Integration of layout components for beam dynamics control

S. Di Mitri (1.0 hr.)

Credits:
S. Milton, P. Emma,
A. Zholents, FERMI Team et al.

x-Ray FEL Requirements

$$P_{FEL}(z) = \frac{P_0}{9} e^{\frac{z}{L_g}} \sim e^{z\frac{\rho}{\lambda_u}} \sim e^{z\left(\frac{I_{pk}}{\sigma_\perp^2}\right)^{1/3}}$$

FEL Peak Power

Short L_G (<3m) $\Rightarrow$ **High $B_{4D} = I/\varepsilon_x\varepsilon_y$** (>$10^{21}$ A/m^2)

Compactness

$$\varepsilon_{x,y}\sigma_\delta < \frac{\lambda\rho}{4\pi}$$

$$\sigma_t \leq 100\ fs$$

e- 6D Phase Space Volume

Small dV^6 (<10^{-26} m^2) $\Rightarrow$ **High $B_{6D} = Q/\varepsilon_x\varepsilon_y\varepsilon_z$** (>$10^{24}$ A/m^2)

Efficiency

$$L_{sl} = N_u \lambda_{FEL}$$

$$\Delta t_{FEL} \approx \frac{\Delta t_{seed}}{2 \div 3\sqrt{N_H}}$$

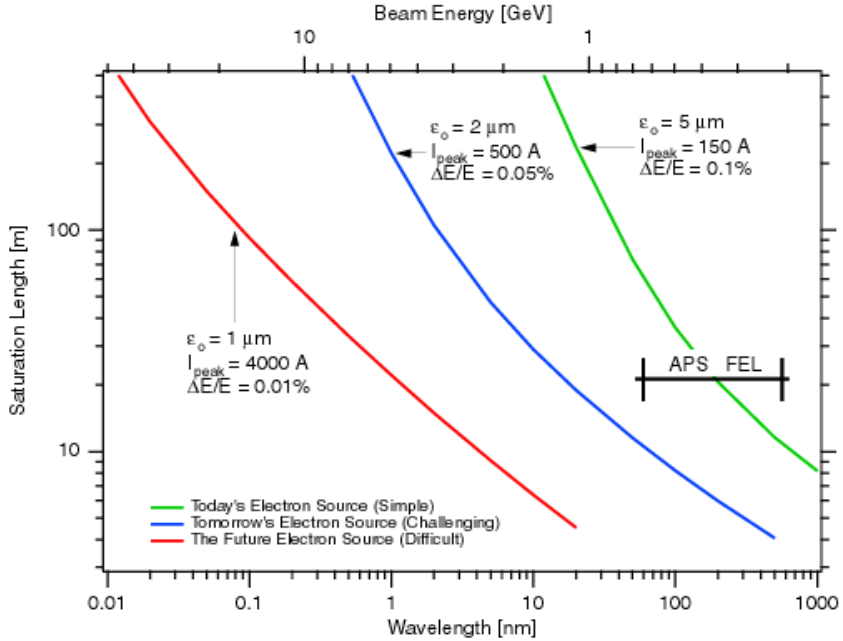
FEL Pulse Duration

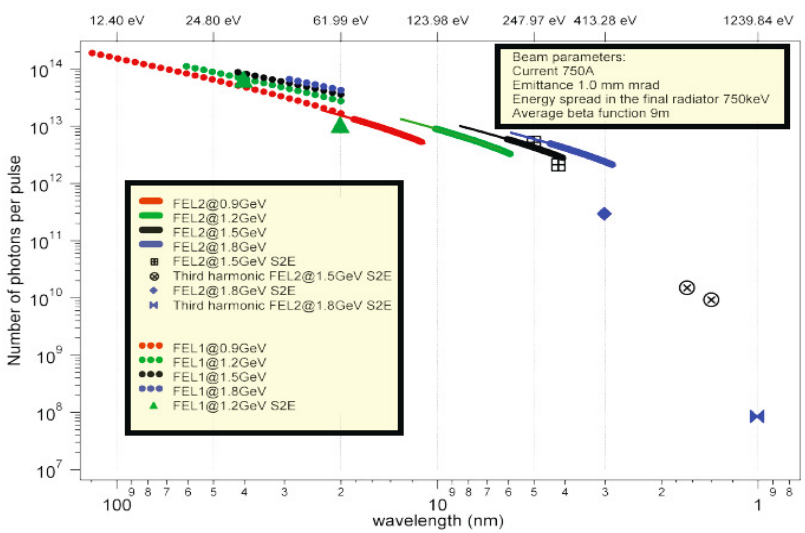
Uniformity over L_{sl} (<30fs) or **Δt_{seed}** (<100 fs)

Coherence

Scaling Laws

Pictures by of S. Milton





Lines predicted using M.Xie formulae for expected FERMI parameters assuming 40fs pulse length

Points Ginger and Genesis simulations for S2E files

$$\rho = \left[\frac{I}{I_A} \frac{\gamma \lambda_r^2}{16\pi^2 \sigma_{trans}^2} \frac{K^2}{\left(1 + K^2/2\right)^2} \left[J_0\left(\frac{K^2}{4+2K^2}\right) - J_1\left(\frac{K^2}{4+2K^2}\right) \right]^2 \right]^{1/3}$$

1. $(\lambda_u, K) \sim \gamma^2 \lambda_r \equiv$ const. → Go to shorter λ_r:

- L_g, L_{sat} grow ~ $1/\sqrt{\lambda_r} \sim \gamma$
- N_{ph} decreases

⇒ Higher e-beam quality required

2. Increase γ to enlarge ρ → what e-beam then?

$$\varepsilon(\gamma) \propto \frac{\varepsilon_0}{\gamma} \le \frac{\lambda_r}{4\pi} \propto \frac{\lambda_u}{\gamma^2}$$

$$\sigma_\delta(\gamma) \propto \frac{\sigma_{\delta,0}}{\gamma} \le \rho \propto \left(\frac{\gamma \lambda_r^2}{\varepsilon(\gamma)}\right)^{1/3}$$

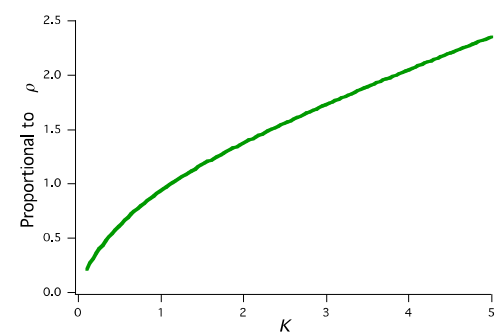
⇒

$$\varepsilon_0 \propto \frac{\lambda_u}{\gamma}$$

$$\sigma_{\delta,0} \propto \left(\frac{\lambda_u}{\gamma}\right)^{1/3}$$

3. We definitely need a better beam/shorter λ_u.

Remind: large K may also help to enlarge ρ. But technically difficult for short λ_u.



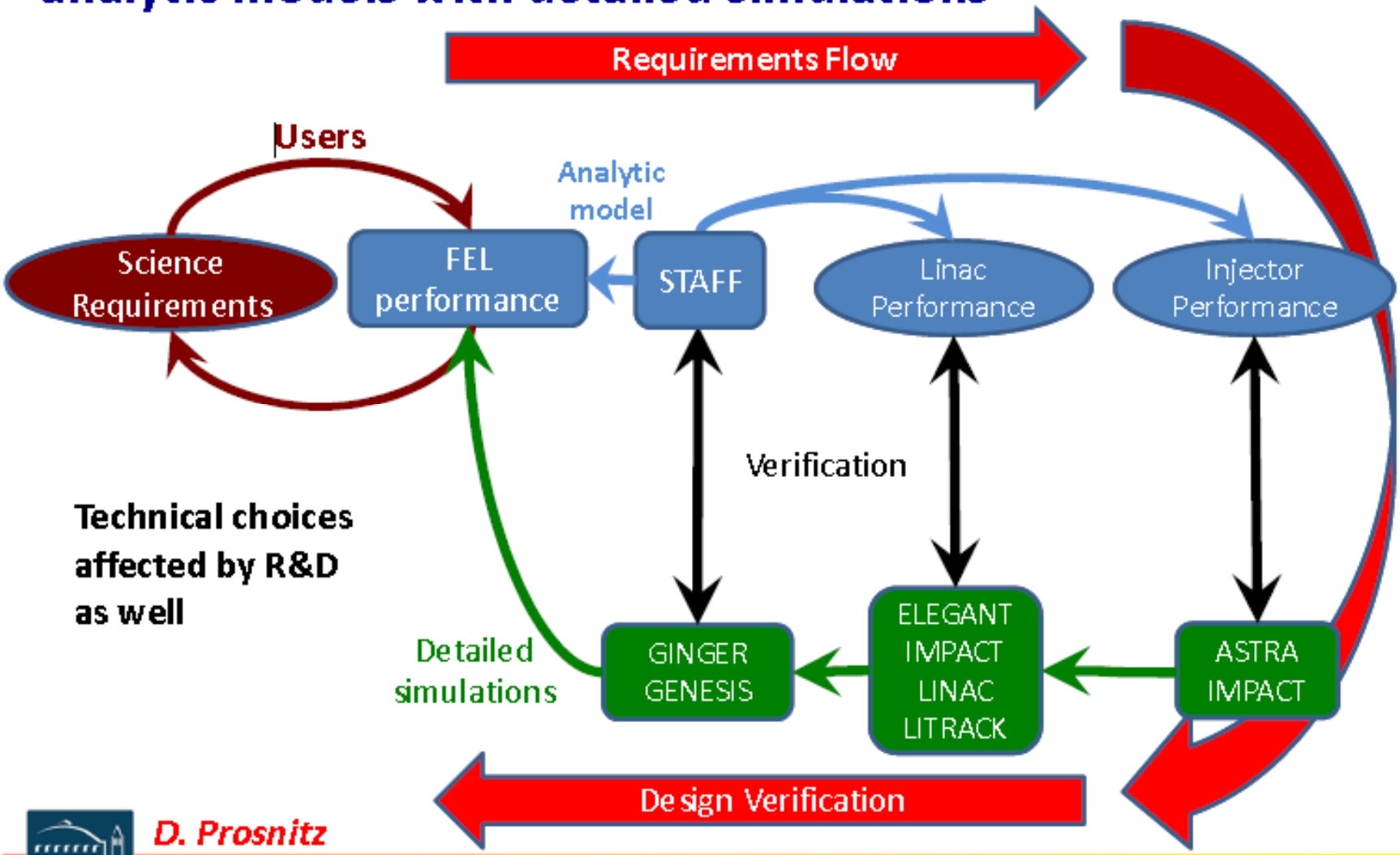
e-Linac Design Challenges

- **RF Photo-Injector**
  - Need ≤1-*μm normalized emittance m all day long*
  - ≤10-ps initial bunch length with up to 1 nC charge
- **Main Linac**
  - Transverse wakefields (misalignments)
  - Spurious dispersion and aberrations (mainly chromatic)
  - Energy chirp manipulation (linear and nonlinear)
- **Magnetic Compressors** and **Transfer Line**
  - Coherent synchrotron radiation induced emittance growth
  - Microbunching Instability (laser heater)
- **Undulator**
  - Collimation upstream
  - Straight trajectory (spurious dispersion; alignment)
  - Longitudinal wakefield in low gap chambers
- **Machine Stability and Diagnostics**
  - Charge, PIL timing and pointing, RF voltage and phase jitter

Design Strategy (one possible among many)

1. **Choose FEL wavelength *range* and undulator parameters** (gap, period,…)
2. **Specify final energy *range*** (λ-tunability)
   - RF distribution and geometric wakefields
3. **Specify transverse emittance *at the undulator***
   - Take margin on the injector emittance
4. **Specify final peak current and bunch length**
   - Shorten gain length
   - Seeding scheme and fel pulse duration
5. **Specify total compression factor**
   - One-stage vs. multi-stage. Compression efficiency.
   - CSR and microbunching instability
6. **Start-to-end, time-dependent simulation + Global jitter study**
   - Codes concatenation (possibly parallel)
7. **Repeat loop from *1.* for tuning.**
   - Point 6. and 7. possibly inverted

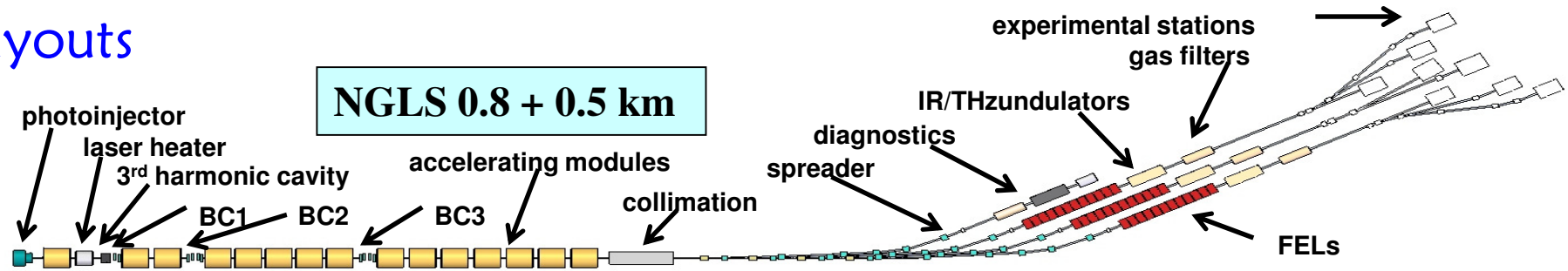
NGLS modeling strategy combines fast analytic models with detailed simulations



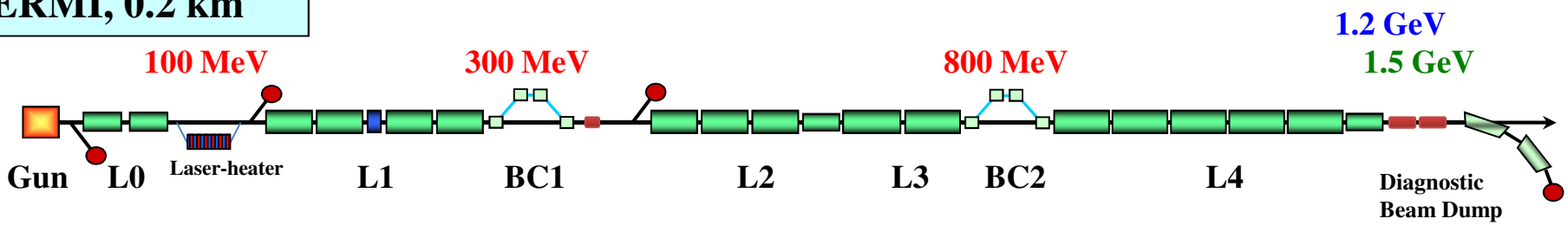
D. Prosnitz

Layouts

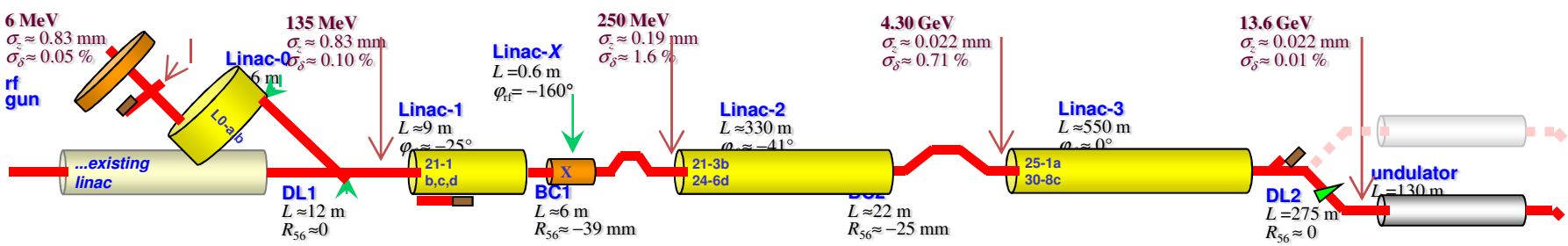
NGLS 0.8 + 0.5 km



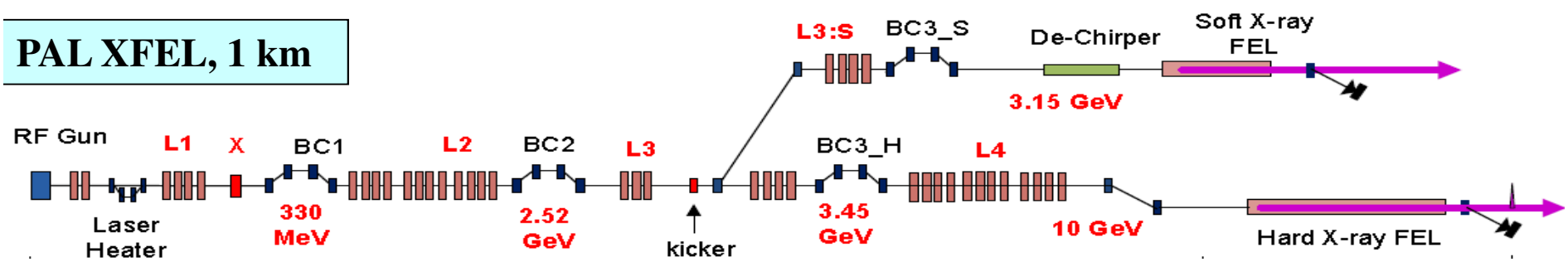
FERMI, 0.2 km



LCLS, 1 km



PAL XFEL, 1 km

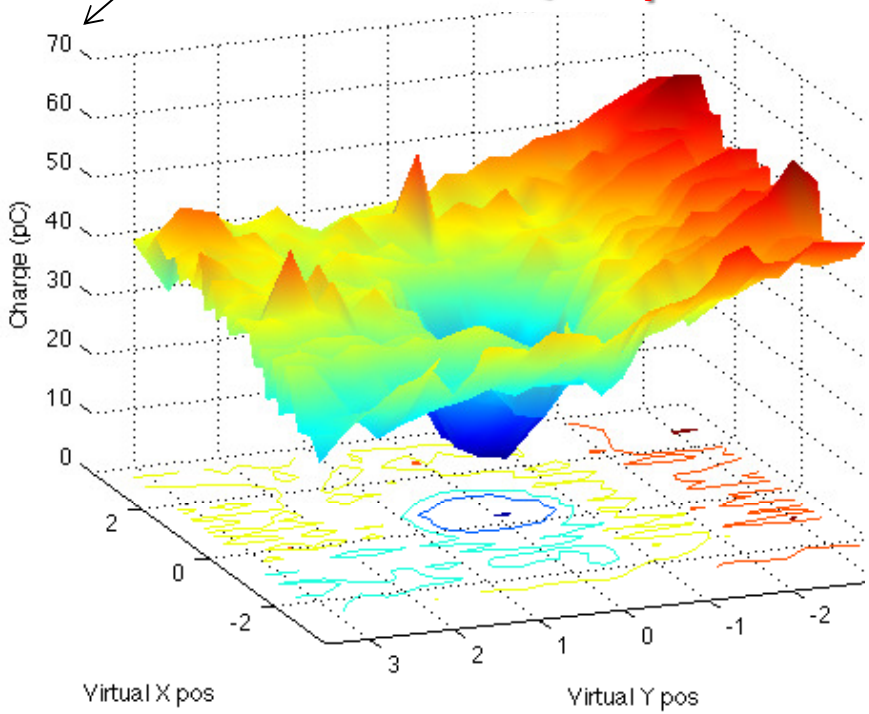


RFPC GUN (~4 MeV)

Pictures courtesy of M. Trovò

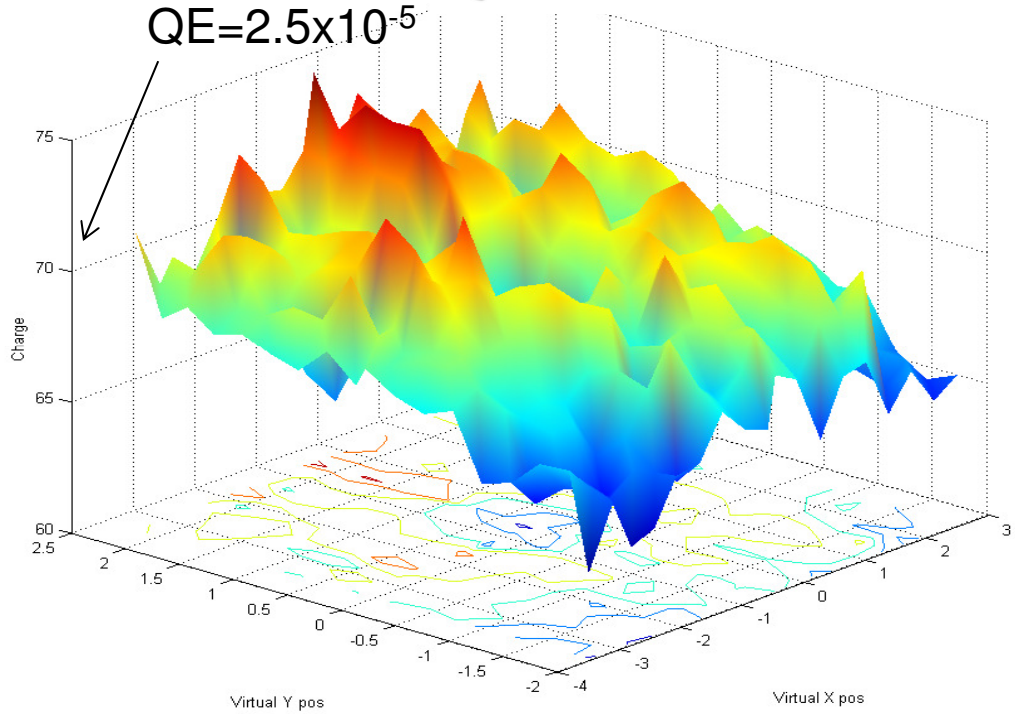
After 2 months operation:
QE depletion

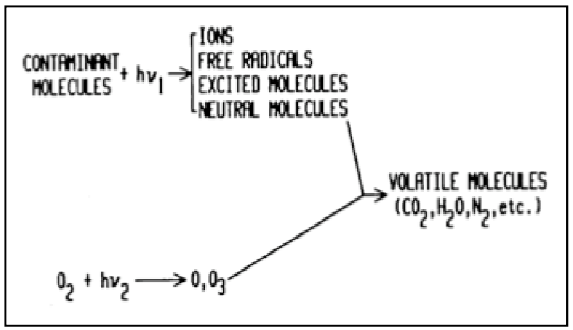
QE=2.5x10^{-5}



After UV/Ozone cleaning* routinely implemented at machine start-up:
QE restored.

QE=2.5x10^{-5}



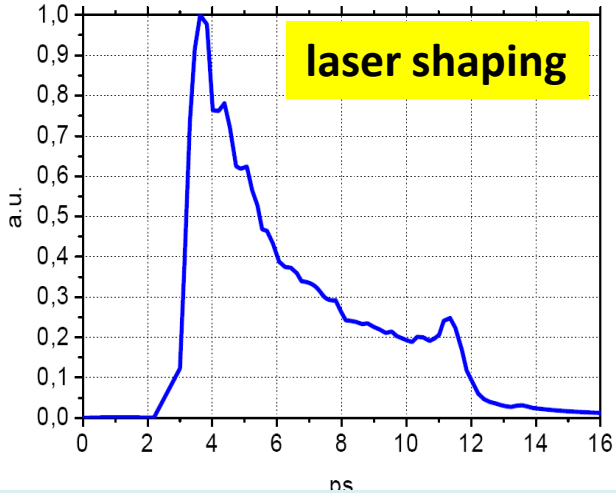


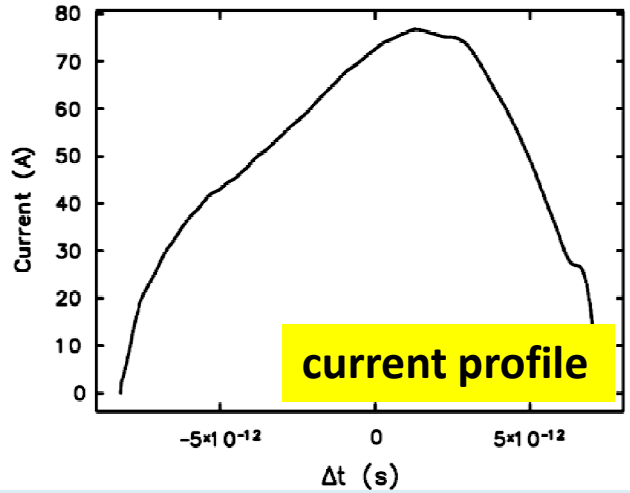
* W. Kern, Handbook of Semiconductor Wafer Cleaning Technology, W. Andrew Publishing/Noyes (1993) .

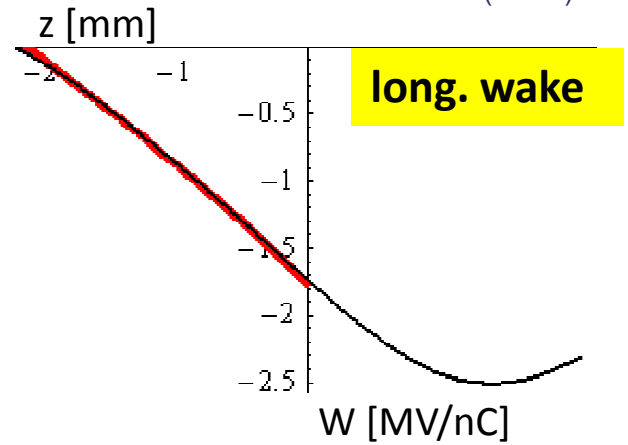
These pictures: the Cu cathode surface is sampled by a 200 μm laser spot and 10 μJ.

INJECTOR (~4–130 MeV)

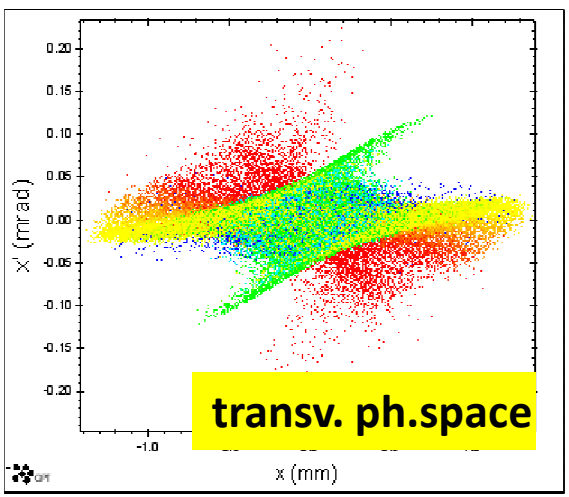
Pictures courtesy of M. Danailov, A. Zholents, M. Trovò, G. Penco, S. Lidia. S. Di Mitri et al. NIM A 609 (2009) 27

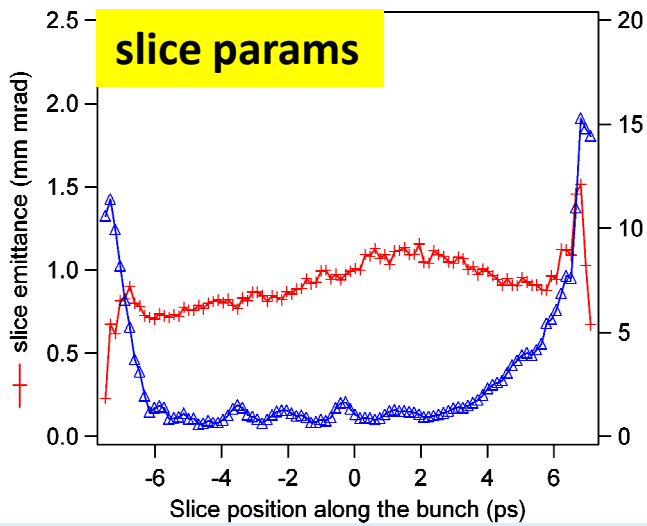


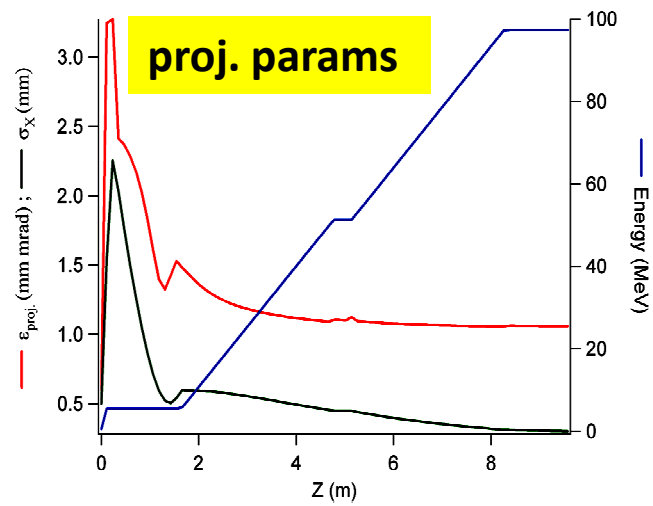




- PIL pulse shaping → current shaping → (linear) long. geometric wakefield



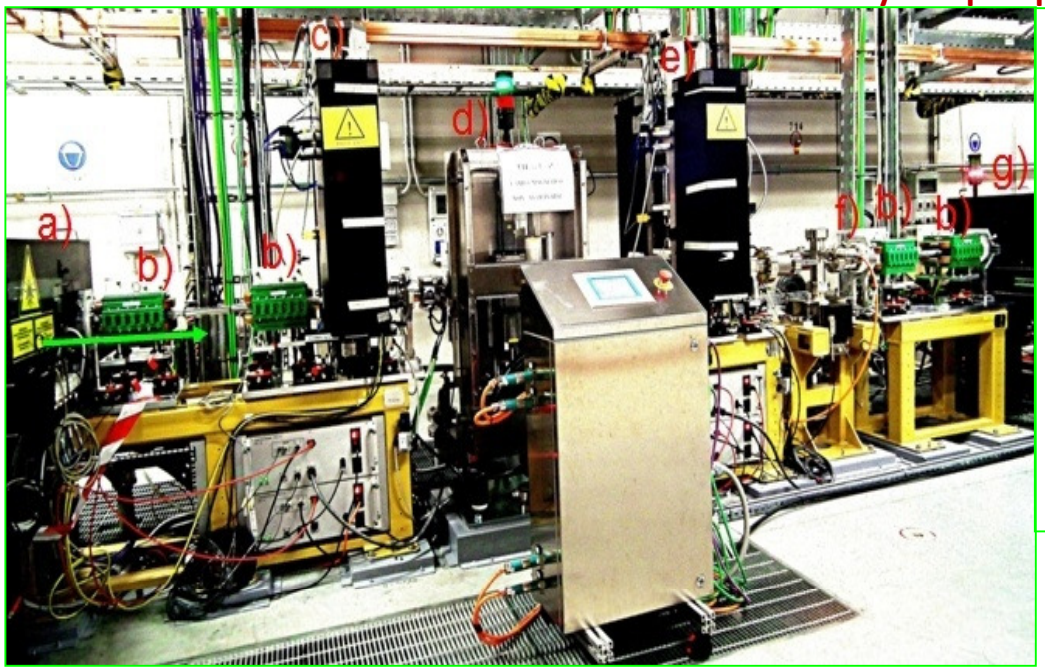




- Emittance compensation → slice distributions → projected emittance

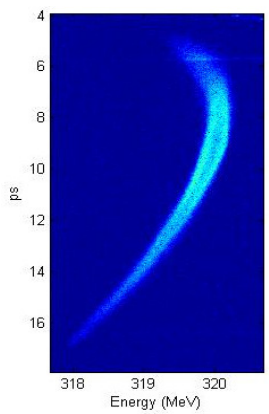
LASER HEATER (~130 MeV)

*** Data collected by: S. Spampinati, B. Diviacco, E. Ferrari, D. Castronovo, C. Spezzani**

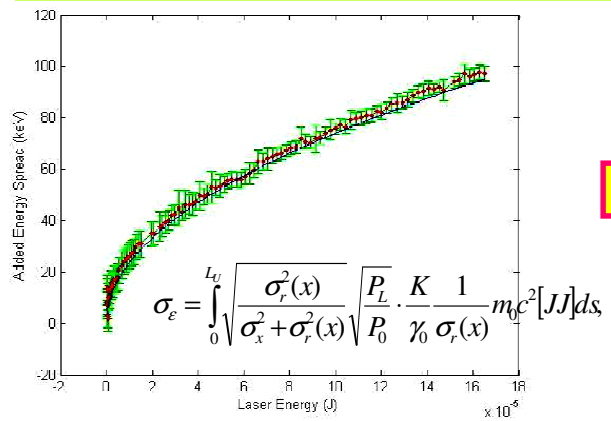


a) Input laser table (Ti:Sa, 783nm, 20ps)
b) Magnetic chicane for γ-injection (3.5°)
c) Cromox targets for e-/ γ spatial overlap
d) Undulator (L=0.4m, λu =40mm, K=0.9)
e) BPM for e- trajectory feedback
f) Laser delay line
g) Output laser table

❑ Beam heating:

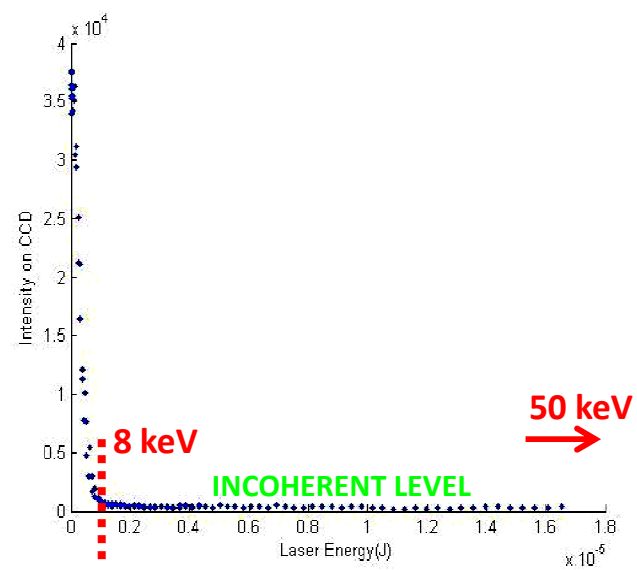


❑ Calibration, $\sigma_{E,LH}$ vs. P_L:

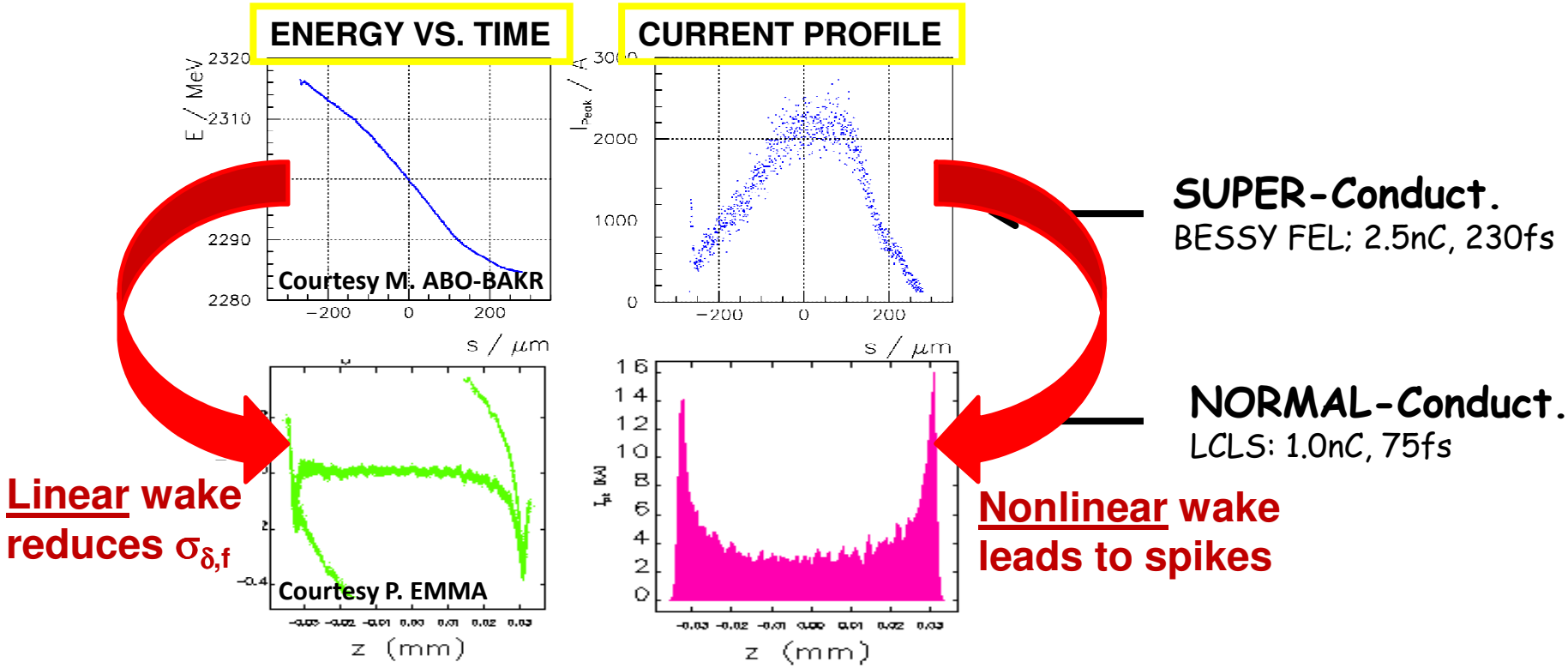


$$\sigma_\varepsilon = \int_0^{L_U} \sqrt{\frac{\sigma_r^2(x)}{\sigma_x^2+\sigma_r^2(x)}} \sqrt{\frac{P_L}{P_0}} \cdot \frac{K}{\gamma_0} \frac{1}{\sigma_r(x)} m_0 c^2 [JJ] ds,$$

❑ Suppression of μbi:

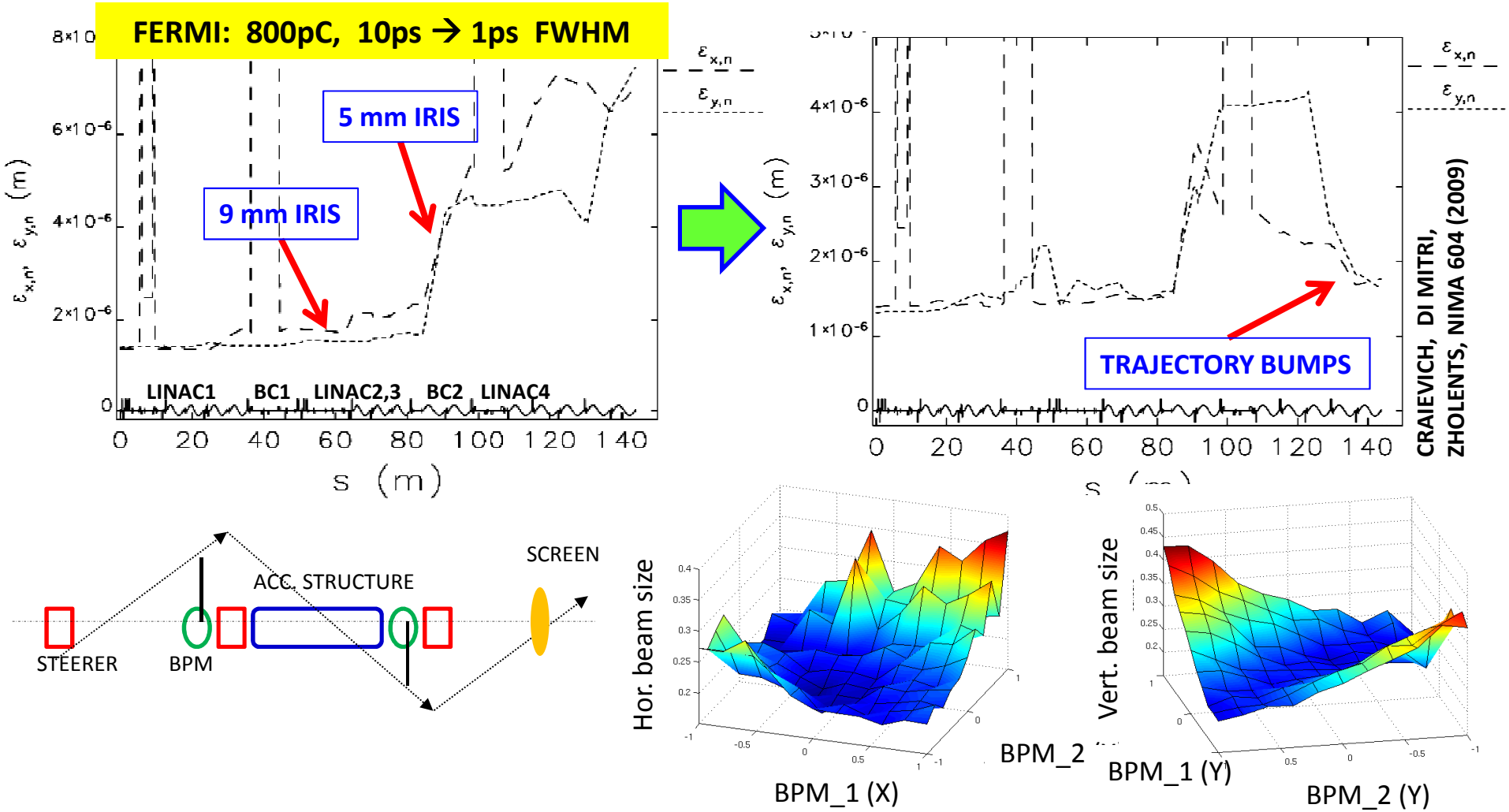


MAIN LINAC – Longitudinal Dynamics (~130MeV – 1/10s GeV)



- Longitudinal wakefields contribute to define final energy, energy spread, RF phasing and compression efficiency.
- De-chirping effect at the linac end.

MAIN LINAC –Transverse Dynamics (~130MeV – 1/10s GeV)



- Transverse wakefields require accurate control of trajectory and focusing.
- Minimized by the fully compressed beam, at the linac end.