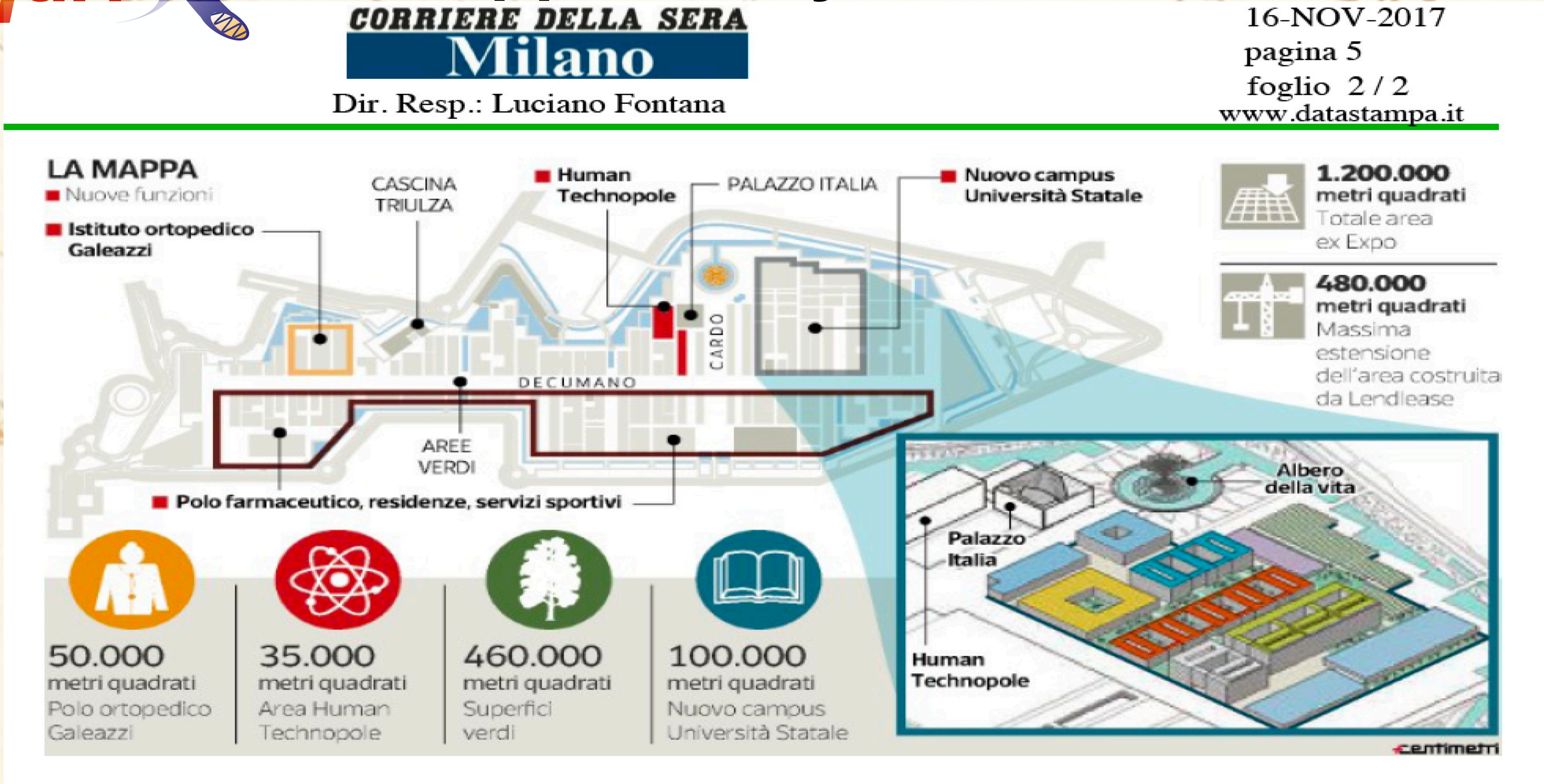
MariX: a Multi-disciplinary Advanced Research Infrastructure for the generation and application of X-rays

Andrea R. Rossi
INFN - Milan
on behalf of the MariX collaboration

Advanced Accelerator Workshop 2019, La Biodola (Italy), September 15th - 21st 2019

The opportunity

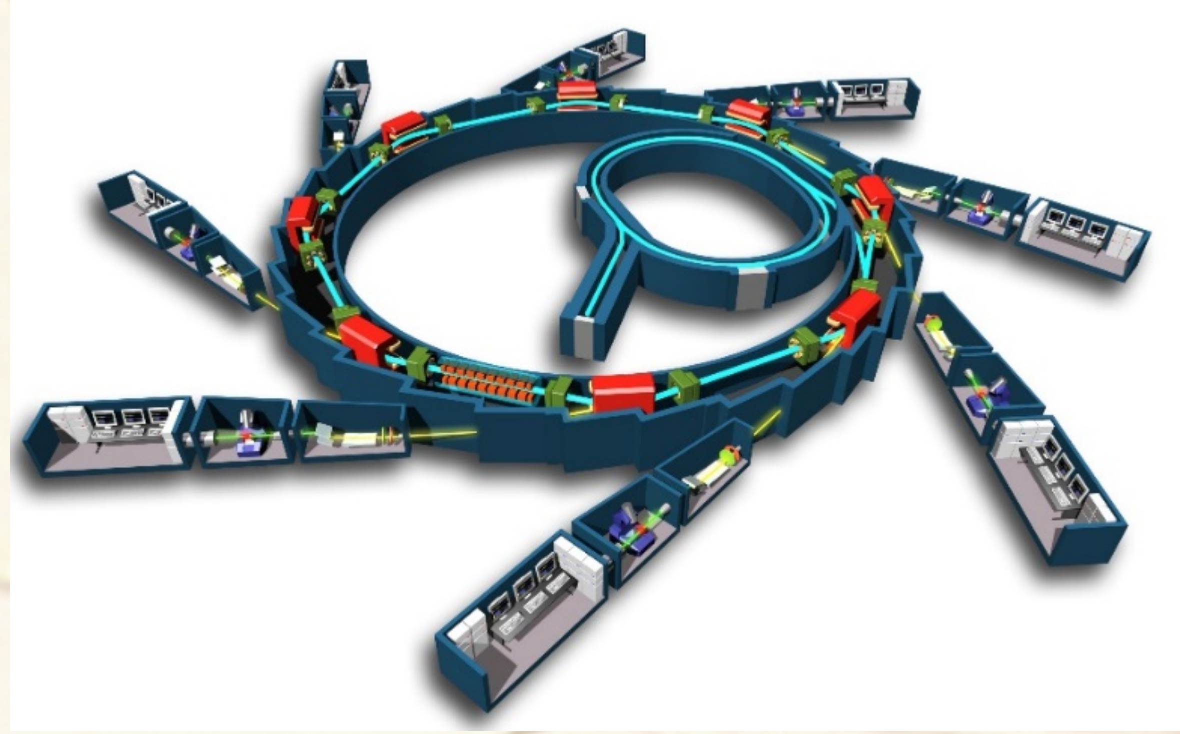


The Innovation Park Project

A rendering of the possible look for Expo area after transformation

Il parco della scienza del sapere e dell'innovazione

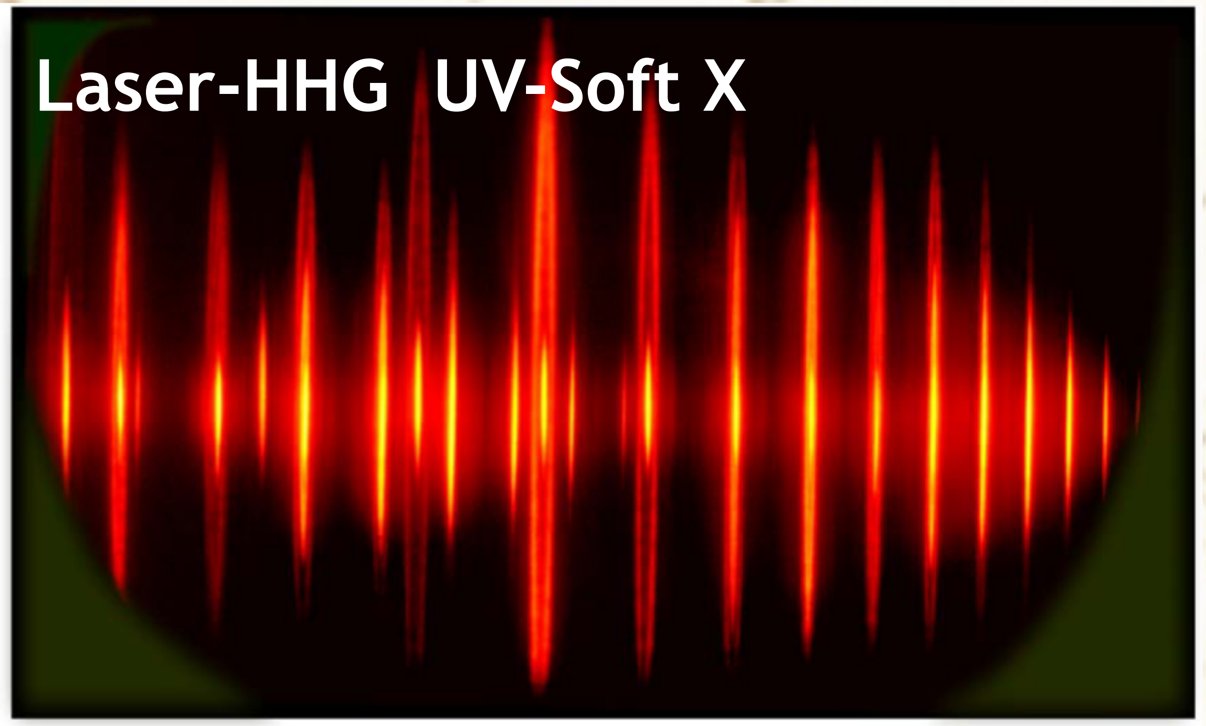
The Goal



Synchrotron Radiation sources

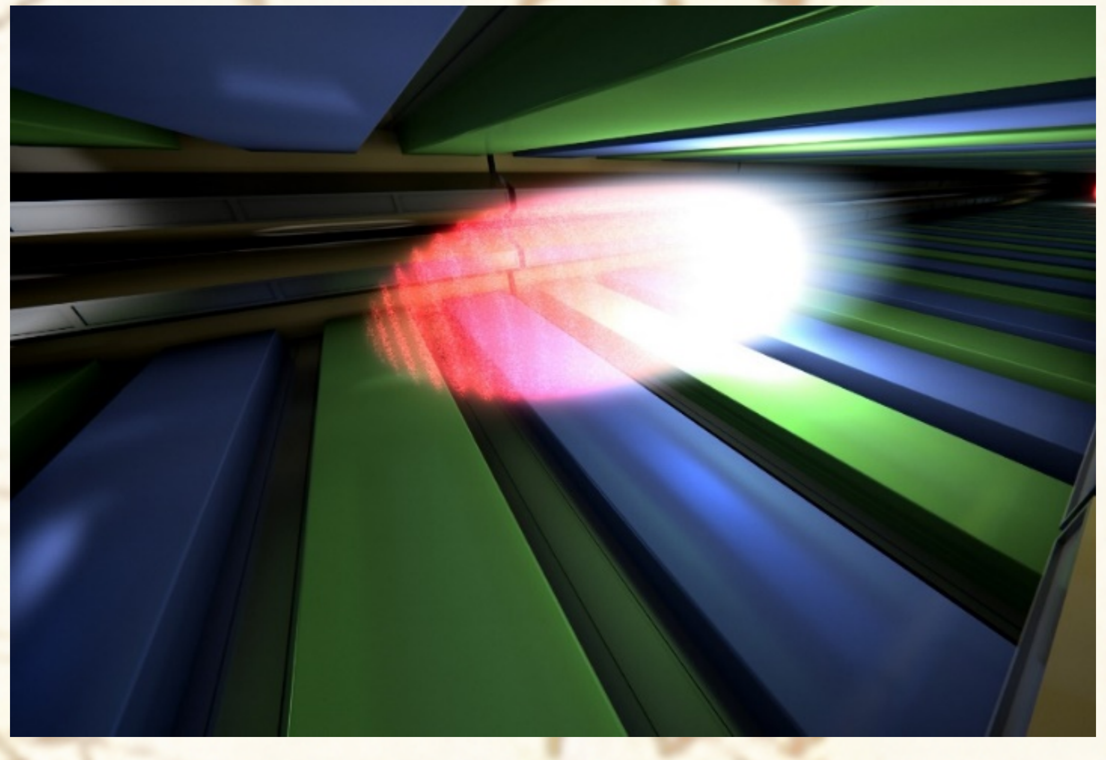
500 MHz repetition
nJ pulse energy; ≈50ps
10^{5-6} photons x (5)x10^{8}pulses

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



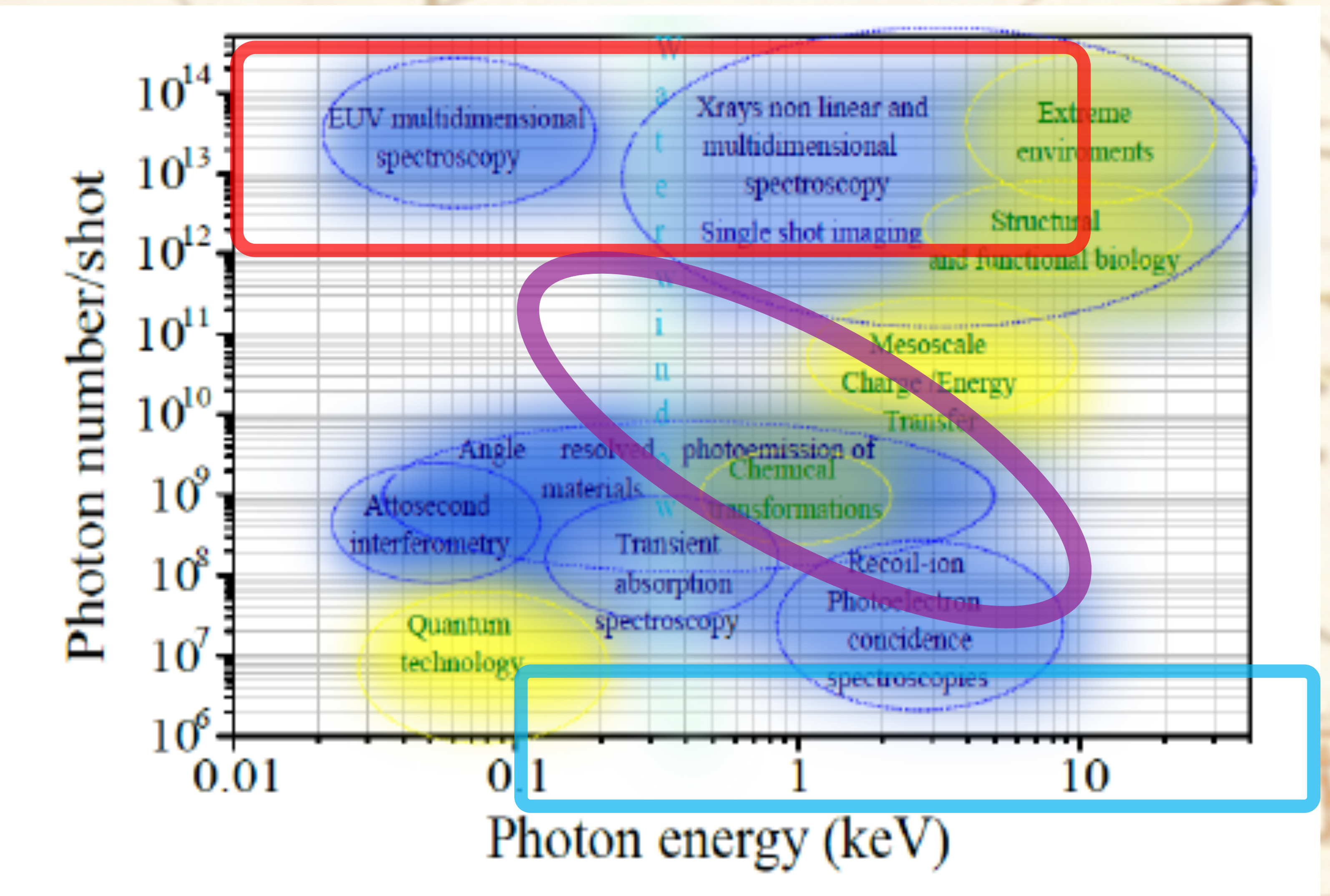
Free Electron Laser sources

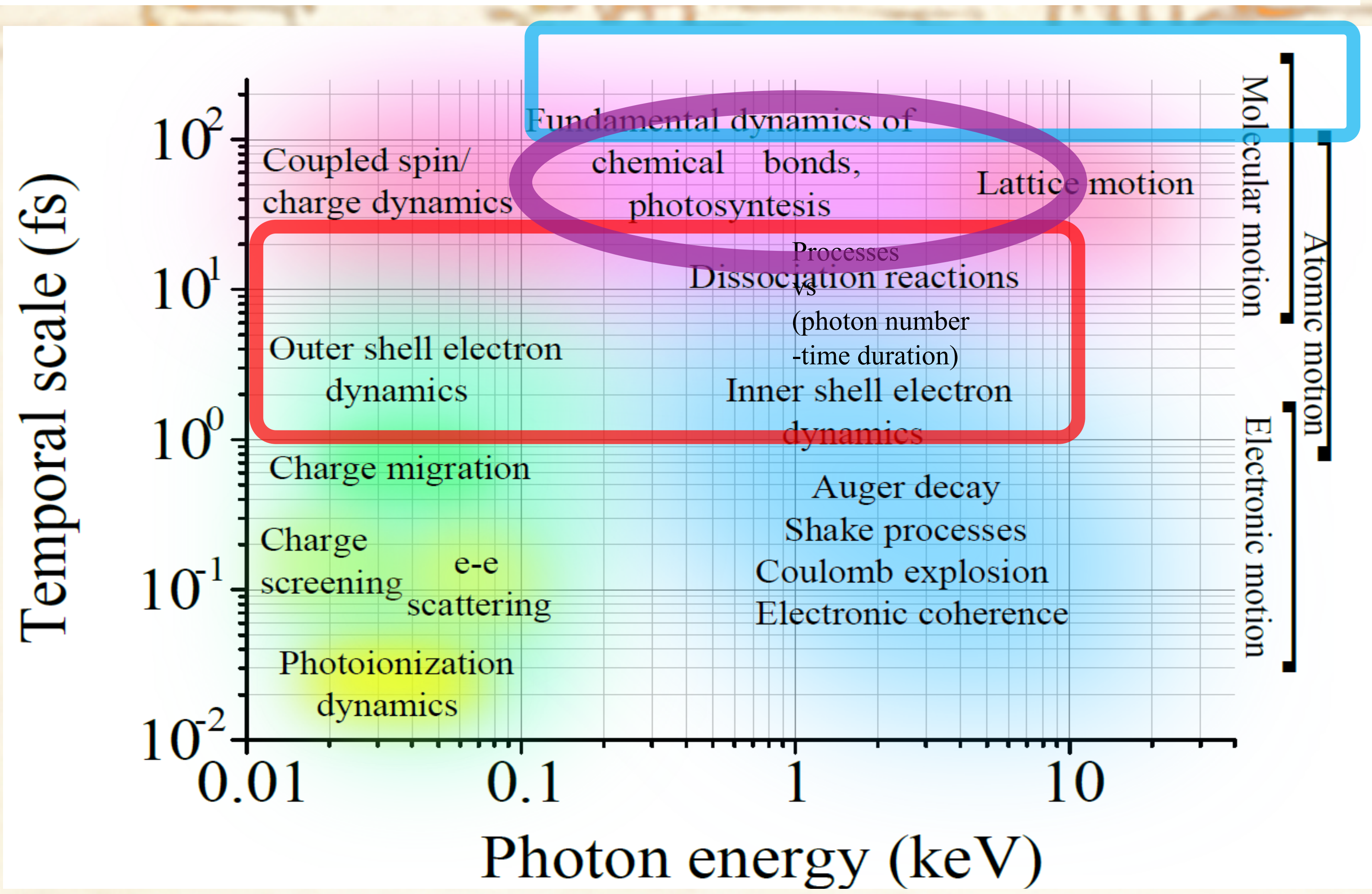
10Hz-27kHz repetition
mJ pulse energy; ≈50fs
10^{12-13} photons x
$10^{1-3-(6)}$pulses

Ultrafast Non-linear response regime
Imaging, flash+destroy

Courtesy Giorgio Rossi – Chair ESFRI

Research areas: photon number, energy and time





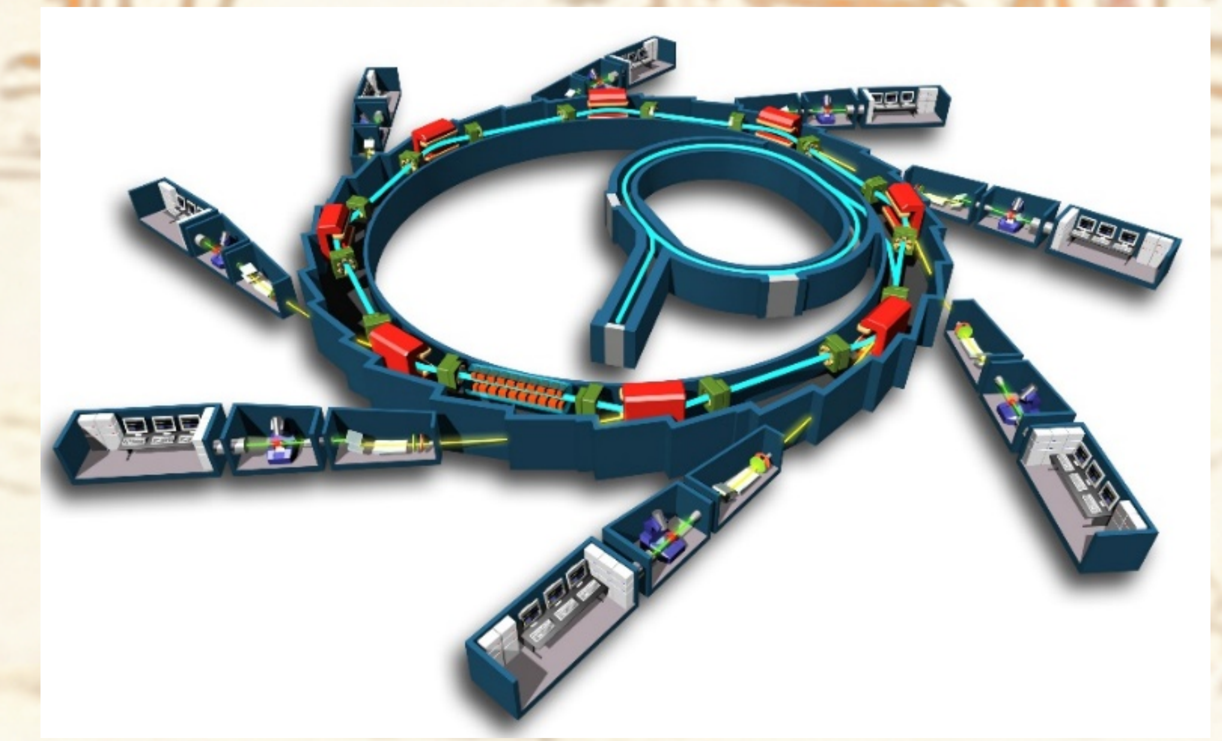
Research areas (yellow) and techniques (blue) mapped onto (photon energy- photon number)

Fine analysis of matter at/under the nanometer scale relies on X-rays produced by

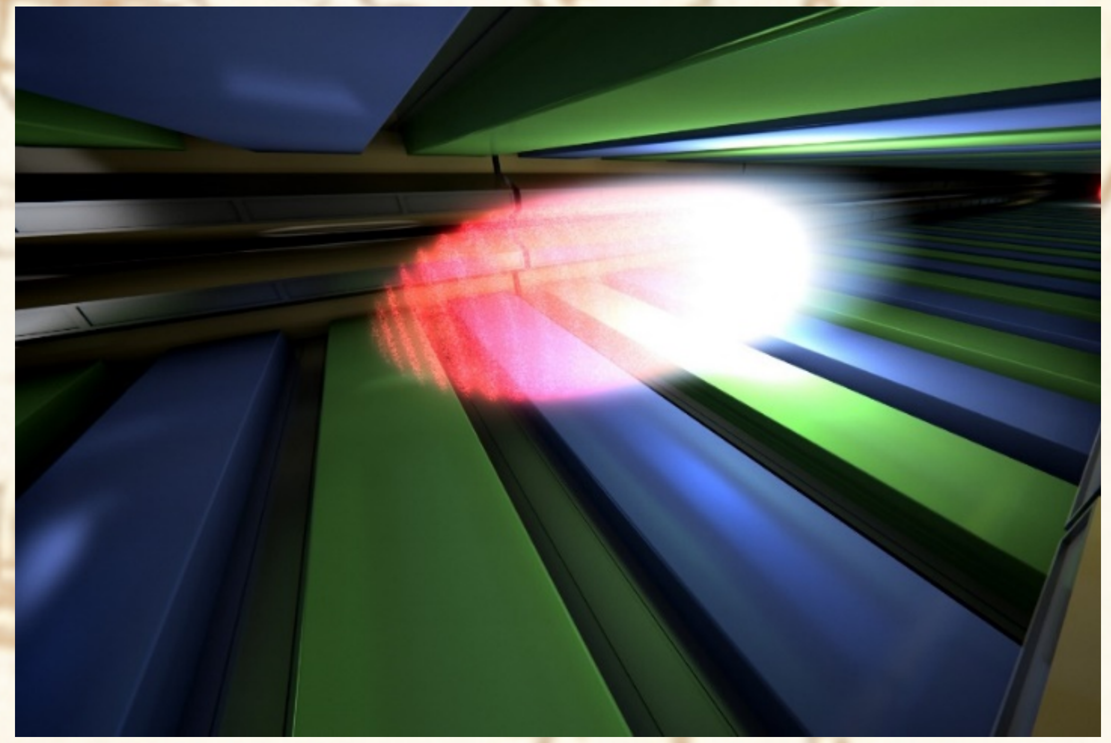
Synchrotrons or FELs

MARIX+FEL (10 keV)

Linear spectroscopy
There is the need of a source:
Low cost, contained dimension
Reaching 8 keV
Low flux/shot: 10^7-10^9 ph per shot
Large rep rate: up to 1 MHz
Possibly large coherence degree.

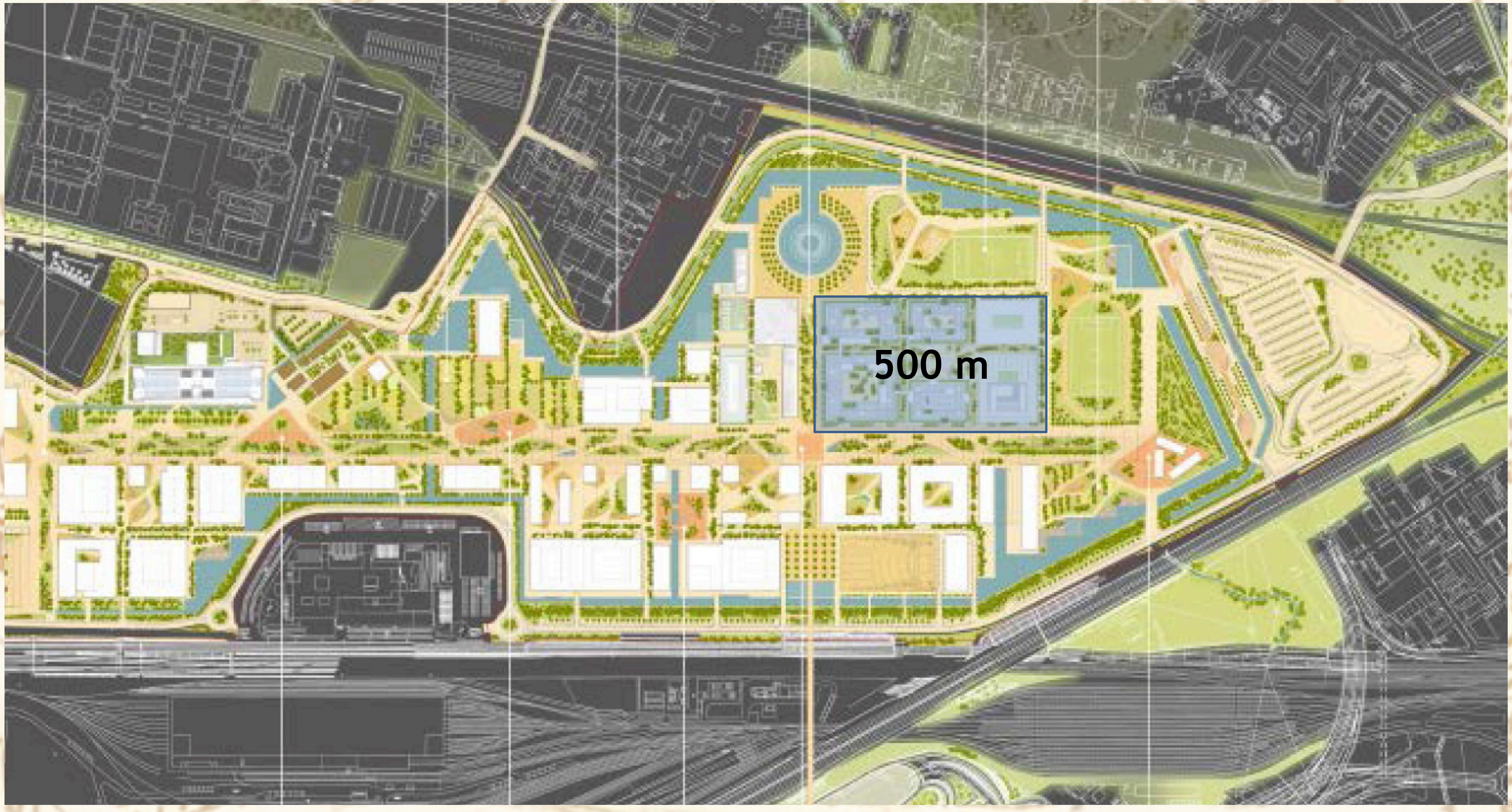


Synchrotron Radiation sources



Free Electron Laser sources

Real estates do matter!



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

Length budget for MariX

3.8 GeV electron energy to FEL-radiate at 8 keV (1.5 Angstrom) with 1.2 cm undulator period

Super-conducting RF Cavities at TESLA frequency (1.3 GHz) can safely operate up to 17 MV/m accelerating gradient in CW (continuous wave) mode (to be compared with 25 MV/m of XFEL in pulsed mode)

This means 3.8 / 0.017 = 224 m active RF Cavity length. Typical filling factor of SC Linacs is 0.5, implying toal effective legnth of about 450 m just for the main SC Linac. Let's add room for:

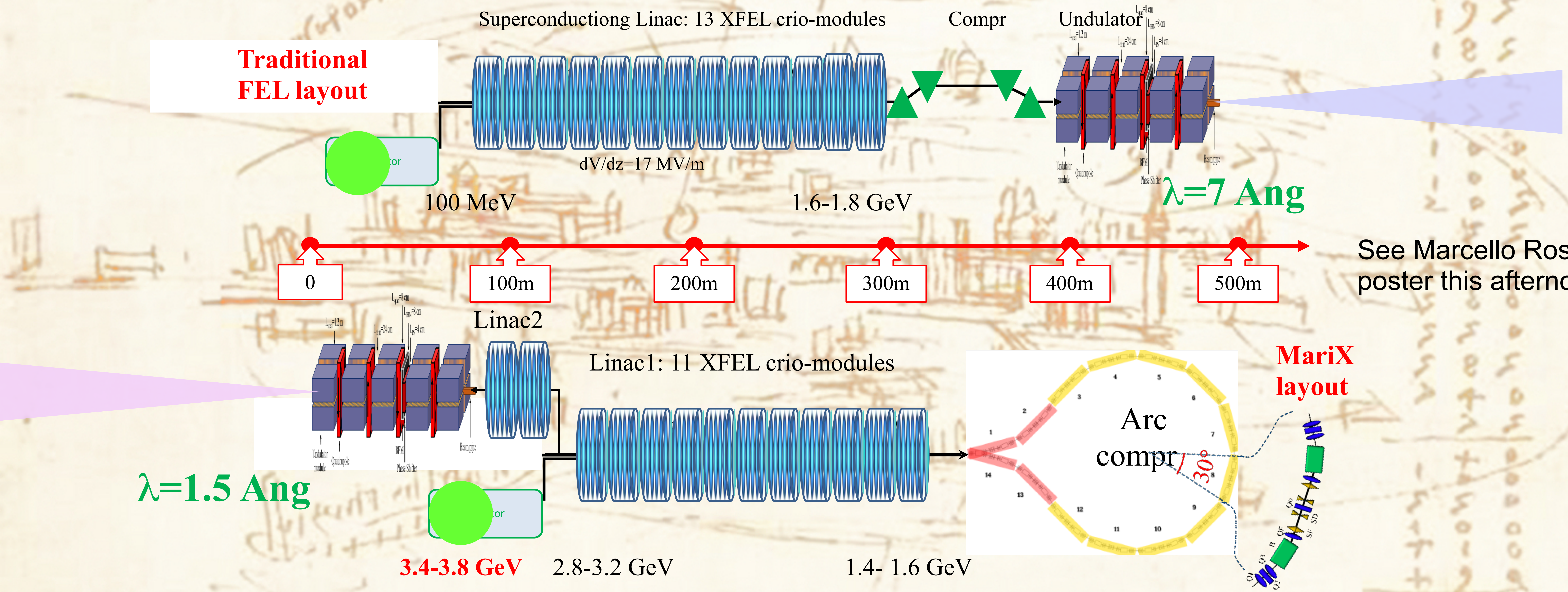
- injectors (30 m)
- transfer lines (20 m)
- magnetic compressors (50 m)
- matching line (20 m)
- undulator (80 m)
- photon beam lines (100 m)…

… it rounds up to about 800 m.
As a matter of fact LCLS-II is a km long.

How can we fit the whole FEL source into a 500 m long Campus available footprint ??

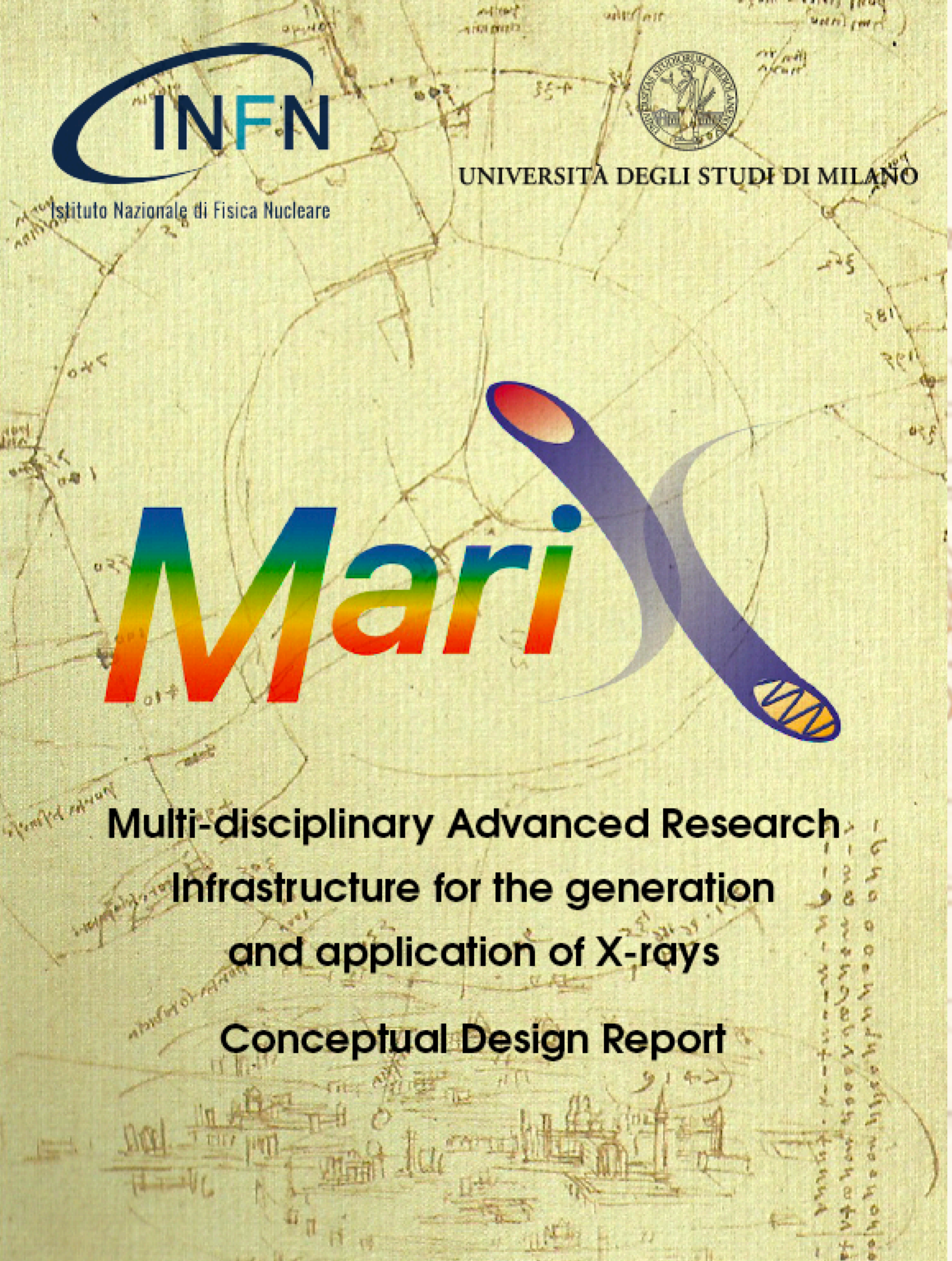
The Solution!

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



See Marcello Rossetti Conti poster this afternoon

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



After 1 year of hard work…

…CDR has been published and available for download at

www.marix.eu

together with all other documents published so far.

Executive summary has been published on NIM A

International team of 93 scientists from 23 different institutions

Nuclear Inst. and Methods in Physics Research, A 930 (2019) 167–172

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

MariX

ELSEVIER

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

Check for updates

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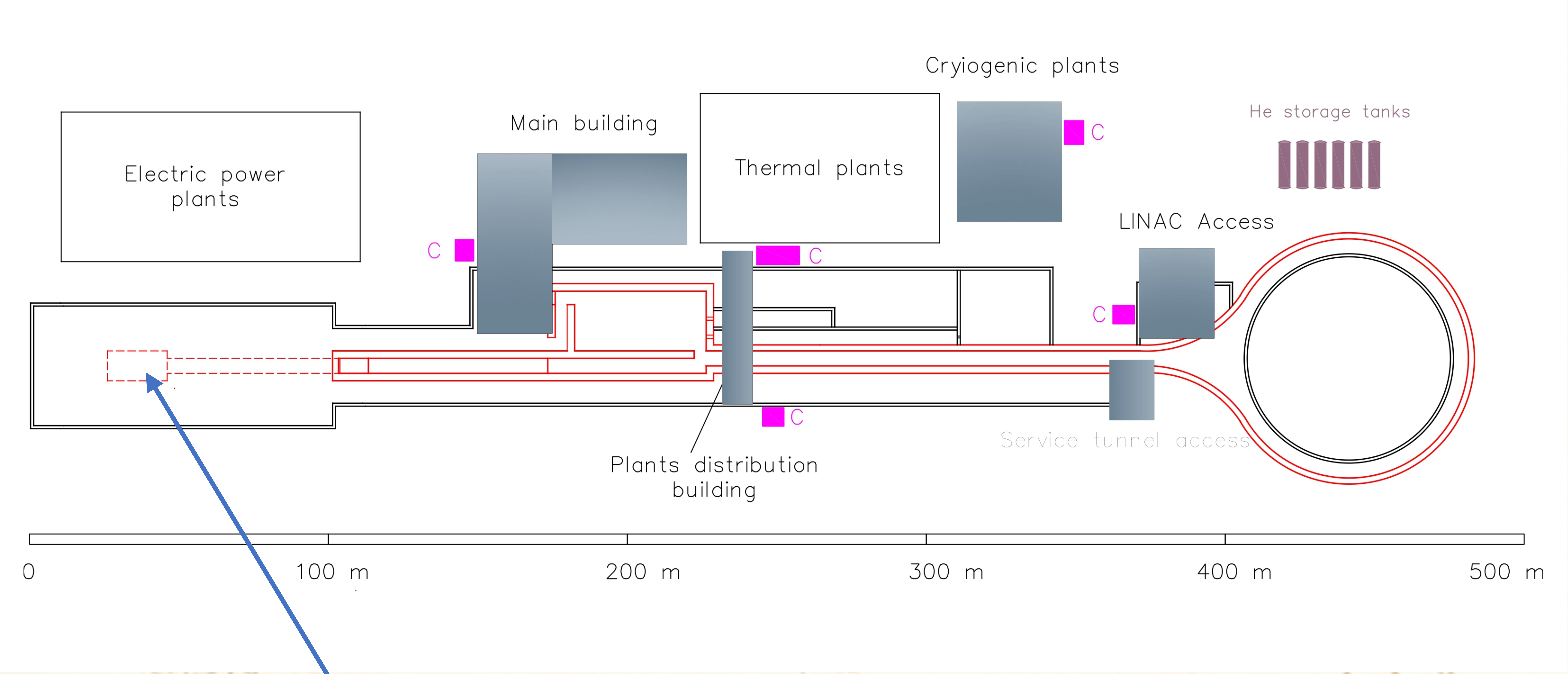
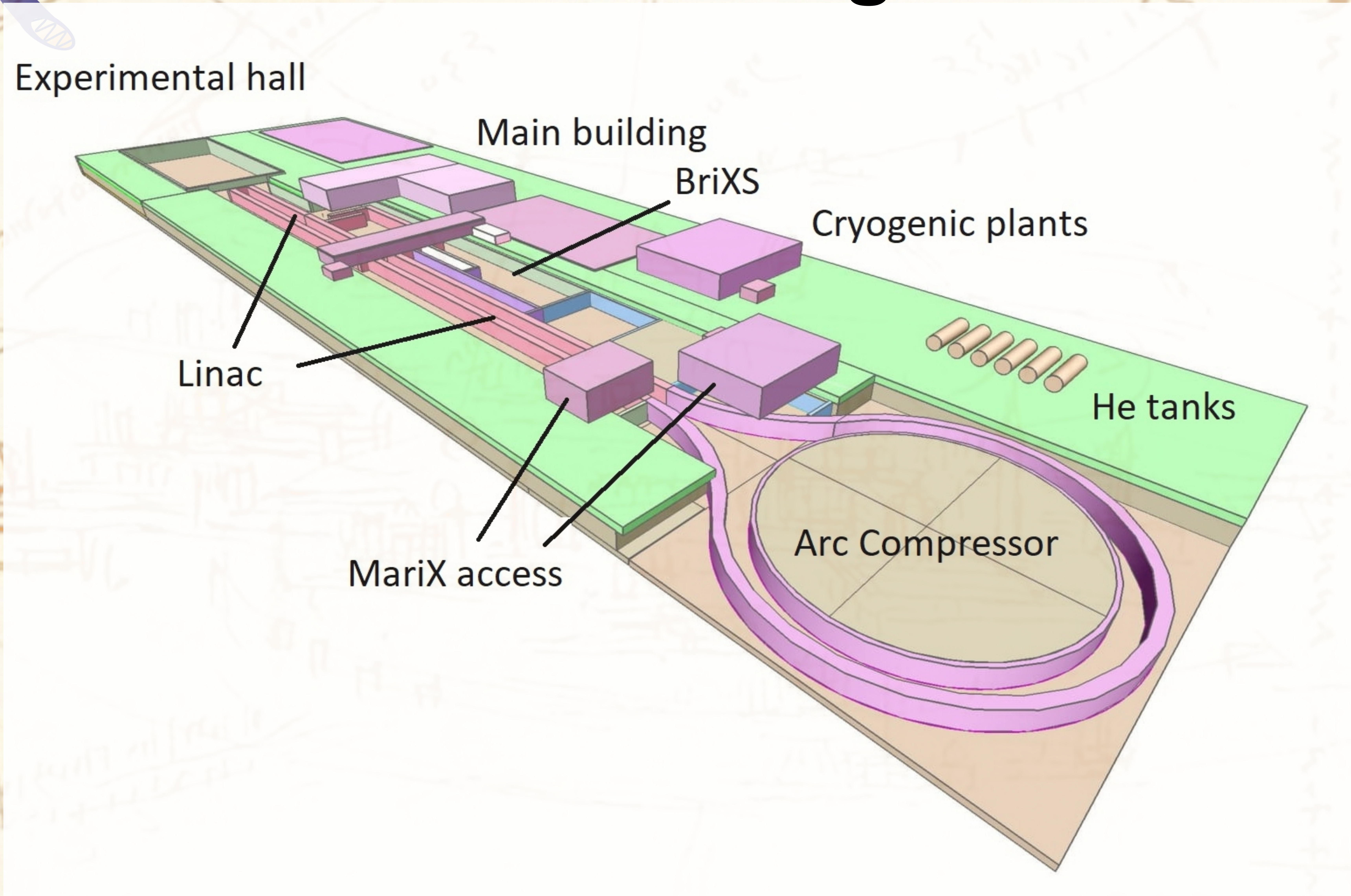
Final conceptual layout…



200 kW underground beam dump @ 3.8 GeV

…and 3D rendering



Considerations about FEL

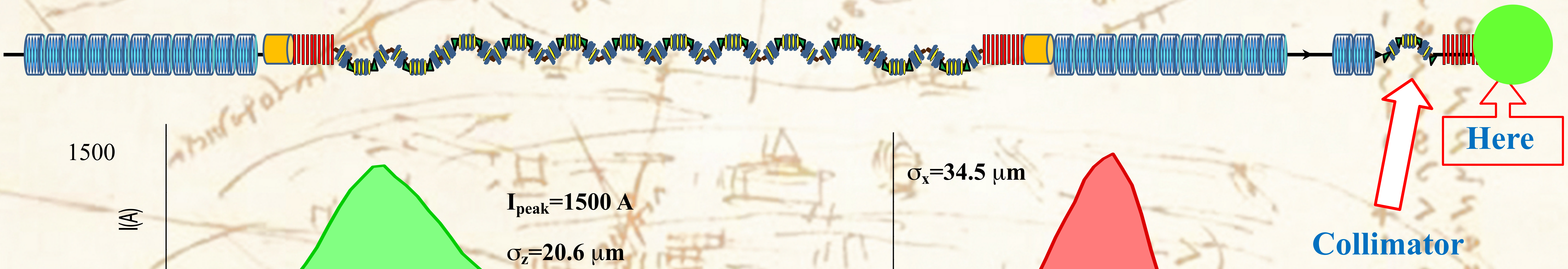
Beam parameters requirements

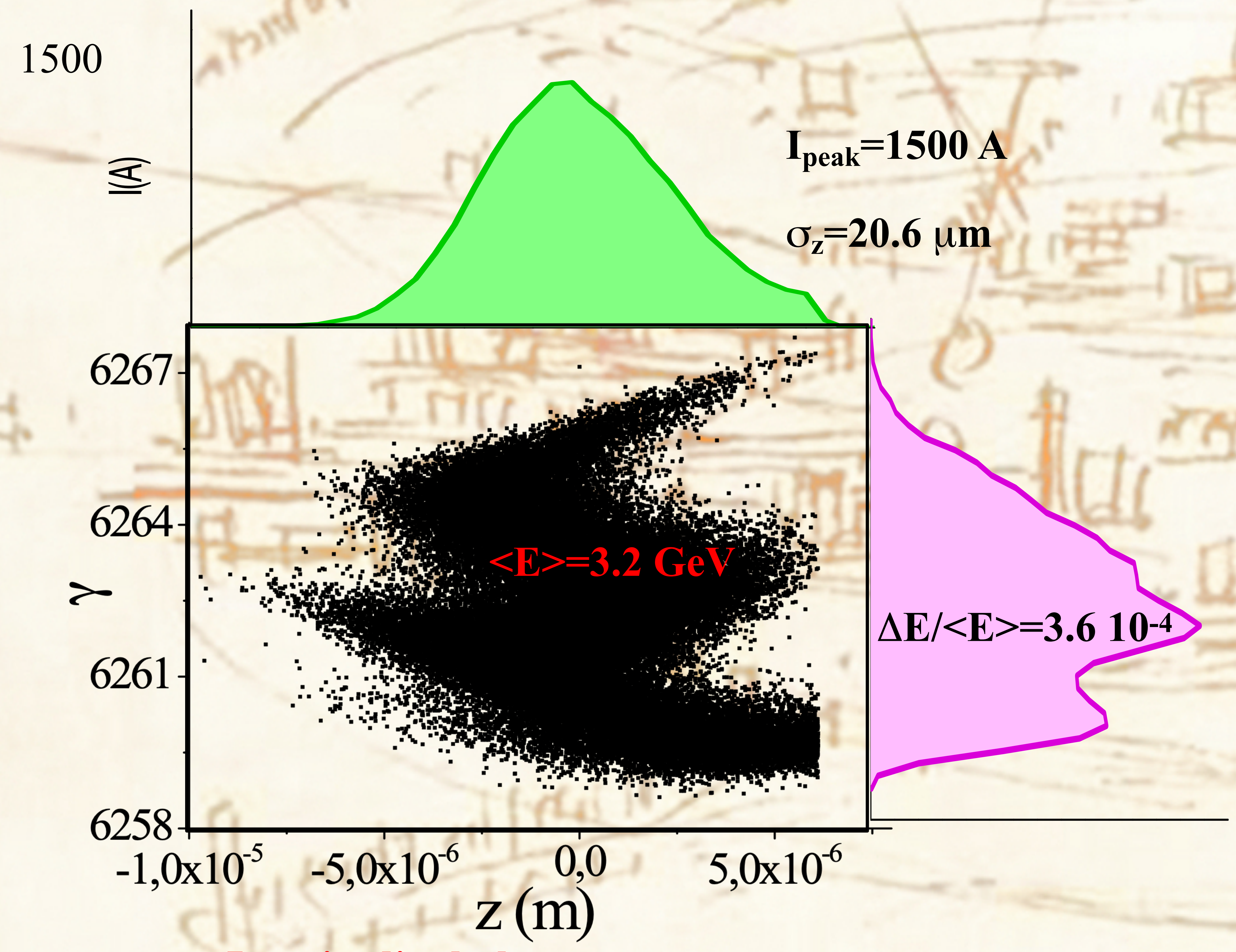
Energy (GeV)	1.8 - 3.8
Bunch charge (pC)	8 - 50
Bunch length (fs)	< 20
$\varepsilon_{x,y}$ (slice) (mm mrad)	0.5
Bunch Energy spread (slice) (%)	0.045 - 0.024
Bunch peak current (kA)	1.6
Bunch separation (μs)	> 1
Energy jitter shot-to-shot (%)	0.1
Time arrival jitter (fs)	< 50
Pointing jitter (μm)	5

Beam parameters requirements

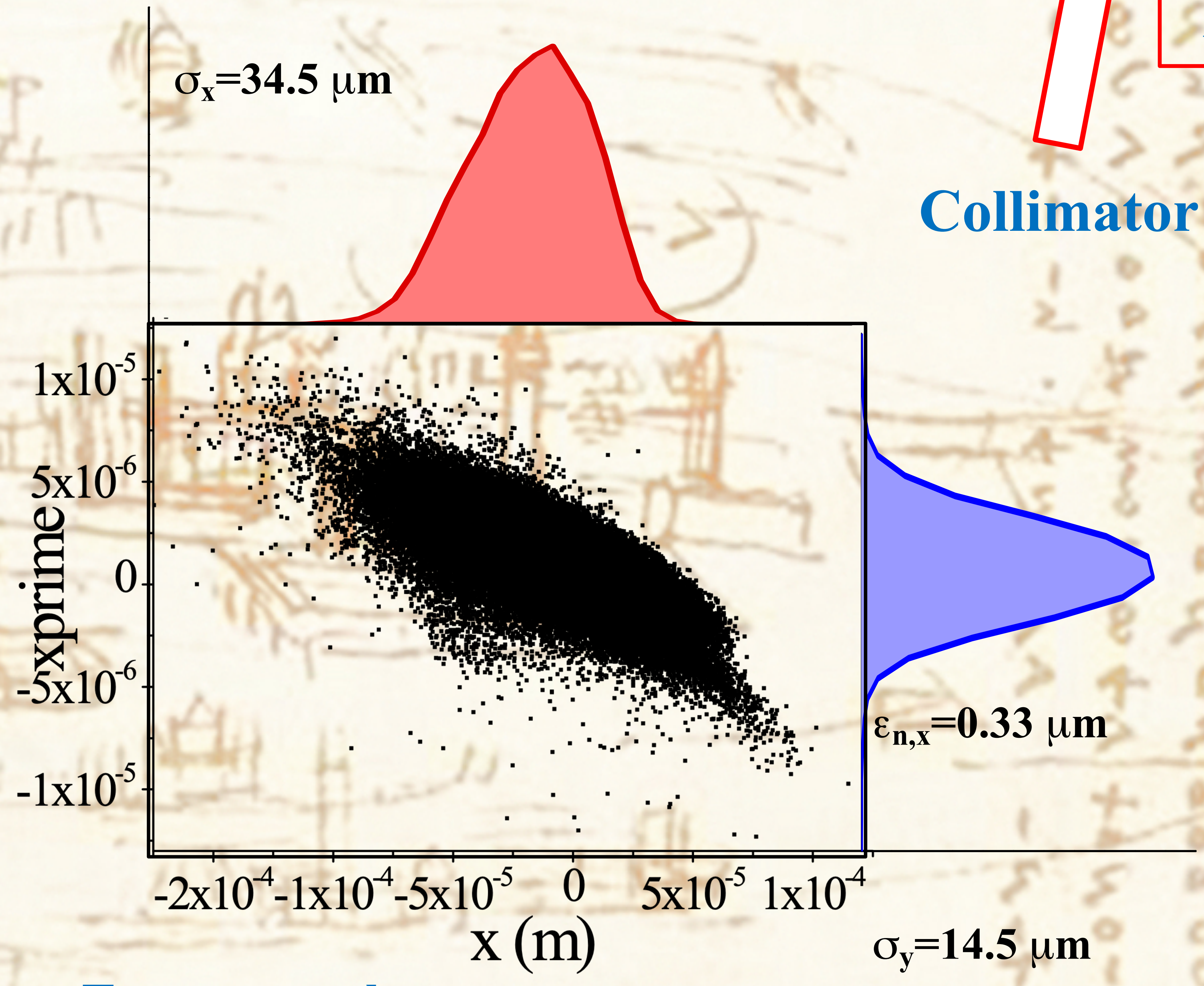
1) To achieve continuous tunability from 100 eV to 8 KeV we need two undulators
2) All components must operate up to 1 MHz repetition rate
3) Max 50 pC bunch charge - beam dump constraints at 3.8 GeV (50 microampere, about 200 kW average beam power)
4) Beam optics in two-way section at arc-entrance-exit must operate in both directions - second order optics adopted (RF-solenoid, no quads!)
5) Lengths have been chosen to avoid collisions between bunches (1 MHz – 1 microsec – 300 m bunch separation)

DB results: 30 pC bunch





Longitudinal phase space



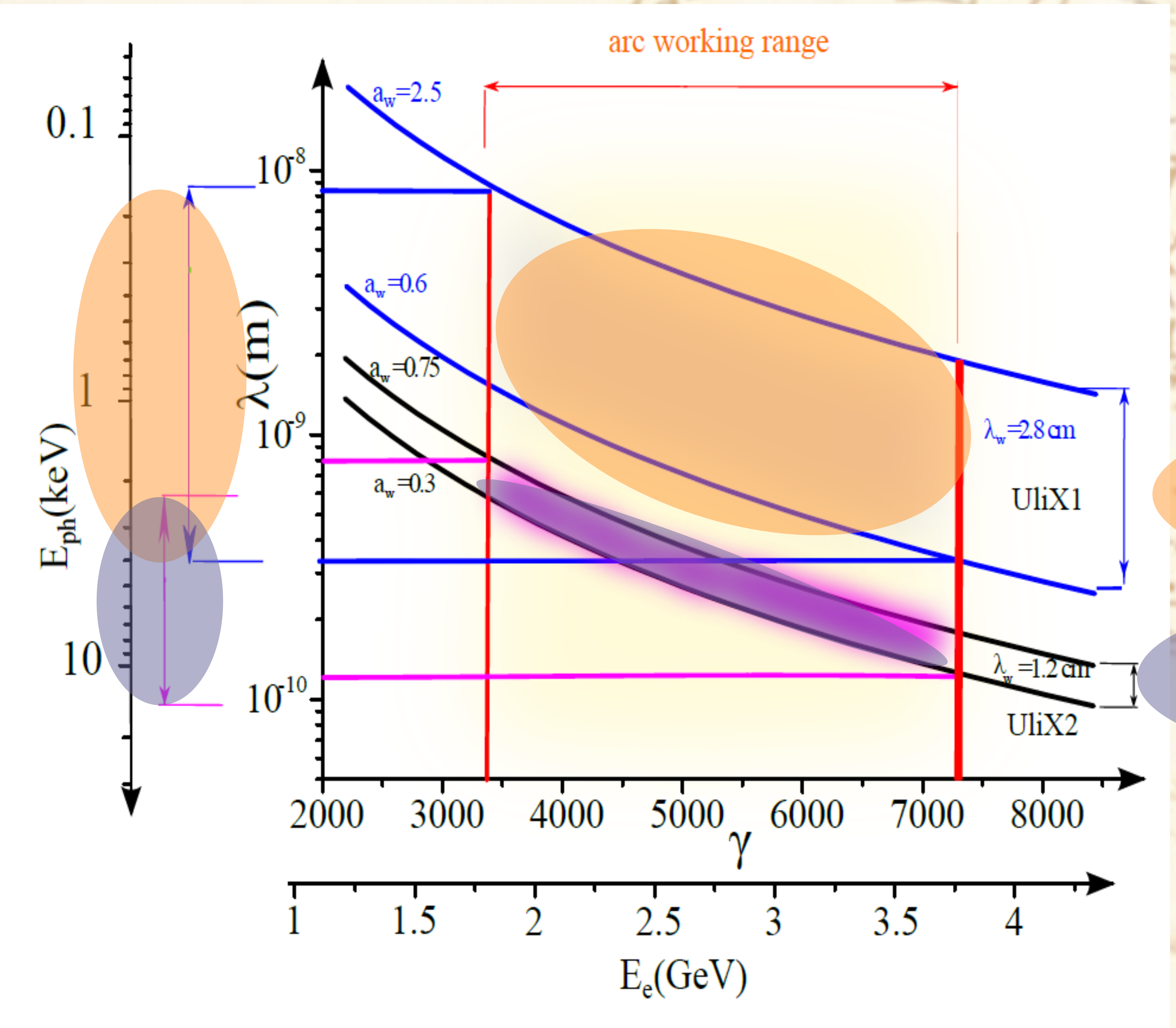
Transverse phase space

σ_y=14.5 μm

$\varepsilon_{n,y}$=0.2 μm

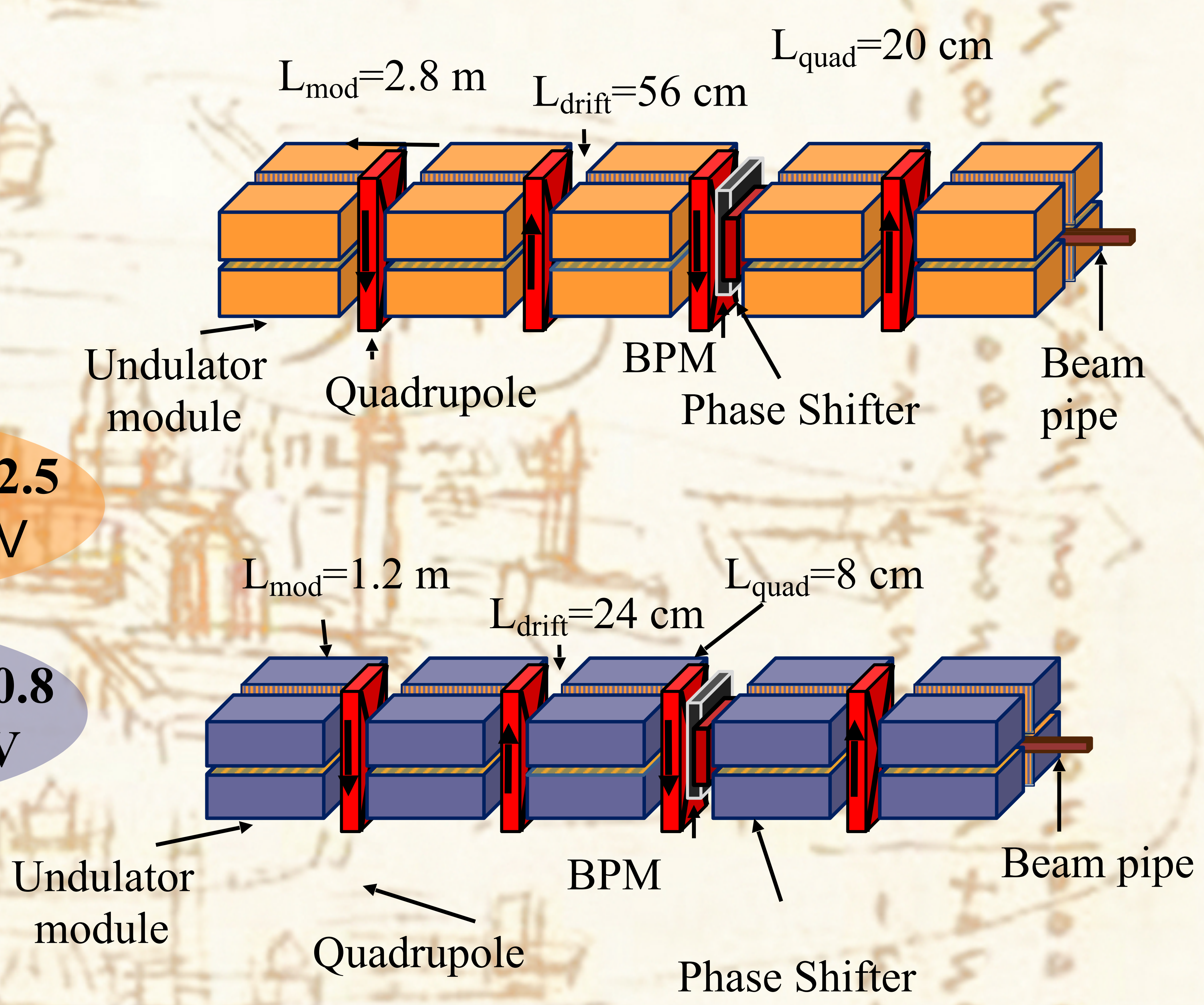
Further considerations on FEL

For emitting with continuity from 100 eV to 8 KeV:



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

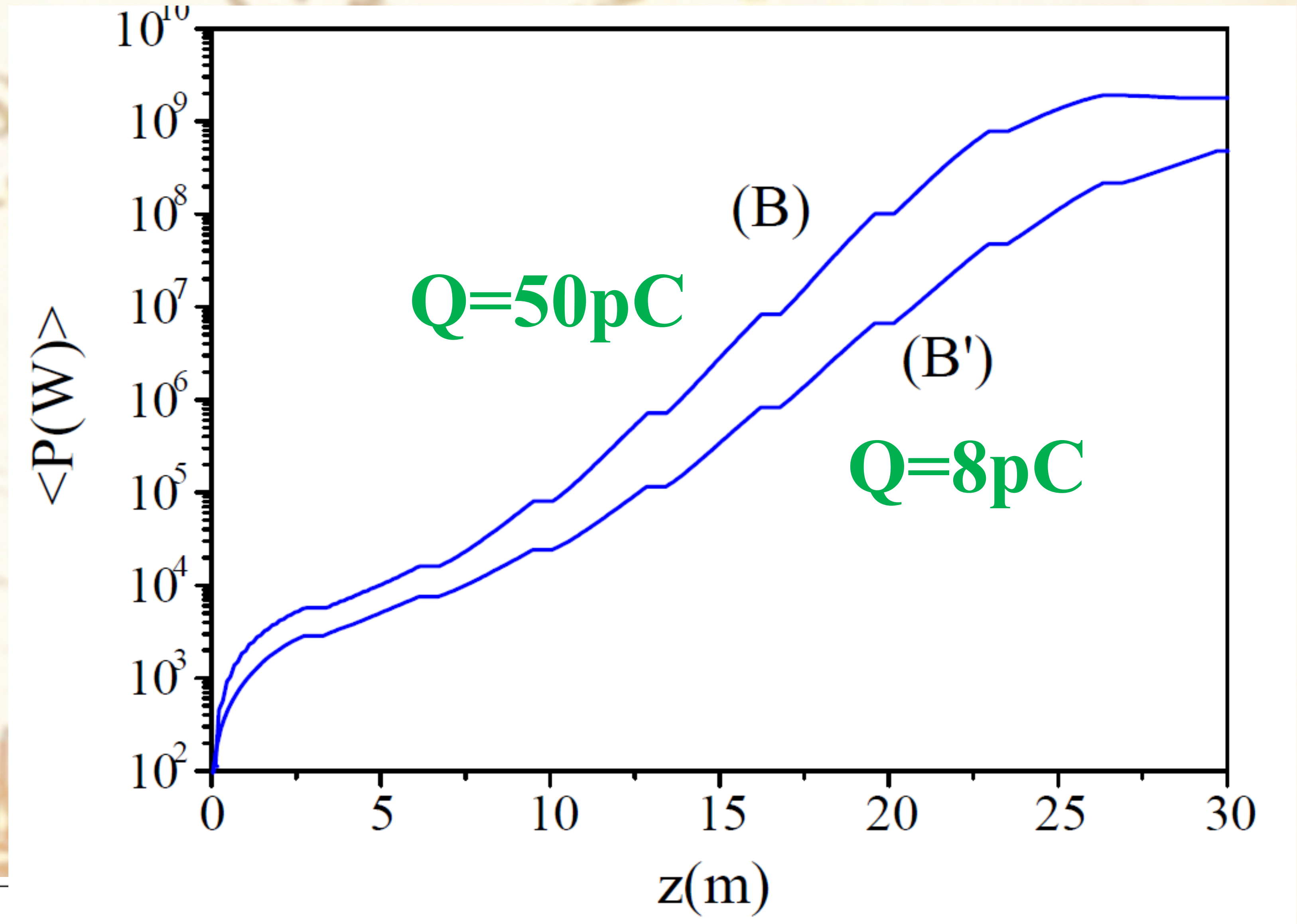


SASE 1: water window 2.77 nm

	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

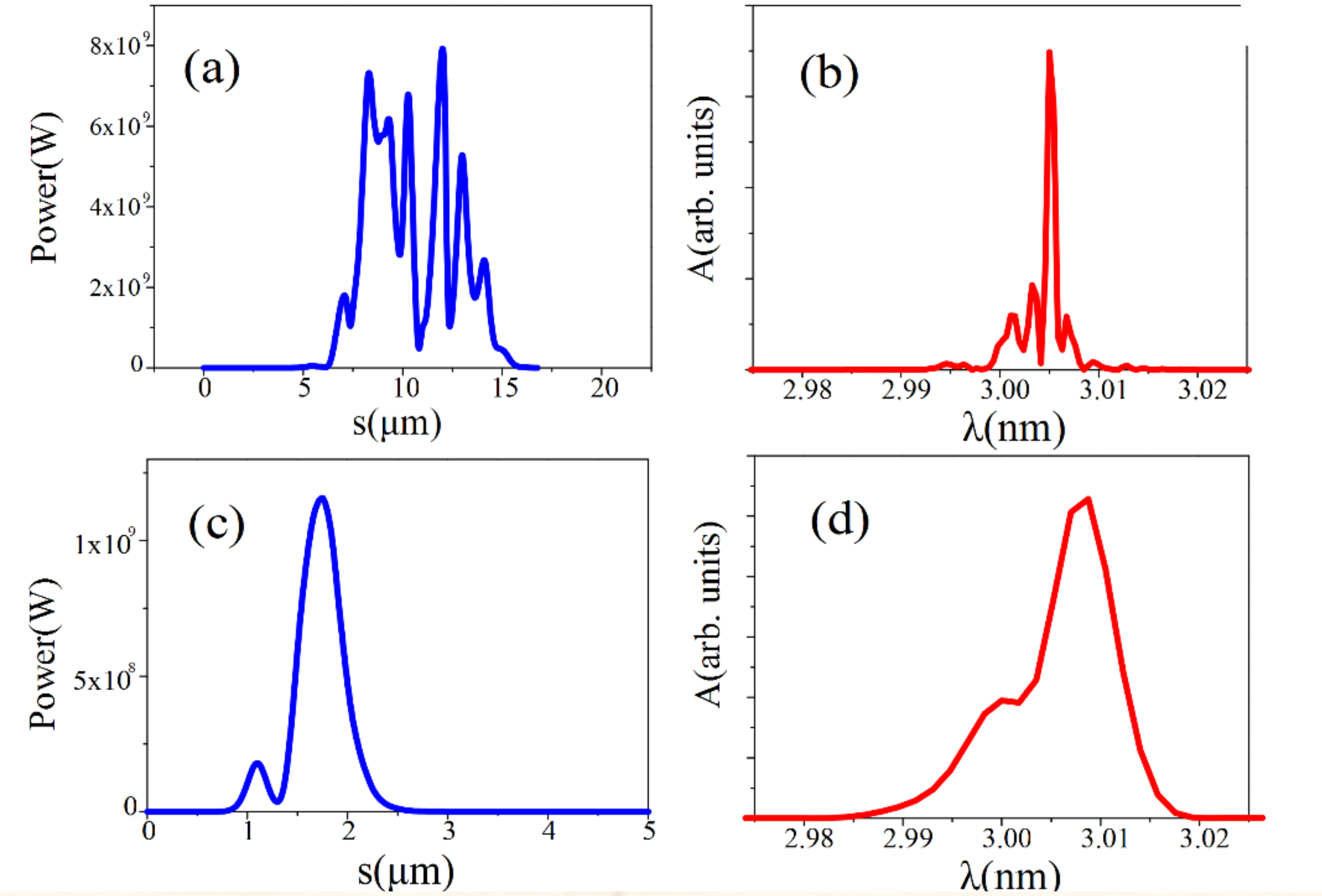
UliX1: 2.8 cm

a_w=2.5



Power
30 m

Spectrum
30 m



Q=50 pC
SASE

Q=16 pC
Single Spike

SASE 2: linear spectroscopy 4.17 Å

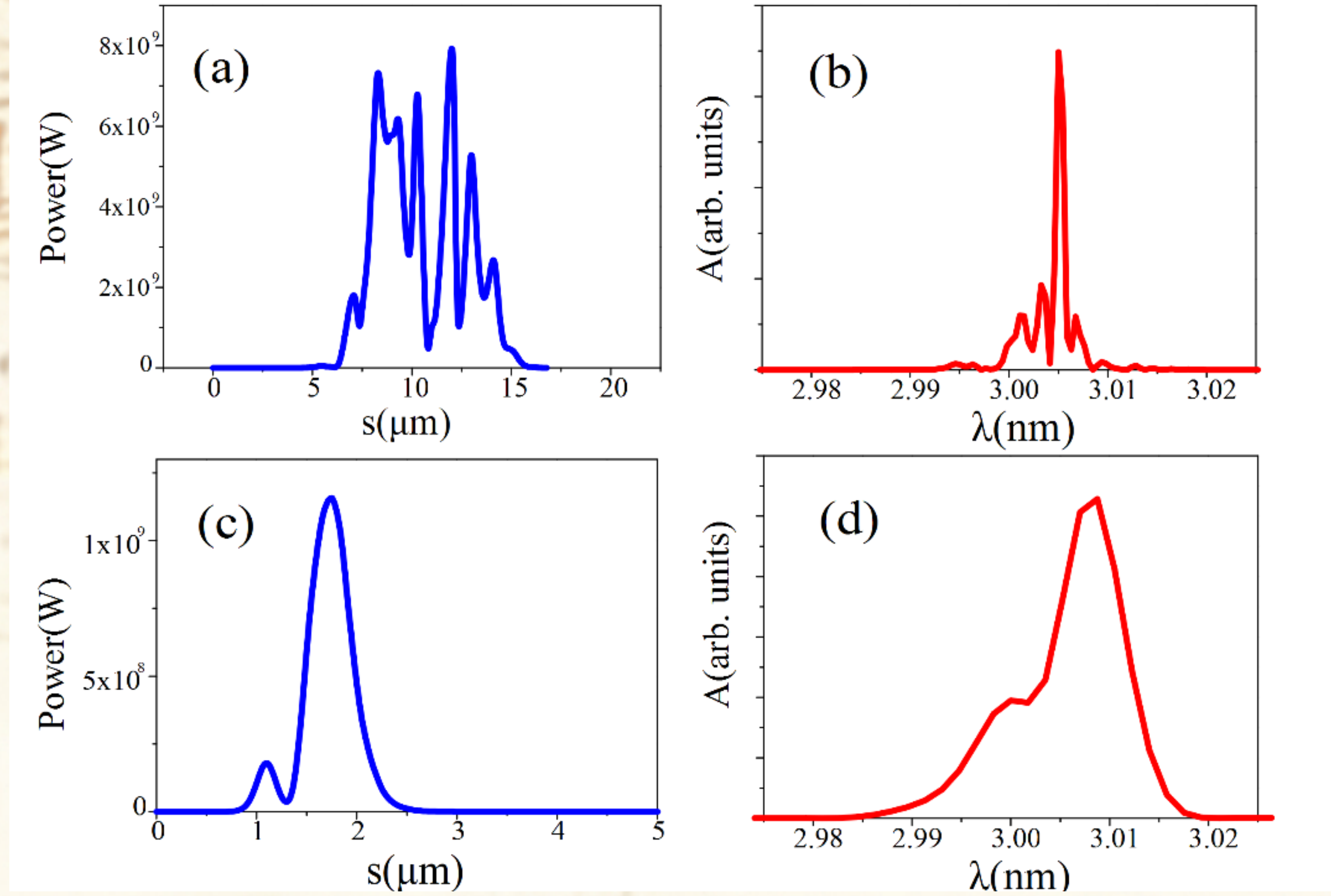
	50 pC	8 pC
e-En (GeV)	3	3
Und λw, L(cm,m)	1.2 60	1.2 60
Ph-en (keV)	3	3
Rep rate (MHz)	1	1
Energy (μJ)	42	2.5
Numb per shot	$8.75\ 10^{10}$	$5.4\ 10^{9}$
Bandwidth (%)	0.45	0.8
Pulse duration (fs)	6.6	1.2
N/ s (s-1)	$8.75\ 10^{16}$	$5.4\ 10^{15}$
S dens(N/shot/%bw)	$1.94\ 10^{10}$	$6.7\ 10^{8}$
Tot. spect dens.	$1.94\ 10^{16}$	$6.7\ 10^{14}$
Radiation size mm	**0.135**	**0.14**
Divergence mrad	**$4\ 10^{-2}$**	**$4.3\ 10^{-2}$**
Coherence	SASE	Single Spike

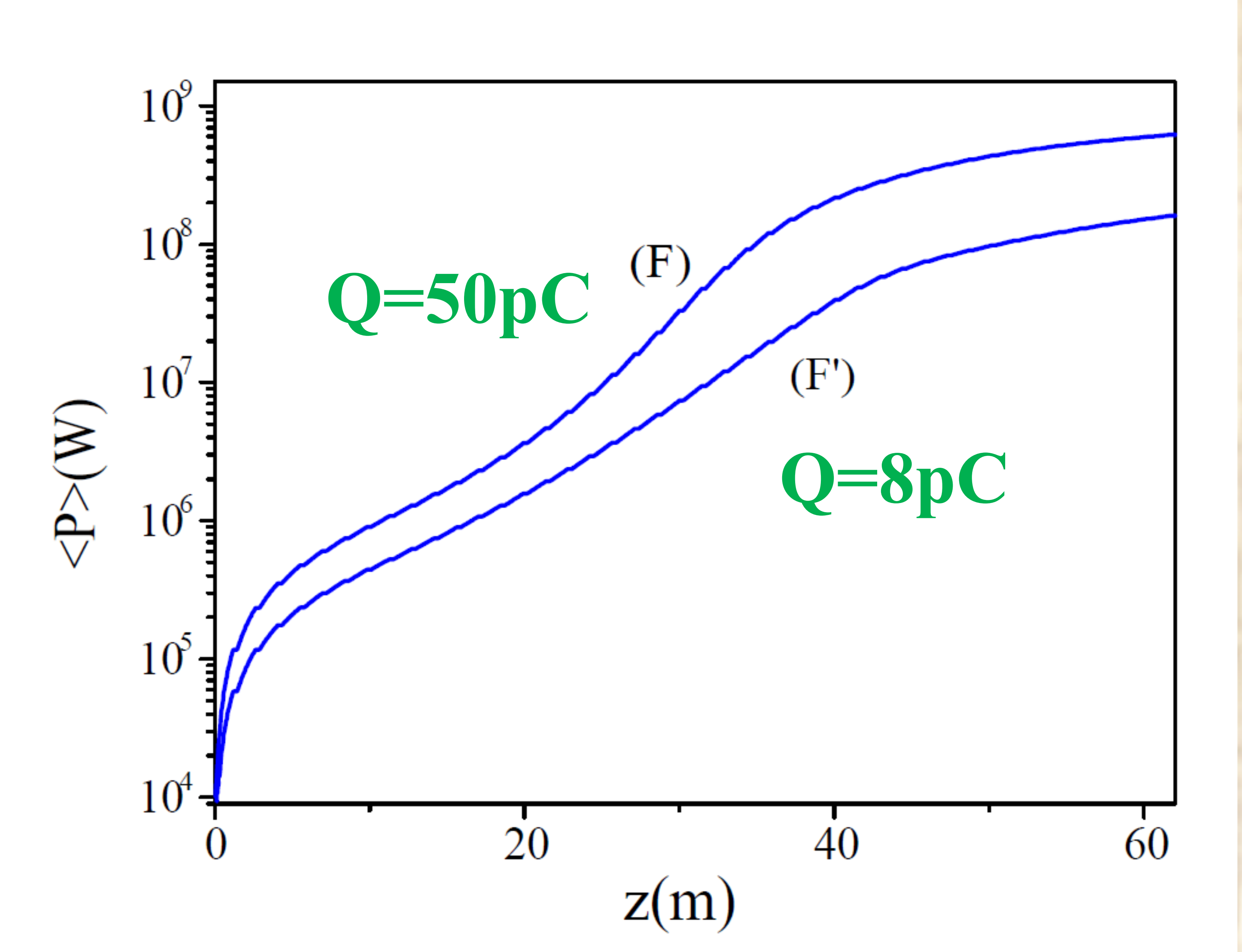
UliX2: 1.2 cm

a_w=0.6

Power
60 m

Spectrum
60 m





Q=50 pC
SASE

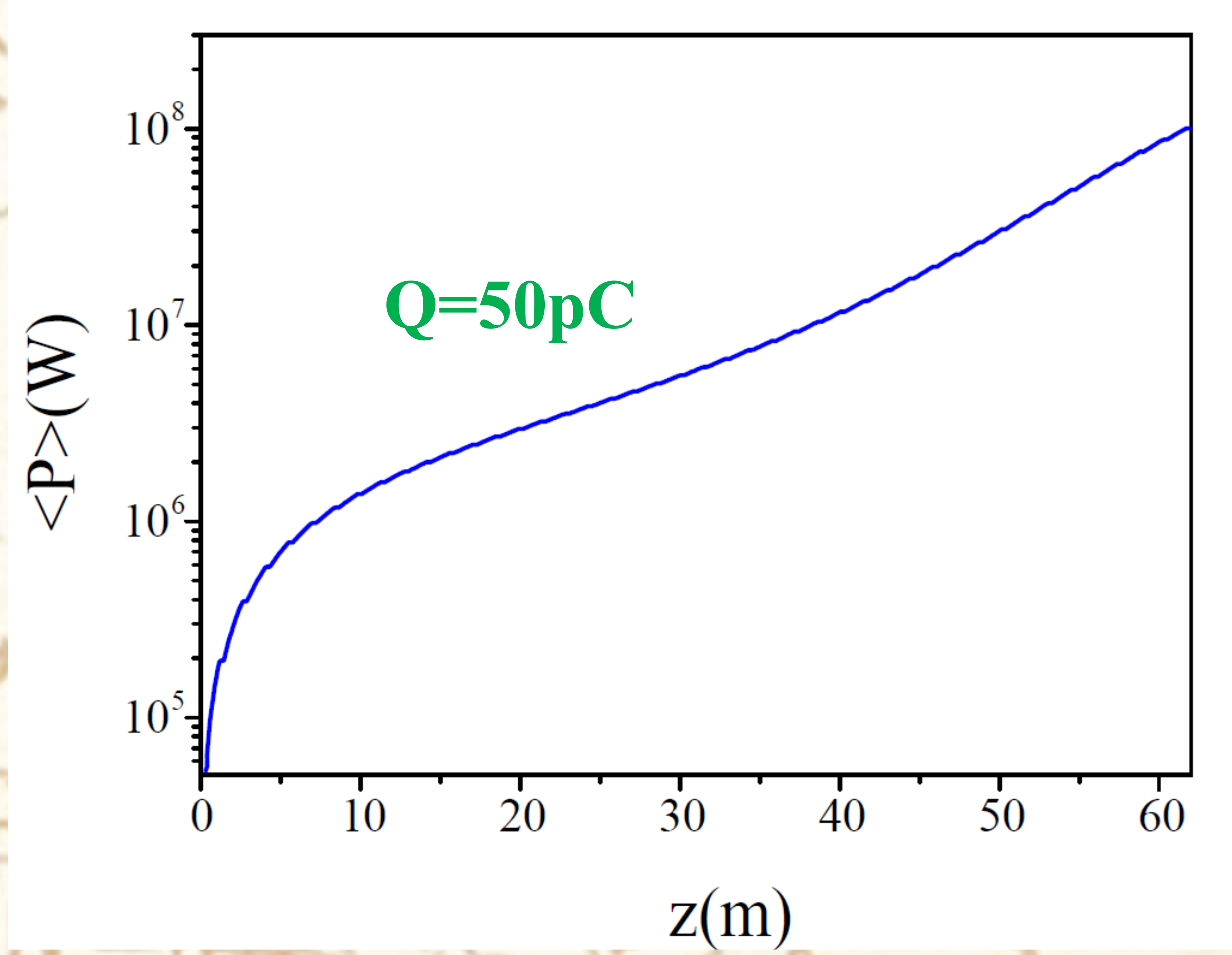
Q=16 pC
Single Spike

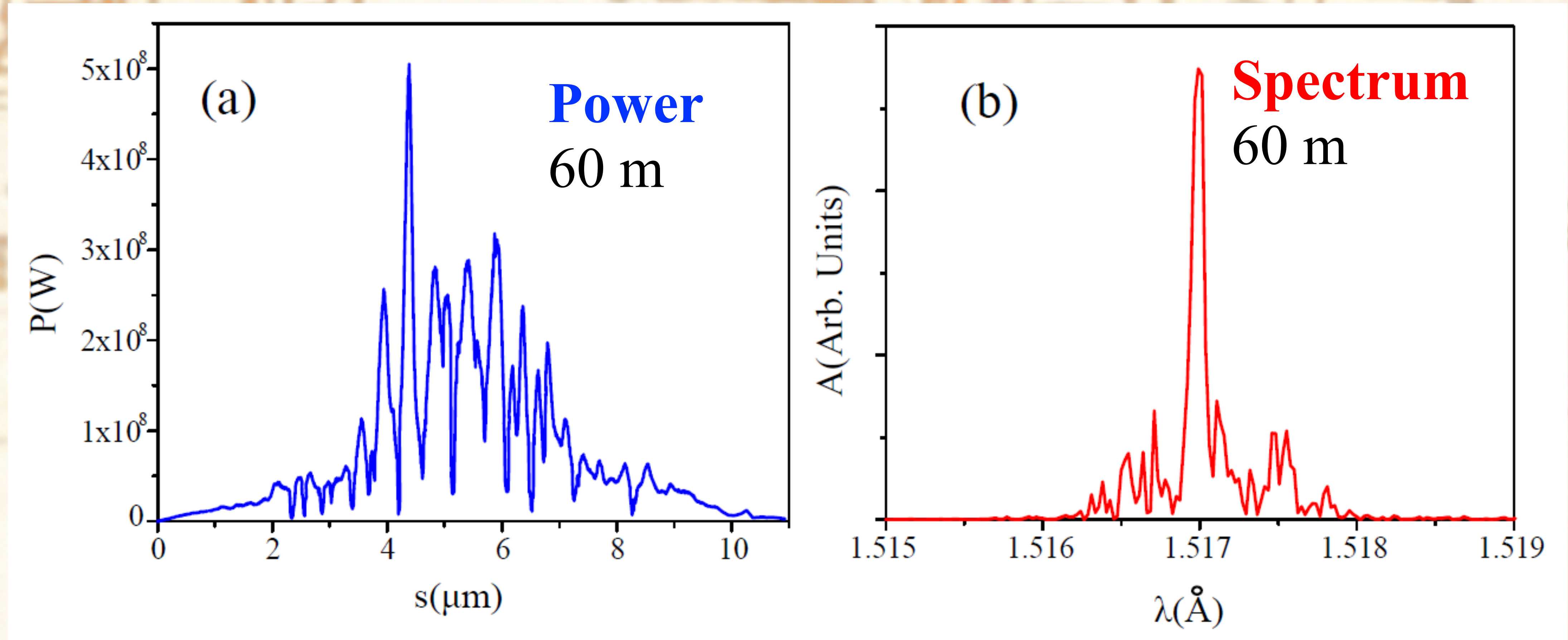
SASE 3: single shot imaging 1.5 Å

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

UliX2: 1.2 cm

a_w=0.6



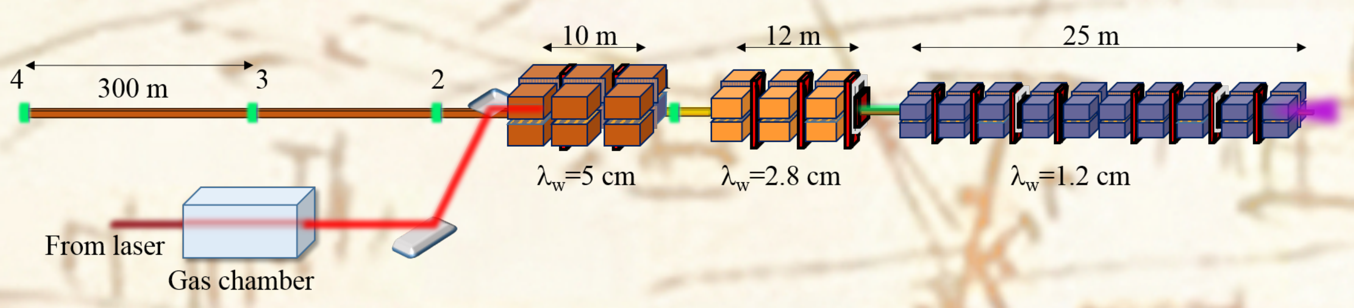


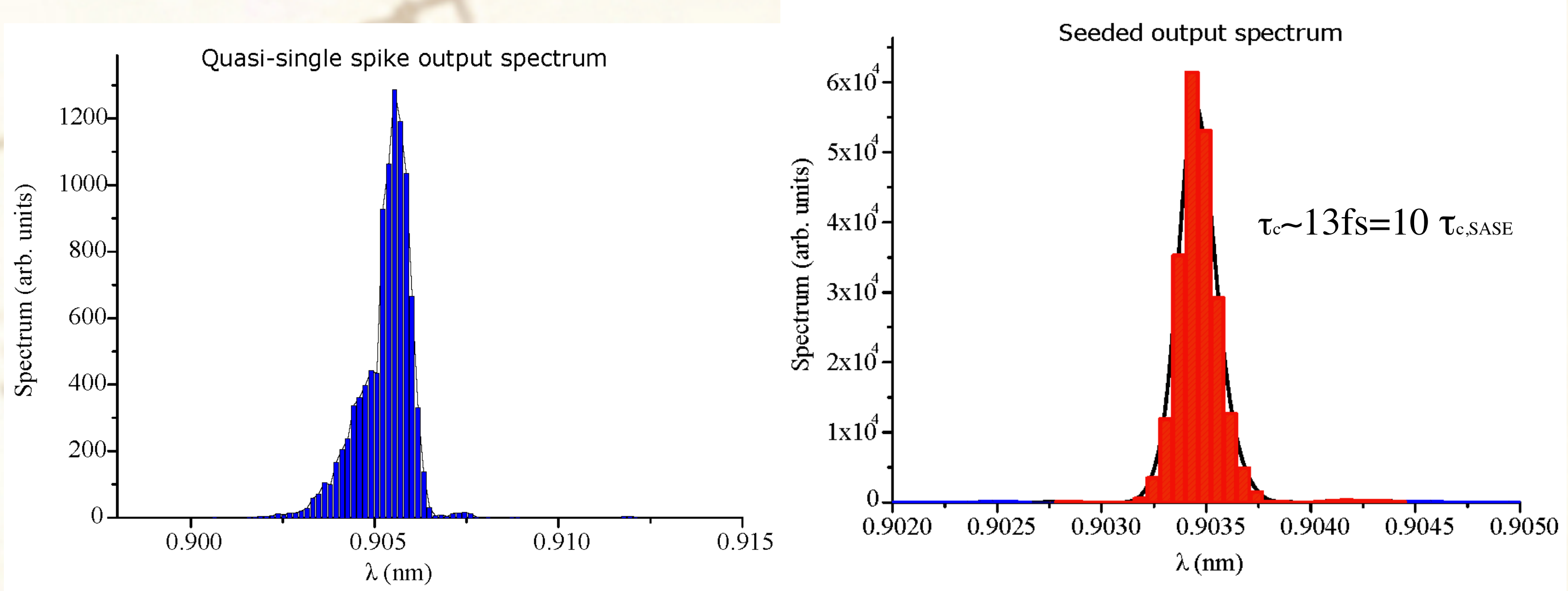
Q=50 pC
SASE

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

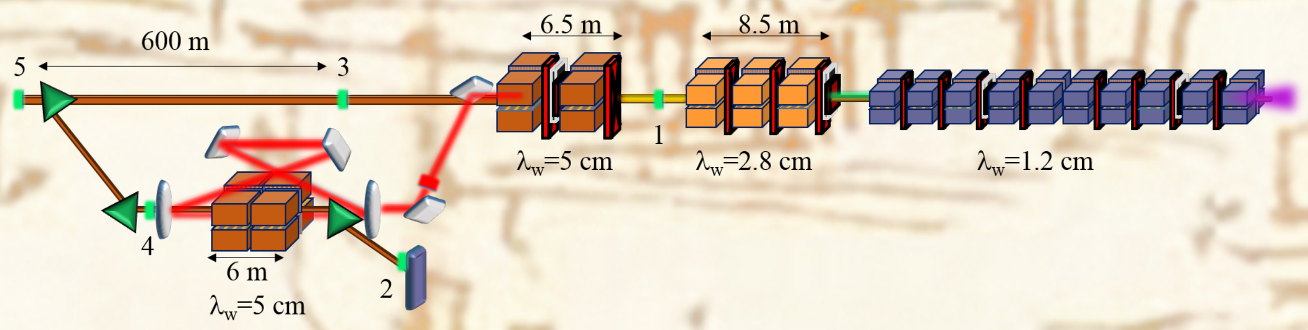
Search for coherence and stability: seeded/cascade operation

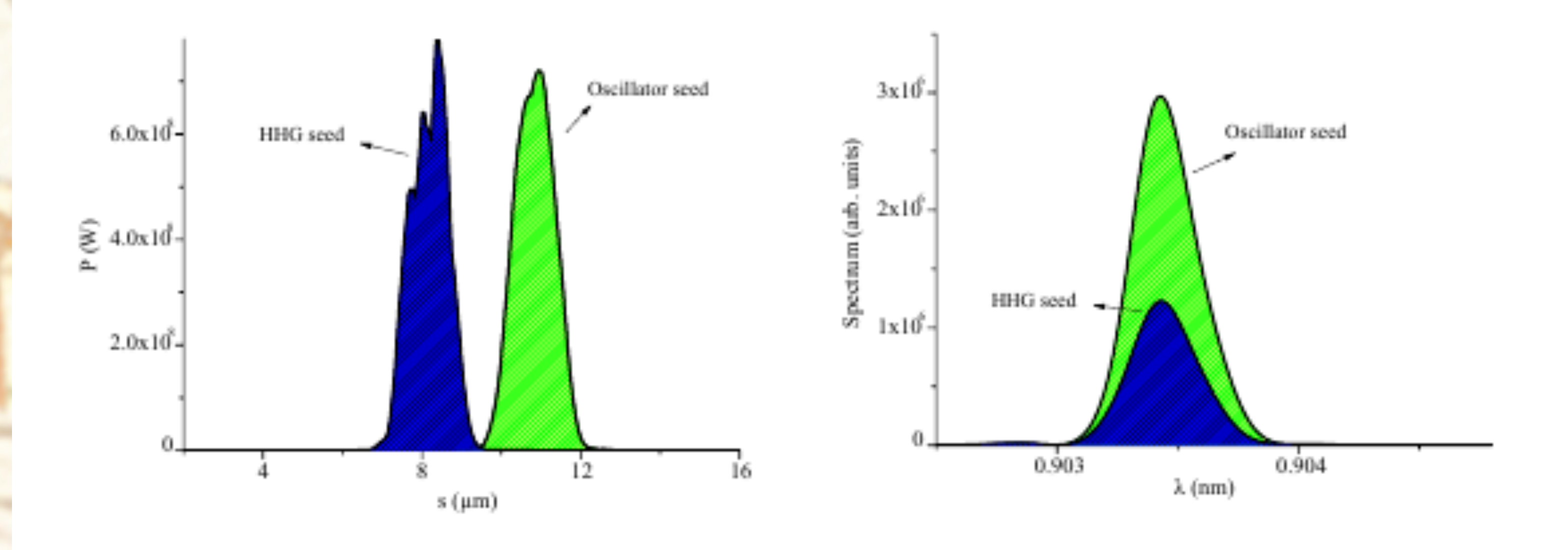
1) Cascaded operation with HGG as seed, fresh bunch





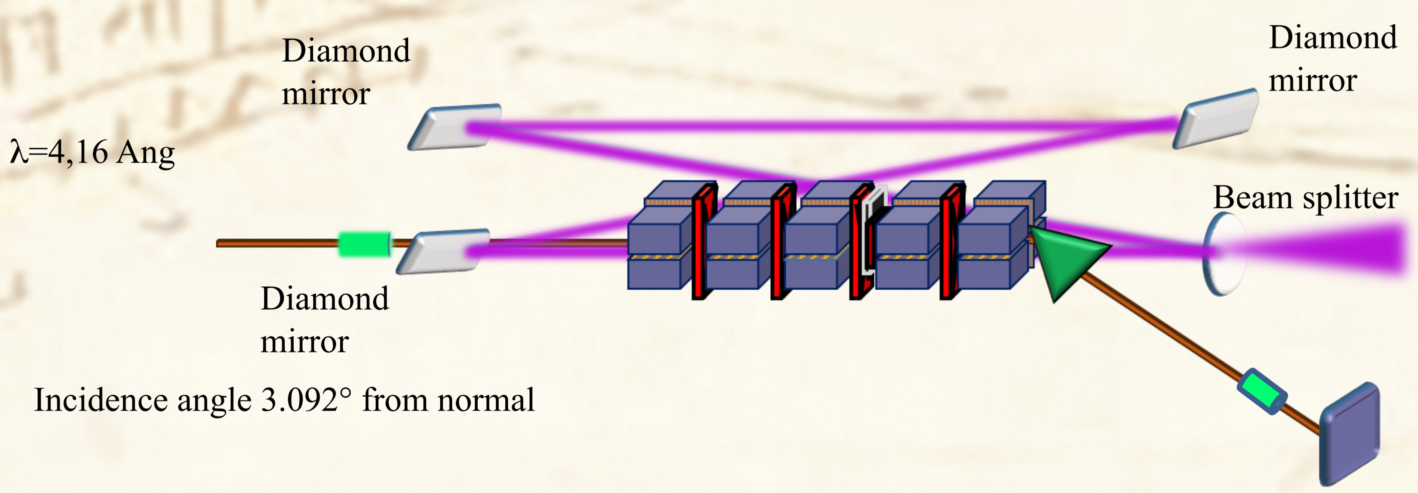
2) Cascade with a FEL oscillator as seed

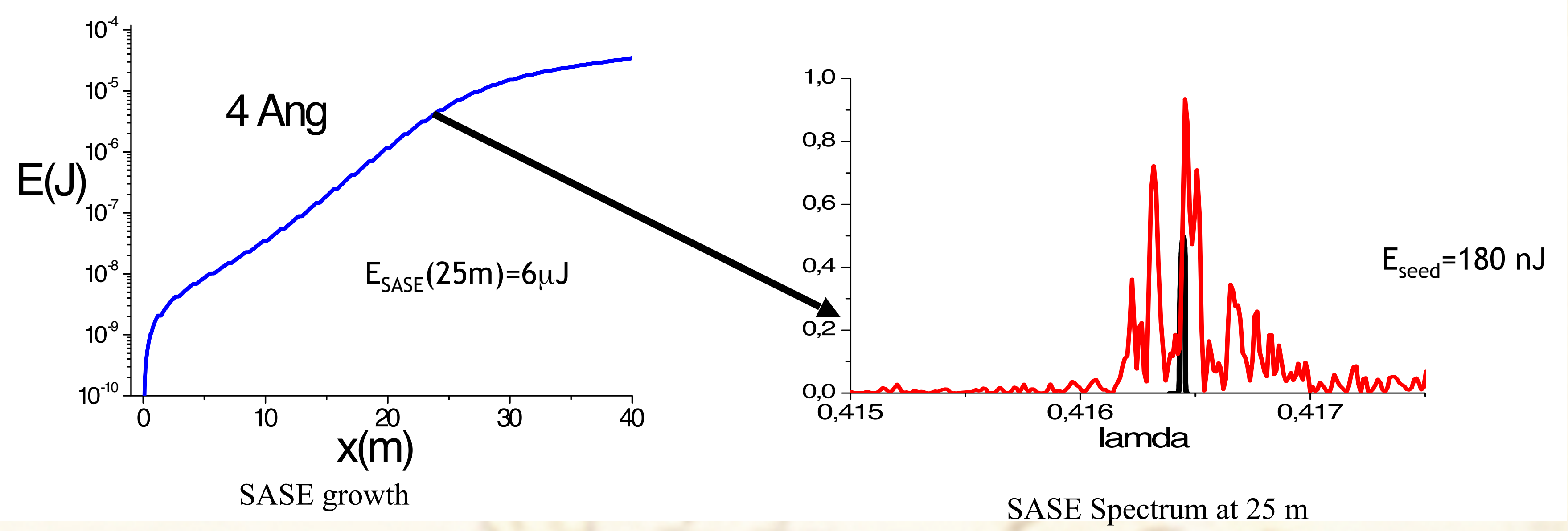




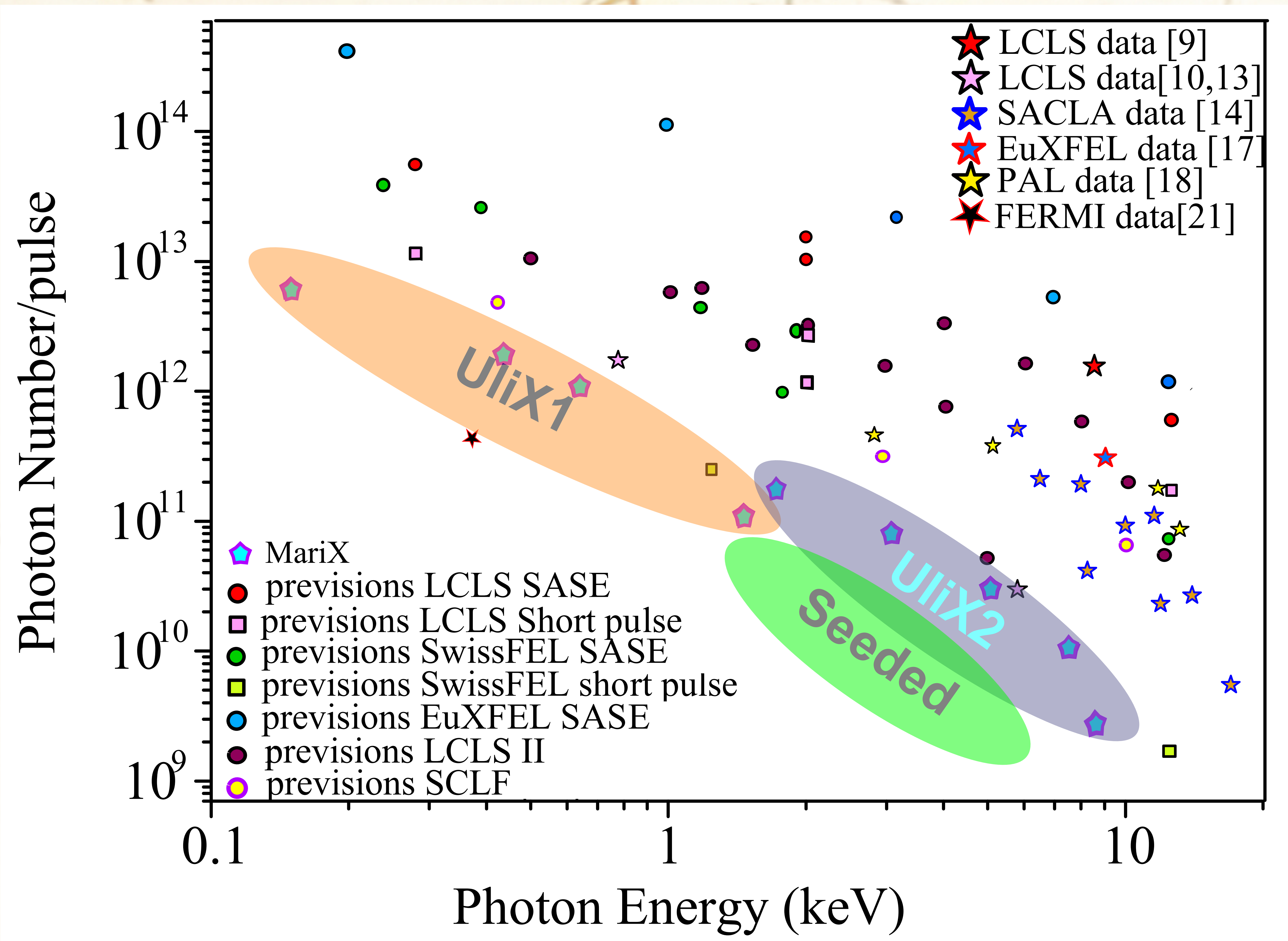
Courtesy: M. Opromolla, Master thesis (www.marix.eu)

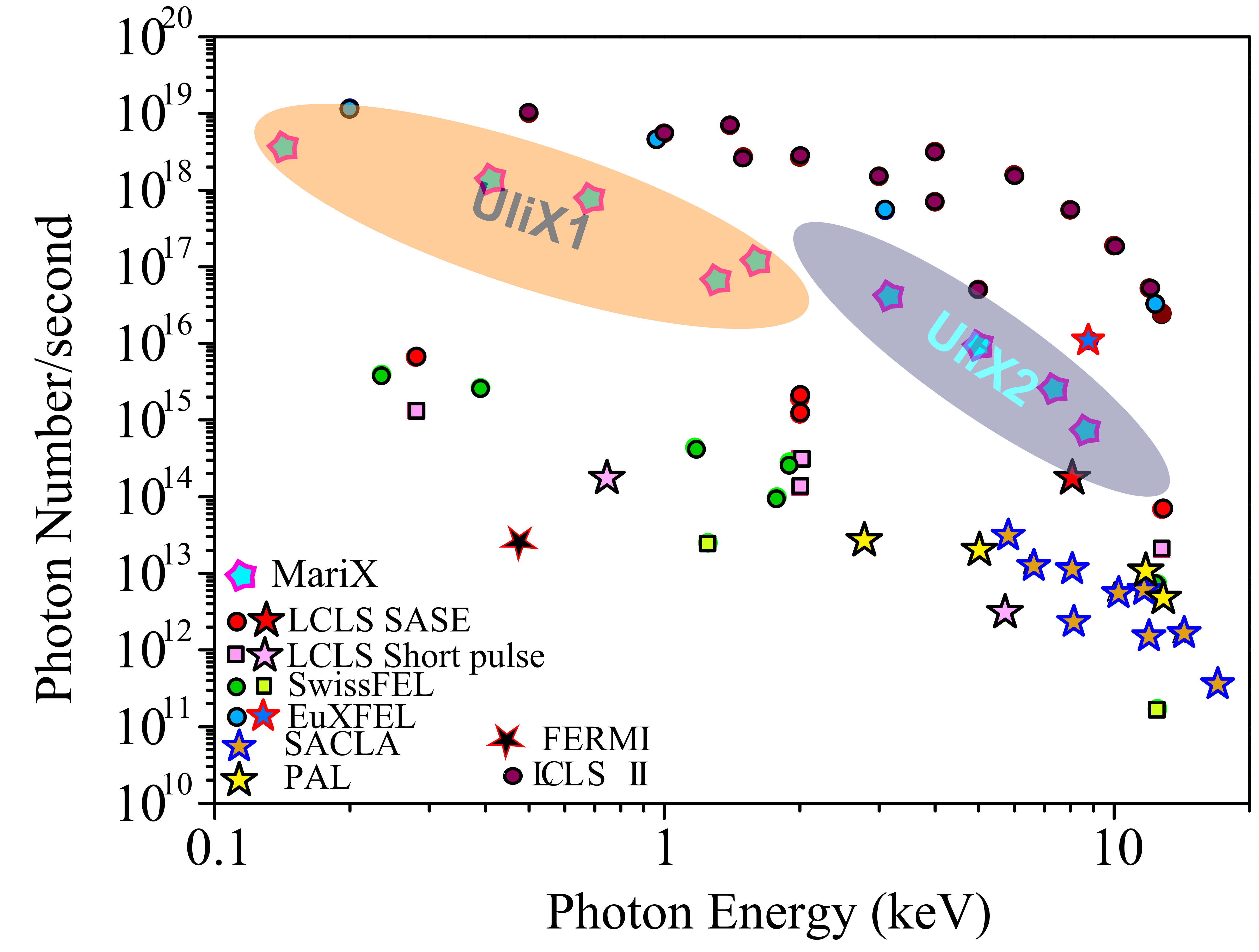
3) Regenerative amplifier





Comparison with other FELs





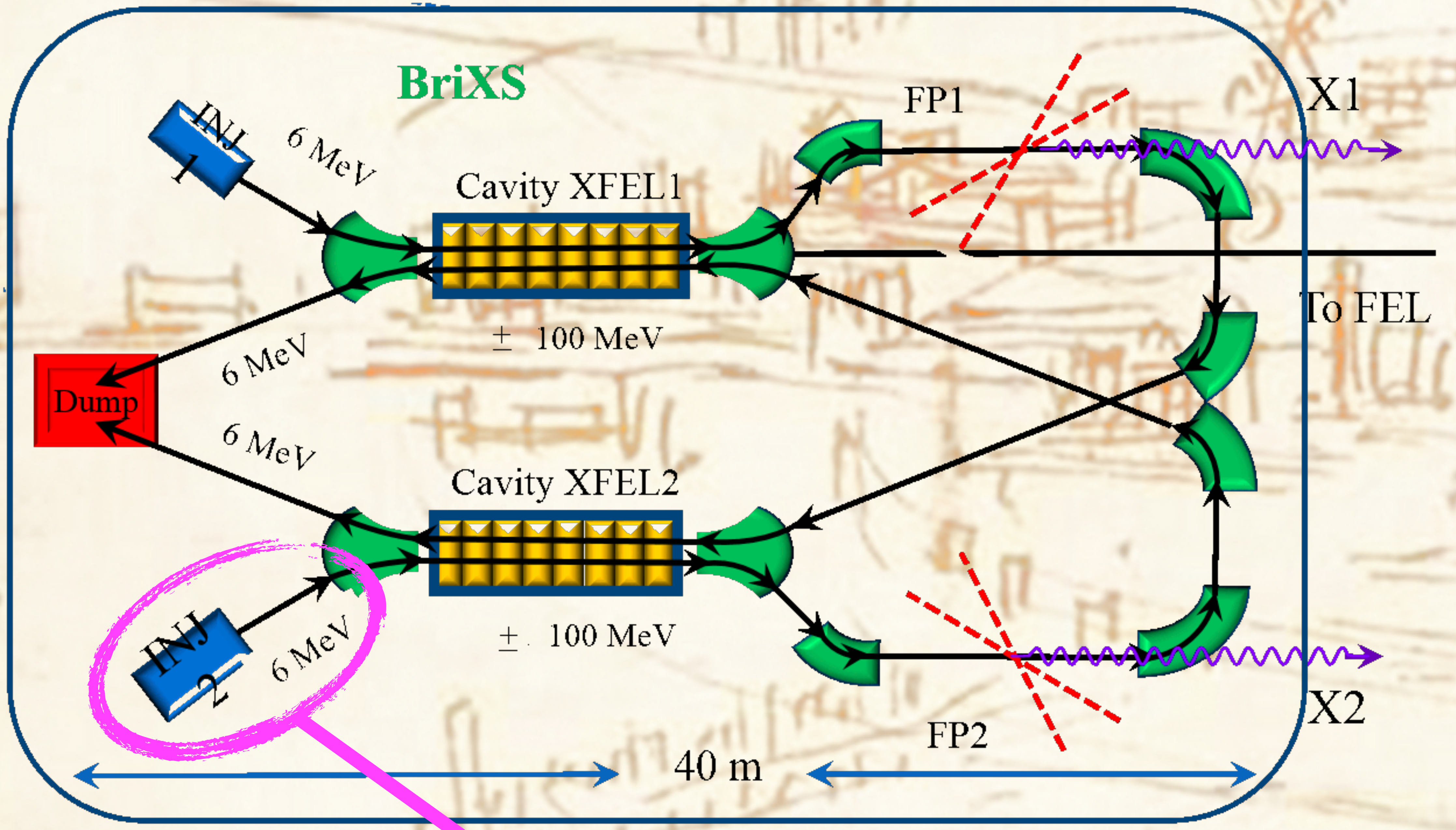
But there's more about MariX…

…BriXS

Bright and compact X-ray Source

About BriXS

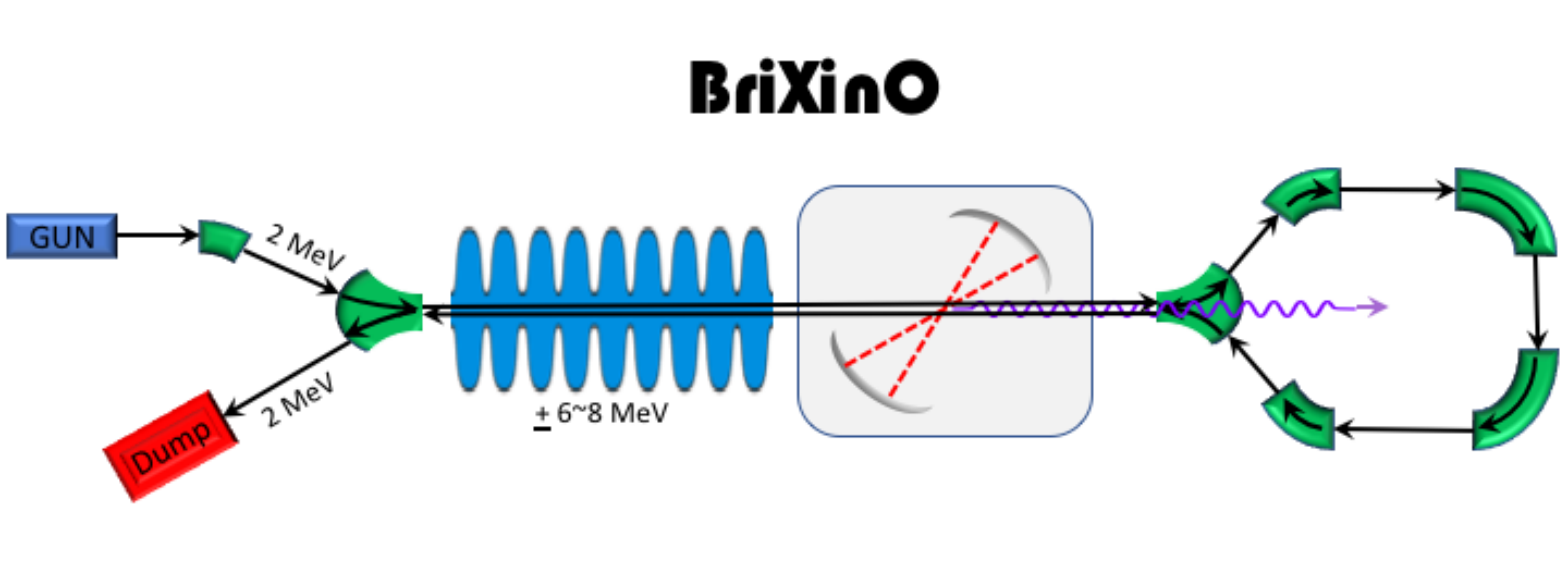
A back scattering Thomson source, working at 100 MHz repetition rate with energy recovery, delivering 20-180 keV mono-chromatic X-rays up to 5 x 10^{12} photons/sec in 5% bandwidth for clinical applications

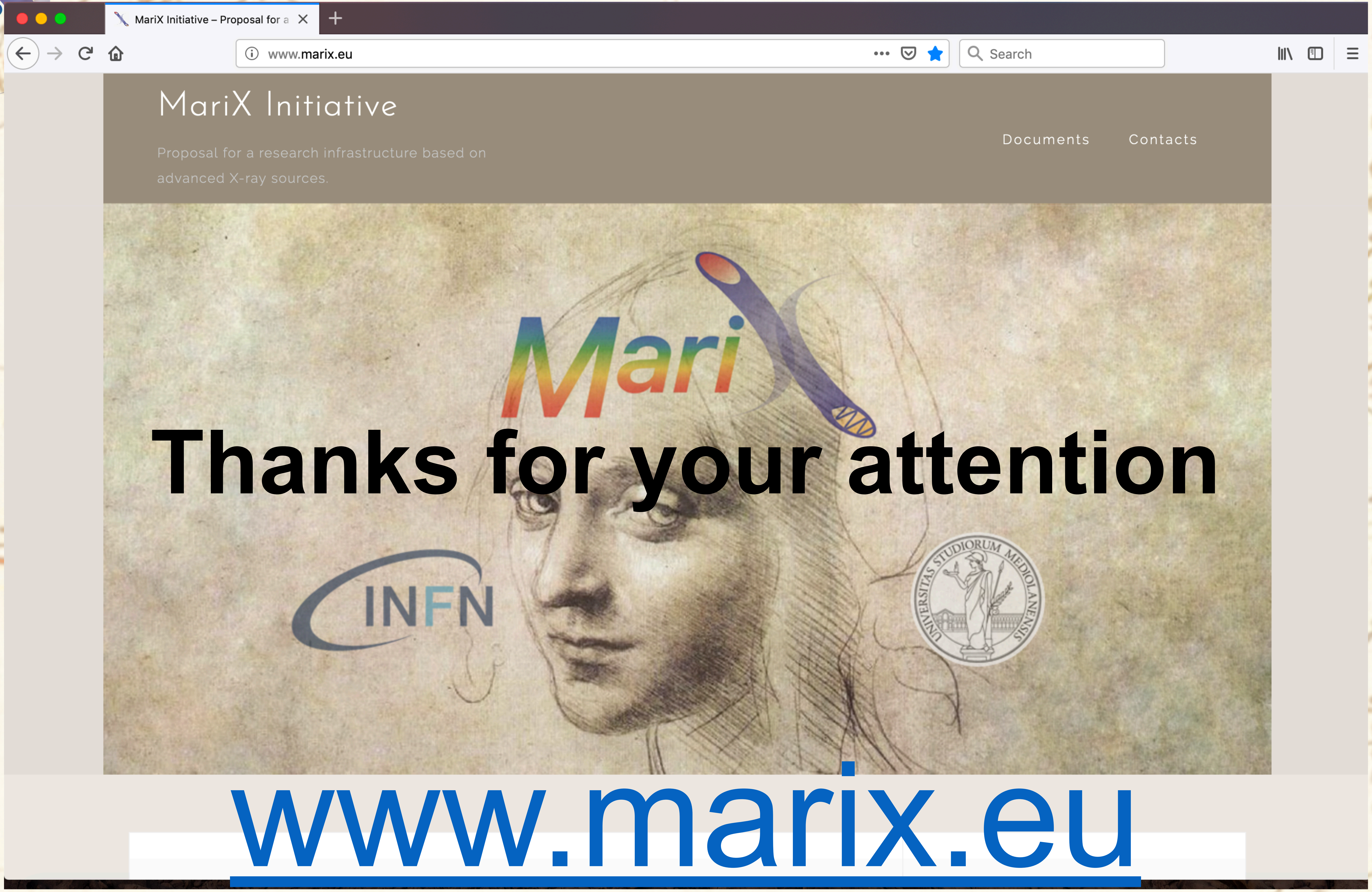


Photon energy (keV)	20 - 180
Bandwidth (%)	1 - 10
# photons per shot within FWHM bdw.	0.05×10^5 - 1.0×10^5
# photons/sec within FWHM bdw.	0.05×10^{13} - 1.0×10^{13}
Source size (µm)	≤ 20
Source divergence (mrad)	6 - 1
Photon beam spot size (FWHM) at $z = 100$ m (cm)	40 - 4
Peak Brilliance†	10^{18} -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

See Luigi Faillace poster this afternoon

BriXS demonstrator: BriXSinO





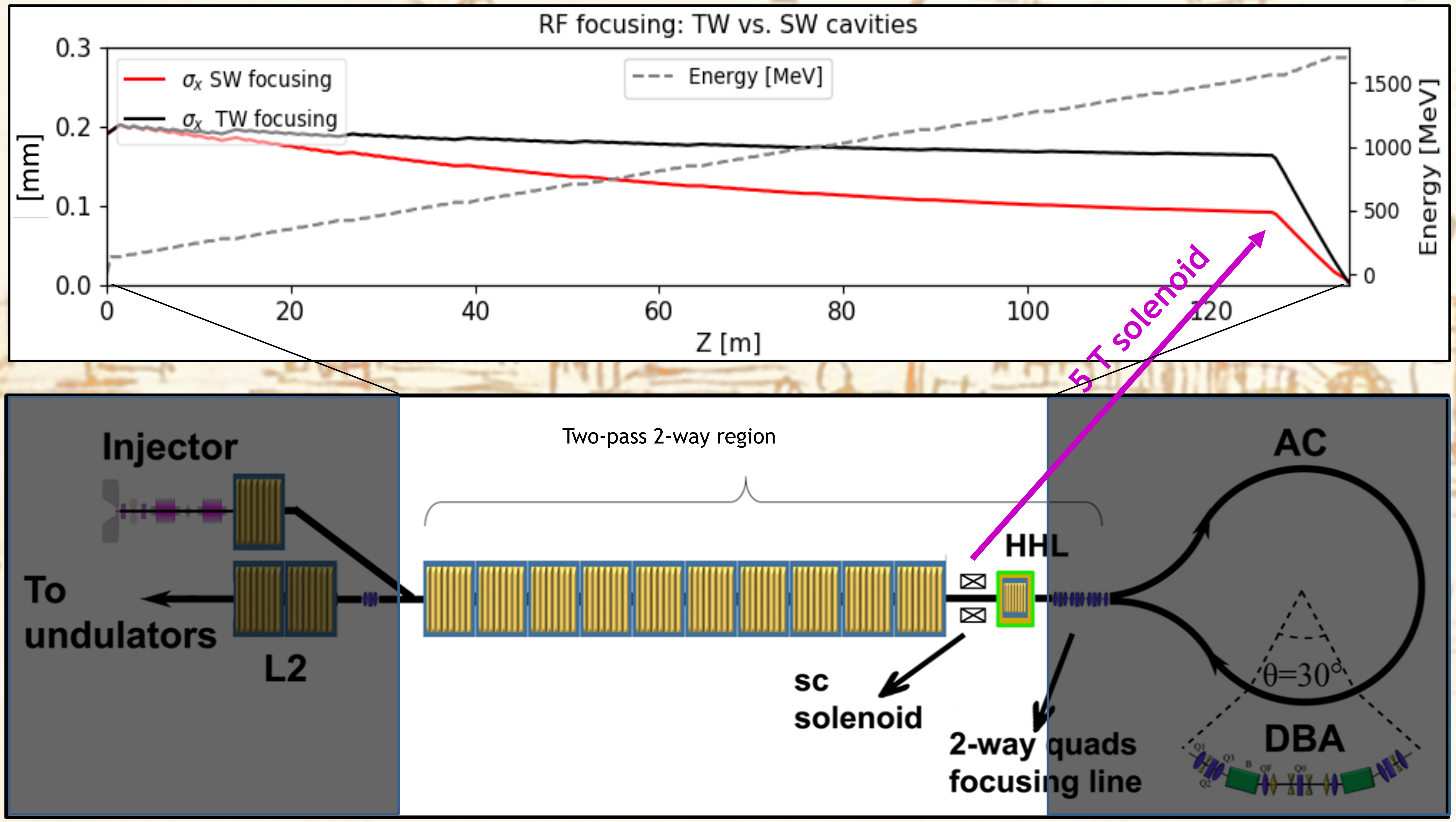
Thanks for your attention

www.marix.eu

Backup slides

Superconductive main linac L1

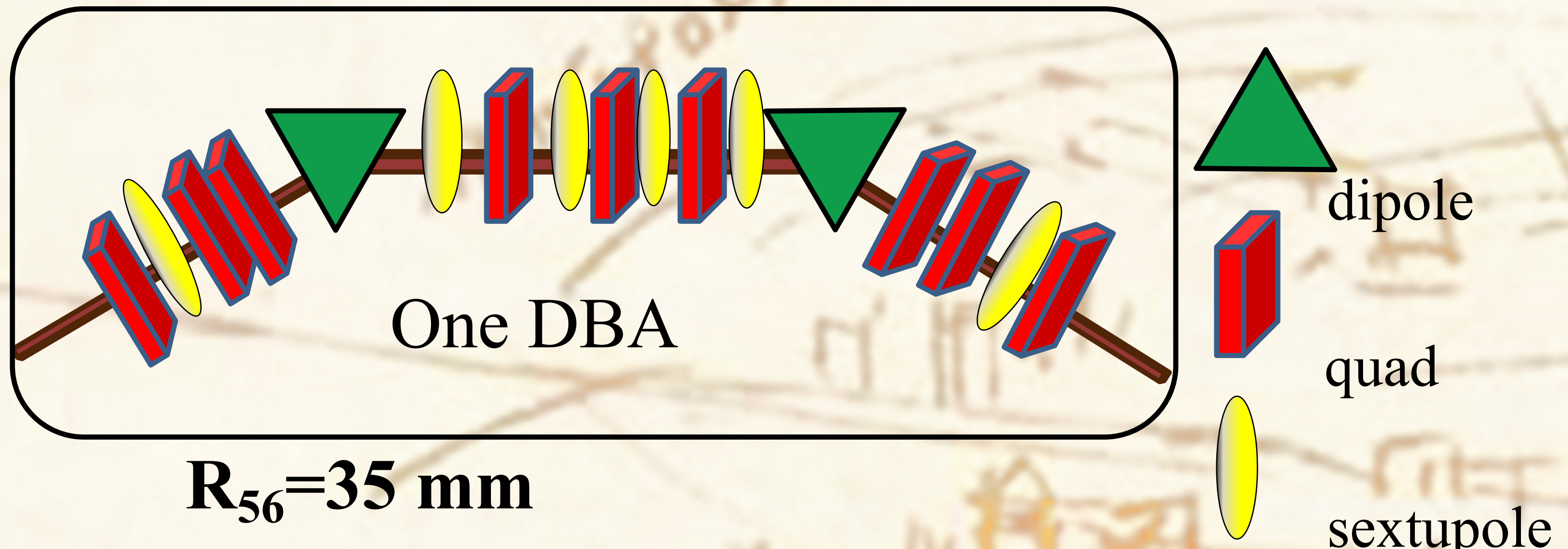
- Ten Tesla like cryomodules: max grad 16 MV/m, 8 cavity per cryomodules
- Chirp for AC-compression is given injecting @ + 6° from RF crest.



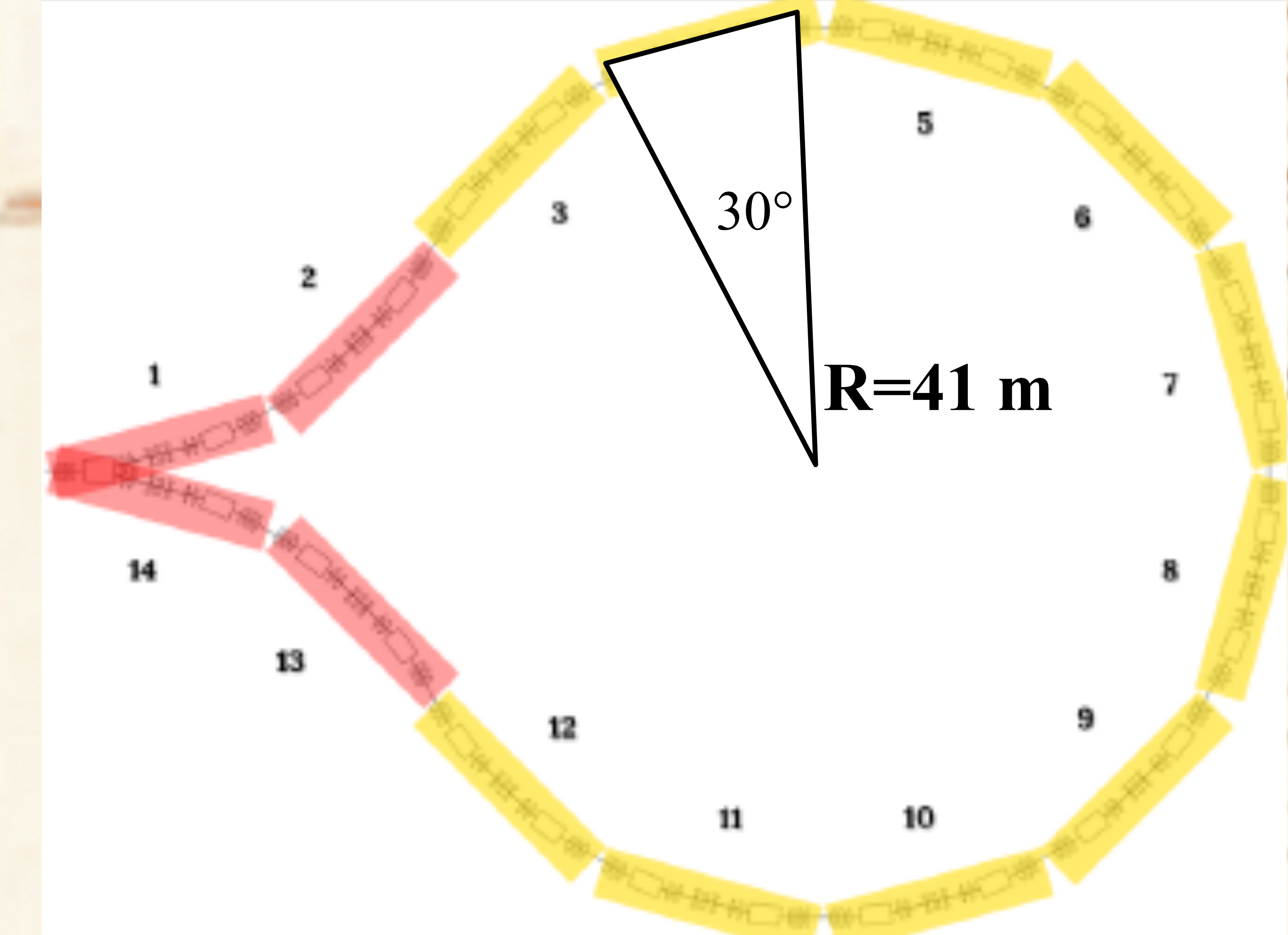
We rely only on second order focusing, symmetric back-and-forth: Rf focusing and solenoid foc.

The Arc Compressor

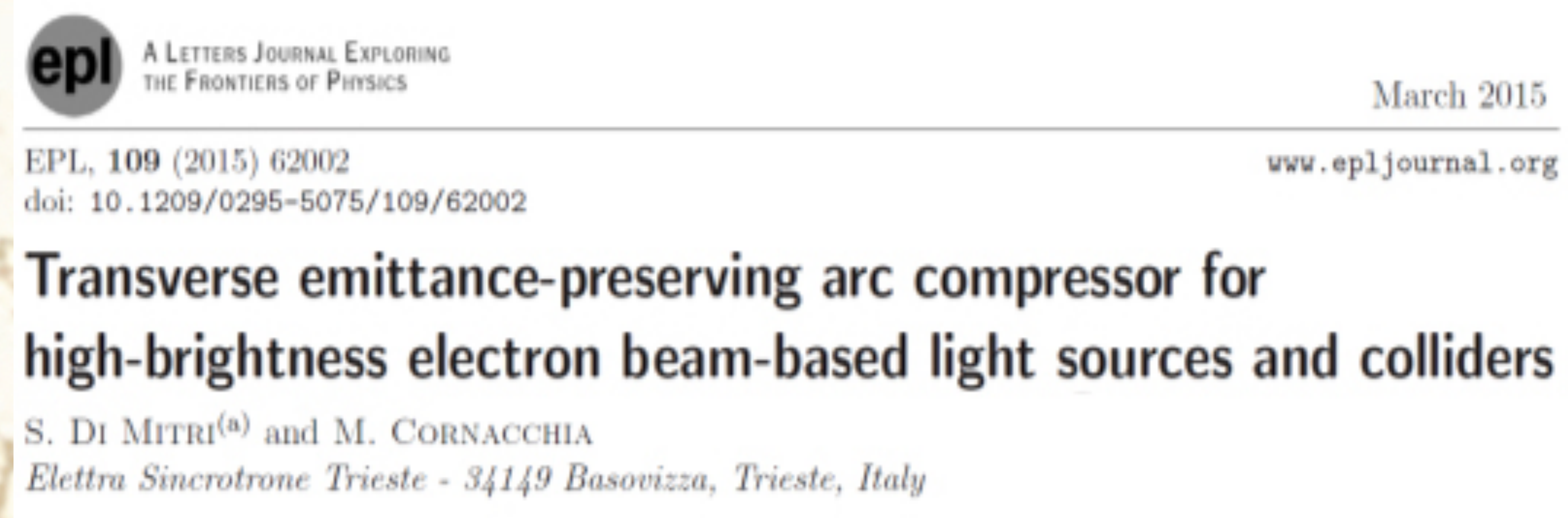
14 Double Bending Achromats Elettra-like



R_{56}=35 mm



Study of the arc compressor done by
M. Rossetti Conti



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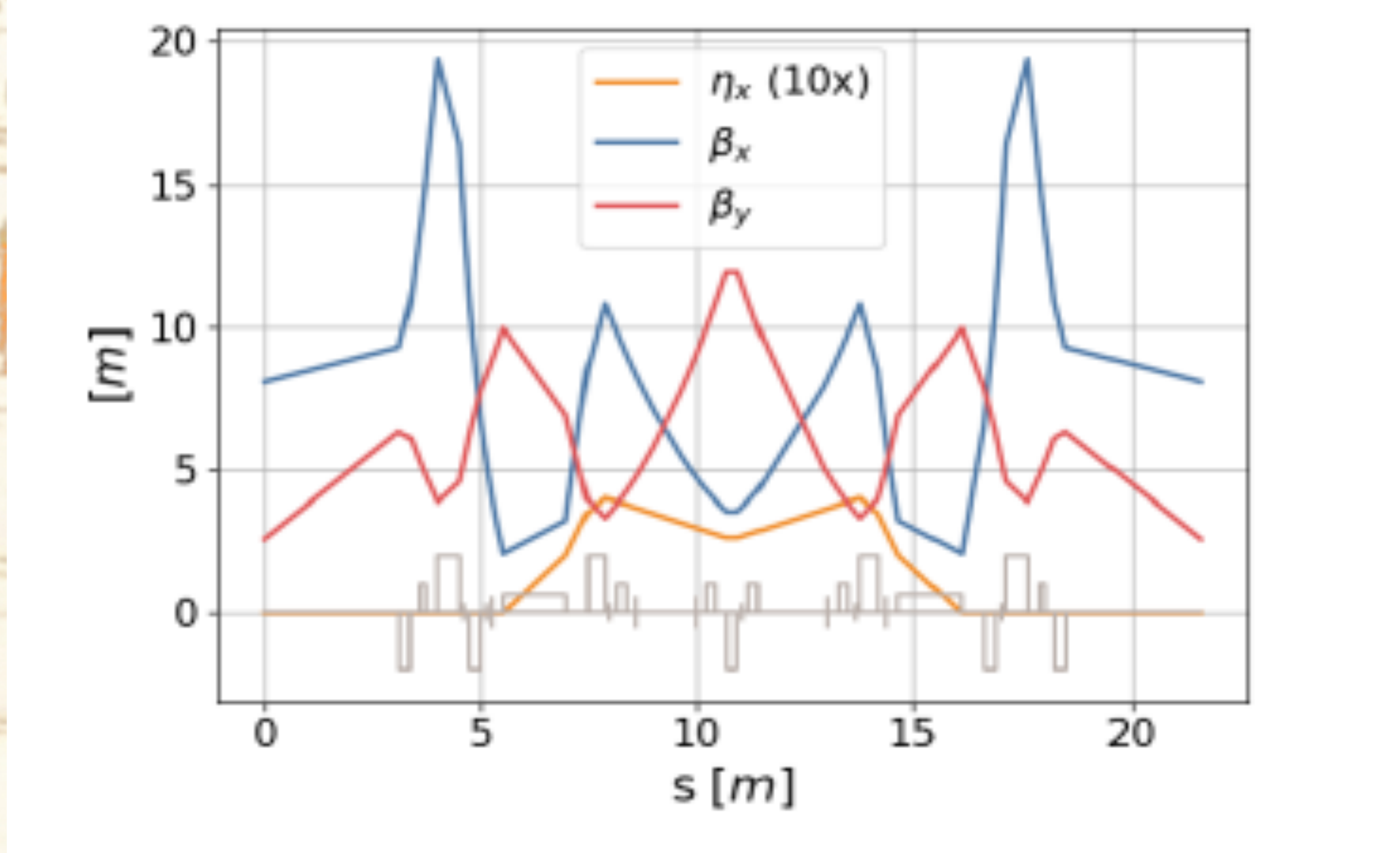
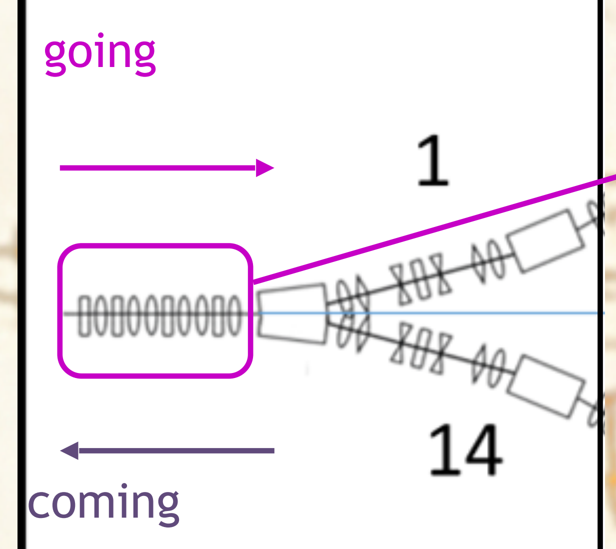
Transverse emittance-preserving arc compressor for high-brightness electron beam-based light sources and colliders

S. Di Mitri[a] and M. Cornacchia

Elettra Sincrotrone Trieste - 34149 Basovizza, Trieste, Italy



Arc Compressor matching line

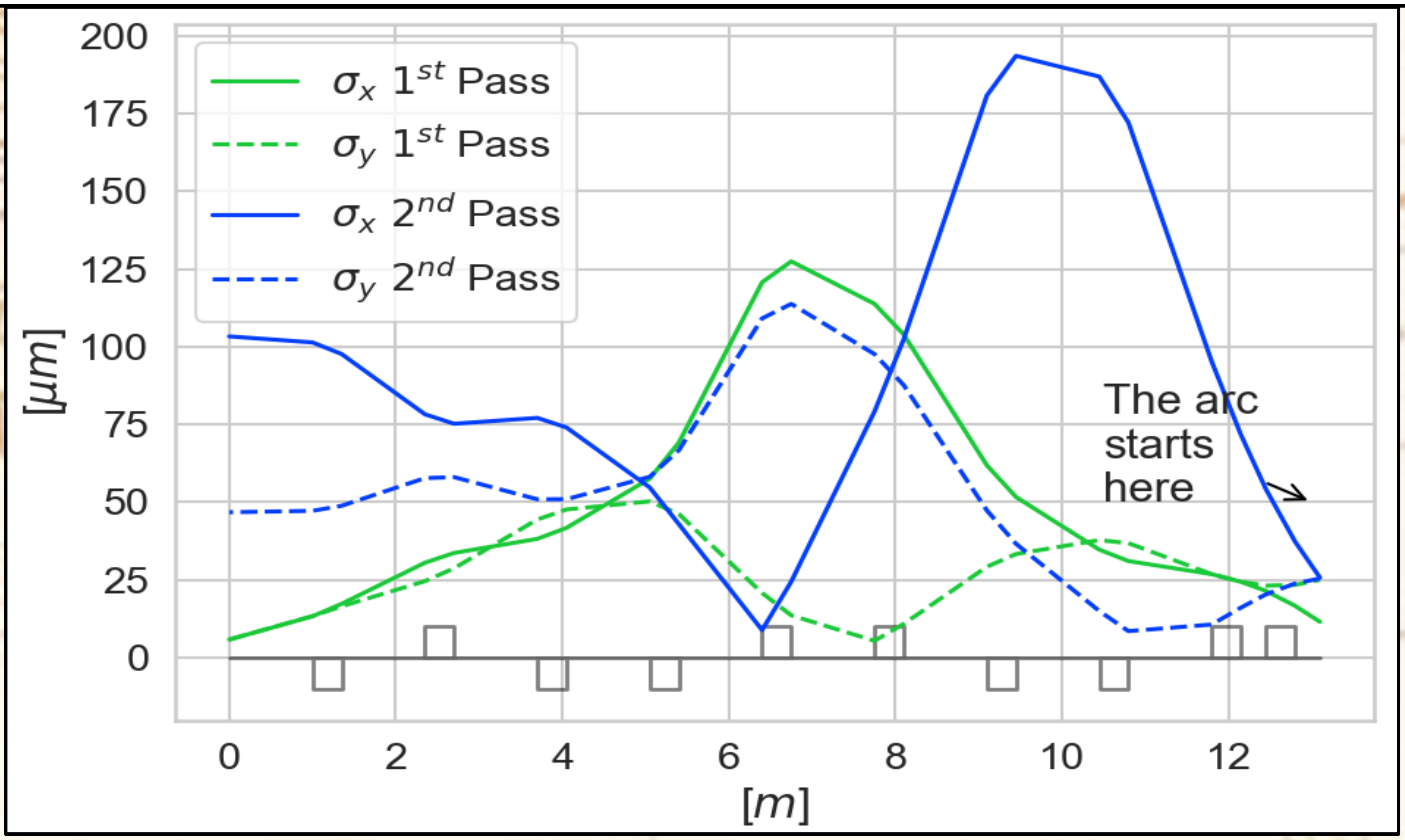


Not trivial 10 quads matching line with 2 SOLUTIONS

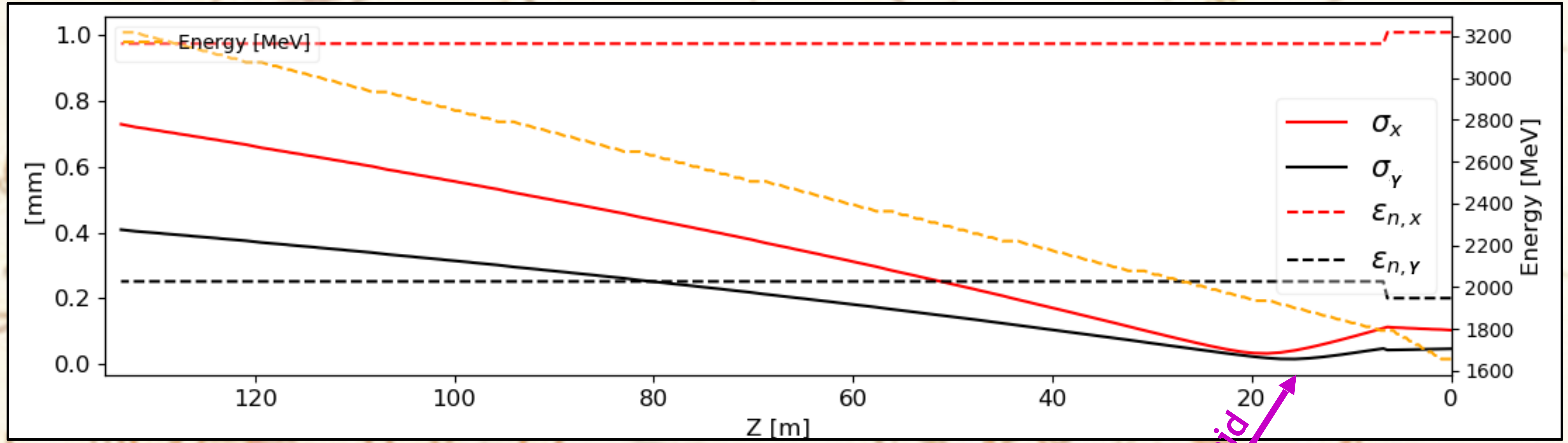
SOL. 1: «going bunch» match perfectly at the DIPOLE entrance

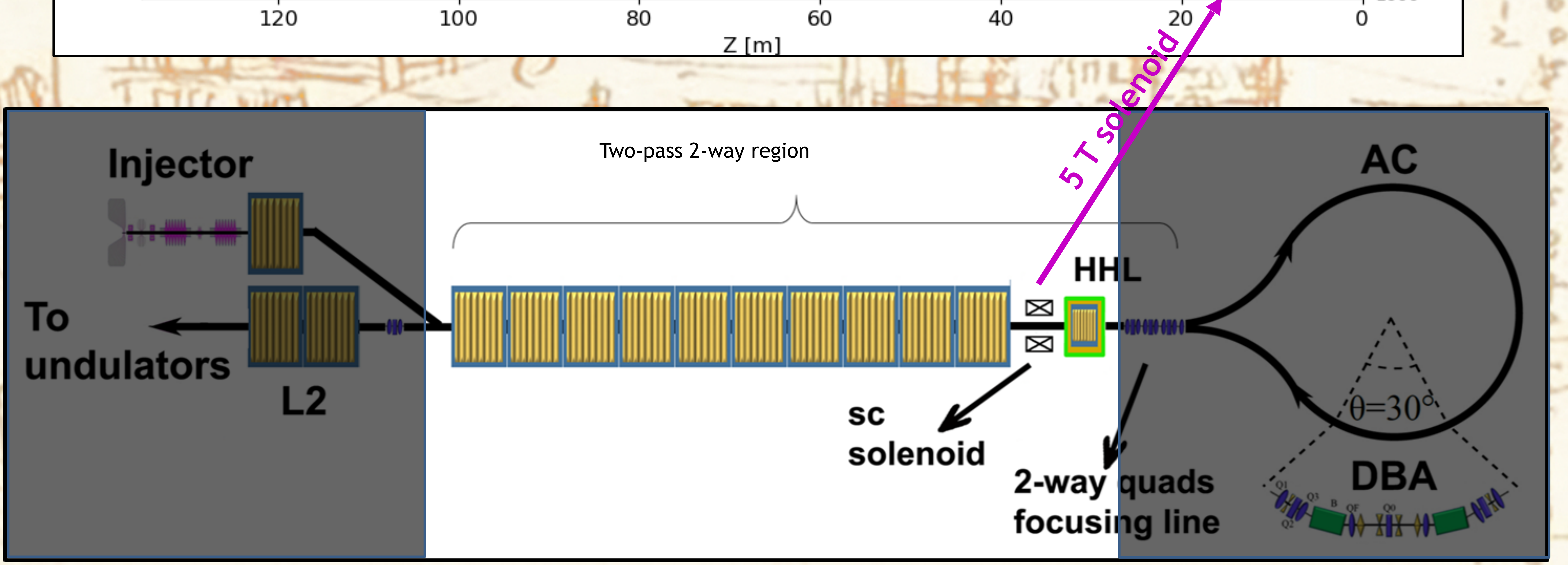
SOL. 2: «the coming back bunch» control bunch envelopes avoiding disastrous emit degradation by chromatic aberrations @ the 5T SOLENOID

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

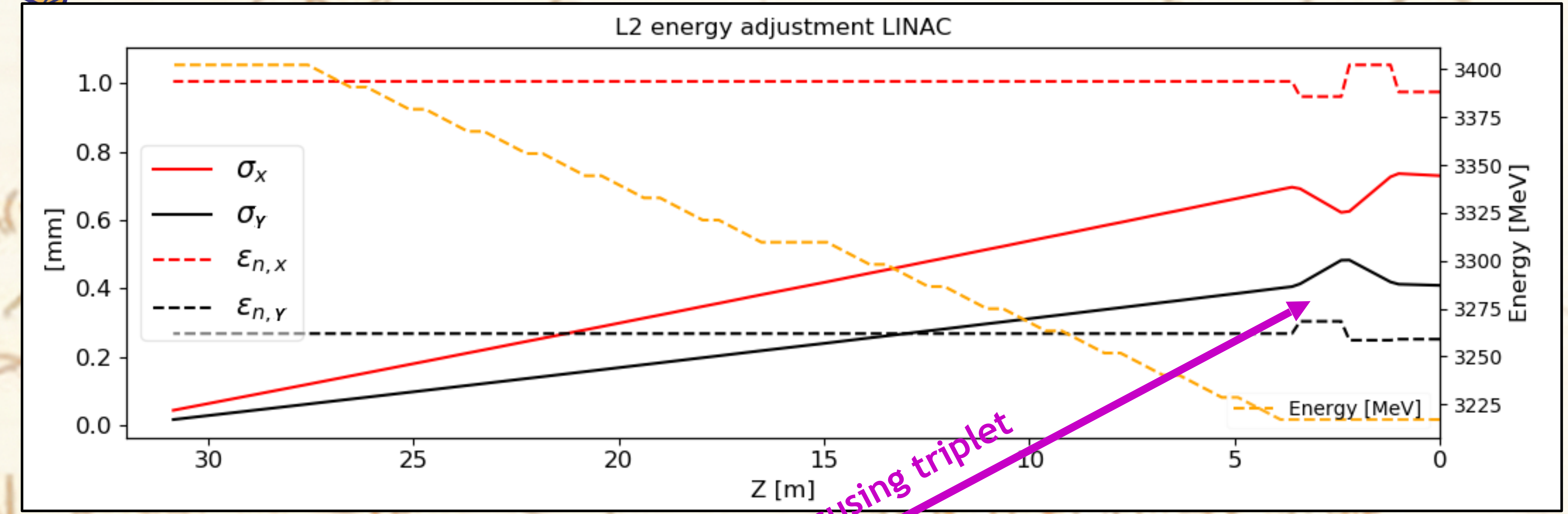


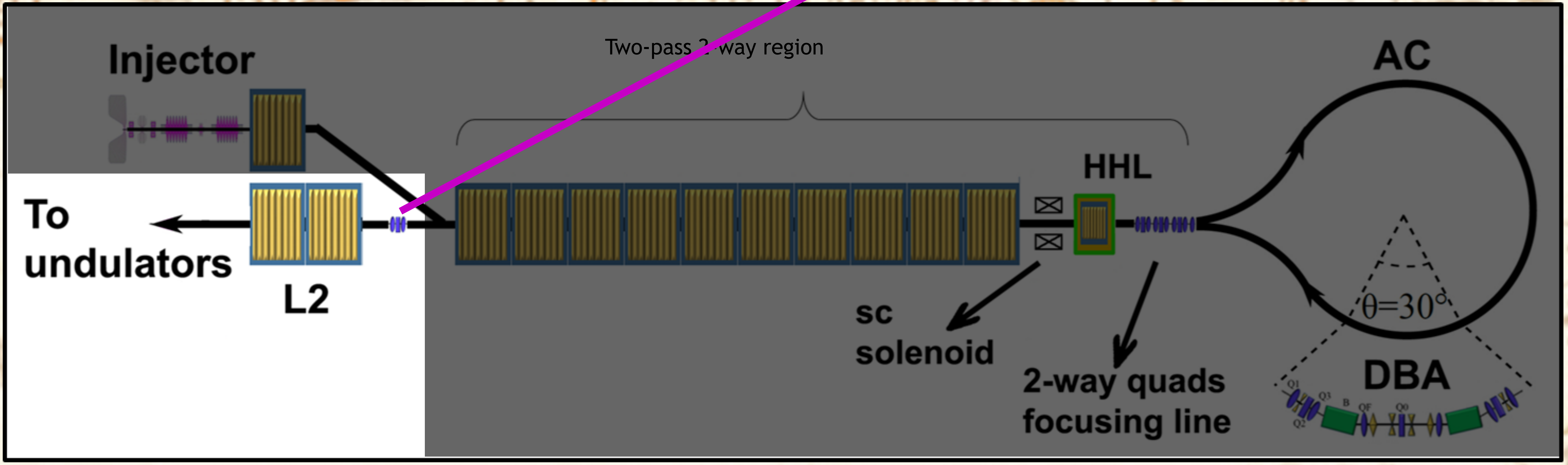
Second passage in main linac





Last energy adjustment: L2





MariX cost estimate

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)
MariX	45.5	35.000
LCLS	110	
XFEL	120	
SIRIUS	35	68.000