The FERMI@Elettra Project

John Adams Institute for Accelerator Science

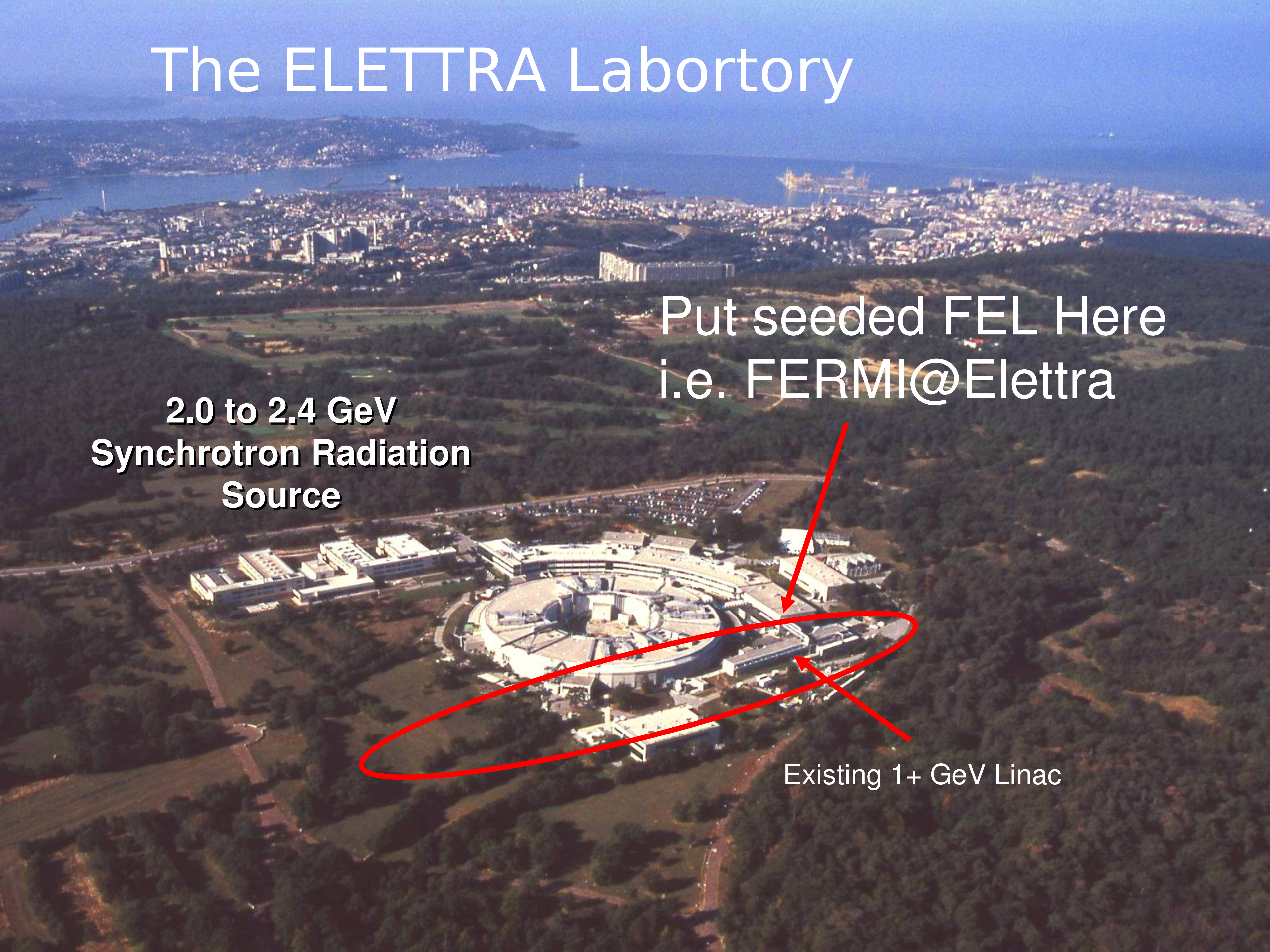
June 12, 2008

Stephen V. Milton

Sincrotrone Trieste, S.C.p.A.

Italy

The ELETTRA Labortory



Some Source Properties of Interest

- Brightness
- Pulse Length
- Flux
- Coherence
- Energy/Pulse
- Photon Energy
- Tunability
- Repetition Rate
- Costs
- Size
- Complexity

Science Drives the Machine?

- Yes…But
  - If you already have a machine and site then you need to determine what the capabilities of the machine is.
  - So in this case the machine partially drives the science and then one must make a determination if the science that the machine is capable of empowering is worth pursuing.

Undulator Magnets: Resonant Condition

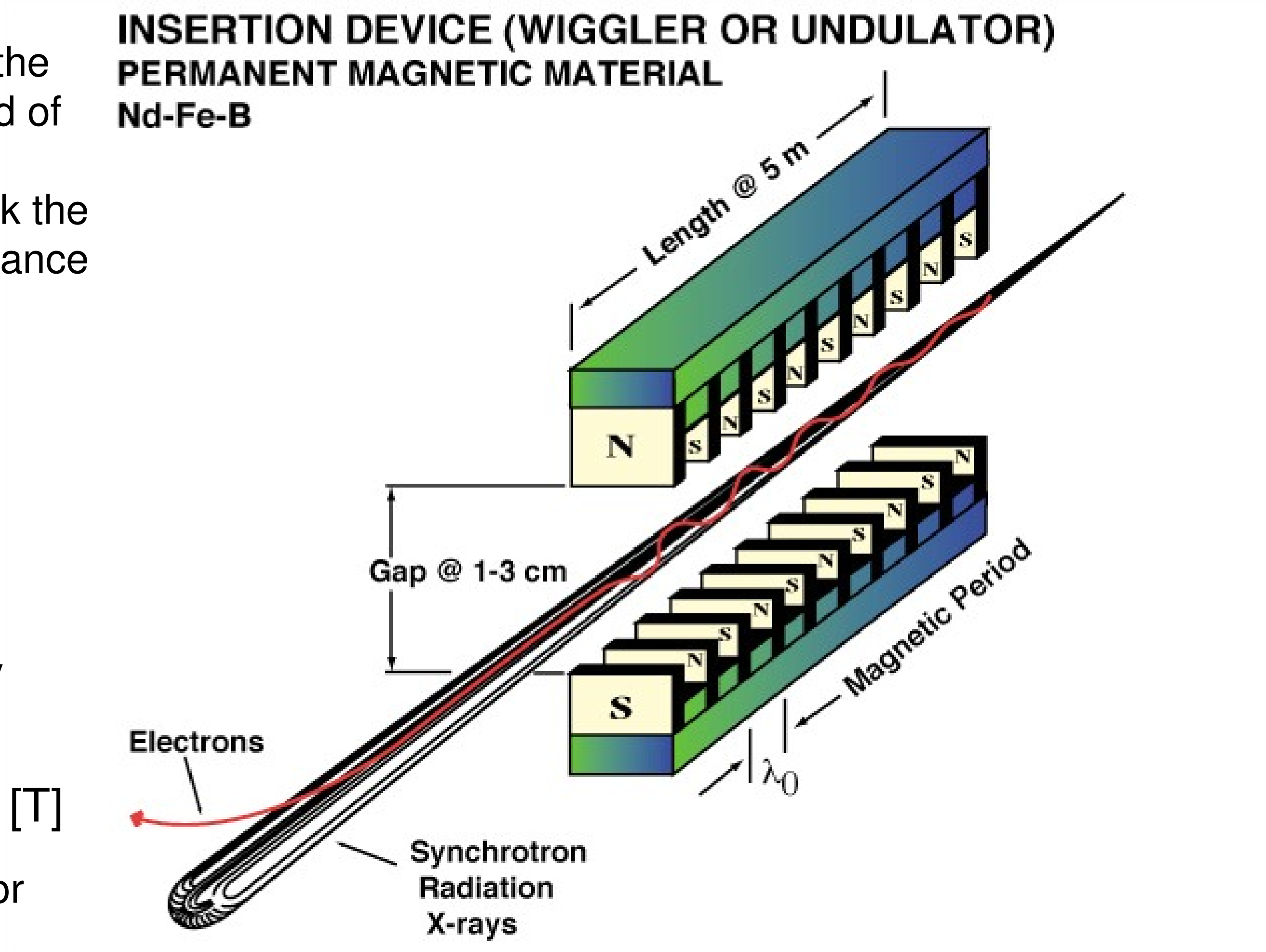
"Resonance" occurs when the light wavefront "slips" ahead of the electron by one optical period in the time that it took the electron to traverse the distance of one undulator period

$$\lambda_{rad} = \frac{l_o}{2g^2}\left(1 + K^2/2\right)$$

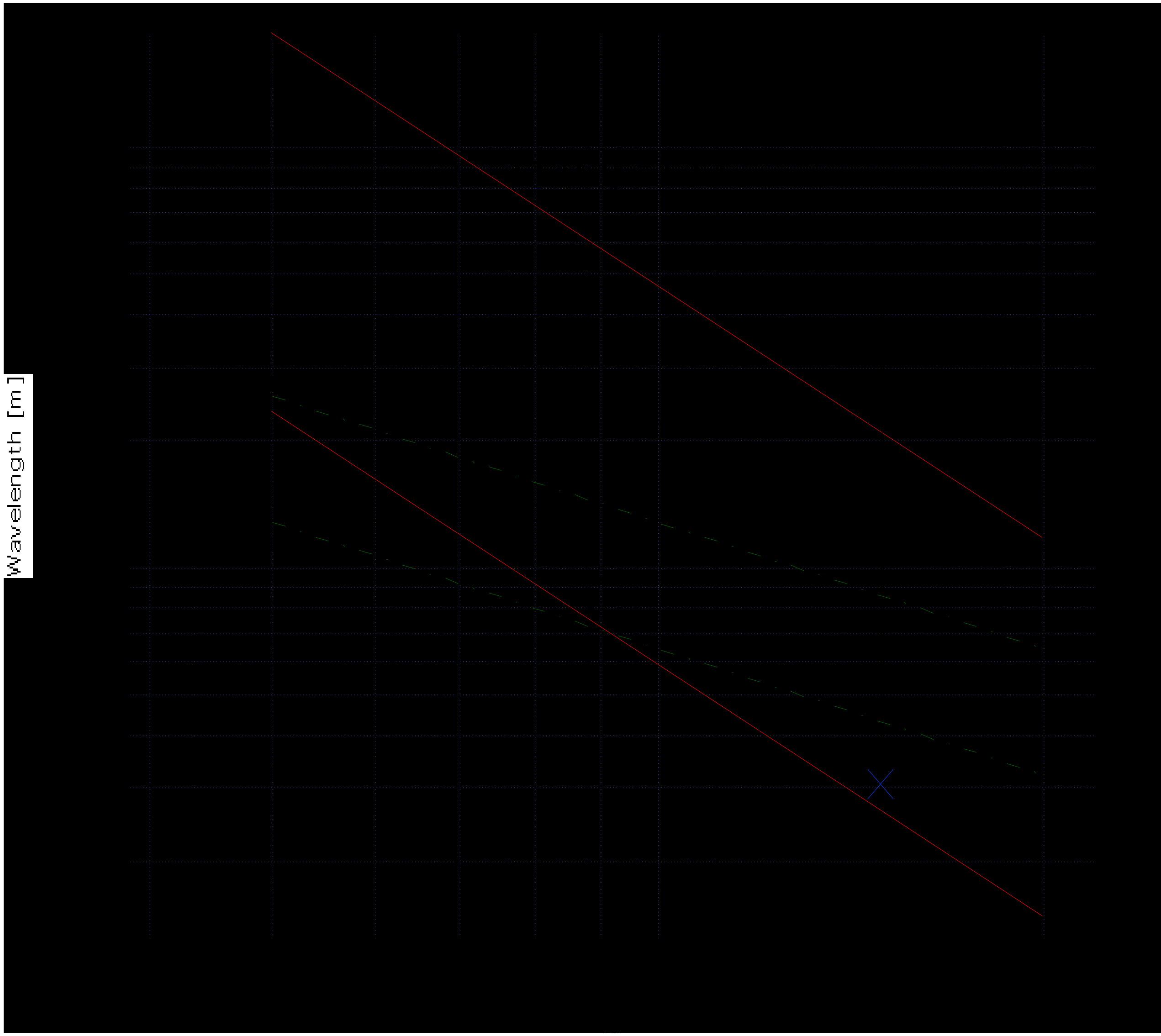
Where γ is the normalized electron beam total energy and

$K = 0.934\ \lambda_{rad}[\mathrm{cm}]\ B_{max}\ [\mathrm{T}]$

Is the normalized undulator field strength parameter

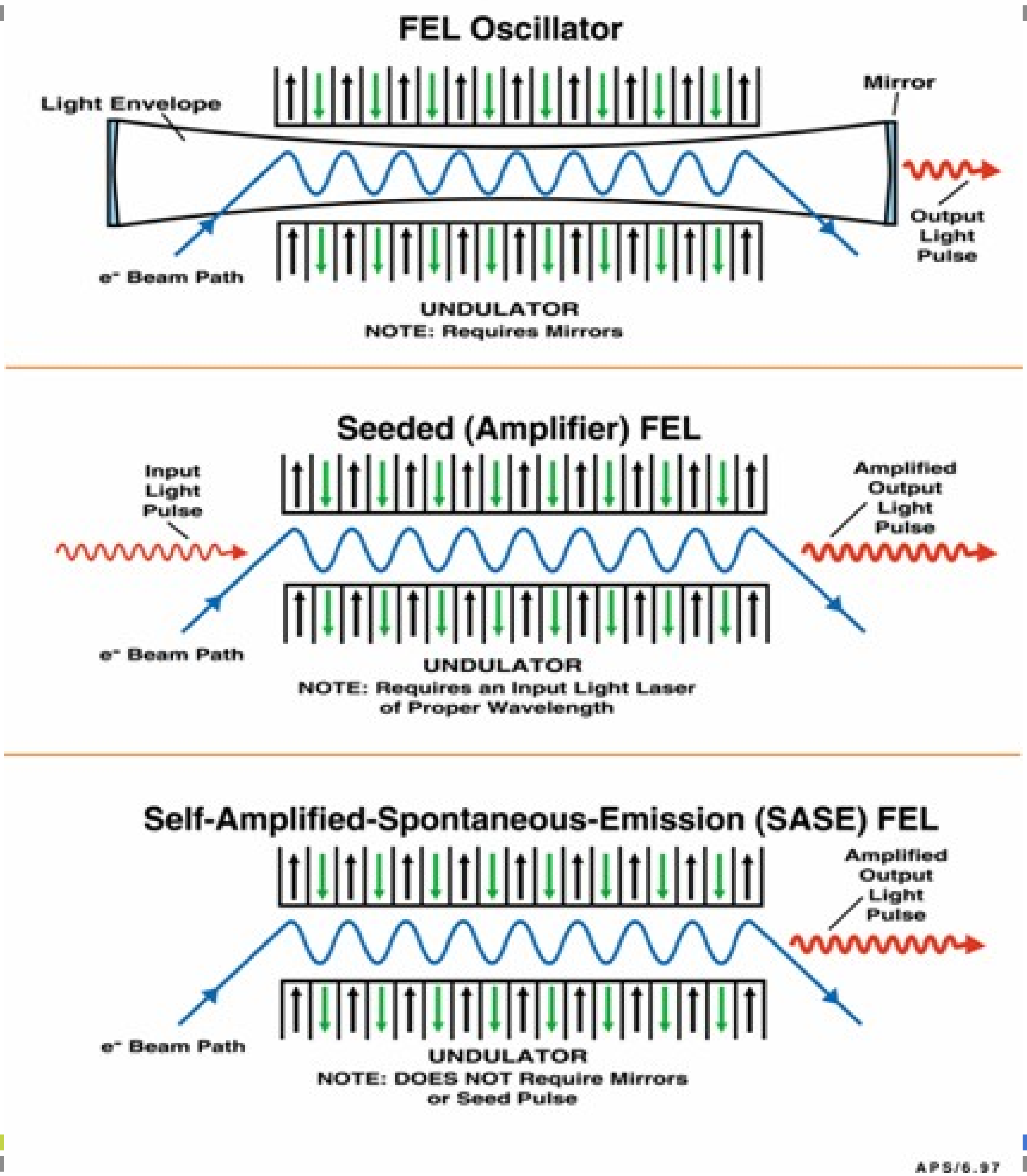


Wavelength Reach



- The resonant condition gives a slope of -2 on he log-log graph (red nes).
- Geometric emittance lecrease inversely with beam energy in a linac.
- FELs work best if the geometric emittance is ess that the photon beam emittance (TEM_{00} node) $\lambda/4\pi$ (green lines)
- Ones need to ealistically assess the apabilities of the linac and electron beam source

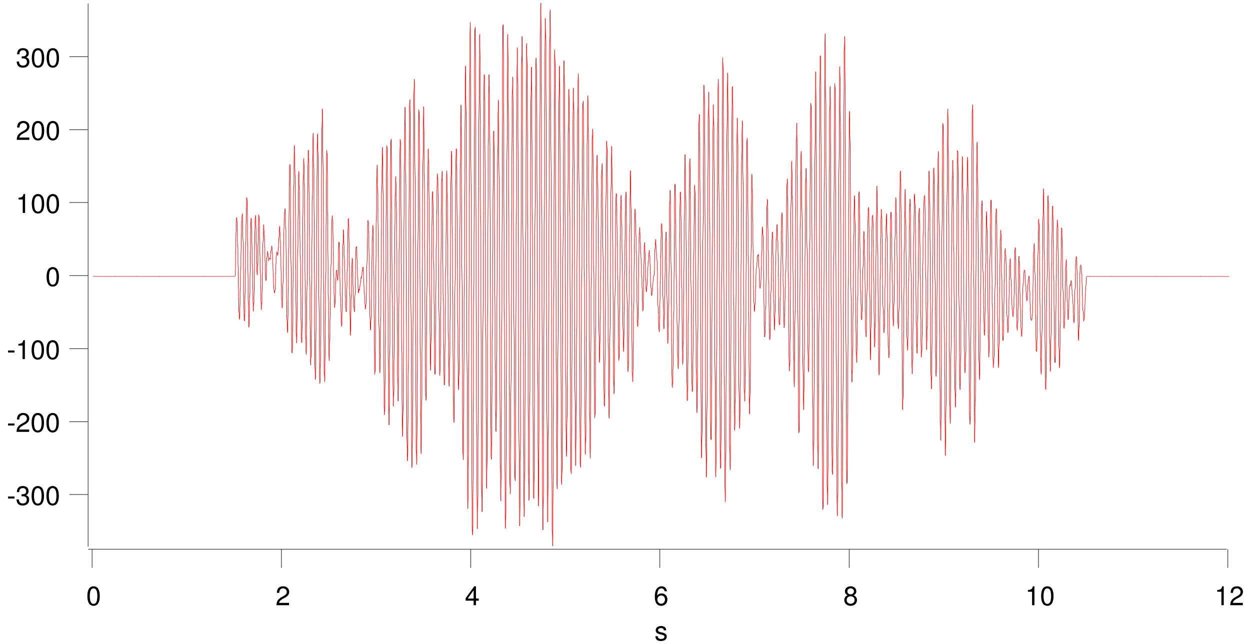
FEL Types: Oscillator, Seeded FEL, SASE



The Start of Microbunching

$$E_{tot}(t) = E_x(t)\sum_{j=1}^{N}\exp(i\phi_j)$$

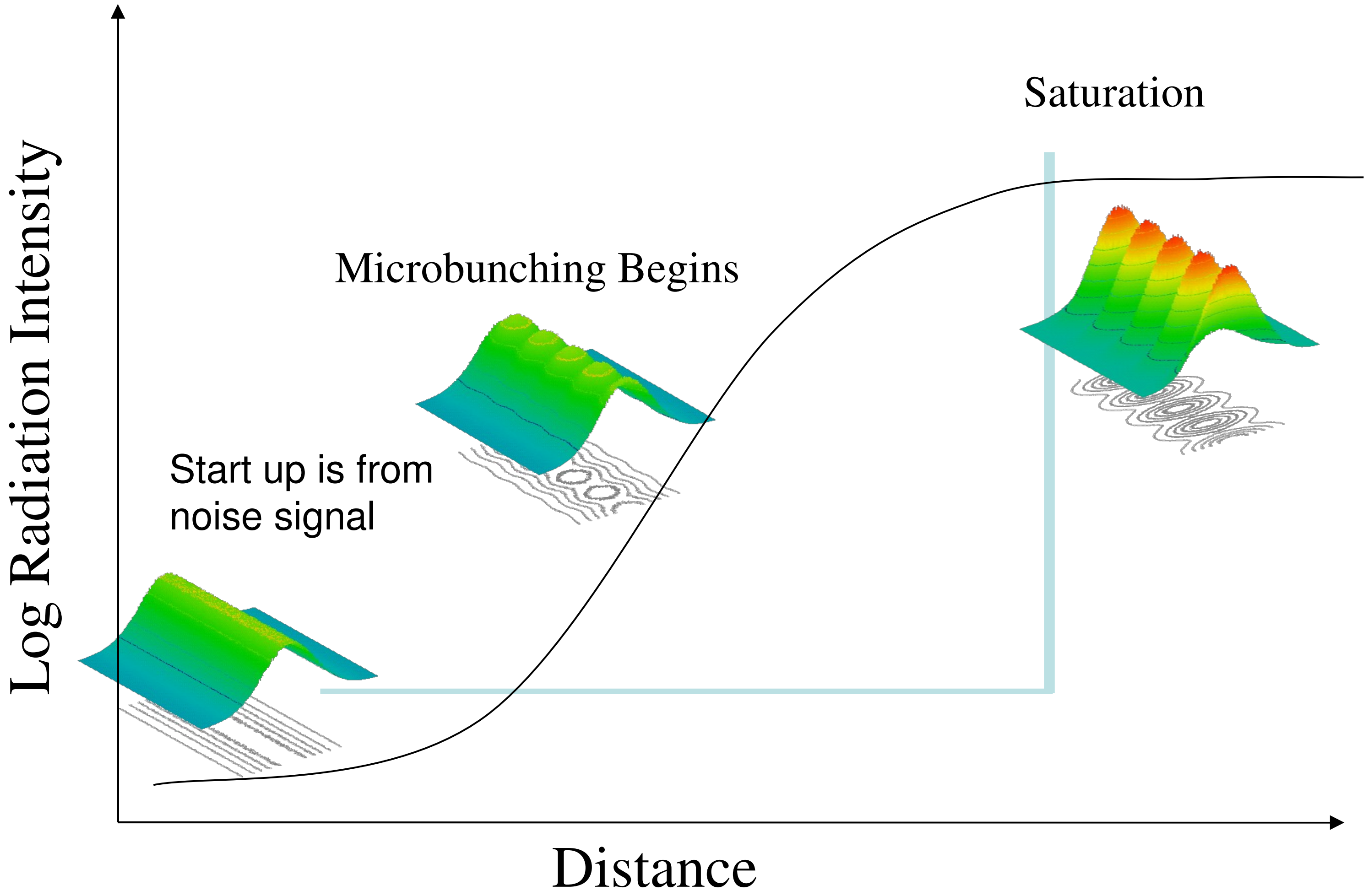
Coherent sum of radiation from N electrons



The SASE light consists of several coherent regions, also known as spikes, randomly distributed over the pulse length of the electron beam.

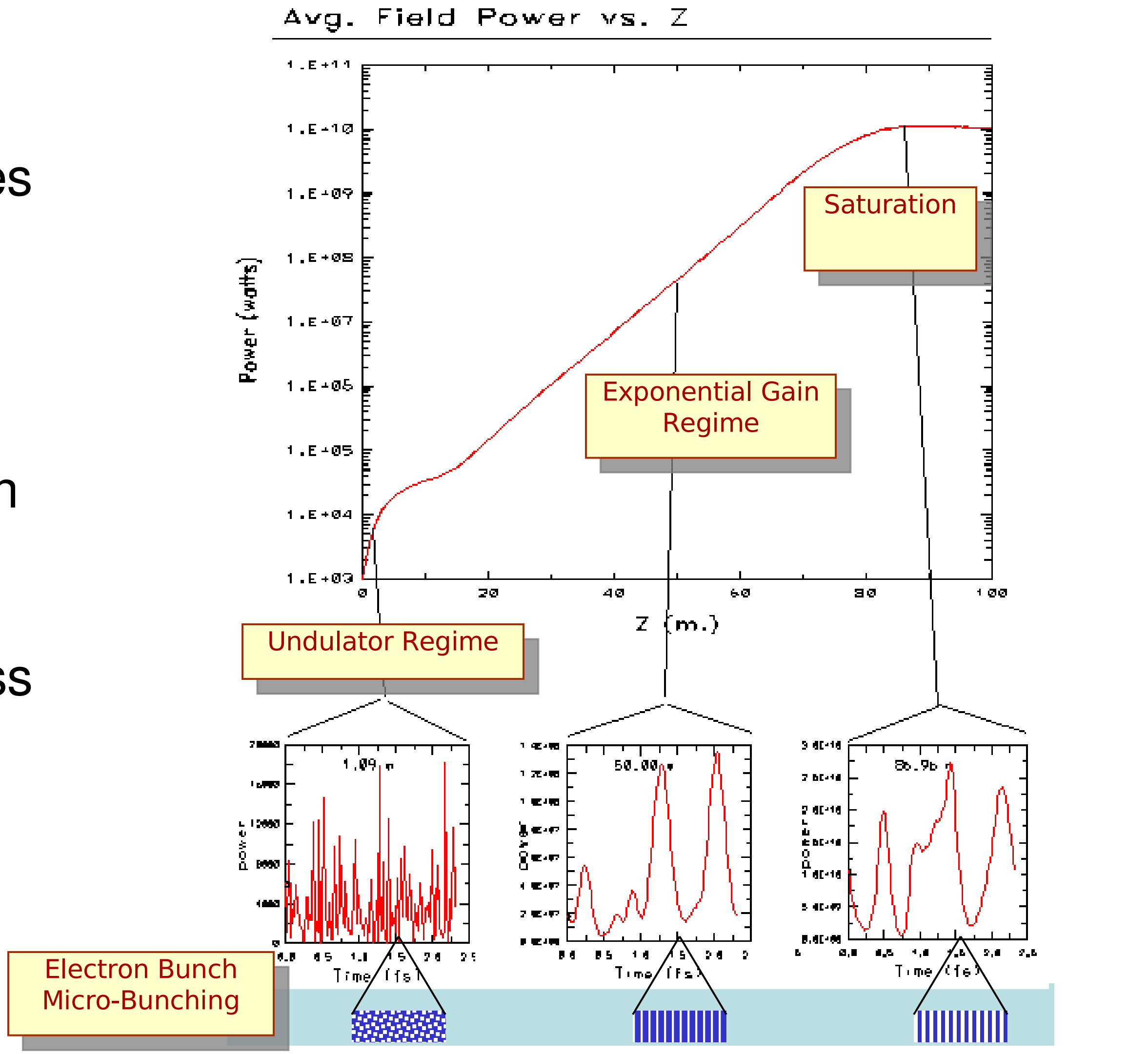
Self-Amplified Spontaneous Emission (SASE)

Exponential Growth



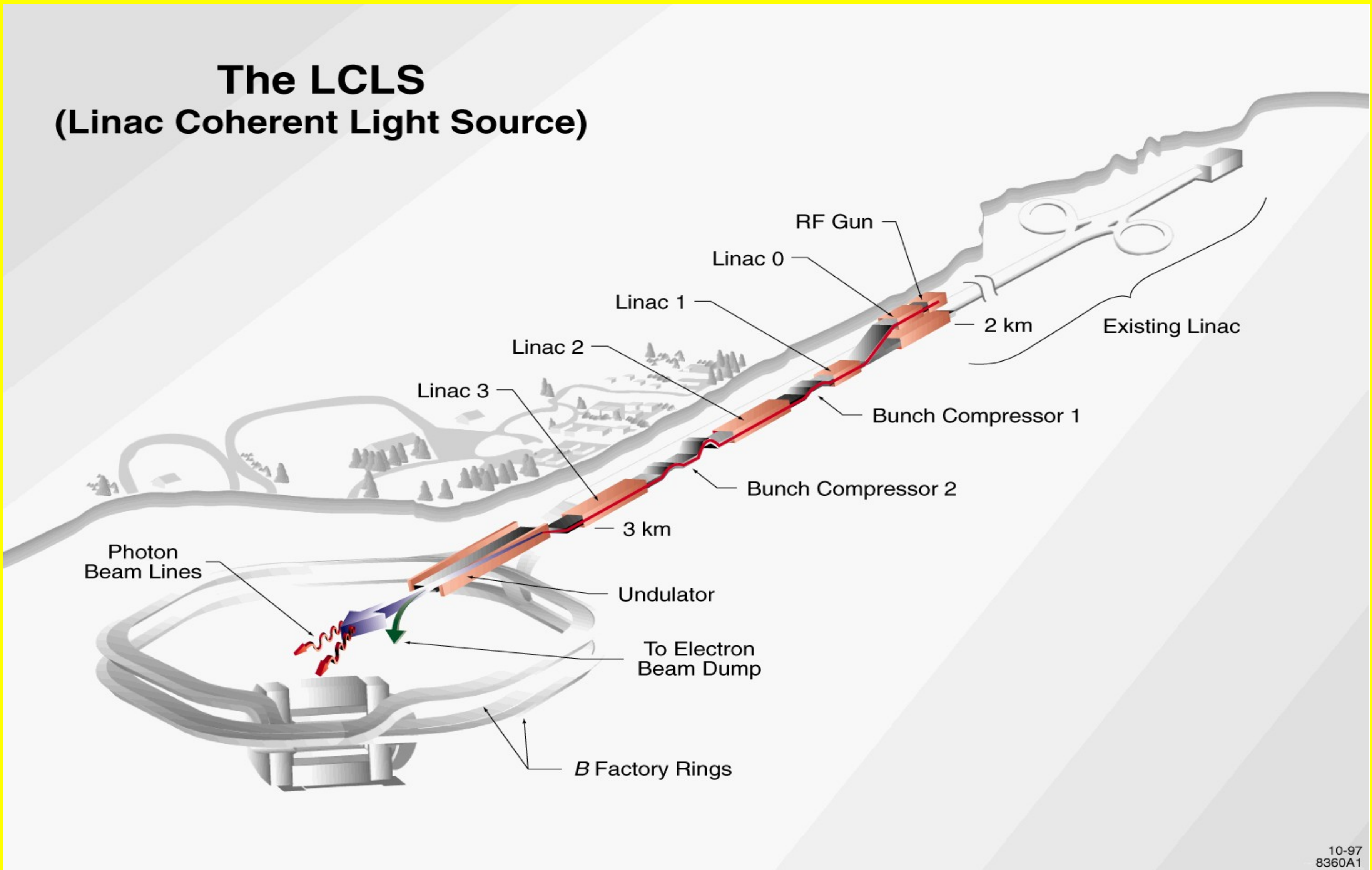
SASE FELs

Since they are regularly spaced, the micro-bunches produce radiation with enhanced temporal coherence. This results in a “smoothing out” of the instantaneous synchrotron radiation power (shown in the three plots) to the right) as the SASE process develops.



The LCLS

The LCLS: An X-ray Laser (1.5 Å)



Capabilities

Spectral coverage: 0.15-1.5 nm

To 0.5 nm in 3rd harmonic

Peak Brightness: 10^{33}

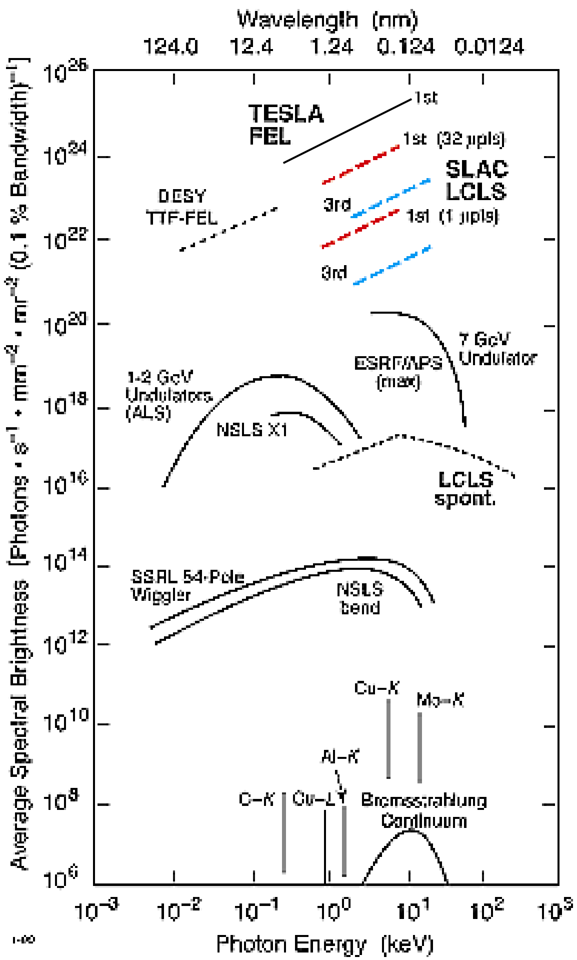
Photons/pulse: 10^{12}

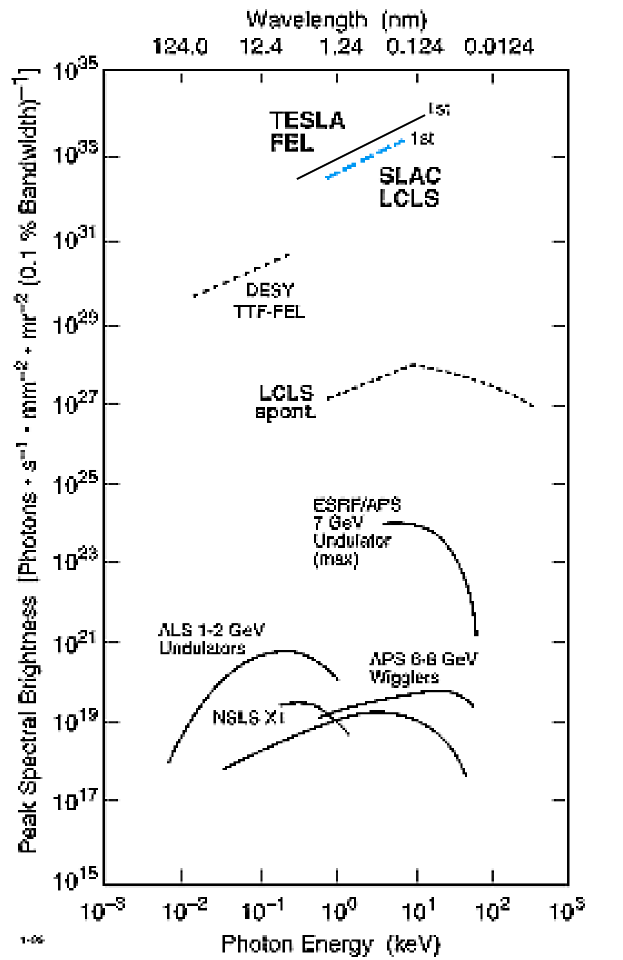
Average Brightness: 3 x 10^{22}

Pulse duration: <230 fs

Pulse repetition rate: 120 Hz

Upgrade – more bunches/pulse



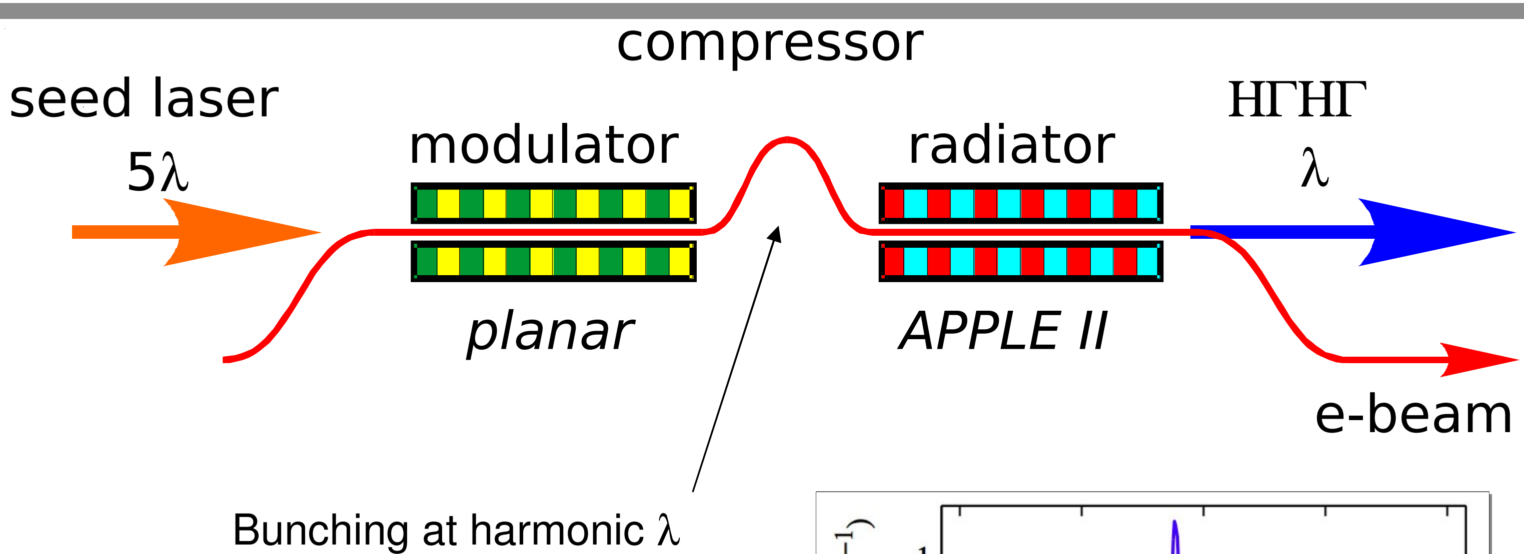


Benefits of a Seeded FEL

- A "seed" laser controls the distribution of electrons within a bunch:
  - Very high peak flux and brightness (comparable to SASE FELs)
  - Temporal coherence of the FEL output pulse
  - Control of the time duration and bandwidth of the coherent FEL pulse
  - Close to transform-limit pulse provides excellent resolving power without monochromators
  - Complete synchronization of the FEL pulse to the seed laser
  - Tunability of the FEL output wavelength, via the seed laser wavelength or a harmonic thereof
  - Reduction in undulator length needed to achieve saturation.

- Giving:
  - Controlled pulses of 10-100 fs duration for ultrafast experiments in atomic and molecular dynamics
  - Temporally coherent pulses of 500-1000 fs duration for experiments in ultrahigh resolution spectroscopy and imaging.
  - Future possible attosecond capability with pulses of ~100 as duration for ultrafast experiments in electronic dynamics

High Gain Harmonic Generation - HGHG



More compact and fully temporally coherent source, control of pulse length and control of spectral parameters.

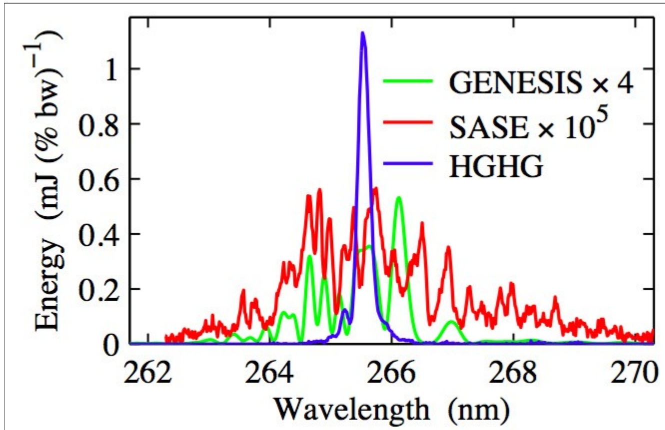
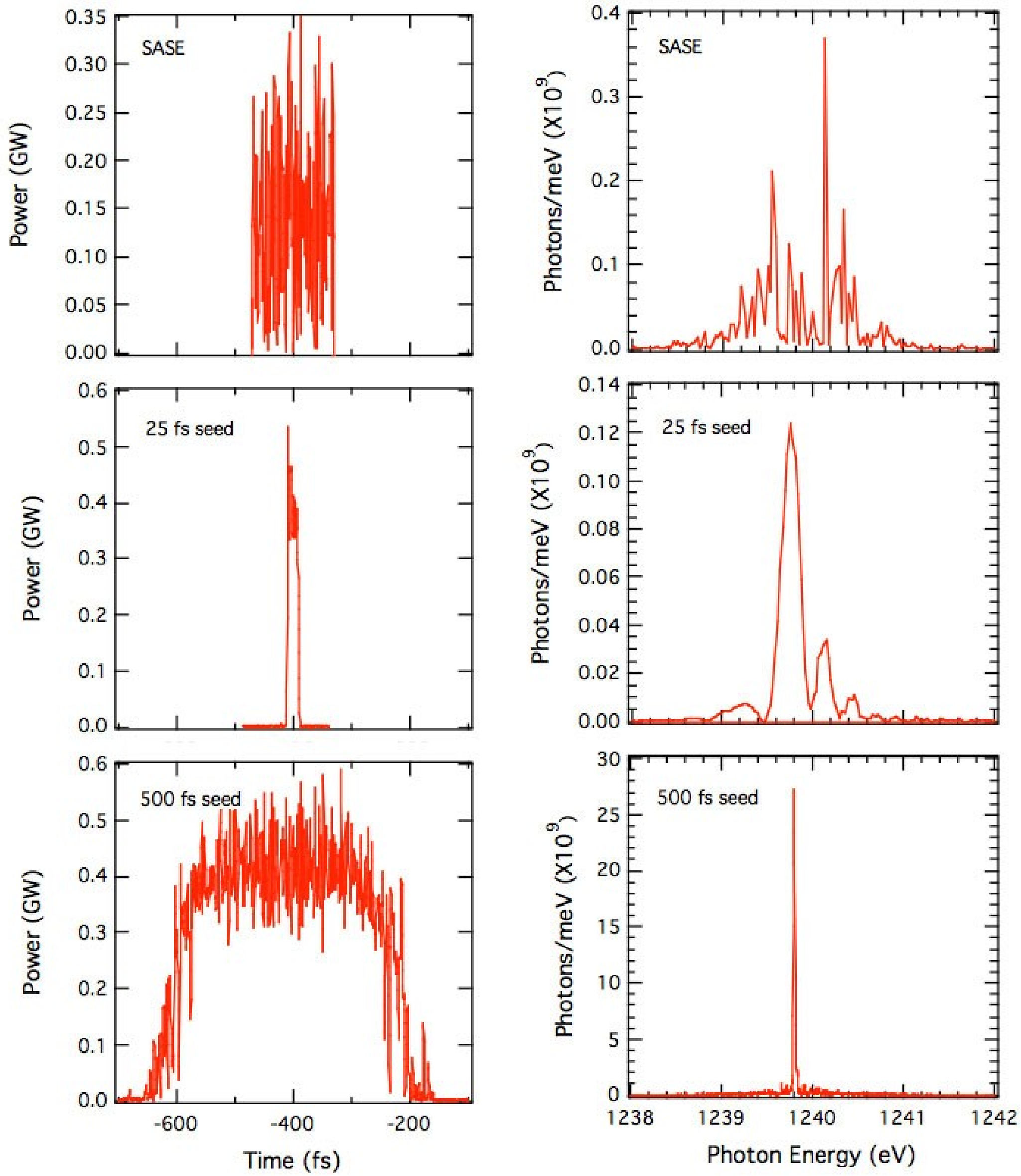


FIG. 4: Single shot HGHG spectrum for 30 MW seed (blue), single shot SASE spectrum measured by blocking the seed laser (red) and simulation the SASE spectrum after 20 m of NISUS structure (green). The average spacing between spikes in the SASE spectrum is used to estimate the pulse length.

Li-Hua Yu
DUV-FEL

FEL Seeding a Long Bunch



SASE

Seeded FEL
Short bunch

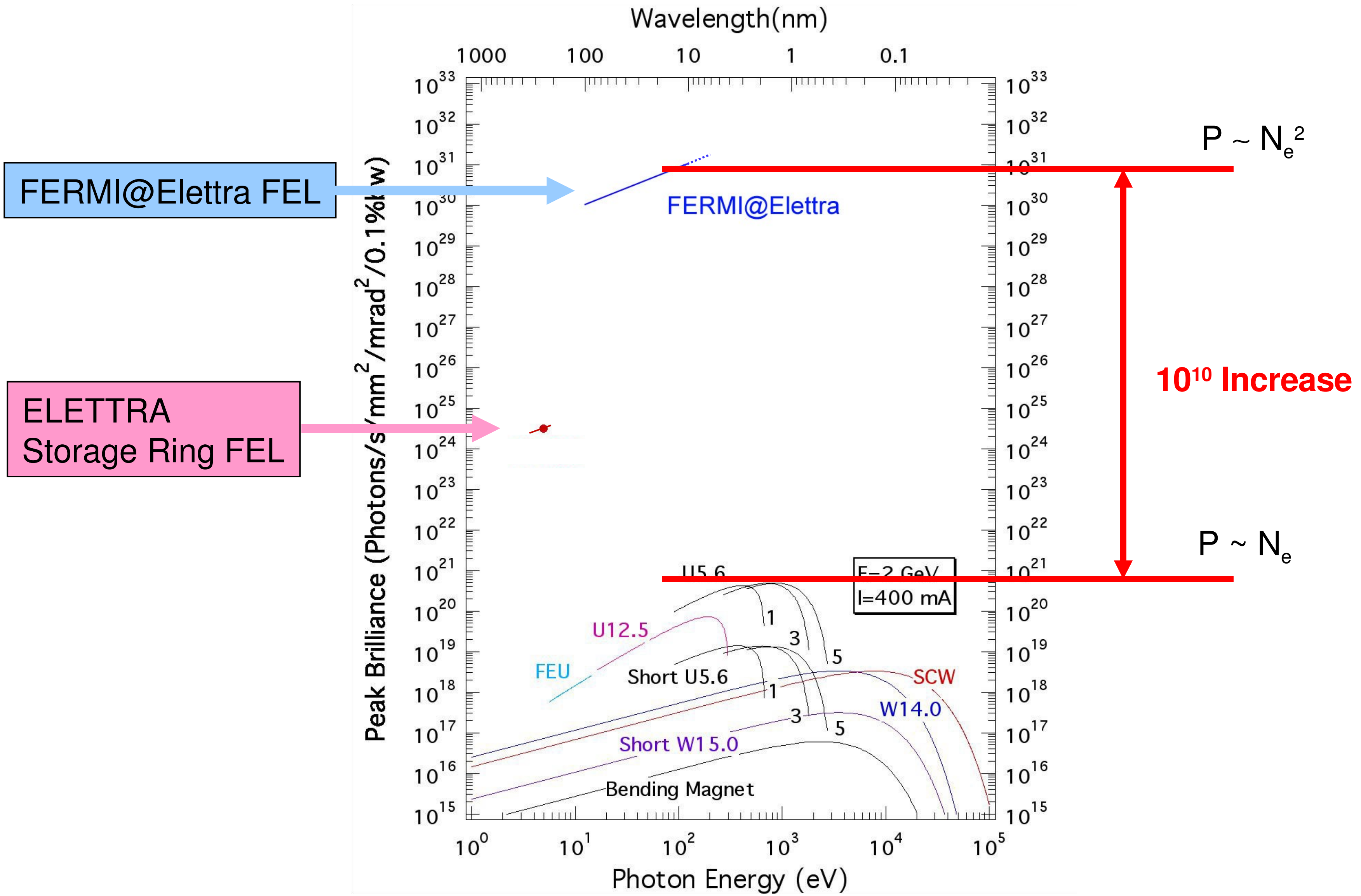
Seeded FEL
Long bunch

Courtesy of J. Corlett, LBNL

FERMI FEL Output Parameters

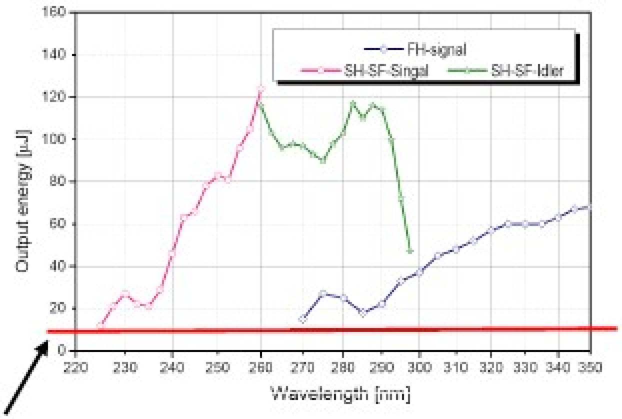
Parameter	FEL-1	FEL-2 (in discussion)
Wavelength range [nm]	100 to 20	40 to 10 (to 3?)
Output pulse length (rms) [fs]	< 100	> 200
Bandwidth (rms) [meV]	17 (at 40 nm)	5 (at 10 nm)
Polarization	Variable	Variable
Repetition rate [Hz]	50	50
Peak power [GW]	1 to >5	0.5 to 1
Harmonic peak power (% of fundamental)	~2	~0.2 (at 10 nm)
Photons per pulse	10^{14} (at 40 nm)	10^{12} (at 10 nm)
Pulse-to-pulse stability	30 %	~50 %
Pointing stability [rad]	< 20	< 20
Virtual waist size [m]	250 (at 40 nm)	120
Divergence (rms, intensity) [rad]	50 (at 40 nm)	15 (at 10 nm)

FERMI Brightness



FERMI Seed Laser: Phase I

Main works since last MAC
-Tests HE TOPAS completed



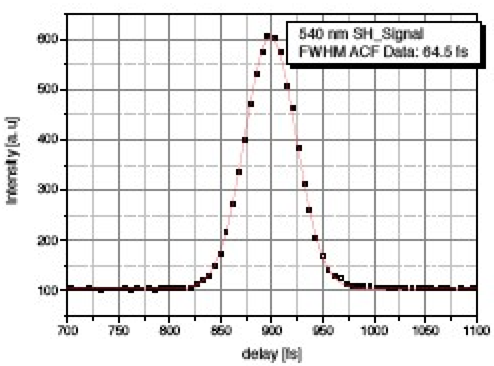
100MW level

Tuning curve in UV

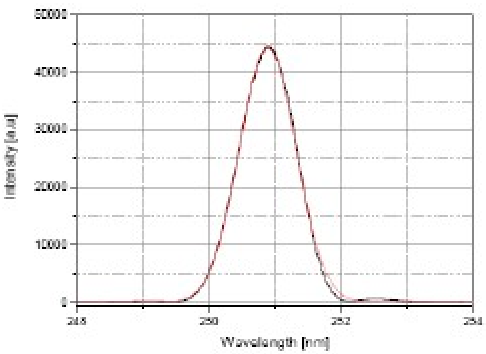
TOPAS

Regen Amp

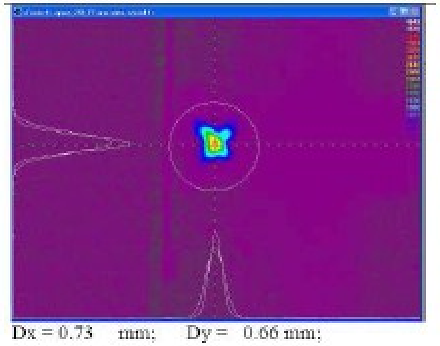
Seed fibre laser



Typical autocorrelator trace



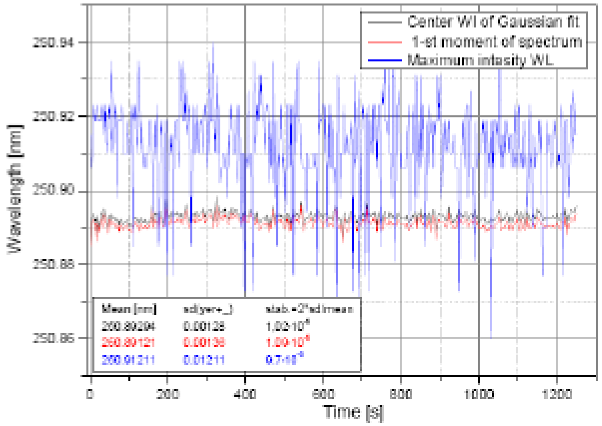
Typical Spectrum



Spatial distribution at focus

Courtesy M. Danailov

FERMI Seed Laser: Phase I



Wavelength stability measurement at 250 nm (SH-SF-signal)
Center WL Gaussian fit: 1×10^{-5}
First moment of spectum: 1.1×10^{-5}
Spectrum peak: 9.7×10^{-5}

Parameter	Specs	Measured	Note
Tunability range (nm)	240-360	230-350	
Peak power (MW)	100	>150	Assuming 100 fs
Pulse duration (fs)	100	<100	Estimated, TBM
Timing jitter (fs RMS)	<100 fs	TBM	
Pointing stab. (μrad)	<20	TBM	
Wavelength stab.	10^{-4}	$<10^{-4}$	
Beam quality (M^2)	<1.5	TBM	For SH-SF-Idler

Measured performance for the 100 fs regime (1 ps not needed!)

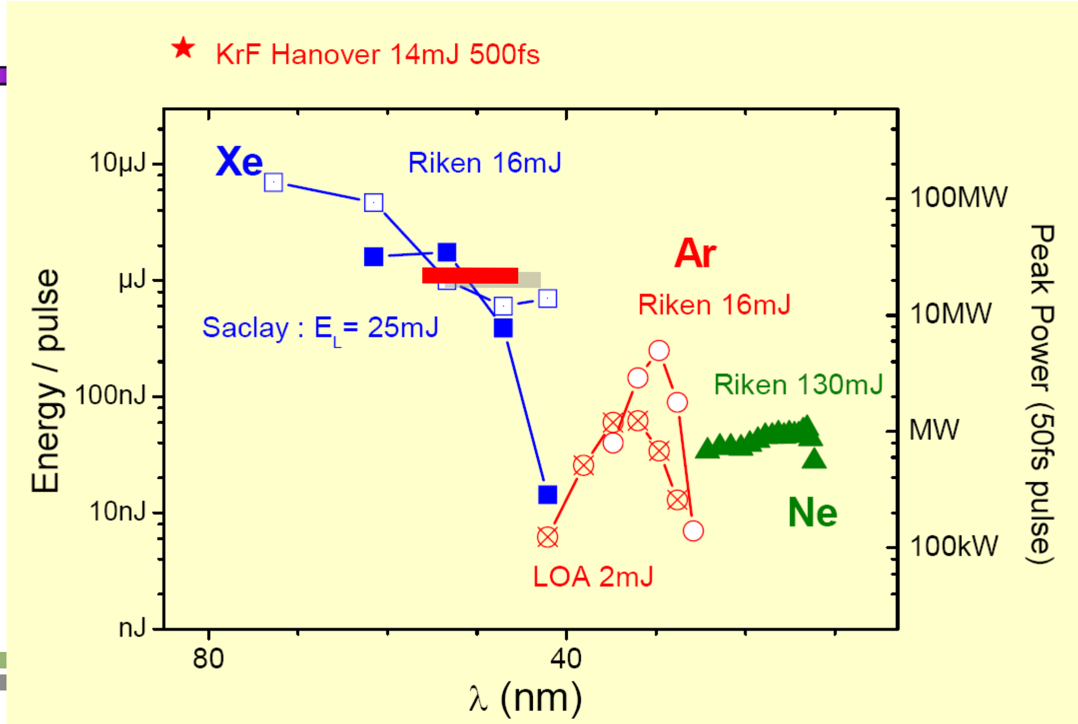
Courtesy M. Danailov

Seeding with an HHG Source?

Synchronized Ti:Sapphire Oscillator → Pulse Shaping → Ti:Sapphire Amplifier τ = 30 fsec λ = 800 nm E = 14 mJ

tunable radiation in
120 nm-12 nm range

FEL ← Transport Optics ←



- Complicated
- Tunability not proven

BUT

More Comments About an HHG Seed

- Direct Seeding Option
  - But now one is limited to the wavelength cutoff of the HHG system
    - 10 nm perhaps a little shorter.
    - 10 kw to 100 kw
      - *Too low for HGHG seed*
- Pulse length
  - Tends to be on the order of 10 fs to 20 fs, even shorter if needed, but difficult to make significantly longer.

Seeded HHG Source

A "problem" with using a HHG source as a seed is that the power is not that high.

The "problems" with using a plasma laser are the timing stability, pulse duration, and longitudinal coherence.

Combined however they could make an ideal seed for future FELs.

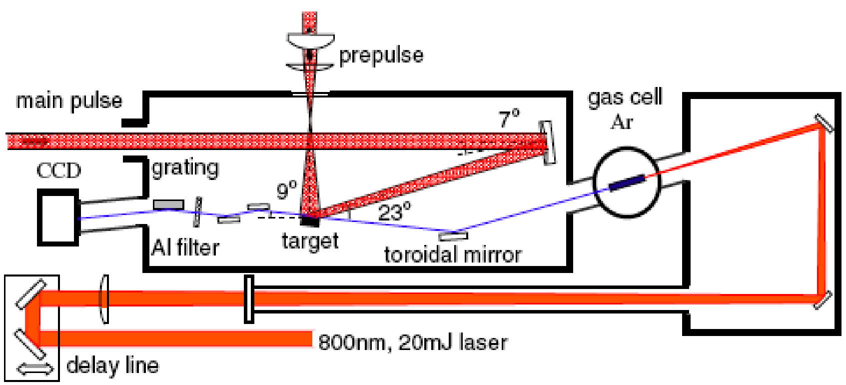


FIG. 1 (color online). Schematic representation of the seeded soft-x-ray-laser amplifier based on a grazing incidence pumped plasma.

Wang et al., Phys. Rev Lett. **97** 123901 (2006)

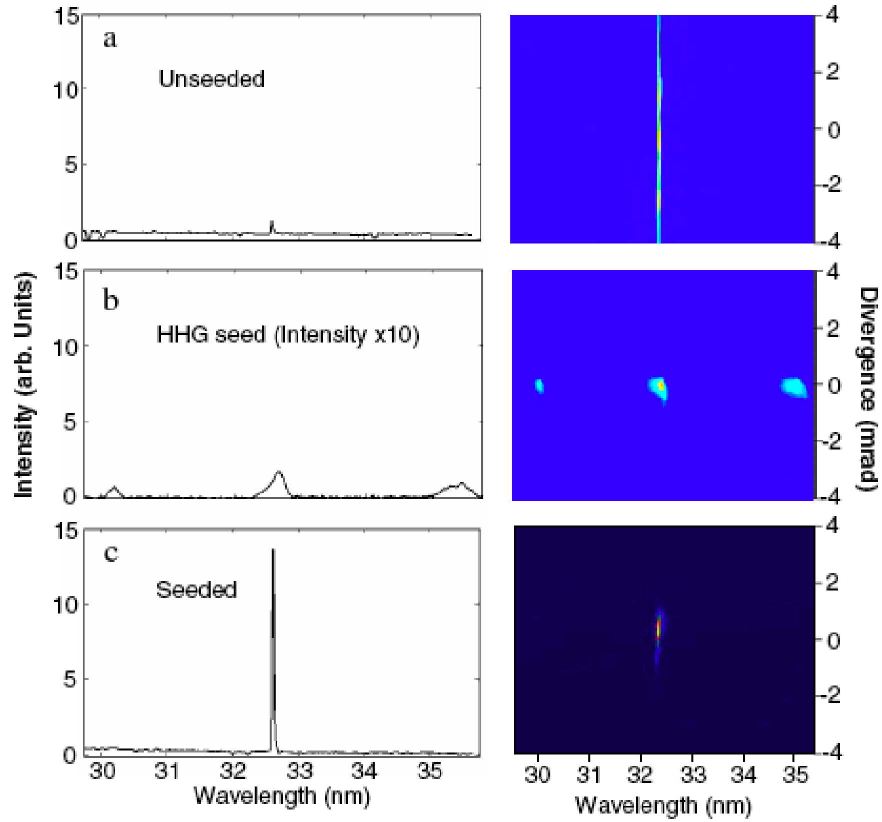


FIG. 2 (color online). Spectra illustrating the relative intensity and beam divergence for the (a) unseeded 32.6 nm soft-x-ray-laser amplifier, (b) high harmonic seed pulse, and (c) seeded soft-x-ray-laser amplifier. The length of the plasma amplifier is 3 mm. The intensity scale of the seed pulse is magnified by 10 times.

User Requirements & Science

User Requirements

- 100 - 10 nm range (and less) - fully tuneable & polarised coherent radiation
- 100’s MW to GW’s of peak power
- 10^{13} to 10^{14} photons/pulse
- 0.05 to > 1ps photon pulse lengths
- good pointing stability
- reasonable pulse to pulse timing jitter
- good pulse reproducibility ~10% $\Delta I/I$

Science

- chemical reaction dynamics
- study of the electronic structure of atoms, molecules and clusters
- biological systems
- inhomogeneous materials on a microscopic scale
- geophysics and study of extra-terrestrial materials
- material properties under extreme conditions (pressure, temperature, etc.)
- surfaces and interfaces
- nano-structures and semiconductors
- polymers and organic materials
- magnetism and magnetic materials
- superconductors and highly correlated electronic materials

Low Density Matter BL (Acting Coordinator: F. Parmigiani)

•**Cluster and nanoparticle spectroscopy**
Spokespersons: **F. Stienkemeier, B. von Issendorff** (Univ. of Freiburg-D)
•**Spectroscopic studies of reaction intermediates**
Spokesperson: **S. Stranges** (University of Rome La Sapienza)
•**Atomic, Molecular and Optical Science Beamline**
Spokesperson: **K. Prince** (Sincrotrone Trieste)
•**Ultrafast processes and imaging of gas phase clusters and nanoparticles**
Spokespersons: **T. Möller, C. Bostedt (TU-Berlin)**

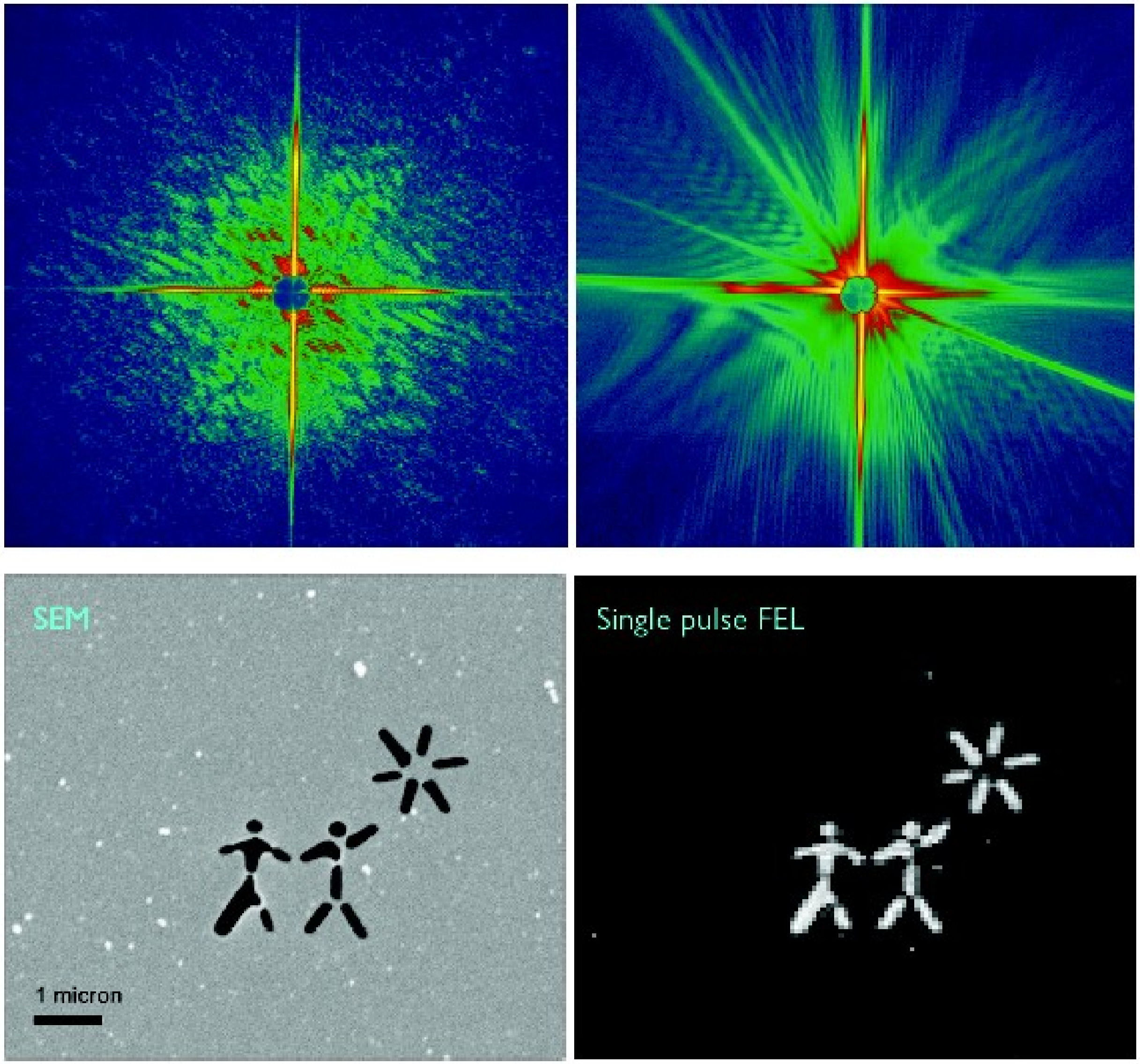
Imaging and Coherent Optics BL (Coordinator: M. Kiskinova)

•**Ultrafast coherent imaging at Fermi**
Spokesperson: **H. Chapman** (LLNL-CA) , **J. Haidu** (Stanford University and Uppsala University)
•**Full Field X-ray Microscopy and lenseless imaging**
Spokespersons: **M. Kiskinova** (ST-Italy), **B. Kaulich**, (ST-Italy),
T. Wilhein, IXO, Rhein Ahr Campus Remagen, Germany

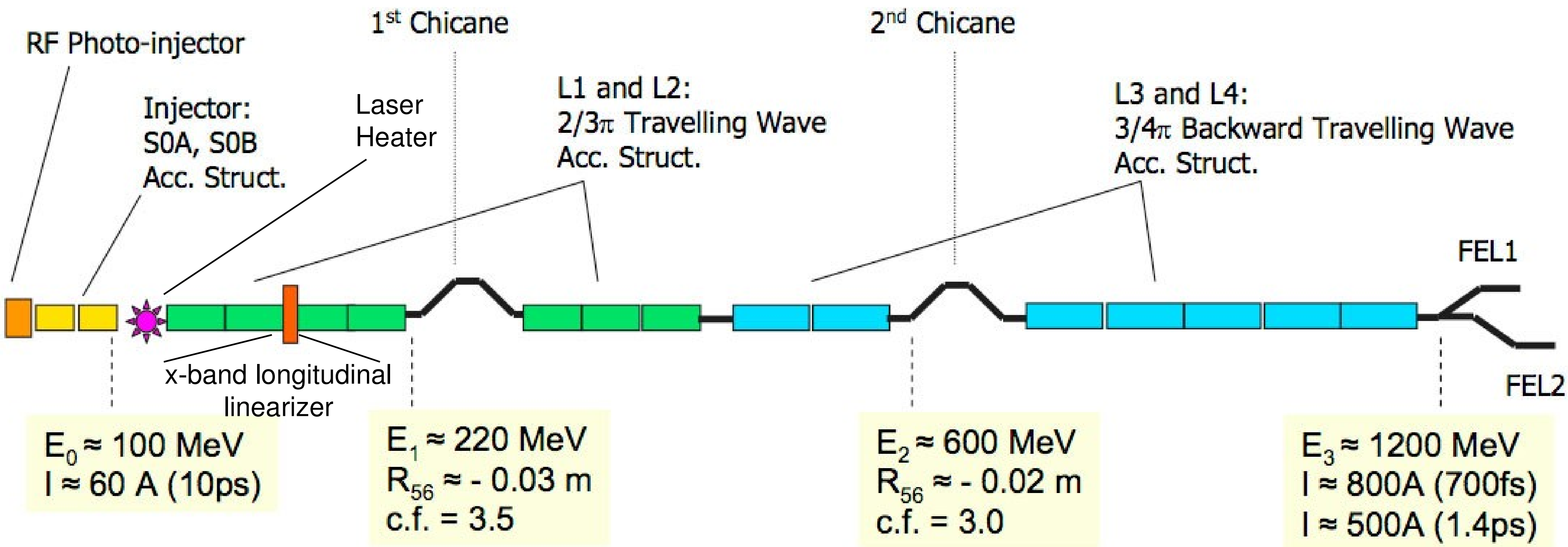
Elastic and Inelastic Scattering BL (Coordinator C. Masciovecchio)

•**Timer and Timex**
Spokespersons: **C. Masciovecchio (Elettra0 - A. Di Cicco (UNICAM & Univ. Paris VI)**
- G. Ghiringhelli (POLIMI)

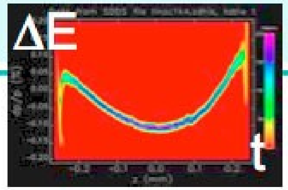
THz beamline (Spokesperson Lupi -La sapienza Roma- under evaluation)


SEM
1 micron
Single pulse FEL

Schematic layout of the FERMI accelerator

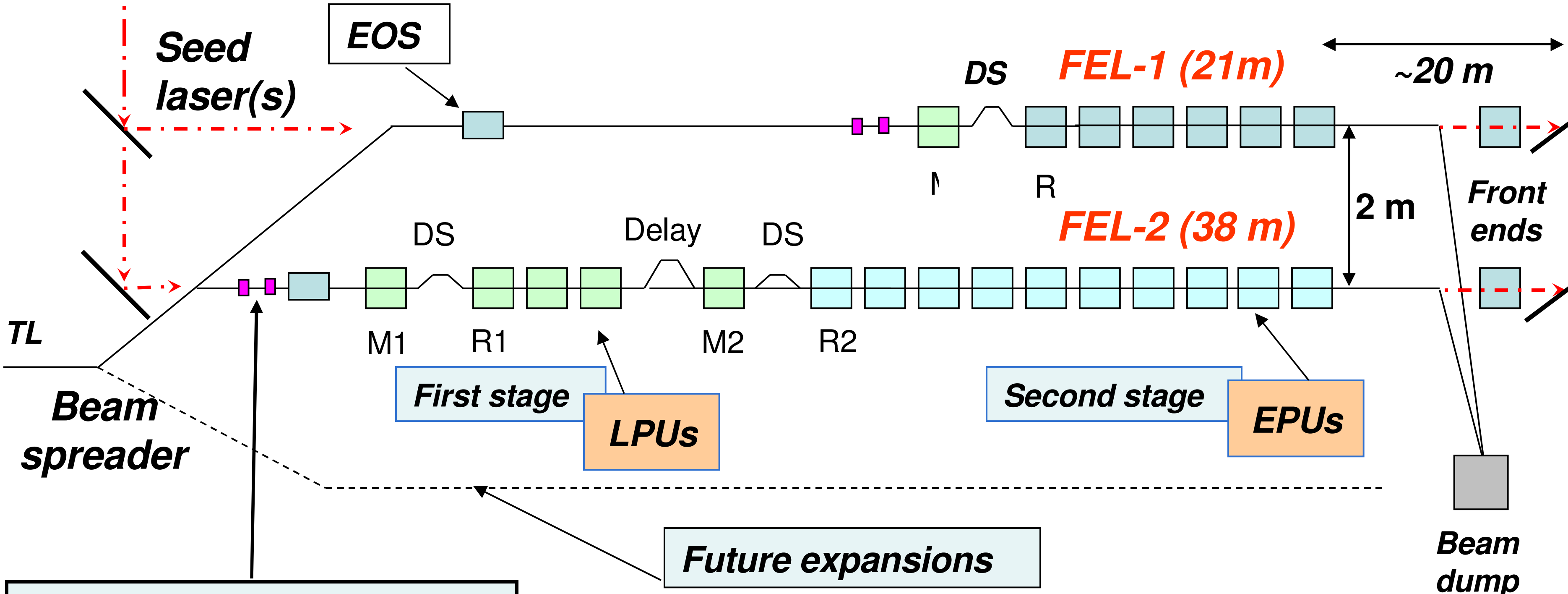


	"Short" bunch	*"Medium" bunch*	*"Long" bunch*
Bunch length	200 fs (flat part)	700 fs (flat part)	1.4 ps (flat part)
Peak current	800 A	800 A	500 A
Emittance(slice)	1.5 μm	1.5 μm	1.5 μm
Energy spread(slice)	<150 keV	<150 keV	<150 keV
Flatness, $|d^2E/dt^2|$		<0.8 MeV/ps²	<0.2 MeV/ps²



Mostly FEL1 **Mostly FEL2**

Conceptual layout of the FERMI FELs, transport line, spreader and beam dump



FEL-2 Configurations
- Fresh bunch
- Whole bunch
- HHG seeding

Description:

- *undulator axes separated by 2 m*
- *transverse/energy collimation incorporated*
- *space for matching optics, BPMs, EOS, other diag.*
- *small angles to CSR effects: ~ 6 deg total*

Limitation

Bunching at the *nth* harmonic:

$$b_n = \exp -\frac{1}{2} n^2 \sigma_\gamma^2 D^2 \quad J_n(nD\Delta\gamma)$$

n: harmonic number

σ_γ: relative energy spread

D: dispersive section strength

$\Delta\gamma$: relative energy modulation

b_n significantly different from zero only if:

On the other hand: $(\sigma_\gamma)_{tot} = \sqrt{\sigma_\gamma^2 + \Delta\gamma^2} \quad \sigma_\gamma \sqrt{1+n^2} < \rho$

→ Limitation on maximum *n*

Is it possible to reach shorter wavelengths (i.e., 10 nm) in a single stage?

yes, but only provided that:

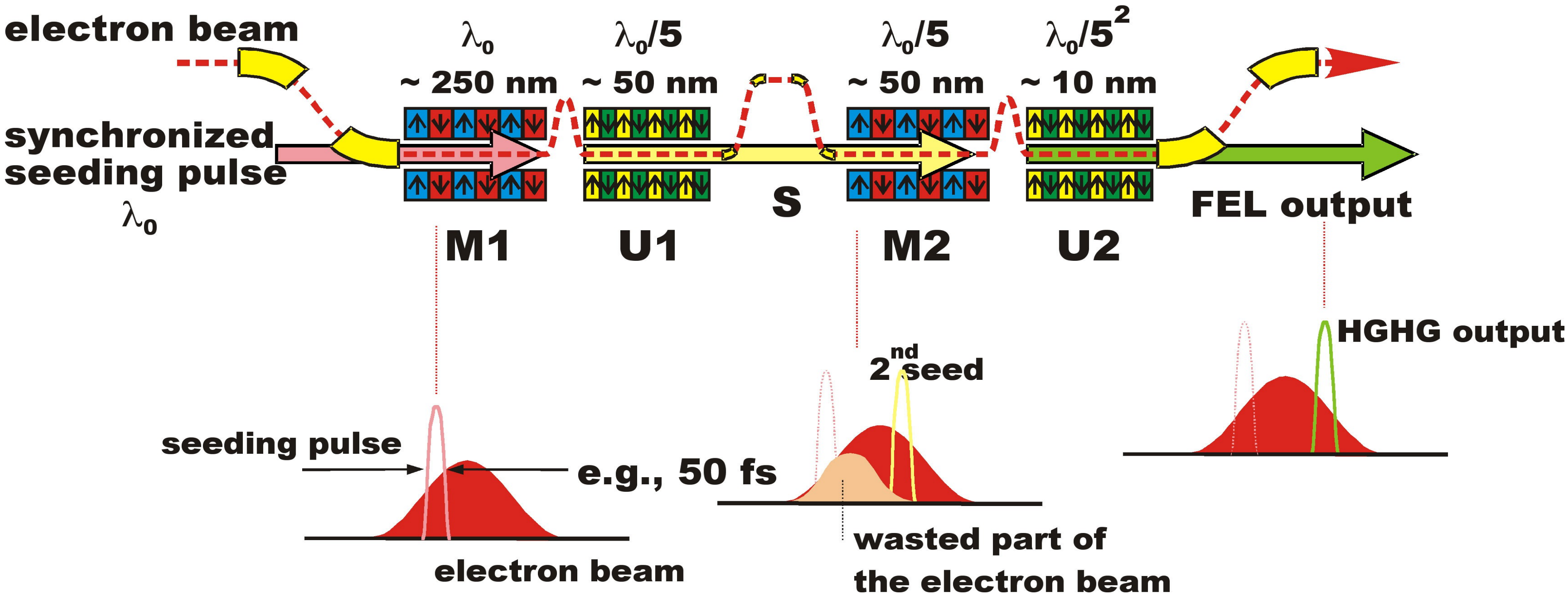
the seed wavelength is reduced

and/or

- the total relative energy spread is reduced

Cascaded HGHG

2-Stage cascade HGH

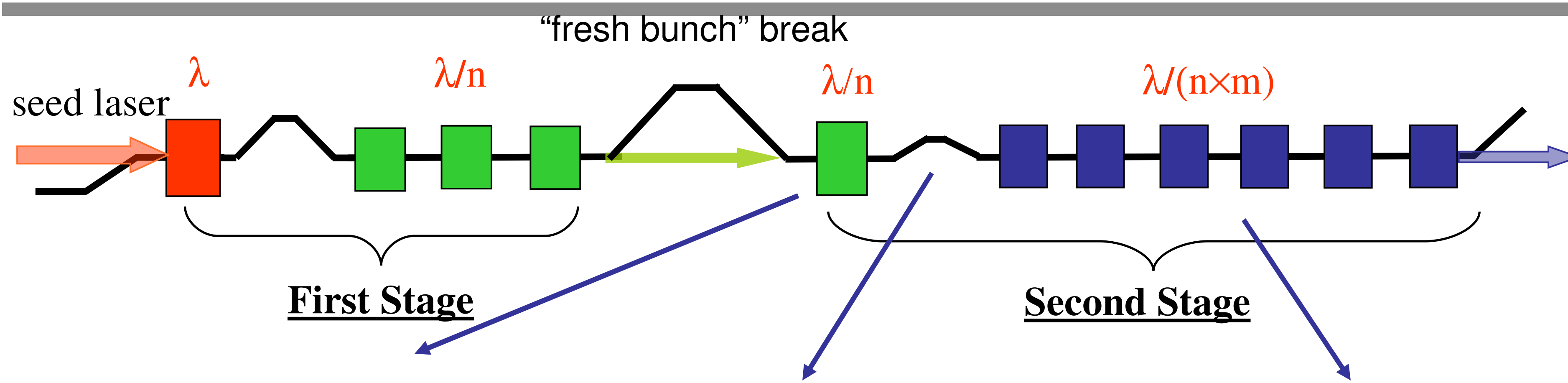


Here one upconverts the frequency by a very large amount. In this example by 25.

But at a price…complexity.

If only the seed wavelength were shorter…

FEL-2 (40-10 nm): fresh-bunch configuration



2nd Stage Modulator

Parameter	*Value*
Type	Planar
Structure	One segment
Period	6.5 cm
K	2.4 - 4
Length	2.08 m

Dispersive section

Parameter	*Value*
R_{56}	~ 6.4 μm (at 10 nm)
Length	~ 1 m

Radiator

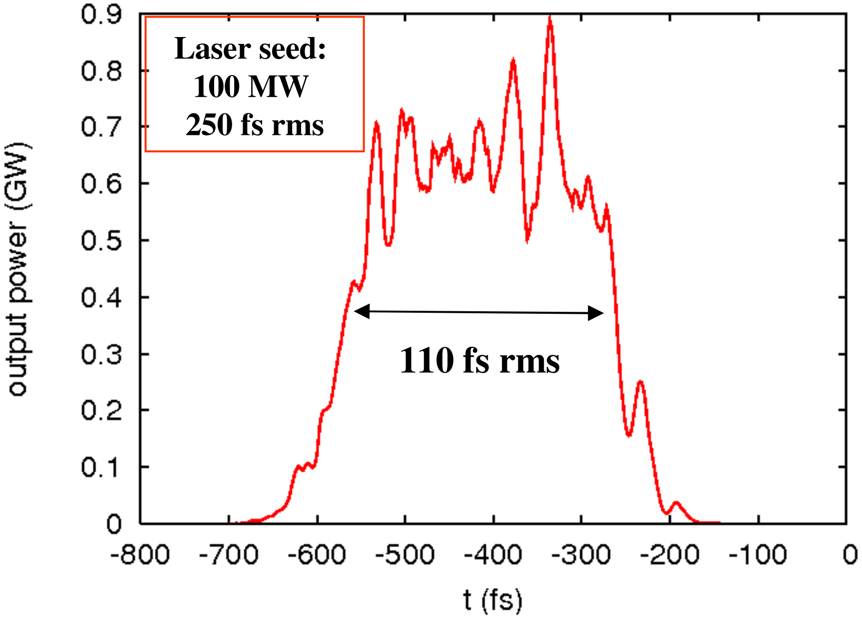
Parameter	*Value*
Type	Apple
Structure	Segmented
Period	5 cm
Segment length	2.4 m
K	1.1 - 2.8
Break length	1.06 m
Total length	19.7 m

Courtesy G. De Ninno

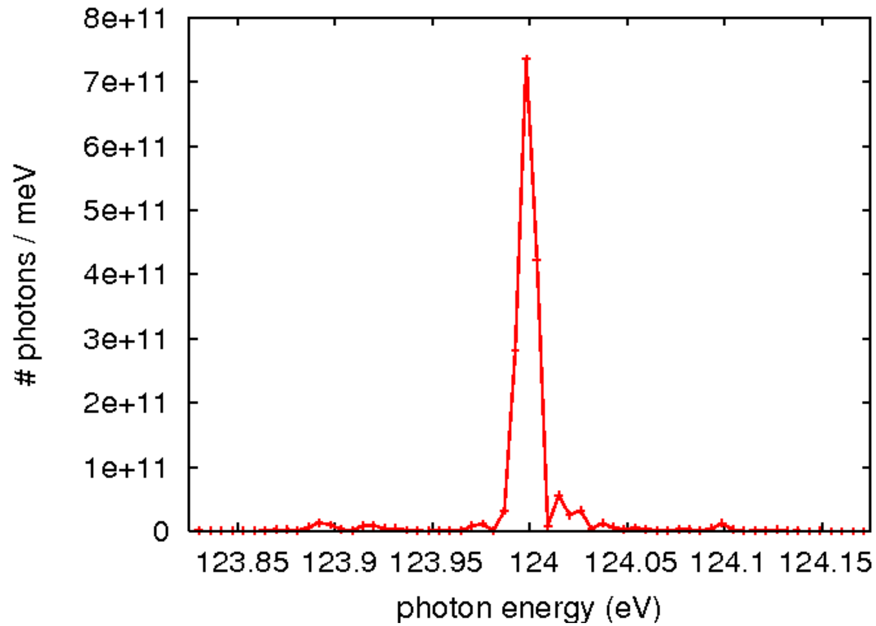
Total length FEL-2 ~ 37.5 m

FEL-2: Results at 10 nm (fresh bunch)

Output power profile



Output spectrum

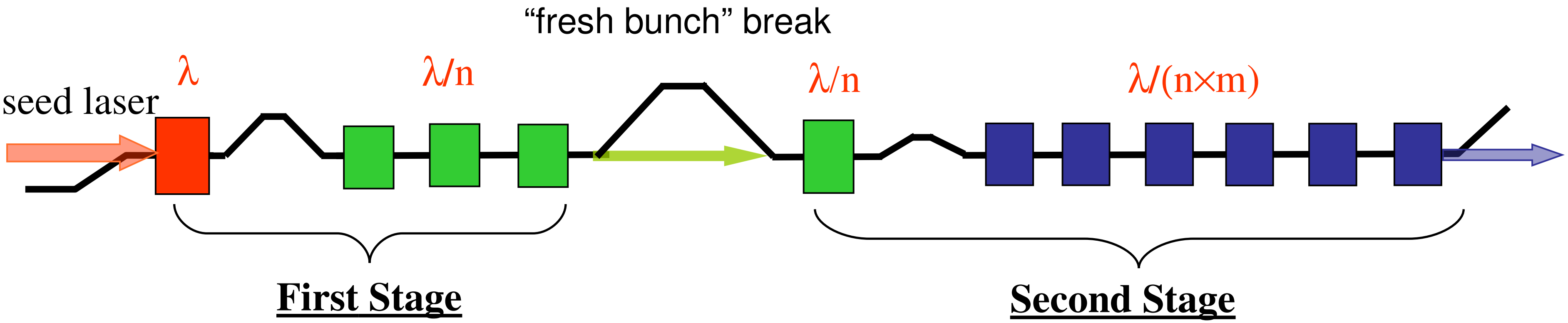


10^{13} photons (93% in single transverse mode)

5 meV bandwidth (rms) (1.5 x transform limit)

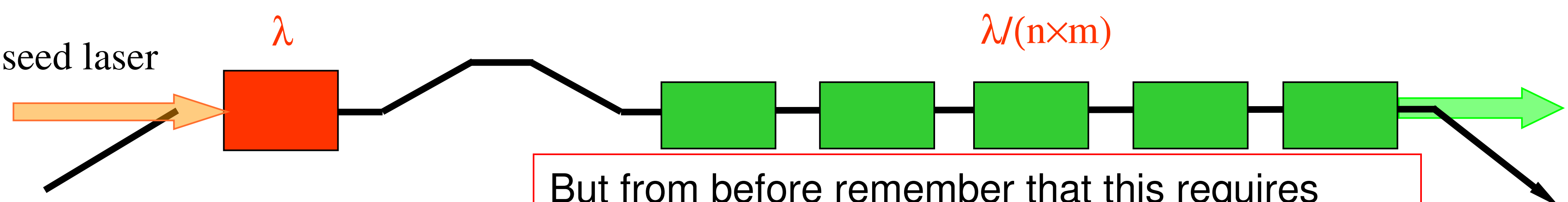
Courtesy G. De Ninno

FEL-2 : CDR configuration



Is it possible to cover the FEL-2 tuning range in a single stage?

(as similar as possible to FEL-1)



But from before remember that this requires either smaller energy spread or shorter wavelength seed

Courtesy G. De Ninno

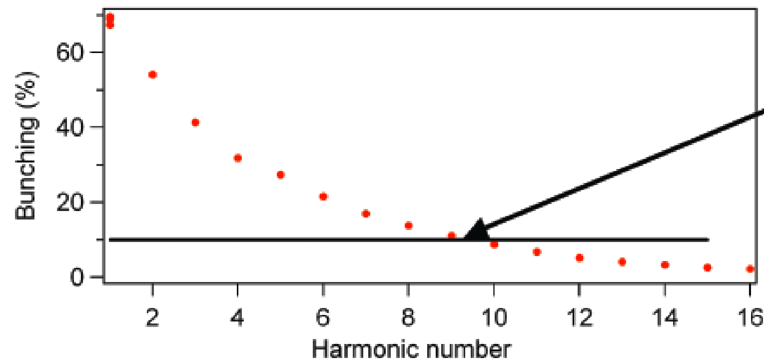
Using HHG as a Seed?

Trying to reach shorter wavelengths...

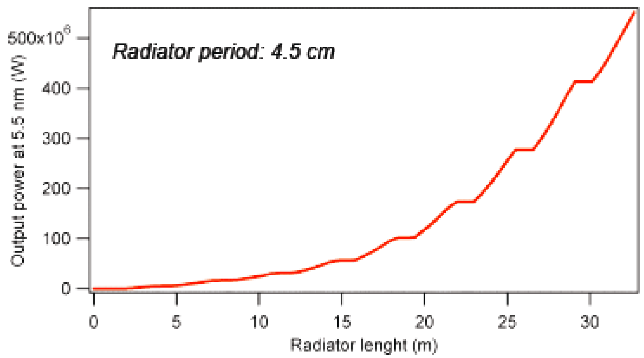
with enhanced e-beam parameters

Electron-beam energy: **1.5 GeV**	Shortest wavelength: 50 nm
Peak current: 750 A	Peak power: 1-5 MW
Energy spread: **100 KeV**	

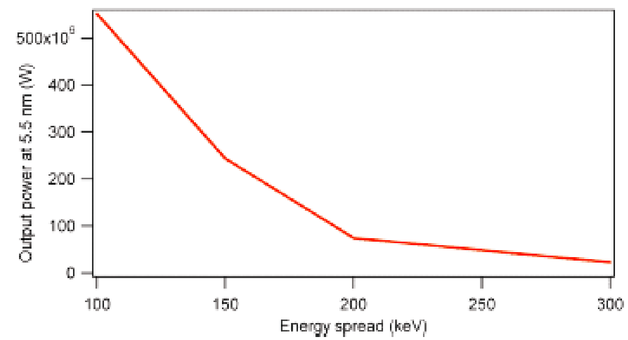
Limit at the 9th harmonic (5.5 nm)



Power along the radiator



Sensitivity to energy spread



Courtesy G. De Ninno

Switching Gears

- I.e. Semi related topics
- Enough for the current FERMI thought process
- What About the Future
- Two Thoughts
  - Wavelength Shifting using beam gymnastics
  - Attosecond pulses

Wavelength Shifting

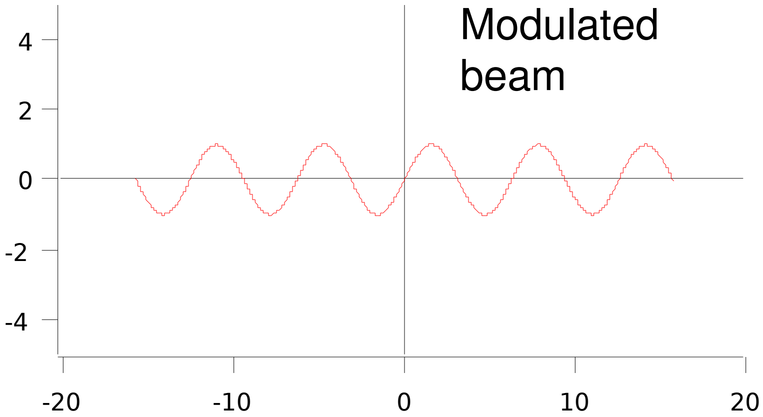
Basic Idea

- Modulate in energy at a fixed wavelength the electron bunch
- Compress the bunch and create a density modulation at a different wavelength than the seed
- Remove any unwanted energy chirp
- Pass the beam through an undulator tuned to the new wavelength

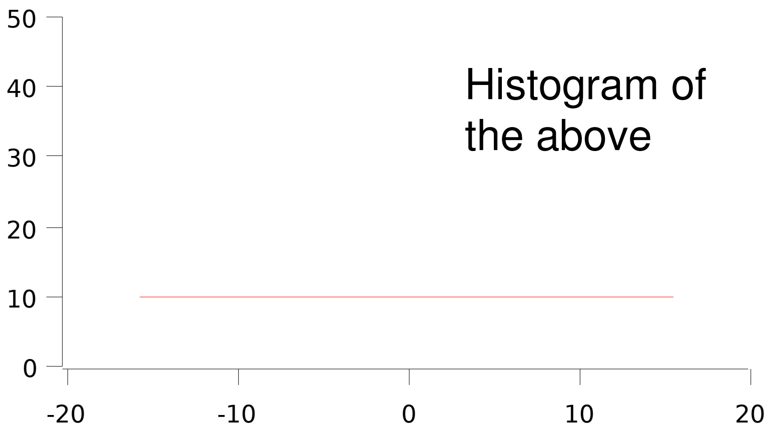
Advantages

- Allows one to seed with a well controlled fixed source
- Allows one to set up the major part of the system and then leave untouched

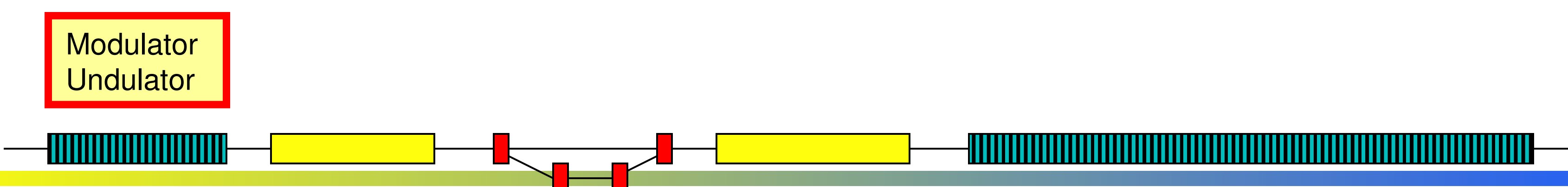
Wavelength Shifting: Graphically



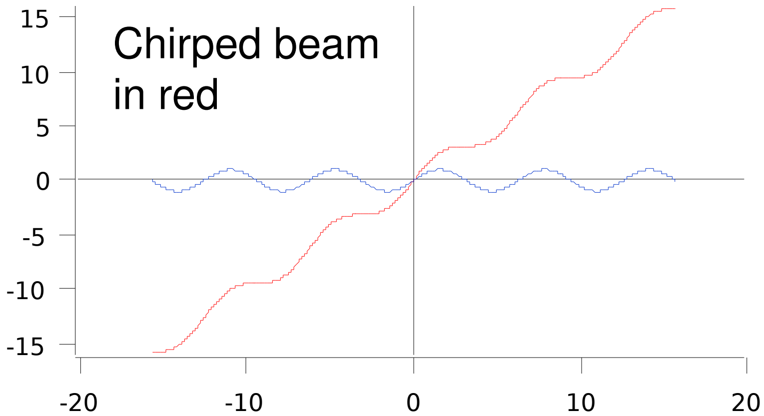
Imprint an energy modulation onto the beam. This is identical to the first step in HGHG, i.e. combine an electron bunch with a laser seed pulse within the field of an undulator resonant at the seed wavelength.



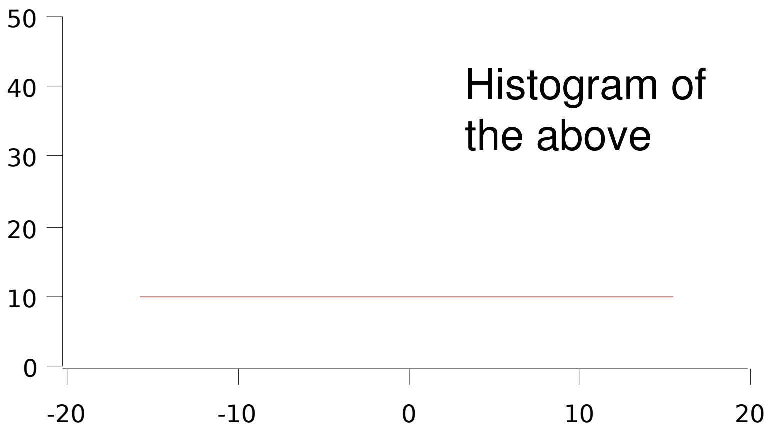
At this point there is no density modulation on the beam and so the beam is not yet suitable for coherent emission



Wavelength Shifting: Graphically



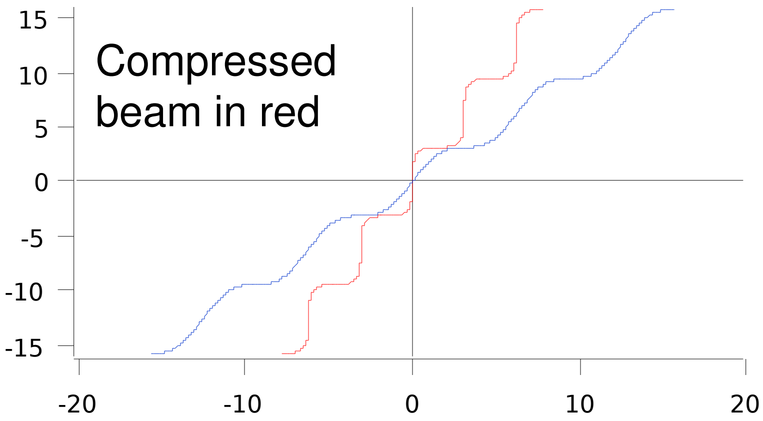
Now pass the beam through an accelerator and add a correlated energy spread to the imprinted beam.



At this point there is still no density modulation on the beam and so the beam is still not yet suitable for coherent emission.

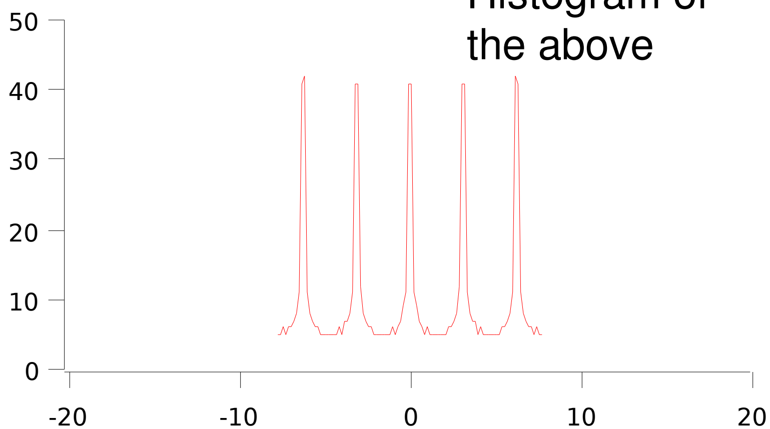
Accelerator one

Wavelength Shifting: Graphically

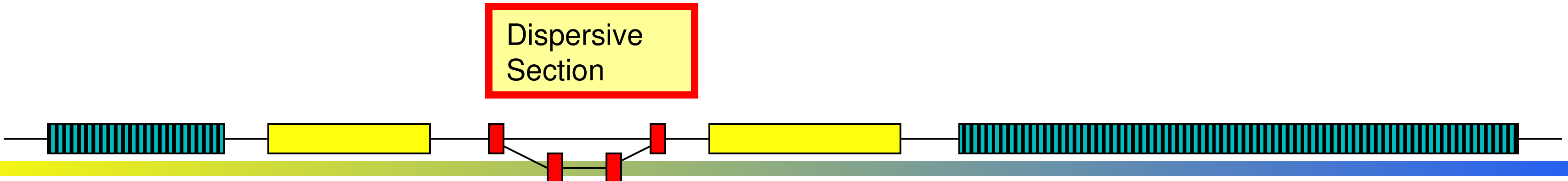


The beam now is passed through a chicane and the high energy tail of the beam catches up with the low energy head of the beam.

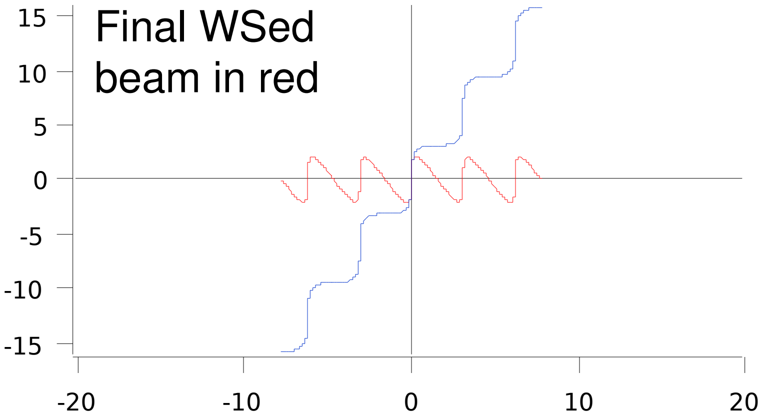
Histogram of the above



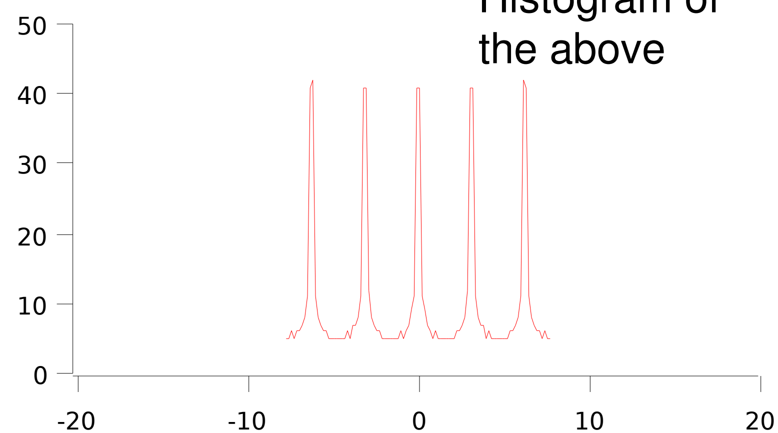
Done correctly there is now a significant density modulation on the bunch, but now it is at a different wavelength than the seed. This wavelength is dependent on the seed wavelength and the depth of the initial modulation. The beam is now ripe for coherent emission.



Wavelength Shifting: Graphically



A second accelerator running off crest is used to remove the energy chirp. Note some of this energy chirp could be left on the beam for further use in compressing the optical pulse duration.

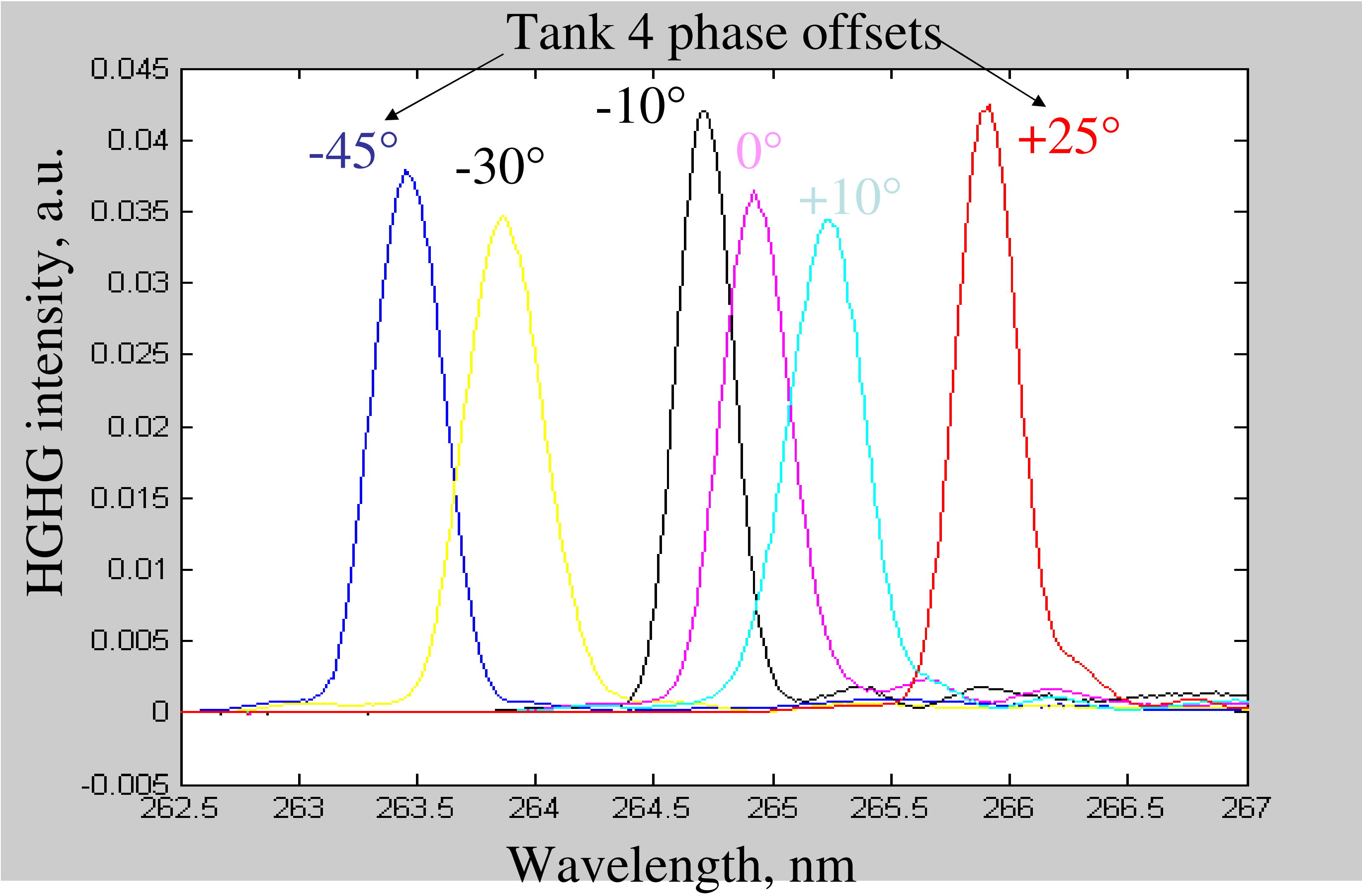


The beam is now ideally bunched at the new desired wavelength. All that was needed in addition to that needed for HGHG are two additional accelerating structures.

Accelerator Two

Final Radiator Undulator

Rough Wavelength Shifting Experiment BNL



Courtesy T. Shaften

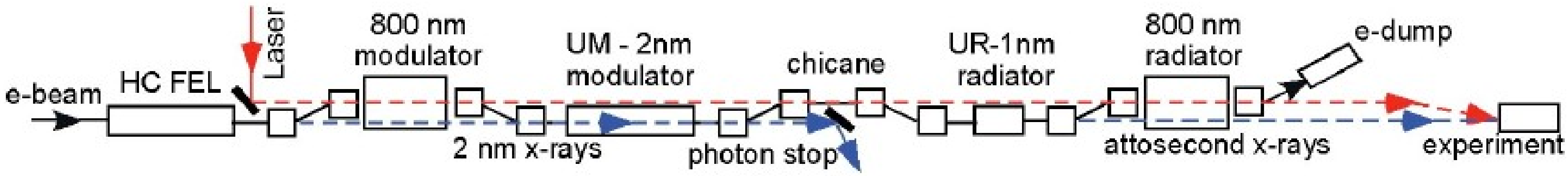


Figure 1: A schematic of the components involved in attosecond x-ray pulse production.

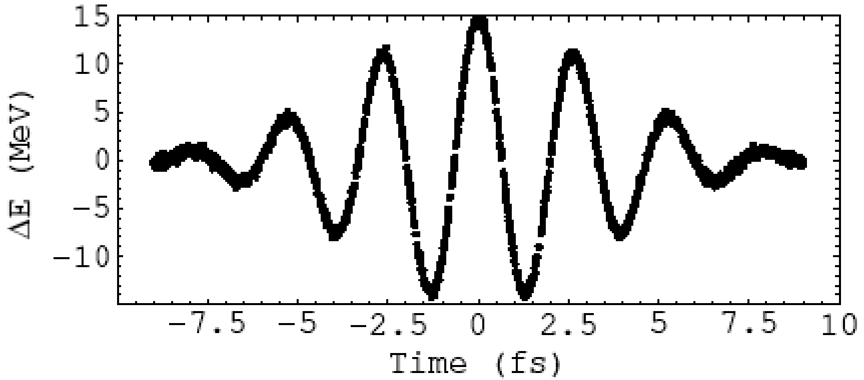


FIG. 2: The calculated energy modulation of the electrons along the electron bunch produced in the interaction with a few-cycle, 800-nm laser pulse in the wiggler magnet presuming an instantaneous electron beam energy spread $\sigma_E = 0.3$ MeV.

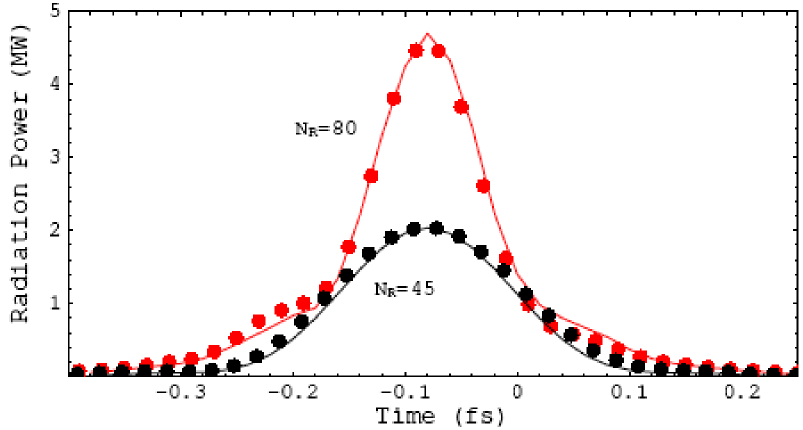


FIG. 4: (Color) Predicted attosecond pulse power at 1-nm wavelength from a radiator with $N_R = 80$ (top line) and $N_R = 45$ (bottom line) using Eq. (7). Both curves were normalized to the peak intensity of the $N_R = 80$ simulation results (dots).

A.A. Zholents, W.M. Fawley, Phys. Rev. Lett., 92, 224801 (2004); LBNL-54084Ext, (2003).

Back to Reality

- We do not have immediate plans for either
  - Wavelength Shifting
  - Attosecond pulses
  - But they are still in our minds
- Status of the FERMI Project
  - Next few slides

Summary FERMI WBS

Major Areas

- Management
- Beam Physics
- PC Gun
- Linac
- Controls
- Diagnostics
- Timing and Synchronization
- eBeam Transport System
- Undulators
- Photon Transport and Beamlines
- LDM Experiments and End Station
- DiProI Experiments and End Station
- EIS Experiments and End Station

Major Phases

- Planning
- Research and Development
- Design Engineering and Prototyping
- Production and Construction
- Integration and Installation
- Commissioning

Note: We are still missing a key hire for leading up the Low Density Matter Experiments and End station.

FERMI Summary Schedule

[redacted]

New master schedule generated.

The previous one was grossly out of date and overly optimistic.

FAPLs asked to create bottoms up linked schedules for their respective areas.

Shown above are the major areas that are either on the critical path or very close.

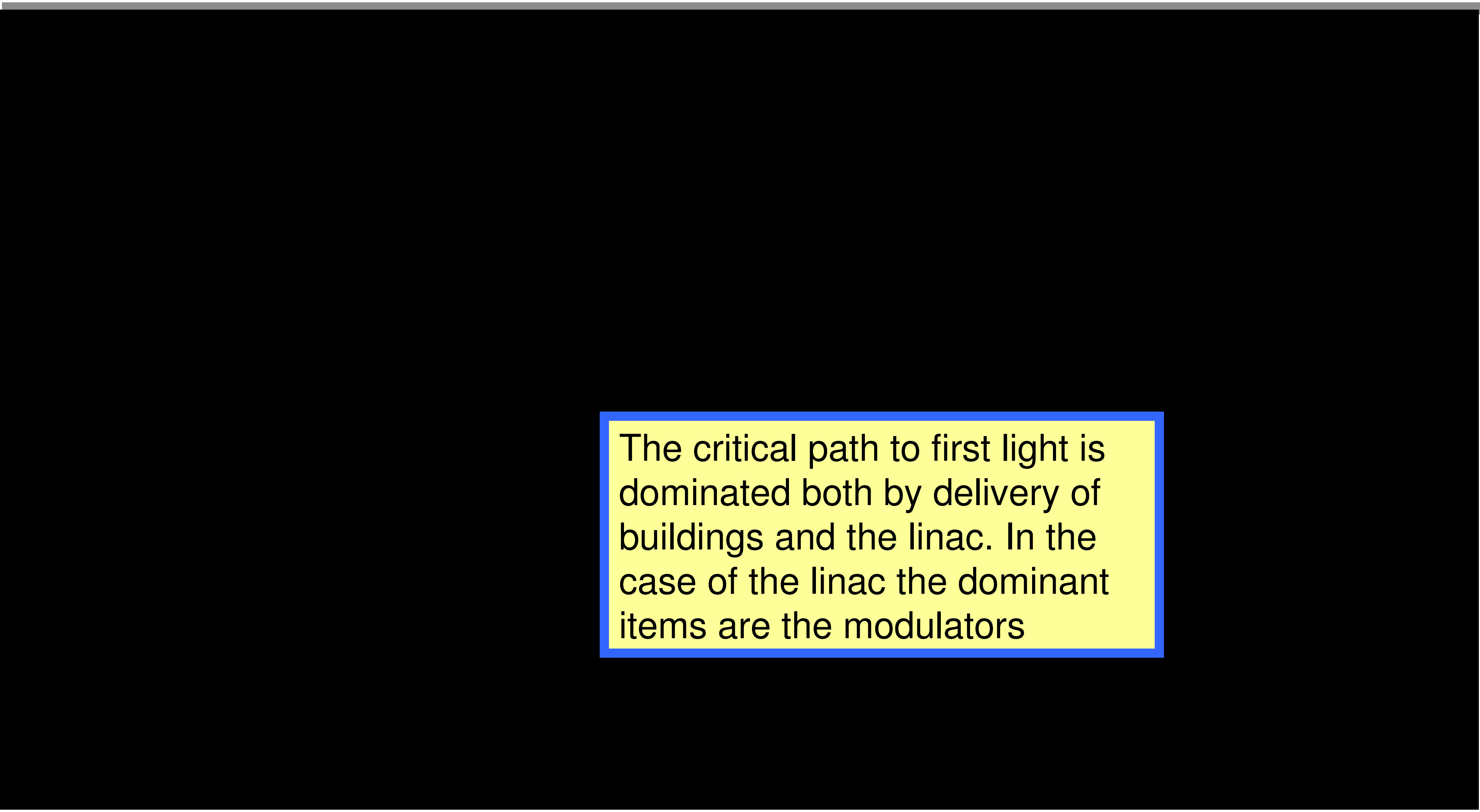
At present we are in the process of logically linking all schedules together, but we already have enough information to make a good estimate of the critical path.

Some Notes:

Some technical items are very close to driving the critical path.

The duration for the undulators (driven by the FEL II undulators) is longer than we want and so we will need to do something to shorten this

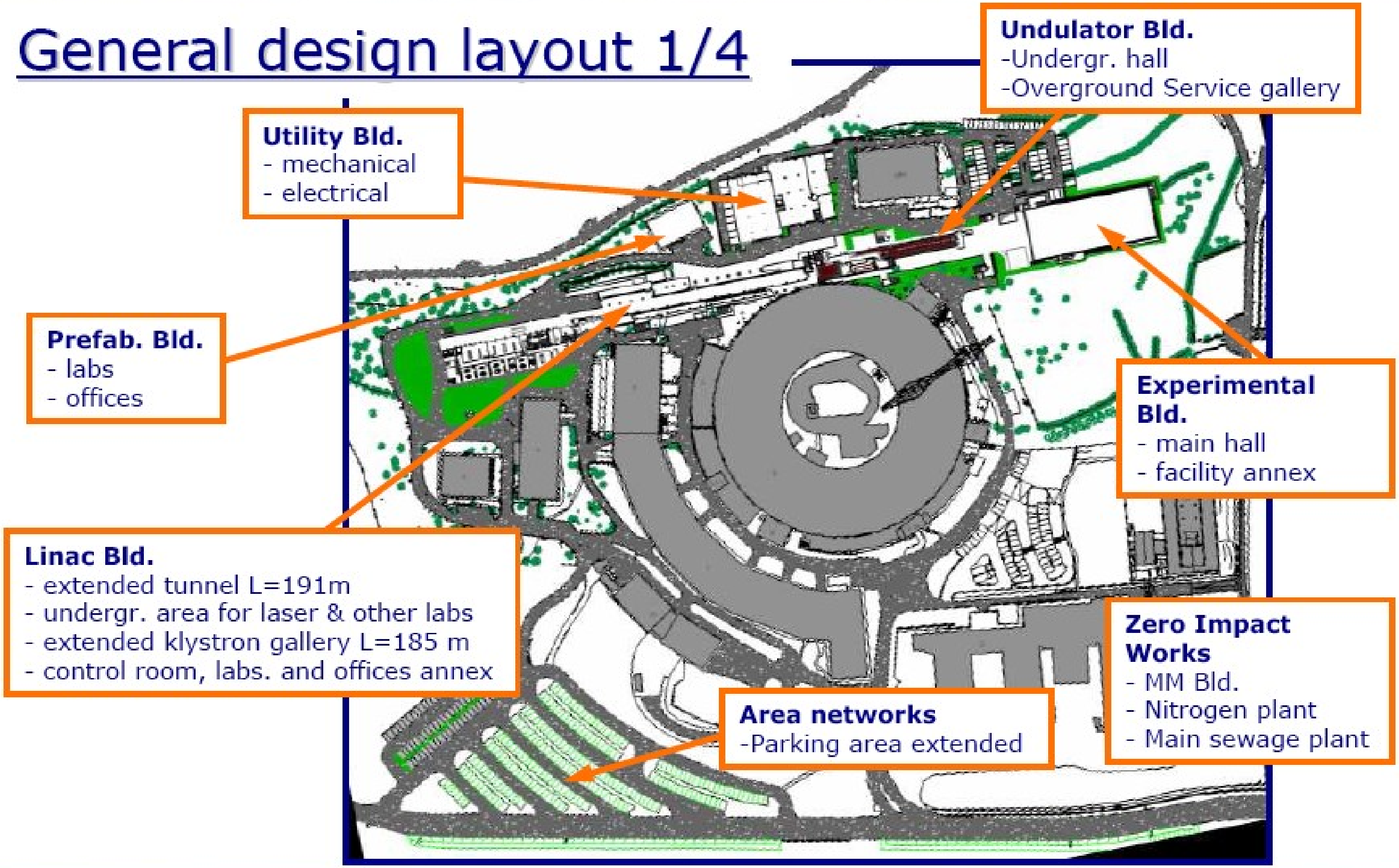
FERMI Critical Path



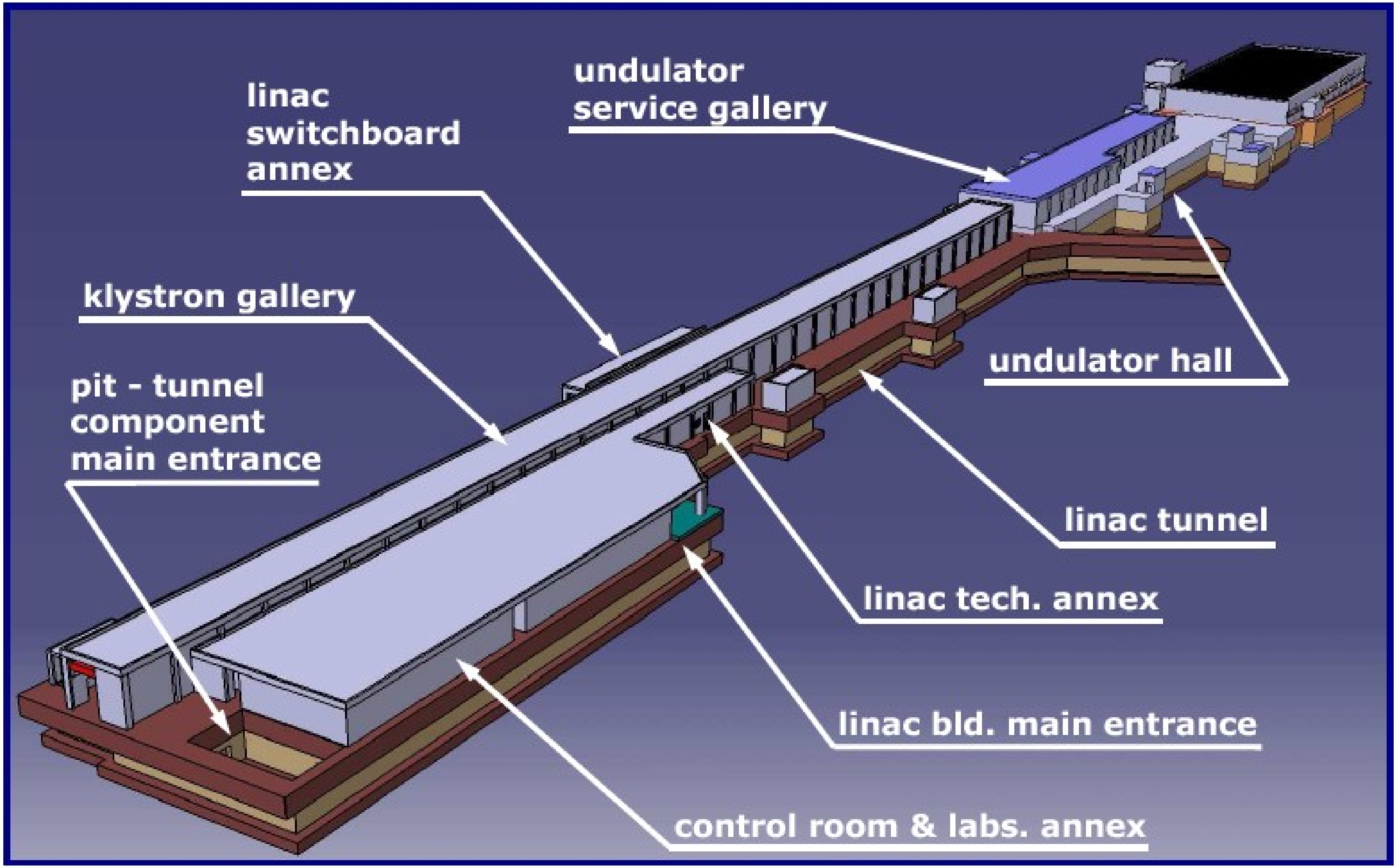
The critical path to first light is dominated both by delivery of buildings and the linac. In the case of the linac the dominant items are the modulators

FERMI Civil Engineering

General design layout 1/4



Main buildings 3D view 1/10



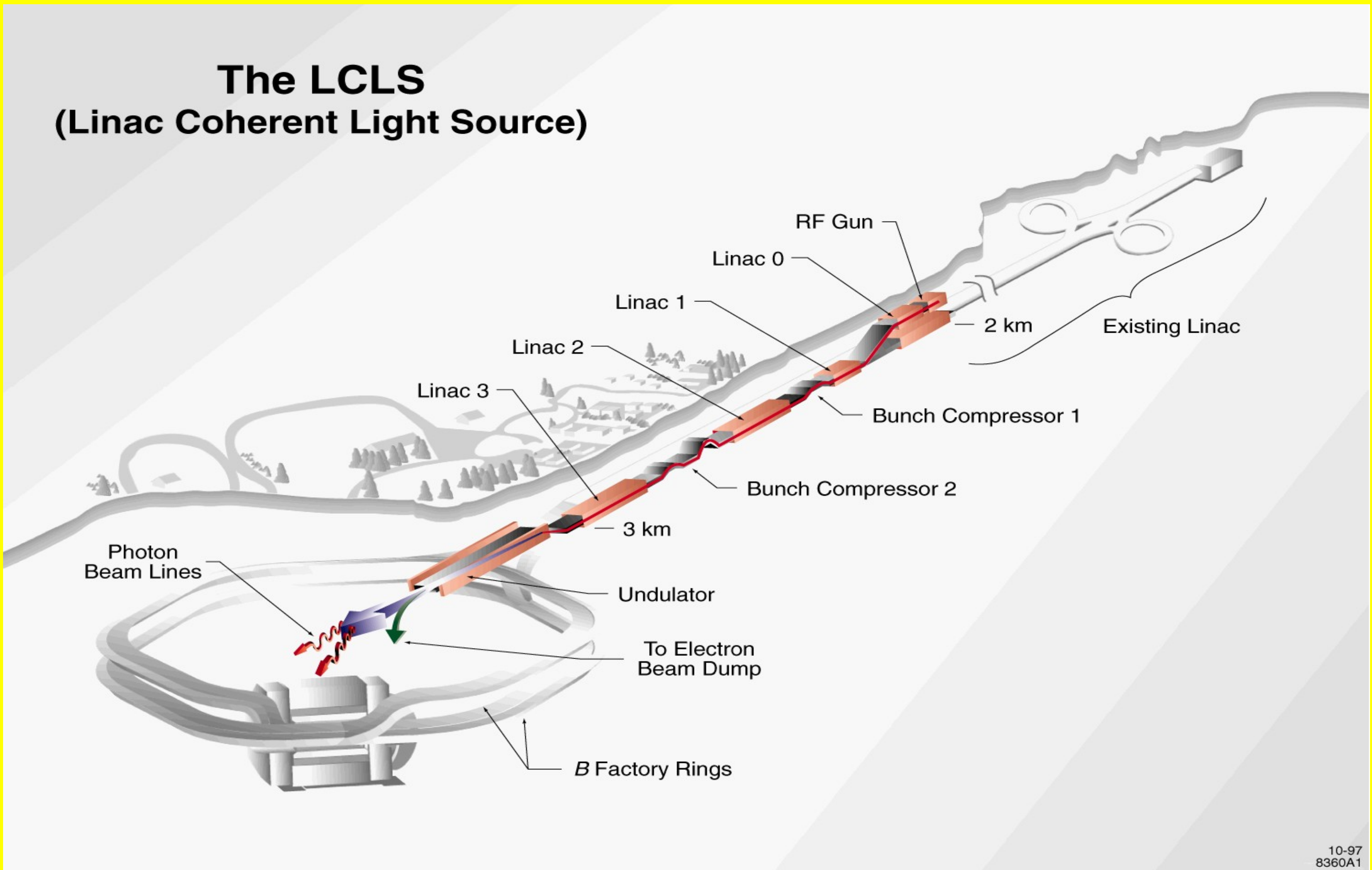
Civil Construction

Linac Underground Concrete Work Complete

Civil Construction

And it has already been put to "good" use!

The LCLS: An X-ray Laser (1.5 Å)



The Challenge

- Comparison to the LCLS

FERMI	LCLS
Linac-Based FEL	Linac-Based FEL
Seeded Operation	SASE
1 PC Gun and Drive Laser	1 PC Gun and Drive Laser
1 Laser Heater System	1 Laser Heater System
1 X-Band RF System	1 X-Band RF System
7 New Accelerating Systems	2 New Accelerating Systems
All New Modulators	No New Modulators
Compete Rebuild of Linac	Moderate Linac Upgrades
2 Bunch Compressors	2 Bunch Compressors
1 Spreader Line	1 Transfer Line
2 FEL Lines	1 FEL Line

The Challenge

- Continued Comparison to the LCLS

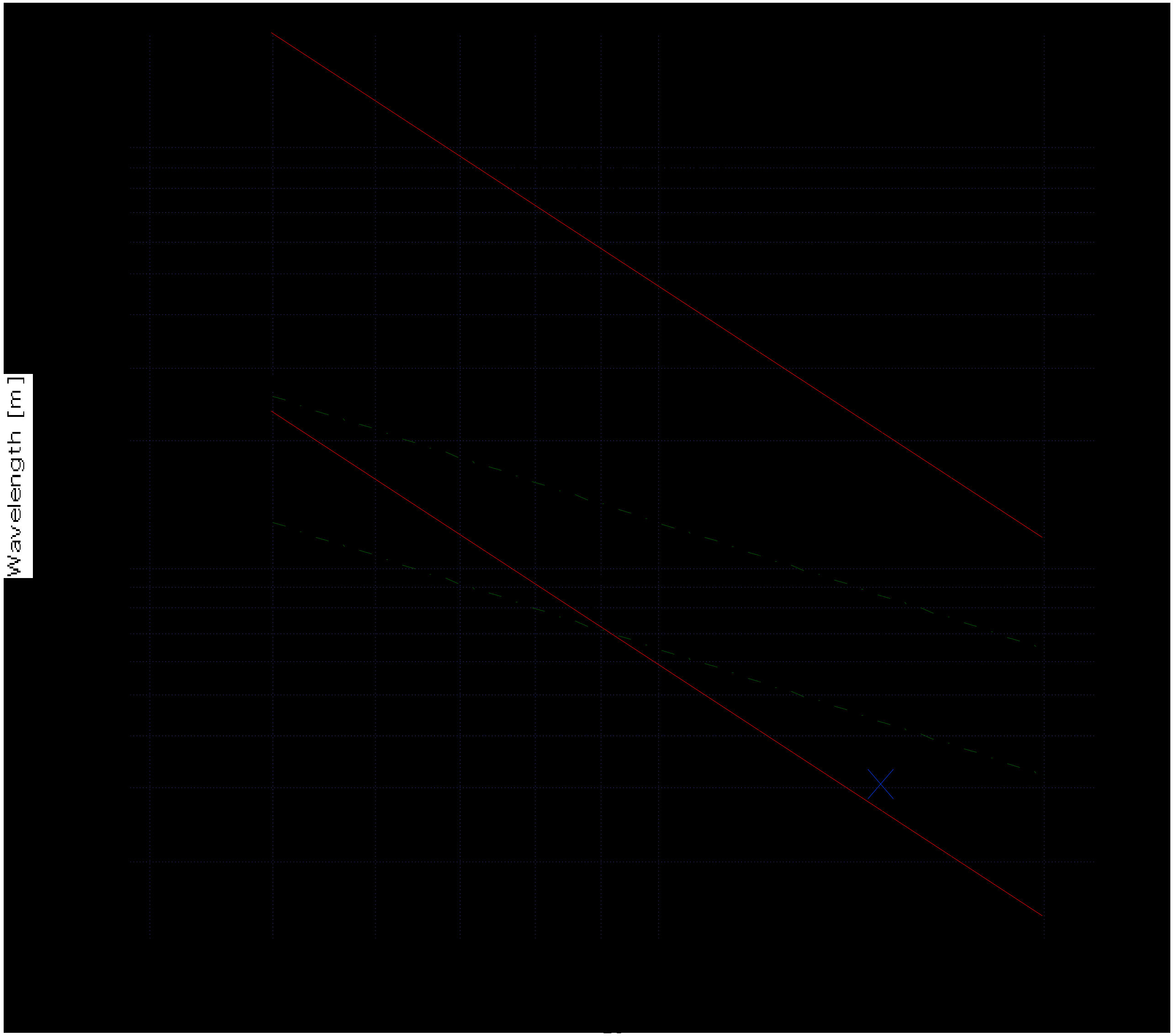
FERMI	LCLS
Multiple Undulator Types with Movable Gaps	Single Undulator Type with Fixed Gap
2 Photon Transport Lines and Optics System	1 Photon Transport Lines and Optics System
3 Starting Experimental Programs	1 Starting Experimental Program
New Linac Building, Und. Hall, and Exp. Hall	New Und. Hall and Exp. Hall
Complete New Plant Infrastructure	Moderate Plant Upgrades
Storage Ring Tradition	Experienced Linac-Based Laboratory
ST plus Collaborations	3 National Laboratories Participating
Short Timeline	Longer Timeline

The Challenge: Conclusion

The LCLS is nothing more than FERMI…

…But on a smaller scale!

Even Shorter Wavelengths?



Although we have promised our user community 100 nm to 10 nm we will design FEL II in a manner that will allow us to press down to 3 nm on the fundamental. We make no guarantee here, but it will be our stretch goal.

FERMI Summary

- Construction
  - Underway
- Recent Technical Success
  - 1st Photoelectons
    - Done in collaboration with MAX Lab and INFN Frascatti
- Schedule
  - Aggressive but plausible
- Goals
  - 1st Light by end of 2009 beginning of 2010
  - Operations begins Start of 2011
  - 100 nm to 10 nm promised
  - 3 nm (fundamental) stretch goal

Thank You.

Thank you

Also Thanks to:

Enrico Allaria, Daniel Bacescu, Laura Badano, Luca Banchi, William Barletta, Silvano Bassanese, Carlo J. Bocchetta, Cristian Bontoiu, Daniele Bulfone, Fabio Cargnello, Katia Casarin, Giuseppe Cautero, Daniele Cocco, Angela Caniglio, Massimo Cornacchia, Paolo Craievich, Francesca Curbis, Miltcho Danailov, Gerardo D'Auria, Giovanni De Ninno, Paolo Del Giusto, Alexander Demidovich, Simone Dimitri, Bruno Diviacco, Mario Ferianis, Giulio Gaio, Andrea Galimberti, Alessandro Gambitta, Mario Giannini, Andrea Goldoni, Fatma Iazzourene, Emanuel Karantzoulis, Maya Kiskinova, Cristina Knapic, Daniele La Civita, Marco Lonza, Claudio Masciovecchio, Fabio Mazzolini, Enrico Menotti, Massimo Milloch, Andrea Milocco, Dario Morelli, Marco Musardo, Salvatore Noe', Giorgio Paolucci, Chris Pappas, Fulvio Parmigiani, Giuseppe Penco, Kevin Prince, Giulia Quondam, Fabio Rossi, Luca Rumiz, Claudio Scafuri, Simone Spampinati, Carlo Spezzani, Luigi Stebel, Massimiliano Stefanutti, Sergio Tazzari, Svetla Tileva, Giuliana Tromba, Mauro Trovo', Alessio Turchet, Alessandro Vascotto, Marco Veronese, Defa Wang, A. Weeks, Dino Zangrando, Marco Zangrando, Sincrotrone Trieste, Trieste, Italy