THE COCKCROFT INSTITUTE *of*
ACCELERATOR SCIENCE AND TECHNOLOGY

# Particle Accelerators and Their Reach for Science: Present and Future

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**Cockcroft Institute**

UNIVERSITY OF LIVERPOOL

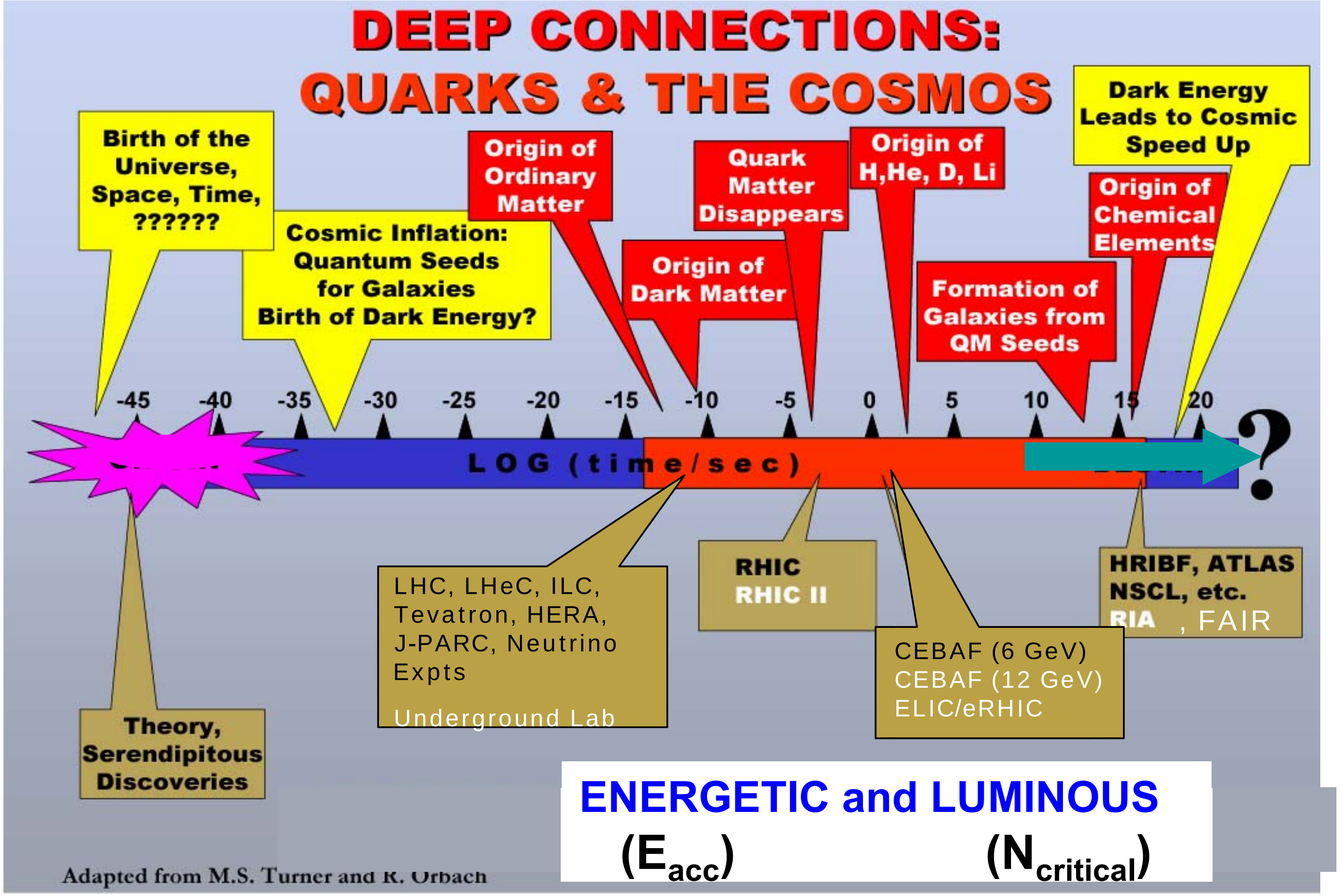
LANCASTER UNIVERSITY
Celebrating 40 Years of Excellence

MANCHESTER 1824
The University of Manchester

Science & Technology Facilities Council

# Science and Instruments of Discovery and Innovation:
## Structures and Forces

**Accelerator-driven Intense Charged Particle Beams serve Sciences from the Sub-atomic to the Cosmic**



LHC, LHeC, ILC, Tevatron, HERA, J-PARC, Neutrino Expts

Underground Lab

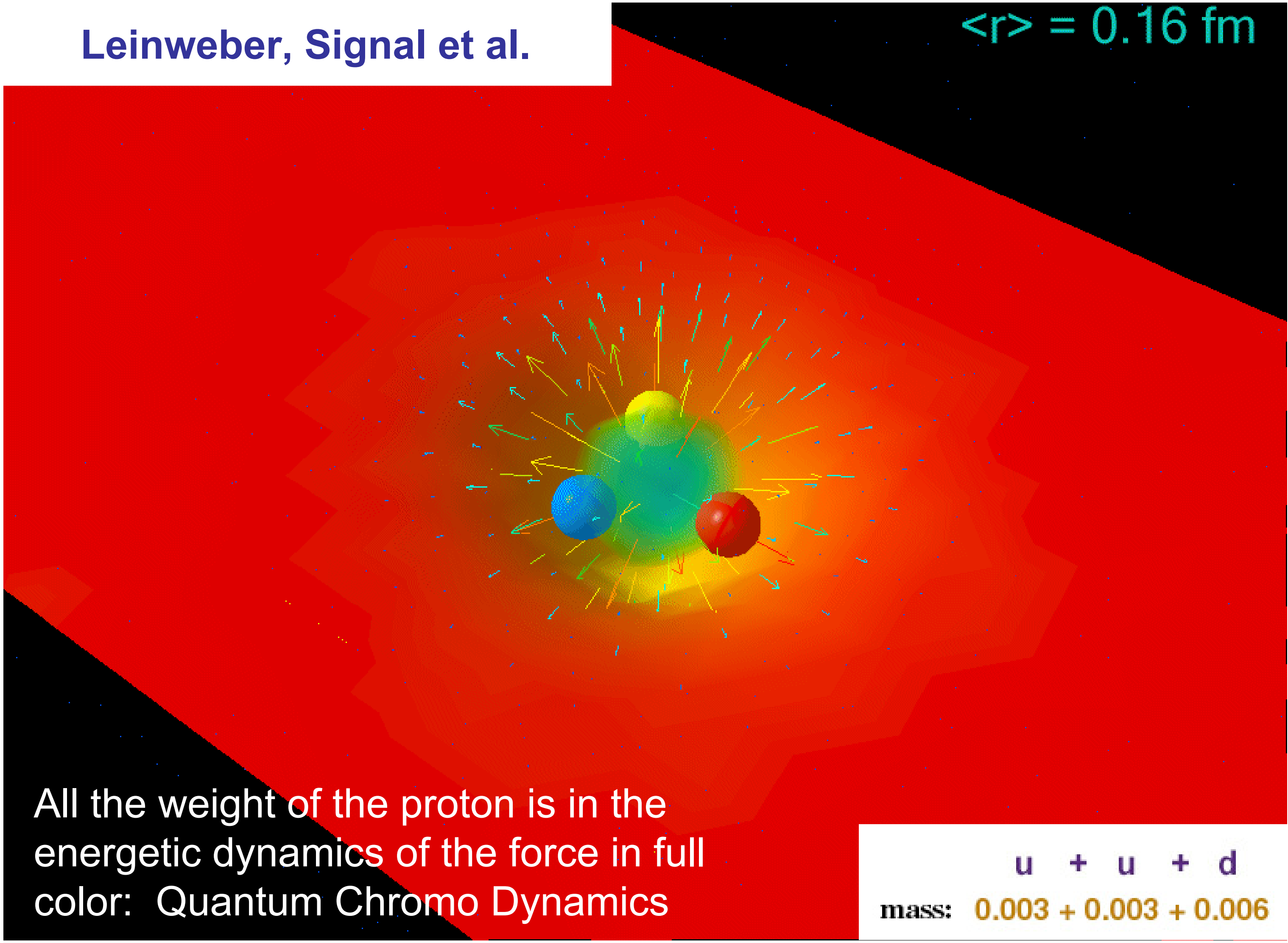
CEBAF (6 GeV)
CEBAF (12 GeV)
ELIC/eRHIC

, FAIR

**ENERGETIC and LUMINOUS**

$(E_{acc})$ $(N_{critical})$

**Leinweber, Signal et al.**



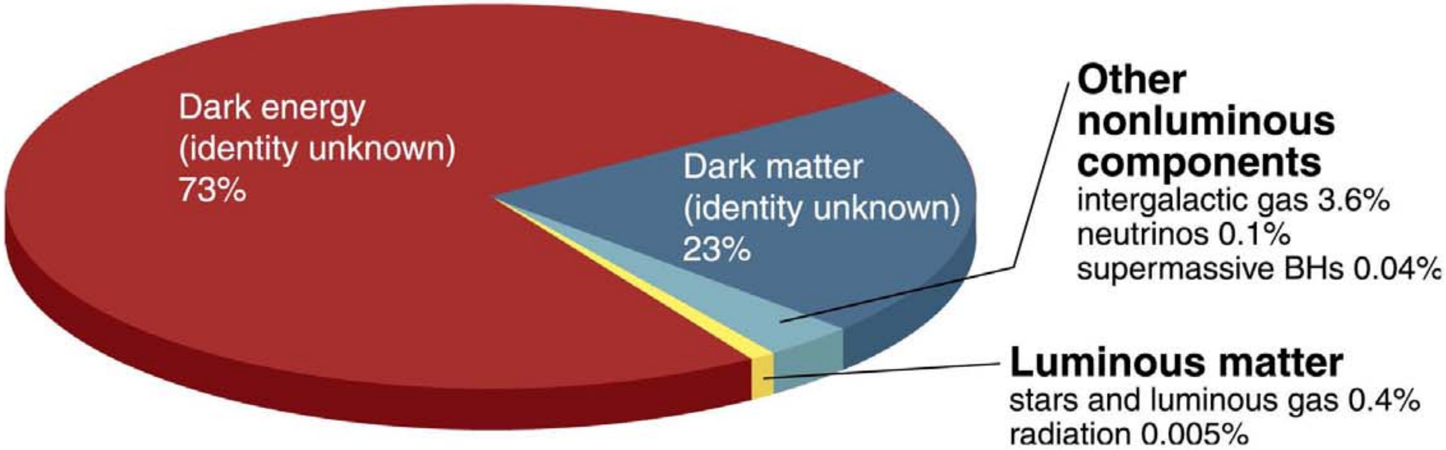
**$E=mc^2$**

All the weight of the proton is in the energetic dynamics of the force in full color: Quantum Chromo Dynamics

| | u | + | u | + | d | = | proton |
|---|---|---|---|---|---|---|---|
| mass: | 0.003 | + | 0.003 | + | 0.006 | ≠ | 0.938 |

# The cosmological inventory is now well-delineated

- But we know neither what the “dark energy” or the “dark matter” is
- A particle relic from the Big Bang is strongly implied for DM
  - WIMPs ?
  - Axions ?



**Other nonluminous components**
intergalactic gas 3.6%
neutrinos 0.1%
supermassive BHs 0.04%

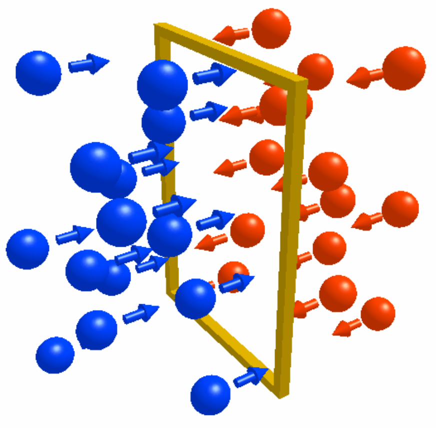
**Luminous matter**
stars and luminous gas 0.4%
radiation 0.005%

1st cyclotron, ~1930 E.O. Lawrence
11-cm diameter
1.1 MeV protons

LHC, 2008
9-km diameter
7 TeV protons

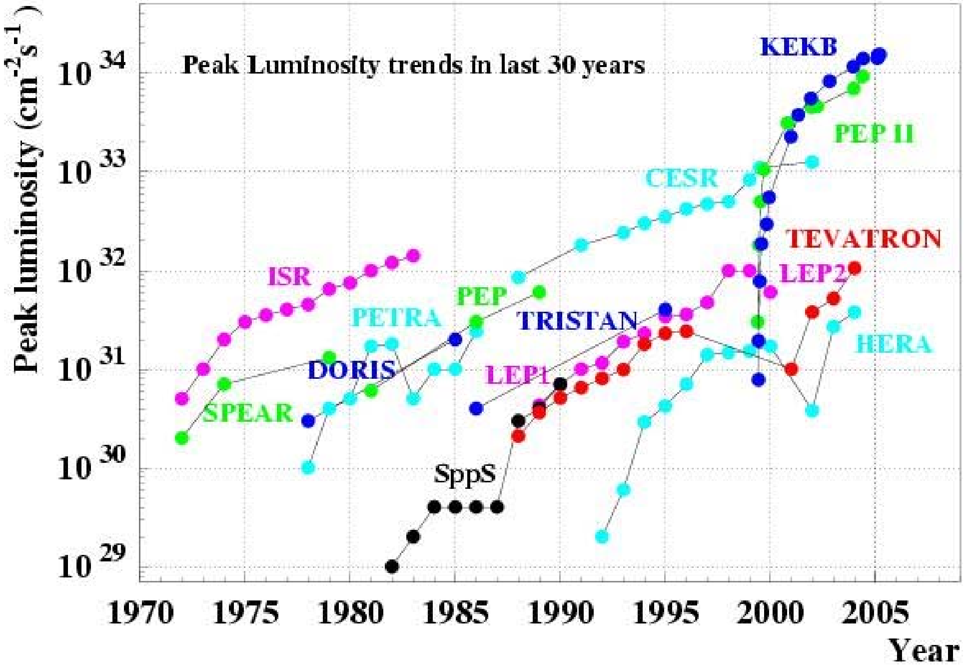
*after ~80 years*
*~$10^7$ x more energy*
*~$10^5$ x larger*

# Luminosity and its continual improvement over time



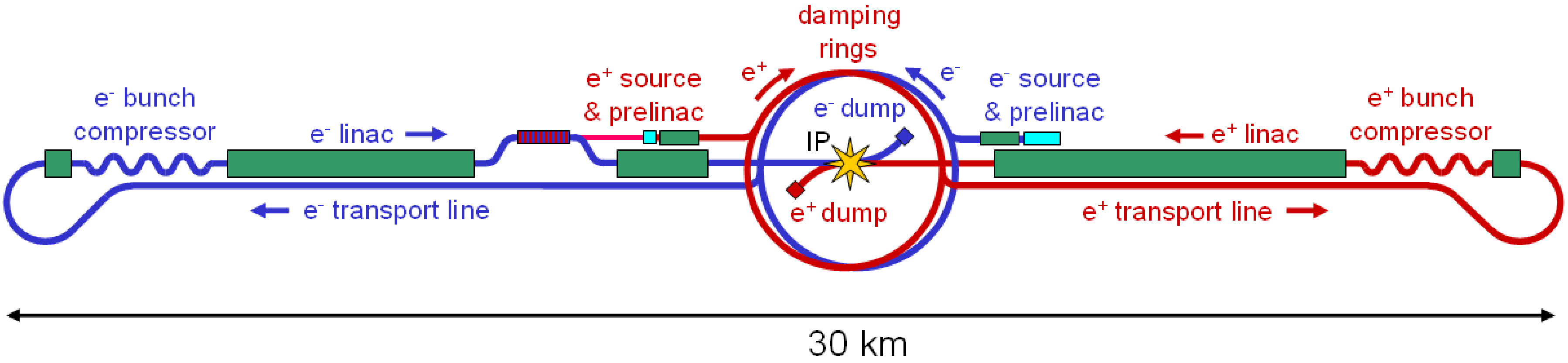
(number of events/unit time)

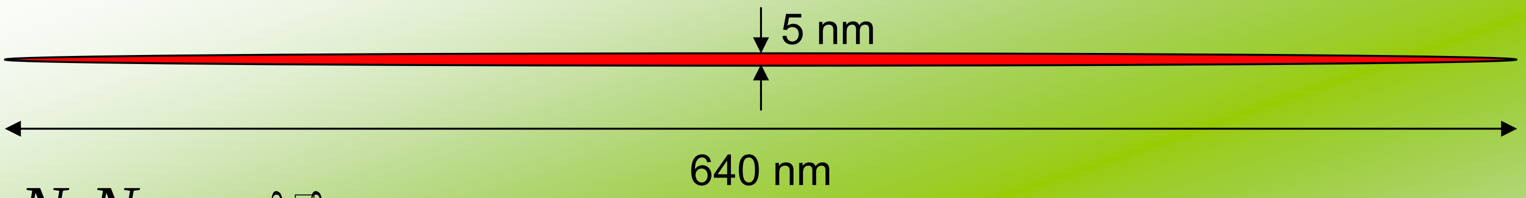
= (cross section) X (luminosity)



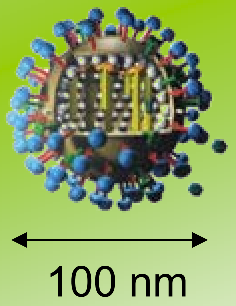
# Beams in future e+e- colliders must be on the nanometer scale

***The International Linear Collider***





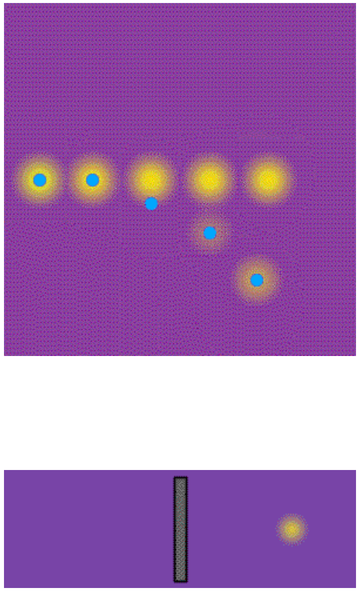
$$L \sim \frac{N_1 N_2}{A} f \sim \underbrace{\frac{\lambda\lambda}{\gamma^{-1}\lambda}\lambda^{-1}}_{\sim\text{constant}} \sim \underline{\underline{(\lambda)^0}}\,\gamma$$



Cross-section of the beam at the interaction point of the ILC should be 1/3 the cross-section of a flu virus.

Courtesy: Andy Wolski, Cockcroft Institute/ University of Liverpool

# Ultrabright, Ultrashort Beams – 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!!

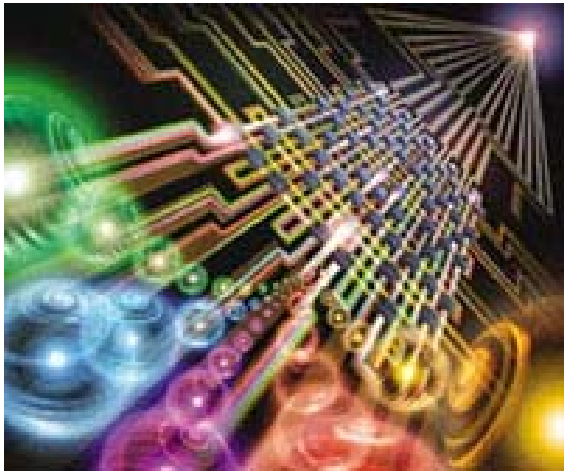
- Opportunities in Ultrafast Science, Nonlinear Dynamics, SCRF, THz Laboratory Astrophysics look exciting!!

**Fascinating graduate research!!**

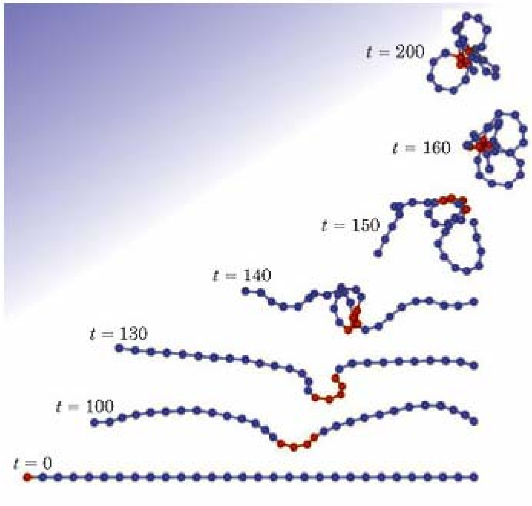
# The science need

The fundamental requirement is to understand the *dynamic* behaviour of matter, often in very small (nm) units, on very fast (fs) timescales

We need not just to determine *structure* with high precision, but to understand *how these structures work*



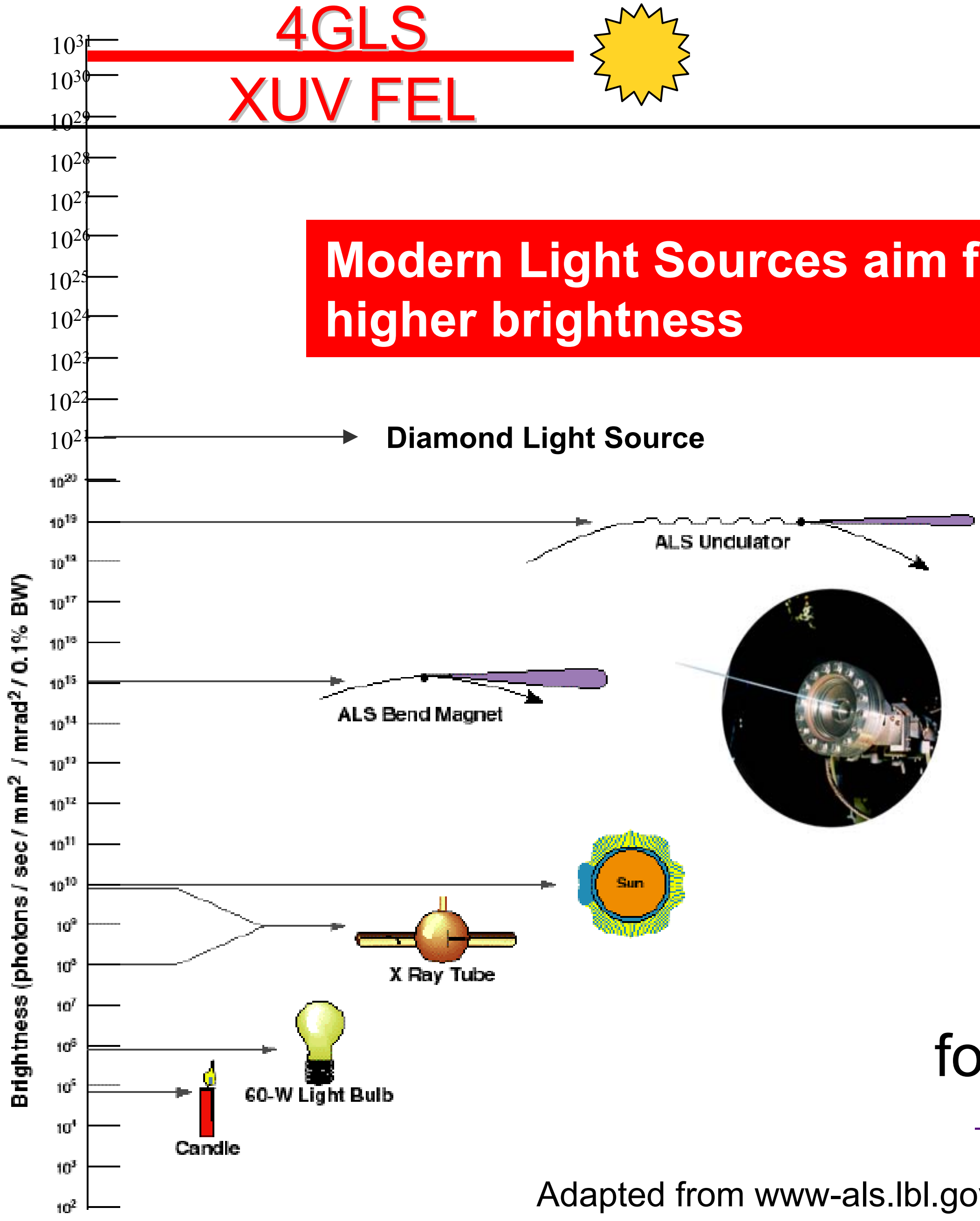
Scientific American Jun 2002



Courtesy: Wendy Flavell, University of Manchester

Physics Today Jan 2004

# Light Fantastic and Bright!



**Modern Light Sources aim for higher brightness**

Adapted from www-als.lbl.gov

## Off the scale brightness….

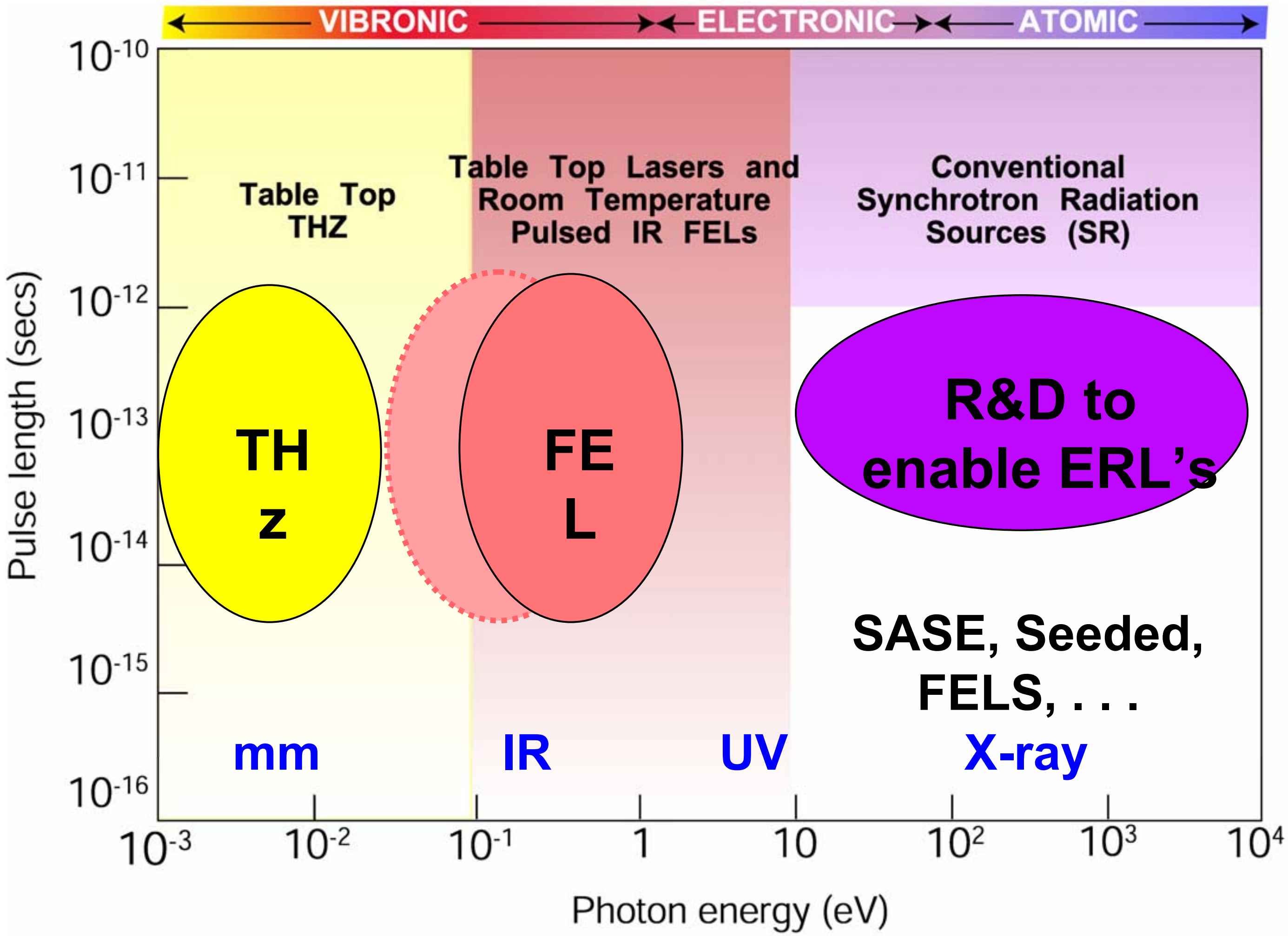
>$10^8$ x brighter than 3rd generation SR

peak power output equivalent to that needed to light every home in London…..

for 100 fs!

Courtesy: Wendy Flavell, University of Manchester

# Intense Charged Particle Beam-generated Photon Beams serve a Colorful Canvas of Photon Sciences



**INTENSE, ULTRABRIGHT and ULTRASHORT**

# Discovery

# 21st CENTURY: AMAZING LIGHT!! Hidden Energies

## Fundamentals at the Core of the Physical World

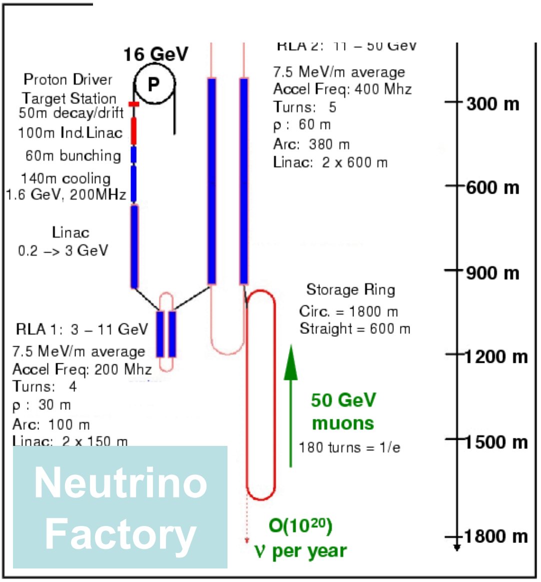
- Hidden Dimensions, Symmetries and Structures
- Origins of Mass, Dark Matter and Dark Energy
- Unification of Gravity
- Exotic States of Matter
- Ultrabright, Ultrashort and Ultrafast Light

**To master the global resources necessary for these discoveries, international effort must be consolidated into only a few carefully selected facilities so large that they can only be supported internationally . . .**

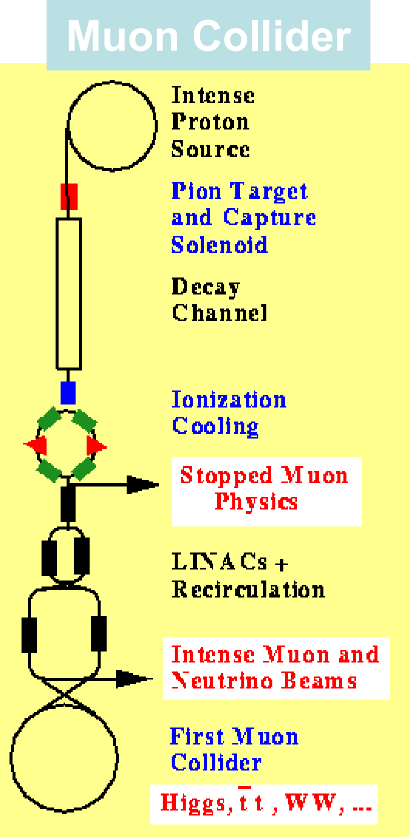
***Emergence of a few grand future machines:***

- **Large Hadron Collider**
- **X-ray Free Electron Laser**
- **International Linear Collider**
- **International Neutrino Factory/Muon Collider**

# Grand Future Machines



**Neutrino Factory**



**Muon Collider**

Intense Proton Source

Pion Target and Capture Solenoid

Decay Channel

Ionization Cooling

Stopped Muon Physics

LINACs + Recirculation

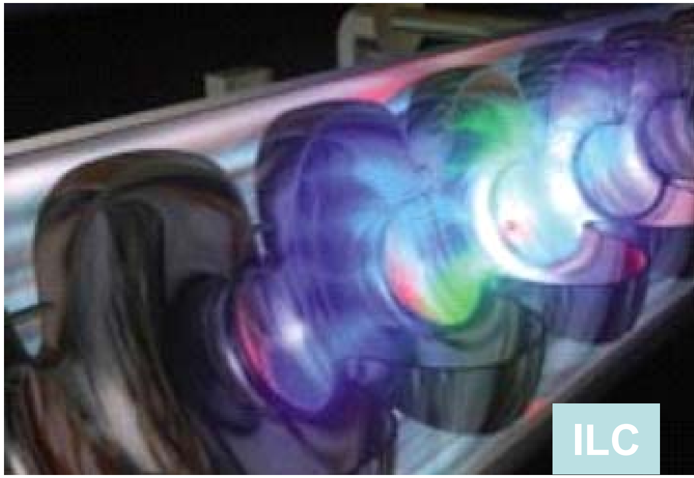
Intense Muon and Neutrino Beams

First Muon Collider

Higgs, $t\bar{t}$ , WW, ...

**X-FEL**

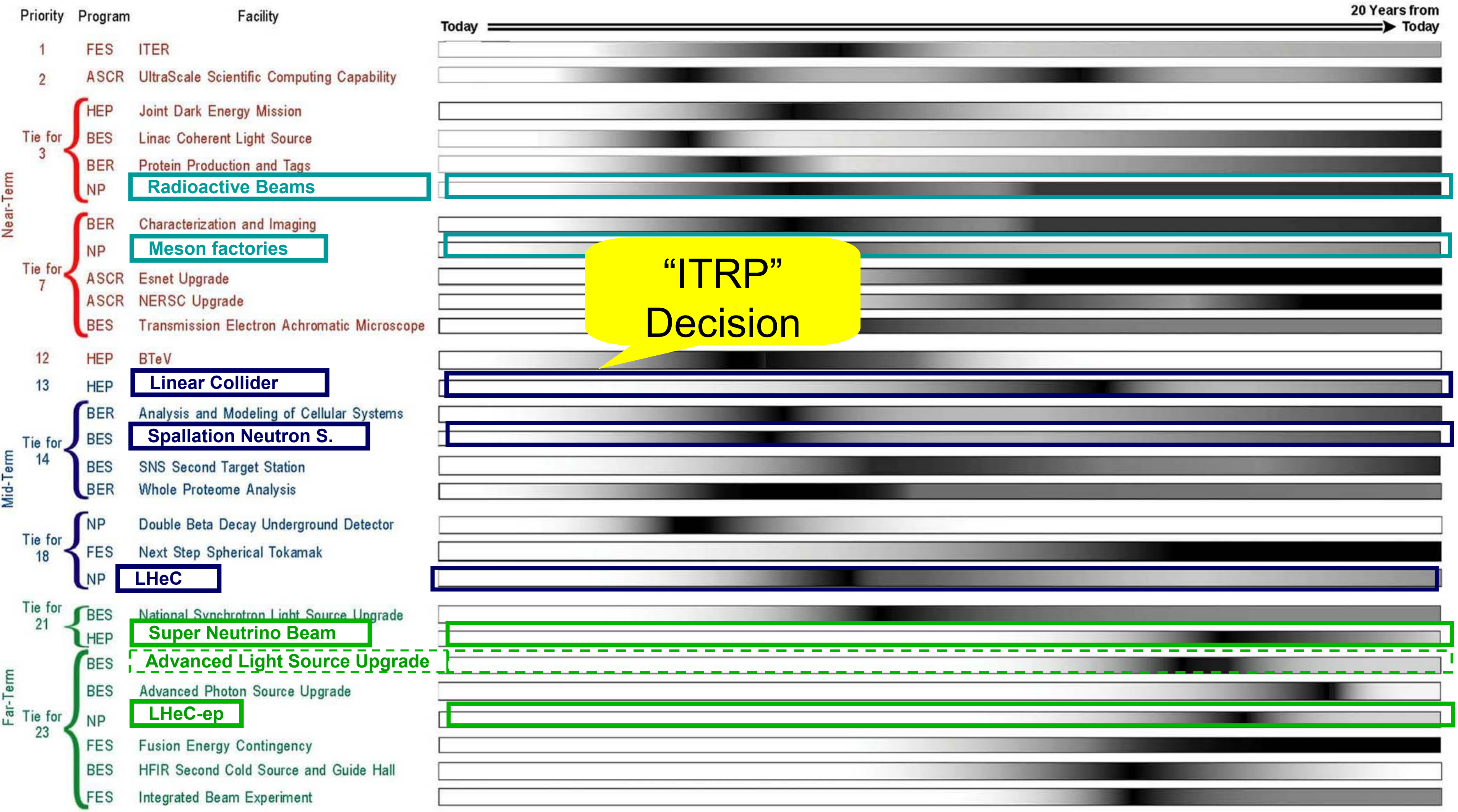
**LHC**



**ILC**

# SRF will play a major role in the future SC facilities

## U.S. Department of Energy Office of Science 20-Year Facility Outlook Peak of Cost Profile



| | Priority | Program | Facility |
|---|---|---|---|
| Near-Term | 1 | FES | ITER |
| | 2 | ASCR | UltraScale Scientific Computing Capability |
| | Tie for 3 | HEP | Joint Dark Energy Mission |
| | | BES | Linac Coherent Light Source |
| | | BER | Protein Production and Tags |
| | | NP | **Radioactive Beams** |
| | Tie for 7 | BER | Characterization and Imaging |
| | | NP | **Meson factories** |
| | | ASCR | Esnet Upgrade |
| | | ASCR | NERSC Upgrade |
| | | BES | Transmission Electron Achromatic Microscope |
| Mid-Term | 12 | HEP | BTeV |
| | 13 | HEP | **Linear Collider** |
| | Tie for 14 | BER | Analysis and Modeling of Cellular Systems |
| | | BES | **Spallation Neutron S.** |
| | | BES | SNS Second Target Station |
| | | BER | Whole Proteome Analysis |
| | Tie for 18 | NP | Double Beta Decay Underground Detector |
| | | FES | Next Step Spherical Tokamak |
| | | NP | **LHeC** |
| Far-Term | Tie for 21 | BES | National Synchrotron Light Source Upgrade |
| | | HEP | **Super Neutrino Beam** |
| | Tie for 23 | BES | **Advanced Light Source Upgrade** |
| | | BES | Advanced Photon Source Upgrade |
| | | NP | **LHeC-ep** |
| | | FES | Fusion Energy Contingency |
| | | BES | HFIR Second Cold Source and Guide Hall |
| | | FES | Integrated Beam Experiment |

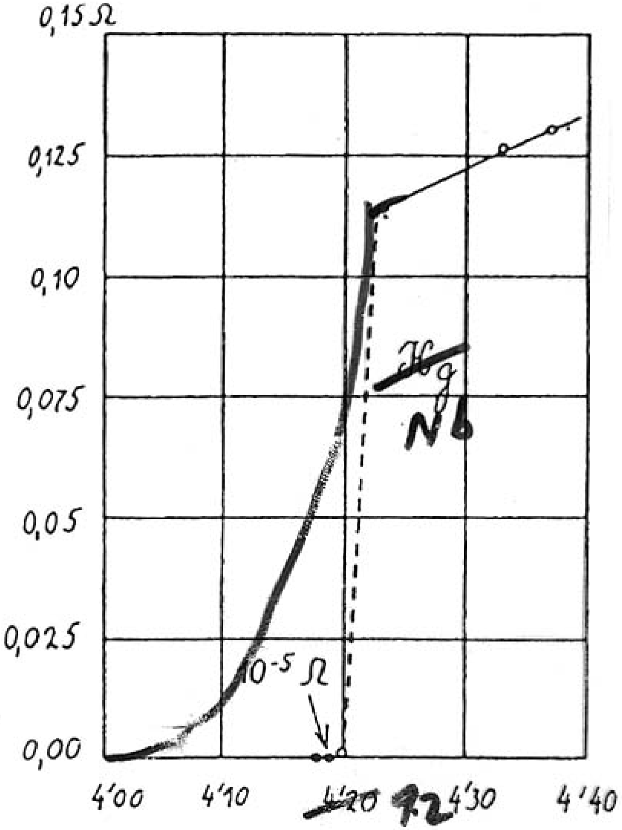
Peak Cost ■ Near-term 🟥 Mid-term 🟦 Far-term 🟩

**Programs:**

ASCR = Advanced Scientific Computing Research
BES = Basic Energy Sciences
BER = Biological and Environmental Research
FES = Fusion Energy Sciences
HEP = High Energy Physics
NP = Nuclear Physics

# Superconductivity

## Heike Kammerlingh-Onnes, 1911: SC in mercury



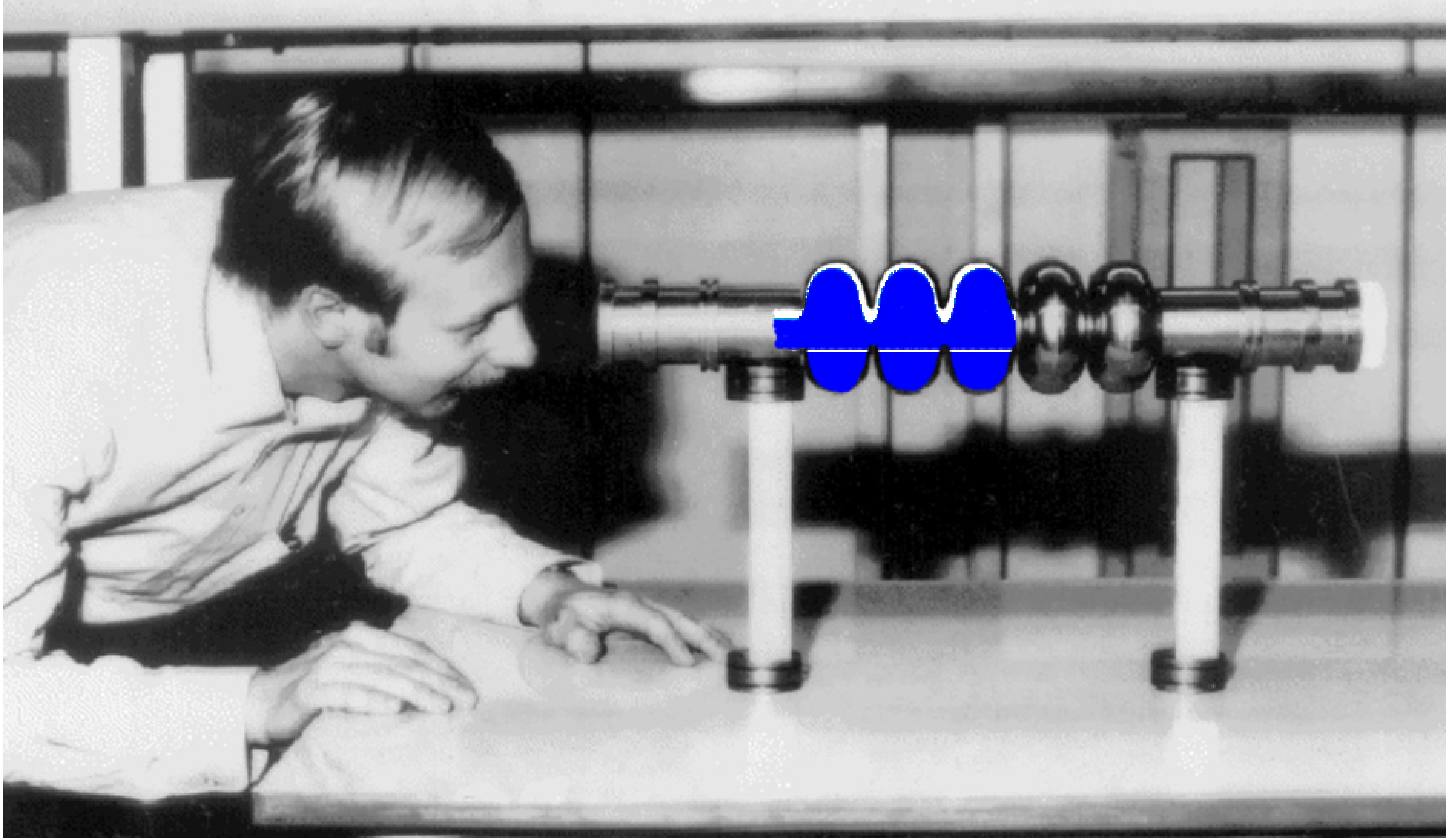
surement of superconductivity by Kamerlingh Onne

4 The Convergence of Classical Concepts circa 1900

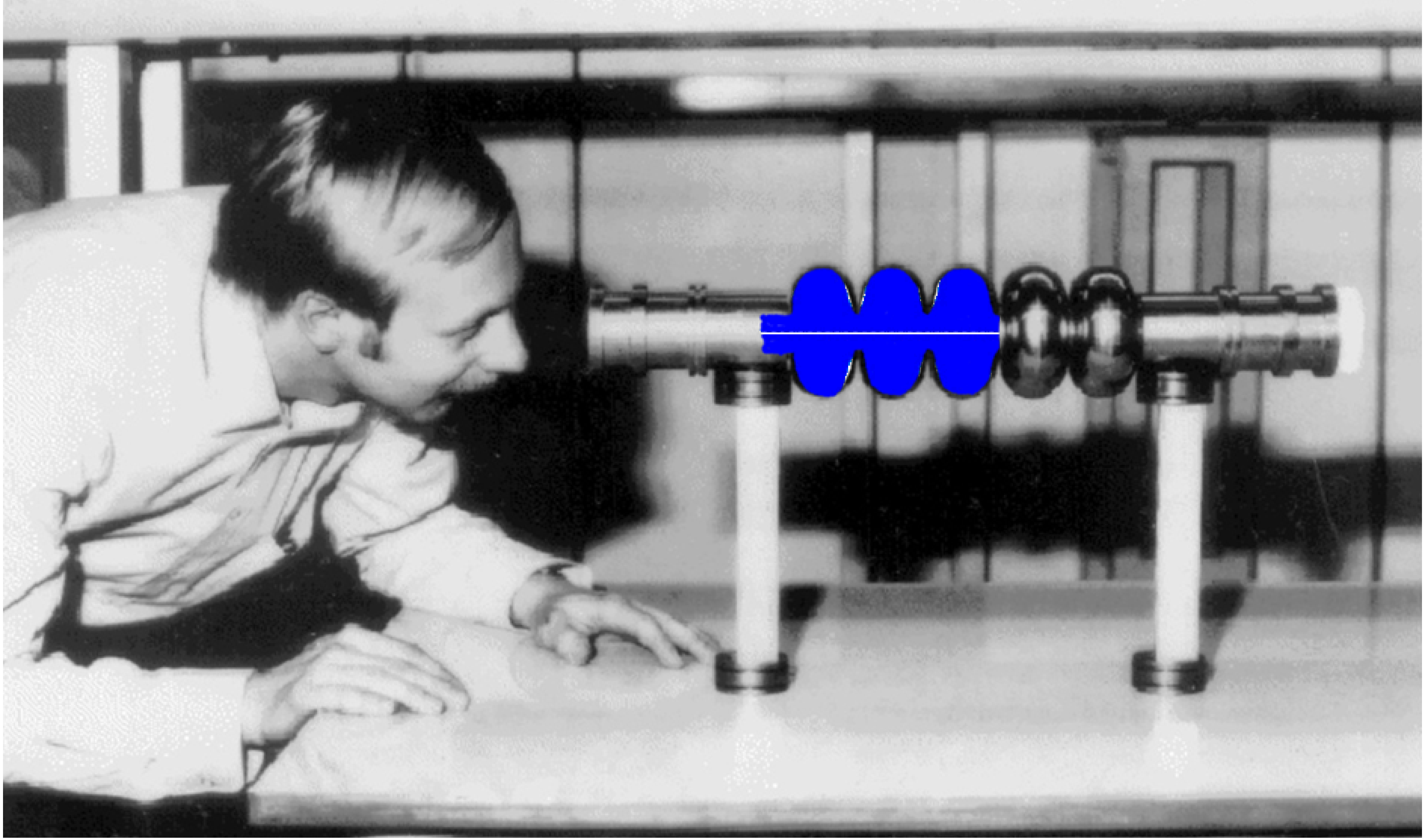
Figure 1-2. Heike Kamerlingh Onnes. Courtesy AIP [illegible] Bohr Library and

**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



# OUTLOOK

# SRF – A Robust Global Technology

**WE MUST LEARN TO COLLABORATE INTERNATIONALLY**

JLab

CESR

CERN

DESY/TESLA

TU Darmstadt

KEK

LANL

FNAL

ANL

Peking University

Center for Advanced Technology, Indore

CEA Orsay

CEA Saclay

INFN Genoa

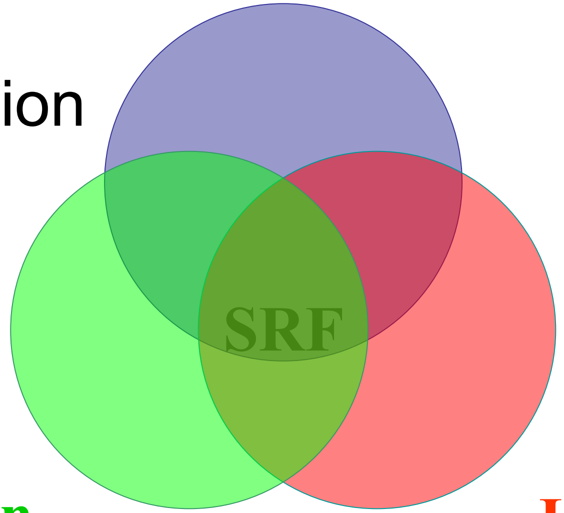
INFN Legnaro

INFN Milan

Australian National University

# Overlap of SRF activities in accelerator projects

SRF technology is central to high-energy/nuclear physics, high current proton drivers, synchrotron radiation sources and free electron lasers.



**Superconducting linear accelerators and colliders**

**Synchrotron Radiation Sources and FELS** (Dylla's talk)

**High Current Proton Drivers**

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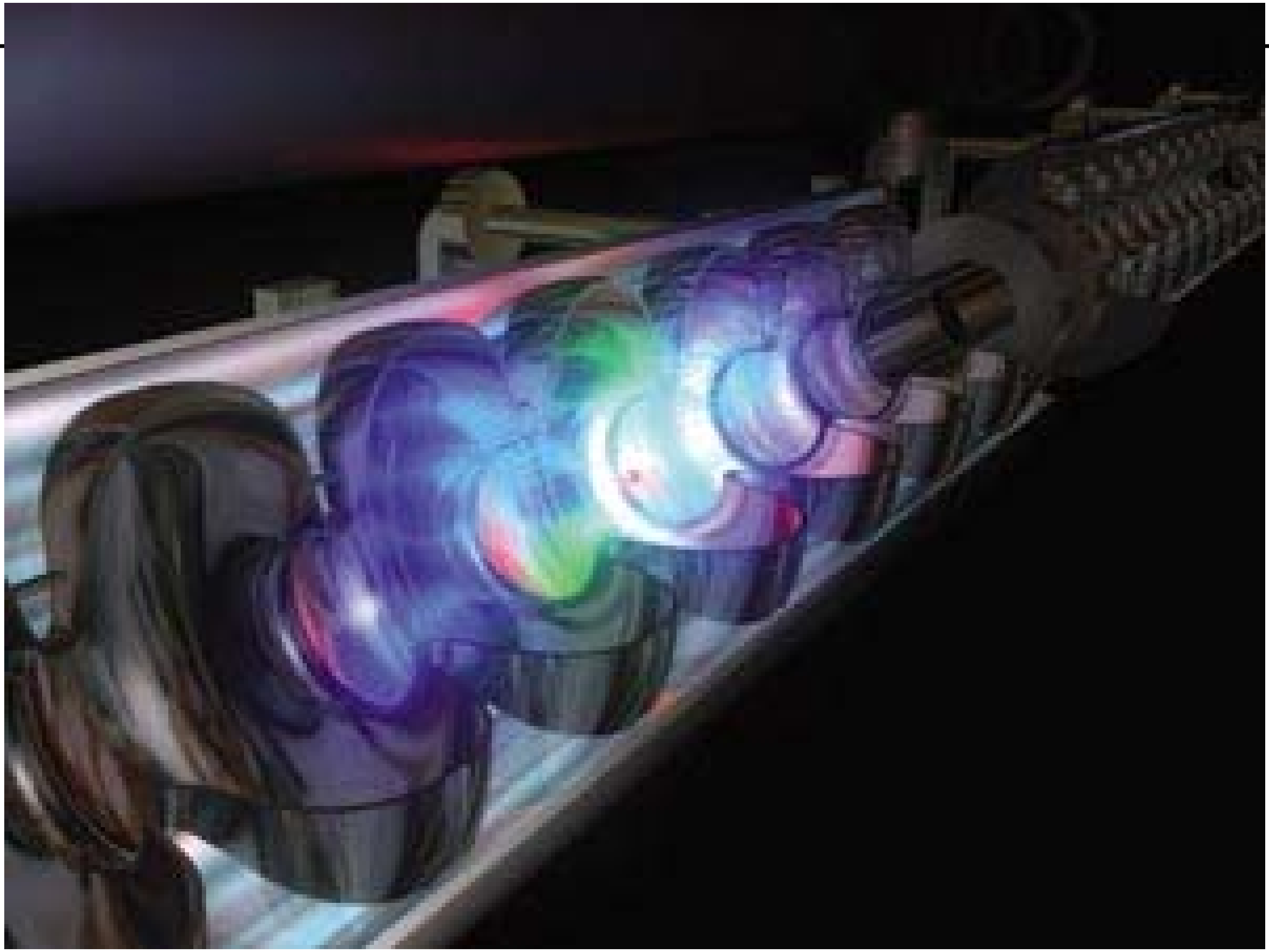
# The Superconducting Linear Accelerator



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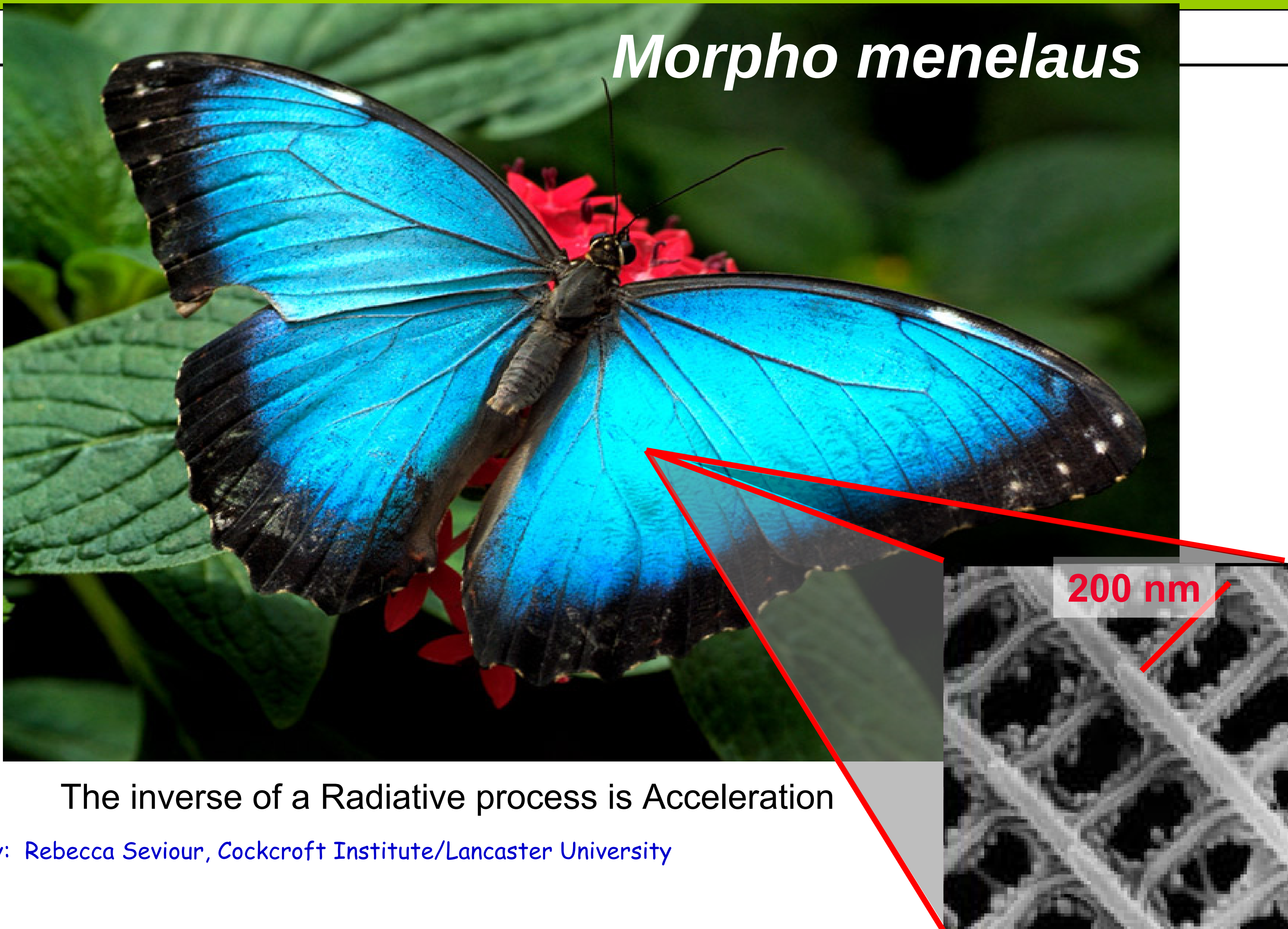
# Amazing Light and Particles!



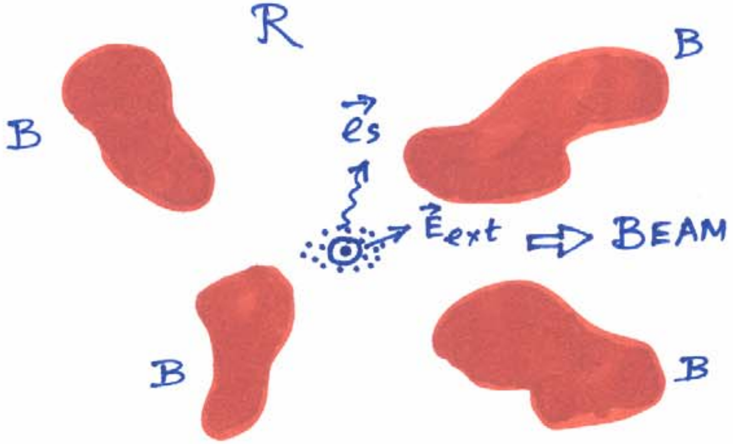
The inverse of a Radiative process is Acceleration

Courtesy: Rebecca Seviour, Cockcroft Institute/Lancaster University

# Acceleration and Radiation: A Tangled Web!

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

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



The field energy density:

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

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

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

ENERGY LOSS TO COHERENT SPONTANEOUS RADIATION

EXTERNAL STORED ENERGY

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

# Scaling

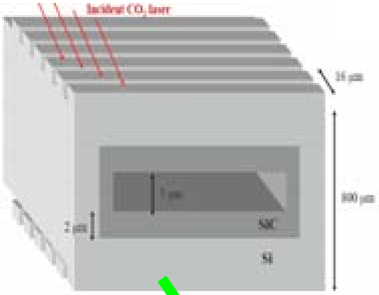
For optimal acceleration/deceleration, linear or otherwise in $\vec{E}_{ext}$, there must be optimal overlap of 'acceleration' mode $\vec{E}_{ext}(\omega,\vec{k})$ with 'radiation' mode $\vec{e}_s(\omega,\vec{k})$. The particles are accelerated if the coherent radiation loss is less than the energy gain,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

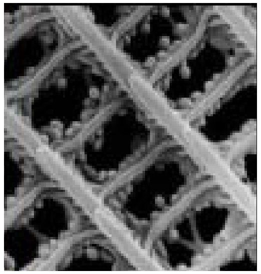
$$\boxed{N \lesssim (|\vec{E}_{ext}|/e)\,\bar{\lambda}^2} \equiv N_{critical}$$

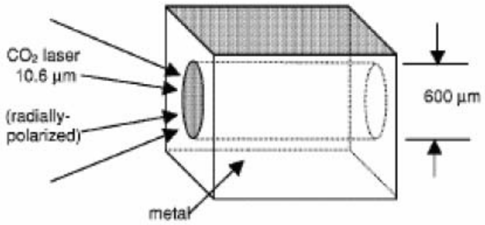
on the number of particles in a bunch that can be effectively accelerated before losses start to dominate, leading to deceleration ($\bar{\lambda} \equiv \lambda/2\pi$ is the reduced wavelength of accelerating mode).

$$E_{acc} \sim (\bar{\lambda})^{-1} \Longrightarrow \boxed{N_{critical} \sim \bar{\lambda}}$$

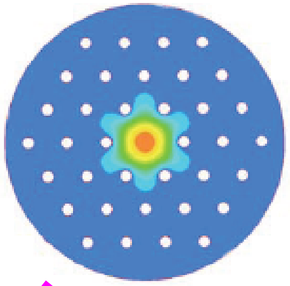
**(SLAC)**

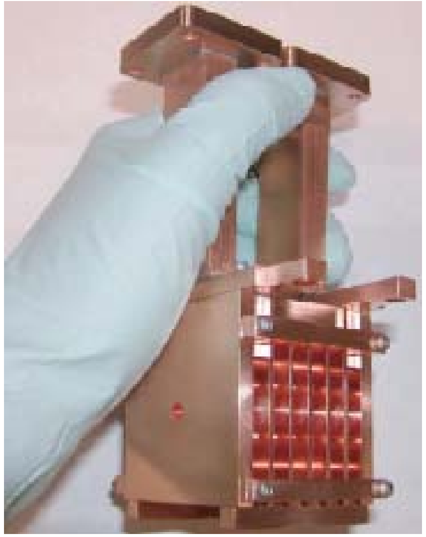


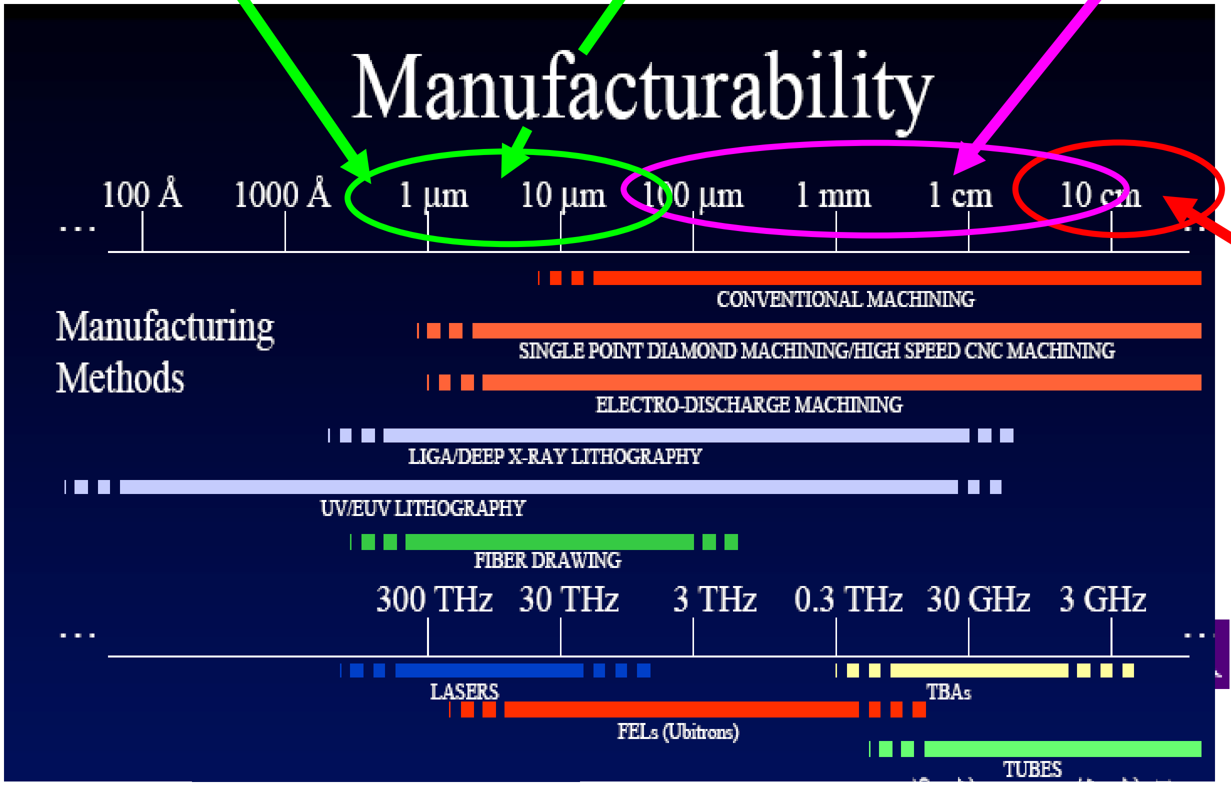




E. Smirnova et. al.
(MIT), metallic photonic
fiber, 17 GHz







CESR cavities

Courtesy: Rebecca Seviour, Cockcroft Institute/Lancaster University

# Technologies and Wavelengths

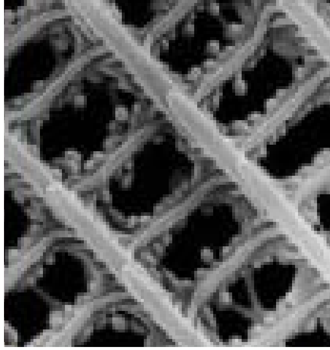
| Technology | Wave-length λ | Potential Gradient | R&D | Technology Details |
|---|---|---|---|---|
| **SCRF**<br>(Superconducting Radio-Frequency) | >20 cm | ~ 100 MV/m | Superconducting materials research; new superconductor | 'Bismuthate' materials and micro-layered thin-film technology |
| **RF**<br>(Radio-Frequency) | <10 cm | ~ 200 MV/m | Power sources prototype, drive beam dynamics<br>sheet beam klystron research | High frequency conventional klystrons and two-beam schemes |
| mm-wave, THz, Photonic Band-Gap | <2 cm | >1 GV/m | Power source invention, structure invention, fabrication tech. | Dielectric and conducting materials |
| Lasers & beams in plasmas & structures | <200 µm | >10 GV/m | Module prototype, rep. rate, guiding, staging, beam dynamics | Laser, structure-based<br>Laser, plasma-based<br>Beam, structure-based<br>Beam, plasma-based |

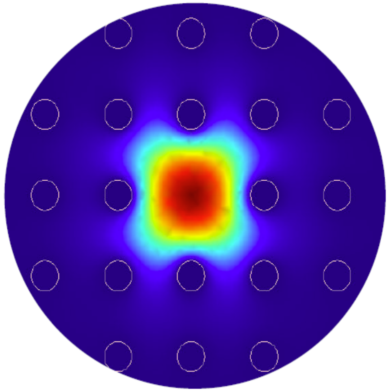
$E_{acc} \sim \lambda^{-1}$

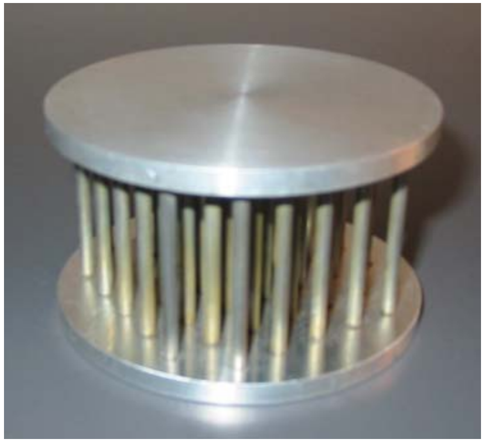
$N_{acc} \sim ??$

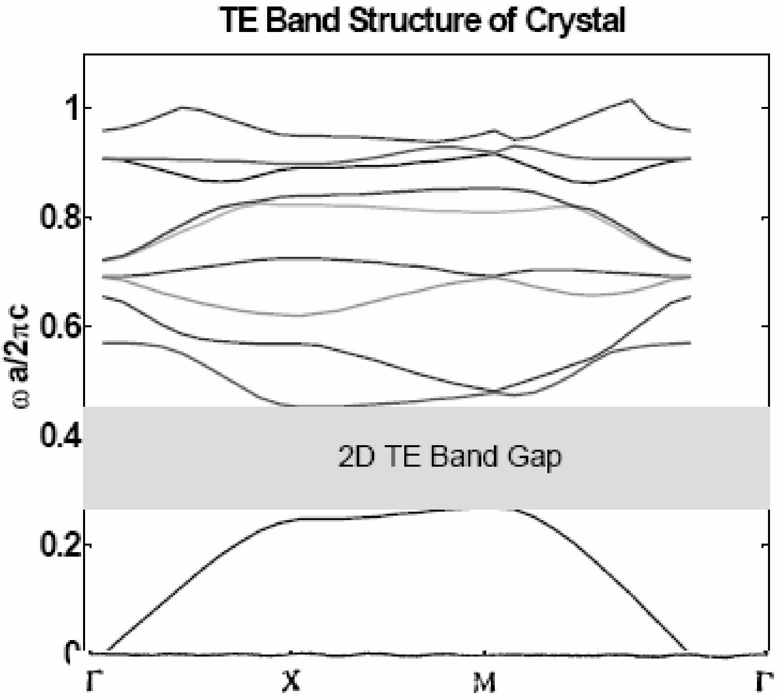
# Photonic Band Gap Structure

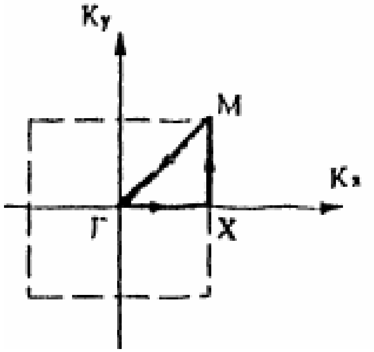
Courtesy: Rebecca Seviour, Cockcroft Institute/Lancaster University

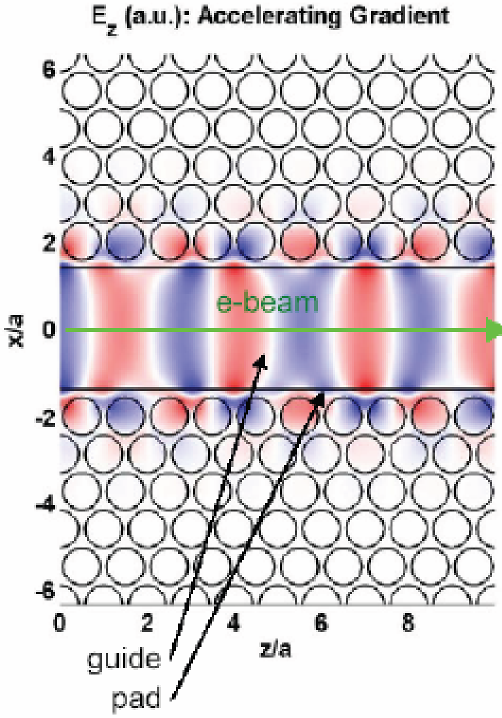







TE Band Structure of Crystal

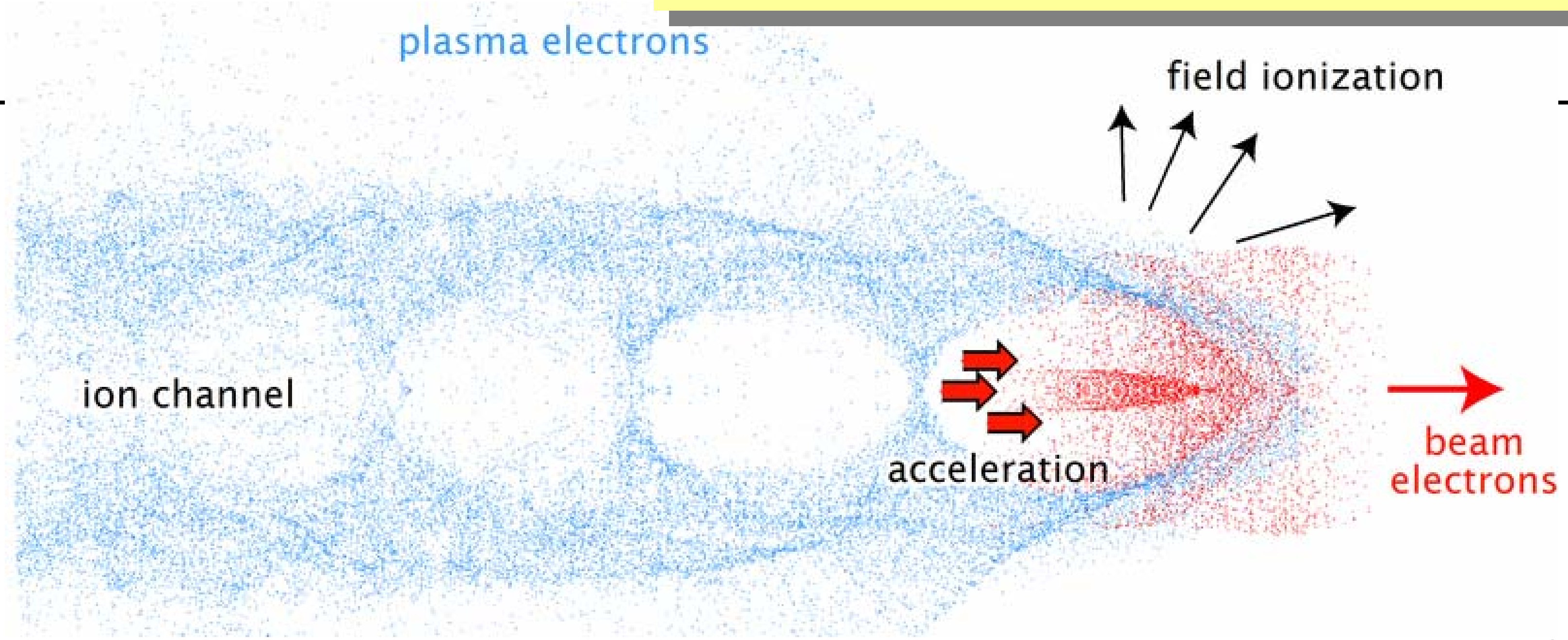




Speed-of-light mode in PC waveguide

B. Cowan (SLAC),

# Plasma Acceleration



Plasma acceleration has several types depending how the plasma wave is formed:

*Plasma Wakefield acceleration*: Plasma wave formed by an electron bunch

*Laser Wakefield acceleration*: Laser pulse is used to form a plasma wave.

*Laser Beat-wave acceleration*: Plasma wave arises based on different frequency generation of two laser pulses.

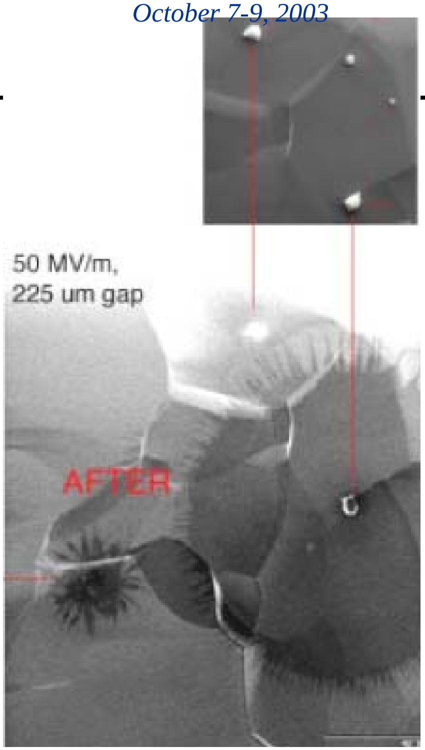
*Self-modulated laser Wakefield acceleration*: Leave for another day

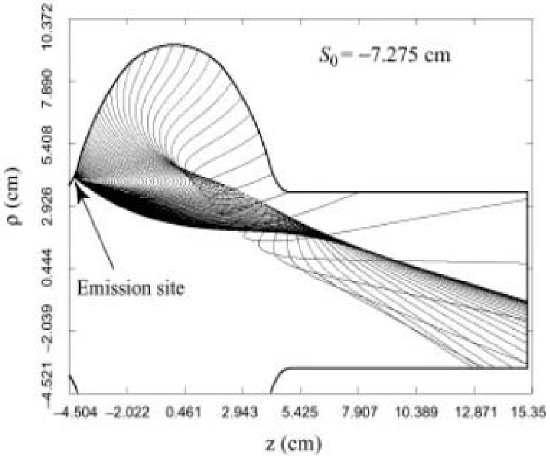
Courtesy: Rebecca Seviour, Cockcroft Institute/Lancaster University

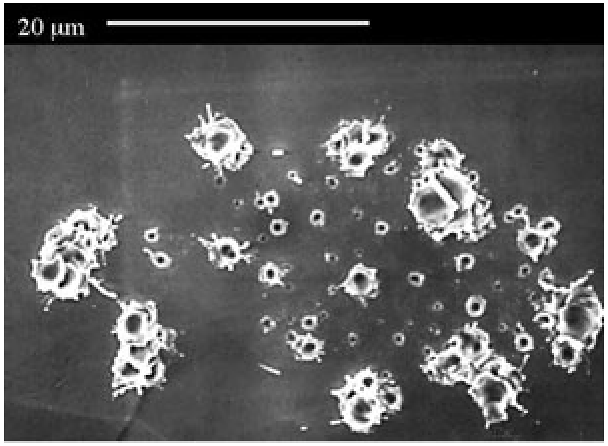
# Delicate Periodicity: Issues of Surface Finish and Medium Homogeneity

Field Emission

Courtesy: Rebecca Seviour, Cockcroft Institute/Lancaster University



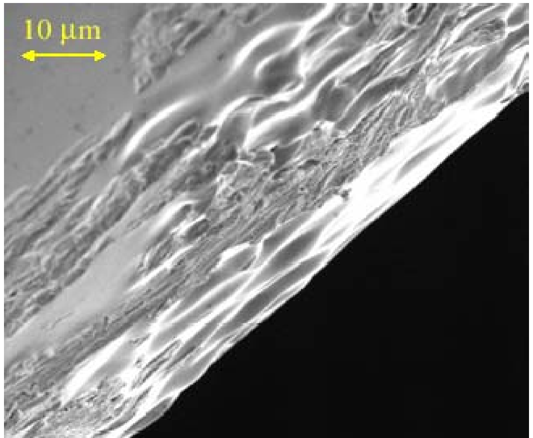


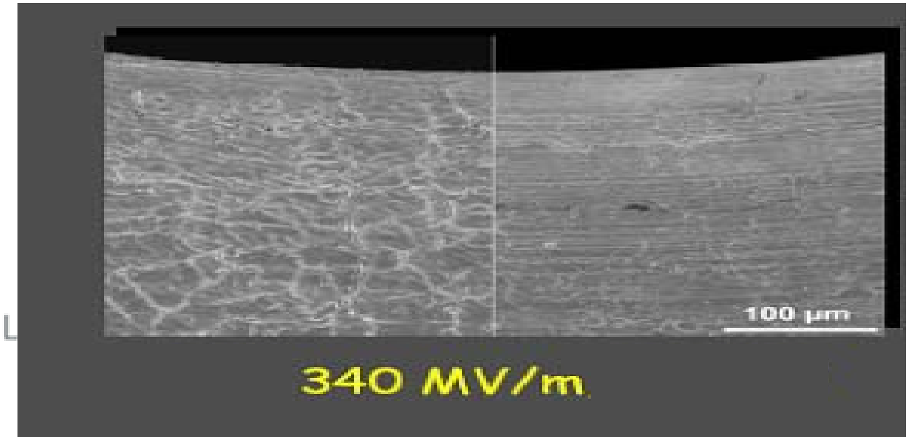


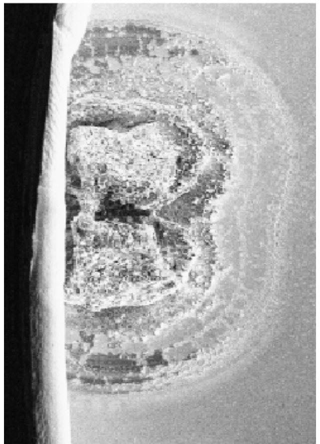
Plasma Spots

Cracking

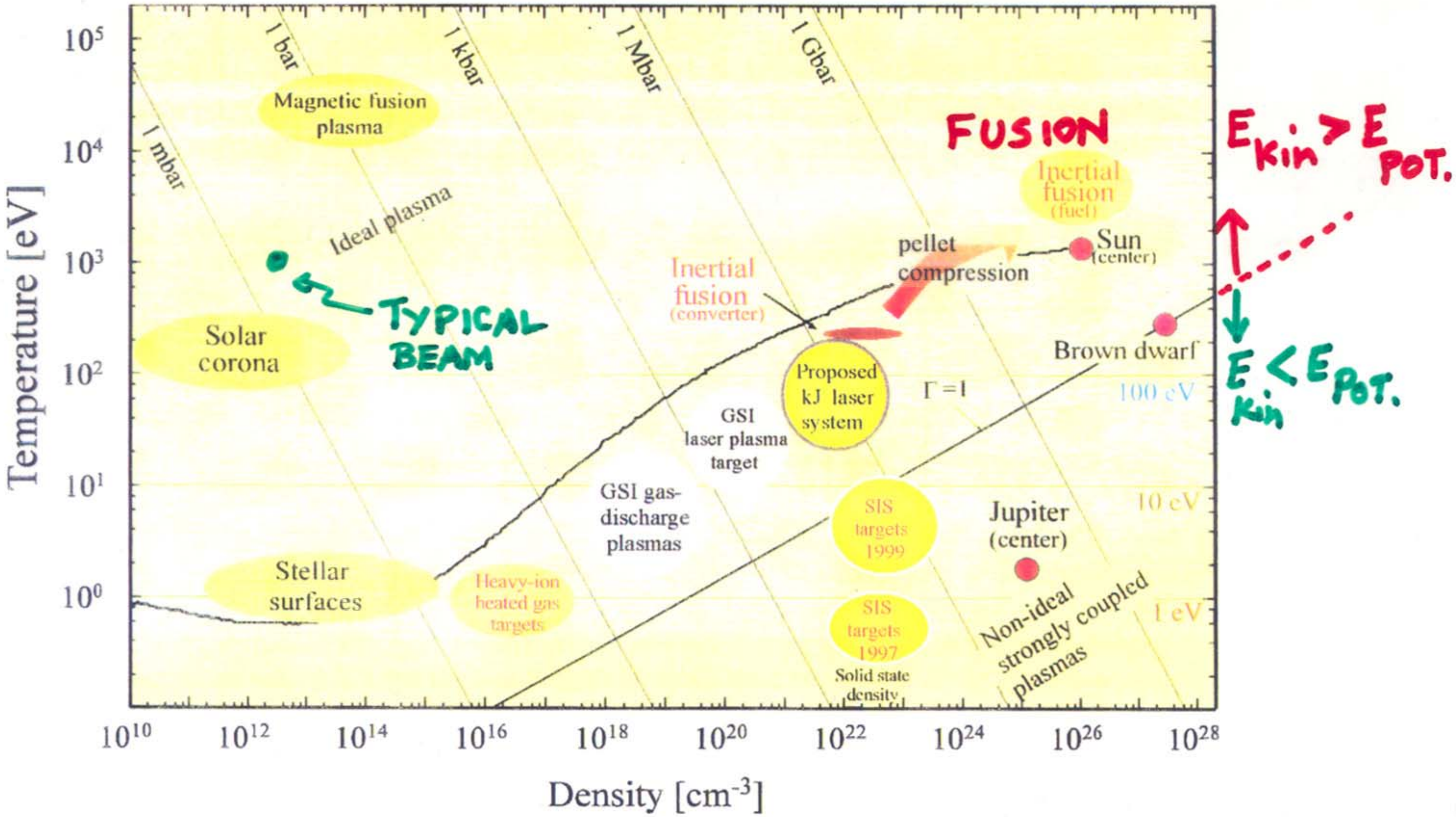
Hot Spots







# States of Matter: Astrophysical & Laboratory Plasmas
# Density and Temperature



Density and temperature diagram of astrophysical and laboratory plasma phenomena. The solid black curve depicts the state diagram of the sun showing the plasma state of its center on the right end. The straight line $\Gamma=E_{pot}/E_{kin}=1$ separates ideal and strongly coupled hydrogen plasmas.

# Beams Under Extreme Conditions

| | | | |
|---|---|---|---|
| E<br>$10^{2} – 10^{6}$ GV/m | $10^{-4}$ eV ↔ 1mm<br>$\tau_{\text{cool}} \sim 10^{-4}$ sec<br>Macroscopic Coulomb Crystal | $\rho \sim 10^{18} - 10^{24}$/cc<br>$\lambda_{\rho}$ = interparticle distance<br>Comparable to solids | $\tau \sim 10^{-18} – 10^{-15}$ second<br>Ultrashort electron and x-ray bursts |
| **Today's Technology:**<br>E<100 MV/m ($10^{-1}$ GV/m) | **Today:**<br>1 eV ↔ 1000 Å<br>$\tau_{\text{cool}} \sim 1$ sec. | **Today:**<br>~ $10^{13} - 10^{14}$/cc | **Today:**<br>$\tau \sim 10^{-14}$ seconds<br>(10 femtoseconds) |
| **DISCOVERY**<br>New Phases of Matter<br>Non-Linear QED<br>Dark Matter<br>Dark Energy | **DISCOVERY**<br>Crystalline Beams<br>Cold Muons<br>Condensate Beams, Fermionic and Bosonic | **DISCOVERY**<br>New Phases of Matter | **DISCOVERY**<br>Ultrafast Dynamics in Condensates and Living Matter |
| **TECHNOLOGY/INNOVATION**<br>• High Intensity Atomic Lasers<br>• Free Electron Accelerators<br>• Laser-Plasma Acceleration | **TECHNOLOGY/INNOVATION**<br>Optical Cooling | **TECHNOLOGY/INNOVATION**<br>High energy-density laser plasma-beam interaction | **TECHNOLOGY/INNOVATION**<br>Optical manipulation of beams |

# ULTRABRIGHT, ULTRAFAST, ULTRACOLD, . . .

--Scientific Possibilities/<u>Discoveries</u>

# Motivation

---

**Scientific Possibilities with :**

Femto- and Atto-second Electron Pulses, X-rays, $\gamma$-rays and FELS
at Extreme High Fields at Extreme Low Temperatures

$10^{-18}$ 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 bright ultrashort pulses with particles/atoms/molecules/bulk matter at the Quantum Limit of

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

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MANCHESTER
1824
The University of Manchester

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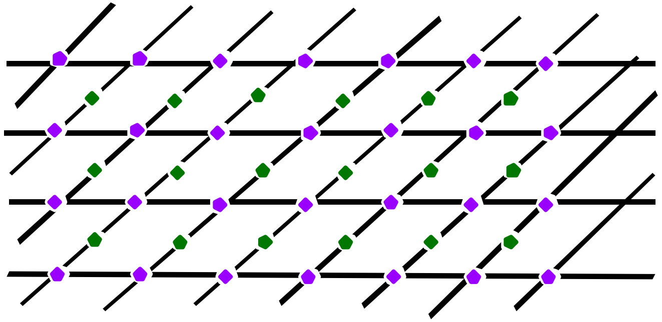
# Phonon Dynamics on a Surface



CONDENSED
MATTER
PHYSICS

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

$$h\nu \approx kT$$

Phonons → $h\nu$

Thermal Bath → $kT$

Lattice relaxation time :

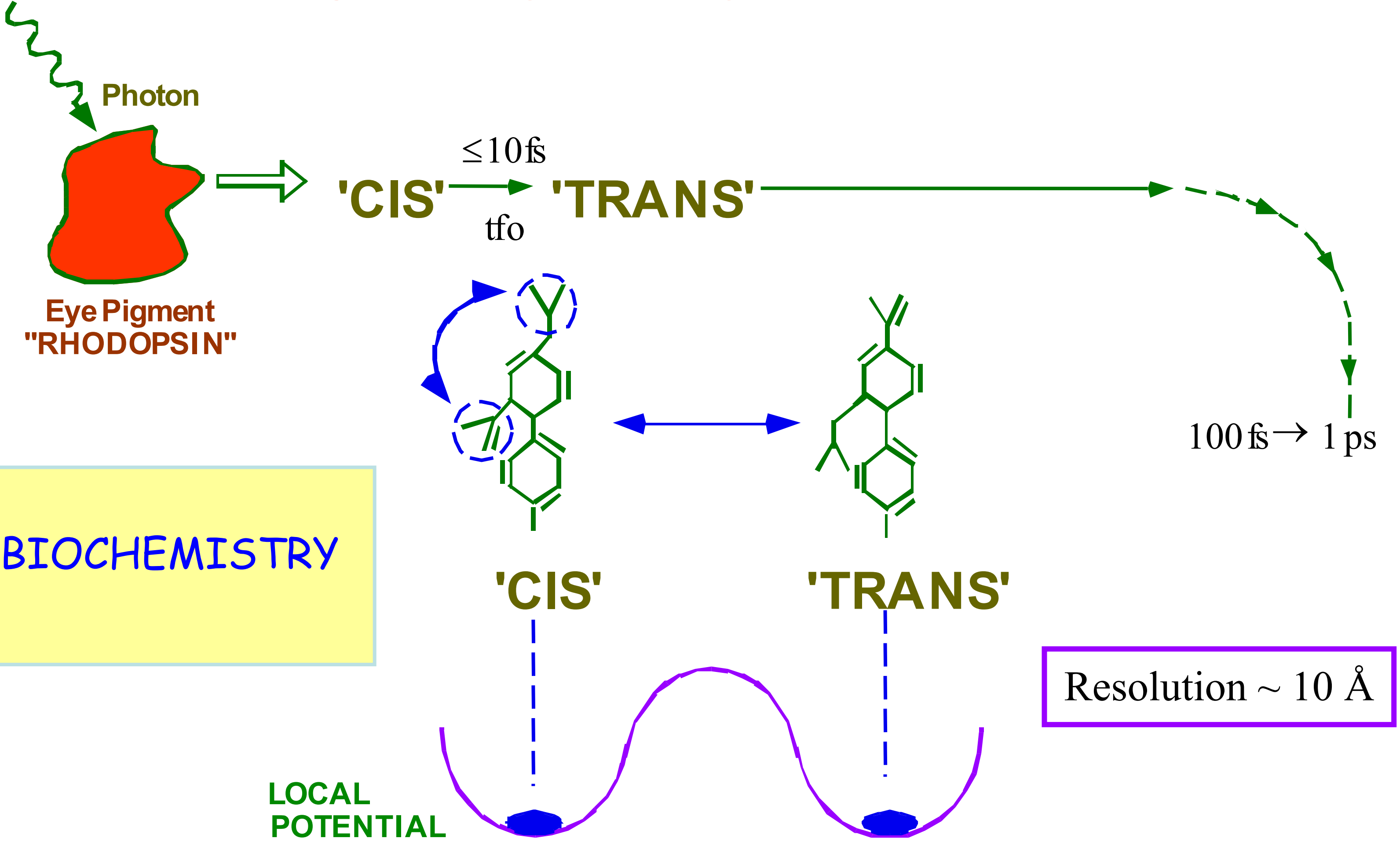
$\boxed{\tau = \nu^{-1} = h/kT}$ ~ 100 fs @ room temp.

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

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

# Primary Event in “Vision”

## Ultrafast Coherent Chemical Reactions



Photon

Eye Pigment
"RHODOPSIN"

'CIS' $\xrightarrow[\text{tfo}]{\leq 10\,\text{fs}}$ 'TRANS'

100 fs → 1 ps

'CIS' ↔ 'TRANS'

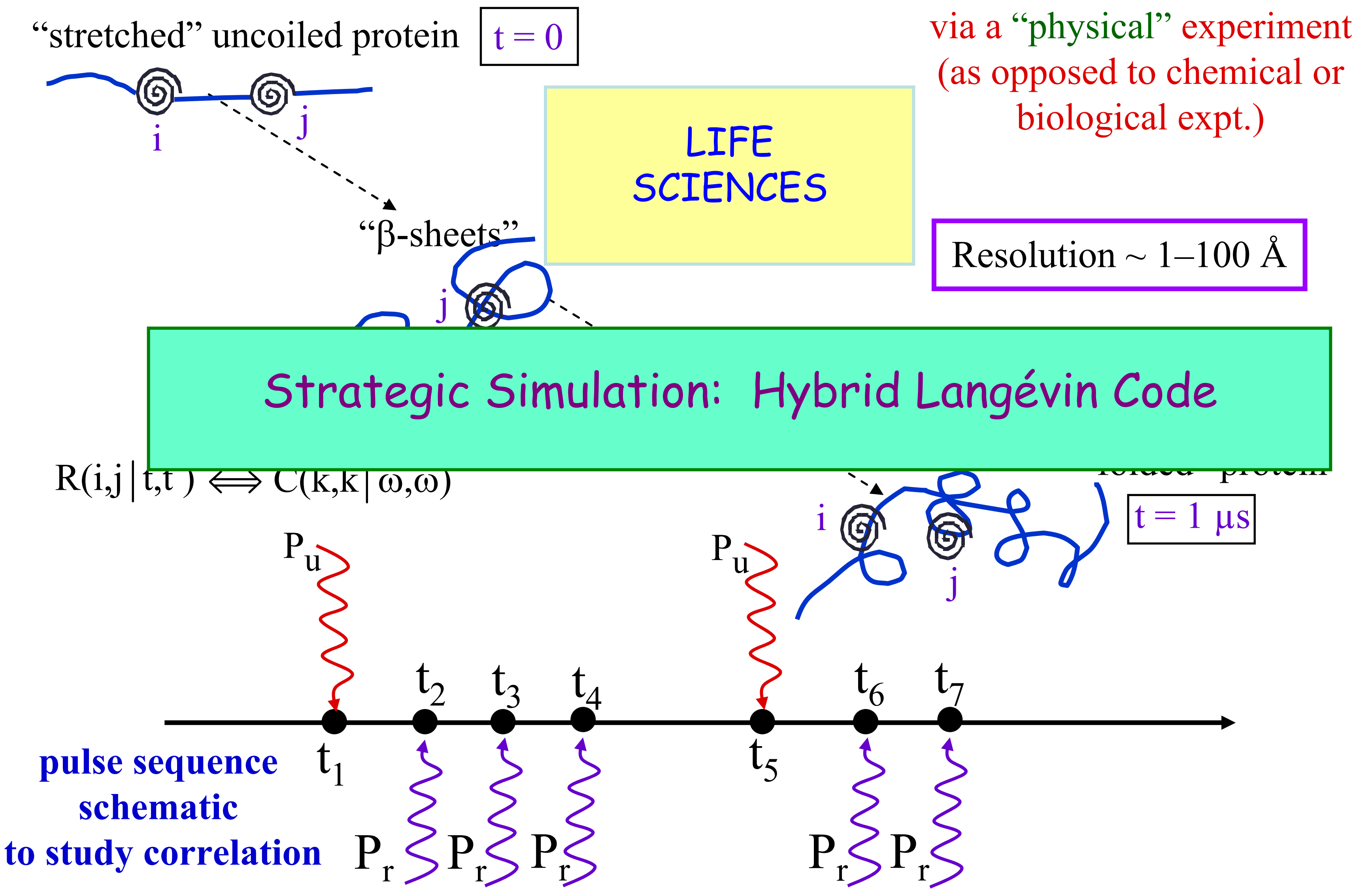
LOCAL
POTENTIAL
WELL

BIOCHEMISTRY

Resolution ~ 10 Å

SLIGHTEST CHANGE IN "STRUCTURE" LEADS TO LARGE CHANGES IN "FUNCTION"

# 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

$t = 1\ \mu s$

**pulse sequence
schematic
to study correlation**

# 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 - Bean

ERMI - Beam

lowest possible temperature

N

**Strategic Simulation: Molecular Dynamics Code**

Quantum relaxation time $\simeq 10^{-17}$sec

Quantum diffraction-limited volume in phase-space :

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

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

Quantum diffraction-limited volume in phase-space :

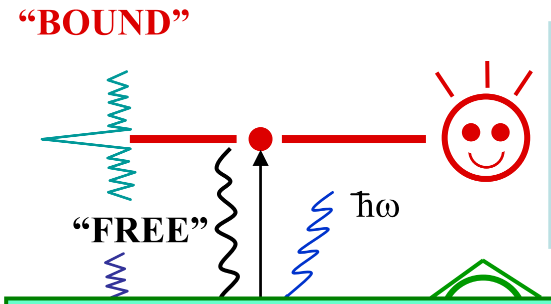
$$\boxed{\varepsilon_x^{(n)}\ \varepsilon_y^{(n)}\ \varepsilon_z^{(n)} \gtrsim \frac{N(\bar{\lambda}_c/2)^3}{(2S+1)}}$$

($S \equiv$ spin of the Fermions)

# STUDY OF

# The Dynamics of Quantum Collapse & Entanglement via Attosecond Bursts

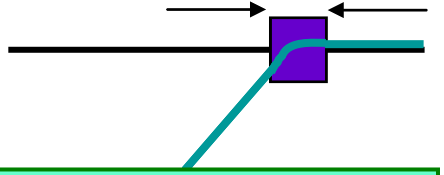
**Although we are comfortable with quantum physics, we still have a hard time with "quantum control". No understanding is complete until one can engineer simple systems.**



ATOMIC
PHYSICS

wave-function collapse

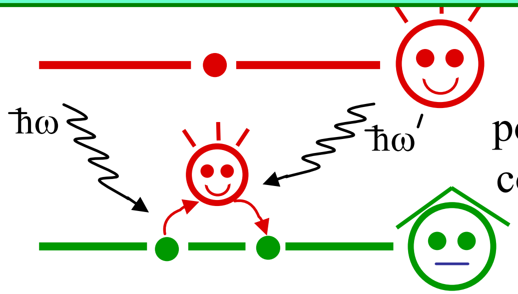
$10^{-17}$ - $10^{-18}$ s



Strategic Simulation: Many-Body Hartree-Fock Code

disentanglement

$10^{-17}$ - $10^{-18}$ s



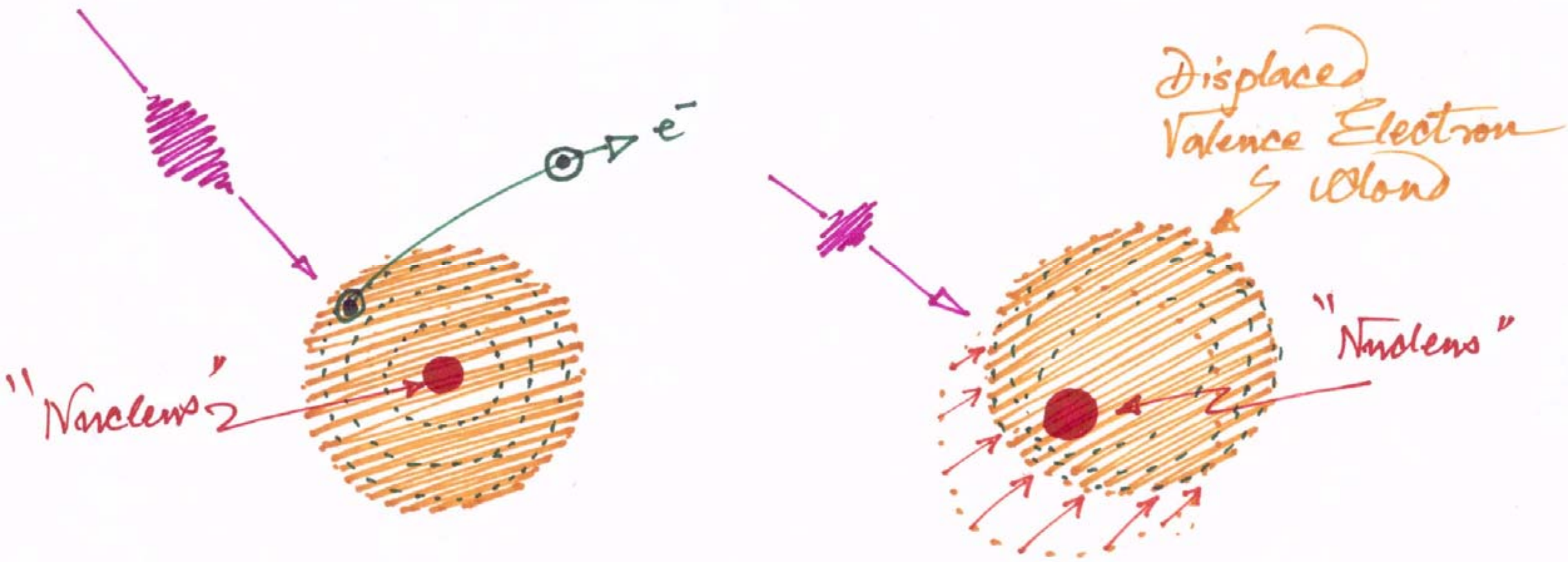
possibility of quantum control & engineering

Resolution ~ Å

# Incoherent vs. Coherent Ionization

"Incoherent" Ionization

"Coherent" Ionization

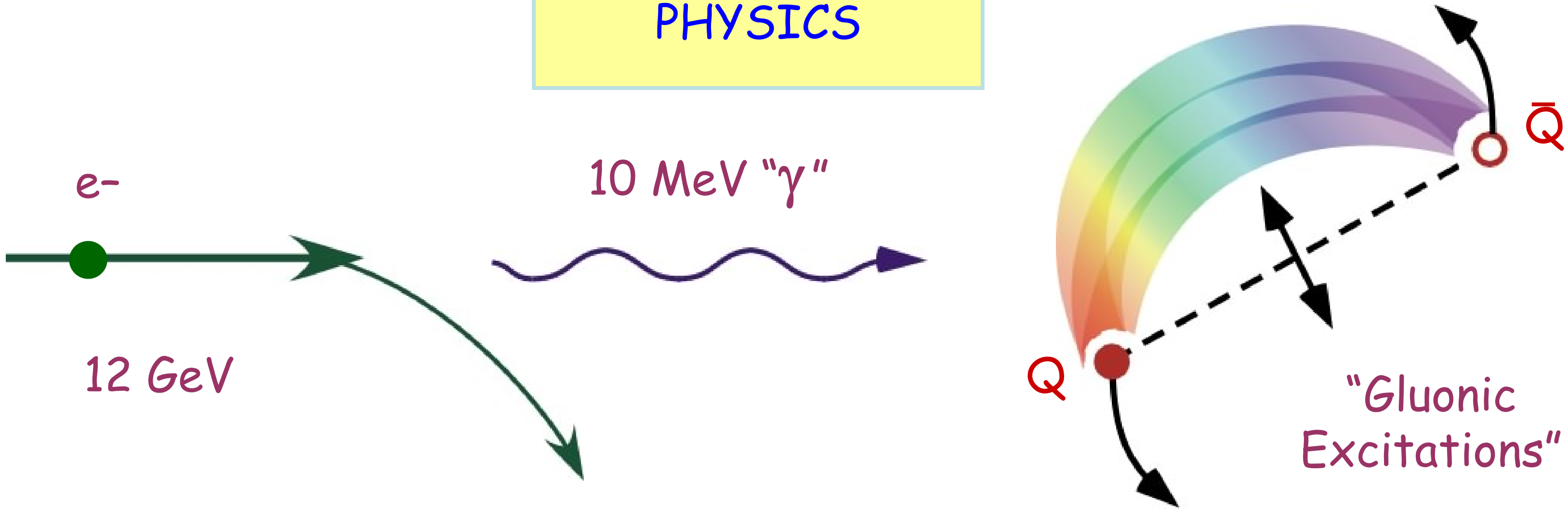


Long Pulse leading to ejection of single valence electrons

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

# Color Mapping in QCD

NUCLEAR
PARTICLE
PHYSICS

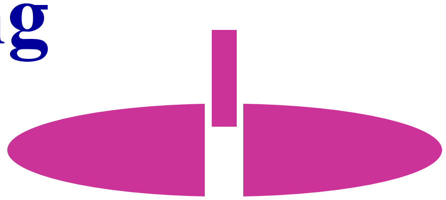


Strategic Simulation: Lattice-gauge QCD Code

# ULTRASHORT PULSES
## -- Innovation and Generation Mechanisms

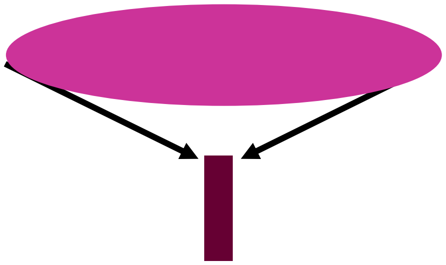
# Thomson/Compton Scattering

## Laser-assisted atto-slicing:



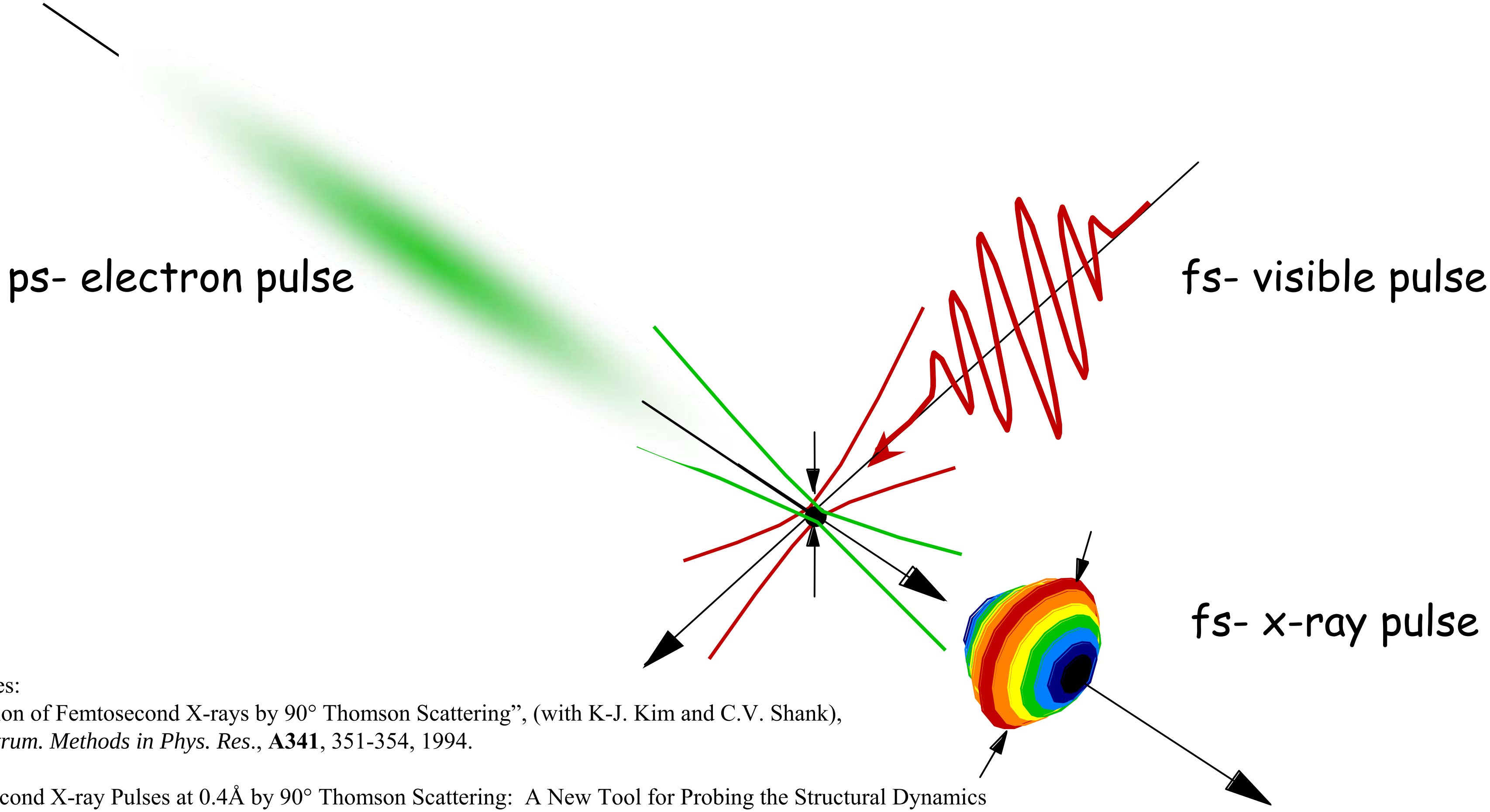
- Possibilities with a storage ring or a stand-alone linac

## Laser-assisted atto-bunching:



- Laser-plasma acceleration
- Ponderomotive acceleration

# Thomson Scattering for Femtosecond X-rays

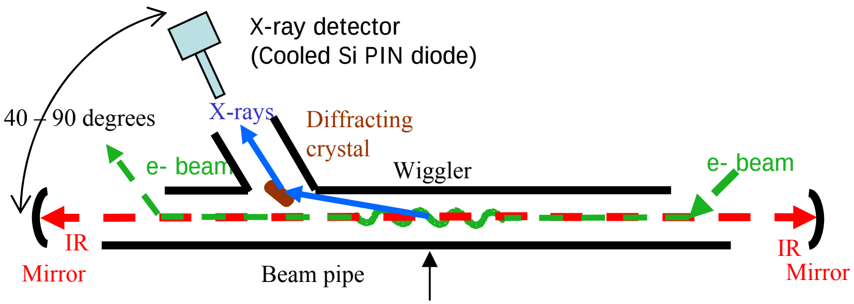


References:
“Generation of Femtosecond X-rays by 90° Thomson Scattering”, (with K-J. Kim and C.V. Shank), *Nucl. Instrum. Methods in Phys. Res*., **A341**, 351-354, 1994.

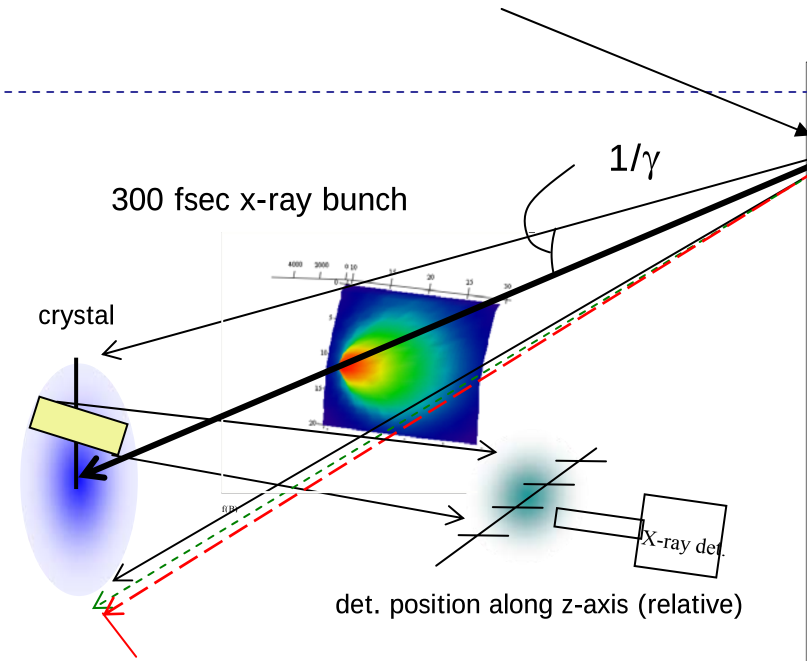
“Femtosecond X-ray Pulses at 0.4Å by 90° Thomson Scattering: A New Tool for Probing the Structural Dynamics of Materials”, (with R. Schoenlein, et. al), *Science*, **274**, 11 Oct. 1996, p. 236.

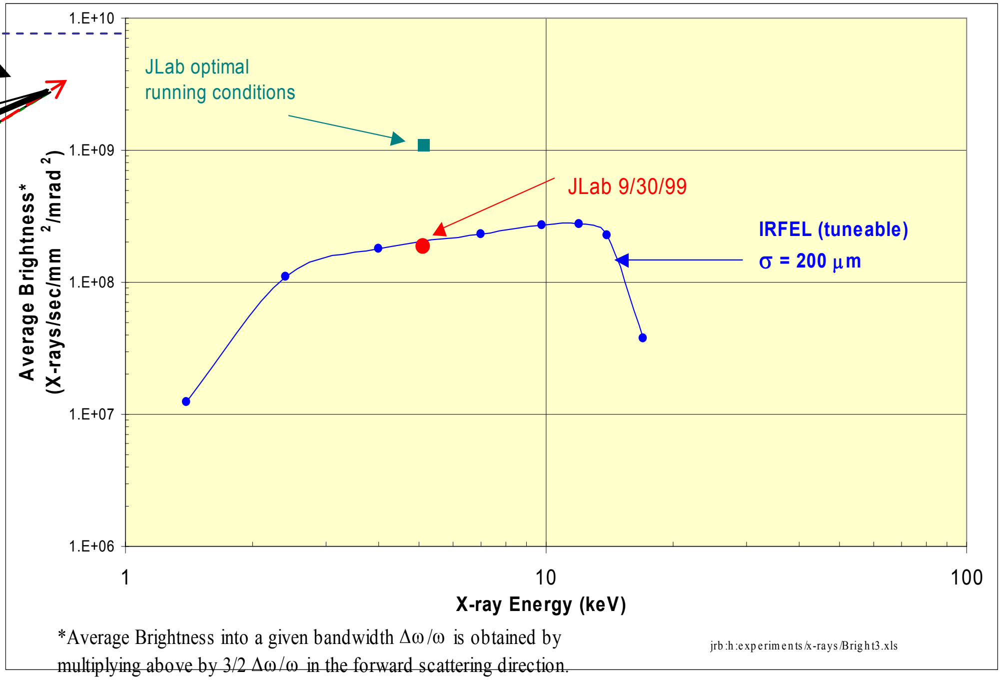
“X-ray based Sub-Picosecond Electron Bunch Characterization using 90° Thomson Scattering”, (with W. Leemans, et al), *PRL*, Vol. **77**, page 4182, 1996.

# X-rays from IR DEMO at Jefferson Lab



Thomson backscatter





*Average Brightness into a given bandwidth Δω/ω is obtained by multiplying above by 3/2 Δω/ω in the forward scattering direction.

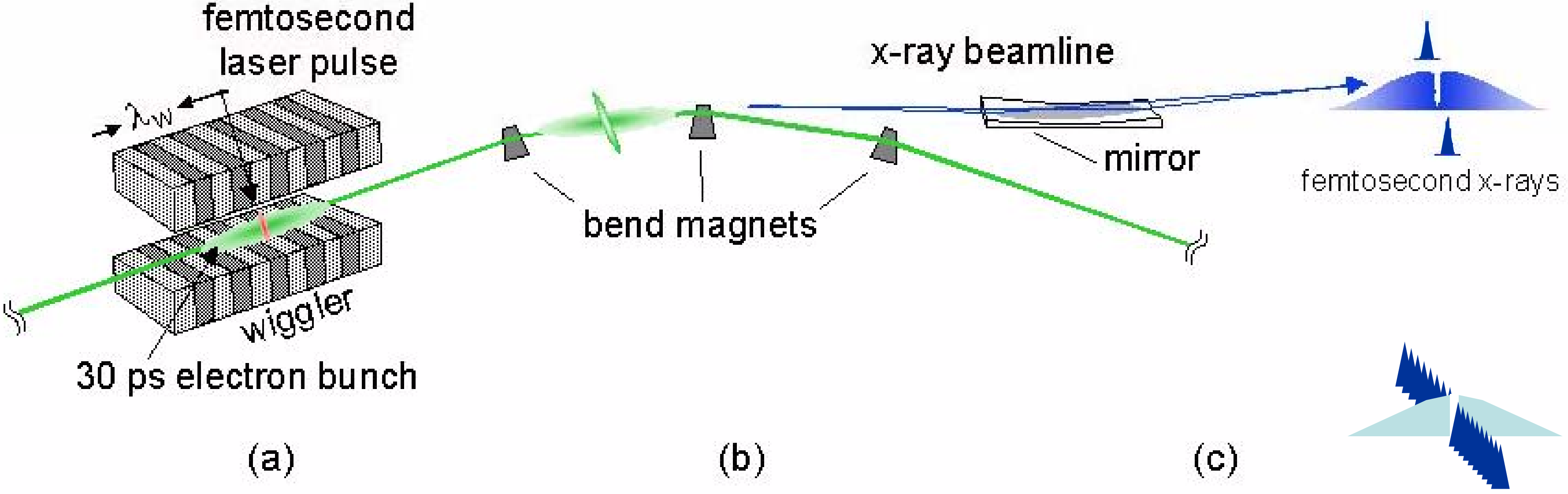
jrb:h:experiments/x-rays/Bright3.xls

## 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.

# Laser Femto-slicing of Electron Beams

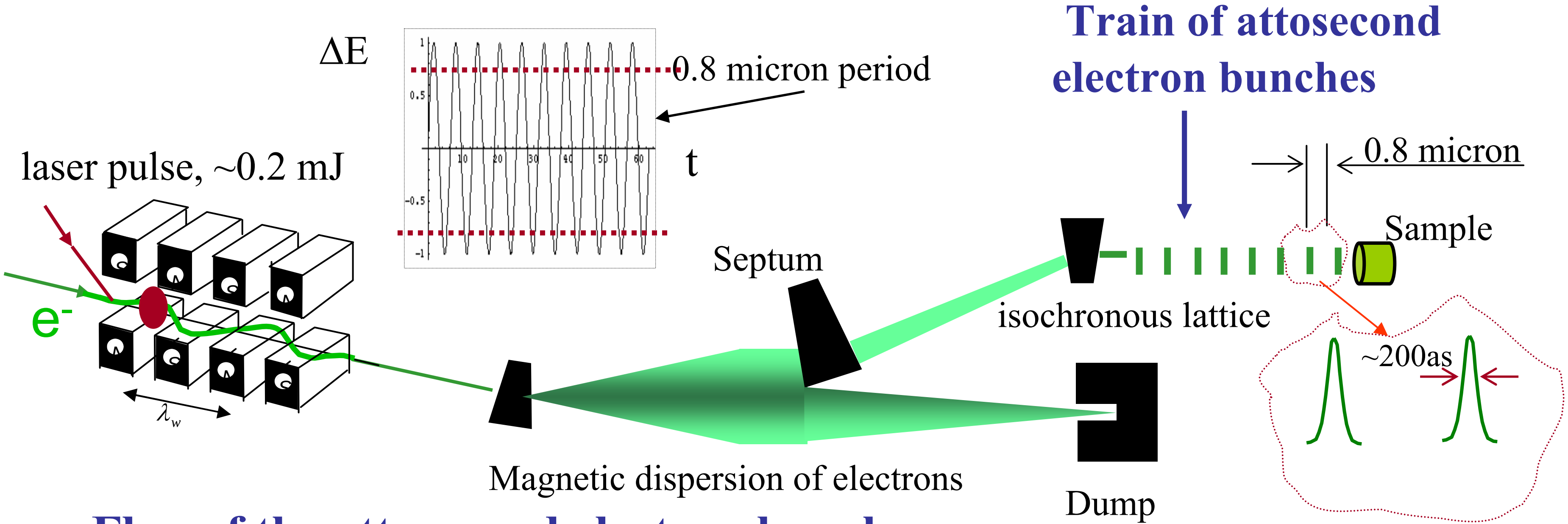


Reference:
*Generation of Femtosecond Pulses of Synchrotron Radiation*
R. Schoenlein, S. Chattopadhyay, H.H.W. Chong, T.E. Glover,
P.A. Heimann, C.V. Shank, A.A. Zholents, M.S. Zolotorev
Science, Vol. 287, No. 5461, March 24, 2000, p. 2237.

→ **Unique experiment in the world**

→ **Optical Manipulation of Beams**

# Atto-Slicing: Laser Slicing Technique



Train of attosecond electron bunches

ΔE

0.8 micron period

t

laser pulse, ~0.2 mJ

$e^-$

$\lambda_w$

Septum

isochronous lattice

0.8 micron

Sample

~200as

Magnetic dispersion of electrons

Dump

**Flux of the attosecond electron bunches:**
**train of ~100 bunches, ~$10^6$ 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.**

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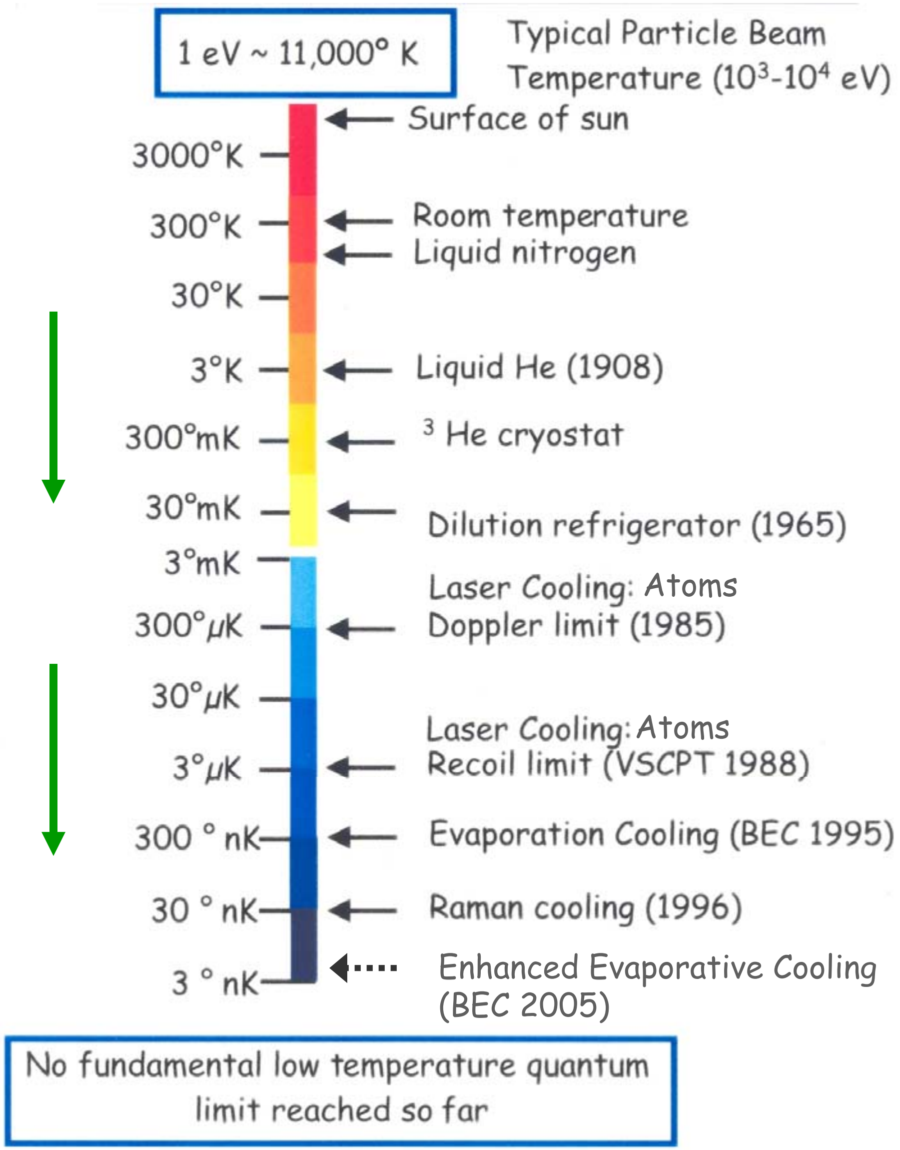
# ULTRACOLD BEAMS
## -- Innovation/Mechanisms

## PHASE-SPACE COOLING:
### Particles and Photons

# Low Temperature

Temperature Scales

Optical Cooling of Electrons/charged Particle Beams?

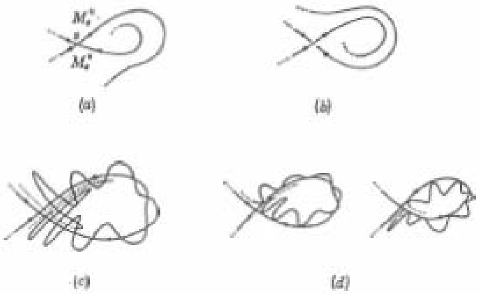


# Dynamical Phase-Space of a Particle

Henri Poincaré

**Geometry and Topology of Phase Space, 1880's, France**

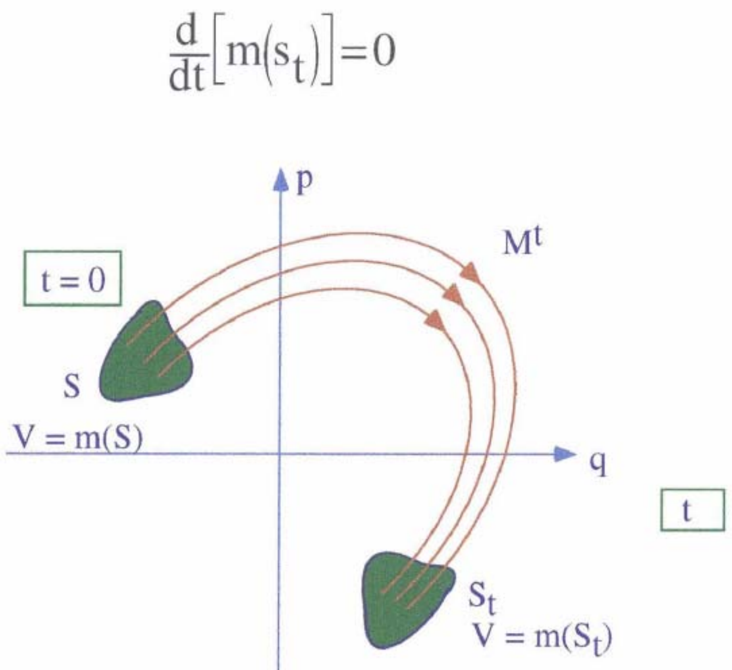
Poincaré looked at Phase-Space as full of geometrical and topological structures



# Flow in Phase Space

Joseph Liouville

**Phase Space Conservation, 1837 and**
**Non-conservation, 1838, France, with Dissipative Forces**



**Hamiltonian Mapping Generating Incompressible Liouvillian Flow in Phase-Space**

To Liouville, it was all a SMOOTH FLOW, nothing violent happening anywhere except for gentle deformations: in fact, phase space volume (measure) is conserved for non-dissipative systems.

# Charged Particle Beam Cooling

Simon van der Meer

**Stochastic Cooling, 1968,**

**CERN, Geneva, Switzerland:**

***introduced 'virtual' dissipation via a Maxwell's Demon!***

Gersh I. Budker

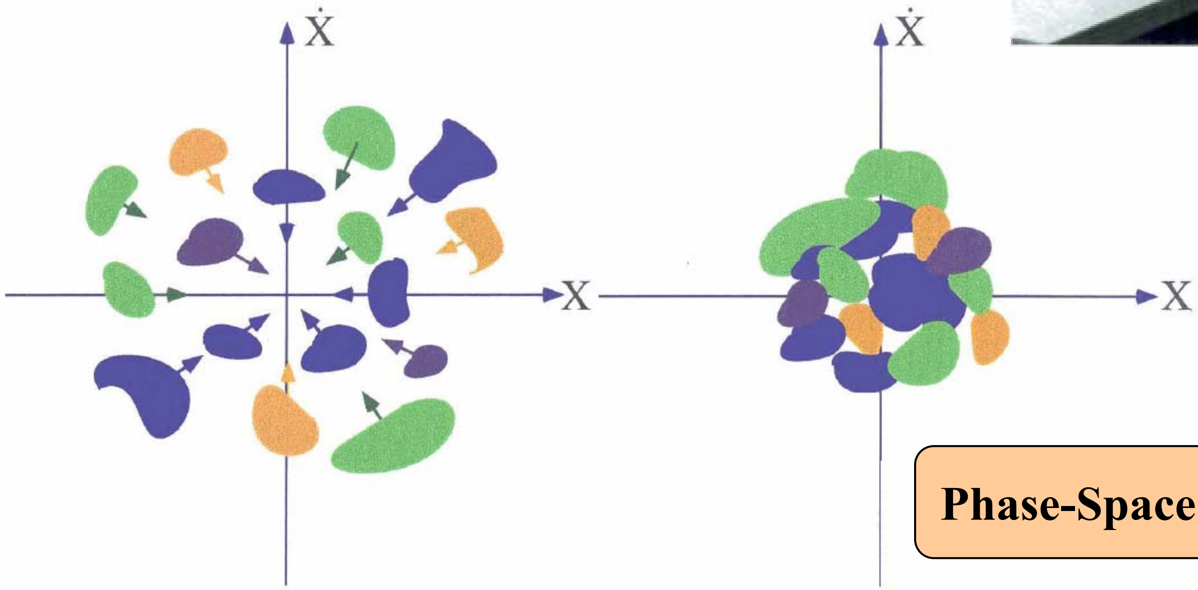
**Electron Cooling, 1978**

**Novosibirsk, Russia:**

***introduced dissipation through Collisional Relaxation***

# Stochastic Cooling

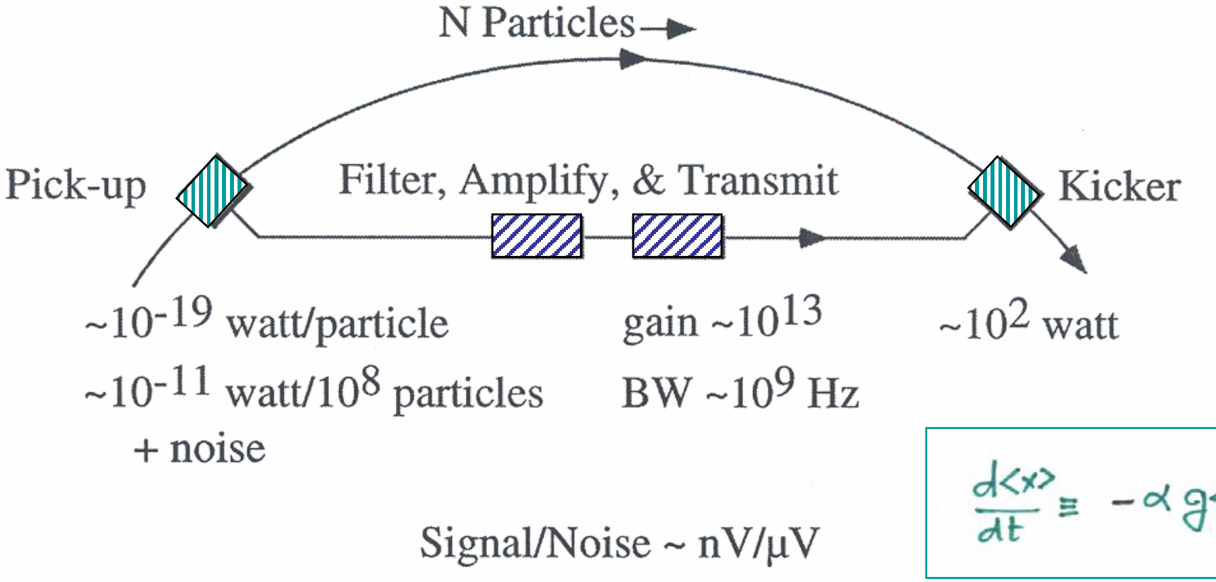
To van der Meer, phase space is mostly empty and where particles live, they cluster together leaving space in between ⟶ Possibility of employing a MAXWELL'S DEMON to herd them into a tight bunch, if only one could see the phase space clutter!



**Phase-Space Cooling in Any One Dimension**

# 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



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

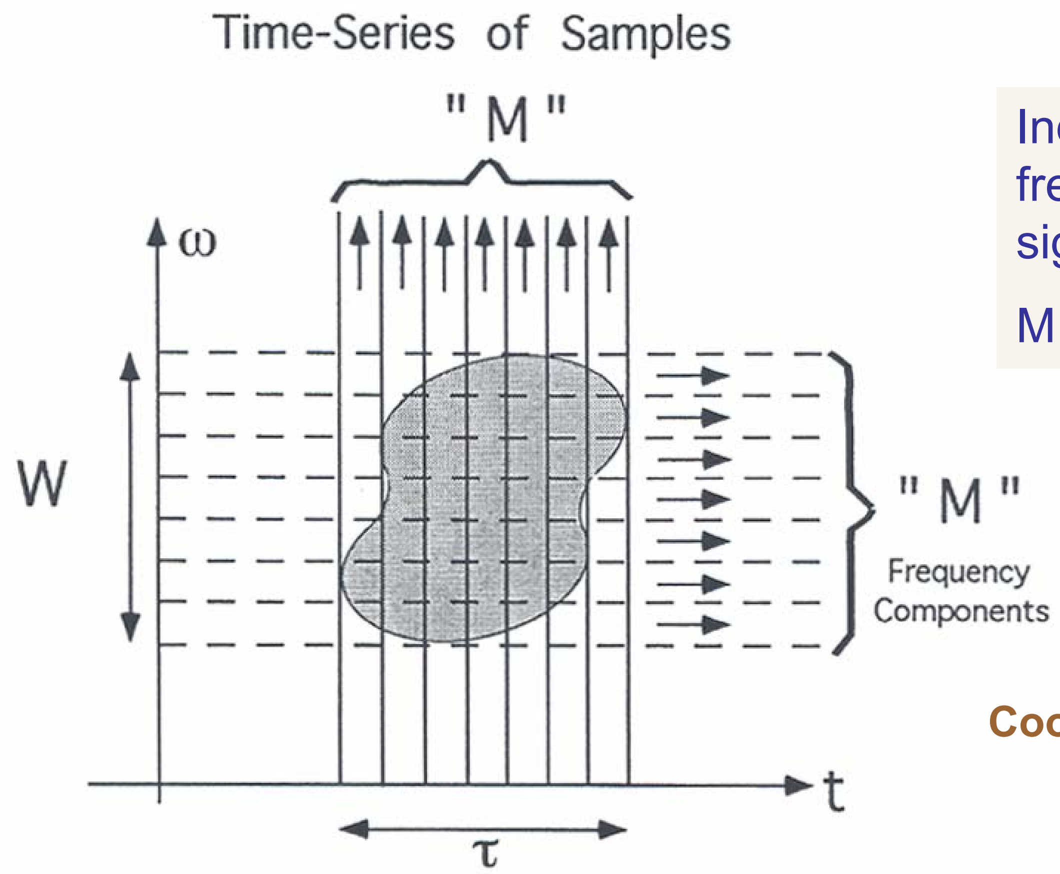
**Microwave Stochastic Beam Cooling**

- Discovery of "W&Z Bosons": Cold "Antiprotons": $p\bar{p} \rightarrow W^{\pm} + X$ (CERN 1983)

  $\rightarrow Z^0 + Y$
- Anti-Hydrogen: $\bar{p} + e^+ \rightarrow \bar{H}$ (CERN 2002)

  Cold "Antiprotons"

# Information Processing in Two-Dimensional Fluctuation Signals



Independent degrees of freedom of fluctuation signal,

M = 2W · t

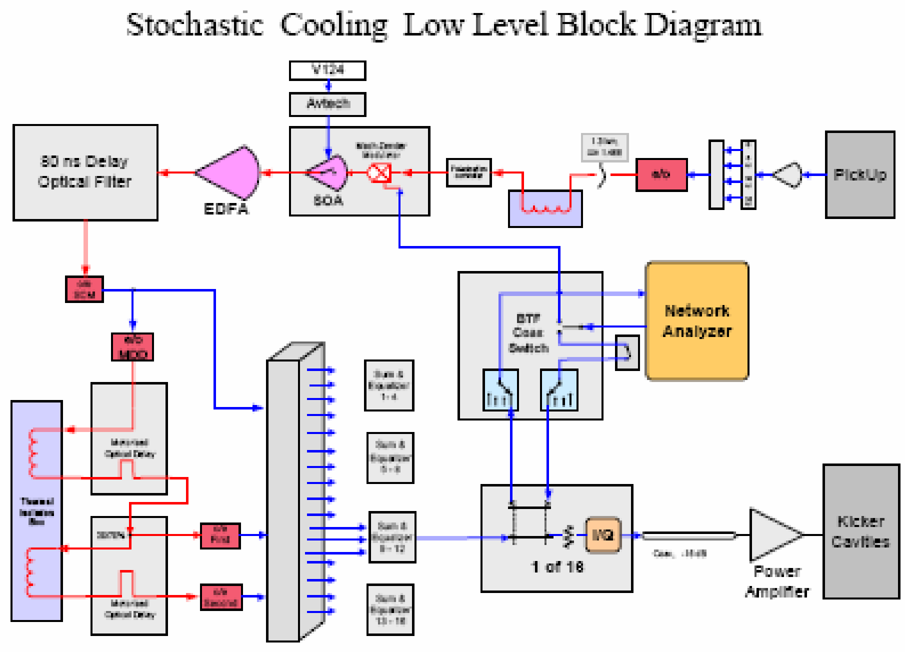
(Nyquist Criterion)

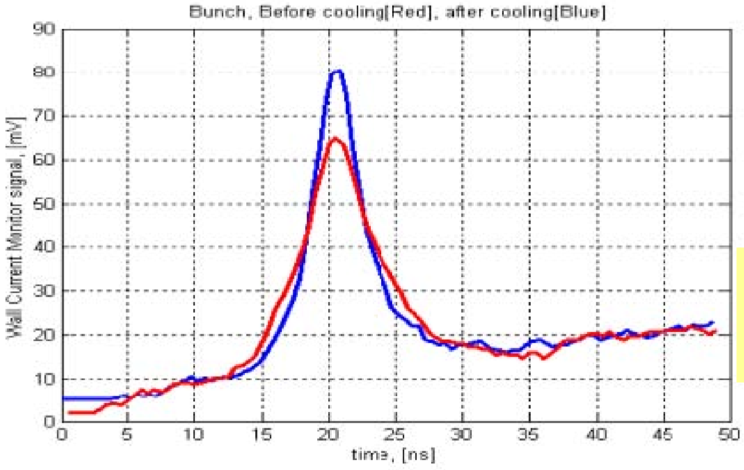
**Cooling rate is proportional to "M".**

**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.**

# Wide-band Cooling Feedback Loop Electronics for Bunched Gold Beams in RHIC (Relativistic Heavy Ion Collider) at BNL

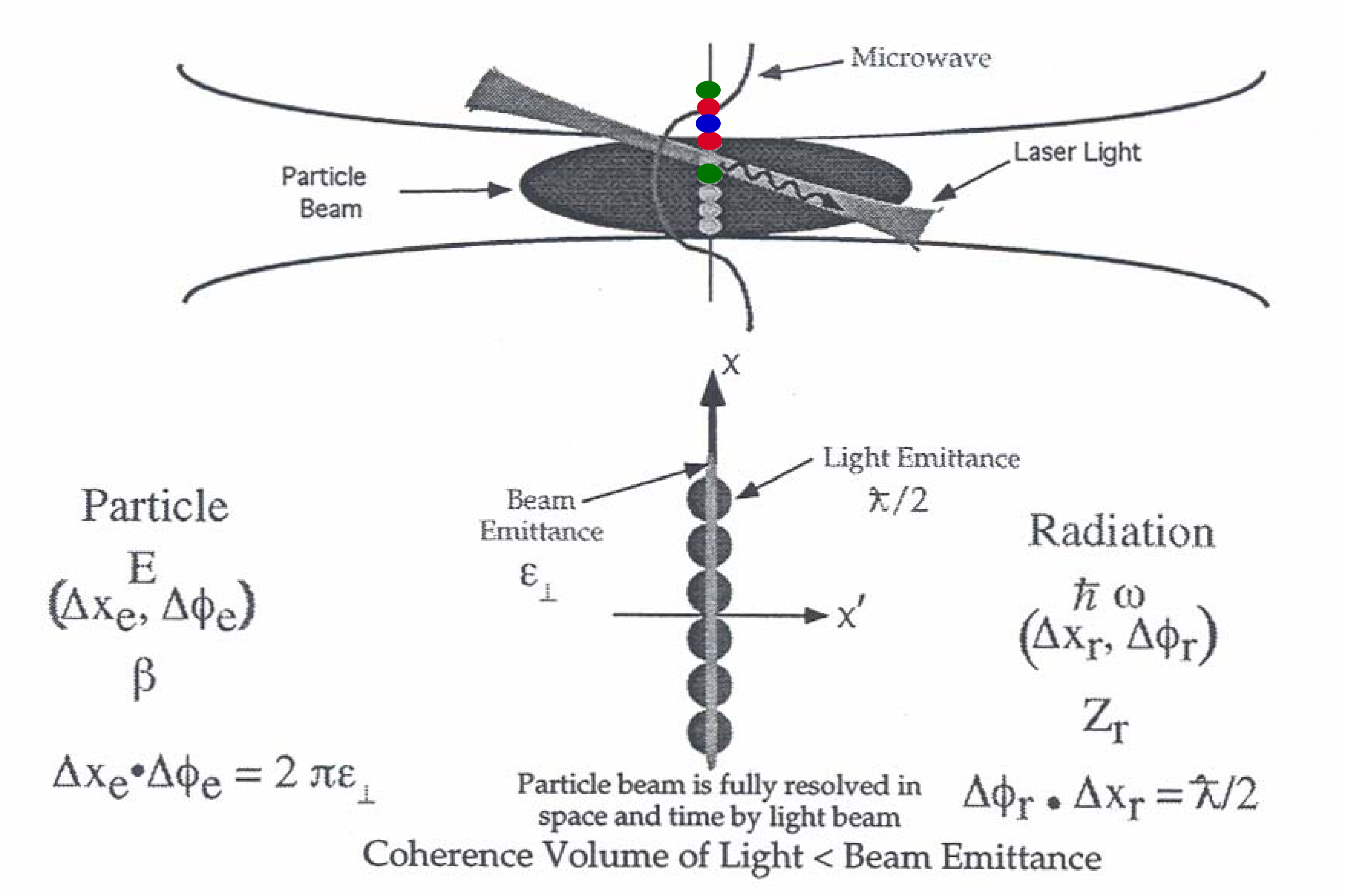

Stochastic Cooling Low Level Block Diagram


Bunch, Before cooling[Red], after cooling[Blue]

Test bunch, before (red) and after (blue) cooling.

# Optical Sampling of Charged Particle Beam

Optical Coherence Volume $<<$ Beam Emittance



Particle beam is fully resolved in space and time by light beam

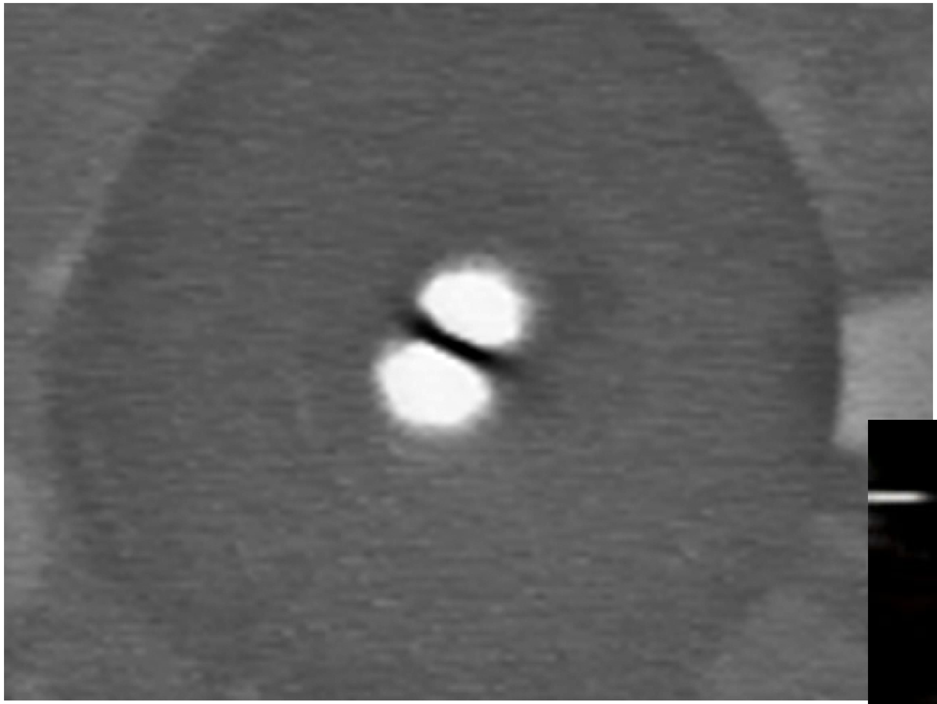
Coherence Volume of Light < Beam Emittance

**Transverse Sampling of Particle Beams by Radiation Beam**

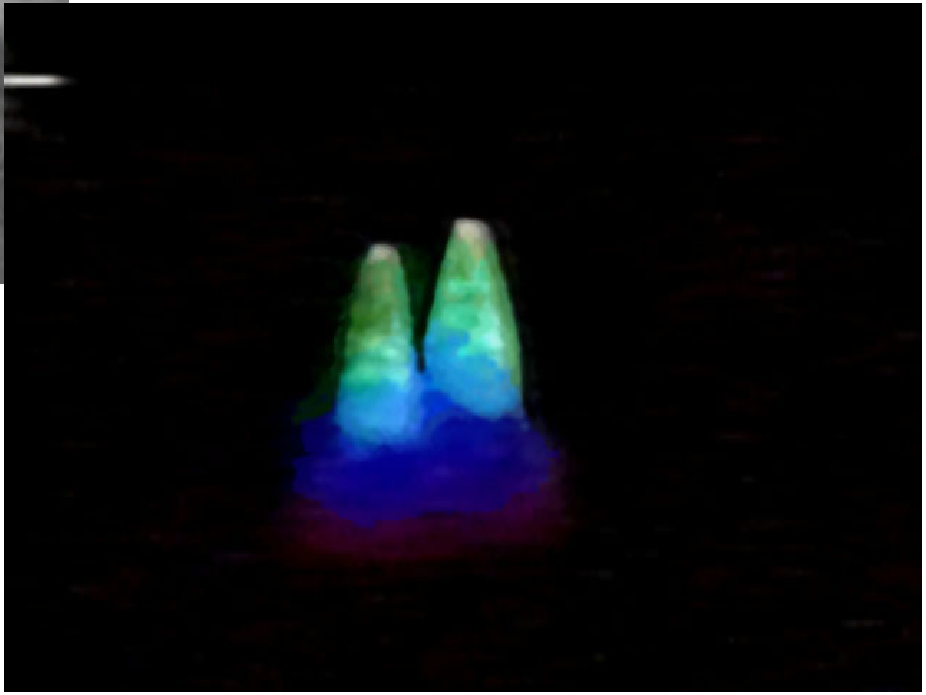
# Second Harmonic Lasing at JLab FEL

resolves transverse beam at “micron” resolution

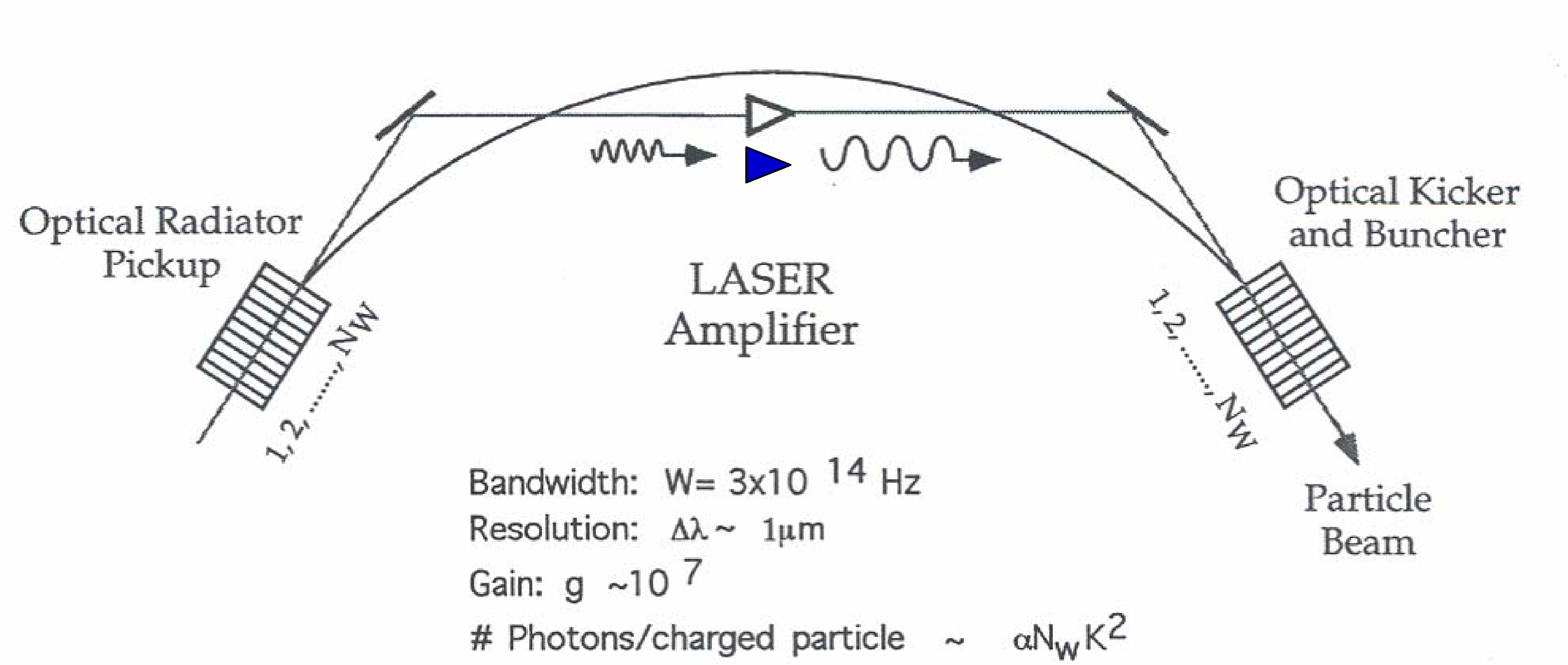
- **2.925 microns, 0.6 micron detuning width**
- **4.5 W average power**



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



# Optical Cooling
# (Mikhailichenko, Zholents, Zolotorev et al.)



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

**Optical Stochastic Cooling**

# Can we do better?

- Can we tame particles as well as we tame light in lasers so we can map the phase-space of a particle beam within a light beam?

- What is the Reward?
  - **A compact Coherent X-ray Source**
  - **Compact Laser-Plasma Injectors for High Luminosity Colliders**

# Compact Coherent SASE X-Ray FEL using a Laser Wiggler

FEL x-ray wavelength

$$\lambda_x = \frac{\lambda_w}{4\gamma^2}(1 + a^2)$$

Inverse gain length

$$\frac{1}{N_g} \approx \frac{2\pi}{1+\varepsilon_b / \varepsilon_x} \sqrt{\frac{1}{2\gamma} \frac{I}{I_A} \frac{a^2}{1+a^2}}$$

Electron beam parameters

$N_e = 10^6$, $c\tau_e = 10^{-8}$ m, $\varepsilon_{nb} = 10^{-8}$ mrad

**(≡ 30 attoseconds)**

Transverse coherence requirement

$\varepsilon_b / \varepsilon_x < 10$

---

**SASE $E_x$=10 keV**

**THz source ($\lambda_w$=100 μm)**

**$\gamma$ = 500 (250 MeV)**

**$E_w$=20 J**

**$N_X = 6\text{x}10^8$**

Possible in 4GLS!!

## Examples

**SASE $E_x$=1 keV**

**Ti laser ($\lambda_w$= 0.8 μm)**

**$\gamma$ = 13 (6.5 MeV)**

**$E_w$=30 mJ**

**$N_X = 2\text{x}10^8$**

Possible on Table-top

# Single Electron Quantum Diffraction Limit

- Ideal optics:

$$d_g = d_v / M^{-1}$$

where Beam Diameter is the virtual source size *d*v and *M* -1 is the demagnification of the column

- Spherical aberrations:

$$d_s = 1/2 C_s a^3$$

where $C_s$ is the spherical aberration coefficient of the final lens and *a* is the convergence half-angle of the beam at the target

- Chromatic aberrations:

$$d_c = C_c \, a \, \mathrm{D}V / V_b$$

where $C_c$ is the chromatic aberration coefficient, D*V* is the energy spread of the electrons, and $V_b$ is the beam voltage

- Quantum mechanics:

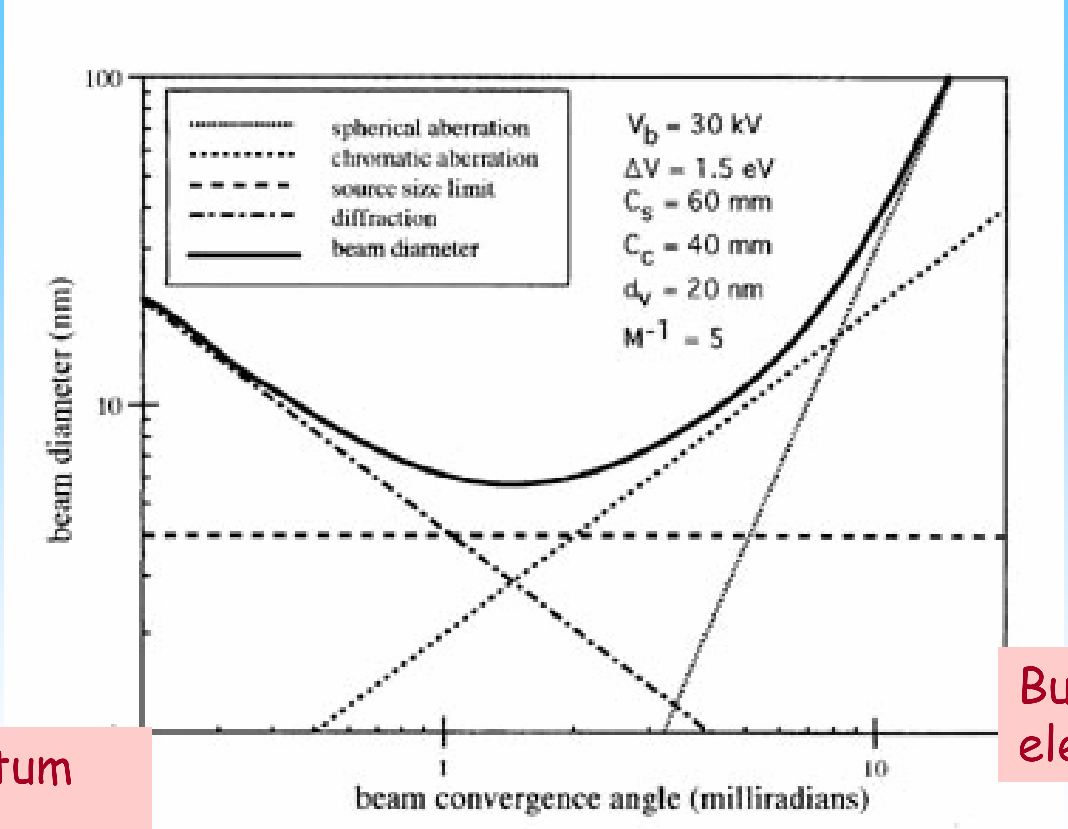
$$d_d = 0.6 \, L / a$$

electron wavelength $L = 1.2/(V_b)^{1/2}$ nm, although much smaller than the wavelength of light (0.008 nm at 25 kV), this wavelength can still limit the beam diameter by classical diffraction effects in very high resolution systems

To determine the theoretical beam size of a system, the contributions from various sources can be added in quadrature:

$$d = (d_g^2 + d_s^2 + d_c^2 + d_d^2)^{1/2}$$

# Pure Single Particle Optics: Classical and Quantum



Could reach Quantum Diffraction Limit . . .

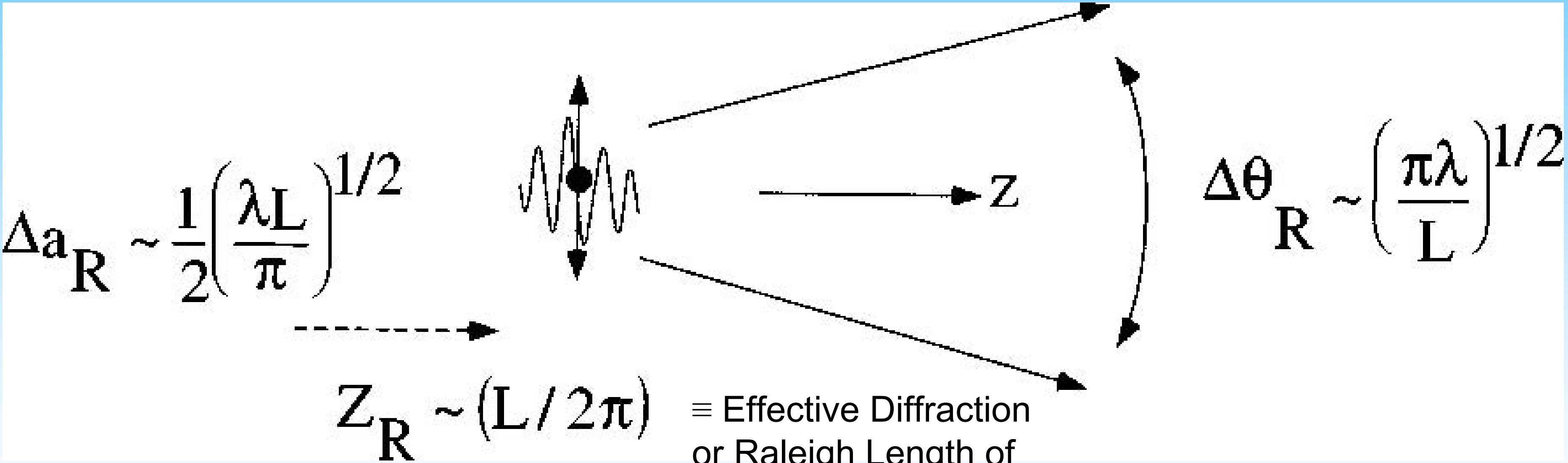
But not if the electron radiates!!!

**A plot showing resolution as a function of beam convergence angle for an electron beam column at 30 kV. The plot assumes an energy spread of 1.5 eV, a source diameter of 20 nm, and a fixed demagnification of 5.**

# Phase Space of a single oscillating electron is already comparable to the phase space of radiation

External Radiation pulse of length L, wavelength $\lambda_o$

Radiated wavelength: $\lambda \sim \lambda_o / 2\gamma^2$



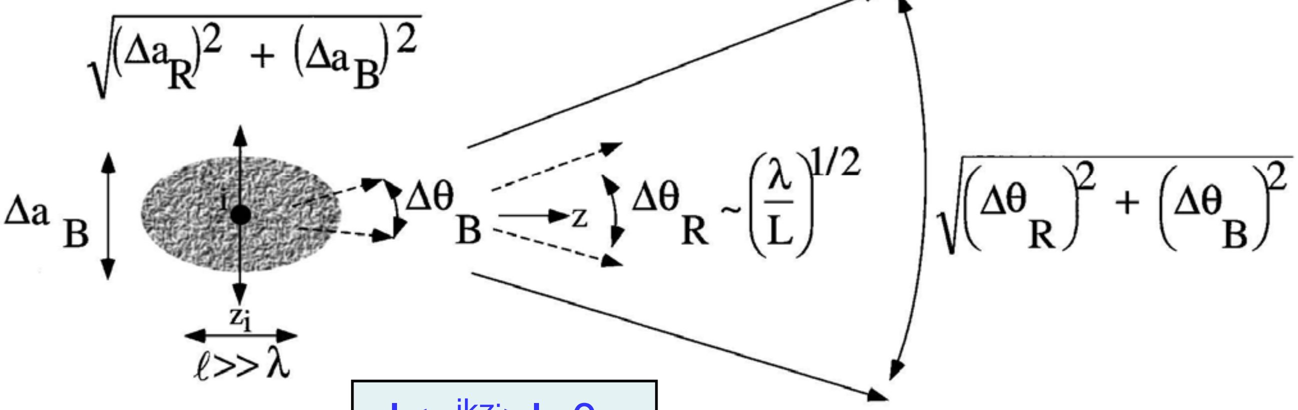
≡ Effective Diffraction or Raleigh Length of Scattered Light

**COHERENCE VOLUME:**

$\Gamma = \Delta a_R \cdot \Delta\theta_R \sim \lambda/2$

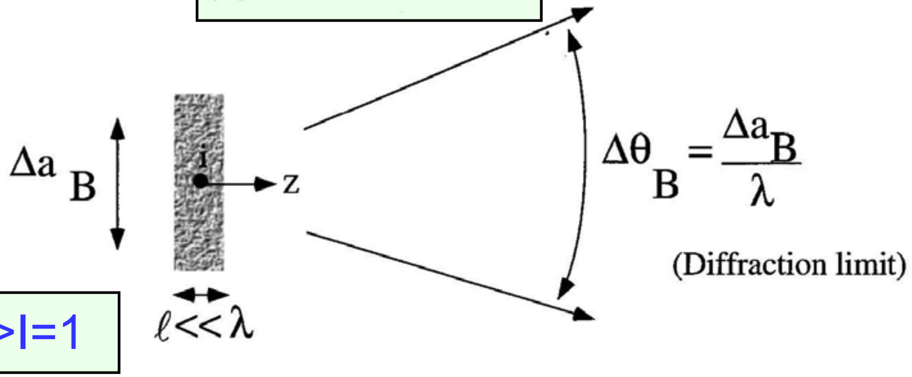
# Taming the Unruly . . . Herding Cats
# Phase Space of Radiation from a Beam

(a) Unbunched beam



$|\langle e^{ikz_i}\rangle| = 0$

(b) Bunched beam



$|\langle e^{ikz_i}\rangle| = 1$

**Diffraction-limited COHERENCE VOLUME:**

$$\Gamma = \Delta a_B \cdot A\theta_B = \frac{\Delta a_B{}^2}{\lambda} \sim \lambda$$

if $\Delta a_B \sim \lambda$

# Intensity-dependent Collective Effects

- High brightness beams of today's accelerators, synchrotron radiation sources, and free electron lasers are dominated by "collective" Coulomb-space charge as well as collisional effects, in addition to single particle classical and quantum optics.

- Typical high-brightness electron beam in today's applications:

Total Charge: $Q \sim 1$ nC **(x $10^{-5}$)**

Normalized: $\varepsilon_\perp \sim 1$ $\text{mm-m}_{\text{rad}} = 10^{-6}$ meter **(x $10^{-2}$)**

**Correlated:**

Transverse Emittances:

**CHALLENGE!!**

**ACHIEVABLE**

Relative Energy Spread: $\frac{\Delta E}{E} \sim 10^{-4}$

Pulse Length: $\tau \sim 200$ fs to 10 ps **(x $10^{-5}$)**

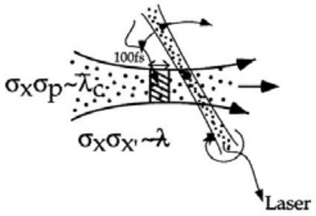
Transverse Size: $r \sim 10\text{-}50$ μm

(can be focused to few nm at high energies such as at the ILC)

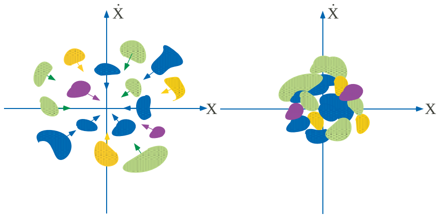
# Innovations in Energy and Quality Control between Particles and Light are Key to Future Discoveries

**Quality Control**

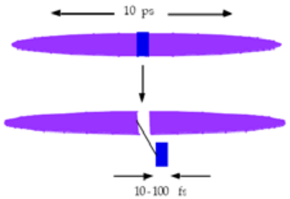
Phase-Space Mapping between Particles and Light



Phase-Space Compression

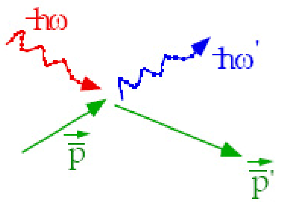


Phase-Space Slicing

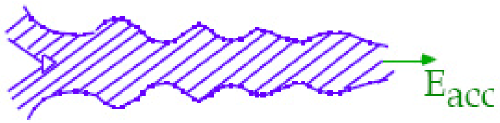


**Energy Control**

Energy Mapping between Particles and Light

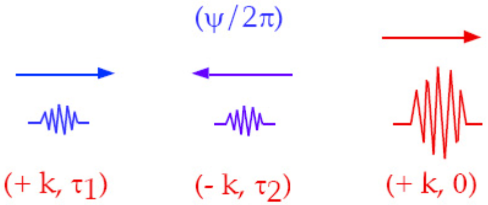


Energy Compression Focusing and Guiding



**Energy and Quality Matching Between Particles and Light**

Energy Mapping between Particles and Light



from Reader's Digest

# Don't Bet on It

AT THE END of every December, when Father Time's odometer is ready to click in another year, experts seem compelled to forecast what the coming year will bring. Economists read their econometric entrails and predict hard times or happy days accordingly; psychics announce that this is the year the San Andreas fault will pitch California into the sea. Well, before you believe any of this year's predictions , consider these vintage prognostications:

—Octave Chanute, aviation pioneer, in 1904 : "The (flying) machine will eventually be fast ; they will be used in sport, but they are not to be thought of as commercial carriers."

—*The Literary Digest, 1889*: "The ordinary 'horseless carriage' is at present a luxury for the wealthy; and although its price will probably fall in the future, it will never come into as common use as the bicycle."

—Thomas Edison, on electricity in the home : "Just as certain as death, [George] Westinghouse will kill a customer within six months after he puts in a system of any size."

—Lt. Joseph C. Ives, Corps of Topographical Engineers, 1861, on the Grand Canyon: "[It] is, of course, altogether valueless .... Ours has been the first, and will doubtless be the last, party of whites to visit this profitless locality."

—Science Digest, August 1948: "Landing and moving around on the moon offers so many serious problems for human beings that it may take science another 200 years to lick them."

—Physicist and mathematician Lord Kelvin (1824-1907), who seemed to have a corner on the wrongheaded oneliner in his day: "X-rays are a hoax." "Aircraft flight is impossible." "Radio has no future."

-Paul Dickson, *The Future File* (Rawson Associates)