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ОИЯИ

Transparent crossing of the induced intrinsic resonance with a synchrotron energy modulation at the JINR Nuclotron

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Resonance crossing with constant rate

Spin resonances: $\nu = \gamma G = \nu_k$,

$\boldsymbol{\nu_k = k + k_x\nu_x + k_y\nu_y + k_\gamma\nu_\gamma}$,

ν_x, ν_y, ν_γ— betatron and synchrotron tunes;

k, k_x, k_y, k_γ— integers.

Froissart-Stora crossing

$$\boldsymbol{S_f = S_i\left(-1 + 2\,exp\left(-\frac{\pi^2\omega^2}{\varepsilon'}\right)\right)}$$

$\varepsilon = \nu - \nu_k$ — resonance detune;

$\varepsilon' = \frac{d\varepsilon}{dN} = \boldsymbol{const}$ —crossing rate;

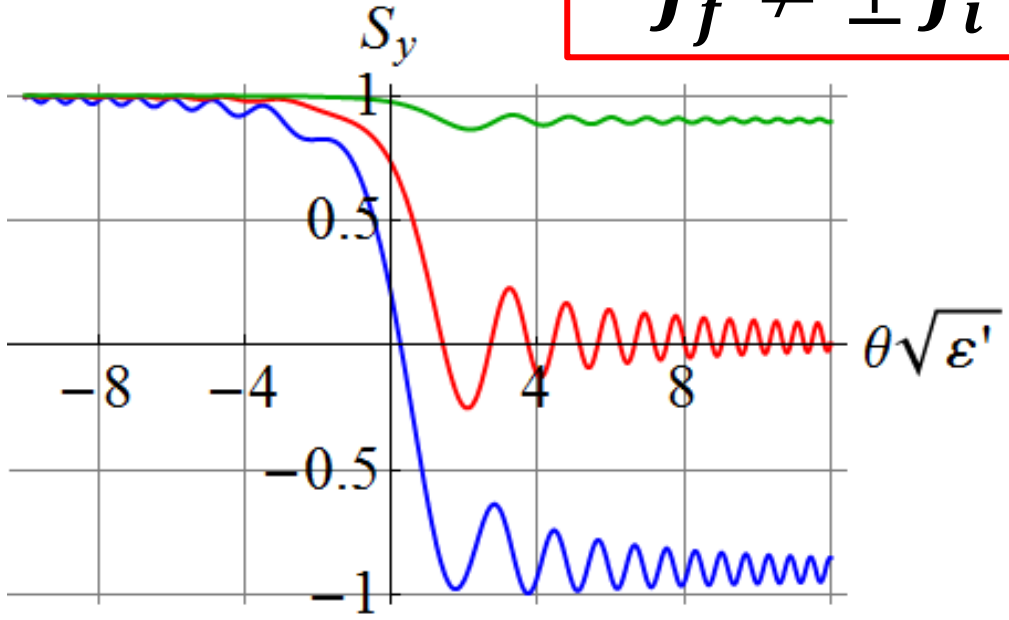
N — number of turns;

ω — resonance strength;

$\theta = 2\pi N$ — generalized azimuth;

D — degree of beam depolarization.

$$\boldsymbol{J_f \neq \pm J_i}$$



Slow crossing: $\boldsymbol{\varepsilon' \ll \omega_k^2}$, $\boldsymbol{D \to 0}$.

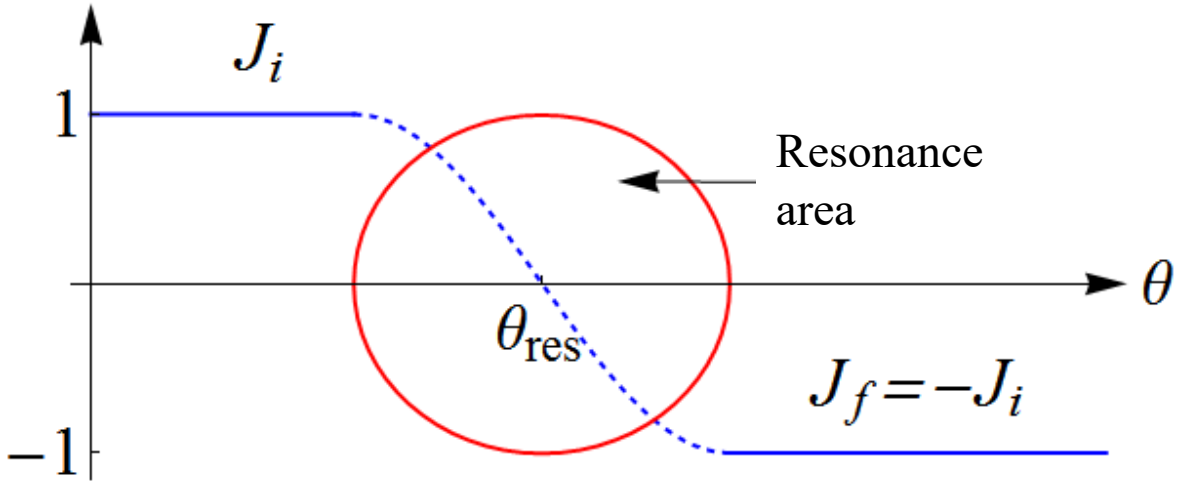
Intermediate crossing: $\boldsymbol{\varepsilon' \sim \omega_k^2}$, $\boldsymbol{D \sim 1}$.

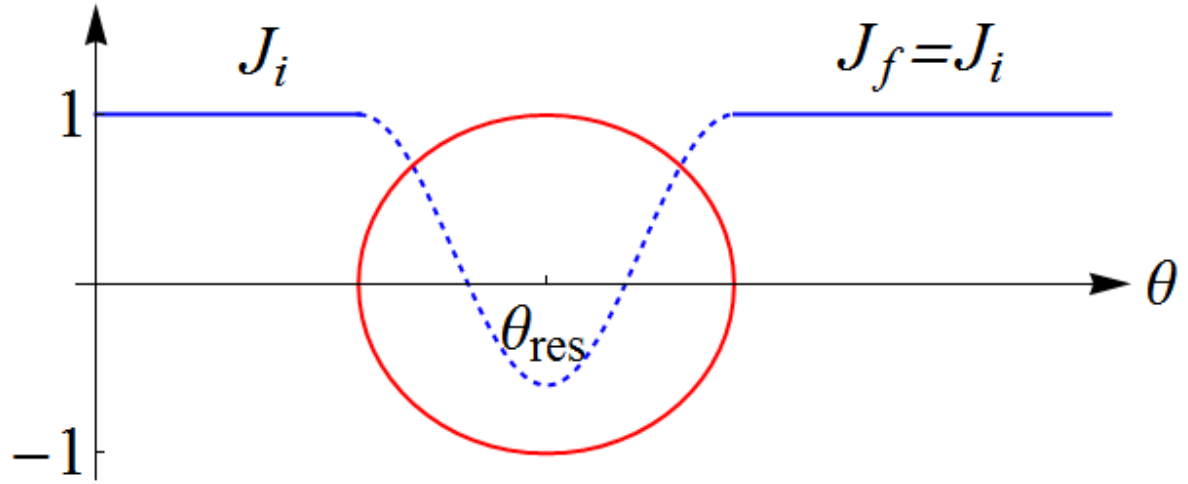
Fast crossing: $\boldsymbol{\varepsilon' \gg \omega_k^2}$, $\boldsymbol{D \ll 1}$.

Preservation of polarization degree

Detune $\boldsymbol{\varepsilon(\theta)}$ during resonance crossing is changing in such a way that spin projection before and after crossing the resonance area (J_i and J_f relatively) fulfilled the condition of polarization degree preservation:

$$\boldsymbol{J_f = \pm J_i}$$

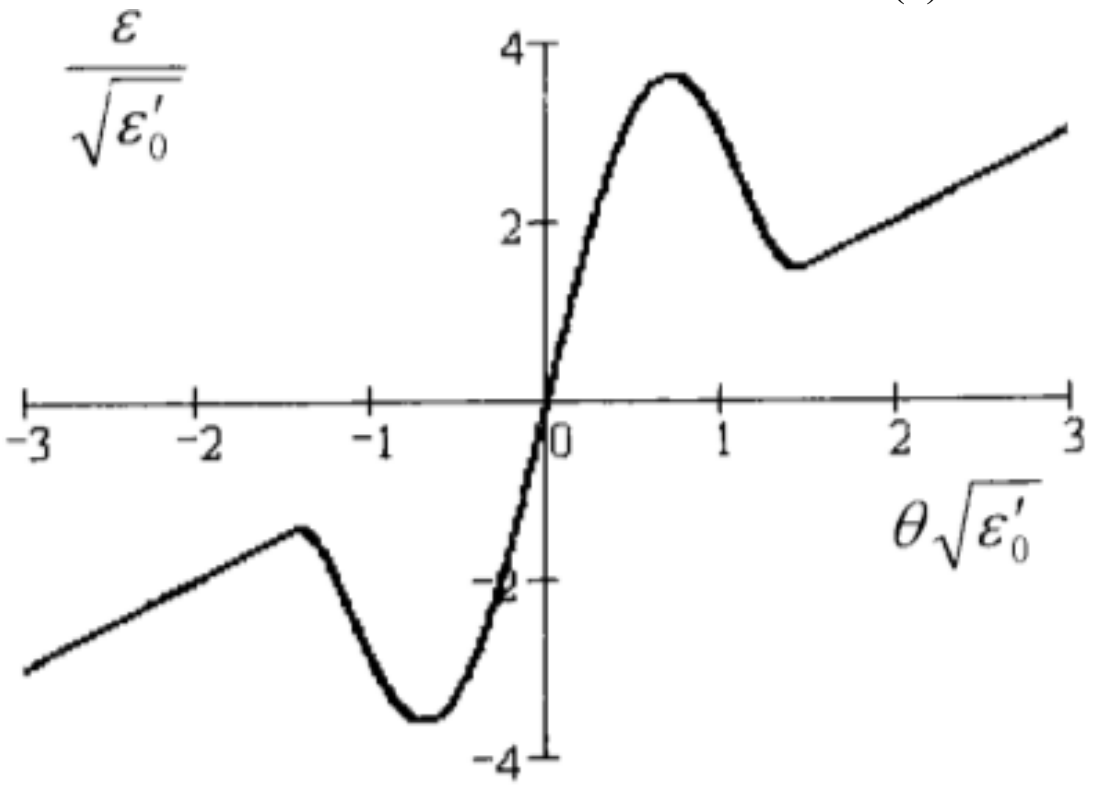




Transparent spin resonance crossing

Transparent spin resonance crossing method excludes depolarization completely via manipulating spin detune in spin resonance area.

Kondratenko A.M., Kondratenko M.A., Filatov Yu.N. Compensation for Particle Beam Depolarization of Spin Resonance Intersection at Accelerators // Particles and Nuclei Letters. 2004. V. 1(5) P. 266–269.



$$\varepsilon(\theta) = \begin{cases} \varepsilon_0'\theta + \varepsilon_1'\theta\left(1 - \frac{\theta^2}{\tau^2}\right), |\theta| \le \tau \\ \varepsilon_0'\theta, \qquad |\theta| > \tau \end{cases}$$

$$\varepsilon_1' \approx 7{,}04\varepsilon_0', \qquad \tau \approx \frac{1{,}45}{\sqrt{\varepsilon_0'}}$$

$$\delta \approx 3{,}6\sqrt{\varepsilon_0'}, \qquad \tau \approx \frac{0{,}71}{\sqrt{\varepsilon_0'}}$$

Experimental verification of transparent spin resonance crossing

- Spin resonance $\boldsymbol{\gamma G = \nu_{res} - 8}$ is induced by two families of structural quadrupoles.
- **Beam energy is *fixed* during the experiment.**
- Resonance detune $\varepsilon(t) = \nu_y(t) - \nu_{res}$ is controlled during the process of crossing the resonance area due to a betatron tunes change by the correction quadrupoles.

Deuteron energy	$E_k = 270$ MeV
Resonance tune	$\nu_r = 7{,}836$
Normalized emittance	$\sim 4{,}5$ mm · mrad
Intrinsic resonance strength	$\omega \sim 6 \cdot 10^{-5}$

Resonance crossing rate	$\varepsilon_0' \sim 10^{-8}$
Effective resonance area (in turns)	~ 2000
Betatron tunes change	$\Delta\nu_y \sim 5 \cdot 10^{-4}$
Resonance area crossing time	$\tau \sim 2 \div 5$ ms

Spin resonance crossing simulation

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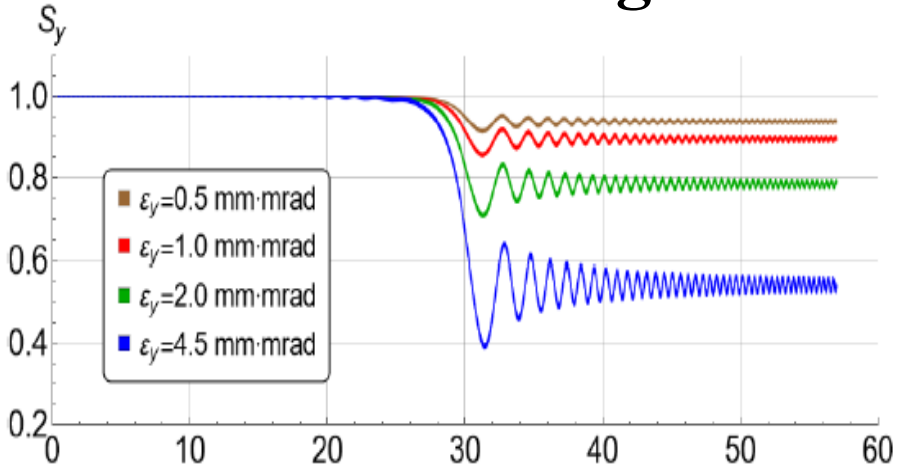
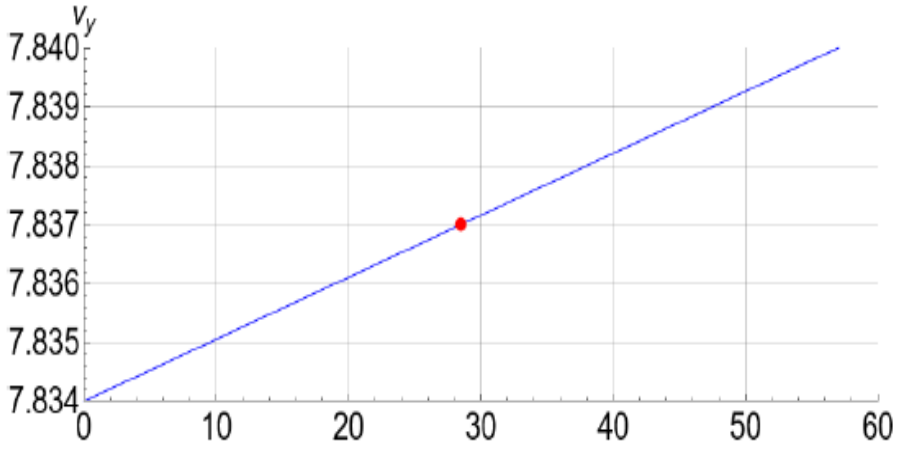
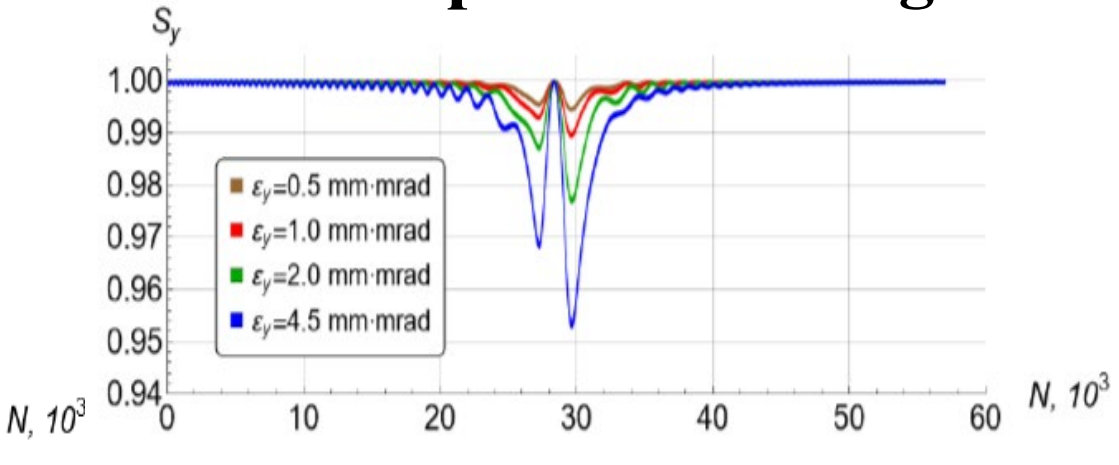
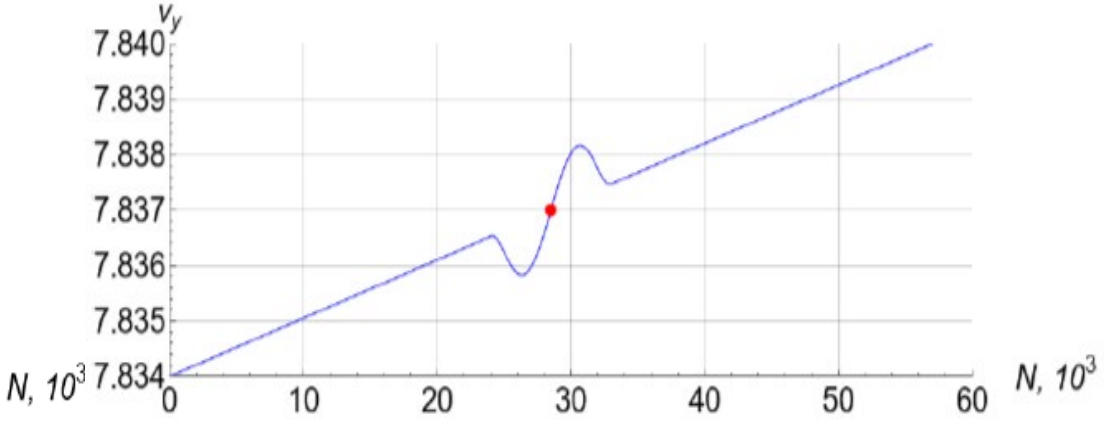
FS-crossing





Transparent crossing





Resonance:

$\gamma G = \nu_y - 8$

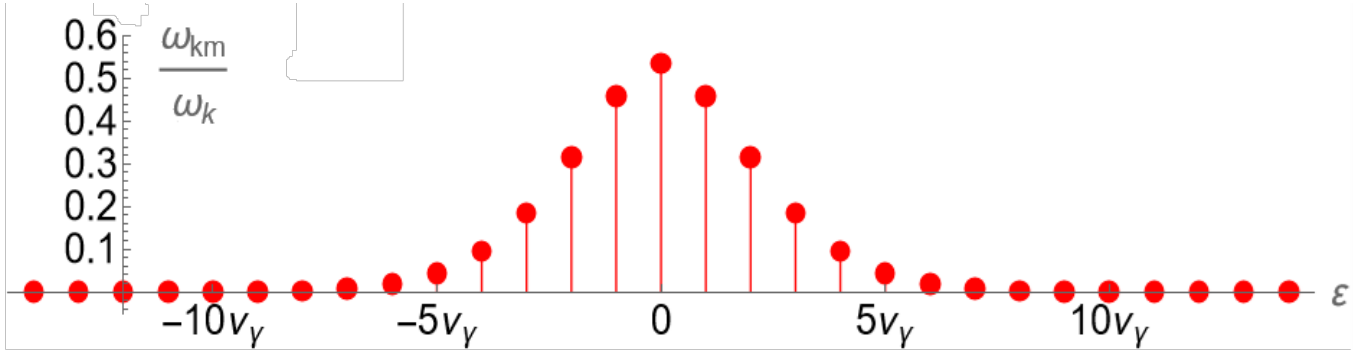
$\nu_{рез} = 7{,}837$

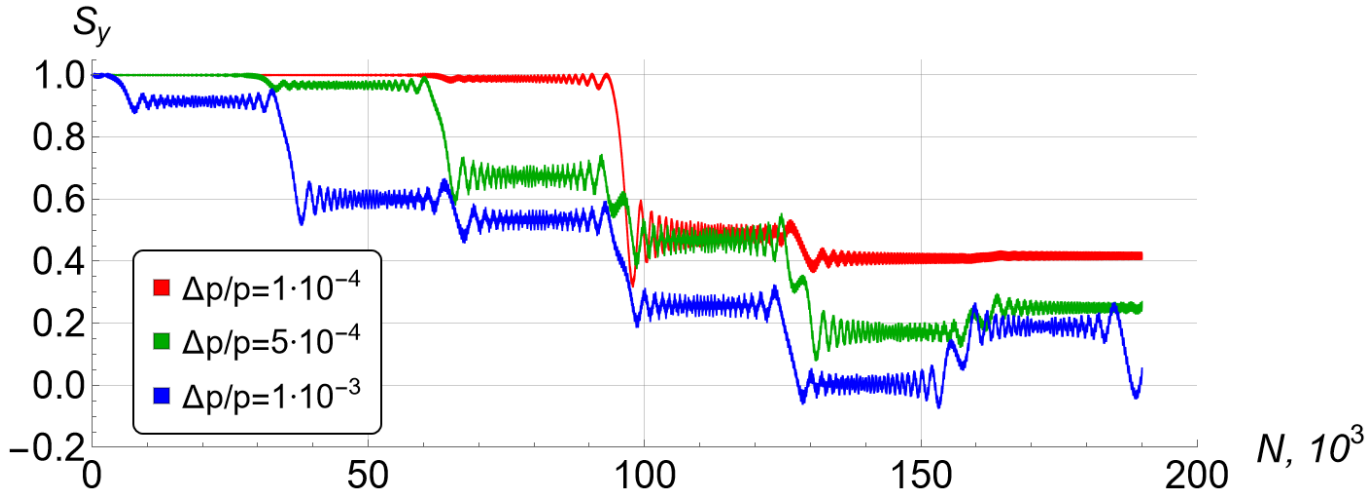
Momentum spread.

$$\frac{\Delta p}{p} = 0$$

Influence of synchrotron oscillations

Taking into an account synchrotron oscillations leads to a single resonance splitting in a series of satellite resonances $\nu_m = \nu_{\text{рез}} + m\,\nu_\gamma$ of equal distances on a scale of synchrotron frequency ν_γ.





Synchrotron resonances' strengths ω_m are connected to the intrinsic resonance's strength via the equation

$$\sum_m |\omega_m|^2 = \omega^2.$$

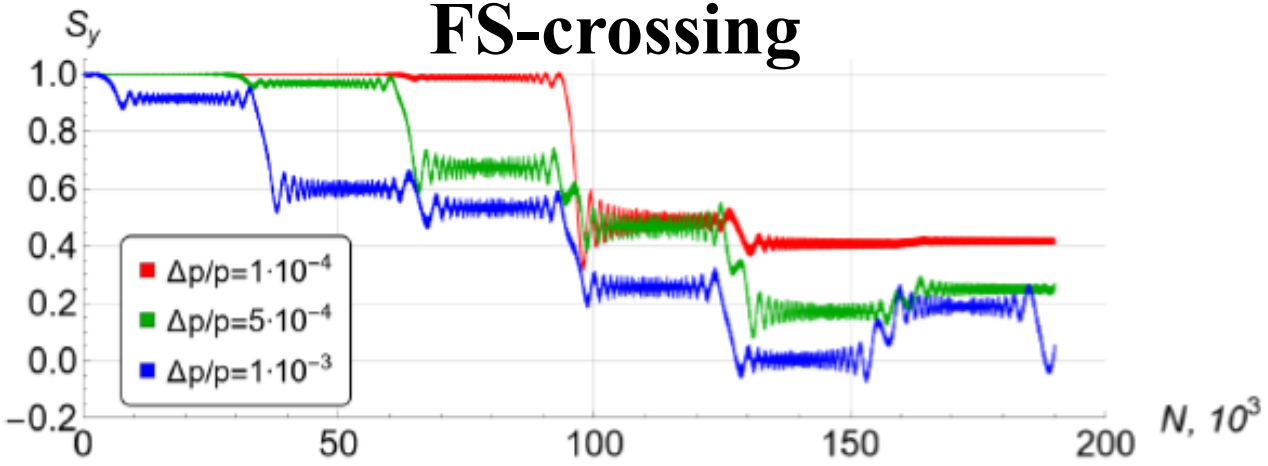
The number of significant satellite resonances is determined by the beam energy spread.

Simulation results of the satellite resonances crossing with the constant rate $\frac{d\nu_y}{dN} \sim 10^{-7}$ in Nuclotron ($\nu_\gamma \sim 4 \cdot 10^{-3}$).

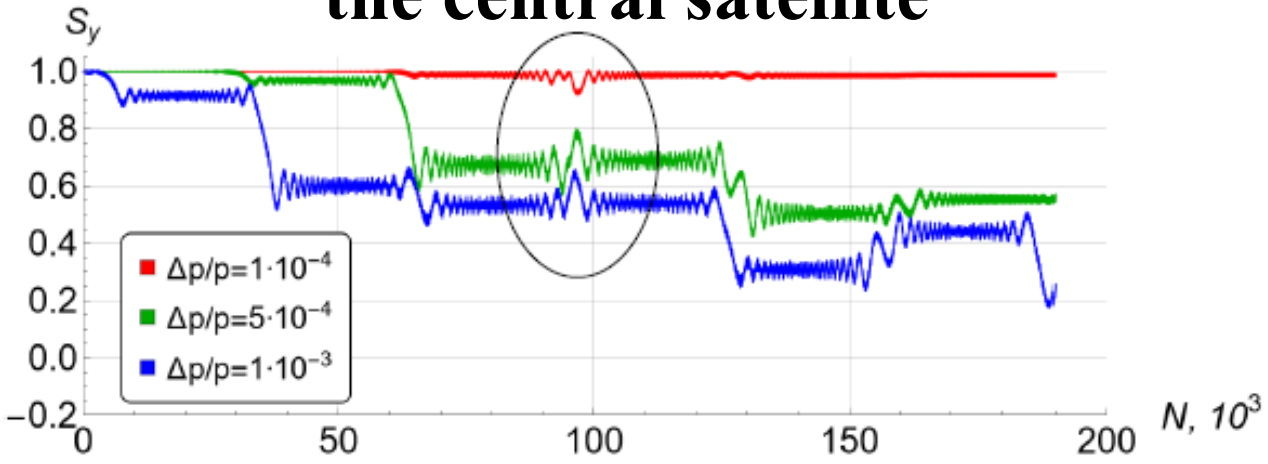
The central resonance is the strongest one.

Transparent crossing of central satellite

FS-crossing



Transparent crossing of the central satellite



$$\gamma G = \nu_y - 8$$

$$E_{kin} = 270\ MeV$$

$$\varepsilon_y = 45\ mm \cdot mrad$$

$$\nu_{res} = 7{,}837$$

$$\frac{d\nu_y}{dN} \sim 10^{-7}$$

Initial and final resonance detune

$$\sim 3 \cdot 10^{-3}$$

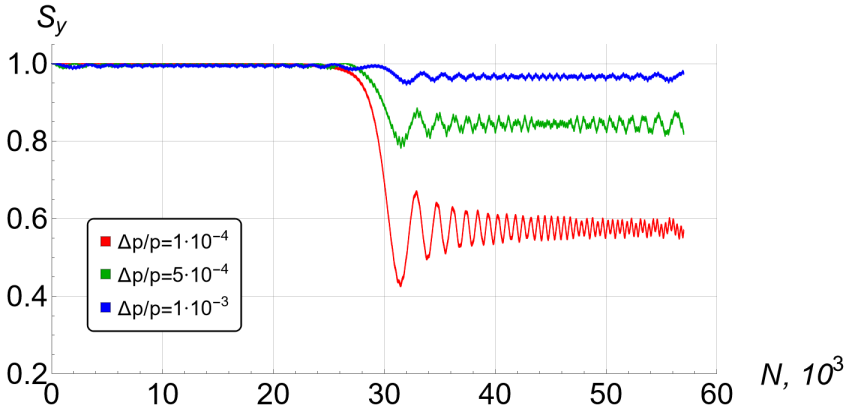
Resonance region

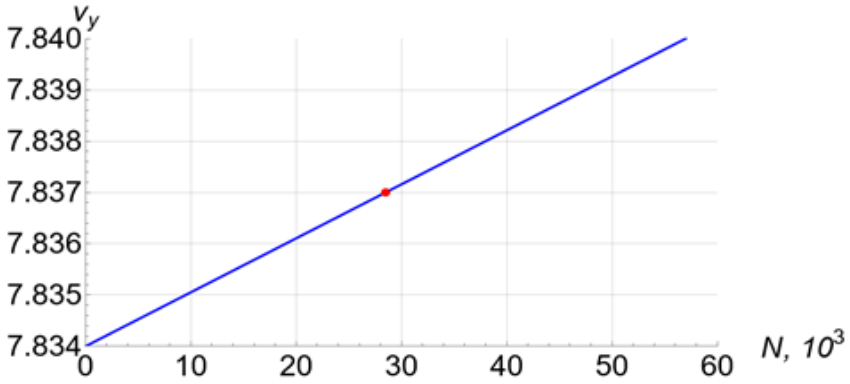
$$\sim 1{,}2 \cdot 10^{-4}$$

$$\nu_y \sim 4 \cdot 10^{-3}$$

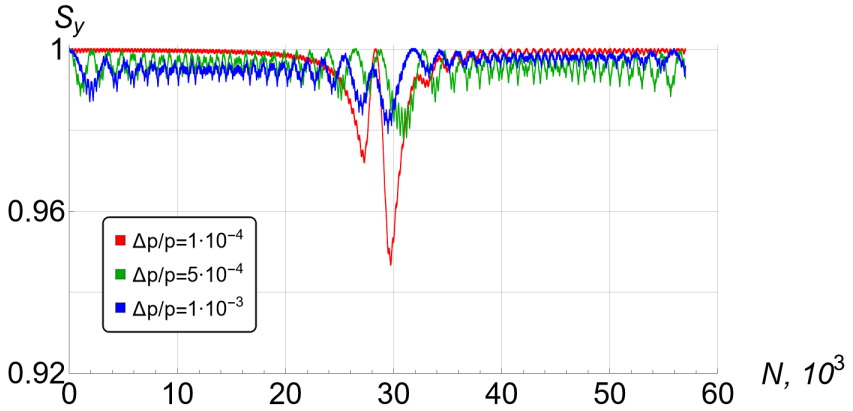
Simulation of the central satellite crossing

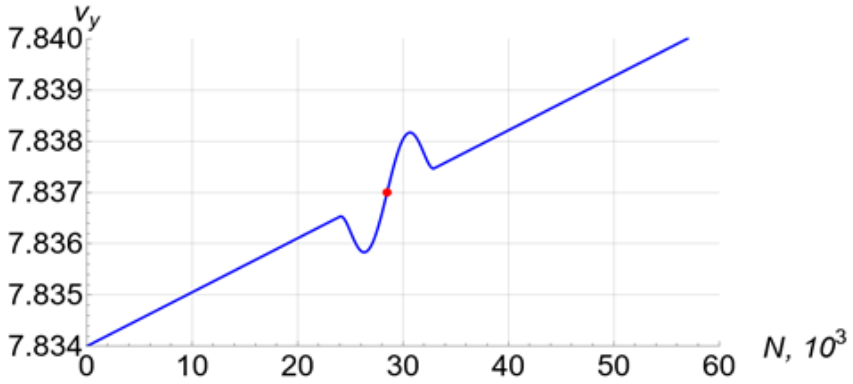
FS-crossing





Transparent crossing





Deuterons

$\gamma G = \nu_y - 8$; $E_{kin} = 270$ MeV $\varepsilon_y = 45$ mm·mrad;

$\nu_{res} = 7.837$

$\frac{d\nu_y}{dN} \sim 10^{-7}$

Initial and final detunes $\sim 3 \cdot 10^{-3}$

Resonance area $\sim 1.2 \cdot 10^{-4}$

$$\nu_\gamma \sim 4 \cdot 10^{-3}$$

Side satellite resonances has to be crossed fast to exclude their influence on the polarization and to reduce the problem to the central satellite crossing.

Conclusion

A methodology of the experimental verification of the transparent crossing of an intrinsic spin resonance at Nuclotron is proposed.

- Resonance $\gamma G = \nu_y - 8$ is induced by the structural quadrupoles.
- Energy is fixed during the experiment.
- Resonance detune is manipulated due to betatron tune ν_y changing by the correction quadrupoles.

Thank you for your attention!

Spin resonances and SAI

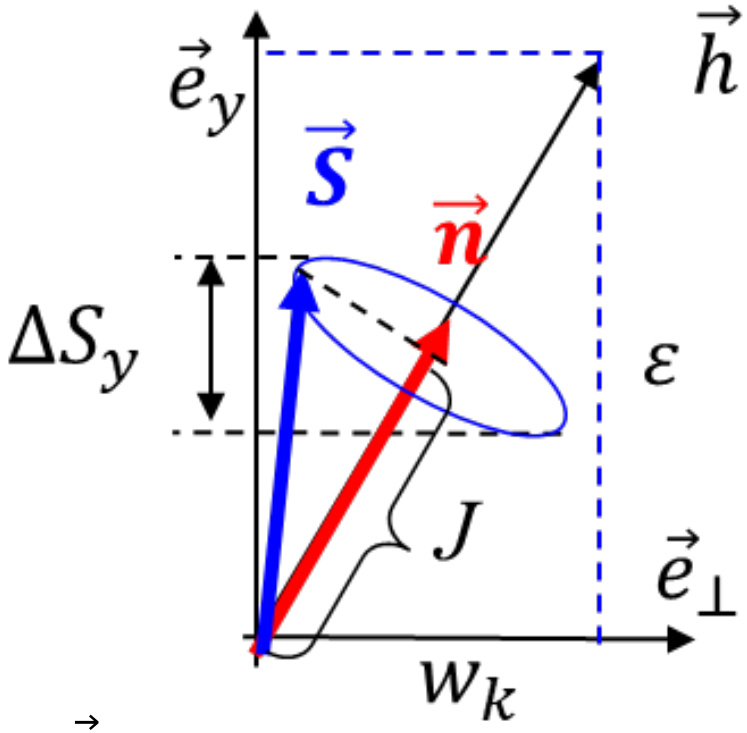
$\boldsymbol{J = \vec{S} \cdot \vec{n}}$ Spin adiabatic invariant (SAI).

$\vec{\Pi} = \langle J \cdot \vec{n} \rangle = \langle J \rangle \langle \vec{n} \rangle, \quad D = 1 - |\langle J \rangle|\,|\langle \vec{n} \rangle|$

$\langle J \rangle$ – SAI change during acceleration process

$\langle \vec{n} \rangle$ – n-axis deviation of the beam

Polarization vector is changing in a close approach of spin resonances: $\nu = \nu_k, \quad \nu_k = k + k_x \nu_x + k_y \nu_y + k_\gamma \nu_\gamma$



Resonance frame is rotating around vertical direction with resonance tune ν_k.

In that frame particle's spin is rotating in the **field**: $\vec{h} = \varepsilon\, \vec{e}_y + w_k\ \vec{e}_\perp$.

$\boldsymbol{w_k}$ – resonance strength (Fourier harmonic)

$\boldsymbol{\varepsilon = \nu - \nu_k}$ – resonance detune

Away from resonance $\langle J \rangle = const$.

***n*-axis:** $\vec{n} = \vec{h}/h$

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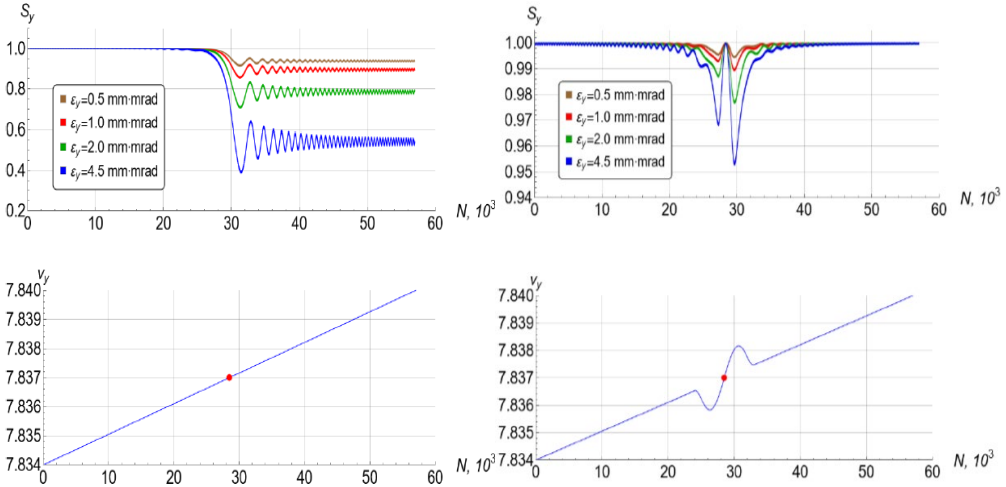
- Simulation results for TC with synchrotron oscillation.
- Conclusion

ST-crossing experiment simulation

Resonance: $\gamma G = \nu_y - 8$

Deutron's energy	$E_{\text{кин}} = 270$ МэВ $= const.$
Normallized emittance	$\varepsilon_y = 4{,}5$ мм · мрад.
Intrinsic resonance strength	$\omega \sim 10^{-4}$.
Crossing rate for intermediate mode of FS-crossing	$\varepsilon' \sim \omega^2 \sim 10^{-8}$.
Intrinsic resonance area	$\sim \frac{1}{(2\pi\sqrt{\varepsilon'})} \sim 2000\ laps.$
Detune change in resonance area	$\Delta\nu_y \sim k\varepsilon' \sim 10^{-3}$.
Betatron frequency changing rate:	$\frac{\Delta\nu_y}{\Delta t} \sim 0{,}1\ \text{с}^{-1}; \left(\frac{d\nu_y}{dN} \sim 10^{-7}\ \frac{1}{\text{об}}\right)$.



A resonance betatron frequency is set by two families of focusing and defocusing quadrupoles $\nu_{\text{рез}} = 7{,}837$.

The detune $\varepsilon = \nu_y - \nu_{\text{рез}}$ is manipulated via correction quadrupoles.

Momentum deviation is considered to be negligible.

$$\frac{\Delta p}{p} = 0$$

Resonance depolarization

Spin is precessing around the leading field in accelerating system from the particle's own reference frame.

Spin tune (spin rotation frequency in units of orbital rotation frequency ω_0):

$$\nu = \gamma G$$

($G \approx -0{,}143$, anomaly part of deutron gyromagnetic ratio).

Spin resonance condition:

$$\boldsymbol{\nu = k + k_x \nu_x + k_y \nu_y}$$

ν_x, ν_y — betatron tunes;

k, k_x, k_y — integers.

