Greenfield FELs

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What is a Greenfield FEL?

- High-gain FELs are proving themselves as research tools in the U.S. and Europe

- Proposals for new facilities in the U.S. and elsewhere in the world are designed to reach the limits of FEL performance as we understand them today. These facilities are intended to begin operation by 2012 or earlier.

- This presentation describes a “Greenfield FEL,” an attempt to imagine the facility that could be built based on lessons learned from experience with the first FEL user facilities and on R&D progress in accelerator science and technology over the next 5-10 years.

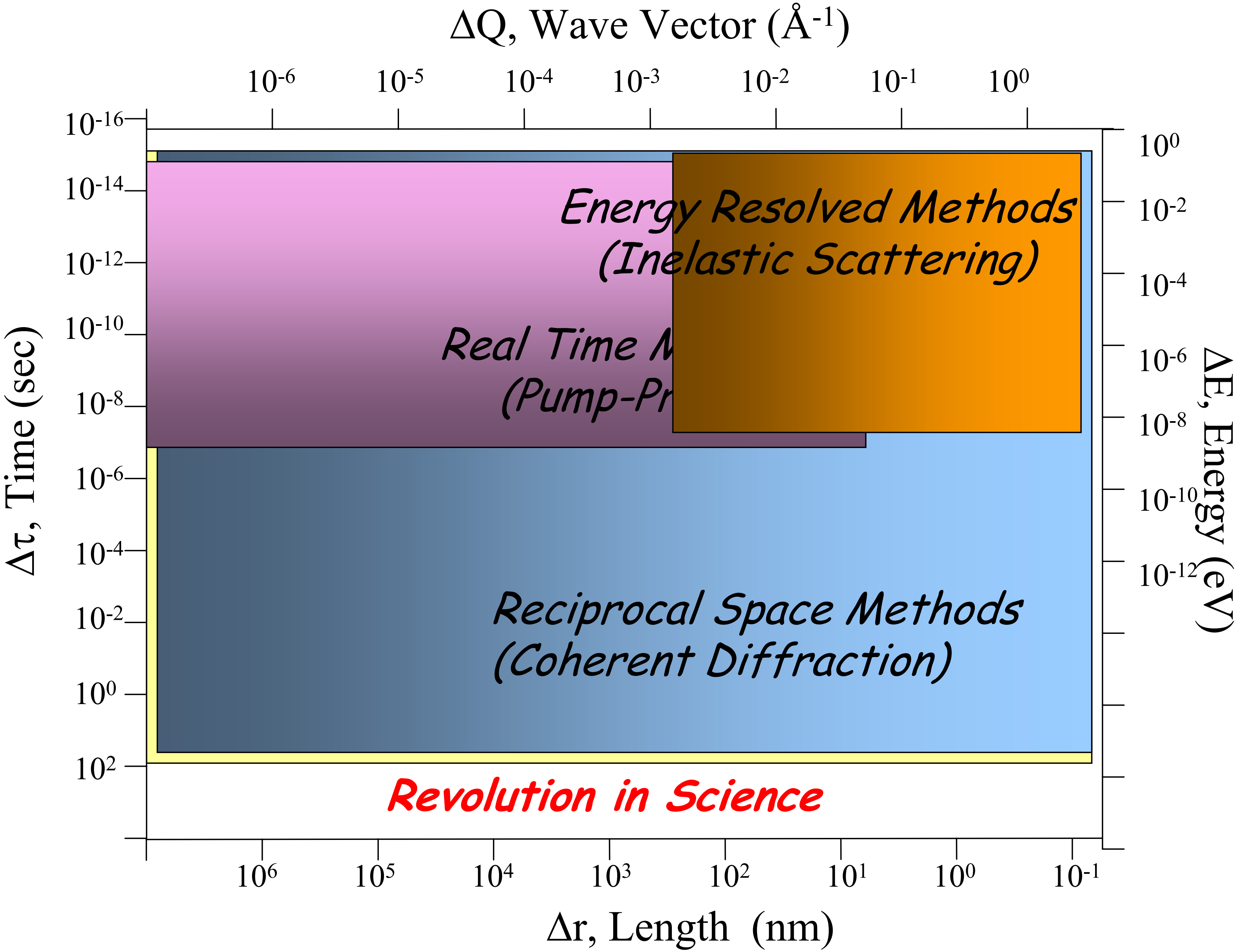
- We will attempt to identify the areas where R&D could have the greatest impact on the capabilities of a Greenfield FEL facility.

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)	≤ 8 keV (<12.4 keV)	≤ 12.4 keV
$\Delta\omega/\omega$	10^{-3} (10^{-6})	10^{-3} (10^{-6})
$\Delta\tau$	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

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 ε_1 up to 12.4 keV with time resolution $\Delta\tau \approx 100$ fs and $\Delta\omega/\omega \approx 10^{-3}$.
- Experimental techniques for x-ray 100-fs sciences have been developed.
- Seeding schemes for $\Delta\omega/\omega \leq 10^{-6}$ and pulse compression or selection schemes for $\Delta\tau \leq 10$ 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.***


ΔQ, Wave Vector (Å^{-1})
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Δτ, Time (sec)
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
ΔE, Energy (eV)
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
Energy Resolved Methods
(Inelastic Scattering)
Real Time M
(Pump-Pr
Reciprocal Space Methods
(Coherent Diffraction)
Revolution in Science
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
Δr, Length (nm)

Greenfield FEL Wish List

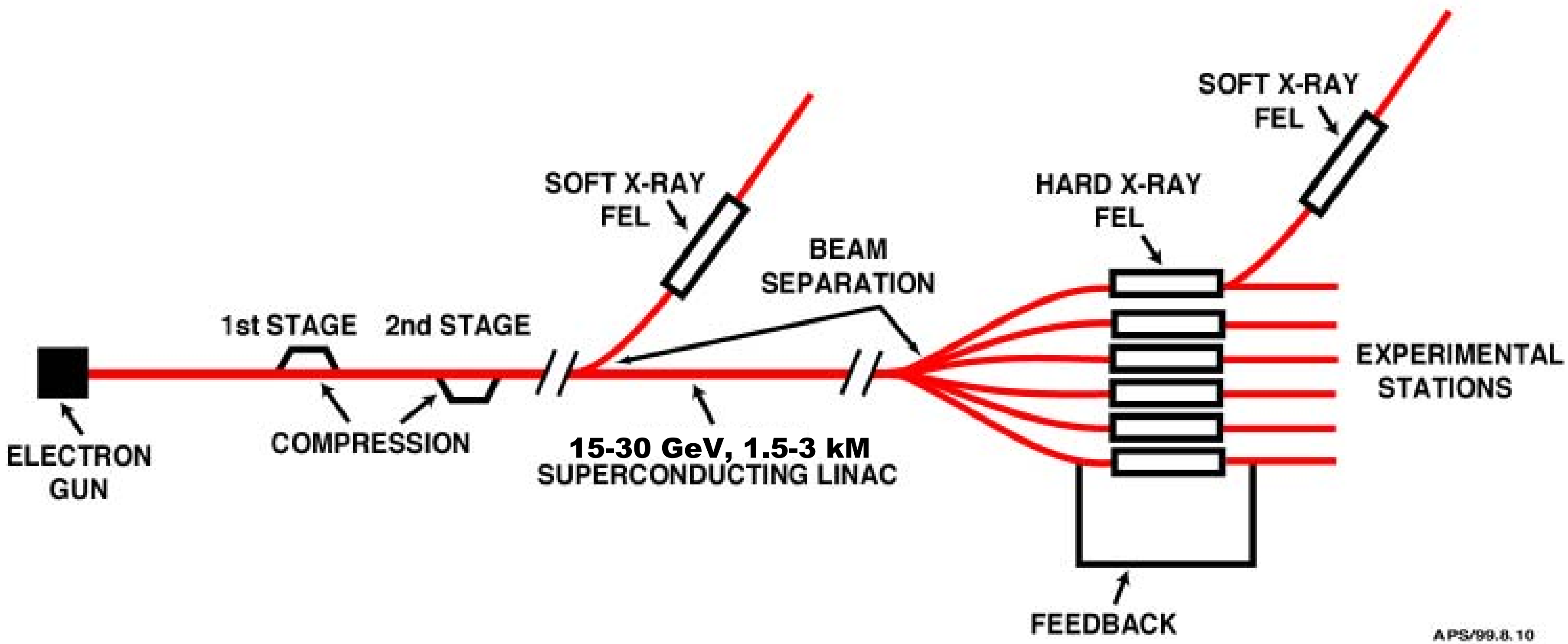
- Spectral coverage to 30 keV in first harmonic
  - Comparable to large 3rd generation facilities
  - One could argue for 60 keV
- X-ray pulse ~10^{12} photons
- Pulse duration – 100 femtosec to 100 attosec
- Narrow spectrum $\Delta\omega/\omega < 10^{-6}$, coherence control
- Multiple undulator facility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

To be sharpened by scientific experiences from the first FEL facilities

Greenfield FEL Accelerator

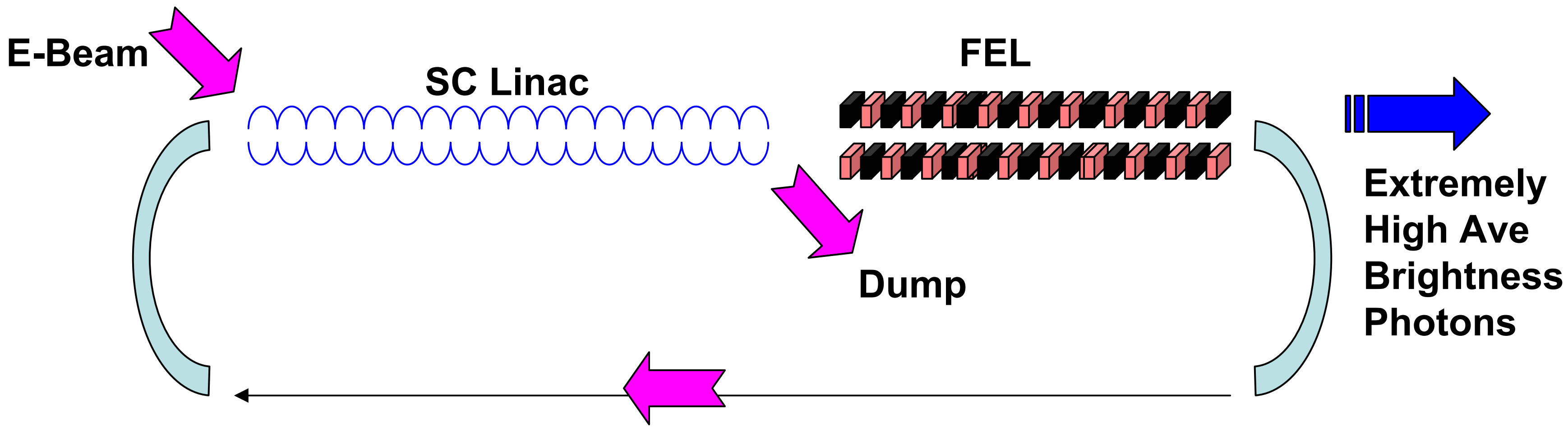
- Superconducting linac operating CW
  - Arbitrary bunch frequency, limited by power bill (ERL?)
    - High duty factor gun
- Energy 10-30 GeV
  - Highly dependent on short wavelength limit
    - Gun performance
    - Bunch compression capability
    - Undulator technology

A Greenfield FEL Facility Layout



- SCRF, CW 10 kHz
- 30-keV fundamental
- Advanced features for $\Delta\omega/\omega$ & $\Delta\tau$
- ~ 1-2 B$

Energy Recovery for FELs

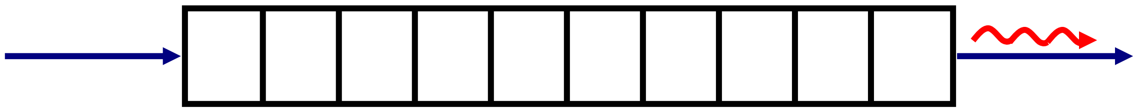


- **Motivation**: Push rep rate past 10 kHz to increase the *average* brightness well beyond rings $\Rightarrow$ **ER**
- **Requirements**: CW SC linac, CW injector, robust samples,…
- Challenging to generalize to tunable undulator farm

An Assortment of GFEL Schemes with Anticipated E-Beam Development

- Basic SASE FEL for 30 keV
- Advanced features via phase-space manipulation
  - Self-seeding
  - Ultrashort pulse
- HGHG scheme

SASE FEL for 30 keV



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

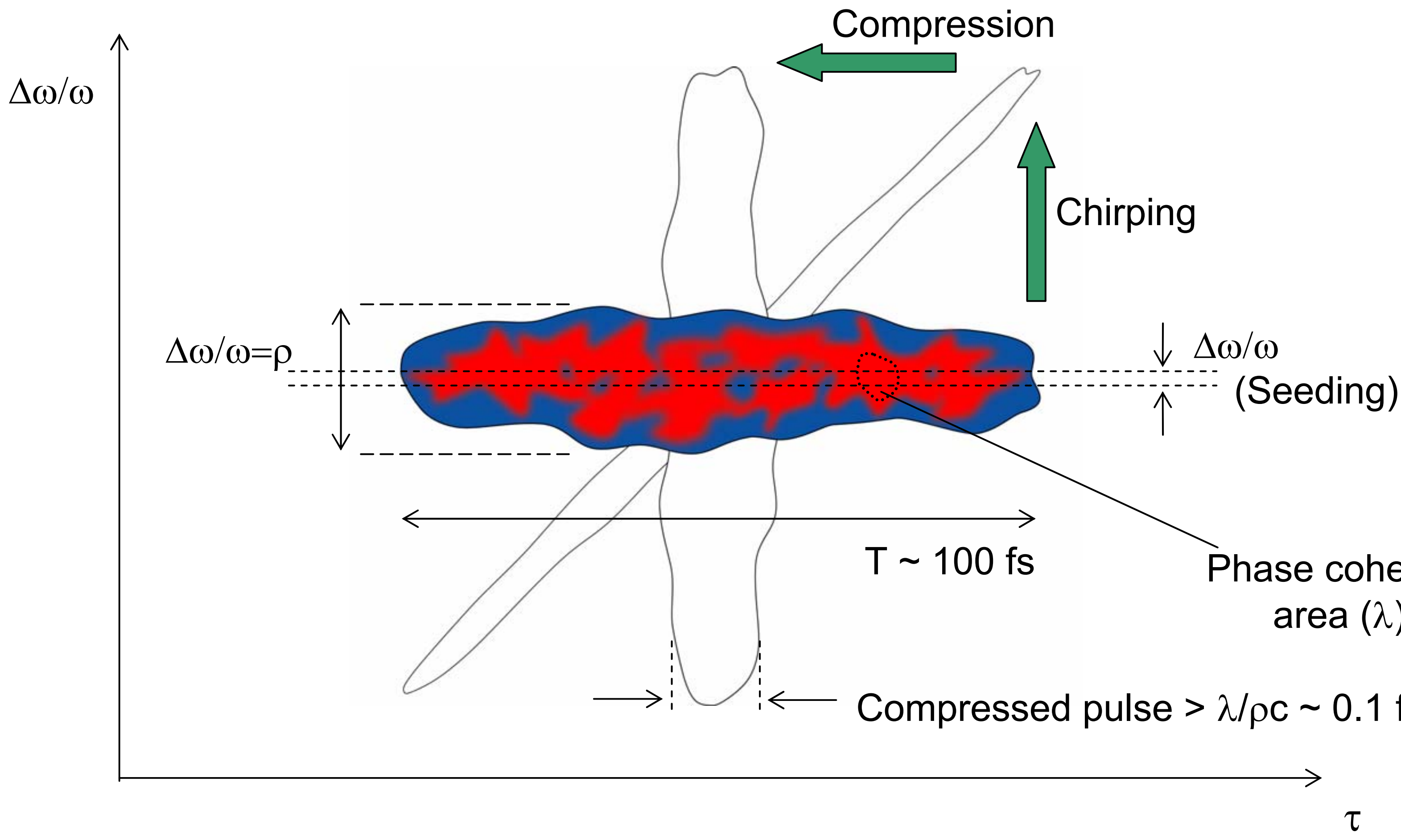
K	E_e (GeV)	ε_n (mm-mrad)	L sat (m)
3.7	**30**	**1.2**	**300**
3.7	**30**	**0.5**	**130**
3.7	**30**	**0.1**	**40**
1	**12**	**0.1**	**60**

← **shorter undulator**

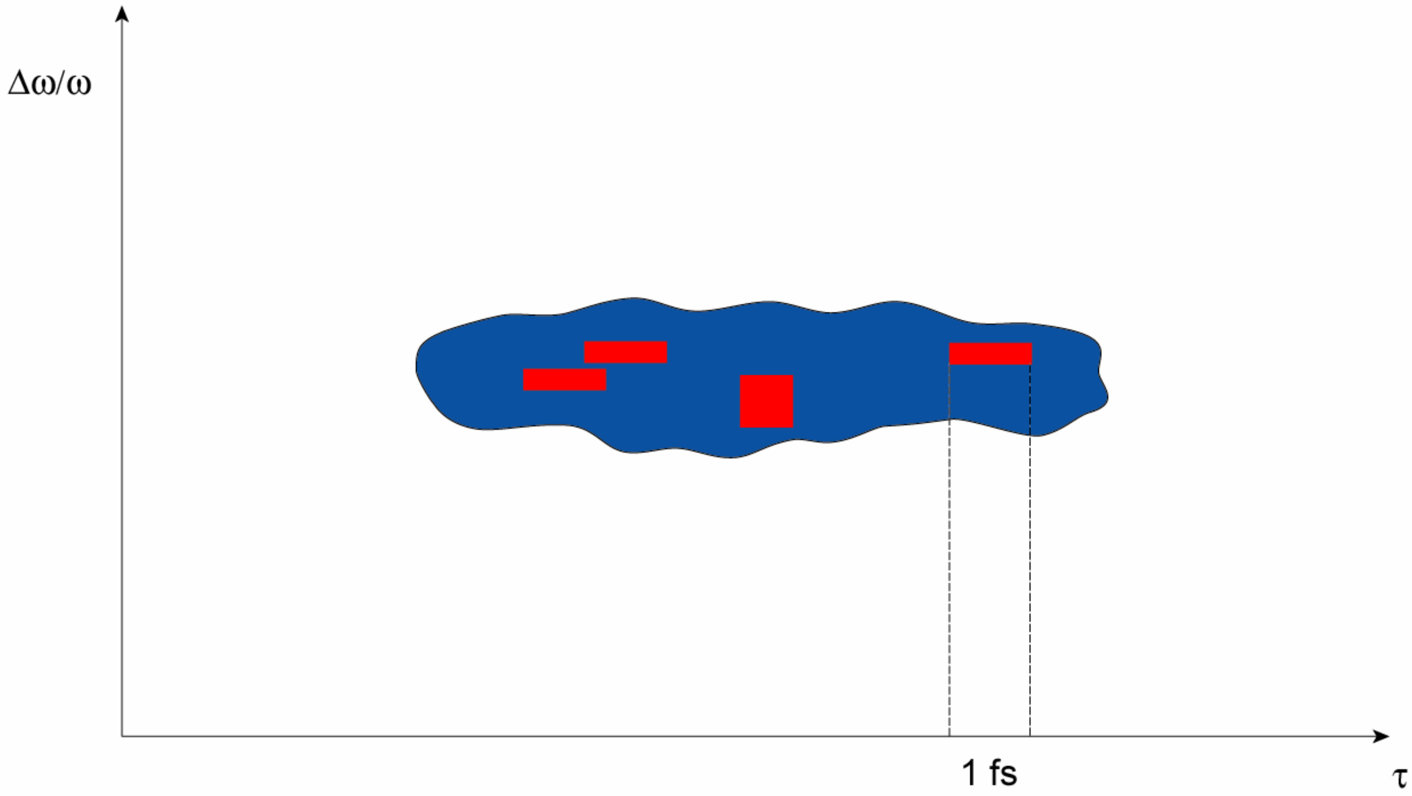
← **shorter undulator and shorter linac**

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

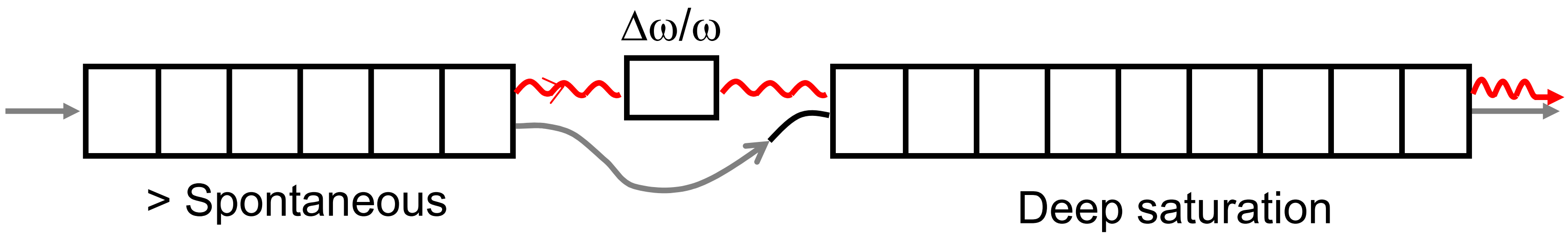
Phase-Space Manipulation of X-ray Beams



Coherence Control



Self-Seeding Scheme (DESY)



- Spectral purity $\Delta\omega/\omega \leq 10^{-6}$
- Concentration of photons in single mode $\rightarrow$ Higher spectral brightness $\times\ 10^{3}$
- Need to develop x-ray optics and e-beam transport.

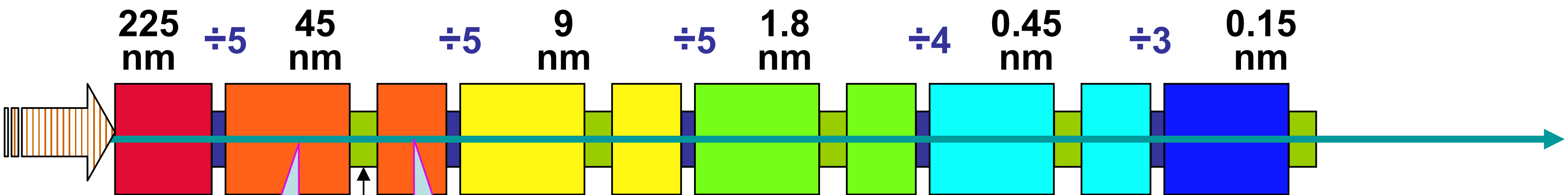
Ultrashort Pulses

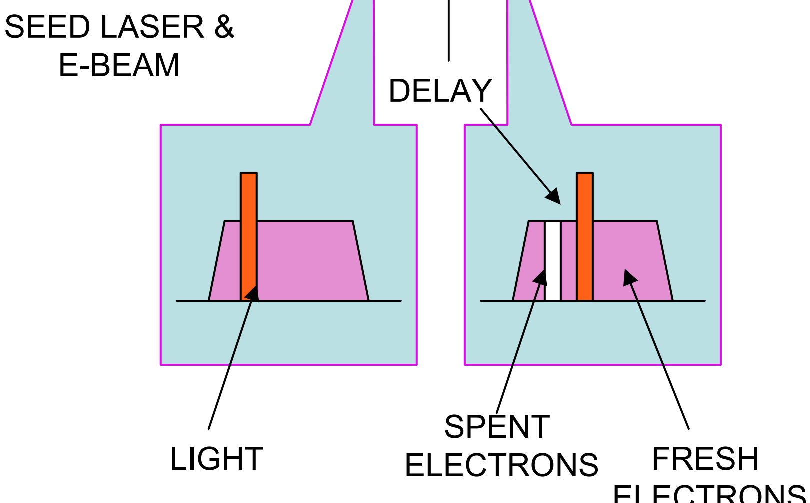
- Chirp & Compress (DESY) or Chirp & $\Delta\omega/\omega$ (UCLA)
- For maximum chirping, the ultimate pulse length

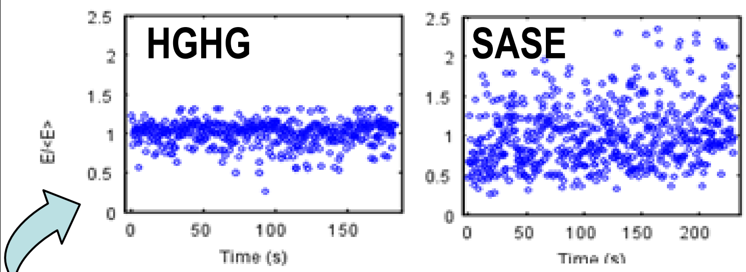
$$\tau \sim \lambda/\rho c \quad \sim \quad 0.1 \text{ fs}$$

- Chirping in rf linacs is limited to 1%, thus $\tau \sim 10$ fs. Need > 10% chirping for $\tau < 1$ fs.
- Need to develop x-ray optics

Cascaded HGHG + Fresh Bunch

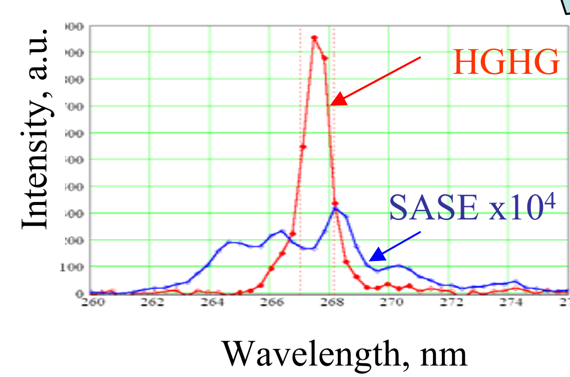






Stable Intensity and λ

Narrow Bandwidth



<u>Short Pulse Possibilities</u>

- ➔ **20 fs Output with 20 fs Seed Laser**
- ➔ **Chirped Pulse Amplification + Compression = Attosecond Pulses**
- ➔ **Needs R&D on X-ray compressor optics and fresh bunch technique**

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 ε e-injector; *such R&D can also enhance the LCLS and TESLA XFEL*
- SC undulators can enhance *storage rings* too!

Anticipation of E-beam Techniques

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

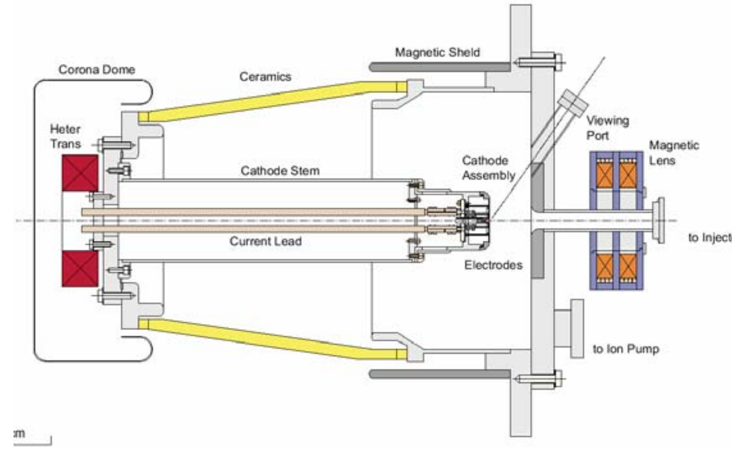
$$\varepsilon_n = 0.1 \text{ mm-mrad or } 10\% \text{ chirping}$$

- *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**
τ [ps]	500	10	<1
I_p [A]	10	100	500
Q [nC]	0.5	1	<0.5
ε_n [μm]	1	1	0.1

500 kV Spring-8 DC Injector



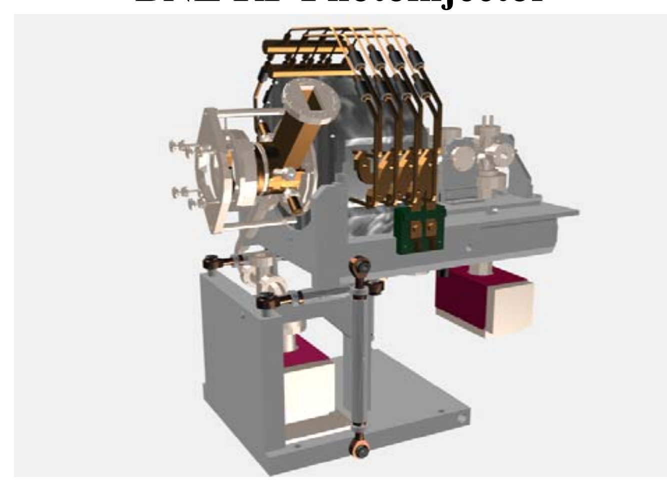
How to create the Greenfield FEL injector?

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

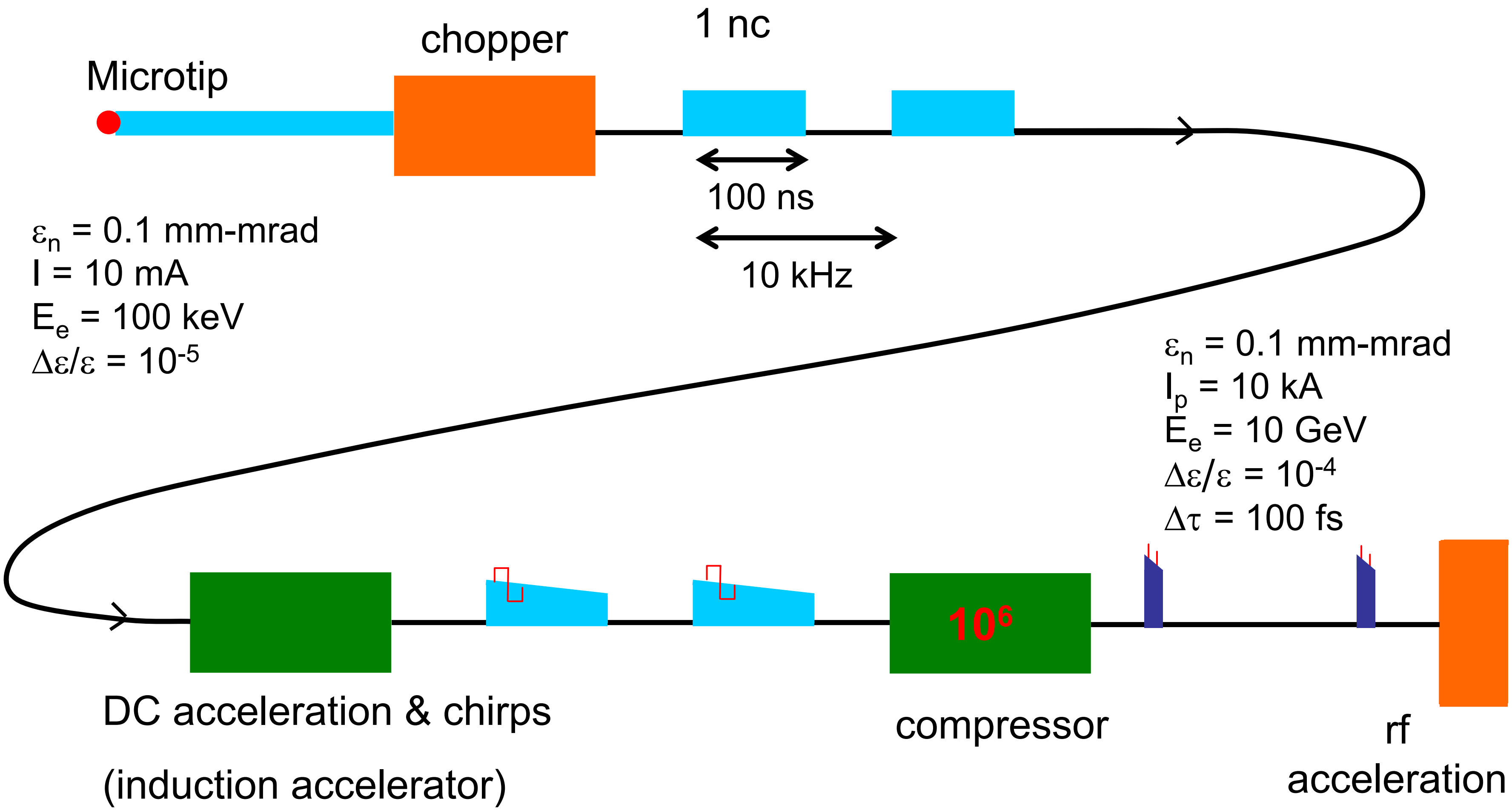
  $G > 500$ MV/m , $E > 50$ MeV

  in order to beat space charge!

BNL RF Photoinjector



A Speculative Greenfield Injector



Development of SC Undulators

Advantages

- SC helical ID represent the shortest possible SASE FEL amplifier
- SC ID has an intrinsic capability of tuning of the wavelength
- SC helical ID delivers lowest heat load on optical components
- SC ID utilizes the same technology as a primary particle source – SC Linac

Challenges

- Stringent requirements for quality of the magnetic field for long-periodic SC magnets
- Reliability of the long SC ID with respect to its interaction with the powerful x-ray source
- Extremely high-level tolerances for mechanical and vacuum systems
- Incorporating compatible diagnostics of electron beam and x-rays

Solution

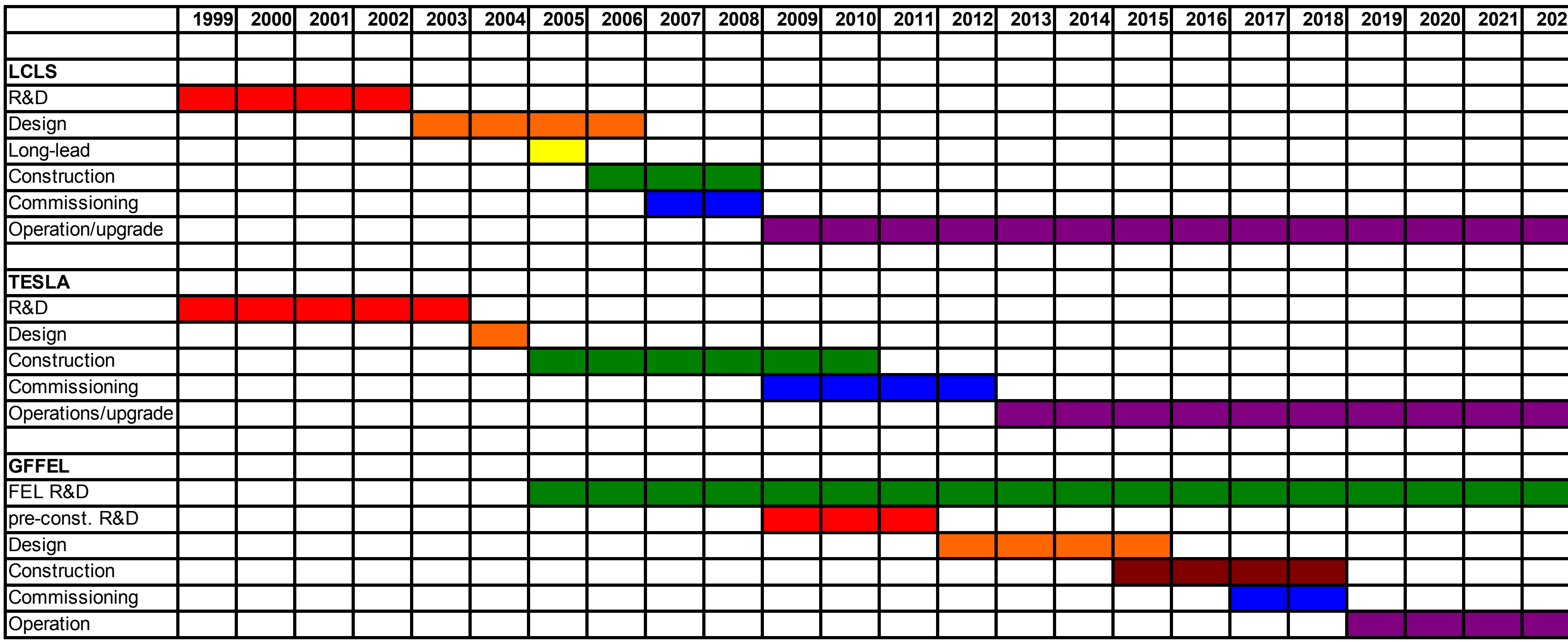
- Extensive prototyping is required. But technical challenges for critical elements of the SC undulator line could be solved in the period of three years with adequate funding.

Detectors and X-ray Optics

- Fastest time-resolving detectors (streak cameras) currently have time resolution of about 500 fs. Also limited by poor quantum efficiency for x-rays. Further R&D could push the resolution down to 100 fs.
- Many fast experiments can use pump/probe, where time resolution depends on pump and probe durations, allowing a variety of slow detectors to be used. R&D on x-ray optics such as pulse splitters and delay lines will benefit this approach.
- Nearly all subpicosecond pulse diagnostics, including measurement of pulse length and calibration of pump/probe system, require correlation methods that detect overlap of two pulses with femtosecond precision. R&D on such methods in the x-ray range has hardly begun. *This is the most critical development area for FEL scientific applications.*
- High FEL pulse intensity invites the use of large-area detectors to collect all data in a single shot. High data rates, high dynamic range, and low noise are all required. Existing x-ray CCD detectors will not suffice; R&D into other technologies, such as pixel array detectors, is needed.

Cost and Schedule

TPC $1B-$2B, depending on R&D progress



GFEL begins operation after TESLA first light, perhaps during TESLA upgrade

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
  - R&D will benefit all FELs: VUV, soft X-ray, LCLS, and GFEL
  - Suggestion: 10 M$/year for next ten years

- Research collaborations with Asia, Europe, and Russia should be pursued

Summary

- The LCLS is an essential component and appropriate first step toward developing the necessary R&D and science programs for success of a GFEL.
- Experience with the upcoming generation of FELs and ERLs will undoubtedly bring additional science/technology advances important to the design and successful utilization of a GFEL.
- Construction, commissioning, and operation of a GFEL facility in the late 2010s will be matched to an already-strong FEL user community, providing the capability to maintain world leadership in accelerator-based photon science.
- R&D in accelerator physics, optics, and experimental science at the national laboratories, in close collaboration with universities in the U.S. and with foreign partners, will insure the success of a GFEL and improve EVERY linac-based light source built over the next 15 years.

LCLS II and “Greenfield” XFEL

- XFEL opens up new scientific horizons
- 20 year vision for full-fledged XFEL-based User-facilities.
- technical challenges include e-gun, detector, e-beam stability, etc.
- LCLS progress towards XFEL feasibility is critical

R&D on XFEL must proceed with emphasis on elucidating future scientific opportunities.