Beam Shaping via 6D Phase-Space Manipulation

Yine Sun

Argonne National Lab.

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Outline

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- 6D Phase-Space Manipulation
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  - Transverse-to-Longitudinal Emittance EXchange (EEX)
    - Theory;
    - Experimental demonstration;
- Beam Shaping via 6D Phase-Space Manipulation
  - Longitudinal phase-space shaping via EEX.
    - Bunch Train Generation;
    - Precise longitudinal bunch shaping.
  - A further step
    - Round-to-Flat Combined with EEX.
    - Double EEX;

Introduction: The Why and How of Beam Shaping

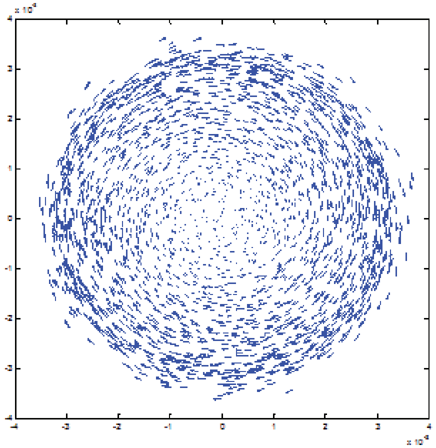
- An electron beam directly out of a photo-injector doesn't always have the phase-space distribution required for its application. Beam shaping is often needed and can be done in many ways, such as:
  - Shaping at cathode by photo-cathode drive laser shaping, or cathode emitting area engineering;
  - Shaping via strong interactions between the electron beam and laser → longitudinal modulations in beam distribution;
  - Often the beam needs to be compressed longitudinally →higher peak current;
    - Velocity bunching or ballistic bunching;
    - Magnetic bunch compression;
    - Space-charge compression via multi-bunch interaction.
- 6D Phase-space manipulation techniques can be used for beam shaping:
  - Round beam → flat beam (to drive planar dielectric wake-field or or enhance beam-wave interaction in radiation generation process such as Smith-Purcell radiation);
  - Longitudinal and transverse phase-space/Emittance of the beam can be EXchanged (EEX);
  - When EEX is combined with the flat beam → repartition of phase-space in 6D can be achieved;
  - The manipulations above are in the root-mean-square sense; the beam profiles can be more precisely tailored, such as bunch train, or linearly ramped current for higher transformer ratio in a wakefield accelerator etc.

Round-to-Flat Beam Transformation
→Transverse Phase-space Manipulation

Round-to-flat Beam transformation: Beam Matrix Formulation

$$\Sigma_{round} = \begin{bmatrix} \varepsilon_{eff}\beta & 0 & 0 & L \\ 0 & \varepsilon_{eff}/\beta & -L & 0 \\ 0 & -L & \varepsilon_{eff}\beta & 0 \\ L & 0 & 0 & \varepsilon_{eff}/\beta \end{bmatrix}$$

General form of the beam matrix of a round beam at beam waist location.

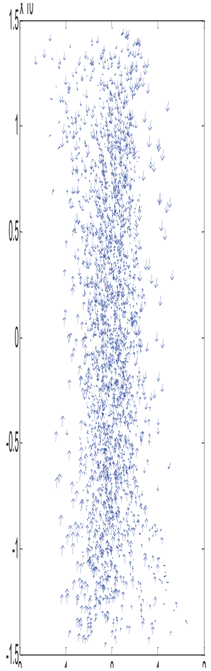


$$\Sigma_{flat} = M\Sigma_{round}\tilde{M}$$

Going through a symplectic round-to-flat beam transformation matrix (via skew quadrupoles)

$$\Sigma_{flat} = \begin{bmatrix} \varepsilon_{-}\beta & 0 & 0 & 0 \\ 0 & \varepsilon_{-}/\beta & 0 & 0 \\ 0 & 0 & \varepsilon_{+}\beta & 0 \\ 0 & 0 & 0 & \varepsilon_{+}/\beta \end{bmatrix}$$

Beam is decoupled in x and y phase space and a flat beam with emittance ε_{-} and ε_{+} is generated.



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Invariants of the Symplectic Transformation → Flat Beam Emit.

$$I_1 = \varepsilon_{4D} = \sqrt{|\Sigma|} \Rightarrow \varepsilon_+ \varepsilon_- = \varepsilon_{eff}{}^2 - L^2$$

$$I_2 = -\frac{1}{2}\mathrm{Trace}(J_4 \Sigma J_4 \Sigma) \Rightarrow \varepsilon_+^2 + \varepsilon_-^2 = 2\left(\varepsilon_{eff}{}^2 + L^2\right)$$

K.-J. Kim, Phys. Rev. St. Accel Beams **6**, 104002 (2003).

Round beam emittance:

$$\varepsilon_{eff} = \sqrt{\varepsilon_u{}^2 + L^2}$$

uncorrelated emittance

Const. related to canonical angular momentum $L = \frac{\langle L \rangle}{2Pz}$

Flat beam emittances are given by:

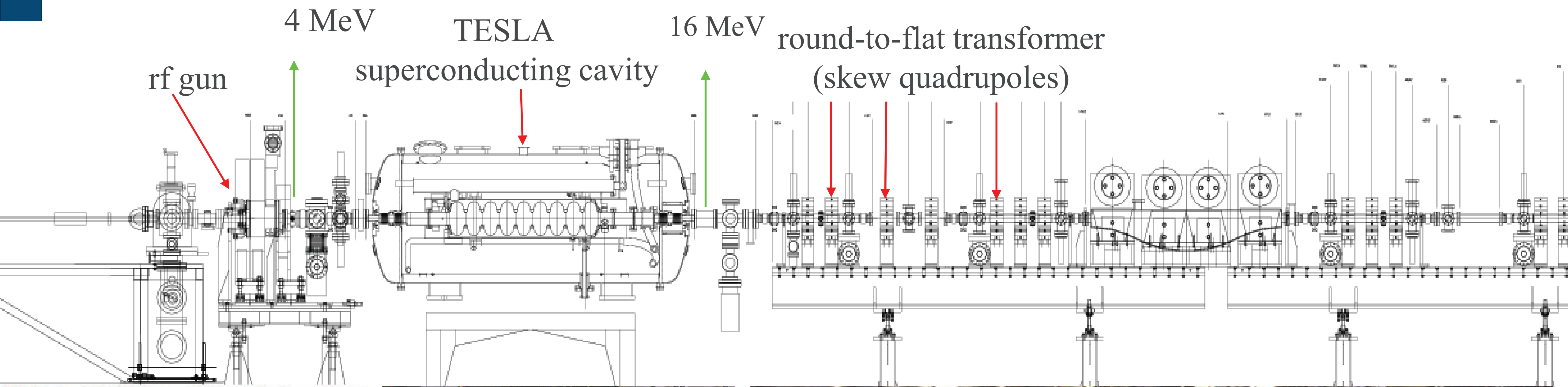
$$\varepsilon_\pm = \sqrt{\varepsilon_u{}^2 + L^2} \pm L$$

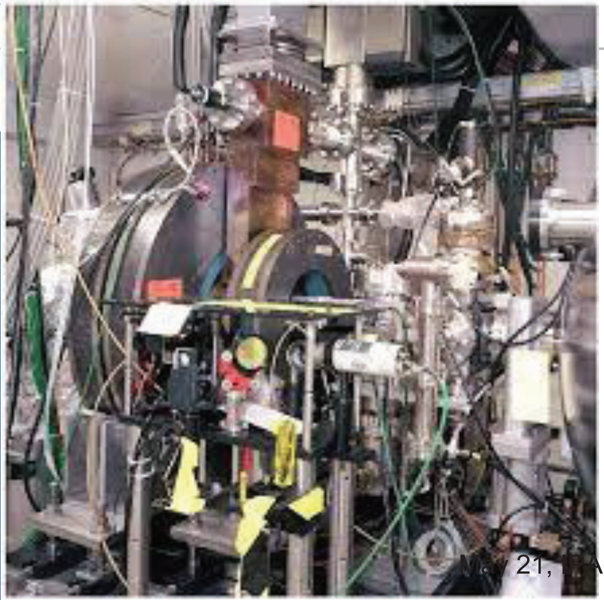
e.g. L=20 μm, ε_u=1 μm
ε_+=47 μm; ε_-=0.02 μm

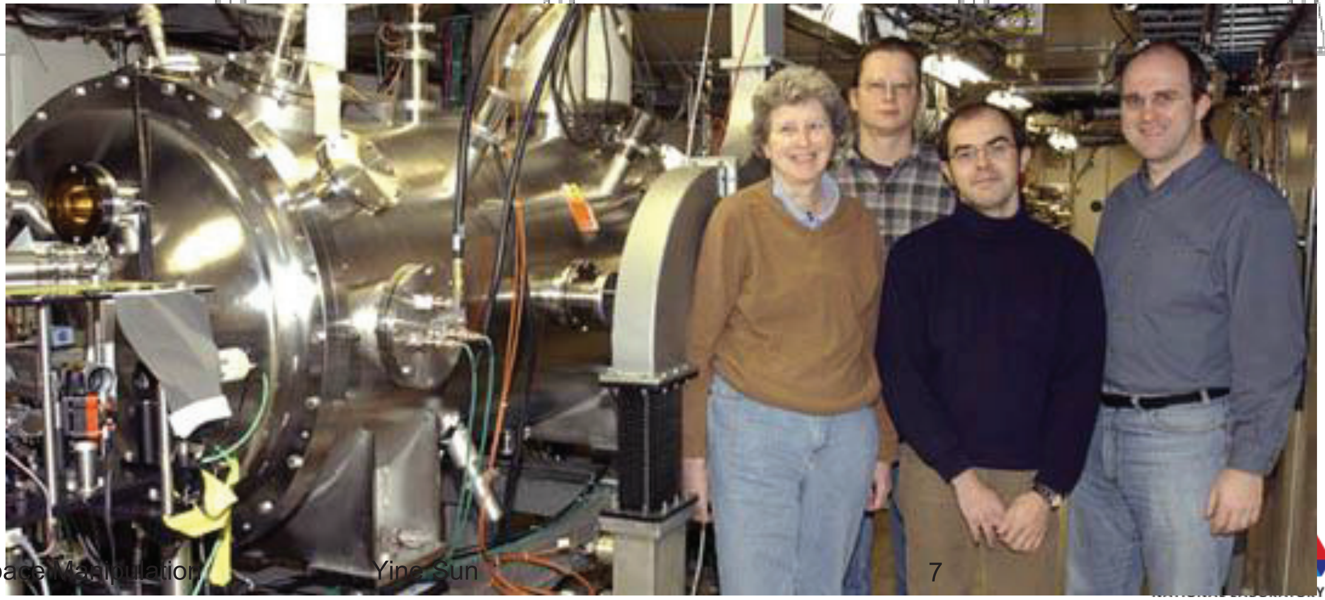
For $L \gg \varepsilon_u$, $\quad \varepsilon_- = \frac{\varepsilon_u^2}{2L} << \varepsilon_u$

Flat beam emit. can be smaller than thermal emit.

Flat Beam Experiment at Fermilab/NICADD Photoinjector Lab (A0)



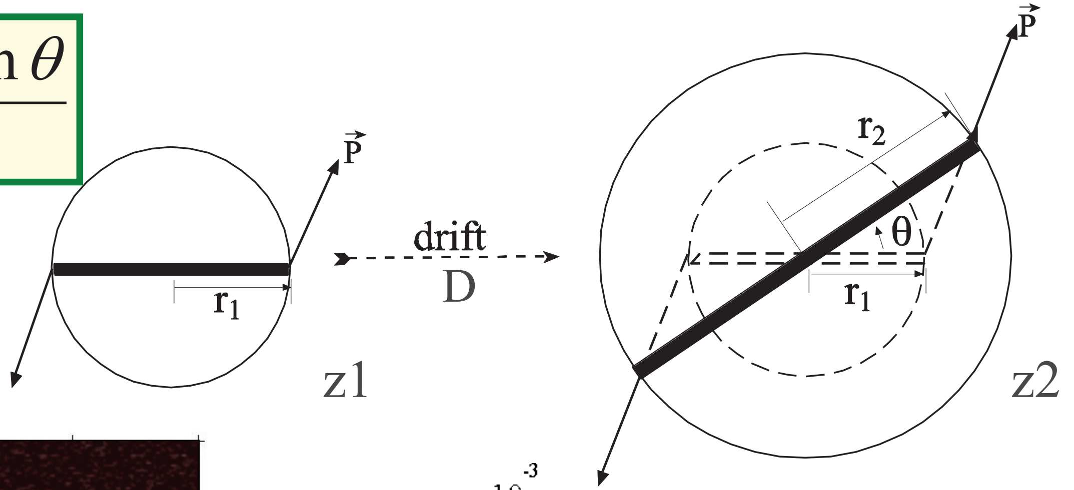


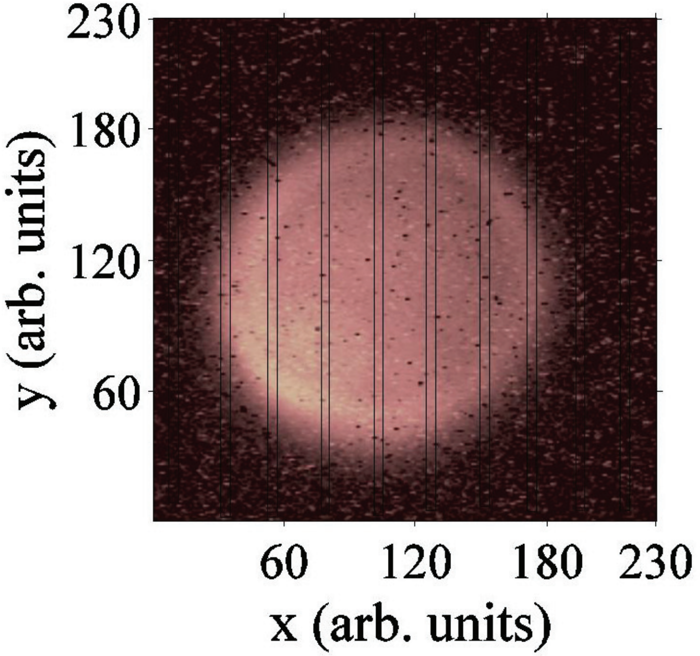


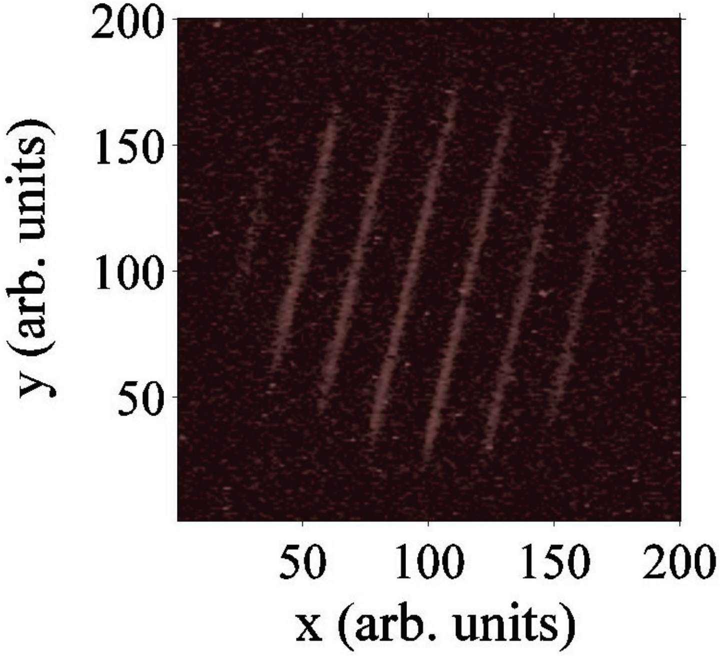
Measurement of canonical angular momentum in a drift space

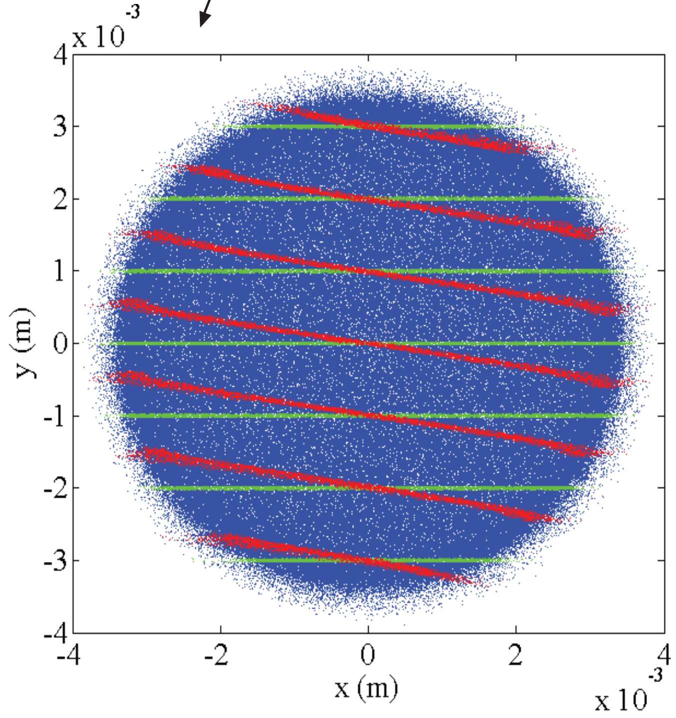
Insert flag or slits at Z_1 →
Measure beam size σ_1 at Z1
Insert flag at Z_2 →
Measure beam size σ_2 and slits rotation angle θ at Z_2

$$\langle L \rangle = 2 p_z \frac{\sigma_1 \sigma_2 \sin\theta}{D}$$









Y. Sun et al, Rev. ST Accel. Beams **7**, 123501 (2004)

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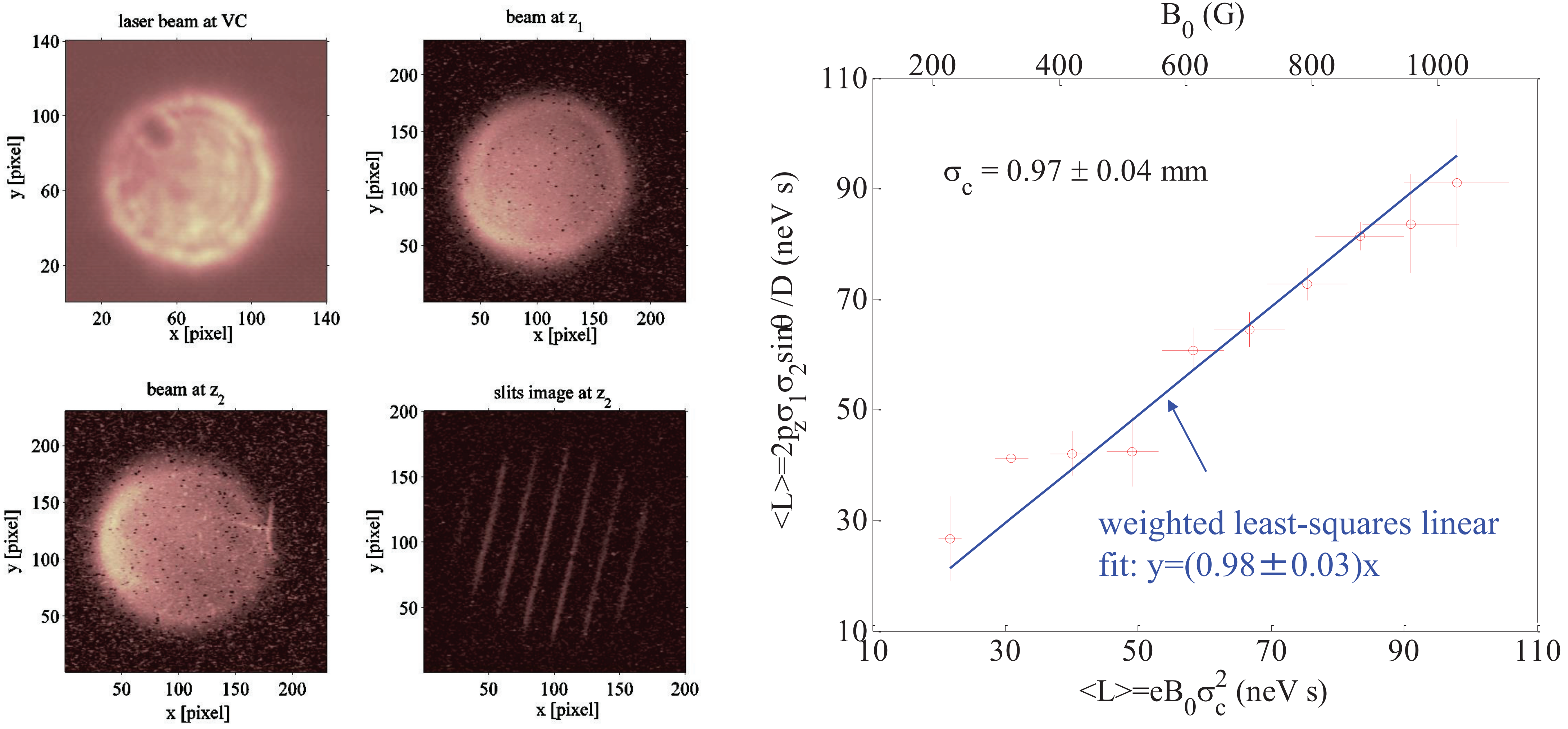
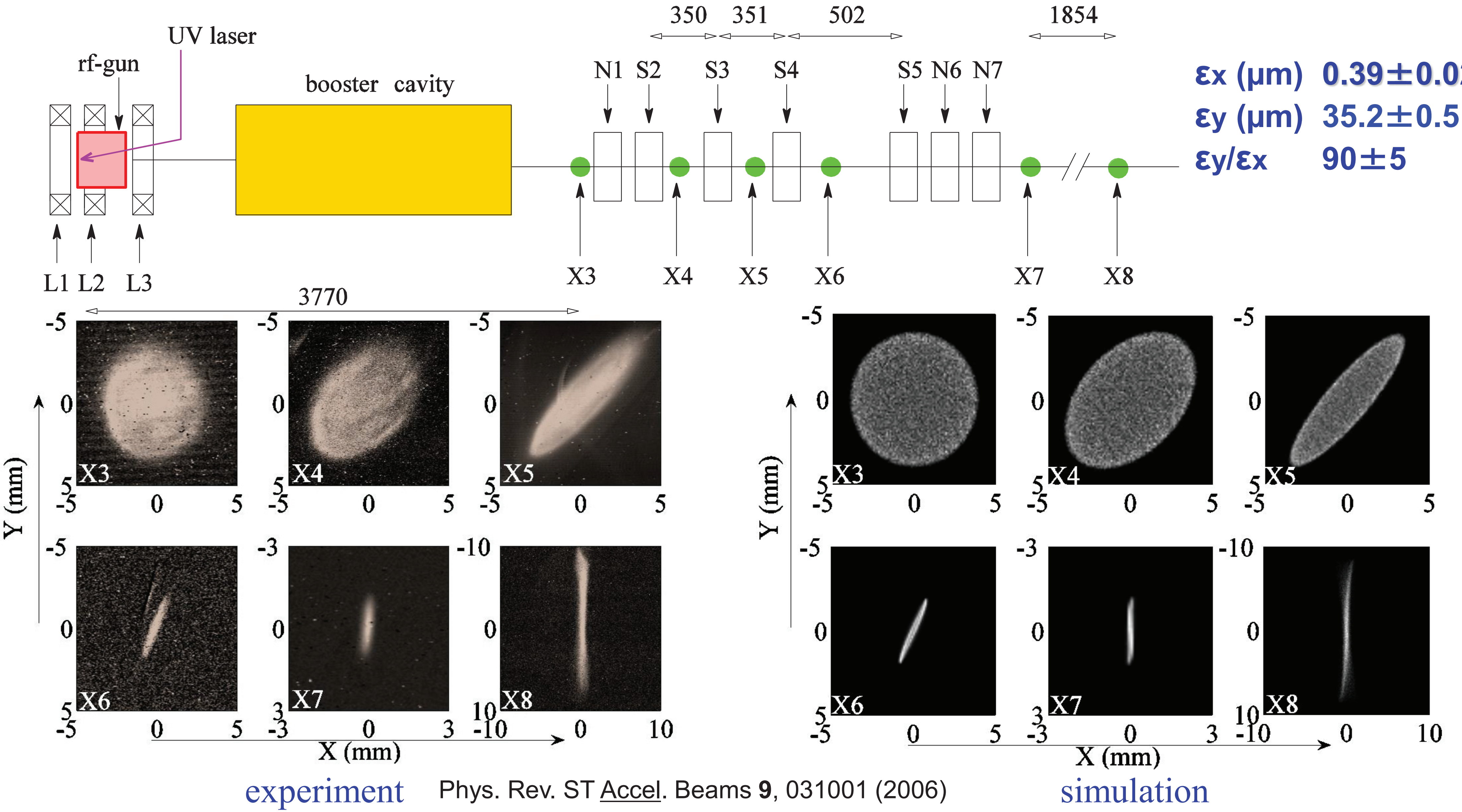
Measurements of the canonical angular momentum

as a function of magnetic field on cathode



Removal of angular momentum → flat beam generation



ε_x (μm) **0.39±0.02**
ε_y (μm) 35.2±0.5
$\varepsilon_y/\varepsilon_x$ 90±5

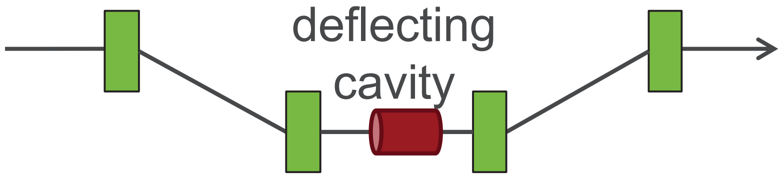
Phys. Rev. ST Accel. Beams **9**, 031001 (2006)

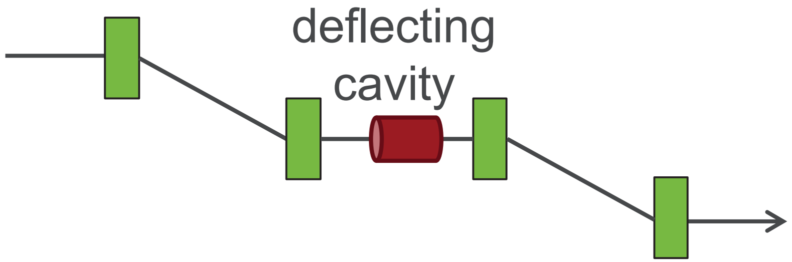
Round-to-Flat Beam Transformation
→transverse phase-space manipulation

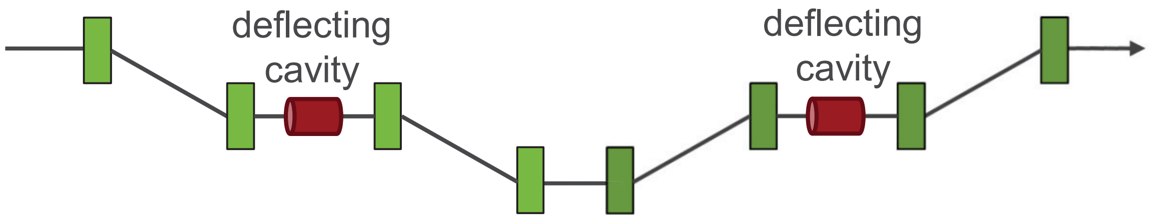
Emittance Exchange (EEX)
Transverse ↔ Longitudinal Phase-space Exchange

Transverse-to-Longitudinal Phase-Space Exchange

- EEX theory:
  - 2002: Cornacchia and Emma, PRSTAB 5, 084001.
    - Partial exchange : chicane
  - 2006: Kim, AIP Conf. Proc. No. 821.
    - Complete exchange: double-dogleg
- 2010: Double-dogleg EEX experiment demonstration:
  - J. Ruan et al., PRL 106, 244801 (2011).
- 2010: Applications of EEX in beam current profile modulation:
  - P. Piot et al., Phys. Rev. ST Accel. Beams 14, 022801 (2011).
  - Y. Sun et al., PRL 105, 234801 (2010).
  - G. Ha et al, PRL 118, 104801 (2017).
- Double Emittance Exchange (DEEX)
  - A. Zholents et al., ANL/APS/LS-327 (2011).

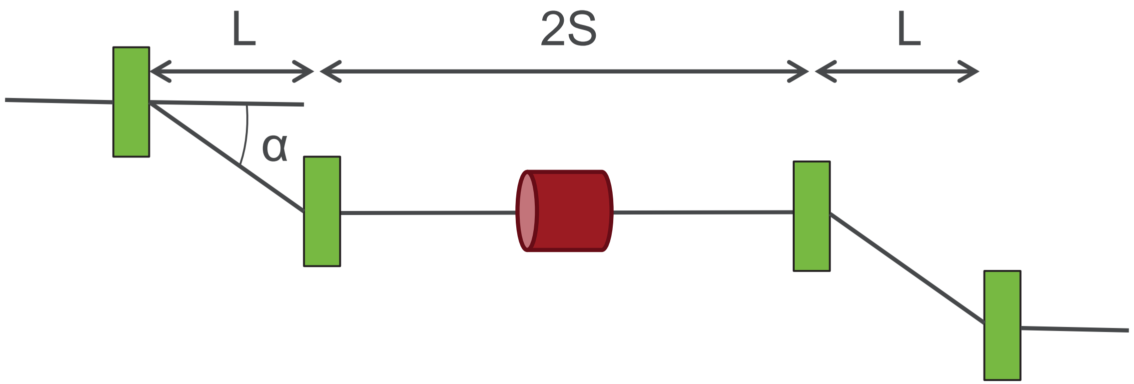






Transverse-to-Longitudinal Phase-space Exchange

- Four dipoles + one deflecting cavity:



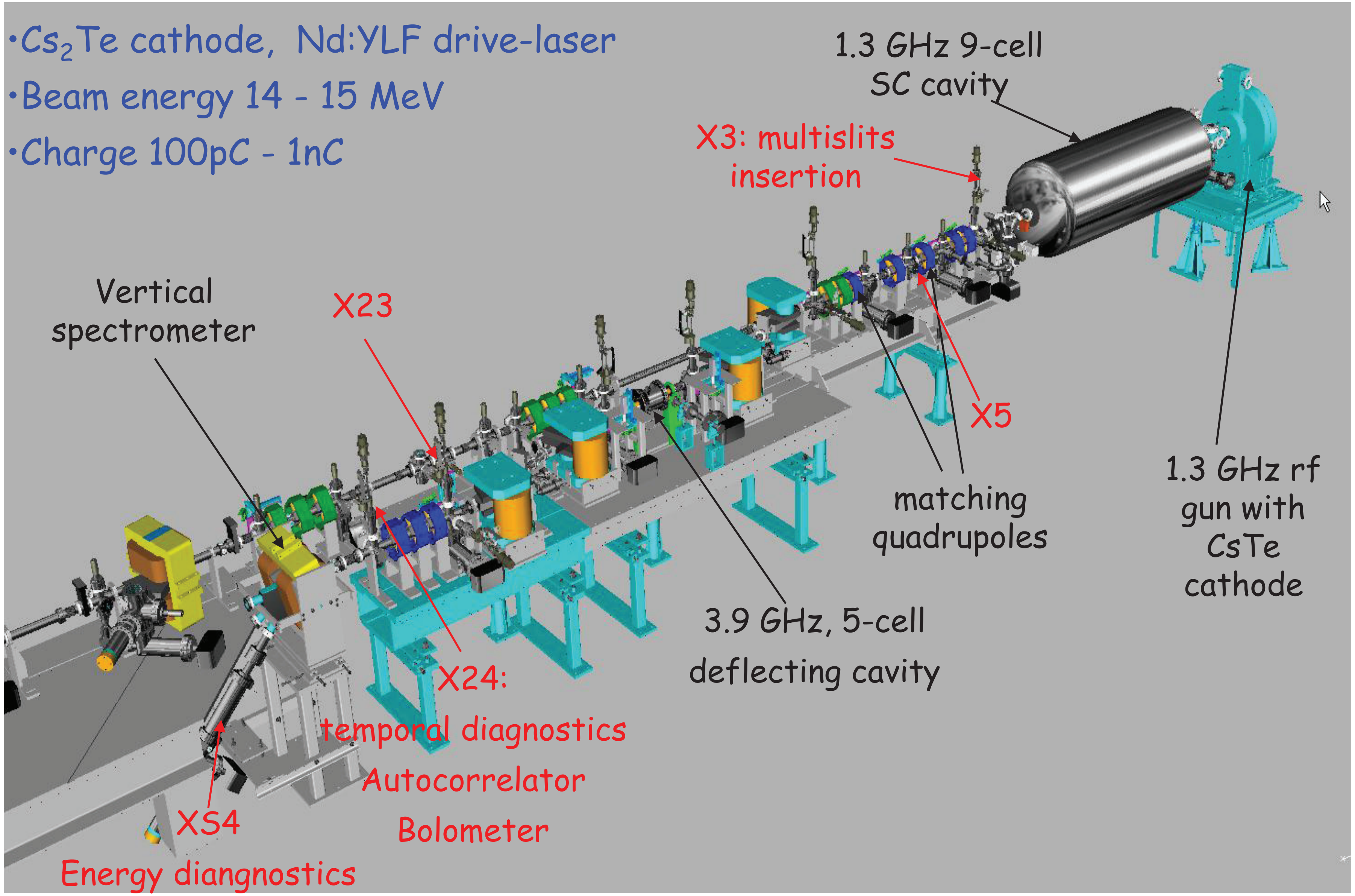
- Under thin-lens approximation, with proper matching of the deflecting cavity strength (k) and the dogleg dispersion (D), i.e., 1+kD=0, the diagonal sub-block elements of the exchanger's transfer matrix are zero ↔ the initial horizontal phase space is mapped into the longitudinal phase space, vice versa.

$$\begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix}_{out} = \begin{pmatrix} 0 & 0 & \frac{L+S}{\alpha L} & \alpha S \\ 0 & 0 & \frac{1}{\alpha L} & \alpha \\ \alpha & \alpha S & 0 & 0 \\ \frac{1}{\alpha L} & \frac{L+S}{\alpha L} & 0 & 0 \end{pmatrix} \begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix}_{in}$$

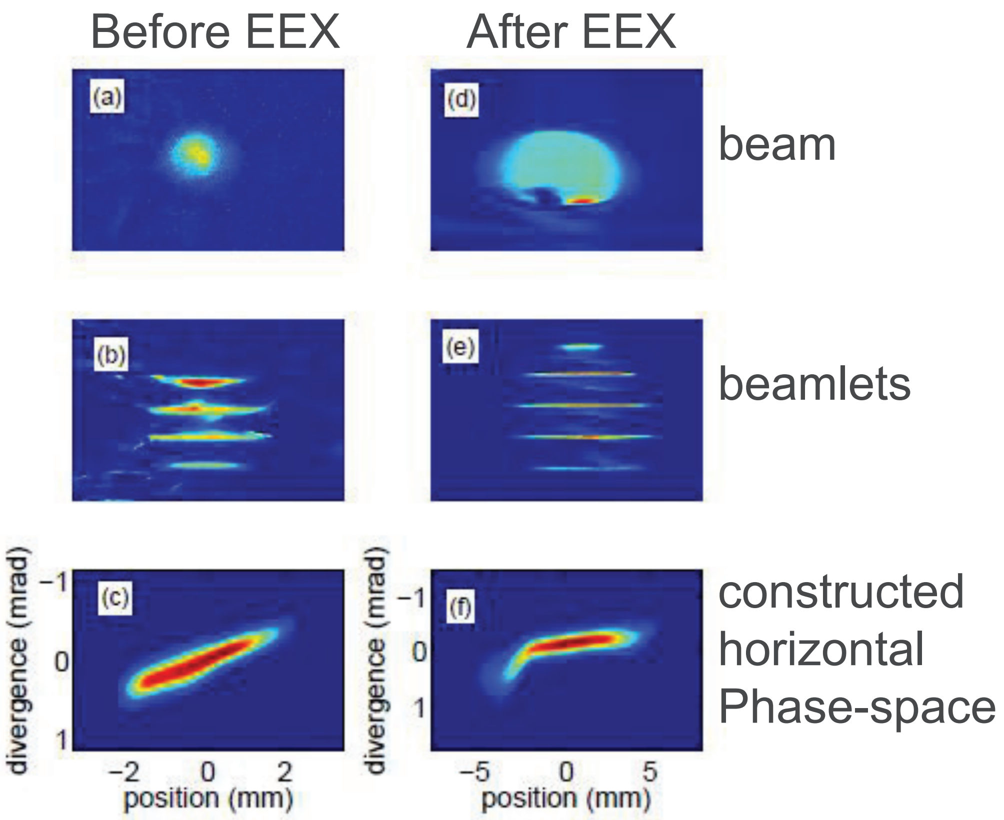
- With finite cavity length included, there will be non-zero terms in the diagonal blocks – which can be corrected by adding accelerating cells on the defecting cavity[1], or reduced by adjusting initial beam transverse and longitudinal phase space correlations.

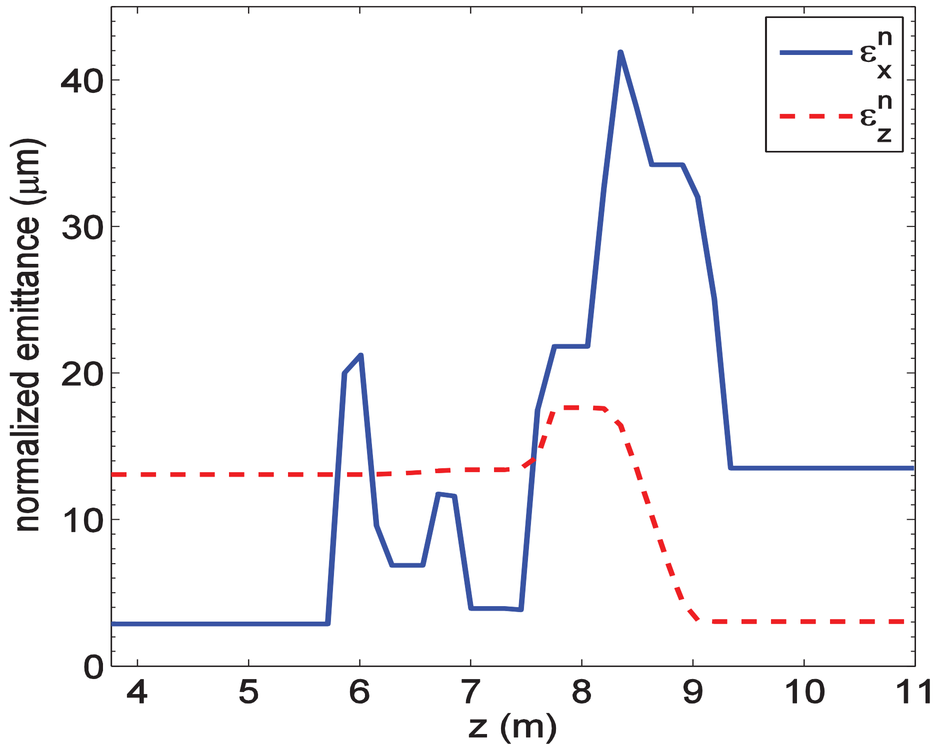
[1] A. Zholents, ANL/APS/LS-327, May 2011

EEX beamline at the Fermilab A0 Photoinjector



A0 EEX Experiment and Simulation at 250pC





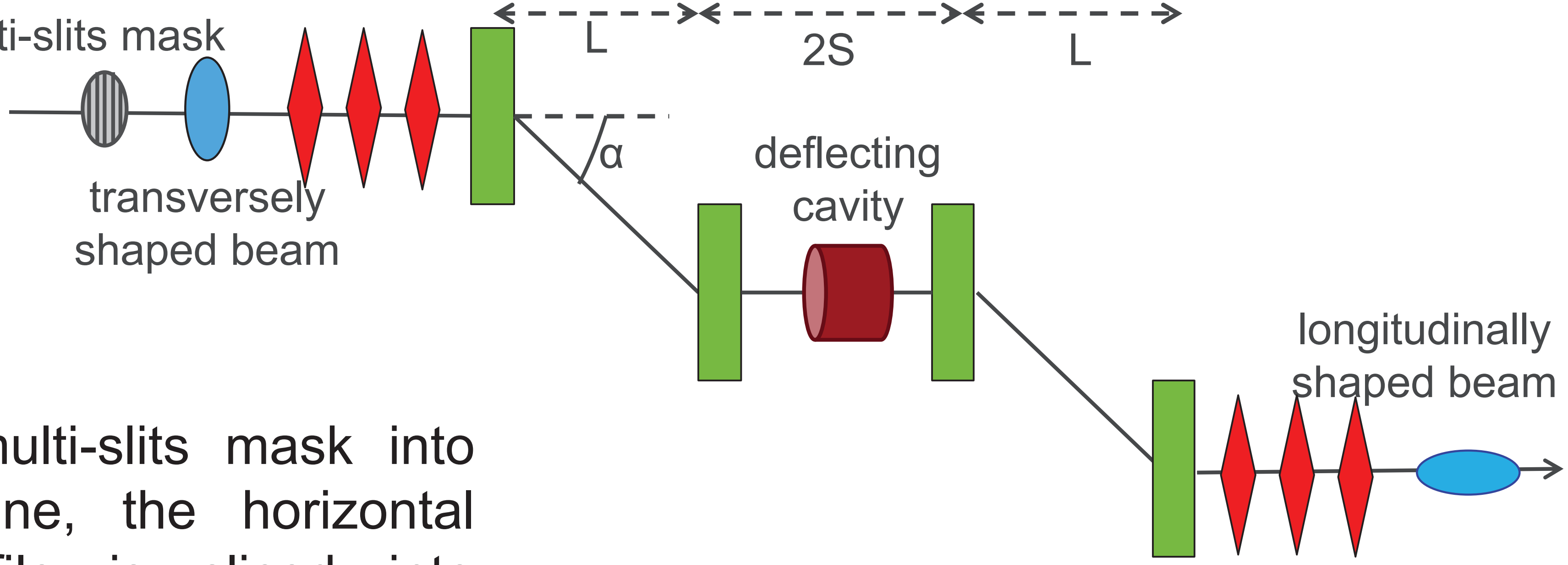
Norm. Emit.	Before EEX (exp.)	After EEX (exp.)	After EEX (simu.)
ε_x^n (μm)	2.9±0.1	11.3±1.1	13.5
ε_z^n (μm)	13.1±1.3	3.1±0.3	2.9
ε_y^n (μm)	2.4±0.1	2.9±0.5	3.0

Round-to-Flat
transverse phase-space manipulation

Emittance Exchange
transverse $\leftrightarrow$ longitudinal phase-space manipulation

Beam Shaping –
Bunch Train Generation via EEX

Longitudinal Shaping using EEX: sub-ps Bunch Train Generation



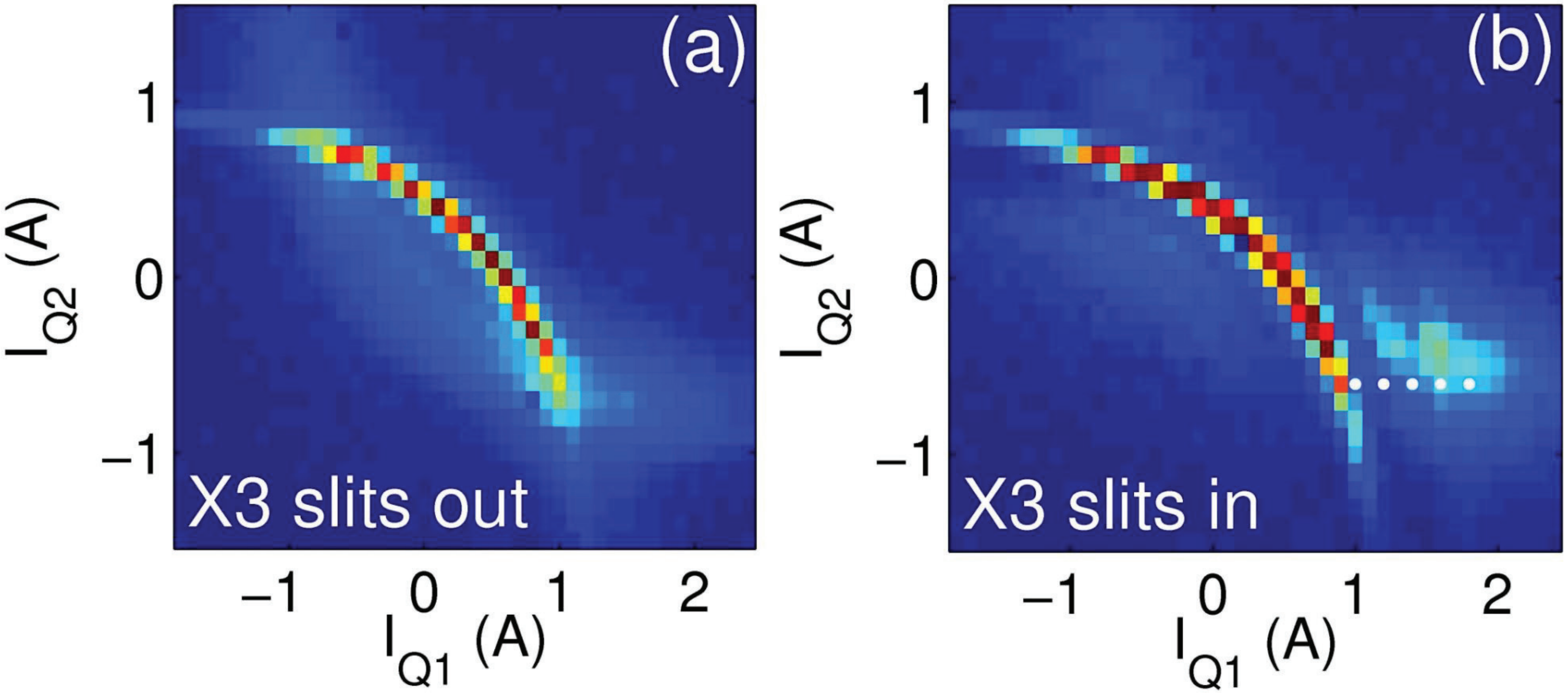
Inserting multi-slits mask into the beamline, the horizontal beam profile is sliced into several beamlets.

After the Phase-space Exchange (PEX), horizontal and longitudinal phase-space are swapped. Therefore, beam is now a bunch-train.

$$\begin{bmatrix} 0 & 0 & \frac{L+S}{L\alpha} & S\alpha \\ 0 & 0 & \frac{1}{L\alpha} & \alpha \\ \alpha & S\alpha & 0 & 0 \\ \frac{1}{L\alpha} & \frac{L+S}{L\alpha} & 0 & 0 \end{bmatrix} \Rightarrow \begin{bmatrix} z_f \\ \delta_f \end{bmatrix} = \begin{bmatrix} \alpha & S\alpha \\ \frac{1}{L\alpha} & \frac{L+S}{L\alpha} \end{bmatrix} \begin{bmatrix} x_i \\ x_i' \end{bmatrix}$$

Quadrupoles before and after EEX to minimize the contribution from x_i'.

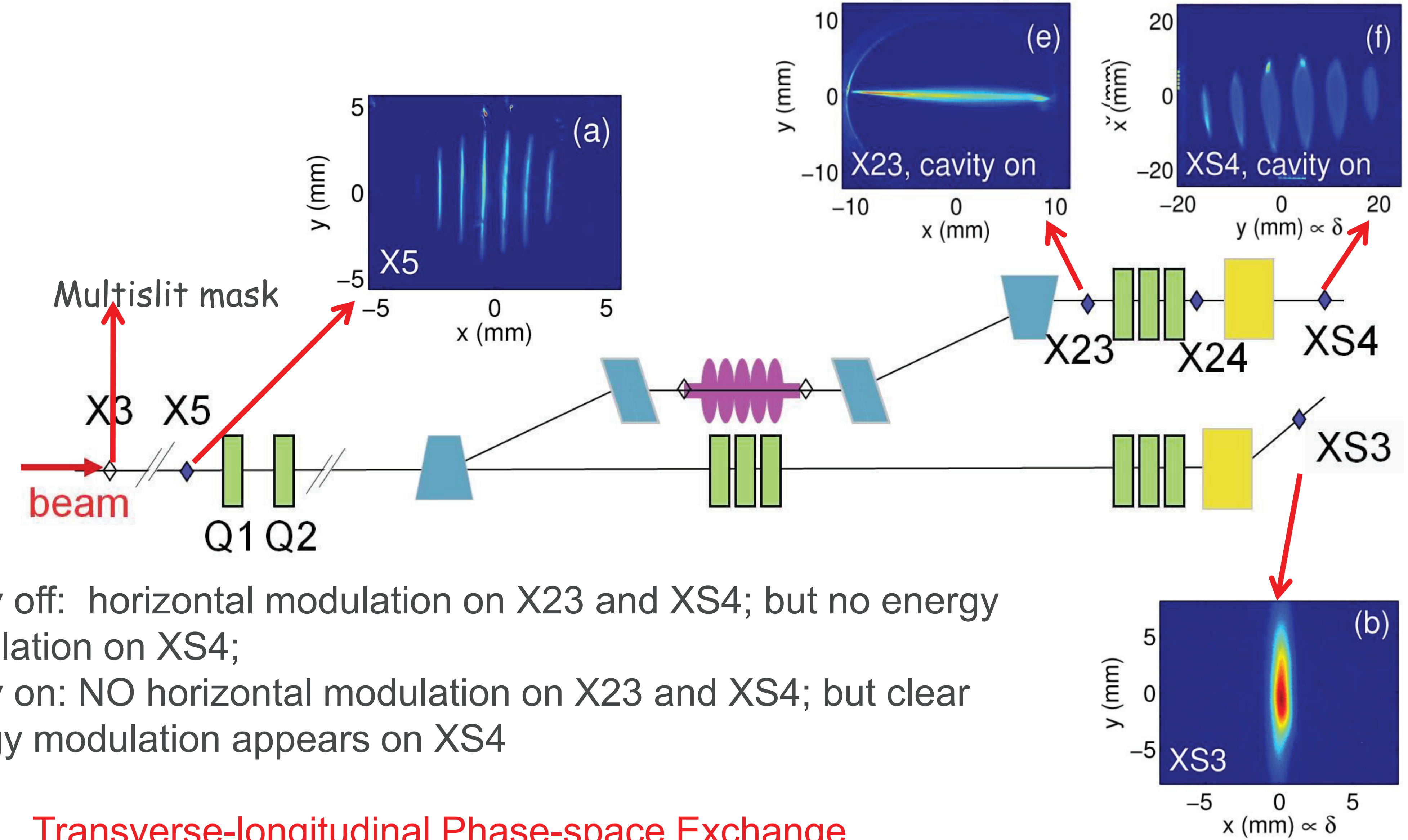
Final bunch length is controlled by initial horizontal beam focusing



While scanning the currents of two quadrupoles upstream of the double-dogleg beamline, the final bunch length after EEX can be monitored using an auto-correlator + bolometer system.

Fig. (a) shows such a quadrupole scan without slits inserted, and (b) with the slits. The small island appeared with the slits inserted is related to the coherent radiation from the bunch-train.

Experimental demonstration of the sub-ps bunch train: energy domain



(1) cavity off: horizontal modulation on X23 and XS4; but no energy modulation on XS4;

(2) cavity on: NO horizontal modulation on X23 and XS4; but clear energy modulation appears on XS4

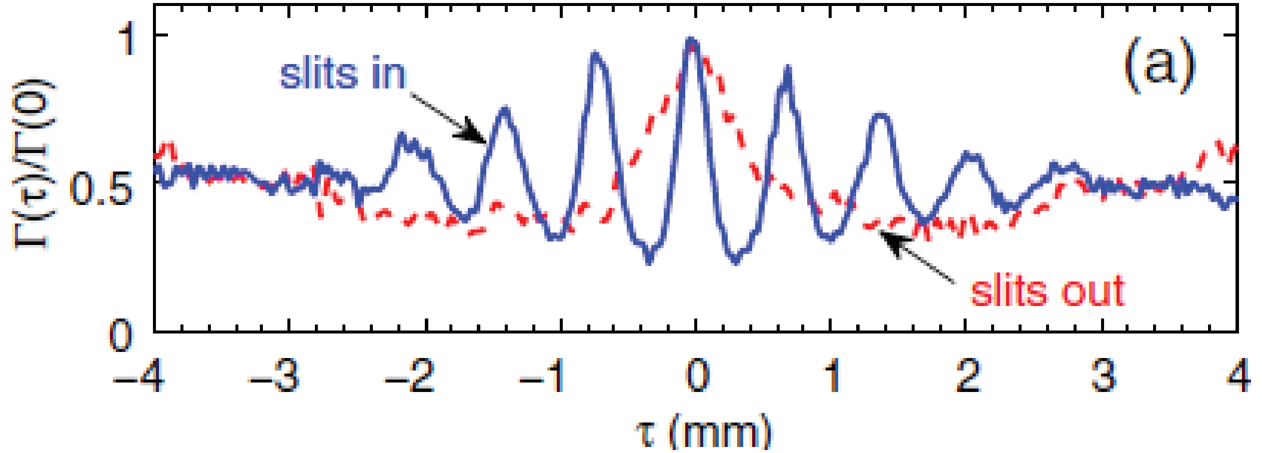
Transverse-longitudinal Phase-space Exchange

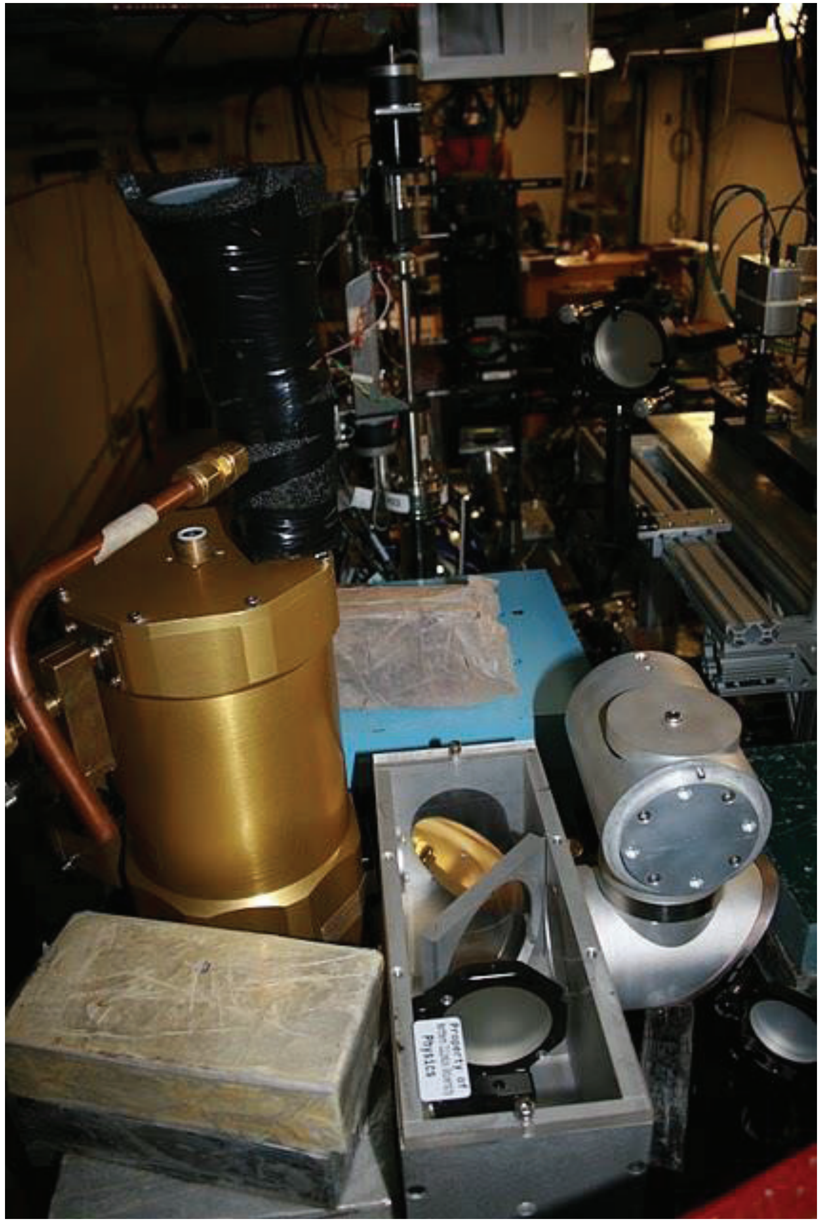
Experimental demonstration of the sub-ps bunch train: time domain

The bunch train temporal structure is measured via the CTR signal measured downstream of EEX.

A liquid-helium-cooled bolometer is used as the detector of the Michelson autocorrelator.

Multipeaks of the autocorrelation function are measured when the slit mask is inserted, compared to a single peak when the mask is out.





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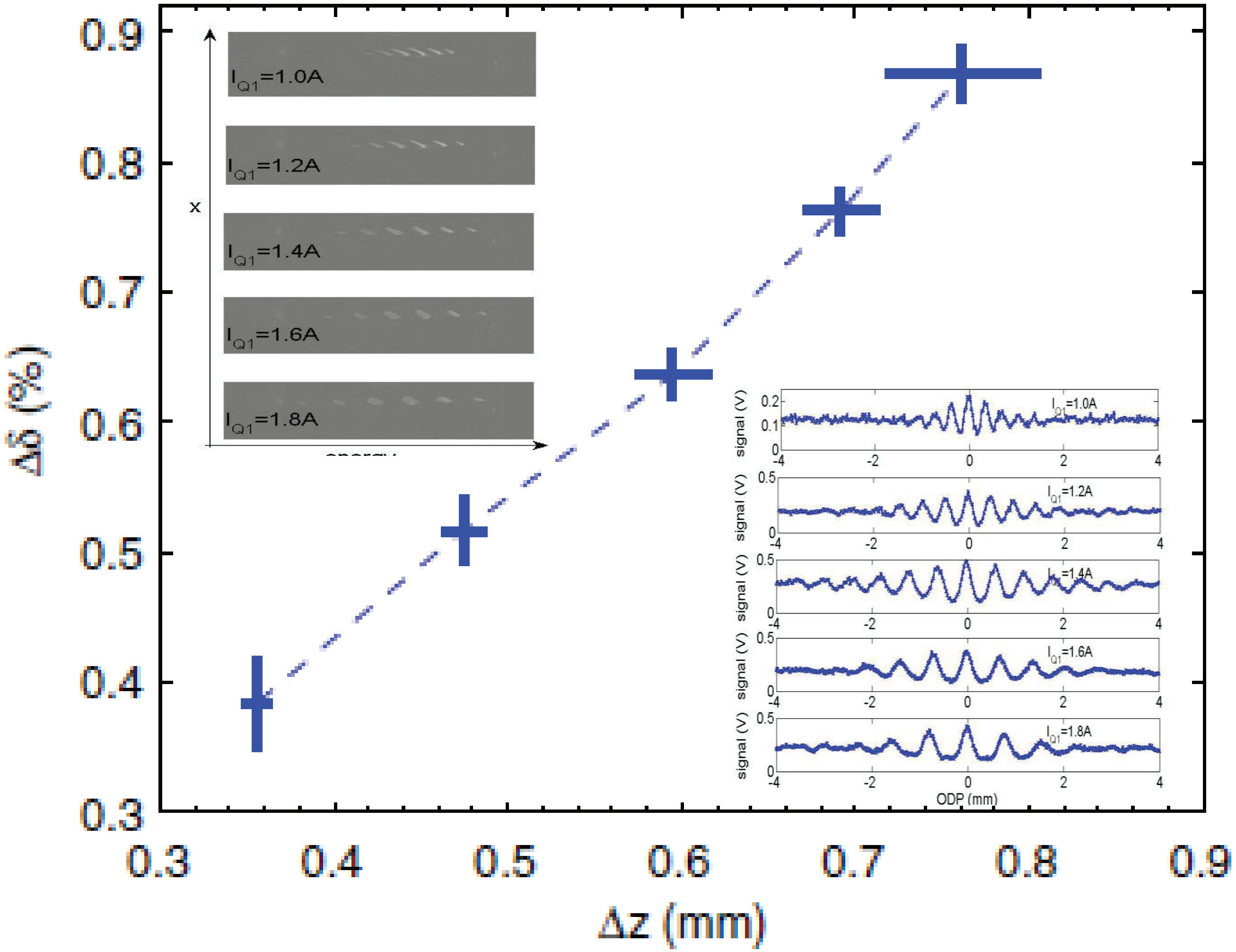
Variable sub-ps bunch train demonstration

The bunch separation is extracted from the autocorrelation function to be [350 ~ 760] μm. The separation can be easily tuned by changing the currents of one single quadrupole upstream of EEX.

The corresponding CTR measured from these bunch trains is a narrow-band (δf/f≈20% at 0.5THz) with tunable frequency of [0.37 0.86] THz. *

Assuming Gaussian distribution, the minimum individual bunch rms duration measured is less than 300 fs.



*P. Piot et al., Applied Physics Letters **98**, 261501 (2011)

Round-to-Flat
transverse phase-space manipulation

Emittance Exchange
transverse ↔ longitudinal phase-space manipulation

Beam Shaping –
Bunch Train Generation via EEX

Longitudinal Bunch Shaping via EEX
-- Precise Beam Profile Control

Arbitrary Longitudinal Beam Profile Shaping

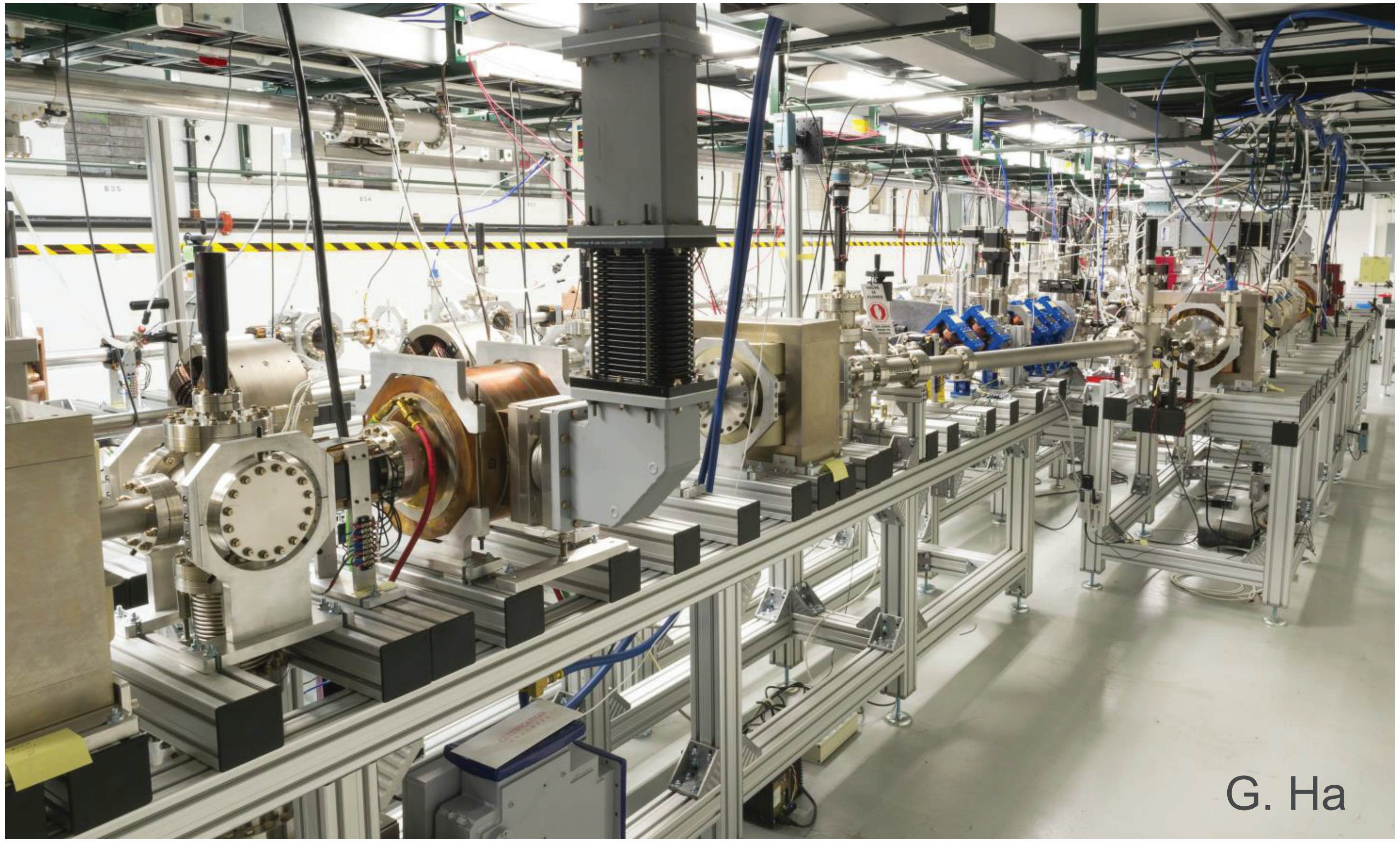
- Lots of mature and emerging techniques are available for transverse beam shaping:
  - Inserting masks in the beam path, using quadrupoles to focus/defocus etc.;
  - Shaping the drive-laser transverse profile for a photo-injector including digital micro-mirror [1] or micro-lens array to generate beamlets [2] or nano-emitter cathode array [3];
  - Nano-modulated electrons via diffraction through a crystal [4].

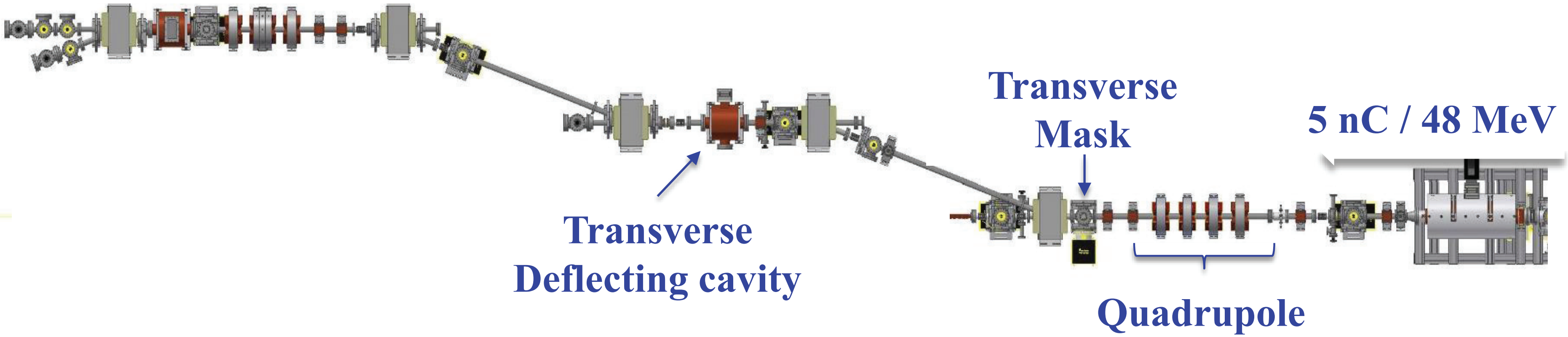
- Specific longitudinal profile is desired for various applications – however longitudinal shaping techniques to achieve arbitrary beam profile are rather limited relative to transverse shaping.

- EEX offers an opportunity to shape the beam transversely and then convert it to longitudinal – it has been demonstrated at the Argonne Wakefield Accelerator (AWA/ANL).

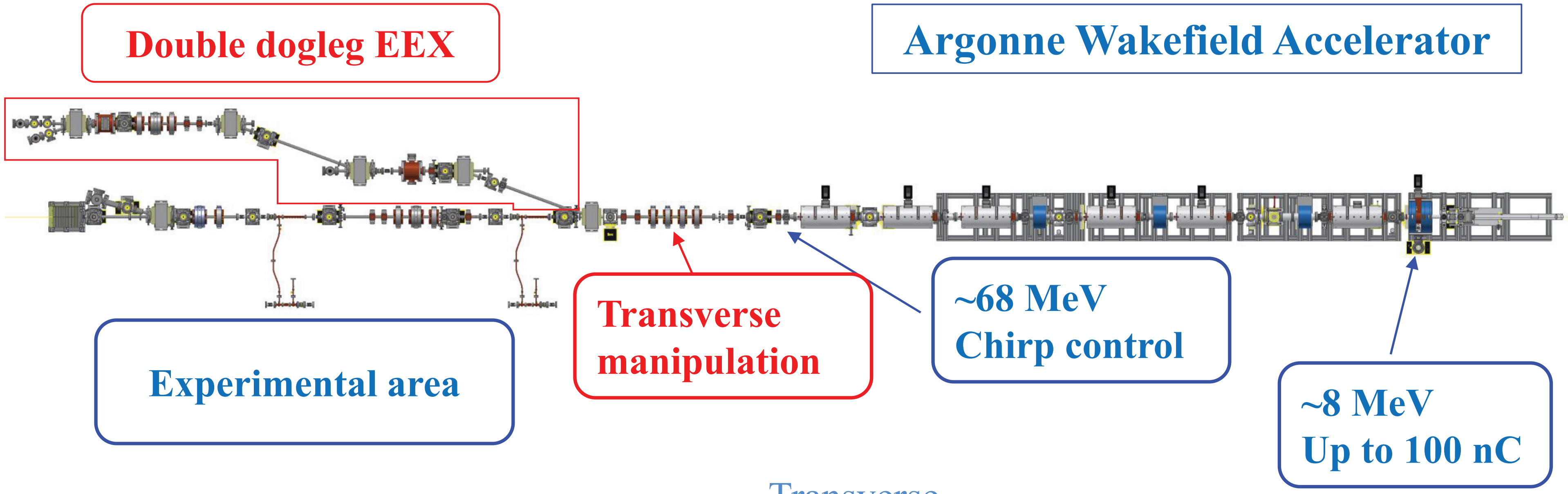
[1] S. Li et al, PRSTAB 20, 080704 (2017)
[2] A. Halavanau et al. PRSTAB 20, 103404 (2017)
[3] W. Graves et al., PRL 108, 263904 (2012)
[4] E. A. Nanni, et al, PRSTAB 21, 014401 (2018)

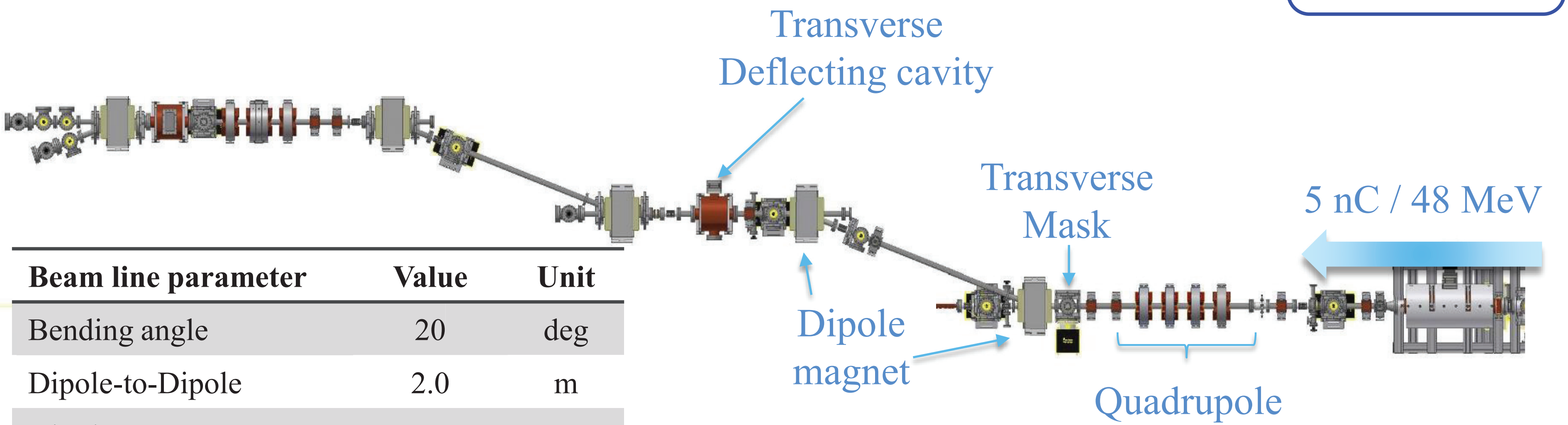
EEX Beamline at Argonne Wakefield Accelerator (AWA)





Double dogleg EEX beam line at AWA



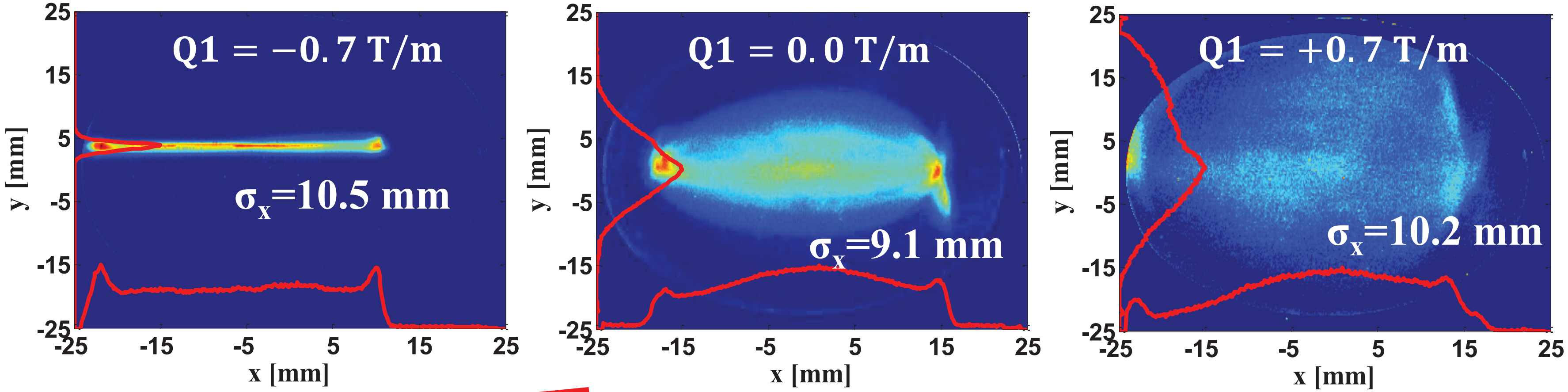


Beam line parameter	Value	Unit
Bending angle	20	deg
Dipole-to-Dipole	2.0	m
Dipole-to-TDC	0.5	m
Power to TDC	1.2	MW

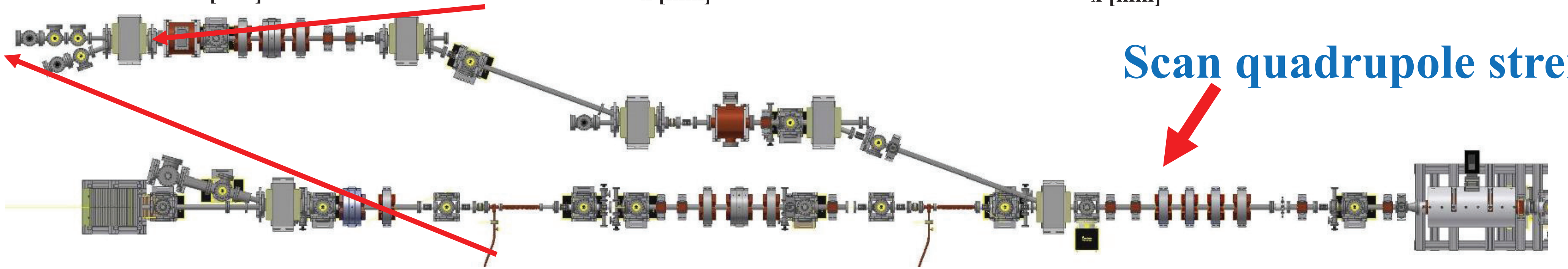
(AWA slides courtesy of J. Power)

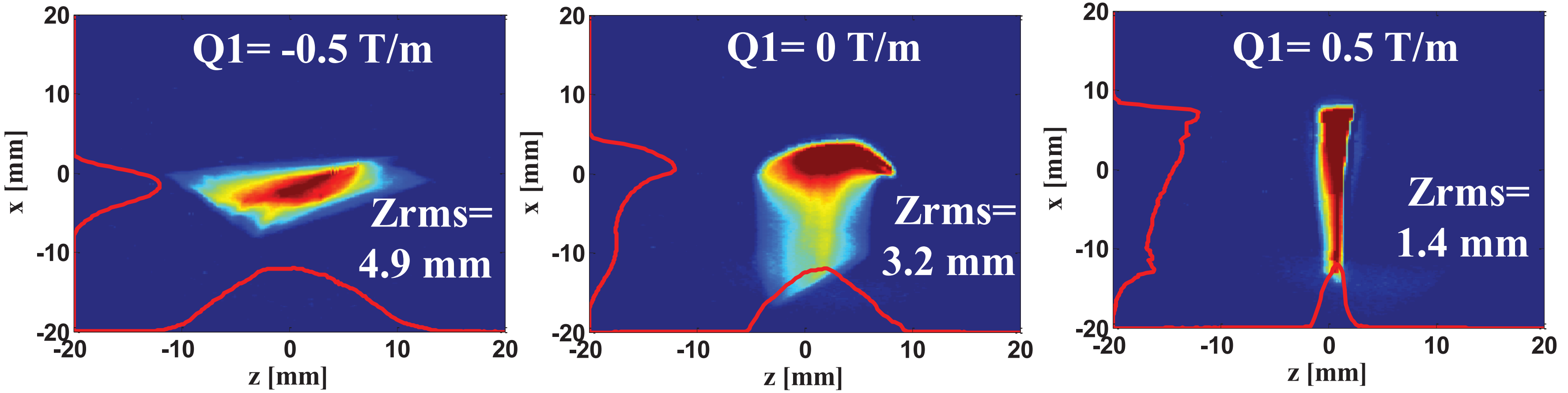
Bunch Length Control via Horizontal Focusing

EXPERIMENT: Quad strength controls bunch length instead of horizontal beam size



Xrms: small variation

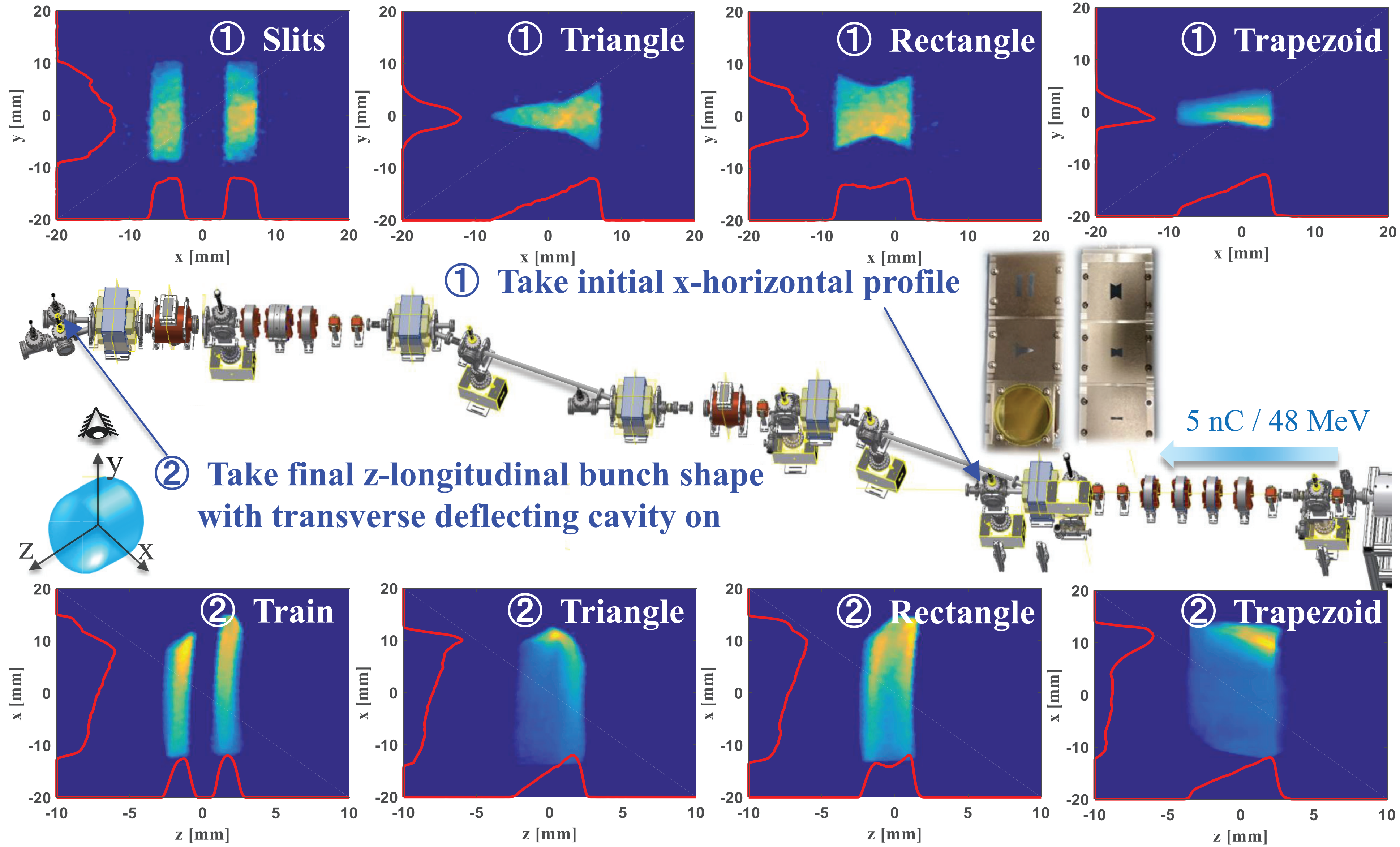




Zrms: large difference

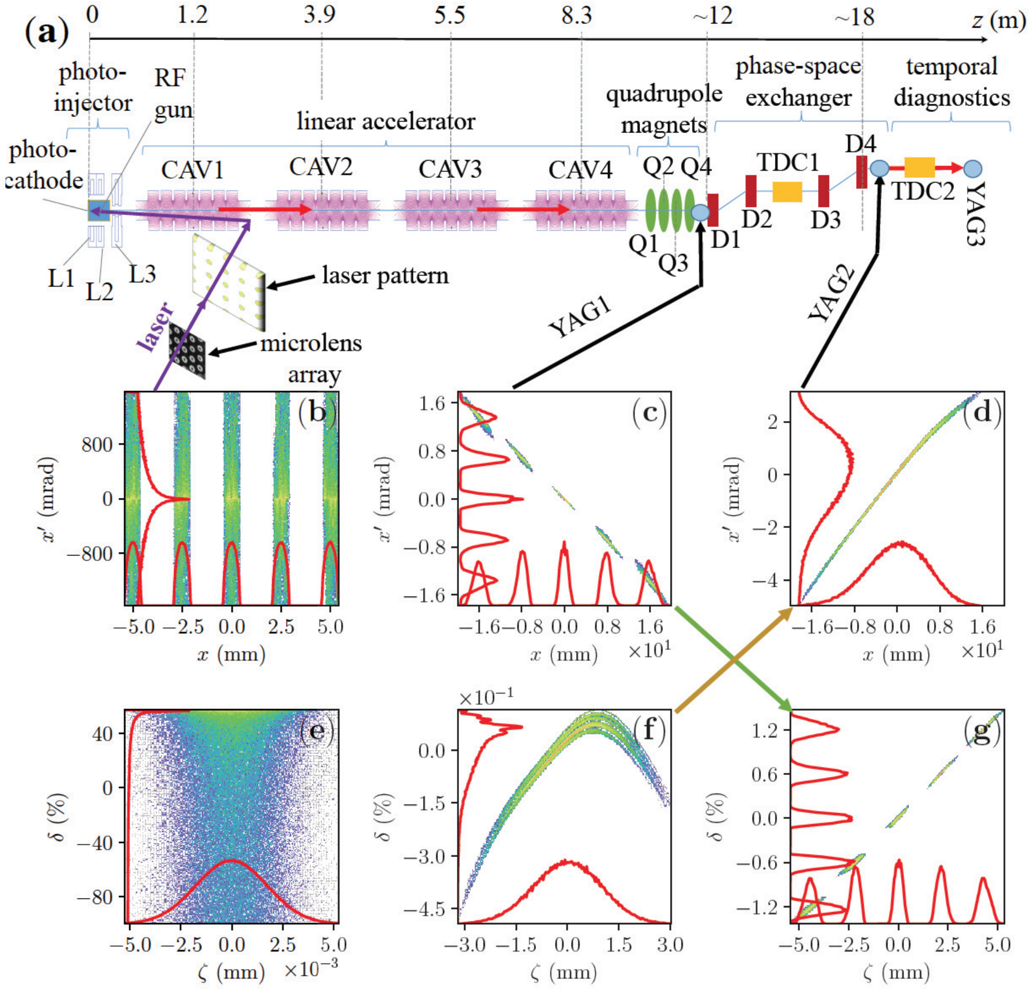
Precision Control of Longitudinal Bunch Shape via EEX

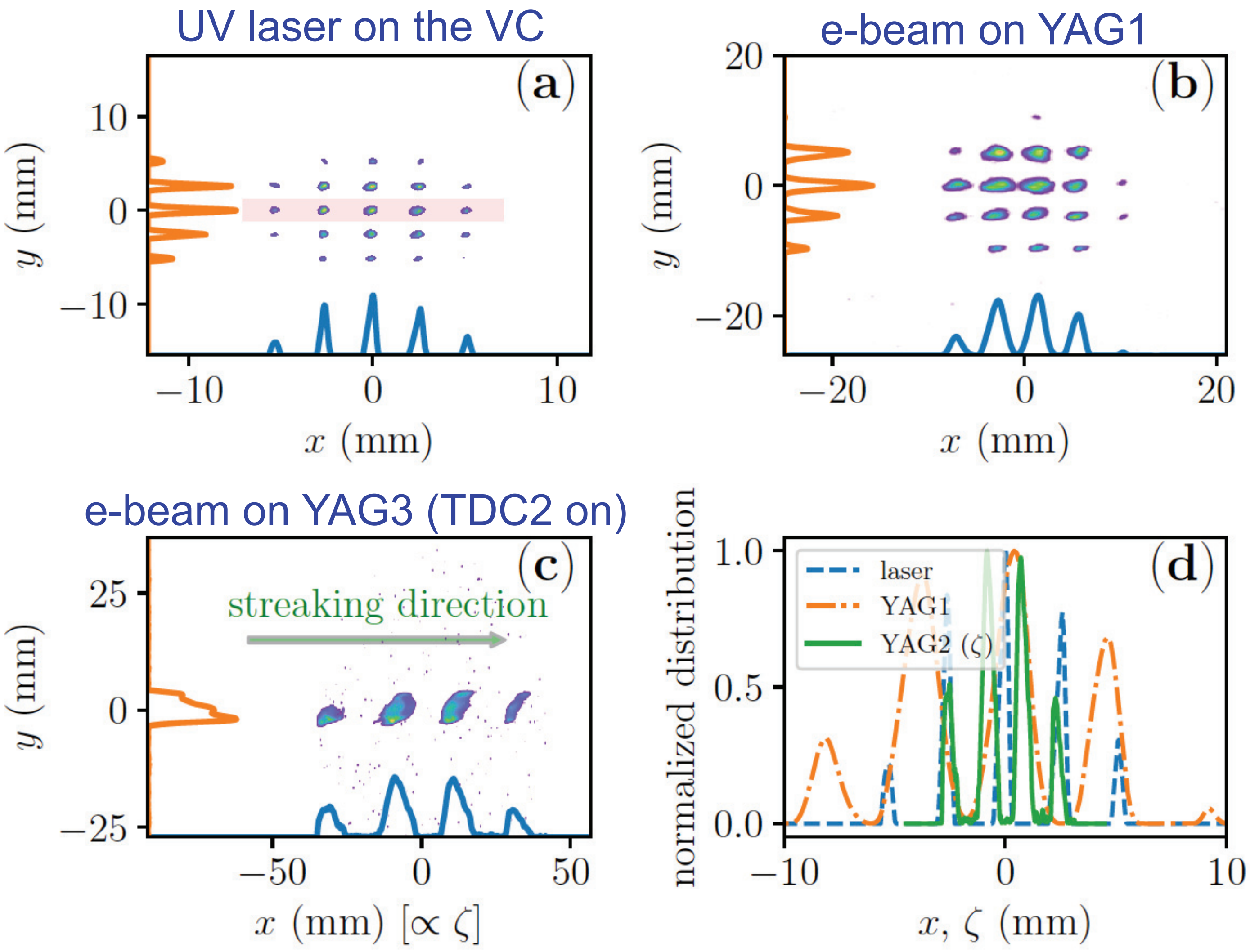
EXPERIMENT: Transverse mask to tailor longitudinal density profile



G. Ha et al, PRL 118, 104801 (2017).

Combining Laser Shaping with EEX

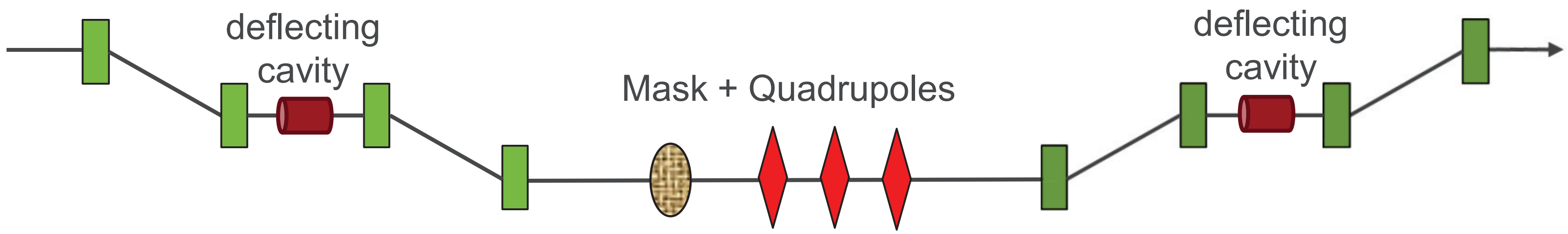




Courtesy of P. Piot and A. Halavanau; to be published.

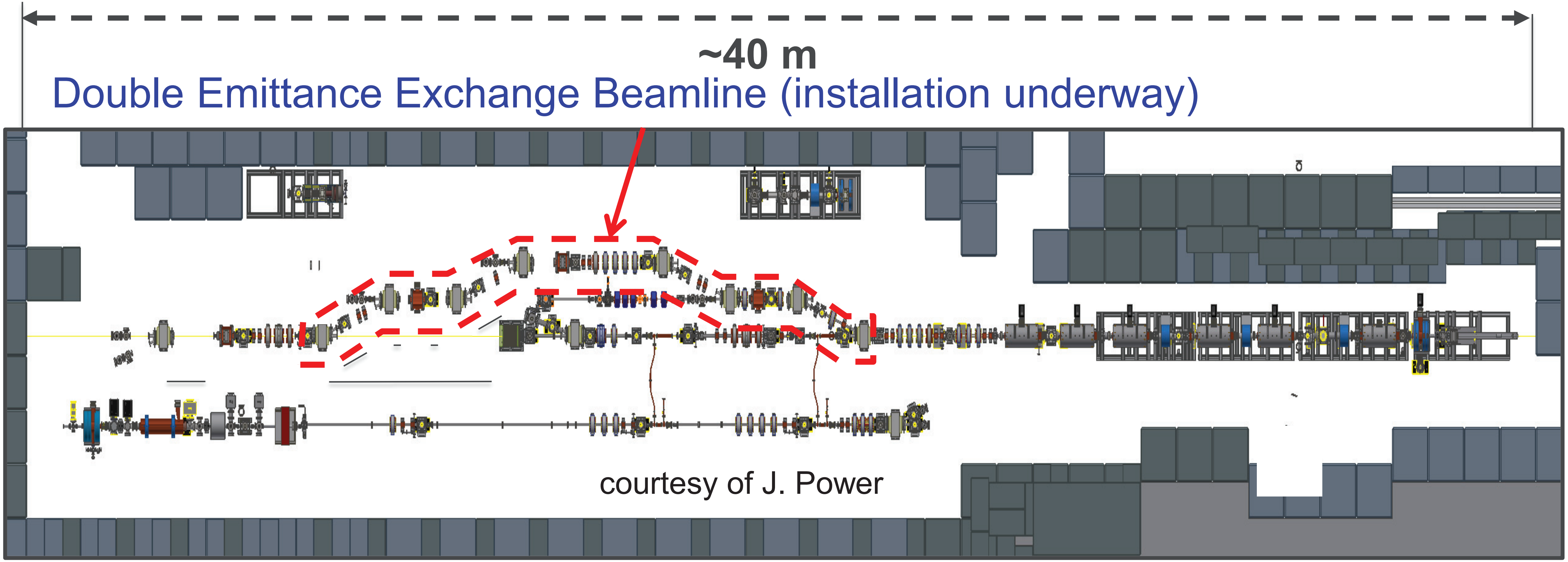
Beam Shaping via 6D Phase-Space Manipulation

- Single-stage EEX:
  - The double-dogleg EEX approach leave the beam line with a transverse offset, not desired in a straight linac accelerator tunnel;
  - As the transverse and longitudinal phase space exchange only once, the final transverse emittance might be larger than before the EEX – which may not be a desired feature for some applications;
  - Timing/energy jitter will be converted into transverse jitter.
- Double-stage EEX
  - Adding another double-dogleg EEX as a second stage will solve the issues encountered above.
  - In between the two stages of EEX, mature transverse phase space manipulation techniques can be deployed to create final longitudinal phase space.



- Round-Flat beam transformation + EEX→ Arbitrary 6D phase-space manipulation
  - Round-to-flat beam transformation between the two transverse phase spaces;
  - Transverse-to-longitudinal EEX between any transverses phase space and the longitudinal phase space.

Double Emittance Exchange Beamline at AWA/ANL



Beam Energy ~ 70 MeV
Single bunch charge <100 nC
Up to 32 bunch trains

AWA EEX related presentations in IPAC2019:
MOPRB071 by M. Conde et al., ***AWA Facility Upgrade***
TUPGW089 by G. Ha et al., ***Tunable Bunch Train Generation***
WEPTS067 by J. Soek et al., ***Suppression of Energy Spread***
For more detailed simulations and experiment planning see G. Ha, NAPAC2019.

Flat Beam Experiment at AWA*

- Round-to-flat beam transformation has been demonstrated recently at AWA with 1 nC bunch charge.

Parameter	Value	units
Laser pulse duration FWHM	12	ps
Laser spot radius	3.2	mm
Laser launch phase	50	deg
Magnetic field on cathode (B_c)	0.125	T
Beam energy	43	MeV
Magnetization ($\gamma\mathcal{L}$)	102	μm

- When combined with EEX or double EEX, 6D phase-space manipulation will increase our beam shaping capabilities.

Measured and simulated Flat beam parameters at AWA*

Parameter	Value	
Bunch charge (nC)	1.0±0.18	
$\varepsilon_+ = \varepsilon_x$ (μm)	213.20±31.9	
$\varepsilon_- = \varepsilon_y$ (μm)	1.93±0.28	
emittance ratio	110	
Skew quads	**measured**	**simulated**
DQ1 B' (T/m)	-3.13	-3.26
DQ2 B' (T/m)	3.93	3.97
DQ3 B' (T/m)	-3.23	-3.13

*WEPTS094 by T. Xu et al, ***Generation of High-Charge Flat Beams at AWA***

Acknowledgements

Thanks to AWA colleagues J. Power and G. Ha for AWA EEX related figures; to P. Piot, A. Halavanau and T. Xu of Northern Illinois University for micro-lens array and AWA flat-beam related figures.