# BoCXS: a Compact X-ray Source for the Bologna Metropolitan Area

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# THE MESSAGE

Bring ADVANCED IMAGING QUALITY and

IMPROVED VISUALIZATION DIAGNOSTICS

for BIOMEDICAL APPLICATIONS to

CLINICS and UNIVERSITY INSTITUTIONS

# MONOCHROMATIC X-ray SOURCES

FIGURE OF MERIT: **BRIGHTNESS**
"SPECIFIC FLUX"

$$\mathcal{B} = \frac{Flux}{4\pi\Sigma_x\Sigma_{x'}\Sigma_y\Sigma_{y'}} \quad [Photons/s/mm^2/mrad^2/0.1\%BW]$$

CONVENTIONAL
- COMPACT
- AFFORDABLE
- COMMERCIALLY AVAILABLE
- **LIMITED BRIGHTNESS**

SYNCHROTRON / UNDULATORS
- **HIGH BRIGHTNESS**
- **ENERGY TUNABILITY**
- **PARTIAL COHERENCE**

ICS: *BRIDGE THE GAP BETWEEN THE ABOVE*
- **LOWER e- ENERGY**
- **HIGHER BRIGHTNESS AND X-ray ENERGY**
- **COMPACT and ACCESSIBLE**
- **CONTAINED FINANCIAL INVOLVEMENT**

} ACCELERATOR DRIVEN

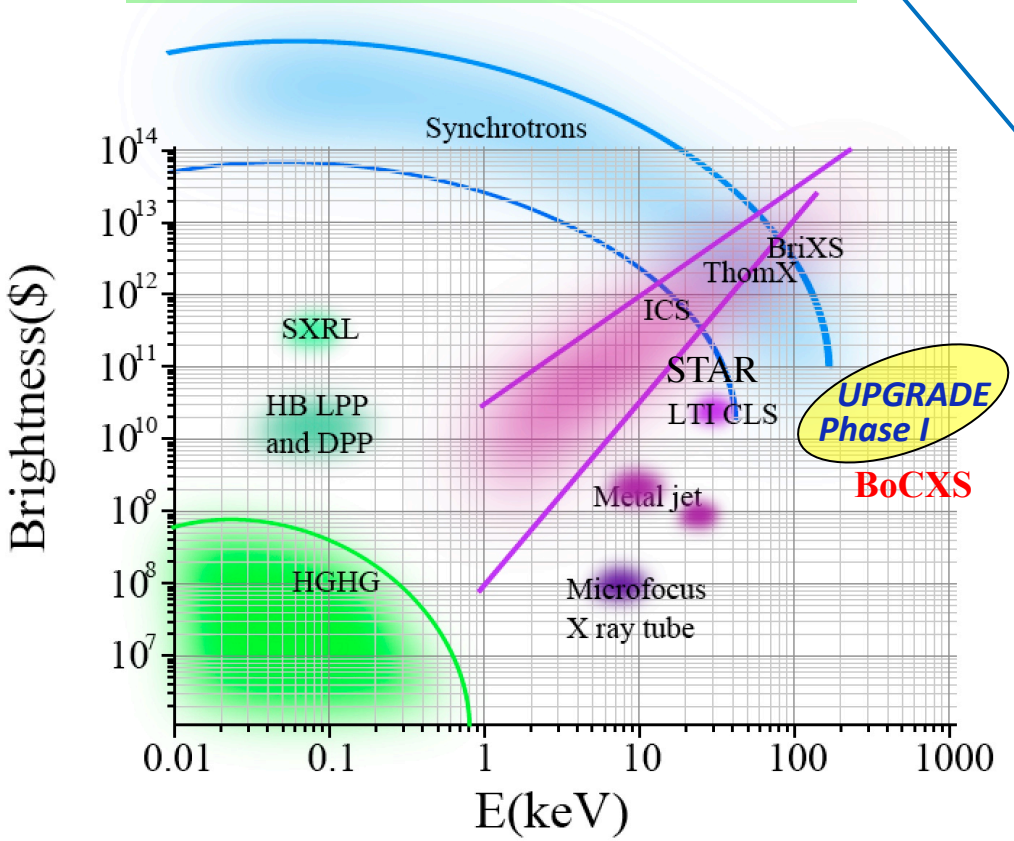
# ICS and Synchrotron Light Brightness

Courtesy: A. Murokh, L. Serafini

ICS and Synchrotron Light Sources compete above 80-100 keV

Critical Frequency in Dipolar Emission

Transverse e- beam sizes in SR (Quantum Emission)




*$: Photons/s/mm²/mrad²/0.1%BW*

# ICS TECHNOLOGY

**ACCELERATOR-DRIVEN COMPACT SOURCE ACCESSIBLE TO**

**ACADEMIC**

**CLINICAL and**

**INDUSTRIAL INSTITUTIONS**

**X-ray BEAMS with SOPHISTICATED CHARACTERISTICS**

**ENERGY TUNABILITY**

**HIGH BRIGHTNESS**

**QUASI-MONOCHROMATICITY**

# APPLICATIONS

## MEDICAL

IMAGING DIAGNOSTICS
COMPUTED TOMOGRAPHY

## COMMERCIAL

NON-DESTRUCTIVE INDUSTRIAL TESTS
BAGGAGE & CARGO INSPECTION / SAFETY

## RESEARCH APPLICATIONS

TRANSIENT STATES IN CONDENSED MATTER
DYNAMICS OF COMPLEX MOLECULES

## CULTURAL HERITAGE SCIENCE

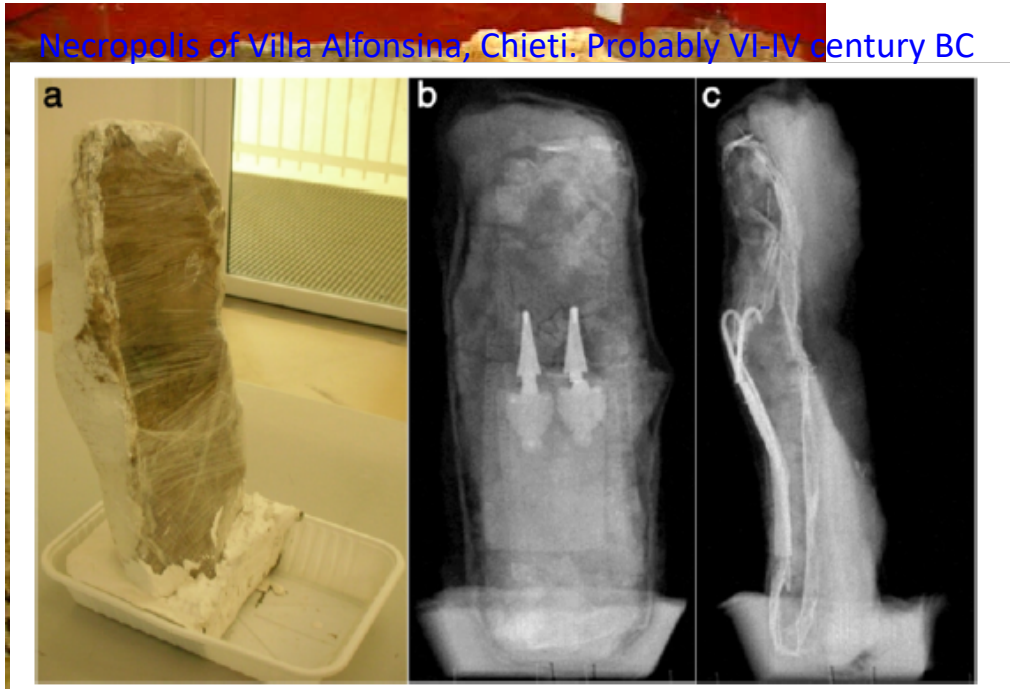
INSPECTION / CHARACTERIZATION
OF MUSEUM ARTIFACTS AND
ARCHAEOLOGICAL FINDINGS

*The OSTUNI MOTHER*

Parco S. Maria di Agnano / Salento

*BURIAL OBJECTS IN SOIL BLOCKS*

Necropolis of Villa Alfonsina, Chieti. Probably VI-IV century BC




A. Re *et al. Heritage Science (2015) 3:4*

Sincrotrone Trieste / **Syrmep beamline**

**Credit:** L. Mancini, G. Tromba

# THE MEDICAL IMAGING CHALLENGE

**IMAGING RESOLUTION** IS AT PREMIUM
IN MEDICAL IMAGING

**CONVENTIONAL SOFT-TISSUE ABSORPTION DIAGNOSTICS**
Cartilages, Angiography, Breast, Brain, Lungs

➡ Low contrast, Long exposure

**Quality usually enhanced** using **contrast agents**
not always patient-friendly

**ADVANCED IMAGING CAPABILITY**

⬇

**BETTER RESOLUTION**

**SHORTER EXPOSURE / DOSE**

**LOWER USE of CONTRAST AGENTS**

↙ ↘

**ADVANCED IMAGING TECHNIQUES** **COMPACT X-ray SOURCES**

# MEDICAL IMAGING TECHNIQUES

X-ray Absorption

X-ray Refraction

Analyzer-Based Imaging (ABI)

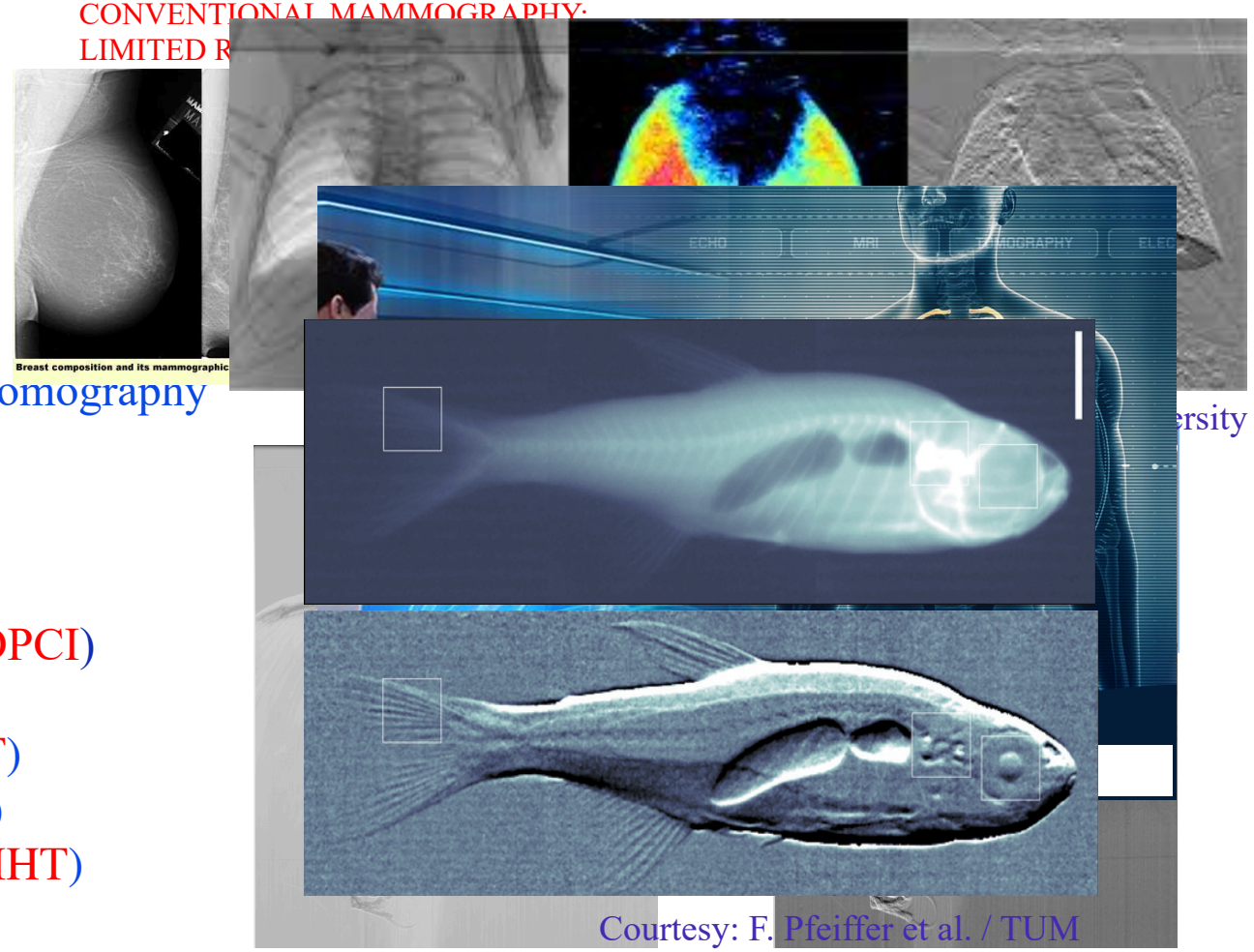
Grating Interferometry (GI)

Diffraction-Enhanced Computerized Tomograpny (DEI-CT)

Nuclear Magnetic Resonance (NMR)

Differential Phase Contrast Imaging (DPCI)

Holographic Imaging Technology (HIT)
Optical Coherence Tomography (OCT)
Interactive Holographic Tomography (IHT)
(Coronary, Angiography)




Courtesy: F. Pfeiffer et al. / TUM

Courtesy: G. Tromba et al. / Elettra TS

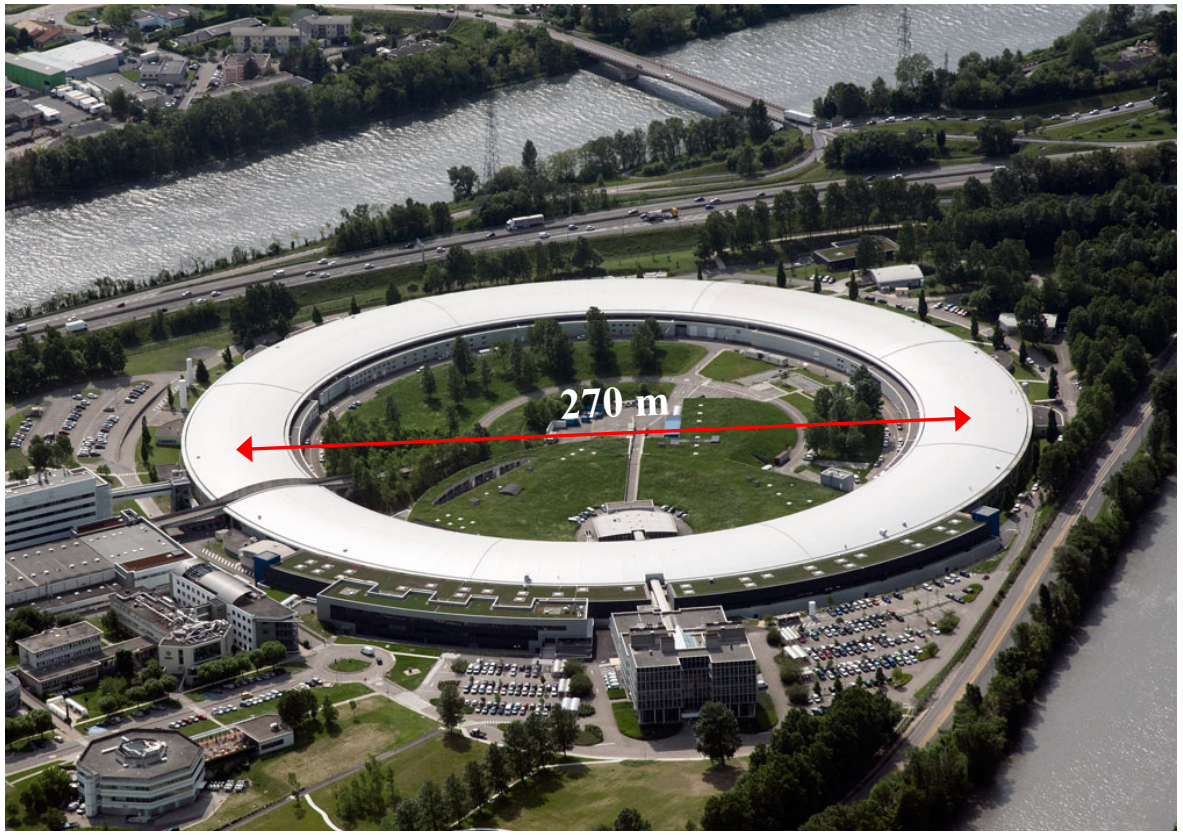
# NMR / DPCI DIAGNOSTICS COMPARISON

Courtesy: R. Calandrino et al. / SRH Milano

| OPTION | | NMR | DPCI |
|---|---|---|---|
| Spatial resolution [mm] | | >3 | 0.01-0.03 |
| Data registration time [s] | | 1200 | 30 |
| Image reconstruction time [s] | | 120 | <1 |
| Primary diagnostics tool? | | NO | YES |
| Vessel system | VISIBILITY w/o contr. agent | NO | YES |
| Nervous system | | NO | YES |
| Lymphatic system | | NO | YES |
| Soft tissues | | NO | YES |
| Skeleton | | YES | YES |
| Claustrophobic patients | | Difficult | Possible |
| Patients with metallic implants | | Impossible | Possible |
| Patients with non-metallic implants | | Limited | Possible |
| Real time examination during surgery | | Impossible | Possible |

# LARGE LIGHT SOURCES


**ELETTRA** / Trieste
**2.4 GeV** e- / **260 m** Circumference
**5-10 keV X-rays**



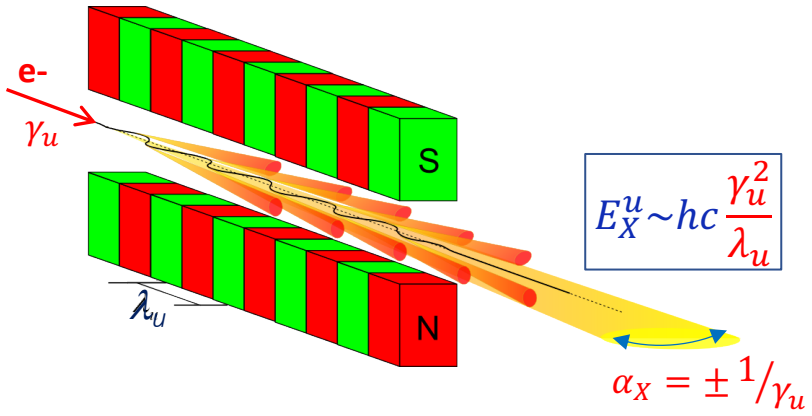

**ESRF** / Grenoble
**6 GeV** e- / **844 m** Circumference
**10-40 keV X-rays**

# UNDULATOR vs ICS RADIATION

***WAVE-PARTICLE LIGHT DUALITY***

**UNDULATOR**: the *WAVE* nature

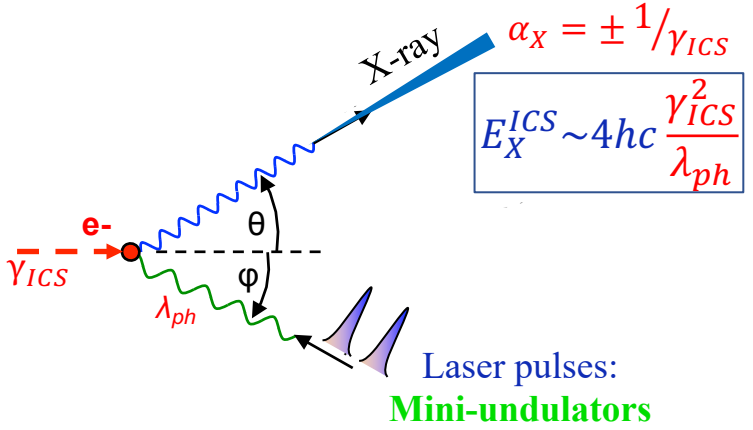
Emitted radiation as result of **e-** transverse acceleration




X-RAY RADIATION EMITTED BY ELECTRONS WIGGLING in an **ALTERNATING POLARITY MAGNETIC FIELD** (PERIOD $\lambda_u$)

**ICS**: the *PARTICLE* approach

Emitted radiation interpreted as scattering from moving **e-**




ELECTRONS WIGGLE IN THE **e.m. FIELD of a LASER PULSE** (WAVELENGTH $\lambda_{ph}$)

# FROM GOLIATH TO DAVID…

**SYNCHROTRONS**
**UNDULATOR**

$$E_X^u \sim hc\left(\frac{E_u^2}{\lambda_u}\right)$$

X-ray energy has similar expressions but…

$$\lambda_{ph} \sim 10^{-4}\,\lambda_u$$

*TWO BIG ADVANTAGES*

$E_{ICS} \sim 10^{-2} E_u$

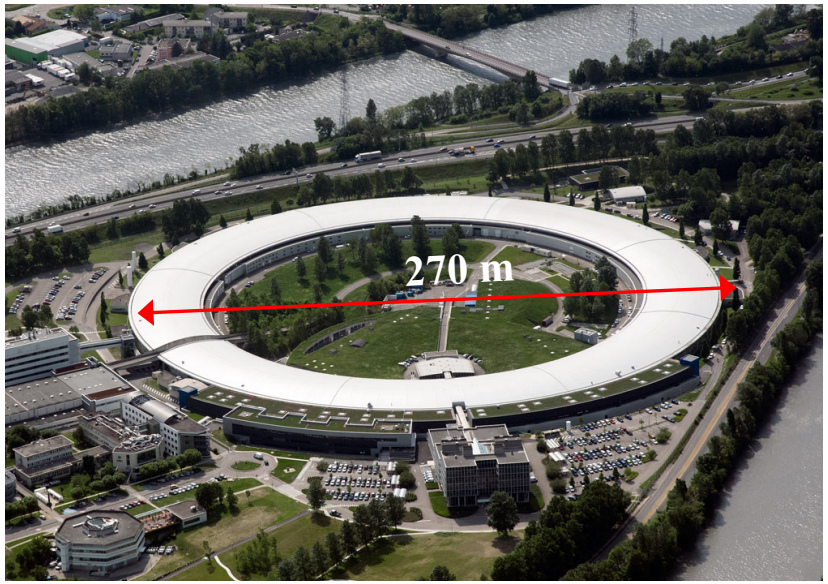
COMPA…STS
*HIGHE…R $E_u$*

$$\alpha_X^{ICS} \gg \alpha_X^u$$

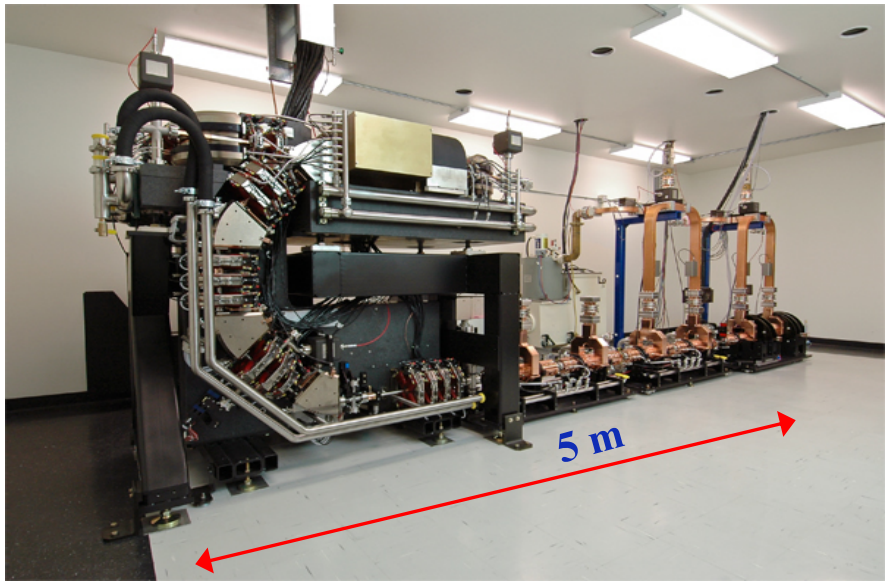
SHORTER IMAGING DISTANCE

**COMPACT SOURCE**
**ICS**

$$E_X^{ICS} \sim 4hc\left(\frac{E_{ICS}^2}{\lambda_{ph}}\right)$$




**ESRF: 6 GeV** e- / **844 m** Circumference
**10-40 keV X-rays**




**CLS: 40 MeV** e- / **5x4 m²** footprint
**30-40 keV X-rays**

# PROPOSED FACILITY

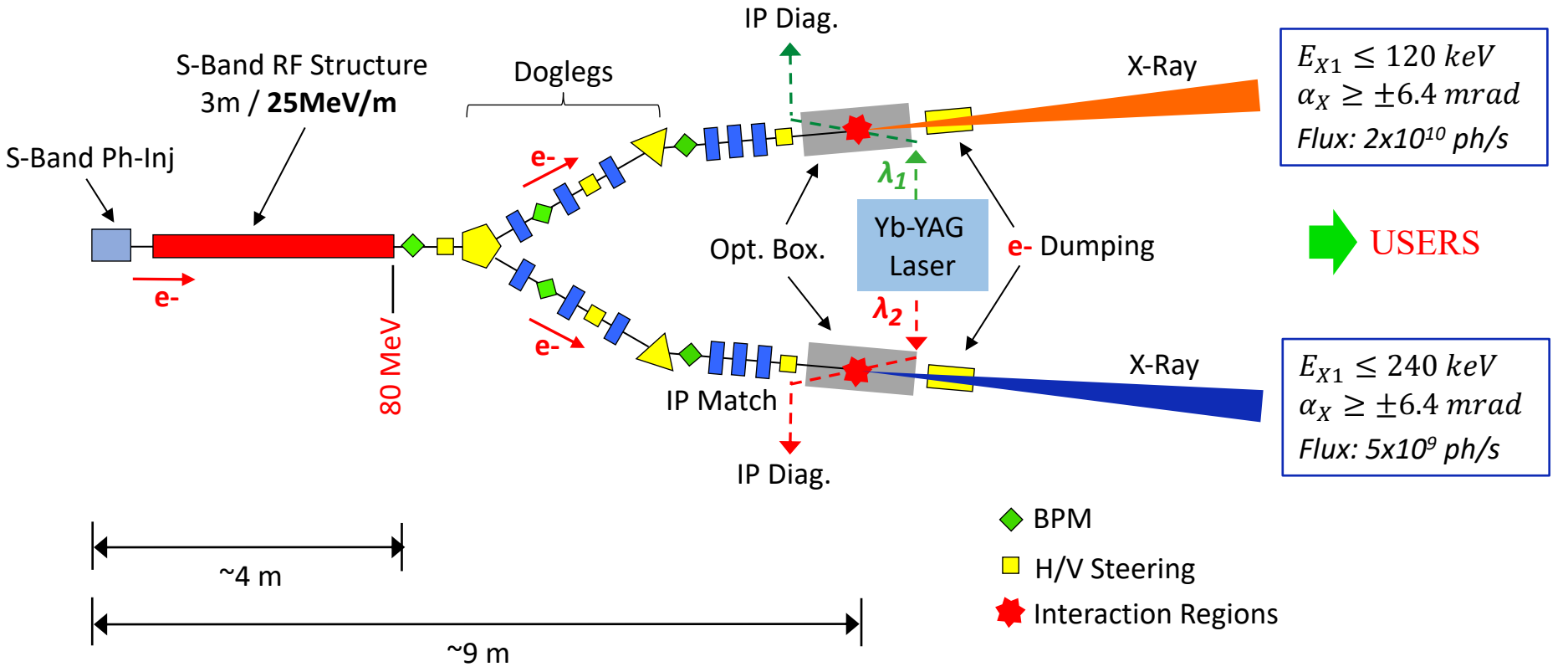
- Accelerator-Driven Compact X-ray Source
- STAR-like
- Energy Tunable and Upgradable
- OTS components
- Contained Footprint
- Twin User Areas

# BoCXS: A COMPACT X-Ray SOURCE

**An Advanced Medical Imaging Facility**
**in the center of a Scientific Triangle**

The availability of a **Compact Source** offering
*Synchrotron-like quality X-ray beams for*
*Improved Medical / Pre-clinic*
*Imaging and Diagnostics*
at a ***fraction of cost and footprint***
would represent an **Invaluable Option**
for **Clinics** and **University-size Laboratories**

# Double Arm S-Band STAR-like Source




$E_{X1} \leq 120\ keV$
$\alpha_X \geq \pm 6.4\ mrad$
*Flux: 2x10¹⁰ ph/s*

USERS

$E_{X1} \leq 240\ keV$
$\alpha_X \geq \pm 6.4\ mrad$
*Flux: 5x10⁹ ph/s*

**FOOTPRINT ~ 3 x 9 m²**

# SHORT PARAMETER LIST

Scattered Photon **Energy** scales with the **square** of the **electron Energy** and the **Laser Harmonic**

$$E_X = 1.9 \cdot 10^{-2} \frac{E_e^2(MeV)}{\lambda_{ph}^0(\mu m)} h_L$$

| SOURCE | PARAMETER | | VALUE |
|---|---|---|---|
| LINAC | Energy | *MeV* | 80 |
| | Bunch charge | *pC* | 500 |
| | Bunch length | *ps* | 3.5 |
| | Peak current | *A* | 140 |
| | Avg. current | *μA* | 0.05 |
| | Rep. Rate | *Hz* | 100 |
| Yb-YAG LASER | Pulse Energy | *J* | 0.85 |
| | Wavelength | *nm* | 1024-512 |
| | Harmonic $h_L$ | | 1-2 |
| | Pulse duration | *ps* | 5 |
| | Rep. Rate | *Hz* | 100 |
| X-ray | Energy | *keV* | 120-240 |
| | Pulse duration | *ps* | <5 |
| | Flux | *ph/s* | (2-0.5)x$10^{10}$ |
| | Divergence | *mrad* | +/- 6.4 |

Scattered Photon **Flux** scales with the **Linac current** and the **Inverse square** of the the **Laser Harmonic**

$$\dot{N}_X = \sigma_T L = \frac{\sigma_T}{A(\varphi)} \frac{E_{LP}^0 I_{linac}}{e\,hc} \frac{\lambda_{ph}^0}{h_L^2}$$

# SYSTEM REQUIREMENTS / COMPETENCES

## Electron beam

- High average current
- Multi-bunch Photo-Injector option

**Linac Technology** — LNF – INFN MI – UNIBO

## Laser system

- High Pulse Energy (close to 1J)
- Recirculator option

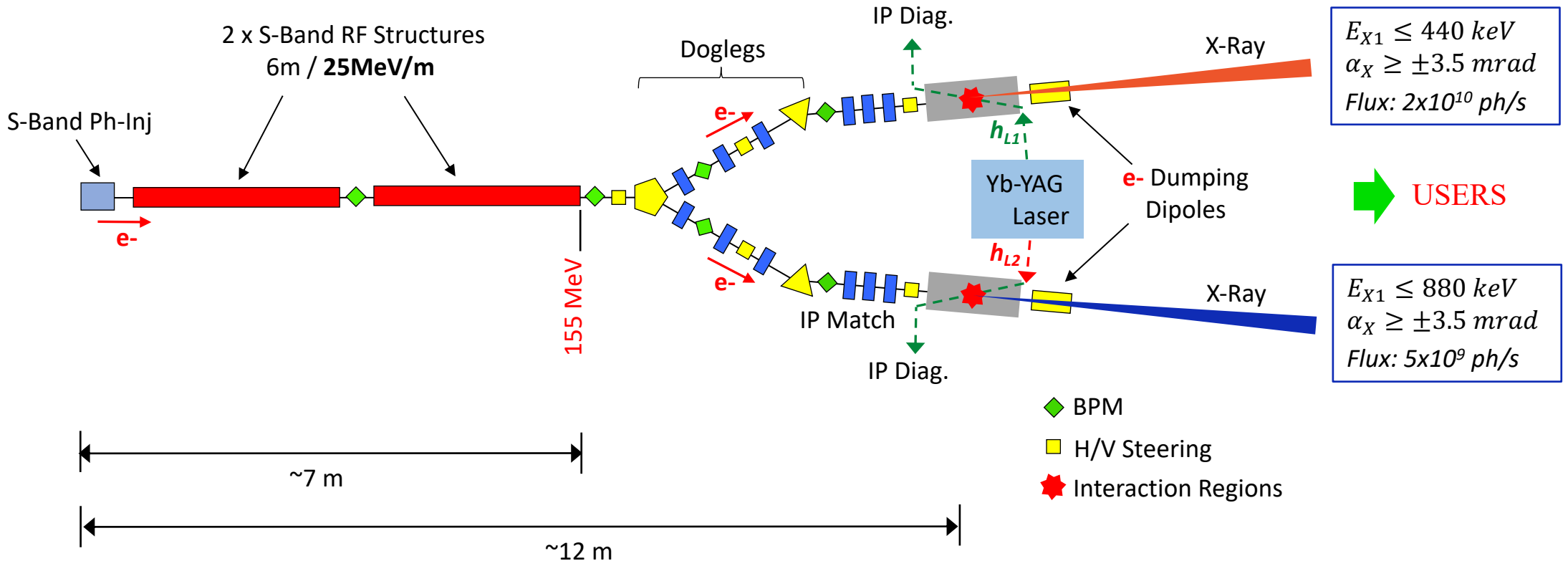
**Non-linear Optics** — LNF – INFN MI

## Scattered radiation

- Monochromaticity
- High Brilliance
- Energy tunability
- Spatial coherence
- Dual color option

**X-ray Characterization and Manipulation** — UNIFE

# Upgraded S-Band STAR-like System




**FOOTPRINT ~ 3 x 12 m²**

# UPGRADING PHASES

***PHASE I*** – *e- ENERGY: 80 MeV*

*X-ray ENERGY : (120 – 240) keV*

*X-ray FLUX : (20 – 5)x10$^{9}$ ph/s*

*X-ray DIVERGENCE : +/- 6.4 mrad*

***PHASE II*** – *e- ENERGY: 155 MeV*

*X-ray ENERGY : (440 – 880) keV*

*X-ray FLUX : (20 – 5)x10$^{9}$ ph/s*

*X-ray DIVERGENCE : +/- 3.3 mrad*

Rep. rate = 100 Hz

Laser: Fund. & 2$^{nd}$ harm.

***PHASE III*** – *e- ENERGY: 155 MeV*

*X-ray ENERGY : (440 – 880) keV*

*X-ray FLUX : (6 – 1.5)x10$^{11}$ ph/s*

*X-ray DIVERGENCE : +/- 3.3 mrad*

Rep. rate = 3 kHz

Laser: Fund. & 2$^{nd}$ harm.

# OUTLOOK

**HIGH BRIGHTNESS, ENERGY-TUNABLE, QUASI-MONOCHROMATIC**

**X-ray BEAMS**

**PROVIDE ADVANCED BIOMEDICAL** AND **SOFT TISSUE IMAGING QUALITY**

- **IMPROVED SPACIAL RESOLUTION**
- **REDUCED BEAM EXPOSURE**
- **NO CONTRAST AGENTS** IN RADIOLOGICAL EXAMINATIONS
- **FRIENDLY TO PATIENTS** CARRYING **METALLIC IMPLANTS** AND/OR **STIMULATORS**

**A POTENTIALLY MULTIDISCIPLINARY**
**COMPACT ICS X-ray SOURCE**
**INSTALLED IN CLINICAL LABORATORIES OR UNIVERSITIES**
**WOULD REPRESENT AN INVALUABLE INSTRUMENT IN**
**BIOMEDICAL IMAGING DIAGNOSTICS**
**AND OTHER APPLICATIONS**

*A PROJECT IS A DREAM WITH A DEADLINE*

*THANK YOU FOR YOUR TIME*

# *SPARE SLIDES*

# MONOCHROMATIC X-ray SOURCES

FIGURE OF MERIT: **BRIGHTNESS**

"SPECIFIC FLUX"

*Photons/s/mm²/mrad²/0.1%BW*

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- **LOWER e- ENERGY**
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} ACCELERATOR DRIVEN

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# FREQUENCY BANDS IN PARTICLE ACCELERATORS

| BAND | $f_{RF}$ (GHz) | $\lambda_{RF}$ (cm) | | COMMON LIFE |
|---|---|---|---|---|
| **S** | 2.998 – 2.856 | 10.0 –10.5 | | Satellite communications |
| **C** | 5.996 – 5.712 | 5.0 –5.25 | S-Band 2nd harmonic | 5G technology |
| **X** | 11.9942 – 11.424 | 2.5 –2.62 | S-Band 4th harmonic | Radar applications |