Study of Beam-Beam interaction at VEPP-4: Tune Plane Appearance and Cubic Non-linearity Effect

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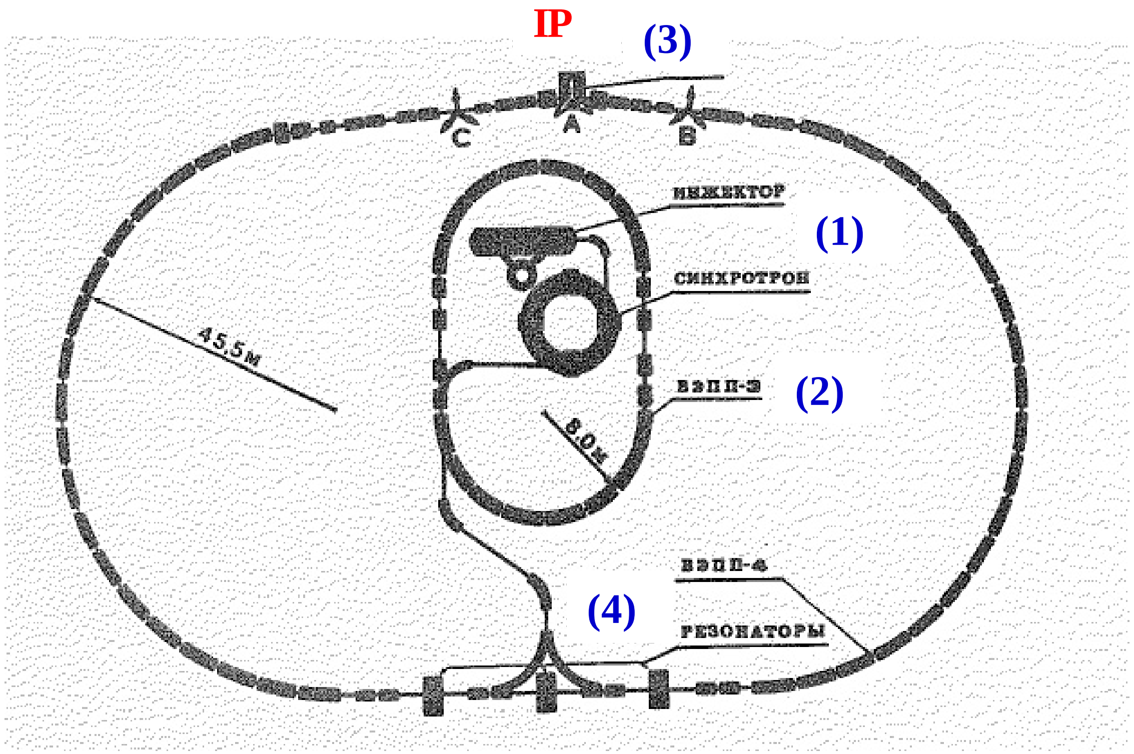
VEPP-4 collider layout

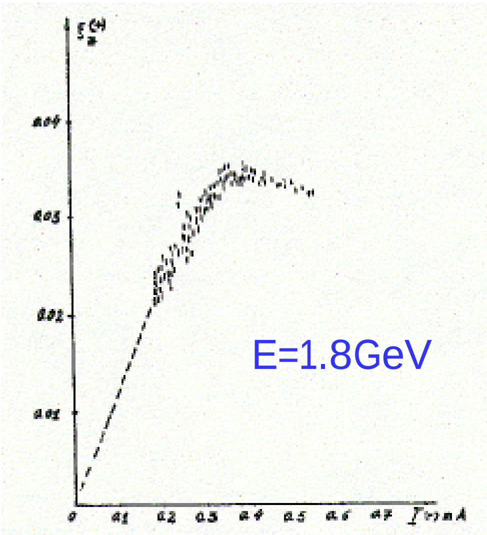


1. Injector and synchrotron
2. Booster (VEPP-3 storage ring)
3. Detector MD-1 (with vertical magnetic field)
4. RF cavities
5. VEPP-4 storage ring, ~400m circumference

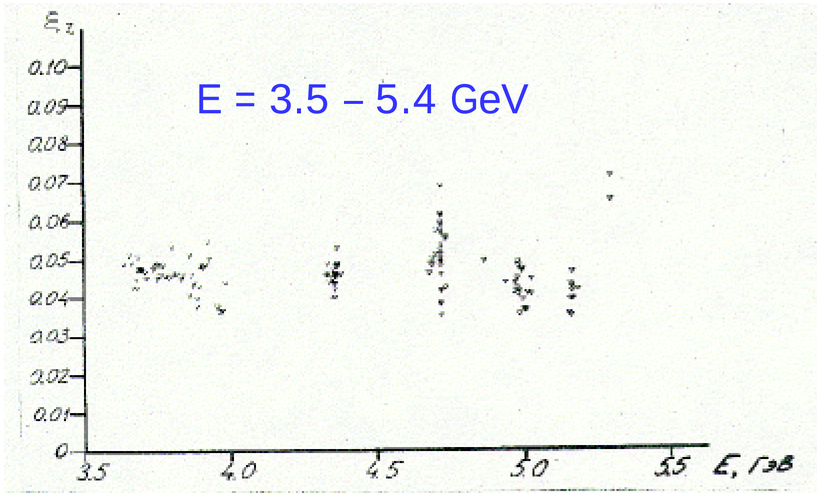
General information

1. Time of operation: 1978 – 1985
2. Operation energy: from 1.8GeV (J/Psi) to 5.5GeV (Y”)
3. Most significant experiments: J/Psi and Y mesons mass calibration.
4. 1x1 bunch operation
5. Achieved luminosity: ~1.3e28 1/cm^2/sec at 1.8GeV and ~6.0e30 1/cm^2/sec at 5.5GeV.

Vertical beam-beam tune shift from luminosity:



Beam-beam tune shift vs bunch current at 1.8GeV, ?v max ~ 0.037



Beam-beam tune shift vs beam energy, ?v ~ 0.045 – 0.07

Tune scan experiment: measurement setup

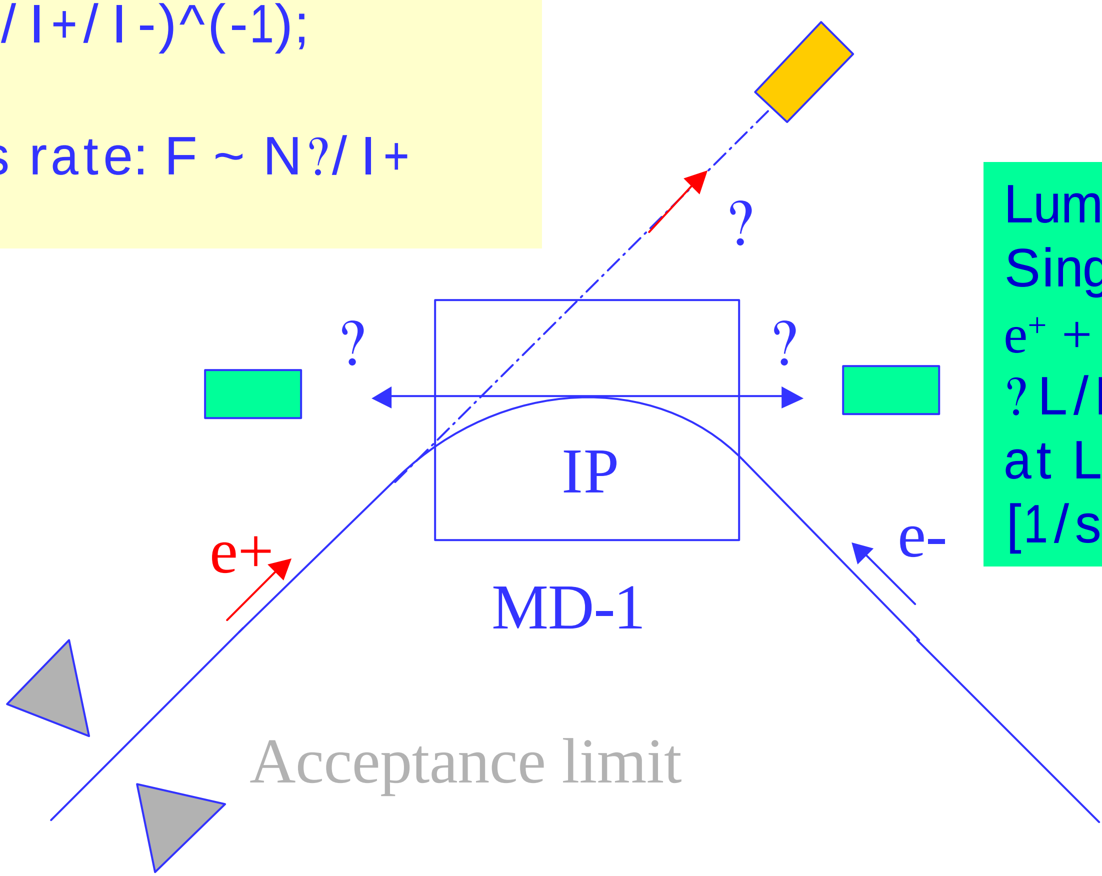
Measured parameters:

1. Vertical beam size from luminosity:

  ?y ~ (L/I+/I-)^(-1);

2. e+ loss rate: F ~ N?/I+

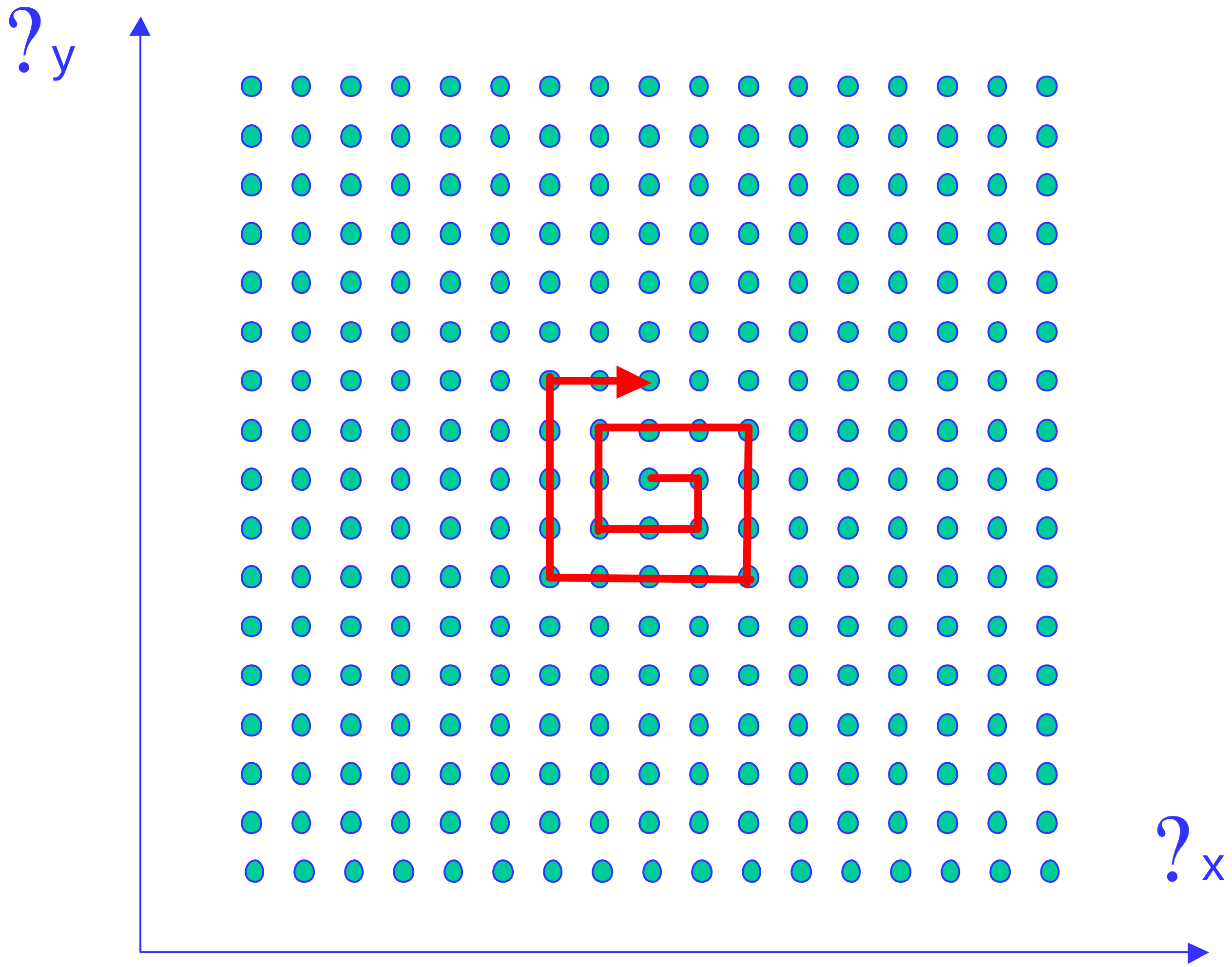
Radiation monitor, N?



Luminosity monitors:
Single beamstrahlung
$e^+ + e^- \Rightarrow e^+ + e^- + ?$
?L/L ~ 0.5% at 100ms at L=1e30 [1/sec/cm^2]

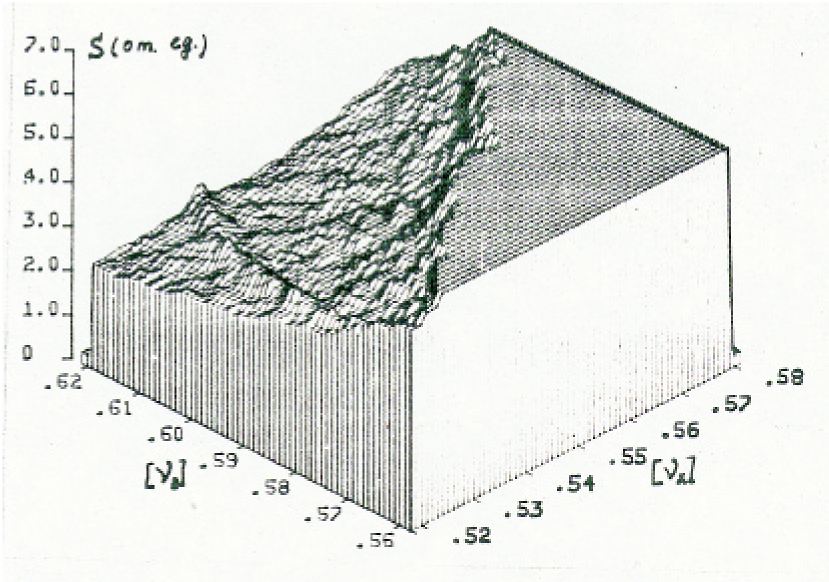
Tune scan experiment: working point trajectory

64x64 grid, ~100ms in each point, ~15min total time

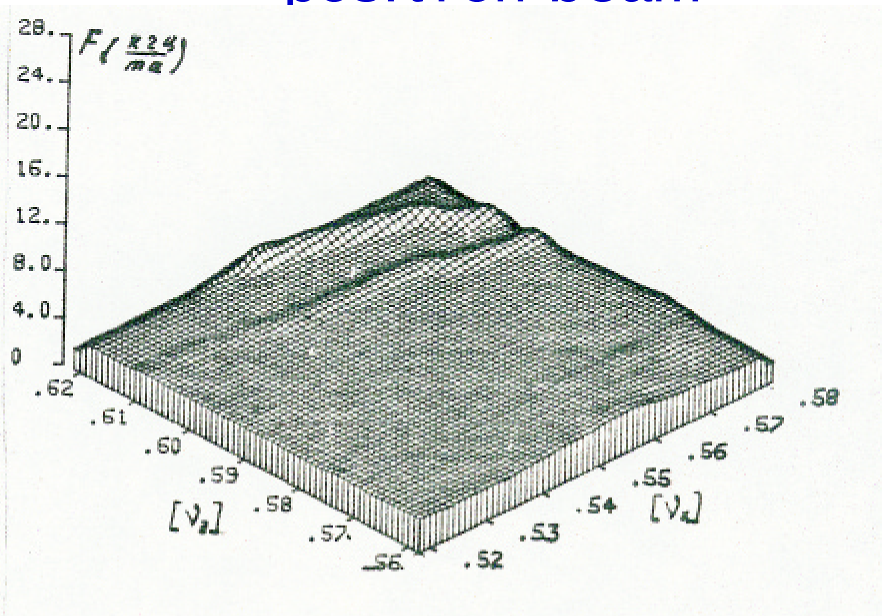


Tune plane appearance: machine resonances

Vertical beam size from luminosity (r.u.)



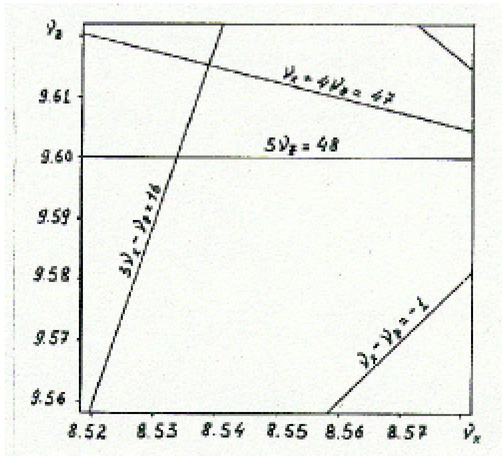
Particle loss rate from positron beam



I+ ~ 0.72mA, I- ~ 1.3mA

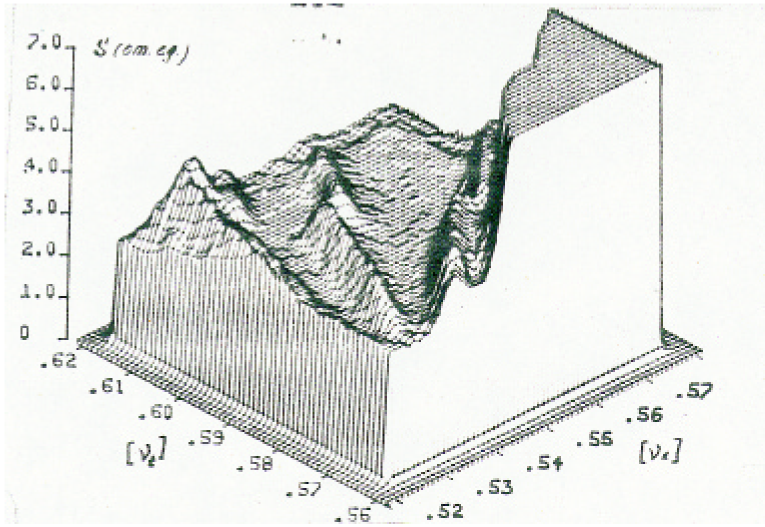
?x = 0.002, ?y = 0.007

Tune plane with up to 5-th order resonances



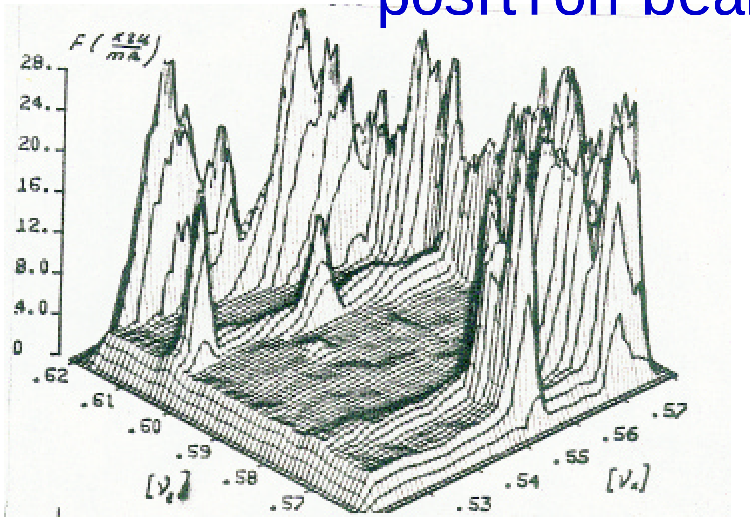
Tune plane appearance: beam-beam interaction

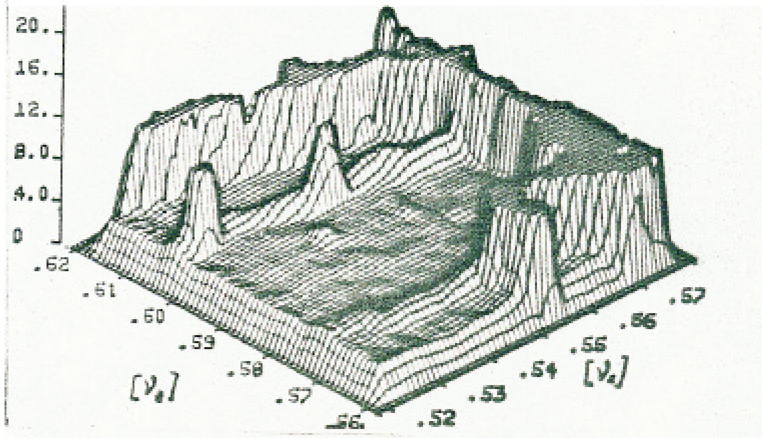
Vertical beam size from luminosity (r.u.)



I+ ~ 1.2mA, I- ~ 5.8mA
?x = 0.009, ?y = 0.035

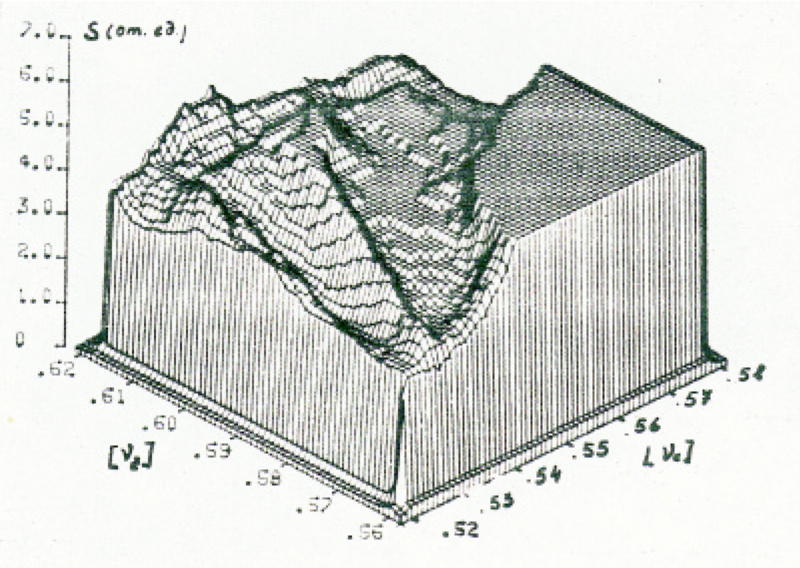
Particle loss rate from positron beam



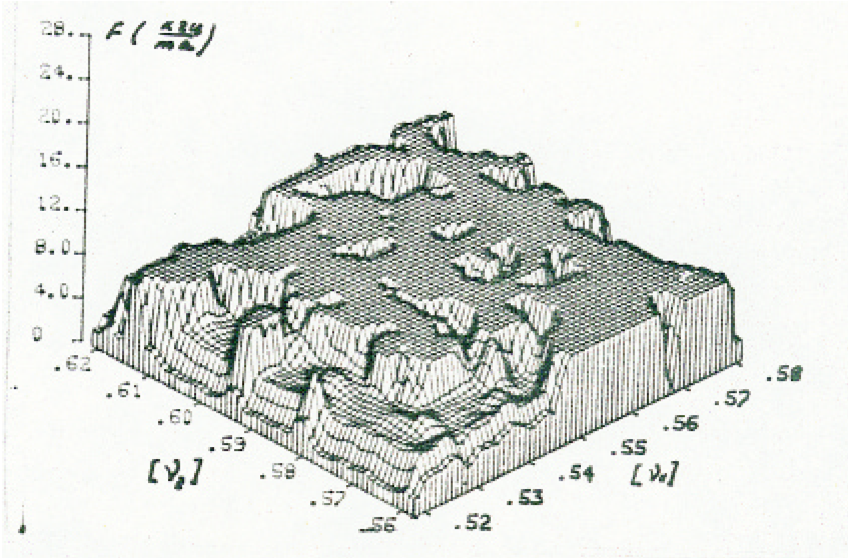


Tune plane appearance: beam-beam interaction

Vertical beam size from luminosity (r.u.)



Particle loss rate from positron beam



I+ ~ 6.2mA, I- ~ 10.2mA
?x = 0.015, ?y = 0.060

Summary

- 2-D tune scan technique has been used to explore tune plane.
- Variety of resonances excited by machine non-linearity and beam-beam interaction and affecting on vertical beam size and beam life time was observed and identified.
- Tune scan result at high ?x,y suggested optimal working point close to half-integer resonance.

Effect of machine cubic non-linearity on a beam-beam interaction (theory and experiments)

2D-Theory: model with one IP and one octupole lens

$$H ? H_0 ? V(x,y) ? (s ? s_1) ? W(x,y) ? (s ? s_2)$$

Beam-beam interaction

$$V(x,y) ? \frac{r_e N}{?} \int_0^{?} dt \frac{1 ? \exp\left(? \frac{x^2}{2(?_x^2 ? t)} ? \frac{y^2}{2(?_y^2 ? t)} \right)}{(?_x^2 ? t)^{1/2} (?_y^2 ? t)^{1/2}}$$

Octupole magnet

$$W(x,y) ? \frac{2}{3} B \left(x^4 ? y^4 ? 6x^2 y^2 \right)$$

Cubic non-linearity effect: theory

After transformation to “action-angle” variables:

$$x, y \; ? \; \sqrt{2 ?_{x,y} J_{x,y}} \cos ? ?_{x,y} ?;$$

$$p_{x,y} \; ? \; ? \sqrt{\frac{2J_{x,y}}{?_{x,y}}} ? \sin ? ?_{x,y} ? ? \frac{?'_{x,y}}{2} \cos ? ?_{x,y} ? ?$$

And Fourier expansion one can write:

$$H \; ? \; J_x ?_x \; ? \; J_y ?_y \; ? \; V_0(J_x, J_y) \; ? \; W_0(J_x, J_y) \; ?$$

$$? \overset{?}{\underset{m,n,k???}{?}} V_{2m,2n}(J_x, J_y) \cos ? 2m?_x \; ? \; 2n?_y \; ? \; k? ? ?$$

$$? \overset{?}{\underset{m,n,k???}{?}} W_{m,n}(J_x, J_y) \cos ? m?_x \; ? \; n?_y \; ? \; k? ?$$

Cubic non-linearity effect: theory

$$V_0(J_x,J_y) = \frac{r_e N}{2\pi\gamma}\int_0^{\infty} dt \frac{1-\exp\left(-\kappa_x-\kappa_y\right) I_0(\kappa_x) I_0(\kappa_y)}{(\sigma_x^2+t)^{1/2}(\sigma_y^2+t)^{1/2}};$$

$$\kappa_{x,y} = \frac{J_{x,y}\beta^*_{x,y}}{2(\sigma_x^2+t)}$$

$$W_0(J_x,J_y) = B\left(J_x^2\tilde{\beta}_x^2 + J_y^2\tilde{\beta}_y^2 - 4J_xJ_y\tilde{\beta}_x\tilde{\beta}_y\right)$$

$\beta^*_{x,y}$ - beta function at IP, $\tilde{\beta}_{x,y}$ - beta functuion at octupole location.

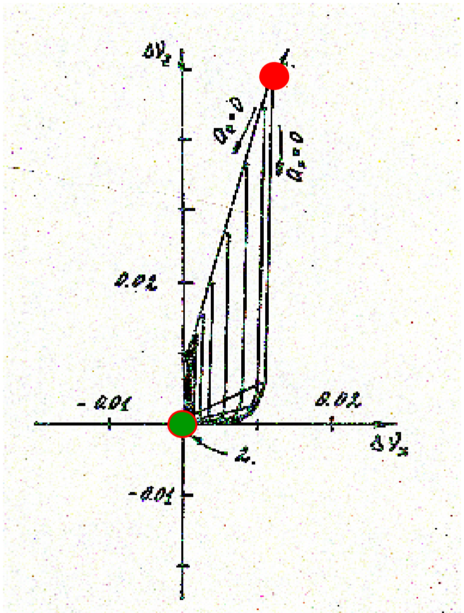
Tune shift as a function of amplitude:

$$\Delta\nu_{x,y}(J_x,J_y) = \frac{\partial V_0(J_x,J_y)}{\partial J_{x,y}} + \frac{\partial W_0(J_x,J_y)}{\partial J_{x,y}};$$

Cubic non-linearity effect: theory

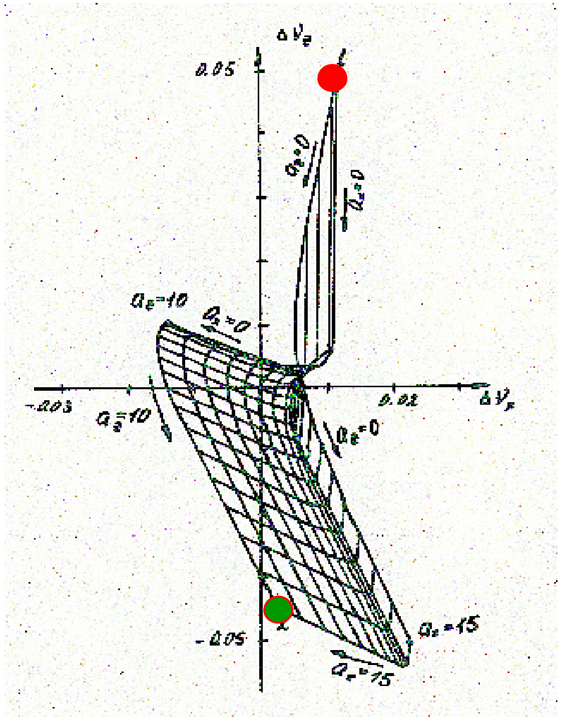
"Foot print" for ?x ??????????y ??????????x/ ?y ????

- ?? beam center, $a_{x,y} = 0$
- ?? beam tail, $a_x = 0.015$m, $a_y = 0.01$m at location with $?_{x,y} = 12$m



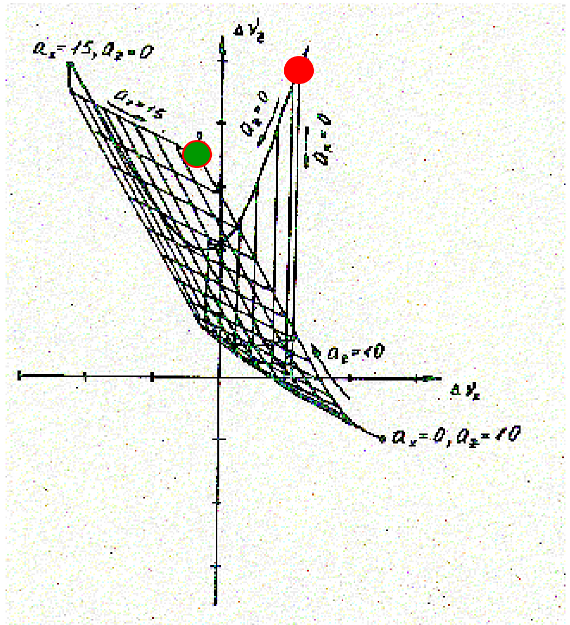
$2B?^2_{x,y}$? 0

Zero cubic non-linearity
Minimum tune spread
Simple topology



$2B?^2_{x,y}$? ?1200[1/ m]

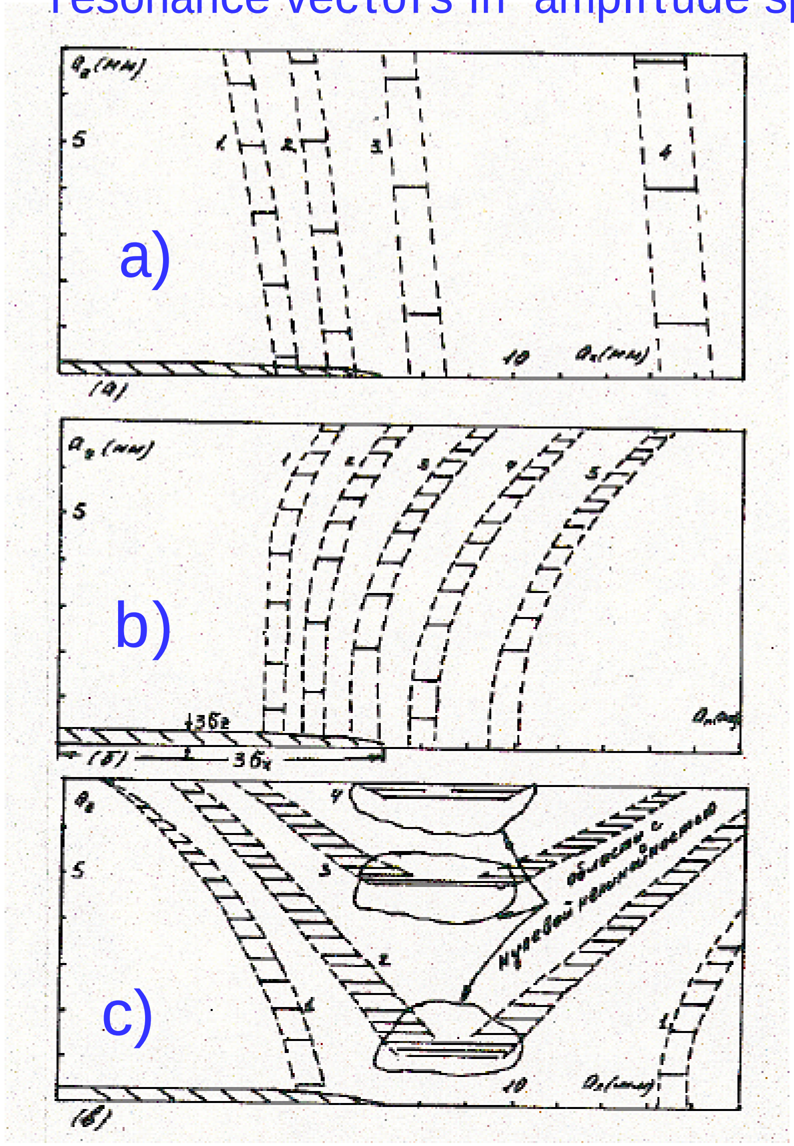
Negative cubic non-linearity
Large tune spread
Not a simple topology



$2B?^2_{x,y}$? 1200[1/ m]

Positive cubic non-linearity
Large spread
Folder type topology

Model calculation: 14?x = 28 resonance lines and resonance vectors in amplitude space for various machine cubic nonlinearity.



?x ????????y ?????

Resonance lines:

??? ?x = 8.568, (2) ?x = 8.569

??? ?x = 8.570, (4) ?x = 8.571

??? ?x = 8.572

a) $2B?^{2}_{x,y}$? 0[1/ m]

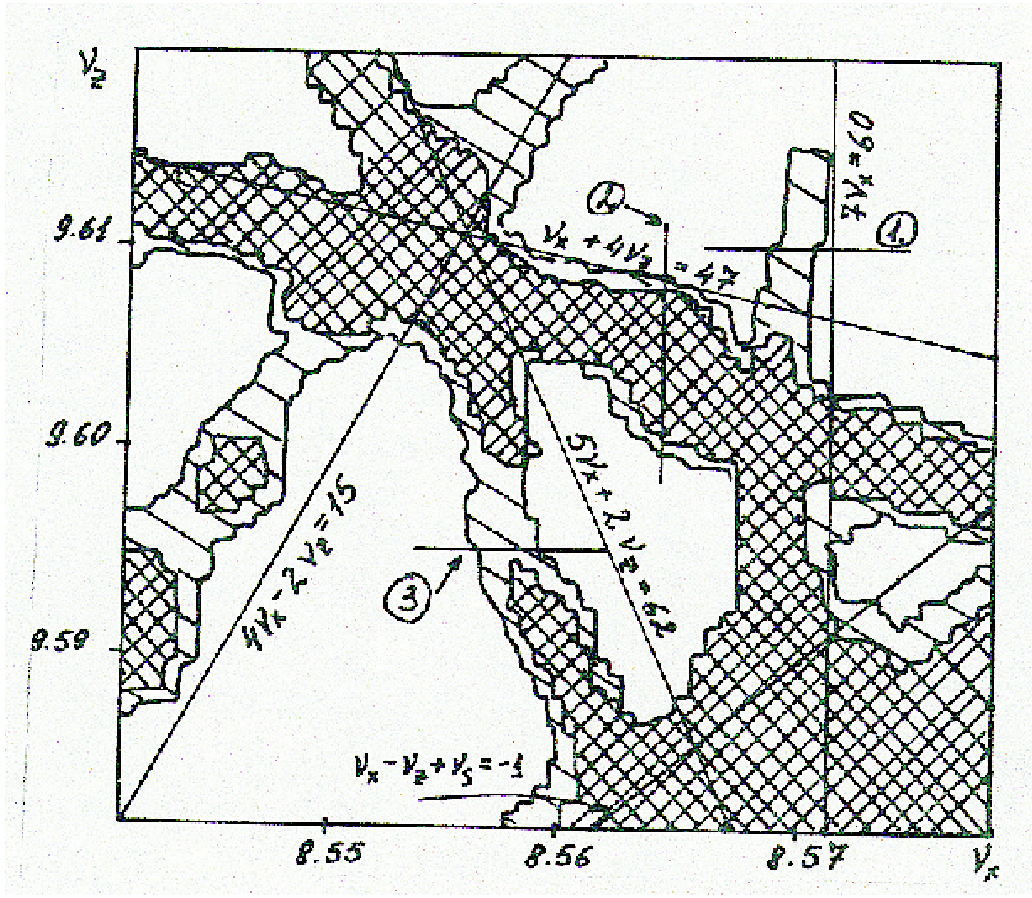
b) $2B?^{2}_{x,y}$? ?1200[1/ m]

c) $2B?^{2}_{x,y}$? 1200[1/ m]

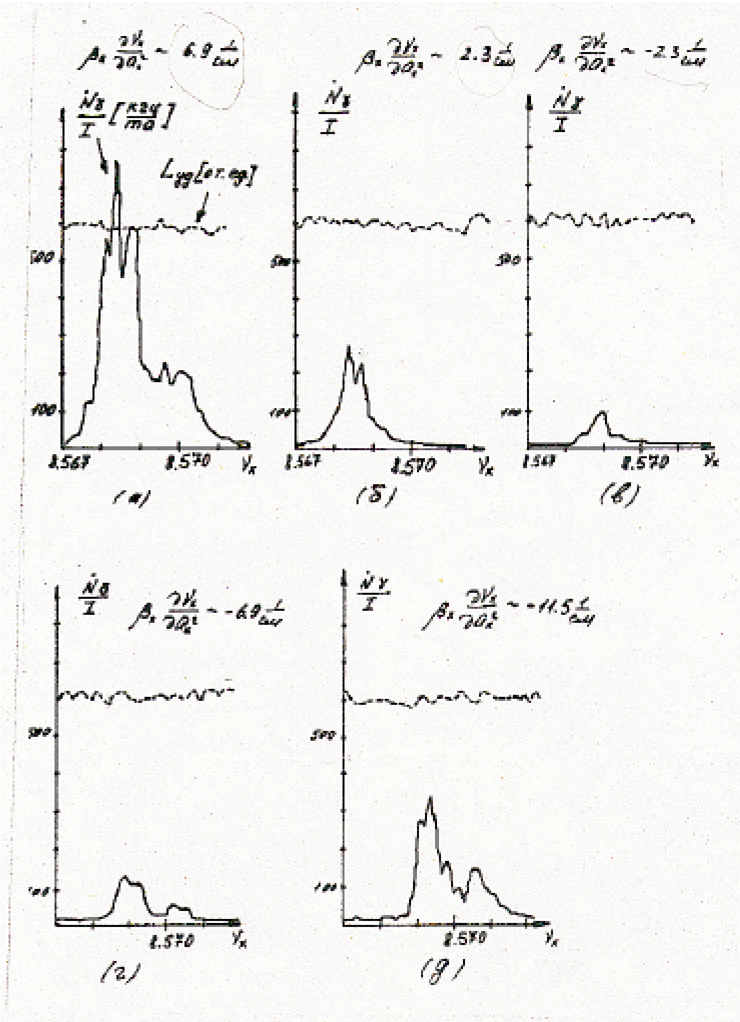
Cubic non-linearity effect: experimental study

2-D tune scan to identify resonances.

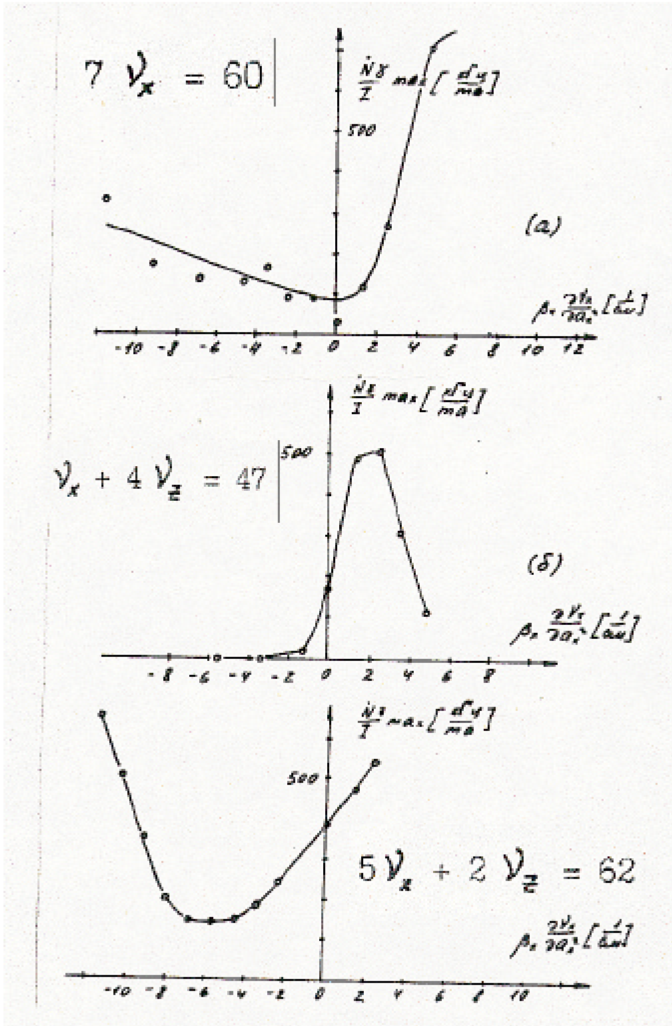
?x = 0.008, ?y = 0.030



E+ loss rate and specific luminosity (L/I+/I-) on resonance 7?x = 14, measured for various machine cubic non-linearity, ?x = 0.009, ?y = 0.035.



Maximum E+ loss rate on 7?x = 14, ?x + 4 ?y = 47 and 5?x + 2?y = 62 resonances as function of machine cubic non-linearity, ?x = 0.009, ?y = 0.035



Summary

- Machine cubic non-linearity may dramatically change beam-beam interaction dynamics

- Cubic non-linearity must be kept close to "zero"

- Negative non-linearity may be little bit less harmful than positive