Electron Beam Current-Profile Shaping Via Transverse-to-Longitudinal Phase-Space Exchange

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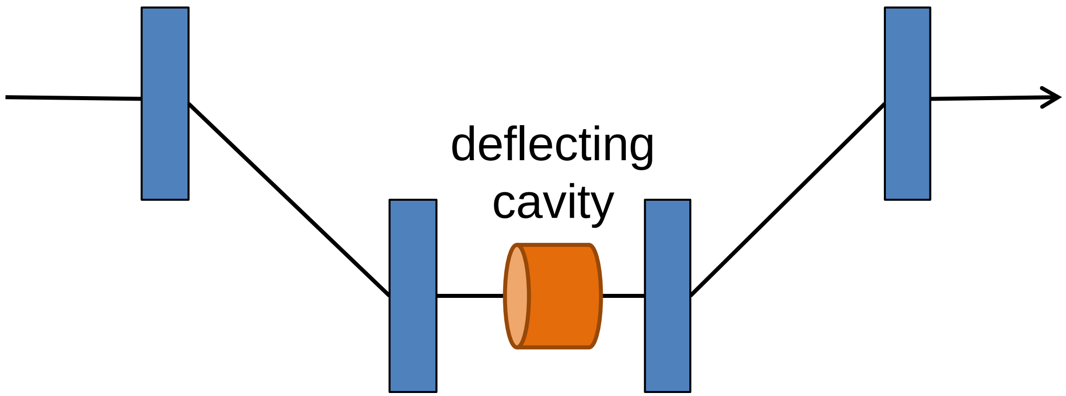
Introduction

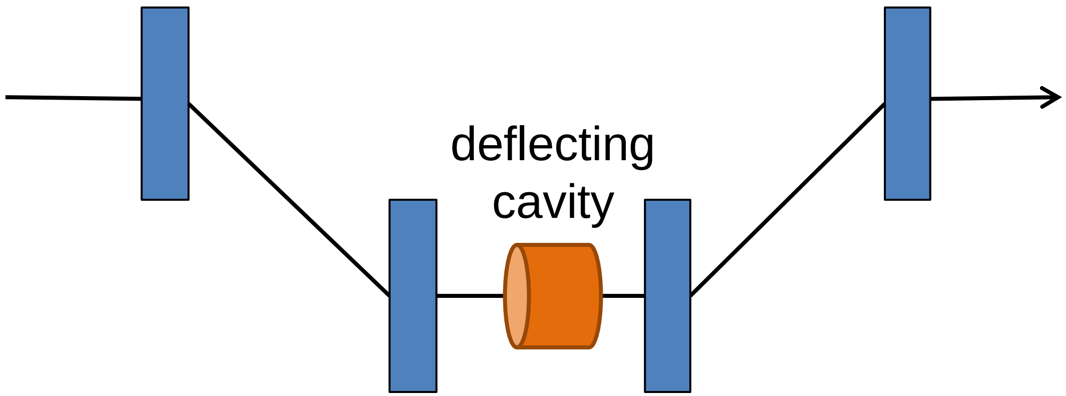
- The electron beam straight out a photo-injector does not always have the phase-space properties required in its applications.
- Phase-space manipulation is necessary to achieve certain beam distributions.
  - In the sub-category of beam current profile shaping:
    - Longitudinally compressed → higher peak current;
    - Phase-Space (Emittance) EXchange→
      - bunch train with subps tunable spacing → coherent radiation in THz or optical wavelength;
      - linearly ramped current → plasma or dielectric wakefield acceleration…

Emittance EXchange (EEX)



Emittance EXchange (EEX)

- EEX therory:
  - 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:
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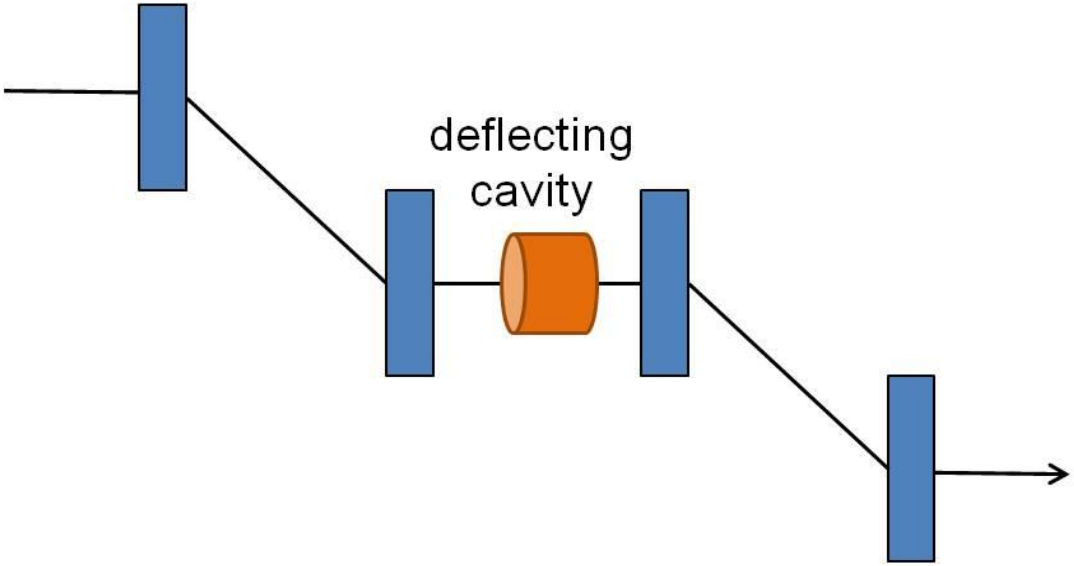

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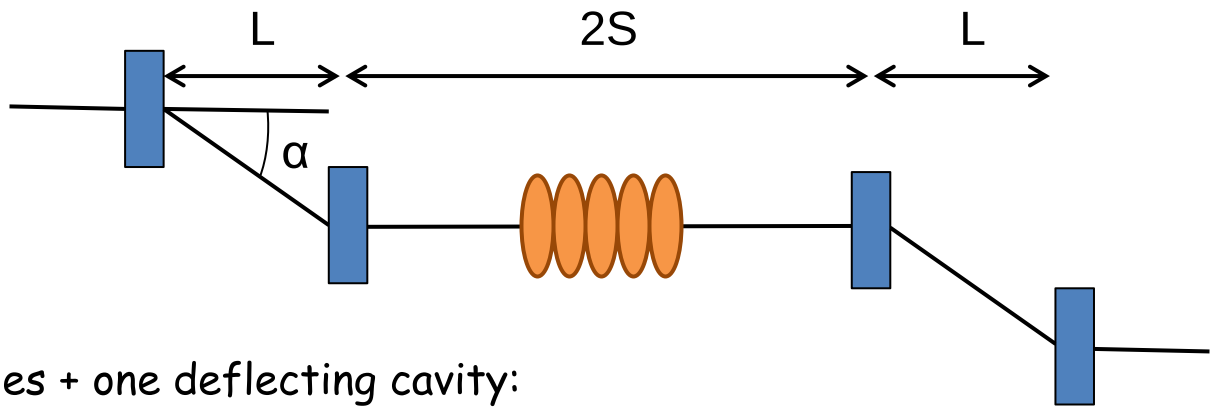
Double-dogleg Emittance Exchanger



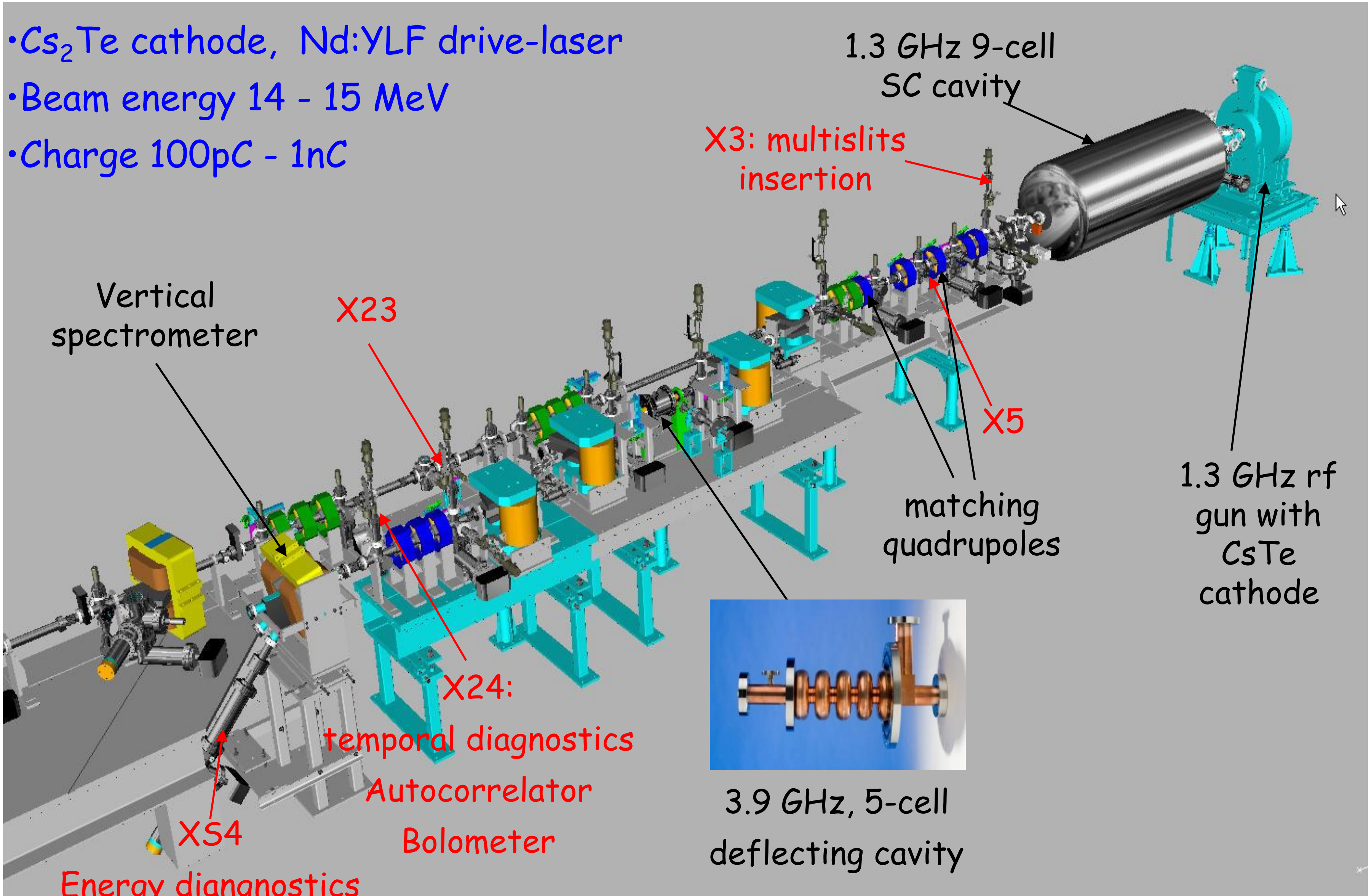
Four dipoles + one deflecting cavity:

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.

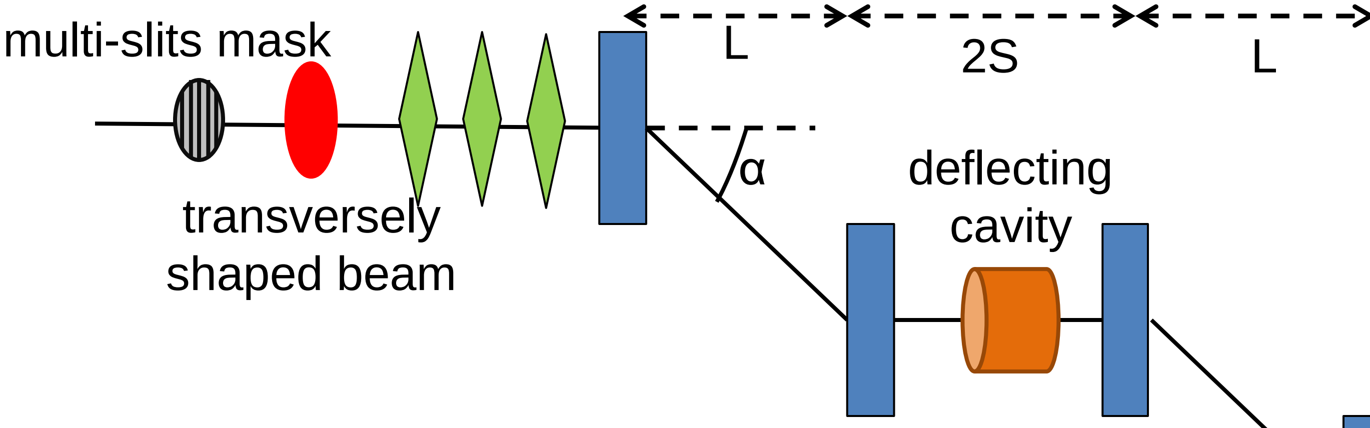
$$\begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix}_{out} = \begin{pmatrix} 0 & 0 & \frac{L+S}{\alpha L} & \alpha S \\ 0 & 0 & \frac{1}{\alpha L} & \alpha \\ \alpha & \alpha S & 0 & 0 \\ \frac{1}{\alpha L} & \frac{L+S}{\alpha L} & 0 & 0 \end{pmatrix} \begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix}_{in}$$

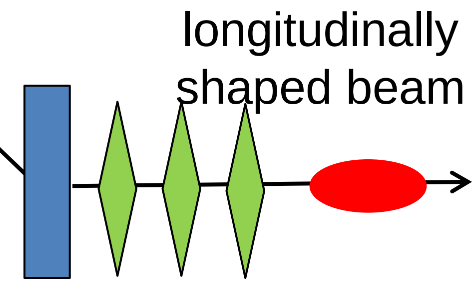
EEX beamline at A0 photoinjector, Fermilab

- Cs_2Te cathode, Nd:YLF drive-laser
- Beam energy 14 - 15 MeV
- Charge 100pC - 1nC



Sub-ps Bunch Train Generation via PEX





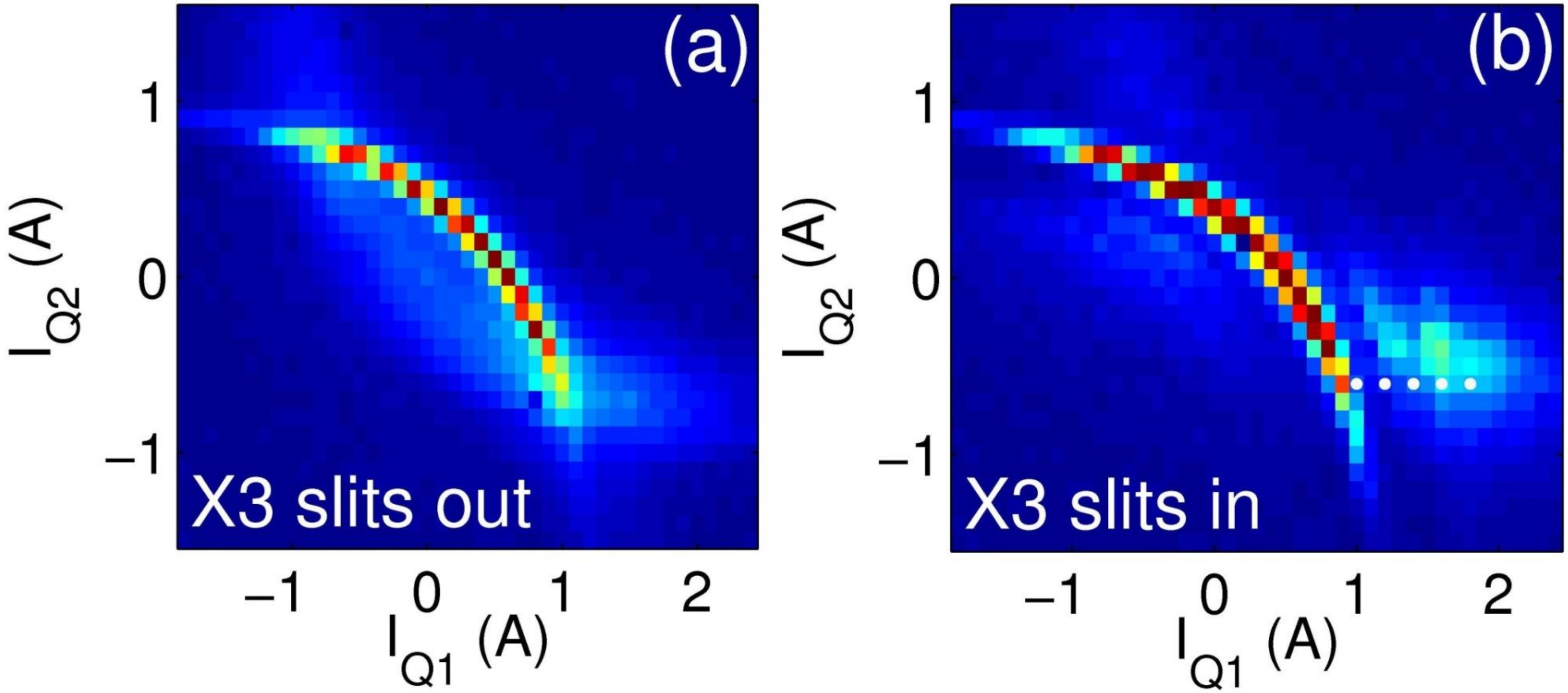
Inserting multi-slits mask into the beamline, the horizontal beam profile is sliced into several beamlets.

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

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

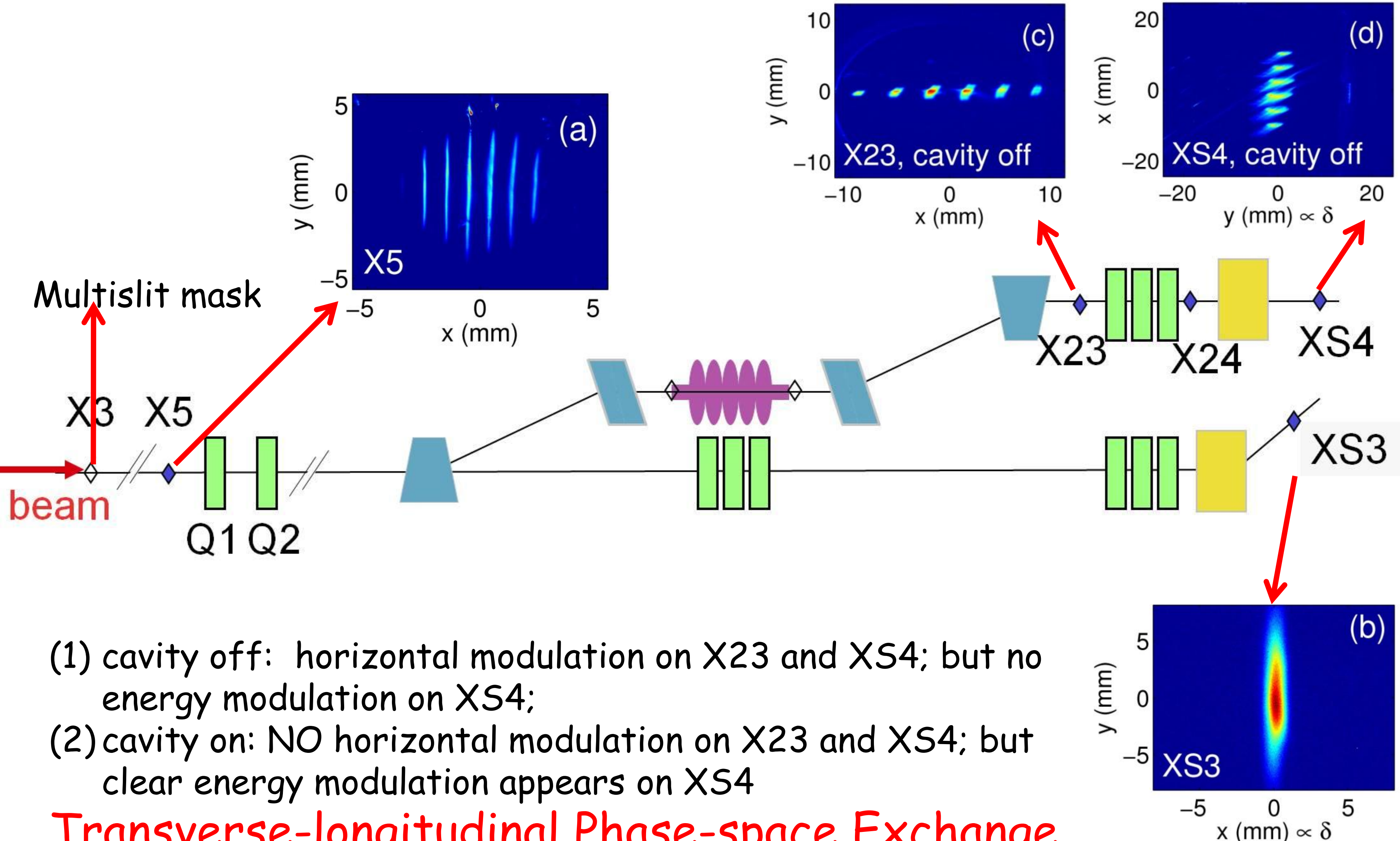
Quadrupole channels before and after EEX to minimize the contribution from x_i'.

Final bunch length control via initial horizontal beam focusing



The final beam longitudinal properties can be controlled by initial horizontal beam parameters.
While scanning the currents of two quadrupoles upstream of the double-dogleg beamline, the final bunch length after PEX can be monitored using an autocorrelator+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 structure.

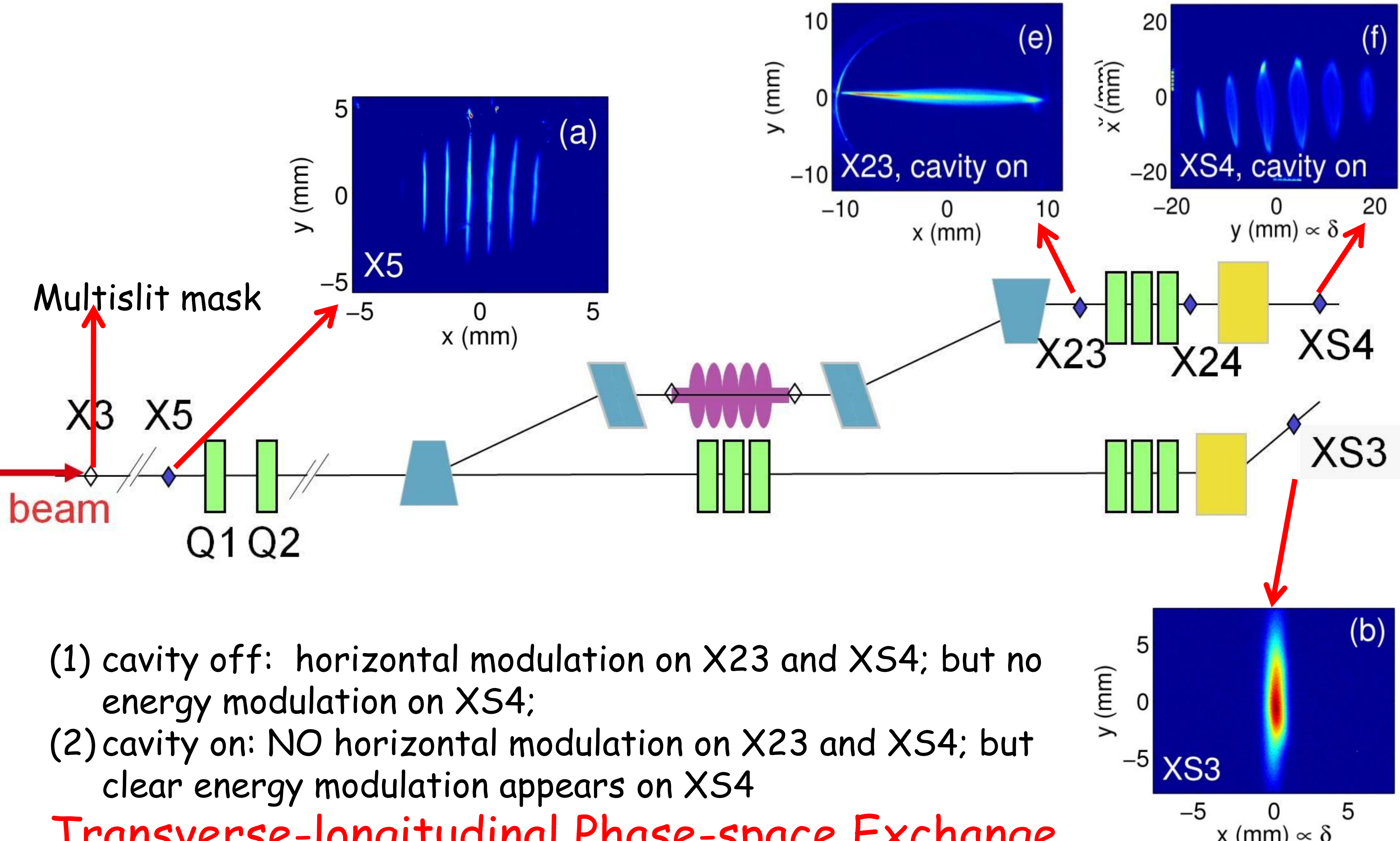
Experimental demonstration of the sub-ps bunch train: energy domain



(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



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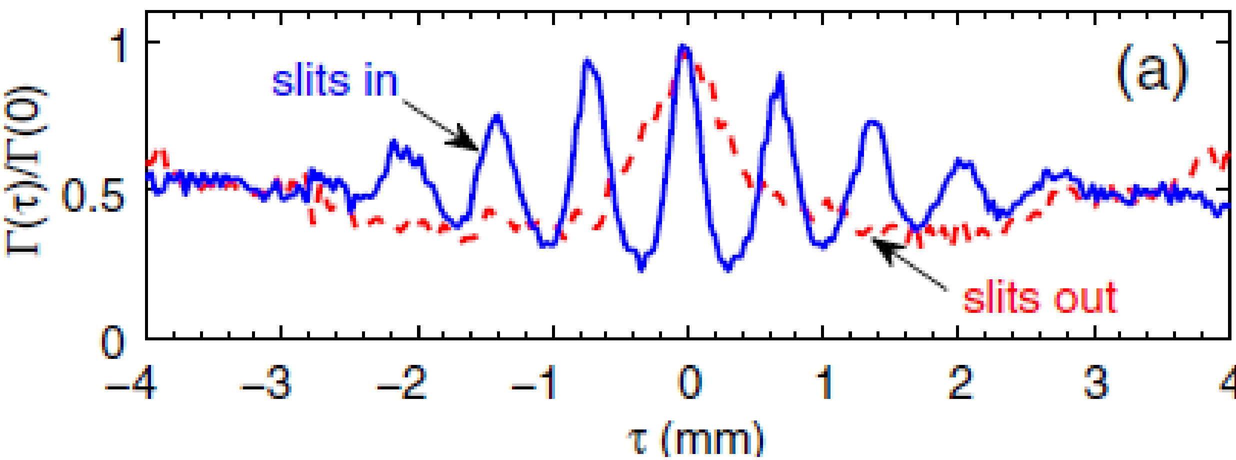
Transverse-longitudinal Phase-space Exchange

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.

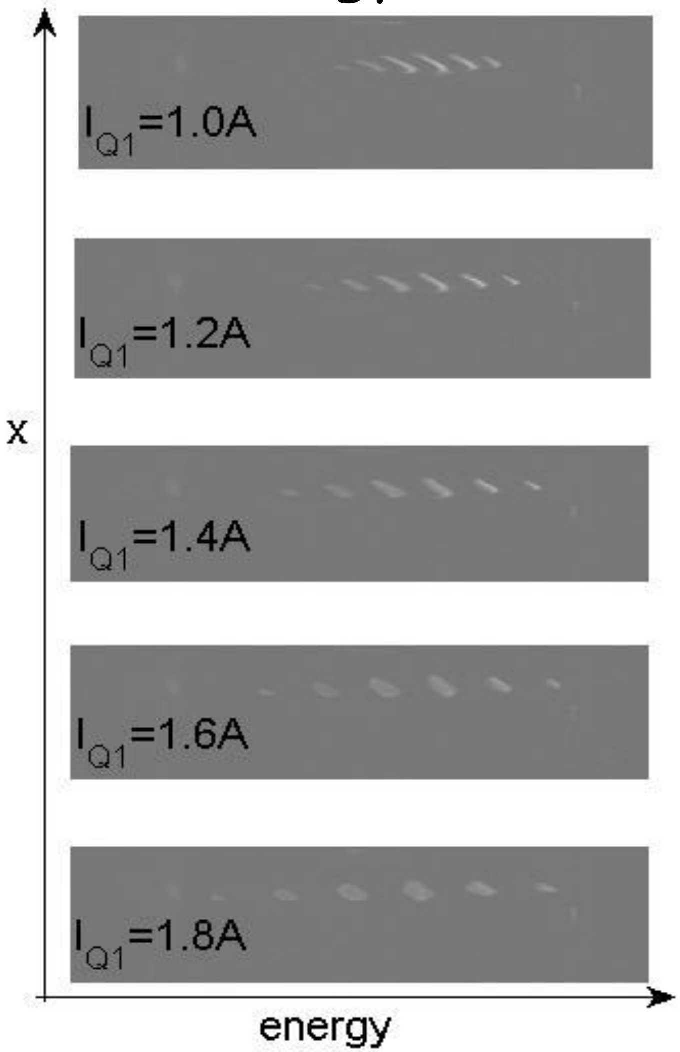
A liquid-helium-cooled bolometer is used as the detector of the Michelson autocorrelator.

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

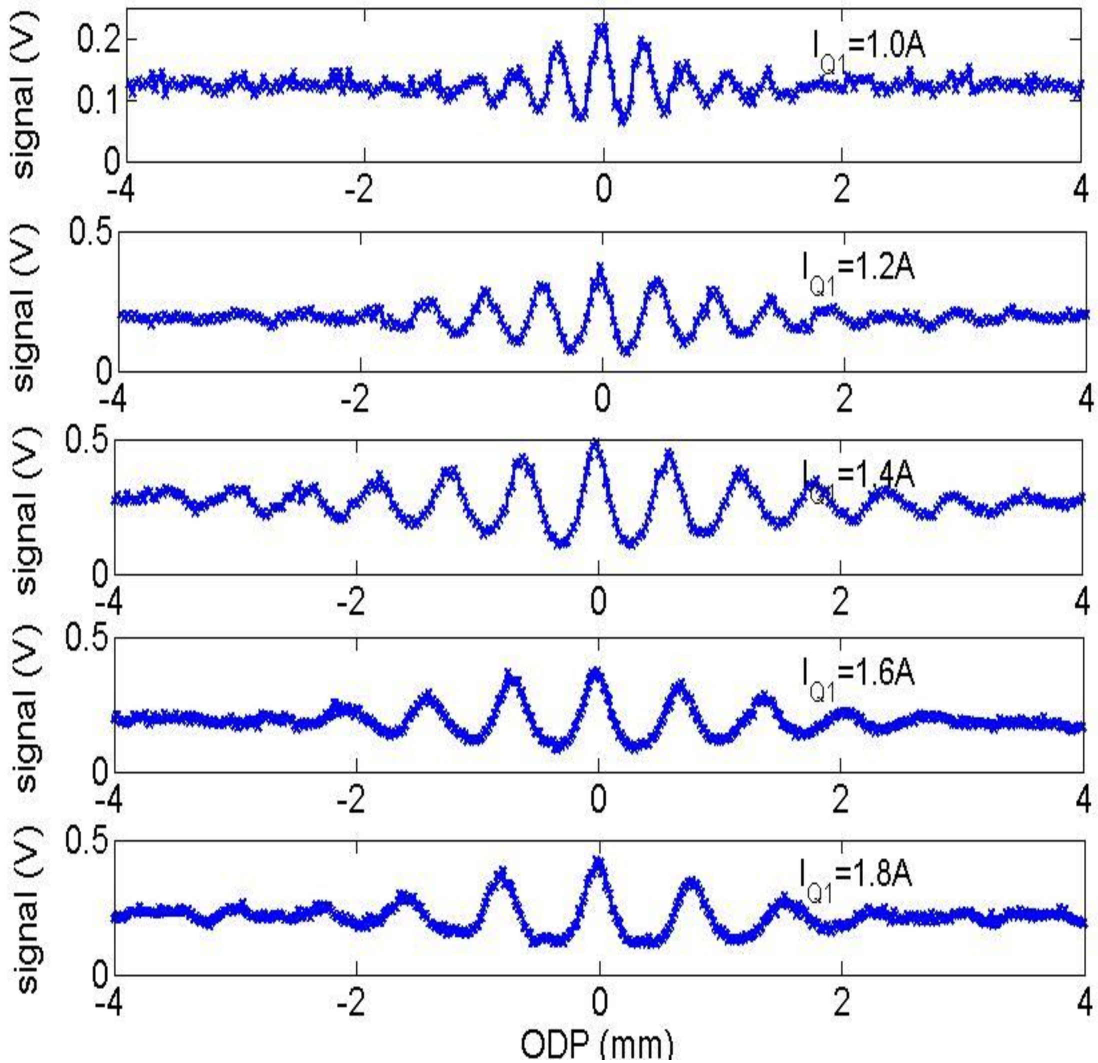


Experimental demonstration of the sub-ps bunch train

energy



time: autocorrelation function



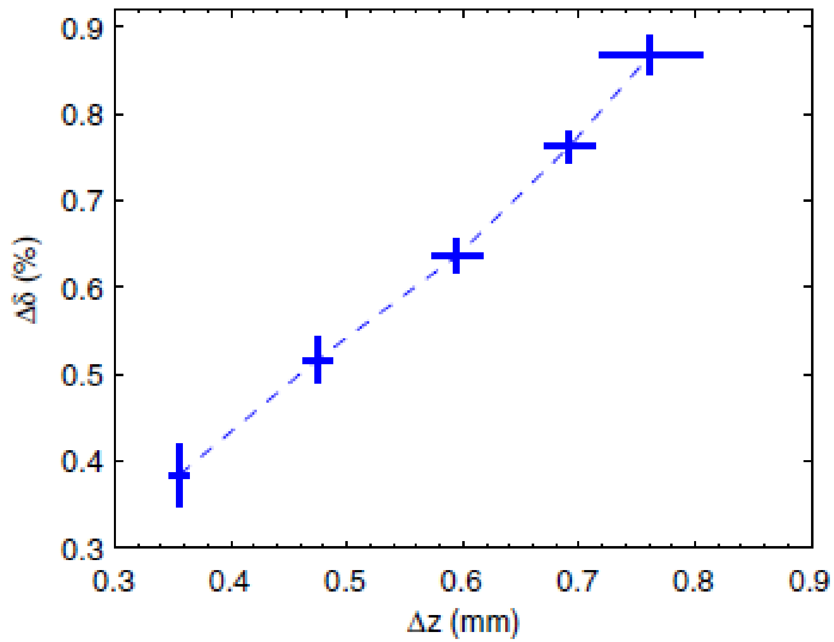
Y.-E Sun et al, PRL 105, 234801 (2010).

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

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

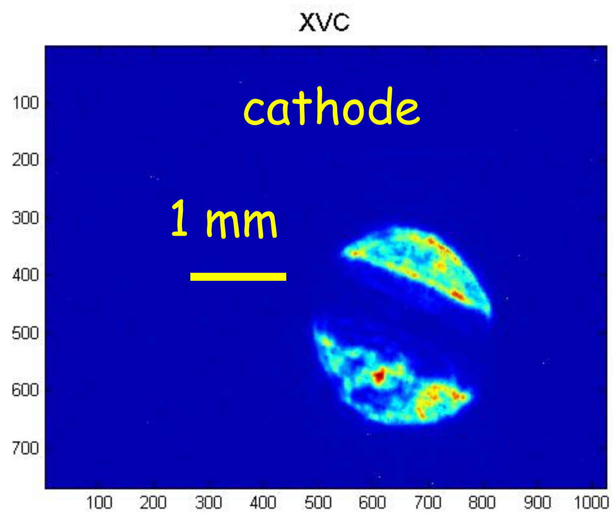
The corresponding CTR measured from these bunch trains is a narrow-band (δf/f≈20% at 0.5THz) with tunable frequency of [0.37 0.86] THz. *

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



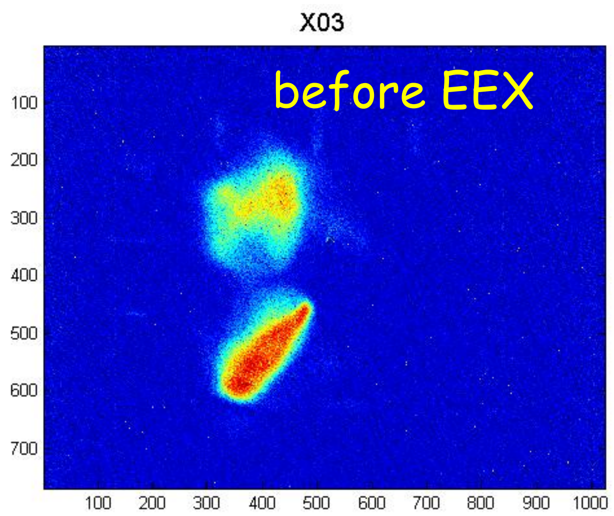
*P. Piot et al., Applied Physics Letters **98**, 261501 (2011)

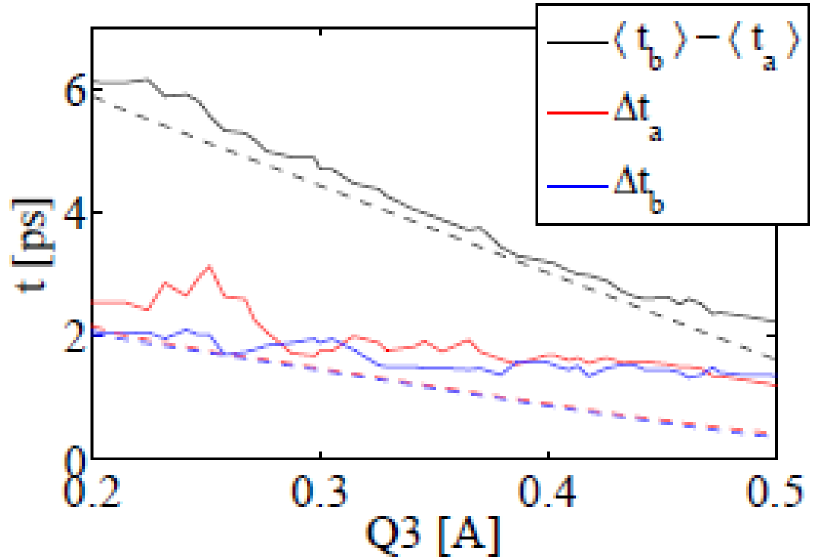
Direct Beam Shaping at the Cathode



By inserting a 1mm diameter rod into the photo-cathode drive laser, the beam is divided into two beamlets on the cathode, then transported through the EEX beamline.

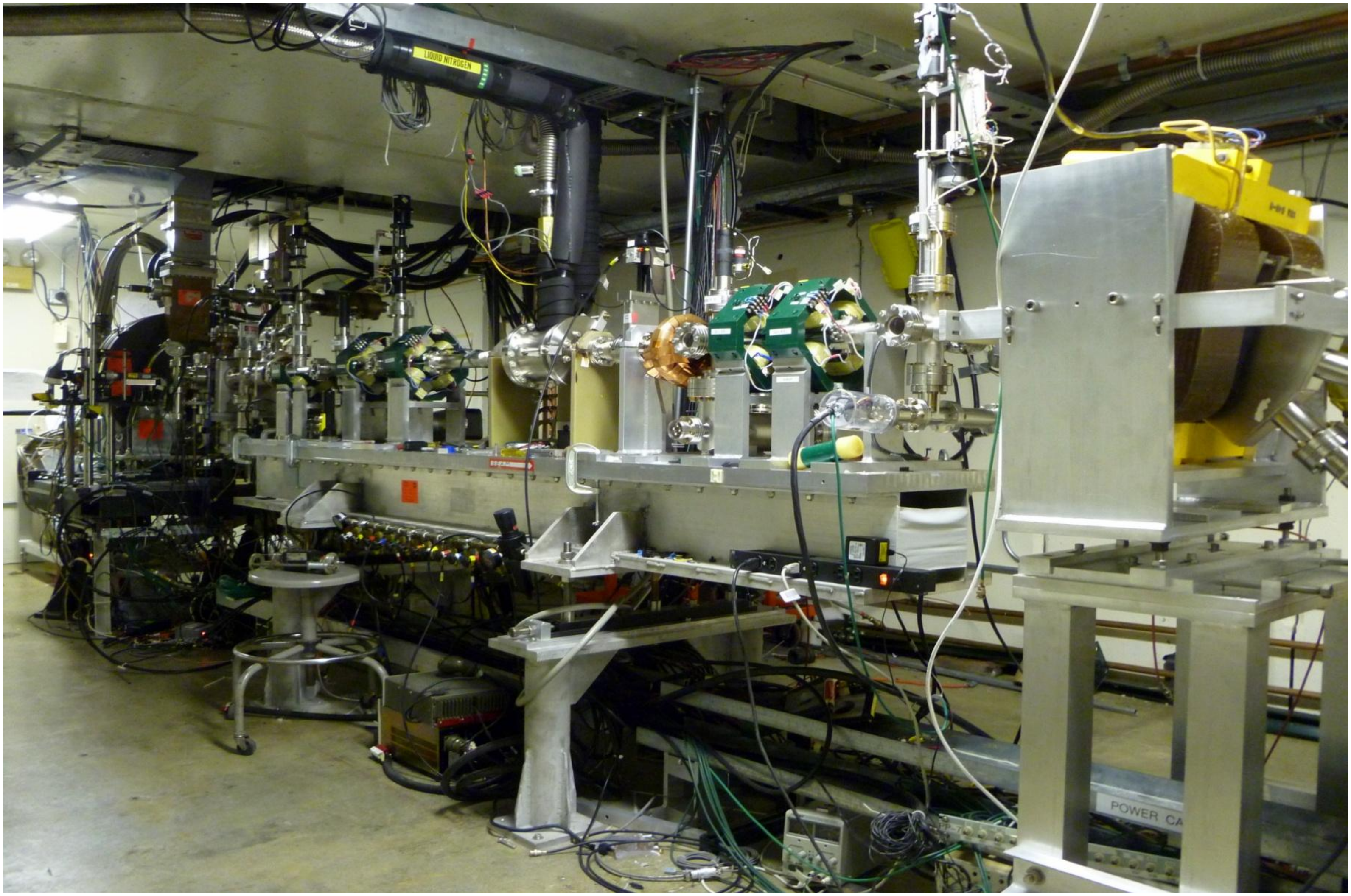
after EEX, two beamlets in time was measured via electro-optical effects: bunch separation, single bunch rms length.





*T. Maxwell et al., WEPP030, IPAC 2012, New Orleans, USA.

From A0 to High Brightness Electron Source Lab.



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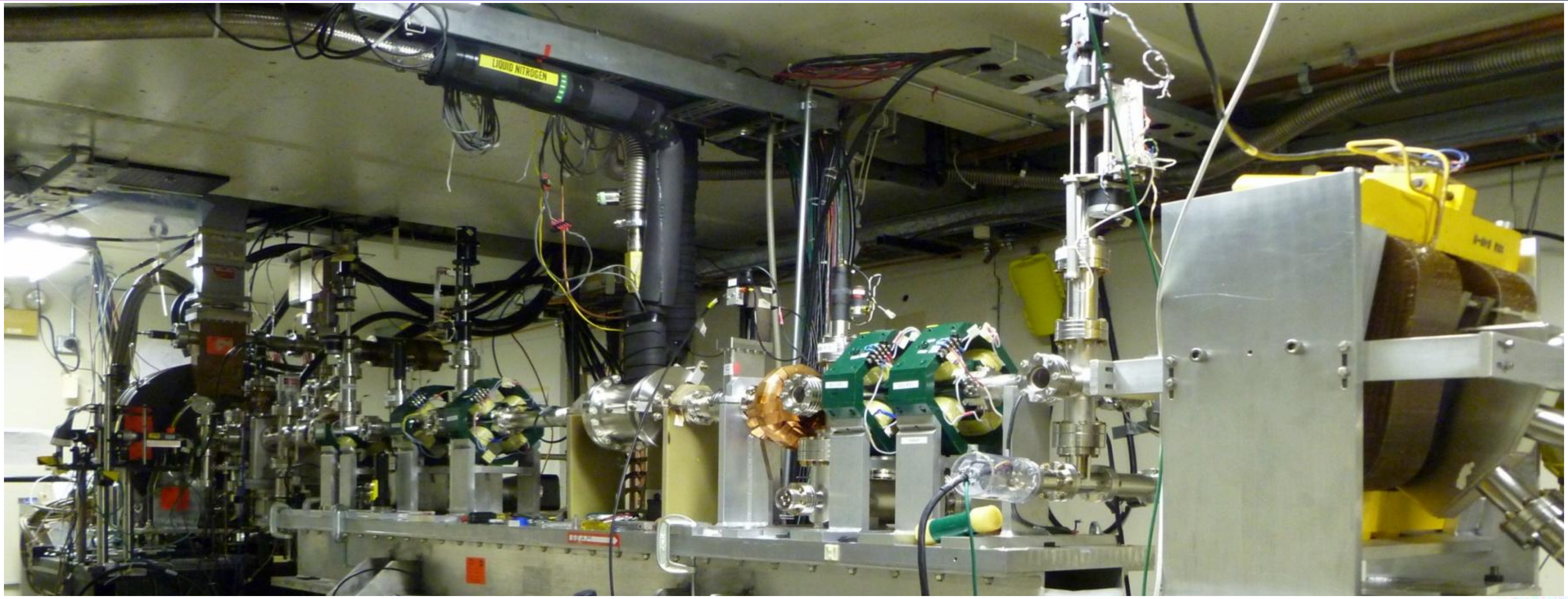
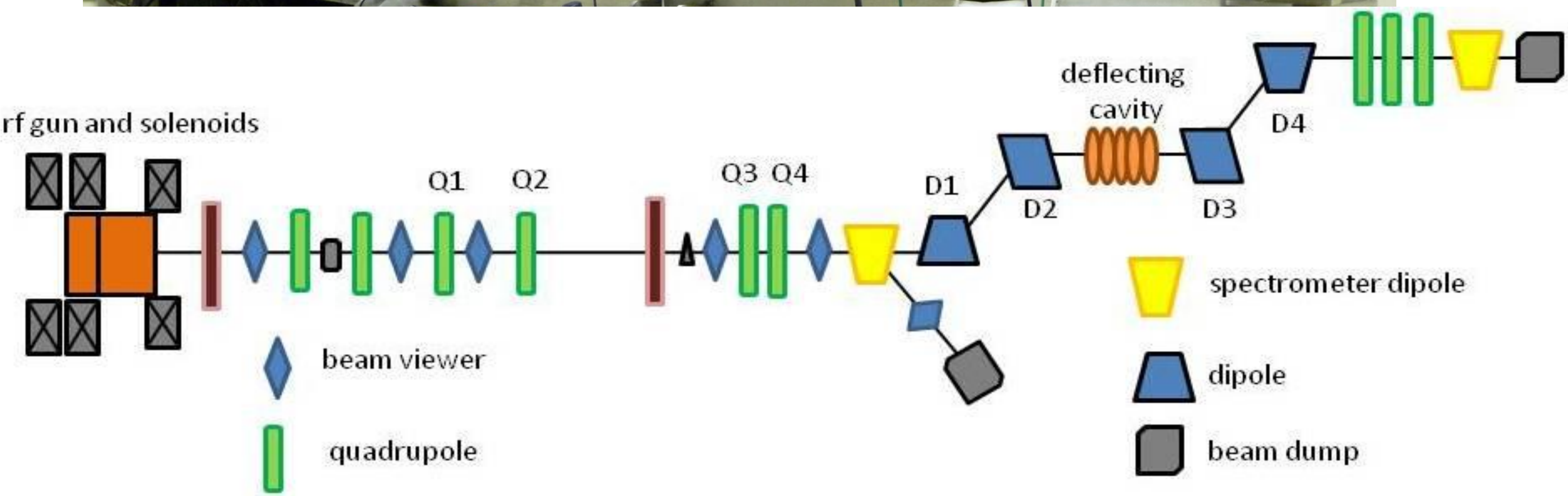
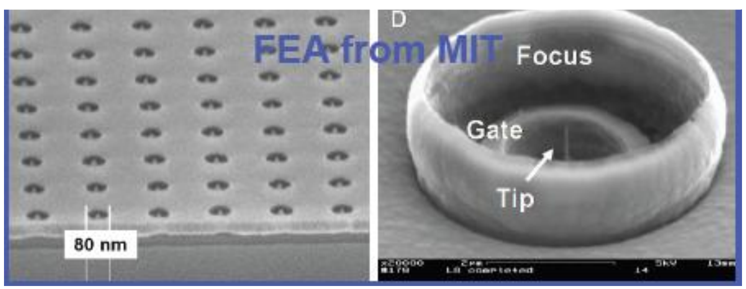
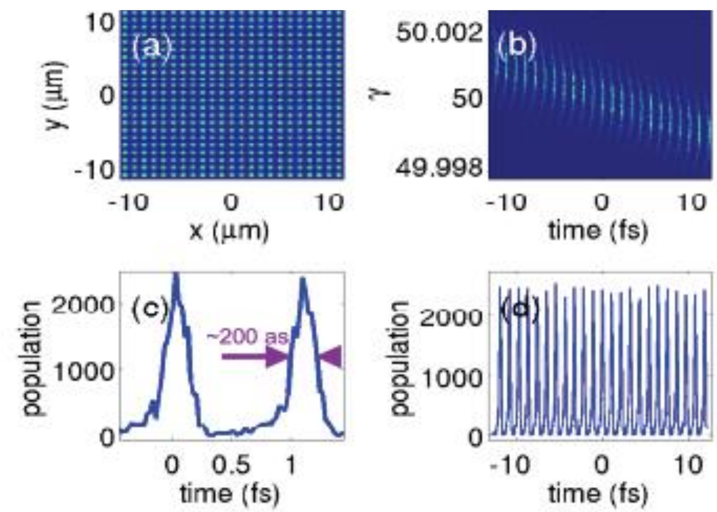




Optically-modulated bunches at HBESL*

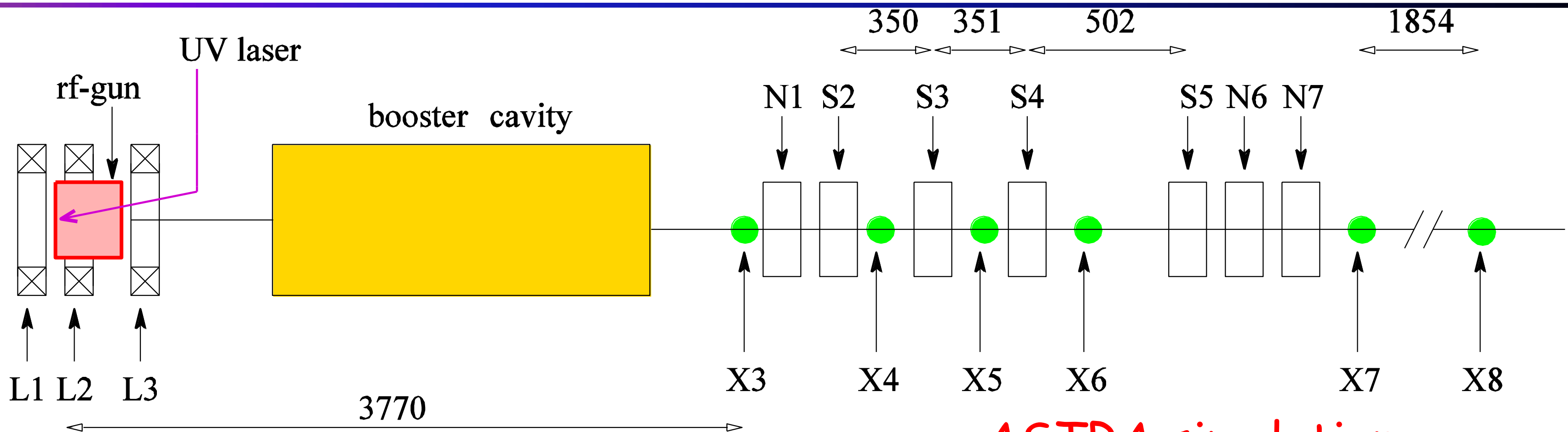
- Method is similar to our demonstration of narrow-band THz radiation;
- The key element is the nano-structured cathode (field- emission array#) triggered with <30 fs laser;
- Phase-space exchange to obtain an optically-modulated bunch train;
- Goal is to observe COTR



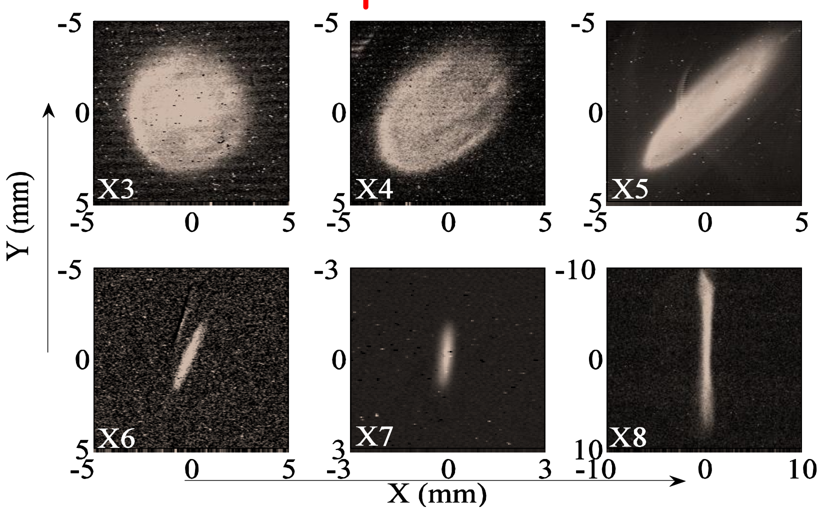


*Y.-E Sun, et al., WEPD19, FEL'2012, Nara, Japan (2012);
W. Graves, et al., PRL 108, 263904 (2012).

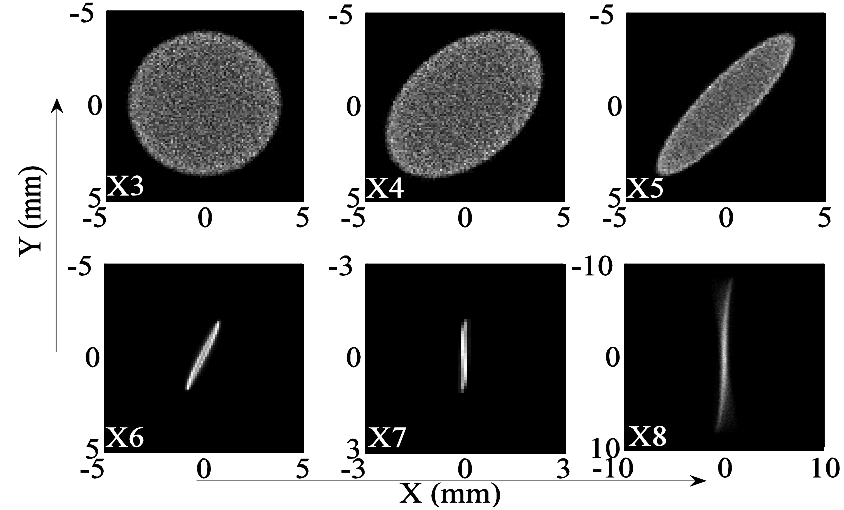
Transformation of a round angular-momentum dominated beam to a flat beam



experiment



ASTRA simulation

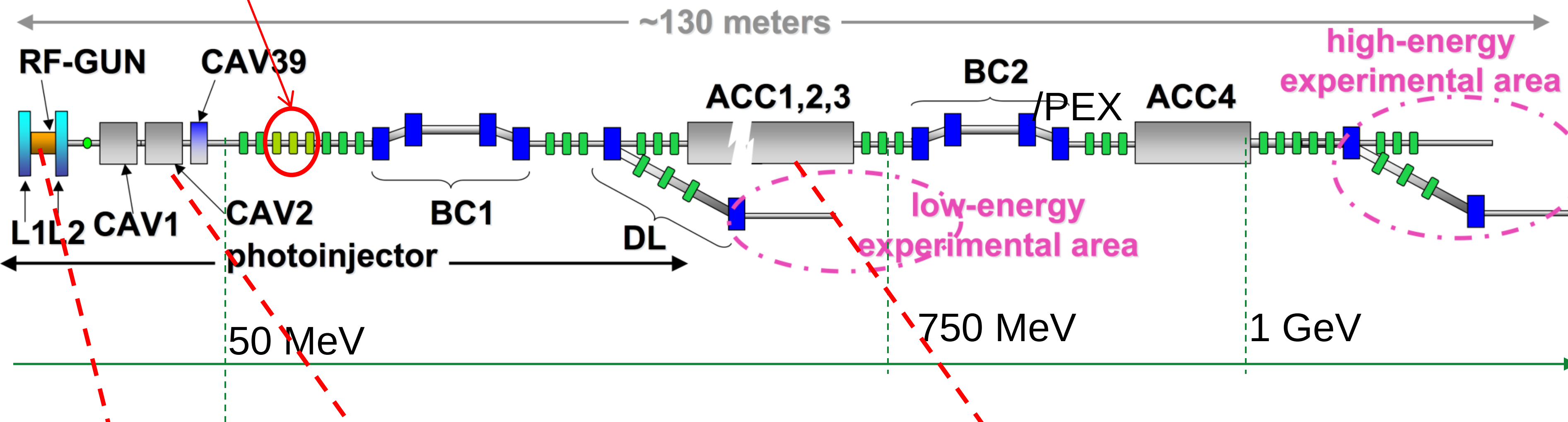


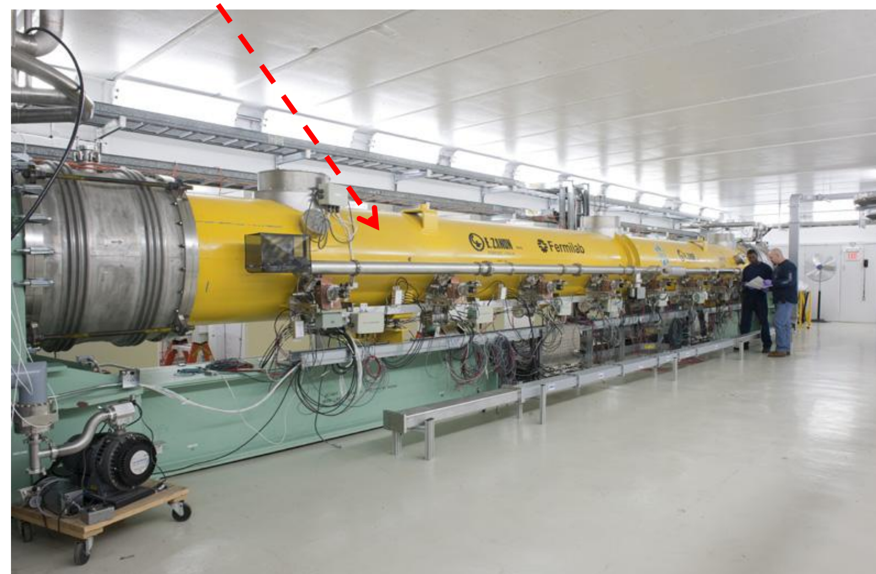
ε_x (mm mrad)	**0.41±0.02**
ε_y (mm mrad)	41.0±0.5
$\varepsilon_y/\varepsilon_x$	**100±5**

Y.-E Sun, Ph. D. dissertation, University of Chicago(2005); available at http://lss.fnal.gov/archive/thesis/fermilab-thesis-2005-17.shtml

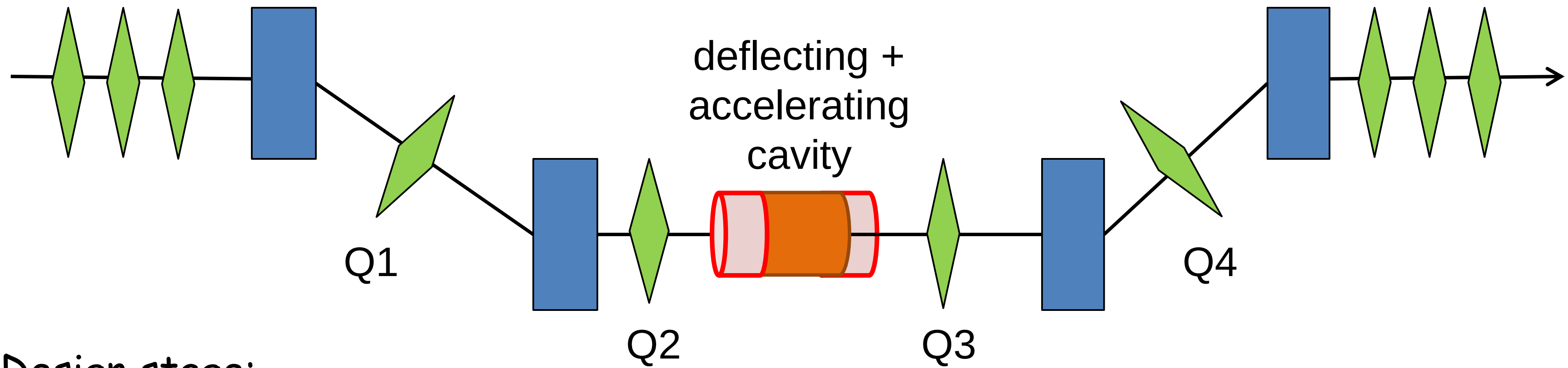
6D Beam Manipulation at ASTA

- Flat beam transformation + transverse-to-longitudinal





Chicane EEX at ASTA Low Energy Beamline (50 MeV)



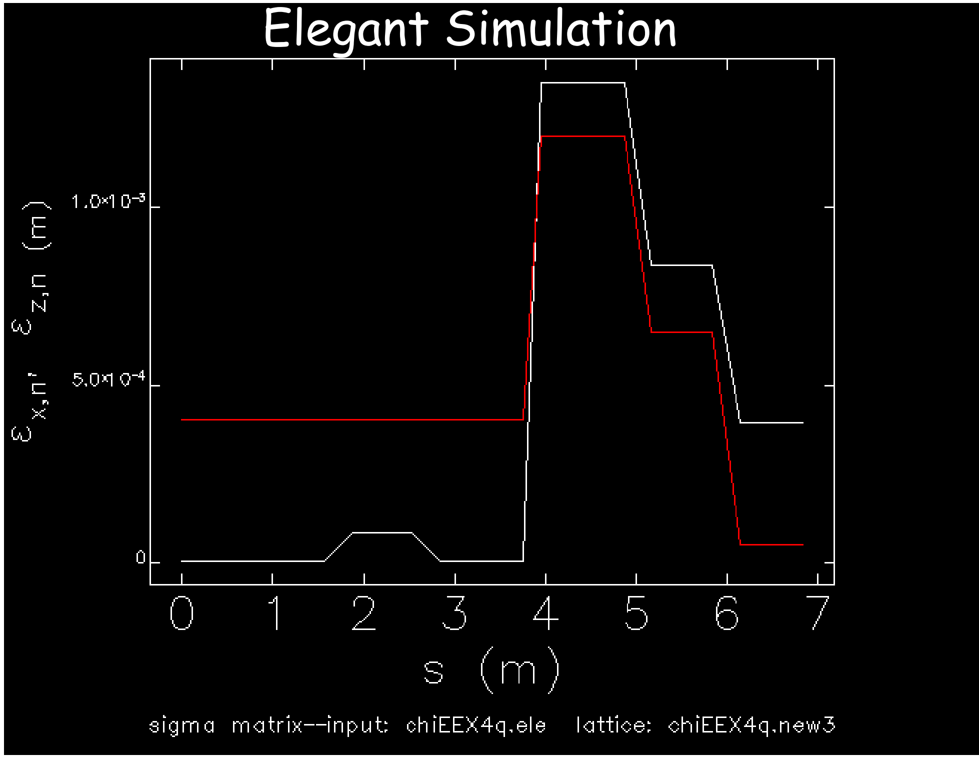
Design stage:

Adding accelerating cavity to the deflecting cavity solves the problem. (A. Zholents, ANL/APS/LS-327, May 2011)

Q1-Q2: control the dispersion at cavity location;

Q3-Q4: tune the beamline to obtain anti-block diagonal matrix;

The other quads at the two ends are available for beam matching.



Summary

- Sub-ps bunch trains are successfully generated using the EEX technique and THz radiation from such bunch trains are observed.
- Numerical simulations shows that bunch trains with optical wavelength spacing are possible; experiments are in planning stage.
- Multi-stage of round-to-flat and EEX offers the possibility of arbitrary phase-space repartition, and innovative beam current profiles can be created to satisfy the demands of certain application.

The future of "beamnastics" is bright.

Talk of Kip Bishofberger (TH1A05).

Credits and Acknowledgements

Thanks to our Fermilab colleagues:

P. Piot, J. Ruan, R. Thurman-Keup, A. Lumpkin, H. Edwards, A. Johnson, T. Maxwell for their contributions to the EEX-related experiments.

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