Nonlinear Optics as a Path to High-Intensity Circular Machines

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Argonne/Fermilab Collaboration in AARD at NML Meeting

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COLLIDING BEAMS: PRESENT STATUS; AND THE SLAC PROJECT*

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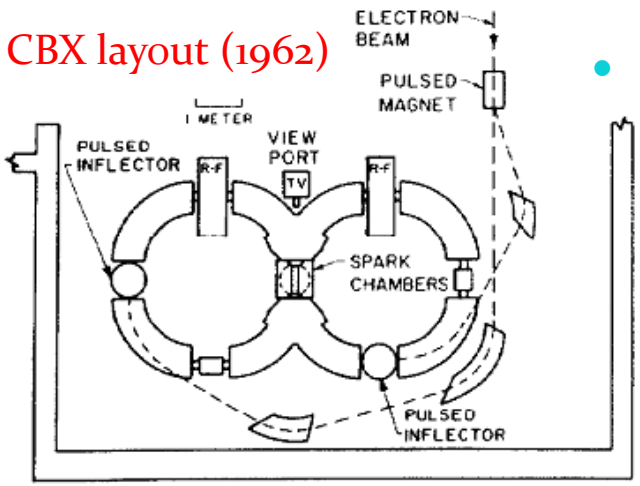
Report at HEAC 1971

The discovery in the early '60's at the Princeton-Stanford ring of what was thought to be the resistive wall instability brought the realization that circular accelerators are fundamentally unstable devices because of the interaction of the beam with its environment. Stability is achieved only through Landau damping and/or some external damping system.

CBX layout (1962)



- 1965, Priceton-Stanford CBX: First mention of an 8-pole magnet
  - Observed vertical resistive wall instability
  - With octupoles, increased beam current from ~5 to 500 mA
- CERN PS: In 1959 had 10 octupoles; not used until 1968
  - At 10^{12} protons/pulse observed (1st time) head-tail instability. Octupoles helped.
  - Once understood, chromaticity jump at transition was developed using sextupoles.
  - More instabilities were discovered; helped by octupoles and by feedback.

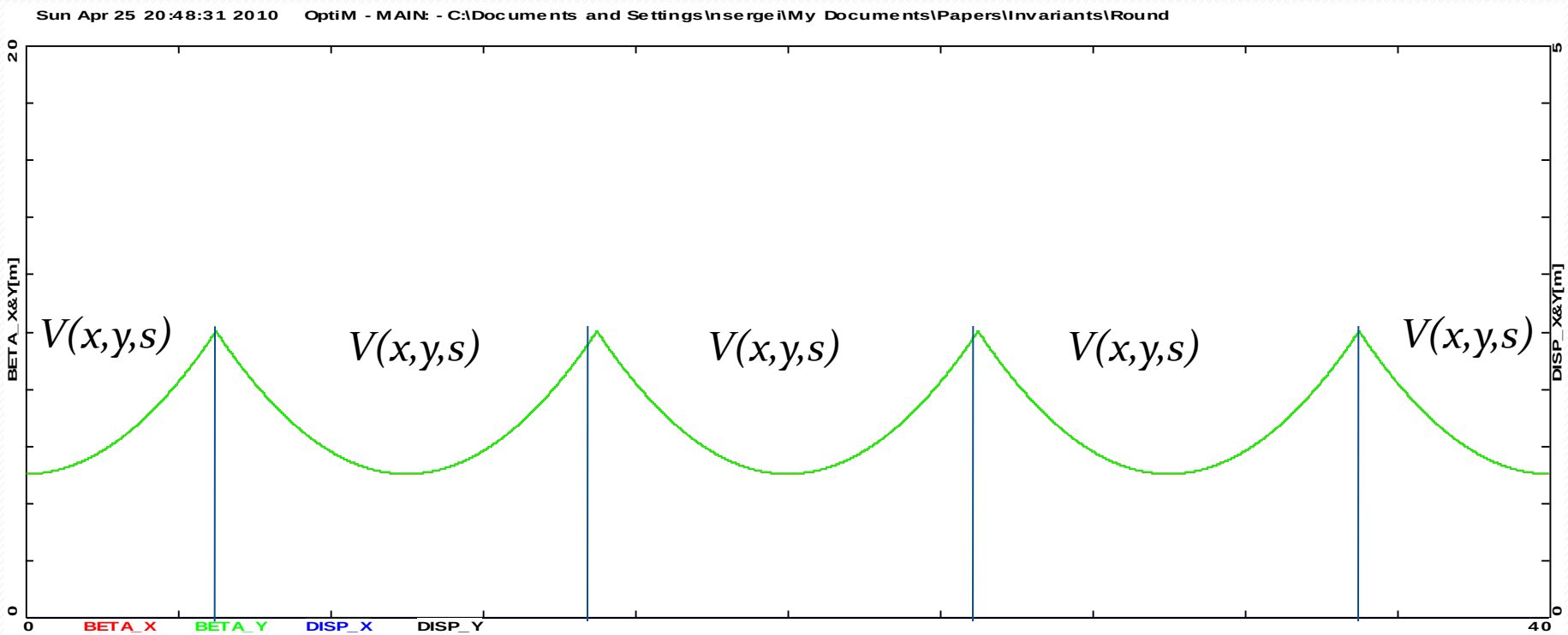
Nonlinear Integrable Optics

- … How to improve beam's immune system (Landau damping through betatron frequency spread)
  - Tune spread not ~0.001 but 10-50%
- The main feature of all present accelerators – particles have nearly identical betatron frequencies (tunes) by design. This results in two problems:
  I. Single particle motion can be unstable due to resonant perturbations (magnet imperfections and non-linear elements);
  II. Landau damping of instabilities is suppressed because the frequency spread is small.

Our approach

- See: Phys. Rev. ST Accel. Beams 13, 084002
- Start with a round axially-symmetric LINEAR focusing lattice (FOFO)
  - Add special non-linear potential *V(x,y,s)* such that

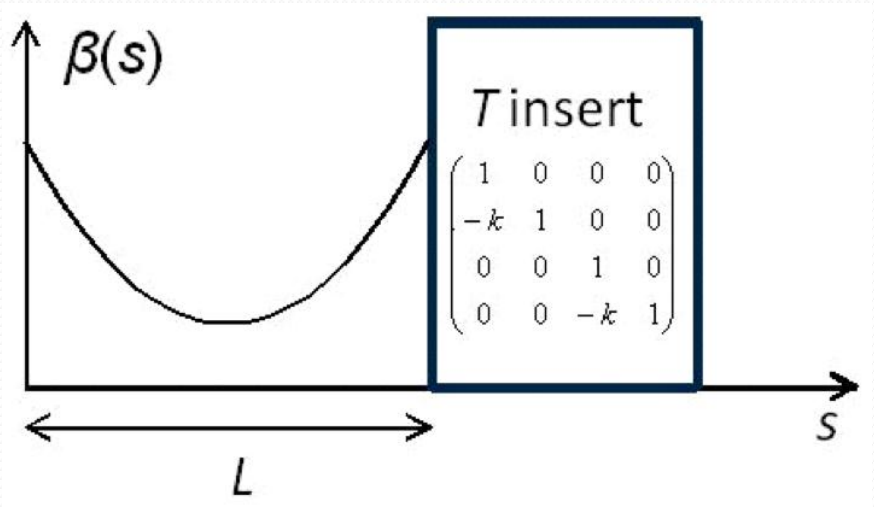
$$\Delta V(x,y,s) \approx \Delta V(x,y) = 0$$



How to realize it?

- Need to create an element of periodicity.
  - The T-insert can also be

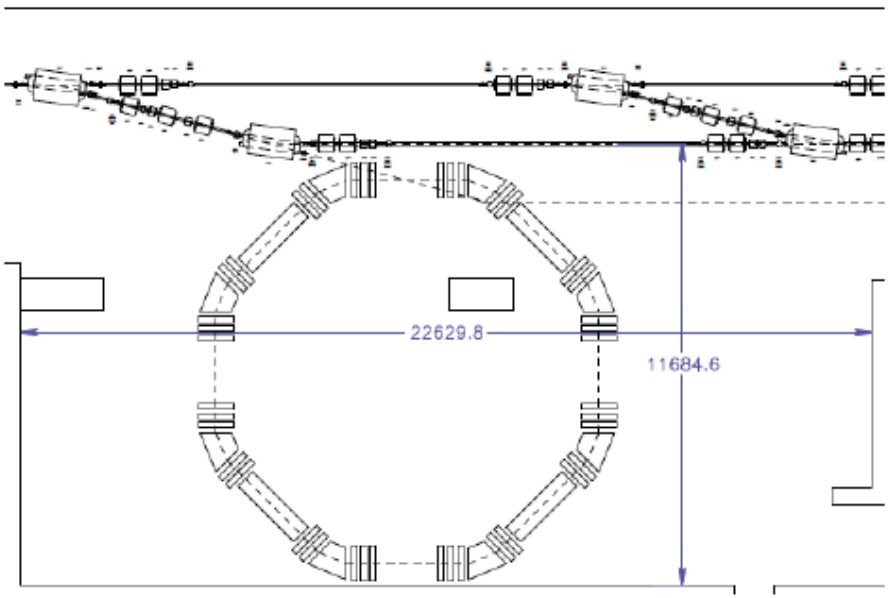
$$\begin{pmatrix} -1 & 0 & 0 & 0 \\ k & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & k & -1 \end{pmatrix}$$



which results in a phase advance 0.5 (180 degrees) for the T-insert.

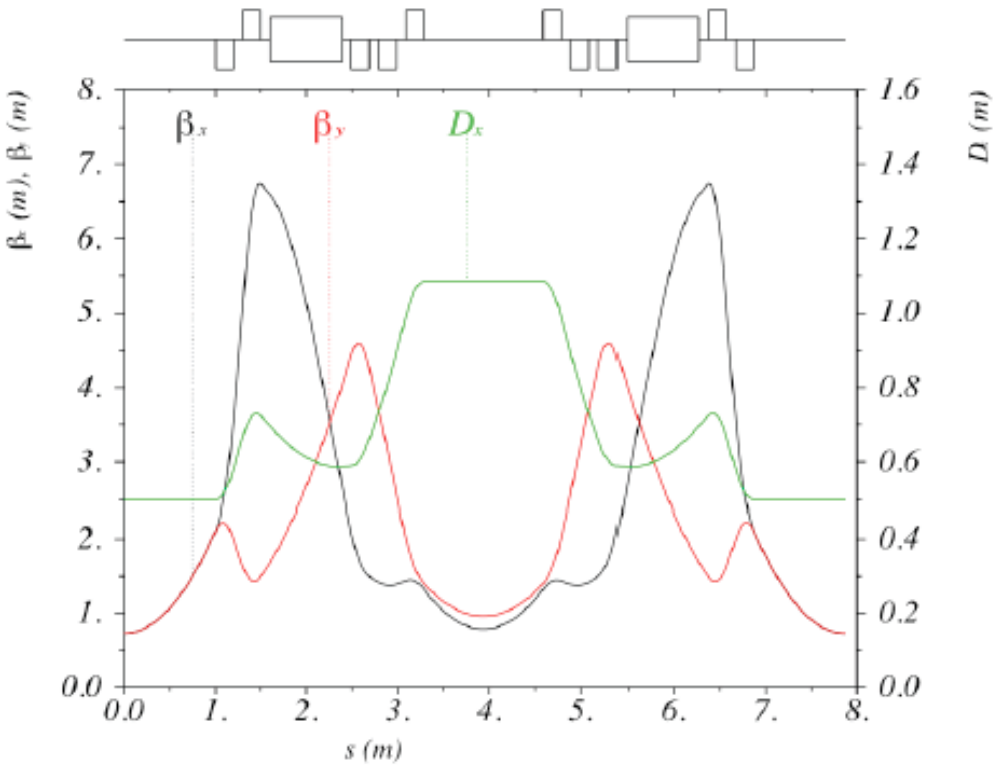
  - The drift space L can give the phase advance of at most 0.5 (180 degrees).

Proof-of-principle experiment at NML



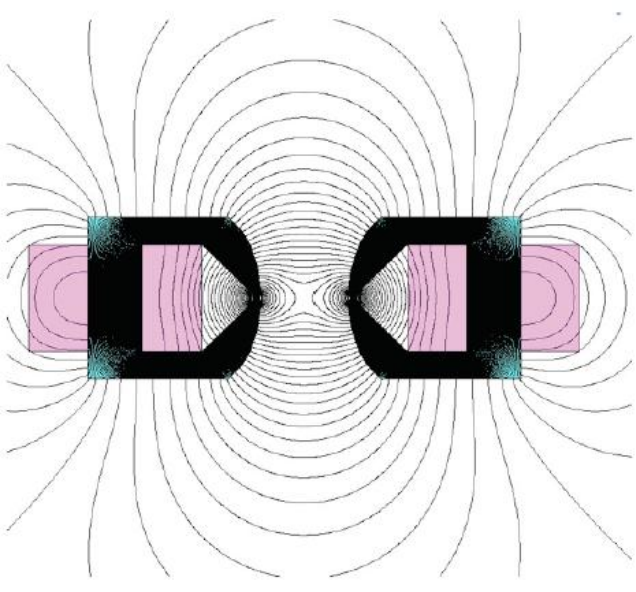
- Small electron ring
  - Inexpensive
  - Easy to operate
- What do we want to demonstrate
  - Large tune spread without degradation of dynamical aperture
  - Suppression of lattice resonances, including integer
  - Suppression of collective instabilities, e.g. TMCI ???

Ring Parameters



e- Energy	**150-300 MeV**
Circumference	32 m
Dipole field	0.5-1 T
RF Voltage	50 kV
Maximum β-function	7 m
Momentum compaction	0.124
Betatron tunes	Qx=Qy=3.2 (2.4 to 3.6)
Radiation damping time	1-2 s (10^7 turns)
Equilibrium emittance, rms, non-norm	0.06 μm

Nonlinear Magnet Parameters



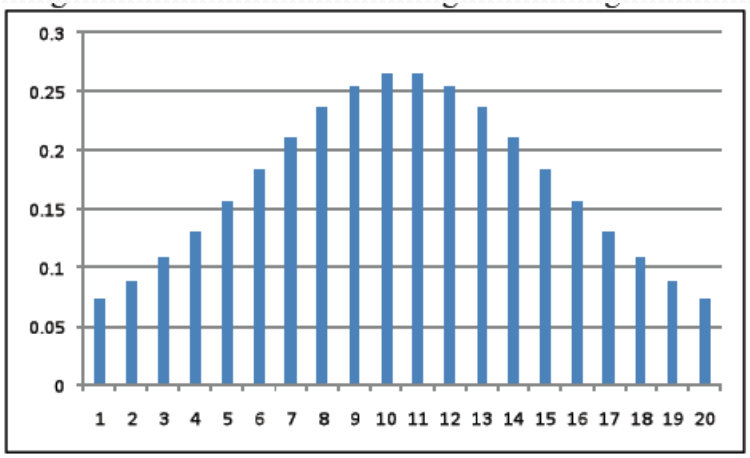
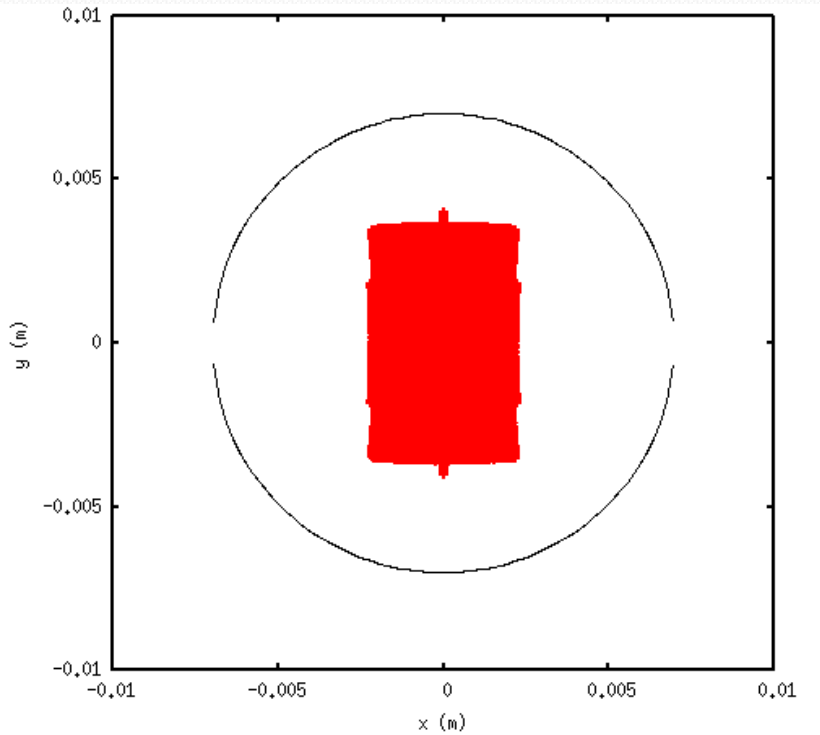


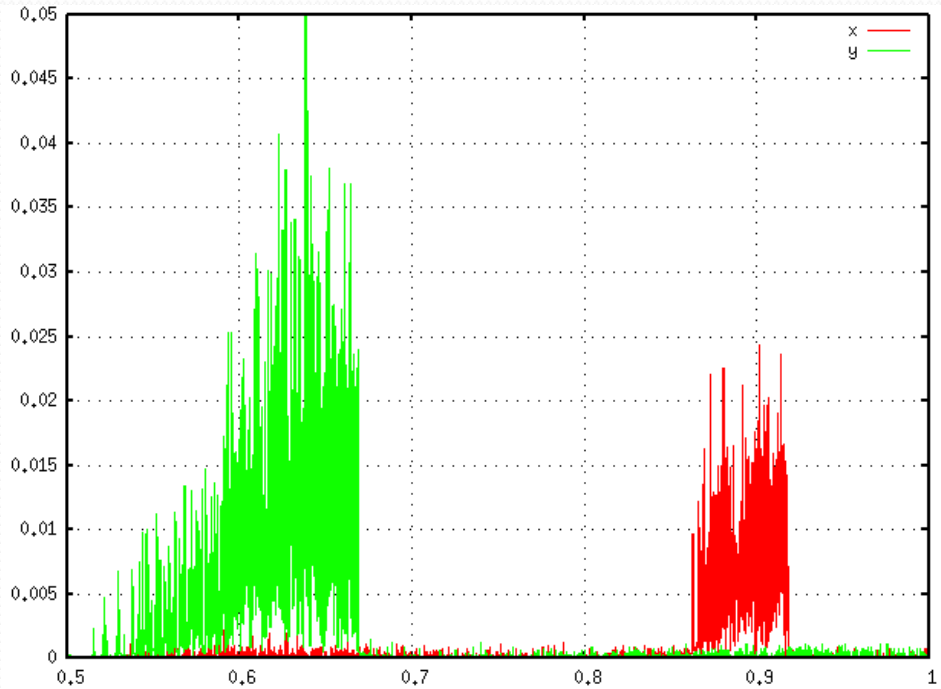
Figure 3: Distribution of quadrupole component (T/m) in the nonlinear magnet section.

Nonlinear lens block	
Length	1.8 m
Number of elements	20
Element length	0.07 m
Max. gradient	1 T/m
Pole-to-pole distance (min)	~ 2 cm

How much tune spread?

Conservative variant: round pipe, Nonlinear lens realized with multipole expansion n=9





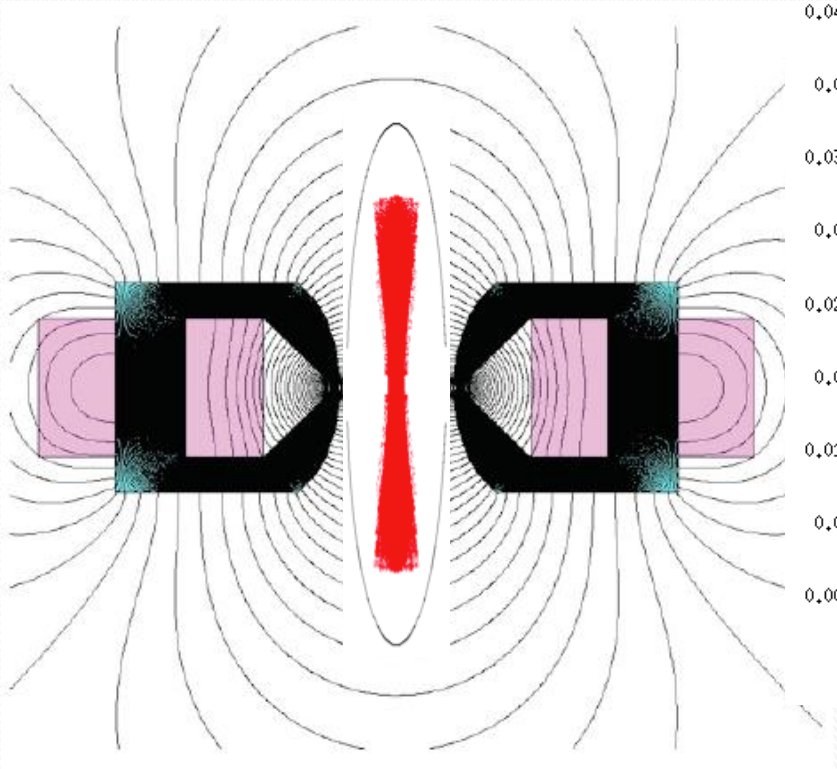
c=10 mm
pipe radius = 7 mm
beam within r=5 mm

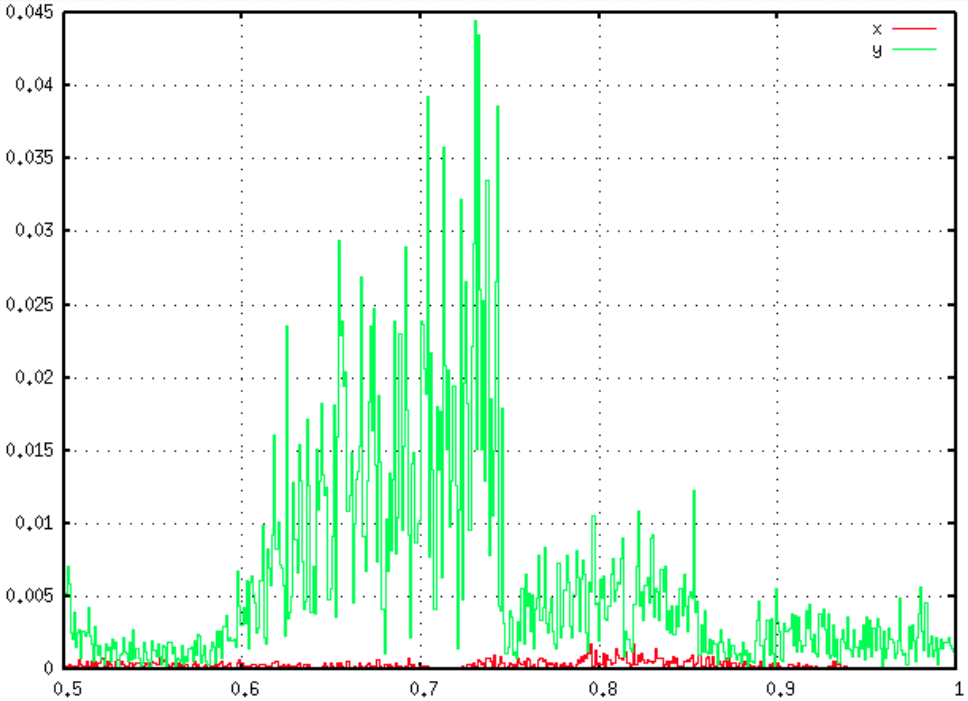
Dipole moment spectrum
tracking one cell Q_o=0.8 δQ_{max}=0.3
δQy=0.15, δQx=0.06
with 4 cells -> δQy=0.45, δQx=0.24

δQ_{max} is determined by phase advance in drift. Maximum is 0.5

How much tune spread?

Full blast: 'true' lens, t=1.5



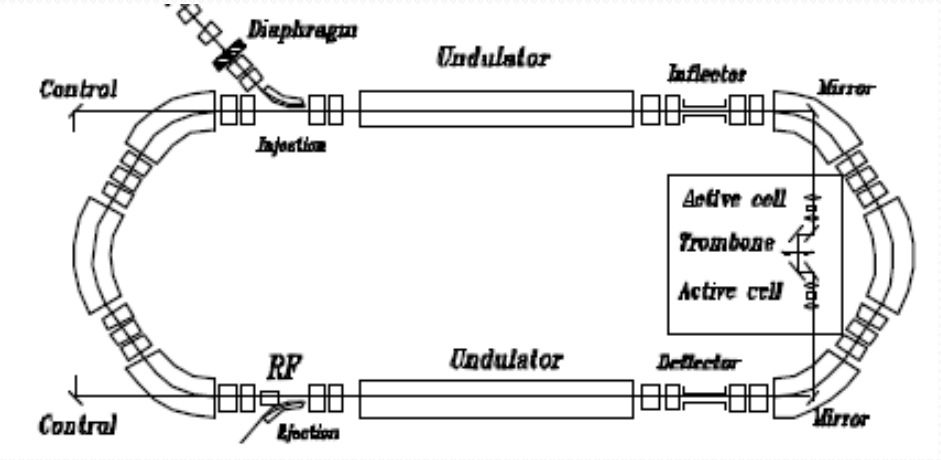


c=10 mm
pipe size x=5 y=35 mm
beam within x=2.5 mm

Dipole moment spectrum
tracking one cell Q_o=0.8 δQ_{max}=0.5
δQy=0.5, δQx=0.2
with 4 cells -> δQy=2, δQx=0.8

Other AAR&D at the Ring

- Optical stochastic cooling
  - A.Mikhailichenko, M.Zolotorev, Phys. Rev. Lett. 71, 4146 (1993)
  - A.Mikhailichenko, EPAC94



- More???