Elettra Sincrotrone Trieste

Designing Future X-ray FELs
Wednesday 31 August - Friday 2 September, 2016
Daresbury Laboratory, UK

Modelling Linacs and their Components*

A Personal Selection of Challenges

S. Di Mitri, ELETTRA SINCROTRONE TRIESTE

*** assigned title**

Prologue

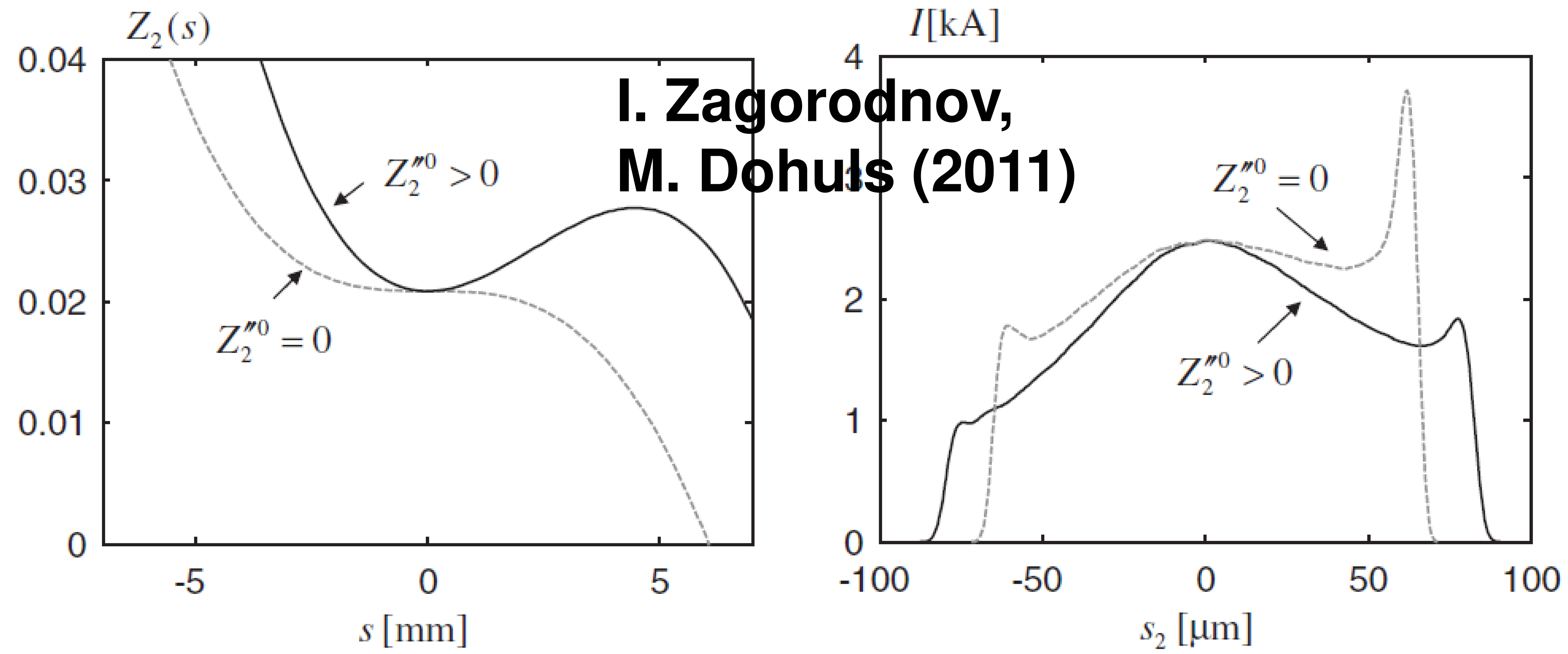
- Will *neither* talk about physics principles, *nor* logic of codes (many here know physics and codes better).
- *Will* report on a selection of topics for linac-driven FELs.

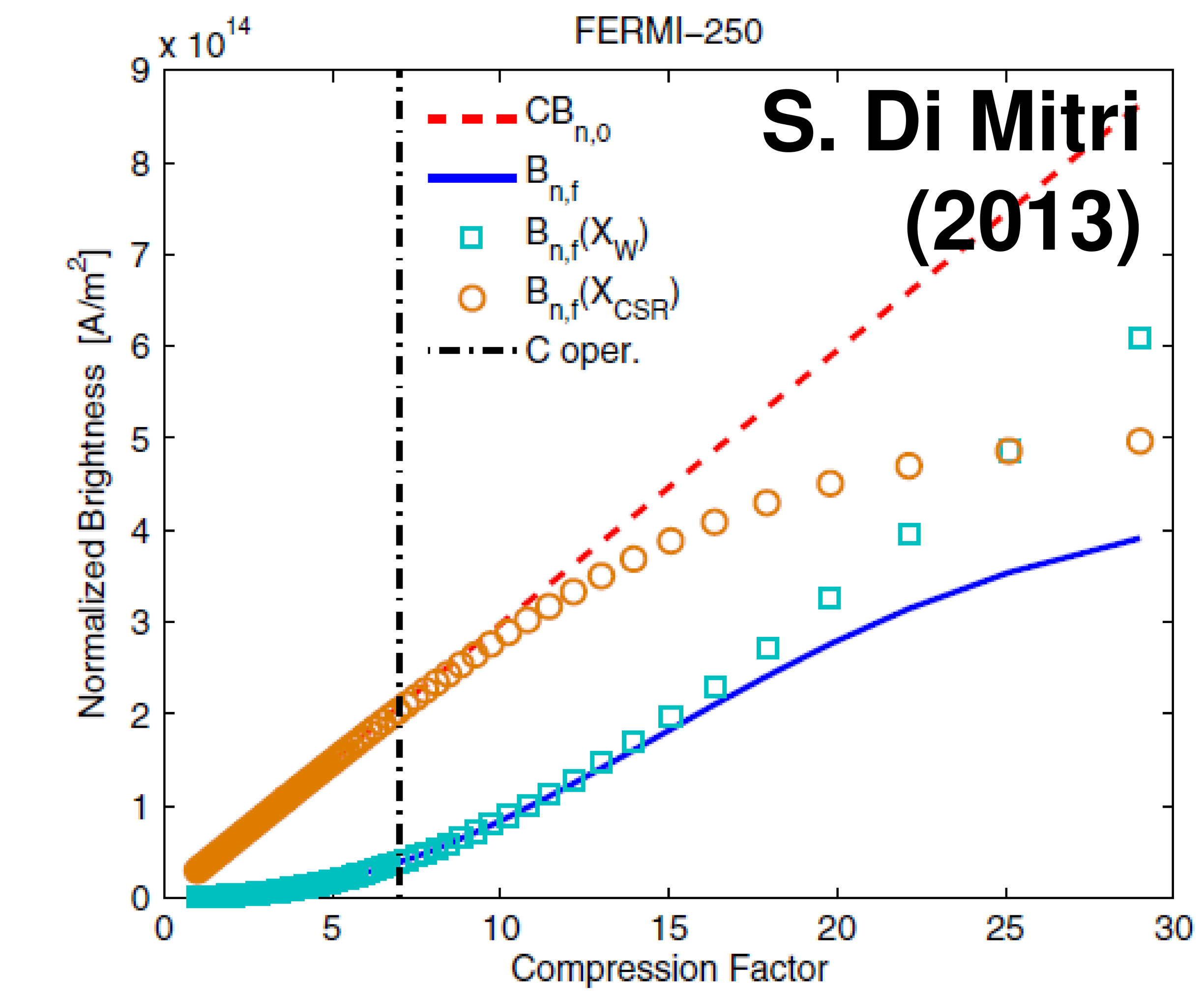
- My feeling is that ~*75%* of e-beam physics for FELs is well understood, and can be modelled reliably.
- ~*25%* uncertainty remains about subtle, but *important* details of charge distribution (noise, bunch edges), 3-D collective effects, etc.…

  - *I might have missed some important points: please raise your hand to complement.*

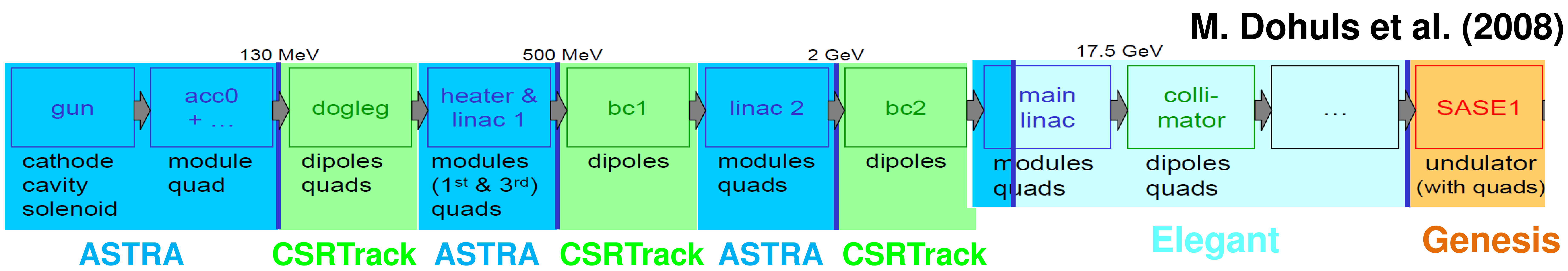
Yes We Can

- **Semi-analytical** models of beam collective dynamics provide guidance to a first step-machine design.

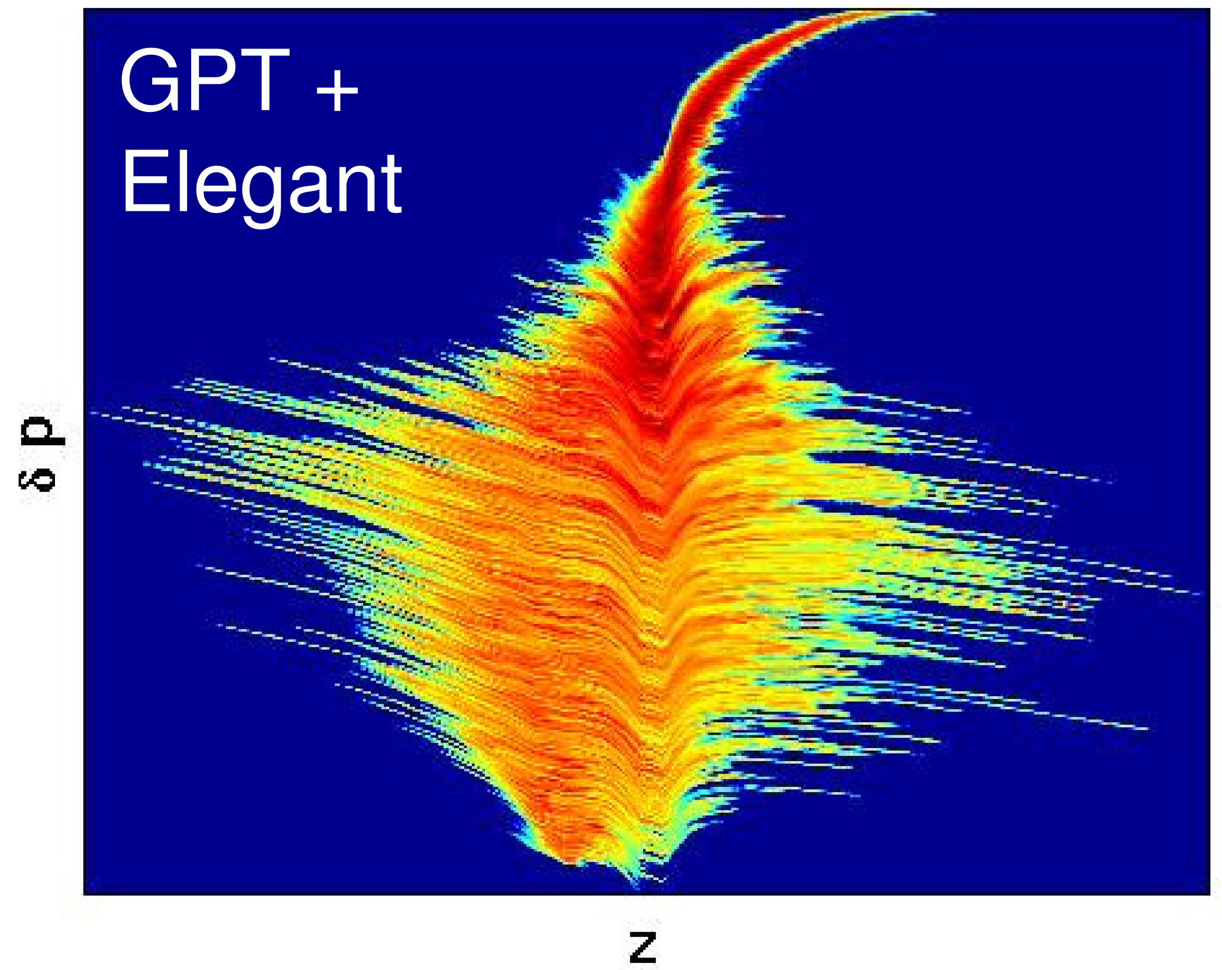


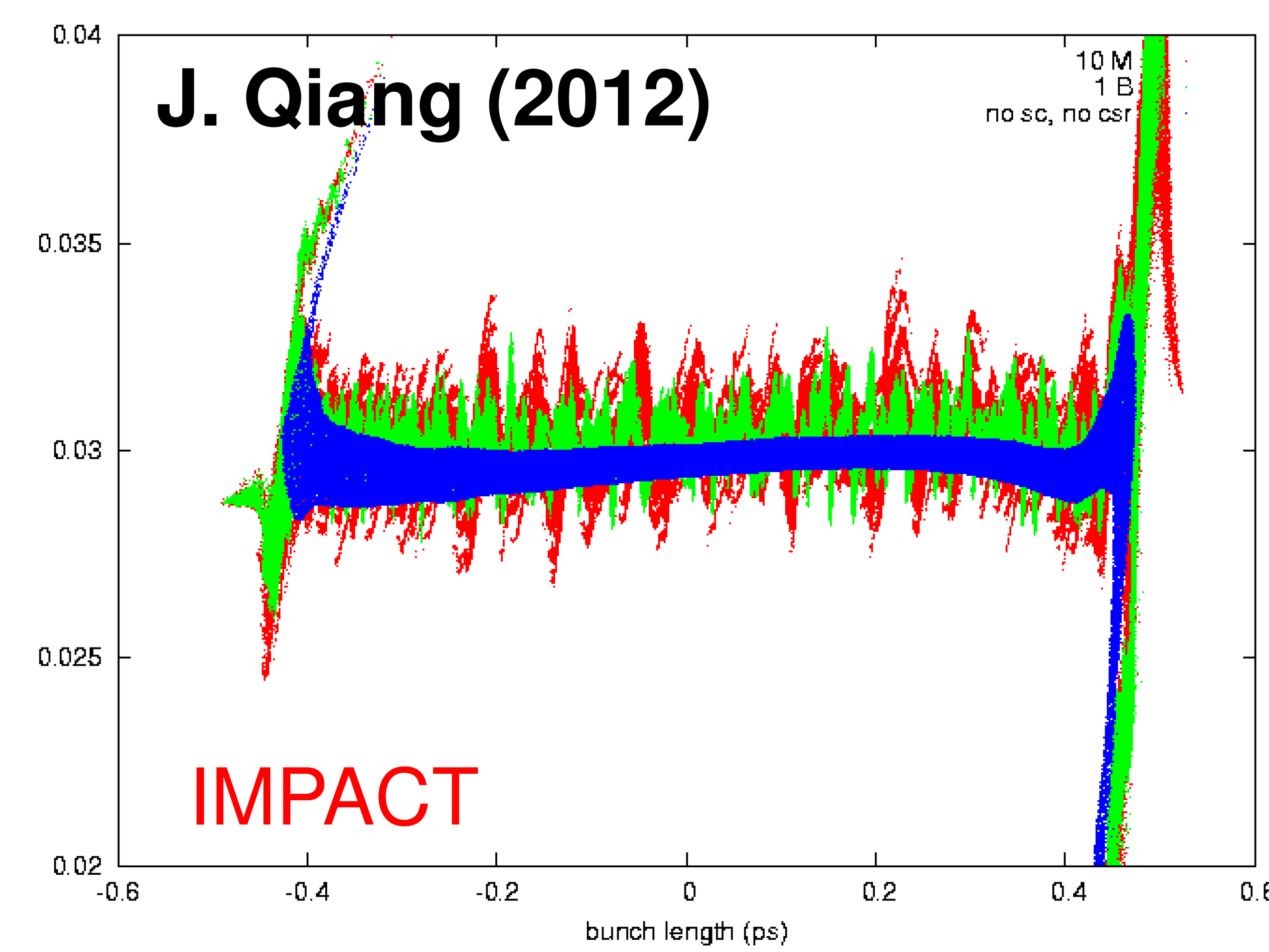


- **Chains** of **specialized codes** allow to balance accuracy vs. CPU time in S2E simulations.



- PIC codes allow tracking with **real number** of electrons, e.g. from 0.4 to 5 billion or so.





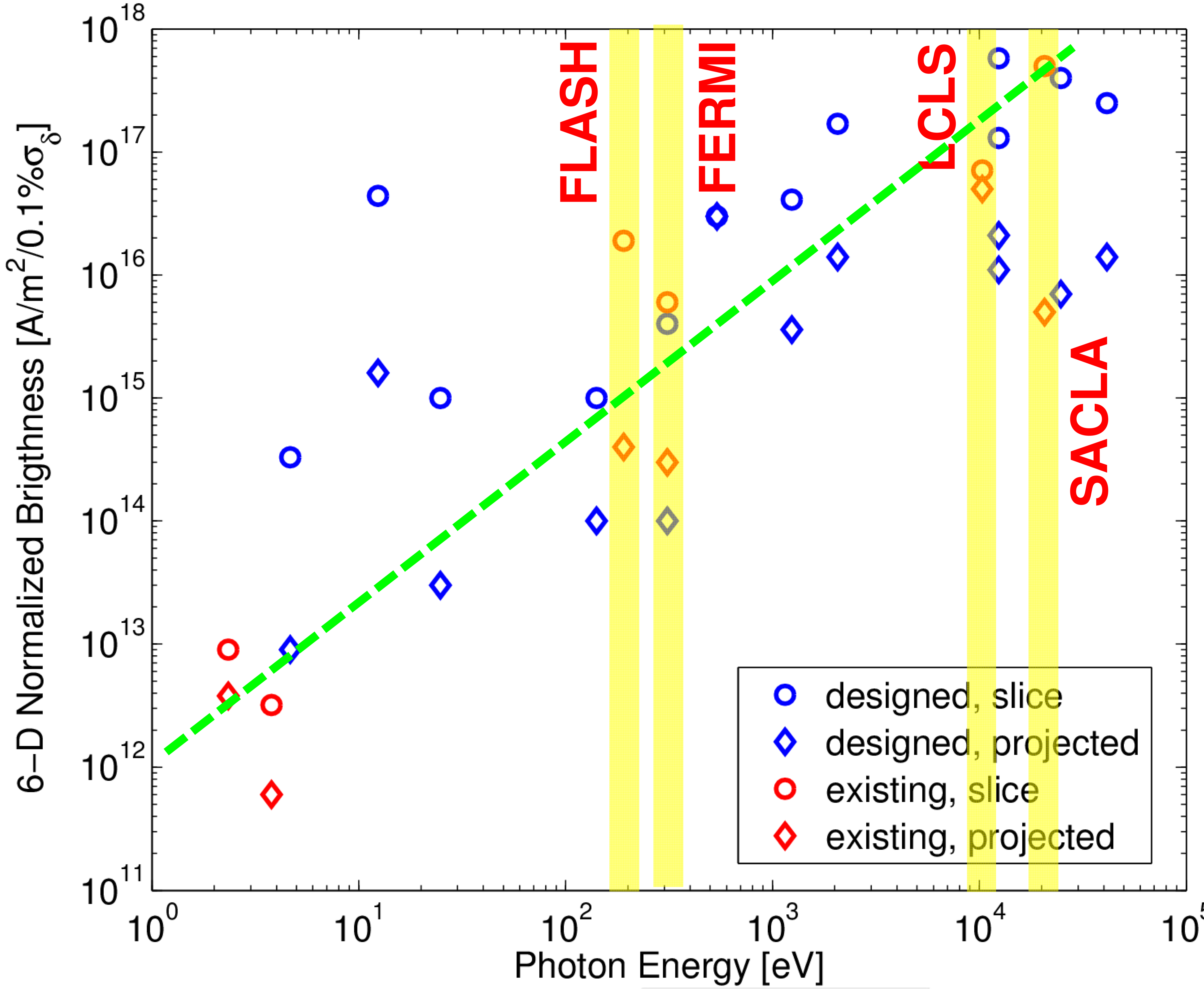
So Far So Good…

- The shorter the wavelength, the higher the **6-D e-beam brightness** one needs for lasing (efficient, or at all):

$$B_{n,0}(\lambda) \equiv \frac{Q}{\varepsilon_{n,x}\varepsilon_{n,y}\varepsilon_{n,z}} = \frac{I}{c\sigma_E\gamma_0^2\varepsilon_0^2} \approx \frac{32\pi^2}{c}\frac{1}{\sigma_E\lambda_u\left(1+K^2/2\right)}\frac{I}{\lambda}$$

- ***But***, future XFELs may be less forgiving about the *actual* beam quality:
  - need more accurate machine modelling and control
  - ask for more aggressive scenarios:
    - ***Lower-Q, higher-I*** e-bunches (3-D "pancake" beams)
    - ***Ultra-low*** $\varepsilon_{x,y}$ e-beams (vs. CSR)
    - ***Higher*** RF ***gradients*** (vs. wakefields)
    - ***Multi-color*** / ***narrow bw FEL*** (vs. microbunching)
    - Robust ***optics*** control (dechirpers; undulators)

"It is a remarkable achievement of the FEL community that the physics and computer model of these effects have found an excellent confirmation in the operation of FEL facilities." (S. Di Mitri, M. Cornacchia, Phys. Rep. 539, 2014, 1-48)



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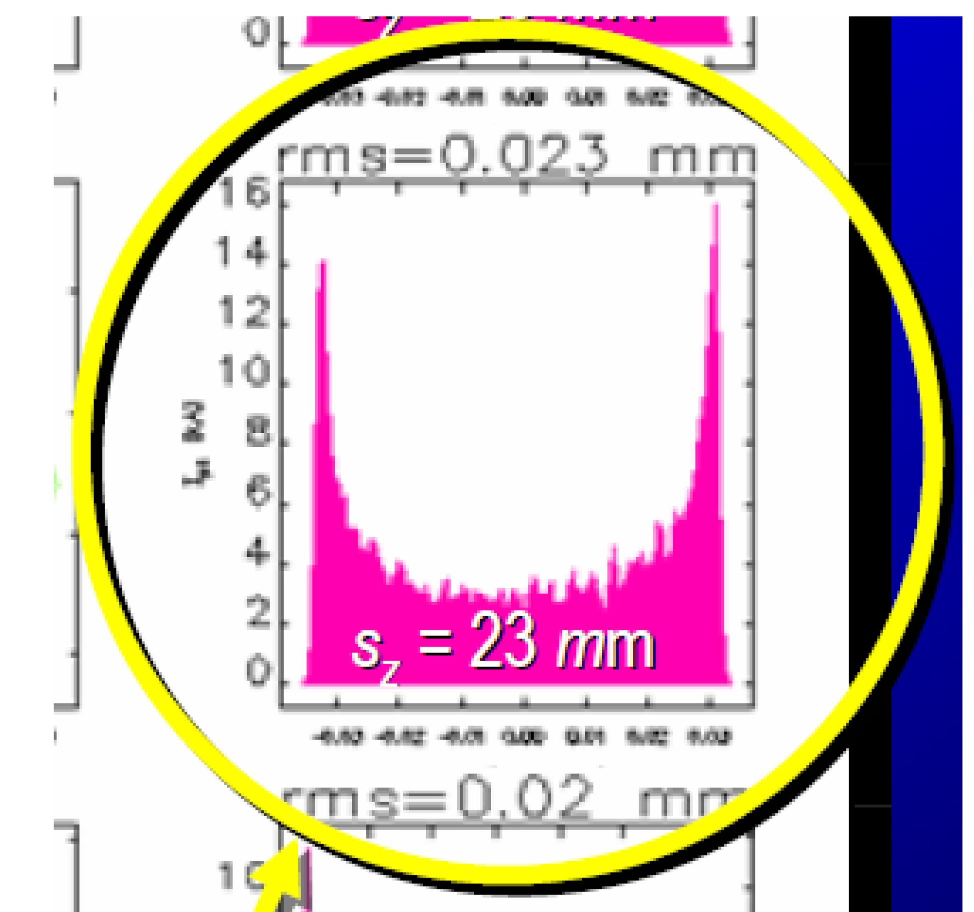
The Devil is in the Detail

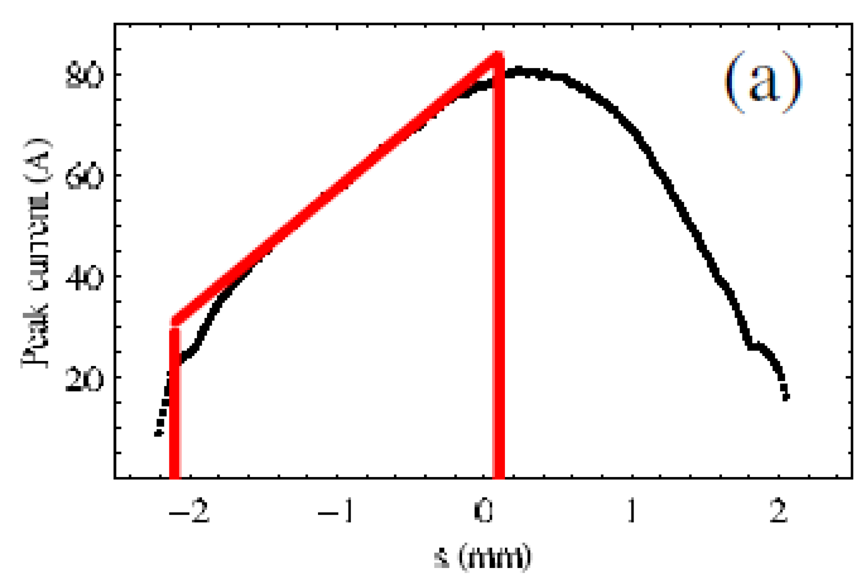
- ❑ Geometric and RW wakefields can be computed accurately, and imported into tracking codes.
- ❑ Strong wake potential + magnetic compression = multi-kA current spikes at bunch edges.
  - Spikes drive CSR instability, RW wake in low-gap pipe, and saturate OTR screens.
  - Their magnitude depends on *details* of Injector *Laser* and Linac *long. wakefield*.

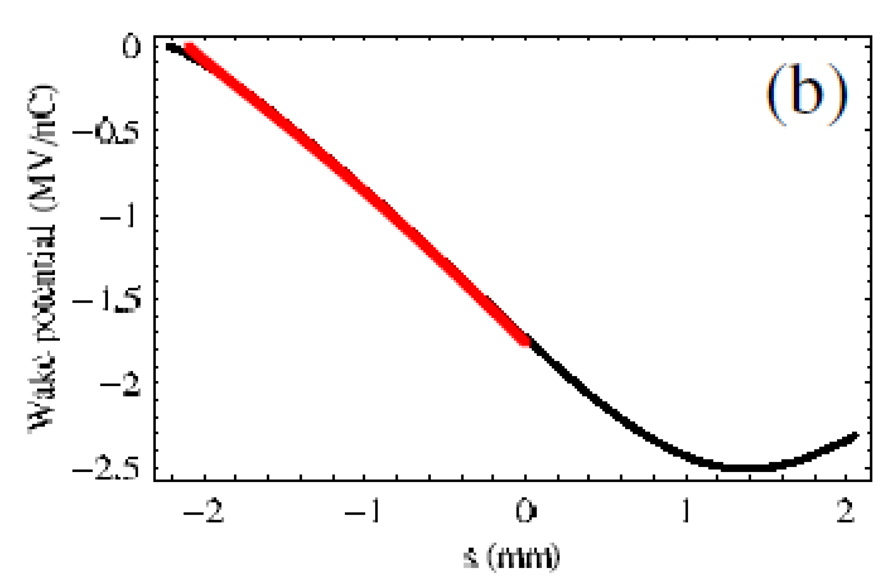
P. Emma for LCLS (2009)

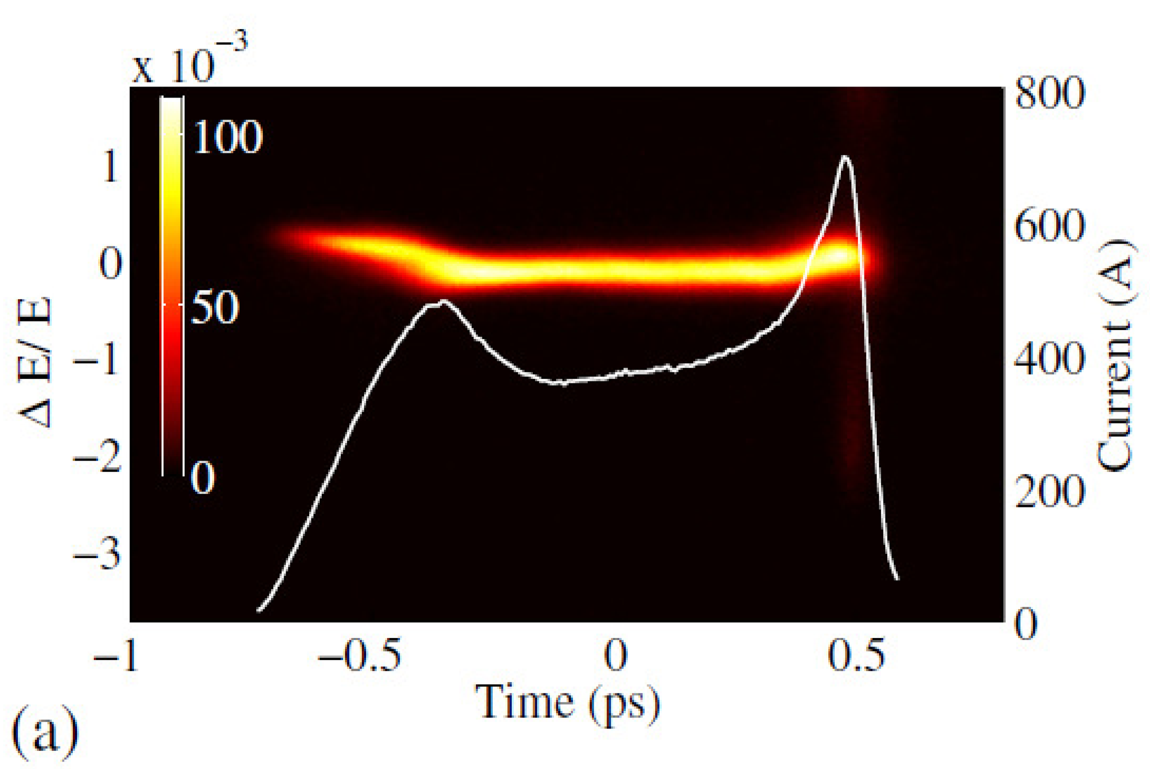


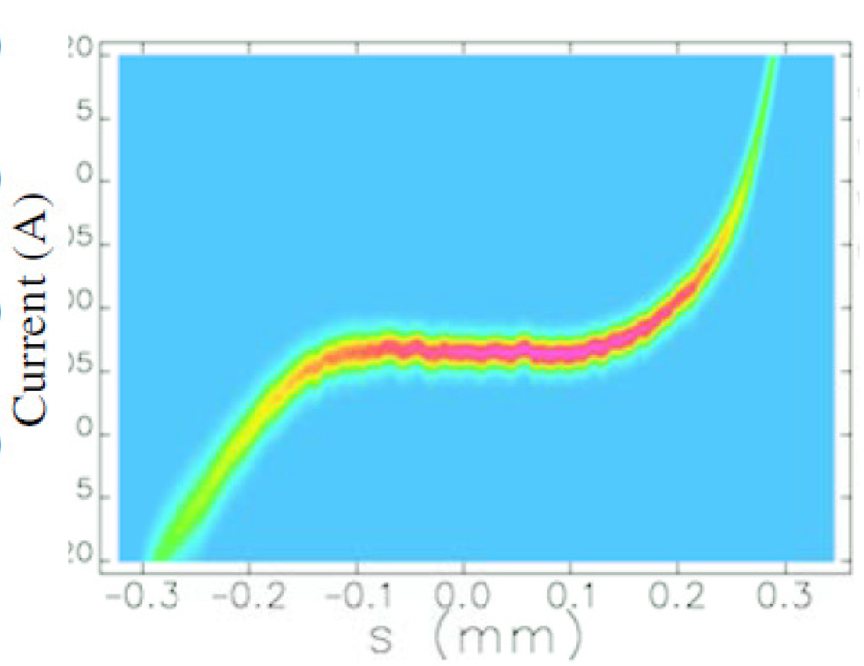
Spikes depend on details of injector distribution

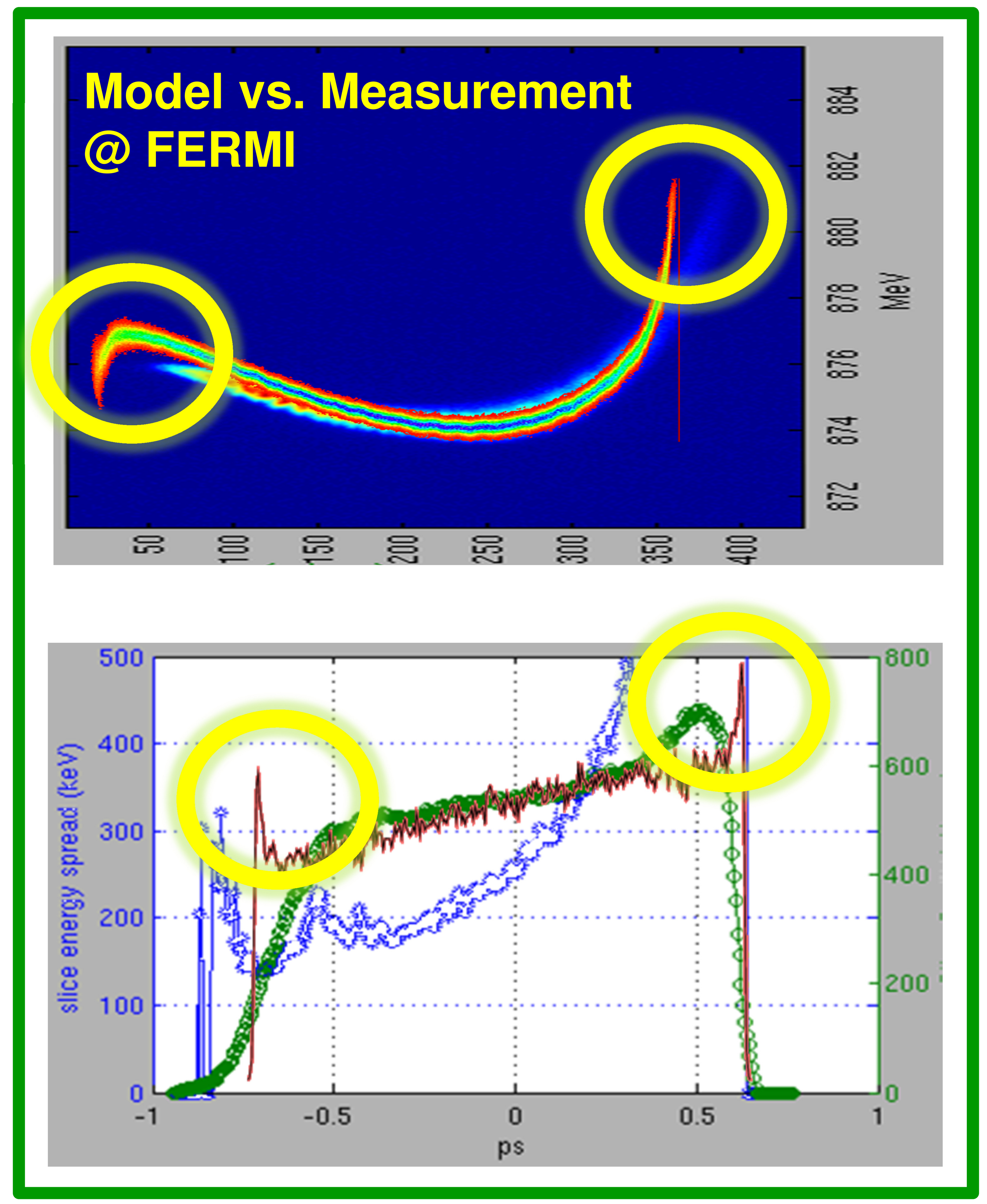
M. Cornacchia et al. (2006)
G. Penco et al. @ FERMI (2014)

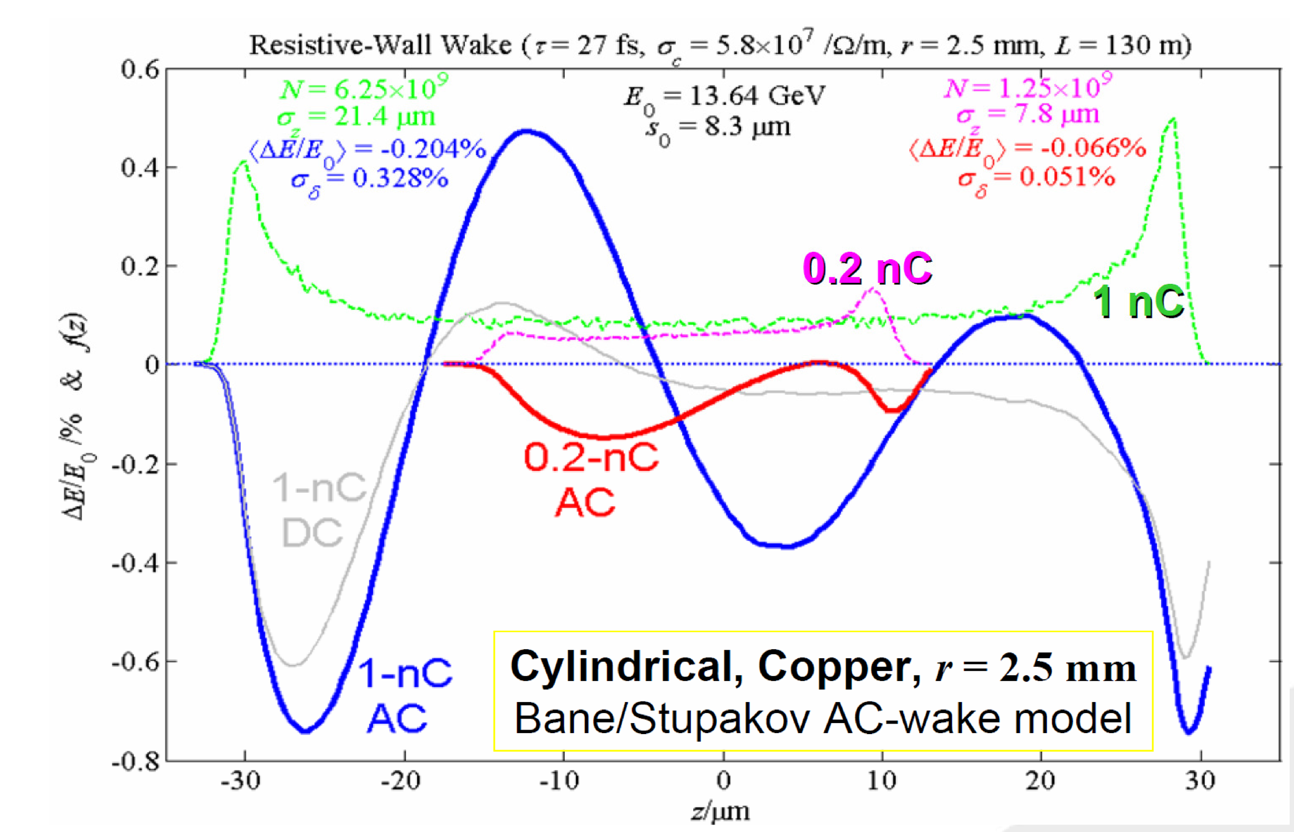


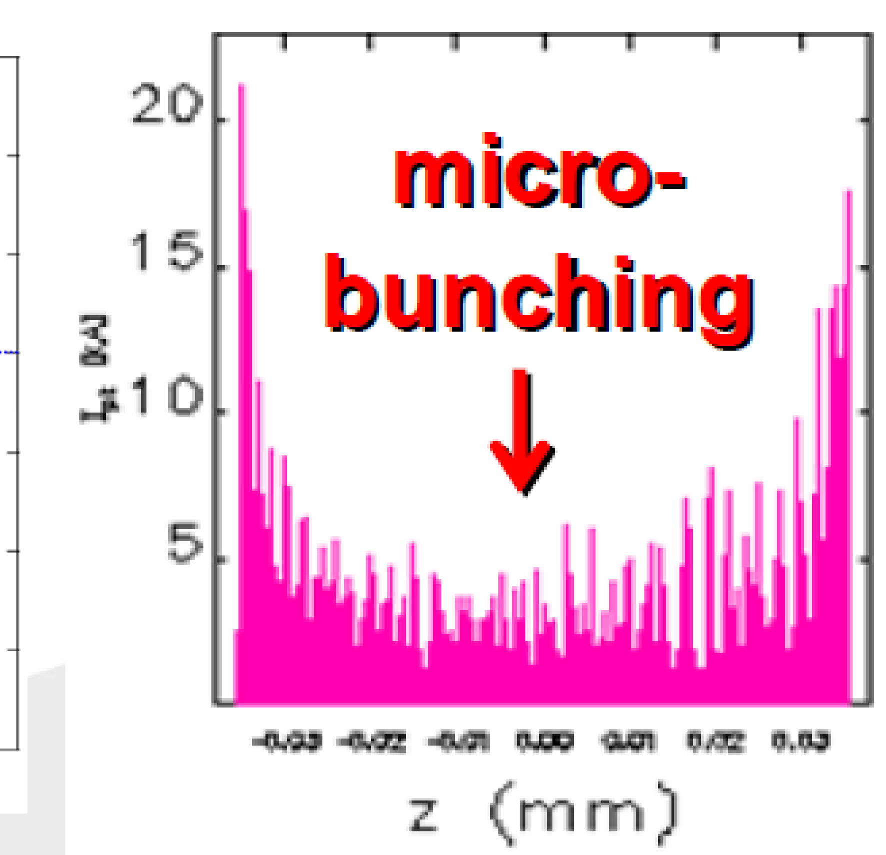












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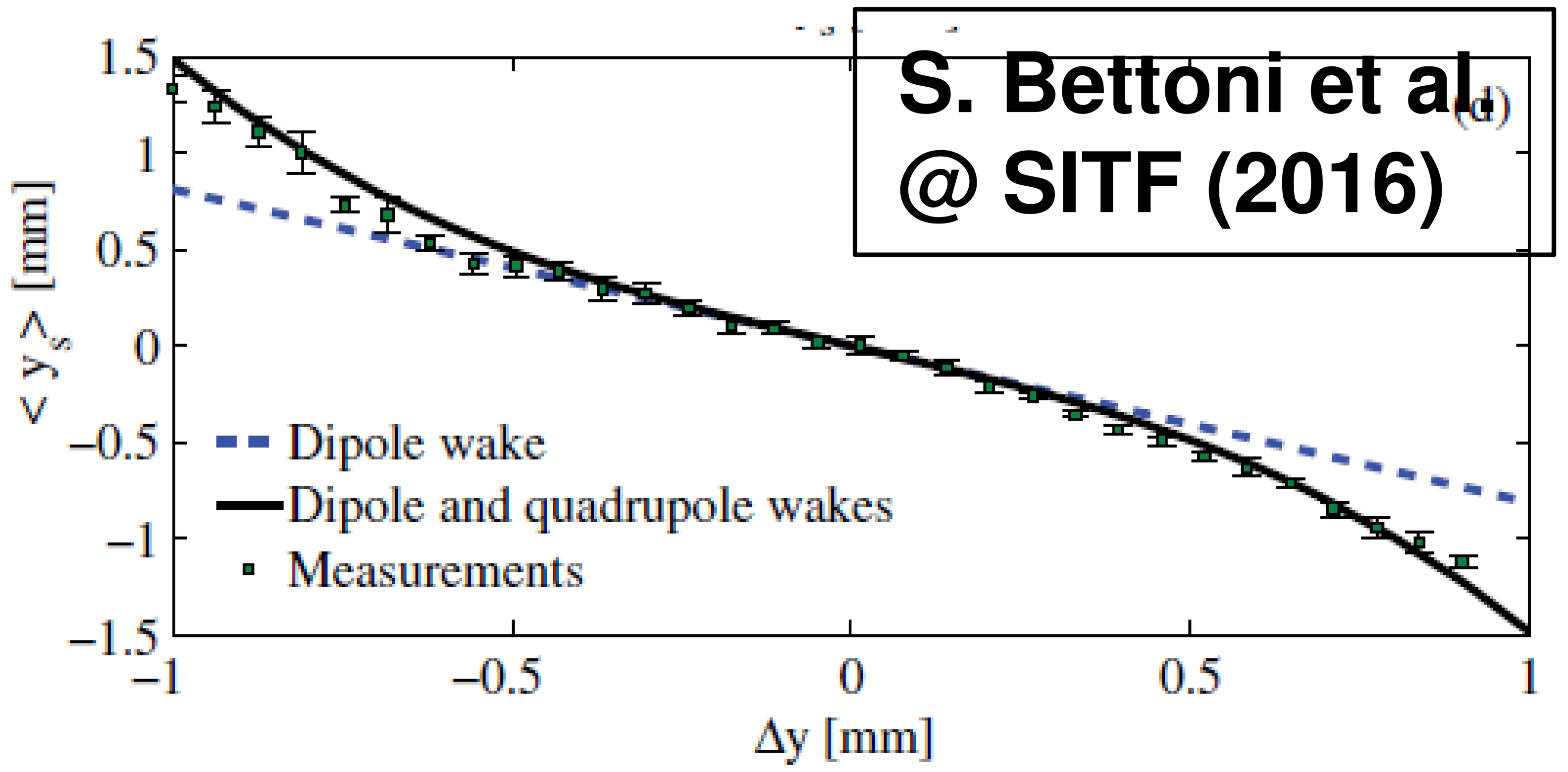
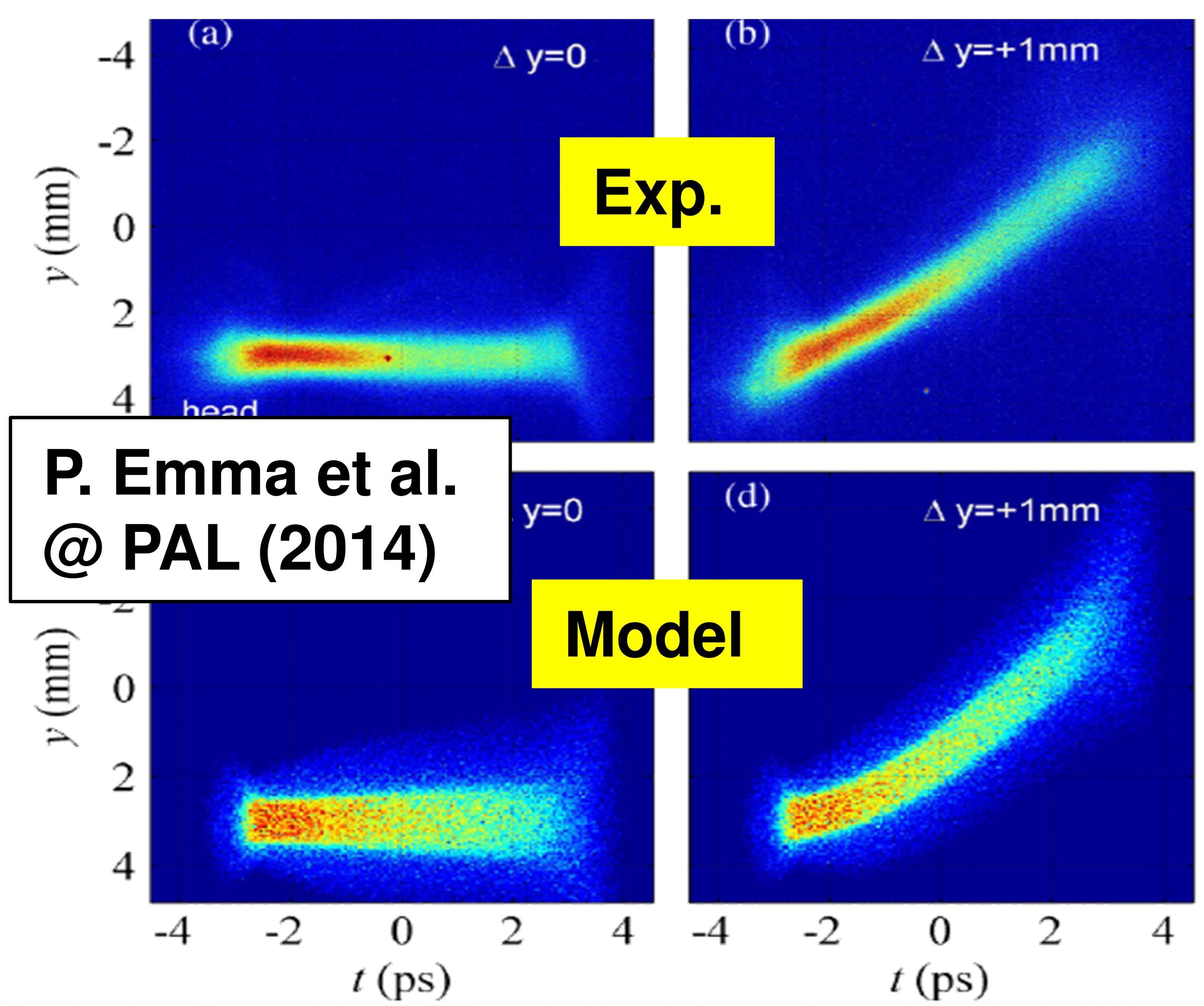
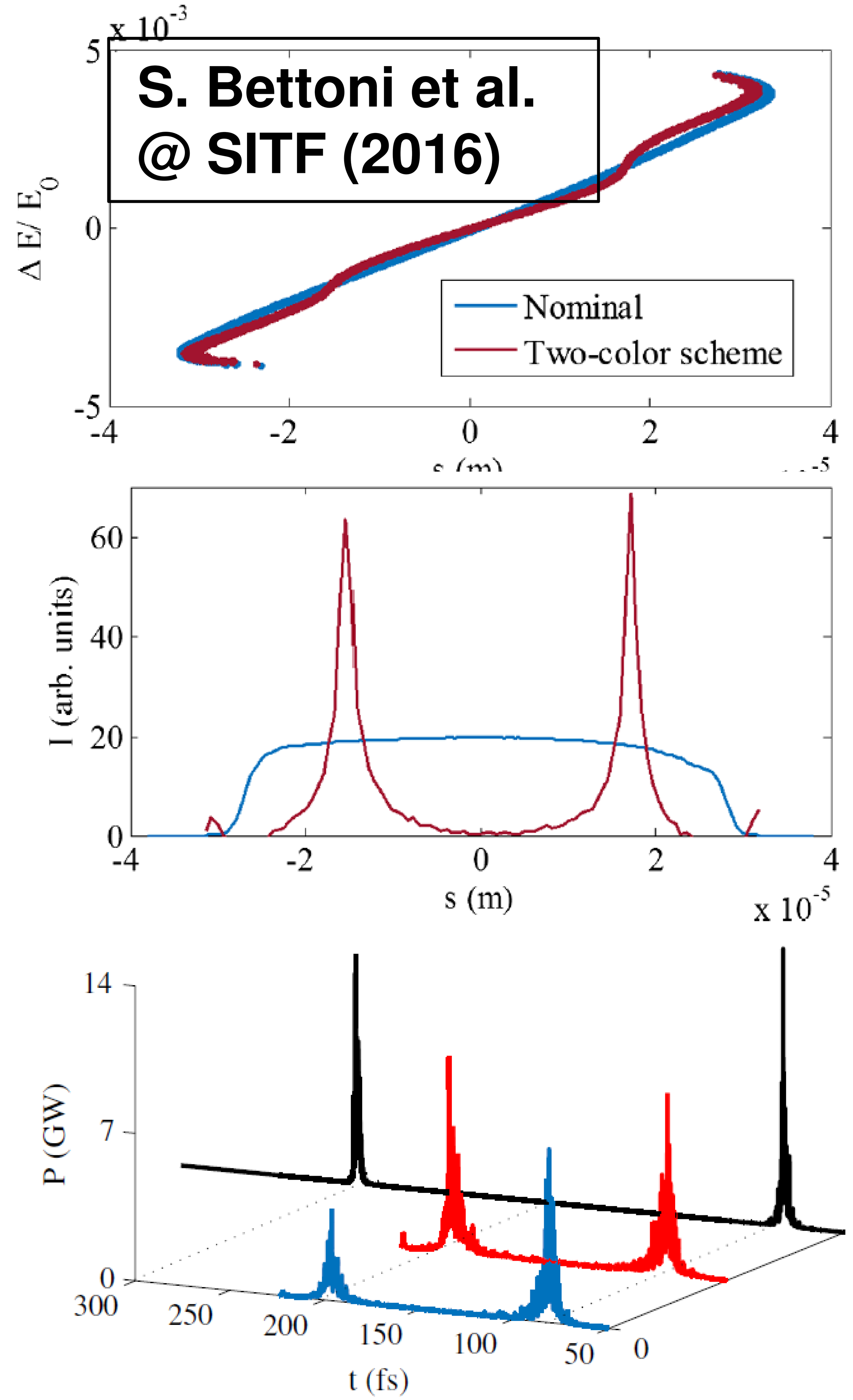
Wakefields, Odi et Amo

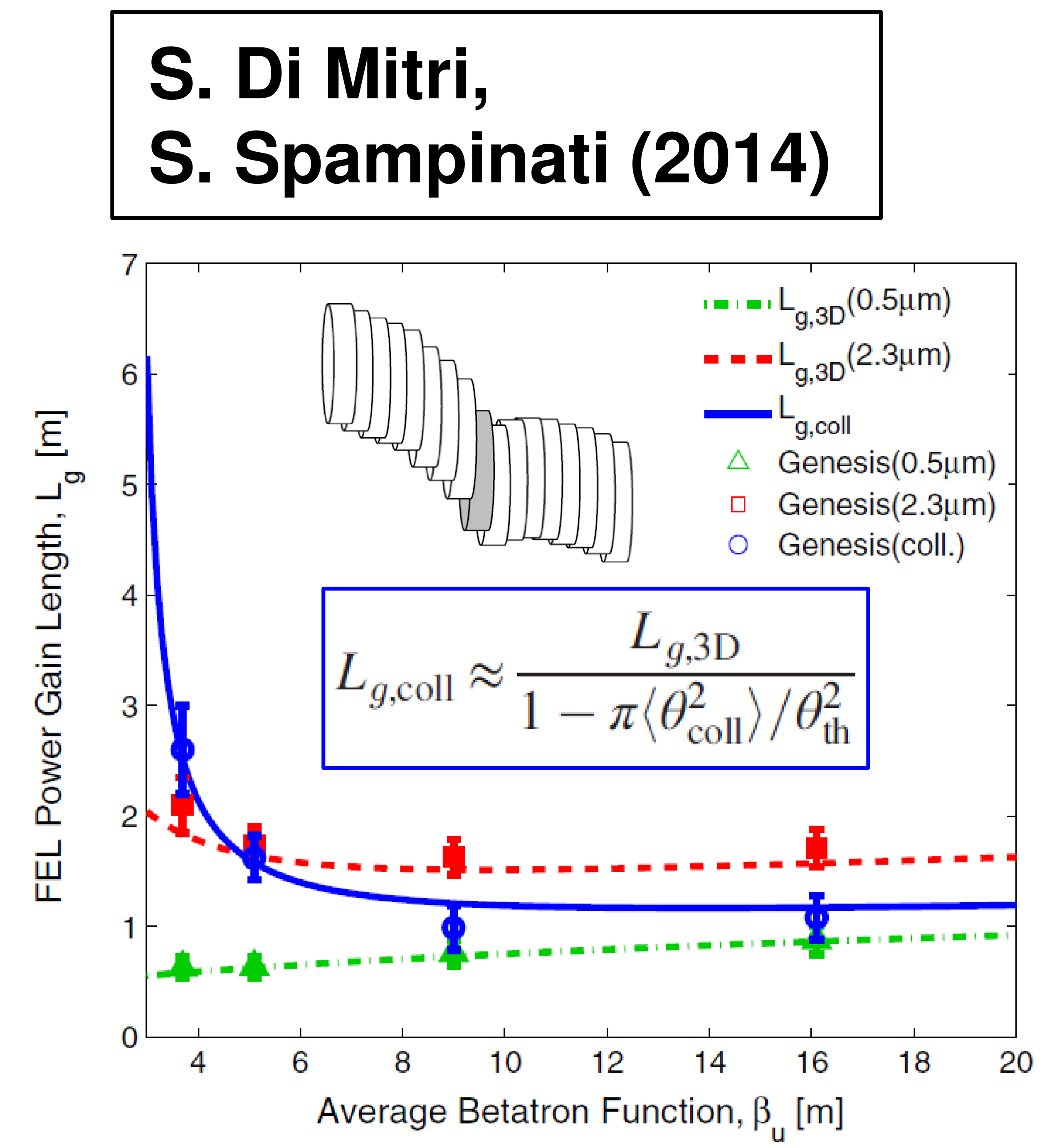
- Recently, attention to geometric impedance of corrugated structures ("dechirper").
  - Longitudinally, allows manipulation of e-beam phase space.
  - Transversally, may "select" short bunch slices for lasing.

Both suitable for short pulse / two-color FELs









Message:

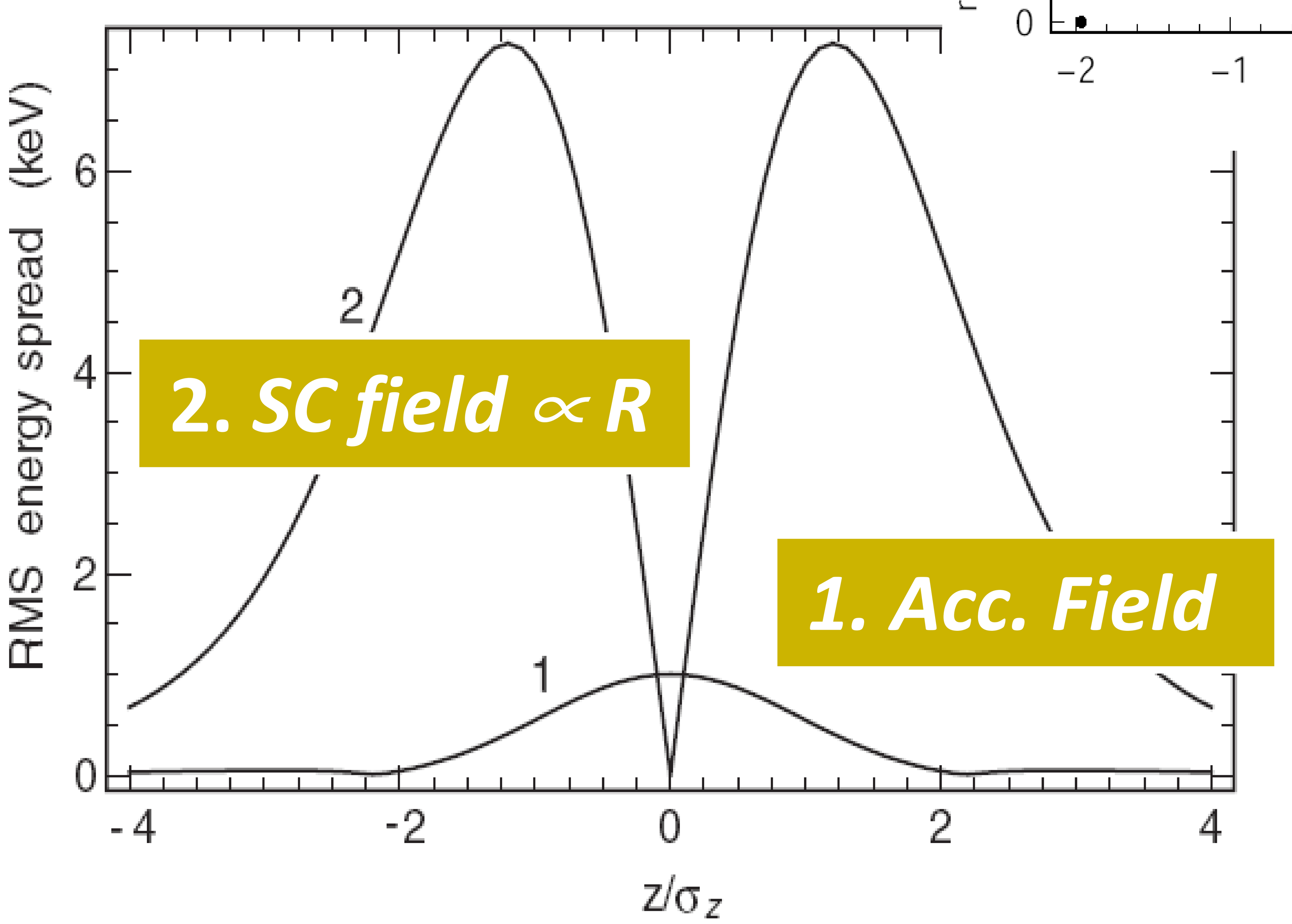
Geometric and RW wakefields can be modelled accurately – We may profit for shaping FEL pulses (in time and bandwidth).

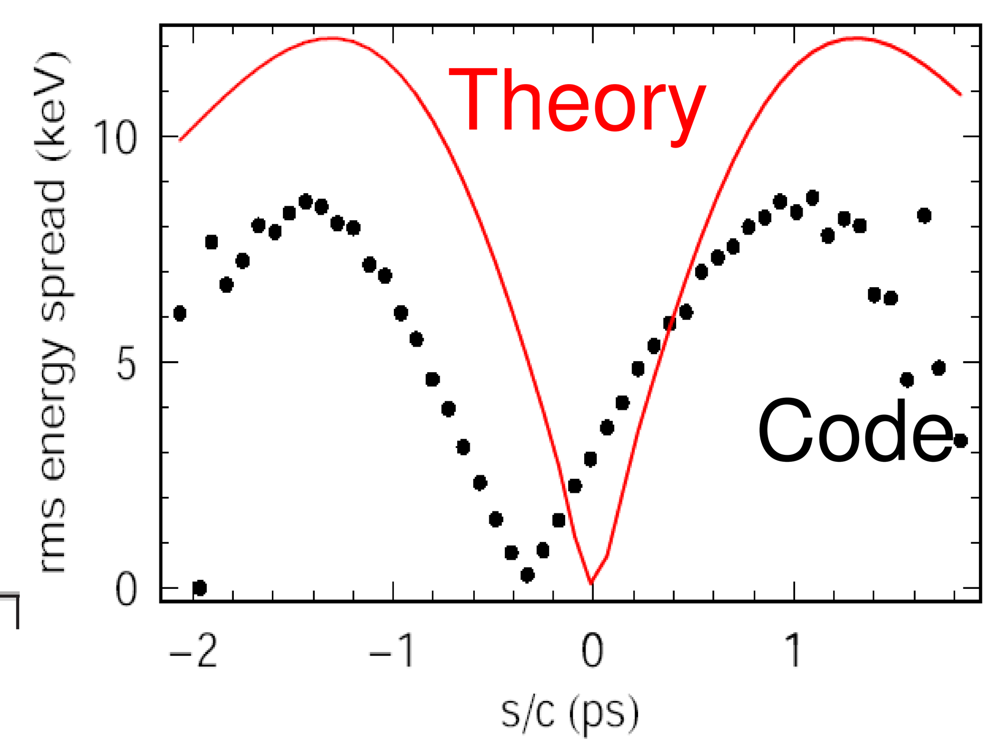
More details on the charge distribution can be captured with care in modelling the PIL pulse.

The Big Chill

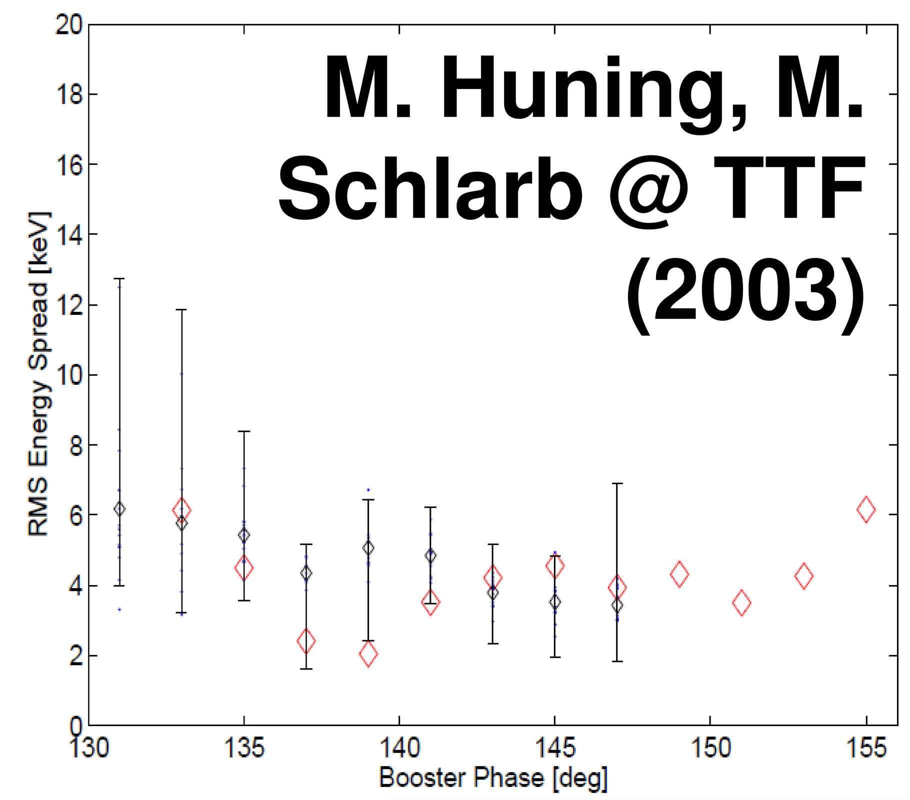
- PI-beam is “cold” and dense enough to be affected by shot-noise-driven microbunching.
  - Most of uncorr. energy spread is attributed to SC-force, but also associated to the “acceleration” field.
  - Accurate prediction only from codes implementing L-W retarded potentials.
  - It typically ranges in 1–3 keV rms out of PI.
    - ➢ Any chance to increase it with a suitable bunch shaping ?

G. Stupakov, Z. Huang (2008)

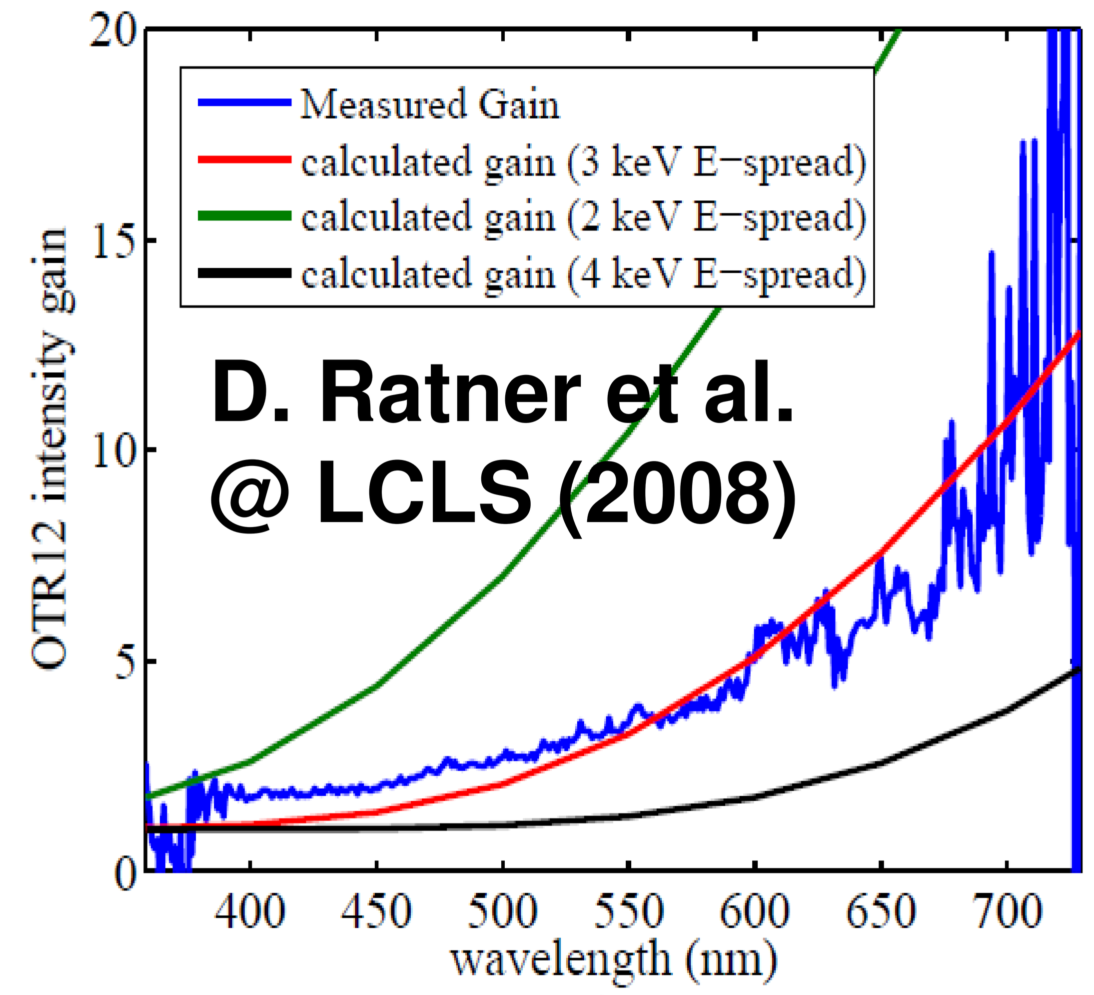




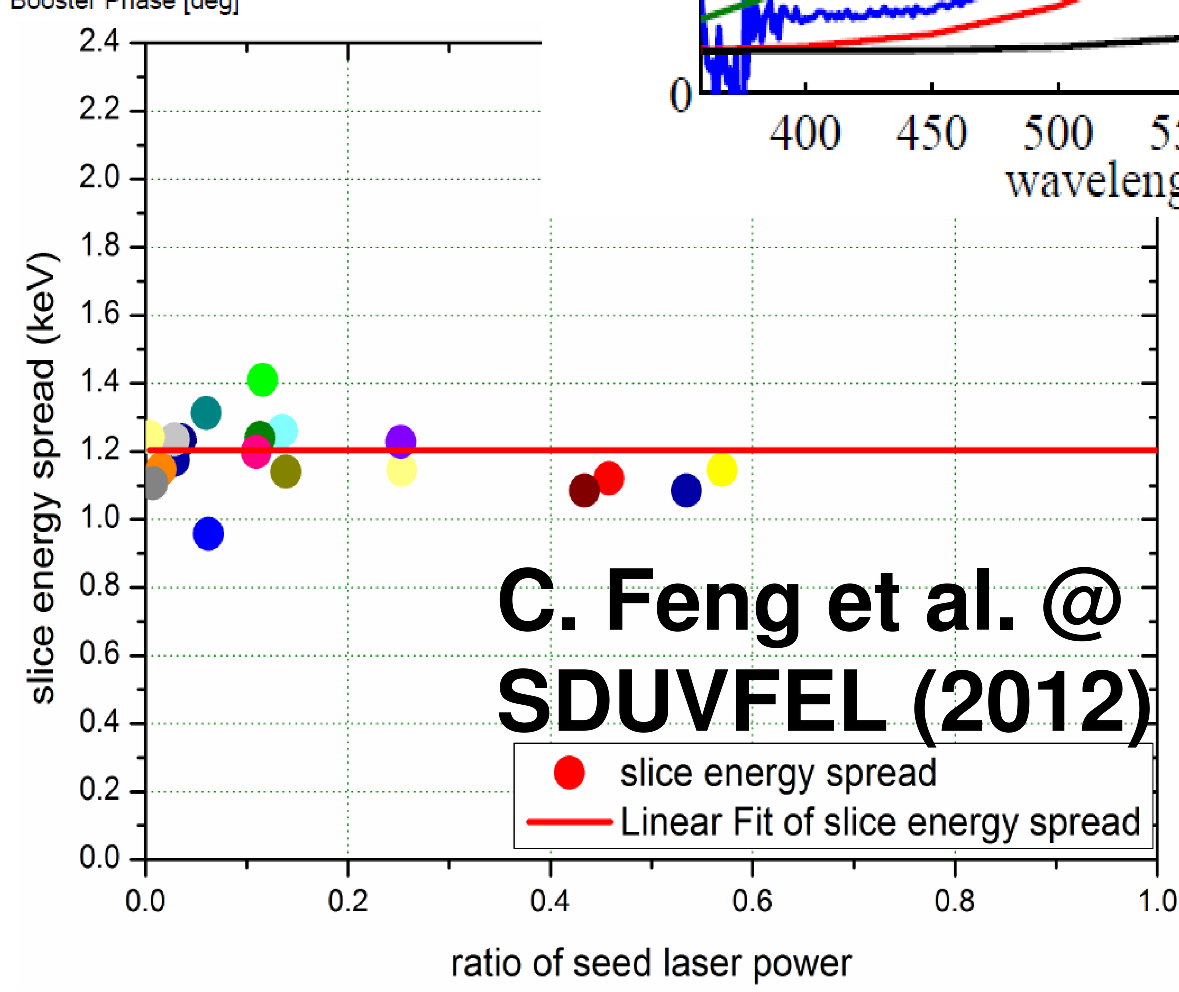
M. Huning, M. Schlarb @ TTF (2003)



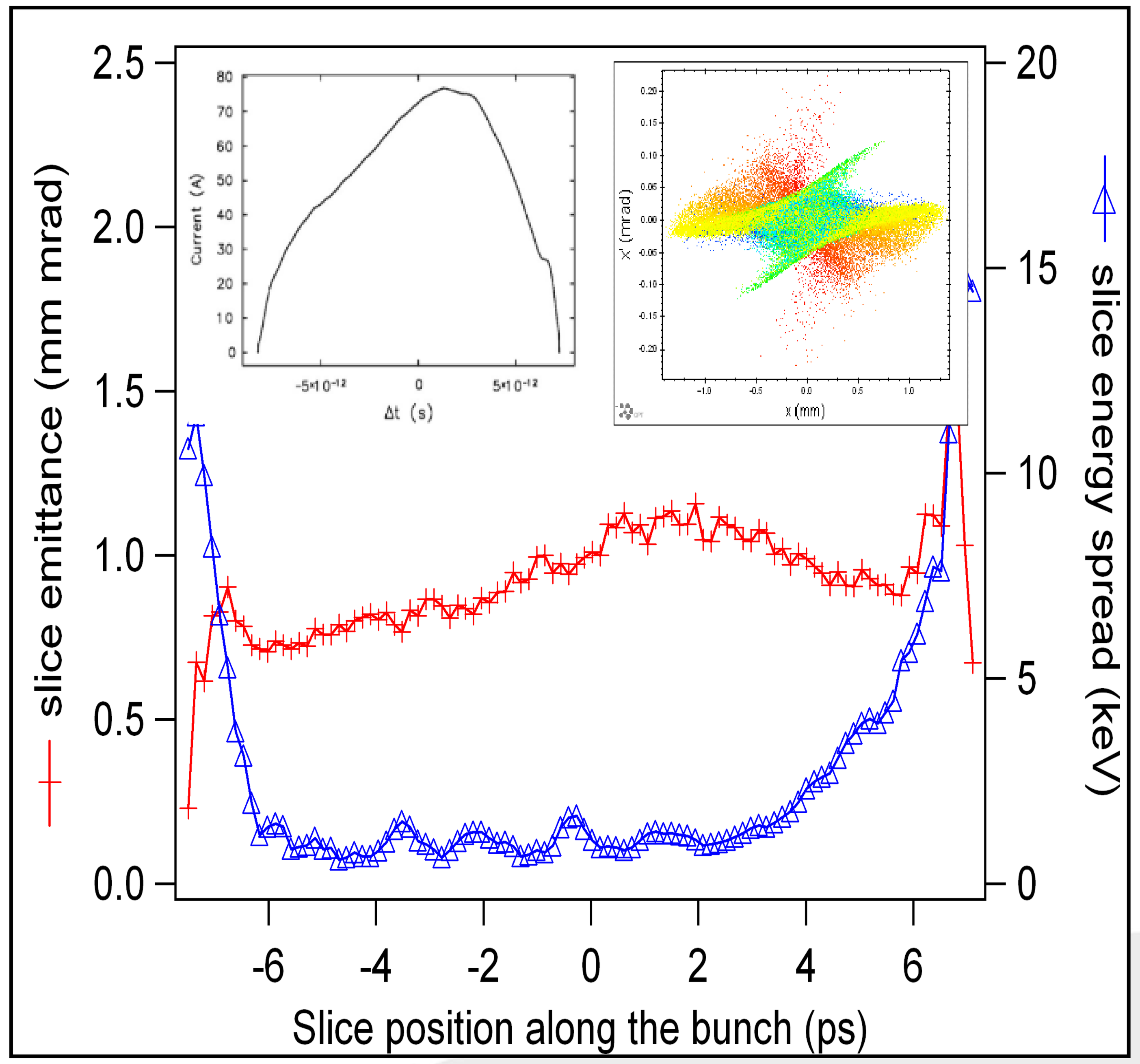
D. Ratner et al. @ LCLS (2008)



C. Feng et al. @ SDUVFEL (2012)



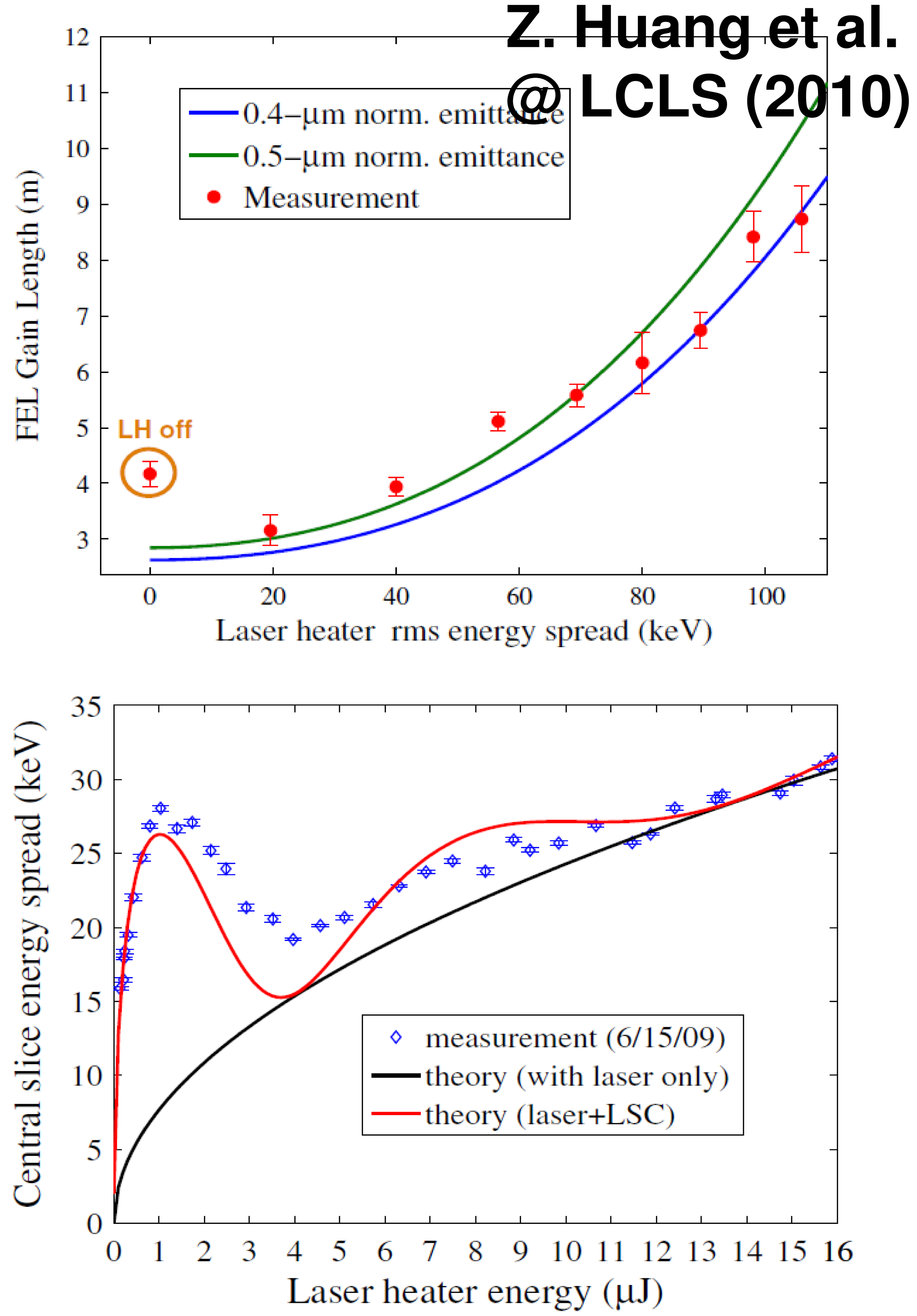
M. Trovò et al. for FERMI (2009)



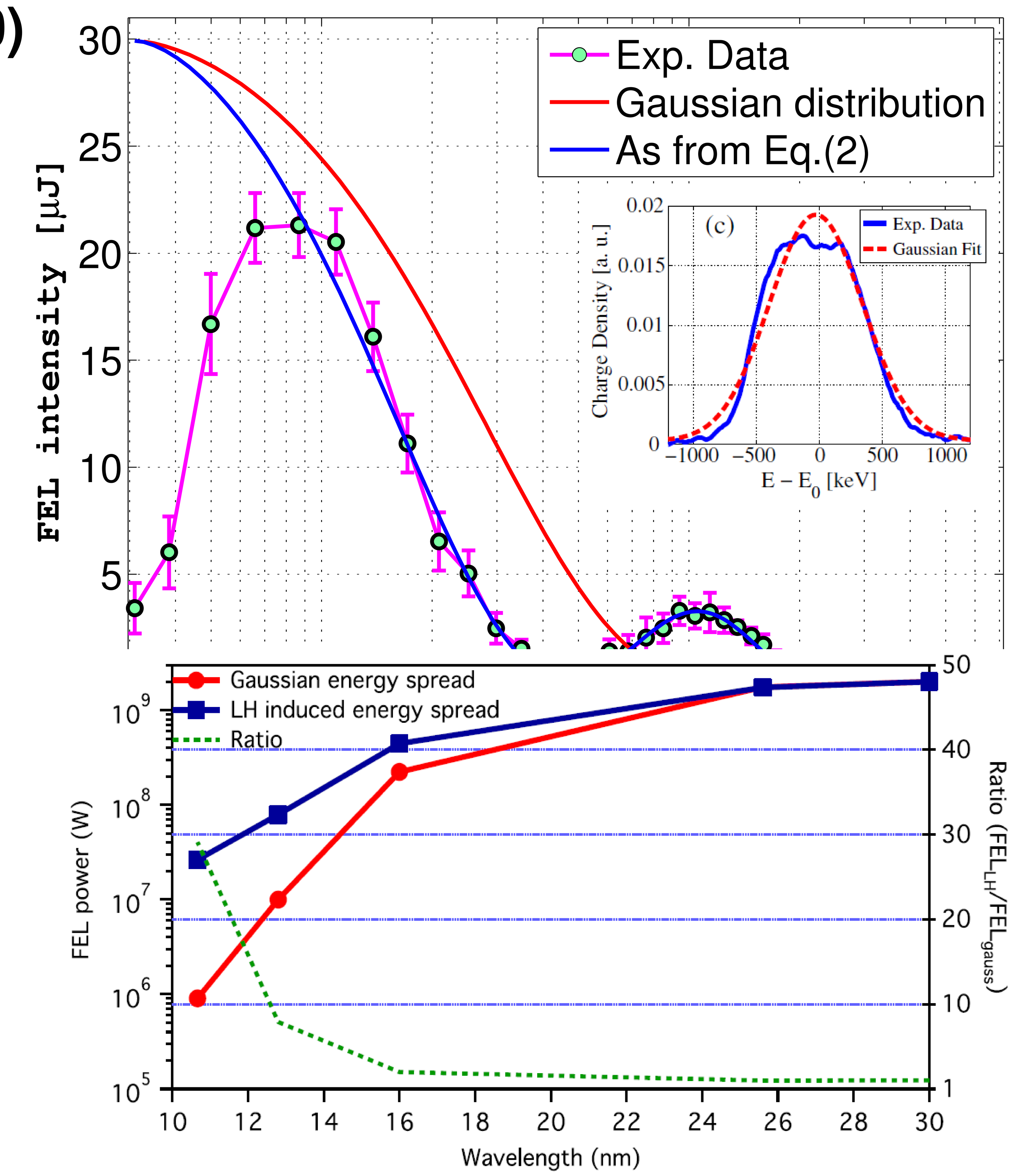
Some Like It Hot

- A Laser Heater makes the beam “hot” enough to suppress MBI. It can actually do more than that…
  - Modelled performance match experiments: FEL intensity may increase by a factor ≤ 3 with LH on.
  - Transverse shaping of the laser pulse improves the FEL power at short wavelengths (non-Gaussian σ_E)
  - Longitudinal shaping of the laser pulse drives multi-color / short pulse FEL

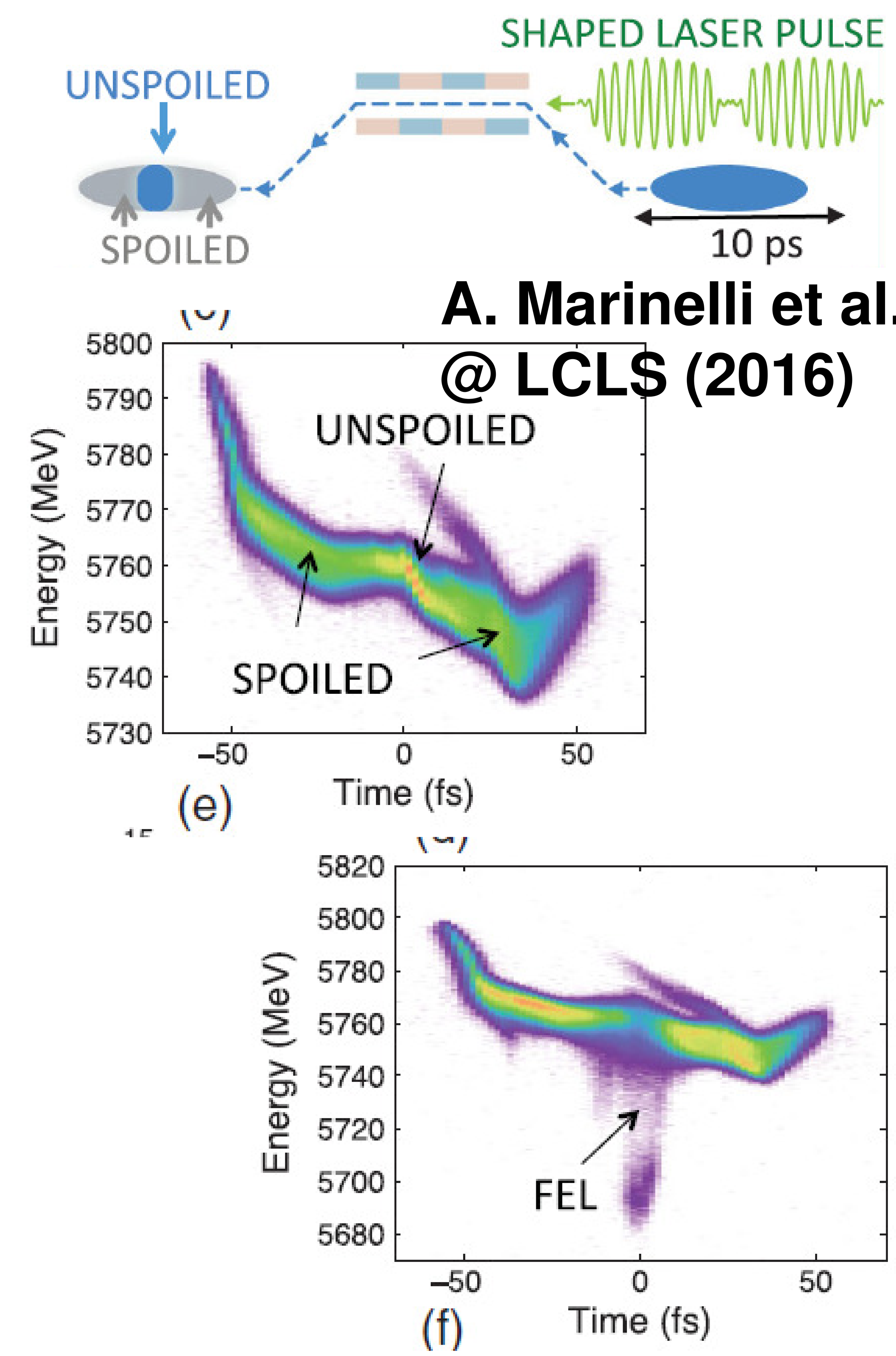
Z. Huang et al. @ LCLS (2010)



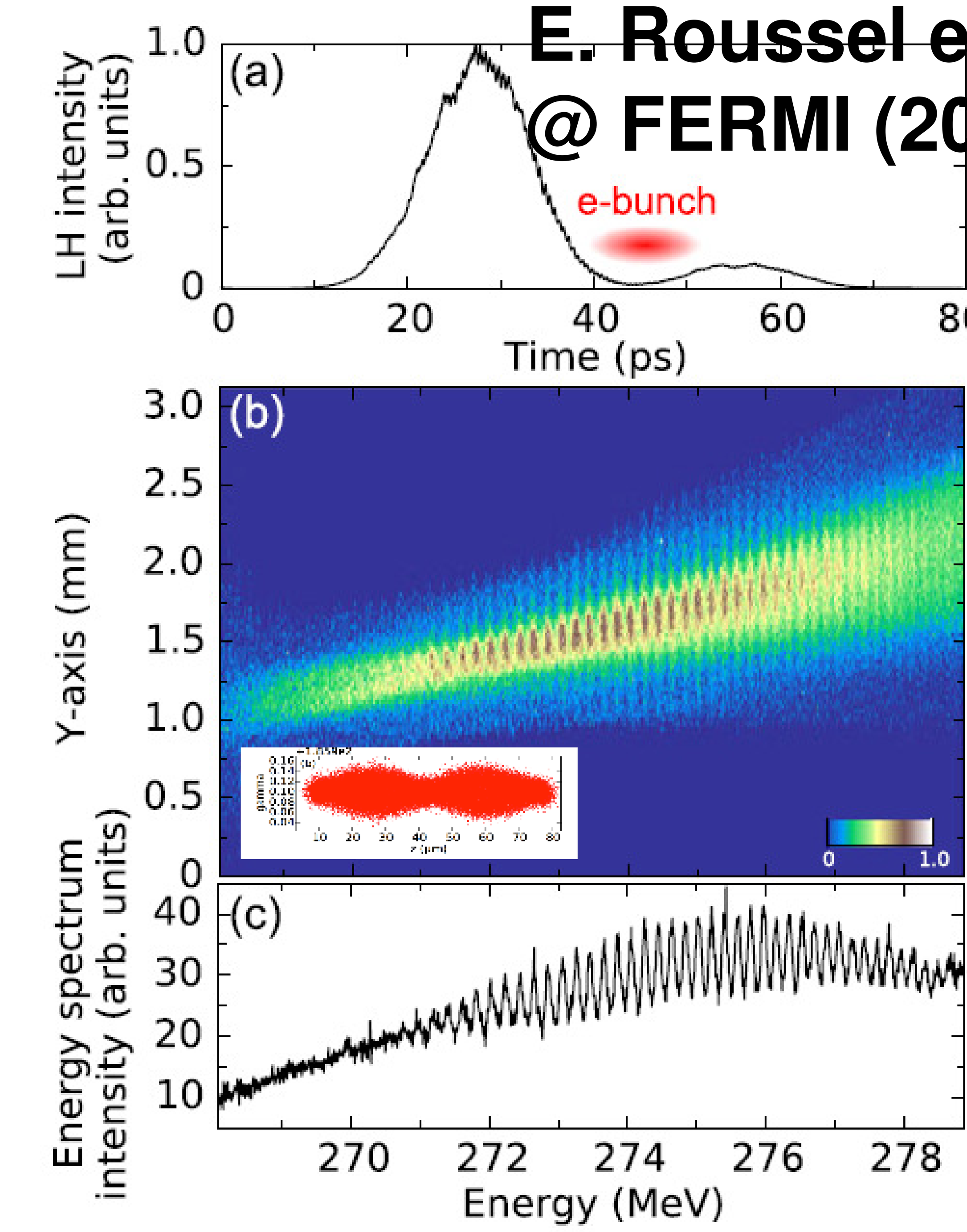
E. Ferrari et al. @ FERMI (2013)

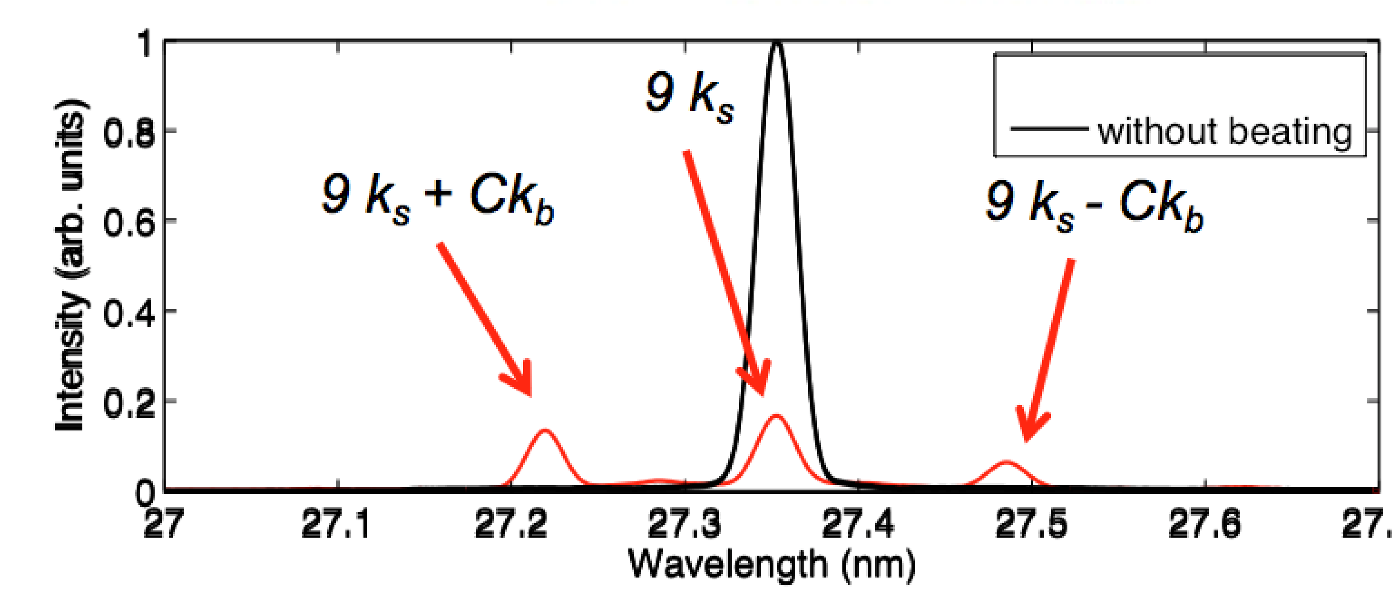


A. Marinelli et al. @ LCLS (2016)



E. Roussel et al. @ FERMI (2015)





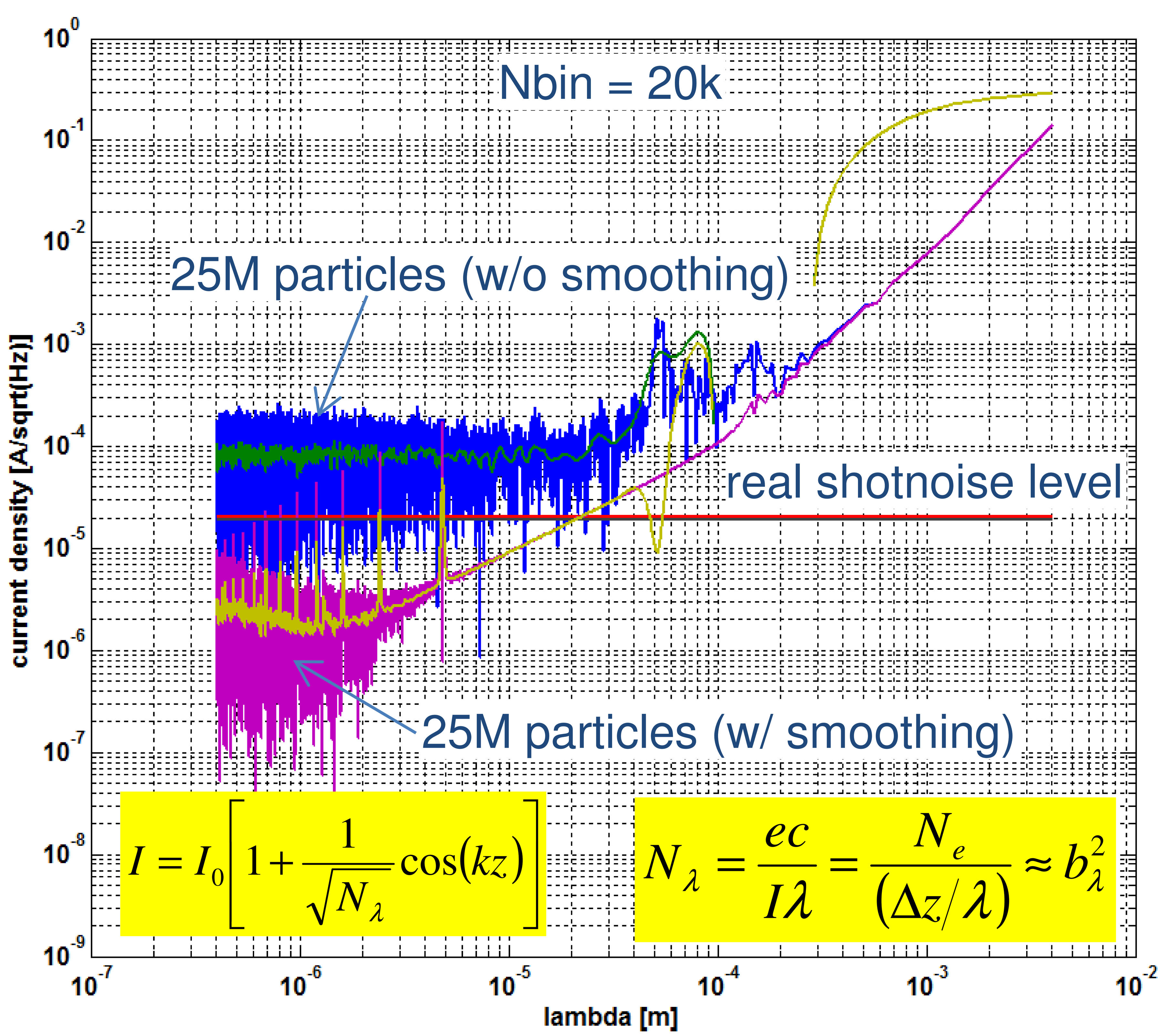
Message:

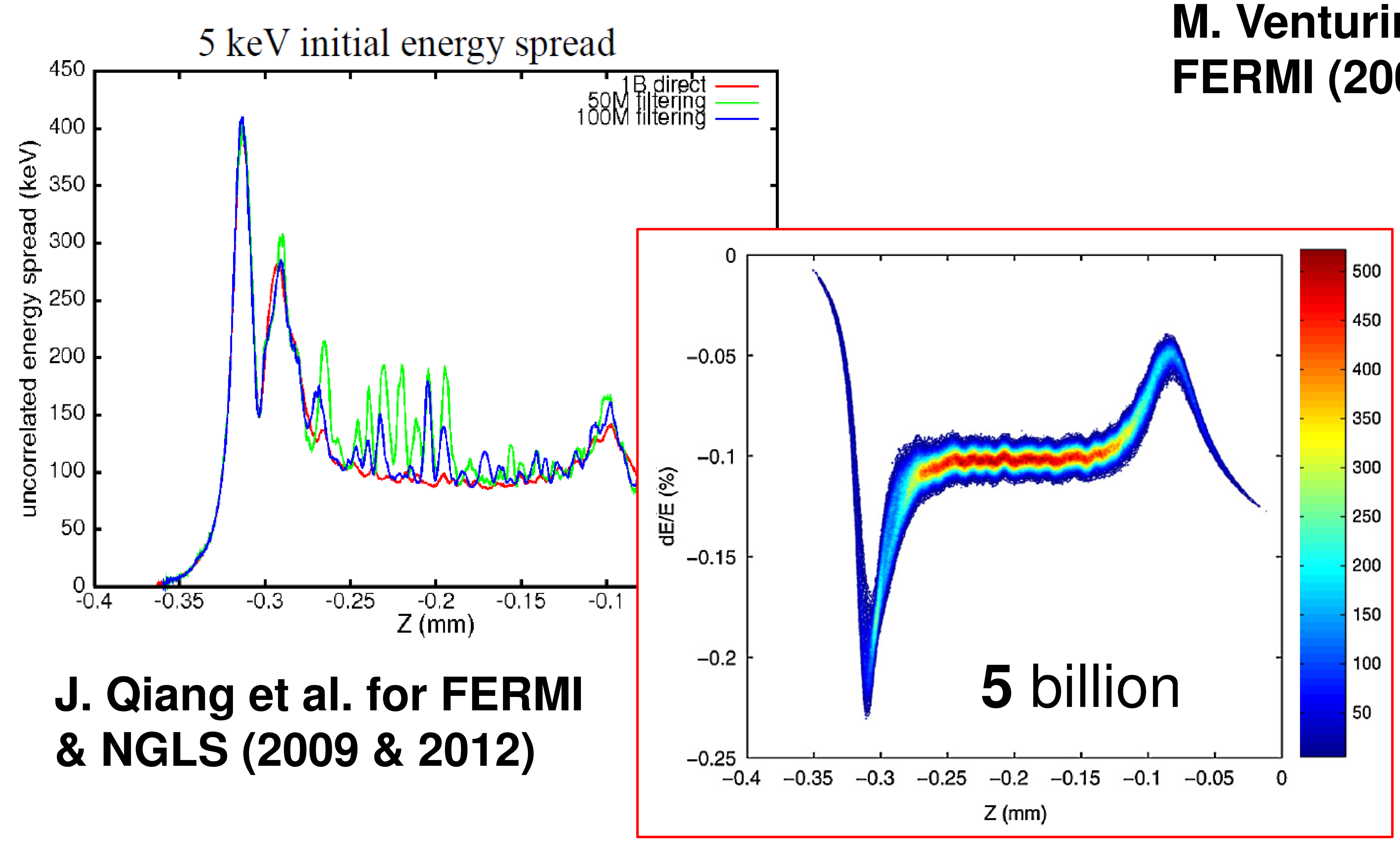
We know how much the energy spread is. We almost know where it comes from. We do not know if we can manipulate it further, in the Gun.

Laser Heater can be modelled reliably. This opens the door to optical shaping of FEL, both in wavelength and in time.

The Right Amount of Noise

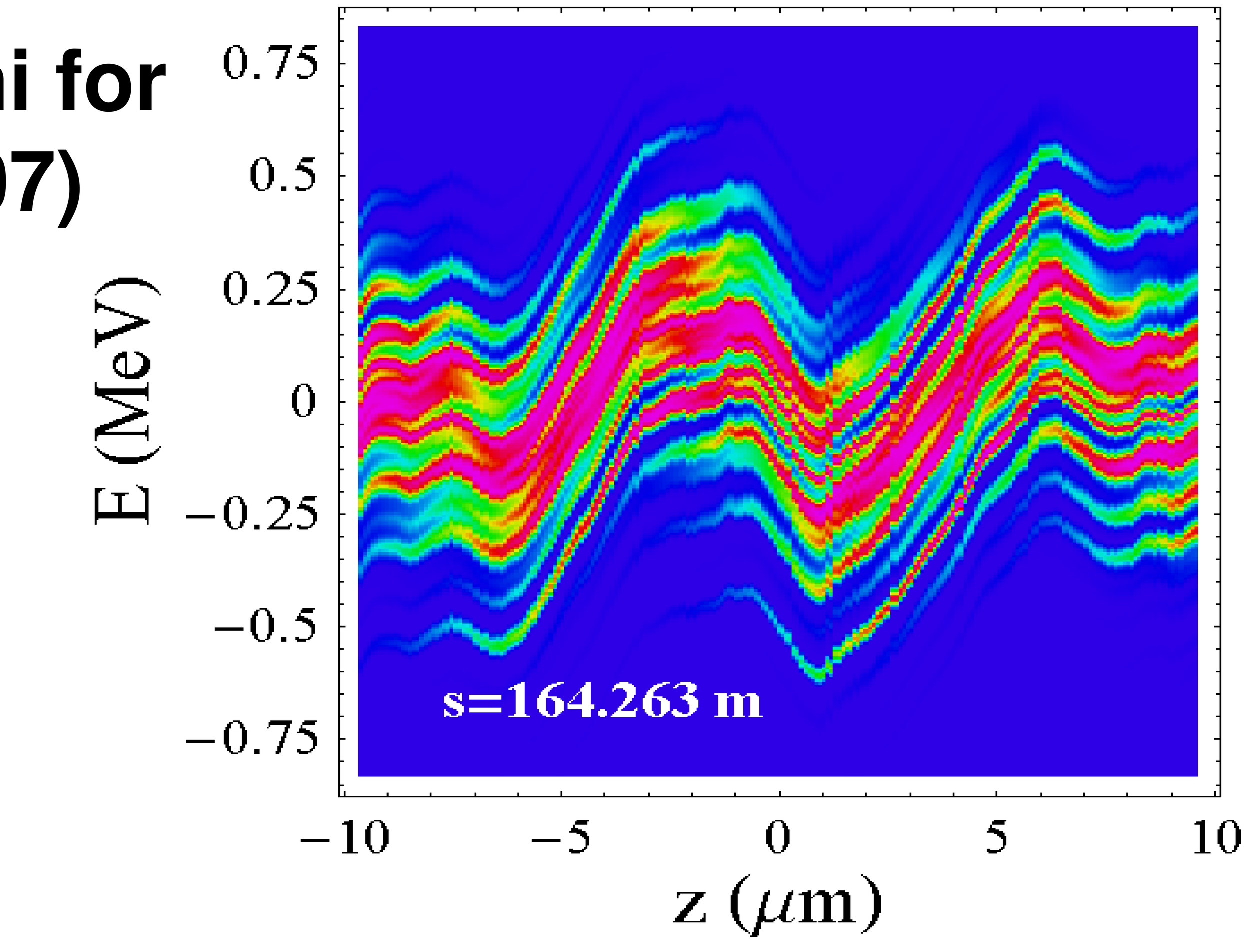
- Control of numerical sampling noise in PIC codes is vital to simulation of microbunching instability.
  - Smoothing charge distribution can be even “too good”.
  - Filtering ok for gain curve, not necessarily for details of charge distribution and slice energy spread.
    - Direct multi-billion particle simulations sound more reliable. Can FEL codes manage those files?
    - Direct Vlasov solvers need input noise. Limited to 1.5-D by practical CPU efforts.

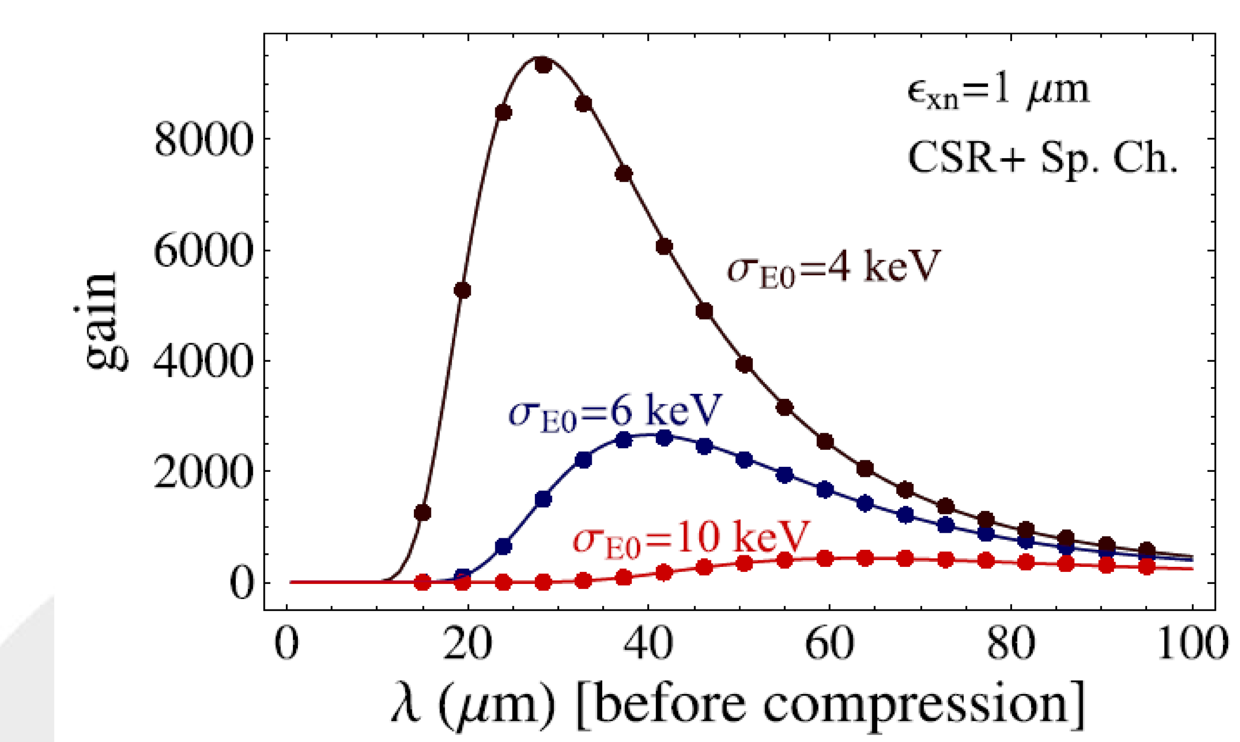




J. Qiang et al. for FERMI & NGLS (2009 & 2012)

M. Venturini for FERMI (2007)





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Message:

Be sure you are not doing better than Nature.

Yet, not a standardized procedure for simulation of microbunching instability

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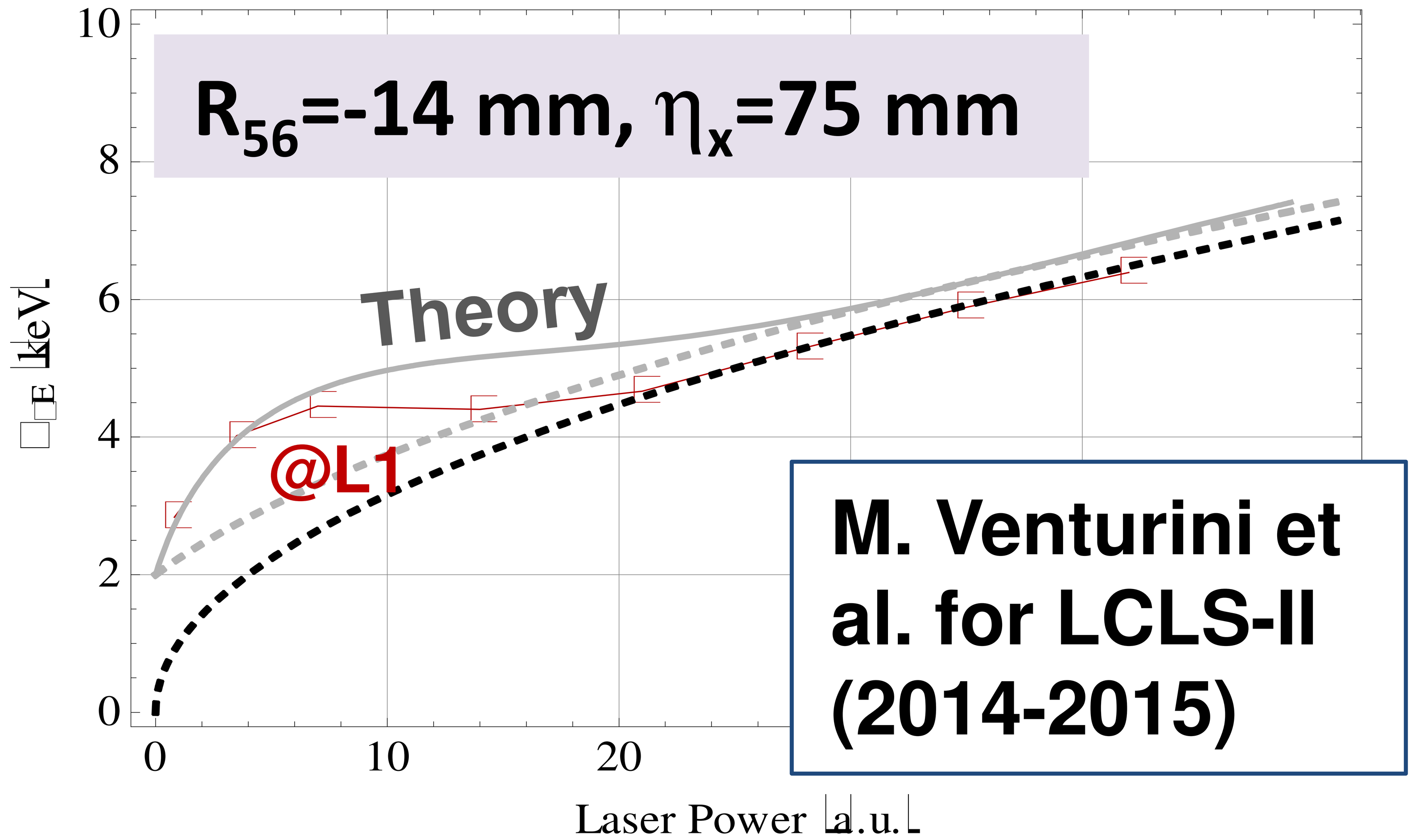
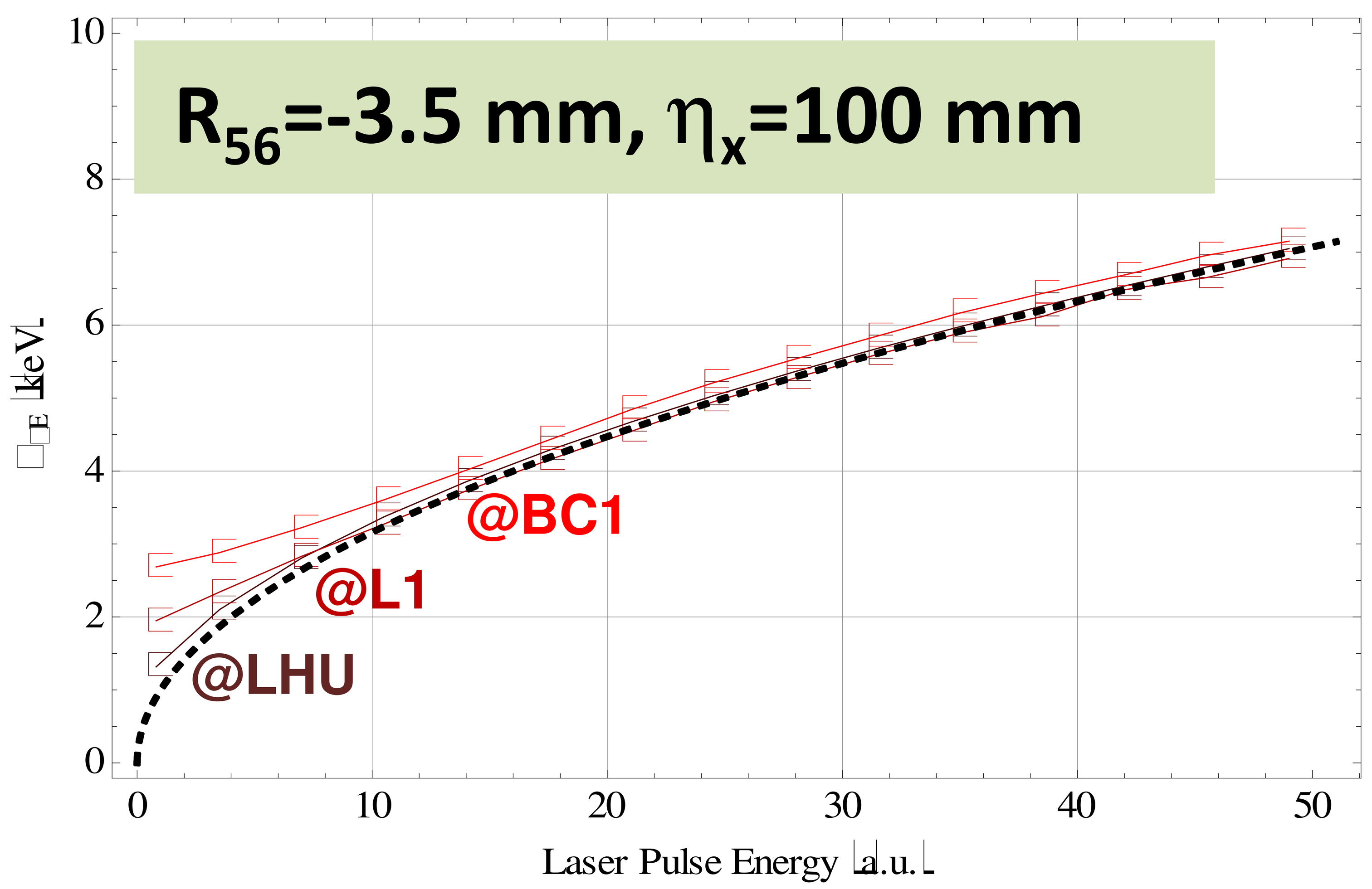
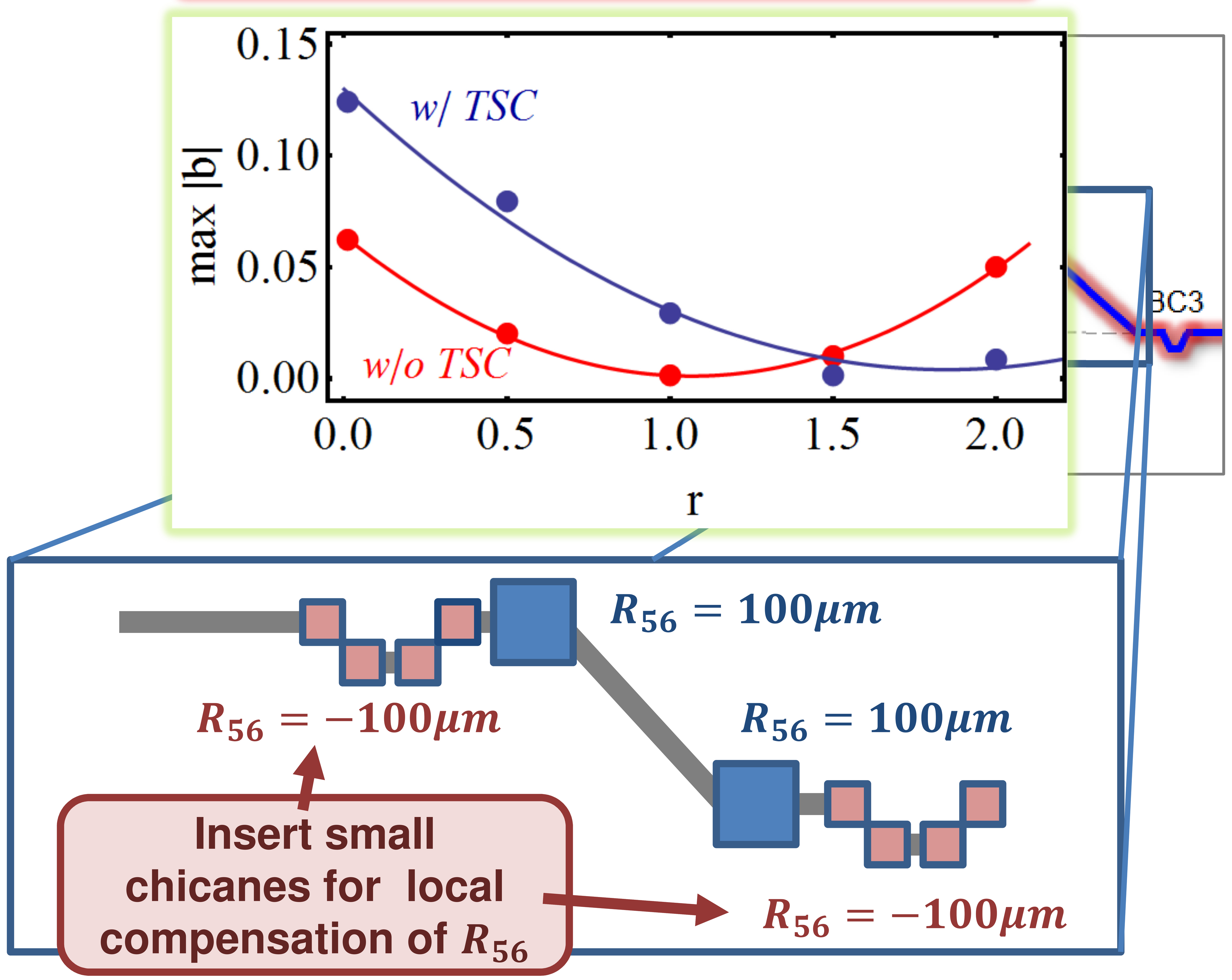
There is no such thing as a free lunch

- Dipoles generate energy (R_{56}) and angular (R_{52}) dispersion. In the presence of SC and CSR, they generate correlations among particle's coordinates, and dilute the 6-D beam emittance.
  - Trickle heating may lower-limit the LH operation.
  - Transport in Spreader lines is affected by LSC, TSC and CSR.

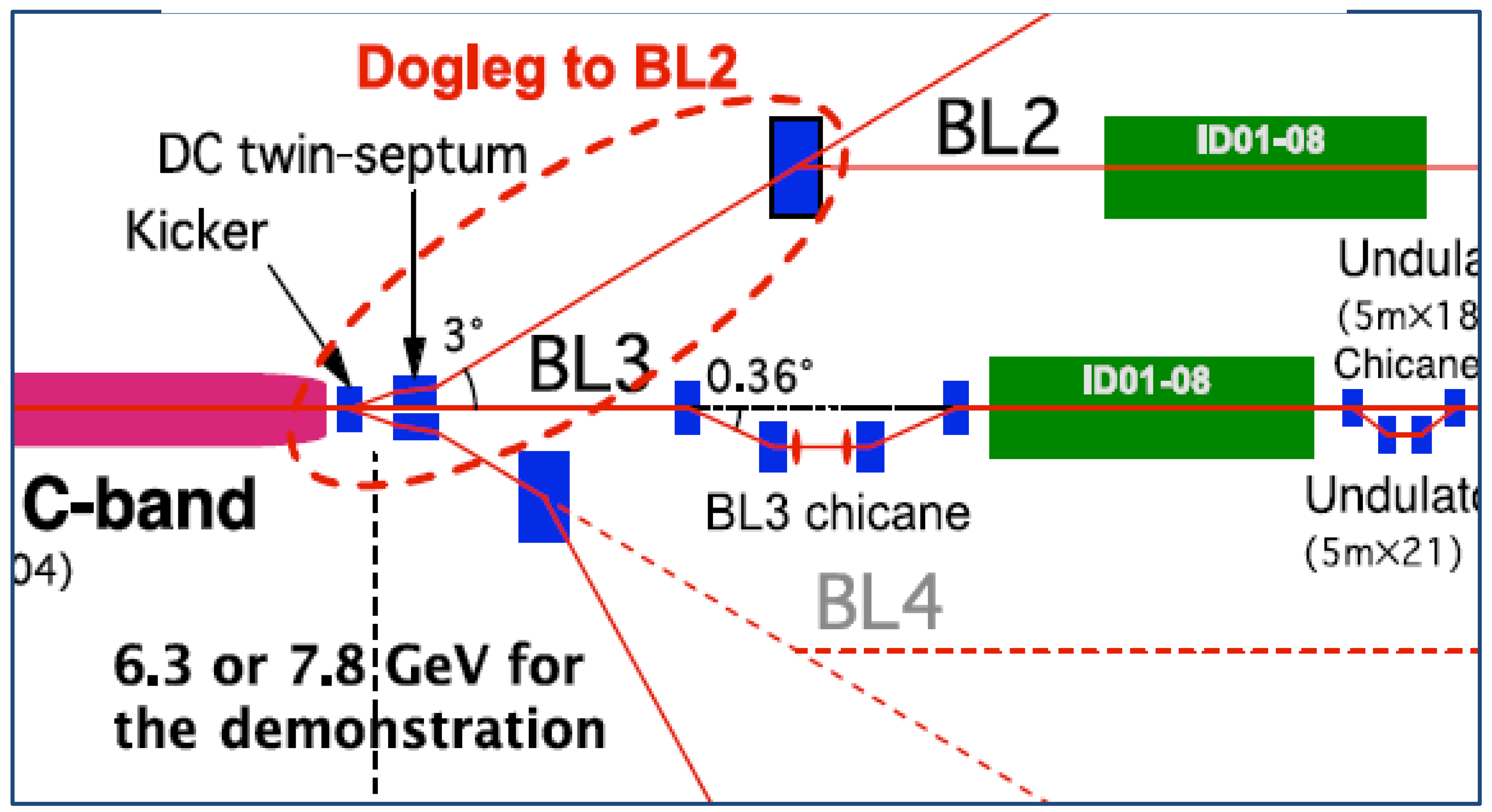


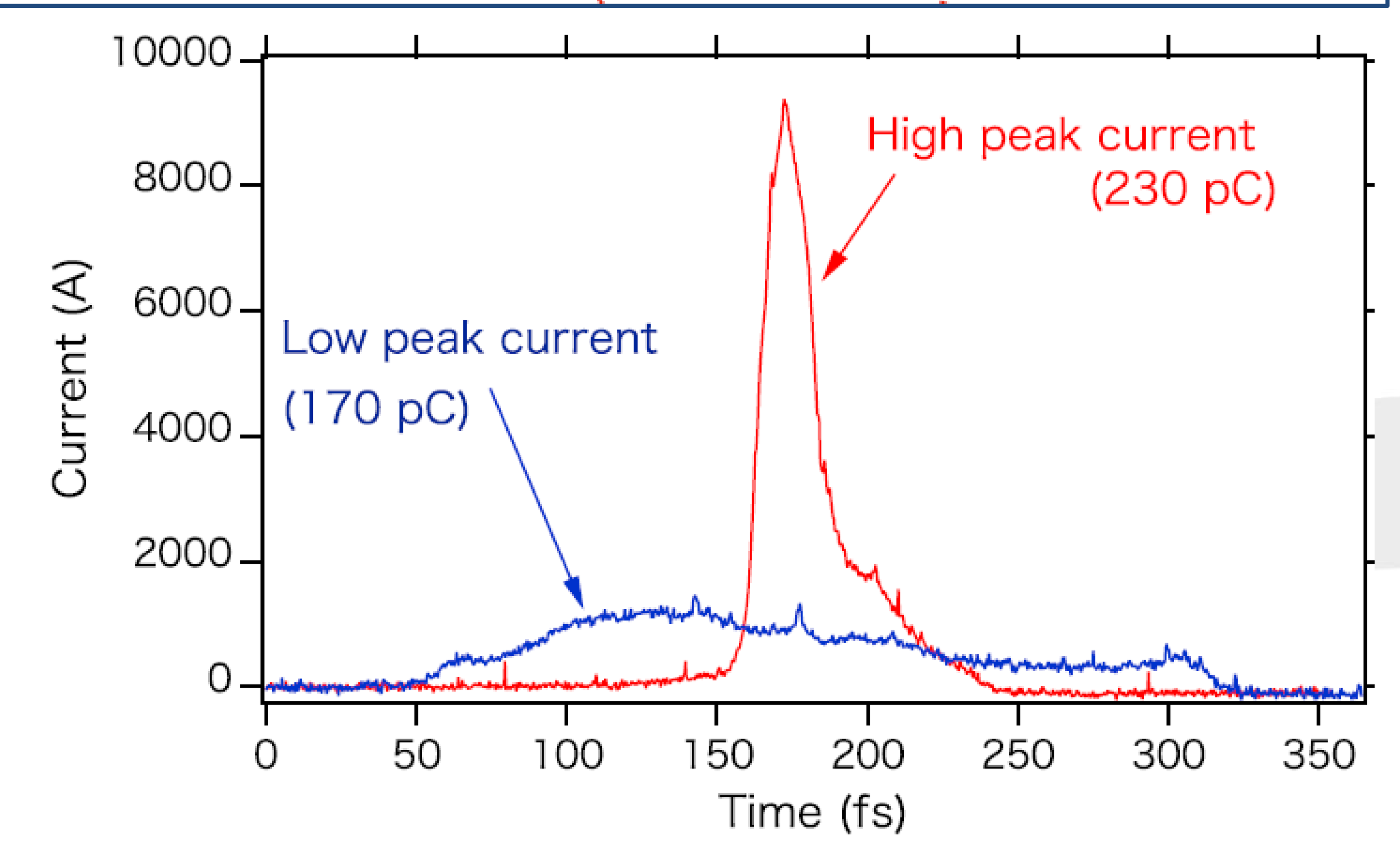


$$b_k \simeq \delta_p \frac{2Ik}{\varepsilon_{xn}\gamma^2 I_A}\int_{s_0}^{s_f} ds \frac{\eta_x^2}{\sqrt{\beta_x\beta_y}} e^{-\frac{\varepsilon_{xn}\eta_x^2 k^2}{\gamma\beta_x}}$$



T. Hara et al. @ SACLA (2016)





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Message:

Collective effects in dispersive regions are intrinsically connected to beam optics. Design to 2^{nd} order seems to be good enough.

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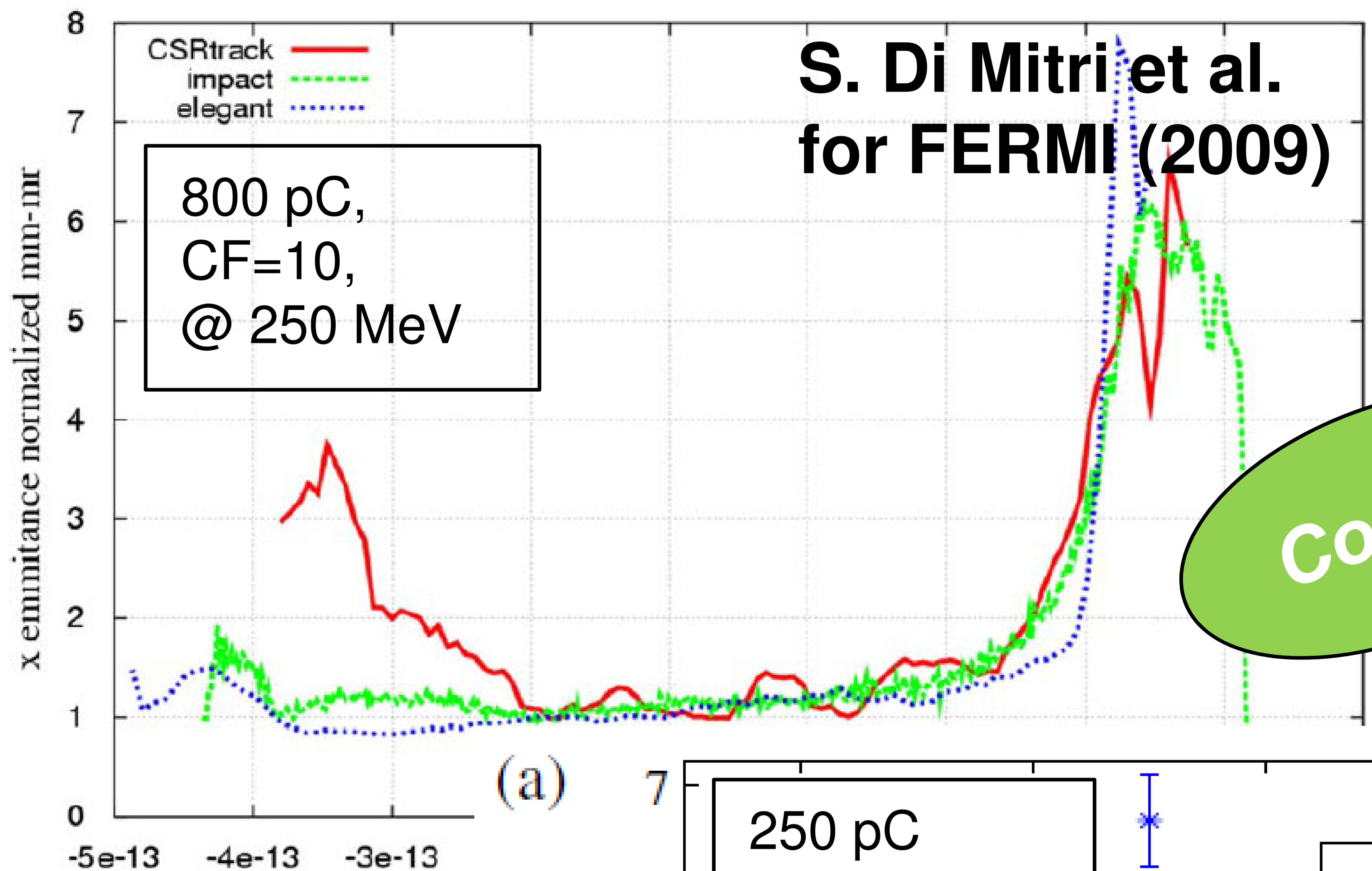
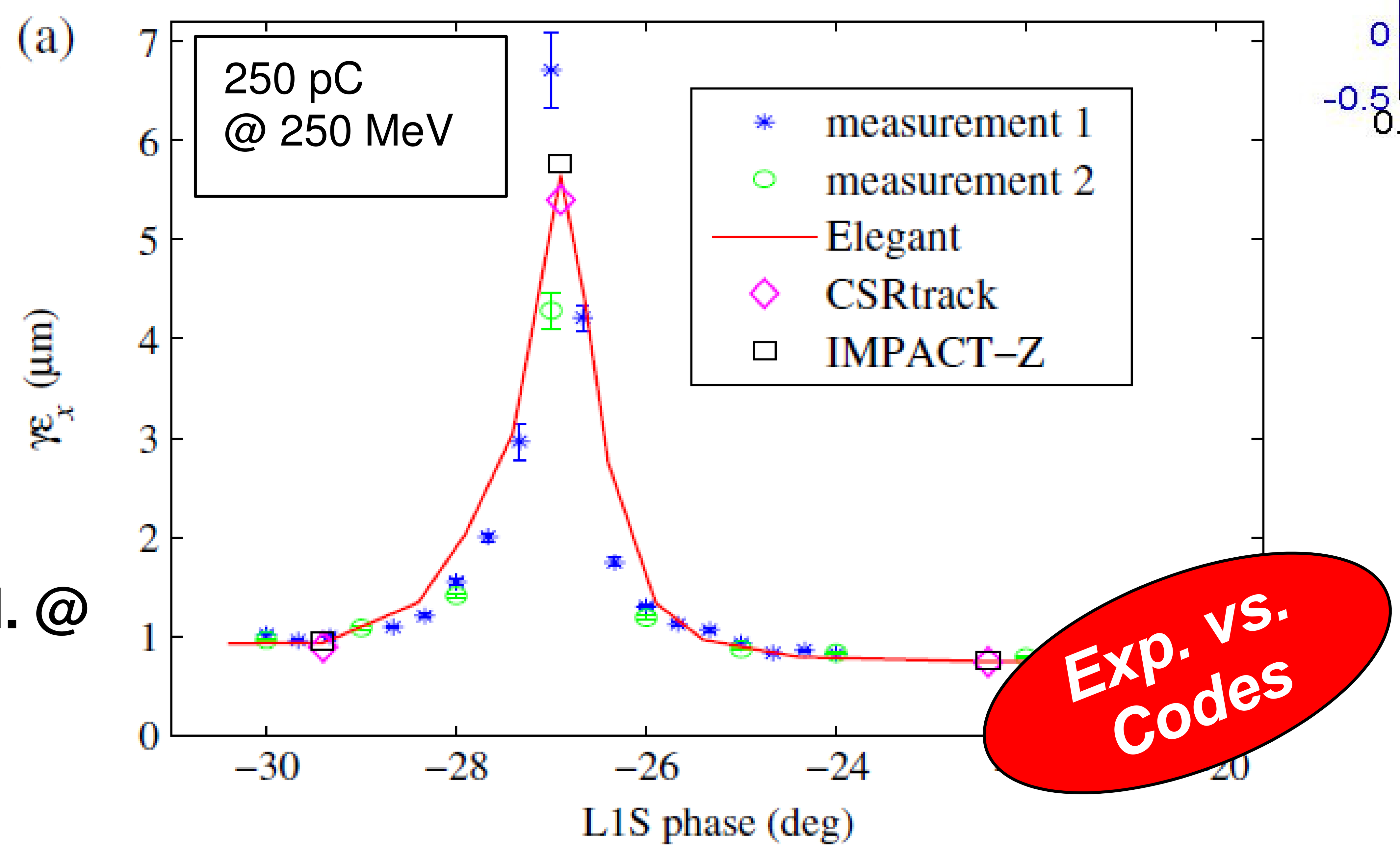
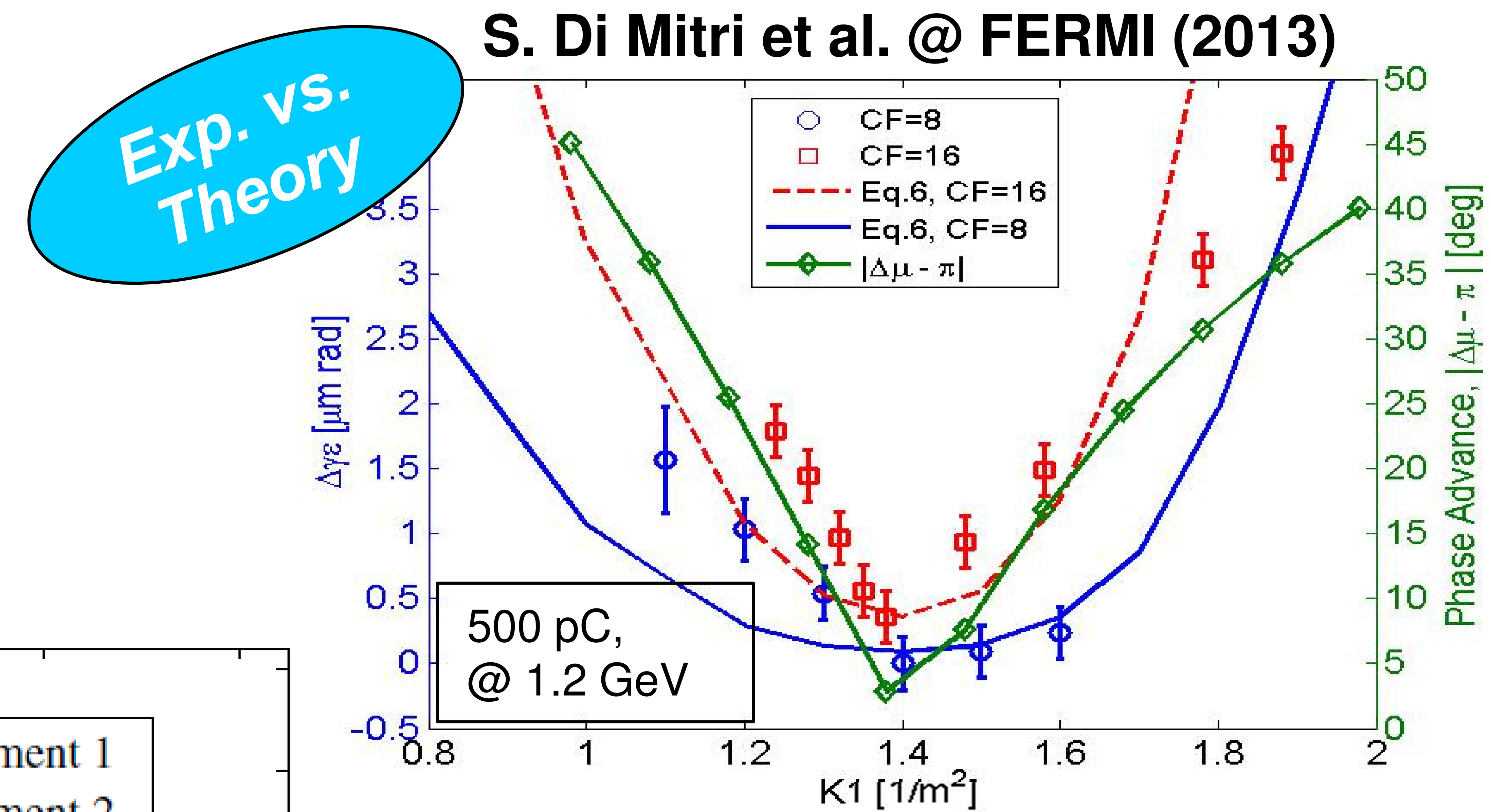
CSR, when 1-D may suffice

- FELs driven by ε_n **> 0.5 μm** and **I < 1 kA**, may rely on **1-D** CSR, and linear optics **analysis**.
  - Several indications that the Derbenev criterion for 1-D can be relaxed, up to $\sigma_x \approx \sigma_z^{2/3} R^{1/3}$

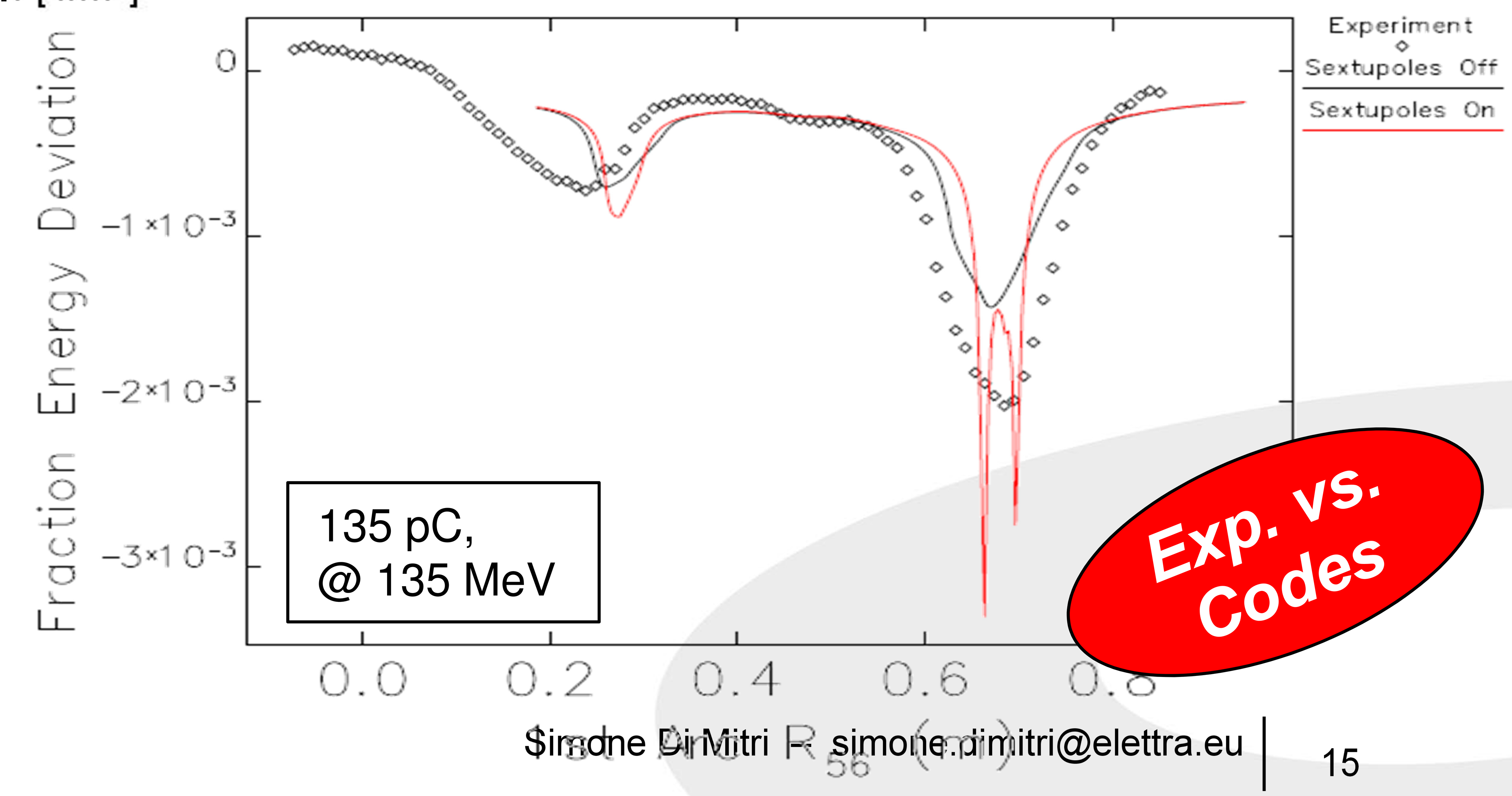




K. Bane et al. @
LCLS (2009)

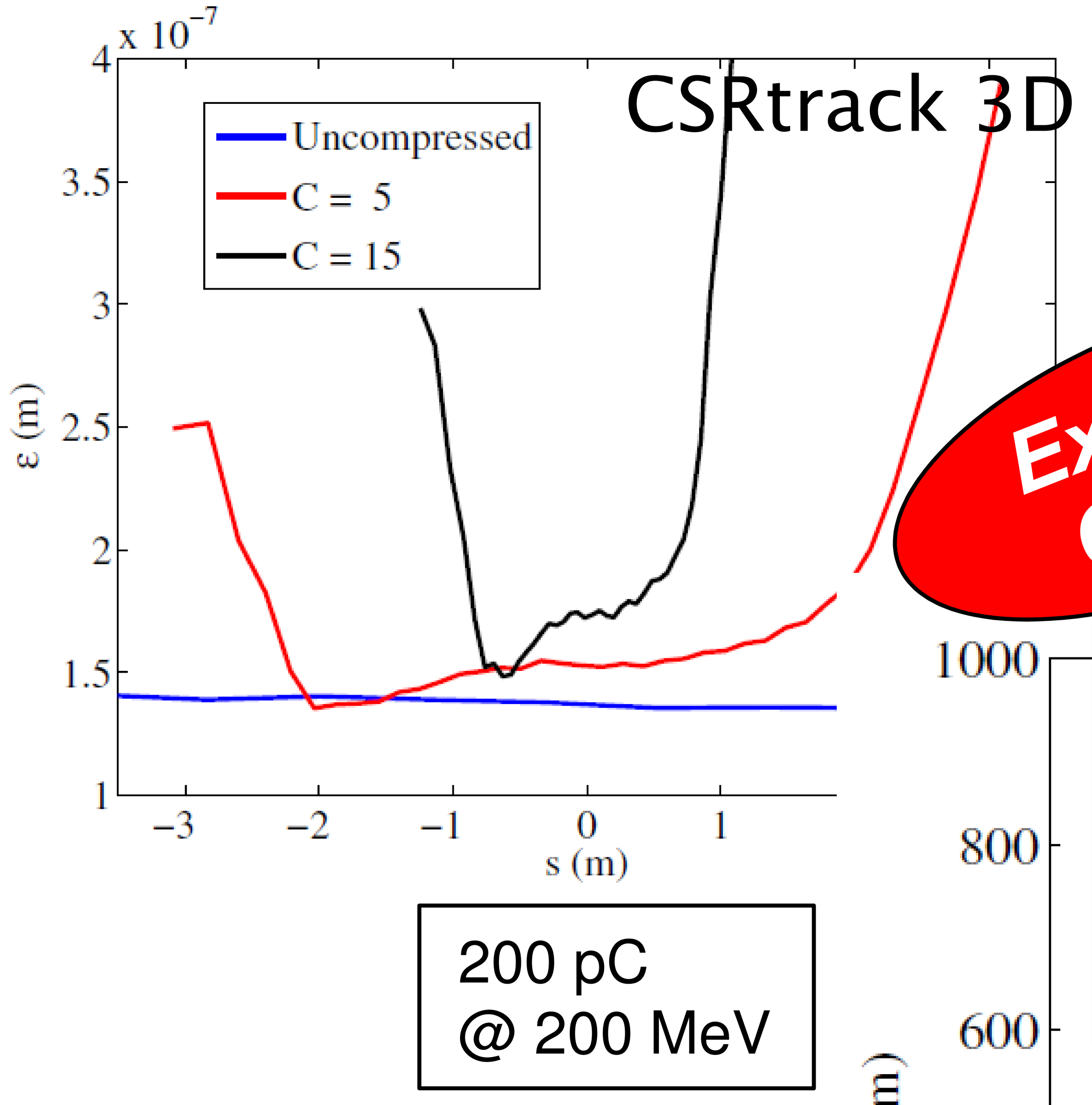


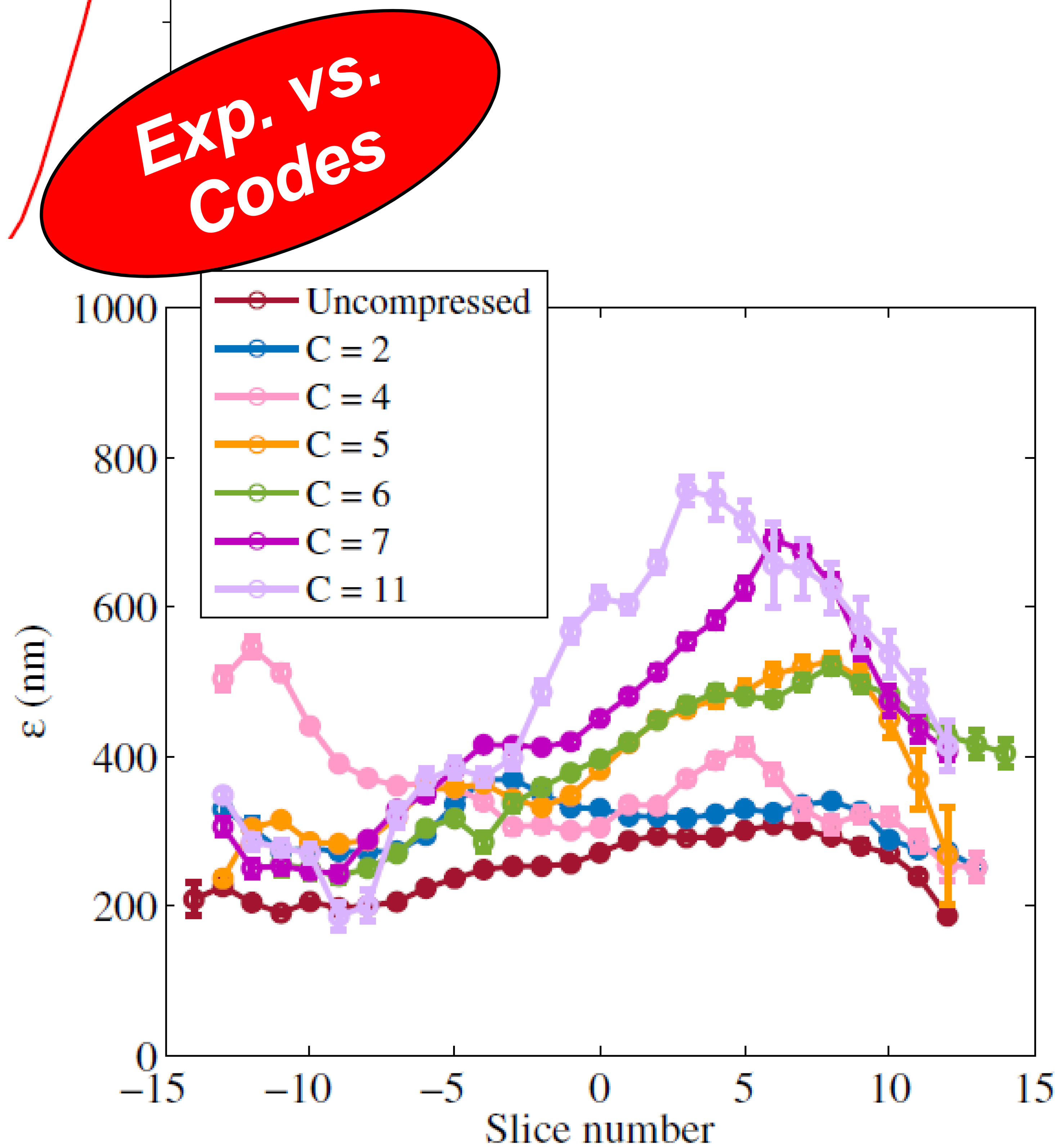
C. Hall et al. @
JLAB FEL (2015)



CSR, when you need 3-D

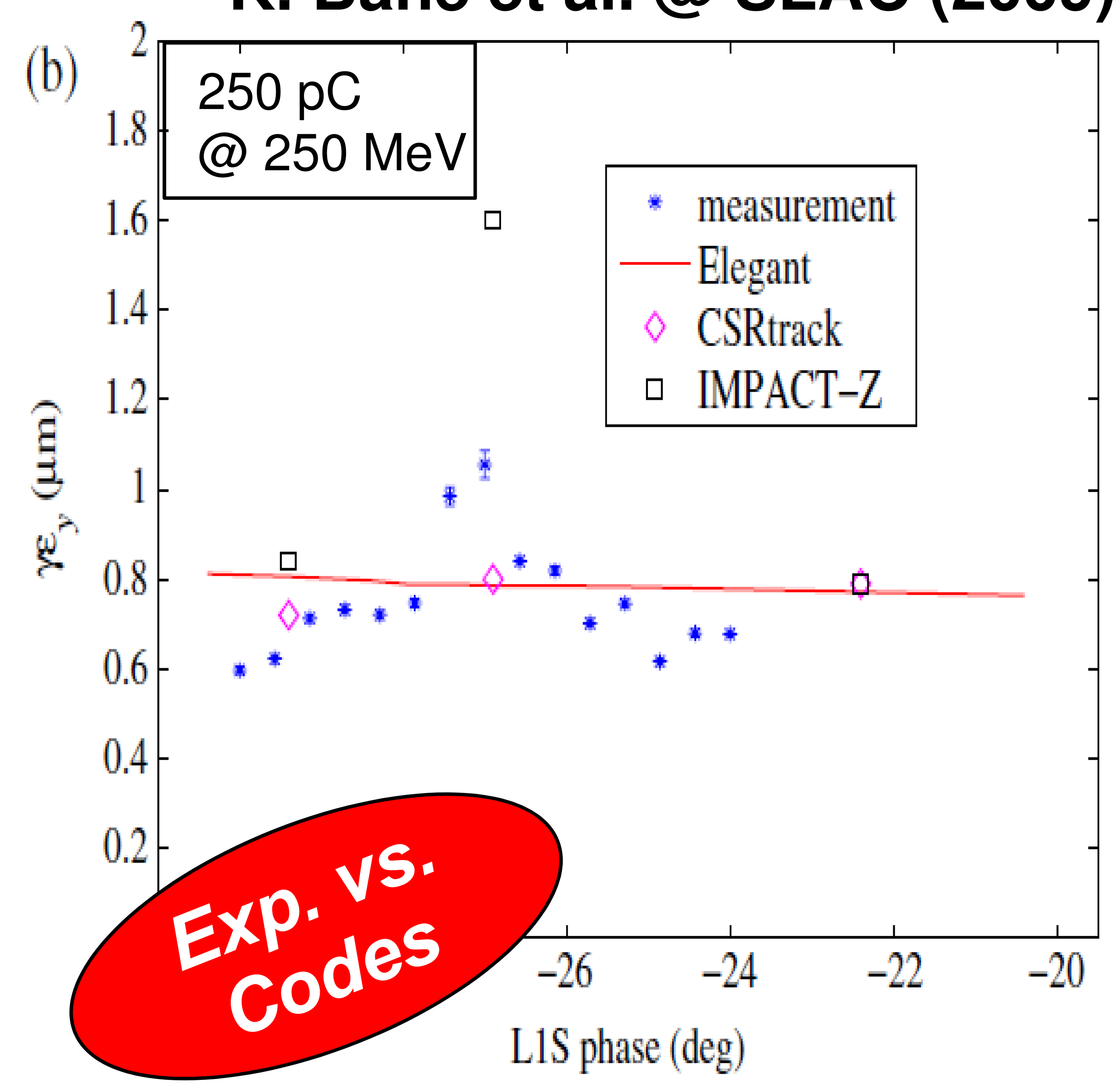
- FELs driven by low charge, ε_n **< 0.5 μm rad** and/or **I > 1 kA** beams require accurate 3-D CSR calculation, and ε_n-growth "resolution" at **< 0.01 μm rad** level.
  - Extreme cases are < 100 MeV beams, or beams at full compression.
    - We may need to update the "2002 CSR Berlin Workshop", for a new range of parameters.



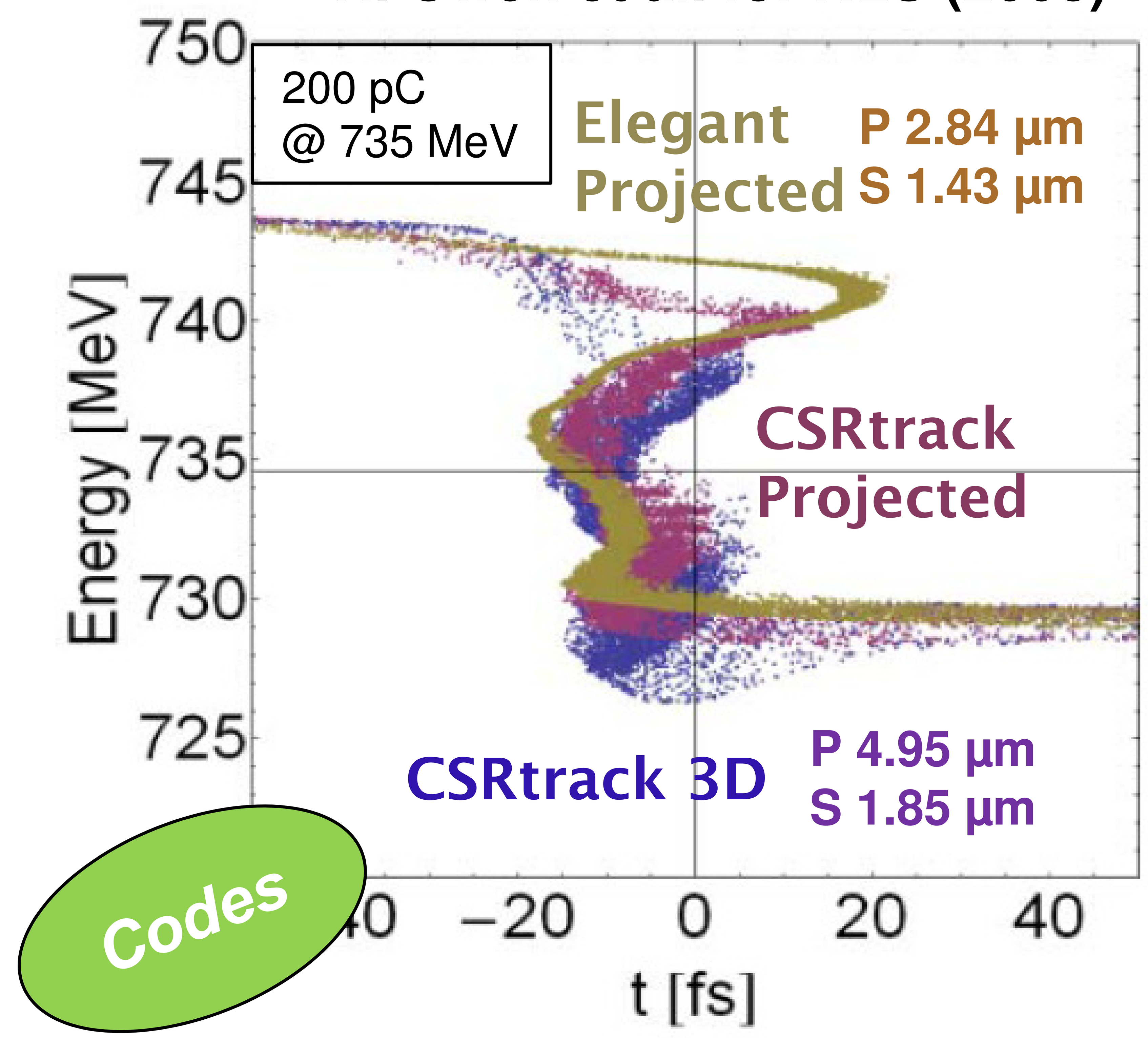


S. Bettoni et al. @ PSI (2016)

K. Bane et al. @ SLAC (2009)



H. Owen et al. for NLS (2008)



Getting Rid of CSR

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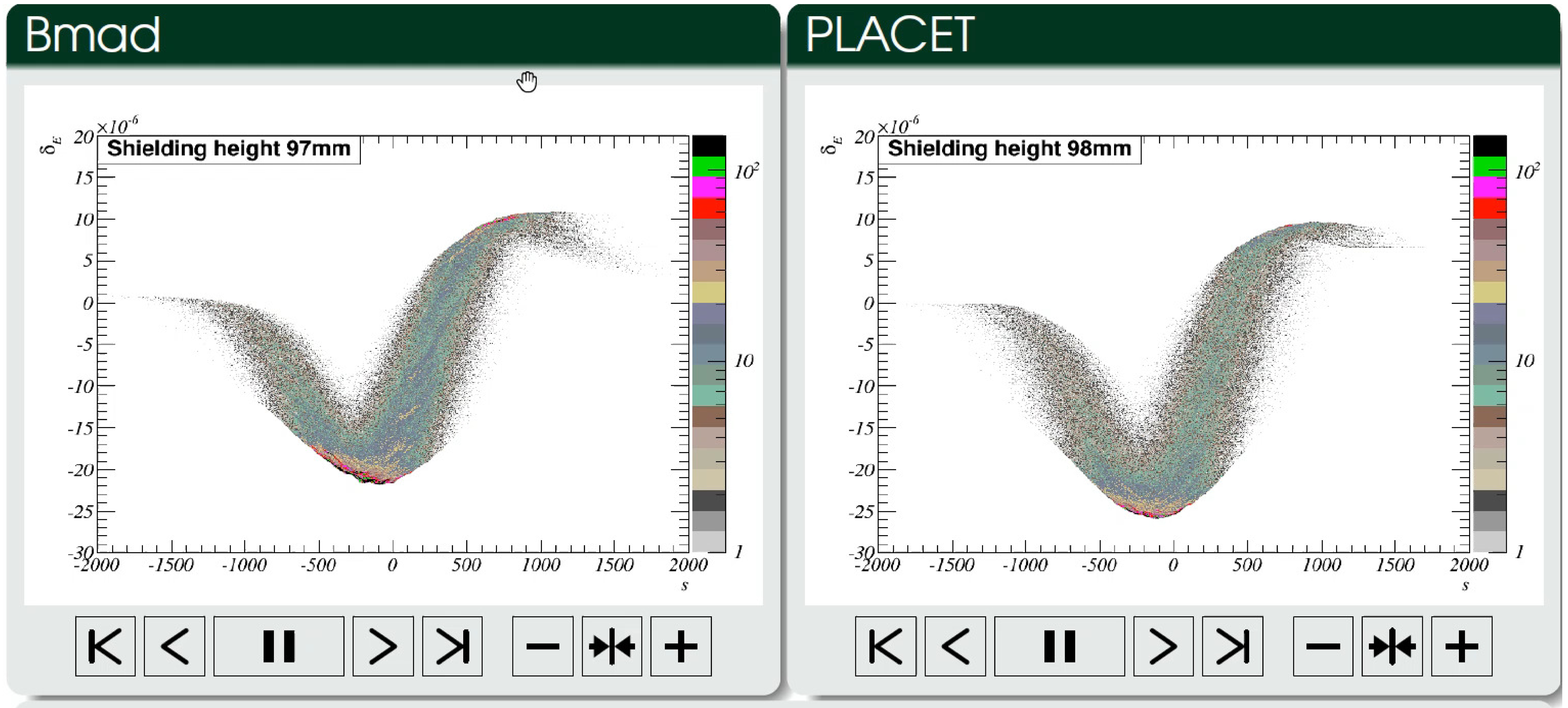
- Shielding of CSR field commonly requires **< 2 mm** beam pipe gap.
  - Several models and codes available. Rare experiments.

J. Esberg et al. for CERN (2015)



- Without shielding, there is some discrepancy between Bmad and PLACET.
- PLACET with no shielding shows perfect agreement with ELEGANT (E. Adli).
- When decreasing the parallel plate distance, the shielding wake can start to interact with the tail of the bunch.
- Large difference between Bmad and new PLACET implementation for small plate separations.

D. Sagan et al. (2009)

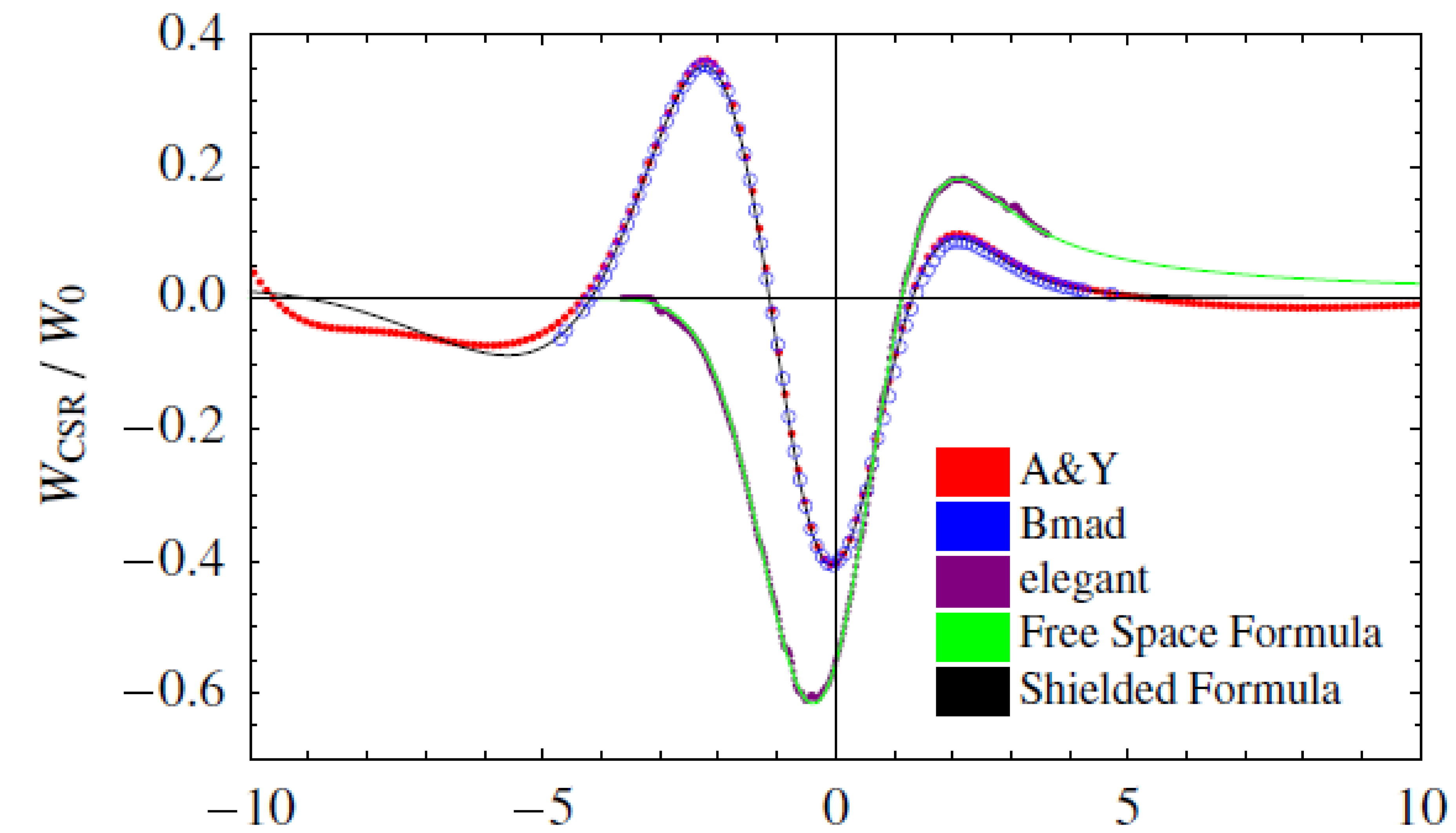
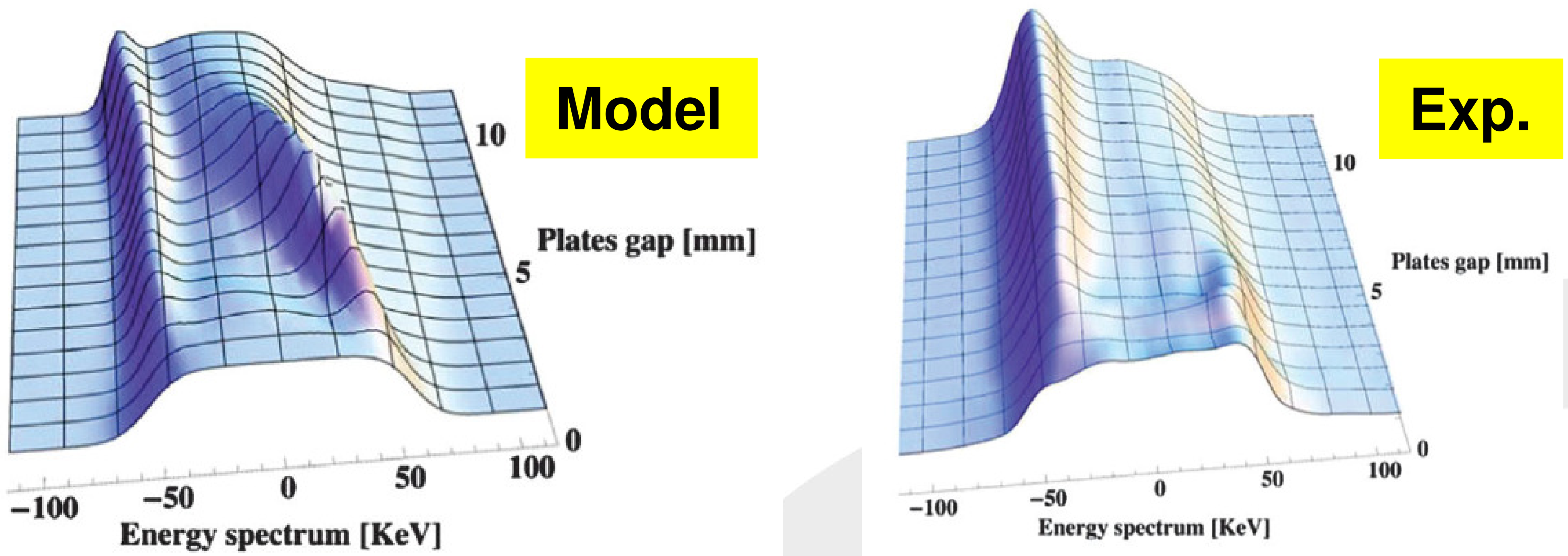


FIG. 14. (Color) Realistic magnets: Parameter set E (JLab TH2 magnet) line (top), set F (CESR analyzer magnet) (bottom). Bmad agrees with the CSR-wake formula Eq. (53) better than the other codes at the bunch tail.

V. Yakimenko et al. @ ATF (2012)



Message:

1-D CSR model works better than expected, but 3-D CSR might be unavoidable for future FELs.

Shielding may be ignored, as long as we feel that CSR can be kept under control with optics.

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To Fit, or Not To Fit ?

- ❑ e-Optics design is not perceived as a challenging task (well-know physics, well-established tools).
- ❑ Yet, β-mismatch and residual-η easily cumulate because of errors (RF, magnets and misalignments).
  - ▪ Matching sections provide a mismatch < 1% *locally*, and allow brute force optimization of FEL.
  - ▪ Residual-η is implicitly minimized via BBA *in the undulator* → "η-knobs" now running at LCLS.
    - ➢ *Potentially, optics control may be improved by fitting procedures (LOCO-like, Orbit Resp. Matr.)*

Message:

Optics fitting techniques might be of some interest for parasitic, non-invasive, global optics control (mumble mumble…)

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Final Remarks

- Semi-analytical and all-numerical tools can model much of high brightness e-linacs
  - Almost standardized modelling procedure.
  - PIL, geometric and resistive wall wakefields play a major role to set "macroscopic" beam features
- Variety of codes for CSR and microbunching studies
  - Not yet definitive prescriptions for control of numerical noise in PIC codes
  - Yet limited 2-D capabilities of Vlasov solvers
- New exciting opportunities of modelling (and experiments!) offered by new trends in:
  - Dechirper → FEL vs. transverse wake
  - Laser Heater → multi-color, multi-pulses
  - Transfer Lines → CSR, LSC, TSC
  - ERL → CSR and microbunching in arcs

Codes offer more and more accurate accelerator modelling, but…to get real beam control, try to make contact with analytical models, when feasible.