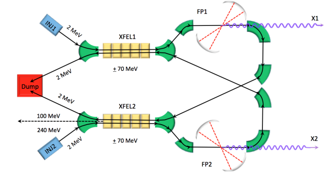
Conceptual Design Study for MariX/BriXS
a user facility with ultra-high flux coherent X-rays



Multi-disciplinary Advanced Infra-structure for Research with X-rays
Macchina Analitica per Ricerca Inter-disciplinare con raggi X

The Opportunity

CORRIERE DELLA SERA
Milano
Dir. Resp.: Luciano Fontana

16-NOV-2017
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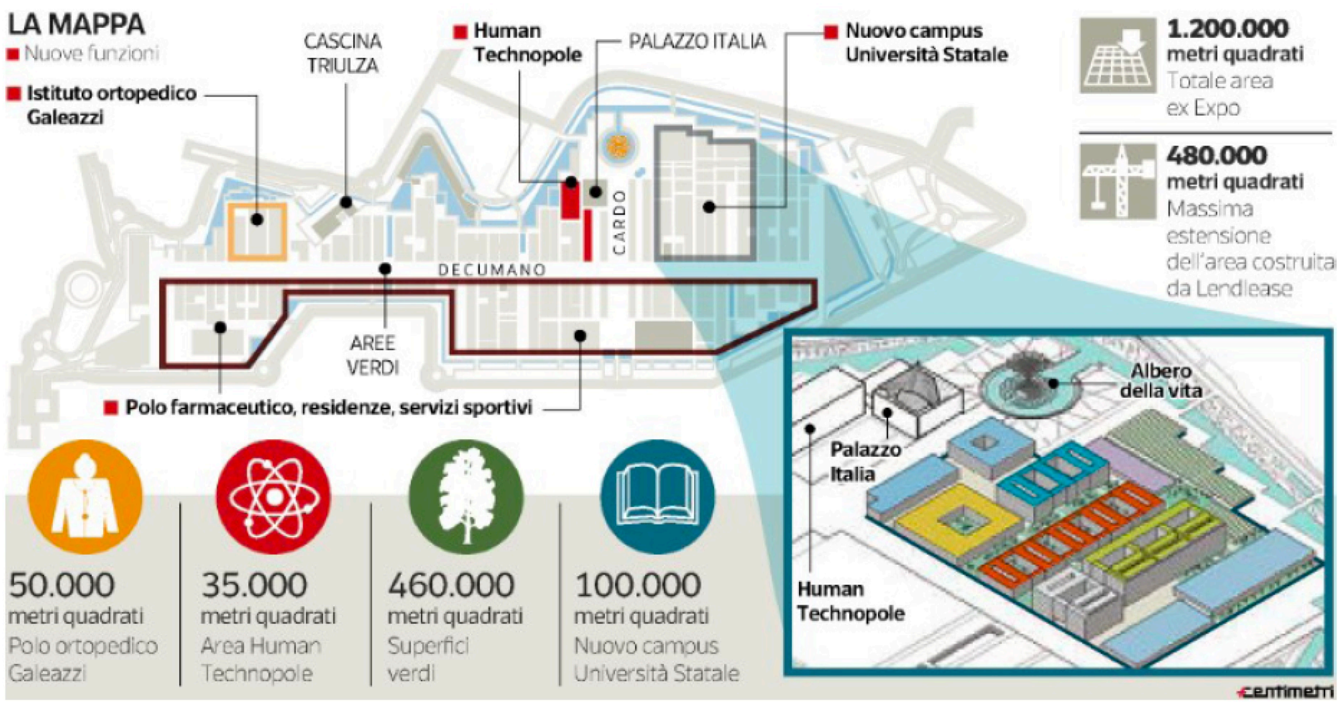

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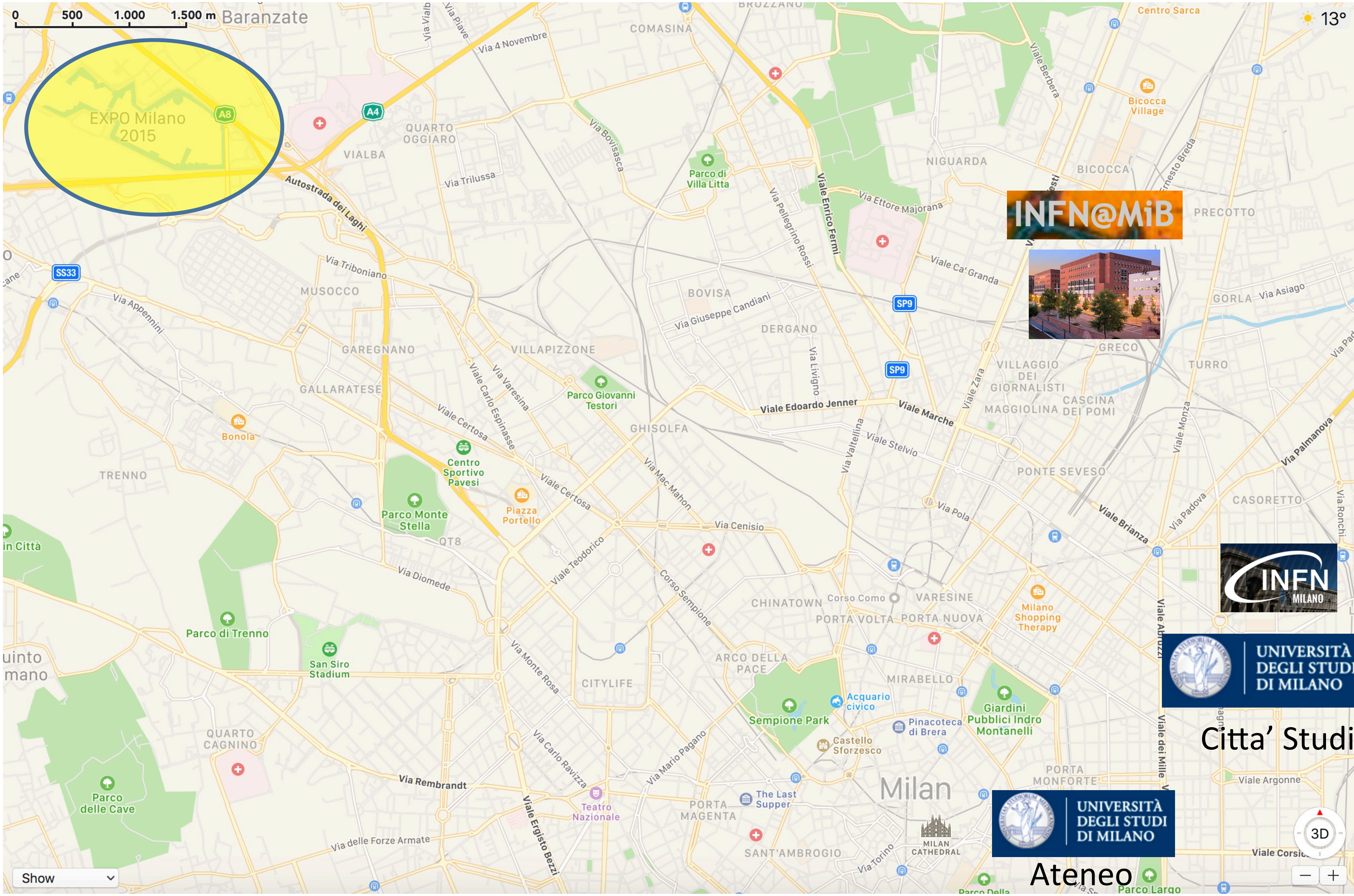
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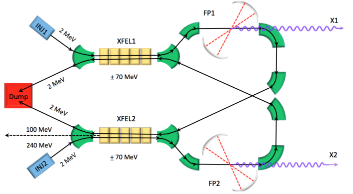

www.fisica.unimi.it/ecm/home/ricerca/marix

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HOMEPAGE > Ricerca > Marix

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- BANDI E ASSEGNI
- SEMINARI
- CONVEGNI
- PHYSICS COLLOQUIA
- **MARIX**

M.A.R.I.X. : UN PROGETTO TRASVERSALE PER IL FUTURO CAMPUS DI UNIMI

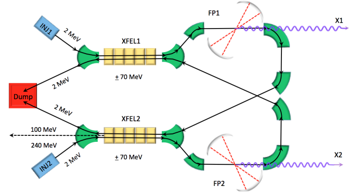
Con un recente accordo il Rettore dell'Università di Milano e il Presidente dell'INFN promuovono la stesura di un "Conceptual Design Study" di un'infrastruttura di ricerca analitica multidisciplinare, con caratteristiche di unicità a livello nazionale, europeo e internazionale, da collocarsi all'interno del futuro Campus Scientifico di UNIMI presso l'area Expo Milano-Rho.

Tale infrastruttura è basata su una sorgente di fasci di fotoni da acceleratori di elettroni: fasci di raggi X altamente coerenti da FEL (Free Electron Laser), nella gamma di energia da 1 a 5 keV, con impulsi ultrabrevi (10-50 fs) e frequenza di ripetizione fino a 1 MHz, e fasci di raggi X Compton monocromatici fino a 150 keV, con flussi elevati fino a 10^{13} fotoni / s. Maggiori dettagli si trovano nei files allegati, in particolare nell'Introduzione a MariX e nella presentazione generale. Tali sorgenti alimenteranno esperimenti (beamlines) nel campo della visualizzazione (imaging) e della spettroscopia (photon in-photon out e photon in-electron out) per ricerca in ambito biomedico, della scienza dei materiali, delle proprietà dinamiche della materia (catalisi, magnetismo, superconduttività, fenomeni non lineari, materia in condizioni estreme).

Il progetto è volto a realizzare un infrastruttura per la ricerca avanzata con forte impatto sulle attività Dipartimenti scientifici del nostro Ateneo e degli EPR.

Si è partiti con una serie di incontri a livello interdipartimentale. Il primo di tali incontri si è tenuto il 30/11/2017 presso il Dipartimento di Fisica, con presentazioni di G. Rossi, G. Ghiringhelli e L. Serafini che sono visibili in questa pagina. Lo scopo degli incontri è quello di giungere ad identificare un piccolo numero di progetti pilota in ambiti disciplinari diversi, che dovranno costituire il "scientific case" da completarsi parallelamente al "Conceptual Design Report" della sorgente già in corso di elaborazione.

www.fisica.unimi.it/ecm/home/ricerca/marix



- PHYSICS COLLOQUIA
- **MARIX**

ripetizione fino a 1 MHz, e laser di raggi X Compton monocromatici fino a 180 keV, con flussi elevati fino a 10^{13} fotoni / s. Maggiori dettagli si trovano nei files allegati, in particolare nell'Introduzione a MariX e nella presentazione generale. Tali sorgenti alimenteranno esperimenti (beamlines) nel campo della visualizzazione (imaging) e della spettroscopia (photon in-photon out e photon in-electron out) per ricerca in ambito biomedico, della scienza dei materiali, delle proprietà dinamiche della materia (catalisi, magnetismo, superconduttività, fenomeni non lineari, materia in condizioni estreme).

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DOCUMENTI CORRELATI

Presentazione generale

Introduction to M.a.r.i.X.

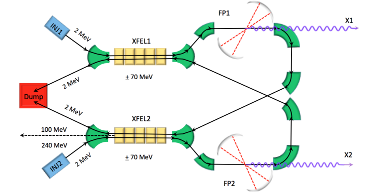
M.a.r.i.X. presentation

BriXS - expression of interest

Slides G. Rossi 30/11/2017

Slides G. Ghiringhelli

Slides L. Serafini 30/11/2017



- **INFN-I ... management to launch ... lled MariX: in July 2(... an Rector, saying**

Lettera d'Intenti INFN per **MARIX**
(Multidisciplinary Advanced) Research Infra-structure with X-rays (ex BriXS)

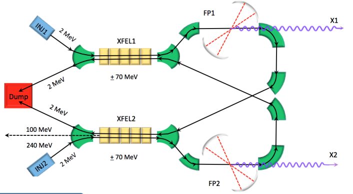
Le infrastrutture di ricerca analitiche sono risorse indispensabili per lo studio della materia in tutte le sue aggregazioni, dai materiali funzionali, alla chimica organica, alla biologia strutturale e funzionale, all'analisi del patrimonio culturale, alla visualizzazione (imaging) per contrasto di fase per diagnosi medica non invasiva, alla visualizzazione per diffrazione per studi con risoluzione nanometrica.

Tutti i principali centri di ricerca e le maggiori università hanno legami stretti o sono direttamente sviluppati attorno alle infrastrutture analitiche, nel mondo ed in Europa. Sorgenti di luce di sincrotrone, laser a elettroni liberi, sorgenti di neutroni da spallazione sono i motori dello sviluppo delle concentrazioni scientifiche e tecnologiche di Grenoble, Oxford (Harwell Campus), Paris-Saclay, Amburgo, Lund. L'investimento in questi plessi della ricerca avanzata, tutti intimamente connessi con università, centri di ricerca e cura medica, centri per l'innovazione, è tipicamente internazionale con contributi specifici basati su accordi bilaterali o con l'intervento di fondi strutturali e di investimento europei –ESIF- coerentemente con la smart-specialization del sito ospitante. L'Italia partecipa con investimenti sostanziali e contribuendo know-how e tecnologie leader, per esempio nel campo della superconduttività, a tutte le infrastrutture analitiche della Roadmap Europea ESFRI al fine di abilitare la propria comunità scientifica al loro sviluppo ed utilizzo.

Le infrastrutture di ricerca analitiche di recente costruzione sono tutte basate su acceleratori di particelle cariche, elettroni o ioni, con tecnologie derivate da quelle della fisica delle alte energie, ma specializzate per gli scopi applicativi: spettroscopie e imaging.

Basic/applied research on science of matter needs analytical machines
Major Labs and Universities are tightly linked to light sources / neutron sources

The Start-up of MariX/BriXS initiative



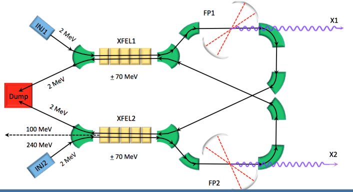
Il back-bone della infrastruttura MARIX sarebbe costituito da un acceleratore lineare super-conduttivo, eventualmente del tipo a recupero di energia (Energy Recovery Linac), capace di generare due tipi di fasci di elettroni per poter servire le due categorie di beam-lines di radiazione previste: quella di raggi X duri da Sorgente Compton e quella di raggi X molli coerenti da Free Electron Laser. Entrambi i fasci di elettroni richiesti devono raggiungere un'altissima brillanza di picco onde garantire le proprieta' dei fasci di radiazione prodotti:

a) i fasci di raggi X con energie nel range 20-150 keV, monocromatici, polarizzati, ultra-veloci (dal psec al fsec), e ad altissimo flusso (fino a 10^12 fotoni/s in una bandwidth del 5%, in una prima fase dell'operativita' della macchina, senza ERL, e fino a 10^13 fotoni/s in modalita' ERL) vengono generati mediante Compton back-scattering tra il fascio di elettroni stesso ed un impulso laser accumulato in una cavita' ottica del tipo Fabry-Perot ad altissima potenza media (fino a 0.5 MW)

b) gli impulsi di radiazione coerente del tipo Free Electron Laser, con durate inferiori ai 50 femto-secondi, energia del fotone compresa tra 1 e 5 keV, completemente coerenti e con altissima frequenza di ripetizione (fino ad 1 MHz) vengono generati dal trasporto del fascio di elettroni, con energia di almeno 500 MeV, attraverso un ondulatore statico di tipo avanzato, o magnetostatico con periodo millimetrico, o del tipo a radio-frequenza ricircolato. Uno schema avanzato del tipo ondulatore-amplificatore a cascata di armoniche e' il candidato piu' promettente per raggiungere le prestazioni del FEL richieste

Back-bone:
CW SC-RF
Linac

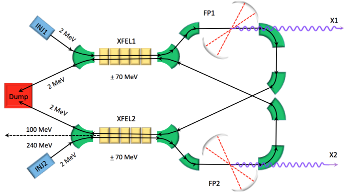
The Start-up of MariX/BriXS initiative



INFN appoggia questa iniziativa congiunta e operera' insieme ad UNIMI per ottenere il riconoscimento e il finanziamento anche internazionale, che questa opera richiede.

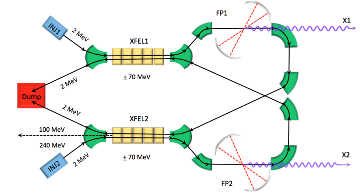
A tal fine INFN intende costituire un gruppo di lavoro che , in collaborazione con il Dipartimento di Fisica di Milano, proceda a elaborare il progetto preliminare (CDR=Conceptual Design Report) che dettagli il caso scientifico e le scelte progettuali che possono portare a questa realizzazione in tempi definiti. Tale progetto dovra' prevedere l analisi delle scelte tecniche , degli sviluppi di R&D e delle risorse necessari sia nel breve che nel lungo periodo, e sara' quindi lo strumento da utilizzare per poter accedere a piani di finaziamento europei , nazionali o regionali. Per arrivare alla stesura del progetto sara' necessario un lavoro di almeno 6 mesi

INFN in collaboration with University of Milan will set up a dedicated working group to prepare a Conceptual Design Report for MariX



We are almost there...

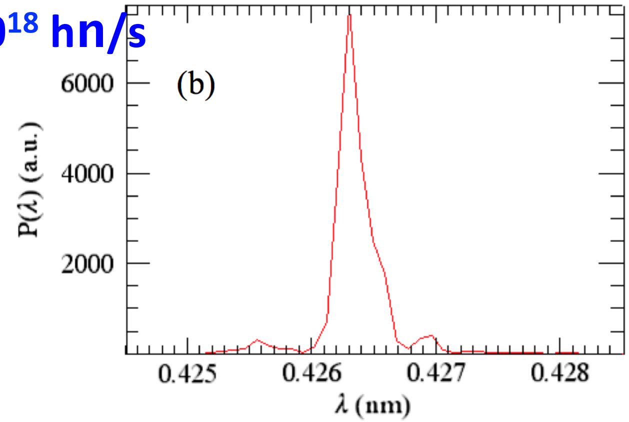
2 different kinds of photon beams



FEL fully coherent diffraction limited X-ray photon beam: $10^{9\text{-}12}$ hn/pulse @ 1 MHz in 0.05% Dn/n, 0.1-8 keV, s_t < 50 fsec, 10^{18} hn/s

$$\lambda_R = \lambda_w \frac{\left(1 + a_w^{\,2}\right)}{2\gamma^2}$$

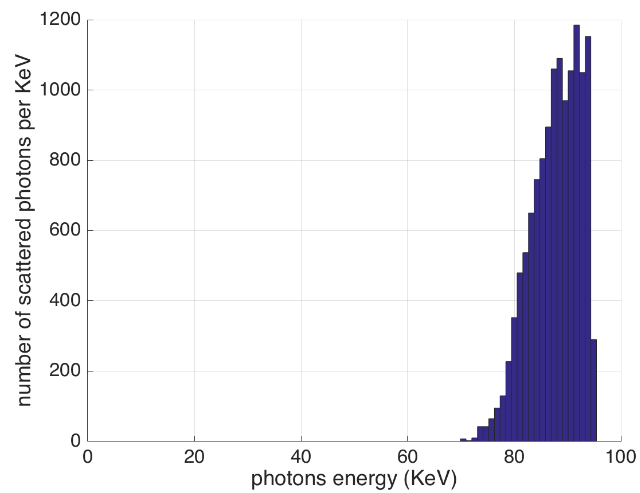
LCLS, 1 Angstrom
15 GeV, l_w=2.5 cm



FEL Spectrum
2.5 GeV, l_w=14 mm

Compton X-ray photon beam: 10^{12} - 10^{13} hn/s (@ 100 MHz) in 5% Dn/n, 20-180 keV, tunable, polarized, s_t = 2 psec, 10 mm round source spot size, mrad divergence

$$N_X^{bw} = 1.4 \cdot 10^{17} \frac{P_{FP}\left[MW\right]\left\langle I_e \right\rangle\left[mA\right]}{f_{FP}\left[MHz\right]\sigma_x^2\left[\mu m^2\right]} bw$$

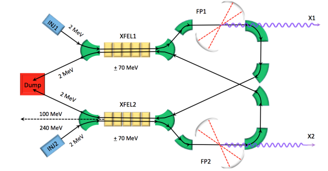


Compton spectrum
FP @ 400 kW, 10 mA

$2.6 \cdot 10^{12}$ photons/s

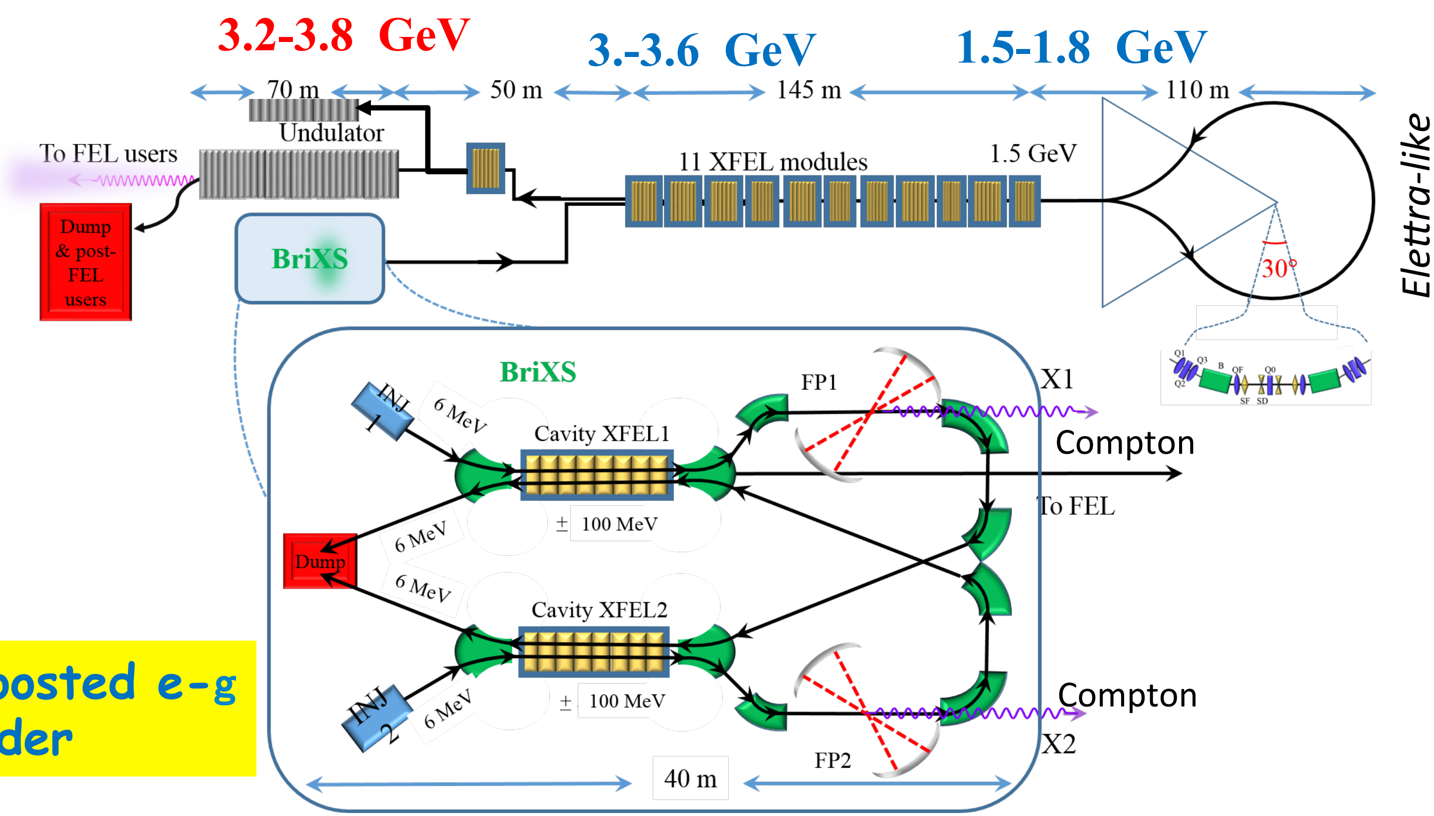
Scientific/Clinical Case: 2 Research Fields enabled by MariX originality (Compton+FEL in CW)

- High resolution low dose Radio-logical Imaging (<100 mm) with mono-chromatic X-rays up to 150 keV: mammography, 2 color angiography, radio-therapy with auger electrons on cis-platine, CAT 3D imaging of Cult.Herit./Archeological/Paleontological samples
- Time resolved spectroscopy with fs coherent X-rays up to 8 keV @ 1 MHz rep rate: catalisys and chemistry in solvents, structure of nano-objects from coherent diffraction, bio-chemistry @ atomic and fs scale, pump&probe spectroscopy of strongly correlated materials, magnetism, superconductivity, topological materials, materials under strong spin-orbit interaction. Protein Crystallography with single-shot imaging (flash-and-destroy)



BriXS & MariX FEL based on bubble arc compressor: we use twice the same 1.5 GeV SC CW Linac

A relativistic-doppler antenna

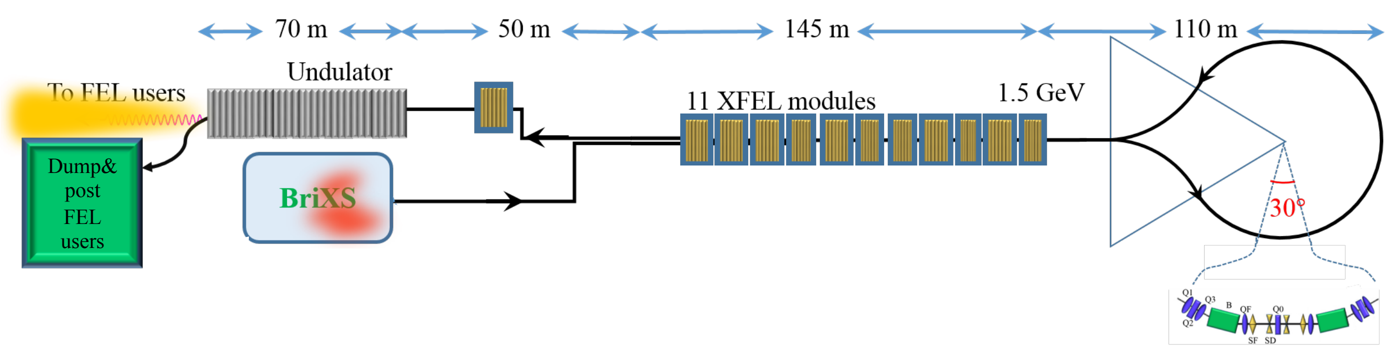


A boosted e-g Collider

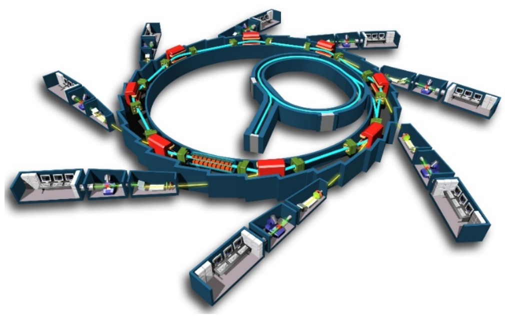
BriXS: 20-150 keV mono-chromatic X-rays up to 5.10^{12} photons/sec in 5% bdw

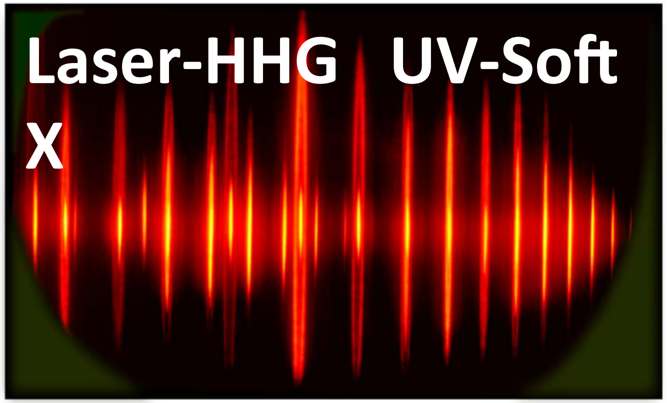
MariX with bubble arc compressor

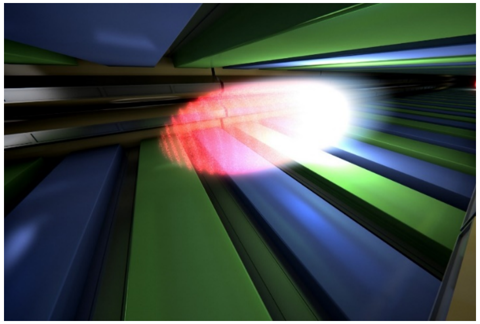
3.2-3.8 GeV **3.-3.6 GeV** **1.5-1.8 GeV**



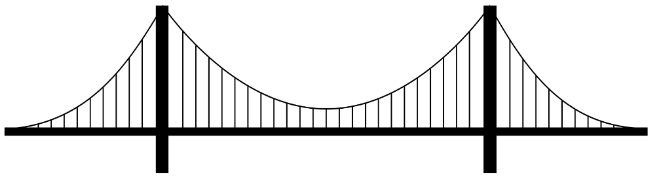
Intra-bunch time separation : 1 micro-second, 300 m
Beam time structure: 1 MHz repetition rate, single bunch CW







Synchrotron Radiation sources



Free Electron Laser sources

500 MHz repetition
nJ pulse energy; ≈50ps
10^{5-6} photons x
(5)x10^{8}pulses

Linear response regime:

Imaging and spectroscopy (perturbation theory)

MARIX+FEL (10 keV)

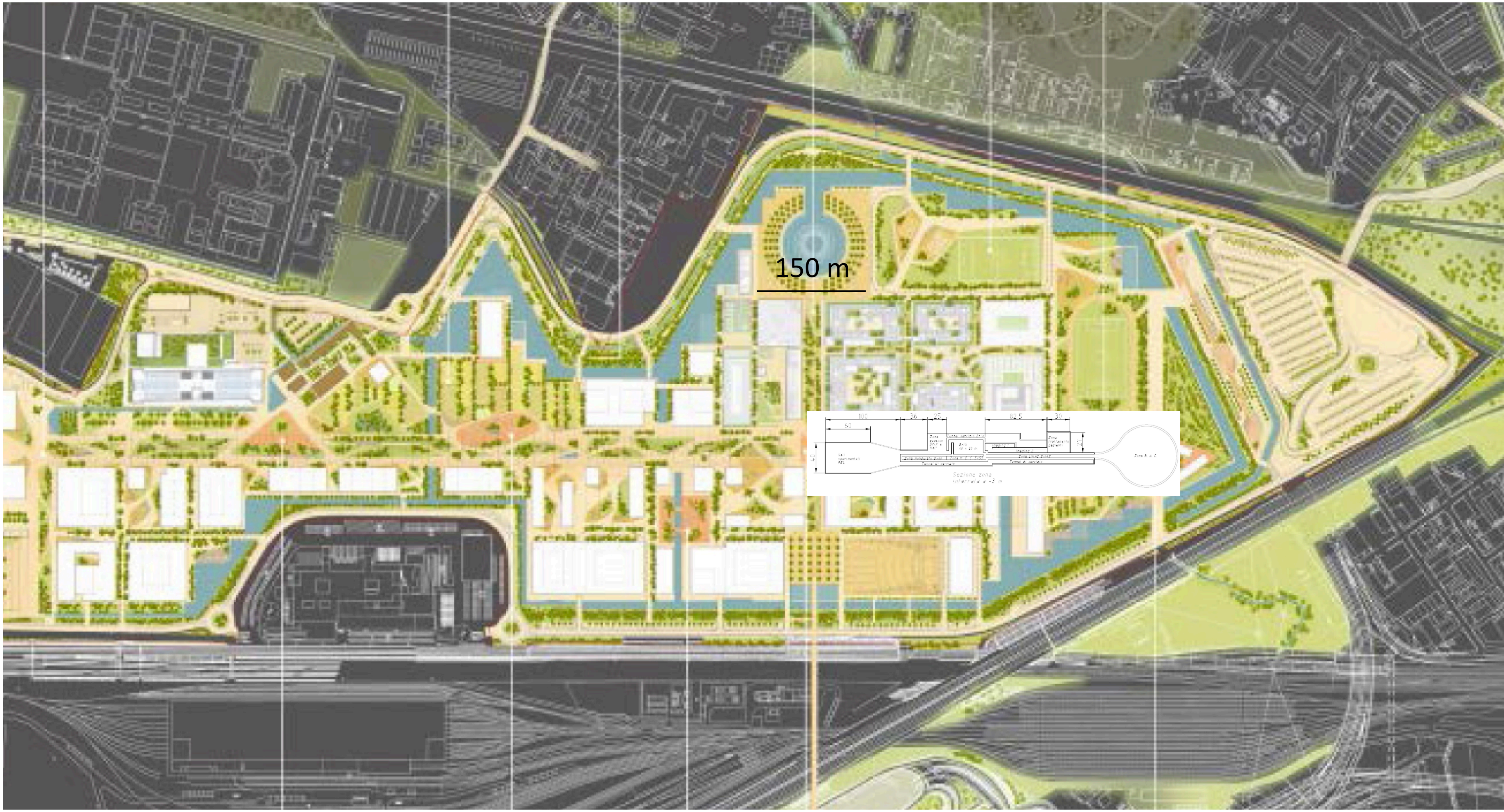
1 MHz repetition
100nJ pulse energy; ≈50fs
10^{9-12} photons x 10^{6}pulses

Ultrafast Linear response

10Hz-27kHz repetition
mJ pulse energy; ≈50fs
10^{12-13} photons x
$10^{1-3-(6)}$pulses

Ultrafast Non-linear response regime
Imaging, flash+destroy

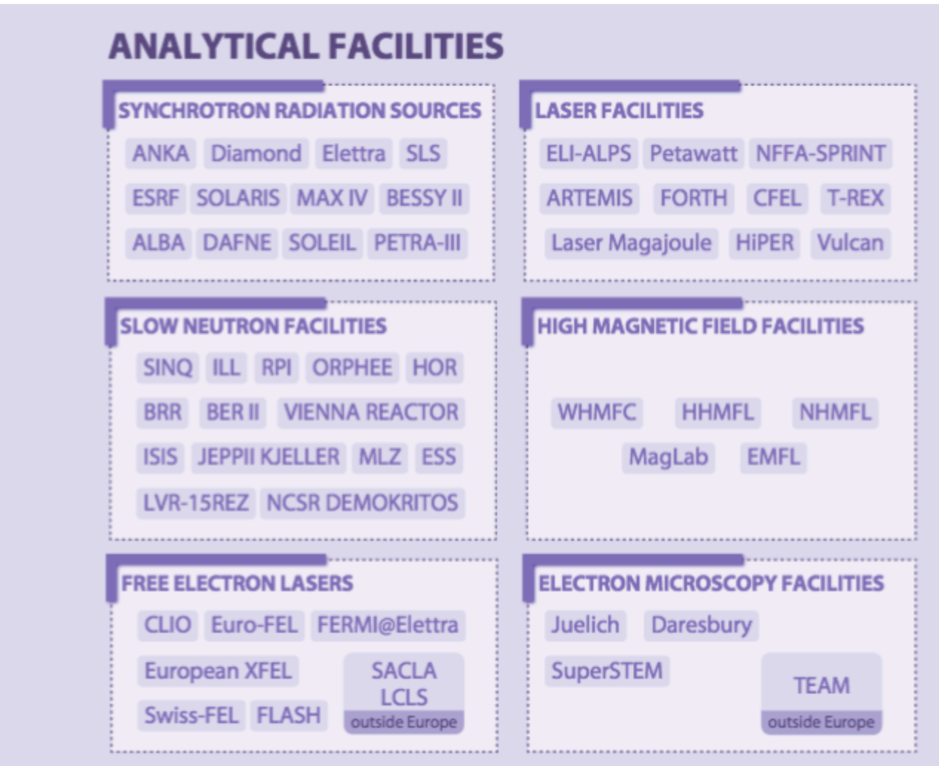
Courtesy Giorgio Rossi – Chair ESFRI


150 m
100
60
36
25
82,5
30
27
40
Sali sperimentali FEL
Zona accesso BriX e Hall
Tunnel servizio BriX
BriX 40 x 20 m
Imaging 1
Imaging 2
Zona trattamento pazienti
Zona Hondulato 5x60
Zona H. E. C. 5x55
Zona LINAC 5x145
Tunnel di servizio
Tunnel di servizio
Zona B. A. C.
Sezione zona interrata a -3 m

Infrastrutture di Ricerca Analitiche aperte all'utenza internazionale che operano in Europa e sedi LERU

Analytical Machines as User Facilities in Europe and League of European Research Universities: a void around Univ. of Milan

LERU members



Da PSE Landscape Analysis ESFRI Roadmap 2016

Courtesy Giorgio Rossi – Chair ESFRI

MariX Free Electron Laser Scientific Case

Fonte dei grafici: SwissFEL Science Case

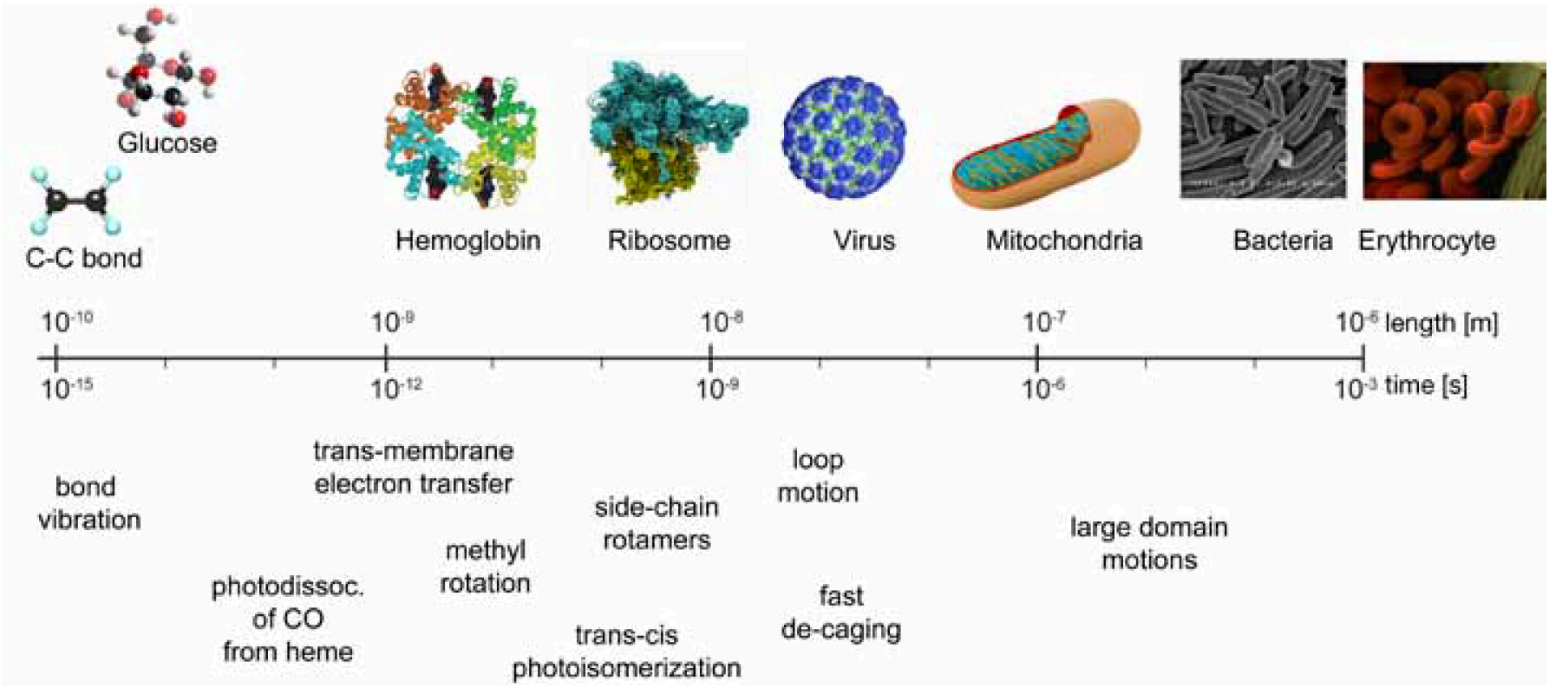


Fig. IV.1. The time and length scales for biochemical proesses match well to the capabilities of the SwissFEL.

La scala sub-nanometrica (piccole molecole), la scala 1-10 nm (proteine e complessi), la scala 10-100 nm (organelle, virus), la scala micrometrica (cellule) sono suscettibili di imaging con la diffrazione coerente con l=0.2 nm)

MariX Free Electron Laser Scientific Case

Coherent Diffraction Imaging di nanoscristalli e macromolecole

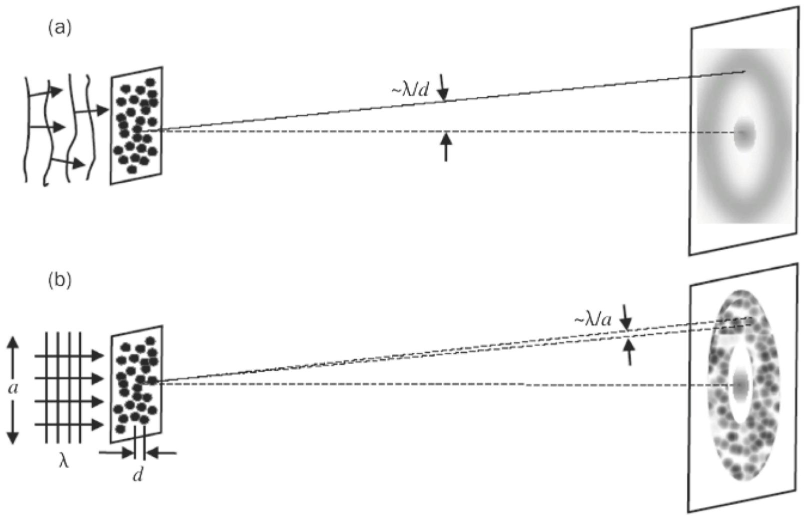


Fig. III.2. Whereas the scattering of incoherent radiation, e.g. from a synchrotron, yields only the average spacing *d* of a collection of scatterers (a), the scattering of coherent radiation (with beam diameter *a*) from the SwissFEL produces a rich speckle pattern (b), which can be inverted to obtain the exact distribution of scatterers (from [1]).

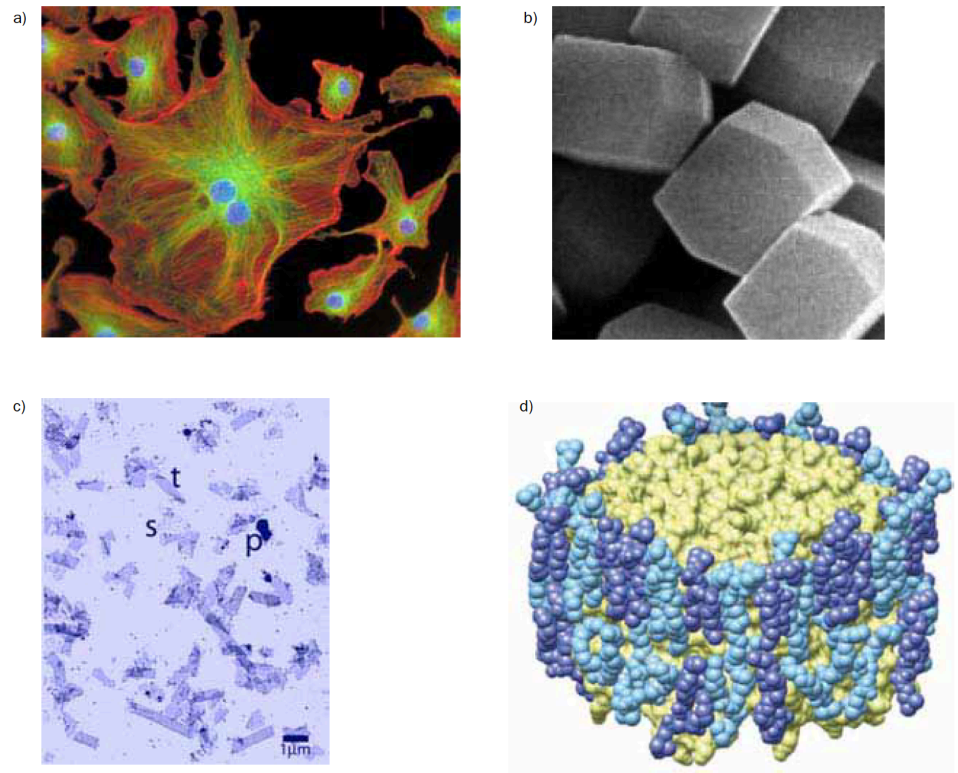
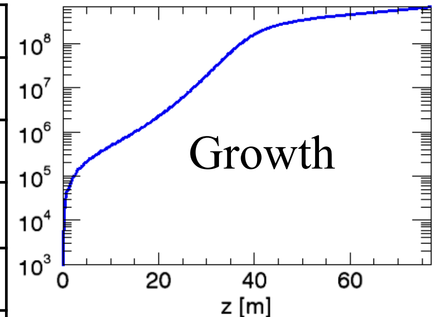


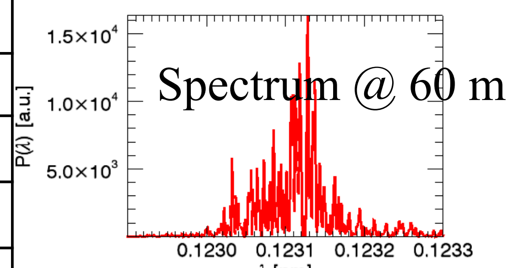
Fig. III.1. Bio-imaging challenges that the SwissFEL will meet: resolving intracellular features at nm resolution, such as the cytoskeleton (a), allowing the use of very small 3d-nanocrystals (b) or of 2d-membrane protein crystals (c) to avoid the crystal growth problem in protein crystallography, and sequentially injecting into the beam individual biomolecules (d), for high-resolution structure determination.

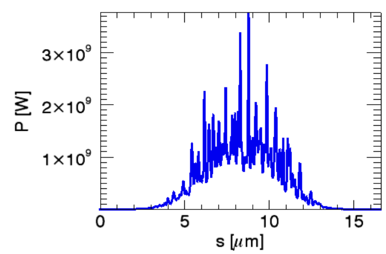
FEL example 2: single shot imaging (λ_{rad} =1.2 Å), Undulator λ_w=1 cm, a_w=0.6, length =60 m

Q=50 pC, I=2 kA, ε_n = 0.4 mm , $\Delta E/E = 2 \cdot 10^{-4}$, a_w=0.6, dt=10 fs

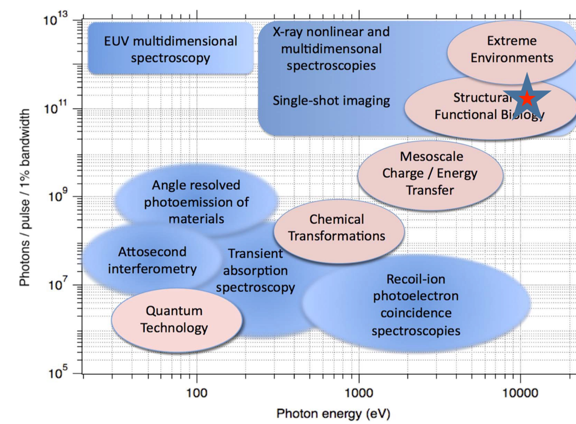
FEL	MariX	LCLS
Electron energy (GeV)	3.8	3
Und (cm,m)	1, 60	3, 100
Photon energy (keV)	10.2	12.5-25
Rep rate	1 MHz	120 Hz
Energy	27.5 mJ	1-5 mJ
Photons per shot	$1.7\ 10^{10}$	10^{12}
Bandwidth (%)	0.12	0.1
Photons / sec	$1.7\ 10^{16}$	$1.2\ 10^{14}$
Spectral density (N/s/ 1%bw)	$1.4\ 10^{17}$	$1.2\ 10^{15}$
Coherence	SASE	SASE







Power @60 m



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J. Phys. B: At. Mol. Opt. Phys. 51 (2018) 032003 (45pp) — https://doi.org/10.1088/1361-6455/aa9735

Roadmap

Roadmap of ultrafast x-ray atomic and molecular physics

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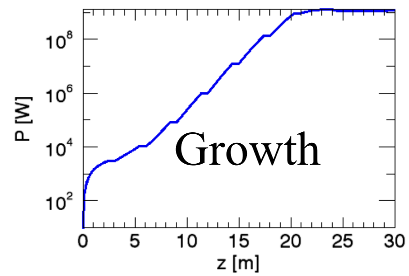
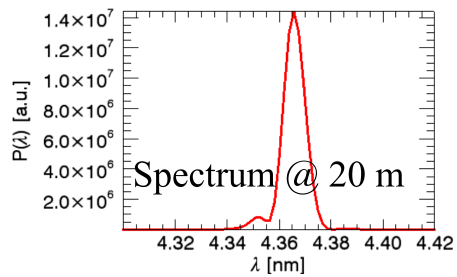
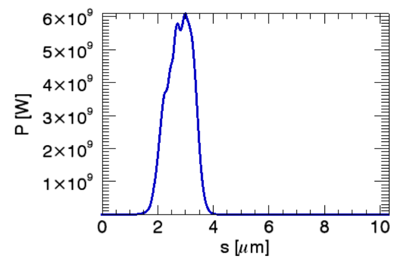
FEL example 1: water window (l_{rad}=3 nm), Undulator l_w=3 cm, a_w=2.5, length =25 m

Q=8-16 pC, I=2 kA, e_n= 0.5 mm DE/E=2.10^{-4}, a_w=2.5, dt=2-3.5 fs

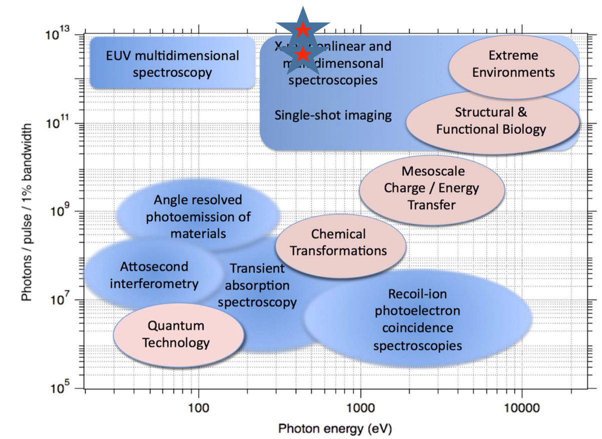
FEL	MariX	FERMI
Electron energy (GeV)	2.5	1.5
Und l_w, L (cm,m)	3, 25	5, 40
Photon energy (keV)	0.45 (2.8 nm)	0.38 (4 nm)
Rep rate	**1 MHz**	10-50 Hz
Energy	8-16 mJ	5-10 mJ
Photons per shot	**3-7 10^{11}**	10^{11}
Bandwidth (%)	**0.1**	0.02-0.07
Photons / sec	**2-7 10^{17}**	5 10^{12}
Spectral density (N/s/%bw)	**2-7 10^{18}**	2.5 10^{14}
Coherence	Single Spike	**Full**

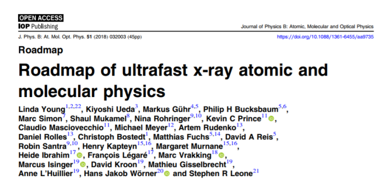


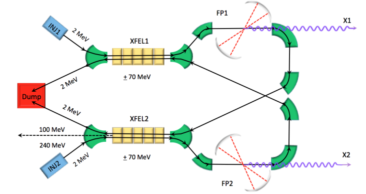




Power @ 20 m







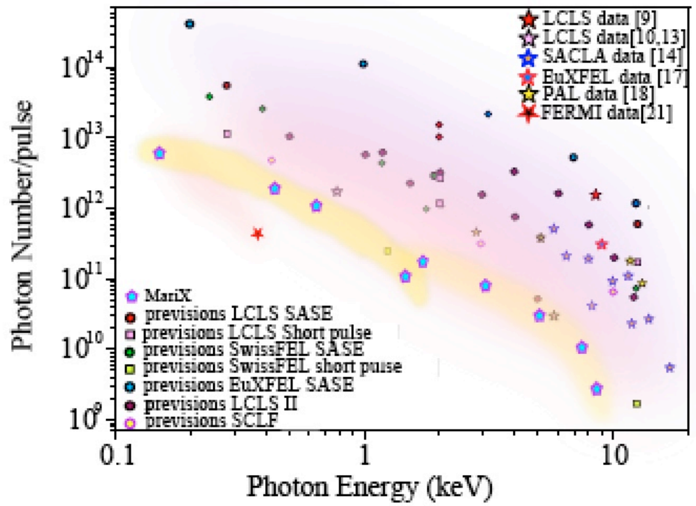


fig:X-ray-FEL-previsions
Figure 21.11: X-ray FEL previsions and experimental data (including MariX) mapped onto photon energy (keV) and number of photons per shot. (For references see Fig. in Chapter 3).

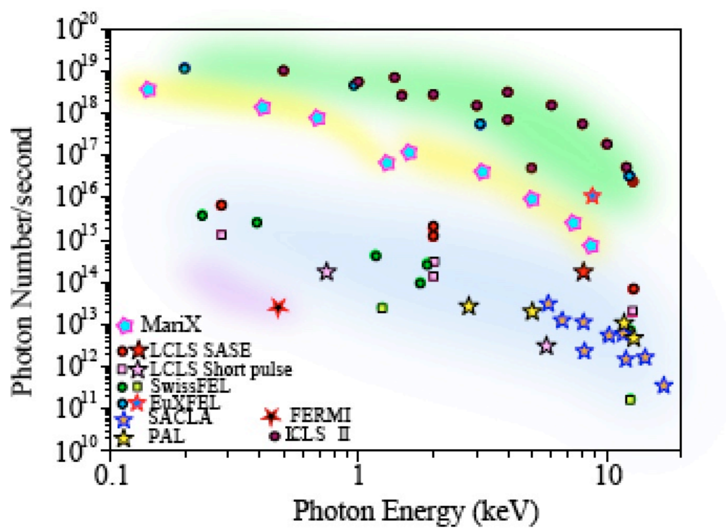
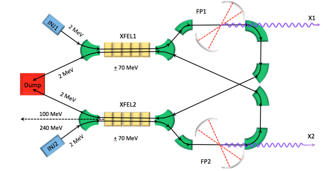
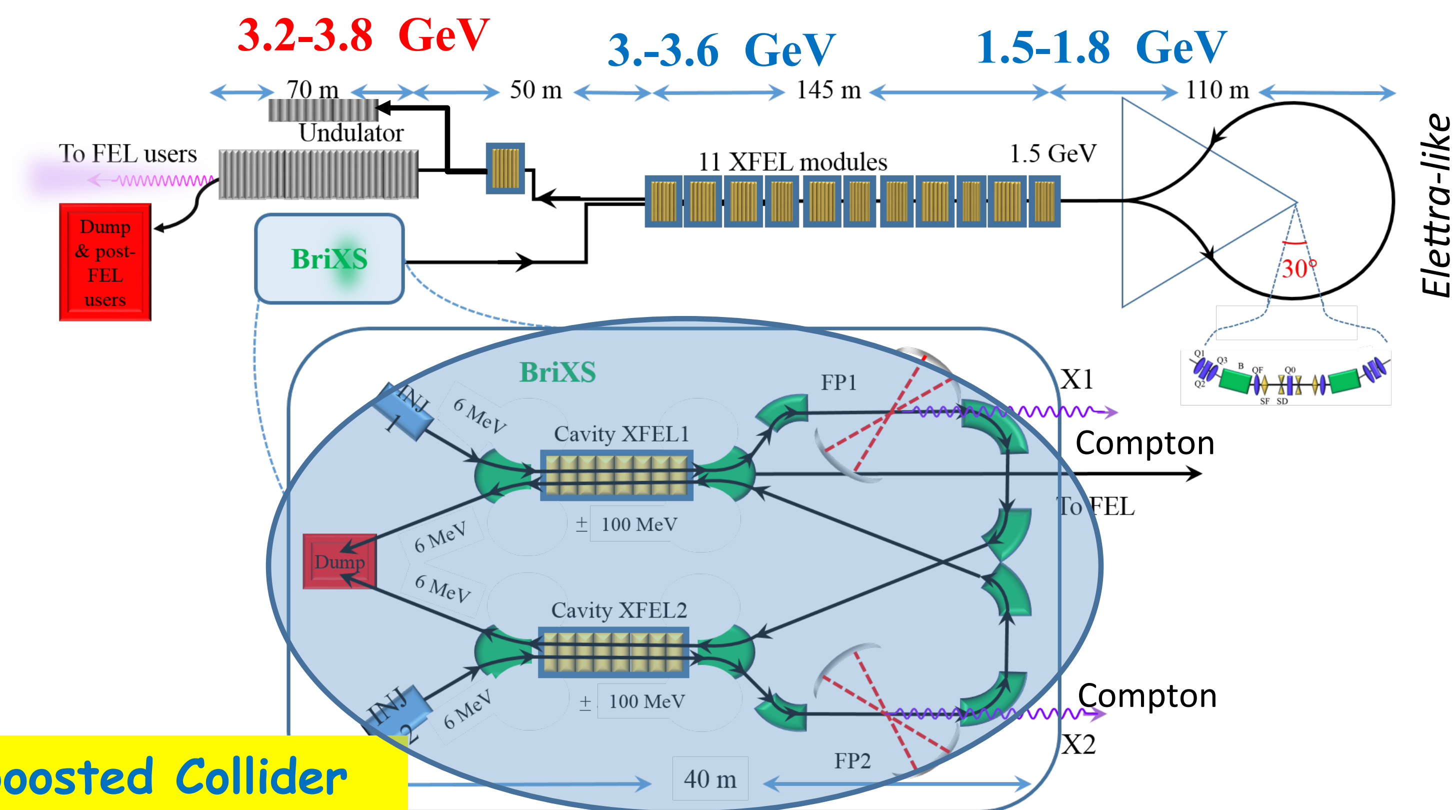


fig:X-ray-FEL-previsions-1
Figure 21.12: X-ray FEL previsions and experimental data (including MariX) mapped onto photon energy (keV) and number of photons per second. (For references see Fig. in Chapter 3).



BriXS: MariX Compton Source

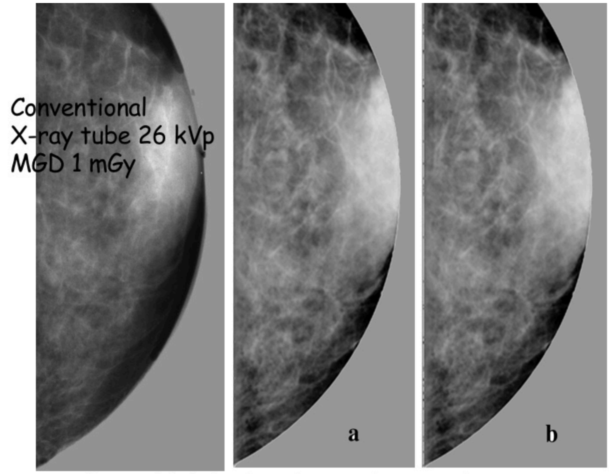


A boosted Collider
e-g as I.C.S.
(in regime Thomson)

BriXS: 20-150 keV mono-chromatic X-rays
up to 5.10[12] photons/sec in 5% bdw

small source size → high resolution (81 μm)
monochromatic → no beam hardening artefacts

Klaus.Achterhold@tum.de

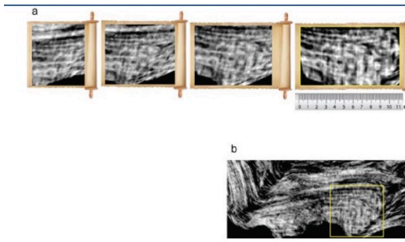


a) SR digital image
Energy 17 keV
Scan step 100 mm
MGD 1 mGy

b) SR digital image
Energy 20 keV
Scan step 100 mm
MGD 0.33 mGy

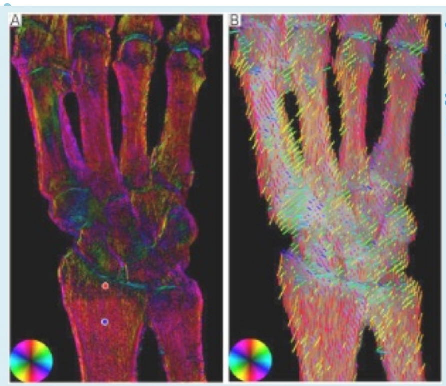
3 cm thick in vitro human breast tissue

BriXS Compton Source Clinical/Scientific Case



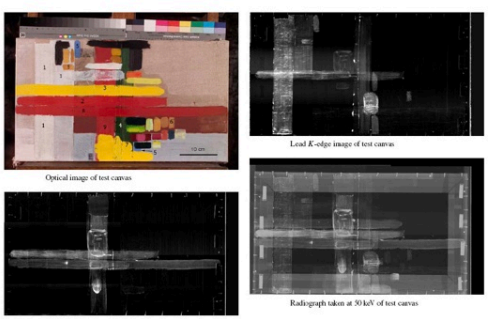
enrolling Ercolano's papyri

Figure 1: ***PHerc*. 375**. **a,** virtual-unrolling; **b** textual portion.

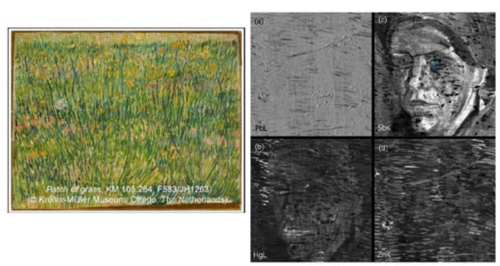


"Trabecular bone anisotropy imaging with a compact laser-undulator synchrotron x-ray source", C. Jud* at al. Scientific Reports 7, Article number: 14477; Online: 03 November 2017 *Tecnical University of Munich

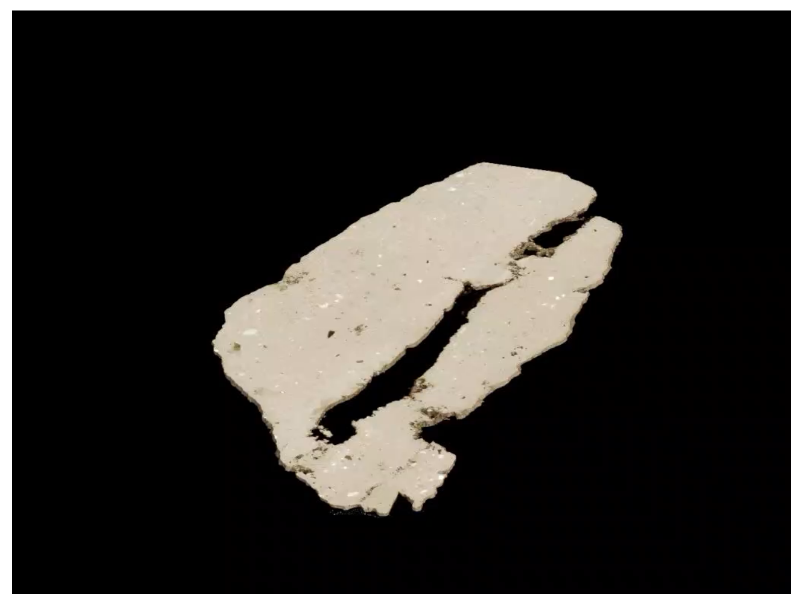
Microfractures without dislocation are often missed in initial radiographs; x-ray vector radiography (XVR) can overcome this limitation: degree of anisotropy and the orientation of scattering structures



J. Dik, ESRF, ID17



Analyse d'une peinture de Vincent Van Gogh par Sy-XRF
K. Janssens, J. Dik, et al. *Anal. Chem.* 2008



Inverse Compton Sources rivaling in Average Brightness with Synchrotron Light Sources at photon energies above 80-100 keV

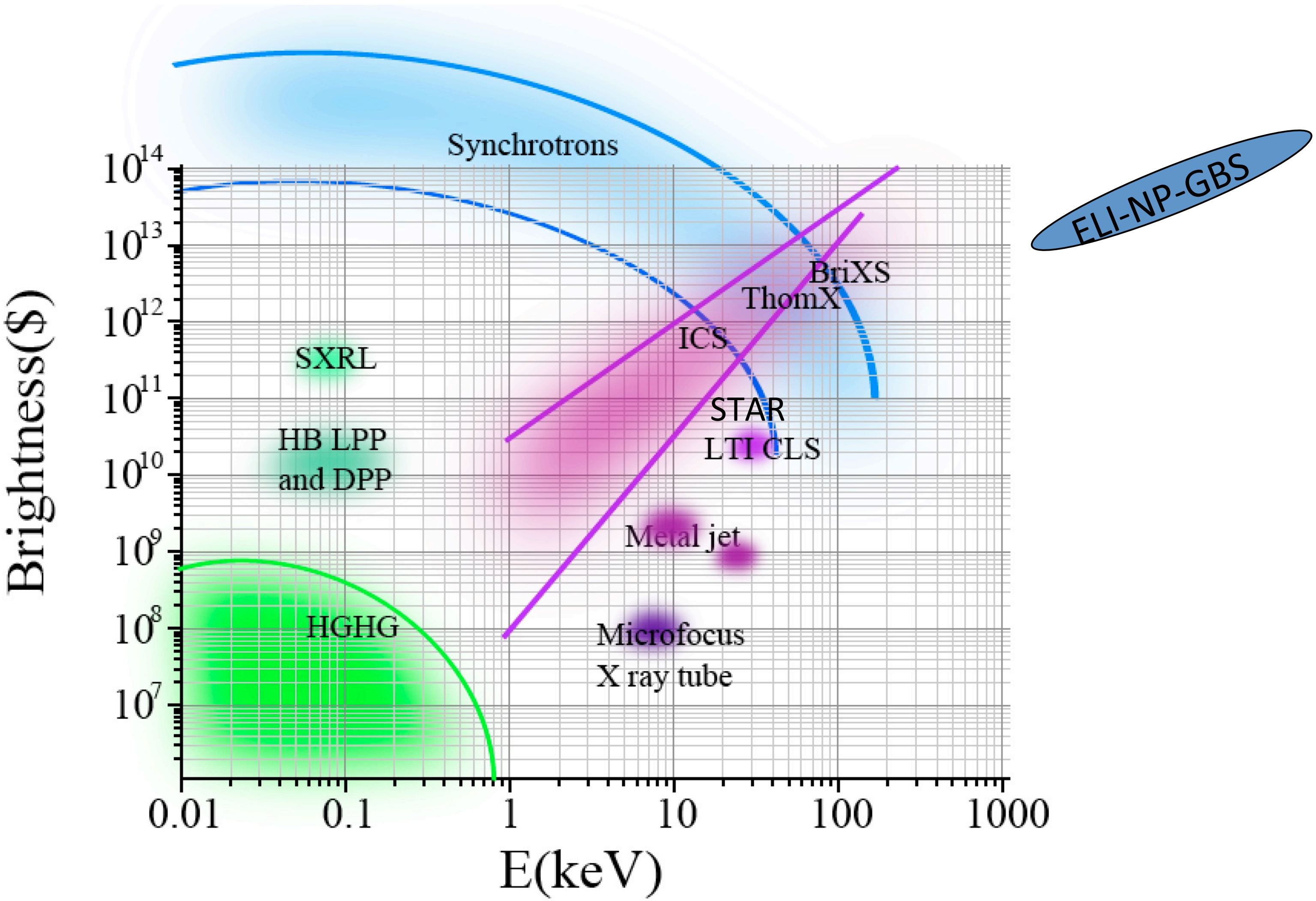
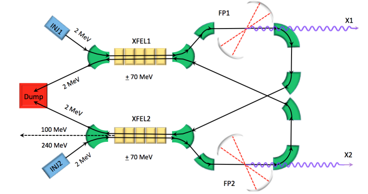


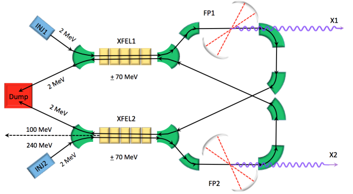
Figure 1: Brightness of several radiation sources as a function of the photon energy. $: Photon $number/s/mm^2/mrad^2/(0.1\%$.
I.C.S. Sources (LTI-CLS,ThomX, STAR, UH-FLUX and BriXS) are compared to Synchrotron Light Sources and the most performing X-ray tube so far (Metal Jet).



Photon energy	20 - keV180
Bandwidth	1 - 10 %
# photons per shot within FWHM bdw.	0.05×10^5 - 1.0×10^5
# photons/sec within FWHM bdw.	0.05×10^{13} - 1.0×10^{13}
Source size	20 μm
Source divergence	6 - 1 mrad
Photon beam spot size (FWHM) at $z = 100$ m	40 - 8 cm
Peak Brilliance†	10^{18} - 10^{19}
Radiation pulse length	0.7 - 1.5 ps
Linear/Circular Polarization	> 99 %
Repetition rate	100 MHz
Pulse-to-pulse separation	10 ns

tab:06_BriXs_compton_pars

Table 6.1: |Summary of BriXS Compton X-ray beam specifications. † = $N_{ph} s^{-1} mm^{-2} mrad^{-2}$ $^0/_{00}$.



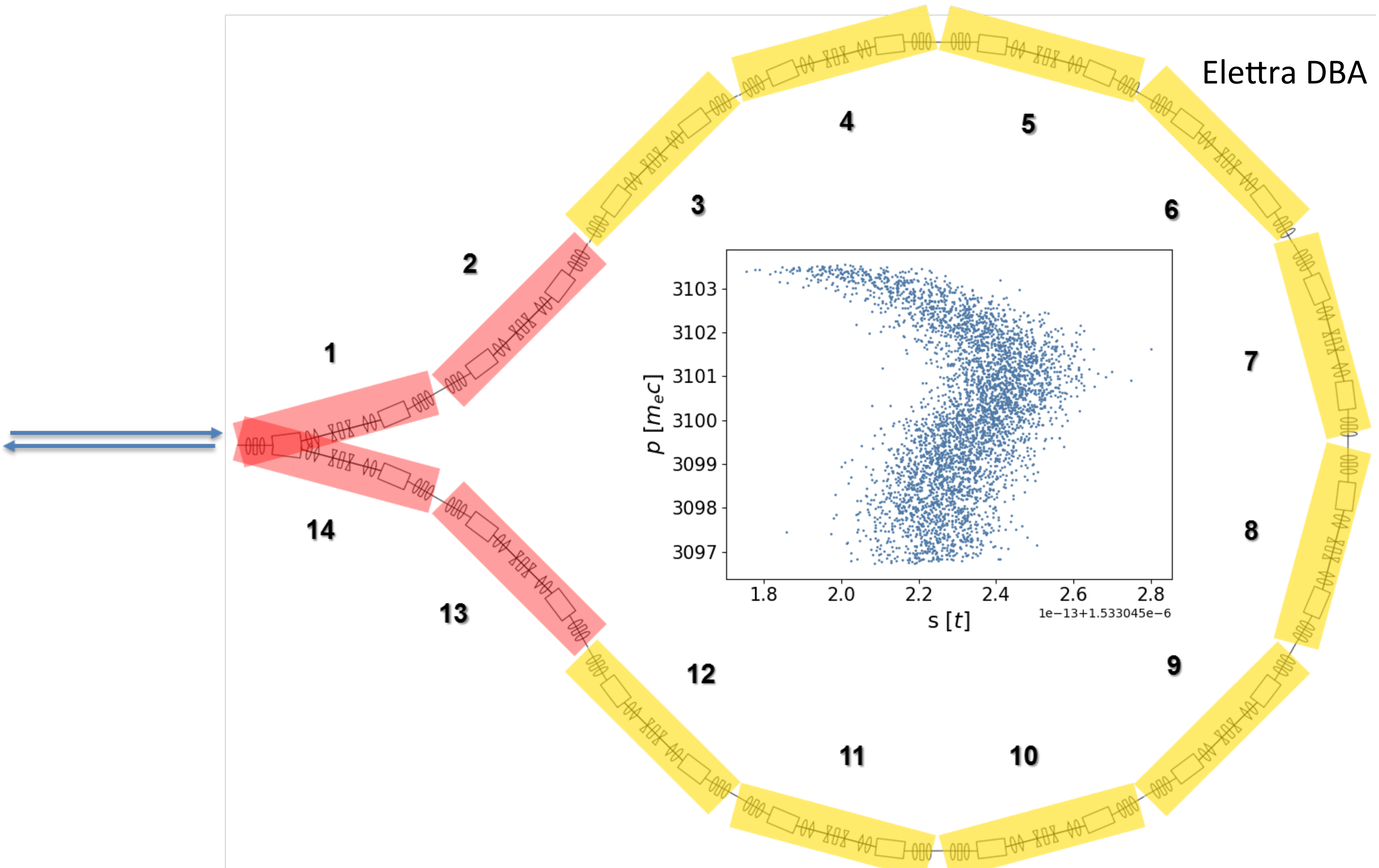
UliX1 Undulator	
Photon energy	0.12 - 1.5 keV
Radiation wavelength	10 nm - 8 Å
# photons per pulse	1.7×10^{12} - 1.2×10^{11}
Bandwidth	2.1×10^{-3} - 7.0×10^{-4}
Peak Brilliance†	1.4×10^{31} - 2.4×10^{32}
Radiation pulse length	3 - 10 fs
Radiation beam divergence	50 - 6 μrad
Repetition rate	1 MHz
Pulse-to-pulse separation	>1 μs
# photons	1.7×10^{18} - $1.2 \times 10^{17}\,s^{-1}$
Average Brilliance†	8.6×10^{22} - 1.4×10^{24}

UliX2 Undulator	
Photon energy	1.5 - 8.0 keV
Radiation wavelength	8.0 Å - 1.5 Å
# photons per pulse	2.4×10^{11} - 2.5×10^{9}
Bandwidth	2.3×10^{-3} - 3.0×10^{-3}
Peak Brilliance†	5.3×10^{29} - 5.5×10^{28}
Radiation pulse length	1 - 7 fs
Radiation beam divergence	45 - 16 μrad
Repetition rate	≤ 1 MHz
Pulse-to-pulse separation	>1 μs
# photons	2.4×10^{17} - $2.5 \times 10^{15}\,s^{-1}$
Average Brilliance†	3.5×10^{23} - 3.7×10^{22}

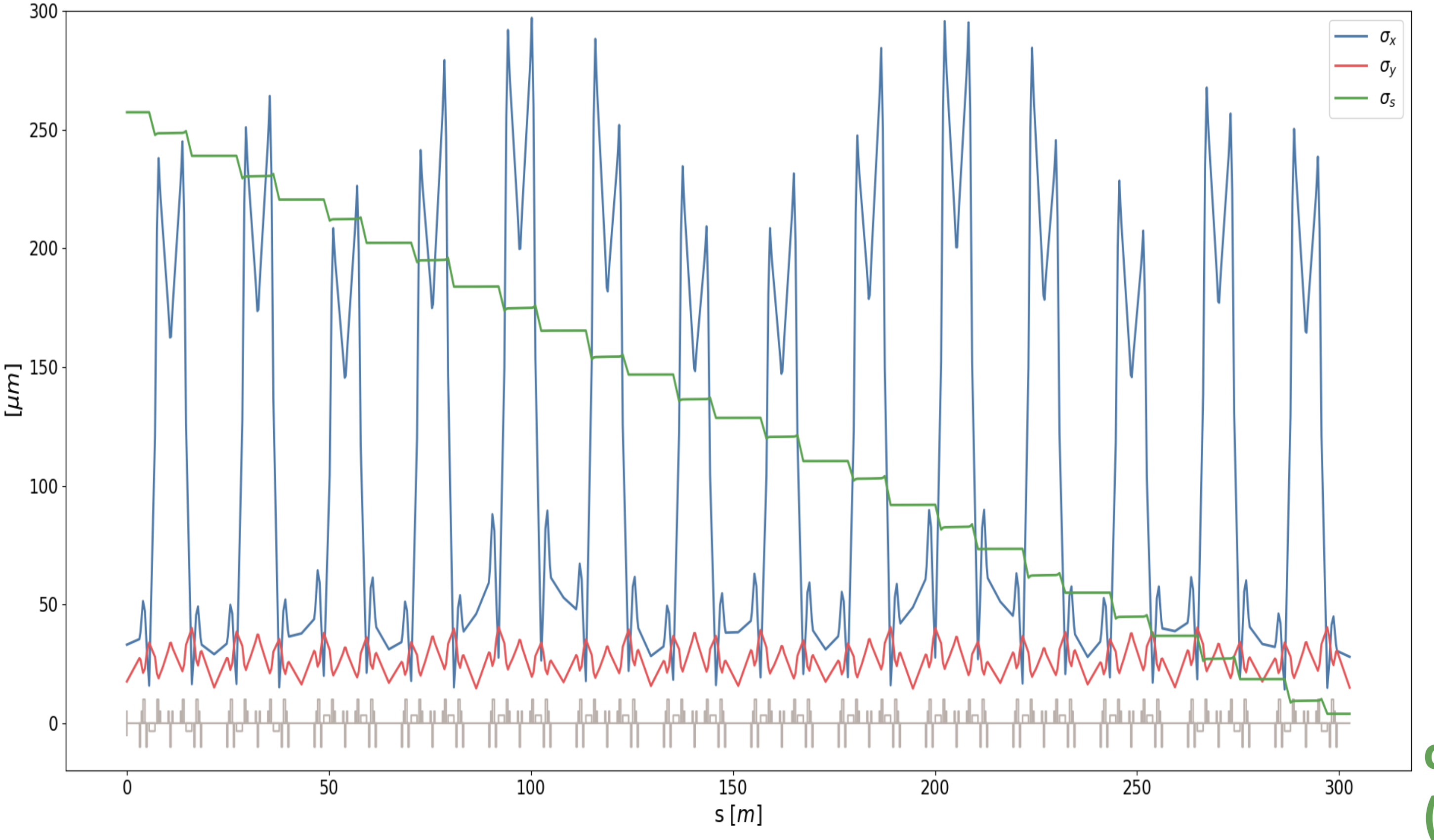
tab:06_FEL_pars

Table 6.2: |Summary of FEL photon beam specifications. $^\dagger = N_{ph}\,s^{-1}\,mm^{-2}\,mrad^{-2}\,{}^{0}/_{00}$.

The arc-compressor



The compressor performances (output emittance= 0.5 um)



σ_s = 3.96μm
($C_f \approx 64.9$)

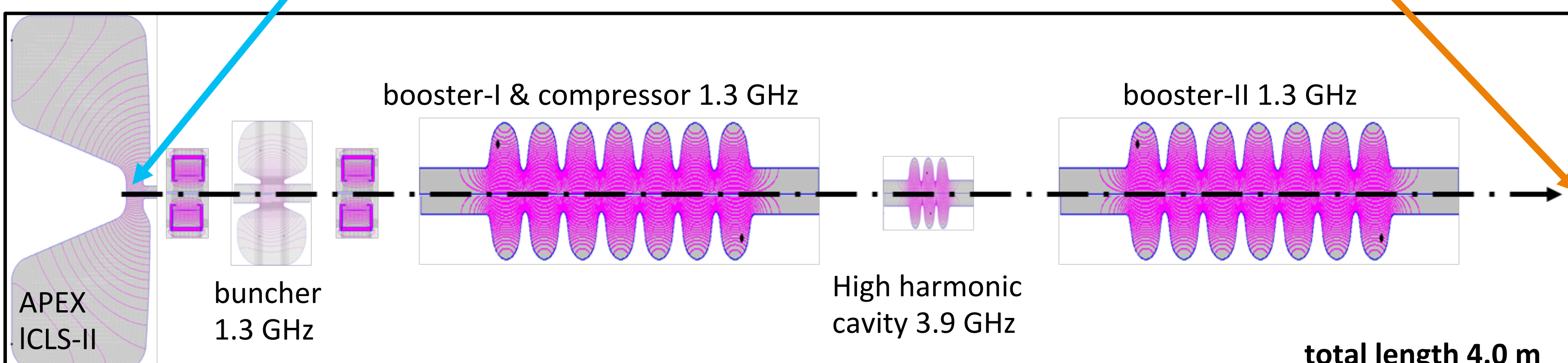
Peak current evaluation
($C_f \approx 64.9$) x (I_p=25A) = 1650 A

Apex MARIX & BriXS working points

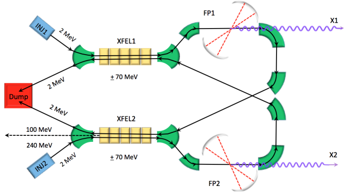
T_{Exit} [KeV]	Qb [pC]	T_{laser} [ps] (plateau)	σ_{x_laser} [mm]	$\varepsilon_{n,t}/\sigma_x$ [μm/1mm]	σ_z [um]	ε_n [μm]	$\Delta\gamma$ [KeV]	T [MeV]
BriXS					Inj. exit			
830	200	48	420	0.5	1000	0.85	5	6.7
MARIX					Inj. exit			
830	50	40	200	0.5	460	0.36	7.0	6.4

GUN Parameters

@ injector exit

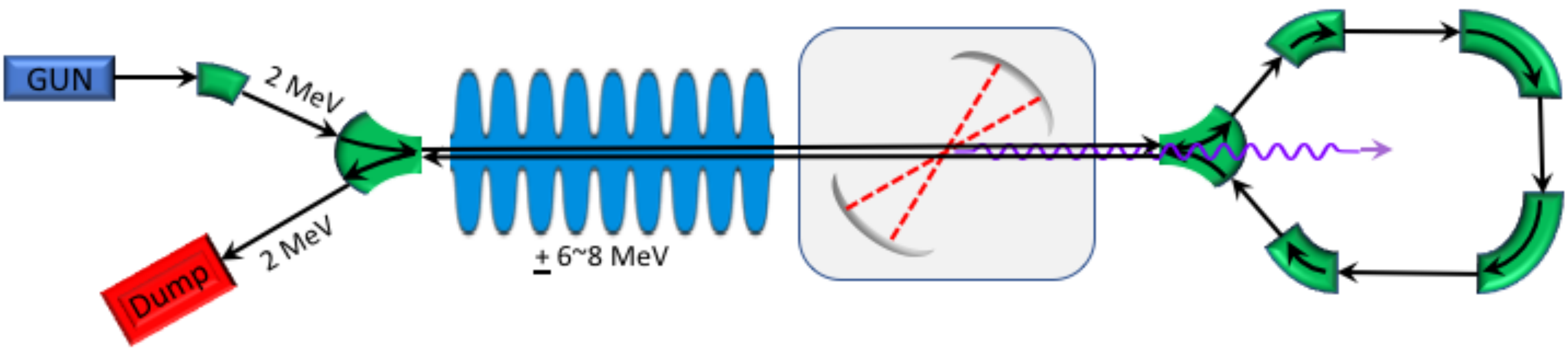


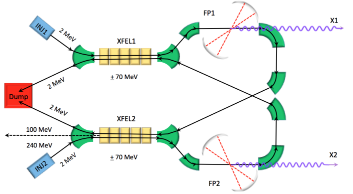
L. Faillace map scheme



We are planning to build a small scale BriXS demonstrator at LASA: BriXsino

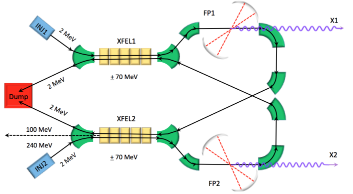
BriXinO

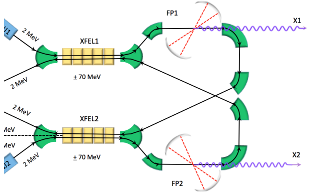




Thank you for your attention, and stay tuned...
MariX-CDR will come out very soon

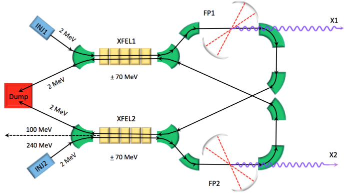
Editorial Board





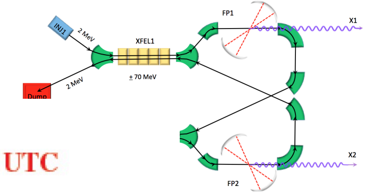
Components	Cost (Meuros)
RF Power Sources (1.3 GHz) + RF Plumbing	4
Cryomodules (1.3 GHz)	27
Magnets + Power Supplies	2
Building + Infrastructure	8
Cryogenics	5
Photoinjector Guns + Power Supplies	4
III Harmonic cryomodule (3.9 GHz)	1
III Harmonic RF power source (3.9 GHz)	0.5
Laser	1
Fabry Perot Cavity	0.5
Diagnostics	5
Beam Dump	1
Control System	5
Radiation Safety	1
Vacuum	2
Experimental Halls	5
Contingency	7.2
Total	**79.2**

Table 40.1: |BriXS Cost Table. tab:41_BriXS_Cost_Table



Components	Cost (Meuros)
RF Power Sources (1.3 GHz) + RF Plumbing	24
Cryomodules (1.3 GHz)	79
Magnets + Power Supplies	26
Building + Infrastructure	88
Cryogenics	55
Photoinjector Guns + Power Supplies	4
III Harmonic cryomodule (3.9 GHz)	21
III Harmonic RF power source (3.9 GHz)	5.5
Laser	1
Fabry Perot Cavity	0.5
Undulators	70
Diagnostics	55
Beam Dump	3
Control System	55
Radiation Safety	11
Vacuum	32
Experimental Halls	65
Contingency	59.5
Total	**654.5**

tab:42_MARIX_Cost_Table
Table 41.1: |MariX Cost Table.



THE MariX SOURCE (MULTIDISCIPLINARY ADVANCED RESEARCH INFRASTRUCTURE WITH X-RAYS)

L. Serafini, A. Bacci, F. Broggi, A. Bosotti, S. Coelli, C. Curatolo, I. Drebot, L.Faillace, D. Giannotti, D. Giove, C. Meroni, P. Michelato, L. Monaco, R. Paparella, F. Prelz, A. R. Rossi, D. Sertore, M. Statera, F. Tomasi, V. Torri, INFN-MI, Milan, Italy
R. Saban (INFN-HeadQuarter), Rome, Italy
A. Esposito, A. Gallo, C. Vaccarezza, INFN-LNF, Frascati, Italy,
F. Camera, F. Castelli, S. Cialdi, F. Groppi, B Paroli, G. Onida, L. Perini, V. Petrillo, N. Piovella, P. Piseri, M. Potenza, M. Rossetti Conti, G. Rossi, University of Milan, Milan, Italy
A. Castoldi, G. Galzerano,G. Ghiringhelli, C. Guazzoni, M. Moretti, E. Pinotti, E. Puppin, A. Tagliaferri, Polytechnic of Milan, Milan, Italy
F. Stellato, INFN-Roma2, Roma, Italy
M. Placidi, G. Turchetti University of Bologna, Bologna, Italy
S. Di Mitri, FERMI-Elettra, Basovizza, Italy
R. Calandrino, A. Delvecchio, San Raffaele H, Milan, Italy
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G. Mettivier, P. Russo, A. Sarno, University of Napoli, Naples, Italy

Abstract

MariX (Multidisciplinary advanced research infrastructure with X-rays) is a joint project of INFN and University of Milan, aiming at developing a twin X-ray Source of advanced characteristics for the future Scientific Campus of the University of Milan. Presently in its design study phase, it will be built in the post Expo area located in north-west Milan district. The first component of the X-source MariX is BriXS (Bright and compact X-ray Source), a Compton X-ray source based on superconducting cavities technology for the electron beam with energy recirculation and on a laser system in Fabry-Pérot cavity at a repetition rate of 100 MHz, producing 20-180 keV radiation for medical applications. The BriXS accelerator is also serving as injector of a 3.8 GeV superconductive linac, driving a X-ray FEL

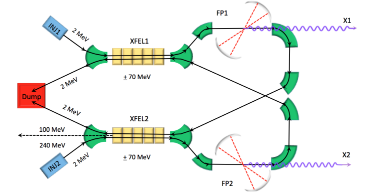
of a superconductive linac driving a X-ray FEL at 1 MHz, for providing coherent, moderate flux radiation at 0.3-10 KeV at 1 MHz.

In this paper, the scientific case, the layout and the typical parameter of the MariX FEL line will be discussed.

SCIENTIFIC CASE

The MariX FEL project is set up as a FEL in the X-rays range with moderate flux per pulse and high repetition rate.The extremely innovative characteristic of the layout allows to operate with relatively low electron energy, with contained dimension and costs.

Table 2 shows electron and photon energy ranges, number of photons per pulse and per second for MariX and for FELs (operating and projected) in a similar X-ray range.



OPTIMISATION STUDY OF THE FABRY-PÉROT OPTICAL CAVITY FOR THE MARIX/BRIXS COMPTON XRAY SOURCE

I. Drebot*, A. Bacci, A. Bosotti, F. Broggi, C. Curatolo, L. Faillace, D. Giannotti, D. Giove,
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Abstract

We present the study of the optimization of the optical cavity parameters, in order to maximise the flux of scattered photons in the Compton scattering process. In the optimisation, we compensate the losses of the photon number due to the elliptical shape of the laser pulse in optical cavity with a high focusing electron beam.

INTRODUCTION

MariX (Multidisciplinary Advanced Research Infrastructure with X-rays) is a project of INFN and University of Milan [1, 2] and has to be constructed at the new scientific campus at the ex-EXPO site in Milan in the next years. The first component of the X-source MARIX is BriXS (Bright and compact X-ray Source), a double Compton X-ray source based on superconductive cavities technology for the electron beam with energy recirculation and on a laser system in Fabry-Pérot cavity at a repetition rate of 100 MHz, producing 20-100 keV radiation. The BriXS accelerator constitutes then the injector of a superconductive linac which drives a X-ray FEL at 1 MHz, for providing coherent, moderate flux radiation at 0.3-10 KeV at 1 MHz. The joint presence of a Compton source and of an hard and soft X-ray FEL will serve a multitude of users, in many fields of science while its characteristics are described in detail in [2].

A main characteristic of this machine is the very high average current. The double Compton X-ray sources will operate at 100 MHz, with 200 pC electron bunches that means 20 mA. These Compton sources are designed to operate with an electron maximum energy of 100 MeV, which for a 20 mA of current means 2 MW. Such a high beam power cannot be dumped without deceleration, and together with the CW (Continuous Wave) regime, it justifies an ERL (Energy Recovery Linac) machine. Our first analysis is based on a projects like CBETA ERL crymodule [3].

The focus on enabled applications by such an energy range and brilliance is on medical oriented research/investigations, mainly in the radio-diagnostics and radio-therapy fields, exploiting the unique features of monochromatic X-rays, as well as in micro-biological studies, and, within this mainstream, material studies, crystallography and museology for cultural heritage investigations. In this paper, the layout and the typical parameter of the BriXS X-ray source will be discussed.

LAYOUT

The BriXS layout, shown in Fig. 1, consists in two symmetric beam lines, fed from two independent photo injectors, where two symmetric (and coupled) Energy Recovery Linacs (ERL) accelerate the beams. The two ERLs are coupled, accelerating and decelerating (recovery) in a push-and-pull scheme. In this unconventional ERL scheme, beams are counter-propagating and bunches coming from guns are accelerated; those coming from the twins ERLs are decelerated and brought simultaneously to a single beam-dump. This push-and-pull coupled scheme permits to drive two Compton X-ray sources with the same degree of freedom of a linac driven source, in terms of energy and electron beam quality. Furthermore, the coupled ERL fed by two independent RF system is more stable. Partial beam line modifications to host additional Compton source Interaction Points (IP) are still under study. CW electron guns capable to produce 20 mA average beam current, as BriXS needs, are not yet state of the art. Some of the most promising photo cathode guns [4] as the Cornell DC gun [5] and the RF CW Apex gun [6] have been compared by simulations.

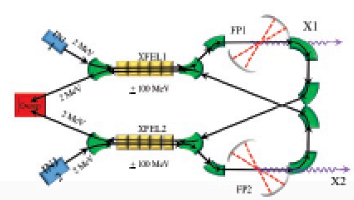
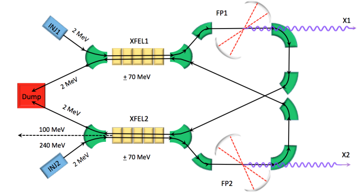


Figure 1: Scheme of BriXS layout.



MULTI COLOUR X-GAMMA RAY INVERSE COMPTON BACK-SCATTERING SOURCE

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Abstract

We present a simple and new scheme for producing multi colour Thomson/Compton radiation with the possibility of controlling separately their polarization, based on the interaction of one single electron beam with two and more laser pulses that can come from the same laser setup or from two different lasers system and that collide with the electrons at different angle inside one optical cavity. One of the most interesting cases for medical applications is to provide two X-ray pulses across the iodine K-edge at $33.2 \sim keV$. The iodine is used as contrast medium in various imaging techniques and the availability of two spectral lines accross the K-edge allows one to produce subtraction images with a great increase in accuracy.

INTRODUCTION

Colour x-ray imaging will provide significant development to screening or diagnostic radiography, because the colour components contain extra information and allow to discriminate the chemical composition of the absorbing tissues [1]. Experiments on dual colour have been recently carried on with free-electron lasers (FELs) as radiation sources [2] and promising proposals aimed to generate two-colour X-ray emission in Compton sources [3–5] have been investigated. Thomson and Compton sources, even though less brilliant than FELs, produce radiation with short wavelength, high power, ultrashort time duration, large transverse coherence and tunability, full polarization control, ensuring limited costs of construction and maintenance and dimensions compatible with the space that can be allocated in hospitals and medical centres. Existing and constructed Thomson sources are important tools for generating tunable quasimonochromatic x/gamma rays suitable for different applications. In this paper we present a simple and new scheme for producing two colour Thomson/Compton radiation with the possibility of controlling independently the polarization of the two beamlets. It is based on the interaction of one single electron beam with two light pulses that can come from K-edge allows to produce subtraction images with a great increase in accuracy. The application to this range of X-rays is presented and discussed.

SCHEME OF THE SOURCE AND BASIC EQUATIONS

The Thomson/Inverse Compton scattering is the process occurring when an electron belonging to a high-brightness electron beam collides with the photons of a laser pulse, generating X or gamma radiation. The geometry of the scattering is represented in Fig. 1, where α_0 is the interaction angle of the scattering.

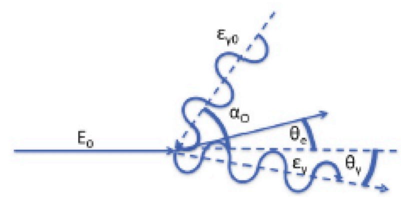
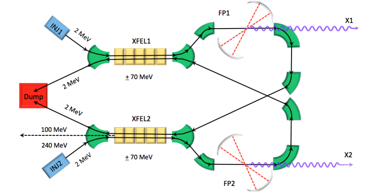


Figure 1: Kinematic of the Compton back scattering.

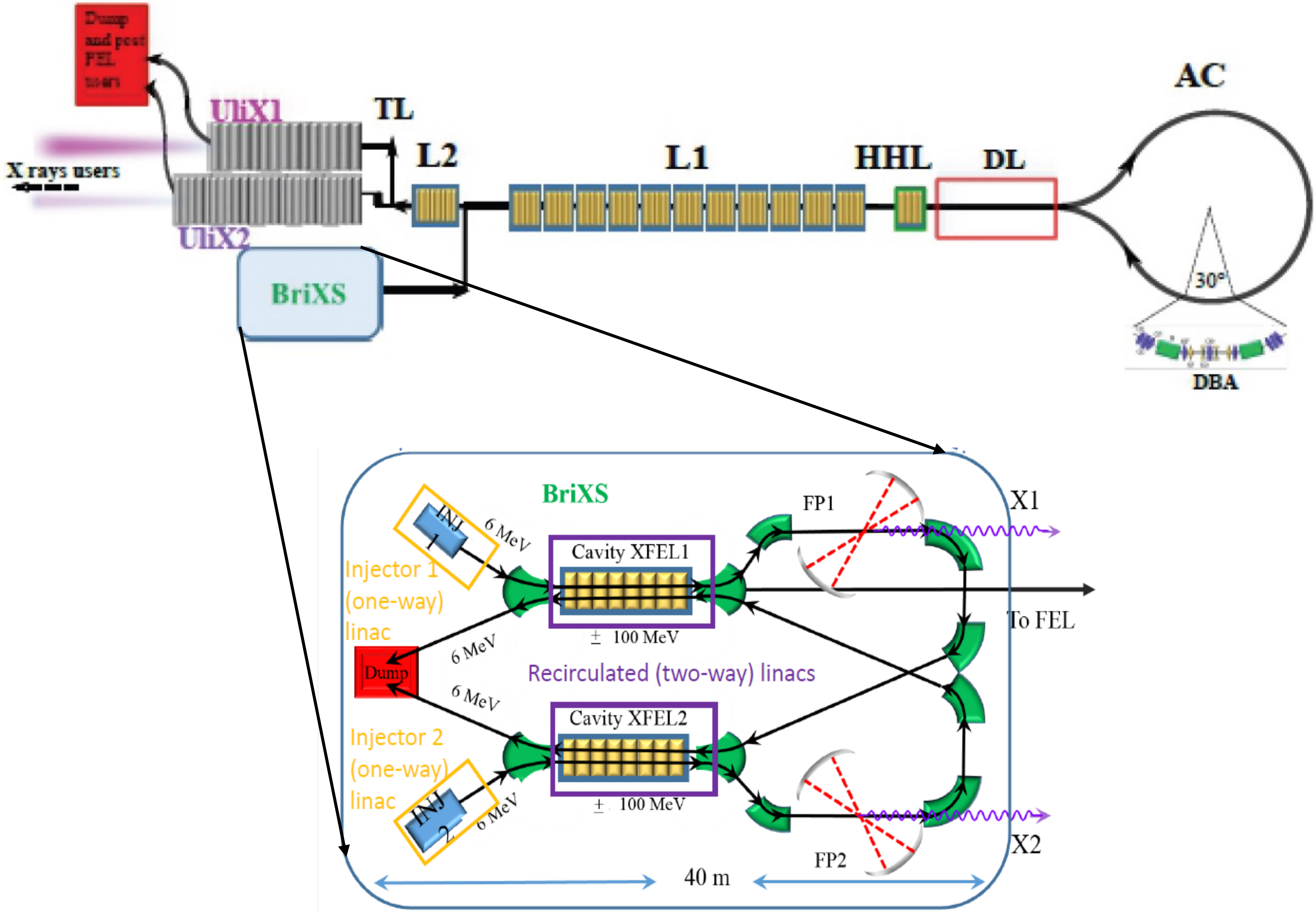
The radiation energy is upshifted with respect to the lasers's by the relation:

$$\varepsilon_{\gamma m} = \frac{4\gamma^2 \varepsilon_L \cos^2\frac{\alpha_0}{2}}{4\gamma\frac{\varepsilon_L}{mc^2}\cos^2\frac{\alpha_0}{2} + 1} \approx 4\gamma^2 \varepsilon_L cos^2\frac{\alpha_0}{2} \qquad (1)$$

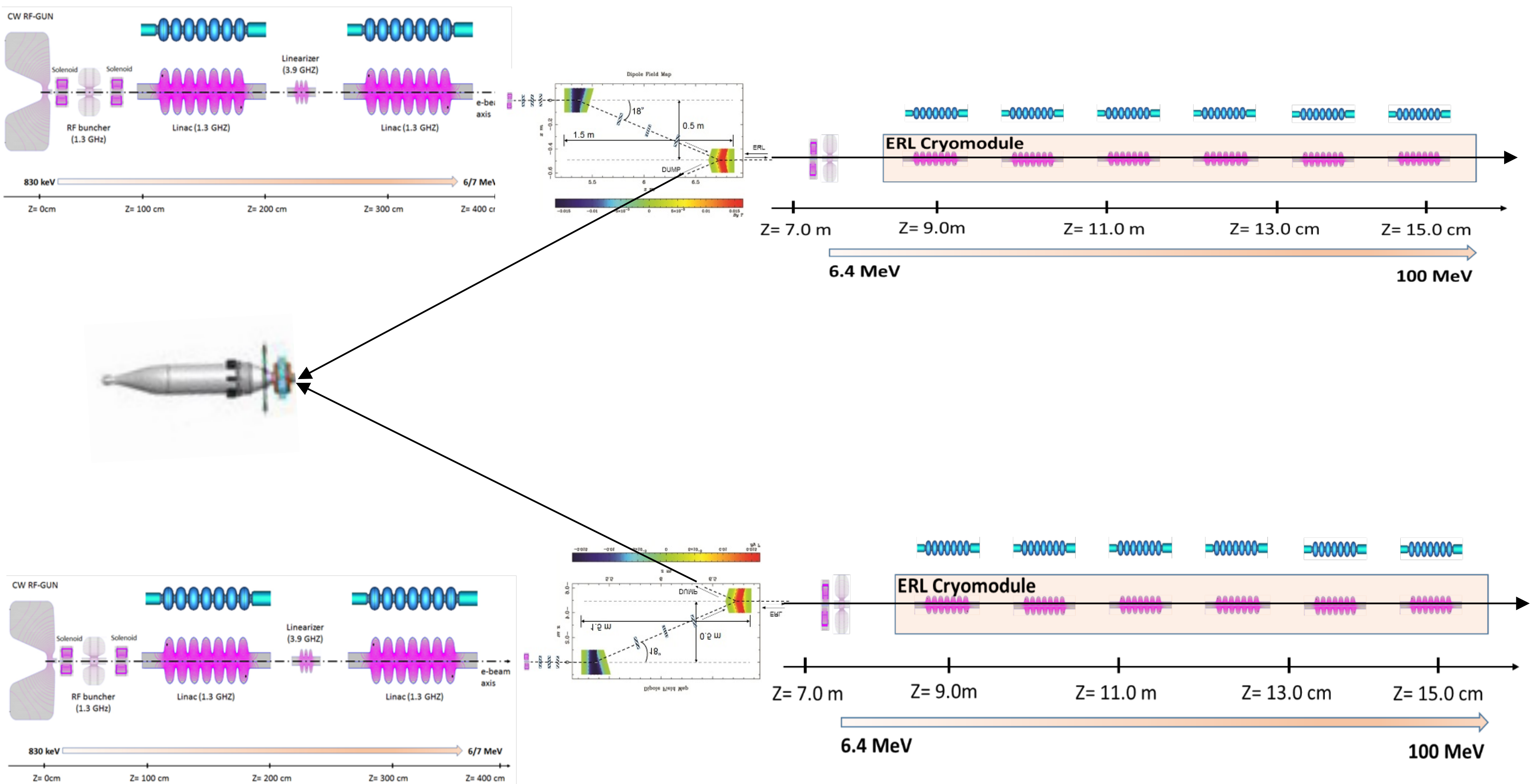
where ε_L is the laser photon energy, γ the electron Lorentz factor and ε_γ the emitted photon energy and the electron recoil term can be disregarded. The scheme we are proposing for producing two colour radiation is based on the interaction of the electron beam with two light pulses that can come from the same laser setup or from two different lasers and that collide with the electrons at different angle, as shown in Fig. 2. If one the first scattering is head-on, the angle of the second one is chosen in order to fix the relative separation


FP1
X1
INJ1
2 MeV
XFEL1
± 70 MeV
2 MeV
Dump
2 MeV
XFEL2
100 MeV
240 MeV
INJ2
2 MeV
± 70 MeV
X2
FP2

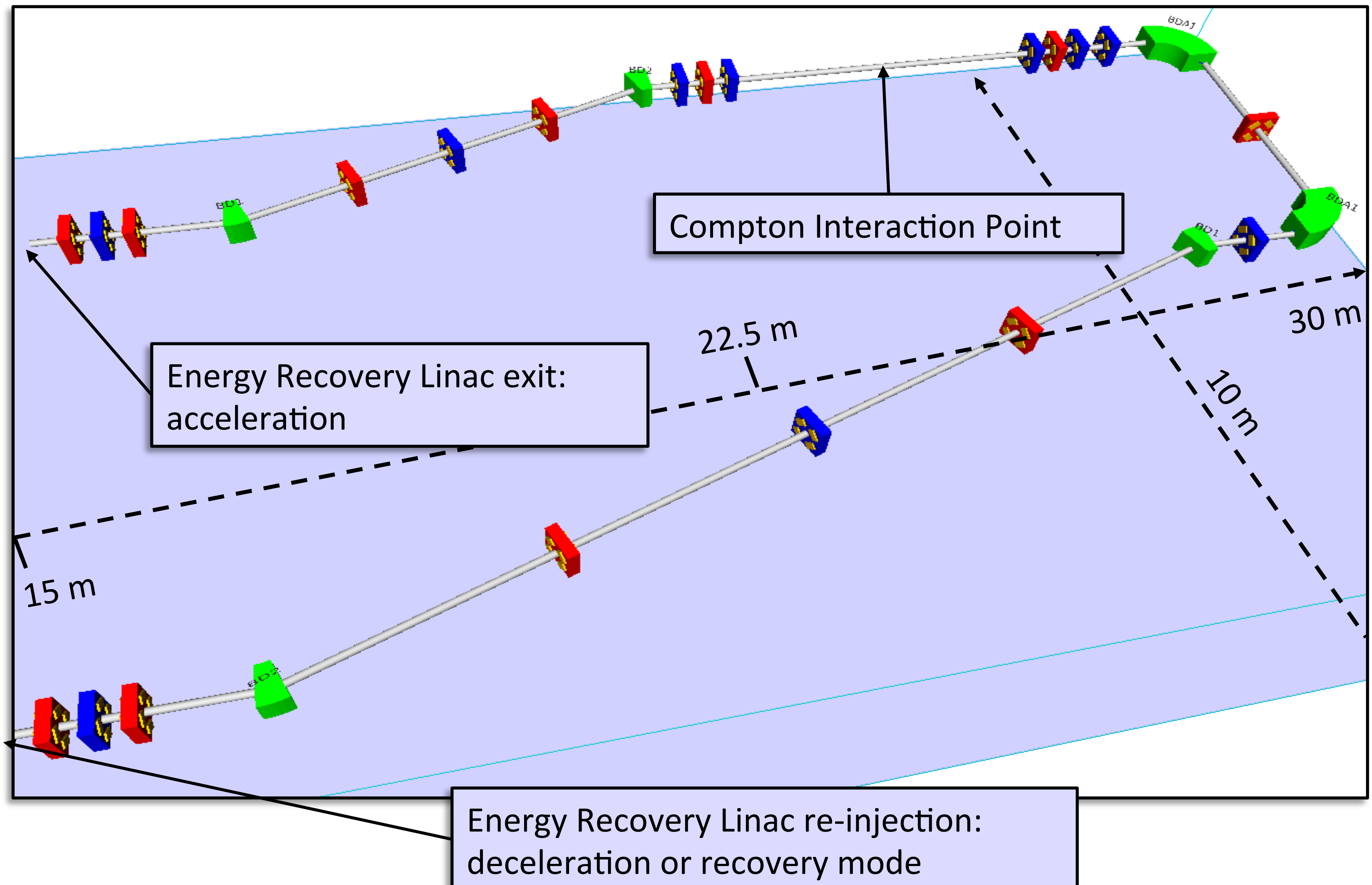
A quite complex machine from BD point of view



The common beamline or BriXs linac layout



One Wing of BriXS WP – NO remarkable open questions

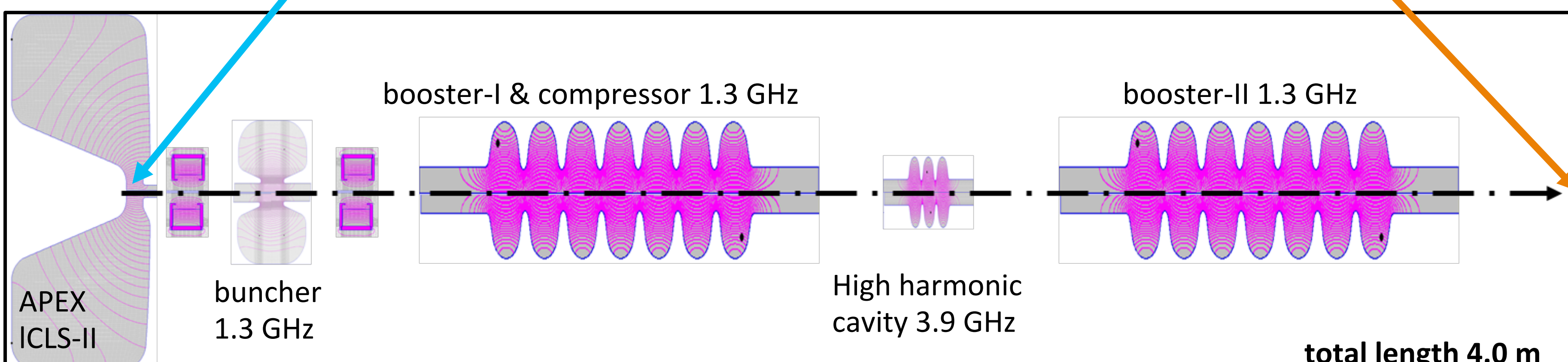


Apex MARIX & BriXS working points

T_{Exit} [KeV]	Qb [pC]	T_{laser} [ps] (plateau)	σ_{x_laser} [mm]	$\varepsilon_{n,t}/\sigma_x$ [µm/1mm]	σ_z [um]	ε_n [µm]	Δγ [KeV]	T [MeV]
BriXS					Inj. exit			
830	200	48	420	0.5	1000	0.85	5	6.7
MARIX					Inj. exit			
830	50	40	200	0.5	460	0.36	7.0	6.4

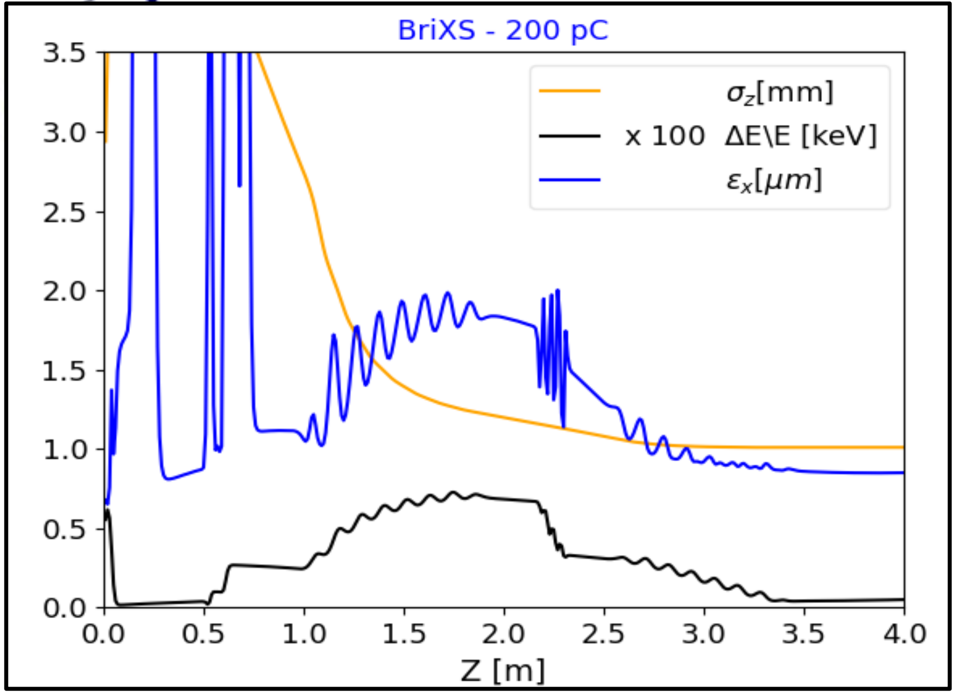
GUN Parameters

@ injector exit

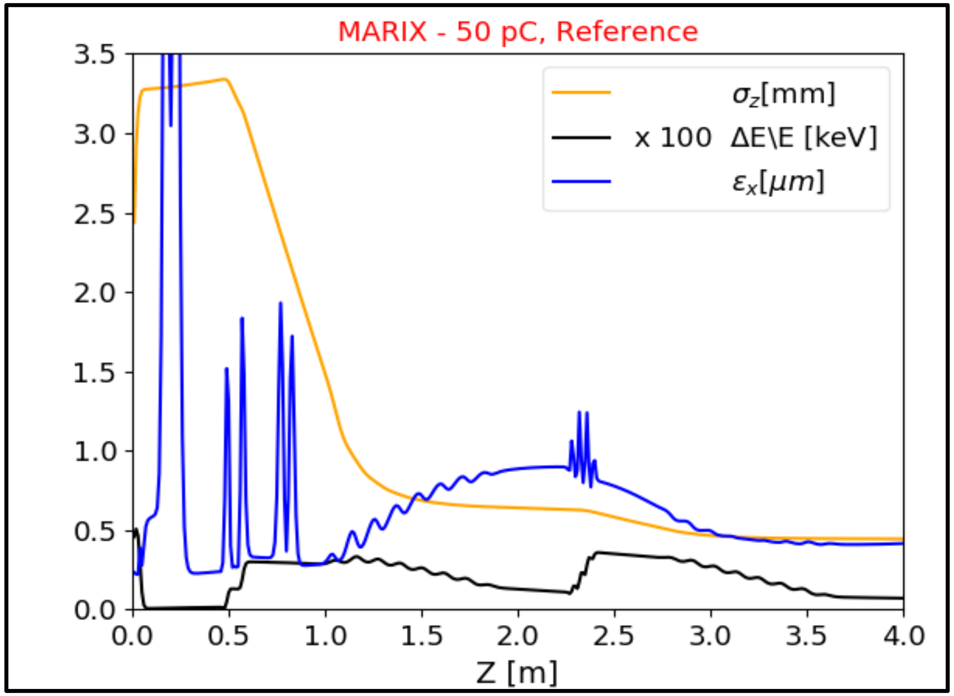


L. Faillace map scheme

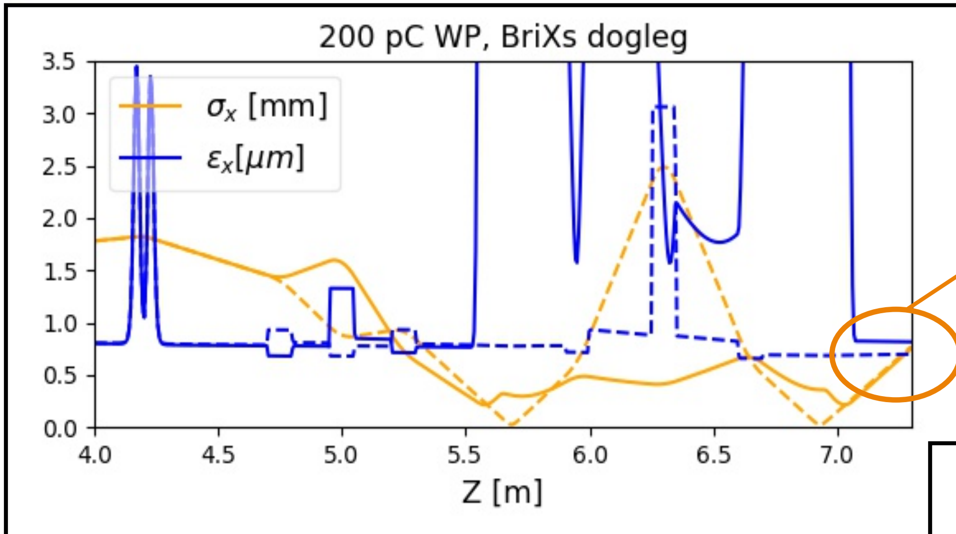
Apex MARIX & BriXS injector dynamics



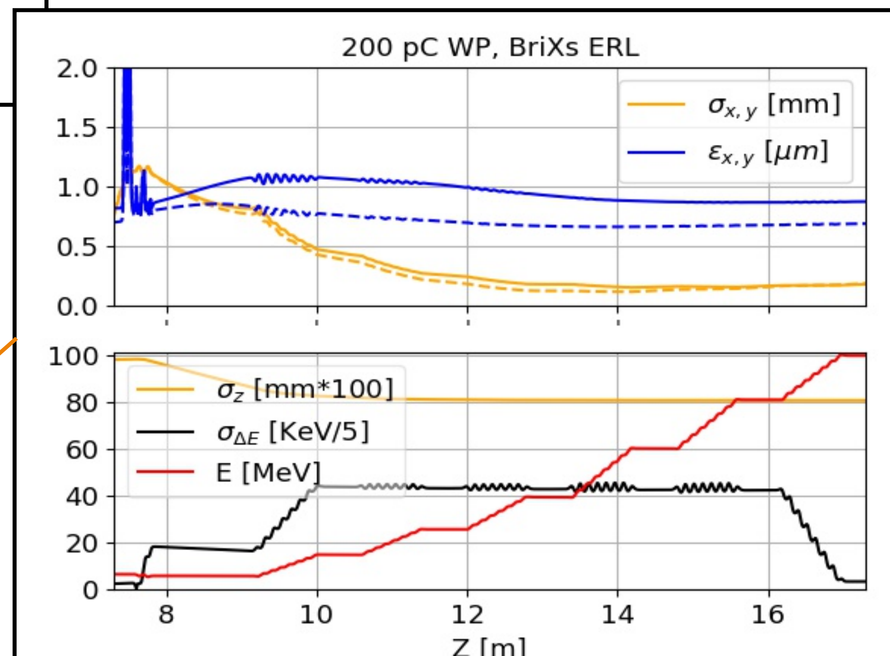
Very good performances for
the both Working Points
@ 6.5 MeV



Dogleg & ERL WP @ 200 pC. GIOTTO optimization

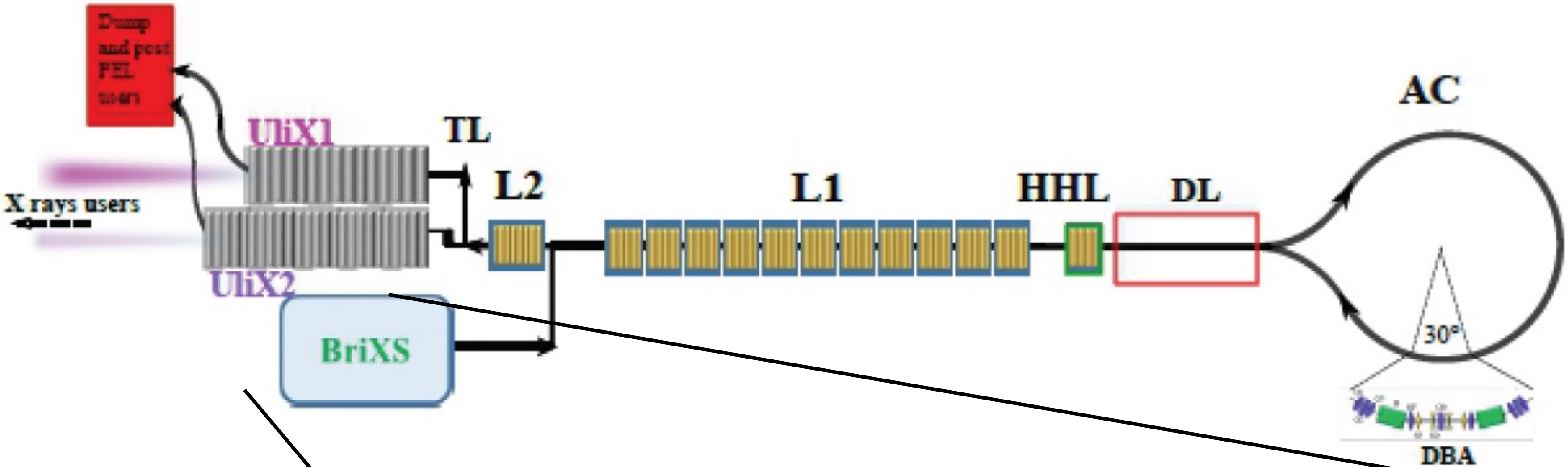


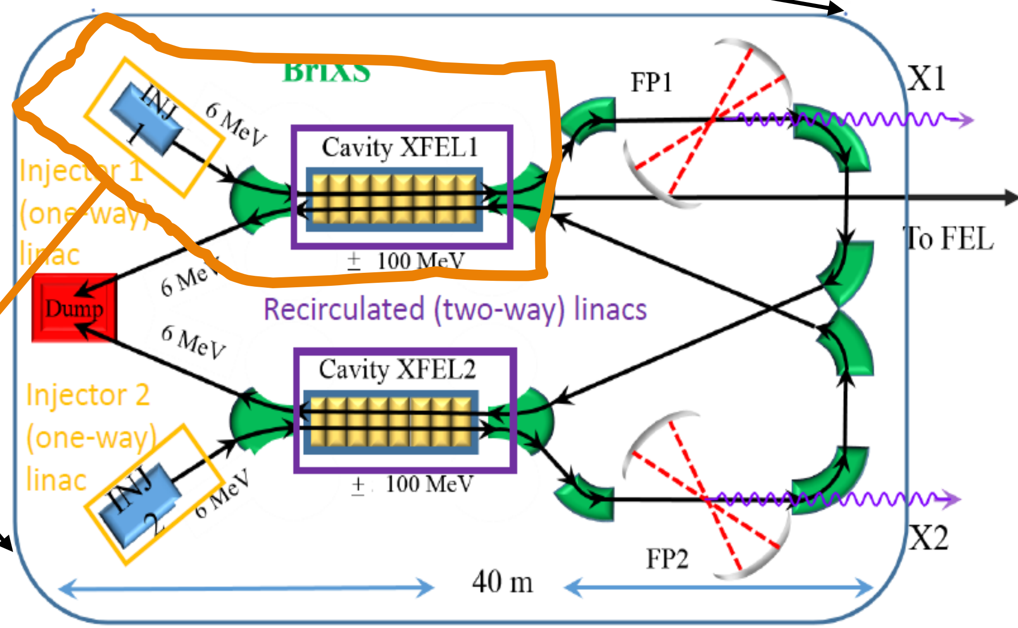
Fully restored in cylindrical symmetry
GIOTTO Genetic Algorithm optimization



- ✓ Emittance oscillation tuning
- ✓ Bunch Longitudinal compression
- ✓ Full energy spread compensation
- ✓ 100MeV target energy

A quite complex machine from BD point of view – open questions



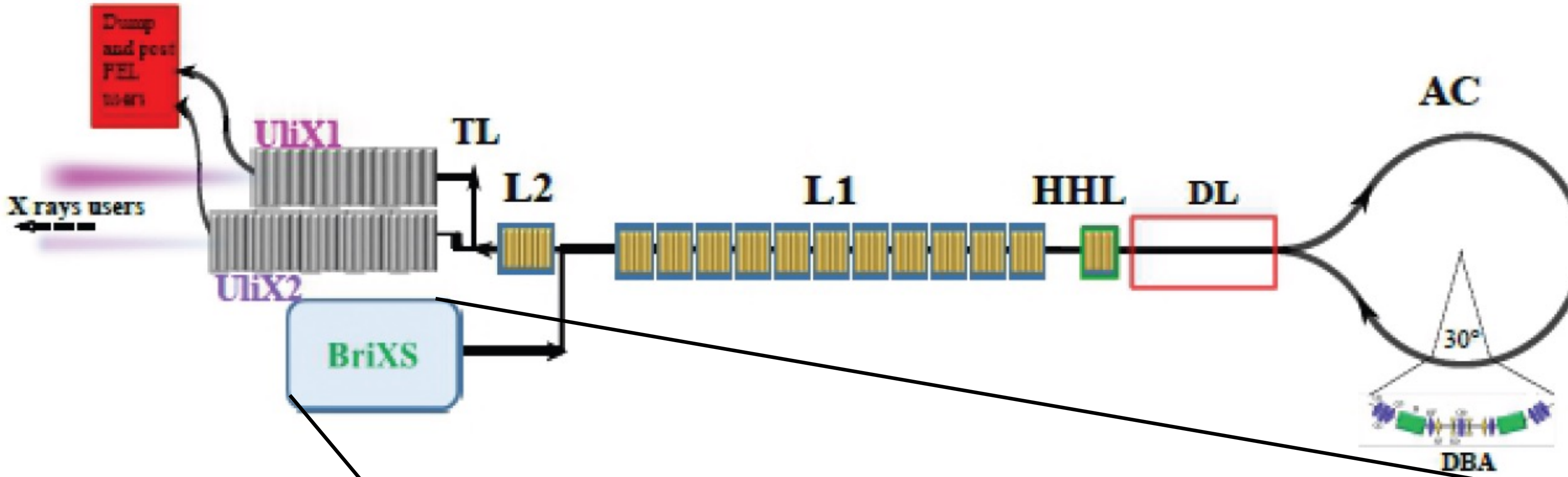


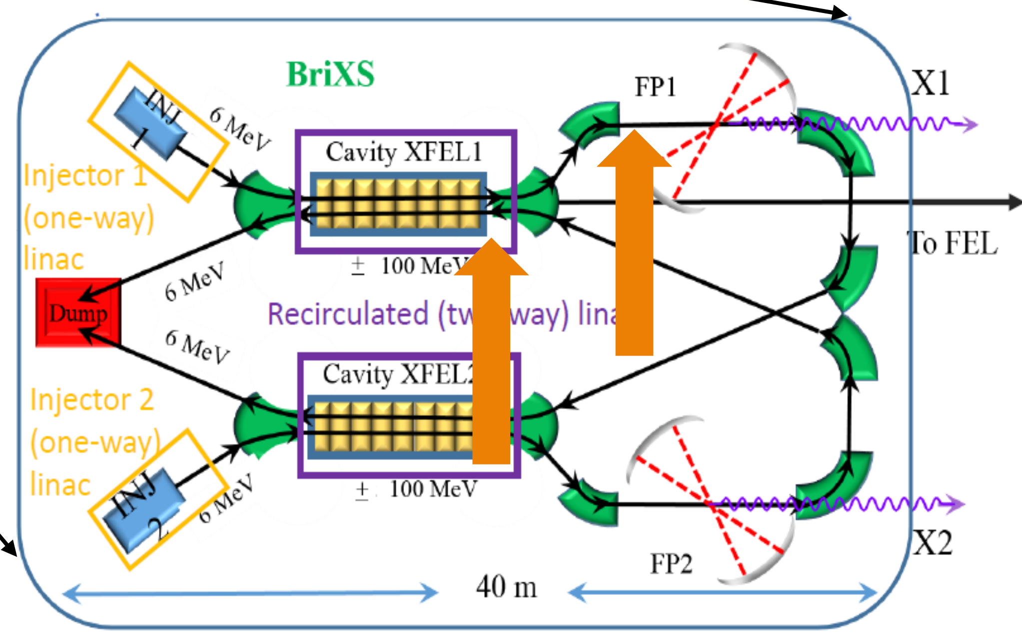
Common part, BriXs/MARIX injector for 200/50 pC.

@CDR^{now}: Frozen positions but Full Knobs optimiztions: phase, grad ecc.
=> Two diff. Working Point (WP)

@soon: all knobs frozen: apart, laser pulse shaping and timing.
=> One WP. change only the laser

A quite complex machine from BD point of view – open questions





Ultra Fast kickers to L1

some good proposal:

Dafne-like 10ns gaussian pulse width (10 years ago)

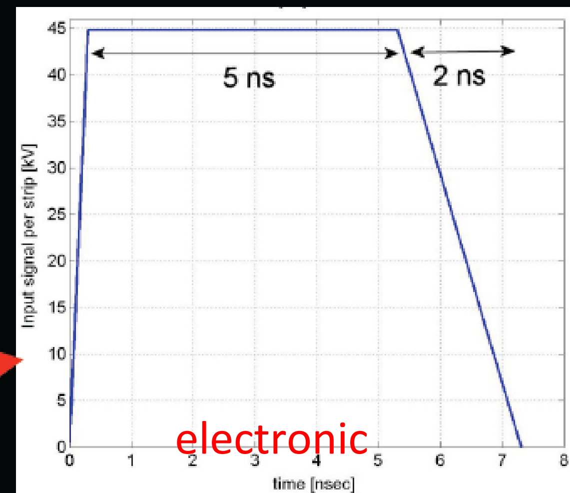
@100 MHz time separetion = 10ns

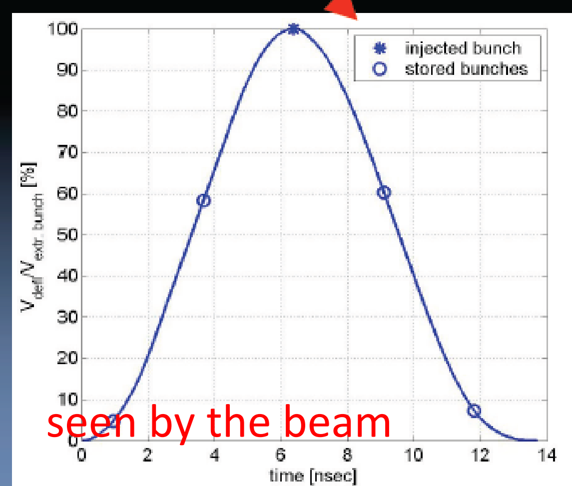
Not yet simulated:
we studied max. performances with a dedicated beamline injection

Stripline Ultra fast kicker Dafne type

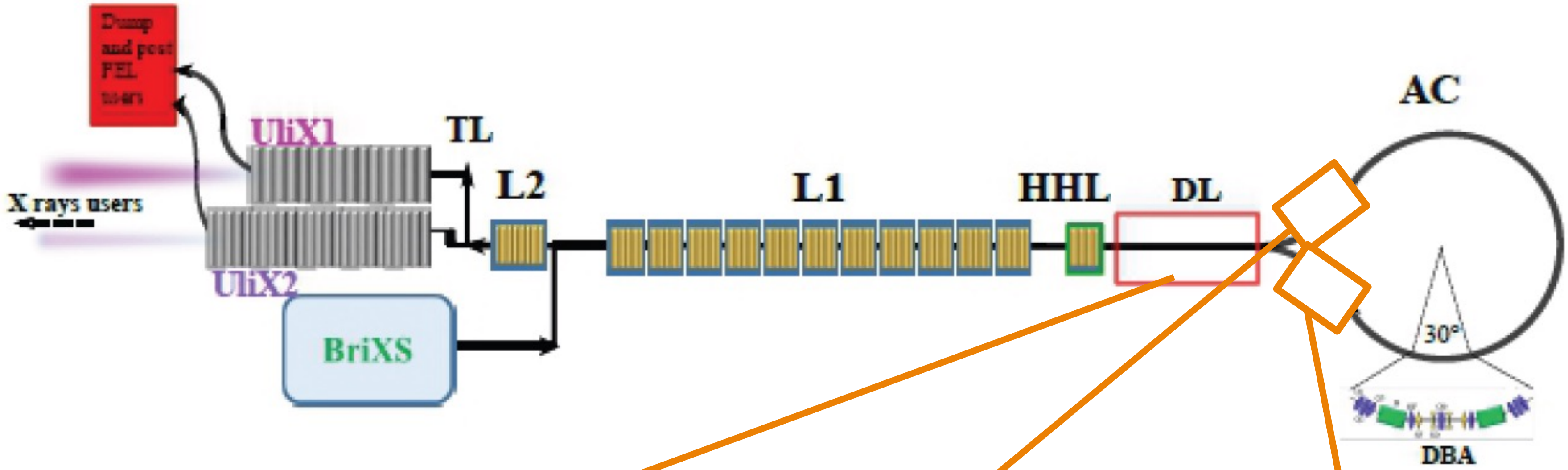
injection kicker design parameters

PARAMETERS	
Beam Energy E [MeV]	510
Time spacing between bunches [ns]	2.7
Deflection [mrad]	5
Total deflecting voltage VT [MV]	2.5
Total kicker length L [cm]	~90
Voltage per strip [kV]	45
Input pulse length [ns]	~ 5
Pulse length "seen" by bunches [ns]	~10
Max rep rate [Hz]	10





A quite complex machine from BD point of view – open questions



Delay Lines

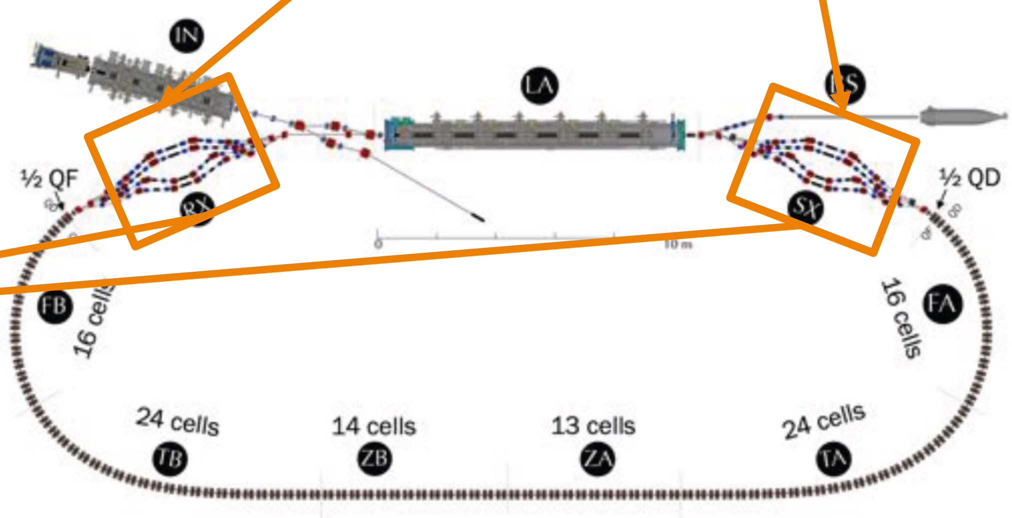
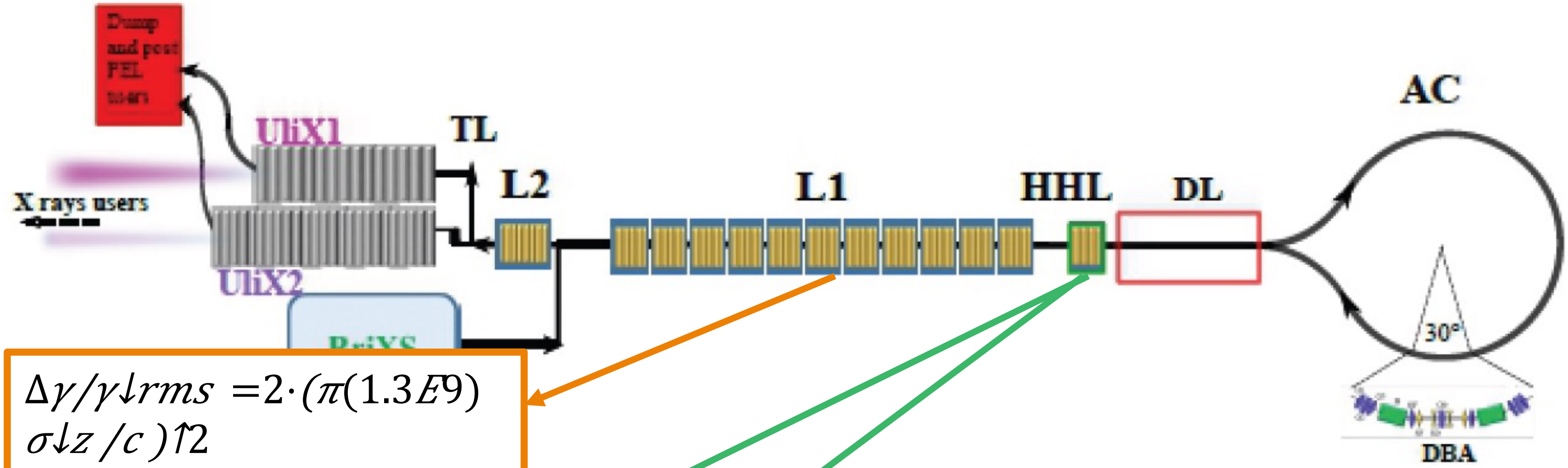


Figure 2.1.1: CBETA layout with all major sections.

In C-beta project reach a phase controll of 20-30°RF

Considering the linearizer HHL @ 3.9 GHz: 60-90°RF

A quite complex machine from BD point of view – open questions

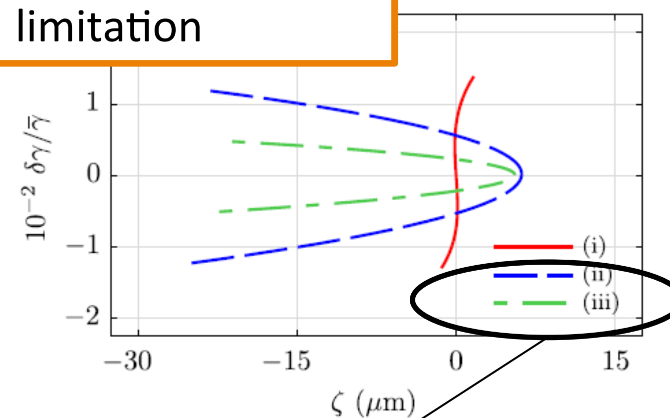


$\Delta\gamma/\gamma_{rms} = 2\cdot(\pi(1.3E9)\,\sigma_z/c)^2$

Second order linearizer

$\Delta\gamma/\gamma_{rms} = 2\cdot(\pi(3.9E9)\,\sigma_z/c)^2$

Second order compression limitation



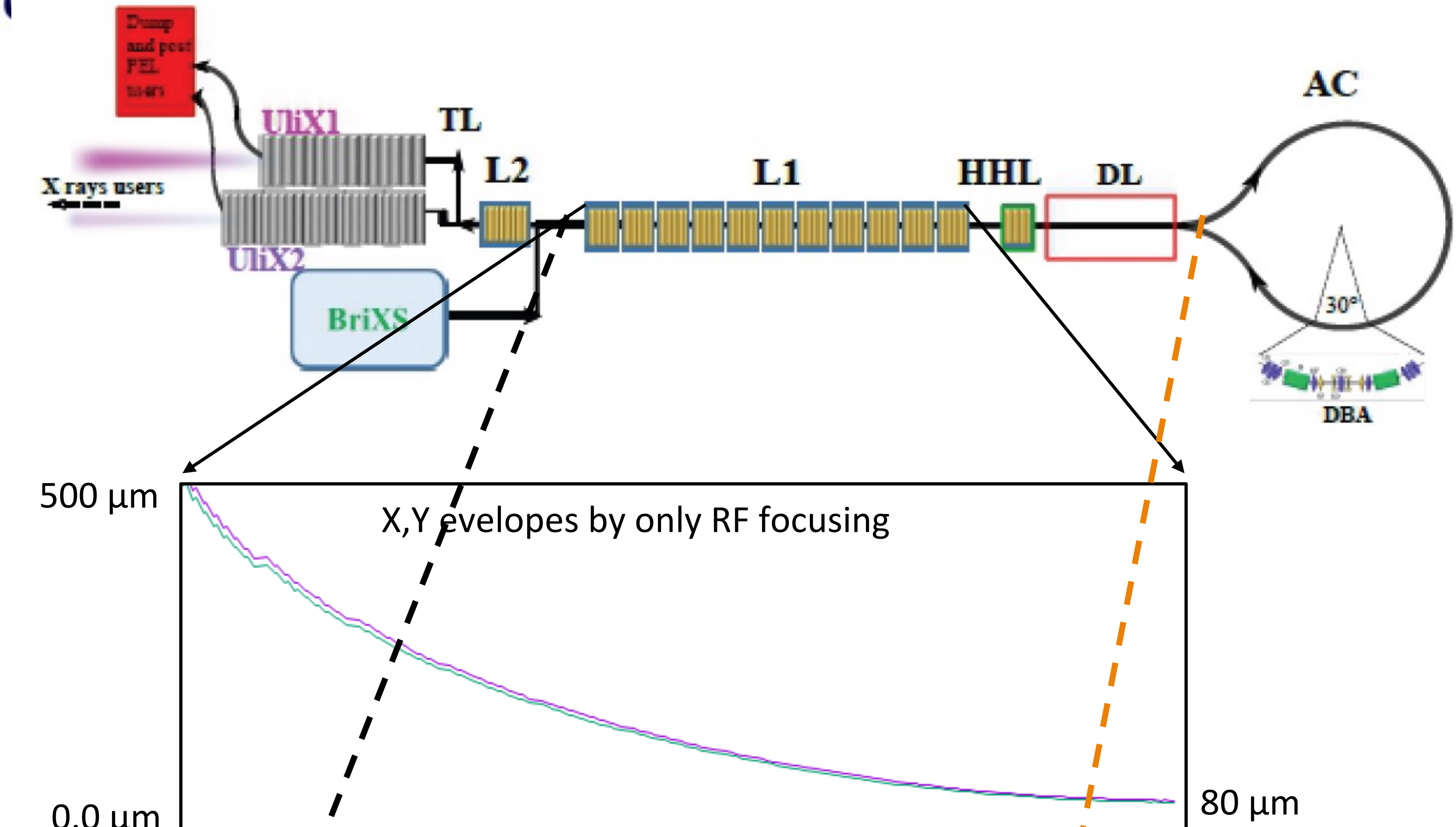
100MeV deceleration = full secondo order correction

20m of 3.9GHz III-harmonic cavities

Currently done by an Elegant single element

(ii) & (iii) cases without II-order correction

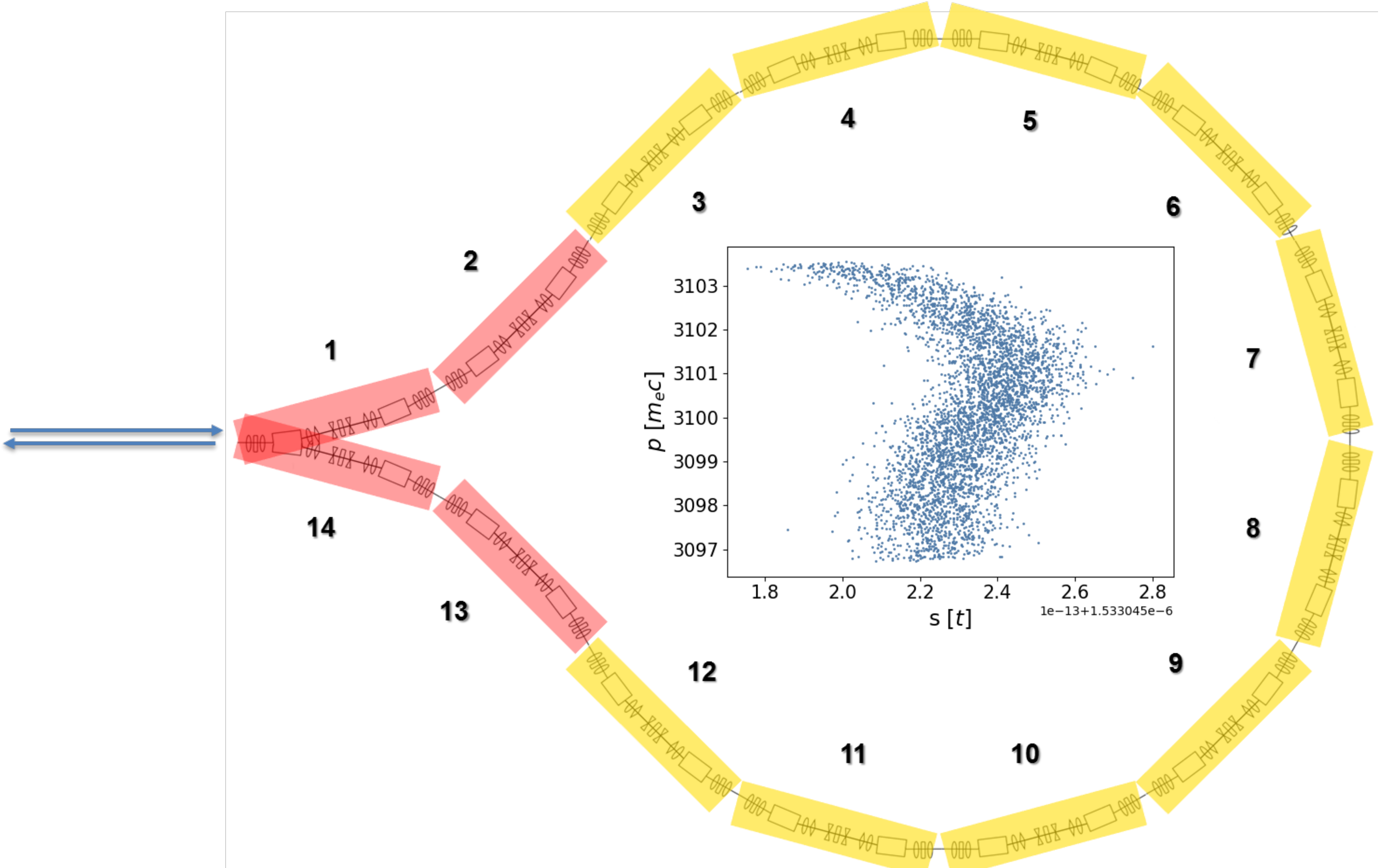
A quite complex machine from BD point of view – open questions



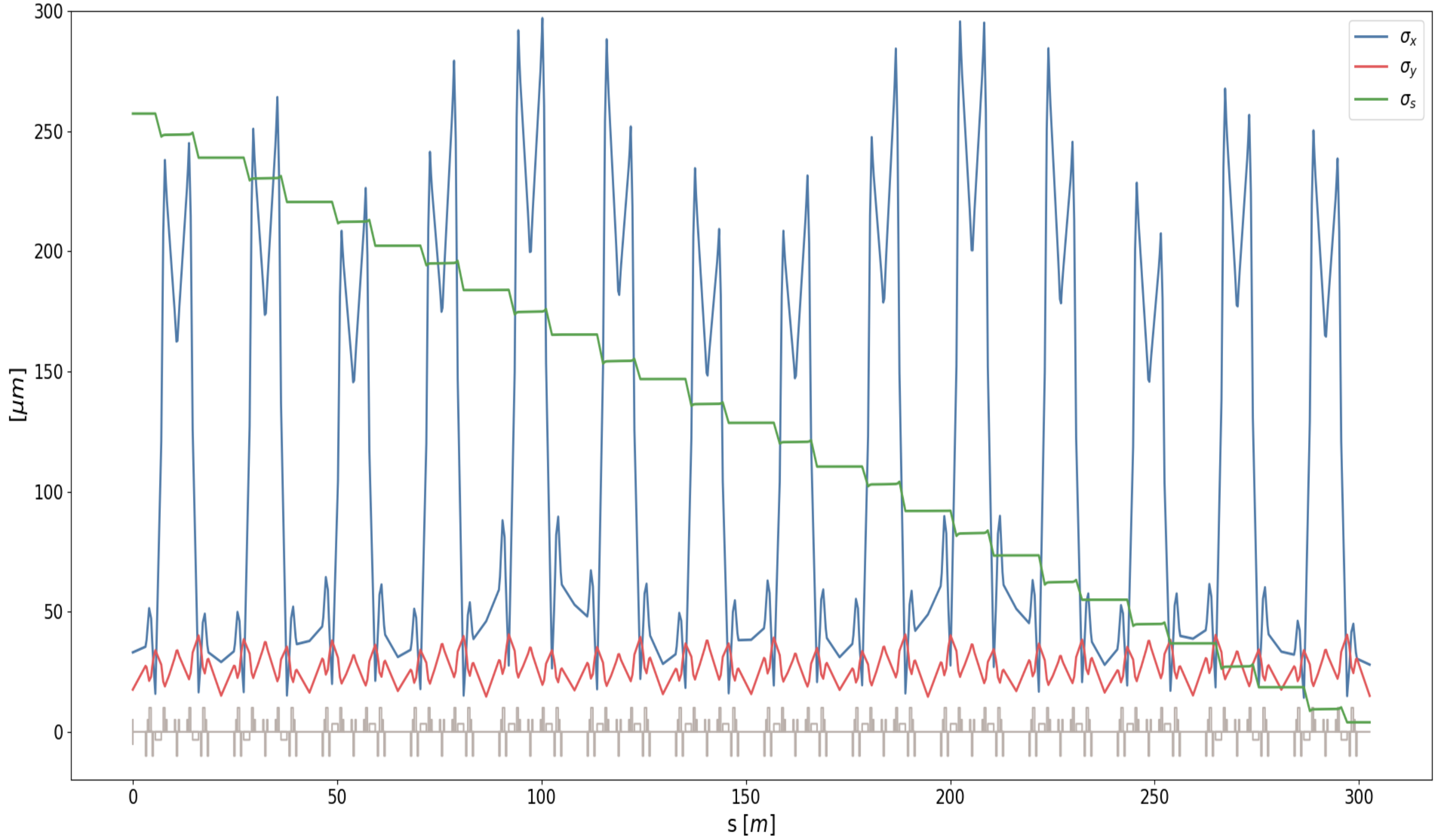
4 quads in 1.5 meters @ 100MeV, max Grad= 15 T/m

Thanks to RF focusing the match to the arc-compressor is easier (4 quads)

The arc-compressor



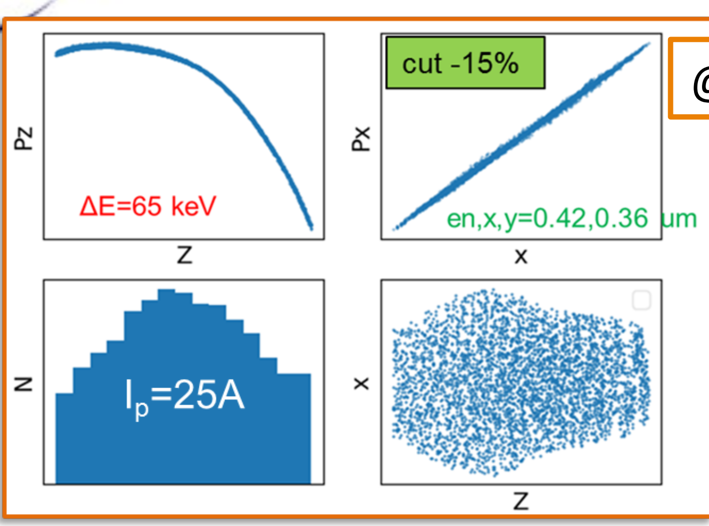
The compressor performances (output emittance= 0.5 um)



σ_s = 3.96μm
($C_f \approx 64.9$)

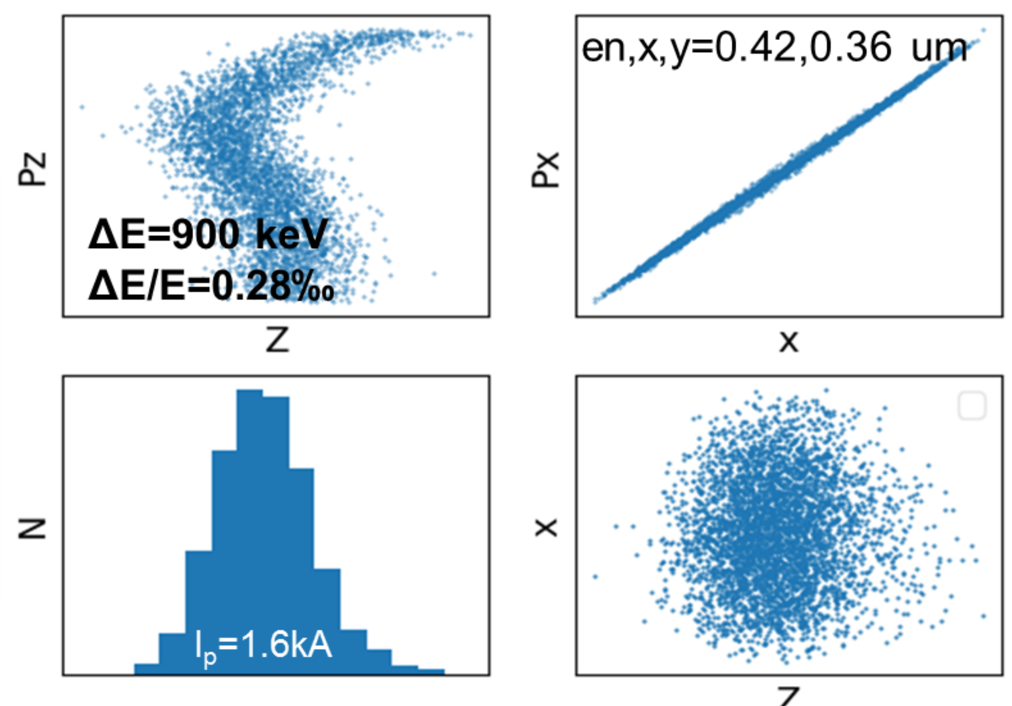
Peak current evaluation
($C_f \approx 64.9$) x (I_p=25A) = 1650 A

From the arc-compressor to the FEL matching line entrance



@1600 MeV, @ arc-compressor entrance

Re-accelerated beam @3200 MeV
@ FEL matching line entrance



- The CSR is still under analysis; first evaluations make us confident on the desired beam quality

- Values here shown have still a good improvement room

Conclusion

The S2E are solid from the two WPs performances point of view & CDR the main goals have been reached. (A final effort on the CSR still dominated by numerical noise)

Further details to be explored (for a TDR ?):

Without a dedicated MARIX injector:

- 50 & 200 pC WPs optimized on exactly the same parameters
- The Ultra fast kickers and its transport line

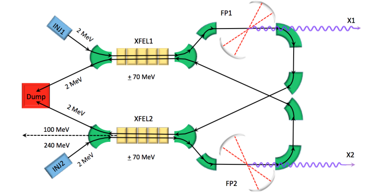
Others

- The matching line: «main linac» → «the arc-compressor»
  ($\sigma_{x,y}$ = 40 um & $\alpha_{x,y}$=0, very close to the actual main Linac exit values - 4 quads)

- III-harmonic more realistic particles tracking
  (now done by one point element in Elegant)

- Linear chirp: «main linac» injection phases
  (now done by one point element in Elegant)

- Transport Line: main linac → L2 last linac



INJ1
2 MeV
XFEL1
± 70 MeV
FP1
X1
Dump
2 MeV
2 MeV
XFEL2
100 MeV
240 MeV
INJ2
2 MeV
± 70 MeV
FP2
X2