Round Beam Related Challenges in Storage Ring Light Sources

Peter Kuske, Helmholtz-Zentrum Berlin and Humboldt-Innovation GmbH

Monday, 5 March 2018, FLS2018, Shanghai, China

Content

I. Round Beams – Why?

ERL community coined the term round beam

Dispersion free straight section: $\beta_x(s)\cdot\varepsilon_x=\beta_y(s)\cdot\varepsilon_y \rightarrow \beta_x(s)=\beta_y(s)$ *and* $\varepsilon_x=\varepsilon_y$

Best overlap of electron and photon beam *with:* $\beta_x(s=0) = \beta_y(s=0) \sim L/\pi$

I. Round Beams – Why?

ERL community coined the term round beam

Dispersion free straight section: $\beta_x(s)\cdot\varepsilon_x=\beta_y(s)\cdot\varepsilon_y \rightarrow \beta_x(s)=\beta_y(s)$ *and* $\varepsilon_x=\varepsilon_y$

Best overlap of electron and photon beam *with:* $\beta_x(s=0) = \beta_y(s=0) \sim L/\pi$

„A significant fraction of the beamline users at Swiss light source (SLS) prefer "round beam" rather than flat beam, ...", M. Aiba, et al., TUPJE045, IPAC2015

- Imaging applications would profit, better match to optics, circular zone plates
- Monochromators without entrance slit and dispersion into the vertical plane prefer flat beams – as long as we are not fully diffraction limited
- A vertical emittance of ~10 pm·rad is foreseen for ESRF-EBS and other similar upgrade and new projects – also for highest coherent flux

What users really prefer most is radiation optimized for their own experiment.

I. Round Beams – Why?

ERL community coined the term round beam

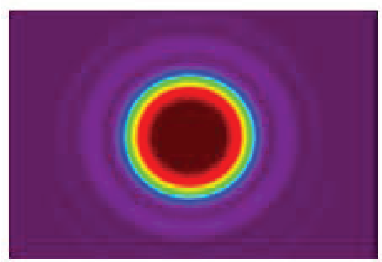
Dispersion free straight section: $\beta_x(s)\cdot\varepsilon_x=\beta_y(s)\cdot\varepsilon_y \rightarrow \beta_x(s)=\beta_y(s)$ *and* $\varepsilon_x=\varepsilon_y$

Best overlap of electron and photon beam *with:* $\beta_x(s=0) = \beta_y(s=0) \sim L/\pi$

„ A significant fraction of the beamline users at Swiss light source (SLS) prefer “round beam“ rather than flat beam, ...“, M. Aiba, et al., TUPJE045, IPAC2015

- Imaging applications would profit, better match to optics, circular zone plates
- Monochromators without entrance slit and dispersion into the vertical plane prefer flat beams – as long as we are not fully diffraction limited
- A vertical emittance of ~10 pm·rad is foreseen for ESRF-EBS and other similar upgrade and new projects – also for highest coherent flux

What users really prefer most is radiation optimized for their own experiment.



Round Beam Workshop, SOLEIL, June 14th - 15th, 2017

https://www.synchrotron-soleil.fr/fr/evenements/mini-workshop-round-beams

1

I. Round Beams – Why?

ERL community coined the term round beam

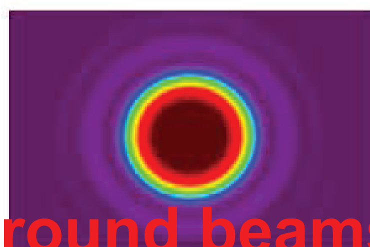
Dispersion free straight section: $\beta_x(s)\cdot\varepsilon_x=\beta_y(s)\cdot\varepsilon_y \rightarrow \beta_x(s)=\beta_y(s)$ *and* $\varepsilon_x=\varepsilon_y$

Best overlap of electron and photon beam *with:* $\beta_x(s{=}0) = \beta_y(s{=}0) \sim L/\pi$

„ A significant fraction of the beamline users at Swiss light source (SLS) prefer "round beam" rather than flat beam, ...", M. Aiba, et al., TUPJE045, IPAC2015

- Imaging applications would profit, better match to optics, circular zone plates
- Monochromators without entrance slit and dispersion into the vertical plane prefer flat beams – as long as we are not fully diffraction limited
- A vertical emittance of ~10 pm·rad is foreseen for ESRF-EBS and other similar upgrade and new projects – also for highest coherent flux

What users really prefer most is radiation optimized for their own experiment.



biggest challenge for round beams – we are still far away from the diffraction limit at high photon energies

Round Beam Workshop, SOLEIL, June 14th - 15th, 2017

https://www.synchrotron-soleil.fr/fr/evenements/mini-workshop-round-beams

I. Round Beams – Why?

Reduced electron density from round electron beam has advantages:

- smaller Touschek losses increase life time
- decreased intra beam scattering (IBS) lowers beam blow up

and disadvantage:

- decreased IBS could increase single bunch instability thresholds

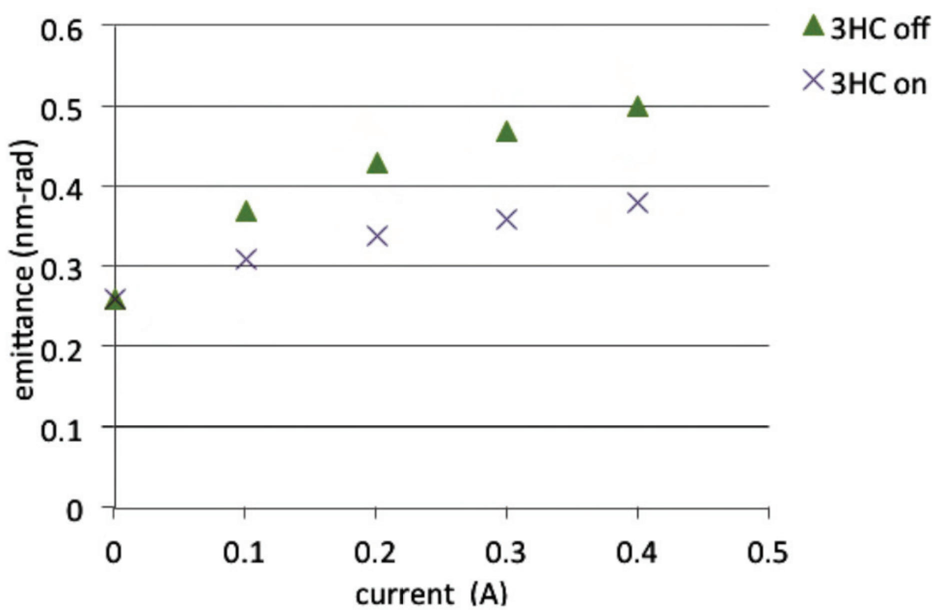


Figure 4.2.2.1: Emittance increase due to IBS for both natural bunch length (triangles) and a bunch 3.5 times lengthened (x).

Can all beamlines cope with a round electron beam?

Elettra today: ε_x=7 nm·rad ε_y= 70 pm·rad – Elettra 2.0: $\varepsilon_x=\varepsilon_y$=154 pm·rad

Situation worse for rings operating today with ε_y<10 pm·rad

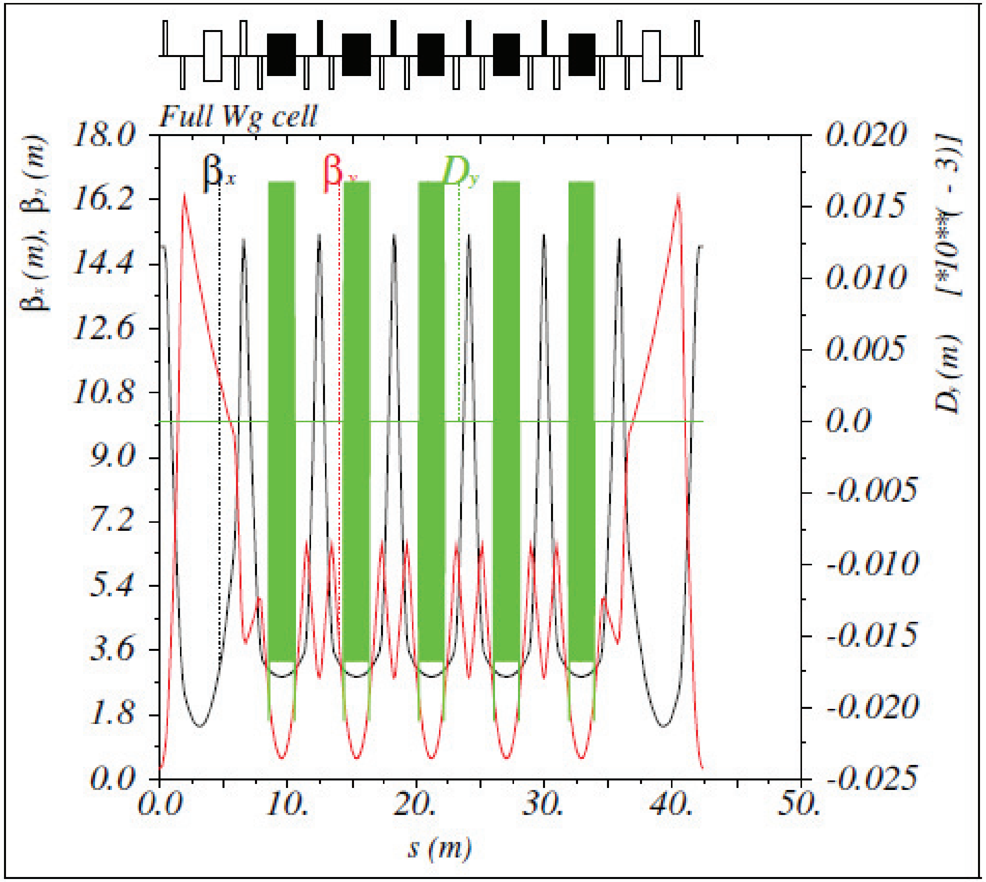
Ultimate synchrotron radiation source with horizontal field wigglers

A. Bogomyagkov, E. Levichev, P. Piminov, S. Sinyatkin

Budker Institute of Nuclear Physics
Novosibirsk

Low Emittance Rings 2014 Workshop
17-19 September 2014 INFN-LNF

Straight section: damping wigglers with horizontal field



Wigglers with horizontal field:
$B = 2.3$ T
$\lambda = 4.8$ cm
$N_\lambda = 42$
$L_{wiggler} = 2.04$ m
$N_{total} = 20$
$L_{total} = 40.8$ m

Parameters of the ring

$$Ring = 4 \times 6 \times \left[5 \times FiveCell + Straight\right]$$

20 straight are sections empty

4 straight sections are occupied by damping wigglers

	Wigg OFF	Wigg ON
Energy, GeV	3	
Circumference, m	1379	
Chromaticity h/v	-184/-251	
Betatron tunes h/v	84.52/91.772	
Horizontal Emittance, pm rad	64	3
Vertical Emittance, pm rad	0.6	8.6
Energy spread	4×10^{-4}	1.2×10^{-3}
Momentum compaction	7.8×10^{-5}	7.8×10^{-5}
Damping times h/v/s, msec	210/210/105	10/10/5
Wiggler field, T	0	2.33

Any emittance ration can be created, however, will depend on ID settings – as in any low emittance ring. Stabilization requires adequate diagnostics and actuators in the form of an idle DW.

Much larger energy spread from DW will cause reduction of brilliance from high undulator harmonics.

Significant space required for DW.

Similar proposal for PEP-X by X. Huang, Nucl. Instr. Meth. A 777 (2015) 118-122

If you want emittance ratios of 10% to 20% : vertical dispersion could help
it is not trivial to create constant 10 pm·rad from a low emittance ring

III. Round Beam in Möbius Accelerator

In the Möbius Accelerator transverse particle coordinates are exchanged every turn by a set of skew quadrupole magnets sharing the natural emittance equally among the two planes.

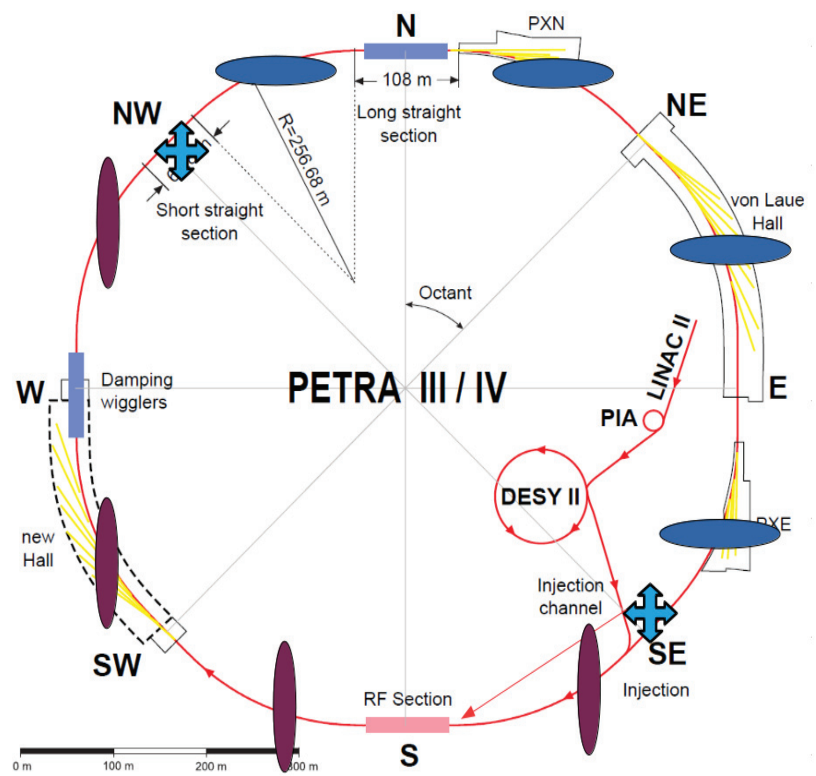
R. Talman, PRL 74, 1590 (1995) and M. Aiba, et al., TUPJE045, IPAC2015, Richmond, VA, USA, and much earlier work on the advantages of colliding round instead of flat beams, see A. Zholents, “Beam-Beam Effects in Electron-Positron Storage Rings”, Lecture Notes in Physics 400, Springer-Verlag Berlin Heidelberg 1992

Award-winning Norwegian architectural firm, Snøhetta, unveiled an innovative proposal for the Max-Lab in Lund, Sweden.
The circular shape is twisted and raised to create a dynamic form based on a Möbius strip that becomes an actual volume, not just a ribbon.

Off-axis injection impossible with this really strong coupling of the horizontal and vertical plane – reason for the SLS to abandon this scheme for SLS-II

Except – you have a large circumference like PETRA IV and can exchange transverse coordinates twice per revolution (see talk of Ilya Agapov, “Round beams at Petra IV”, NOCE, Arcidosso, Italy, September, 2017)

25/25 pm lattice



Flat beams are more desirable, scheme discarded as well (LER-workshop, CERN, January 2018)

E. Wilson „Linear Coupling“, CERN 85-19, p. 114, with time dependent skew quadrupole:

$$\ddot{x} + \omega_x^2 x = -y \cdot k \cdot (e^{i\omega t} + e^{-i\omega t})/2$$
$$\ddot{y} + \omega_y^2 y = -x \cdot k \cdot (e^{i\omega t} + e^{-i\omega t})/2$$

Ansatz – small coupling:

$$x(t) = X(t) \cdot e^{i\omega_x t}$$
$$y(t) = Y(t) \cdot e^{i\omega_y t}$$

X(t) and Y(t) are slowly varying functions – second time derivatives as well as fast

$$2i\omega_x \dot{X} = -Y \cdot k \cdot \left[e^{i(\omega-\Delta\omega)t} + \cancel{e^{-i(\omega+\Delta\omega)t}} \right]$$
$$2i\omega_y \dot{Y} = -X \cdot k \cdot \left[e^{-i(\omega-\Delta\omega)t} + \cancel{e^{i(\omega+\Delta\omega)t}} \right]$$

oscillating terms are ignored

$$\Delta\omega = \omega_x - \omega_y$$

coupled first order turned into uncoupled second order differential equation:

$$\ddot{X} - i(\Delta\omega - \omega)\dot{X} + \frac{k^2}{16\omega_x\omega_y} X = 0$$

on resonance – the fast oscillation *x(t)* shows a harmonic modulation and beating with energy exchange to the vertical plane occurs

General resonance condition: $Q_x - Q_y = n \pm \omega/\omega_0$

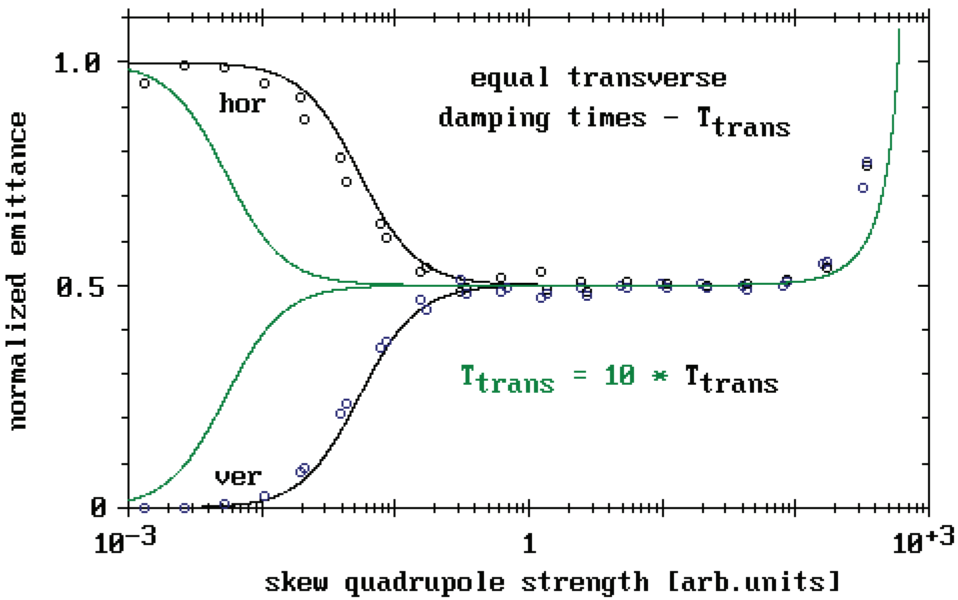
with the revolution frequency, ω_0, and the frequency of the skew gradient, ω.
Identical results for coupling created by constant or time dependent fields in solenoids.

V. Emittance Sharing – Coupling Resonance

linear coupling due to skew quadrupole gradient:

$$Q_x\text{-}Q_y\text{=n, n=integer}$$

on resonance emittance sharing - $\varepsilon_y=\varepsilon_x=\varepsilon_0/2$
with equal damping times, $T_x=T_y$, in both planes



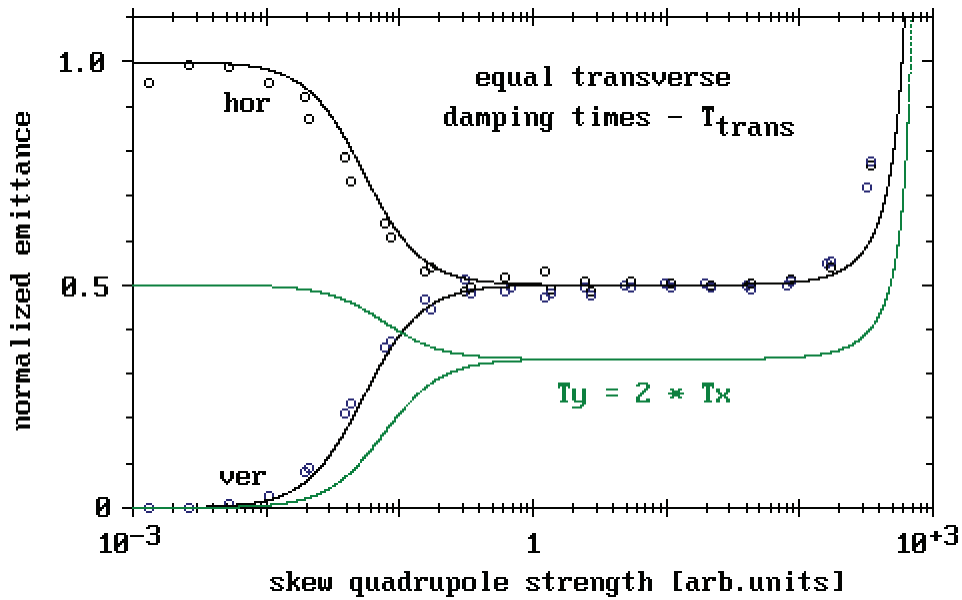
Comparison of solutions from multi particle tracking and first modeling attempts with analytical solutions based on moment mapping.

V. Emittance Sharing – Coupling Resonance

linear coupling due to skew quadrupole gradient:

Q_x-Q_y=n, n=integer

on resonance emittance sharing - ε_y=ε_x=ε_0/2
with equal damping times, T_x=T_y,in both planes



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

With T_x=T_y/2 and on resonance **$\varepsilon_y = \varepsilon_x$ = 2/3 ε_0**

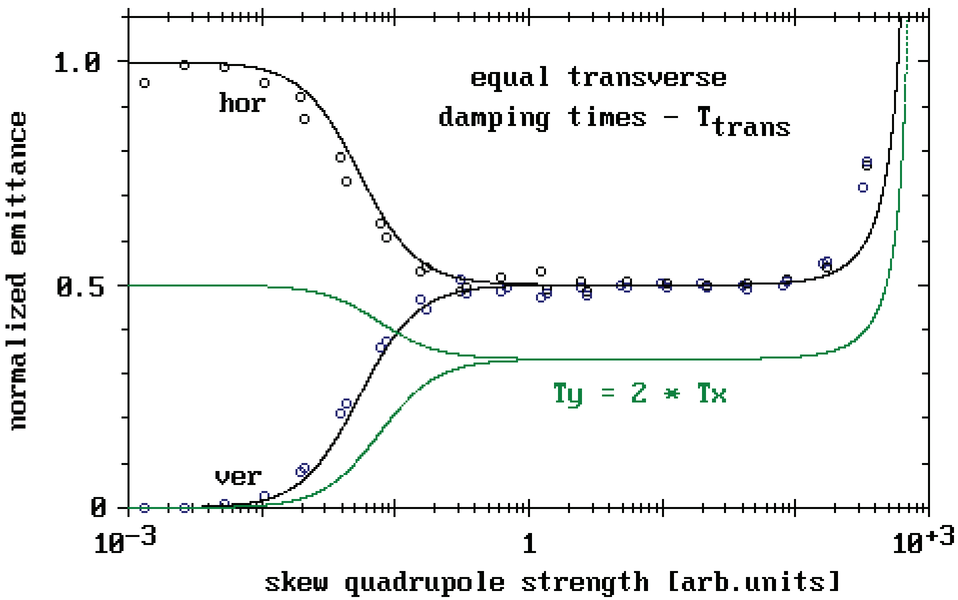
Elettra 2.0:

$\varepsilon_y = \varepsilon_x$ = 22.2ms/(22.2ms +14.6ms) ε_0=154pm·rad

linear coupling due to skew quadrupole gradient:

Q_x-Q_y=n, n=integer

on resonance emittance sharing - $\varepsilon_y=\varepsilon_x=\varepsilon_0/2$ with equal damping times, $T_x=T_y$, in both planes

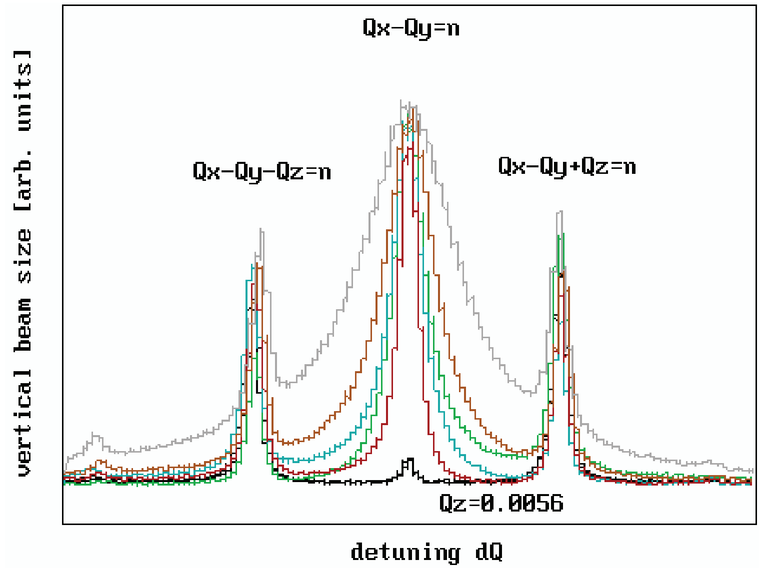


Comparison of solutions from multi particle tracking and first modeling attempts with analytical solutions based on moment mapping.

With $T_x=T_y/2$ and on resonance **$\varepsilon_y=\varepsilon_x$ = 2/3 ε_0**

Elettra 2.0:

$\varepsilon_y=\varepsilon_x$ = 22.2ms/(22.2ms +14.6ms) ε_0=154pm·rad



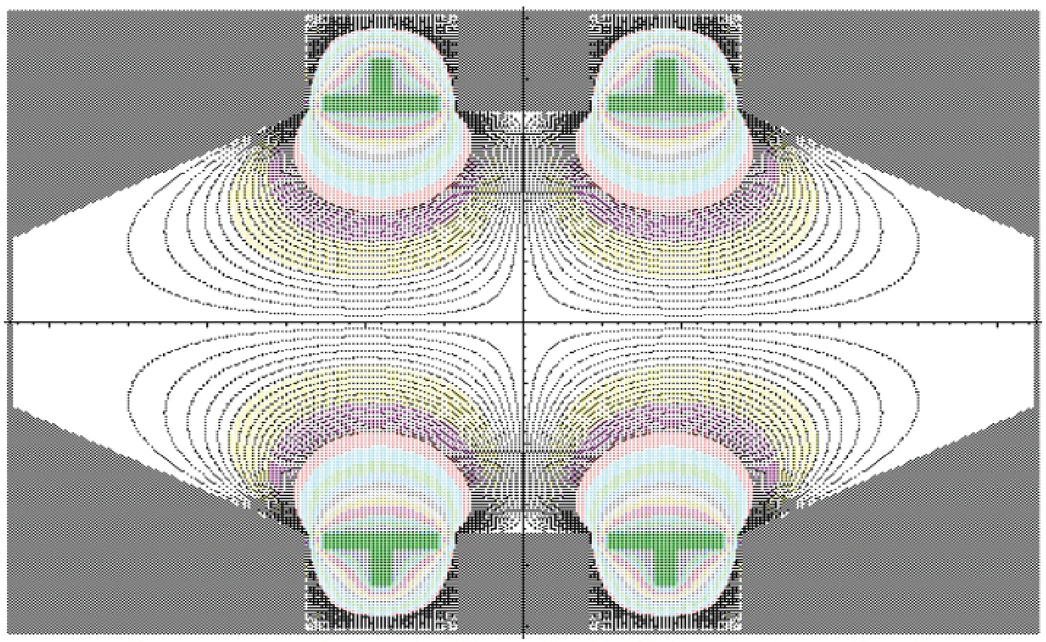
Compensation of the coupling resonance in the BESSY II storage ring – as expected: damping dominates for very small coupling coefficients, and width depends on coupling strength: „power broadening“, will be helpful later on

VI. Emittance Sharing – by Exciting the Coupling Resonance

For better control of the coupling and in case the storage ring can not be operated at the coupling resonance the resonance can be excited artificially. With a time dependent sinusoidal varying skew gradient the resonance condition is:

$$Q_x - Q_y = n \pm \omega/\omega_0$$

with the revolution frequency, ω_0, and the frequency of the skew gradient, ω.



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

Neighboring currents in opposite directions.

Full coupling and emittance sharing achievable –

- little power broadening,
- sensitive to tune jitter.

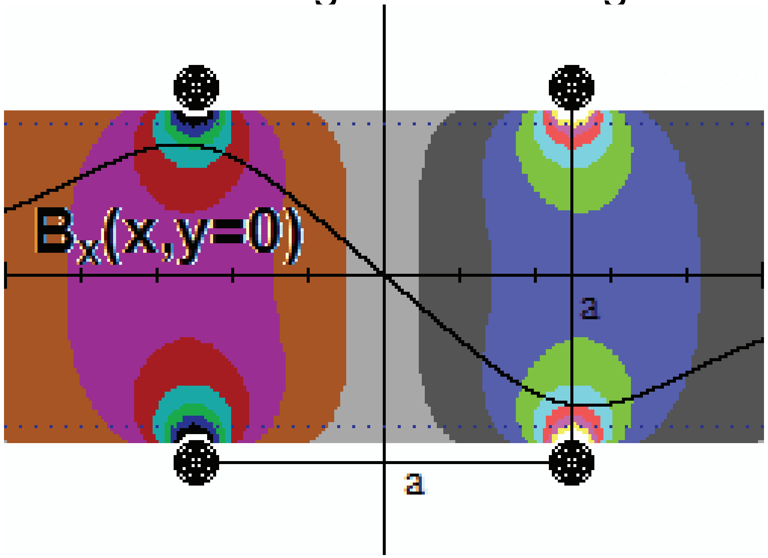
P. Kuske, R. Görgen, EPAC 2002, WEPLE015

VI. Emittance Sharing – by Exciting the Coupling Resonance

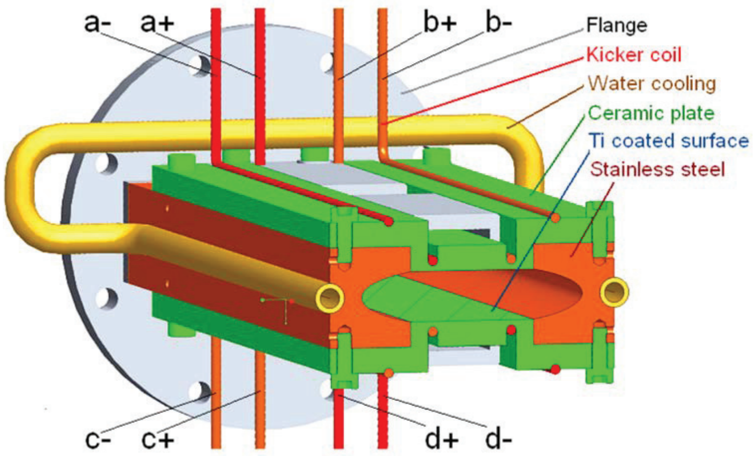
The required frequency, F_{sq}, for the skew quadrupole is on the order of 100 kHz. Gated excitation could blow up only the short bunches (BESSY VSR).

Striplines are not required and simpler design could look like this:

skew quadrupole with four wire arrangement and currents flowing in alternating directions



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

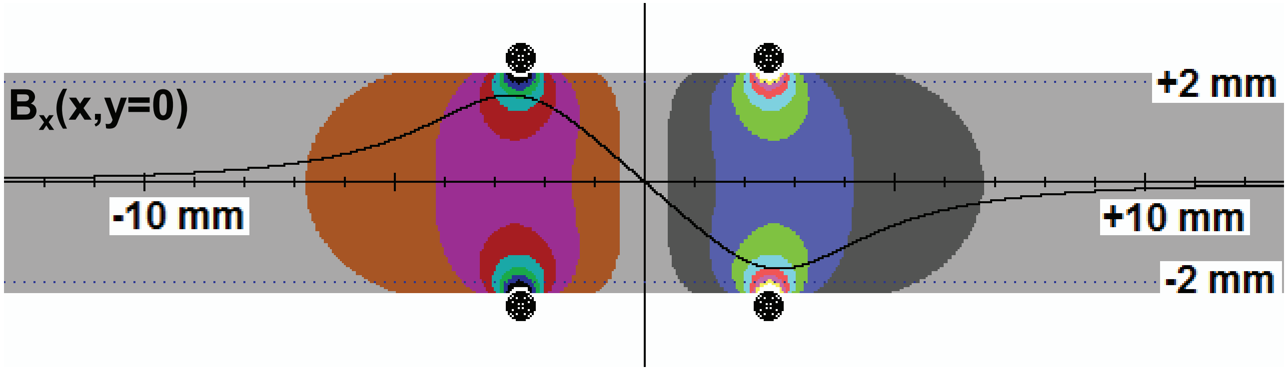


quite similar and even simpler than our non-linear injection kicker magnet

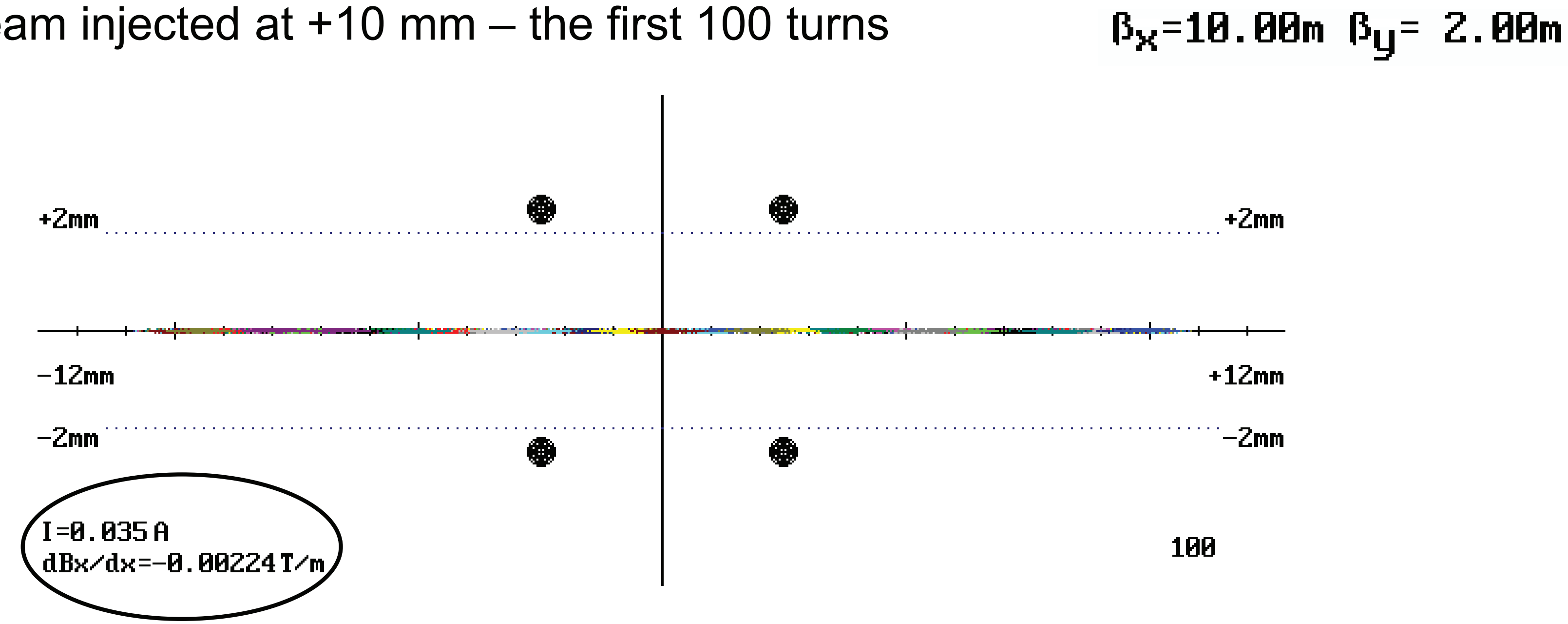
(T. Atkinson, et al., THPO024, IPAC2011)

A time dependent solenoid might even be simpler to construct – fields very high.

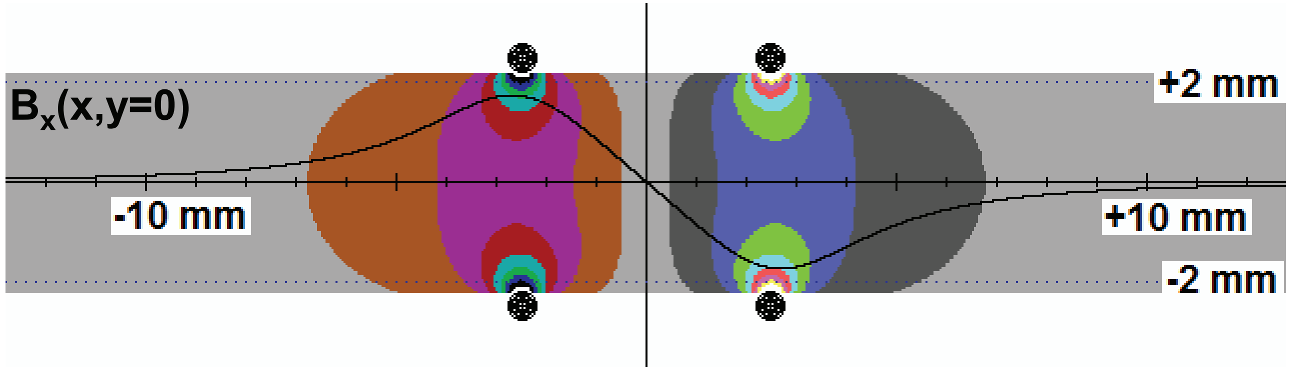
Required acceptance – non-linear skew quadrupole magnet:



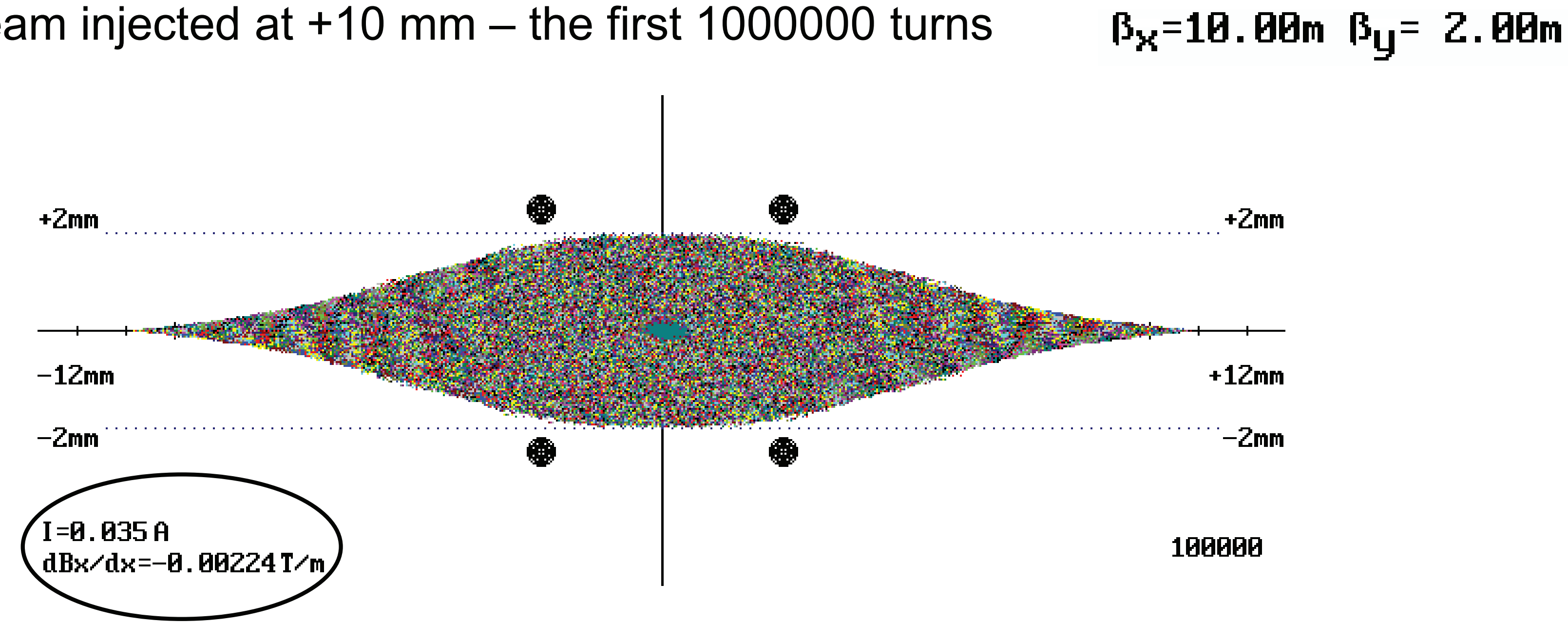
Beam injected at +10 mm – the first 100 turns



Required acceptance – non-linear skew quadrupole magnet:

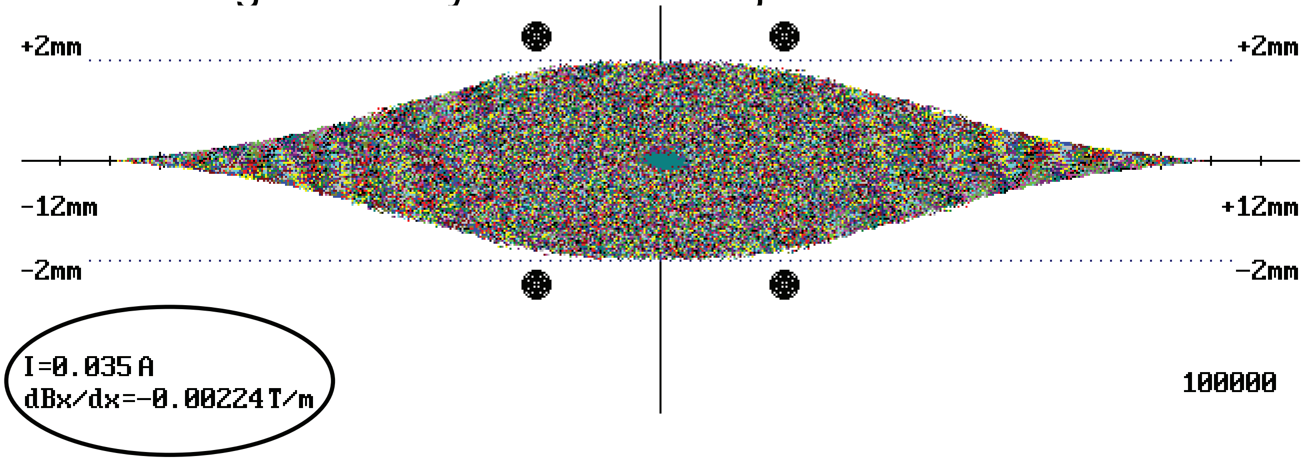


Beam injected at +10 mm – the first 1000000 turns



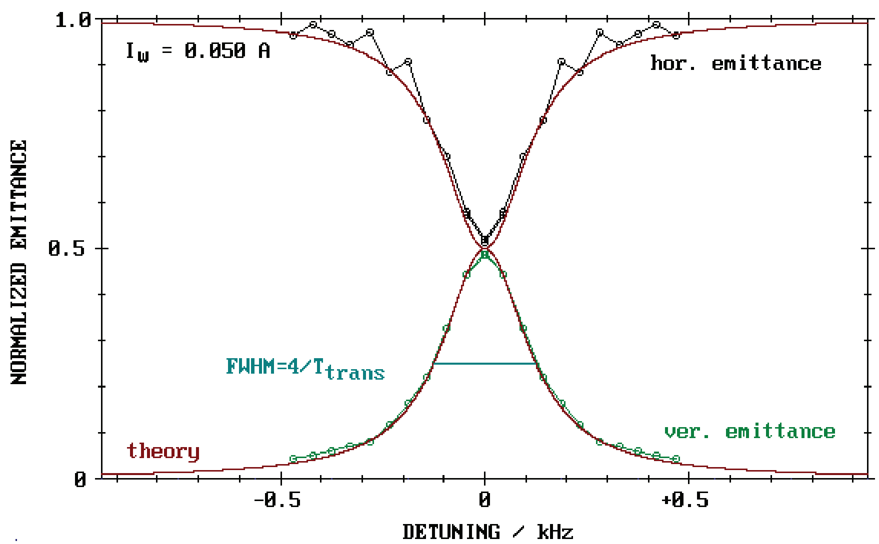
Required acceptance fits vertical acceptance – with non-linear skew quadrupole magnet

Level of excitation as large as not yet to cause injection losses



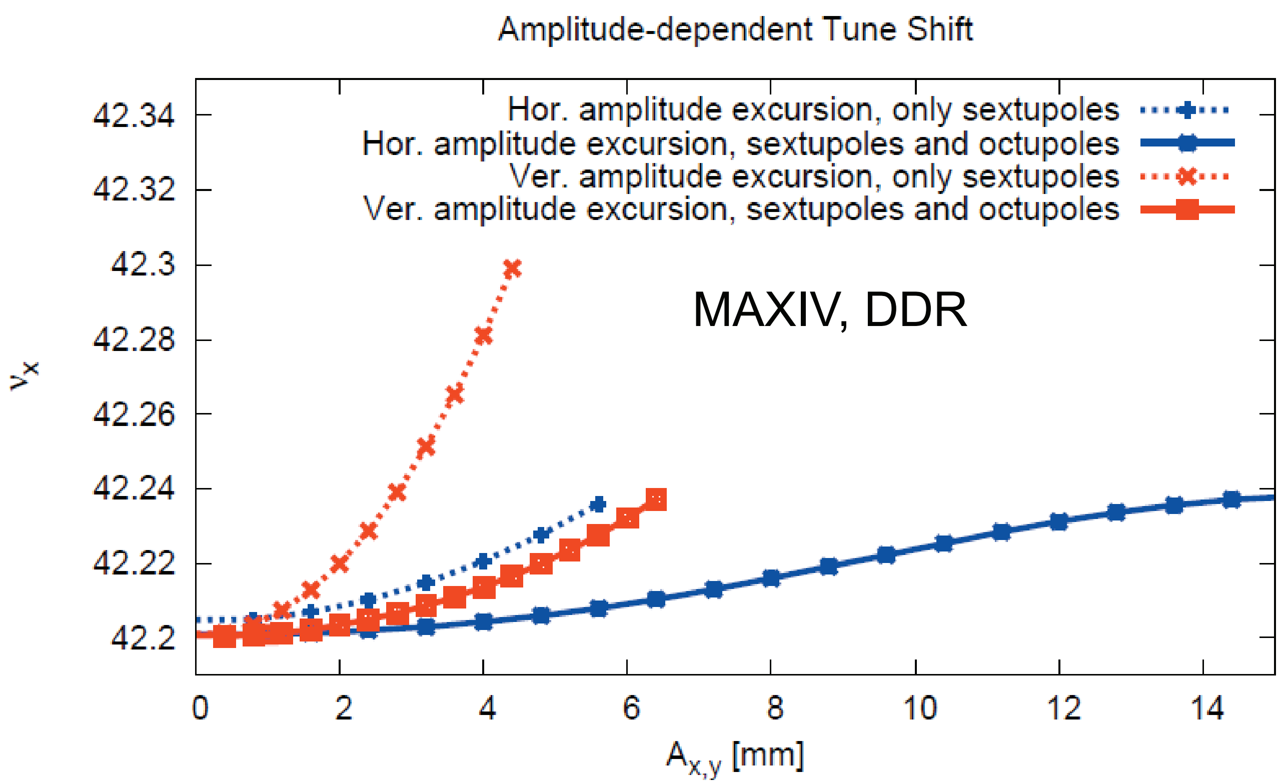
Level of excitation will still be too small to broaden the coupling resonance considerably

Small resonance width – stability of the tunes sufficient? → active tune stabilization



VII. Exciting the Coupling Resonance – Operational Aspects

Tune shift with amplitude would help – resonance condition only fulfilled for small amplitudes, stronger excitation could be used



$\Delta\nu_x$=0.02 $\rightarrow$ ΔF_x=11.4 kHz – much larger than the natural resonance width $\cong 4/\tau_{trans}$ or width due to non-linear chromatic effects

Tune shift with amplitude would help – resonance condition only fulfilled for small amplitudes, stronger excitation could be used

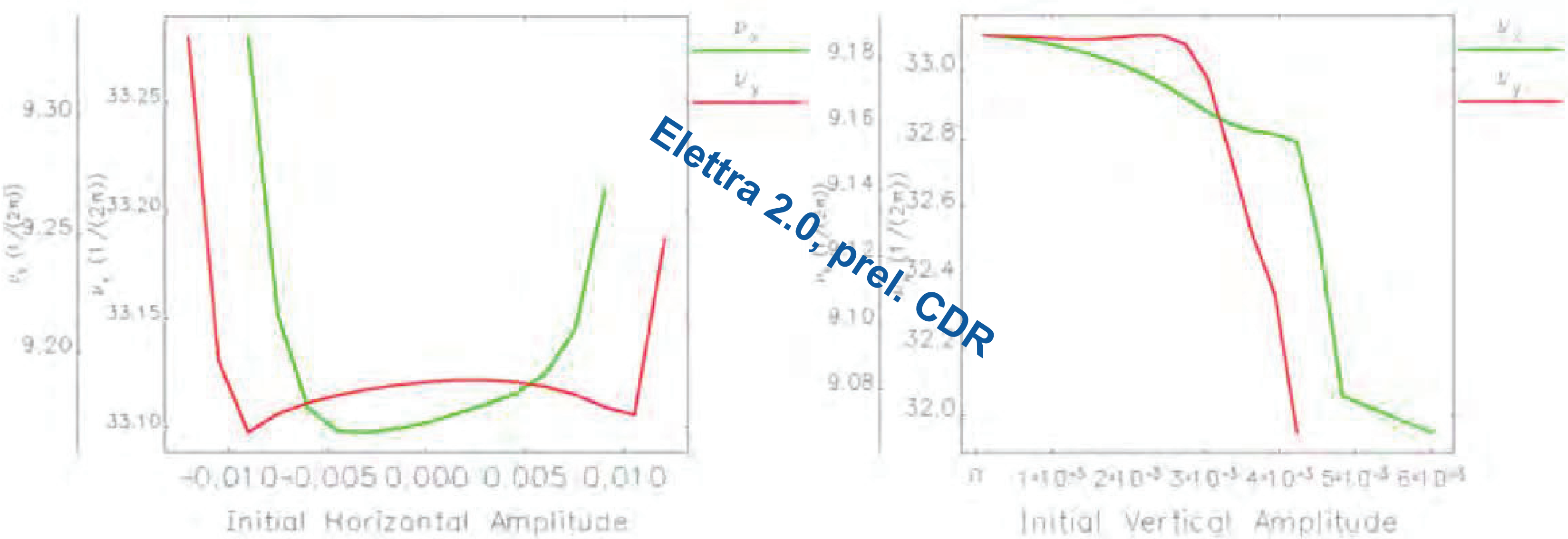
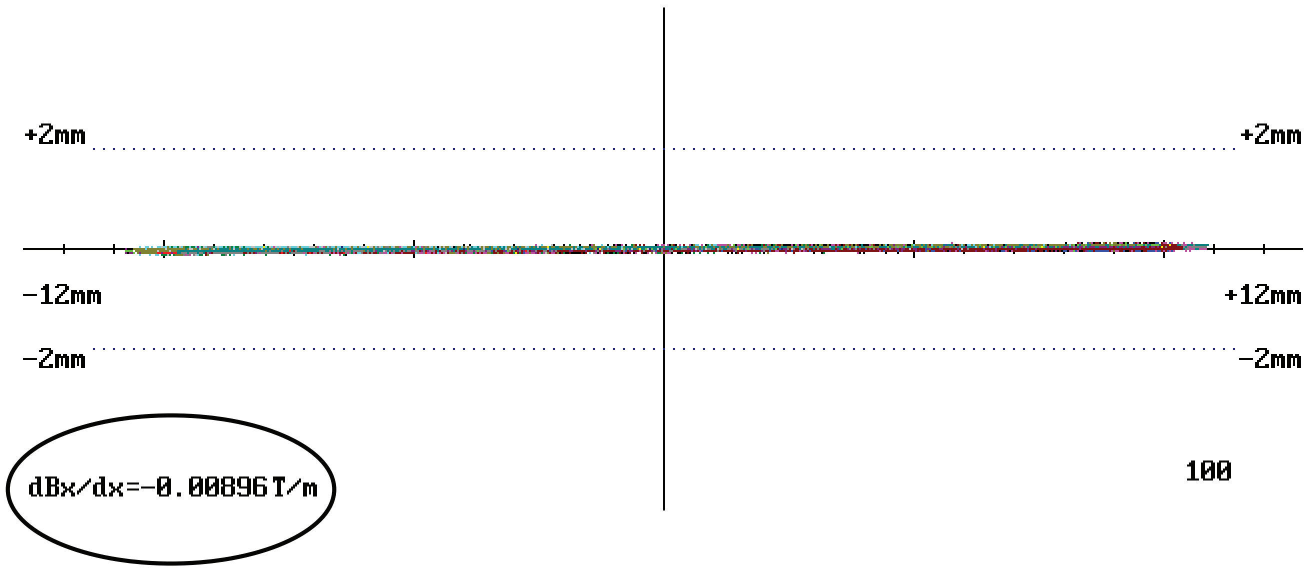


Figure 3.1.1.7: Left: horizontal and vertical tune vs. horizontal amplitude in m. Right: horizontal and vertical tune vs. vertical amplitude in m.

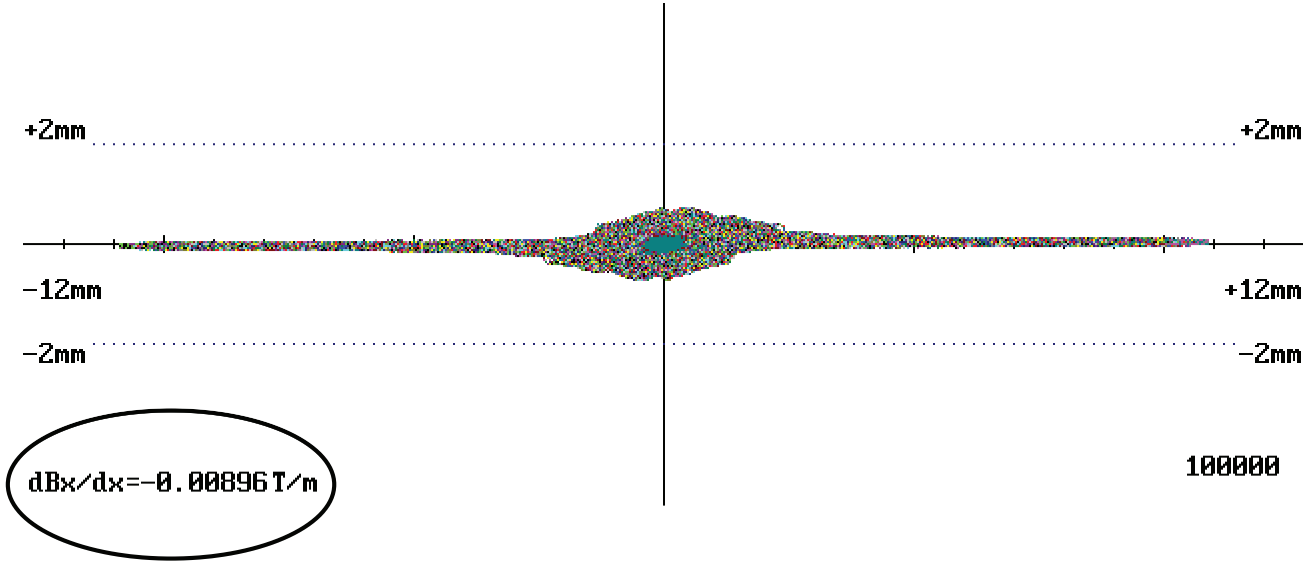
$\Delta\nu$~0.018 @ +5mm $\rightarrow$ ΔF=21 kHz – much larger than the natural resonance width $\cong 4/\tau_{trans}$ or width due to non-linear chromatic effects

Beam injected at +10 mm – with tune shift with amplitude - the first 100 turns



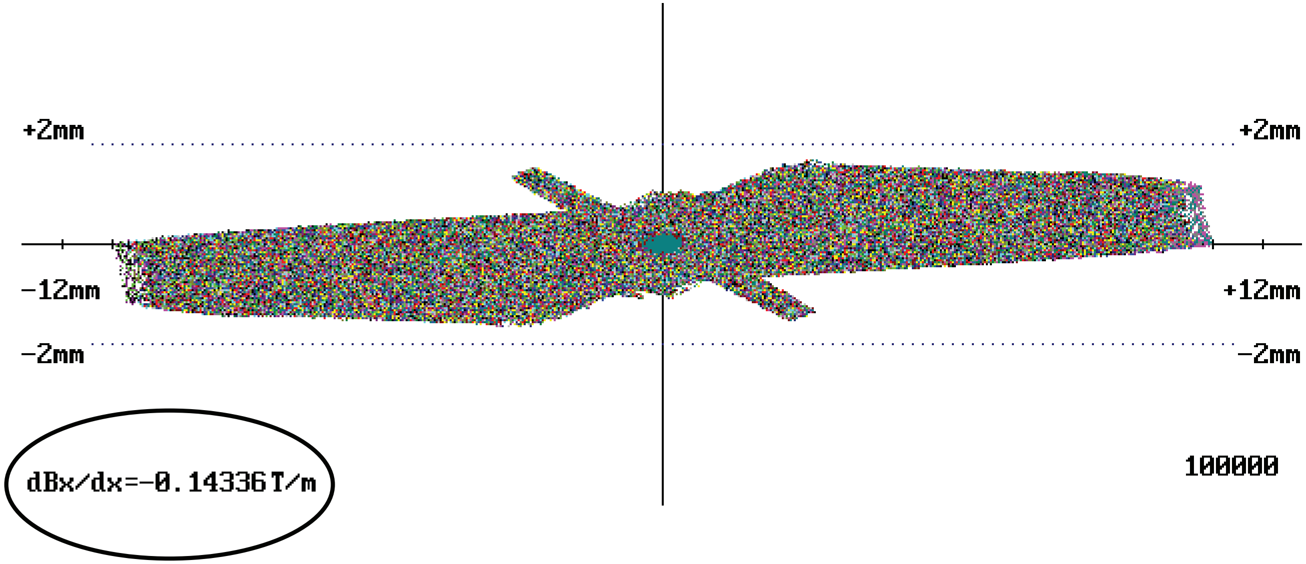
4 times larger skew gradient – fast filamentation of the injected beam due to non-linearity which creates $2{\cdot}10^{-2}$ tune shift for 10mm horizontal amplitude

Beam injected at +10 mm – with tune shift with amplitude – over 100000 turns



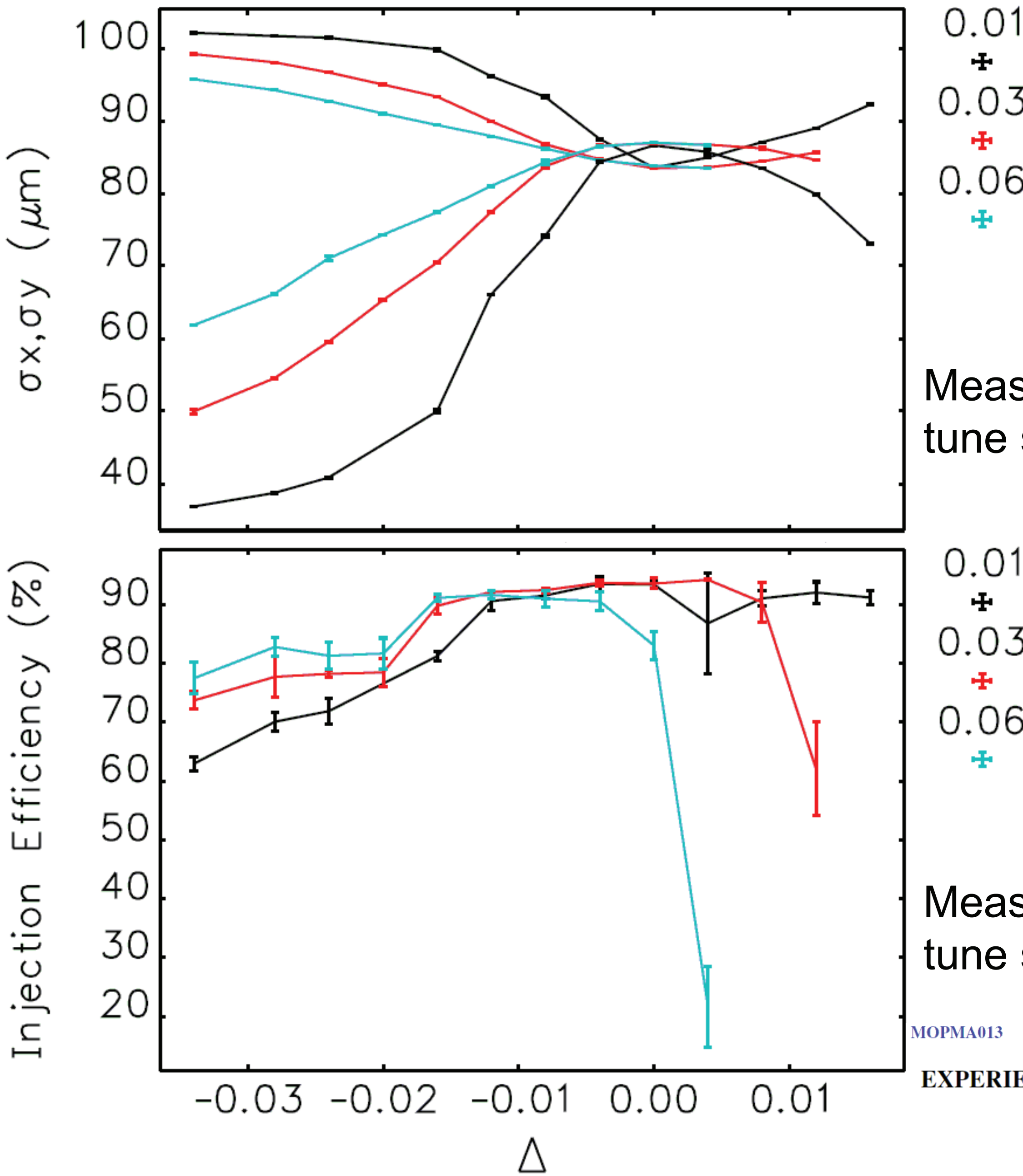
4 times larger skew gradient – relaxed aperture requirement due to tune shift with amplitude

Beam injected at +10 mm – with tune shift with amplitude – over 100000 turns



Even with a much larger skew gradient the injected beam remains within the vertical acceptance

VIII. Experimental Studies at the APS (MOPMA013, IPAC2015)



$$|\kappa| = \frac{1}{2\pi B\rho}\frac{\partial B_x}{\partial x} L \sqrt{\beta_x\beta_y}$$

Measured beam size (raw data) vs. tune separation Δ at different κ (legend)

Measured top-up injection efficiency vs. tune separation Δ at different κ (legend)

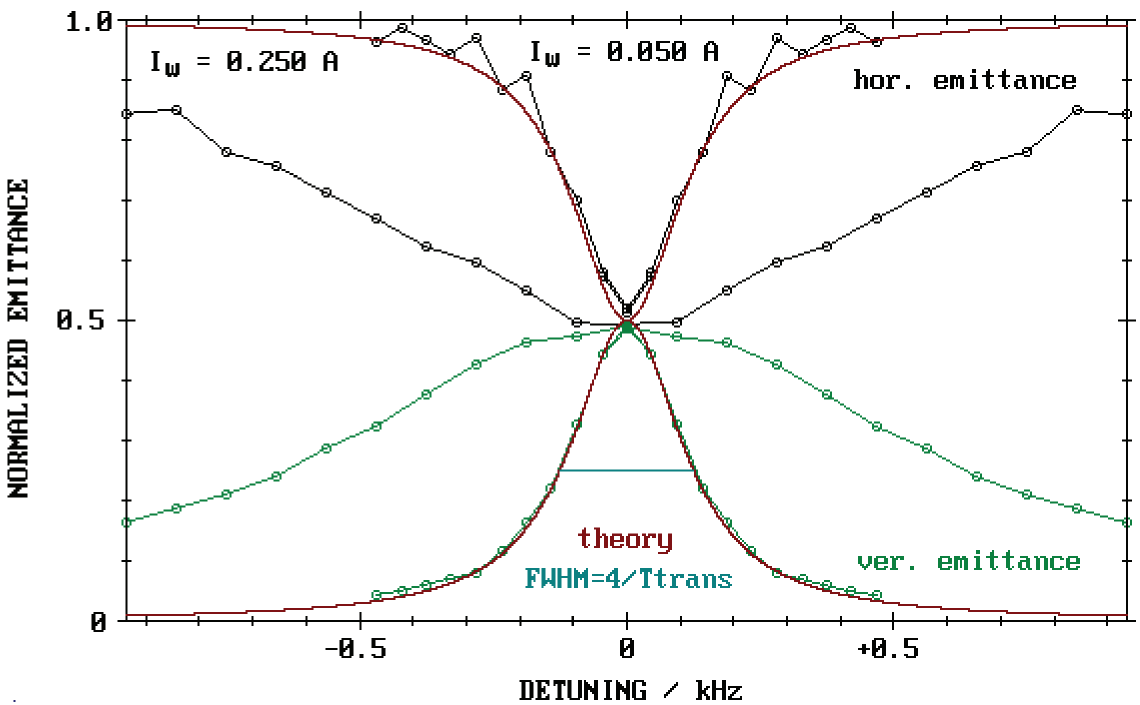
MOPMA013 Proceedings of IPAC2015, Richmond, VA, USA

EXPERIENCE WITH ROUND BEAM OPERATION AT THE ADVANCED PHOTON SOURCE *

A. Xiao[†], L. Emery, V. Sajaev, B. Yang, ANL, Argonne, IL 60439, USA

VIII. Exciting the Coupling Resonance – Operational Aspects

The resonant coupling sets in for small horizontal oscillation amplitude. Stronger skew gradients will not cause losses of injected particles and the "power broadening" can be made as large as desirable and acceptable by the amplitude dependent tune shift. Tune drift and jitter become less important.



This could be tried out at MAXIV with the tune of the ring set to the coupling resonance and the result would be equal emittances in both planes of ~200 pm·rad
Elettra 2.0 will reach ~154 pm·rad

IX. SUMMARY

Techniques proposed for the production of round beams:

- **Local flat-to-round beam transformation** (A. Chao and P. Raimondi, SLAC-PUB-14808)
- **Radial wiggler fields**
- **The Möbius accelerator**
- **Excitation of the coupling resonance with time dependent coupling fields**
  (this presentation)
- **Sitting on the coupling resonance and tune shift with amplitude**

Flat-to-round beam transformation requires far to high longitudinal fields and occupies too much straight section space.
Radial damping wigglers need straight sections and increases energy spread.
Last two techniques require careful tune stabilization or adjustment of excitation frequency and strength of coupling fields (skew gradients or solenoid field)

Operating on the coupling resonance most likely will be the method of choice for many of the future fully diffraction limited storage ring light sources.

Time dependent skew quadrupole magnet can be chosen in case the beam dynamics prohibits to sit on the coupling resonance directly.

IX. SUMMARY

Technical Approach	Injection	Emittance Control	Complexity
Local Emittance Adapter	off- and better, on-axis	no	large
Radial Damping Wigglers	off-axis	yes	large
Möbius Accelerator	on-axis*	no	moderate challenging*
Coupling Resonance Excitation	off-axis	(no)	moderate
On Coupling Resonance	on-axis* off-axis, tune shift with amplitude	(no) (no)	challenging* trivial

* vertical aperture dependent, inject closer to axis and accumulate beam without swap-out

biggest challenge for round beams – our emittance still far away from the diffraction limit at high photon energies