BriXS: BRIght and compact X-ray Source

Expression of Interest[1]

This document delineates the motivations and the guidelines for the development of a compact machine to produce beams of high brilliance mono-chromatic tunable *X*-rays with energy in the range from 30 to 150 keV, aimed at constituting a unique facility located in the Milan metropolitan area, with performances comparable to those of modern synchrotron light sources, although associated to costs and dimensions smaller by at least one order of magnitude (from 100x100 m^2 down to 10x10 m^2, and from 100s M€ down to 10s M€), so to be compatible with locations inside a University Campus, a large Hospital, a Museum or a mid-size research infrastructure.

The focus on enabled applications by such a machine is on medical oriented research/investigations, mainly in the radio-diagnostics and radio-therapy fields, exploiting the unique features of mono-chromatic *X*-rays, as well as in micro-biological studies, and, within this mainstream, material studies, crystallography and museology for cultural heritage investigations. Mono-chromatic bright *X*-ray beams have been already proven to be a unique tool for advanced imaging at the sub 0.1 mm resolution scale with tremendous reduction in the radiation dose to tissues, joined to an upgraded signal-to-noise and visibility enhancement via phase contrast imaging.

The underlying enabling technology is the one on the strong rise over the last decade, with an effective ongoing transition from R&D and demonstrative machines towards effective user facilities, based on Thomson/Compton back-scattering *X/γ*-ray Sources, also known as Inverse Compton Sources (ICS).

INFN, University of Milan and Politecnico di Milano hold a strong leadership in the strategic fields of expertise at the backbone of the development and implementation of the involved technologies for a machine like BriXS: design and theory of Compton Sources, advanced Optical Cavities, high intensity Lasers, Super-conducting RF Cavities and Linacs, high gradient Magnets, Detectors for characterization of ultra high brilliance *X*-ray beams as those typical of 4th generation Light Sources (FEL's).

A strong synergy among all these fields of expertise, combined to a long term vision of evolutionary development for BriXS, would give to the Milan metropolitan area and its possible stake-holders like University of Milan, Politecnico di Milano, INFN and local Hospitals/IRCCS, a unique opportunity to develop in a reasonable short time (3 years) and with a moderate investment (30-50 M€) a unique facility in Europe, where to conduct inter and multi-disciplinary research with advanced *X*-rays, electron beams and photon beams, bringing to the Lombardia Region and the whole national community a research infrastructure with world-wide rank performances.

As a matter of fact the most commonly used figure of merit for radiation sources is the brightness, *i.e.* the number of photons delivered per second, per unit bandwidth and per unit solid angle of beam collimation. As shown in Fig.1, synchrotron light sources stand well above all other radiation sources in the photon energy range 10 eV – 50 keV. Free Electron Lasers are even higher out of scale of the figure (several orders of magnitude above) in the 100 eV – 20 keV range. Conventional *X*-ray tubes, even in the new upgraded Metal Jet version, Plasma discharge sources and HHG sources are well below in brightness performances.

On the other hand, Thomson/Compton Sources can compete in the region above 20 keV with mid-size synchrotrons (like Elettra) and above 100 keV even with large size synchrotrons like APS, ESRF or Spring8, the few facilities world-wide capable to deliver *X*-ray beams in excess of 100 keV, though costing of the order of 1 G€. As a matter of fact synchrotron light sources are very powerful tools of investigation but not very practical for some applications, due to the limited

[1] Version 2.3

access time and the large scale of costs and dimensions: compact sources like BriXS could exploit methods currently used at synchrotrons (diffraction, absorption, diffusion, imaging, spectroscopy) and implement them in a laboratory size environment. In particular, while patients are very occasionally taken to a synchrotron light source facility for clinical investigations, due to obvious logistic and legal issues, a machine like BriXS may offer the opportunity to take the machine into the hospital and diagnose/treat patients where they belong.

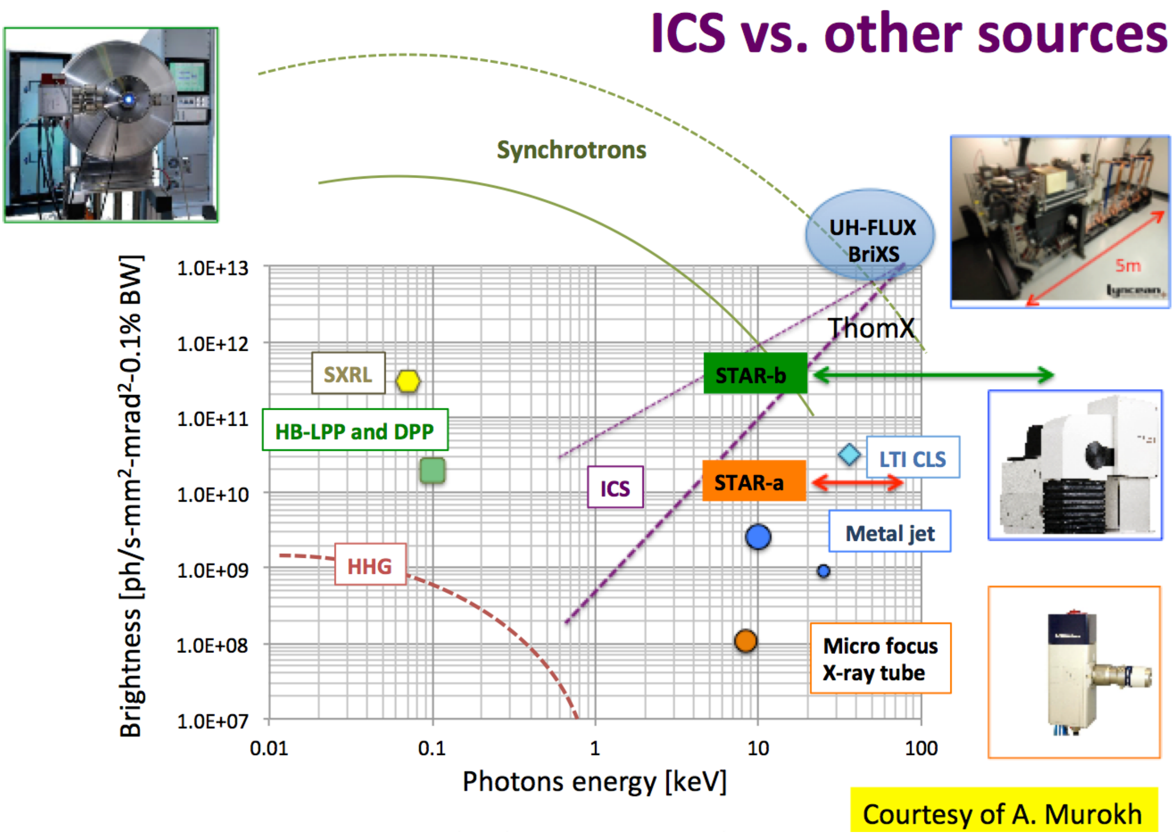


Fig.1 *– Brightness of several radiation sources as a function of the photon energy. Thomson Sources (LTI-CLS,ThomX, STAR, UH-FLUX and BriXS) are compared to Synchrotron Light Sources and the most performing X-ray tube so far (Metal Jet).*

1) Thomson back-scattering – a new technology for compact, bright X-ray Sources

Thomson/Compton Sources are based on the collision between a high brightness electron beam and a high intensity laser pulse, in order to create back-scattered photons via Thomson/Compton back-scattering. They consist basically in mini electron-photon colliders, exploiting the large blue-shift imparted to the laser optical photon by the back-scattering mechanism, promoting (*accelerating*) the photon to *X*-ray energies according to $E_X = 4\gamma^2 E_L / \left(1+\gamma^2\vartheta^2\right)$; $\gamma = 1 + \frac{T_e}{m_e c^2}$; $m_e c^2 = 0.511\ MeV$, where E_L is the laser photon energy, T_e the electron kinetic energy and E_X the energy of the *X*-ray back-scattered photon (ϑ is the scattering angle). As an example, with $E_L = 1.2\ eV$ (typical of a 1 μm wavelength laser) and $T_e = 70\ MeV$ (typical of a compact electron accelerator) we obtain an energy for the forward scattered photons (at $\vartheta = 0$, *i.e.* in the direction of the electron, and opposite to the laser photon that is back-scattered) of E_X = 91 keV. When the electron energy is below 100 MeV and the *X*-ray energy typically lower than 200 keV, the back-scattering reaction doesn't imply any recoil of the electron in its own rest frame, so that the scattering is at all similar to elastic Thomson scattering and can be treated by means of classical electro-dynamics (quantum effects are negligible). For this reason in the literature sometimes Compton Sources are referred as Thomson Sources when the *X*-ray energies are lower than about 200 keV. In the following we'll use ICS for both regimes (Inverse Compton Source), but we recall that a machine like BriXS will operate in the Thomson regime.

The price to pay to such a nice "*photon accelerator*" scheme is a low efficiency in transforming the laser photons into *X*-ray photons via the back-scattering mechanism. The cross section of Thomson/Compton back-scattering is unfortunately very small, so we need to run a high luminosity collider in order to generate an intense *X*-ray beam: to achieve an operating regime so that almost each electron scatters at least one laser photon, the luminosity required must exceed that of large colliders like LHC! This in turns implies the need to collide extremely dense laser and electron beams, with the request for micron sized beams at the collision point, carried by pulses which are picosecond long. It is quite like making two thin hairs travelling at the speed of light to collide precisely one against each other… However, the production of intense laser beams and high brightness electron beams meeting these tight requirements is nowadays state of the art. The real challenge of ICSources is to make these electron-photon collisions to occur in a stable and controllable fashion, such to generate *X*-ray beams with the requested stability, reliability and tunability to the end users, as much as it is routinely achieved in the operation of synchrotron light sources.

The achievable *X*-ray flux by an ICS is approximately given by:

$$N_X^{bw} = 5.8 \cdot 10^8 \frac{U_L[J]Q[pC]f_{RF}}{\sigma_x^2[\mu m^2]} \gamma^2 \vartheta^2 \qquad [1]$$

where N_X^{bw} is the number of *X*-ray photons produced per second within a collimation forward angle ϑ, a rms bandwidth specified by *bw*, while U_L is the energy carried by the laser pulse (1 μm wavelength) colliding with an electron bunch of charge Q (f_{RF} is the repetition rate of the collision, in unit of 1/second). Both laser and electron beams collide at an interaction point (IP) with rms transverse sizes σ_x. Just as a reference mark, radiological imaging is currently applied with fluxes at least from 10^{11} up to 10^{12} *X*-ray photons/sec with the typical broad-band spectrum (*bw*>40%) of bremsstrahlung radiation sources (conventional *X*-ray tubes). In order to achieve similar fluxes with a quasi-monochromatic *X*-ray beam ($bw \cong 10\%$) an ICS should be operated with the following parameters: $U_L = 0.4\ J, Q = 1\ nC, f_{RF} = 3.2\ kHz, \sigma_x = 15\ \mu m$, which implies an achievable flux of about $N_X^{bw} = 3.3 \cdot 10^{11}$ photons/second.

The rms *X*-ray beam bandwidth bw is instead approximately given by:

$$bw = \frac{\Delta\nu_X}{\nu_X} \cong \sqrt{\left(\frac{\gamma^2\vartheta^2}{\sqrt{12}} \Big/ \left(1+\gamma^2\vartheta^2/2\right) + \frac{2\varepsilon_n^2}{\sigma_x^2}\right)^2 + \left(2\frac{\Delta\gamma}{\gamma}\right)^2 + \left(\frac{\Delta\nu_L}{\nu_L}\right)^2 + \left(\frac{M^2\lambda_L}{2\pi w_0}\right)^4 + \left(\frac{a_0^2/3}{1+a_0^2/2}\right)^2} \qquad [2]$$

expressed in terms of the *X*-ray photon frequency ν_X, scaling like the collimation angle ϑ, and the electron beam overall quality (defined by its energy spread $\frac{\Delta\gamma}{\gamma}$ and rms normalized transverse emittance ε_n) and the laser beam quality (defined by its bandwidth $\frac{\Delta\nu_L}{\nu_L}$, its mode purity M^2 and laser parameter a_0, accounting for non-linear multi-photon effects in the back-scattering – this dimensionless parameter must be kept well below 1 to avoid serious bandwidth broadening due to non linearities, which in turns forbid using *Ti:Sa* high intensity ultra short laser systems as interaction laser). It is clearly evident the need of high brightness electron beams, carrying high charge bunches at low emittance and energy spread, combined with high quality high intensity lasers, carrying high energy per pulse with picosecond long pulses with small bandwidth and high mode purity ($M^2 \cong 1$). The former requirement points clearly to electron accelerators typical of Free Electron Lasers, while the latter indicates laser systems capable of high repetition rate and large average power, combined to short pulses and mode-locking to assure synchronization at the sub-picosecond level between the electron beam and the laser pulse at the Interaction Point.

For an overview of the physics and technology challenges of Inverse Compton Sources see a selection of publications reported in the references [1-8].

Presently there are 3 main Paradigms for high performance ICS:

A) RF Photo-injector producing a high charge 1-2 nC electron bunch against a J-class laser pulse delivered by an amplified *Yb:Yag* laser system, tightly focused down to 10-20 μm, running collisions at 100 Hz. Best example of this model is STAR [9] (Southern europe Thomson source for Applied Research), in construction as a dedicated user facility at the University of Calabria (Italy) by a collaboration INFN-ST-CNISM-UniCal. Maximum achievable fluxes in excess of $3 \cdot 10^{11}$ with maximum photon energy 200 keV.

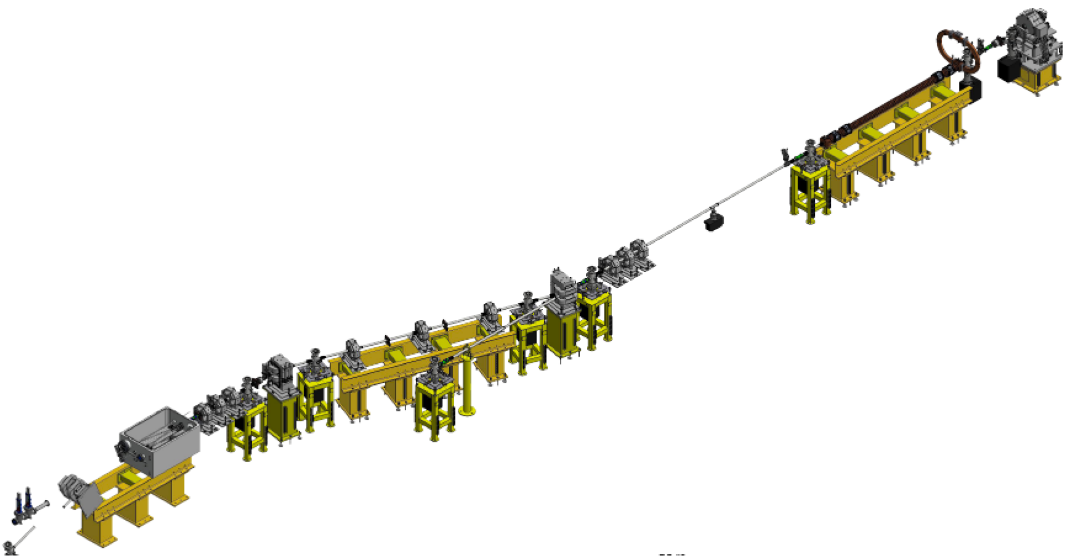


Fig.2 *– STAR machine as an example of Paradigm A. Overall length about 12 m.*

B) Compact Storage Ring for the electron beam, colliding at a high repetititon rate (up to 25 MHz, *i.e.* an average beam current of 15 mA) a moderately high charge electron bunch with a mJ-class laser pulse stored in an optical Fabry-Perot Cavity [17], focused to 70 μm spot size at collision. Best example of this category is ThomX, in construction at Orsay-LAL by a collaboration IN2P3-Universite' de Paris Sud. Maximum achievable fluxes about $5 \cdot 10^{12}$. Maximum photon energy 90 keV [10]. A commercially available ICS of this type is currently available from the company Lyncean Tech., named LTI-CLS: its performances are a maximum photon flux of $5 \cdot 10^{10}$ and a maximum photon energy of 35 keV. The unofficially declared cost of such a system is about 8-10 M€.

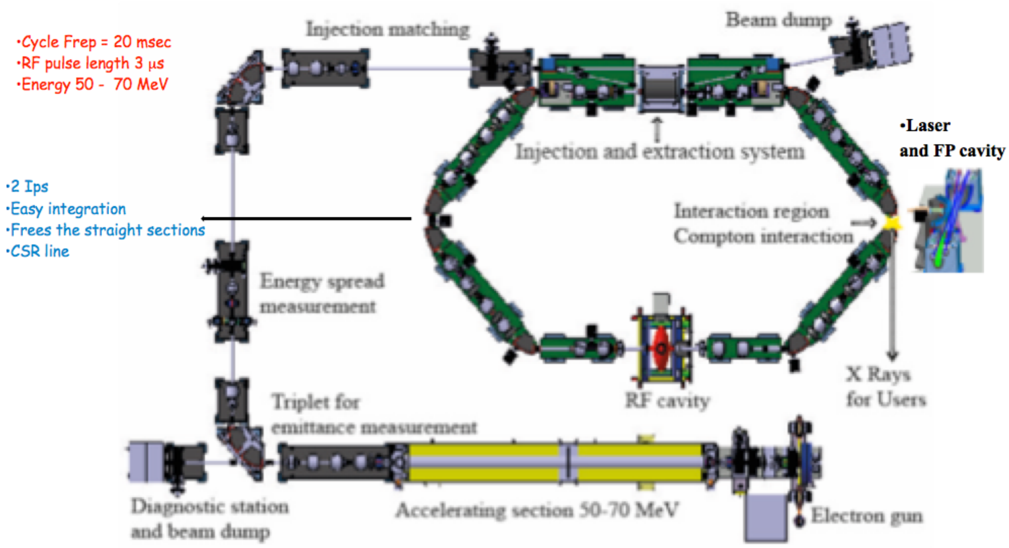
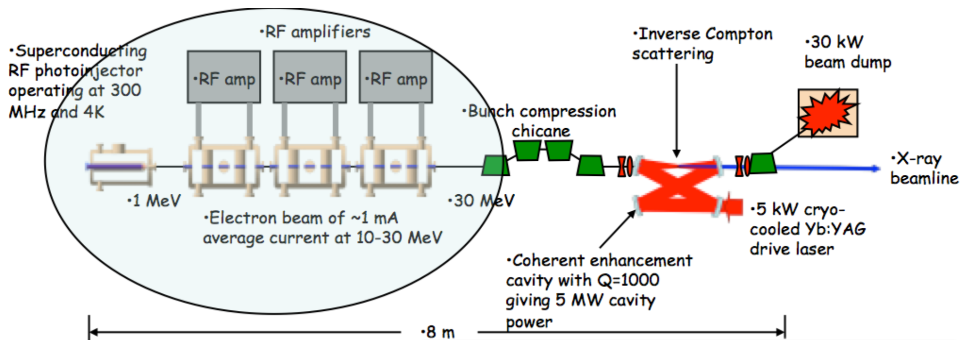


Fig.3 *– ThomX as an example of Paradigm B. Size is about 10x10 m^2.*

C) Super-Conducting RF Photo-Injector delivering a low charge (tens of pC) electron bunch at a very high rep. rate (up to 100 MHz), colliding with a mJ-class laser pulse stored in an optical Fabry-Perot Cavity (up to 1 MW stored laser power), focused to 20-30 μm spot size at collision. Maximum achievable fluxes about $3.5 \cdot 10^{12}$ without energy recovery (average electron beam current 1 mA) while in excess of an impressive 10^{15} with energy recovery at an average electron current of 100 mA. Maximum photon energy 200 keV. BriXS would belong to this type of ICS, together with UH-FLUX, a similar project [11] in development in UK (with energy recovery) and CUBIX, an ongoing project [12] at MIT (without energy recovery).



SRF Linac Parameters	
Energy gain [MeV]	25
RF frequency [MHz]	352
Average current [mA]	1
Operating temperature [K]	4.2
RF power [kW]	30

Parameter	Single shot	High flux
Tunable photon energy (keV)	3–30	
Pulse length (ps)	2	0.1
Flux per shot (photons)	1×10^{10}	3×10^{6}
Repetition rate (Hz)	10	10^{8}
Average flux (photons/s)	1×10^{11}	3×10^{14}
On-axis bandwidth (%)	2	1
RMS divergence (mrad)	5	1
Source RMS size (mm)	0.006	0.002
Peak brilliance (photons/(s mm^2 mrad^2 0.1%bw))	6×10^{22}	6×10^{19}
Average brilliance (photons/(s mm^2 mrad^2 0.1%bw))	6×10^{11}	2×10^{15}

•W.S.Graves

Fig.4 *– MIT CUBIX SC-CW ICS as an example of Paradigm C without energy recovery (average electron beam current up to 1 mA).*

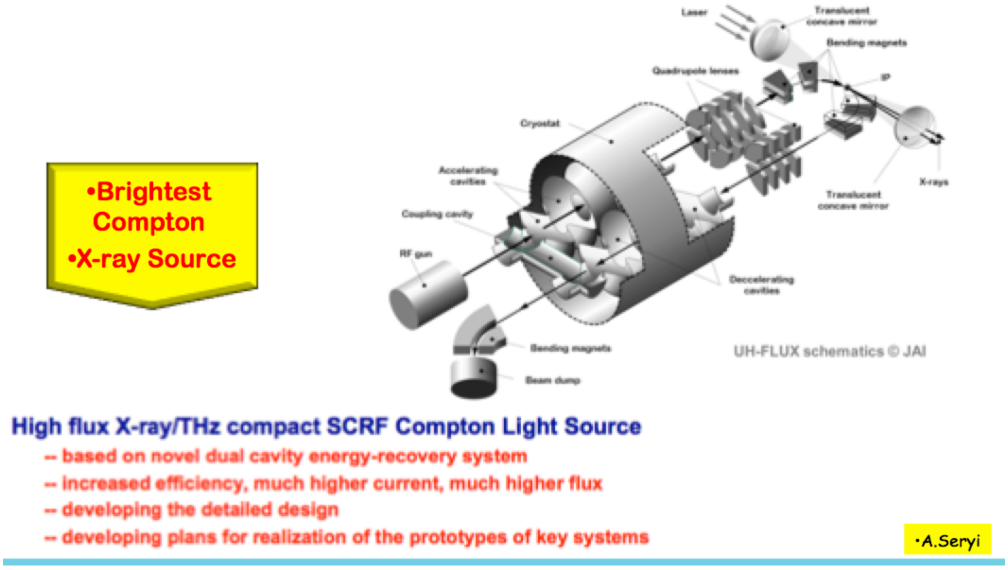


Fig.5 *– UH-FLUX as an example of Paradigm C with energy recovery (average electron beam current up to 100 mA).*

The performances in terms of achievable brightness of the *X*-ray beam delivered to users by these 3 types of ICS's are summarized in Figure 1. Only BriXS with energy recovery and UH-FLUX can reach and even overcome synchrotrons. This will happen when the average electron beam current will exceed 100 mA, and the laser power stored in the Fabry-Perot optical cavity will reach 1 MW. Indeed the *X*-ray flux achievable by this ICS configuration is expressed approximately in Eq. 3 below, in terms of the average electron beam current $\langle I_e \rangle$, the laser power P_{FP} stored in the Fabry-Perot cavity and the effective repetition rate of collisions f_{FP} .

$$N_X^{bw} = 1.4 \cdot 10^{17} \frac{P_{FP}[MW]\langle I_e \rangle [mA]}{f_{FP}[MHz]\sigma_x^2[\mu m^2]} \gamma^2 \vartheta^2 \qquad (3)$$

In any of the 3 paradigms mentioned above the ICS delivers a sequence of picosecond long *X*-ray radiation pulses (quite shorter than synchrotron light sources) with full control of the polarization of the emitted radiation, from linear to circular to elliptical. Furthermore, the small and round size of the emitting source (round spots in the range 10-80 μm), makes possible to fully exploit the edge enhancement effect due to phase contrast associated to local transverse coherence of the radiation beam (after propagating a significant length from the source to the end user – tens of meters). A key issue for advanced radio-logical imaging applications.

The advantages of paradimg A) are: the beam emittance is quite smaller thanks to high gradient RF fields in the accelerator, allowing to focus the electron beam to smaller spot sizes at IP (10-20 μm). Thanks also to the fact that the electron beam is dumped after any collision. Same holds for the laser pulse, except for a possible option of implementing a laser recirculator [8] as for the ELI-NP-GBS project [7], that allows to multiply at each RF pulse the number of collisions by a significant factor (16 to 32), hence the effective *X*-ray flux to the end user (the effective rep. rate goes up from 100 Hz to a few kHz). Main drawback of this paradigm is the low repetition rate achievable, about 100 Hz in the present state of the art (limited not only by RF but also by collision laser capabilities) without laser recirculation, that is to be still experimentally proven. The machine can be easily upgraded in energy just by adding more RF accelerating structures: as a matter of fact nuclear photon energies in excess of 20 MeV can be achieved by GeV-class RF Linacs based ICS like the one in development for ELI-NP-GBS.

The advantage of paradigm B) is the high rep rate allowed by storing the electron beam in a ring, which is also its main source of limitations, mainly due to beam instabilities at such low energies (50 MeV) that prevent to focus tightly the beam at IP and to use a very intense laser colliding with the electron beam. Energy upgrade is also an issue, since it involves re-designing the machine. Pulsed operation is also quite hard to implement.

The appealing characteristic of paradigm C) is the possibility to merge the typical Linac based operation (dumping the beam after collision at IP) with the typical high repetition rate of a storage ring (tens up to hundreds of MHz) thanks to the super-conducting operation of RF cavities used to accelerate the electron beam. In case of energy recovery the average electron beam current can easily overpass 20 mA, which is sort of the maximum level for storage rings of paradigm B) operated at low electron energy (50 MeV typically, to be compared to 1-5 GeV of synchrotron light sources), reaching 100 mA, comparable to synchrotron light sources. One of the main challenge of this paradigm is the electron beam injector, in particular in terms of the achievable average electron beam current associated to small emittance and overall good beam quality. Present state of the art is about 10 mA [13], with several projects world-wide aiming at 100 mA and above [14]. The conceivement of BriXs has been mutuated in spirit from a previous proposal dealing with CW SC Linacs driving FEL's and Compton Sources in the context of a broad spectrum inter-disciplinary large research infrastructure aiming at delivering advanced beams of electrons, photons, neutrons and positrons for basic and applied physics [21].

A strategic vision of development for BriXS would certainly envision an evolutionary mode of construction modulated into 2 phases: a first phase without energy recovery (electron beam current 1 mA), assuring moderate risk associated to performances capable to serve all medical applications ($3.5\cdot 10^{12}$ photons/s), followed by a second phase of upgrade to energy recovery, reaching up to 100 mA average electron beam current, to achieve 10^{15} photons/s, so to enable several other applications in micro-biology, crystallography, material studies and more advanced medical applications.

Such an evolutionary strategy for the development of BriXS is delineated in the parameter lists of performances representing the goals of each of the 2 phases, as shown in Tables 1 and 2 below. Table 0 lists the performance parameters expected during the commissioning phase.

***Table 0** – BriXS commissioning phase performances*

Electron beam energy (MeV)	Electron beam average current (μA)	Stored laser power in FP cavity (MW)	X-ray photon energy range (keV)	X-ray flux (photons/s) @ 10% bdw
70	**300**	**0.15**	**20-90**	**10^{11}**

***Table 1** – BriXS first phase performances*

Electron beam energy (MeV)	Electron beam average current (mA)	Stored laser power in FP cavity (MW)	X-ray photon energy range (keV)	X-ray flux (photons/s *) @ 10% bdw
70	**1**	**0.3**	**20-90**	**10^{12}**

* effective collision repetition rate 100 MHz and collision spot size 20 μm

Table 2 – BriXS second phase performances

Electron beam energy (MeV)	Electron beam average current (mA)	Stored laser power in FP cavity (MW)	X-ray photon energy range (keV)	X-ray flux (photons/s *) @ 10% bdw
100	**100**	**1**	**20-200**	$\mathbf{10^{15}}$

* effective collision repetition rate 100 MHz and collision spot size 12 μm

A tentative conceptual lay-out for BriXS may be as the one shown in Fig.6 below. It is based on a Tigner-Variola *push-and-pull* 2-Linac ERL (Energy Recovery Linac) scheme, just wrapped on itself in order to halve the overall length of the machine (this is possible at the typical BriXS low electron energies, unlike in the TeV electron-positron collider scenario where Tigner firstly proposed his concept [20]).

In BriXS first phase there would be only one injector and one electron beam (max average current 1 mA), that would be accelerated into the first XFEL module (5 SC cavities operated at about 10 MV/m accelerating gradient, plus an initial matching section made of SC solenoids and bunching/matching short RF SC cavities). The second XFEL module would de-celerate the beam down to about 2 MeV energy so to lower the demands on the beam dump about the effective beam power (lower than 5 kW). Running at low beam currents (*i.e.* below 100 μA) the second XFEL module would instead accelerate the electron beam up to higher energies (in the range 100-240 MeV), so to drive experiments of radiation generated in crystals, micro-undulators, etc.

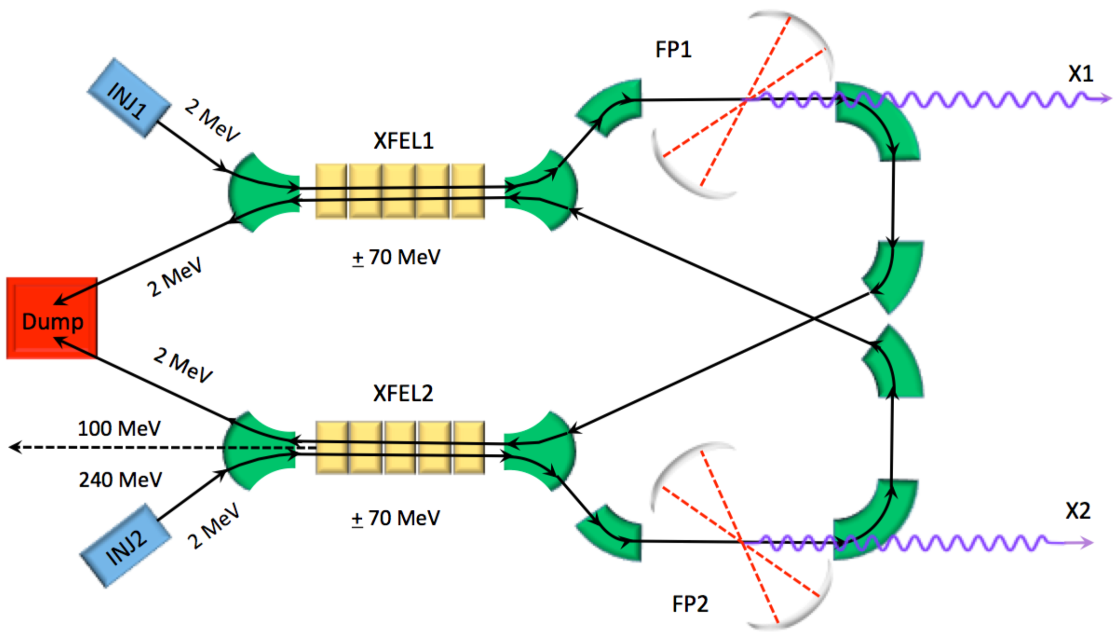


Fig.6 *– BriXS conceptual lay-out, based on a wrapped push-and-pull modified Tigner-Variola scheme.*

In BriXS second phase there would be a second injector delivering a second electron beam with same characteristics of average beam current and beam quality of the first one, so to drive a second Fabry-Perot optical cavity and a second independent *X*-ray beam-line. The two electron beams would then be re-combined at the exit of the 2 XFEL modules in such a way to counter-propagate inside the modules and compensate for the average beam current seen by cavities, hence the beam power transferred from-to the RF power sources. This energy recovery scheme should allow to reach much higher average currents, say up to 100 mA, compatibly with capabilites of the injectors. A possible option for a further optimized and simplified lay-out is shown in Fig. 6b, where a single Fabry-Perot cavity is driven by two electron beams in such a way to feed 2 independent *X*-ray beam-line. A complete analisys at the stage of project design is clearly required in order to evaluate advantages and drawbacks of both schemes.

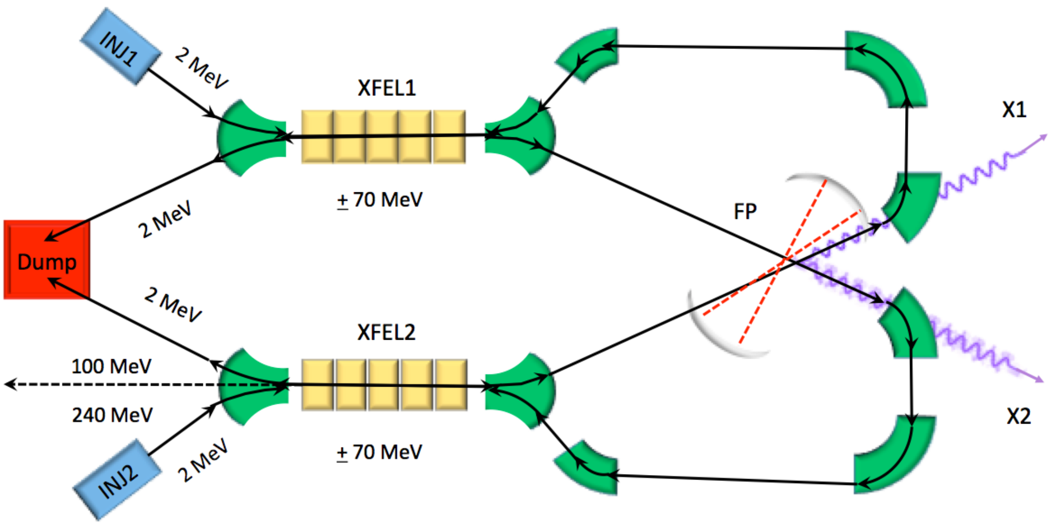


Fig.6b *– Optimized BriXS conceptual lay-out, capable to feed 2 independent X-ray beam lines with one single Fabry-Perot optical cavity.*

Furthermore, the choice on RF frequency for the Super-Conducting accelerating cavities, and the corresponding cryo-module for the Linac structure, should be taken in the course of preparing a detailed project for the BriXS electron machine, making a reasonable compromise between a higher accelerating gradient achievable with XFEL L-band SC cavities and a higher substainable average beam current that low frequency cavities like LEP-II ones can obtain (taking HOM coupler requirements/limitations under careful consideration).

2) Applications and Research enabled by BriXS

In the following we present some of the main applications enabled by BriXS. Most of them are actually based on imaging of biological and/or living tissues, *i.e.* radiology. This will be the field of investigation best suited for performances expected in phase 1. Material Science applications are on the other hand more challenging and demanding for higher fluxes, brightness, so they will typically be fully enabled by BriXS phase 2.

2.1) Radio-logical Imaging

According to a very comprehensive overview recently presented at the PAHBB-2016 Workshop (see https://agenda.infn.it/conferenceDisplay.py?confId=11130) by A. Variola (INFN-LNF), there is a rich bouquet of radio-logical imaging applications that can be pursued with mono-chromatic, tunable and micron-sized *X*-ray beams. These range from edge-enhanced imaging based on phase contrast to seleptive absorption around a K-edge of a selected material, to micro-tomography with sub-mm spatial resolution. Some impressive results obtained at synchrotrons are shown schematically in Fig.7 below.

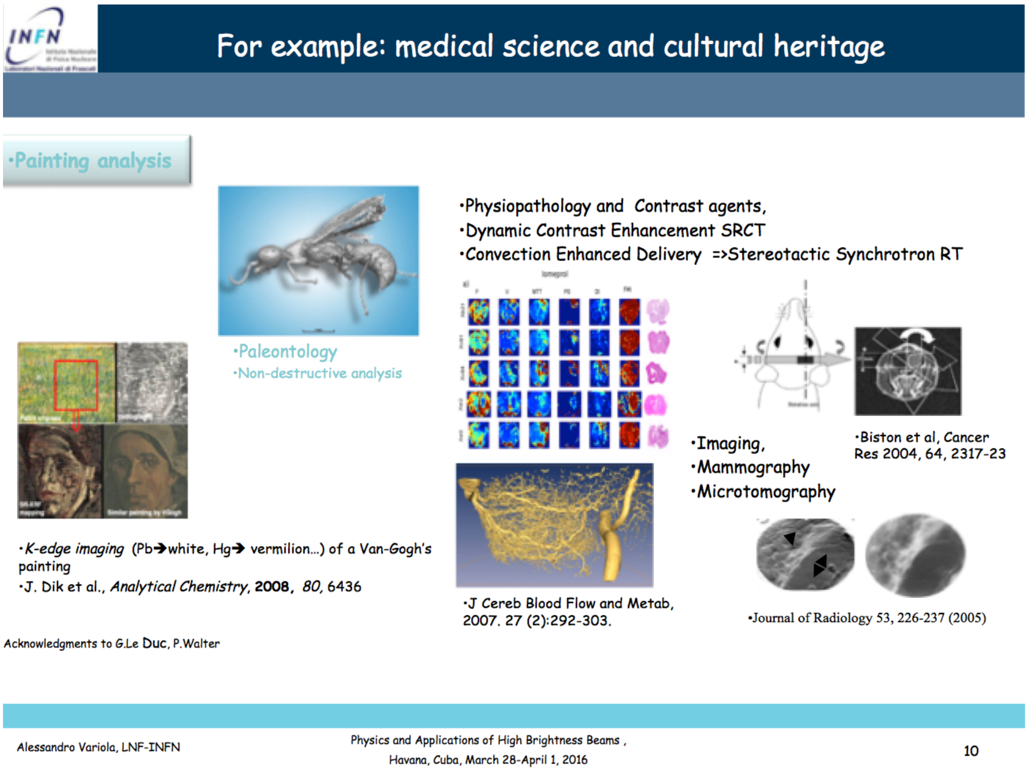


Fig.7 *– Overview of radio-logical imaging applications enabled by BriXS.*

Fig. 8 shows some important results achieved in mammography, displaying again high spatial resolution (sub mm) and high visibility of micro-calcification nodules, combined to lower dose delivered to tissue (a very crucial figure of merit for mass screening diagnostics, where the sensitivity of the radio-diagnostics to the presence of possible tumors must be balanced to the risk of inducing secondary tumors by the dose delivered to healthy tissues [18]).

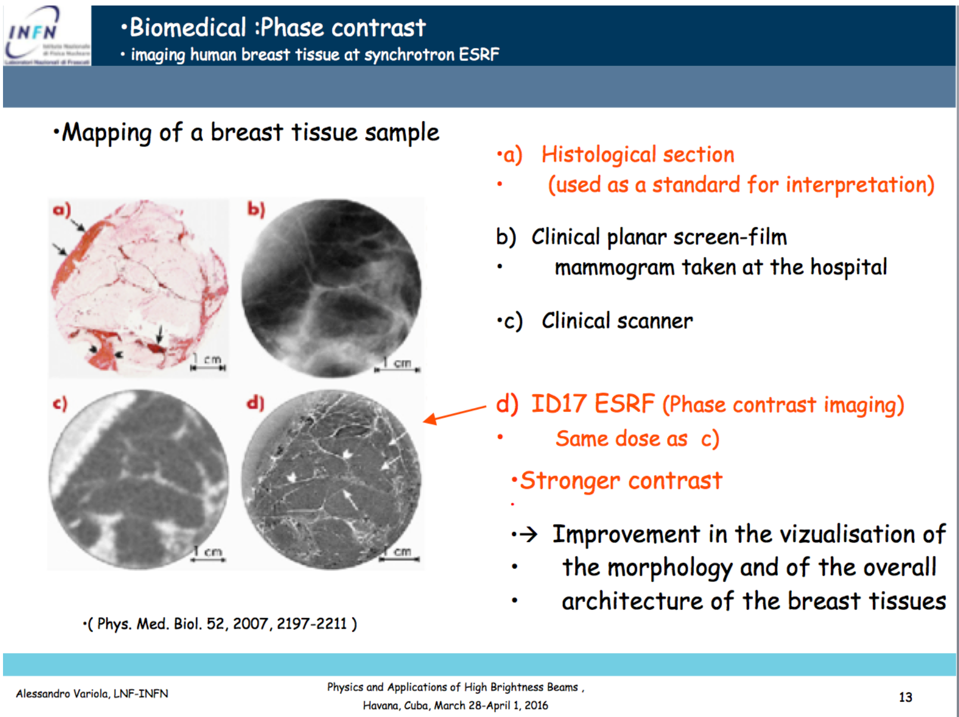


Fig.8 *– Mammographic applications with mono-chromatic X-rays.*

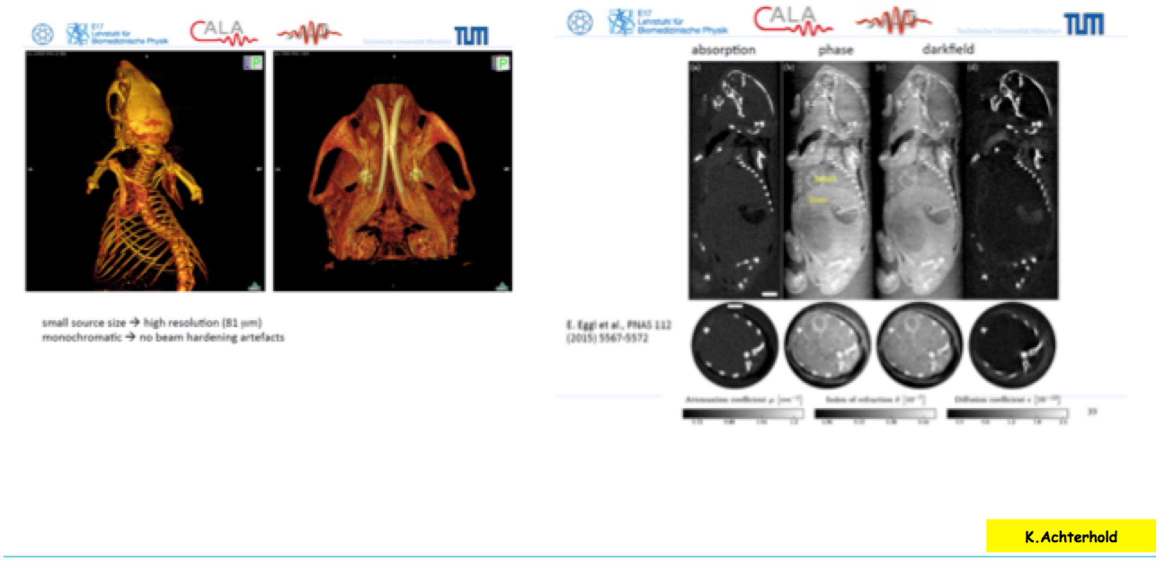


Fig.9 *– Phase contrast edge-enhancement imaging with ICS (LTI-CLS at CALA).*

Fig. 9 shows instead some of the first results achieved by an ICS presently in operation [15] at CALA in Munich (LTI-CLS), the very first Thomson Source supplied by a private company (Lyncean Technologies, www.lynceantech.com) and succesfully operated since early 2015, with measured *X*-ray spectra as shown in Fig.9b. As clearly shown by the radiographs, an impressive 80 μm spatial resolution was achieved, allowing to spot very fine details of the object under analysis (rat skeleton).

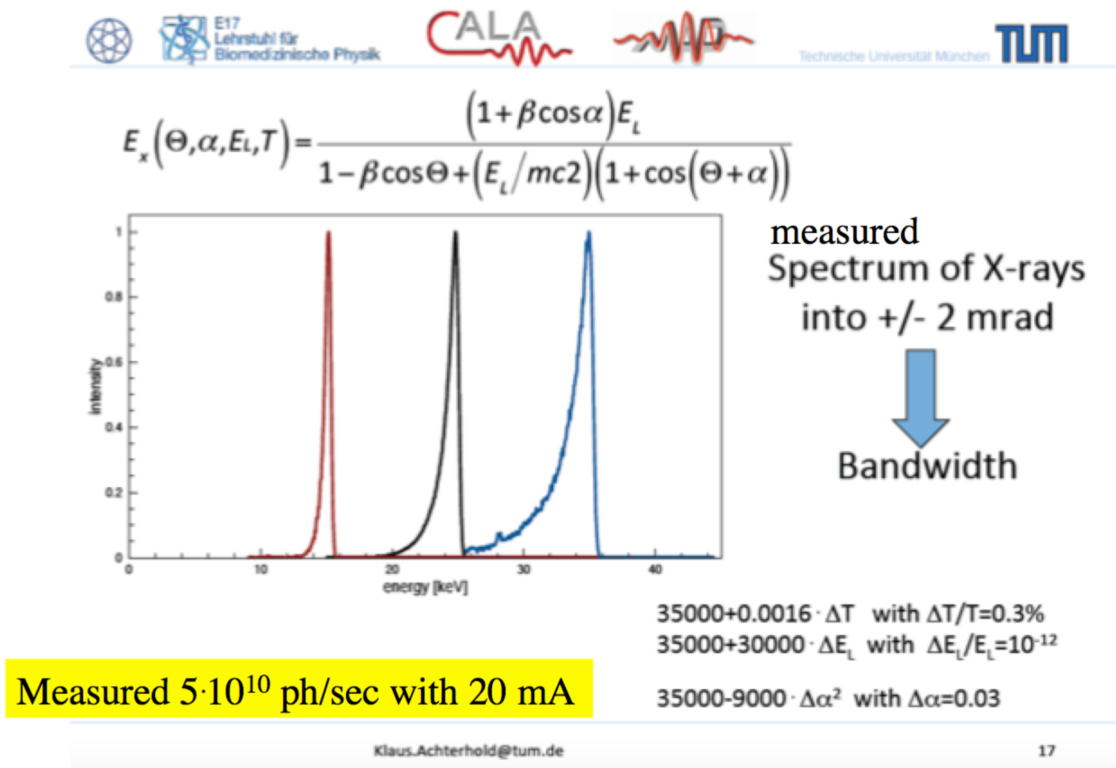


Fig.9b *– Measured X-ray spectra in use to obtain results shown in Fig.9.*

2.2) Radio-therapy with mono-chromatic X-rays

The most impressive achievement possibly enabled by a machine like BriXS is a new technique of radio-therapy[16] based on the use of nano-materials properly absorbed by the tumoral cells, which are targeted by the mono-chromatic *X*-ray beam with a preferential absorption via a K-edge selective excitation of Platinum (or Gadolinium) atoms, typically transferred into tumoral cells by a chemio-therapic drug like cisplatine, as illustrated in Fig.10. The requirement on photon flux of this technique is about 10^{13} photon/s with a moderate mono-chromaticity of 10% bandwidth and a tunable *X*-ray energy within the 50-90 keV range. Absorbed photons by platinum atoms trigger an Auger dis-excitation cascade that in turns deposits energy/dose very locally into the cell, with a substantial DNA damage caused by the radiation dose deposited almost only inside the tumor mass, where platinum atoms are present. Healthy tissues surrounding the tumor mass are substantially spared by being irradiated. Clearly the opportunity to locate a compact machine like BriXS inside a Hospital for full clinical implementation of such a radio-therapy technique on patients would be invaluable and likely the only viable solution for curing patients inside hospitals with this technique.

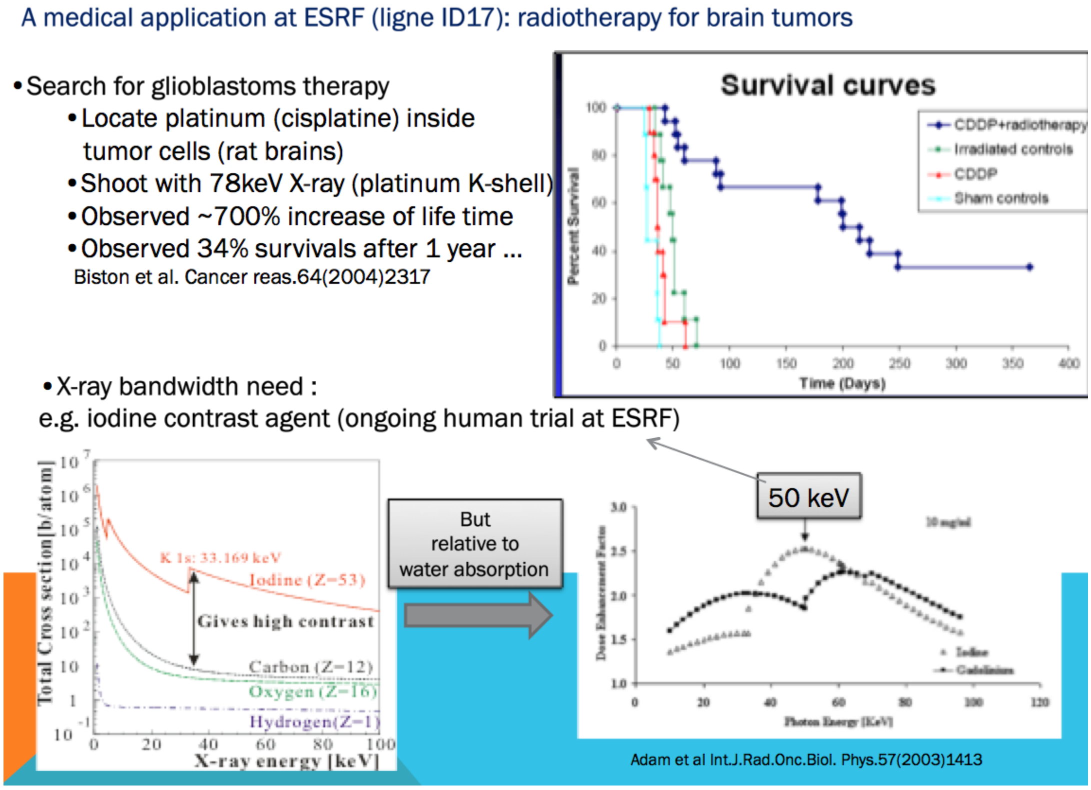


Fig.10 *– Radio-Therapy using mono-chromatic X-rays joined to cisplatine chemio-therapy for selected X-ray absorption inside tumoral cells.*

2.3) XRF applications with tunable, mono-chromatic, polarized, psec hard X-Rays

X-rays have become a powerful and widely used probe of the properties of matter, both in fundamental research and also in many different fields such as biology, chemistry, medicine, and so on. Nowadays more than 100 synchrotrons are in operation or under construction, along with several Free Electron Lasers emitting in the *X*-ray regime: these are the most powerful *X*-ray sources presently available, holding the record in average and peak brilliance of the photon beams. BriXS belongs to a new generation, with potentials to meet the major requests for *X*-ray sources, which actually consist in easily tuning their physical properties such as energy, polarization, time and spatial structure of the source. In BriXS the properties of the *X*-rays are directly determined by the properties of the colliding optical photons. This is a major advantage since tuning the properties of optical photons is straightforward and the ensuing flexibility is unmatched by synchrotrons and FEL's. The possibility to generate *X*-rays by easily tuning their properties might open a variety of applications not even conceivable until now.

On the other hand, by increasing the energy of the colliding electrons, the energy of the *X*-rays increases by reaching, for electron energies in the order of a few hundreds of MeV, the γ-ray range. This would represent the only possibility to generate, in a controlled way, high energy *X*-rays in a spectral region inaccessible by synchrotrons (> 150-200 keV).

One further aspect of BriXS is that the *X*-rays are generated by head-on collisions between bunches of electrons and laser light pulses. This leads to a true point-like *X*-ray source (round spots of about 10 μm in size), and the produced radiation beam has a spatial coherence unmatched by other sources and makes BriXS especially suitable for imaging, as discussed above in this document.

Furthermore, the *X*-ray experimental station of BriXS may be equipped with an *X*-ray fluorescence (XRF) spectroscopy detection system. It is well known that *X*-ray techniques are useful tools for the non-destructive investigation in the field of cultural heritage. Micro-XRF can be applied for the identification of reliable marker elements, which may be used for classification and provenance studies (Fig. 11). The availability of *X*-ray beam spot sizes of few tens of microns on the sample may be exploited for micro-*X*-ray fluorescence elemental mapping. By moving the sample laterally, and recording different XRF spectra, spatially resolved plots of the fluorescence intensities of the different elements in the sample can be obtained. Normally radiation has to be focused onto the sample using poly-capillary lenses and this reduces the available flux. Using the BriXS *X*-ray beam with optimized lay-out and a matrix of energy dispersive SDDs (Silicon Drift Detectors) fast micro-XRF mapping of samples can be performed. On the other hand also 3D micro-XRF can be exploited using the BriXS beam and an energy dispersive SDD detector coupled with a poly-capillary half lens (Fig. 11b). In this case the three-dimensional nature, *i.e.* the depth-resolved elemental composition as well as density variations of samples can be investigated.

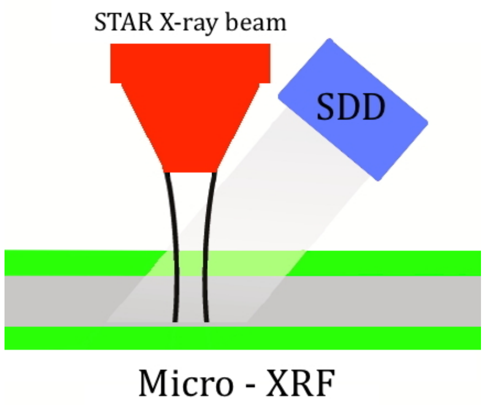


***Fig.11** – Micro-XRF system*

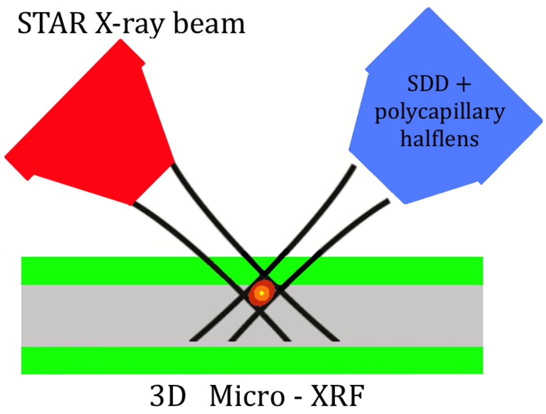


Fig.11b *– 3D micro-XRF system*

Despite the effort in developing suitable detectors for *X*-ray fluorescence measurements at synchrotron light sources, *i.e.* for XRF and XAFS experiments, in many applications the capability of fluorescence spectroscopy detectors is rather limited. The high-rate performances of current detectors may be further challenged due to the ongoing machine upgrades or for the use in future sources where a factor between 10 and 100 of beam-on-sample fluxes may be increased with respect to the present conditions. This will be a challenge also for ICS of type C, where rep. rate in excess of 10 MHz are expected. A new detector development aimed to cope with this challenge in the following years is ongoing [19]. The detector is based on monolithic arrays of SDDs (e.g. 8x8 units of 1mm2 area each) bump bonded to a readout ASIC containing the full CMOS readout chain, from the charge preamplifier to the ADC. Although the detector-ASIC bump bonding architecture is rather popular in *X*-ray imaging detectors domain, it has not been significantly explored for *X*-ray spectroscopy-grade detectors and surely not for SDDs. At the shortest possible processing time, *i.e.* 100 ns, an energy resolution better than 150 eV at 5.9 keV can be obtained, with an output counting rate larger than 1Mcps/channel, that, multiplied by the number of channels could allow to achieve several tens of Mcps/detector. This development could lead to a new generation of *X*-ray spectroscopy detectors for the next generation of high-brightness synchrotron and ICS experiments.

2.4) Basic and Applied Physics research feasible with photon beams and electron beams delivered by BriXS

Hard *X*-rays, with an energy larger than 20 keV, are ideal for the study of "real" materials and technological objects because they can penetrate deeply under the surface even in the presence of heavy atoms (from tens of micrometers at 20 keV to millimeters at 100 keV). There, *X*-ray diffraction, microscopy and tomography are currently used at the high energy synchrotrons around the world, with a rapid evolution of the techniques and diversification of applications. Unfortunately only 4 high energy modern synchrotrons are operational at the moment (ESRF (FR), Petra III (DE), APS (US), Spring8 (JP)), and space remains for increasing the offer of competitive beamlines dedicated to materials science. The average photon flux foreseen for BriXS, particularly in its Phase 2, would allow advanced applications in several fields. Using bulk *X*-ray diffraction on all kinds of materials, for example: on single crystals and powders performances, unthinkable with traditional lab *X*-ray sources, would allow the quick and accurate mapping of reciprocal space of high quality samples, but also fast recognition of different phases in natural specimens; diffraction tomography would allow the imaging of grains in technological materials (*e.g.* metals), including the determination of their crystallographic orientation and strain tensor; microscopy could be used to detect inclusion of spurious phases and contaminants.

To give an impression of the strategic importance and great diversity of subjects susceptible of being studied by hard *X*-ray techniques we provide in Fig.12-13 few recent highlights of the ESRF (ESRF News, March 2016, http://www.esrf.eu/UsersAndScience/Publications/Newsletter). We note that the wiggler/undulators sources serving these state of the art beam lines are producing $\sim 10^{14}$ - 10^{15} photons/s (before being monochromatized), not far from the expected performances of BriXS phase 2.

High-energy beamlines at the ESRF

- **ID11 (18–140 keV)** Materials science beamline dedicated to moderate- to high-energy diffraction and/or imaging studies of a wide variety of systems.
- **ID15A (20–750 keV)** Dedicated to high-energy studies in materials chemistry and engineering, especially *in situ* catalysis experiments.
- **ID16B (6–65 keV)** Nano-analysis end station linking distribution, concentration and speciation of trace elements to morphology and crystallographic orientation.
- **ID17 (25–115 keV)** Dedicated to large field-of-view imaging, radiation biology and radiation therapy both *in vitro* and *in vivo*.
- **ID19 (6–250 keV)** Microtomography beamline devoted to 3D and phase-contrast imaging for a wide variety of topics including palaeontology.
- **ID22 (6–80 keV)** Dedicated to high-resolution powder diffraction for structural, dynamic and *in situ* experiments.
- **ID27 (20–90 keV)** Premier X-ray powder and single crystal diffraction station dedicated to research at extreme pressures and temperatures.
- **ID31 (20–150 keV)** Portfolio of hard X-ray techniques including reflectivity, wide- and small-angle scattering and imaging for time-resolved studies in materials processing.

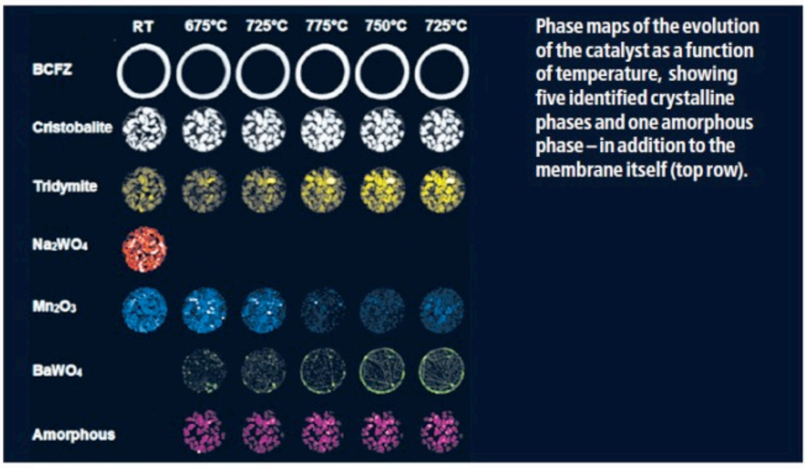


Fig 12 *- Left: the high energy beam line portfolio of the ESRF: 7 of them comprise the 20-100 keV range of BriXS phase 2. Right: X-ray diffraction computed tomography has allowed users to investigate the chemical evolution of a working catalytic reactor for the conversion of methane into ethylene.*

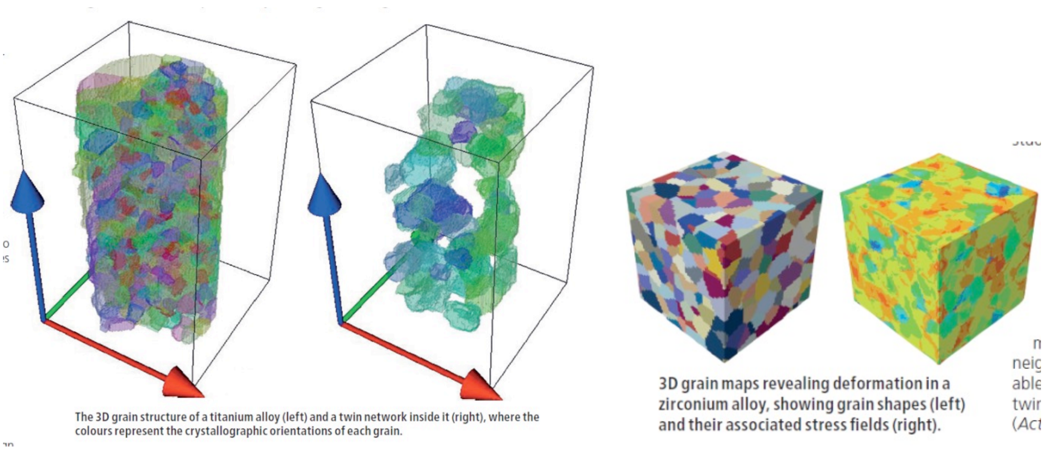


Fig 13 *- Diffraction computed tomography (DCT) and 3D X-ray diffraction (3DXRD) allowed seeing the grains inside of materials by looking at diffraction from their crystal lattices.*

A further subject of great relevance in the general scenario of scientific research enabled by BriXS is Quantum Optics Science pursued with high intensity high average power lasers, like those requested to operate the BriXS photon machine.

As a matter of fact, the Fabry-Perot cavity that we expect to implement in the BriXS project is injected by an amplified mode-locked laser system. This laser delivers a train of pulses with an average power of about 100 W and a repetition rate of 100 MHz (1 μJ per pulse). These numbers are very promising for the development of an optical system for the generation of non-classical states of light.

In order to investigate states of light exhibiting stronger non-classical features, pulsed lasers are required for two main reasons: to exploit the stronger nonlinear effects caused by the higher peak intensity and to provide a synchronization clock which gives the opportunity to prepare the state in a conditional way.

Presently there are 3 main regimes about pulsed lasers system in the quantum optics field: (a) high repetition rate (100 MHz) and low energy per pulse (1-10 nJ) [24,25]. Essentially in this regime it is possible to generate Fock states with $n=1$ via parametric down-conversion (PDC). (b) medium rep. rate (1 MHz) and medium energy (about 100 nJ) [26,27]. With this numbers we can generate photons in non perturbative regime via PDC. (c) high energy (1 μJ or more) and about 1 kHz rep. rate. In this case it is possible to generate quantum radiation with high numbers of photons [28].

The preparation of non-classical states requires an homodyne apparatus able to detect them, *i.e.* a time-domain homodyne scheme (in Fig.14 is reported a typical scheme from [26]). It is clear that it is very important to perform the measure in the high repetition rate regime in order to acquire a lot of statistics in a small time window. In this way we can avoid the long term fluctuations arising from the phase instabilities of the optical setup. Thus the laser system of the BriXS project gives us the unprecedented possibility to cover the three energy regimes at high repetition rate.

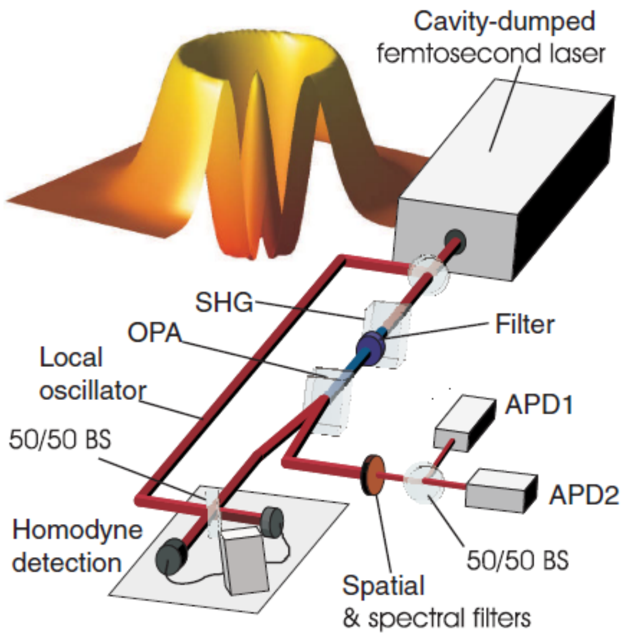


***Fig 14 -** Experimental set-up and Wigner function for n=2 Fock state.*

As a matter of fact, the development of the BriXS photon machine, aimed at delivering a CW train of laser pulses with a repetition rate of 100 MHz and about 10 mJ of energy per pulse (1

MW average power), will have to address the construction of a high finesse Fabry-Perot cavity injected by a high average power (100 W) and high repetition rate pulsed laser system. In Fig. 15 we can see the general layout of the system.

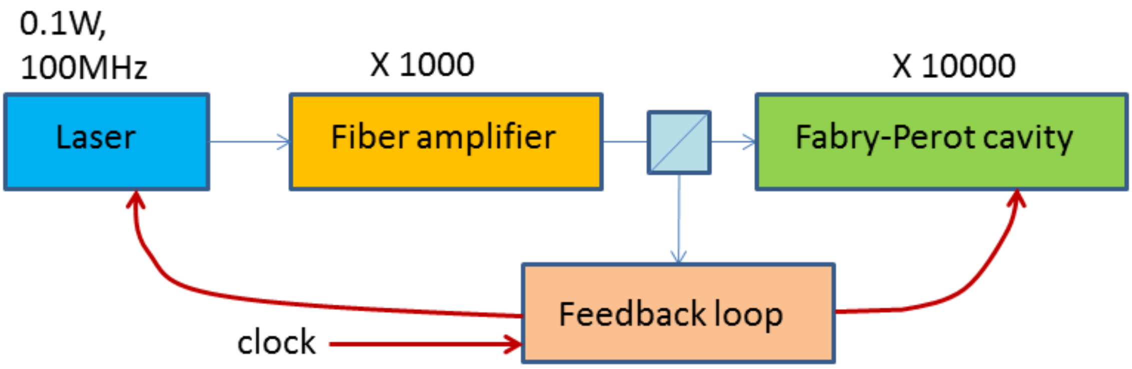


Fig. 15 *- General layout of BriXS photon machine*

In particular, concerning the laser in order to obtain a finesse of 30000 (that means a gain of about 10000) it is necessary [29] to implement an active control of the carrier-to-envelope phase shift (CEP). The required amplifier is not commercial and it is based on a chirped-pulse-amplification (CPA) scheme. In order to obtain about 100 W of average power, good spatial profile (TEM_{00} mode) and high stability, we propose to use a single mode double clad large active area fiber as active medium [30]. The laser amplification chain will be completed by a multipass amplifier based on *Yb:YAG* or *Yb:LuAG* pumped by semiconductor lasers. This stage will be used to further increase the power obtained from the fiber preamplifier, which could be limited by the occurrence of non linear self phase modulation (SPM) effects (due to the very high peak intensity reached in the fiber). SPM effects in turn result in amplitude-to-phase coupling potentially ruining the locking procedure to the FP cavity, as pointed out in [30]. To minimize thermal beam distortions, structured ceramics gain elements (with non uniform distribution of the dopant aimed to minimize thermal lensing effects, see [31]), will be adopted in the multipass amplifier.

About the FP cavity we have to compare the stability of different types of cavities: 2mirros, 4mirros bow-tie [32], 2D crossed cavity, 4 mirros 3D non planar [30], 4mirros with parabolic reflectors [33], all curved mirror cavity [32] and we have to implement the feedback system to actively stabilize the FP cavity *w.r.t.* the laser and the external clock [34]. Also the spectrum width of the pulse is critical. In order to perform the CPA at high power we need a large spectrum (10 nm), but the high reflectivity mirrors of the FPC are thick and they introduce a not negligible dispersion with 10nm of spectrum . The dispersion inside the FPC means that there is a CEP and in turn a reduction of the cavity finesse.

One further research of great relevance that can be pursued with BriXS, thanks to its very large *X*-ray fluxes, is the development and study of *X*-ray Optics for beam manipulation. To further improve the feature of the BriXS facility, we propose to exploit a Laue lens to manipulate the photon beam produced from the collision of laser and electron beams.

A Laue lens is an optical component composed of a set of crystals arranged in concentric rings, each of these rings is characterized by an appropriate crystallographic orientation. As shown in Fig. 16, this configuration is used to focus a photon beam toward a small focal spot, by using Bragg diffraction in Laue geometry (transmission).

The geometry of this focusing device and the feature of the crystals depend on the energy of the beam to be focused and on the specific application.

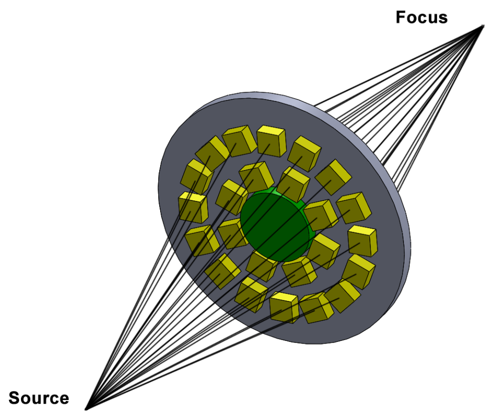


Fig 16 - *Sketch of the working principle of Laue Lens*

Laue lenses were initially proposed by the astrophysics community for the realization of a high-energy telescope [35] and subsequently for the application in diagnostic nuclear medicine and radiotherapy. In nuclear medicine, the photons emitted by the radiopharmaceutical lying inside the patient's body can be focused by a Laue lens onto a detector without the need of collimators [36]. In radiotherapy, a Laue lens can be used to concentrate the photons emitted from an *X*-ray tube toward a tumor target [37]. Due to the focusing of *X*-rays in energy range of 40 – 200 keV, it is possible to obtain a dose distribution that maximizes the damage to diseased tissue while preserving healthy tissue.

As discussed earlier in this document, Thomson sources are not intrinsically monochromatic. The maximum energy of the backward scattered photons depends on the collision conditions between laser beam and electrons. Usually, a bandwidth around the maximum energy is selected through a proper collimation. By using a Laue lens, it would be possible to perform the selection of an energy within the whole emission band without changing the collision parameters. Indeed, it is possible to exploit the correlation between energy and angular distribution of the Thomson scattered photons and properly tune the impinging angle of the photons onto the crystals by axially translating the lens or titling the crystals. By stopping the propagation if the primary beam with an absorber on the lens plane, a monochromatic beam, whit an energy selected by the Bragg diffraction angle, can be focused at a focal point determined by the lens geometry.

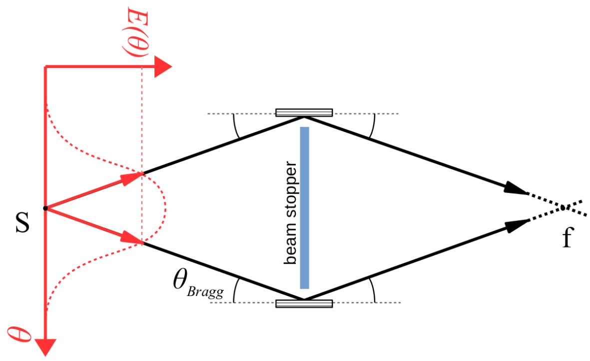


Fig 17 - *Example of the application of a Laue Lens with an emission distribution Thomson-like. In the case depicted it is possible to focus the emission at an angle close to the spectrum peak.*

Furthermore, with a proper design of the optical system it is possible to control the focusing property of the lens and adjust the focal spot size according to the needs of the specific application. For example, it would be possible to obtain downstream of the lens a slowly convergent photon beam with a cross section of a few cm at a given distance in order to irradiate with an uniform field a given region, like requested for example by the cisplatinum application discussed in section 2.2.

2.5) Fully coherent low brilliance ultra-high flux X-ray FEL: filling the gap between SRS and XFELs

A specific design for a fully coherent FEL operated at low brilliance (10^8-10^9 photons/shot) in the few keV photon energy range, with CW 100 kHz to 1 MHz repetition rate is also being pursued in the frame of the present initiative, with the aim to promote BriXS toward a unique machine capable to launch unprecedented research in the science of matter with coherent low energy *X*-rays.

The rationale of such source is to serve time-resolved spectroscopies with *X*-rays (3-15 keV) with individual pulses not exceeding the space charge regime (high density excitation threshold) that nowadays imply a $10^{-3}/10^{-4}$ attenuation of X-ray beams at e.g. SACLA, but gaining 4-5 orders of magnitude in repetition rate to the benefit of statistics. Such source (10^8-10^9 photons/shot at up to 1 MHz) is not available today at X-FELs (either normal conducting and limited to 30-120 Hz or superconducting at 27.000 pulses/second in 10 Hz macro-bunches of 4.5 MHz micro-bunches). High longitudinal coherence will enable pump-probe methods at 10-100 fs accuracy, and with high statistics. Such source will fill in the XAS/XMCD (with polarization control from quarter-wavelength blades or undulators) and bulk photoemission to become highly efficient probes of matter at the nanoscale but in bulk environments, like buried interfaces of interest in materials science, or biological matter in physiologic environment, or catalysers at work.

Users from fundamental physics of condensed matter (phase transitions, exotic material properties, materials under extreme conditions) as well as from applied research (spectroscopic characterization of buried nanostructures and in-operando conditions) will find such unique facility of extreme interest. These communities have a good track record as of designing and building advanced instruments for innovative experiments at radiation sources, and also a good track record for finding the resources.

If higher energies (60-100 Kev) will be available the source may represent a very attractive tool for applied nanoscience and nanotechnology R&D by means of powder diffraction encountering interest in a broad industrial sector from tires manufactures to concrete, to metallurgy for advanced applications like 3D metal printing, to the chemical industry at large.

Such source will fill a gap that is now open between Synchrotron Radiation Sources (ESRF, Elettra, other advanced national SR Sources in Europe) that are intrinsically limited to the ps scale as of X-ray pulse duration, but provide high repetition rates (500 MHz) with a small number of photons per /pulse, and the FEL sources that on the countrary provide extremely brilliant pulses averaging the same total number of photons per pulse as in one second of a modern storage ring at 500 MHz in flashes of 10-50 fs, with very high transverse coherence and poorer longitudinal coherence in the case of SASE-FELs (the only operating at X-ray energies). High longitudinal coherence is a special feature of seeded FELs, but the only operational facility is FERMI@Elettra, based on a normal-conducting Linac and therefore limited to 50Hz.

The novel source will therefore create absolutely novel conditions for experiments that cannot be performed satisfactorily at the present and foreseen sources based on storage rings or SASE-FEL. The R&D campaign necessary to develop such a FEL beam-line is at all consistent with the development of high quality high rep. rate laser pulses (see Fabry-Perot cavities discussed above in this document) to be used as electro-magnetic undulators [see ref.38 and other references therein].

CONCLUSIONS

A unique window of opportunity is opening up in the Milan metropolitan area to develop a unique advanced *X*-ray source that will allow to target medical and other applications with a completely new tool. A significant synergy between the advanced expertise accumulated in the last decade at Physics Dept. of University of Milan and INFN Milan Section in Compton Sources[2], SC Linacs, Optical cavities, radiation detection, in combination to a broad community of potential users ranging from material scientist (Univ. of Milan and Politecnico di Milano) to medical doctors and researchers in radio-imaging and radio-therapy (local IRCCS's), can bring to the development of a dedicated unique machine like BriXS that would allow to pursue a strategic initiative leading to a broad spectrum of high social impact research activities within the Science of Life domain.

Fundamental and applied physics could also be pursued with advanced experiments feasible at BriXS by implementing an additional *X*-ray beam line, as well as with BriXS photon machine in quantum optics field.

The first phase of BriXS would cost around 50 M€, approximately split among the electron machine (19 M€), the photon machine (5 M€), the ancillary plants and civil engineering (18 M€) and the beam line (8 M€), requesting an available space similar to STAR or ThomX, and a completion time comprising 1 year for design, 2 years for component acquisition and 1 year for installation and commissioning - just for phase 1. Phase 2 would request approximately 20 M€ more funding and 2-3 further years for its implementation, in order to achieve an unprecedented *X*-ray photon flux and to install a second *X*-ray beam line. A dedicated team of at least 12-15 members covering the diverse expertise requested to build and operate the machine is certainly required.

A fully coeherent *X*-ray FEL would add a unique opportunity and capability of pursuing fundamental and applied research in matter science. An additional gross estimated 5 M€ budget would be needed for this additional feature (excluding the dedicated *X*-ray beam-line).

Several Institutions, Universities, Laboratories and Research Centers located outside the Milan metropolitan area have shared interest in this document, as illustrated by the list of signatures reported below. We'd like to underline the National Institute of Optics (INO, belonging to C.N.R.), with an established expertise in laser studies, characterization of innovative laser materials and development of all-optical, intense laser-based radiation sources. University of Ferrara, with leader experts in *X*-ray beam generation, characterization and manipulation, along with advanced radiation sources based on crystal channeling.

The Frascati National Laboratories of INFN, leader in Italy and Europe for electron accelerators and fundamental physics and related applications. INFN-Pisa and University of Pisa with a well established expertise both in medical applications of radiation/particle sources and non linear optics/lasers applied to plasma accelerators. INFN/CS and Universita' della Calabria are presently developing one of the very few european research infrastructures based on a Thomson *X*-ray source, *i.e.* STAR/Materia, in the context of a long term development plan funded by the Italian Government for regions of convergence.

The experience on clinical trials for mammography with mono-chromatic X-rays has been pioneered in our country by Universita' di Trieste and INFN-Trieste at the Syrmep beam-line of the Elettra synchrotron light source. Orsay/LAL of Universite' de Paris Sud carries a world-wide renowned leadership in the physics and technology of accelerators and, of particular relevance for BriXS, an excellence in Fabry-Perot cavities coupled to accelerators for Compton back-scattering sources. PBPL laboratory at UCLA is among world leaders in high brightness electron beams and radiation sources – physics and applications.

This actually shows that BriXS, although prevalent on local interests acting in the Milan metropolitan area, would be a user facility with a National and European character and valence.

Milan, October, 10th, 2016

[2] Also in tight collaboration with INFN National Laboratories in Frascati (INFN-LNF) at the SPARC-LAB test facility [22,23]

INFN/Milan and Universita' degli Studi di Milano: *Alberto Bacci, Francesco Broggi, Fabrizio Castelli, Simone Cialdi, Camilla Curatolo, Carlo De Martinis, Illya Drebot, Grazia Gambarini, Dario Giove, Flavia Groppi, Maurizio Maugeri, Paolo Michelato, Stefano Olivares, Carlo Pagani, Matteo Paris, Vittoria Petrillo, Paolo Pierini, Nicola Piovella, Paolo Piseri, Marco Potenza, Massimiliano Rome', Andrea R. Rossi, Giorgio Rossi, Luca Serafini[3], Daniele Sertore, Roberta Vecchi, Ivan Veronese*

INFN/Milan and Politecnico di Milano: *Stefano Agosteo, Andrea Castoldi, Alberto Fazzi, Carlo Fiorini, Chiara Guazzoni, Andrea Pola*

CNISM, Politecnico di Milano and INFN/Milan: *Ezio Puppin*

Politecnico di Milano: *Giacomo Ghiringhelli*

CNR-INO Pisa: *Leo Gizzi, Luca Labate*

CNR-INO Sesto F.: *Barbara Patrizi (LENS), Guido Toci, Matteo Vannini*

INFN/LNF: *Rodolfo Bonifacio, Andrea Ghigo, Bruno Spataro, Cristina Vaccarezza, Alessandro Variola*

INFN/CS and Universita' della Calabria: *Gianluca Borgese, Calogero Pace, Antonio Policicchio*

INFN/Ferrara and Universita' di Ferrara: *Paolo Cardarelli, Mauro Gambaccini*

INFN/Pisa and Universita' di Pisa: *Ubaldo Bottigli, Alessandro Curcio (also with INFN-LNF and Univ. Roma La Sapienza), Pasquale Delogu, Danilo Giulietti*

Universita' di Trieste and INFN-Trieste: *Renata Longo*

LAL, Universite' de Paris Sud, Orsay: *Fabian Zomer, Kevin Cassou, Ronic Chiche, Denis Douillet, Kevin Dupraz, Pierre Favier, Aurelien Martens, Y. Peinaud, Viktor Soskov*

University of California at Los Angeles: *James B. Rosenzweig*

[3] *corresponding author,* ***luca.serafini@mi.infn.it***

Endorsers:

Universita' degli Studi di Milano - Radioterapia Oncologica 1 / Programma Prostata and IRCCS Istituto Nazionale dei Tumori: *Riccardo Valdagni*

Universita' degli Studi di Milano - Fisica Medica and IRCCS Istituto Nazionale dei Tumori: *Mauro Carrara*

Universita' degli Studi di Milano – Radiologia and Niguarda Cancer Center, SC Radiologia ASST Niguarda: *Angelo Vanzulli*

IRCCS Ospedale San Raffaele – Experimental Imaging Center / Direction: *Carlo Tacchetti*

IRCCS Ospedale San Raffaele – Experimental Imaging Center / Fisica Sanitaria: *Riccardo Calandrino*

Universita' degli Studi di Milano - Dipartimento di Fisica and INFN/Milan: *Alessandro Lascialfari, Giuseppe Battistoni, Alberto Vailati*

RadiaBeam Technology: *Alex Murokh*

Acknowledgments: we thank K. Achterhold (CALA-Munich) and A. Murokh (RadiaBeam Technologies) for providing material and references for this EoI.

References

1. - M. Carpinelli and L. Serafini, *Compton Sources for X/γ rays: Physics and Applications*, NIM-A **608** (1), 2009 and references therein
2. - C. Sun and Y.K. Wu, PRSTAB **14** (2011) 044701
see also P. Tomassini, A. Giulietti, D. Giulietti, L.A. Gizzi, *Thomson Backscattering X-rays from ultrarelativistic electron bunches and temporally shaped laser pulses* Appl. Phys. B **80**, 419-436 (2005)
3. - V. Petrillo et al., NIM-A **693** (2012)
4. - A. Bacci et al., JAP **113** (2013) 194508
5. - C. Maroli et al., PRSTAB **16** (2013) 030706
6. - V. Petrillo et al., PRSTAB **18** (2015) 110701

7. - L. Serafini et al., *ELI-NP-GBS Tech. Des. Report*, http://arxiv.org/abs/1407.3669
8. - K. Dupraz et al., PRSTAB **17** (2014) 033501
9. - A. Bacci et al., *The STAR Project*, Proc. of IPAC-2014, THPRO013
10. - F. Zomer et al., *The Compact X-ray Source ThomX*, Proc. of PAHBB-2016 Workshop, https://agenda.infn.it/conferenceDisplay.py?confId=11130
11. - W.S. Graves, *High Brilliance X-rays from Compact Sources: CUBIX*, Proc. of HBEB-2013 Workshop, http://pbpl.physics.ucla.edu/HBEB2013/index.html
12. - A. Seryi et al., *UH-FLUX Project*, Proceedings of EAAC-2015 Workshop, https://agenda.infn.it/conferenceDisplay.py?confId=8146
13. - F. Sannibale et al., *Status, plans and recent result from the APEX Project at LBNL*, Proc. of FEL-2015 Conf., MOP024
14. **-** D. Kayran et al., *Status and commissioning results of the R&D ERL at BNL*, Proc. of ERL-2015 Workshop, MOPDTH014
15. **-** K. Achterhold, *Biomedical imaging with the lab-sized laser-driven synchrotron source Munich Compact Light Source*, presented at OSA-2015 Workshop, http://www.osa.org/en-us/2015compactlight/
16. **-** Biston et al., Cancer Reas. **64** (2004) 2317
Adam et al., Int.J.Rad.Onc.Biol. Phys. **57** (2003) 1413
S. Corde et al., Cancer Reas. **63** (2003) 3221
Int.J.Rad.Onc.Biol. Phys. **68** (2007) 943
17. **-** A. Martens et al., *Developments of optical resonators and optical recirculators for Compton X/gamma ray machines*, Proc. of NPNSNP-2014 Workshop, http://www.jaea.go.jp/english/npnsnp/index.html
18. **-** R. Longo et al., *Towards breast tomography with synchrotron radiation at Elettra:first images,* Phys. Med. Biol. 61 (2016) 1634–1649
see also P. Oliva et al., Nuclear Instruments and Methods A **615** (2010) 9399
19. **-** C. Fiorini et al., *A new High-Rate and High-Resolution X-ray Spectroscopy Detector for Synchrotron XRF and XAFS Applications*, ATTRACT Symposium 2016
20. **-** M. Tigner, *A possible Apparatus for Electron Clashing-Beam Experiments*, Letter to Nuovo Cimento, Feb. 1965
21. **-** M. Ferrario et al., *IRIDE: Interdisciplinary research infrastructure based on dual electron linacs and lasers*, NIM-A **740** (2014)
22. **-** M. Ferrario et al., *SPARC-LAB present and future*, NIM-B **309** (2013)
23. **-** C. Vaccarezza et al., *The SPARC-LAB Thomson Source*, NIM-A, 58557, DOI information: 10.1016/j.nima.2016.01.089
24. - A. Zavatta, S. Viciani, M. Bellini, Science, **306**, 660 (2004)
25. - H. Jeong et al., Nature Photonics, **8**, 564 (2014)
26. - A. Ourjoumtsev, R. Tualle-Brouri, and P. Grangier, Phys. Rev. Lett. **96**, 213601 (2006)
27. - J. Etesse et al., Phys. Rev. Lett. **114**, 193602 (2015)
28. - A. Allevi, M. Bondani, M. G. A. Paris and A. Andreoni, Phys. Rev. A **78**, 063801 (2008)
29. - A. Borzsonyi et al., Appl. Opt. **52**, 8376 (2013)
30. - J. Bonis et al., Arxiv Eprint: 1111.5833

31. - P. Ferrara, M. Ciofini, L. Esposito, J. Hostaša, L. Labate, A. Lapucci, A. Pirri, G. Toci, M. Vannini, L.A. Gizzi, *3-D numerical simulation of Yb: YAG active slabs with longitudinal doping gradient for thermal load effects assessment*, Opt. Express **22**(5), 5375-5386, 2014
32. - H. Carstens et al., Ept. Exp. 21, 11606 (2013)
33. - K. Dupraz et al., Opt. Comm. **353**, 178 (2015)
34. - Yan You PhD thesis, Dissertation Supervisor : Professor Chuanxiang Tang, Joint Supervisor : Professor Fabian Zomer (*A Study of Optical Enhancement Cavity with Short Pulse Lasers for Laser Electron Beam Interaction*)
35. – R.K. Smither, *New method for focusing X-rays and gamma rays*, Rev. Sci. Instrum. (1982) **53**, 131
36. - G. Paternò, V. Bellucci, R. Camattari and V. Guidi, *Design study of a Laue lens for nuclear medicine*, J. Appl. Cryst. (2015) **48**, 125-137
37. - G. Paternò, M. Marziani, R. Camattari, V. Bellucci, A. Mazzolari, M. Gambaccini and V. Guidi, *Laue lens to focus an X-ray beam for radiation therapy*, J. Appl. Cryst. (2016) **49**, 468-478
38. - V. Petrillo et al., PRSTAB **11** (2008) 070703