Review of the Worldwide SASE FEL Development

(Accelerator Based X-ray Laser)

Tsumoru Shintake

For all XFEL contributors

RIKEN/SPring-8

Current status
and
Future

DESY inFORM
06/2007

Norman Conquests
Remember 1066? In a Bridfas talk about the Bayeux Tapestry Dr. Colin Bailey will discuss the history of the events and the famous work of art. Auditorium, June 14, 20 h. More info: *www.bridfas.de → Programme*

Physics with FELs
Daniel Zajfman from the Weizmann Institute of Science will give a talk in the Jentschke Lecture Series on 'Atomics and Molecular Physics with FEL: A New Opportunity for Laboratory Astrophysics'. Auditorium, June 22, 15 h

Alimentary Agony Aunts
If you have suggestions for the improvement of the canteen, please e-mail them to kantinen.kommission@desy.de. A new website will soon be online, too.
http://kantinen-kommission.desy.de

Women's Meeting
The equal opportunities representative and the women's association will report about their work and the outcomes. All women are invited to a exchange of views: in Zeuthen on July 5 at 10:30 h, in Hamburg on July 10 at 10:30 h in seminar room 4a

Director's Corner

The end of HERA operation is also the end of a great era. For many colleagues, a considerable part of their working life consisted of designing, constructing and operating HERA; for me it was 25 years.
In the seventies, we actually planned an electron-positron storage ring at DESY with a circumference of 30 kilometers. Proposals for possible sites were already at hand, for example in the Lüneburg Heath. This project, however, was realized as LEP at CERN. The new HERA project seemed a bit suspect to many people, including me. Experience with protons already existed, but not with superconducting magnets. Moreover, the proton ring was supposed to be built by people from the research sector, an "amateur play group" with little accelerator experience, to which also I belonged. In case that this part of the project would be delayed, a positron injection was built to make positron electron collisions possible. As we all know, those fears were unnecessary. You should never underestimate 'newcomers'!

(continued overleaf)

World Class!
Minister Schavan at DESY for the official starting shot

"This is world class!" These words of Minister for Education and Research Annette Schavan marked the official launch of the European X-ray free-electron laser facility XFEL. On June 5, high-ranking representatives from the participating countries met in the Grand Elysée Hotel in Hamburg where the ECRI Conference took place. "With the XFEL, a brilliant research landscape will be established in Europe that will be a great attraction to talents from all over the world," said Schavan. The funding negotiations with the 12 interested countries have advanced so far that the construction of the XFEL can now begin. The partner countries are convinced that construction should start as soon as possible in view of international competition. In the signed communiqué they stated: "We have agreed to set up the first construction phase of the XFEL with construction costs of 850 million Euros."
After the launch, Minister Schavan and EU Research Commissioner Janez Potocnik visited DESY. They were welcomed by around 1100 eagerly waiting DESY staff from Hamburg and Zeuthen. Schavan affirmed that "the European X-ray free-electron laser XFEL is a milestone, also for the development of DESY and a symbol for excellent work here." EU Commissioner Potocnik added: "The XFEL is one of the most exciting research projects in Europe and marks the beginning of the ESFRI roadmap." He praised the team spirit of the DESY crew by calling them a star team.
After the speeches, the Ministers, Helmholtz President Jürgen Mlynek and members of the DESY Directorate visited the free-electron laser FLASH and signed the DESY visitors book.
After the visit of the important guests, the DESY crew also celebrated the launch of the XFEL project. The beginning of the call for bids is the first step towards turning all plans that have so far only existed on drawing boards or as computer simulations into reality. *(uw)*

Info: *www.xfel.net*

The start of the XFEL project will not only strengthen the research regions Hamburg and Schleswig-Holstein, but also Germany and Europe, said Minister Schavan in her speech.

Visiting the FLASH tunnel: Albrecht Wagner, Minister Schavan, Massimo Altarelli and the Russian Research Minister Andrej

Storage Ring SR → Linac FEL

- **Circular Machine**
  Quantized SR photon radiation → Energy spread
  → higher horizontal emittance, longer bunch length 30 psec,

  → FEL at short-wavelength becomes not feasible

- **Linear Accelerator Base**
  No SR radiation → Small energy spread, and small emittance.
  → longitudinal bunch length in femto-sec is possible

  → FEL at short wavelength below 1 nanometer becomes possible.

FEL Map

copied from M. Ferrario, "OVERVIEW OF FEL INJECTORS", EPAC06

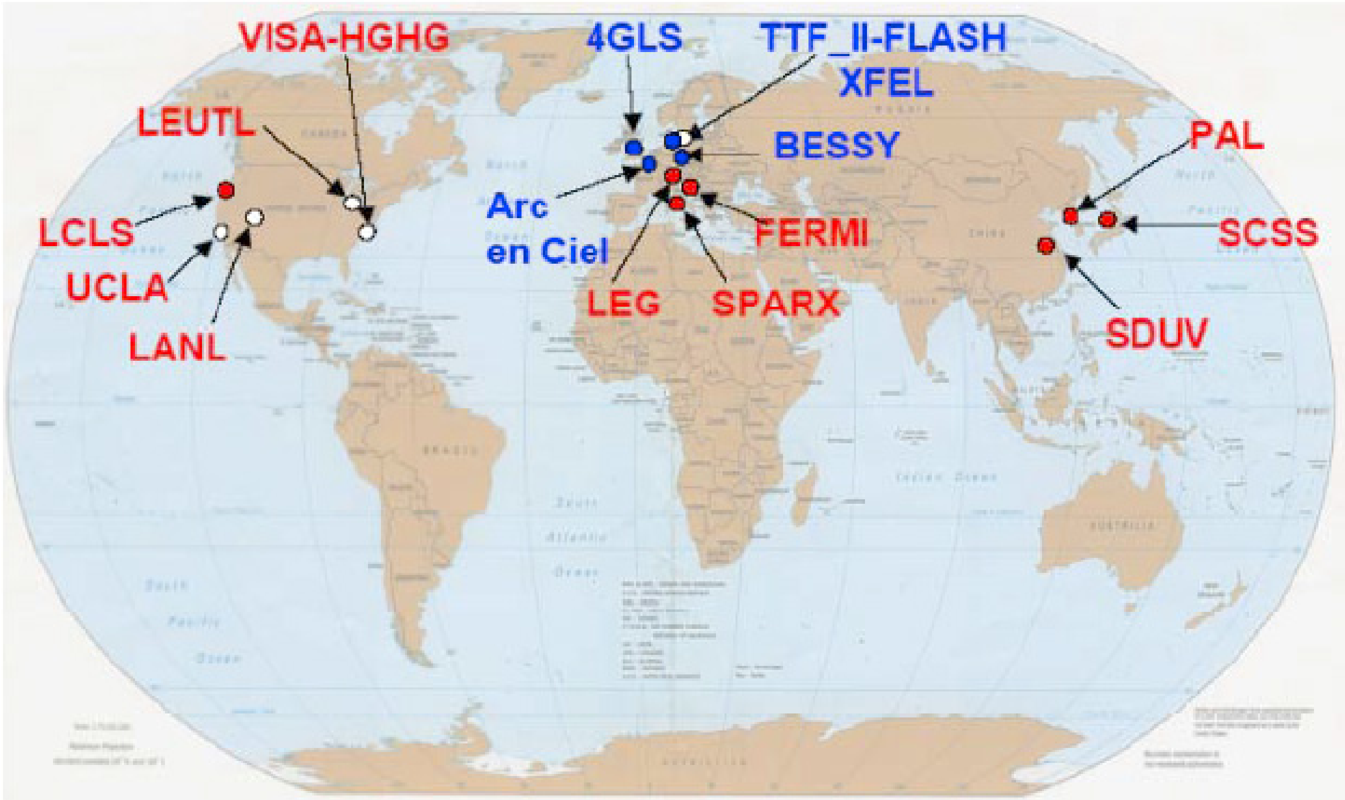


Figure 1: IV generation synchrotron light sources based on short wavelength FEL world distribution. Red and blue lables: FEL projects based on normal conducting or superconducting technology respectively. White circles: first SASE demonstrative experiments.

XFELs around the world

Project	Type	Location	Country	e-Beam(GeV)	Photon (nm)	Status
LEUTL	SASE	APS	USA	0.22	660-130	Since 2001
TTF I	SASE	DESY	Germany	0.3	125-85	Since 2002
SDL DUV-FEL	HGHG	SDL/NSLS	USA	0.145	400-100	Since 2002
FLASH (TTF)	SASE	DESY	Germany	1.0	12 - 6	Since 2006
SCSS Prototype	SASE	SPring-8	Japan	0.25	150-50	Since 2006
LCLS	SASE	SLAC	USA	15	0.15	In 2008
SCSS XFEL	SASE	SPring-8	Japan	8	0.1	In 2011
Euro XFEL	SASE	DESY	Germany	20	0.1	(in 2014)
SPARC	SASE	INFN Frascati	Italy	0.15	500	in 2007
FERMI	HGHG	Trieste	Italy	1.2	10	In 2009
Soft X-ray FEL	HGHG	BESSY	Germany	2.3	64 - 1.2	proposal
SPARX	HHG	INFN Frascati	Italy	1 – 2	1.5	proposal
4GLS	HGHG	Daresbury	GB	0.6	100 - 19	proposal
ARC-EN CIEL	HHG	Saclay	France	0.7	1	proposal
PAL XFEL	SASE	Pohang	Korea	3.7	0.3	proposal
PSI XFEL	SASE	PSI	Swiss	3.7	1	proposal

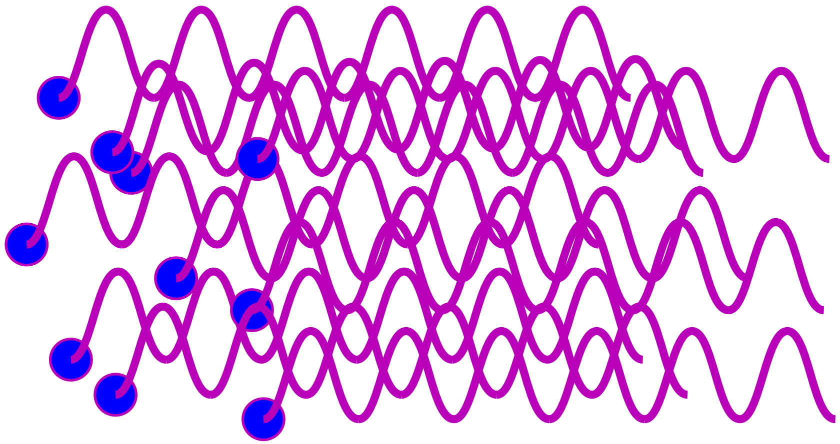
XFELs Technology Choice

Project	Electron Gun	Main Accelerator
LEUTL	**S-band RF-Photocathode**	**NRM– S**
TTF I	**L-band RF-Photocathode**	**SCC– L**
SDL DUV-FEL	**S-band RF-Photocathode**	**NRM– S**
FLASH (TTF)	**L-band RF-Photocathode**	**SCC– L**
SCSS Prototype	**Pulse HV Themionic Gun**	**NRM–C**
LCLS	**S-band RF-Photocathode**	**NRM– S**
SCSS XFEL	**Pulse HV Thermionic Gun**	**NRM–C**
Euro XFEL	**L-band RF-Photocathode**	**SCC– L**
Soft X-ray FEL	**L-band RF-Photocathode**	**SCC– L**
SPARC	**S-band RF-Photocathode**	**NRM– S**
SPARX	**S-band RF-Photocathode**	**NRM– S**
FERMI	**S-band RF-Photocathode**	**NRM– S**
4GLS	**DC HV Photocathode**	**NRM–**
ARC-EN CIEL	**L-band RF-Photocathode**	**SCC– L**
PAL XFEL	**S-band RF-Photocathode**	**NRM– S**
PSI XFEL	**S+L-band RF Gun with Field Emission Array**	**NRM– S**

From SR to FEL

SR or ERL

Spontaneous Radiation



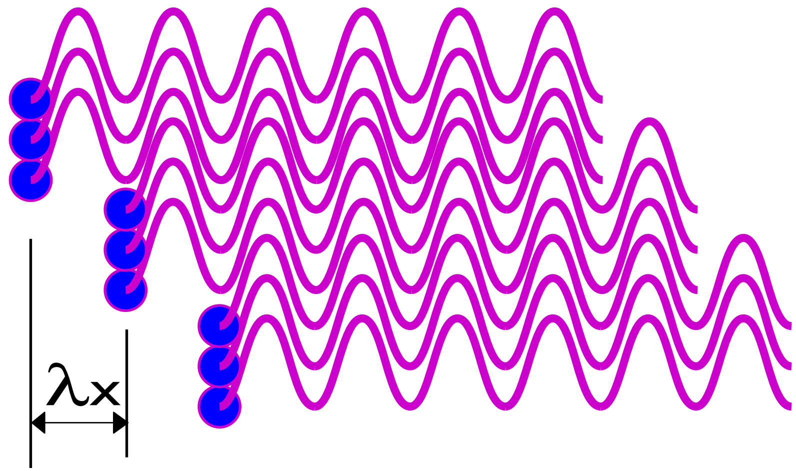
***N*-electrons random distribution**

$E_{spt} \sim \sqrt{N}\, E_1$

$P_{spt} \sim N\, P_1$

FEL: Free Electron Laser

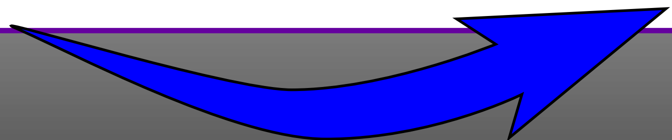
Coherent Radiation



***N*-electrons micro-bunched**

$E_{coherent} \sim N\, E_1$

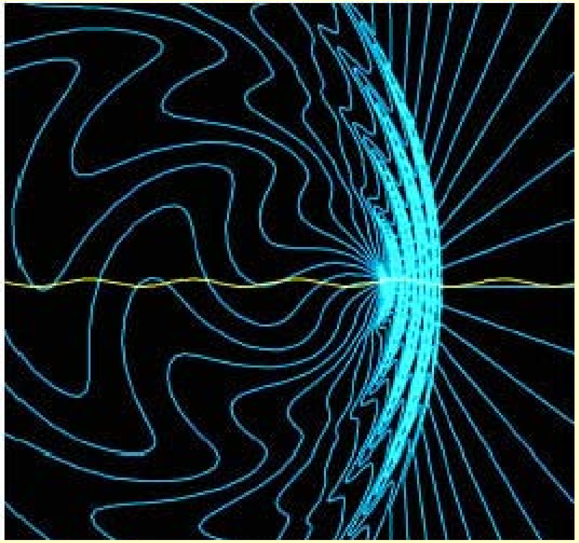
$P_{coherent} \sim N^2 P_1$



Optical Power Enhancement

x $10^5 \sim 10^8$

Feeling & Experience are very important in science.



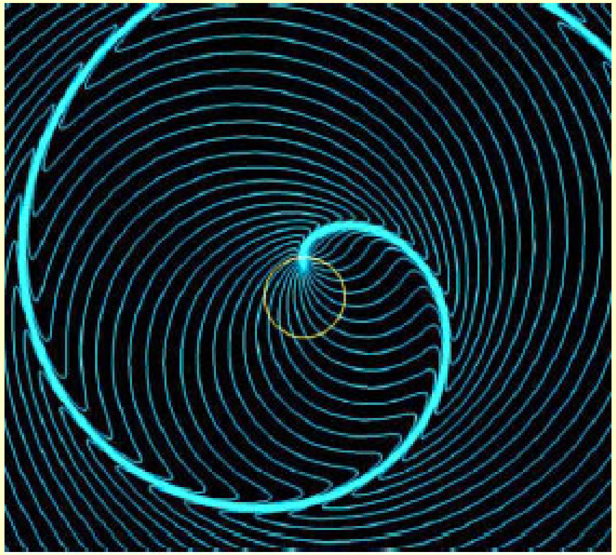
Radiation2D simulator gives you reality as if you are in front of running noisy electron.

Radiation2d,
available from (freeware)

http://www-xfel.spring8.or.jp

or

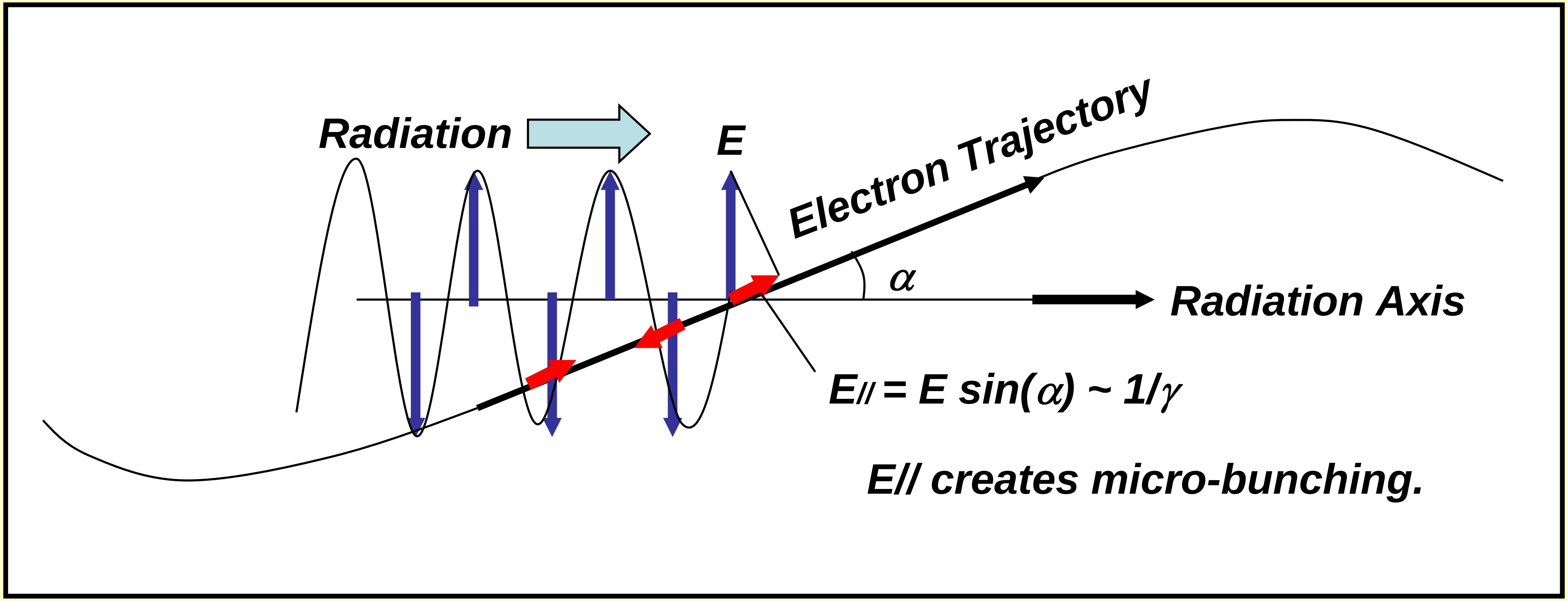
www.ShintakeLab.com

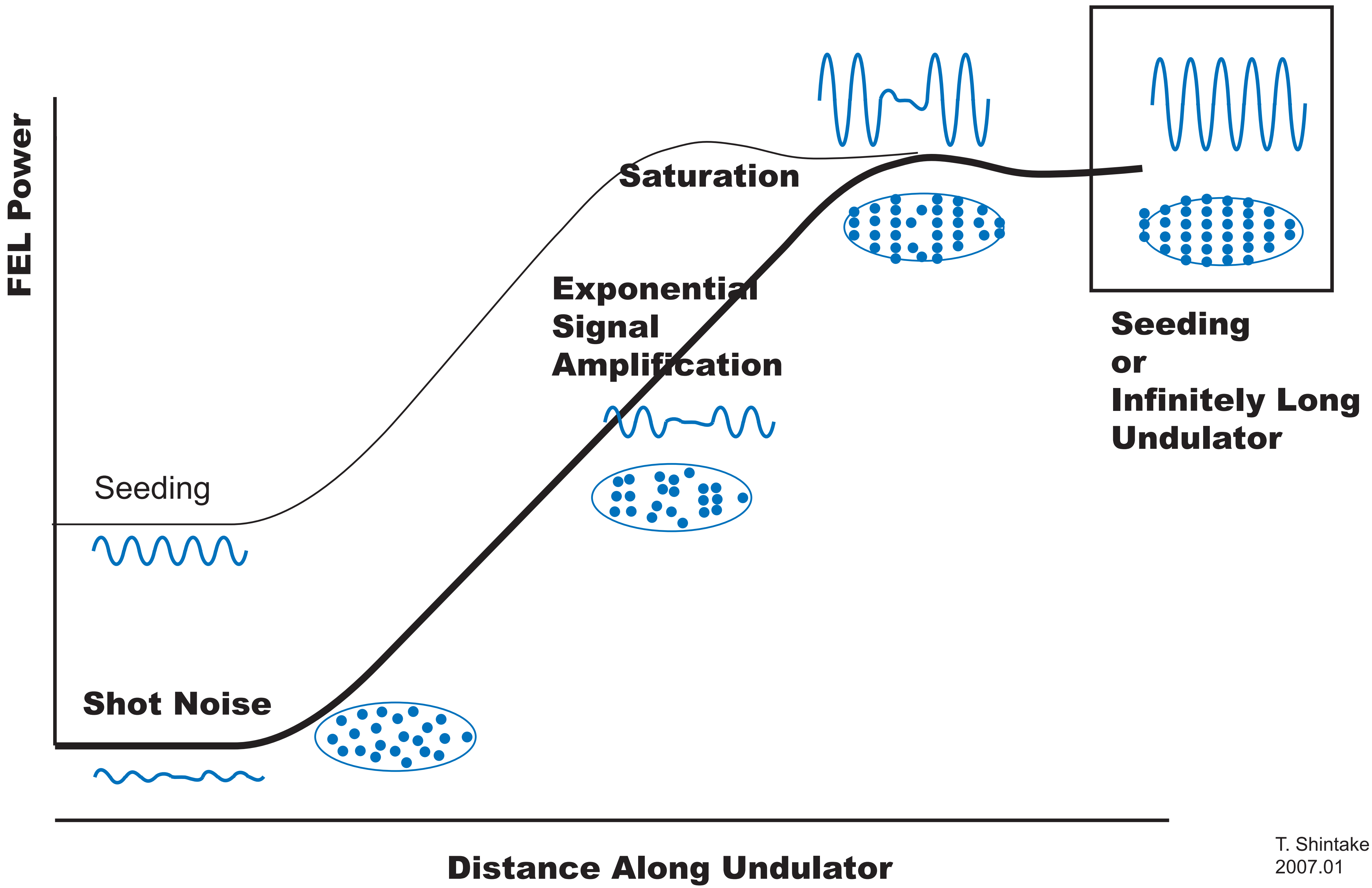


Power Spectrum
Scattering Model

Physical Origin of Micro-bunching (FEL Action)

- Undulator field produces curved trajectory. From this slope, the tangential component of EM wave creates longitudinal field.




FEL Power
Saturation
Exponential
Signal
Amplification
Seeding
or
Infinitely Long
Undulator
Seeding
Shot Noise
Distance Along Undulator
T. Shintake
2007.01

Crystal Diffraction Analogy

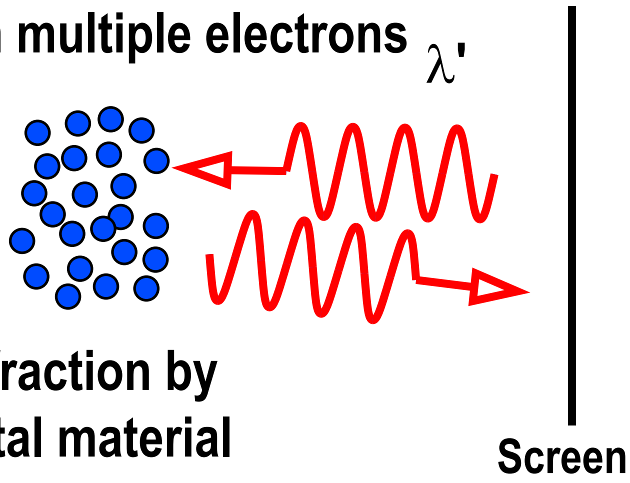
T. Shintake, 2006

Scattering by Electron

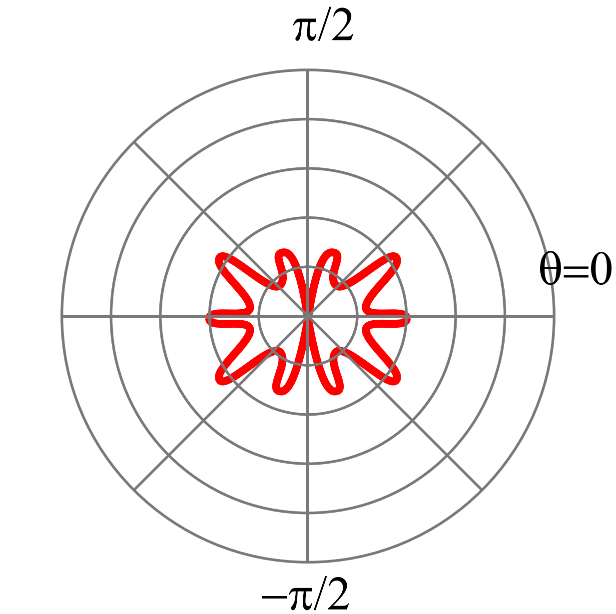
Radiation Pattern

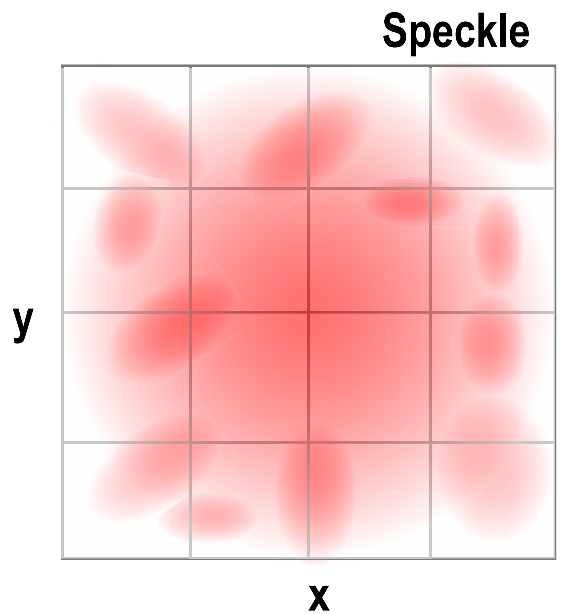
Power on Screen

Random multiple electrons

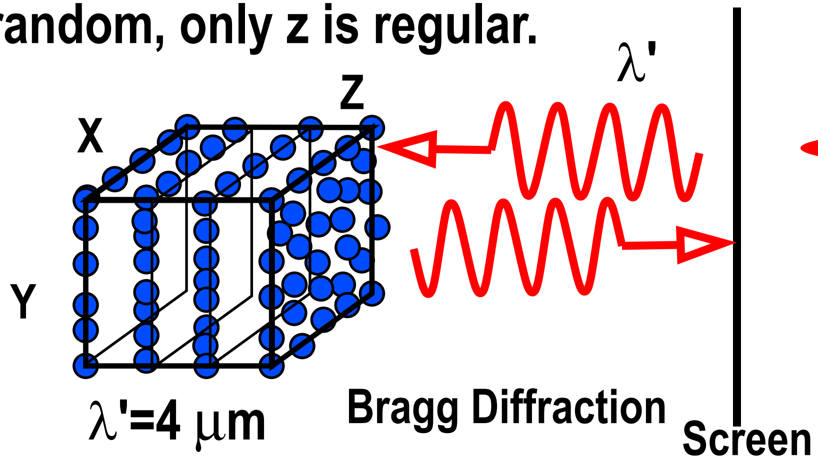


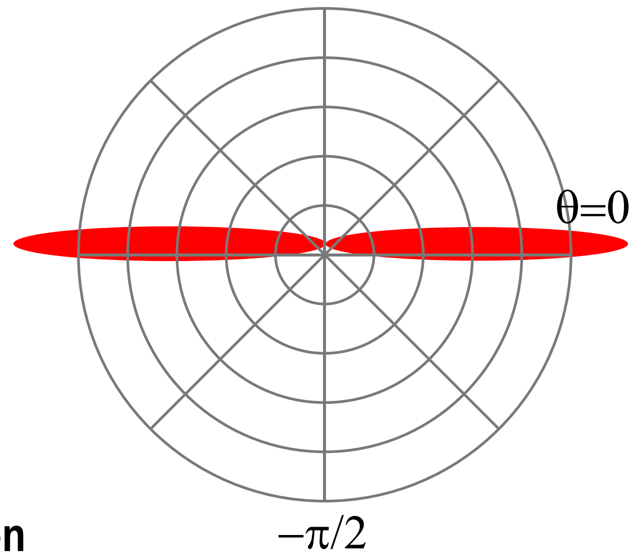
Wave diffraction by non-crystal material

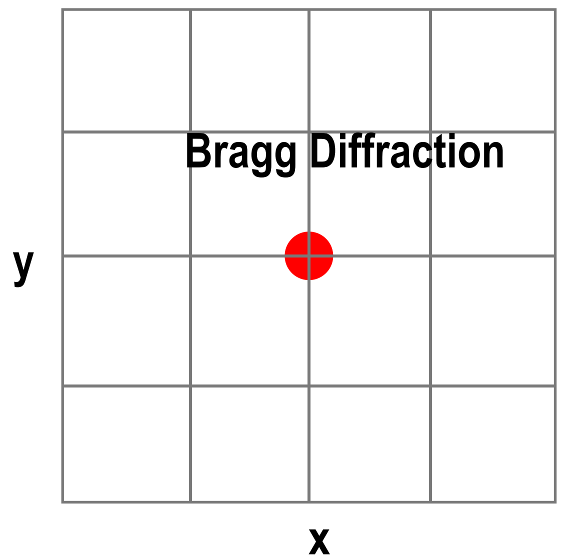




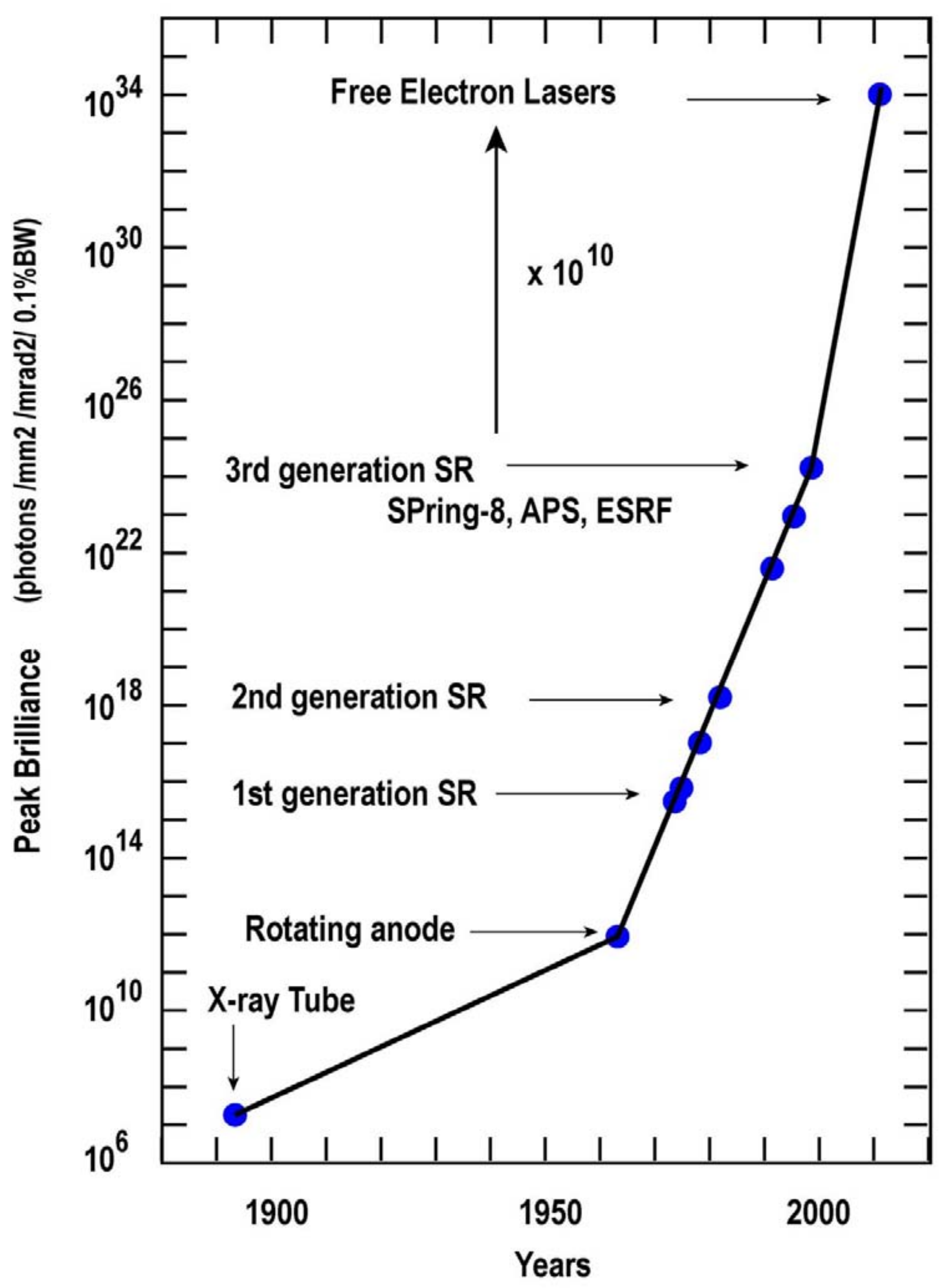
Crystal Structure
xy-random, only z is regular.







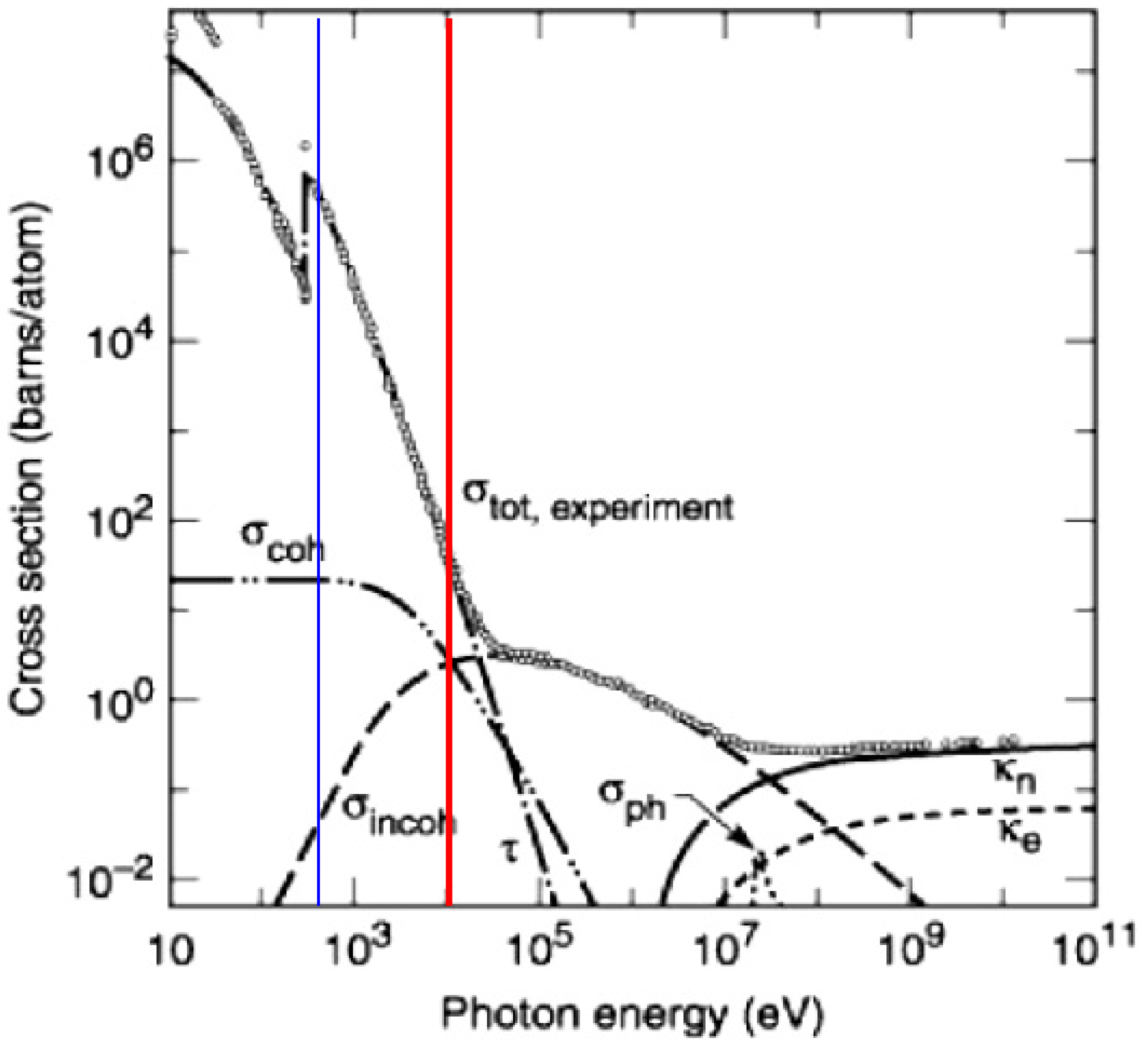
Peak Brilliance Evolution



- Peak brilliance will be enhanced by factor of 10^{10} from 3rd generation SR to XFEL.
- $10^{10} = 10^1 \times 10^1 \times 10^1 \times 10^7$

  = peak current by factor 10
  x lowered emittance by 10
  x energy spread lowered by 10
  x interference effect 10^7 by micro-bunching formation.

Why 1 Angstrom?



Cross-section of X-ray with Carbon

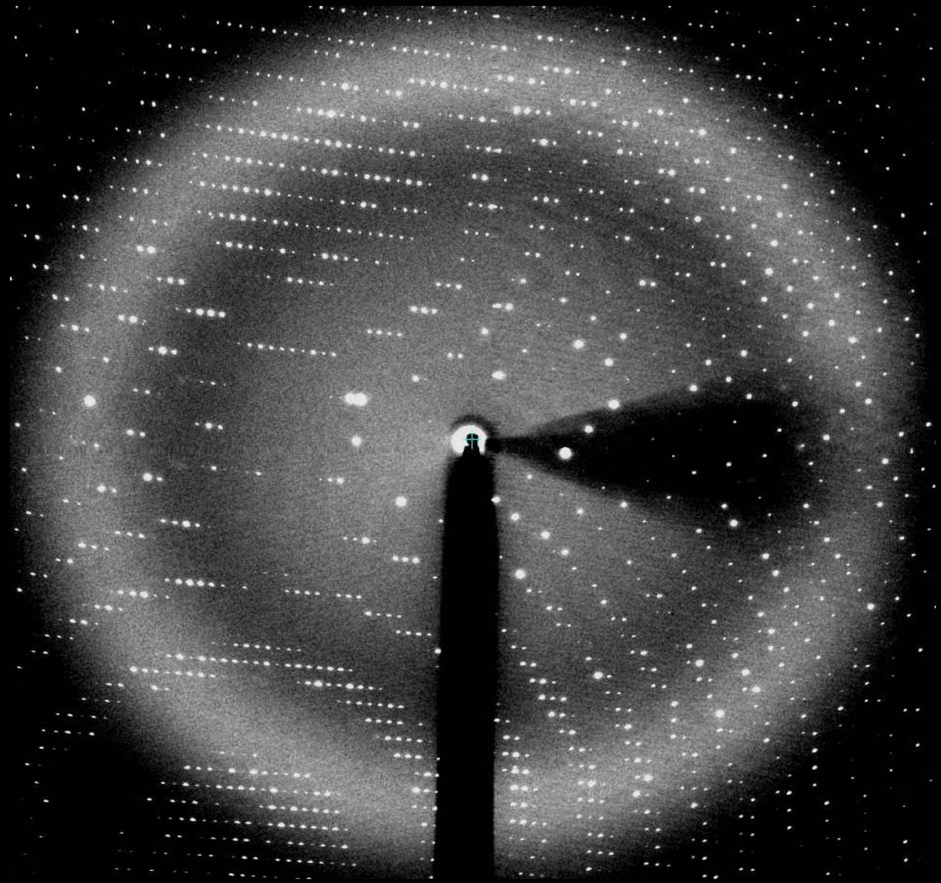
- Photo-ionization becomes lower as X-ray energy.
- Around 1 A, 8 keV, photo-ionization becomes low enough to see coherent scattering.
- Spatial resolution becomes a few Angstrom, which resolves macromolecular crystal in biology.

  → Imaging, crystallography

- **water window** (2.3-4.4nm light) is also another candidate.

(a few micron-meter thick water)

Protein Crystal ~0.1 mm



Rodopsin Structure

Dr. Masashi Miyano

Courtesy of M. Yamamoto

We need high energy electron beam

- **1 Angstrom X-ray**
  - Using undulator: Period = 30~40 mm, K = 2~3
    → Electron energy = **~20 GeV** **large scale accelerator**

- **Water Window 3 nm**
  - Using undulator: Period = 30~40 mm, K = 2~3
    → Electron energy = **~3 GeV** **middle scale accelerator**

  - *SCSS Concept*
    Using short period undulator: Period 18 mm, K = 1.5,
    *→ Electron energy = **1 GeV*** ***small scale accelerator***
    (need low emittance beam, use thermionic gun 0.6 π.mm.mrad)

We need low emittance beam and high peak current

$$L_g = 1.67\left(\frac{I_A}{I}\right)^{1/2} \frac{(\varepsilon_n \lambda_u)^{5/6}}{\lambda^{2/3}} \frac{(1+K_{rms}^2)^{1/3}}{K_{rms} A_{JJ}} (1+\delta),$$

E. L. Saldim, E. A. Schneidmiller and M. V. Yurkov, Opt. Commun. 235 (2004) 415

- For 0.1 nm, and L =< 10 m (Saturation ~100 m)
- Beam emittance ~ **1 π.mm.mrad** (normalized, slice)
- Peak current ~ **a few kilo Amp**.

How to obtain such high quality beam

- **RF-photocathode gun + magnetic bunch compression**

  RF-Photocathode gun 0.5 nC, 10 psec, 50 A

  → Chicane Compression 1/100 → 100 fsec, 5 kA

- **Thermionic gun + velocity bunching + magnetic bunch compression**

  Thermionic gun 0.5 nC, 500 psec, 1 A

  → Velocity Bunching 1/20 → 20 psec, 20 A

  → Chicane Compression 1/150 → 150 fsec, 3 kA

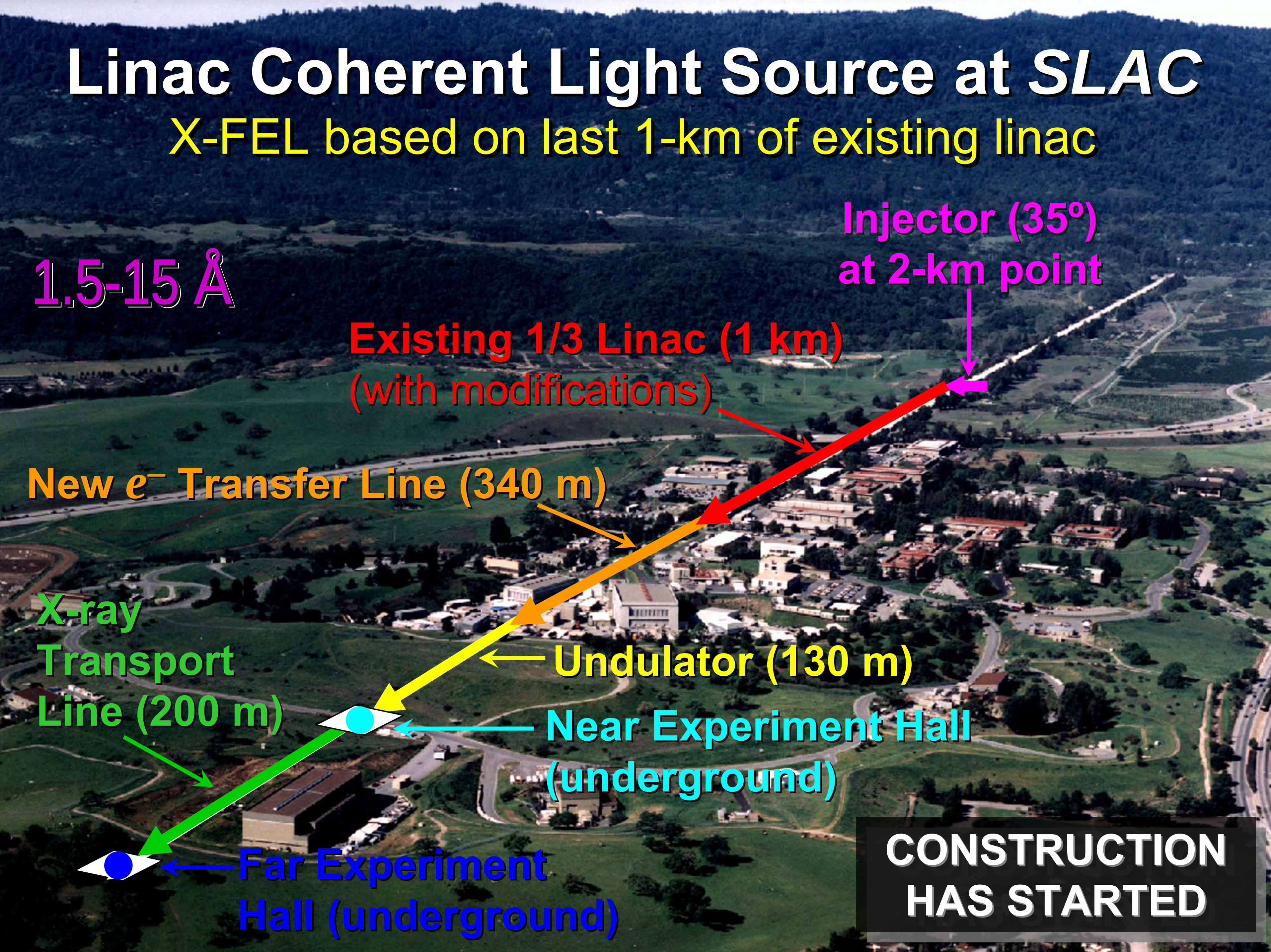
Big technical challenge!

To Realize XFEL
Technical Challenges

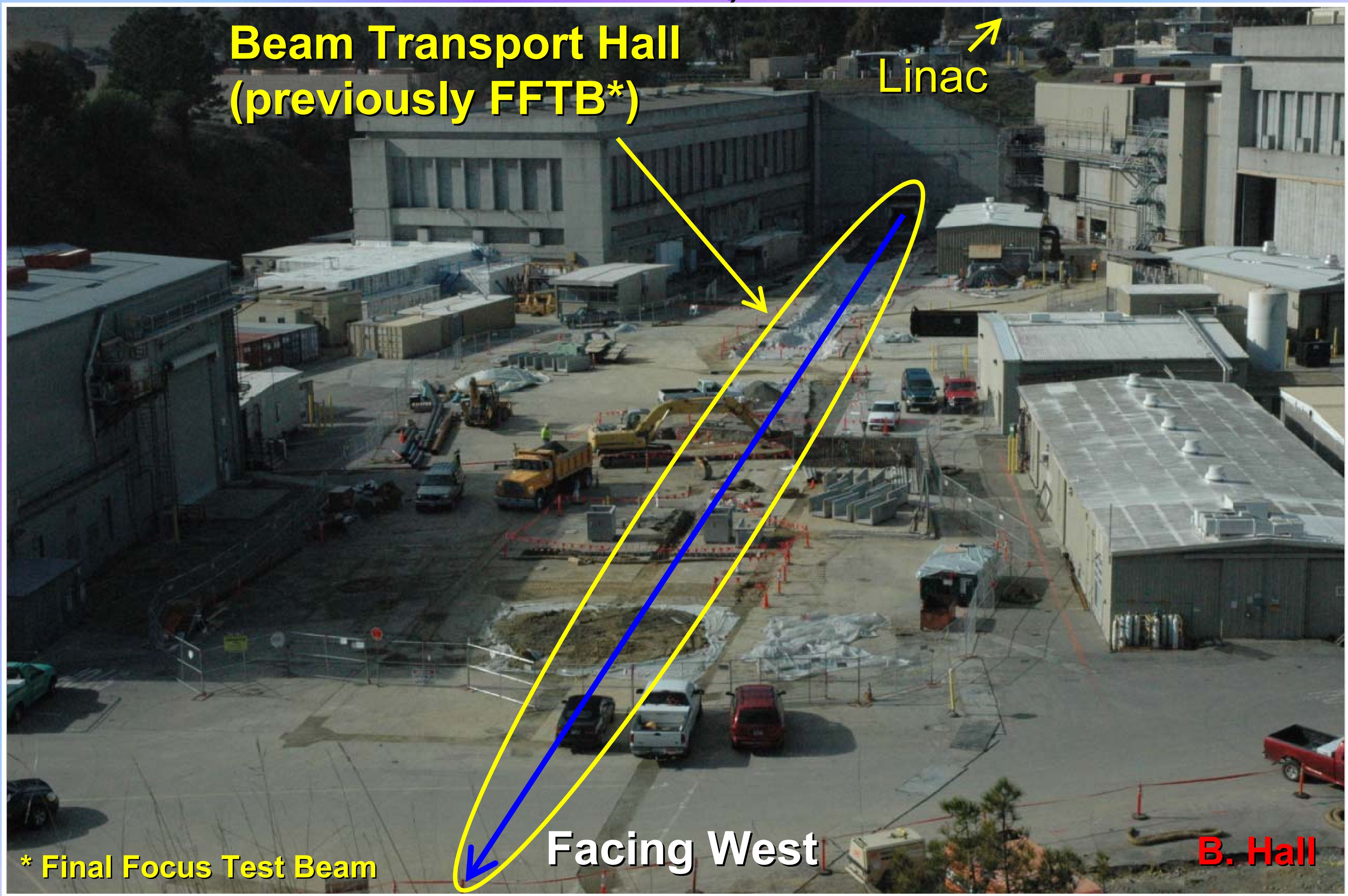
- Need high density electron cloud. (high peak current ~ kA)
  → bunch compressions, CSR problem, short bunch monitoring.
- Maintain overlap of electron and undulator radiation in a same axis for long distance. (highly accurate undulator field, and tight beam alignment ~ a few μm / 10 m)
  → undulator tuning, BPM, beam based alignment
- Minimize radiation spread, thus we need parallel electron flow, needs very low emittance. (1 π.mm.mrad normalized)
  → RF-photocathode gun, thermionic gun
- Low energy spread (10^{-4}), do not run beam in circle at high energy.

Comparison of X-ray FELs

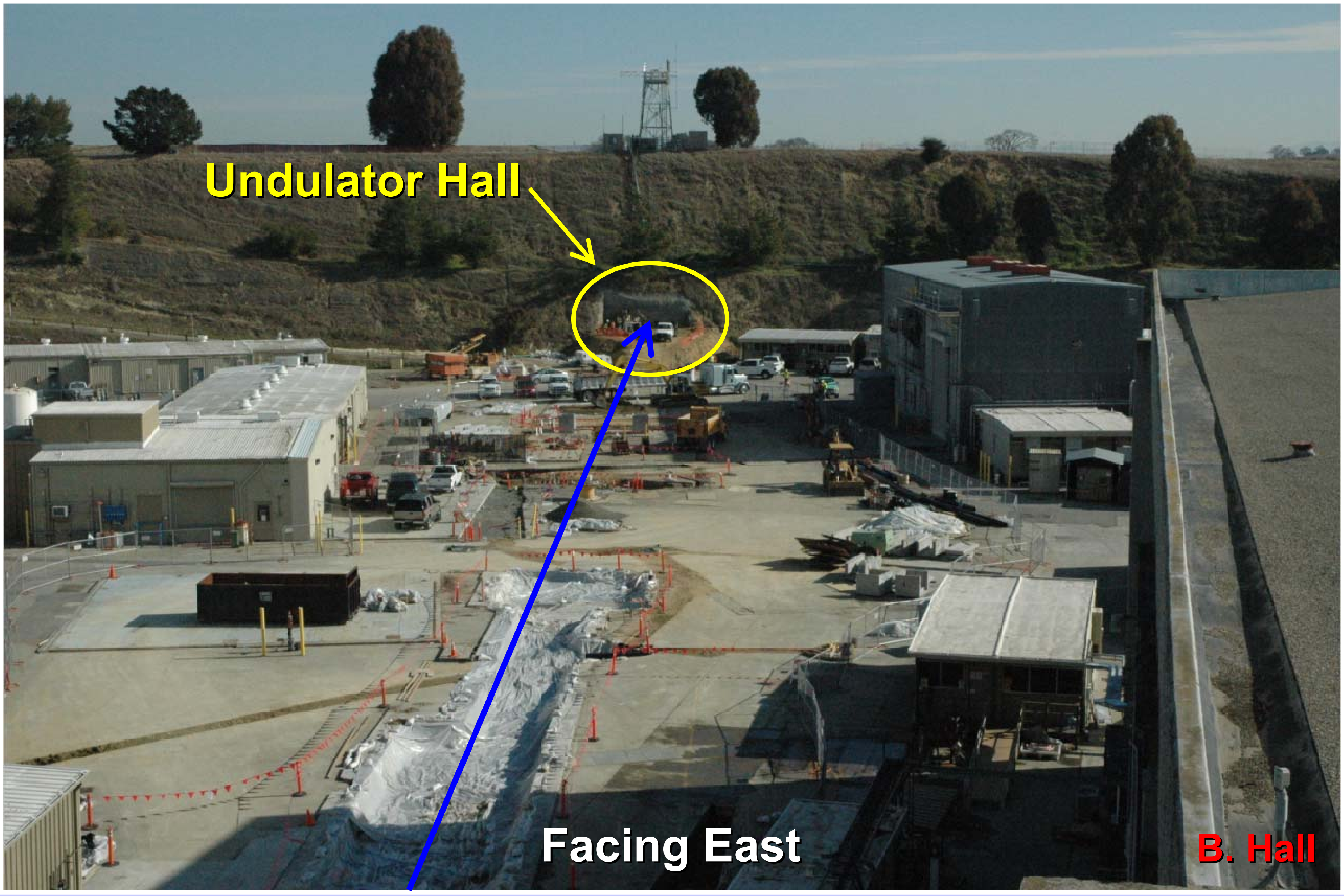
Projects	Euro-XFEL	LCLS	XFEL/SPring8 (SCSS)
Wavelength	6 – 0.085 nm	1.5 – 0.15 nm	6 – 0.08 nm
Beam Energy	10 - 20 GeV	14.3 GeV	2 - 8 GeV
Main Accelerator	Super Conducting	S-band Normal Conducting	C-band Normal Conducting
Accelerator Length Gradient x Active Length	2.1 km 23.5 MV/m x 900 m	1 km 19 MV/m x 800 m	400 m 35 MV/m x 230 m
Undulator Period Total undulator Length	26 mm 133 m	30 mm 113 m	18 mm 90 m
Total Length Undulator Lines (X-ray)	3.4 km 3 (5)	1.6 km 1 (5)	700 m 1 (3), max 5
Construction Cost	850 M-Euro	380 M$	300 M$


Linac Coherent Light Source at SLAC
X-FEL based on last 1-km of existing linac
1.5-15 Å
Injector (35º)
at 2-km point
Existing 1/3 Linac (1 km)
(with modifications)
New e⁻ Transfer Line (340 m)
X-ray
Transport
Line (200 m)
Undulator (130 m)
Near Experiment Hall
(underground)
Far Experiment
Hall (underground)
CONSTRUCTION
HAS STARTED

Beam Transport Hall (BTH) Construction (Jan. 2007)



Undulator Hall (UH) Construction (Jan. 2007)



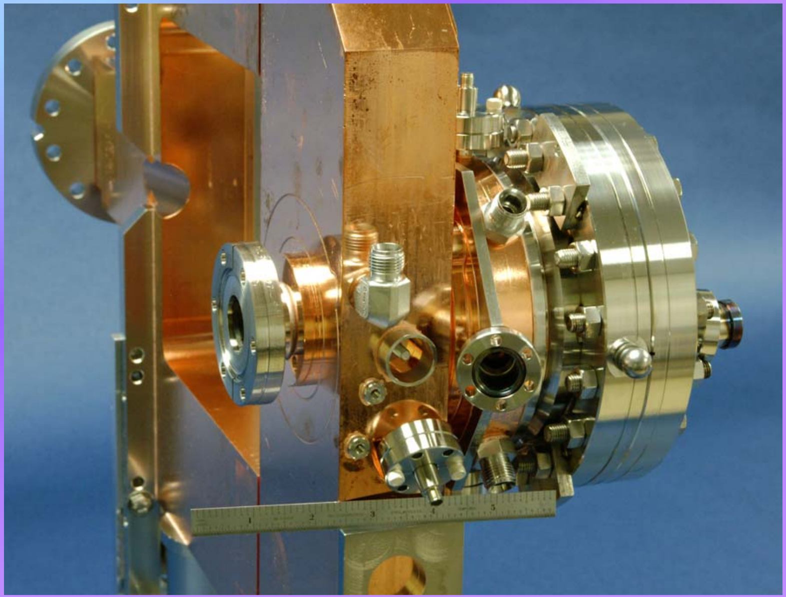
Near Experimental Hall (NEH) Construction (Jan. 2007)

First Measurements and the SLAC MMF

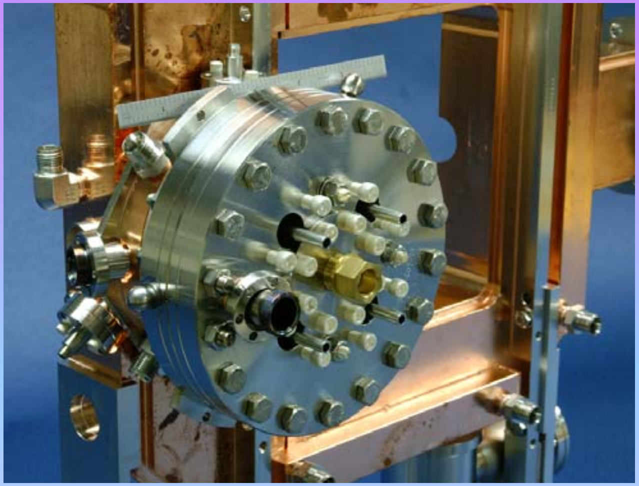
There are 7 productions undulators now at SLAC, 1 at ANL

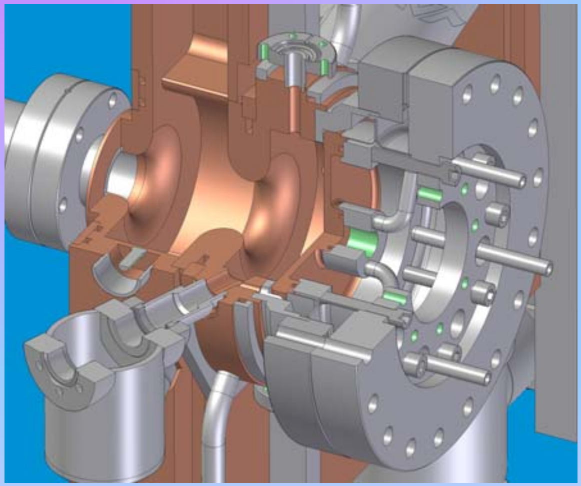
The vendor has roughly 4 more and is completing > 2 per week

RF Gun Fabrication and Cold RF Testing Finished & Preparing for High-Power Tests



Gun only pictures

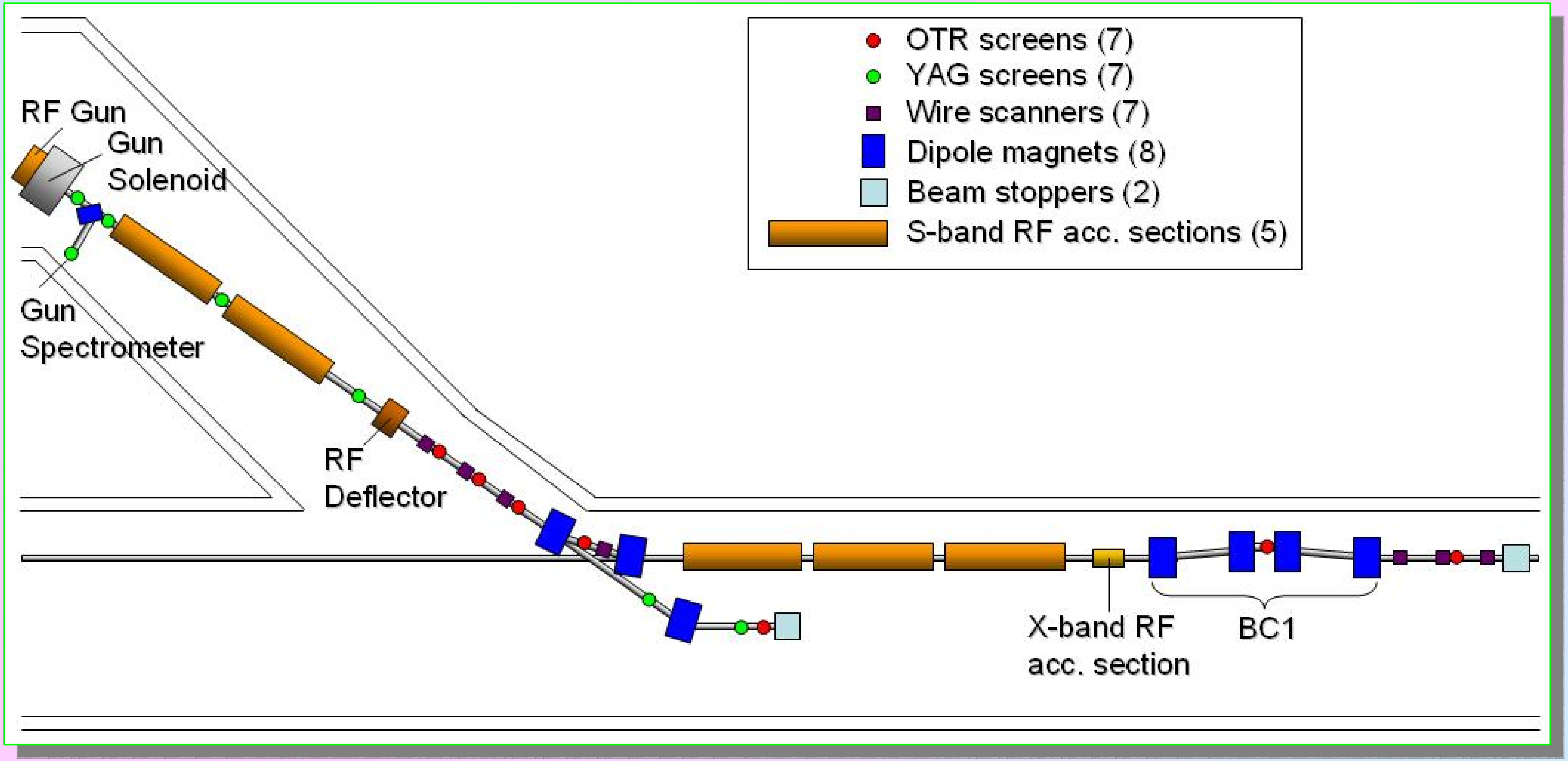




CAD cut away view of gun interior

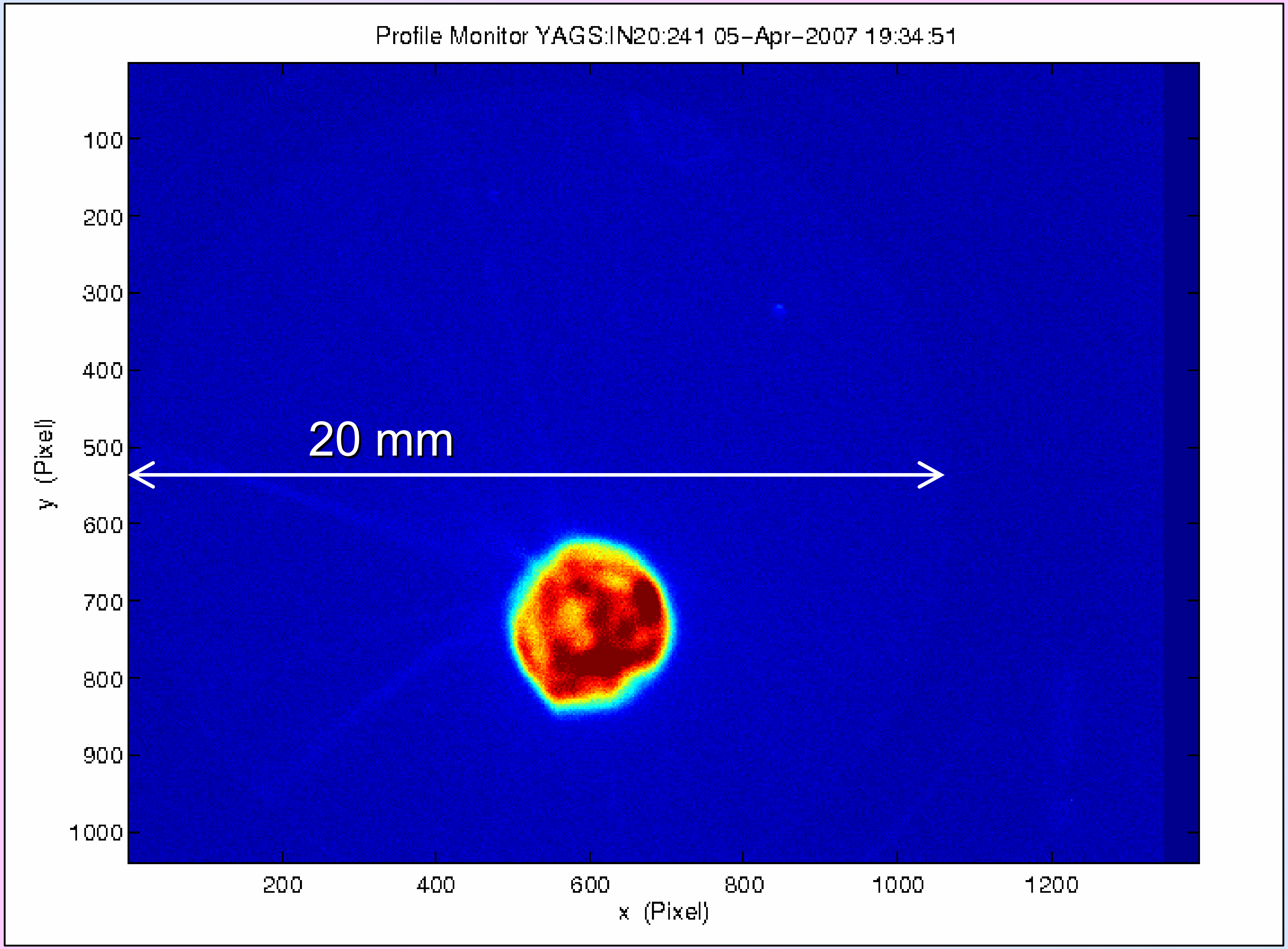
LCLS Injector Layout

Gun through BC1-Chicane at 250 MeV



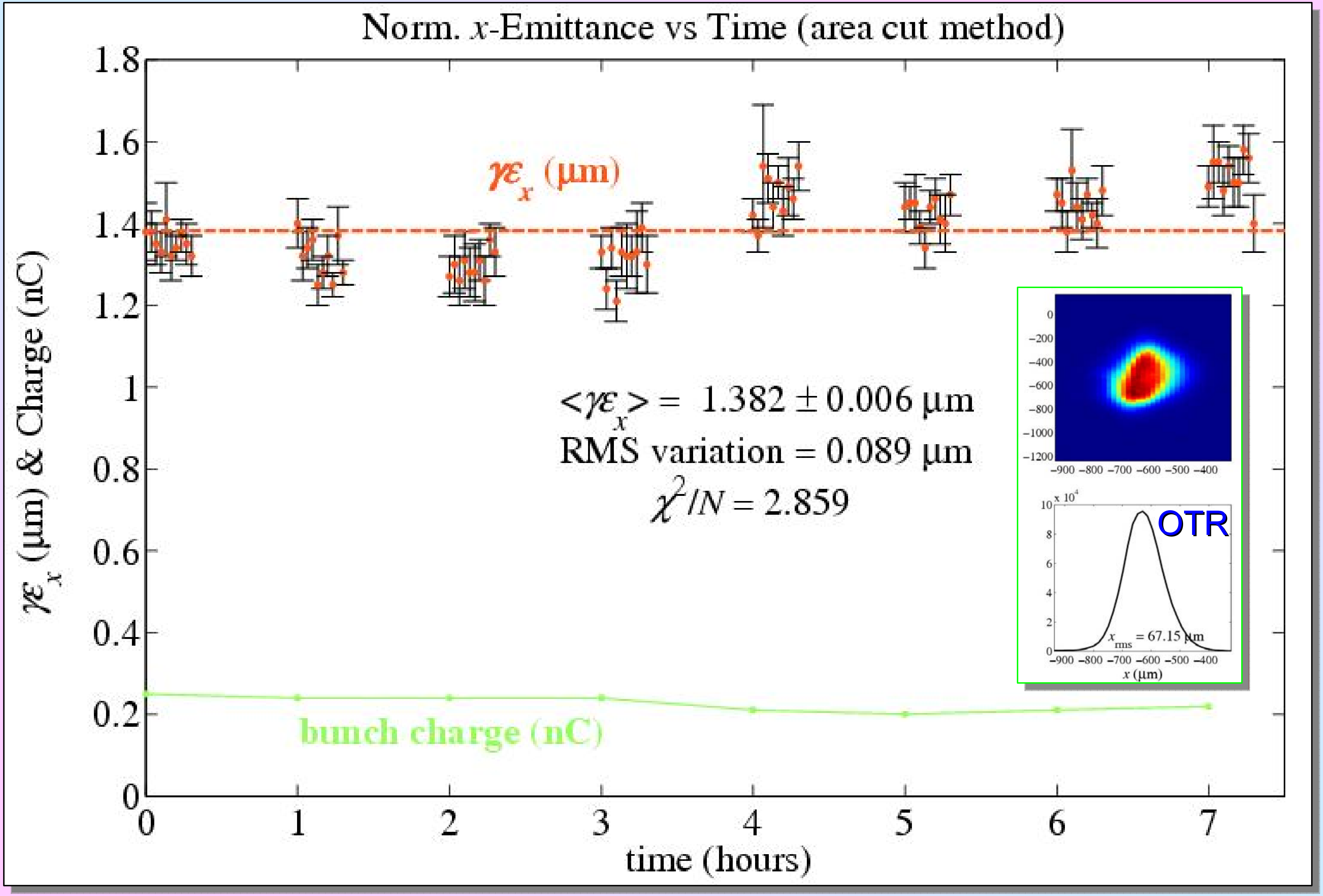
Injector Electron Commissioning April – August, 2007

First Electron Beam on April 5, 2007

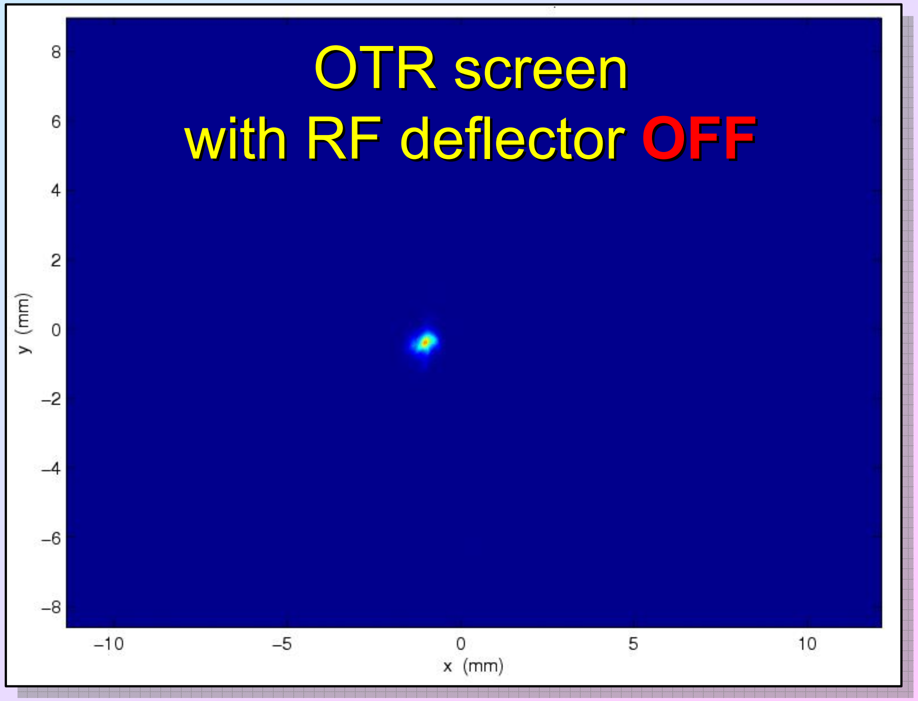


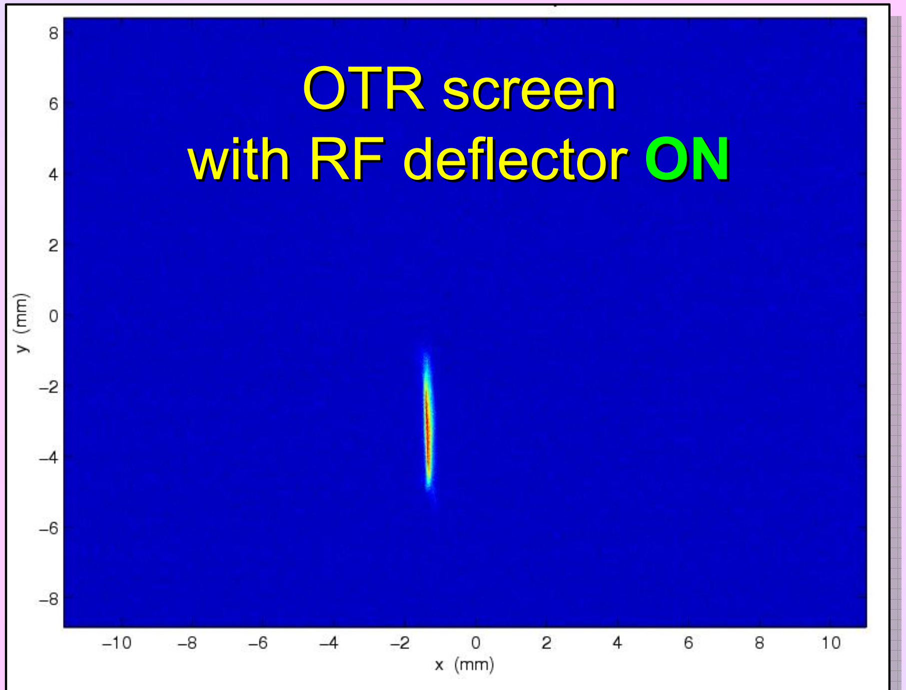
(YAG screen 80 cm from gun cathode)

Projected Emittance Measured 80 Times Over 8 Hours

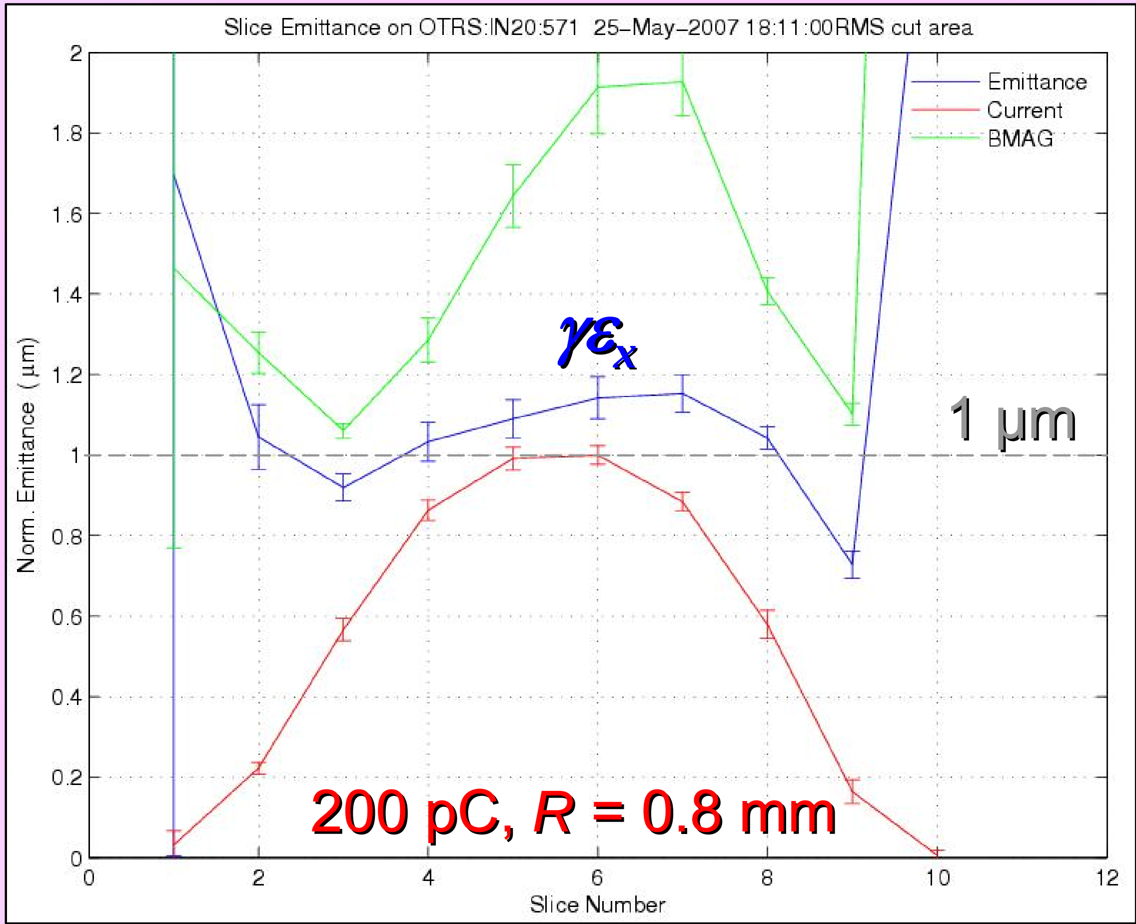


Transverse RF Deflector Used to Time-Resolve Emittance (into "slices")





Time-Sliced Emittance and β-Match



← 10 ps →

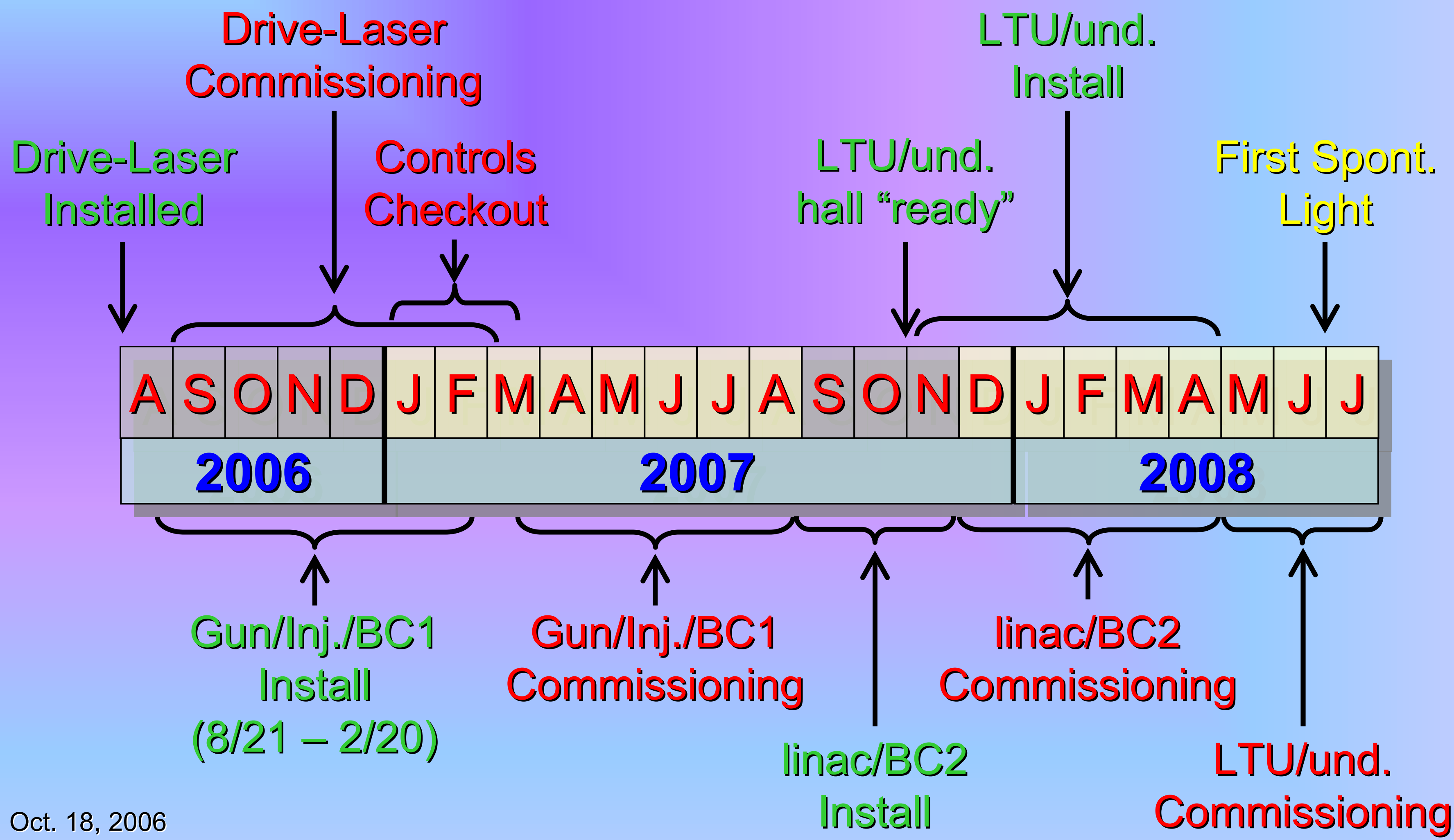
Emittance still variable - parameters not design yet

Approximate and Typical *LCLS* Machine Parameters at Present

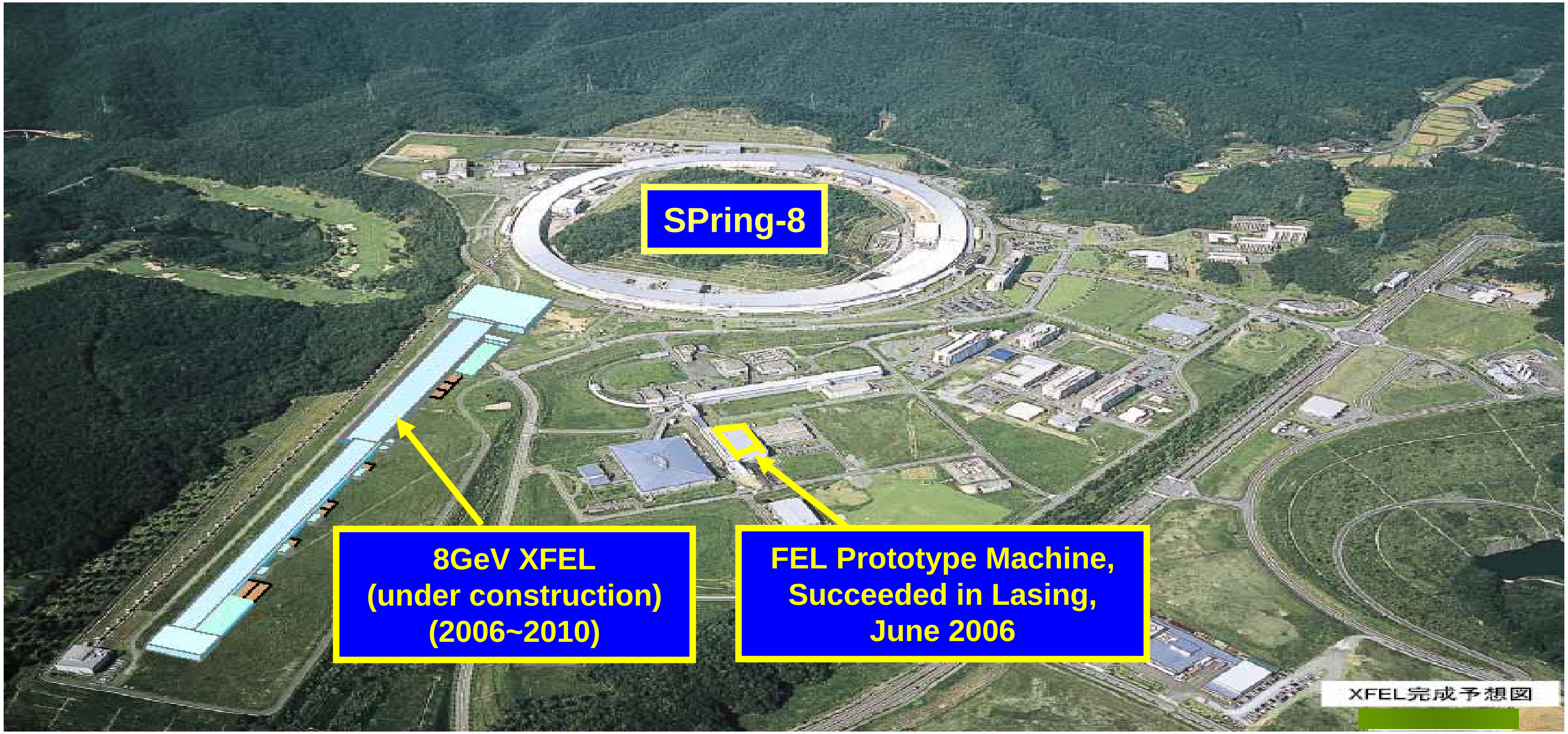
Parameter	sym	dsgn	meas.	unit
Final e^- energy	γmc^2	250	250	MeV
Bunch charge	Q	1000	200	pC
Init. bunch length (fwhm)	Δt_0	10	6.5	ps
Fin. bunch length (fwhm)	Δt_f	2.3	1.5	ps
Initial peak current	I_{pk0}	100	30	A
Final peak current	I_{pkf}	450	130	A
Projected norm emittance	$\gamma\varepsilon_{x,y}$	1.2	1.5, 1.8	μm
Slice norm. emittance	$\gamma\varepsilon^s{}_{x,y}$	1.0	1.2, 1.3	μm
Slice rel. E-spread (rms)	σ_E/E	<10	<10	keV
Single bunch rep. rate	f	120	10-30	Hz
RF gun field at cathode	E_g	120	110	MV/m
Laser energy on cathode	u_l	250	250	μJ
Laser wavelength	λ_l	255	255	nm
Laser diameter on cath.	$2R$	1.5	2	mm
Cathode material	-	Cu	Cu	
Cathode quantum eff.	QE	2	0.4	10^{-5}
Commissioning duration	-	8	5	mo

parameters still quite variable

LCLS Installation and Commissioning Time-Line



Oct. 18, 2006

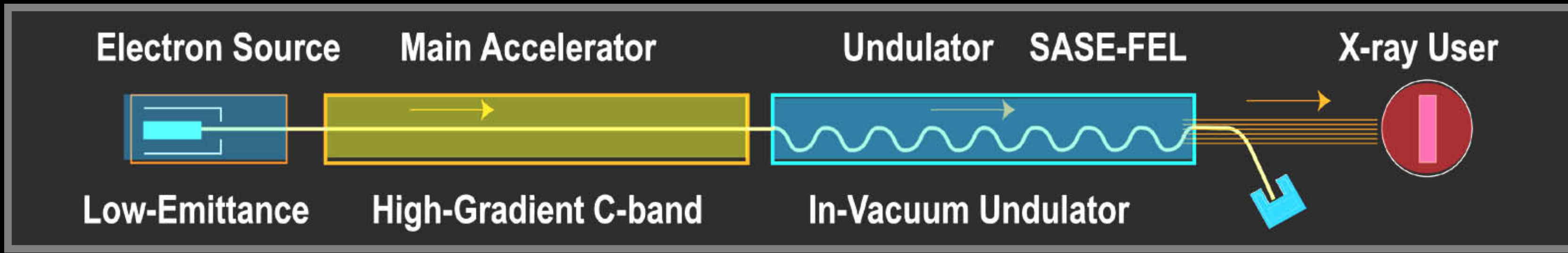


"X-ray Free Electron Laser, XFEL"

National Project of Next-Generation Light Source

RIKEN-JASRI Joint-Project Team for SPring-8 XFEL Construction

SCSS:SPring-8 Compact SASE Source



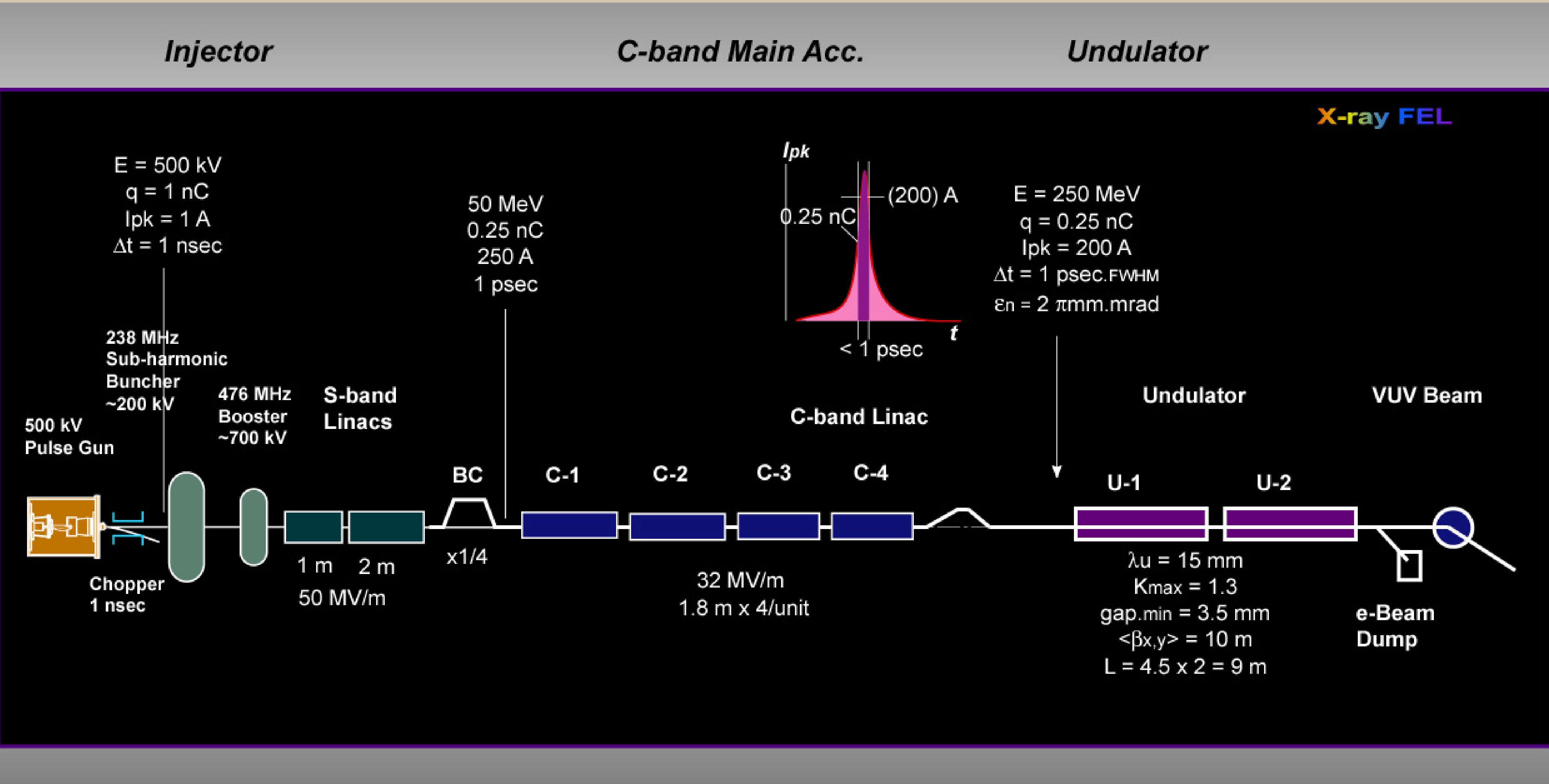
- **Low Emittance Injector** → **Short Saturation Length**
- **High Gradient Accelerator** → **Short Accelerator Length**

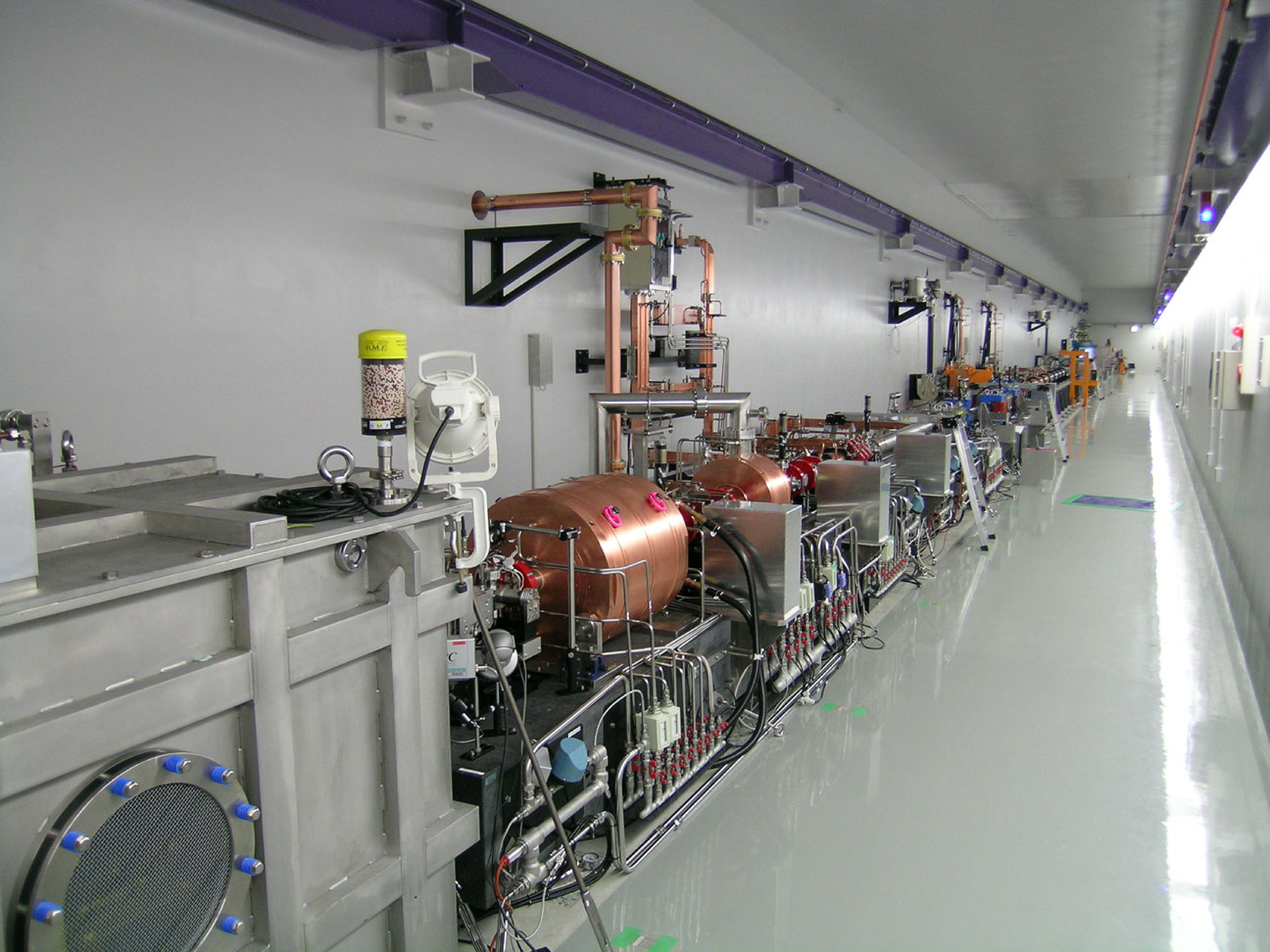
KEK C-band 35 MV/m x 30 m = 1 GeV

- **Short Period Undulator** → **Lower Beam Energy**
  Short Saturation Length

Kitamura's In-Vacuum Undulator : E = 1GeV, λu = 15 mm, λx = 3.6 nm

Test Accelerator Layout





SCSS Test Accelerator

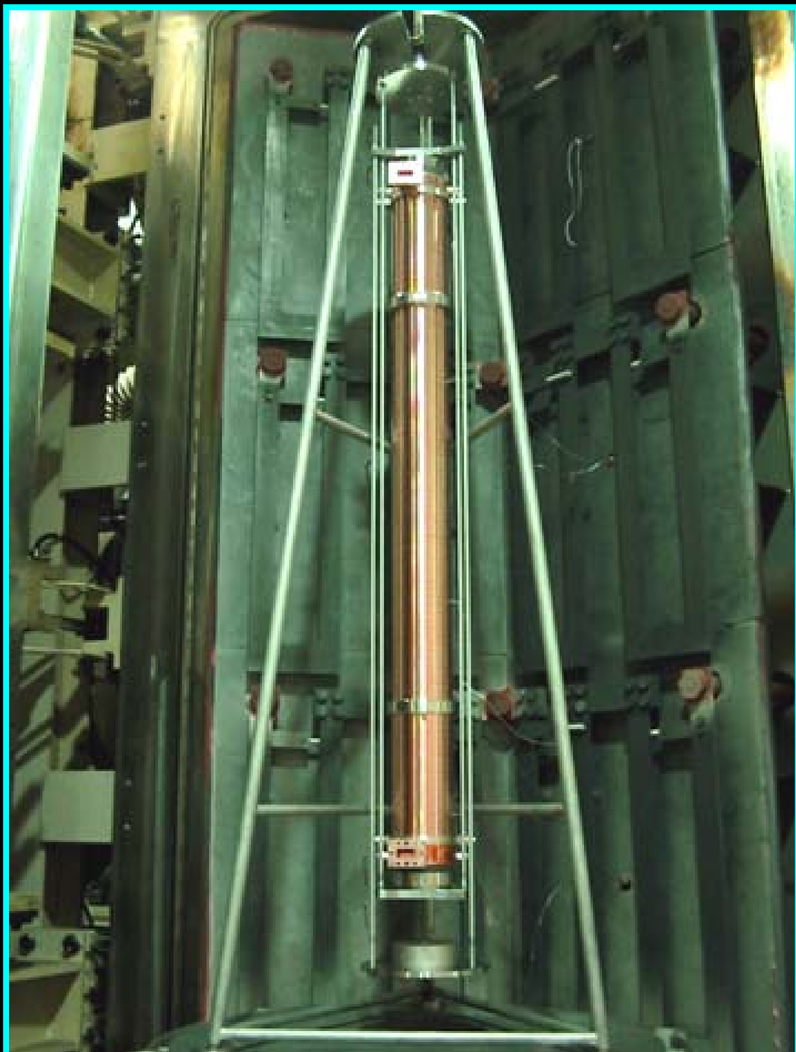
- Undulator 4.5 m x 2 unit
- 15 mm period
- 4 mm gap

- C-band Accelerator
- 50 MW Klystron x 2
- Acc Structure 1.8 m x 4
- 250 MeV

C-band Accelerating Structure for SCSS

X-ray FEL

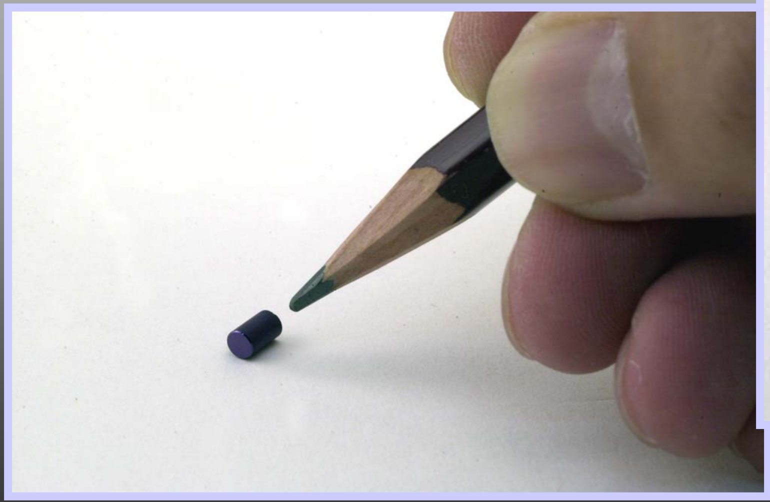
Ver. 2002



- HOM Damping by Choke-Mode Cavity
- 1.8 m long, 91 Cells, CG-structure
- $3\pi/4$-mode
- Brazing Bonding
- SiC by Tungsten wire-spring.
- Double-feed Coupler
- High-power test will be Summer 2003

CeB_6 Cathode & Heater Assembly

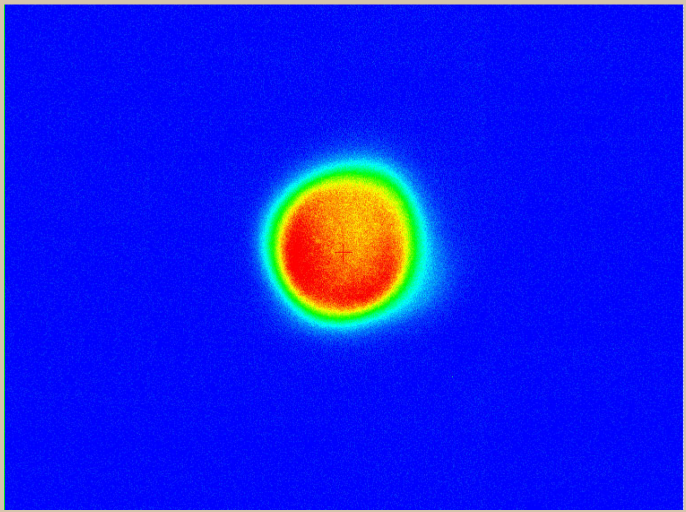
- CeB_6 Cathode 3 mm Diameter
- Emittance 0.4 π.mm.mrad (thermal emittance, theoretical)
- Beam Current 3 Amp. at 1450 deg.C (using graphite heater)
- Current Density > 40 A/cm^2



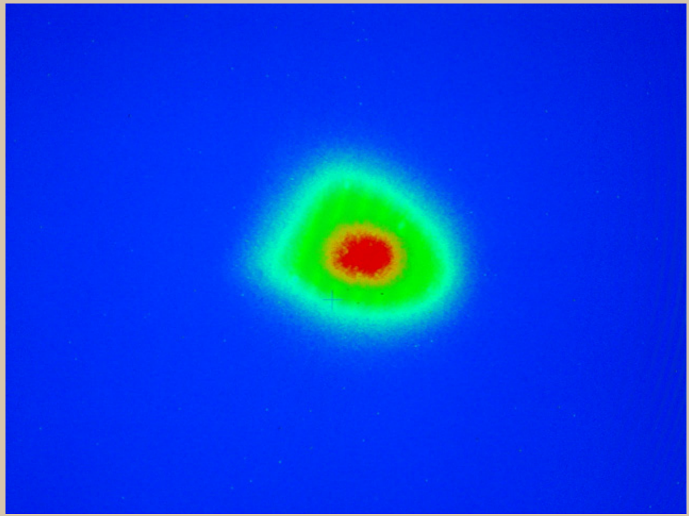
T. Shintake, FEL06

CeB_6 Thermionic Gun provides stable beam.

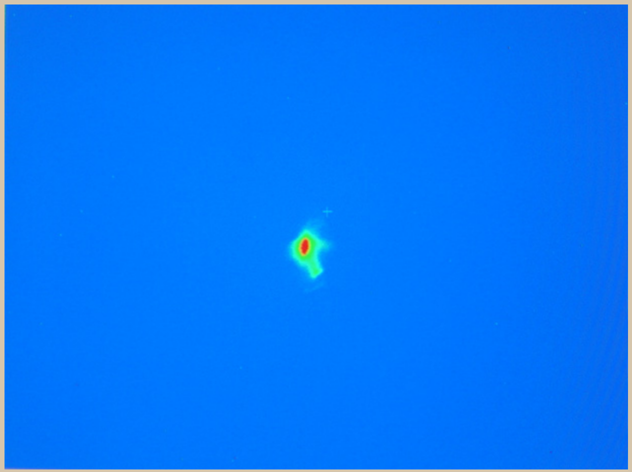
Beam Profile
CCD Image
Scale 10 mm



500 kV Gun

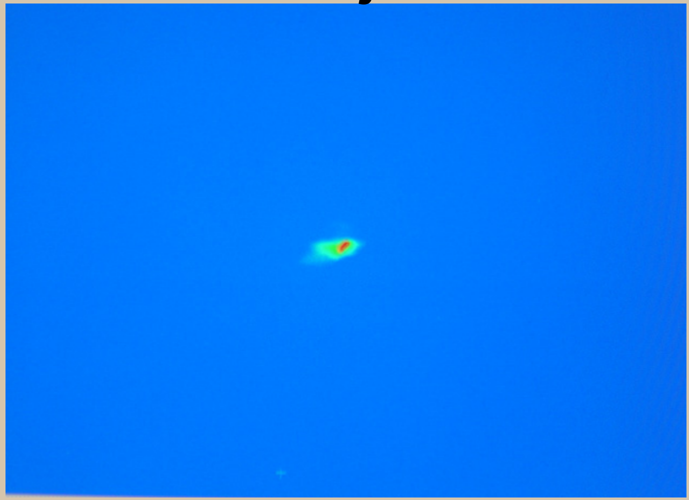


50 MeV Injector Out



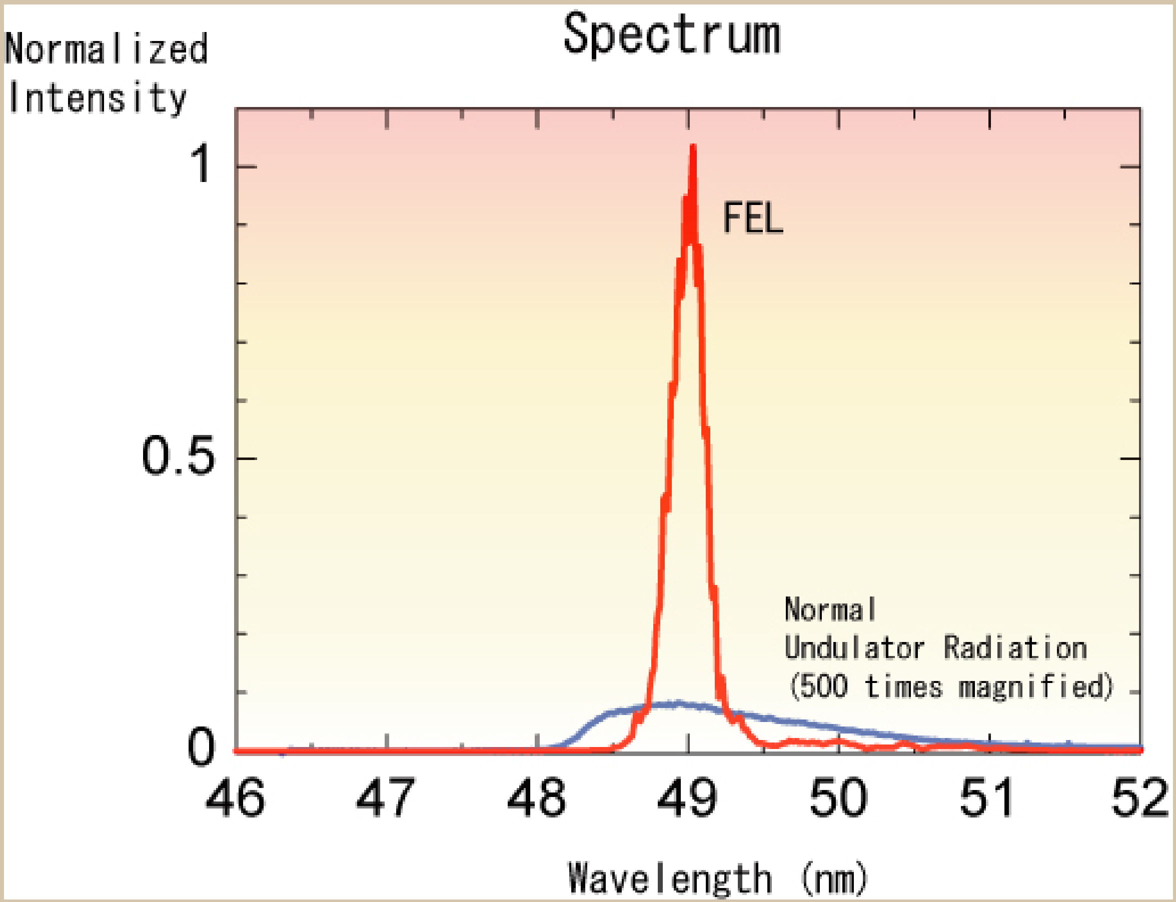
250 MeV Compressor

Undulator Input



Undulator Output

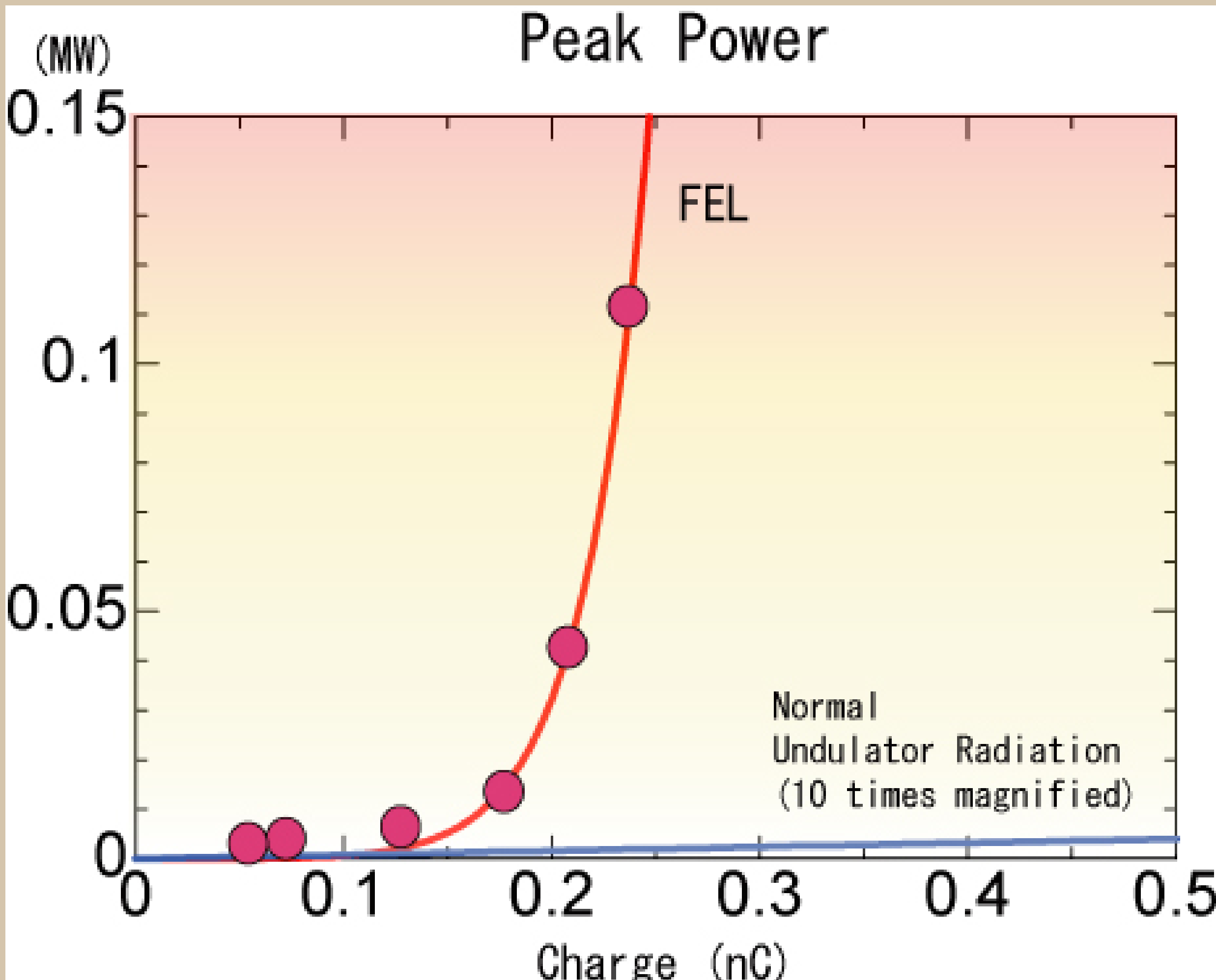
First Lasing at SCSS Prototype Accelerator.



- The first lasing: 49 nm
- E-beam energy : 250 MeV
- Bunch charge: 0.25 nC
- Bunch length: (< 1 pse)
- Peak Current (> 300 A)

- At moment spectrum width 0.5 nm is dominated by e-beam energy fluctuation ~ 0.2%.

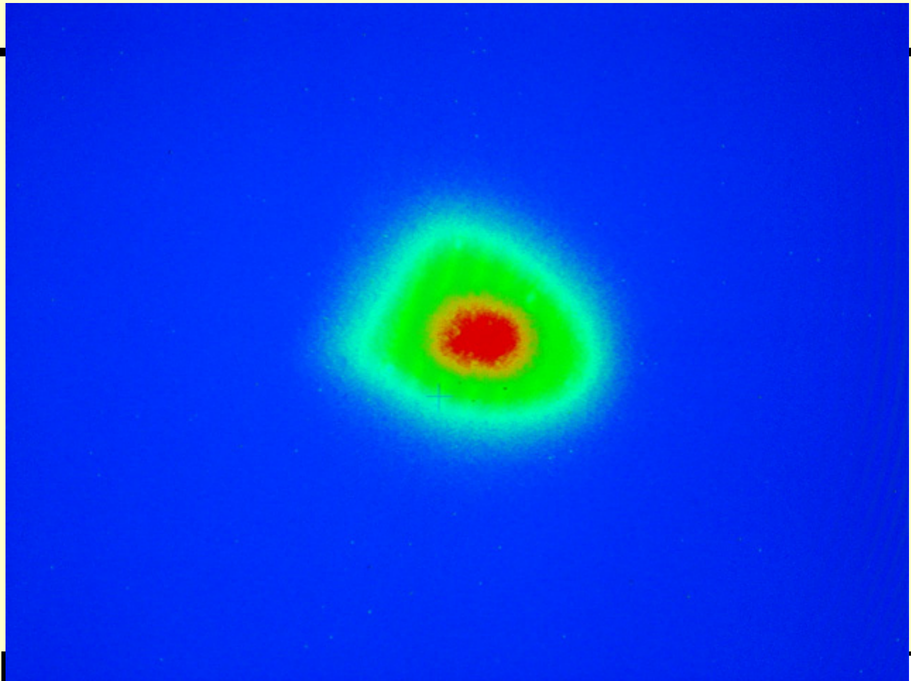
First Lasing at SCSS Prototype Accelerator.

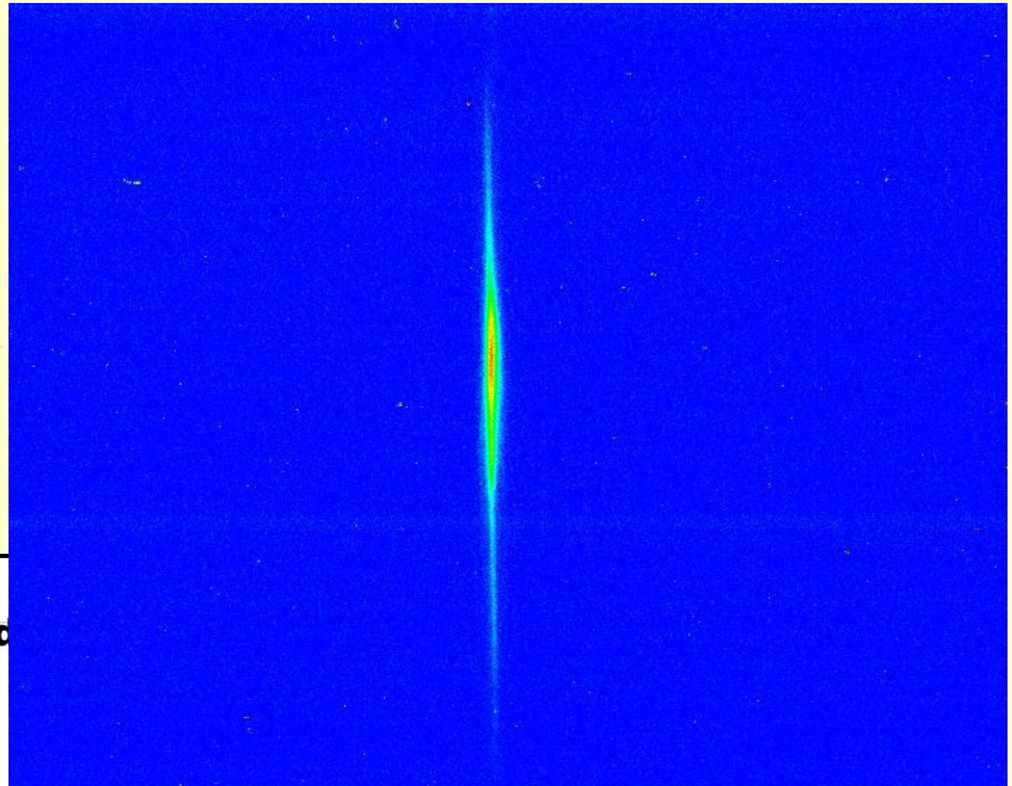


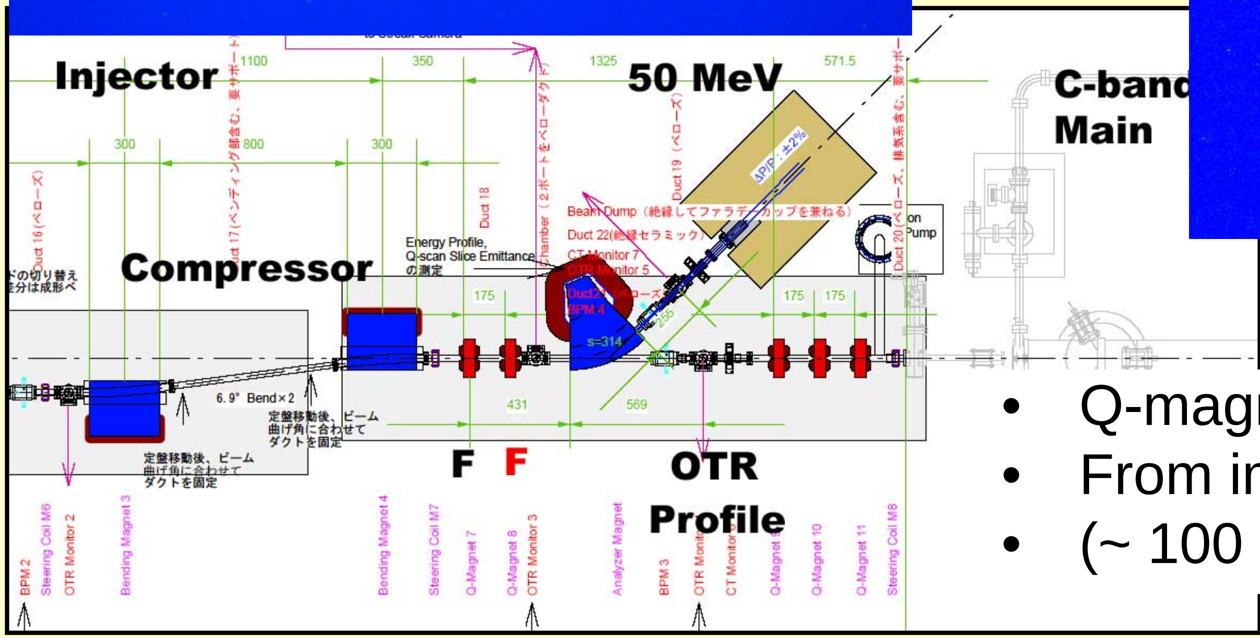
- **The first lasing: 49 nm**
- **E-beam energy : 250 MeV**
- **Bunch charge: 0.25 nC**
- **Bunch length: (< 1 pse)**
- **Peak Current (> 300 A)**

- **Laser pulse length has not yet measured, (will be ~ 100 fsec).**
- **Peak power estimation assumed 1 psec width.**

Q-scan Emittance Measurement







- Q-magnet provide horizontal focusing.
- From image width emittance is estimated.
- (~ 100 micron-meter)

SCSS & X-ray FEL Beam Parameter

at undulator section

		Prototype	X-ray FEL	
Beam Energy	E	0.25	8.0	GeV
X-ray Wavelength	λ	60	0.1	nm
Beam Emittance	ε_n	2	1.0	πmm.mrad
Bunch Length	Δ_z FWHM	100 0.3	100 0.3	µm psec
Transverse Beam Size	$\sigma_{x,y}$	100	25	µm
Peak Current	I_p	1	3	kA
Charge per bunch	q	0.3	1	nC
Undulator Parameter	λ_u K	15 1.3	18 1.3	mm
Length	L	10	80	m
FEL Saturation Length	L_{sat}	20	60	m

Status of XFEL/SPring-8

- **2006 April, Funding was made, 300 M$**
  injector, accelerator, one undulator line, user lines, infrastructure.

- **2007 June, Construction of tunnel started**
- **2007 June, Production of the accelerating cavity started.**

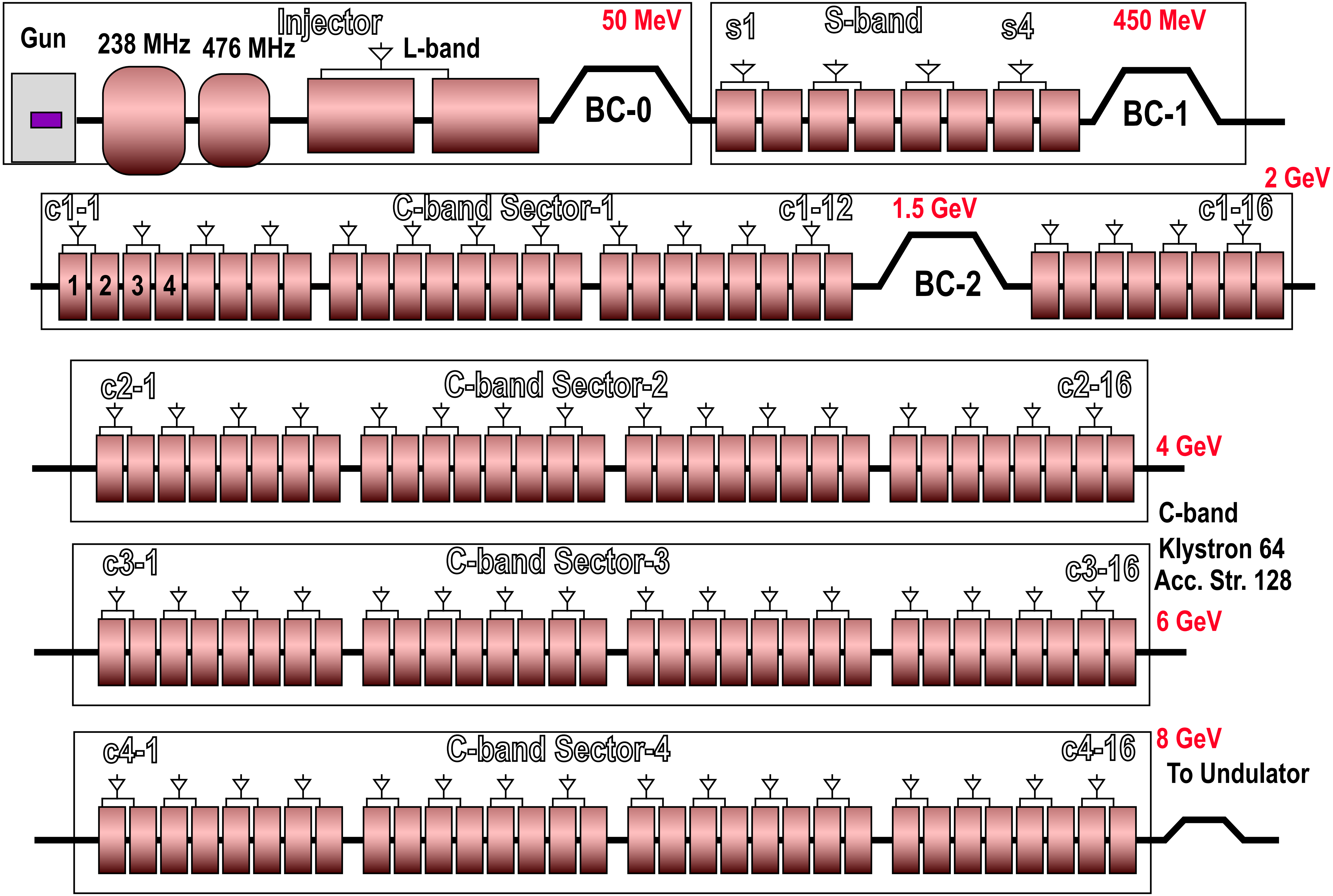
- **Beam commissioning will start in end of FY2010**

Tunnel Construction started June 2007

- Accelerator tunnel, on surface.
- Site length 700 m

RF Acceleration System in 8 GeV SPring-8 XFEL

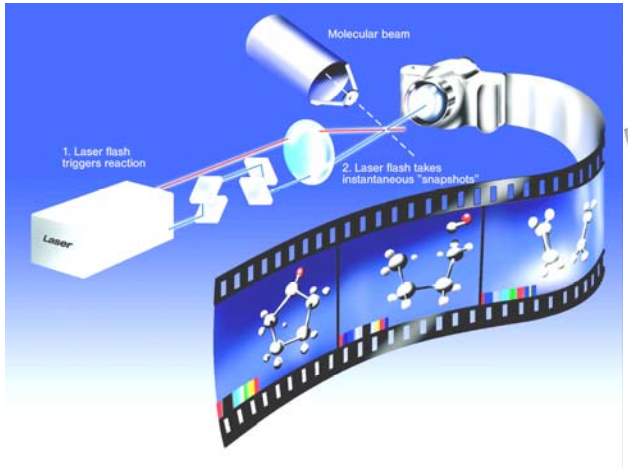
T.Shintake 2007 March

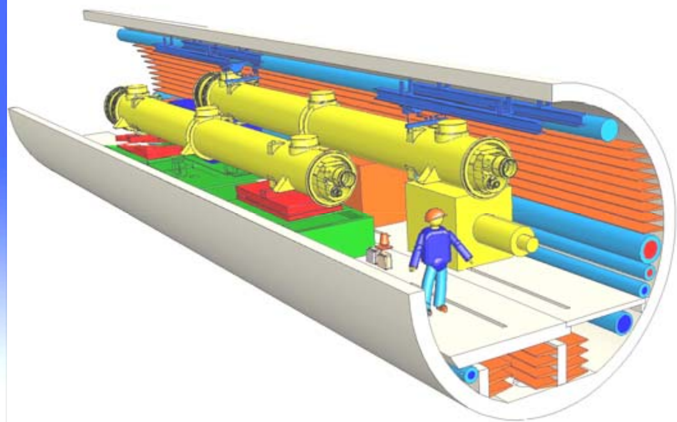


• 400 m Long C-band Main Accelerator

European XFEL Project Status and Industrialisation Programme

R. Brinkmann, DESY
for the XFEL team





Introduction

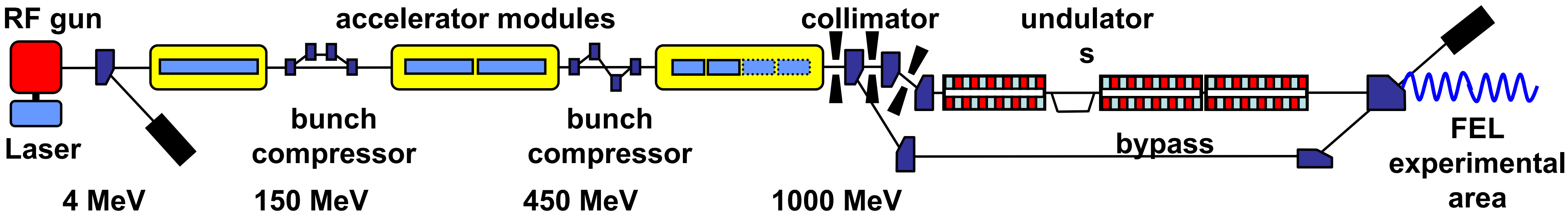
Proposal Oct. 2002 – X-ray FEL user facility with 20 GeV superconducting linear accelerator in TESLA technology

Approval by German government Feb. 2003 as European Project

Commitment for 50% of funding + 10% by Hamburg & Schleswig-Holstein, 40% European & international partners

Introduction cont'd

TESLA Test Facility and the VUV-FEL:



→ Pilot facility regarding practically all aspects (accelerator technology, beam physics, FEL process, user operation) of the XFEL

→Test bed for technical developments specifically required for the XFEL

→ Injector development at PITZ, DESY-Zeuthen

FLASH.

The Free-Electron Laser in Hamburg

New technologies for new science: Soon X-ray free-electron lasers will enable us to probe ultrafast physical, chemical and biochemical processes at atomic resolution, opening new frontiers for science and technology. At long last we may see, and not just model, how molecular machines really work.

Accelerators | Photon Science | Particle Physics

Deutsches Elektronen-Synchrotron
Member of the Helmholtz Association

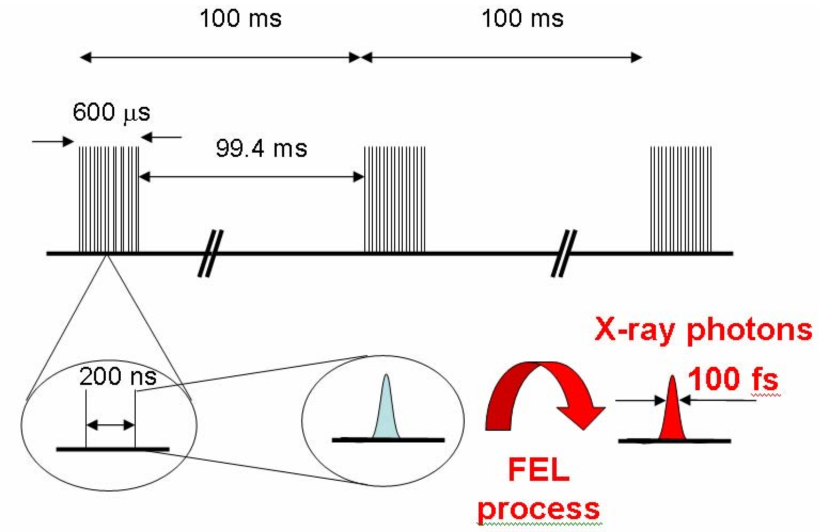
Properties of XFEL radiation

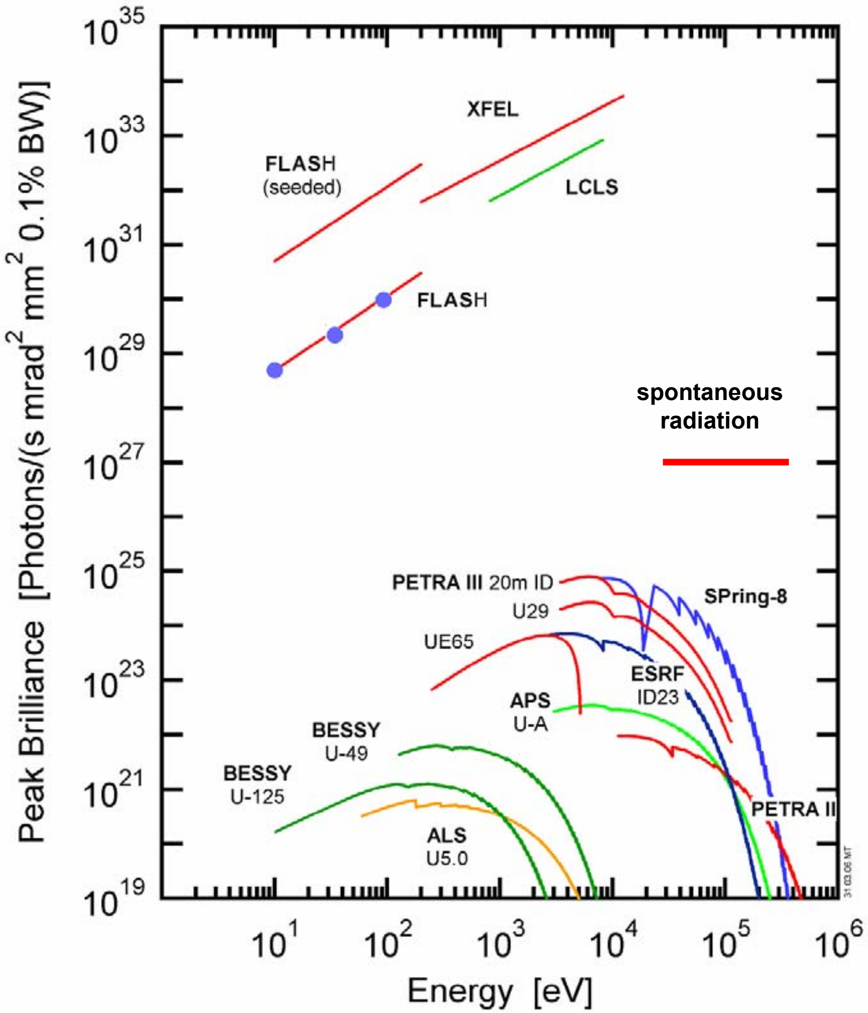
X-ray FEL radiation (0.2 - 14.4 keV)

- ultrashort pulse duration <100 fs (rms)
- extreme pulse intensities 10^{12}-10^{14} ph
- coherent radiation x10^{9}
- average brilliance x10^{4}

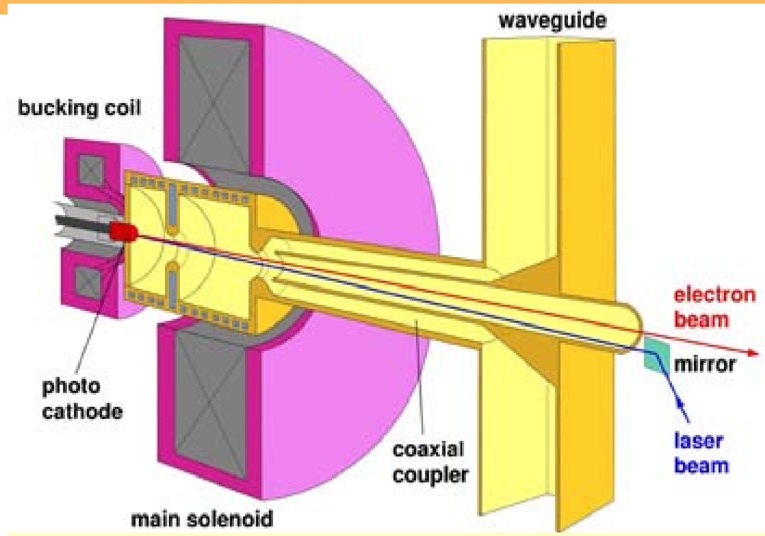
Spontaneous radiation (20-100 keV)

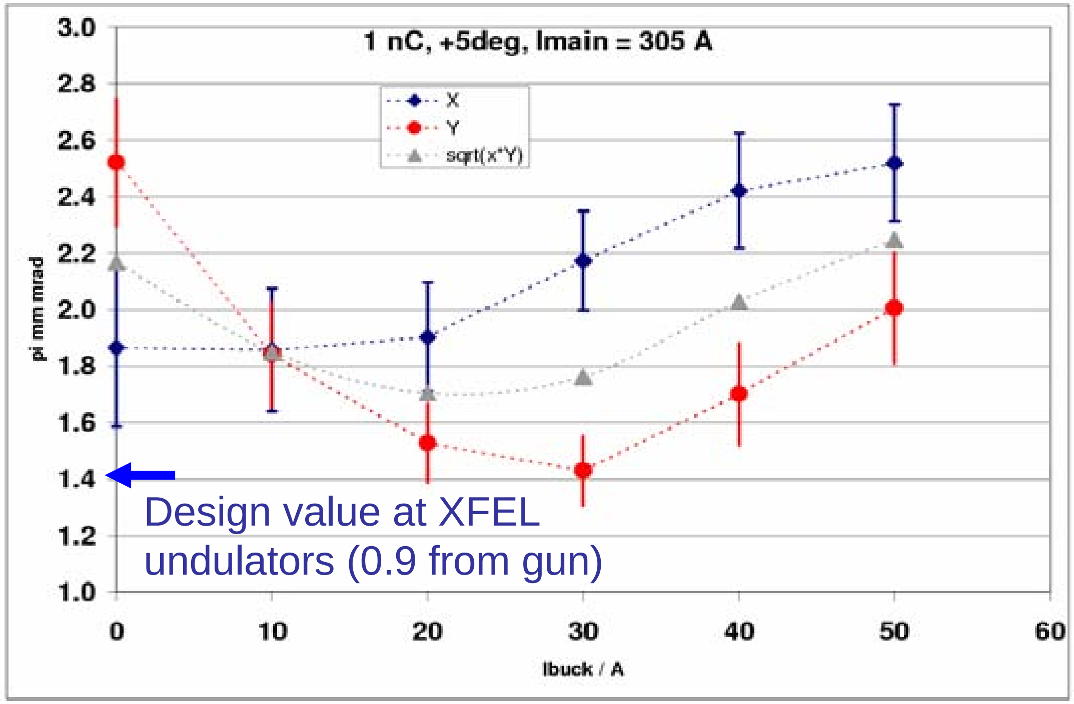
- ultrashort pulse duration <100 fs (rms)
- high brilliance





Injector development (DESY Zeuthen & FLASH)





On-going programme:

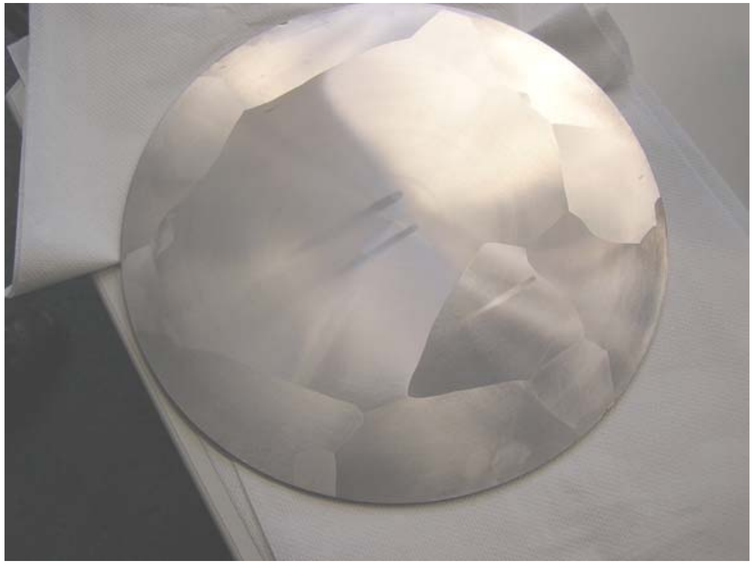
- **increase the gradient on the cathode from 40 MV/m to 60 MV/m**
- **further improve the transverse and longitudinal laser profile (collab. Max-Born Institute, Berlin)**
- **PITZ gun now part of FLASH injector**

Preparation of the superconducting cavities in the DESY cleanroom: A string of eight cavities, each welded into its own liquid-helium tank, is being assembled and prepared for installation in an acceleration module. On the right: a single nine-cell cavity equipped with vacuum flanges and a radio-frequency input coupler for the performance test in a liquid-helium bath cryostat.

Alternative fabrication – large grain Nb

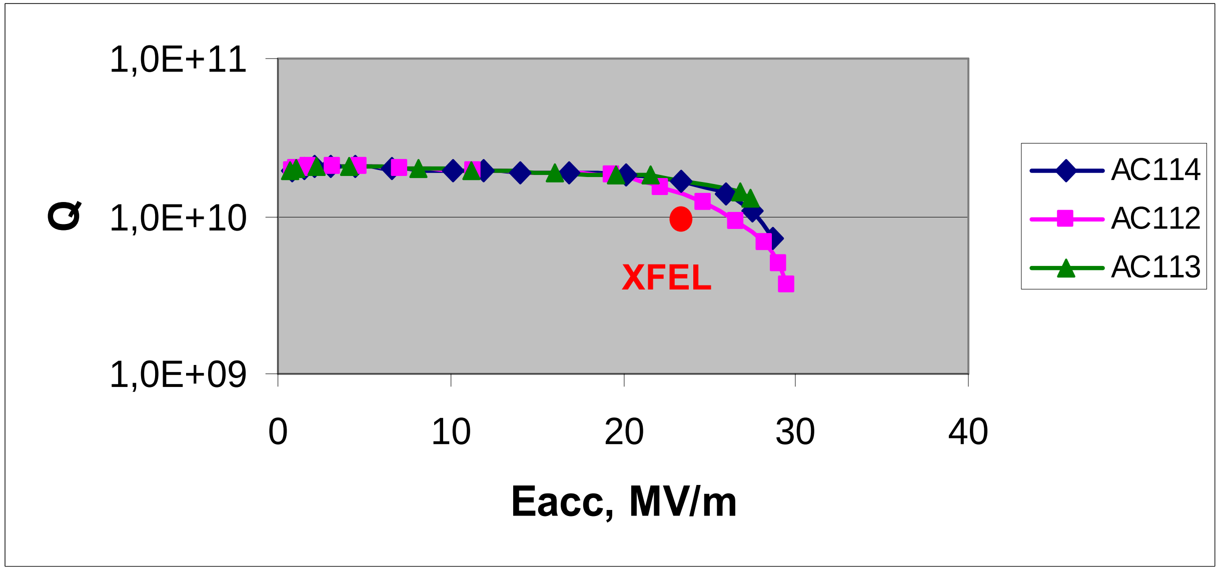
Fabrication from large-grain Niobium – cut sheets directly from ingot (method pioneered at JLAB)

After initial good results with single cells, fabricated and tested three 9-cell cavities – only BCP-treated, no EP!

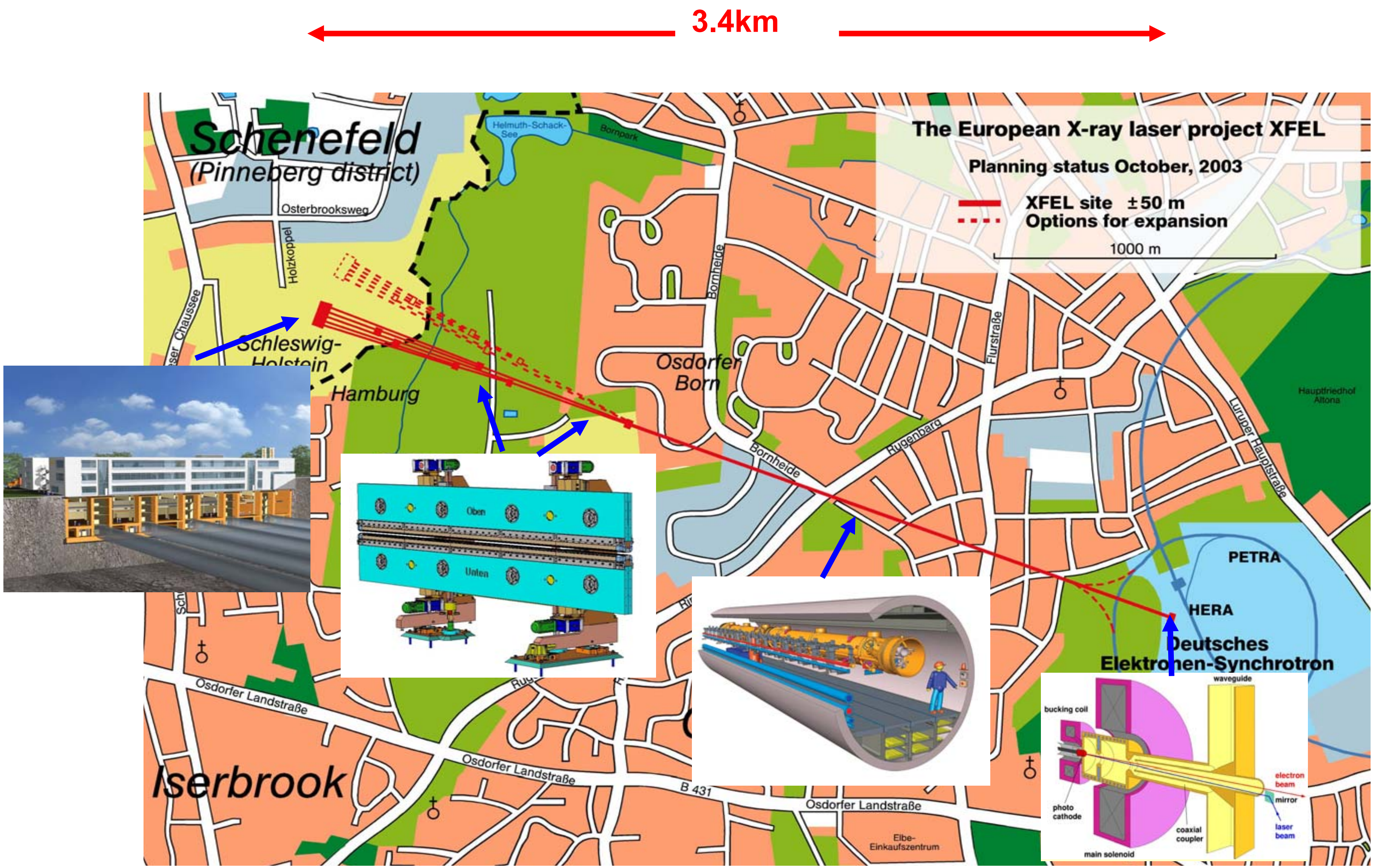


→Will build 6 more cavities, possibly alternative fabrication/treatment procedure

→Could later choose the more economic method for industrial production



Overall layout of the European XFEL



Accelerator technology - collaborative effort

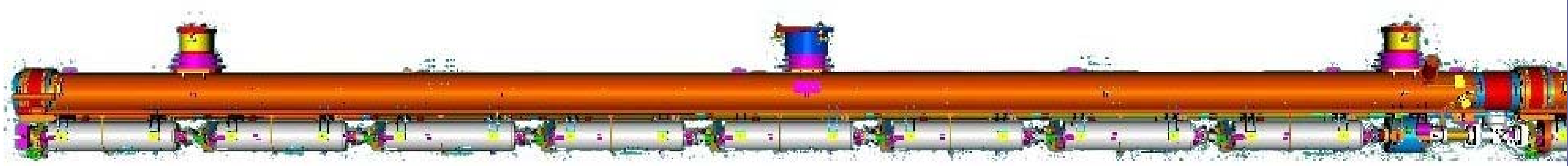
Industrial study module assembly (M6 done, M8 autumn 2007)

2 more cryostats (TTF3/INFN) delivered

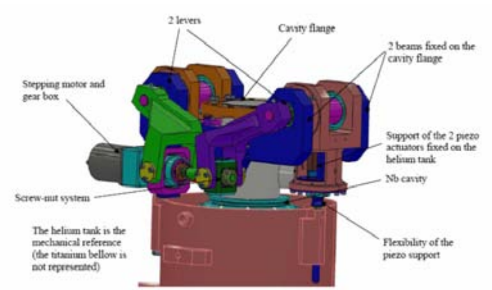
Superferric magnet (CIEMAT)

BPM (Saclay)

Integrated HOM absorber

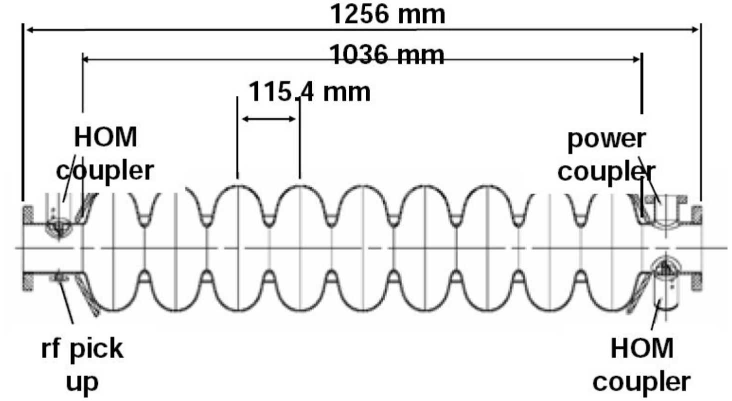


Length quantized n·λ/2 (possibility of ERL)

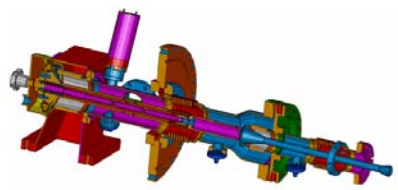


Tuner w/piezo (Saclay)

Industrialization in preparation



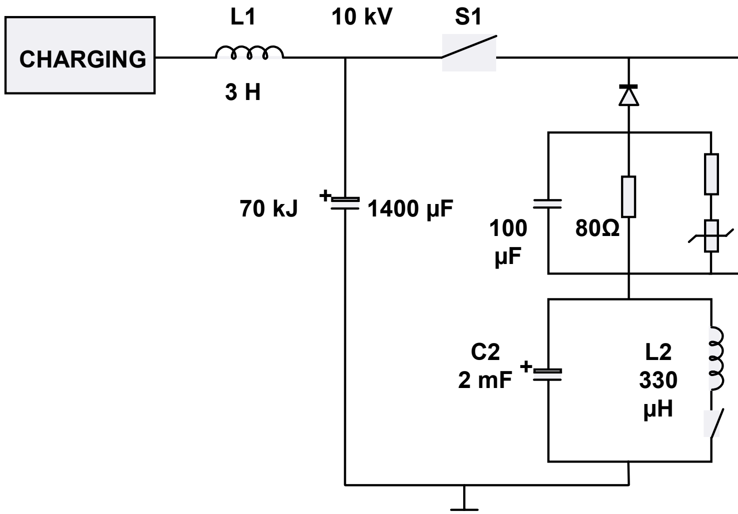
LLRF development (collab. Warsaw/Lodz)

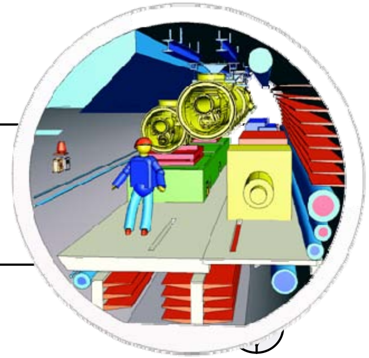


TTF3-type coupler

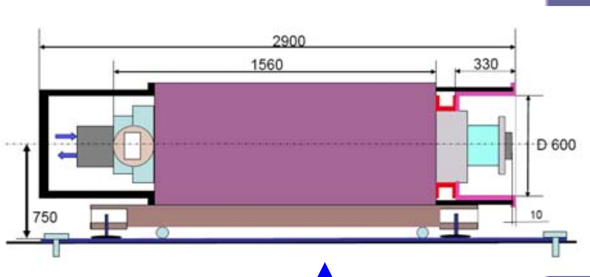
Industrialization launched (Orsay)

High Power RF System
(Modulator, Pulse Cable, Pulse Transformer, Klystron)



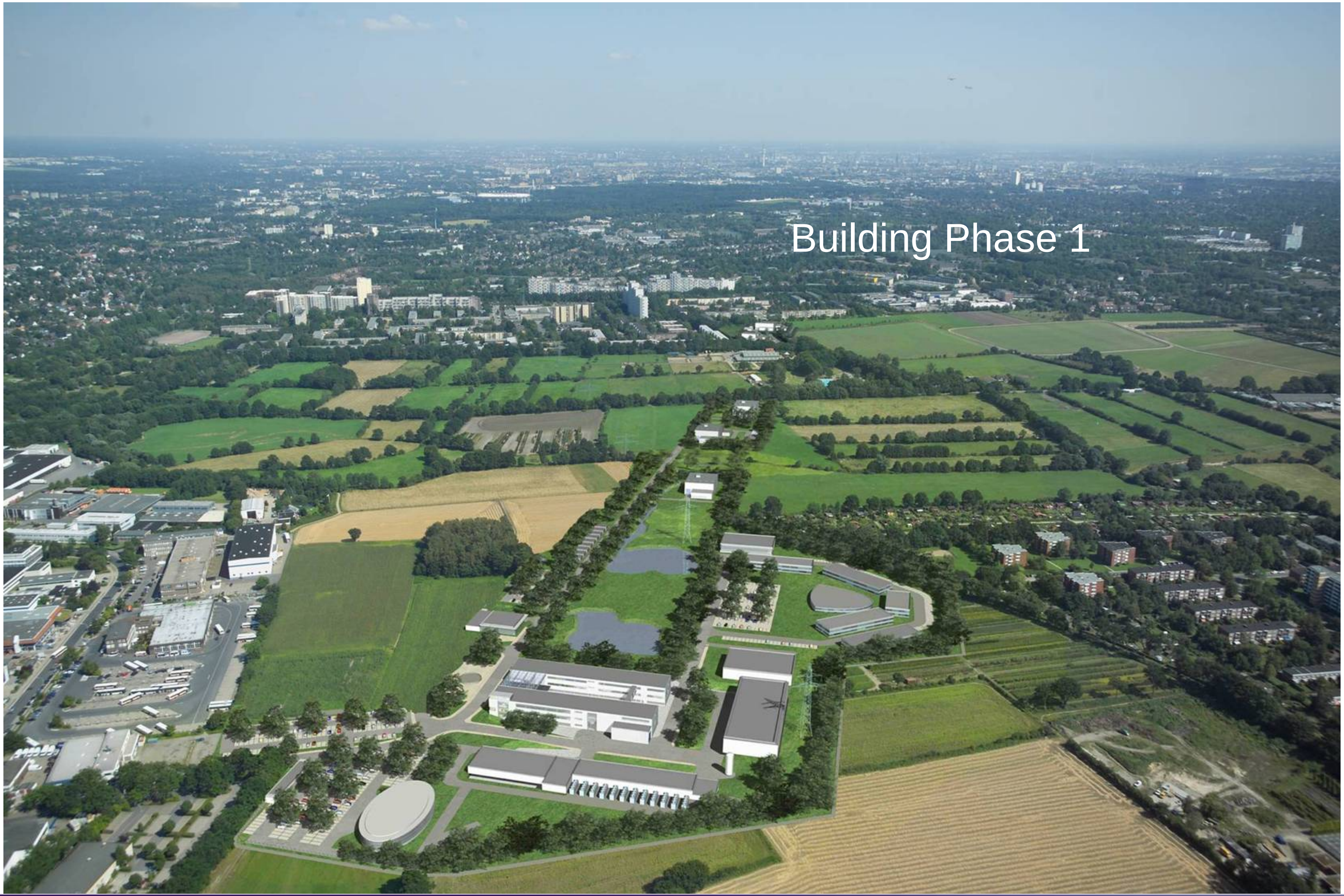


1:12 Pulse Transformer



XFEL site in Hamburg/Schenefeld

… after construction *(computer simulation)*



XFEL Radiation Characteristics

- High Peak Power ~ GW
  → high field non linear physics
  → high flux photons for single shot diffraction imaging
  single molecular structural analysis
- Short Pulse 10 ~ 100 fsec
  → Time resolving experiment (Pump probe)
  Chemical reaction
- Coherent
  → Holography, Coherent Imaging

Gabor's Holography

Originally invented as electron microscope

May 15, 1948 NATURE

A NEW MICROSCOPIC PRINCIPLE

By Dr. D. GABOR
Research Laboratory, British Thomson-Houston Co., Ltd., Rugby

IT is known that the spherical aberration of electron lenses sets a limit to the resolving power of electron microscopes at about 5 A. Suggestions for the correction of objectives have been made; but these are difficult in themselves, and the prospects of improvement are further aggravated by the fact that the resolution limit is proportional to the fourth root of the spherical aberration. Thus an improvement of

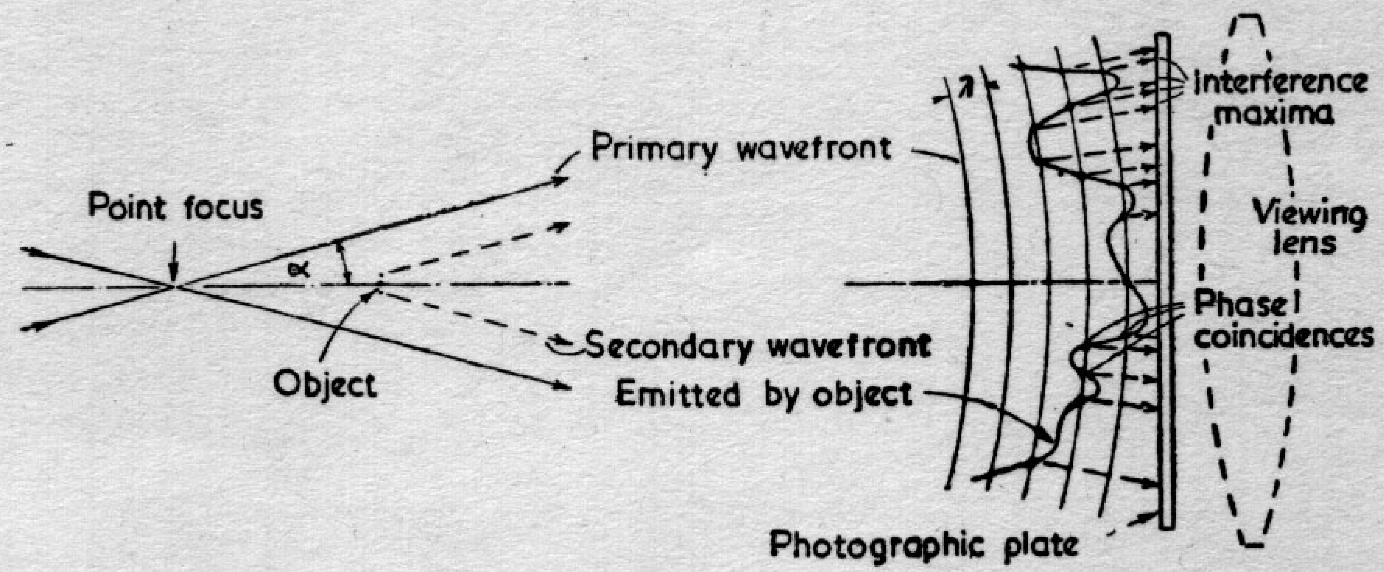
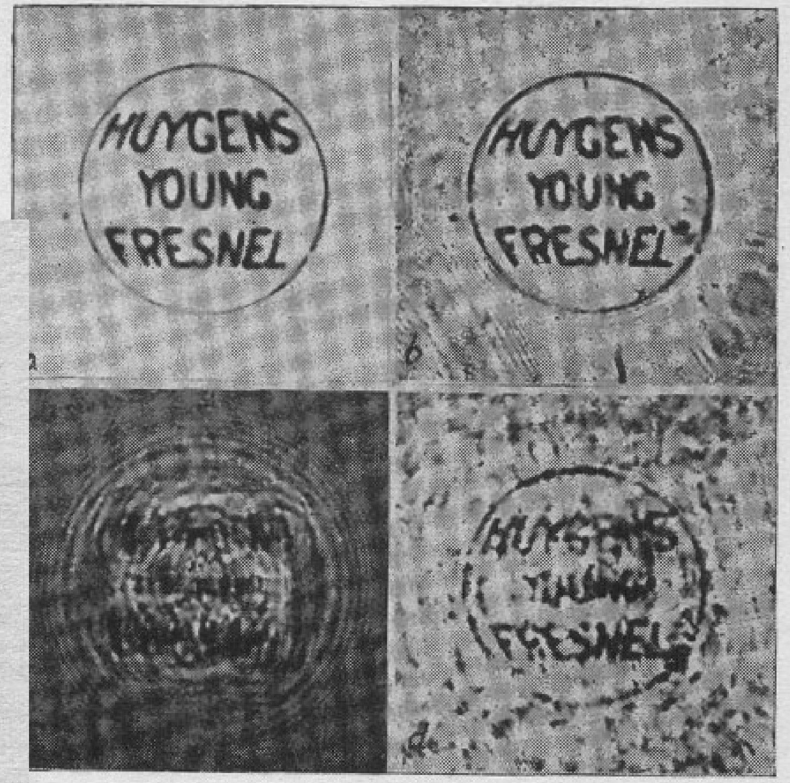


Fig. 1. INTERFERENCE BETWEEN HOMOCENTRIC ILLUMINATING WAVE AND THE SECONDARY WAVE EMITTED BY A SMALL OBJECT



'ig. 2. (a) ORIGINAL MICROGRAPH, 1·4 MM. DIAMETER. (b) MICRO-RAPH, DIRECTLY PHOTOGRAPHED THROUGH THE SAME OPTICAL YSTEM WHICH IS USED FOR THE RECONSTRUCTION (d). AP. 0·04. c) INTERFERENCE DIAGRAM, OBTAINED BY PROJECTING THE IICROGRAPH ON A PHOTOGRAPHIC PLATE WITH A BEAM DIVERGING 'ROM A POINT FOCUS. THE LETTERS HAVE BECOME ILLEGIBLE BY IFFRACTION. (d) RECONSTRUCTION OF THE ORIGINAL BY OPTICAL YNTHESIS FROM THE DIAGRAM AT THE LEFT. TO BE COMPARED WITH (b). THE LETTERS HAVE AGAIN BECOME LEGIBLE

Dream of X-ray Microscope for single molecular imaging

- **1948, Gabor invented, "Holography" waterfront reconstruction by recording phase on hologram using reference wave.**

~ ***No coherent light source was available for 10 years.***

- **1957, Laser was invented: C. Townes and A. L. Schawlow**
- **1960, The first working laser was made by T. H. Maiman**
- **1963, 3D Hologram was made by E. N. Leith and J. Upatnieks**
  ***Twin-image problem was solved*.**
- **1970's X-ray holography was studied theoretically**

~ ***No intense coherent X-ray source was available for 30 years.***

- **2000~ VUV laser 90 nm was realized by SASE FEL at DESY TTF.**
- ***20XX 3D single molecular imaging***

Problems in Holographic Imaging using X-ray

- It becomes hard to obtain **spherical reference wave** at X-ray wavelength with enough NA (Numerical aperture)
- **Speckle** on reference wave dominates image quality.
- Fresnel diffraction lens or X-ray mirror **limit NA small**, thus resolution is limited.

- **Eliminate Reference Wave → Diffraction Microscopy**

→ Direct phase retrieval on object Wave

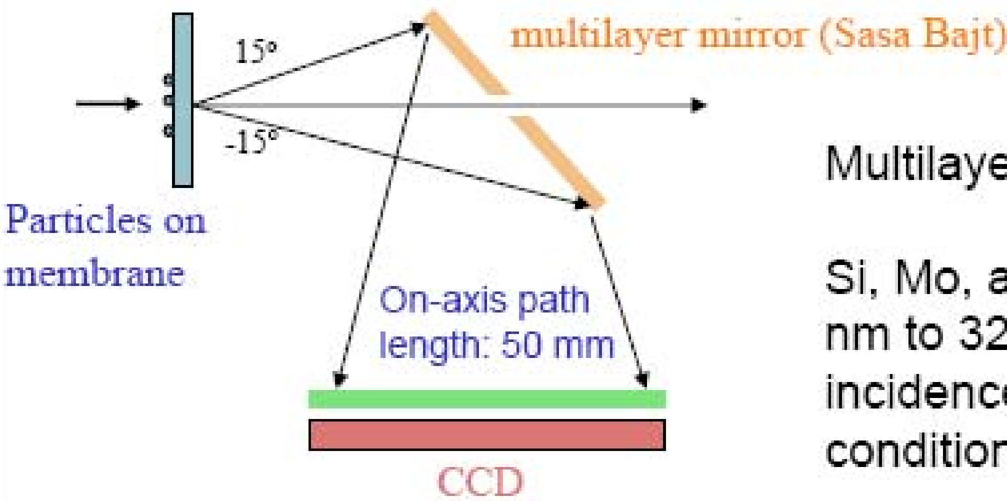
→ XFEL provides high peak power and highly coherent beam, thus high quality object wave.

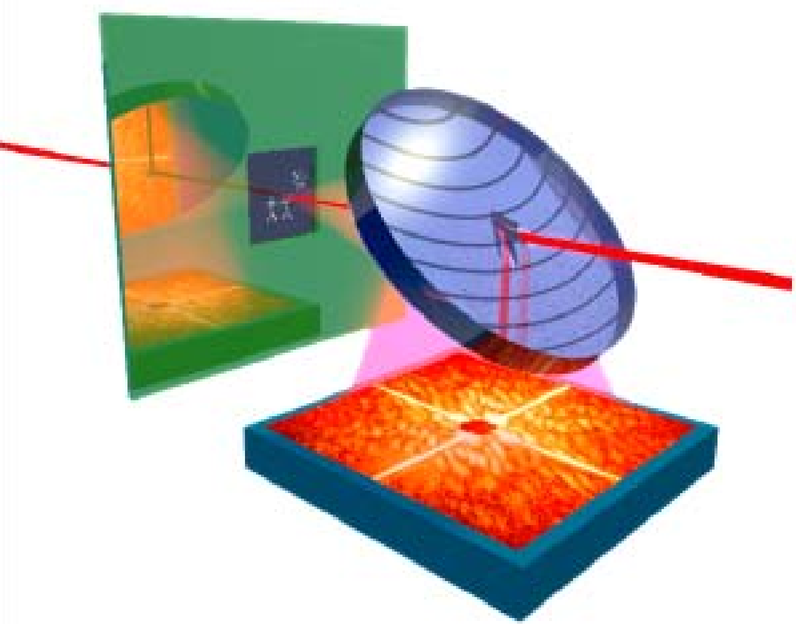
X-ray Diffraction Microscopy
- *historical background* -

By Y. Nishino

- **Possibility of Phase Retrieval by Oversampling X-ray Diffraction Pattern**
  - D. Sayre, Acta Cryst. 5, 843 (1952).
- **Iterative Phase Ritrieval Method**
  - W. Gerchberg & W. O. Saxton, Optik 35, 237 (1972).
  - J. R. Fienup, Applied Optics 21, 2758 (1982).
- **Concept of X-ray Diffraction Microscopy for Non-Periodic Objects**
  - D.Sayre, in *Direct Methods of Solving Crystal Structures*, (Plenum, 1991) p. 353.
- **Experimental Demonstrations**
  - J. Miao, P. Charalambous, J. Kirz & D. Sayre, Nature 400, 342 (1999). "2D Reconstruction"
  - J. Miao *et al*., Phys. Rev. Lett. 89, 088303 (2002). "3D Reconstruction"
  - I.K. Robinson *et al*., Phys. Rev. Lett. 87, 195505 (2001). "Reflection Geometry for Nanocrystal"
- **Image Reconstruction Exclusively from X-ray Diffraction Data**
  - S. Marchesini et al., Phys. Rev. B 68, 140101(R) (2003). "Shrink Wrap"
  - Y Nishino *et al*., Phys. Rev. B 68, 220101(R) (2003). "Iterative Normalization"
- **Single Shot Experiment**
  - R. Neutze et al., Nature (London) 406, 752 (2000). "Concept & Simulation"
  - H.N. Chapman *et al*., Nature Physics 2, 839 (2006). "Experiment using VUV FEL FLASH"

CAMERA USED in the VUV-FEL EXPERIMENTS
Multilayers: Sasa Bajt, Engineering: Bruce Woods (LLNL)





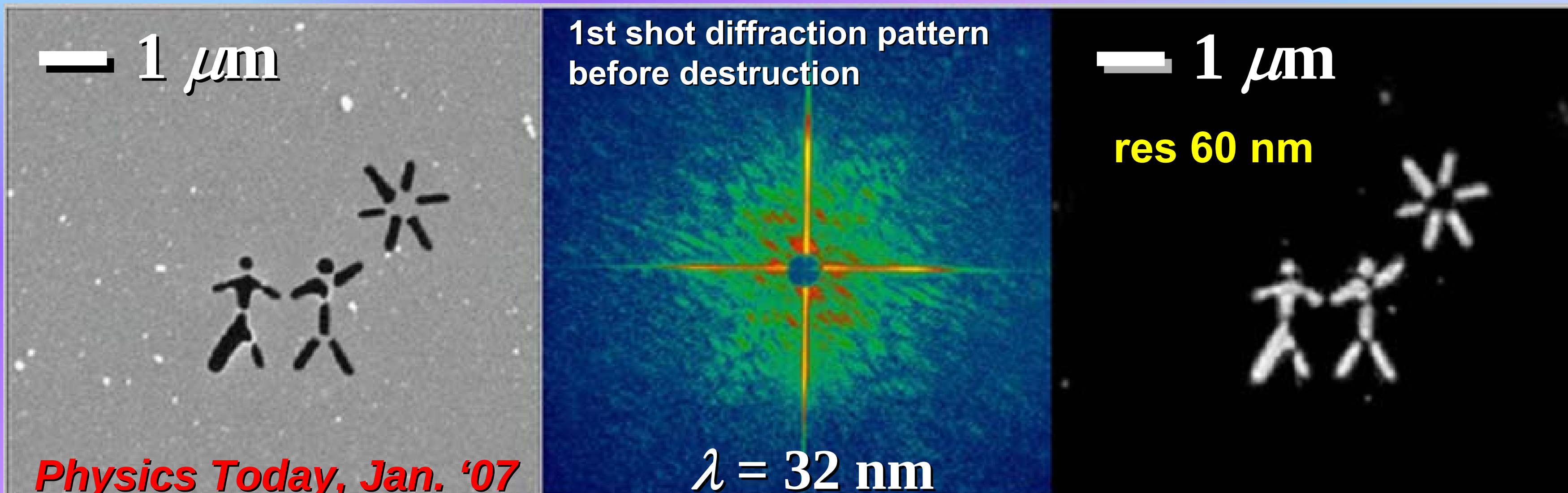
Multilayer mirror:

Si, Mo, and B_4C, gradually increasing from 18 nm to 32 nm period. Variation matches angle of incidence (30° to 60°) to maintain Bragg condition for λ = 32 nm.

Reflectivity: 45% over the surface for 32 nm.

The mirror protects the CCD and works as a
(i) bandpass filter (bandwidth = 9 nm at 45°)
(ii) filter for off-axis stray light (1% reflectivity)

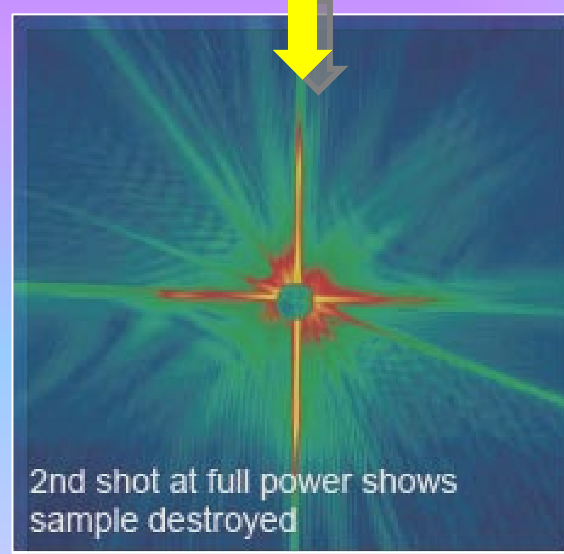
Image Reconstructed from an Ultra-Fast (25 fs) FEL Diffraction Pattern at *FLASH*



Starting Image
(etched into silicon nitride film)

Reconstructed Image

The 20-μm-wide square film was destroyed by the laser pulse, but a computer algorithm reconstructed the original image from the diffraction pattern.

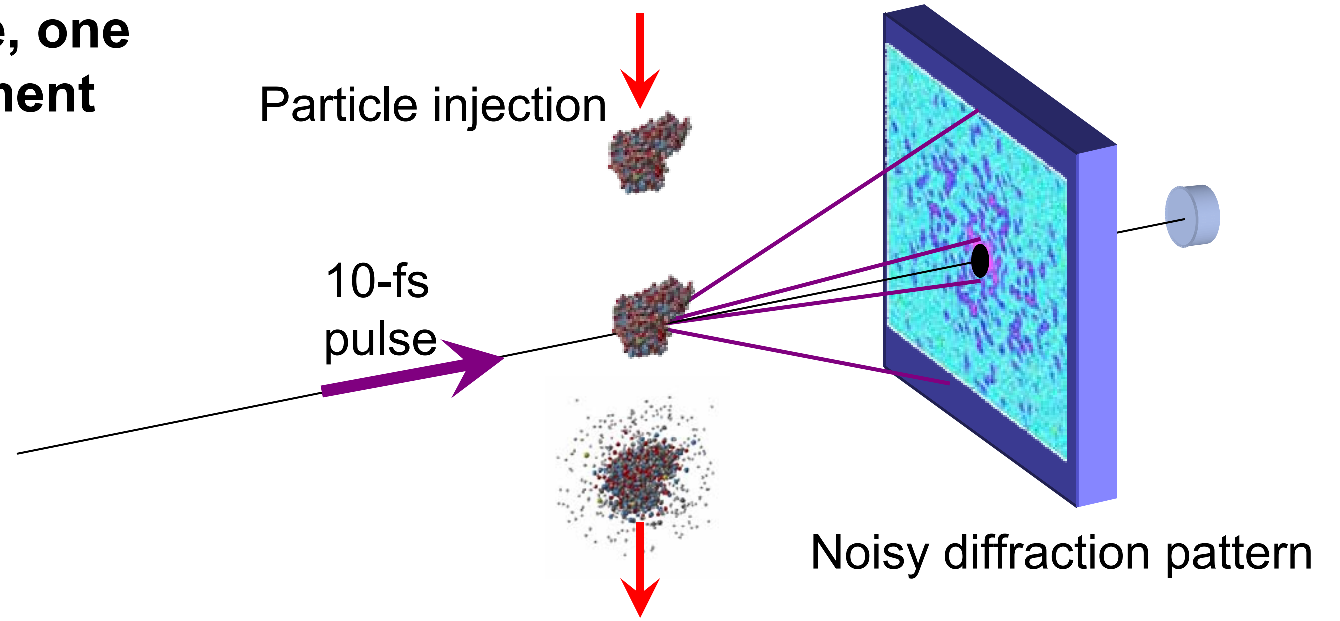


H. Chapman, J. Hajdu

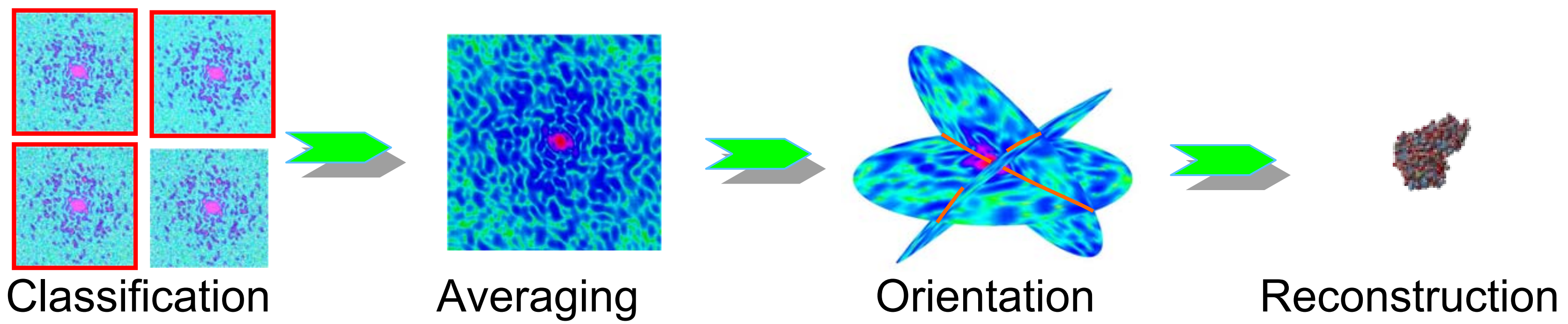
Reconstruction by A. Barty, Feb. '06

X-ray free-electron lasers may enable atomic-resolution imaging of biological macromolecules

One pulse, one measurement



Combine 10^5-10^7 measurements



H. Chapman

Summary

- XFEL technology will provide powerful probe to look into atomic scale structure and femto-sec time frame evolution, which will contribute in material science, nano-technology, and biology, etc.
- XFEL technology development will also provide feedback into future accelerators, including ILC.
- There are many technical challenges, waiting your contributions.   Thank you!