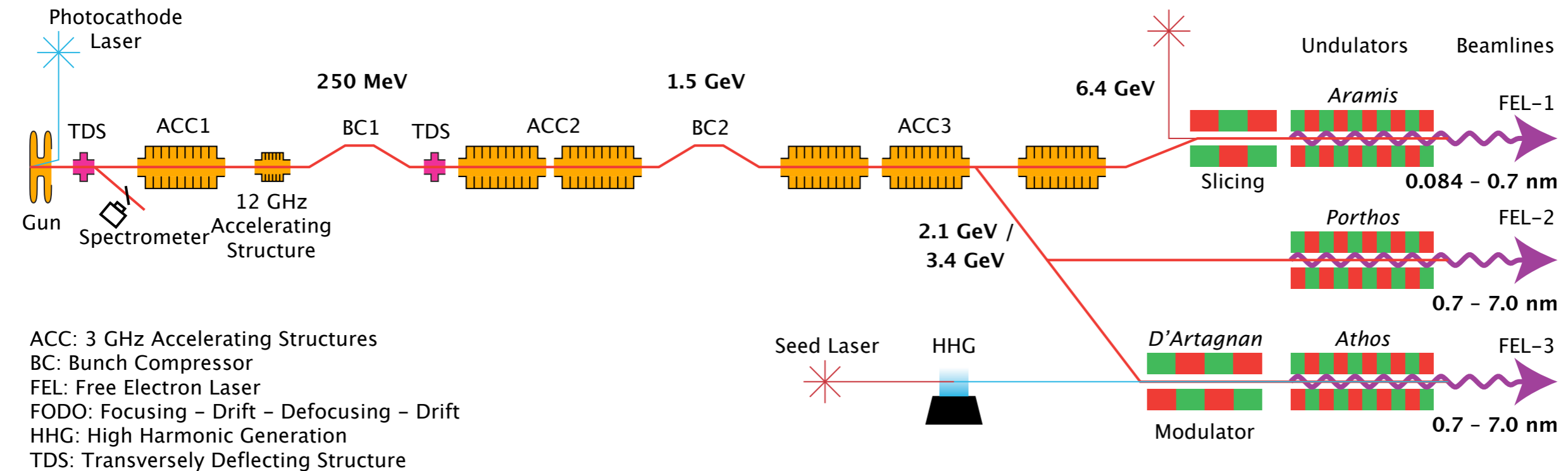


# The PSI-XFEL

A Compact Free Electron Laser for X-Ray Wavelengths

Rasmus Ischebeck

# Schematic Layout for the PSI-XFEL (RF Gun Option)



## Advantages of new layout (Sven Reiche, Fall 2008)

- Decoupled operation of all FEL beamlines
- Wavelength range optimized for optics, resulting one hard-X-ray and two soft X-ray beamlines.
- Undulator modules fulfill minimum gap requirement of  $g > 6.5$  mm for all wavelengths.
- Identical modules for both soft X-ray FELs allows for more flexible electron beam distribution.

# Electron Source

- Low emittance gun project at PSI
  - Goal: develop a pulsed-DC gun
  - Develop a two frequency cavity for optimal longitudinal phase space manipulation
  - Cathodes:
    - Single-tip field emitter
    - Field emitter array
    - Photocathode
- New: RF photocathode gun as an alternative electron source
  - CTF-5 Gun from CERN
  - Larger slice emittance
  - Lower energy spread when compressed to the same peak current
  - Alternatively: larger peak current

# The PSI-XFEL Status

- Re-optimization of the PSI-XFEL design is in progress
- As a consequence, please note that all numbers stated in this talk are still converging towards their final values
- In this talk, I will present the current baseline
- Possible extensions to this baseline will not be presented



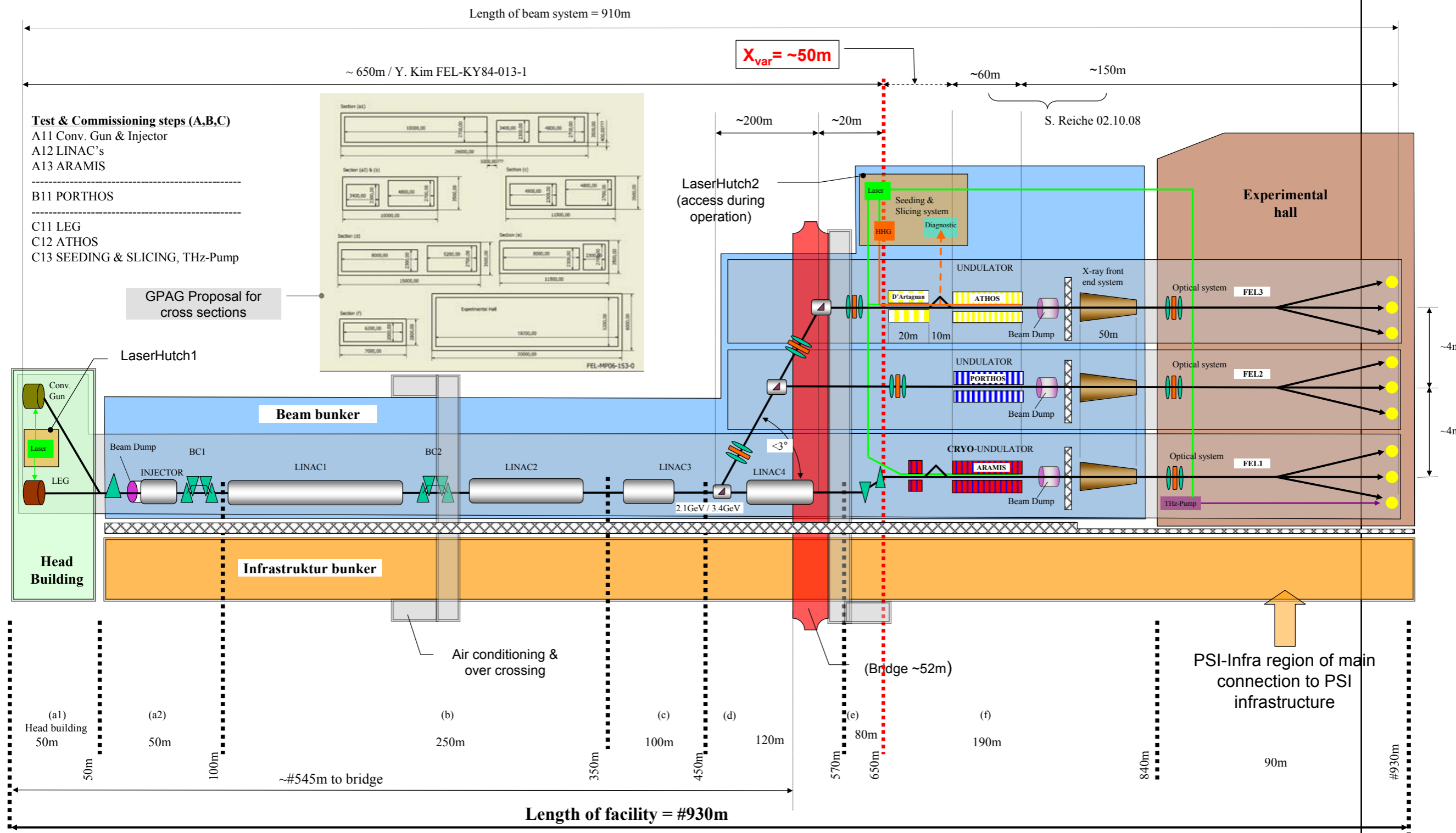
# 3 Beamlines, 5 Operating Modes

|                            | Beamline 1<br>Aramis | Beamline 2<br>Porthos | Beamline 3<br>d'Artagnan / Athos |
|----------------------------|----------------------|-----------------------|----------------------------------|
| Wavelength                 | 0.1 – 0.7 nm         | 0.7 – 7.0 nm          | 0.7 – 7.0 nm                     |
| Photon Energy              | 1.71 – 12 keV        | 0.17 – 1.71 keV       | 0.17 – 1.71 keV                  |
| Tuning                     | Electron Energy      | Undulator Gap         | Undulator Gap                    |
| Undulator Type             | Cryo, in-vacuum      | APPLE                 | APPLE                            |
| Undulator Length           | 60...70 m            | 50...60 m             | 50...60 m                        |
| K-Value                    | 1.2                  | 1.0 – 3.2             | 1.0 – 3.2                        |
| Period                     | 15 mm                | 40 mm                 | 40 mm                            |
| Gap                        | 4 mm                 | 6.5 – 50 mm           | 6.5 – 50 mm                      |
| Electron Energy            | 2.2 – 5.8 GeV        | 2.1 / 3.4 GeV         | 2.1 / 3.4 GeV                    |
| Normalized Slice Emittance | 0.45 $\mu\text{m}$   | 0.45 $\mu\text{m}$    | 0.45 $\mu\text{m}$               |
| Electron Bunch Charge      | 200 pC               | 200 pC                | 200 pC                           |

# 3 Beamlines, 5 Operating Modes

|        | Wavelength   | Photon Energy   | Type   | Tuning | Undulator       |
|--------|--------------|-----------------|--------|--------|-----------------|
| Mode 1 | 0.1 – 0.7 nm | 1.71 – 12 keV   | SASE   | Energy | Aramis          |
| Mode 2 | 0.7 – 2.8 nm | 0.43 – 1.71 keV | SASE   | Gap    | Athos / Porthos |
| Mode 3 | 1.8 – 7.0 nm | 0.17 – 0.67 keV | SASE   | Gap    | Athos / Porthos |
| Mode 4 | 1* – 7 nm    | 0.17 – 1.2 keV  | seeded | Gap    | Athos           |
| Mode 5 | 7 – 25 nm    | 48 – 170 eV     | seeded | Gap    | d'Artagnan      |

# Schematic Layout



# The PSI-XFEL

- FEL experiments
  - Demonstration of FEL principle
  - Limited use as a user facility
- X-Ray FEL as spin-offs from linear collider development
  - SLC → LCLS, TESLA → EU-XFEL, JLC(C) → SCSS
  - Bunch parameters and time structure constrained by original linear collider design!
- FELs designed from the outset user facilities
  - Beam parameters, time structure & coherence properties
  - More compact design
  - Synergy with PSI expertise
    - Detector development
    - User facility operation

# Comparison of XFELs

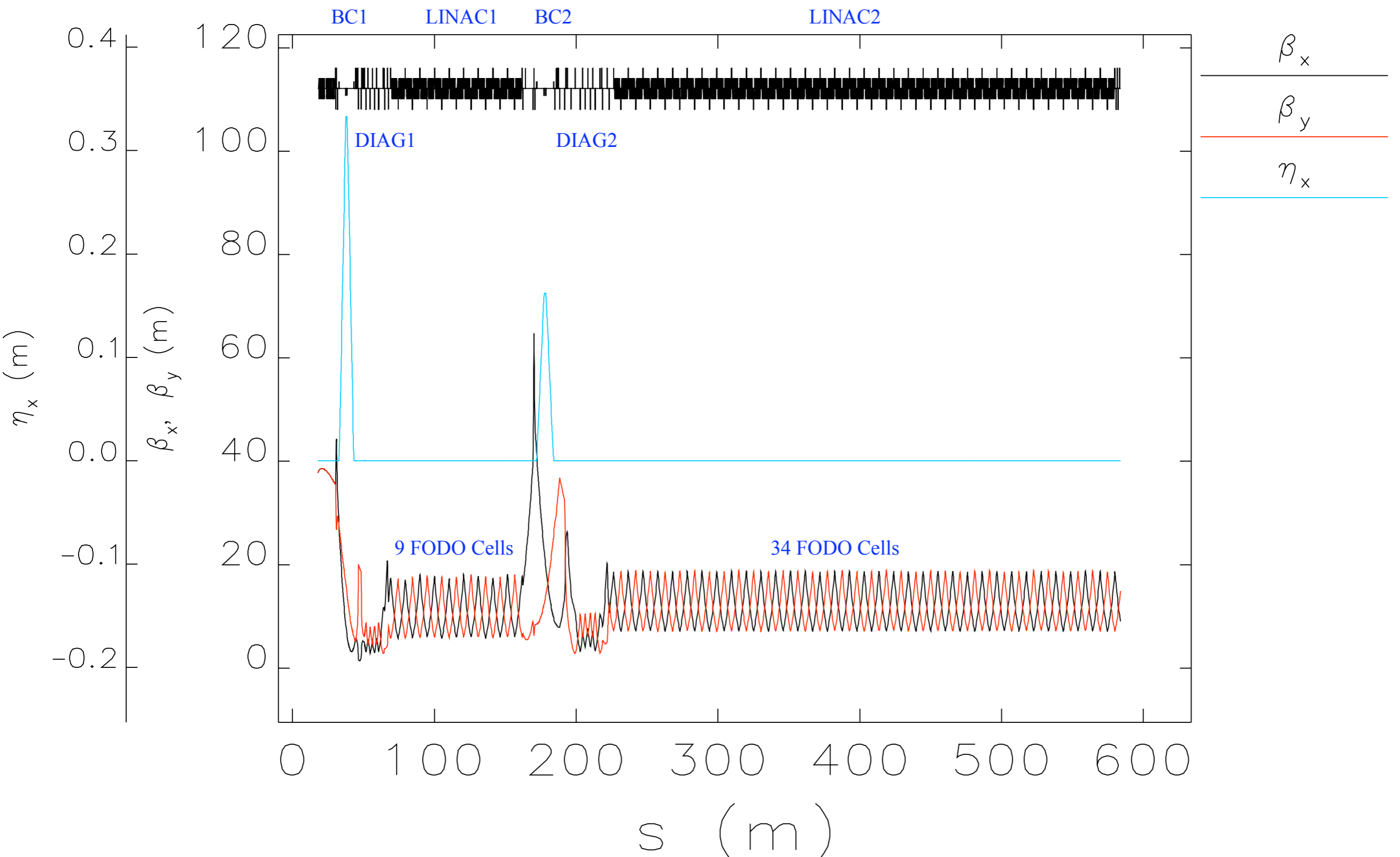
|                                   |               | LCLS                     | SCSS              | EU XFEL                     | PSI-XFEL             |
|-----------------------------------|---------------|--------------------------|-------------------|-----------------------------|----------------------|
| Wavelength                        | nm            | 0.15                     | 0.1               | 0.1                         | 0.1                  |
| Design Peak Brilliance            | *             | $8 \cdot 10^{32}$        | $5 \cdot 10^{33}$ | $5 \cdot 10^{33}$           | $1 \cdot 10^{33}$ ** |
| Electron Energy                   | GeV           | 14.35                    | 6.1               | 17.5                        | 5.8                  |
| Normalized Slice Design Emittance | $\mu\text{m}$ | 1.2                      | 0.85              | 1.4                         | 0.45                 |
| Undulator Period                  | mm            | 30                       | 15                | 35.6                        | 15                   |
| Gain Length                       | m             | 4.8                      | 3.7               |                             | 2.5                  |
| Saturation Length                 | m             | 92                       | 80                | 140                         | 39                   |
| Facility Length                   | m             | 3000                     | 750               | 3400                        | 910                  |
| Start of Operation                |               | 2009                     | 2010              | 2014                        | 2016                 |
| Source                            |               | LCLS TDR<br>(SLAC-R-593) | SCSS CDR          | XFEL TDR<br>(DESY 2006-097) |                      |

\* number of photons / s mm<sup>2</sup> mrad<sup>2</sup> 0.1% bandwidth

\*\* calculated with Ming Xie formulae

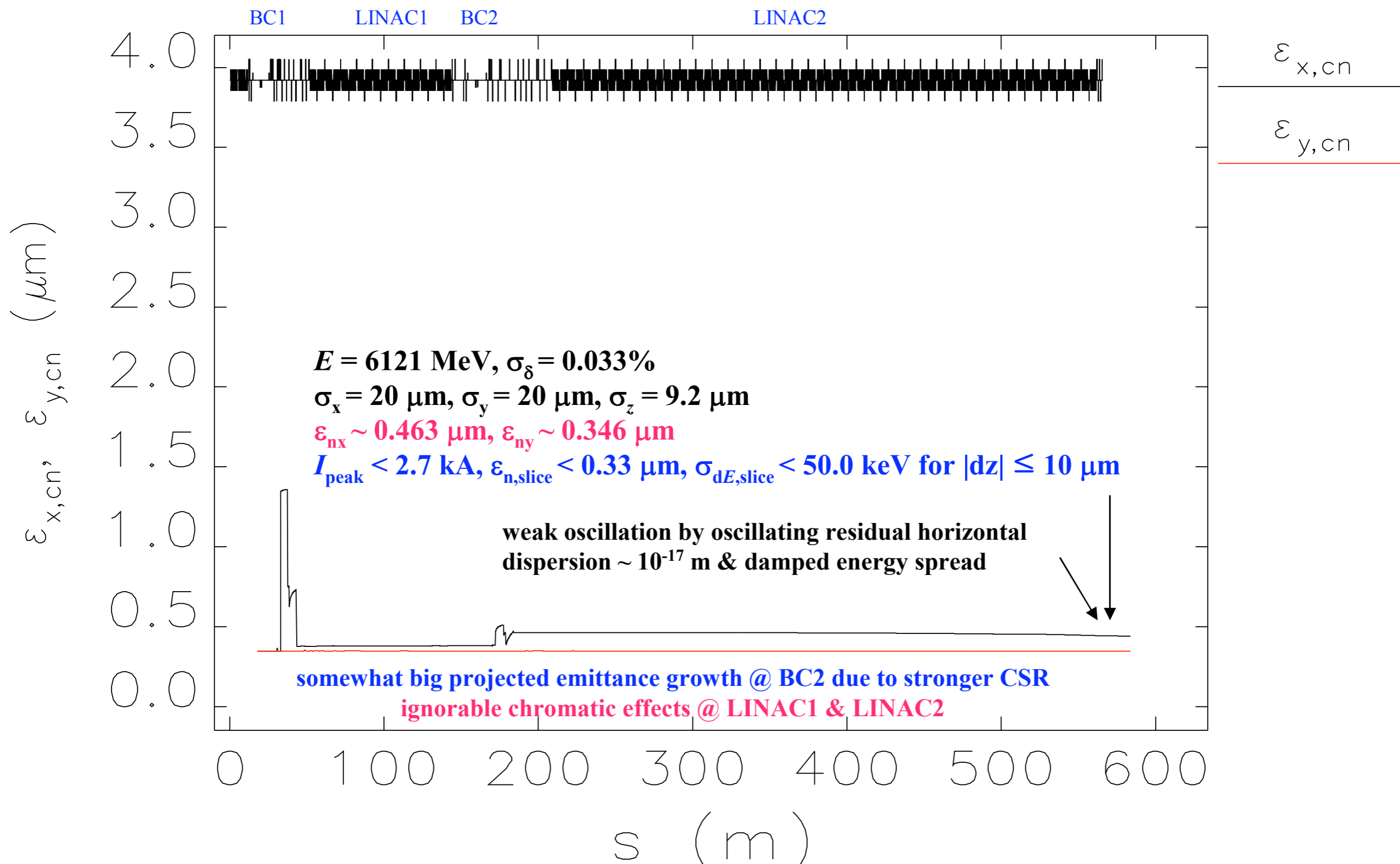
# Simulations

## Linac with RF Gun – Design Optics



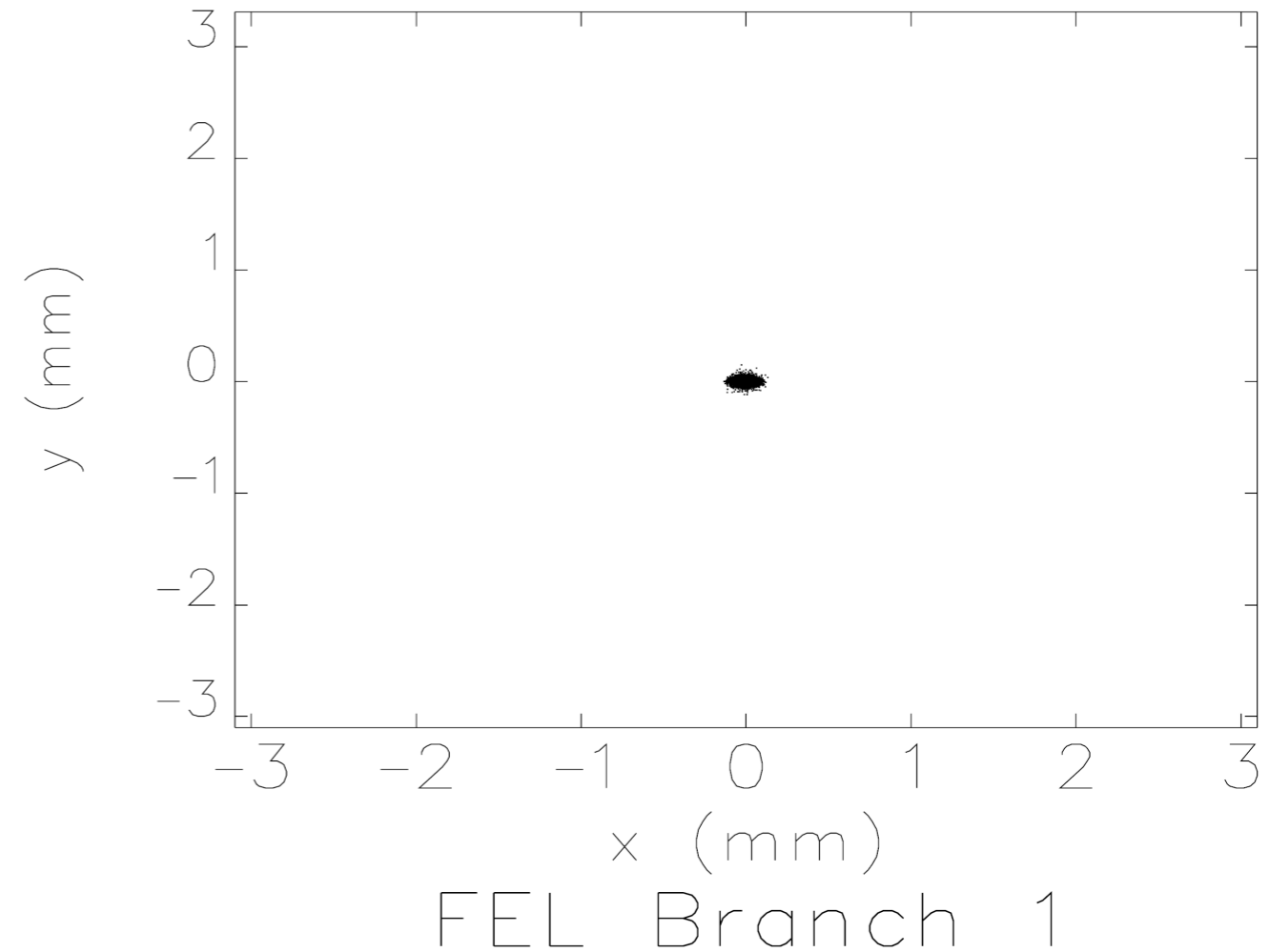
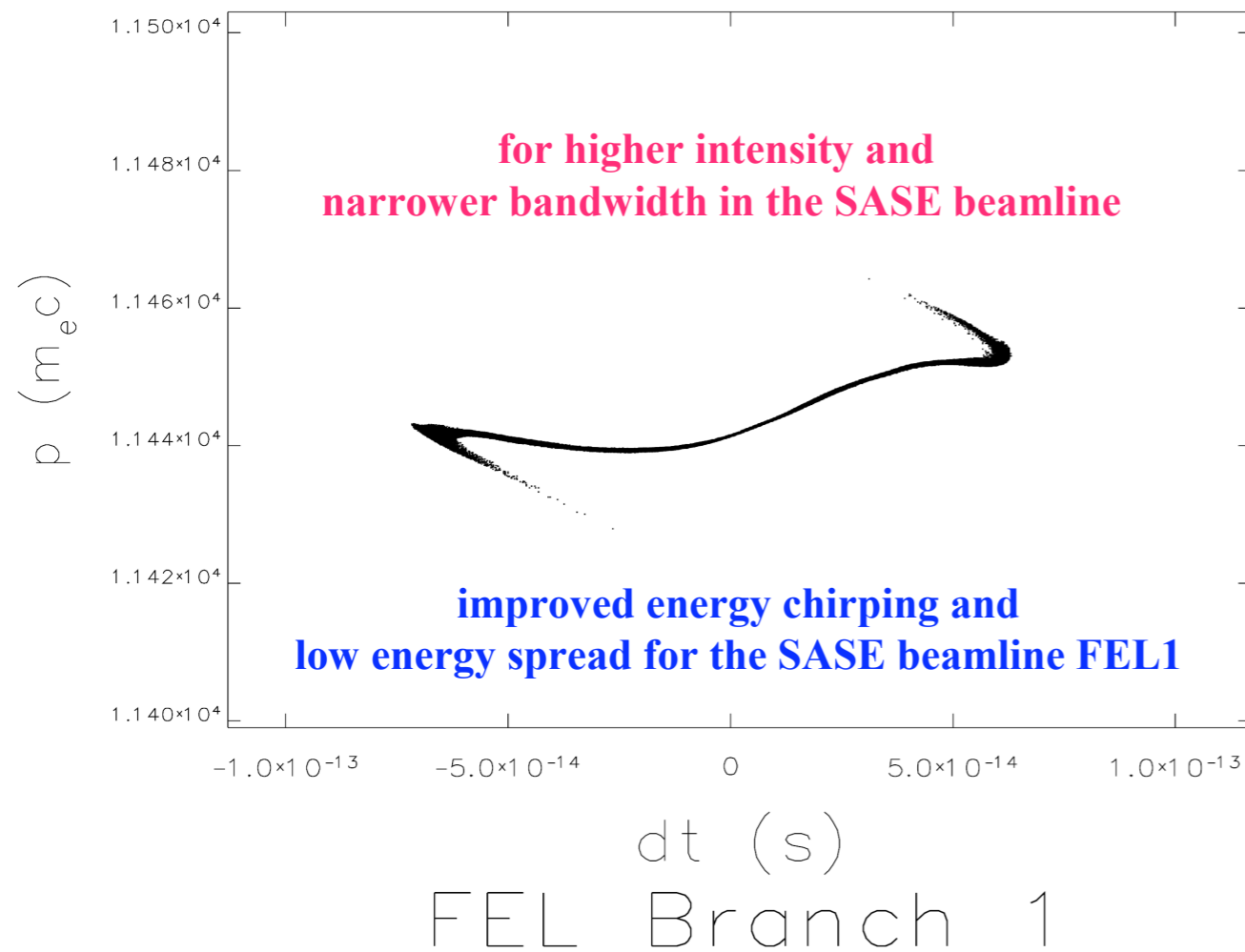
# Simulations

## Linac with RF Gun – Projected Emittance



# Simulations

## Linac with RF Gun – Phase Space at FEL-1



$$E = 5847 \text{ MeV}, \sigma_\delta = 0.039\%$$

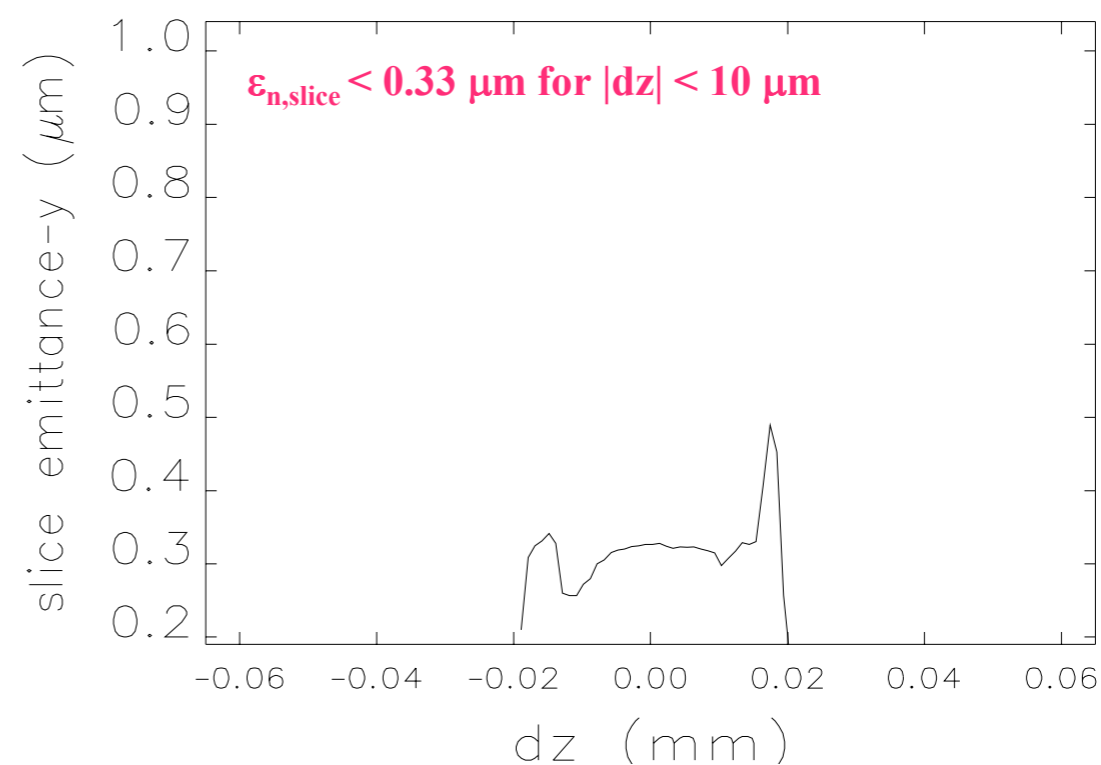
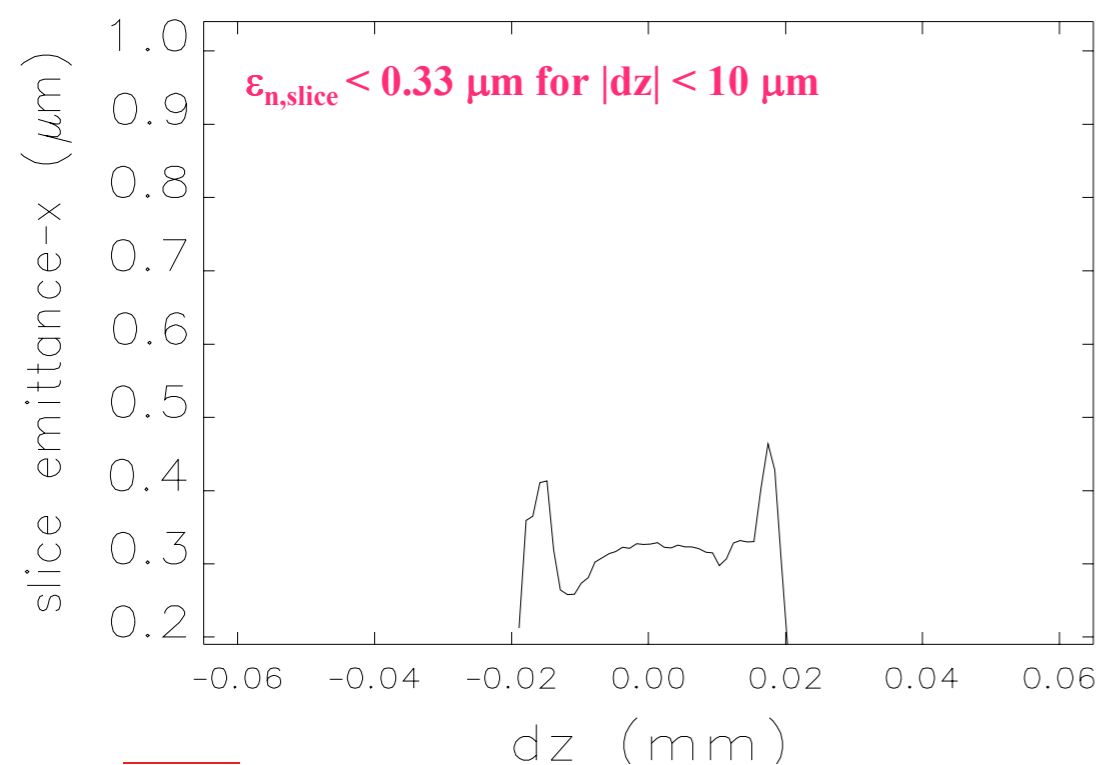
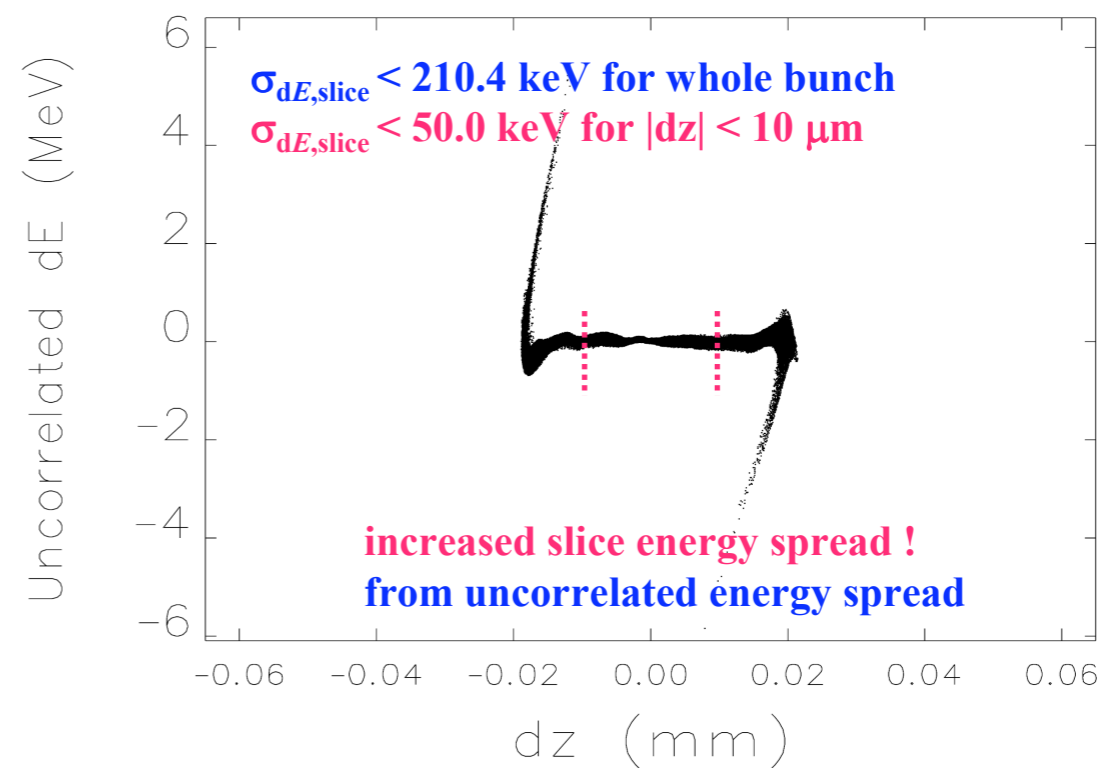
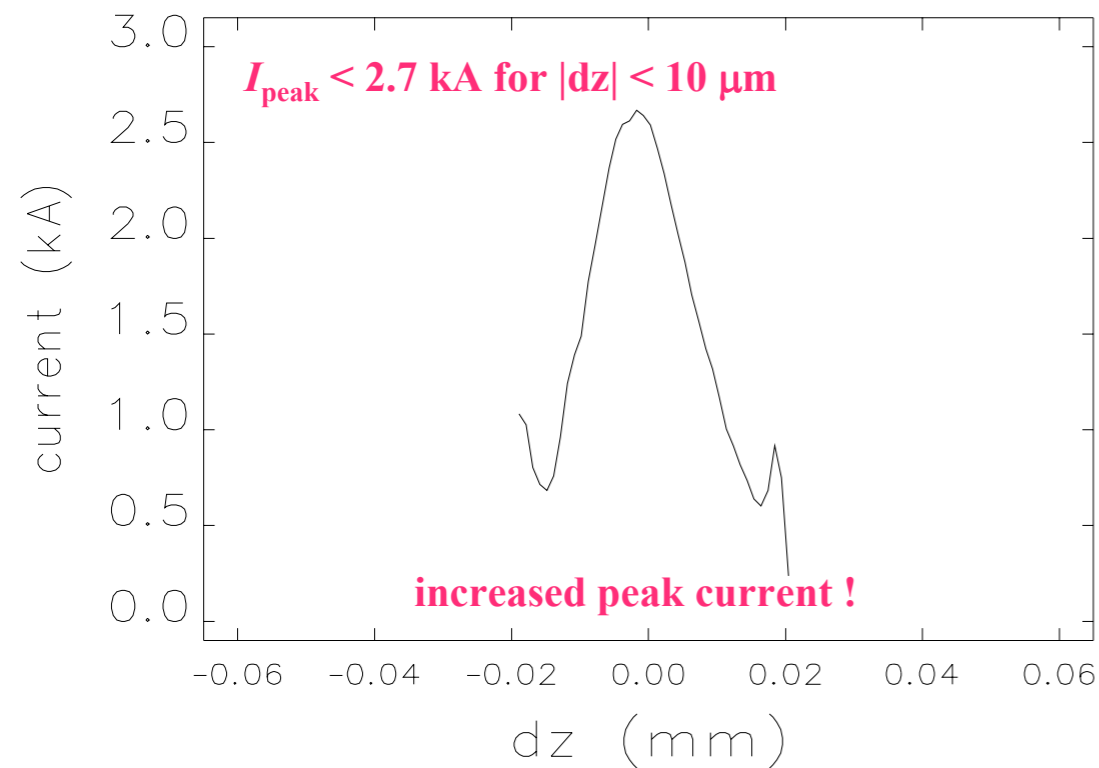
$$\sigma_x = 25 \text{ } \mu\text{m}, \sigma_y = 15 \text{ } \mu\text{m}, \sigma_z = 9.2 \text{ } \mu\text{m}$$

$$\varepsilon_{nx} \sim 0.463 \text{ } \mu\text{m}, \varepsilon_{ny} \sim 0.346 \text{ } \mu\text{m}$$

$$I_{\text{peak}} < 2.7 \text{ kA}, \varepsilon_{n,\text{slice}} < 0.33 \text{ } \mu\text{m}, \sigma_{dE,\text{slice}} < 50.0 \text{ keV for } |dz| \leq 10 \text{ } \mu\text{m}$$

# Simulations

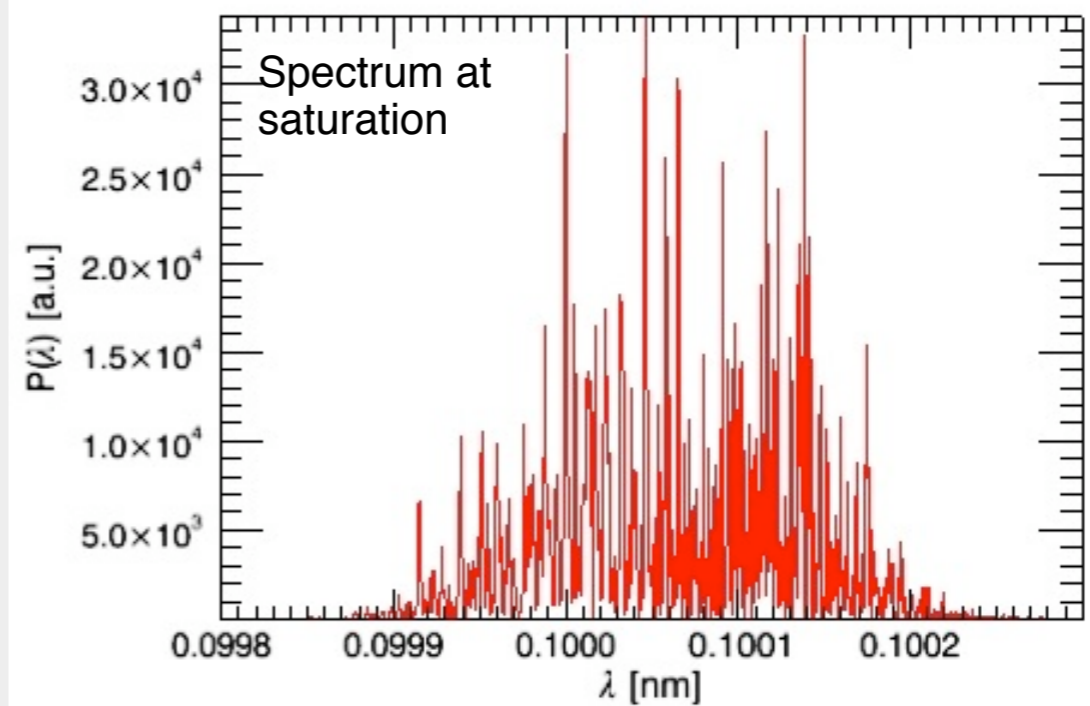
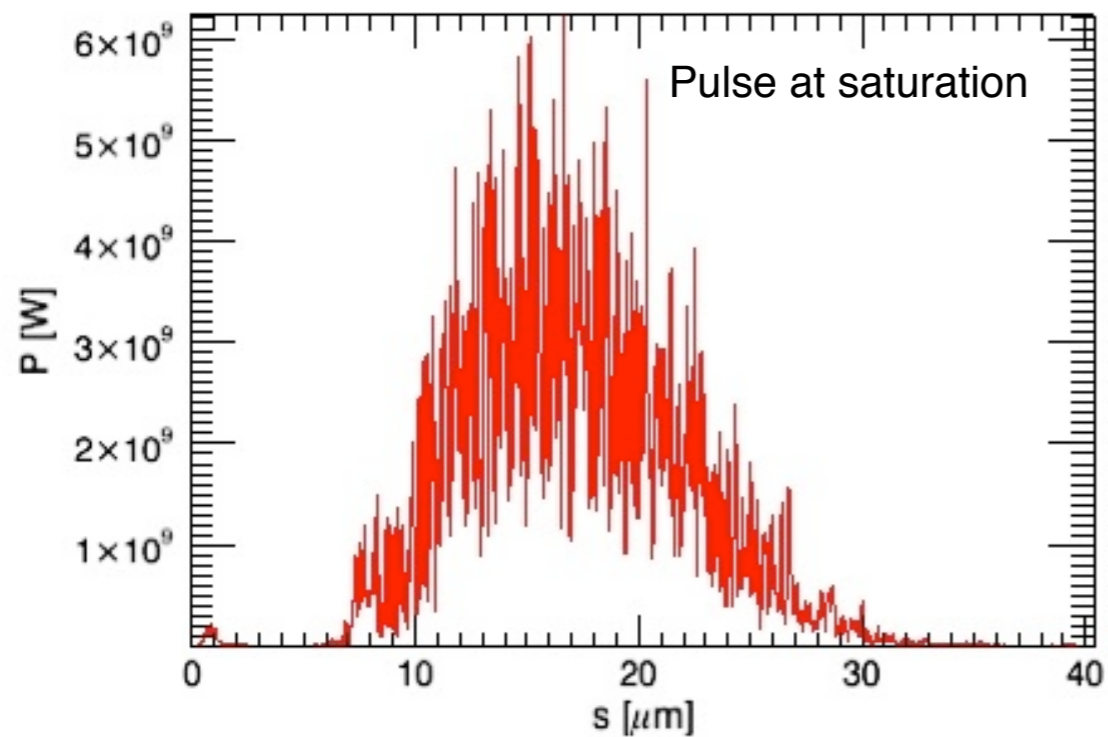
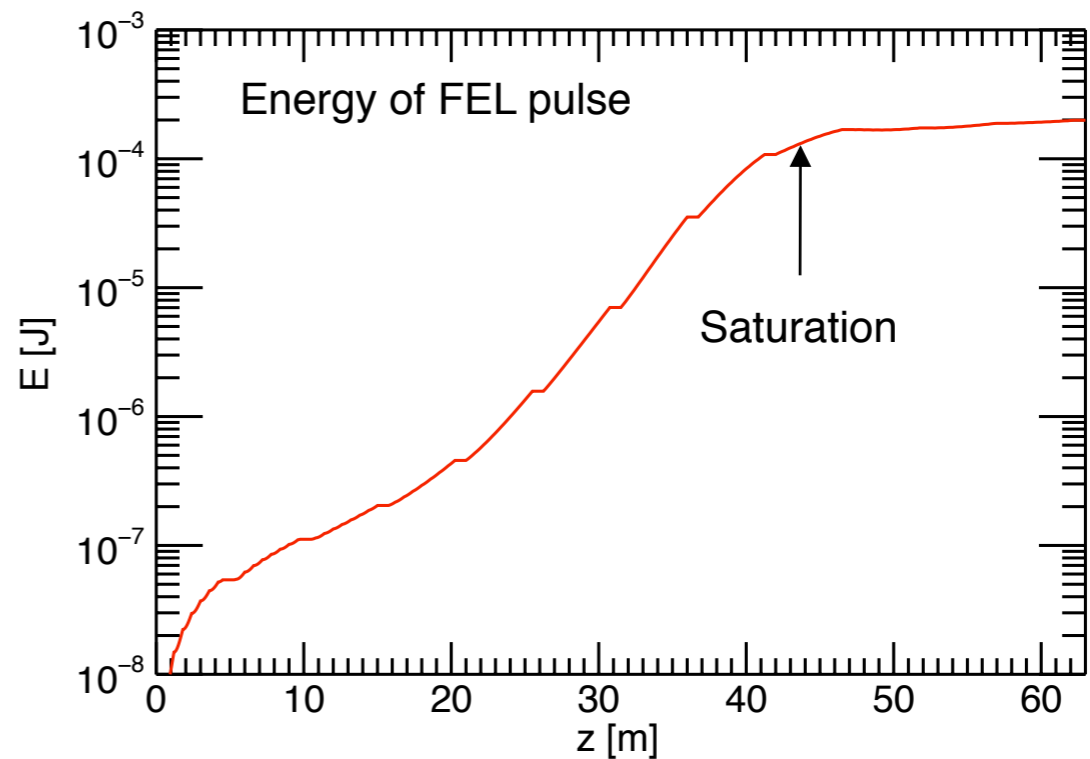
## Linac with RF Gun – Slice Parameters at 6 GeV



# Simulations

## FEL-1 at 0.1 nm – RF Gun

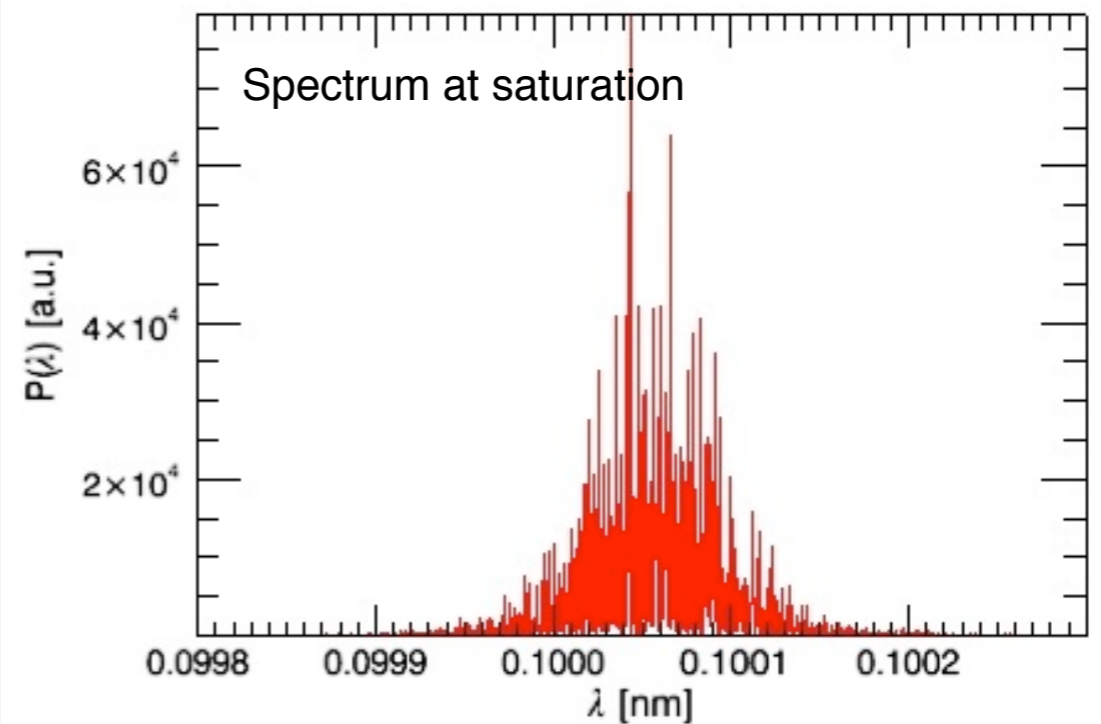
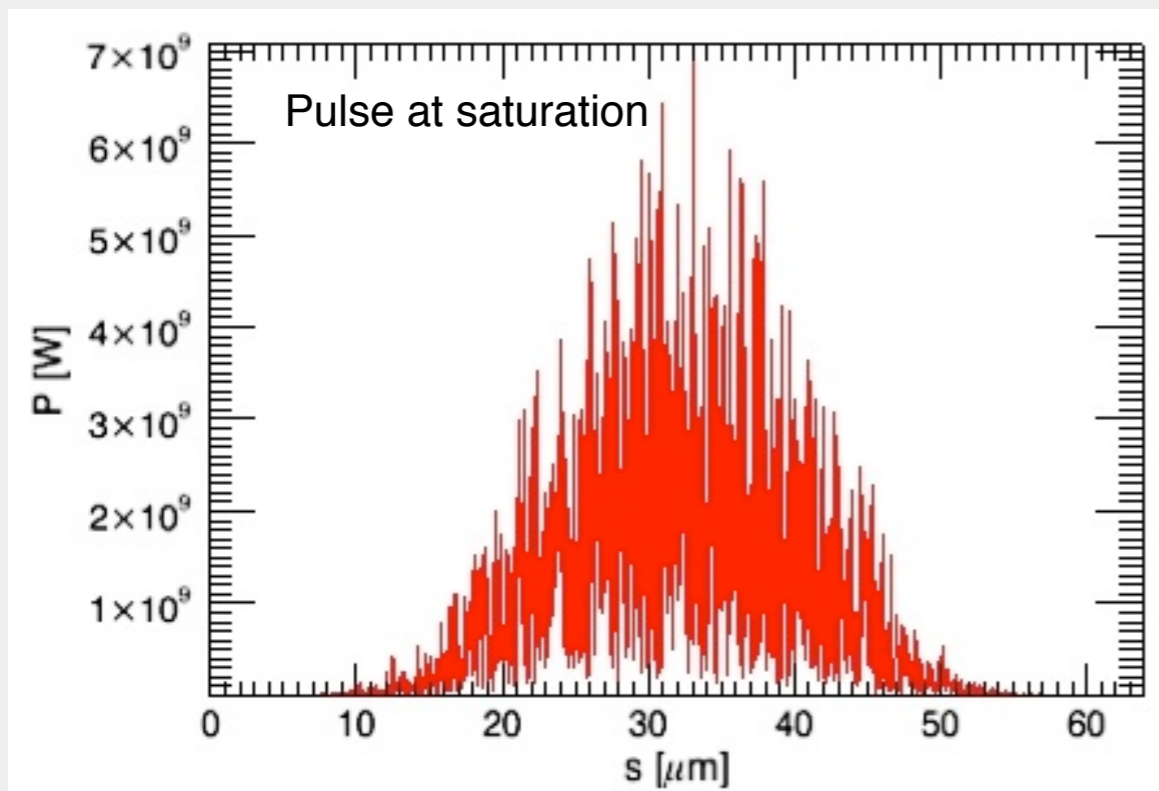
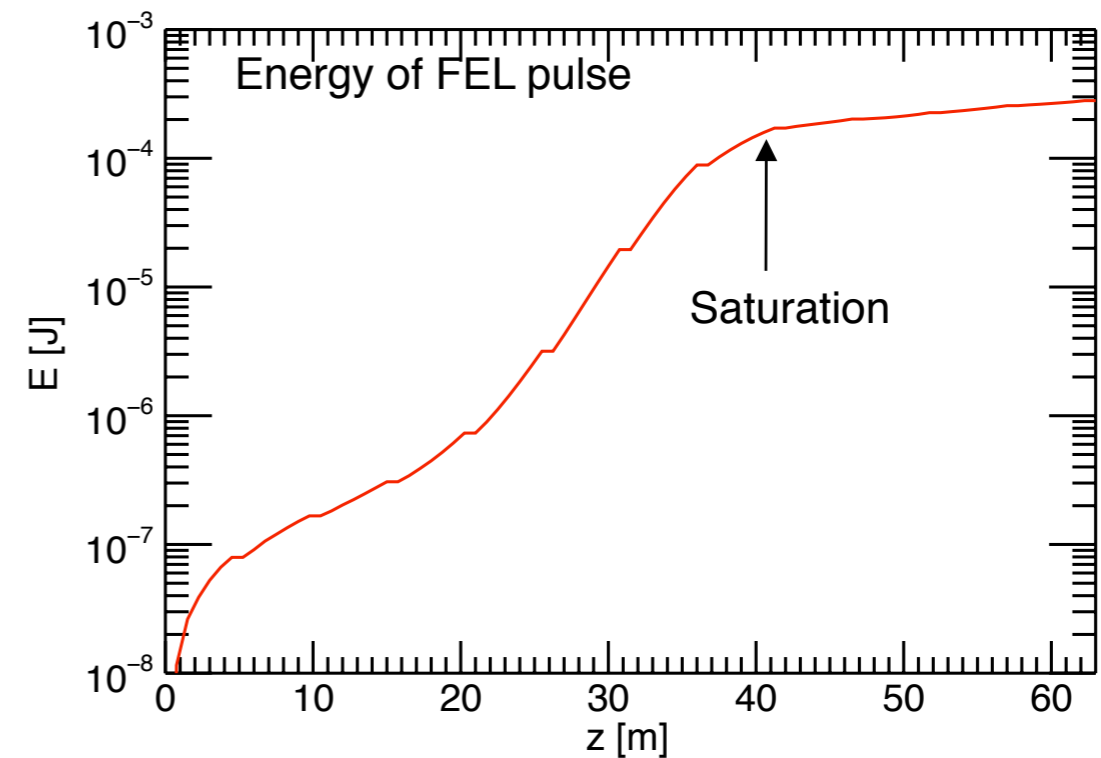
|                   |                     |
|-------------------|---------------------|
| Saturation Length | 43 m                |
| Pulse Energy      | 110 $\mu\text{J}$   |
| Average Power     | 2.9 GW              |
| Bandwidth (rms)   | 0.07 %              |
| Divergence (rms)  | 1.5 $\mu\text{rad}$ |
| Size (rms)        | 25 $\mu\text{m}$    |



# Simulations

## FEL-1 at 0.1 nm – Low Emittance Gun

|                   |                     |
|-------------------|---------------------|
| Saturation Length | 40 m                |
| Pulse Energy      | 130 $\mu\text{J}$   |
| Average Power     | 2 GW                |
| Bandwidth (rms)   | 0.04 %              |
| Divergence (rms)  | 1.5 $\mu\text{rad}$ |
| Size (rms)        | 20 $\mu\text{m}$    |

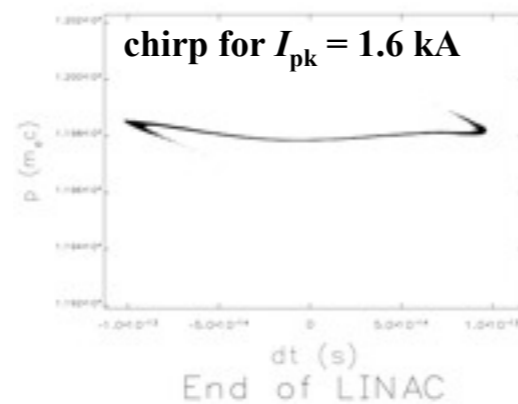
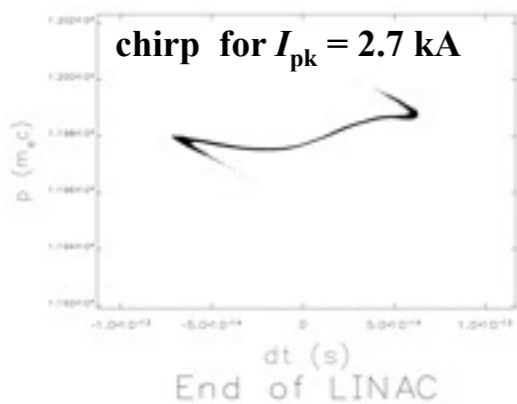


# Simulations

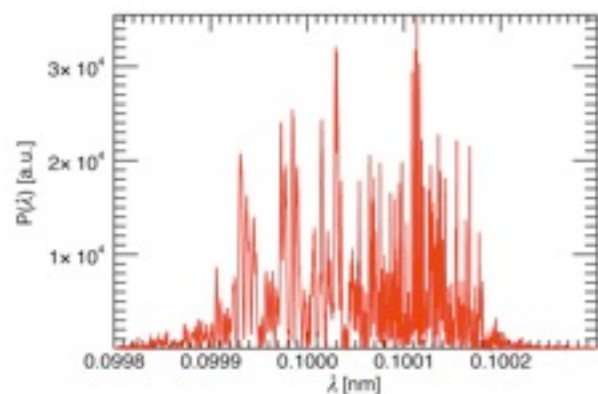
- Accelerator: ASTRA, ELEGANT (Yujong Kim)
- Undulator: GENESIS 1.3 (Sven Reiche)

According to our recent ASTRA+ELEGANT+GENESIS S2E simulations for the PSI-XFEL project, recently, we could control electron energy chirp and energy spread with a lower peak current easily, and we could get much improved spectrum bandwidth with  $I_{pk} = 1.6$  kA instead of 2.7 kA for 0.2 nC. Other FEL performance are similar for both cases.

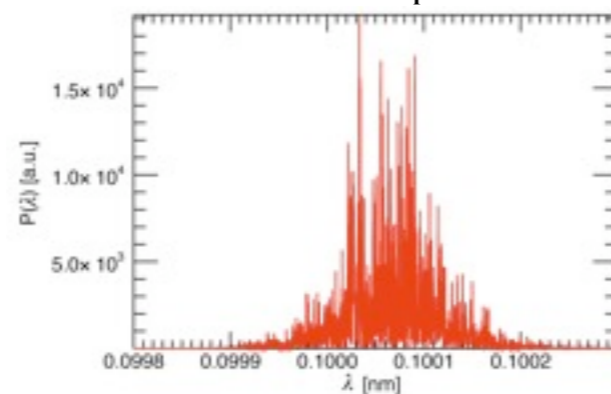
## ASTRA + ELEGANT Simulation Results



BW  $\sim 0.1\%$  for  $I_{pk} = 2.7$  kA

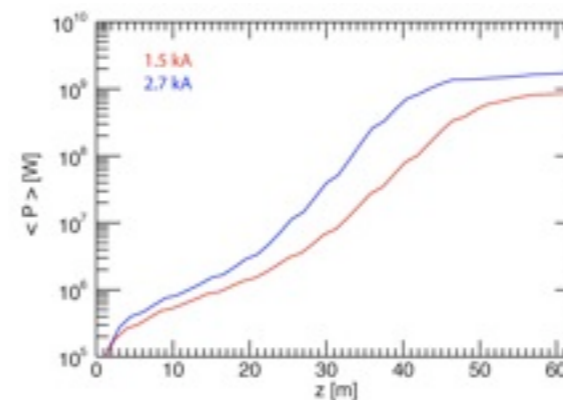


BW  $\sim 0.05\%$  for  $I_{pk} = 1.6$  kA



## GENESIS Simulation

No of photon per pulse  $\sim 1.0 \times 10^{11}$   
Saturation length  $\sim 45$  m for 2.7 kA  
Saturation length  $\sim 55$  m for 1.6 kA

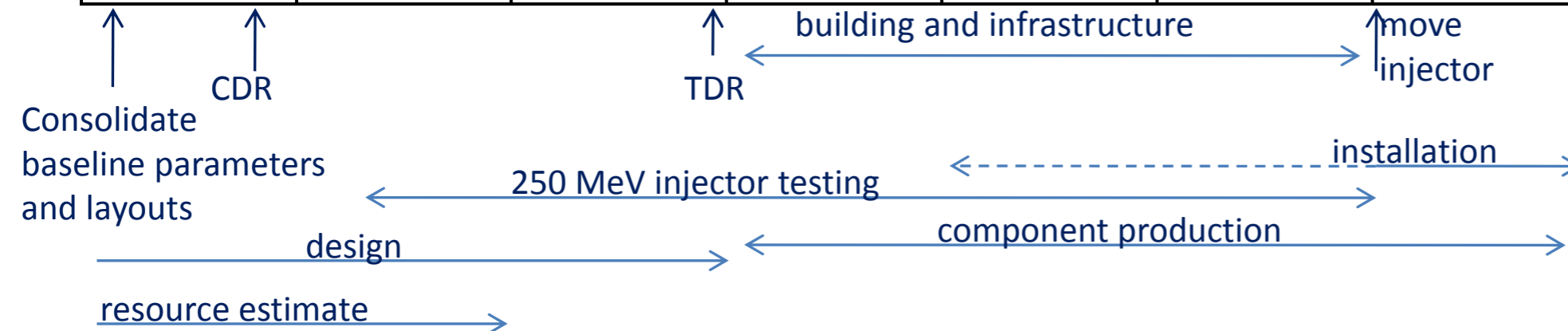
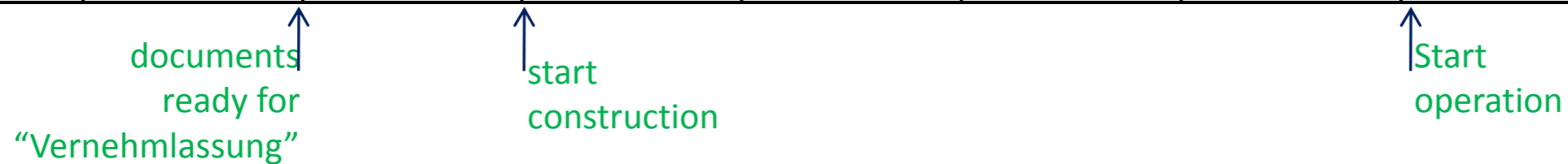
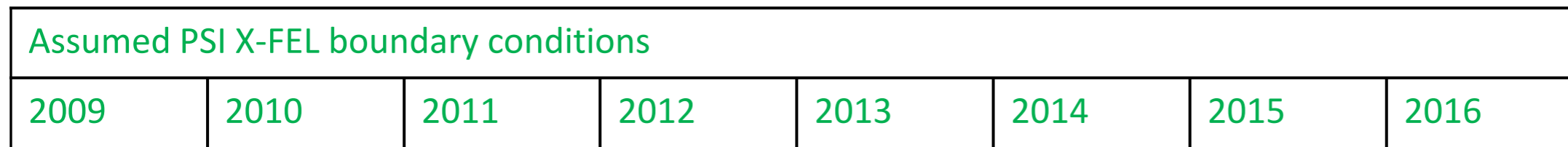
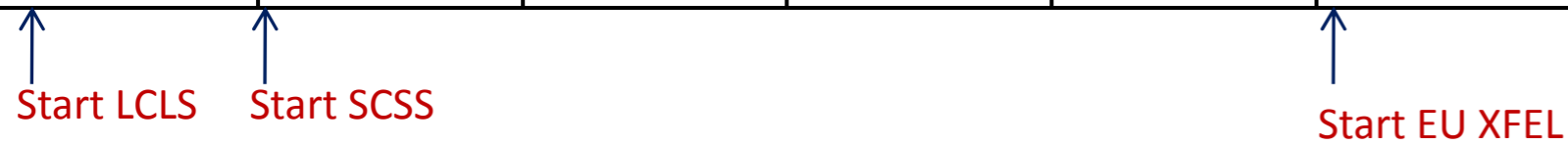


# Parameters – Photons GENESIS Simulations

|                           |                   | Mode 1              |                     | Mode 2              |                     | Mode 3              |                     |
|---------------------------|-------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| Wavelength                | nm                | 0.7                 | 0.1                 | 2.8                 | 0.7                 | 7                   | 1.8                 |
| Photon Energy             | keV               | 1.71                | 12.00               | 0.43                | 1.71                | 0.17                | 0.67                |
| Saturation Length         | m                 | 21.52               | 39.27               | 25.54               | 41.52               | 20.08               | 32.81               |
| Effective Gain Length     | m                 | 1.24                | 2.49                | 1.23                | 2.24                | 0.96                | 1.60                |
| Peak Power                | GW                | 1.6                 | 2.04                | 7.76                | 5.16                | 6.38                | 5.06                |
| Pulse Energy              | mJ                | 0.09                | 0.13                | 0.51                | 0.32                | 0.46                | 0.33                |
| Peak Brilliance           | *                 | $7.4 \cdot 10^{30}$ | $1.2 \cdot 10^{32}$ | $1.8 \cdot 10^{30}$ | $2.3 \cdot 10^{31}$ | $2.7 \cdot 10^{29}$ | $5.5 \cdot 10^{30}$ |
| Bandwidth                 | % rms             | 0.08                | 0.04                | 0.31                | 0.12                | 0.42                | 0.17                |
| Beam Size                 | $\mu\text{m}$ rms | 34.28               | 19.33               | 58.07               | 41.52               | 95.56               | 49.51               |
| Divergence                | $\mu\text{rad}$   | 5.87                | 1.46                | 15.84               | 4.88                | 30.24               | 9.29                |
| Intensity<br>(50 m drift) | J/cm <sup>2</sup> | 0.03                | 0.72                | 0.03                | 0.17                | 0.01                | 0.05                |

# Timeline

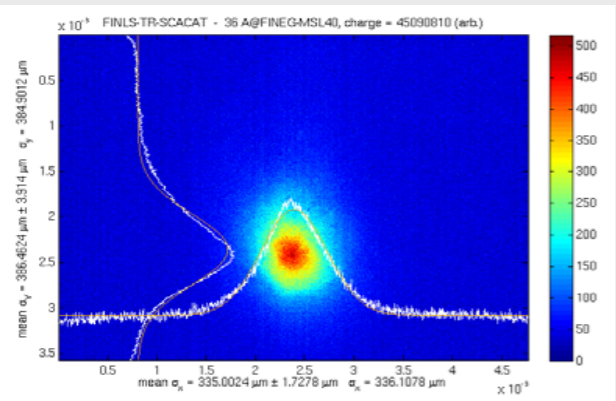
## PSI X-FEL, three agendas



# Status – Low Emittance Gun Test Stand

- Completed measurements at 250–500 keV

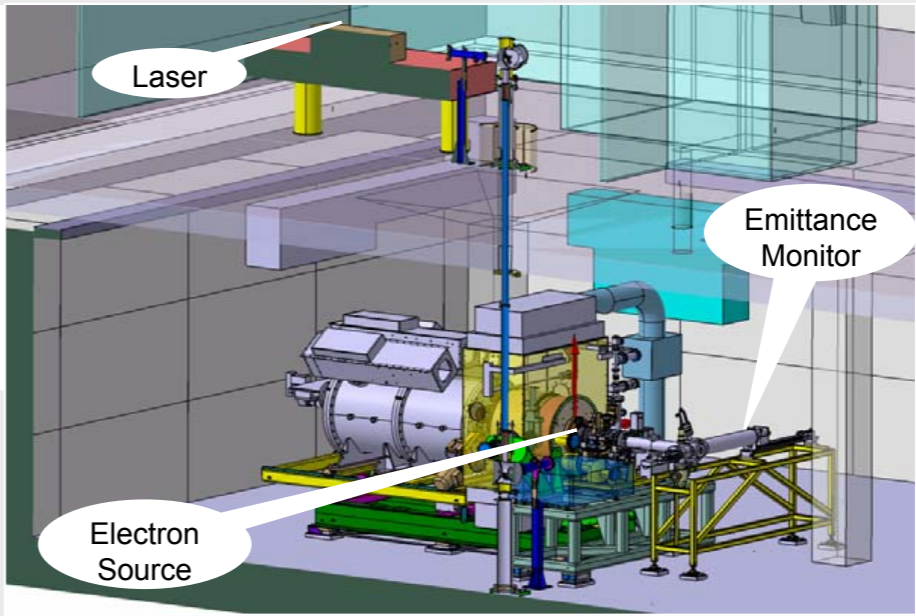
## Photo cathodes



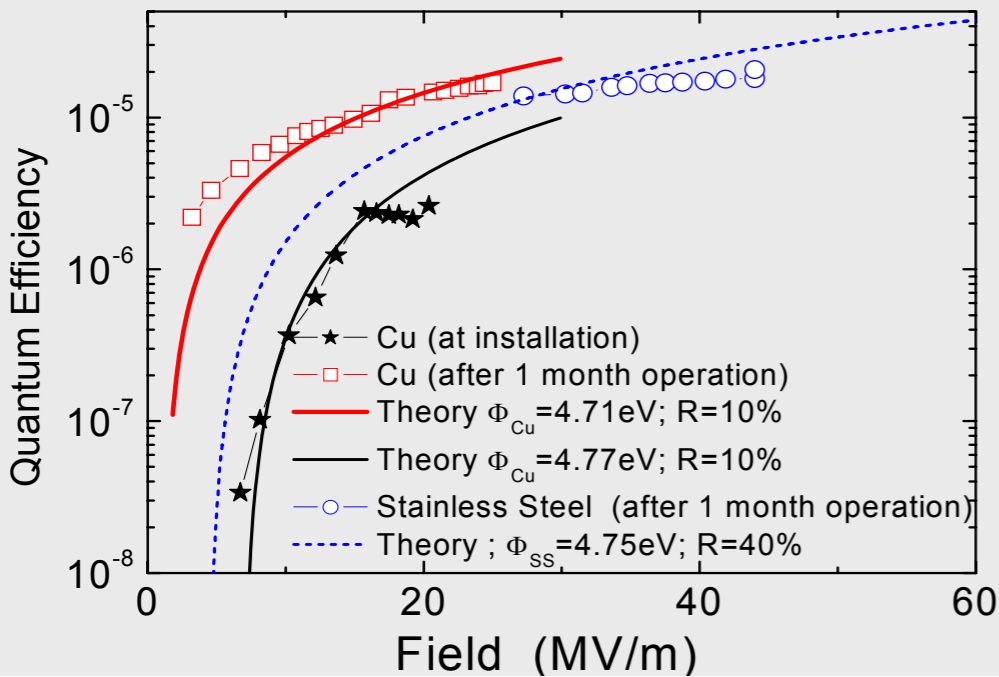
Laser pointing stability: <math><10 \mu\text{m}</math> (p. to p.)

## 500 kV test facility

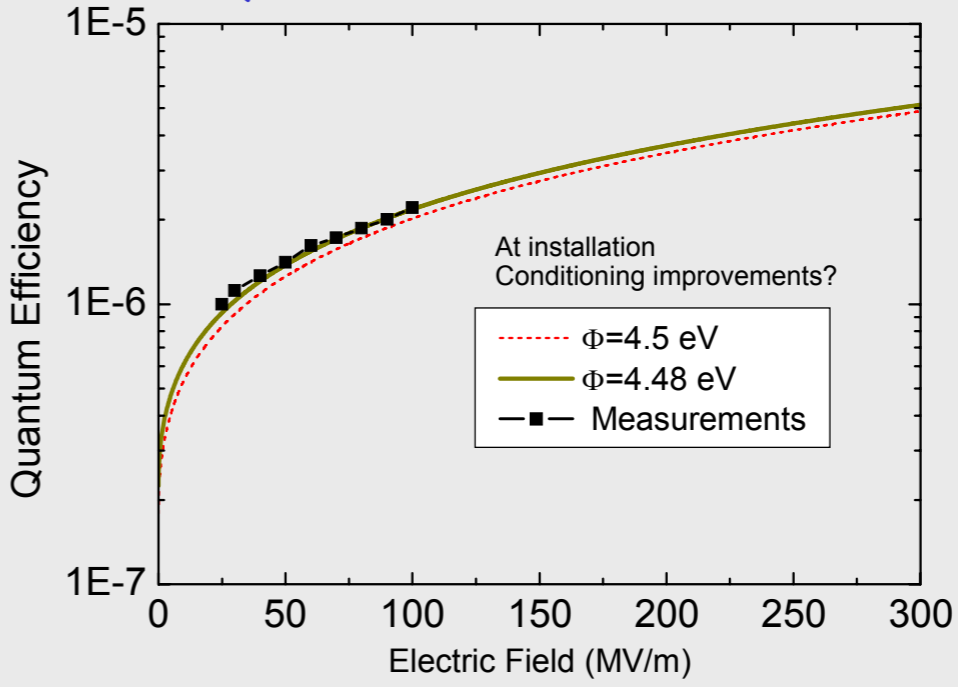
- Operated from December 2007 until September 2008
- > Laser optimization
  - > QE measurements
  - > Thermal  $\epsilon$  photo cath.
  - > High gradient tests



## QE measurements metals

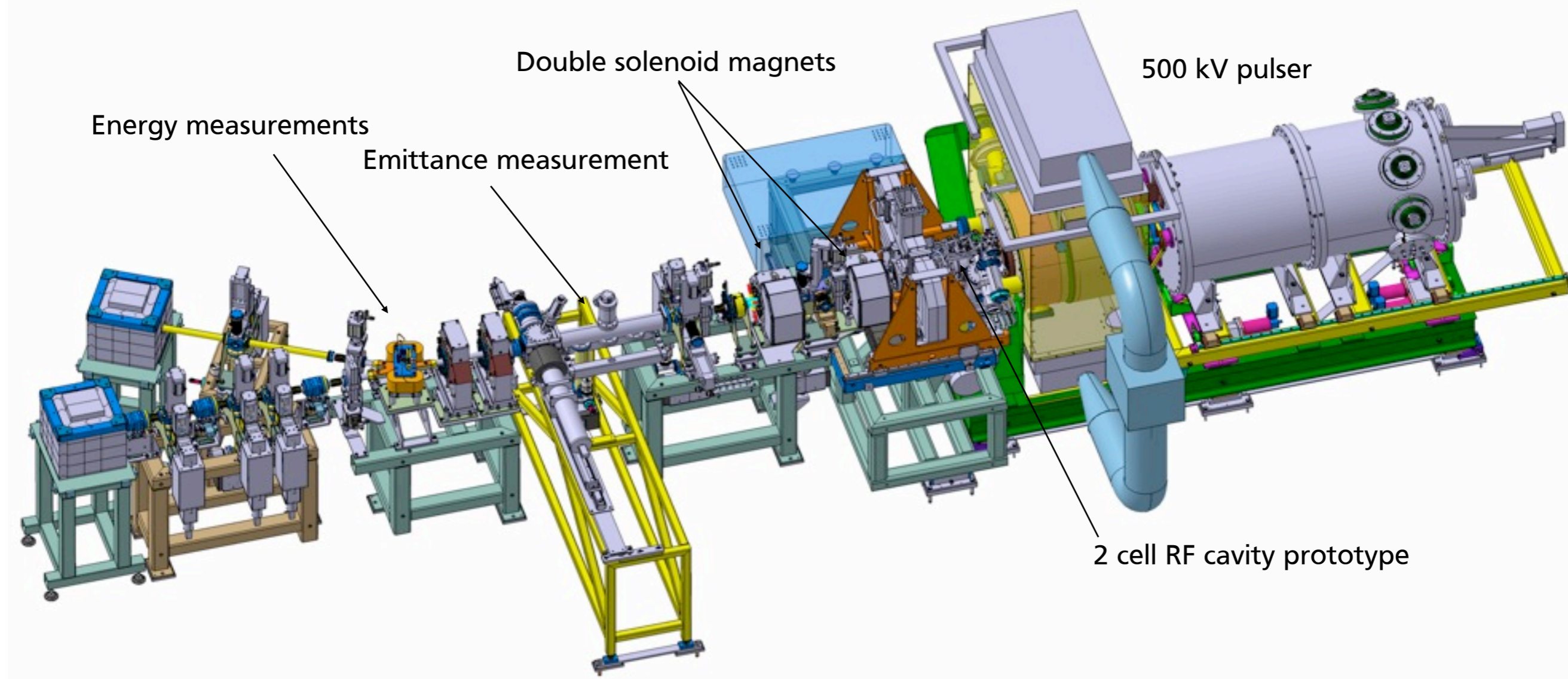


## QE measurements DLC coated SS



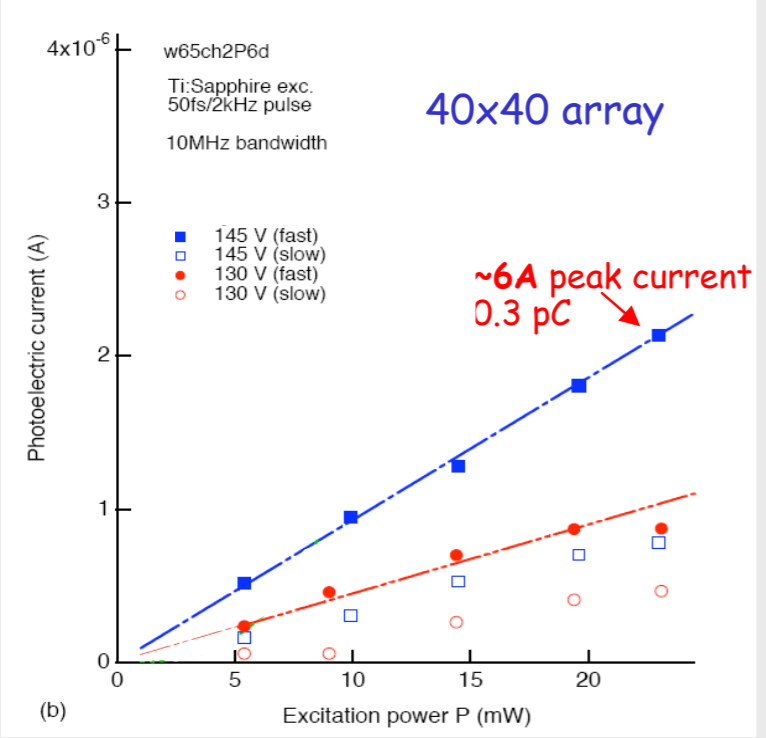
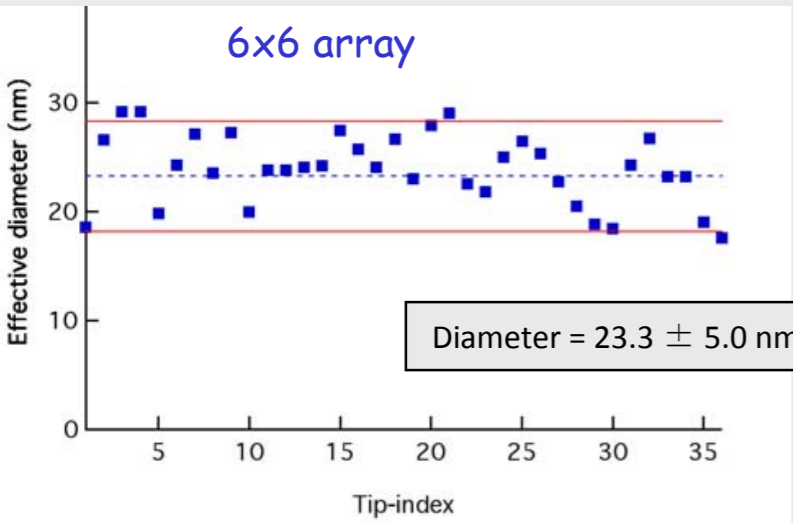
# Status – Low Emittance Gun Test Stand

- Commissioning of 4 MeV Upgrade



# Status – Field Emitter Arrays

## FEA progress



• Improved control of apex aspect ratio with double oxidation method. Reduced edge emission with blunted tip.

• Improved apex uniformity

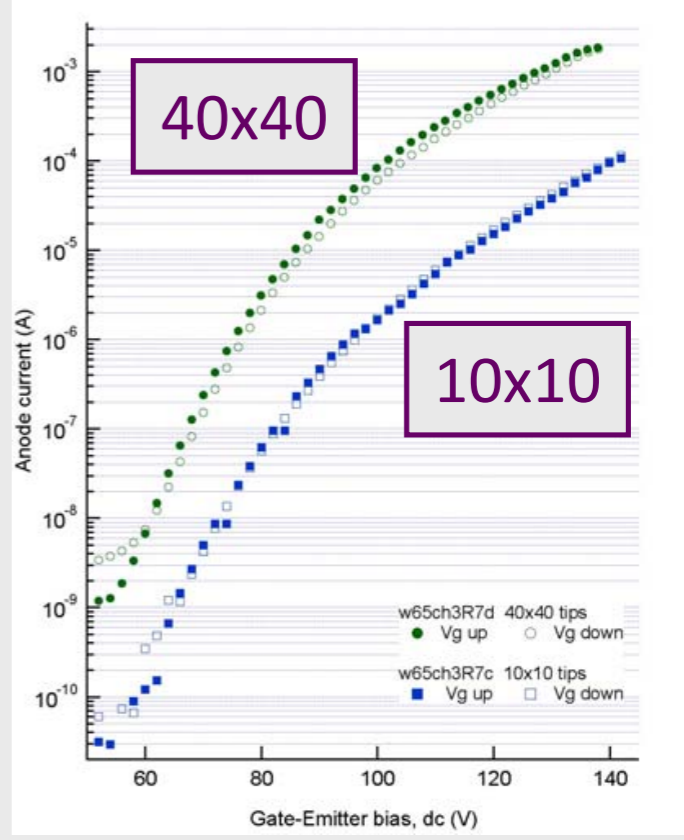
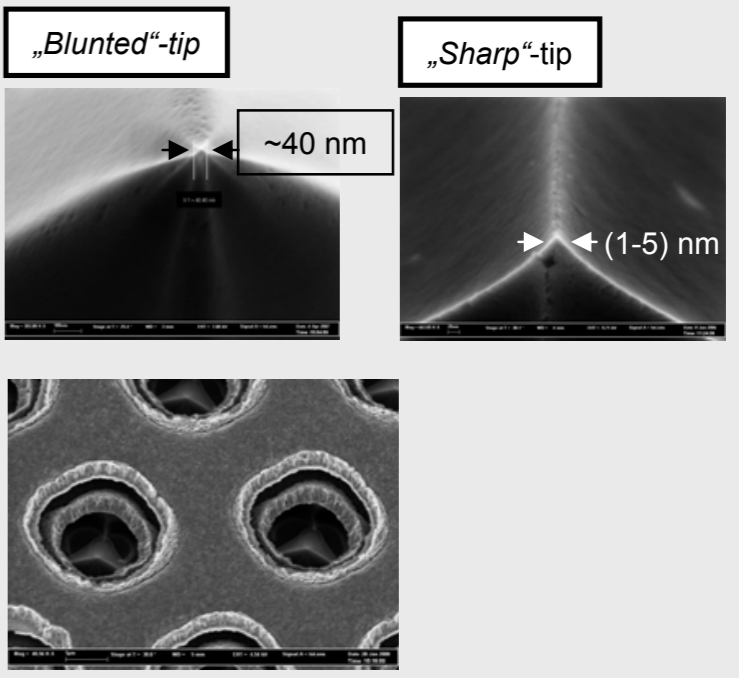
• Production of first double gated FEA, March 2008

• Improved emission stability (comparison after 20 hours continuous emission, single gated FEA)

• Preliminary characterization of laser triggered photo field emission with single gated FEA (50fs, 800nm).

• 100 KV DC test stand being reinstalled in LMN for FEA investigation at higher accelerating gradient.

Considerable improvement of the manufacturing process. Achieved results to be combined in High Gradient environment for LEG.



# Status – 250 MeV Injector

- Civil Construction – November 10



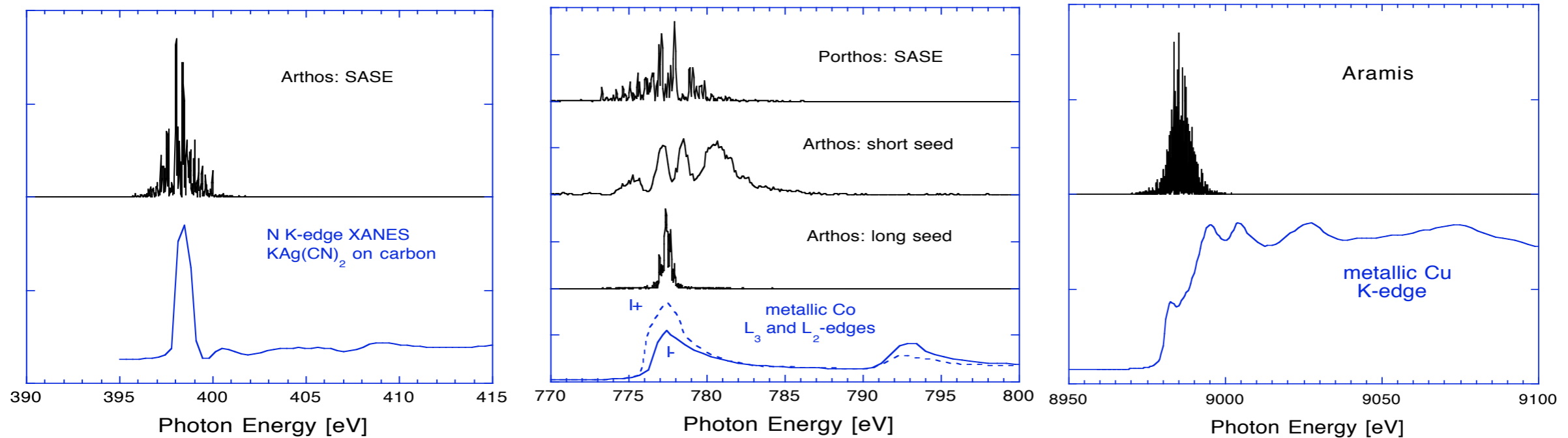
# Status – 250 MeV Injector

- Civil Construction – November 26

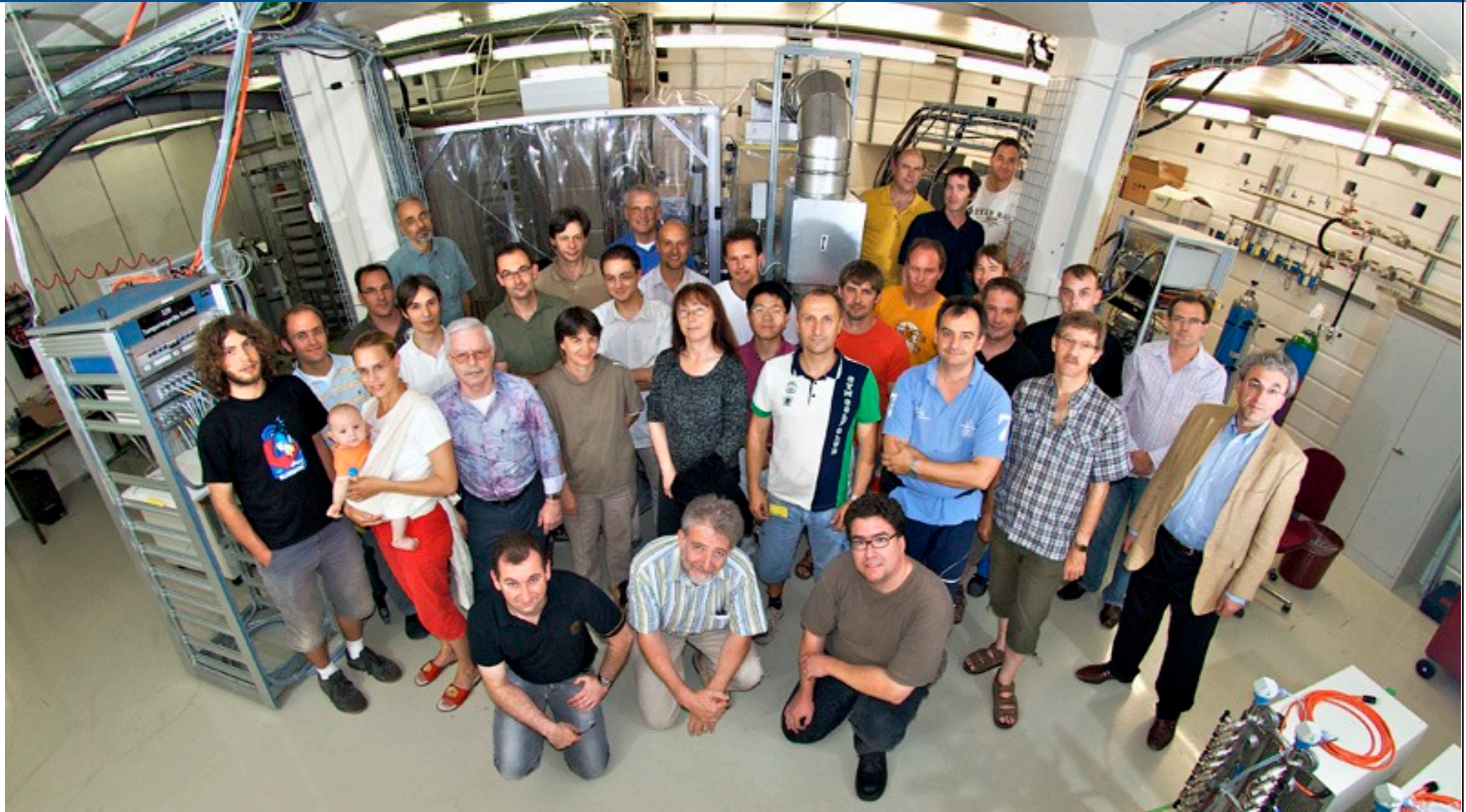


# Status – PSI-XFEL

- Preparation of the scientific case
- Re-optimization of the FEL design
- Preparation of Technical Design Report



# Thank You to the PSI-XFEL Team



- Special Thanks for slides and illustrations:  
Hans Braun, Yujong Kim, Peter Ming, Bruce Patterson, Marco Pedrozzi, Sven Reiche