FELs, Red and Green

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Andrew Sessler's 75th Birthday Celebration
March 15, 2003
LBNL

My Interaction with Andy Sessler

- Bunched Beam Microwave Instability
  1979
- High-Gain FELs, Optical Guiding, SASE
  ~1985
- “Free Electron Lasers: Present Status and Future Prospects”
  1990
- Photon Storage Cavities
  1991
- □-□Colliders
  1995
- Equation of Motion of Electron
  1999

Science, Vol. 250, 88 (1990)

Free-Electron Lasers: Present Status and Future Prospects

KWANG-JE KIM AND ANDREW SESSLER

Free-electron lasers as scientific instruments are reviewed. The present status and future prospects are delineated with attention drawn to the size, complexity, availability, and performance capability of this new tool.

THE FREE-ELECTRON LASER (FEL) WAS PROPOSED BY JOHN Madey in 1970 (*1*), although earlier work, relevant to the concept, had been done by Motz (*2*) and by Phillips (*3*). Experimental demonstration was achieved by Madey and his associates in 1975 and 1976 (*4*). Since that time, FELs of diverse configurations have been operated at several laboratories around the world. At present, FEL development is focused in two directions: in the construction of reliable FELs for scientific research in the infrared (IR) region and in the extension of FEL capability to vacuum ultraviolet (VUV) and even shorter wavelengths. In this article we shall briefly review the principles of an FEL, putting emphasis on those aspects that limit performance. Then we shall discuss the applications, present status, and future prospects of FELs.

Brau (*5*) has described the history, the basic principles, various experiments, and potential applications of FELs. The textbooks on FELs (*6*) provide even more material, and there have been a number of other review articles (*7, 8*). In addition, the interested reader may consult the Proceedings of the International FEL Conferences (the 12th will be held this year) where many of the original research

where the wiggler peak field strength, B, is expressed by (meter-kilogram-second units)

$$a_w = eB\lambda_w/(2^{3/2}\pi mc) \qquad (2)$$

The tremendous interest in FELs derives from this resonance condition, namely, the easy tunability of an FEL and the wide range of wavelengths that are available to the FEL. There are three ways to tune an FEL: (i) it is possible to design wigglers having a range of wiggler period lengths (usually in the centimeter range); (ii) it is easy to generate electron beams having various energies (in γ units, from near unity to thousands); and (iii) it is possible to change the wiggler magnetic field.

Thus, as compared to a conventional laser, which is tied to the natural resonance frequency of the atom or molecule, for an FEL all frequencies are possible. The electromagnetic spectrum is shown in Fig. 2, where we also show some alternative sources of radiation. One can see that sources are lacking both in the IR region ($1\ \mu m \leq \lambda \leq 1$ mm) and in the UV and shorter wavelength region ($\lambda \leq 1000$ Å). FELs could presumably fill these gaps. In Fig. 3 we show the performance of FELs to date; the features of operation in different wavelength ranges and tunability have already been demonstrated.

The wiggler can be constructed from either electromagnets or permanent magnets. Attention must be given to the field quality and alignment of the wiggler. The development of high-field, short-period wigglers, made with permanent magnets, has been an important factor in constructing efficient FELs. One can easily

Table 4. Parameters of some planned facilities (IR).

Parameter	FELIX (*15*)	NIST-NRL (*16*)	CLIO (*17*)	CDF (*18*)
Accelerator	RF linac	Microtron	RF linac	RF linac
Electron energy	15–45 MeV	185 MeV	30–70 MeV	56 MeV
Wavelength range	5–160 μm	0.2–10 μm	2–20 μm	3–50 μm
Micropulse duration	3 ps	3 ps	10–15 ps	10 ps
Macropulse duration	20 μs		10 μs	100 μs
Repetition rate*		74 MHz		
Micropulse	1000 MHz		30–500 MHz	37 MHz
Macropulse	10 Hz		50 Hz	60 Hz
Micropulse energy	25 μJ	0.1–3.0 μJ	100 μJ	200 μJ
Average output power	5 W	25–200 W	10–100 W	20 W

*As clarified in the footnote to Table 3.

Table 5. Parameters for representative short-wavelength FEL projects.

Parameters	Los Alamos National Laboratory (*19*)	Duke (*20*)	Lawrence Berkeley Laboratory (*21*)	Brookhaven National Laboratory (*22*)
Accelerator	RF linac	Storage ring	Storage ring	Superconducting linac
Electron energy	100–500 MeV	800–1000 Mev	750 MeV	250 MeV
FEL type	Oscillator	Oscillator	Amplifier	Amplifier
Wavelength	10–4000 Å	50–4000 Å	400 Å	1000–3000 Å
Micropulse duration	10–30 ps	300 ps	100 ps	5 ps
Repetition rate*		3 MHz	10 Hz	3–10 kHz
Micropulse	10–100 MHz			
Macropulse	30 Hz			
Peak output power	1–10 MW	10 kW	50 MW	300 MW
Average output power	1–10 W	10 W	50 mW	15 W

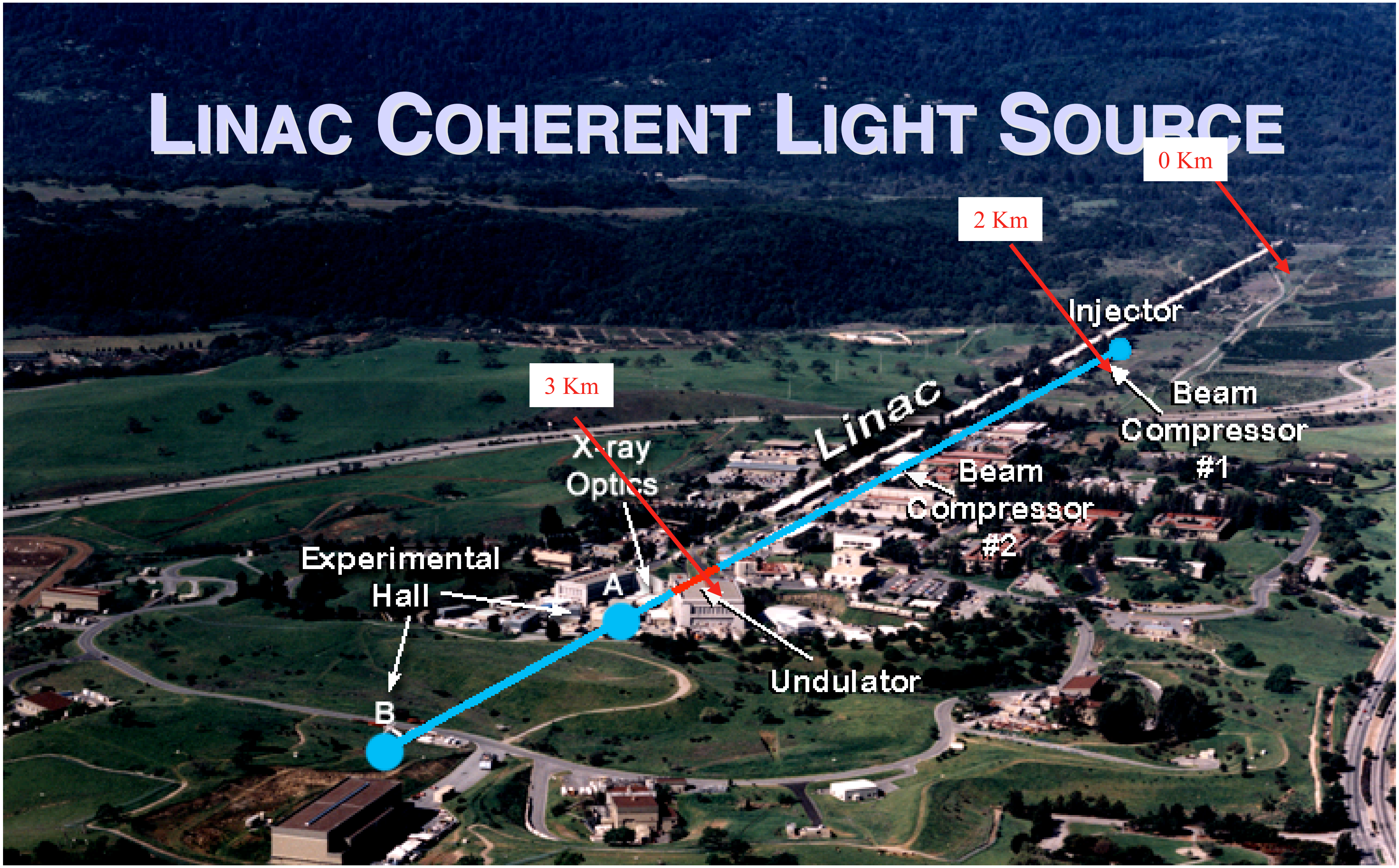
*As clarified in the footnote to Table 3.

My Advice to Young Scientists about Andy

- He is open, entertaining, and encouraging.
- He knows much more, despite his beard and despite his low-resolution handwriting.
- He may slap you hard if you talk a nonsense.
- However his goal is not your pain but fairness.
- You will become a better person, in physics and in living by knowing him.

7 19 '93

LINAC COHERENT LIGHT SOURCE



X-ray FEL Projects in Preconstruction

	LCLS (upgrade)	**TESLA (upgrade)**
Operation start	2009 (2013)	2012 (?)
# endstations/FEL	6	5
# FEL undulators	1 (8)	3 (5)
Spectral coverage (fundamental)	$\leq$ 8 keV (<12.4 keV)	$\leq$ 12.4 keV
□□/□	10^{-3} (10^{-6})	10^{-3} (10^{-6})
□□	100 fs (10 fs)	100 fs (10fs)
Peak spectral brightness*	10^{33} (10^{36})	10^{33} (10^{36})
Linac	S-band RT	L-band SCRF
Electron energy	15 GeV (15-45 GeV)	20 GeV
Pulse format (linac)	1 (<32) pulses per 1-μs burst _ 120 Hz	4000 pulses per 1 ms _ 10 Hz
Burst format (@endstation, per undulator)	120 Hz to one (40 Hz to three)	5 Hz to three (2.5 Hz to five)
I_p ($Q/\Delta t_{FWHM}$)	4.3 kA	5 kA
Emittance	1.2 mm-mrad (?)	1.4 mm-mrad (?)
λ_u minimum	3 cm (?)	3.8 cm
K	3.7	3.8
Undulator length	115 m	145 m

Greenfield FELs

John Galayda, SLAC
Kwang-Je Kim, ANL (Presenter)
James Murphy, BNL

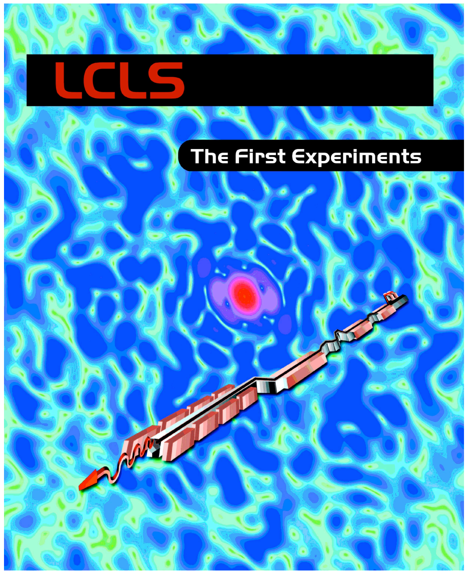
BESAC Subcommittee on
BES 20-year Facility Road Map
February 22-24, 2003

Status of X-ray FELs in 2015

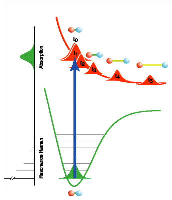
- LCLS and TESLA FEL, and perhaps others, have been constructed and have been in operation for several years.
- Basic SASE operation for $\square_1$ up to 12.4 keV with time resolution □□□100 fs and □□/□ □10^{-3}.
- Experimental techniques for x-ray 100-fs sciences have been developed.
- Seeding schemes for □□/□ □10^{-6} and pulse compression or selection schemes for □□□10 fs or □0.1 fs have been studied (successfully).
- ***With exciting scientific results achieved and with a set of experimental questions identified, the world is ready for a Greenfield FEL.***

LCLS - The First Experiments

Team Leaders:

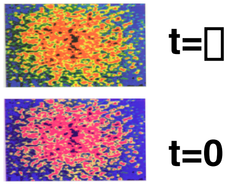


Report developed by international team of ~45 scientists working with accelerator and laser physics communities



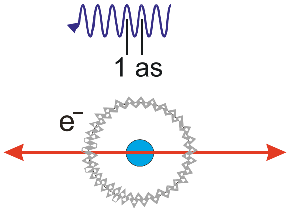
Femtochemistry

Dan Imre, BNL



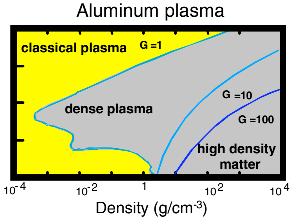
Nanoscale Dynamics in Condensed Matter

Brian Stephenson,
APS



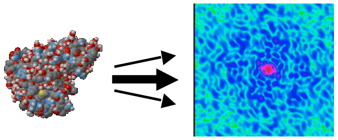
Atomic Physics

Phil Bucksbaum,
Univ. of Michigan



Plasma and Warm Dense Matter

Richard Lee, LLNL



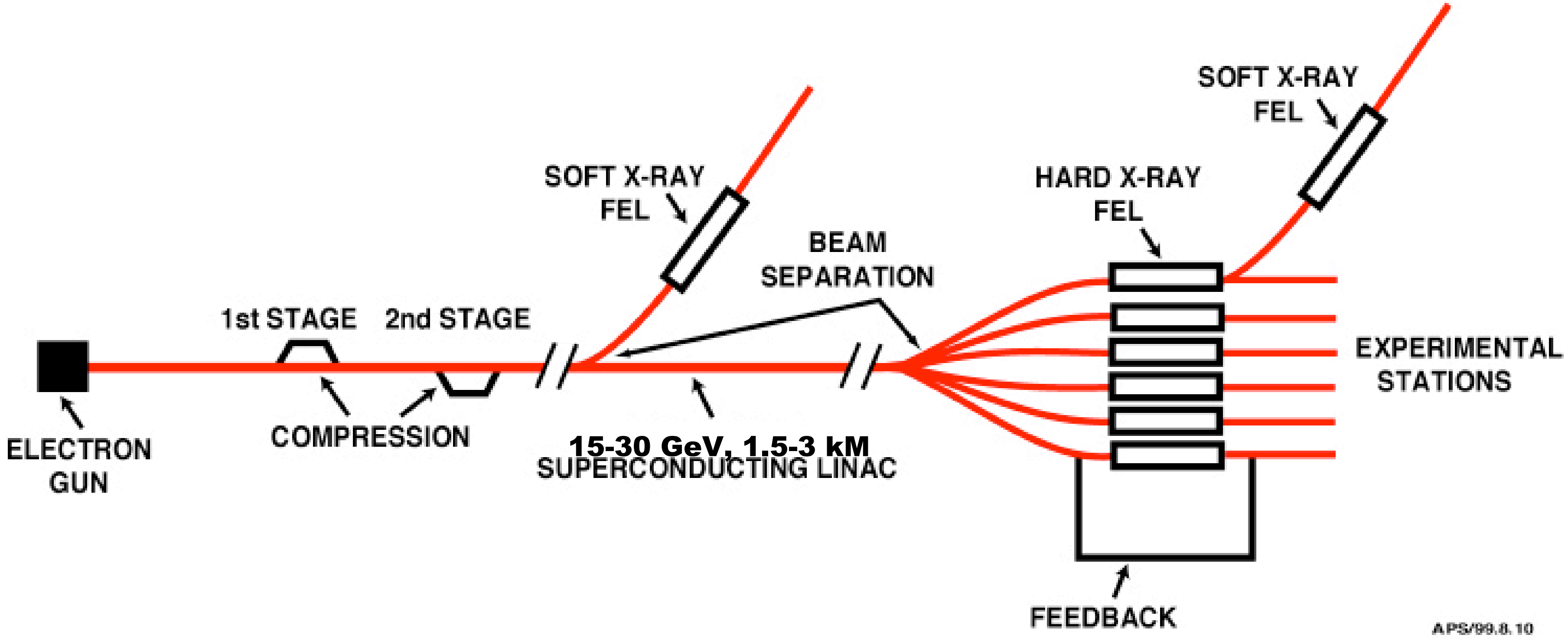
Structural Studies on Single Particles and Biomolecules

Janos Hajdu,
Uppsala Univ.

Greenfield FEL Wish List

- Spectral coverage to 30 keV in first harmonic
  - Comparable to large 3rd generation facilities
  - One could argue for 60 keV
- X-ray pulse 10^{12} photons, *may be* 10^{14}
- Pulse duration – 100 femtosec to 100 attosec
- Narrow spectrum □□/□ $< 10^{-6}$, coherence control
- Multiple undulator facility
  - At least 10 FEL undulators, several beamlines per undulator
- 1-10 kHz rate at undulator

A Greenfield FEL Facility Layout

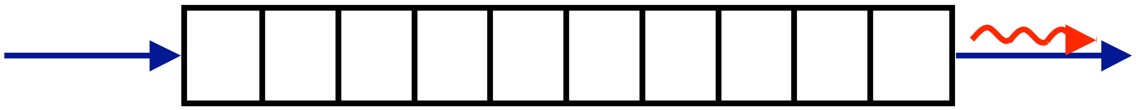


- SCRF, CW 10 kHz
- 30-keV fundamental
- Advanced features for □□/□ & □□
- ~ 1-2 B$

An Assortment of GFEL Schemes

- Basic SASE FEL for 30 keV
- Advanced features via phase-space manipulation
  - Self-seeding
  - Ultrashort pulse
- HGHG scheme
- Tapering for higher power, 100 times

SASE FEL for 30 keV



- LCLS reference parameters:
  $\square$ = 8 keV, $\square_u$ = 3 cm, K = 3.7, I_p = 3.5 kA, E_e = 15 GeV,
  $\square$E/E = 0.01%, $\square_n$ = 1.2 mm-mrad, L_{sat} = 100 m
- Vary K, $\square_n$, and E_e

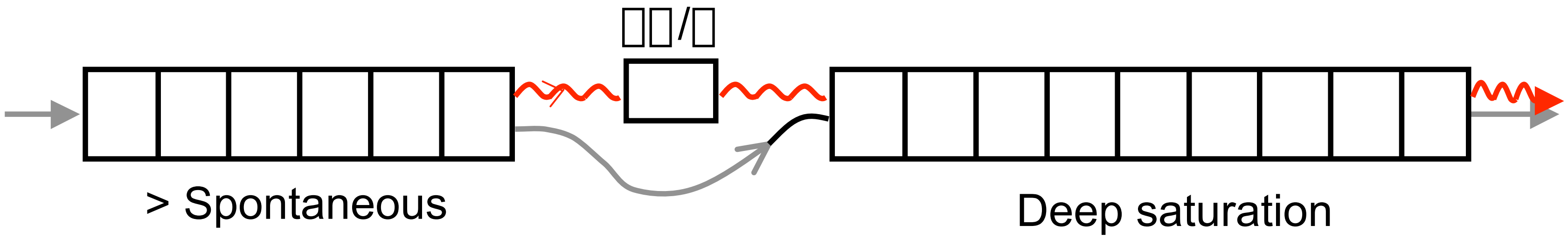
K	**E_e (GeV)**	**$\square_n$ (mm-mrad)**	**L sat (m)**
3.7	**30**	**1.2**	**300**
3.7	**30**	**0.5**	**130**
3.7	**30**	**0.1**	**40**
1	**12**	**0.1**	**60**

← shorter undulator

← shorter undulator and shorter linac

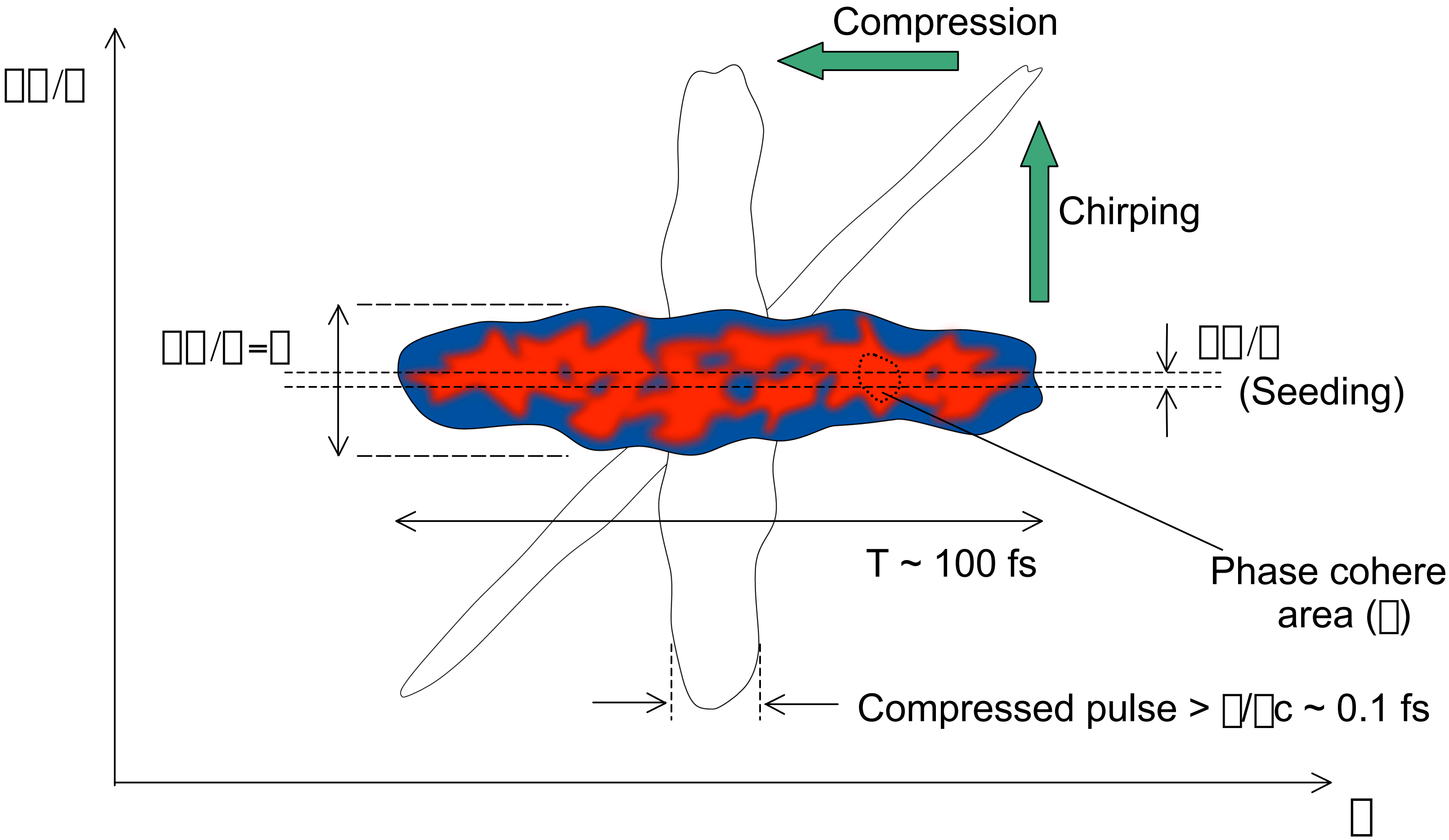
- ***It pays to strive for an ultralow emittance e-beam***

Self-Seeding Scheme (DESY)

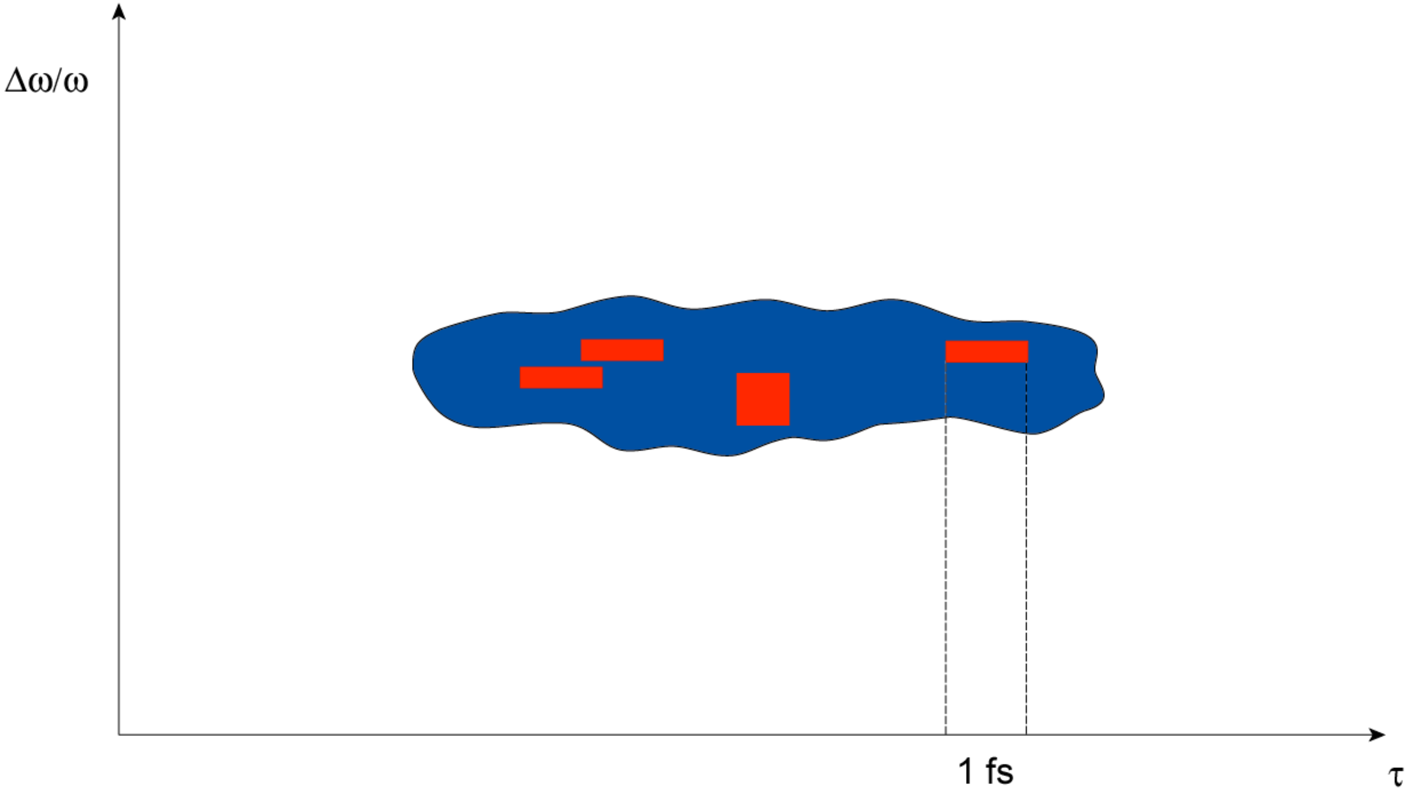


- Spectral purity □□/□ □ 10^{-6}
- Concentration of photons in single mode _ Higher spectral brightness _ 10^3
- Need to develop x-ray optics and e-beam transport
- Can add a tapering section for higher power

Phase-Space Manipulation of X-ray Beams



Coherence Control



R&D Leading Up to the GFEL

- Key R&D Issues
  - Ultralow emittance e-injector; also “CW” e-injector
  - Electron and photon bunch compression; wakes
  - Ultrashort electron and photon beam diagnostics
  - X-ray optics and detectors
  - Seeded FEL schemes for longitudinal coherence
  - Superconducting undulators
- Advances in several of these issues are expected with progress of the existing X-ray FEL projects, *however*—
- **Focused R&D programs are essential for the GFEL, e.g., developing an ultralow □e-injector; *such R&D can also enhance the LCLS and TESLA XFEL***

Anticipation of E-beam Techniques

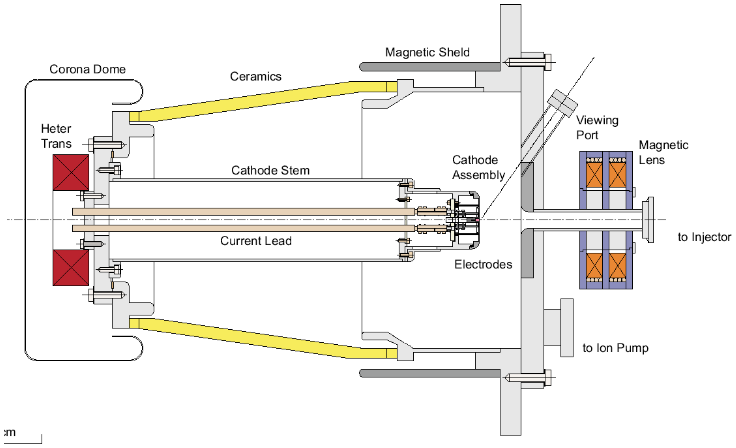
- We do not know at this time (2003) how to achieve necessary peak current with:

  ϵ_n = 0.1 mm-mrad or 10% chirping
- *However, these capabilities do not violate fundamental laws of physics (far from quantum limits).*
- *The advances will have great impact to light source development as well as HEP machines.*
- Some possibilities:
  - PC-RF hybrid for 1 GV/m
  - Manipulation of DC beams (tip cathodes, …)
  - Laser plasma…

High Brightness Electron Injectors

Type	DC Gun	RF Gun	Greenfield
E [MeV]	0.5	5	50
G[MV/m]	10	100	500
□[ps]	500	10	<1
I_p [A]	10	100	500
Q [nC]	0.5	1	<0.5
□$_n$ [□m]	1	1	0.1

500 kV Spring-8 DC Injector



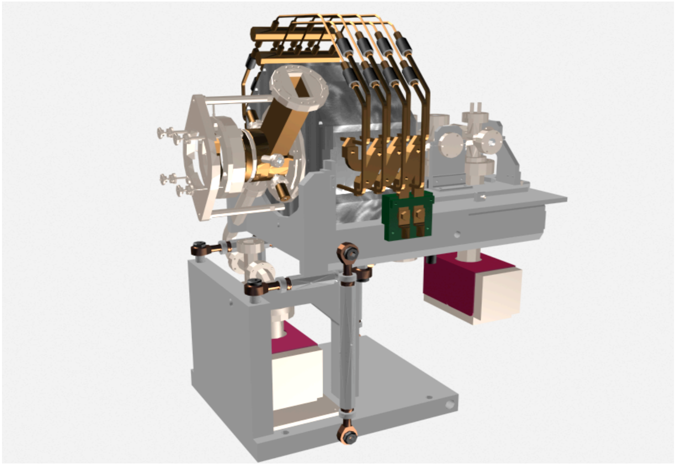
How to create the Greenfield FEL injector?

- *Optimize 6-D phase space, not just □$_n$ or I_p*
- *To realize this the GFEL injector should achieve:*

$G > 500$ MV/m , $E > 50$ MeV

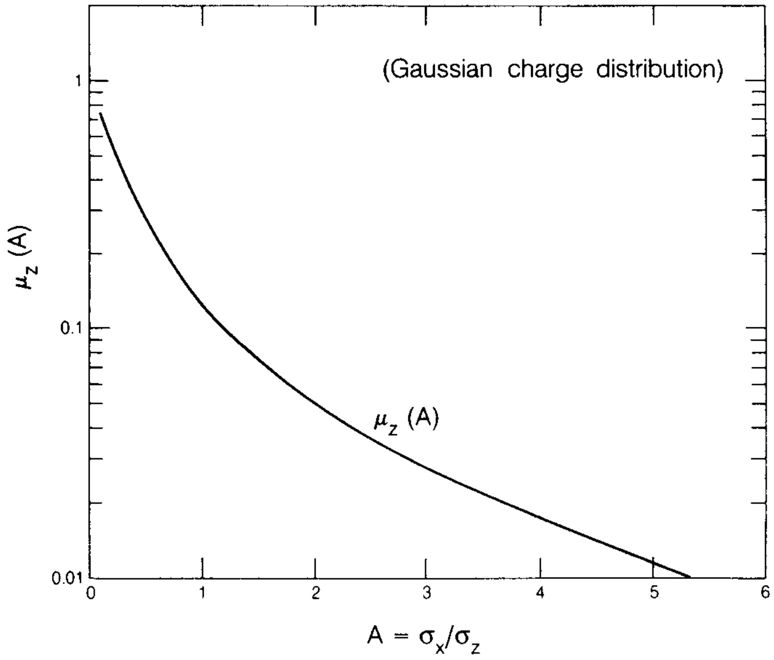
in order to beat space charge!

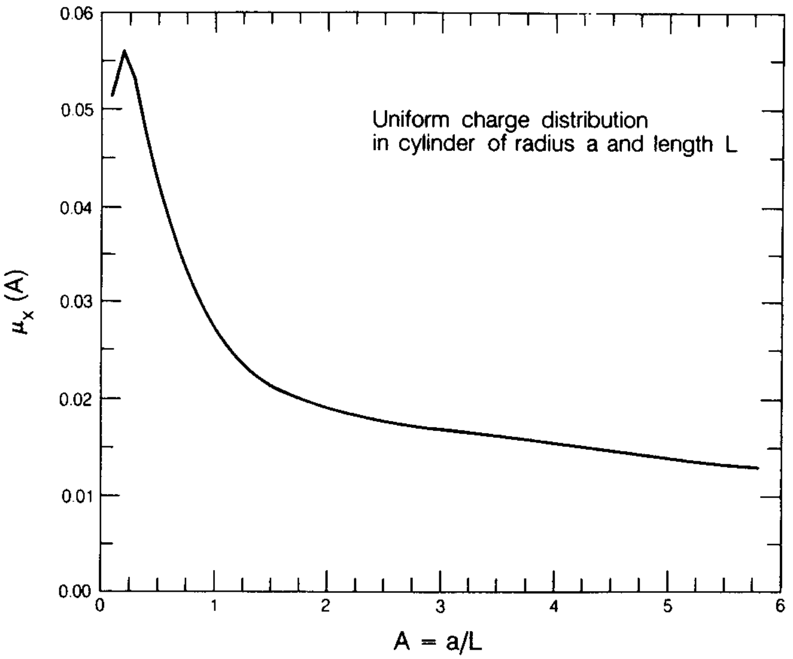
BNL RF Photoinjector



Linear Space-Charge Induced Emittance

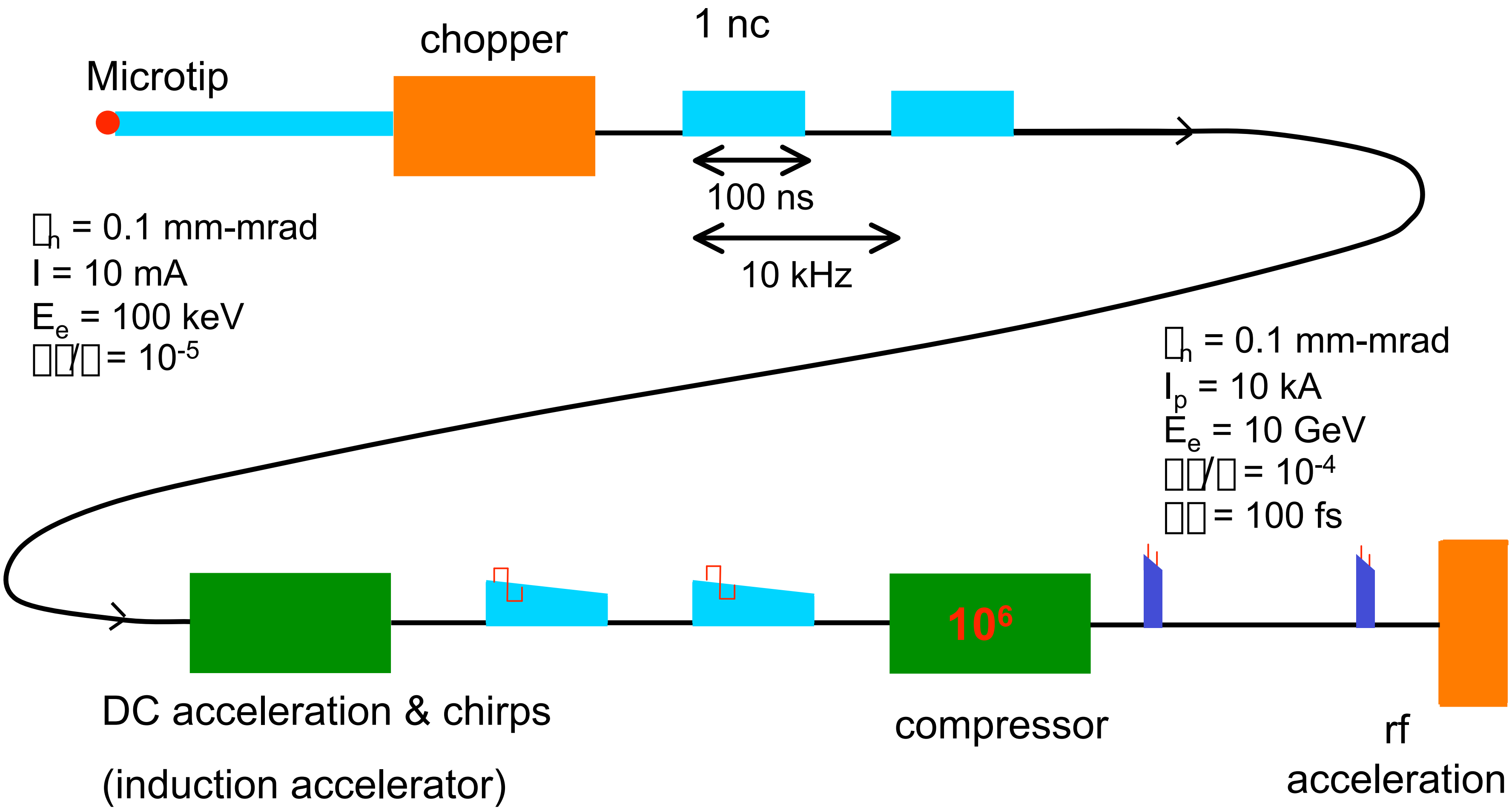
$$\square^{sc}_{x,z} = \frac{\square}{4}\frac{1}{\sin\square_0}\frac{2mc^2}{eE_0}\frac{I}{I_A}\square_{x,z}(A)$$





KJK, NIM A275 (1989) 201-218

A Speculative Greenfield Injector



Microtip

chopper

1 nc

100 ns

10 kHz

ϵ_n = 0.1 mm-mrad
I = 10 mA
E_e = 100 keV
$\Delta\gamma/\gamma = 10^{-5}$

ϵ_n = 0.1 mm-mrad
I_p = 10 kA
E_e = 10 GeV
$\Delta\gamma/\gamma = 10^{-4}$
$\Delta\tau$ = 100 fs

10^6

DC acceleration & chirps

(induction accelerator)

compressor

rf
acceleration

BES R&D Funding for a GFEL

- **A GFEL is a 1-2 gigabuck project**
  - ***With its many technical challenges, the GFEL demands R&D funds to insure success***
  - A few R&D issues require an x-ray FEL for development, while most are “standalone” issues, e.g., ultralow emittance e-injector, SC undulators, seeding schemes, compression, …
  - This research may be pursued as university-based, national lab-based, or university-national lab collaborations
  - DOE labs compete for funding on “standalone” issues
- **Suggestion: 10M$/year for nexy ten years for R&D**