Электрон-позитронный коллайдер ВЭПП-2000 – опыт работы с круглыми пучками

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Научная сессия секции ядерной физики ОФН РАН

03 апрель 2024

Outline

VEPP-2000 collider overview

Main sources of the luminosity limitations

Suppression of the flip-flop effects by a beam shaker

Beam-beam parameter world records at VEPP-2000

Runs 2010-2024 luminosity results

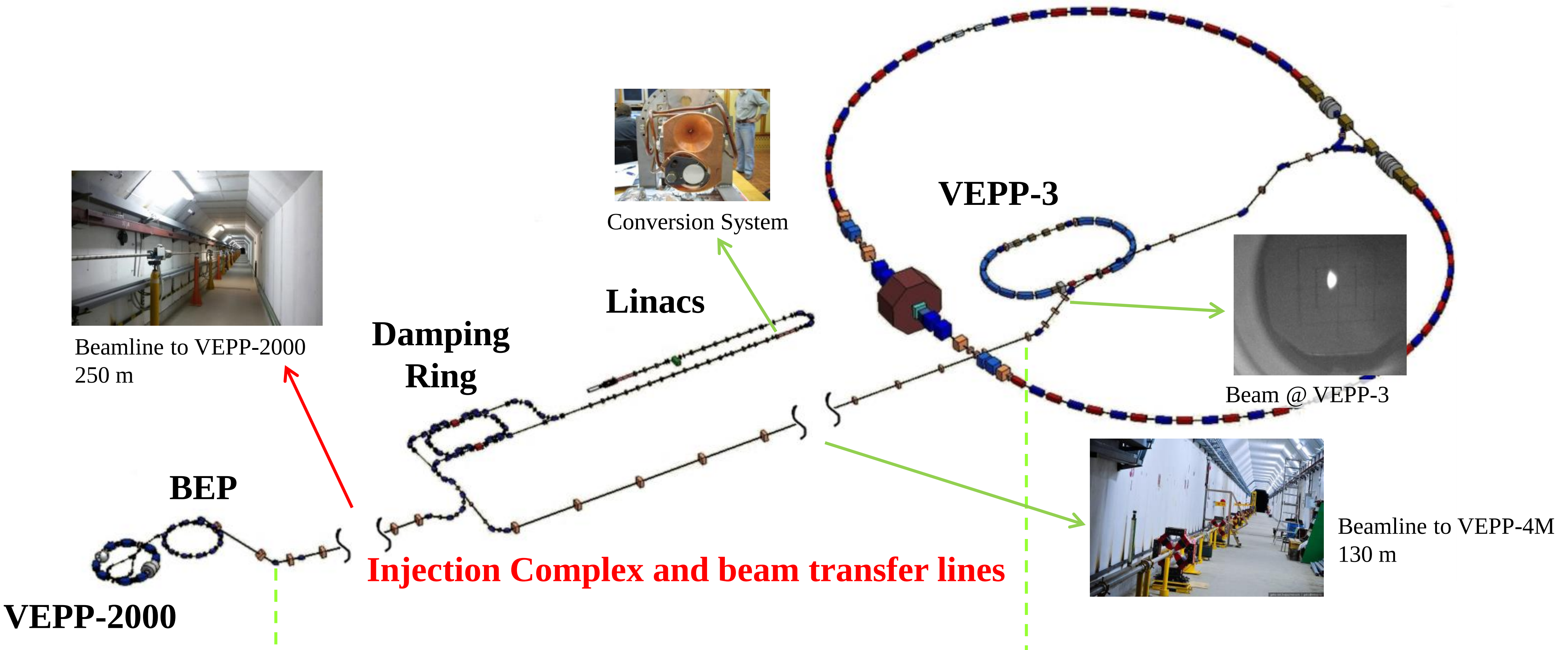
Conclusion

BINP accelerator complex layout

D. Berkaev et al., "VEPP-5 Injection Complex: Two Colliders Operation Experience", in Proc. IPAC'17, Copenhagen, Denmark.

IC Parameters (2016)

Beam Energy:	**395 MeV**
Storage rate e^- @ 12.5 Hz:	**$4.0\cdot10^{10}$/s** (70 mA/s)
Storage rate e^+ @ 12.5 Hz:	**$4.0\cdot10^{9}$/s** (7 mA/s)

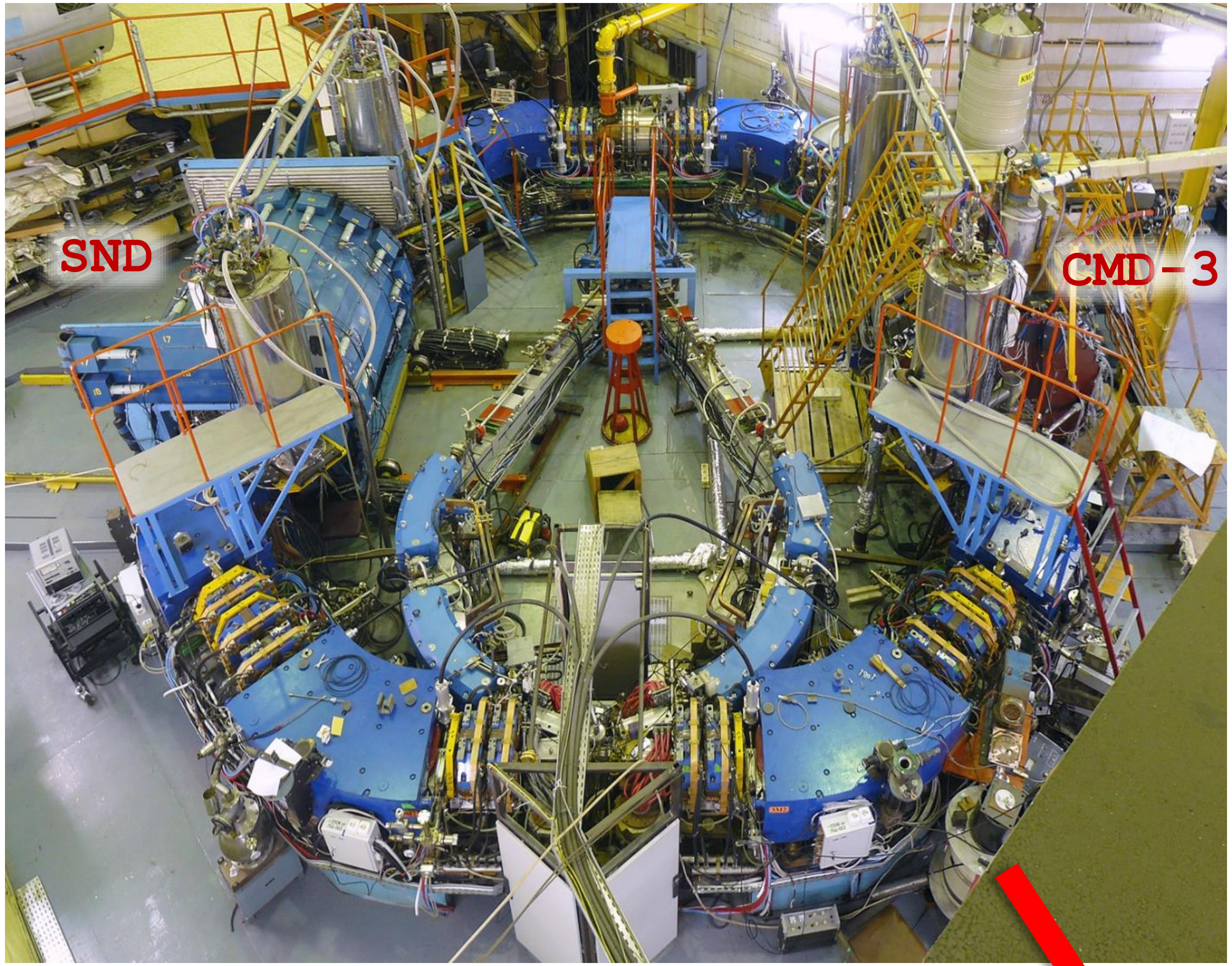


F. Emanov et al., "Status of VEPP-5 Injection Complex", presented at the IPAC'21, Campinas, Brazil, May 2021, paper THPAB021.

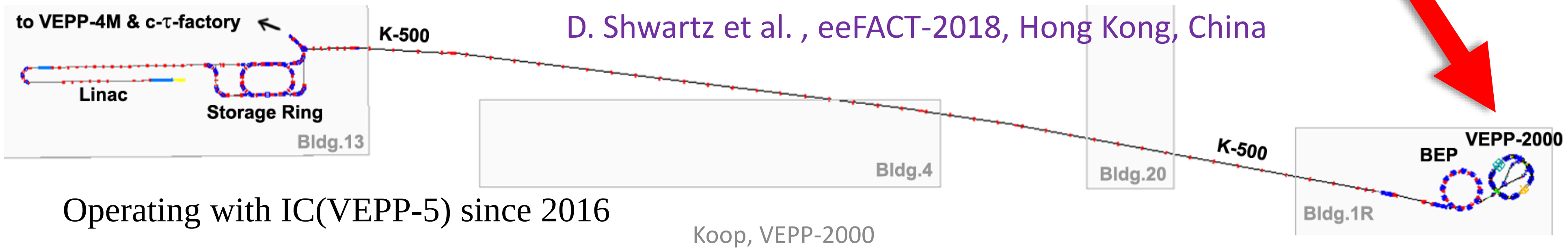
VEPP-2000 overview

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 T NC dipoles @ 1 GeV
- CBS for energy control



D. Shwartz et al. , eeFACT-2018, Hong Kong, China



Operating with IC(VEPP-5) since 2016

Experimental program

*Dedicated talks by **BINP** speakers*

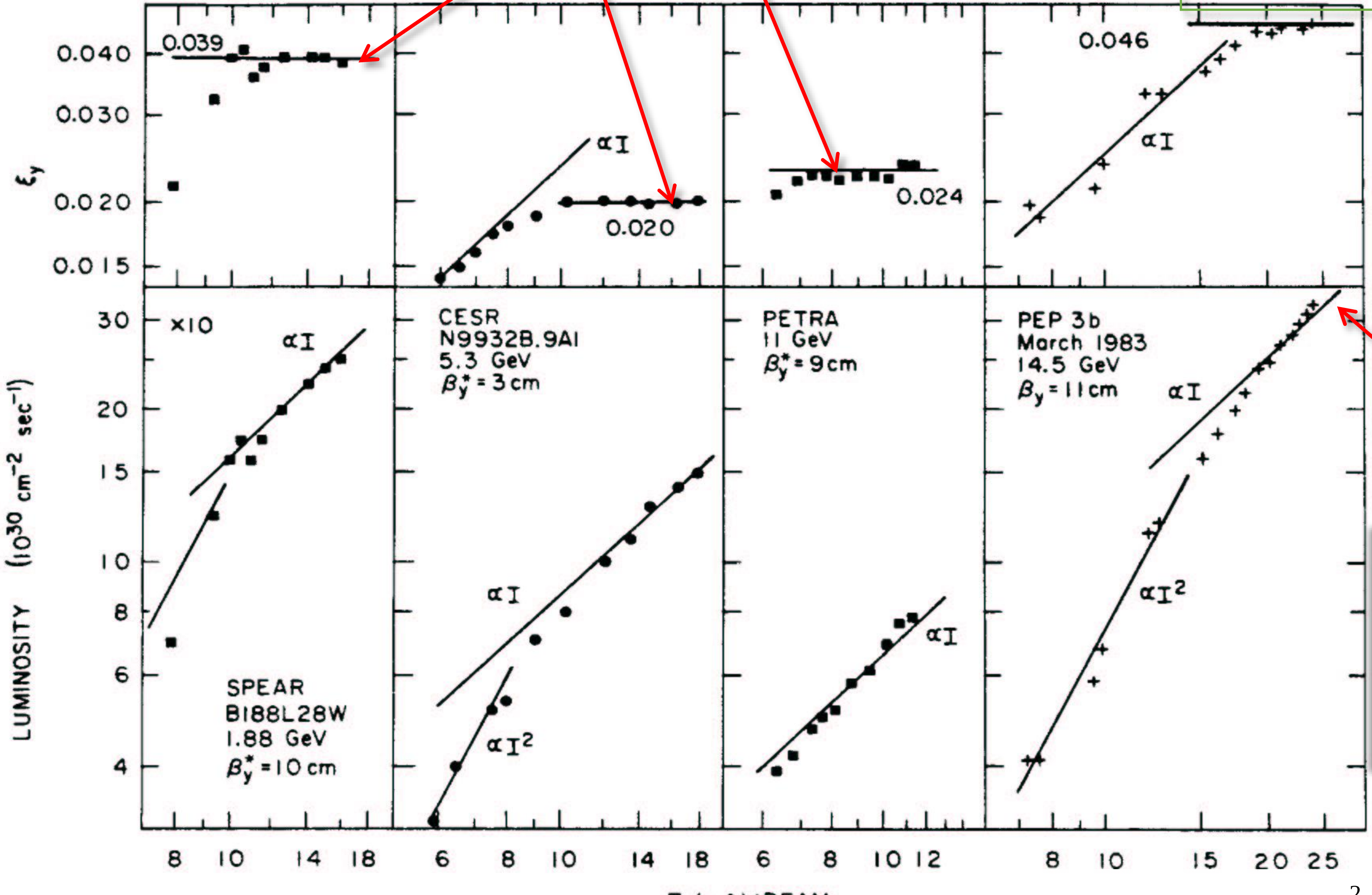
1. Precision measurement of $R = \quad (e^+e^- \to hadrons)/\,\sigma(e^+e^- \to \mu^+\mu^-)$
   exclusive approach, up to <1% for major modes
2. Study of hadronic final states:
   $$e^+e^- \to 2h, 3h, 4h, \ldots \quad h = \pi, K, \eta$$
3. Study of vector mesons and theirs excitations:
   $$\rho', \rho'', \omega', \varphi', \ldots$$
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 - reached in march 2024!

Beam-beam limit in 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 limitation:
1) emittance blowup,
2) lifetime reduction,
3) flip-flop effect

By J.Seeman (1983)

Koop, VEPP-2000

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

The concept of Round Colliding Beams

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

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: $\beta_x = \beta_y$
- Equal beam emittances: $\varepsilon_x = \varepsilon_y$
- Equal fractional parts of betatron tunes: $\nu_x = \nu_y$

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

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

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

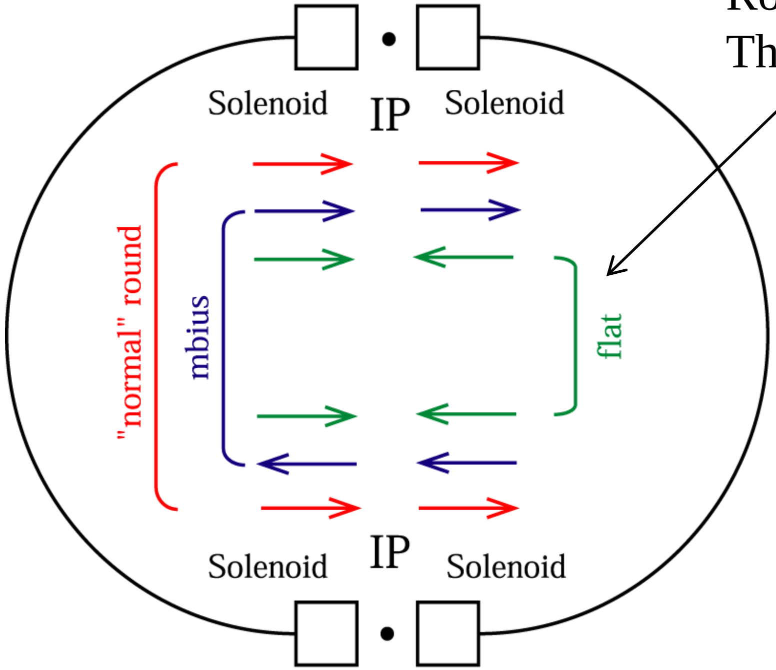
L.M. Barkov, et. al, Proc. HEACC'89, Tsukuba, Japan, p.1385.

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

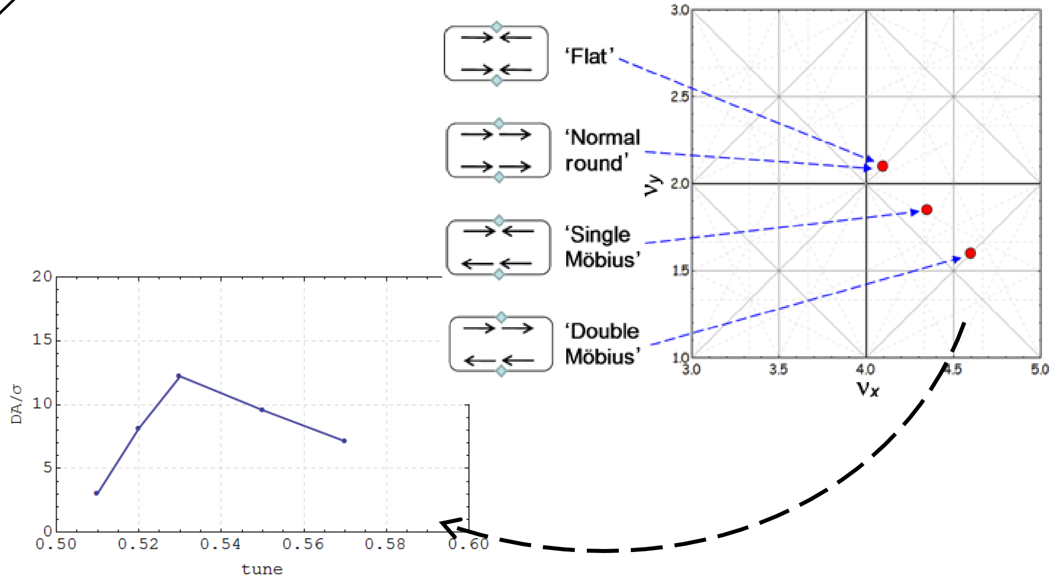
V.V. Danilov et al., EPAC'96, Barcelona, p.1149.

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

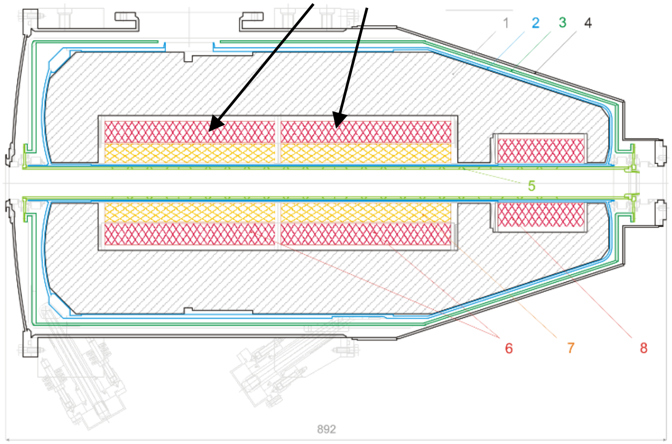
Round Beams Options at VEPP-2000



Round beam due to coupling resonance?
The simplest practical solution! Best beam-beam limit achieved!



Solenoid main coils

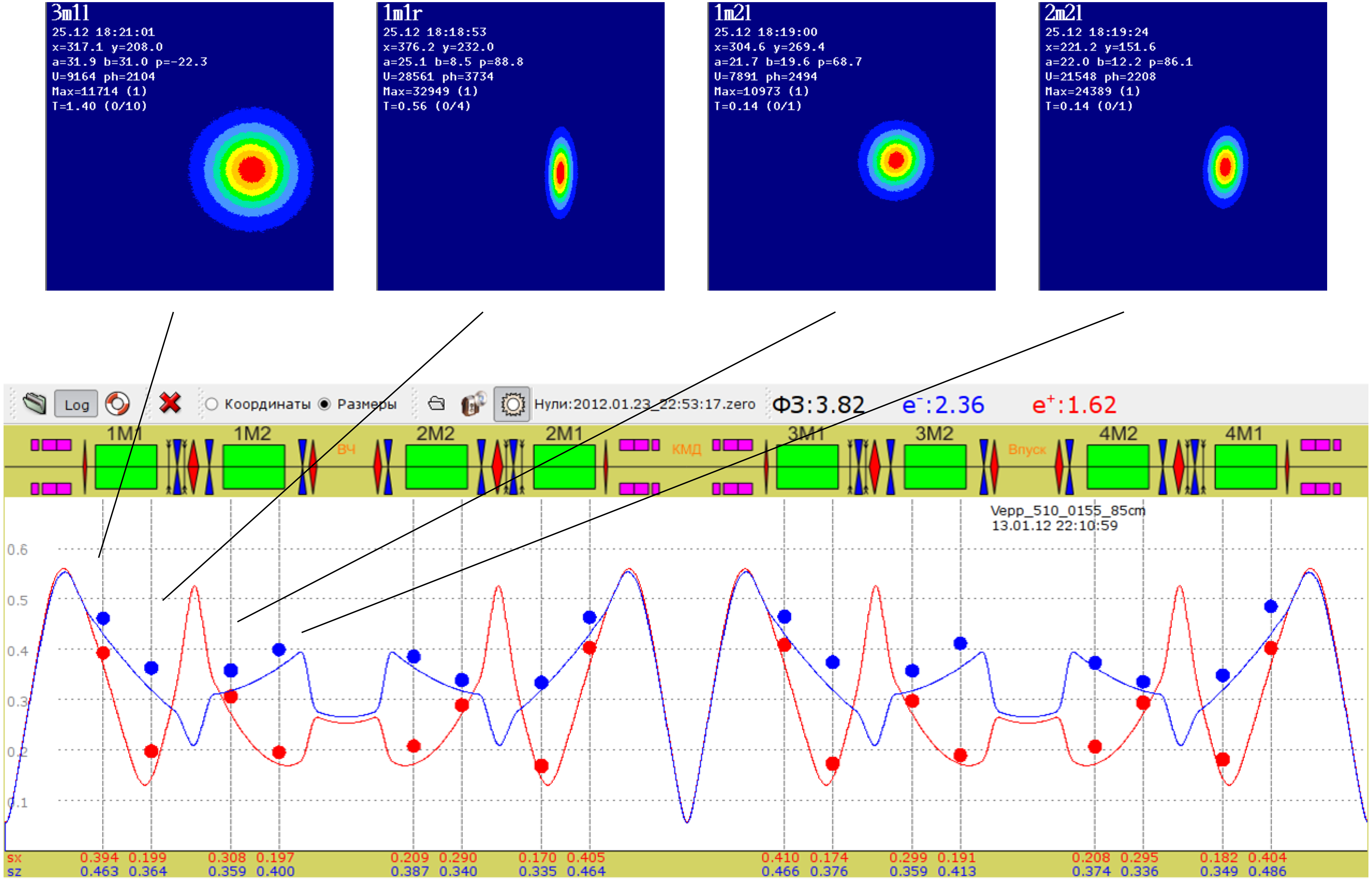


Both simulations and experimental tests showed insufficient dynamic aperture for regular work in circular modes options.

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.

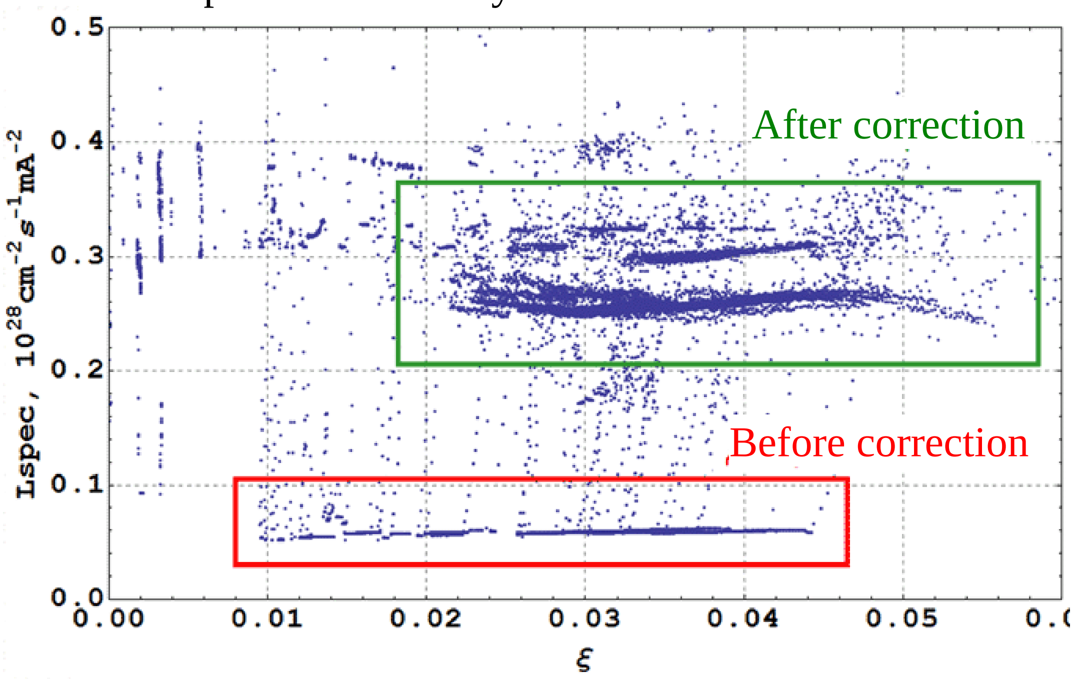
Beam size measurement via SR @ CCDs

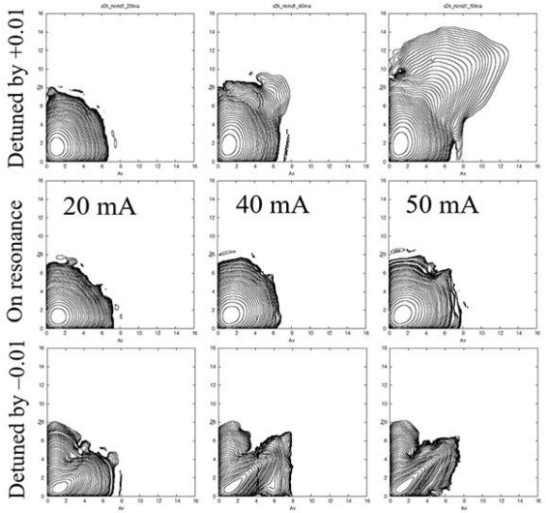


Machine tuning

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

Specific luminosity & linear lattice correction





Lifetrac by D.Shatilov, 2008

Beam-beam effects

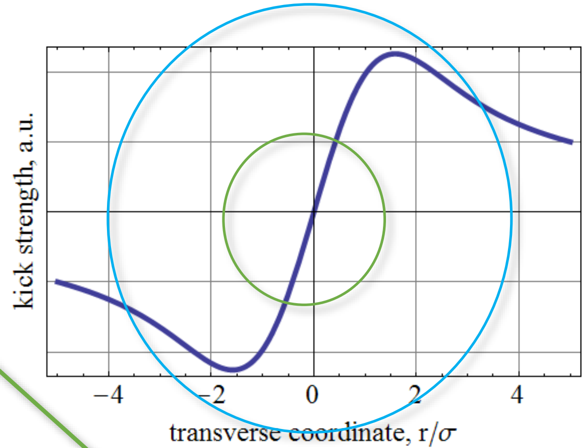
How many interacts? $\frac{L \cdot \sigma_{process}}{f_0} \sim \frac{10^{32}\,cm^{-2}s^{-1} \cdot 10^{-24}\,cm^2}{12 \cdot 10^6\,Hz} \sim 10$ Compare to $N_{bunch} \sim 10^{11}$

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

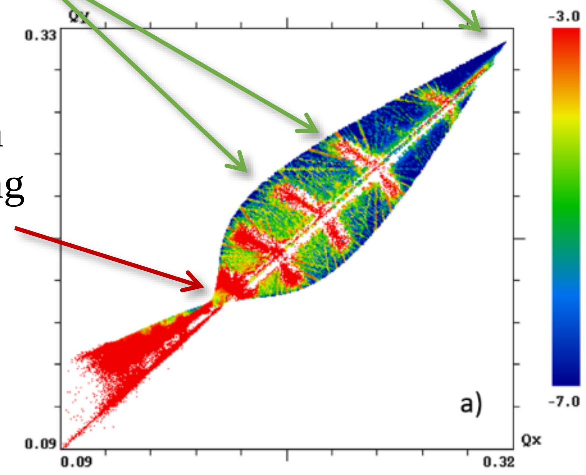
Linear beam-beam: tune shift

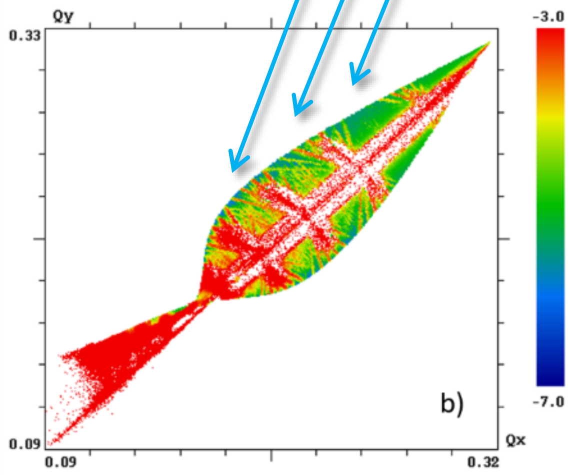
Resonances

Design working point



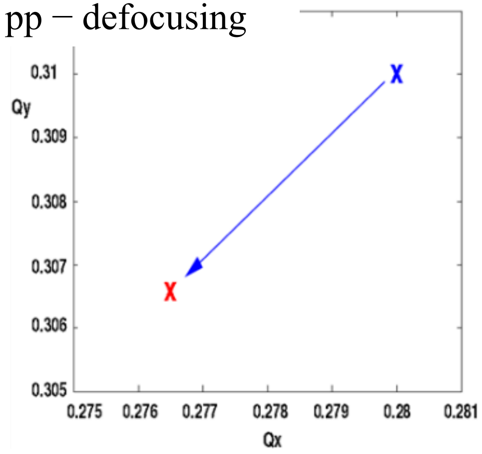
Nonlinear beam-beam: tune spread (footprint)
&
high-order resonance grid

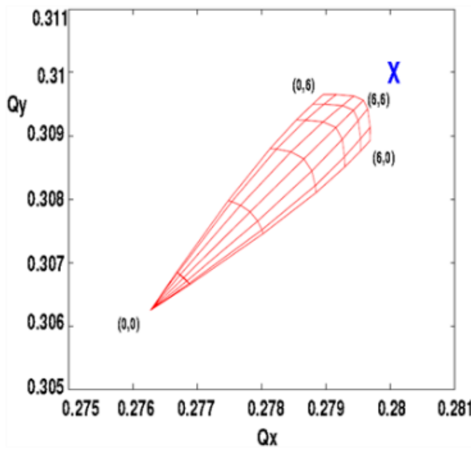




FMA: beam-beam simulations by Lifetrac

LHC example:
pp – defocusing



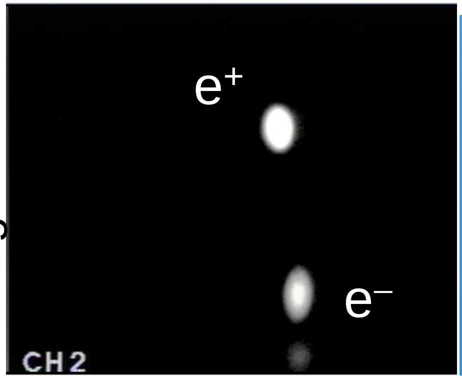


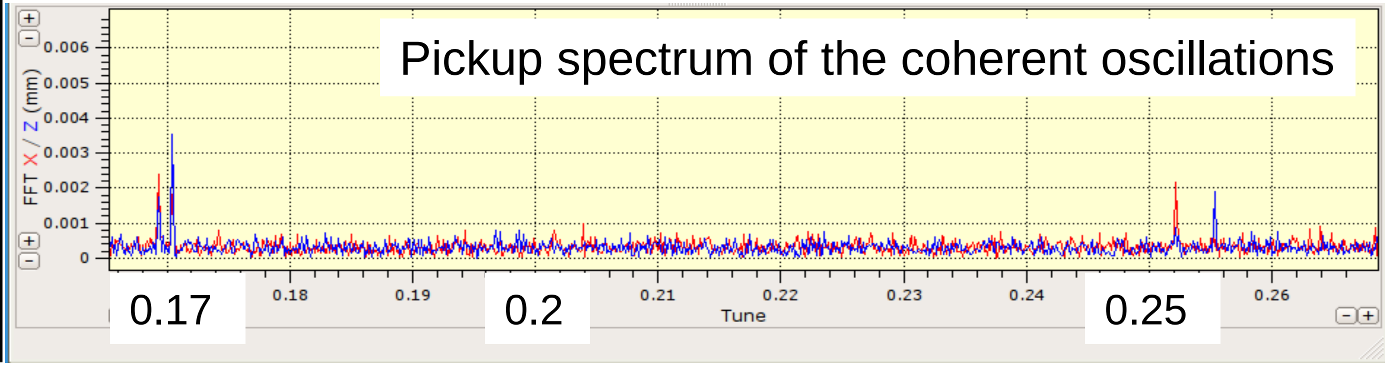
"Flip-flop" effect

TV

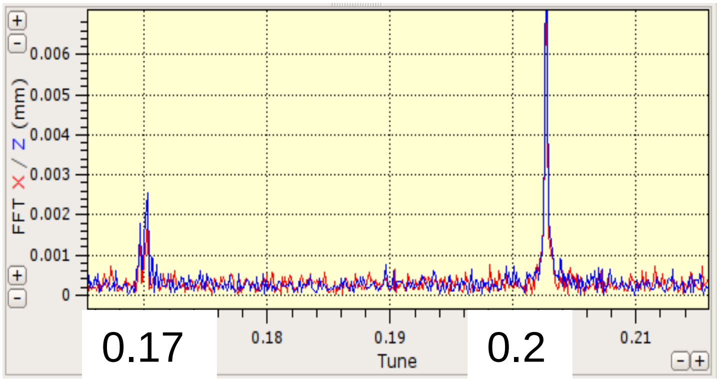
σ π

regular



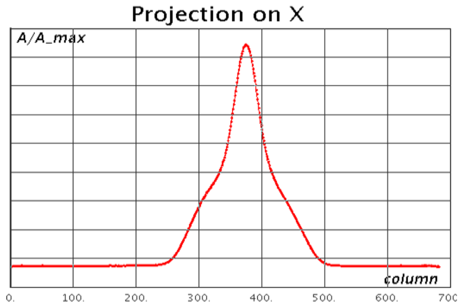


blown-up e–

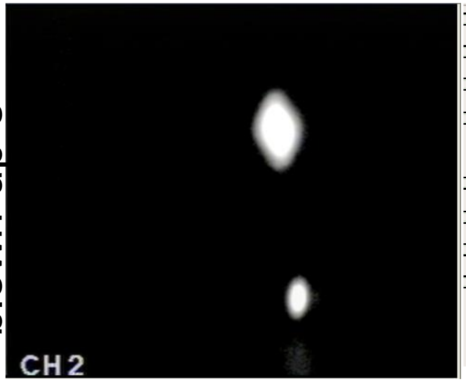


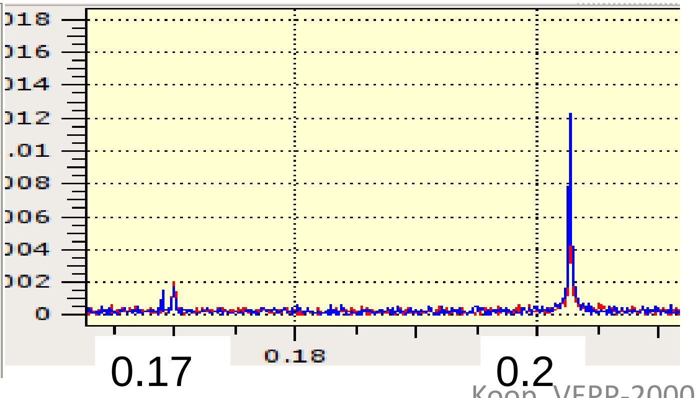
E = 240 MeV,

I_{beam} ~ 5×5 mA



blown-up e+

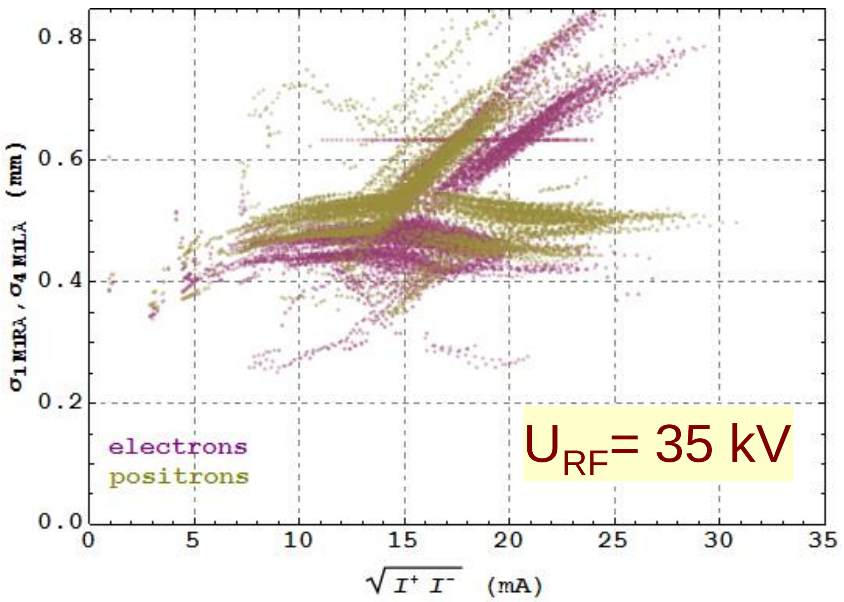


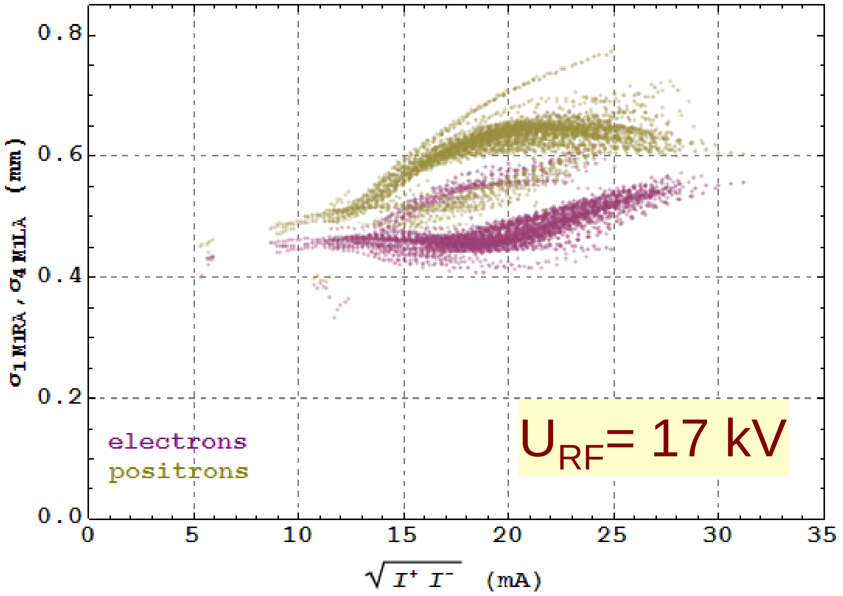


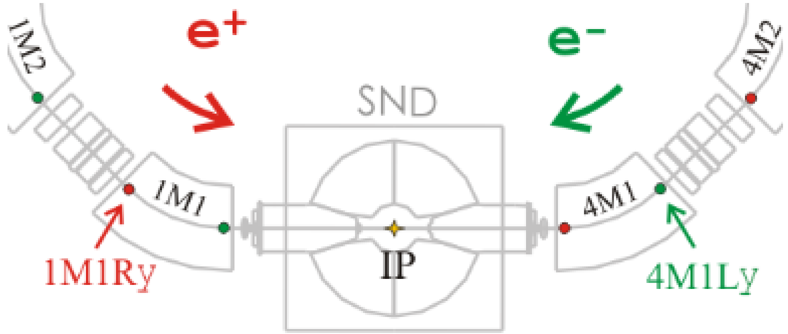
Coherent beam-beam π-mode interaction with machine nonlinear resonances?

Flip-flop suppression with longer bunches

E= 392.5 МэВ

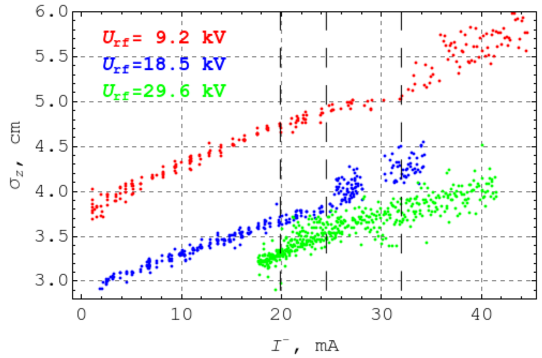




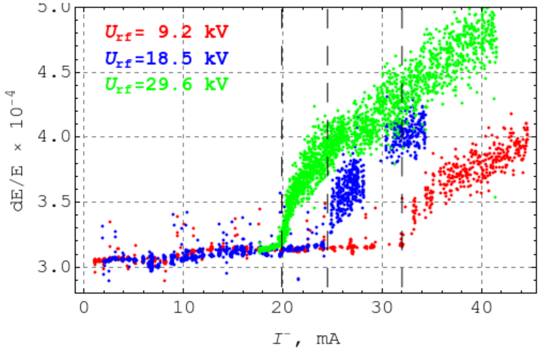


Bunch lengthening & mw instability

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.



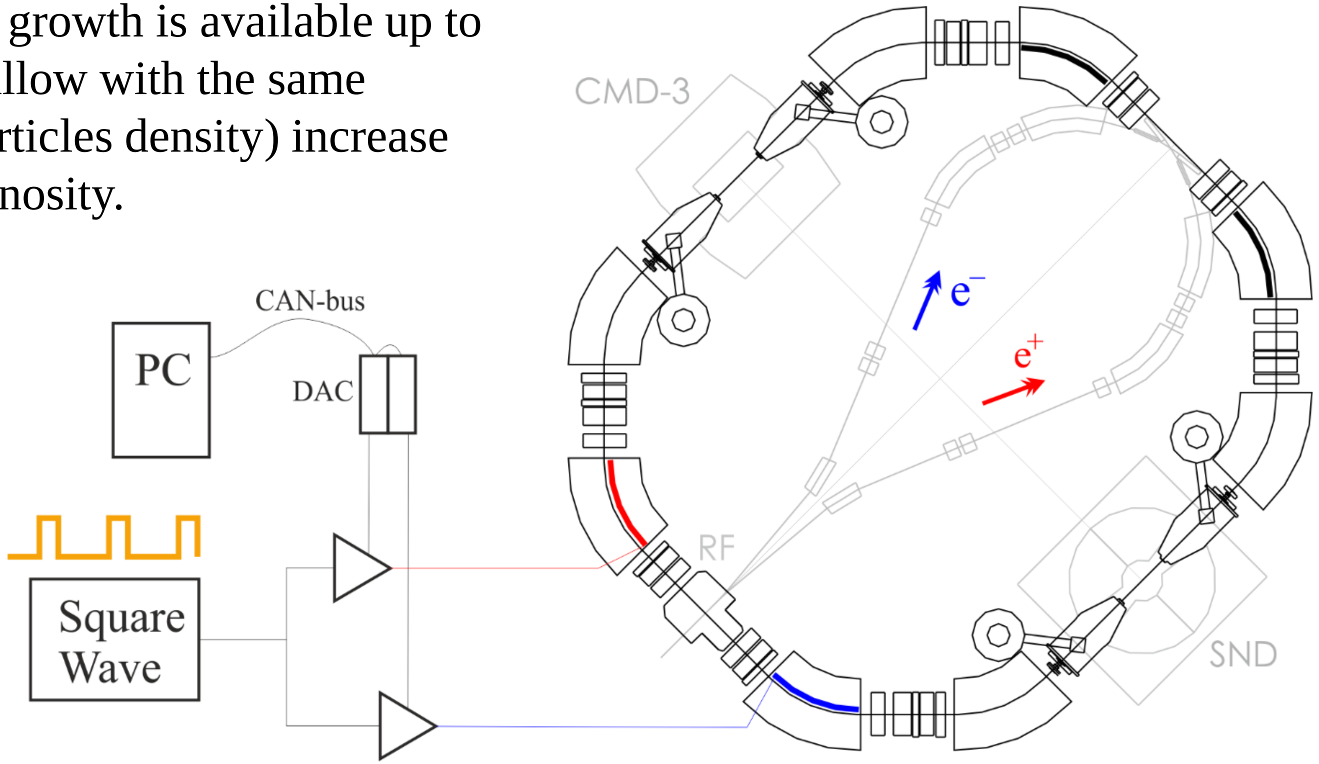
Beam Shaker (Run 2017/18)

Idea: 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 SR.

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)



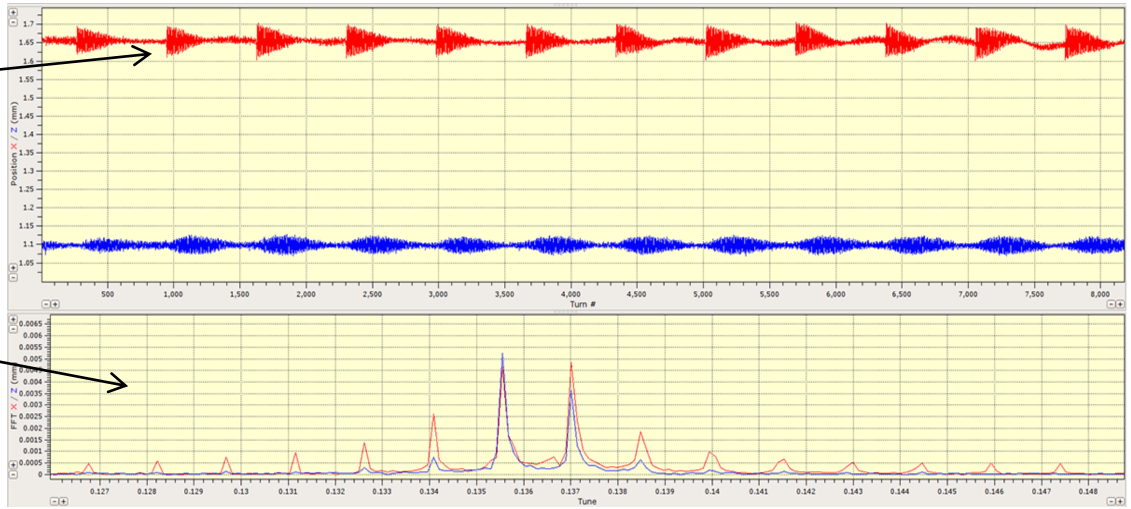
Experimentally: permanent excitation of "strong" beam size prevent it from shrinkage to natural value during injection cycle of "weak" beam, or whatsoever. Very effective suppression of flip-flop meta-stable states.
In addition large emittance results in a lifetime enhancement.

Shaking, as seen by Pickup

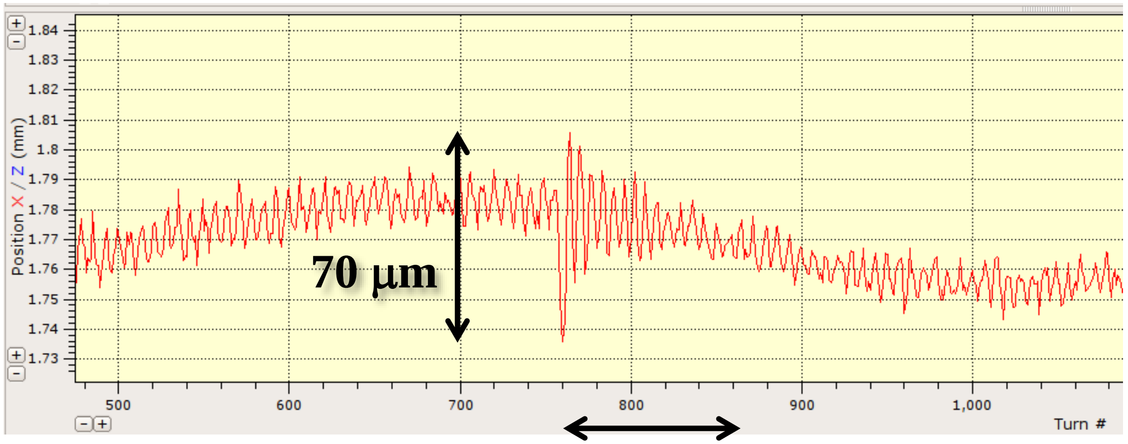
Beam is kicked in the horizontal plane

Periodically excited oscillations gives the line spectrum

Pickup signal, without counter beam, 360 MeV



Pickup signal, with strong counter beam, 274 MeV



100 turns - decoherence time

@ 274 MeV:

σ_x = 250 µm @ pickup

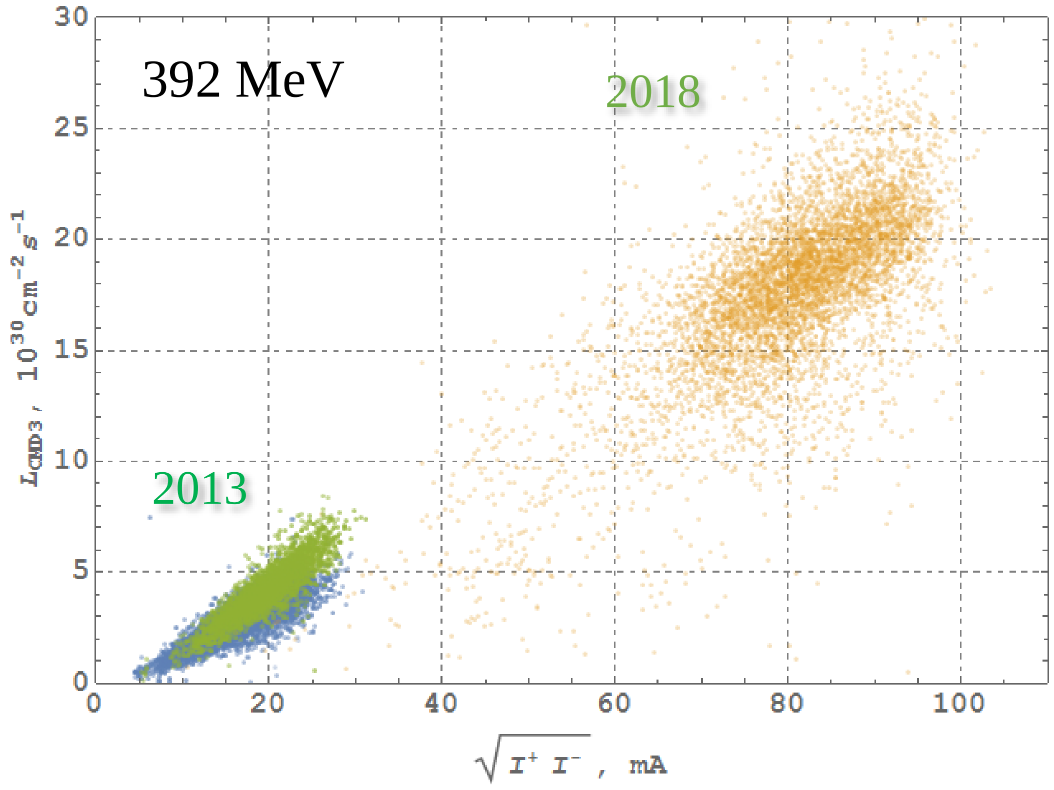
τ_{damp} = 130 ms = 1.6×10^6 turns

Luminosity and beam-beam parameter

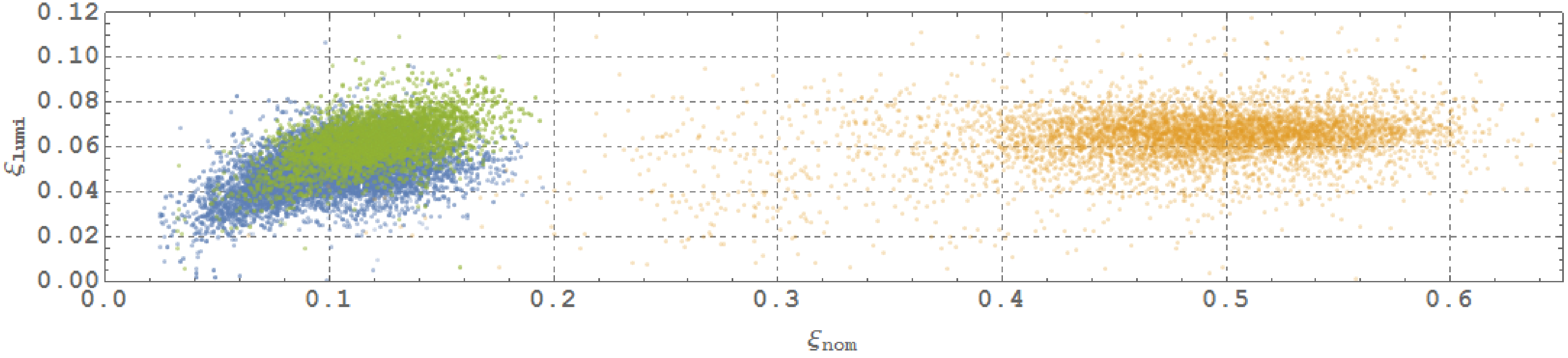
$$\xi_{nom} = \frac{N^- r_e \beta^*_{nom}}{4\pi\gamma\sigma^{*2}_{nom}}$$ - normalized beam current

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

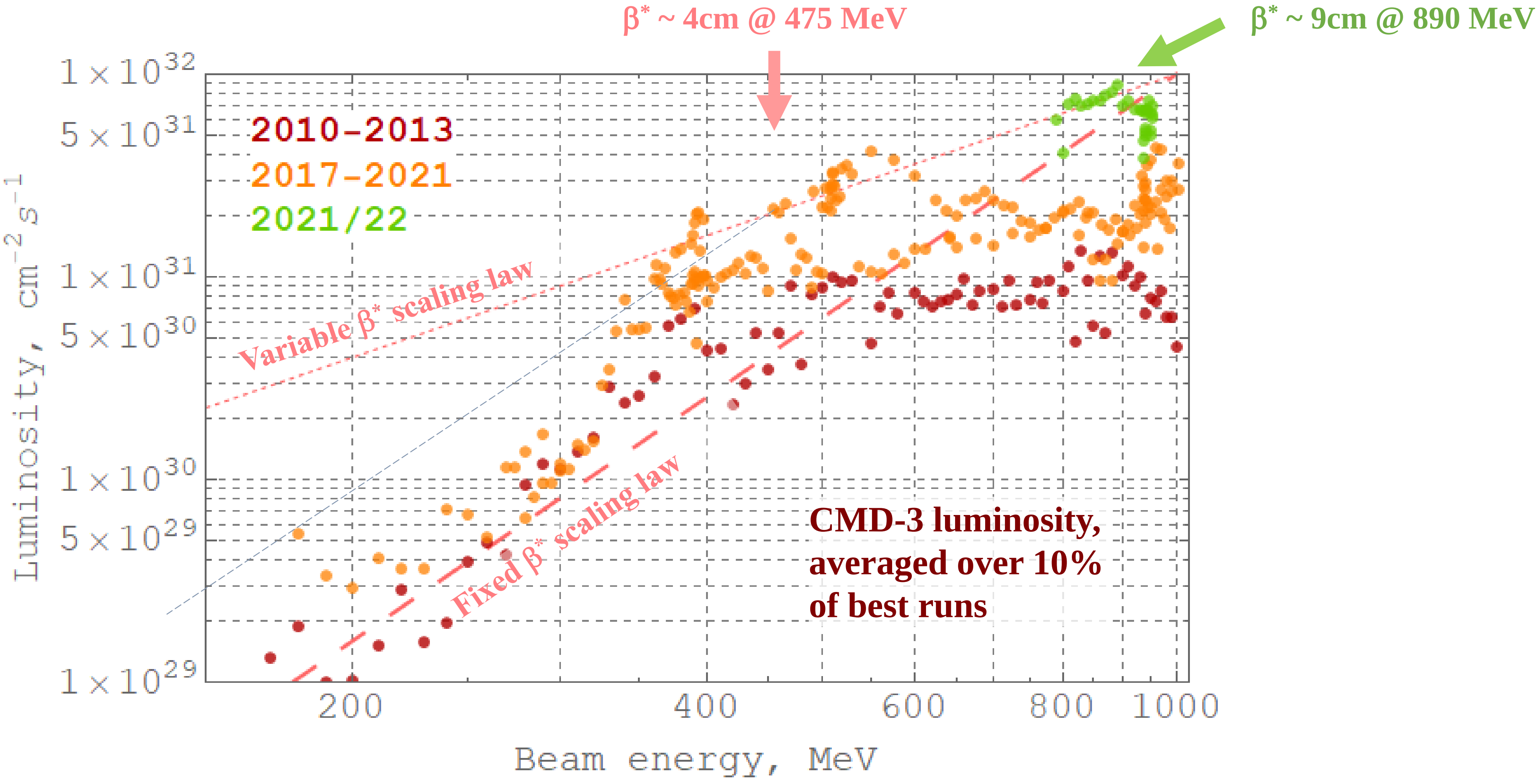
$$L = \frac{N^+ N^-}{4\pi\sigma^{*2}} f_0 = \frac{N f_0 \gamma}{r_e} \frac{\xi_{lumi}}{\beta^*_{nom}}$$



4-fold increase of the luminosity with a shaker!

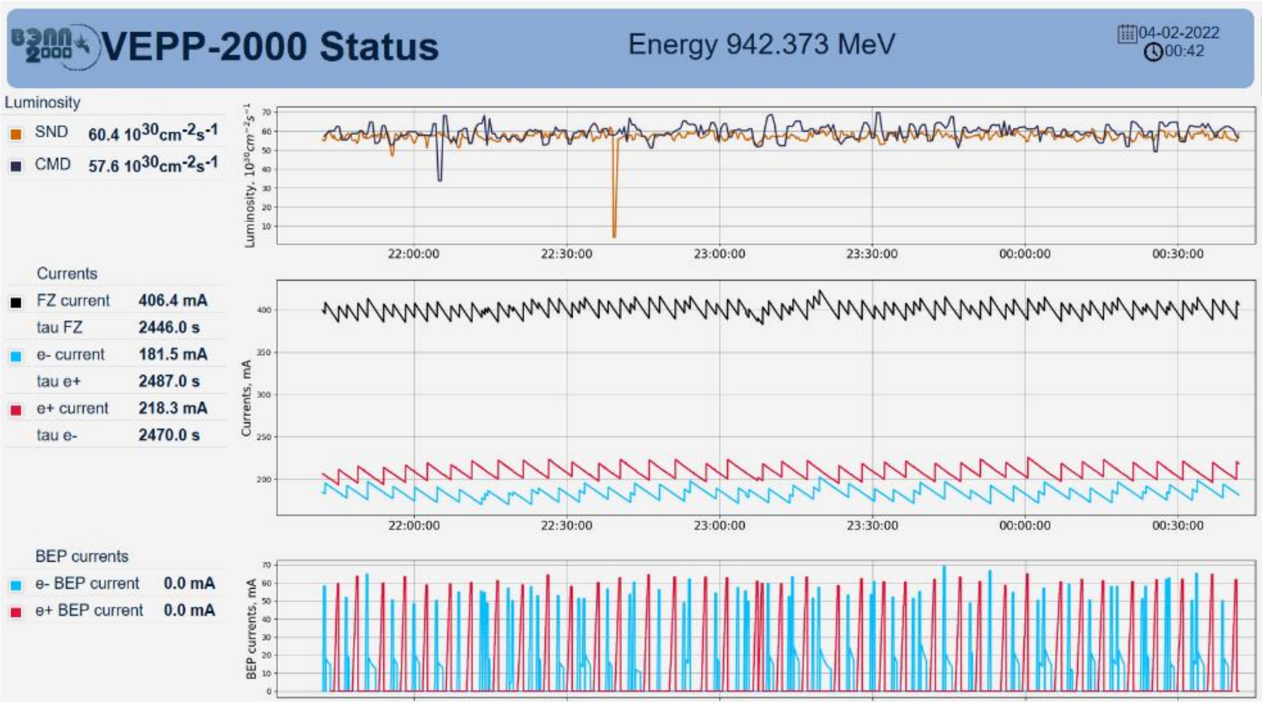


Best luminosity runs: 2010 - 2022



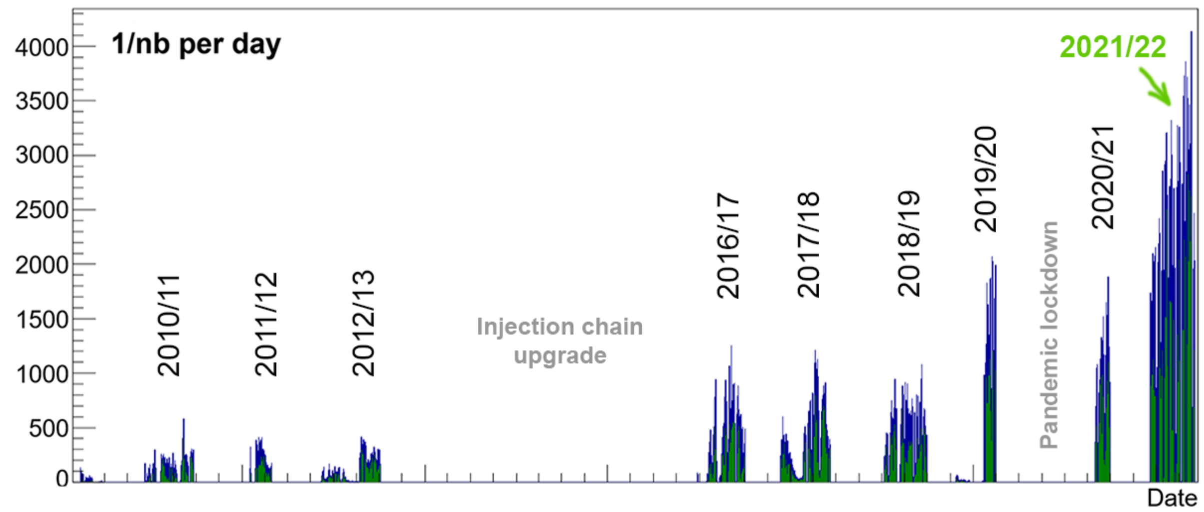
Текущий абсолютный рекорд пиковой светимости: $L_{peak} = 9\times10^{31}$ $cm^{-2}s^{-1}$ @ 890 MeV

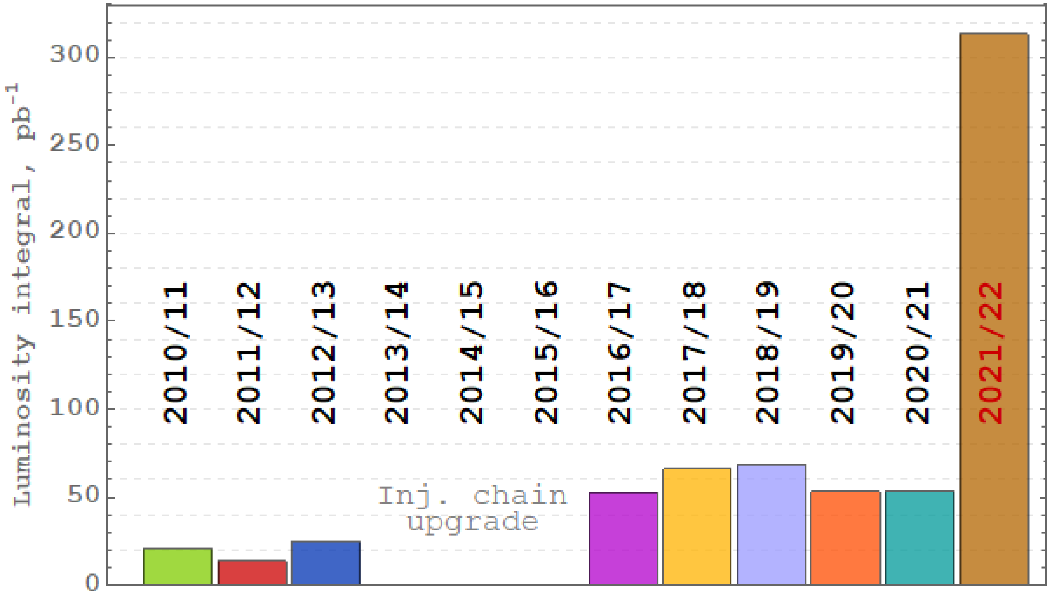
Total luminosity integral - 2022



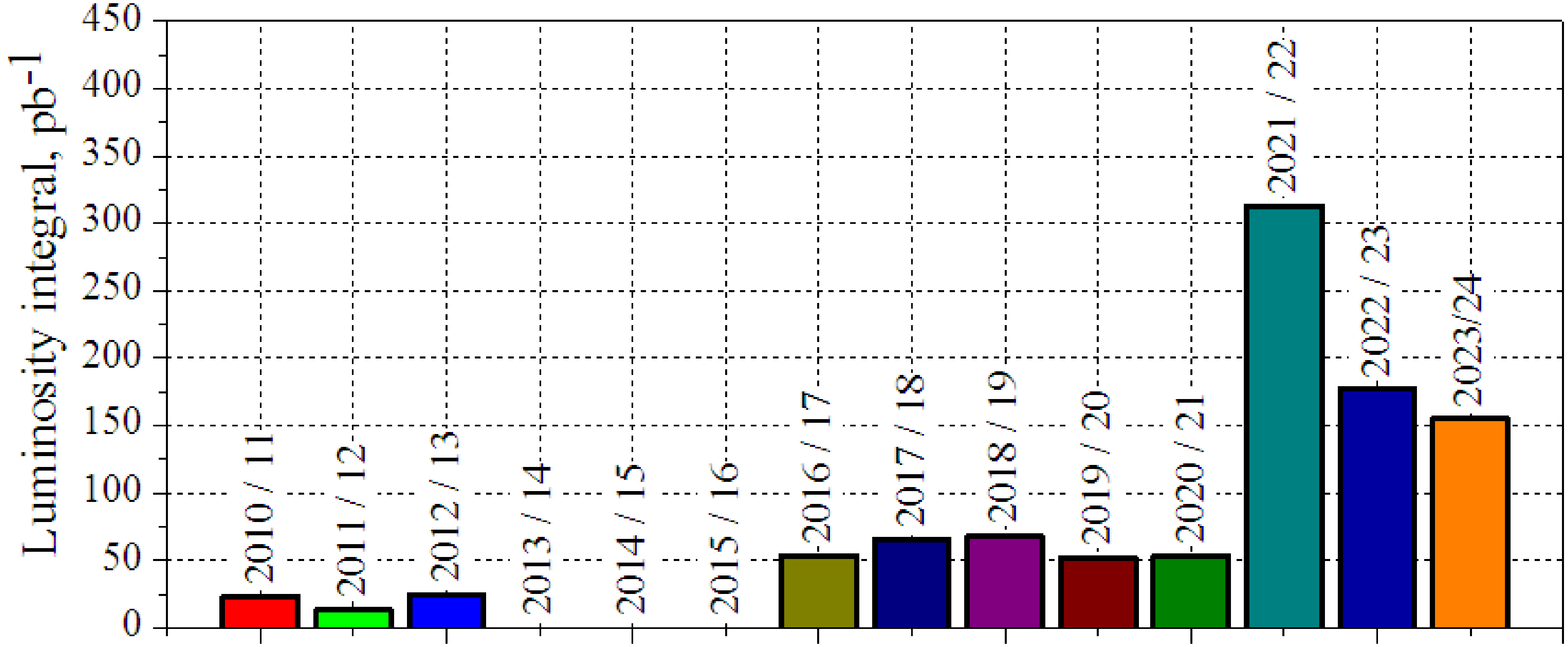
Скриншот статусной страницы регулярной работы коллайдера на пороге рождения нейтрон-антинейтронных пар. 02 Апреля 2022.

Наибольший суточный интеграл: 4.14 pb^{-1}, получен 21.05.2022

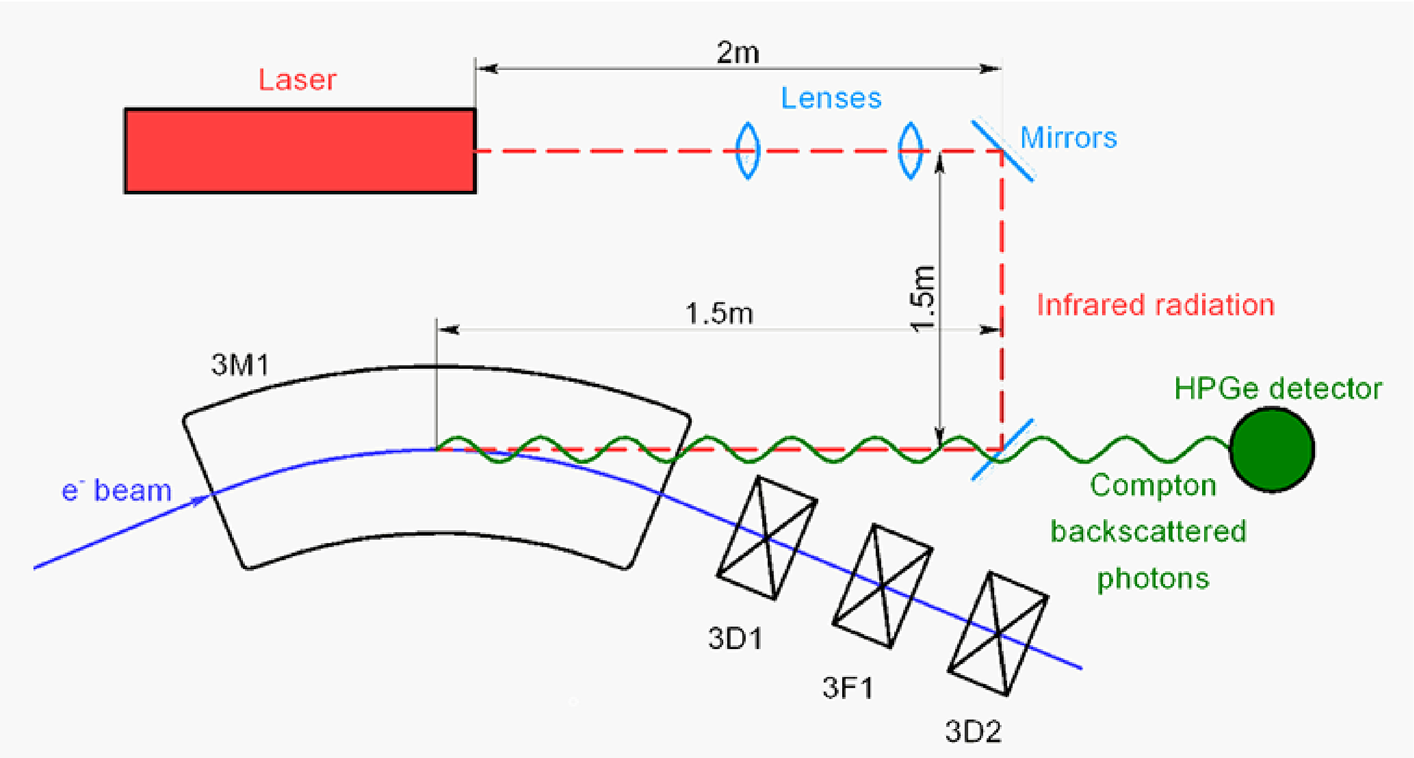




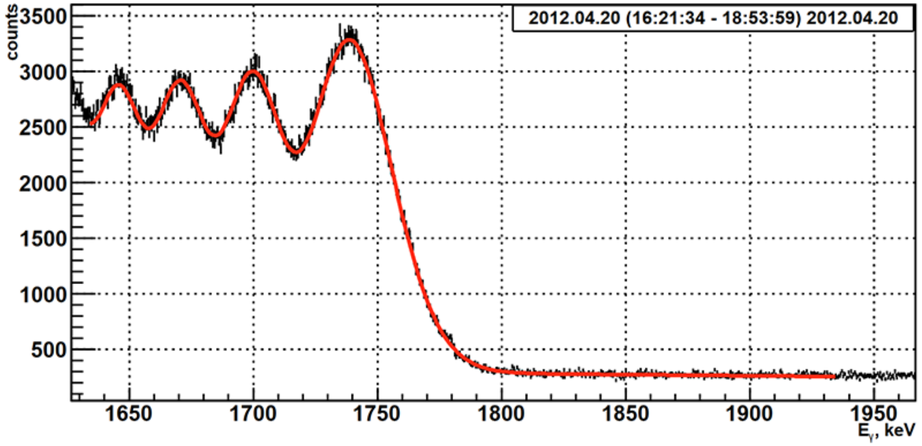
Total luminosity integral: 2010- 2024



Beam energy measurements: CBS system



Backscattered photons spectrum edge:



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

Заключение

- Круглые пучки дали значительный выигрыш в светимости
- На коллайдере ВЭПП-2000 получена рекордная в мире светимость в односгустковом режиме
- Параметр встречи на верхнем диапазоне энергий превышает $\xi > 0.13$
- При самых низких энергиях предложенная нами импульсная раскачка пучков стабилизирует неустойчивость типа “флип-флоп” и в несколько раз повышает светимость позволяя увеличить токи встречных пучков
- Для предельно низких энергий круглые пучки предпочтительны из-за большего времени жизни по Тушеку

Размышления о будущем..

- Сезон 2023-2024: сканирование выше фи-мезона
- Весна 2024: сканирование ниже фи-мезона, интересна область вокруг ро-мезона
- Сезон 2025: самые низкие энергии + добираем недобранное

- Осень 2025: выключение, модернизация детекторов и систем ВЭПП-2000
- Осень 2027: включение
- Набор интеграла во всем диапазоне энергий при повышенной стабильности
- Работы по созданию ц-тау фабрики

Спасибо за внимание!