Phase Space Manipulations of Electron Beams Between Two Degree-of-Freedoms & Potential Applications

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Credits

- Contributor on emittance exchange
  - P. Emma, Wei Gai, Z. Huang, K.-J. Kim, J. Power, Yin-e Sun, M. Rihaoui

- Contributor on flat beam generation
  - N Barov, K. Flottmann, D. Edwards, H. Edwards, D. Mihalcea, S. Lidia, Y.-e Sun, N. Vinogradov

- Experimental work is done as part of a collaboration between ANL/U. of Chicago, FNAL, NIU, and Tsinghua University.

Outline

- Motivations

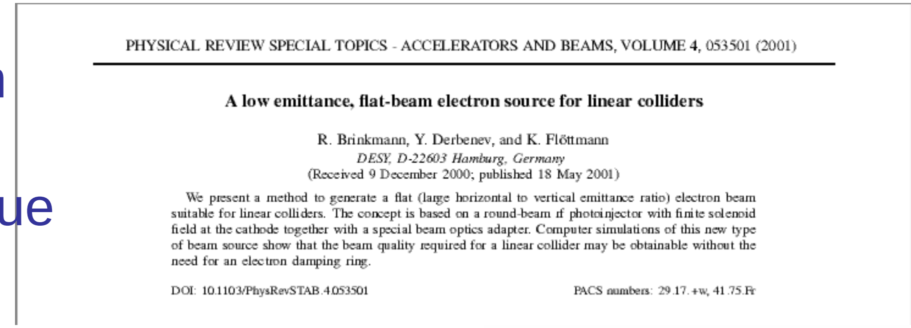
- Flat beam transform
  - Theoretical background
  - Experimental measurements
    - Historical remarks
    - Potential applications

- Transverse-to-longitudinal emittance exchange
  - Theoretical background
  - Potential applications
  - Plans for proof-of-principle experiment

- Summary

Production of flat beams

- Flat beam production relies on:
  - Generation of magnetized beam
  - A linear transformation devised by Ya. Derbenev to apply a torque on the beam



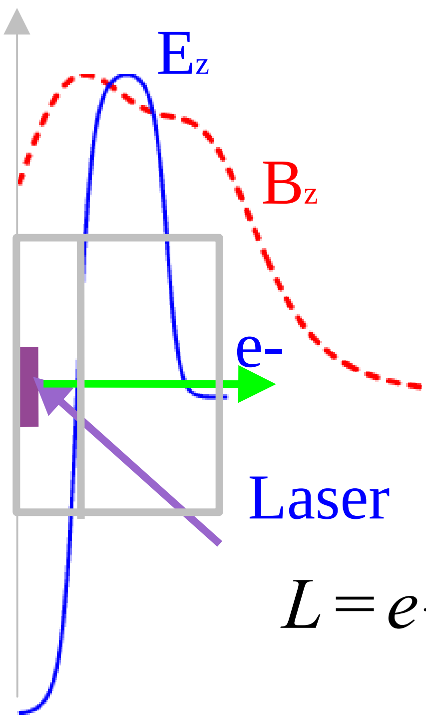
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 4, 053501 (2001)

A low emittance, flat-beam electron source for linear colliders

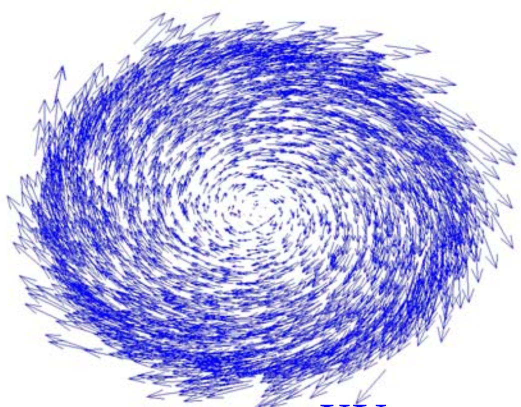
R. Brinkmann, Y. Derbenev, and K. Flöttmann
DESY, D-22603 Hamburg, Germany
(Received 9 December 2000; published 18 May 2001)

We present a method to generate a flat (large horizontal to vertical emittance ratio) electron beam suitable for linear colliders. The concept is based on a round-beam rf photoinjector with finite solenoid field at the cathode together with a special beam optics adapter. Computer simulations of this new type of beam source show that the beam quality required for a linear collider may be obtainable without the need for an electron damping ring.

DOI: 10.1103/PhysRevSTAB.4.053501 PACS numbers: 29.17.+w, 41.75.Fr

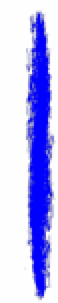


$$L = e\frac{B_z \sigma_c^2}{2mc}$$



Skew quadrupole

channel



Production of flat beams

- A B-field on the photocathode imposes an averaged (over the beam) canonical angular momentum (CAM):

$$L_0 = \frac{eB}{2mc}\sigma_C^2$$

- Outside of the solenoid this CAM is converted into mechanical angular momentum (MAM)

$$L = \frac{eB}{2p_z}\sigma_C^2$$

- The MAM can then be removed by a properly design skew quadrupole channel (Derbenev's transform) to yield a flat beam

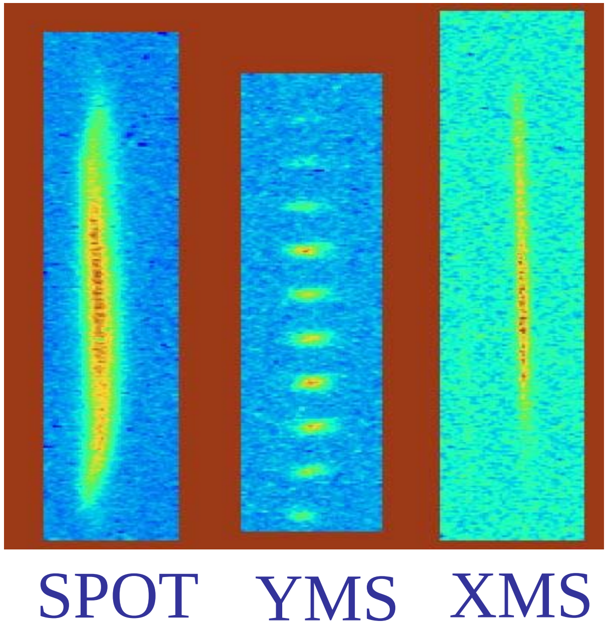
$$\varepsilon_{\pm} = \sqrt{L^2 + \varepsilon^2} \pm L \text{ , and } \quad \varepsilon_+ \varepsilon_- = \varepsilon^2$$

Angular momentum

Transverse uncorrelated emittance

Historical notes

- 1988: *Reich et al. p*artial decorrelation noted downstream of an ECR source using one skew quadrupole
- 1999: Proposal for a flat beam injector Brinkmann, Flottmann and Derbenev
- 2000: *D. Edwards et al.* total décor-relation and production of flat beam demonstrated at Fermilab
- 2004: *Y.-E Sun et al*., generation and characterization of angular momentum-dominated beams



[D. Edwards et al. LINAC 2000 Y.-E Sun Phd dissertation Univ. Of Chicago (2005)]

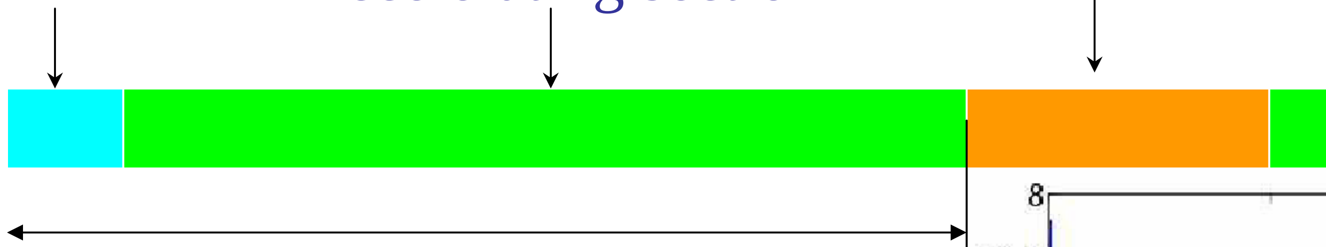
- 2006: *P. Piot et al*. demonstration of emittance ratio>100

Applications: flat beam for linear collider? (1)

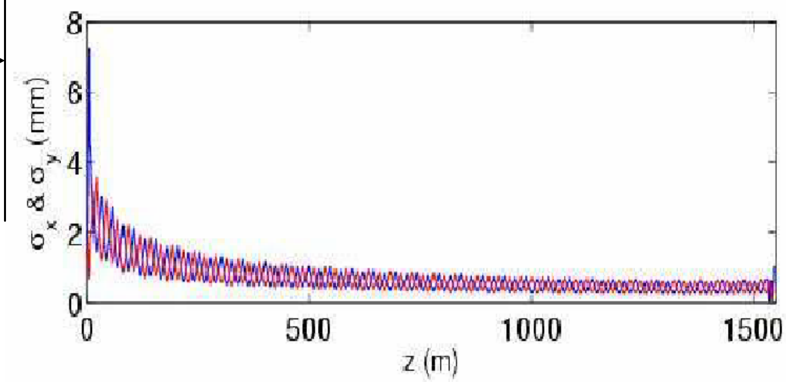
Flat beam transformation

e^- source

Accelerating section



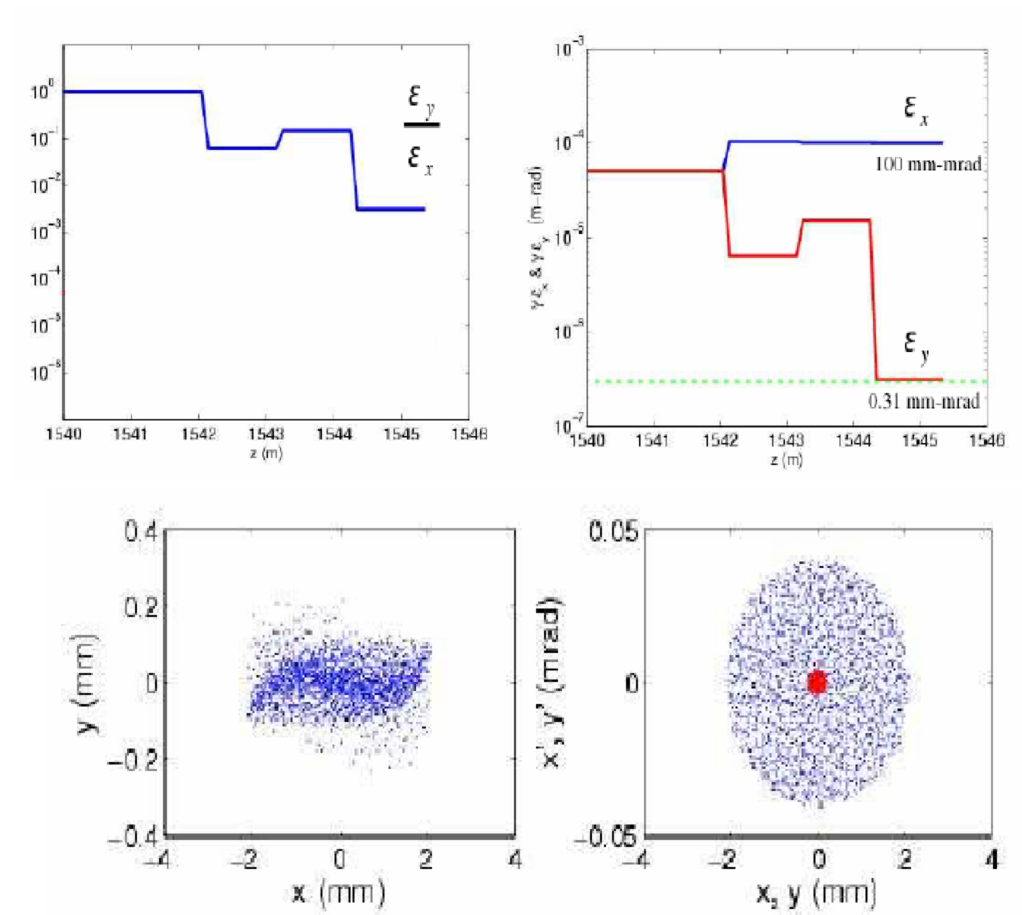
Optimized to "reasonably" minimize $\varepsilon_\perp$ while transporting a high L beam

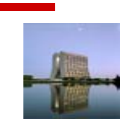


- Design and numerically optimize an injector capable of providing emittance ratio compatible with linear collider requirements
- Minimize 4D emittance

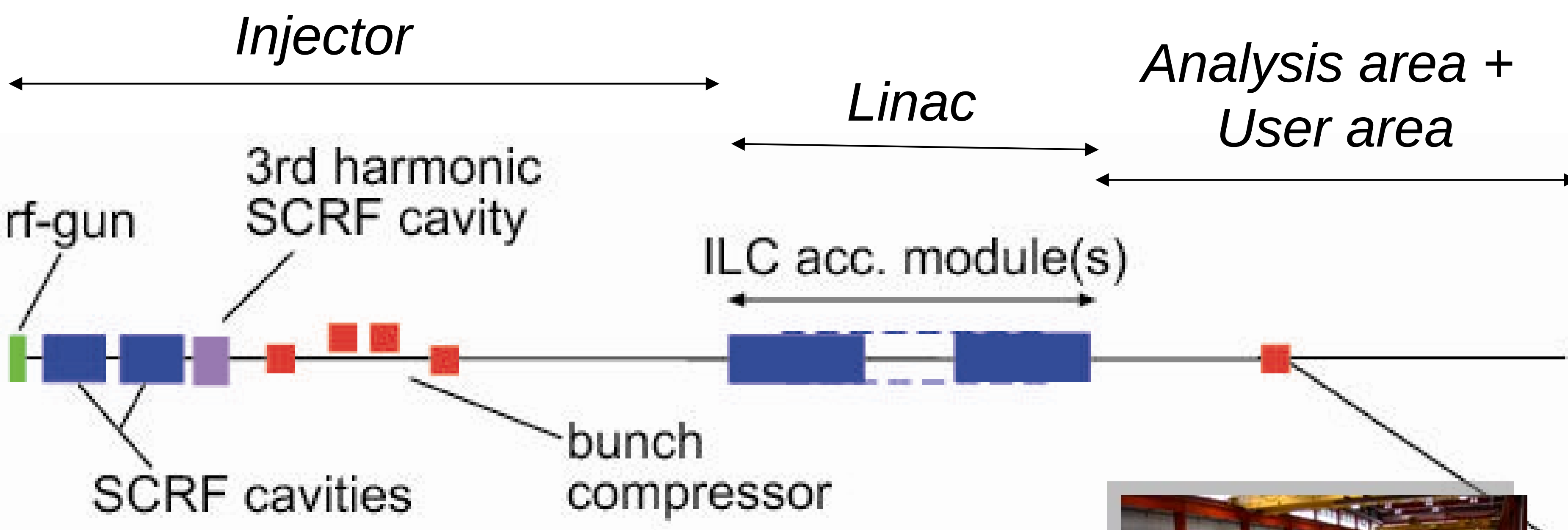
Applications: flat beam for linear collider? (2)

- Flat beam transformer at 5 GeV yields: emittance ratio of 320
- However both emittances are too high
- A photoinjector cannot provide the adequate 4-D emittance at 3.2 nC
- Could add on a “cooling” to decrease both emittance by a factor ~10.





Application to some Advanced Accelerator R&D topics at ILCTA

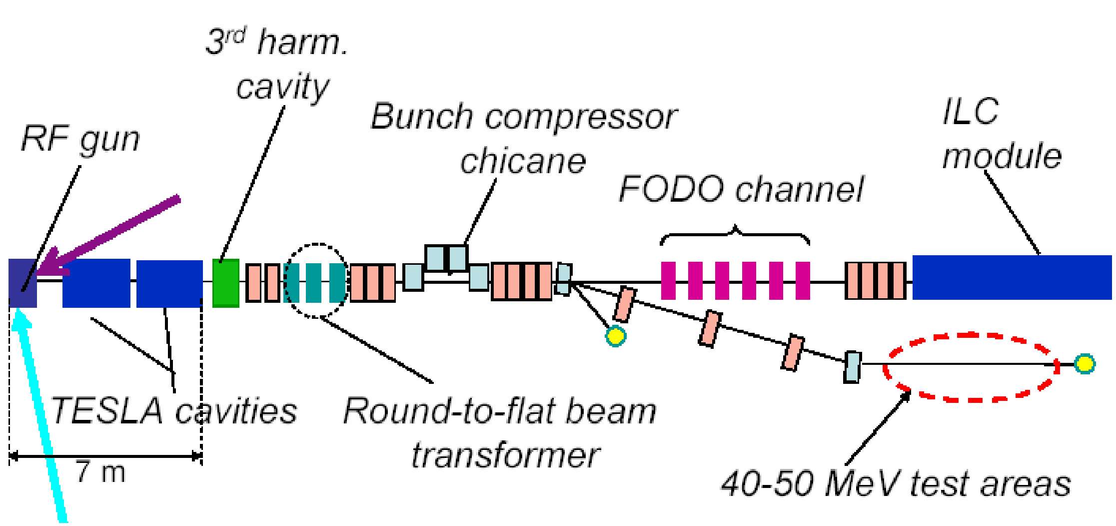


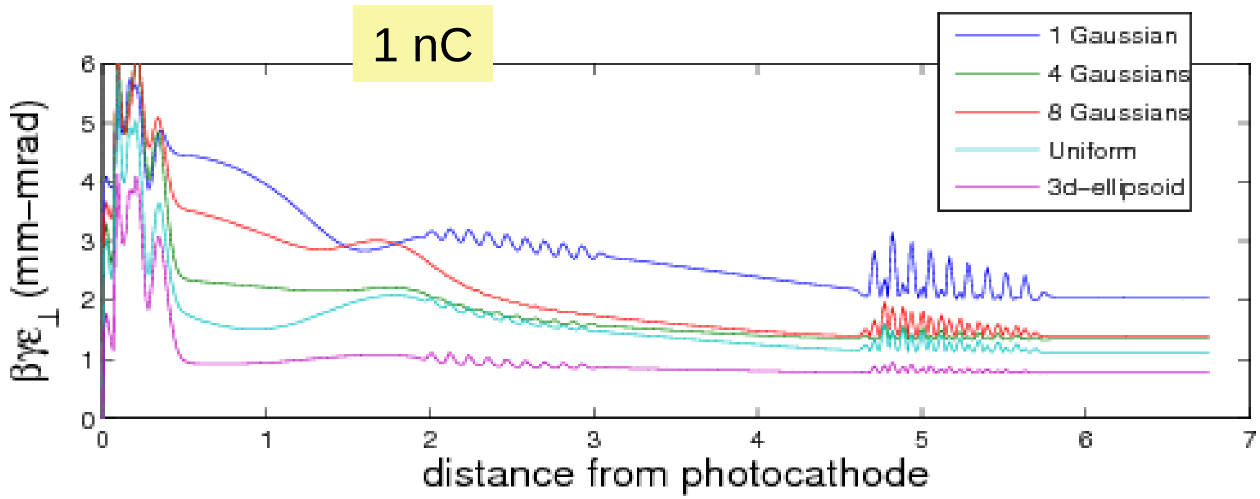
- Main goal: test ILC critical components
- Hidden agenda: do some advanced accelerator R&D and beam physics studies

(M. Church, S. Nagaitsev, P. Piot, PAC 2007)

Application to some Advanced Accelerator R&D topics at ILCTA

- A high brightness injector was designed (NIU/FNAL collaboration)
- Can achieve (simulation) the “canonical” 1 nC/ 1 μm (without compression)

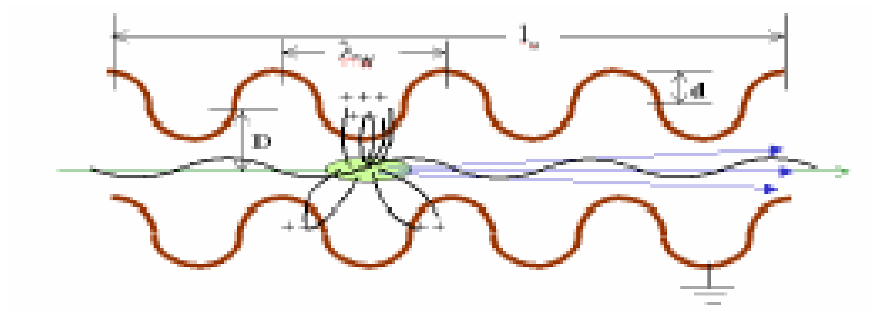




Applications: Image charge undulator

- An e- propagating next to a grating emits radiation (so-called Smith-Purcell radiation)

$$\lambda = \frac{\lambda_w}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$



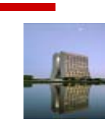
(Y. Zhang et al. PAC 2003 p. 941)

- *K* is the "undulator parameter"

$$K = \frac{\lambda_w}{2\pi}\frac{eB}{mc}$$

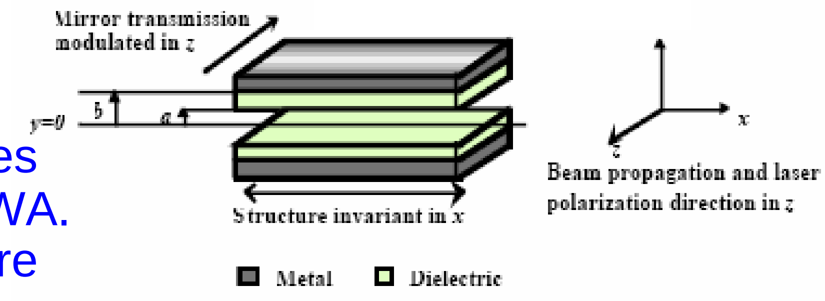
(usually $K = \frac{\lambda_w}{2\pi}\frac{eE}{mc^2}$)

- A 8 GeV beam, with 300x4x100 μm at 10 nC passing through a grating with 10 μm period *K*=0.2 (equivalent to a 60 T magneto-static undulator), λ=1 Angstrom, and gain length is 2 cm -- **compare to TESLA X-ray FEL ~10 m with ~25 GeV linac**
- Scale down to optical regime 250 MeV and implement at ILCTA? Collaboration with JLab?



Applications: Dielectric slab as accelerating structures

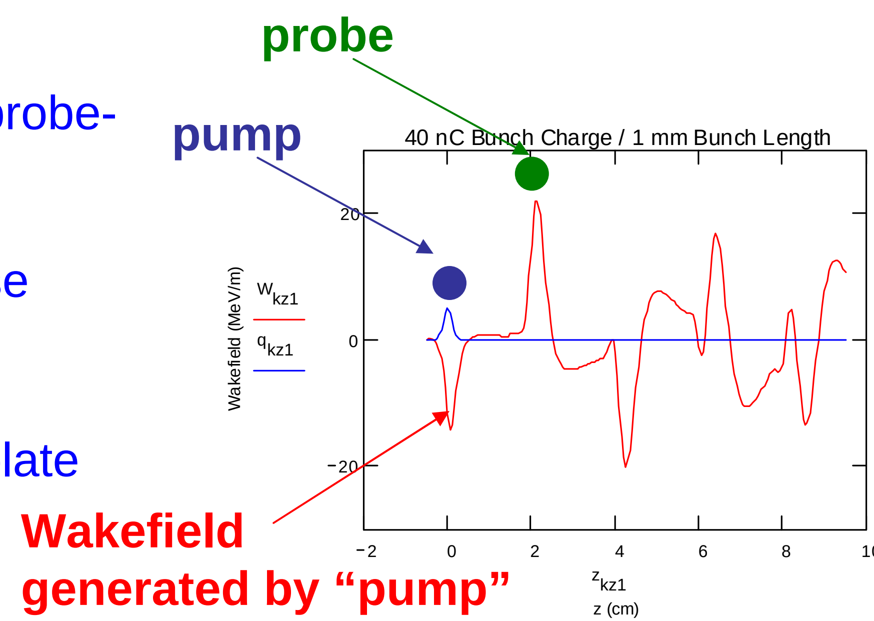
(Courtesy of John Power and Wei Gai of Argonne Wakefield Accelerator)

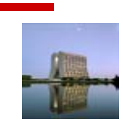


- Wakefield scales as:

$$W_{\|} \propto \frac{Q}{\sigma_z^2}$$

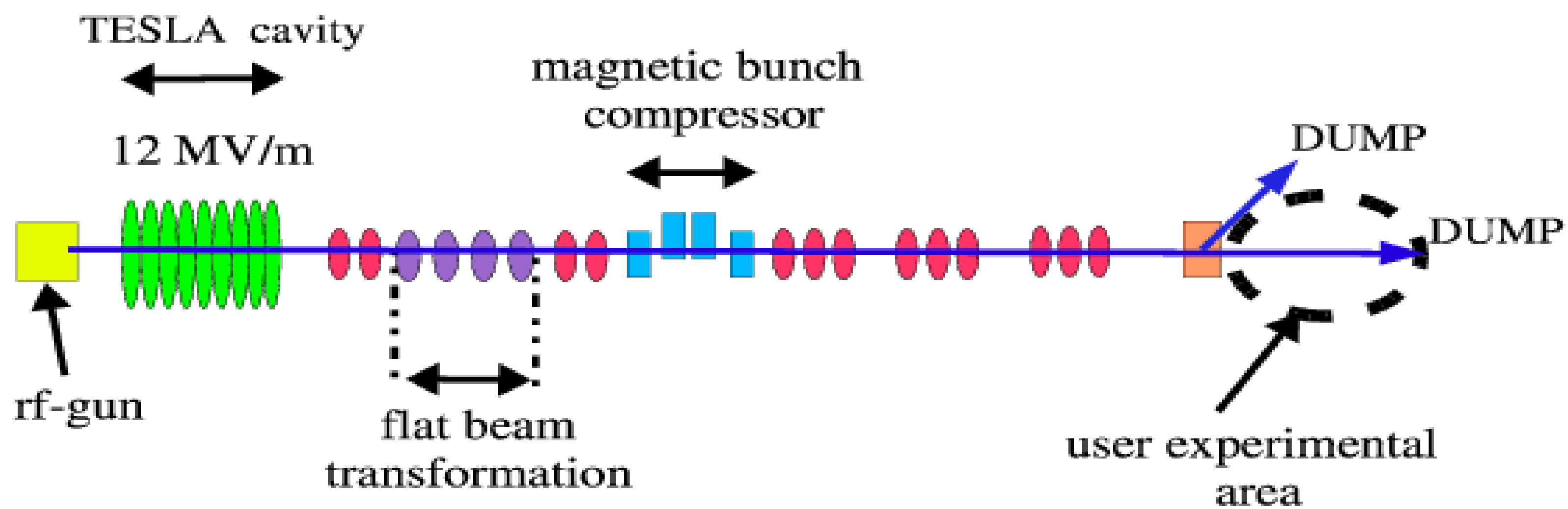
- Dielectric cylindrical-symmetric structures (MgTiO3 ; ε=16) have been tested in AWA. Axial average gradient of 100 MV/m were measured
- Wakefield accelerators based on a probe-pump configuration
- Slab-type structure reduce transverse wakefield sensitivity
- With ILCTA parameters we contemplate gradients of the order of GeV/m





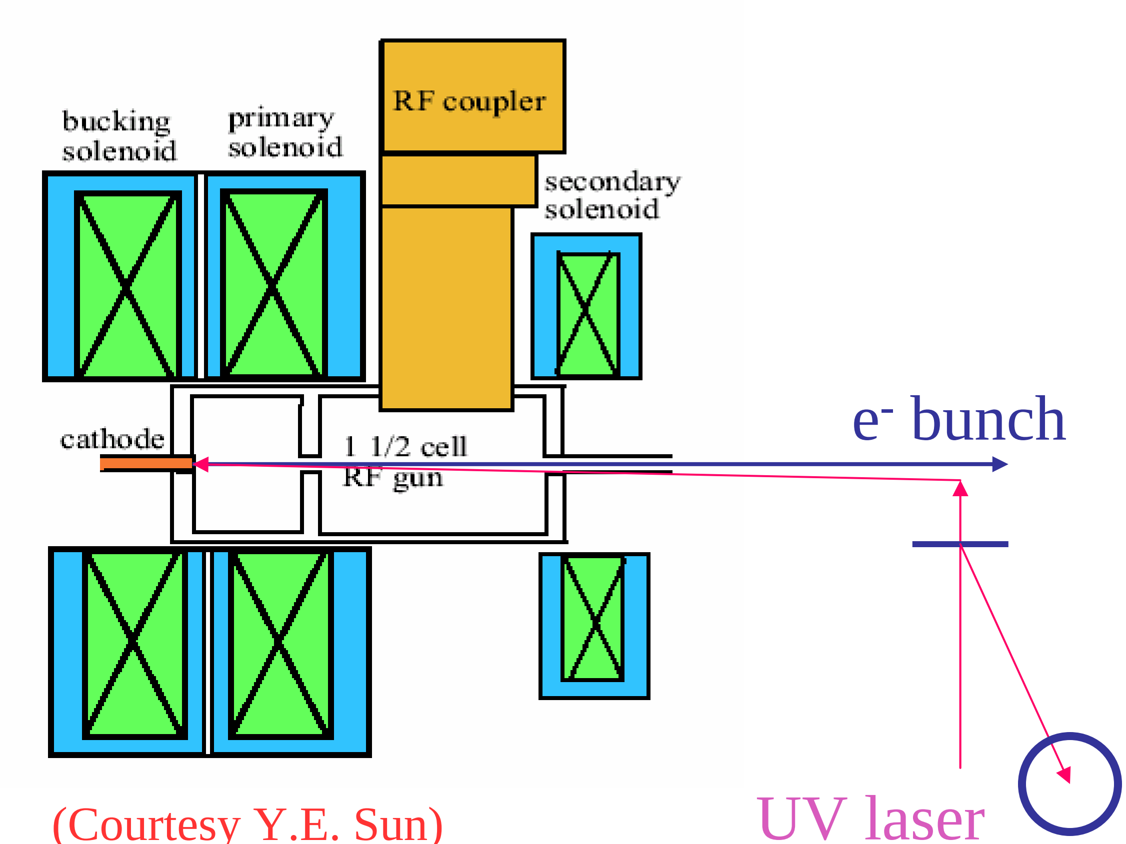
Experiment at the Fermilab/NICADD photoinjector laboratory (FNPL)

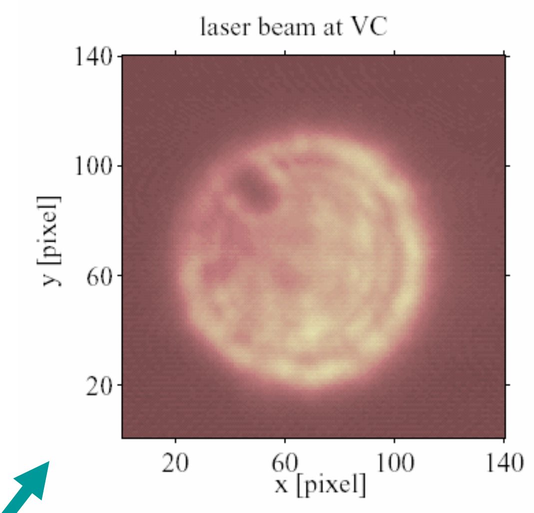
- Photo-emission electron source
- A TESLA cavity operating at 12 MV/m
- Quads, correctors magnets, dipoles and extensive diagnostics (OTR and YaG-based screens, electromagnetic beam position monitors)
- Bunch compression possible with a magnetic chicane
- Soon to be decommissioned



The FNPL 1+1/2 rf-gun

- High quantum efficiency photo-cathode (Cesium Telluride)
- A 1.3 Ghz rf-gun
- Three solenoids with independent power supplies





(Courtesy Y.E. Sun)

Scaling of angular momentum (1)

- Conversion of canonical angular momentum (CAM) into mechanical angular momentum is as predicted

- CAM calculated from:

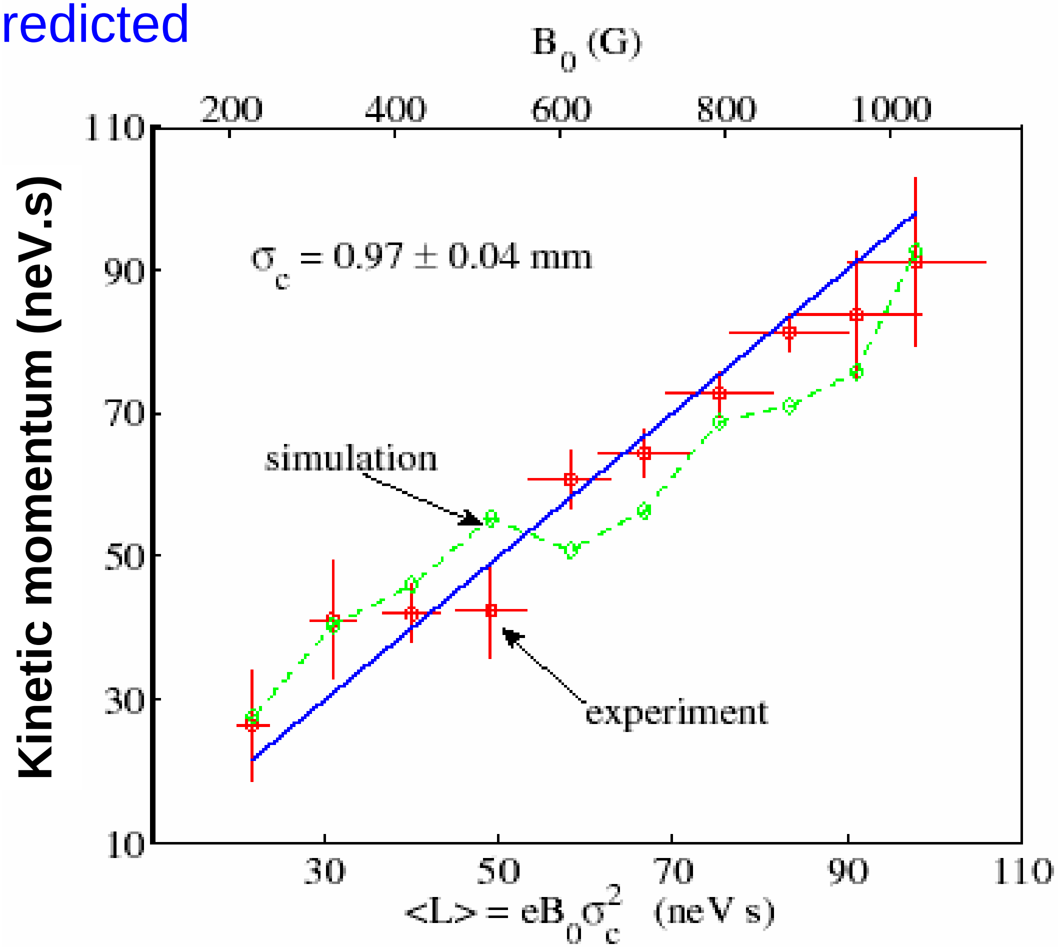
B-field on cathode
(POISSON)

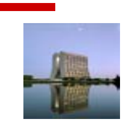
$$\langle L \rangle = e\boxed{B_0}\sigma_C^2$$

averaged CAM

transverse rms size
on photocathode

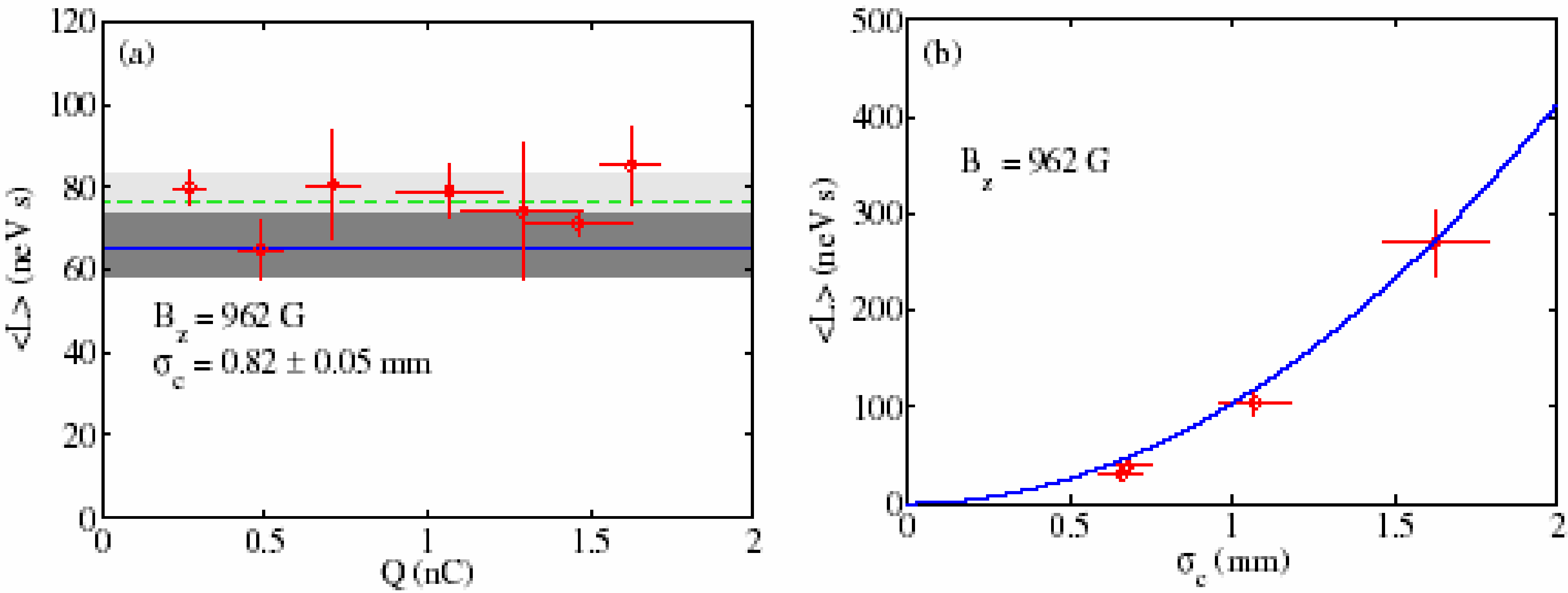
[Y.E. Sun et al. PRSTAB (2005)]





Scaling of angular momentum (2)

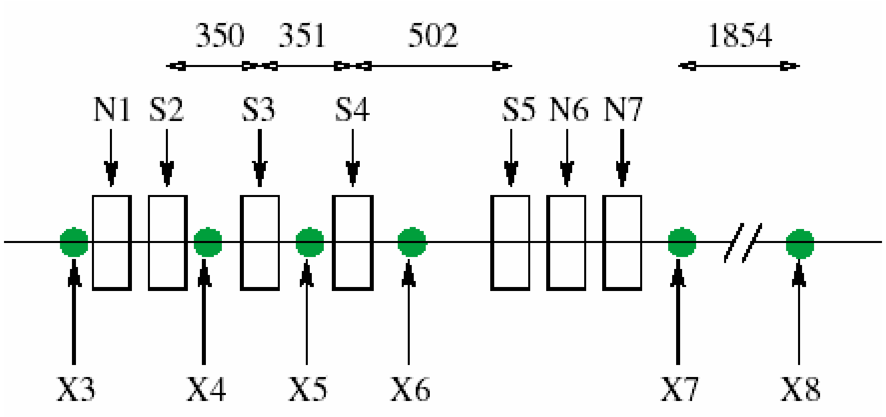
- Other scaling law and MAM conservation rules were verified

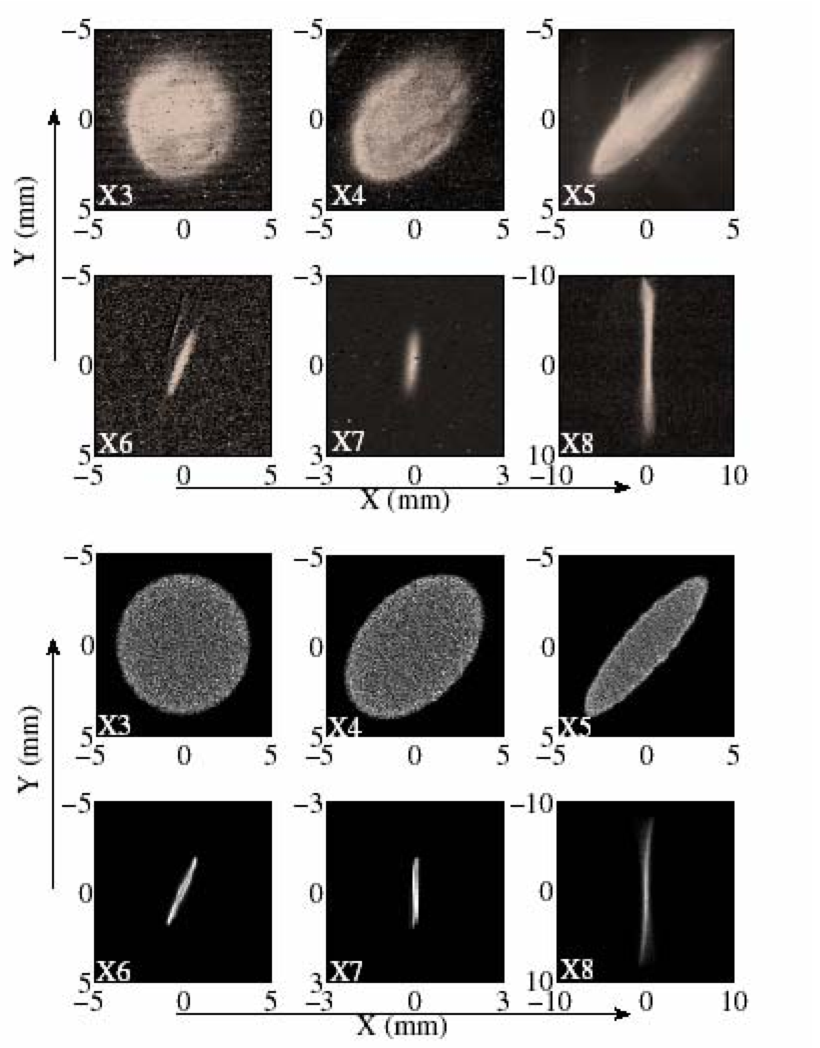


[Y.E. Sun et al. PRSTAB (2005)]

Removal of angular momentum: flat beam generation

- From angular momentum measurement and beam size one can compute the correlation matrix <XY>
- The skew quadrupole settings can the be computed to apply the proper torque





[Y.E. Sun et al. PRSTAB (2005)]

Demonstration of emittance ratio of 100 (1)

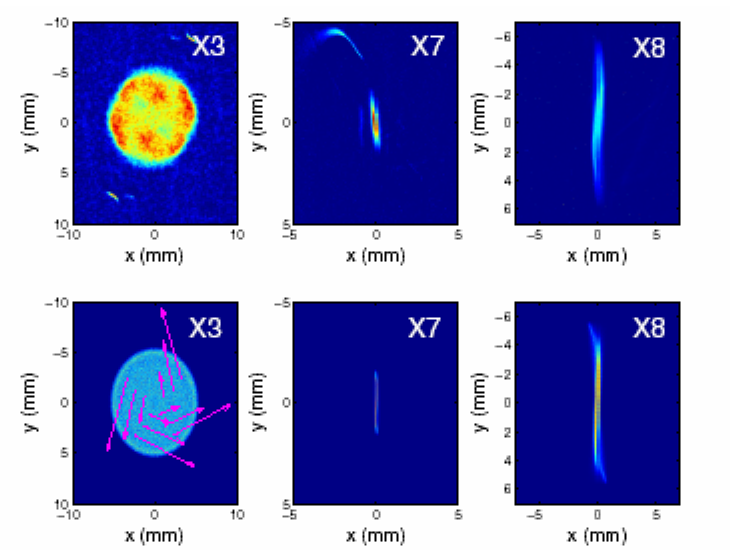
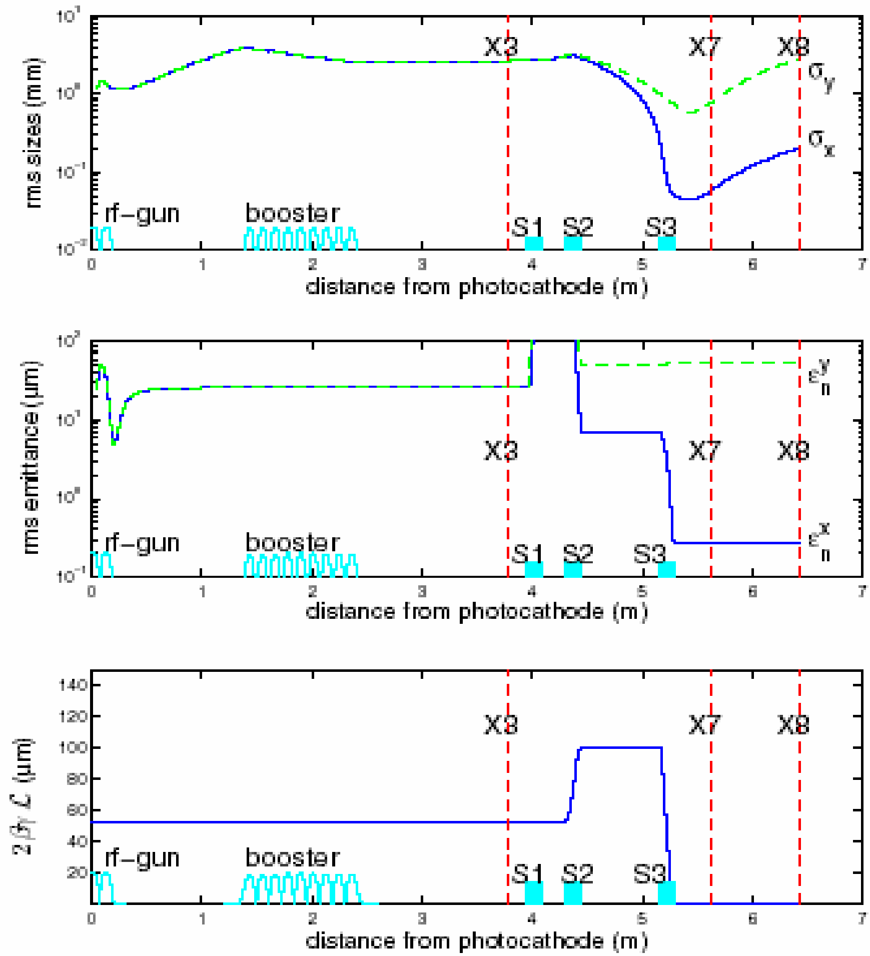
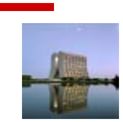


TABLE III. Measured and simulated flat-beam parameters for $\sigma_c = 0.97$ mm. Both systematic and statistical (in brackets) error bars are included.

Parameter	Experiment	Simulation	Unit
σ_x^{X7}	0.088 ± 0.01 (± 0.01)	0.058	mm
σ_y^{X7}	0.63 ± 0.01 (± 0.01)	0.77	mm
$\sigma_x^{X8,v}$	0.12 ± 0.01 (± 0.01)	0.11	mm
$\sigma_y^{X8,h}$	1.68 ± 0.09 (± 0.01)	1.50	mm
ε_n^x	0.41 ± 0.06 (± 0.02)	0.27	μm
ε_n^y	41.1 ± 2.5 (± 0.54)	53	μm
$\varepsilon_n^y / \varepsilon_n^x$	100.2 ± 20.2 (± 5.2)	196	



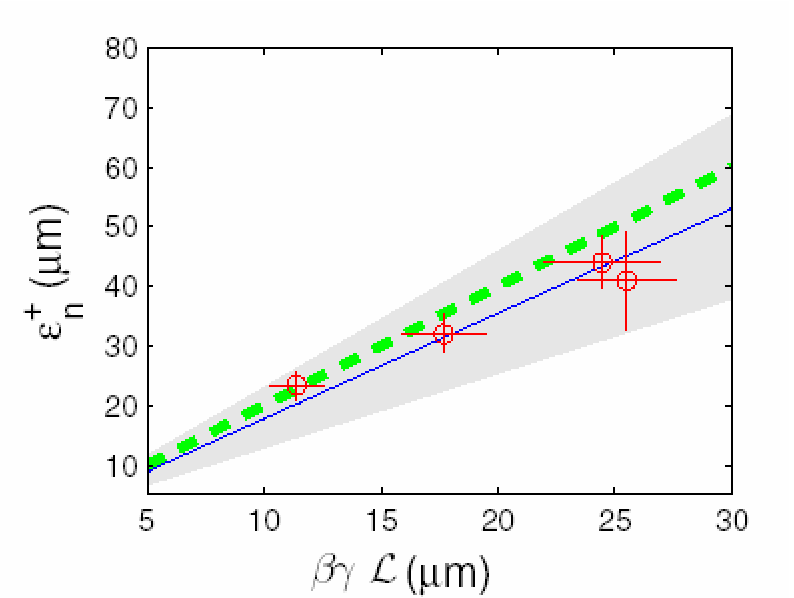
[P. Piot et al. PRSTAB (2006)]

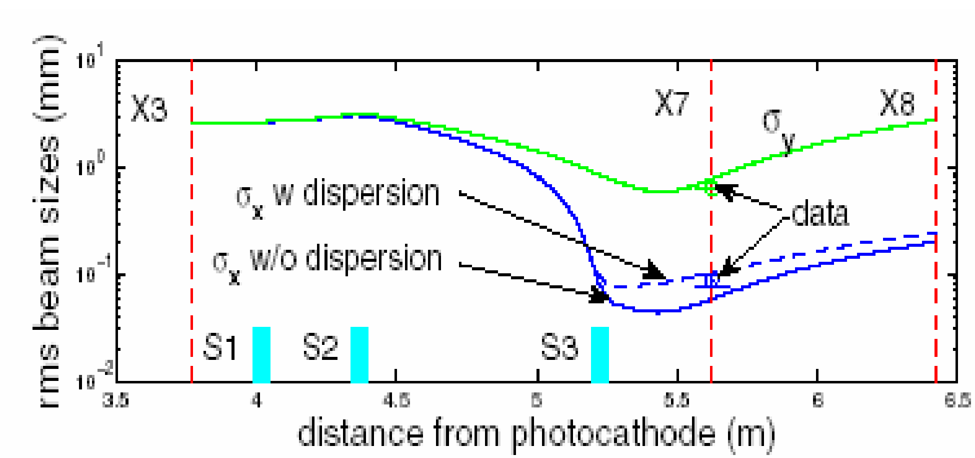


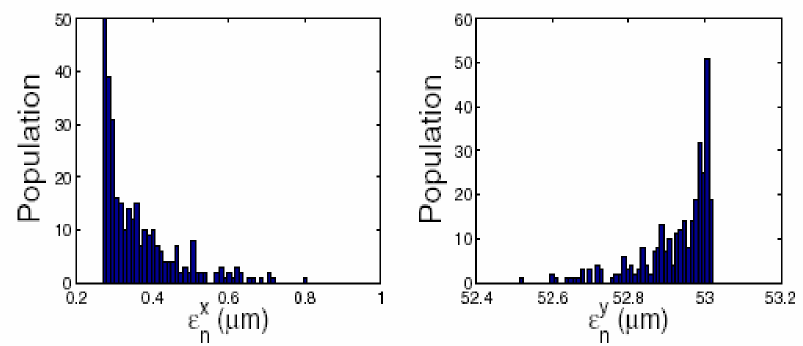
Demonstration of emittance ratio of 100 (2)

- Linear scaling of larger emittance on angular momentum was verified

- Discrepancy between simulation & experiment attributed to emittance measurement.





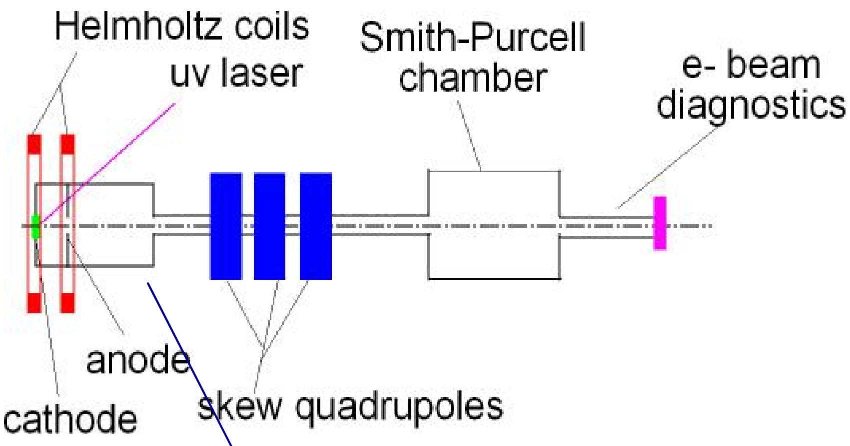


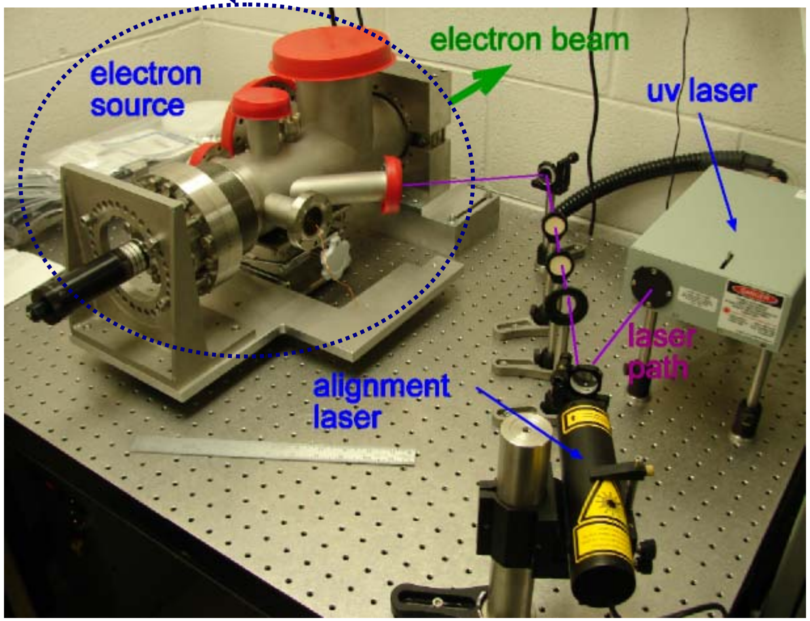
[P. Piot et al. PRSTAB (2006)]

Applications: low energy Smith-Purcell free-electron laser

- A low energy electron source for time resolved electron microscopy was developed at NIU
- With minor upgrade (Helmoltz coils and skew quadrupoles), the source could generate sheet electron beam with suitable parameters to drive a low energy Smith-Purcell FEL (proposed in the late 80's by Walsh) Typical average power of 1 W is expected
- This could result in a table-top Terahertz light source with advantage compared to laser –based source making use of optical rectification

[N. Vinogradov et al. PAC 2007]



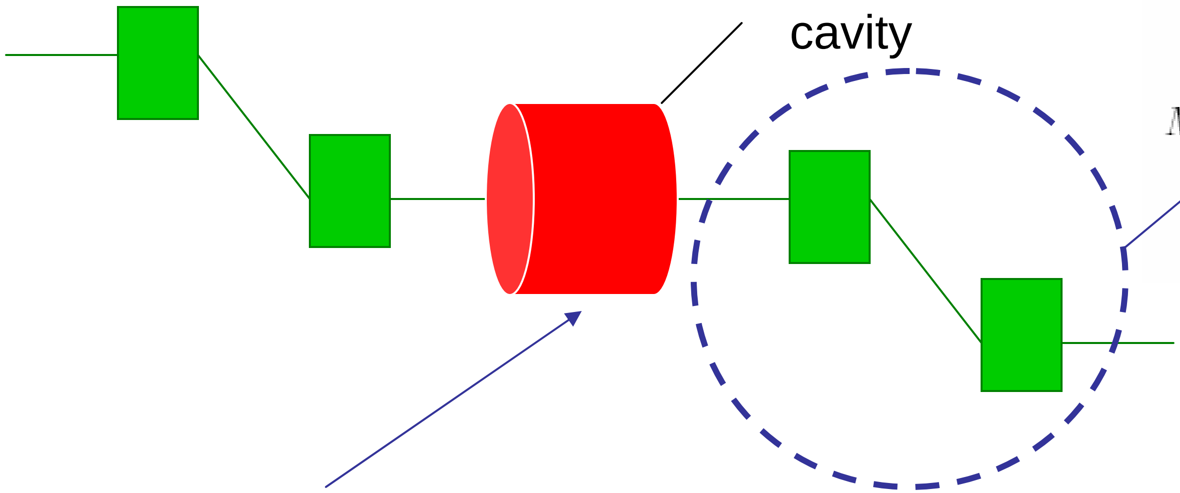


Emittance exchange between one transverse and the longitudinal d.o.f

- Basic idea suggested in the early days [Robinson
- Proposed by Cornacchia and Emma (PRSTAB 2002) to increase the incoherent momentum spread in LCLS and thereby alleviate micro-bunching instabilities (due to CSR or LSC)
- When used with the round-to-flat beam transformation, can fully repartition emittances within the three degree-of-freedom and taylor the partition for specific applications
  - Greenfield FEL
  - MW power FEL ?
  - ILC (?)

Emittance exchange principle

- Uses a deflecting mode cavity flanked by two dispersive sections (dogleg)



$$M_{DL} = \begin{bmatrix} 1 & L/2 & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi/2 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

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

- The total matrix is

$$M = M_{DL} M_{CAV} M_{DL} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}$$

Emittance exchange principle

- When the condition $\kappa = -1/\eta$ is satisfied

$$B = -\frac{1}{\eta}\left[\begin{array}{cc} (L_c + 2L)/4 & (2\xi L - 8\eta^2 + \xi L_c)/8 \\ 1 & \xi/2 \end{array}\right] = C$$

$$A_{1,2} = \frac{L_c}{4}$$

$$D = \frac{L_c}{4\eta^2}\left[\begin{array}{cc} \xi/2 & \xi^2/4 \\ 1 & \xi/2 \end{array}\right]$$

- For $L_c=0$, the total matrix is block diagonal And ε_x and ε_z are exchanged.

- Generally however we have (See Emma and Cornacchia PRSTAB)

$$\left[\begin{array}{c} \varepsilon_x^2 \\ \varepsilon_z^2 \end{array}\right] = \left[\begin{array}{cc} |A|^2 & |B^2| \\ |C^2| & |D^2| \end{array}\right]\left[\begin{array}{c} \varepsilon_{x,0}^2 \\ \varepsilon_{z,0}^2 \end{array}\right] + \lambda^2 \varepsilon_{x,0}\varepsilon_{z,0} I,$$

Emittance exchange principle

- In our case the coupling term is given by

$$\lambda^2 = \frac{L_c^2(1+\alpha_x^2)(\xi^2 + (\xi\alpha_z - 2\beta)^2)}{64\eta^2\beta_x\beta_z}.$$

- And can be minimized by a proper choice of incoming longitudinal Twiss parameters

- A possible choice for the optimum chirp ($\alpha_z = -\frac{\langle z\,\delta\rangle}{\varepsilon_z}$) is

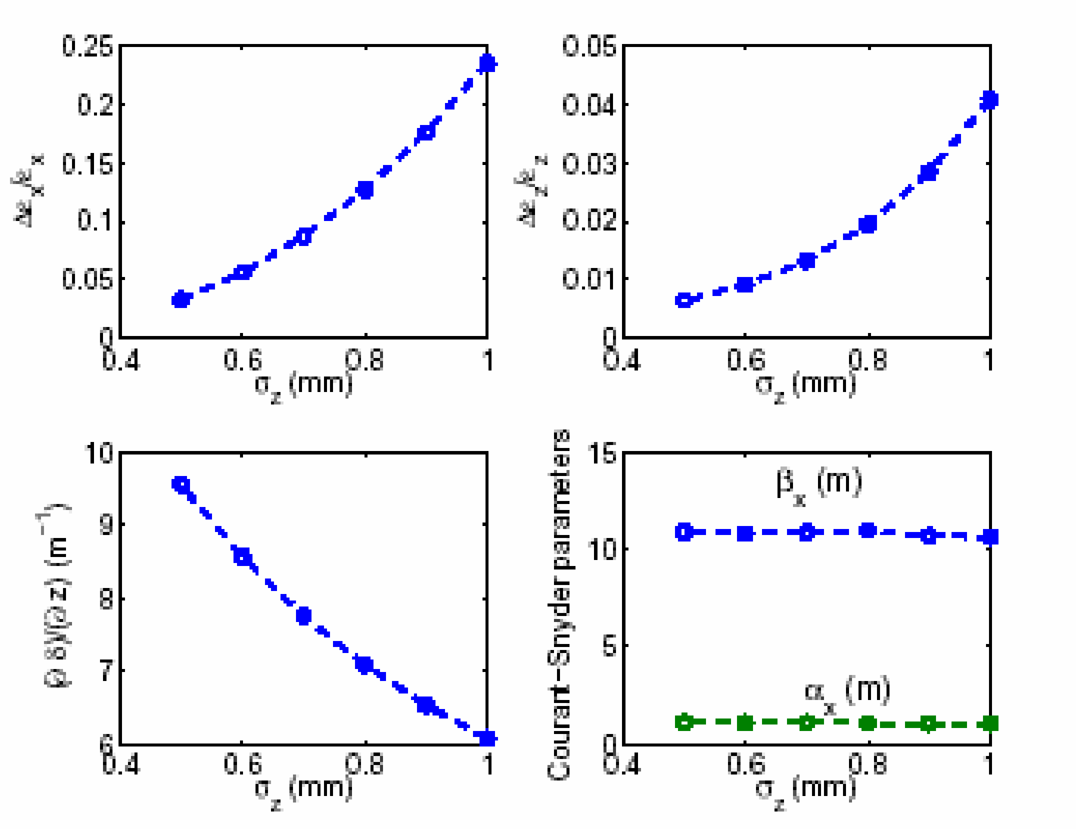
$$\alpha_{z,m} = \frac{2\beta_z}{\xi}$$

- And the residual coupling term is

$$\lambda_m^2 = \frac{1}{64}\frac{\xi^2 L_c{}^2\left(1+\alpha_x{}^2\right)}{\beta_x\,\eta^2\beta_z} = \frac{1}{64}\frac{\xi^2 L_c^2}{\eta^2}\frac{\varepsilon_{z,0}}{\varepsilon_{x,0}}\left(\frac{\sigma_{x'}}{\sigma_z}\right)^2$$

Optimizing the emittance exchange

- The scheme was tested with particle tracking
- The exchange aims at swapping ε_x and ε_z
- Here initial emittance values are ε_x =3 μm, and ε_z =10 μm.



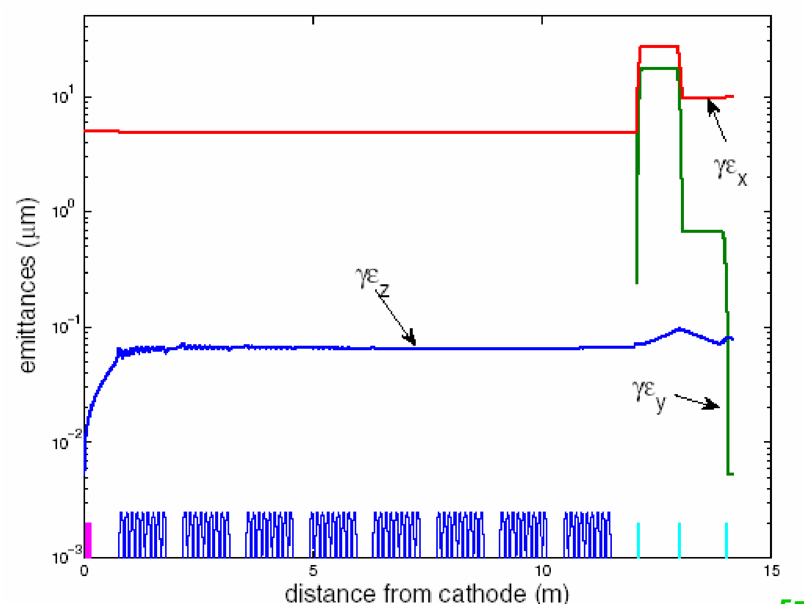
Applications: Greenfield FEL

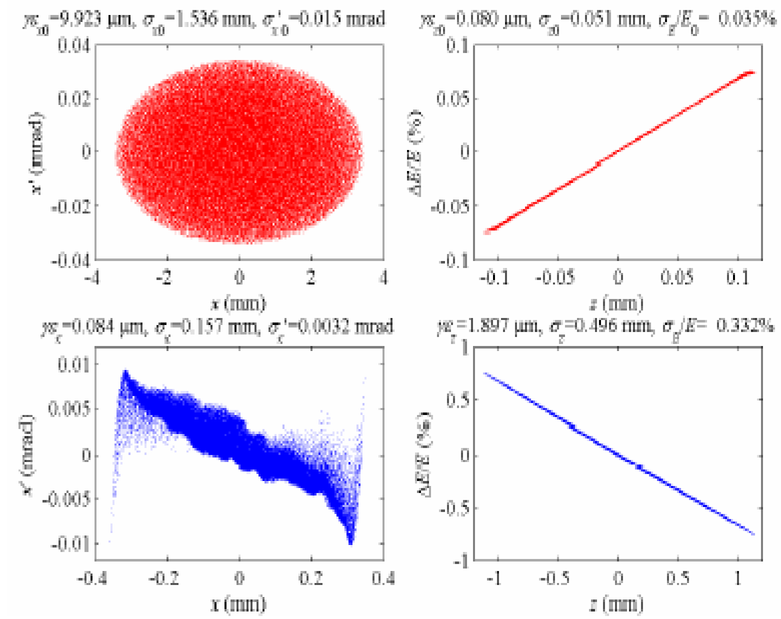
- Greenfield FEL (λ=1 A) require tranverse emittance of 0.1 mm
- This can be achieved with an the two transformations discussed
  - Flat beam

$$\gamma\varepsilon_x \otimes \gamma\varepsilon_y : \quad \left(10^{-6}\right)^2 \rightarrow 10^{-5} \otimes 10^{-7}$$

  - εx-εz exchange

$$\gamma\varepsilon_x \otimes \gamma\varepsilon_y \otimes \gamma\varepsilon_z : \left(10^{-6}, 10^{-6}, 10^{-7}\right) \rightarrow \left(10^{-5}, 10^{-7}, 10^{-7}\right) \rightarrow \left(10^{-7}, 10^{-7}, 10^{-5}\right)$$

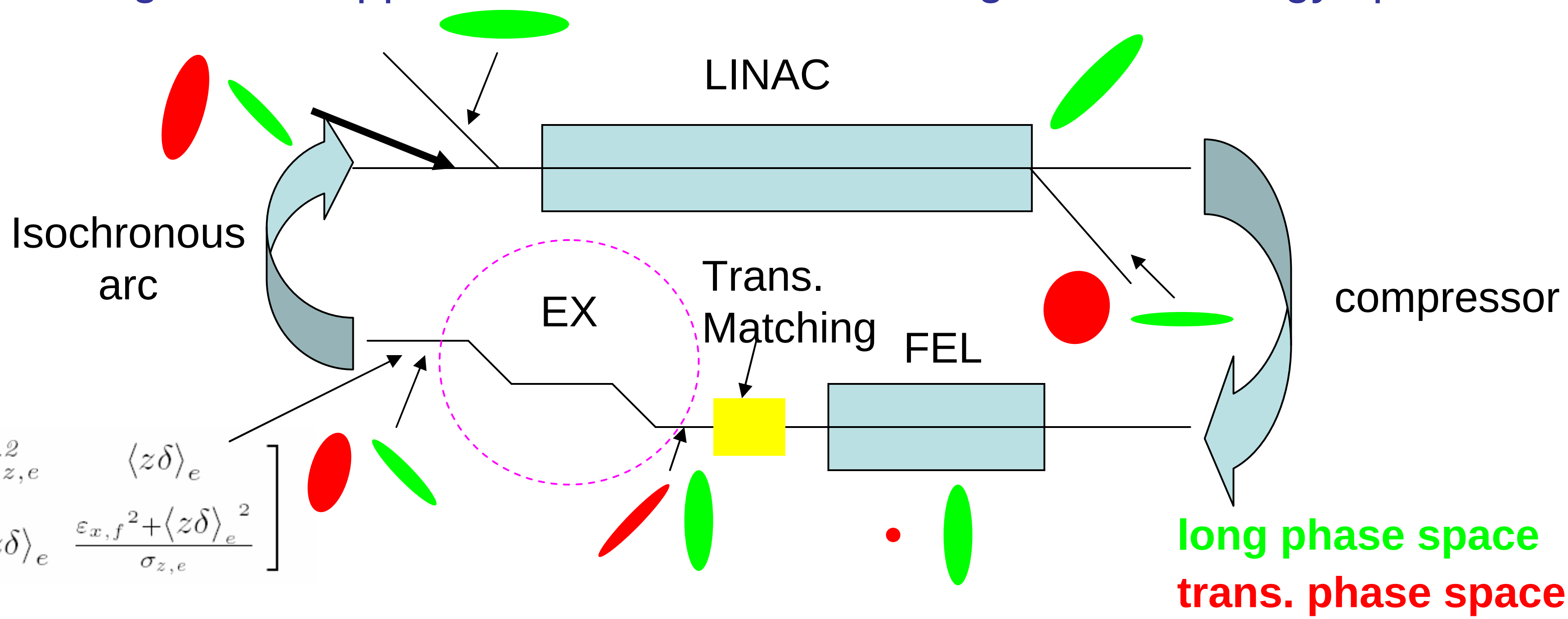




[Emma, Huan Kim and Piot. PRSTAB (2006)]

Applications: MW ERL (1)

- Might have application in ERL to enable higher final energy spread



$$\begin{bmatrix} \sigma_{z,e}^{2} & \langle z\delta\rangle_e \\ \langle z\delta\rangle_e & \frac{\varepsilon_{x,f}{}^{2}+\langle z\delta\rangle_e{}^{2}}{\sigma_{z,e}} \end{bmatrix}$$

- After the FEL, the transverse beam parameter are matched such that they provide the desired bunch length and correlated energy spread after the emittance exchanger
- The beam is then decelerated

Applications: MW ERL (2)

- The final transverse matrix is

$$\begin{bmatrix} \frac{1}{4}\frac{\varepsilon_{z,f}\left({\beta_{z,f}}^2L^2+\eta^4\right)}{\beta_{z,f}\,\eta^2} & \frac{1}{2}\frac{\varepsilon_{z,f}\left({\beta_{z,f}}^2L^2-\eta^4\right)}{\beta_{z,f}\,\eta^2 L} \\ \frac{1}{2}\frac{\varepsilon_{z,f}\left({\beta_{z,f}}^2L^2-\eta^4\right)}{\beta_{z,f}\,\eta^2 L} & \frac{\varepsilon_{z,f}\left({\beta_{z,f}}^2L^2+\eta^4\right)}{\beta_{z,f}\,\eta^2 L^2} \end{bmatrix}$$

- Issues:
  - After the exchanger transverse emittance is huge and so is the transverse beta function (but this can be controlled)
  - No clear advantage compared to usual longitudinal phase space manipulation (at least not obvious from this first look)
  - Real question is does one prefer a large longitudinal or transverse emittance?
  - One advantages might be BBU mitigation?

ILC revisited (work in progress)

- Flat beam (see before) seems not able to provide the proper emittance values for ILC (ε_x, ε_z) $\rightarrow$ (0.02,8) μm

- ILC target $(0.02 \times 8)^{1/2}$~0.4 μm for 3.2 nC is not reachable a conventional electron source

- These bunches are produced by a 5 GeV, 6 km damping ring Considering the 6-D emittance after the damping ring we have (ε_x, ε_y, ε_z)=(8, 0.02, 3000) μm

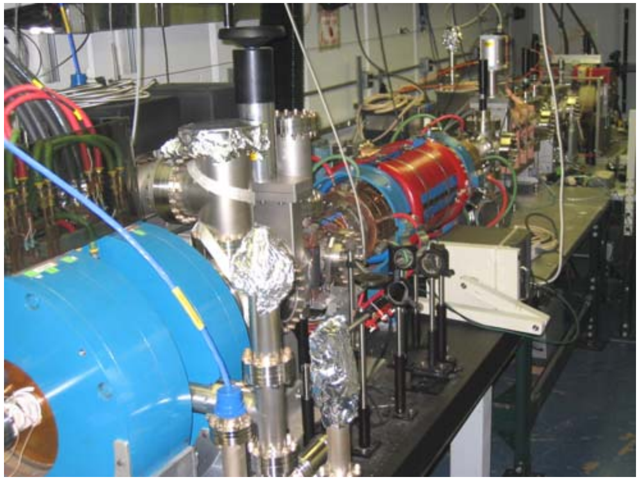
- A possibility: (5, 5, 8)→(**1250**, **0.02**, 8)→(8, 0.02,1250) μm

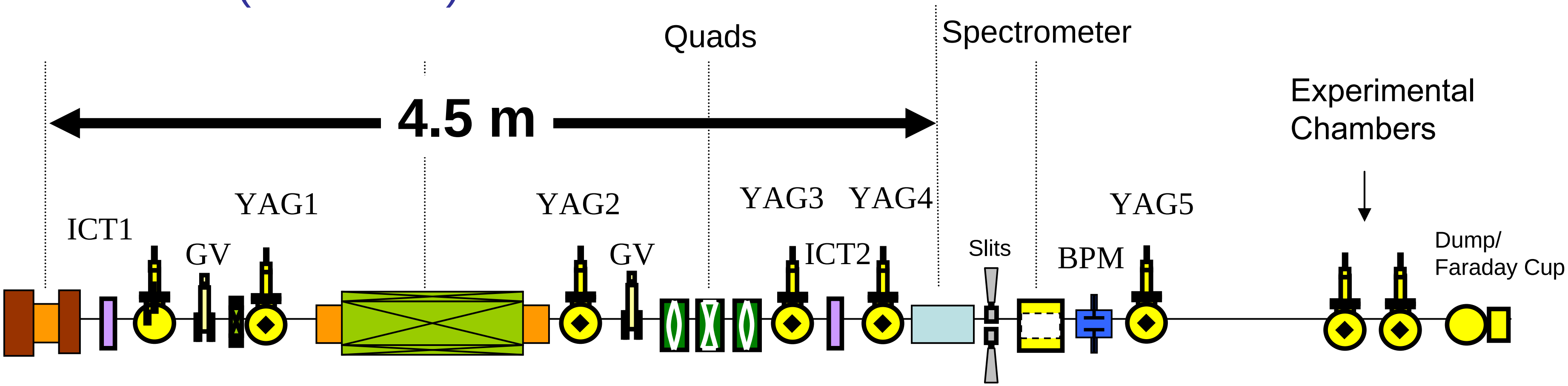
- The problem is to produce the "low" initial **longitudinal emittance** (self generating scheme are hopeless with GaAs cathode)

Plans for POF experiment at AWA (1)

- Argonne wakefield accelerator
  - 15 MeV maximumenergy
  - Few pC to 100 nC bunches
  - Many diagnostics

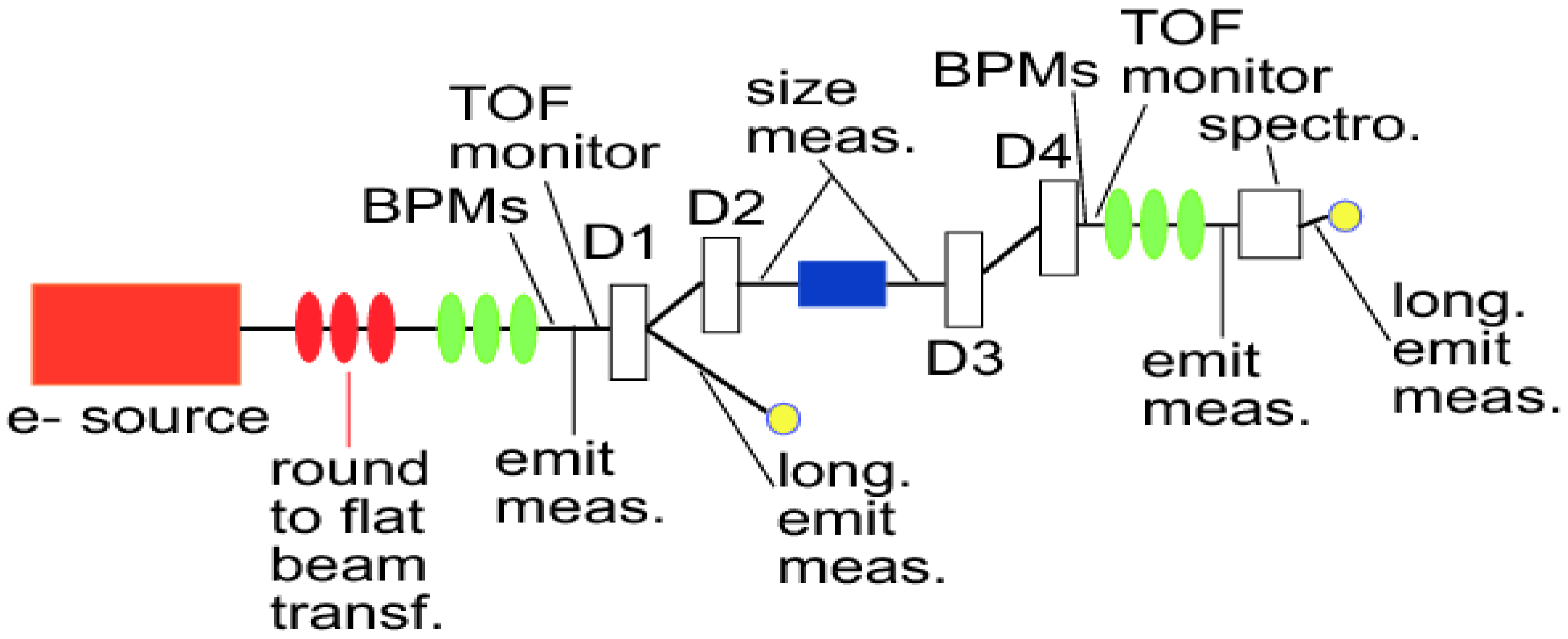
- Managed/Operated by Wei Gai and John Power (HEP/ANL)





Plans for POF experiment at AWA (2)

- Emittance exchange include extensive diagnostics currently being developed
- We included both the flat beam transform and transverse-to-longitudinal exchanger



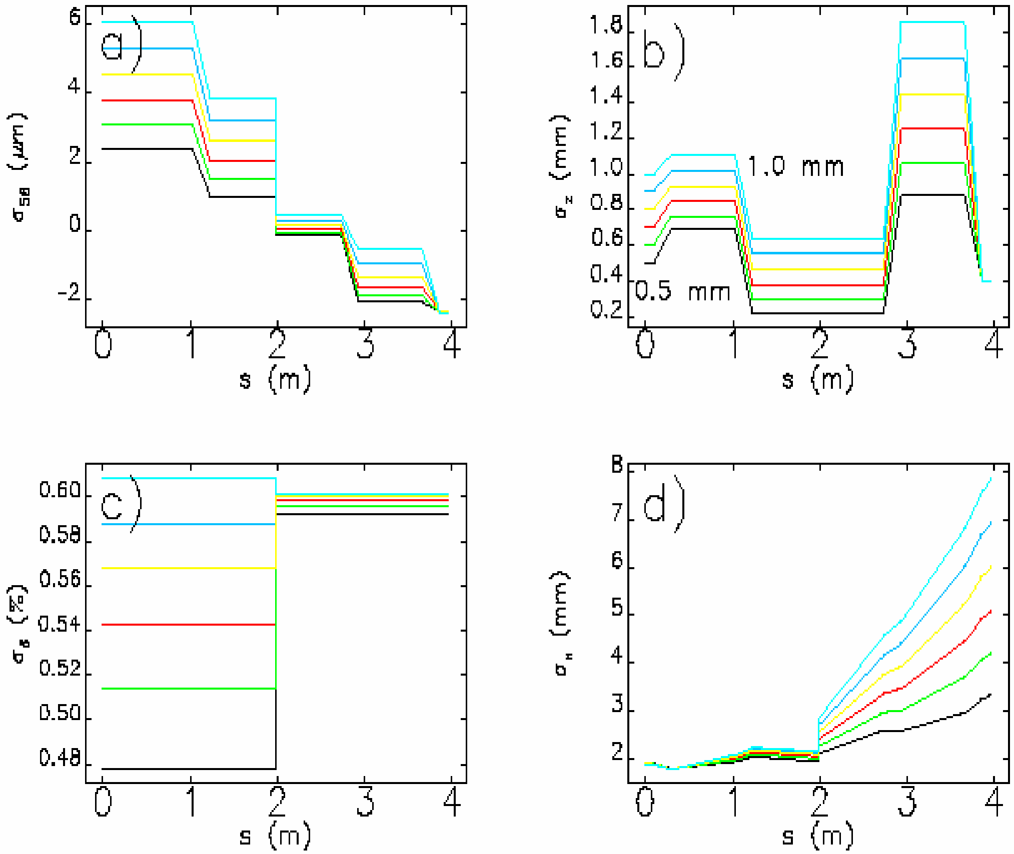
Second order effects problems…

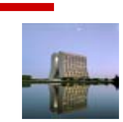
- Bunch length at AWA larger than cases studied in litterature

- Second order effects spoil the final emittance

$$\varepsilon_x \simeq \left| M\Sigma_0\widetilde{M} + \sum_j \left[\begin{array}{c} T_{1jj} \\ T_{2jj} \end{array} \right] [T_{1jj}, T_{2jj}]\langle x_j^4\rangle \right|^{1/2}$$

- Photocathode drive laser will need to be shortened

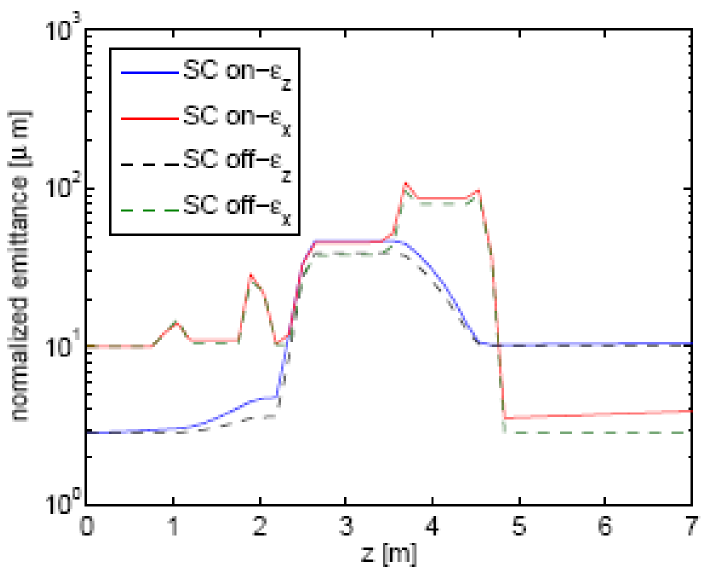


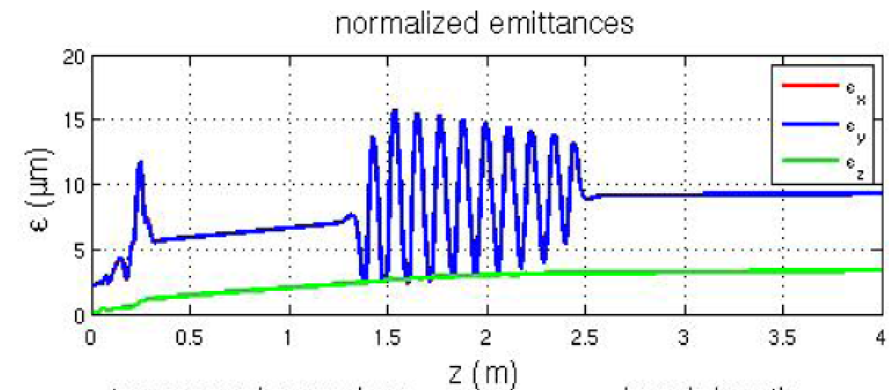


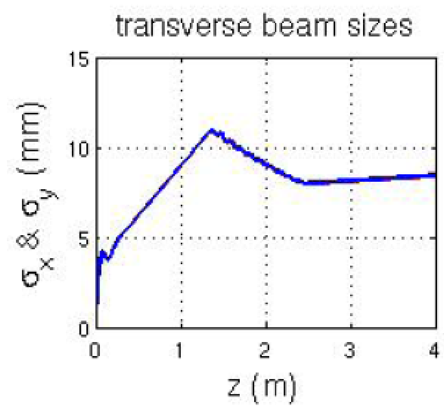
Start-to-end simulation of the POP at AWA

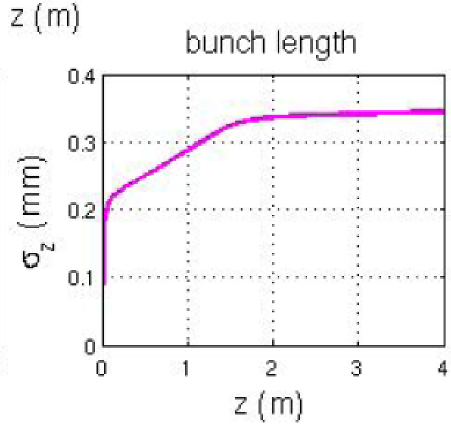
- Round beam simulation
  (M. Rihaoui, NIU)

- Simulation of exchanger including space charge
  (Yin-e Sun et al., PAC 07)









- Flat beam optimization

$$(17, 17, 5) \rightarrow (34, 0.2, 5) \text{ with a ratio } e_x/e_y = 210.$$

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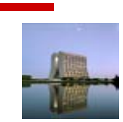

Summary

- Phase space tailoring are emerging techniques

- Flat beam generation has been demonstrated and is now implement in the standard design of ILCTA. It will open opportunities to test concept such as image-charge undulator and dielectric wakefield

- Emittance exchange between the transverse and longitudinal phase spaces together with the flat beam technique provides control of emittance partitioning within the three degree-of-freedoms.

- Possible application might include longitudinal phase space management in FEL-driver ERL’s