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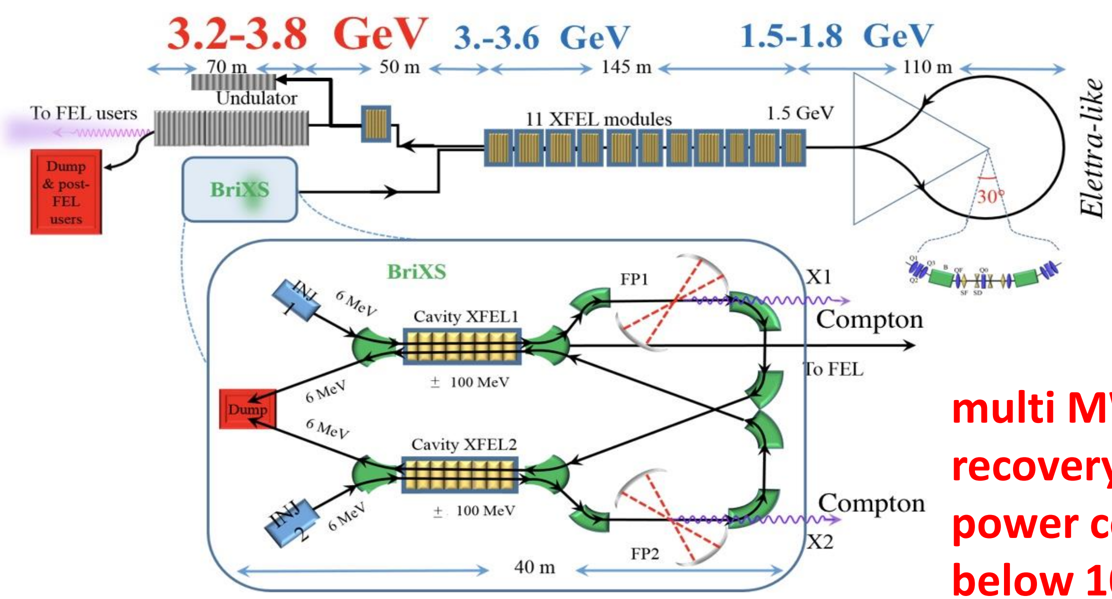
MariX: a Multi-disciplinary Advanced Research Infrastructure for the generation and application of X-rays

Luca Serafini – *INFN-Milan and University of Milan* –
on behalf of MariX-C.D.R. Collaboration

The Challenge:

sustainable CW (50 W) coherent X-ray FEL & (W-class) ICS inside and compatible with a University Campus



multi MW electron beams with recovery/recirculation to keep power consumption / radio-protection below 100 kW

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Il parco della scienza del sapere e dell’innovazione

arexpo | MEF Ministero dell'Economia e delle Finanze | Regione Lombardia | Milano Comune di Milano | Fondazione Fiera Milano | Città metropolitana di Milano | COMUNE DI RHO

Multi-disciplinary Advanced Research Infrastructure for the generation and application of X-rays: MariX C.D.R.

- **Scientific Case for a low jitter CW FEL was conceived by Giorgio Rossi, Giacomo Ghiringhelli, Ezio Puppin, Francesco Stellato/Silvia Morante, Bruno Paroli, Martino Bolognesi:** ***Linear Spectroscopy in 0.2-8 keV at femtosecond time scale***
- **Clinical Case for ICS monochromatic X-ray Source delineated by metropolitan Milan Hospitals: San Raffaele, Niguarda, Istituto Naz. dei Tumori, in collaboration with Ferrara and Naples Univ.**
- **Design of a High Sustainability CW combined FEL & ICS X-ray Source for UniMi Scientific Campus spanning 0.2-180 keV (delivering 200kW to 2 MW sustainable beam power to client,** ***cfr. Fermi 100 W, EupraXia 30 W, LCLS 2 kW*** **)**

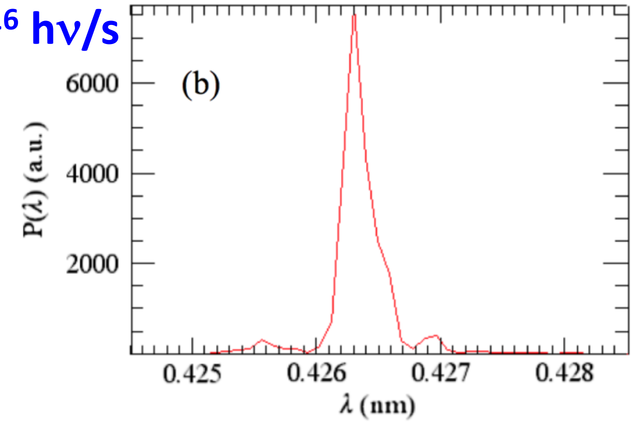
The Mission: coherent femto-second X-rays @ (0.2-8) keV, and ultra-high brilliance hard X-rays @ 20-180 keV

FEL fully coherent diffraction limited X-ray photon beam: 10^{8-10} hν/pulse @ 1 MHz

in 0.05% Δν/ν, 0.2-8 keV, σ_t < 50 fsec, 10^{16} hν/s

$$I_R = I_w \frac{\left(1 + a_w^2\right)}{2g^2}$$

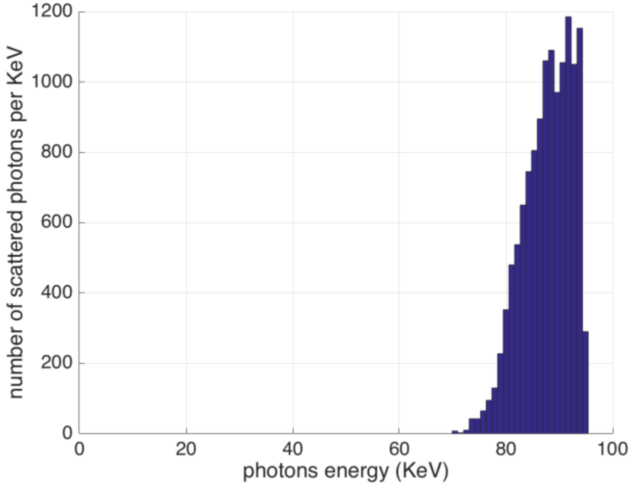
LCLS, 1 Angstrom
15 GeV, λ_w=2.5 cm



FEL Spectrum
2.5 GeV, λ_w=12 mm

Compton X-ray photon beam: 10^{12} - 10^{13} hν/s (@ 100 MHz) in 5% Δν/ν, 20-180 keV, tunable, polarized, σ_t = 2 psec, 10 μm round source spot size, mrad divergence

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



Compton spectrum
FP @ 400 kW, 10 mA, e^- beam 1 MW

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

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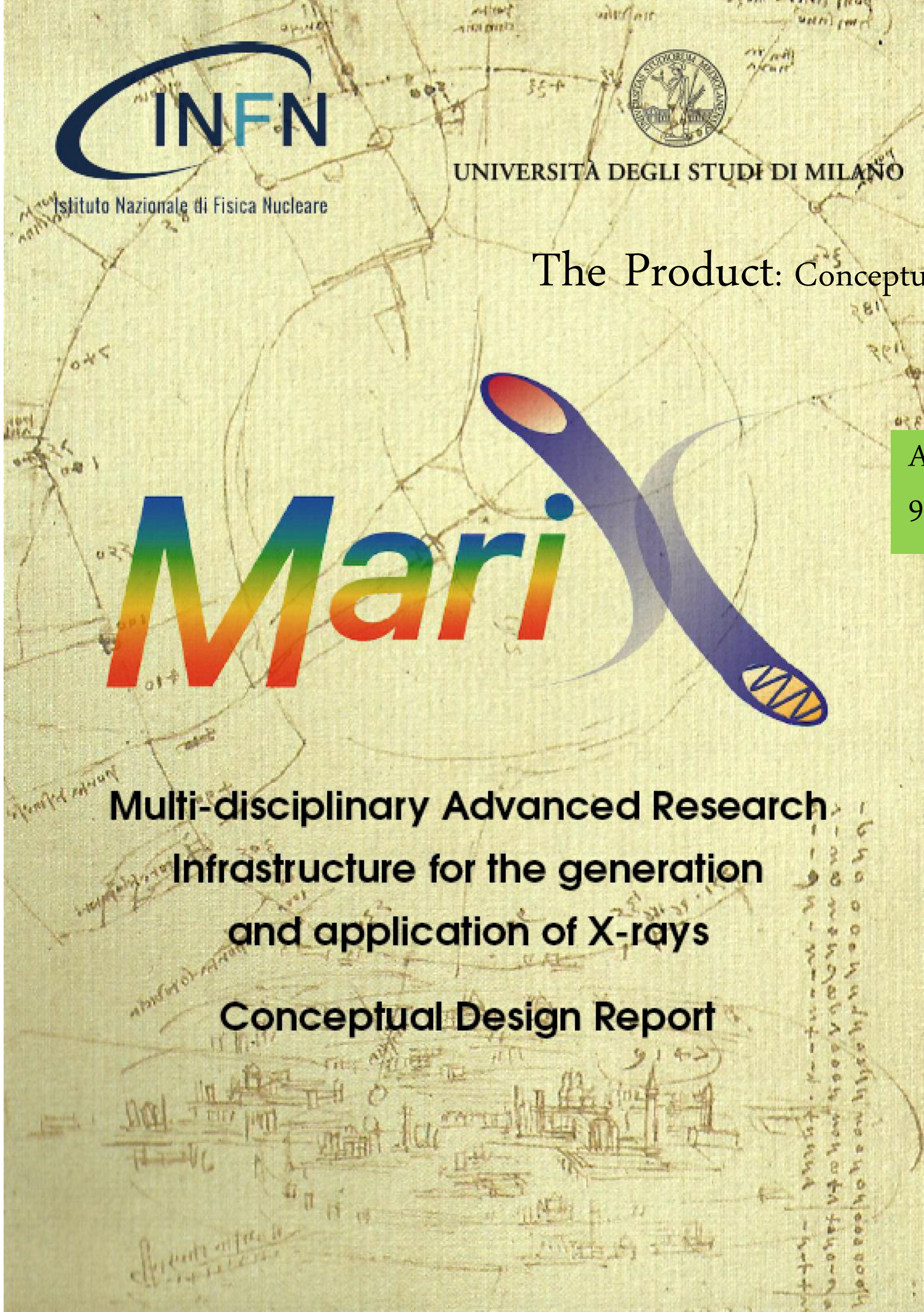
The Product: Conceptual Design Report



After 1 year of hard work by
96 Authors from 25 Institutions

CDR has been published and
available for download at

www.marix.eu

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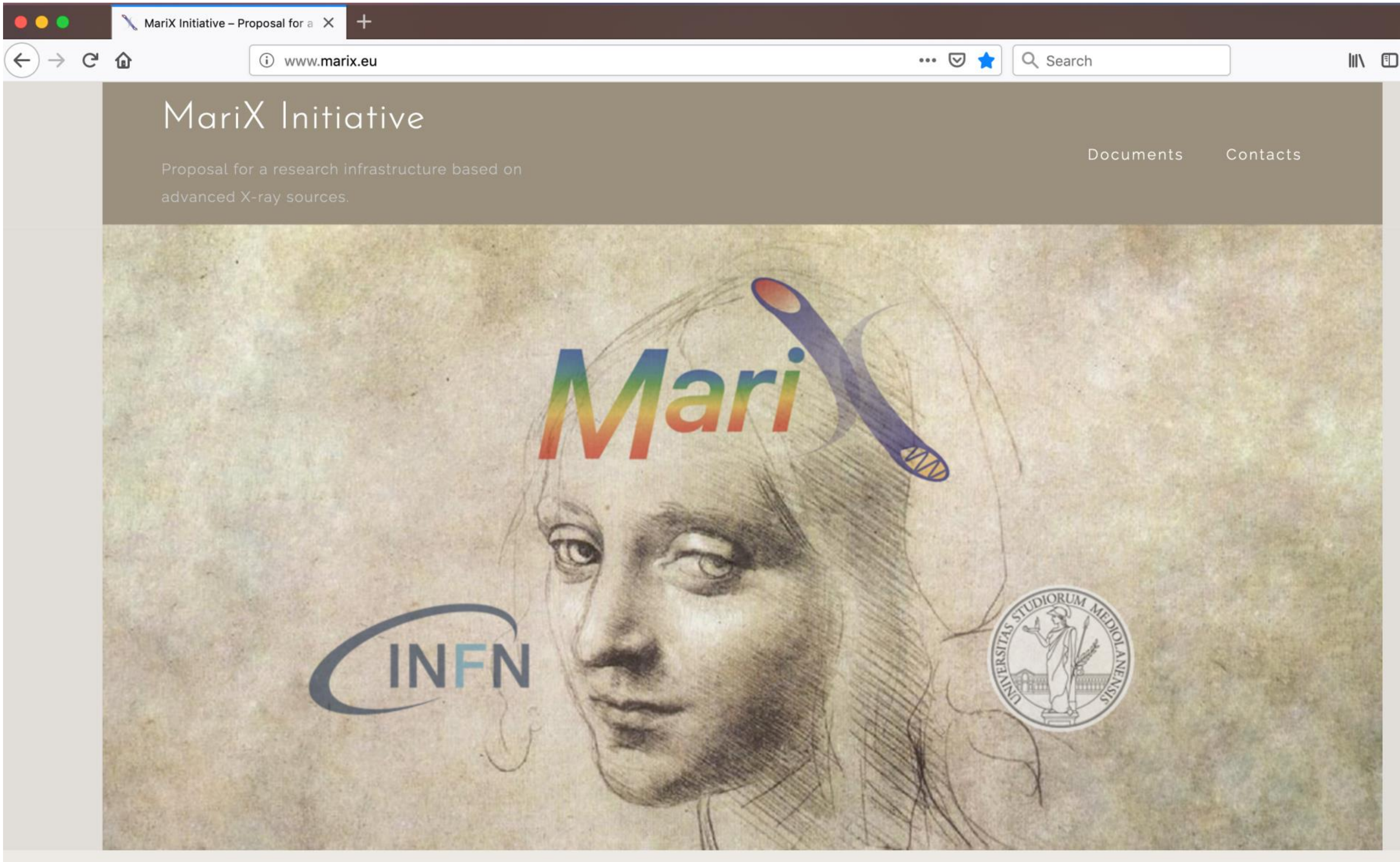

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MariX, an advanced MHz-class repetition rate X-ray source for linear regime time-resolved spectroscopy and photon scattering

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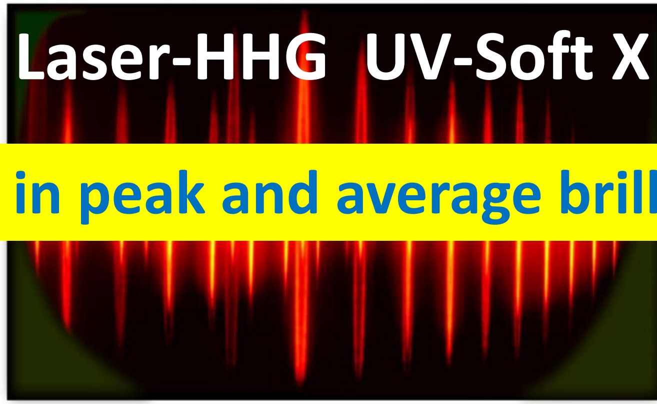
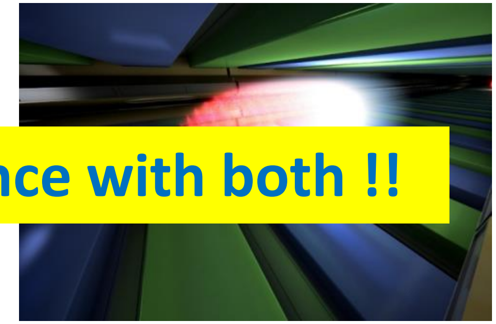




MariX is rivaling in peak and average brilliance with both !!

Synchrotron Radiation sources

500 MHz repetition

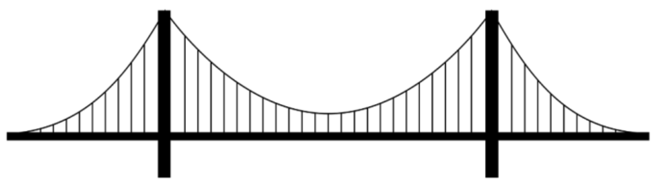
nJ pulse energy; ≈50ps

$10^{5\text{-}6}$ 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

$10^{8\text{-}11}$ photons x 10^{6}pulses

Ultrafast Linear response

Free Electron Laser sources

10Hz-27kHz repetition

mJ pulse energy; ≈50fs

$10^{12\text{-}13}$ photons x

$10^{1\text{-}3\text{-}(6)}$pulses

Ultrafast Non-linear response regime

Imaging, flash+destroy

DLSR: vertical emittance 2-8 picorad, horizontal emittance 200-300 picorad

MariX: vertical/horizontal emittance 30 picorad

⇒ Round vs. Flat beams

Courtesy Giorgio Rossi

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

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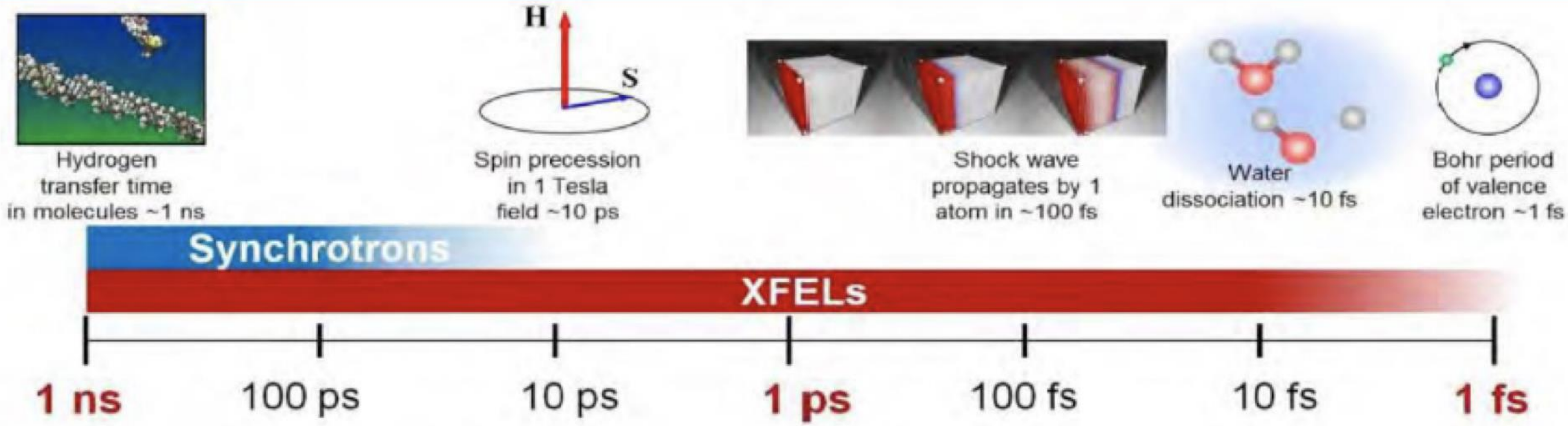
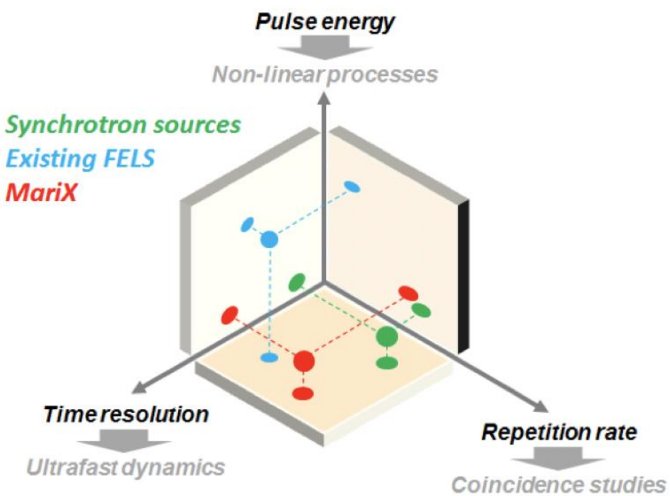
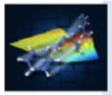
- High resolution low dose Radio-logical Imaging (<100 μm) with mono-chromatic X-rays up to 150 keV: mammography, 2 color angiography, radio-therapy with auger electrons on cis-platine, CAT 3D imaging of Cult.Herit./Archeological/Paleontological samples
- Time resolved spectroscopy with fs coherent X-rays 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)

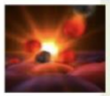
SCIENTIFIC OPPORTUNITIES



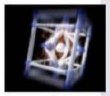




Chemical dynamics:
Reaction dynamics, charge transfer, molecular photocatalysts, natural & artificial photosynthesis



Catalysis:
Homogeneous and heterogeneous catalysis, interfacial & geo/environmental chemistry



Materials Physics:
Heterogeneity, nonequilibrium dynamics & spontaneous fluctuations

Quantum Materials:
Emergent phenomena & collective excitations

Biological Function & Structural Dynamics
Dynamics in physiological environments

Courtesy Giorgio Rossi

Comparison between X-FELs
Electron Beam Energy to radiate at ~ Angstrom

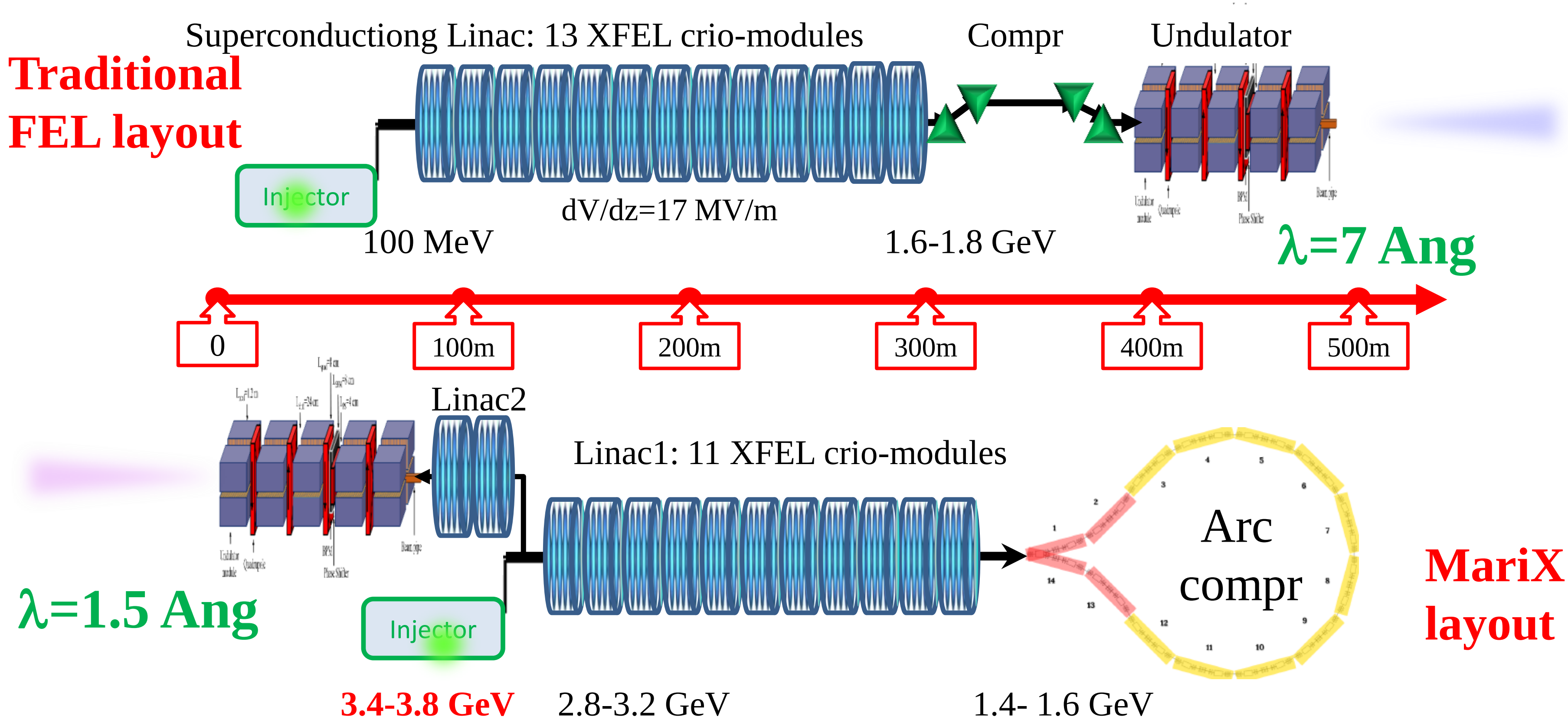
$$\lambda_R = \lambda_w (1+a_w^2)/ 2\gamma^2 \quad , \quad \lambda_w \div 1.2\text{-}3 \text{ cm}$$

FEL	Radiation Wavelength (A)	Electron Beam Energy (GeV)	Linac Length (m)
LCLS	0.5	14.3	1000.
PSI	1.0	5.8	500.
EuXFEL	0.15	17.5	1700.
LCLS II	2.4	4.0	650.
MariX	1.5	3.8	???? < 200

In quest of High Sustainability we had to conceive a new kind of machine: the Two-Way Linac (TWL)

All Accelerators are one way – the beam propagates in one direction (ERL too)

MariX uses the CW Linac twice – forward and backward



Only Standing Wave RF Cavities can accelerate particles in both directions!

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Acceleration in opposite directions through a Linac (*two-way acceleration*) is possible if:

1) RF fields can accelerate in both directions (Standing Waves can do it)

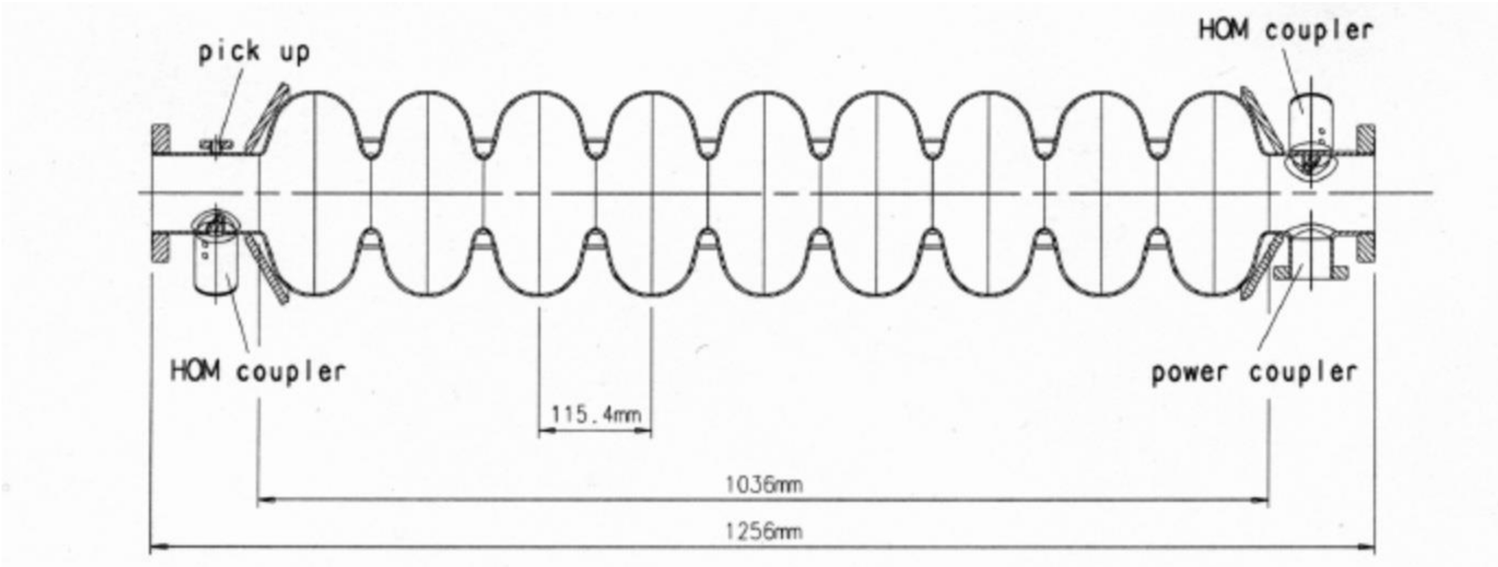
2) Focusing effective in both directions and weakly energy dependent (RF focusing and/or solenoids)

3) No bunch crossing –> Twice the Linac Length < Bunch separation

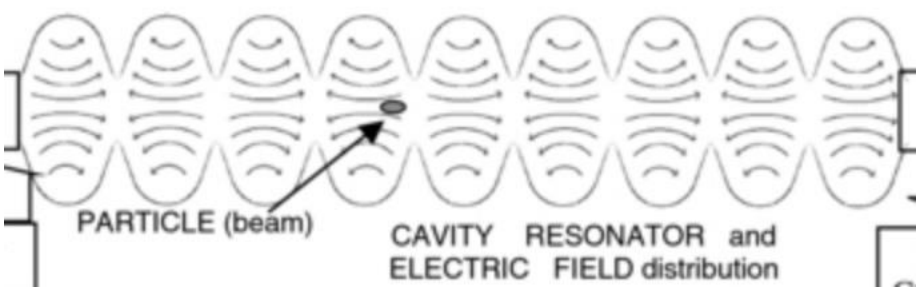
4) RF fields must be on for a time longer than bunch back-and-forth travel time (CW recommended)

5) Orbit position must not be dependent on magnetic rigidity (no two-way through dipoles, except bifurcations)

TESLA 9-cell superconducting 1.3 GHz cavity longitudinal cross-section.



Modo risonante $TM_{010\text{-}\pi}$ ad Onda Stazionaria



9 celle = 4.5 λ = 1.04 m

$$k = \frac{\omega}{c} = \frac{2\pi\nu}{c} = \frac{2\pi\nu}{\lambda}$$

phase velocity = c

ν=1.3 GHz ; λ=0.23 m

Standing RF Waves

standing wave

$$E_0 \sin(kz)\cos(\omega t-\phi_0) \quad =$$

$$(1/2)\, E_0 \sin(kz-\omega t+\phi_0) \;+\; (1/2)\, E_0 \sin(kz+\omega t-\phi_0)$$

forward traveling wave, synchronous to z = ct

backward traveling wave, synchronous to z = -ct

ampiezza della componente di onda viaggiante sincrona rispetto all'elettrone

$$\Delta E = e \frac{E_0}{2} \sin\phi_0 \;\; L_{cav}$$

RF Focusing effective only in Standing Wave RF Cavities a lesson we learned long time ago

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PHYSICAL REVIEW E VOLUME 49, NUMBER 2 FEBRUARY 1994

Transverse particle motion in radio-frequency linear accelerators

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(Received 18 October 1993)

The transverse motion of a relativistic charged particle in a radio-frequency linear accelerator (rf linac) is examined. The spatially averaged equations of motion are derived for a particle in a periodic accelerating cavity system, and solved exactly in the ultrarelativistic limit. These solutions, along with an impulse treatment of the transients at the entrance and exit of the linac cavities, allow derivation of a linear transport matrix through the cavity. This generalized matrix is improved over previously derived results in that it is applicable to both traveling- and standing-wave structures, allows for arbitrary injection phase and spatial-harmonic content of tl
charged-particle motion.

PACS number(s): 41.75.−i, 41.85.−p, 29.17.

RF transport matrix

$$\begin{bmatrix} \cos(\alpha)-\left[\dfrac{2}{\eta(\Delta\phi)}\right]^{1/2}\cos(\Delta\phi)\sin(\alpha) & \left[\dfrac{8}{\eta(\Delta\phi)}\right]^{1/2}\dfrac{\gamma_i}{\gamma'}\cos(\Delta\phi)\sin(\alpha) \\ -\dfrac{\gamma'}{\gamma_i}\left[\dfrac{\cos(\Delta\phi)}{\sqrt{2\eta(\Delta\phi)}}+\left[\dfrac{\eta(\Delta\phi)}{8}\right]^{1/2}\dfrac{1}{\cos(\Delta\phi)}\right]\sin(\alpha) & \dfrac{\gamma_i}{\gamma_f}\left[\cos(\alpha)+\left[\dfrac{2}{\eta(\Delta\phi)}\right]^{1/2}\cos(\Delta\phi)\sin(\alpha)\right] \end{bmatrix} . \quad (13)$$

PHYSICAL REVIEW E VOLUME 55, NUMBER 6 JUNE 1997

Envelope analysis of intense relativistic quasilaminar beams in rf photoinjectors: A theory of emittance compensation

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(Received 11 November 1996)

RMS Envelope Equation for laminar beams: a path towards the Invariant Envelope Theory for High Brightness el. beams (1997, L.S and J.Rosenzweig)

The equation we base our analysis on is Lawson's expression for the evolution of the rms envelope in the paraxial limit [5],

$$\sigma'' + \sigma'\left(\frac{\gamma'}{\beta^2\gamma}\right) + K_r\sigma - \frac{\kappa_s}{\sigma\beta^3\gamma^3} - \frac{\epsilon_n^2}{\sigma^3\beta^2\gamma^2} = 0, \quad (1.1)$$

$$\epsilon_n = \beta\gamma\epsilon = \frac{\beta\gamma}{2}\sqrt{\langle r^2\rangle\langle r'^2\rangle - \langle rr'\rangle^2}. \quad (1.2)$$

Cauchy

$$\begin{cases} \dfrac{d^2\tau}{dy^2} + \dfrac{\tau}{8} = \dfrac{e^{-y}}{\tau}, \\ \hat{\tau} = \sqrt{8/3}\,e^{-y/2}, \end{cases}$$

which governs the evolution of the cylindrical symmetric rms transverse beat spot size $\sigma(z)$ under the effects of an external linear focusing channel of strength $K_r \equiv -F_r/r\beta^2\gamma mc^2$. Here the prime indicates differentiation with respect to the independent variable z, the distance along the beam propagation axis, γmc^2 is the mean beam energy, and $\beta \equiv v_b/c = \sqrt{1-\gamma^{-2}}$ is the normalized mean beam velocity. The defocusing space charge term in Eq. (1.1) is proportional to the beam perveance κ_s, and the final term represents the outward pressure due to the normalized rms emittance, which in the case of cylindrical symmetry can be

$$\sigma = (2/\gamma')\sqrt{I/3I_0\gamma}$$

In Eq. 1.1 the perveance $\kappa_s(\zeta)$ explicitly retains a functional dependence on the longitudinal position ζ of the particular slice in the bunch, so that $\kappa_s(\zeta) = Ig(\zeta)/2I_0$. As

RF (ponderomotive) Focusing

$$K_r = \left[\frac{\eta}{8} + b^2\right]\left(\frac{\gamma'}{\gamma \sin(\phi)}\right)^2, \qquad (1.3)$$

where $b = cB_z/E_0$ $[eE_0 = 2\gamma' m_e c^2/\sin(\phi),\ \gamma' = \alpha k \sin(\phi)]$ for the particular case of a constant solenoidal magnetic field, ϕ is the particle phase with respect to the rf field wave, $\phi = \omega t - kz + \phi_0$, and ϕ_0 is the rf phase of the bunch centroid at injection. The quantity η, which is a measure of the higher spatial harmonic amplitudes of the rf wave is defined in Sec. III and is generally quite close to unity in practical rf structures.

$$\eta = \sum_{n=1}^{\infty} a_{n-1}^2 + a_{n+1}^2 - 2a_{n-1}a_{n+1}\cos(\phi) \quad (a_0 = 0).$$

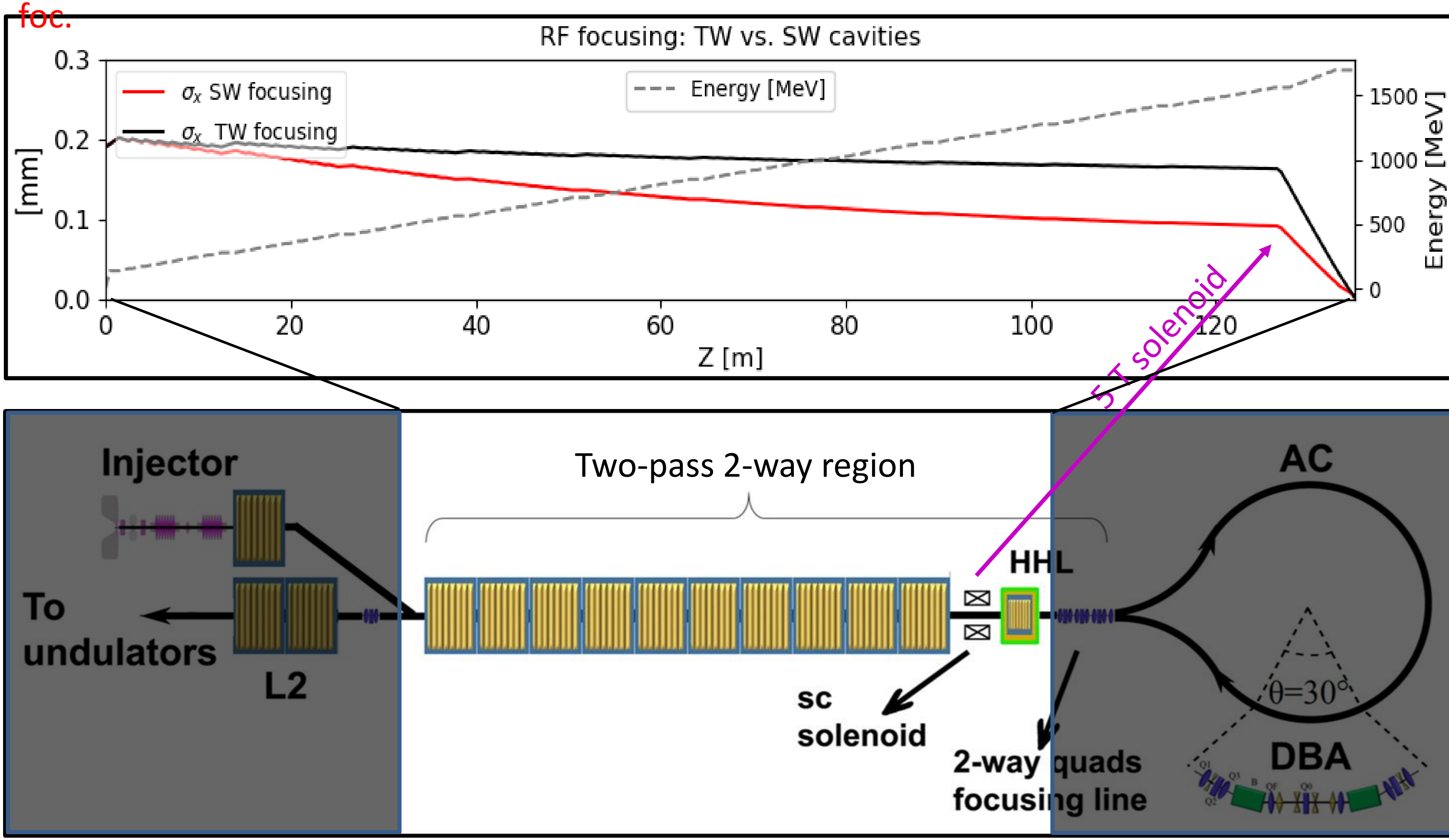
~ 1 Standing

~ 0 Traveling

The Super Conductive Main Linac

- Ten Tesla like cryomodules: max grad 16 MV/m, 8 cavity per cryomodules
- Chirp for AC-compression is given injecting @ + 6° from RF crest.

We rely only on second order focusing, symmetric back-and-forth: Rf focusing and solenoid foc.



Source layout 5: The arc compressor

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March 2015
EPL, 109 (2015) 62002 www.epljournal.org
doi: 10.1209/0295-5075/109/62002

Transverse emittance-preserving arc compressor for high-brightness electron beam-based light sources and colliders

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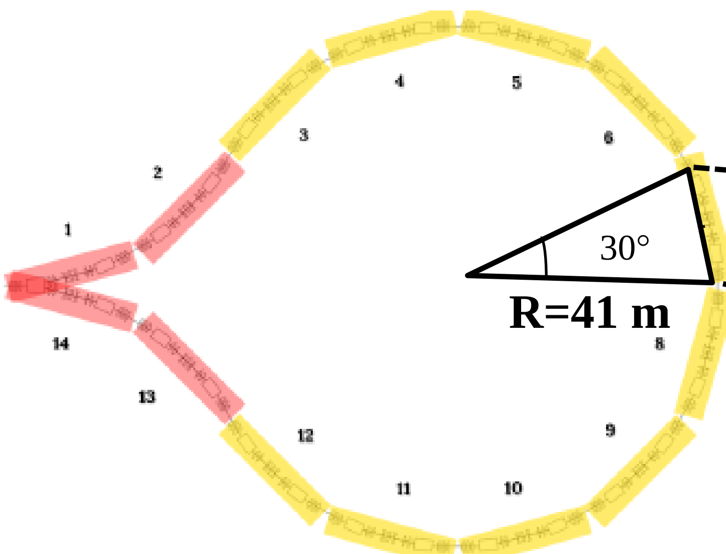
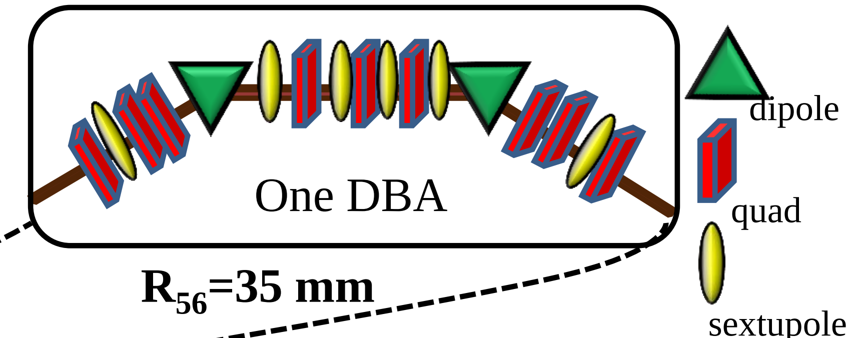
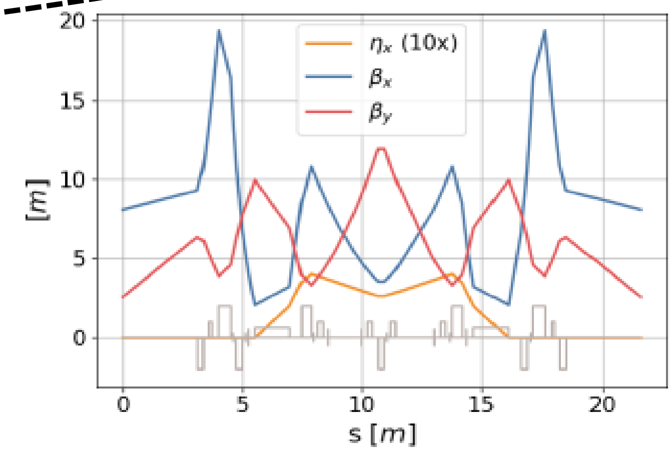
14 Double Bending Achromats Elettra-like



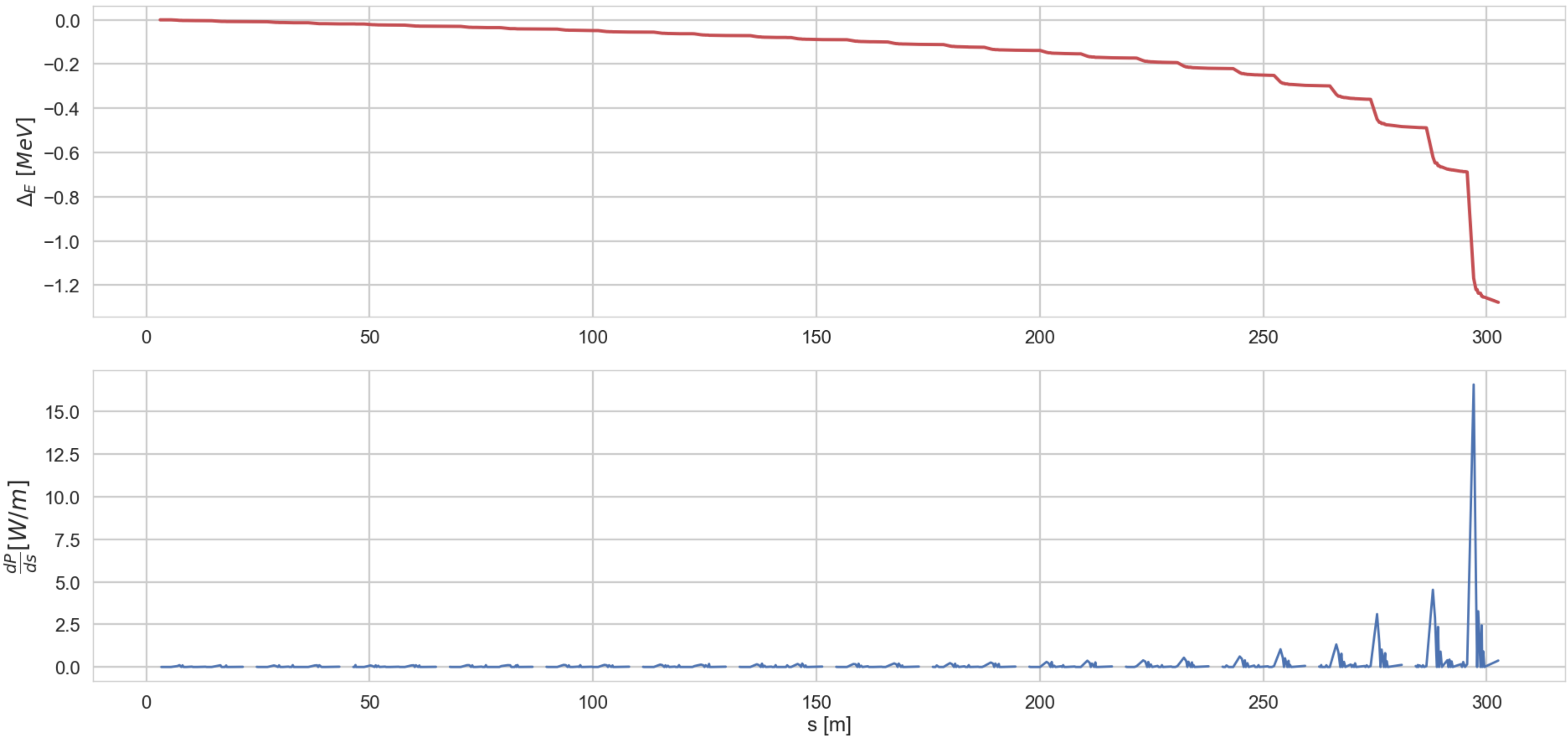


R_{56}=35 mm



Study of the arc compressor done by
M. Rossetti Conti

ISR and CSR through Arc Compressor



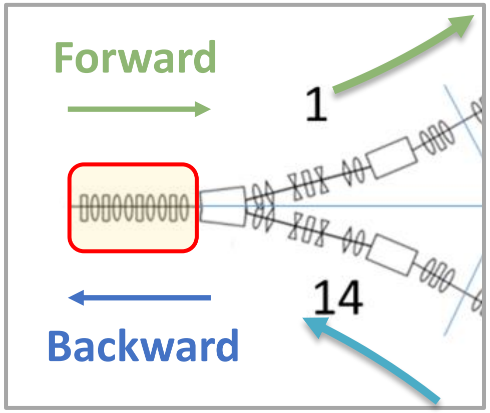
Bubble Arc matching line

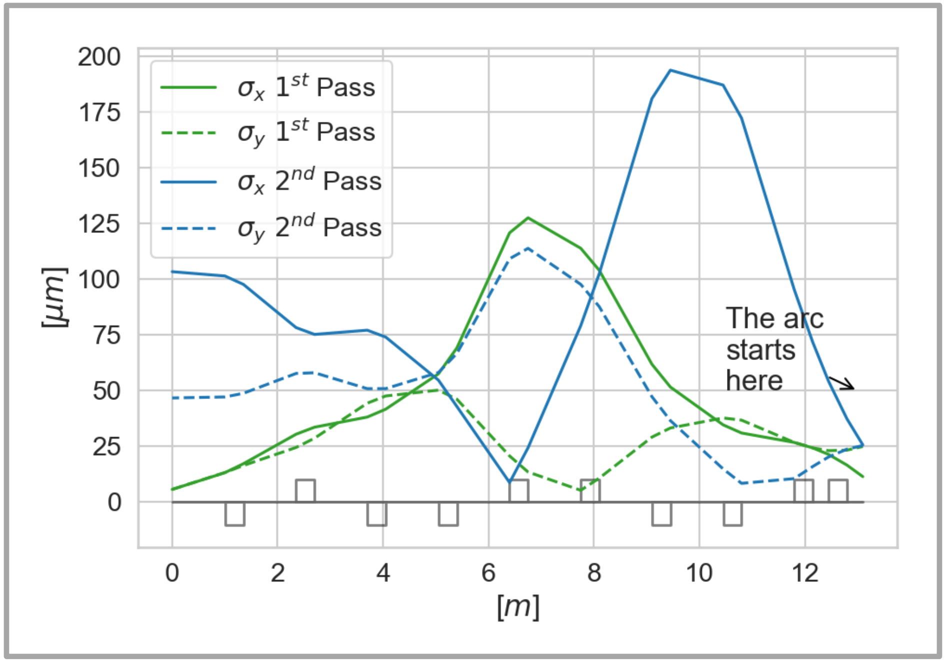
10 quads matching line with two different objectives:

- The **forward traveling bunch** is **matched** to the BAC (in first DBA bending).
- The **bunch traveling back** divergence is controlled to avoid **strong $\varepsilon_{n,x-y}$ degradation**

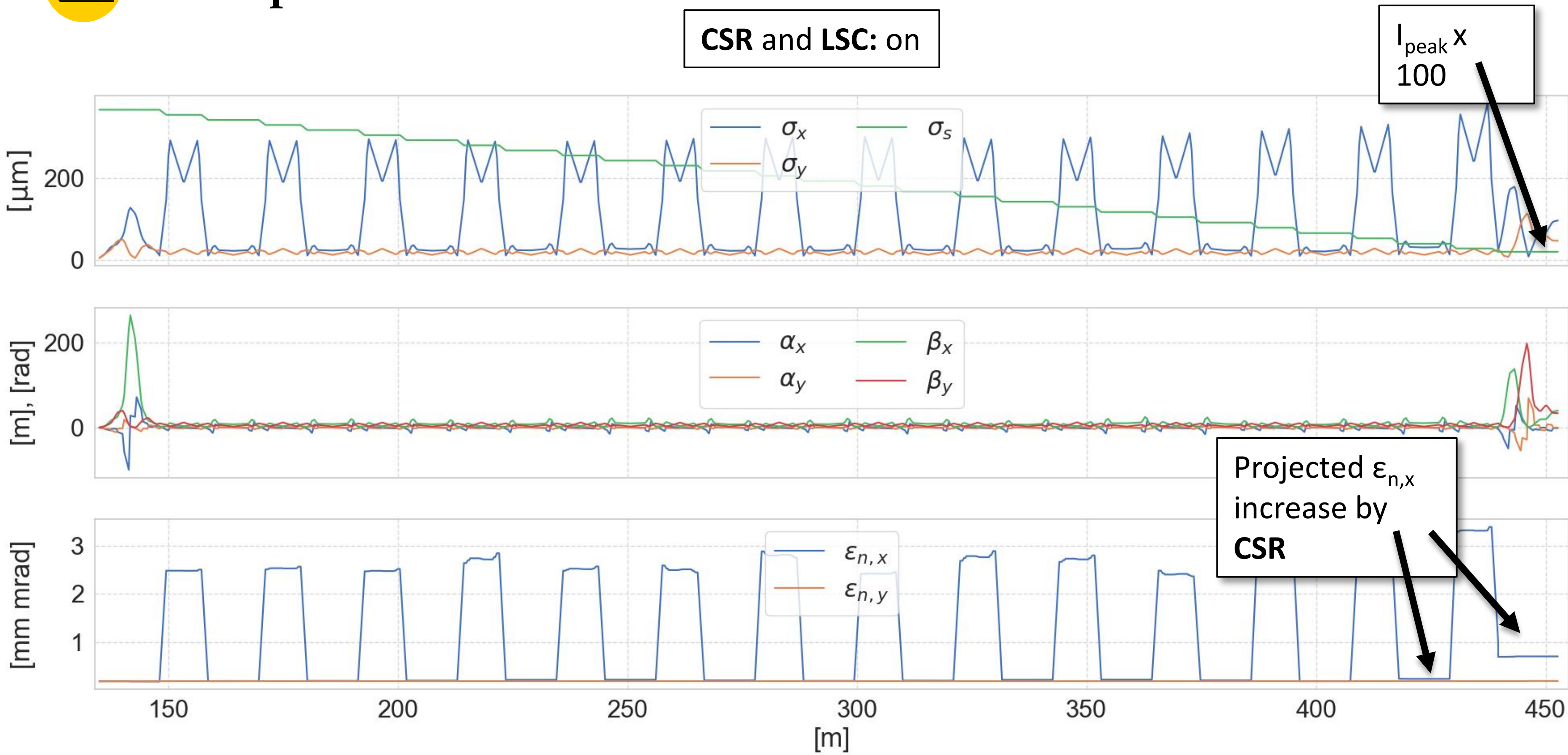
by chromatic effects in the SC solenoid.

$$\epsilon_{n,chromatic} = \beta\gamma K \sigma_x^2 (\sin KL + KL\cos KL)\frac{\sigma_p}{p}$$



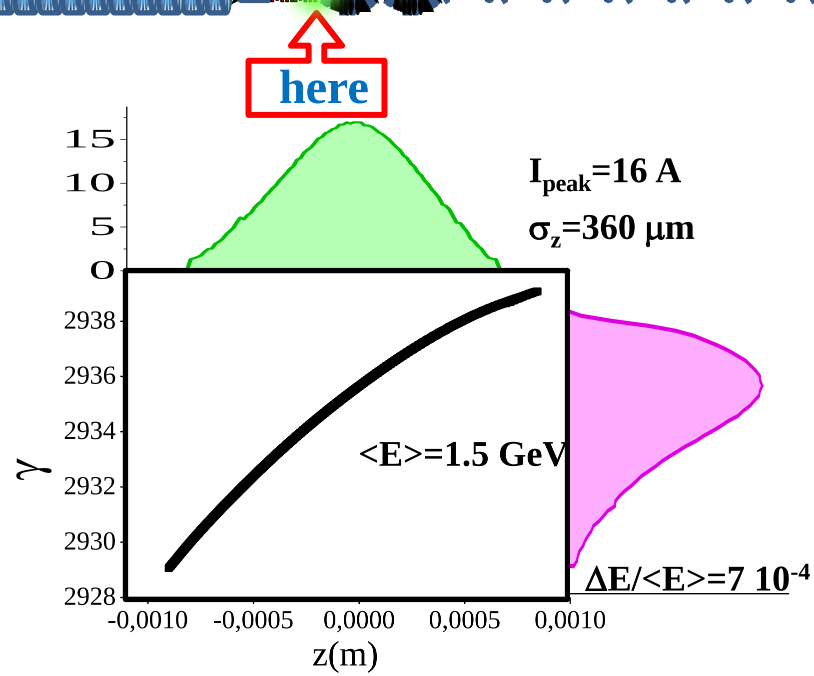


Beam parameters in BAC

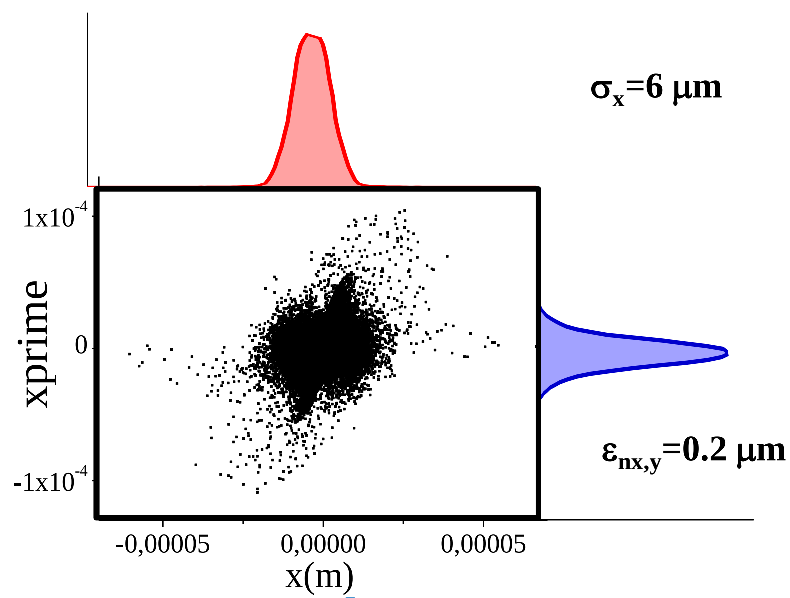


Beam dynamics 1: before the arc, Q=50 pC

Beam dynamic study made by A. Bacci



Longitudinal phase space



Transverse phase space

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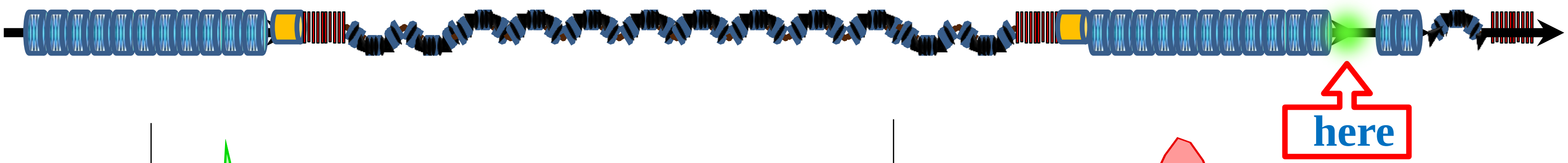
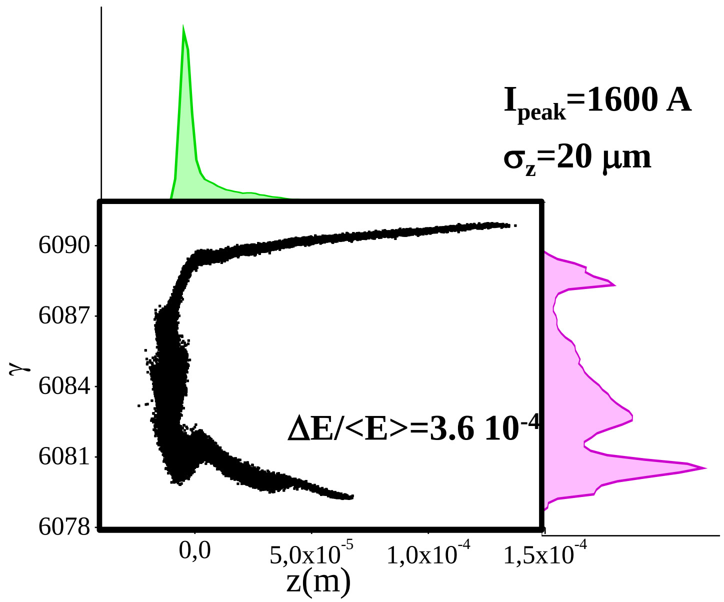
Beam dynamics 2: after the arc, Q=50 pC

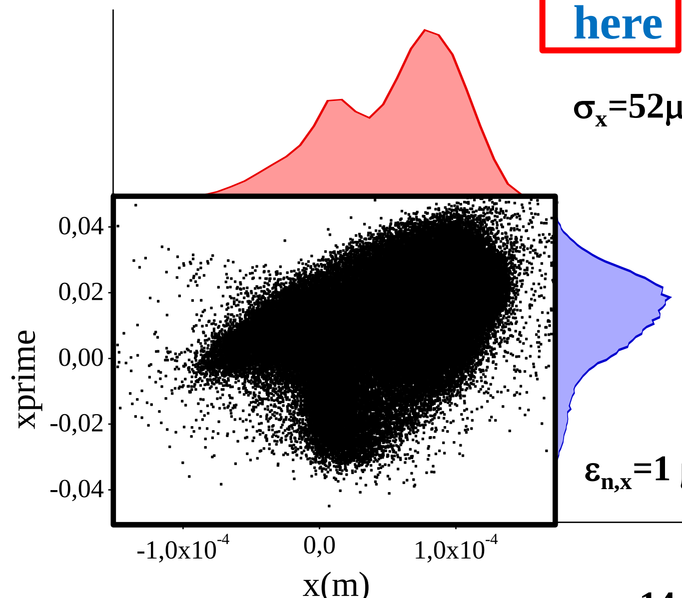




I_{peak}=1600 A

σ_z=20 μm

Longitudinal phase space



σ_x=52μm

$\varepsilon_{n,x}$=1 μm

σ_y=14.5 μm

$\varepsilon_{n,y}$=0.2 μm

Transverse phase space

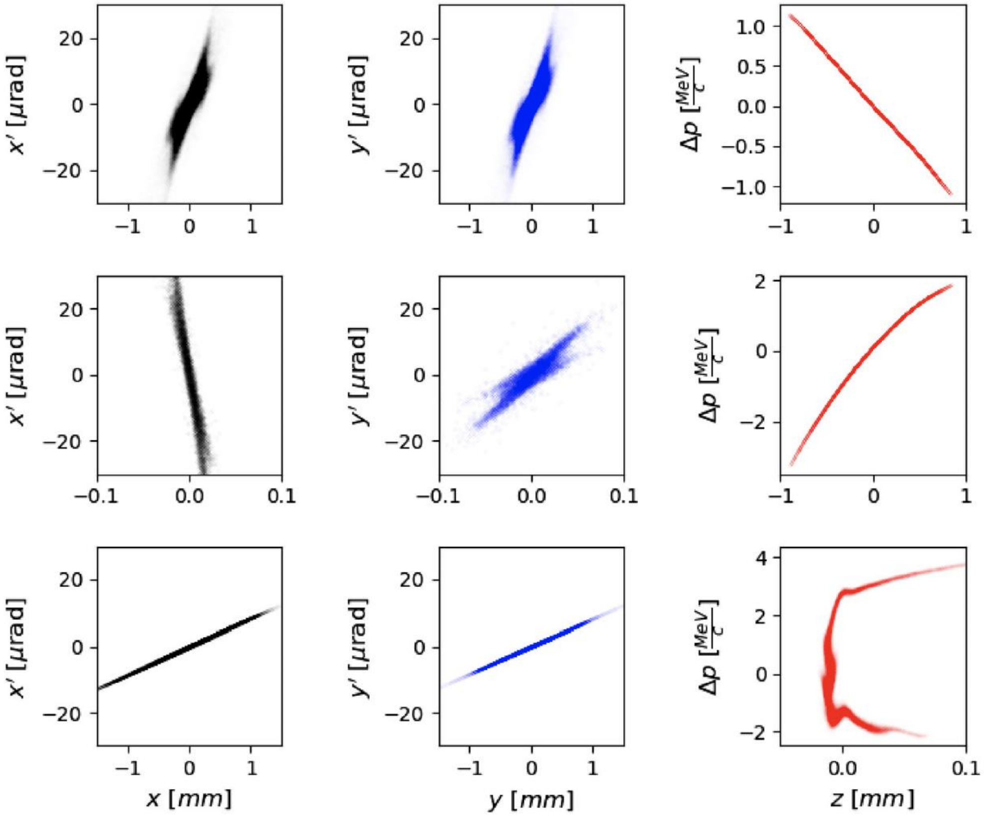


FIG. 16. First row: (x, x′), (y, y′) and (z, Δp) bunch phase spaces at the injector exit, ∼130 MeV. Second row: (x, x′), (y, y′) and (z, Δp) bunch phase spaces at the BAC entrance, ∼1.6 GeV. Third row: (x, x′), (y, y′) and (z, Δp) bunch phase spaces at L2 entrance, ∼3.0 GeV.

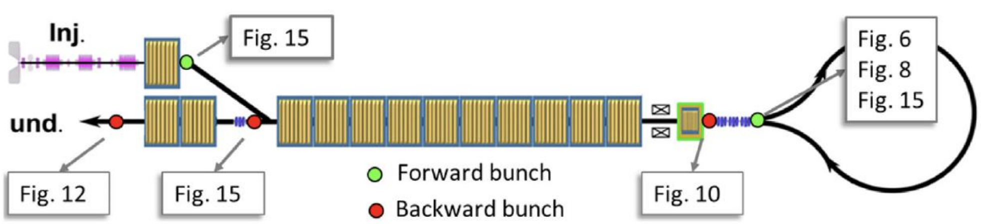


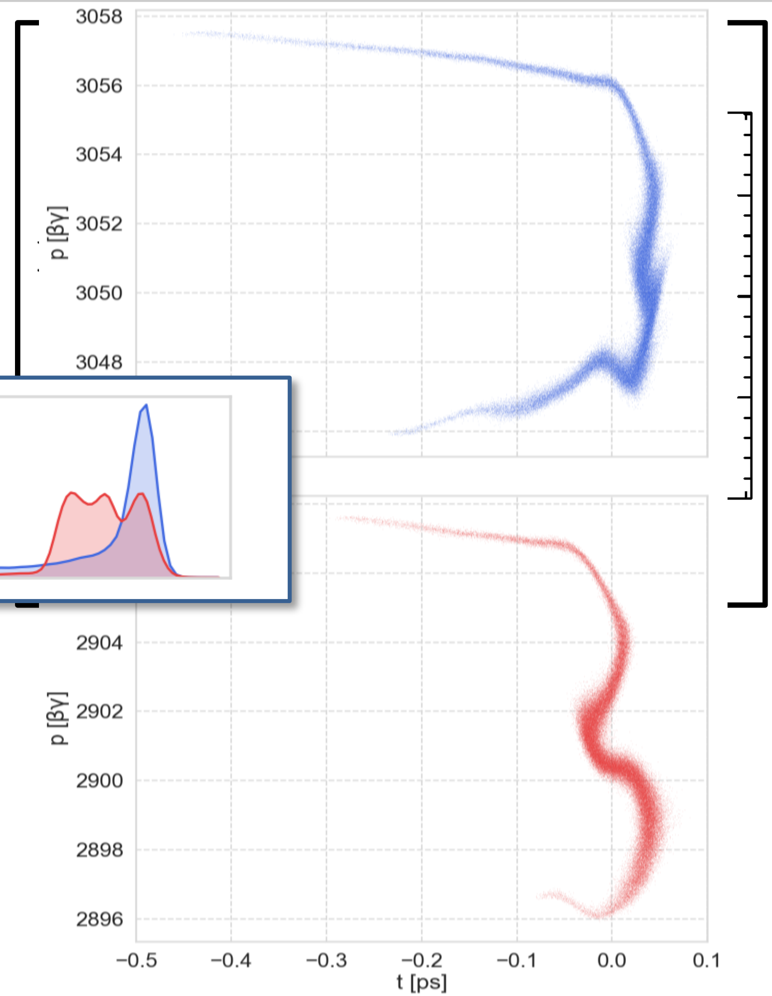
FIG. 17. MariX’s beam line with positions of phase spaces shown in this study.

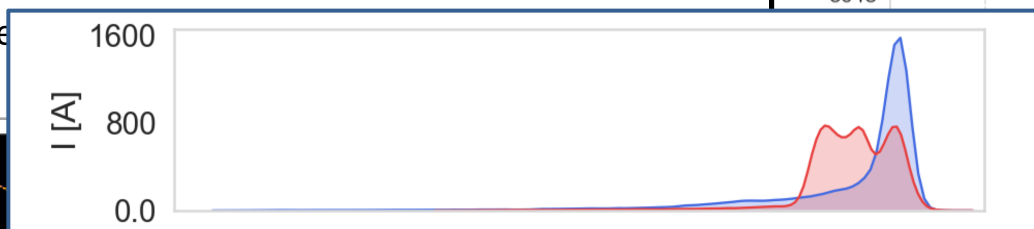
CSR compensation

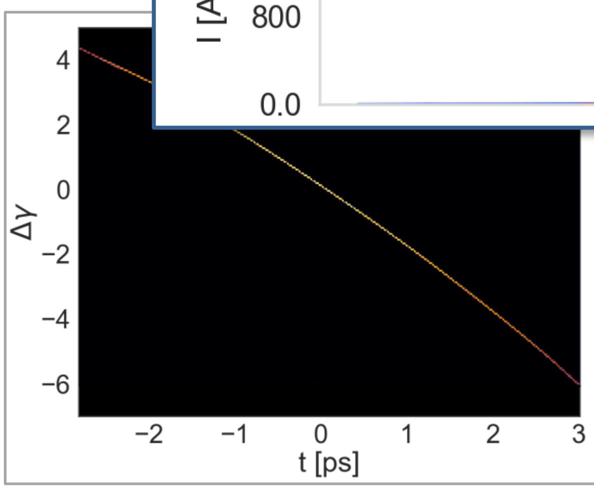
Two main factors contribute in CSR compensation:

- **Current** profile **shaping** (injector) reduce CSR kick.
- The **HHL** in acc. phase (+100 MeV) increases LPS curvature

compensating the







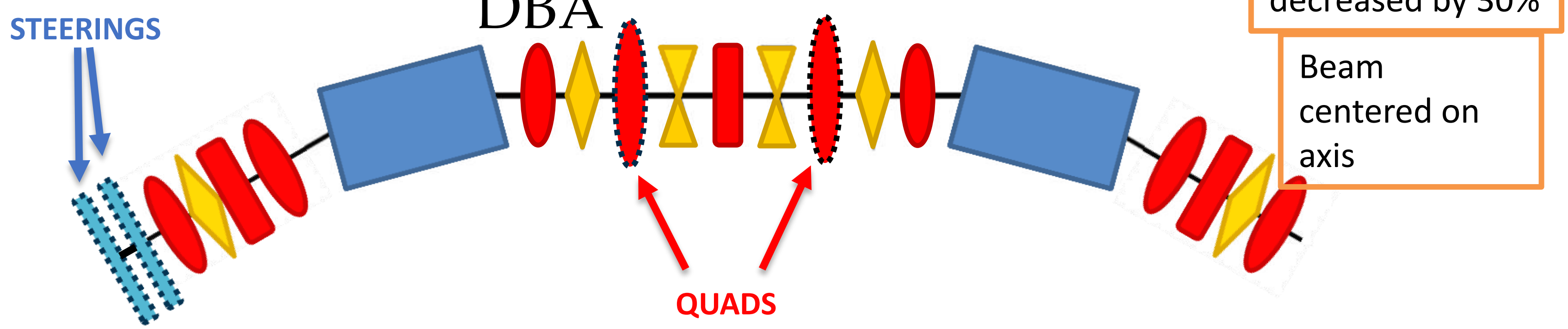
Beam dispersion damping

The CSR kick induces **dispersive effects** on the beam:

Increase η and η', <x> and <x'> and **spoils FEL emission**

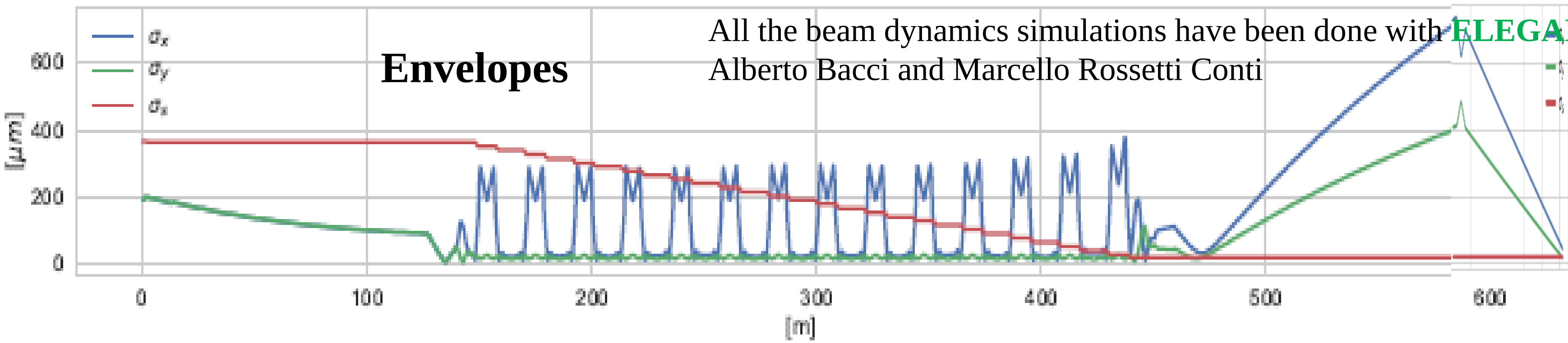
$$\eta_x = \frac{\langle x\, p_r \rangle}{\sigma_{p_r}^2} \qquad \eta'_x = \frac{\langle x'\, p_r \rangle}{\sigma_{p_r}^2}$$

$$with:\ \ p_r = \frac{p - \langle p \rangle}{\langle p \rangle}$$

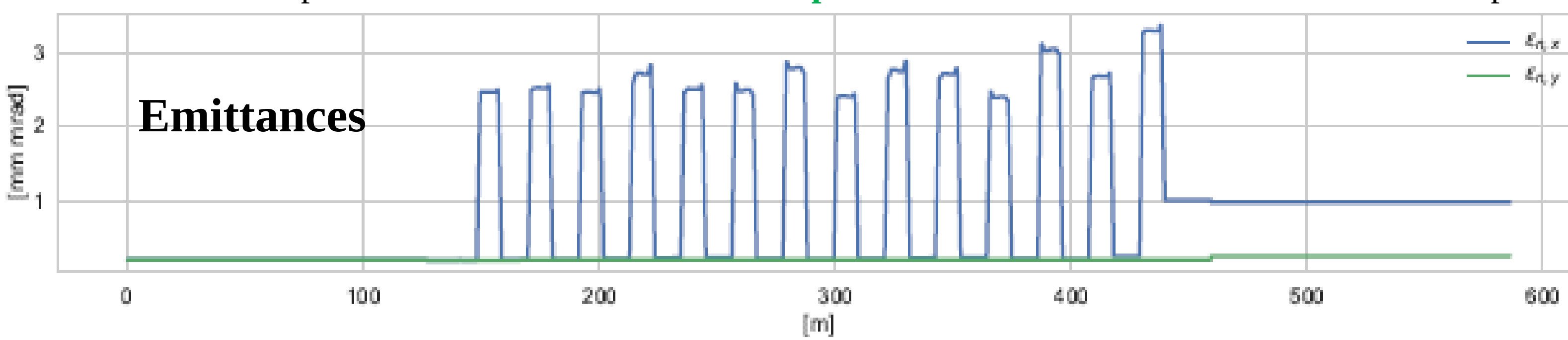


beam dynamics w/o optimization in last DBA with special lay-out

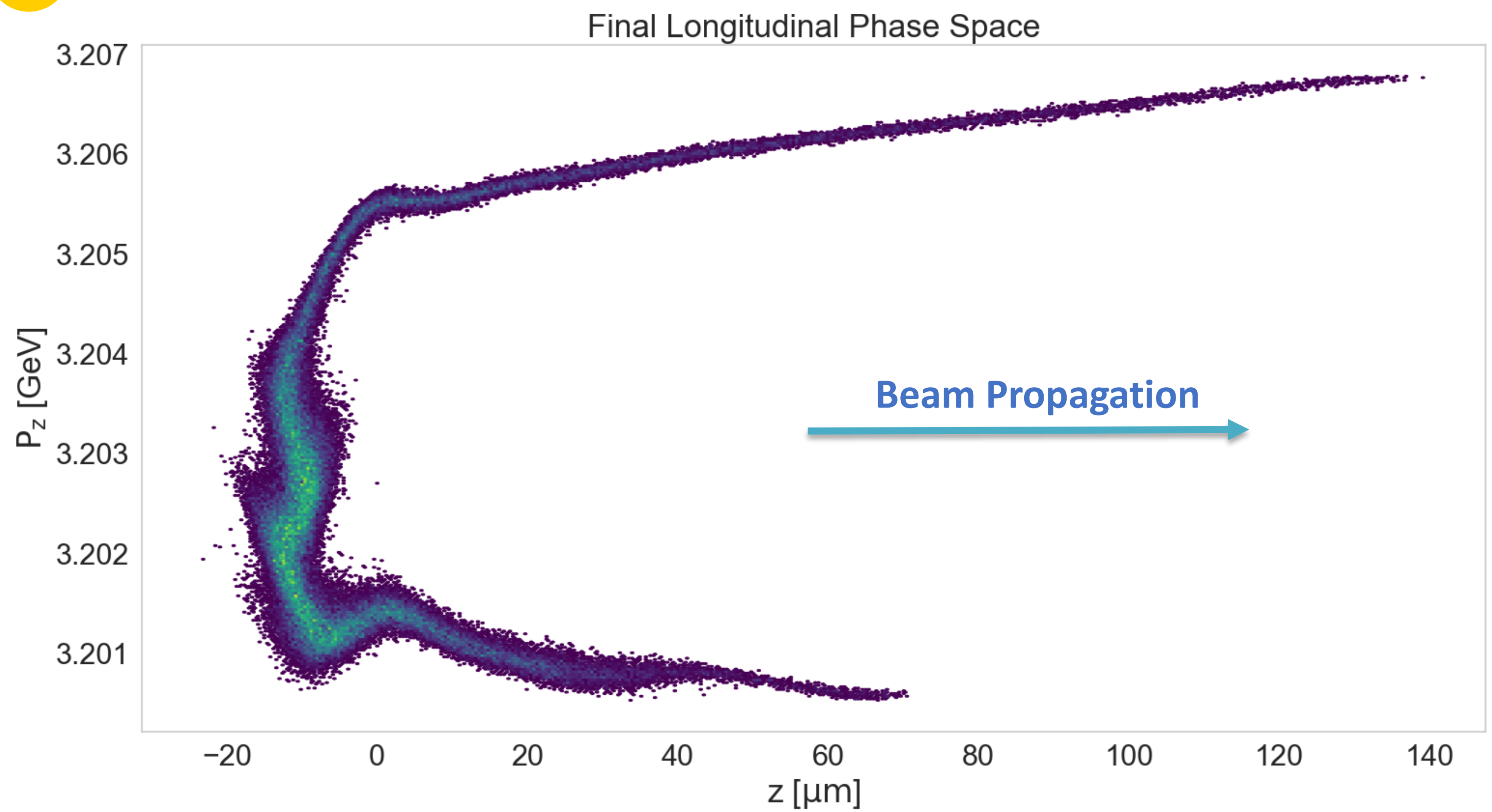
All the beam dynamics simulations have been done with **ELEGANT** by Alberto Bacci and Marcello Rossetti Conti



Linac 1 1st pass TL **Arc compressor** TL **Linac 1** 2nd pass **Linac2**

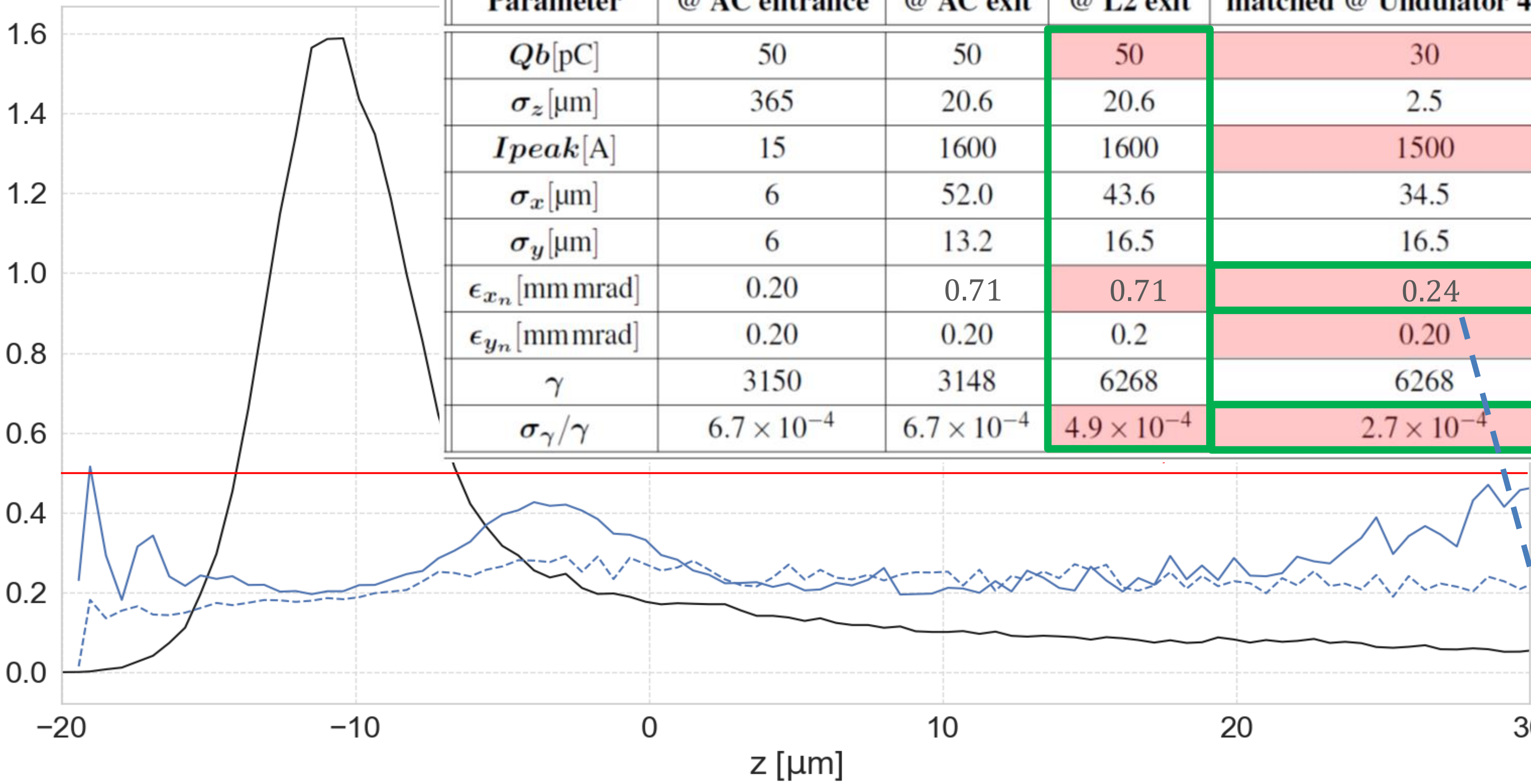


The Bunch


Final Longitudinal Phase Space
3.207
3.206
3.205
3.204
3.203
3.202
3.201
P_z [GeV]
−20
0
20
40
60
80
100
120
140
z [μm]
Beam Propagation

The Bunch

Parameter	@ AC entrance	@ AC exit	@ L2 exit	matched @ Undulator 40% cut
Qb[pC]	50	50	50	30
σ_z[μm]	365	20.6	20.6	2.5
$Ipeak$[A]	15	1600	1600	1500
σ_x[μm]	6	52.0	43.6	34.5
σ_y[μm]	6	13.2	16.5	16.5
ϵ_{x_n}[mm mrad]	0.20	0.71	0.71	0.24
ϵ_{y_n}[mm mrad]	0.20	0.20	0.2	0.20
γ	3150	3148	6268	6268
σ_γ/γ	6.7×10^{-4}	6.7×10^{-4}	4.9×10^{-4}	2.7×10^{-4}



$\varepsilon_{x,y}$ = 30 pm @ 3.2 GeV

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 111304 (2019)

Two-pass two-way acceleration in a superconducting continuous wave linac to drive low jitter x-ray free electron lasers

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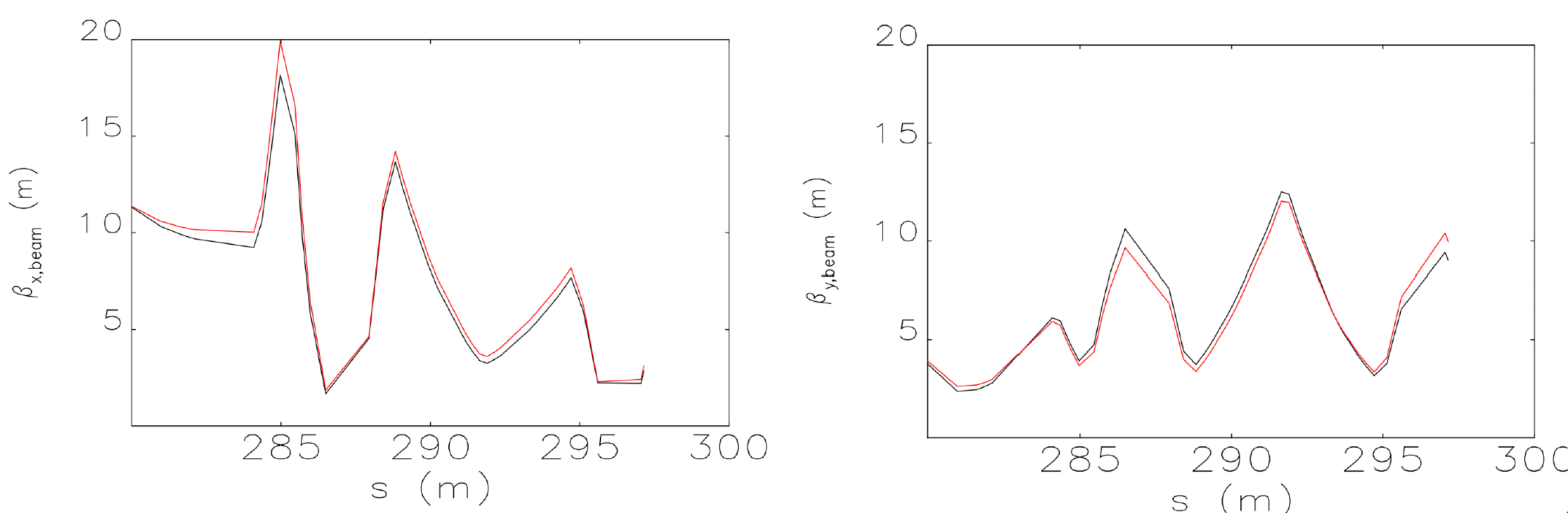
(Received 27 June 2019; published 13 November 2019)

We present a design study of an innovative scheme to generate high rep rate (MHz-class) GeV electron beams by adopting a two-pass two-way acceleration in a superconducting (SC) linac operated in continuous wave (CW) mode. The electron beam is accelerated twice by being reinjected in opposite direction of propagation into the linac after the first passage. Acceleration in opposite directions is accomplished thanks to standing waves supported in rf cavities. The task of recirculating the electron beam when it leaves the linac after first pass is performed by a bubble-shaped arc compressor composed by a sequence of double bend achromat. In this paper we address the main issues inherent to the two-pass acceleration process and the preservation of the electron beam quality parameters (emittance, energy spread, peak current) required to operate x-ray free electron lasers (FEL) with low jitters in the amplitude, spectral and temporal domain, as achieved by operating in seeding and/or oscillator mode a CW FEL up to 1 MHz rep rate. Detailed start-to-end simulations are shown to assess the capability of this new scheme to double the electron beam energy as well as to compress the electron bunch length from picoseconds down to tens of femtoseconds. The advantage of such a scheme is to halve the requested linac length for the same final electron beam energy, which is typically in the few GeV range, as needed to drive an x-ray FEL. The AC power to supply the cryogenic plant is also significantly reduced with respect to a conventional single-pass SC linac for the same final energy. We are reporting also x-ray FEL simulations for typical values of wavelengths of interest (in the 200 eV–8 keV photon energy range) to better illustrate the potentiality of this new scheme.

DOI: 10.1103/PhysRevAccelBeams.22.111304

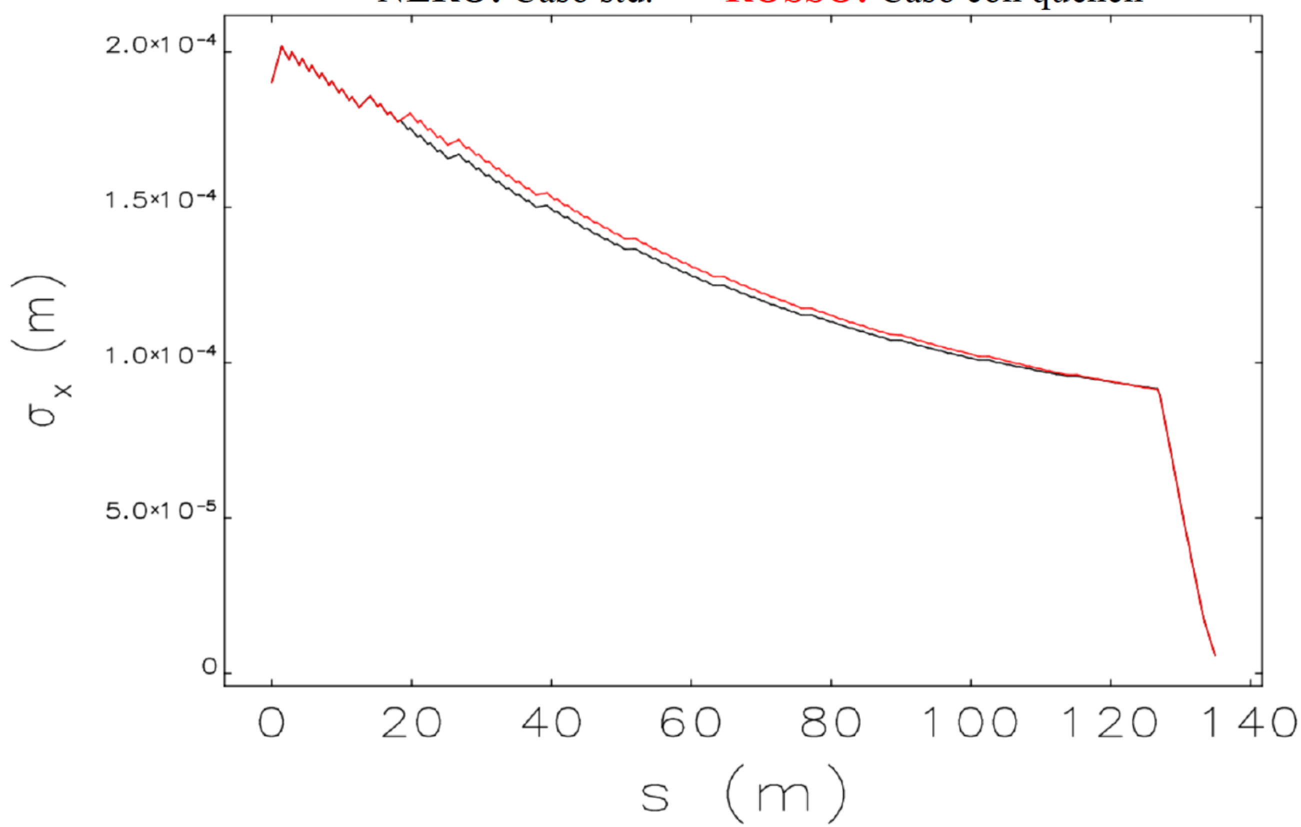
MAC-INFN LASA, Giugno 2019
estratto dal report:

- *Per il progetto MariX il MAC si congratula vivamente per la pubblicazione del CDR che appare un documento estremamente articolato e che rappresenta sicuramente una prima fondamentale milestone per il progetto. Il contesto di opportunità e stato accuratamente descritto e appare solido. Il MAC raccomanda che, nell'ottica del miglioramento del documento, un comitato esterno lo possa valutare.*
- *Per Marix si raccomanda che sia anche effettuata una risk analysis sul funzionamento del LINAC con focalizzazione RF per valutare il range dinamico di funzionamento e l'opportunità di inserire degli elementi magnetici che garantiscano il funzionamento anche in caso di failure di una o più sezioni acceleranti*

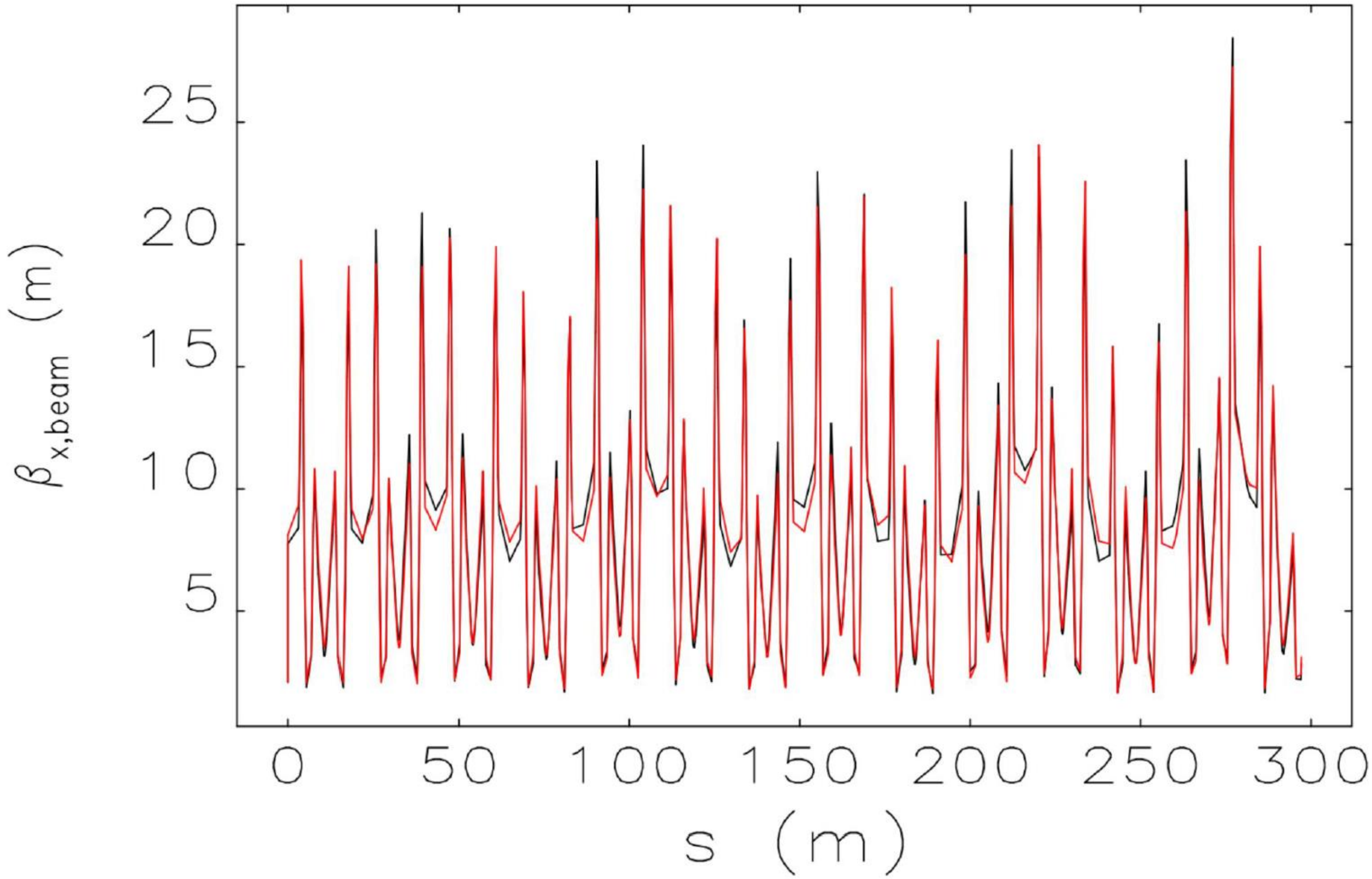


Quench nella quarta cavità del secondo cryomodulo, tutte e 16 le cavità dei **cryomoduli 9 e 10** compensano la perdita di energia.
Risultato: energia finale uguale al caso std (γ=3130.77) ma **σ_x compensato meglio**: 5.804 μm contro 5.748 μm del caso std (+0.97%).

NERO: Caso std. - **ROSSO:** Caso con quench



Trasportando nell'arco un fascio con un jitter del 4% sui beta ed alpha diversi da 0 (=0.1) si nota che la linea dell'arco è stabile, non perde il fascio. (Zoom sugli ultimi metri nella prossima pagina).
La dinamica longitudinale invece è immutata.



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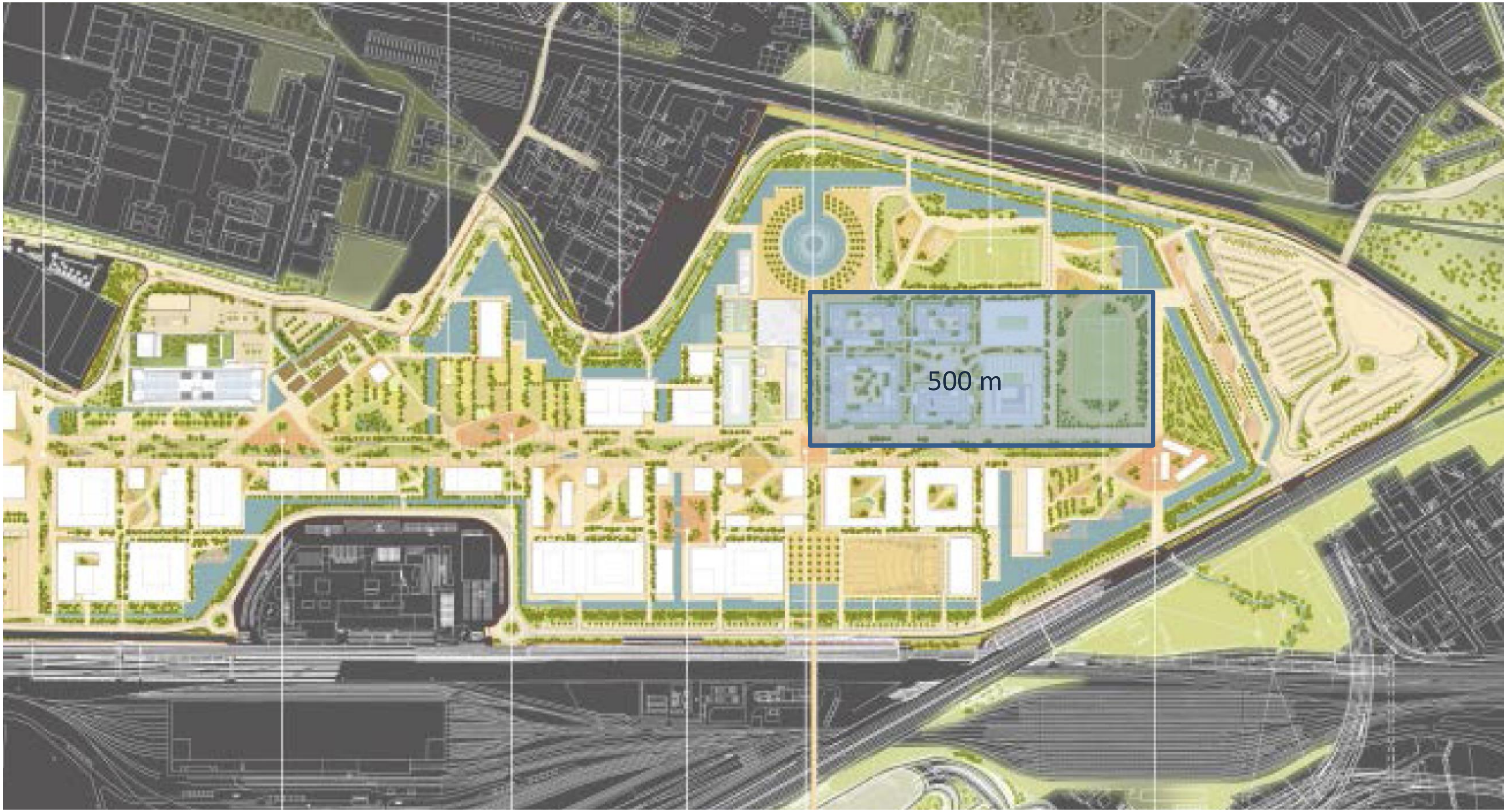

Next generation CW FELs like LCLS-II are km-long: not enough space in new UniMi Campus

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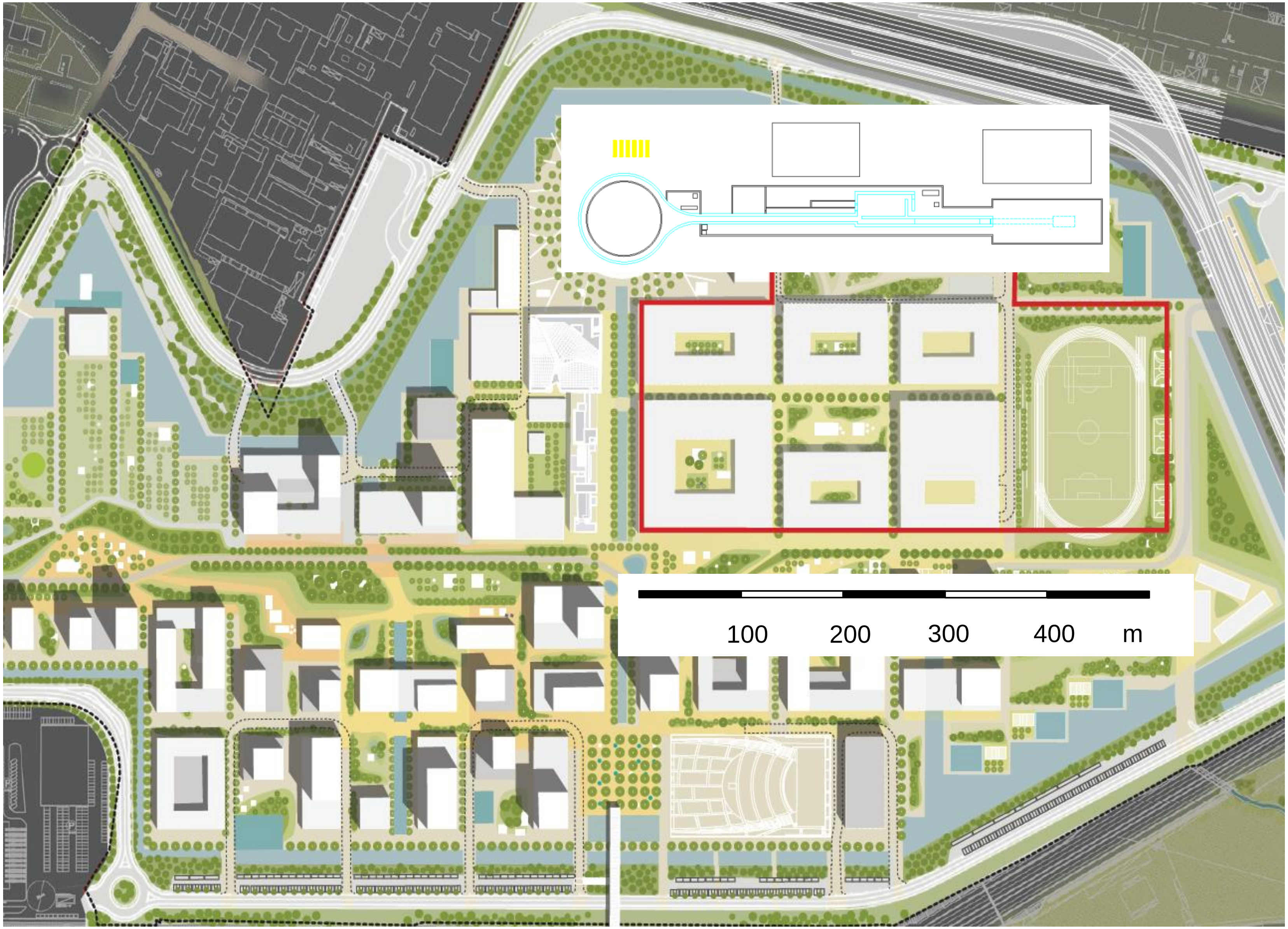

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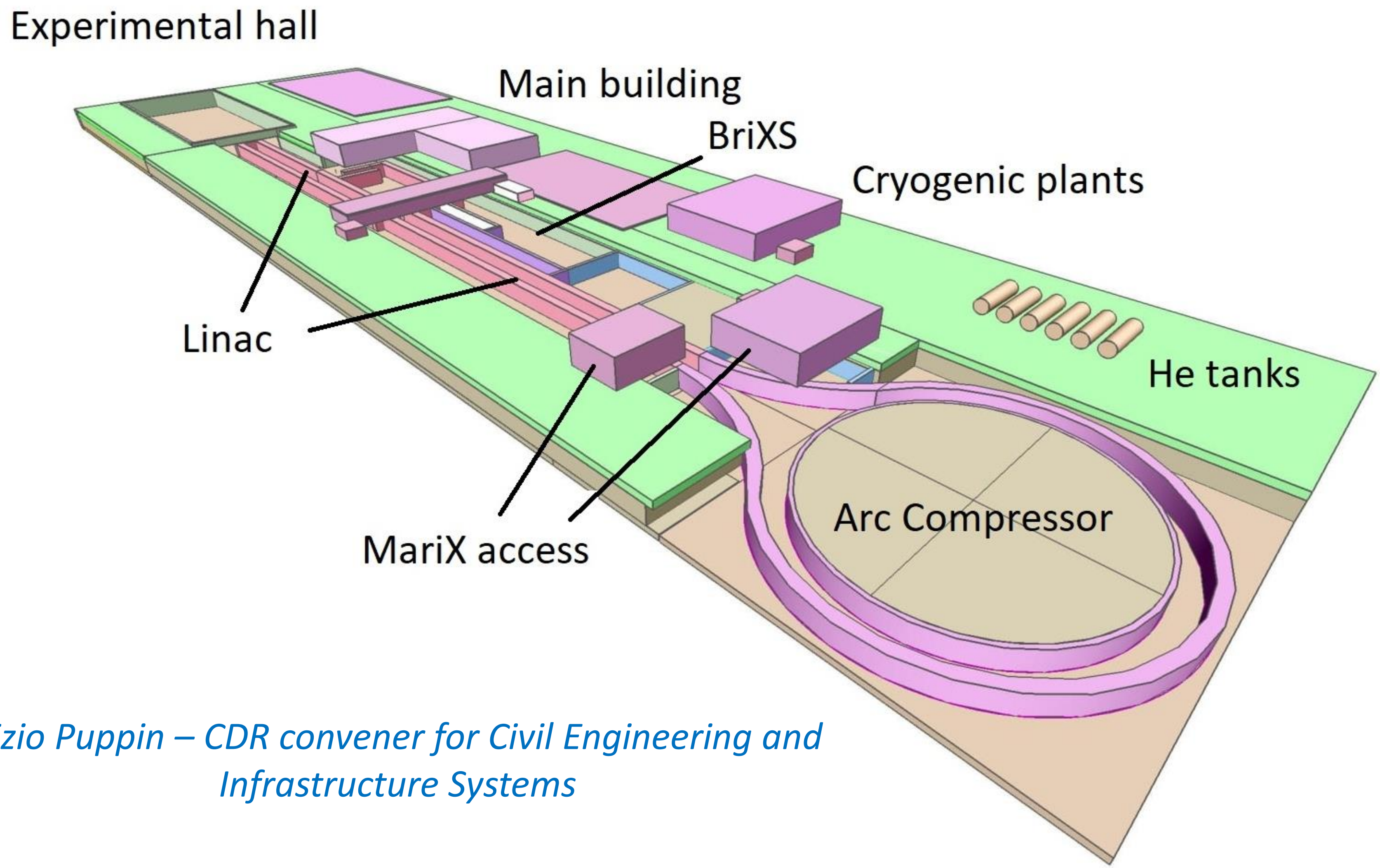

Ezio Puppin – CDR convener for Civil Engineering and Infrastructure Systems

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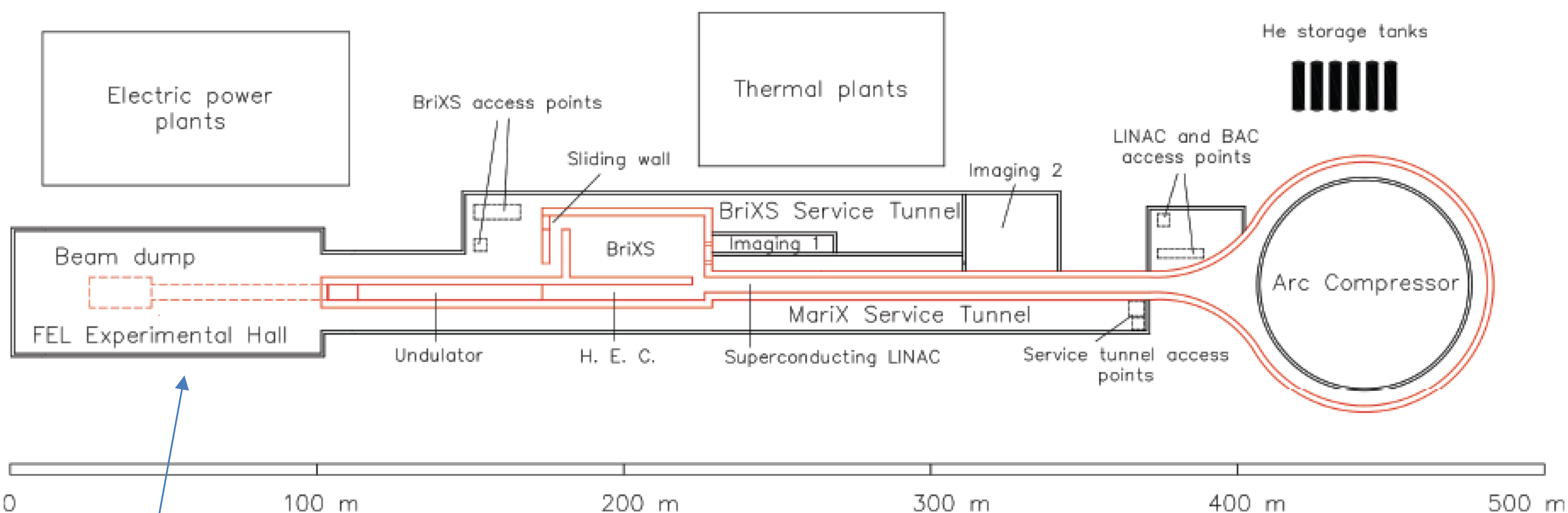


Figure 21.1: General layout of the BriXSMariX facility with all the underground buildings and the various areas reserved for plants.

200 kW underground beam dump @ 3.8 GeV

23.1 Electric power required

The electric power required by the various MariX components is listed in Table 23.1.

Table 23.1: Summary of the most relevant electric power distribution.

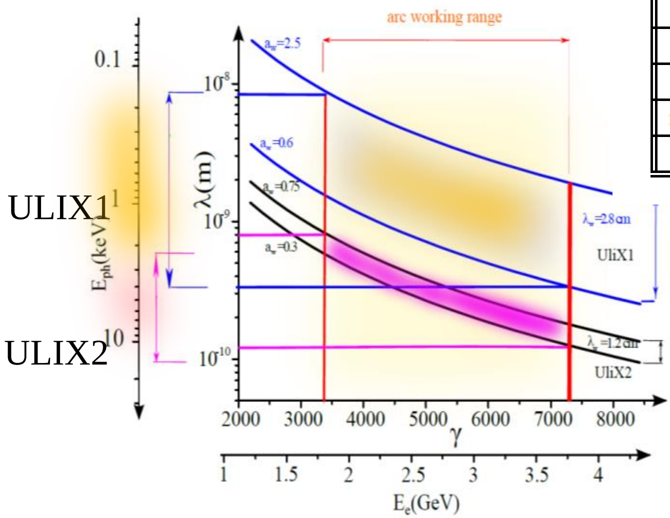
Item	Component	Power (MW)	Notes
Cryogenics	MariX	5	Compressors motors run at 3 kV
	BriXS	1	
Cavity RF	MariX	1.35	
	BriXS	0.25	
Water cooling	Bending magnets	4	
	BriXS dipoles	1.5	
	BriXS photoinjectors	0.25	
	Bunchers	0.05	
Experimental Hall		1	
Air conditioning		1	
Ventilation		1	
General services		1	
Total		**17.4**	

The location of the most relevant power consumers in the BriXS and MariX complex is shown in Figure 23.1. Most of the electric power is absorbed by the cryogenic, water cooling, air conditioning

Convener: Ermanno Pinotti (ermanno.pinotti@fisi.polimi.it)

General considerations on MariX FEL

1) For emitting with continuity from 100 eV to 8 KeV:

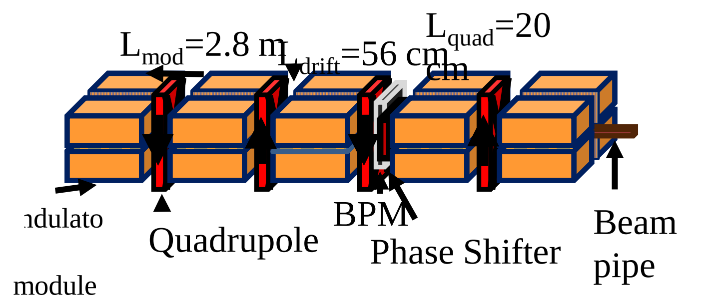


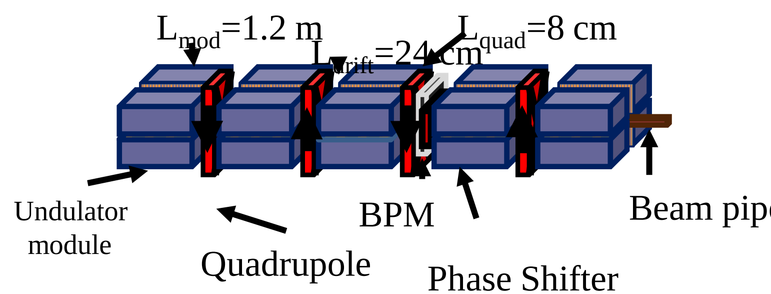
Nominal electron beam

Quantity	Units	
Energy	GeV	1.6 - 3.8
Charge Q	pC	8-50
Current	kA	1.2-1.6
norm. emit.	mm mrad	0.4-0.6
rms relative en. spread	10^{-4}	4-2
rms pulse duration	fs	2.5-16

UliX1 **λ=2.8 cm a_w<2.5**
from 100 eV to 4KeV

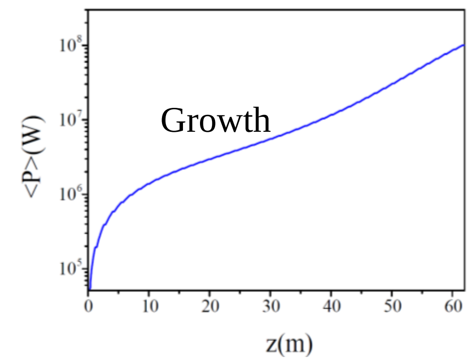
UliX2 **λ=1.2 cm a_w<0.8**
from 2 KeV to 8 KeV





SASE3: single shot imaging (1.5 Å), ULIX2, 1.2 cm

e-En (GeV)	**3.8**
Und (cm,m)	1.2 60
Ph-en (keV)	9.25
Rep rate	1 MHz
Energy	3.3 uJ
Numb per shot	**$2.5\ 10^{9}$**
Bandwidth (%)	0.3
N/ s (s-1)	**$2.5\ 10^{15}$**
Spectral dens(N/shot/1%bw)	**$0.8\ 10^{9}$**
Radiation size mm	**0.1**
Divergence mrad	**$15\ 10^{-3}$**
Tot. spect dens. (N/s/1%bw)	**8 10^14**
Coherence	SASE



Q=50 pC, SASE

I=1.5 kA

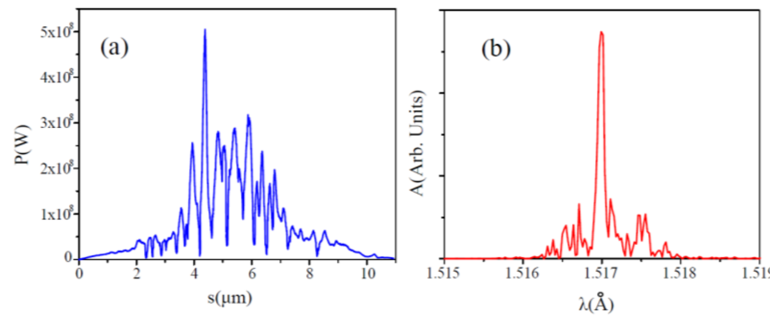
emit=0.35 um

$\Delta E/E = 3.6\ 10^{-4}$

$a_w = 0.64$

dt=10 fs

Power
60 m



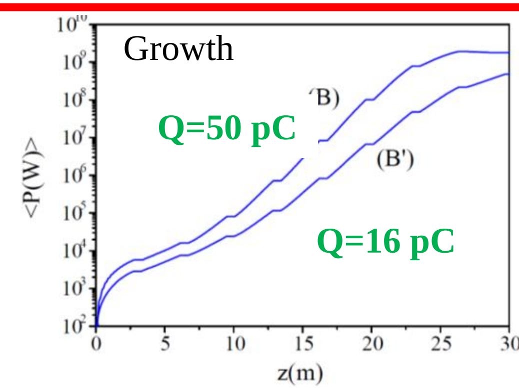
Spectrum
60 m

SASE spikes undersampled
in the graph (but not in the calculus)

$\rho \times 10^{-3}$	0.36	L_g (m)	1.5
$\rho_{3d} \times 10^{-3}$	0.17	L_{g3d} (m)	3.1
L_{sat} (m)	62	L_c (μm)	0.067
L_{beam} (μm)	3.75	M	>10

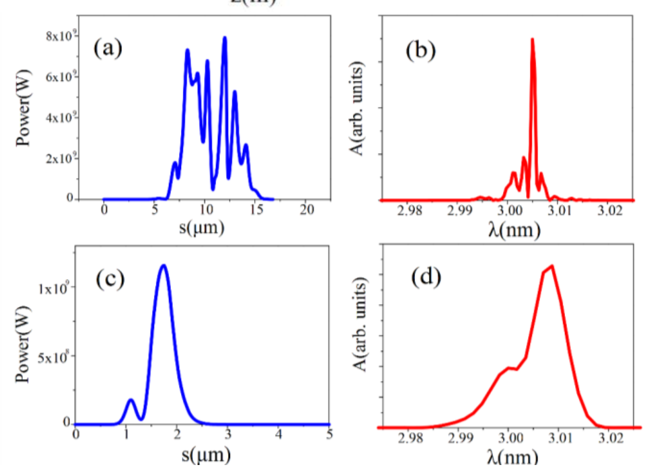
SASE1: water window (2.77 nm) ULIX1, λ_w=2.8 cm

	16pC	50 pC
e-En (GeV)	3.2	3.2
Und l_w, L(cm,m)	3 , 25	5, 25
Ph-en (keV)	0.45 (2.8nm)	0.45 (2.8nm)
Rep rate	1 MHz	1 MHz
Energy	21 μJ	156 μJ
Numb per shot	$3\ 10^{11}$	$2.2\ 10^{12}$
Bandwidth (%)	0.1	0.15
Pulse duration (fs)	3	10
N/ s (s^{-1})	$3\ 10^{17}$	$2.2\ 10^{18}$
S dens(N/shot/%bw)	$1.7\ 10^{12}$	$1.5\ 10^{13}$
Radiation size mm	0.15	0.07
Divergence mrad	$2.5\ 10^{-2}$	1.810^{-2}
Tot. S. d. (N/s/%bw)	$1.7\ 10^{18}$	$1.5\ 10^{19}$
Coherence	Single Spike	SASE



I=1.5 kA
emit=0.35 um
$\Delta E/E=3.6\ 10^{-4}$
a_w=2.5
dt=10-3 fs

Power
30 m



Q=50 pC
SASE
Spectrum
30 m

Q=16 pC
Single Spike

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FEL simulations

With **ELEGANT** simulations we obtained an electron beam with parameters very similar to the nominal ones

Energy (GeV)	1.6 - 3.8
Bunch charge (pC)	8 - 50
Bunch length (fs)	< 20
$\varepsilon_{x,y}$ (slice) (mm mrad)	0.5-0.35
Bunch Energy spread (slice) (%)	0.05 - 0.02
Bunch peak current (kA)	1.6
Bunch separation (μs)	> 1
Energy jitter shot-to-shot (%)	0.1
Time arrival jitter (fs)	< 20
Pointing jitter (μm)	5

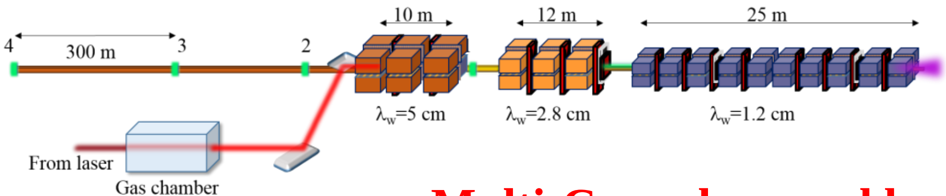
UliX1 Undulator	
Photon energy (keV)	0.12 - 1.5
Radiation wavelength (Å)	100 - 8
# photons per pulse	1.7×10^{12} - 1.2×10^{11}
Bandwidth	2.1×10^{-3} - 7.0×10^{-4}
Peak Brilliance†	1.4×10^{31} - 2.4×10^{32}
Radiation pulse length (fs)	3 - 10
Radiation beam divergence (μrad)	50 - 6
Repetition rate (MHz)	≤ 1
Pulse-to-pulse separation (μs)	> 1
N_{ph}/s	1.7×10^{18} - 1.2×10^{17}
Average Brilliance†	8.6×10^{22} - 1.4×10^{24}

UliX2 Undulator	
Photon energy keV	1.5 - 8.0
Radiation wavelength (Å)	8.0 - 1.5
# 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 (fs)	1 - 7
Radiation beam divergence (μrad)	45 - 16
Repetition rate (MHz)	≤ 1
Pulse-to-pulse separation (μs)	> 1
N_{ph}/s	2.4×10^{17} - 2.5×10^{15}
Average Brilliance†	3.5×10^{23} - 3.7×10^{22}

Average Brilliance same as Sirius and ESRF-upgrade – with just 50 micro-A average current !!!

Seeded pulses for linear spectroscopy (3-6 Ang): three options

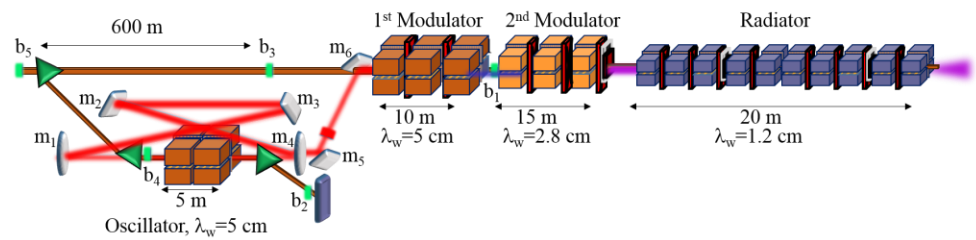
Multi-Cascade Seeded by HHG in gas at 13 nm



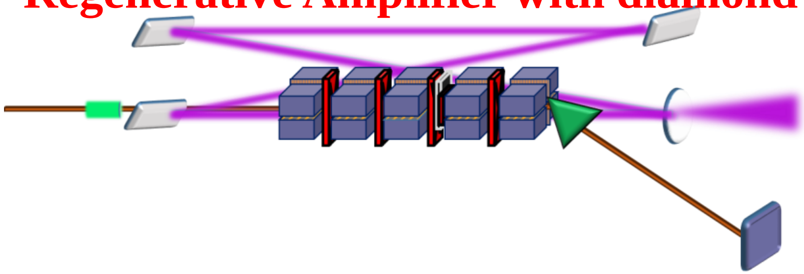
Possible only at low repetition rate

Multi-Cascade seesed by a FEL Oscillator at 13 nm, MoSi mirrors

Possible at 0.5 MHz



Regenerative Amplifier with diamond mirrors



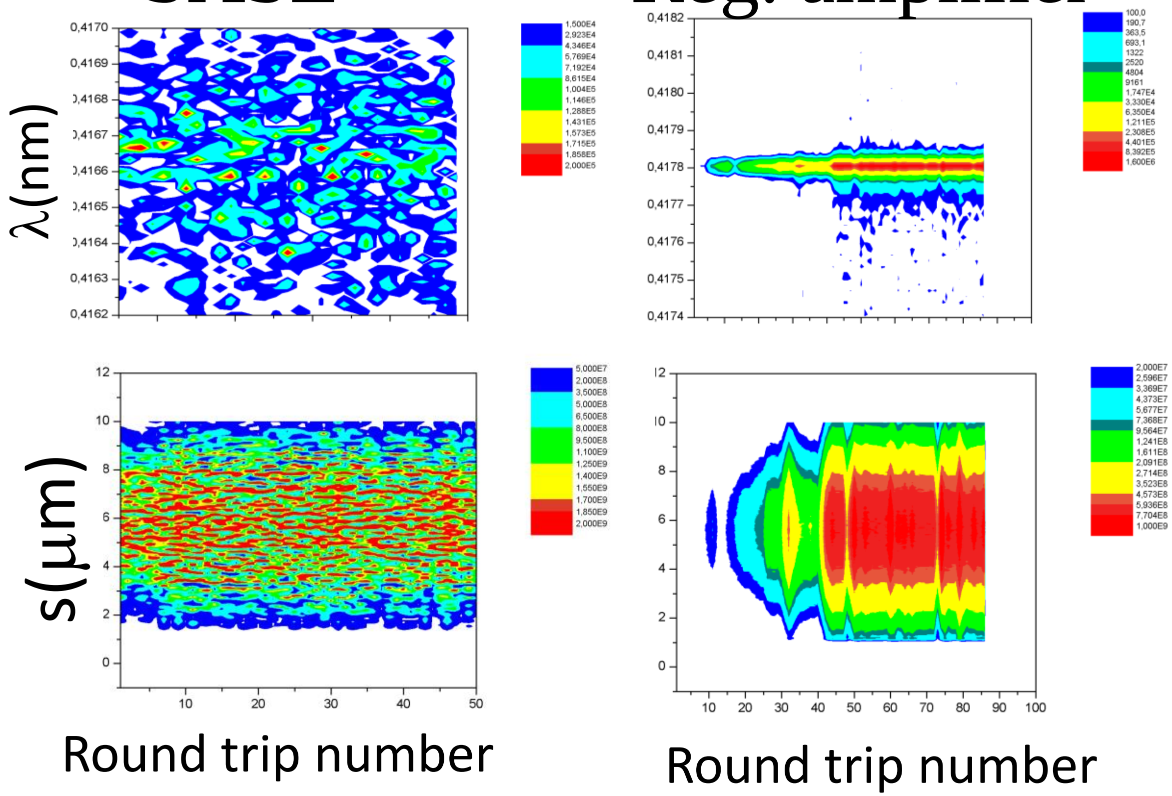
1 MHz, Optical line by **Alberto Tagliaferri**

3° option: Regenerative amplifier at 4 Ang with Diamond mirrors

SASE | Reg. amplifier

Spectrum

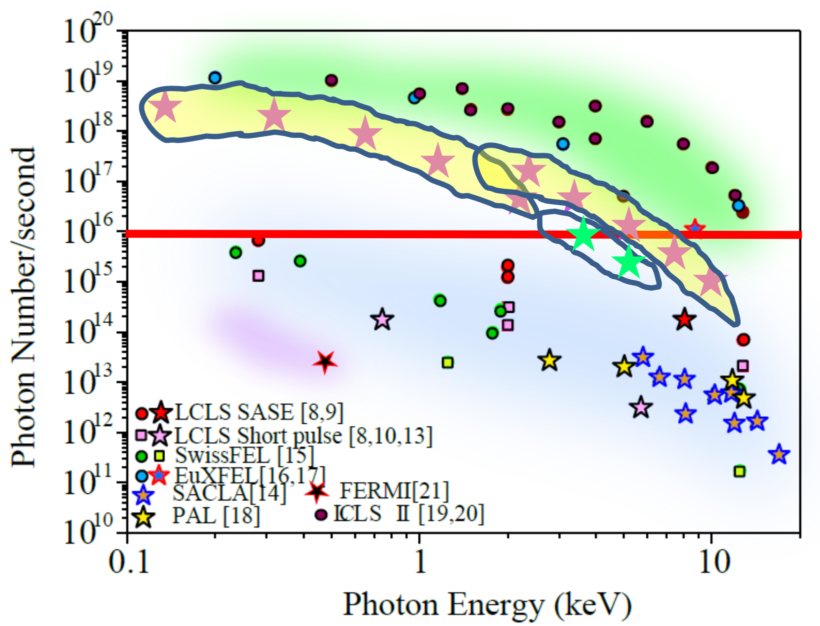
Temp. distr.



$$\lambda_R = \lambda_u / 2\gamma^2$$

Comparison between X FELs, photons per second, Electron Beam Energy to radiate at ~ Angstrom

FEL	Pulse per second
LCLS	120 Hz
SACLA	30-60 Hz
FERMI	10-50 Hz
PAL	30-60 Hz
PSI	100 Hz
EuXFEL	27 kHz
LCLS II	1 MHz
MariX	1MHz



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instruments

MDPI

Article

High Repetition Rate and Coherent Free-Electron Laser in the X-Rays Range Tailored for Linear Spectroscopy

Vittoria Petrillo [1,2,3], Michele Opromolla [1,2,3,*], Alberto Bacci [2,3], Illya Drebot [2,3], Giacomo Ghiringhelli [4], Alberto Petralia [5], Ezio Puppin [4], Marcello Rossetti Conti [2,3], Andrea Renato Rossi [2,3], Alberto Tagliaferri [4], Sanae Samsam [2,3,6] and Luca Serafini [2,3] and Giorgio Rossi [1]

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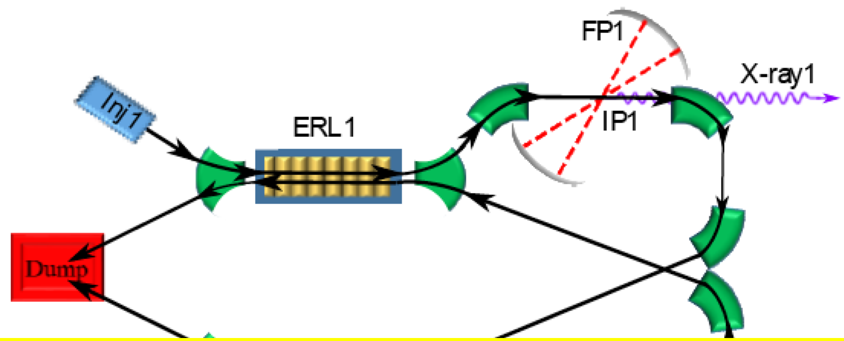
check for updates

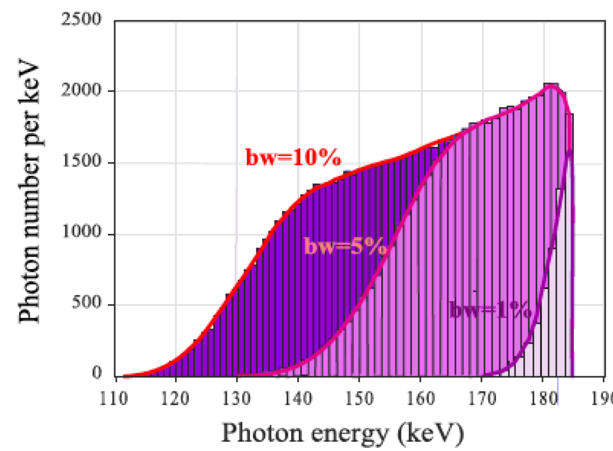
BriXS: an example of high sustainability. High power 2 MW beam delivered to user with only 200 kW power consumption/dissipation with outstanding beam quality (larger than storage rings, same current)



Energy (MeV)	30 - 100
Bunch charge (pC)	100 - 200
Repetition rate (for CW operation) (MHz)	100
Average Current (mA)	10 - 20
Nominal beam power (MW)	0.3 - 2.0
Energy recovered beam power (kW)	60 - 120
rms bunch length (μm)	400 - 900
$\varepsilon_{x,y}$ (mm mrad)	< 1.0
Bunch Energy spread (%)	< 0.05
	15 - 40
	10
	0.2
	< 0.15
Pointing jitter (μm)	3

Great advantage of BriXS ERL vs. storage ring based ICS: we do not care about electron beam quality preservation after collision (tighter focusing, round beam) – we just need to recover its kinetic energy by deceleration

Photon energy (keV)	20 - 180
Bandwidth (%)	1 - 10
# photons per shot within FWHM bw	0.05×10^5 - 1.0×10^5
# photons/sec within FWHM bw	0.05×10^{13} - 1.0×10^{13}
Source size (μm)	≤ 20
Source divergence (mrad)	6 - 1
Photon beam spot size (FWHM at z = 100 m) (cm)	40 - 4
Peak Brilliance†	10^{18} - 10^{19}
Radiation pulse length (ps)	0.7 - 1.5
Linear/Circular Polarization (%)	> 99
Repetition rate (MHz)	100
Pulse-to-pulse separation (ns)	10



PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 080701 (2017)

Analytical description of photon beam phase spaces in inverse Compton scattering sources

C. Curatolo,[1,*] I. Drebot,[1] V. Petrillo,[1,2] and L. Serafini[1]

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(Received 9 March 2017; published 3 August 2017)

4th order variational expansion over rms phase space distribution of e-hν colliding beams

$$\frac{\Delta E_{\rm ph}}{E_{\rm ph}} \simeq \sqrt{\left[\frac{\Psi^2/\sqrt{12}}{1+\Psi^2} + \frac{\bar{P}^2}{1+\sqrt{12}\bar{P}^2}\right]^2 + \left[\left(\frac{2+X}{1+X}\right)\frac{\Delta\gamma}{\gamma}\right]^2 + \left(\frac{1}{1+X}\frac{\Delta E_L}{E_L}\right)^2 + \left(\frac{M^2\lambda_0}{2\pi w_0}\right)^4 + \left(\frac{a_0^2/3}{1+a_0^2/2}\right)^2}$$

- acceptance angle $\Psi = \gamma_{\rm CM}\theta_{\rm max}$
- relative energy spread
- beam quality factor
- laser wavelength
- $\bar{P} = \gamma_{\rm CM}\frac{\sqrt{2}\epsilon_x}{\sigma_x} = \frac{\sqrt{2}\epsilon_n}{\sigma_x\sqrt{1+X}}$
- laser bandwidth
- laser focal spot size
- laser parameter

$$\mathcal{N}^\Psi = 6.25\cdot 10^8 \frac{U_L(J)\,Q(pC)\,r}{E_L(eV)\,(\sigma_x^2(\mu m)+\sigma_L^2(\mu m))}\cdot \frac{\left(1+\sqrt[3]{X}\,\Psi^2/3\right)\Psi^2}{(1+(1+X/2)\Psi^2)\,(1+\Psi^2)}, \qquad (20)$$

$$S = \frac{\mathcal{N}^\Psi}{\sqrt{2\pi}\,4\,E_L\gamma_{CM}^2\,\frac{\Delta E_{ph}}{E_{ph}}}. \qquad (21)$$

instruments

Article

BriXs Ultra High Flux Inverse Compton Source Based on Modified Push-Pull Energy Recovery Linacs

Illya Drebot [1,*], Alberto Bacci [1], Angelo Bosotti [1], Francesco Broggi [1], Francesco Canella [2], Paolo Cardarelli [3], Simone Cialdi [1,2], Luigi Faillace [1], Gianluca Galzerano [4], Mauro Gambaccini [3,5], Dario Giannotti [1], Dario Giove [1], Giovanni Mettivier [6,7], Paolo Michelato [1], Laura Monaco [1], Rocco Paparella [1], Gianfranco Paternó [3], Vittoria Petrillo [1,2], Francesco Prelz [1], Marcello Rossetti Conti [1], Andrea Renato Rossi [1], Paolo Russo [6,7], Antonio Sarno [7], Edoardo Suerra [2], Angelo Taibi [3,5] and Luca Serafini [1]

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

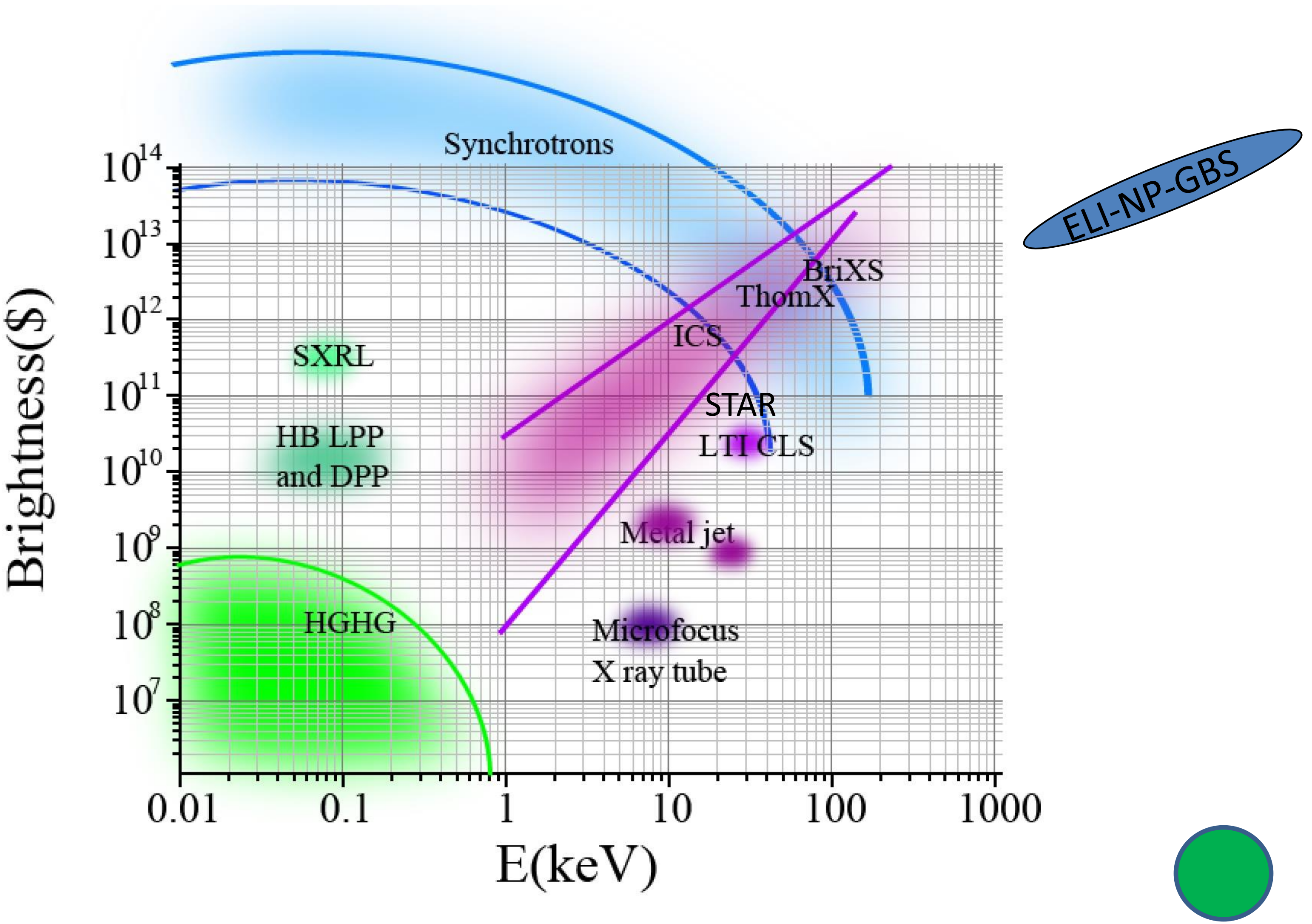
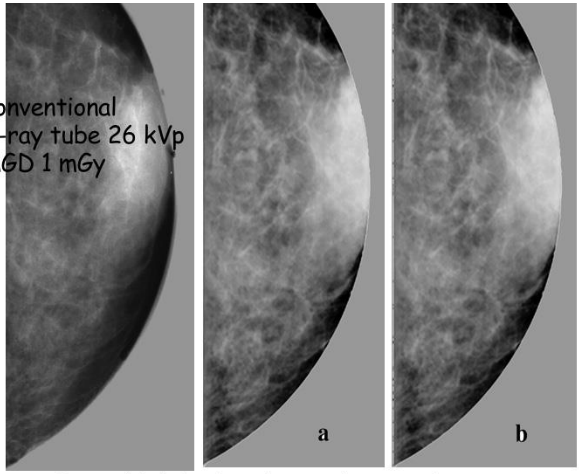


Figure 1: Brightness of several radiation sources as a function of the photon energy. $: Photon $number/s/mm^2/mrad^2/(0.1\%$. I.C.S. Sources (LTI-CLS,ThomX, STAR, UH-FLUX and BriXS) are compared to Synchrotron Light Sources and the most performing X-ray tube so far (Metal Jet).

BriXS Compton Source Clinical/Scientific Case

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

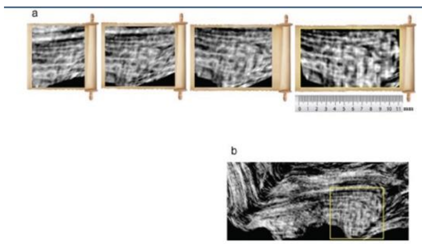
Klaus.Achterhold@tum.de



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

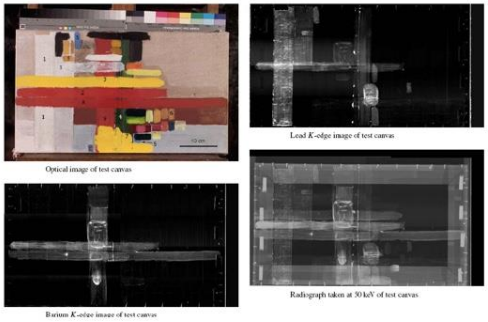


enrolling Ercolano's papyri

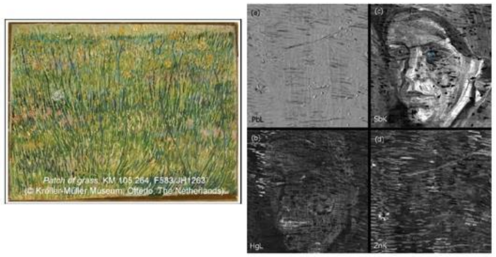
Figure 1: *PHerc.* 375. **a,** virtual-unrolling; **b** textual portion.

"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

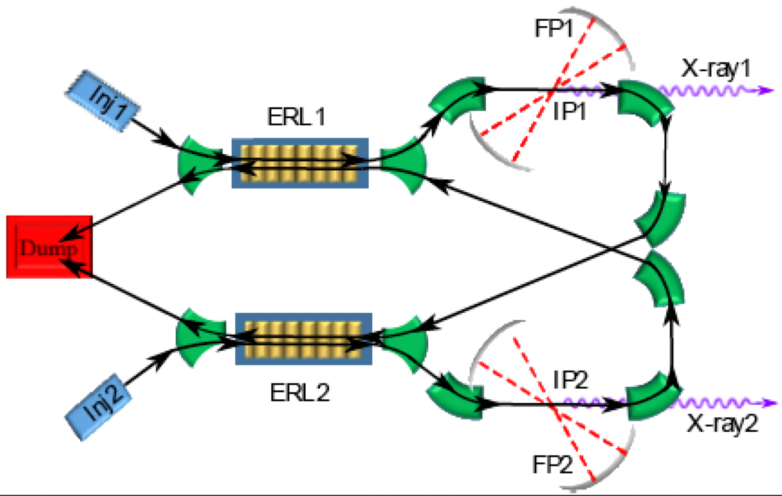
Microfractures without dislocation are often missed in initial radiographs; x-ray vector radiography (XVR) can overcome this limitation: degree of anisotropy and the orientation of scattering structures

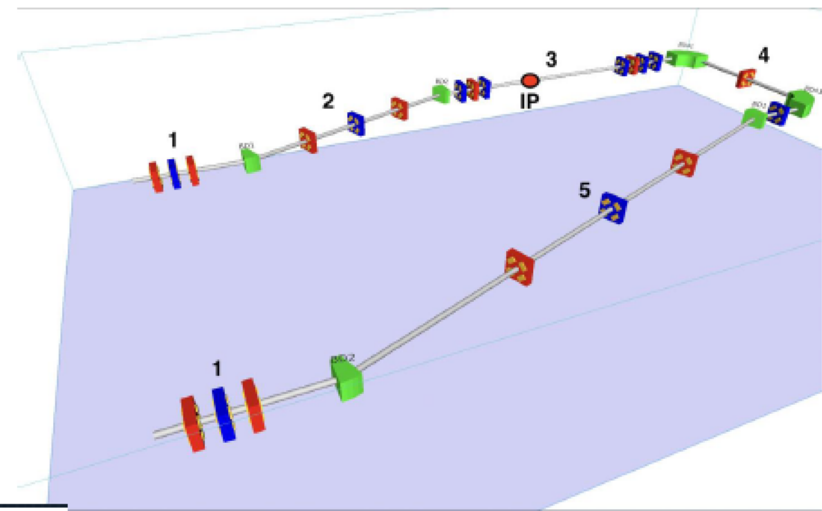


J. Dik, ESRF, ID17



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





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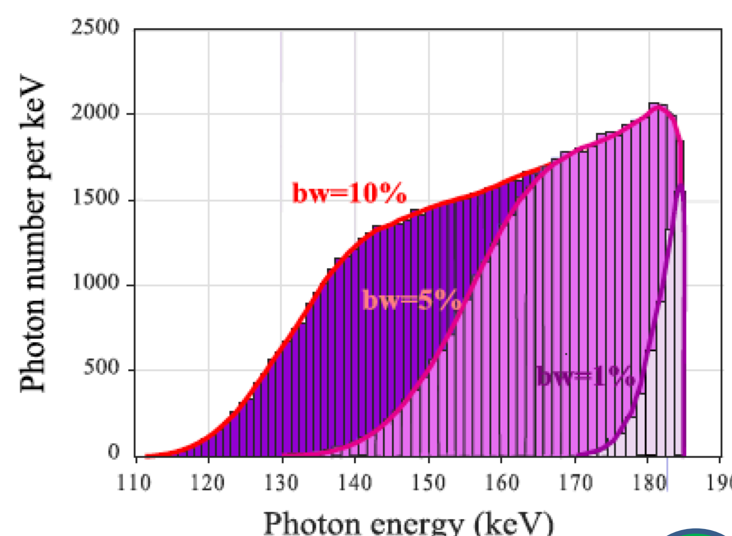
August 2018 Volume 52, Supplement 1, Page 74

[OA192] Kilovoltage rotational radiotheraphy with the marix/brixs source for partial breast irradiation

Giovanni Mettivier, Illya Drebot, Alberto Bacci, Vittoria Petrillo, M. Rosetti, Andrea Rossi, Luca Serafini, Riccardo Calandrino, Mauro Cattaneo, Claudio Fiorini, Roberta Castriconi, Antonio Sarno, Francesca Di Lillo, Marica Masi, Paolo Russo

DOI: https://doi.org/10.1016/j.ejmp.2018.06.264



IOP Publishing Phys. Med. Biol. 64 (2019) 185002 (17pp) https://doi.org/10.1088/1361-6560/ab325c

Physics in Medicine & Biology

IPEM Institute of Physics and Engineering in Medicine

UNIVERSITÀ DEGLI STUDI DI MILANO

PAPER

Inverse Compton radiation: a novel x-ray source for K-edge subtraction angiography?

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Keywords: inverse Compton, monochromatic x-ray source, K-edge subtraction, dual-energy, angiography

MariX-RAD CSN5-INFN (FE, MI, NA)
Resp. Naz. Paolo Cardarelli - Univ. di Ferrara and INFN-FE

9th International Particle Accelerator Conference IPAC2018, Vancouver, BC, Canada JACoW Publishing
ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMF057

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

I. Drebot*, D. Giannotti, L. Serafini, INFN, Milan, Italy
S. Cialdi, V. Petrillo, Universitá degli Studi di Milano & INFN, Milan, Italy
P. Cardarelli, M. Gambaccini, G. Paternó, A. Taibi, Universitá di Ferrara & INFN, Ferrara, Italy
R. Calandrino, A. Delvecchio, Ospedale San Raffaele, Milan, Italy
G. Galzerano, Politecnico di Milano, Milano, Italy

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 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 EOUATIONS

9th International Particle Accelerator Conference
ISBN: 978-3-95450-184-7

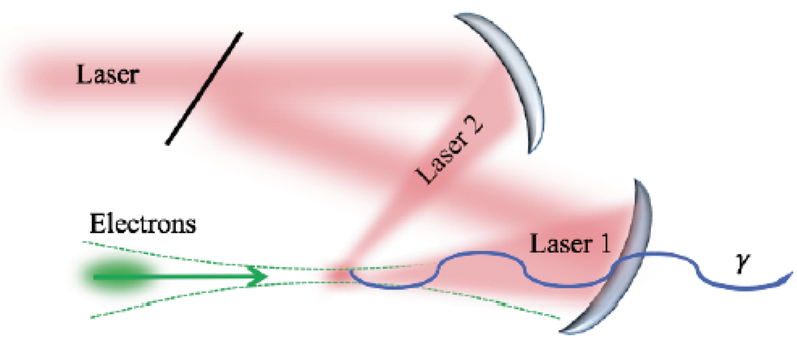

Figure 2: Scheme of the use of a split laser sent interaction point at two different interaction angle.

9th International Particle Accelerator Conference I
ISBN: 978-3-95450-184-7

the author(s), title of the work, publisher, and DOI.

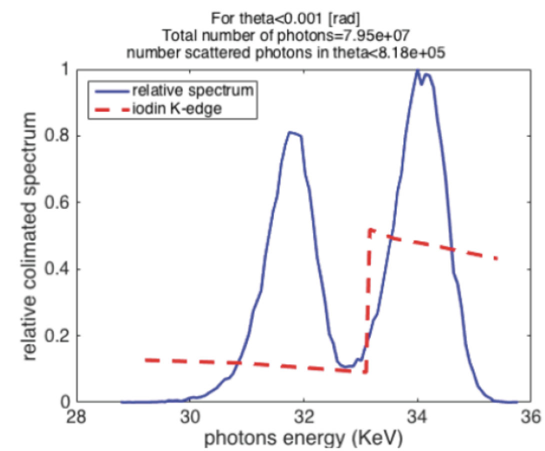

Figure 6: Relative spectrum of the scattered radiation for the $\alpha_{02} = 30$ deg.

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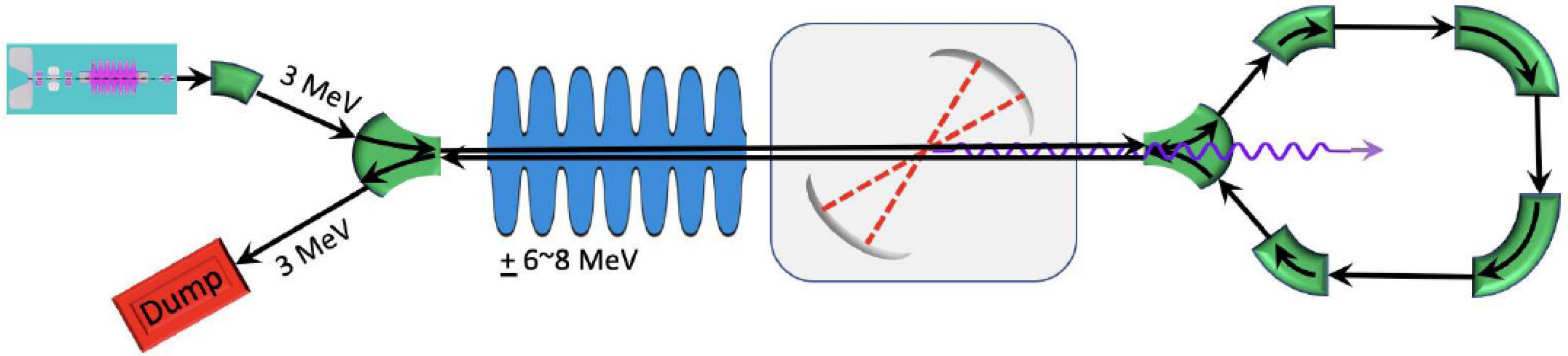
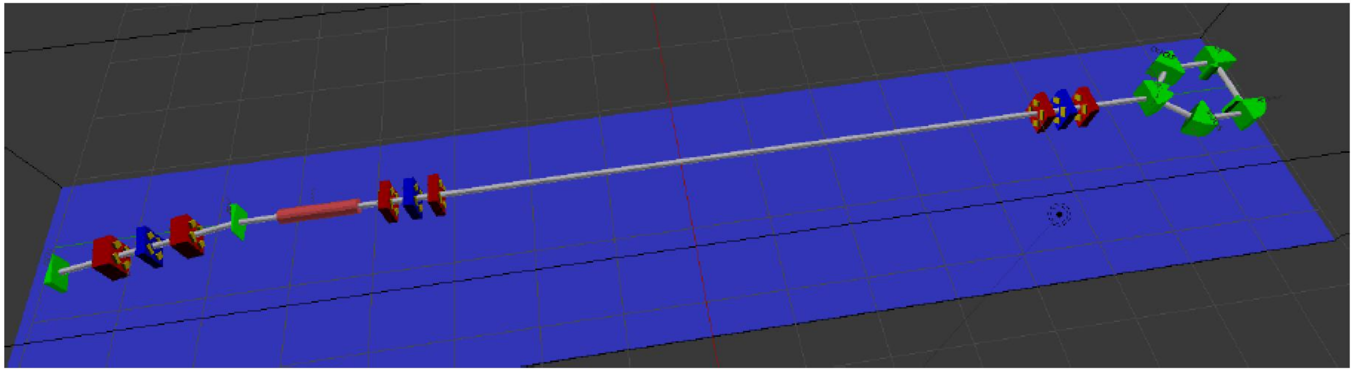
BriXSinO

20 mA, 100 MHz, 10 MeV
> 60% energy recovery



Proposed layout for the BriXSino minimal test-bench demonstrator of the modified push-pull folded ERL scheme, as conceived for BriXS.



≈ 6 M€, TDR preparation approved by INFN, due by Sept. 2020

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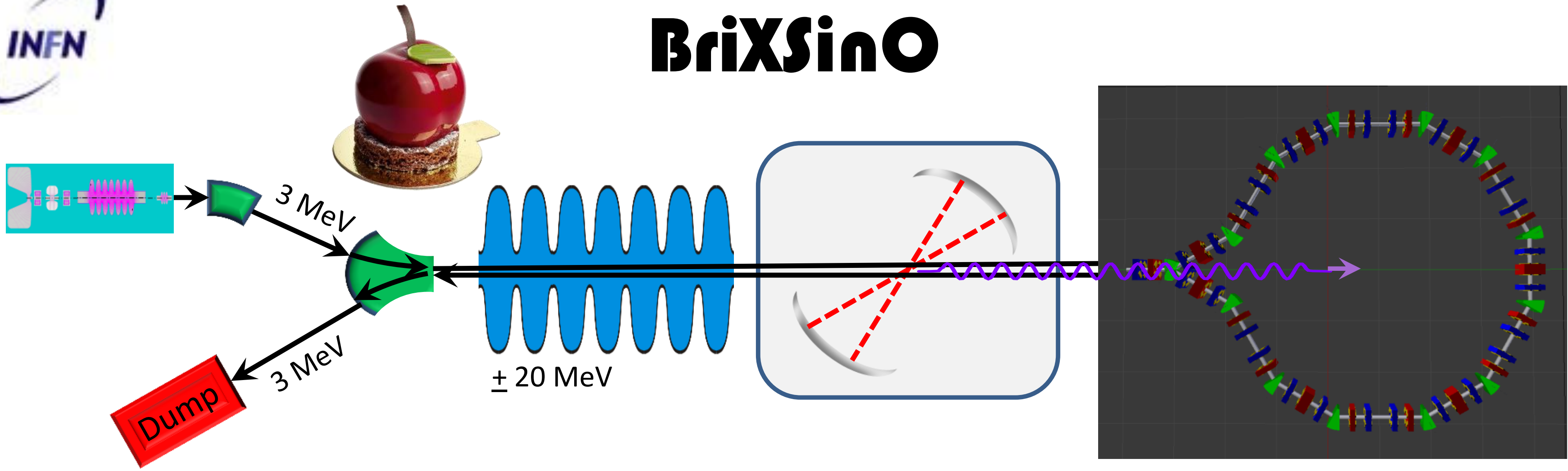
BriXSinO



Advantage of ARC in possibility be spitted and upgraded into two beam line scheme. In place of splitting dispersion is close.

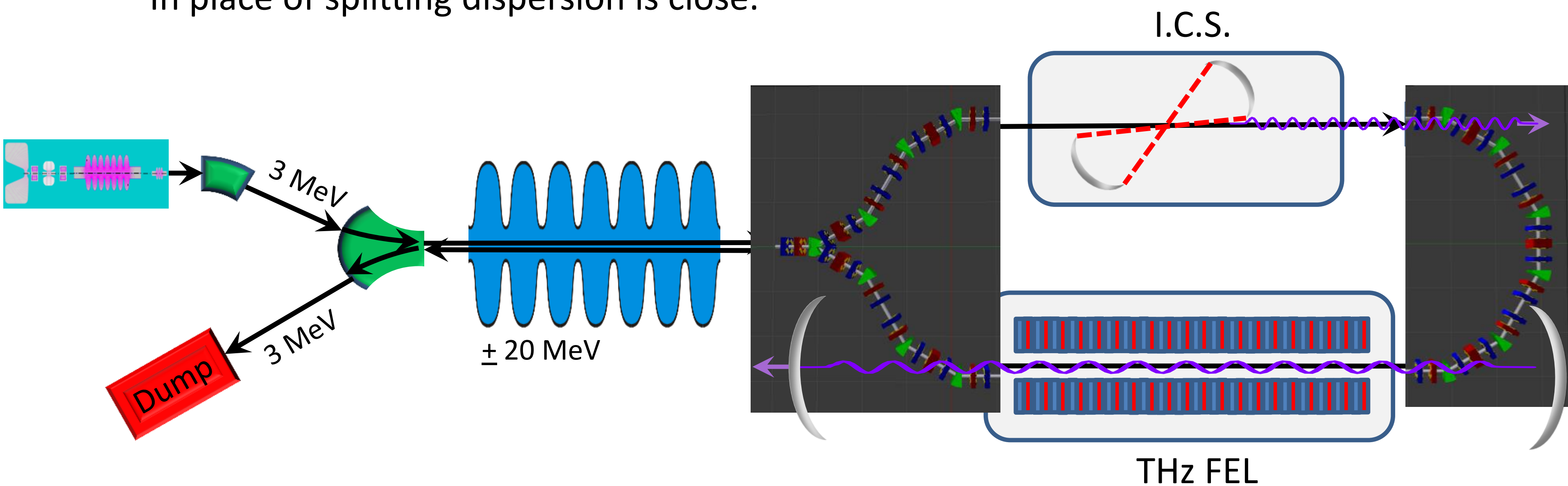


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Table 31.1: MariX Cost Table.

COMPONENT	COST (M€)
RF Power Sources (1.3 GHz) + RF Plumbing	24
Cryomodules (1.3 GHz)	79
Magnets + Power Supplies	34
Building + Infrastructure	88
Cryogenics	55
Photoinjector Guns + Power Supplies	4
3rd Harmonic cryomodules (3.9 GHz)	21
3rd Harmonic RF power source (3.9 GHz)	5.5
ICS Laser	3
ICS Fabry Perot Cavity	1.5
ICS Experimental Hall	5
Undulators	70
Accelerator Diagnostics	55
Beam Dumps	3
Accelerator Control System	55
Accelerator Radiation Safety	11
Accelerator Vacuum	32
FEL Photon Beam Shaping and Diagnostics	40
FEL End Stations	40
FEL Experimental Hall (Building and Infrastructure)	80
Contingency	69.8
TOTAL	**767.8**

MariX 2-Phases	(M€)
BriXS	82.5
MariX-FEL	685.3

cmp. LCLS-II > 1 G€
XFEL > 1 G€

	Operational Costs (M€/year)	Footprint (m^2)	(€/kwh)
MariX	45.5 (18 A/C)	35.000	0.234
LCLS	110		
XFEL	120		
SIRIUS	35	68.000	0.11

- **MariX/BriXS/BriXSino – the Italian way towards sustainable high power e^- (e^+) accelerators (*MW and multi-MW class*)**
- **A new genetic line in accelerator zoology (2-way 2-pass)**
- **Both are strategic motivations for INFN (BriXSino aims at filling an Italian void in this field)**
- **Why Milano: unique overlap among expertise in accelerator & laser physics and technology, like High Brightness Beams/FEL/ICS Physics - SC/RF technology - High QE photocathodes - High Power Optical FP cavities, and a qualified User Community in Synchro-tron Light and FELs, with the endorsement in MariX-CDR and BriXS-EoI from IRCCS San Raffaele, Niguarda, Istituto Nazionale dei Tumori**

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