Generation of electron bunches with tailored current profiles at FLASH: Recent measurements and future applications

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Outline

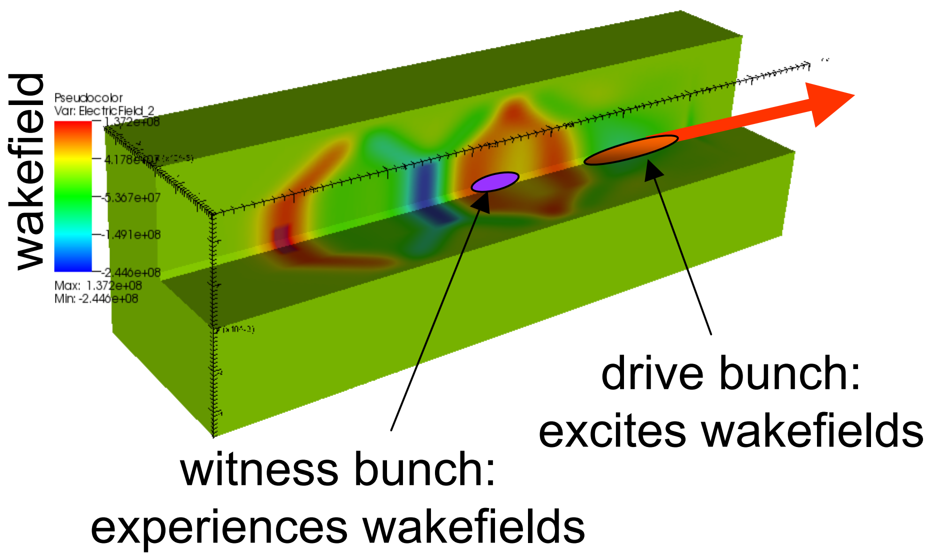
- **Motivation**: Collinear beam-driven acceleration with enhanced transformer ratio,
- Current shaping methods,
- Multi-frequency linacs to shape the current profile,
- Experiment at FLASH,
- Preliminary thought on next steps at FLASH,
- Conclusion.

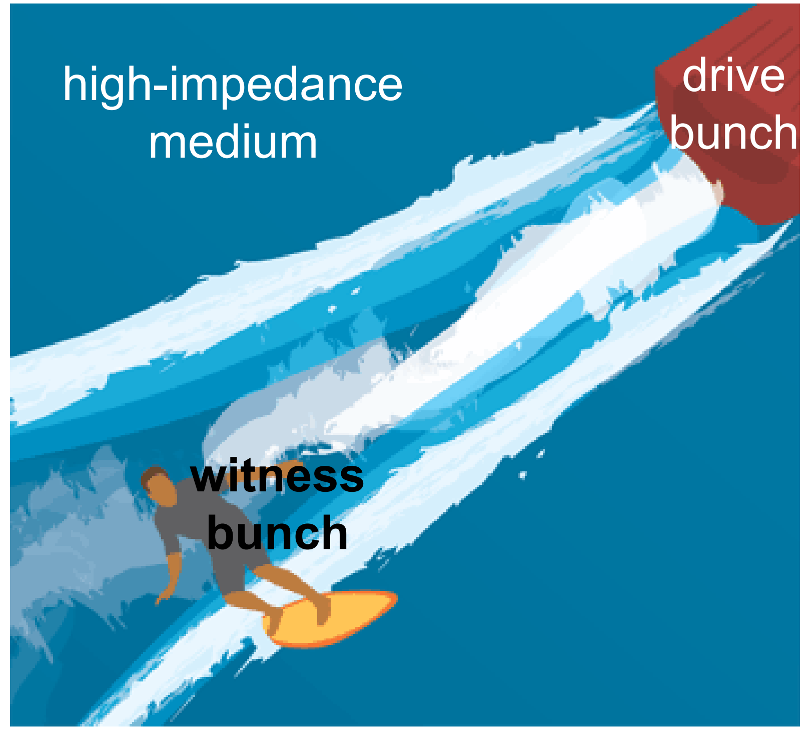
Credit

- At DESY,
  - Experiment: C. Behrens, C. Gerth, Operation/support: V. Ayvazian, B. Faatz, K. Honkavaara, S. Schrieber, E. Vogel, M. Vogt, S. Welsch,
  - Simulation: M. Dohlus
  - Discussion: K. Flöttmann, T. Limberg, J. Osterhoff, I. Zagorodnov,
- At Northern Illinois University
  - F. Lemery [student, will come for next round of experiment (if beamtime granted],
  - D. Mihalcea, research associated, contributed to modeling
- At Tech-X,
  - VORPAL modeling in collaboration with P. Stoltz

Introduction: beam-driven acceleration

- Drive bunch induces electromagnetic wakes,
- Witness bunch, with proper delay, sees an accelerating field.





- structure size not limited by availability of rf sources…

Dielectric-loaded structures

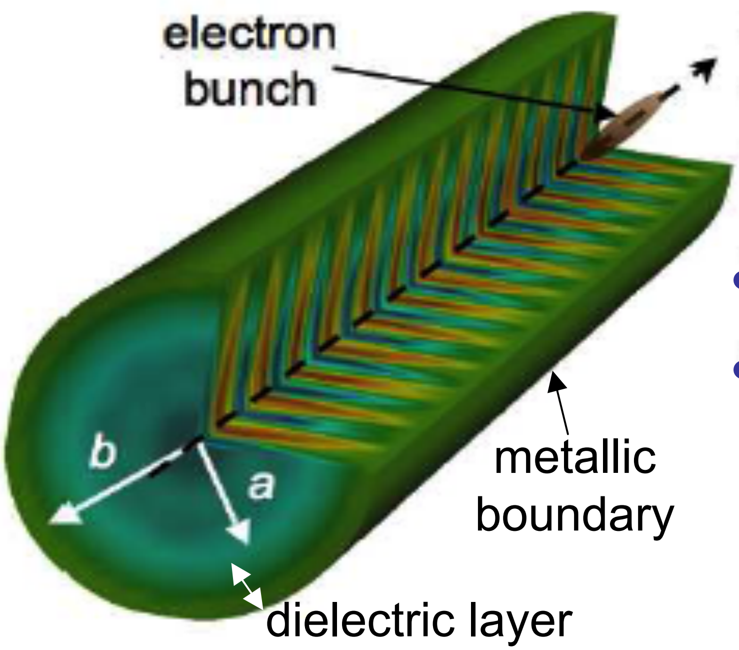
- Wakefield in a dielectric structure with inner radius *a*

bunch charge

rms bunch length

$$W_n(\zeta) \simeq \frac{Q}{a^2} \cos(k_n \zeta) \exp\left(-\frac{k_n^2 \sigma_z^2}{2}\right)$$

wavevector (solution of dispersion equation)



- dielectric layer of thickness b-a
- relative permittivity of dielectric taken to 4.7 (diamond) for our studies

Path toward high fields

bunch charge — rms bunch length

$$W_n(\zeta) \simeq \frac{Q}{a^2}\cos(k_n\zeta)\exp\left(-\frac{k_n^2\sigma_z^2}{2}\right)$$

structure aperture — wavevector (solution of dispersion equation)

- High charge, short bunch ($\sigma_z \leq \frac{\lambda}{2\pi}$)
  - Argonne Wakefield Accelerator ~ 100 nC w GHz structures
- Small-size structures
  - **Need small emittance beams**
  - **Need compressed beam**

Transformer ratio (TR)

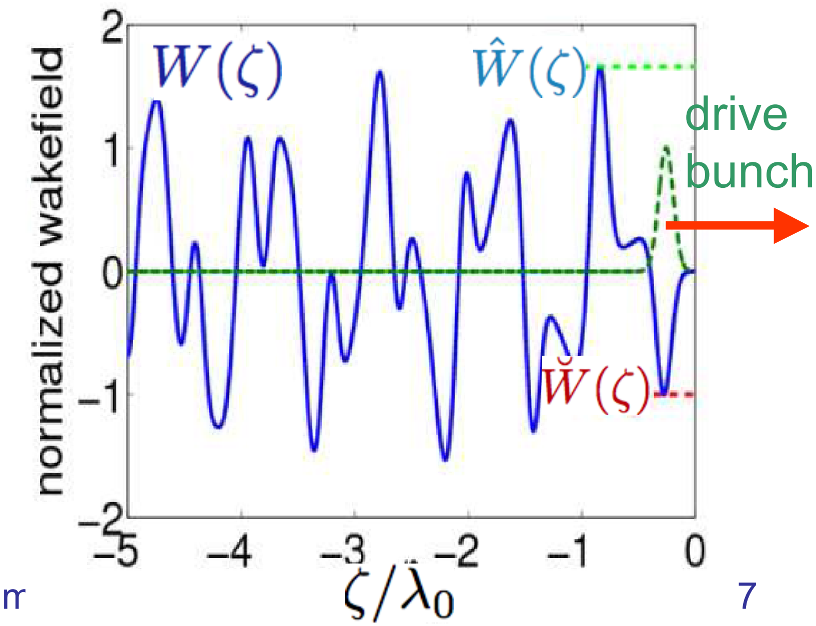
- TR defined as $\mathcal{R} \equiv \frac{\hat{W}(\zeta)}{\breve{W}(\zeta)}$

accelerating field behind bunch

decelerating field within bunch

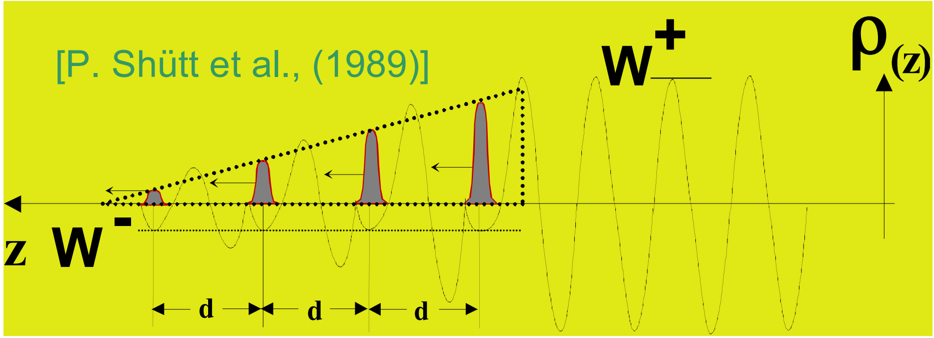
- Figure of merit for beam driven-acceleration
  - High-TR desired for multistage acceleration,
  - At low energies high TR increase interaction length.

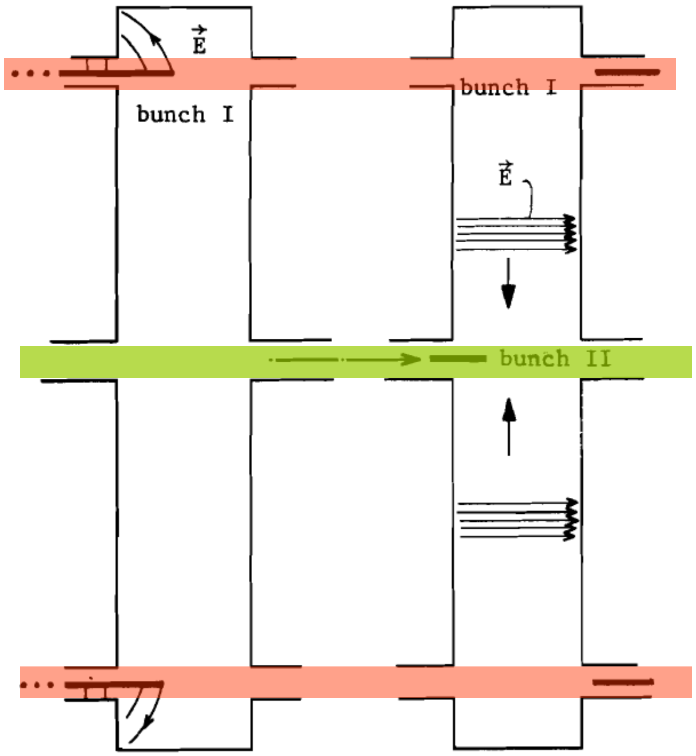
- For a bunch with symmetric current profiles $\mathcal{R} \leq 2$ (fundamental beam loading "theorem")



TR enhancement

- Non-collinear configurations:
  - Two-beam accelerator,
  - Two-beam in same structure (e.g. DESY hallow beam config.)
- Use of different species:
  - Wakeatron [A. Ruggiero, 1985]: drive bunch is a proton beam (adapted to plasma wakefield acceleration recently!)





[G. A. Voss, Th. Weiland (1982)]

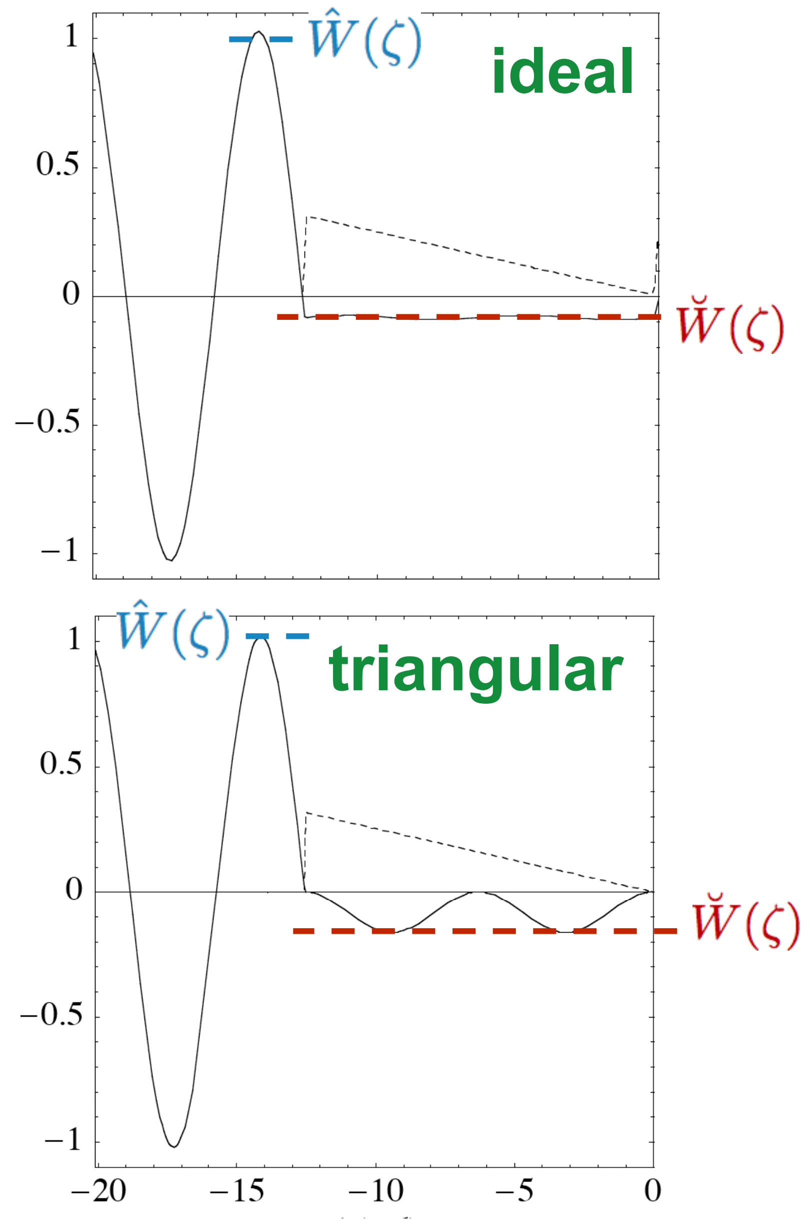
- Bunch train:
  - OK in the GHz regime
  - Difficult when dealing with THz structures
- Tailored bunch current profile:
  - Asymmetric bunch

TR enhancement: shaping

- Asymmetric bunch current profile enhance TR,

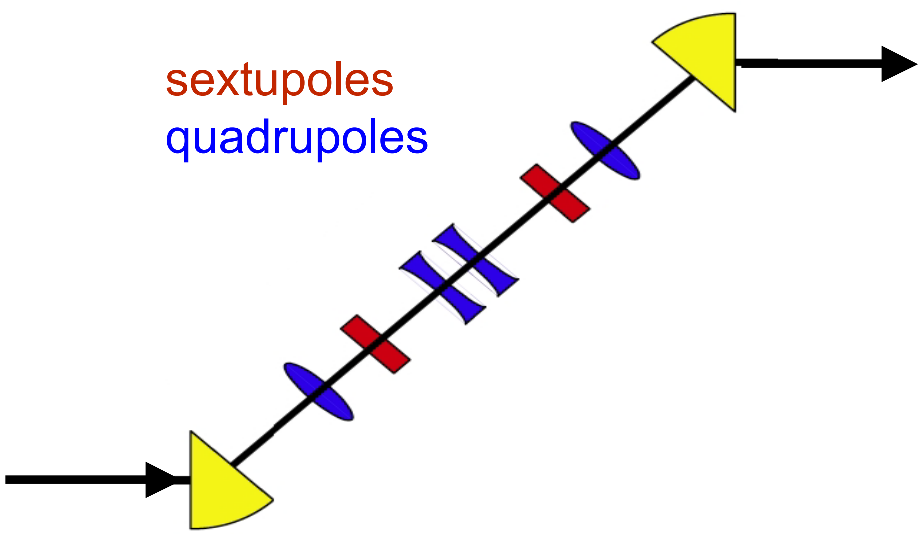
- Few examples discussed by [Bane et al. 1985], ideal distribution is not experimentally achievable,

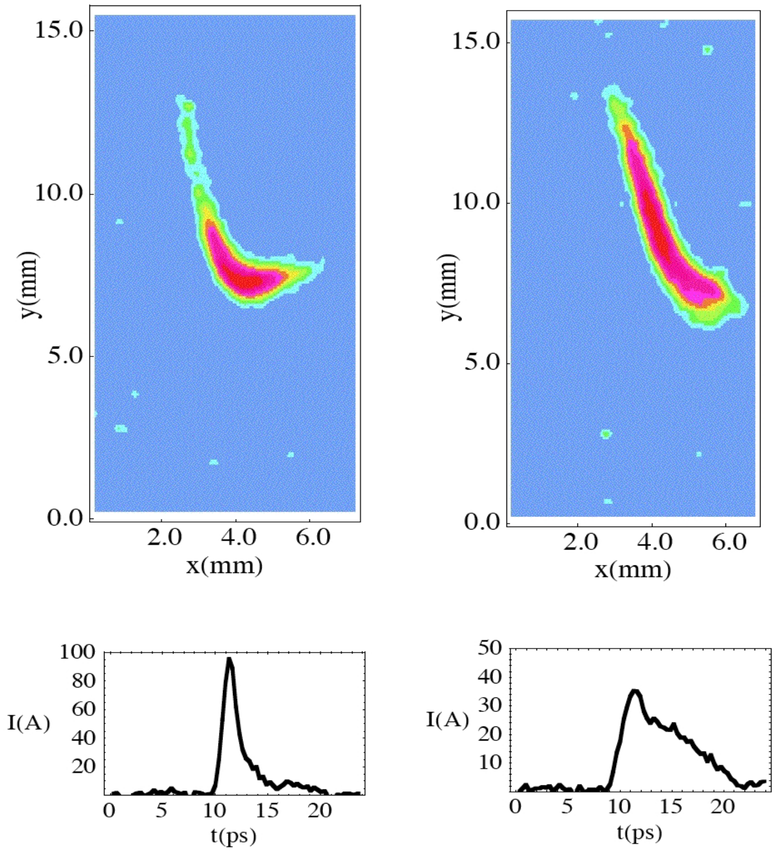
- Linearly-ramped bunch is a good compromise.



Current shaping: experiment at UCLA

- Only one experiment demonstrated single-bunch current shaping [England, et al. PRL 2008]
- Use sextupole in dispersive section to control nonlinea-rities in LPS



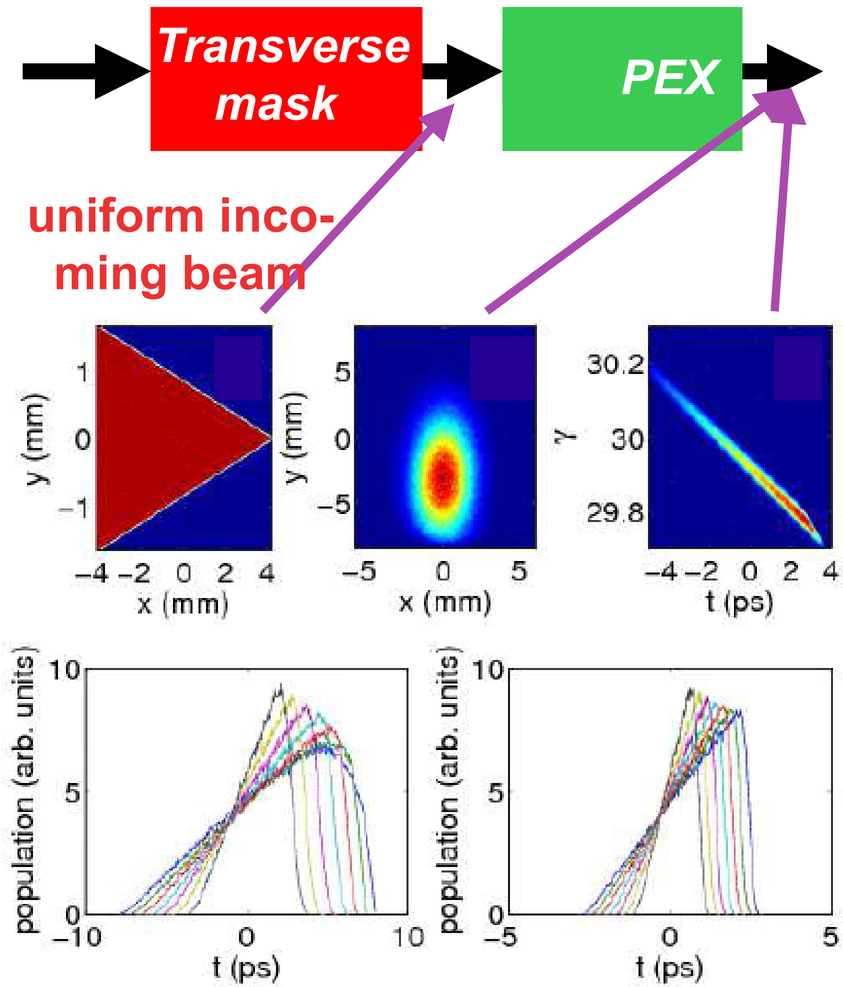


Shaping with phase space exchange (PEX)

- Principle:
  - Shape transverse beam distribution
  - Exchange transverse and longitudinal phase spaces

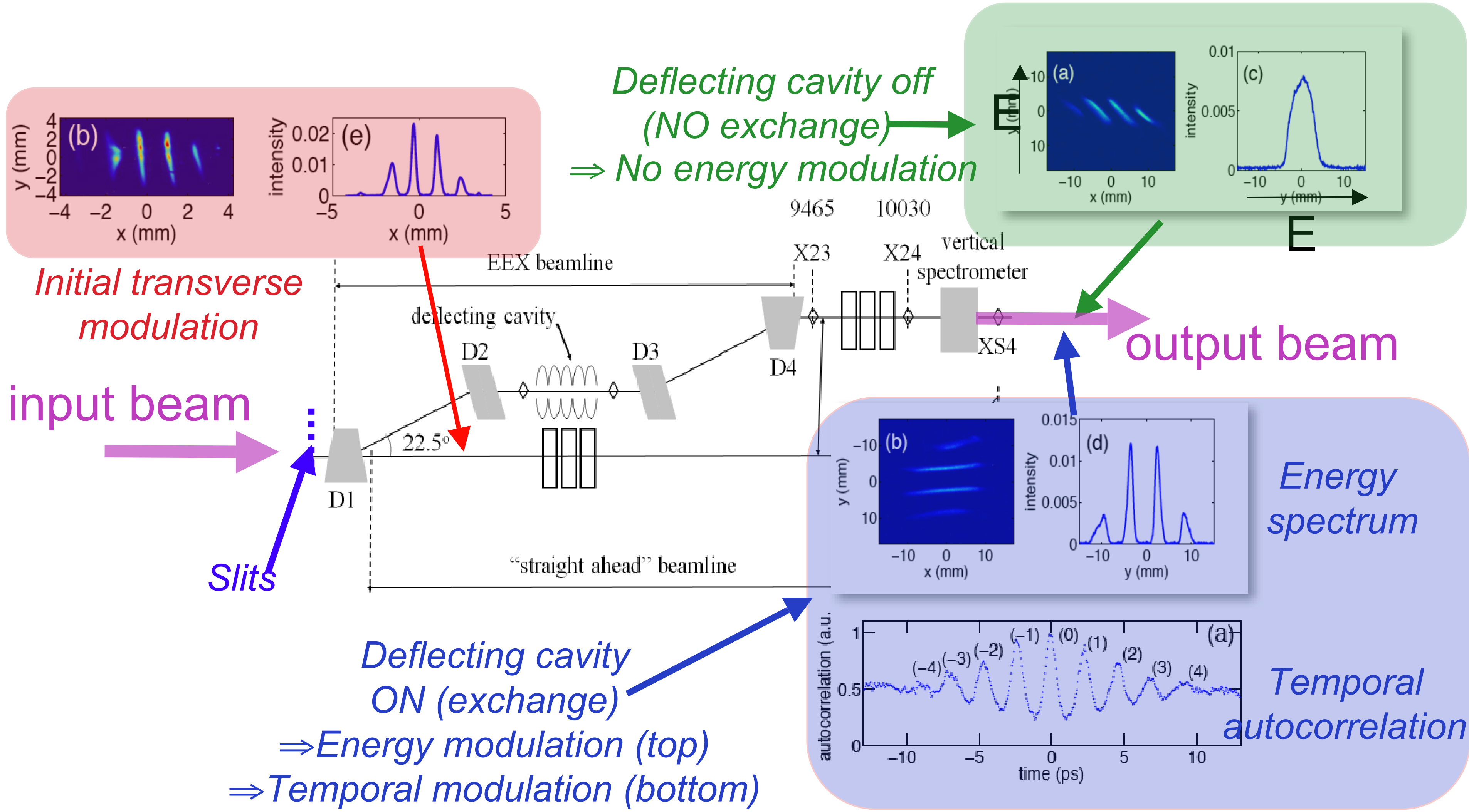
$$z = ax_0 + bx'_0$$
$$\delta = cx_0 + dx'_0$$

- A beamline capable of such an exchange was first pointed out by Cor-nacchia and Emma.



[P. Emma et al., PRSTAB 2006;
P. Piot et al., PRSTAB 2011]

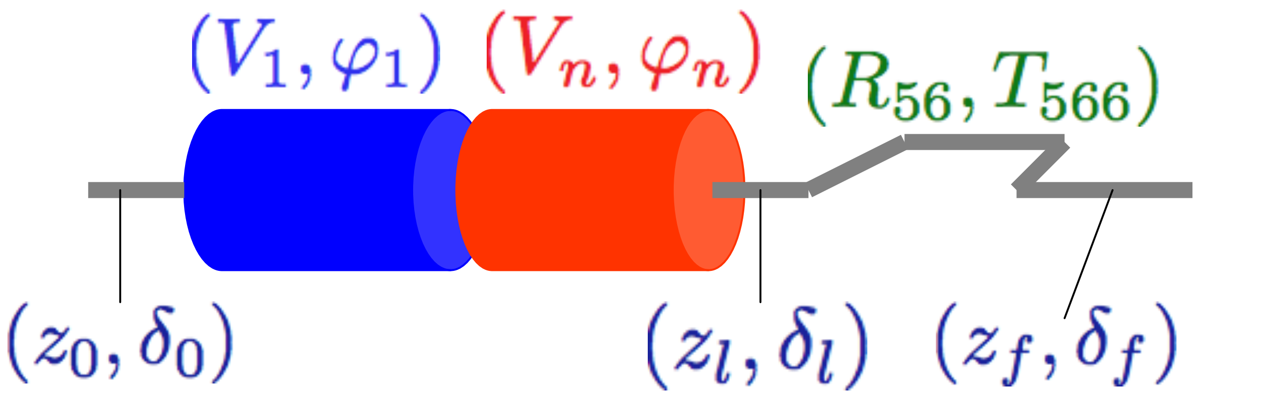
Shaping with PEX: experiment at Fermilab



[Y.-E Sun et al., PRL 2010; P. Piot et al., APL 2011]

Shaping with a two-frequency (2-f) linac

- 1D-1V model of the LPS dynamics



- Coordinates of electron downstream of source:

$$(z_0, \delta_0 = a_0 z_0 + b_0 z_0^2 + \mathcal{O}(z_0^3))$$

- Downstream of a 2-f linac with voltage

$$V(z) = V_1 \cos(k_1 z + \varphi_1) + V_n \cos(k_n z + \varphi_n) \; ,$$

$$(z_l = z_0, \delta_l = a_l z_0 + b_l z_0^2)$$

where

Shaping with a 2-f linac (2)

- Downstream of bunch compressor

$$z_f = R_{56}\delta_l + T_{566}\delta_l^2$$

- So finally $z_f = a_f z_0 + b_f z_0^2$

beam energy

$$a_f \equiv 1 + a_l R_{56} \qquad b_f \equiv b_l R_{56} + a_l^2 T_{566}$$
$$a_l \equiv a_0 - (k_1 V_1 \sin\varphi_1 + k_n V_n \sin\varphi_n)/\bar{E}_l$$
$$b_l \equiv b_0 - (k_1^2 V_1 \cos\varphi_1 + k_n^2 V_n \cos\varphi_n)/(2\bar{E}_l)$$

$\rightarrow$ the parameters provide control over the correlation within the LPS

Shaping with a 2-f linac (3)

- Assume initial Gaussian distribution,

$$I_0(z_0) = \hat{I}_0 e^{-\frac{z_0^2}{2\sigma_{z,0}^2}}$$

- charge conservation $I_0(z_0)dz_0 = I_f(z_f)dz_f$

$$\rightarrow \quad I_f(z_f) = \int d\tilde{z}_f I_f^u(\tilde{z}_f) e^{-\frac{(z_f-\tilde{z}_f)^2}{2\sigma_u^2}}$$

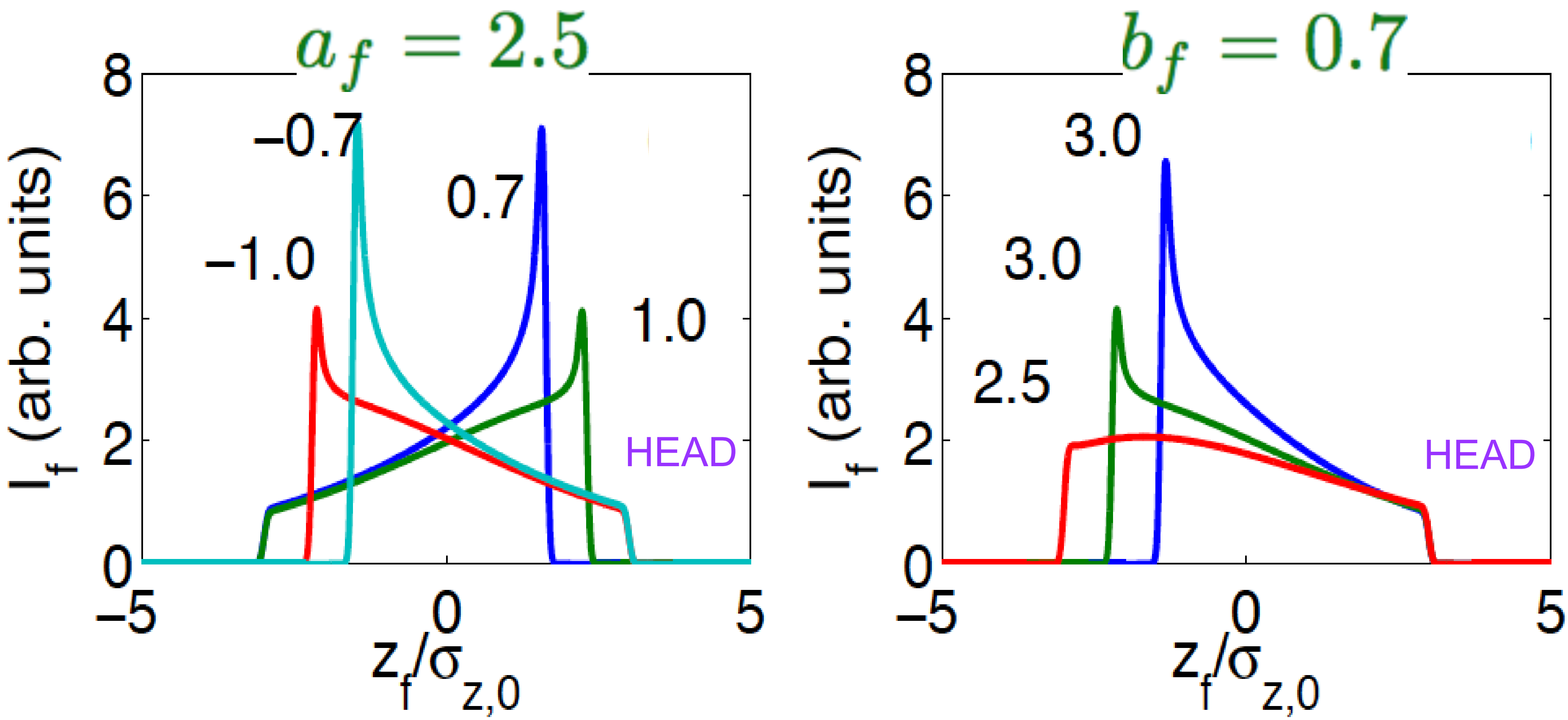
with $$I_f^u(z_f) = \frac{\hat{I}_0 \Theta[a_f^2 + 4b_f z_f]}{\sqrt{a_f^2 + 4b_f z_f}} e^{-\frac{a_f + \sqrt{a_f^2 + 4b_f z_f}}{8b_f^2 \sigma_{z,0}^2}}$$

and $\sigma_u \simeq R_{56}\sigma_\delta^u$ (accounts for σ_δ^u uncorrelated δ).

Shaping with a 2-f linac (4)

$$z_f = a_f z_0 + b_f z_0^2$$

- Example of computed profiles



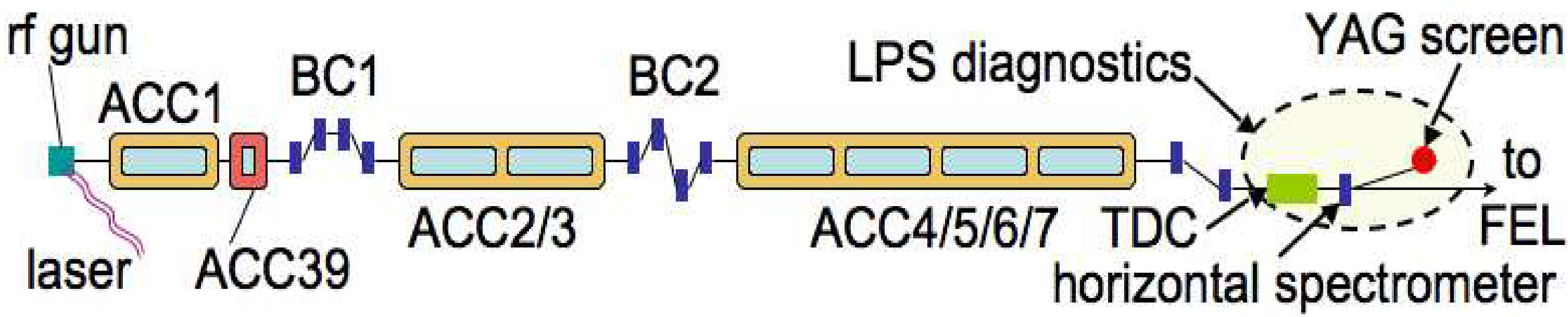
- 3rd order treatment gives similar results (more cumbersome to treat)

Pros/Cons of 2-f linac shapers

- No coupling between difference degree of freedoms (dispersive section might lead to noxious effects?),
- Can be implemented to non ultra-relativistic energies (2-f version of velocity bunching) → no need for a dispersive section at all.
- Works with high-duty-cycle linacs,
- Needs a harmonic linac section,
- Does not provide precise control over the bunch shape compare to PEX shapers (but can add more harmonics!).

Proof-of-principle experiment at FLASH

- FLASH incorporate a linac with 1.3 and 3.9-GHz accelerating sections → ideal place to test the 2-f linac shaping technique
- Beamtime allocated during the Jan 2011 beam study (three 12-hour shifts)



Proof-of-principle experiment at FLASH

- ACC 2-3 and 4-7 operated on crest
- BC2 bending angle reduced

  → minimize longitudinal motion in BC2 and DL

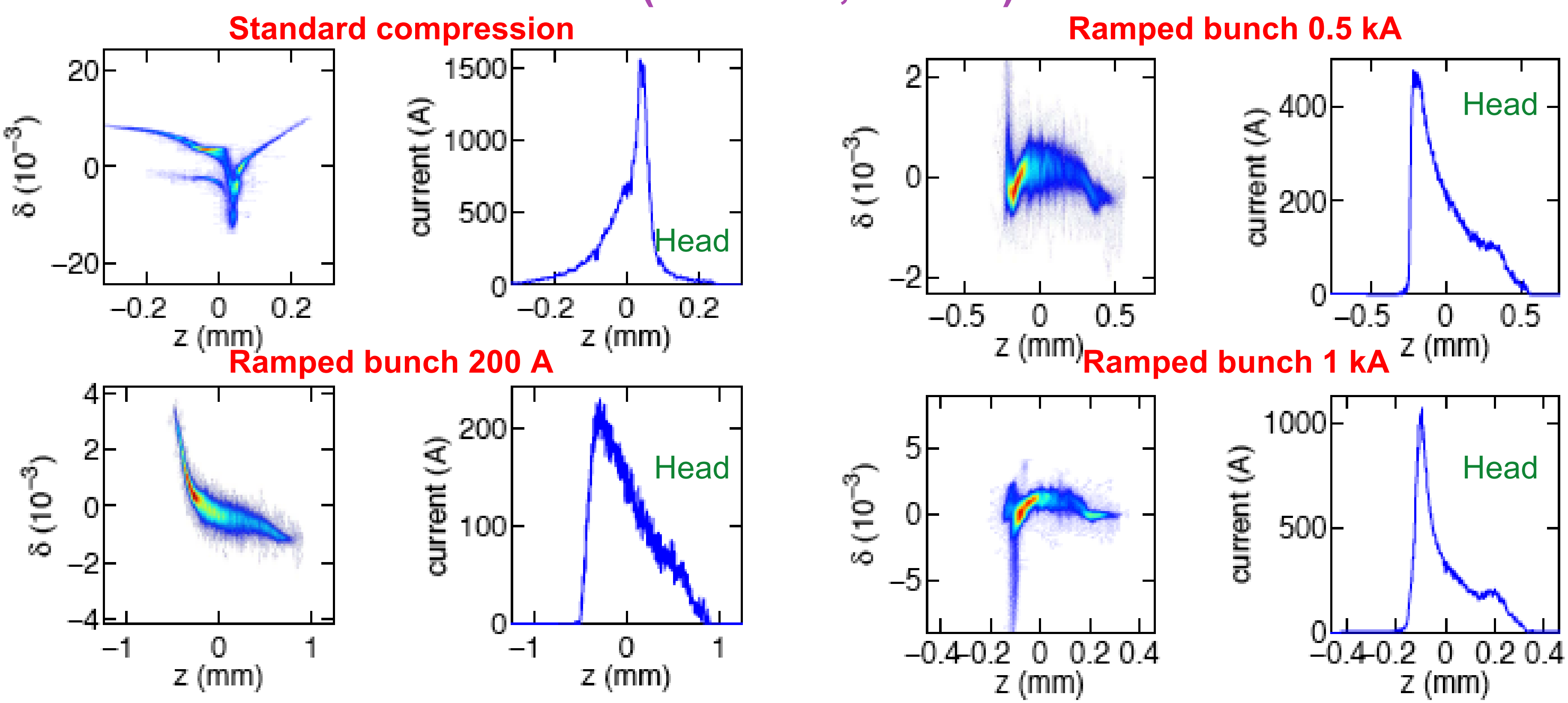
- Reduced energy at BC1 (~130 MeV)
- Operated the 3.9-GHz cavity up to 21 MV

  → increase “relative strength” of the 3.9 GHz section.

Proof-of-principle experiment at FLASH (3)

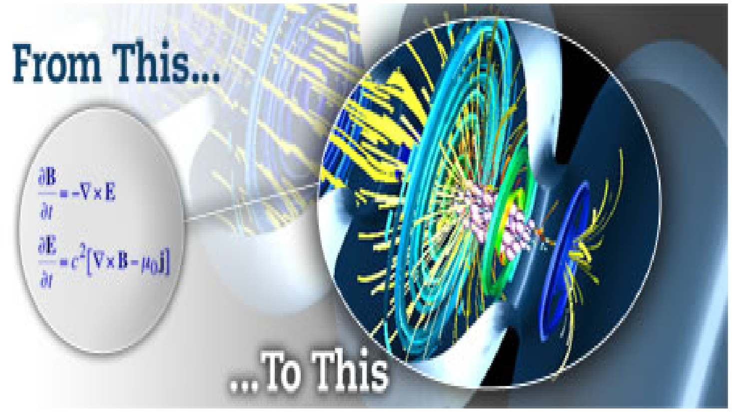
- Varies the phase/amplitude of the 3.9-GHz module (ACC39)

(700 MeV, 0.5 nC)



Performance modeling

- High-fidelity simulation using the finite-difference time-domain (FDTD) particle in cell (PIC) program VORPAL from Tech-X → detailed understanding of particle dynamics in DWA,

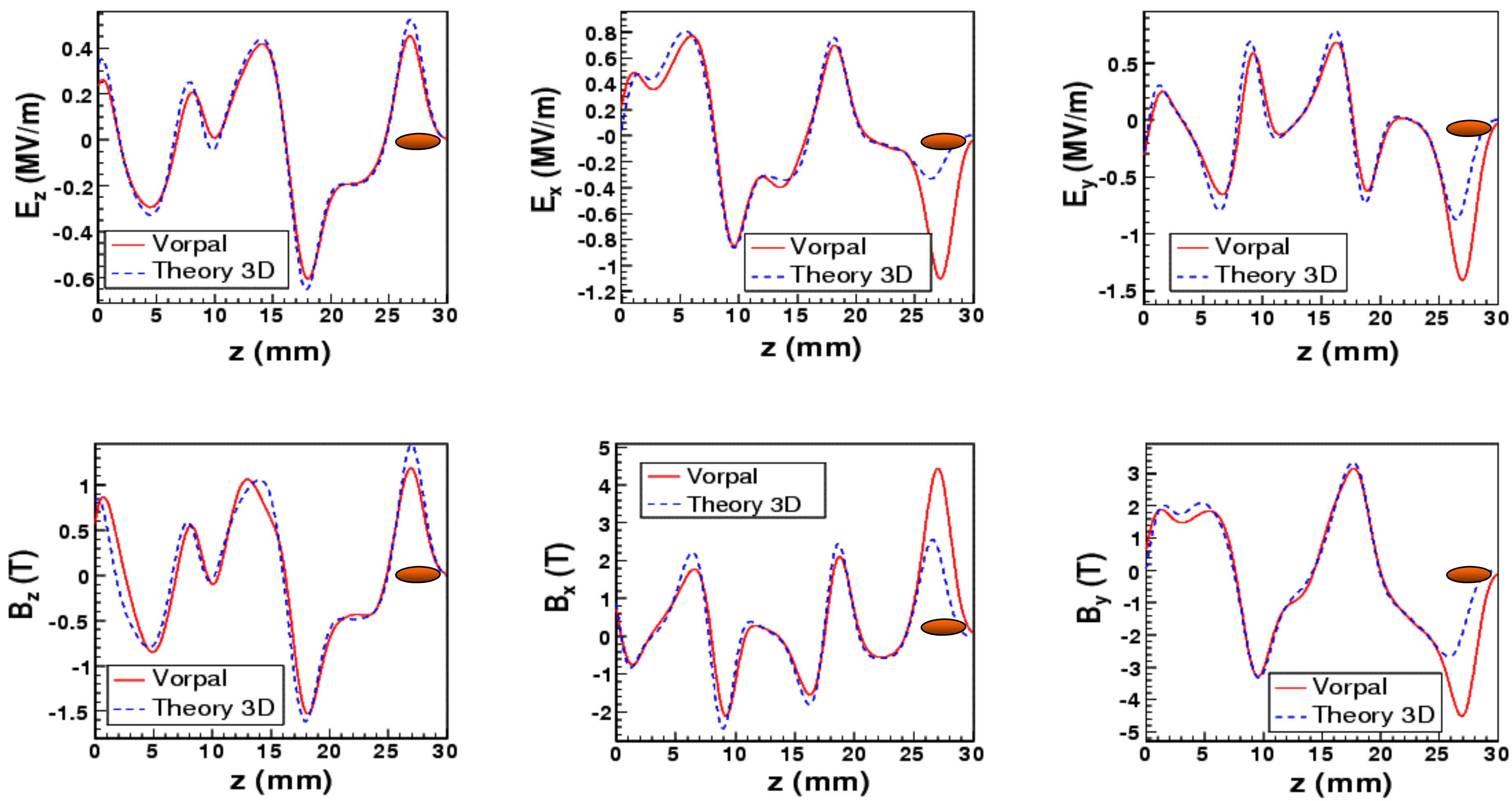


- Develop a fast semi-analytical model → fast simulations (optimization, performances studies),

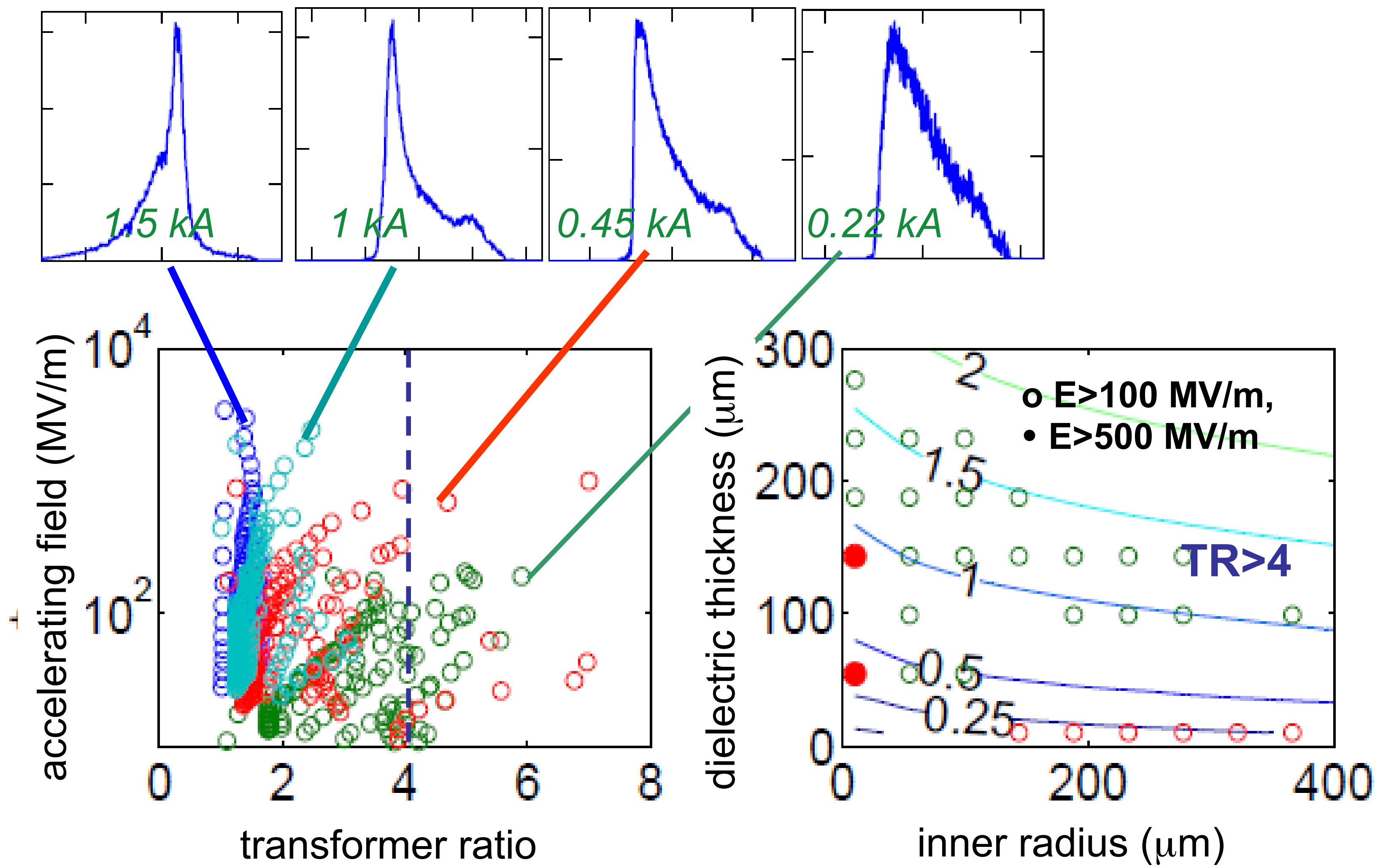
- Use the developed well-benchmarked model for design and optimization of a possible experiment at FLASH.

benchmarking PIC modeling/theory

- Benchmarked semi-analytical results with PIC simulations



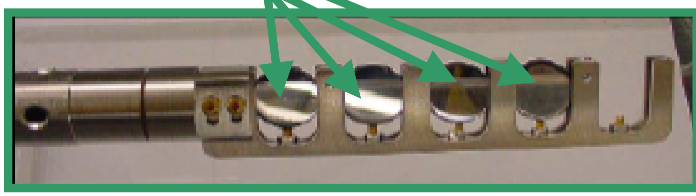
Simulated performances of measured beam current profiles

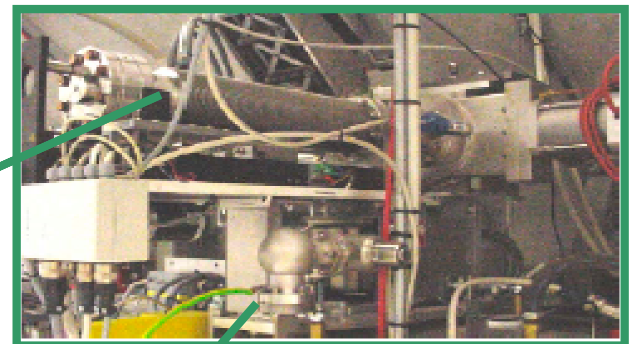


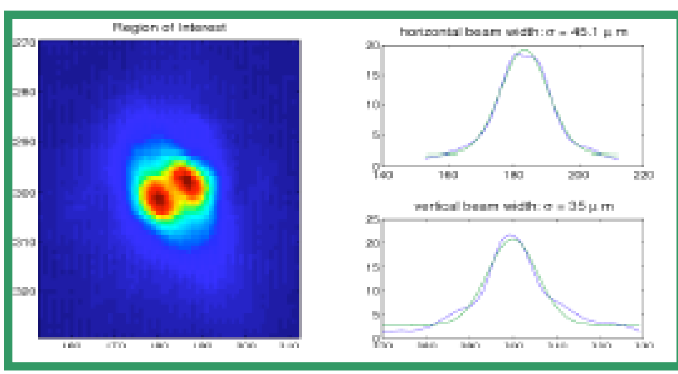
[isoclines: fundamental-mode wavelengths (in mm)]

Next-step experiment: test DLA at FLASH

- Experimental setup (MTF) available at FLASH
- Minor modifications would enable the insertion of dielectric structures





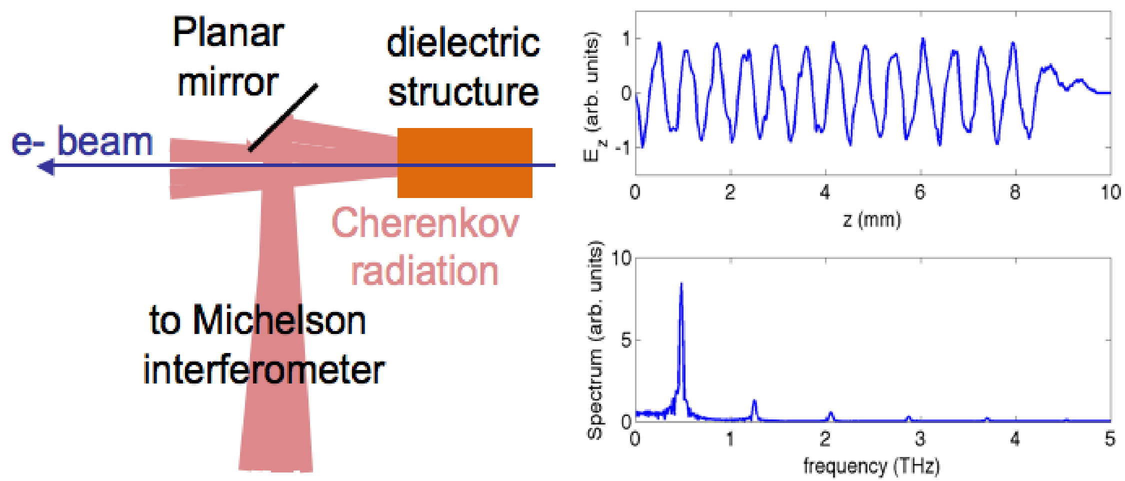


- Beam size at experiment ~30 μm round,
- Possibility of launching 3000 bunches in ~1 ms,
- Beam diagnostics.

Proposed experiments

- Two experiments:
  - Produce high-field in dielectric structure (no shaping needed) and look at temperature issues by driving the structure with a 1-ms train (thermocouple on structure)
  - Try to see an enhancement of transformer ratio (need shaped beams), and a "witness" bunch (being worked out -- not easy)

- Diagnostics needed
  - Measure energy loss (spectrometer),
  - Emitted Cherenkov radiation,
  - Temperature of die-lectric structure(s).



Summary

- A technique to tailor the current profile a relativistic electron bunch was proposed,
- FLASH was successfully used to test the method,

- The generated profile were shown to enable the production of ~GV/m peak accelerating fields with transformer ratios in excess of 6,

- A follow-up experiment is proposed to study dielectric-wakefield acceleration at FLASH.