Northern Illinois Center for Accelerator and Detector Development

Transverse-to-Longitudinal Phase-Space Exchange: Recent Experiments and Future Applications

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Credit

- A0 experiment:
  - Students: T. Maxwell,
  - Staff: H. Edwards, R. Flliller, A. Johnson, T. Koeth, A. Lumpkin, J. Ruan, Y.-E Sun, R. Thurman-Keup, J. Thangaraj,
- Modeling/theory:
  - Student: C. Prokop, F. Lemery
  - Staff: Y.-E Sun, D. Mihalcea
  - Collaborators: W. Graves (MIT), B. Carlsten (LANL)

Outline

- Introduction and motivation for transverse-to-longitudinal phase space exchange (PEX),
  - Emittance exchange,
  - Pulse shaping.
- Theoretical background
- Experimental demonstrations
- Future plans at Fermilab

Introduction

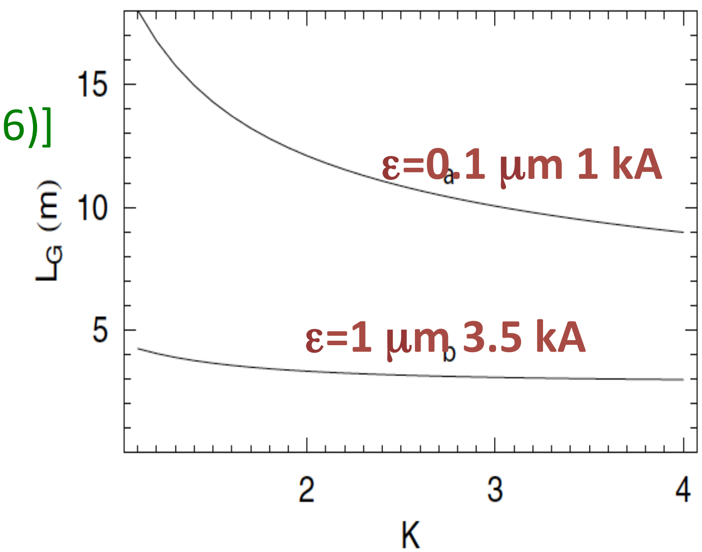
- Historically phase space manipulations occurs in one degree of freedom (e.g. bunch compression, beam focusing, emittance compensation,…)
- Phase space manipulations between two (or three) degrees of freedom
  - Flat beams generation,
  - Transverse to longitudinal phase space exchange

  have become available
- New opportunities…

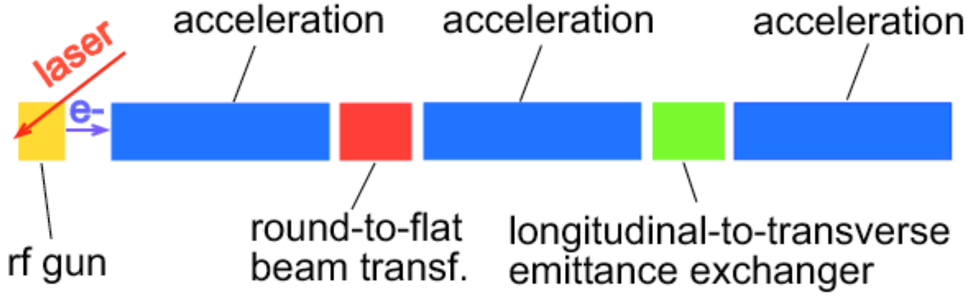
Emittance exchange

- Mitigation of microbunching instability in high-brightness electron beams

  [M. Cornacchia, P. Emma, PRSTAB 9, 100702 (2006)]



- Repartioning of emittances



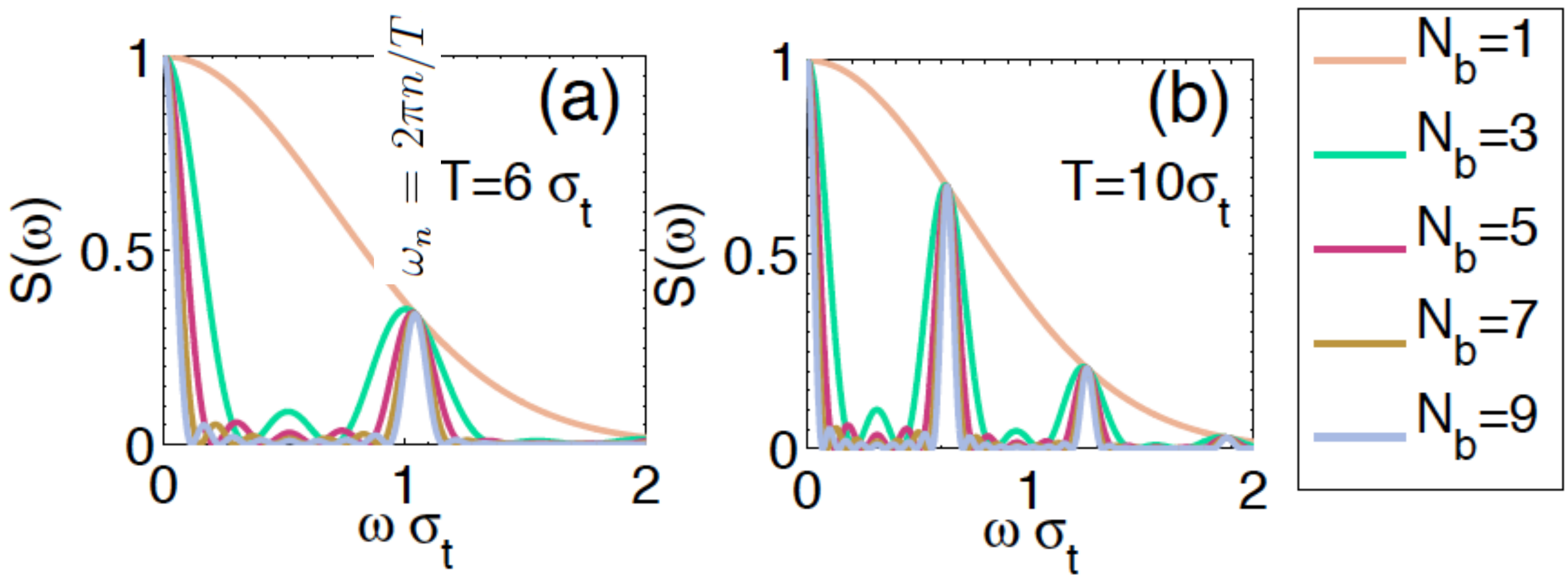
  – FELs: (1,1,0.1) ⟶ (0.1,10,0.1) ⟶ (0.1,0.1,10)
  – ILC: (5,5,10) ⟶ (1250,0.02,10) ⟶ (10,0.02,1250)

  [emittance (ε_x, ε_y, ε_z) partition in μm]

Pulse shaping for radiation sources

- Bunch/modulate the beam
  at the desired radiation wavelength
- Coherent enhancement

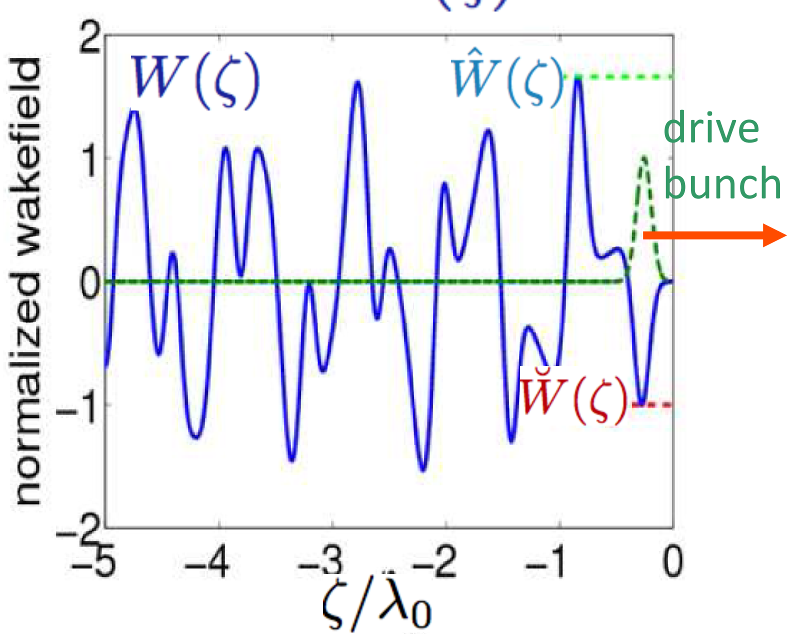
$$\frac{d^2W}{d\omega d\Omega}\Big|_N \simeq \frac{d^2W}{d\Omega d\omega}\Big|_1 [N + N^2|S(\omega)|^2]$$



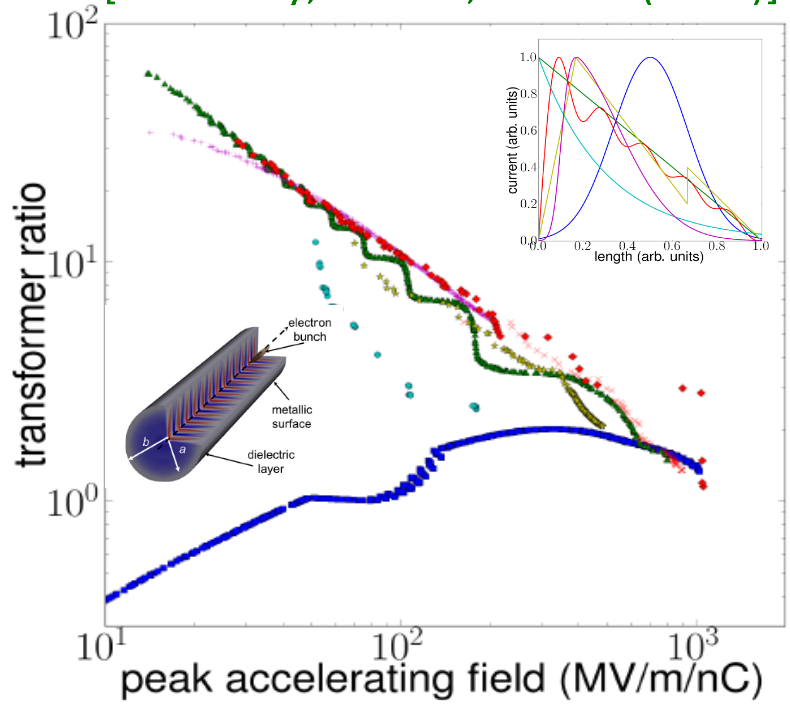
Pulse shaping for wakefield acceleration

- Beam-driven acceleration methods characterized by the "transformer ratio"

$$\mathcal{R} \equiv \frac{\hat{W}(\zeta)}{\breve{W}(\zeta)}$$



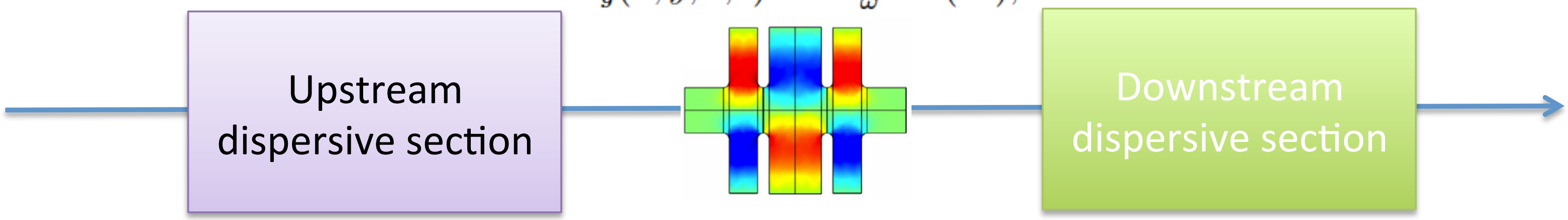
[F. Lemery, P. Piot., IPAC12 (2012)]



Principle of PEX

- Beam line composed of a deflecting cavity flanked by two dispersive sections

$$E_z(x,y,z,t) = E_0' x \cos(\omega t)$$
$$B_y(x,y,z,t) = \frac{E_0'}{\omega} \sin(\omega t),$$



- Conditions for exchange:

1

$$\vec{\eta}_d = \begin{pmatrix} R_{11,d} & R_{12,d} \\ R_{21,d} & R_{22,d} \end{pmatrix} \vec{\eta}_u$$

transfer matrix downstream section

Dispersion vector downstream beamline

Dispersion vector upstream beamline

$$\vec{\eta} \equiv (\eta, \eta' \equiv d\eta/ds)$$

2

$$\kappa = -\frac{1}{\eta_u}$$

Normalized deflecting strength:

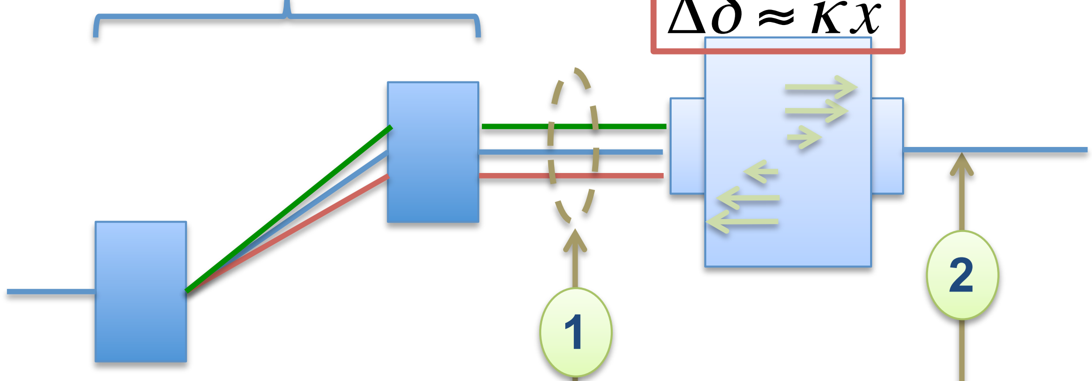
$$\kappa \equiv \frac{ekV_\perp}{\mathcal{E}}$$

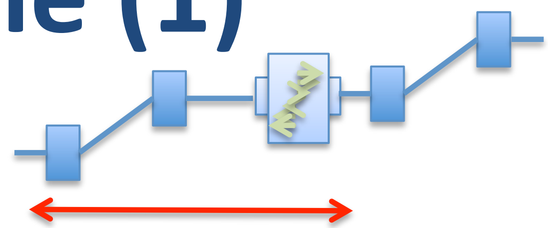
[R. Fliller, FNAL BeamDocs 2271-v2 (2007)]

Simple PEX beamline (1)

Dogleg beamline
(dispersive section)

$$\Delta x' \approx \kappa z$$
$$\Delta \delta \approx \kappa x$$





For phase space exchange choose

$$1 + \kappa\eta = 0$$

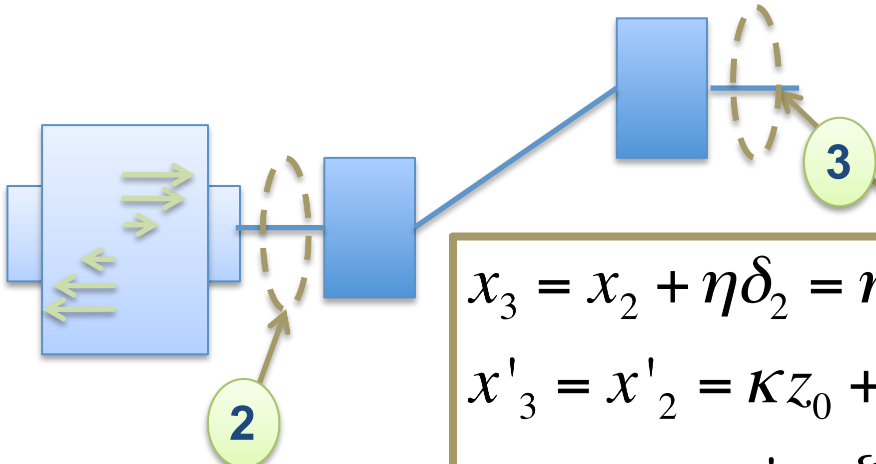
Deflecting cavity strength

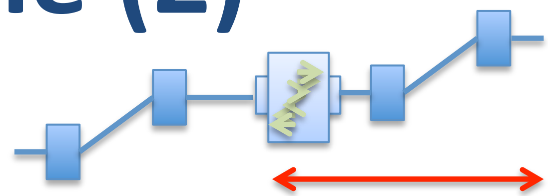
dispersion

$$x_1 = x_0 + \eta\delta_0$$
$$x'_1 = x'_0$$
$$z_1 = z_0 + \eta x'_0 + \zeta\delta_0$$
$$\delta_1 = \delta_0$$

$$x_2 = x_1 = x_0 + \eta\delta_0$$
$$x'_2 = x'_1 + \kappa z_1 = x'_0(1+\kappa\eta) + \kappa z_0 + \kappa\zeta\delta_0$$
$$z_2 = z_1 = z_0 + \eta x'_0 + \zeta\delta_0$$
$$\delta_2 = \delta_1 + \kappa x_1 = \delta_0(1+\kappa\eta) + \kappa x_0$$

Simple PEX beamline (2)





$$x_2 = x_0 + \eta\delta_0$$
$$x'_2 = \kappa z_0 + \kappa\zeta\delta_0$$
$$z_2 = z_0 + \eta x'_0 + \zeta\delta_0$$
$$\delta_2 = \kappa x_0$$

$$x_3 = x_2 + \eta\delta_2 = \eta\delta_0 + \cancel{(1+\eta\kappa)}x_0$$
$$x'_3 = x'_2 = \kappa z_0 + \kappa\zeta\delta_0$$
$$z_3 = z_2 + \eta x'_0 + \zeta\delta_2 = \eta x'_0 + \zeta\delta_0\cancel{(1+\eta\kappa)} + z_0\cancel{(1+\eta\kappa)}$$
$$\delta_3 = \delta_2 = \kappa x_0$$

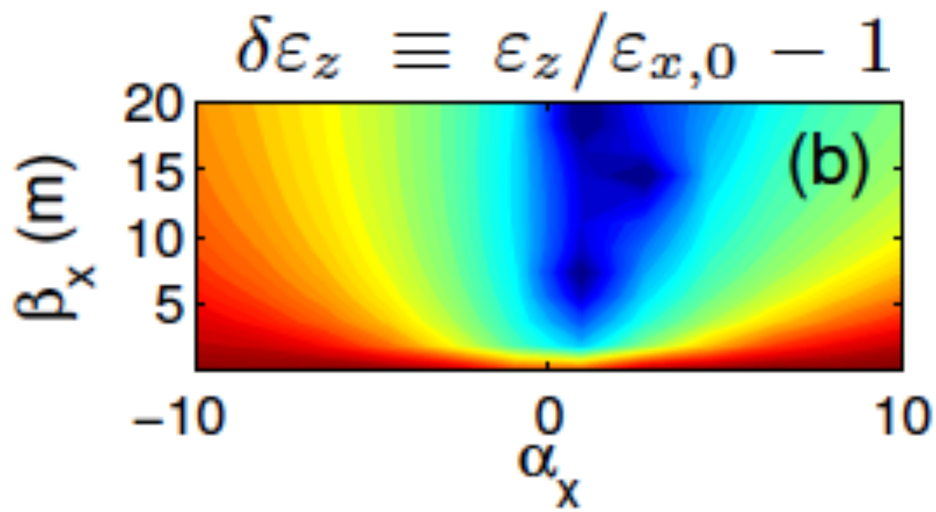
$$x_3 = \eta\delta_0$$
$$x'_3 = \kappa z_0 + \kappa\zeta\delta_0$$
$$z_3 = \eta x'_0$$
$$\delta_3 = \kappa x_0$$

phase-space coordinates exchanged

Limitations for emittance exchange

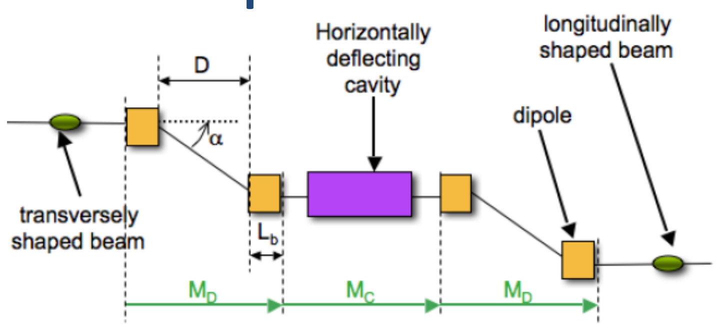
$$M_C = \begin{bmatrix} 1 & L_c & \kappa L_c/2 & 0 \\ 0 & 1 & \kappa & 0 \\ 0 & 0 & 1 & 0 \\ \kappa & \kappa L_c/2 & \kappa^2 L_c/4 & 1 \end{bmatrix}.$$

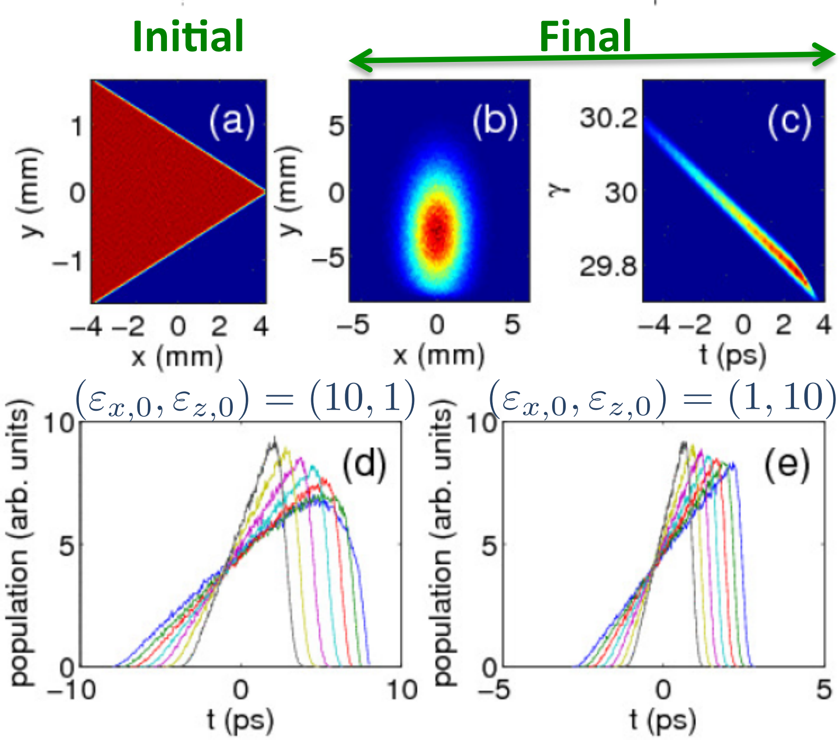
- Thick-lens effect ($L_c \neq 0$)
- Non-zero M65 results in spurious coupling between (x,x') and (z,δ) phase spaces downstream of PEX -> Non-perfect emittance exchange
- Can be corrected
  – Optimum incoming chirp, Twiss param.,
  – Add a TM_{010} cavity

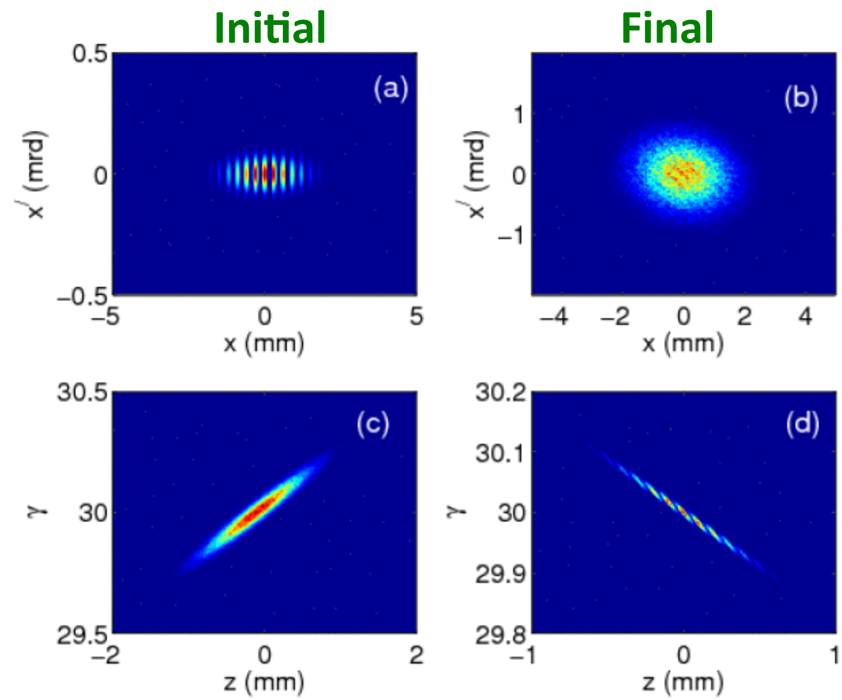


Pulse Shaping

- Generation of train of sub-ps bunches





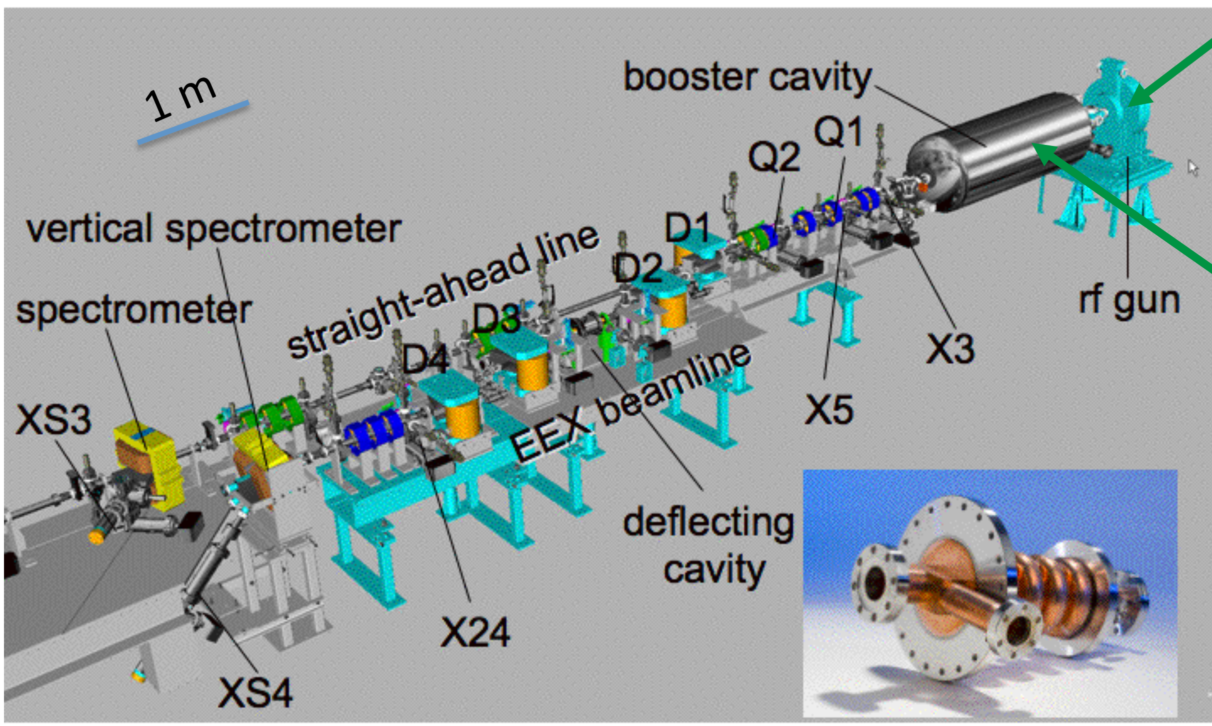


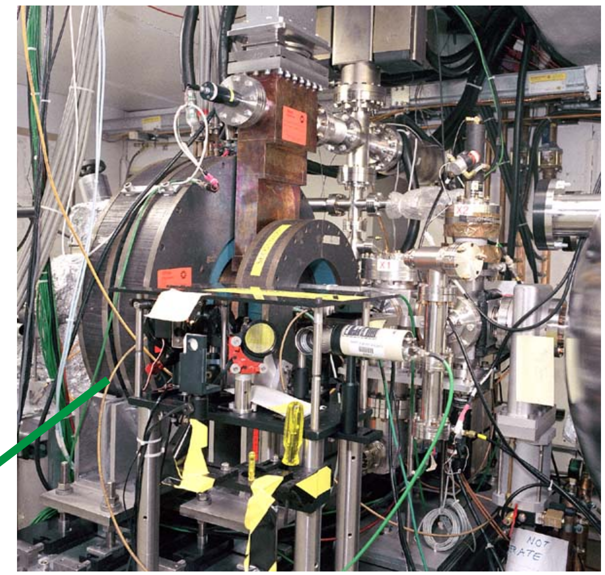
- Generation of bunches with linearly-ramped current profiles

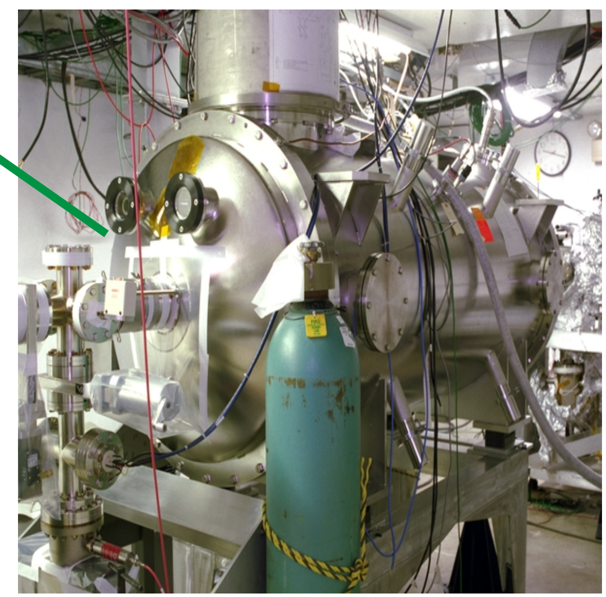
[P. Piot et al., PRSTAB 14, 022801 (2011)]

The A0 photoinjector (1996-2011)

- Electron accelerator based on 1.3 GHz rf-gun with Cs_2Te photocathode → Q< 10 nC
- TESLA SCRF cavity → E=16 MeV
- Emittance exchange beamline (ε_x, ε_z) → (ε_z, ε_x)
- Round-to-flat-beam transformer → $\varepsilon_x/\varepsilon_y$=100
- Extensive diagnostics
- Two photocathode lasers (Nd:YLF + Ti:Sp)



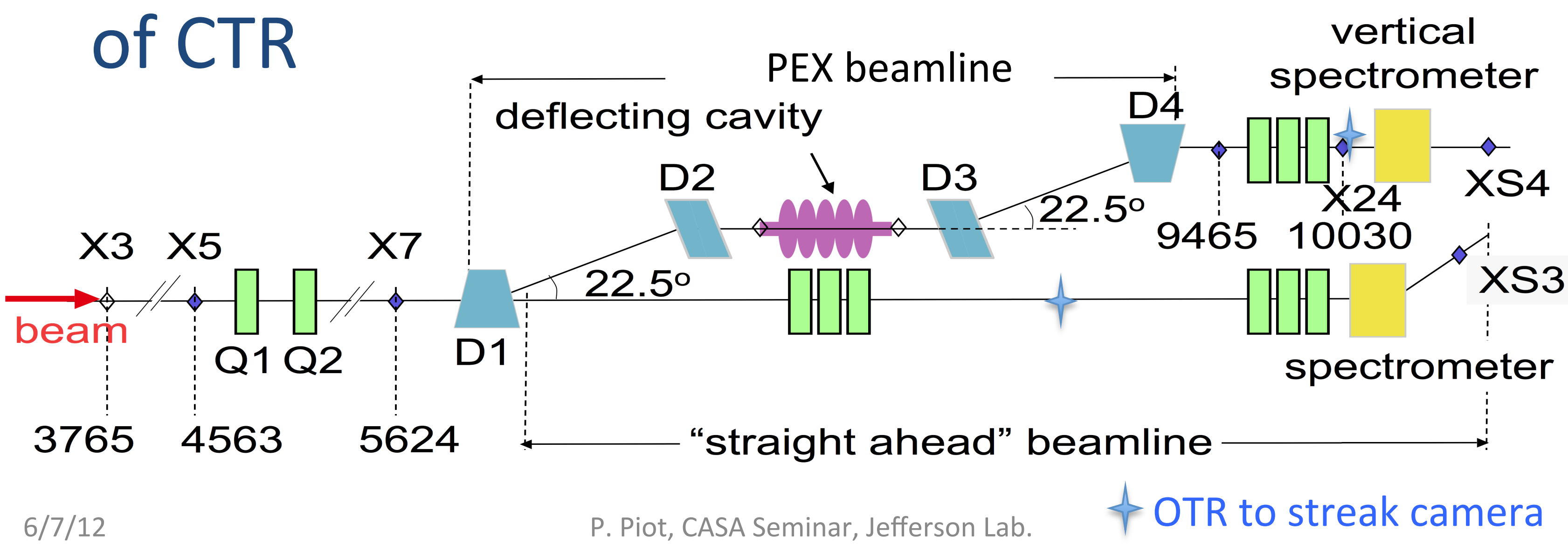




Experimental methods

[A. Lumpkin et al., PRSTAB 14, 060704 (2011)]

- Transverse emittances measured at X3, X24 with mutlislit technique
- Longitudinal emittances (over)estimated as $\varepsilon_z \simeq \sigma_\delta \sigma_z$ phase space is made upright
- Bunch length measured using autocorrelation of CTR



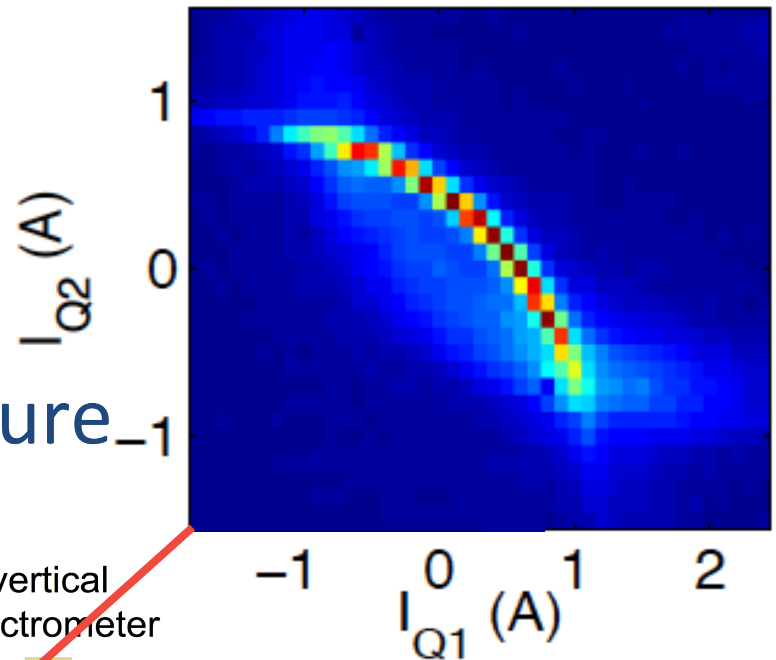
Quadrupole magnets to compress!

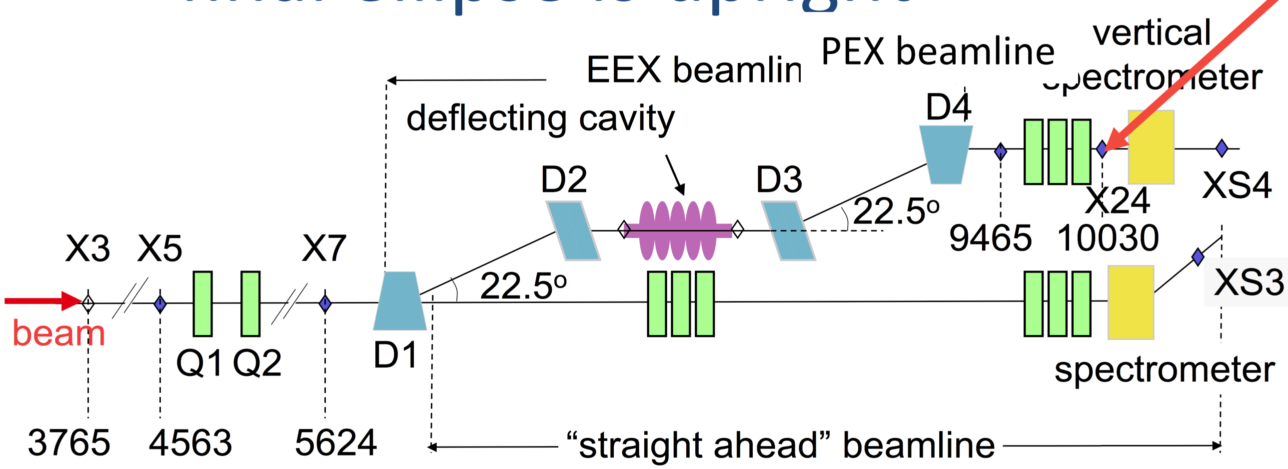
- Scanning Q1 and Q2 affects bunch final bunch length

$$\begin{cases} z = & -\frac{\xi}{\eta} x_0 - \frac{L\xi - \eta^2}{\eta} x_0' \\ \delta = & -\frac{1}{\eta} x_0 - \frac{L}{\eta} x_0', \end{cases}$$

- Method can be used to insure final ellipse is upright

f-integrated CTR intensity
“quadscan map”





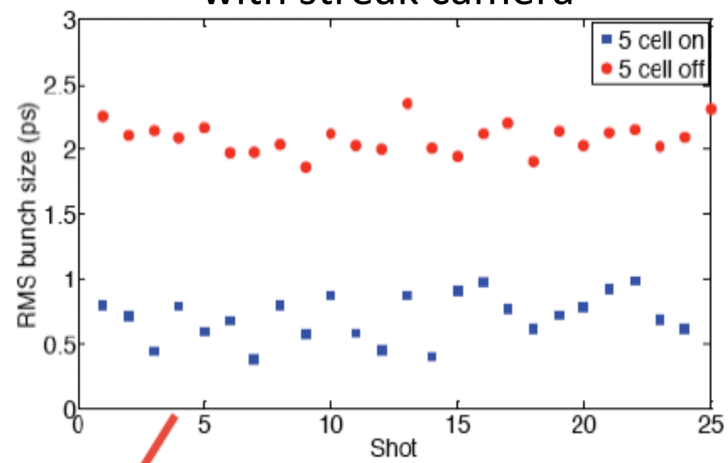
Observation of emittance exchange

[J. Ruan et al., PRL 106 244801 (2011)]

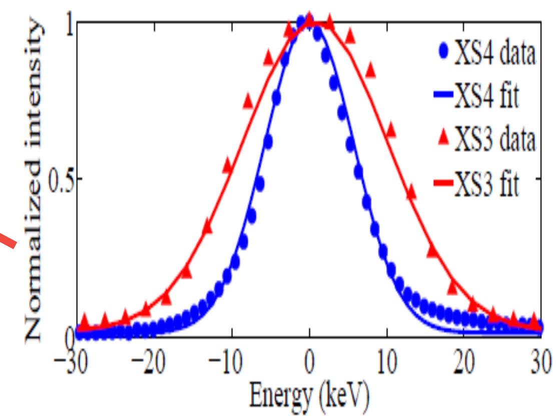
- Demonstrated emittance can be swap $\varepsilon_z \leftrightarrow \varepsilon_x$
- Q=250 pC

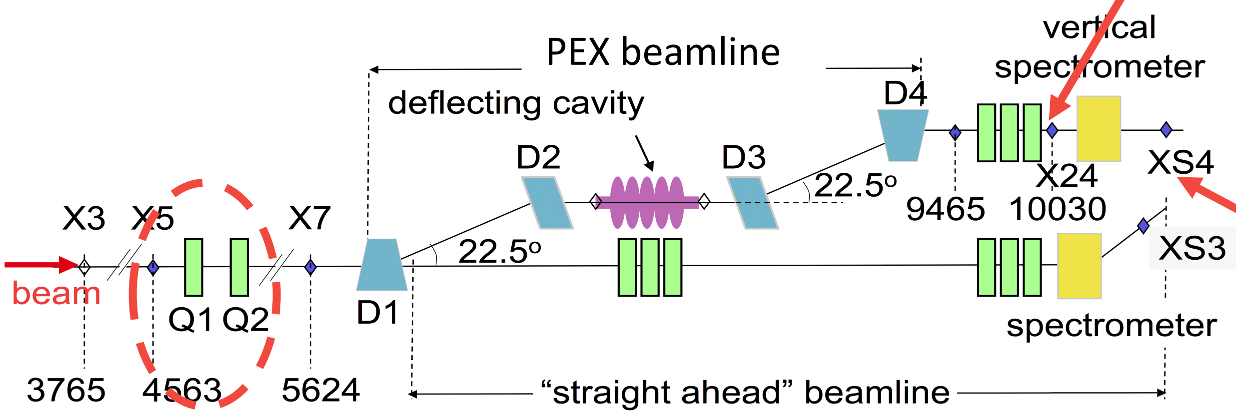
	Simulated		Measured	
	In	Out	In	Out
ε_x^n	2.9	13.2	2.9 ± 0.1	11.3 ± 1.1
ε_y^n	2.4	2.4	2.4 ± 0.1	2.9 ± 0.5
ε_z^n	13.1	3.2	13.1 ± 1.3	3.1 ± 0.3

Bunch duration measurement with streak camera



Energy spread

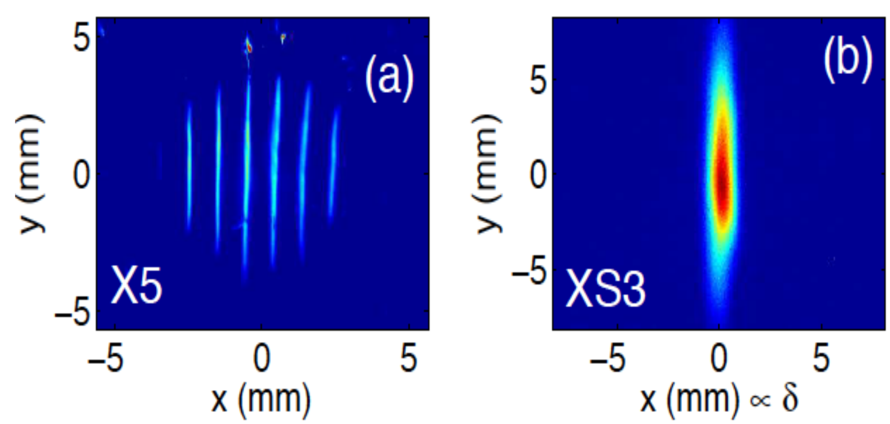




Fragmented longitudinal phase spaces (1)

- Set of slits upstream PEX -> transversely-segmented beam
- PEX maps modulation in the longitudinal phase space -> train of μbunches
- Initial beam parameters:

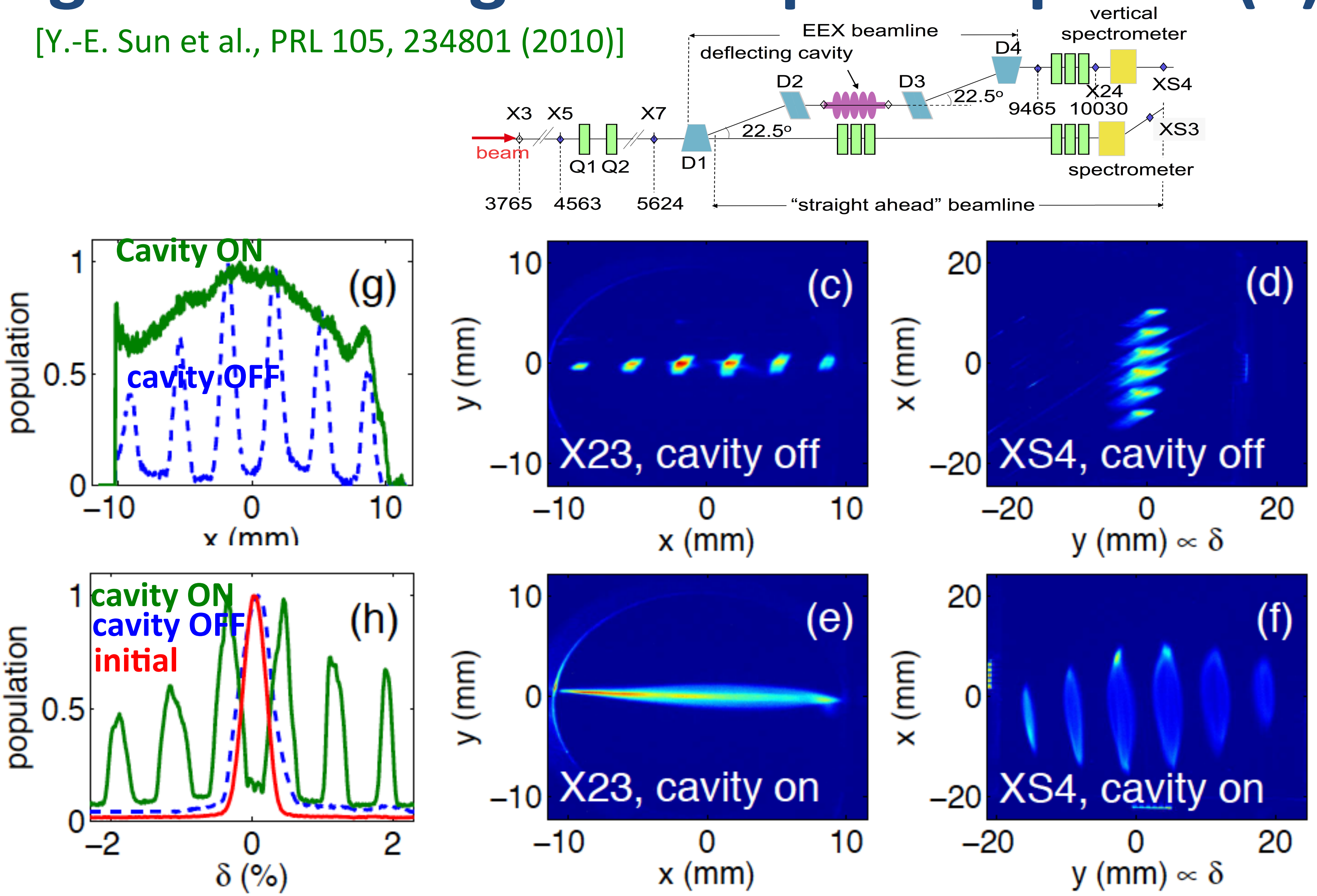
Parameter	Symbol	Value	Units
Energy	E	14.3 ± 0.1	MeV
Charge	Q	500 ± 50	pC
rms duration	σ_t	3.0 ± 0.5	ps
horizontal emittances	ε_x^n	3.5 ± 0.5	μm
vertical emittances	ε_y^n	3.5 ± 0.5	μm
rms frac. energy spread	σ_δ	33.7 ± 0.2	%
horizontal C-S param.	(α_x, β_x)	$(10 \pm 0.1, 0 \pm 0.2)$	(–,m)
vertical C-S param.	(α_y, β_y)	(10,0)	(–,m)



- Used 50-μm slits with 1-mm spacing

Fragmented longitudinal phase spaces (2)

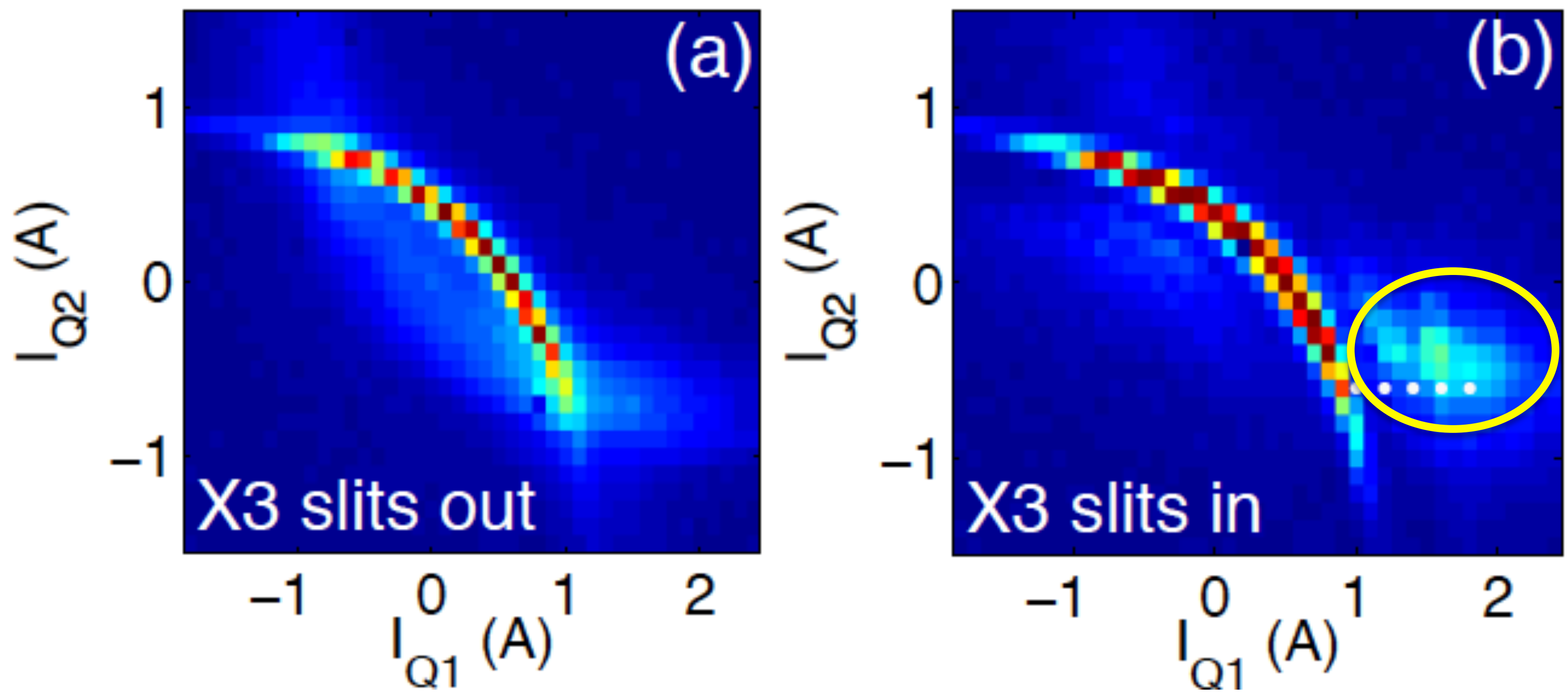
[Y.-E. Sun et al., PRL 105, 234801 (2010)]



Sub-picosecond bunch trains (1)

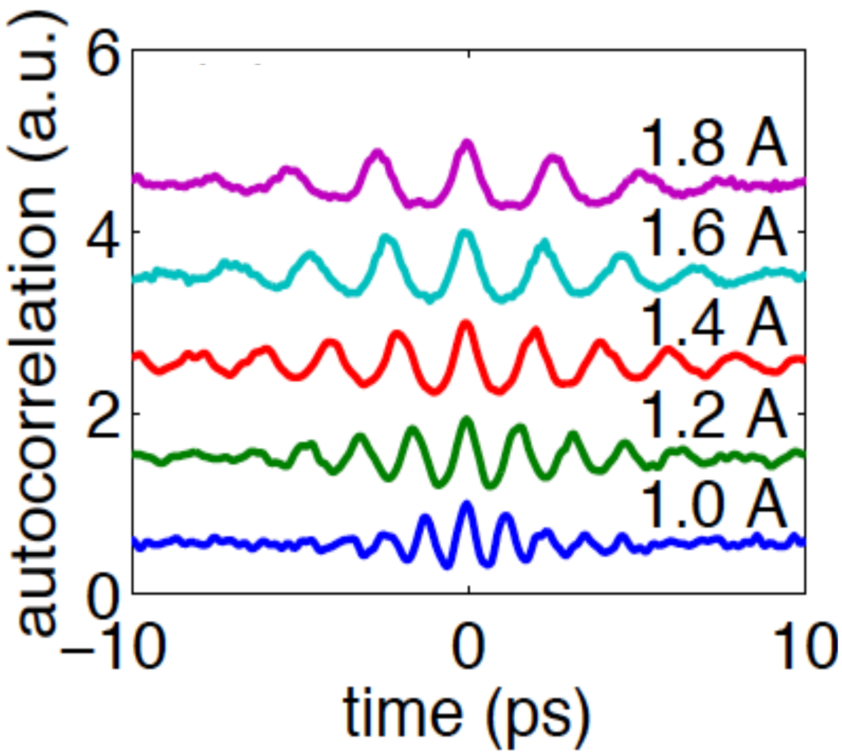
[Y.-E. Sun et al., PRL 105, 234801 (2010)]

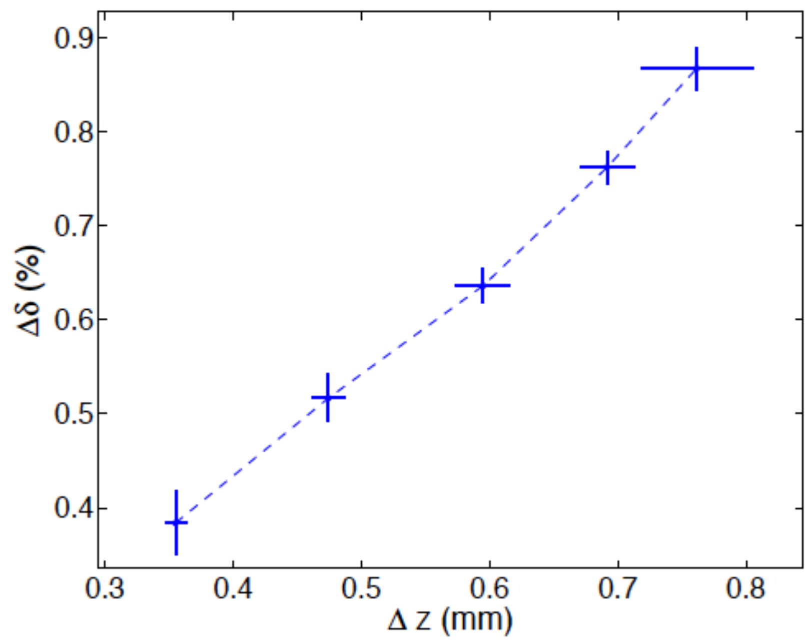
- Effects of slits -> "island of coherence" in quadscan maps
- Evidence of current modulation -> μbunches?



Sub-picosecond bunch trains (2)

- Quadrupoles can be used to vary the microbunches spacing within the train

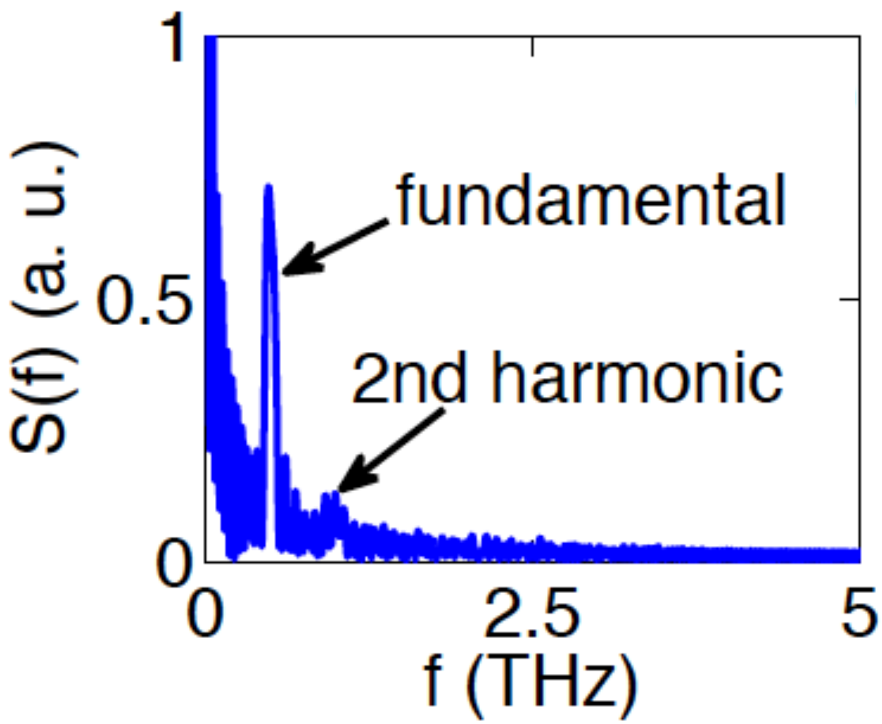


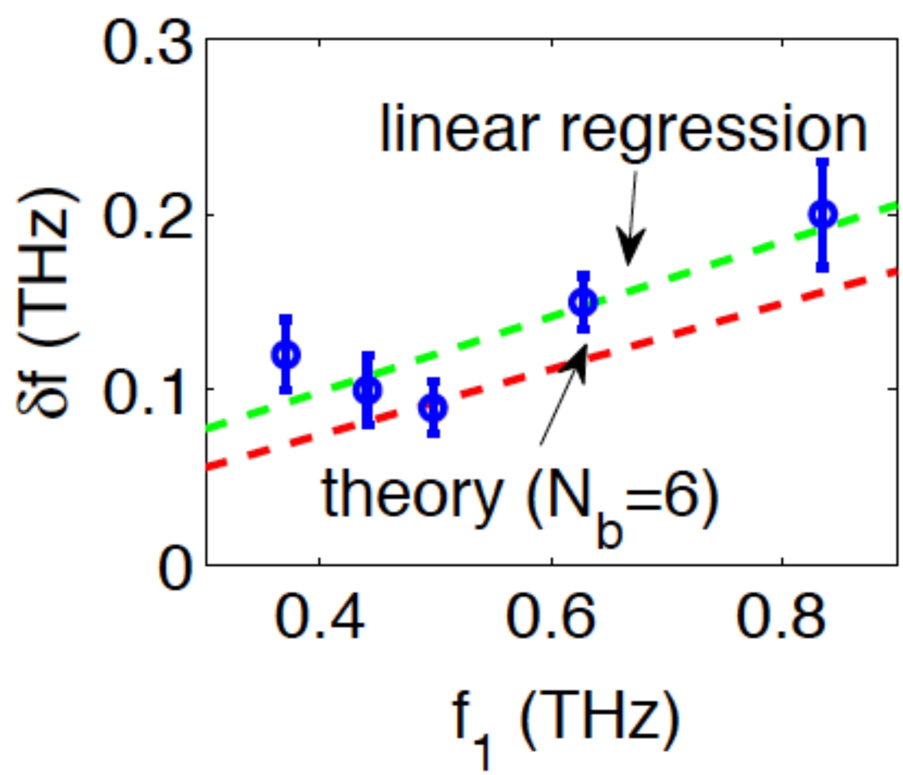


Production of narrowband THz CTR

[P. Piot et al., APL 98, 261501 (2011)]

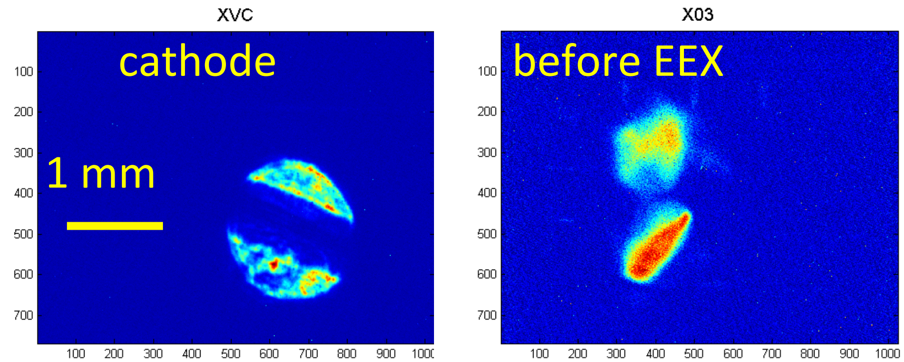
- Train of 6 μbunches used to generate narrowband CTR with tunable frequency

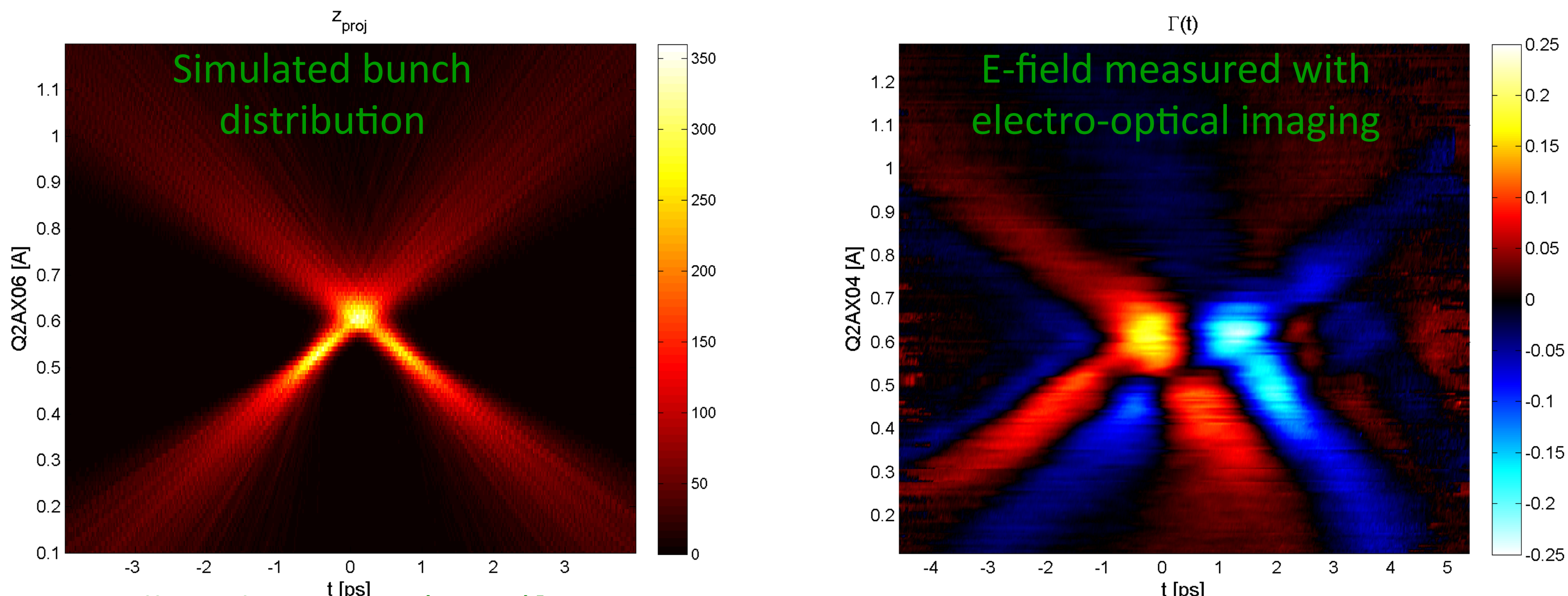




Mask-free double-bunch generation

- Interceptive mask introduces limitations -> transverse shaping of photocathode laser





[T. Maxwell et al., IPAC12 (2012)]

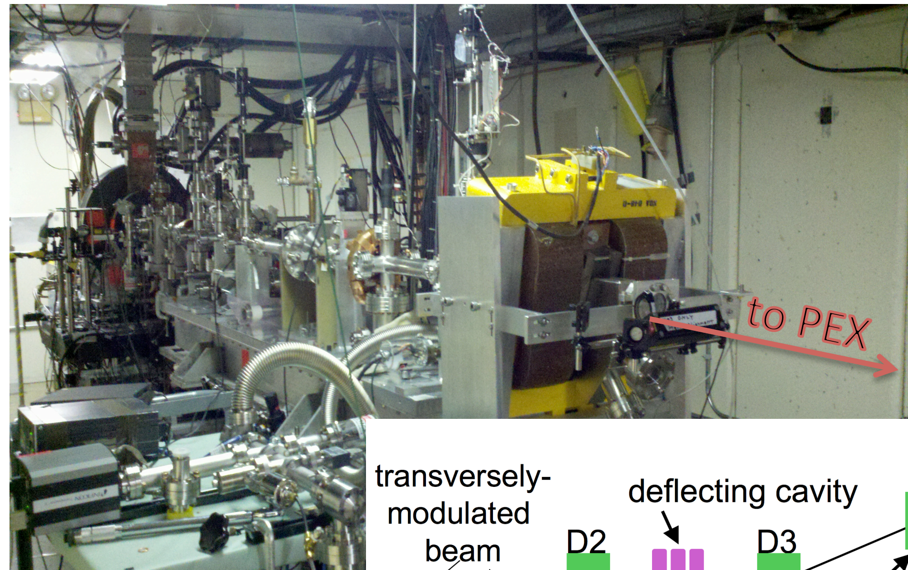
A0 last day 10/31/2012…

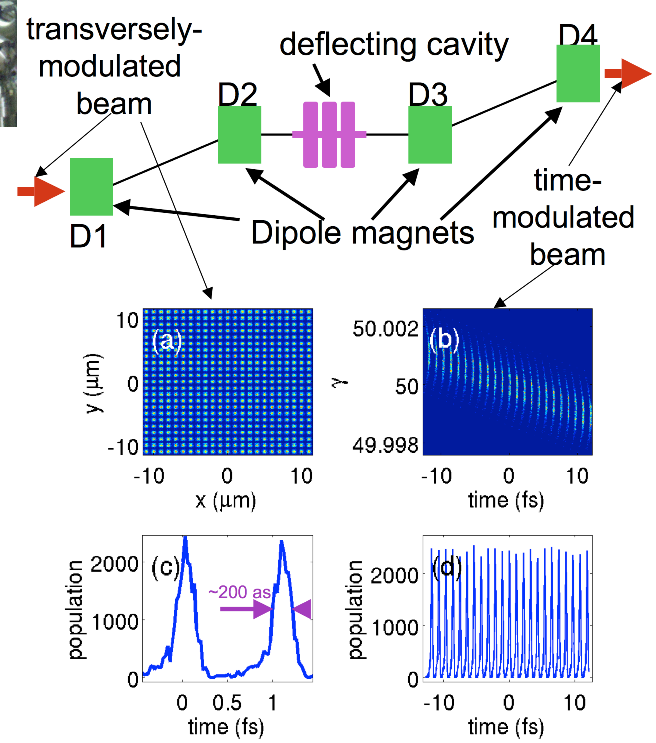
- Operated from 1996 to 2011
- Next steps:
  - High-Brightness Electron Source Laboratory (HBESL)
    - RF gun,
    - Concentrate on new cathodes (especially field emitters) + low energies (< 5 MeV) beams.
  - The Advanced Superconducting Test Accelerator (ASTA):
    - Eventually 900-MeV beams,
    - User-driven facility

Optically-modulated bunches at HBESL

- RF gun to produce 4.5 MeV beam
- Nano-structured cathode (field-emission array) triggered with <30 fs laser
- PEX produce an optically-modulated bunch train
- Goal is to observed COTR

[Y.-E Sun, et al. to be presented at FEL12]

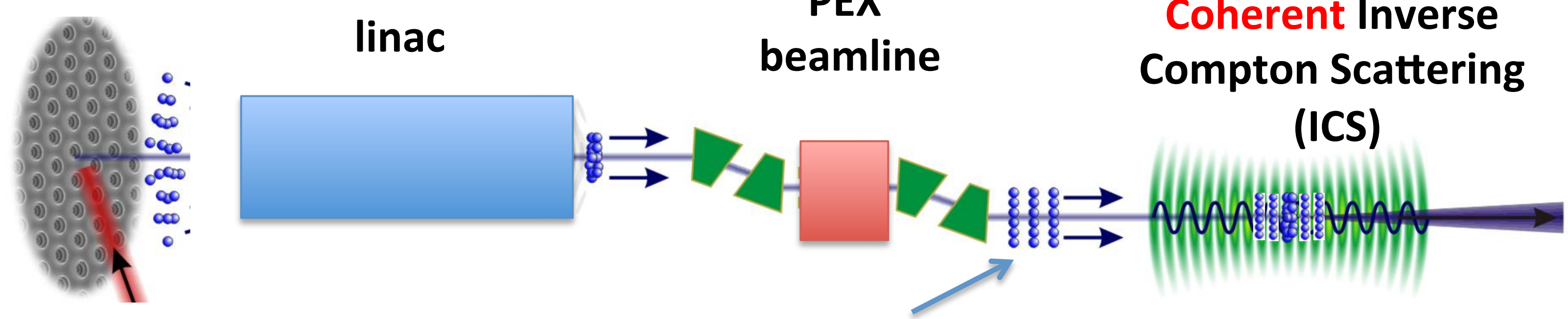


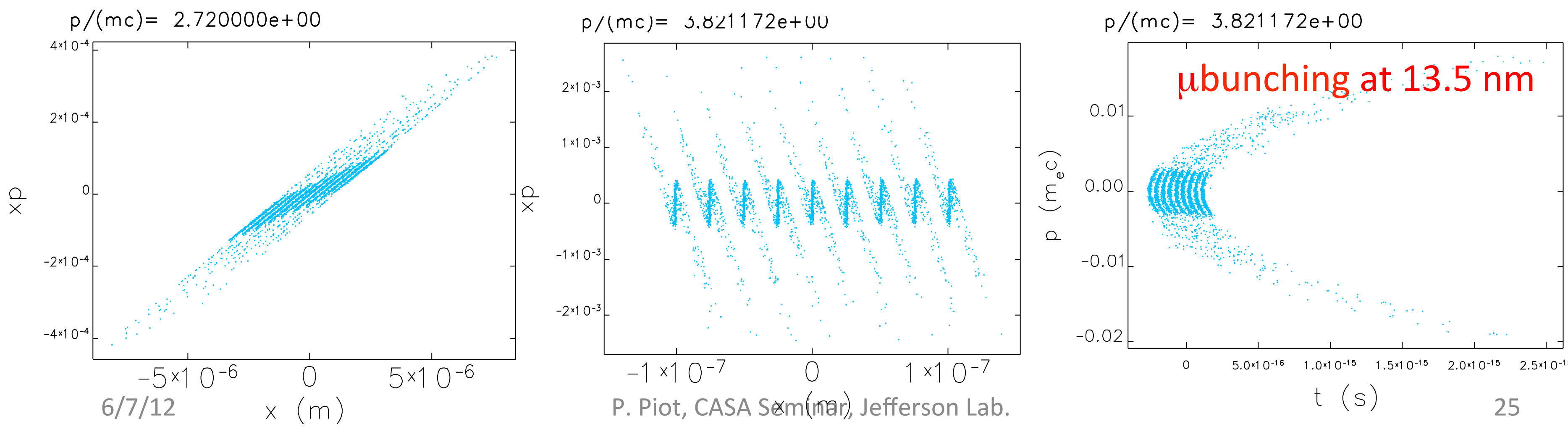


Concept for a compact VUV ICS source

[W.S. Graves, F. Kaertner, D. Moncton, P. Piot, PRL, in press (2012)]

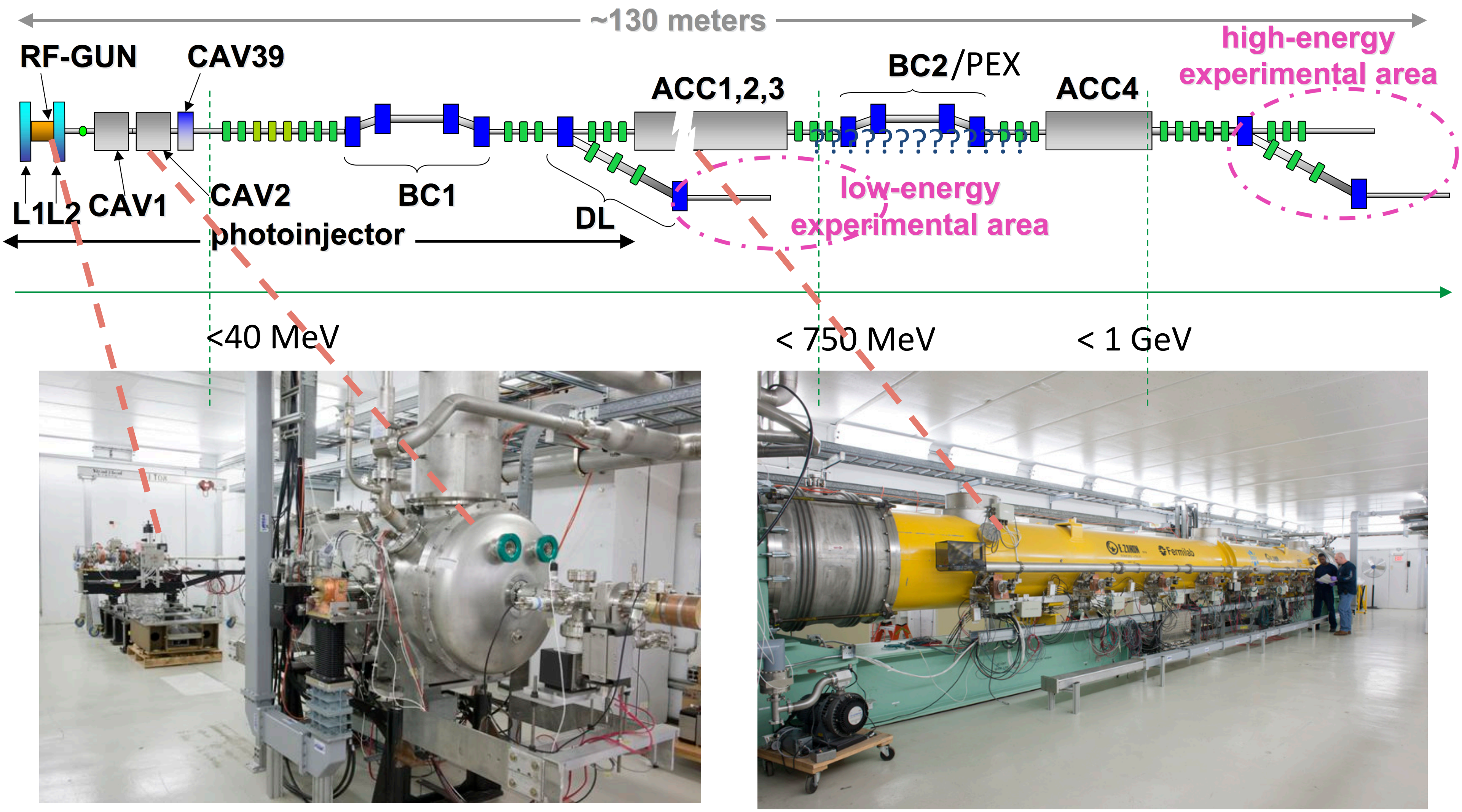
[drawing, courtesy of Franz Kaertner]





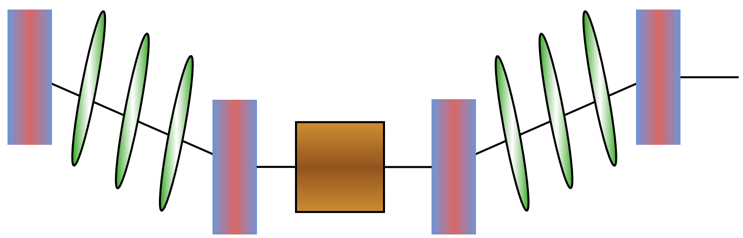
3D bunch manipulation at ASTA

- Flat beam transform + PEX

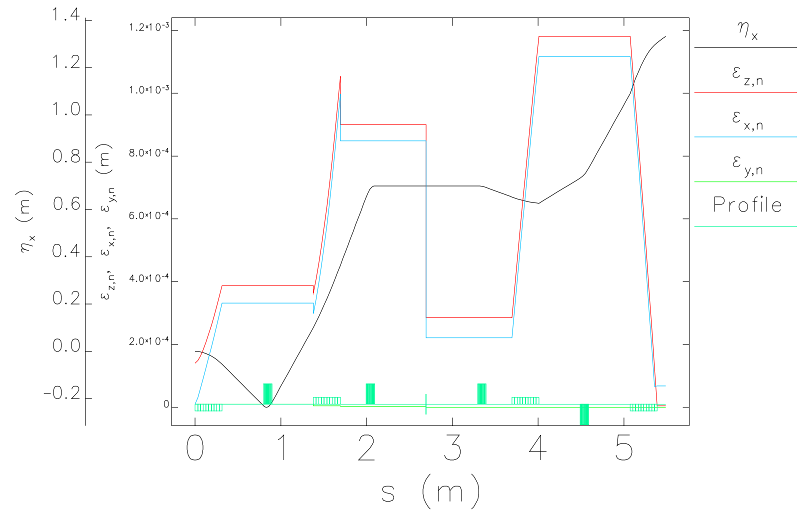


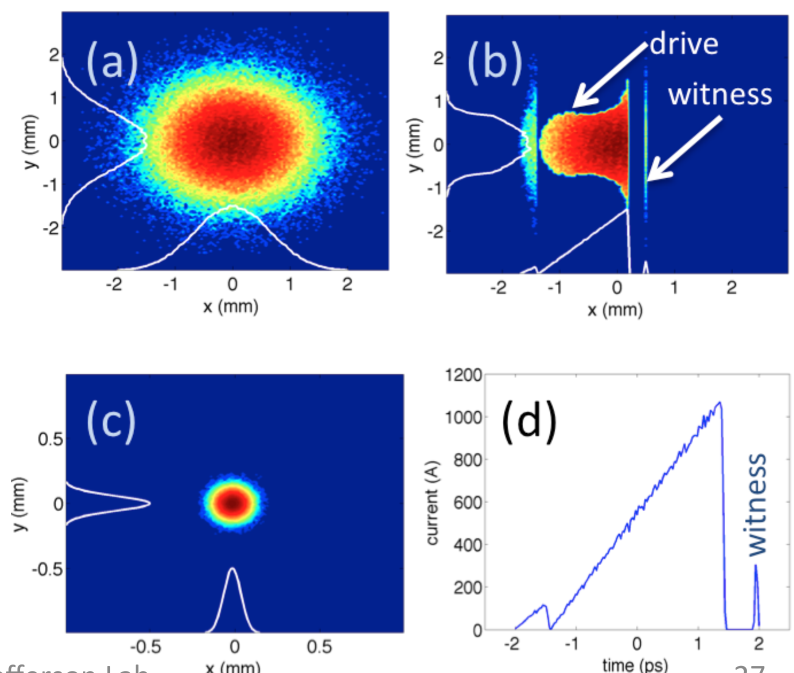
PEX beamline for ASTA

- Chicane-type PEX



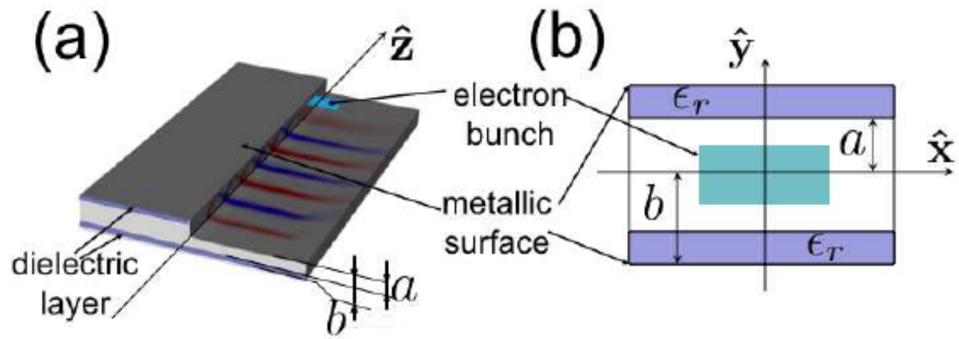
- Emittance exchange of incoming flat beams
- “Doubly-ramped” bunches with witness for wakefield accelera-tion (f~1 THz)

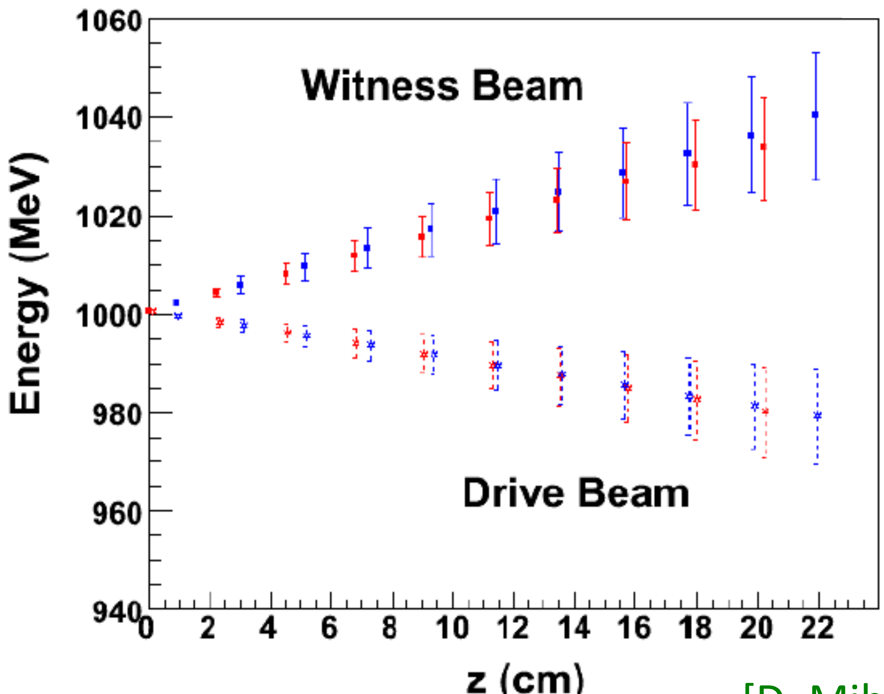


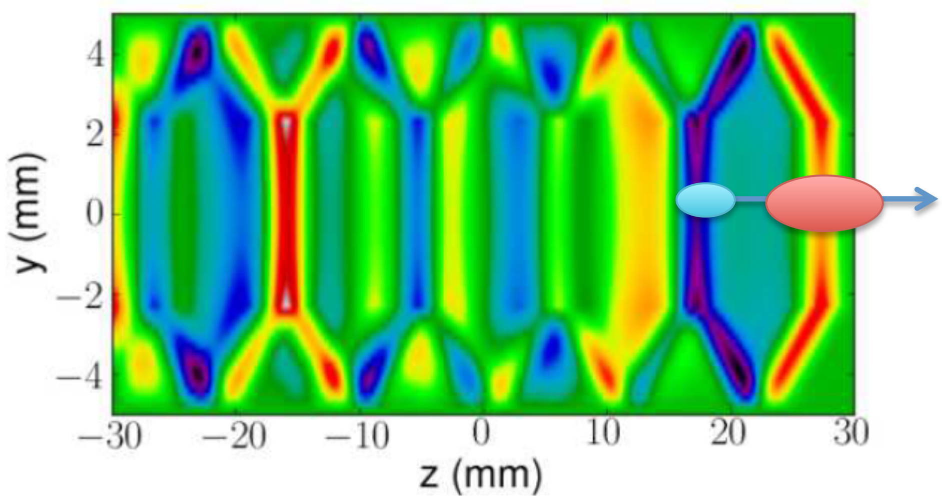


Application: wakefield acceleration in dielectric slabs

- NIU-TechX-Fermilab experiment in preparation at ASTA







[D. Mihalcea, P. Piot,P. Stoltz, ArXiV 1204:6724 (2012)]

Summary

- PEX techniques have been experimentally investigated,
- PEX have opened new opportunities for emittance repartioning and current shaping,
- Promising applications include accelerator-based light source, beam-driven acceleration,…
- A second generation of PEX experiments will be carried at Fermilab's ASTA and HBESL facilities (both in construction or commissioning).