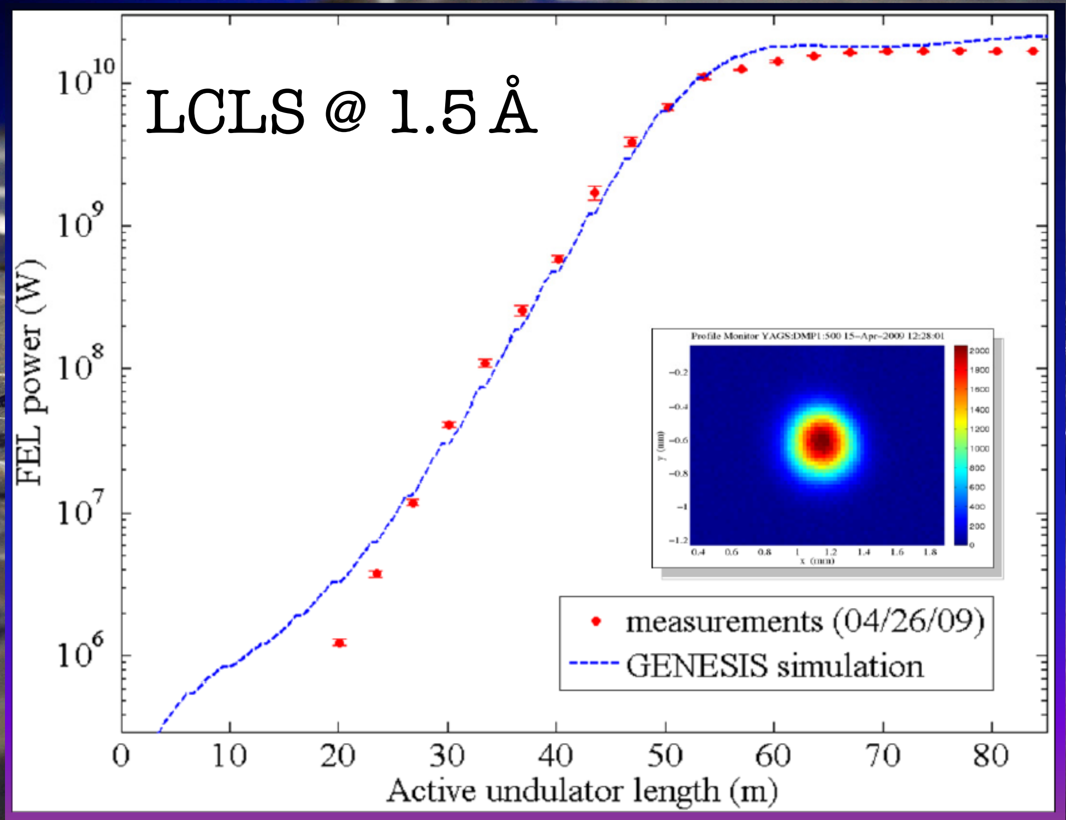
A possible hard X-ray Free Electron Laser with the SuperB 6 GeV electron linac

Massimo.Ferrario@LNF.INFN.IT

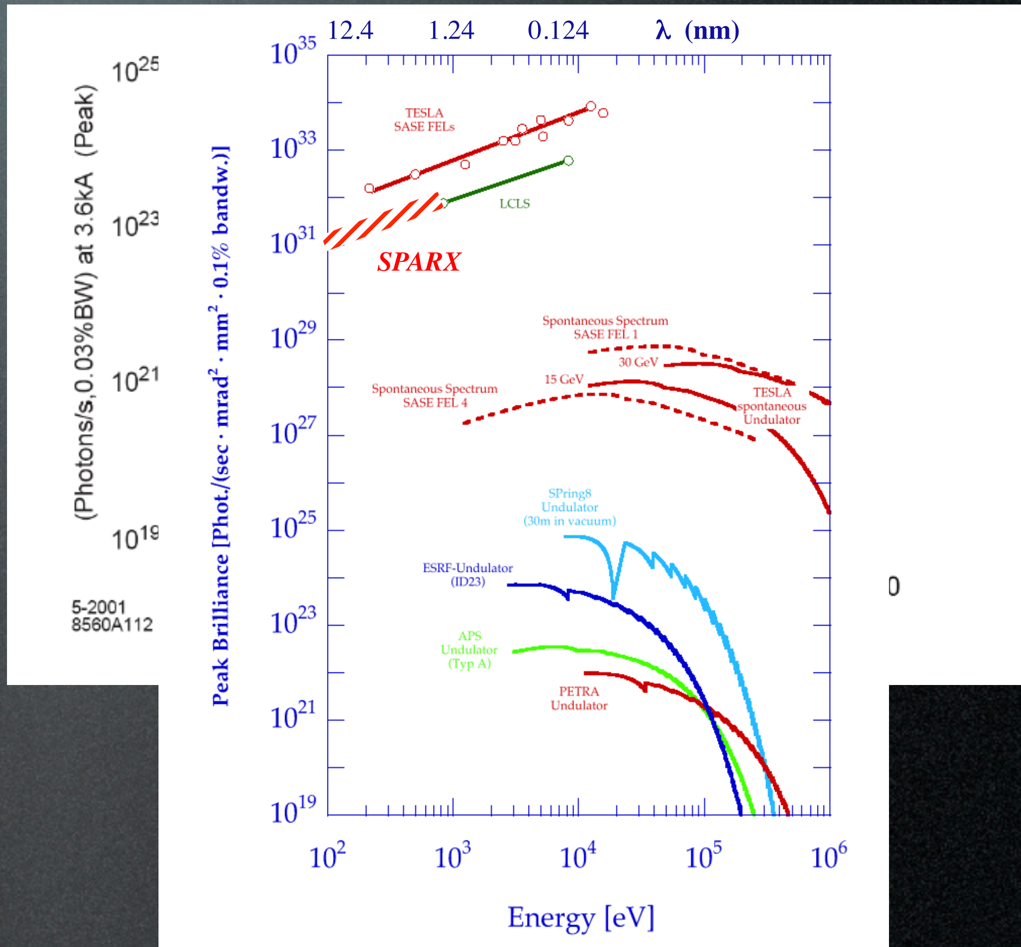


Biodola -4 June 2012

	LCLS	LCLS II	Eu-XFEL	SACLA	FLASH	FLASH II	FERMI	SwissFEL	PAL XFEL	Shanghai XFEL	NGLS	MaRIE
Shortest wavelength	1.5Å	1Å	0.5Å	1 Å	40Å	40 Å	40Å	1 Å	1(0.6) Å	1 Å	10Å	0.3 Å
Undulator type hard X-ray.	Fixed gap	Variable gap	Variable gap	In-vacuum Var. gap	n.a.	n.a.	n.a.	In-vacuum var. gap	Variable gap	Variable gap	n.a.	?
Undulator type soft X-ray.	n.a.	Variable gap	Variable gap	n.a.	Fixed gap	Variable gap	Apple II	Apple II	Apple II	?	Var. gap & Apple	n.a.
Injector	S-band RF gun	S-band RF gun	L-band RF gun	Pulsed Diode	L-band RF gun	L-band RF gun	S-band RF gun	S-band RF gun	S-band RF gun	S-band RF gun	VHF c.w. RF Gun	?
Cathode	Cu	Cu	Cs_2Te	CeB_6 (thermionic)	Cs_2Te	Cs_2Te	Cu	Cu	Cu	Cu	K_2CsSb	?
Main linac technology	n.c. Pulsed	n.c. pulsed	s.c. pulsed	n.c. pulsed	s.c. pulsed	s.c. pulsed	n.c. pulsed	n.c. pulsed	n.c. pulsed	n.c. pulsed	s.c. c.w.	n.c. pulsed
RF frequency	S-band	S-band	L-band	C-band	L-band	L-band	S-band	C-band	S-band	C-band	L-band	S–band
RF Rep. rate	120 Hz	120 Hz	10 Hz	60 Hz	10Hz	10 Hz	10-50 Hz	100 Hz	120Hz	60 Hz	n.a.	60 Hz
FEL pulses/RF pulse	1	1	2700	1	2700	2700	1	2	1	1	1 MHz c.w.	100
max. bunch charge	0.25 nC	0.25nC	1 nC	0.2nC	1nC	1 nC	0.5 nC	0.2nC	0.2 nC	0.2 nC	0.3nC	0.1 nC
max. electron energy	13.6 GeV	14 GeV	17.5 GeV	8 GeV	1.2 GeV	1.2GeV	1.5 GeV	5.8GeV	10 GeV	6.4GeV	2.4GeV	12GeV
No. RF stations	81	81	29	69	5	5	15	34	49	?	?	?
Approx. facility length	1.7km	1.7km	3.4 km	0.8km	0.32 km	0.32km	0.5 km	0.7km	1.1 km	0.6 km	?	1.0 km
Start operation	2009	2017	2015	2011	2005	2013	2010	2016	2015	2019	2023	?

Courtesy H. Braun

A Free Electron Laser is a device that converts a fraction of the electron kinetic energy into coherent radiation via a collective instability in a long undulator



$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\vartheta^2\right)$$

Radiation properties:
GW power - Monocromaticity - Tunability from IR to X– Short pulses

SYNCHROTRON LIGHT OPTIONS AT SUPER-B*

W. Wittmer, Y. Nosochkov, A. Novokhatski, J. Seeman, M.K. Sullivan
SLAC National Accelerator Laboratory, Menlo Park, CA, USA

M.E. Biagini, P. Raimondi
INFN/LNF, Frascati (Roma), Italy

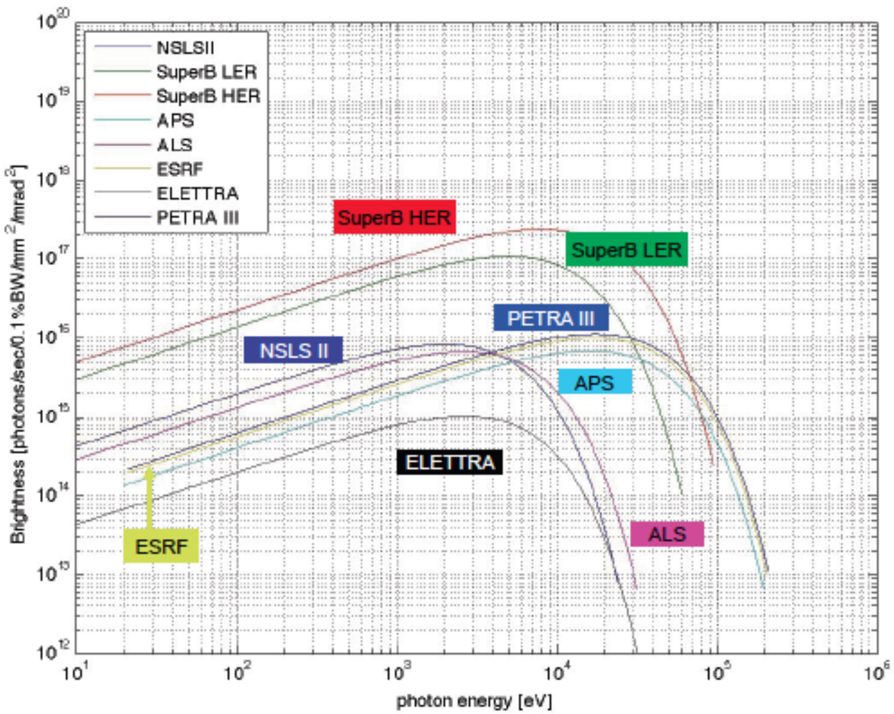


Figure 1: Brightness generated from bend magnets as a function of photon energy.

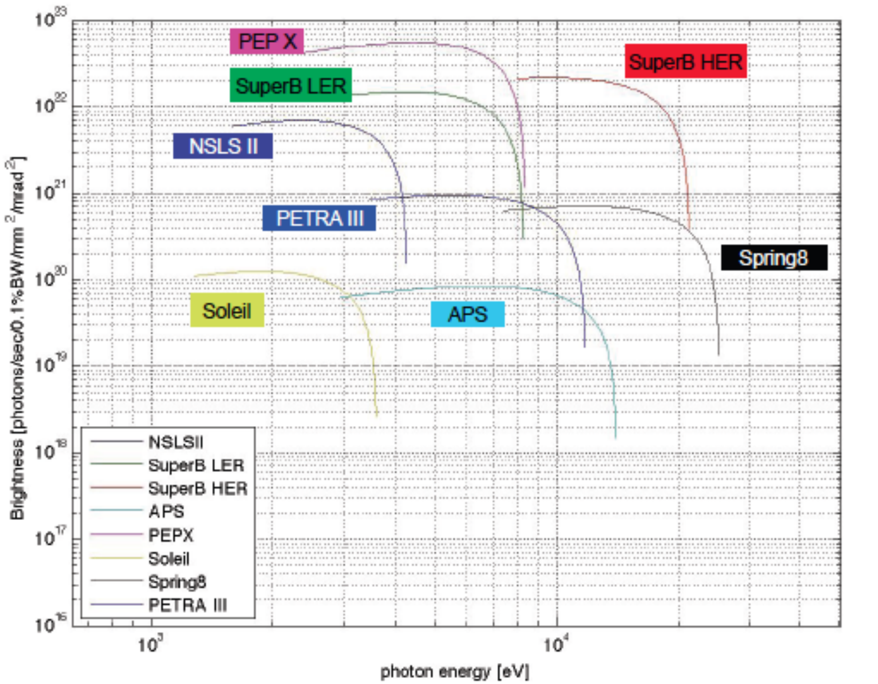
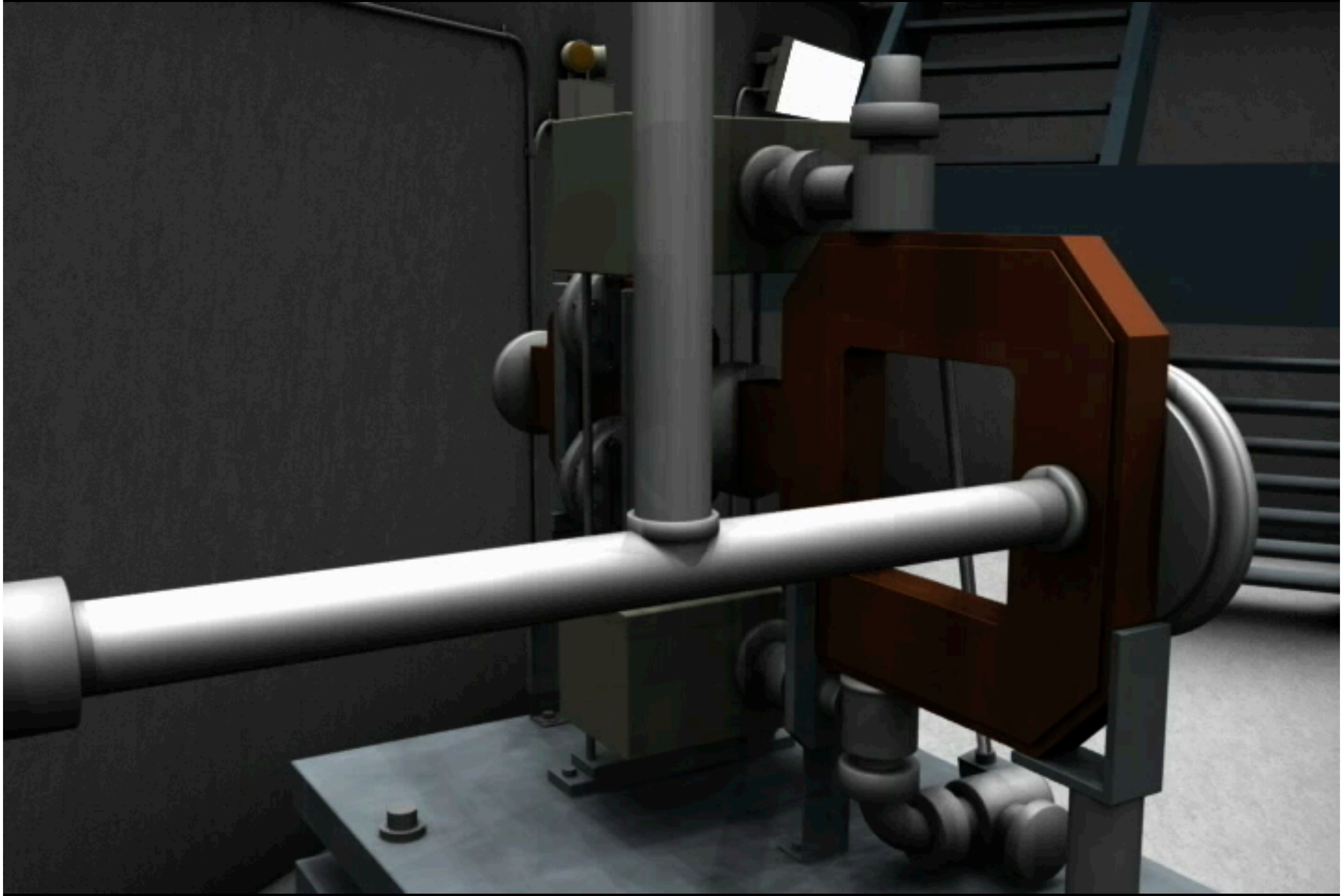


Figure 2: Brightness as a function of photon energy for different reference undulator radiation calculated for benchmarking different facilities.

Electron source and acceleration

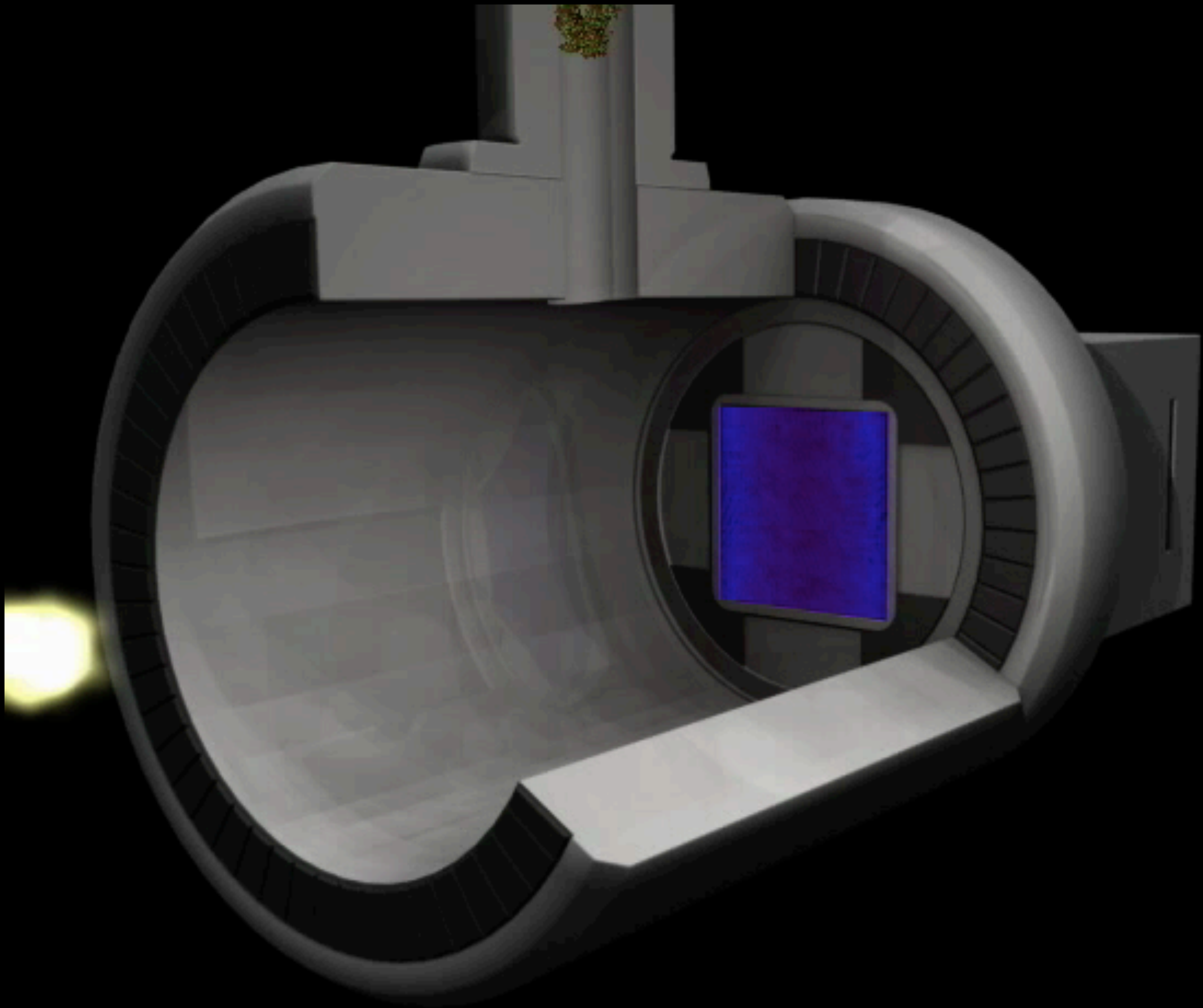


Magnetic bunch compressor (< 1 ps)

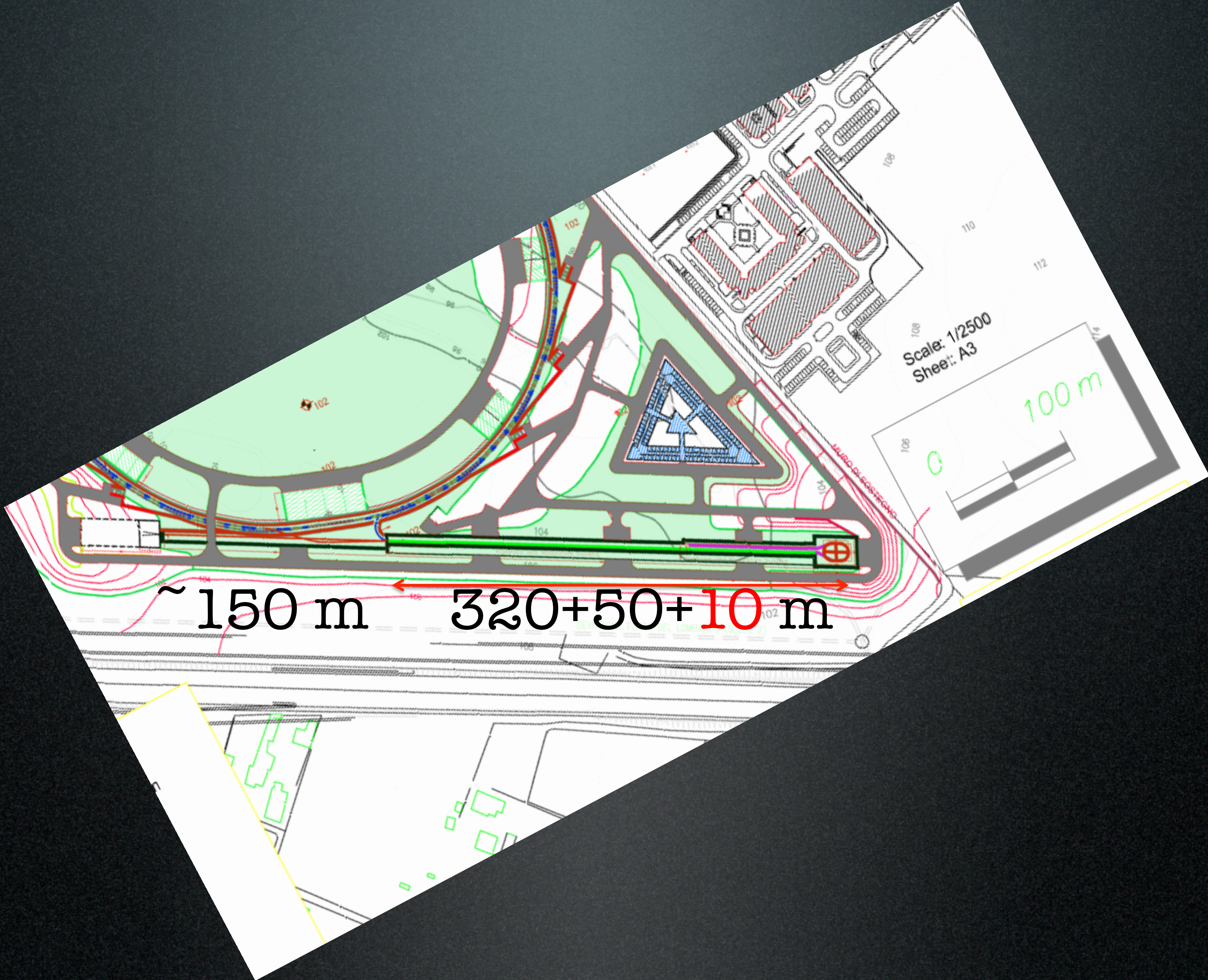
Long undulators chain

Beam separation and THz source

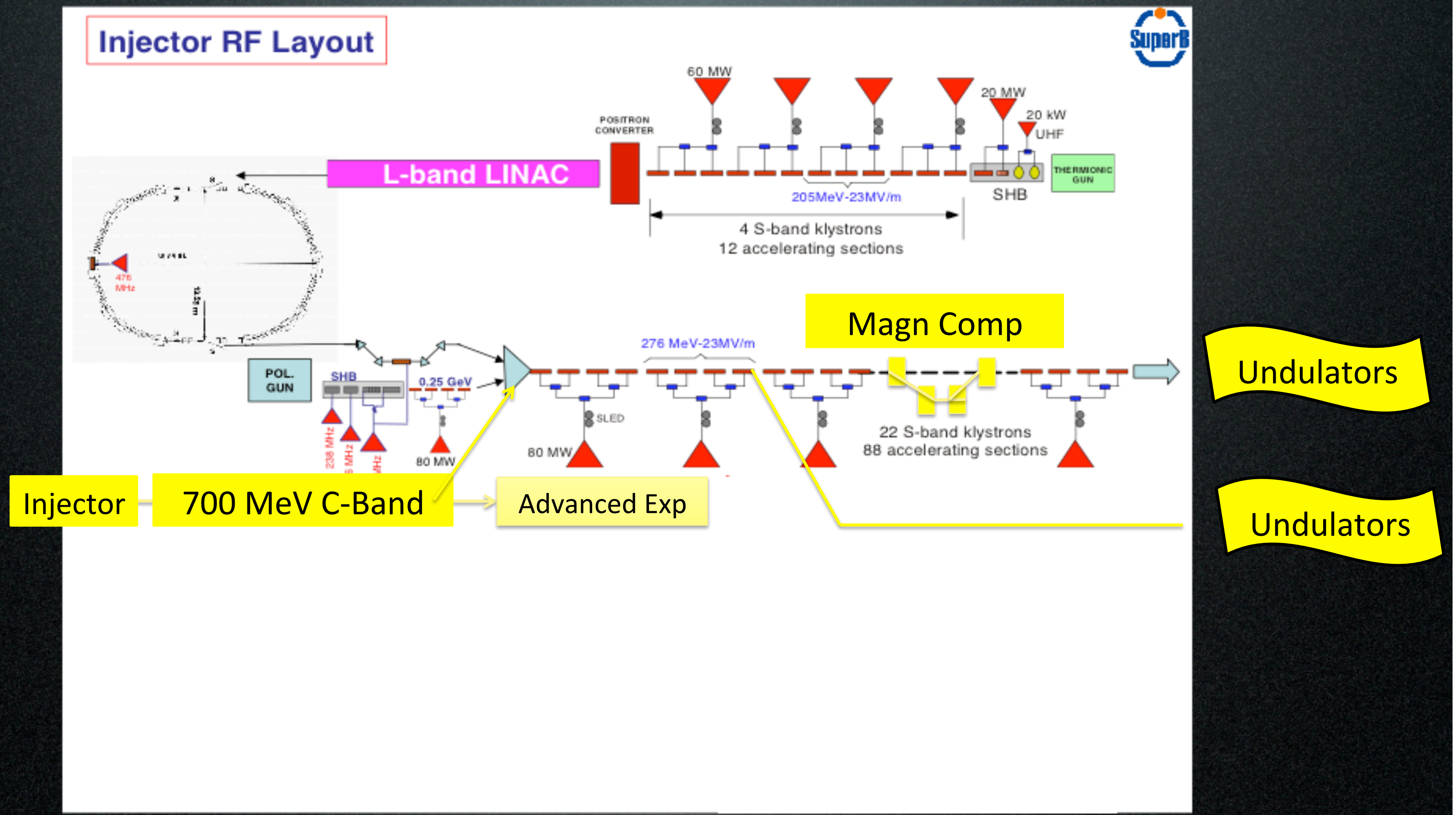
Experimental hall (Single Protein Imaging)



http://lcls.slac.stanford.edu/AnimationViewLCLS.aspx

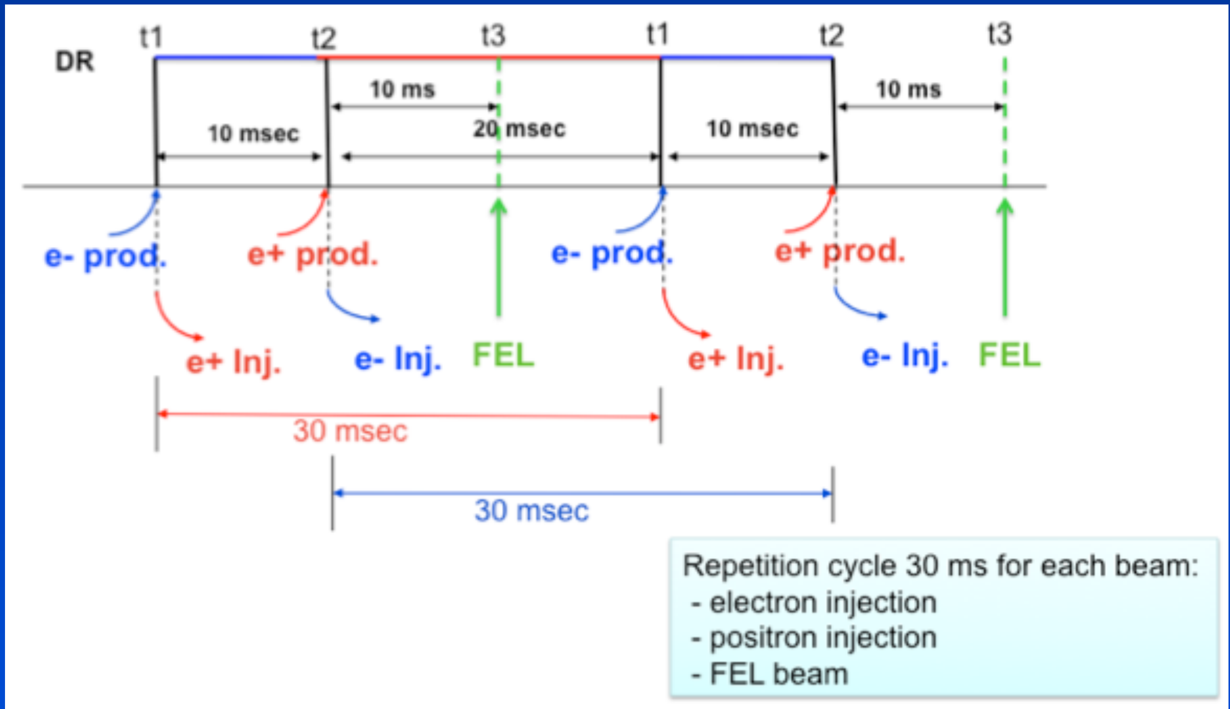

~150 m
320+50+10 m
Scale: 1/2500
Sheet: A3
0
100 m

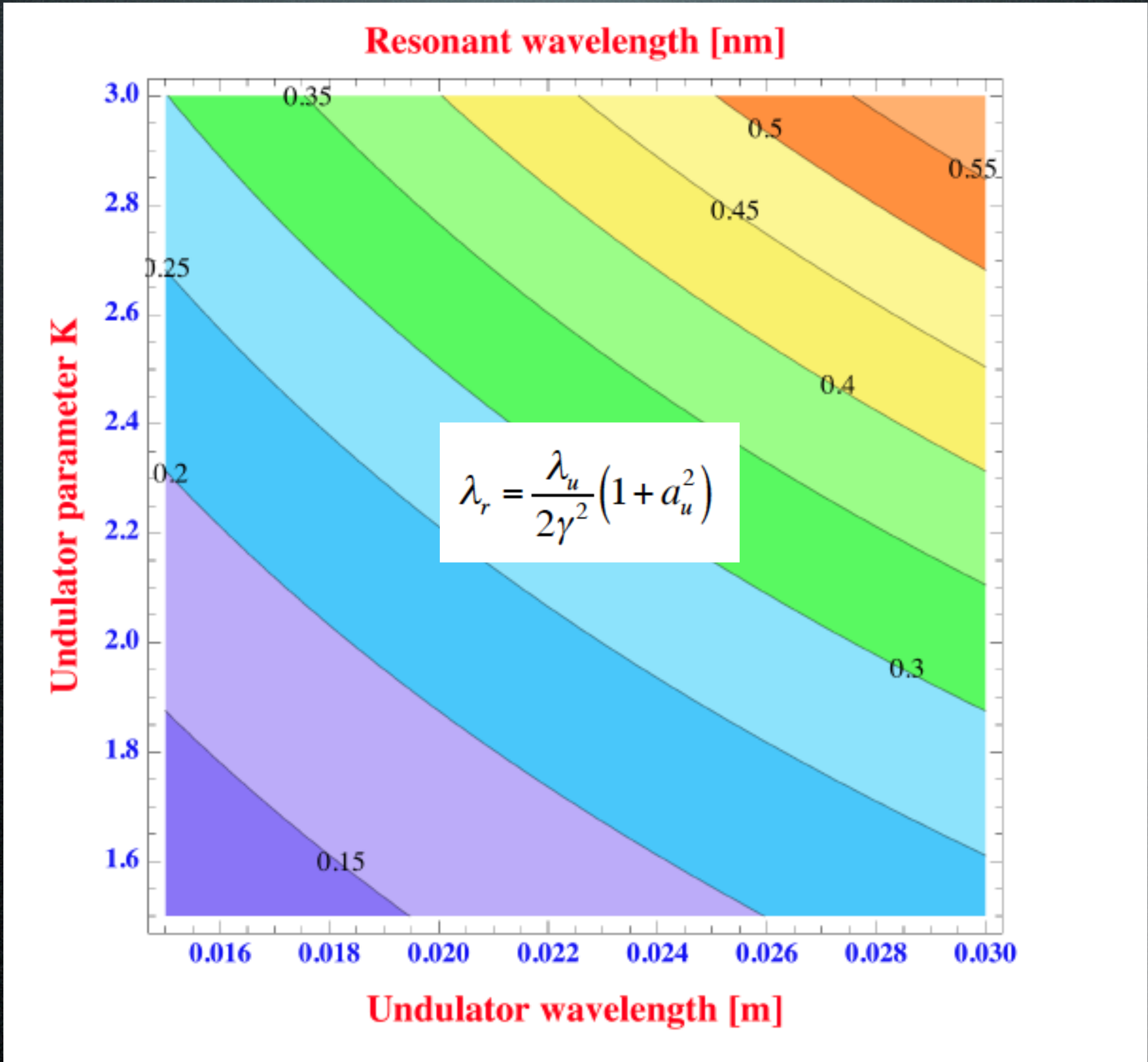
A hard X-ray FEL with the SuperB linac



Shared time between FEL and SuperB injection

If the linac repetition frequency is 100 Hz it is possible to accelerate in the linac a pulse for the XFEL during the store time of the positrons in the DR without affecting the injection rate for SuperB.
As it is shown in the sketch **below it is possible to provide a repetition cycle of 30 ms for each beam: positron injection, electron injection and a dedicated linac pulse for XFEL.** The time duration available for the XFEL pulse, due to the SLED system used for the linac cavities, is of the order of 100 ns.




Resonant wavelength [nm]
Undulator parameter K
Undulator wavelength [m]
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
0.016
0.018
0.020
0.022
0.024
0.026
0.028
0.030
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + a_u^2\right)$

Saldin et al. SASE FEL scaling laws

$$\lambda_r^{MIN} \propto \sigma_\delta \sqrt{\frac{\left(1+K^2/2\right)}{\gamma B_n K^2}}$$

minimum radiation wavelength

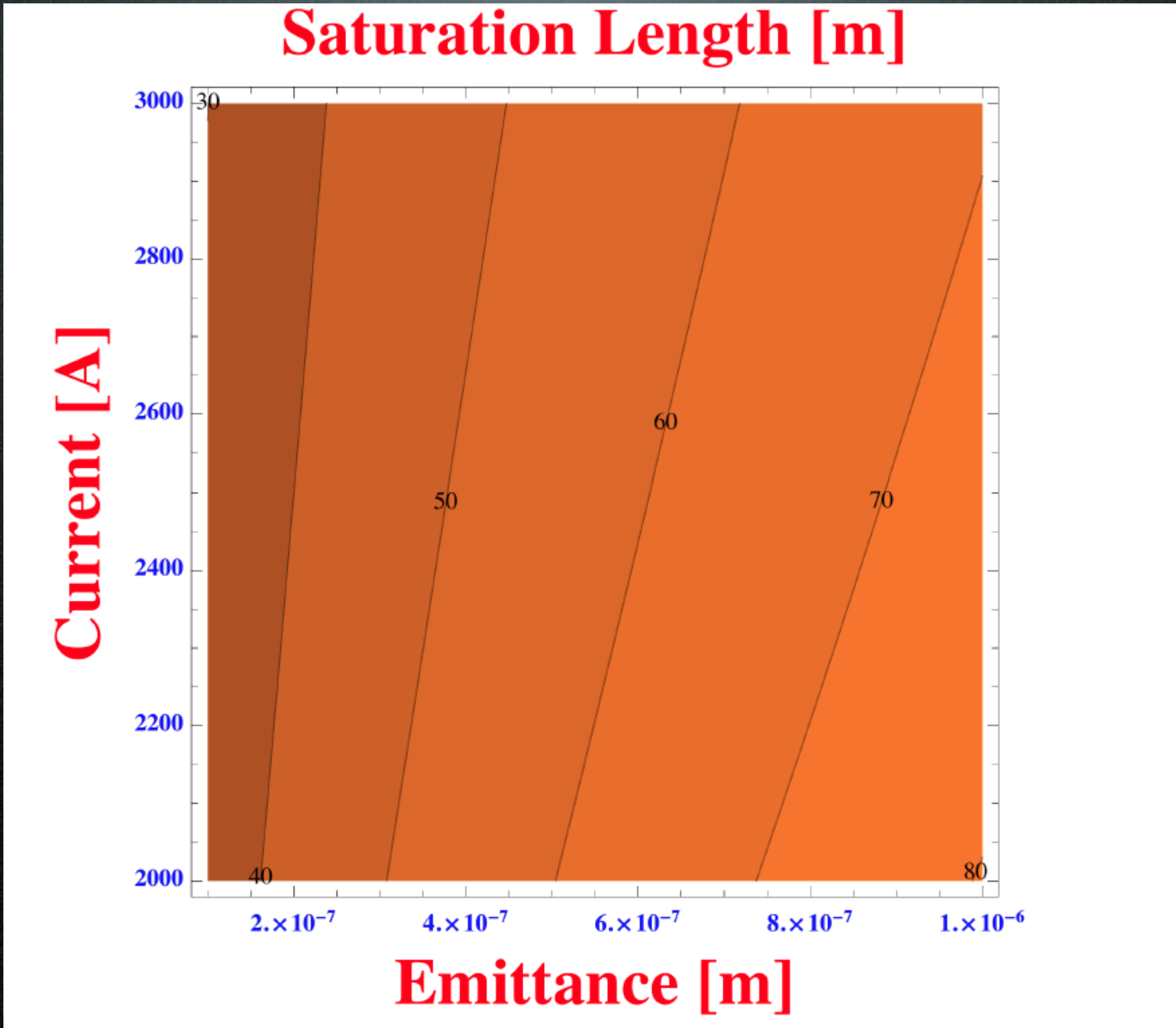
energy spread

undulator parameter

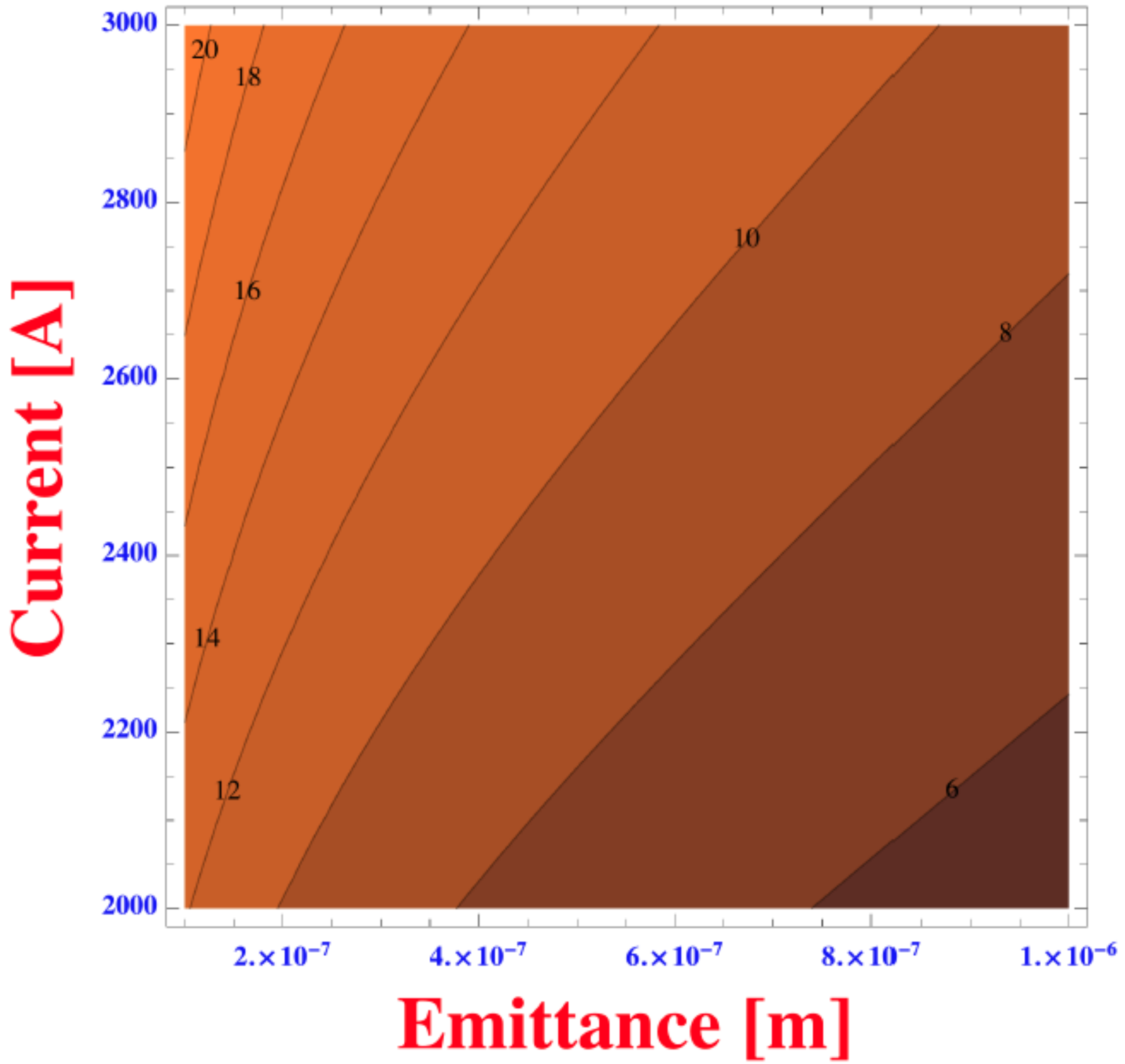
$$B_n = \frac{2I}{\varepsilon_n^2}$$

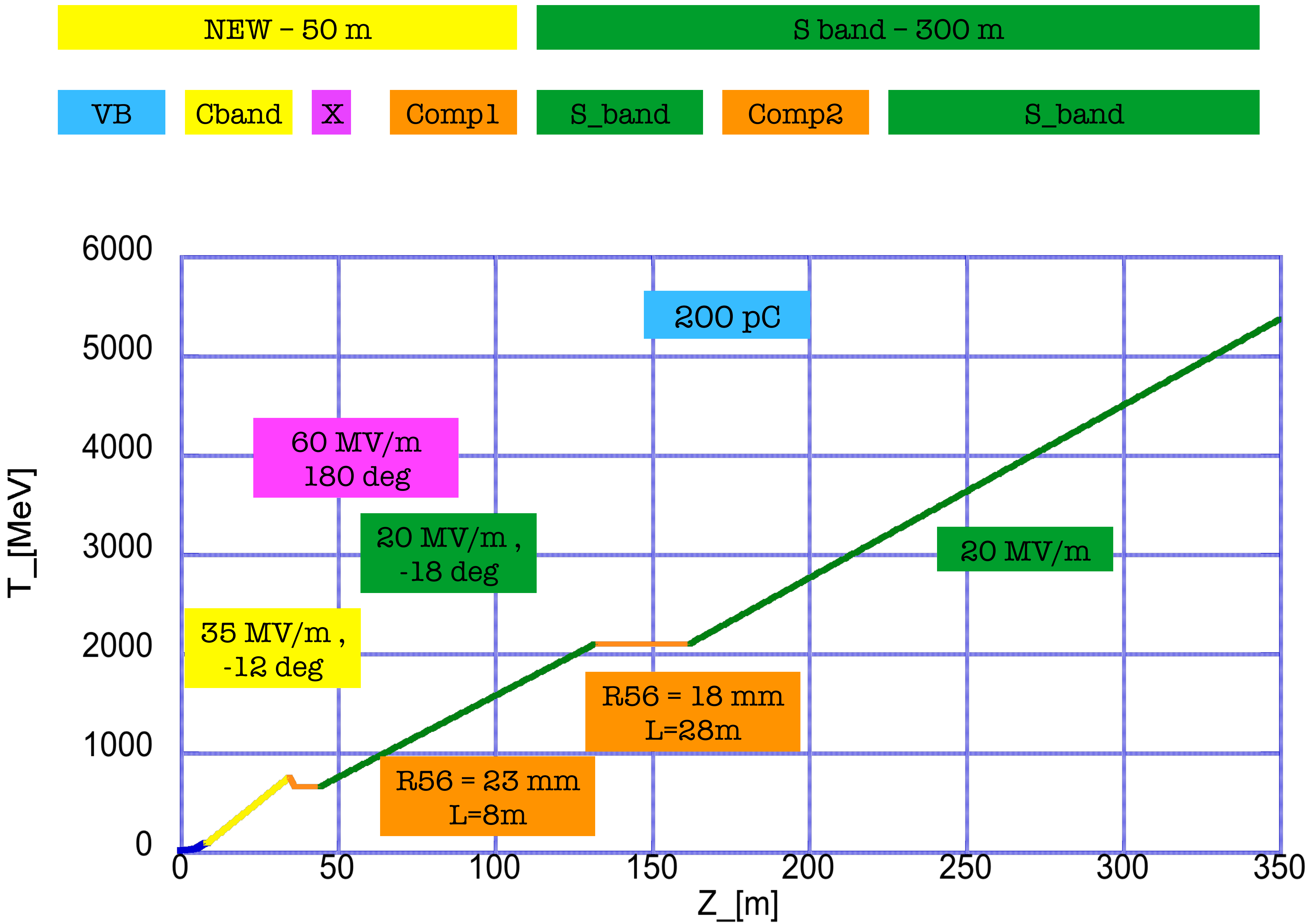
$$L_g \propto \frac{\gamma^{3/2}}{K\sqrt{B_n\left(1+K^2/2\right)}}$$

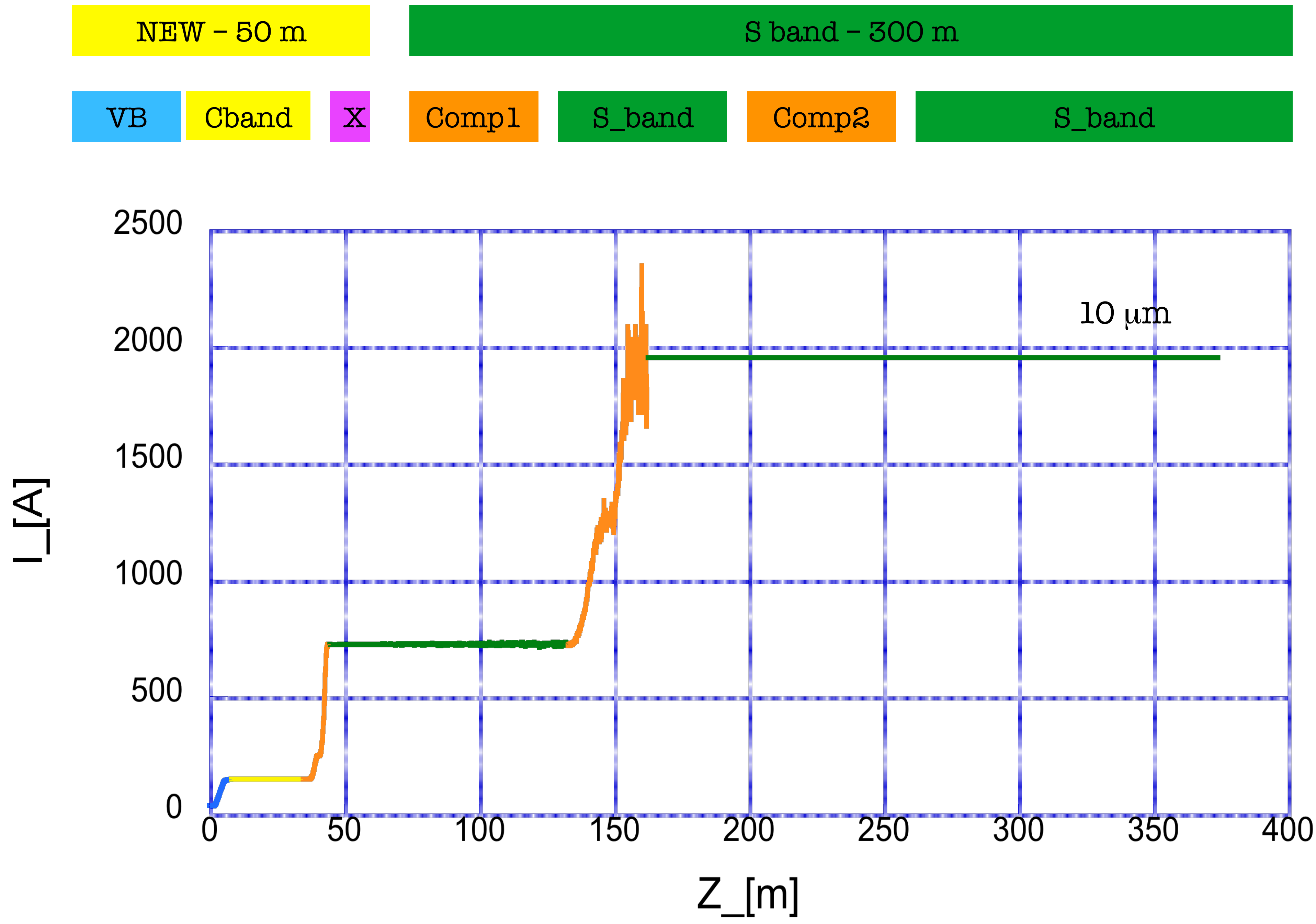
gain length

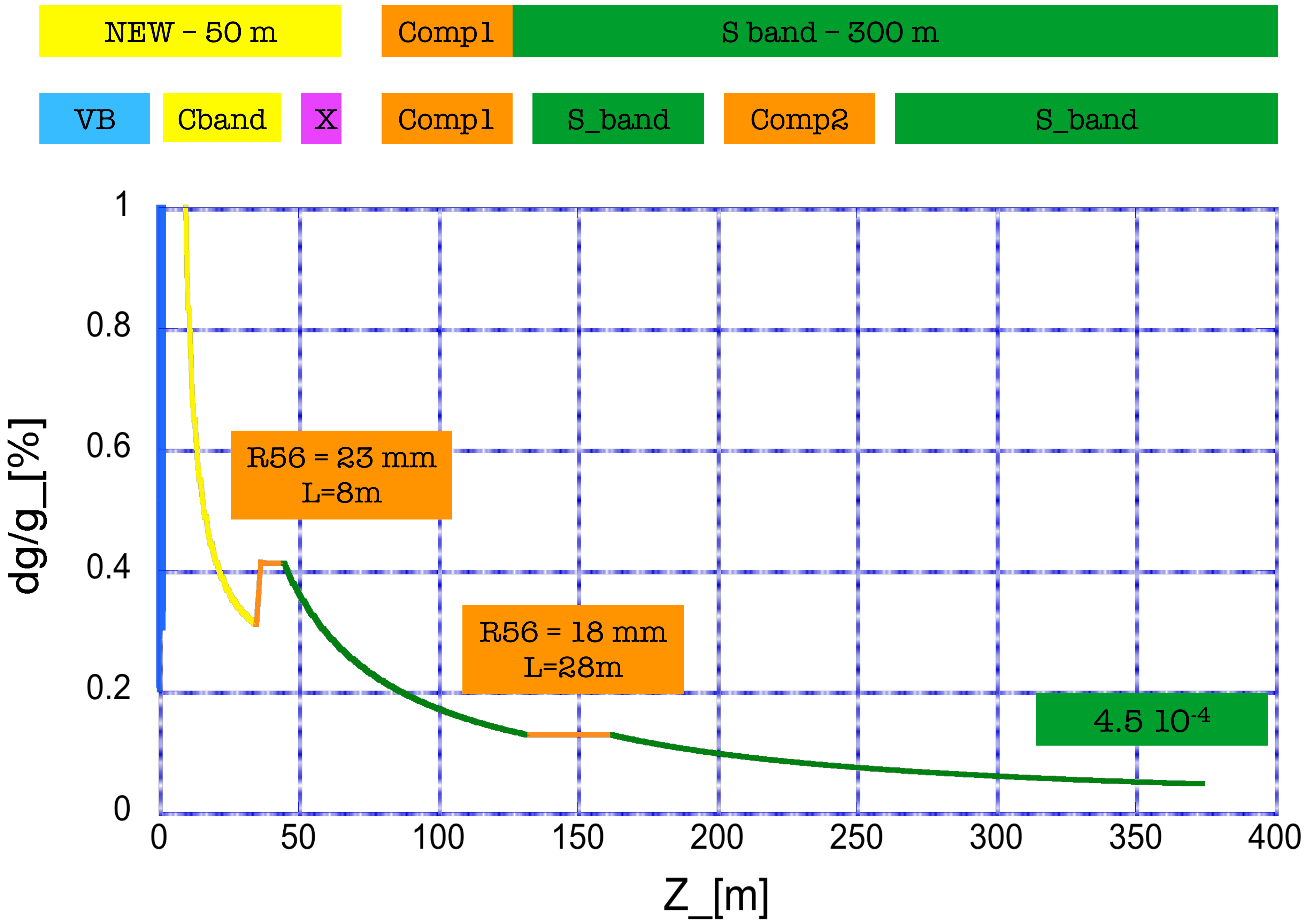

Saturation Length [m]
Current [A]
3000
2800
2600
2400
2200
2000
30
40
50
60
70
80
2.×10⁻⁷
4.×10⁻⁷
6.×10⁻⁷
8.×10⁻⁷
1.×10⁻⁶
Emittance [m]

Saturation Power [GW]

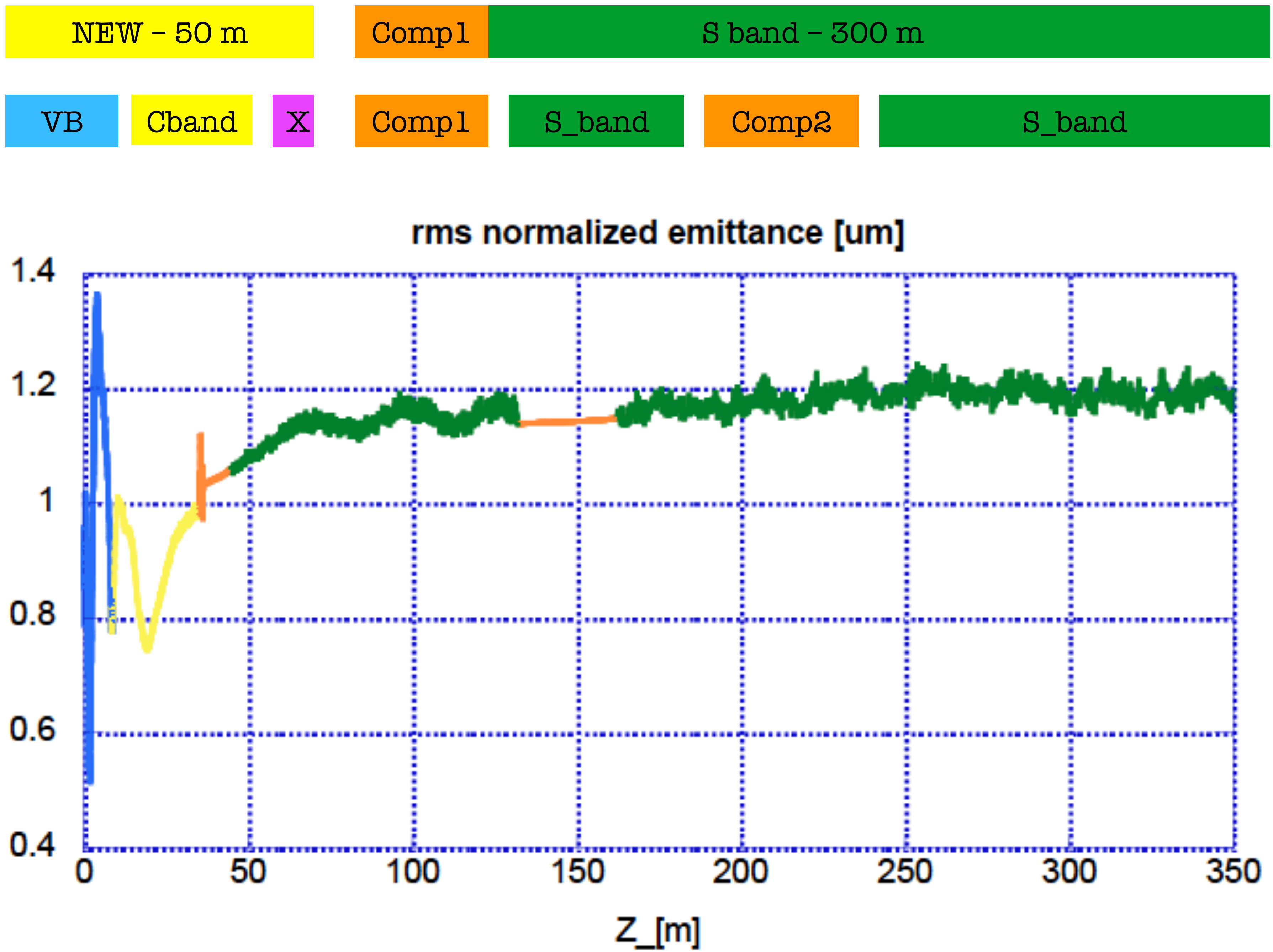



NEW - 50 m
S band - 300 m
VB
Cband
X
Comp1
S_band
Comp2
S_band
200 pC
60 MV/m
180 deg
20 MV/m ,
-18 deg
20 MV/m
35 MV/m ,
-12 deg
R56 = 18 mm
L=28m
R56 = 23 mm
L=8m
T_[MeV]
Z_[m]
0
1000
2000
3000
4000
5000
6000
0
50
100
150
200
250
300
350


NEW - 50 m
S band - 300 m
VB
Cband
X
Comp1
S_band
Comp2
S_band
10 μm
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
350
400
I_[A]
Z_[m]



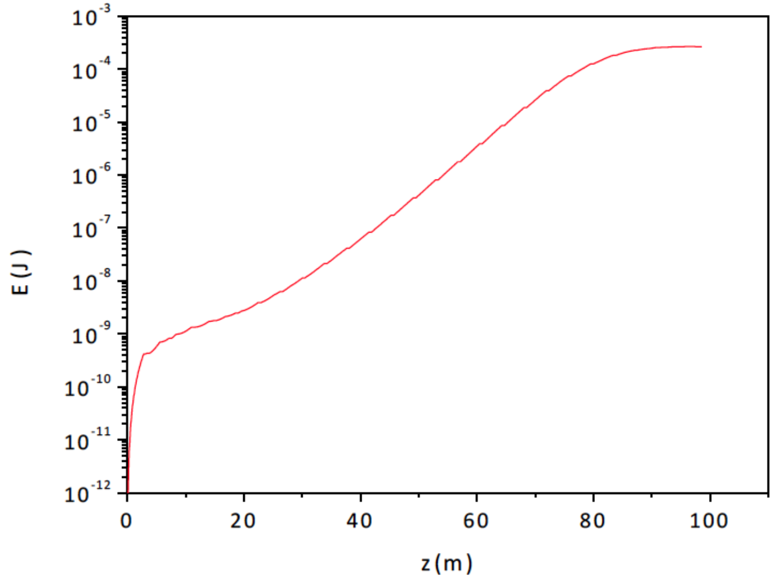
NEW - 50 m
Comp1
S band - 300 m
VB
Cband
X
Comp1
S_band
Comp2
S_band
R56 = 23 mm
L=8m
R56 = 18 mm
L=28m
4.5 10-4
dg/g_[%]
Z_[m]
0
0.2
0.4
0.6
0.8
1
0
50
100
150
200
250
300
350
400



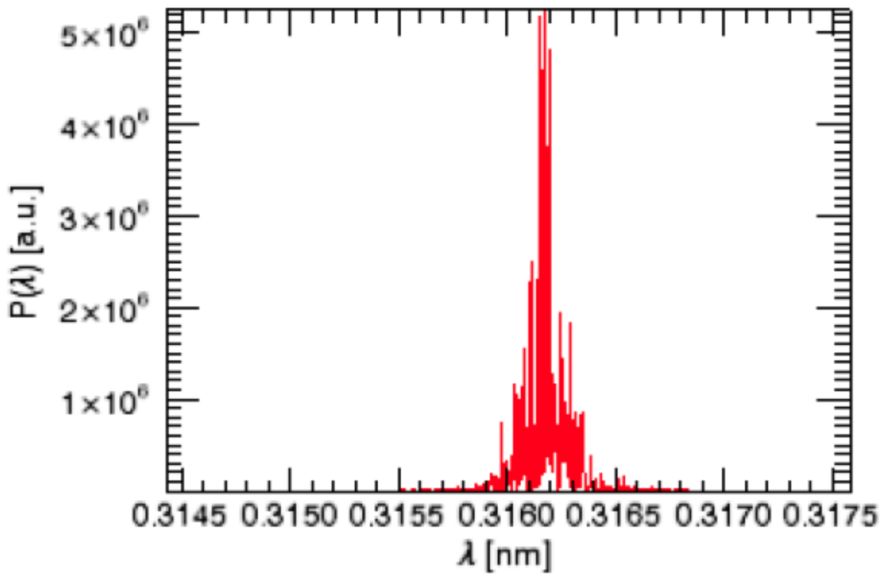
NEW - 50 m
Comp1
S band - 300 m
VB
Cband
X
Comp1
S_band
Comp2
S_band
rms normalized emittance [um]
1.4
1.2
1
0.8
0.6
0.4
0
50
100
150
200
250
300
350
Z_[m]

Preliminary GENESIS simulations

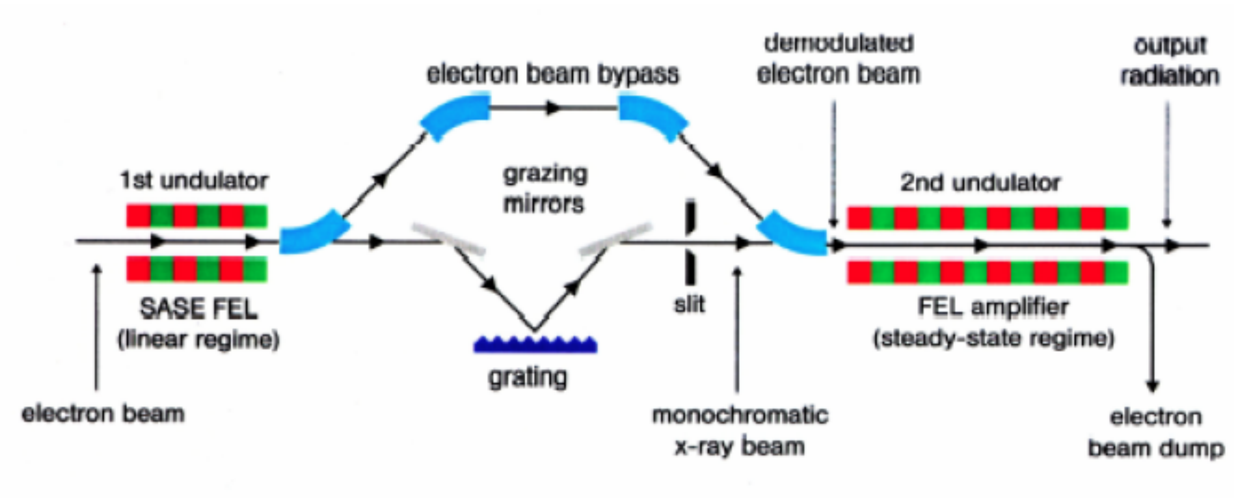
	SPARC-like	Short period
Period λ_u (cm)	2.8	1.8
a_{w0} (=$K/\sqrt{2}$)	1.51	1.2
Section length (m)	3.36	2.16
Gap length (m)	0.42	0.27
λ_r(Å)	3.16	1.525



	SPARC-like	Short period
λ_r(Å)	3.16	1.525
L_s(m)	~90	~78
E_s(μJ)	270	114
bw(%)	0.04	0.023
L_g(m)	~4.8	~4.4

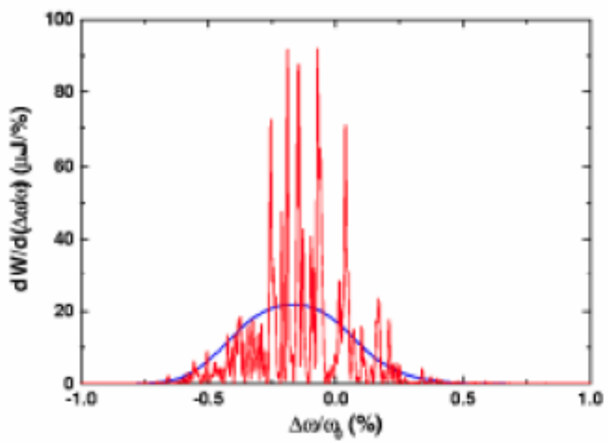


Self-seeded SASE FEL

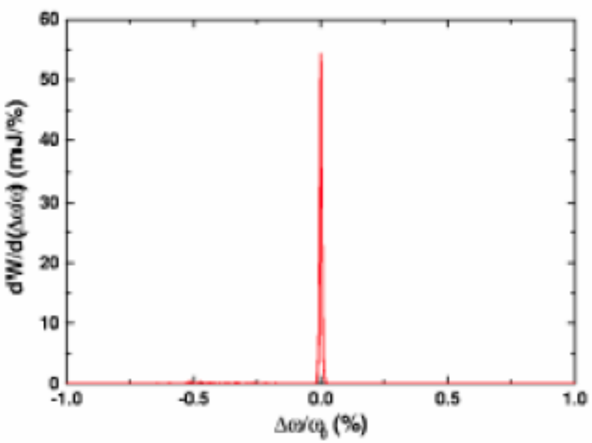


Spectral power distribution

Behind 1st undulator



Behind 2nd undulator



J. Corlett,

SPARC-BD-12/002
21 May 2012

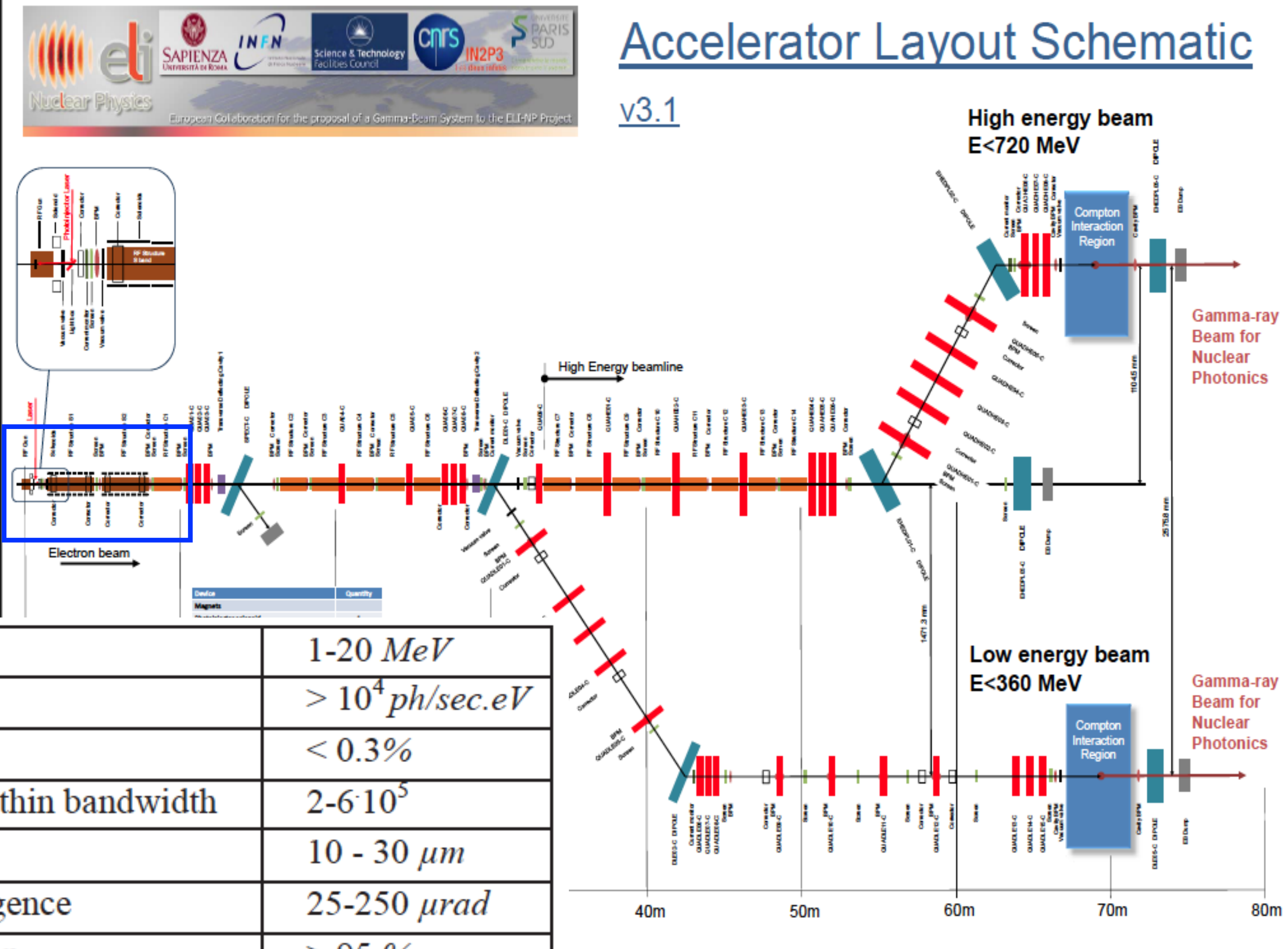
A POSSIBLE HARD X-RAY FEL WITH THE SuperB 6 GeV ELECTRON LINAC

D. Alesini[1], M. P. Anania[1], P. Antici[2], D. Babusci[1], A. Bacci[3], A. Balerna[1], R. Bartolini[5], M. Bellaveglia[1], M. Benfatto[1], R. Boni[1], R. Bonifacio[8], M. Boscolo[1], B. Buonomo[1], M. Castellano[1], L. Catani[4], M. Cestelli-Guidi[1], A. Cianchi[4], R. Cimino[1], E. Chiadroni[1], S. Dabagov[1], A. Gallo[1], D. Di Gioacchino[1], D. Di Giovenale[1], G. Di Pirro[1], A. Drago[1], A. Esposito[1], M. Ferrario[1], F. Ferroni[2], M. Gambaccini[12], G. Gatti[1], S. Guiducci[1], R. Gunnella[9], S. Ivashyn[13], S. Lupi[2], A. Marcelli[1], M. Mattioli[2], G. Mazzitelli[1], A. Mostacci[2], M. Migliorati[2], E. Pace[1], A. Perrone[10], V. Petrillo[3], R. Pompili[4], C. Ronsivalle[6], J. B. Rosenzweig[11], A. R. Rossi[3], W. Scandale[7], L. Serafini[3], O. Shekhovt[13], B. Spataro[1], C. Vaccarezza[1], A. Vacchi[14], A. Variola[7], G. Venanzoni[1], F. Villa[1].

(1) INFN-LNF
(2) INFN and Universita' di Roma"La Sapienza"
(3) INFN and Universita' di Milano
(4) INFN and Universita' di Roma"Tor Vergata"
(5) Diamond Light Source Ltd.
(6) ENEA, Frascati
(7) Laboratoire de l'Accélérateur Linéaire
(8) Universidade Federal da Paraiba, Brazil
(9) Universita' di Camerino
(10) INFN and Universita' del Salento
(11) UCLA, Los Angeles, USA
(12) INFN and Universita' di Ferrara
(13) ITP NSC KIPT, Kharkov, Ukraine
(14) INFN, Trieste

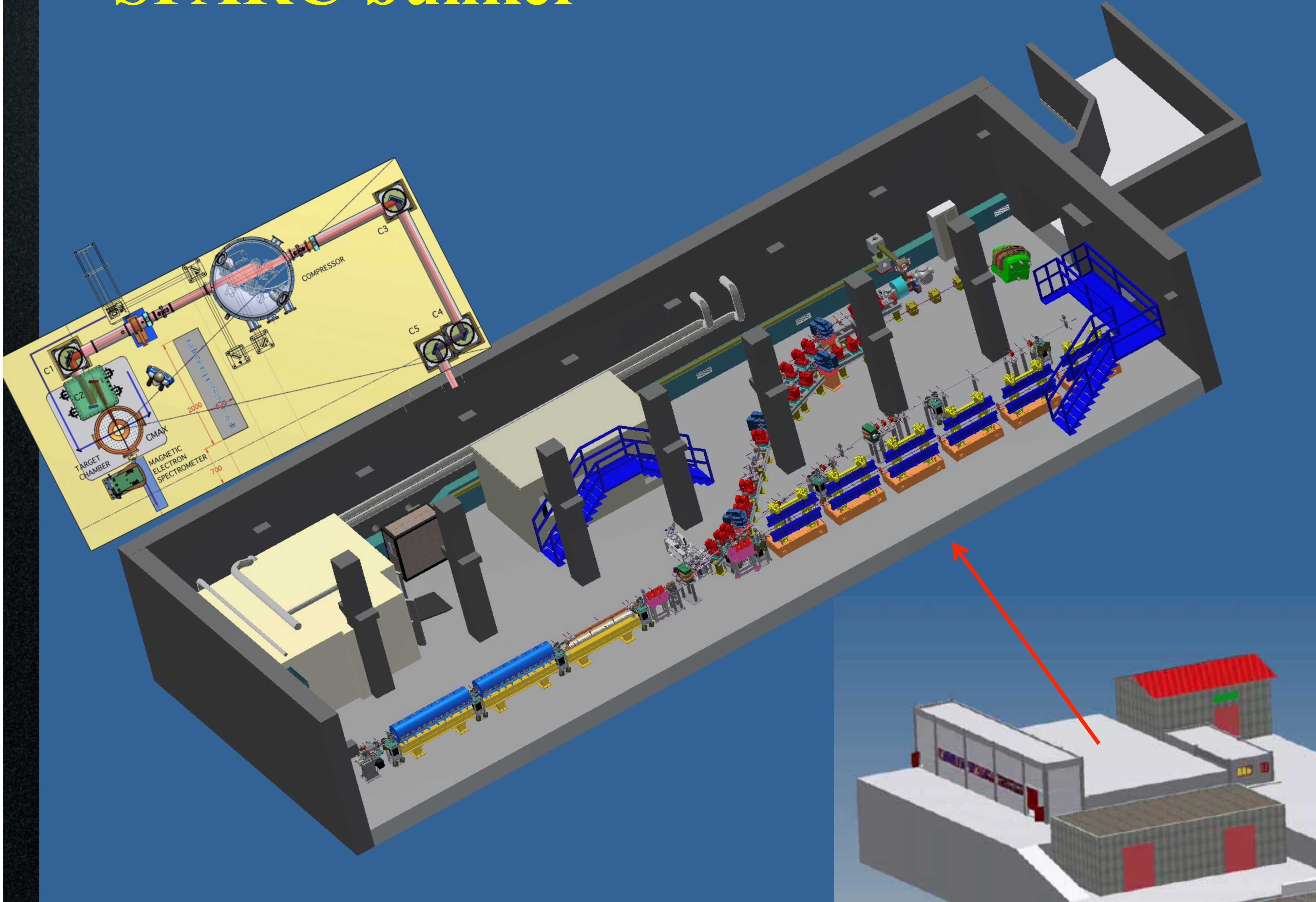
Accelerator Layout Schematic

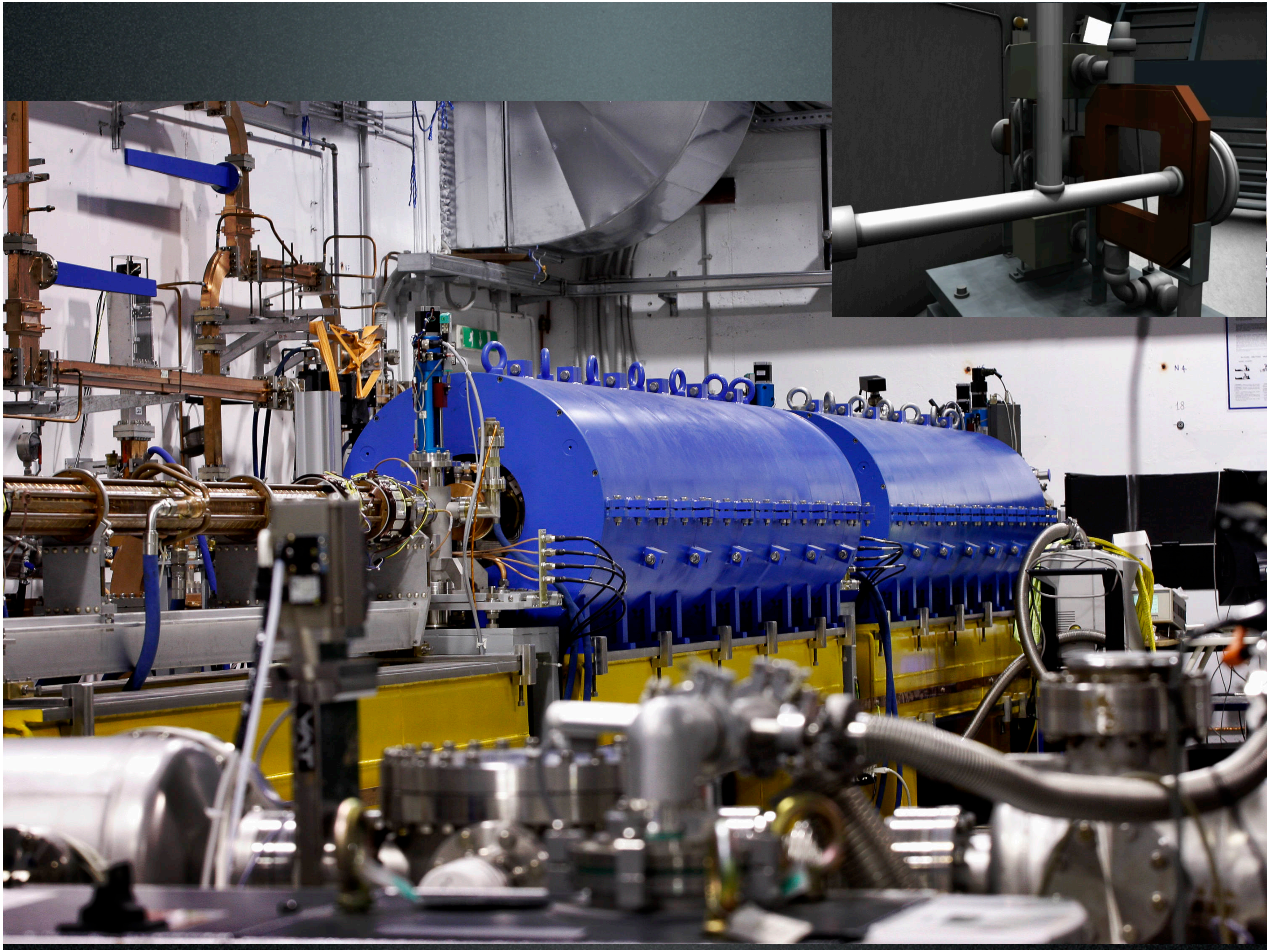
v3.1

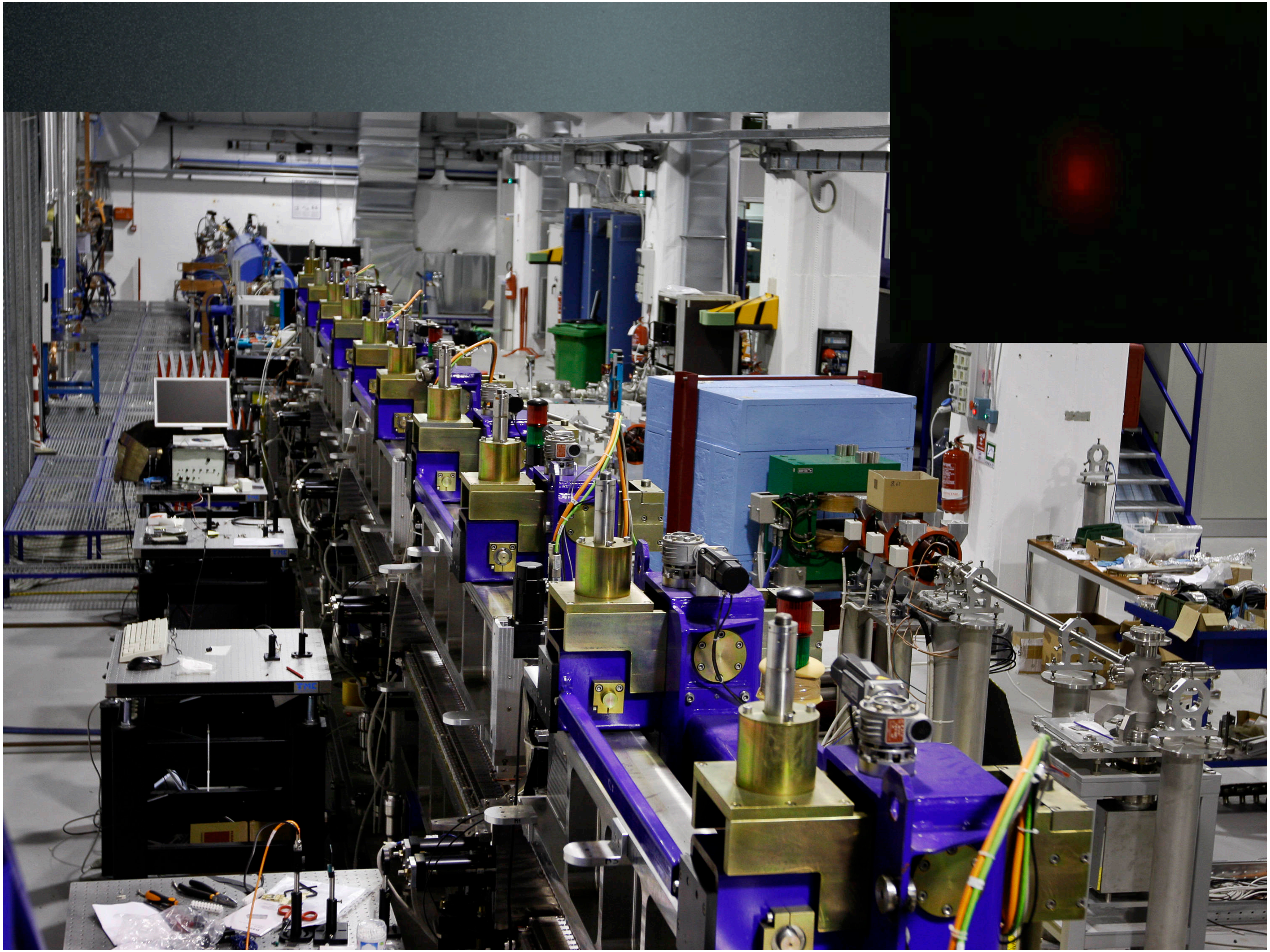


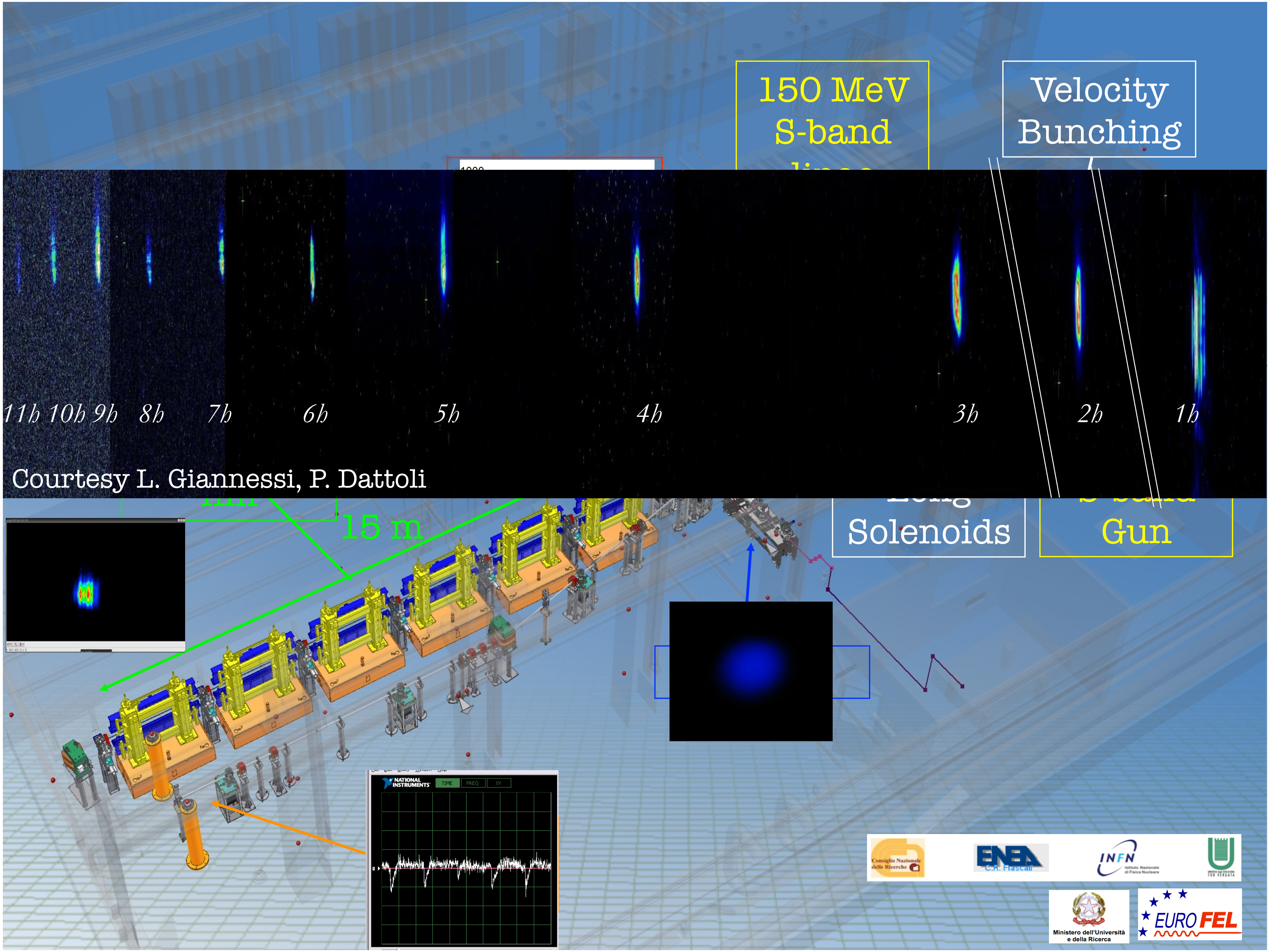
Photon energy	1-20 MeV
Spectral Density	$> 10^4$ $ph/sec.eV$
Bandwidth (rms)	$< 0.3\%$
# photons/shot within bandwidth	$2\text{-}6\,10^5$
Source rms size	10 - 30 μm
Source rms divergence	25-250 μrad
Linear Polarization	$> 95\ \%$
Macro rep. rate	100 Hz
# of pulses per macropulse	< 25
Pulse-to-pulse separation	> 15 $nsec$

SPARC bunker

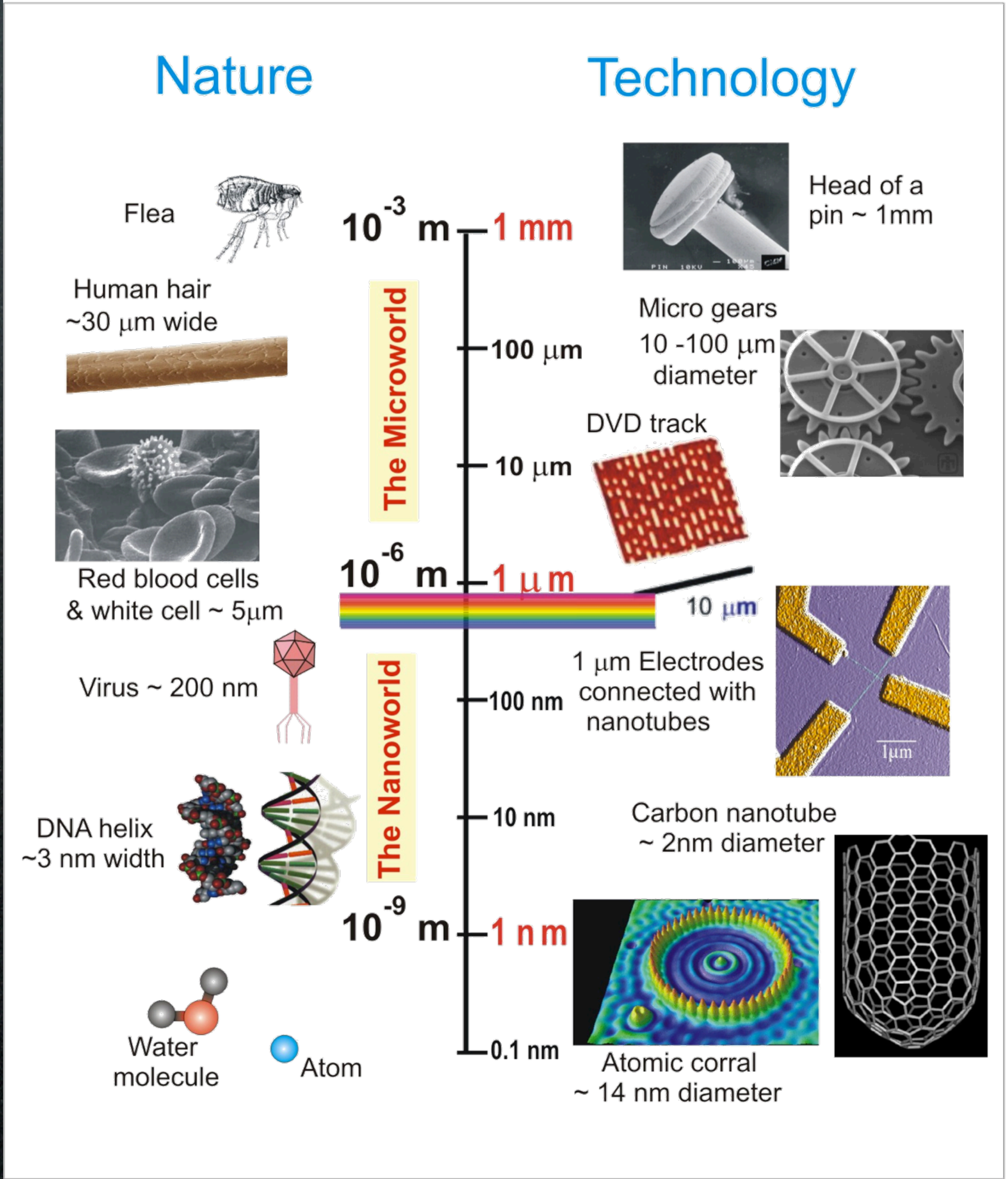







150 MeV
S-band
Velocity
Bunching
11h 10h 9h 8h 7h 6h 5h 4h 3h 2h 1h
Courtesy L. Giannessi, P. Dattoli
15 m
Solenoids
Gun
ENEA
C.R. Frascati
INFN
Ministero dell'Università
e della Ricerca
EURO FEL

Ultra-Small



Nature
Technology
Flea
10^{-3} m
1 mm
Head of a pin ~ 1mm
Human hair ~30 μm wide
The Microworld
Micro gears 10 -100 μm diameter
100 μm
DVD track
10 μm
Red blood cells & white cell ~ 5μm
10^{-6} m
1 μm
10 μm
1 μm Electrodes connected with nanotubes
Virus ~ 200 nm
100 nm
The Nanoworld
1μm
DNA helix ~3 nm width
10 nm
Carbon nanotube ~ 2nm diameter
10^{-9} m
1 nm
Water molecule
Atom
0.1 nm
Atomic corral ~ 14 nm diameter

"Plenty of Room at the Bottom"
Richard P. Feynman
December 1959

I imagine experimental physicists must often look with envy at men like Kamerlingh Onnes, who discovered a field like low temperature, which seems to be bottomless and in which one can go down and down. Such a man is then a leader and has some temporary monopoly in a scientific adventure.

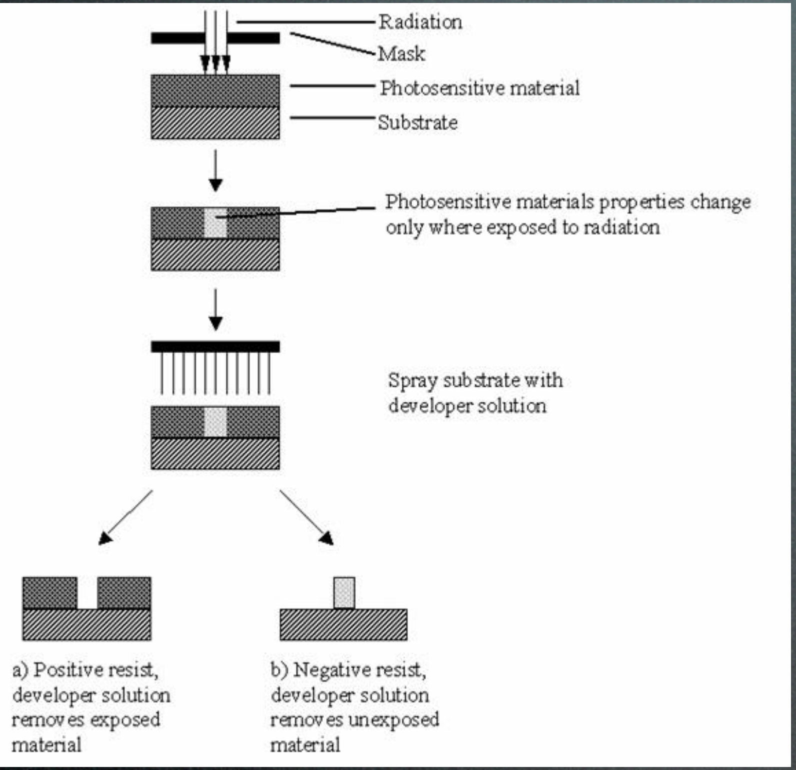
I would like to describe a field, in which little has been done, but in which an enormous amount can be done in principle. Furthermore, a point that is most important is that it would have an enormous number of technical applications.

What I want to talk about is the problem of manipulating and controlling things on a small scale.

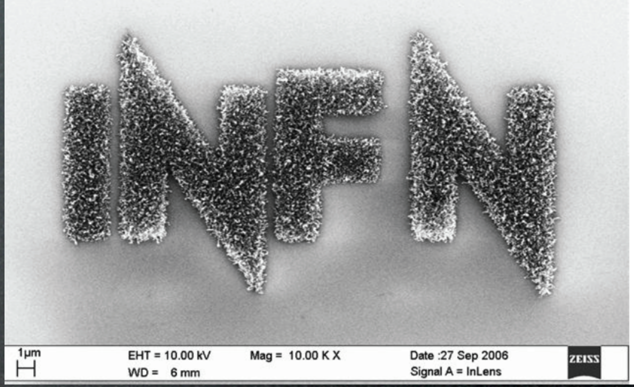
As soon as I mention this, people tell me about miniaturization, and how far it has progressed today. They tell me about electric motors that are the size of the nail on your small finger. But that's nothing; that's the most primitive, halting step in the direction I intend to discuss. It is a staggeringly small world that is below. In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction.

Why cannot we write the entire 24 volumes of the Encyclopedia Brittanica on the head of a pin?

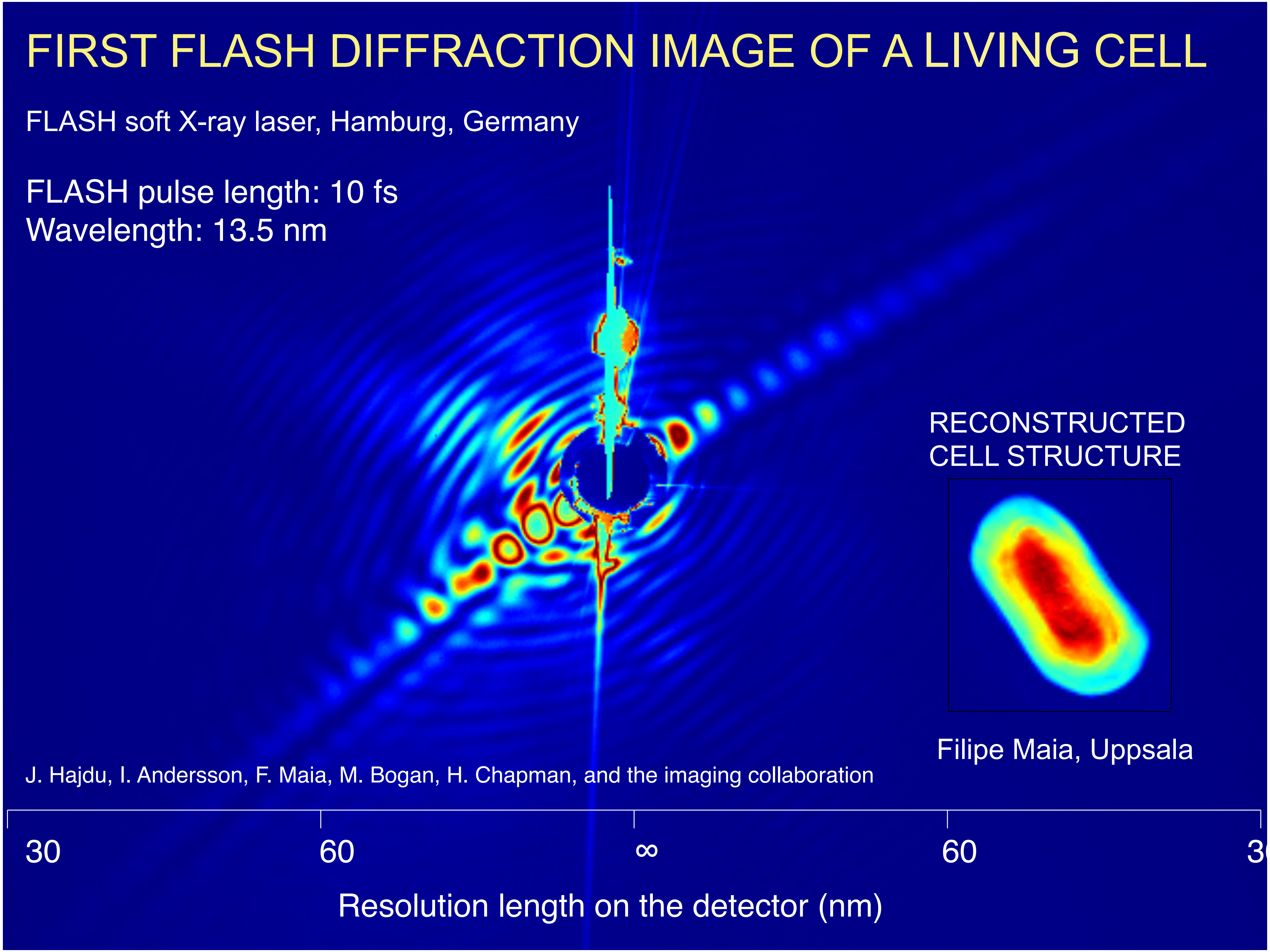
nano lithography



Michelangelo Ambrosio INFN-GINT



- Extreme UV Lithographt is the candidate technology with <50-35 nm
- Cost effective solutions based on FEL sources can be foreseen


FIRST FLASH DIFFRACTION IMAGE OF A LIVING CELL
FLASH soft X-ray laser, Hamburg, Germany
FLASH pulse length: 10 fs
Wavelength: 13.5 nm
RECONSTRUCTED
CELL STRUCTURE
Filipe Maia, Uppsala
J. Hajdu, I. Andersson, F. Maia, M. Bogan, H. Chapman, and the imaging collaboration
30
60
∞
60
Resolution length on the detector (nm)

cluster and nanoparticle

Clusters are small bits of matter composed of anywhere from a few to tens of thousands of atoms.

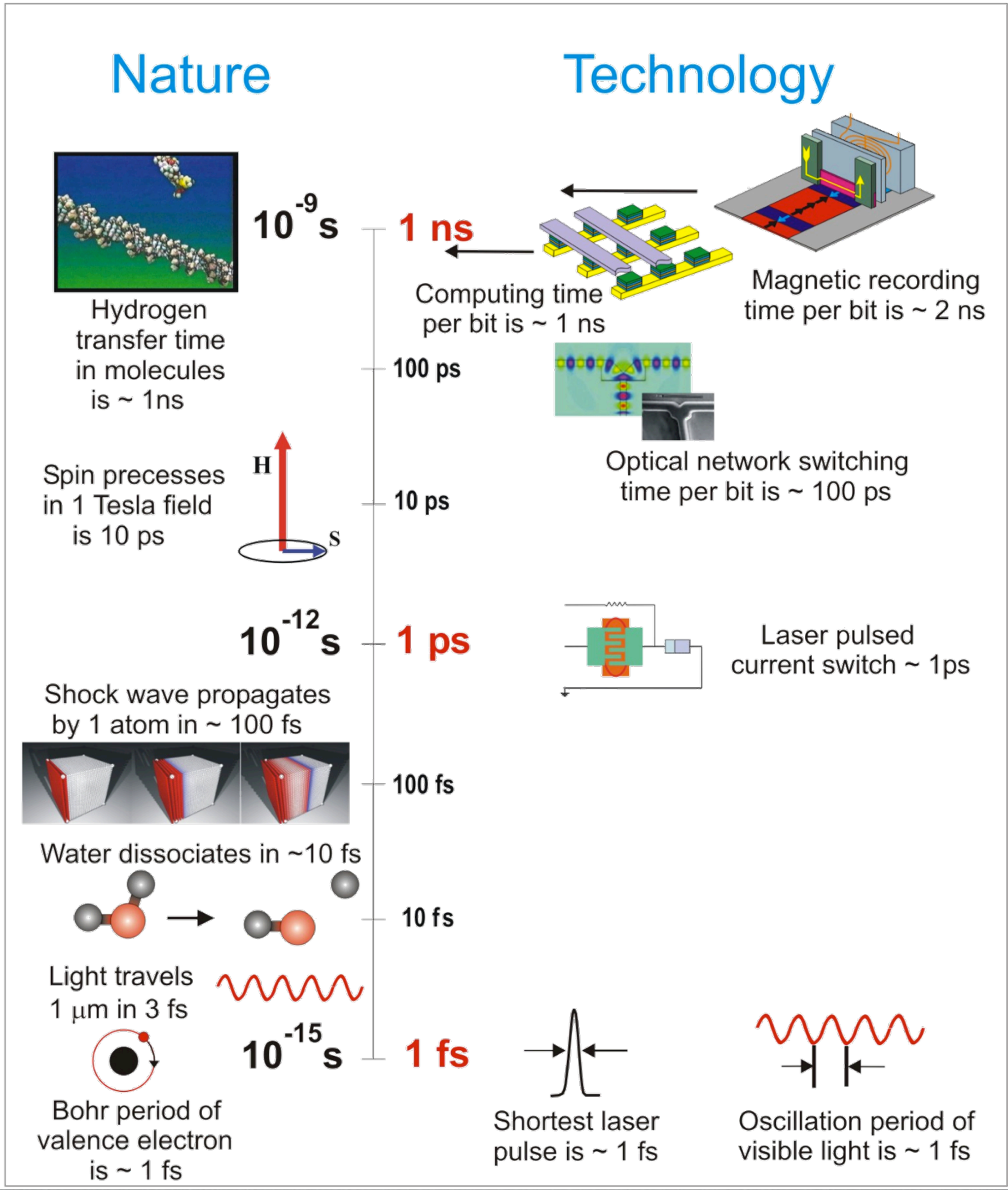
Small particles are different from bulk matter; finite size effects influence all properties of matter.

Examples are tiny carbon spheres and carbon tubes that are considered promising candidates for use as nanotechnological components.
(17 000 copper atoms in the picture on the right).

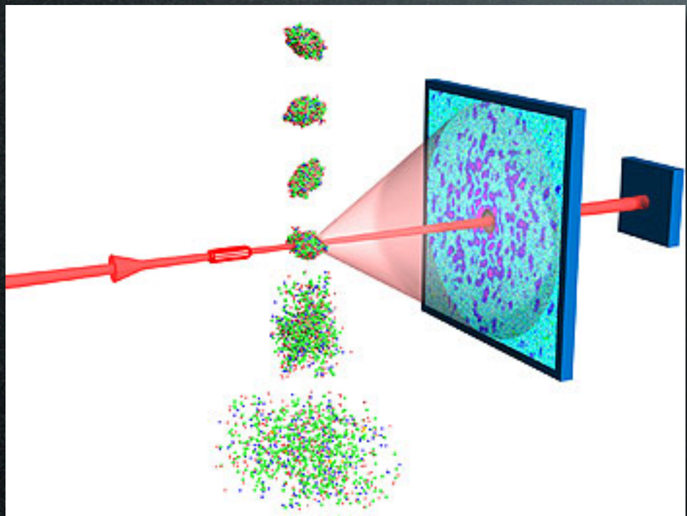
Limited photon energy of standard laser systems prevents measuring the full valence electron structure as well or performing photon energy dependent spectroscopy across shallow core edges

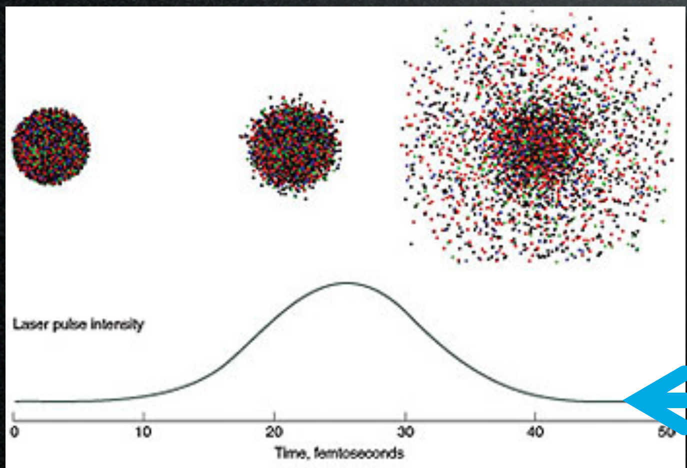
The beam intensities available at 3rd generation synchrotron radiation facilities are still far below what is required for meaningful gas phase experiments.

Ultra-Fast


Nature
Technology
10^{-9} s
1 ns
Hydrogen transfer time in molecules is ~ 1ns
Computing time per bit is ~ 1 ns
Magnetic recording time per bit is ~ 2 ns
100 ps
Optical network switching time per bit is ~ 100 ps
H
S
Spin precesses in 1 Tesla field is 10 ps
10 ps
10^{-12} s
1 ps
Laser pulsed current switch ~ 1ps
Shock wave propagates by 1 atom in ~ 100 fs
100 fs
Water dissociates in ~10 fs
10 fs
Light travels 1 µm in 3 fs
10^{-15} s
1 fs
Bohr period of valence electron is ~ 1 fs
Shortest laser pulse is ~ 1 fs
Oscillation period of visible light is ~ 1 fs

Protein imaging





Lawrence Livermore National Laboratory (LLNL)

Using extremely short and intense X-ray pulses to capture images of objects such as proteins before the X-rays destroy the sample.

Single-molecule diffractive imaging with an X-ray free-electron laser.

Individual biological molecules will be made to fall through the X-ray beam, one at a time, and their structural information recorded in the form of a diffraction pattern.

The pulse will ultimately destroy each molecule, but not before the pulse has diffracted from the undamaged structure.

The patterns are combined to form an atomic-resolution image of the molecule.

The speed record of 25 femtoseconds for flash imaging was achieved.

Models indicate that atomic-resolution imaging can be achieved with pulses shorter than 20 femtoseconds.

make a movie of chemical reactions

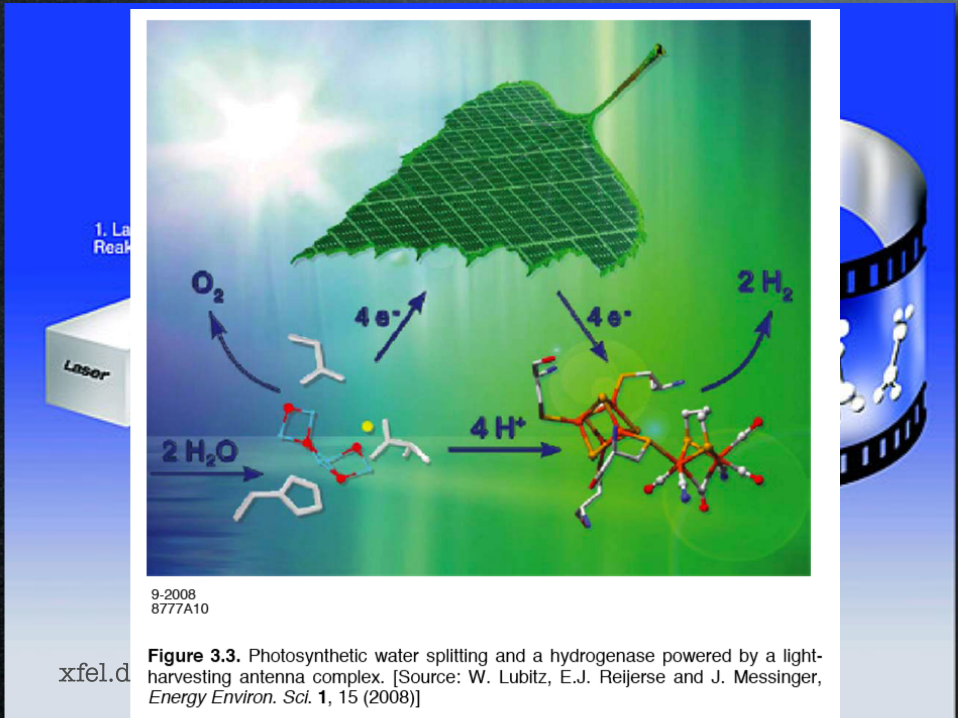


Figure 3.3. Photosynthetic water splitting and a hydrogenase powered by a light-harvesting antenna complex. [Source: W. Lubitz, E.J. Reijerse and J. Messinger, *Energy Environ. Sci.* **1**, 15 (2008)]

Chemical reactions often take place incredibly quickly: orders of magnitude of femtosecond are not rare. The atomic changes that occur when molecules react with one another take place in moments that brief.

The XFEL X-ray laser flashes make it possible to film these rapid processes with an unprecedented level of quality.

Since the flash duration is less than 100 femtoseconds, images can be made in which the movements of detail are not blurred.

And thanks to the short wavelength, atomic details become visible in the films.

To film a chemical reaction, one needs a series of pairs of X-ray laser flashes.

The first flash in each pair triggers the chemical reaction. With the second flash, a snapshot is then made.

The delay between the two flashes can be precisely modified to within femtosecond and a series of snapshots can be made at various times following the start of the reaction.

In each case, the images are of different molecules, but these images can be combined into a film.

Axion-Like Particle Generation with the Free-Electron Laser VUV-FEL

A. Ringwald
http://www.desy.de/~ringwald

- AR, "Fundamental physics at an X-ray free-electron laser," arXiv:hep-ph/0112254
- R. Rabadan, AR and K. Sigurdson, "Photon regeneration from pseudoscalars at X-ray laser facilities," arXiv:hep-ph/0511103
- U. Kötz, AR and T. Tschentscher, "Production and detection of axion-like particles at the VUV-FEL: A study of feasibility," in progress

“Plenty of Room also in the Vacuum”

Polarization experiments

- Send linearly polarized laser beam through transverse magnetic field $\Rightarrow$ measure changes in polarization state
- Real and virtual production induce
  - **rotation:** photons polarized $||$ $\boldsymbol{B}$ will disappear leading to apparent rotation of polarization plane by

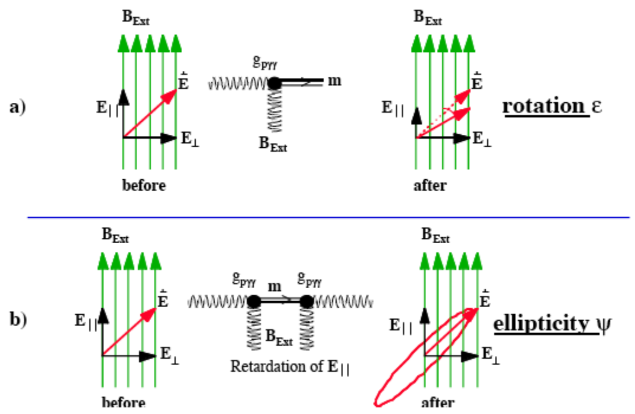
$$\varepsilon_\phi = -N_r \left(\frac{gB\ell}{4}\right)^2 F(q\ell)\,\sin 2\theta$$

  - **ellipticity:** virtual production causes retardation between $\boldsymbol{E}_{||}$ and $\boldsymbol{E}_\perp \Rightarrow$ elliptic polarization

$$\psi_\phi \approx \frac{N_r}{6}\left(\frac{g\,B\,\ell}{4}\right)^2 \frac{m_\phi^2\,\ell}{\omega}\,\sin 2\,\theta$$

for small masses, $m_\phi^2 \ell/4\omega \ll 1$.

“Vacuum magnetic dichroism and birefringence” [Maiani,Petronzio,Zavattini ‘86]



[Brandi *et al.* ‘01]

Photon regeneration

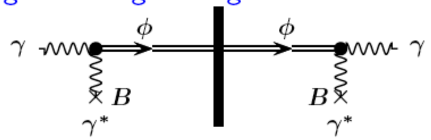
- **Production:** Polarized laser beam along transverse magnetic field, such that $\boldsymbol{E}\,||\,\boldsymbol{B} \Rightarrow$ conversion $\gamma \to \phi$
- Absorb laser beam in wall
- **Detection:** Detect photons behind wall from back conversion ($\phi \to \gamma$) in second magnetic field:

$$\dot N_\gamma = \underbrace{\frac{\langle P\rangle}{\omega}}_{\dot N_0} \frac{N_r}{2} \underbrace{\frac{1}{16}(g\,B\,\ell)^4 F^2(q\ell)}_{P^2_{\gamma\leftrightarrow\phi}}$$

with $F \approx 1$ for $q\ell \ll 1$ (coherence),

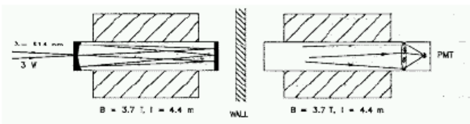
$$m_\phi \lesssim 10^{-3}\ \mathrm{eV}\left(\frac{\omega}{1\ \mathrm{eV}}\frac{1\ \mathrm{m}}{\ell}\right)^{1/2}$$

“Light shining through a wall”



[Sikivie (1983);Ansel'm (1985);Van Bibber *et al.* (1987)]

BFRT experiment:
(Brookhaven, Fermilab, Rochester, Trieste)



[Cameron *et al.* (1993)]

$B = 3.7\ \mathrm{T}, \ell = 4.4\ \mathrm{m}, \underbrace{\langle P\rangle = 3\ \mathrm{W}, \omega = 2.4\ \mathrm{eV}}_{\dot N_0 = 8\times 10^{18}/\mathrm{s}}, N_r = 200$


Thank you