Transverse Emittance Exchange for



Improved Injection Efficiency







- I INJECTION PROCESS WHAT CAN WE GAIN
- **II EMITTANCE EXCHANGE** HOW FAR CAN WE GO
- **EMITTANCE SHARING –** *MODERATE REDUCTION*
 - **III. 1 ON THE COUPLING RESONANCE**
 - **III. 2 EXCITATION OF THE RESONANCE**
- **IV EMITTANCE EXCHANGE** FULL REDUCTION
 - **IV. 1 RESONANCE CROSSING**
 - IV. 2 π -PULSE EXCITATION
 - IV. 3 IN THE TRANSFER LINE

V SUMMARY





before injection



1.



at injection – stored beam kicked close to the septum injected beam arrives at the septum



required acceptance > $6 \cdot \sigma_{inj}$ + $6 \cdot \sigma_{sto}$ + effective septum thickness dominated by large emittance of injected beam

1.



smaller emittance of injected beam



Swiss light source – synchrotron and storage ring in same tunnel Spring8 – horizontal collimation in the transfer line MAXIV – injection LINAC

1.



Can we take advantage of the flat beam delivered by the synchrotron and use emittance exchange to reduce the horizontal emittance?



Ш.



scraper measurements at β_y =1.25m and α_y =0 yield A=2mm:

Π.

vertical acceptance > $3 \cdot \varepsilon_{ini}$



EMITTANCE EXCHANGE AT BESSY II





At Bessy II full emittance exchange feasible – considerable reduction of horizontal emittance

Π.



linear coupling due to skew quadrupole gradient: $Q_x-Q_y=n$, n=integer on resonance emittance sharing - $\varepsilon_y=\varepsilon_x=\varepsilon_0/2$



Comparison of solutions from multi particle tracking and first modelling attempts with analytical solutions based on moment mapping



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detuning dQ

Compensation of the coupling resonance in the BESSY II storage ring – as expected: damping dominates for very small coupling coefficients, and width depends on coupling strength: "power broadening", will be helpful later on



emittance sharing on resonance: $\varepsilon_y = \varepsilon_x = \varepsilon_0/2$, already valuable reduction

In case the synchrotron can not be operated at the coupling resonance the creation of an artificial resonance could help. With a time dependent sinusoidal varying skew gradient the resonance condition is:

$$Q_x - Q_{y_} = n \pm F_{sq}/F_0,$$

with the revolution frequency, F_0 , and of the skew gradient, F_{sq} .



Skew quadrupole-like field distribution in the centre of the stripline arrangement.

P. Kuske, F. Kramer, IPAC'16, Busan, Korea, May 8-13, 2016

Neighboring currents in opposite directions.

Full coupling and equal horizontal and vertical emittances achievable – little power broadening, sensitivity to tune jitter.

Could produce round beams compatible with horizontal off-axis injection.

P. Kuske, R. Görgen, EPAC 2002, WEPLE015 ¹¹



Slow crossing of the coupling resonance approaches the steady state solution for the beam emittances – dotted lines



Horizontal axis is also a time axis. Tunes are swept within a sweep time of 314.1 ms across the resonance. Transverse damping time of the BESSY synchrotron is 9.8 ms.

C. Carli, et al., "Emittance Exchange by Crossing a Coupling Resonance", EPAC 2002 12





Horizontal axis is also a time axis. Tunes are swept within a sweep time of 78.5 ms across the resonance. Transverse damping time of the BESSY synchrotron is 9.8 ms.

C. Carli, et al., "Emittance Exchange by Crossing a Coupling Resonance", EPAC 2002 13

P. Kuske, F. Kramer, IPAC'16, Busan, Korea, May 8-13, 2016





x,y-distribution:

Horizontal axis is also a time axis. Tunes are swept within a sweep time of 19.6 ms across the resonance. Transverse damping time of the BESSY synchrotron is 9.8 ms.

C. Carli, et al., "Emittance Exchange by Crossing a Coupling Resonance", EPAC 2002 14





Horizontal axis is also a time axis. Tunes are swept within a sweep time of 9.8 ms across the resonance. Transverse damping time of the BESSY synchrotron is 9.8 ms.

C. Carli, et al., "Emittance Exchange by Crossing a Coupling Resonance", EPAC 2002 15

P. Kuske, F. Kramer, IPAC'16, Busan, Korea, May 8-13, 2016





Horizontal axis is also a time axis. Tunes are swept within a sweep time of 4.9 ms across the resonance. Transverse damping time of the BESSY synchrotron is 9.8 ms.

C. Carli, et al., "Emittance Exchange by Crossing a Coupling Resonance", EPAC 2002 16

P. Kuske, F. Kramer, IPAC'16, Busan, Korea, May 8-13, 2016





Horizontal axis is also a time axis. Tunes are swept within a sweep time of 2.5 ms across the resonance. Transverse damping time of the BESSY synchrotron is 9.8 ms.

C. Carli, et al., "Emittance Exchange by Crossing a Coupling Resonance", EPAC 2002 17





Horizontal axis is also a time axis. Tunes are swept within a sweep time of 1.2 ms across the resonance. Transverse damping time of the BESSY synchrotron is 9.8 ms.

C. Carli, et al., "Emittance Exchange by Crossing a Coupling Resonance", EPAC 2002 18

P. Kuske, F. Kramer, IPAC'16, Busan, Korea, May 8-13, 2016



Crossing of the coupling resonance fast compared to the transverse damping times results in an attractive emittance exchange and 10 times smaller horizontal emittance



Quadrupole magnets and power supplies of ramped synchrotrons can produce the desired tune shifts shortly before the beam is extracted. The White-circuits of the BESSY synchrotron do not allow this.

P. Kuske, F. Kramer, IPAC'16, Busan, Korea, May 8-13, 2016

C. Carli, et al., "Emittance Exchange by Crossing a Coupling Resonance", EPAC 2002 19



Like in many two-level systems (NMR, atomic transitions, spin=1/2-system, ...) the inversion of the states is achieved with π -pulse. This can be applied to create also an emittance exchange. On the coupling resonance we need a pulsed skew quadrupole magnet with a duration short compared to the transverse damping times.





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For π -pulse the time integrated gradient is constant: peak skew gradient, $\frac{\partial B_{\chi}}{\partial x}$, pulse length $n \cdot T_0$



With a short and strong skew gradient pulse the power broadening helps to exchange the emittance even slightly off-resonance. Tunes still close to the coupling resonance – resonance needs to be decoupled.



The necessary peak field for a half sinusoidal π -pulse can be determined by mapping the moments of the particle distribution turn-by-turn with a time dependent skew quadrupole. Damping and excitation can be ignored because of the short pulse length.

P. Kuske, F. Kramer, IPAC'16, Busan, Korea, May 8-13, 2016



Design of a pulsed skew quadrupole magnet At BESSY a 6 turn long π -pulse requires a peak skew gradient of:

$$\frac{\partial B_x}{\partial x} \approx 4.94/n \frac{B\rho}{\sqrt{\beta_x \beta_y} \cdot L_{skew}} \approx 4.94/6 \frac{5.7Tm}{\sqrt{4.7m \cdot 5.0m} \cdot 0.3m} \approx 3.2 \text{T/m}$$



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skew quadrupole - 4 wire arrangement with currents in alternating directions



$$\left|\frac{\partial B_x}{\partial x}\right| = \frac{4 \cdot \mu \cdot I}{\pi \cdot a^2} = \frac{1.6 \cdot 10^{-6} \cdot I[A]}{a^2 [m^2]} [T/m]$$
$$\left|\frac{\partial B_x}{\partial x}\right| = 4 T/m \quad \text{for a=2 cm and I=1 kA}$$



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quite similar to our non-linear injection kicker magnet



BESSY II transferline overview in control system



Felix Kramer, DPG-Frühjahrstagung, Darmstadt, 14. - 18. März 2016

IV.3



Transfer matrix of emittance exchange structure – with 6 skew quadrupole magnets:

 $R = \begin{pmatrix} 0 & D \\ D & 0 \end{pmatrix}$ with: $D = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ $L_{tot}=9$ m, too long for any optics matching

Transfer matrix of emittance exchange structure – with 5 skew quadrupole magnets:



IV.3





No control of the dispersion – contribution from the energy spread of the injected beam spoils gain from emittance exchange completely

IV.3



Smaller emittance of injected beam eases injection

Beam delivered by synchrotrons usually have quite large horizontal to vertical emittance ratios – horizontal injection can profit from emittance sharing or exchange – if vertical acceptance is sufficiently large

Emittance sharing on linear coupling resonance or excited by oscillating skew gradient

Emittance exchange by:

V.

- 1) fast crossing the coupling resonance operating close to the coupling resonance
- 2) π -pulse excitation operating very close to the coupling resonance
- 3) skew quadrupole arrangement in transfer line dispersion is very critical

Which option to choose depends on the actual boundary conditions of the facility