# Beam current profile manipulation using the transverse to longitudinal emittance exchange technique

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# Outline

- Introduction:
  - various beam manipulation techniques;
- The theory and simulations of emittance exchange;
- The experimental facility: A0 photoinjector at FermiLab;
- Experimental demonstrations of the emittance exchange ;
- Observation of the bunch train generation in energy domain;
- Observation of the bunch train generation in time domain;
- Summary.

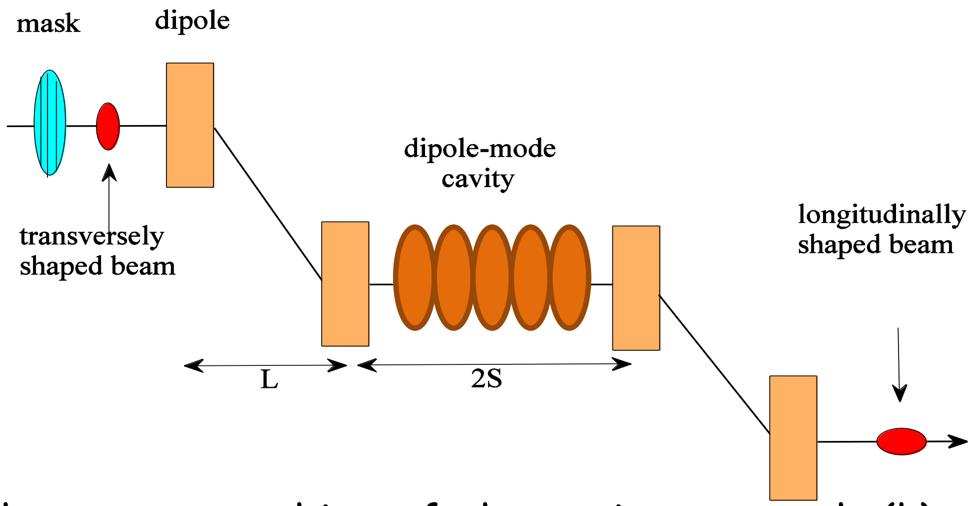
# Introduction

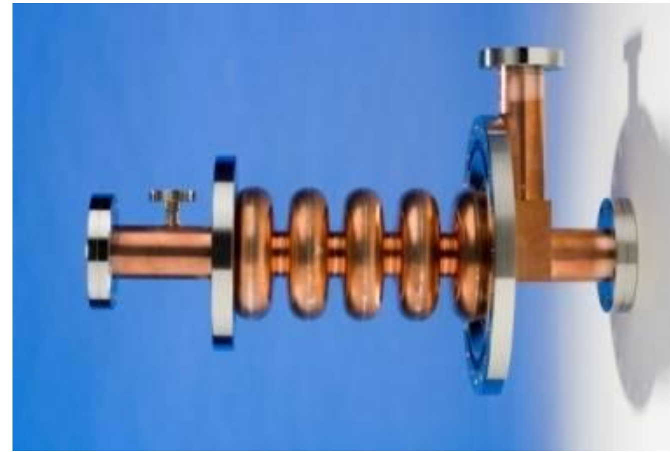
- Electron beam directly coming out a photoinjector does not always have the phase space properties required in its applications.
- Phase space manipulation in 3-D is often required to achieve certain beam distribution, for example:
  - the beam can be compressed to achieve higher peak current (to drive FELs, et al.);
  - the beam can be produced with a large angular momentum at the cathode and later transformed into transversely very flat beam using several skew quadrupoles (to drive planar dielectric wakefield acceleration, planar image charge undulator, and possible simplification of the storage ring for a linear collider, et al)
  - the longitudinal emittance and transverse emittance of the beam can be swapped using the emttance exchange technique, and when combined with the flat beam manipulation, one can repartition of the beam in the 6-D phase space;
  - the above manipulations are in the rms sense; however the beam profiles can be manipulated more precisely, such as micro bunch train within a macro bunch; or linear ramped bunch current et al…

# Transverse-longitudinal emittance exchange (EEX)

- EEX therory:
  - Cornacchia and Emma, PRSTAB 5, 084001 (2002).
    - Partial exchange
  - Kim and Sessler, AIP Conf. Proc. No. 821, 2006.
    - Complete exchange
- EEX experiment:
  - T. Koeth et al, PAC2009; T. Koeth, Ph.D. dissertation, Rutgers University, 2009.
  - A. Johnson et al, IPAC2010.
- Applications of EEX in beam current profile modulation:
  - Y.-E Sun and P. Piot, Proc. LINAC08, 498 (2008).
  - Y.-E Sun et al, be published in the proceedings of the 47th ICFA Advanced Beam Dynamics Workshop, HBEB, Maui, Hawaii, November 16-19, 2009. Currently available at http://arxiv.org/abs/1003.3126 .

# The scheme: Transverse-longitudinal emittance exchange (EEX)



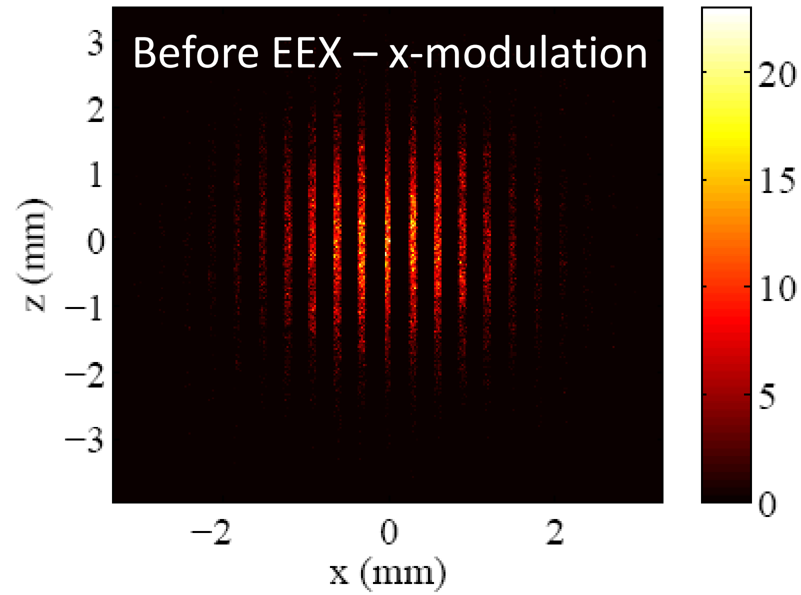
With proper matching of the cavity strength (k) and the dogleg dispersion (D), i.e., 1+kD=0, the diagonal sub-block elements of the exchanger's transfer matrix are zero, therefore the initial horizontal phase space is mapped into the longitudinal phase space, and verse versa.

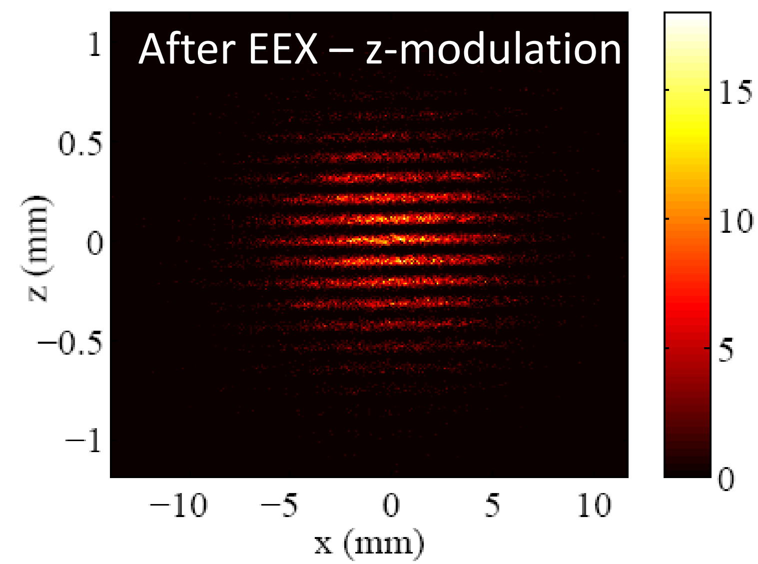
$$\begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix}_{out} = \begin{pmatrix} 0 & 0 & \frac{L+S}{\alpha L} & \alpha S \\ 0 & 0 & \frac{1}{\alpha L} & \alpha \\ \alpha & \alpha S & 0 & 0 \\ \frac{1}{\alpha L} & \frac{L+S}{\alpha L} & 0 & 0 \end{pmatrix} \begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix}_{in}$$

# Multipulse generation: GPT simulations of an optimized case:

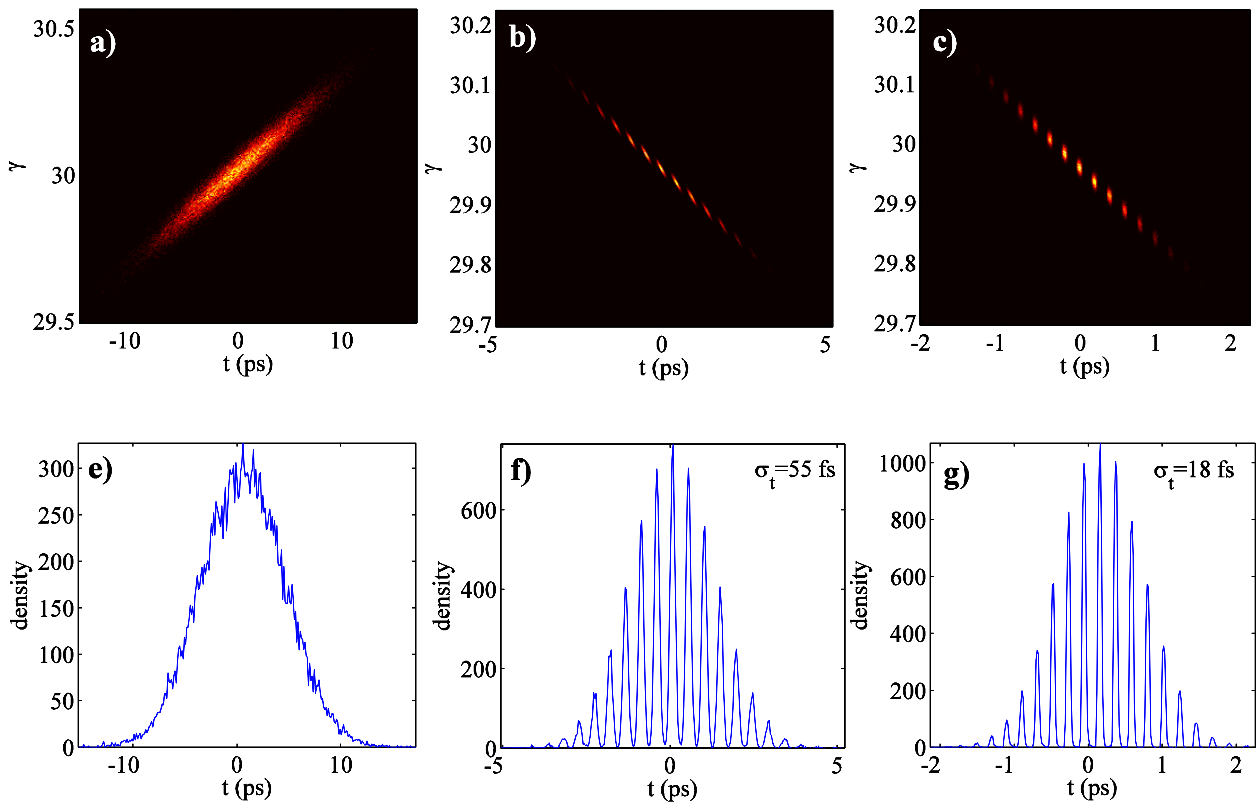
Table 1: Parameters prior to the emittance exchange

| | |
|---|---|
| beam energy (MeV) | 15 |
| bunch charge (pC) | 100 |
| normalized horizontal emittance ($\mu$m) | 1 |
| normalized longitudinal emittance( $\mu$m) | 27 |
| horizontal beta function (m) | 20 |
| longitudinal chirp $\partial\delta/\partial z$ ($m^{-1}$) | -4.5 |
| rms bunch length (mm) | 0.9 |
| slit width ( $\mu$m) | 80 |
| slit separation ( $\mu$m) | 300 |



# Longitudinal phase space of the optimized case



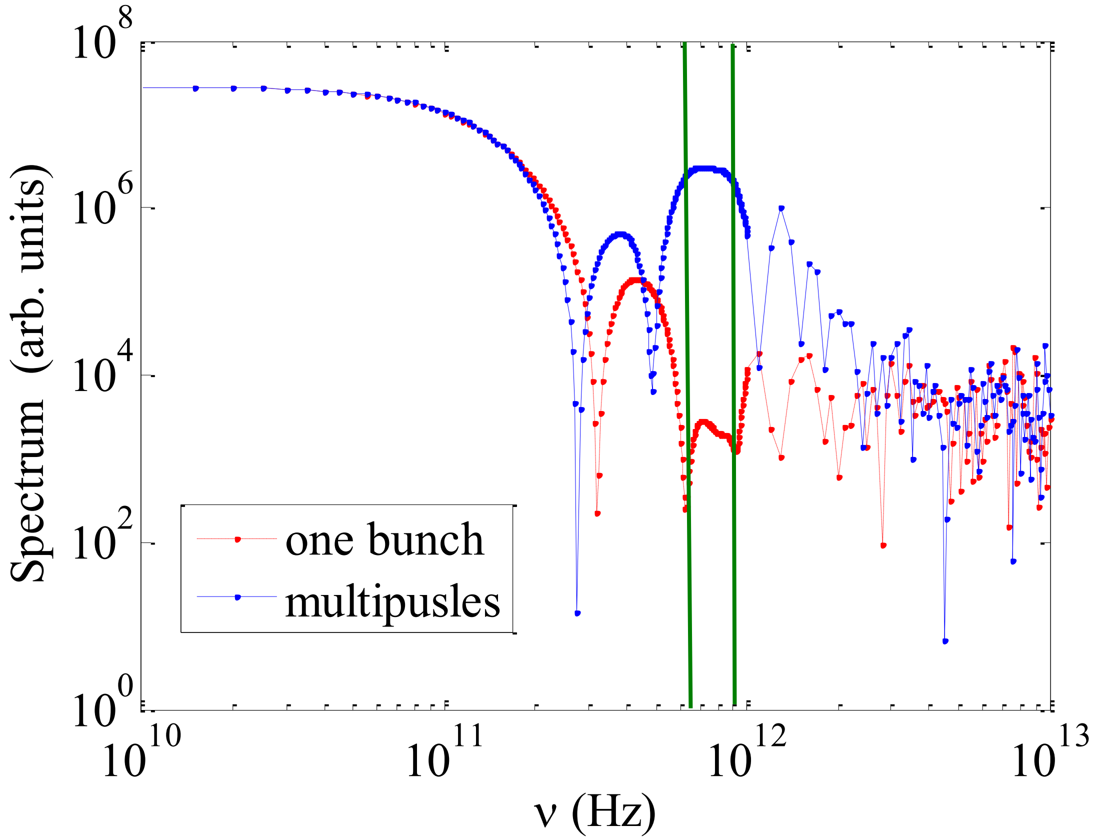

Pulse rms length ~ 55fs at the end of the EEX.

The individual beamlets have a slope (correlation between energy and position) that is different from the slope of the whole bunch train.

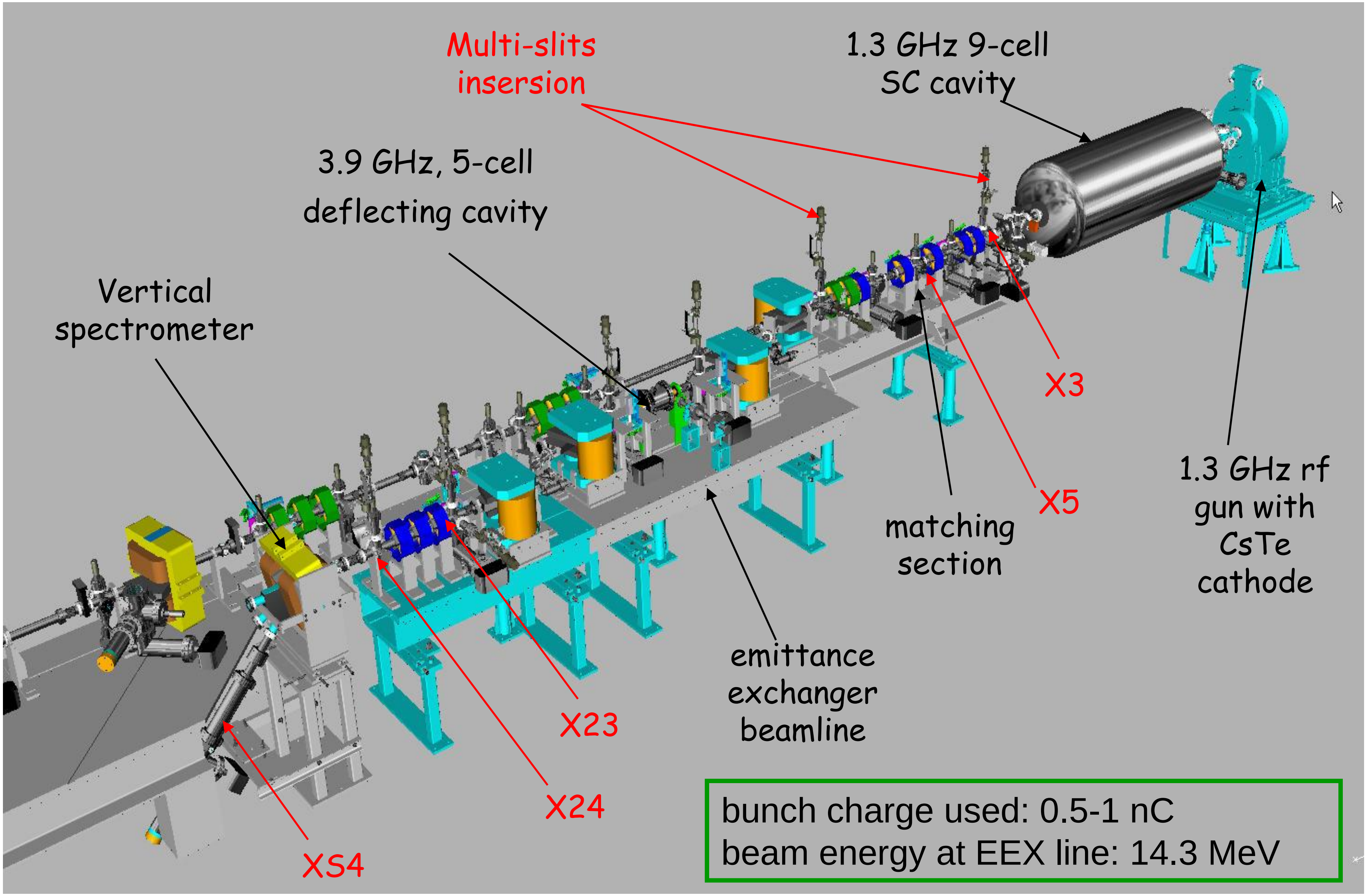
A two-dipole achromatic single dogleg compressor can be used to remove the correlation, and pulses with rms lengths of 18 fs and 120 fs separations can be achieved.

# Bunch form factor with and without slits

- We see that in the frequency range between the two green lines (0.5-0.9 THz), the intensity of the radiation spectrum increases by several orders of magnitudes. This coherent radiation can be detected experimentally using an autocorrelator and He-cooled bolometer.

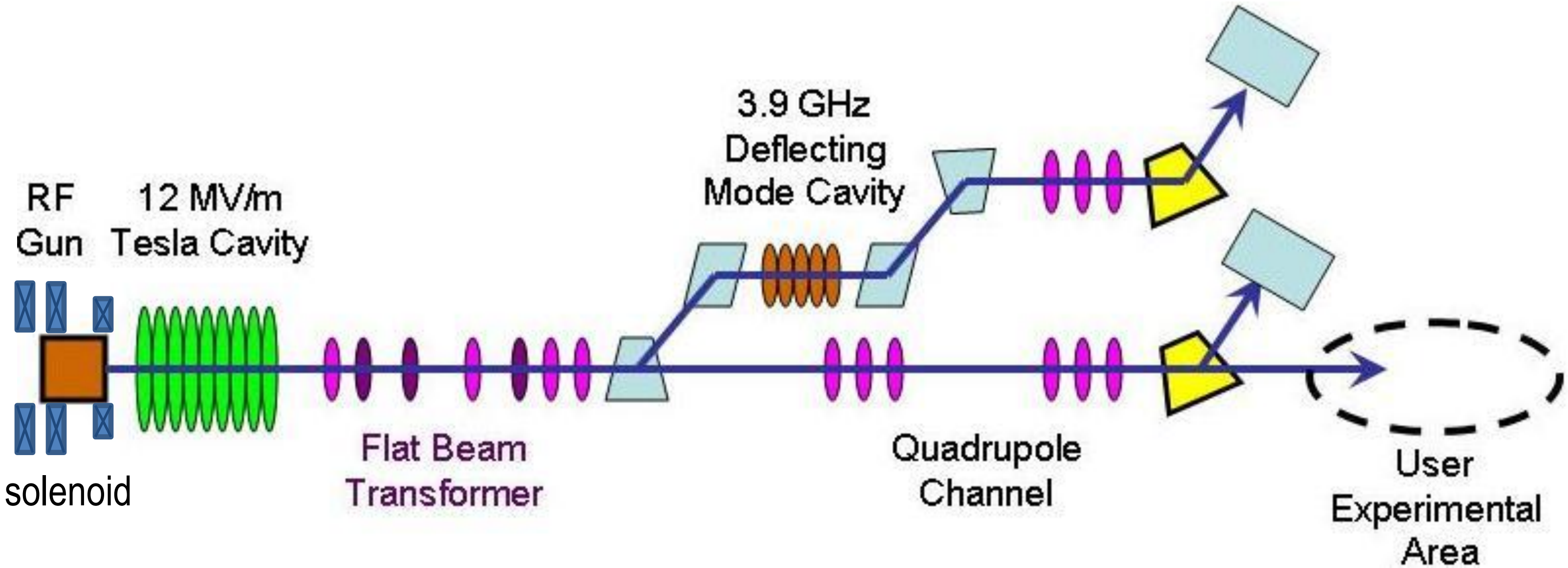


# The A0 photoinjector




bunch charge used: 0.5-1 nC
beam energy at EEX line: 14.3 MeV

# A0 Photoinjector




- $Cs_2Te$ photocathode
- Nd:YLF drive-laser
- Typically the bunch charge is set to 1nC, it can be higher
- 1.5-cell 1.3 GHz NC rf-gun with three solenoids for emittance manipulation
- 9-cell TESLA type booster cavity
- Beam energy ~15 MeV
- Round-to-flat beam transformer
- Double dogleg + 3.9 GHz dipole mode cavity for long.-trans. emittance exchange
- Quadrupoles and steering magnets along the beamline for focusing and steering

# EEX measurements

Before EEX After EEX

$$\varepsilon^n{}_x = 3 \sim 5\ \mu m \qquad 18\ \mu m$$

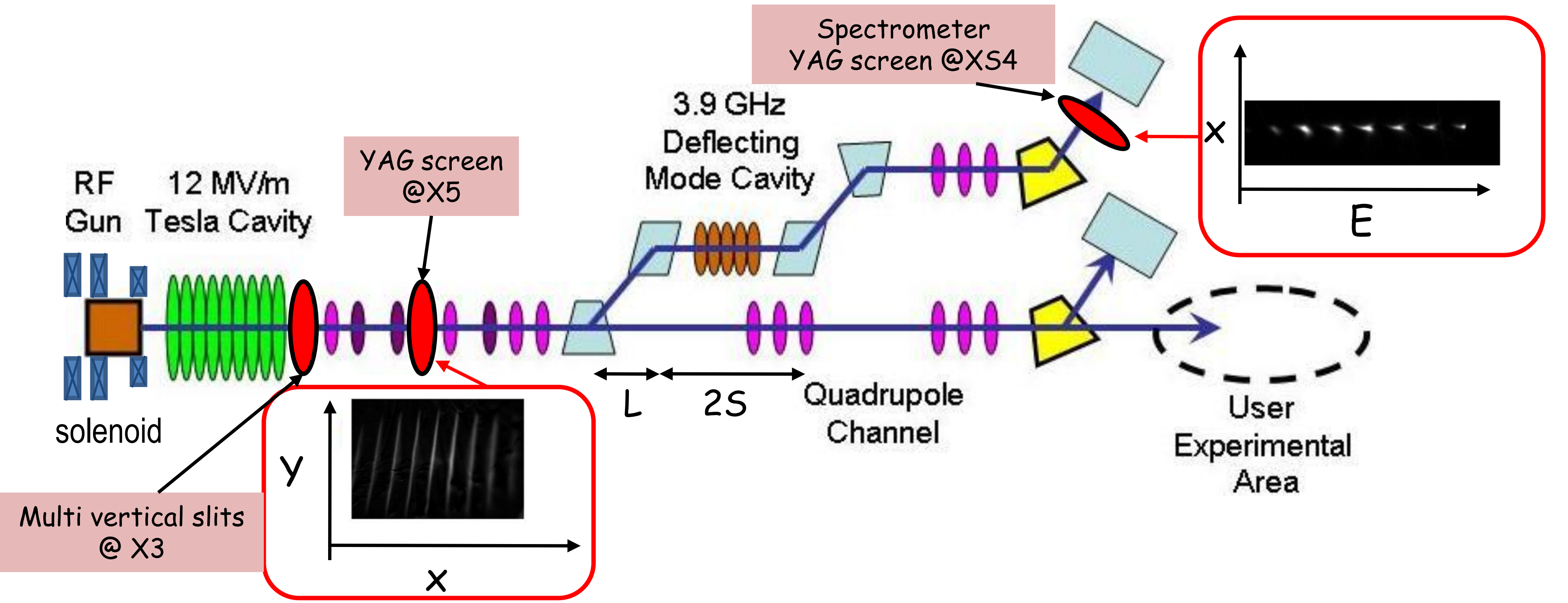
$$\varepsilon^n{}_z = \quad 21\ \mu m \qquad 7\ \mu m$$

$$\varepsilon^n{}_y = 4 \sim 5\ \mu m \rightarrow 6\ \mu m$$

- The numbers are obtained directly from the images, they didn't include any contribution from
  - YAG screen resolution,
  - imaging system resolution,
  - betatron function contribution for the energy spread measurement.

- Taking the corrections of the above three terms, the transverse emittance is 3-4 um, and longitudinal is 13-16 um; see A. Johnson et al, THPE043, IPAC2010, Kyoto, Japan.

# Beam longitudinal phase space modulations




$$\begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix}_f = \mathrm{M} \begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix}_i = \begin{pmatrix} \frac{L+S}{\alpha L} z_i + \alpha S \delta_i \\ \frac{1}{\alpha L} z_i + \alpha \delta_i \\ \alpha x_i + \alpha S x'_i \\ \frac{1}{\alpha L} x_i + \frac{L+S}{\alpha L} x'_i \end{pmatrix}$$

**See Y.-E Sun and P. Piot, Proc. LINAC08, 498 (2008)**

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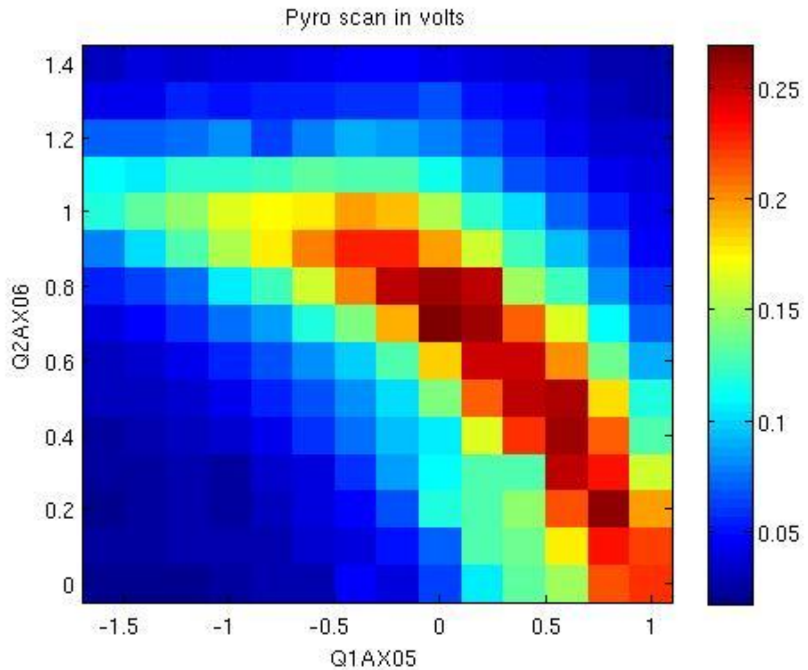
# Quadrupole setting

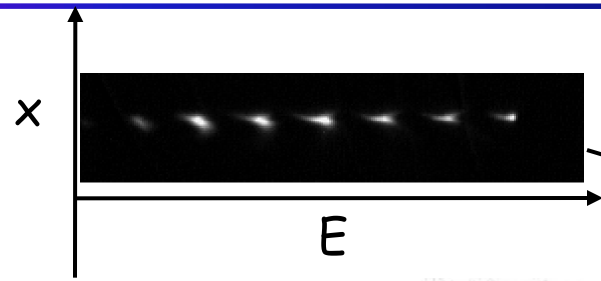
- A scan of the strengths of two quads upstream of the EEX line is performed, coherent transition radiation beam signal downstream of the EEX line is detected and energy spread measured
- Pick the quads settings for higher CTR power ® shortest bunch length downstream of the EEX beamline.
  - pick Q1AX05=0A, and scan Q2AX06 for best energy modulation at the spectrometer downstream of EEX beamline.

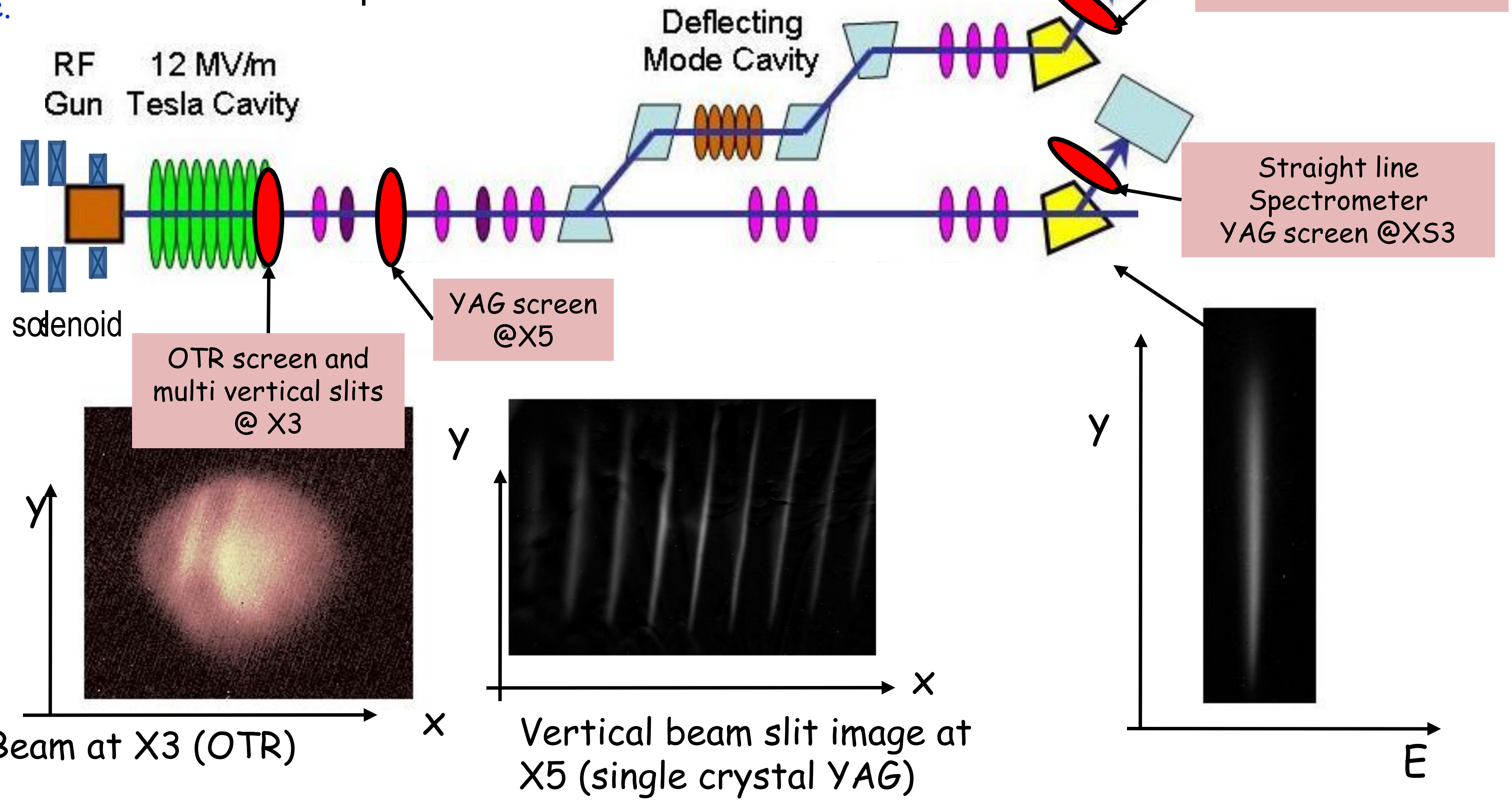
| Quadrupole | Current (A) |
|---|---|
| Q1AX03 | -0.23 |
| Q1AX05 | 0 |
| Q2AX06 | 0.34 |
| Q1AX23 | -2.0 |
| Q2AX23 | +3.0 |
| Q3AX23 | -1.3 |



# data on 10/30/2009:transverse to energy modulation

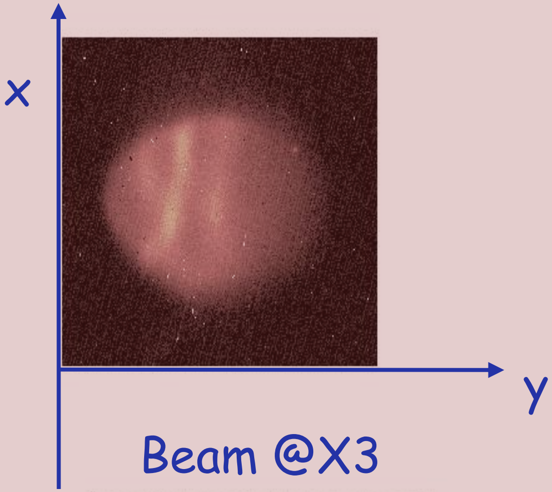
From simulations we know the longitudinal phase space is chirped so the modulation is probably also present on the temporal profile.



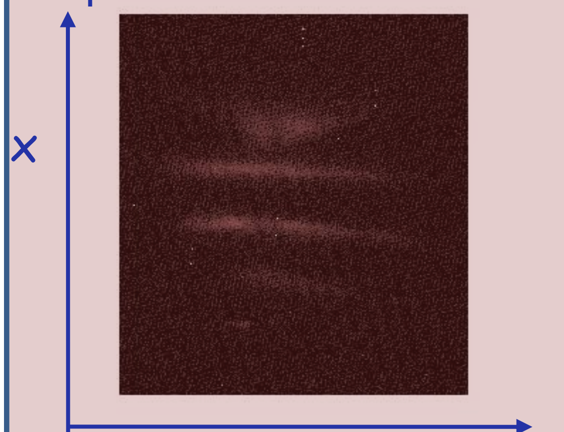



# Beam images along the beamline

Normalized horizontal emittance = 4 mm mrad.

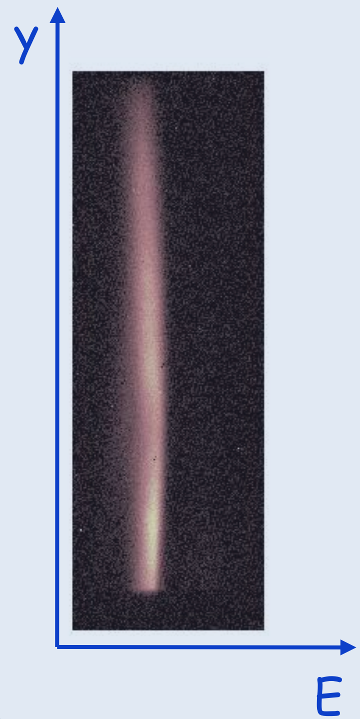



Beam @X3

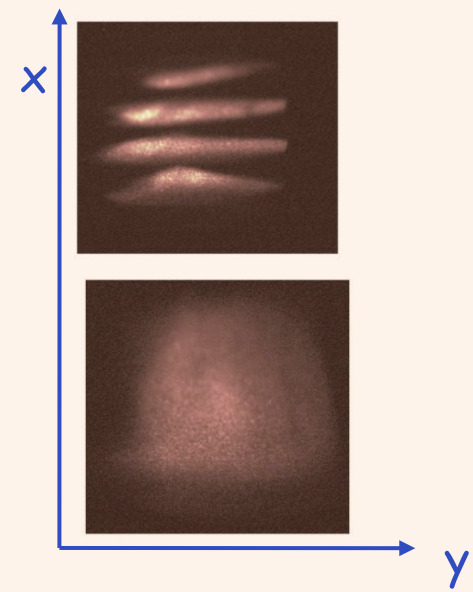



V-slit image @X6

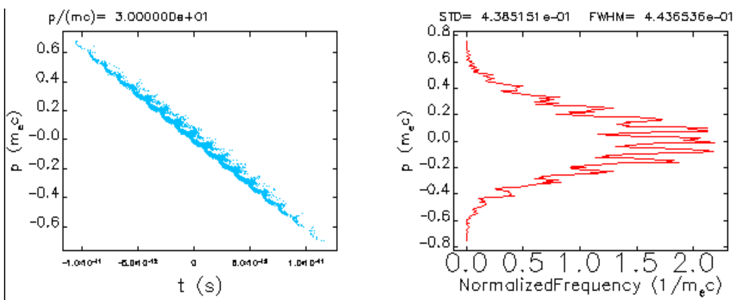
Vertical slits at X3 inserted,
beam image on the spectrometer:
no energy modulations

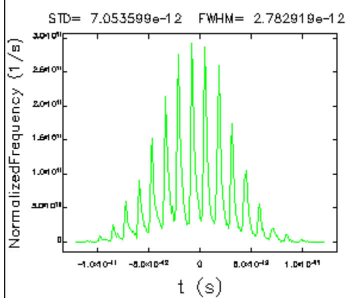



Vertical slits at X3 inserted,
beam image at the end of EEX beamline:
Top: dipole cavity off;
bottom: dipole cavity on.

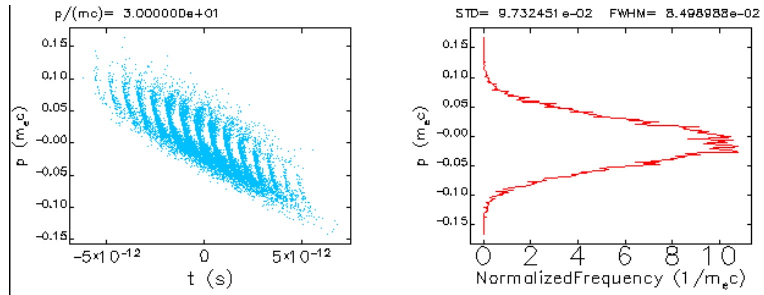


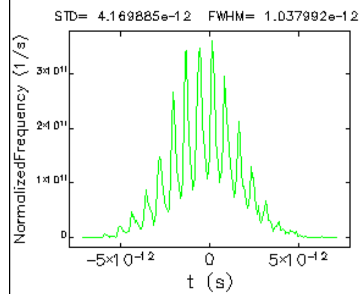
# ELEGANT simulations



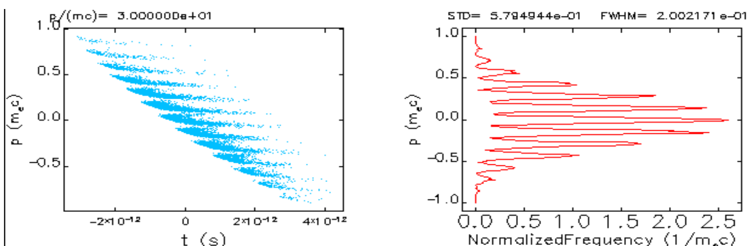



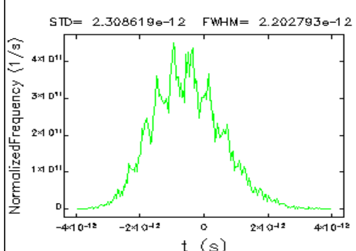

Under one set of initial transverse
phase space condition: clear time and energy modulations




initial transverse phase space condition: only clear time modulation




initial transverse phase space condition: strong energy modulation

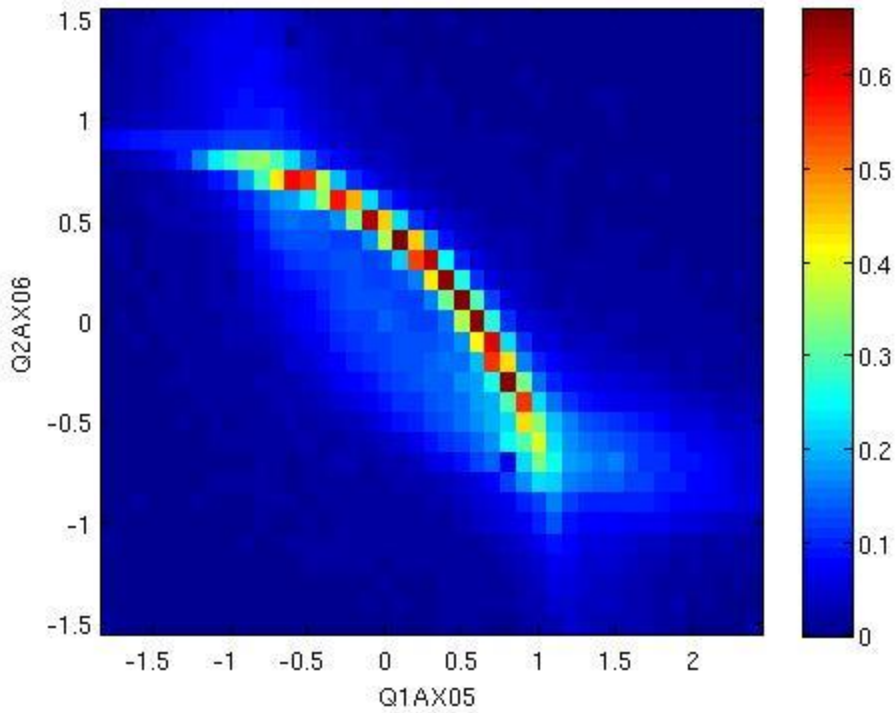
# Time domain measurement tools: bolometer and interferometer

A helium cooled bolometer was purchased for this experiment.

Used in conjunction with an interferometer, it can measure the multipulse structure in time domain directly from the coherent transition radiation generated by the electron beam hitting on a OTR screen.

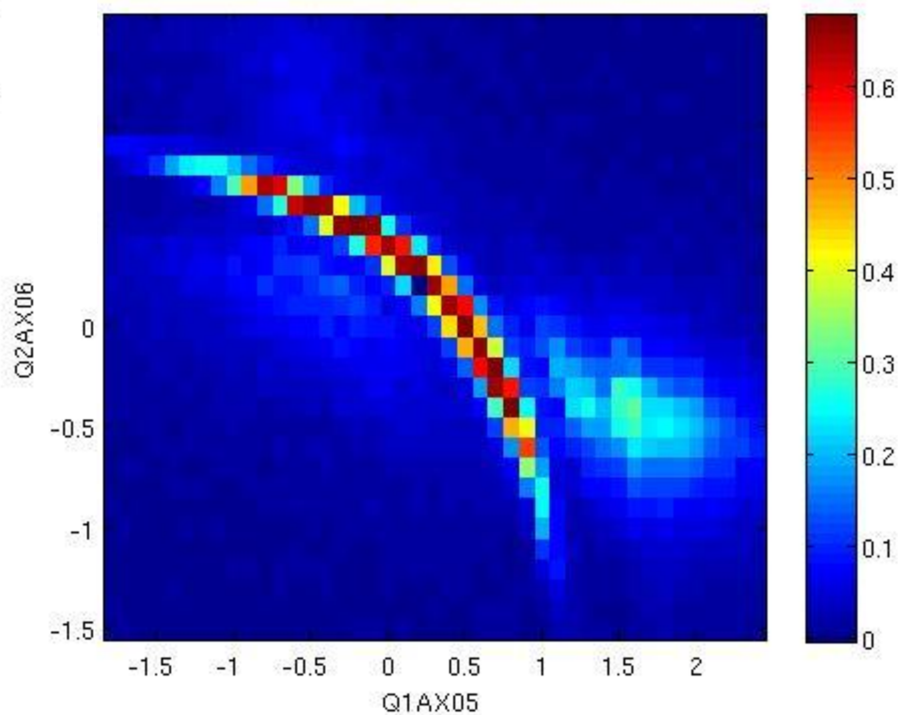
The set up was commissioned in the past several months, and is now fully functioning now.

# CTR signal from the beam during quadrupole scan

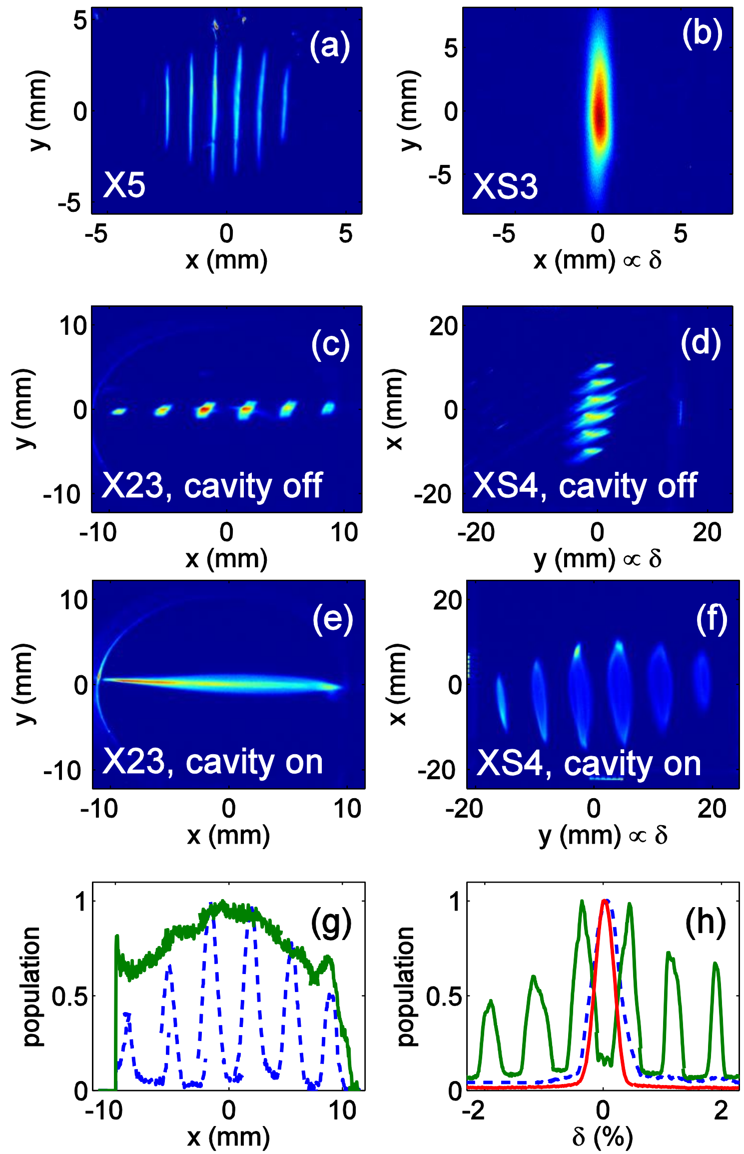



Total normalized CTR energy detected at X24 as a function of quadrupole magnets currents with X3 slits out ( left) and in (bottom) the beamline.

The insertion of the multislit mask results in the appearance of a small island of coherent radiation at the lower right corner.



# Beam profiles before and after EEX



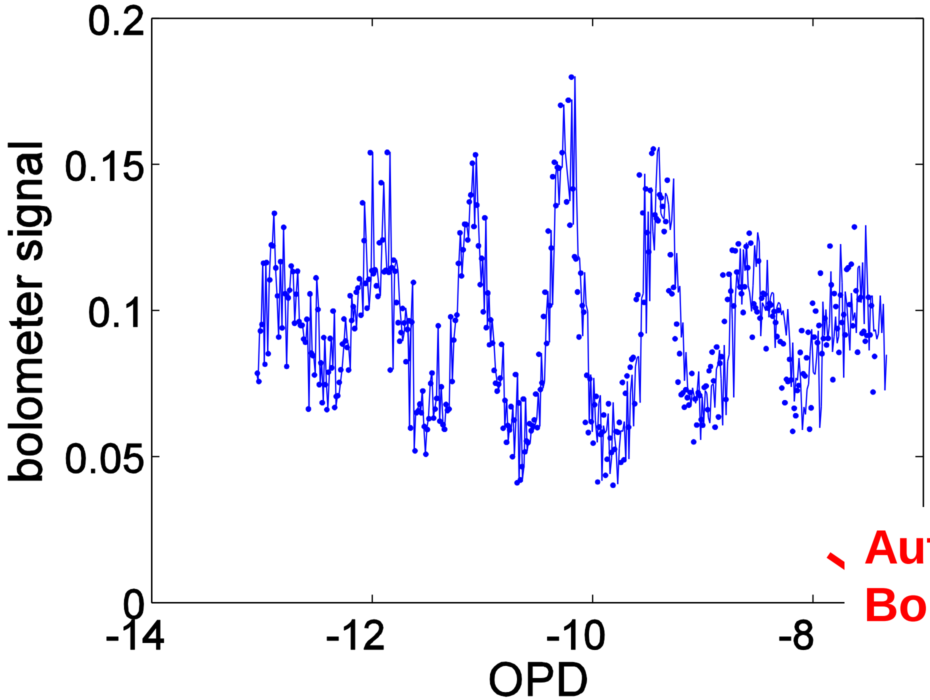

Straight beamline: Transverse initial beam density before EEX with horizontal beam modulations (a); no energy modulations (b)

EEX beamline, deflecting cavity off : beam density with horizontal beam modulations (c) but no energy modulations (d)

EEX beamline, deflecting cavity on: No horizontal modulations (e) ; has energy modulations (f)

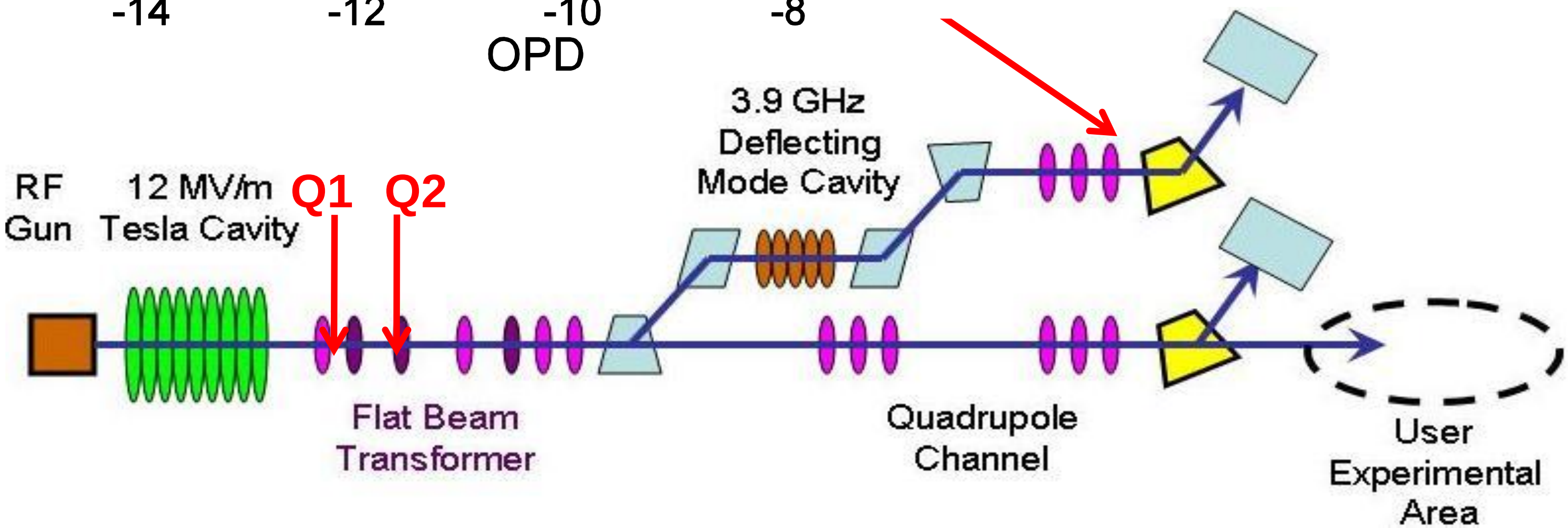
(g): The corresponding relevant intensity normalized horizontal profile of (c), (e) and fractional energy spread
(h): profiles of (a) red, (d) green and off (f) dashed blue

# Longitudinal pulse shaping using EEX: direct measurement of temporal modulation



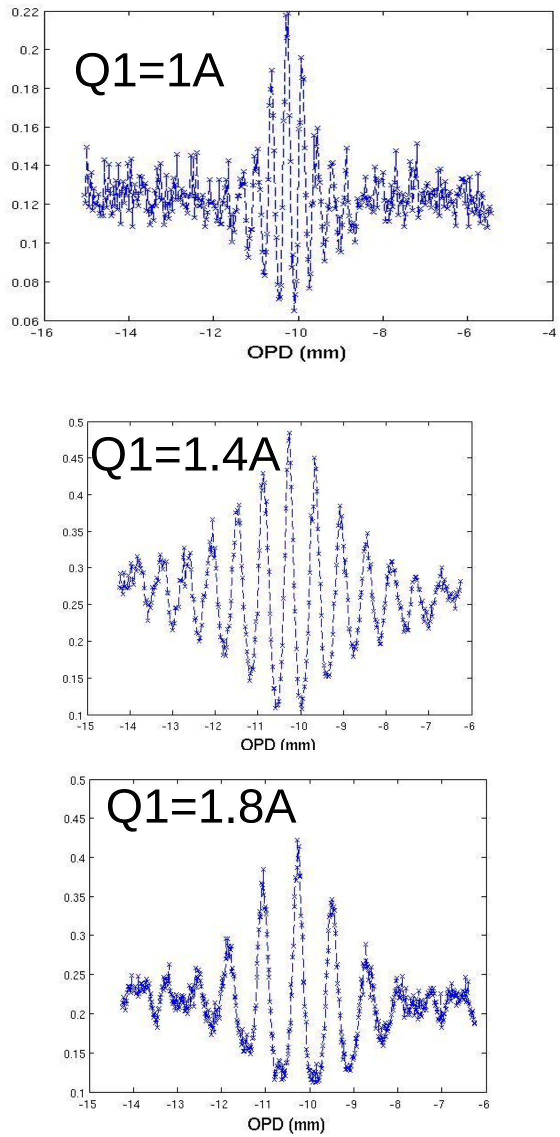

Left figure: signal measured by the He-cooled bolometer as a detector of the autocorrelator —this is a direct measurement of the multibunch structure in time domain.

**Autocorrelator/ Bolometer**



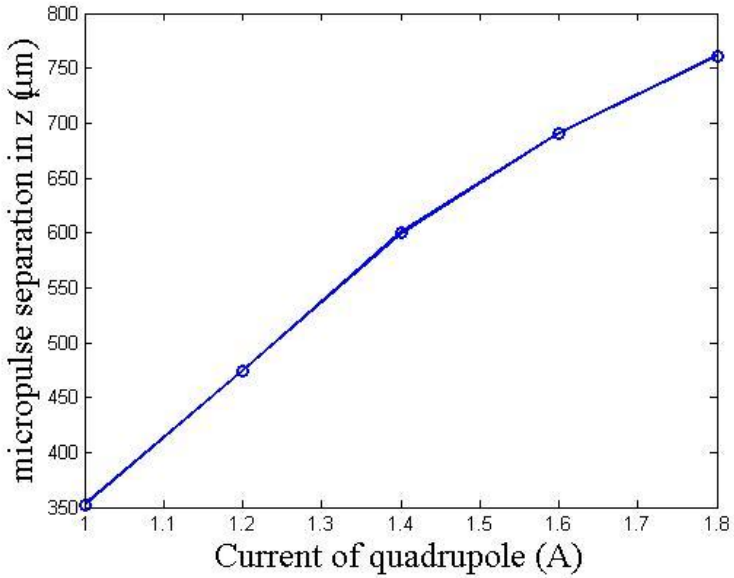
# Control of the bunch train separation: time

autocorrelation curves

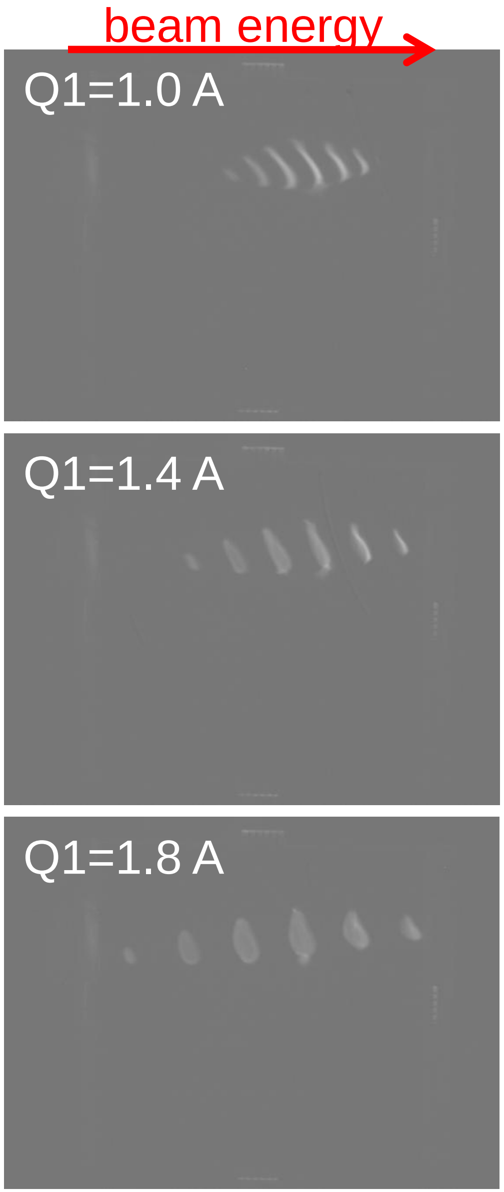



From the autocorrelation curve, we can extract the bunch train separation. The separation can be varied by adjusting the transverse beam parameters upstream of the EEX line using quadrupole magnets.

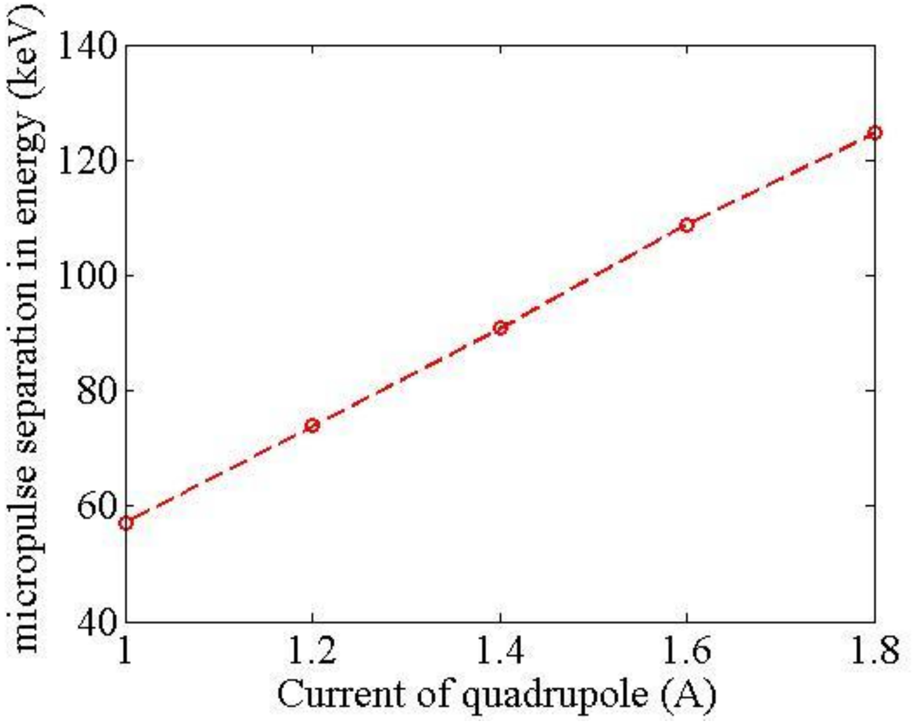
By varying the current of one quad only, we were able to adjust the separation from 760 um to 350 um. The bunch train separation is further reduced by varying two quadrupole strengths.



# Control of the bunch train separation: energy




Corresponding to the time domain measurement presented, the bunch train is also directly observed on a YAG screen downstream of an energy spectrometer as a function of quadrupole current.



# Summary

- An proof-of-principle emittance exchange experiment was successfully carried out at A0 photoinjector, using two magnetic dogleg and one 5-cell 3.9 GHz dipole mode cavity;
- The EEX technique is used to modulate electron beam current profile. An incoming transverse horizontal density modulation was mapped onto the longitudinal phase space using the EEX beamline; Clear energy and time modulation was observed.
- The control of the bunch train separation is easily achieved by adjusting the horizontal beam properties upstream of the EEX line. A wide range of bunch separation is observed.
- Further reduction of the bunch separation can be achieved by using a different multi-slits plate upstream of the EEX line.