Current Dependence of Bunch Dimensions in VEPP-2000 Collider

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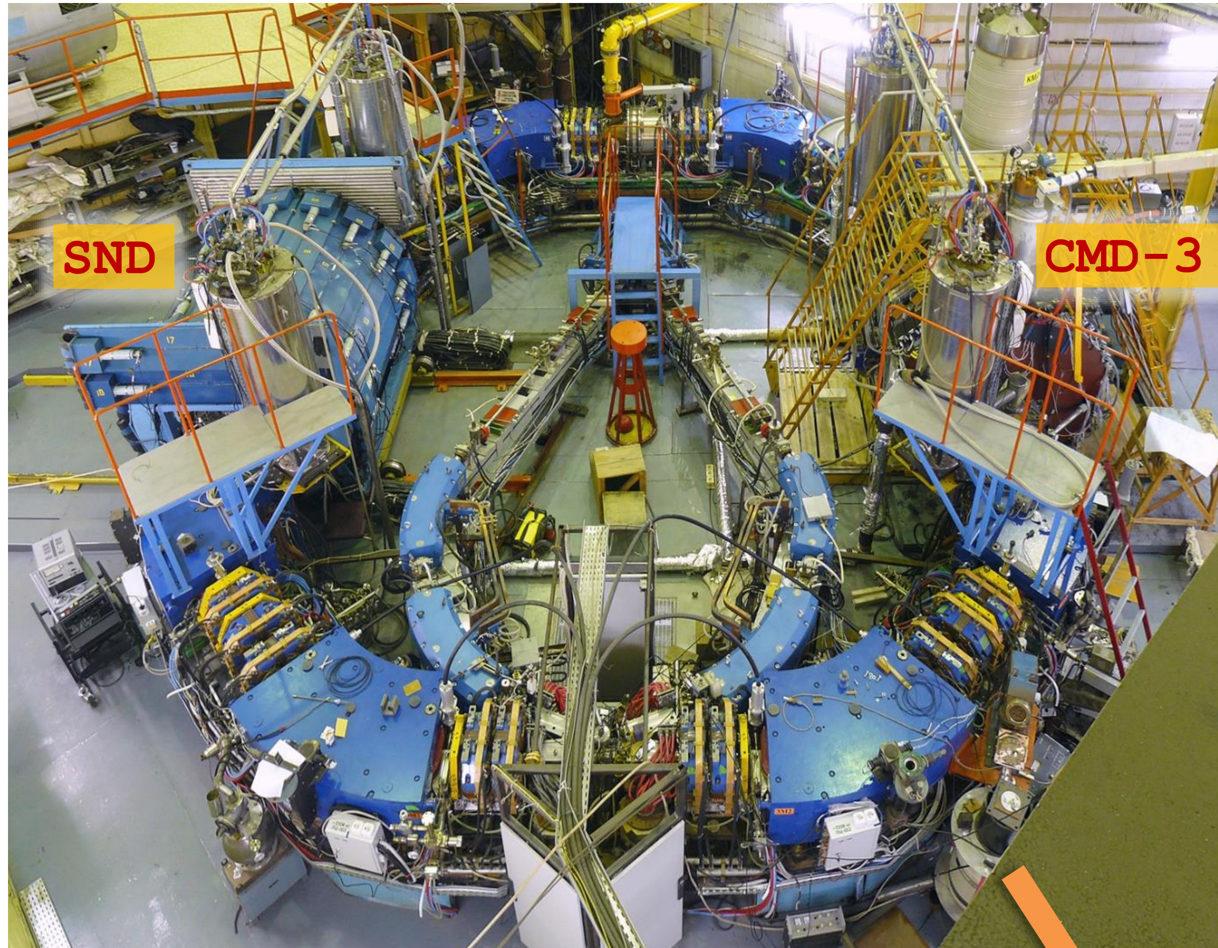
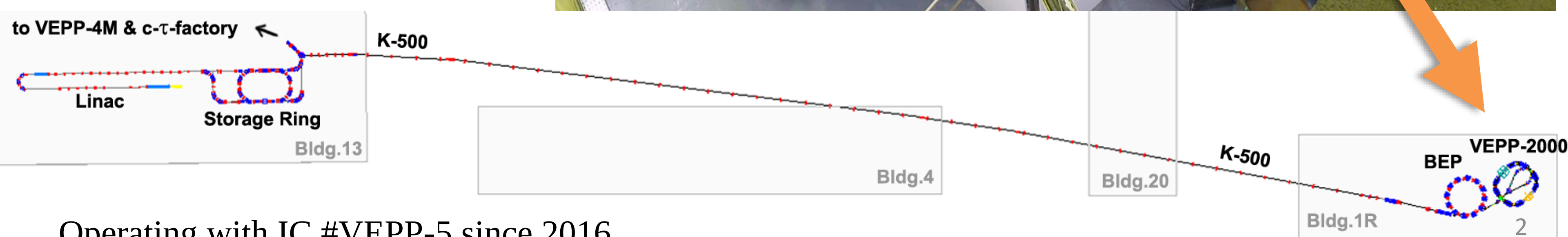
VEPP-2000 overview

Design parameters @ 1 GeV	
Circumference	24.388 m
Beam energy	150 ÷ 1000 MeV
N of bunches	1×1
N of particles	1×10^{11}
Betatron tunes	4.14 / 2.14
Beta*	8.5 cm
BB parameter	0.1
Luminosity	1×10^{32} $cm^{-2}s^{-1}$



- Round beams concept
- 13 T solenoids for FF
- 2.4 NC dipoles @ 1 GeV
- CBS for energy control



Operating with IC #VEPP-5 since 2016

The concept of Round Colliding Beams

Axial symmetry of counter beam force + X-Y symmetry of transfer matrix IP2IP

⇩

Additional integral of motion (angular momentum $M_z = x'y - xy'$)

Particle dynamics remains nonlinear, but becomes 1D

Lattice requirements:

- Head-on collisions!
- Small and equal β-functions at IP:
- Equal beam emittances:
- Equal fractional parts of betatron tunes:

$$\beta_x = \beta_y$$

$$\varepsilon_x = \varepsilon_y$$

$$\nu_x = \nu_y$$

Round beam

$M_x = M_y$

F.M. Izrailev, G.M. Tumaikin, I.B. Vasserman. Preprint INP 79-74, Novosibirsk,(1979).

L.M. Barkov, et. al, Proc. HEACC'89, Tsukuba, Japan, p.1385.

S. Krishnagopal, R. Siemann, Proc. PAC'89, Chicago, p.836.

V.V. Danilov et al., EPAC'96, Barcelona, p.1149.

S. Henderson, et al., Proc. PAC'99, New York, p.410.

VEPP-2000 Equipment

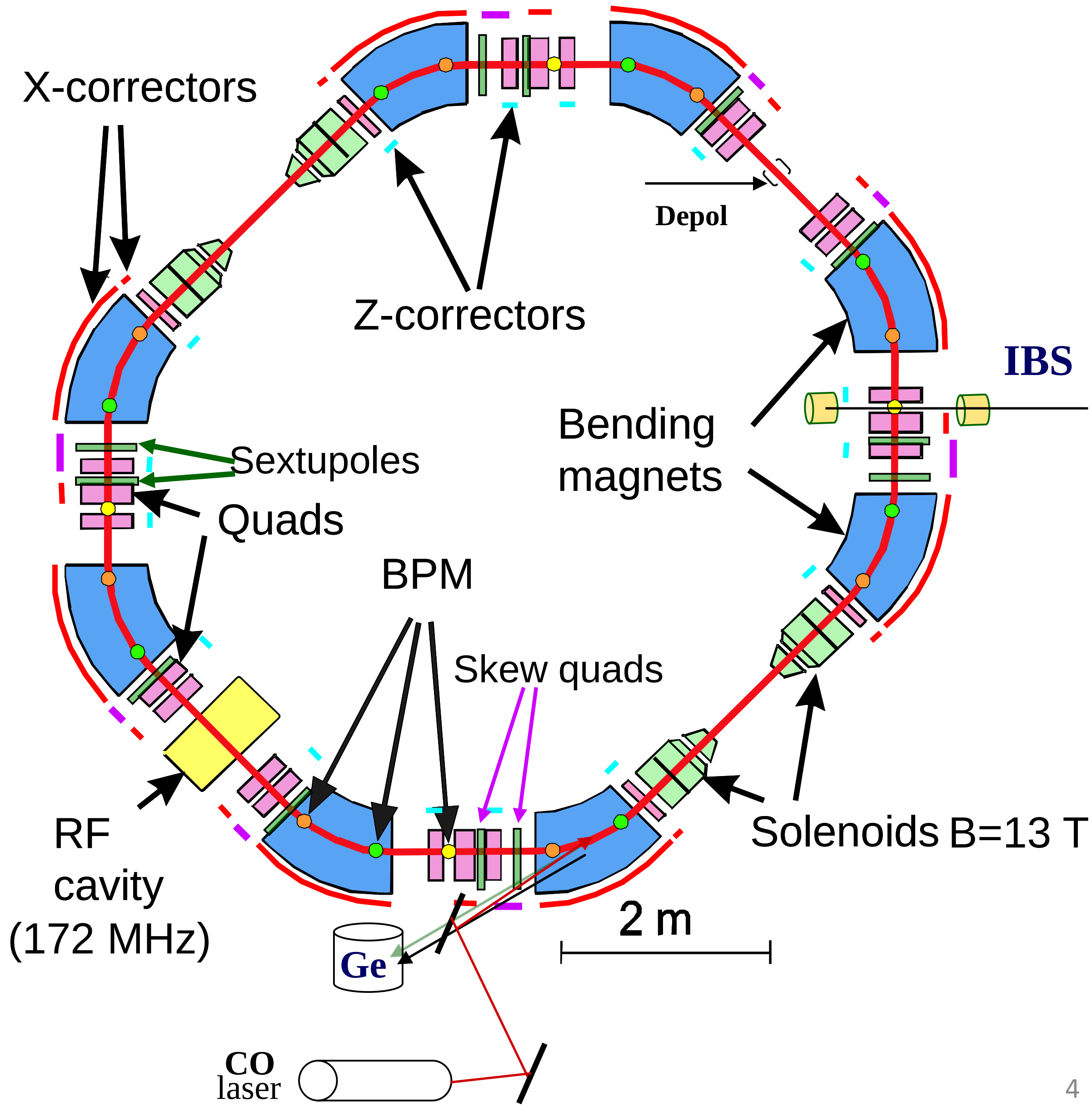
Main lattice:
8 dipole magnets
24 quadrupole magnets
4 sup. cond. solenoids

Correctors:
24 hor. dipole corr.
20 vert. dipole corr
12 sextupoles
12 skew-quad

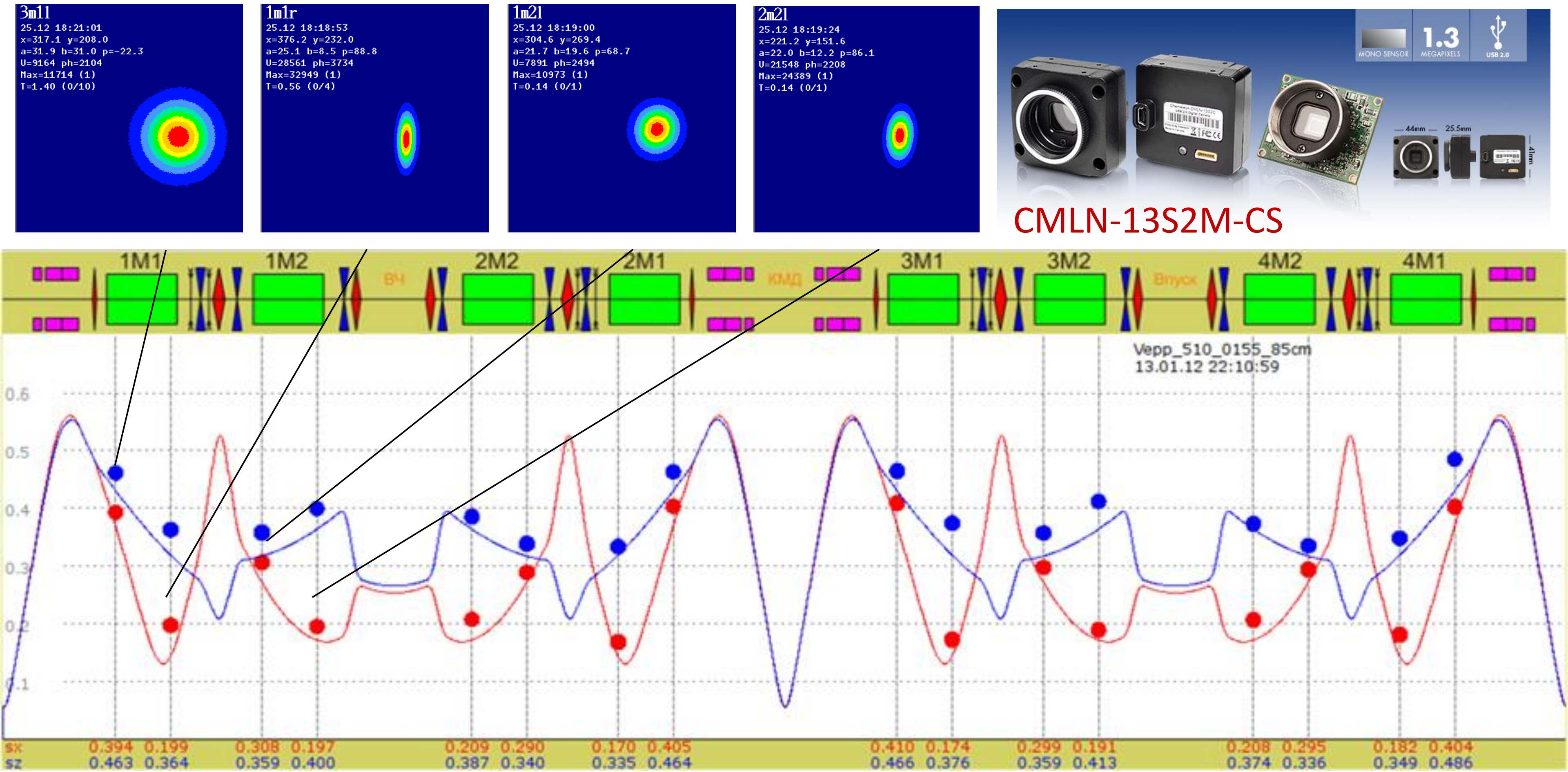
Observation:
16 CCD cameras
4 electrostatic BPMs
1 DCCT
2 PhMT (e^+, e^-)
2 Phi-Dissectors (e^+, e^-)

Energy meas:
Depolarization, 16 NMR,
Compton backscatter.

Detectors: CMD-3, SND

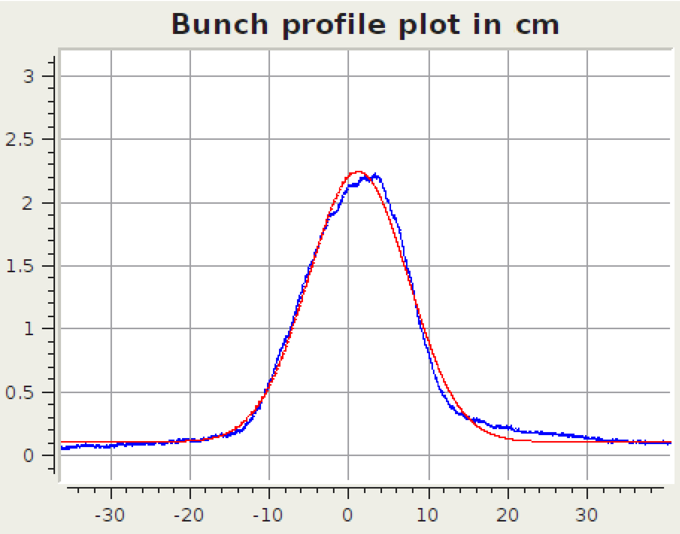


Bunch tansv. size measurements



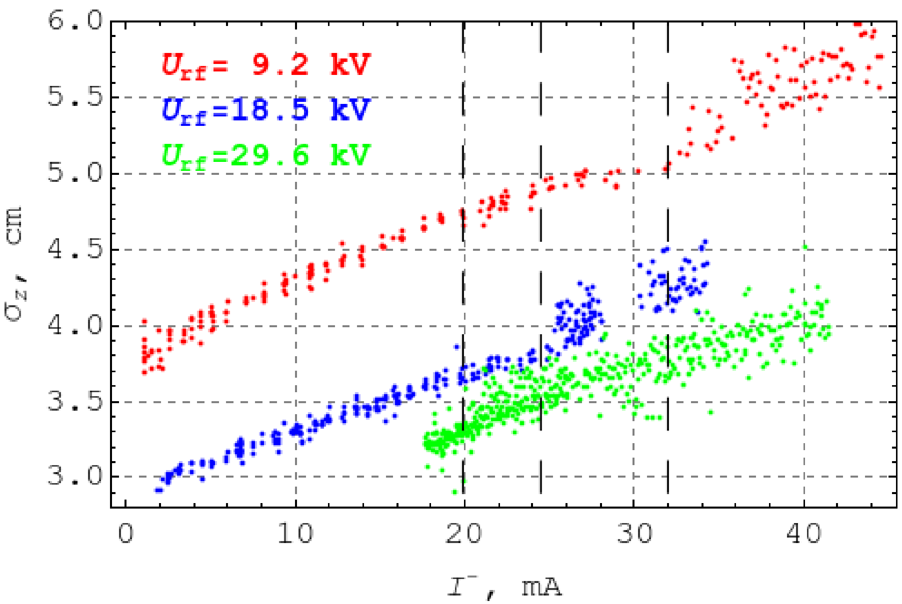
- Optics: Conversion 1:3 to fit (5.6 x 7) mm sensor
- CCD: Monochrome, 1296x964, 18FPS, https://www.ptgrey.com/support/downloads/10108
- Software: Home-made. Optimized for acquisition, 2D fit and bunch parameters extraction
- System Bandwidth: 5 FPS @ 640 x 480 resolution @ 16 CCD simultaneous
- Resolution: orbit – 2-3 μm, sizes – 5-10 μm

Bunch longit. Size measurements

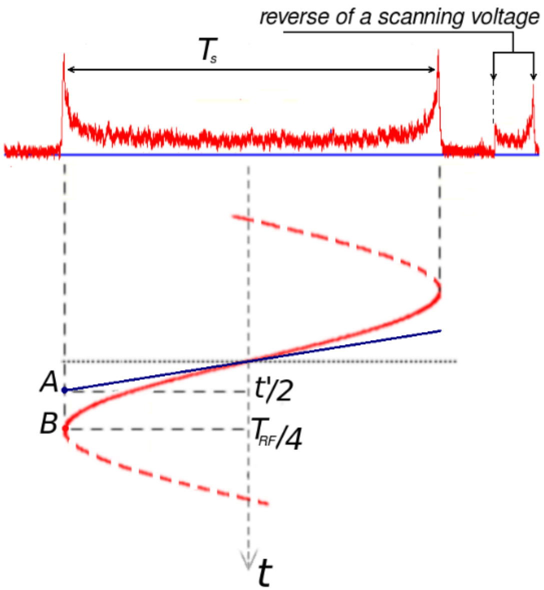


- Longitudinal particles distribution measured with phi-dissector (BINP) with stroboscopic nature of registration (electron-optical chorography)
- Bunch length estimated from Gaussian fit to data

- Bandwidth: 8-12Hz @ 2÷4k pts, 3Hz @ 32k pts
- Min. bunch length: 50 ps (achieved), 30-40 ps
- Accuracy: 1-2 mm (depends on phase motion)



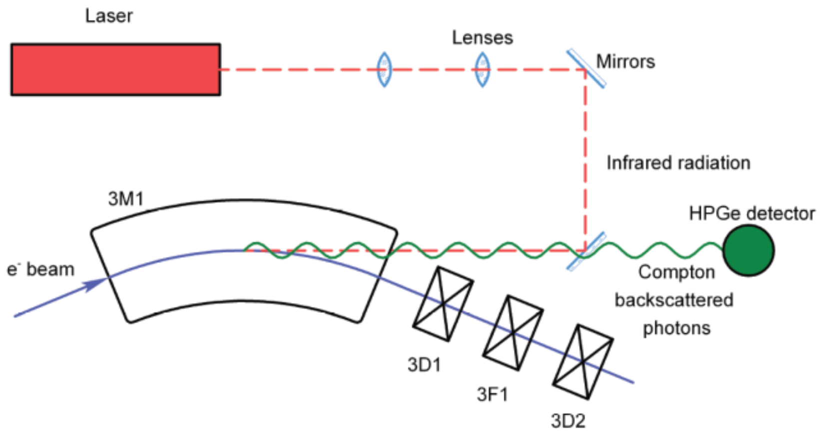
Measurements @ VEPP-2000, 480 MeV, 2013

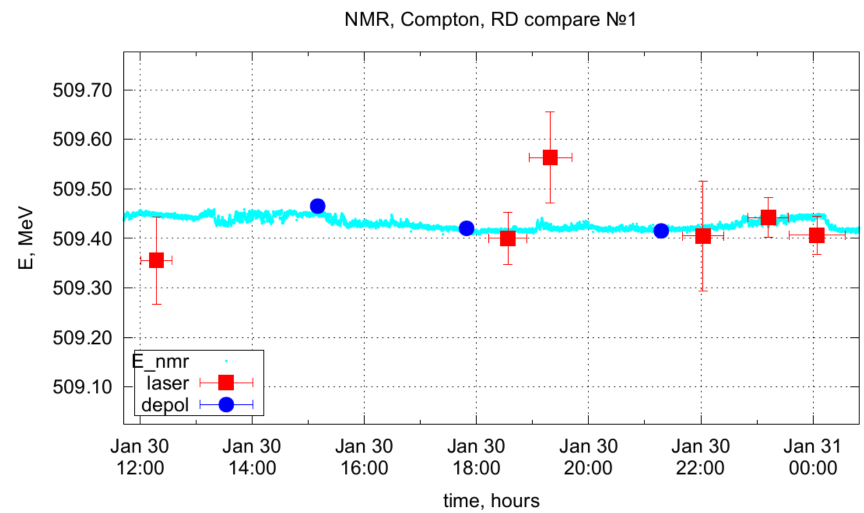


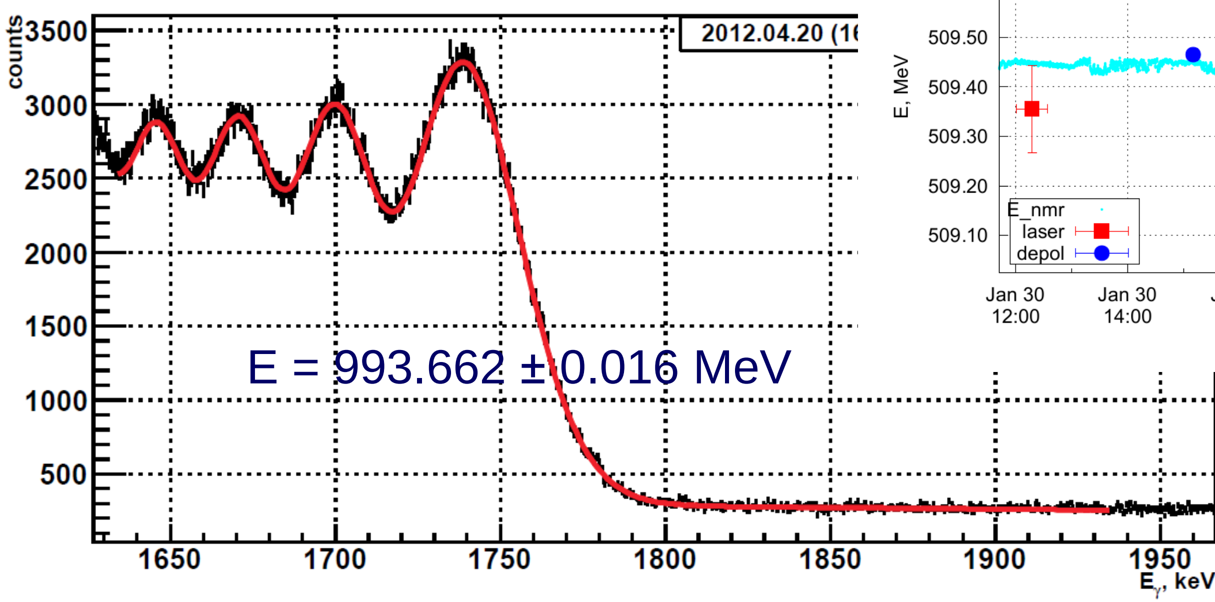
Technical details => see THPSC27 poster

Bunch energy measurements (CBS)

- Bunch parameters extracted from histogram fit: Energy, Energy Spread.
- Statistics. Accurate aiming at the beam.
- Relatively high bunch current: ≥20 mA
- Accuracy E: $2 \cdot 10^{-5}$, σ_E/E: 10^{-1} @ 1h







NMR control. $\delta E/E \sim 10^{-3}$

Laser CBS. $\delta E/E \sim 10^{-5}$

Resonance depol. $\delta E/E \leq 10^{-6}$

M.N. Achasov et al. arXiv:1211.0103v1 [physics.acc-ph] 1 Nov 2012

Bunch sizes: why changes?

Transvers

$$\sigma_x^2 = \beta_x \varepsilon_x + \left(D \frac{\sigma_E}{E} \right)^2$$

$$\sigma_y^2 = \beta_y \varepsilon_y$$

If β_x, βy, D is constant and known:

$$\sigma_x = \sigma_x\left(\varepsilon_x, \frac{\sigma_E}{E}\right)$$

$$\sigma_y = \sigma_y\left(\varepsilon_y \quad\quad \right)$$

Intrabeam scattering

Microwave instability

Longitudinal

- *I→0, quantum excitation only*

$$\sigma_l = \frac{c\alpha_p}{2\pi f_0 \nu_s} \frac{\sigma_E}{E}$$

- *$I < I_{th}$, potential well distortion*

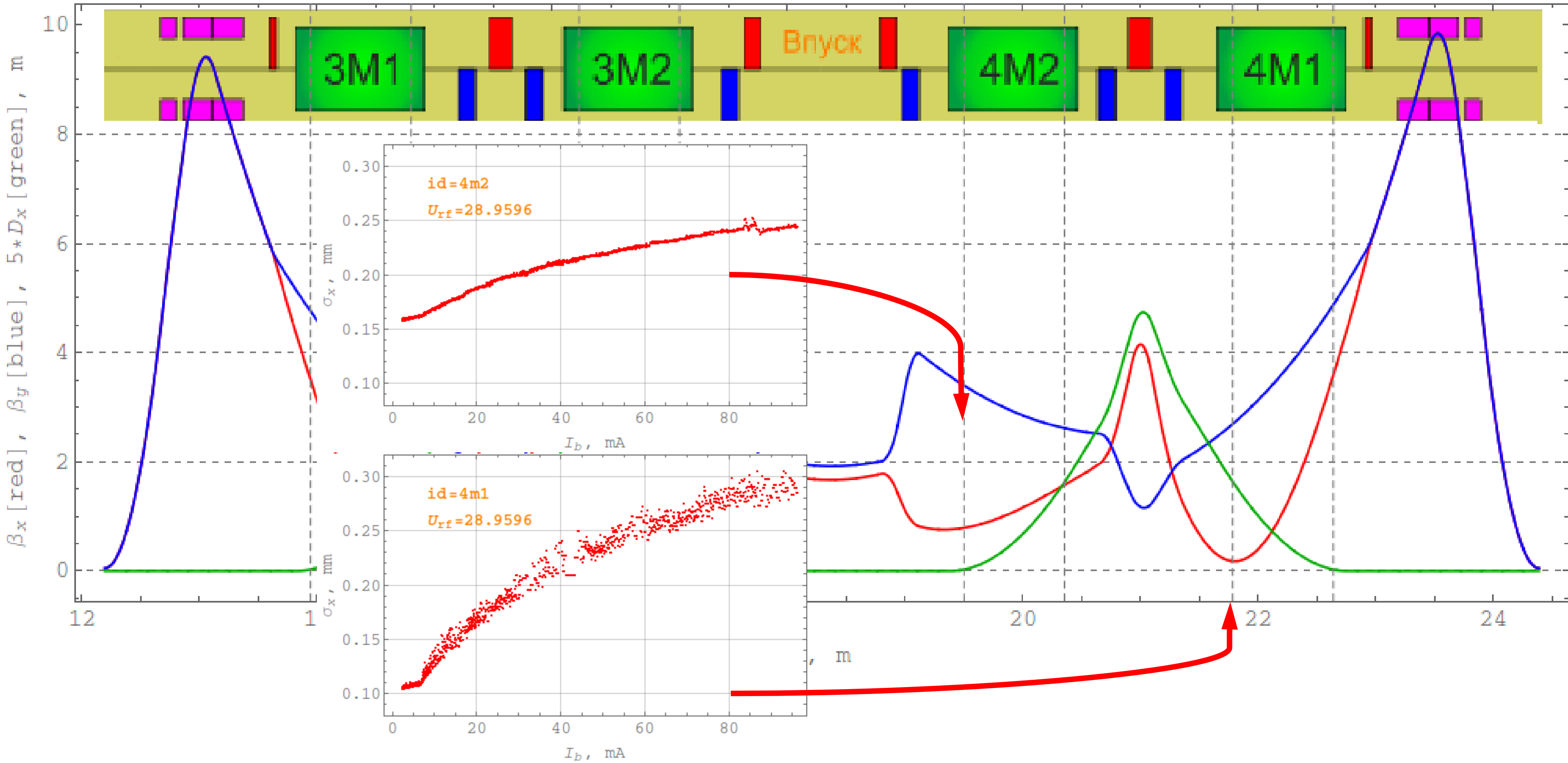
$$\nu_s^2 = \nu_{s_0}^2 \left(1 + A \left(\frac{\sigma_{l_0}}{\sigma_l} \right)^3 Im \left(\frac{Z}{n} \right)_{eff} \right), \quad A = \frac{(2\pi R)^3 I_b}{3h\sigma_0^3 U_0 \cos\phi_s}$$

$$\left(\frac{\sigma_l}{\sigma_{l_0}} \right)^3 - \left(\frac{\sigma_l}{\sigma_{l_0}} \right) = -A \cdot Im \left(\frac{Z}{n} \right)_{eff}$$

- *$I > I_{th}$,* *Potential well distortion* + *Microwave instability*

** in case of single bunch without collisions*

Bunch parameters estimation: idea

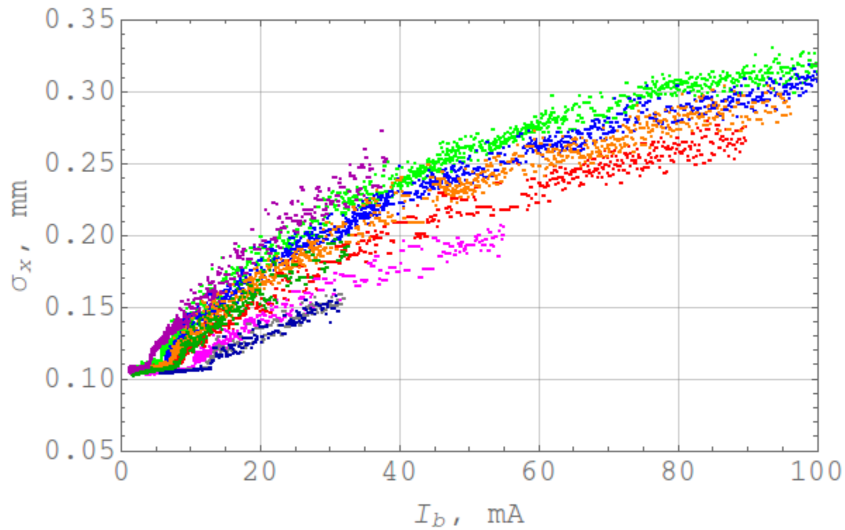


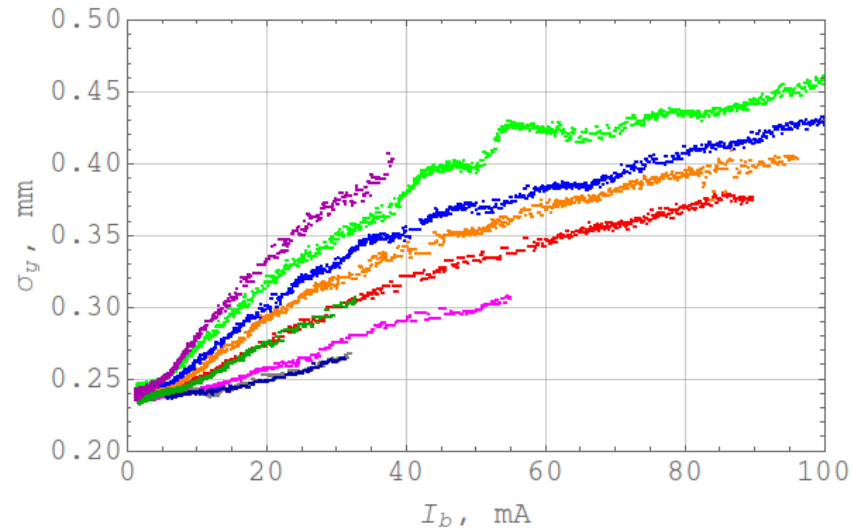
$$\chi^2 = \left\{ \left[\sigma_{x_i}^2 - \left(\beta_{x_i}\varepsilon_x + \left(D_i \frac{\sigma_E}{E} \right)^2 \right) \right]^2 + \left[\sigma_{y_i}^2 - (\beta_{y_i}\varepsilon_y) \right]^2 \right\} \longrightarrow min$$

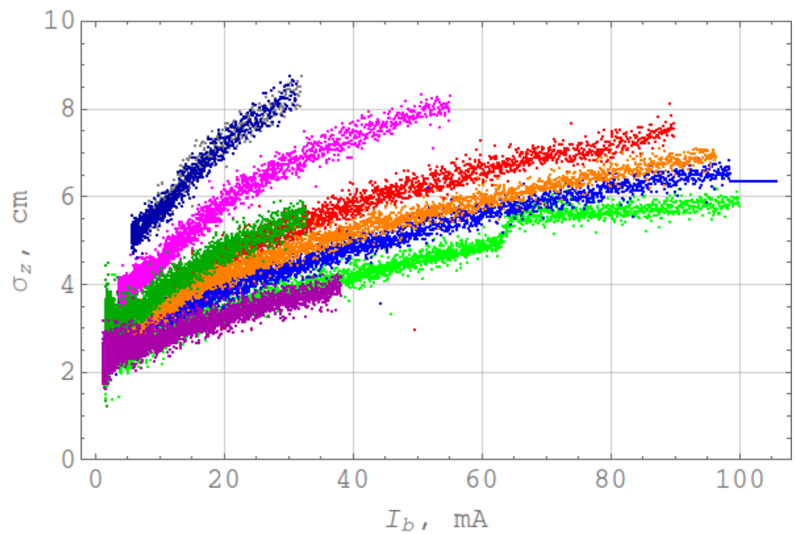
At least 2 observation points with different dispersion.
One point with lower dispersion is preferable.

More observations – lower error?
Depends on data quality.

Bunch sizes: while U_{rf}/I_b changes



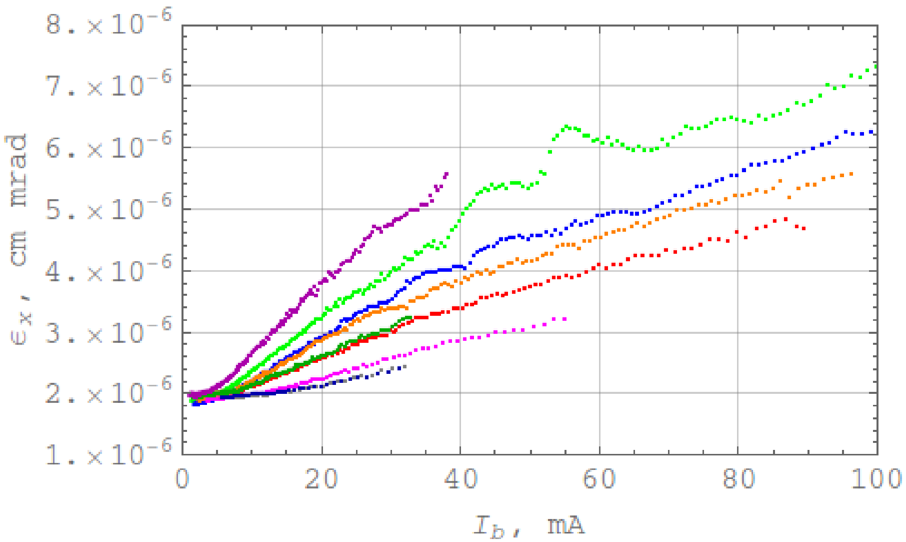


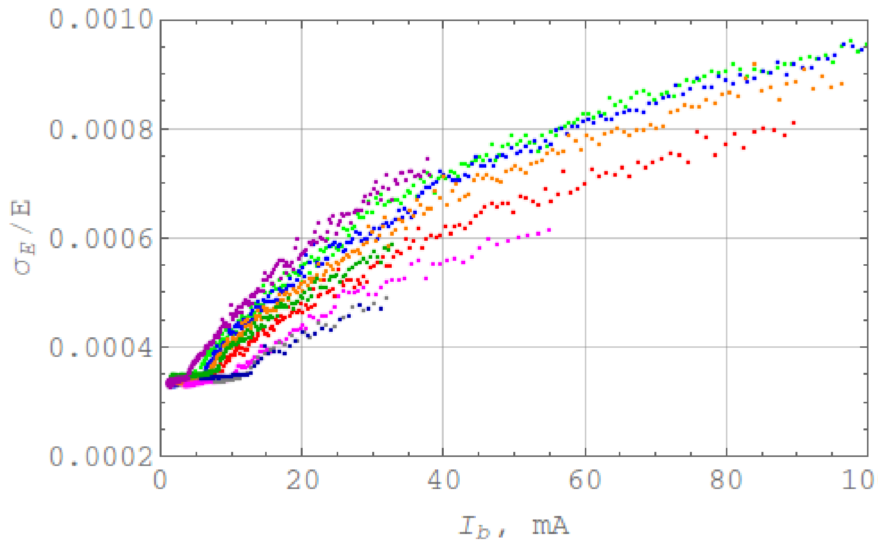


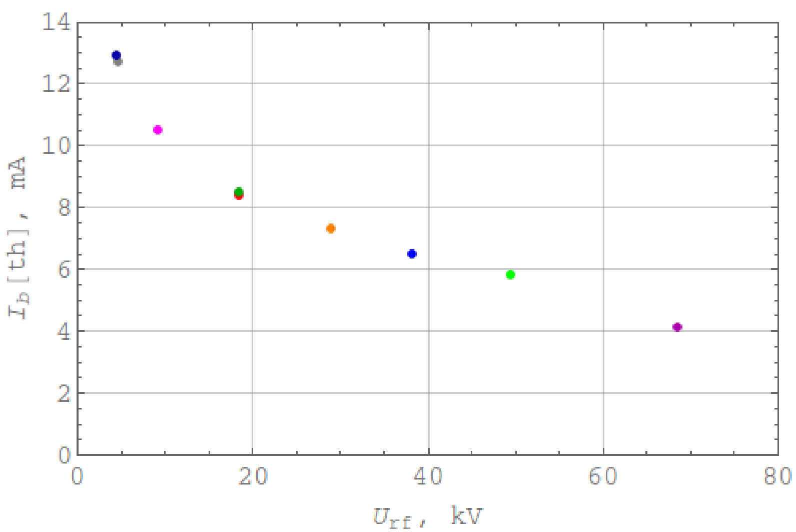
- Optics with "Short" FF solenoids
- Orbit and optics corrected to model
- This optics used for luminosity run @ 2018
- E = 348 MeV, a_p= 0.035879 (SAD*, model)
- I_b = 2÷100 mA, single bunch, no collision
- U_{rf} = 18.5 / 49.5 / 38.5 / 9.3 / 4.7 / 4.6 / 18.6 / 68.5 kV
- Data shown for 4M1L observation point, recorded / used for 8 observation points

SAD code: http://acc-physics.kek.jp/SAD/

Bunch parameters: estimation (I)







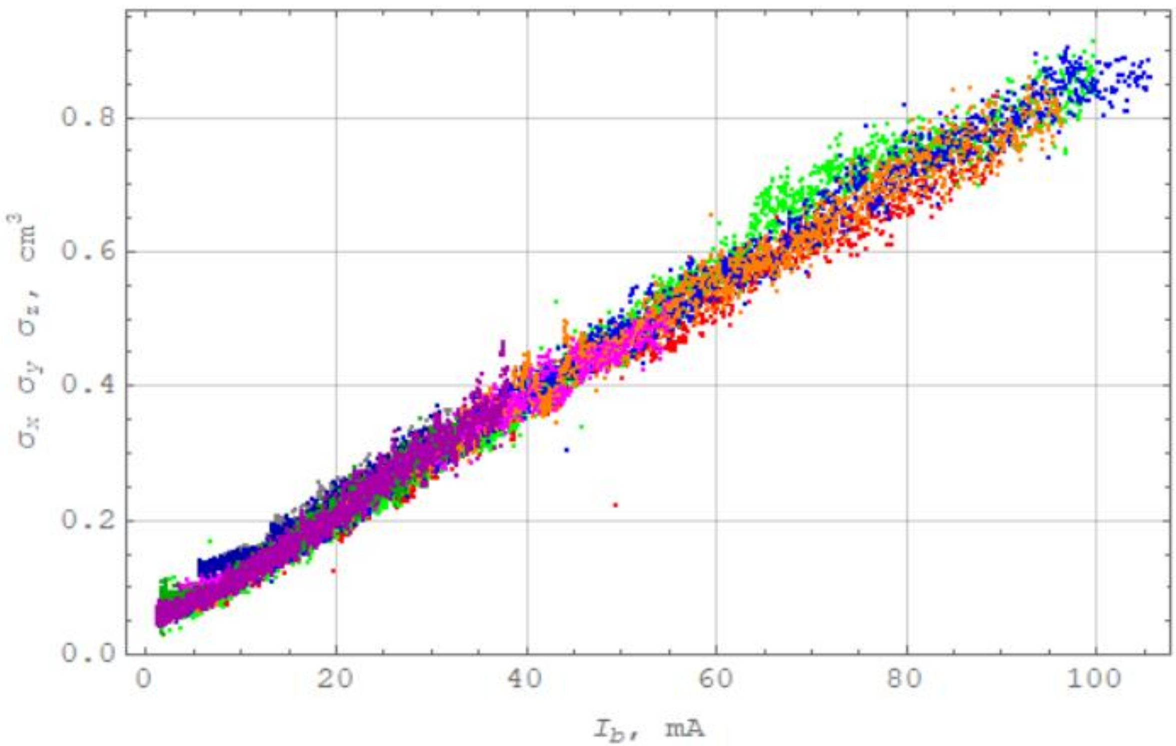
MWI threshold dependence vs. U_{rf}

U_{rf} = 18.5 / 49.5 / 38.5 / 9.3 / 4.7 / 4.6 / 18.6 / 68.5 kV

From machine model (SAD code):

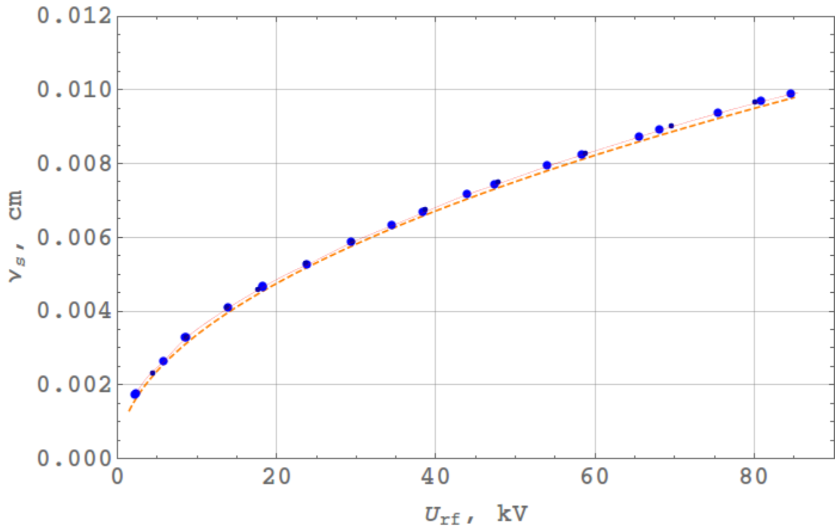
- $\sigma_E/E = 2.46 \times 10^{-4}$
- $\epsilon_x = 2 \times 10^{-6}$ cm × mrad
- Low current limit

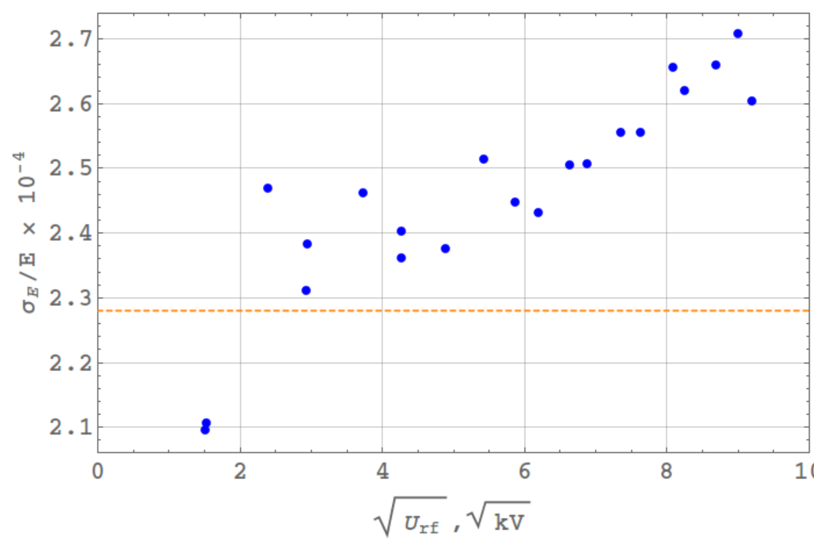
Bunch parameters: estimation (II)

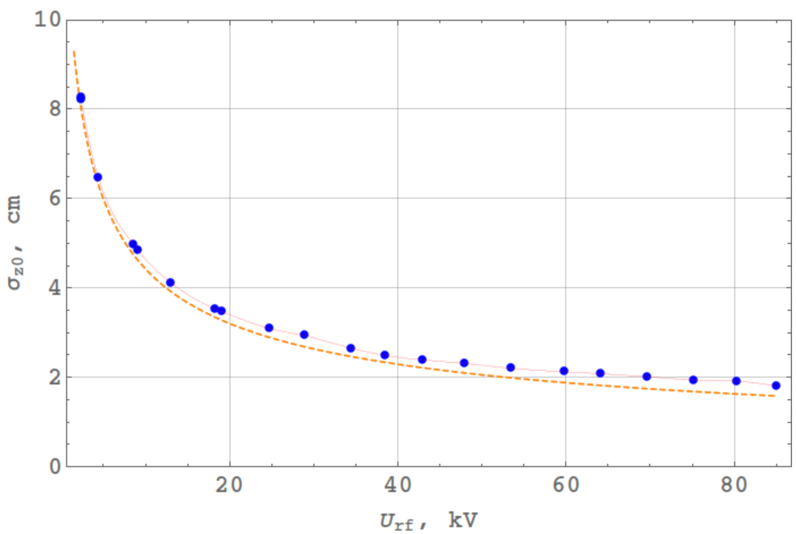


- Bunch volume as a simple product of bunch rms. dimensions growth almost linearly with bunch intensity
- The slope of the curve changes: below / above the threshold

Measurements at "zero" current







$$\sigma_l = \frac{c\,\alpha_p}{\Omega_s}\frac{\sigma_E}{E} \propto \sqrt{\frac{\alpha_p}{qU_0}}$$

- Warm optics => no FF solenoids
- Orbit and optics corrected to model
- E = 348 MeV, a_p= 0.17598 (SAD*, model)
- U_{rf} = 2.5÷85 kV, I_b ≤ 50 uA

Dissector measurements. Technical detail => see THPSC27 poster

SAD code: http://acc-physics.kek.jp/SAD/

Why to control energy spread

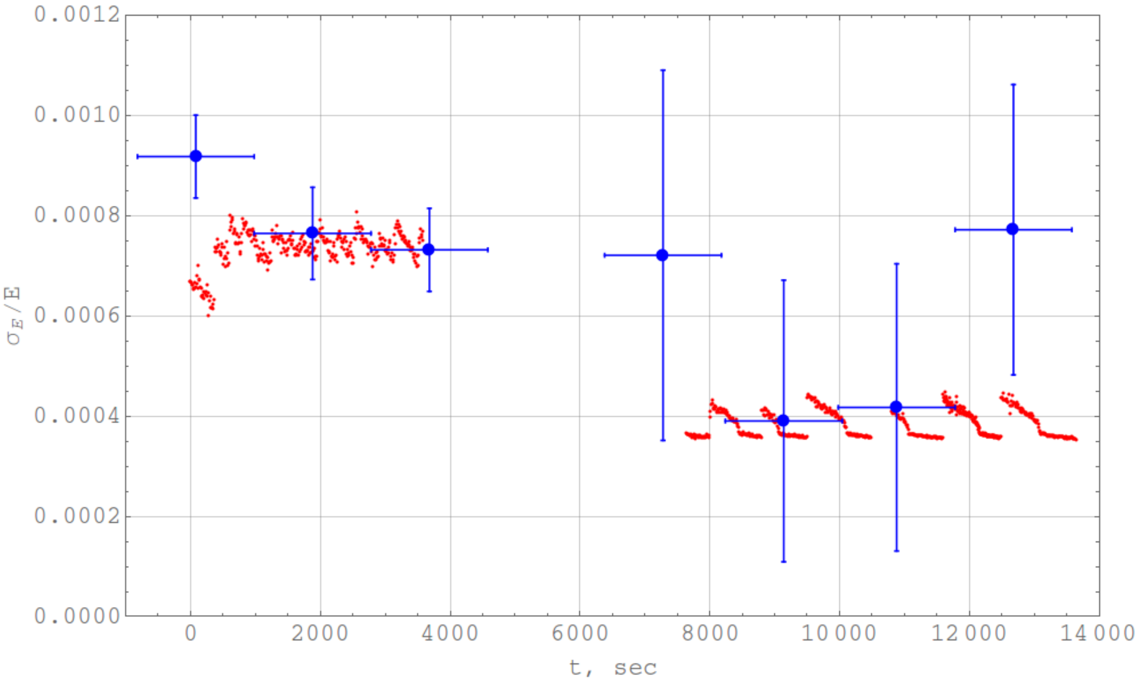
Visible cross-sections reduction at narrow resonances $\varphi(1080)$, $\omega(782)$ depends quadratically on c.m. energy spread, and achieve values of ~5%. To measure real cross-sections with accuracy better then 1% the energy spread control needed at level of at least 10%.

The ultimate limits on rare decays $\eta \to e^+e^-$, $\eta' \to e^+e^-$ obtained at VEPP-2000 (in inverse processes) are also determined by the beam energy spread.

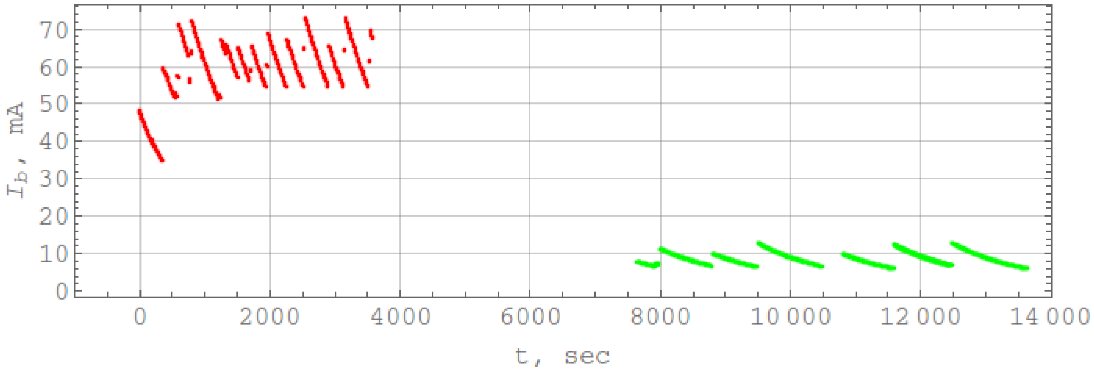
E.A. Kozyrev et al., Study of the process $e^+ e^- \to K^+ K^-$ in the center-of-mass energy range 1010–1060 MeV with the CMD-3 detector, Phys. Lett. B 779 (2018) 64-71

M. N. Achasov et al. , Search for the process $e^+e^- \to \eta$, Phys. Rev. D 98, 052007

Bunch energy spread: FIT vs CBS



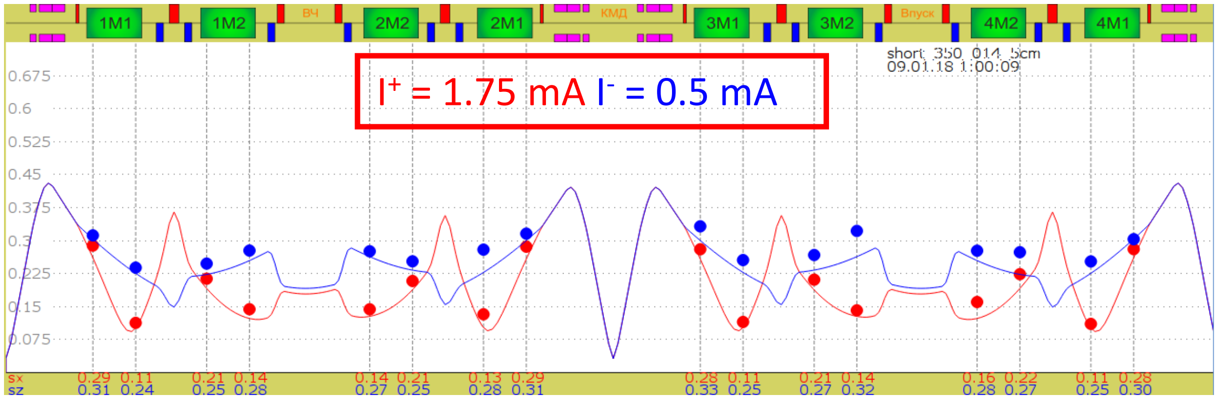
- Optics: “Short” FF solenoids
- Orbit / optics => close to model
- For Luminosity run @ 2018
- E = 348 MeV
- Single bunch, no collision
- Special CBS run: 30min period

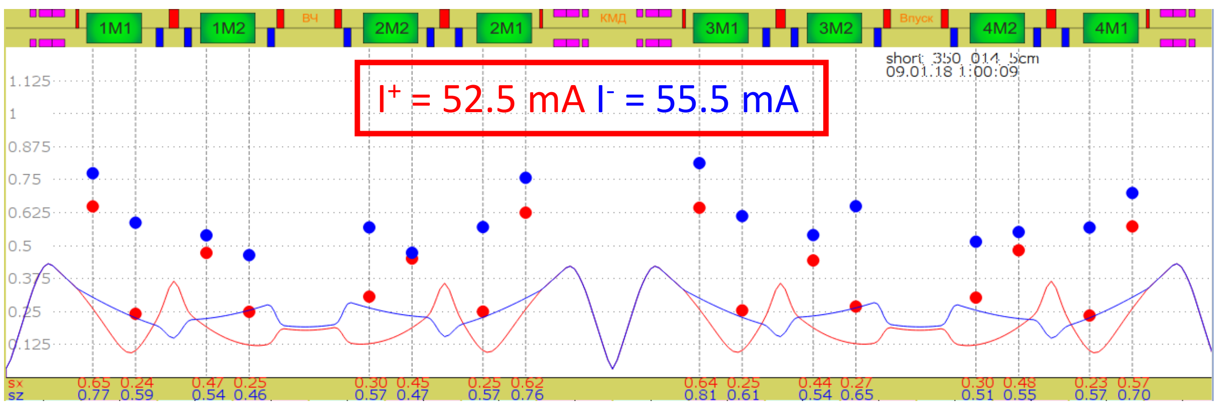


CBS results depends:

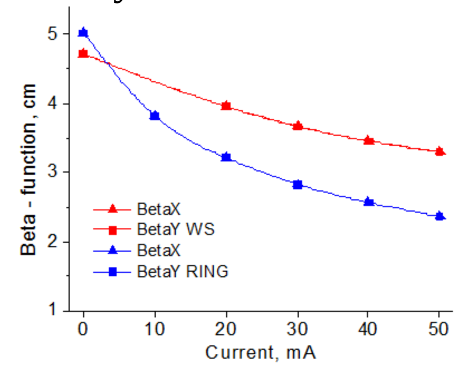
- Bunch stability: orbit, sizes
- Stability: E and σ_E/E drifts
- Statistics: run length

Beam-Beam effects

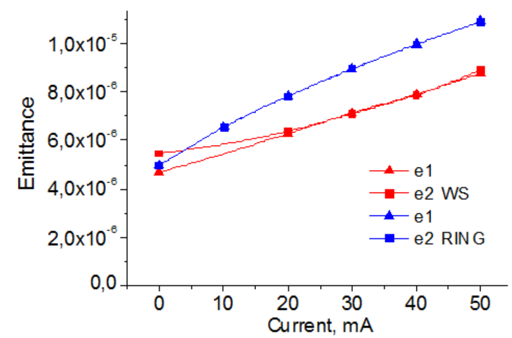




Dynamic beta*:

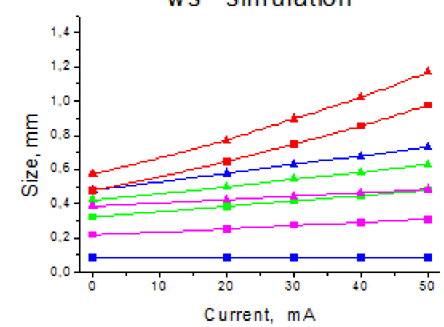


Dynamic emittance:



Sizes @ CCD:

ws - simulation



Beam (transverse) sizes in collision strongly depends on counter beam intensity

- Dynamic beta (shrinks @ IP, growth along the ring)
- Dynamic emittance (growth)
- Stochastic emittance growth + non-Gaussian distribution +…

Conclusion

- Bunch dimensions changes with bunch current
- MWI (turbulent bunch lengthening) has been observed over a wide range of U_{rf} values

- Emittance growth caused mainly by IBS (Continuously)
- Energy spread growth caused by MWI (Threshold)
- Bunch volume increases linearly with bunch current

- Energy spread can be estimated quite accurate from transverse bunch profile(s) for single bunch
- Such “online” estimation (Emittance / Energy spread) should be used for routine operation during luminosity runs

- Ideas should be tested (modified?) in presence of opposite counter bunch

Main control room of VEPP-2000