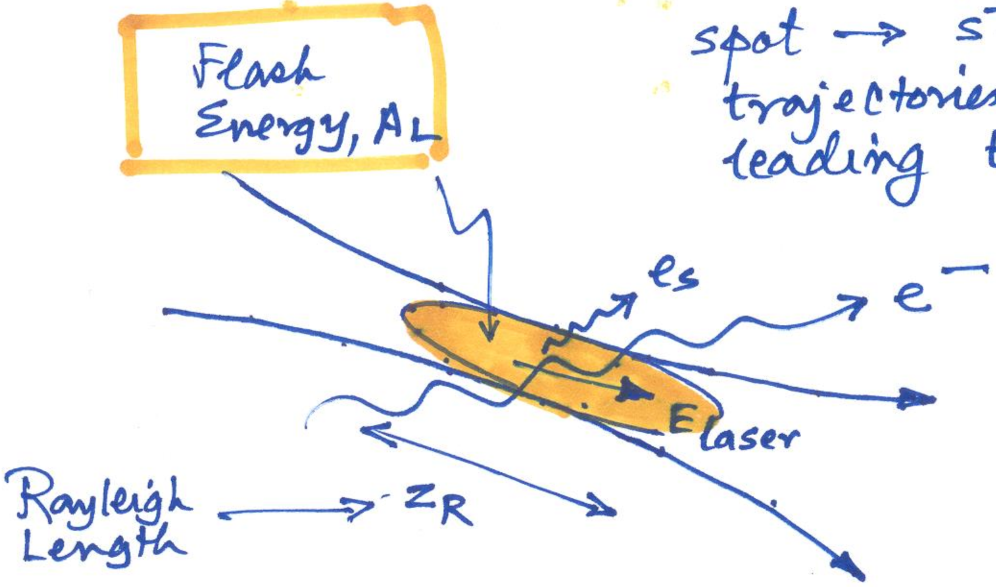
EXAMPLE: Closed System



Spontaneous radiation fields $\vec{e}_s$ via Cerenkov or Transition radiation through the apertures — cross-term $\vec{e}_s \cdot \vec{E}_{ext}$ non-zero: acceleration is possible and is the basis of all linear accelerators in microwave cavities or wave-guides.

EXAMPLE: **Nonlinear Interaction**

Intense light focussed in a small spot → strong fields → particle trajectories bend in oscillating fields leading to spontaneous synchrotron radiation

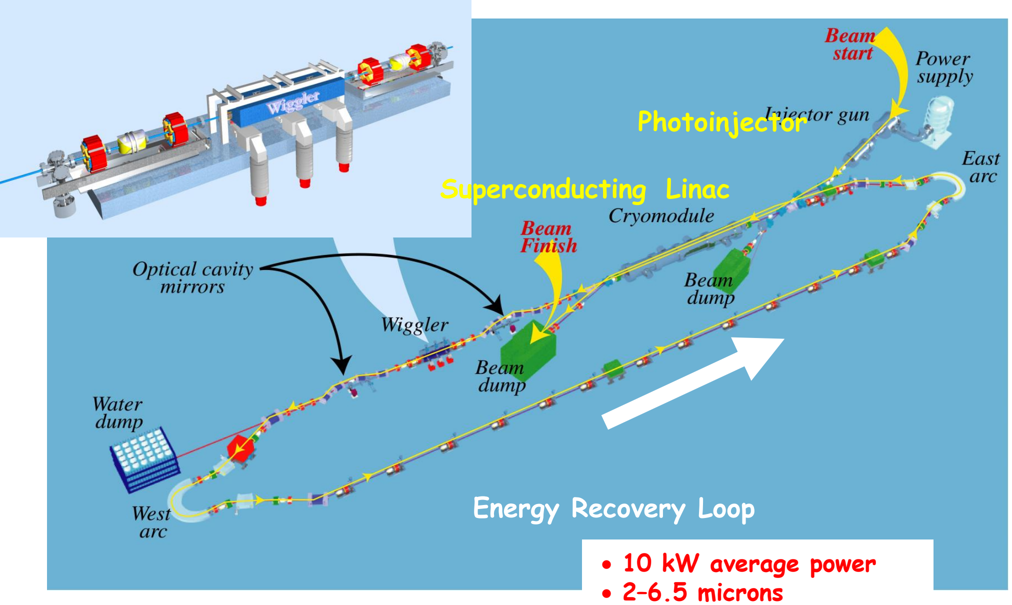


Radiation field: $\boxed{e_s \sim \ddot{x} \propto E_{laser}}$

$$\boxed{\Delta E|_{gain} \sim (E_{laser} \cdot e_s) \propto E_{laser}^2 = A_L \left(\frac{r_e}{Z_R}\right)}$$

Nonlinear acceleration, energy gain quadratic in electric field, with small coefficient is still small compared to linear acceleration but has been experimentally observed.

Energy Recovery and its Potential



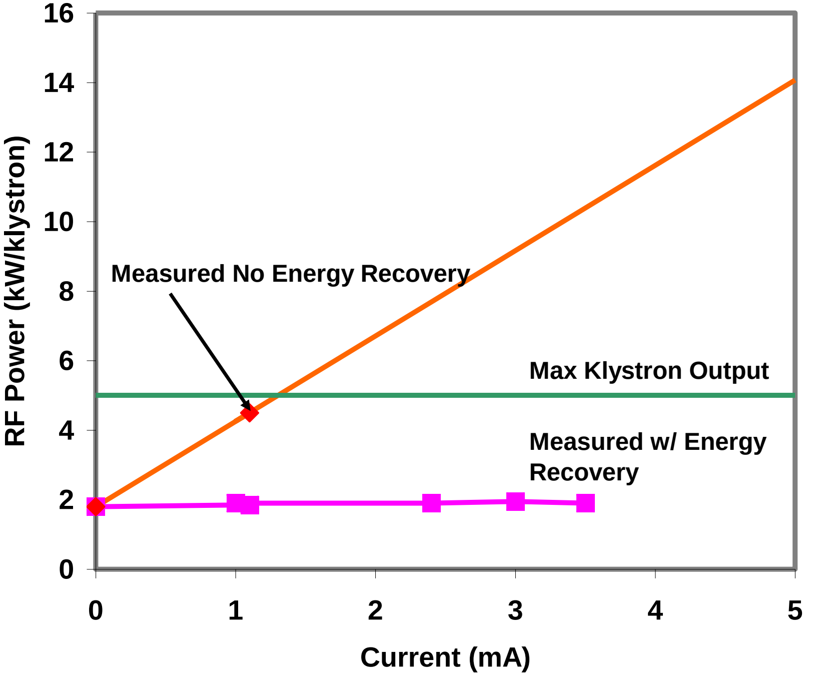
- 10 kW average power
- 2–6.5 microns
- 500 femtosecond pulses
- 75 MHz rep rate

JLab ERL-based

Free Electron Laser

First high current energy recovery experiment at JLab FEL, 2000

RF Power Draw in Energy Recovery



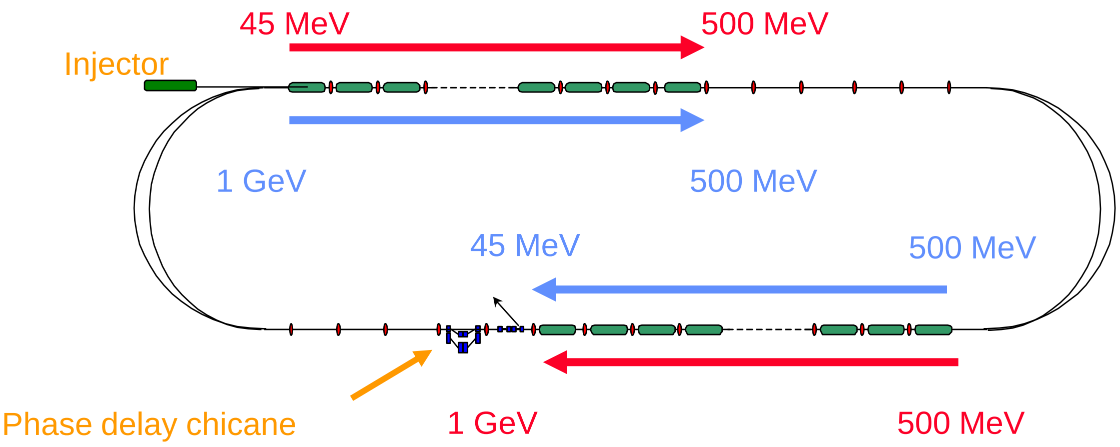
1 MW class electron beam, (100 MeV x 10mA), comparable to beam power in CEBAF accelerator (1 GeV x 1mA), but supported only by klystrons capable of accelerating 10-100 kW electron beam.

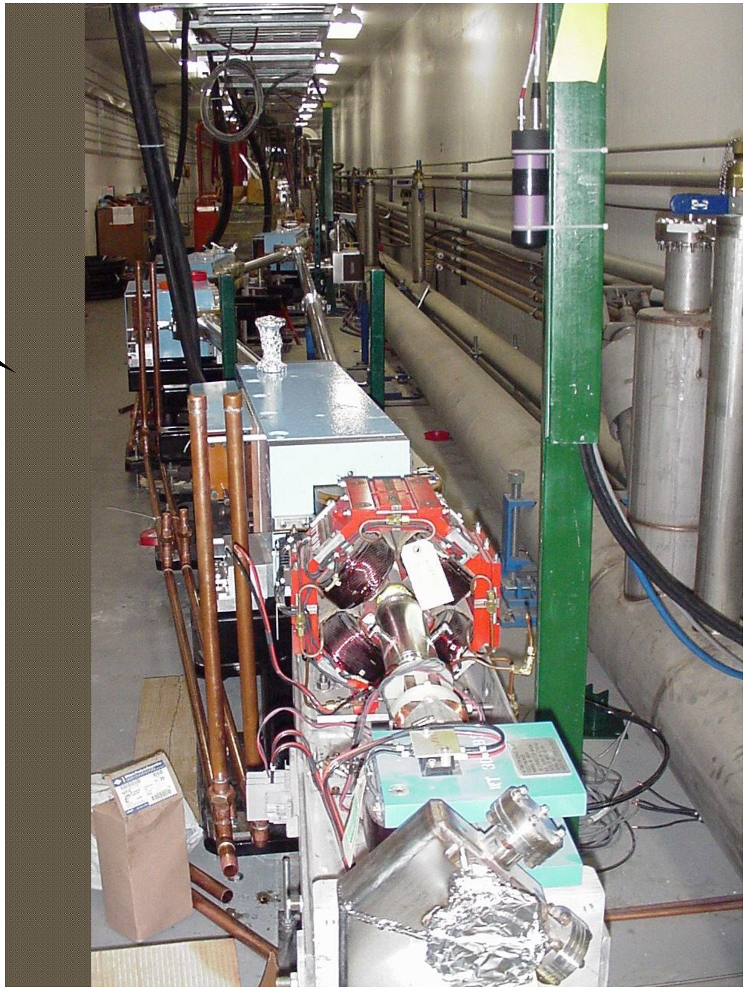
to Nuclear Physics and
petency (cont'd)

Graduate Research: possibilities of Energy Recovery plus Current Doubling for future facilities

H overy

- Beam will be accelerated fr eV to 1 GeV and energy recovered to 45 MeV to inject at 10 to 20 MeV and test energy recov with energy ratio up to ~100
- Beam properties, beam halo to be measured at several locations
- Experiment was approved and performed for March-April 2003

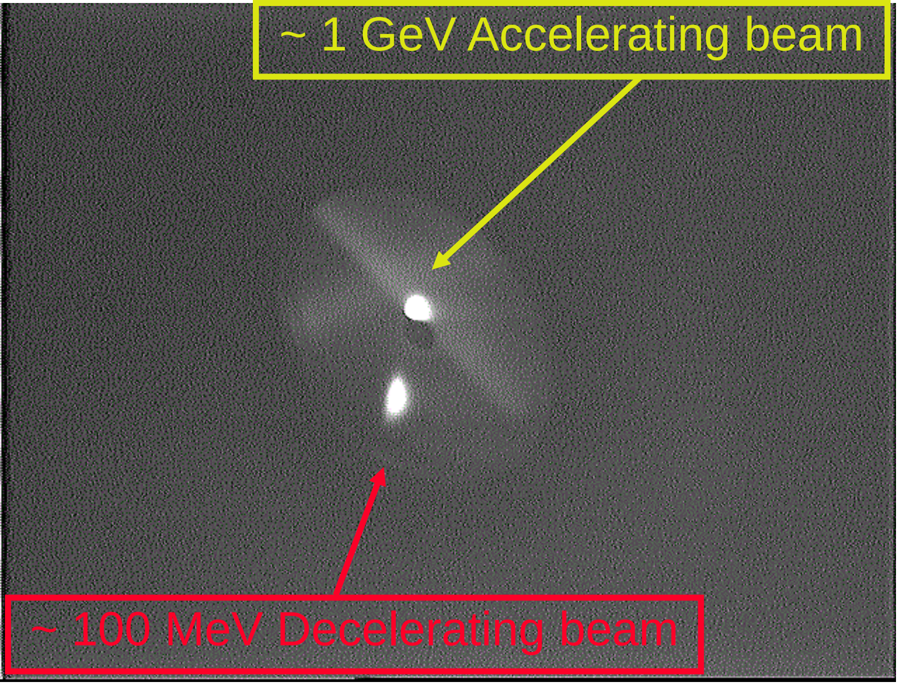




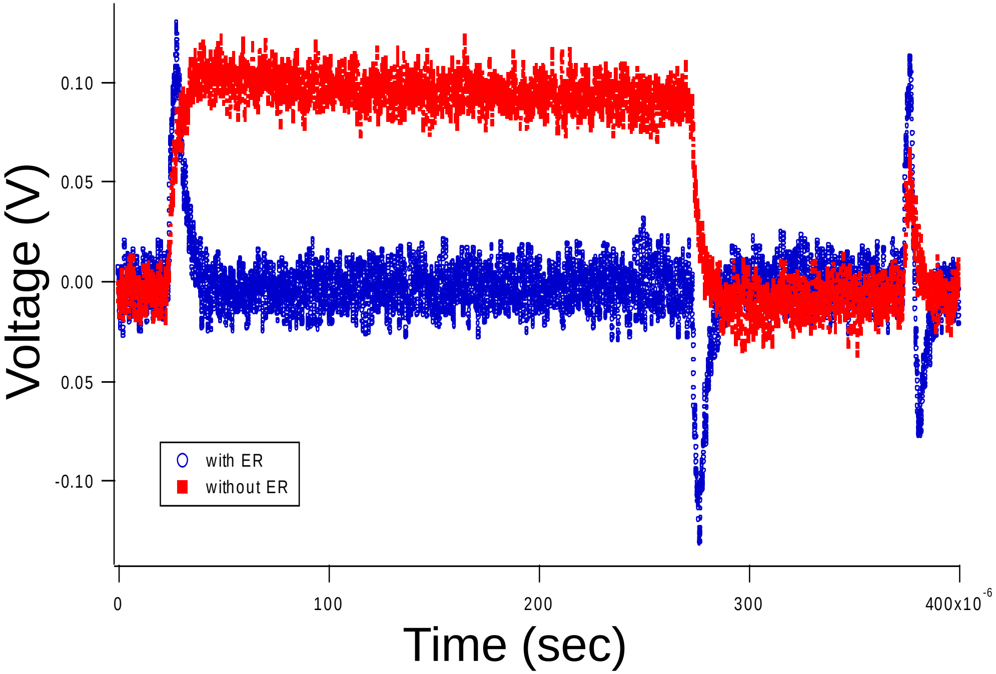
CEBAF-ER Installation

First Energy Recovery Experiment at High Energy at CEBAF, April 2003

Beam profiles at end (SL16) of South Linac



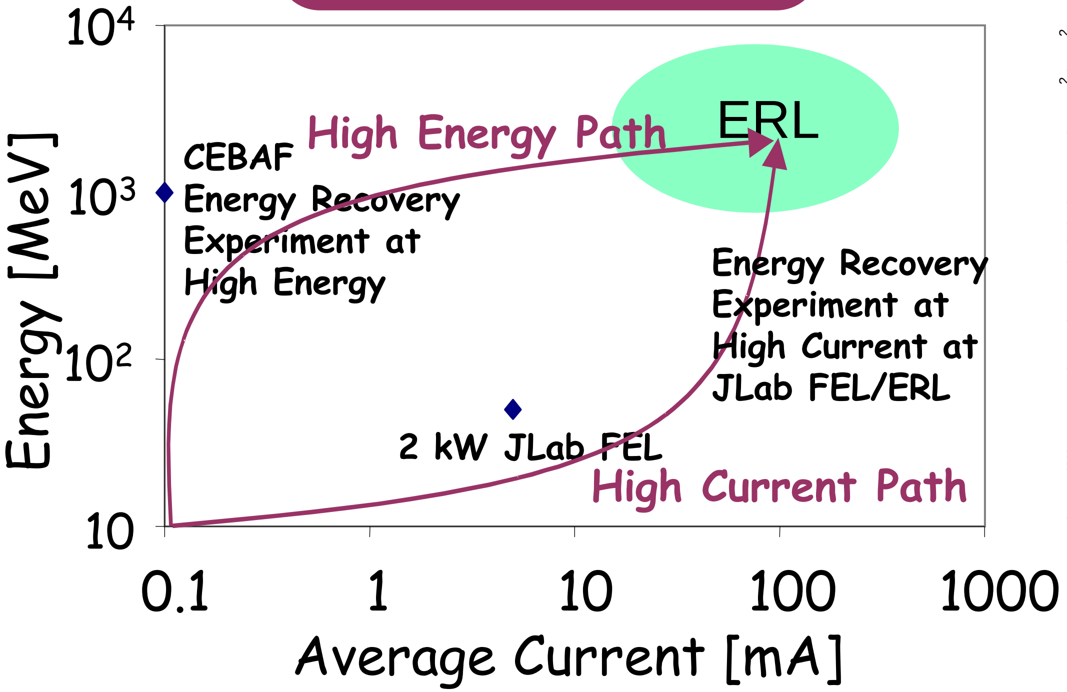
Gradient modulator drive signals with and without energy recovery in response to 250 μsec beam pulse entering the rf cavity



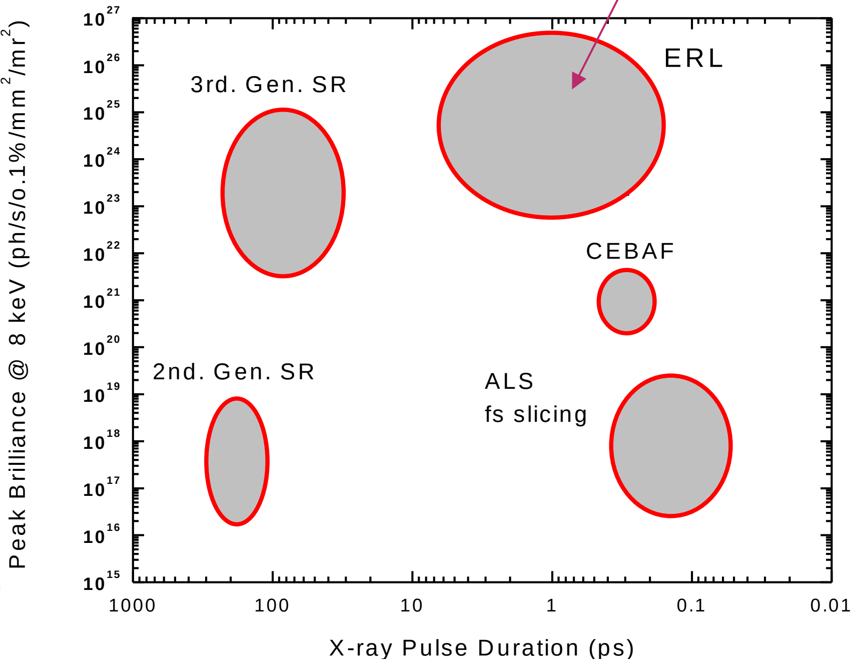
Energy Ratio of up to 1:50 tested at CEBAF (20 MeV ⇆ 1 GeV)

ERL R&D for Electron-Ion Colliders, Electron Cooling of Ion Beams and Bright Light Sources

Two complementary and orthogonal branches to complete the required ERL R&D.



JLab/Daresbury/Cornell Collaboration



Accelerator R&D Issues

Creation, transport and acceleration of extremely low-emittance, high-current beams up and down the “energy cycle”

ULTRASHORT PULSES

--Science and Generation Mechanisms

Motivation

Scientific Possibilities with :

Femto- and Atto-second Electron Pulses, X-rays, γ-rays and FELS

10^{-18} seconds $\lesssim \tau \lesssim 10^{-15}$ seconds

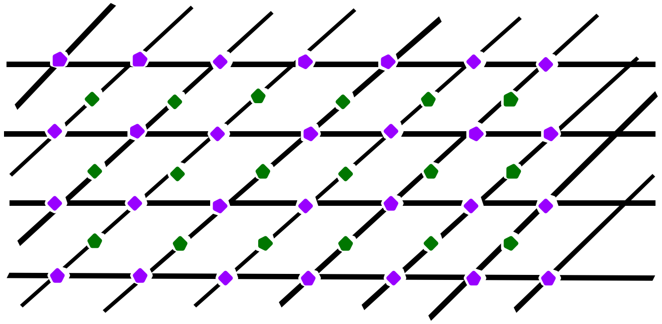
Femtosecond Laser → *Attosecond Electron Beam Pulse* → *Attosecond Light and X-rays*

allows pump-probe experiments @ 10^{-17} second scale

Novel interactions of ultrashort pulses with particles/atoms/molecules/bulk matter at the Quantum Limit of Rapidity

- Condensed Matter Physics
- Biochemistry
- Life Sciences
- Statistical Physics
- Exotic Atomic Physics:
  “Coherent Ionization” and
  “Quantum Entangled States”
- Particle Physics
- Nuclear Physics

Phonon Dynamics on a Surface



CONDENSED
MATTER
PHYSICS

Lattice vibrations and 'Phonon' spectrum characterized by Debye time-scale :

$$h\nu \approx kT$$

Phonons

Thermal
Bath

Lattice relaxation time :

$\boxed{\tau = \nu^{-1} = h / kT}$ ~100 fs @ room temp.

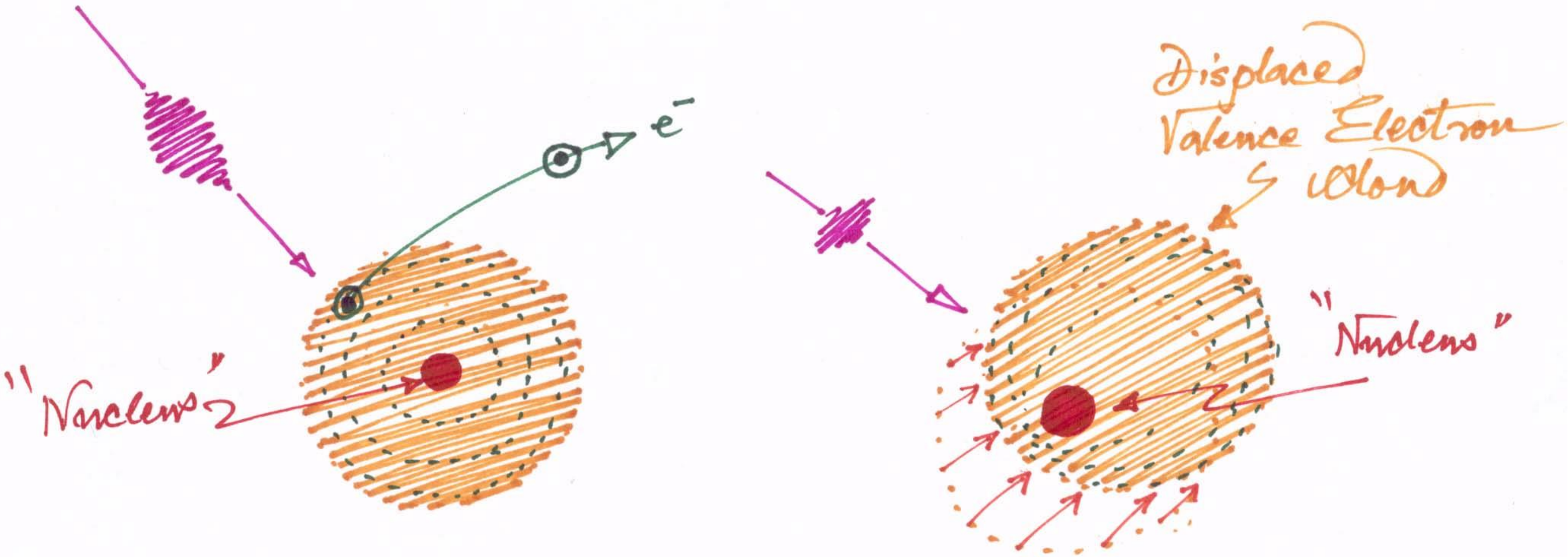
$\boxed{\text{Resolution} \sim \text{Å}}$

PHASE TRANSITIONS like surface melting etc. take place on this 1 - 100 fs time-scale.
EXTREMELY VALUABLE INFORMATION for SEMICONDUCTOR PHYSICS. e.g. silicon

Incoherent vs. Coherent Ionization
"Quantum Entanglement"

"Incoherent" Ionization

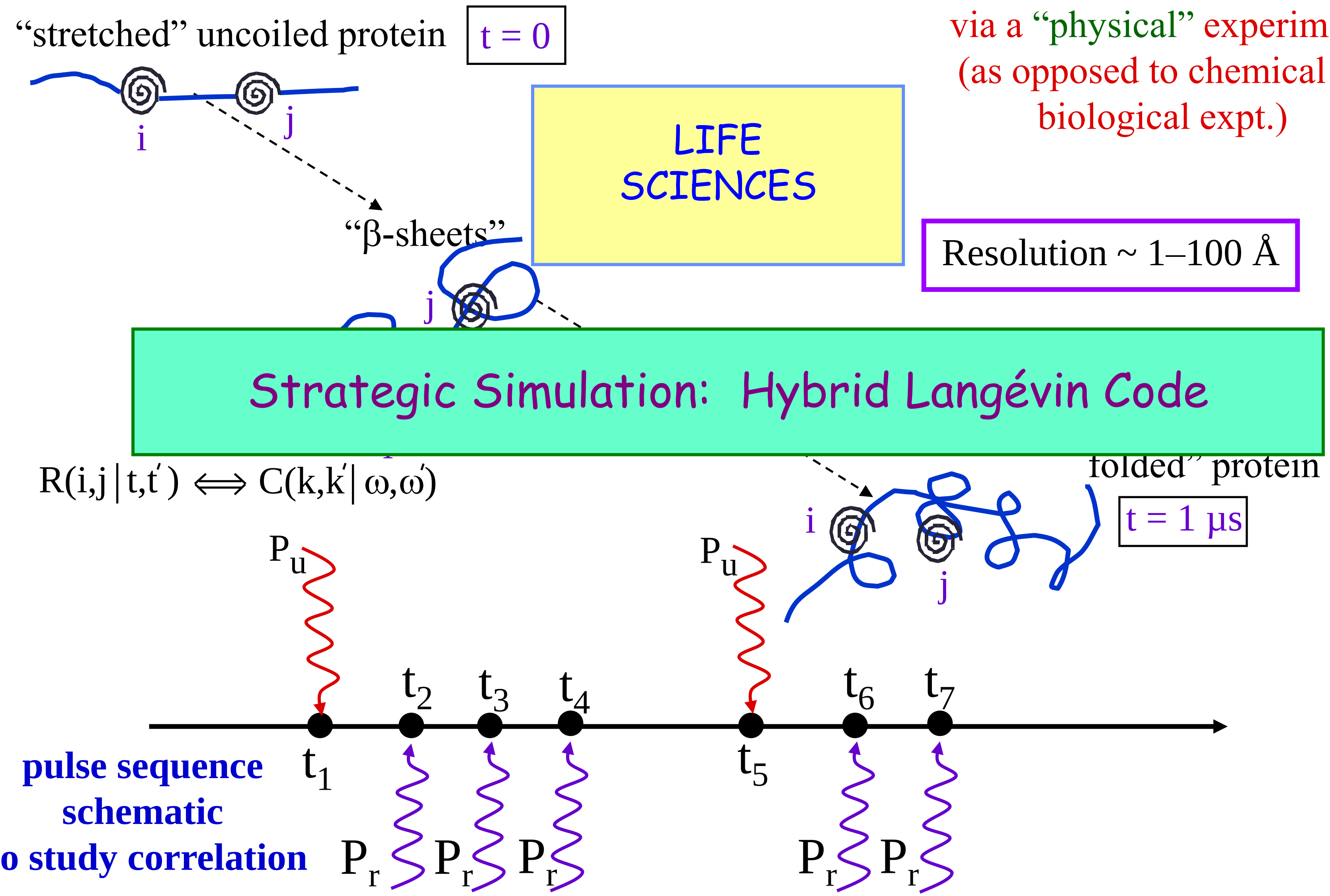
"Coherent" Ionization



Long Pulse leading to ejection of single valence electrons

Ultrashort "attosecond" pulse leading to coherent displacement of the valence "electronic cloud" with respect to the nucleus

Controlled Study of "Protein Folding"



"stretched" uncoiled protein

t = 0

via a "physical" experiment
(as opposed to chemical or
biological expt.)

LIFE
SCIENCES

Resolution ~ 1–100 Å

Strategic Simulation: Hybrid Langévin Code

$R(i,j\,|\,t,t') \Longleftrightarrow C(k,k'\,|\,\omega,\omega')$

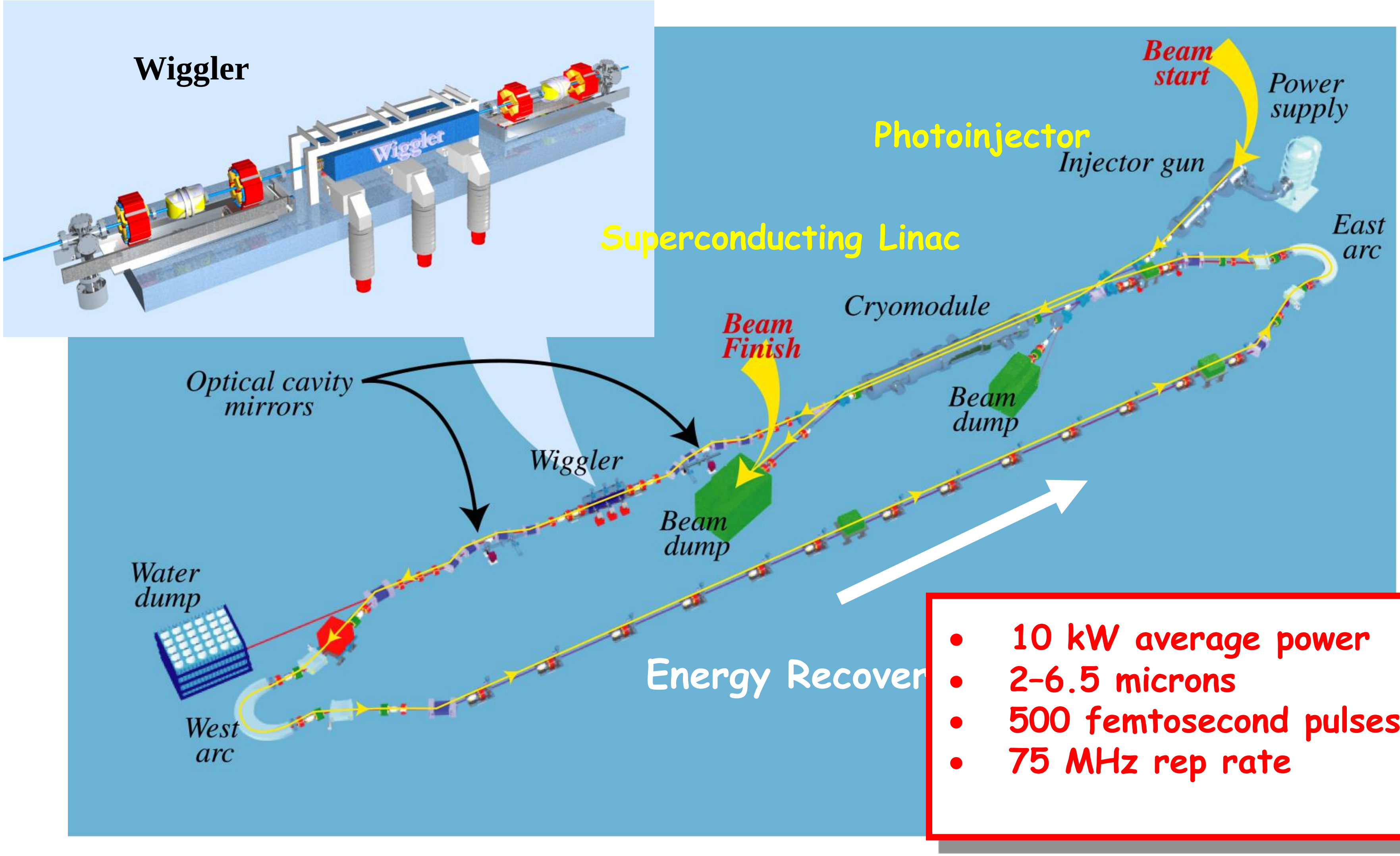
"folded" protein

t = 1 μs

**pulse sequence
schematic
to study correlation**

The JLab Laser

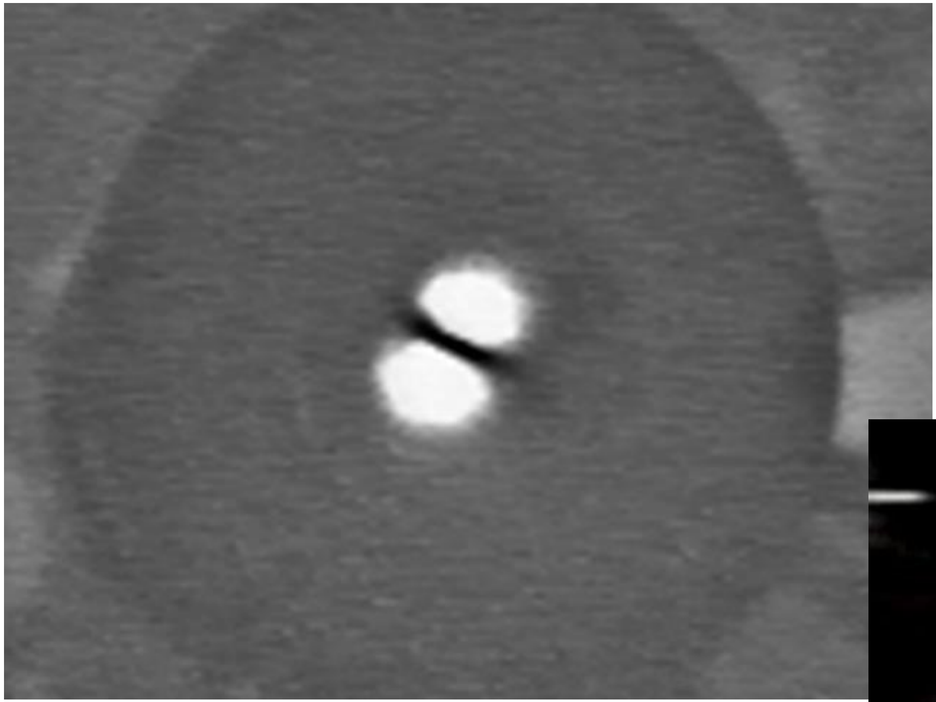
the world's most powerful femtosecond free electron laser
the world's most powerful tunable IR free electron laser

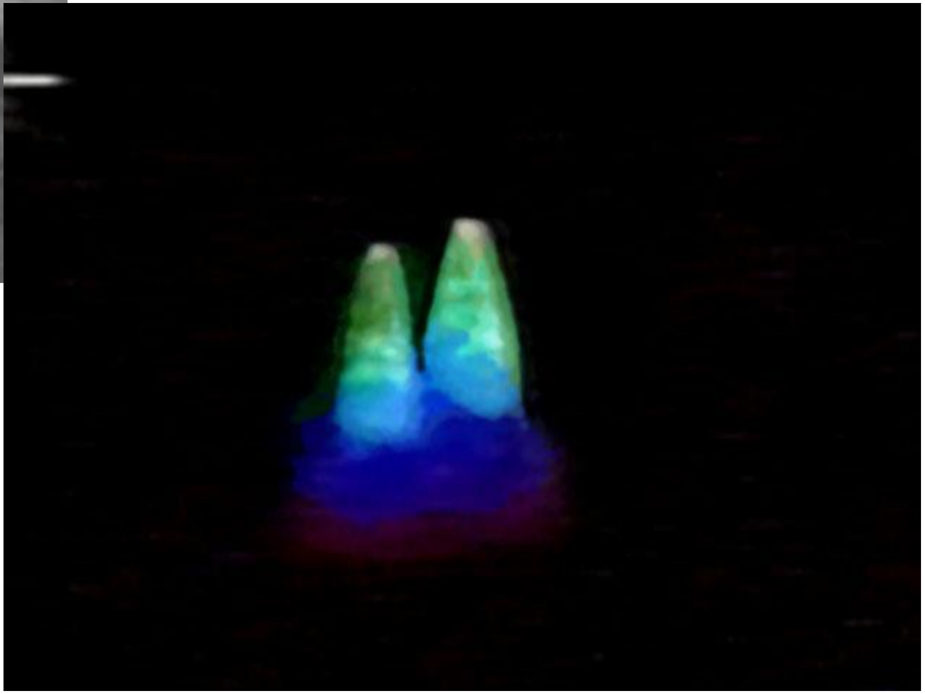


- 10 kW average power
- 2-6.5 microns
- 500 femtosecond pulses
- 75 MHz rep rate

Second Harmonic Lasing

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



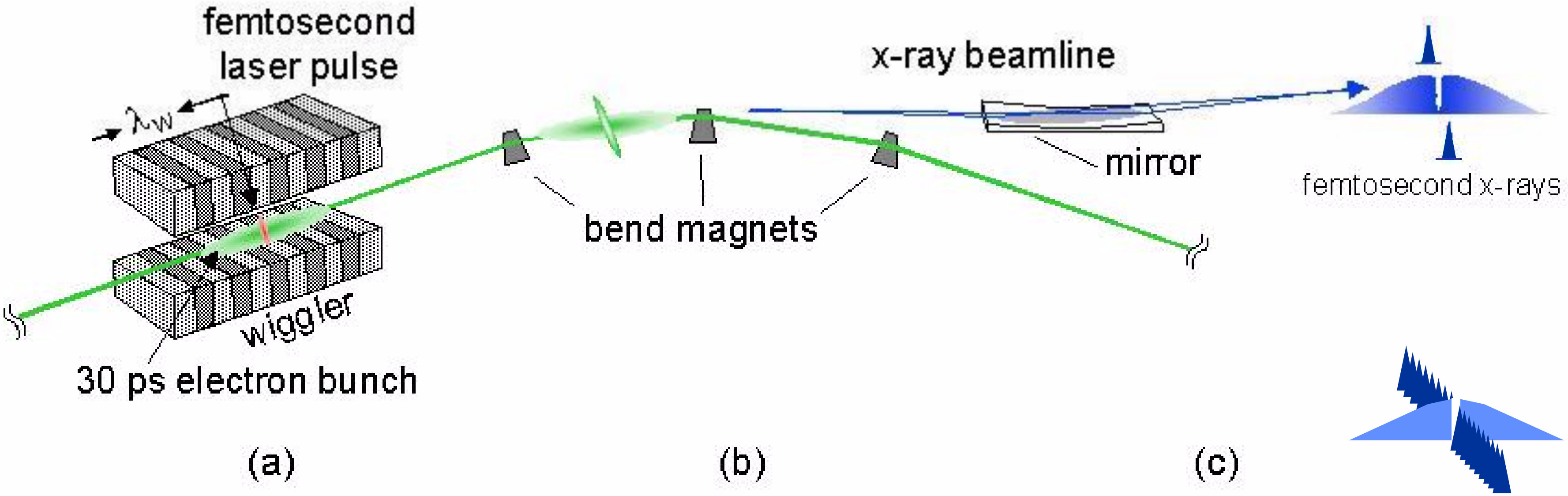


$\tau \approx 300$ fs

- Gain of 1.35% per pass

Submitted to PRL

Laser Femto-slicing of Electron Beams

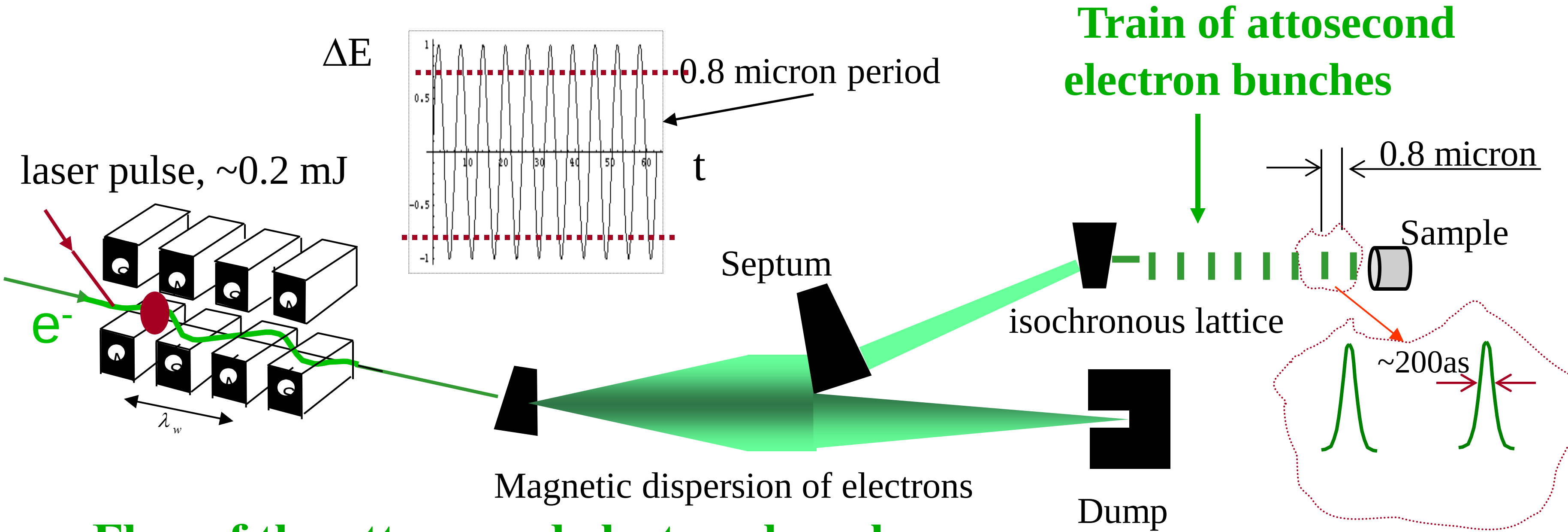


Reference:
Generation of Femtosecond Pulses of Synchrotron Radiation
R. Schoenlein, S. Chattopadhyay, H.H.W. Chong, T.E. Glover, P.A. Heimann, C.V. Shank, A.A. Zholents, M.S. Zolotorev
Science, Vol. 287, No. 5461, March 24, 2000, p. 2237.

→ **Unique experiment in the world**

→ **Optical Manipulation of Beams**

Atto-Slicing: Laser Slicing Technique



Flux of the attosecond electron bunches:

train of ~100 bunches, $\sim 10^6$ e/bunch, 10 kHz rep. rate

- **Energy modulation was demonstrated at the ALS for femtosecond x-ray generation**
- **Micro-bunching at 10 μm was demonstrated at ATF/BNL**
- **Electron pulse separation (slicing) down to 0.1 μm must be studied**

A. Zholents, et al.

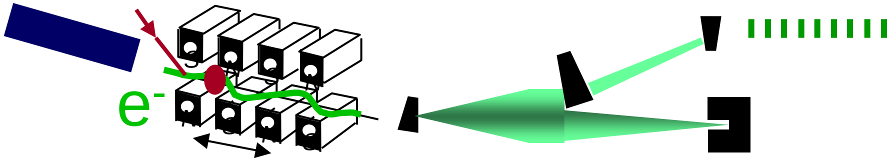
Laser Slicing Technique (cont’d)

Source of electrons:

Being explored at JLab

1) SC rf linac:
~100 MeV , 10 nC,
5 mm-mrad, 10 kHz

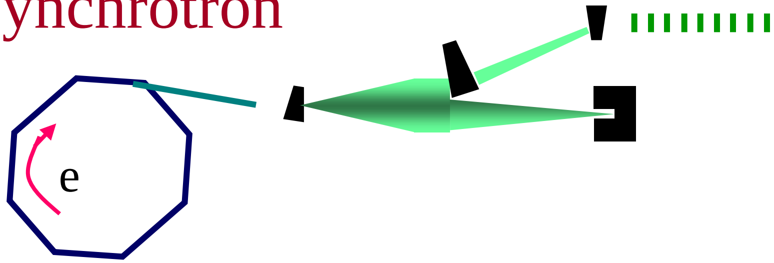
linac



(higher average flux, high brightness)

2) Synchrotron:
~1500 MeV , 300 x 1 nC,
5 mm-mrad, 1 kHz,
continues injection

synchrotron



(shorter pulses)

ULTRACOLD BEAMS

Particle Beam Condensates

Beams of BOSONS and FERMIONS at the limit of quantum degeneracy where quantum mechanical collective behavior is important. Can one ever cool particle beams to t **nsates"** ??

STATISTICAL PHYSICS

BOSE - Bea

ERMI - Beam

lowest possible

temperature

Strategic Simulation: Molecular Dynamics Code

Quantum relaxation time

$\simeq 10^{-17}$sec

Quantum diffraction-limited volume in phase-space :

$$\boxed{\varepsilon_x^{(n)}\ \varepsilon_y^{(n)}\ \varepsilon_z^{(n)} \geqslant \left(\frac{\bar{\lambda}_c}{2}\right)^3}$$

$$\bar{\lambda}_c = \frac{\hbar}{mc} = \text{Compton Wavelength}$$

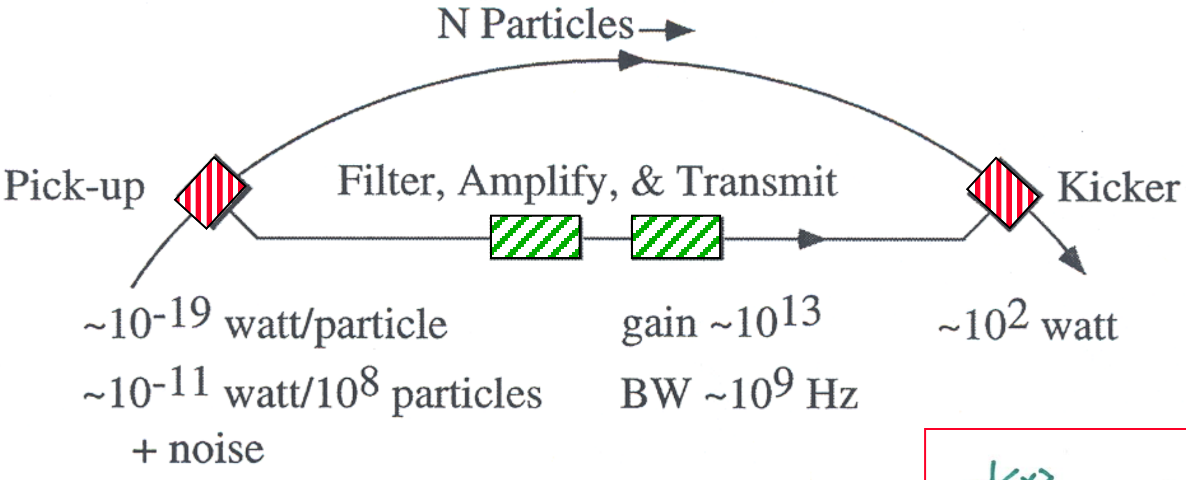
Quantum diffraction-limited volume in phase-space :

$$\boxed{\varepsilon_x^{(n)}\ \varepsilon_y^{(n)}\ \varepsilon_z^{(n)} \geqslant \frac{N(\bar{\lambda}_c/2)^3}{(2\ S+1)}}$$

($S \equiv$ spin of the Fermions)

Phase Space Control and Cooling of Charged Particles in a Storage Ring

Laser cooling limited due to "fixed" narrow-band laser spectral lines. Circumvented in storage rings by microwave "Broadband" stochastic



Signal/Noise ~ nV/μV

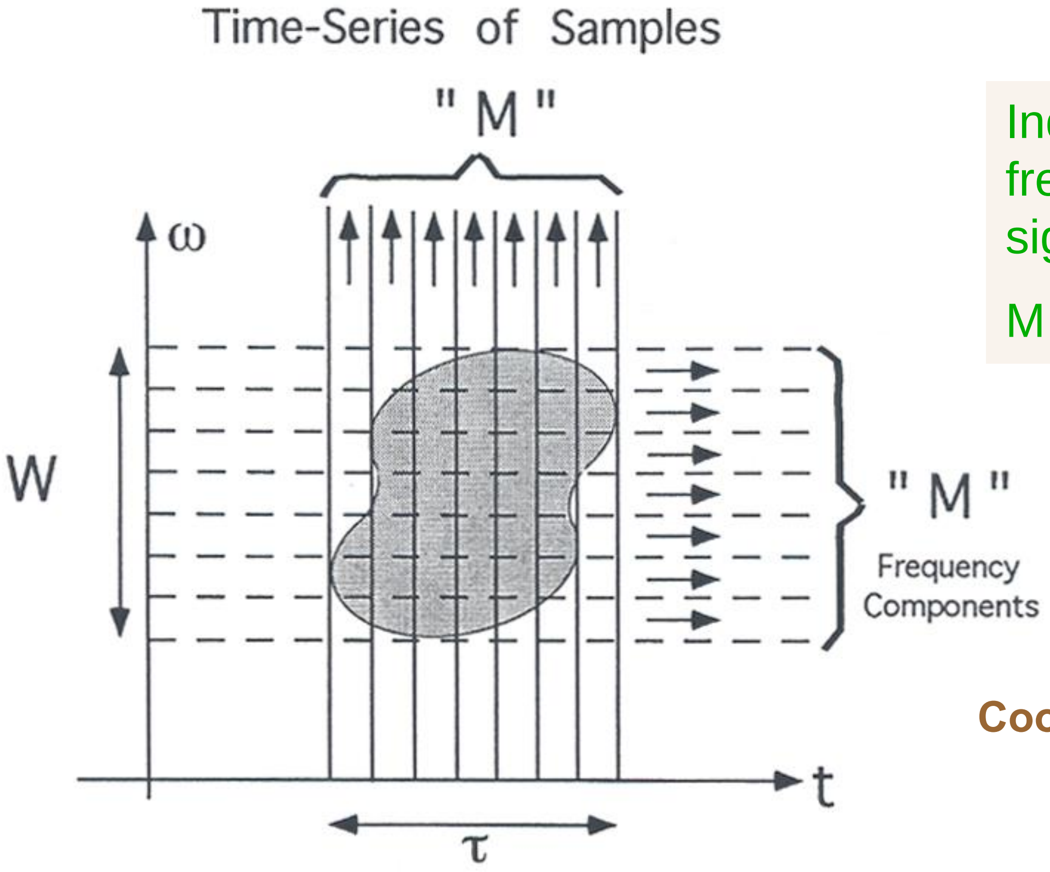
$$\frac{d\langle x\rangle}{dt} \equiv -\alpha g\langle x\rangle + \beta g^2\langle x^2\rangle$$

Microwave Stochastic Beam Cooling

- Discovery of "W&Z Bosons": Cold "Antiprotons": $p\bar{p} \to W^{\pm} + X$ (CERN 1983)
  $\to Z^0 + Y$
- Anti-Hydrogen: $\bar{p} + e^{+} \to \bar{H}$ (CERN 2002)

Cold "Antiprotons"

Information Processing in Two-Dimensional Fluctuation Signals



Independent degrees of freedom of fluctuation signal,

$M = 2W \cdot t$

(Nyquist Criterion)

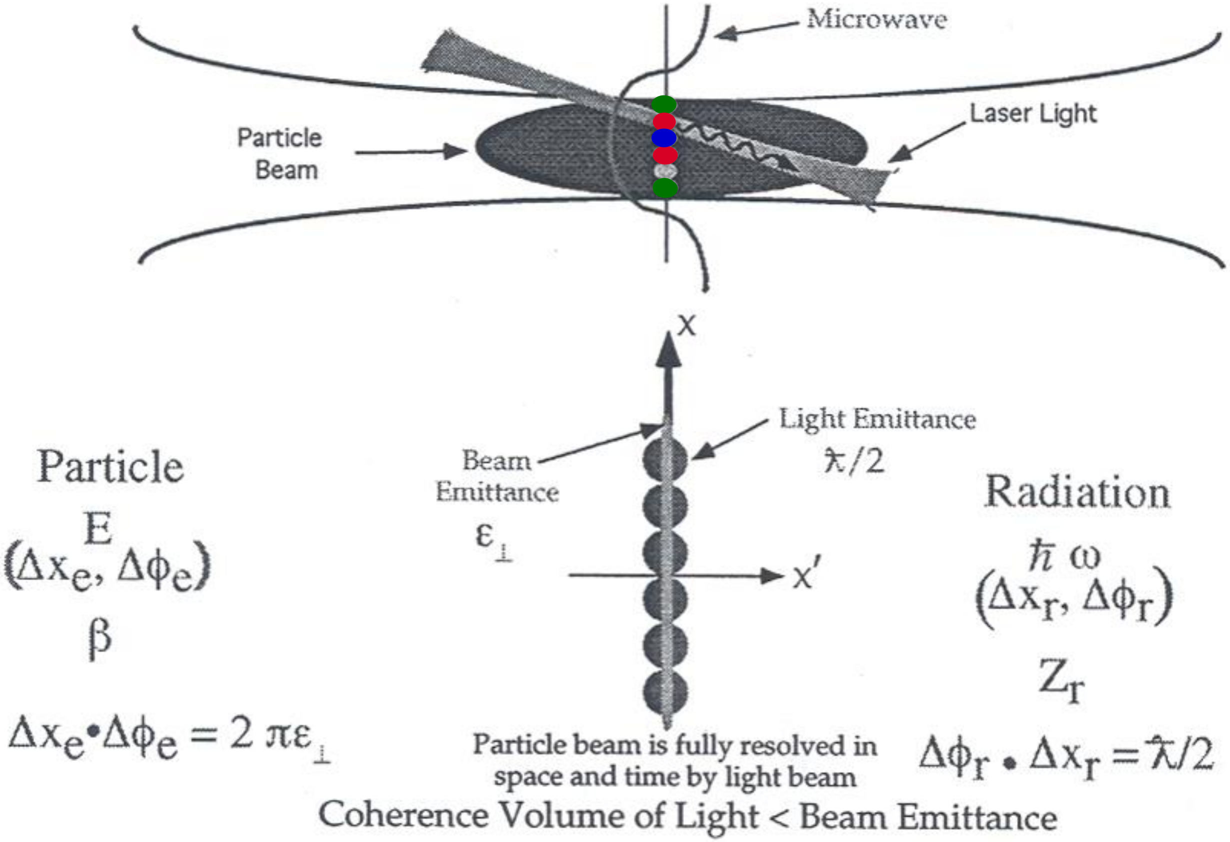
Cooling rate is proportional to “M”.

Degrees of freedom of fluctuation signals in time (t)-frequency(ω) plane

These are “temporal” samples or slices in time. How about transverse “spatial” samples? Microwaves are too long in wavelength.

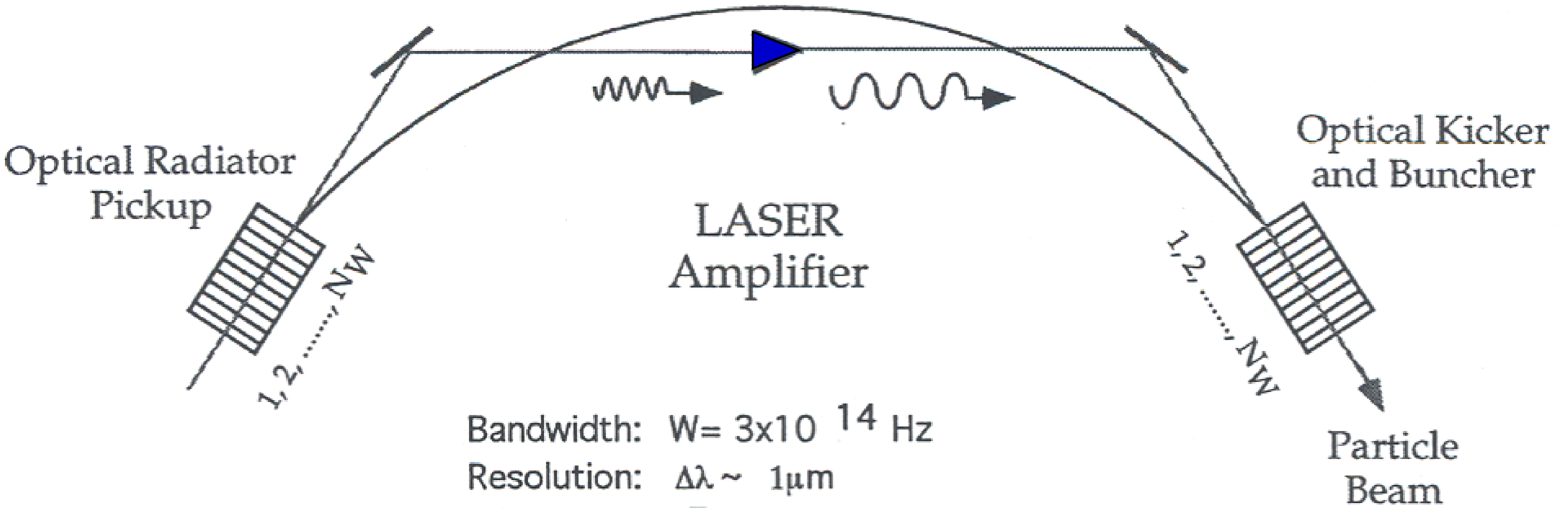
Optical Sampling of Charged Particle Beam

Optical Coherence Volume << Beam Emittance



Transverse Sampling of Particle Beams by Radiation Beam

Possible Application of Optical Cooling in Heavy Ion Rings (e.g. RHIC)



Bandwidth: W= 3x10 ^{14} Hz

Resolution: $\Delta\lambda \sim$ 1μm

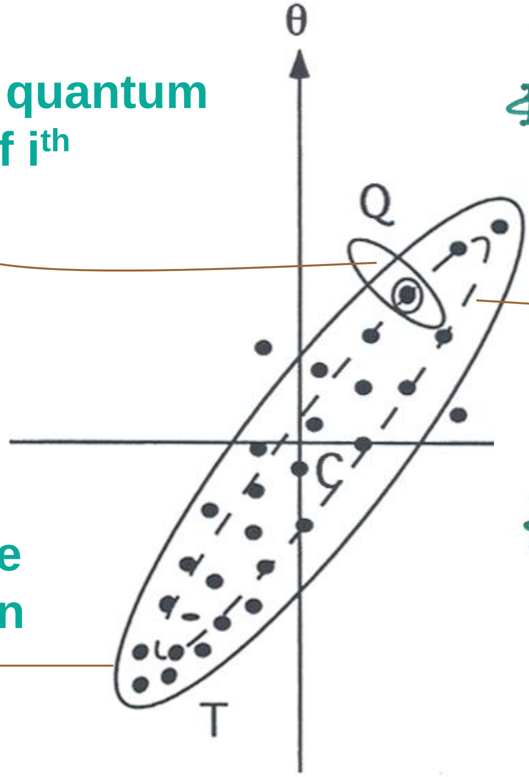
Gain: g ~10 ^{7}

Photons/charged particle ~ $\alpha N_W K^2$

Ultimate limitation by the “quantum” degeneracy parameter => number of photons/sample

Optical Stochastic Cooling

Classical and Quantum Phase Space of Beam and Radiation System: Seeded Coherence



$\Phi_Q^i \equiv$ **Single particle quantum phase-space of ith particle**

$\Phi_C^i \equiv$ **Classical Beam Phase Space of ith particle**

$\Phi_T =$ **Total Phase Space of Beam-Radiation System**

$$\Phi_T = \sum_{i,M} \Phi_Q^i \otimes \Phi_C^i \otimes \Phi_R^M$$

Radiation phase-space of Mth mode

Classical and quantum phase space of multiparticle, multimode beam-radiation system

$$\delta\Phi \equiv \Phi_T - \langle \Phi_T \rangle$$

Can be used as "Seed" for Coherent Amplification of Radiation, e.g., "Seeded FELS" such as BNL, MIT, LBNL, etc., studies.

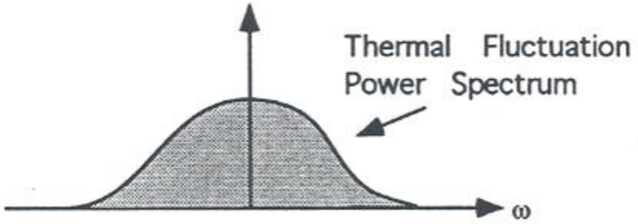
Evolution of Coherence through "Seeding"

Fluctuations and "Coherent/Condense" Beams

$$\sigma^2(s)= \in\beta^* \left(1+\frac{s^2}{\beta^{*2}}\right)$$

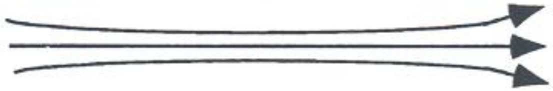
$$\equiv \frac{\lambda}{\pi} Z_R \left(1+\frac{s^2}{Z_R^2}\right) \text{ for light}$$

$$P_o(\omega)=<x_o(\omega)x_o^*(\omega)>$$



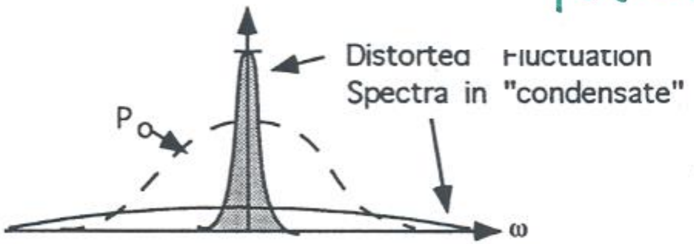
(a)

Incoherent



$$\sigma^2(s)= \bar{\lambda}_c\beta^* \left(1+\frac{s^2}{\beta^{*2}}\right)$$

$$P(\omega)=<x(\omega)x^*(\omega)> = \frac{P_o(\omega)}{|\epsilon(\omega)|^2}$$



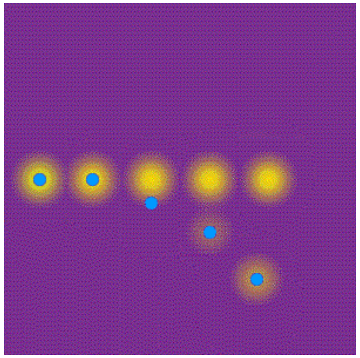
(b)

Coherent: $\sigma\sigma' \simeq (\lambda/2)$

Diffraction - limited

Incoherent (a) and coherent (b) beams and their fluctuation spectra

Outlook



"only a few photons in coherence volume"

- Understanding "Quantum Optics" driven by accelerated charges will be critical in these studies. → Coherence and degeneracy of an attosecond light pulse in the THz!!

- Opportunities in Ultrafast Science, Nonlinear Dynamics, SCRF, THz Laboratory Astrophysics look exciting!!

Fascinating graduate research!!

For the rest of my life I want to reflect on what light is. 1916