PAUL SCHERRER INSTITUT PSI

Overview of Proposals for major FEL Facilities

Hans-H. Braun, PSI

XXV International Linear Accelerator Conference, Tsukuba
September 13-17, 2010

FELs in operation or under construction

Project	Status	First Lasing	T_{e-}	λ_{min}	Main Linac technology	Overall length
FLASH	running	2005 (2000 TTF)	1.2 GeV	45 Å	Pulsed SC 1.3 GHz	315 m
LCLS	running	2009	14. 3GeV	1.5 Å	Pulsed NC 2.85 GHz	1700 m
FERMI@ELETTRA	construction	2010	1.5 GeV	40 Å	Pulsed NC 3.0 GHz	375 m
SCSS	construction	2011	8 GeV	1 Å	Pulsed NC 5.7 GHz	750 m
European XFEL	construction	2015	17.5 GeV →14 GeV	1 Å →0.5 Å	Pulsed SC 1.3 GHz	3400 m

15 GeV Electrons **LCLS** 1.5 Å X-Ray

Linac Coherent Light Source

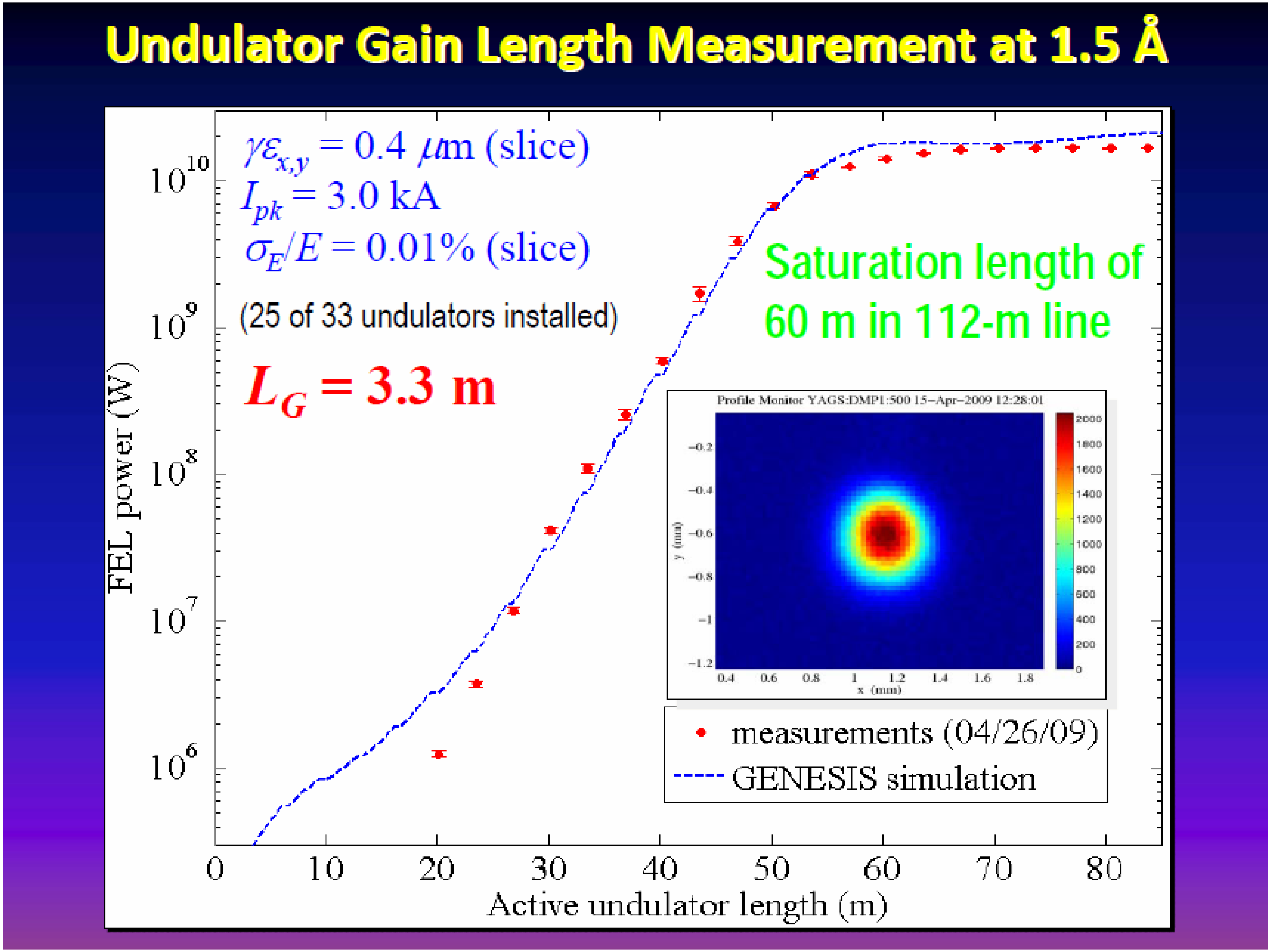
LCLS Parameters

Undulator Type	planar NdFe:B	planar NdFe:B	
Wavelength	15	1.5	A
Norm. RMS Emittance	1.2	1.2	mm mrad
Peak Current	3.4	3.4	kA
Electron Energy E	4.54	14.35	GeV
Average b -Function	7.3	18	m/rad
s E/E (X-rays)	0.47	0.13	%
Pulse Duration (FWHM)	230	230	fs
Pulses per macropulse	1	1	
Repetition Rate	120	120	Hz
Undulator Period	3.0	3.0	cm
Peak Field	1.32	1.32	T
FEL parameter r	1.45	0.50	10^{-3}
Power Gain Length	1.3	4.7	m
Saturation Length	27	86	m
Peak Power	19	8	GW
Average Power	0.61	0.25	W
Coherent Energy per Pulse	2.6	2.3	mJ
Coherent Photons per Pulse	27.9	1.1	10^{12}
Peak Brightness	0.64	8.5	10^{32} **
Average Brightness	0.2	2.7	10^{22}**
Transverse RMS Photon Beam Size	40	33	µm
Transverse RMS Photon Beam Divergence	3.4	0.42	µrad

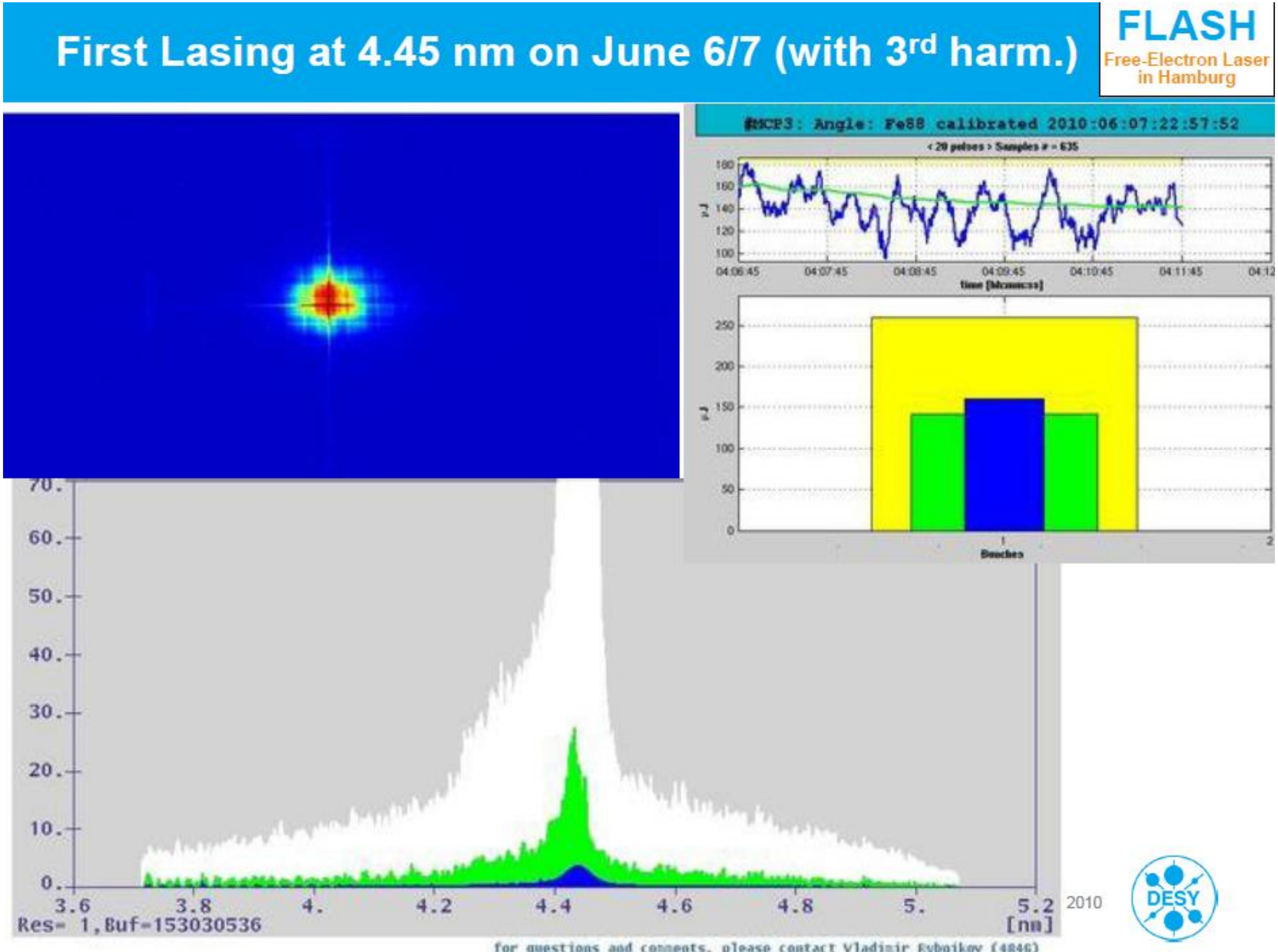
** photons/(s,mm^2,mrad^2,0.1%BW)

10 April 2009, first 1.5Å lasing !

LCLS results (courtesy P. Emma/SLAC)



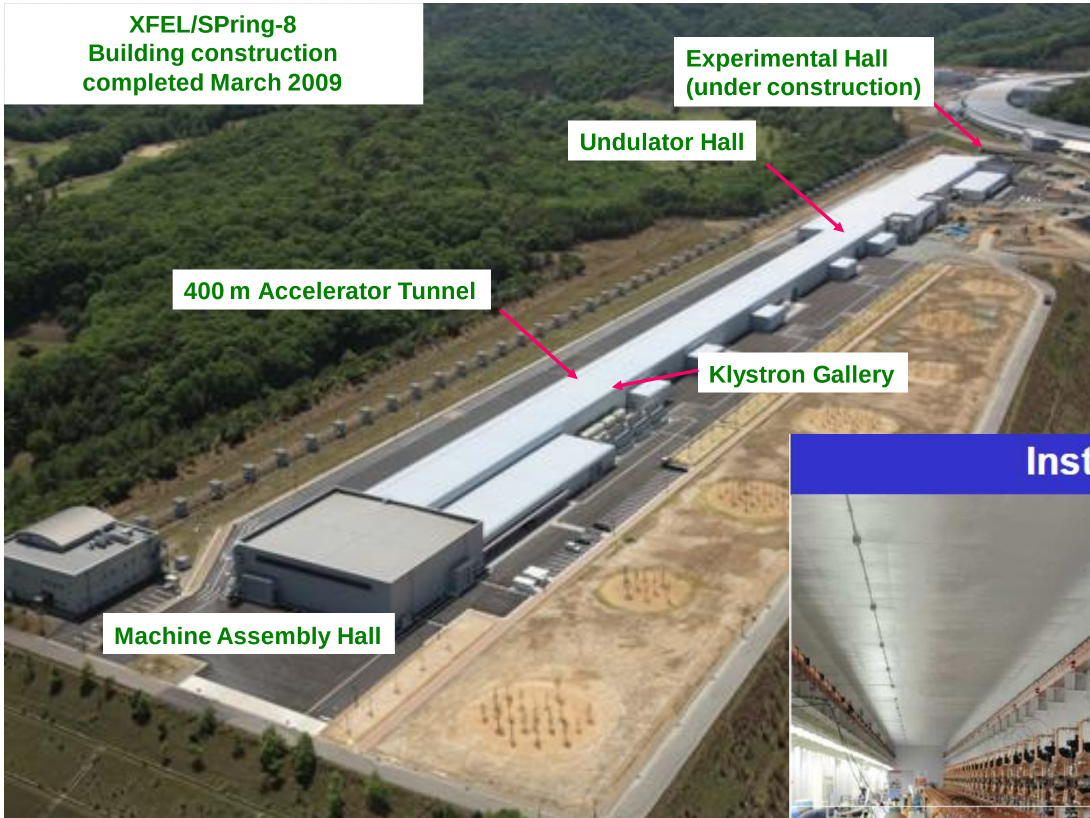
FLASH results (courtesy B. Faatz/DESY)



Lessons from LCLS and FLASH for future projects

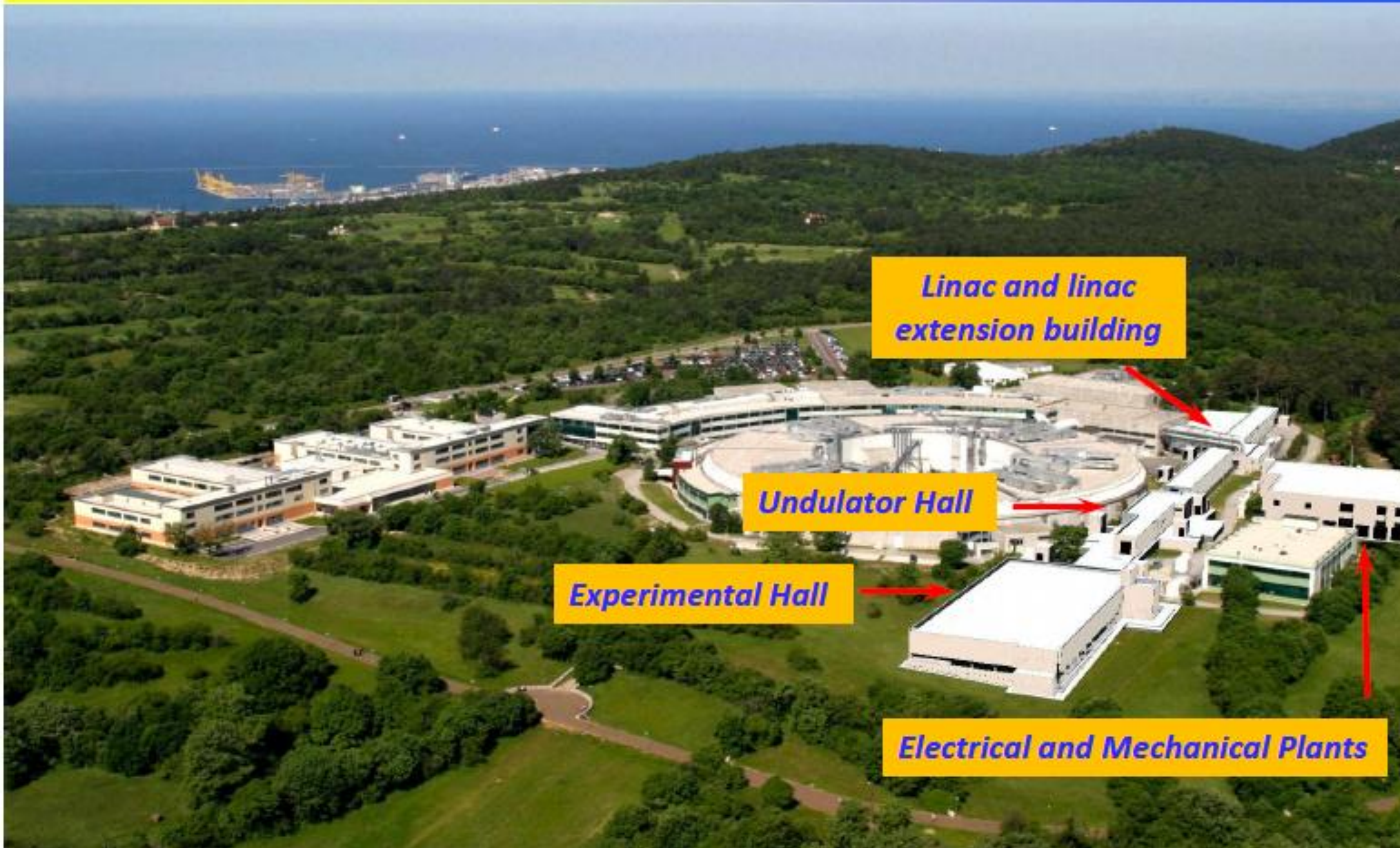
- Principle of SASE FEL works from VUV to hard X-ray regime
- State of the art FEL Theory and Design tools give also for this wavelength range reliable predictions.
- It is definitely not easy, but at least we know now what the difficulties are
- There are enough users out there for many FELs in this wavelength range

SCSS (courtesy T.Shintake)



FERMI@Elettra

courtesy S. Milton/ELETTRA



Lessons expected soon from next facilities coming online

SCSS

- 8 GeV is sufficient for lasing at 1 Å
- C-band technology is a good choice for compact FEL driver linacs
- Small period, in-vacuum PM undulators are a good choice for compact hard X-ray FELs

FERMI@ELETTRA

- Principle of HGHG seeding works at nm wavelength range
- Polarization control with Apple II undulators works for soft X-ray FELs

Rational for future X-ray FELs

Worldwide >50 SR storage rings with ≈1000 user stations total

- wide range of applications in many disciplines of science for high brightness X-ray photon sources
- there was so far no other X-ray photon source of similar brightness

Potential X-FELs vs. SR storage rings

+ much higher peak brightness
+ higher average brightness
+ much better time resolution
+ much better coherence
+ more jobs for linac builders

Difficulties X-FELs vs. SR storage rings

- less photon flux
- less beamlines/facility
- much higher cost per user station

How to overcome “difficulties” X-ray FELs vs storage rings

Approach A)

Reduce cost/facility by reducing facility size

$$\$ \propto \gamma$$

$$\lambda = \frac{\lambda_U}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$\varepsilon_N \approx \gamma \frac{\lambda}{4\pi}$$

$$\varepsilon_N \propto \sqrt{q_B}$$

- Lowest beam energy technically possible
- Small period undulators with low K values
- Low bunch charge q_B
- High gradient
- Normal conducting, high frequency linac

How to overcome “difficulties” X-ray FELs vs storage rings cont.

Approach B)

Increase number of user stations and photon flux per user station

- 1kHz-1MHz bunch repetition rate
- Distribute beam on many FEL beamlines

$\Rightarrow$ *Super conducting linac with c.w. operation*

Proposals for new X-FEL facilities

	Project	Status	T_{e-}	λ_{min}	Main Linac technology	Overall length
Approach A)	**SPARX**	design report	2.4 GeV	5 Å	Pulsed NC 2.85 or 5.7 GHz	500 m
	SwissFEL	design report	5.8 GeV	1 Å	Pulsed NC 5.7 GHz	715 m
	PAL XFEL	design in progress	10 GeV	0.6 Å	Pulsed NC 2.85 or 5.7 GHz	900 m
	Shanghai XFEL	design in progress	6.4 GeV	1 Å	Pulsed NC 5.7 GHz	600 m
	MAX IV FEL	optional extension of MAX IV 3.5 GeV linac	?	?	Pulsed NC 2.85 GHz	?
Approach B)	**NLS**	design report	2.25 GeV	12 Å	C.W. SC 1.3 GHz	700 m
	NGLS	design in progress	2.4 GeV	12 Å	C.W. SC 1.3 or 1.5 GHz	?
	BESSY soft X-ray FEL	design report	2.3 GeV	12.4 Å	C.W. SC 1.3 GHz	450 m

sparX-fel

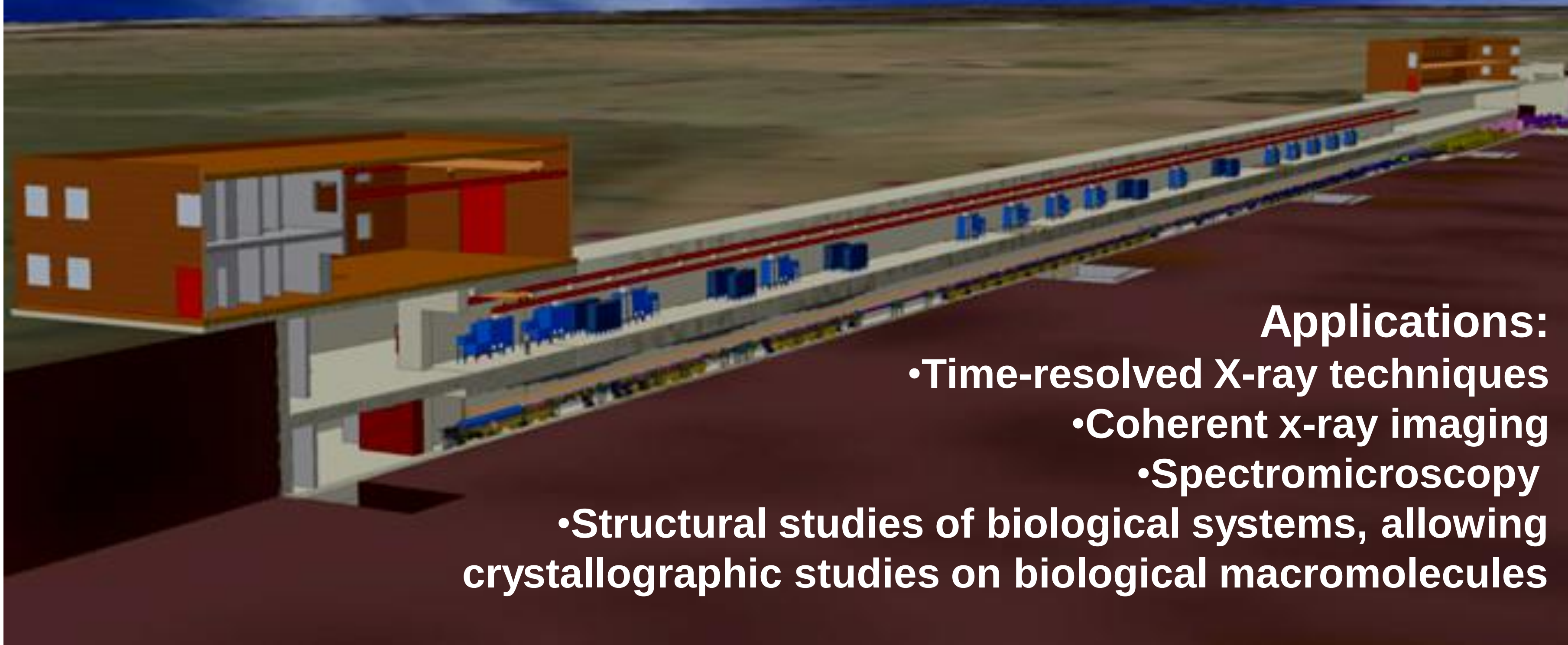
www.sparx-fel.eu

courtesy
M. Ferrario/INFN

Ministero dell'Università
e della Ricerca

REGIONE
LAZIO

Free Electron Laser ranging from 40 nm a 0.5 nm
4 different Beamlines with dedicated experimental stations
Peak Brillance: 10^{27} sec.mrad².mm.0.1 % BW – 80-200 fs pulses
Site : Università di Roma Tor Vergata
Costruction of the 500 m tunnel: 2010 - 2014



Applications:

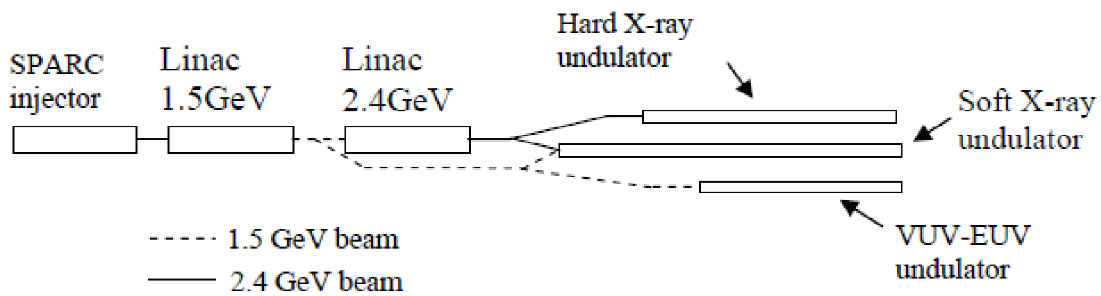
- **Time-resolved X-ray techniques**
- **Coherent x-ray imaging**
- **Spectromicroscopy**
- **Structural studies of biological systems, allowing crystallographic studies on biological macromolecules**

Consiglio Nazionale delle Ricerche

ENEA C.R. Frascati

INFN Istituto Nazionale di Fisica Nucleare

Università degli Studi di Roma Tor Vergata www.sparx-fel.eu



Layout of SPARX

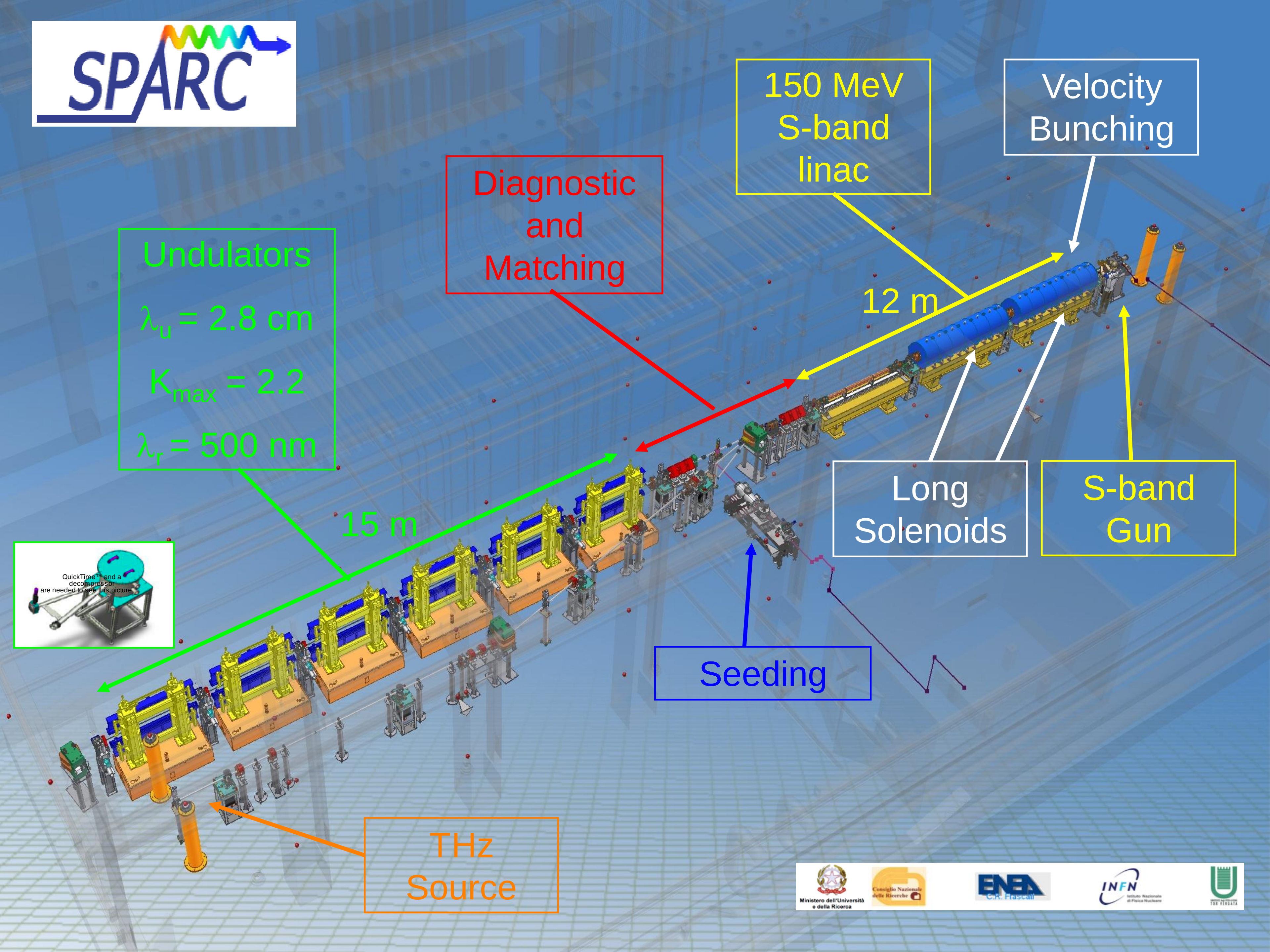
Electron beam parameter list

Energy	(GeV)	E	1÷1.5	2.4
Peak current	(kA)	I_{pk}	1	2.5
Normalized transverse emittance slice	(μm)	ε	1	1
Correlated energy spread	(%)	σ_δ	0.1	0.1
Photon Radiation wavelength	(nm)	λ	40÷3	3÷0.6

Radiation parameters of the FEL sources

	Units	*U1*	*U2*	*U2*	*U3*
Electron beam energy	GeV	0.96-1.5	0.96-1.5	1.9-2.4	1.9-2.4
Wavelength	nm	40–10	15–4	4-1.2	1.2 – 0.6
Photon Energy	eV	30-120	80-300	300-1000	1000-2000
Peak power	GW	1.7-3.4	~2	3-20	0.8@2.4GeV
Average power	W	-	0.1-0.2	0.03-0.1	-
Photon beam size (FWHM)	*μm*	~140	~150	~130	~120
Photon beam divergence (FWHM)	*μ*rad	33	25	19	17
Bandwidth (FWHM)	%	0.2	0.2-0.1	0.15-0.1	0.09@2.4GeV
Pulse duration (FWHM)	fs	200	30-250	70-30	70-80
Repetition rate	Hz	100-50	100-50	100-50	100-50
Number of photons per pulse	#	$1.0 \cdot 10^{14}$	$1.5\text{-}8.5 \cdot 10^{13}$	$5 \cdot 10^{12}$	$0.5\text{-}1.5 \cdot 10^{12}$
Peak brilliance*			$\approx 10^{28}$		$\approx 10^{27}$
Average brilliance*			$\approx 10^{20}$		$\approx 10^{19}$

* *standard units:* *Number of photons (sec·mrad²·mm²·0.1 % BW). Mean values have been considered for the different cases.*


SPARC
150 MeV S-band linac
Velocity Bunching
Diagnostic and Matching
Undulators
λ_u = 2.8 cm
K_{max} = 2.2
λ_r = 500 nm
12 m
15 m
QuickTime™ and a decompressor are needed to see this picture.
Long Solenoids
S-band Gun
Seeding
THz Source
Ministero dell'Università e della Ricerca
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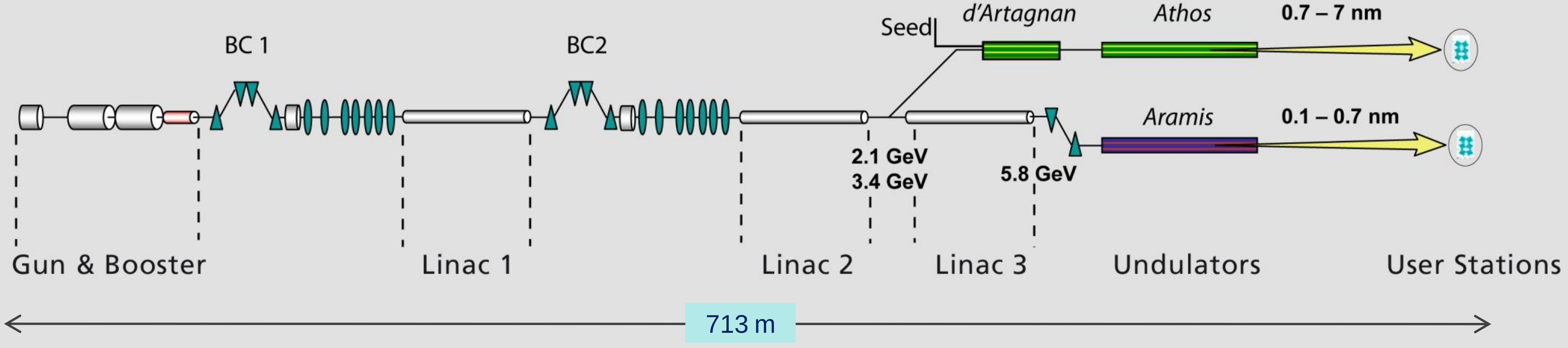
SwissFEL

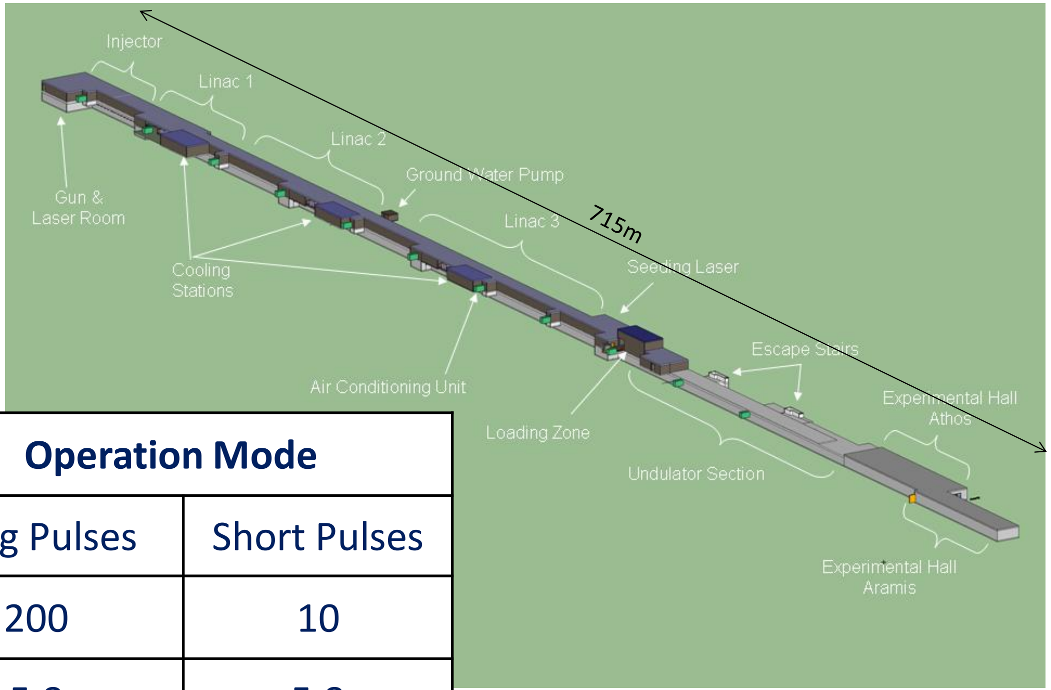


Aramis: 1-7 Å hard X-ray SASE FEL,
In-vacuum , planar undulators with variable gap.

Athos: 7-70 Å soft X-ray FEL for SASE & Seeded operation .
APPLE II undulators with variable gap and full polarization control.

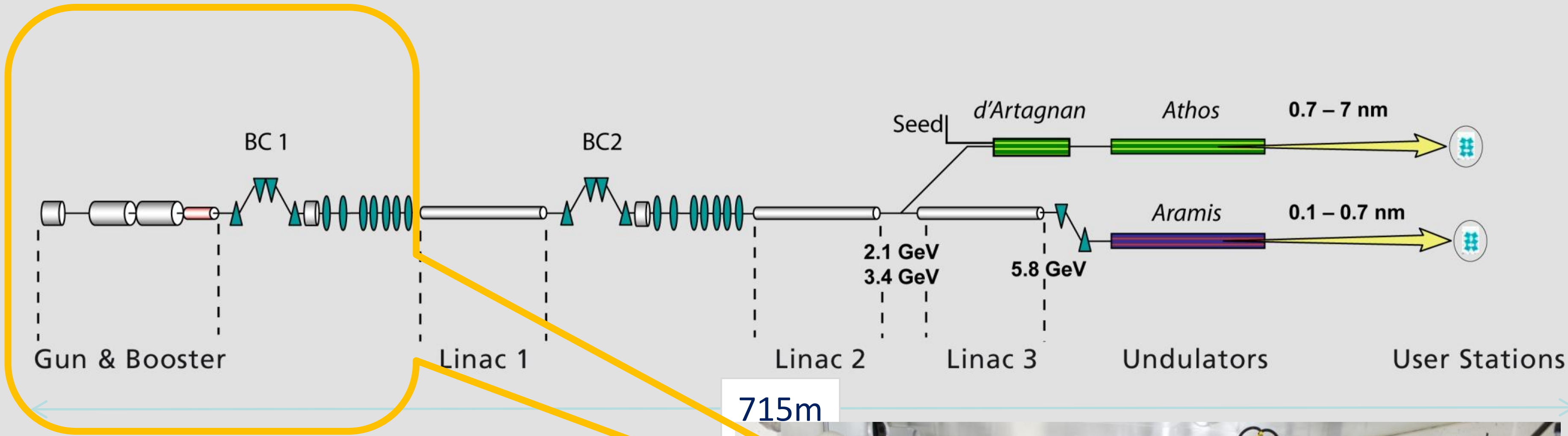
D'Artagnan: FEL for wavelengths above Athos, seeded with an HHG source. Besides covering the longer wavelength range, the FEL is used as the initial stage of a High Gain Harmonic Generation (HGHG) with **Athos** as the final radiator.

SwissFEL key parameters



Parameters for lasing at 1Å	**Operation Mode**	
	Long Pulses	Short Pulses
Charge per Bunch (pC)	200	10
Beam energy for 1 Å (GeV)	5.8	5.8
Core Slice Emittance (mm.mrad)	0.43	0.18
Peak Current at Undulator (kA)	2.7	0.7
Repetition Rate (Hz)	100	100
Undulator Period (mm)	15	15
Effective Saturation Power (GW)	2	0.6
Photon Pulse Length at 1 Å (fs, rms)	13	2.1

First existing part of SwissFEL: 250 MeV Injector

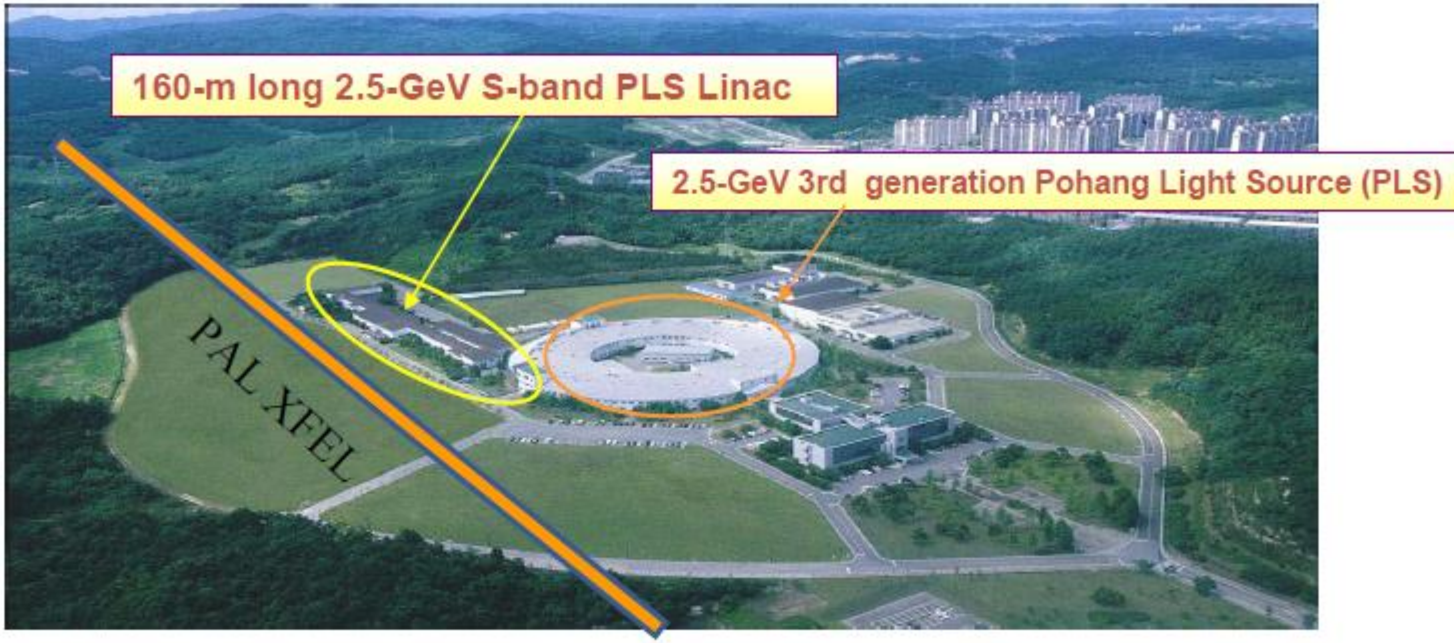


First beam to dump 9.8.2010

TUP009,
"First Commissioning Experience at the SwissFEL Injector,"
T. Schietinger et al.

Characteristics of PAL XFEL

courtesy W. Namkung/PAL

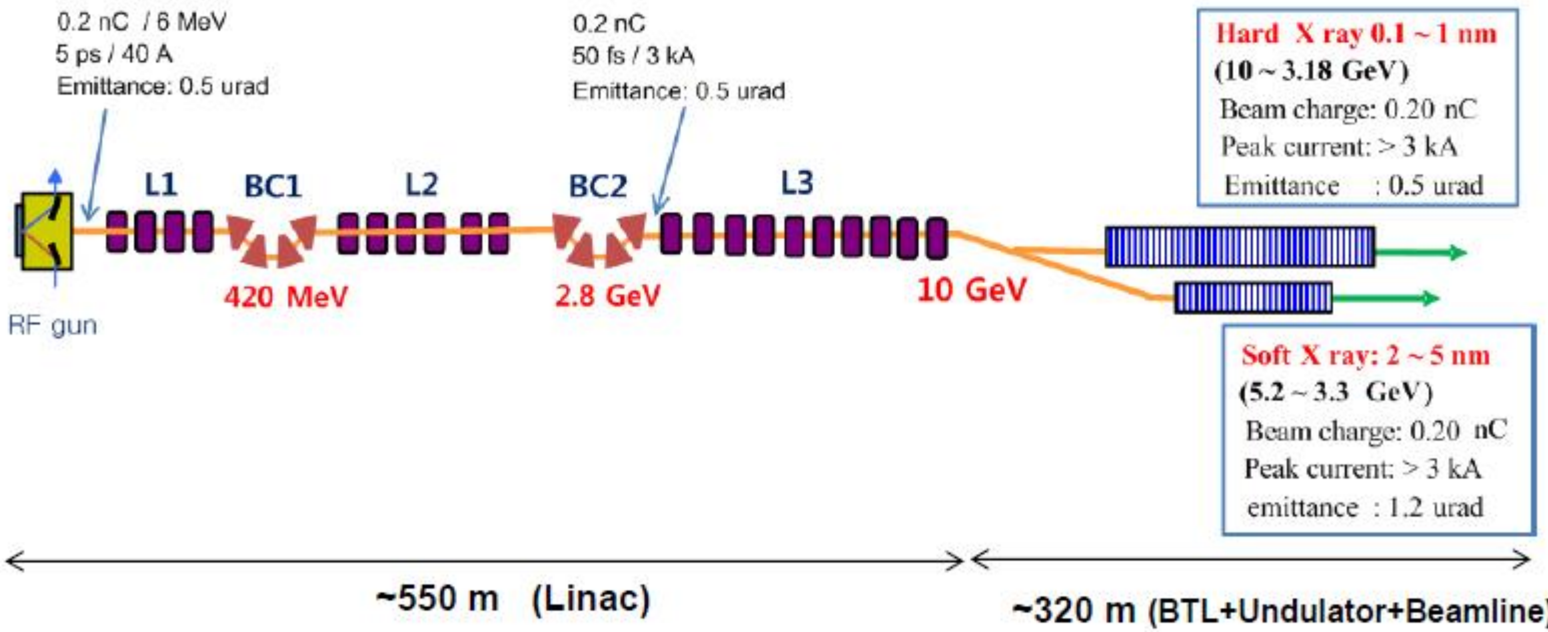


- Due to the limitation of available ***space & budget,***

- 10 GeV beam energy for short Wavelength (0. 1 nm / 0.06 nm)
- High Accelerating Gradient in Linac: 30 MV/m
- Short-period in-vacuum undulator with small gap
- Atto-second Hard X-ray Scheme

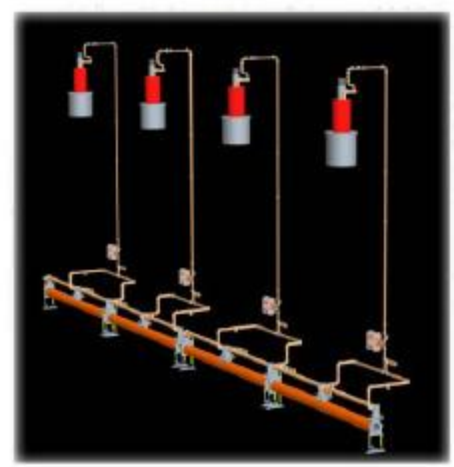
Schematic Layout of the PAL XFEL

courtesy W. Namkung/PAL



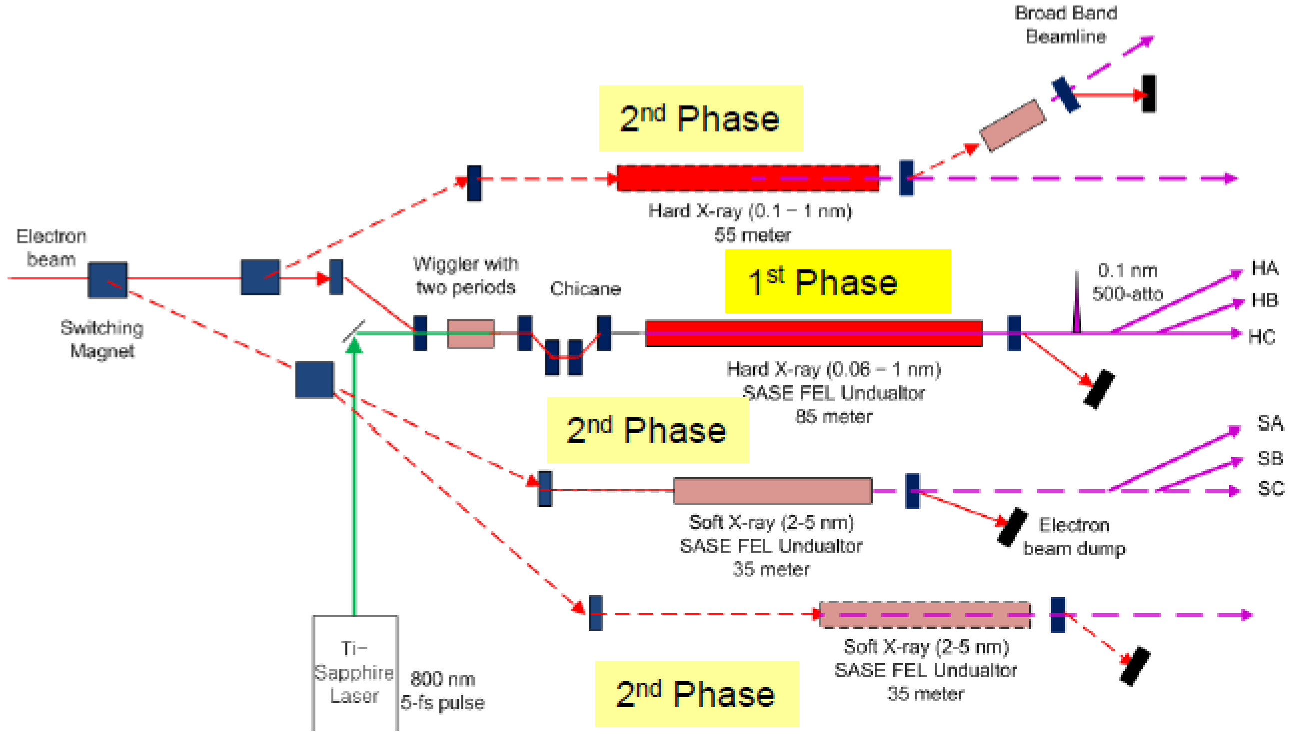
S-Band Photo-cathode RF-gun

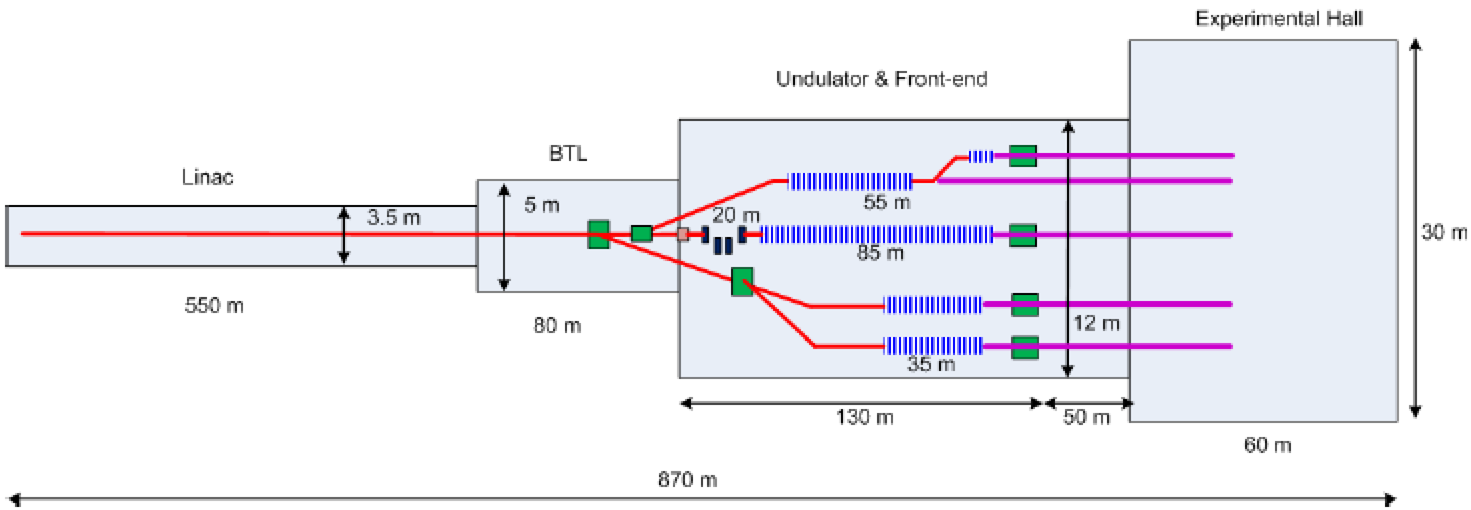
S-Band NC cavity



PAL XFEL

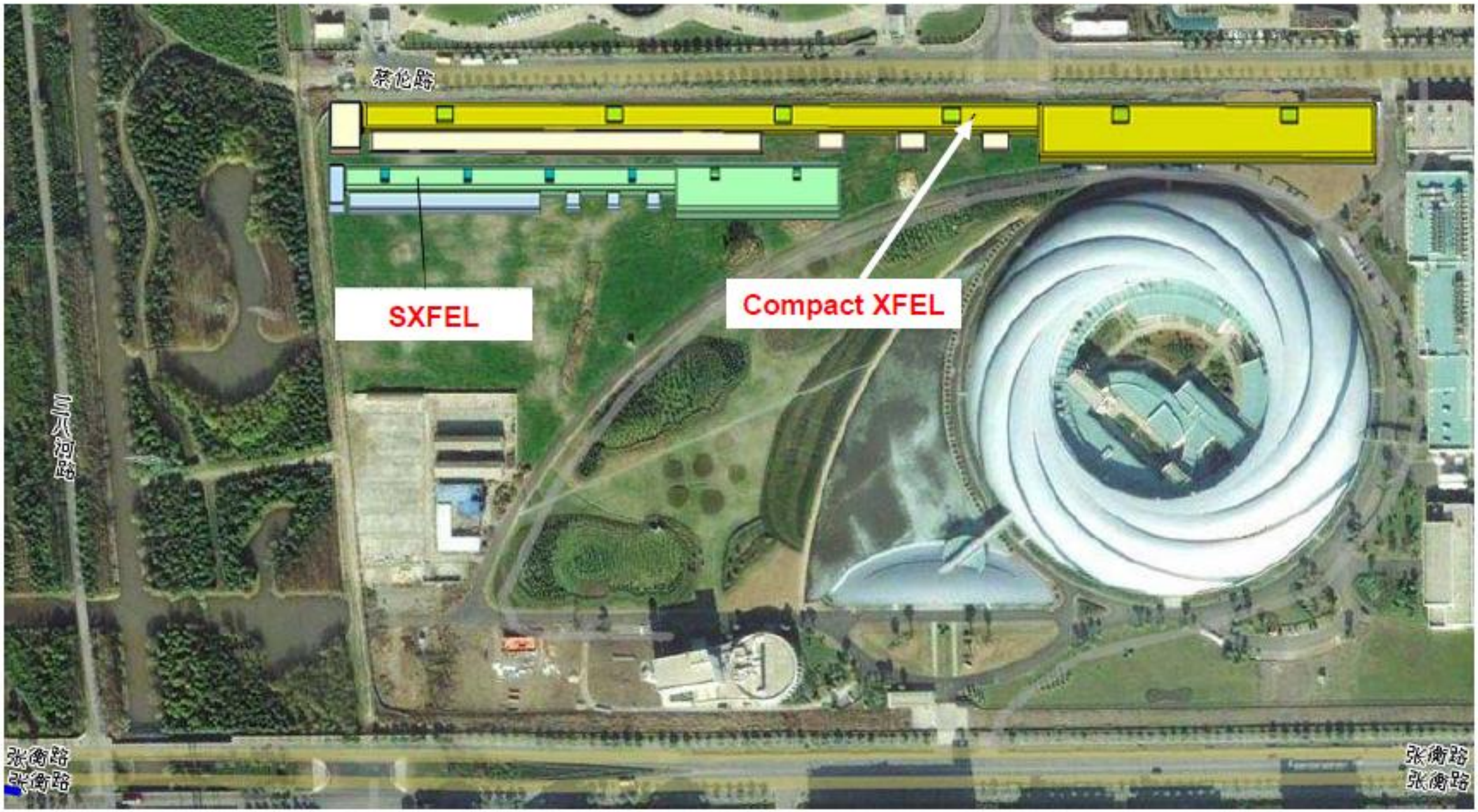
Beamline Plan





Layout of Shanghai XFELs

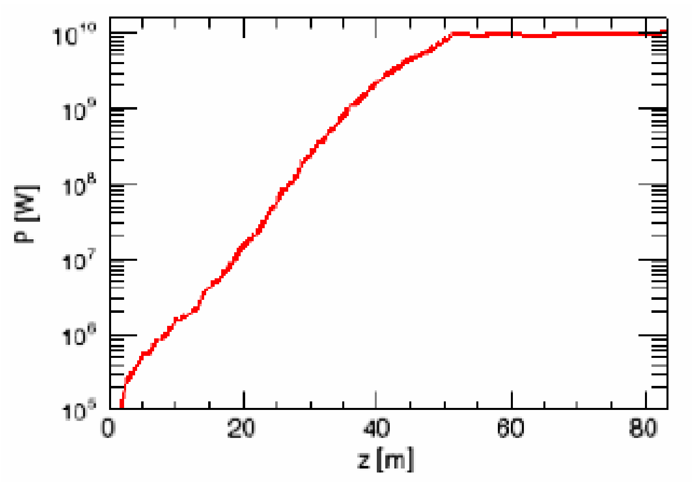
courtesy Zhentang Zhao/SINAP



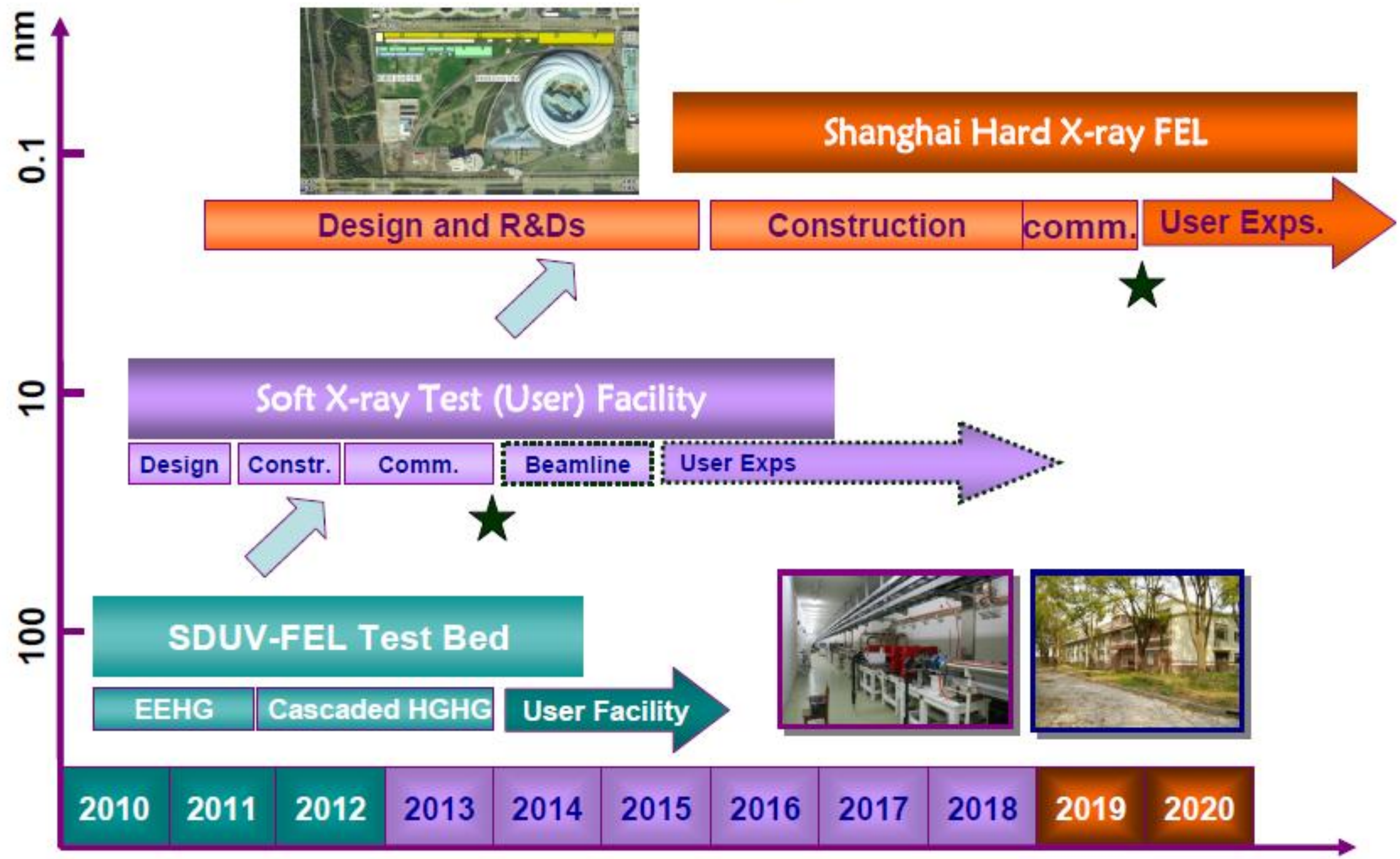
Parameters of Compact XFEL

Electron beam parameters	
Energy/GeV	6.4
Peak current/kA	3
Bunch charge/pC	250
Normalized slice emittance/mm-mrad	0.4
RMS slice energy spread	0.01%
Full bunch length/fs	100
Undulator parameters	
Period/cm	1.6
Segment length/m	4.8
Full undulator length	70
Peak undulator field/T	0.93
K	1.4
Gap/mm	6
Average beta function/m	20

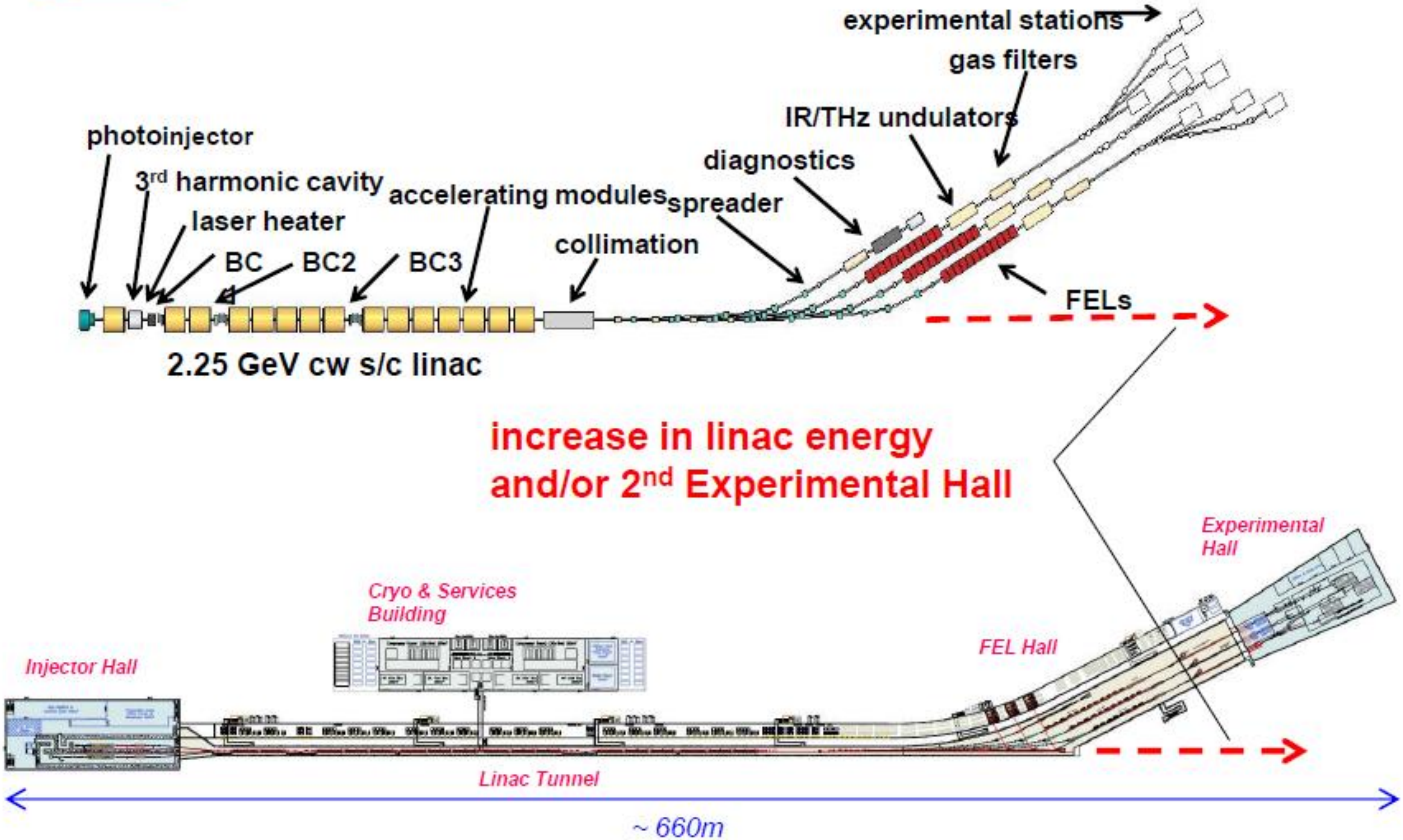
FEL parameters	
Radiation wavelength/nm	0.1
ρ	3.41e-4
Peak coherent power/GW	10
Peak brightness/*	2e33
Pulse repetition rate (Max.)/Hz	60
3D gain length/m	2.156
Saturation length/m	50



Roadmap of Shanghai FELs



NLS Facility Layout



The UK's New Light Source (NLS) Project

Phase I FEL Performance:

	FEL1	FEL2	FEL3
Photon energy	50 - 300 eV	250 - 850 eV	430 - 1000 eV
Seeded/SASE	seeded*	seeded*	seeded*
Pulse length (FWHM)	20 fs	20 fs	20 fs
Peak power	6 - 12 GW	1.7 - 5 GW	1.5 - 4 GW
Polarization	variable	variable	variable
Rep. rate	1 kHz	1 kHz	1 kHz

Future Phases:

→ *Additional FELs and increased photon energy*

→ *Down to ~ 450 as with single spike or slicing*

→ *Up to 1 MHz with 2nd stage gun*

*for reproducibility of pulses, longitudinal coherence and synchronisation with conventional laser sources (60 meV-50 eV)

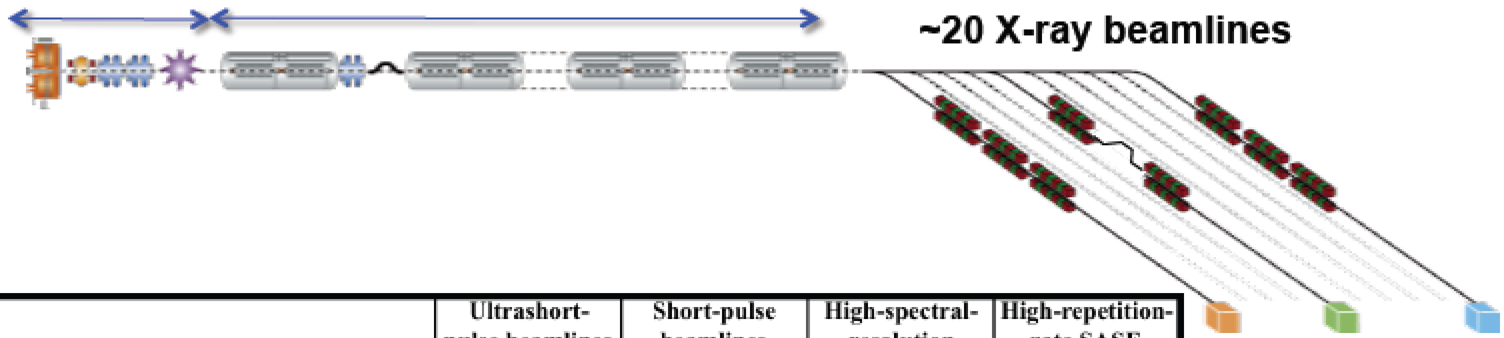
More: http://www.newlightsource.org/

NGLS Facility Performance Goals

High Rep-Rate Electron Injector

~2 GeV CW SC LINAC

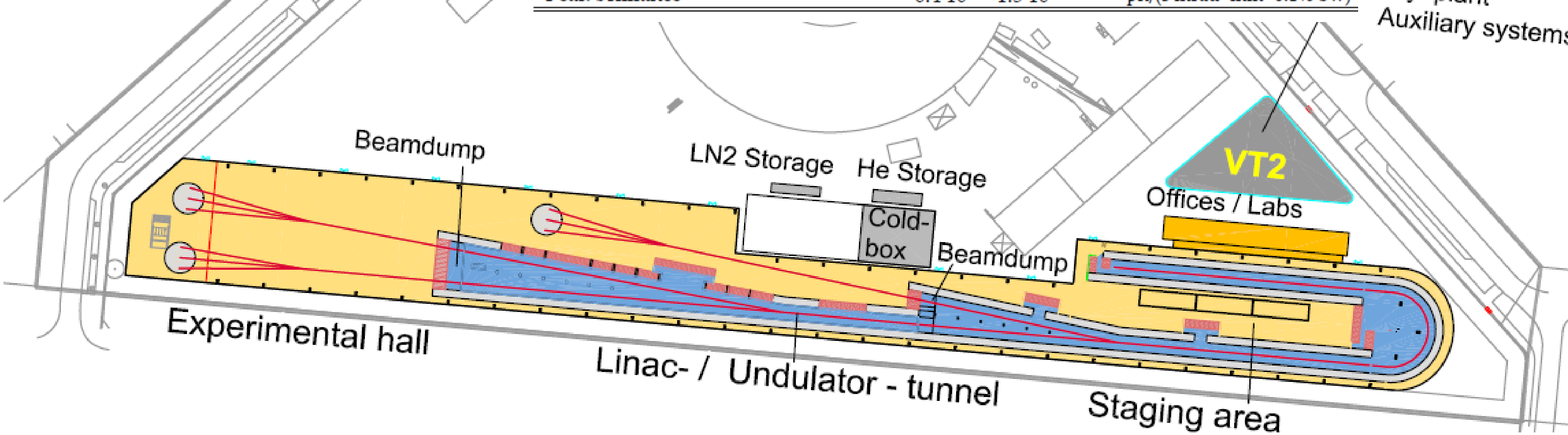
Capability for
10 FEL beamlines
~20 X-ray beamlines



	Ultrashort-pulse beamlines	Short-pulse beamlines	High-spectral-resolution beamlines	High-repetition-rate SASE
Pulse length (fs)	0.25–10	10–100	100–500	1–100
Wavelength range (nm)	1–30	1–100	1–100	1–2 (single beamline)
Repetition rate (kHz)	1–10 (goal 100)	100	100	≥1,000
Peak power (GW)	0.1–1	0.1–5	0.1–5	~1
Photons/pulse (@ 1 nm)	1.5 x 10^{8} (0.25 fs, 0.1 GW)	5 x 10^{11} (100 fs, 1 GW)	2.5 x 10^{12} (500 fs, 1 GW)	5x10^{10} (10 fs, 1 GW)
Bandwidth	transform limit (FTL)	Few x FTL	Few x FTL	Several x FTL
Photons/pulse (@ 3rd harmonic 0.3 nm)	~ 10^{6} (in 250 as)	~ 10^{9} (in 100 fs)	~ 10^{10} (in 500 fs)	~ 10^{8} (in 10 fs)
Polarization	Variable, linear/circular	Variable, linear/circular	Variable, linear/circular	Variable, linear/circular
Maximum peak brightness (@ 1 nm) (ph/s/mm^2/mr^2/0.1%BW)	~ 10^{29} (0.1 GW)	~ 10^{33} (1 GW)	~ 10^{33} (1 GW)	~ 10^{31} (1 GW)
Maximum average brightness (@ 1 nm) (ph/s/mm^2/mr^2/0.1%BW)	~ 10^{18} (10 kHz, 0.1 GW)	~ 10^{25} (1 GW)	~ 10^{26} (1 GW)	~ 10^{24} (1 GW)

BESSY soft X-ray FEL

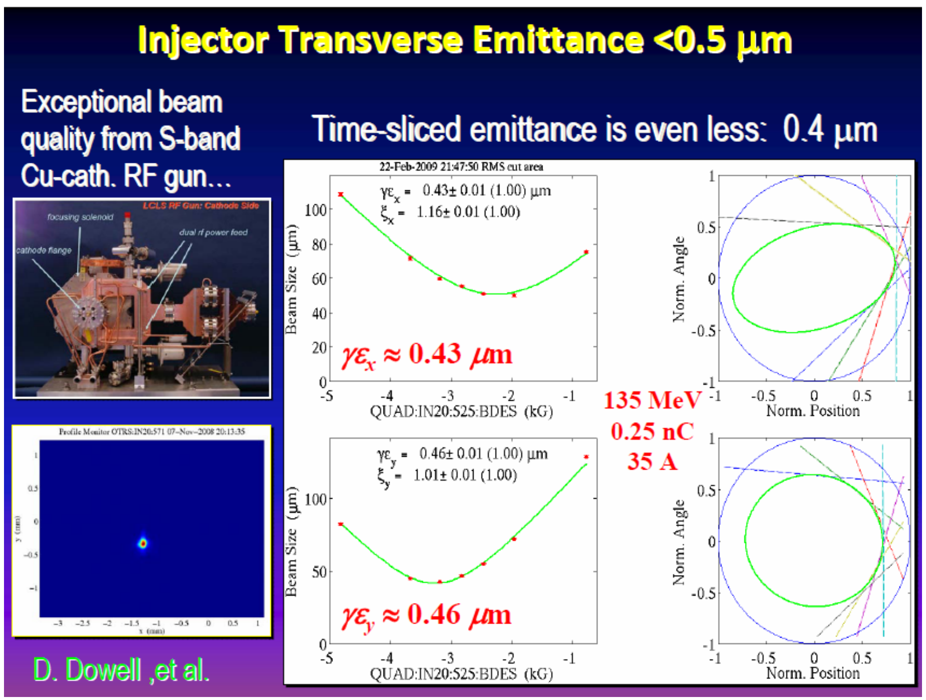
Parameter	Value	Unit
Number of FEL lines	3	
Number of beamlines	9 (15)[#]	
Electron beam energy	2.3	GeV
Electron beam emittance	1.5	π mm mrad
Electron bunch length[†]	290	µm
Electron peak current	1.75	kA
Total beam power	18* (150)	kW
Wavelength range	51 - 1.24	nm
Photon beam peak power	1.5 - 14	GW
Photon beam average power	0.260 - 0.016 * (2.0 - 0.12)	W
Photon beam size (fwhm)	14 - 160	µm
Photon beam divergence (fwhm)	37 - 140	µrad
Photon beam spec. bandwidth	~ 0.001	
Photon beam pulse duration	≤ 20	fs
Min. pulse separation	2	µs
No. of pulses in a train	3* (1)[§]	
Repetition rate	1000* (>25000)	Hz
Number of photons per pulse	$2{\cdot}10^{11}$ - $7{\cdot}10^{13}$	
Average flux of photons	$2{\cdot}10^{14}$ - $7{\cdot}10^{16}$	
Peak brilliance	$6.4{\cdot}10^{29}$ - $1.3{\cdot}10^{31}$	$ph/(s{\cdot}mrad^2{\cdot}mm^2{\cdot}0.1\%\ bw)$



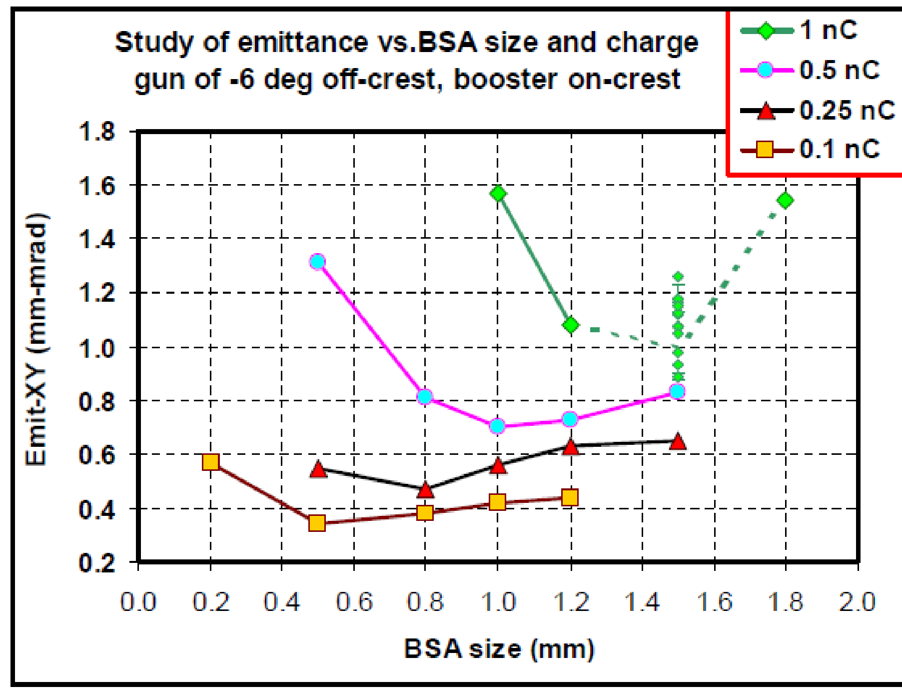
RF gun state of the art

$\varepsilon_N \approx 1\ \mu m\ q_B^{1/2}$ (with q_B in nC)

LCLS/SLAC



PITZ/DESY



Reduction of intrinsic emittance with laser wavelength tuning

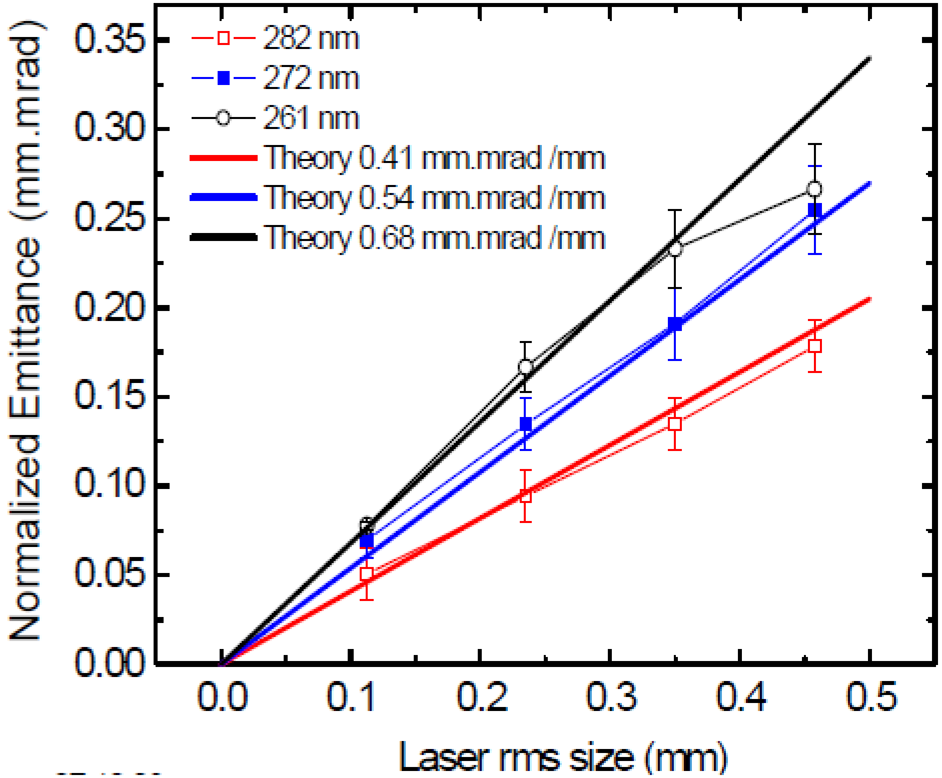
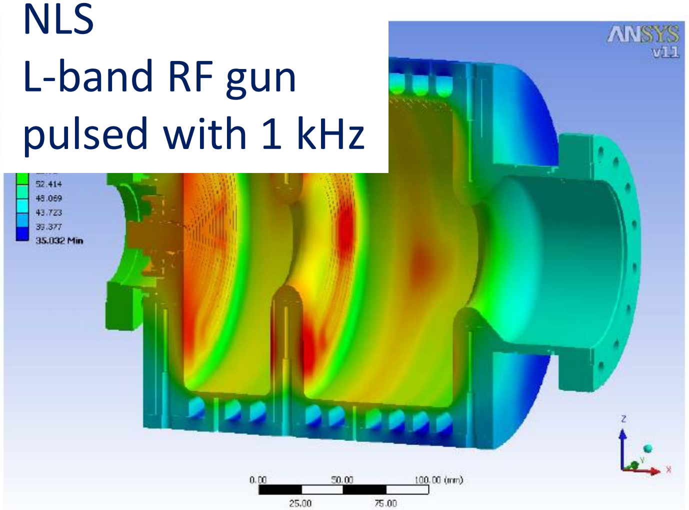


Fig 4. Normalized projected emittance versus laser spot size for 3 different wavelengths on copper. (Q < 1 pC; solenoid scan method, Cu insert). Theory corresponds to Eq. 1 assuming Φ_{Cu}=4.3 eV (thermal effects not included).

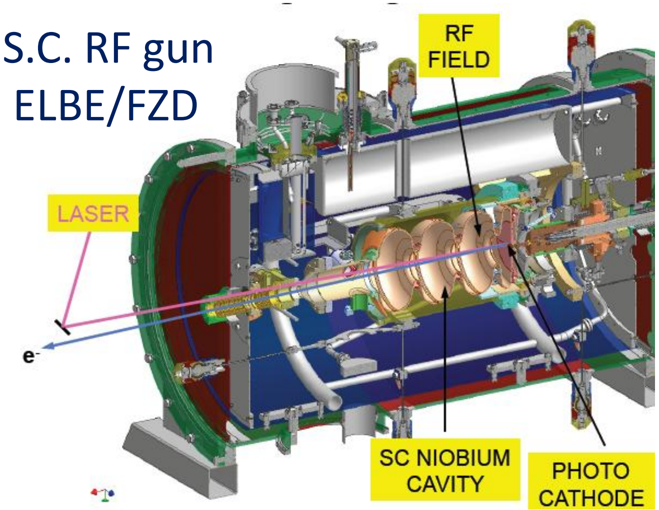
C. Hauri et al., Phys. Rev. Lett. 104, 234802 (2010)

Injector concepts for c.w. FELs

NLS
L-band RF gun
pulsed with 1 kHz

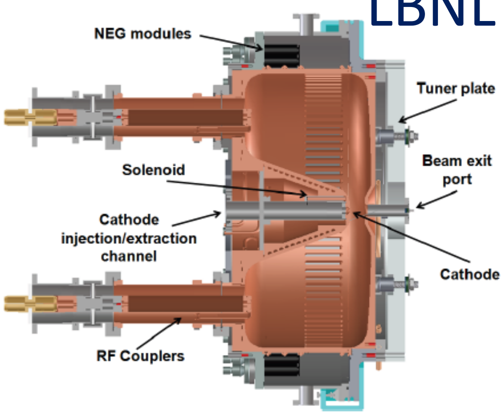


S.C. RF gun
ELBE/FZD



A High Rep-rate VHF Cavity Electron Gun

LBNL



Frequency	187 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19 MV/m
Q_0	30887
Shunt impedance	6.5 MΩ
RF Power	90 kW
Stored energy	2.3 J
Peak surface field	24 MV/m
Peak wall power density	25 W/cm²
Accelerating gap	4 cm
Diameter/Length	70/35 cm
Operating pressure	$< 10^{-11}$ Torr

Table 2: Measurement Results and Designed Parameters of the FZD SRF Gun

IPAC'10

	measured	Designed	
		FEL mode	high charge mode
Max. energy	3 MeV	3 MeV	
peak field	17.6 MV/m	18 MV/m	
laser rep. Rate	1-125 kHz	13 MHz	2-250 kHz
laser pulse length (FWHM)	15 ps	4 ps	15 ps
laser spot size	1~6 mm	5.2 mm	5.2 mm
bunch charge	≤ 300 pC	77 pC	400 pC
average current	18 μA	1 mA	100 μA
peak current	20 A	20 A	26 A
transverse rms emittance	3±1 mm·mrad @ 80 pC	2 mm·mrad	7.5 mm·mrad

J. Corlett July 2010

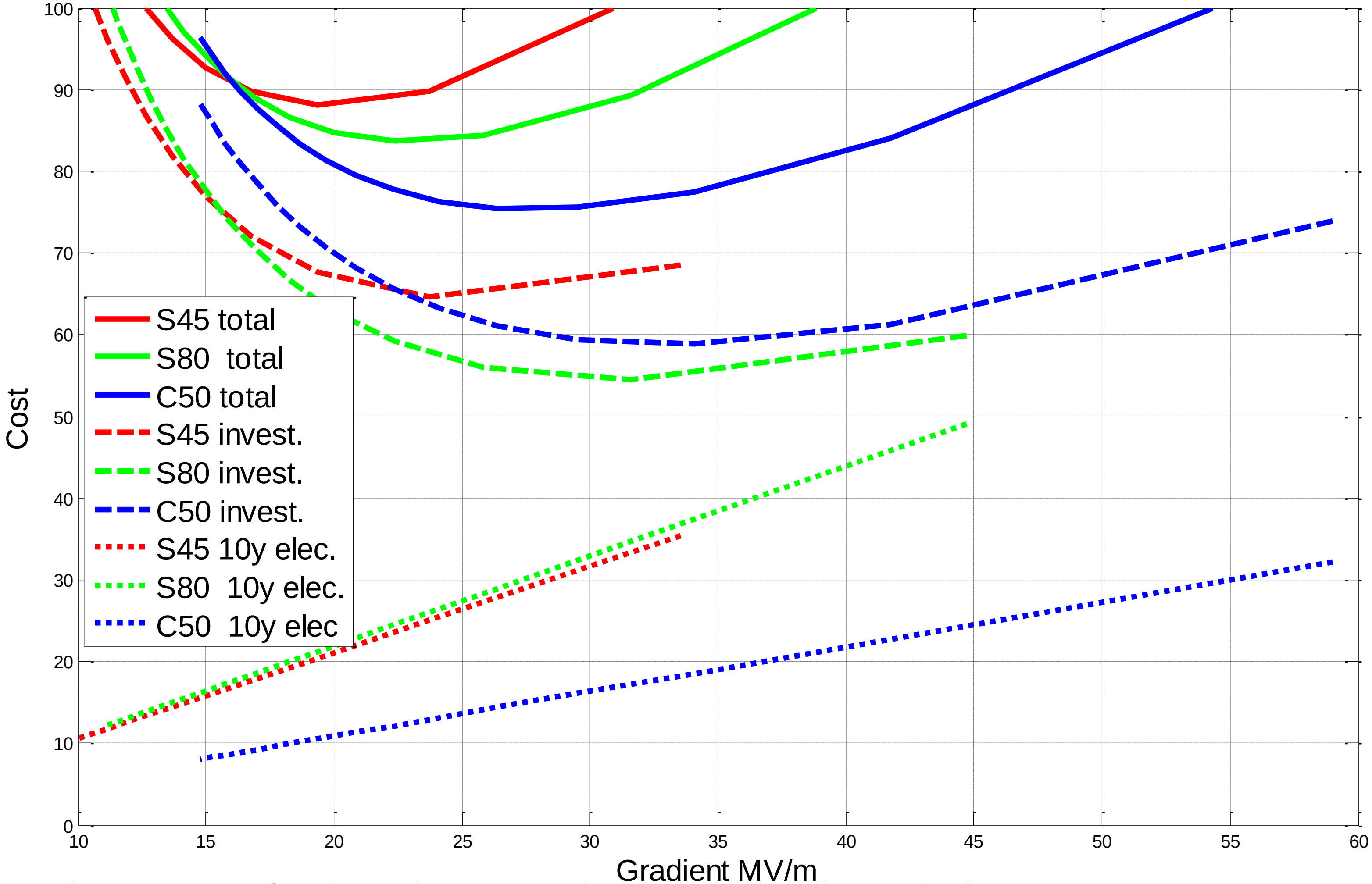
Cost comparison linac technologies
or
Why doesn’t everybody take s.c. & c.w.

Technology	Linac investment cost w/o building	Typical gradient	Electric consumption
Pulsed n.c. with SLED	<10 M€/GeV	20 MV/m (S-band) 30 MV/m (C-band)	0.5 MW/GeV
Pulsed superconducting	≈20 M€/GeV	24 MV/m	0.5 MW/GeV
c.w. superconducting	? 30 M€/GeV ?	15 MV/m	5 MW/GeV

Beware!
This is not exact science !

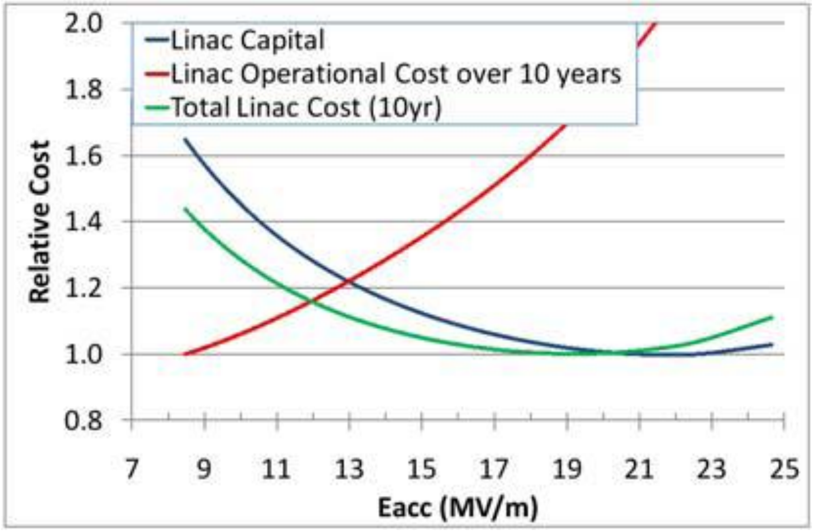
cost optimization pulsed n.c. linac

Cost vs. gradient for S-band with 45 MW klystron,
S-band with 80MW klystron
and C-band with 50 MW klystron

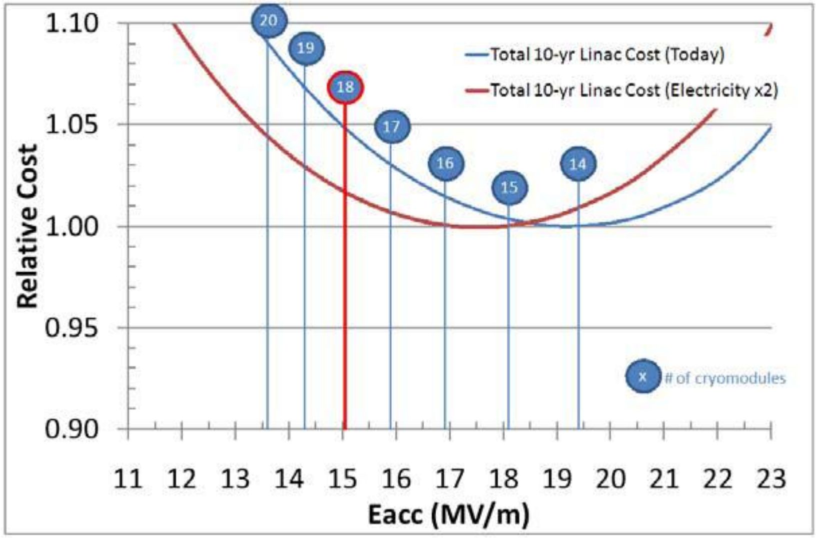


Advantage of C-band is in real-estate needs and electricity consumption

cost optimization s.c. linac in c.w. mode from NLS design report



Relative total capital and
10-year operational linac costs



Effect of increased energy cost
on Eacc optimisation over 10 years

Undulators

SCSS undulators

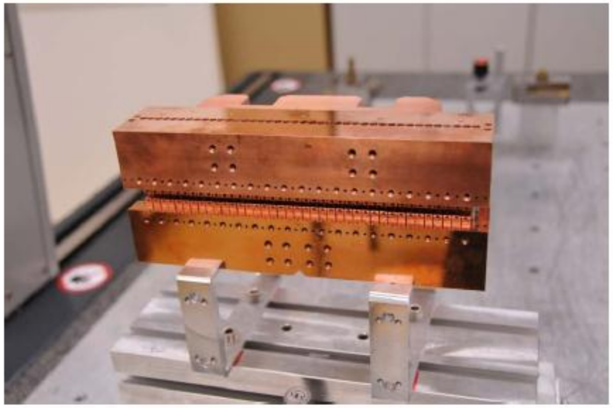
λ_U=18mm

E_{el}= 8 GeV for 1 Å lasing

J. Bahrdt et al., "Cryogenic Design of a PrFeB-Based Undulator," Proc. IPAC (2010)

test sample:
period: 9mm
fixed gap: 2.5mm / 2.0mm
20 periods

HZB (BESSY)
LMU Munich



effective fields:

2.5mm*:	B_r = 1.18T	K = 1.0	E_{el} = 4.2GeV for 1Å
2.0mm*:	1.43T	1.2	4.5GeV

*vacuum gap 0.2mm lower

Thank you for your attention!