Technical challenges producing Round Photon Beams in future Storage Ring based Diffraction Limited Light Sources

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Monday, 4 December 2017, PHANGS, ICTP, Trieste, Italy

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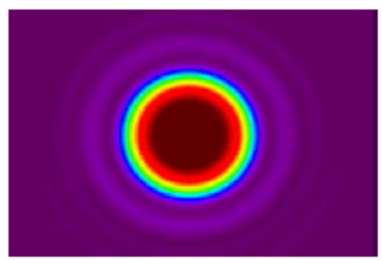
I. Round Beams – Why?

„ 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

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

SOLEIL SYNCHROTRON



MAX IV

Round Beam Workshop, SOLEIL, June 14th - 15th, 2017
https://www.synchrotron-soleil.fr/fr/evenements/mini-workshop-round-beams

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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

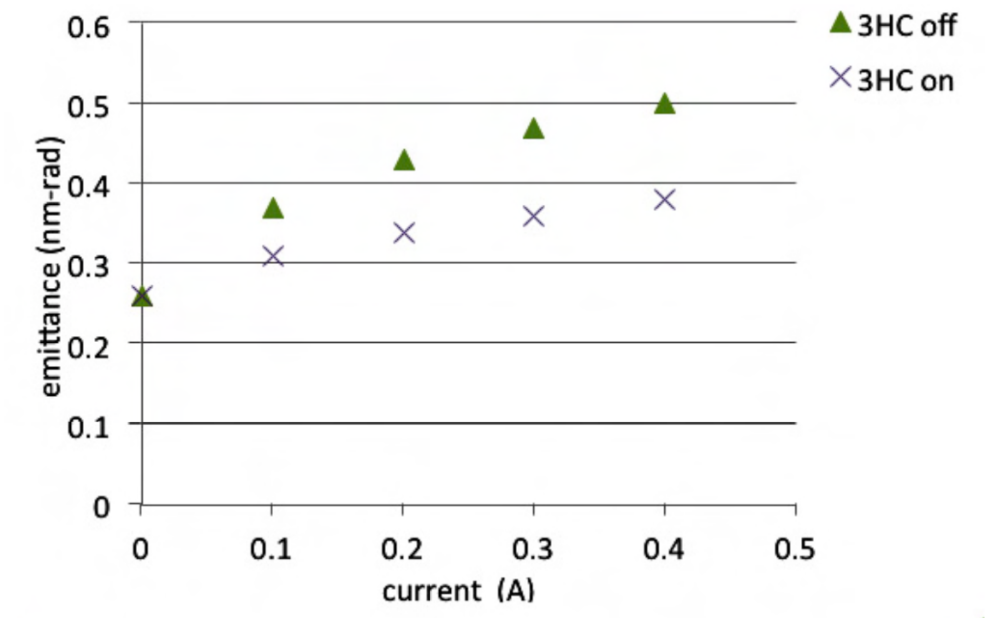


Figure 4.2.2.1: Emittance increase due to IBS for both natural bunch length (triangles) and a bunch 3.5 times lengthened (x).

Can all beamlines cope with a round electron beam?

Elettra today: ε_x=7 nm·rad ε_y= 70 pm·rad – Elettra 2.0: ε_x=ε_y=154 pm·rad

Spectral brilliance and coherent fraction

Liu Lin:"Towards Diffraction Limited Storage Ring Based Light Sources"

- Spectral brilliance: Flux density in phase space

$$B(\lambda) \propto \frac{F(\lambda)}{\left(\epsilon_{x,e^-} \otimes \epsilon_r(\lambda)\right)\ \left(\epsilon_{y,e^-} \otimes \epsilon_r(\lambda)\right)}$$

Photon flux [photons/s/0.1% bw]

electron beam emittance

photon limiting emittance

$$\epsilon_r = \sigma_r \sigma_{r'} = \frac{\lambda}{4\pi}$$ for Gaussian beam

$$\epsilon_r = \sigma_r \sigma_{r'} \approx \frac{\lambda}{2\pi}$$ for undulator beam

- Coherent fraction for undulator radiation

$$f_{coh} = \frac{(\lambda/2\pi)^2}{\left(\epsilon_{x,e^-} \otimes \epsilon_r(\lambda)\right)\ \left(\epsilon_{y,e^-} \otimes \epsilon_r(\lambda)\right)}$$

- Diffraction limited storage ring

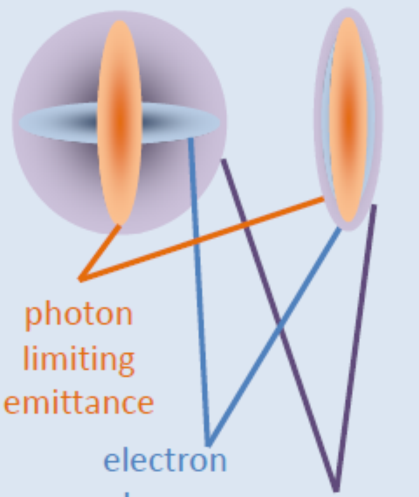
$$\epsilon_{x,y} \approx \epsilon_r(\lambda) = \frac{\lambda}{2\pi}$$

$\varepsilon_{x,y} \approx$ 100 pm.rad
diffraction limit for 2 keV

$\varepsilon_{x,y} \approx$ 20 pm.rad
diffraction limit for 10 keV

Diffraction Limit: low emittance is not all! Phase space matching

Electron beam and radiation phase-space



Matching condition

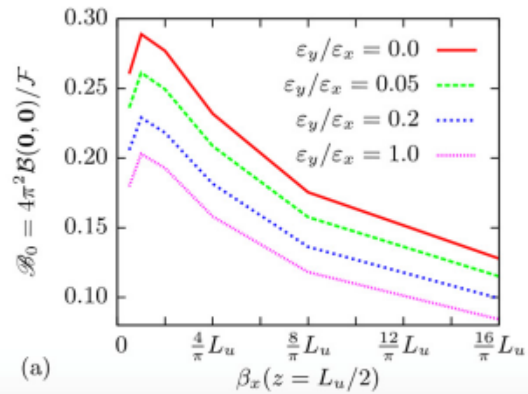
$$\beta_e = \frac{\sigma_e}{\sigma'_e} = \frac{\sigma_r}{\sigma'_r}$$

Highest brilliance from undulator of length L is achieved when

$$\beta^{opt}_{x,y} \approx \frac{L}{\pi} \qquad \beta^{opt}_{x,y} \sim 1 - 2m$$

Ryan R. Lindberg and Kwang-Je Kim (2015)

COMPACT REPRESENTATIONS OF PARTIALLY … Phys. Rev. ST Accel. Beams **18,** 090702 (2015)



(a)

IV. CONCLUSIONS

In this paper we have described three different coherent mode representations of partially coherent undulator radiation. We began with the well-known Gaussian-Schell decomposition in terms of Gauss-Hermite modes, which is valid provided the electron beam emittance is much larger than the natural radiation emittance $\lambda/4\pi$. In this largely incoherent case the specifics of the single-electron undulator field are unimportant. We then refined our analysis to include the situation when the electron beam emittance ε_y in one direction is arbitrary, and found that the modes along y are determined by solving a matrix

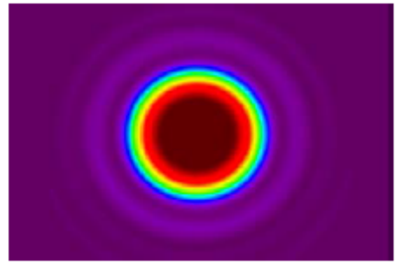
Figure 8(a) shows that the coherence is maximized when $\beta_x \approx L_u/\pi$ (or $\hat{\beta}_x \approx 1$), which indicates that the "natural" Rayleigh range of undulator radiation $Z_R \approx \beta_x \approx L_u/\pi$. Unfortunately, it is nearly impossible for lattice designers to make the beta functions in both x and y be simultaneously that small, and typically $\beta_x > 3L_u/\pi$.

very similar: the profiles when β_x is increased by a factor of 16 can be approximately obtained by multiplying those in Fig. 8(b) by 1.3. Figure 8(c) plots the profiles along x as we vary β_x. Each plot is approximately Gaussian, and we see that the angular spread decreases as β_x increases. More careful inspection shows that the width of the angular

Liu Lin:"Towards Diffraction Limited Storage Ring Based Light Sources"

→ **The best approximation therefore appears to be:**

	$\sigma_{R'}$	σ_R	$\varepsilon_R = \sigma_R \sigma_{R'}$	$\beta_R = \sigma_R / \sigma_{R'}$	
Kim (NIM 1986)†	$\sqrt{\lambda/L}$	$\sqrt{\lambda L}/4\pi$	$\lambda/4\pi$	$L/4\pi$	❶
Kim (PAC 1987)	$\sqrt{\lambda/2L}$	$\sqrt{2\lambda L}/4\pi$	$\lambda/4\pi$	$L/2\pi$	❷
Borland (IPAC 2012) Hettel & Borland (PAC 2013) Hettel (IPAC 2014)	$\sqrt{\lambda/2L}$	$\sqrt{2\lambda L}/2\pi$	$\lambda/2\pi$	L/π	❸
Huang (IPAC 2013)	$\sqrt{\lambda/2L}$	$\sqrt{2\lambda L}/4\pi$	$\lambda/4\pi$	$L/2\pi$	❷
Lindberg & Kim (PRSTAB 2015)	$\sqrt{\lambda/4L}$	$\sqrt{\lambda L}/2\pi$	$\lambda/4\pi$	L/π	❹
Liu (IPAC 2017)	$\sqrt{\lambda/2L}$	$\sqrt{2\lambda L}/2\pi$	$\lambda/2\pi$	L/π	❸

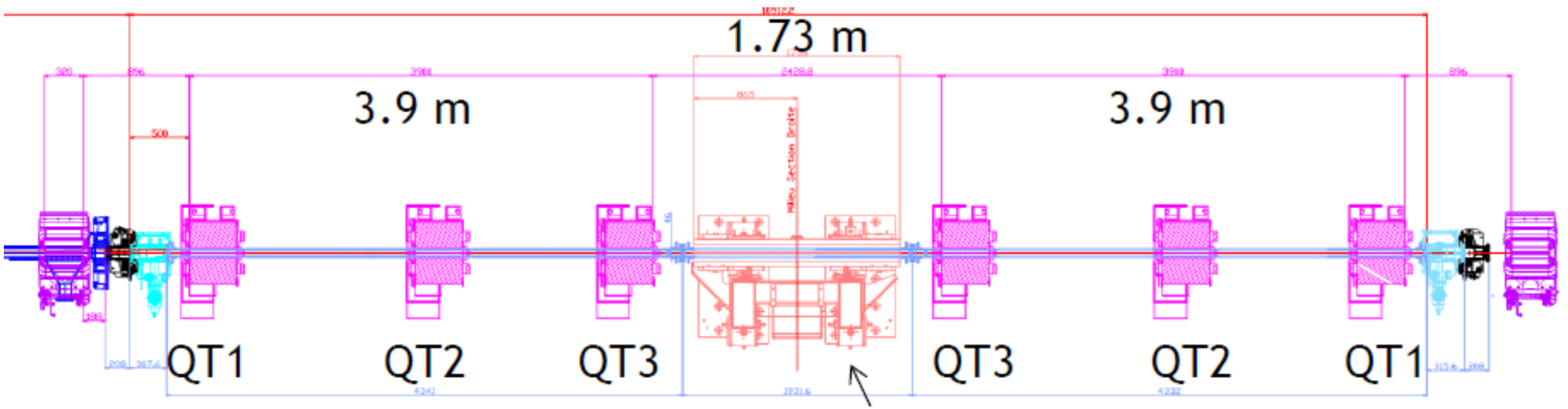


Application of the Emittance Adapter to SOLEIL and MAX IV

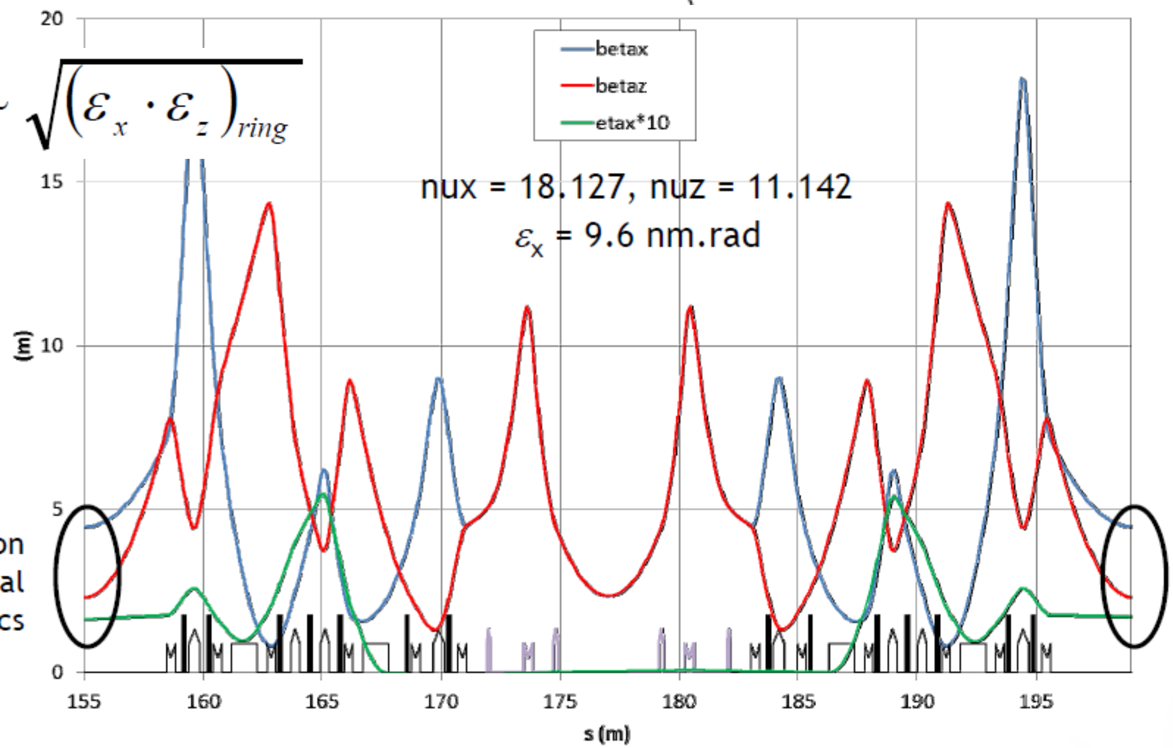
Pascale Brunelle
on behalf of the Round Beam Project Team

Round Beam Workshop, SOLEIL, June 14th - 15th, 2017
https://www.synchrotron-soleil.fr/fr/evenements/mini-workshop-round-beams

II. Round Beam Locally – Flat-Round-Transformation



$$\left(\varepsilon_x\right)_{apparent} \sim \sqrt{\left(\varepsilon_x \cdot \varepsilon_z\right)_{ring}}$$



A. Chao and P. Raimondi (SLAC-PUB-14808)

Summary

Pascale Brunelle

For the two SOLEIL beamlines tested as example, it has been demonstrated that :

→ The gain in flux density at the sample is mainly due to the reduction of the horizontal electron beam size at source.

→ A reduction by a factor ~3 is obtained on the present SOLEIL and MAX-IV storage rings with a 10 T solenoid field (perfect adaptation is obtained with a solenoid field of ~140 T for an undulator length of 2 m).

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

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

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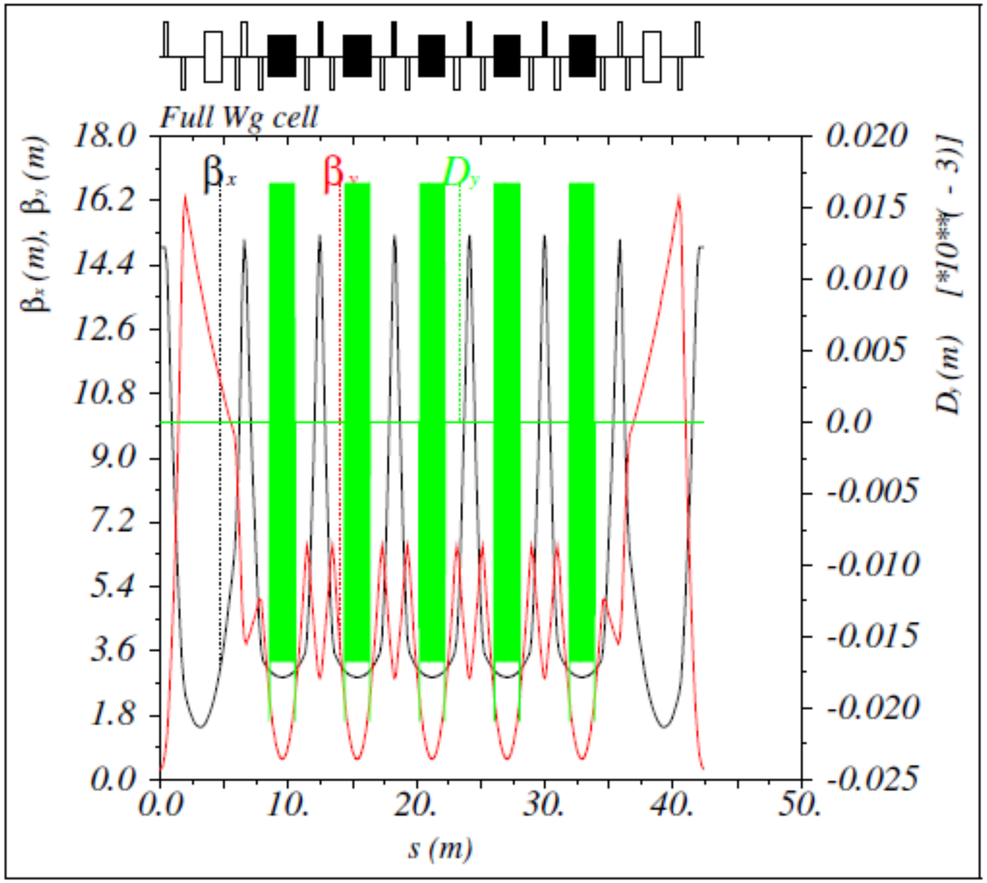
Ultimate synchrotron radiation source with horizontal field wigglers

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

A. Bogomyagkov (BINP) Ultimate ring 12 / 18

III. Radial Damping Wiggler Fields or Vertical Dispersion

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

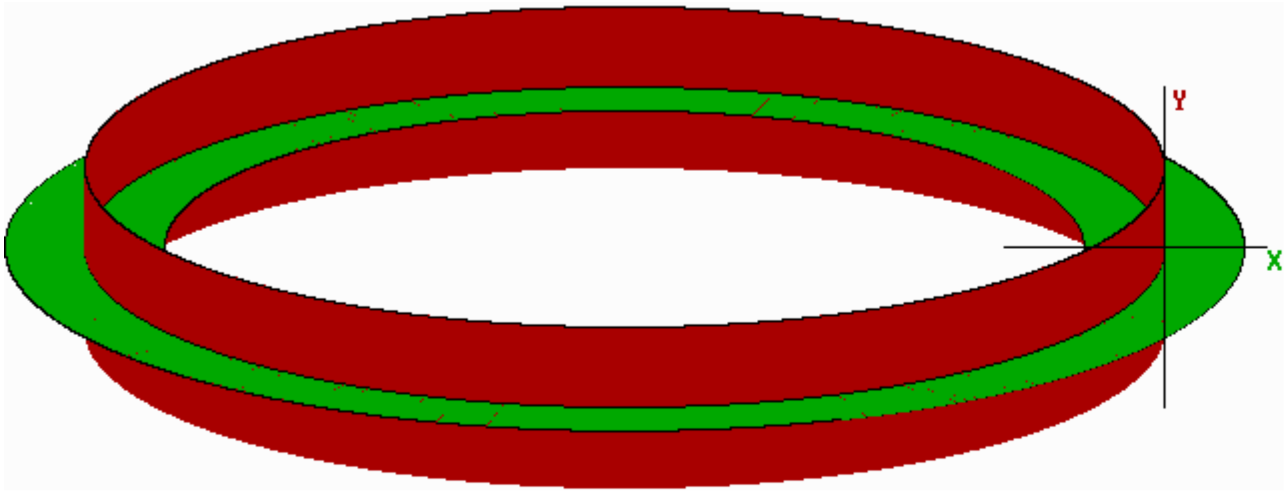
If you want 10% to 20% coupling: vertical dispersion helps

- **Has been used to create slightly enlarged vertical emittance – coupling on the %-level (BESSY II, ALS, …) – less sensitive to impact of IDs on ß-coupling**
- **A vertical chicane in a straight section easily produces sufficient dispersion and vertical emittance on the 20%-level**

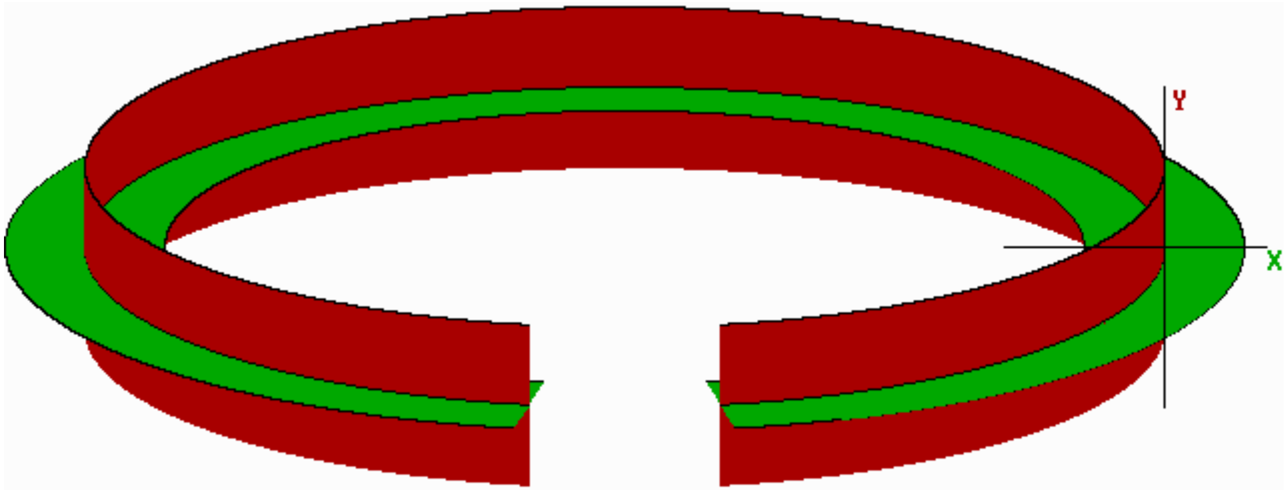
IV. Round Beam in Möbius Accelerator

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)

Uncoupled storage ring:

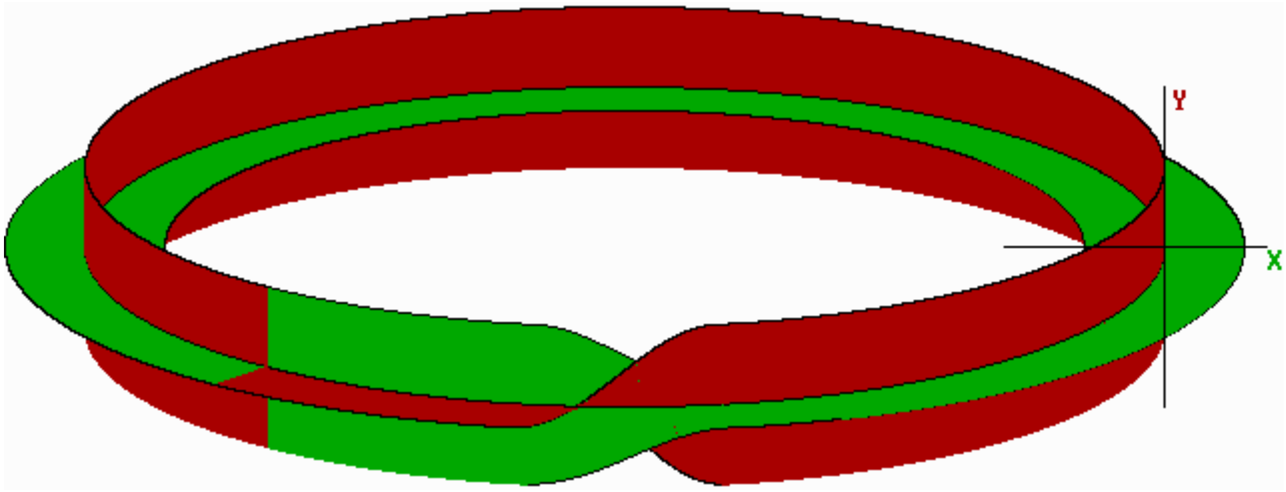


Uncoupled storage ring:



insertion

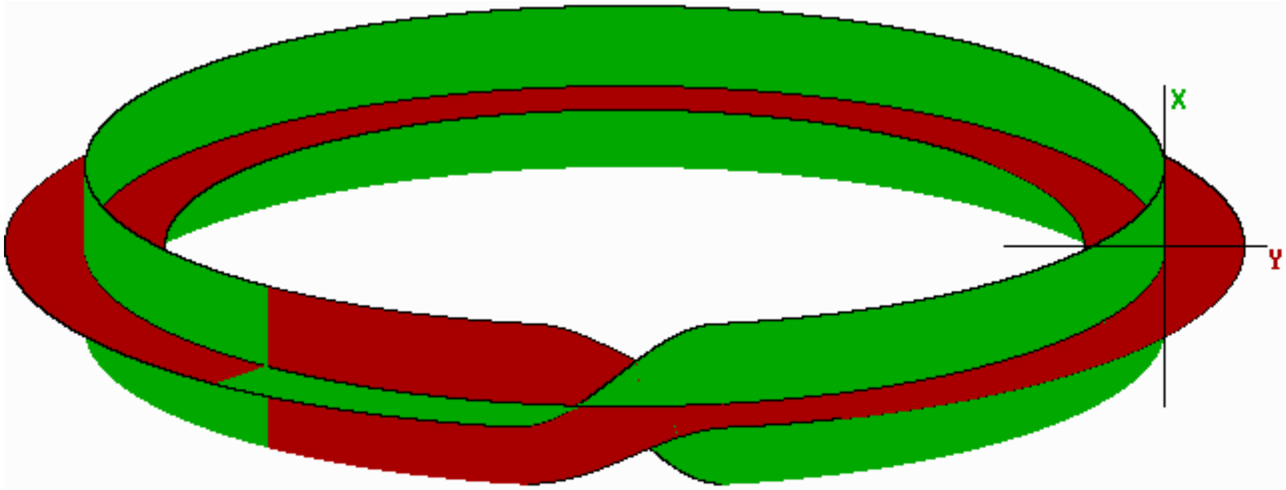
Orbit and optics repeat every second turn:



rotator – complete exchange of horizontal and vertical motion

transverse particle coordinates are exchanged every turn by a set of skew quadrupole

Orbit and optics repeat every second turn:



rotator – complete exchange of horizontal and vertical motion

transverse particle coordinates are exchanged every turn by a set of skew quadrupole

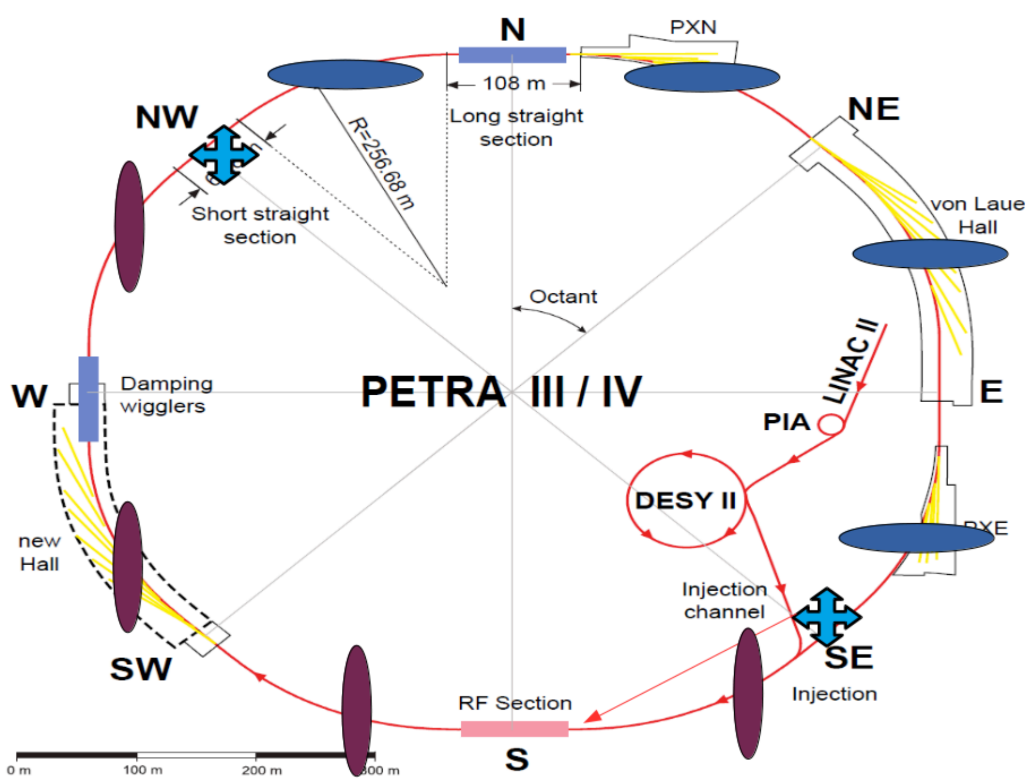
IV. Proposal for MAXIV-Building

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.

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



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

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

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

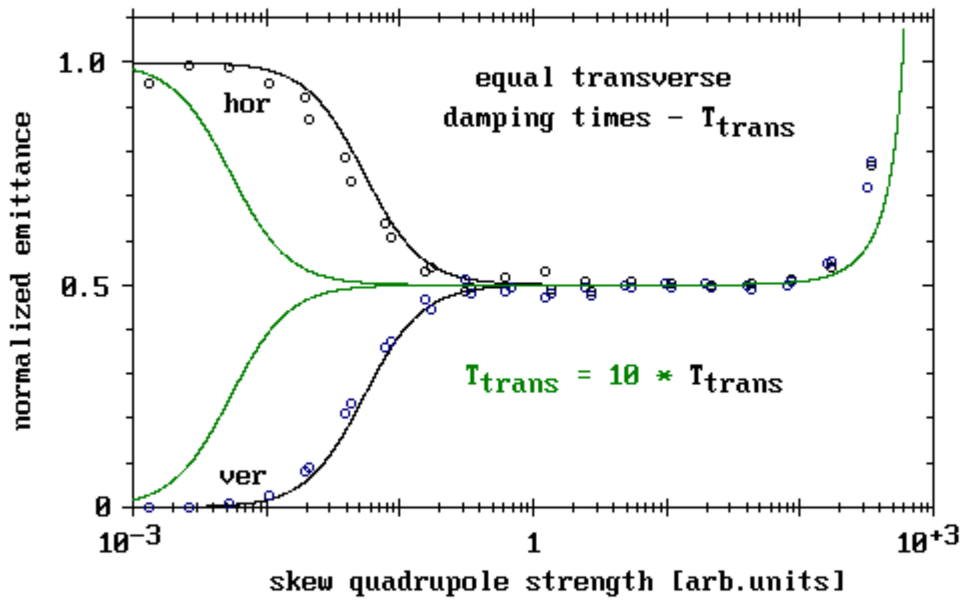
General resonance condition: $Q_x - Q_y = n \pm \omega/\omega_0$

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.

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.

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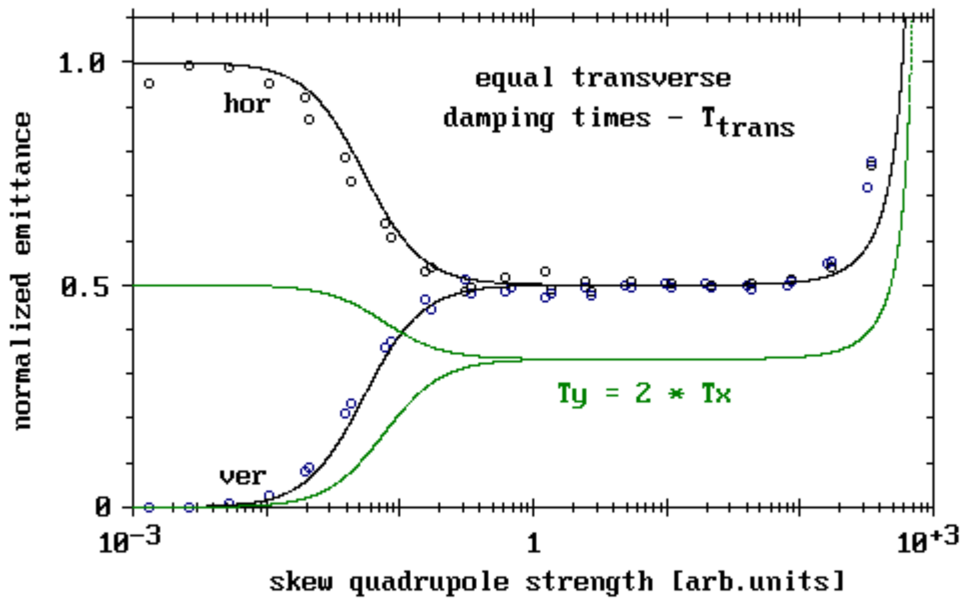

Comparison of solutions from multi particle tracking and first modeling attempts with analytical solutions based on moment mapping.

With $T_x=T_y/2$ and on resonance **$\varepsilon_y = \varepsilon_x = 2/3\ \varepsilon_0$**

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

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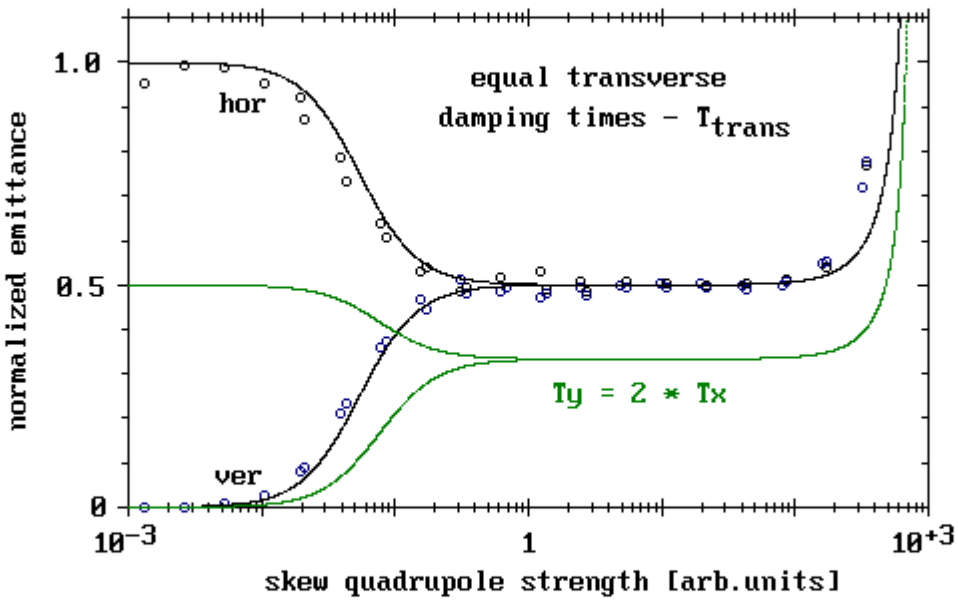

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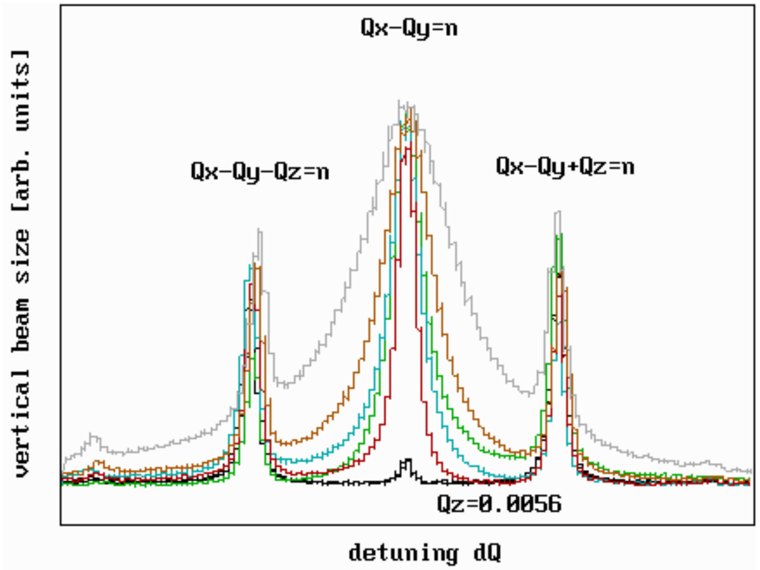


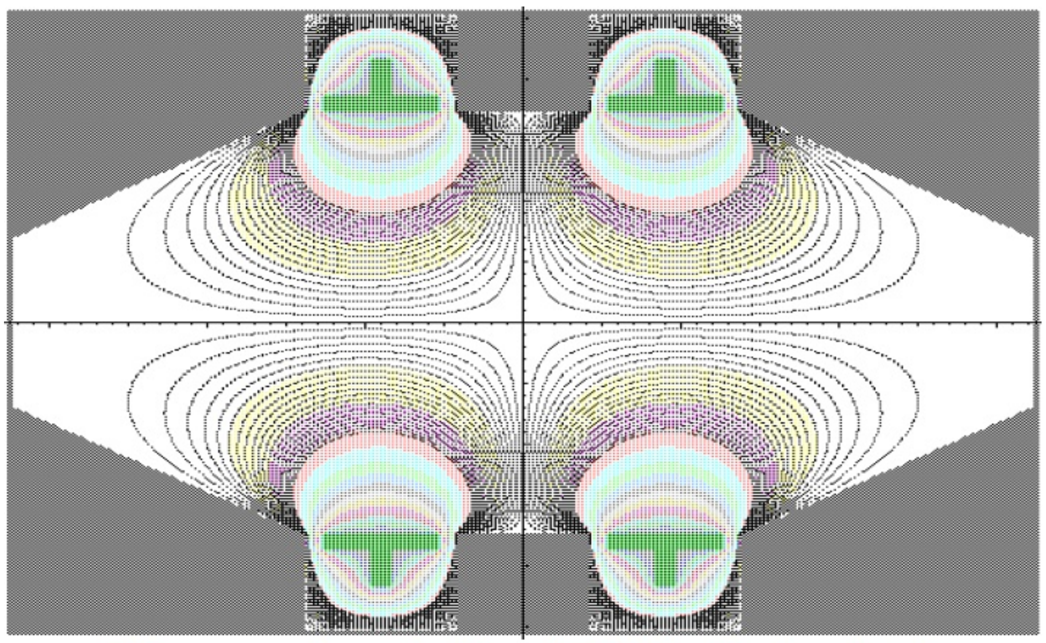
Compensation of the coupling resonance in the BESSY II storage ring – as expected: damping dominates for very small coupling coefficients, and width depends on coupling strength: „power broadening“, will be helpful later on

VII. 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:

$$\mathbf{Q_x - Q_y = n \pm \omega/\omega_0}$$

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.

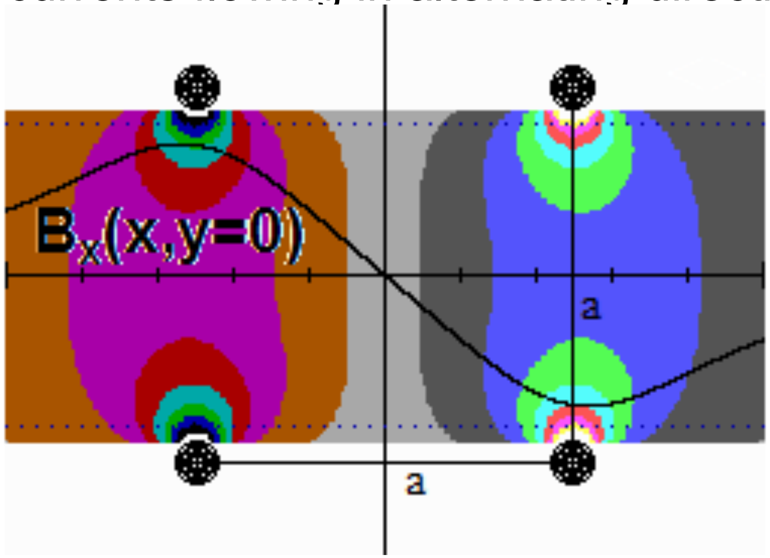
Full coupling and emittance sharing achievable –

- little power broadening,
- sensitive to tune jitter.

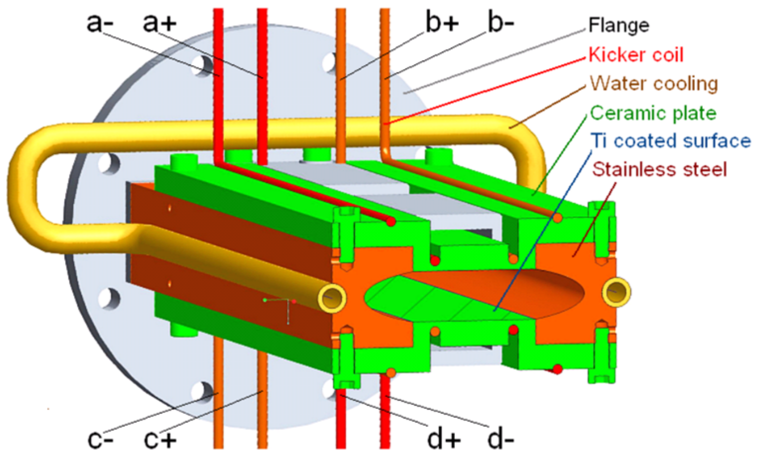
P. Kuske, R. Görgen, EPAC 2002, WEPLE015

The required frequency, F_{sq}, for the skew quadrupole is on the order of 100 kHz. striplines are not required. Simpler design could look like this:

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



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

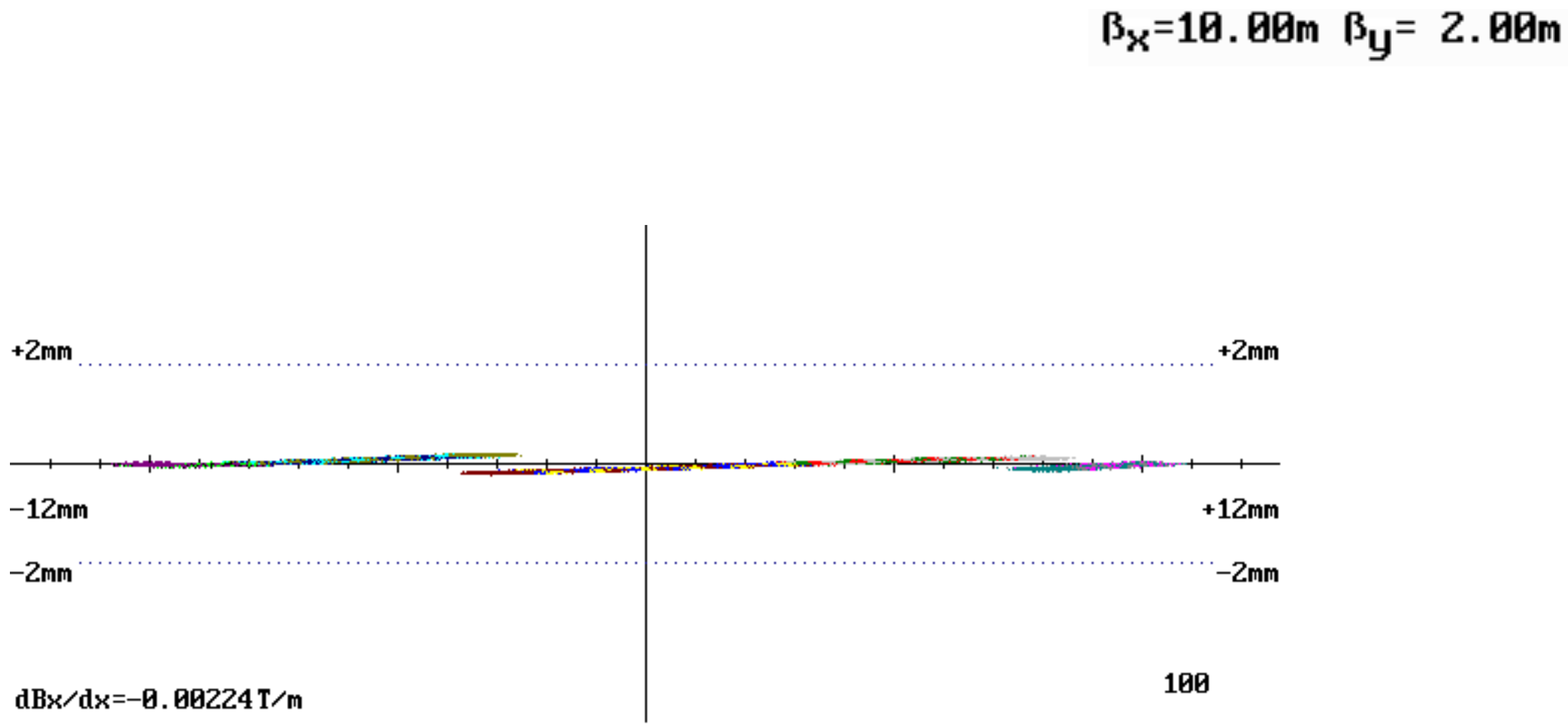


quite similar to our non-linear injection kicker magnet

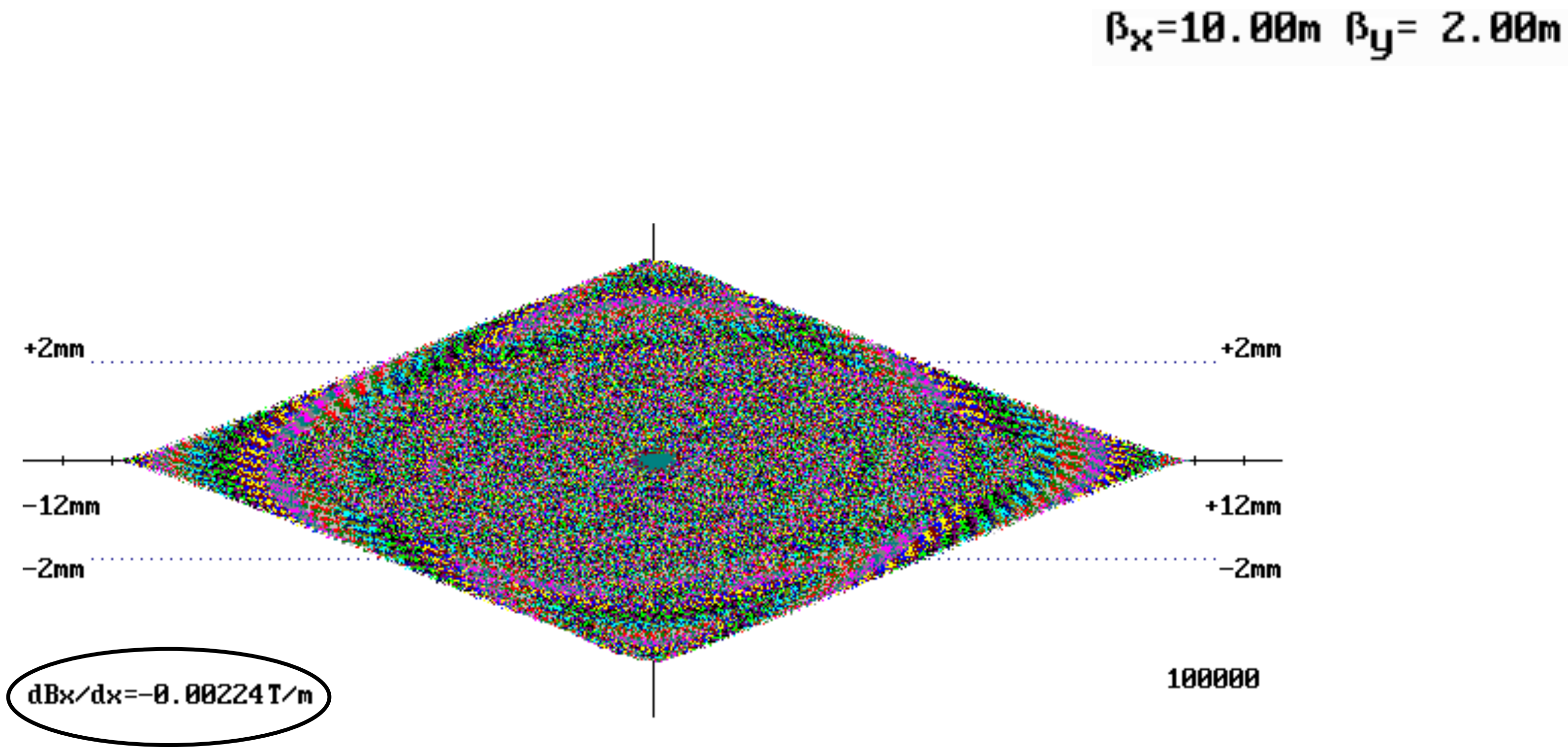
(T. Atkinson, et al., THPO024, IPAC2011)

A time dependent solenoid might even be simpler to construct.

Beam injected at +10 mm – the first 100 turns



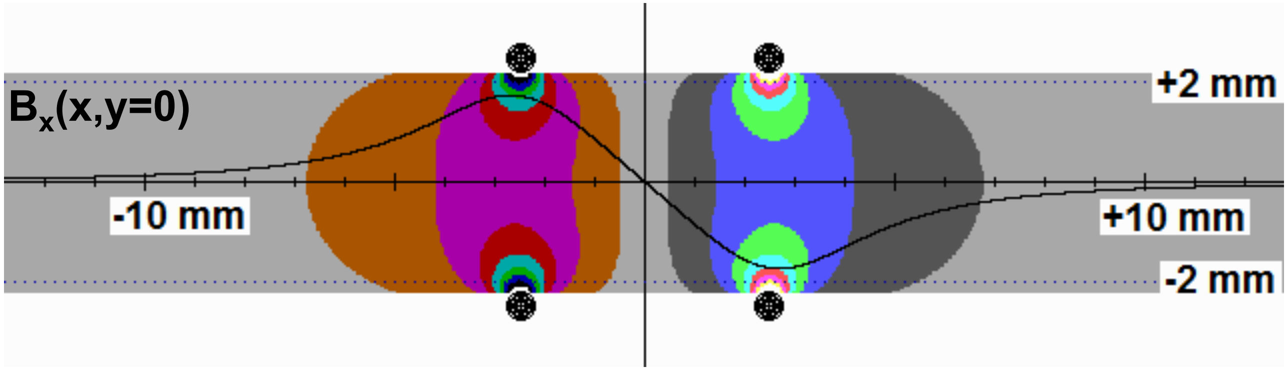
Beam injected at +10 mm – the first 100000 turns



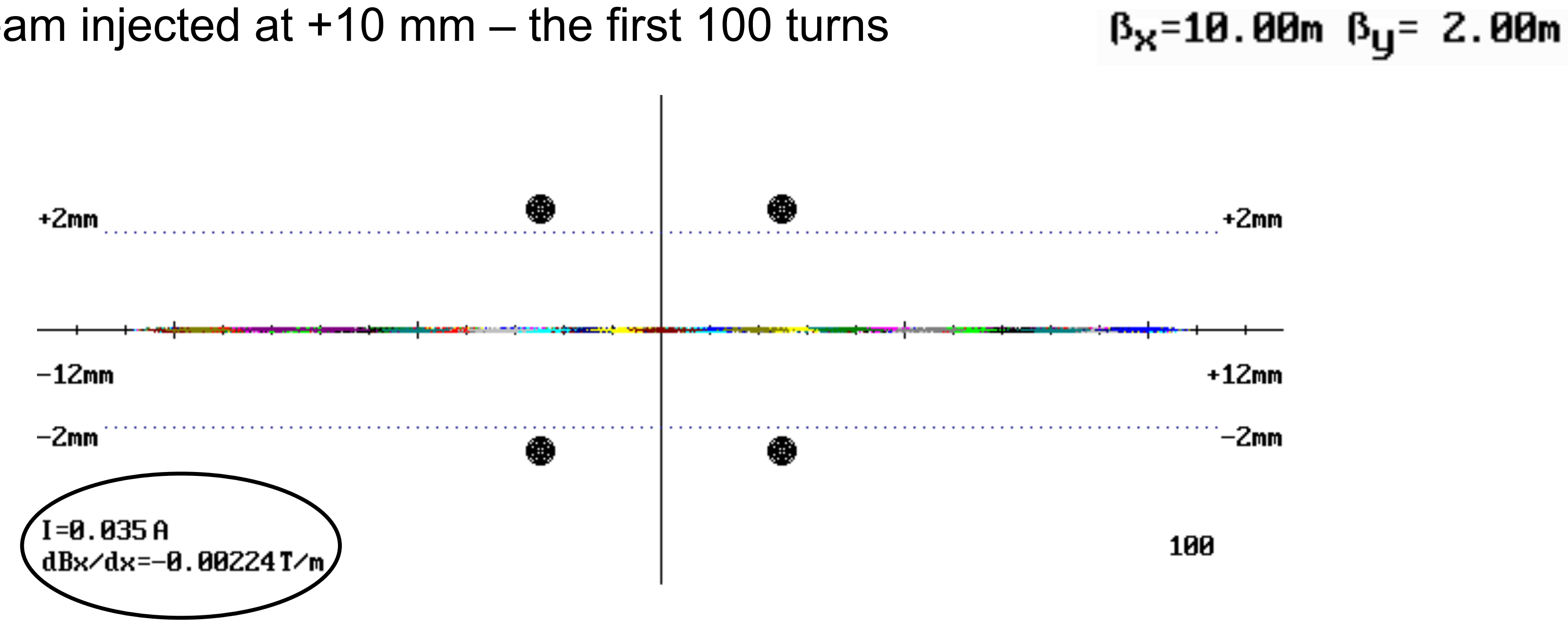
with skew quadrupole magnet the required acceptance exceeds physical vertical aperture if X_{inj} > vertical aperture · $(ß_{Xinj}/ß_{Yap})^{1/2}$

Inject with smaller initial amplitude, X_{inj}, because of small dynamic aperture

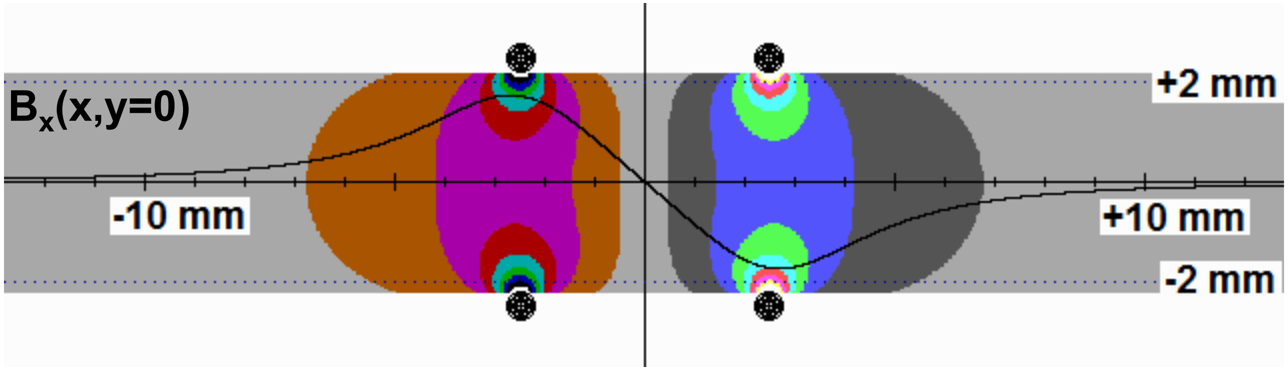
Required acceptance – non-linear skew quadrupole magnet:



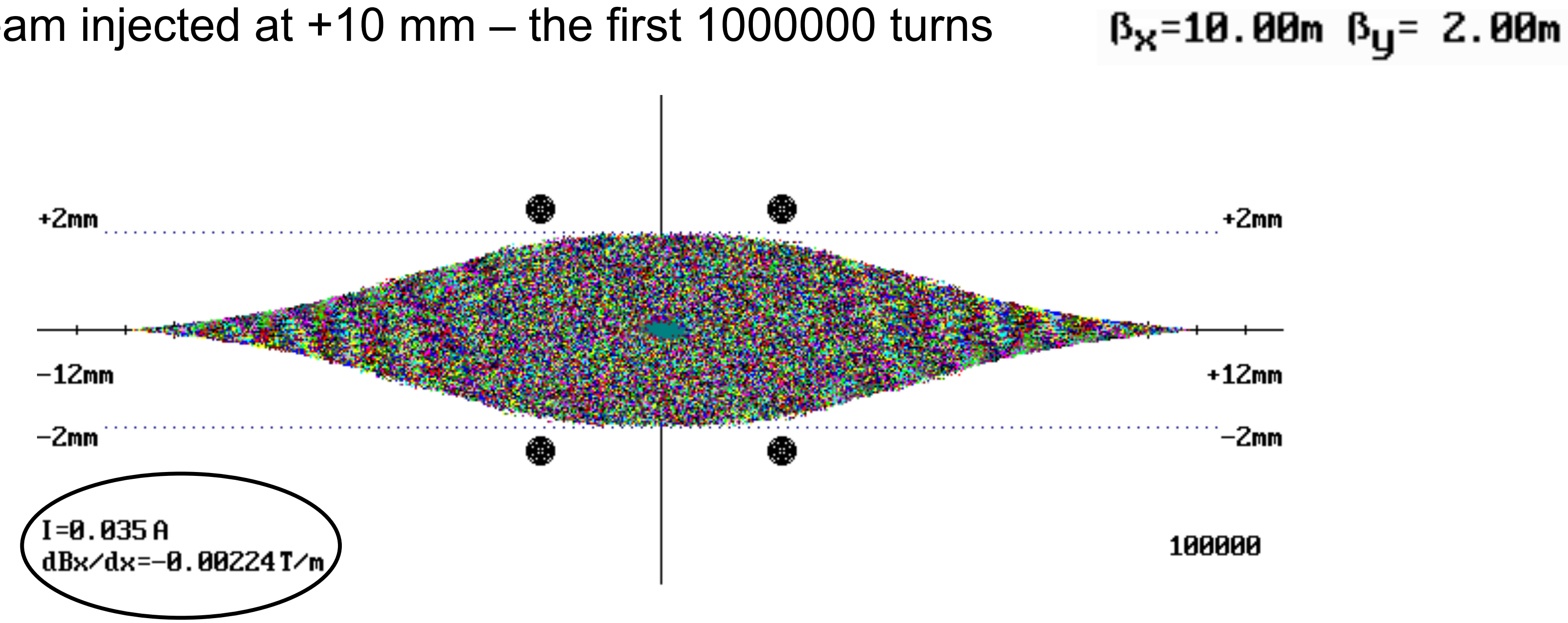
Beam injected at +10 mm – the first 100 turns



Required acceptance – non-linear skew quadrupole magnet:

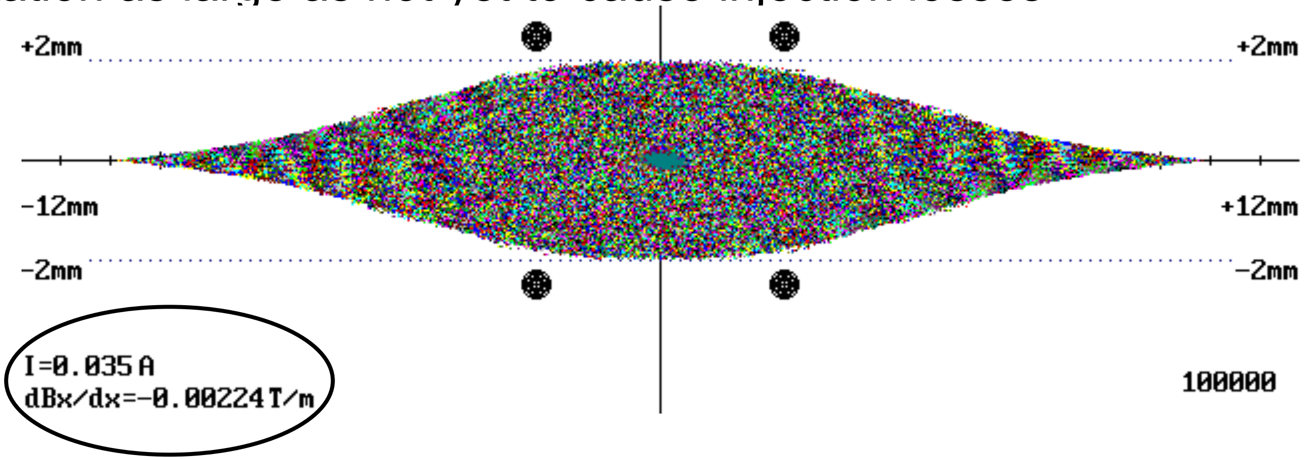


Beam injected at +10 mm – the first 1000000 turns

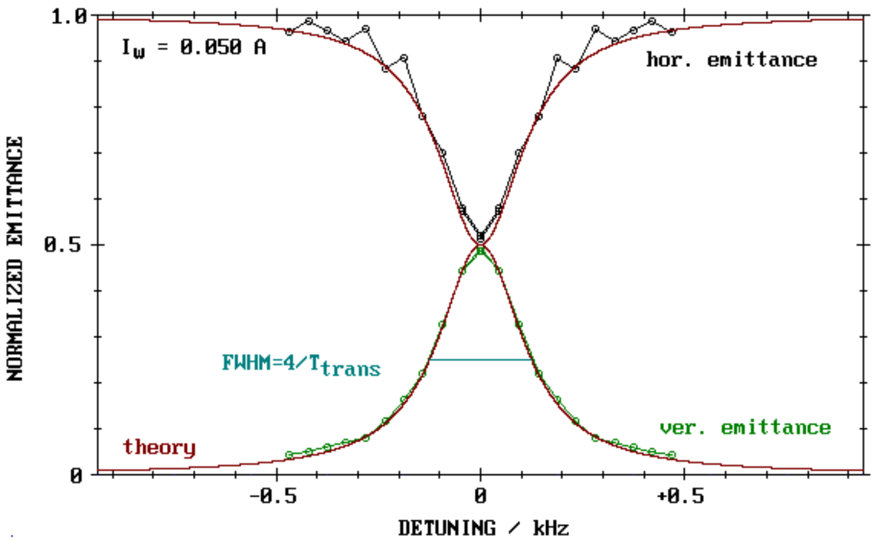


Required acceptance fits vertical acceptance – with non-linear skew quadrupole magnet

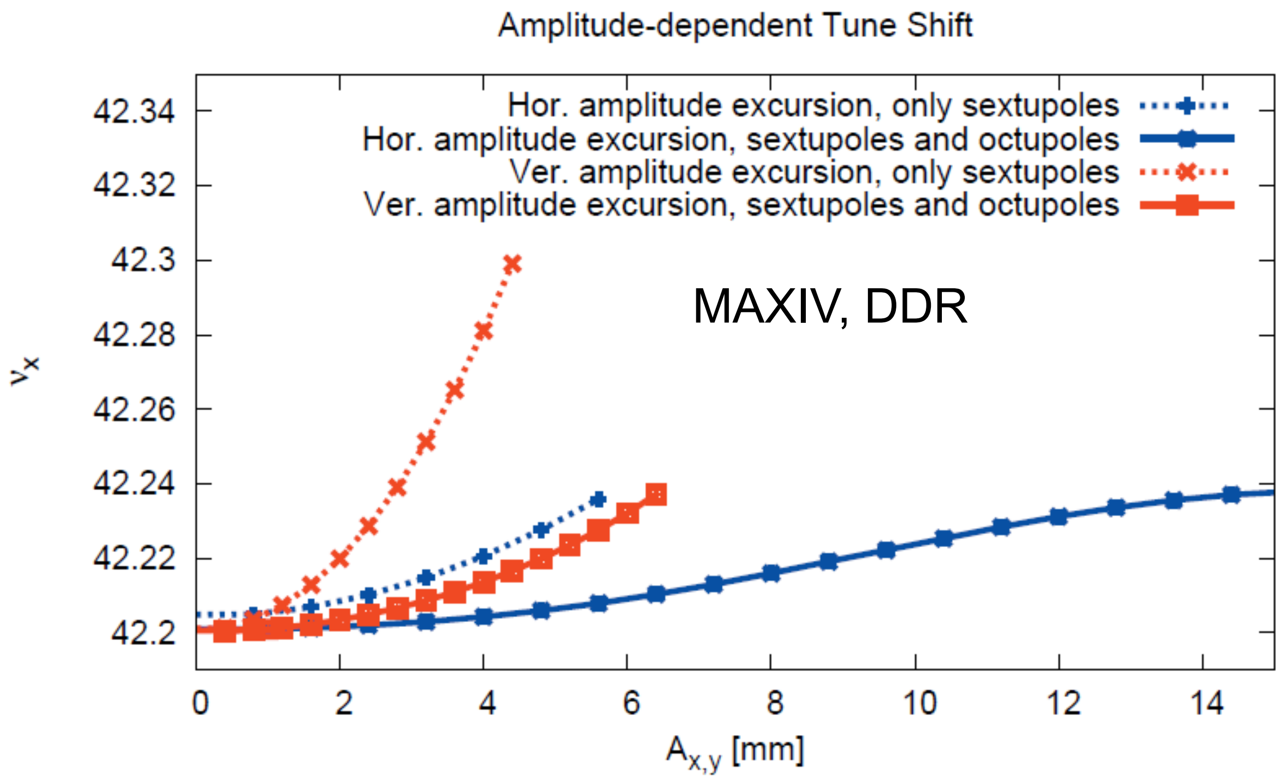
Level of excitation as large as not yet to cause injection losses



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



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



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

VIII. EXCITING THE COUPLING RESONANCE – OPERATIONAL ASPECTS

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

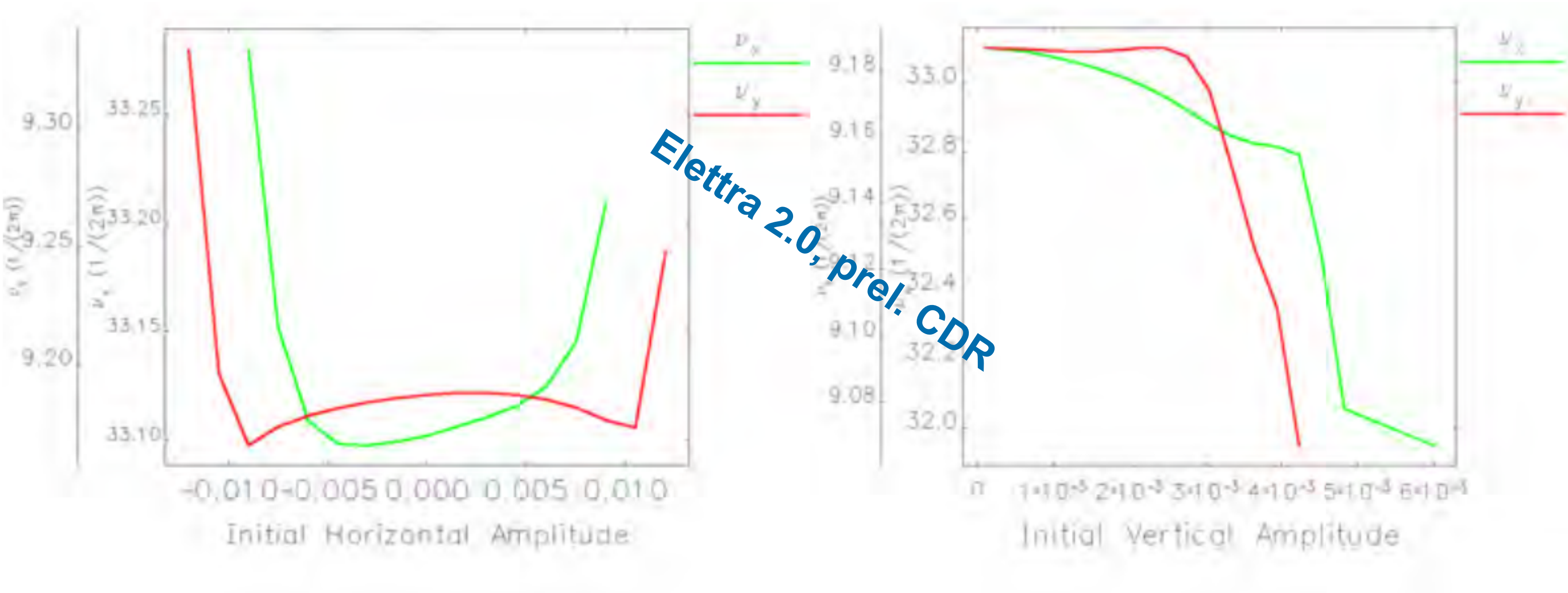
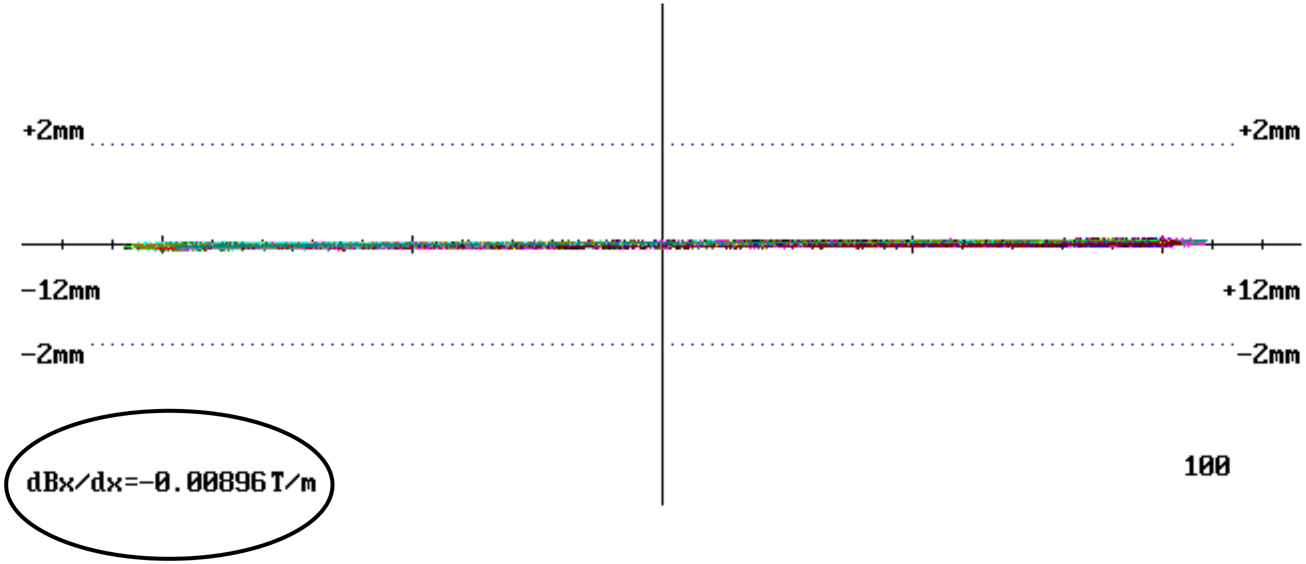


Figure 3.1.1.7: Left: horizontal and vertical tune vs. horizontal amplitude in m. Right: horizontal and vertical tune vs. vertical amplitude in m.

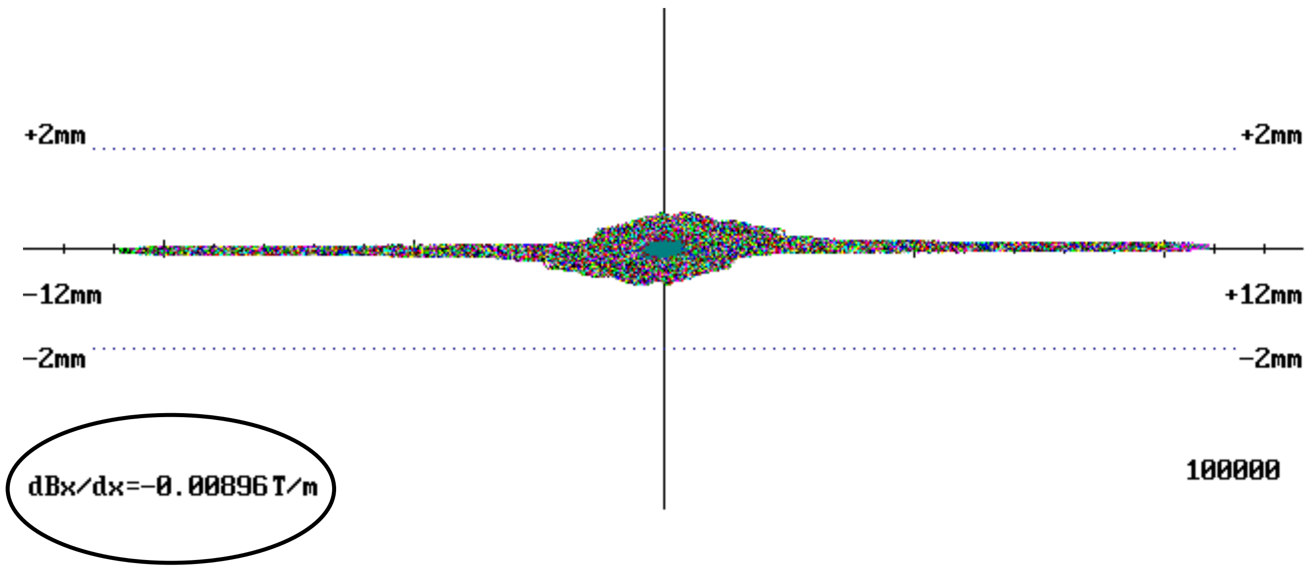
$\Delta\nu$~0.018 @ +5mm → ΔF=21 kHz – much larger than the natural resonance width ≅ $4/\tau_{trans}$ or width due to non-linear chromatic effects

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



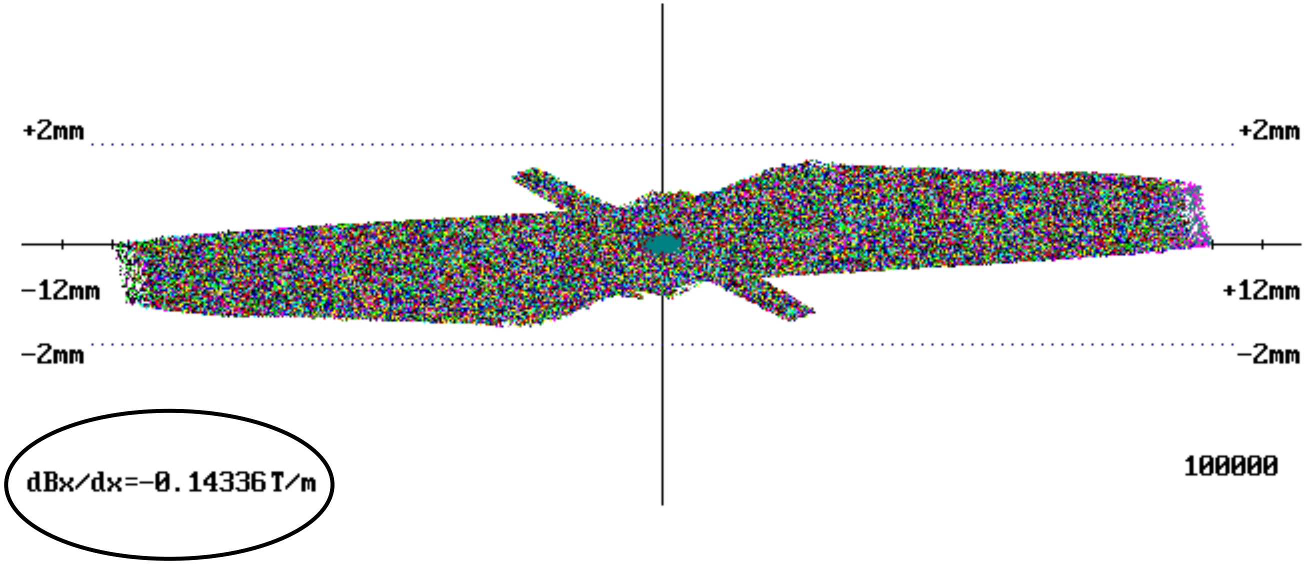
4 times larger skew gradient – fast filamentation of the injected beam due to non-linearity which creates $2{\cdot}10^{-2}$ tune shift for 10mm horizontal amplitude

Beam injected at +10 mm – with tune shift with amplitude - over100000 turns



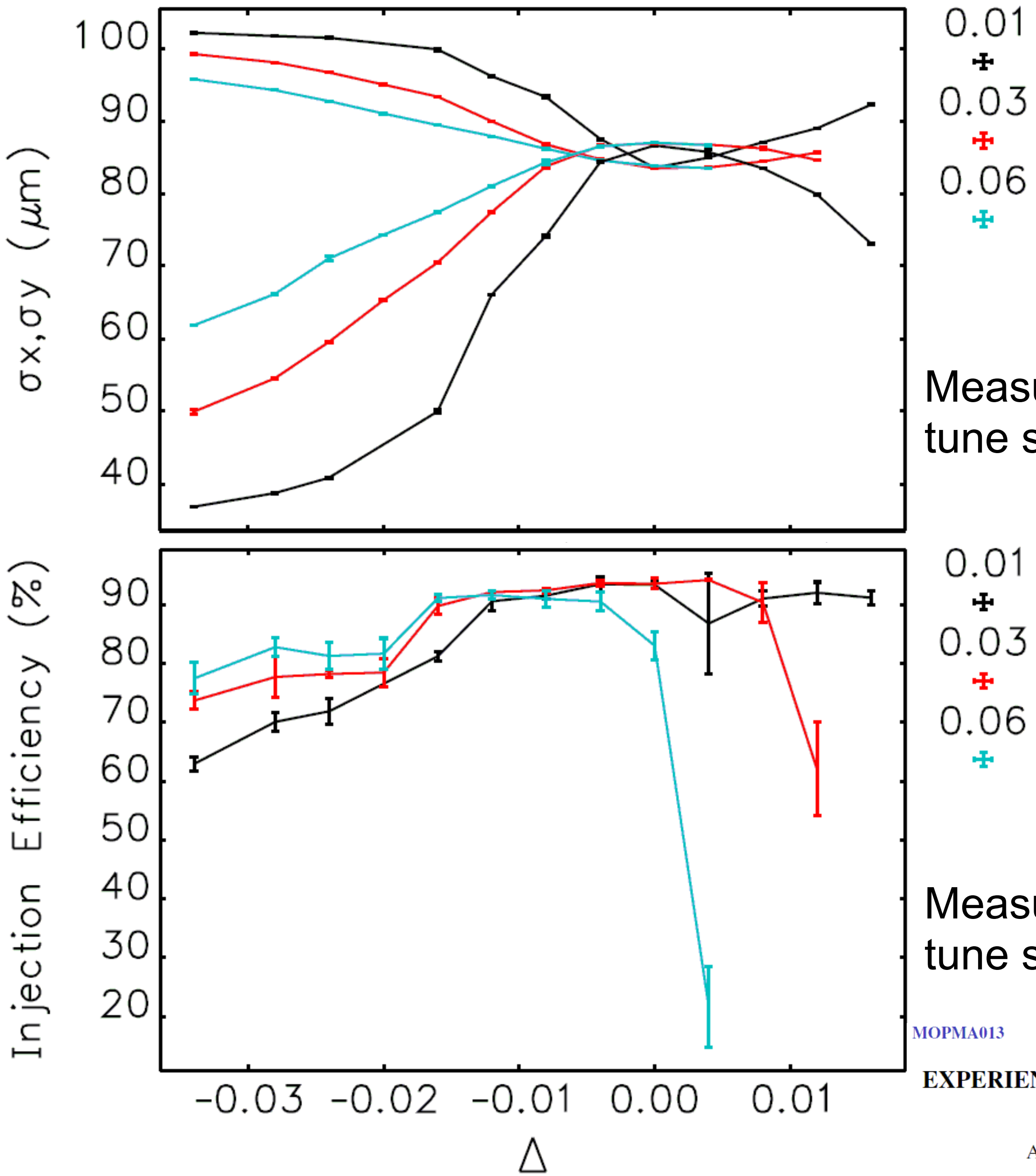
4 times larger skew gradient – relaxed aperture requirement due to tune shift with amplitude

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 *

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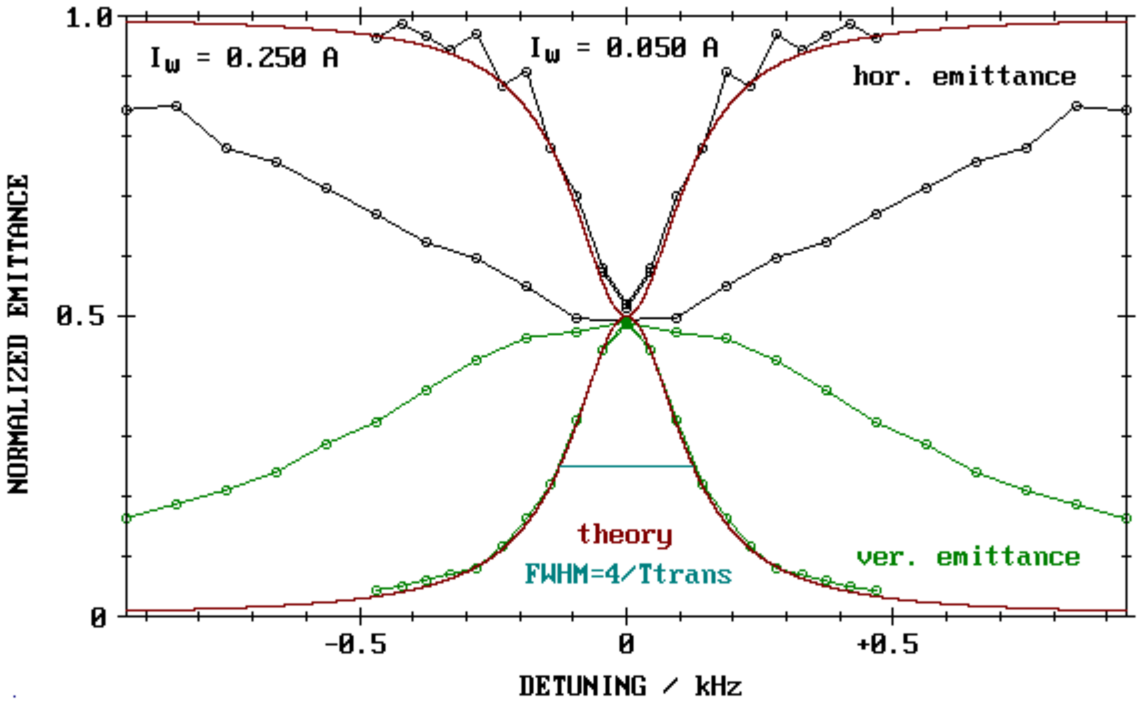
The resonant coupling sets in for small horizontal oscillation amplitude. Stronger skew gradients will not cause losses of injected particles and the “power broadening” can be made as large as desirable and acceptable by the amplitude dependent tune shift. Tune drift and jitter become less important.



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

Five techniques for the production of round beams have been proposed:

- **Local flat-to-round beam transformation** (A. Chao and P. Raimondi, SLAC-PUB-14808)
- **Radial wiggler fields** (A. Bogomyagkov, et al., „Ultimate synchrotron radiation source with horizontal field wigglers“, LER Workshop, September 2014, Frascati, Italy)
- **The Möbius accelerator** (R. Talman, PRL 74, 1590 (1995) and M. Aiba, et al., TUPJE045, IPAC2015, Richmond, VA, USA)
- **Excitation of the coupling resonance with time dependent coupling fields** (this presentation)
- **Sitting on the coupling resonance and tune shift with amplitude**

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 will be the method of choice for Elettra 2.0

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