Advanced Photon Source

Flat Beam Generation

Kwang-Je Kim
Argonne National Laboratory
and
The University of Chicago

26th Advanced ICFA Beam Dynamics Workshop on Nanometre-Size Colliding Beams
Lausanne, Switzerland

September 2-6, 2002

Flat Beam Generation

Beam adapter:

Ya. Derbenev

Theory:

A. Burov, S. Nagaitsev, Ya. Derbenev

Application to flat beam:

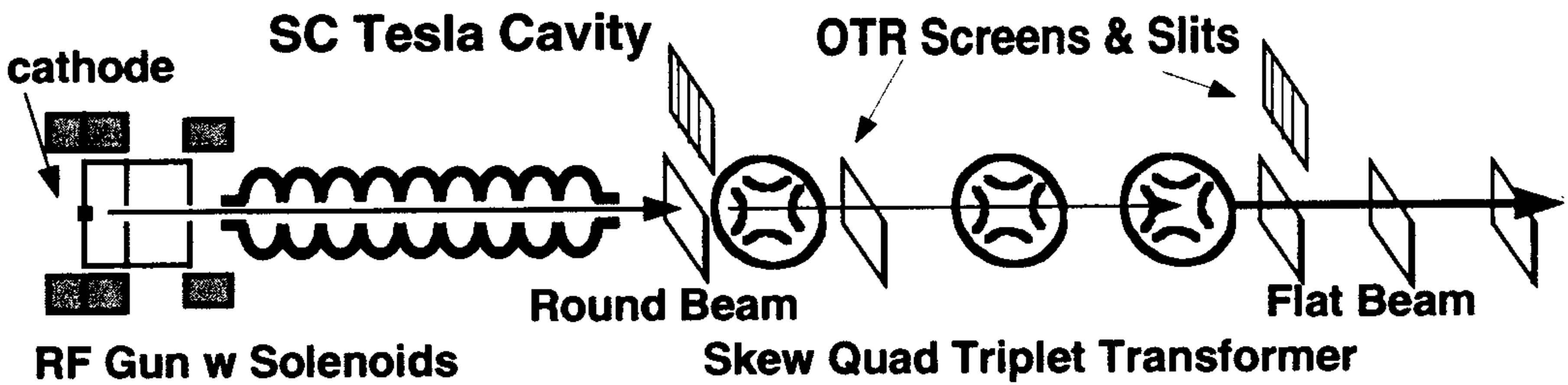
R. Brinkmann, Ya. Derbenev, and K. Floetmann

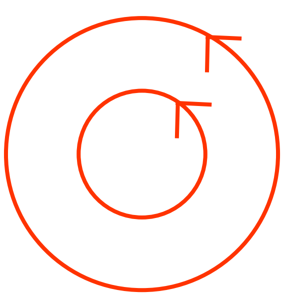
Experiment:

FNPL at Fermilab

D. Edwards, H. Edwards, et al.

Schematic rendition of the layout at Fermilab for flat beam experiment

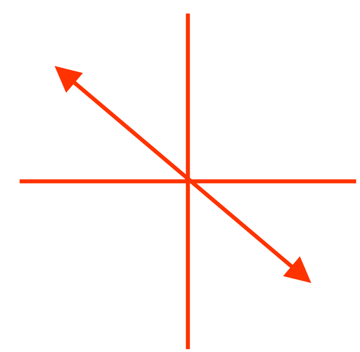




$$\begin{cases} x = A\cos \kappa z \\ y = A\sin \kappa z \end{cases} \longrightarrow \begin{cases} A\cos \kappa z \\ A\sin(\kappa z + \pi/2) \end{cases}$$

vortex beam

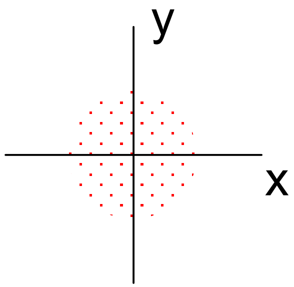
flat beam



Phase Space Coordinates

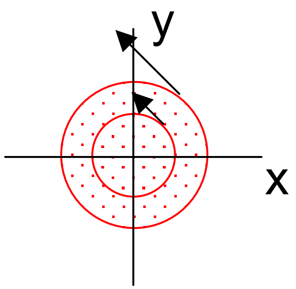
I. After cathode

$X_I = (x, x', y, y')$



II. After solenoid (short) $\kappa = \left(\frac{eB}{2P_s}\right)$

$X_{II} = (x, x' + \kappa y, y, y' - \kappa x')$,



III. After quadrupole channel

$$X_{III} = R^{-1} \begin{bmatrix} M, & 0 \\ 0 & FM \end{bmatrix} R \cdot X_{II}$$

$$R = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}, M = \begin{bmatrix} \cos\mu, & \beta \sin\mu \\ -(\sin\mu)/\beta, & \cos\mu \end{bmatrix}, F = \begin{bmatrix} 0, & \beta \\ -\frac{1}{\beta}, & 0 \end{bmatrix}$$

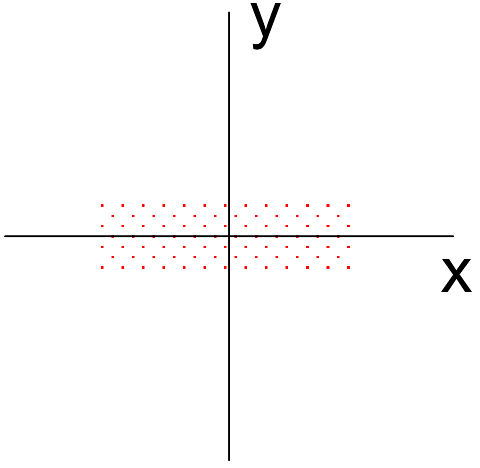
skew — quadrupole channel — 90º phase advance

- Match by choosing β.

$$X_{IV} = \begin{pmatrix} 2bx + 2ay + \beta(ax' - by') \\ -\frac{2a}{\beta}x + \frac{2b}{\beta}y + bx' + ay' \\ -\beta(bx' - ay') \\ ax' + by' \end{pmatrix}$$

$$a = \frac{1}{2}(\cos\mu + \sin\mu),\ b = \frac{1}{2}(\cos\mu - \sin\mu)$$

- Match $\beta \approx \kappa^{-1}$



Flat beam for $x' = y' = 0$!

Beam Moment Matrix

$$\Sigma = \left\langle XX^T \right\rangle = \begin{pmatrix} \left\langle x^2 \right\rangle, \left\langle xx' \right\rangle, \left\langle xy \right\rangle \left\langle xy' \right\rangle \\ \left\langle x'x \right\rangle, \left\langle x'^2 \right\rangle, \left\langle x'y \right\rangle, \left\langle x'y' \right\rangle \\ \left\langle yx \right\rangle, \left\langle yx' \right\rangle, \left\langle y^2 \right\rangle, \left\langle yy' \right\rangle \\ \left\langle y'x \right\rangle, \left\langle y'x' \right\rangle, \left\langle y'y \right\rangle, \left\langle y'^2 \right\rangle \end{pmatrix}$$

$$\Sigma_I = \begin{pmatrix} \sigma^2 & 0 & 0 & 0 \\ 0 & \sigma'^2 & 0 & 0 \\ 0 & 0 & \sigma^2 & 0 \\ 0 & 0 & 0 & \sigma'^2 \end{pmatrix} \text{(round beam, no correlation)}$$

$$\mathrm{Det}\left(\Sigma_I\right) = \left(\sigma\sigma'\right)^2$$

Beam Moment Matrix after Exiting Solenoid

$$\Sigma_{||} = \begin{pmatrix} \sigma^2 & 0 & 0 & -\kappa\sigma^2 \\ 0 & \sigma'^2 + \kappa^2\sigma^2 & \kappa\sigma^2 & 0 \\ 0 & \kappa\sigma^2 & \sigma^2 & 0 \\ -\kappa\sigma^2 & 0 & 0 & \sigma'^2 + \kappa^2\sigma^2 \end{pmatrix} = \begin{bmatrix} \varepsilon_x \mathrm{T}, & \mathcal{L}\mathrm{J} \\ -\mathcal{L}\mathrm{J}, & \varepsilon_x \mathrm{T} \end{bmatrix}$$

$$\mathrm{T} = \begin{bmatrix} \beta & 0 \\ 0 & 1/\beta \end{bmatrix}, \quad \mathrm{J} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$

$$\varepsilon_x = \sqrt{\sigma^2\left(\sigma'^2 + \kappa^2\sigma^2\right)}, \quad \mathcal{L} = \kappa\sigma^2$$

$$\beta = \frac{\sigma}{\sqrt{\sigma'^2 + \kappa^2\sigma^2}}$$

- Emittance = phase space density = Det $(\Sigma_{||}) = (\sigma\sigma')^2$

Beam Moment Matrix After Quad Transport

- Matching by $\beta = \frac{1}{\kappa}\sqrt{1-\frac{\beta^2\sigma'^2}{\sigma^2}}$ (Chun-xi Wang)

$$\Sigma_{III} = \frac{1}{2}\begin{bmatrix} \beta\varepsilon_x & 0 & 0 & 0 \\ 0 & \varepsilon_x/\beta & 0 & 0 \\ 0 & 0 & \beta\varepsilon_y & 0 \\ 0 & 0 & 0 & \varepsilon_y/\beta \end{bmatrix} \quad !!$$

$$\varepsilon_x = \frac{1}{2}\left[\frac{(1+\kappa\beta)^2}{\beta}\sigma^2 + \beta\sigma'^2\right], \quad \varepsilon_y = \frac{1}{2}\left[\frac{(1-\kappa\beta)^2}{\beta}\sigma^2 + \beta\sigma'^2\right]$$

- Emittance = $\varepsilon_x\varepsilon_y = (\sigma\sigma')^2$
- Flat beam ratio:

$$\frac{\varepsilon_x}{\varepsilon_y} \approx 4\frac{\kappa^2\sigma^2}{\sigma'^2}$$

Another Matching $\beta = \kappa^{-1}$

$$\Sigma_{III} = \begin{bmatrix} \varepsilon_x \mathbf{T} & \varepsilon_{xy} \mathbf{S} \\ \varepsilon_{xy} \mathbf{S} & \varepsilon_y \mathbf{T} \end{bmatrix}$$

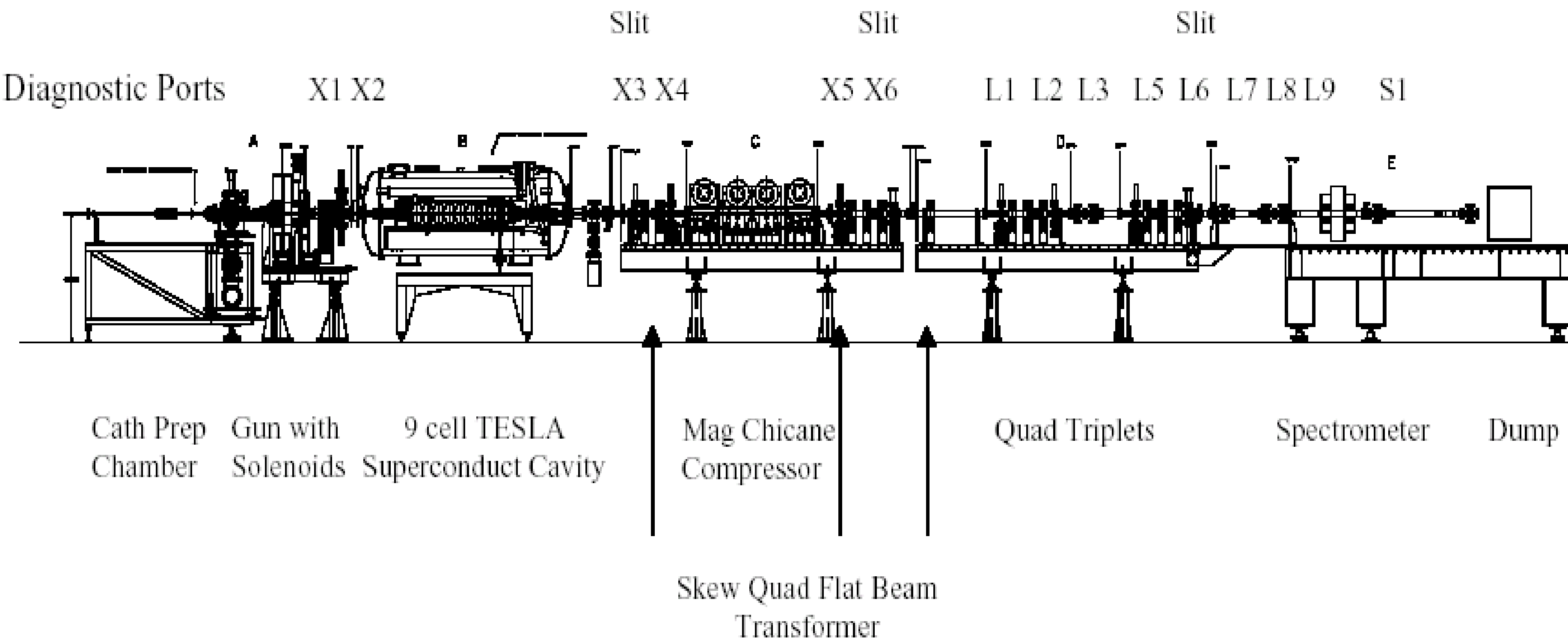
$$\varepsilon_x = \frac{2\sigma^2}{\beta} + \frac{\beta\sigma'^2}{2}, \ \varepsilon_y = \frac{\beta}{2}\sigma'^2, \quad \mathbf{T} = \begin{bmatrix} \beta, & 0 \\ 0, & 1/\beta \end{bmatrix}, \quad \varepsilon_{xy} = \frac{\beta\sigma'^2}{2}$$

$$\mathbf{S} = \begin{bmatrix} -\beta\cos\mu, & \sin 2\mu \\ \sin 2\mu, & \dfrac{\cos\mu}{\beta} \end{bmatrix} \qquad \text{Det } \mathbf{S} = -1$$

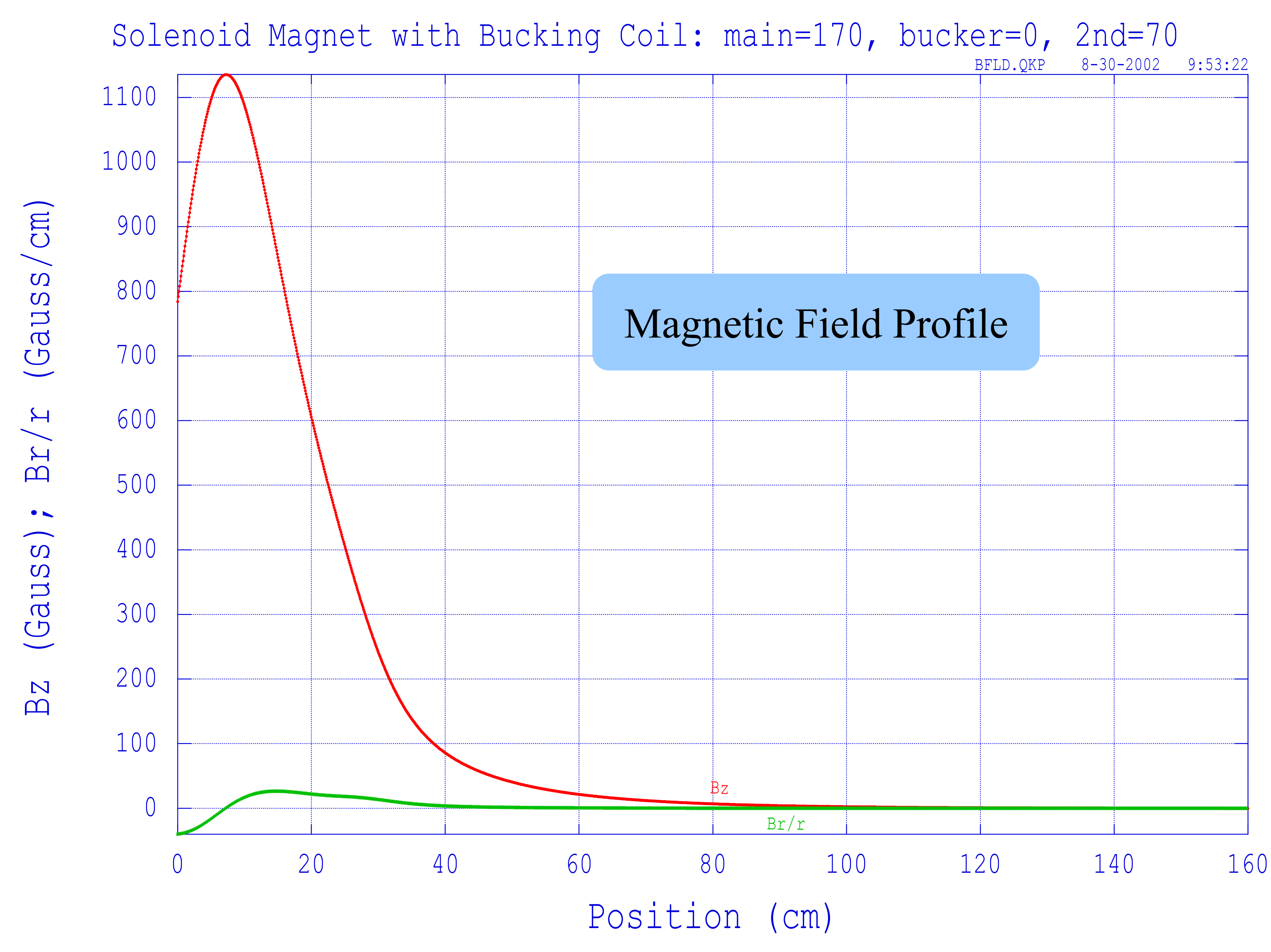
$$\varepsilon_y \varepsilon_x = (\sigma\sigma')^2 + \left(\frac{\beta\sigma'^2}{2}\right)^2, \quad \frac{\varepsilon_x}{\varepsilon_y} = \left(\frac{2\sigma}{\beta\sigma'}\right)^2 + 1$$

$$\text{Det } \Sigma_{IV} = \varepsilon_x \varepsilon_y - (\varepsilon_{xy})^2 = (\sigma \cdot \sigma')^2$$

FermiLab/NICADD PhotoInjector

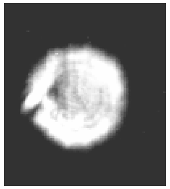


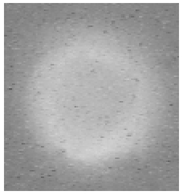
Layout taken from PAC01 paper of D. Edwards etc.

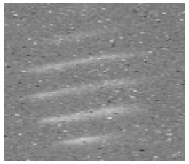


Solenoid Magnet with Bucking Coil: main=170, bucker=0, 2nd=70
BFLD.QKP 8-30-2002 9:53:22
Magnetic Field Profile
Bz (Gauss); Br/r (Gauss/cm)
Position (cm)
Bz
Br/r
1100
1000
900
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
120
140
160

Cathode and beam prior to the skew-quad channel


Virtual Cathode (VC)


X3


X4 slit image


X5 slit image

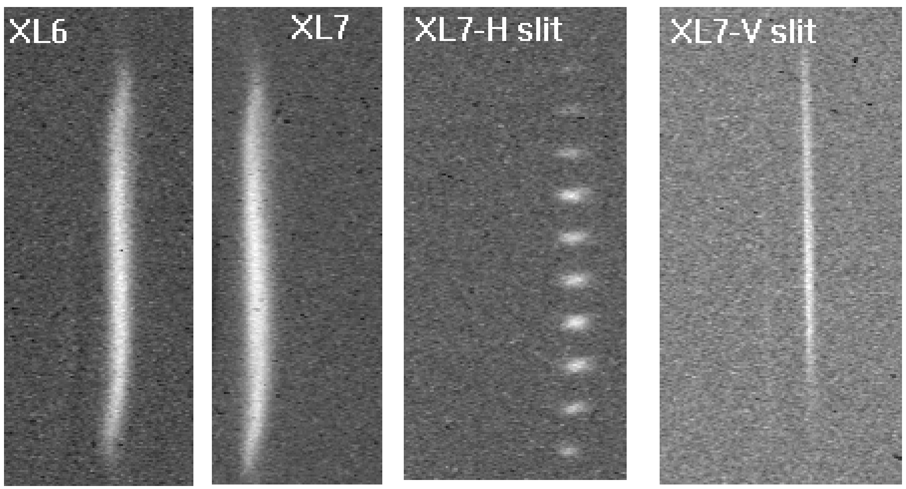

XS4

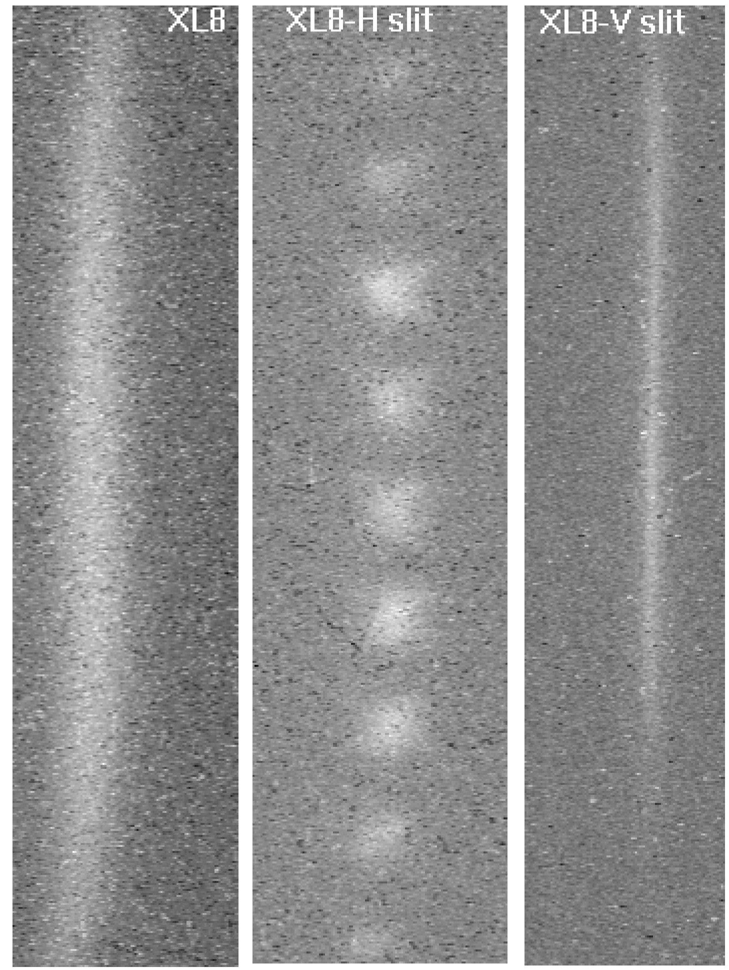
RMS VC	RMS beam size at X3	Normalized Emittance
0.73mm	1.66mm	6.44 mm mrad

VC is an image of the laser spot on the cathode.

Beam energy at the exit of the 1.6 RF gun is about 4 MeV. After the 9-cell SC cavity, beam energy is about 16 MeV. Notice that X3 is after the 9-cell SC cavity.

Flat electron beam profile at 9.6m from the cathode (XL6) and horizontal and vertical beamlets used for emittance measurements downstream at XL7 and XL8. The transverse emittance ratio is about 41 in the example shown here.





$$\frac{\varepsilon_n^y}{\varepsilon_n^x} = \frac{38.85 \quad mm \quad mrad}{0.95 \quad mm \quad mrad} = 41$$

Beam Specs for Linear Colliders

	TESLA	NLC	CLIC
Q (nc)	3	1.6	0.6
ε_x (mm-mrad)	12	4.5	0.68
ε_y (mm-mrad)	0.03	0.1	0.02
$\sqrt{\varepsilon_x \varepsilon_y}$ (mm-mrad)	0.6	0.7	0.12

Current rate of art:

$$\sqrt{\varepsilon_x \varepsilon_y} \sim 1\text{mm-mrad} \ @\ Q \approx 1\ \text{nC}.$$