PAL Linac Upgrade for a 1-3 Å XFEL

The XXII International LINAC Conference

Lübeck, Germany
August 16-20, 2004

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DESY, Hamburg, Germany

Pohang Light Source and 2.5-GeV Linac

POSCO, the World's Largest Steel Company

POSCO established the first research-intensive university in Korea, Pohang University of Science and Technology (POSTECH) in 1986, and Pohang Accelerator Laboratory (PAL) with a 3rd generation light source (PLS) in 1988.

POSTECH, Korea's Premier University

PAL XFEL

POSTECH got many donations from POSCO.

For the university future, 133 M$ in 2000
For the largest library in Korea, 42 M$ in 2001
For a biological research center, 27 M$ in 2002

In 1998 Asiaweek ranked POSTECH "No.1" among the specialized sciences and technology universities in Asia.

In 1994, 1996, 1997, 2002, and 2003, the Joong-Ang Ilbo, a Korean daily newspaper, ranked POSTECH the "No.1" university in Korea.

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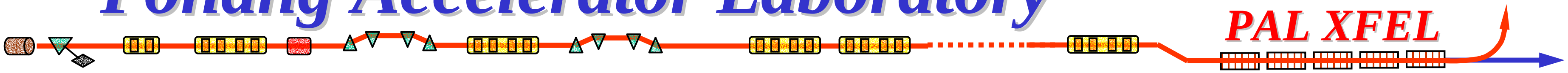
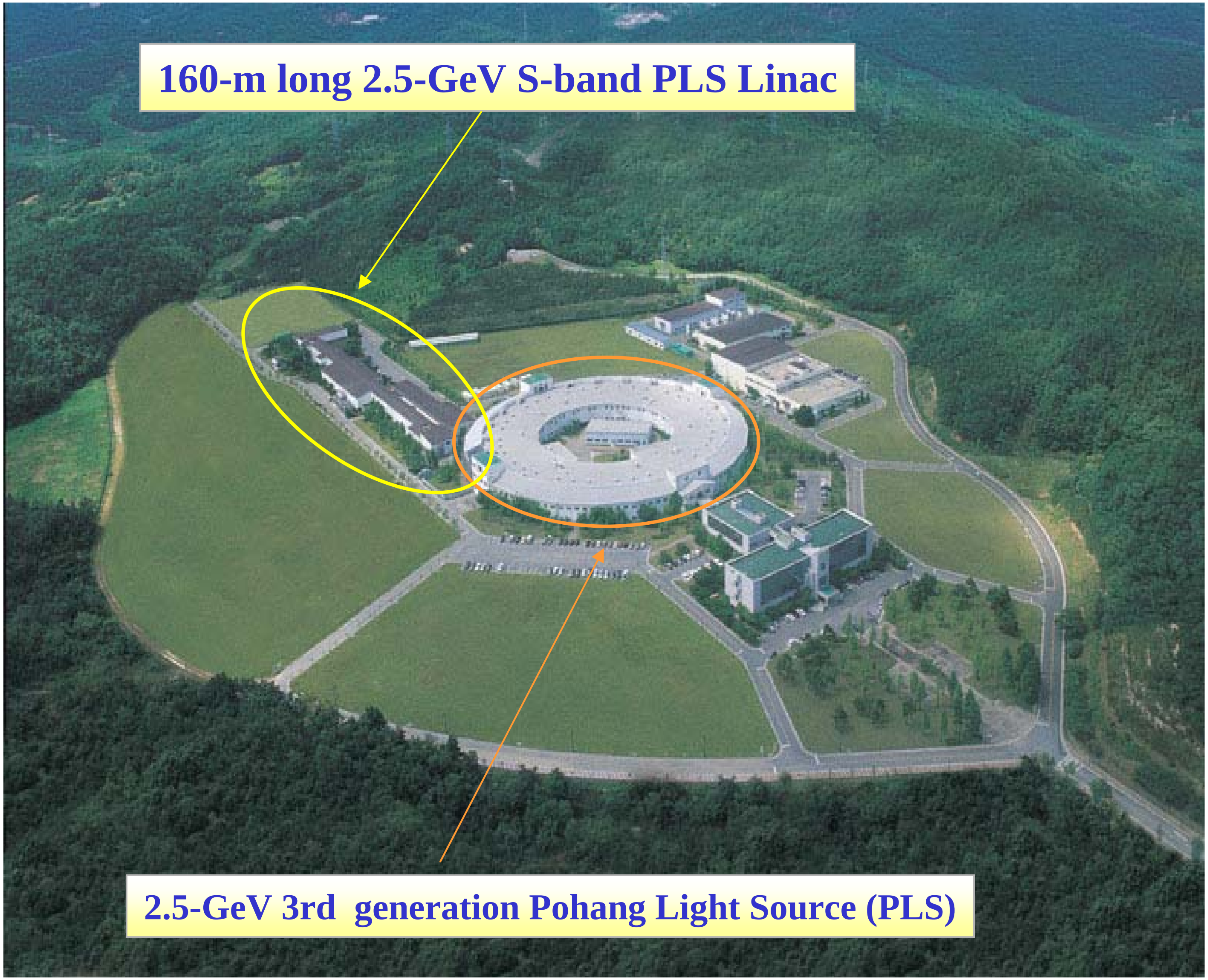
POSTECH and PAL

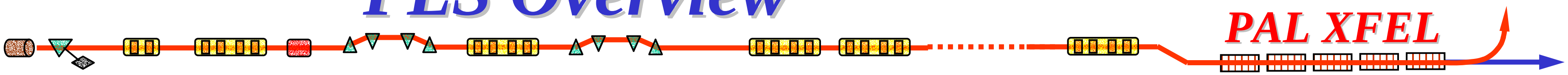
PAL XFEL

Pohang Accelerator Laboratory





PLS Overview



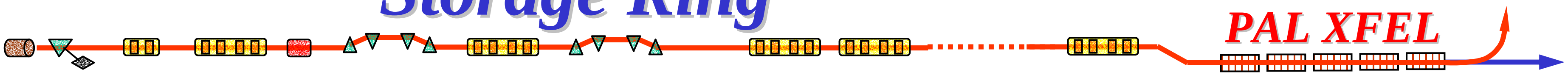
- In 1987, POSTECH, a newly established university, proposed to construct a synchrotron light source on its campus.

- **PLS is a 3rd generation synchrotron radiation source:**
  - 2 GeV injector linac and storage ring with upgrade option to 2.5-GeV.

- **Construction Project: April 1988 ~ December 1994**
  - **Funded by POSCO (60%) & Government (40%)**

- **Operation: funded by Government (80%) & POSCO (20%)**

Storage Ring



Tunnel

Parameters

Beam Energy (GeV)	2.5
Emittance (nm-rad)	12.1
Beam Lifetime (Hours) (@ 170mA)	20
Number of Bunches	400
Beam Current (mA)	170

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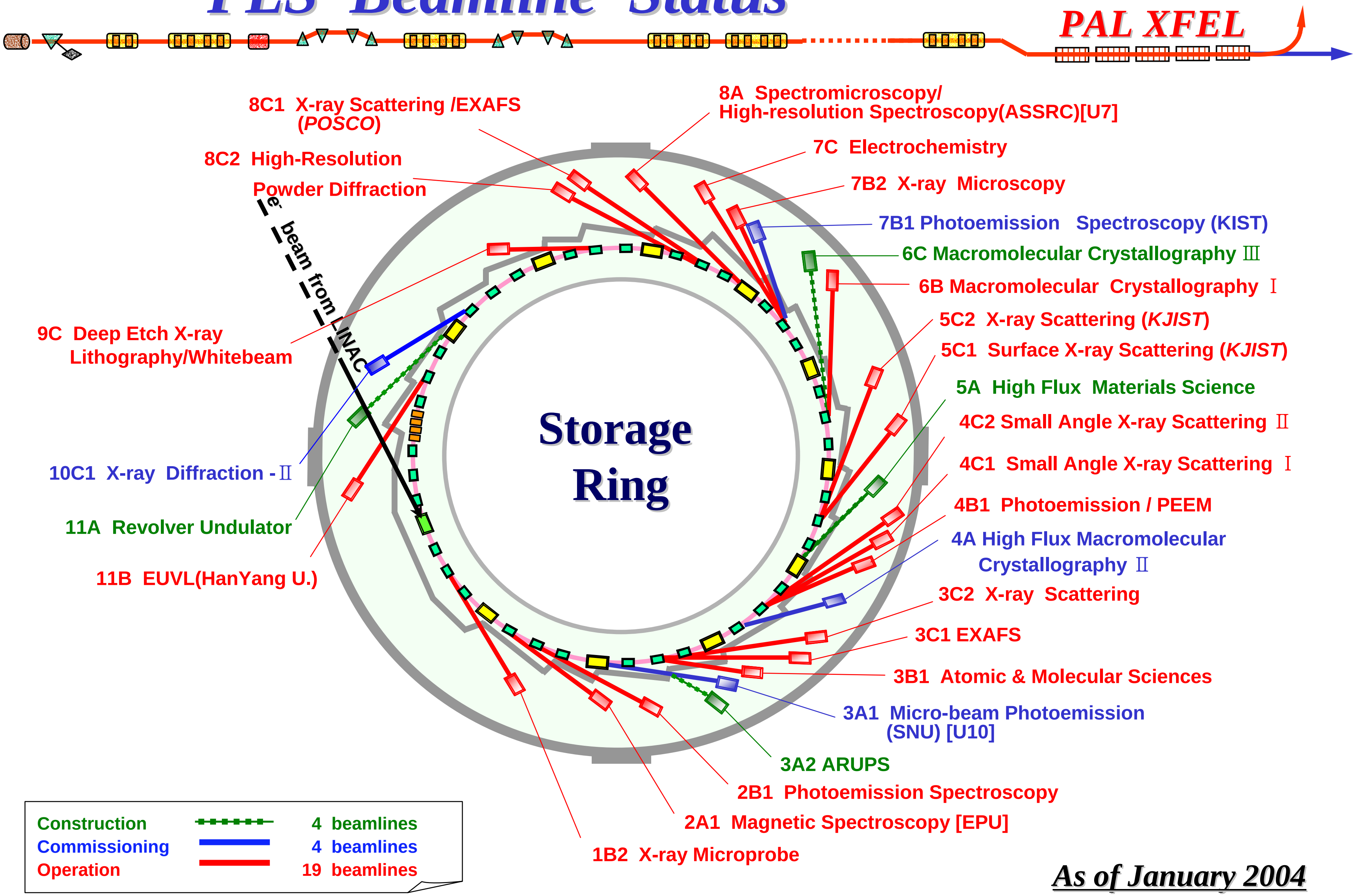
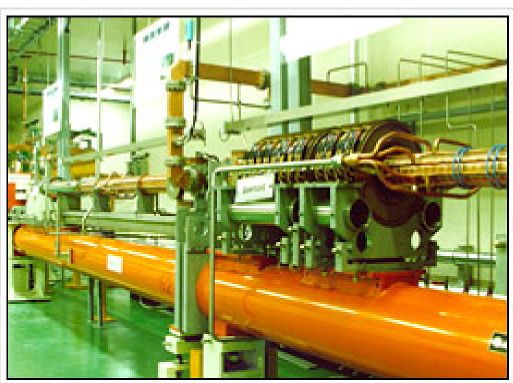
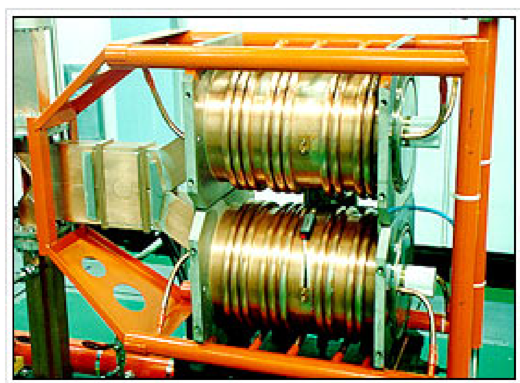
PLS Beamline Status



PLS 2.5 GeV Linac

Beam energy (GeV)	2.5
Frequency (MHz)	2,856
Energy spread (%)	0.26
Bunch length (ps)	13
Beam current (A)	33
Normalized emittance (um)	150
Number of klystrons	12
Klystron power (MW)	80
SLED Gain	1.6
No. of accelerating columns	44
Total length (m)	160





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Demand on a Next Generation Light Source

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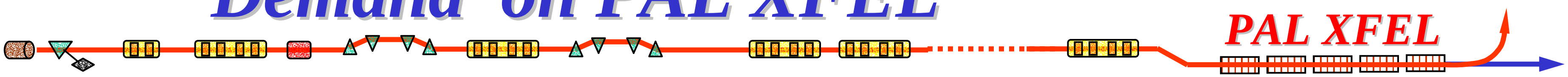
Demand on PAL XFEL



Radiation wavelength: 1 Å (0.1nm) <= Undulator/users
Radiation pulse length: 20 fs (FWHM) <= Beamline/users

Beam energy: 3.0 GeV <= Accelerator
Bunch length: 100 fs (RMS) <= Accelerator

Project period: 2005-2009 <= Administrator/users
Project cost : ~ 40 M$ <= Administrator/users

Draft by Prof. W. Namkung
February, 2003

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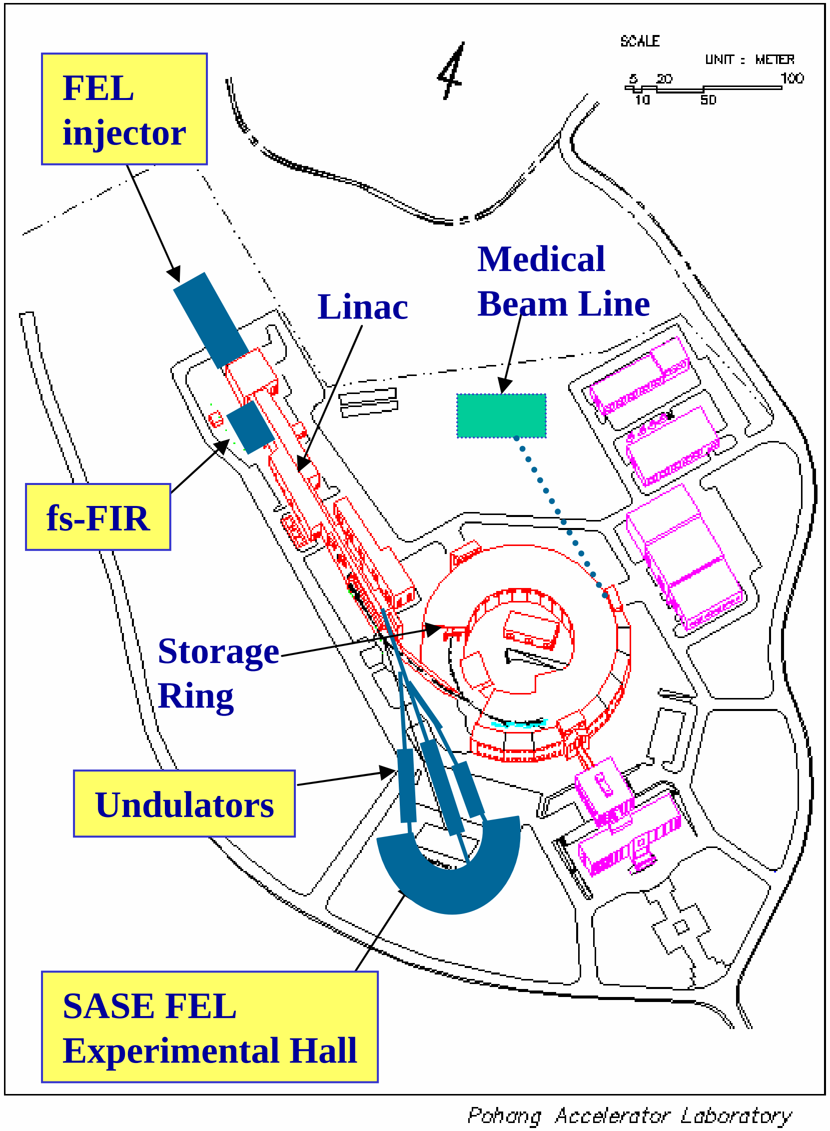
A Future FEL Program at PAL



Public Hearing
February, 2004

- **femto-second FIR**
  - **Energy: 80 MeV**
  - **Radiation: 1 ~ 20 μm**
- **SASE FEL**
  - **Energy: 3.0 GeV**
  - **XFEL: 0.1 ~ 0.3 nm**
  - **VUV FEL: 1 ~ 5 nm**

Project Approval and Funding

On July 16, 2004

- **Korean President visited PAL.**
- **He gave a strong promise to support PAL XFEL project.**
- **Design budget of 0.4 M$ in 2005**
- **We are under discussion about total construction budget with government.**

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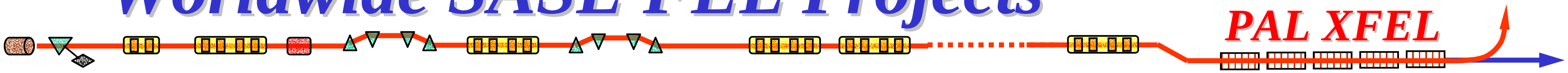
Worldwide SASE FEL Projects



LUX at LBNL (1.2-60 nm)
LCLS at SLAC (1.5-15 Å)
LEUTL at APS (51-530 nm)
X-ray FEL at MIT Bates (3-1000 Å)
DUV-FEL at BNL (266/400 nm)

4GLS at Daresbury (124 Å)
TESLA XFEL at DESY (0.86-64 Å)
SASE-FEL at BESSY (12-600 Å)
FERMI at ELETTRA (12-15 Å)
SPARX in INFN Rome (15-135 Å)

PAL XFEL at PAL (1-50 Å)
SCSS at SPring-8 (36 Å)

Toward XFEL …

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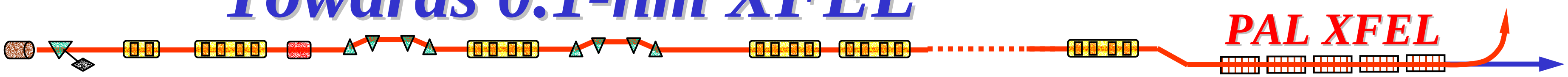
Towards 0.1-nm XFEL



0.1 nm XFEL

+ 3rd harmonic enhancement technique

0.3 nm XFEL

- S-band Photoinjector
- S-band FEL Injector Linac
- Two Bunch Compressors
- 60 m long In-vacuum Undulator
- SASE XFEL Experimental Hall

2.5 GeV PLS Linac

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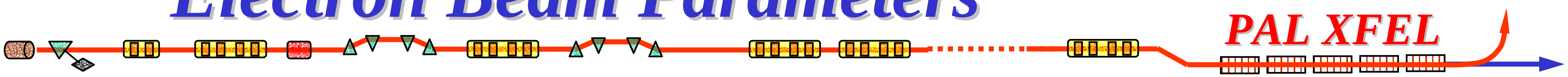
Electron Beam Parameters



For the Microbunching in Undulator

- **Slice normalized rms emittance:**

$$\varepsilon_{ns} < \gamma \frac{\lambda}{4\pi}$$

- **Slice rms relative energy spread:**

$$\sigma_{\delta s} < \rho \approx \frac{1}{4}\left[\frac{1}{2\pi^2}\frac{I_{pk}}{I_A}\frac{\lambda_u^2}{\beta\varepsilon_n}\left(\frac{K}{\gamma}\right)^2\right]^{1/3}$$

- **Total undulator length:**

$$L_u > L_{sat} \approx L_G \ln\left(\frac{P_{sat}}{\rho E e \Delta\omega}\right) \approx 20 L_G$$

$$\text{where } L_G \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

$$\lambda_{\min} \propto \frac{\varepsilon_n^{5/4}}{L_u^{3/2} I_{pk}^{3/4}}\left[1 + 6\left(\frac{\sigma_\delta}{\rho}\right)^2\right]^{1/2}$$

Low emittance & high peak current !!!

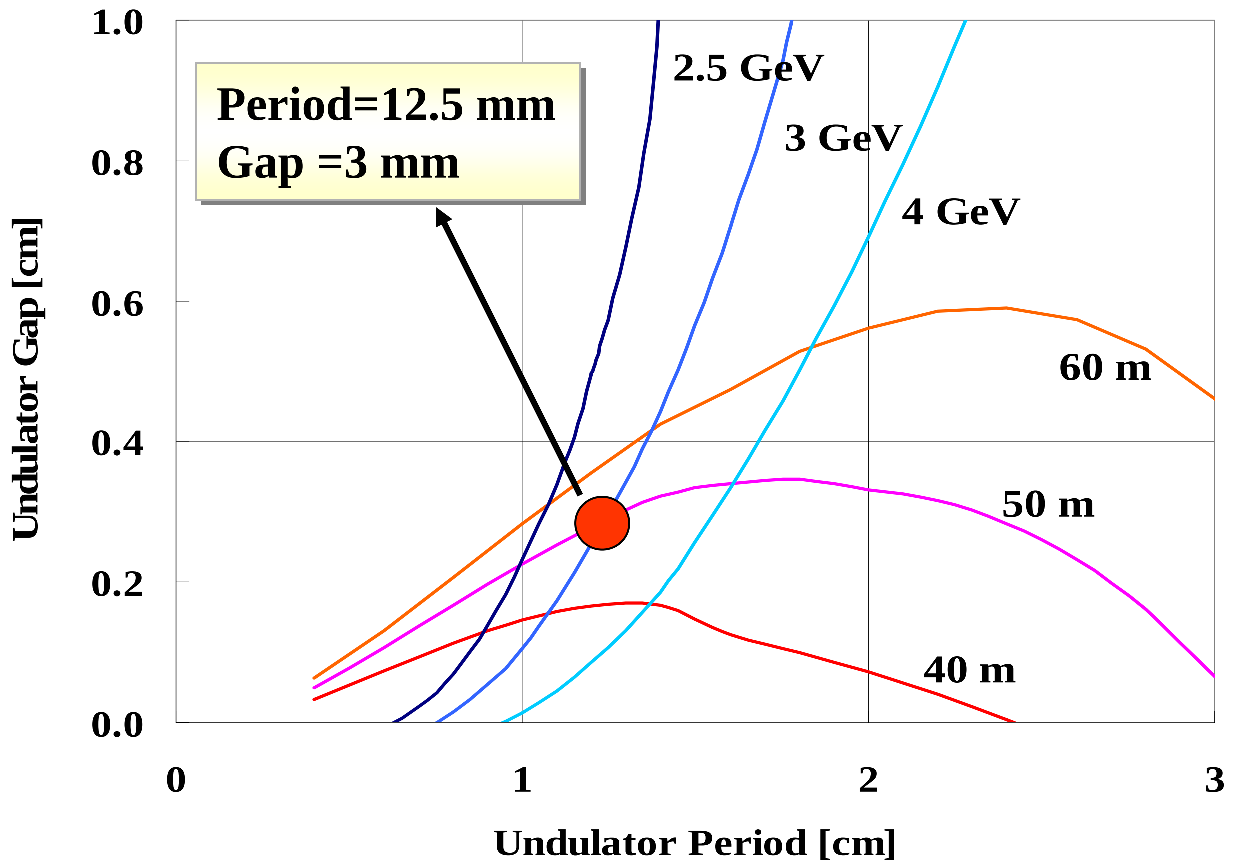
For 3 Å PAL XFEL Project

Electron beam energy	≥	3.0 GeV
rms bunch length	≤	100 fs = 30 μm
Normalized slice emittance	≤	1.5 μm
Slice rms energy spread	≤	0.02% = 600 keV
Peak current	≥	4 kA

Undulator Optimization

PAL XFEL

3 Å SASE FEL
Bunch charge: 1 nC
Energy spread: 0.02%,
Emittance: 1.5 mm-mrad
Bunch length (rms): 100fs



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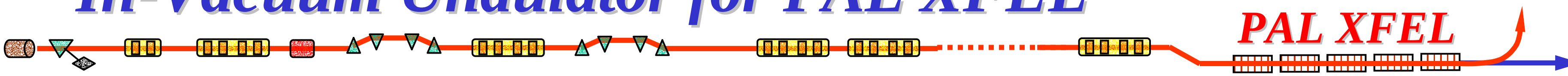
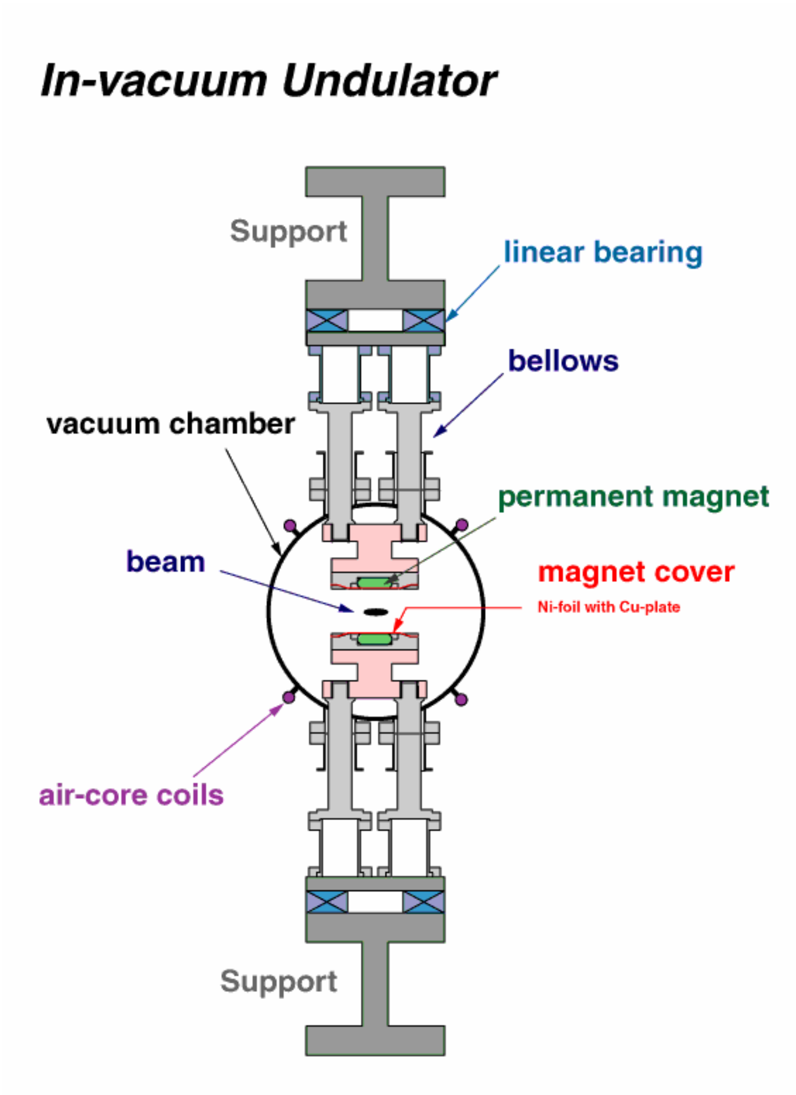
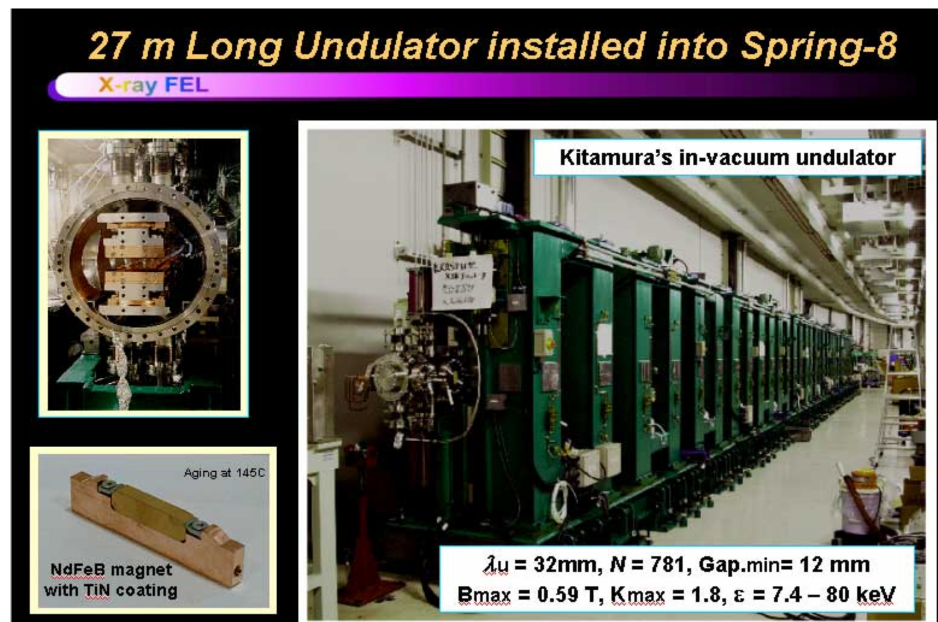
In-Vacuum Undulator for PAL XFEL

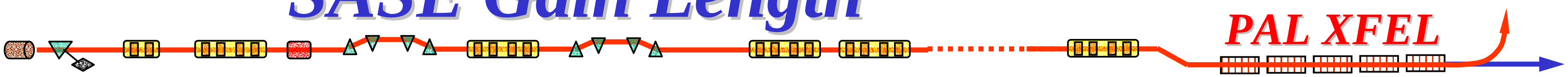




- We will use **in-vacuum mini gap undulator** developed by **SPring-8 and BNL**.
- 1st in-vacuum undulator at KEK in 1992 by Kitamura
- 19 in-vacuum undulators at SPring-8
- The longest undulator is 35 m long undulator at SPring-8.



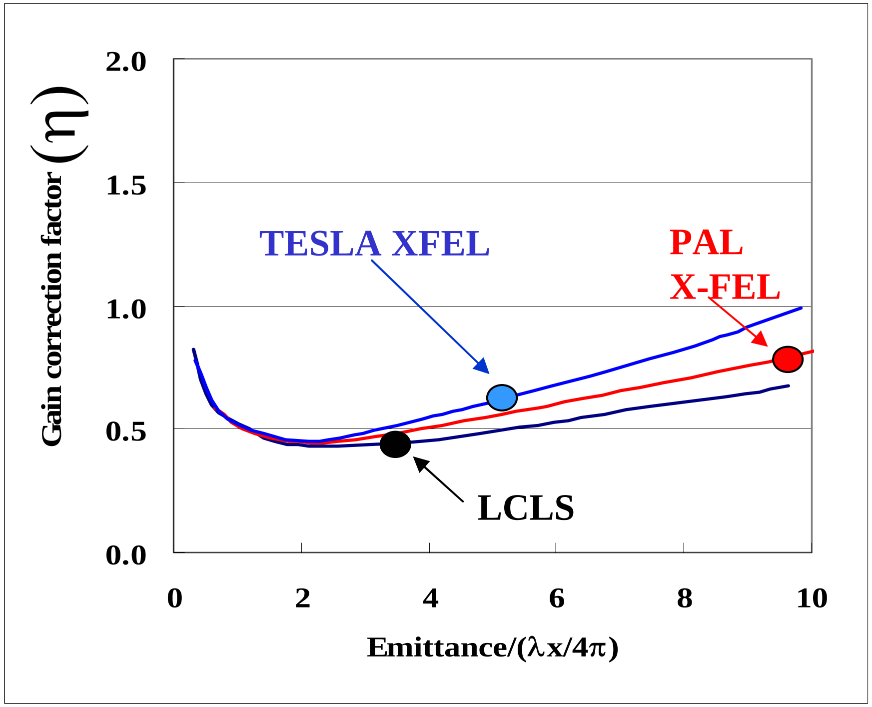
SASE Gain Length

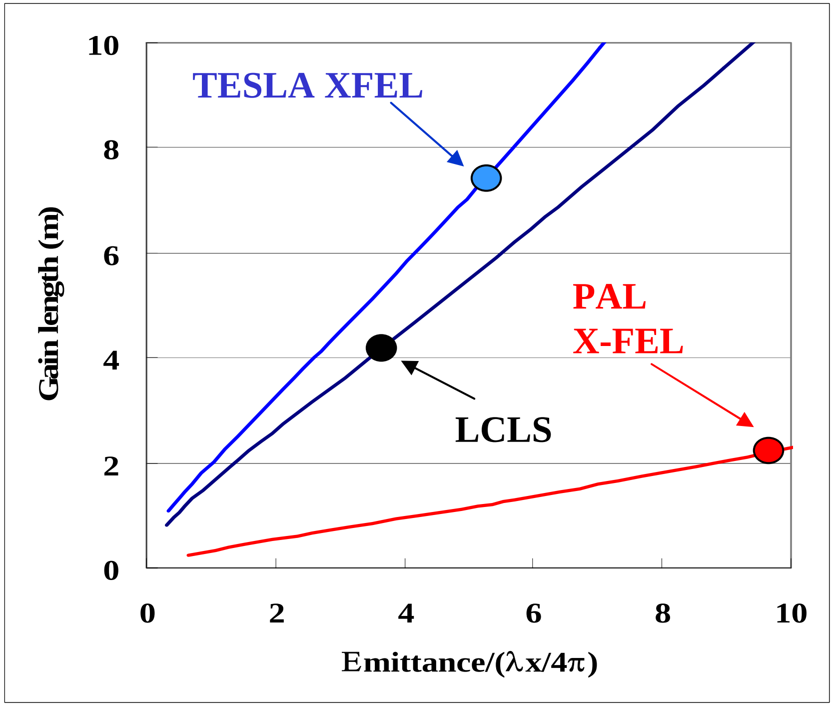


Undulator saturation length ≈ 20 L_G

3D Gain length $L_G = (1+\eta)\, L_{G,1D}$

$$L_{G,1D} \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$





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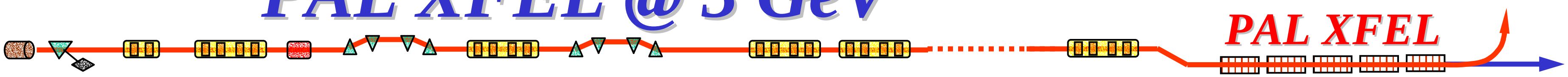
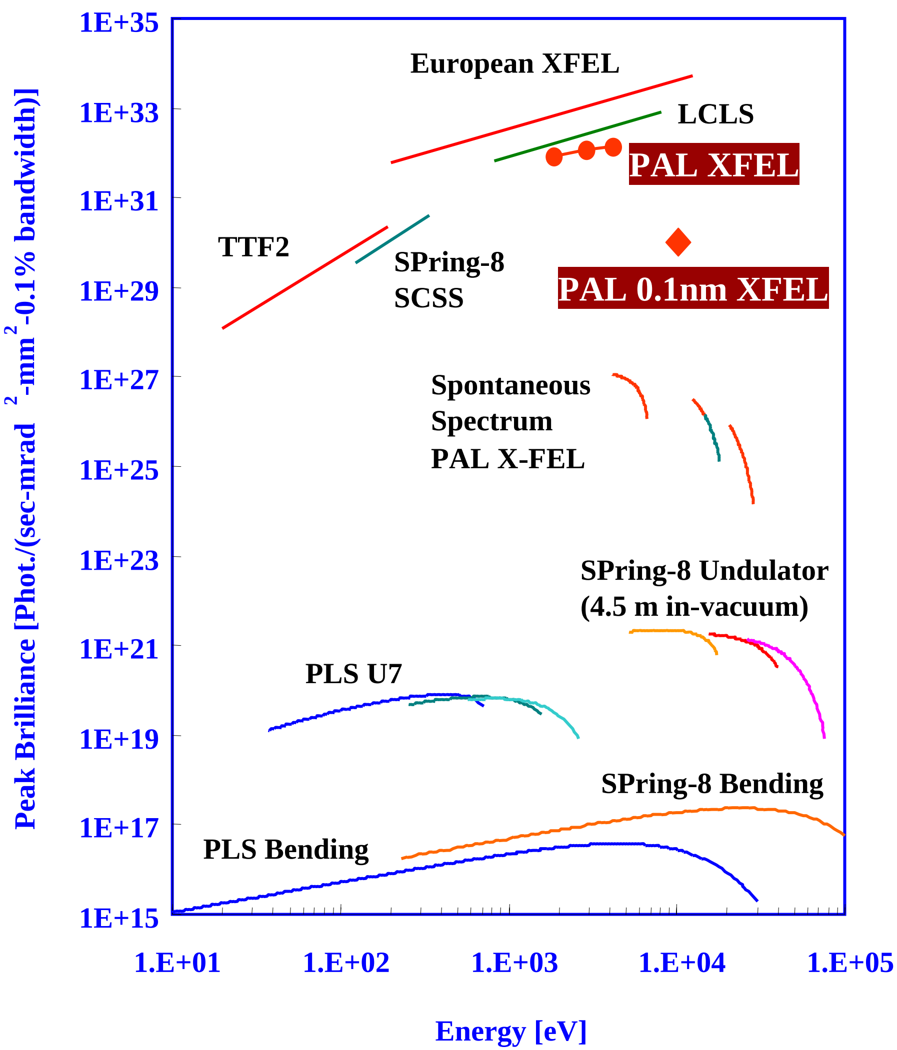
PAL XFEL @ 3 GeV

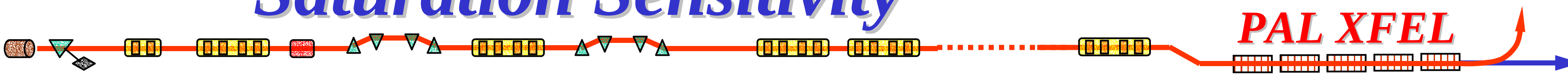




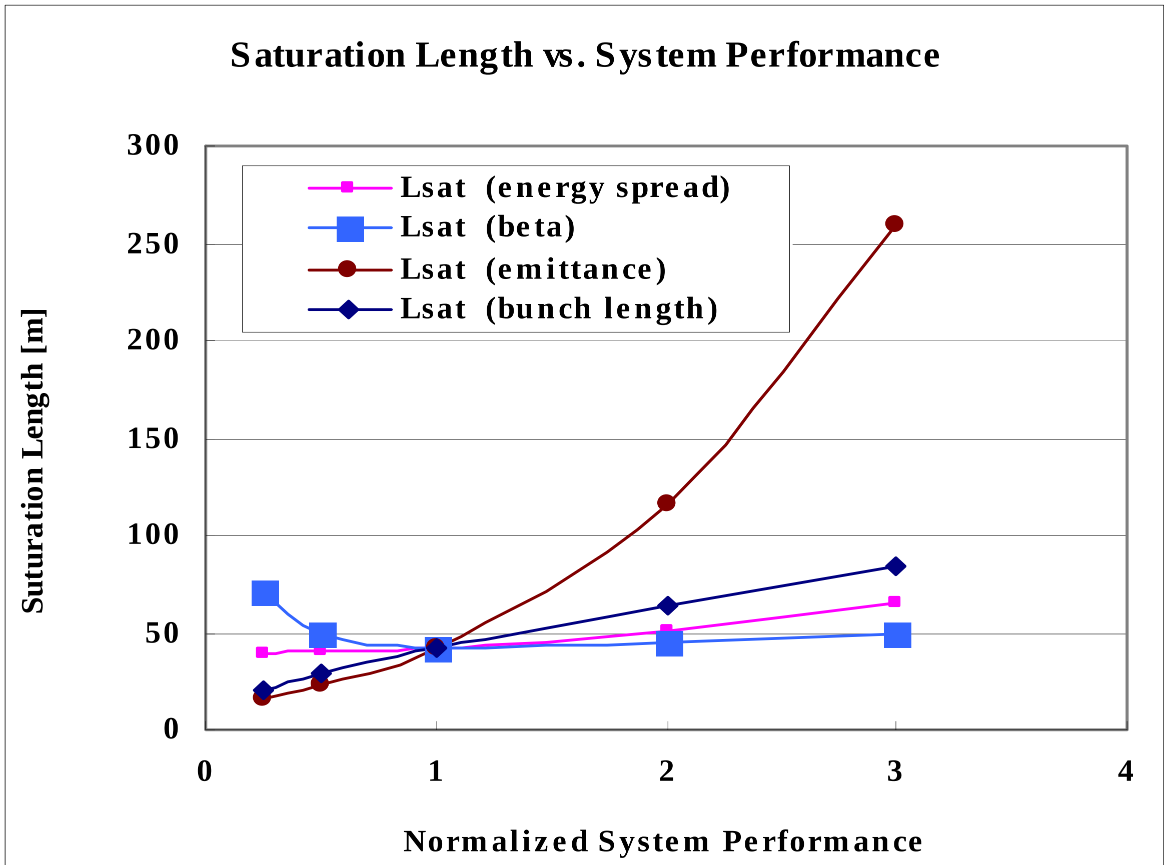
λ_x (Å)	3.0
ε_n (mm)	1.5
τ (fs)	100
λ_u (mm)	12.5
gap (mm)	3.0
K	1.14
ρ	4.3e-4
β(m)	15
L_{undtor}(m)	58.5
PB ($\times 10^{32}$)	1.4

PAL 0.1 nm XFEL: 3rd harmonic amplification

Saturation Sensitivity



3 Å SASE FEL @ 3 GeV	Bunch charge: 1 nC
Energy spread: 0.02%,	Emittance: 1.5 mm-mrad
Bunch length (rms): 100fs,	Beta: 15 m



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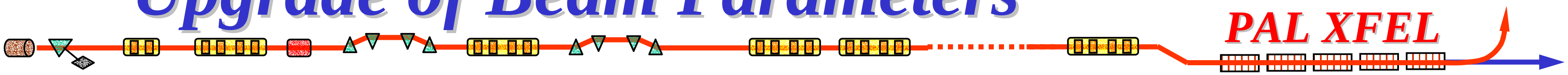
Linac Upgrade

Upgrade of Beam Parameters



Parameter	PLS Linac	XFEL Linac
Beam energy	2.5 GeV	3.0 GeV
Normalized emittance	150 μm-rad	1.5 μm-rad
Bunch length (FWHM)	13 ps	0. 23 ps
Energy spread (RMS)	0.26%	0.02%
Bunch charge	0.43 nC*	1.0 nC
Peak current	33 A*	4 kA

* 2-A gun current and 62% transmission

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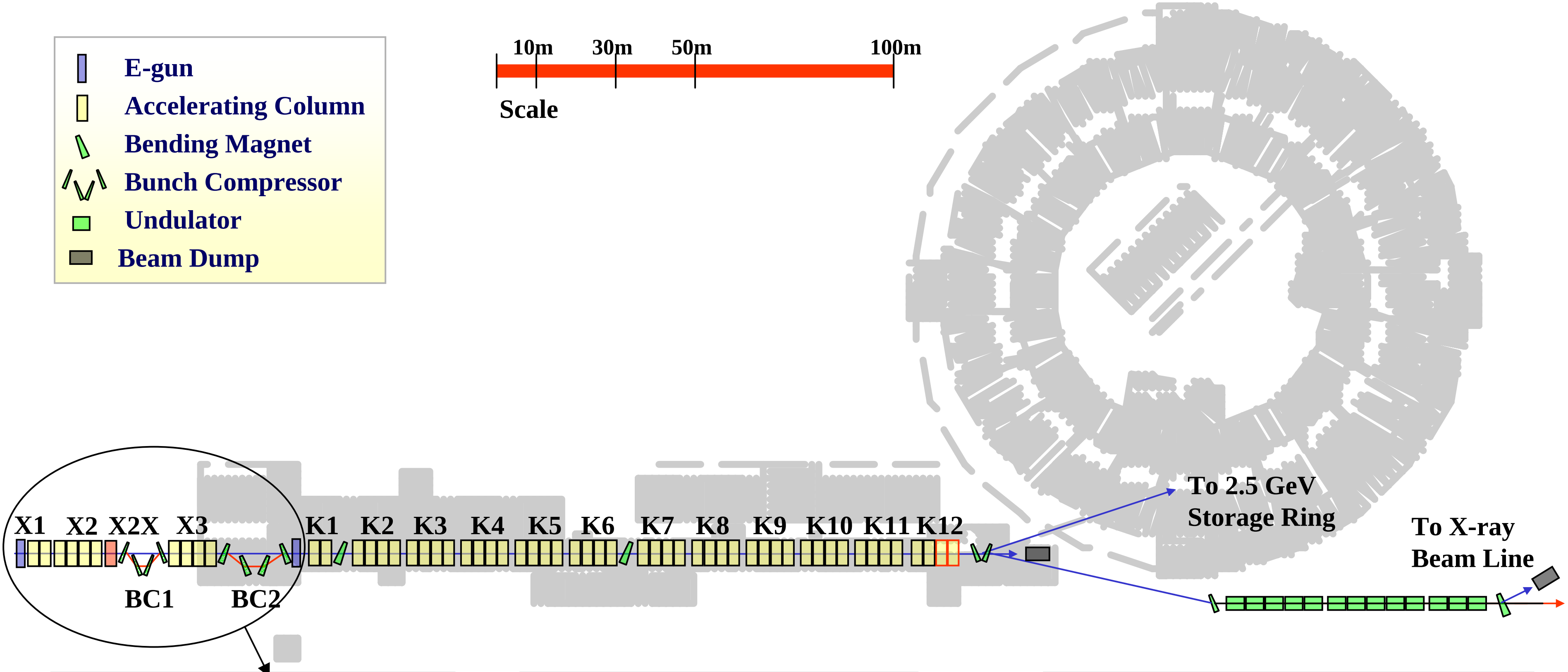
Acceleration Upgrade



XFEL Injector Linac;

X1 (150 MeV) + X2 (290 MeV) + X2X (-33 MeV) + BC1 + X3 (260 MeV) + BC2

PAL 2.5 GeV Main Linac;

K1= 100 MeV Injector

K2~K12=250 MeV

Add 2 A/C @ K12

Undulator (λ_x=0.3 nm);

E_o=3.0 GeV, ε_n=1.5um-rad

I_P=4.0 kA, σ_E=0.02%

λ_U=1.25 cm, g=3.0mm, L_U=60 m

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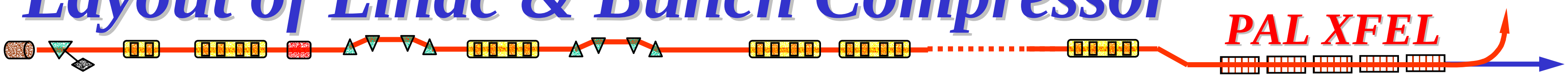
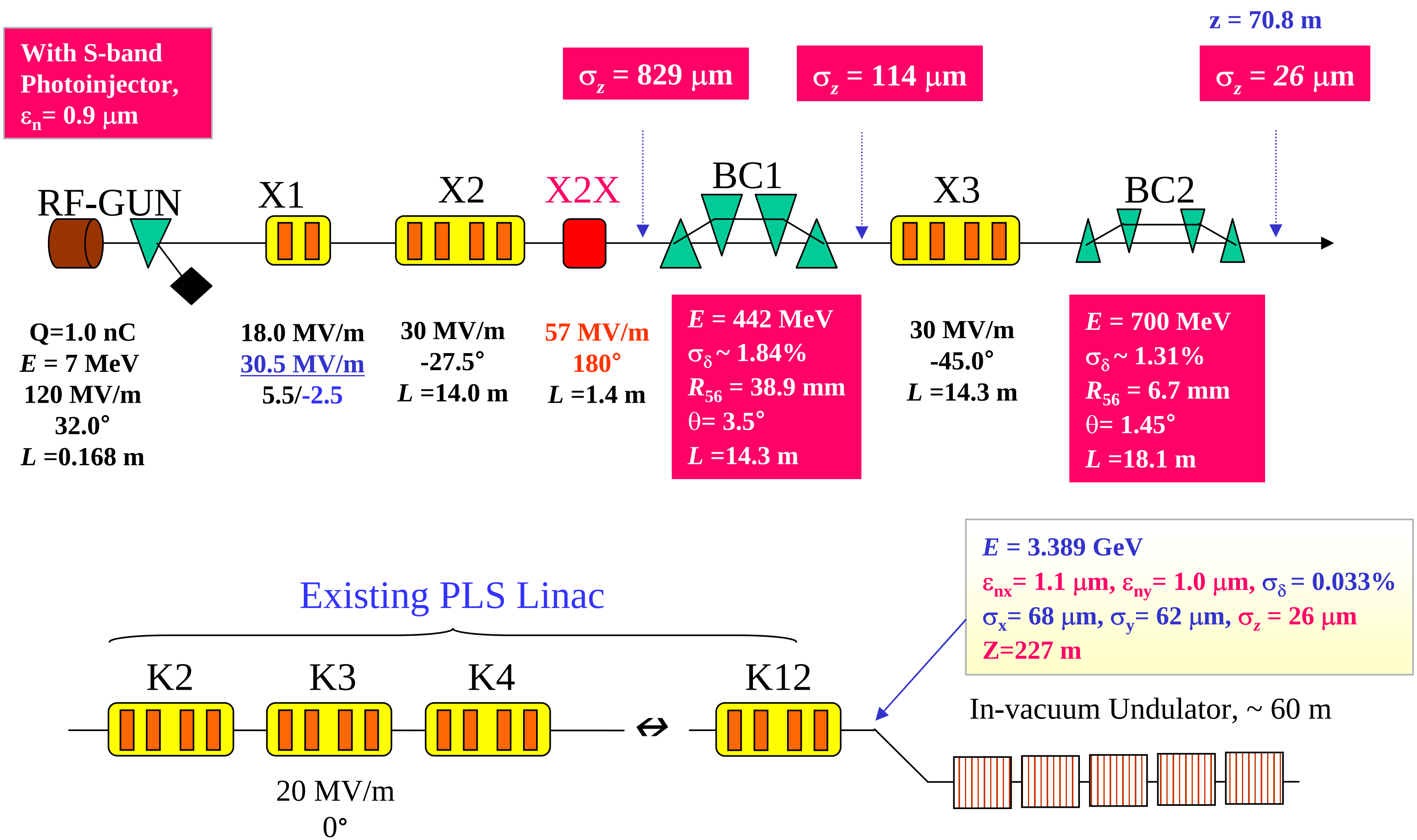
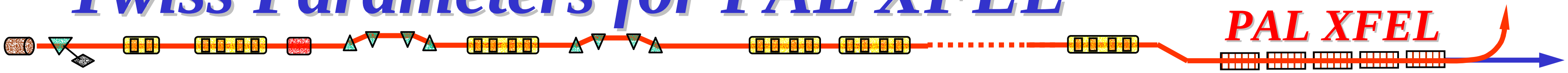
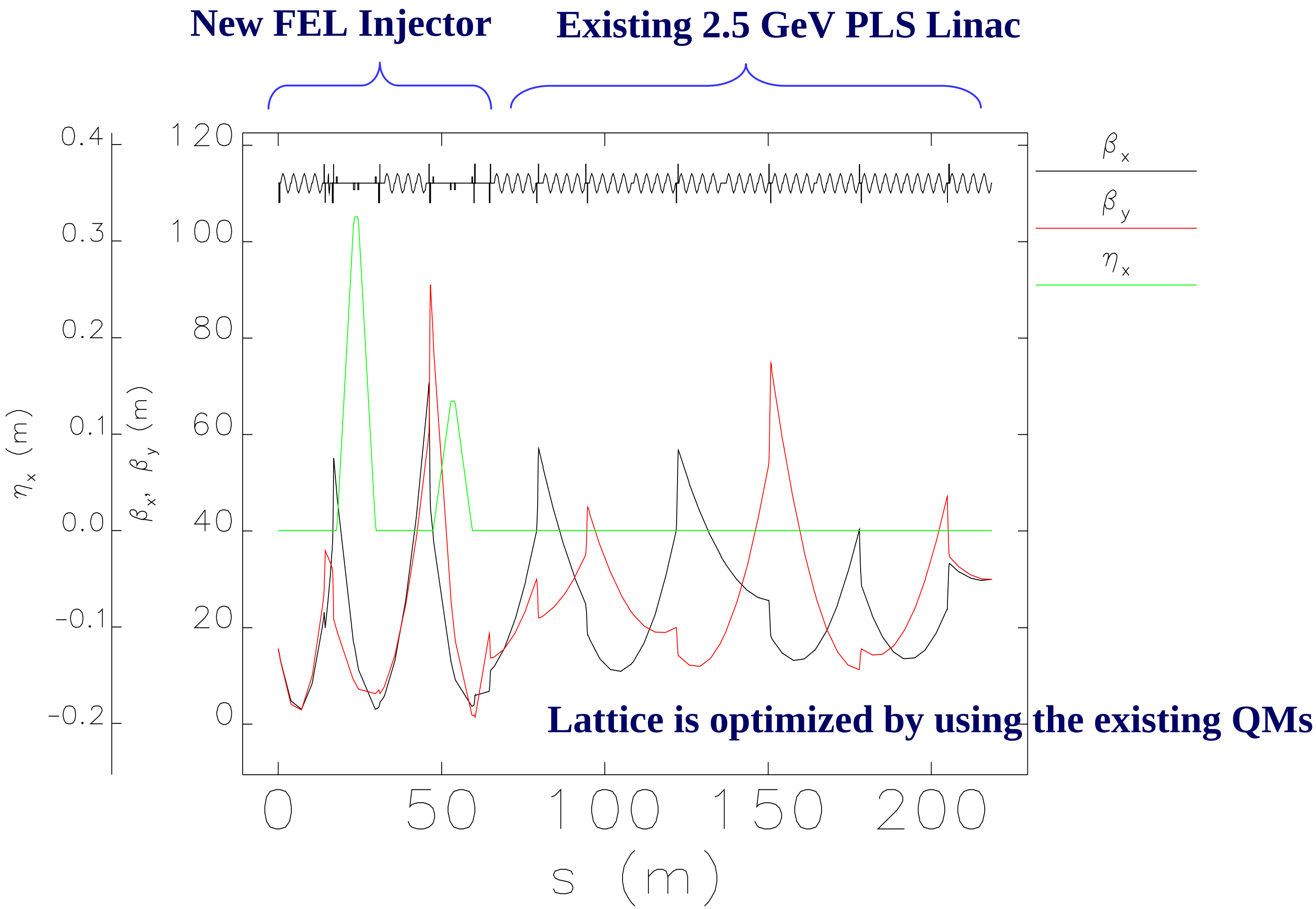
Layout of Linac & Bunch Compressor





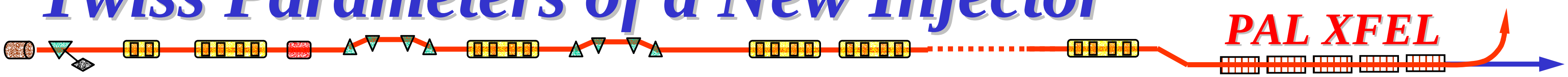
Twiss Parameters for PAL XFEL



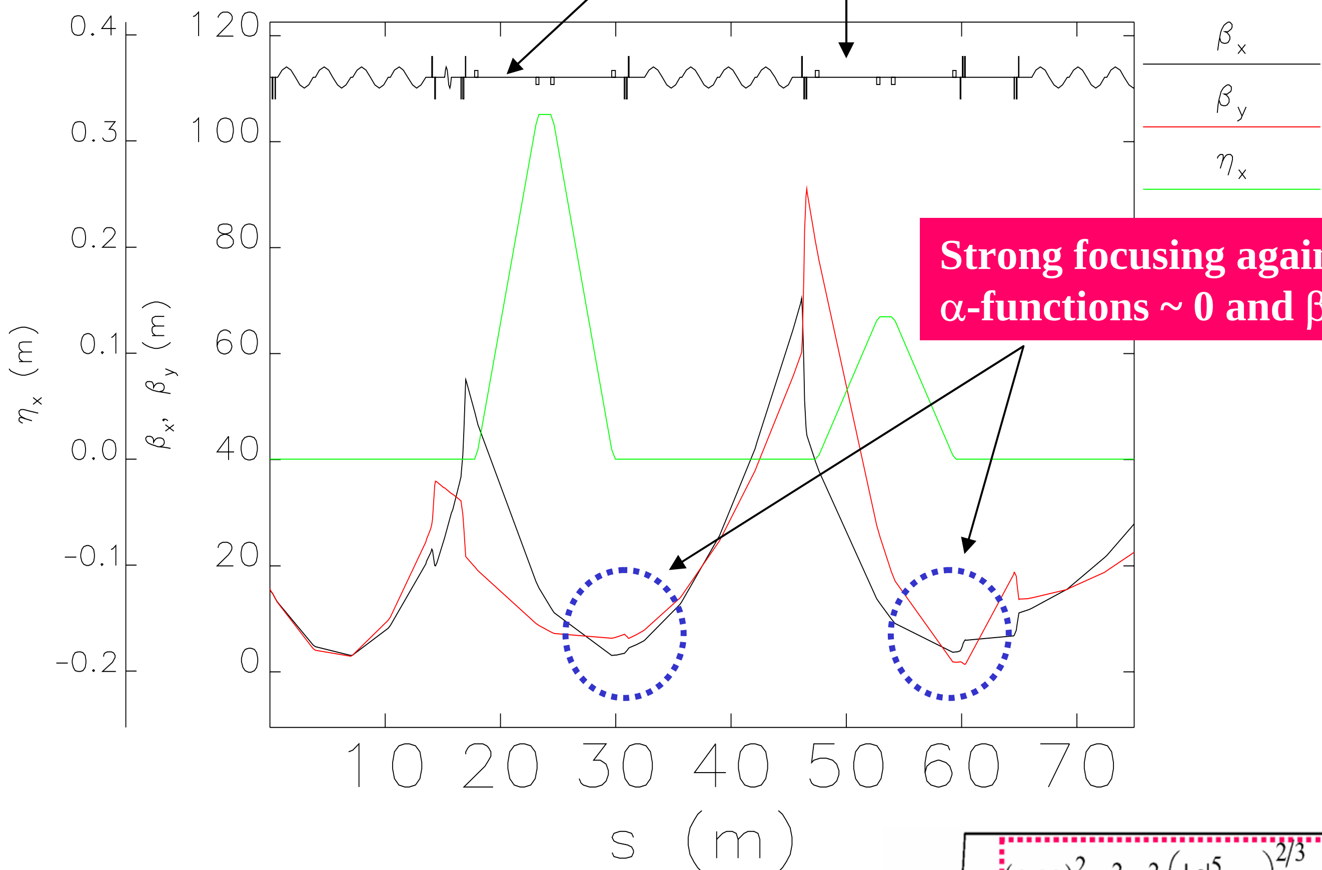


Twiss parameters in the existing linac can be further optimized !

Twiss Parameters of a New Injector



Reduced dipole strengths with a long chicane length

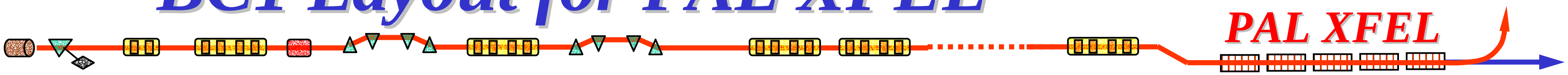


Strong focusing against CSR
α-functions ~ 0 and β-functions ~ 3

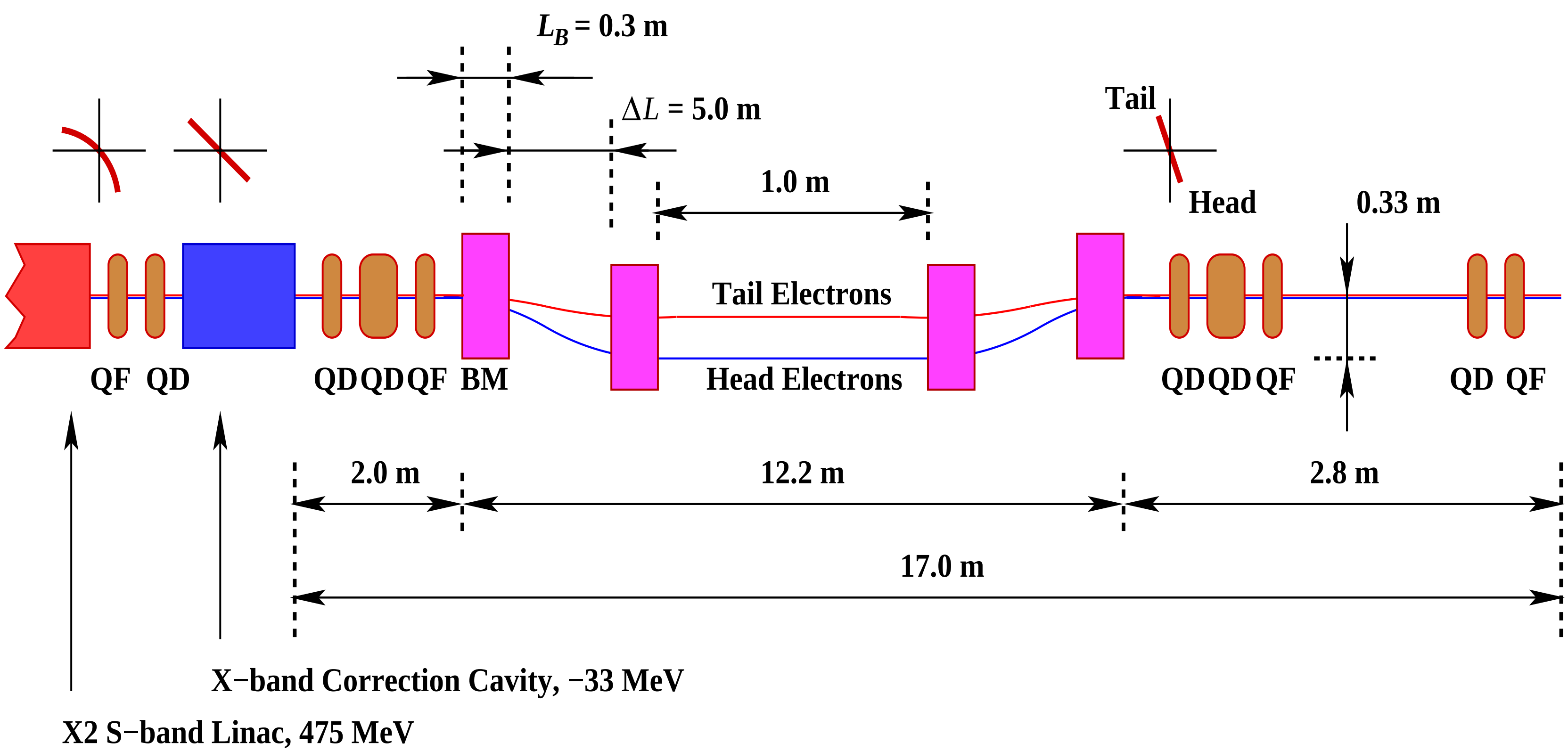
$$\frac{\varepsilon}{\varepsilon_0} \approx \sqrt{1 + \boxed{\frac{(0.22)^2}{36}\frac{r_e^2 N^2}{\gamma \varepsilon_N \beta}\left(\frac{|\theta|^5 L_B}{\sigma_z^4}\right)^{2/3}\left[L_B^2\left(1+\alpha^2\right)+9\beta^2+6\alpha\beta L_B\right]}}$$

Lattice optimization to minimize this term

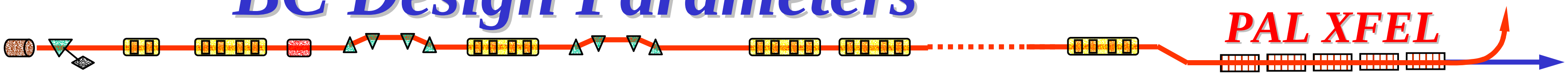
BC1 Layout for PAL XFEL



BC2 layout is same and almost same total chicane length ~ 12.2 m



BC Design Parameters



Parameter	BC1	BC2
Beam energy	442 MeV	700 MeV
Relative energy spread	1.84%	1.31%
Uncorrelated energy spread	9.2e-6	4.3e-5
Bending angle	3.50 deg	1.45 deg
Momentum compaction R56	38.9 mm	6.70 mm
Total chicane length	12.2 m	12.2 m
Dipole length	0.3 m	0.3 m
Drift length DL	5.0 m	5.0 m
Initial rms bunch length	820 μm	114 μm
Final rms bunch length	114 μm	26 μm
Compression factor	7.2	4.38
Initial projected emittance	0.90 μm	1.01 μm
Final projected emittance	1.01 μm	1.12 μm

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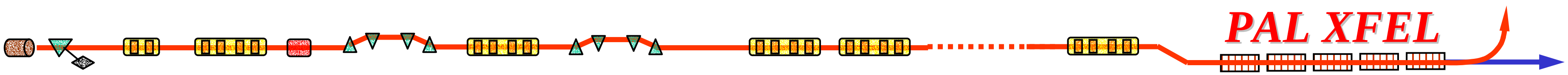
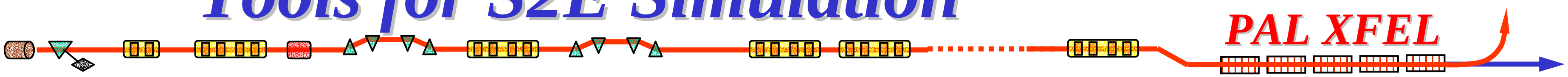
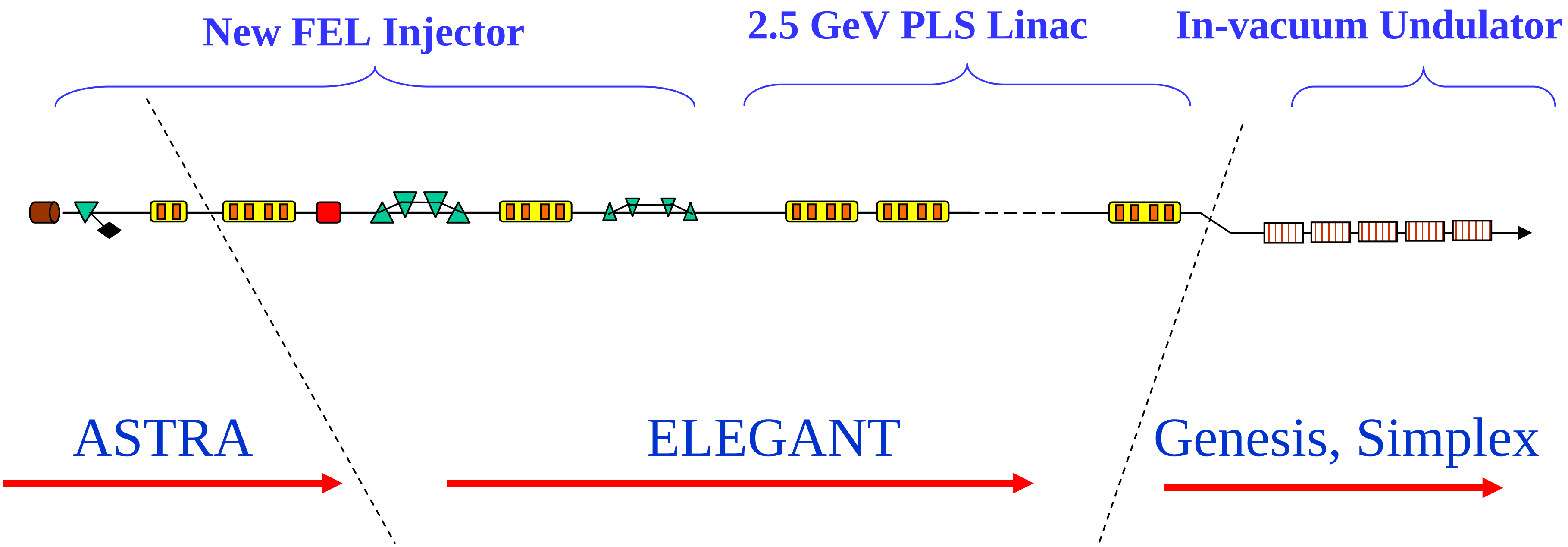


S2E Simulation and Results

Tools for S2E Simulation

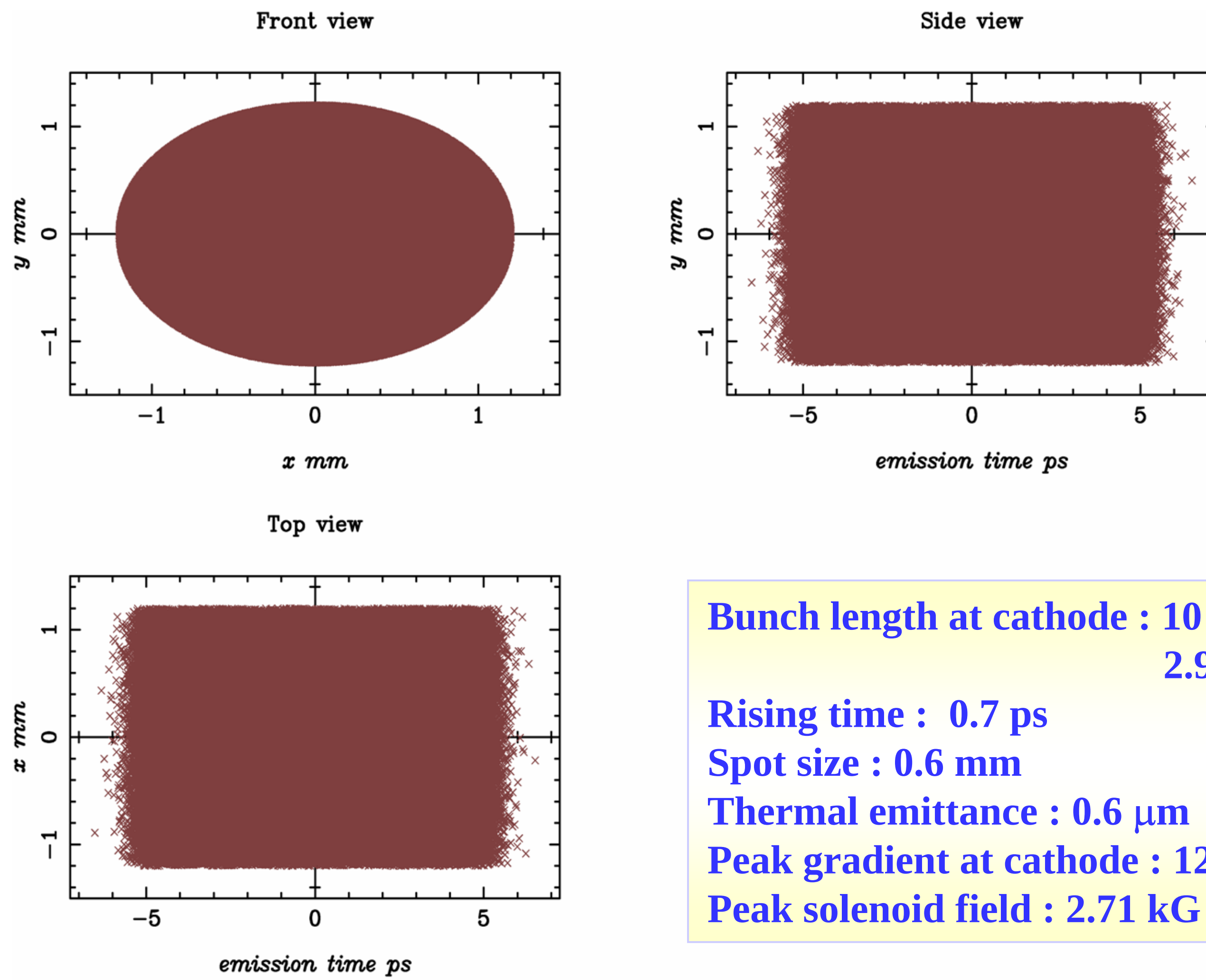




Simulated Particles = 200,000

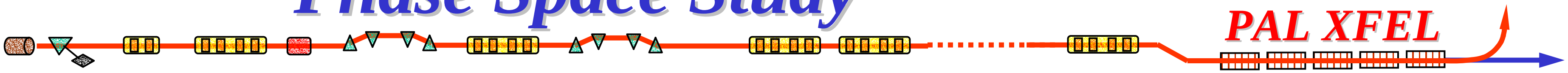
ASTRA Simulation of Photo-injector

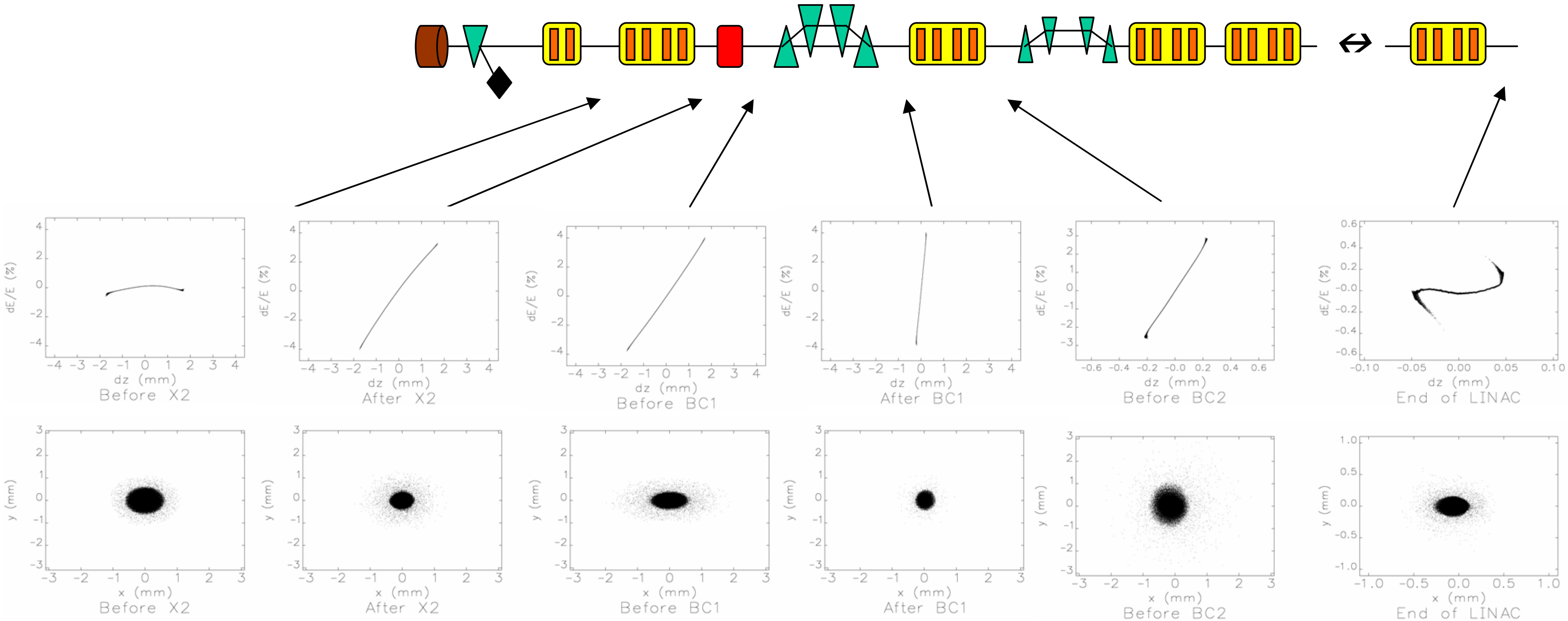
At cathode



Bunch length at cathode : 10 ps (FWHM)
2.9 ps (rms)
Rising time : 0.7 ps
Spot size : 0.6 mm
Thermal emittance : 0.6 μm
Peak gradient at cathode : 120 MV/m
Peak solenoid field : 2.71 kG at 19.1 cm

Phase Space Study





Before X2	After X2	Before BC1	After BC1	Before BC2	End of LINAC
E = 149.4 MeV	E = 475.3 MeV	E = 441.5 MeV	E = 441.3 MeV	E = 700.8 MeV	E = 3.389 GeV
σ_δ = 0.125%	σ_δ = 1.726%	σ_δ = 1.835%	σ_δ = 1.819%	σ_δ = 1.310%	σ_δ = 0.033%
σ_x= 219 μm,	σ_x= 143 μm,	σ_x= 230 μm,	σ_x= 61.7 μm,	σ_x= 174 μm,	σ_x= 68.1 μm,
σ_y= 222 μm,	σ_y= 158 μm,	σ_y= 147 μm,	σ_y= 85.6 μm,	σ_y= 240 μm,	σ_y= 61.9 μm,
σ_z = 829 μm	σ_z = 829 μm	σ_z = 829 μm	σ_z = 114 μm	σ_z = 114 μm	σ_z = 26 μm
ε_{nx}= 0.909 μm,	ε_{nx}= 0.910 μm,	**ε_{nx}= 0.953 μm,**	ε_{nx}= 1.012 μm,	ε_{nx}= 1.069 μm,	**ε_{nx}= 1.116 μm,**
ε_{ny}= 0.925 μm	ε_{ny}= 0.926 μm	**ε_{ny}= 0.945 μm**	ε_{ny}= 0.946 μm	ε_{ny}= 0.990 μm	**ε_{ny}= 1.004 μm**

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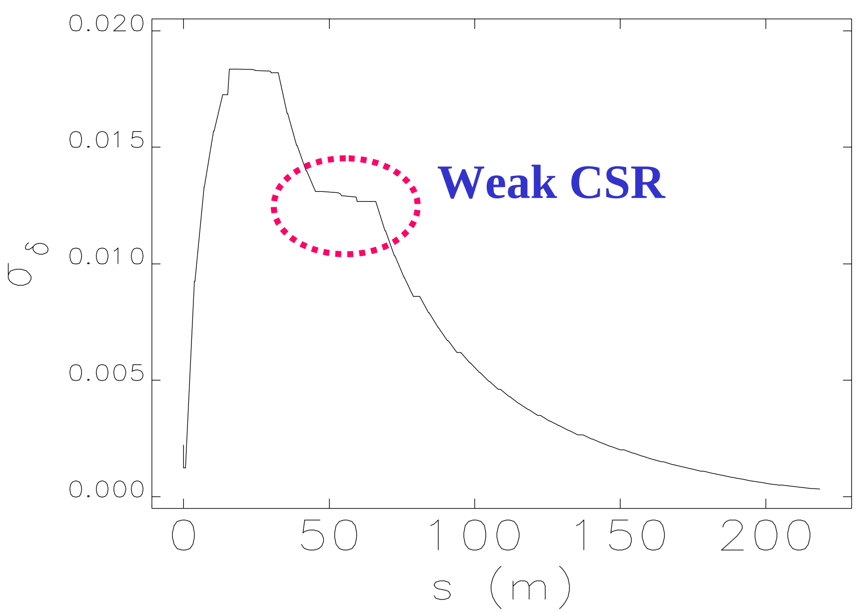
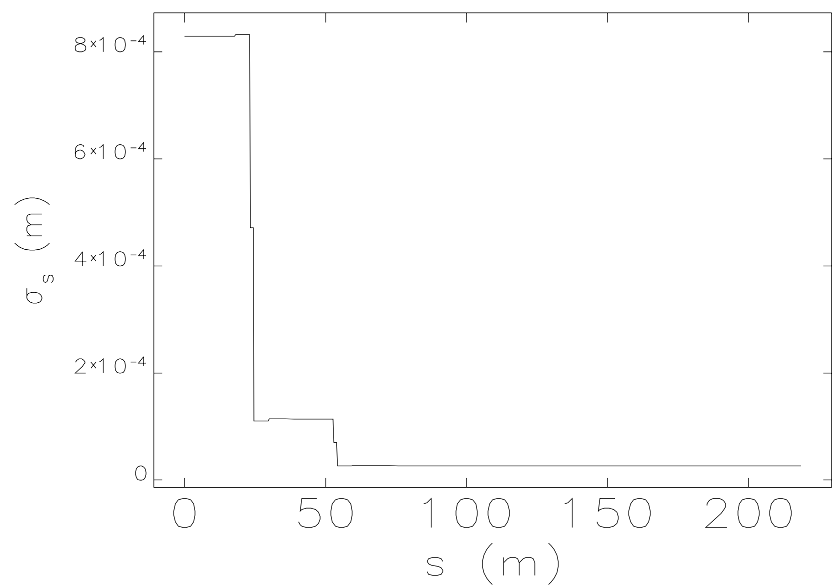
Projected Parameters along Linac

σ_δ = 0.033%

σ_z = 26 μm

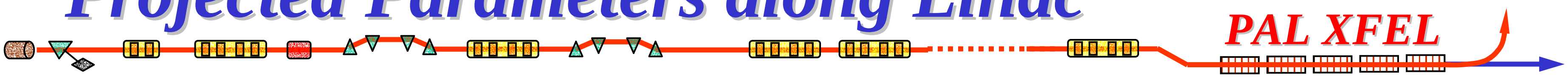


Relative energy spread



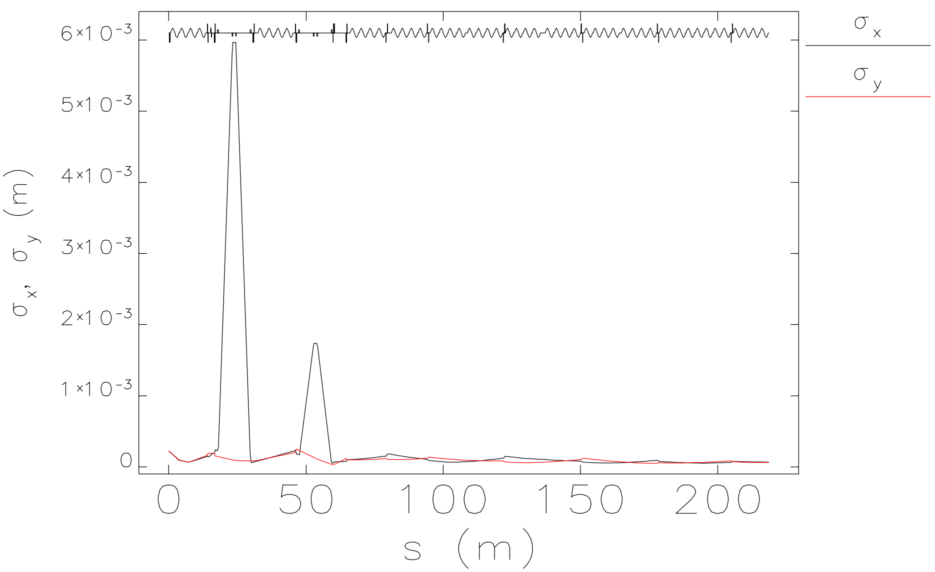
Bunch length

Projected Parameters along Linac

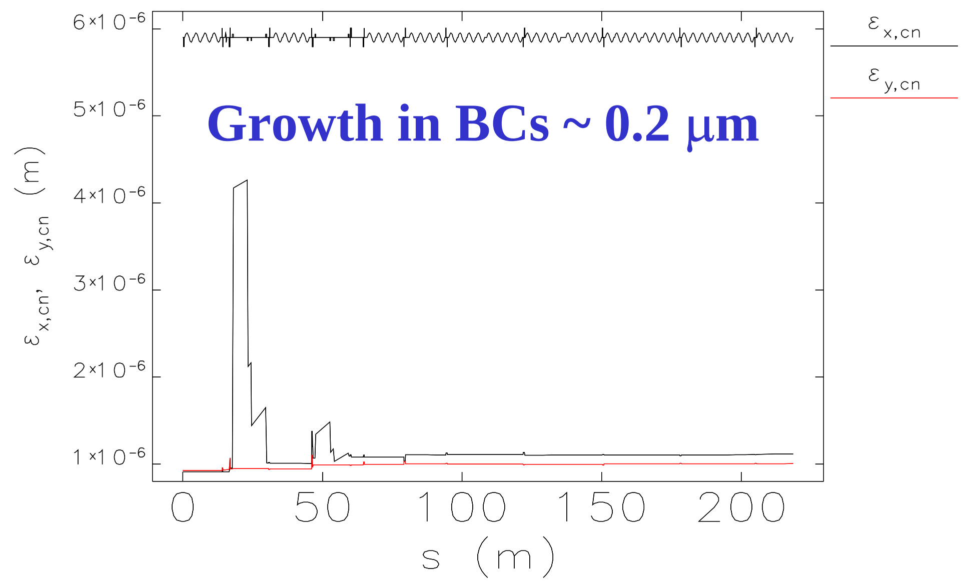


$\sigma_x = 68\ \mu m$, $\sigma_y = 62\ \mu m$

$\varepsilon_{nx} = 1.1\ \mu m$, $\varepsilon_{ny} = 1.0\ \mu m$

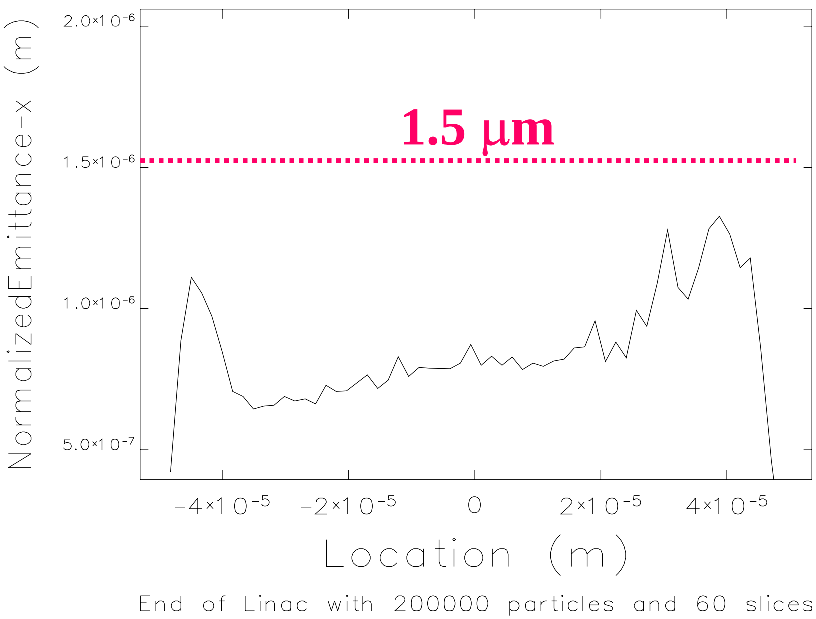


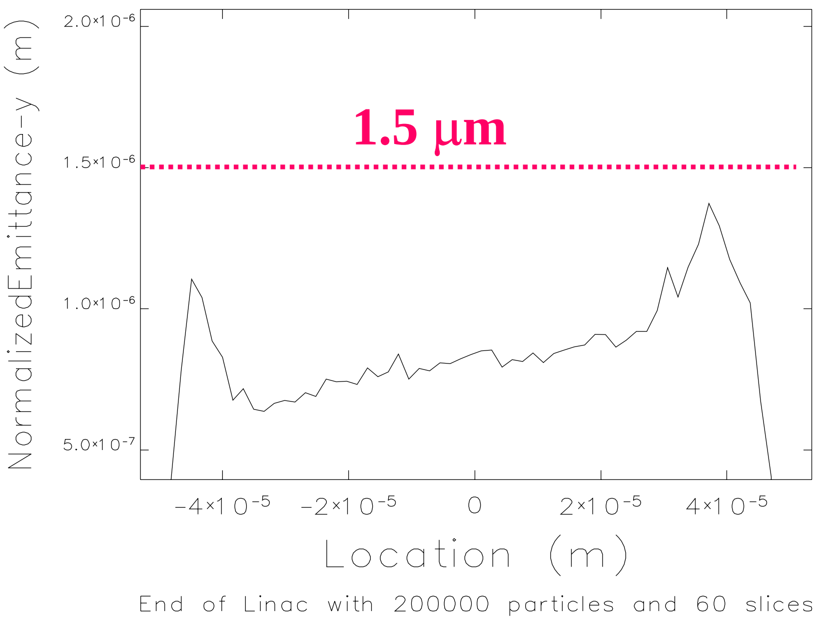
RMS beam size



Normalize emittance

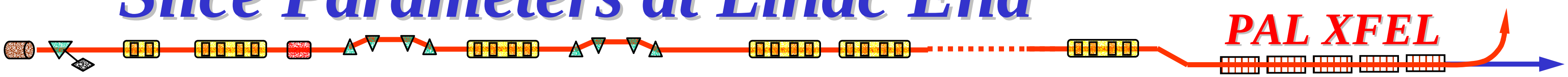
Slice Parameters at Linac End

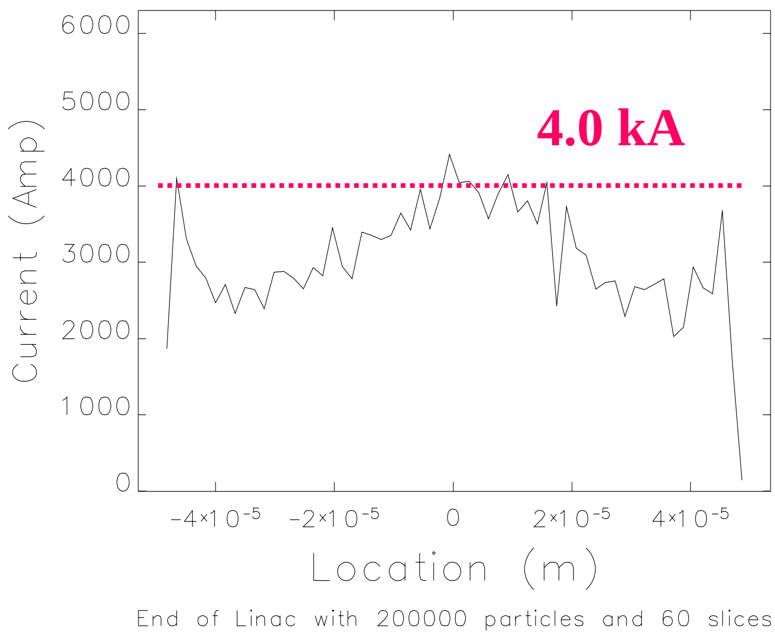


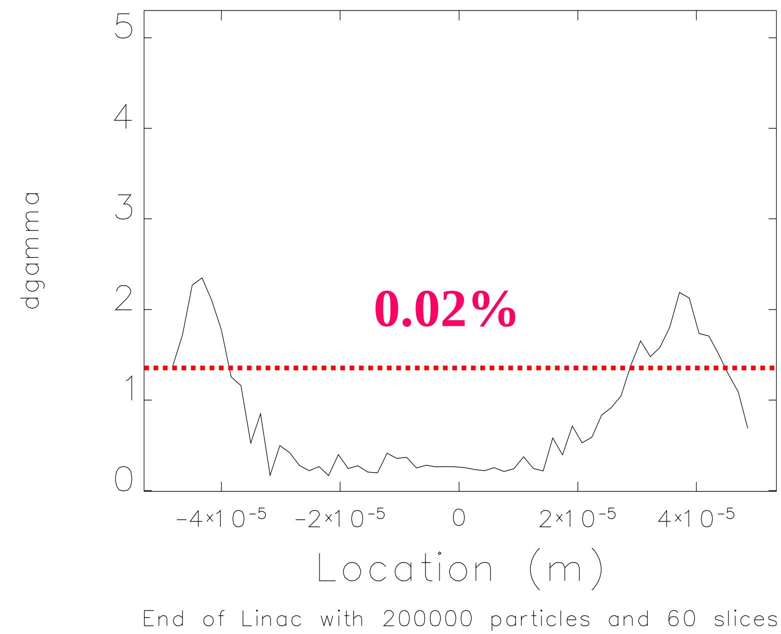


Horizontal emittance **Vertical emittance**

Slice Parameters at Linac End



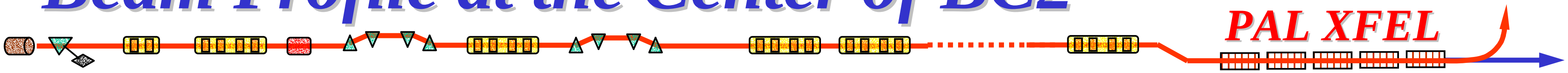


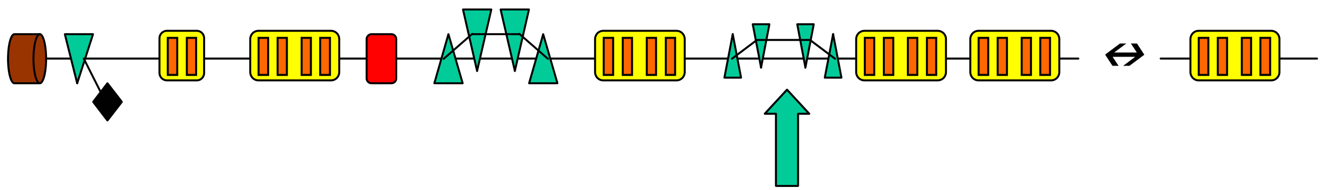


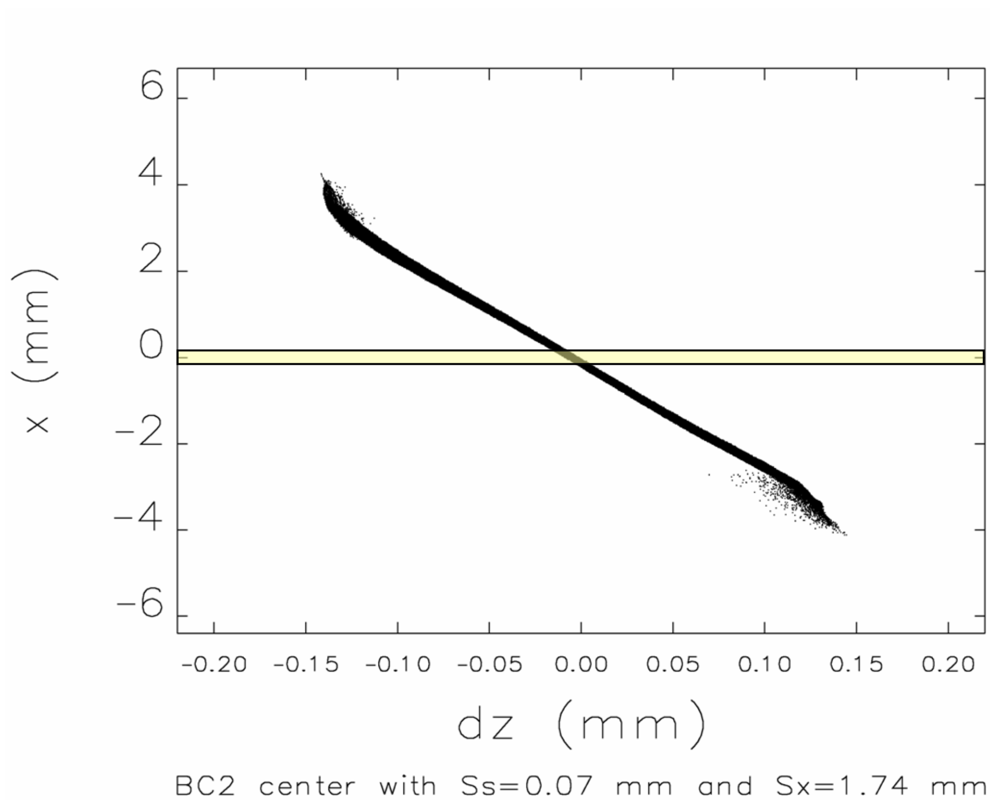
Peak current

RMS energy spread

Beam Profile at the Center of BC2



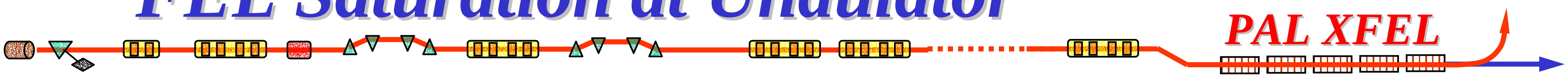


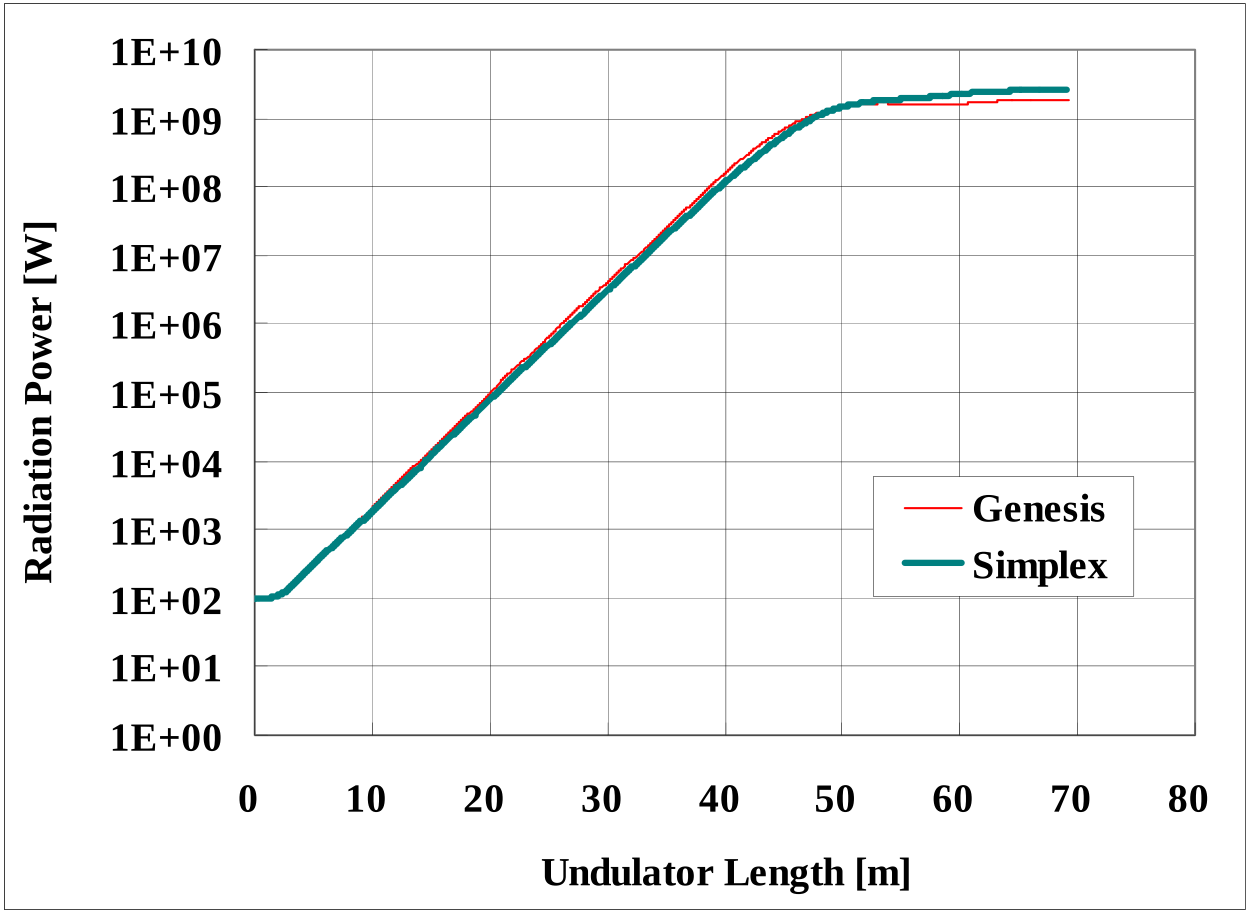


At the center of BC2
σ_x= 1.74 mm,
σ_z = 70 μm

With 300 μm slit,
σ_z = *6.2* μm
rms bunch length 20 fs

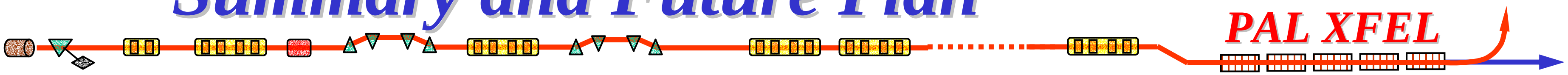
FEL Saturation at Undulator





Summary

Summary and Future Plan



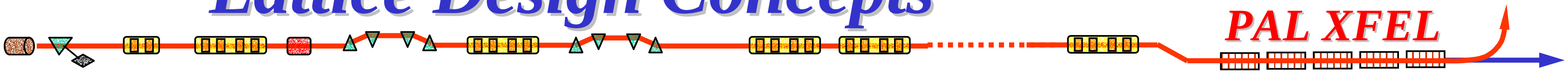
1. By adding an S-band RF photo-injector, a 700 MeV injector linac, and two bunch compressors, PLS linac will be converted to an XFEL driving linac.

2. Optimized parameters of PAL XFEL are very promising and good enough to generate 3.0 Å SASE source.

3. The construction is planed to start in 2006.

4. Commissioning for the first SASE source is scheduled in 2009.

Lattice Design Concepts



☐ Against Projected Parameter Dilution due to CSR and Chromatic Effect

- Long drift space ΔL to reduce bending angle for a required R56
- Small bending angle at a large energy spread
- Large compression factor at BC1 and small compression factor at BC2
- Using strong focusing lattice around BC to reduce CSR induced emittance growth
- Small quadrupole length (shortest = 0.05 m) around BC to reduce the chromatic effects
- Smaller maximum beta-function at BC1 entrance ~ 60 m
- After reducing energy spread at BC2, larger maximum beta-function at BC2 entrance

☐ Against Slice Parameter Dilution due to the Microbunching Instability

- Normal 4-bend chicane instead of S-type chicane is used.
- Keep large uncorrelated energy spread at BC2 by putting the BC2 at low energy region
- No need any laser beam heater or Superconducting wiggler !!!

☐ Against the Tight Jitter Tolerance

- Two BC stage is used.
- RF gun will be driven by its own Klystron.
- Each S-band accelerating column before BC2 will be driven by each own Klystron
- X-band correction cavity will be possibly driven by two X-band Klystron

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