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# Particle Accelerators: Diagnostics and Correction


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# Diagnostics and Correction

- Zeroth Moment: Current
- First Moment: Position
- Second Moment: Size
- Emittance and Beta function
- Tune
- Beam-beam diagnostics
- Orbit correction
- Tune correction

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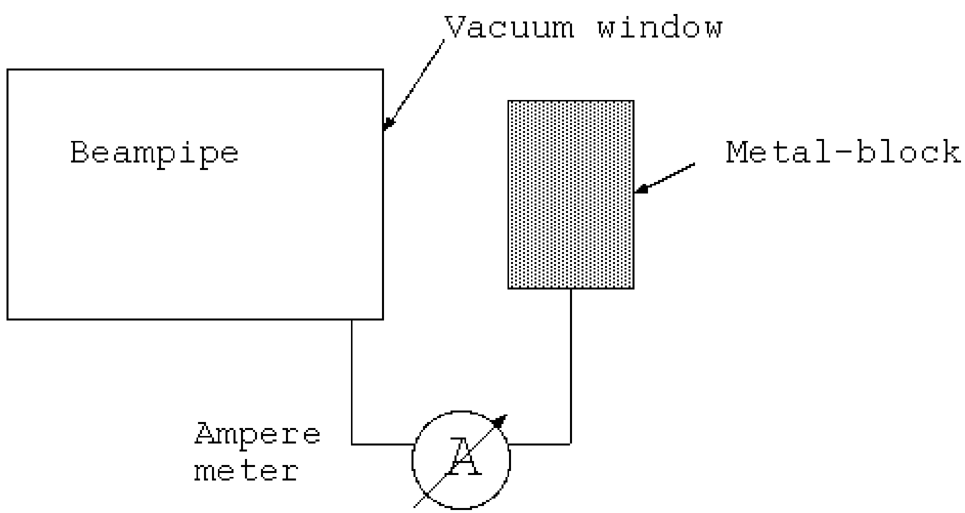
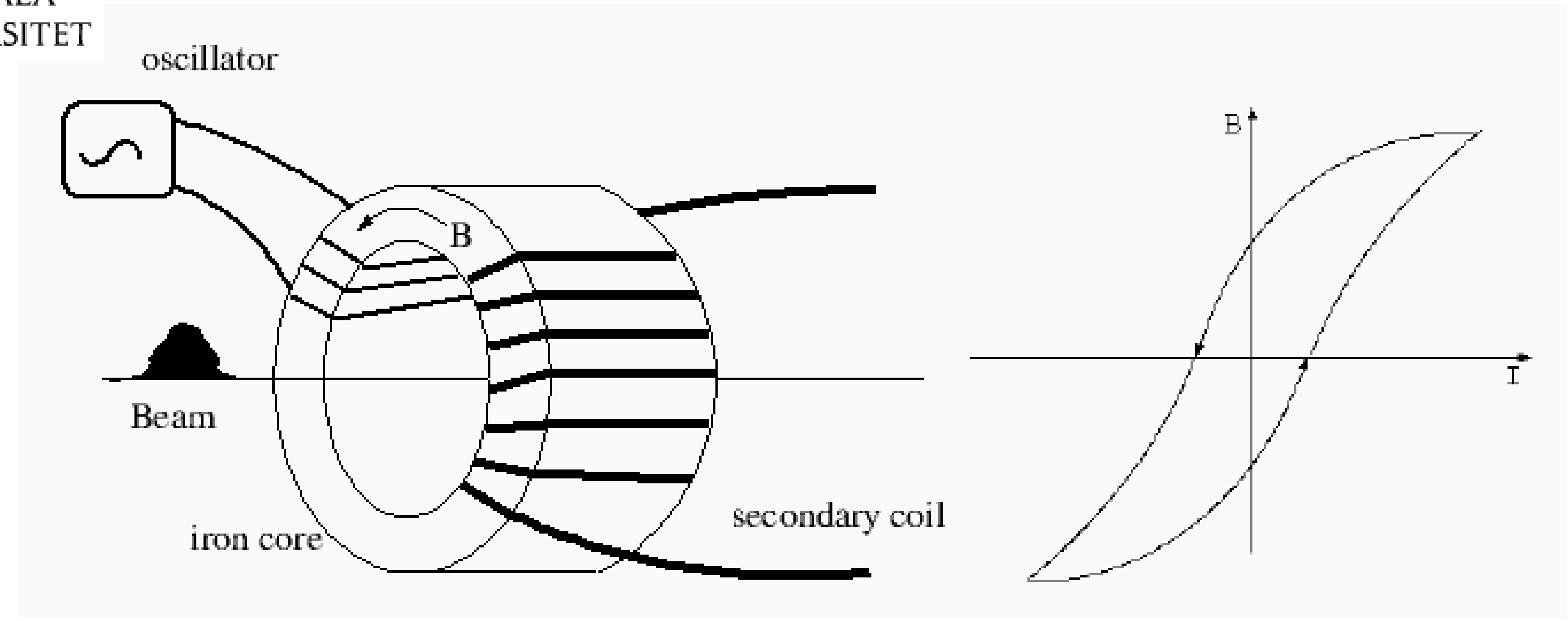
# Faraday Cup

- Dump current in a shielded metal block that stops the beam and meassure current to ground




- Invasive
- Needs to be thick enough to stop beam
- Might need cooling
- Need to shield secondary electrons
- Needs careful attention if time-resolved signal is required

# DCCT




- External oscillator drives the core through hysteresis curve
- Without beam only odd harmonics in secondary coil
- With beam the hysteresis-curve is displaced and even harmonics are generated and can be compensated to zero with extra current that can be measured.

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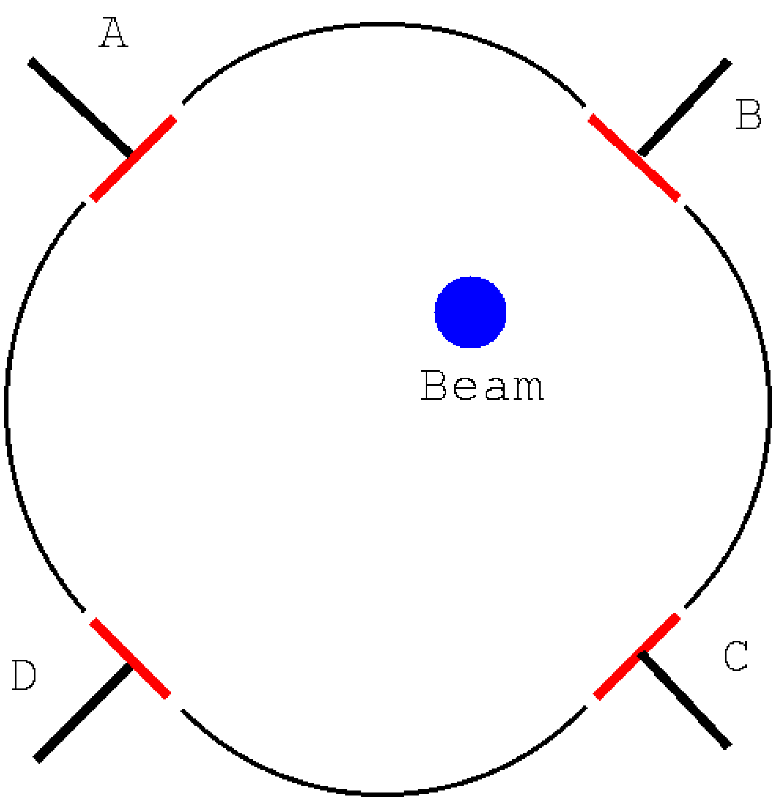
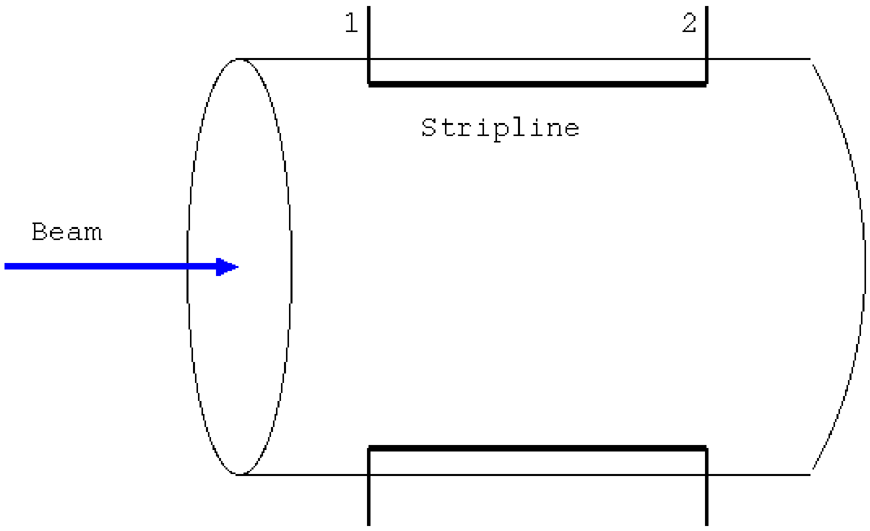
# Beam Position Monitor




$$x = k_x \frac{(A+D)-(B+C)}{A+B+C+D} \quad , \quad y = k_y \frac{(A+B)-(C+D)}{A+B+C+D}$$

- Picks up the wall currents at several positions
- If more signal on the left (A+D) compared to (B+C) then the beam is further to the left.
- $k_x = k_y = R/\sqrt{2}$
- Small signal in small buttons
- Used in high intensity machines with short bunches. Synchrotron light sources
- Non-linear at large amplitudes

# Stripline BPM

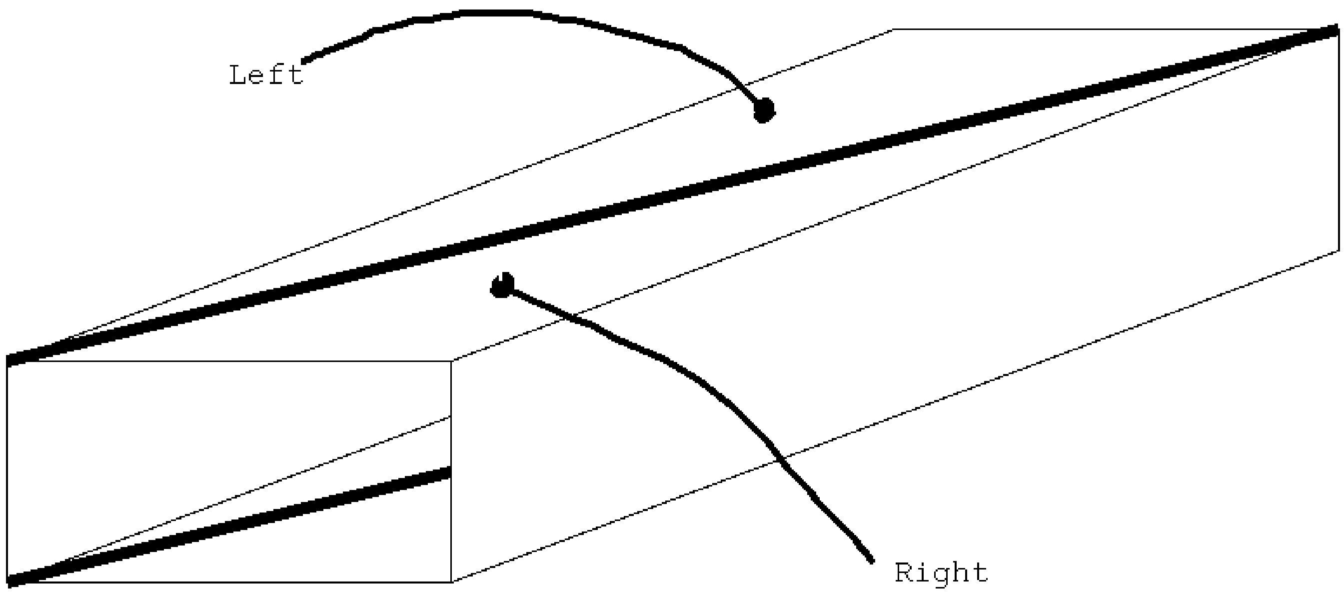



$$V_1(t) = \frac{Z_s\phi}{4\pi}\left[I(t) - I(t - l/v_b - l/v_s)\right]$$

$$V_2(t) = \frac{Z_s\phi}{4\pi}\left[I(t - l/v_s) - I(t - l/v_b)\right]$$

- Magnetic flux in the small area between strip and wall changes and induces a voltage in wires.
- Signals with opposite polarity from the ends.
- Directional if bunch length smaller than stripline.
- Can be used to separate signals from counter-propagating beams.
- Position information from four striplines similar to button BPM.

# Shoebox BPM




- Large electrodes make it sensitive to weak currents in ion storage rings
- CELSIUS used these

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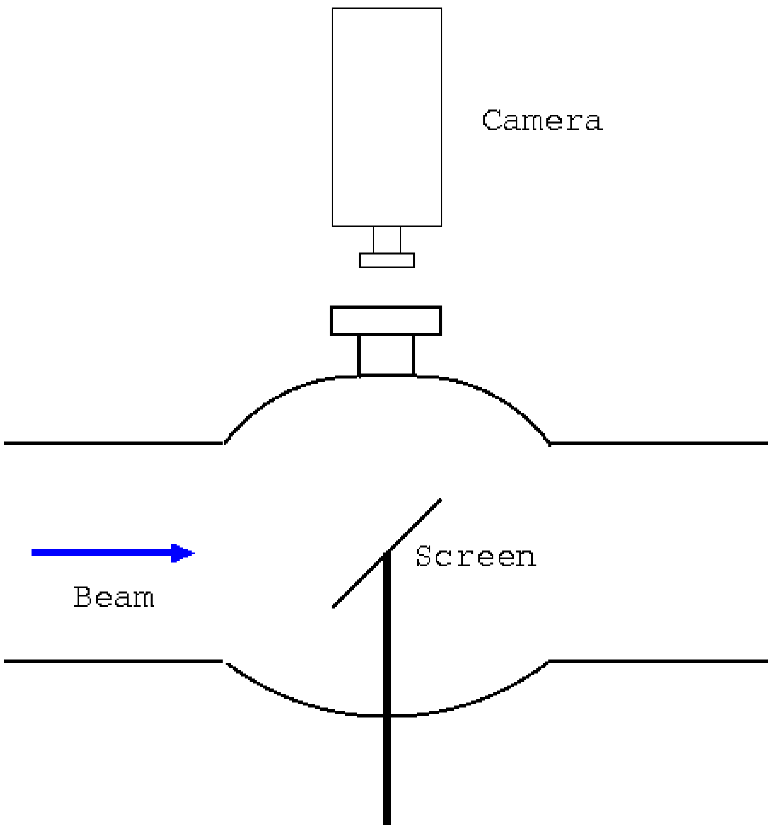
# Luminescent and OTR Screen

- Now to 2nd Moments




- Place either movable or static luminescent screen in path of beam → invasive
- Blind spots and burn-out
- Limited dynamic range
- Failing cameras
- Optical transition radiation due to refractive index of screen
- thin foil of e.g. $AlO_2$
- Disturbs high energy beams very little if thin enough

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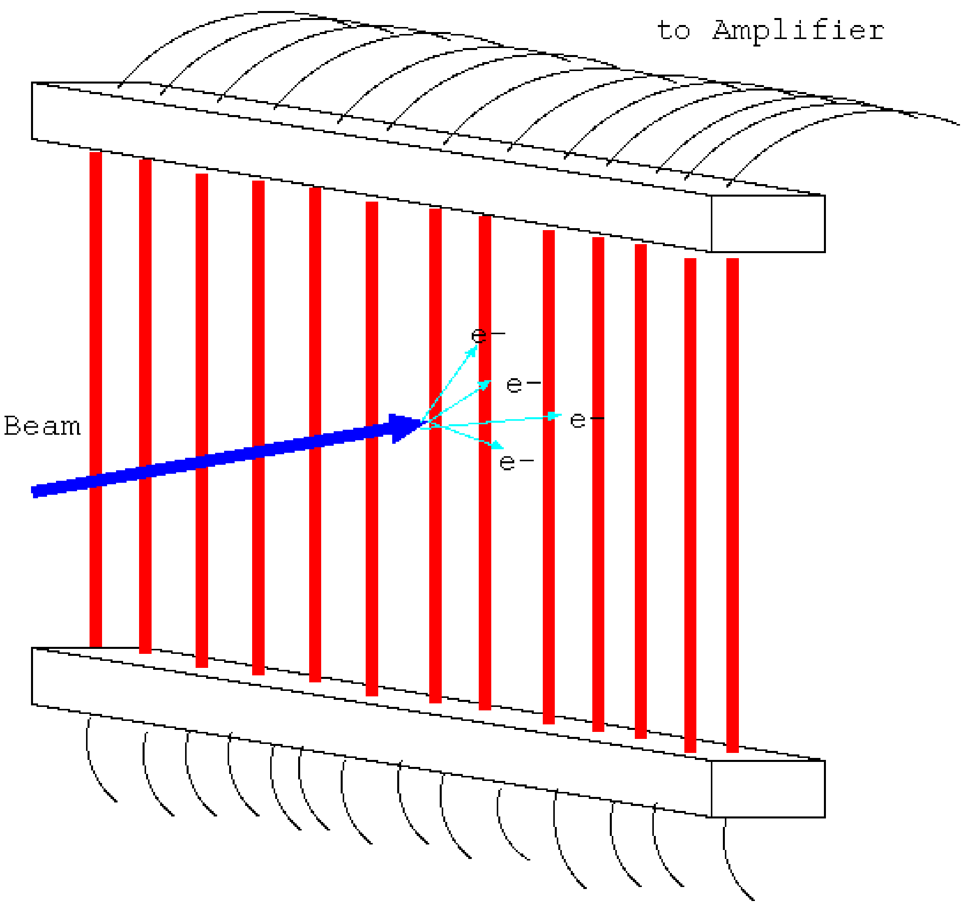
# SEM Grid




- Secondary emission monitor
- Beam intercepts thin wires and knocks out electrons
- Parallel readout of many wires
- One amplifier per wire makes this expensive
- Heat deposition in wires
- Plot current from wire as function of wire number
- Histogram
- Position and size of beam

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# Other size measurements

- Wire scanner, use single movable wire instead
  - position encoder
  - need to move fast in ring
- Magnesium Jet Profile Monitor
  - use evaporated MG as 'wire'
  - record the ionized electrons
- Residual gas profile monitor
  - ionize residual gas and catch electrons on position sensitive sensors
  - use magnetic fields to guide the electrons

# Tune

- Kick the beam with a pulsed magnet
- Measure the position on every turn with beam position monitor
- Time series: $x_1, x_2, x_3, \ldots, x_n$
- Fourier transform, usually FFT is used.
- Aliasing: can observe only fractional tune.
- Alternatively: Observe tune sideband of the revolution harmonics in spectrum nalyzer

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# Example: Tune from time series

$$x_n = \sin(\omega_\beta t_n)$$

$$= \sin(\omega_\beta n T_0)$$

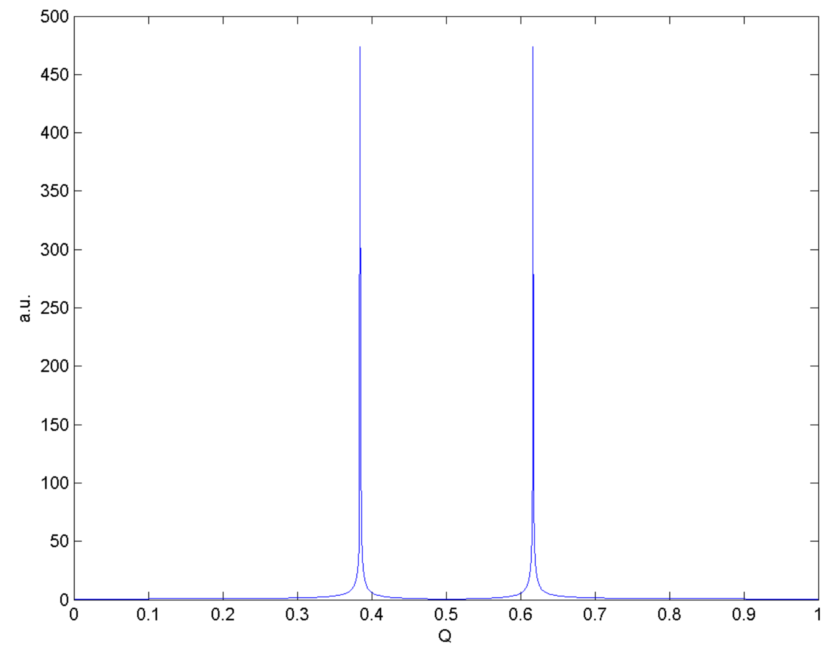
$$= \sin(Q_x 2\pi f_0 n T_0)$$

$$= \sin(2\pi n Q_x)$$

$$= \sin(2\pi n [Q_x])$$

[Q]= fractional part of tune

```
Qx=0.616
n=1:1:1024;
x=sin(2*pi*Qx*n);
plot(n/1024,abs(fft(x)));
```




- cannot distinguish Q and 1-Q
- change QF and see how tune line moves

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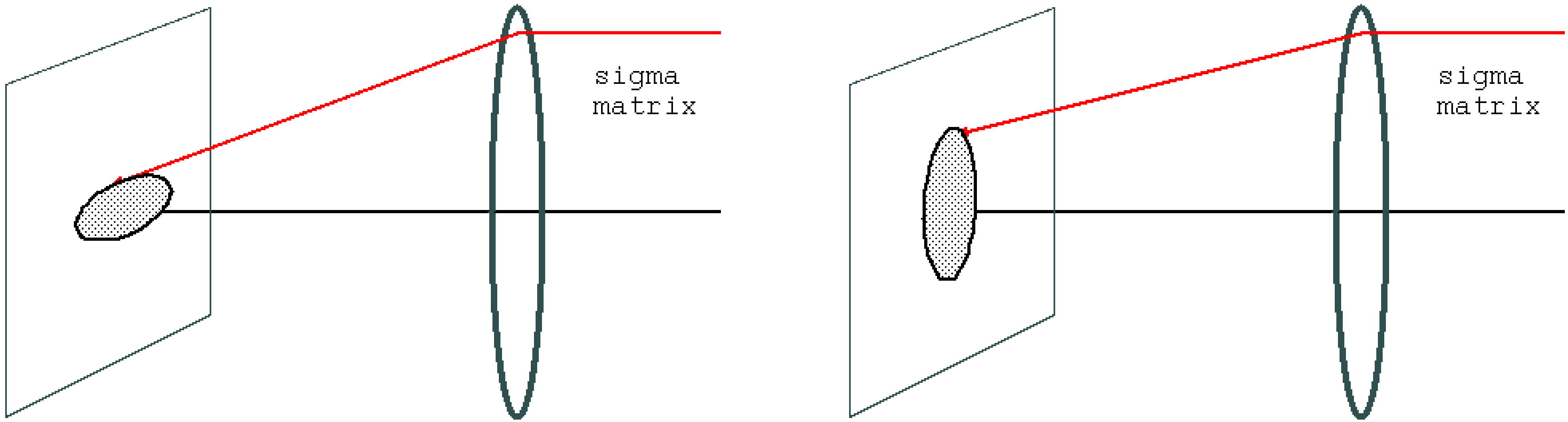
# Emittance and Beta function




- Quadrupole scan: vary quadrupole and observe how the measured spot size changes
- Depends on all parameters of the beam before the quadrupole

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{pmatrix} = \begin{pmatrix} \langle x^2 \rangle & \langle xx' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle \end{pmatrix} = \varepsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$$

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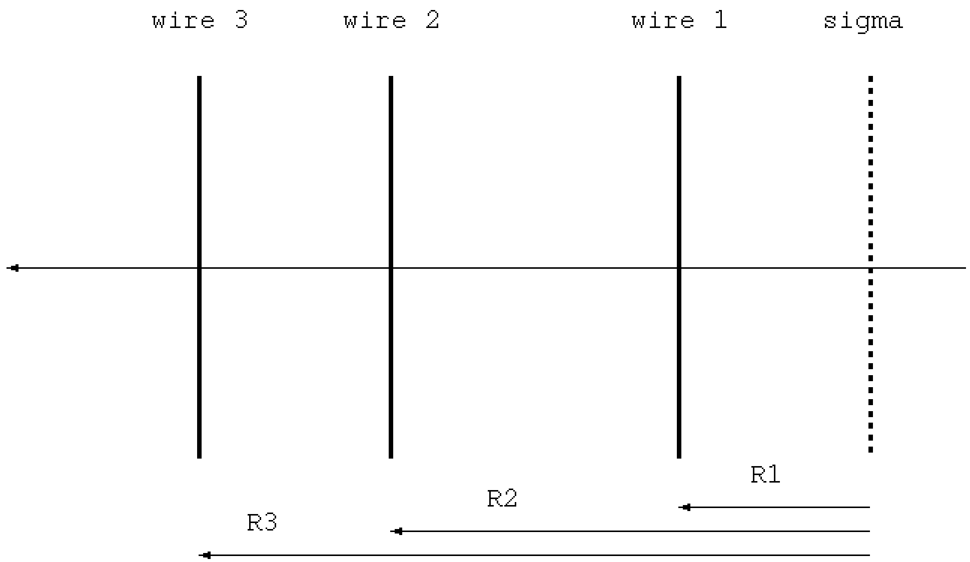
# Several wire scanners

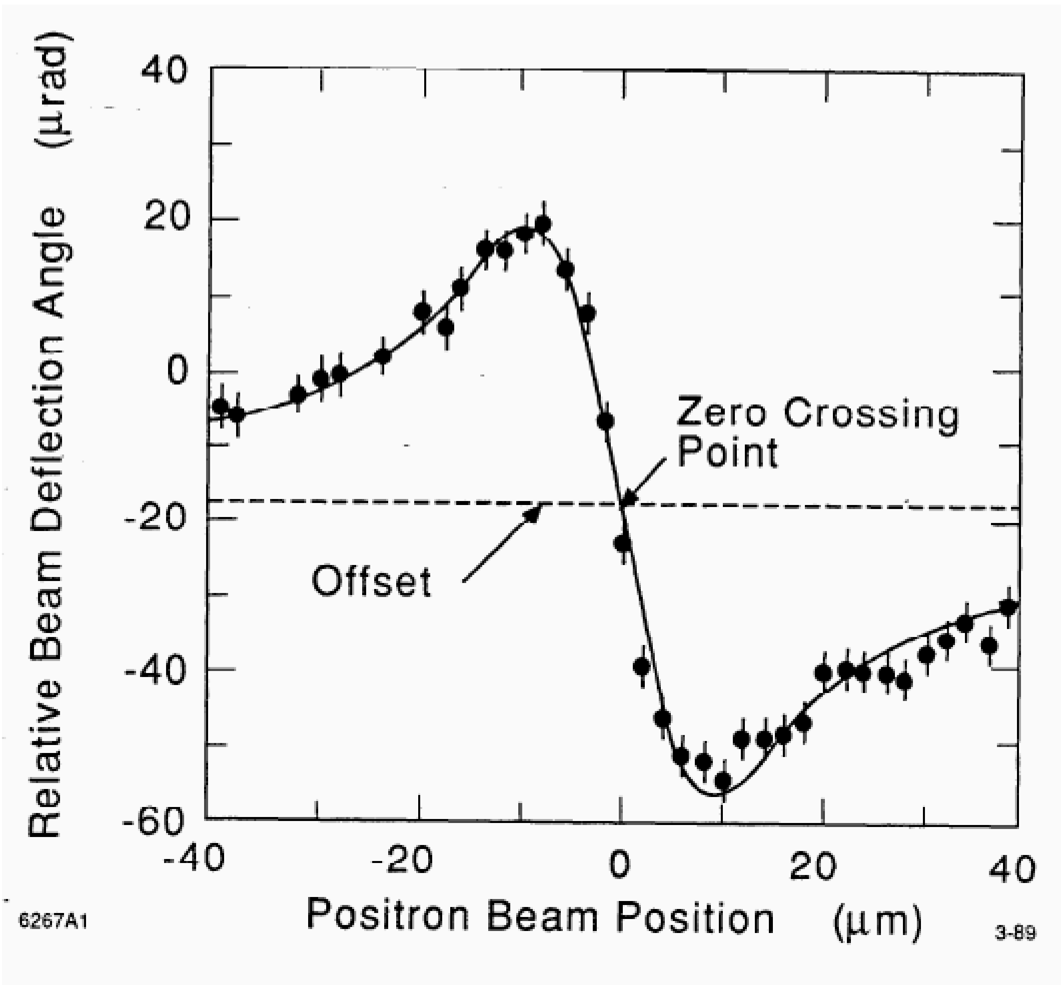


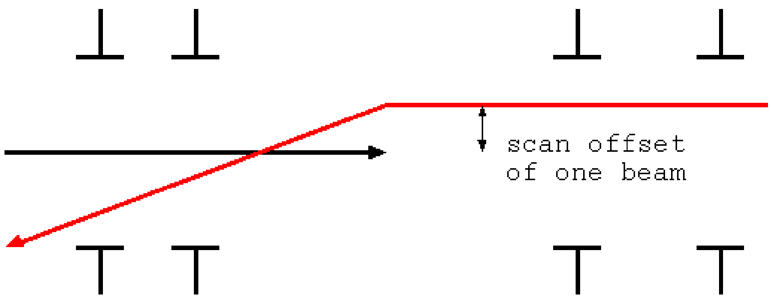

$$
\begin{aligned}
\sigma_1^2 &= (R^1)_{11}^2\sigma_{11} + 2R_{11}^1R_{12}^1\sigma_{12} + (R^1)_{12}^2\sigma_{22} \\
\sigma_2^2 &= (R^2)_{11}^2\sigma_{11} + 2R_{11}^2R_{12}^2\sigma_{12} + (R^2)_{12}^2\sigma_{22} \\
\sigma_3^2 &= (R^3)_{11}^2\sigma_{11} + 2R_{11}^3R_{12}^3\sigma_{12} + (R^3)_{12}^2\sigma_{22}
\end{aligned}
$$

$$
\begin{pmatrix} \sigma_1^2 \\ \sigma_2^2 \\ \sigma_3^2 \end{pmatrix} = \begin{pmatrix} (R^1)_{11}^2 & 2R_{11}^1R_{12}^1 & (R^1)_{12}^2 \\ (R^2)_{11}^2 & 2R_{11}^2R_{12}^2 & (R^2)_{12}^2 \\ (R^3)_{11}^2 & 2R_{11}^3R_{12}^3 & (R^3)_{12}^2 \end{pmatrix} \begin{pmatrix} \sigma_{11} \\ \sigma_{12} \\ \sigma_{22} \end{pmatrix}
$$

- $(A^t A)^{-1}A^t$ - gymnastics with error bar estimates
- Derive emittance in same way, once σ is known
- Can use several more wire scanners which allows $\chi^2$ calculation for goodness-of-fit estimate

# SLC Beam-beam Diagnostics

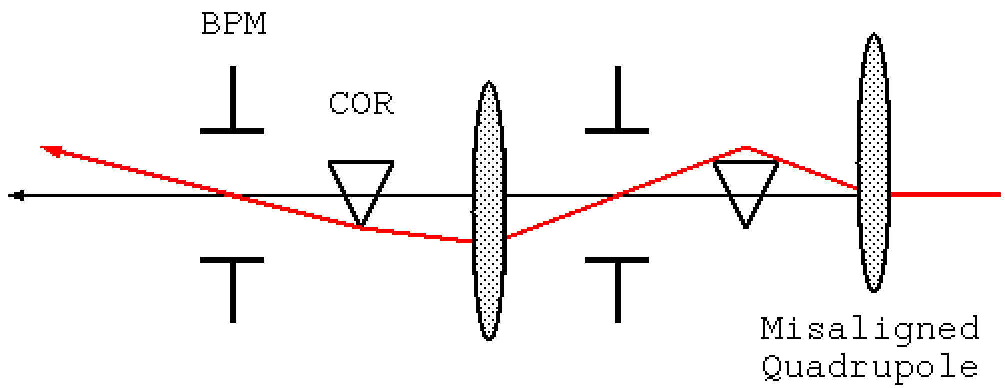



- Micron-size bunches deflect each other
- deflection angle is a measure of size and intensity
- Centering
- Beam size
- Luminosity

# Correction: Orbit

- Observe the orbit on beam-position monitors
- and correct with steering dipoles
- How much do we have to change the steering magnets in order to compensate the observed orbit either to zero or some other 'golden orbit'.
- In beam line the effect of a corrector on the downstream orbit is given by transfer matrix $R_{12}$
- One-to-one steering



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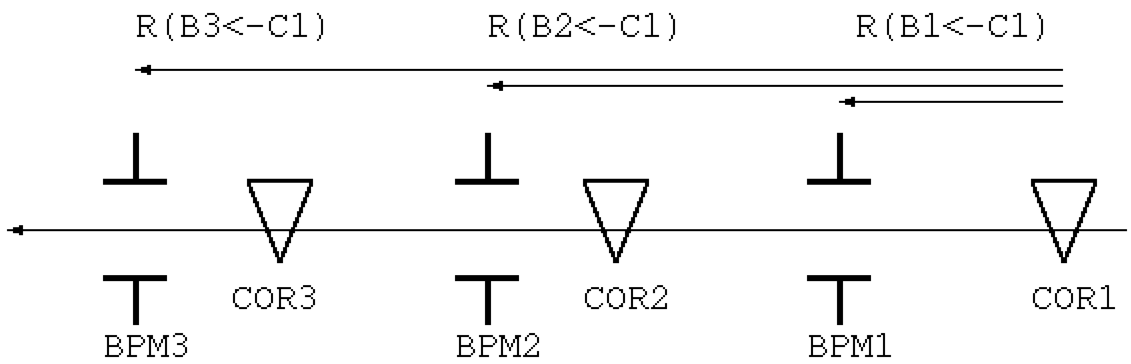
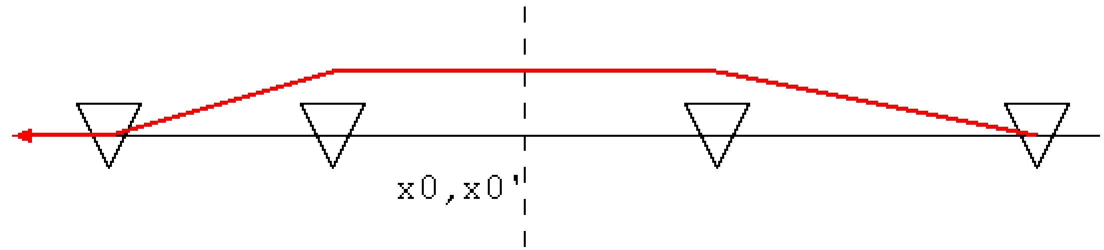
# Orbit correction in a Beamline




$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} R^{11} & 0 & 0 \\ R^{21} & R^{22} & 0 \\ R^{31} & R^{32} & R^{33} \end{pmatrix} \begin{pmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{pmatrix}$$

- Observed beam positions $x_1$, $x_2$, and $x_3$
- Implicitly assume 12 or 34 matrix element in R
- Only downstream BPM can be affected
- Linear algebra problem $(A^tA)^{-1}$, etc to find required corrector excitations $\theta_j$ to explain $x_i$
- Reverse sign of calculated $\theta_j$ to correct the orbit to zero

# 4-Bump




- Use four steerers to adjust angle and position at a center point and then flatten orbit downstream of the last steerer.

$$\begin{pmatrix} x_0 \\ x_0' \\ x_f = 0 \\ x_f' = 0 \end{pmatrix} = \begin{pmatrix} R_{12}^{01} & R_{12}^{02} & 0 & 0 \\ R_{22}^{01} & R_{22}^{02} & 0 & 0 \\ R_{12}^{f1} & R_{12}^{f2} & R_{12}^{f3} & R_{12}^{f4} \\ R_{22}^{f1} & R_{22}^{f2} & R_{22}^{f3} & R_{22}^{f4} \end{pmatrix} \begin{pmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_3 \end{pmatrix}$$

- Solve upper part first, insert into third and fourth equation and solve that.
- Gives the required steering excitations $\theta_j$ as a function of $x_0$ and $x_0'$ $\rightarrow$ Multiknob

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# Multi-knobs

```
! ==============================================
! SCNFF IP:  CLOSED BUMP Y POSITION KNOB
! USING A3Y AND A6Y NORTH AND SOUTH
! UNITS: BDES[KG-M]/MICROMETER
! IN ELECTRON COORDINATE SYSTEM
!
SET/LABEL=YIP36
SET/SENS=64
SET/NOWARN
DEF/DEV=(YCOR,FF11,5180,BDES)/COEF= -52.039E-6   ! A6Y NORTH
DEF/DEV=(YCOR,FB69, 530,BDES)/COEF= 532.812E-6   ! A3Y NORTH
DEF/DEV=(YCOR,FB69, 570,BDES)/COEF= 532.812E-6   ! A3Y SOUTH
DEF/DEV=(YCOR,FF01,5180,BDES)/COEF= -52.039E-6   ! A6Y SOUTH
```

- Linear combination of device excitations as a function of a physics parameter
- Examples:
  - two steerer power supply that change position without changing the angle at IP.
  - two quadrupoles to change the z-position of one waist at the IP without changing the other.
  - two quadrupole power supplies that change the horizontal and vertical tunes independently.
- Orthogonal control of physics parameters

# Correcting the Orbit in Ring

$$\begin{pmatrix} x_1 - \hat{x}_1 \\ x_2 - \hat{x}_2 \\ \vdots \\ x_N - \hat{x}_N \end{pmatrix} = \begin{pmatrix} C_{12}^{11} & C_{12}^{12} & \dots & C_{12}^{1M} \\ C_{12}^{21} & C_{12}^{22} & \dots & C_{12}^{2M} \\ \vdots & \vdots & \ddots & \vdots \\ C_{12}^{N1} & C_{12}^{N2} & \dots & C_{12}^{NM} \end{pmatrix} \begin{pmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_M \end{pmatrix}$$

- $x_i$ are the measured positions
- x^ is the desired orbit
- Its back to linear algebra again
- Bad placement, $M<N$, $N<M \rightarrow$ least squares, SVD, Micado

# Inversion Algorithms

- N=M and response matrix well-behaved

$$\vec{\theta} = -A^{-1}(\vec{x} - \vec{\bar{x}})$$

- M<N: too few correctors, least squares

$$\vec{\theta} = (A^T A)^{-1} A^T \Delta\vec{x}$$

- M>N or degenerate , SVD
- Micado: pick the most effective, fix orbit, the next effective,... (Householder transformations)
  - good for large rings with many BPM and COR

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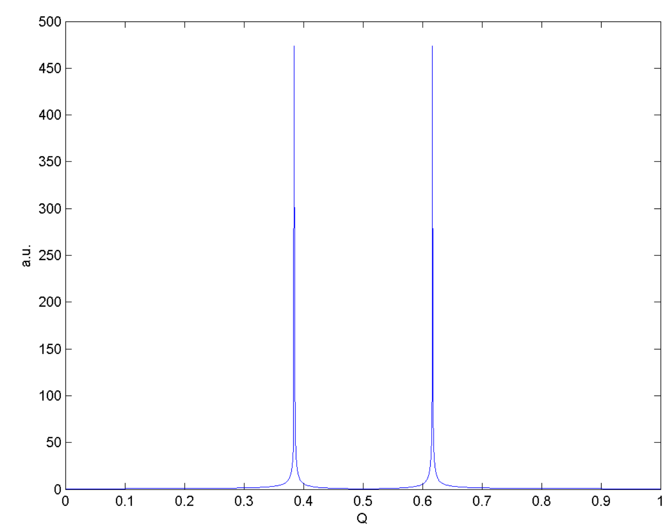
# Tune Errors

- Solenoidal fields
- Unknown quadrupole geometry (eff. length)
- Power supply calibration errors
- Off-center orbit in Sextupoles
- Measure tune by exciting transverse oscillations and looking at FFT of positions
- Is it Q or 1-Q?
- Fix by tweaking quads.



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# Tune correction

- Consider effect of single quadrupole on the tune

$$
\begin{aligned}
R &= \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \begin{pmatrix} \cos(2\pi Q) & \beta \sin(2\pi Q) \\ -\sin(2\pi Q)/\beta & \cos(2\pi Q) \end{pmatrix} \\
&= \begin{pmatrix} \cos(2\pi Q) & \beta \sin(2\pi Q) \\ -\sin(2\pi Q)/\beta - \sin(2\pi Q)/f & \cos(2\pi Q) - \beta \sin(2\pi Q)/f \end{pmatrix}
\end{aligned}
$$

- $Tr(R) = 2\cos(2\pi(Q+\Delta Q))$
- $\Delta Q \approx \beta/4\pi f$ (~ beta and quad strength 1/f)
- Use 2 quadrupoles with different $\beta_x$ and $\beta_y$ to correct both horizontal and vertical tune

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# Summary

- Discussed several devices that determine
  - position,
  - size
  - tune
- Methods to correct errors of
  - position, or the orbit
  - tune
- These are the two correction procedures that are most commonly done in a storage ring