CREMLIN PLUS
Connecting Russian and European Measures for Large-scale Research Infrastructures

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 871072

BINP electron-positron colliders: VEPP-4M & VEPP-2000

Dmitry Shwartz

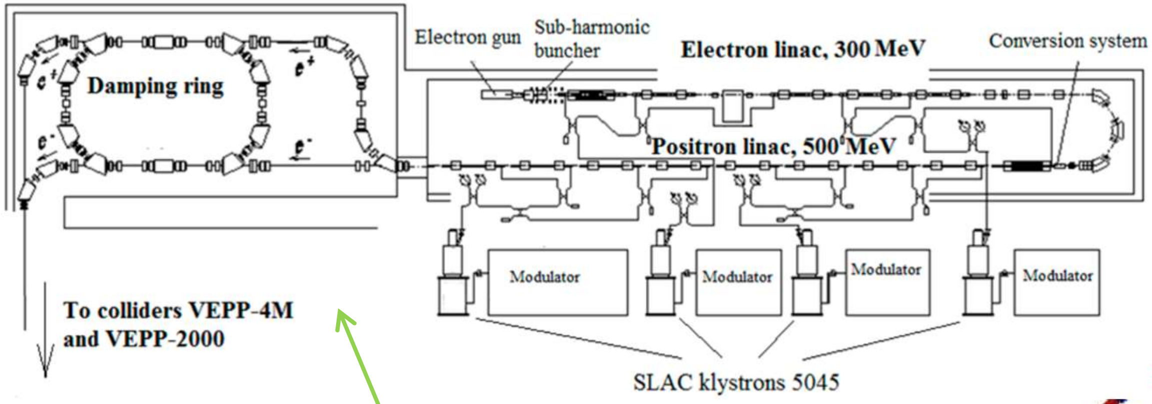
on behalf of

IC, VEPP-4M, VEPP-2000 teams

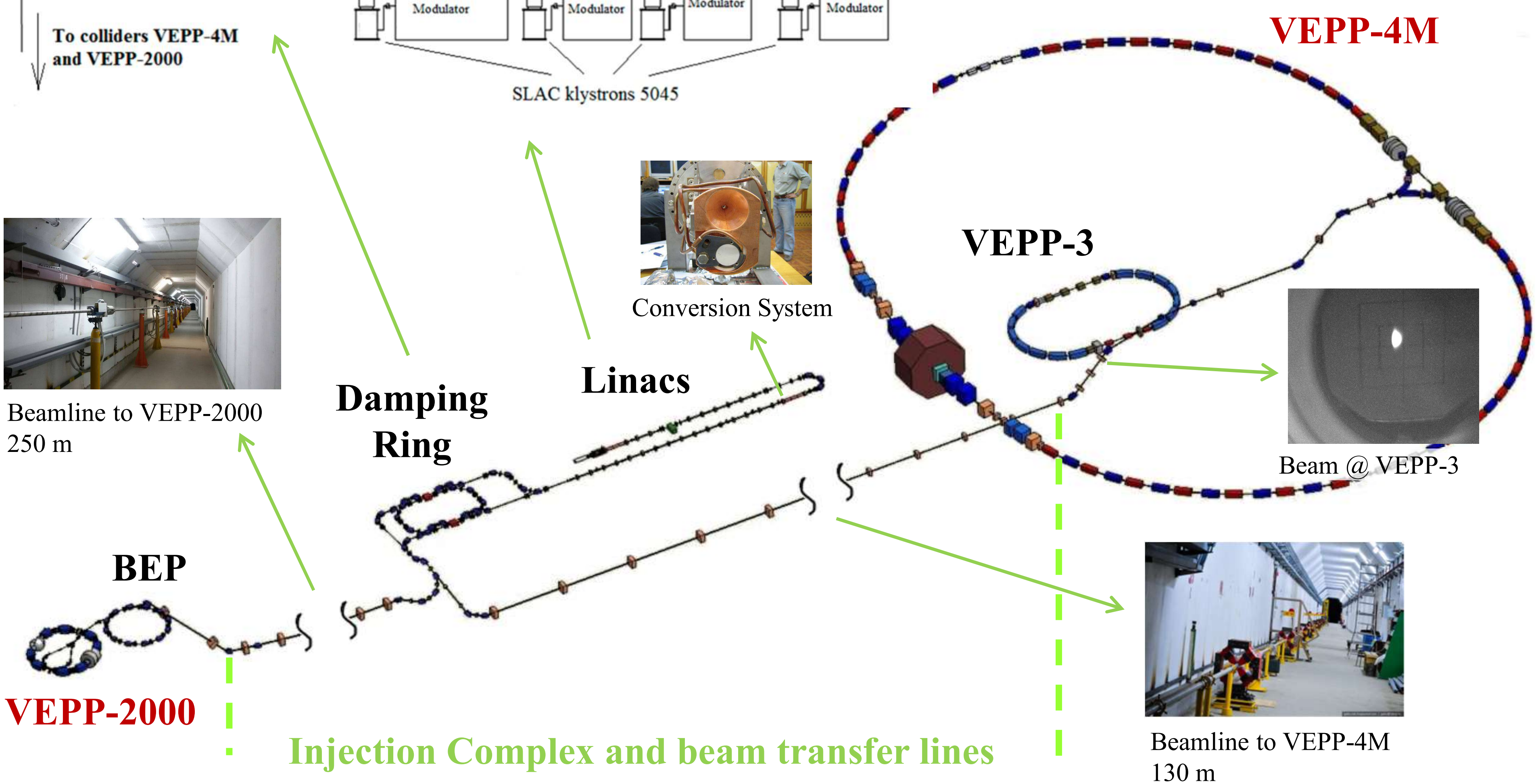
May 29, 2020

WP8 kick-off web-conference

BINP accelerator complex layout



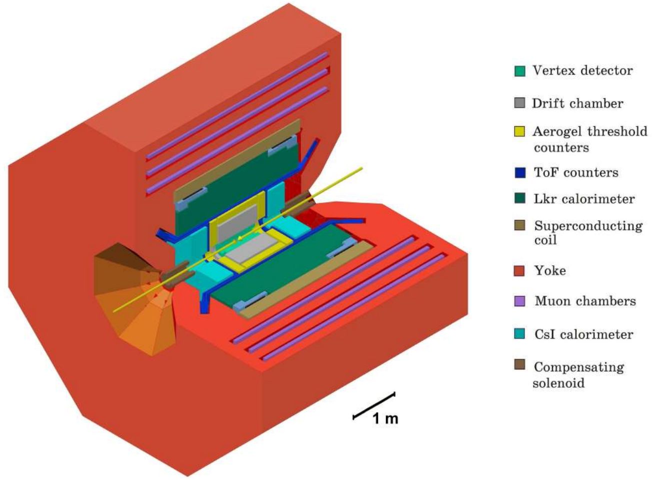
IC Parameters (2016, @ 12.5 Hz)
Beam Energy: **395 MeV**
Storage rate e^-: **$4.0 \cdot 10^{10}$/s** (70 mA/s)
Storage rate e^+: **$4.0 \cdot 10^{9}$/s** (7 mA/s)



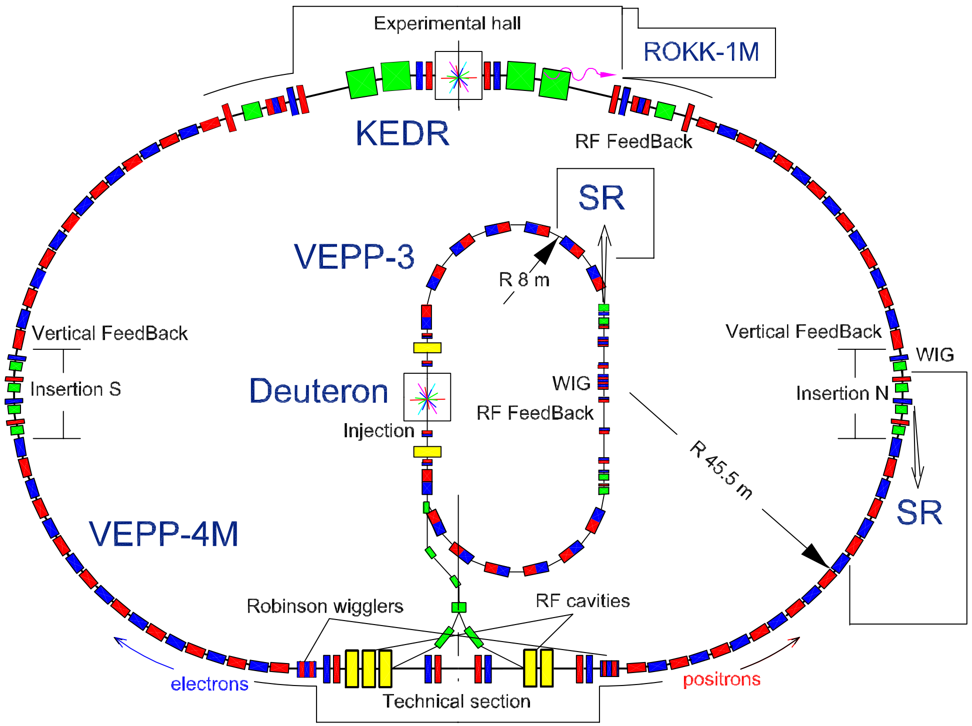
Injection Complex and beam transfer lines

VEPP-4M complex

- e^+e^- HEP at VEPP-4M with KEDR detector
- SR at VEPP-3 (2 GeV)
- SR at VEPP-4M (2÷4 GeV)
- Nuclear physics at VEPP-3 with Deuteron facility
- Test Beam Facility at VEPP-4M
- Accelerator physics activity

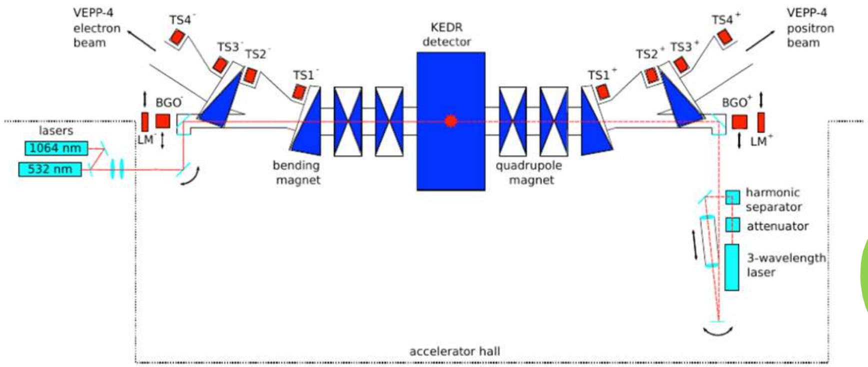


Energy	**0.925 ÷ 4.75 (5.3)**				
Circumference	366				m
N of bunches	$2e^+ \times 2e^-$ ($16e^-$)				
Harmonic number	222				
Betatron tunes, h/v	8.54/7.57				
Coupling	0.05%				
Bunch length	5				cm
Beam Energy	1.5	1.9	*4.7*	*5.2*	GeV
Emittance	16	25	*167*	*200*	nm·rad
Energy Spread	2.5	3.0	*7.8*	*8.5*	$\cdot 10^{-4}$
Bunch Current	1.6	3.5	*25*	*25*	mA
Luminosity	0.9	**3.3**	*44*	*25*	10^{30} cm$^{-2}\cdot$s^{-1}



HEP @ VEPP-4M with KEDR

- ★ Universal magnetic detector KEDR
- ★ Electron-positron tagging system
- ★ Wide energy range 0.9÷5 GeV
- ★ Energy spread control
- ★ Precision beam energy calibration by resonance depolarization
- ★ First collider with beam energy monitoring by Compton backscattering



2001-2017 low energy luminosity run 2x(0.9÷1.9) GeV

- ✓ J/ψ, ψ', ψ'', $\psi(3770)$ meson masses
- ✓ τ lepton mass
- ✓ D^0 mesons masses
- ✓ $D^{\pm}$ mesons masses
- ✓ Search for narrow resonances 1.85÷3.1 GeV
- ✓ R-scan 1.85÷3.1 GeV
- ✓ Ruds- and R- scan 3.12÷3.72 GeV
- ✓ $J/\psi \to \gamma\eta_c$
- ✓ ψ-mesons, η_c, … parameters

High energy luminosity run 2x(1.9÷Max energy) GeV

- ✓ R scan 2x(2.3÷3.5) GeV (~ 10 bp^{-1})
- ✓ Υ-mesons study (~ 50 pb^{-1})
- ✓ gamma-gamma physics (~ 200 pb^{-1})

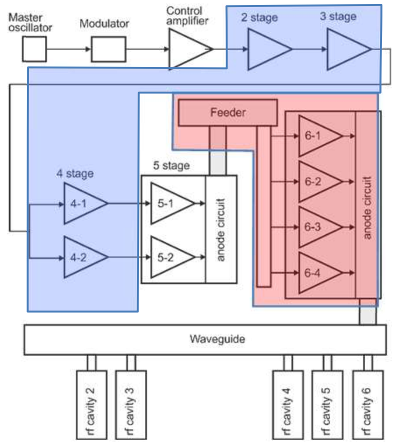
You are here

VEPP-3: ±15 kA ±40 V 600 kW

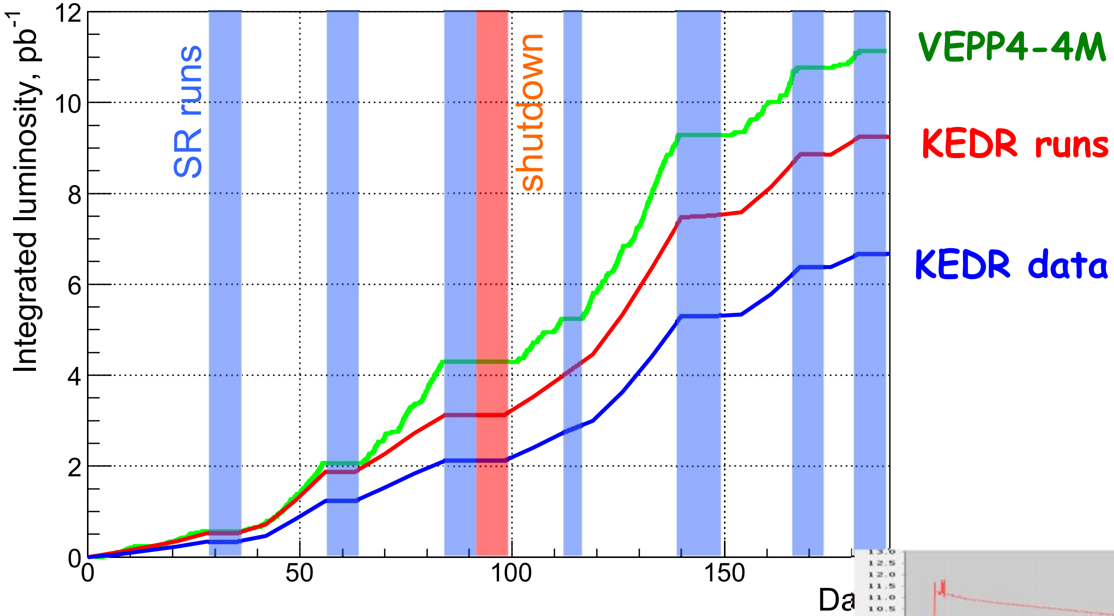
VEPP-4M: +7.5 kA +70 V 525 kW 4.75 → 5.2 (6.0) GeV

- ★ RF system Upgrade
- ★ Power Supplies upgrade

4 x GU-101A tetrode
2 MV → 4 MV
200 kW → 400 kW
100 mA @ 4.75 GeV



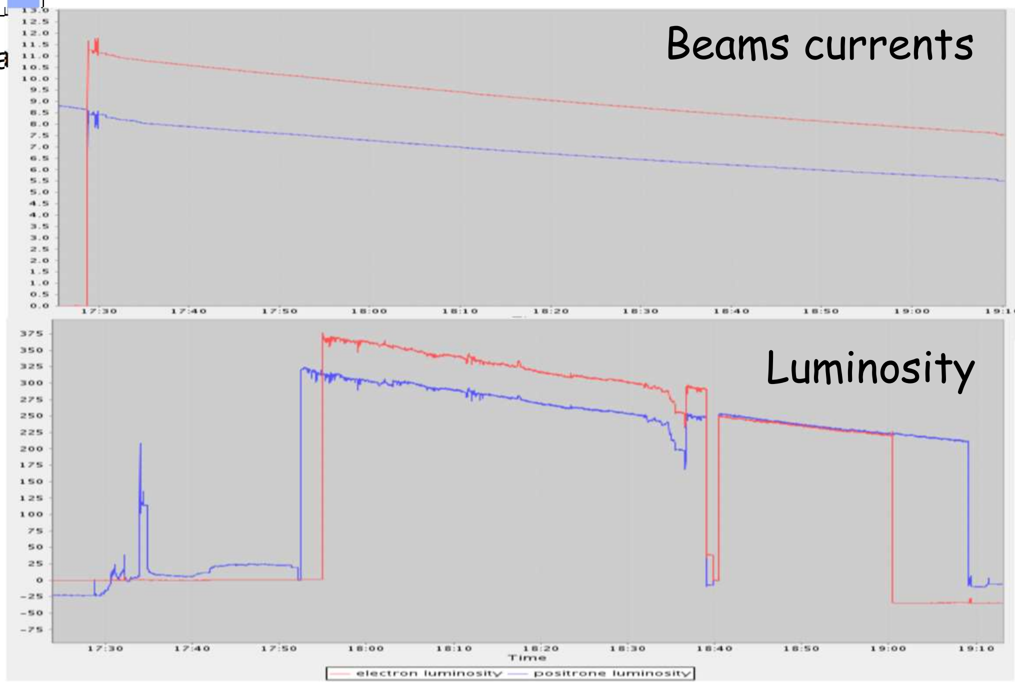
Latest VEPP-4M highlights



In 2017-2020 hadron cross section measurement from 2.3 to 3.5 GeV has been performed with ~10pb^{-1} of integrated luminosity.

Further KEDR program is related to higher energies.

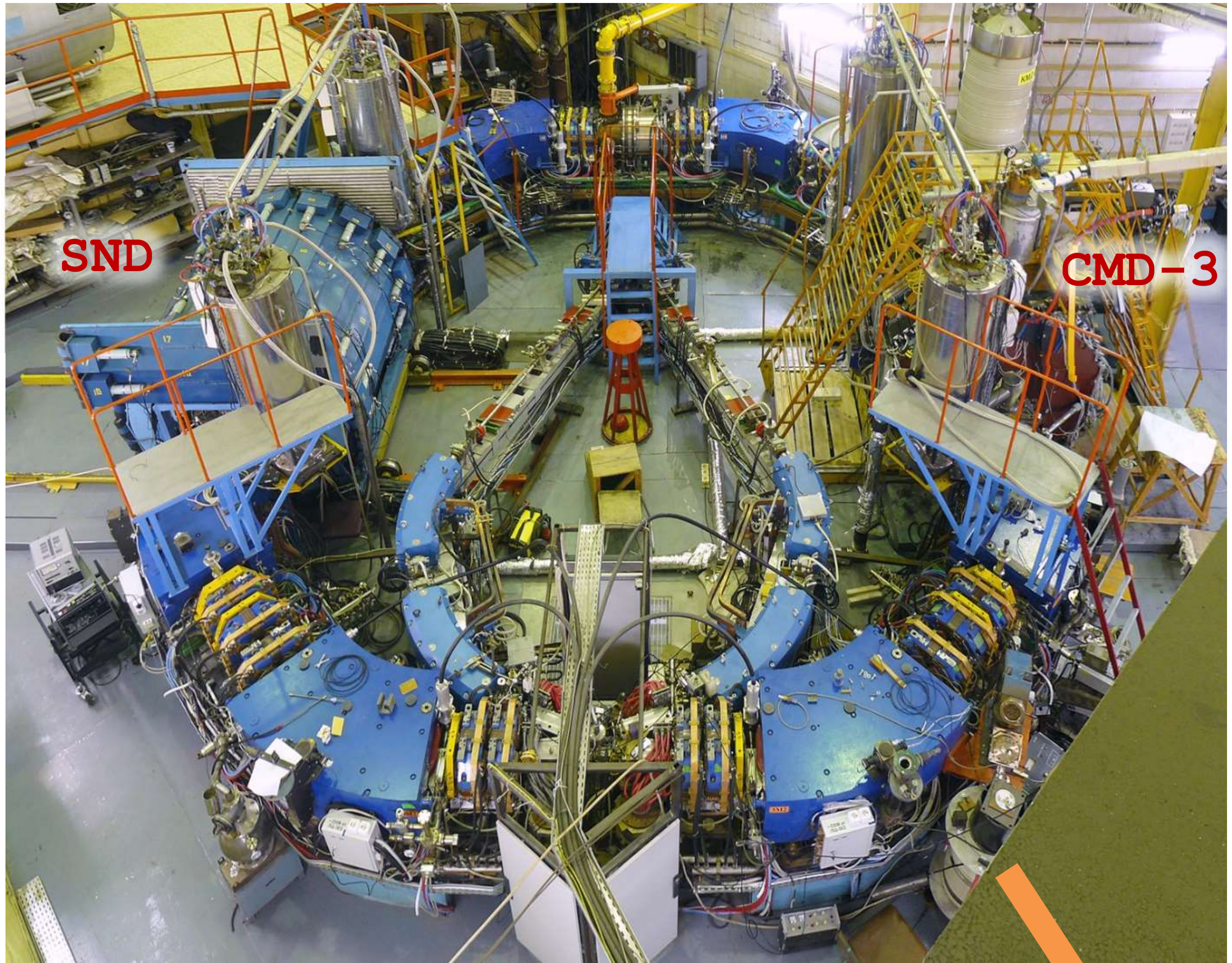
First luminosity tests @ ϒ(1S),
E=4.75 GeV, 28 Nov 2019



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
- Single-ring head-on collisions
- 13 T solenoids for FF
- 2.4 NC dipoles @ 1 GeV
- CBS for energy control



Operating with IC#VEPP-5 since 2016

Experimental program

1. Precision measurement of $R = \sigma(e^+e^- \to hadrons)/\,\sigma(e^+e^- \to \mu^+\mu^-)$ exclusive approach, up to <1% for major modes
2. Study of hadronic final states:
$$e^+e^- \to 2h, 3h, 4h, \ldots \quad h = \pi, K, \eta$$
3. Study of vector mesons and theirs excitations:
$$\rho', \rho'', \omega', \varphi', \ldots$$
4. Comparison of cross-sections $e^+e^- \to hadrons\ (T = 1)$ with spectral functions of τ-decays
5. Study of nucleon electromagnetic formfactor at threshold
$$e^+e^- \to p\bar{p}, n\bar{n}$$
6. Measurement of the cross-sections using ISR
7. Study of higher order QED processes

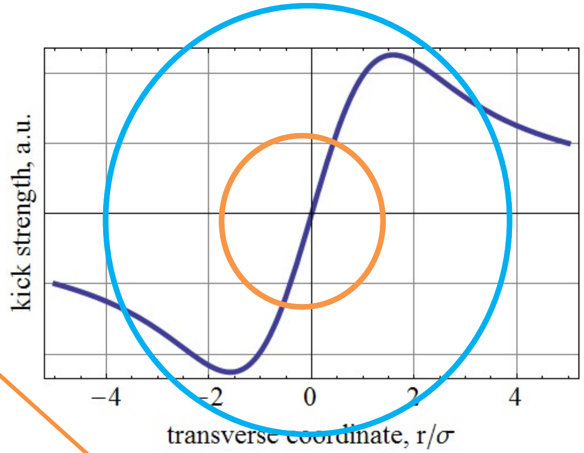
Target luminosity integral is 1 fb^{-1} per detector

Why Round Beams? Introduction.

How many interacts? $\frac{L \cdot \sigma_{process}}{f_0} \sim \frac{10^{32} cm^{-2} s^{-1} \cdot 10^{-24} cm^2}{12 \cdot 10^6 Hz} \sim 10$ Compare to $N_{bunch} \sim 10^{11}$

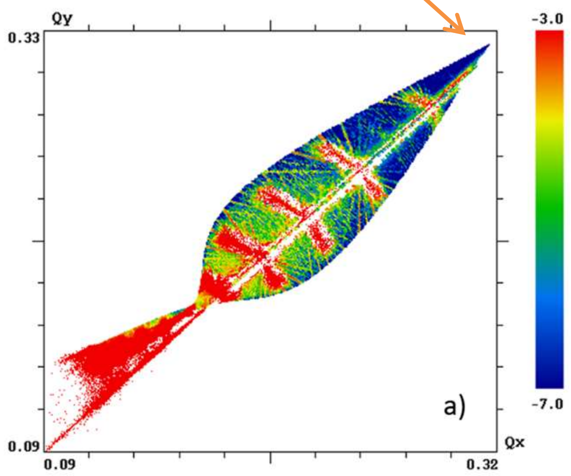
Particles unlikely interact with each other. Instead it every turn interact with collective field of the charged opposite bunch: **beam-beam effects**.

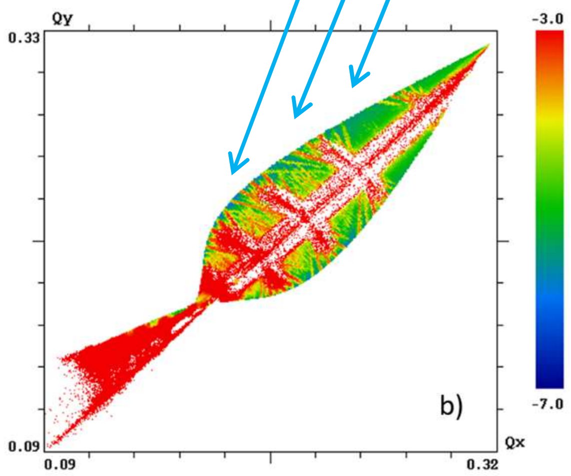
Linear beam-beam: tune shift



Nonlinear beam-beam:
tune spread (footprint)
&
high-order resonance grid

FMA:
beam-beam
simulations
by Lifetrac

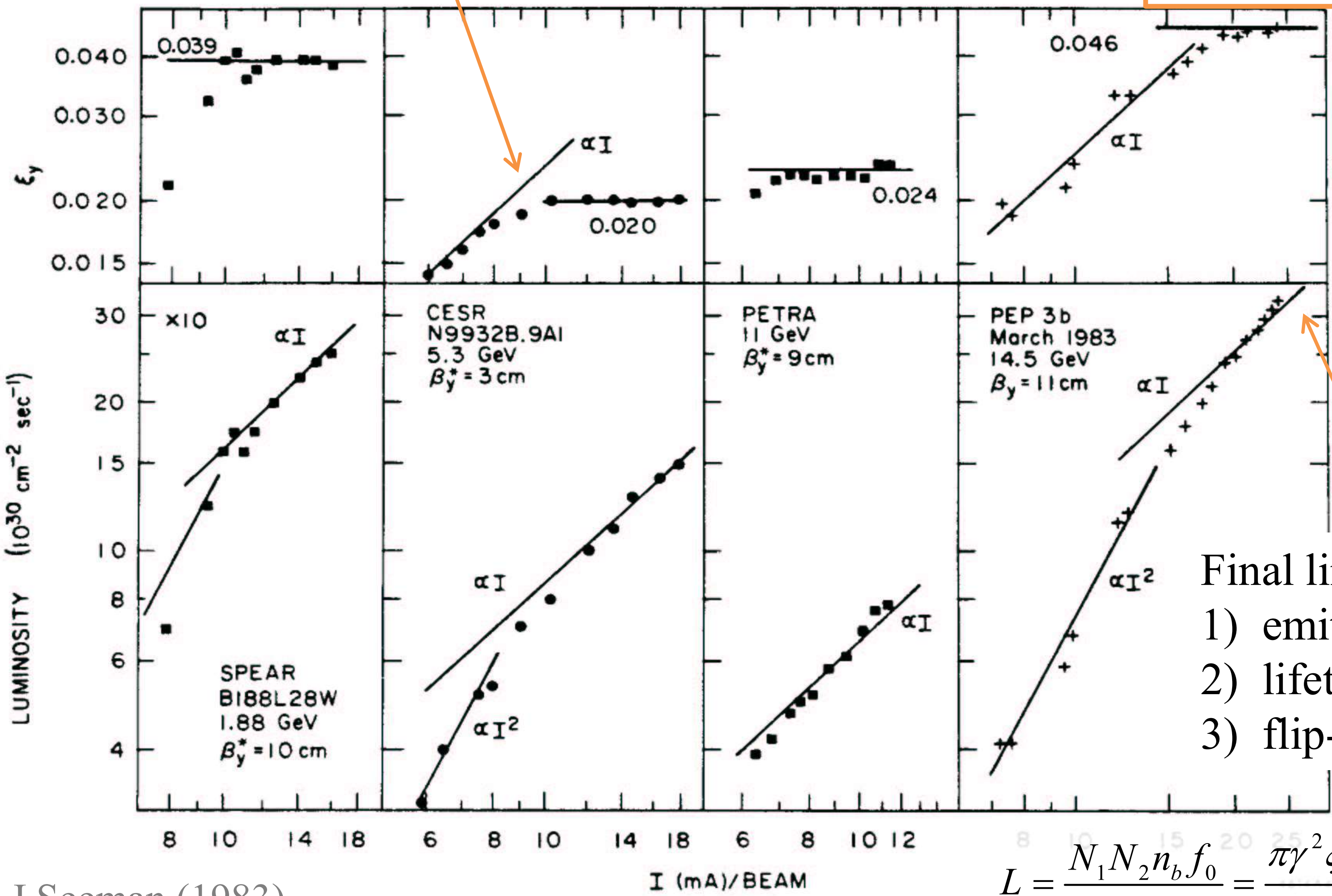




Beam-beam limit @ lepton colliders

Beam-beam parameter saturation,
emittance (and beam size) growth

$$\xi_{x,z} = \frac{r_e \beta^*_{x,z}}{2\pi\gamma} \cdot \frac{N_2}{\sigma_{x,z}(\sigma_x + \sigma_z)}$$



Final limit:
1) emittance blowup,
2) lifetime reduction,
3) flip-flop effect

$$L = \frac{N_1 N_2 n_b f_0}{4\pi\sigma_x\sigma_z} = \frac{\pi\gamma^2 \xi_x \xi_y \varepsilon_x f}{r_e^2 \beta_y^*}\left(1 + \frac{\sigma_y}{\sigma_x}\right)^2$$

J.Seeman (1983)

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 becomes 1D; thinned resonance net; higher beam-beam threshold!

Lattice requirements:

- Head-on collisions!
- Small and equal β-functions at IP: $\beta_x = \beta_y$
- Equal beam emittances: $\varepsilon_x = \varepsilon_y$
- Equal fractional parts of betatron tunes: $\nu_x = \nu_y$

$\beta_x = \beta_y$ and $\varepsilon_x = \varepsilon_y$ → Round beam

$\beta_x = \beta_y$ and $\nu_x = \nu_y$ → $M_x = M_y$

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.

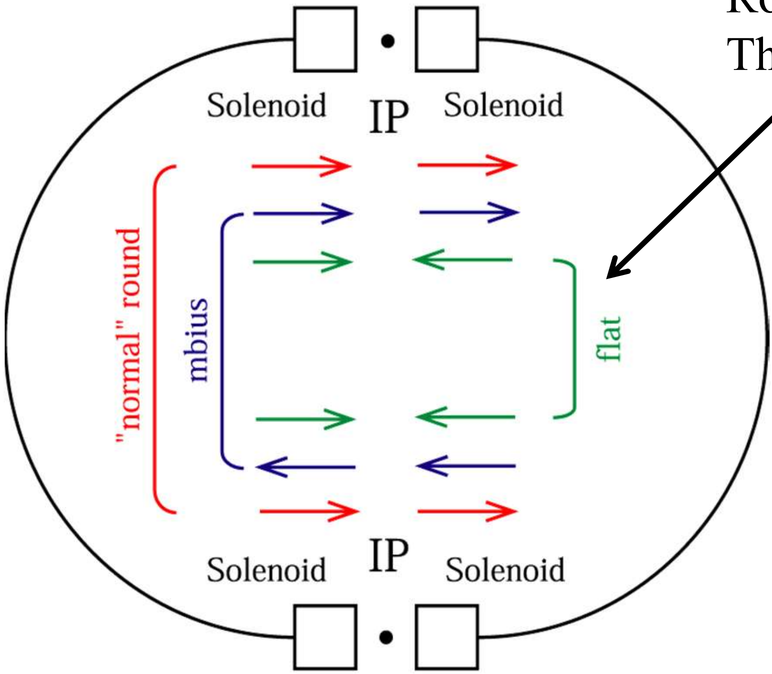
S. Krishnagopal, R. Siemann, Proc. PAC'89, Chicago, p.836.

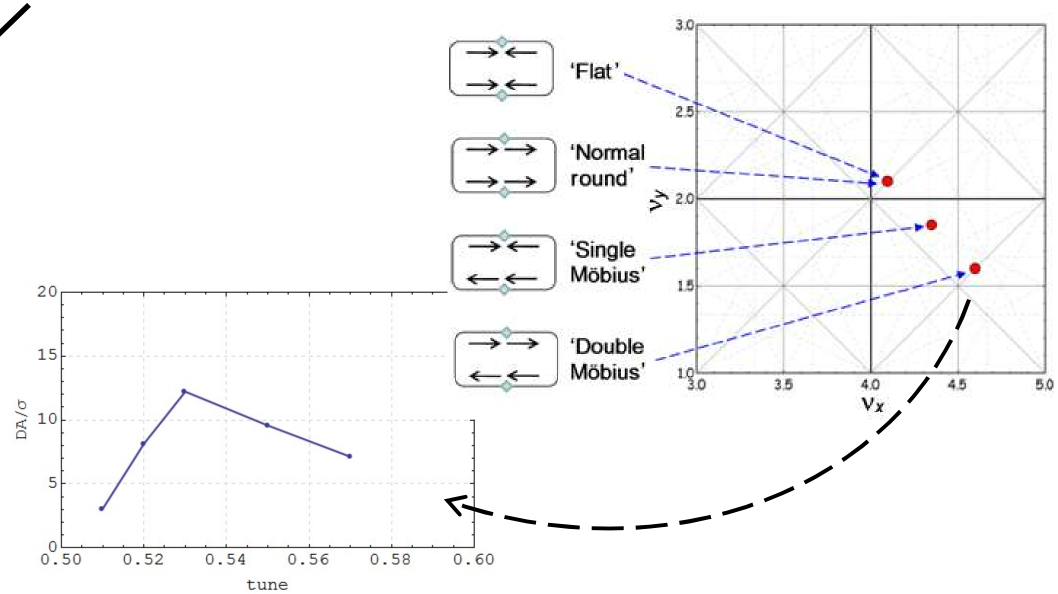
V.V. Danilov et al., EPAC'96, Barcelona, p.1149.

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

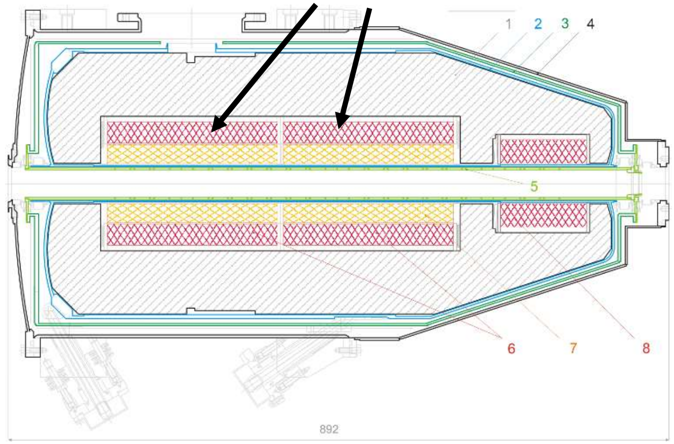
Round Beams Options @ VEPP-2000

Round beam due to coupling resonance?
The simplest practical solution!





Solenoid main coils (13 T)

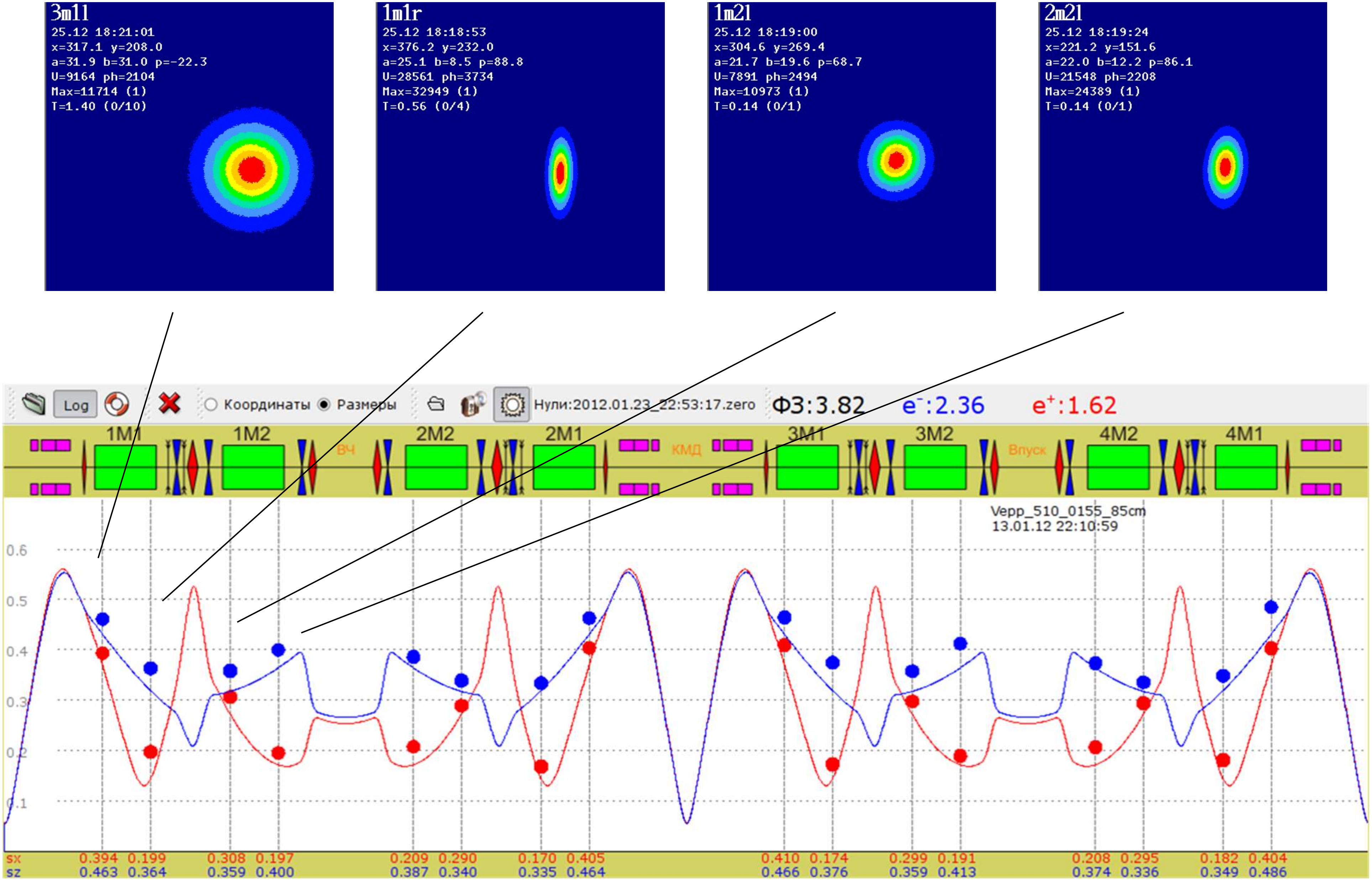


Both simulations and experimental tests showed insufficient dynamic aperture for regular work in circular modes options.

Below 600 MeV “short” FF solenoids are available.

Flat to Round/Mobius or Long to Short change needs polarity switch in solenoids, realignment and new orbit correction.

Beam size measurement via SR @ CCDs

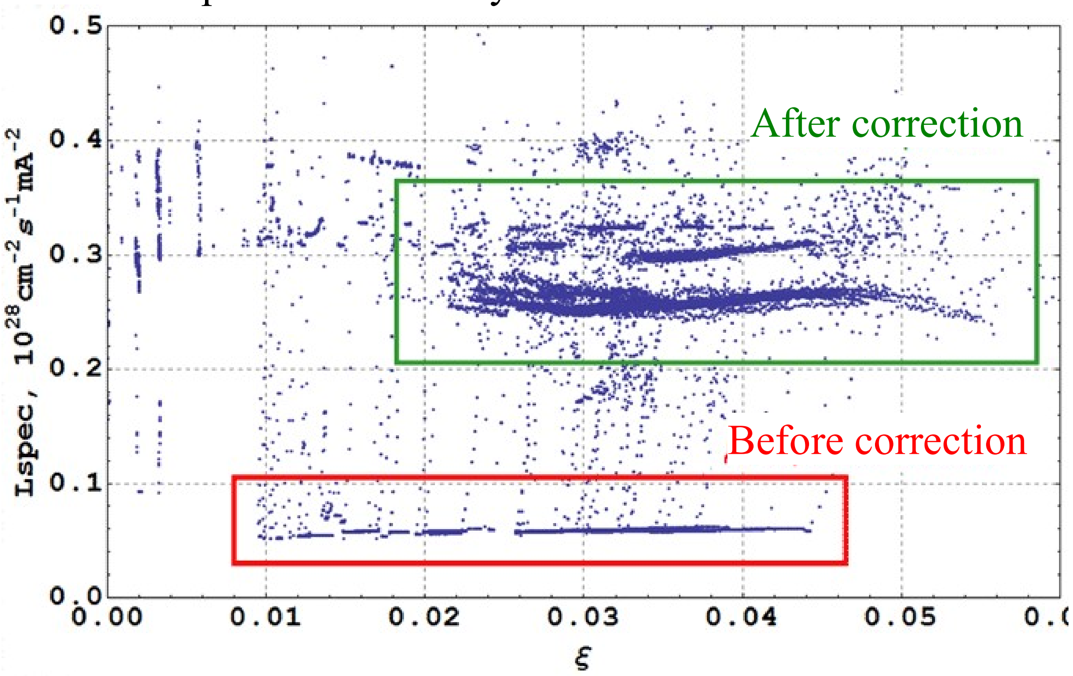


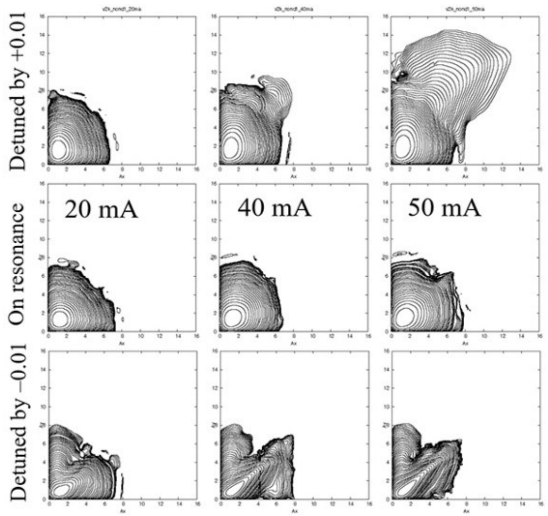
Machine tuning

1) Orbit correction & minimization of steerers currents using ORM techniques
2) Lattice correction via ORM SVD analysis ($\delta\beta < 5\%$)
3) Symmetry break due to CMD detector field (1.3 T) careful compensation
4) Betatron coupling correction in arcs ($\delta\nu_{min} \sim 0.001$)
5) Working point fine tuning & small shift below coupling diagonal
6) Sextupoles fine tuning (chromaticity slightly undercompensated)

Crucial for luminosity optimization!

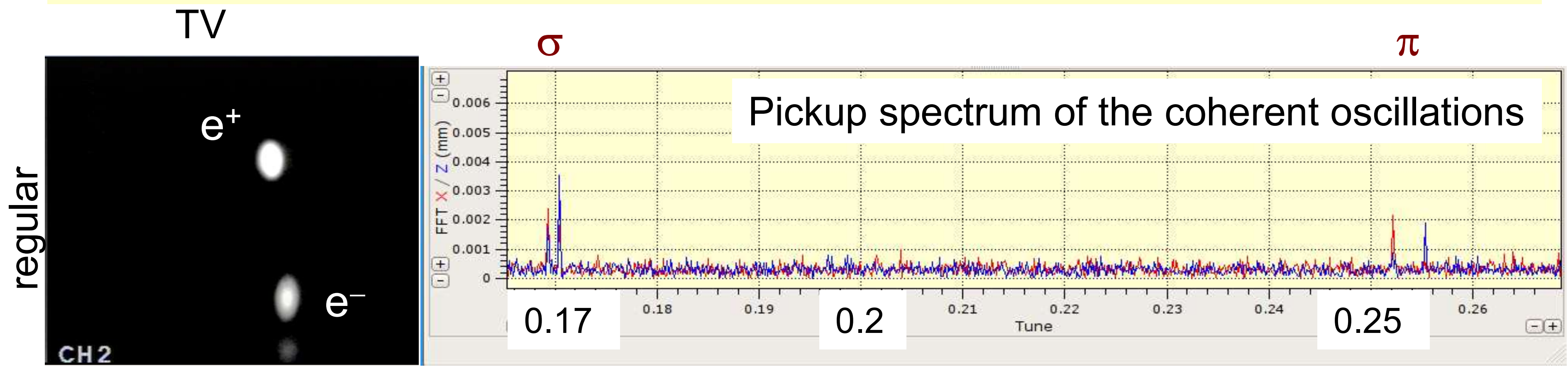
Specific luminosity & linear lattice correction

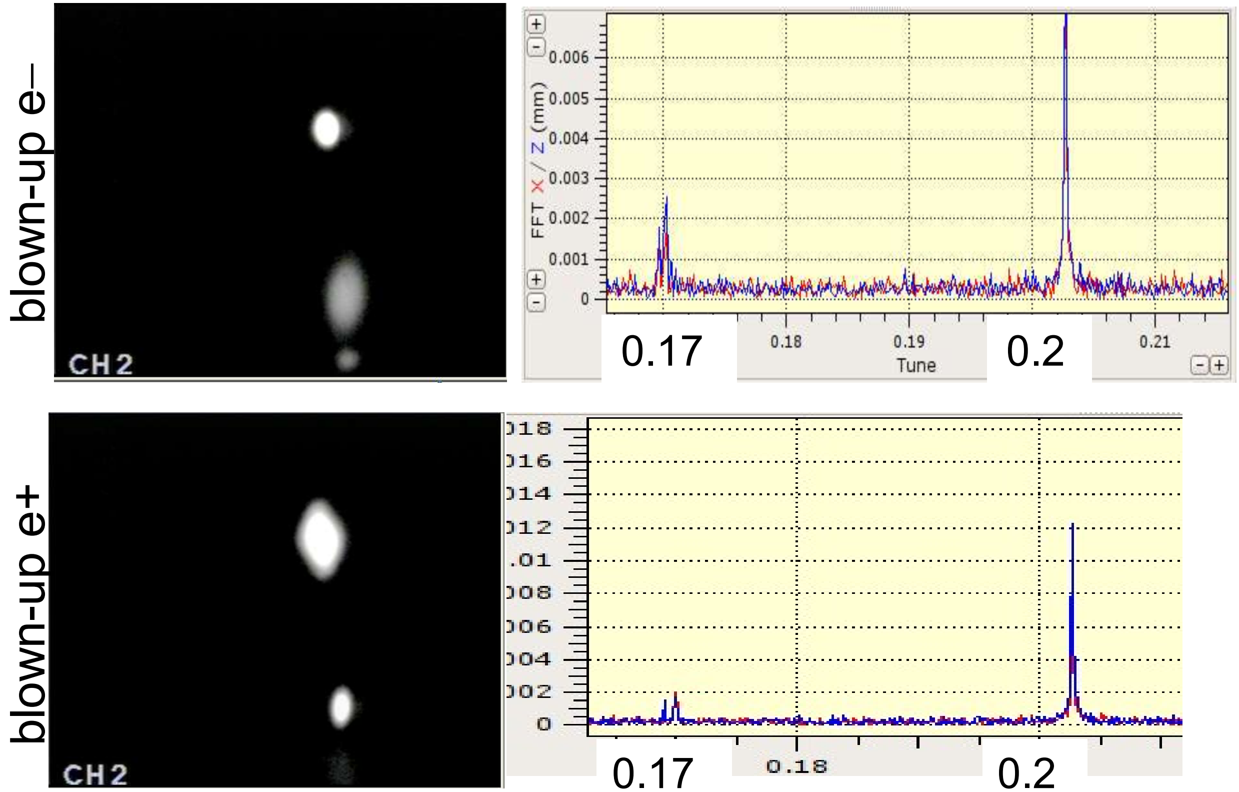




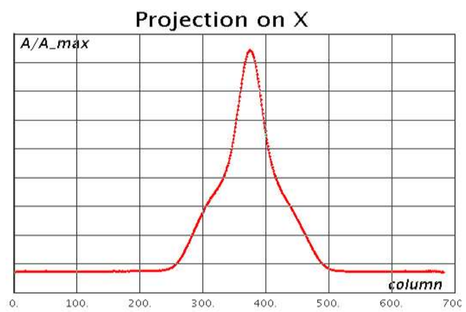
Lifetrac by D.Shatilov, 2008

“Flip-flop” effect





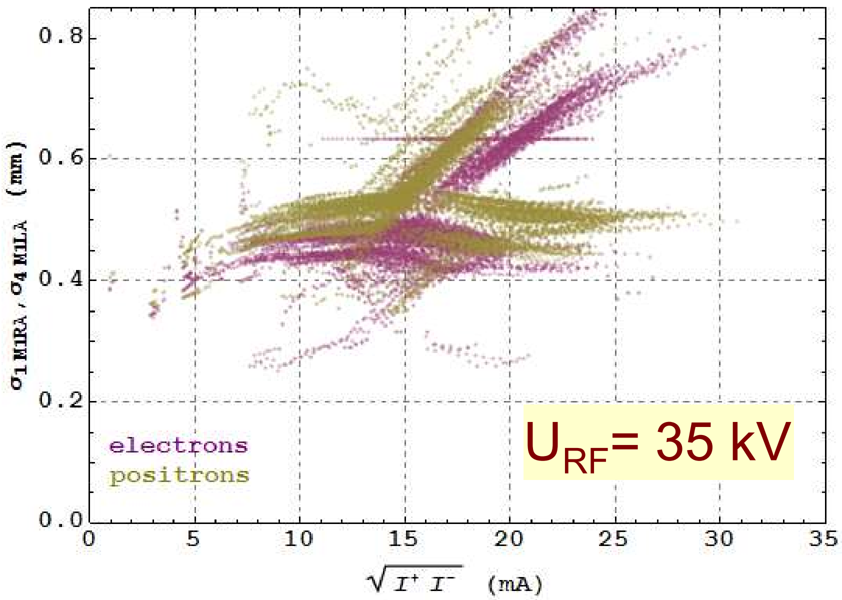
$E = 240$ MeV,
$I_{beam} \sim 5\times5$ mA

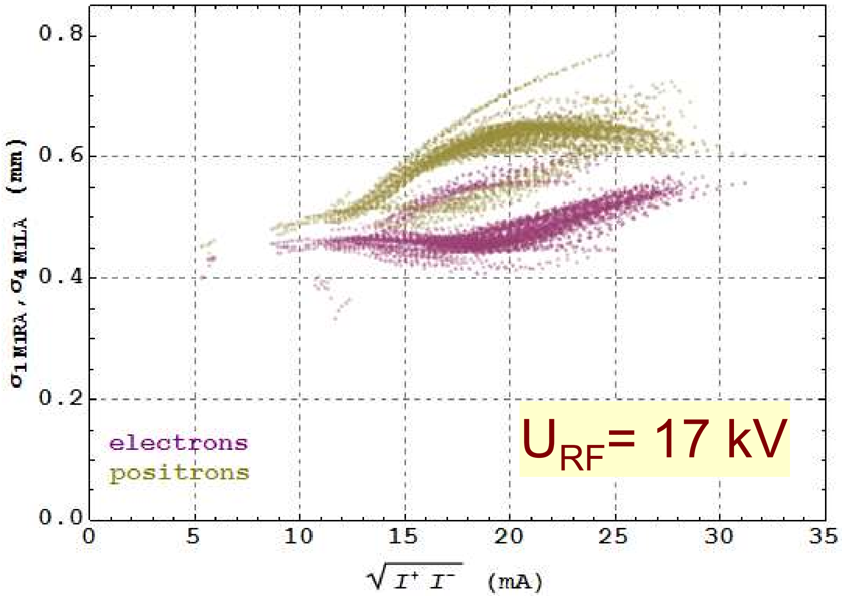


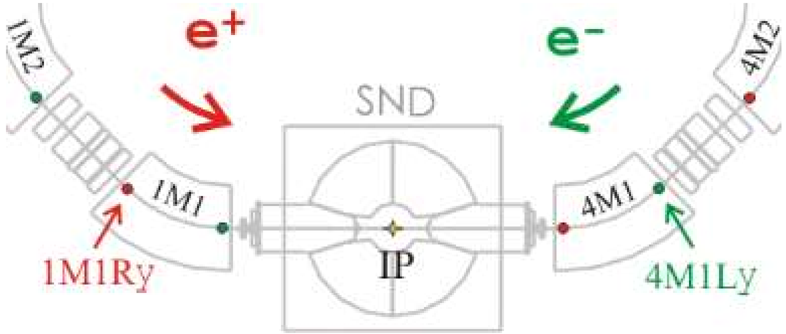
Coherent beam-beam π-mode interaction with machine nonlinear resonances?

Flip-flop suppression with long bunch

E= 392.5 МэВ

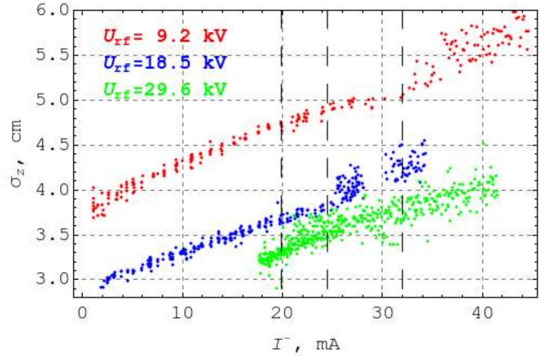




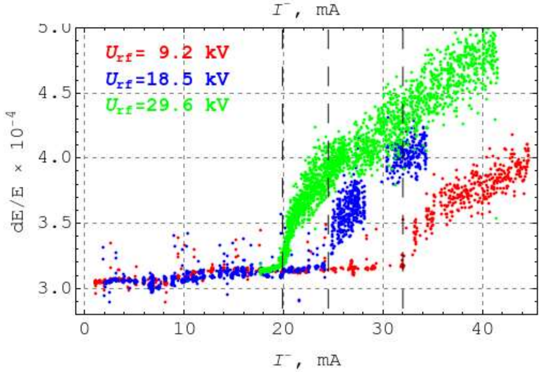


Bunch lengthening & mw instability

Single bunch length measurement with phi-dissector as a function of single beam current for different RF voltage @ 478 MeV.



Energy spread dependence, restored from beam transverse profile measurements.



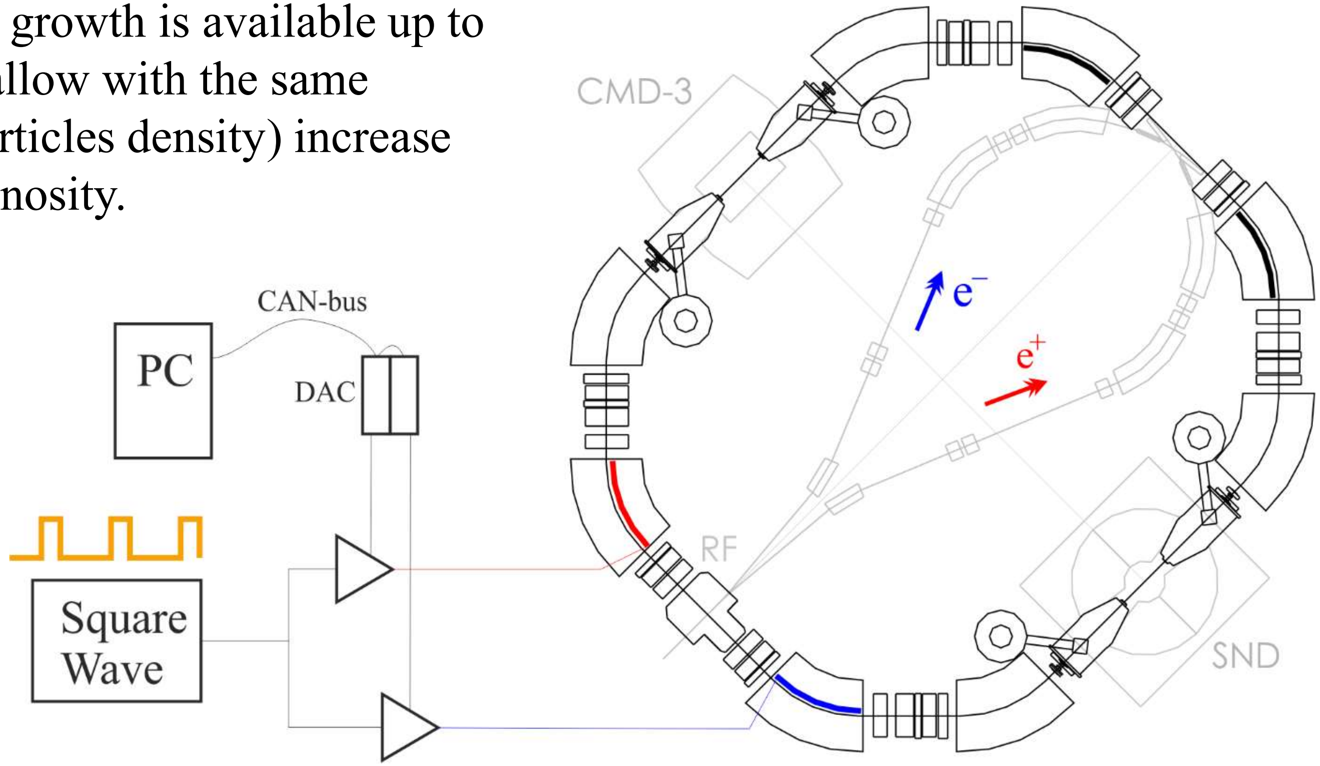
BeamShaker (Run 2017/18)

<u>Idea (I.Koop)</u>: kicked bunch oscillations decoheres very fast in the presence of counter beam's strongly nonlinear field. Weak and frequent kicks should effectively increase the emittance, similarly to quantum excitation by wiggler.

At low energies emittance growth is available up to aperture restriction. That allow with the same beam-beam parameter (particles density) increase the beam current and luminosity.

Typical values:
50-100 V, 300 ns, 50 μs

(T_{rev} = 81.4 ns)



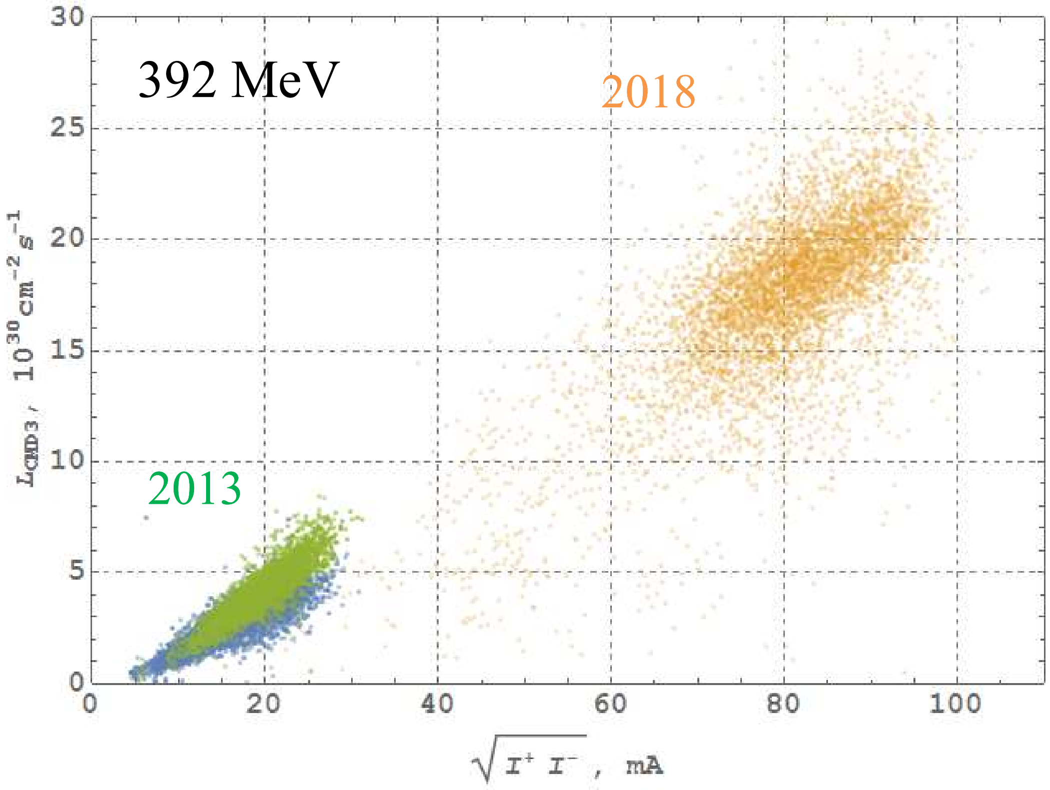
<u>Experimentally</u>: permanent excitation of "strong" beam size prevent it from shrinkage to natural value during injection cycle of "weak" beam, or whatsoever. Very effective suppression of flip-flop meta-stable states.
In addition large emittance results in a lifetime enhancement.

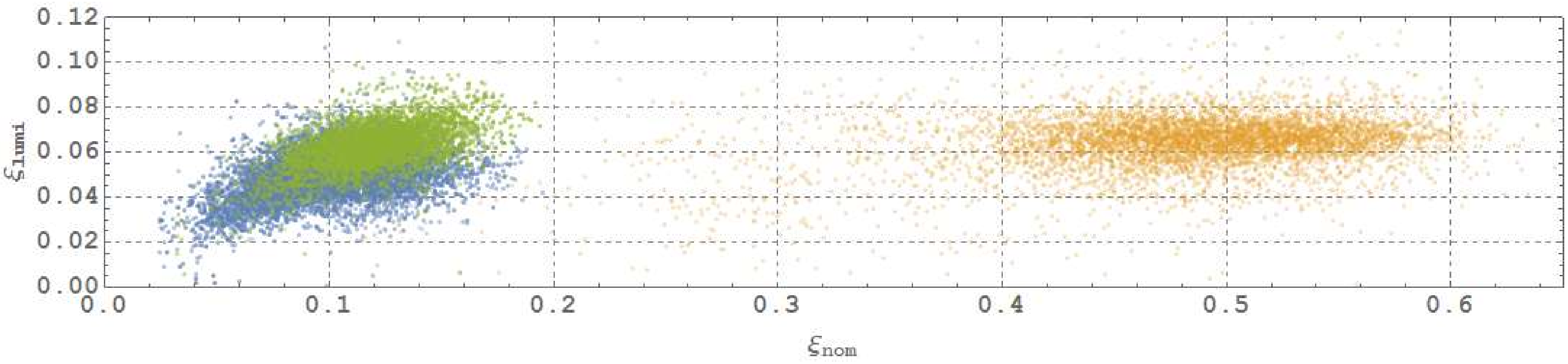
Luminosity and beam-beam parameter

$$\xi_{nom} = \frac{N^- r_e \beta^*_{nom}}{4\pi\gamma\sigma^{*2}_{nom}}$$ - normalized beam current

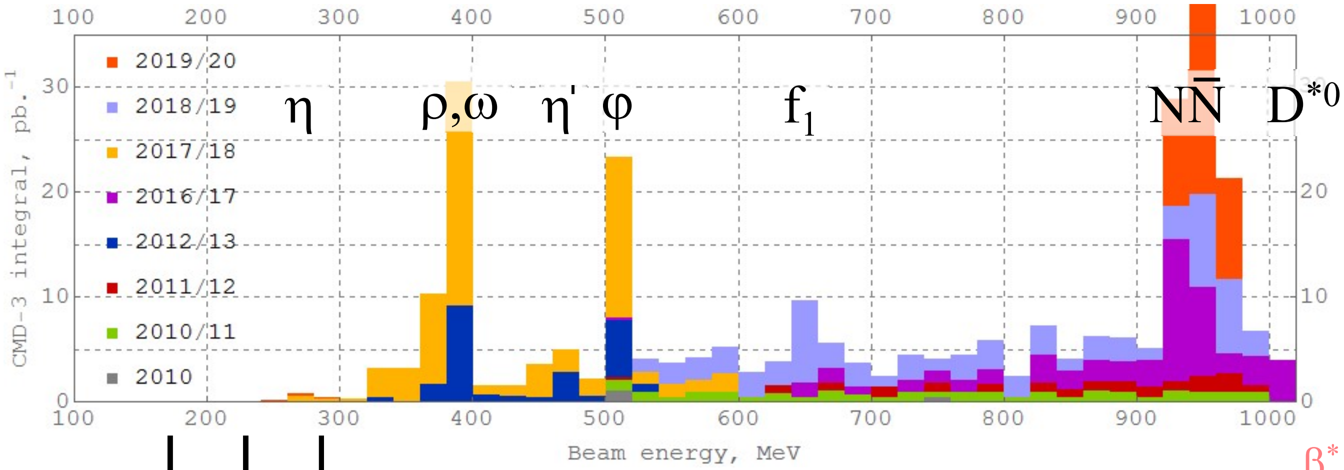
$$\xi_{lumi} = \frac{N^- r_e \beta^*_{nom}}{4\pi\gamma\sigma^{*2}_{lumi}}$$ - "beam-beam parameter"

$$L = \frac{N^+ N^-}{4\pi\sigma^{*2}} f_0 = \frac{N f_0 \gamma}{r_e} \frac{\xi_{lumi}}{\beta^*_{nom}}$$

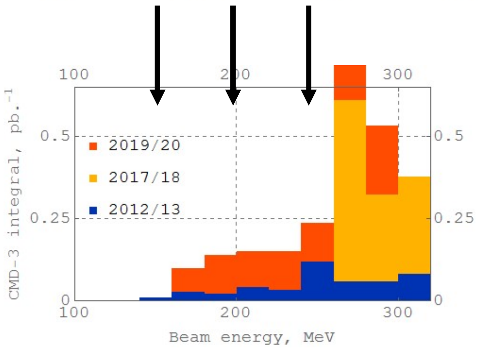




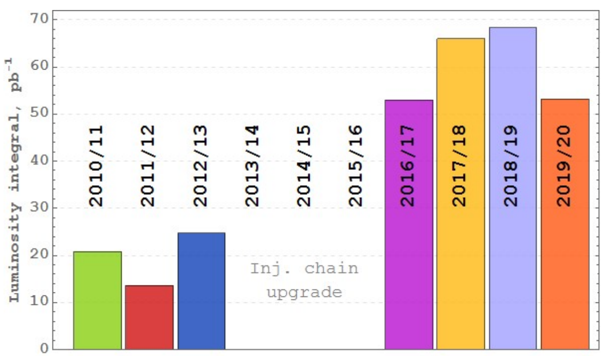
Luminosity & data taking

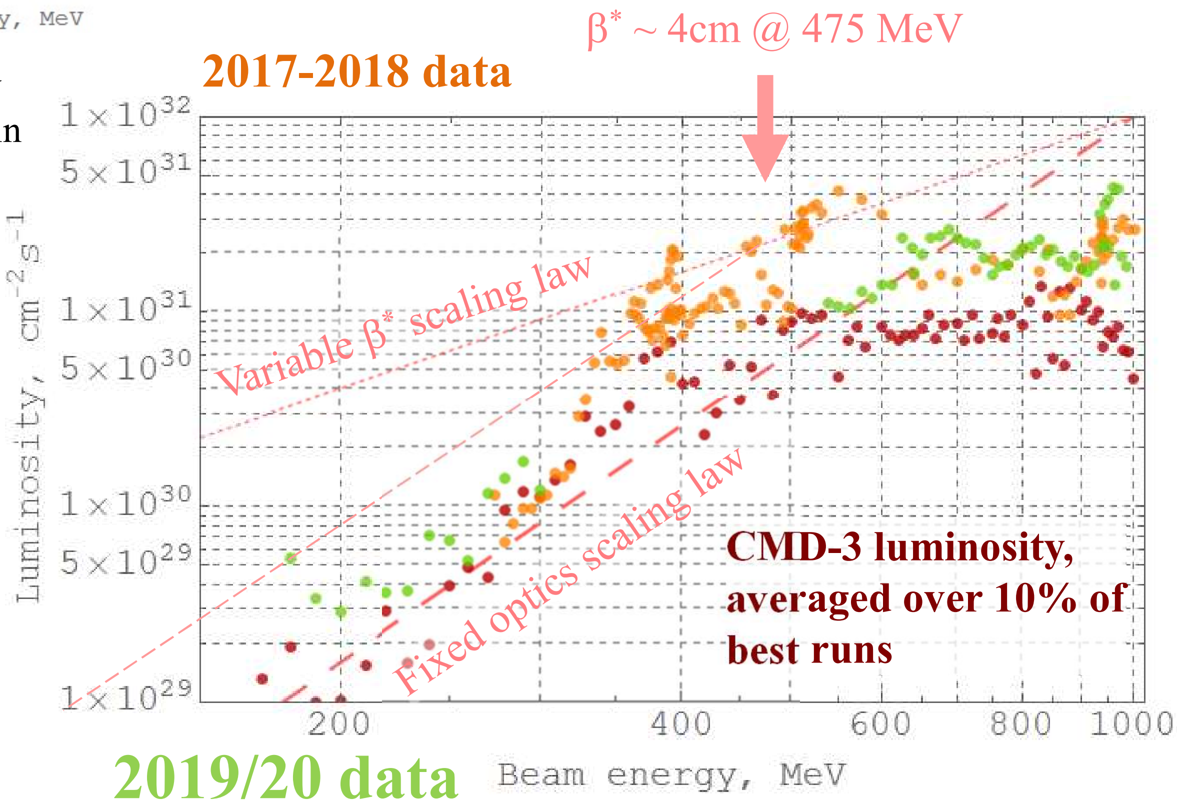


Highest luminosity achieved
$L_{peak} = 5\times10^{31}$ $cm^{-2}s^{-1}$
@ 550 MeV

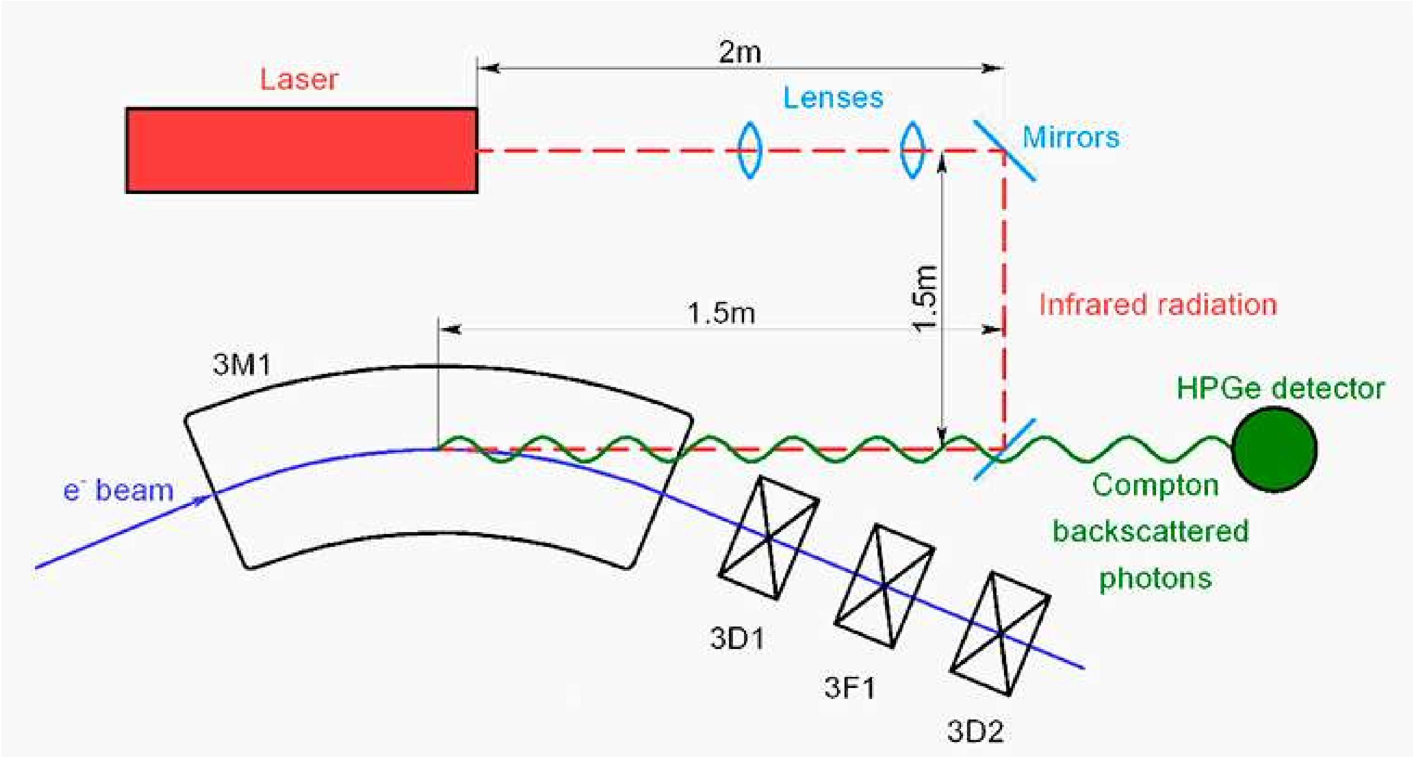


Lowest energy ever obtained in e^+e^- colliders

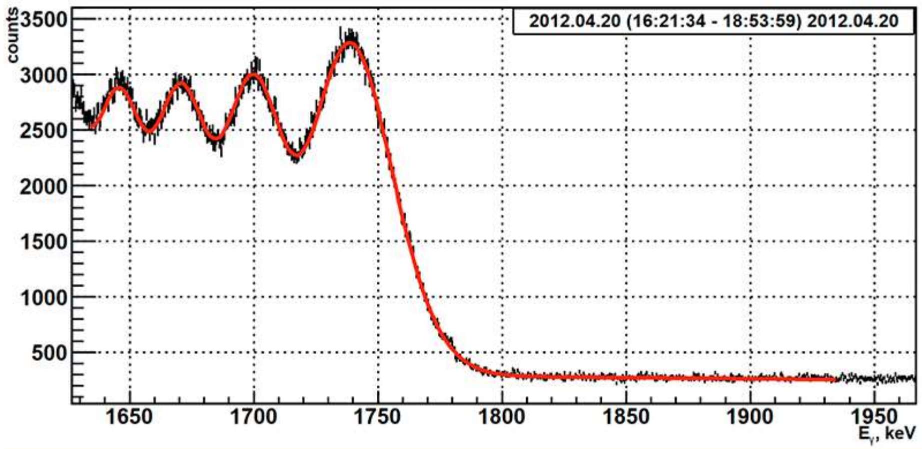




Beam energy measurements: CBS system



Backscattered photons spectrum edge:



E.V. Abakumova et al., PRL 110 2013 140402

Summary

- BINP has a long history of experiments with colliding beams (VEP-1, 1963).
- New BINP injection complex routinely serves both colliders.
- VEPP-4M has started the program at it’s high energy range with resonance depolarization system for precise energy control.
- VEPP-2000 with new BINP injector and upgraded booster started data taking in all energy range of 160–1000 MeV with a luminosity increased in a factor of 2-5.
- Round beams concept gives the luminosity enhancement @ VEPP-2000.
- Novel technique (“beamshaking”) for effective emittance control allow to suppress flip-flop effect and increase beams intensity at middle energies.

Thank you for your attention!