Istituto Nazionale di Fisica Nucleare

Injector Design for the MARIX-FEL Project

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15/05/2018@INFN-LNF

OUTLINE

1. The Marix project
    - Compton and FEL sources

1. BriXS
    - The injector layout
    - Electron source
    - Photocathode choice

2. Status of BriXS injector design
    - 2D RF simulations
    - Beam Dynamics Simulations
      (GIOTTO and Parmela)
    - Comparison with ASTRA

3. Wakefields

Proceedings of IPAC2018, Vancouver, BC, Canada - Pre-Release Snapshot 06-May-2018 12:00 UTC

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

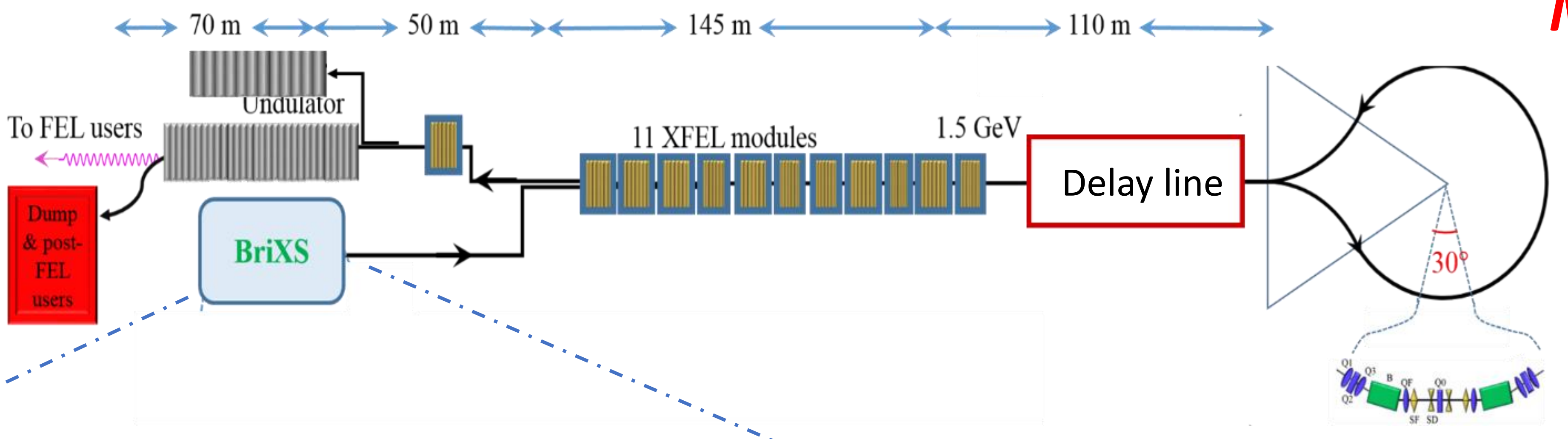
Proceedings of IPAC2018, Vancouver, BC, Canada - Pre-Release Snapshot 06-May-2018 12:00 UTC

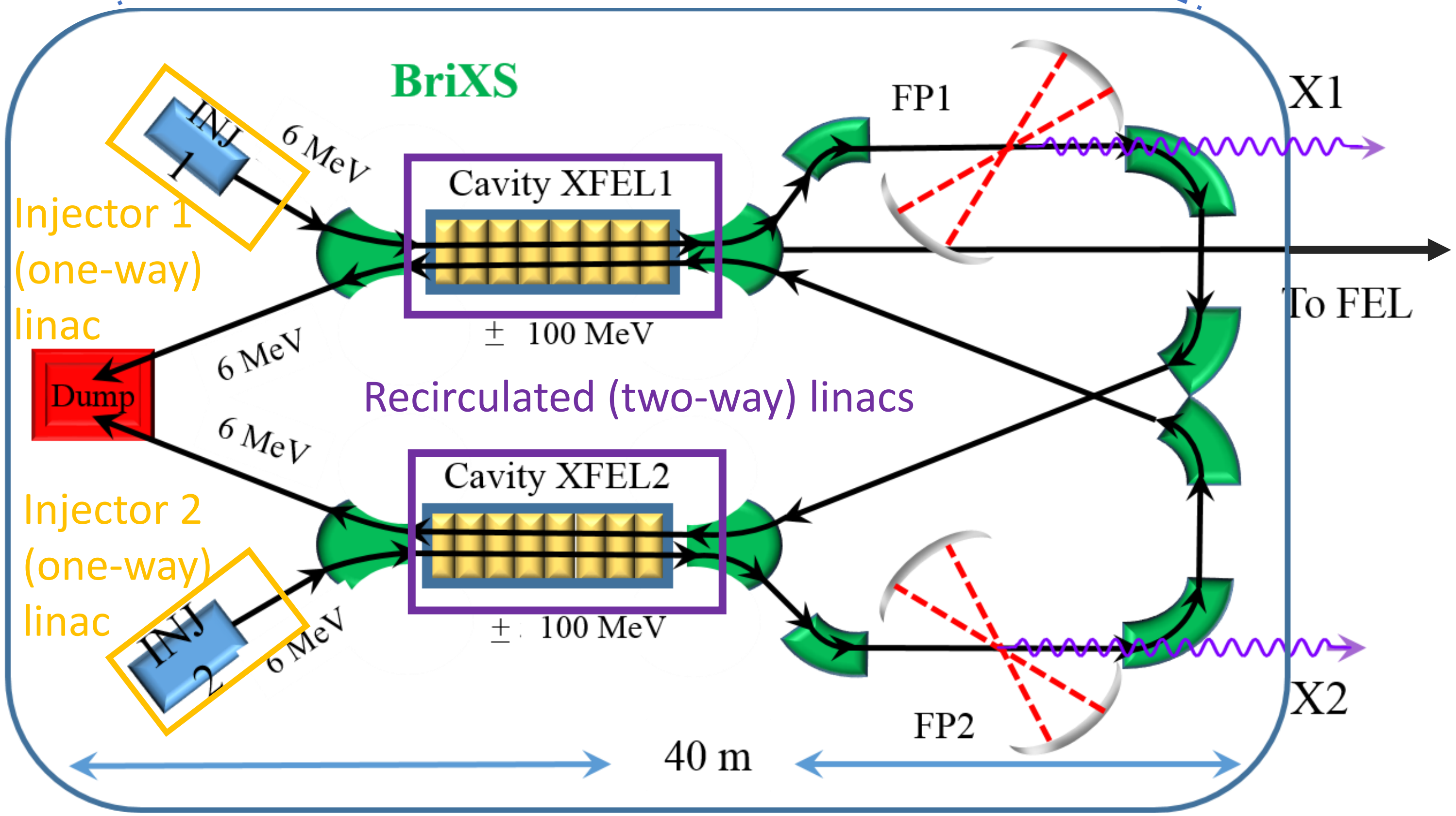
OPTIMISATION STUDY OF THE FABRY-PÉROT OPTICAL CAVITY FOR THE MARIX/BRIXS COMPTON XRAY SOURCE

Proceedings of IPAC2018, Vancouver, BC, Canada - Pre-Release Snapshot 06-May-2018 12:00 UTC

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

MARIX-FEL



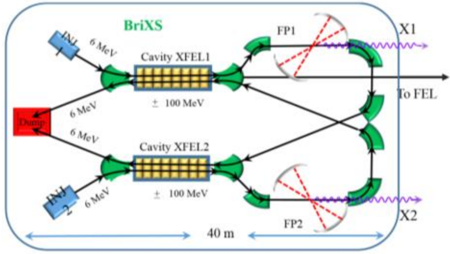


MARIX: Multidisciplinary Advanced Research Infrastructure with X-rays

- Joint project of INFN-Mi and University of Milan
- Twin X-ray Source of advanced characteristics for the future Scientific Campus:

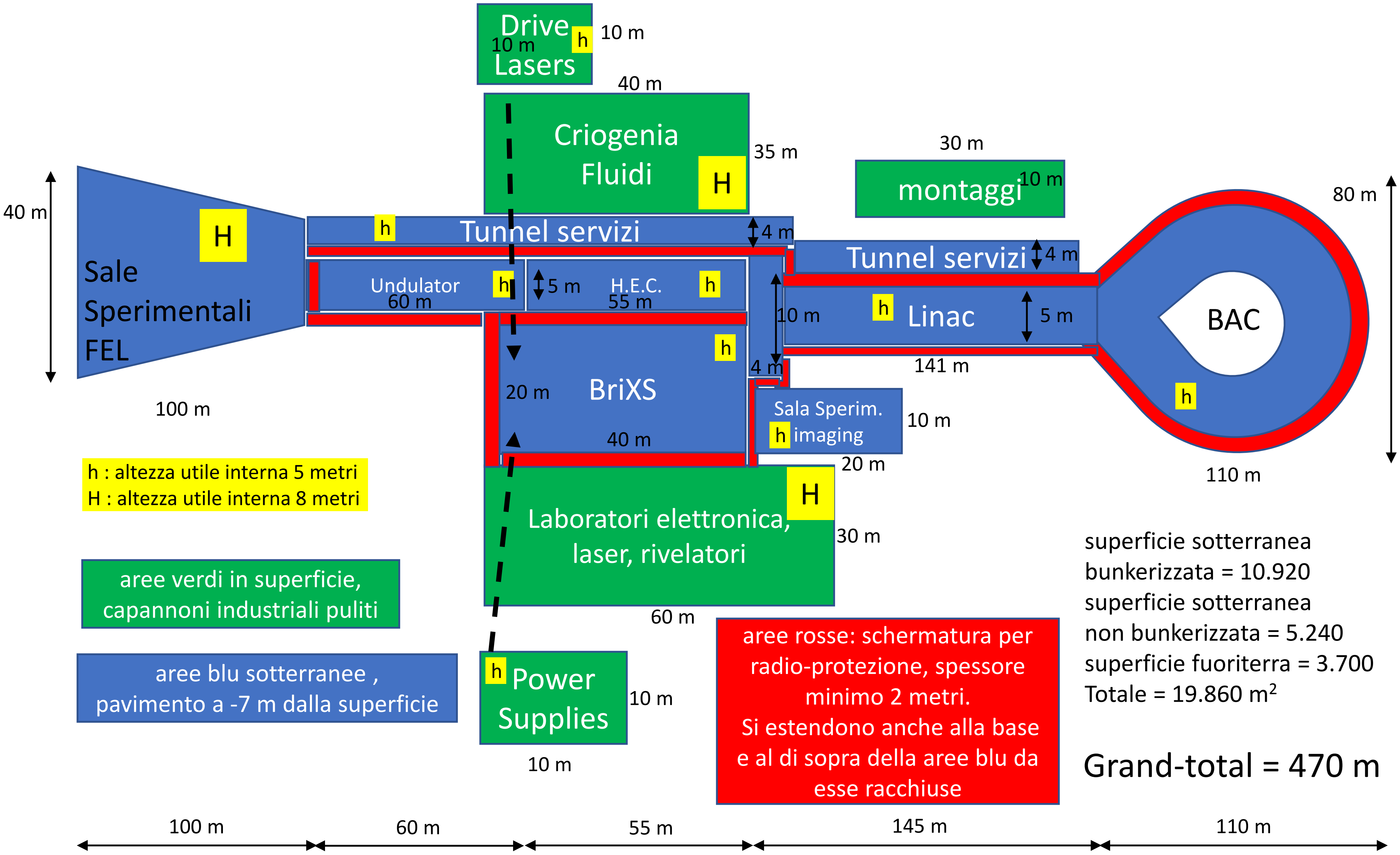
1. **BriXS** (Bright and compact X-ray Source): Compton X-ray source based on superconducting cavities technology with energy recirculation and on a laser system in Fabry-Pérot cavity at a repetition rate of 100 MHz.
2. **FEL** (Free Electron Laser): the BriXS accelerator is also the injector of a 3.8 GeV superconducting linac driving an X-ray FEL at 1 MHz, for providing coherent, moderate flux radiation.

BRIXS and MARIX Baseline Parameters



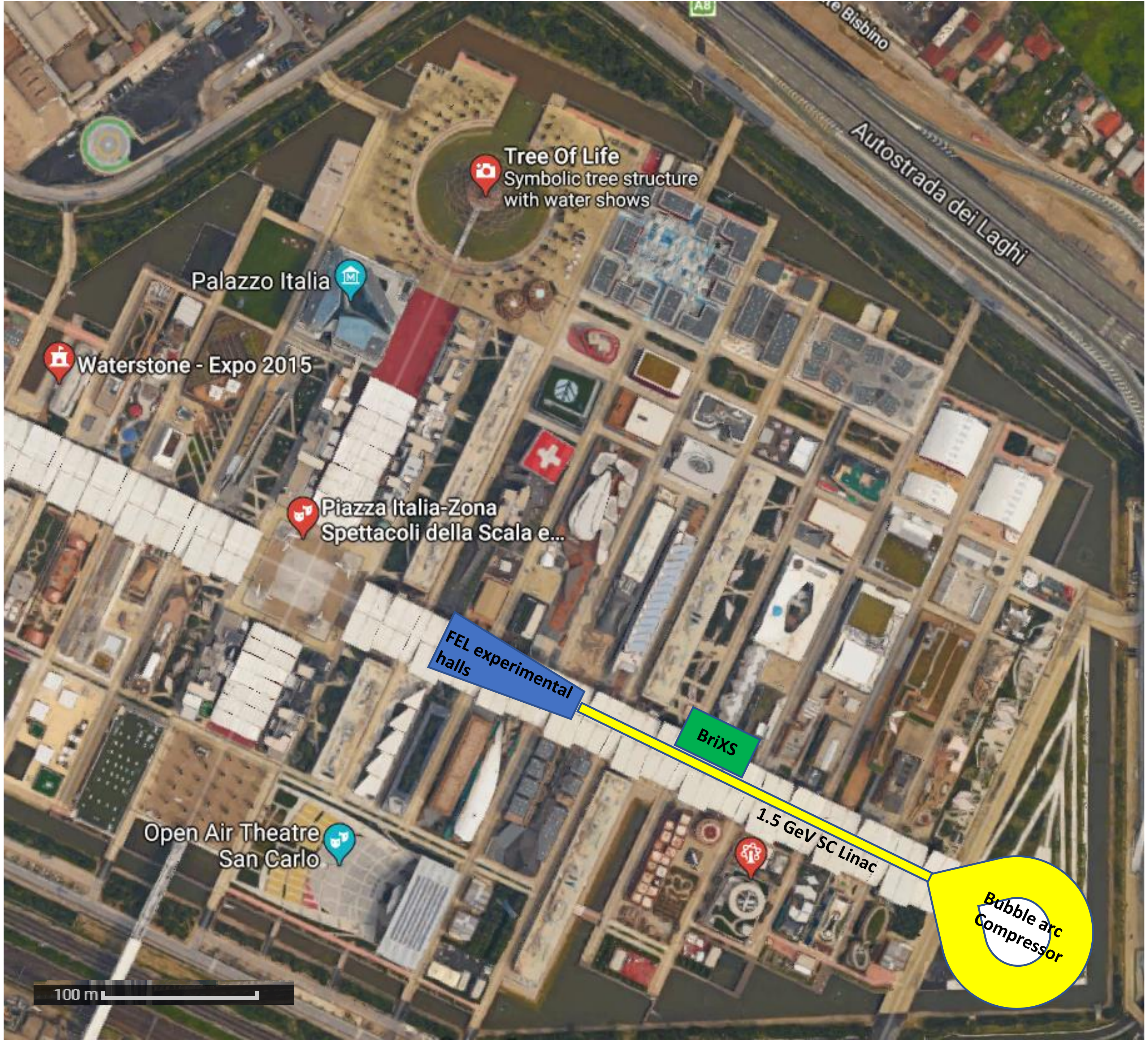
Parmeters		BRIXS	MARIX	
Electron Energy	E_e	0.1	3.2 – 3.8	GeV
Bunch Charge	Q_b	200	10-50	pC
Bunch Repetition Rate	f_b	100	1	MHz
Average e - current	$\langle I \rangle$	20	0.01-0.05	mA
Electron beam energy at linac end	P_b	Up to 0.1	Up to 3.8	GeV
Norm. transverse emittance at FP cavity	ε_n	≤ 1	-	mm-mrad
Norm. transverse emittance at undulator	ε_n	-	≤ 0.5	mm-mrad
Final peak current (at undulator)	$\hat{I}$	-	1.5 – 2	kA
RF frequency	f_{rf}	1.3	1.3	GHz
Avg. CW RF gradient	E_{acc}	12.5	16-17	MV/m
Avg. Cavity	Q_0	2.0E10	2.0E10	
Photon energy range	E_{ph}	20-180	5 – 12.4 (2.5 – 1)	keV (Å)
Numbers of photons per shot	$N_{ph}/shot$	1.5E5	5E9	
Numbers of photons per second	N_{ph}/sec	1.5E13	5E15	

MariX – Draft Civil Engineering version2 – option2

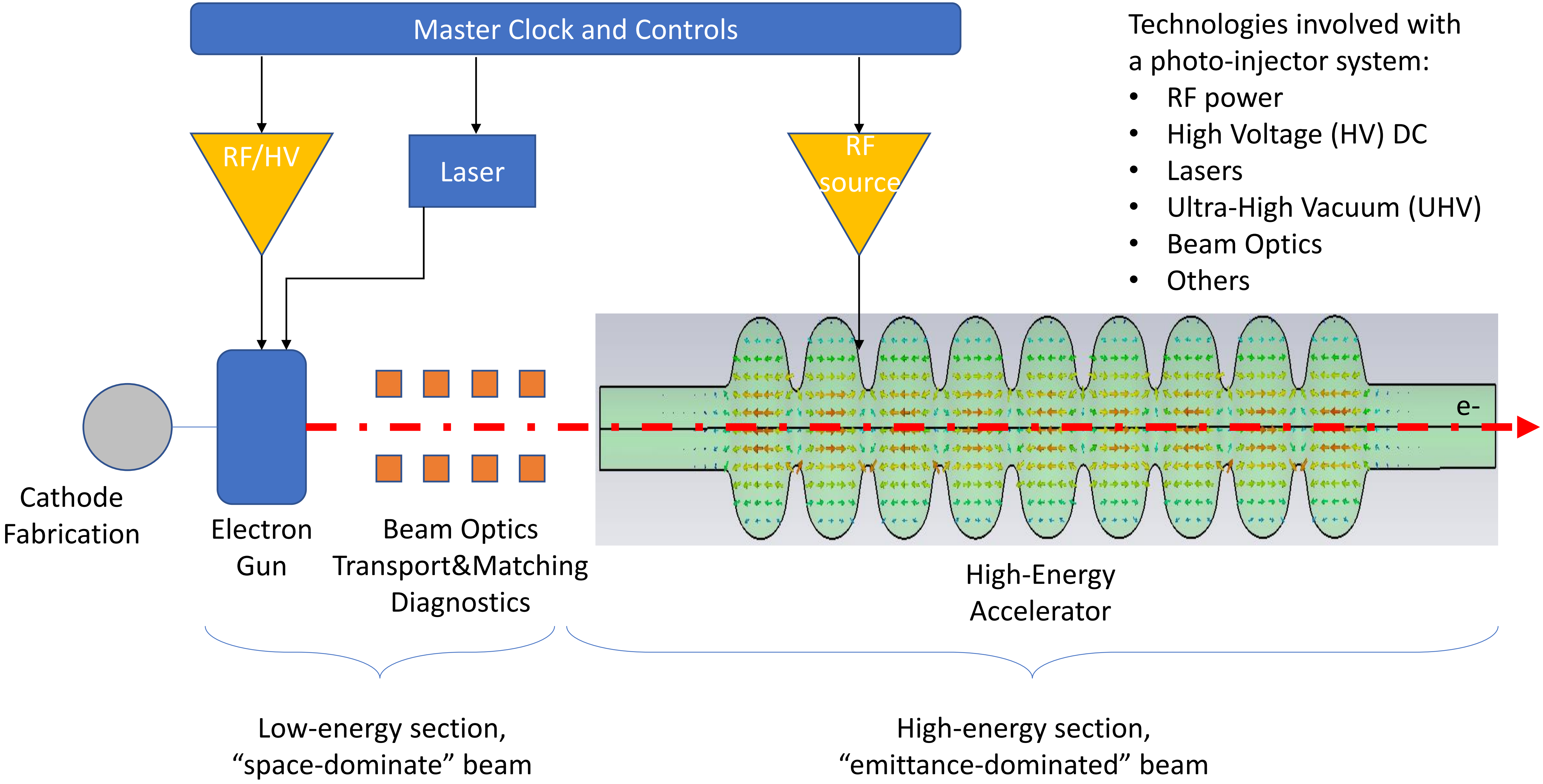


superficie sotterranea bunkerizzata = 10.920
superficie sotterranea non bunkerizzata = 5.240
superficie fuoriterra = 3.700
Totale = 19.860 m^2

Grand-total = 470 m


Tree Of Life
Symbolic tree structure
with water shows
Autostrada dei Laghi
Palazzo Italia
Waterstone - Expo 2015
Piazza Italia-Zona
Spettacoli della Scala e...
FEL experimental
halls
BriXS
1.5 GeV SC Linac
Bubble arc
Compressor
Open Air Theatre
San Carlo
100 m

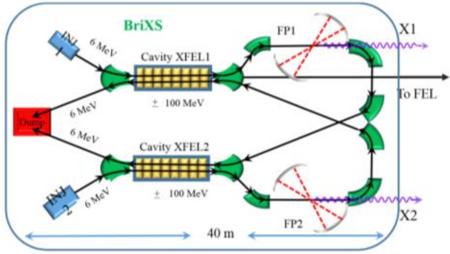
Injector system: main parts

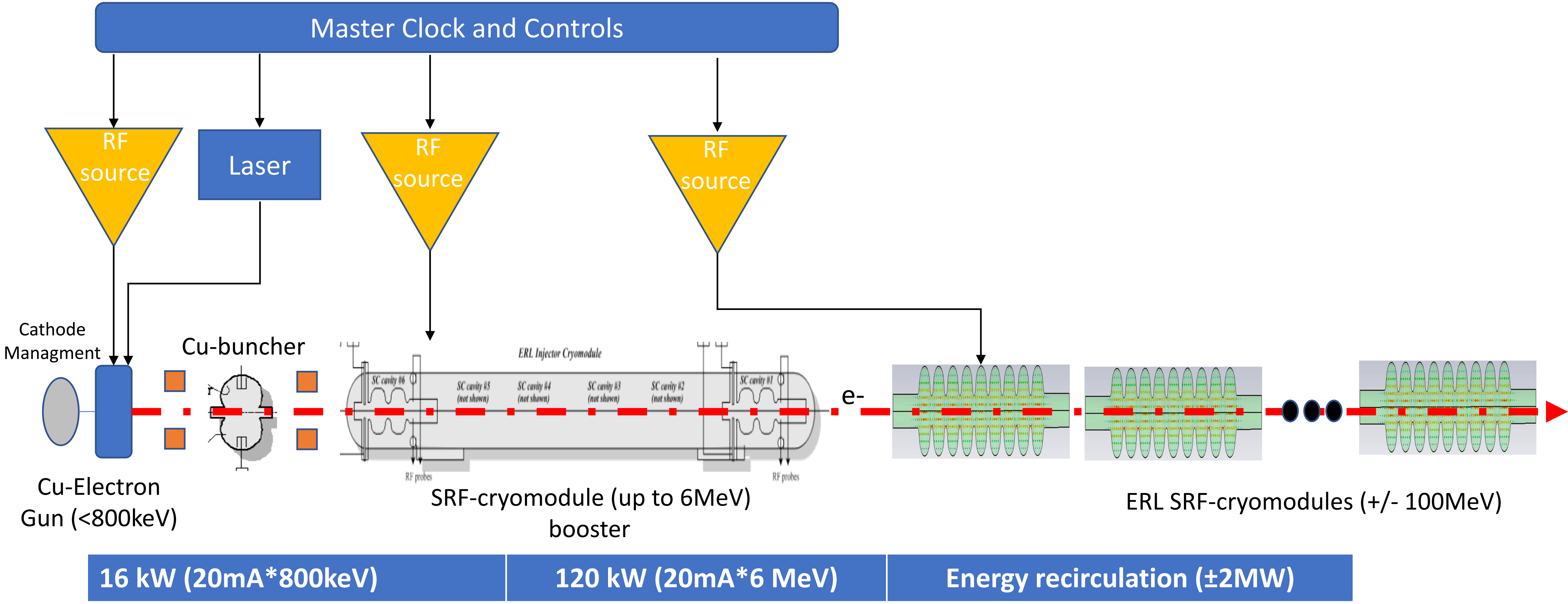


Technologies involved with a photo-injector system:

- RF power
- High Voltage (HV) DC
- Lasers
- Ultra-High Vacuum (UHV)
- Beam Optics
- Others

BriXS: RF power delivery (schematics)



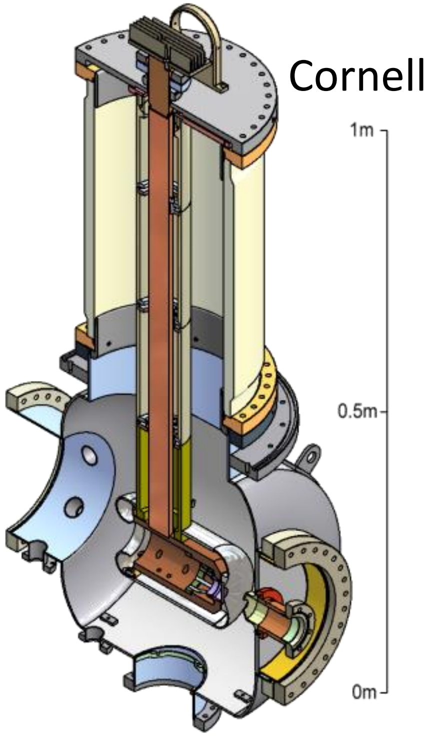


Beam power

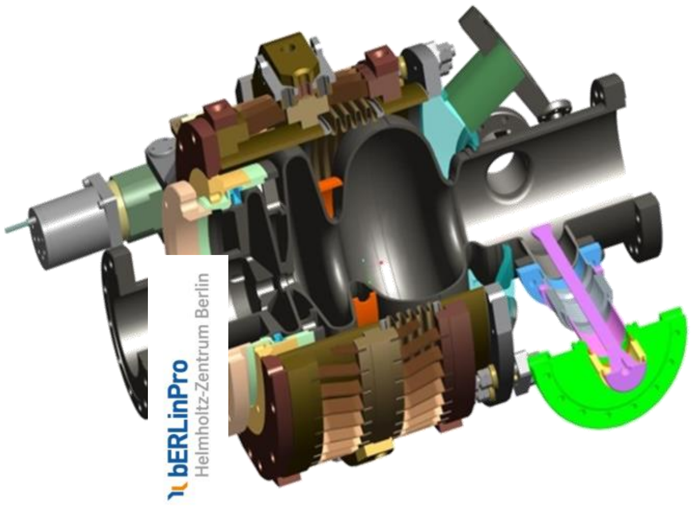
Which Photoinjector is best for CW operation?

- **Main Requirements**
  - **High Average beam current (>20mA for the Compton)**
  - **High QE (>0.5%)**
  - **Low emittance (<0.5μm for the FEL)**

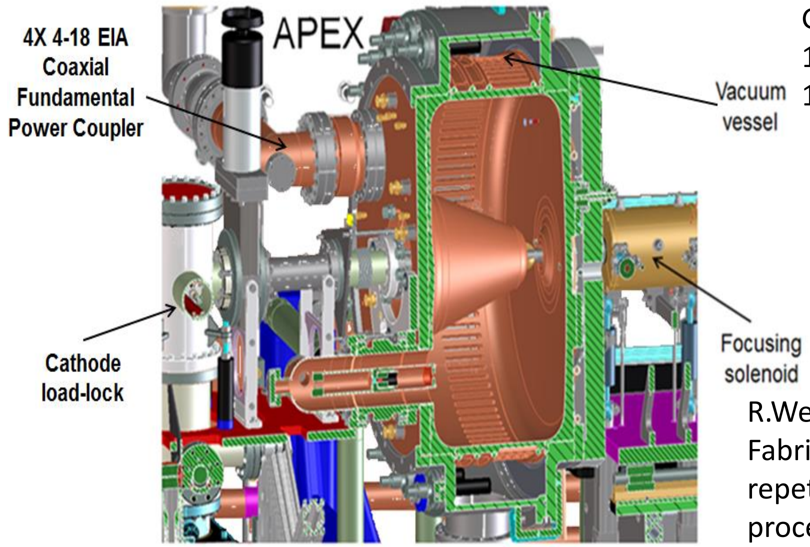
- **Technology**
  - **CW DC-Gun (<500kV)**
  - **CW RF Gun (operating at sub-harmonic,<187MHz)**
  - **Superconducting RF (SRF) multi-cell gun**



Gulliford et al., Appl. Phys. Lett. 106, 094101 (2015); doi: 10.1063/1.4913678



-A.Burrill et al., First horizontal test results of the hzb srf photoinjector for bERLinPro, Proceedings of IPAC2015.



R.Wells et al., Design and Fabrication of a VHF high repetion rate electron gun, proceedings of IPAC2014.

INFN

Which Photoinjector technology is best for CW operation?

CW DC-Gun	CW RF-Gun	SRF multi-cell gun
DC Voltage (<500 kV, Cornell)	Low frequency (187 MHz, APEX)	High Frequency (1.3GHz, bERLinPRO)
Gradient at cathode is limited (E_{peak}=6MV/m)	Gradient at cathode is higher (E_{peak}=20MV/m)	Gradient at cathode is higher (E_{peak}=30MV/m)
Multipacting, ion-back-bombardment and dark current are under control.	Multipacting, ion-back-bombardment and dark current are under control.	• Multipacting, ion-back-bombardment and dark current need to be under control. • Implications due to high QE cathode/ SRF cavity interface → impact on cavity performance
Lower output energy (300keV) → Higher space-charge	Higher output energy (800keV) but possible upgrade to multi-cell (APEX-II, >2MeV) → Lower space-charge	Higher output energy (up to 2.3MeV) → Lower space-charge
• 0.4/0.6 µm emittance@100/300 pC (@injector exit <9MeV) • Stable operation at high average current (>100mA, laser reprate 1.3GHz)	• 0.4/0.6 µm emittance @100/300 pC (@injector exit <9MeV) • Operation at low average current (<1mA limited by their laser reprate at 1MHz)	No measurements found! Prediction: 100mA, 1mm-mrad
Start-to-end simulations (LCLS-II, SLAC group) showed better behavior of the APEX gun with respect to Cornell's in terms of beam quality and performance: 1. High-order modes in the longitudinal phase space 2. Microbunching instability 3. CSR inside the bunch compressors (BC1 and BC2)		Relatively young technology, need more experimental setups* *SRF Gun Development for High Brightness, Short Pulse Applications by Thorsten Kamps, kamps@helmholtz-berlin.de Ultra Fast Beams and Applications, Yerevan, Armenia 05.07.2017

Photocathode Choice I: Quantum Efficiency (QE)

$$QE = 1240 \frac{\langle I \rangle (Amperes)}{P_{laser}(watts) \times \lambda(nm)}$$

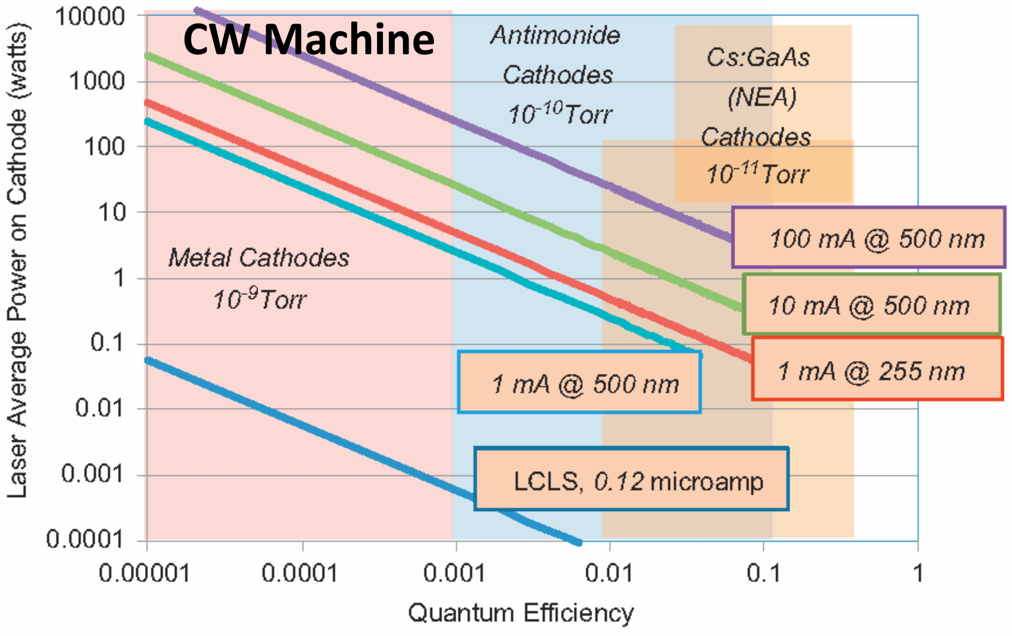
- **Semiconductor** photocathodes have high QE !!!
  - Their sensitivity to gas exposition requires UHV conditions.

- Requirements inside an electron Gun:

1. QE uniformity
2. Low dark current
3. Long operative lifetime
4. Stable operation along the train
5. Fast response time

- High QE photocathodes (like Cs_2Te) have typical QE ≥ 10 % (fresh cathode, λ = 254 nm), good spatial uniformity and high robustness. UHV condition needed. ← @LASA (INFN-MI)
- With λ = 262 nm (E_{ph} = 4.7 eV), with a conservative value of QE = 0.5 % (Cs_2Te) to produce 200 pC

Laser Pulse Energy = 19.1 nJ
corresponding to
Laser Power = 19.1 W (at 100 MHz)



Cathode type	Cathode	Typical wavelength & energy, λ_{opt} (nm), (eV)	Quantum efficiency (electrons per photon)	Vacuum for 1000 h (Torr)
PEA: mono-alkali	Cs_2Te	211, 5.88	0.1	10^{-9}
		264, 4.70	–	–
		262, 4.73	–	–
	Cs_3Sb	432, 2.87	0.15	?
	K_3Sb	400, 3.10	0.07	?
	Na_3Sb	330, 3.76	0.02	?
	Li_3Sb	295, 4.20	0.0001	?
PEA: multi-alkali	Na_2KSb	330, 3.76	0.1	10^{-10}
	$(Cs)Na_2KSb$	390, 3.18	0.2	10^{-10}
	K_2CsSb	543, 2.28	0.1	10^{-10}
	$K_2CsSb(O)$	543, 2.28	0.1	10^{-10}
NEA	GaAs(Cs,F)	532, 2.33	0.1	?
		860, 1.44	0.1	?
	GaN(Cs)	260, 4.77	0.1	?
	$GaAs(1-x)Px$ $x\sim0.45$ (Cs,F)	532, 2.33	0.1	?
S-1	Ag–O–Cs	900, 1.38	0.01	?

D. Dowell et al., NIM A 622(2010) 685

Photocathode Choice II: Quantum Efficiency (QE)

- Thermal emittance is the lower limit of the emittance
- It depends on:
  - Eg+Ea (for a semiconductor) or to the ϕ work function for a metal
  - The laser photon energy

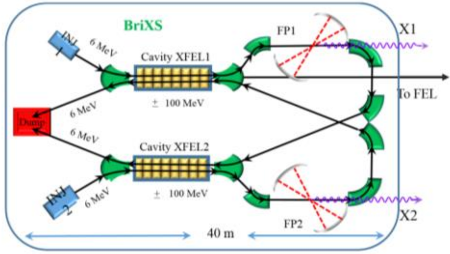
$$\frac{\varepsilon_{th}}{\sigma_x} = \sqrt{\frac{h\nu - (E_g + E_a)}{3mc^2}}$$

$$\frac{\varepsilon_{th}}{\sigma_x} = \sqrt{\frac{h\nu - \phi}{3mc^2}}$$

$$\varepsilon_{th,min} = \sqrt{\frac{Q}{12\pi\varepsilon_0 mc^2}\frac{\hbar\omega - \phi}{E_{rf}}}$$

material	Eg + Ea (or ϕ)	λ laser	ε_{th} (Formula)	ε_{th} (Exp.)	QE (%)
Cs_2Te	3.5	264 nm	0.9	0.5 ± 0.1	10
K_2CsSb	2.1	543 nm	0.4	0.36 ± 0.04	5
Cu	4.6	250 nm	0.5	1.0 ± 0.1	$1.4\ 10^{-2}$

Data from LASA (INFN-Milan)

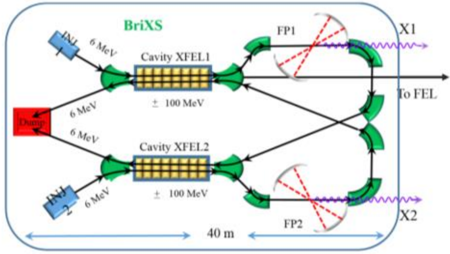


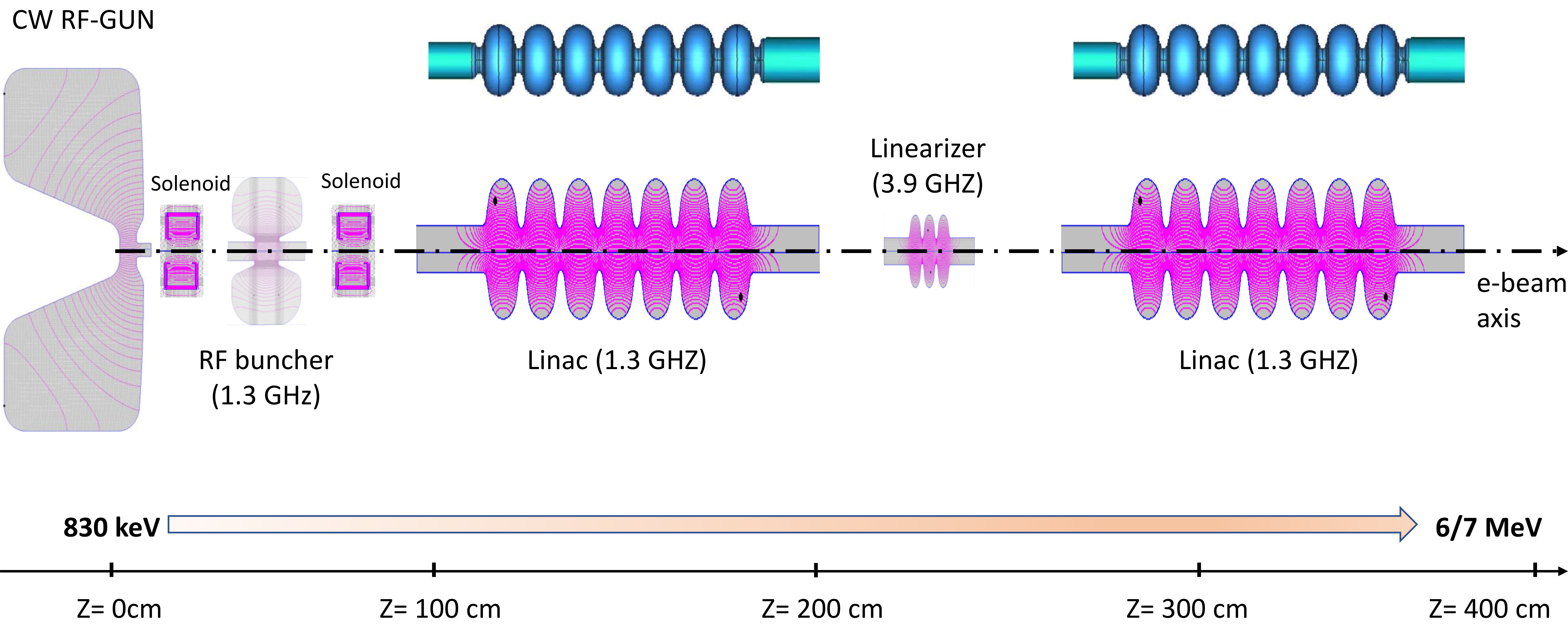
RF and Beam Dynamics Simulations for the BriXS injector

- After many tests and discussions about beam dynamics, we focused on the final injector layout;

- Crucial was the contribute of the Genetic Algorithm GIOTTO, to find the active element positions, fields intensity and the final optimal beam parameter (emittance, current, energy spread).

Injector layout (1 beam-line) (SuperFish 2D model)

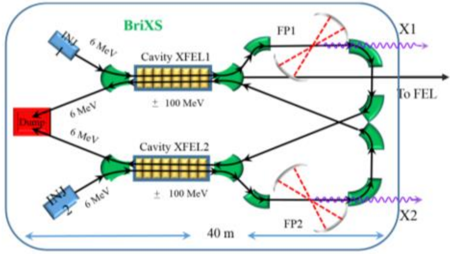




BRIXS injector
RF power specifications

	CW RF-Gun	Buncher	Linac I	Linearizer	Linac II
Technology	Normal Conducting	Normal Conducting	Super Conducting	Super Conducting	Super Conducting
Frequency (MHz)	187	1300	1300	3900	1300
Effective Shunt Impedance per unit length (Ω/m)	162.5E6	37.5E6	2.0E13	3.46E13	2.0E13
Effective Shunt Impedance (Ω)	6.5E6	17E6	1.61E13	6.91E12	1.61E13
Quality Factor Q_0	30880	25000	2.0E10	3.46E10	2.0E10
Accelerating Voltage V_{acc} (MV)	0.83	0.35	3.26	1.2	3.8
Gap Length (cm)	4	16	100	20	100
Accelerating Gradient E_{acc} (MV/m)	20.75	2.1875	3.83	6	4.47
Injection Phase *inj* (°)	-3.8	-80.1	11.05	-156.5	22.7
Energy Gain (MeV) [=V_{acc}cos(*inj*)]	0.83	0.06	3.2	-1.1	3.5
Cavity wall dissipation power (W), beam OFF	87500	7200	0.64	0.37	0.76
Total RF power (W), beam ON	102500	~7200	64000	22000	70000
RF power supply	>100kW CW Triode	<10kW CW IOT	100kW CW Klystron	<30kW CW IOT	100kW CW Klystron

BRIXS injector
Beam Dynamics Simulations



Input beam

- 50pC case
  - Parmela results
  - Parmela and Giotto Comparison

To the MARIX FEL

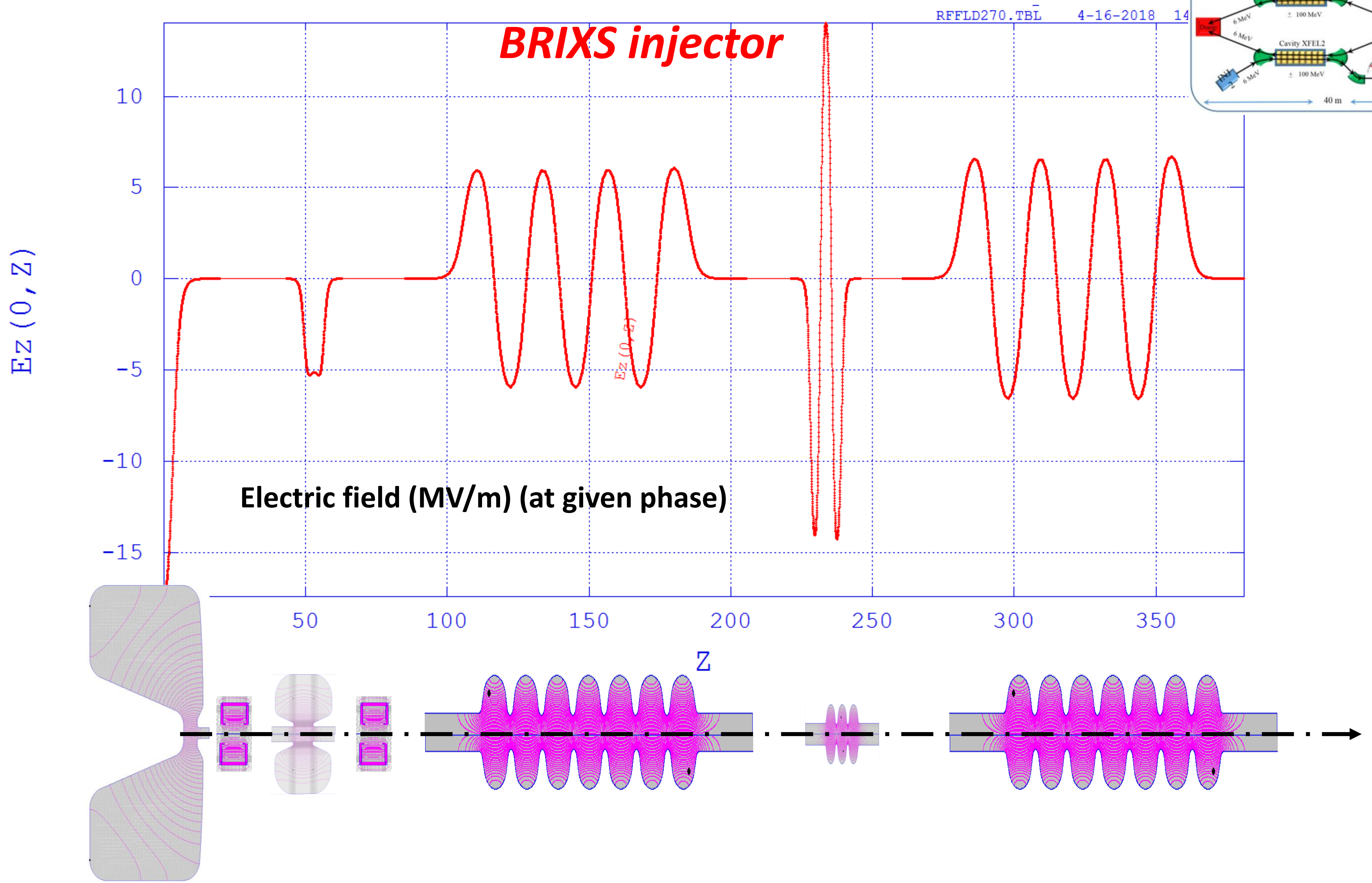
Q=50 pC
σ_x=200μm
Bunch length
~40ps (18.7°)

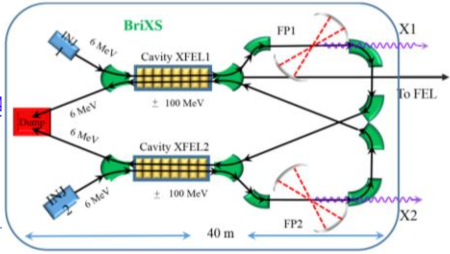
- 200pC case
  - Parmela results

To the Compton source

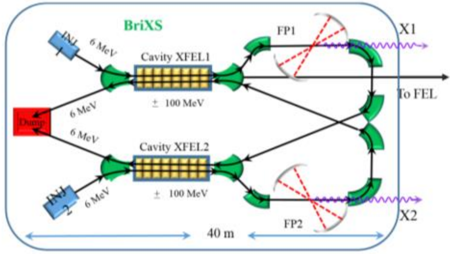
Q=200 pC
σ_x=420μm
Bunch length
~48ps (22.5°)

Parmela Simulations
BRIXS injector



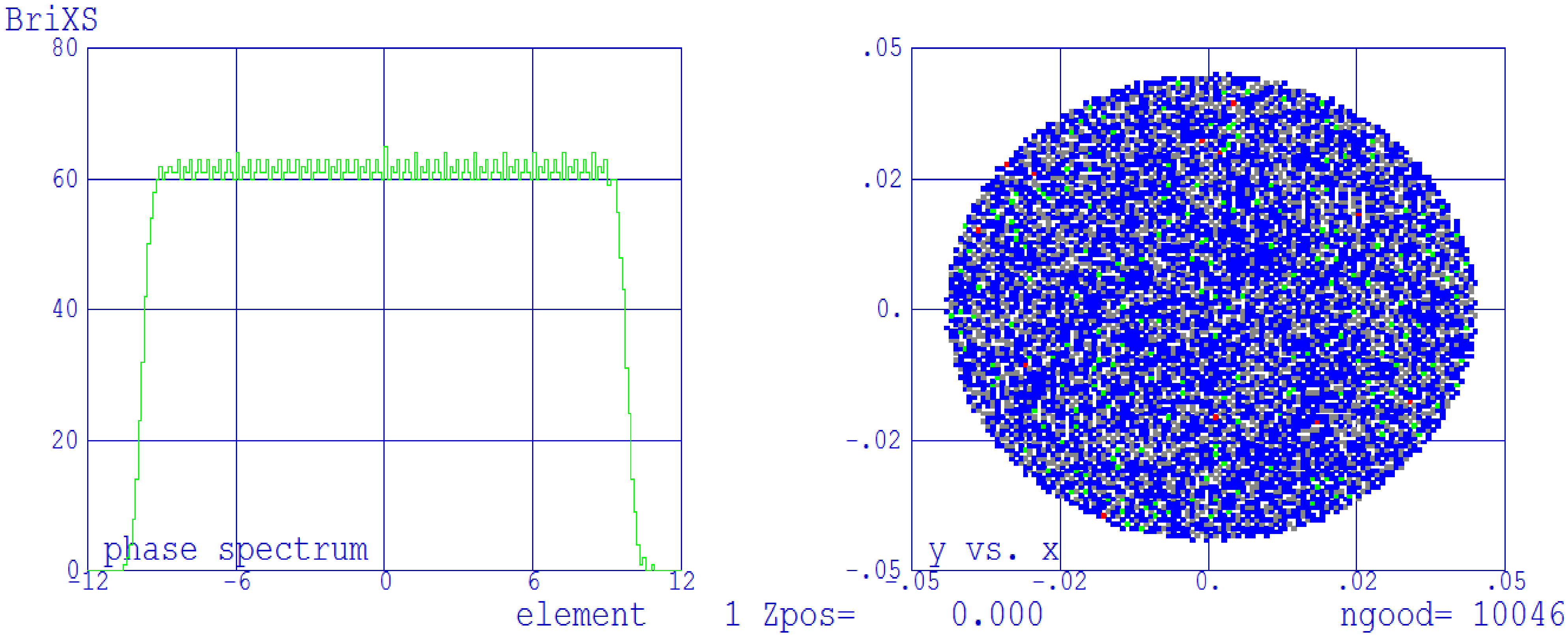


Input Beam Phase Space



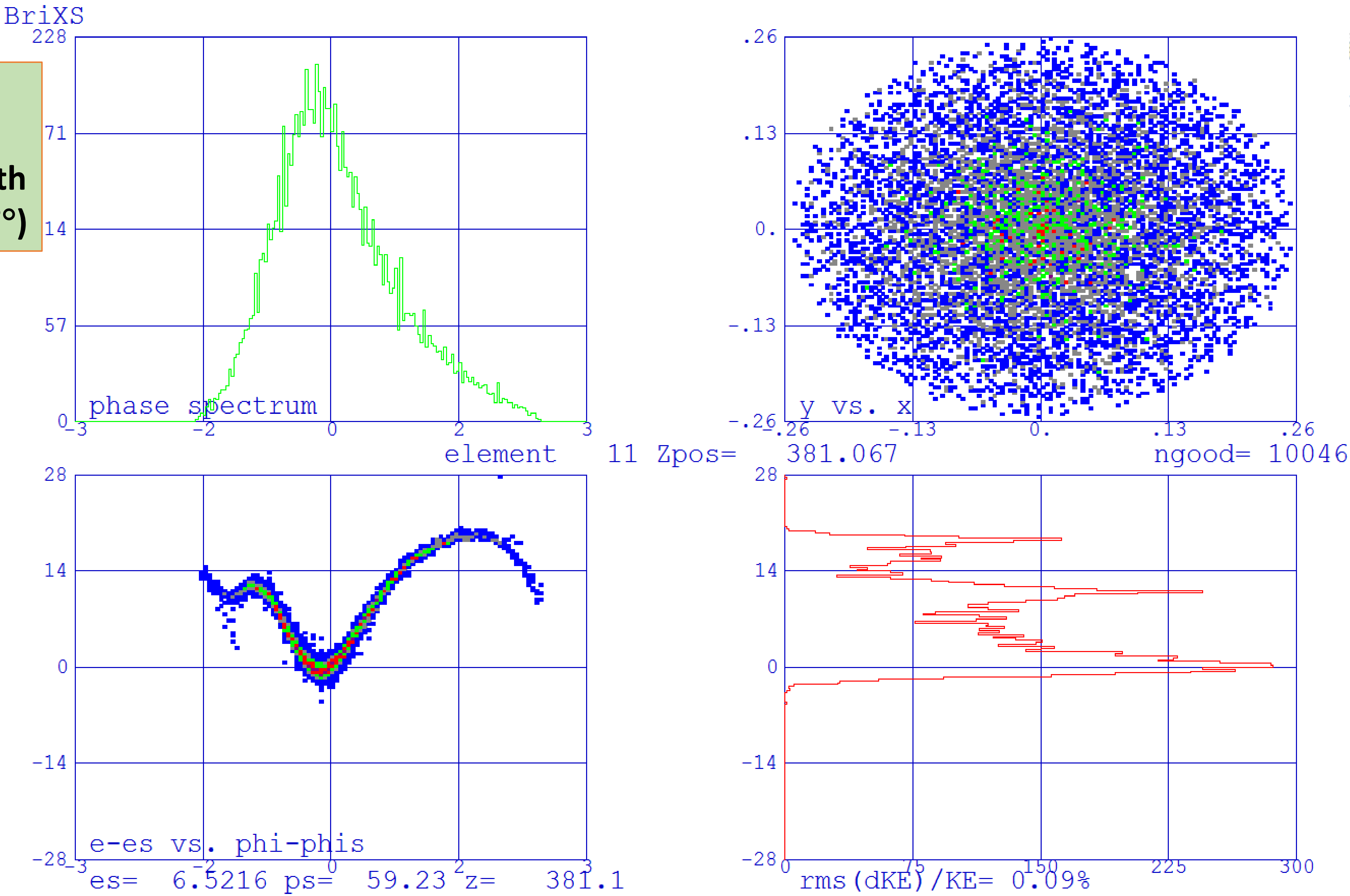
"Low charge case"

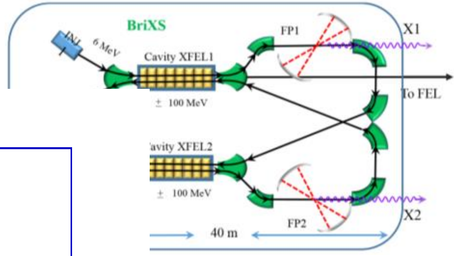
Q=50 pC
σ_x=200μm
Bunch length ~ 40ps (18.7°)
1ps rise time



Output Beam Phase Space

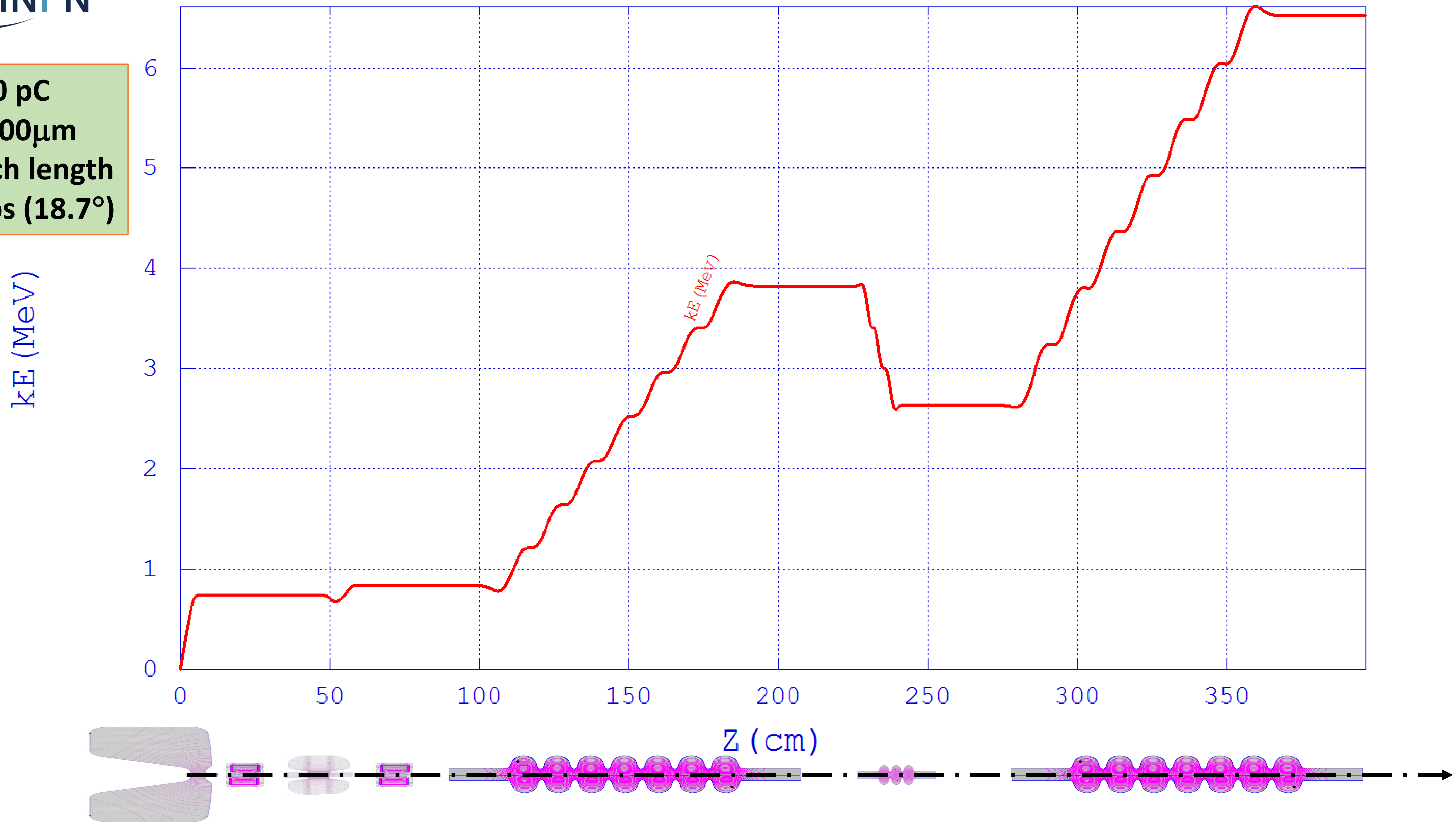
Q=50 pC
σ_x=200µm
Bunch length ~40ps (18.7°)





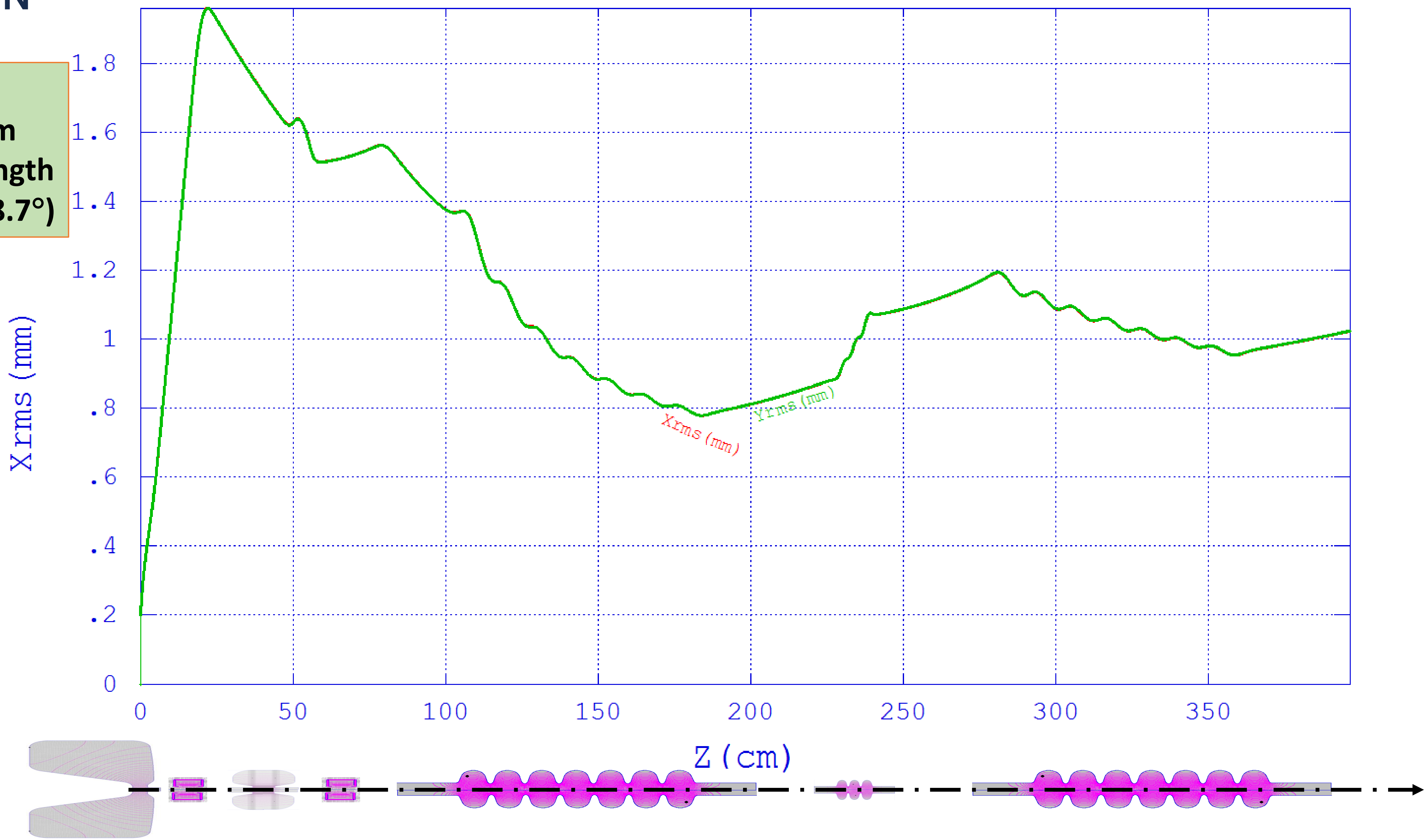
Energy

Q=50 pC
σ_x=200μm
Bunch length ~40ps (18.7°)



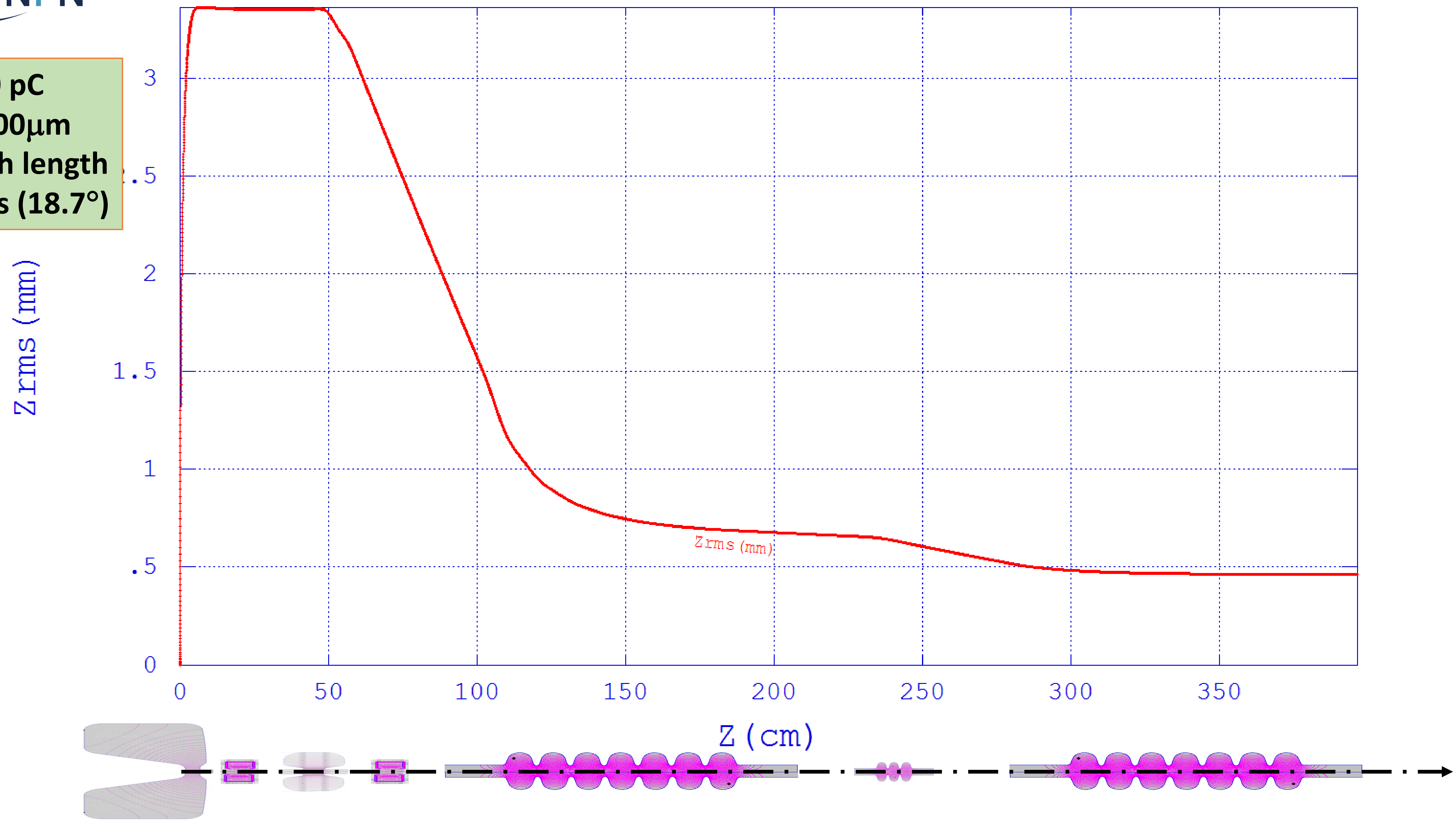
Transverse Profile sigmaX,Y

Q=50 pC
σ_x=200μm
Bunch length
~40ps (18.7°)



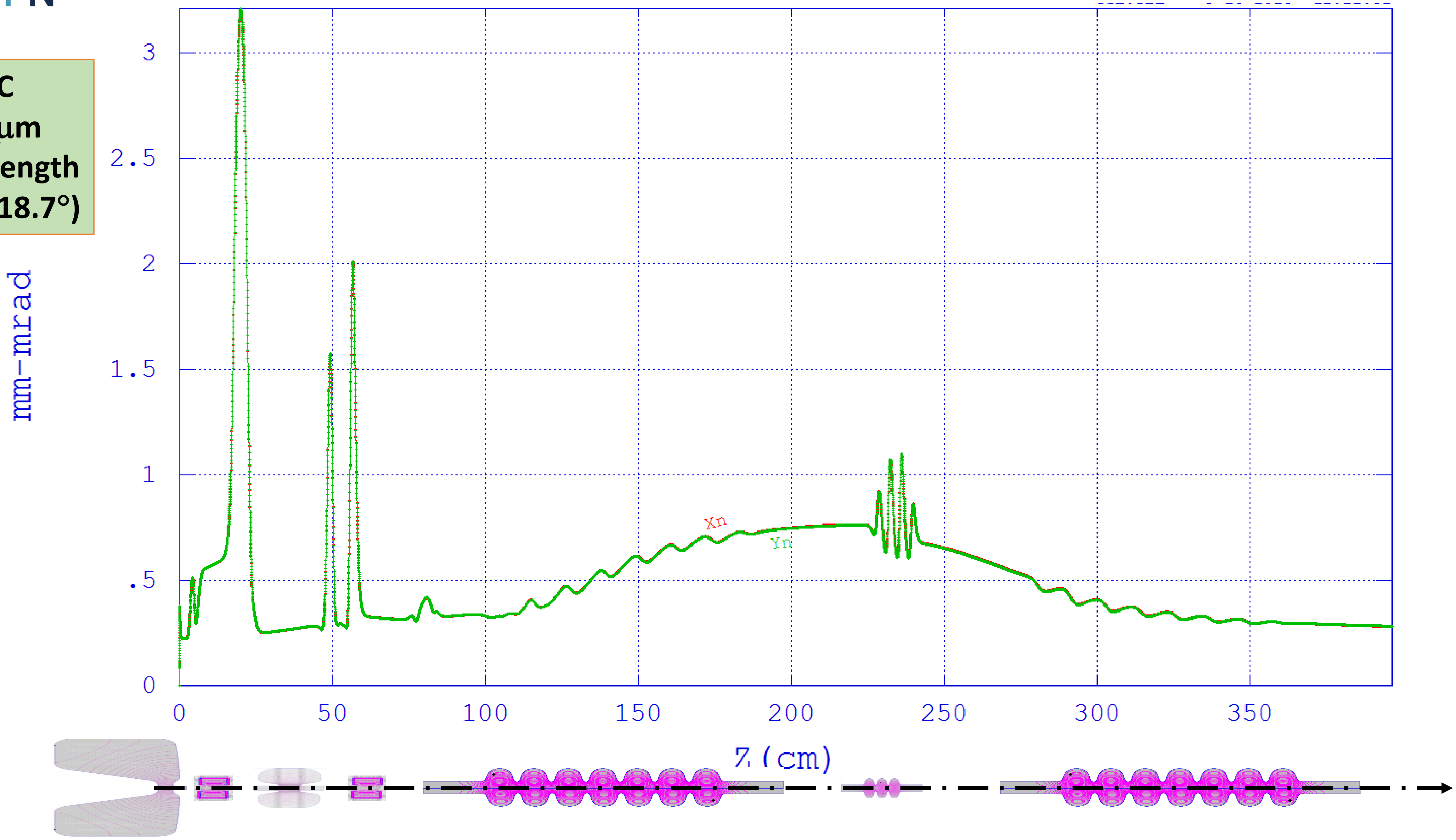
Longitudinal Profile SigmaZ

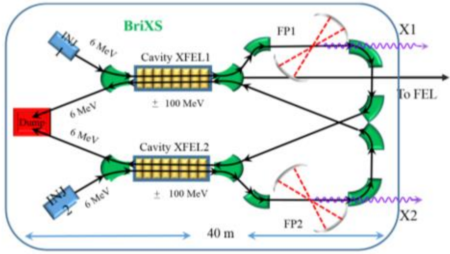
Q=50 pC
σ_x=200µm
Bunch length
~40ps (18.7°)



Normalized Transverse Emittance Xn, Yn

Q=50 pC
σ_x=200μm
Bunch length
~40ps (18.7°)



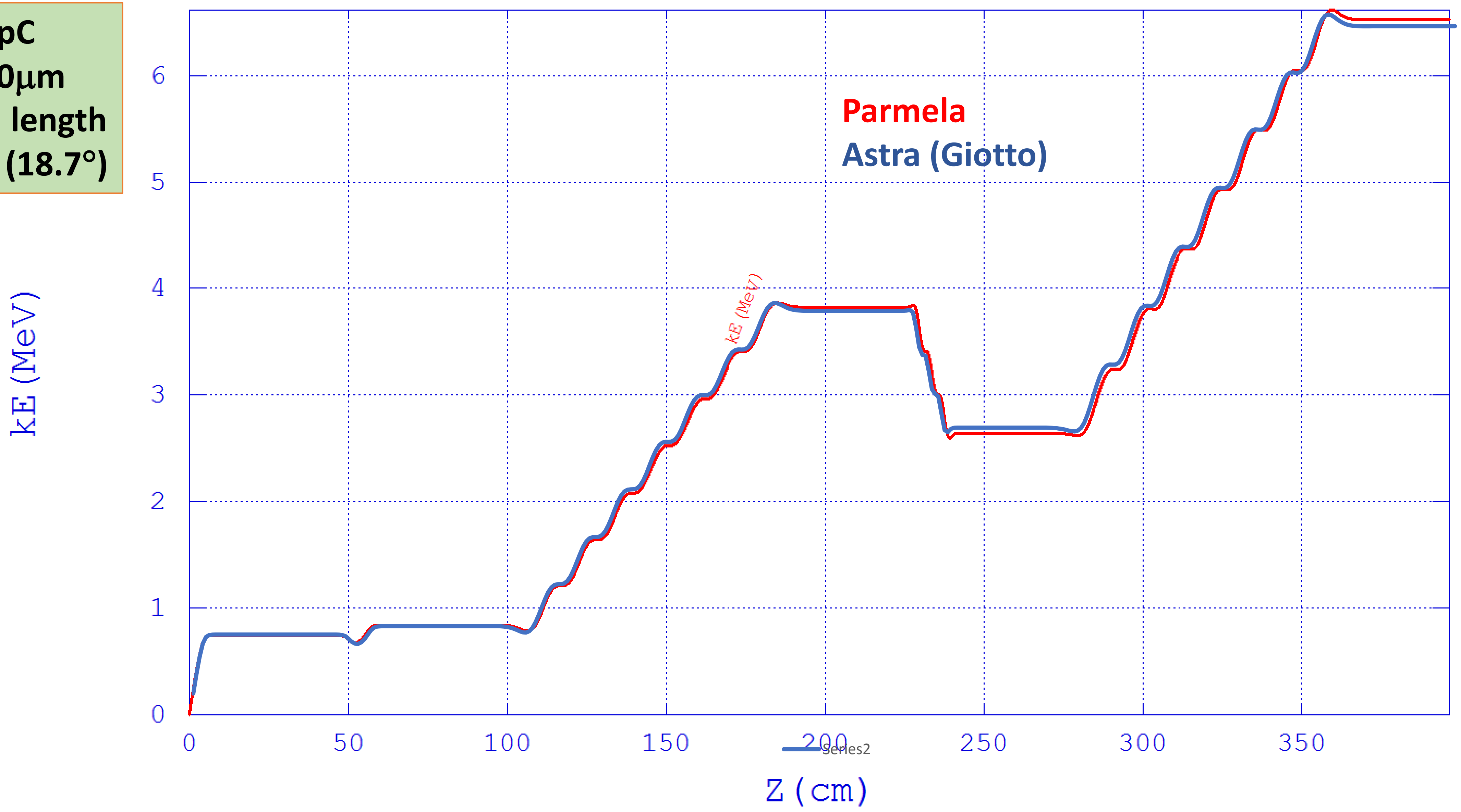


Comparison between Parmela and Astra results

Optimized with algorithm code GIOTTO (A.Bacci)

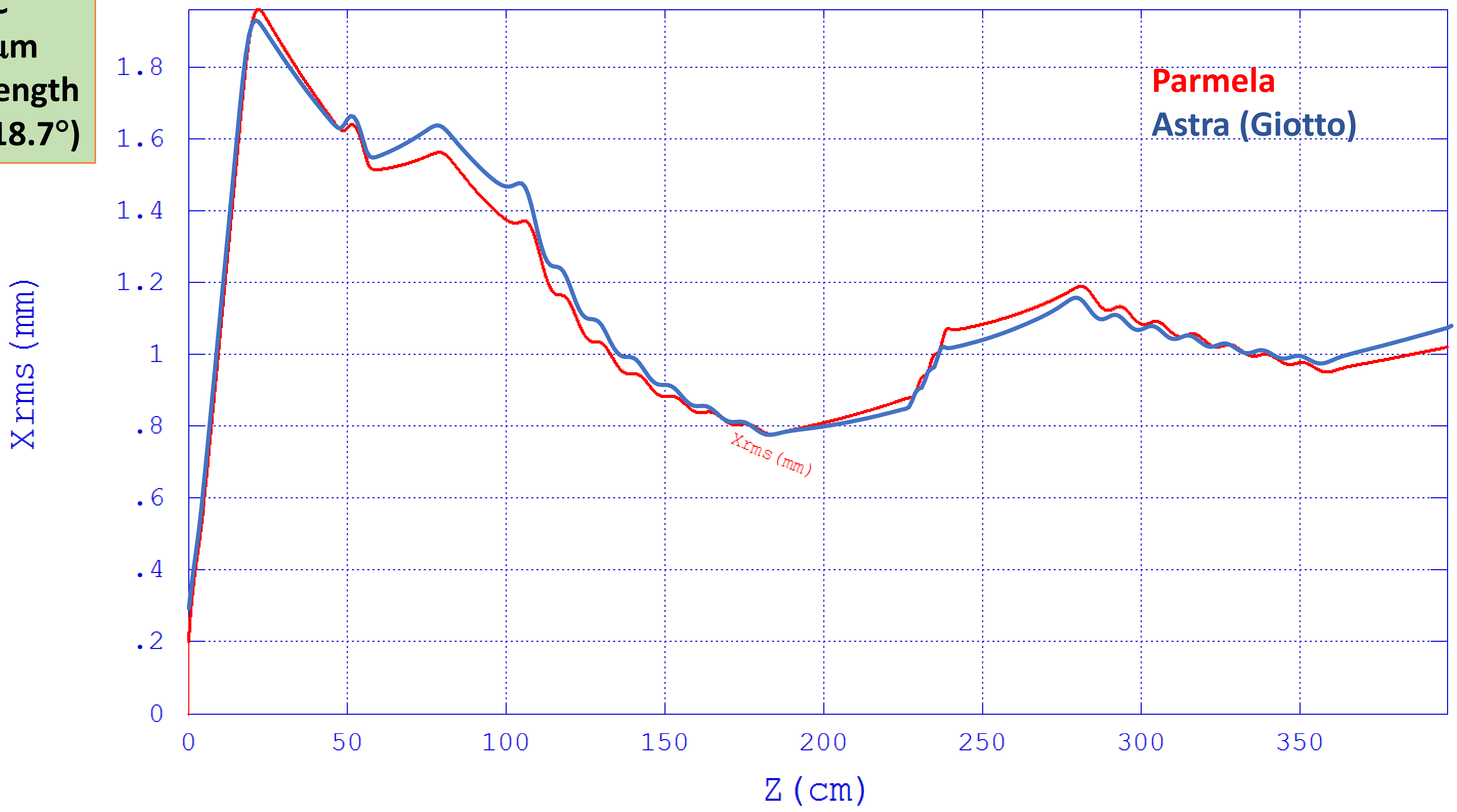
Energy

Q=50 pC
σ_x=200µm
Bunch length ~40ps (18.7°)



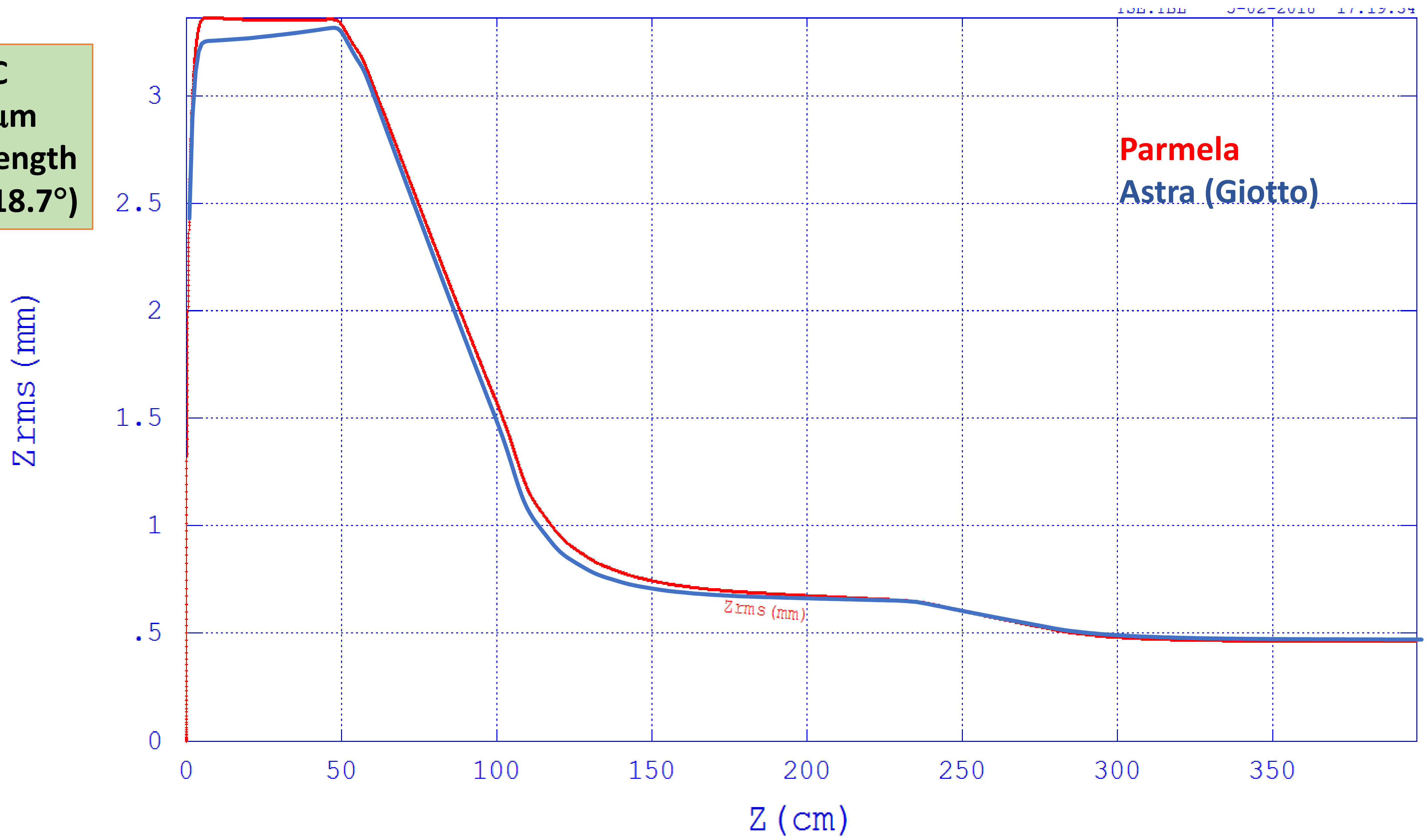
Transverse Profile sigmaX,Y

Q=50 pC
σ_x=200μm
Bunch length
~40ps (18.7°)



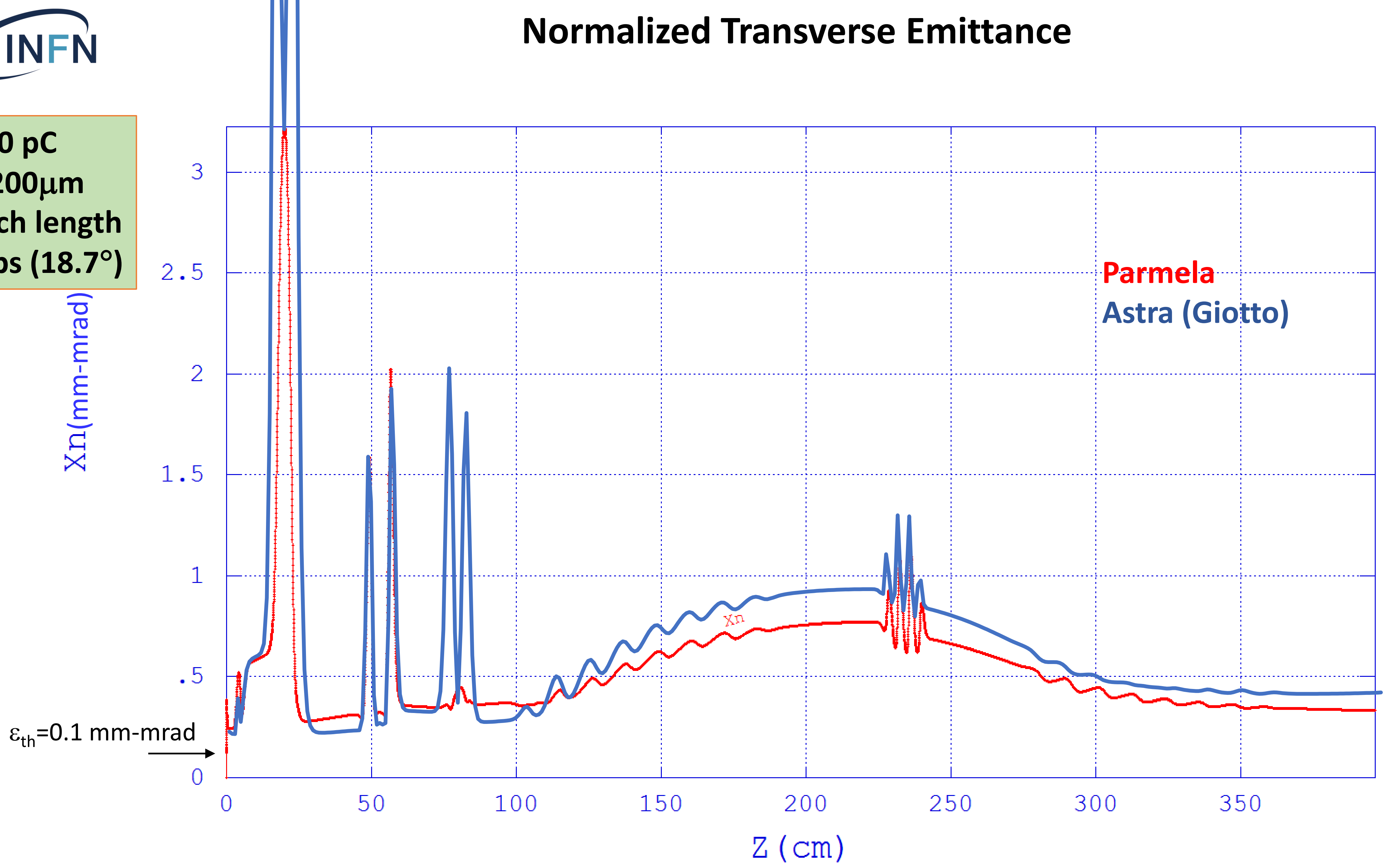
Longitudinal Profile SigmaZ

Q=50 pC
σ_x=200μm
Bunch length
~40ps (18.7°)



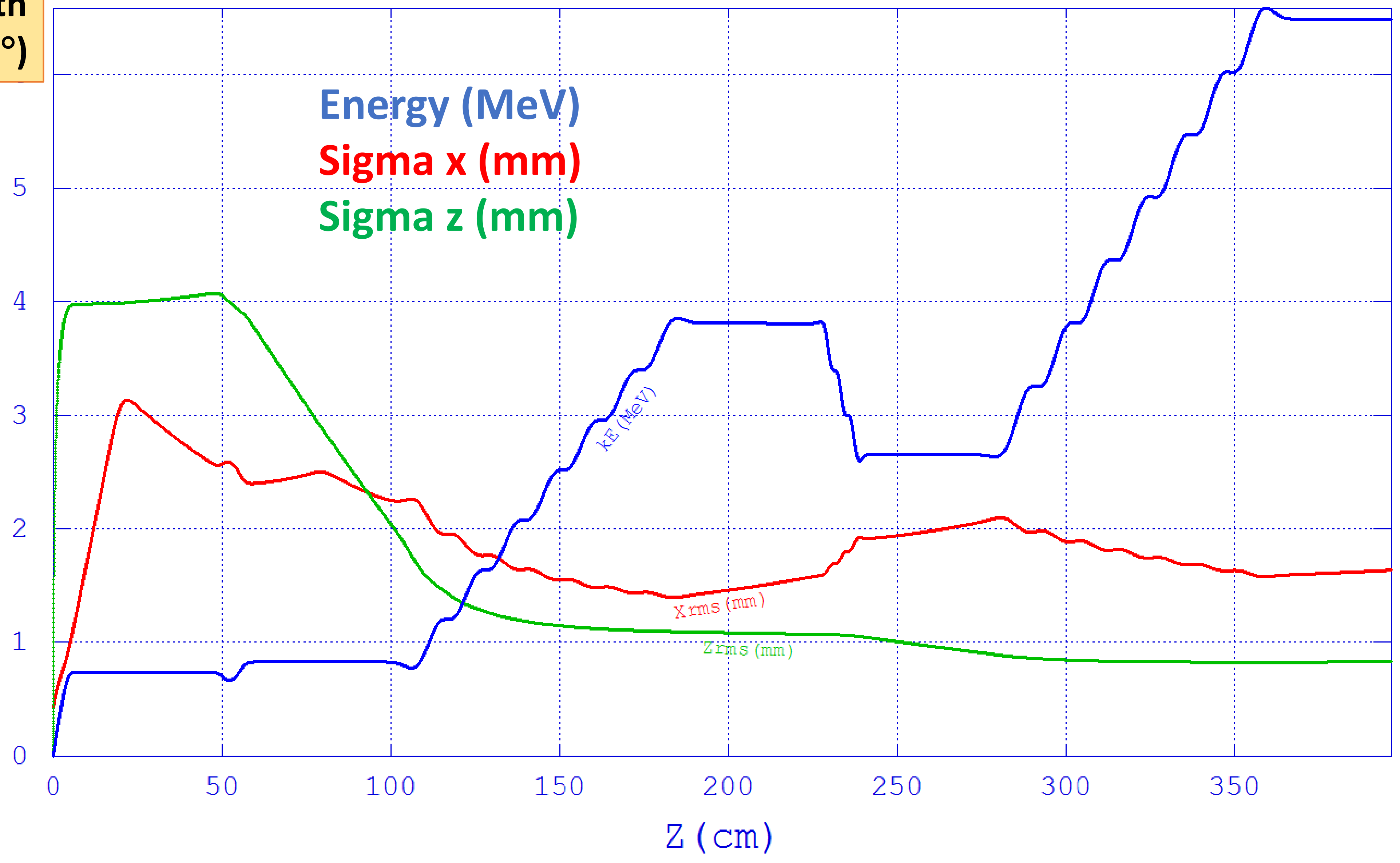
Normalized Transverse Emittance

Q=50 pC
σ_x=200μm
Bunch length
~40ps (18.7°)



Q=200 pC
σ_x=420μm
Bunch length
~48ps (22.5°)

“High charge case”



Q=200 pC
σ_x=420μm
Bunch length
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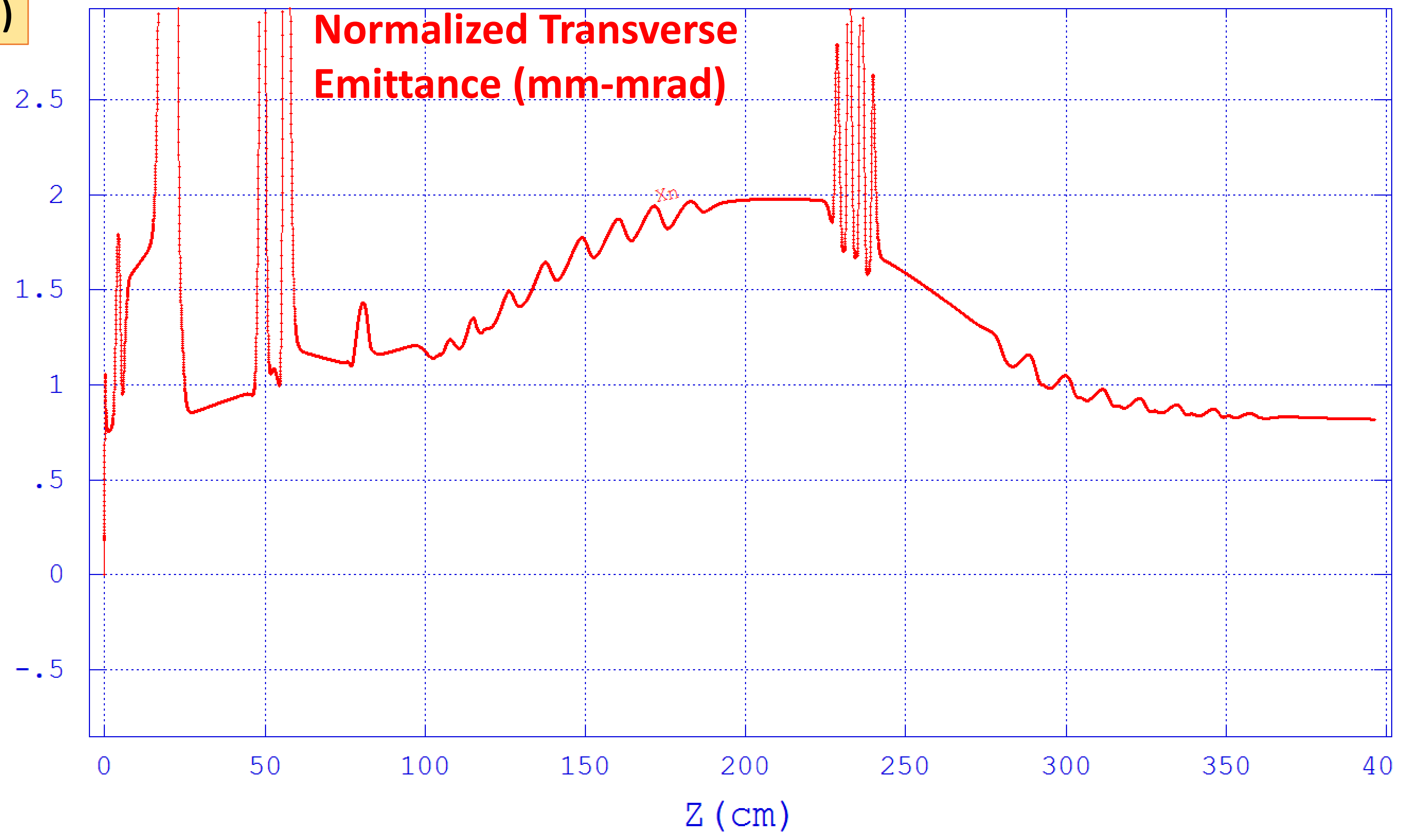
"High charge case"



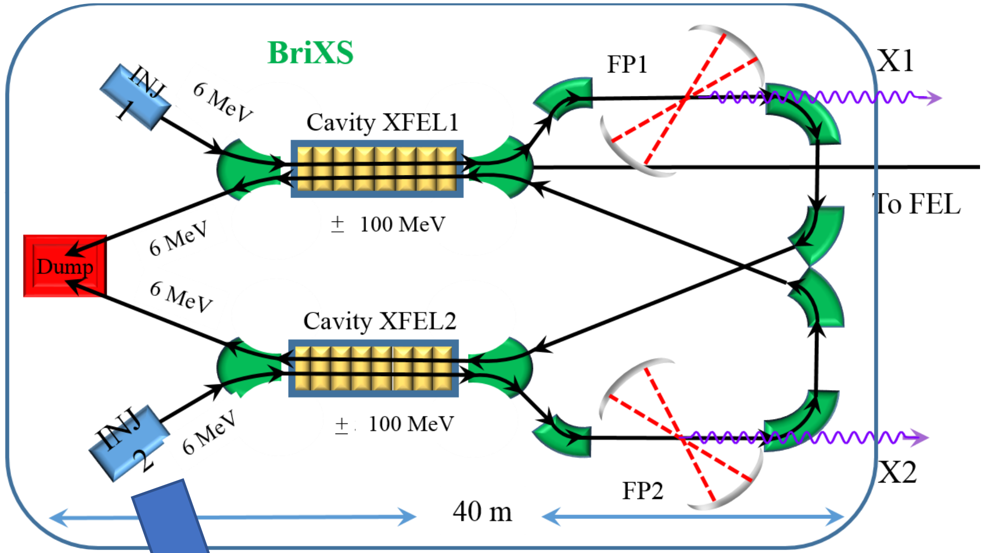
BRIXS – Wakefields

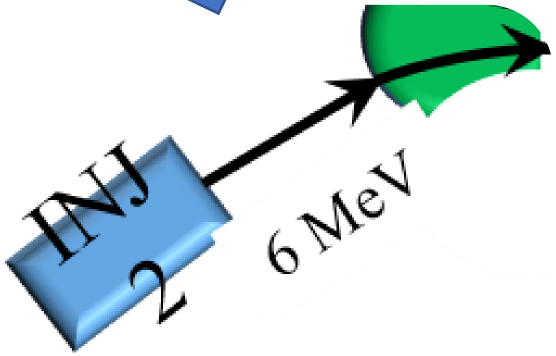
work in progress

BRIXS - Injector Linac

Power lost to wakefields

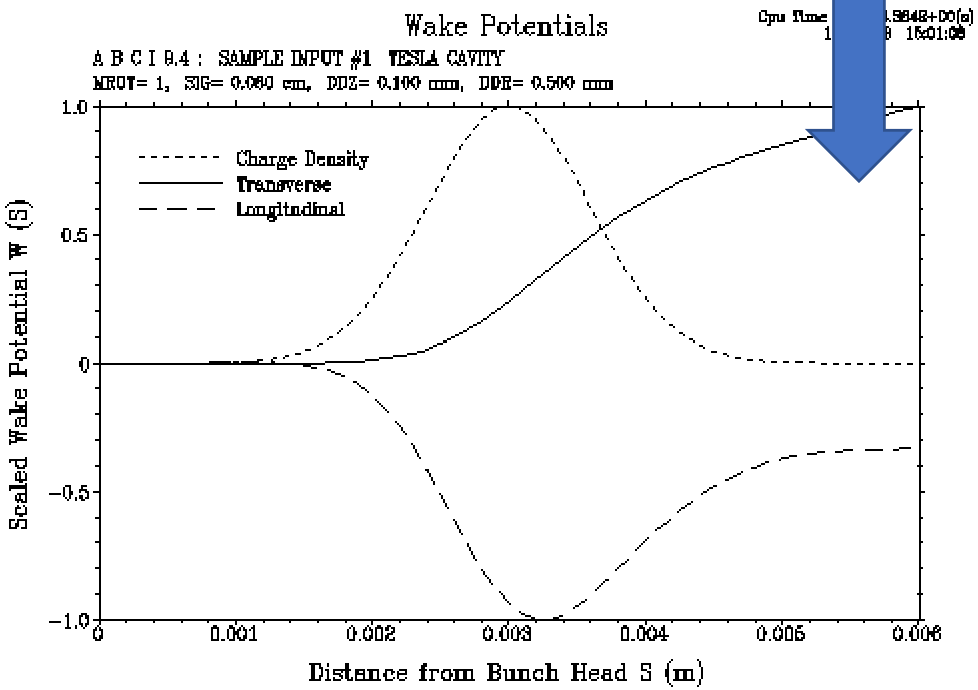
$$P = k_{\parallel} q I_{avg}$$





BRIXS injector
Frep = 100 MHz
Tesla Cavity $k_{\parallel}$~11V/pC
$Q = 200pC$
$I_{avg} = 20mA$
$P_{HOM} = 44W$

σ_{rms} =0.6mm	Padamsee	ABCI (simulated)
Loss Factor $k_{\parallel}$	1.88 V/pC	1.81 V/pC
Kick Factor $k_{\perp}$	23.0 V/pC	23.57 V/pC-m



Next step: 3D simulations!

Thanks for your attention!