2014 FEL Conference, Basel

Advanced beam manipulation in modern accelerators

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Beam manipulation

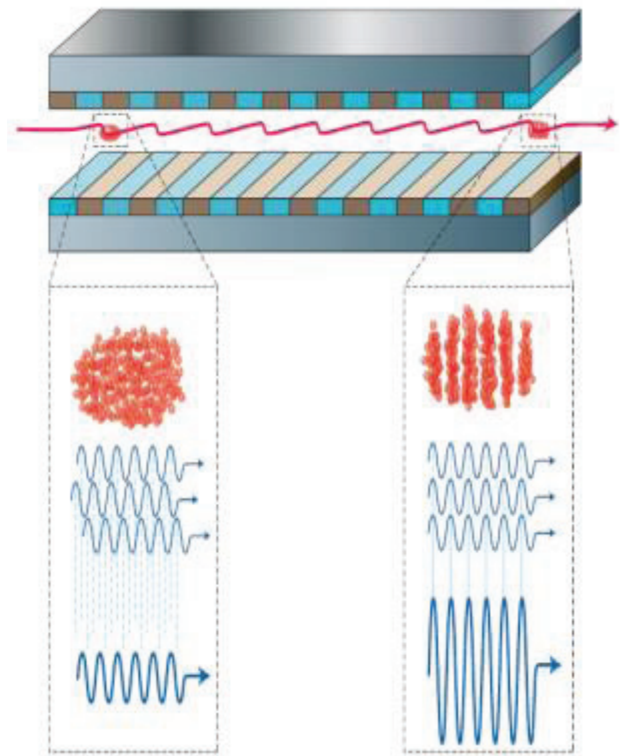
Rearrange beam's distribution in 6-D phase space

Courtesy of Youtube

Hemsing, Stupakov, Xiang, Zholents, Rev. Mod. Phys. 86, 897 (2014)

Xiang, AIP Conf. Proc. 1507, 120 (2012); see also SLAC-PUB-15196

Free-electron laser (FEL)



McNeil and Thompson, Nature Photonics, 2010

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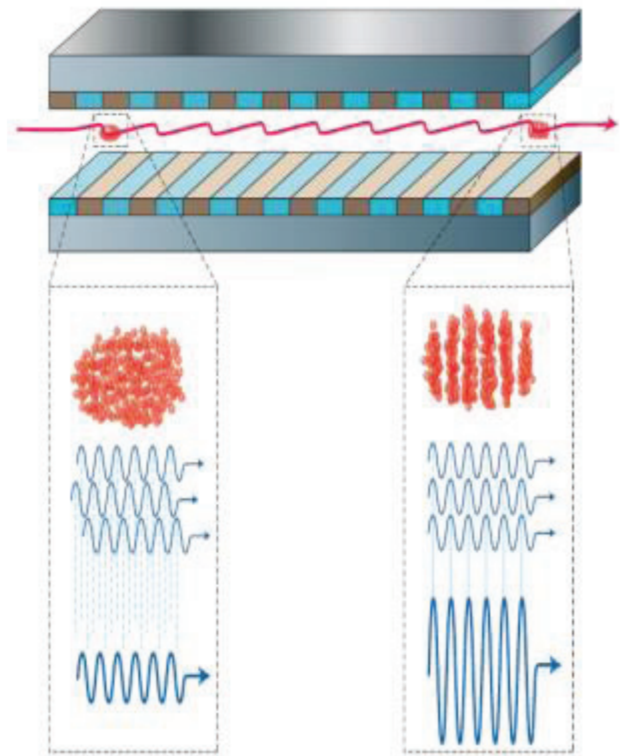

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Outline

On the one hand:

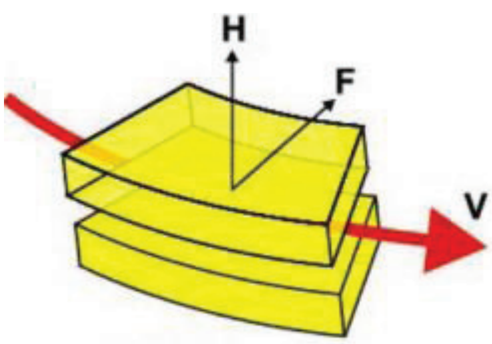
One may tailor the beam distribution at high precision for specific applications;

On the other hand:

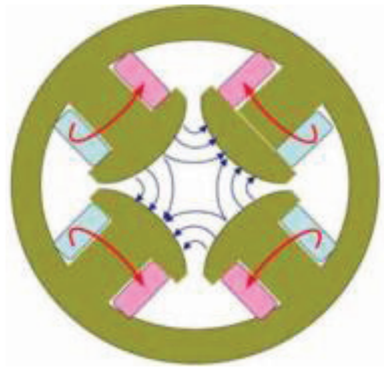
Beam manipulation has to obey basic rules as well as technological limitations.

1. 2-D beam manipulation
2. 4-D beam manipulation
3. 6-D beam manipulation
4. Ultrafast Electron Diffraction and Microscopy

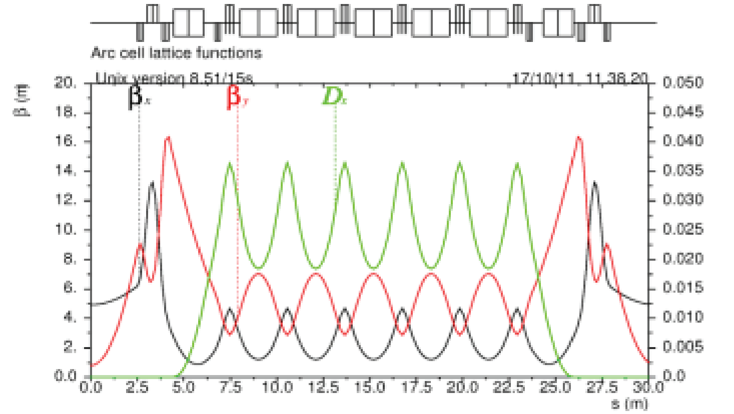
2-D manipulation : transverse plane



Dipole

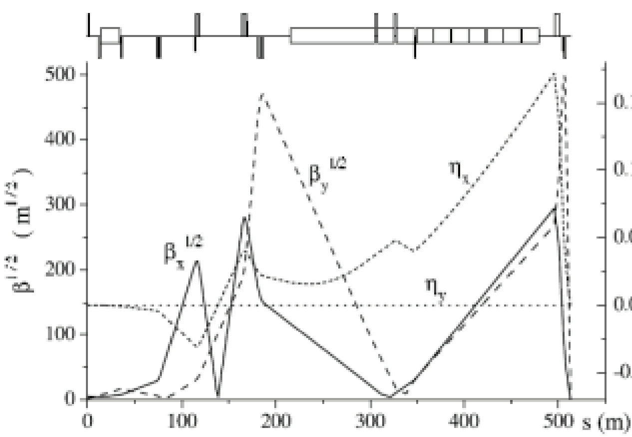


Quadrupole



7-bend achromat for ultimate storage ring

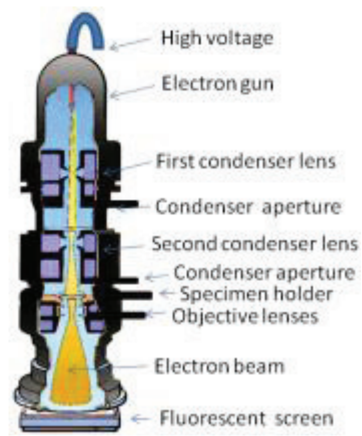
❑ Linear collider

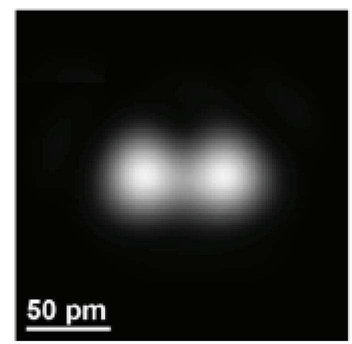


500 m final focus

Raimondi and Seryi, PRL, 86, 3779 (2001)

❑ Electron microscope



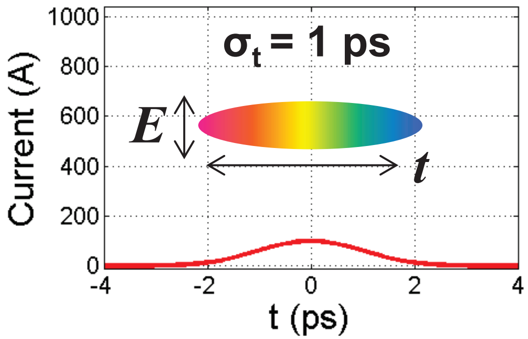


5^{th} order aberration correction

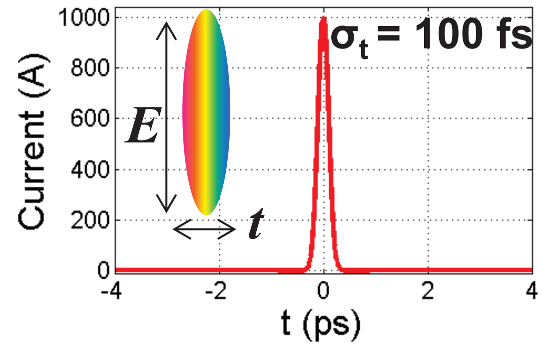
Erni et al., PRL, 102, 096101 (2009)

2-D manipulation : longitudinal plane

- A dispersive element is required for manipulation in longitudinal plane

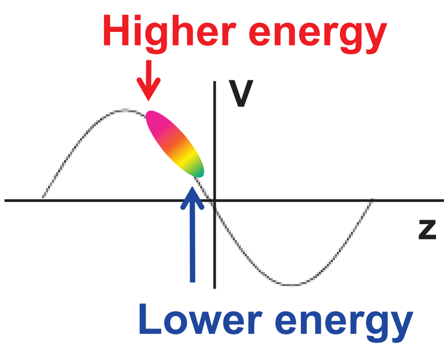


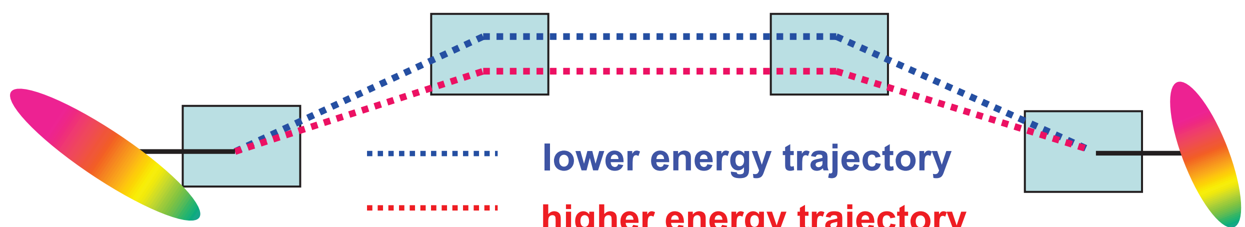
Before BC



After BC

Bunch compression

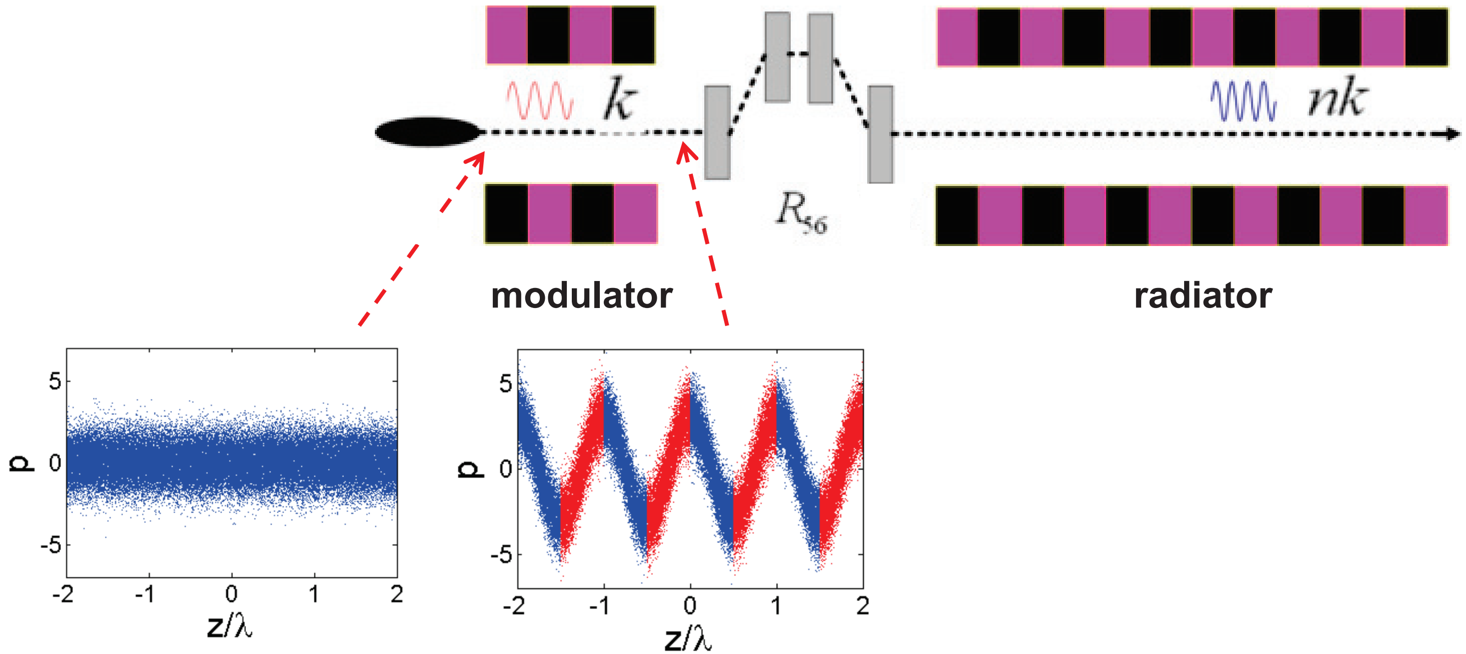




Low energy electrons slow down; high energy electrons catch up

Bunch compression with laser induced energy chirp

- ❑ **High-Gain Harmonic Generation (HGHG)**
- ❑ ***Single* modulator-chicane system**



- **Energy modulation in a modulator**
- **Energy modulation converted to density modulation**
- **Coherent radiation at *nk* amplified to saturation in a radiator**
- **Harmonic number $n \approx \Delta E / \sigma_E$**

Yu et al., Science, 2000
Yu et al., PRL, 2003

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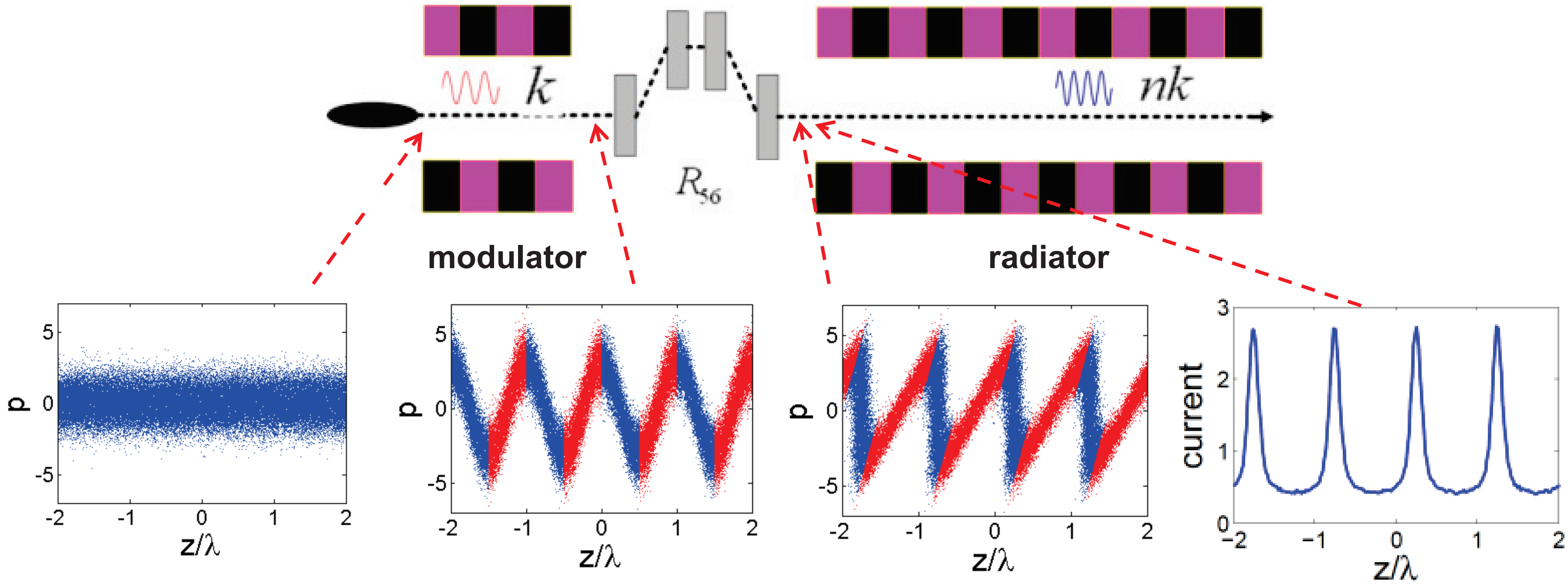

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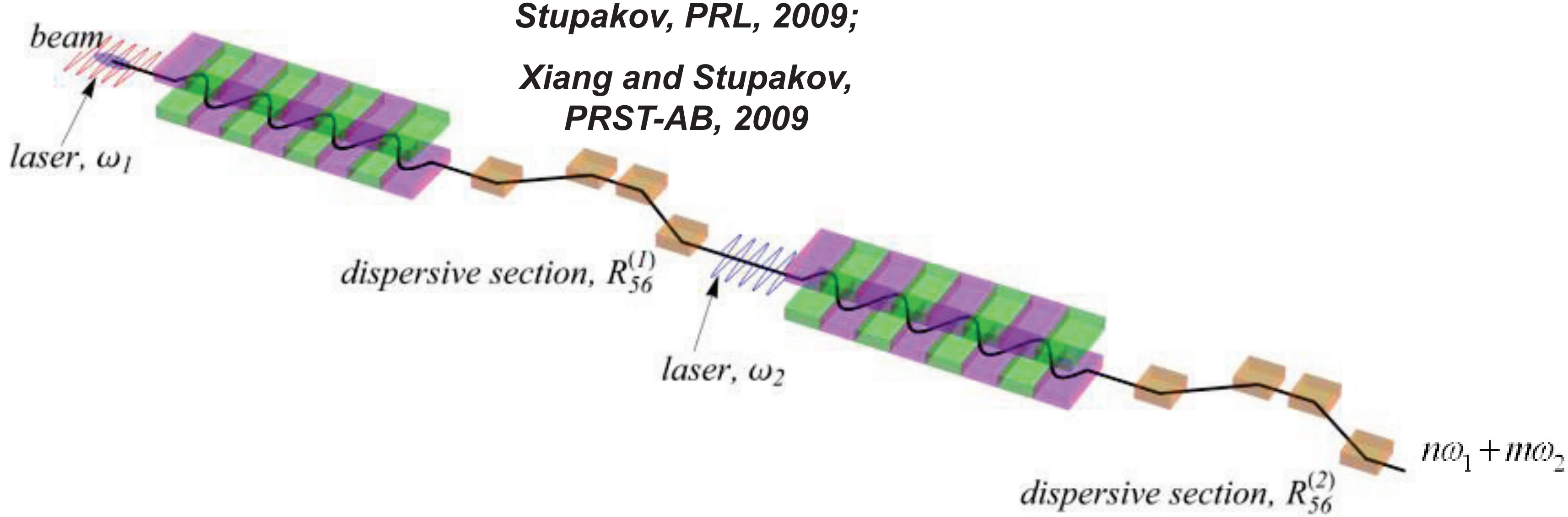
- ***Double* modulator-chicane system**

Stupakov, PRL, 2009;

Xiang and Stupakov, PRST-AB, 2009



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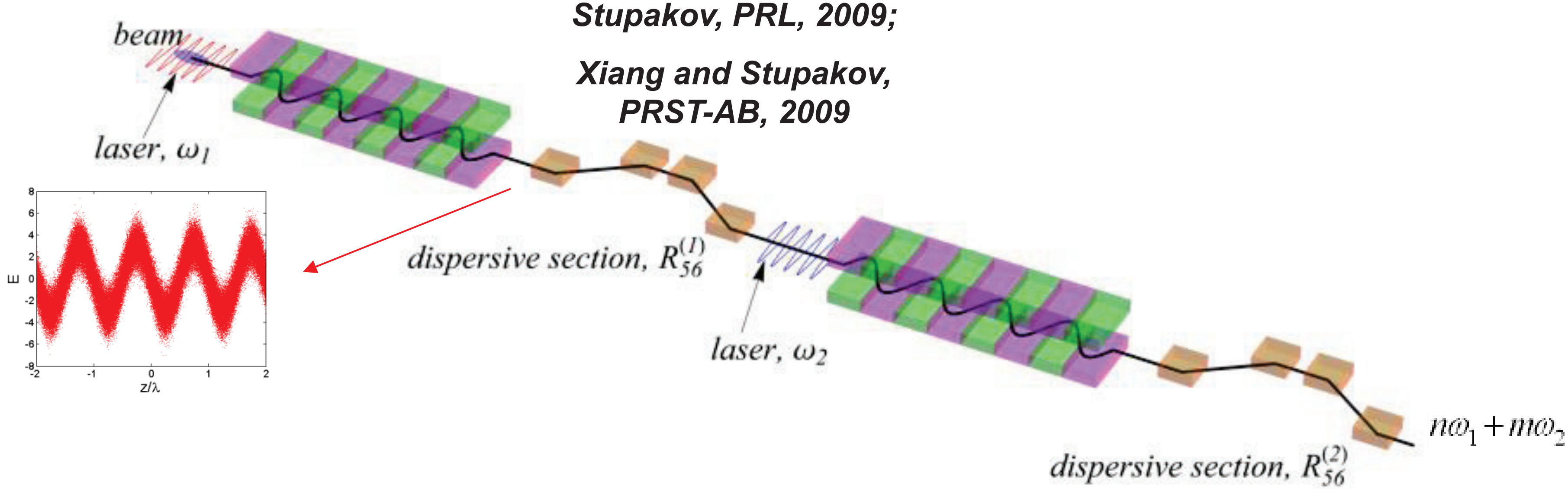

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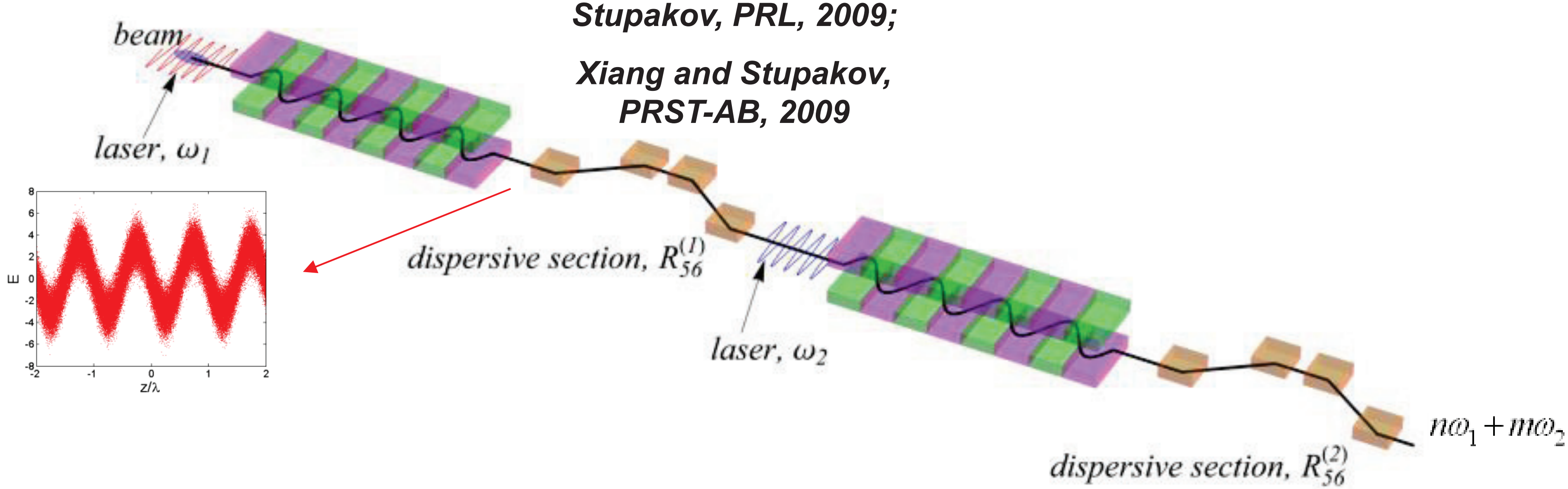

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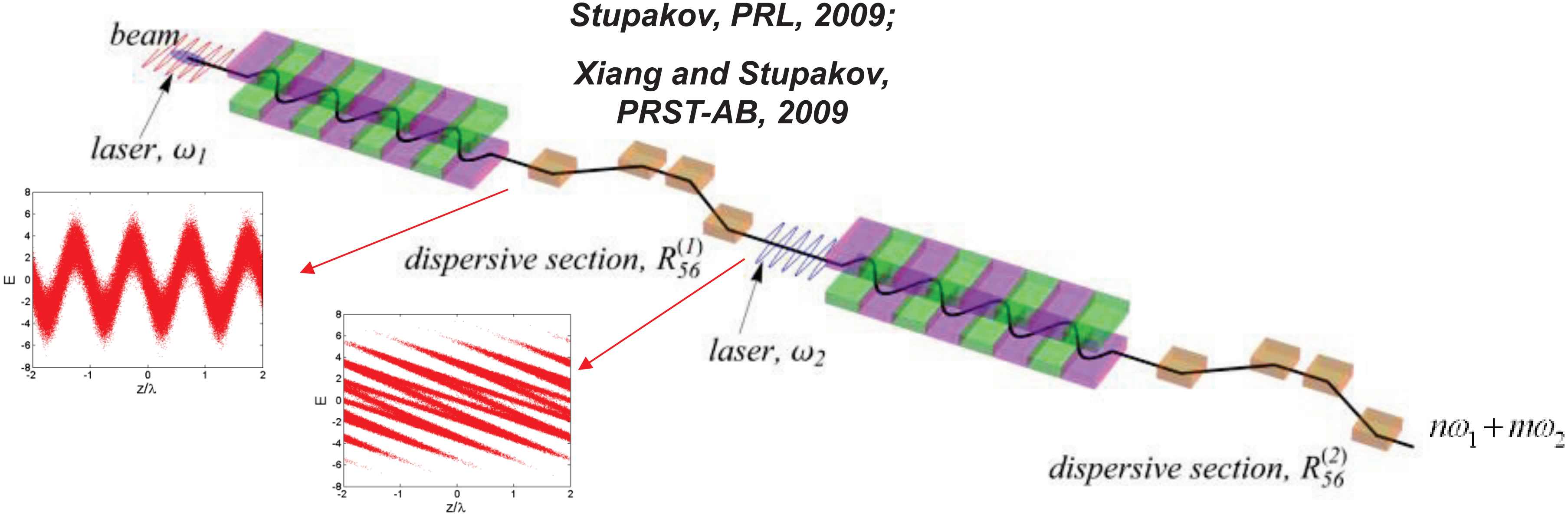

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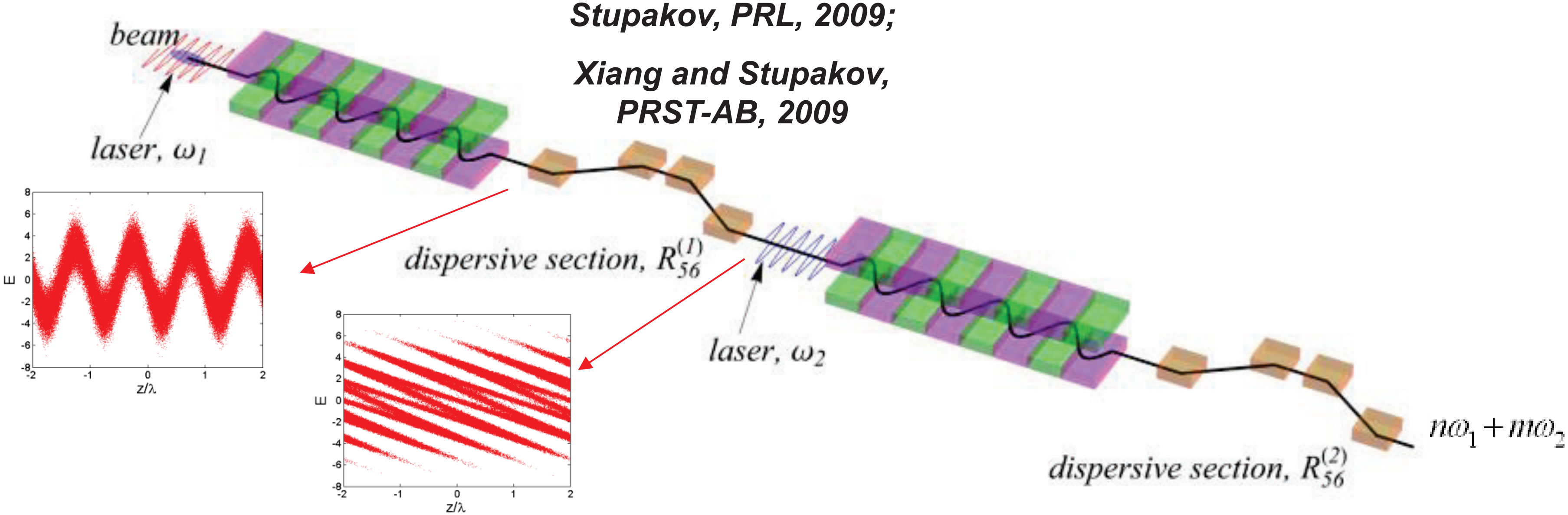

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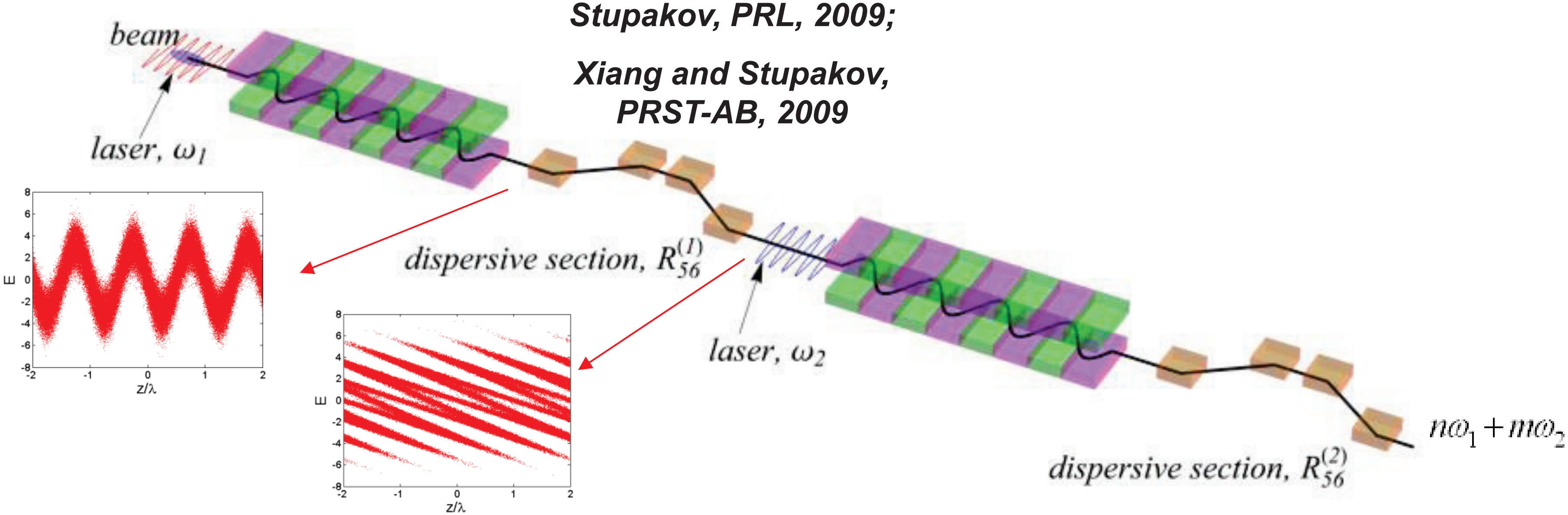

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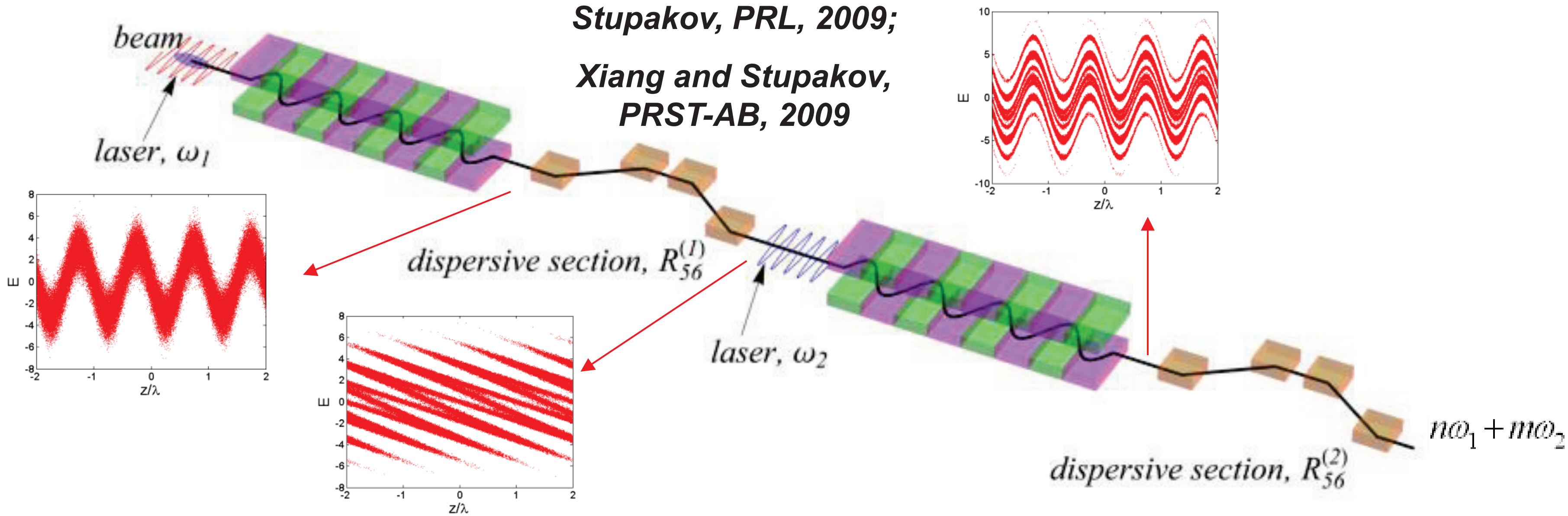

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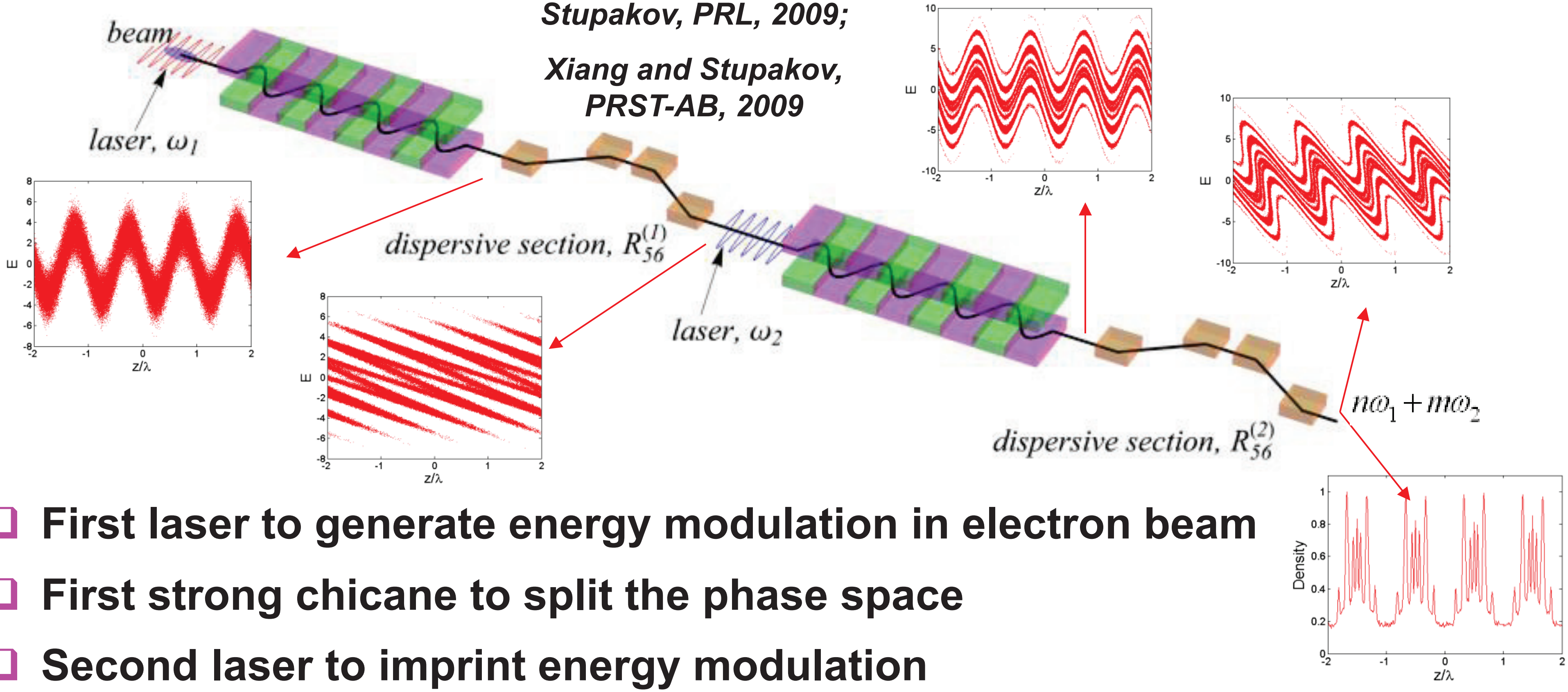

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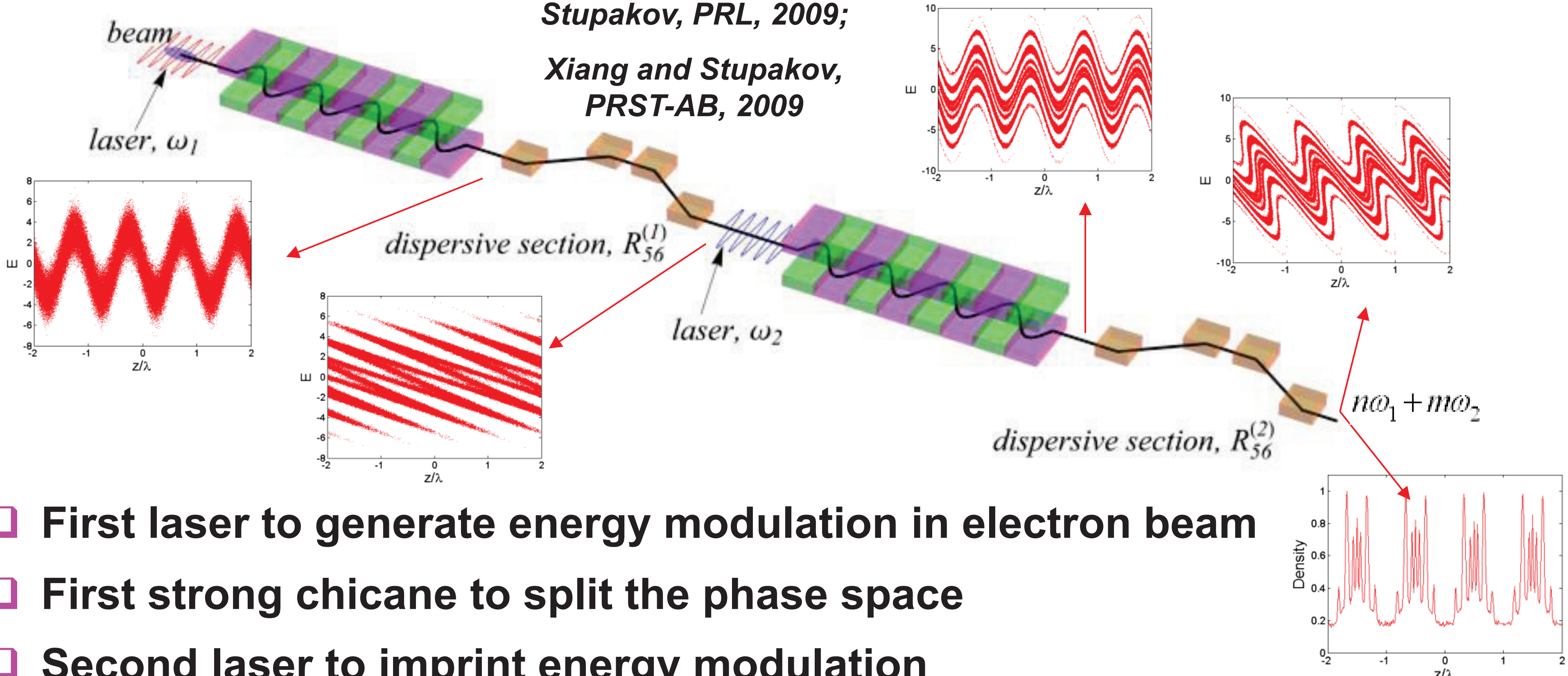

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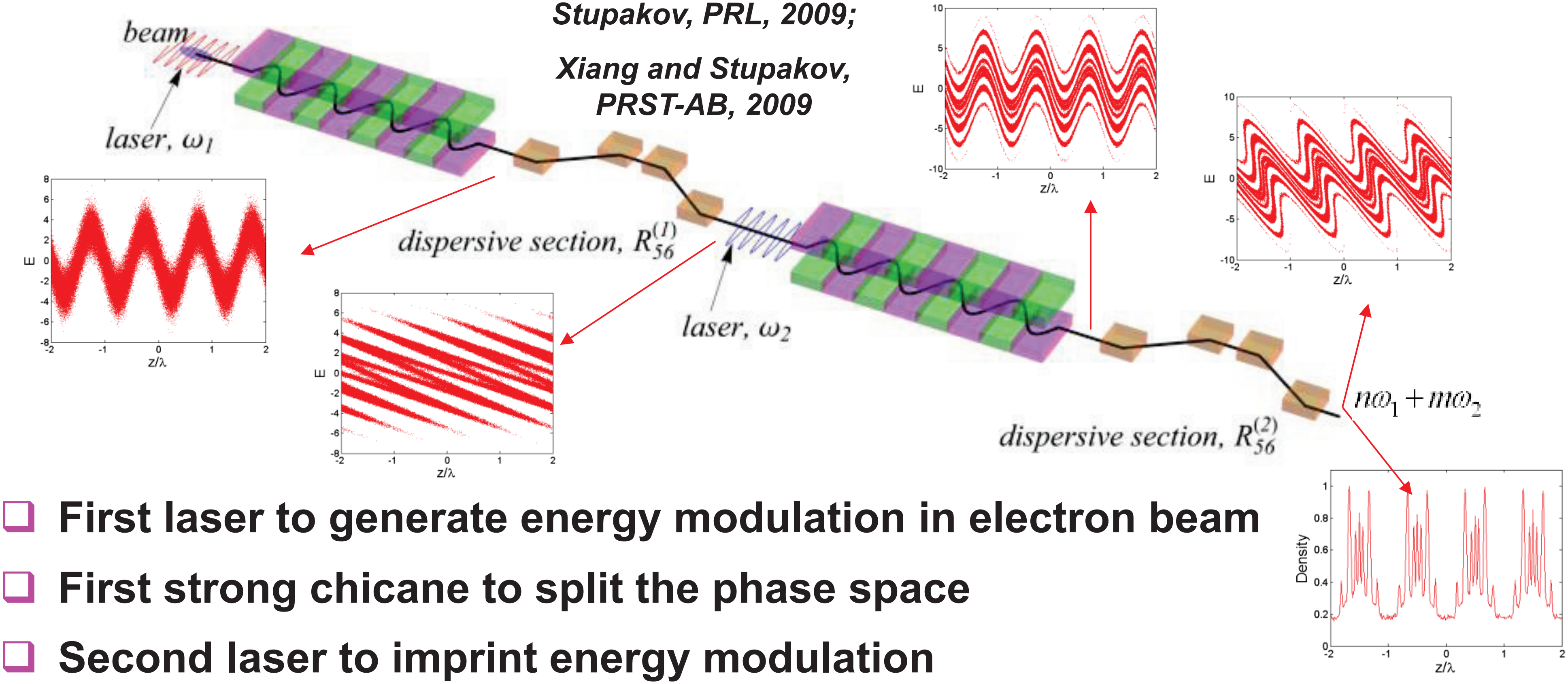

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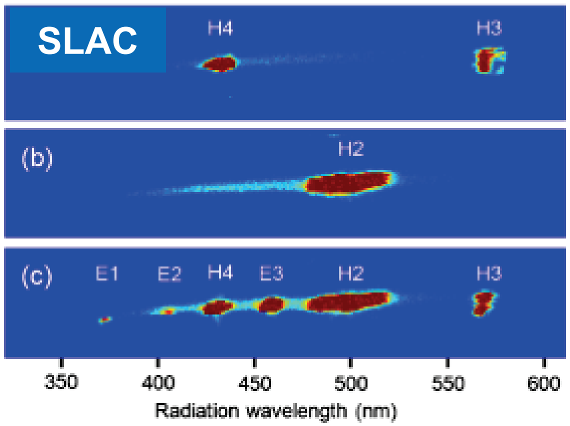
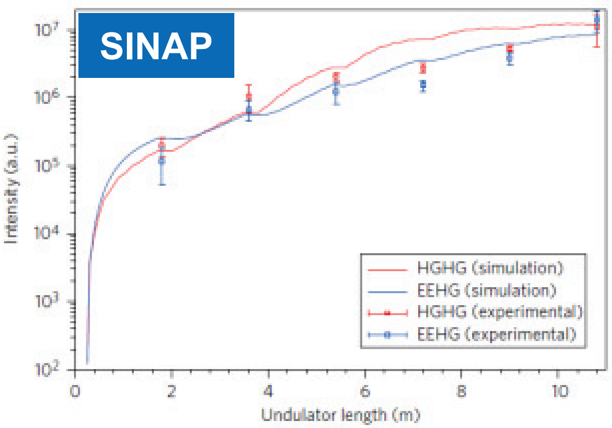
$$n \gg \Delta E / \sigma_E$$

Bunch compression with laser induced energy chirp

EEHG experiments (SLAC&SINAP)

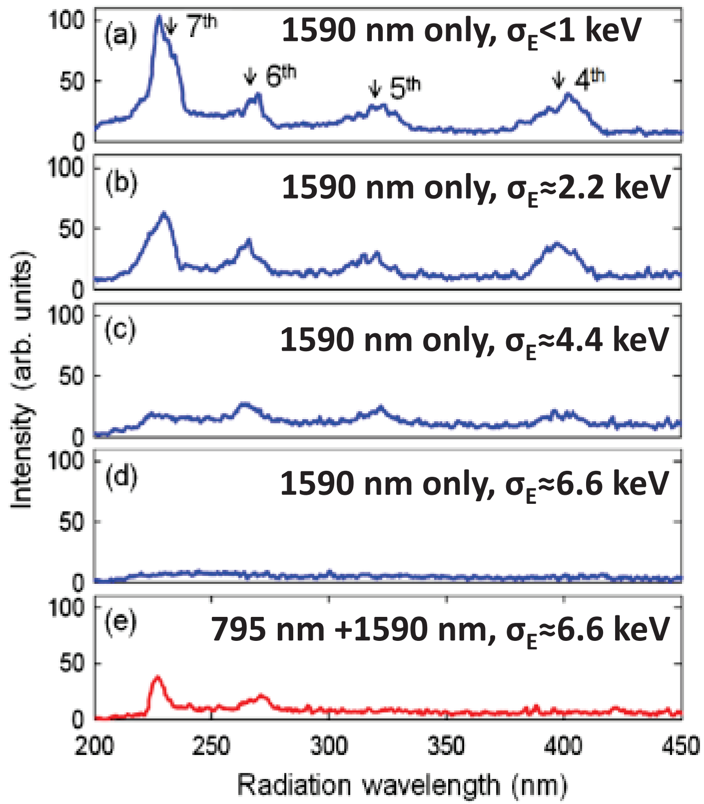
ECHO-3





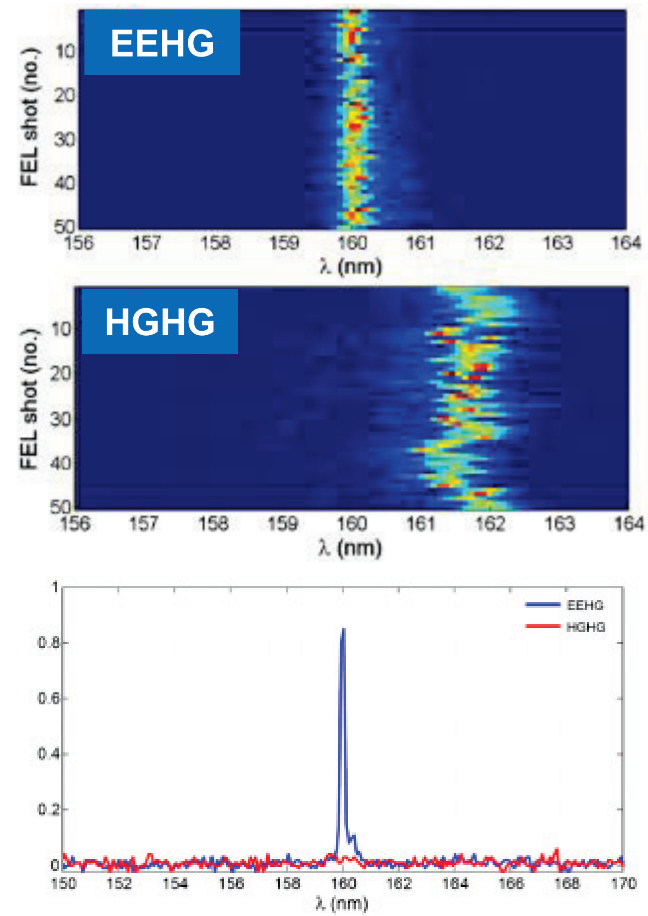
Xiang et al., PRL (2010)
Zhao et al., Nat. Photon. (2012)
Huang et al., FEL09 (2009)

ECHO-7



Xiang et al., PRL (2012)
Behrens, Huang, Xiang, PRST-AB (2012)

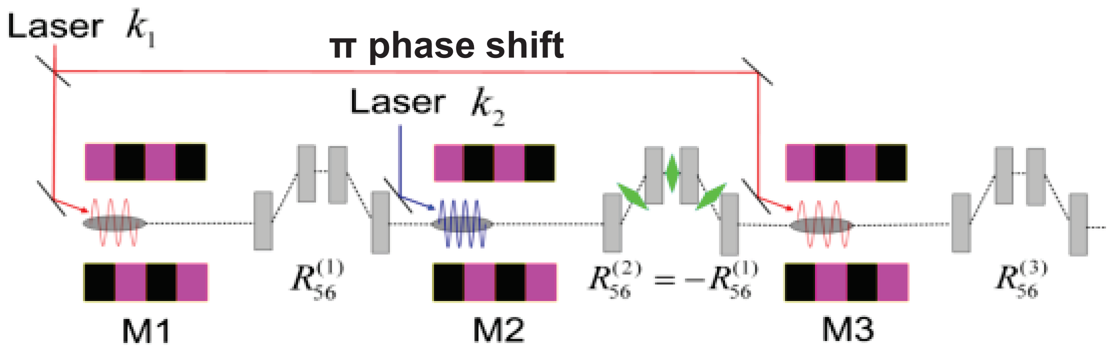
ECHO-15



Hemsing et al., PRST-AB (2014)

Bunch compression with laser induced energy chirp

- ❑ ***Triple*** **modulator-chicane system**



Xiang and Stupakov, New Journal of Physics, 13, 093028 (2011)

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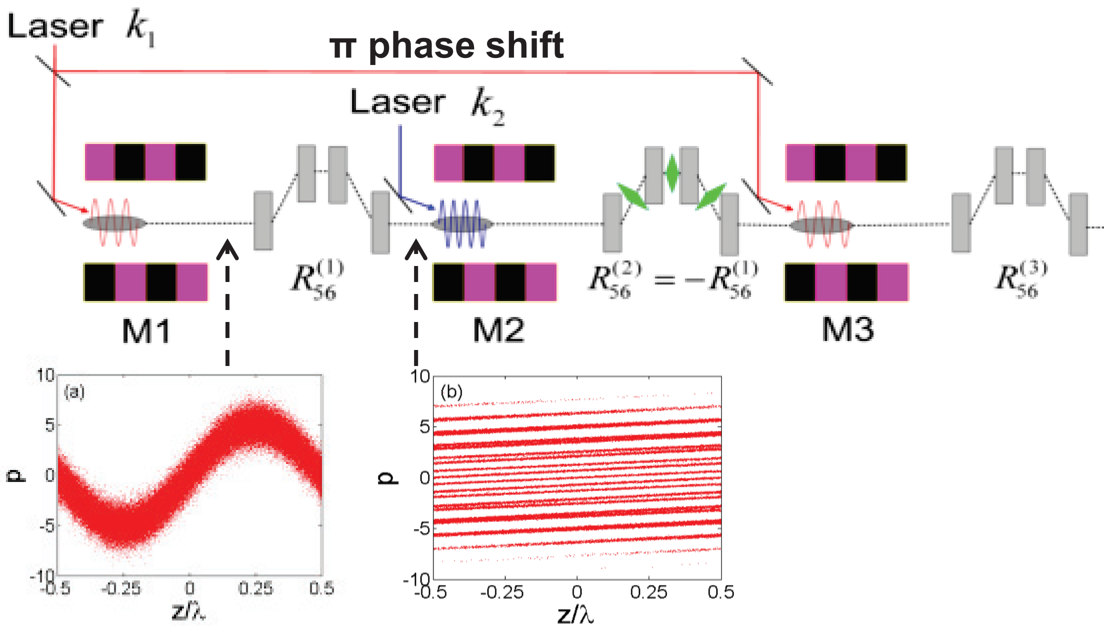

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Bunch compression with laser induced energy chirp

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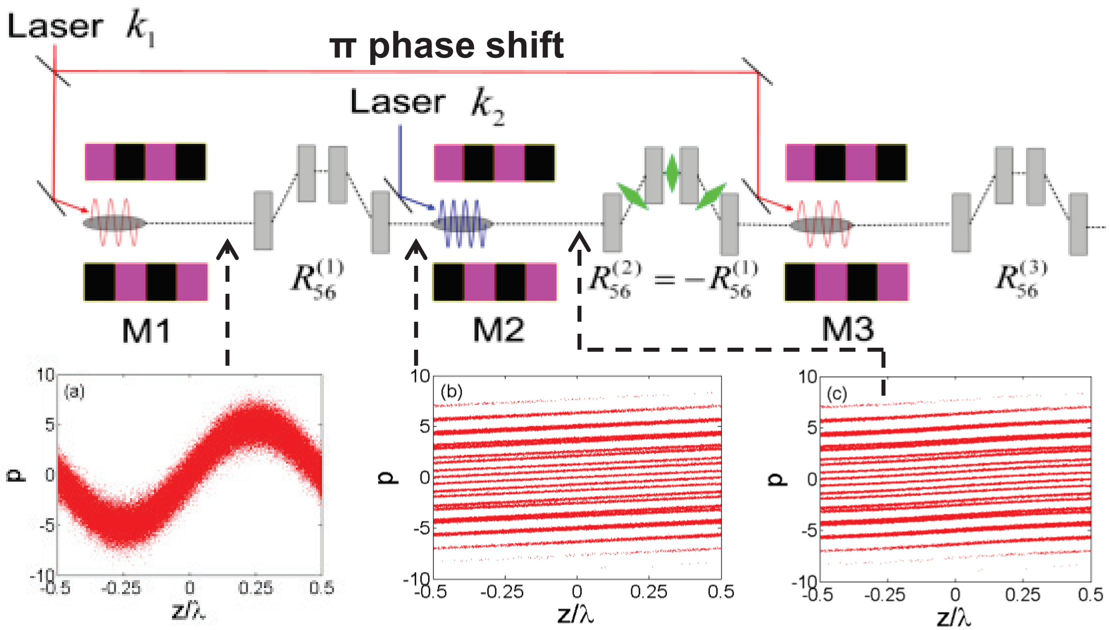

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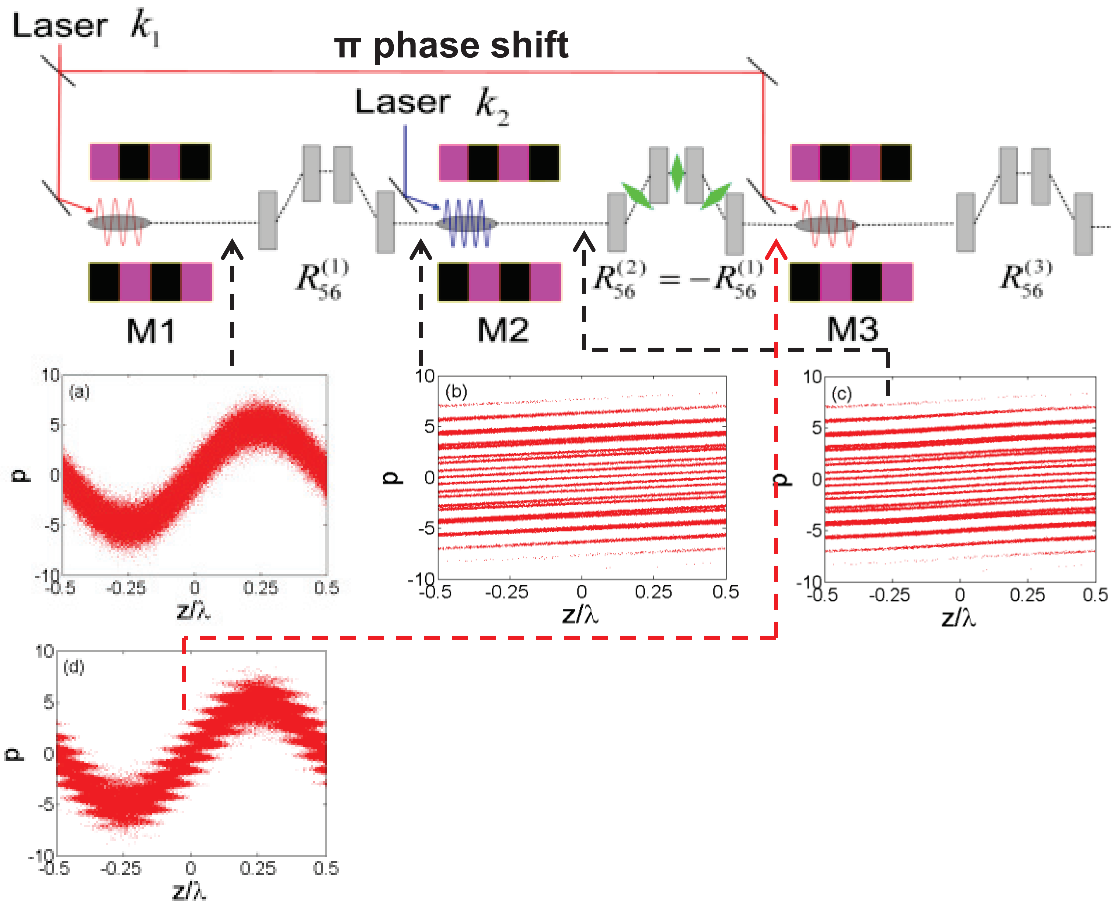

- Bunch decompression in chicane 1 to split phase space
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- Bunch compression in chicane 2
- Modulation in M2 compressed and superimposed on modulation from M1

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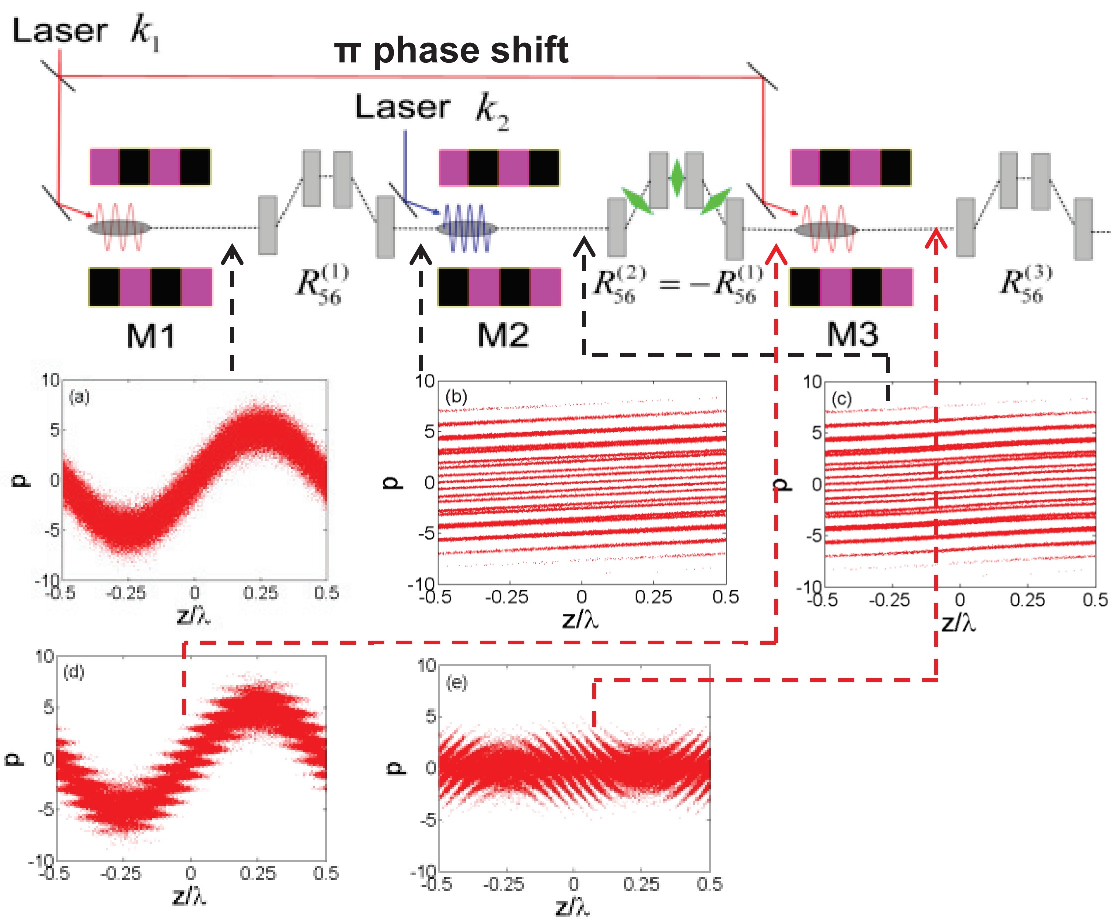

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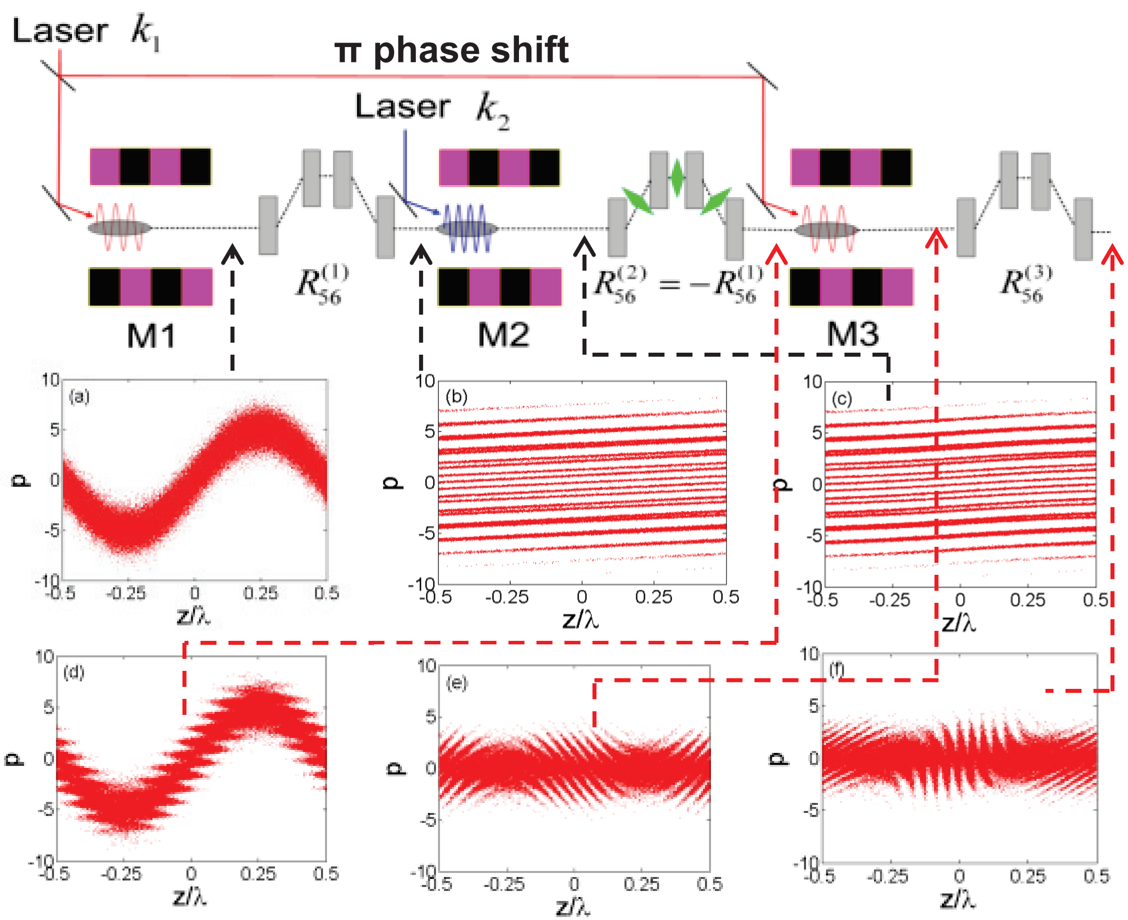

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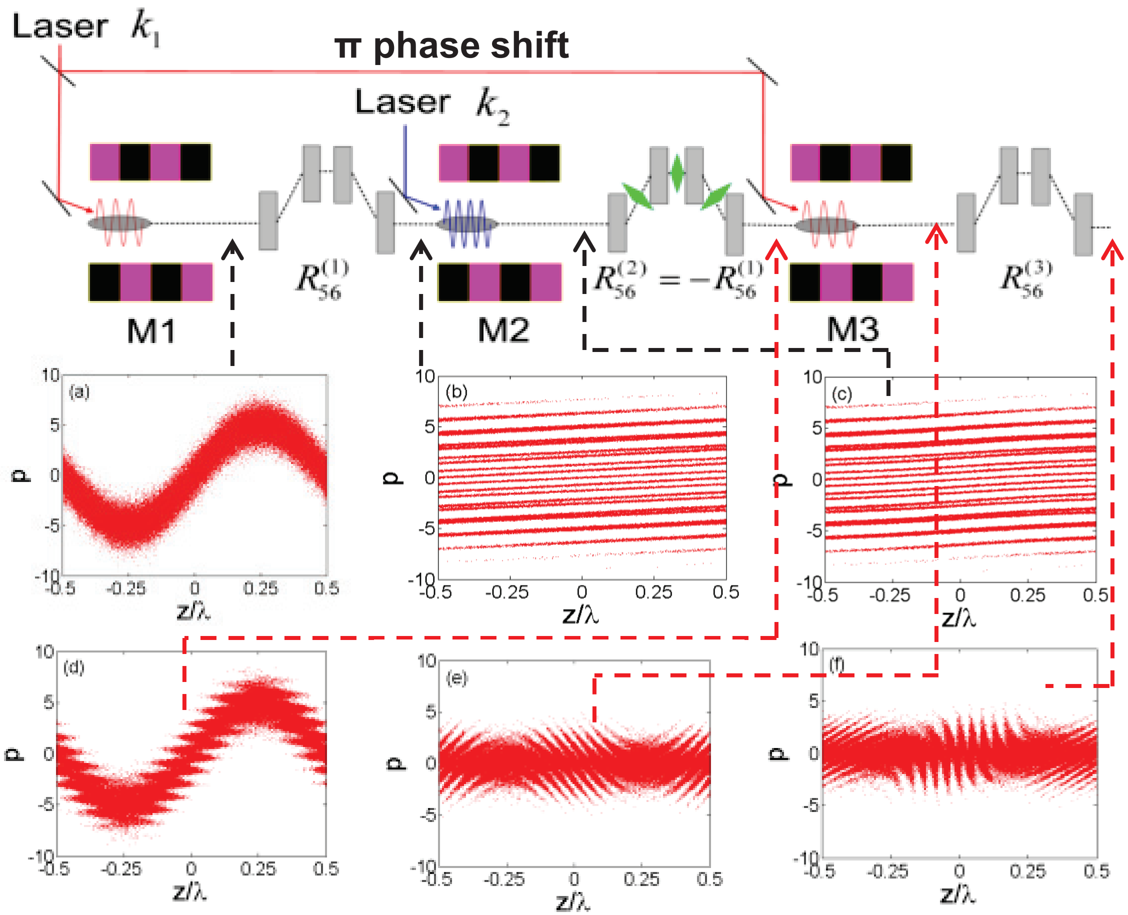

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- Small modulation in M2
- Bunch compression in chicane 2
- Modulation in M2 compressed and superimposed on modulation from M1
- Modulation in M3 to cancel modulation in M1

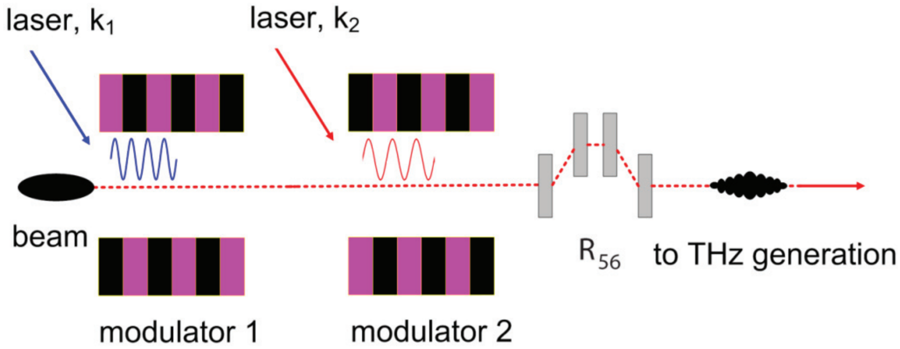
- Modulation in M2 can be produced with a HHG source
- Energy spread growth is negligible
- Seeding in the sub-nm regime

Xiang and Stupakov, New Journal of Physics, 13, 093028 (2011)

Hemsing and Xiang, PRST-AB, 16, 010706 (2013)

Frequency down-conversion for THz

- **Using the relativistic electron beam as the nonlinear medium**



Xiang and Stupakov, PRST-AB, 12, 080701 (2009)

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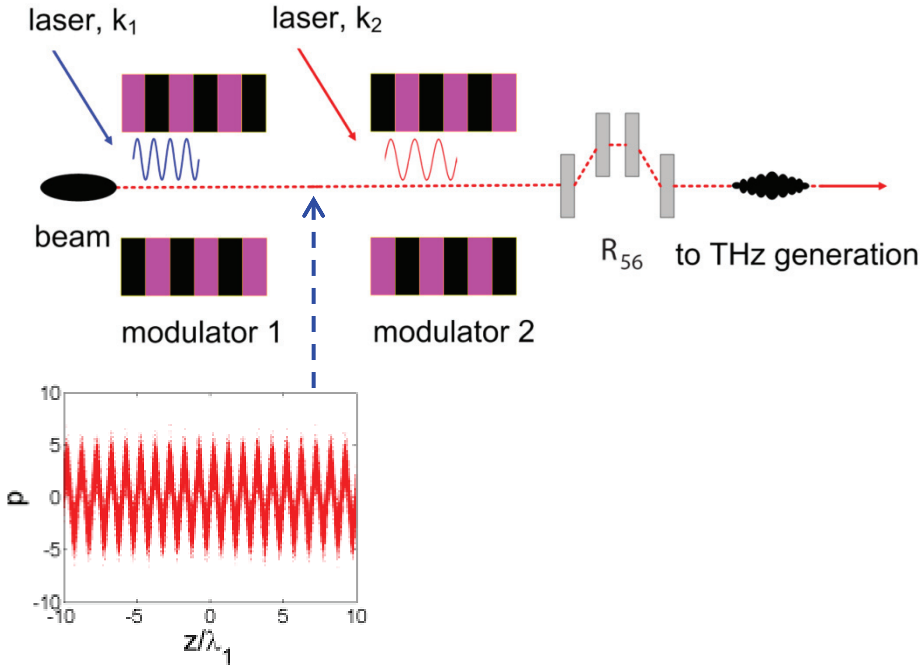

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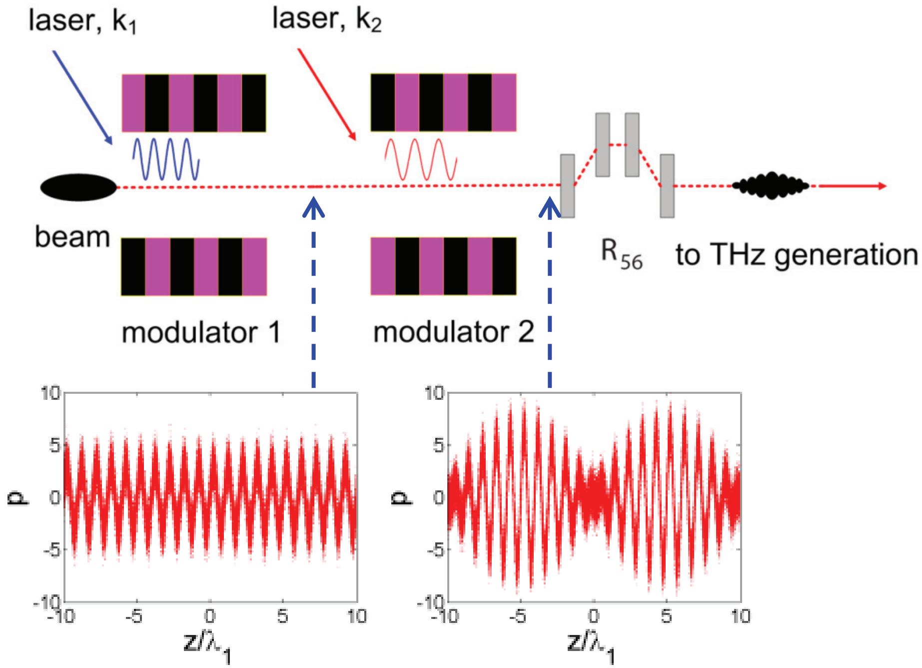

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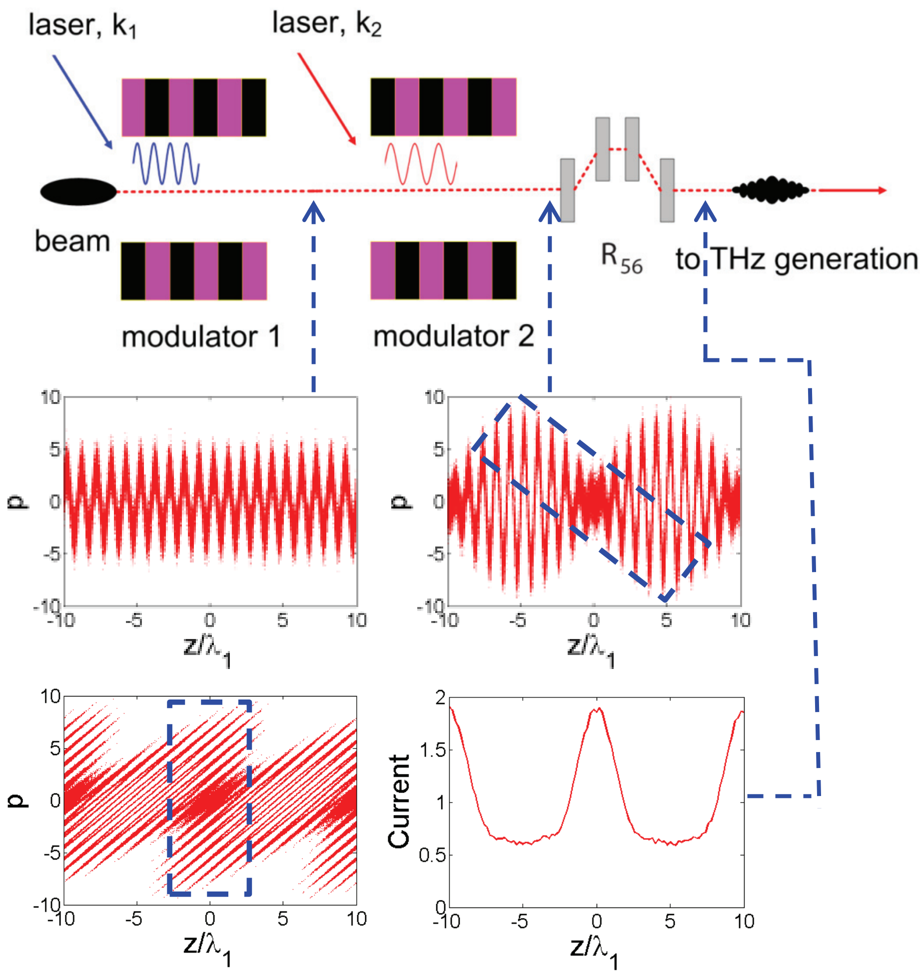

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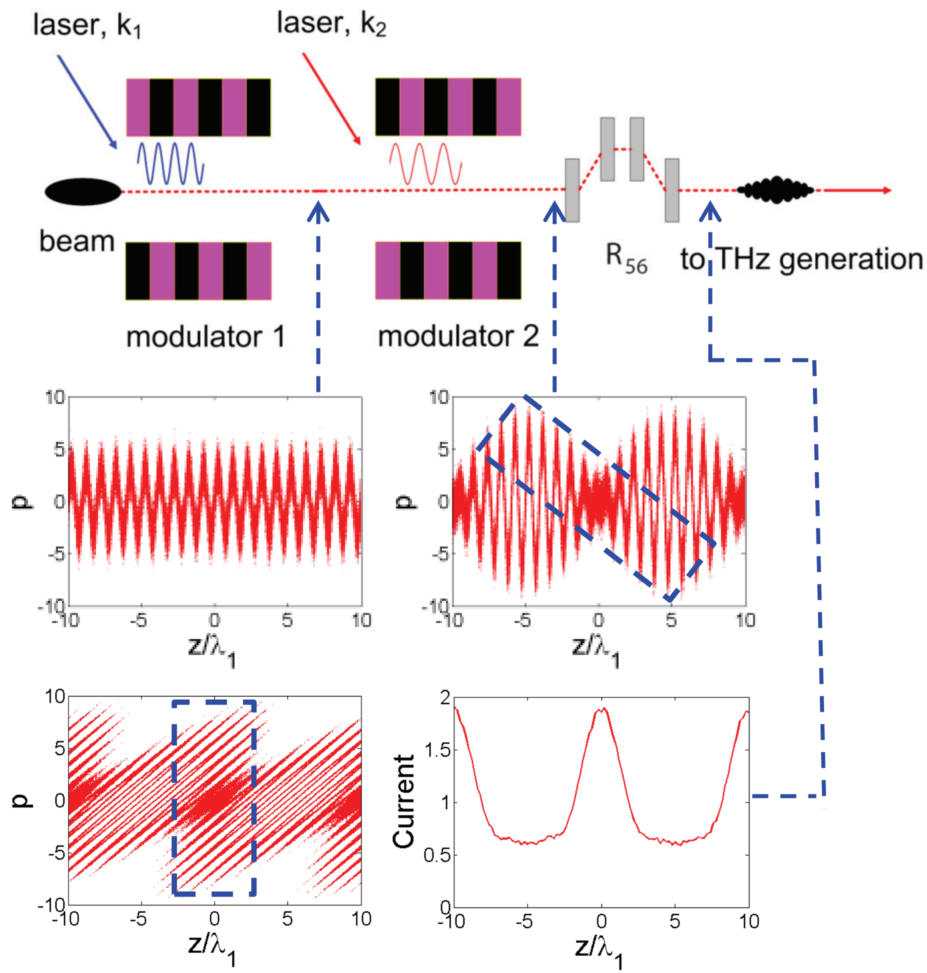

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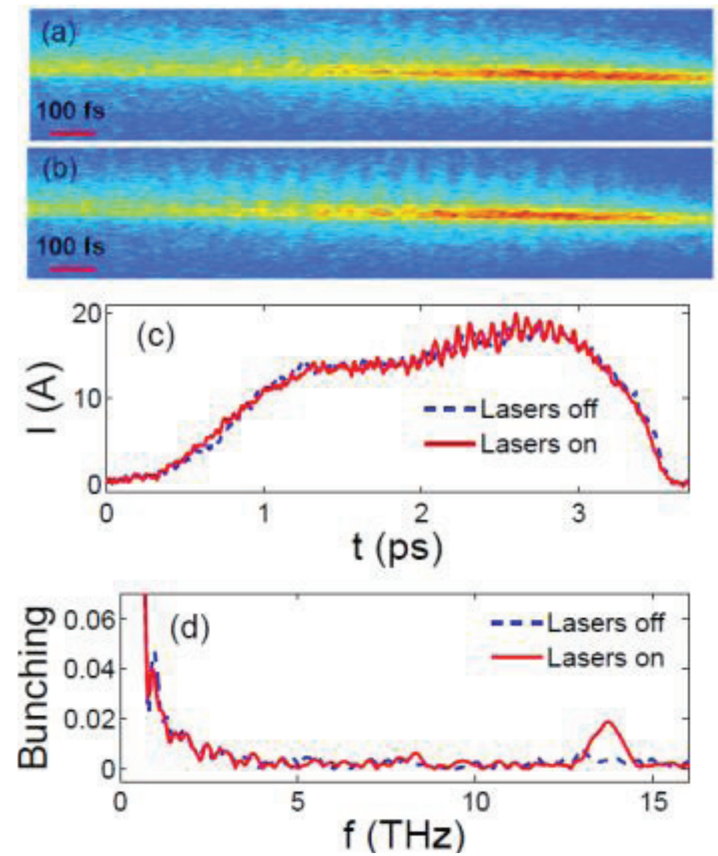
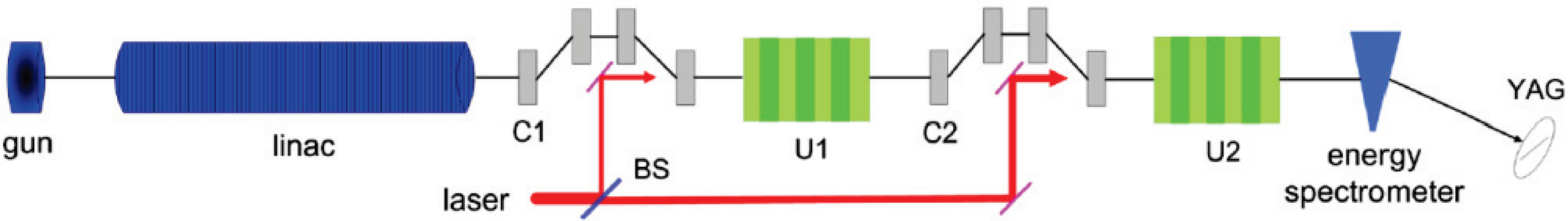


Dunning et al., PRL, 109, 074801 (2012)

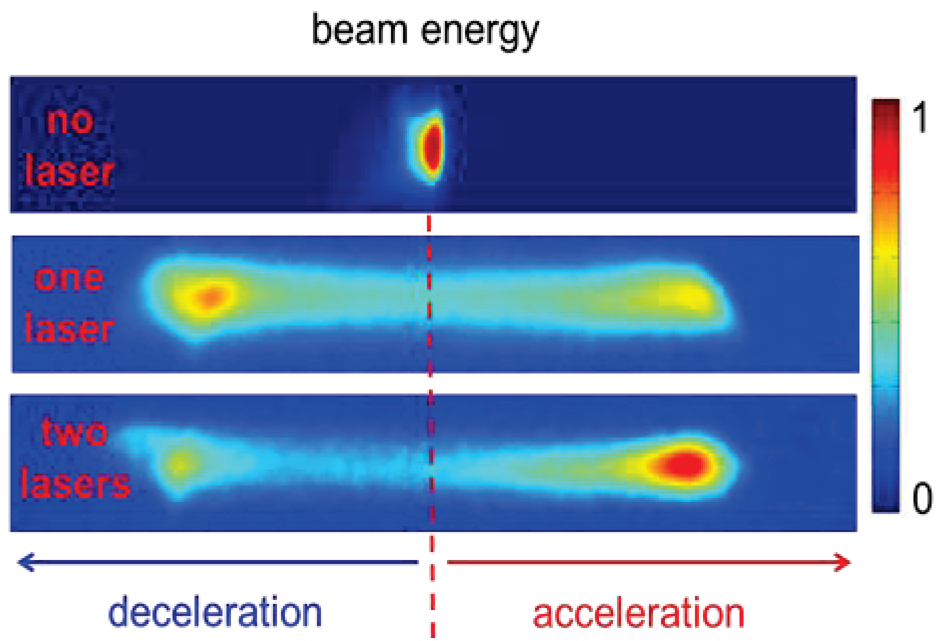
Cascaded optical inverse FEL



Cascaded inverse FEL experiment at SLAC's NLCTA

Cascading in an optical inverse FEL accelerator leads to significantly improved beam quality

- In a single stage inverse FEL, half of the electron beam are accelerated while the other half decelerated. This leads to a beam with large energy spread.
- In a cascaded inverse FEL, by matching the laser bucket with microbunches, the beam quality can be significantly improved.

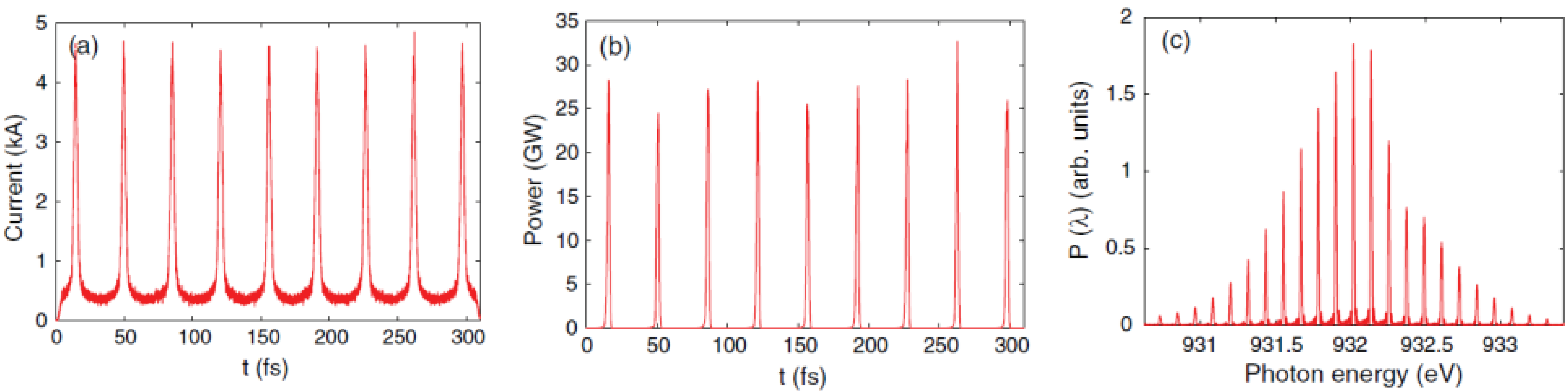


Dunning et al., PRL, 110, 244801 (2013)

Mode-locked x-rays

Drive a seeded FEL with density modulated beam

Xiang et al., PRST-AB, 15, 050707 (2012)



Beam current | **Radiation profile** | **Spectrum**

Gain length of current bumps<<current dips; FEL output copies the beam current distribution.

- **Slippage length smaller than separation of the microbunches**
- **Time domain: attosecond pulse train equally separated by the laser wavelength**
- **Frequency domain: span a wide frequency with equally spaced sharp lines**

Other schemes to generate mode-locked x-rays:

Thompson and McNeil., PRL, 100, 203901 (2008)
Kur et al., New J. Phys, 13, 063012 (2011)
Feng et al., PRST-AB, 15, 080703 (2012)

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One may tailor the beam distribution at high precision for specific applications;

On the other hand:

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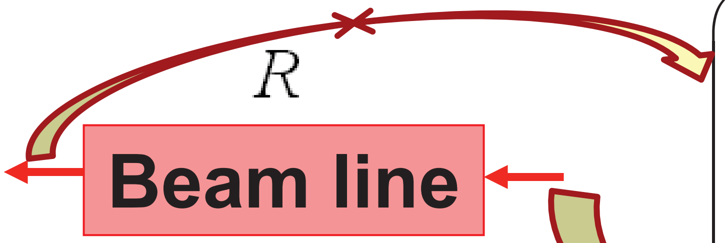
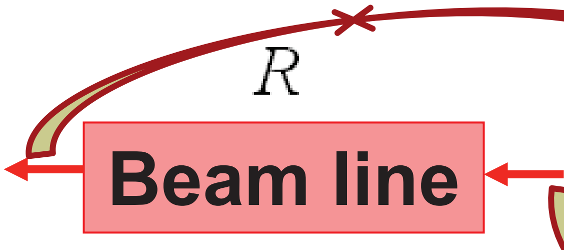
3. 6-D beam manipulation
4. Ultrafast Electron Diffraction and Microscopy

Emittance exchange



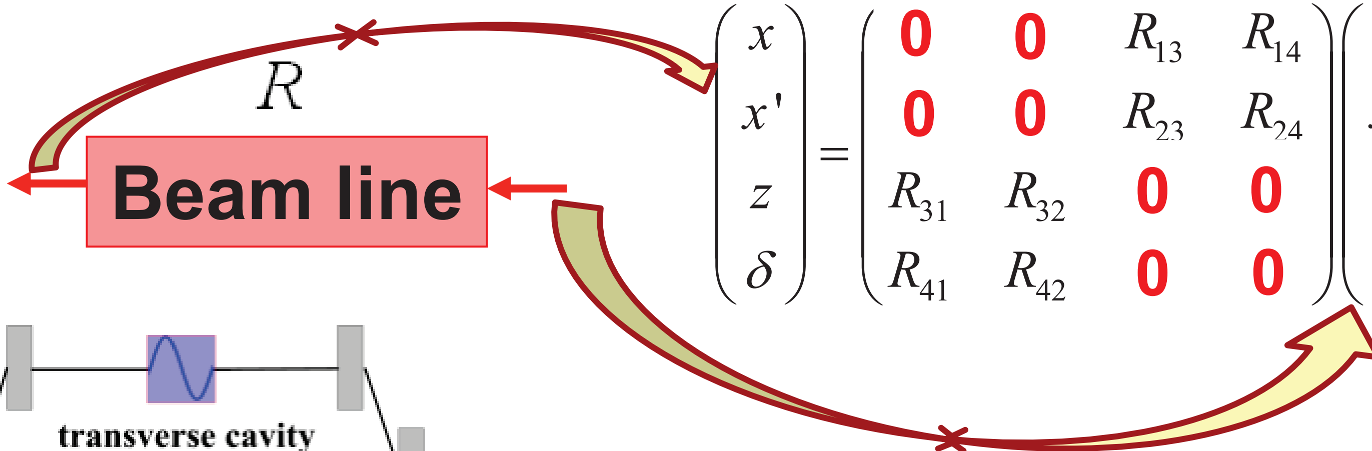
$$\begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix} = \begin{pmatrix} R_{11} & R_{12} & R_{13} & R_{14} \\ R_{21} & R_{22} & R_{23} & R_{24} \\ R_{31} & R_{32} & R_{33} & R_{34} \\ R_{41} & R_{42} & R_{43} & R_{44} \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \\ z_0 \\ \delta_0 \end{pmatrix}$$

Emittance exchange

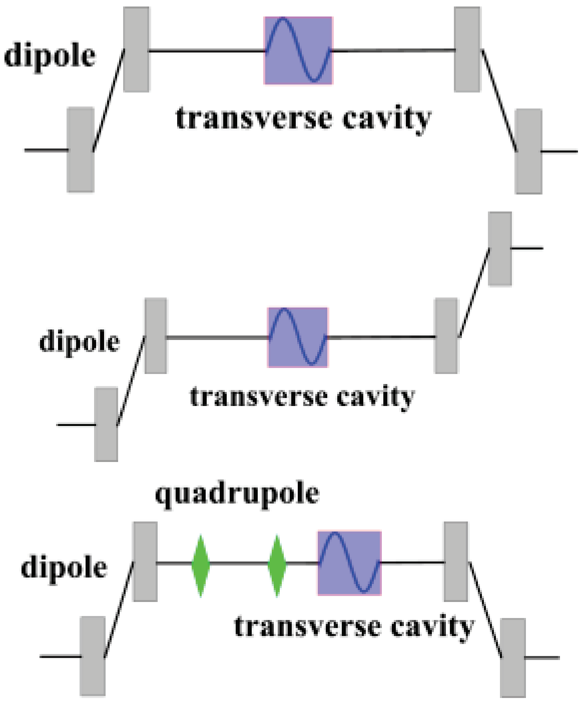


$$\begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix} = \begin{pmatrix} 0 & 0 & R_{13} & R_{14} \\ 0 & 0 & R_{23} & R_{24} \\ R_{31} & R_{32} & 0 & 0 \\ R_{41} & R_{42} & 0 & 0 \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \\ z_0 \\ \delta_0 \end{pmatrix}$$

Emittance exchange



$$\begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix} = \begin{pmatrix} 0 & 0 & R_{13} & R_{14} \\ 0 & 0 & R_{23} & R_{24} \\ R_{31} & R_{32} & 0 & 0 \\ R_{41} & R_{42} & 0 & 0 \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \\ z_0 \\ \delta_0 \end{pmatrix}$$

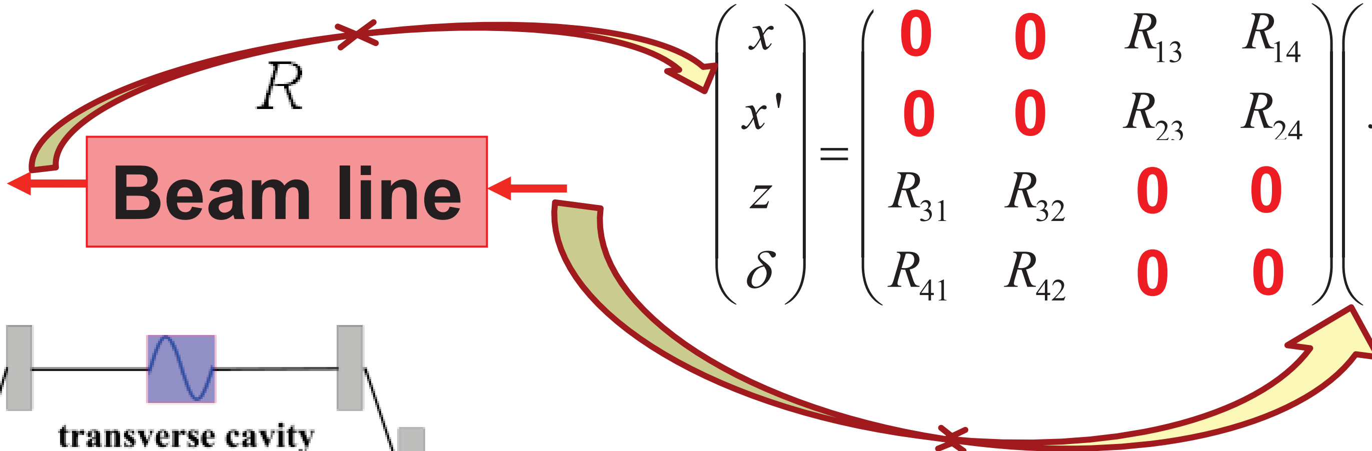


Cornacchia and Emma PRST-AB, 5, 084001 (2002);

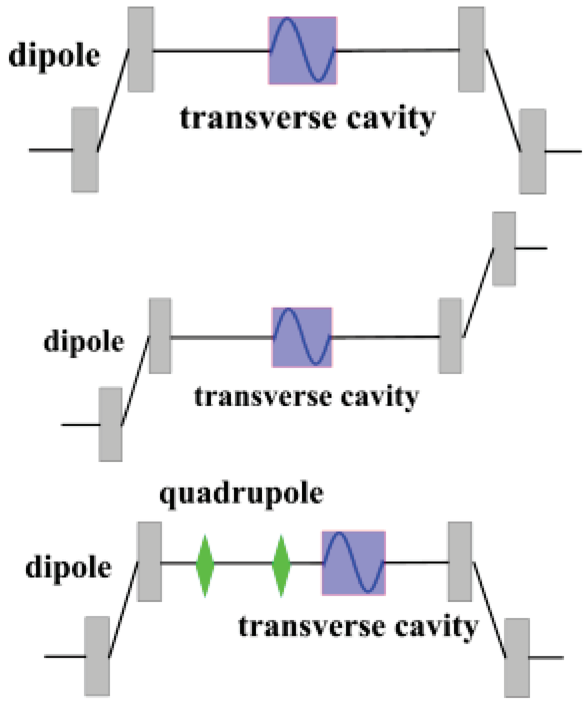
Emma et al., PRST-AB, 9, 100702 (2006);

Xiang and Chao, PRST-AB, 14, 114001 (2011)

Emittance exchange

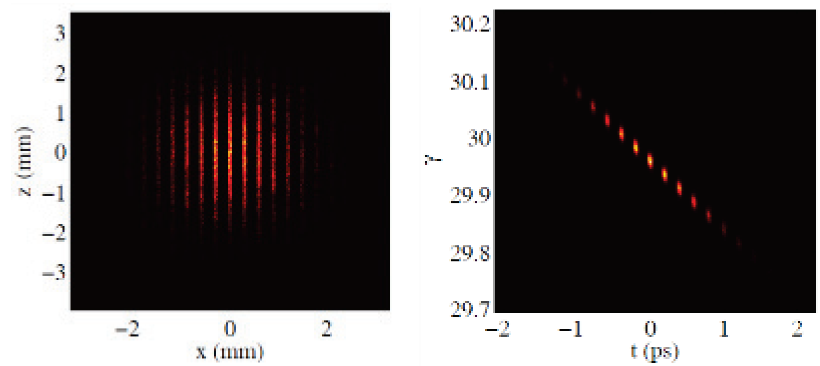


$$\begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix} = \begin{pmatrix} 0 & 0 & R_{13} & R_{14} \\ 0 & 0 & R_{23} & R_{24} \\ R_{31} & R_{32} & 0 & 0 \\ R_{41} & R_{42} & 0 & 0 \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \\ z_0 \\ \delta_0 \end{pmatrix}$$



Cornacchia and Emma PRST-AB, 5, 084001 (2002);
Emma et al., PRST-AB, 9, 100702 (2006);
Xiang and Chao, PRST-AB, 14, 114001 (2011)

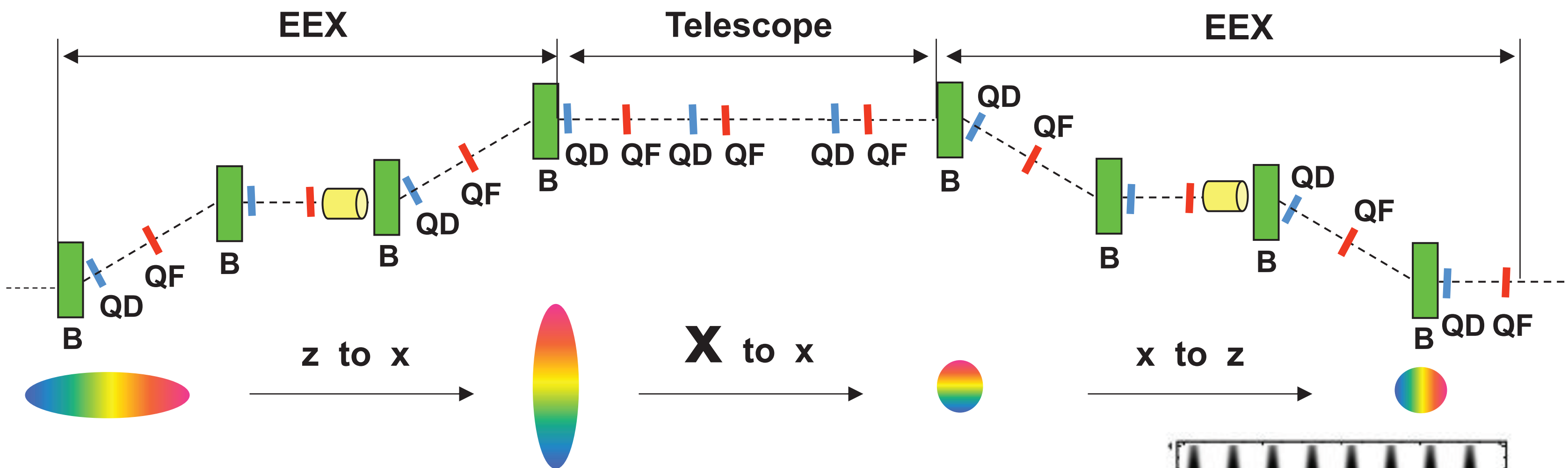
Shaping longitudinal distribution with transverse mask



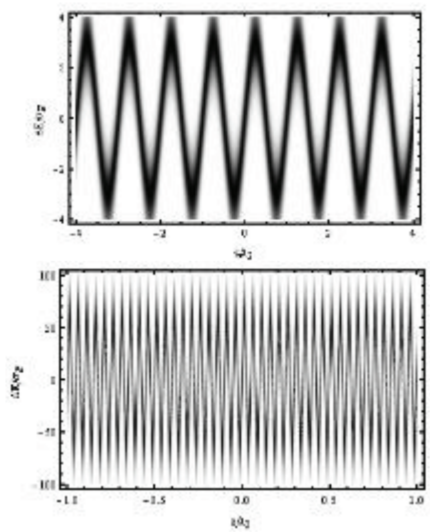
Sun and Piot, Linac08; Sun et al., PRL, 105, 234801 (2010); Ruan et al., PRL, 106, 244801, (2011); Piot et al., PRST-AB, 14, 022801 (2011); Jiang et al., PRL, 106, 114801 (2011)

Emittance exchange

Chirp-free bunch compression



- NO energy chirp required
- NO requirement on linearity of longitudinal phase space
- Longitudinal telescope
- Compression of laser modulation to shorter wavelength for FEL seeding



Zholents and Zolotorev, ANL Report No. ANL/APS/LS-327, (2011)

Outline

On the one hand:

One may tailor the beam distribution at high precision for specific applications;

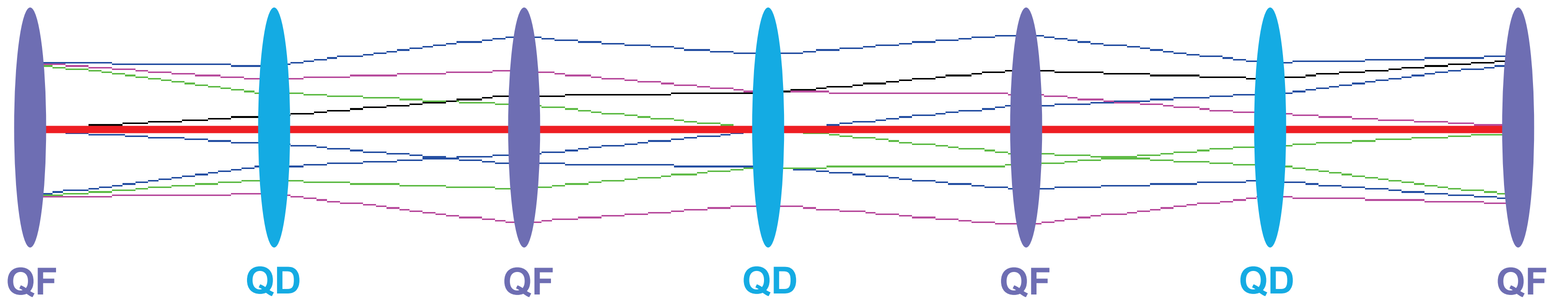
On the other hand:

Beam manipulation has to obey basic rules as well as technological limitations.

1. 2-D beam manipulation
2. 4-D beam manipulation
3. 6-D beam manipulation
4. Ultrafast Electron Diffraction and Microscopy

Beam conditioning

- **Beam transverse emittance effects in FELs**



Particles with larger betatron amplitudes have longer path lengths

$$\sigma_{\Delta s} \approx \frac{L\sqrt{\varepsilon_{nx}^2 + \varepsilon_{ny}^2}}{\gamma\langle\beta\rangle\cos^2(\mu/2)} \approx \frac{\sqrt{2}L\varepsilon_n}{\gamma\langle\beta\rangle} << \frac{\lambda}{2\pi}$$

$$\varepsilon < \frac{\lambda}{2\pi}\frac{\langle\beta\rangle}{L_g}$$

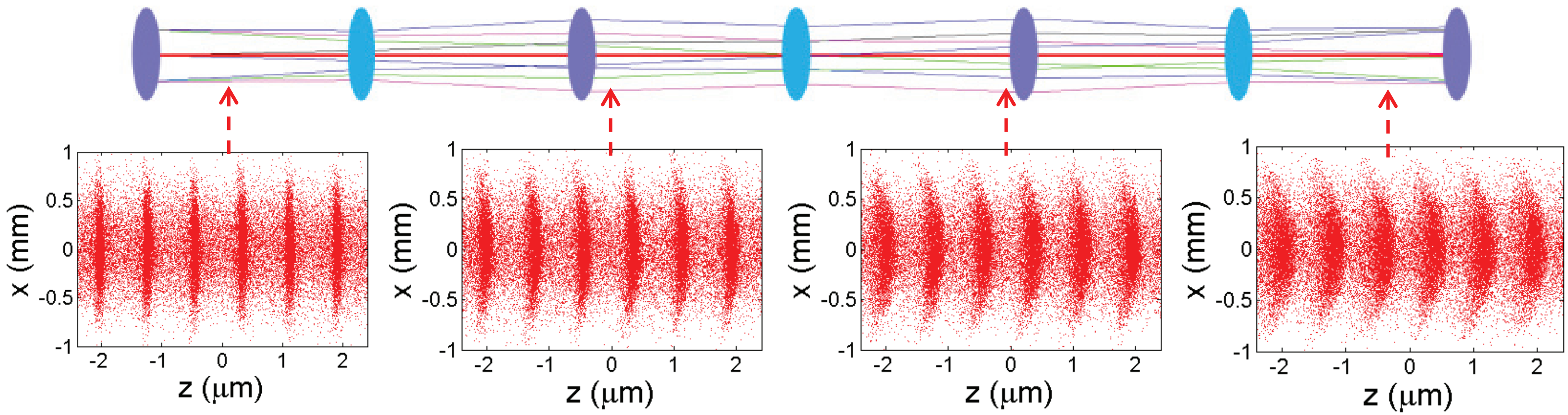
From P. Emma

FEL requirement

- **Counteract bunching and reduce FEL gain**

Beam conditioning

- Smearing of micro-bunches when they propagate in a FODO lattice



- Establish a correlation between particle's energy and betatron amplitude

$$-\frac{A^2}{4\beta^2}+\frac{\Delta\gamma}{\gamma}\frac{1+K^2/2}{\gamma^2}=0$$

$\left\langle \frac{\delta v_z}{c} \right\rangle$ → $\frac{A^2}{4\beta^2}$; R_{56} → $\frac{1+K^2/2}{\gamma^2}$

Particles with larger betatron amplitudes are given extra energy to compensate for the longer path lengths

Sessler et al., PRL, 68, 309 (1992); Vinokurov., NIM A, 375, 264 (1996) ; Emma and Stupakov, PRST-AB, 6, 030701 (2003) ; Wolski et al., PRST-AB, 7, 080701 (2004); Zholents, PRST-AB, 8, 050701 (2005); Schroeder et al., PRL, 93, 194801 (2004)

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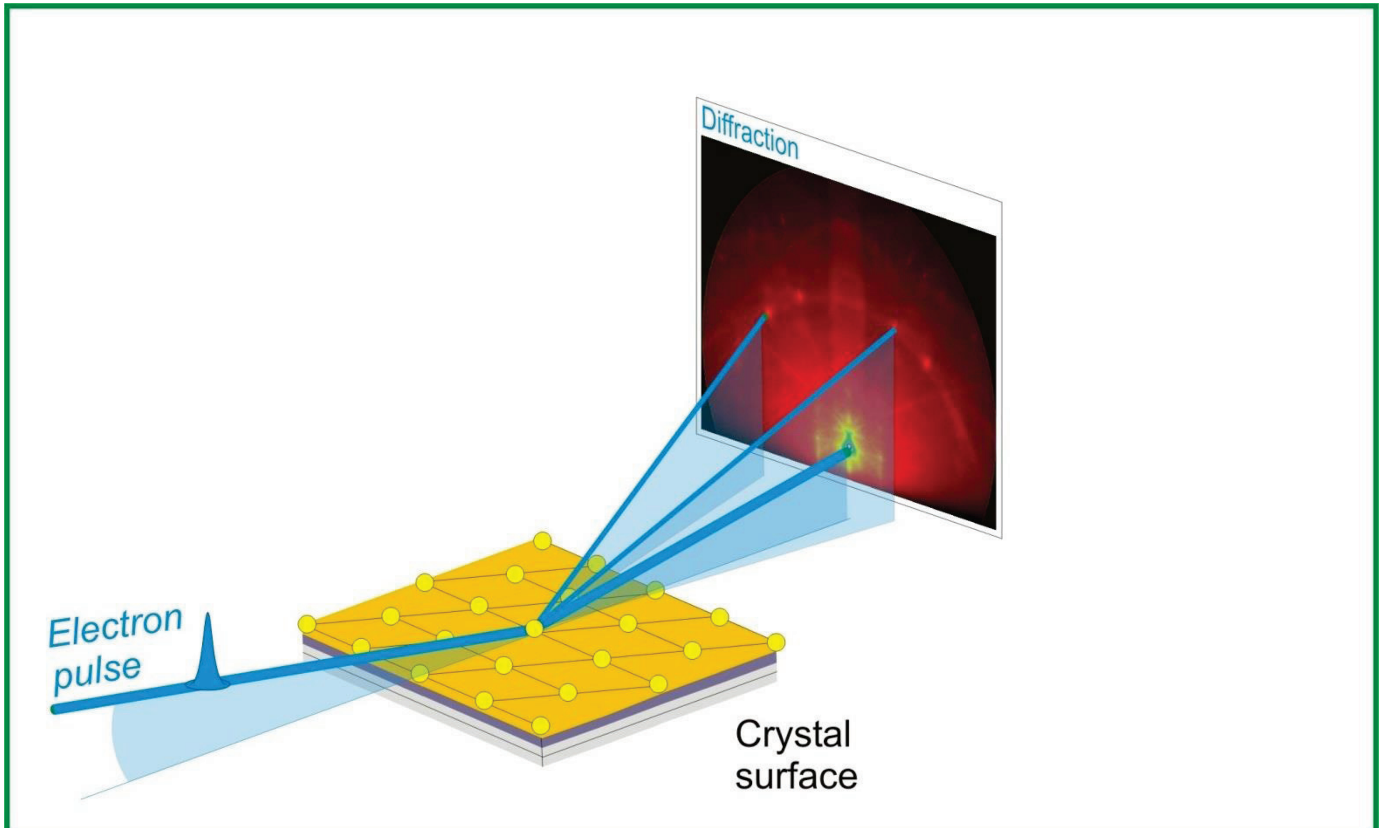
From FEL to UED/UEM

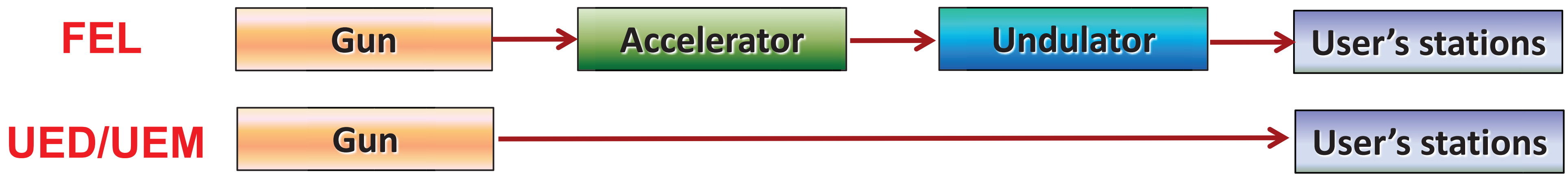
Ultrafast electron diffraction/microscope: poor man's FEL

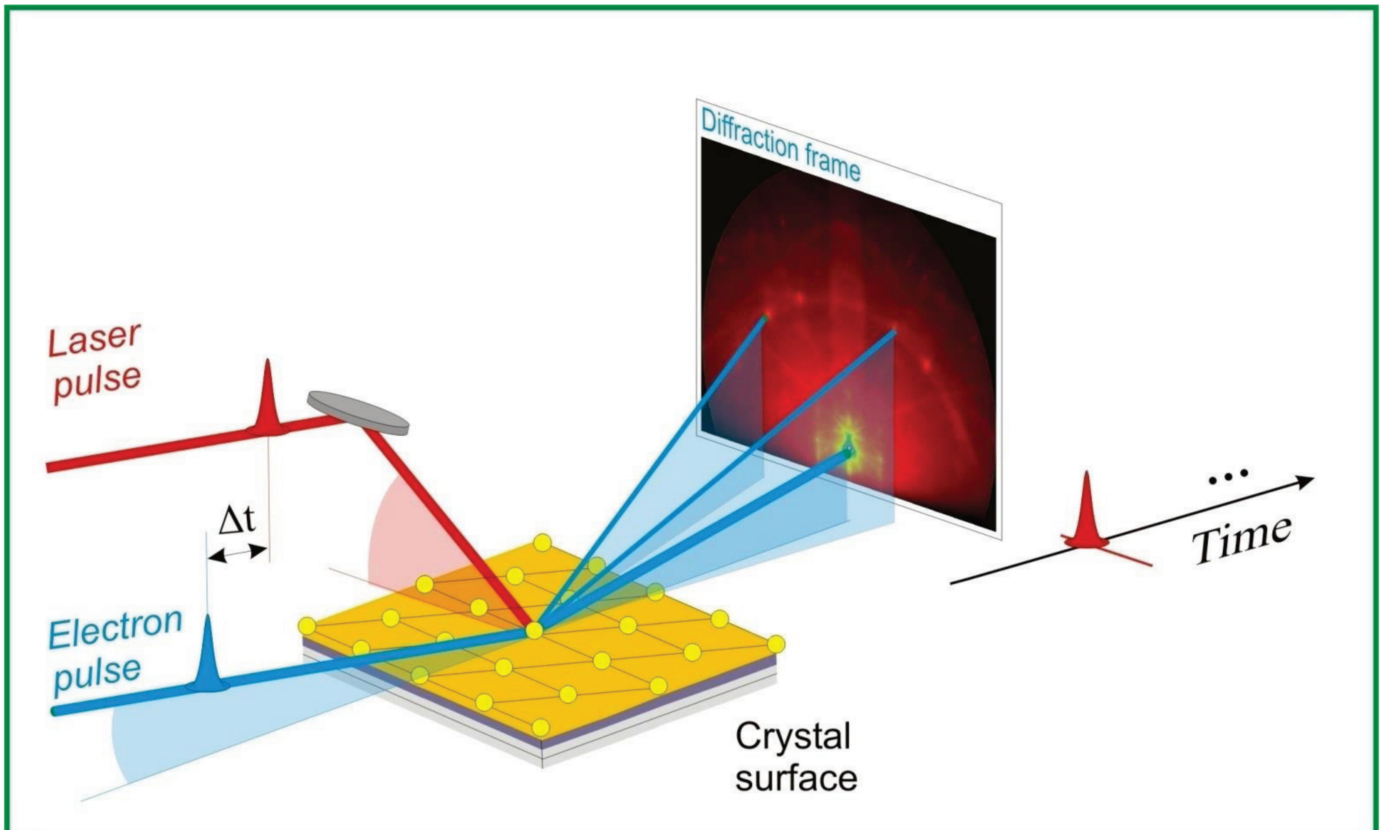
FEL	Gun →	Accelerator →	Undulator →	User's stations
UED/UEM	Gun →			User's stations



From FEL to UED/UEM

Ultrafast electron diffraction/microscope: poor man's FEL



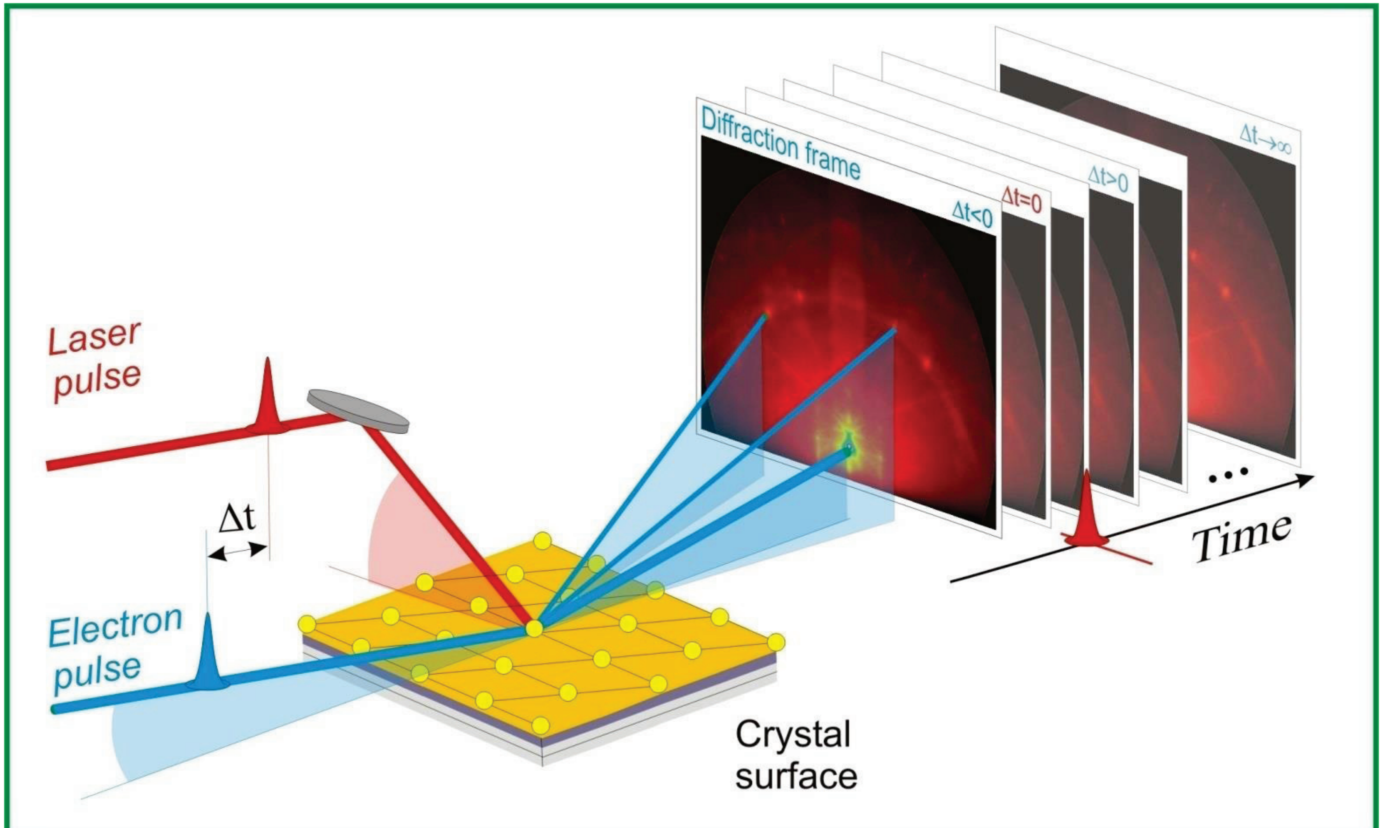


From FEL to UED/UEM

Ultrafast electron diffraction/microscope: poor man's FEL

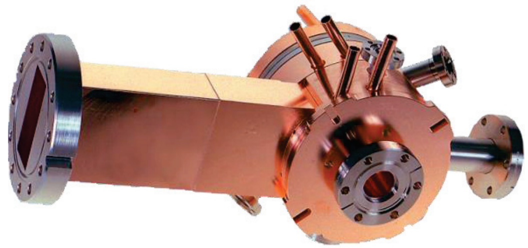
FEL: Gun → Accelerator → Undulator → User's stations

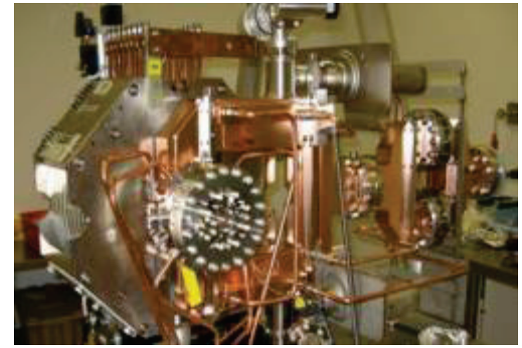
UED/UEM: Gun → User's stations

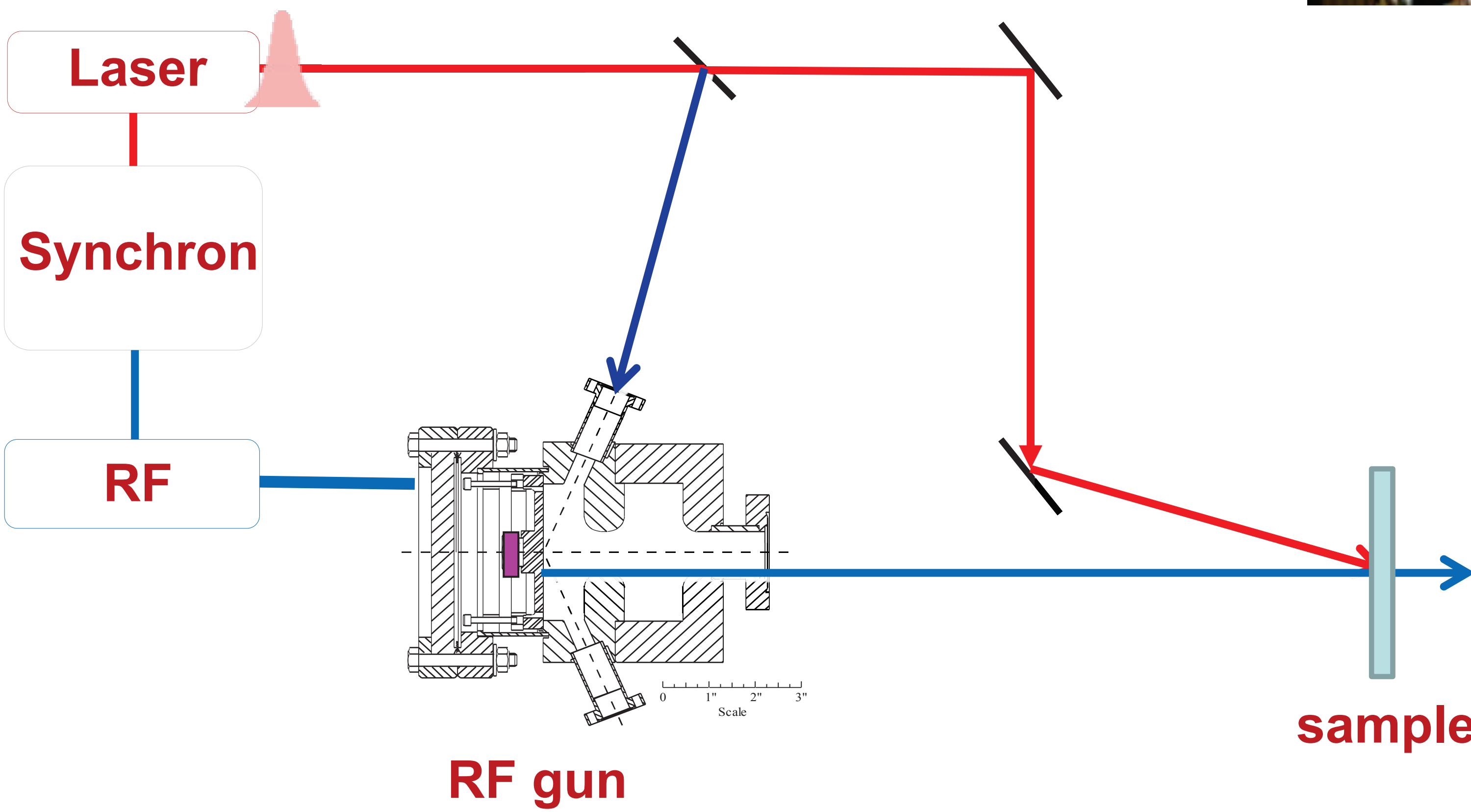


Accelerator based UED

A representative configuration

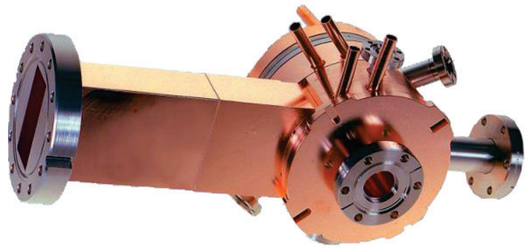


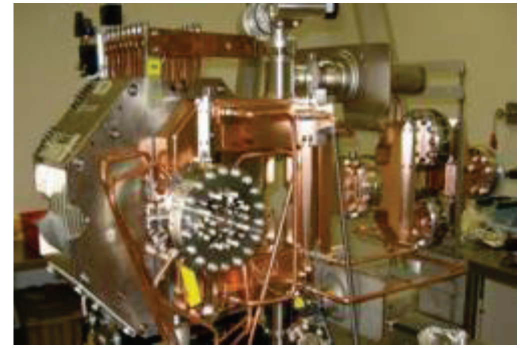


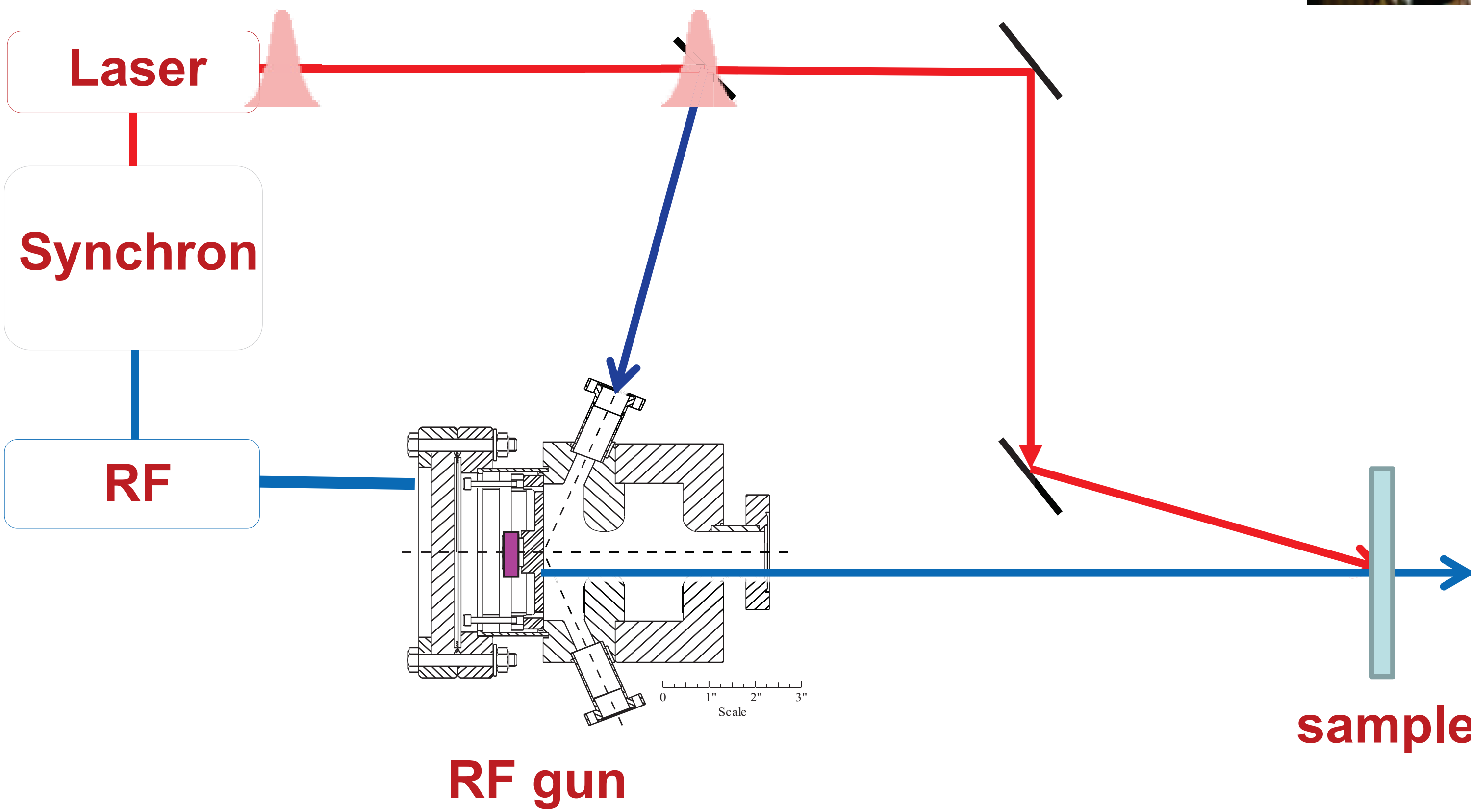


Accelerator based UED

A representative configuration

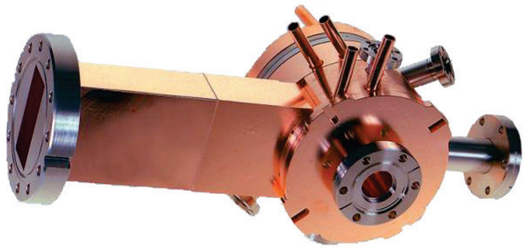


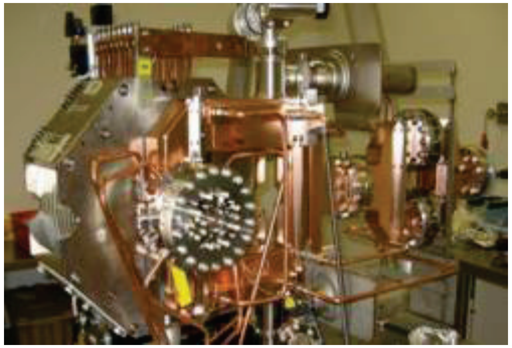


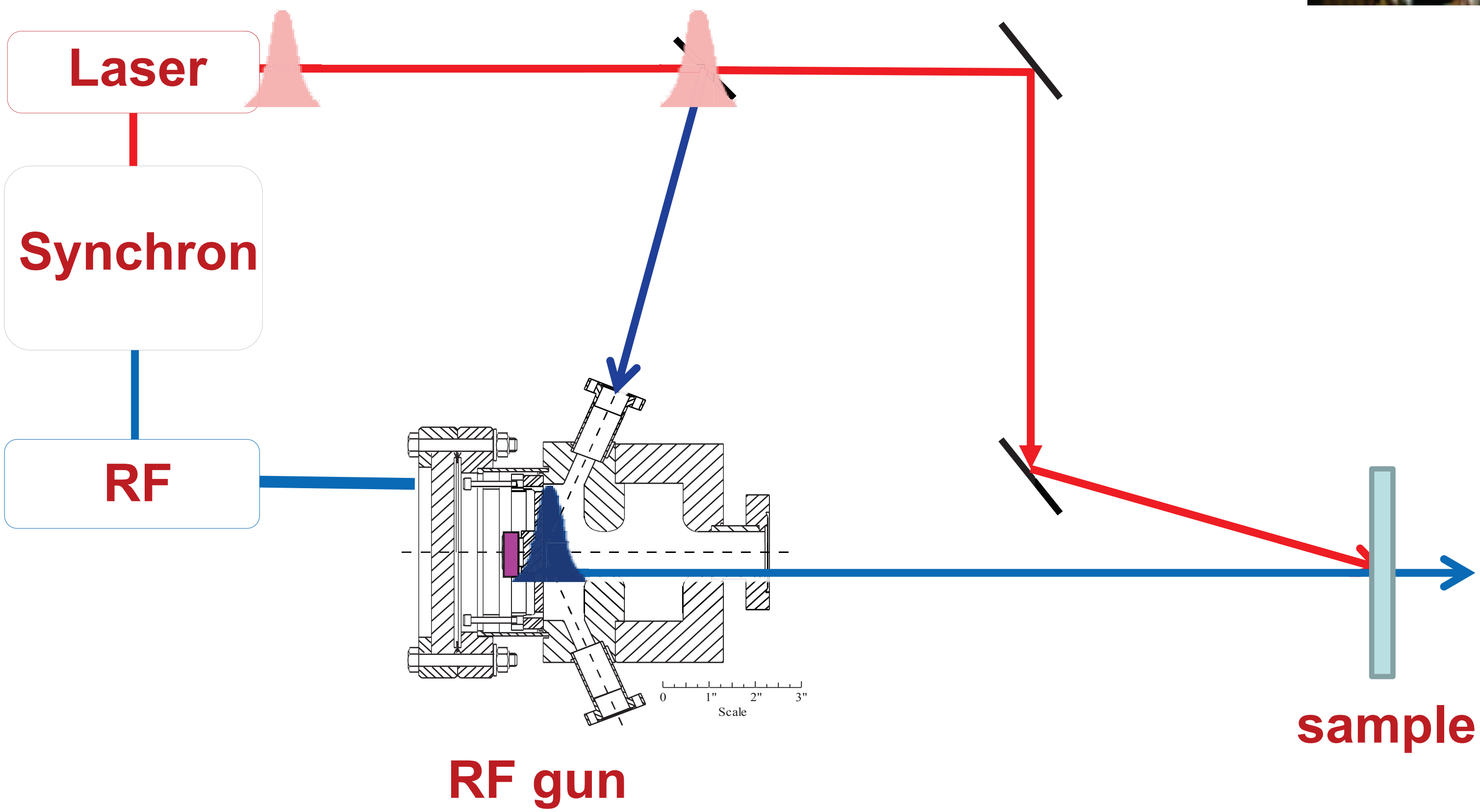


Accelerator based UED

A representative configuration

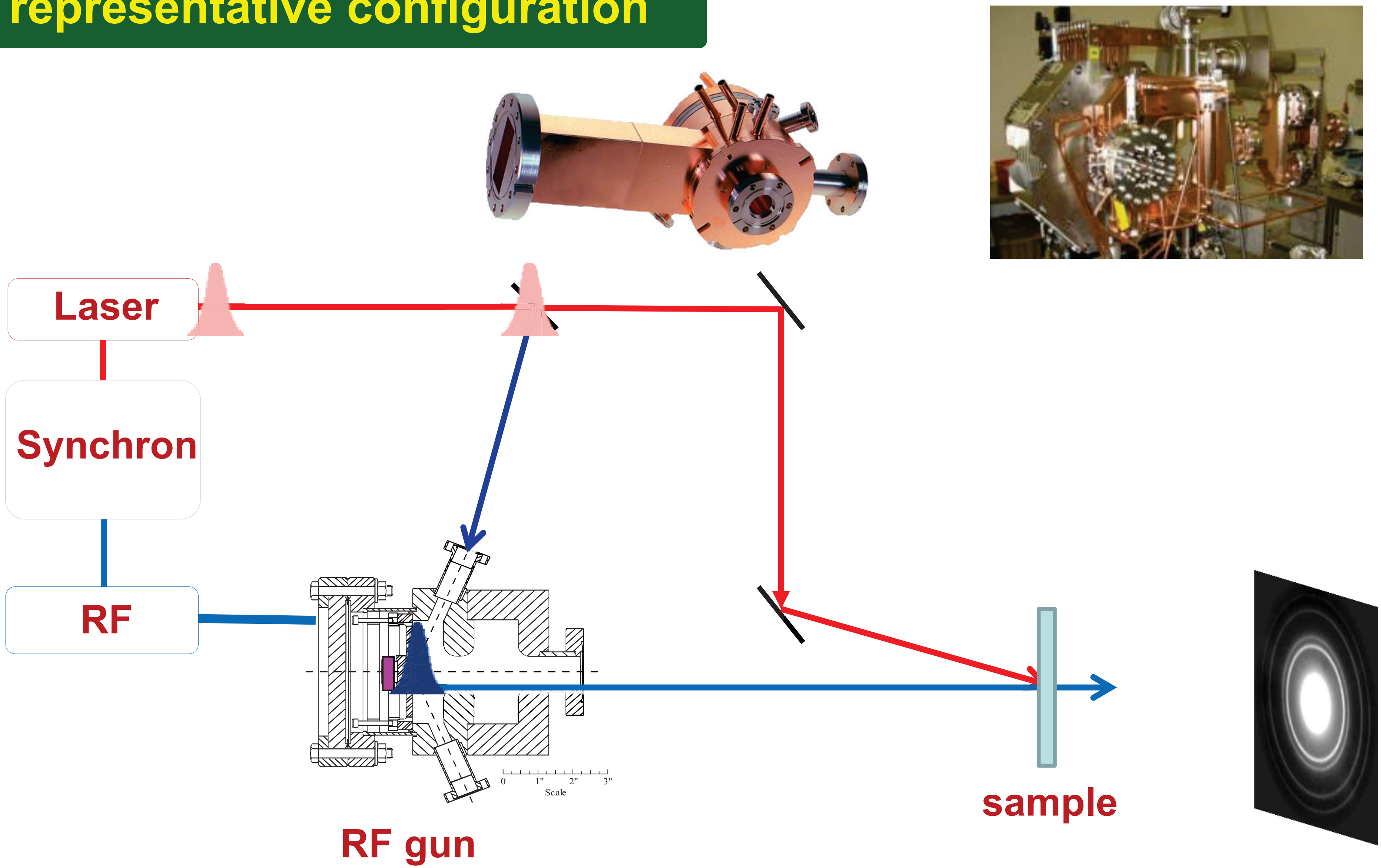






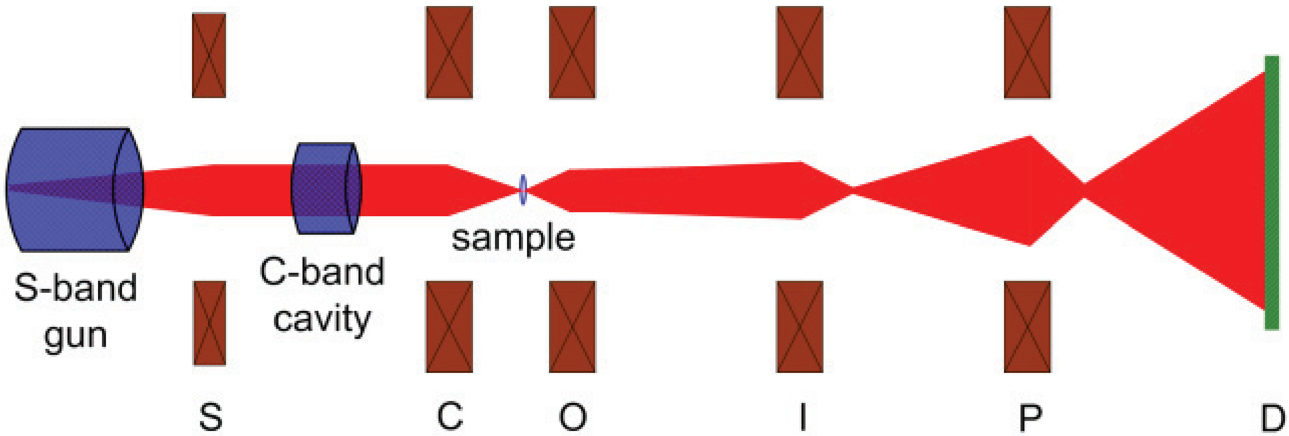
Accelerator based UED

A representative configuration

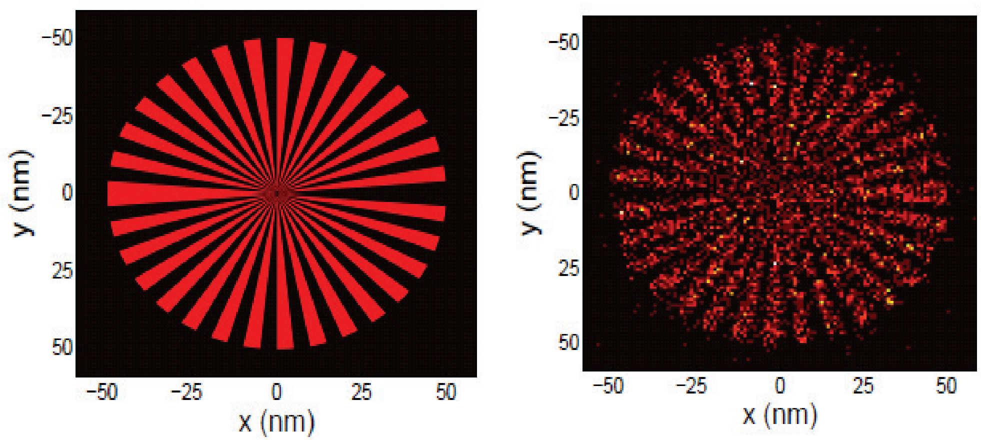


Accelerator based UEM

A representative design



- S: solenoid
- C: condenser lens
- O: objective lens
- I: intermediate lens
- P: projection lens
- D: detector

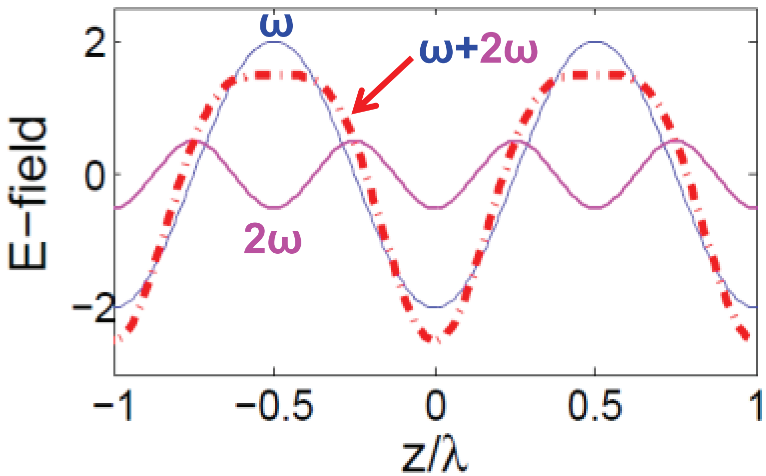


- **10 ps**
- **10 nm**

Xiang et al., NIM A 759, 74 (2014); Li and Musumeci, PRA 2, 024003 (2014)

Beam manipulation for accelerator based UEM

Nonlinear longitudinal phase space needs correction



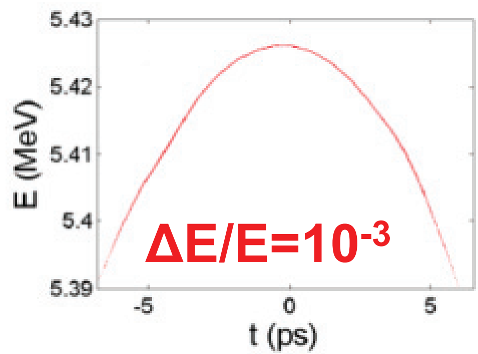
In FELs, harmonic cavities are used to linearize the longitudinal phase space;

In UEMs, harmonic cavities are used to reduce the beam energy spread.

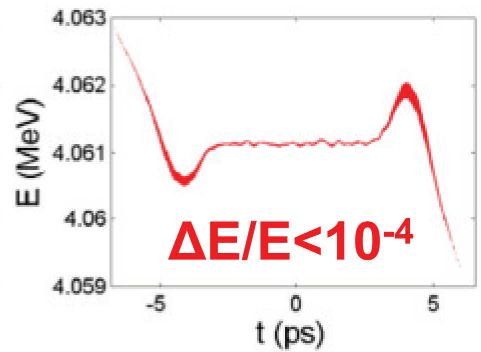
$$E(z) = E_i + E_s\cos(\phi_s + k_s z) + E_x\cos(\phi_x + k_x z)$$

$$\frac{\Delta E(z)}{E_0} = -\frac{E_s k_s \sin\phi_s}{E_0} z + \frac{1}{2}\frac{E_x k_x^2 - E_s k_s^2\cos\phi_s}{E_0} z^2 + \Theta(z^3) + \dots$$

Xiang et al., NIM A 759, 74 (2014); Li and Musumeci, PRA 2, 024003 (2014)



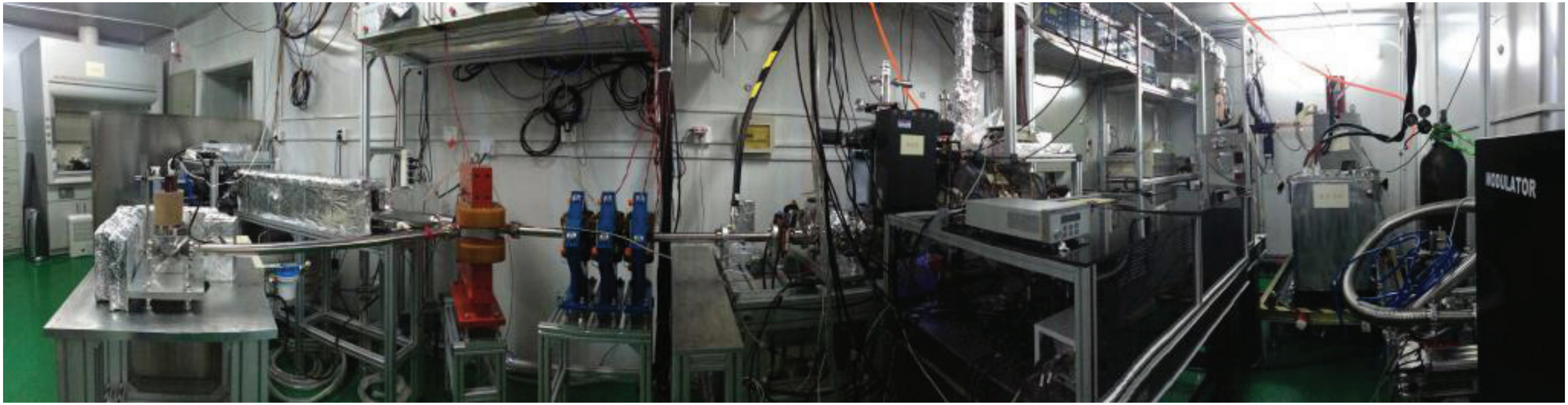
At the exit of the S-band gun

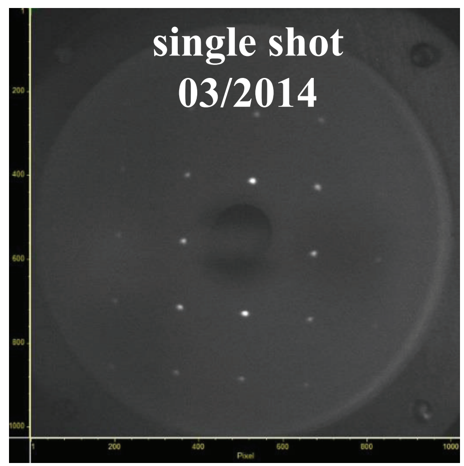


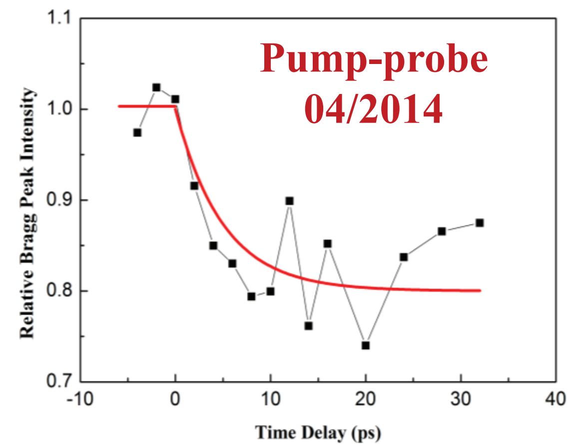
At the exit of the C-band harmonic cavity

UED/UEM center at Shanghai Jiao Tong University

MeV UED facility @ SJTU







High quality diffraction pattern of polycrystalline Al and single crystal Gold

Fu et al., Rev. Sci. Instru. 85, 083701 (2014); Zhu et al., Chinese Phy. Lett. in press, (2014)

Summary

Beam manipulation becomes a new focus in accelerator physics and may significantly enhance the performance of accelerator based scientific facilities, e.g. FELs, advanced accelerators, UED/UEM, etc.

Acknowledgement

- Alex Chao and Tor Raubenheimer for hiring me to SLAC
- Gennady Stupakov for introducing me to the ECHO business
- Tor Raubenheimer for giving me an opportunity to lead the ECHO experiment
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- FEL prize committee for giving me the award

Thanks!