

### Laser ad elettroni liberi nei soft X-ray: sorgenti di radiazioni coerenti ultra-brillanti per applicazioni a campioni biologici

Soft X-rays Free Electron Lasers: ultra-bright, coherent radiation sources to look at biological samples

Francesco Stellato

INFN Roma Tor Vergata

May 16<sup>th</sup> , 2018



### **Free Electron Laser - Applications**

FELs are very large (???) X-ray microscopes...





Structural investigation

**Biomolecules:** Proteins, viruses, cells

Materials: magnetic materials, semiconductors, nanoparticles, sooth, ashes

#### Giornata della luce UNESCO



May 16<sup>th</sup> , 2018

### **Free Electron Lasers**

Optical microscopes use visible light Diffraction limited resolution:







#### X-rays are needed to look at nano/micro- scale Synchtrotrons & Free Electron Lasers provide photons in this range

Giornata della luce UNESCO

May 16<sup>th</sup> , 2018



### **FELs Vs Synchrotrons**

- FELs have higher peak brilliance than synchrotrons → Diffract-and-destroy
- FELs emit femtosecond pulses, synchrotrons picosecond pulses → Ultrafast time-resolution
- FELs have higher coherence than synchrotrons Coherent imaging experiments
- FELs & synchrotrons are both tunable in wavelength and polarization







### **FEL Time structure**

#### Besides exploiting FELs high number of photons,

#### one can also exploit their time structure

May 16<sup>th</sup> , 2018



FELs deliver about the same number of photons/s as synchrotrons, but packed in short pulses



May 16<sup>th</sup> , 2018

### **Diffract & Destroy @ Free Electron Lasers**



One pulse, one measure

A detectable signal must be recorded before the sample is destroyed

Many (10<sup>6</sup>) patterns need to be measured and analyzed Experimentally & computationally challenging...

May 16<sup>th</sup> , 2018



# **Coherent Imaging**

When the FEL photons hit the sample, a **diffraction pattern** is originated **The diffraction pattern is the |FT| of the sample electron density** 

|FT|<sup>-1</sup>



Diffraction pattern k - space



May 16<sup>th</sup> , 2018



### **Diffract & Destroy @ Free Electron Lasers**



May 16<sup>th</sup> , 2018



# **Bio-samples Coherent Imaging**

2D images can be obtained from a single shot

Cells, organelles, protein aggregates





May 16<sup>th</sup> , 2018



# **Bio-samples Coherent Imaging**

#### **2D images** can be obtained from a single shot



Diffraction Pattern

2D images of C. gracile living cells acquired at the **LCLS FEL** 

Van der Shoot, ..., FS, et al. Nature Comm (2015) Van der Shoot, ..., FS, et al. Sci Data (2016)

May 16<sup>th</sup> , 2018



# **Bio-samples Coherent Imaging**

**3D images** can be obtained by merging info from several shots

Since the sample is destroyed by the interaction with FEL photons, many identical samples are needed

Viruses, protein fibrils, single protein molecules...



May 16<sup>th</sup> , 2018



### **Bio-samples Coherent Imaging**

**3D images** can be obtained merging info from several shots Since the sample is destroyed by the FEL photons, many identical samples are needed



#### **Giornata della luce UNESCO**



#### May 16<sup>th</sup> , 2018

### **FEL Coherent Imaging**

FEL feature	Method	
Brilliant pulses	«high» signal-to-noise ratio	High resolut
Short pulses	Diffraction before destruction	Damage-fre observed wl
Many pulses	Time-resolved experiments	Irreversible
PHOTOGRAPHY	→ MOVIE	

#### The to-be movie catalogue Viruses vs Nuclei

The birth of a protein filament **Light on plants** 

. . .

May 16<sup>th</sup> , 2018



Seibert *et al* **Nature (2011)** Single mimivirus particles intercepted and imaged with an X-ray laser.

Starodub *et al* **Nature Communications** (2012) Single-particle structure determination by correlations of snapshot X-ray diffraction patterns.

Hantke *et al* **Nature** Photonics (2014) High-throughput imaging of heterogeneous cell organelles with an X-ray laser.

Van Der Schot *et al* **Nature Communications (2014)** Imaging single cells in a beam of live cyanobacteria with an X-ray laser.

Ekeberg *et al* **Physical Review Letters (2015)** Three-dimensional reconstruction of the giant mimivirus particle with an x-ray free-electron laser.

Reddy *et al* Scientific Data (2017)

Coherent soft X-ray diffraction imaging of coliphage PR772 at the Linac coherent light source.

Huang *et al* **Nanoscale (2018)** Free-Electron-Laser Coherent Diffraction Images Individual Drug-Carrying Liposome Particles in Solution



Istituto Nazionale di Fisica Nucle

May 16<sup>th</sup> , 2018



# What energy range?

In principle, the lower the wavelength, the higher the resolution but **X-ray cross section** decreases with wavelength Small molecules only scatter very few photons



Maybe in the future, with **huge accelerators** or **plasma sources**...



Röntgen's wife hand

May 16<sup>th</sup> , 2018



### Water Window Coherent Imaging

Energy region between Oxygen and Carbon K-edge 2.34 nm – 4.4 nm (530 eV -280 eV)

Water is almost transparent to radiation in this range while nitrogen and carbon are absorbing (and scattering)

Coherent Imaging of biological samples living in their native state Possibility to study dynamics

> Wavelength limited, photon flux depending resolution





May 16<sup>th</sup> , 2018

### **Coherent EUV-soft x-ray FELs**





### Water Window Coherent Imaging

**Coherent Diffraction Pattern** 



A typical coherent imaging experimental setup

May 16<sup>th</sup> , 2018

Time-resolved experiments are possible (mainly, but not necessarily only, photo-induced processes)

#### **Giornata della luce UNESCO**



May 16<sup>th</sup> , 2018



#### Giornata della luce UNESCO



#### May 16<sup>th</sup> , 2018

- Ultra-high vacuum chamber
- Beam diagnostics: photon-in and phot
  I<sub>0</sub> monitor and atte
- Sample diagnostics: time-of-flight spec
- Synchronized external lasers
  (tunable, high power optical, IR, THz)
- Split-and-delay element
- Sample delivery systems Liquid jets Aerosols Fixed targets

Villa et al. Rev Sci Instr (2018)



Micrometer-sized liquid jets are produced

May 16<sup>th</sup> , 2018



### Outlook

Plasma acceleration a new way to generate FEL radiation



# FEL imaging – Time-resolved experiments *in vivo* molecular movies

#### Giornata della luce UNESCO



May 16<sup>th</sup> , 2018

### Acknowledgments





#### SPARC\_LAB, LNF, La Sapienza, Uni Ts, CNR, ...

A. Cianchi, D. Cirrincione, M. Coreno, S. Dabagov,M. Ferrario, L. Giannessi, S. Lupi, C. Masciovecchio,A. Marcelli, V. Minicozzi, S. Morante, A. Ricci,F. Stellato, A.Vacchi, F. Villa

### & many others... Thank you for the attention The Biophysics Group in Tor Vergata



Silvia Morante Giancarlo Rossi Francesco Stellato Emiliano De Santis Ayshwaria Dhar Giulia Romoli