

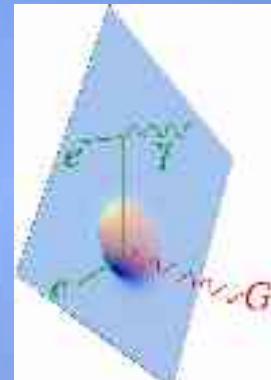


Accelerators of the Twenty-First Century: **Einstein's Legacy**

Oxford University
John Adams Institute Series Lecture

December 1, 2005

Swapan Chattopadhyay
Jefferson Lab



Thomas Jefferson National Accelerator Facility



Outline

- **Einstein and Particle Acceleration**
- **Colliders/Accelerators for Particle Physics**
 - **International Linear Collider**
 - *Superconducting Accelerators*
 - *SRF R&D*
 - **Neutrinos/Muons**
 - *Neutrino Complex/Schemes*
 - *Main R&D*
- **Advanced X-ray Facilities**
 - **ERL X-ray Sources**
 - *ERL R&D*
 - *Cornell 5 GeV X-ray Source*
 - *Daresbury 4GLS*
 - *Future Challenges*
 - **SASE X-FELS**
 - *Principle of Operation*
 - *Potential of e-SASE*
- **Light, Einstein and Tagore**

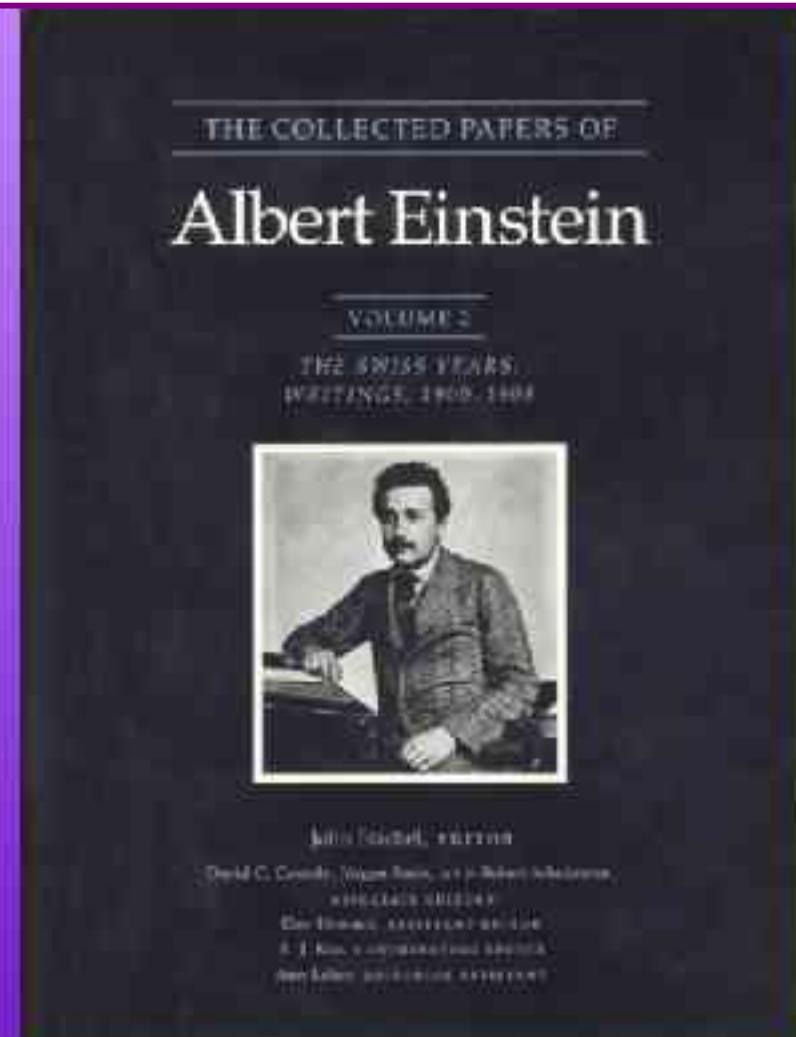
2005: World Year of Physics, 100 years since 1905: Einstein's Annus Mirabilis with three significant papers: Photoelectricity, Brownian Motion and Special Theory of Relativity

Einstein's Annus Mirabilis

Albert Einstein. "Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt." *Annalen der Physik* 17 (1905), 132-148.

Albert Einstein. "Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen." *Annalen der Physik* 17 (1905), 549-560.

Albert Einstein. "Zur Elektrodynamik bewegter Körper." *Annalen der Physik* 17 (1905), 891-921.

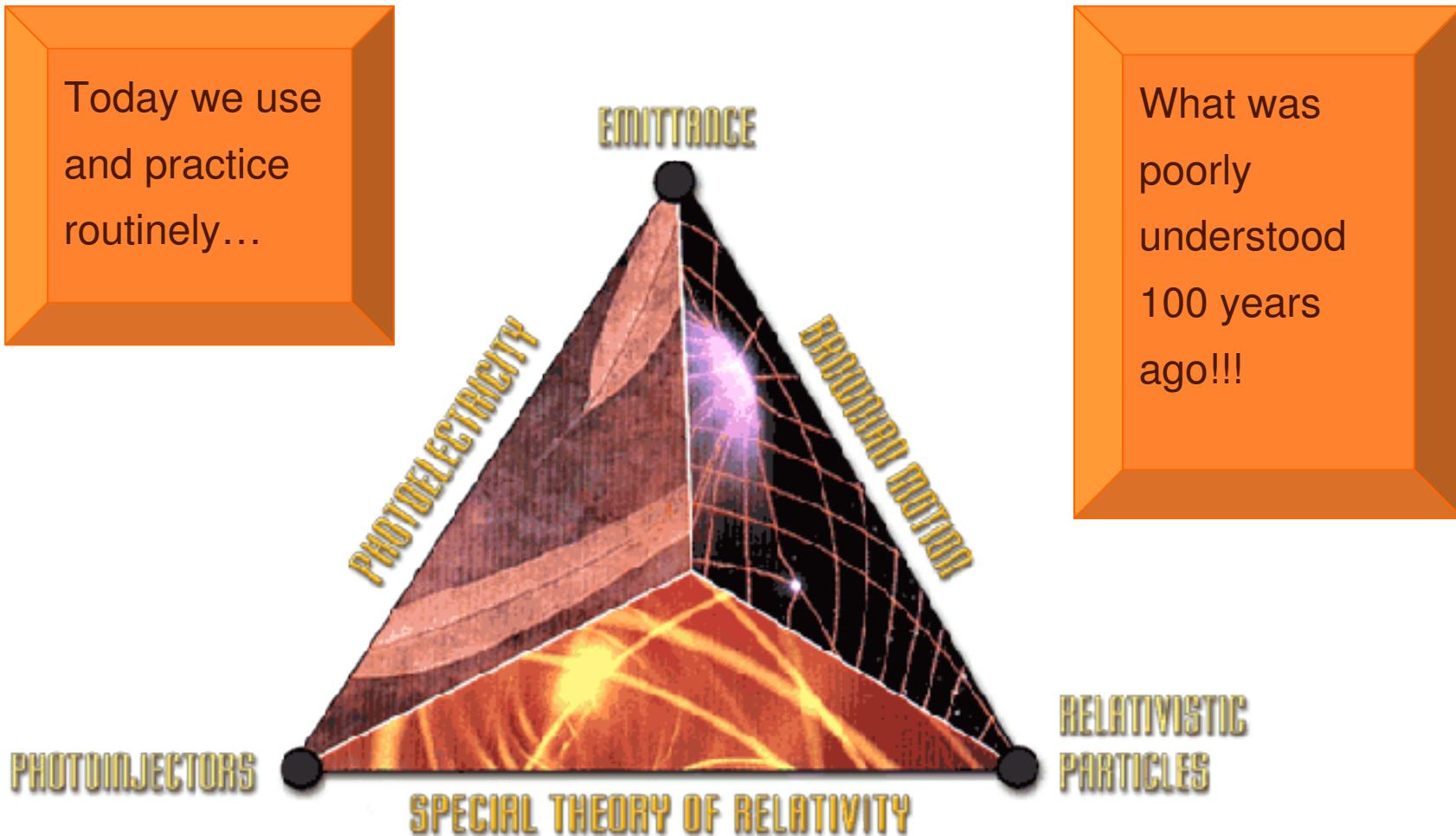


Photoelectricity, Brownian Motion & Special Theory of Relativity

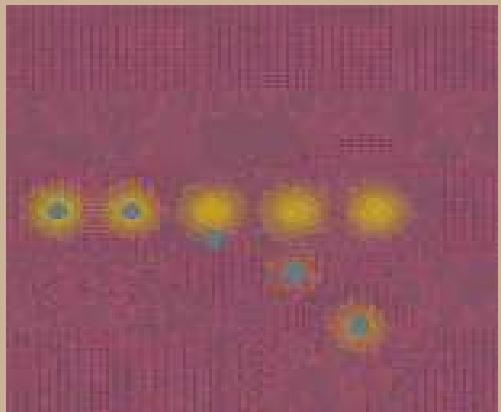
→ all three are related to ERLS via Photocathode Guns,
Emittance Dilution and Speed-of-Light Particles

Today we use
and practice
routinely...

What was
poorly
understood
100 years
ago!!!



Manipulation of charged particles to achieve controlled emission of light



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

- ‘Spontaneous’ and ‘Stimulated’ Emission of Light
- Einstein Coefficients ‘A’ and ‘B’
- Lasers

Emerging Sciences of the Twenty-First Century Driven by Particle Accelerators



Elementary Particle/Nuclear/Astro-Physics and Cosmology (Collider, Rare Isotope and Neutrino Facilities)



Probing with Photons: Nano/Femto/Atto-World (X-ray FELS and Ultrafast Synchrotron Light Sources)

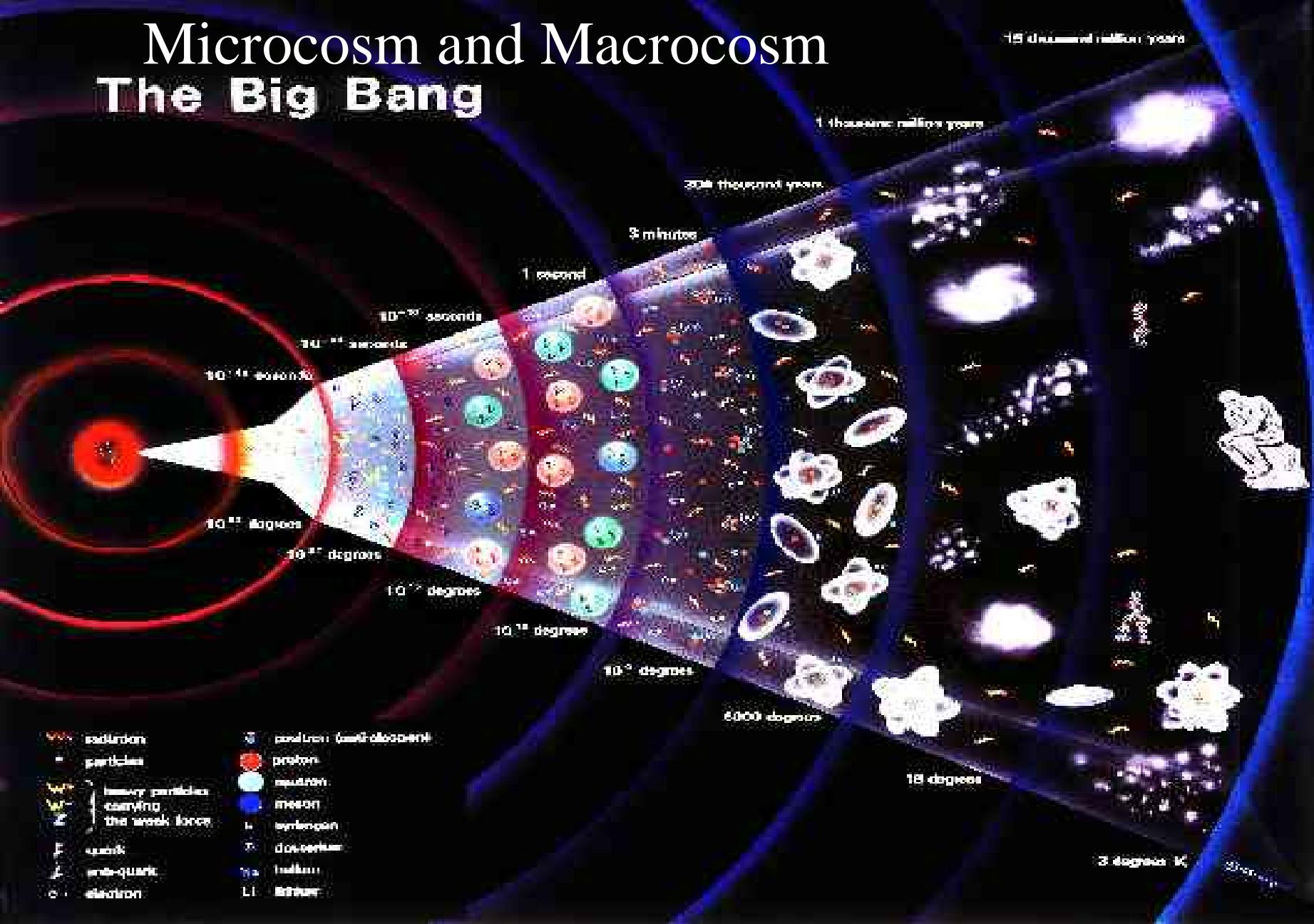


New materials via Neutron Scattering (Spallation Neutron Sources via High Current Proton Drivers)

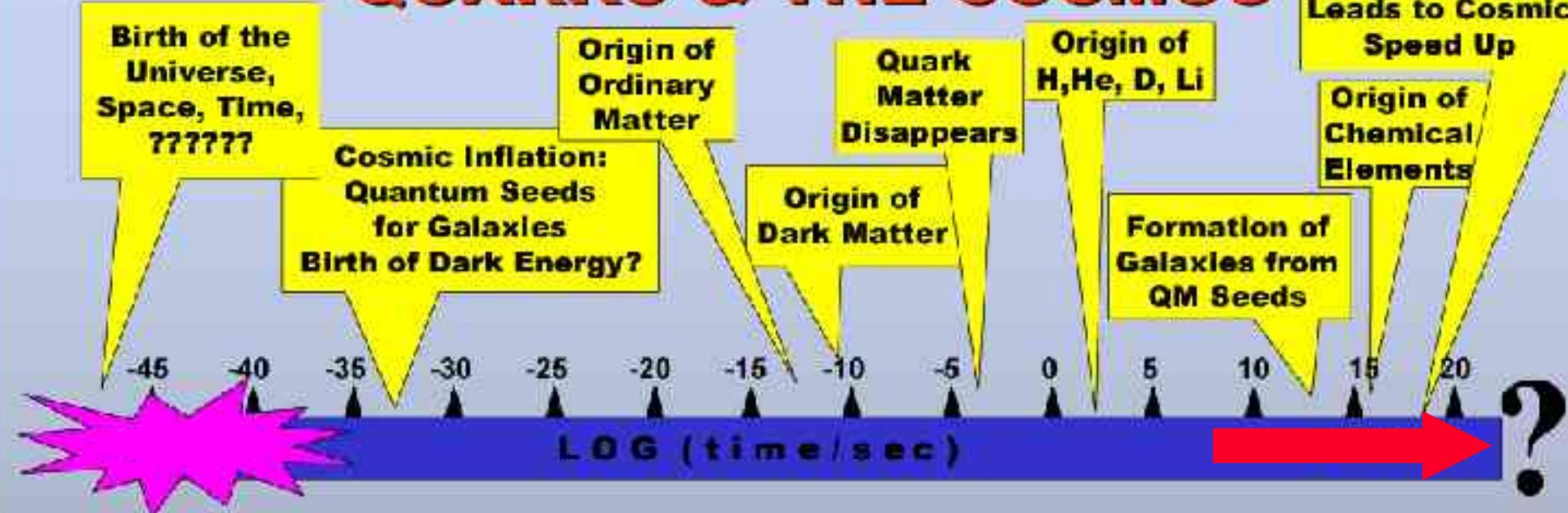
Future Colliders/Accelerators for Particle/Nuclear Physics

Microcosm and Macrocosm

The Big Bang



DEEP CONNECTIONS: QUARKS & THE COSMOS



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

Quark
Matter
Disappears

Origin of
H,He, D, Li

Dark Energy
Leads to Cosmic
Speed Up

Origin of
Chemical
Elements

Formation of
Galaxies from
QM Seeds

-45 -40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20

LOG (time / sec)

Theory,
Serendipitous
Discoveries

Neutrino Expts,
Underground Lab

RHIC
RHIC II

HRIBF, ATLAS
NSCL, etc.
RIA

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

High Energy Colliders
Tevatron, B-Factories, LHC,
ILC

Two Major Particle Physics Frontiers in the Lepton Sector:



International Linear Collider (ILC)



Neutrino Factories/Muon Collider

ILC/SRF R&D

ILC Schematic

The Global Design Effort (GDE) plan and schedule

2005

2006

2007

2008

2009

2010

2011

2012

GDE

CLIC

project

baseline configuration

reference design

technical
design

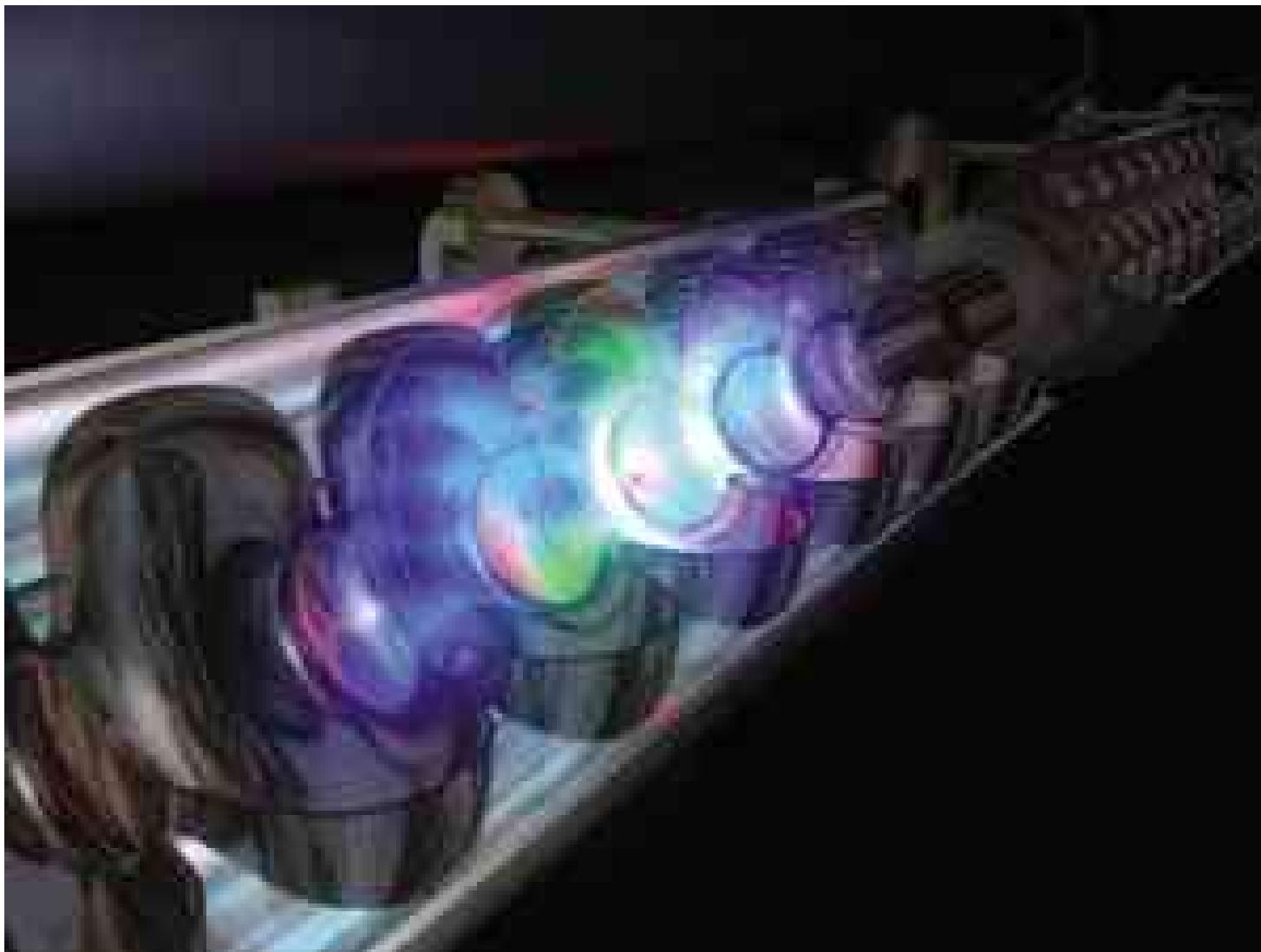
Large
Hadron
Collider
physics

International Linear Collider
R&D programme

expression of
interest to host

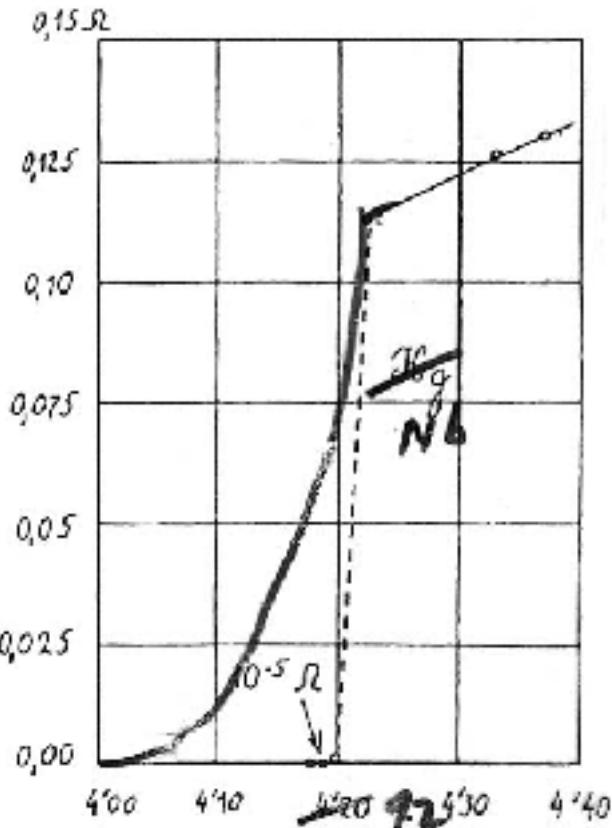
international management

The Superconducting Linear Accelerator



Superconductivity

Heike Kammerling-Onnes, 1911: SC in mercury



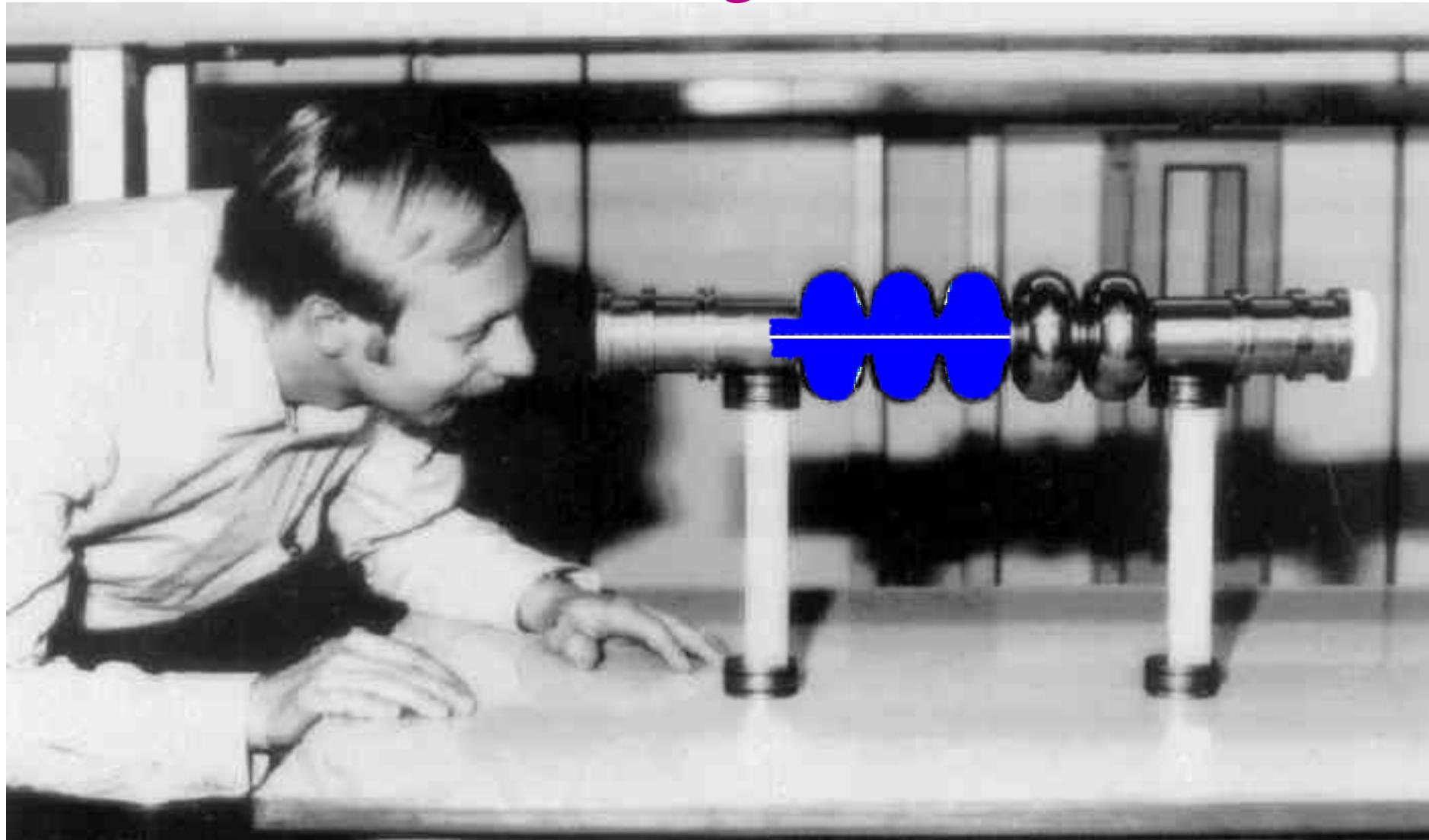
surement of superconductivity by Kammerling-Onnes



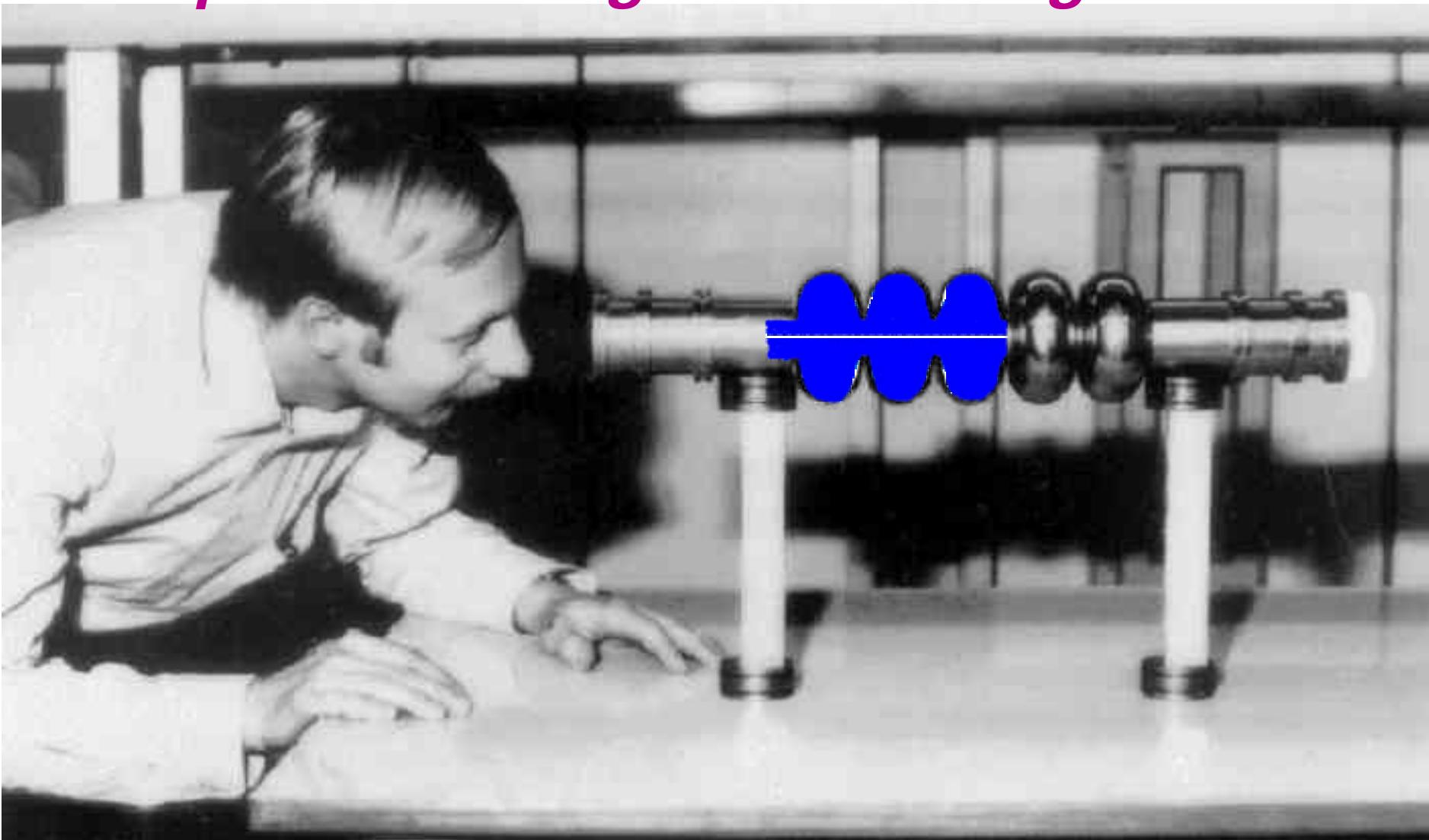
Figure 1.2. Heike Kamerlingh Onnes. Courtesy: AIP Emilio Segrè Visual Archives

In fact, the “Onnes Road” at Jefferson Lab, home of much of Superconducting Radio Frequency Science and Technology, is named after him.

“Pulsed” Operation of “Normal” Conducting Accelerating Cavities



“Continuous” Operation of “Superconducting” Accelerating Cavities

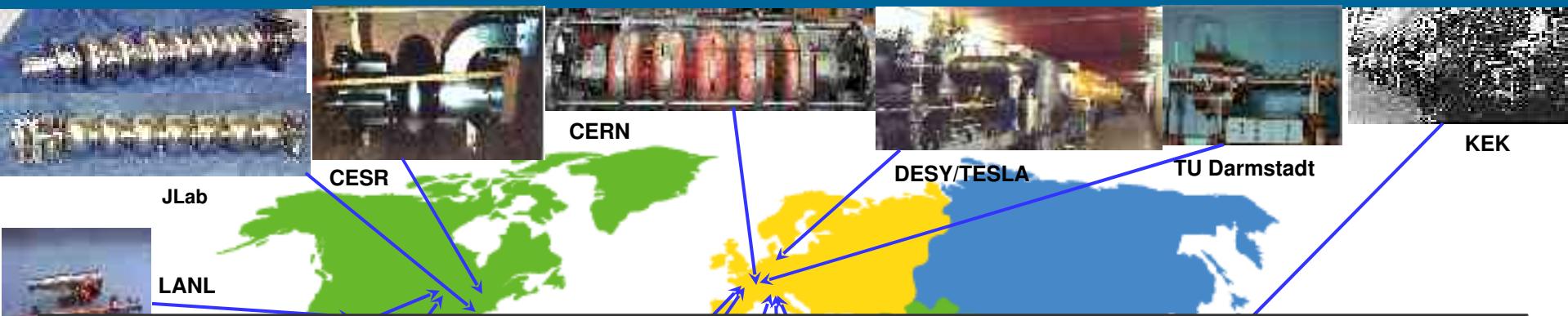




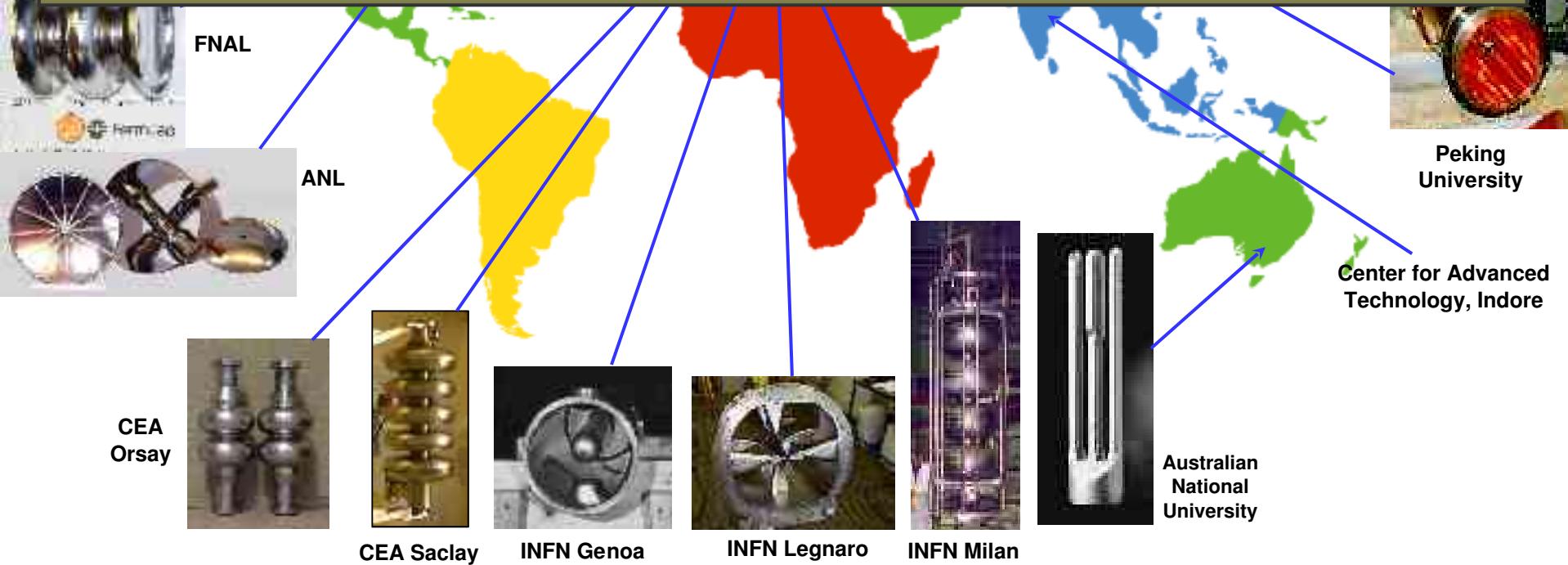
Applied Superconductivity today

Today, Superconducting RF is a robust global technology that is still evolving. It occupies a central place in the Coordinated Accelerator Research in Europe (CARE program). It is a focus of many U.S. laboratories. It is also emerging in Asia (China, Japan, Australia).

Global View of Accelerator Technology



WE MUST LEARN TO COLLABORATE INTERNATIONALLY



SRF Re&D

Advances in SRF, Combined with Beam Recirculation and Energy Recovery

Gradient [MV/m]

Accelerator Length to reach 200 MeV

1985 →



5 MV/m, CEBAF design, 5 cells

1995 →



~7 MV/m, CEBAF as built, 5 cells

1998 →



10 MV/m, JLab FEL, 5 cells

2001 →



~20 MV/m, CEBAF Upgrade Prototype, 7 cells



2005 →



~45 MV/m, JLab R&D single grain, single cell result @ 2.2 GHz

SRF enables: compact FELs to Linear Colliders

With ***recirculation***: 12 GeV, 25 GeV, ν Factory

With ***energy recovery***: e-cooling , EIC, Light Sources, MW FELs

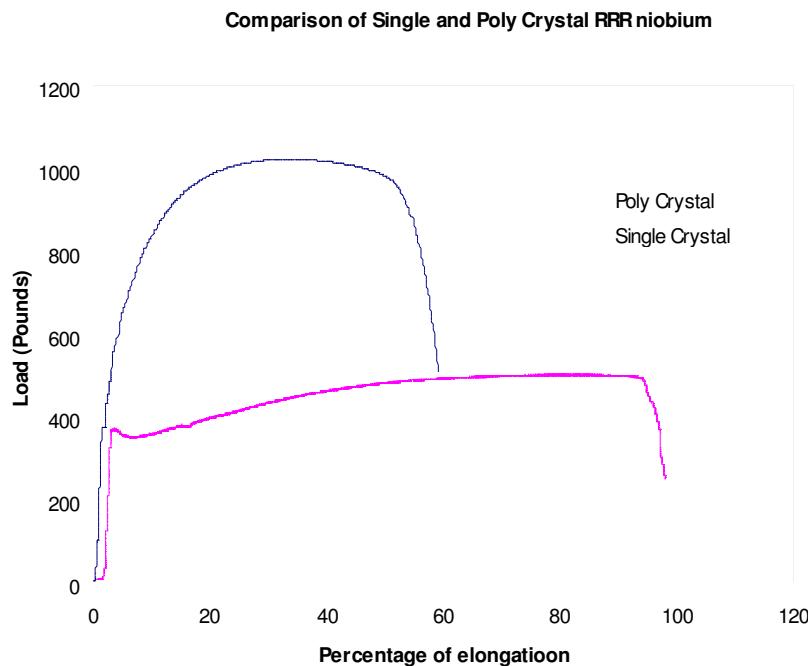
Cost Saving Subjects

- **Cavity fabrication and Treatment**
("The Jlab/CBMM Technology")
- **Superstructures**

*Courtesy: Peter Kneisel
Ganapati Myneni*

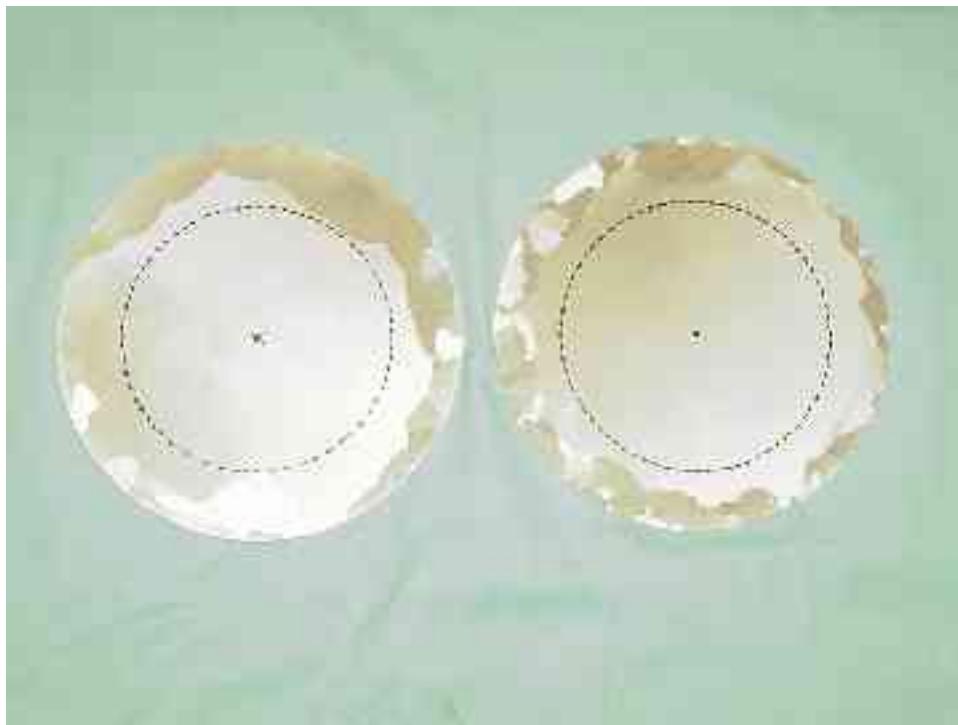
Jlab/CBMM Technology

- *Development started with the need for understanding mechanical properties of niobium from different manufacturers (G. Myneni)*
- *Ingot material supplied by CBMM with large grains (T. Carneiro)*
- *Mechanical properties –especially elongation – excellent, permitting forming of cavity cells*



Jlab/CBMM Technology

Discs from Ingot



Cavity

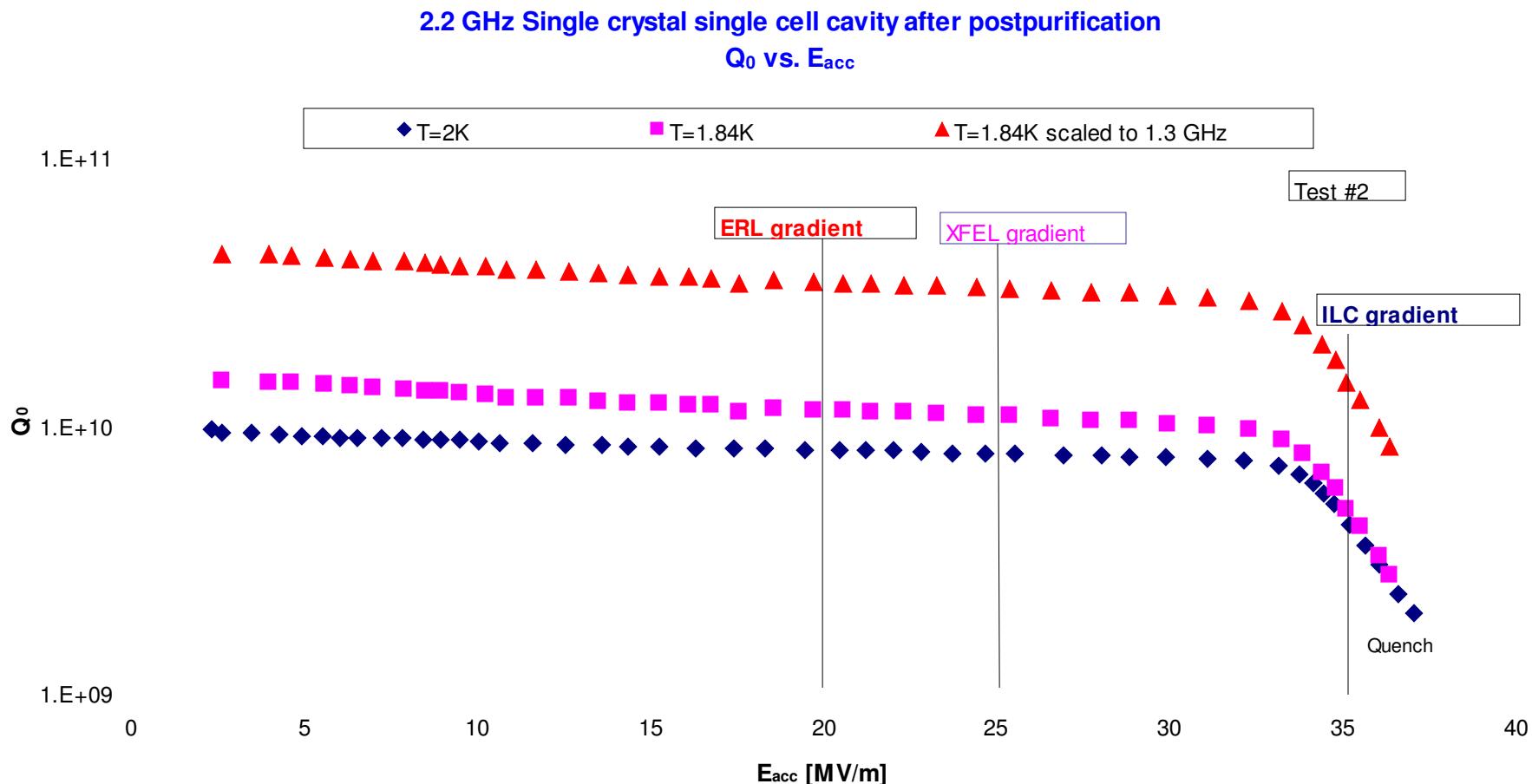
$$E_{peak}/E_{acc} = 1.674$$

$$\mathcal{H}_{peak}/E_{acc} = 4.286 \text{ mT/MV/m}$$



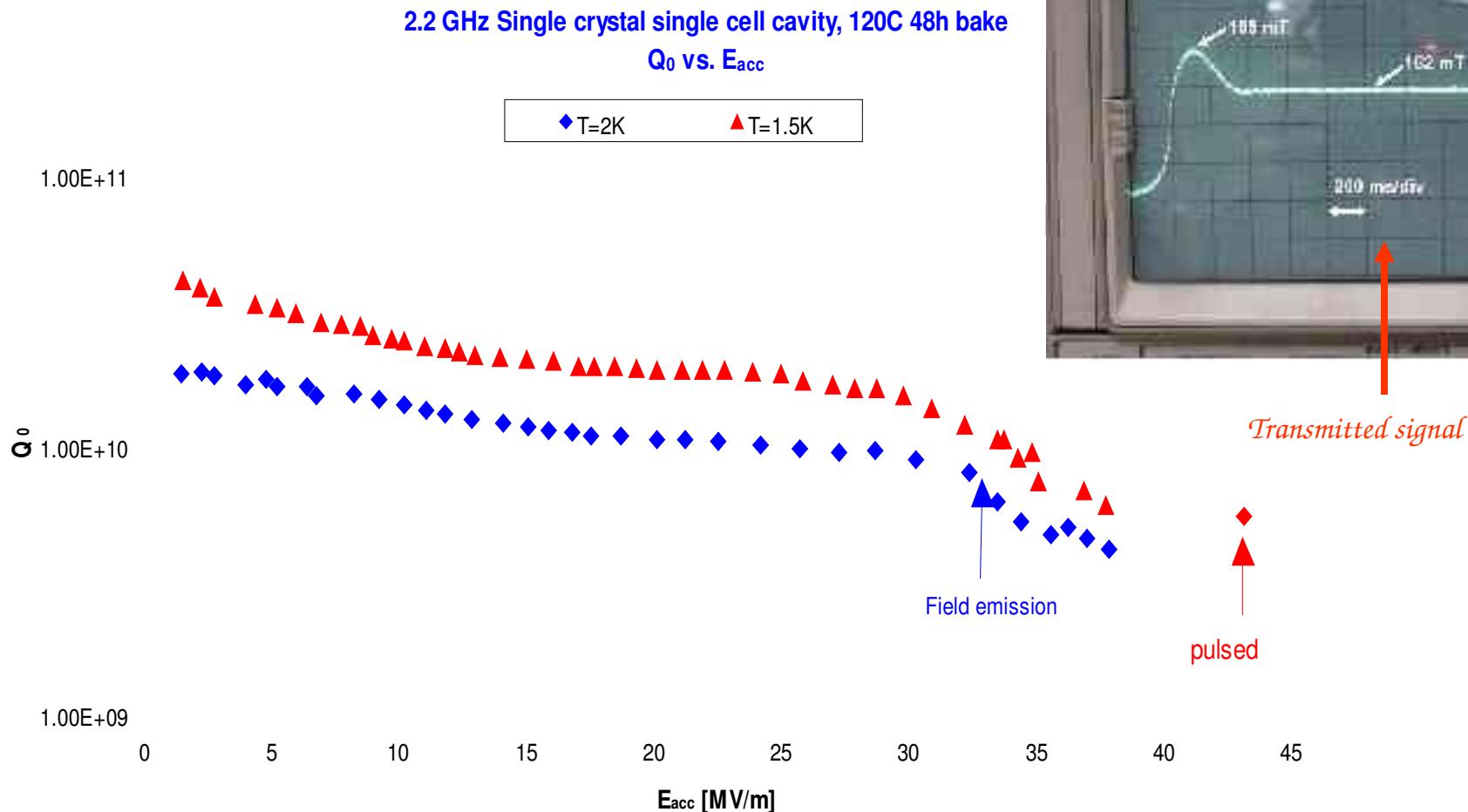
Jlab/CBMM Technology

Test #2: post-purification heat treatment at 1250 C for 10 hrs, 100 μ m BCP, high pressure rinsing



Jlab/CBMM Technology

Test #1b: Treatment 100 μm BCP, 800C hydrogen degassing, 100 μm BCP, high pressure rinsing, “in situ” baked at 120C for 48 hrs



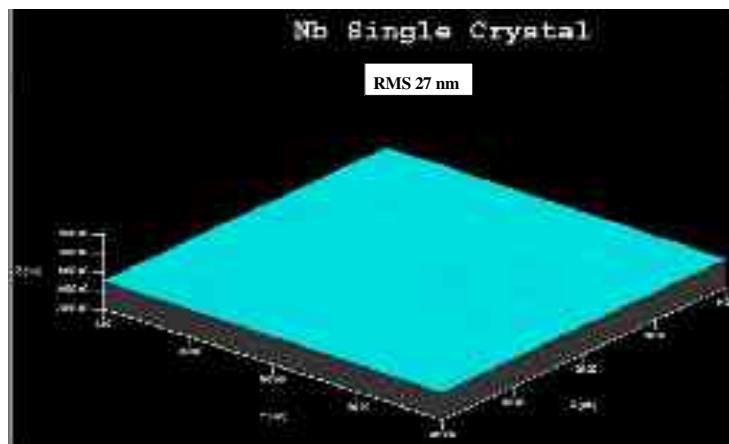
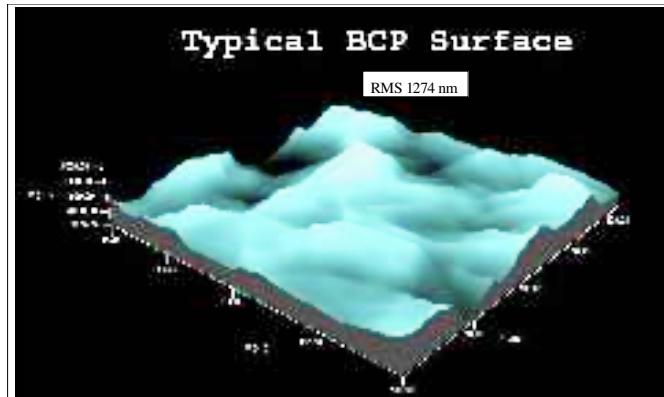
Jlab/CBMM Technology

BCP provides very smooth surfaces as measured by A. Wu, Jlab

RMS: 1274 nm fine grain bcp

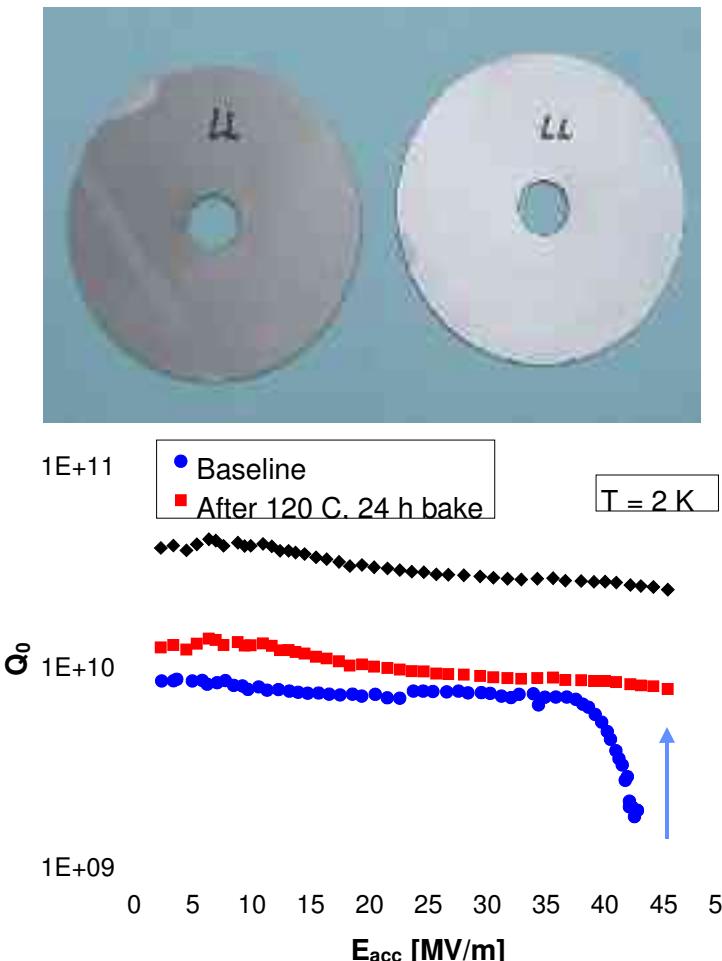
27 nm single crystal bcp

251 nm fine grain ep



Jlab/CBMM Technology

Nb Discs



LL cavity 2.3GHz

$$\mathcal{E}_{peak}/\mathcal{E}_{acc} = 2.072$$

$$\mathcal{H}_{peak}/\mathcal{E}_{acc} = 3.56 \text{ mT/MV/m}$$



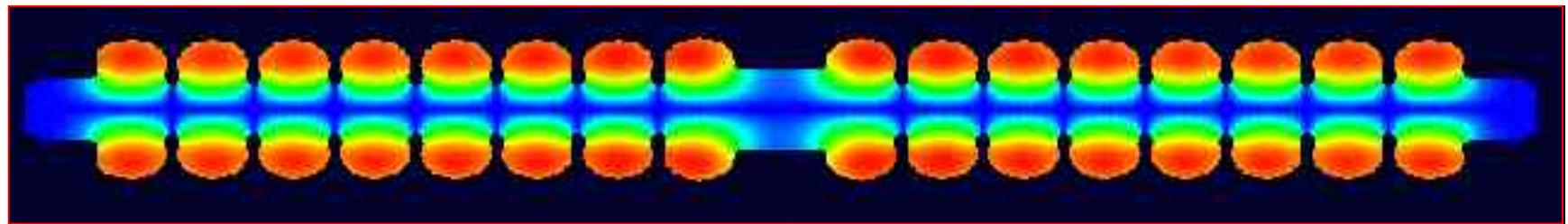
Jlab/CBMM Technology

- *Estimated savings per cavity due to use of less expensive ingot material and “streamlined” procedures*
~ \$ 12,000
- *Total savings for ILC (~ 20 000 cavities)*
~ \$ 240,000,000

Superstructures

To push the SRF limits for ILC accelerator Kenji Saito proposed to refresh the idea of weakly coupled pairs for the ILC upgrade. (J. Sekutowicz, 1. ILC workshop)

Example: 2x8-cells based on the RE-shape.



RE 2x8-cells; Contour of B field

Superstructures

Jefferson Lab has “flirted” with the idea of using SST for the upgrade of the FEL; two SST’s (2 x 5 cells and 2 x 2 cells) are in fabrication and is gaining some experience in the near future

The estimated cost savings for the replacement of “regular” cavities with superstructures is of the order of

\$ 250,000 000

Therefore it might be worthwhile to pursue this option

Possible Cost Savings

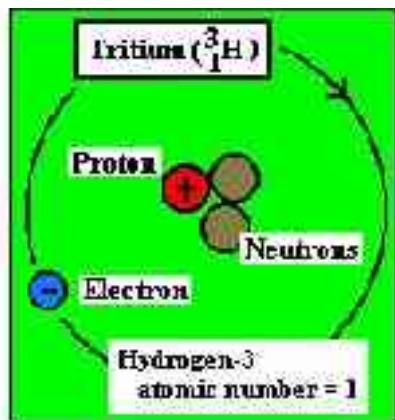
*By pursuing the “Jlab/CBMM” technology
for cavity fabrication and “streamlined”
procedures and implementing
superstructures based on the LL cavity
Design cost savings in the range of*

\$ 0.5 to 1 Billion

Seem to be possible

Neutrino Factories/Muon Collider

Ubiquitous Neutrinos



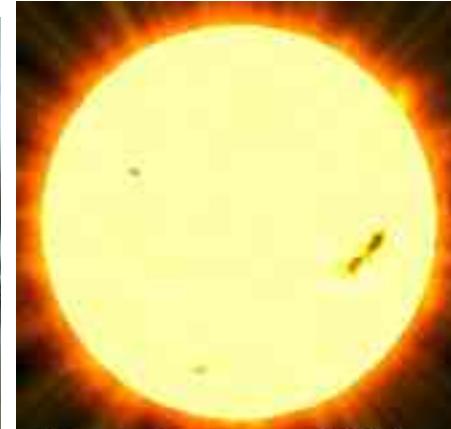
From radioactivity ~ MeV



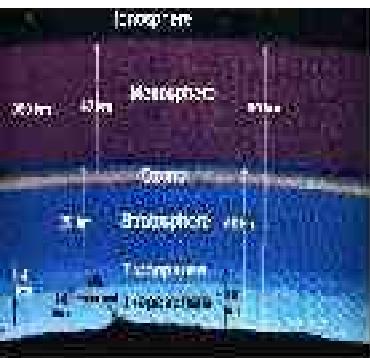
From reactors - ~MeV



From accelerator - ~GeV



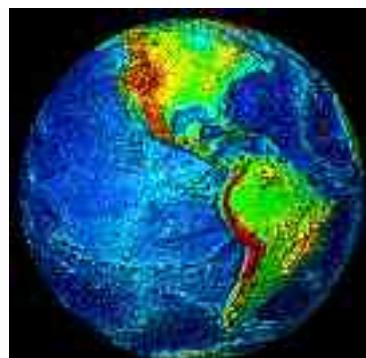
From the sun ~ MeV



From atmosphere ~GeV



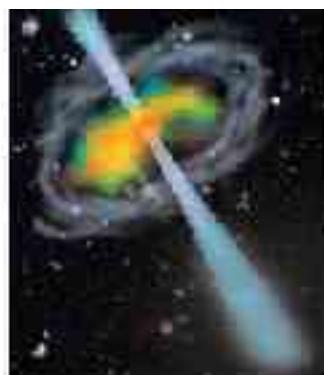
From Supernova ~ 10 MeV



From the earth ~ MeV



From Big Bang - ~10⁻⁴ eV



Extra-galactic - ~TeV



The International Scoping Study of a Neutrino Factory and Super-beam Facility

Invaluable physics is at stake in this field of particle physics. Neutrinos are special among the elementary particles in that they are not charged, electric or color neutral. This neutrality allows them to carry information about the fundamental laws of the universe which have in turn had a major impact on astrophysical processes, from the first minutes after the Big Bang to supernovae explosions observed today. The demonstration of natural sources that neutrinos have mass and that the three generations mix has been the major event in particle physics in the last decade. The observation can be traced to the experiments conducted at the Super-Kamiokande detector. The discovery leading to the Nobel Prize will have led to the prediction that light to the scale of charged fermions never seen since the Big Bang, perhaps connected to the Unification of all forces. Precise measurements of the masses and mixing angles of the three families of neutrinos is a unique window of observation into these early times.

The recently discovered properties of neutrinos open the possibility of detecting a difference in the oscillations of neutrinos and anti-neutrinos, called co-leptonic CP violation. This discovery would be extremely important and likely to give essential input to understand how the universe has evolved from the time it was born, equally as the matter/antimatter ratio might do in the early universe. An international study

These fascinating physics questions require an ambitious accelerator-based long baseline neutrino experimental program. Several neutrino sources have been envisaged to feed light-entitled and medium-energy neutrinos to the currently proposed neutrinooscillation programs. It is well known that the Neutrino Factory and intense high-energy neutrino source based on a storage ring or beam gives the best performance experimentally of all the parameter space to come scale and cost within. However, important question may arise. Second-generation superbeam experiments may be an attractive option to complement Neutrino Factory. Many other parameters in neutrino will. The Neutrino Factory, if the storage ring and other resources for anti-neutrinos, are provided from the decay of storage ring positrons or beams, in combination with a second-generation superbeam, may be a competitive option.

The scoping study will therefore review the state-of-the-art level of the various proposed facilities and make feasibility assessments very clearly. These comparisons will be used to define the programme needed to achieve international consensus on the facility or facilities required to an optimal programme for high precision neutrino measurements. The two models, the particle and the beam, will be simultaneously considered, thus involving the reactor scenario being evaluated. The conceptual design of the neutrino facility is being developed in the context of the EU Framework-Programme-6 funded EUR 30M design study. Therefore, this scoping study will focus on evaluating the various options for the Neutrino Factory and the second generation superbeam.

In recent years, feasibility studies of possible configurations for a Neutrino Factory have been carried out in Europe, in Japan, and in the U.S. These studies have concluded that such facilities, although the performance expected in some parameters will differ and the overall design will be different, the basic idea is the same. This key R&D will be carried out in parallel, and the final results will be included. Many of these studies, mostly in the way, most as international collaborations involving all three regions.

Cont'd

Experimental demonstration of muon ionization cooling is the aim of the International Muon Ionization Cooling Experiment (MICe) at Rutherford Appleton Laboratory's ISIS accelerator. It will test the operation and performance of an actual section of cooling channel under a variety of conditions, and will provide a solid indication of component fabrication costs. First beam is expected in Spring 2007. A second key area involves demonstrating a target technology capable of withstanding bombardment with a multi-MW proton beam while operating in a high electric field. This experiment, in D-11, also proposed by an international collaboration, is approved. In turn CERN in 2007. Efforts to study the performance of fixed-field alternating gradient (FFAG) synchrotrons are also underway. Two examples of prototype 'scaling' machines have already been built in Japan, and a proposal to build an electron model of a non-scaling ring has been submitted in Europe by an international team from all three regions.

What has not been done—and will be a focus of the International Scoping Study (ISS)—is to compare and contrast the different approaches to a Neutrino Factory to identify the optimum and/or the most cost-effective choice. This will be accomplished by an international group comprising experts in all of the proposed technical approaches. Lastly the ISS will serve to review the R&D plan in support of a Neutrino Factory, modifying and augmenting it as necessary to make it consistent with the latest thinking on Neutrino Factory design.

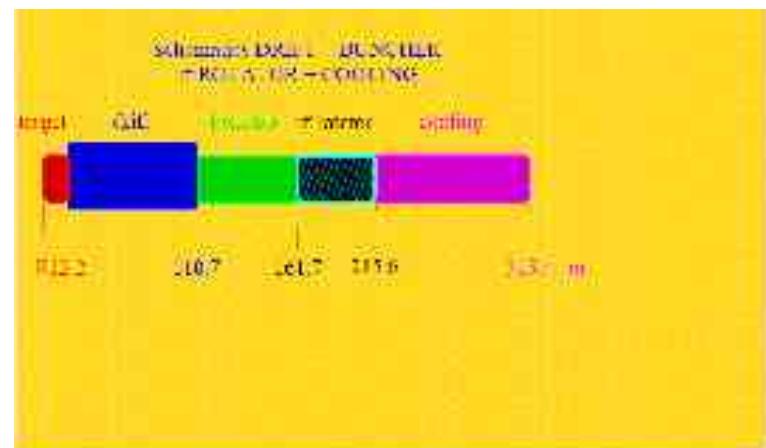
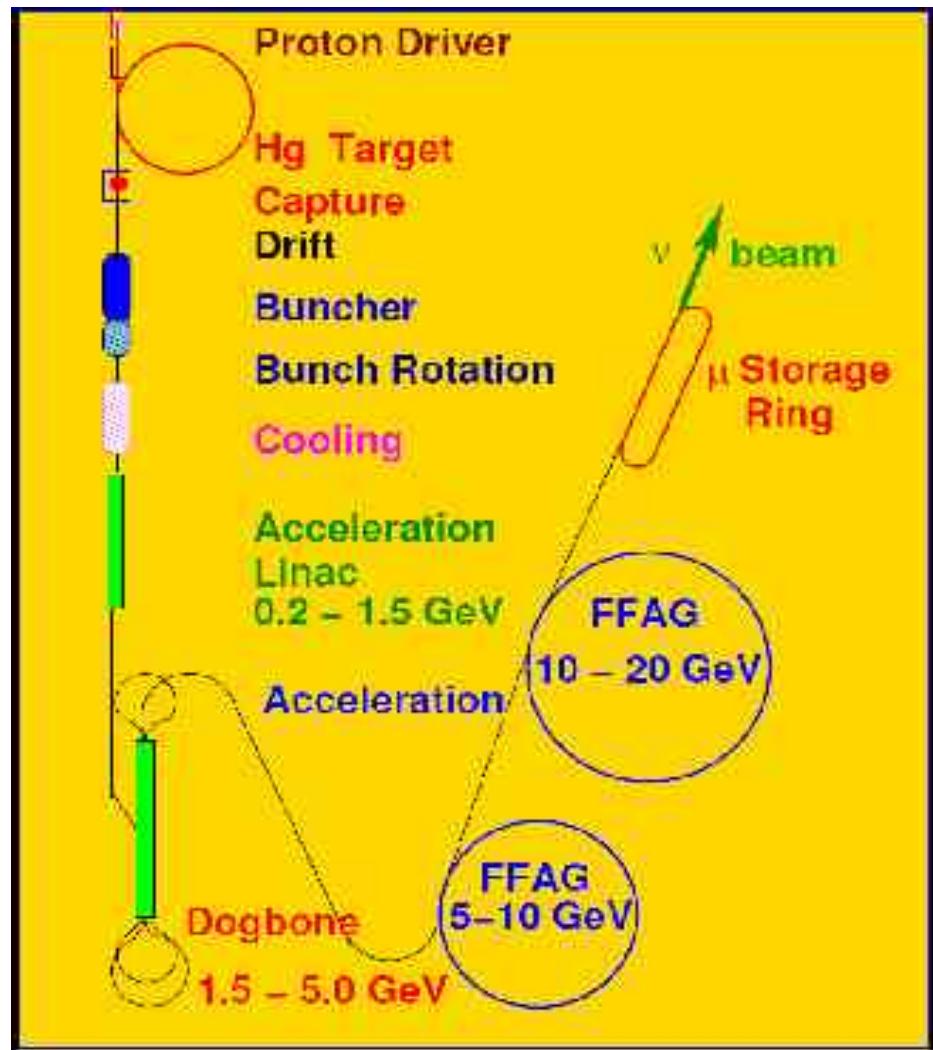
In order to establish the cost and performance of the overall facility, the ISS will not consider the accelerator solution but will examine it in conjunction with the cost and performance of the detector as well. Several technologies have been discussed to match the tremendous challenge of providing very large mass detector while preserving the ability to perform precision measurements.

Super-beam or neutrino beam provide essentially one flavour of neutrinos and the emphasis is on large detector mass and muon and electron particle identification. These requirements are well matched by megaton-scale water Cherenkov detectors for low energy beams or perhaps as well by liquid argon or large volume scintillator detectors. The Neutrino Factory has the advantage of the golden channel—appearance of wrong sign muons—which requires a magnetic field. This leads most naturally to the magnetized iron calorimeter design. Another unique feature of the Neutrino Factory is the possibility to observe the silver channel, the $\nu_e \rightarrow \nu_\tau$ transition, which could be observed with either emulsion based detectors, or a magnetized liquid argon TPC. In all detector concepts, there are important questions concerning cost, feasibility and time scales, as well as design optimizations to be made e.g. between energy, angle resolution, and mass. A realistic set of performance estimates is an important to serve as input to the physics comparisons between different options.

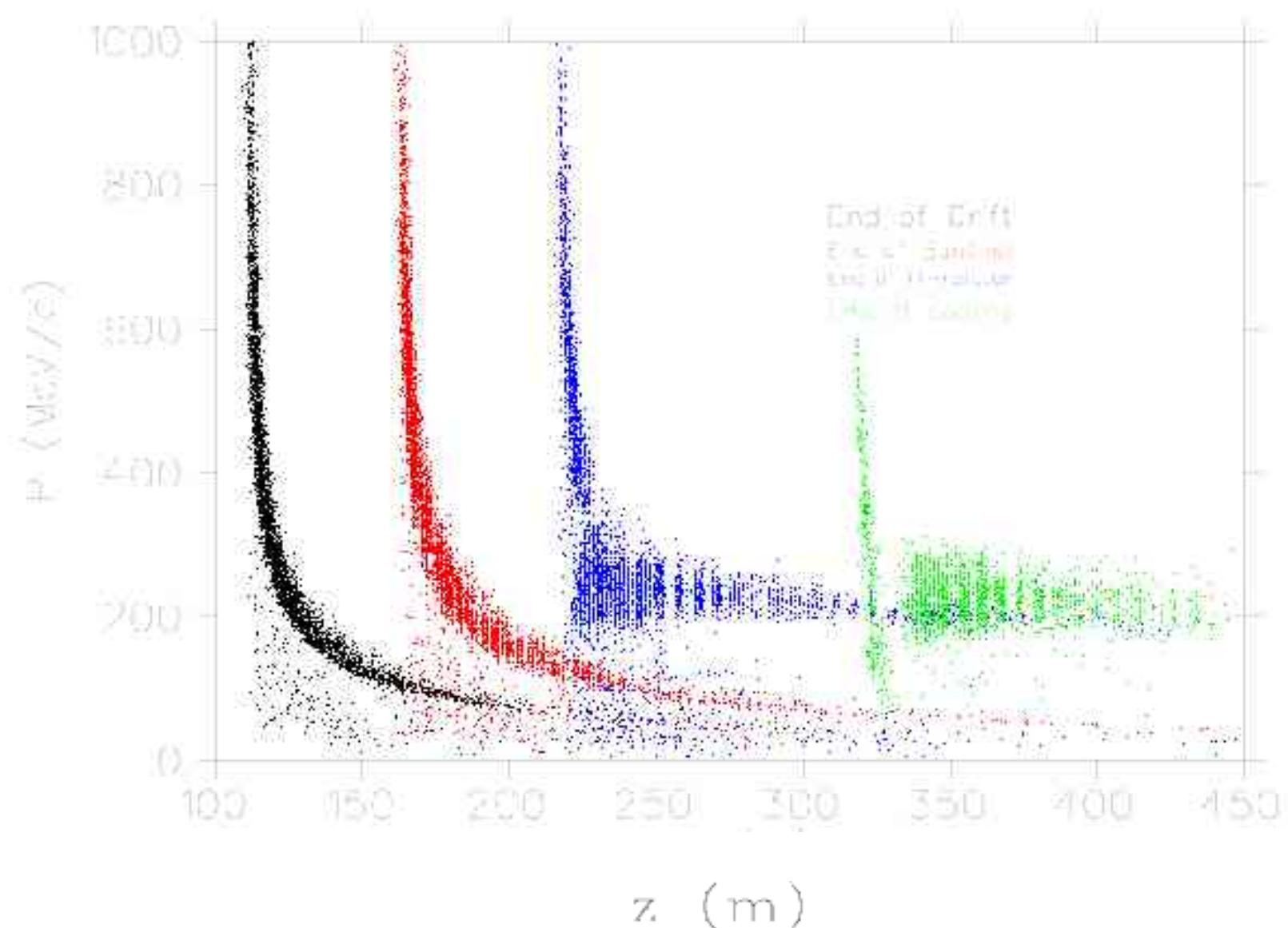
Finally, precise knowledge of flux and cross sections will be a fundamental requirement. The study of detector concepts for the near detector stations will be an important aspect of the international scoping study.

A fair Bluncet, Peter Colman, Yui Nagashima, Mike Zisman ISS website <http://hepux.rl.ac.uk/uksf/wpt/scoping/>.

Schematics of a Neutrino Factory (US Study IIa)



Front End Performance – Bunching, Rotation, Cooling



Initial beam emittance/acceptance – prior to acceleration

after the cooling channel at 273 MeV/c

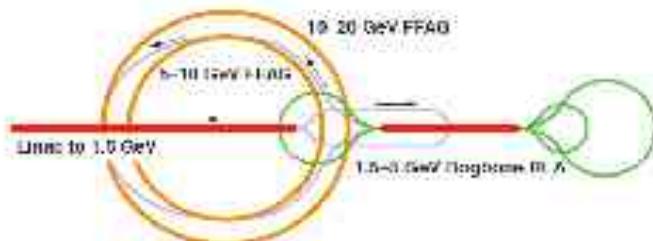
Study IIa		ϵ_{rms}	$A = (2.5)^2 \epsilon$
normalized emittance: ϵ_x/ϵ_y	mm·rad	4.8	30
longitudinal emittance: ϵ_l $(\epsilon_l = \sigma_{\Delta p} \sigma_z / m_\mu c)$ momentum spread: $\sigma_{\Delta p/p}$ bunch length: σ_z	mm	27 0.07 176	150 ± 0.17 ± 442

Acceleration - Beam Parameters

Study Ila		
Final energy	GeV	5
Number of bunches per pulse		89
Number of particles per pulse		$3 \cdot 10^{12}$
Bunch/accelerating frequency	MHz	200/200
Average repetition rate	Hz	15
Average beam power	kW	144

Muon Acceleration Complex – Four Major Schemes

Four major schemes (US Study IIa)



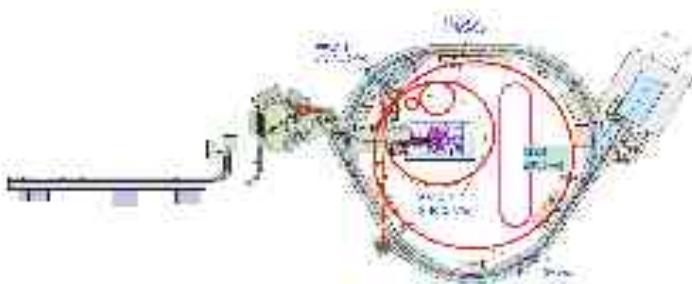
- AGS or Fermilab upgrade as a proton driver.
- Lines and RLA up to 5 GeV.
- Two non-scaling FFAG from 5 to 20 GeV.
- Bunching and cooling to create a multi-bunched fit into 300 MHz RLA.

Four major schemes (CERN NF)



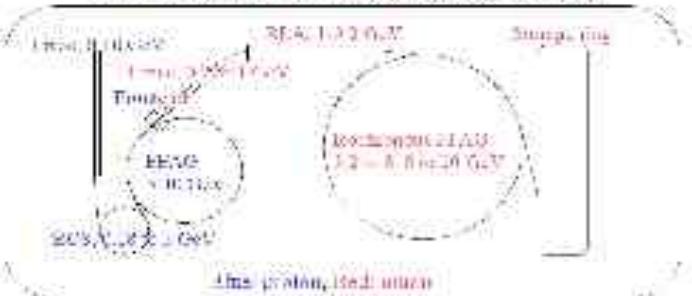
- Lines and compressor ring as a proton driver.
- Lines and RLA up to the final muon energy.

Four major schemes (NuFactJ)



- J-PARC as a proton driver.
- Four scaling FFAG accelerate muons from 0.3 to 20 GeV.
- No bunching, no phase rotation, and no cooling.
- Single muon bunch throughout the cycle.

Four major schemes (UK originated)



- Proton driven with H-AG.
- Lines and RLA up to 3.2 GeV
- Two non-scaling FFAG from 3.2 to 20 GeV in the same tunnel.
- RF frequency of H-AG can be very pick up 260 MHz

NFMCC R&D Program

- Neutrino Factory and Muon Collider Collaboration program aimed at developing theoretical and simulation tools and carrying out component R&D unique to development of a neutrino factory and a muon collider
 - extensive experimental effort to verify component performance and cost, and to validate simulation predictions, is major part of program
- NFMCC includes 135 scientists/engineers from 37 institutions
 - sponsoring Labs: BNL, FNAL, LBNL
- Key experimental issues include demonstrating the technique of muon ionization cooling (**MICE**) and demonstrating a target technology capable of withstanding a multi-MW proton beam (**MERIT**)

Present Activities

- Simulations
 - feasibility studies of neutrino factory concepts
 - leadership role in International Scoping Study of high-intensity neutrino source
 - studies of muon collider concepts, e.g., cooling rings
 - code development in support of above studies (**ICOOL**)
- Component development
 - LH₂ absorbers with thin (180 µm) aluminum windows
 - 201 MHz high-gradient NCRF cavities (operating in high B field)
 - MUCOOL test area (MTA) constructed at Fermilab
 - 201 MHz SCRF cavities for muon acceleration
 - 20 m/s Hg jet target
- System tests
 - **MERIT** (Mercury Intense Target experiment at CERN)
 - **MICE** (Muon Ionization Cooling Experiment at RAL)

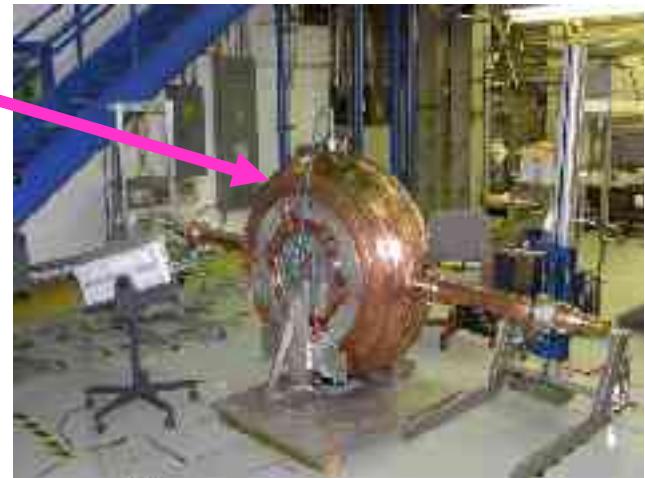
Absorber Hardware

- LH₂ absorbers and windows being tested at Fermilab



NCRF Cavity Hardware

- 201 MHz NC cavity fabricated by LBNL, Jlab, U.-Miss
- To be tested at MTA



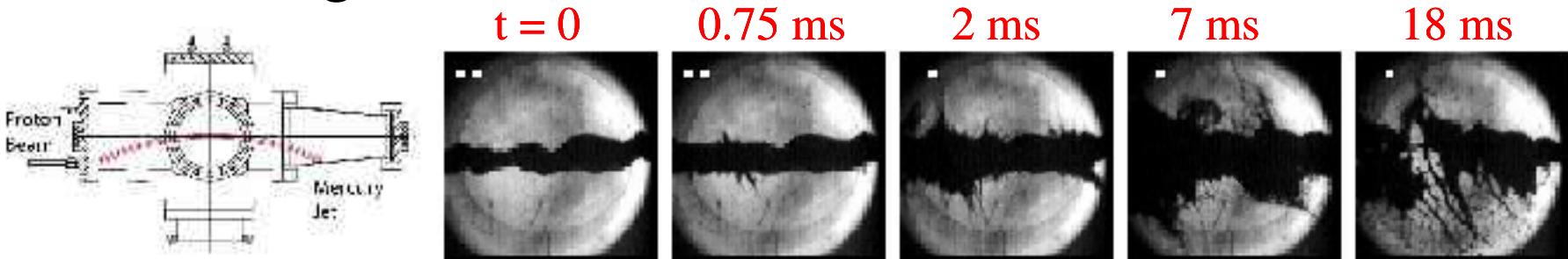
SCRF Hardware

- **Developing 201 MHz SC cavity at Cornell (with help from CERN)**
 - reached 11 MV/m in initial tests
 - exhibits marked Q slope that needs to be



Mercury Jet Target

- Studied Hg-jet target with 24 GeV protons at AGS
 - no magnetic field



- Developing 20 m/s Hg jet



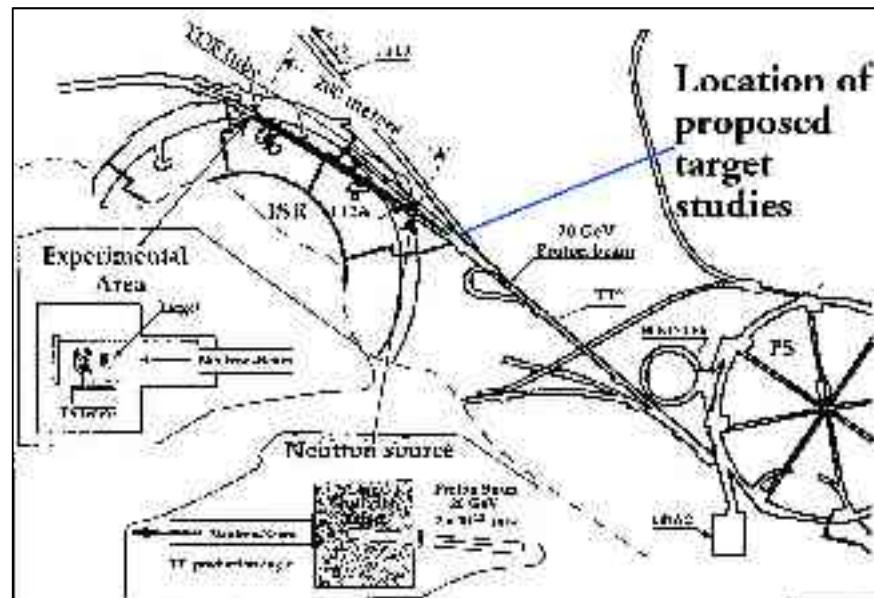
MERIT Experiment (CERN nTOF11)

A Proposal to
the ISOLDE and Neutron Time-of-Flight Experiments
Committee

Studies of a Target System for a 4-MW, 24-GeV Proton Beam

J. Roger J. Palmer¹, Louis Beaulieu², Gérard J. Daoust³, Paul V. Diakon¹,
Adam Delynski¹, Jean A. Faibisoff⁴, John R. Haines⁵, Helmut Jäger⁶,
Vassilis Kermani⁷, François Lebel⁸, Jacques Létourneau⁹, Georges Léveillé¹⁰,
Hugues G. Katz¹¹, Kirk T. McDonald¹², Robert E. Pinston¹³, Frédéric Pichot¹⁴,
Natalia Shvetsova¹⁵, Werner V. Stenzel¹⁶, Peter H. Thibault¹⁷, Kofi Yekini¹⁸

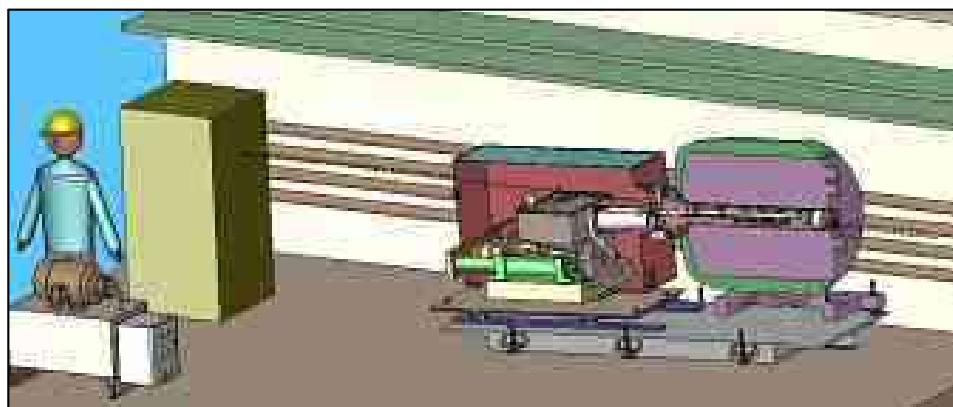
¹Université de Montréal, U.G., C.N.E., N.S.T., M. McDonald,
²Laval University, E. Esposito,



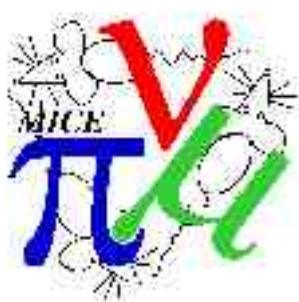
Approved 4 April 2005, to run
in 2007.

Each beam pulse is a separate experiment.

~ 200 beam pulses in total.



Free mercury jet target in 15-T Solenoid magnet

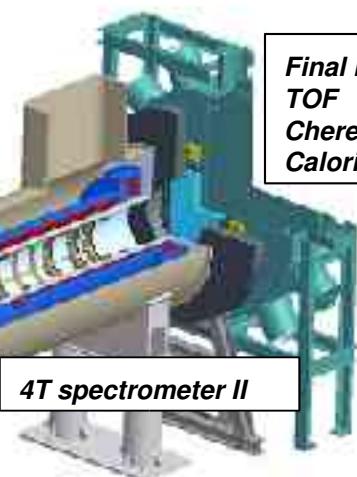
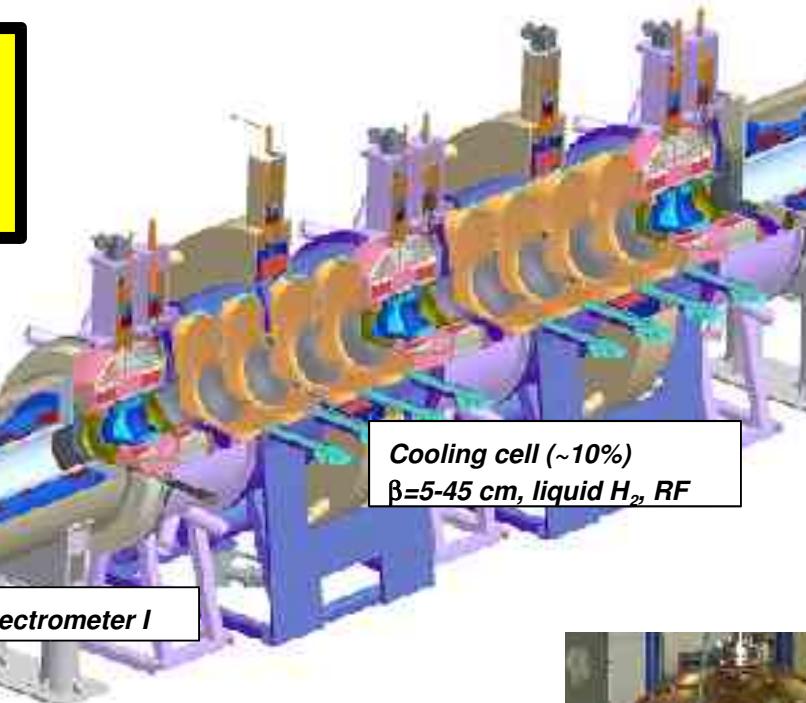


Muon Ionization Cooling Experiment

Aims: demonstrate feasibility and performance of a section of cooling channel

Main challenges:

RF in magnetic field!
 10^3 meas. of emittance
Safety issues



Final PID:
TOF
Cherenkov
Calorimeter

Status:
Approved at RAL(UK)
First beam: 04-2007
Funded in: UK,CH,JP,NL,US
Requests: Be,CH,It,JP,US

Single- μ beam
~200 MeV/c



Scintillating-fiber tracker



Liquid-hydrogen absorbers



MUCOOL 201 MHz RF cavity with beryllium windows

Some prototyping:

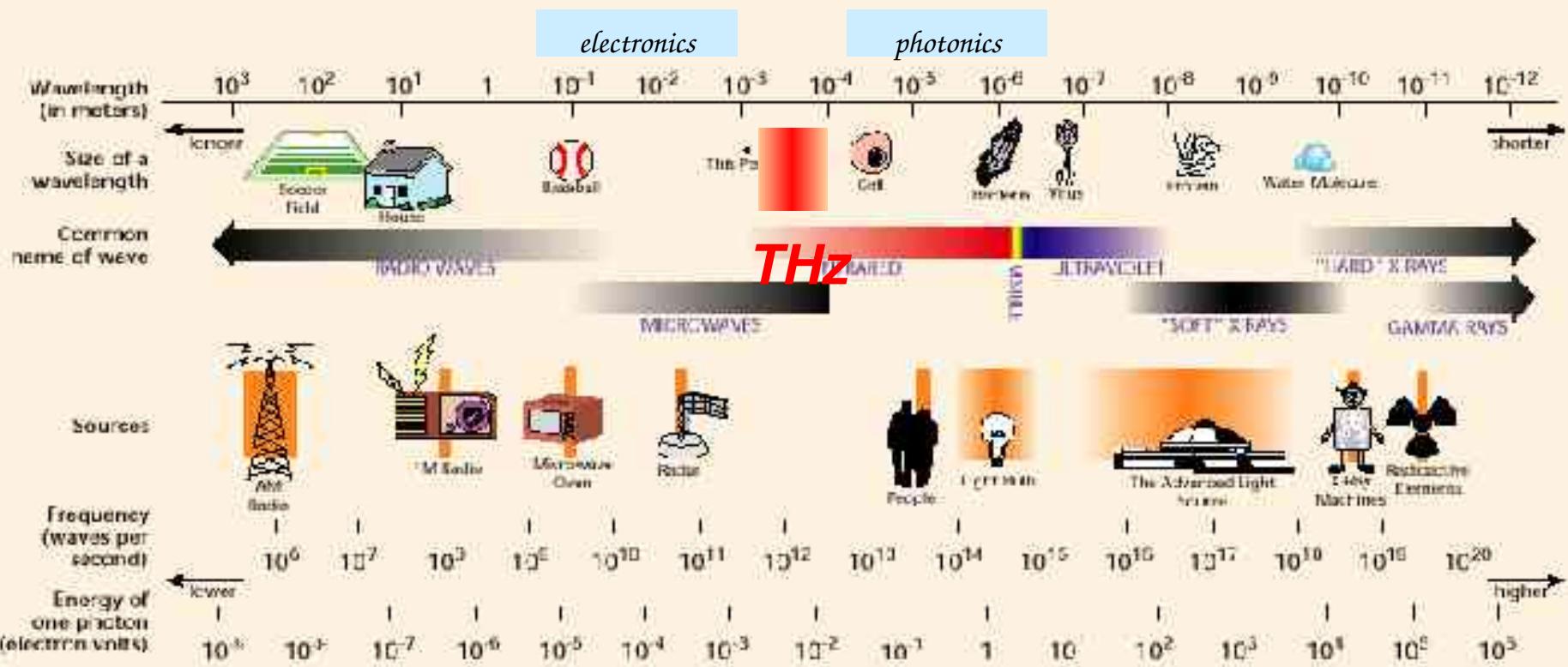
Expected Status in 2010

- **MERIT** experiment completed
 - viable target scheme for 4 MW proton beam in hand
- **MICE** experiment close to completion
 - demonstration of muon ionization cooling being carried out
- **ISS** completed
 - optimized design concept for neutrino factory developed by international team
 - follow-up “World Design Study” of neutrino factory (facility engineering design) being completed ⇒ **ready for CDR**
 - end-to-end simulations of muon collider in progress
- **Component R&D** on optimized neutrino factory designs well advanced
 - specialized component R&D for muon collider under way

Advanced X-ray Facilities

IR/THz: Rich Science (Nano-/Bio-), but no powerful light source except for JLab/FEL

THE ELECTROMAGNETIC SPECTRUM

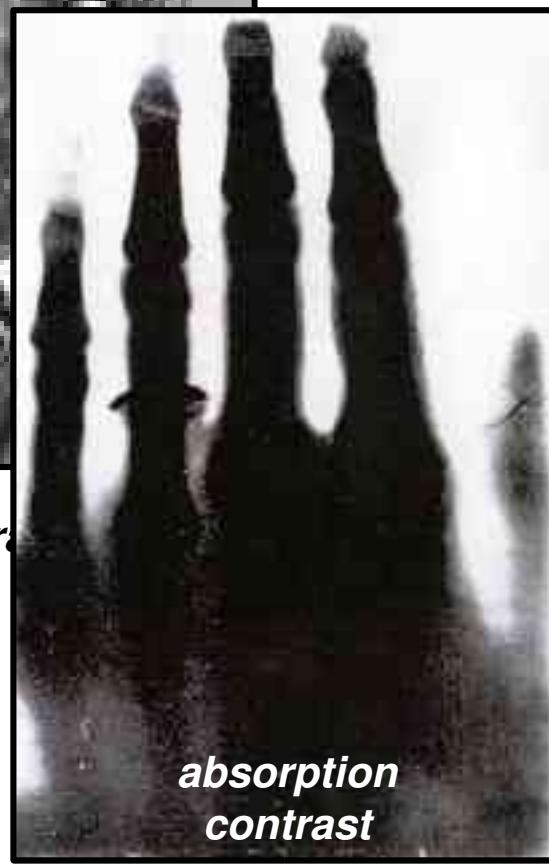


$$1 \text{ THz} \sim 33 \text{ cm}^{-1} \sim 300 \mu\text{m} \sim 4.1 \text{ meV} \sim 1 \text{ ps} \sim 47.6 \text{ K}$$

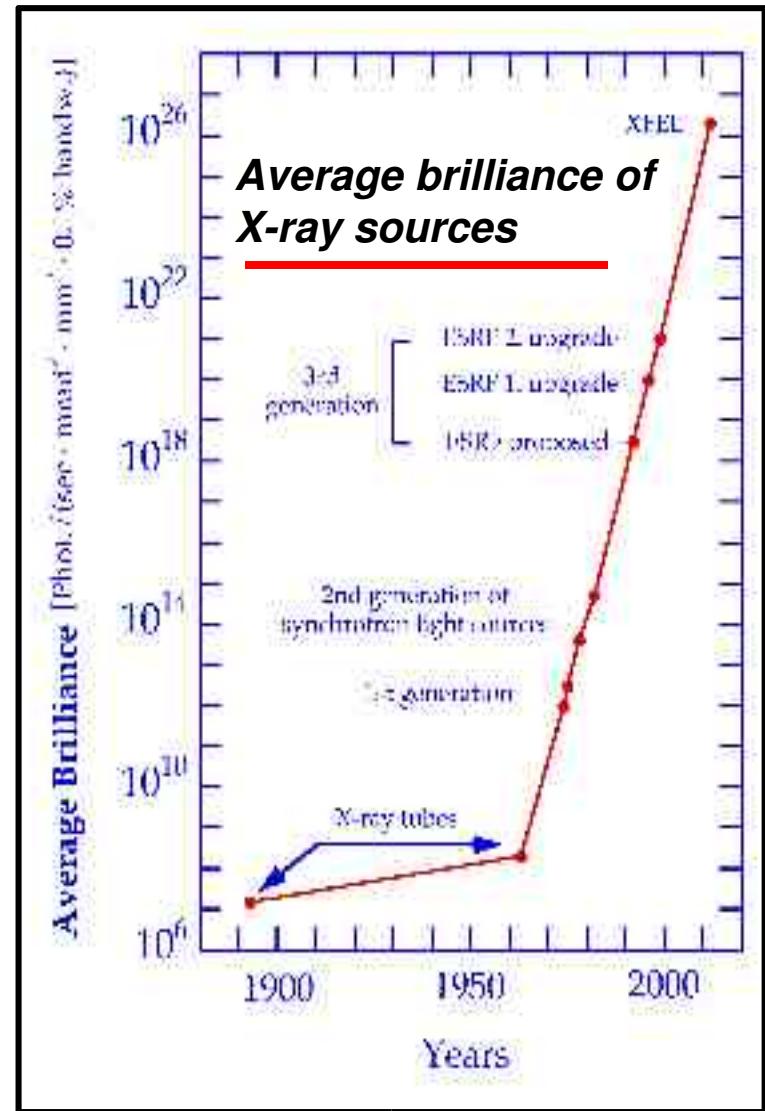
Discovery of X-rays in 1895



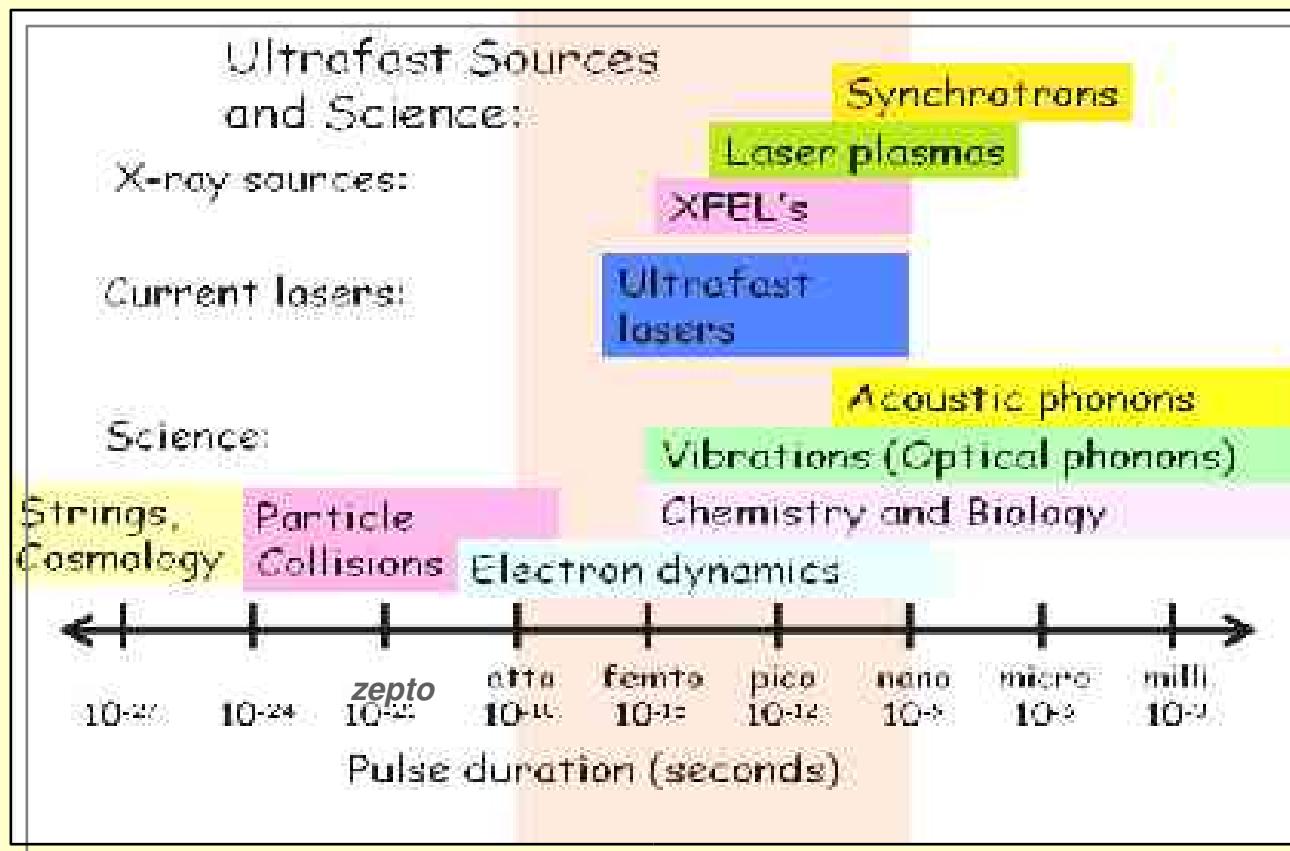
Wilhelm Conrad



*absorption
contrast*



Nature's time scales



Femtoseconds: The new dimension in nano-space

Two Directions towards “Brighter” X-ray Sources:



ERL

Energy Recovering Linacs

Incoherent, bright, ultrashort (femtosecond)
x-rays with High Average Flux and Power



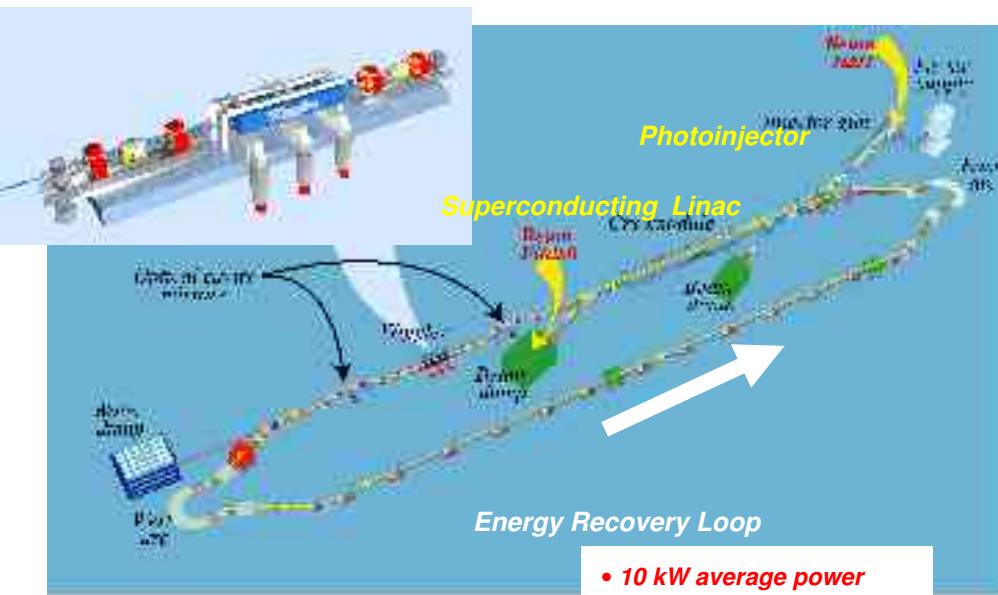
SASE – FELs

Self Amplified Spontaneous Emision – Free
Electron Laser

Coherent, bright, ultrashort (femtosecond) x-rays
with High Peak Power (low average flux)

Energy Recovery R&D

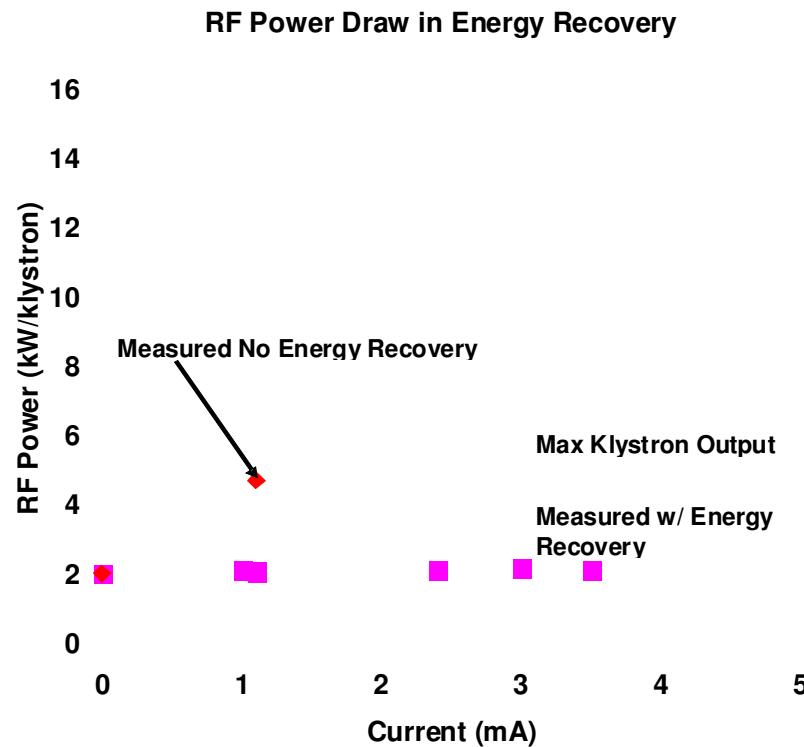
Energy Recovery and its Potential



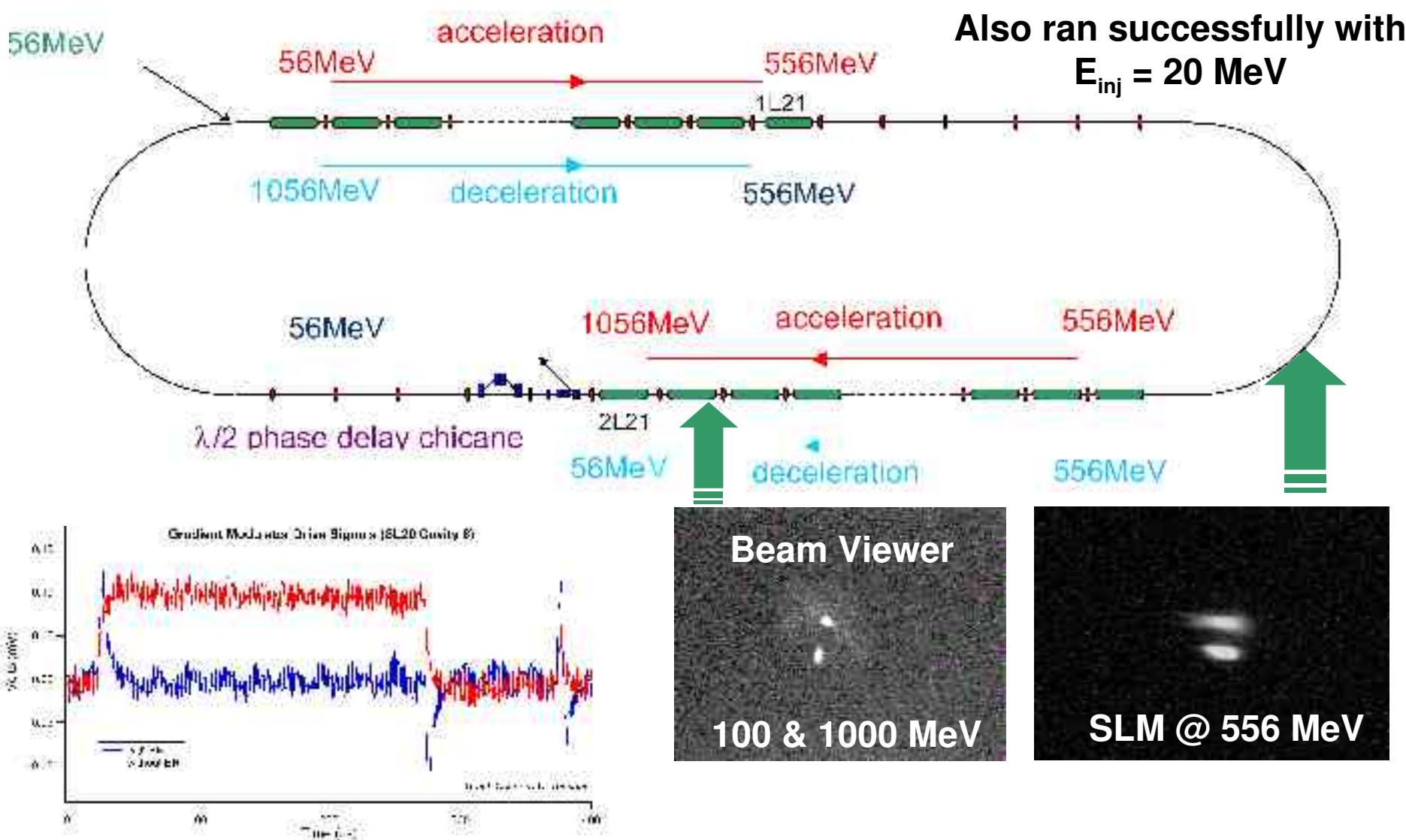
*JLab ERL-based
Free Electron Laser*

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.

First high current energy recovery experiment at JLab FEL, 2000



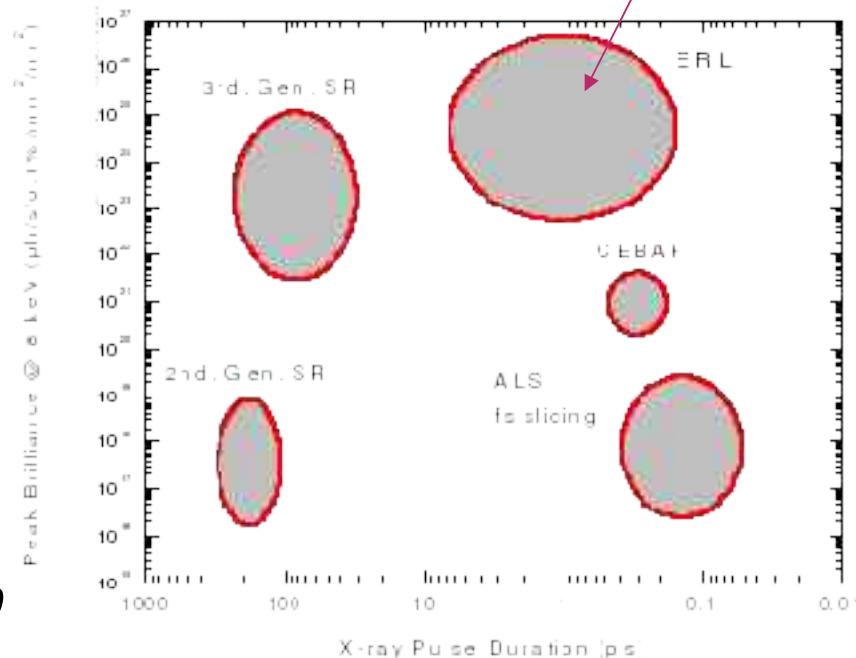
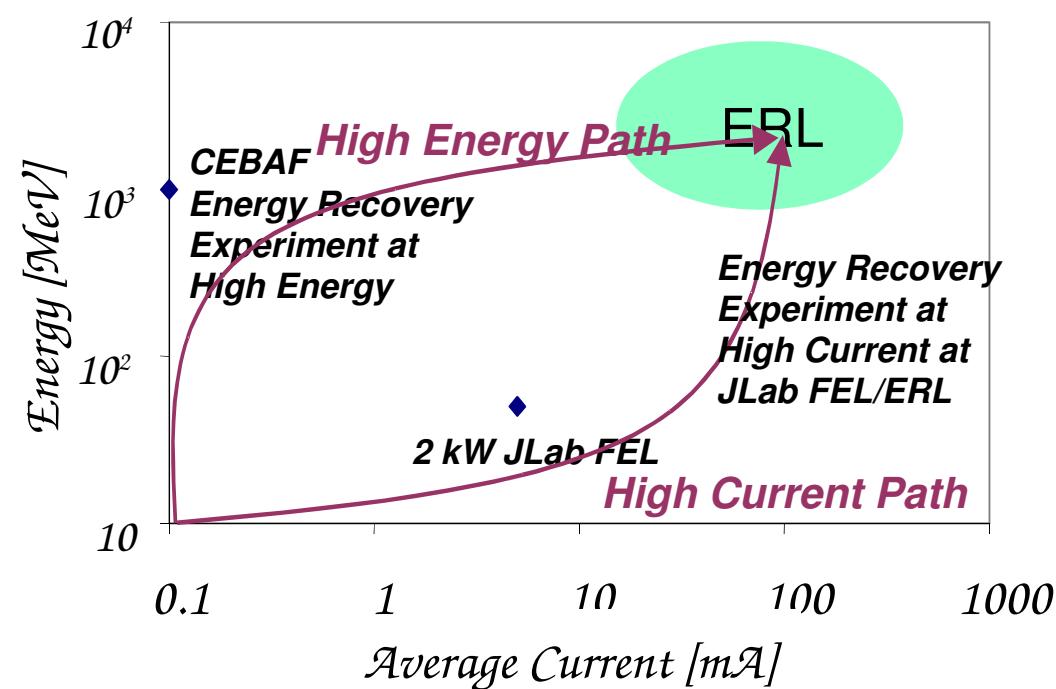
Energy Recovery at 1 GeV – 1st CEBAF Experiment



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

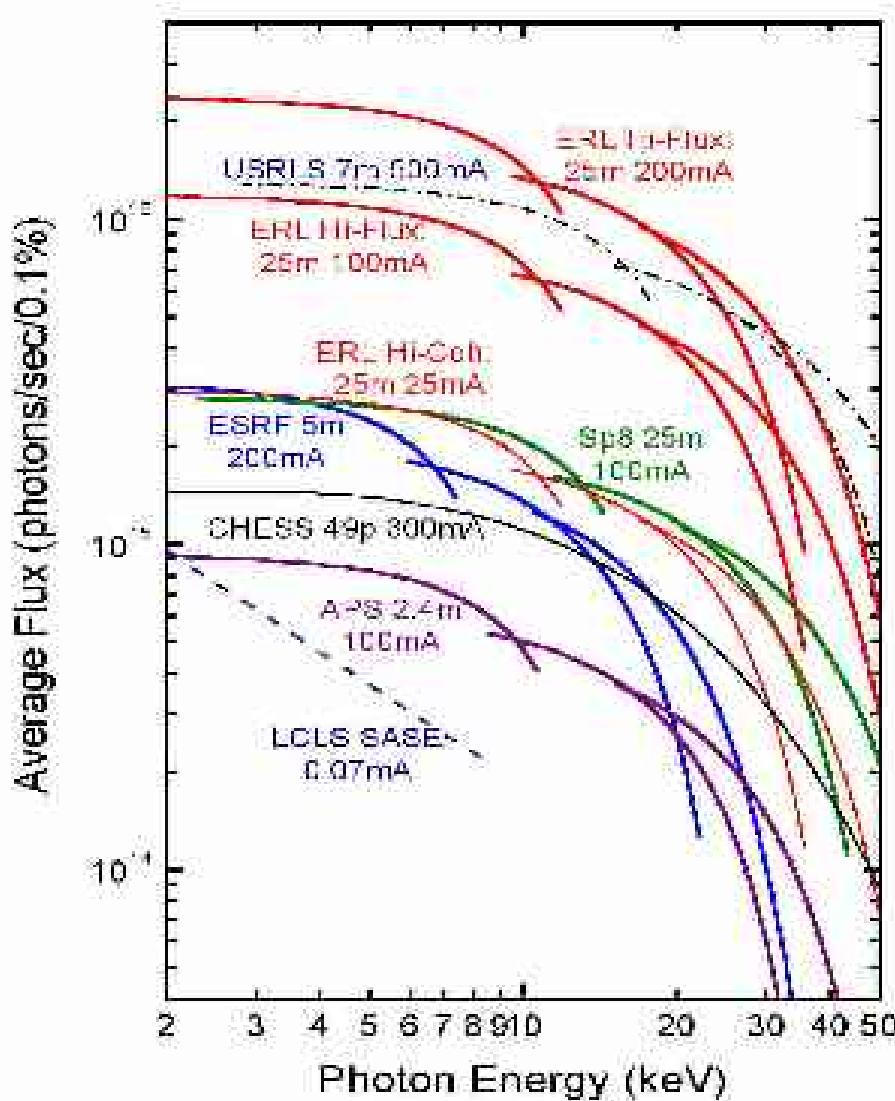


Accelerator R&D Issues

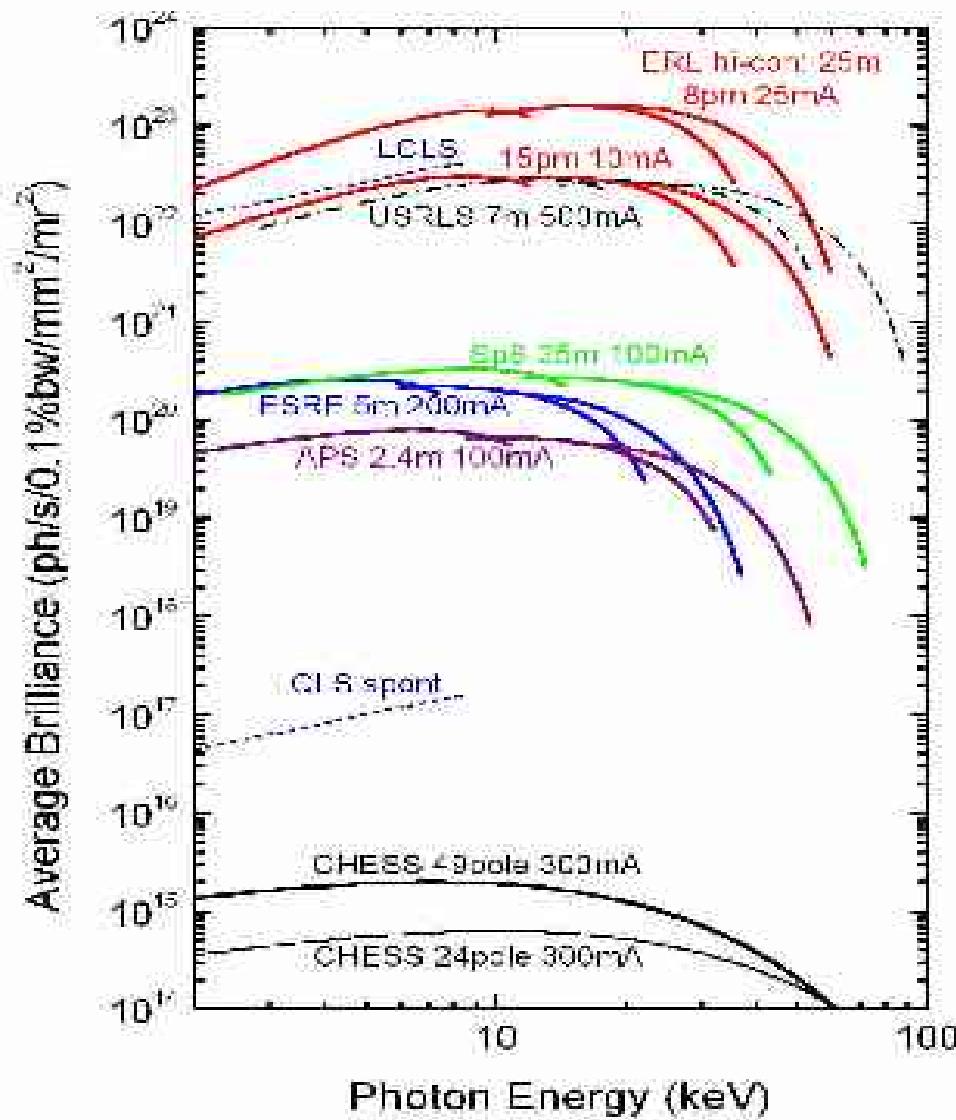
Creation, transport and acceleration of
extremely low-emittance, high-current beams
up and down the “energy cycle”

Cornell ERL

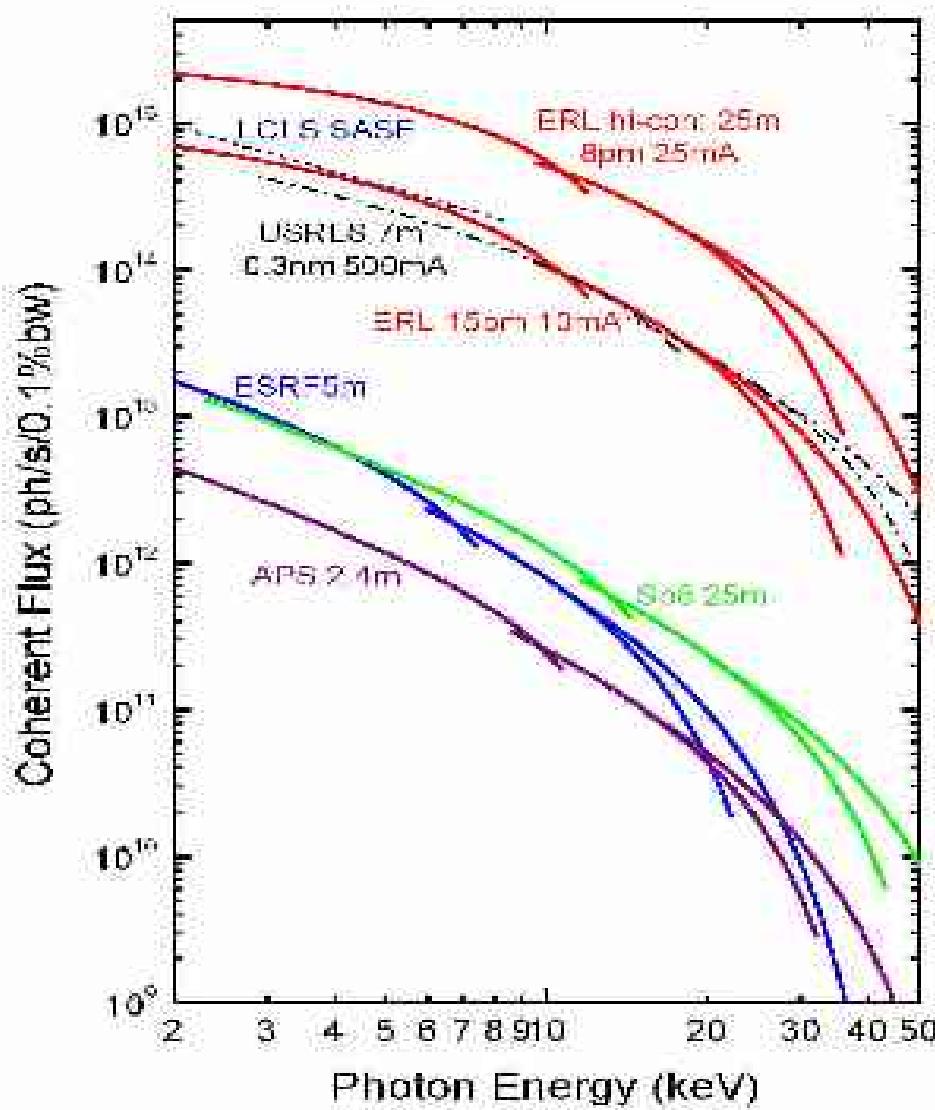
5 GeV ERL – Average Flux



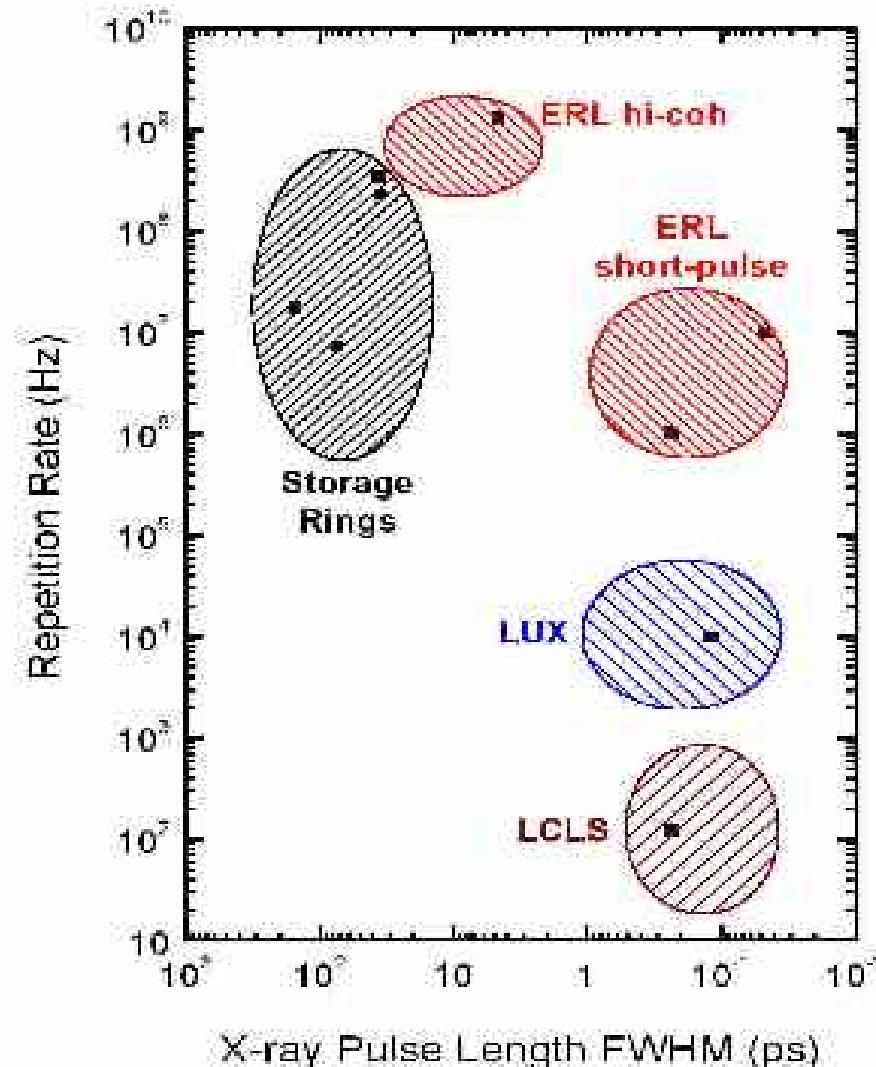
5 GeV ERL – Average Brilliance



5 GeV ERL – Coherent Flux



Short Pulses at High Rep Rate



Typical ERL Light Source Parameters

- Beam Energy – 5 GeV
- Fundamental frequency – 1300 MHz
- Average beam current – normal mode – 100 mA (77 pc/bunch)
- Average beam current – short pulse mode - > 1 mA (~ 1 nC/bunch)
- Normalized transverse emittance at full energy – below 2 mm-mrad rms in normal mode
- Bunch length before compression - ~ 2 ps rms
- Bunch length after compression - < 100 fs rms
- Uncompressed $\Delta E/E \sim 2 \times 10^{-4}$ rms

Cornell vision of ERL light source

To continue the long-standing tradition of pioneering research in synchrotron radiation, Cornell University is carefully looking into constructing a first ERL hard x-ray light source.

But first...



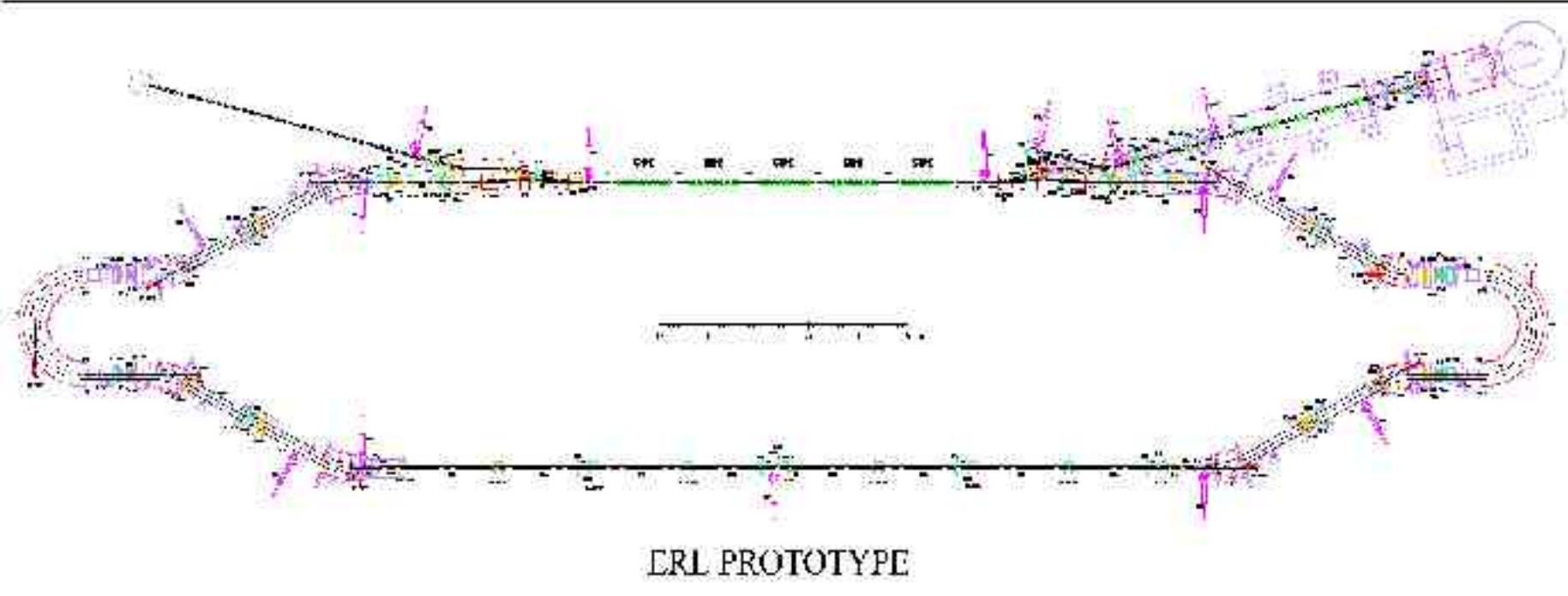
Need for the ERL prototype

Issues include:

- CW injector: produce $i_{avg} \geq 100$ mA, $q_{bunch} \sim 80$ pC @ 1300 MHz, $\epsilon_n < 1$ mm mr, low halo with very good photo-cathode longevity.
- Maintain high Q and E_{acc} in high current beam conditions.
- Extract HOM's with very high efficiency ($P_{HOM} \sim 10x$ previous).
- Control BBU by improved HOM damping, parameterize $i_{thr.}$
- How to operate with hi Q_L (control microphonics & Lorentz detuning).
- Produce + meas. $\sigma_t \sim 100$ fs with $q_{bunch} \sim 0.3\text{--}0.4$ nC ($i_{avg} < 100$ mA), understand / control CSR, understand limits on simultaneous brilliance and short pulses.
- Check, improve beam codes. Investigate multipass schemes.

Our conclusion: An ERL Prototype is needed to resolve outstanding technology and accelerator physics issues before a large ERL is built

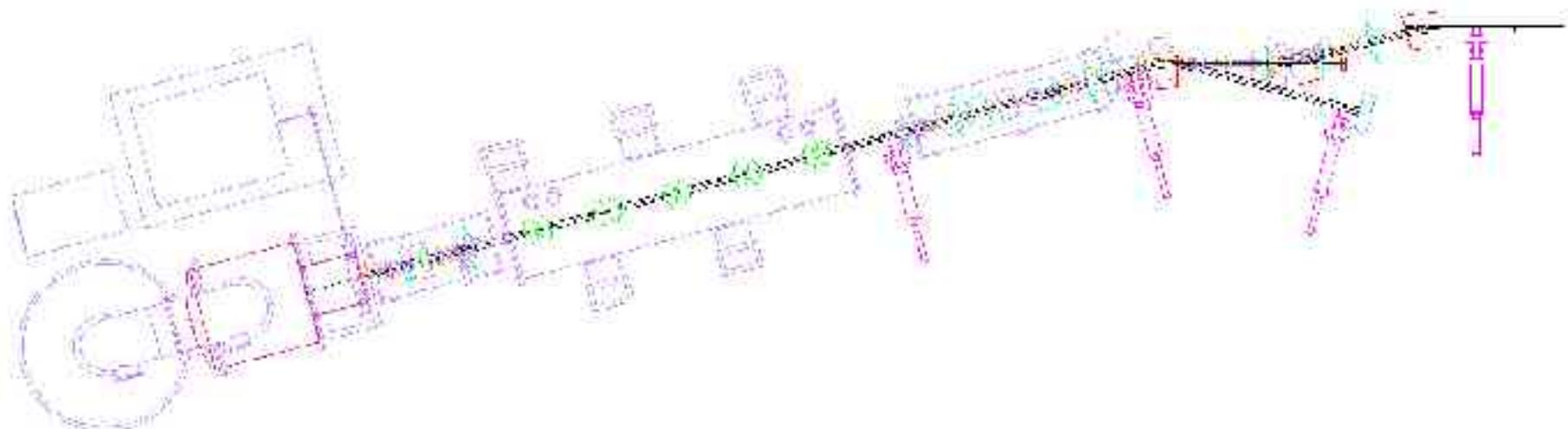
Cornell ERL Prototype



Energy 100 MeV
Max Avg. Current 100 mA
Charge / bunch 1 – 400 pC
Emittance (norm.) \leq 2 mm mr@77 pC

Injection Energy 5 – 15 MeV
 E_{acc} @ Q_0 20 MeV/m @ 10^{10}
Bunch Length 2 – 0.1 ps

Cornell ERL Phase I: Injector



Injector Parameters:

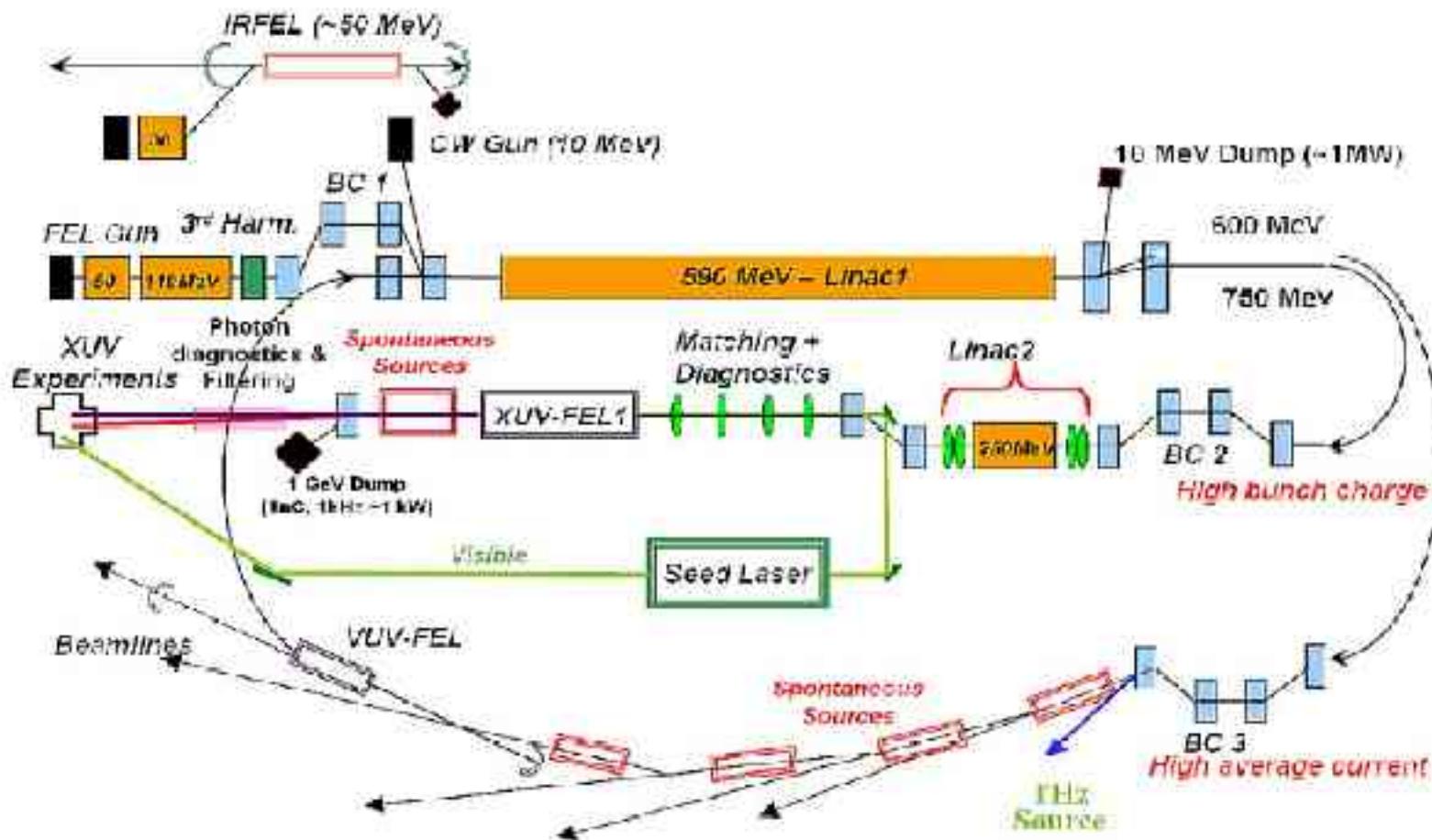
Beam Energy Range	5 – 15 ^a MeV
Max Average Beam Current	100 mA
Max Bunch Rep. Rate @ 77 pC	1.3 GHz
Transverse Emittance, rms (norm.)	< 1 ^b μ m
Bunch Length, rms	2.1 ps
Energy Spread, rms	0.2 %

^a at reduced average current

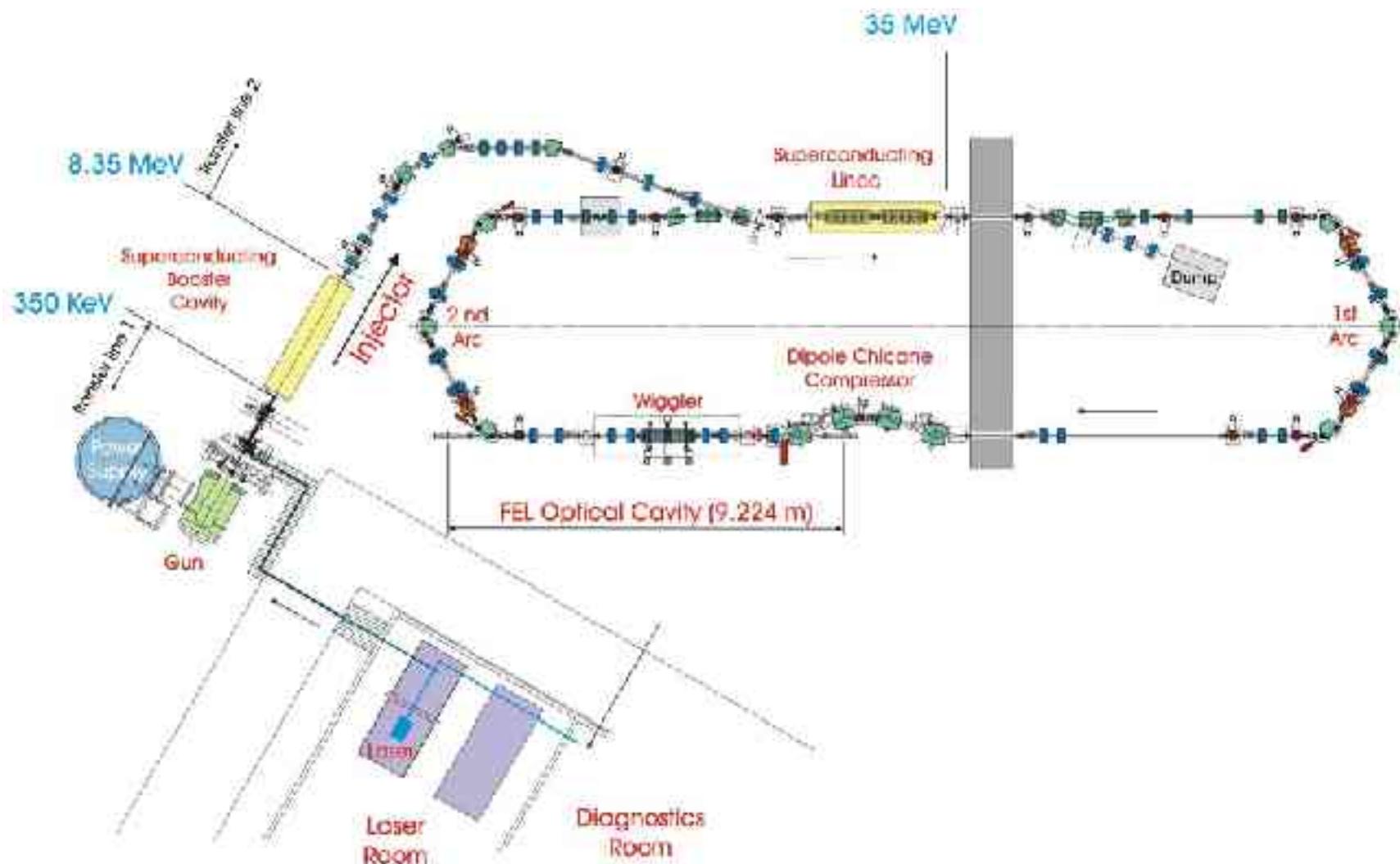
^b corresponds to 77 pC/bunch

Daresbury 4GLS

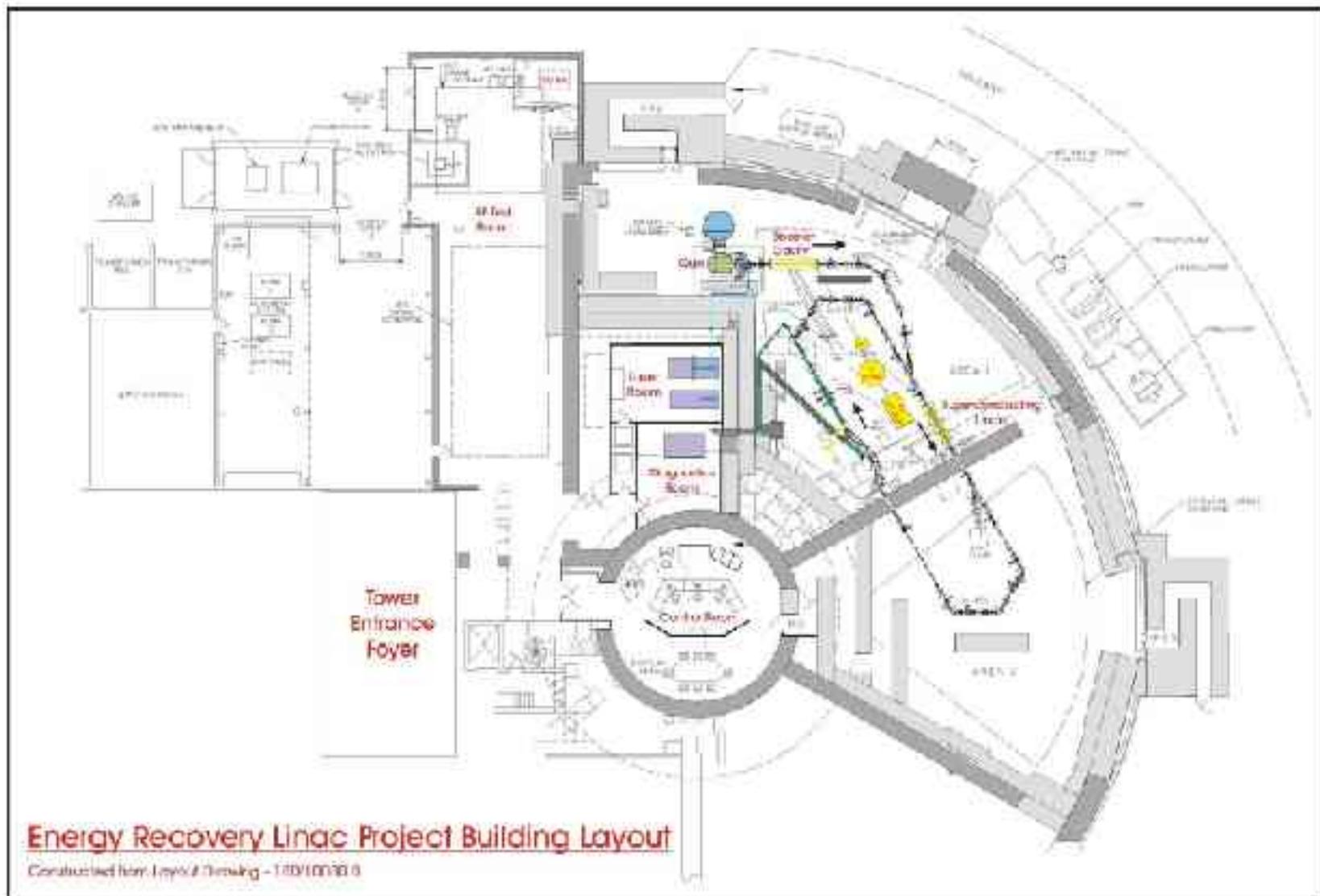
Conceptual layout of 4GLS



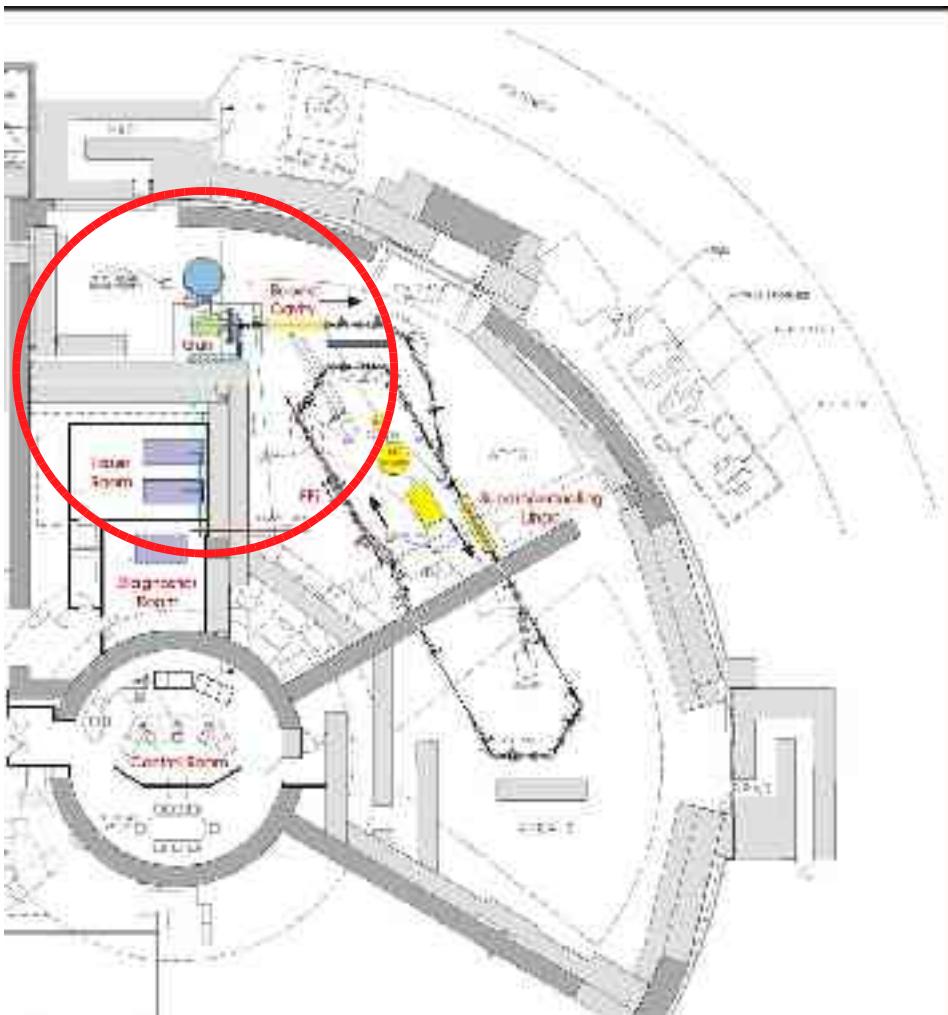
Energy Recovery Linac Prototype (ERLP)



ERLP Building Layout



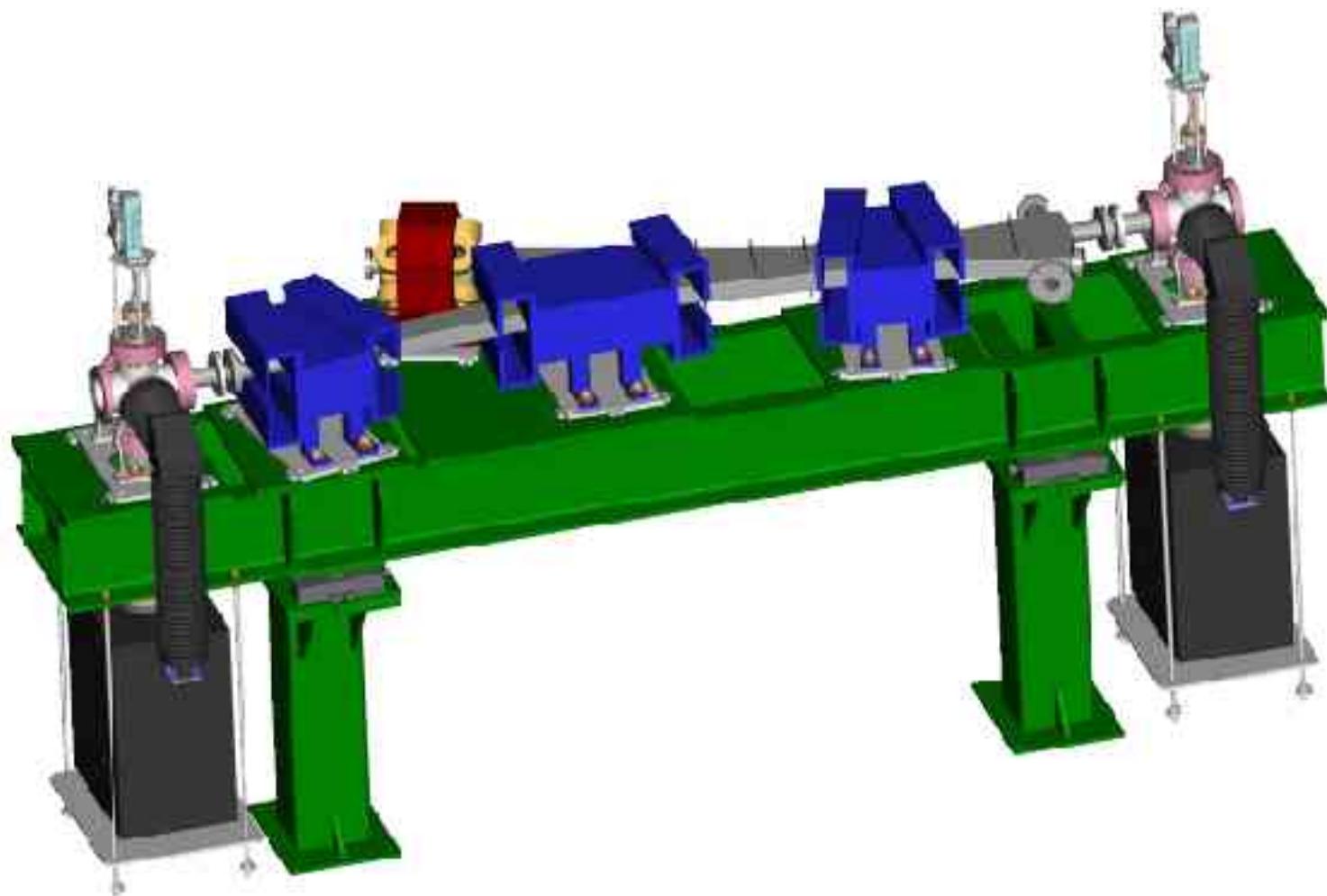
ERLP Parameters



Electron Beam Parameters	Goal
Energy (MeV)	30-50
Accelerator frequency (MHz)	1300
Charge per bunch (pC)	>80
Average current (mA)	>0.8
Peak Current (A)	~150
Beam Power (kW)	~30

Output Light Parameters	Goal
Wavelength range (microns)	3-75
Bunch Length (FWHM psec)	0.1-few
Laser power / pulse (mJoules)	90
Laser power (kW)	0.9
Rep. Rate (MHz)	10
Macropulse format	CW

Injection and Extraction Chicanes

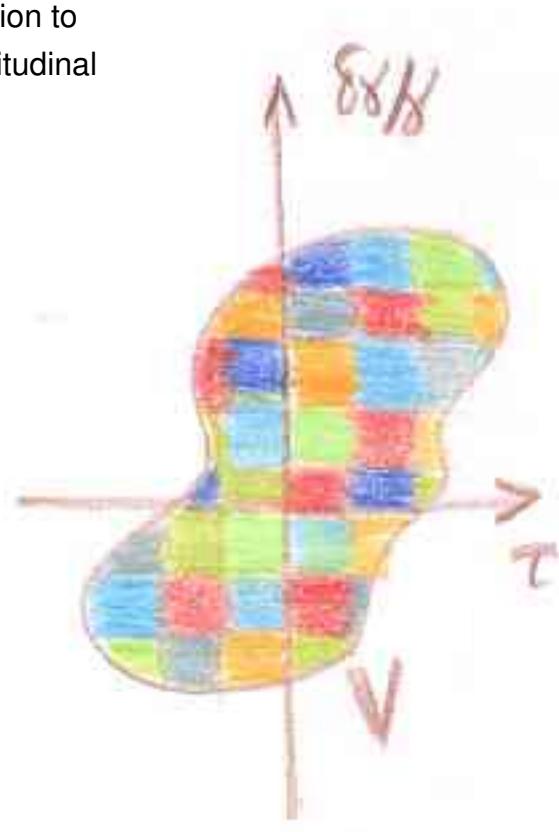
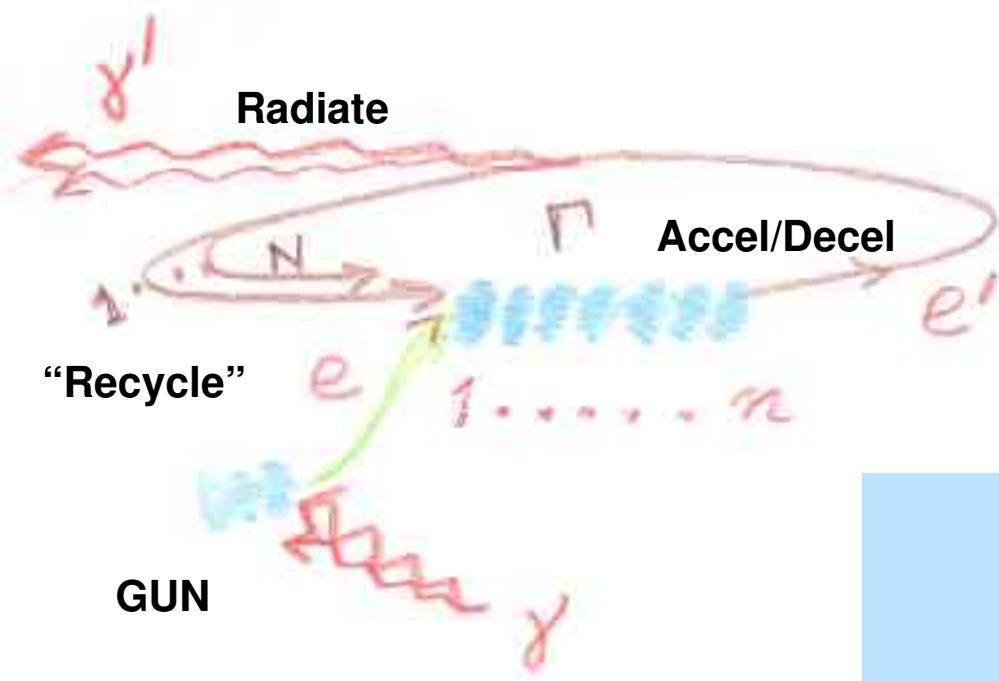


JLab Wiggler



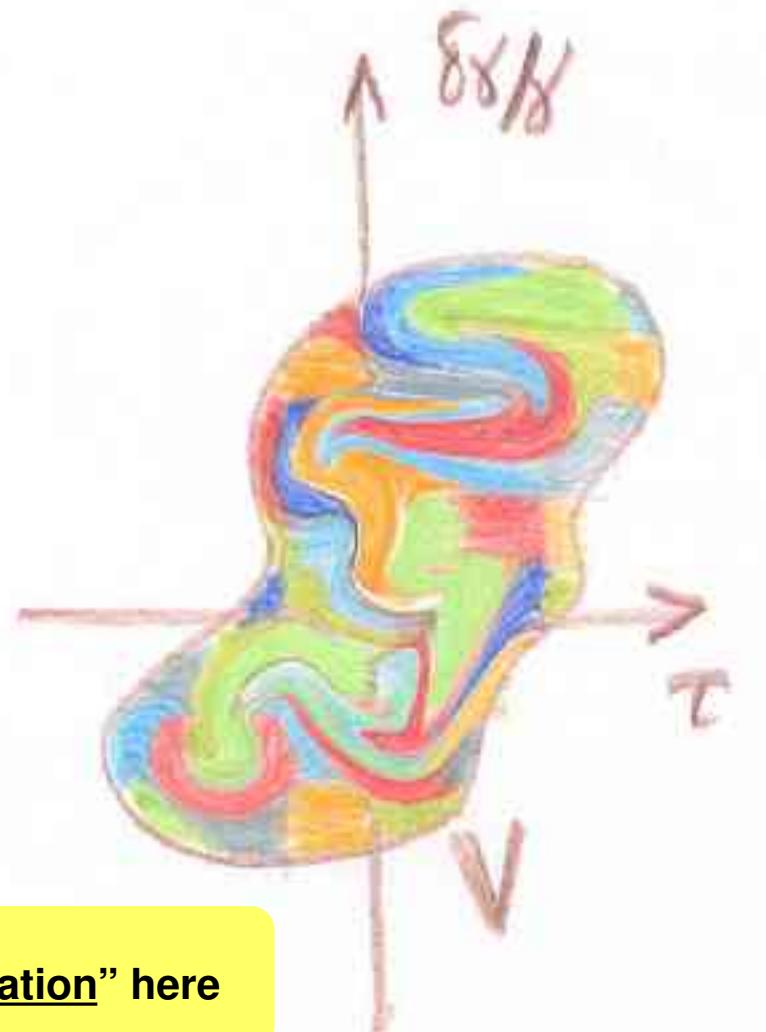
ERL-induced Phase Space Fluctuations

- ❖ “Fluctuations” are inherent in the thermodynamic energy exchange between particles and fields at sub-phase-space level demanding spatio-temporal and phase-space resolution to resolve “graininess” at a level higher than low order moments of transverse and longitudinal distributions → phase space “slicing,” “imaging” and synchronization techniques



→ Room for “innovation” here

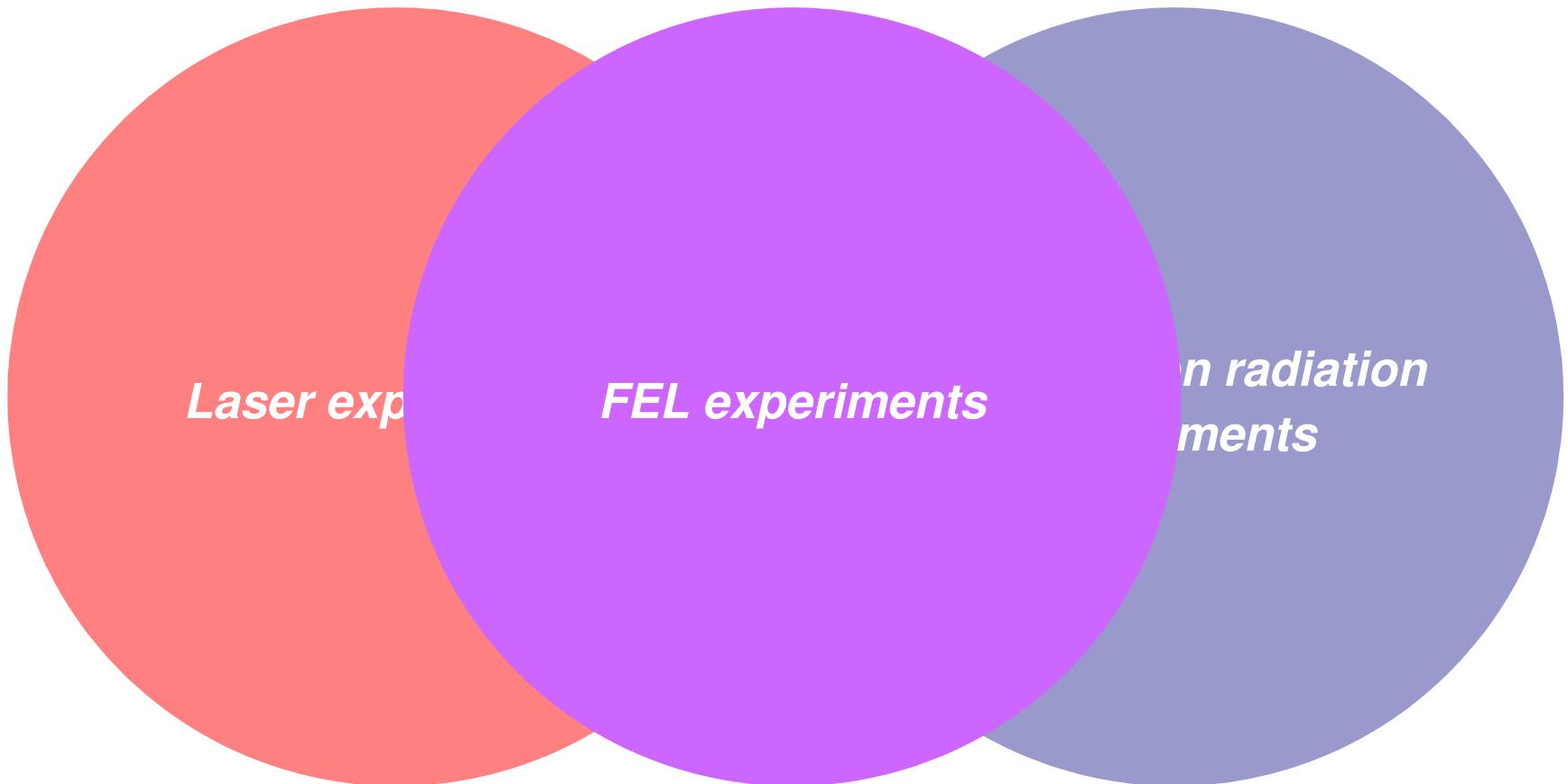
ERL-induced Phase Space Fluctuations



$$\sim \sqrt{N}^{-1/2}$$

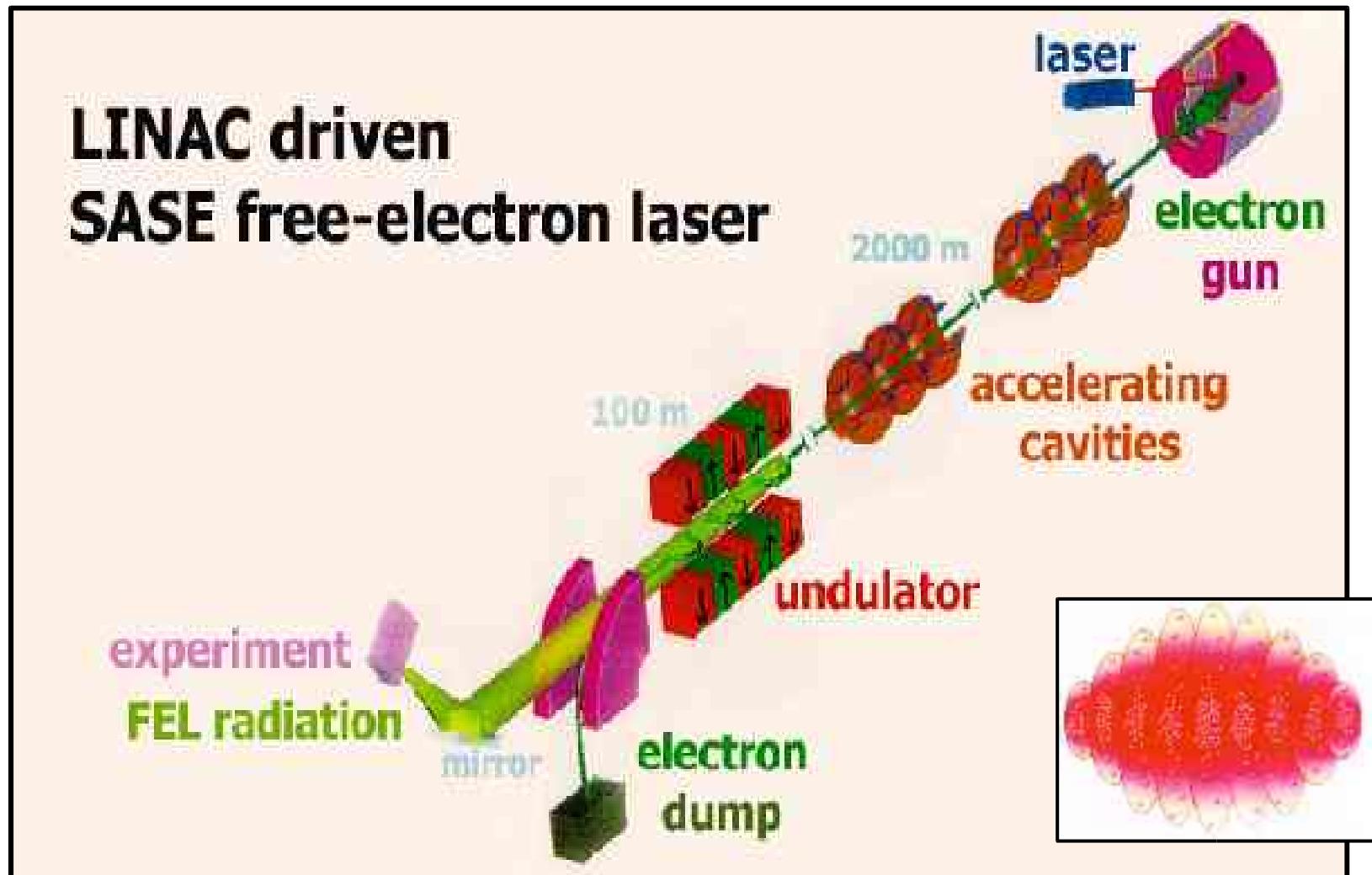
→ Room for “innovation” here

Synergies for new science at FELs



Accelerator Science & Particle Physics methodology

Schematic layout of a single pass FEL

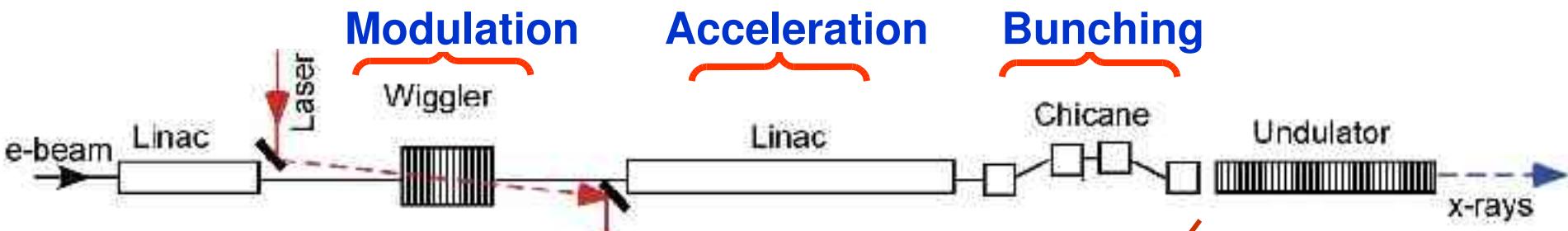


→ LCLS planned at SLAC (S-band, warm linac)
X-FEL planned at DESY (L-band, superconducting linac)

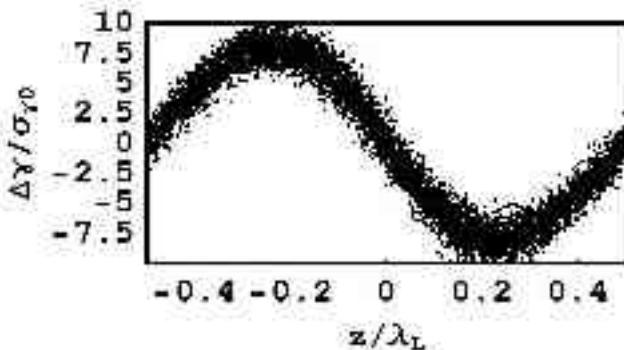
e-SASE

*A scheme to produce stable, systematic
attosecond x-ray pulses*

ESASE: “nuts and bolts” ¹

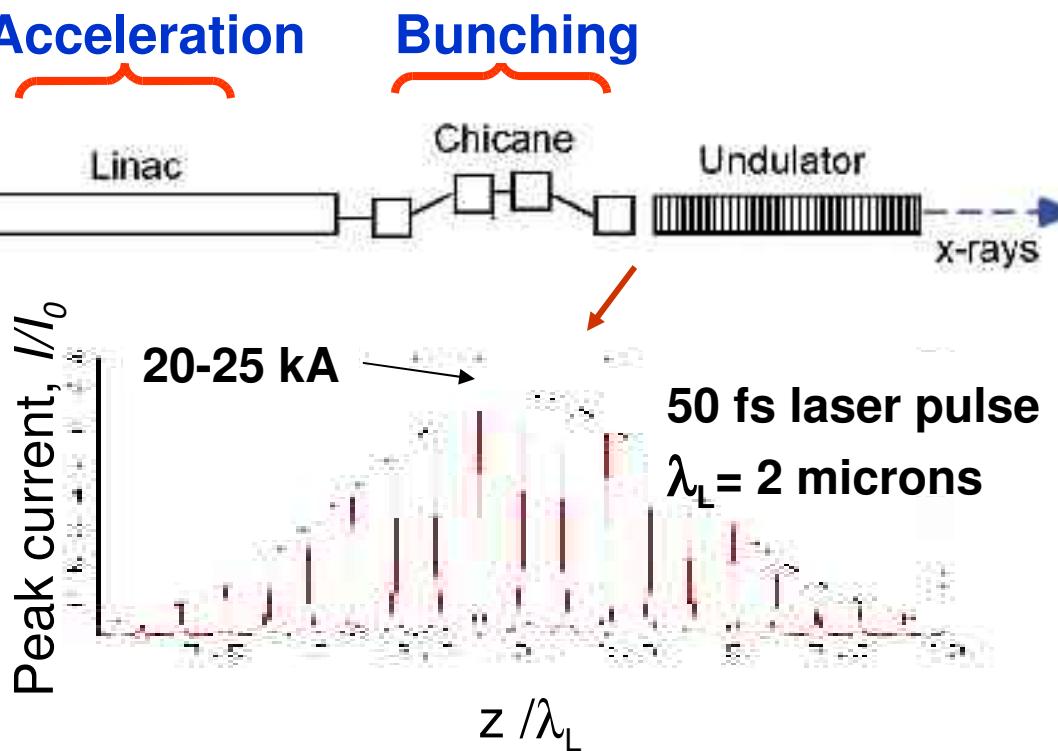


Energy modulation in the wiggler at ~ 4 GeV



Only one optical cycle is shown

- Laser peak power ~ 10 GW
- Wiggler with ~ 10 periods

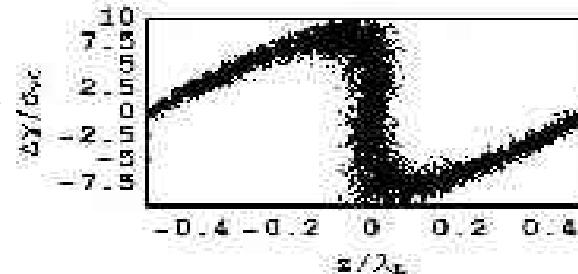


• Electron beam after bunching at optical wavelength

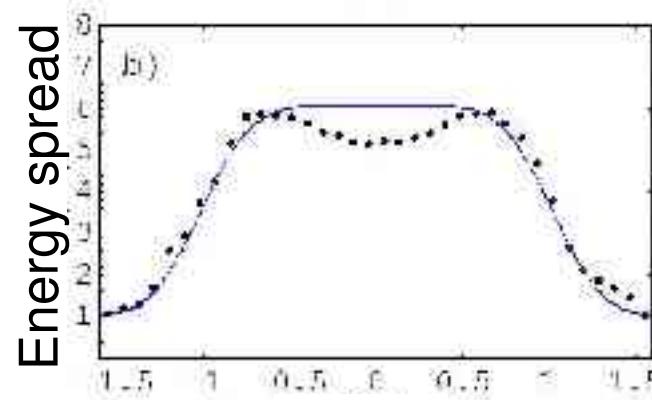
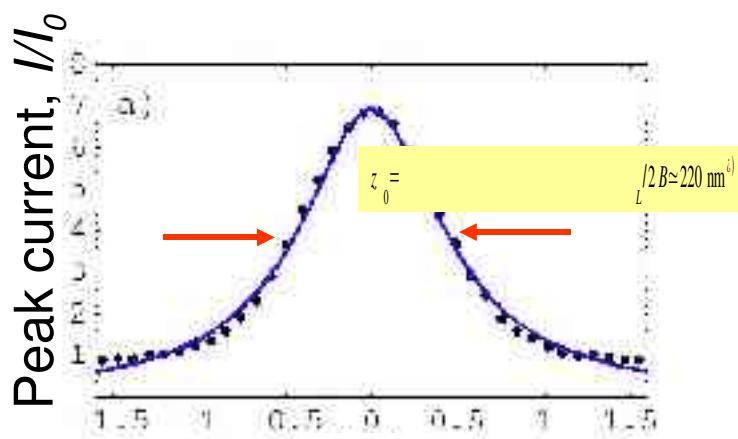
1) A. Zholents, PRST-AB, **8**, 040701(2005).

Zoom-in on a single spike

Electron beam phase
space after bunching



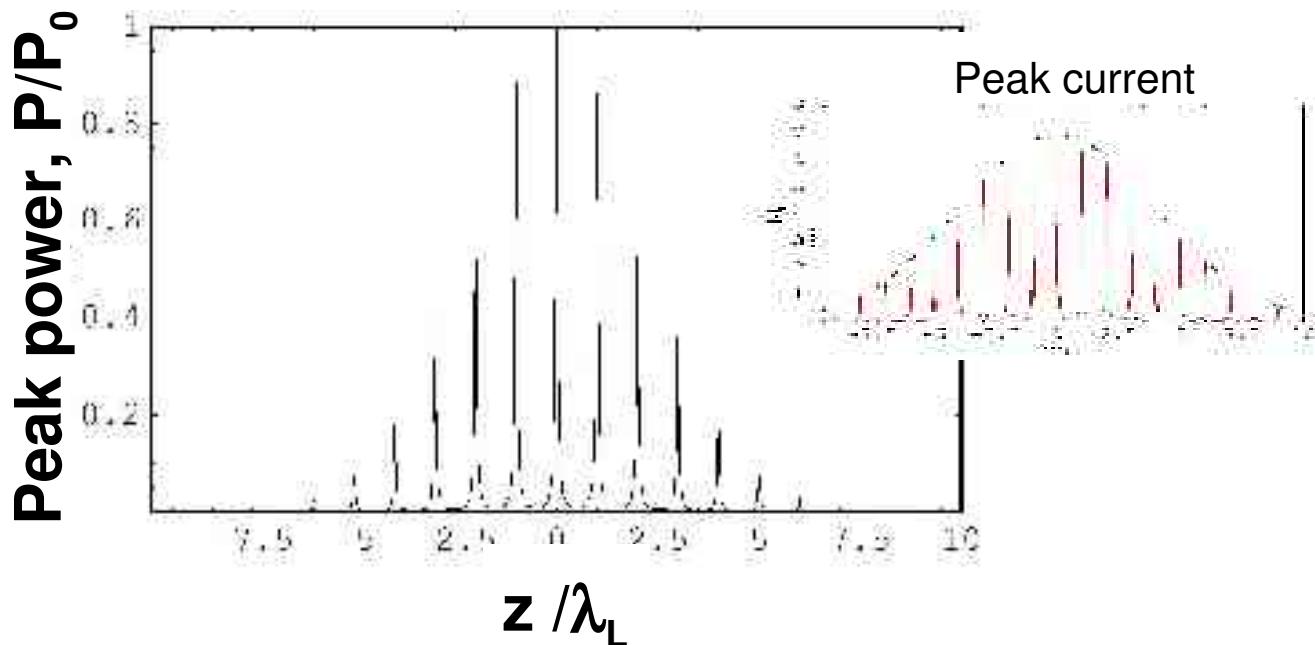
$$B = \Delta\gamma/\sigma_\gamma$$



Peak current and energy distribution within one micro-bunch

^{*}) Δz_0 should be > slippage $\sim 8 M_G \lambda_x = 240 \text{ nm}$

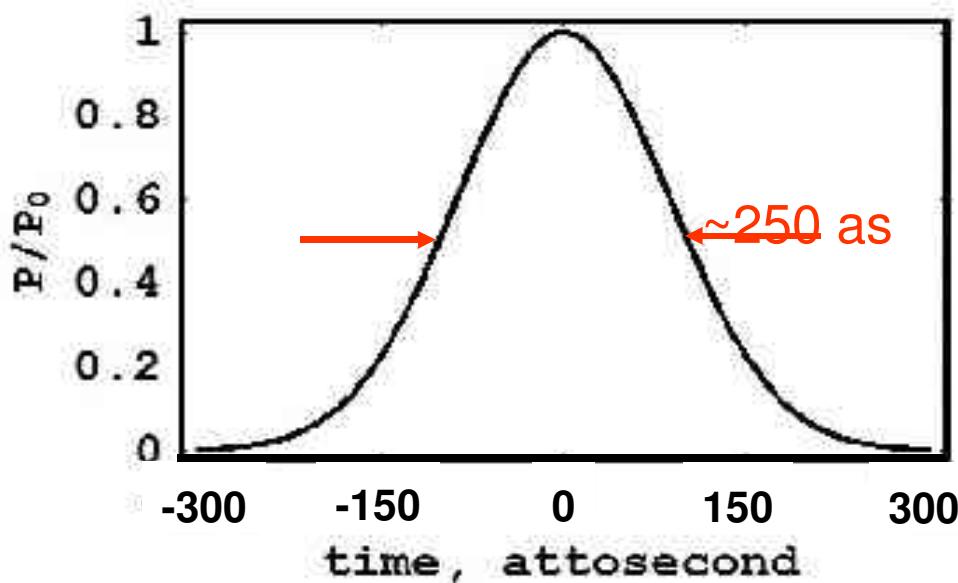
Shaping x-ray pulse



The x-ray radiation output from the entire electron bunch

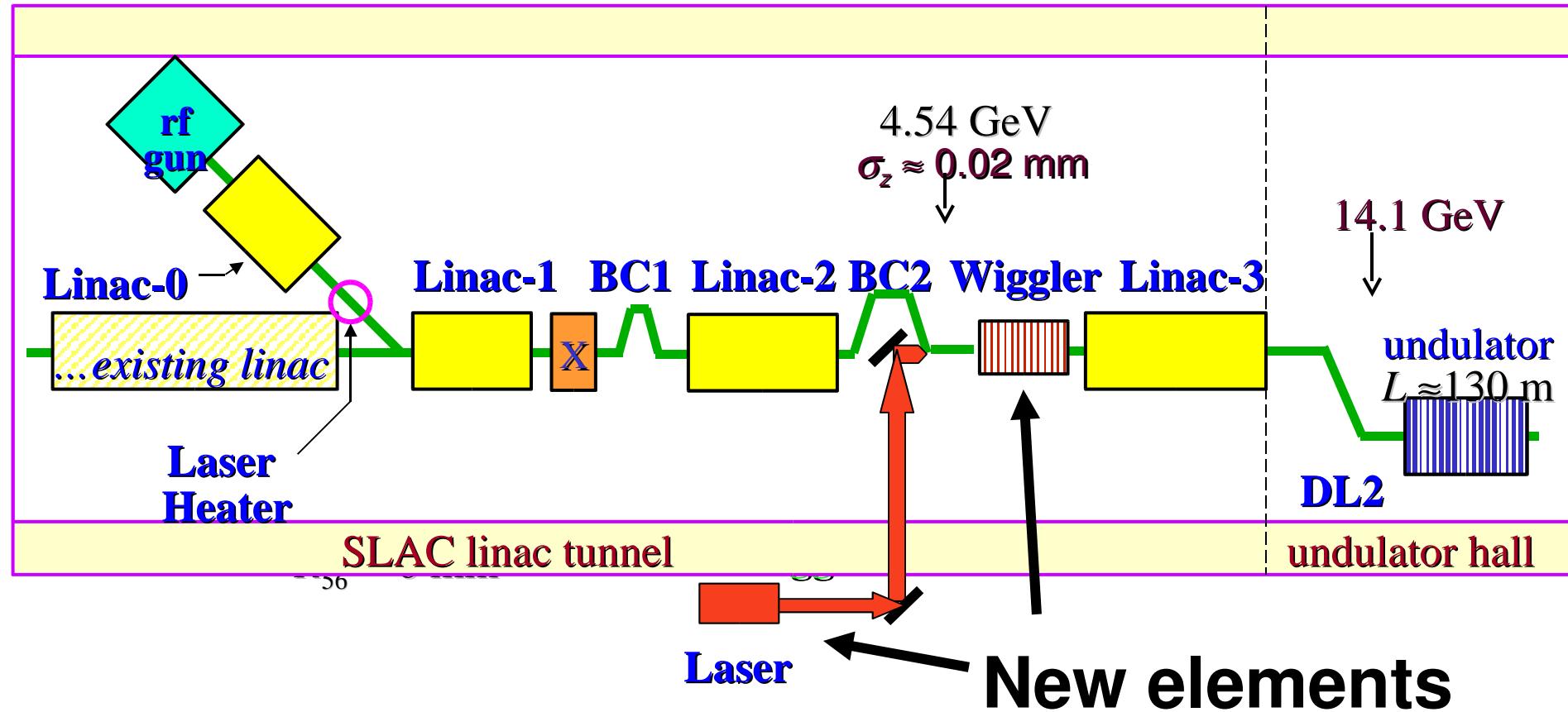
- Radiation from electrons interacted with laser dominate, thus
- Absolute synchronization to the pump laser source for ultra-fast experiments with x-rays

The output x-ray radiation from a single micro-bunch



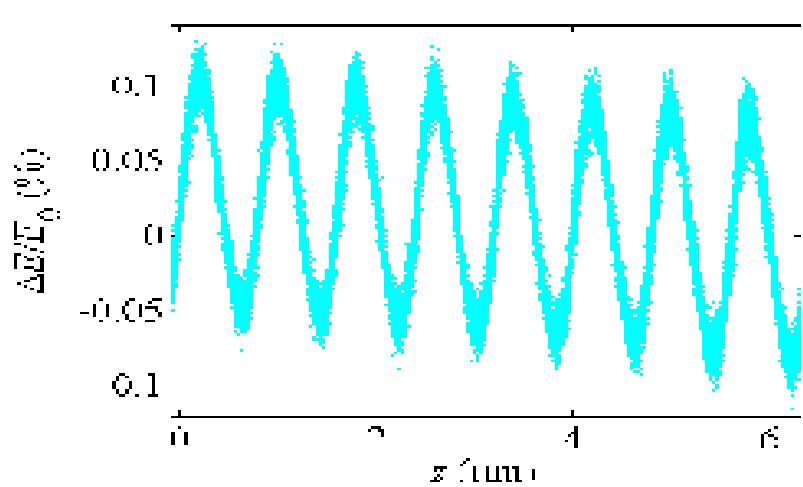
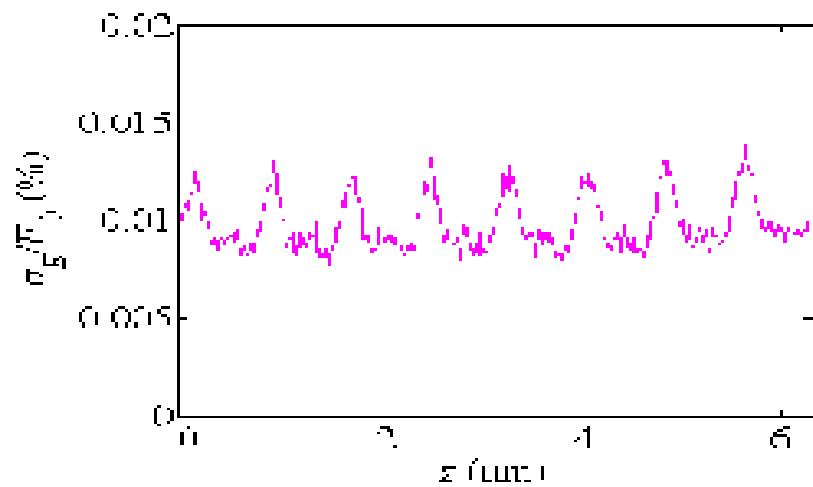
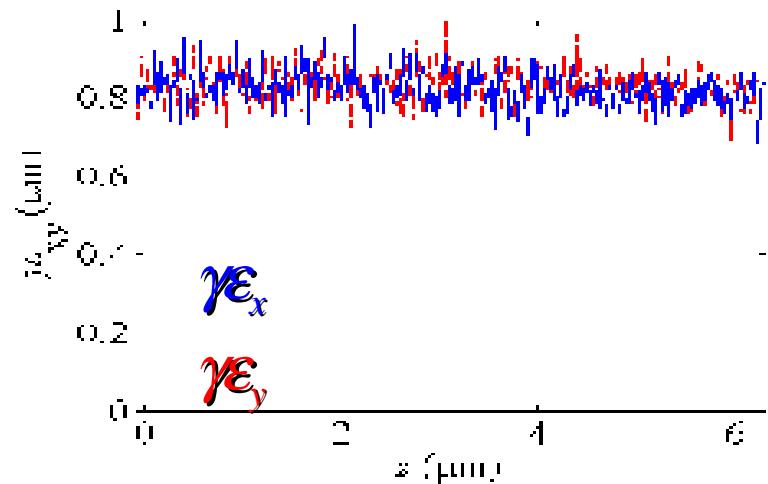
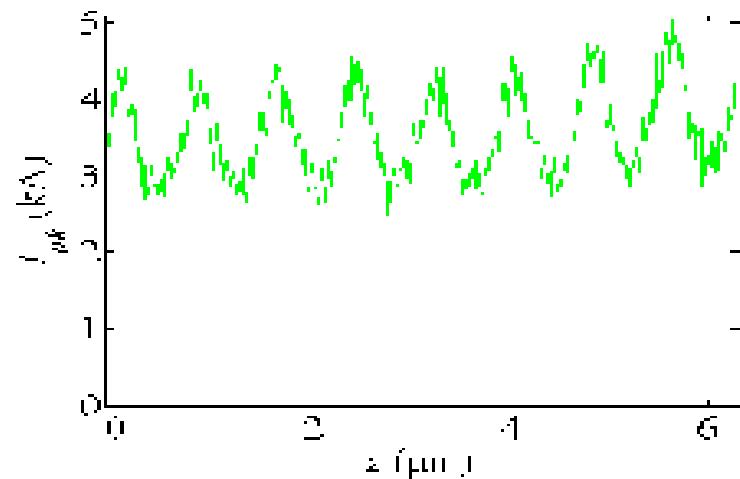
- Each spike is nearly temporally coherent and Fourier transform limited
- Carrier phase for an x-ray wave is random from spike to spike
- Pulses less than 100 attoseconds may be possible with 800 nm laser

A schematic of the LCLS with ESASE¹

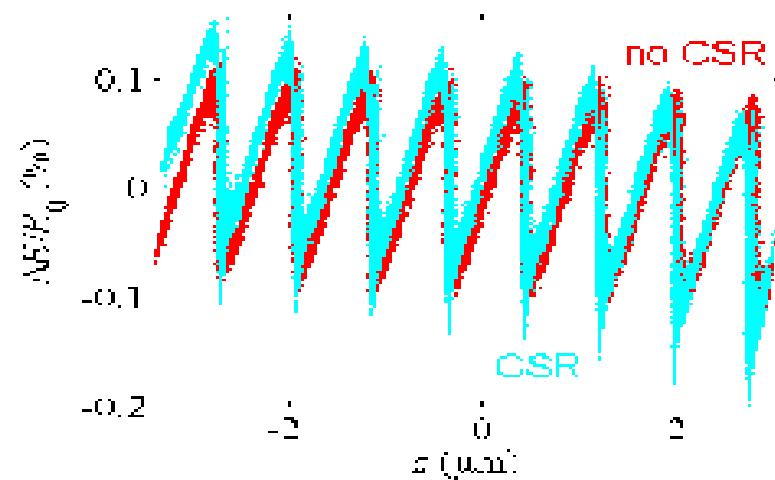
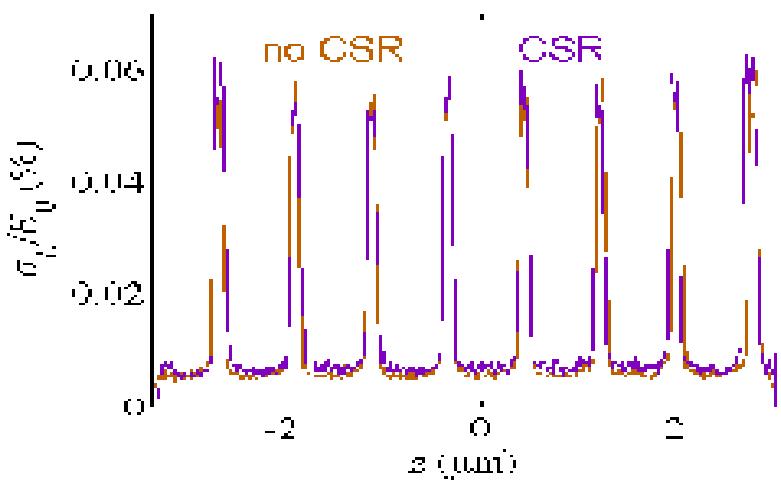
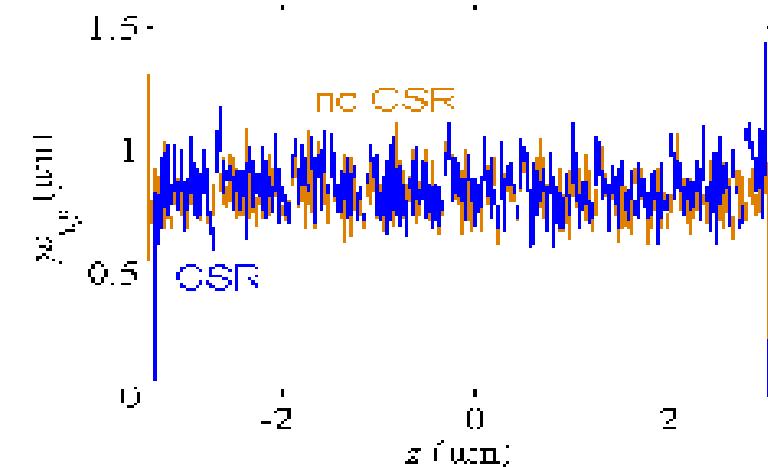
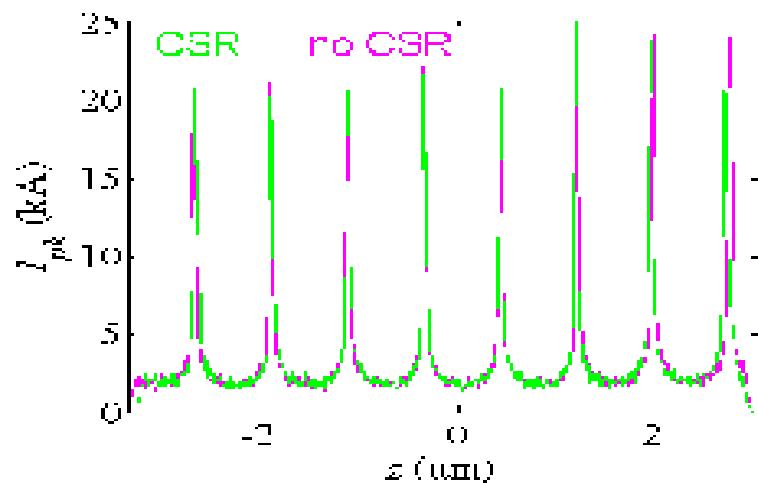


1) A. Zholents, P. Emma, W. Fawley, Z. Huang, S. Reiche, G. Stupakov, Proc. FEL conference, FEL2004, Trieste, Italy, p.582.

Peak current, emittance and energy spread at the end of the linac and before chicane



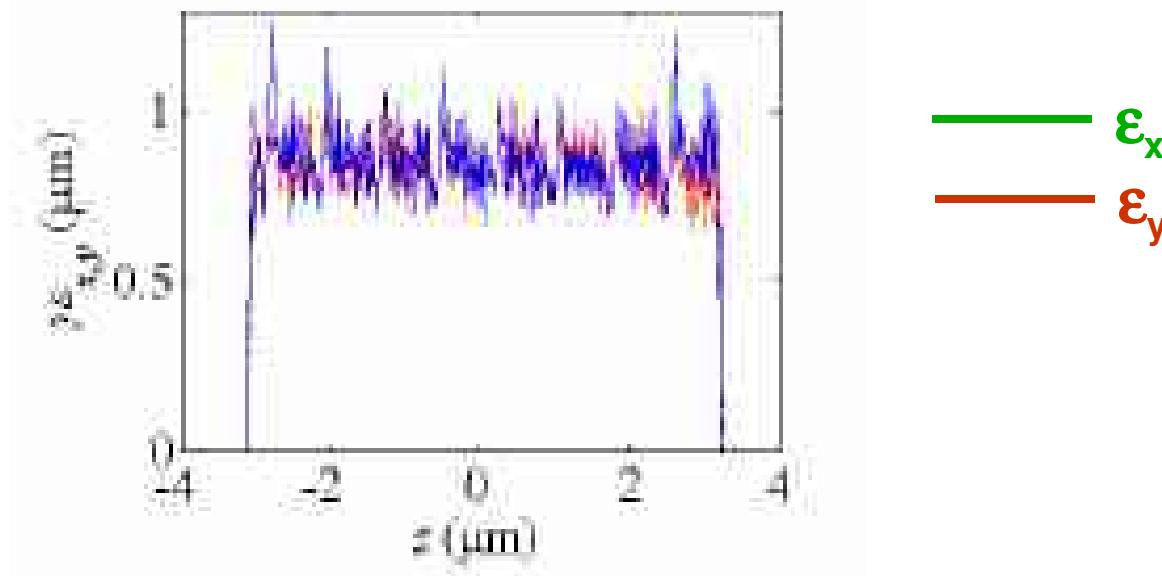
Peak current, emittance and energy spread after chicane



Coherent synchrotron radiation in the chicane

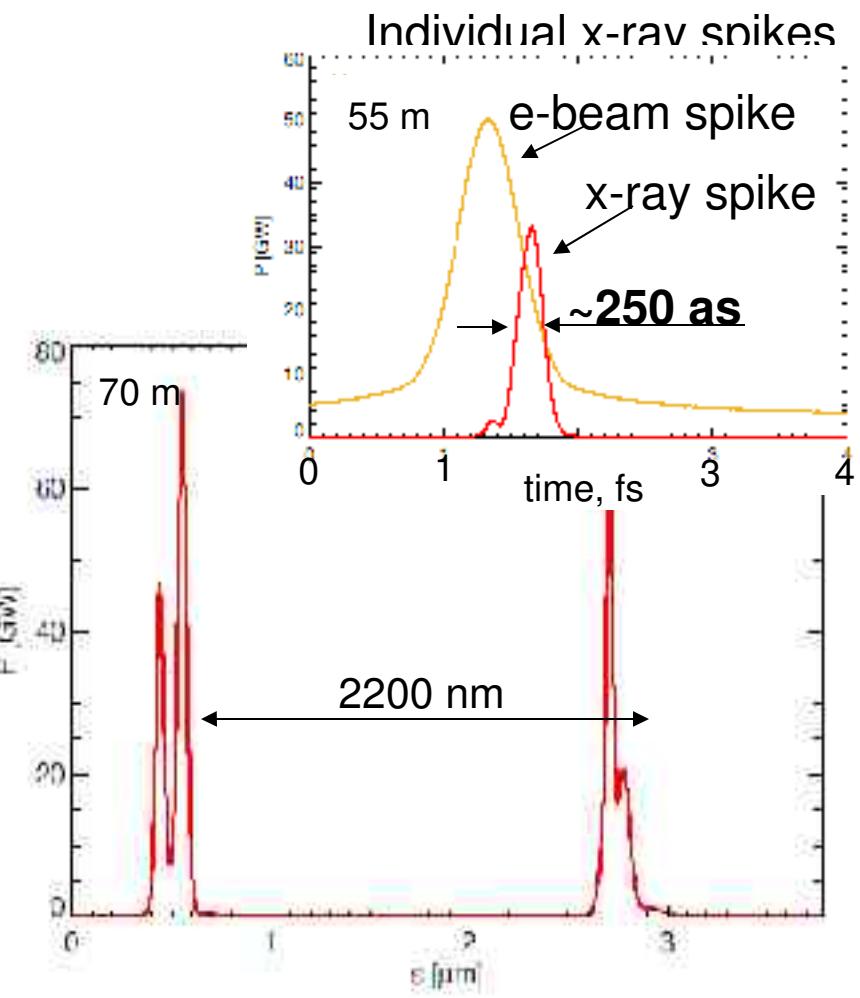
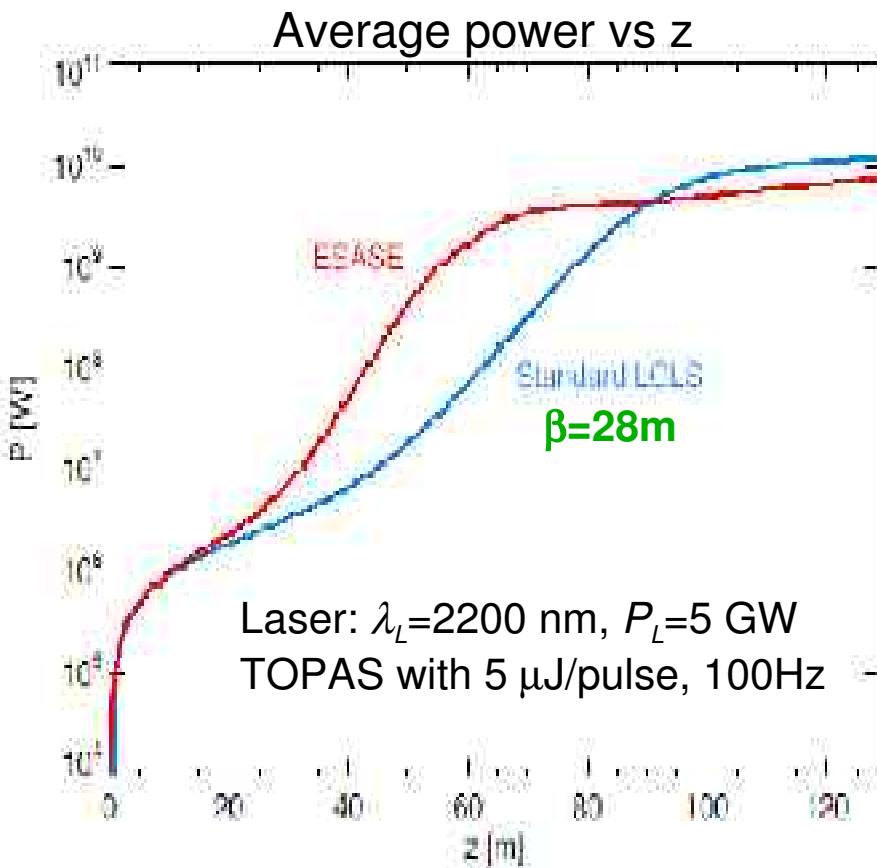
Does not look bad at all !

A finite horizontal beam extent prevents the micro-bunching until almost the very end of the chicane.

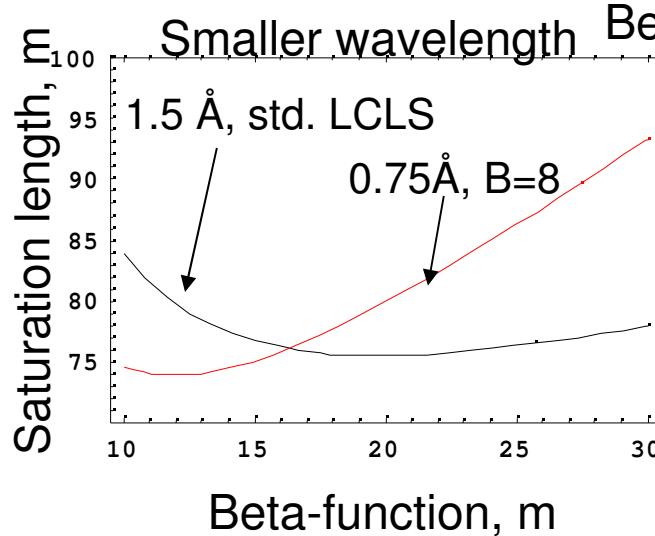
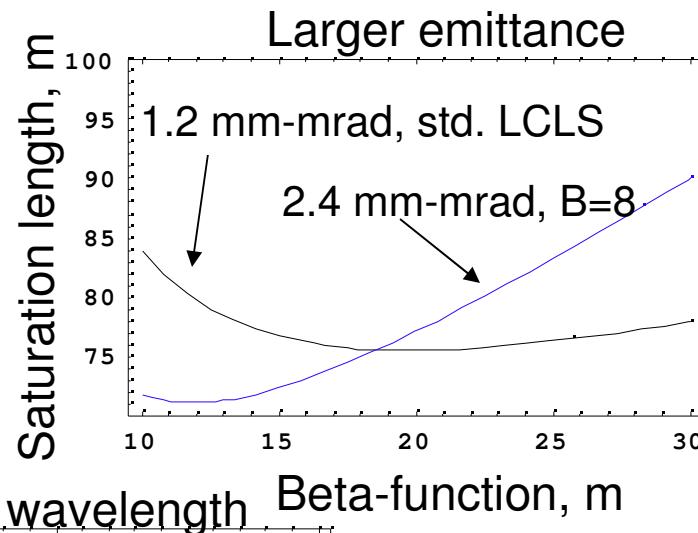
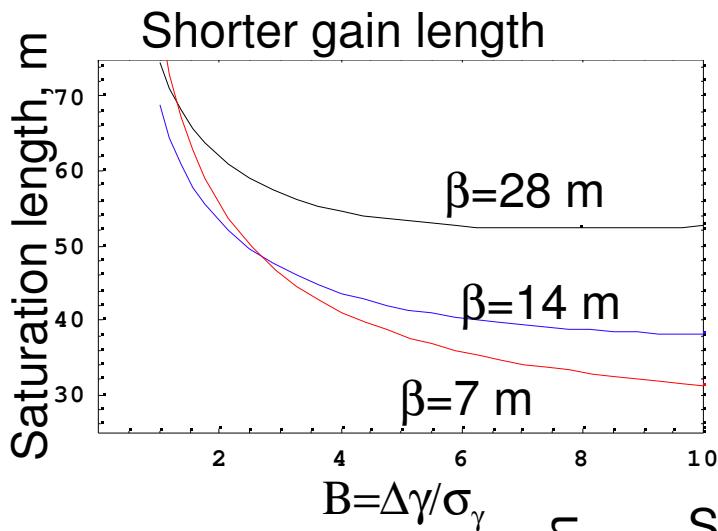


Slice emittance after chicane at various locations along the e-beam

X-ray radiation at LCLS



Potential of e-SASE



Summary of e-SASE

e-SASE offers:

- 1)** Short gain length, high peak power, comparable average power.
- 2)** Easy tunability for a duration of x-ray pulse by laser pulse shaping. Possibility for a solitary attosecond x-ray pulse.
- 3)** Nearly temporally coherent and Fourier transform limited radiation within the spike with random carrier phase between spikes.
- 4)** Absolute synchronization between laser pulse and x-ray pulse.
- 5)** Relaxing emittance requirement.
- 6)** Shorter x-ray wavelengths.

Musings on Light, Einstein and Tagore

*Einstein was fascinated
with Light!!*

Albert Einstein's theory of relativity is one of the most important theories in physics.

It describes how space and time are related to matter and energy.

The theory has been tested many times and it is still considered to be accurate.

Albert Einstein was born in Germany in 1879 and died in 1955.

He is best known for his theory of relativity and his work on the theory of quantum mechanics.

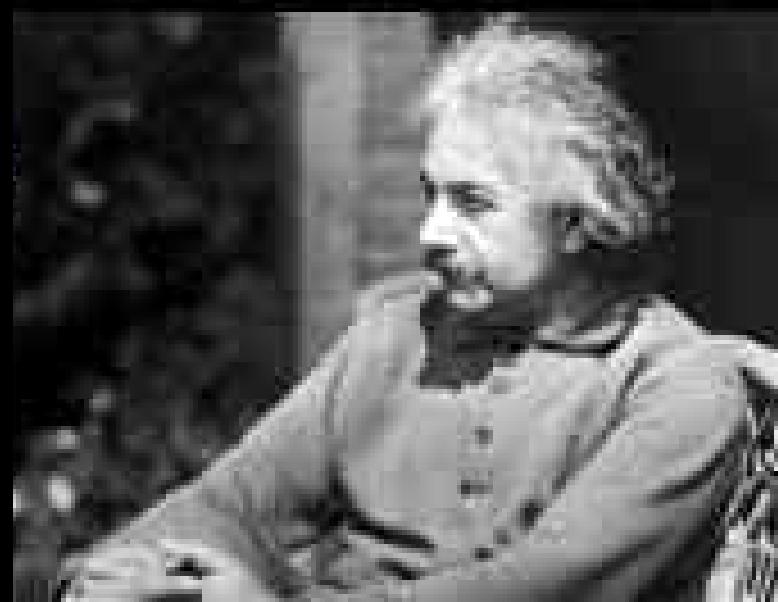
He also made significant contributions to the field of astrophysics and cosmology.

Albert Einstein was a very intelligent man and his work has had a lasting impact on science.

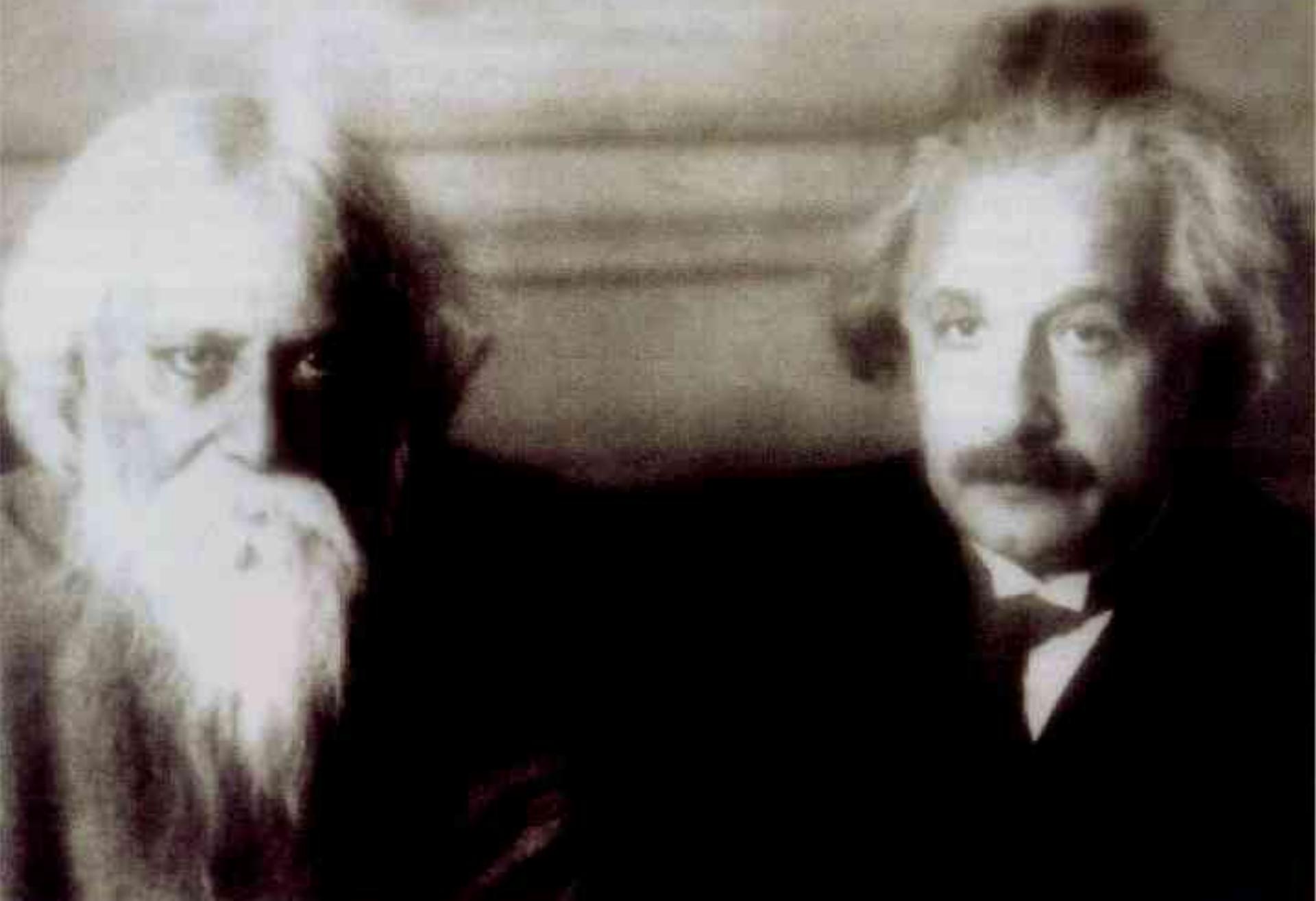
If you want to learn more about Albert Einstein and his work, there are many books available on the subject.

You can also find information online or visit a library to read more about him.

Albert Einstein was a very important figure in the history of science and his work will continue to be studied and appreciated for many years to come.



So was a Bengali poet: Rabindranath Tagore



the first frost
when soft mists hover over /
the first frost
and sun under clouds,
first frost after first
frost day,
comes - comes (with)
Hush! app. 103

the first frost
when soft mists /
hang and drifts
over land and water,
when first frost app.
comes - comes - !

"paper" door
comes -
C. H. 2

While the frosty hand shows our way
The two-of-us follow the wind's way -
While the sun of frost at the colorful hour,
Sprays his spirit with snow!
And the horizons dance in the wake of
The Monsoon cloud's flight,
My heart's song is -
The flash of a sudden-light!

Gardens of Magnolia - we know not!
Did flowers fill the broken lot.
The sudden breeze carrying the flower,
Scent of what unknown flower,
Why at this unadorned evening hour!
Christened tips of haughty
Branches of Rhododendron,
Ignore the sun-clad clouds
A trifle in the morn!