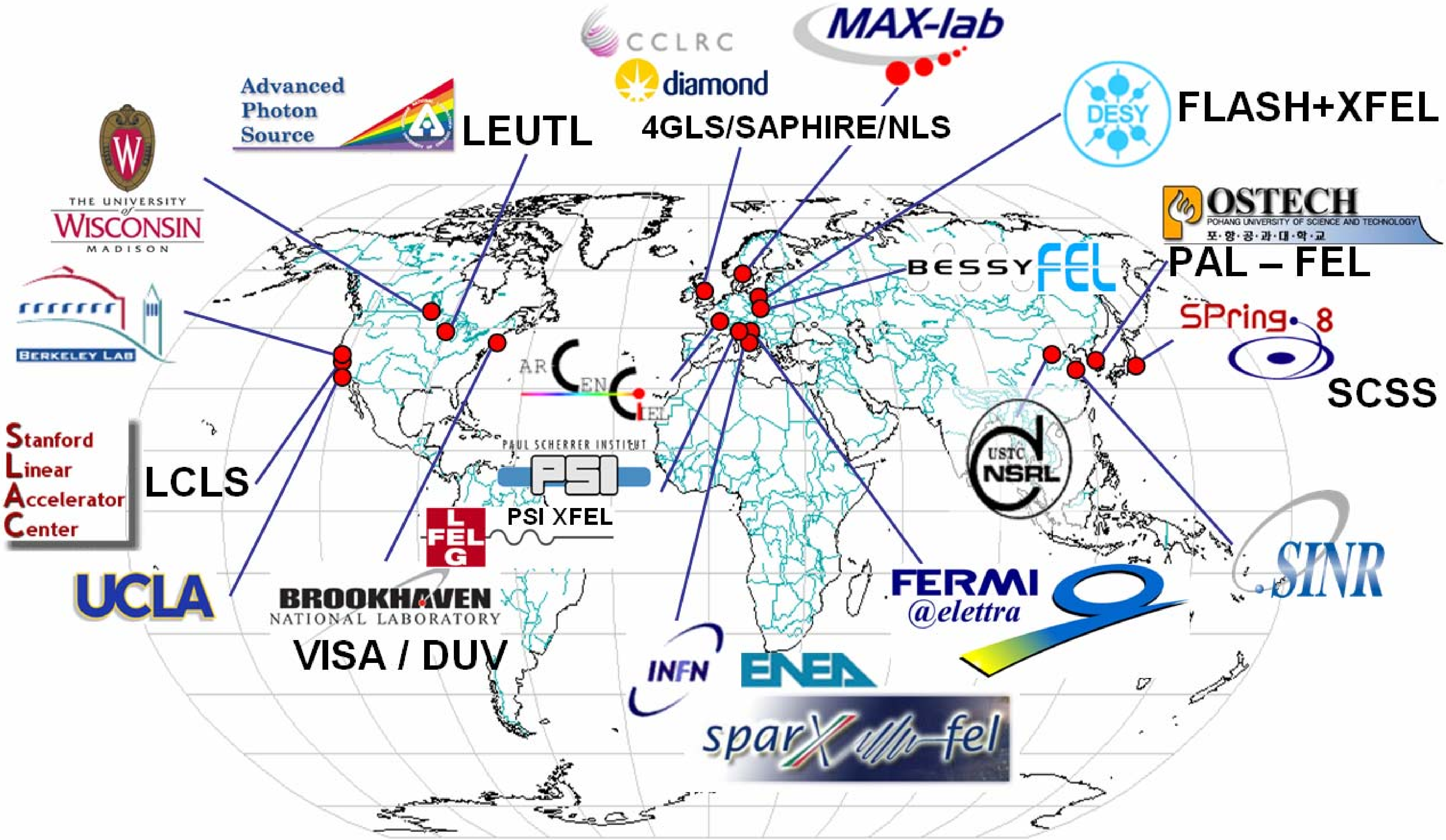
Overview of VUV and Soft X-ray FELs

R.J. Bakker
for all project contributions

Paul Scherrer Institute

Courtesy: NASA, earthlights.jpg

Single Pass FEL Activity



Outline

- Introduction
- Key issues
  - seeding
  - choice of accelerator technology
  - need for experience
- Further reference

Outline

- Introduction

- Key issues
  (examples along various projects)
  - X-ray FELs, which generate VUV and soft X-rays
  - Dedicated VUV and soft X-ray projects

→ Scientific case for short-pulse (fs), high-brightness VUV and soft X-ray pulses:

e.g., probing of material properties and electron transitions in materials (pump-probe experiments, spectroscopy, &c.)

- Further reference

here:

- UV ≤ 400 nm (3 eV)
- VUV ≤ 100 nm (12 eV)
- XUV / soft X-ray ≤ 10 nm (0.12 keV)
- X-rays ≤ 3 nm (4 keV)

DESY TELEGRAMM

8. Oktober 2007

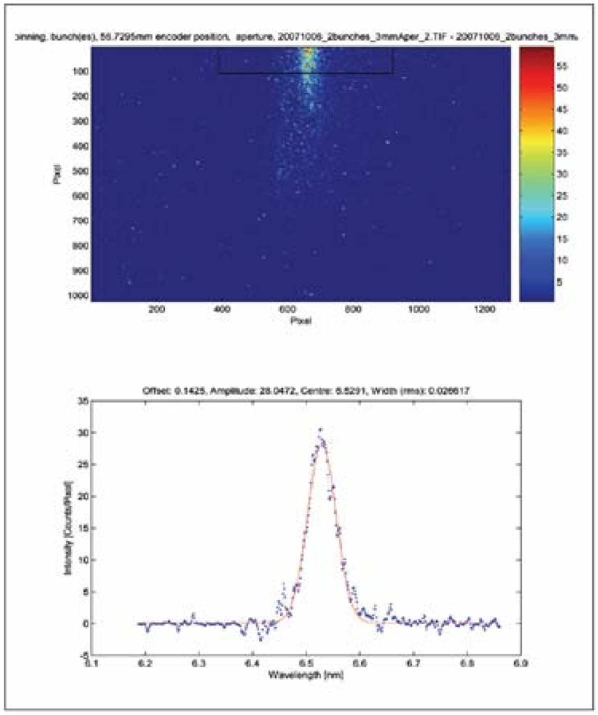
Wellenlängen-Weltrekord bei FLASH: 6,5 Nanometer!

Geplanter Designwert für die Laserblitze erzielt

Wavelength World Record at FLASH: 6.5 Nanometers!

Design value for laser flashes reached

Zwei Wochen nach dem Erreichen der maximalen Strahlenergie von 1 Gigaelektronenvolt kam aus dem Kontrollraum die Meldung: „Am 4. Oktober haben wir in den Abendstunden zum ersten Mal bei FLASH das Lasen bei einer Wellenlängen von 7 Nanometern (nm) beobachtet.“ Schon 24 Stunden später gelang es dem FLASH-Team, den für die Anlage geplanten Designwert von 6,5 nm zu erzielen. Die in den sechs supraleitenden Modulen auf eine Energie von 986



'lot und Zahlen für Experten:
)as Wellenlängenspektrum bei 6,5 nm. Zahl der
Bunche: 2 - Apertur: 3 mm - Wellenlänge: 6,523 nm

Two weeks after the maximum beam energy of 1 gigaelectronvolt was reached, the control room announced another milestone: "On the evening of October 4, we observed lasing at a wavelength of 7 nanometers (nm) at FLASH for the first time." Only 24 hours later, the FLASH team achieved the facility's design value of 6.5 nm. In FLASH, the electrons are accelerated to an energy of 986 megaelectronvolts in six superconducting modules. On their flight through the undulator, the electrons now demonstrated the desired behavior also at this high energy: the spontaneous radiation they emit amplified itself to form the

Courtesy S. Schreiber (DESY)

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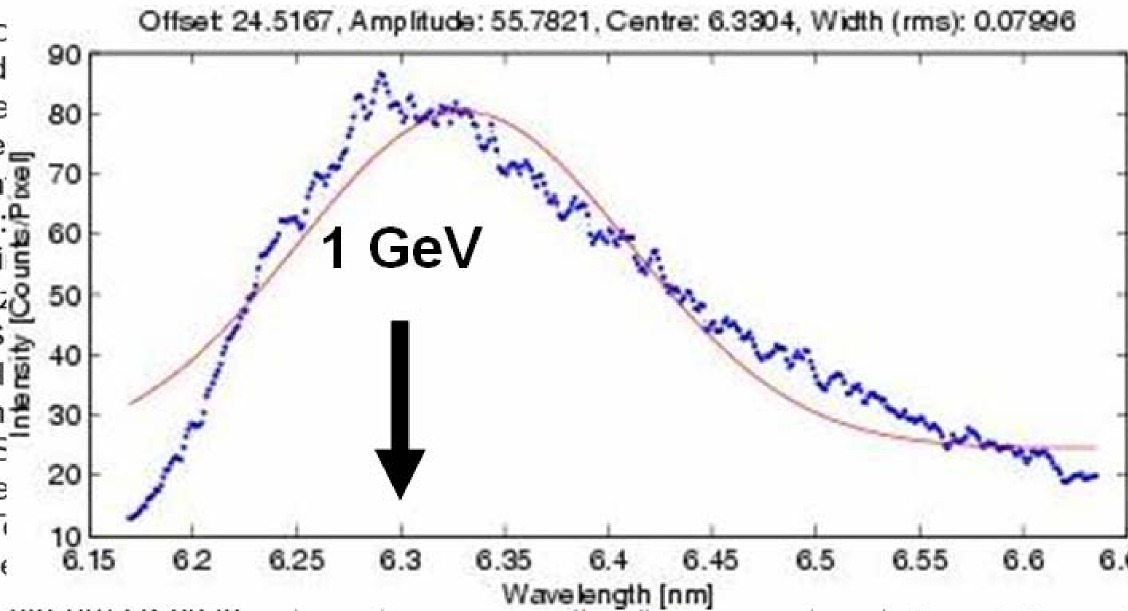

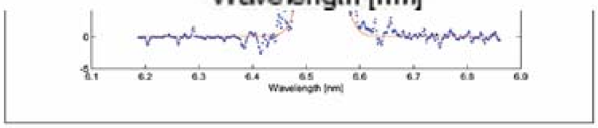

Plot und Zahlen für Experten:
Das Wellenlängenspektrum bei 6,5 nm. Zahl der
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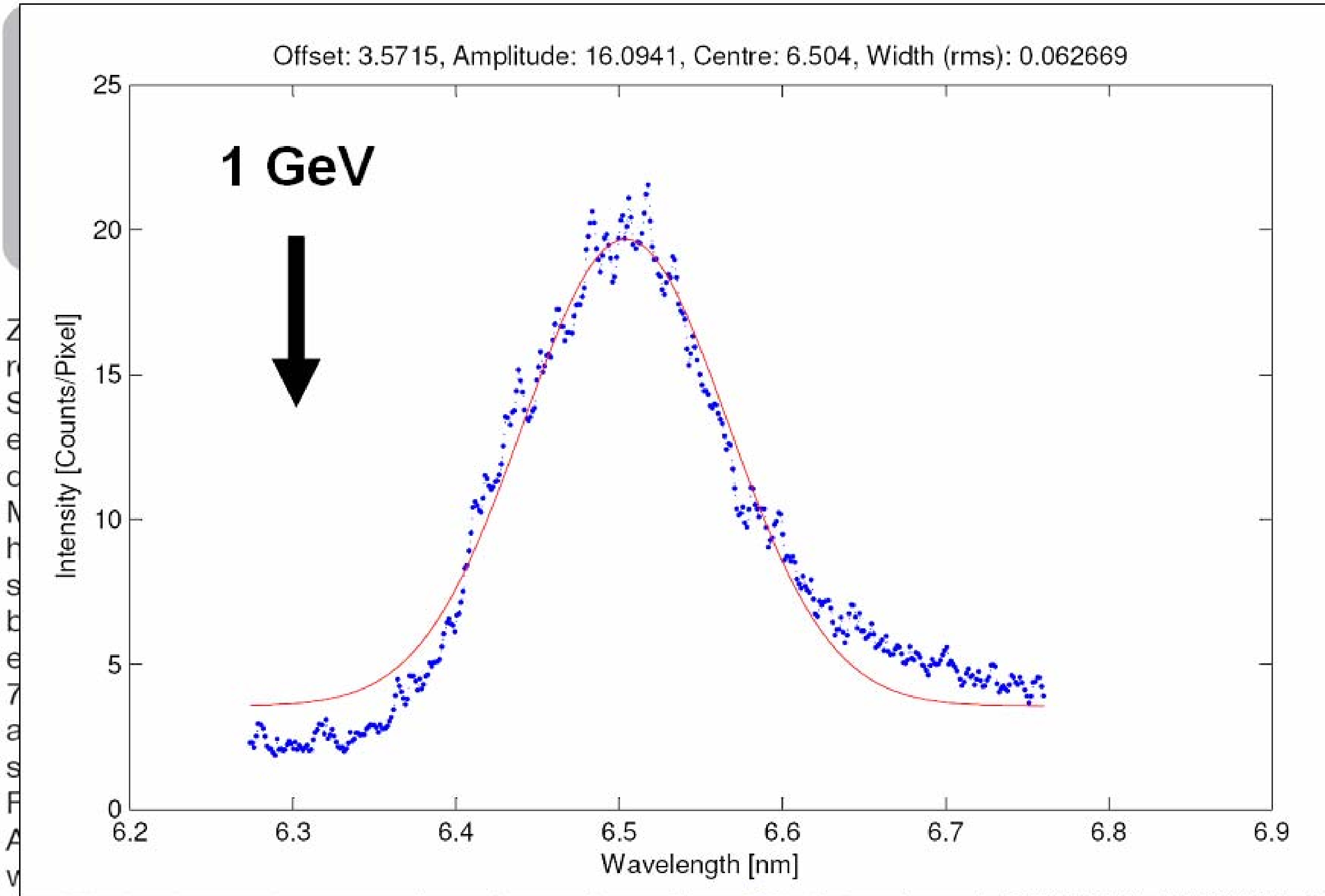
Courtesy S. Schreiber (DESY)

DESY TELEGRAMM

8. Oktober 2007



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Plot und Zahlen für Experten: Das Wellenlängenspektrum bei 6,5 nm. Zahl der Bunche: 2 - Apertur: 3 mm - Wellenlänge: 6,523 nm

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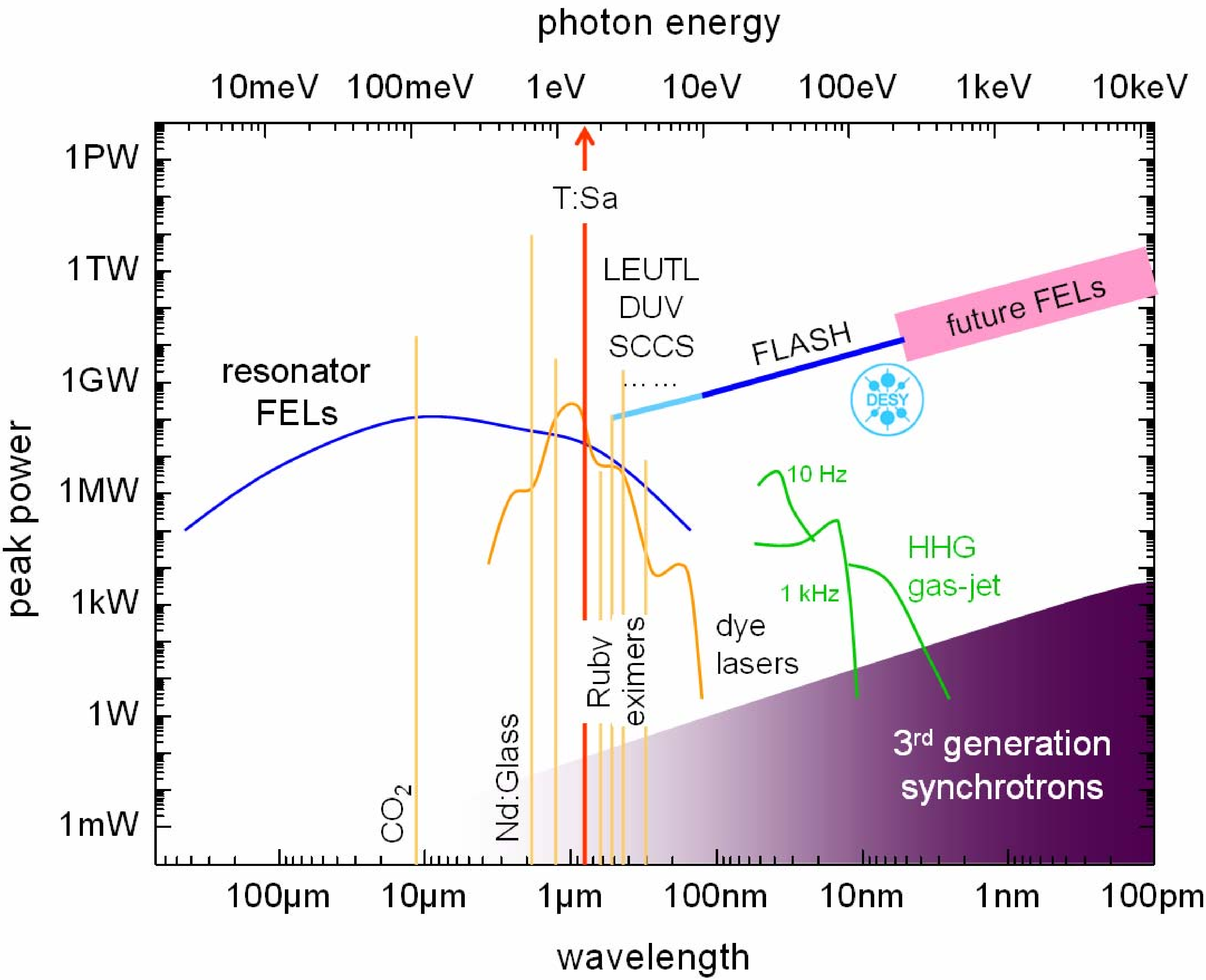
Courtesy S. Schreiber (DESY)

Not Discussed Further

Stanford, USA
→ Next presentation


photon energy
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1PW
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1W
1mW
peak power
T:Sa
LEUTL
DUV
SCCS
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FLASH
future FELs
DESY
resonator
FELs
10 Hz
1 kHz
HHG
gas-jet
dye
lasers
CO_2
Nd:Glass
Ruby
eximers
3rd generation
synchrotrons
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10µm
1µm
100nm
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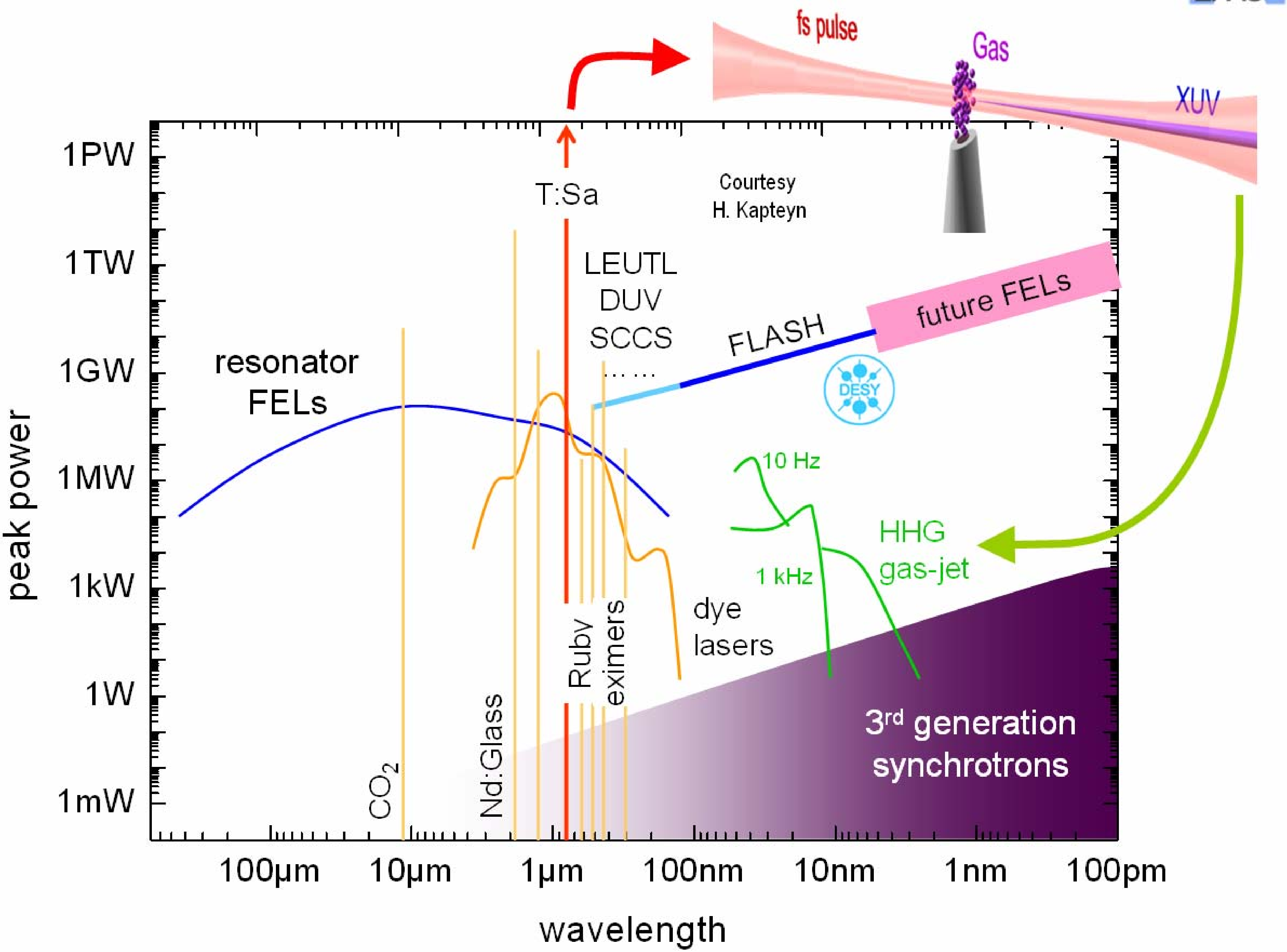
1nm
100pm
wavelength


fs pulse
Gas
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Courtesy
H. Kapteyn
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FLASH
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DESY
resonator
FELs
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1 kHz
HHG
gas-jet
dye
lasers
Ruby
eximers
CO_2
Nd:Glass
3rd generation
synchrotrons
1PW
1TW
1GW
1MW
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peak power
100µm
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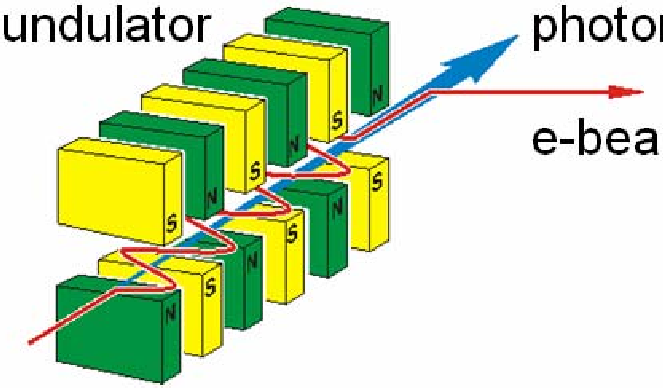
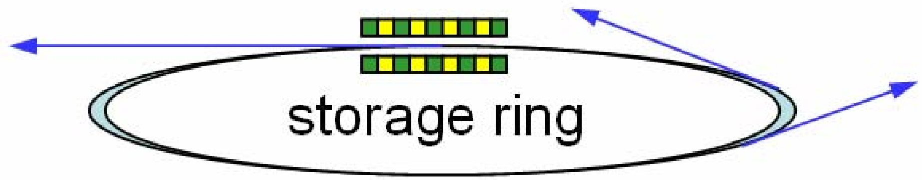
10nm
1nm
100pm
wavelength

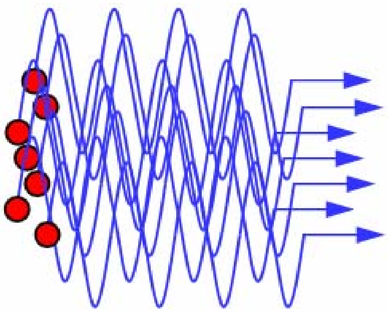
Synchrotron Radiation

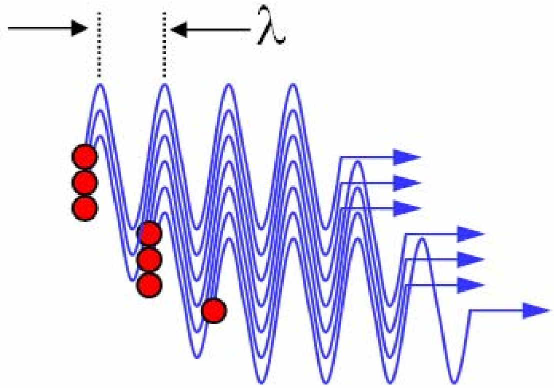


$$\lambda = \frac{\lambda_u}{2n\gamma^2}(1 + K^2)$$



Synchrotron Radiation



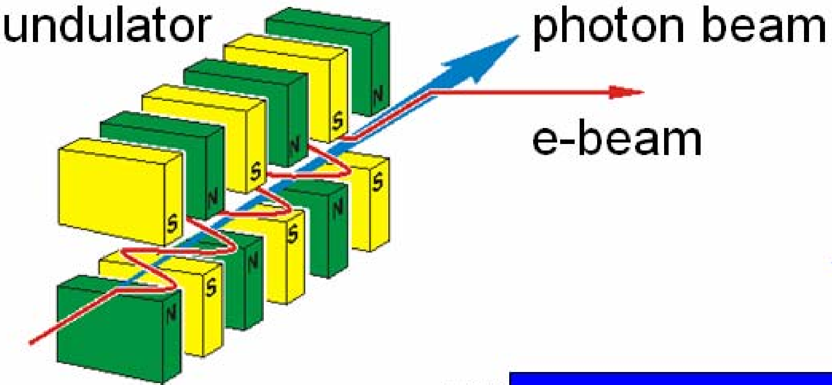


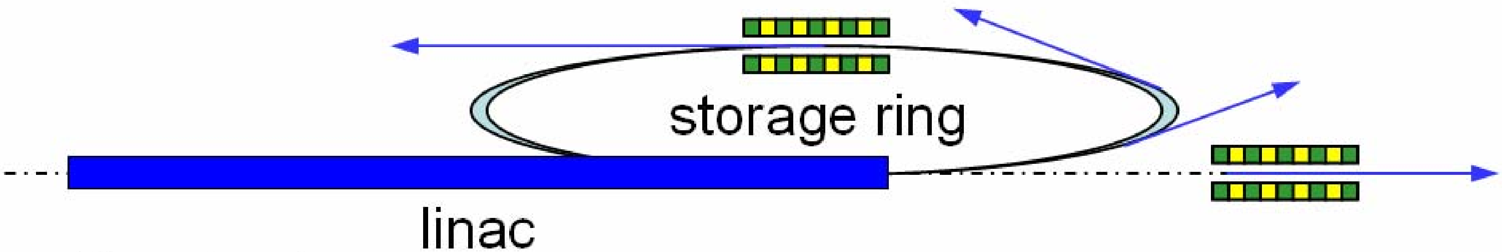
incoherent radiation:

$P \sim N$

coherent radiation:

$P \sim N^2$ *($10^5 - 10^7$ enhancement)*
(narrow bandwidth)





$$\lambda = \frac{\lambda_u}{2\cancel{n}\gamma^2}(1 + K^2)$$

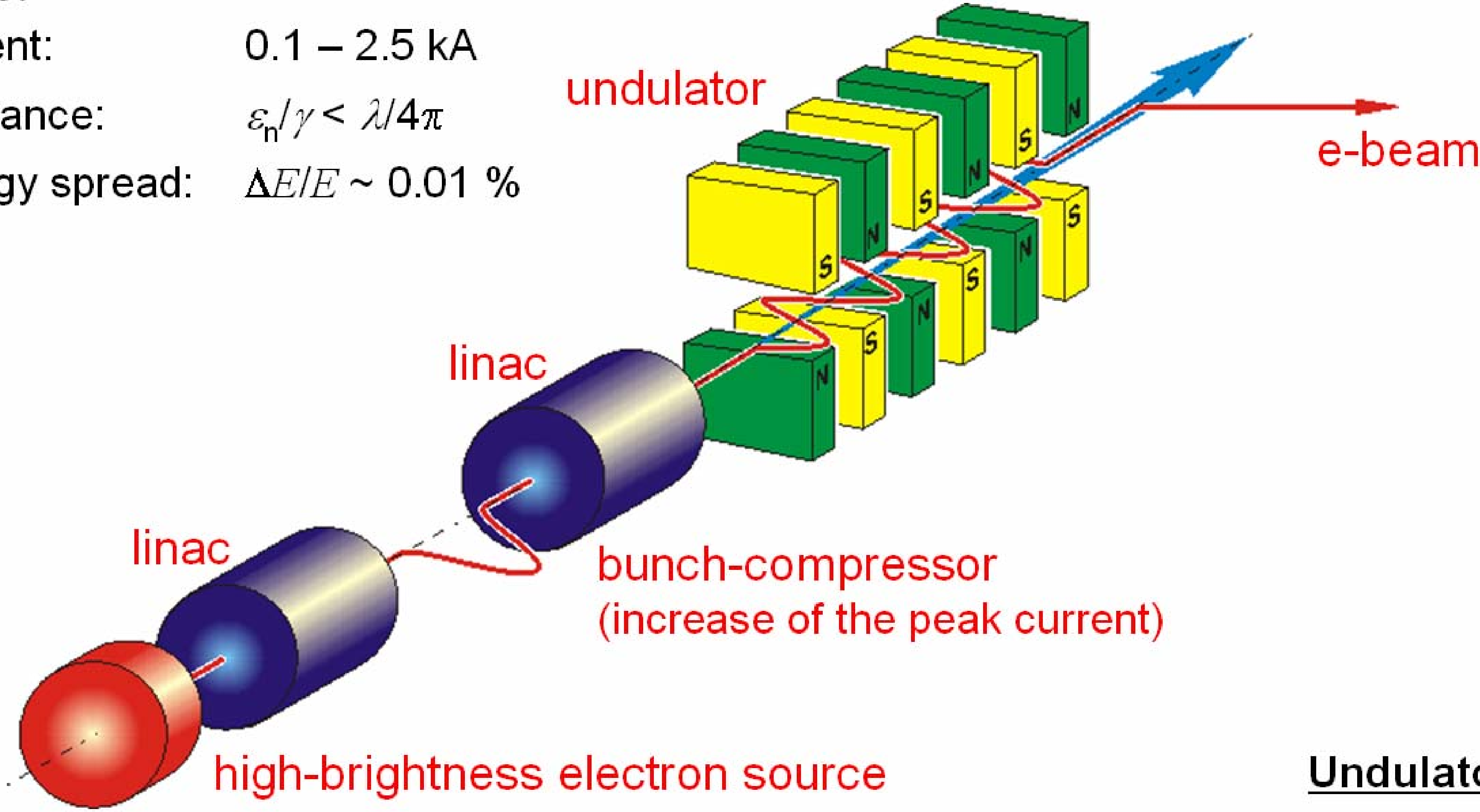
<u>Required</u>:

- higher current & energy
- beam quality: energy spread & emittance

Typical Requirements (VUV & soft X-ray)

Electron beam

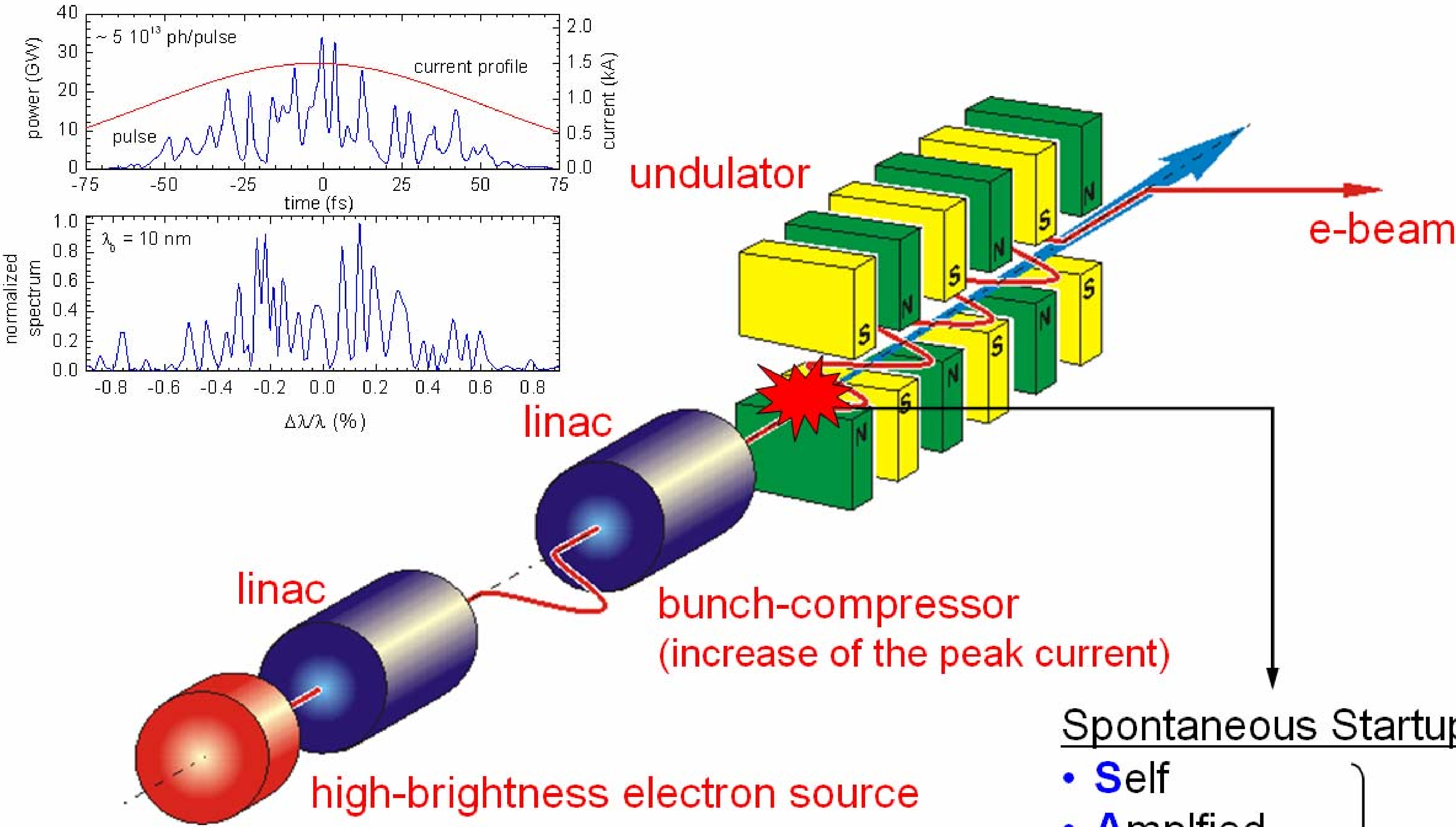
- energy: 0.2 – 3 GeV
- current: 0.1 – 2.5 kA
- emittance: $\varepsilon_n/\gamma < \lambda/4\pi$
- energy spread: $\Delta E/E \sim 0.01$ %



Undulator

- single pass (no optics)
- variable polarization (APPLE)
  → user facilities

Single-Pass Configuration



Spontaneous Startup:

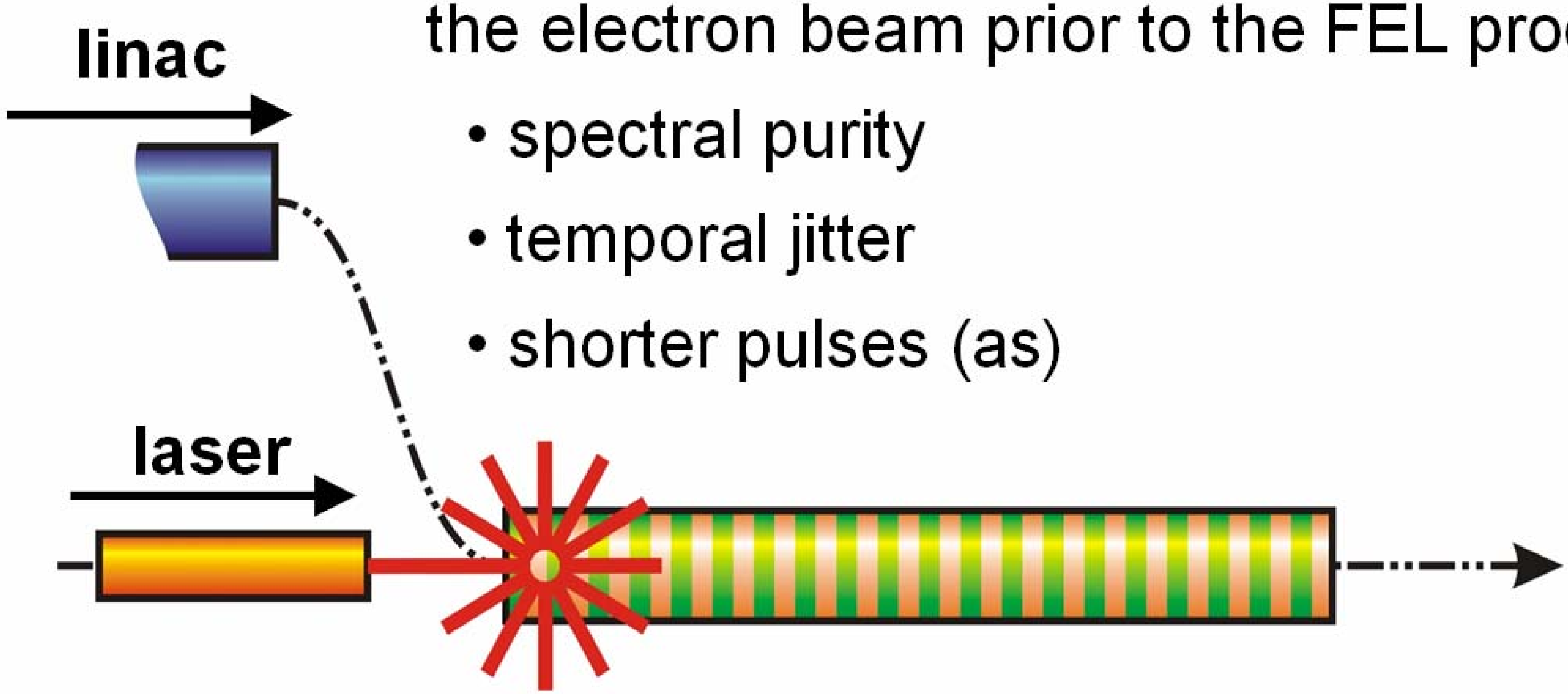
- **S**elf
- **A**mplfied
- **S**pontaneous
- **E**mission

} **SASE**

Seeded FEL

Improve the FEL output with an imprint of the phase and temporal properties of a laser on the electron beam prior to the FEL process:

- spectral purity
- temporal jitter
- shorter pulses (as)



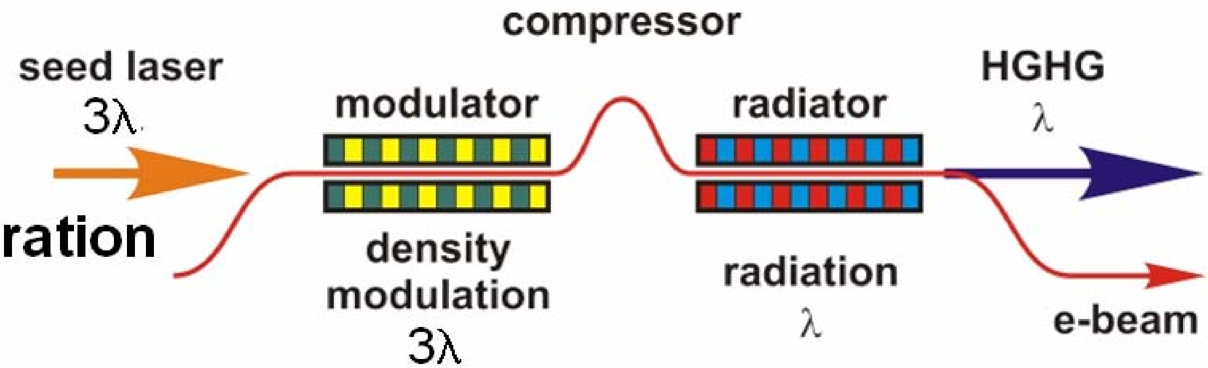
laser → classical laser system (e.g., T:Sa)
laser → laser + harmonics generation
laser → other free-electron laser

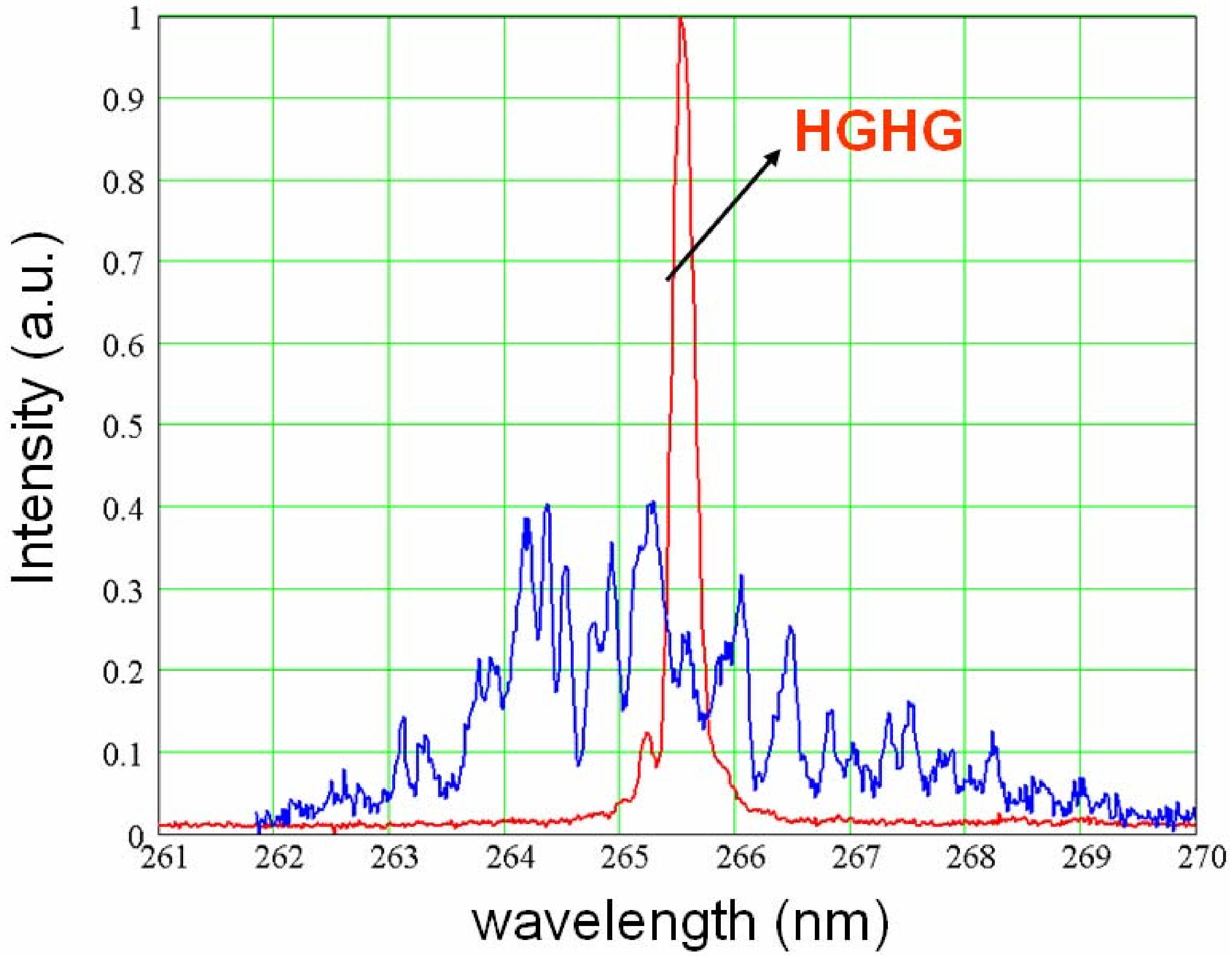
Seeding: HGHG

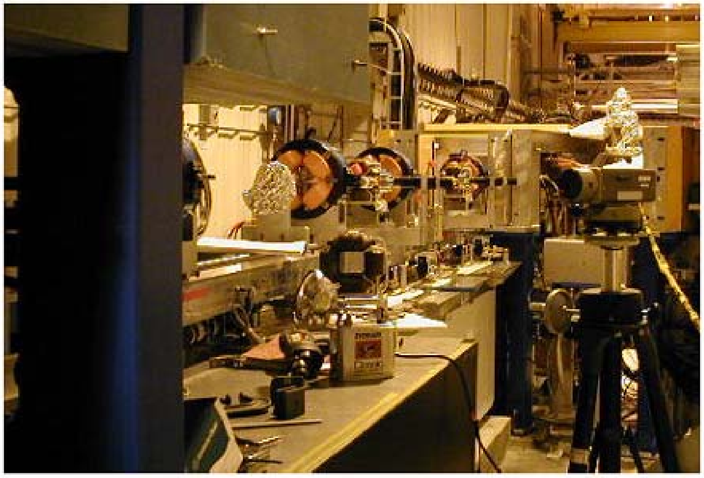
2002

800 nm → 266 nm

High Gain Harmonics Generation







Courtesy Li Hua Yu (BNL)

Seeding: HGHG

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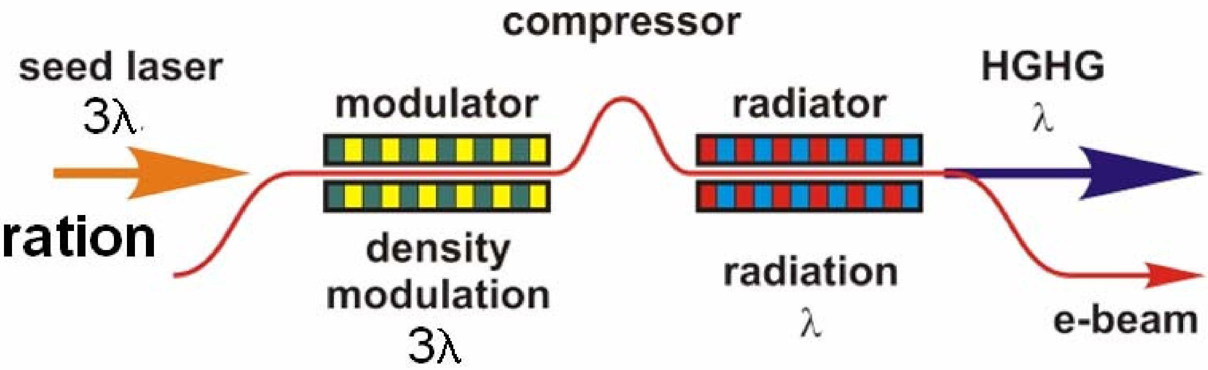
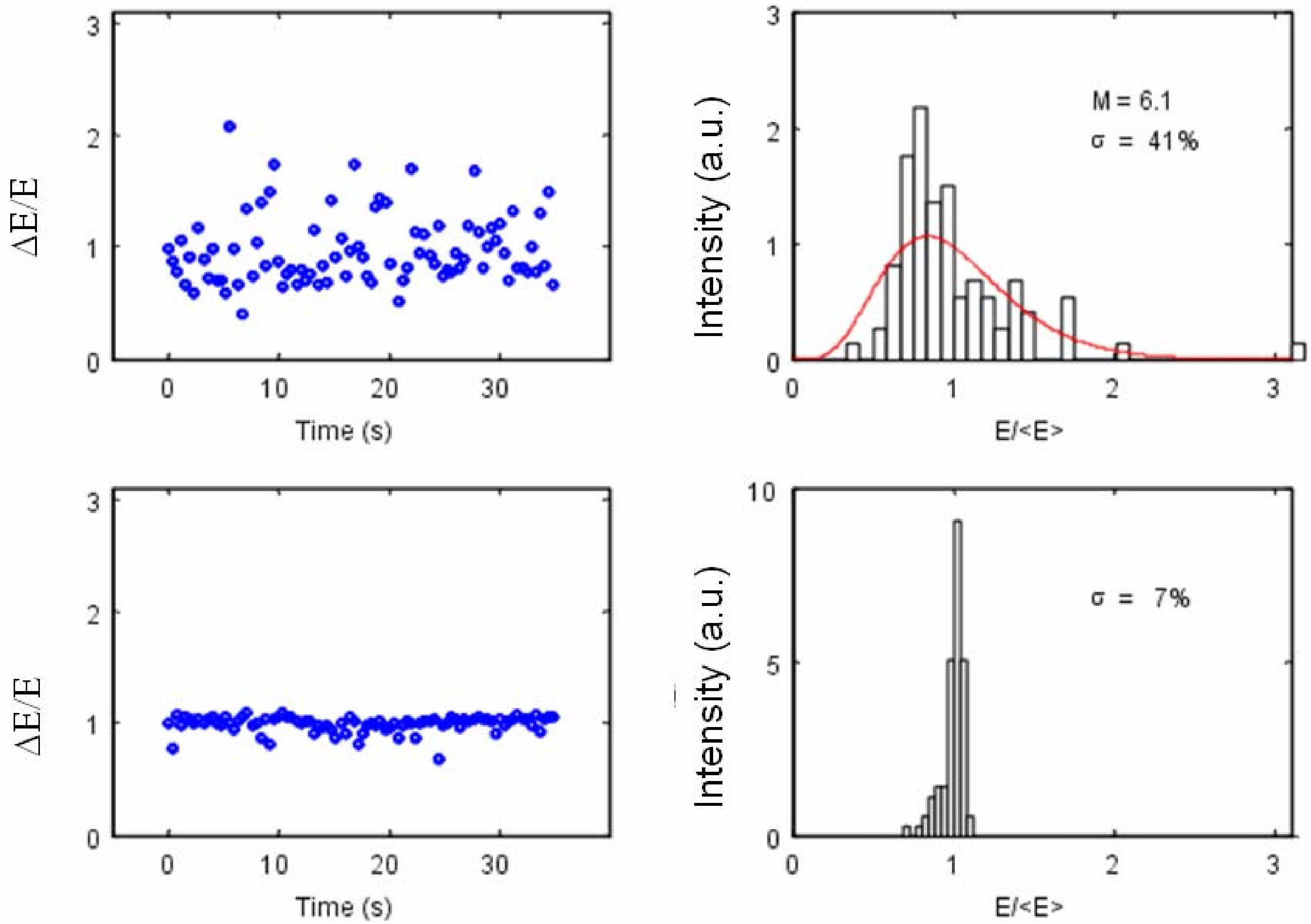
High Gain Harmonics Generation



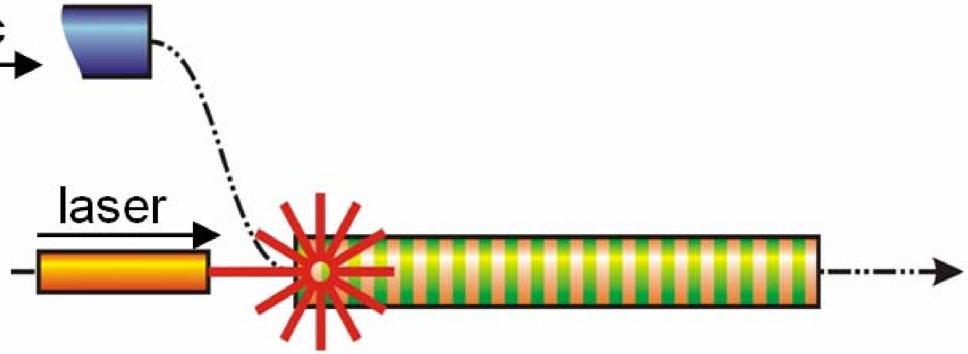
SASE

HGHG



Courtesy Li Hua Yu (BNL)

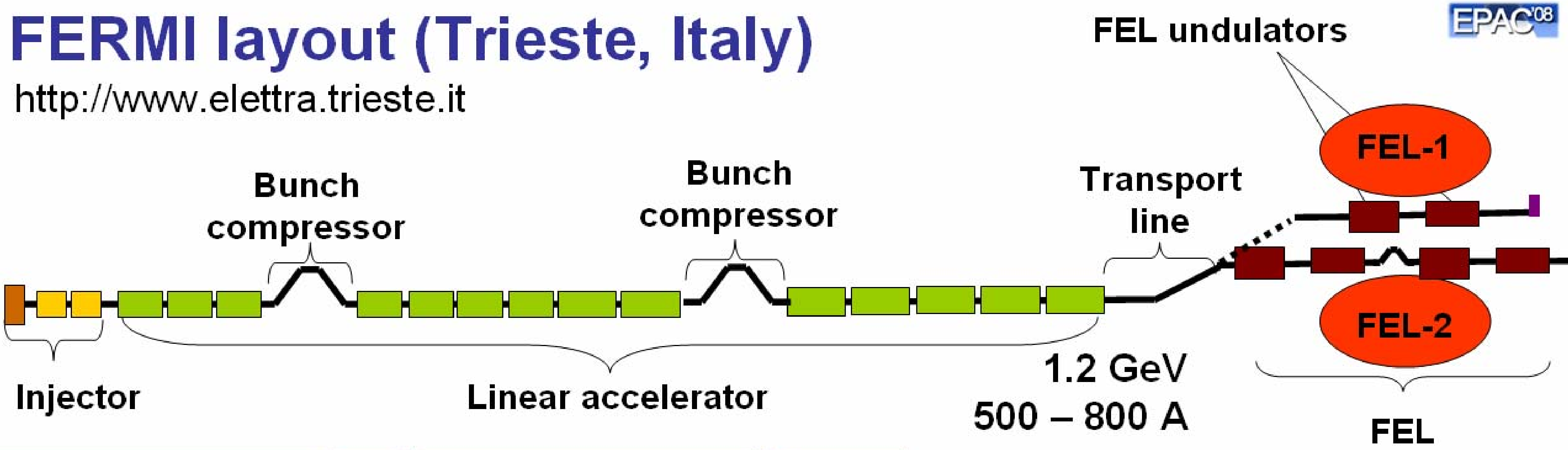
Seeding: at this conference

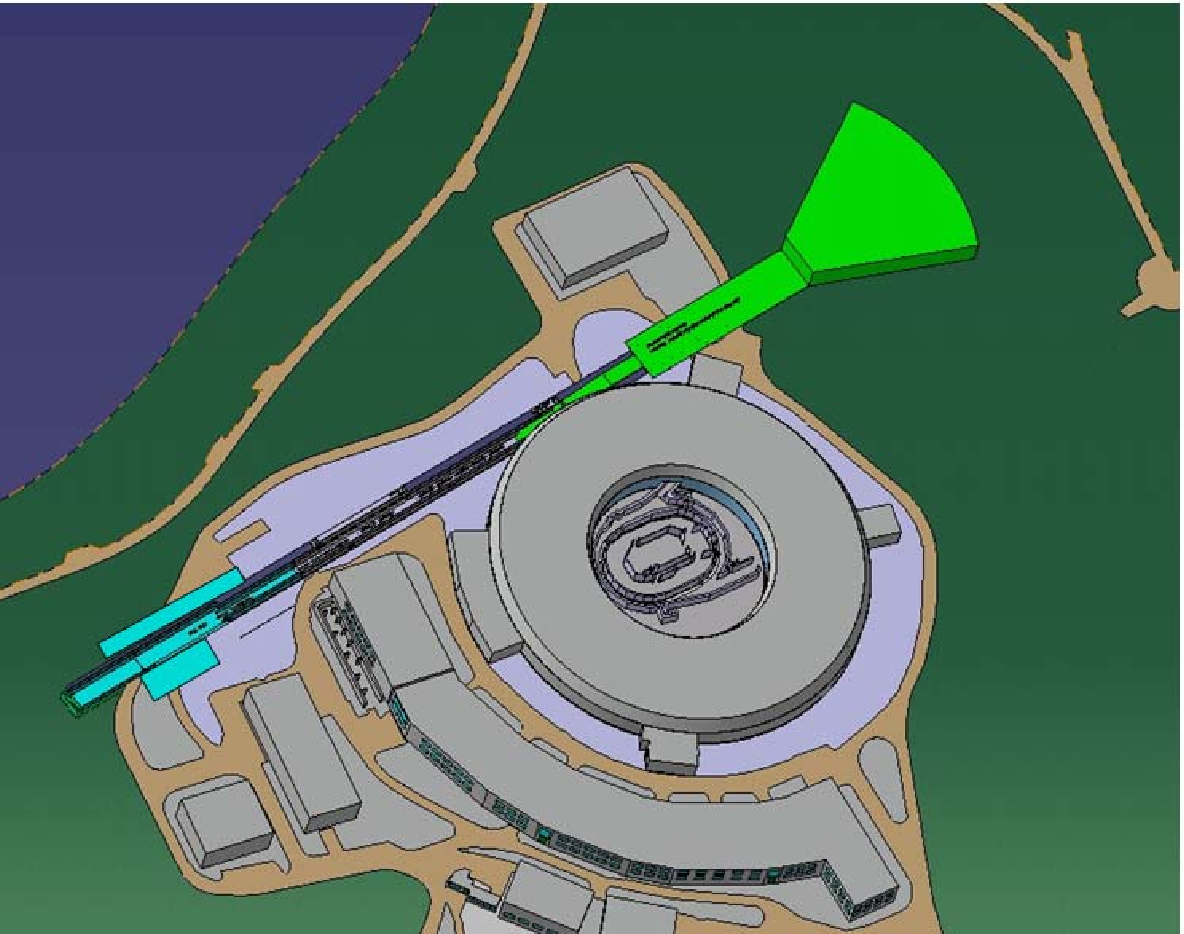


1. MOPC005 Couprie et. al
2. MOPC006 Cutic et. al
3. MOPC009 de Nino et. al
4. MOPC017 Labat et. al
5. MOPC018 Lambert et. al
6. MOPC028 Miltchev et. al
7. MOPC032 Thorin et. al
8. THPC160 Schulz et. al

FERMI layout (Trieste, Italy)

http://www.elettra.trieste.it





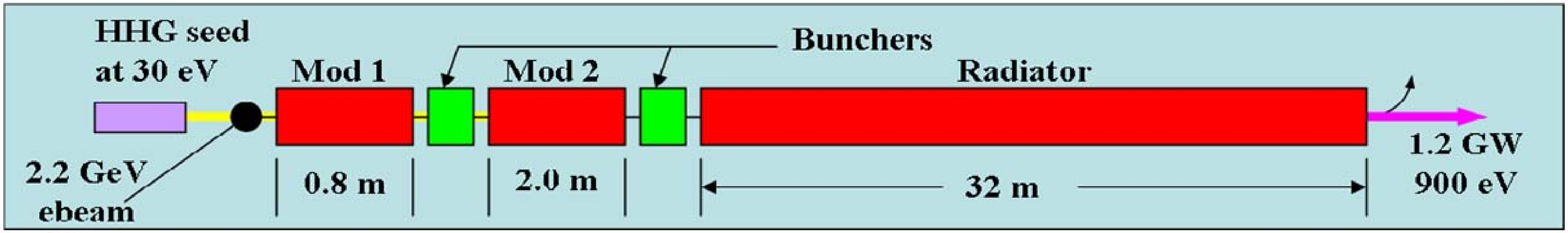
FEL 1: 100 – 40 nm
(single-stage)

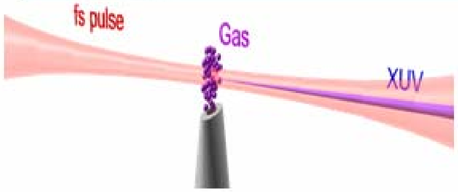
FEL 2: 40 – 10 nm
(double-stage)

Important aim:
→ spectral purity

Courtesy Enrico Allaria

Wisconsin FEL Proposal

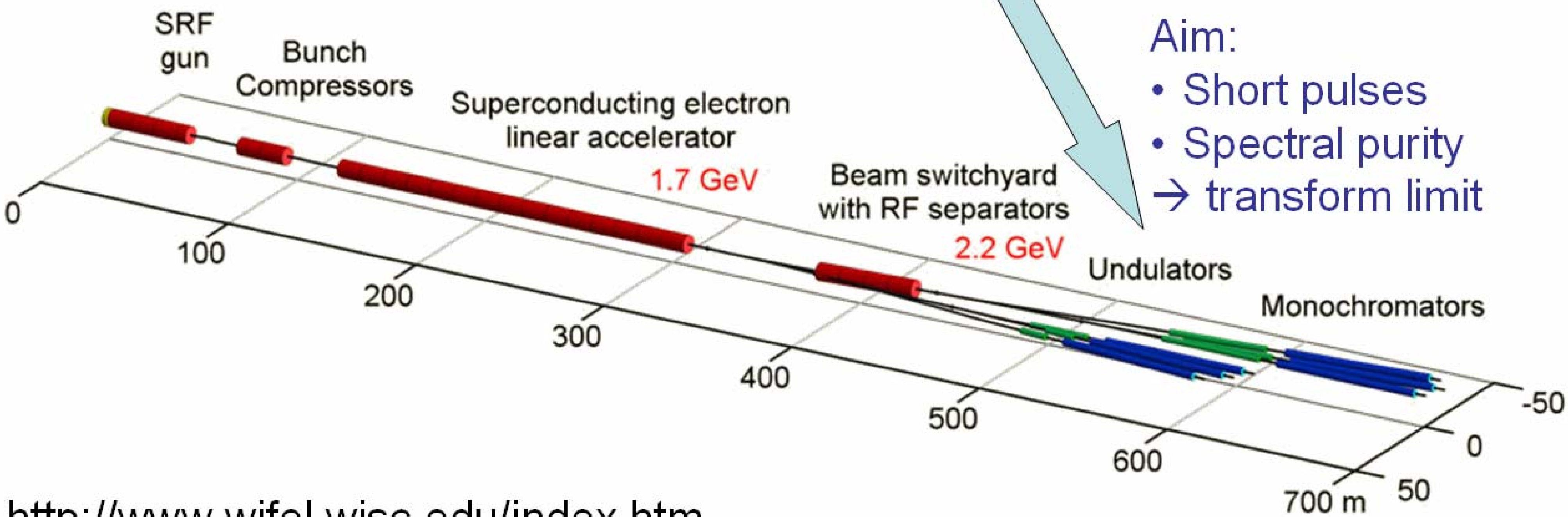




- HHG Seed
- Multipe stages FEL

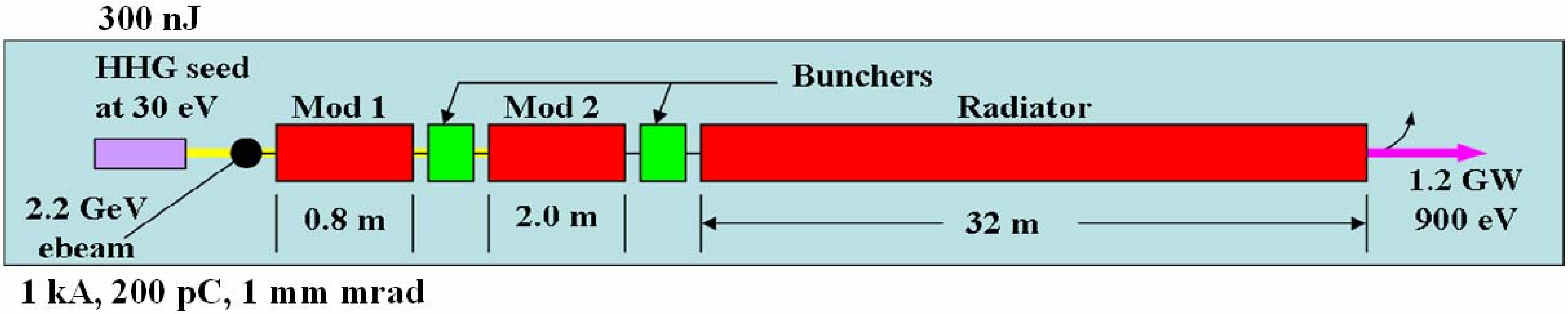
Aim:
- Short pulses
- Spectral purity

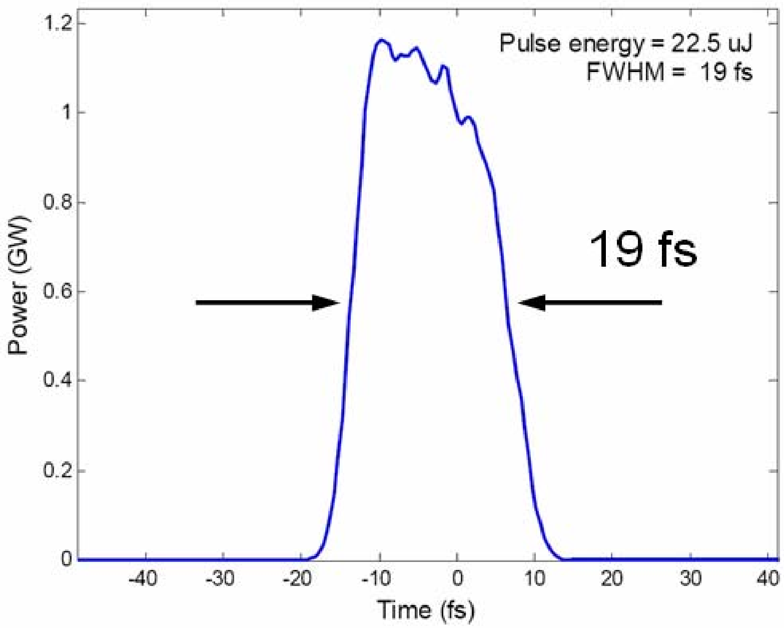
→ transform limit

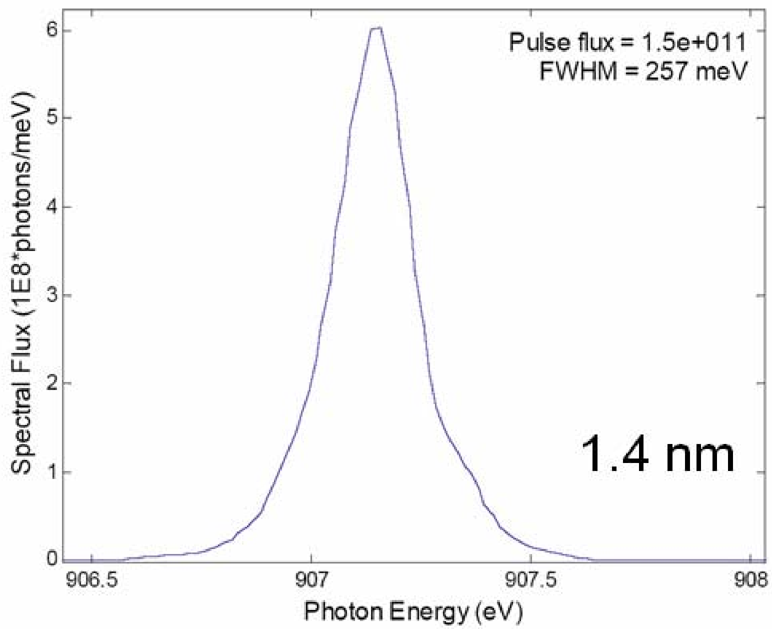


http://www.wifel.wisc.edu/index.htm

Wisconsin FEL Proposal

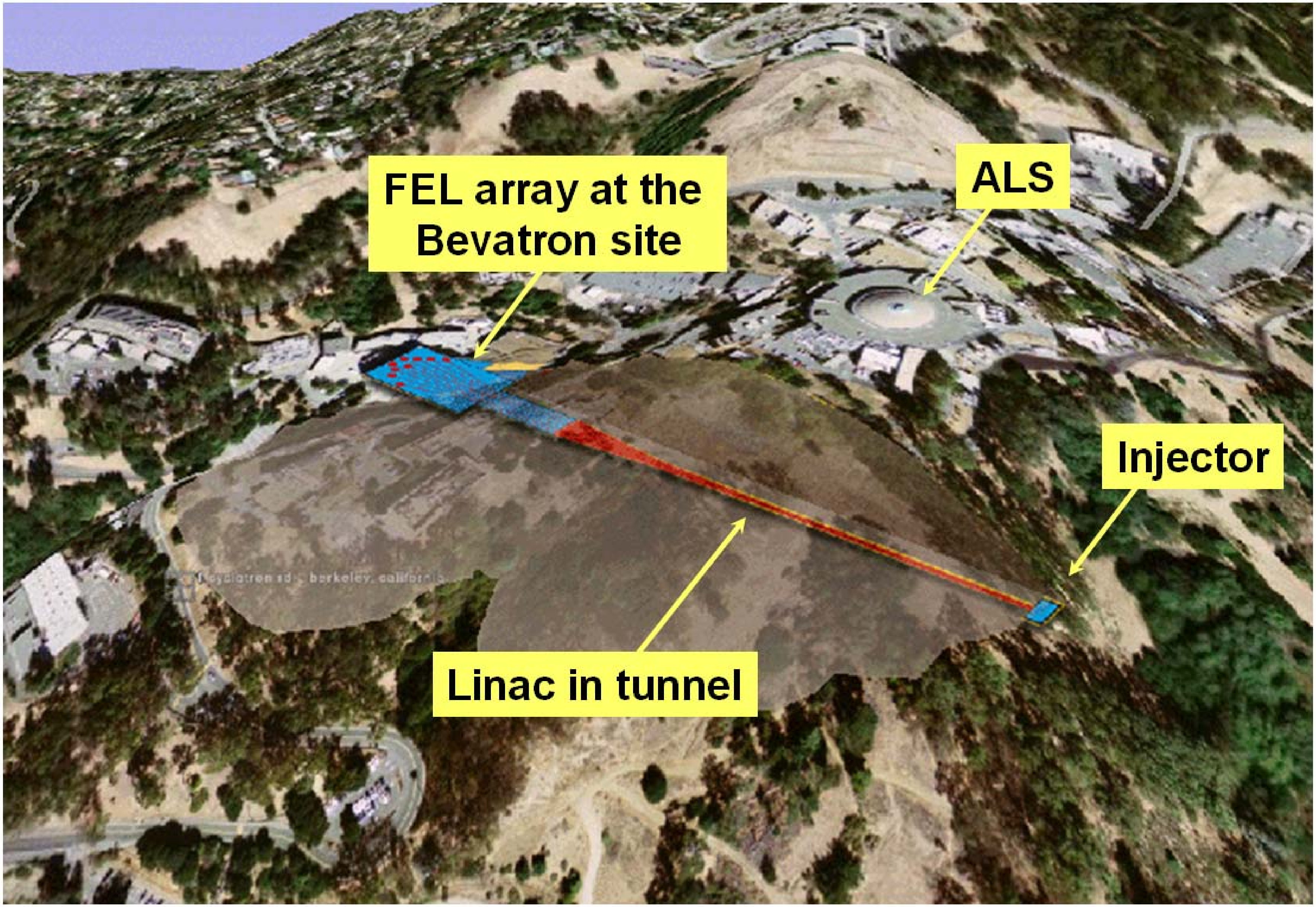






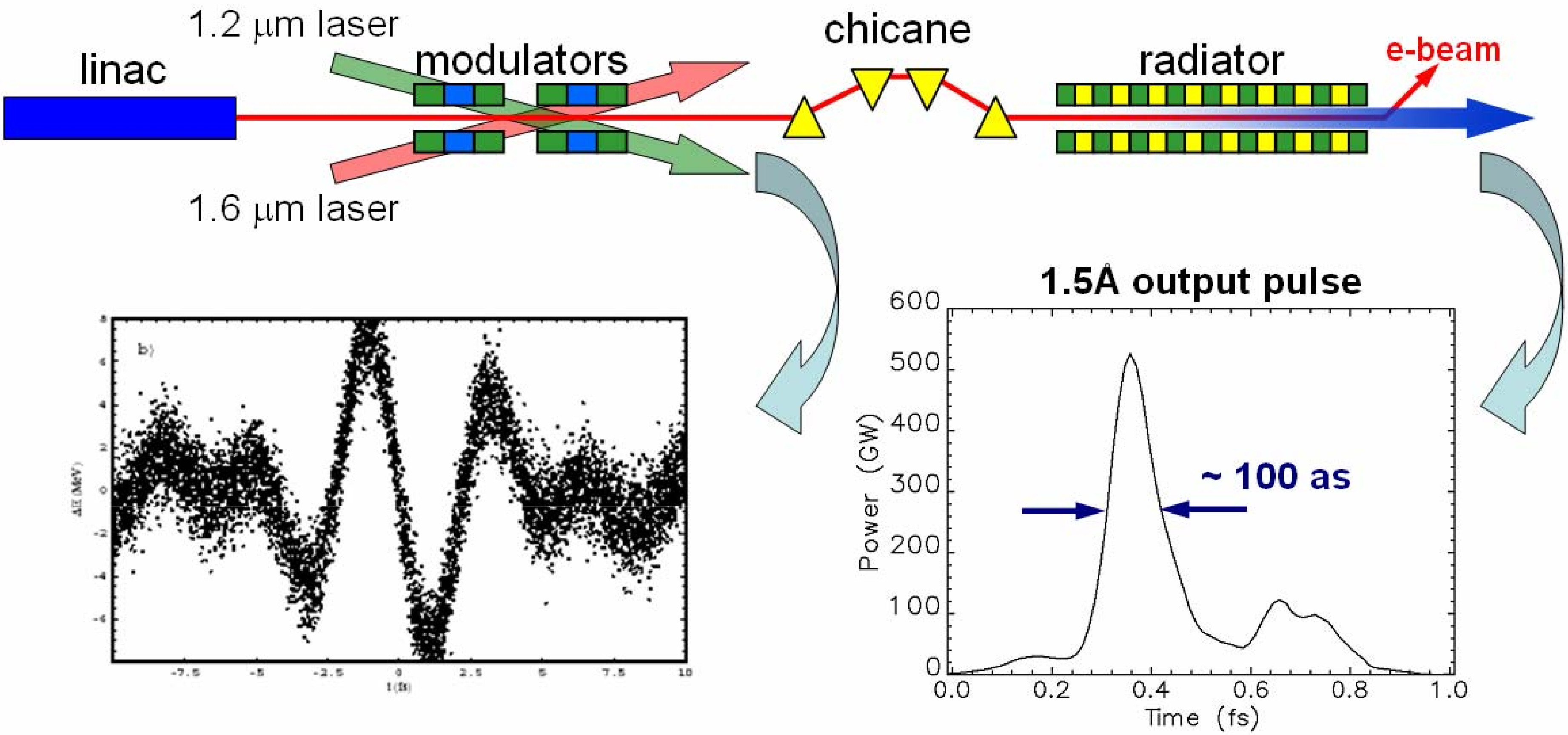
http://www.wifel.wisc.edu/index.htm

Vision for a future LBNL light source



Source: J.S. Wurtele

2-Laser Seeding: attosecond pulses

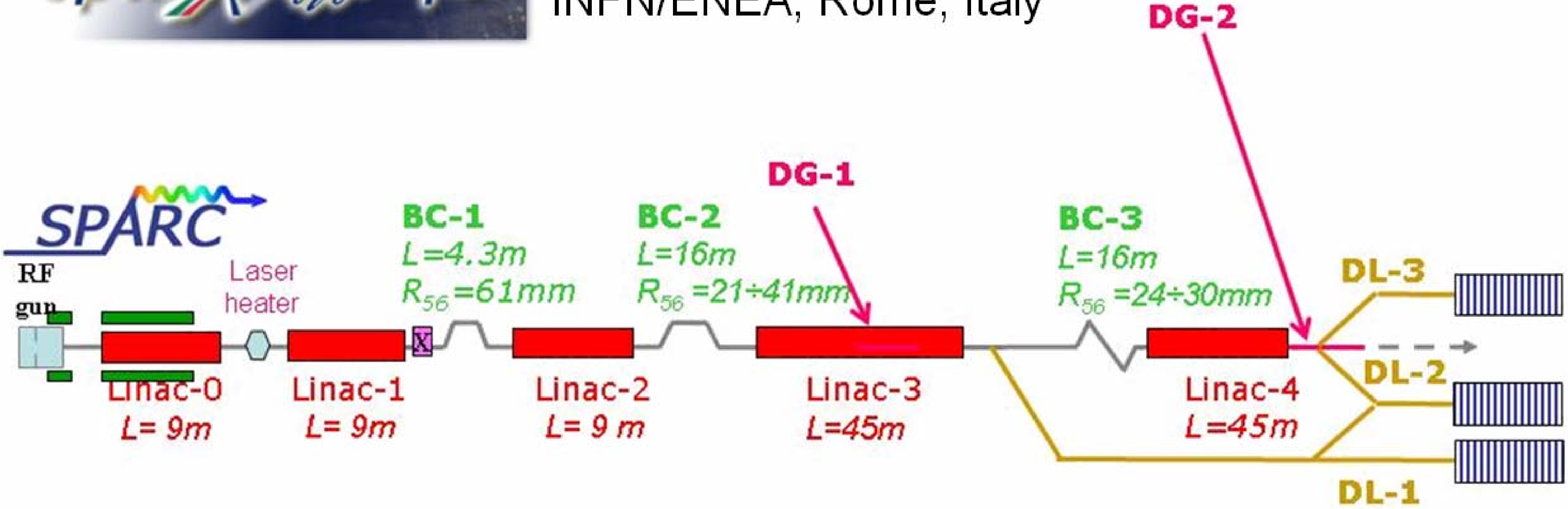


A.Zholents, W.M. Fawley, Phys. Rev. Lett. 92, 224801 (2004)
A.Zholents, G. Penn, Phys. Rev. ST Accel. Beams 8, 050704 (2005)

Seeding

- Very few seeding schemes tested experimentally
- Specific seeding schemes are interesting to specific user experiments
- Calculations indicate that some of the seeding schemes may be very sensitive to the starting condition:
  - Jitter of electron beam parameters or position
  - power and position jitter of seeding lasers
- Effort to get more experience with seeding:
  - HHG seeding at the SCSS test facility (Japan) → MOPC018
  - Seeding experiment at Max Lab (Sweden) → MOPC032
  - STARS proposal BESSY (Germany)
  - Planned seeding experiments at FLASH

sparX-fel INFN/ENEA, Rome, Italy

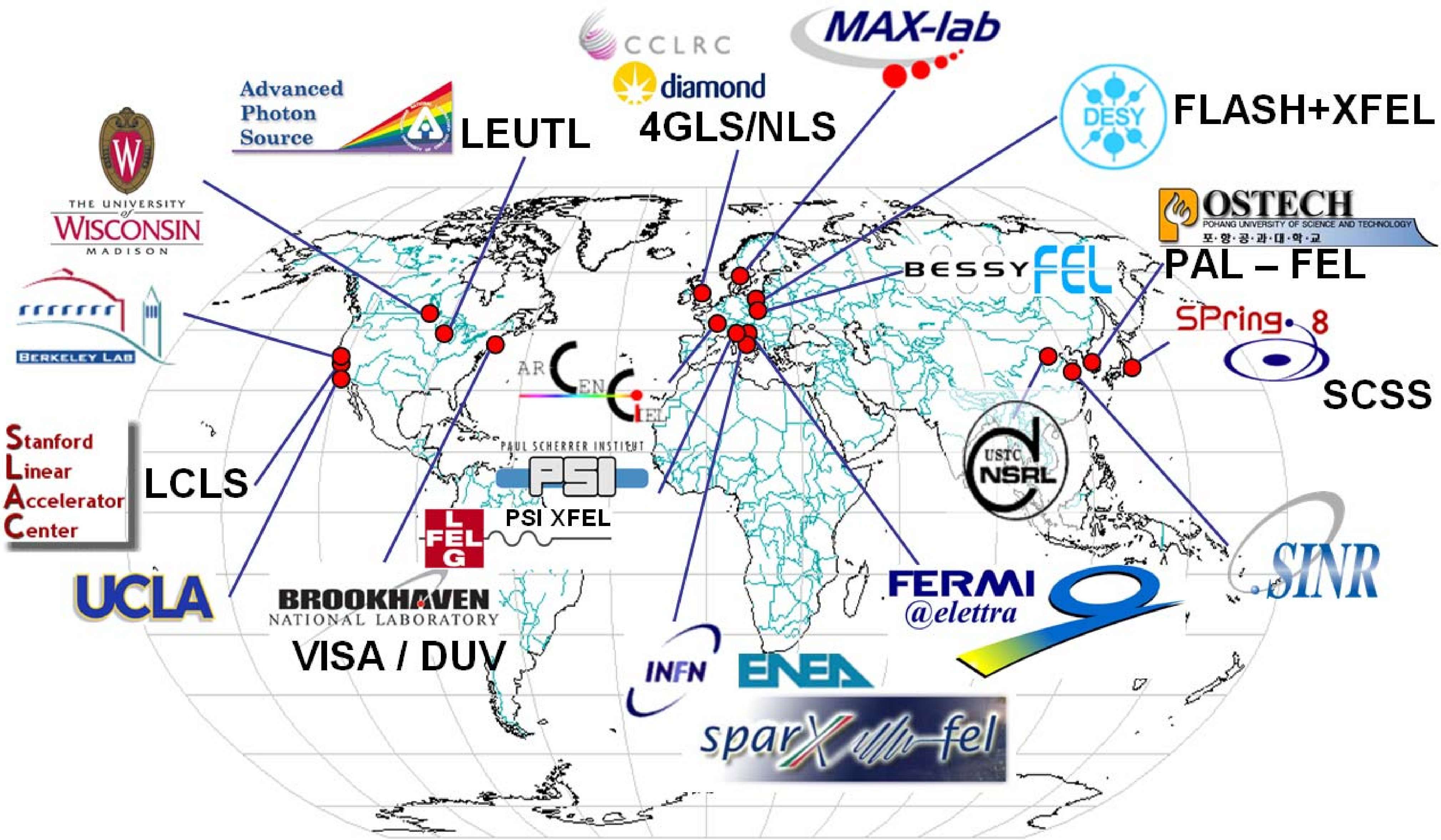


- S-band accelerator technology
- 1.5 – 2.4 GeV
- 40 – 0.2 nm
- SASE & Seeding options

http://www.sparx-fel.it

EPAC'08

Choice of Accelerator Technology



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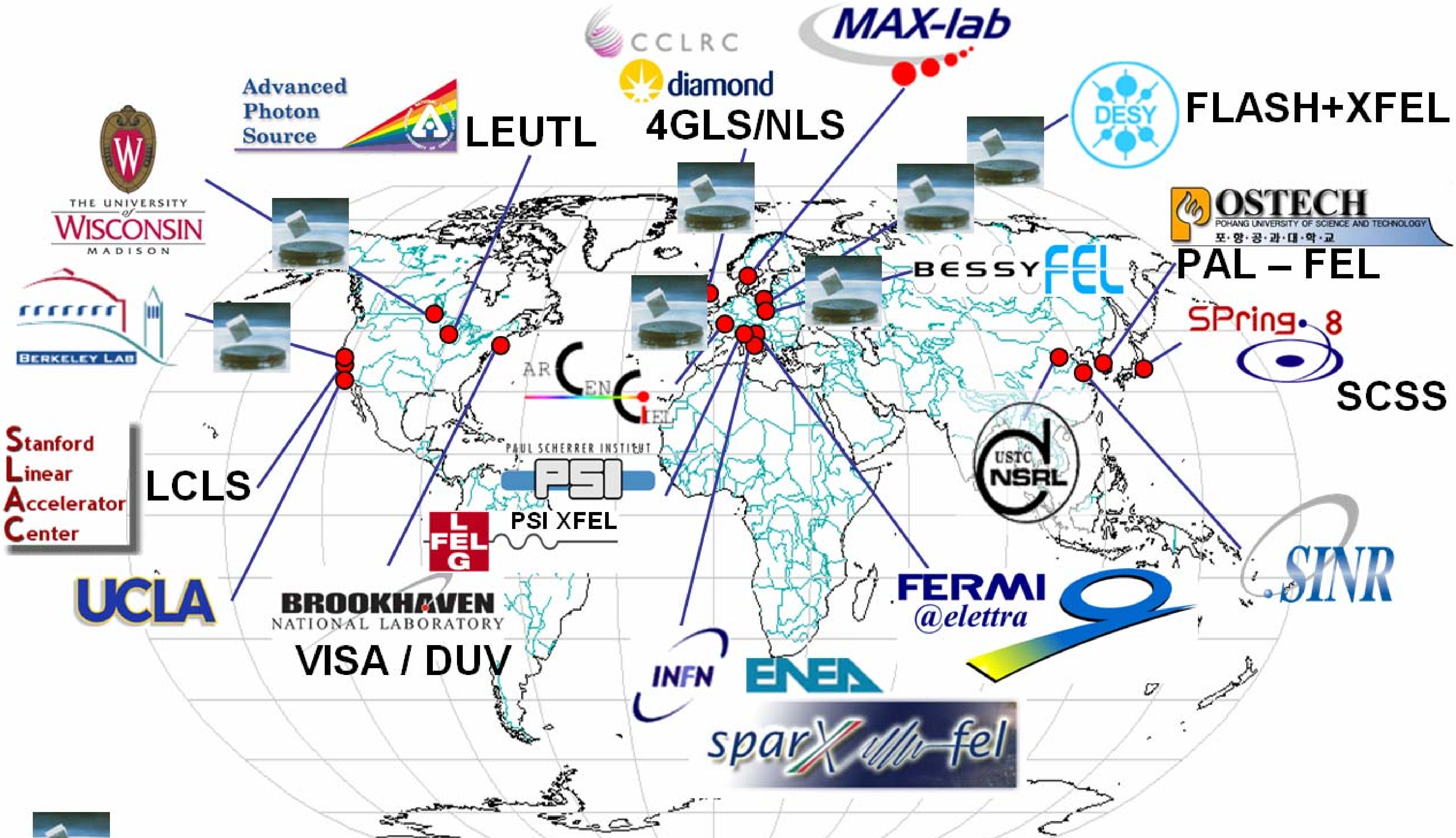


Superconducting accelerator technology

R.J. Bakker - WEXM01

Super Conducting Technology

Super-conducting linacs:

- Main push: high duty cycle (higher average output)
  - Superconductivity is particularly interesting for VUV and soft X-ray FELs since they can run at a modest beam-energy (< 3 GeV) and cope with the required cryogenic budget in a CW mode of operation.
- Stability potentially better (?)

Room temperature linacs:

- Cost of the accelerator (GeV/€).
- Many experiments do not need a high repetition rate.

SPring8 Compact SASE Source (SCSS)

C-band room temperature linac

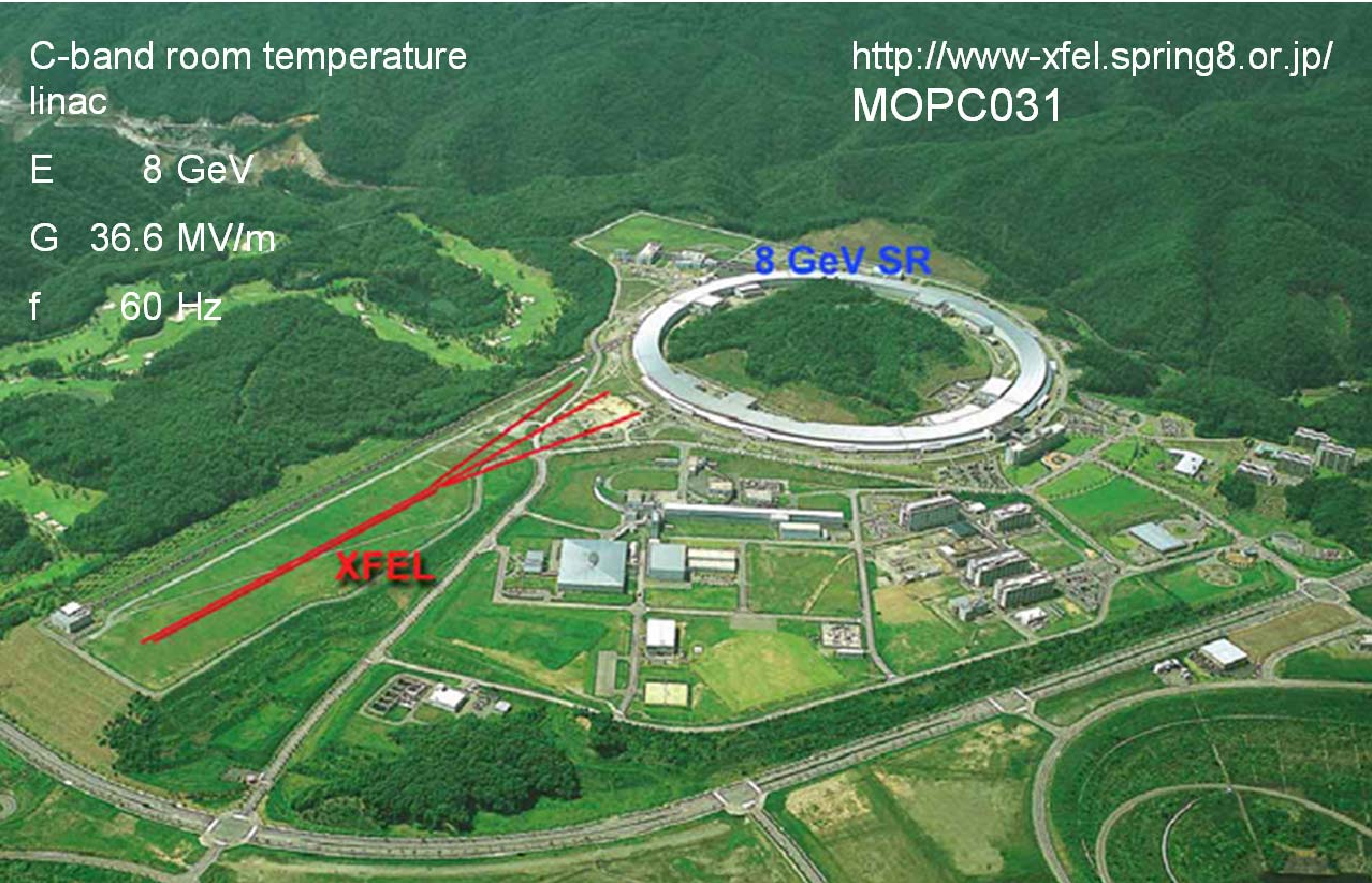
E 8 GeV

G 36.6 MV/m

f 60 Hz

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

MOPC031



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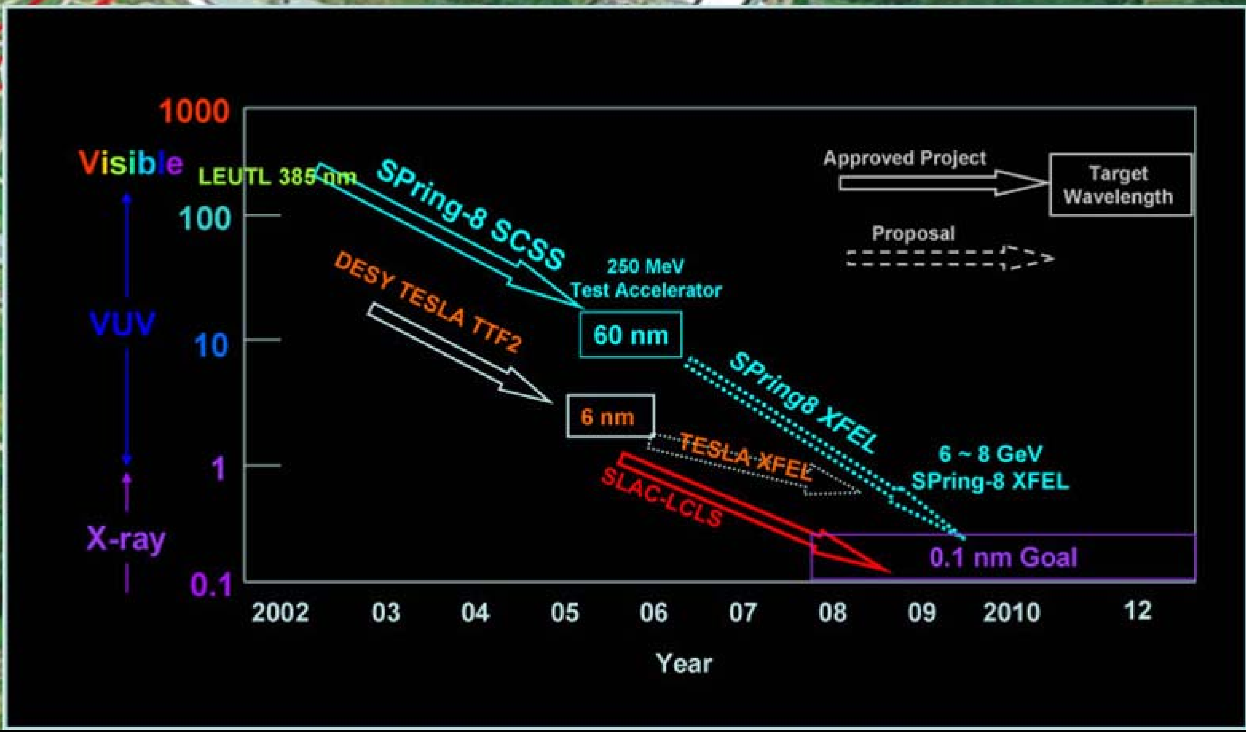
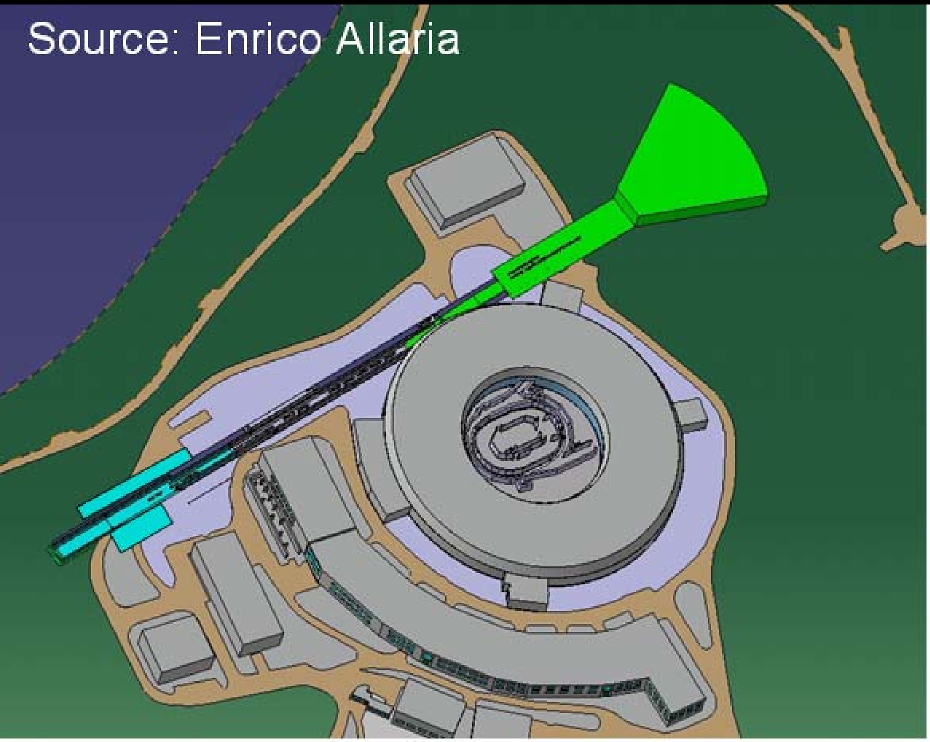


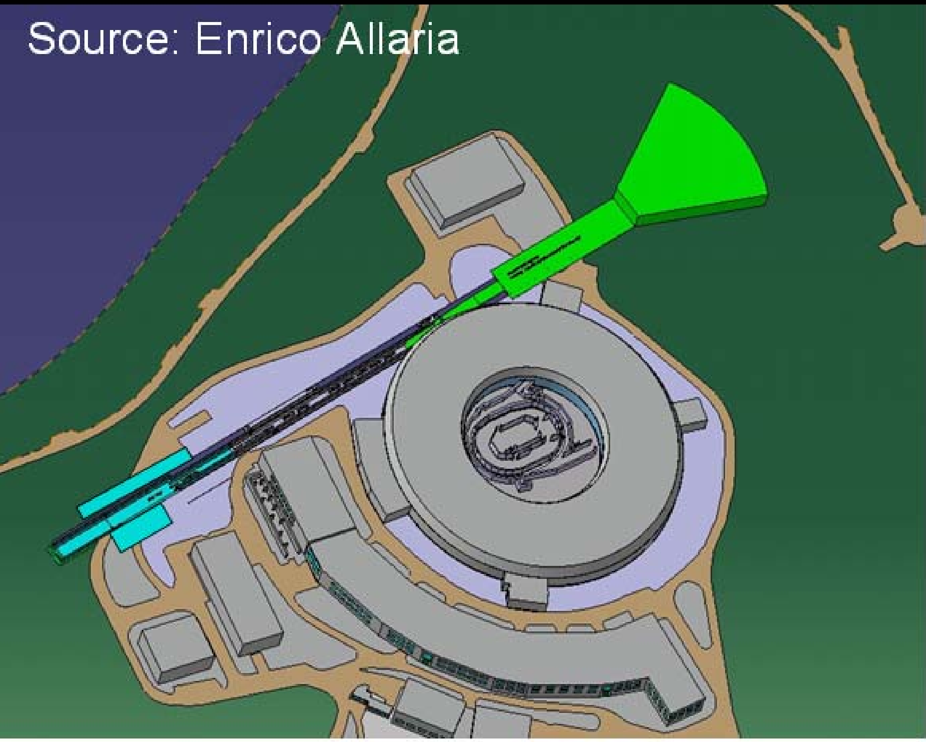


EPAC'08

FERMI@Elettra, Trieste, Italy

1.2 GeV, 40 – 10 nm

Status: under construction, FL 2010



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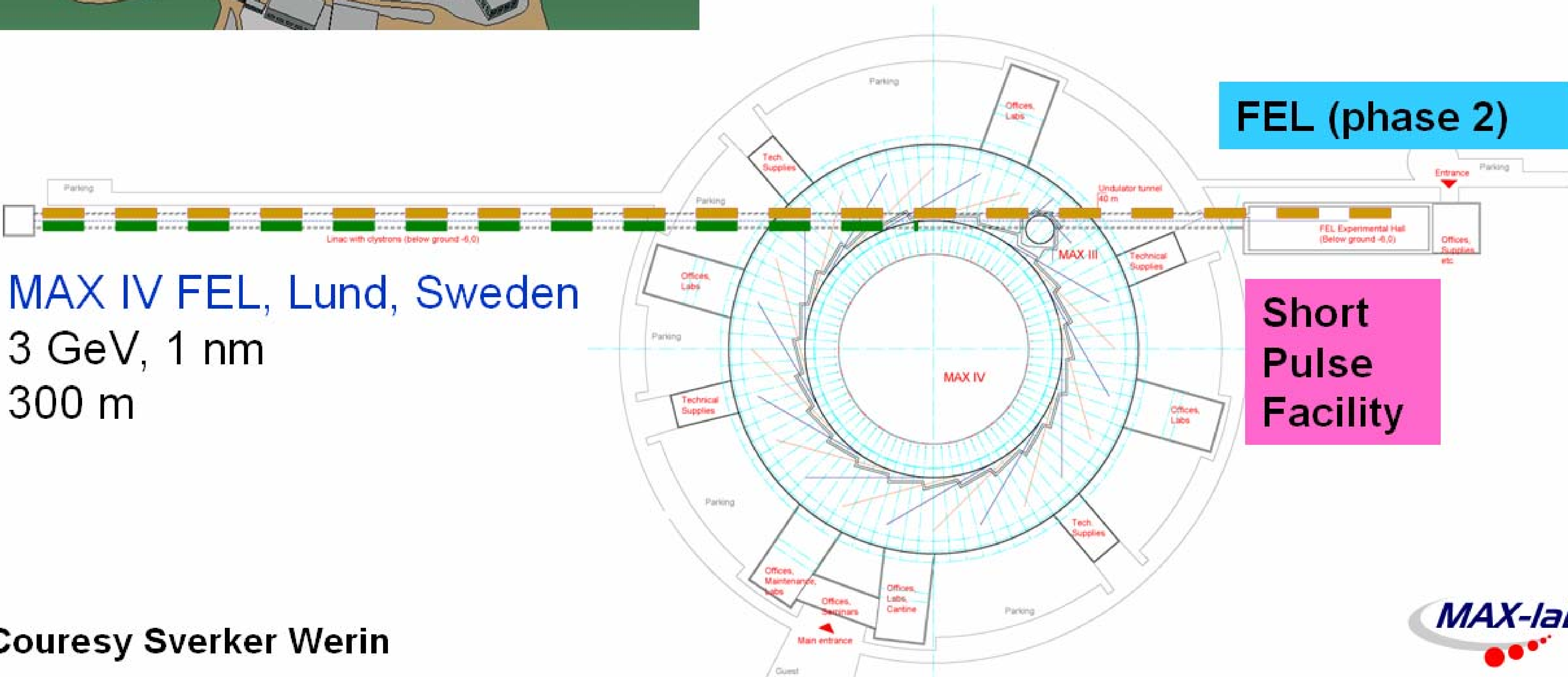


FEL (phase 2)

Short Pulse Facility

MAX IV FEL, Lund, Sweden

3 GeV, 1 nm

300 m

Couresy Sverker Werin

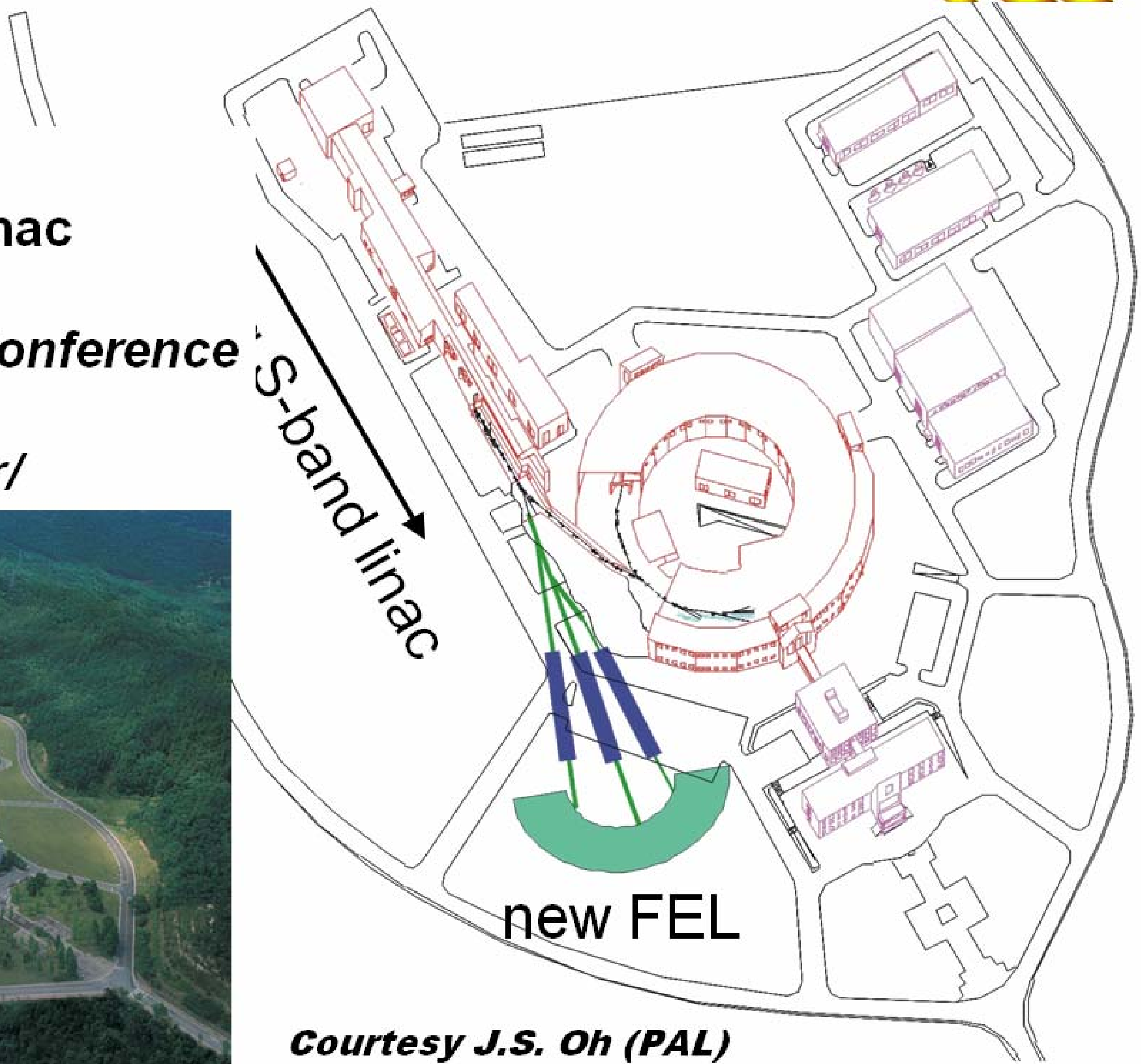
MAX-lab

PAL Pohang Light Source (Korea)

0.3 nm user facility

SASE FEL based on existing 3 GeV S-band linac

Host of this years FEL Conference August 24-29 http://fel08.postech.ac.kr/



Courtesy J.S. Oh (PAL)

BESSY FEL

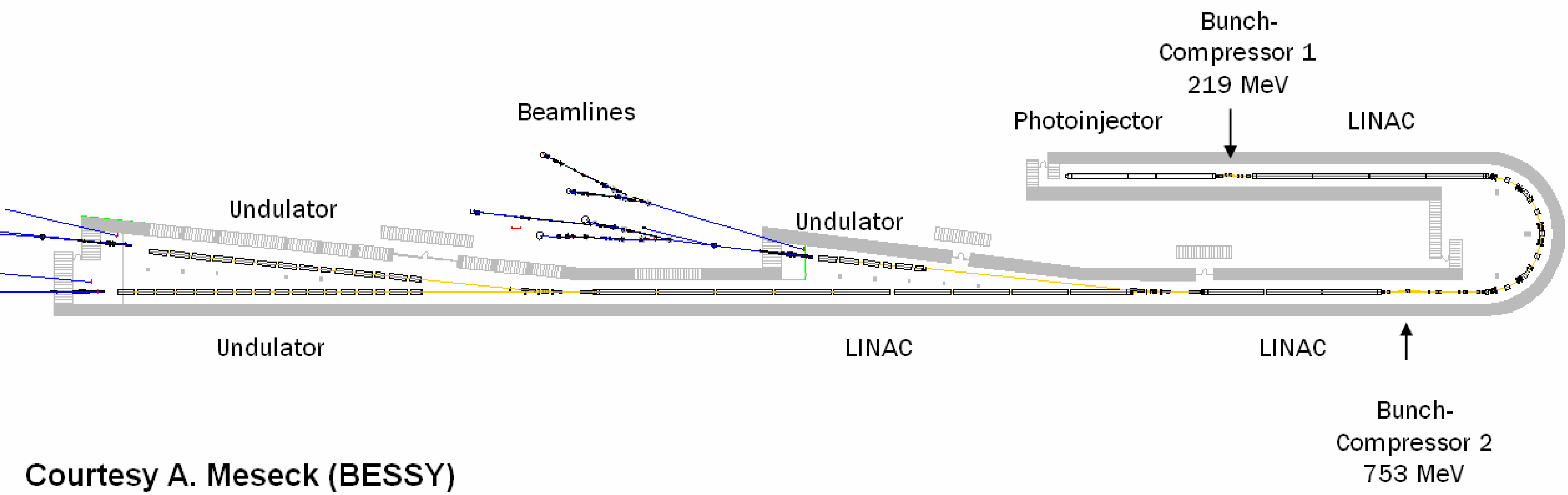
(http://www.bessy.de)

ELECTRON BEAM

Beam energy	1-2.3 GeV
Peak current	1.8 kA
Bunch charge	2.5 nC
Emittance (slice)	1.5 π mm mrad
Repetition rate	1 kHz (later 25)

FEL OUTPUT

Photon energy	24–1000 eV
Peak power	1.5–14 GW
Pulse duration	< 20 fs



Courtesy A. Meseck (BESSY)

BESSY FEL

(http://www.bessy.de)

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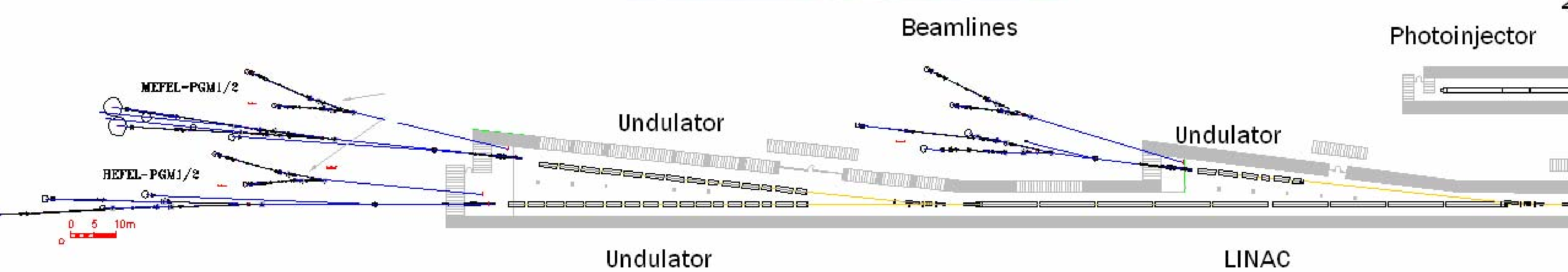
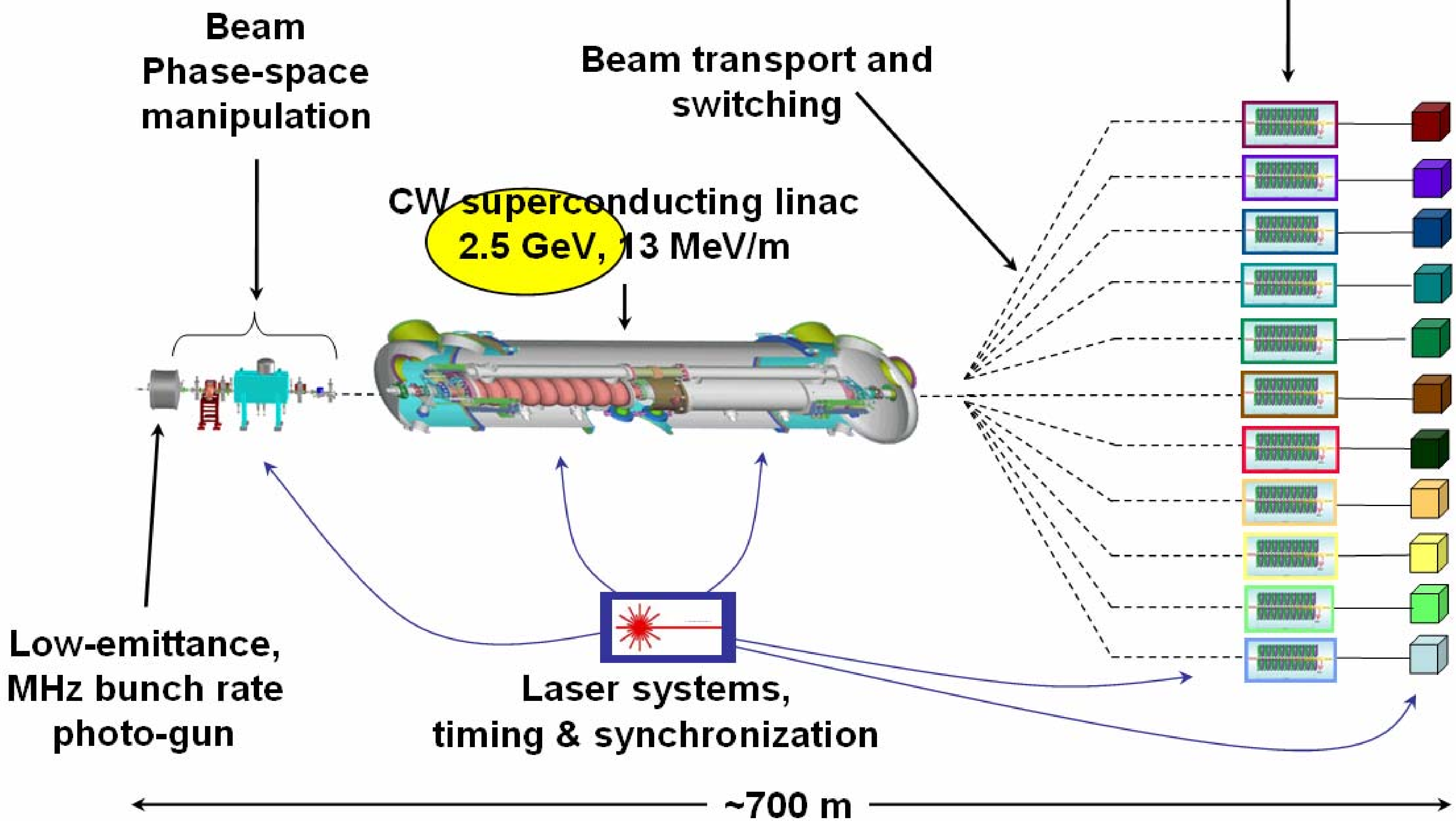


Courtesy A. Meseck (BESSY)

LBNL is Developing Concepts for a High-Repetition Rate, Seeded, VUV - Soft X-ray FEL Facility

Array of ~10 configurable FELs, each 1-100 kHz bunch rate
Independent control of wavelength, pulse duration, polarization
Each FEL configured for experimental requirements; seeded, attosecond, ESASE, etc

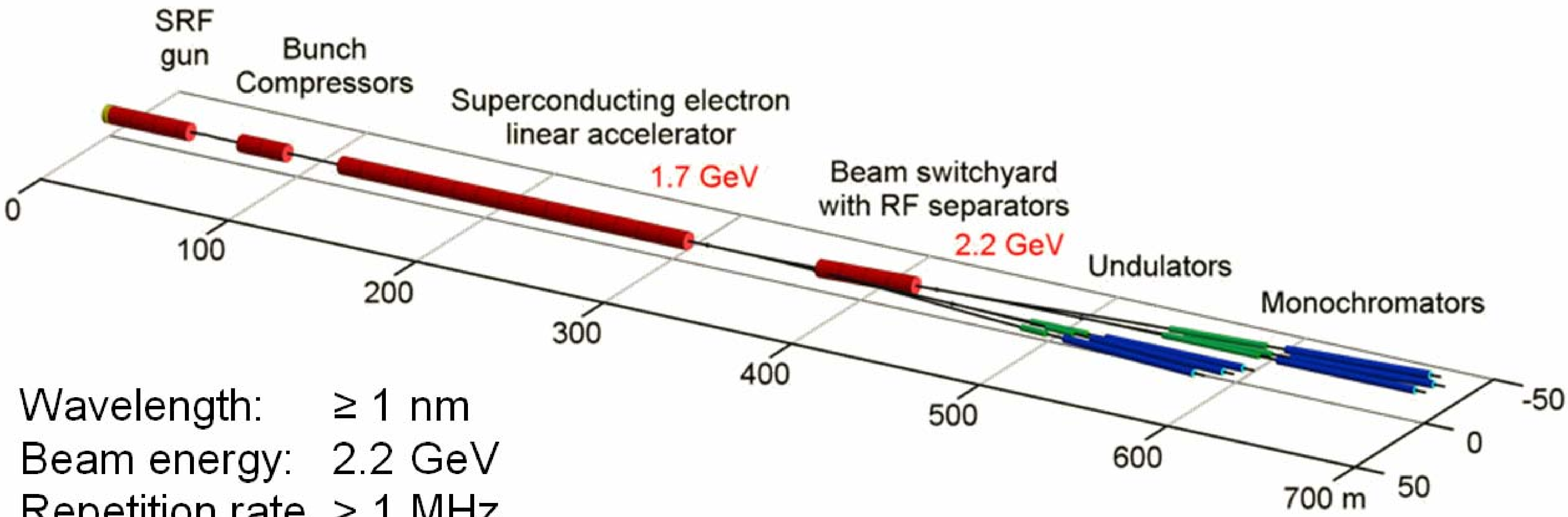


Courtesy J. Corlett (LBNL)

Wisconsin FEL Proposal

THE UNIVERSITY of WISCONSIN MADISON

WiFEL Layout



Wavelength: ≥ 1 nm
Beam energy: 2.2 GeV
Repetition rate > 1 MHz

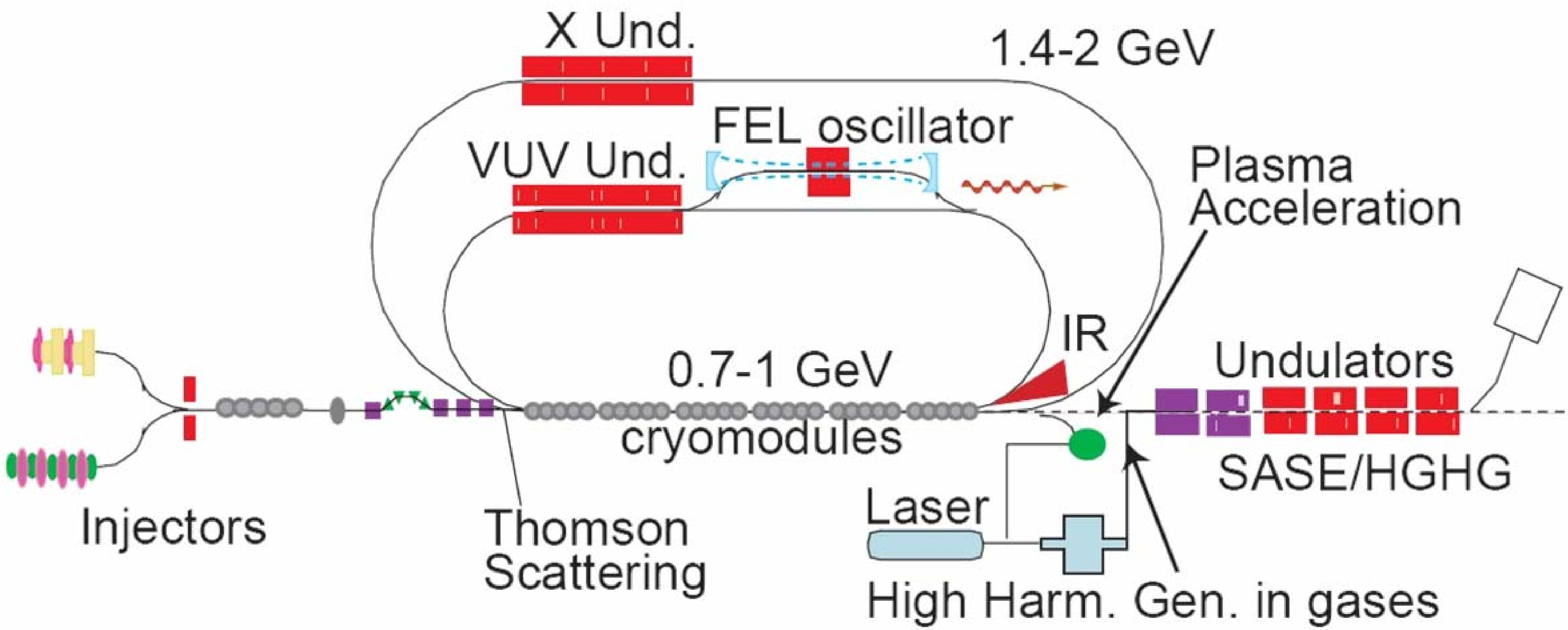
http://www.wifel.wisc.edu/index.htm

Arc-en-Ciel (Sacley, France)

http://arcenciel.synchrotron.fr/portal/page/portal/Arc-En-Ciel

- User Light-Source Facility
- ERL + FELs (VUV → X-rays)
- Seeding

3 GeV, 100 MHz

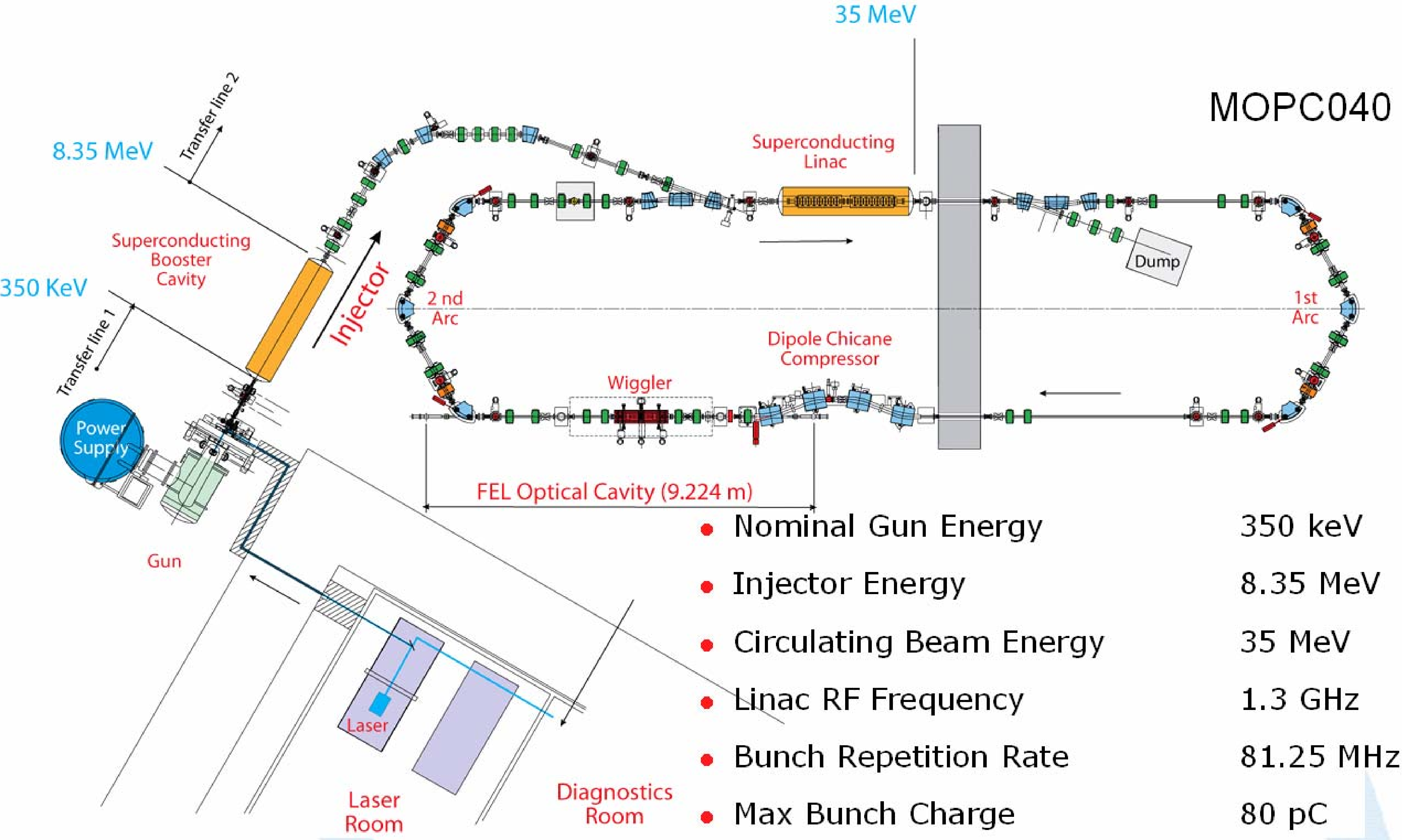


M.E. Couprie et al., EPAC04, p. 366

Alice
Accelerators and Lasers
In Combined Experiments

Accelerator Layout

MOPC040



• Nominal Gun Energy	350 keV
• Injector Energy	8.35 MeV
• Circulating Beam Energy	35 MeV
• Linac RF Frequency	1.3 GHz
• Bunch Repetition Rate	81.25 MHz
• Max Bunch Charge	80 pC
• Max Average Current	13 μA

Courtesy S. Smith (Daresbury)

New Light Source Project

New Light Source Project (NLS)
aiming for unique studies of microscopic motions in matter of all kinds

"We seek to examine the case for a New Light Source (NLS) Facility, based on advanced conventional and free electron lasers, with unique and world leading capabilities"

http://www.newlightsource.org/

- **MOPC035: "PULSE – A High Repetition Rate Linac Driver as a Possible Option for a Next Generation UK Light Source" Williams…**
- **MOPC033 "Sapphire – An Ultra-fast High Peak Brightness X-Ray Source as a Possible Option for a Next Generation UK Light Source" Walker…**

Test Facilities

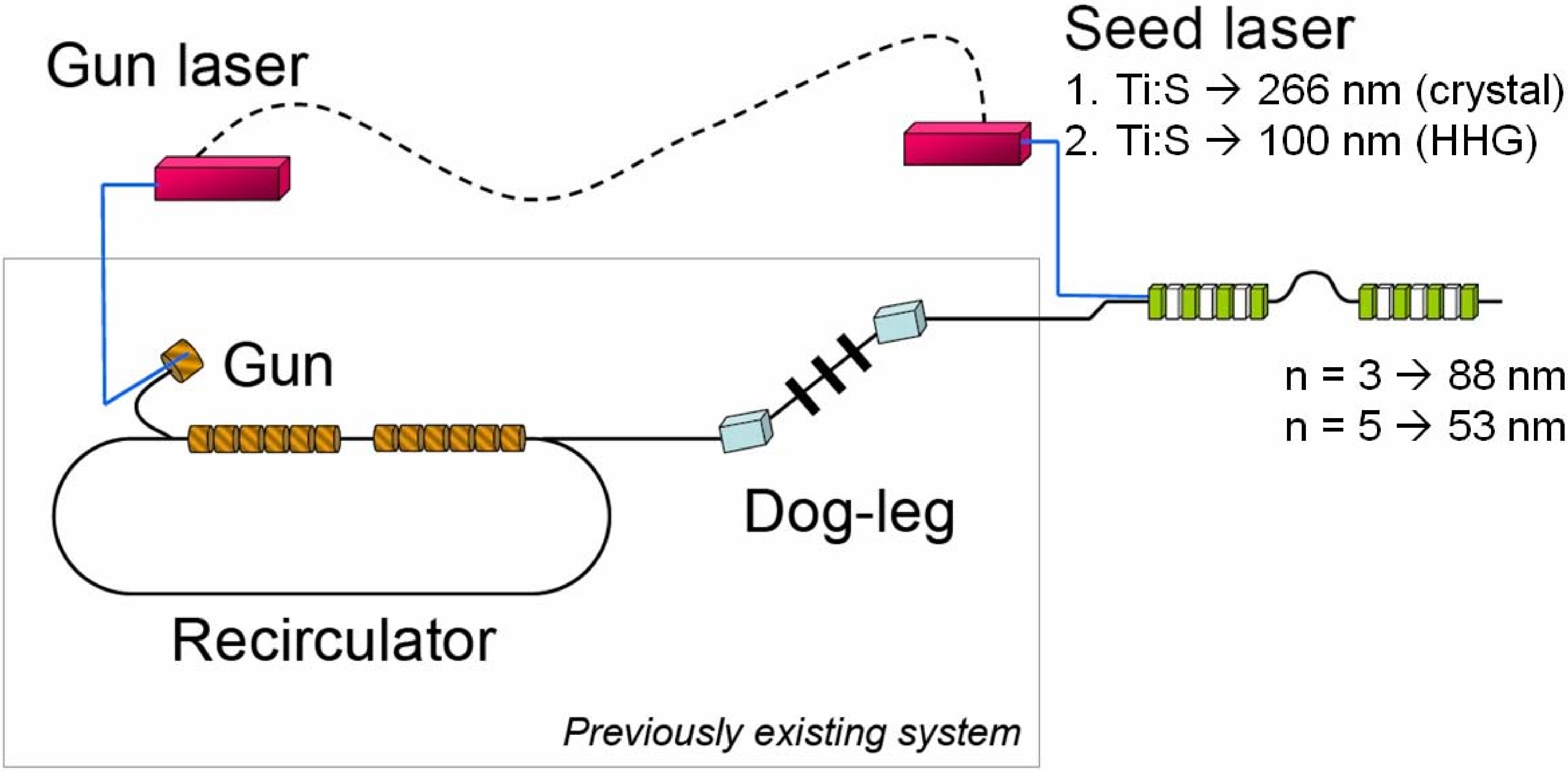
- FLASH used to be the Tesla Test Facility
- SCSS went for a 250 MeV test machine
- ....

} good idea to
- test
- gain experience

Not everybody tests the same thing:

- Daresbury: energy recovery
- Max-Lab: seeding
- BESSY: cascaded seeding
- INFN/ENEA: SPARC → SPARX (FEL physics)
- PSI: high brightness e-source & acceleration

Seeding @ Max-Lab, Lund, Sweden
(in collaboration with BESSY)



Next: STARS @ BESSY, Berlin, Germany
2-stage HGHG with a 325 MeV electron beam (project proposal)

MOPC006
MOPC032

SPARC INFN, ENEA, Frascati, Italy

Undulator parameters:

- Period 2.8 cm
- Sections 6
- Periods per section 75 (77 + ph. shifter*)
- K (nom./max) 2.145 / 3.2

Linac parameters:

- Beam Energy (MeV) 155 – 200
- Bunch charge (nC) 1.1 – 1
- Repetition rate (Hz) 1 – 10
- Bunch peak current (A) 85 – 100
- Solenoids for optimized velocity bunching & beam dynamics studies

http://fel.web.psi.ch

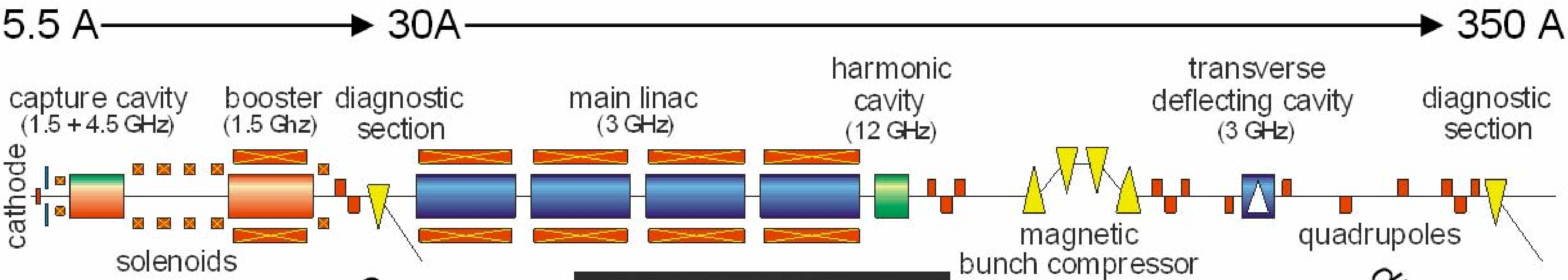
PSI XFEL

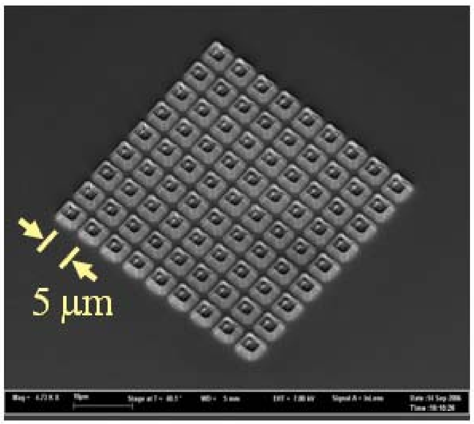
National X-Ray & VUV Laser User Facility

10 nm – 0.1 nm

Construction of an ultra-high brightness 250 MeV accelerator

- ε_n = 0.2 mm mrad
- Q = 0.2 nC





Source based
on field emission

EPAC'08

Name	location		stt*	λ_{min} (nm)	E (GeV)	linac type f (GHz)		rate (Hz)	type#
Arc-en-Ciel	Orsay	F	P	0.2	3	SC/CW	1.3	1×10^8	LS
BESSY FEL	Berlin	D	P	1.2	2.3	SC/CW	1.3	$1\text{-}25\times10^3$	LS
DUVFEL	Upton	USA	S	100	0.3	NC	2.86	10	LS
ERLP	Daresbury	UK	T	IR	0.035	SC/CW	1.3	20×8125	S/LS
FERMI	Trieste	I	F	10	1.2	NC	3.0	50	LS
LCLS	Stanford	USA	F	0.15	14.4	NC	2.86	120	S
LEUTL	Argonne	USA	S	130	0.4	NC	2.86	6	S
LBNL	Berkeley	USA	P	1	2.5	SC/CW	1.3	1×10^5	LS
MAX	Lund, S	S	P/T	1	3.0	NC	3.0	-	LS
Wisconsin	Madison	USA	P	1	2.3	SC/CW	1.3	1×10^6	LS
PAL X-FEL	Pohang	K	P	0.3	3.0	NC	2.86	60	S
PSI XFEL	Villigen	CH	P/T	0.1	5.8	NC	3.0	100	S/LS
SCSS	Hyogo	J	F	0.1	8.0	NC	5.7	60	S
SDUV-FEL	Shanghai	PRC	F	88	0.3	NC	2.86	-	LS
SPARC	Frascati	I	T	533	0.155	NC	2.86	10	S/LS
SPARX	Frascati	I	F	0.2	1.5-2.4	NC	2.86	100	S/LS
TESLA X-FEL	Hamburg	D	F	0.085	30.0	SC	1.3	72×10^3	S/SS
FLASH	Hamburg	D	O	6	1.0	SC	1.3	72×10^3	S/SS/LS

* F- funded, O – operational, P – proposal, S – suspended, T – Test experiment

\# S – SASE, LS – laser seeded, SS – self-seeded

see also: W.B. Colson p. 756, proceedings FEL2006 (JACoW)