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Stochastic Cooling of a Polarized Proton Beam at COSY

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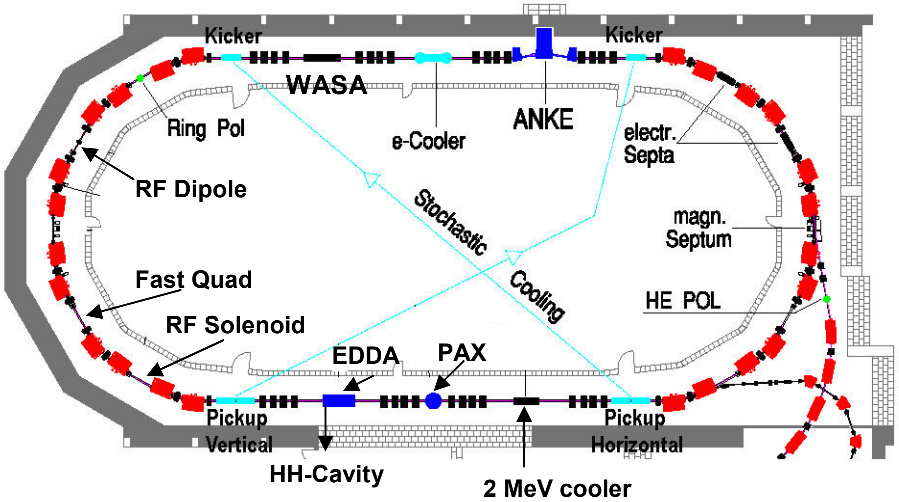
update

Introduction

- Main COSY Parameters:
  - Ring length 184 m, telescopes 40 m each
  - *Polarized* protons and deuterons up to N = 10^{10}.
  - Momentum range 300 MeV/c (600 MeV/c) to 3.3 GeV/c
  - *Stochastic cooling* p > 1.5 GeV/c
  - *Electron cooling* at injection
  - *2 MeV cooler* in preparation
  - *Internal* and *external* target experiments



- *Higher Harmonic Cavity*
- *Barrier Bucket Cavity* to compensate mean energy loss due to beam-target interaction.
- *RF solenoid and dipole*
- *Fast quad*

Introduction

- Experiments at COSY with a *vertically* polarized beam and internal target (gas jet, pellet, target cell) at p > 1.5 GeV/c require:
  - Stochastic cooling to avoid background counting rates and heating due the beam-target interaction.
  - Barrier bucket to compensate mean energy loss.
  - Polarization life time must be large.

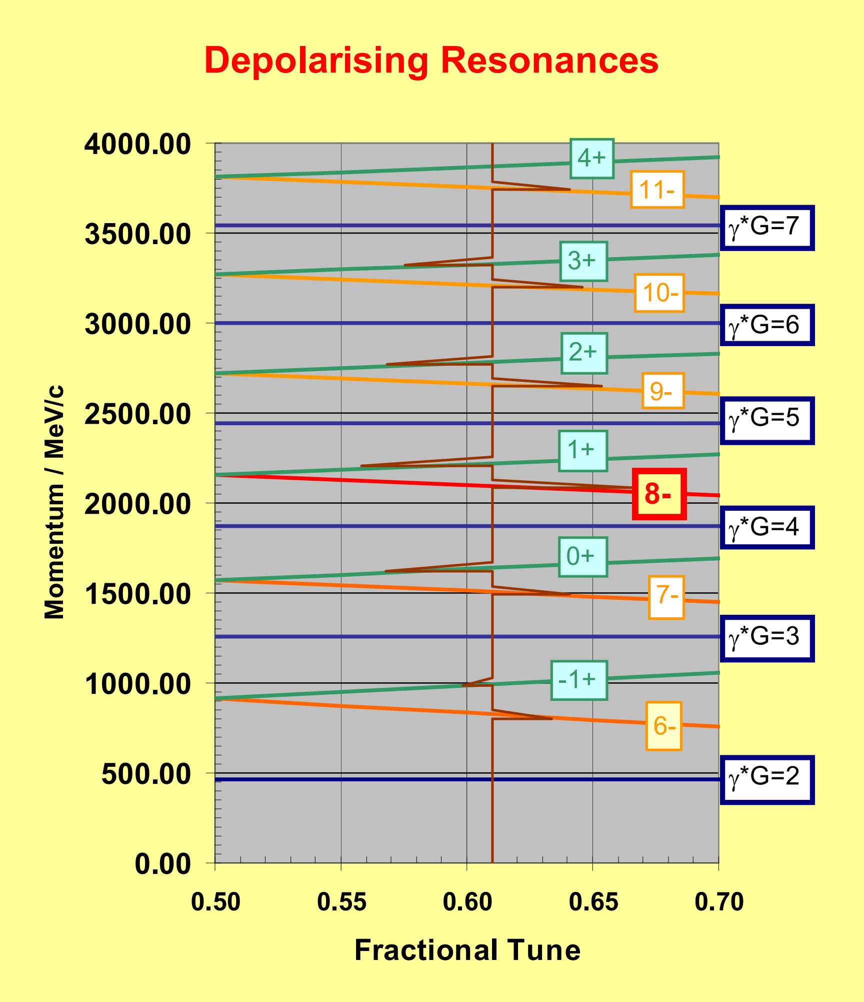
- Challenging future program at Juelich: Search for proton/deuteron electric dipole moments (EDM)

  JEDI ***J***uelich ***E***lectric ***D***ipole Moment ***I***nvestigation Group
  - Precursor Experiments to search for permanent electric dipole moments of protons and deuterons at COSY
  - Long spin coherence time necessary, therefore **small momentum spread** is essential.
  - **Small emittances** necessary to avoid depolarization by higher order resonances

Introduction

- Influence of electromagnetic kicker fields of the stochastic cooling system on polarization?
- Vertical or longitudinal polarization: Radial magnetic fields can depolarize.
- What is the short time effect on polarization?
- What is the long time effect on polarization?

Depolarizing Resonances at COSY
- Choice of Experiment Energy -



- The ***imperfection resonances*** (γG = integer) are increased in strength and perform a total spin flip (closed orbit distortion with a vertical steerer magnet).
- The ***intrinsic resonances*** ($\gamma G = k\,P \pm (Q_y - 2)$) are cured by a fast jump quadrupoles.

Exception:

Strong 8- Resonance

$\Rightarrow$ Experiment Momentum 1965 MeV/c

Stochastic Cooling Experiment with a Polarized Proton Beam

- Polarized proton beam at 1965 MeV/c with $N = 3 \cdot 10^8$
  - Vertical polarization at injection 85 %
  - Acceleration from injection 294.5 MeV/c to 1965 MeV/c: 1.7 s
  - Flat Top time 5 minutes and 30 minutes with/without cooling

Betatron tune at flat top $Q_x = 3.54$ and $Q_y = 3.56$ (measured)

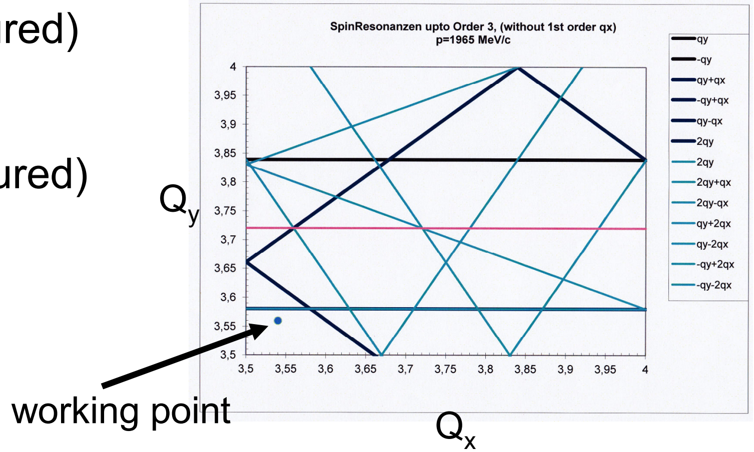
Frequency slip factor $\eta = 0.15$ (measured)

Revolution frequency $f_0 = \omega_0/2\pi = 1.474516$ MHz (measured)

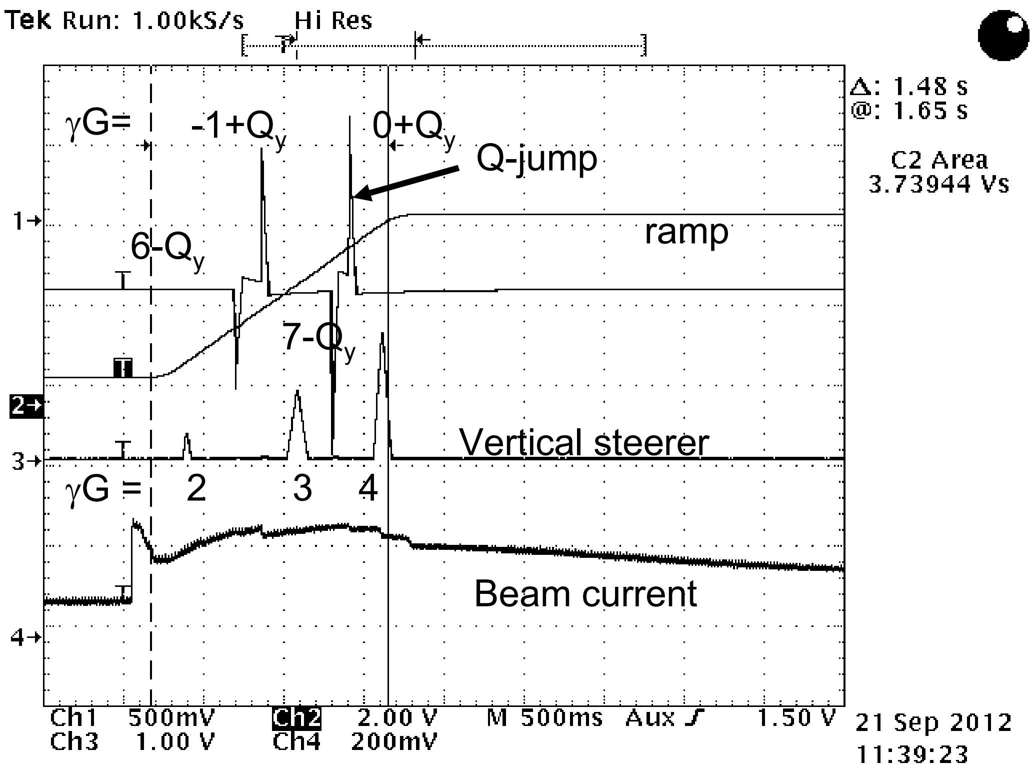
Measured Relative Momentum Spread (FWHM) at flat top:

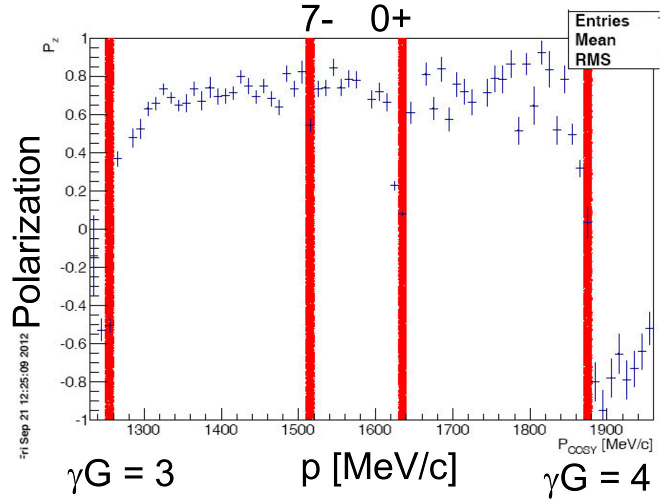
$$\Delta p/p = 3 \cdot 10^{-4} \; (1.27 \cdot 10^{-4} \text{ (rms)})$$

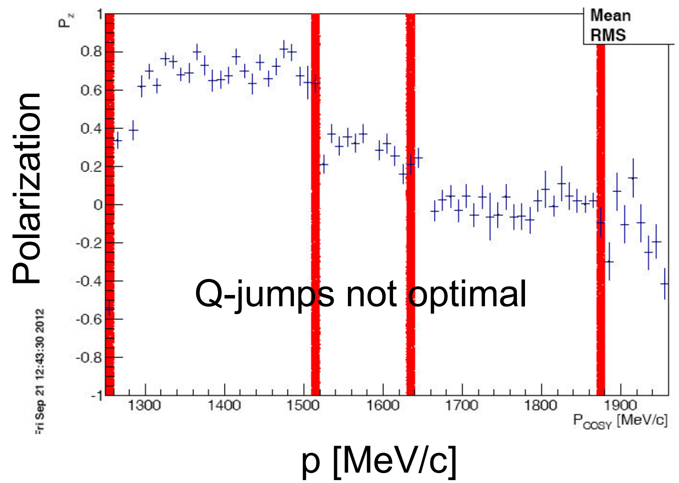
Depolarizing Resonances
Up to order 3



Stochastic Cooling Experiment with a Polarized Proton Beam (continued)







Polarization measurement with EDDA fiber target:

- Polarization at Begin of Flat Top: 75 %

Stochastic Cooling Experiment with a Polarized Proton Beam (continued)

Stochastic Cooling Experiment with a Polarized Proton Beam (continued)

Stochastic Cooling System (1 – 3) GHz

Vertical cooling band II (1.8 – 3 GHz)

Pickup:

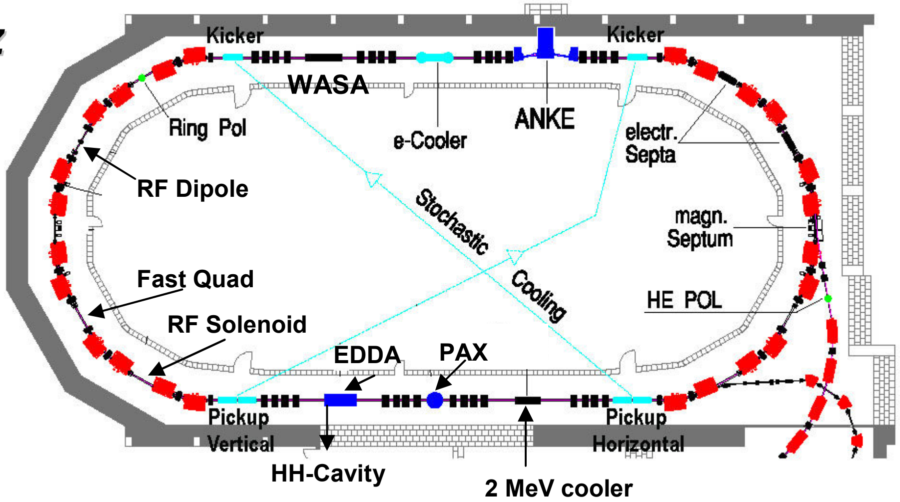
Number of loops $n_P = 32$
Gap height $h_P = 50$ mm
Loop width: w = 20 mm
Loop length L = 22 mm
Beta function vertical $\beta_P = 11$ m (MAD)

Kicker:

Number of loops $n_K = 8$
Gap height $h_K = 50$ mm
Loop width w = 20 mm
Loop length L = 22 mm
Beta function $\beta_K = 13$ m (MAD)

Distance PU to KI: $s_{PK} \approx 94$ m

Phase advance Pu to KI: $\mu \approx 7.3\ \pi/2$

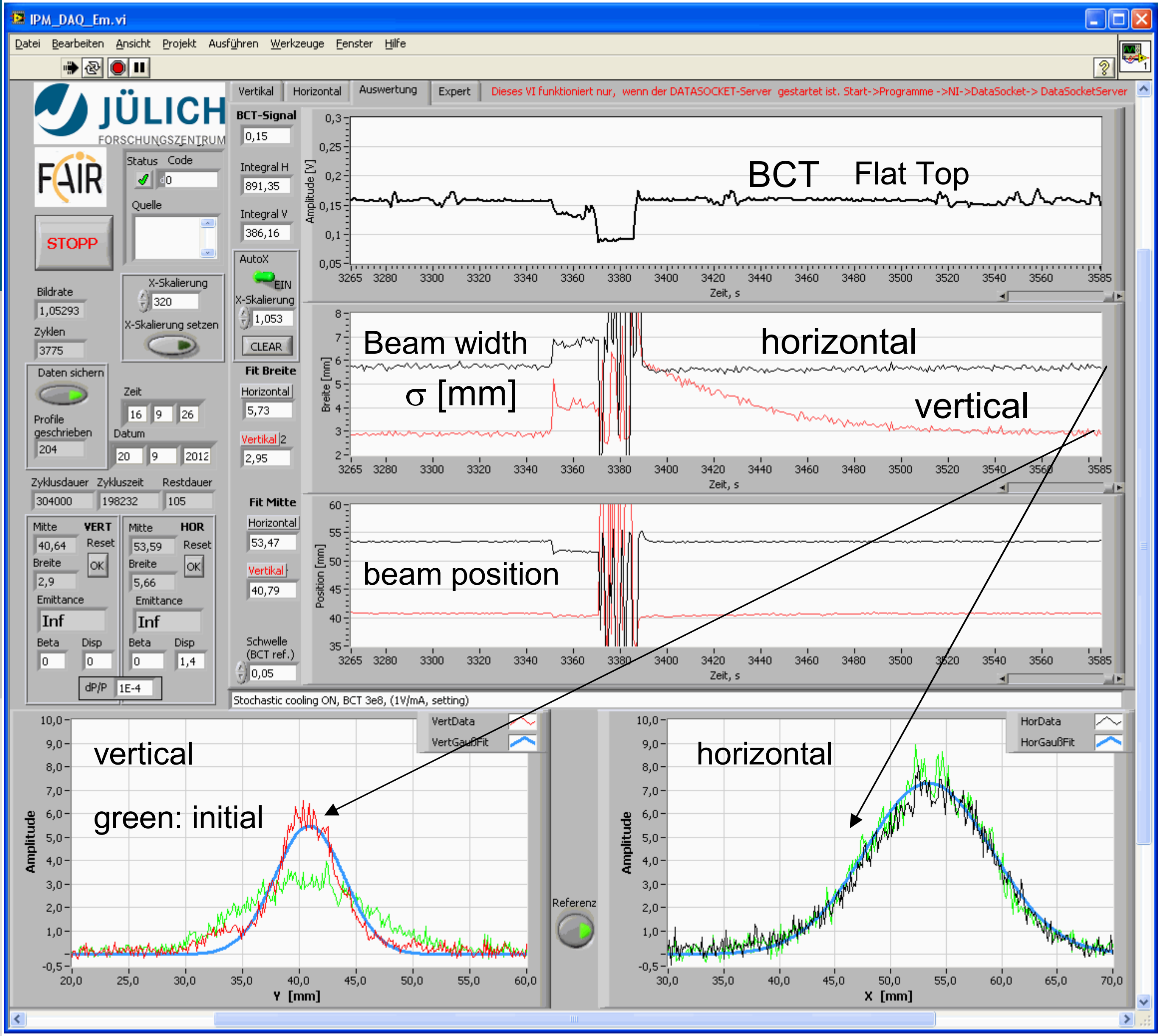


Pickup: two tanks each
band I (1 – 1.8) GHz: 24 loops
band II (1.8 – 3) GHz: 32 loops
Kicker: one tank

Installed electronic power 500 W/plane

Max voltage gain 150 dB

Beam Profile Measurements during Cooling



- Flat top 5 minutes
- no beam losses
- the cooling planes can be easily adjusted independently in stochastic cooling
- only vertical cooling
- initial beam width (standard deviation):

  σ_x = 6 mm

  σ_y = 6 mm
- beam position does not change

At position of profile measurement device:

β_x = 60 m

β_y = 8 m

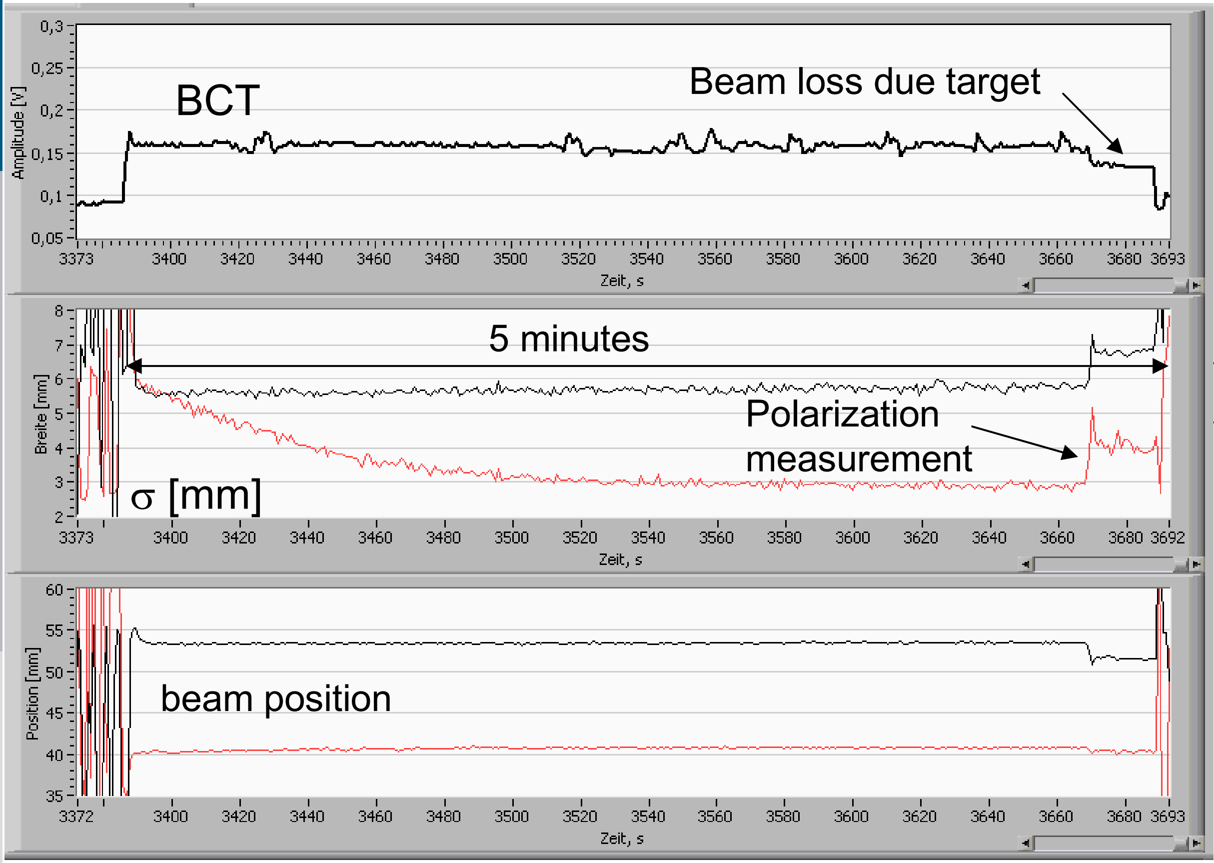
MAD

Emittances (rms):

$\varepsilon_x \approx$ 0.5 mm mrad

$\varepsilon_y \approx$ 5 mm mrad

Stochastic Cooling Experiment with a Polarized Proton Beam (continued)



- Full flat top 5 minutes
- **Polarization at the end of flat top 75 %**
- **No polarization losses observed**

Emittance increase due to target

Vertical Cooling:

emittance reduction

$\varepsilon_y \approx 5$ mm mrad

$\rightarrow$

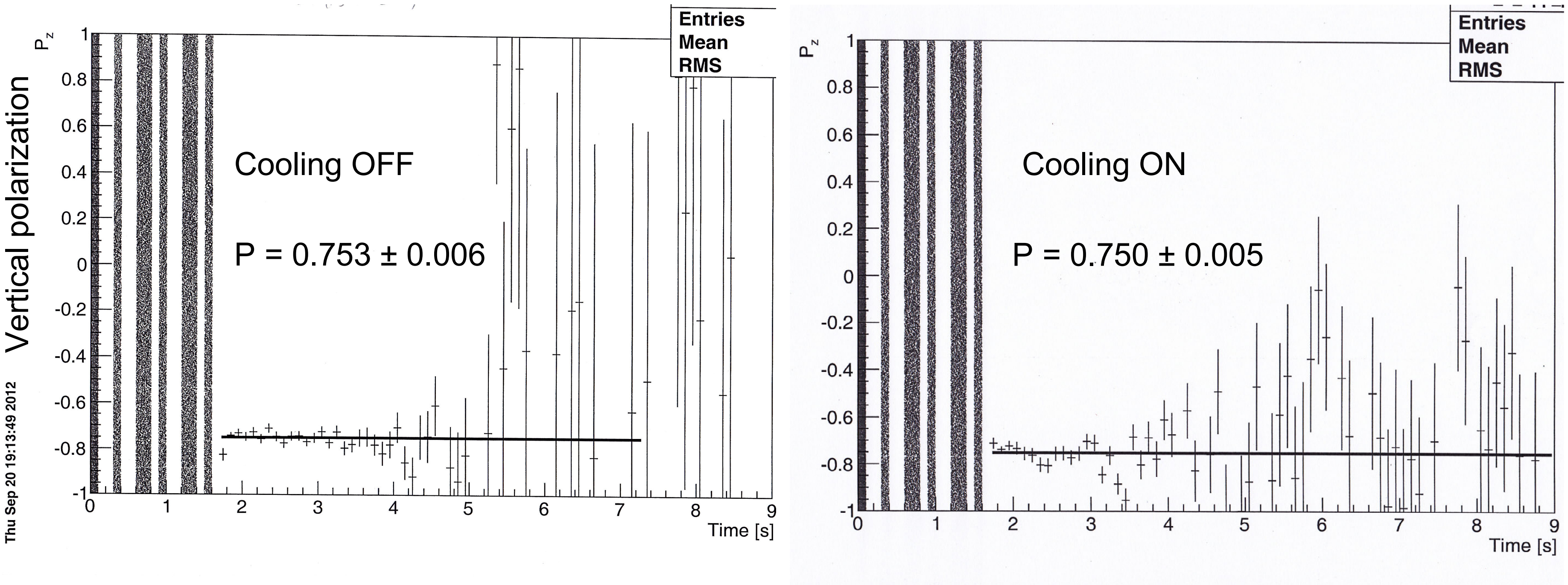
$\varepsilon_y \approx 1.3$ mm mrad

in 160 s

beam remains in equilibrium

Statistics

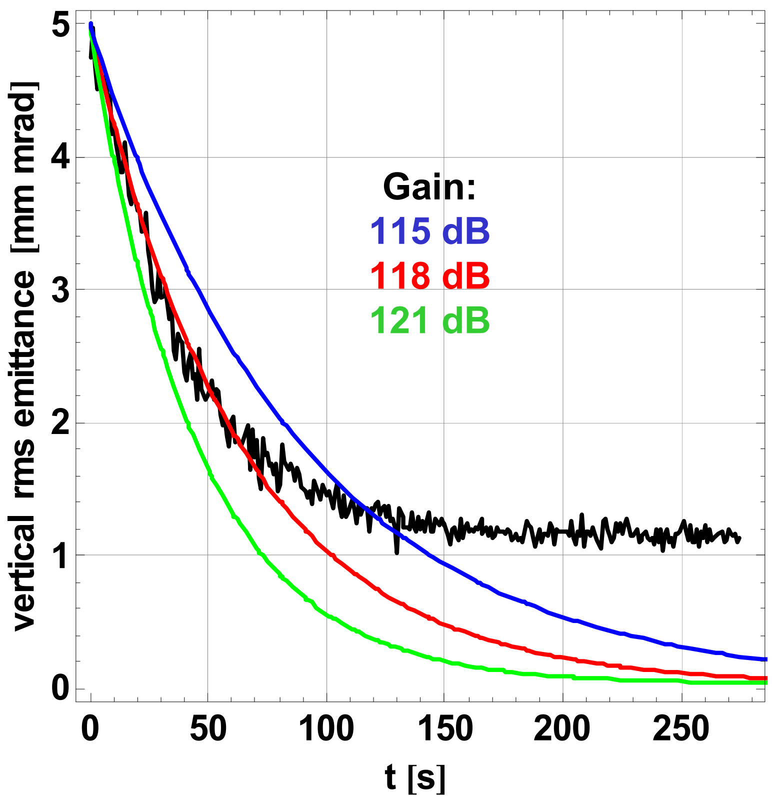
Polarization measurement **at the end** of 5 minute flat top:

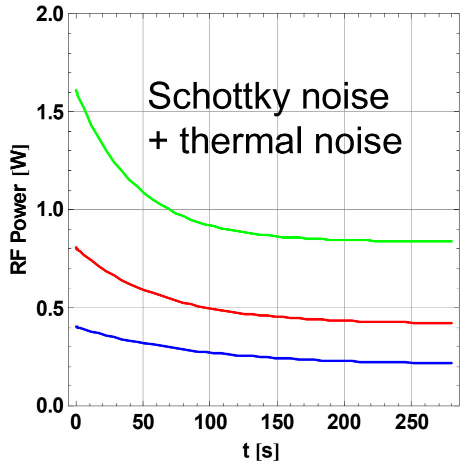


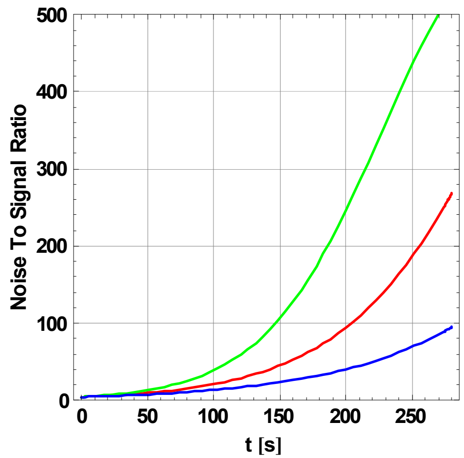
- One polarization measurement point: Two cycles (UP and DOWN states)
- For good statistics at least 8 cycles necessary

- 1 hour cycle length → **8 hours measurement time**

Comparison of measured and predicted emittance







- Discrepancy for t > 50 s unclear
- The larger measured equilibrium emittance can not be explained with residual gas scattering.
- IBS plays no role at this energy

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Summary Experimental Results

- Within possible systematic errors: During vertical stochastic cooling over 5 min (30 min) no polarization loss was observed.
- A longer flat top time needs a long measurement time and thus a long beam run time.
- Emittance decrease due to cooling can only described for t < 50 s. The model predicts a smaller equilibrium emittance as measured. Still unclear.

Theory: Does stochastic cooling influence polarization?

Theoretical Description of Spin Motion

Thomas-BMT (Thomas-Bargman, Michel,Telegdi) equation for spin motion of a moving particle with rest mass m_0 in an electro magnetic field given in the Lab-system:

$$\frac{d\vec{S}}{dt} = \frac{qe}{m_0\gamma}\vec{S} \times \left[(1+\gamma G)\vec{B}_{\perp} + (1+G)\vec{B}_{//} + (\gamma G + \frac{\gamma}{\gamma+1})\frac{\vec{E}\times\vec{\beta}}{c} \right]$$

$\vec{S}$ Spin vector in the particle's rest frame

G anomalous g-factor, for protons G = 1.79 for deuterons G = -0.14

The fields are given in the Lab-system

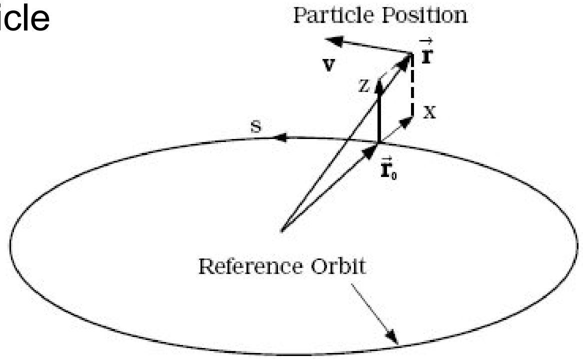
The magnetic field $\vec{B}$ is decomposed in the transverse $\vec{B}_{\perp}$ and longitudinal component $\vec{B}_{//}$ with respect to the particle velocity $\vec{\beta}c$

Simple Model Assumptions

- Perfect planar machine
- The only perturbing fields are the localized kicker fields

In the Frenet-Serret coordinate system $(\hat{x},\hat{s},\hat{z})$ moving with the particle

$$\vec{E} = E_z\hat{z} \qquad \vec{B} = B_x\hat{x} + B_z\hat{z} = \vec{B}_\perp \qquad B_{//} = 0$$



The Thomas-BMT equation is equivalent with

$$\frac{d\vec{S}}{d\theta} = \vec{S}\times\vec{\Omega} \qquad \vec{\Omega} = \left[w\hat{x} + (\gamma G)\hat{z}\right]$$

$$d\theta = \frac{ds}{\rho}$$

With fields $B_x(\theta) = \frac{1}{c}E_z(\theta)$ for vertical kicker and $B_z = -B$ the vertical dipole field

$$w(\theta) = \left\{(1+\gamma G) - \beta\gamma\left(G + \frac{1}{\gamma+1}\right)\right\}\frac{B_x(\theta)}{B} =: \alpha\frac{B_x(\theta)}{B}$$

In the rotating frame:

If $w(\theta) = 0$

$$\Delta\varphi = \gamma G\Delta\theta$$

Spin tune: γG

- Kicker fields sampled once per turn by the particle (spin)

$$E_z(\theta)=\frac{\hat{E}_z\ell}{L}\cos((m+q_z)\theta+\varphi)\sum_{n=-\infty}^{\infty}\delta(\frac{\theta}{2\pi}-n)$$

$\varphi\in[0,2\pi[$ random phase

$$f=(m+q)f_0 \qquad |m|\in[m_-,m_+]$$

q_z vertical fractional tune

ℓ length of the kicker

L ring length

which can be transformed to

$$E_z(\theta)=\frac{1}{2}\hat{E}_z\frac{\ell}{L}\sum_{n=-\infty}^{\infty}\left\{e^{i[(n+q_z)\theta+\varphi]}+e^{-i[(n+q_z)\theta+\varphi]}\right\}$$

then

$$w(\theta)=\frac{\alpha}{4\pi}\frac{\hat{B}_x\ell}{B\rho}\sum_{n=-\infty}^{\infty}\left\{e^{i[(n+q_z)\theta+\varphi]}+e^{-i[(n+q_z)\theta+\varphi]}\right\}$$

- ***Spin-Resonance Condition***
  - Resonance occurs if the perturbing fields contain a frequency component equal to the spin tune γG.

$$\varepsilon(K) = \frac{1}{2\pi}\int_{-\infty}^{\infty} w(\theta) e^{iK\theta} d\theta \qquad w(\theta) = \int_{-\infty}^{\infty} \varepsilon(K) e^{iK\theta} d\theta$$

$$\varepsilon(K) = \frac{\alpha}{4\pi}\frac{\hat{B}_x \ell}{B\rho}\sum_{n=-\infty}^{\infty}\left\{ e^{i\varphi}\delta(K-(n+q_z)) + e^{-i\varphi}\delta(K+(n+q_z)\right\}$$

Resonance occurs if: $K = n \pm q_z$

Resonance strength: $|\varepsilon(K)| = \frac{\alpha}{4\pi}\frac{\hat{B}_x \ell}{B\rho}$

Distance to the resonance $\delta = K - \gamma G = n \pm q_z - \gamma G$

$\gamma G = n \pm q_z$ is a intrinsic resonance

COSY: $f_0 = 1.5\,MHz$ $f_- = 1.8\,GHz$ $f_+ = 3\,GHz$ $q_z = 0.56$ $\gamma = 2.31$ $G = 1.79$

$m_- = 1200$ $m_+ = 2000$

Then nearest integer to $\gamma G - q_z = 3.575$ $[\gamma G - q_z] = 4$

- ***Resonance condition not fulfilled in the experiment***

Change $\gamma \to \gamma = 2.55$ then $\delta \approx 0$

$p = 1.965\,GeV/c \rightarrow p = 2.2\,GeV/c$

But: strong 8- intrinsic resonance

Resonance strength for a ***single*** frequency:

$$\varepsilon = \frac{\alpha}{4\pi} \frac{\hat{B}_x \ell}{B\rho}$$

Effective resonance strength of kicker: $\varepsilon_{kicker} = \frac{\alpha}{4\pi} \frac{\hat{B}_x \ell}{B\rho}$

Then $\varepsilon_{Kicker} \approx 5.2 \cdot 10^{-10}$ (rf-dipole $\varepsilon \approx 4 \cdot 10^{-5}$)

Note:

$\varepsilon_{Kicker} \propto \sqrt{emittance}$

The vertical spin component S_3 oscillates

$$S_3(n) = 1 - 2\frac{\varepsilon_{eff}^2}{\varepsilon_{eff}^2 + \delta^2} Sin^2\left(\frac{\sqrt{\varepsilon_{eff}^2 + \delta^2}}{2} n \cdot 2\pi\right)$$

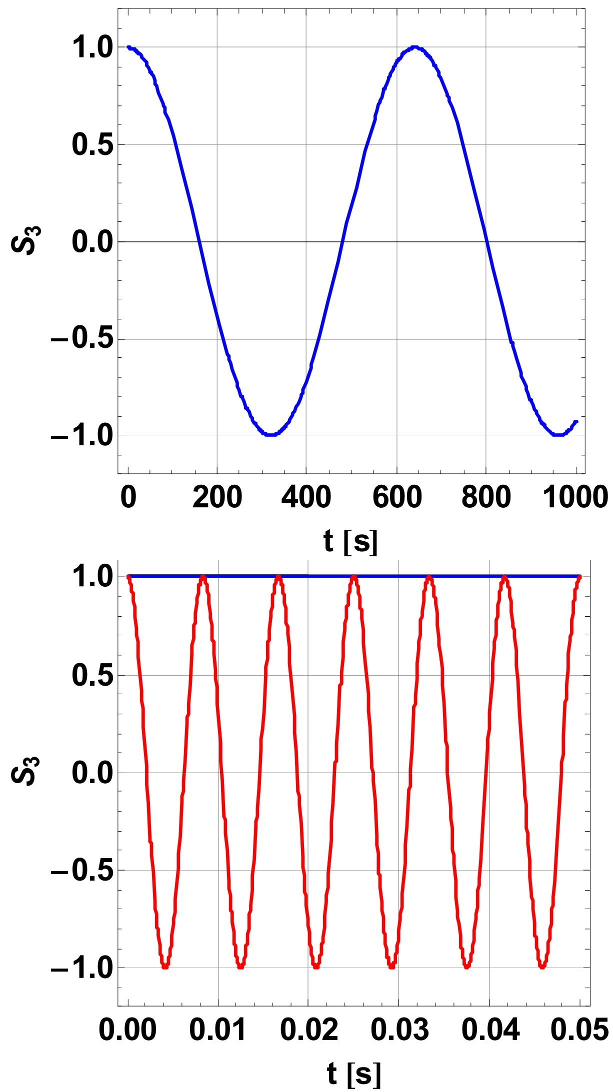
with turn number *n*

Comparison of rf-solenoid and kicker initial resonance strength

- The model predicts no polarization loss for the experiment.

$$2\frac{\varepsilon_{eff}^2}{\varepsilon_{eff}^2+\delta^2} \approx 3\cdot 10^{-18}$$

- On resonance: The vertical spin component oscillates: polarization is lost (blue curve).
- In comparison: rf-dipole (red)



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Summary

- Vertical stochastic cooling has been applied with a polarized proton beam. The flat top time was 5 minutes and 30 minutes. In both cases no influence on the beam polarization was observed.
- In a run with only momentum cooling (not presented here) also no influence on the beam polarization was observed.
- In a first order approach the resonance strength has been derived for the spin motion with a kicker electrode configuration (quarter wave loops) assuming TEM waves.
- The vertical kicker fields can excite intrinsic resonances $\gamma G = n \pm q_z$
- The resonance strength depends on the bandwidth of the cooling system and the kicker field strength.
- During cooling the resonance strength decreases $\varepsilon_{kicker} \propto \sqrt{emittance}$
- In the experiment no resonance was excited and the polarization is conserved.
- The cooling down time to an equilibrium was 160 s. The emittance was reduced by a factor of 5. Correspondingly the kicker fields were reduced by a factor of 2.2.
- Not yet clear: Discrepancy between model prediction and measured beam emittance for t > 50 s

Outlook

- For the future plans to search EDMs at COSY
  - Stochastic Cooling (SC) can be an option to achieve long spin coherence times necessary for EDM measurements.
  - More detailed study of spin motion under SC necessary
  - Include transverse and longitudinal SC
  - The BMT equation for the spin motion must include not only the interaction of MDM with kicker fields but also the EDM to study the effect of SC on EDM measurements.

Cooling Model

$$\frac{d\varepsilon}{dt} = -\frac{W}{N}\left(2gM^* - g^2 M\right)\cdot\varepsilon + g^2\frac{W}{N}(U\varepsilon)$$

$$M^* = \frac{f_0}{W}\sum_{n=n_1}^{n_2} \cos(n2\pi f_0 \Delta T_{PK}) \approx 1$$

Mixing PU to Ki

$$M = \frac{f_0}{W}\sum_{n=n_1}^{n_2} M_n = \frac{f_0}{2\sqrt{2\pi}\,\eta\,\delta f_C}$$

Wanted mixing

$$U = \frac{k(T_R + T_A)}{\frac{N}{2}(Qe)^2 f_0 \frac{|Z_P|^2}{Z_C}\cdot\beta_P\cdot\varepsilon}$$

Noise-to-signal ratio

$$g = N(Qe)^2 f_0 \sqrt{\beta_P \beta_K}\, Z_P G_A \frac{K_\perp}{p_0 \beta c}$$

Gain

$$Z_P \approx \sqrt{n_P}\sqrt{\frac{Z_L Z_C}{2}}\frac{\sigma}{h}$$

Pickup coupling impedance

$$K_\perp \approx \sqrt{n_K}\,\frac{2}{\pi}\sqrt{\frac{Z_L}{2Z_C}}(1+\beta)\frac{\sigma}{h}\ell$$

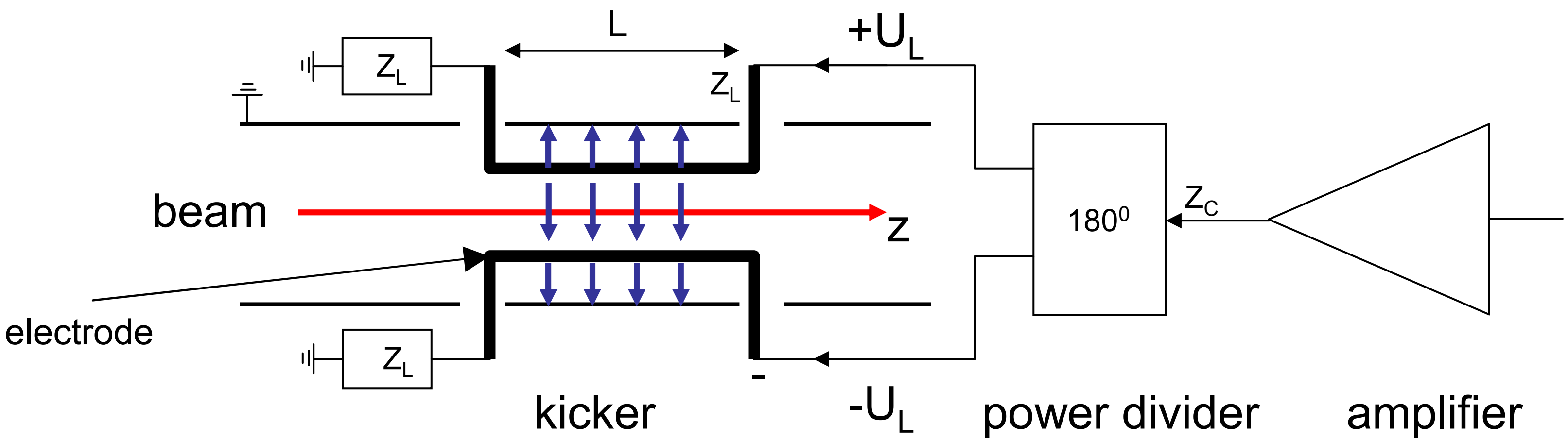
Kicker sensitivity

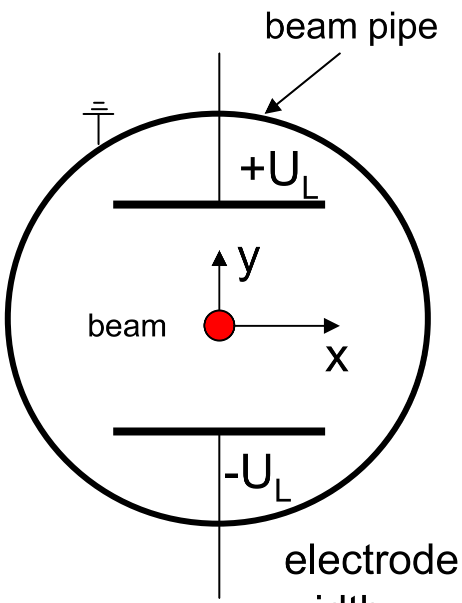
$$\sigma = 2\tanh\left(\frac{\pi w}{2h}\right)$$

Cooling Parameters

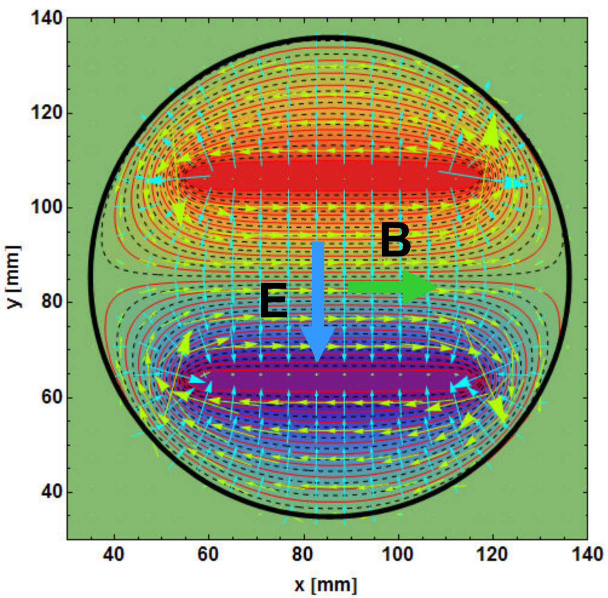
Number of protons $N = 3 \cdot 10^8$
Revolution frequency $f_0 = \omega_0/2\pi = 1.5$ MHz
Number of PU loops $n_P = 32$
Number of kicker loops $n_K = 8$
Cooling bandwidth $W = 1.2$ GHz
Gap height $h = 50$ mm
Geometry factor $\sigma = 1.15$
Line impedance $Z_L = Z_0 = 50\ \Omega$
$T_R + T_A = 40$ K
Voltage gain $G_A = 7.9 \times 10^5$ (= 118 dB)
Beta function at PU $\beta_P = 8$ m
Beam emittance $\varepsilon_{tot} = 4\ \varepsilon = 18$ mm mrad

Model of Stripline Kicker and Pickup





electrode
width: w
gap height: h



- Electromagnetic fields in the kicker are essentially TEM waves with cut-off frequency zero
- Characteristic electrode impedance Z_L
- Higher order modes can be suppressed

$$B_x = \frac{1}{c} E_y$$

Electromagnetic Field Strength in a Kicker

Fields in the kicker induced by Schottky and Thermal noise power:

Schottky noise at kicker entrance:

For constant gain G_A in the cooling bandwidth W

$$P_S = S \cdot G_A^2 W = \frac{N}{2}(Qe)^2 \frac{\omega_0}{2\pi} n_P \frac{Z_L}{2}\left(\frac{\sigma}{h}\right)^2 \varepsilon_{tot} \beta_P G_A^2 W$$

Thermal noise at kicker entrance:

$$P_{th} = k(T_R + T_A) \cdot G_A^2 W$$

Total power: $P = P_S + P_{th}$

Experimental Data

Kicker fields $\propto \sqrt{\varepsilon_{tot}}$

Number of protons N = 3 10^8
Revolution frequency $f_0 = \omega_0/2\pi$ = 1.5 MHz
Number of PU loops n_P = 32
Number of kicker loops n_K = 8
Cooling bandwidth W = 1.2 GHz
Gap height h = 50 mm
Geometry factor σ = 1.15
Line impedance Z_L = 50 Ω
$T_R + T_A$ = 40 K
Voltage gain G_A = 7.9 x 10^5 (= 118 dB)
Beta function at PU β_P = 8 m
Beam emittance ε_{tot} = 4 ε = 18 mm mrad

$$P_S = 0.4W$$

$$P_{th} = 0.4W$$

$$P_{tot} \approx 0.8W$$

Peak voltage at one electrode: $U_L = \pm 2.2V$

Peak vertical electrical field: $E_y = 88\frac{V}{m}$

Peak horizontal magnetic field:

$$B_x = \frac{1}{c}E_y = 3 \cdot 10^{-4}\, mT$$

Compare with:

RF dipole peak field at COSY: $B_x \approx 1mT$

RF solenoid peak field: $B_z \approx 2mT$

Deflection in a Kicker

Kicker sensitivity $K_\perp = \dfrac{\Delta p_y \beta c / (Qe)}{U_K}$

Wave propagating in **opposite direction to the beam** $E_y(z,t) = \dfrac{2U_L}{h} e^{-i(k_L z + \omega t)}$

in vacuum: $k_L = \dfrac{\omega}{c}$

particle velocity: v

Lorentz Force $F_y = (Qe)\left(E_y + vB_x\right)$

Vertical deflection $\Delta p_y = \int_0^{L/v} F_y(t)dt$ where L is the line length

yields

$$\Delta p_y(\omega) = \frac{2(Qe)U_L}{h}\left(\frac{1}{v}+\frac{1}{c}\right)L\frac{\sin\theta(\omega)}{\theta(\omega)}e^{-i\theta(\omega)}$$

with $\theta(\omega) = \left(\dfrac{1}{v}+\dfrac{1}{c}\right)\dfrac{\omega L}{2}$

L: electrode length

Note: If beam and wave travel in the same direction: deflection is zero for v = c

Pickup Transverse Coupling Impedance

Pickup output voltage $U_P(\omega) = Z_P(\omega) d(\omega)$

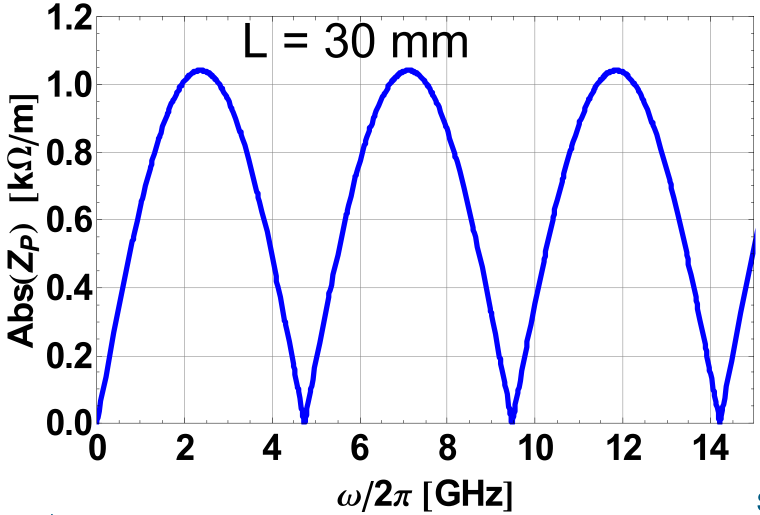
From antenna theory:

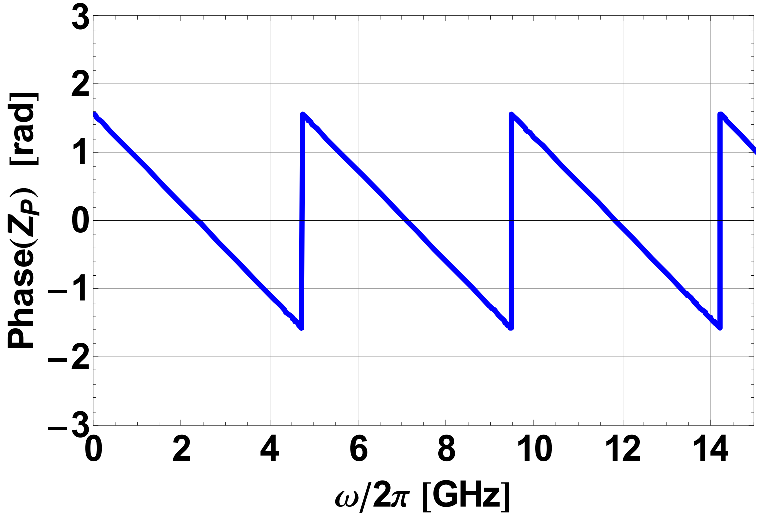
- Each kicker device can be used as pickup if the beam direction is reversed

$$Z_P(\omega) = \sqrt{n_P}\sqrt{\frac{Z_L Z_C}{2}}\frac{\sigma}{h}\sin\theta(\omega)e^{-i(\pi/2-\theta(\omega))} \quad [\Omega/m]$$

n_P: number of loops
$\sigma \approx 2$ geometry factor

Example with same parameters as for kicker (one electrode pair):





Transverse Kicker Sensitivity

Kicker sensitivity $K_\perp = \frac{\Delta p_y \beta c / (Qe)}{U_K}$

$$K_\perp(\omega) = \sqrt{n_K}\sqrt{\frac{Z_L}{2Z_C}}(1+\beta)\frac{g\,L}{h}\frac{\sin\theta(\omega)}{\theta(\omega)}e^{-i\theta(\omega)}$$

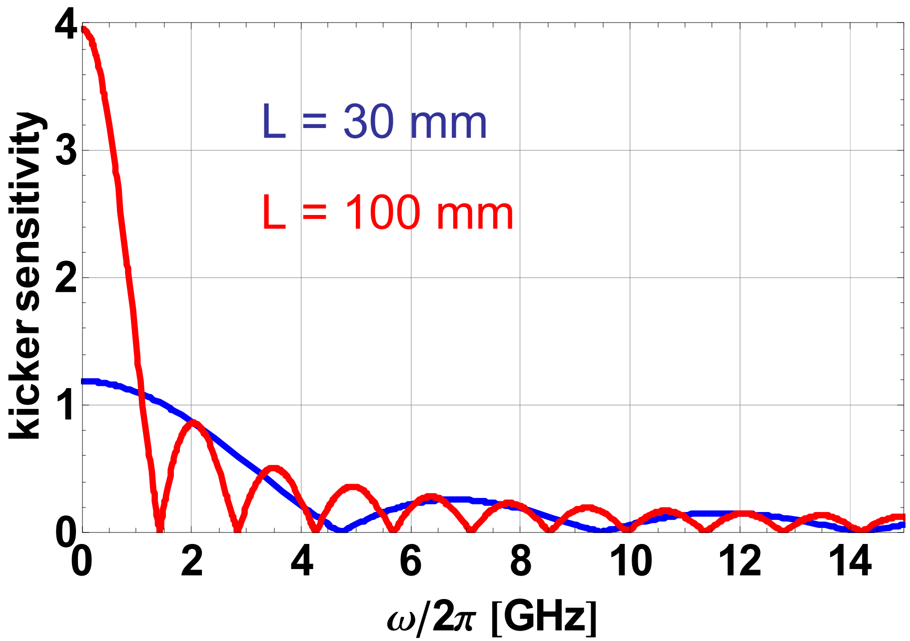
n_K: number of kicker loop pairs

Geometry factor $g = 2\tanh\left(\frac{\pi w}{2h}\right)$

U_K is the input voltage at the power divider with characteristic impedance Z_C:

$$U_K = \sqrt{\frac{2Z_C}{Z_L}}\cdot U_L$$

with $\theta(\omega) = \left(\frac{1}{v}+\frac{1}{c}\right)\frac{\omega L}{2}$



Example:

- $\beta = 0.9$
- w = 30 mm
- h = 50 mm
- $Z_L = Z_C = 50\ \Omega$
- $n_K = 1$

$\Rightarrow g = 1.5$