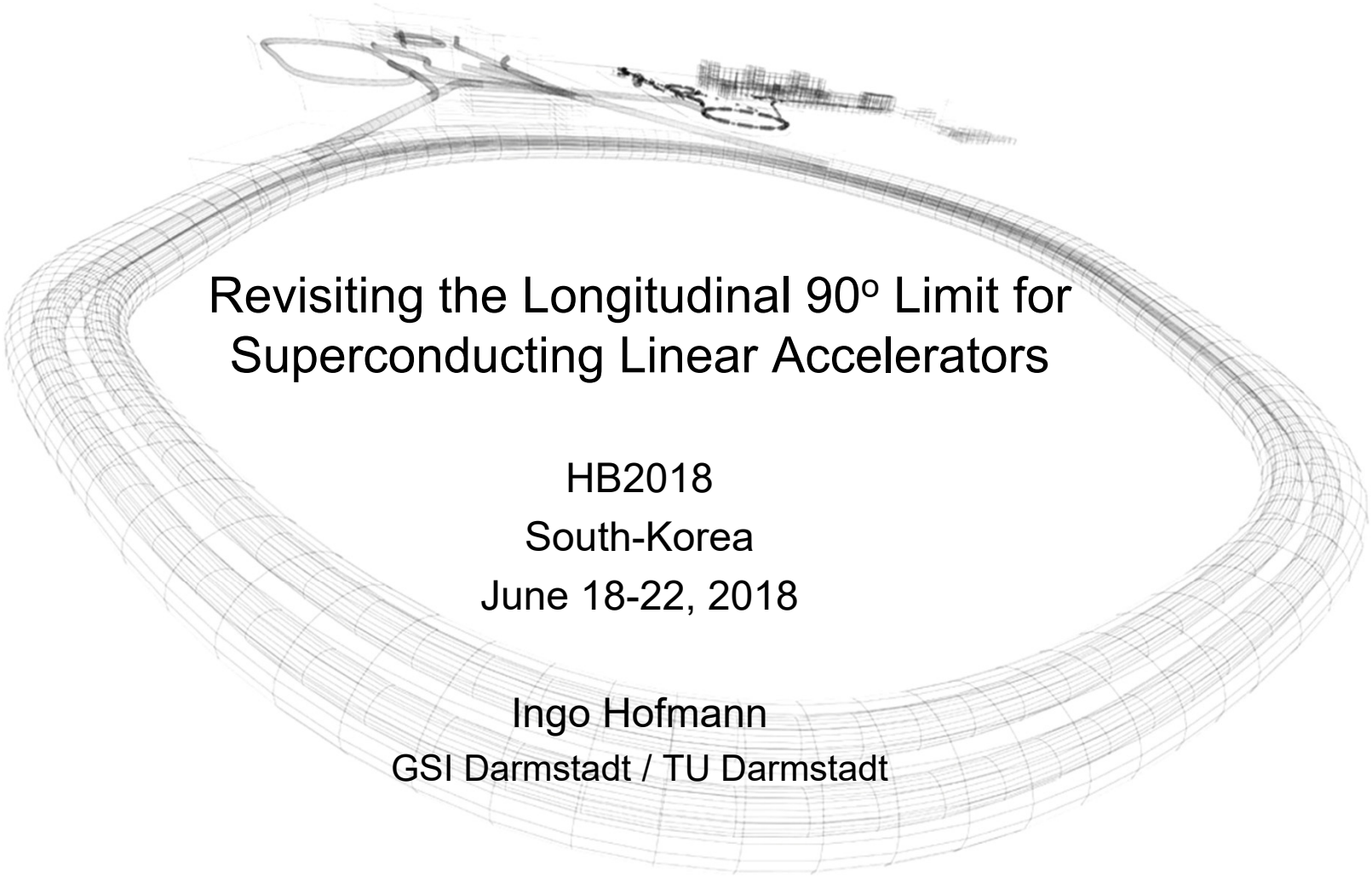


Revisiting the Longitudinal 90^{o} Limit for Superconducting Linear Accelerators

HB2018

South-Korea

June 18-22, 2018

Ingo Hofmann

GSI Darmstadt / TU Darmstadt

Overview

- **Introduction**
- The longitudinal „90^0 structure resonance stopband“
- The sum „envelope instability“
- Irregular periodic lattices
- Discussion
- Conclusions

Acknowledgments: O. Boine-Frankenheim, J. Struckmeier, Y. Yuan

“Accepted criteria” for lattice design

in high intensity accelerators

1. Keep **zero current phase advance per cell below 90^0** for transverse and longitudinal to avoid structure resonance/parametric instability
2. Smooth (adiabatic) changes in transverse and longitudinal focusing
3. Avoid transverse-longitudinal emittance transfer via space charge resonance
4. Provide good matching between lattice transitions to avoid halo

1, 3 and 4 are resonant processes

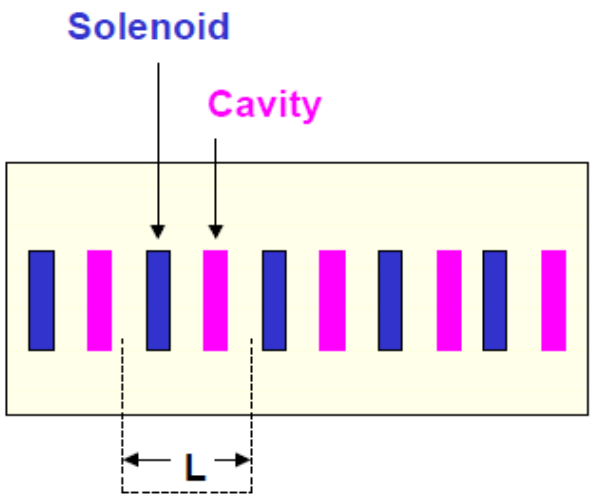
Overview on discussion of 90^0 stopband

- Was of concern as “envelope Instability” from envelope equations in 1970’s *(Lambertson et al., 1977, Reiser and Struckmeier, 1984)*
- some early experimental evidence in Berkeley coasting beam channel experiment *(M. Tiefenbach et al., 1985)*
- transverse 90^0 stopband confirmed first time experimentally in a Linac – GSI-UNILAC *(L. Groening et al., PRL 2009)*
- no experiment on longitudinal 90^0 mode!
- taken for granted and 90^0 applied to linac design transversely **and** longitudinally
- we found in 2017 (PRL) that longitudinally 90^0 limitation in some cases unnecessary and re-visiting is appropriate!

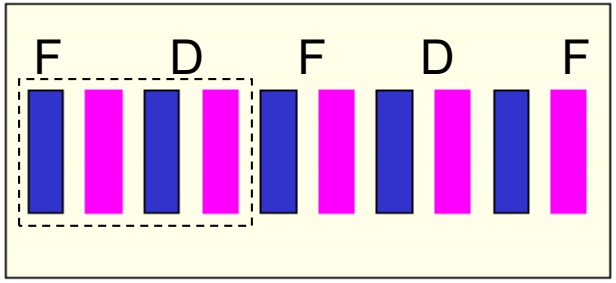
Tom Wangler- discussion of 2002
- ADS proposal -

Wangler:
- longitudinal 90^0 stop-band can limit the accelerating gradient at low velocities
- → shorten focusing period by SR- rather than FRDR-
- → higher accelerating gradients possible

Example of two cryomodules: Cryomodules are short FODO lattices with different focusing periods. Each period consists of one cavity and one solenoid.



Cryomodule (β_1)



Cryomodule 2 (β_2)

source:

Longitudinal Beam-Dynamics Constraint on Accelerating Gradient

T.P.Wangler, Los Alamos National Laboratory and K.R.Crandall, TechSource

Workshop on Advanced Design of Spoke Resonators
Los Alamos, NM

October 7-8, 2002

Overview

- Introduction
- **Review longitudinal „90^0 structure resonance stopband“**
- The sum „envelope instability“
- Irregular periodic lattices
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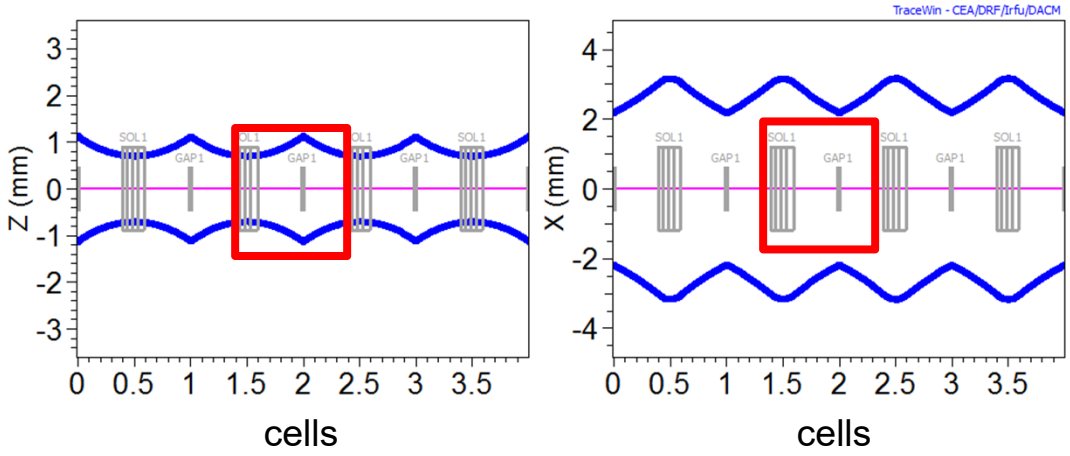
1st lattice example: idealized solenoid + RF gap

"toy lattice" - for simplicity

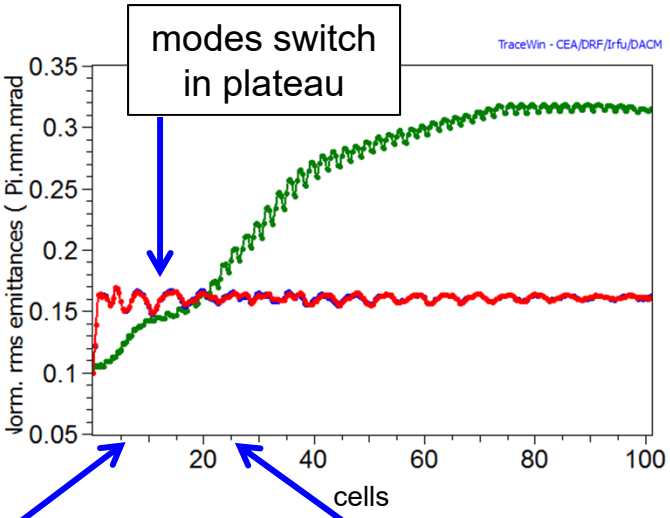
TRACEWIN -simulations



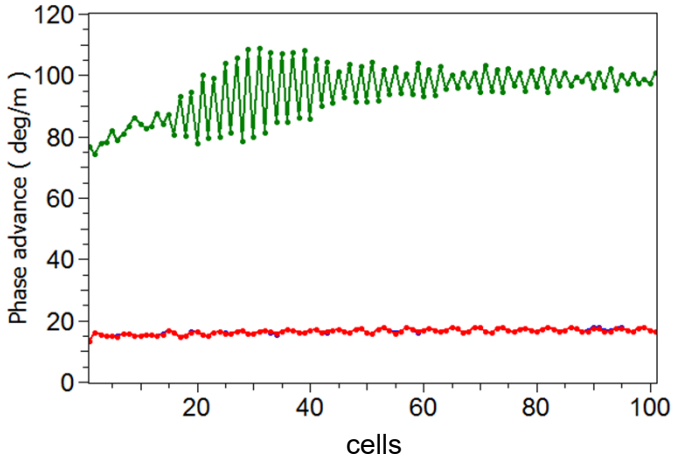
- periodic cell: solenoid + RF gap (no acceleration)
- 3D Gaussian bunches
- strong 90^0 effect - "as expected"
  - transversely similar to FODO
  - longitudinally ?

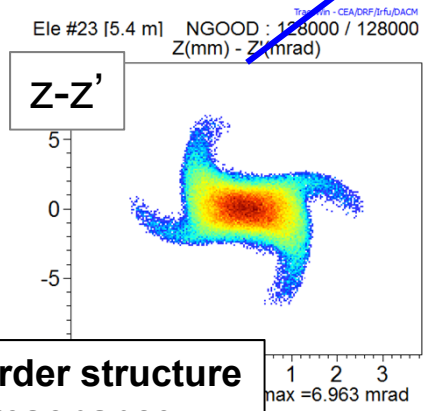
Evidence of longitudinal
4th order structure resonance + envelope instability

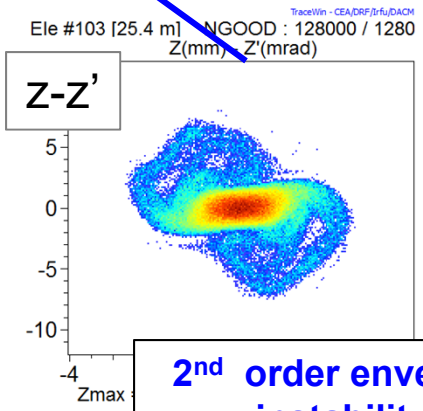
$k_{0z}=120^0$ $k_z=76^0$



3D Gaussian distribution







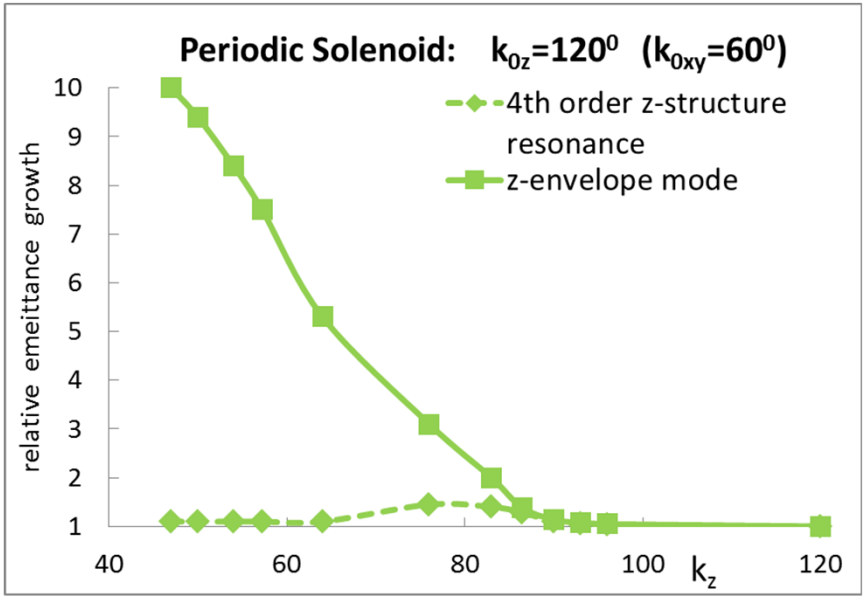
longitudinal envelope instability will occur earlier if larger mismatch

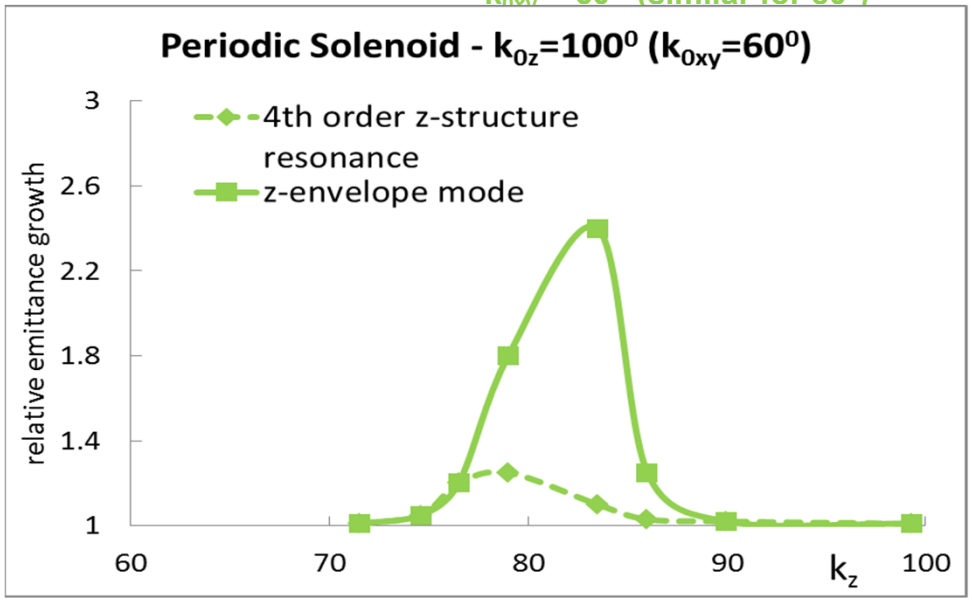
4th order structure resonance
$4k_z \sim 360^0$
→ compare with transverse UNILAC experiment

2nd order envelope instability
$2k_z \sim 180^0$

Periodic solenoid lattice 90^0 longitudinal stopband confirming serious effect beyond certain intensity

$k_{0xy} = 60^0$ (similar for 80^0)

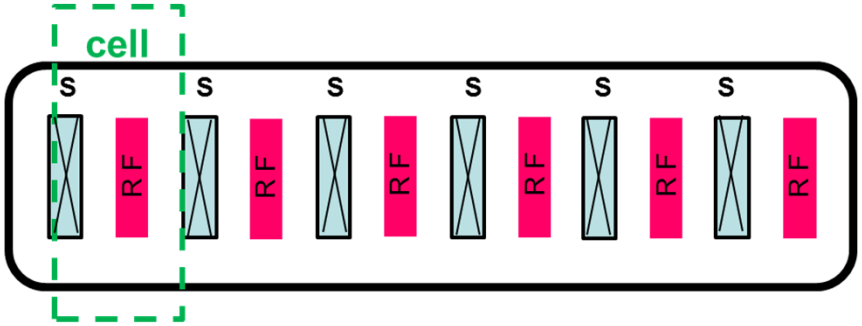




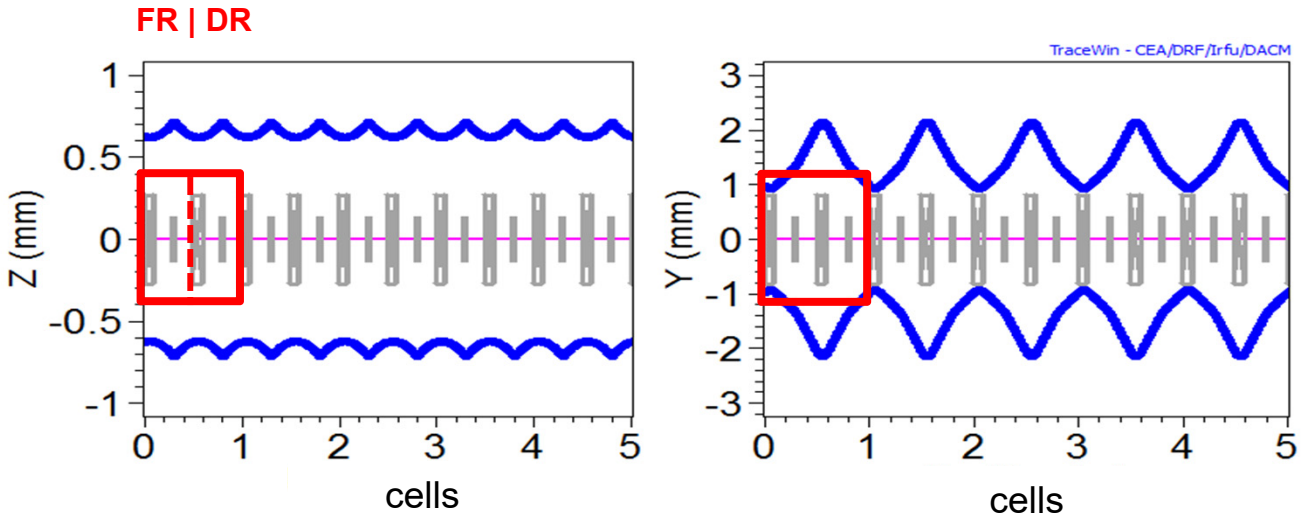
intensity

initial 4th order followed by env-instability

no emittance growth
is it useable???
probably not as SR cells short!



2nd lattice example: FODO + RF gap

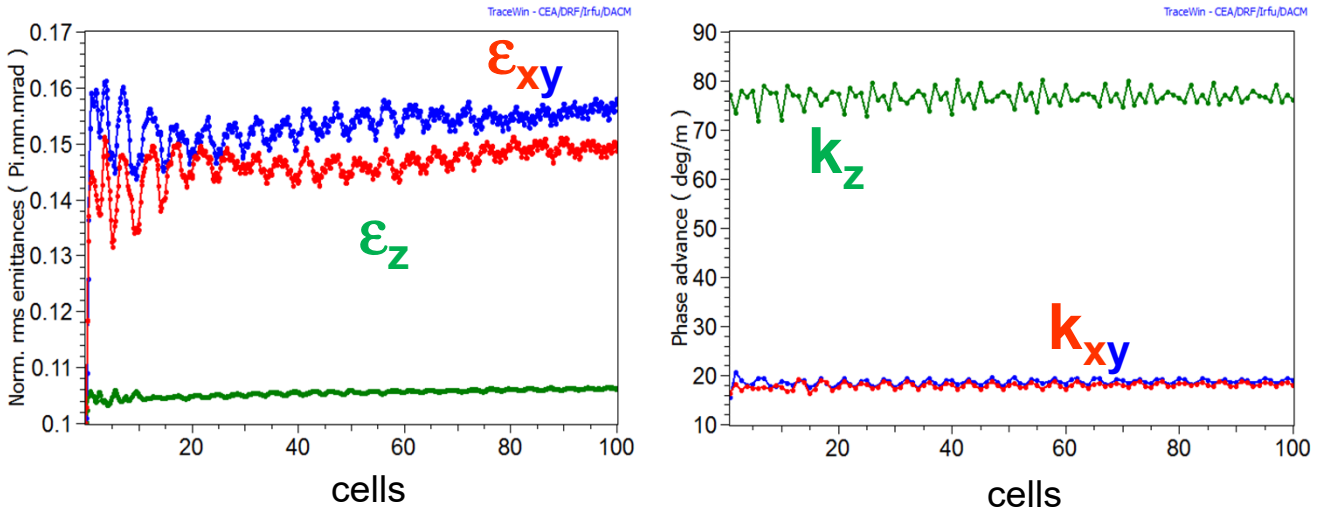


space charge forces:

- transverse force in FR half-cell different from DR half-cell
- in an exact sense longitudinal period same as transverse due to space charge coupling
- coupling to longitudinal in practice very small

→ Simulation for k_{0z}=120° k_z=76° (k_{0x}=60°)

3D Gaussian distribution

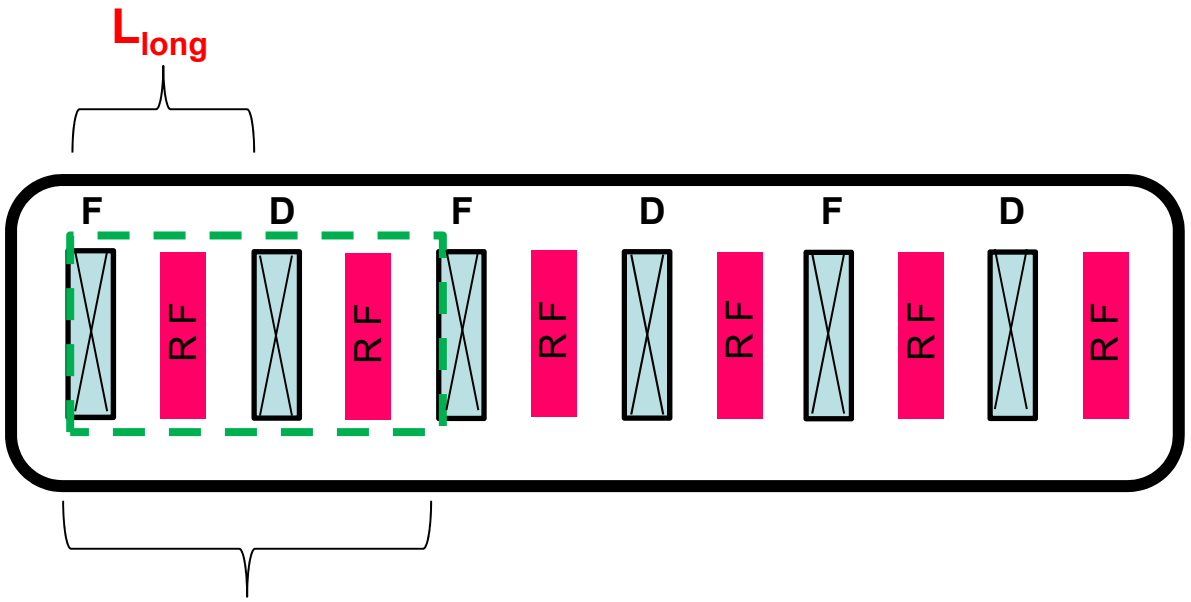


found no resonant effect (only initial nonlinear field energy jump)

- contrary to same k_{0z}, k_z in periodic solenoid case
- apparently longitudinal space charge force in FR half-cell can be assumed nearly identical to that in DR half-cell → "identical" cells

→ In FODO + RF longitudinal 90° stopband

absent as long as k_{0z} < 180°



L_{trans} = transverse period
= lattice cell (long!)

- ✓ allows choice of k_{0z} above 90°
- ✓ more design flexibility
- ✓ unless other sources of emittance degradation

Overview

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- **The sum „envelope instability“**
- Irregular periodic lattices
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- Conclusions

"Sum envelope instability" – a new mode of some concern

O. Boine-Frankenheim, I. Hofmann and J. Struckmeier, POP 2016
I. Hofmann and O. Boine-Frankenheim , PRL 2017
Y. Yan et al, PRAB 2018

For **split tunes**

$k_{0xy} < 90^0$ and $k_{0z} > 90^0$

(both defined on transverse focusing period)

a "sum envelope instability" was found to exist provided that

$$\mathbf{k_{0xy} + k_{0z} > 180^0}$$

smooth approximation criterion for center of stopband of sum envelope instability:

$$\mathbf{k_{0xy} + k_{0z} = 180^0 + \Delta k_{coh,sum}}$$

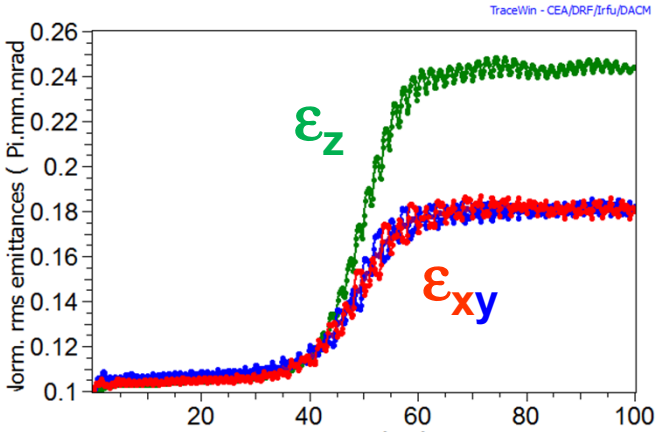
(single envelope instability $k_{0xyz} = 90^0 + \Delta k_{coh}$)

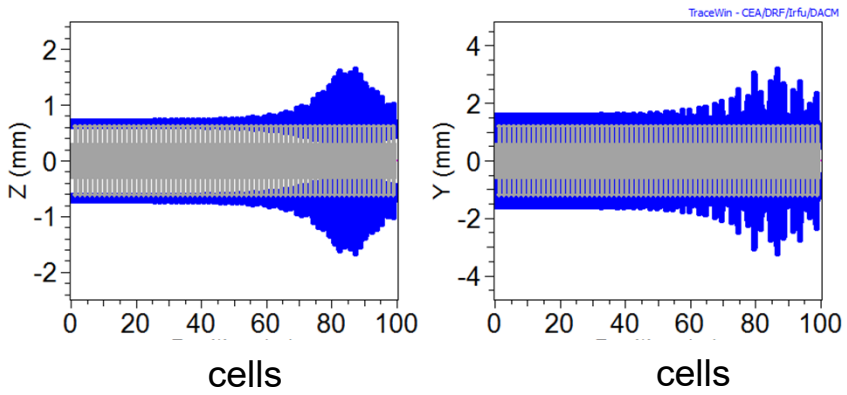
- not to be confused with "sum resonance" $k_{0x} + k_{0y} = 360^0$ by skew quads, which is a single particle resonance!

Sum envelope instability criterion:

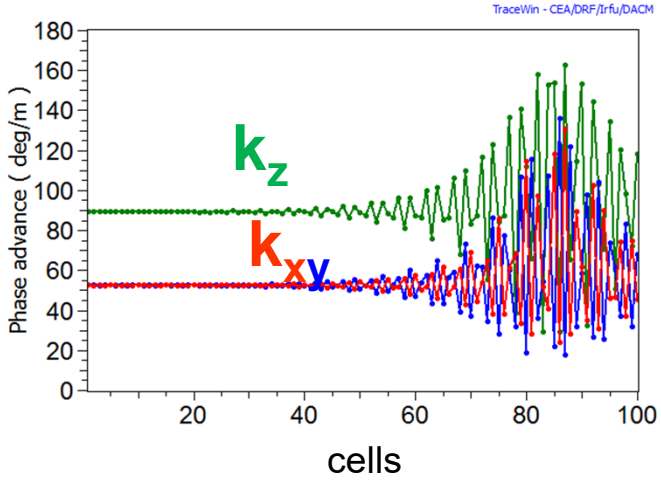
$k_{0z} + k_{0xy} = 180^o + \Delta k_{coherent}$

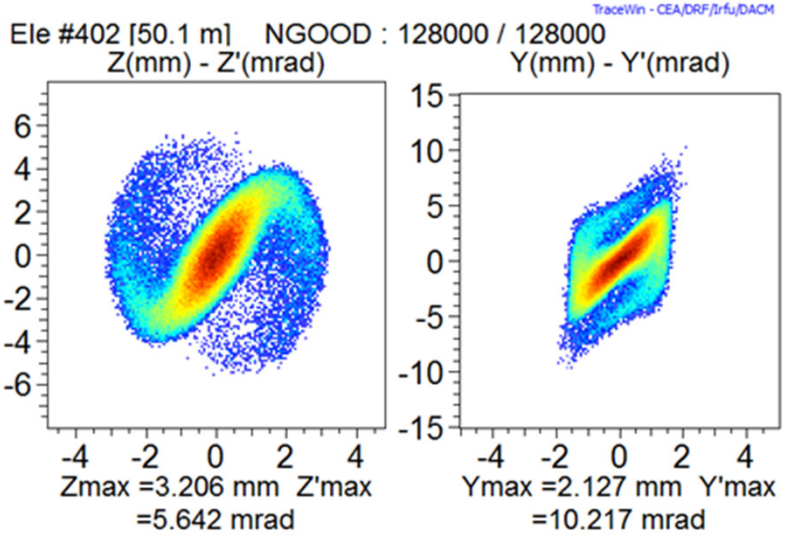
$k_{0z}=120^o$ ($k_z=92^0$) and $k_{0xy}=90^o$





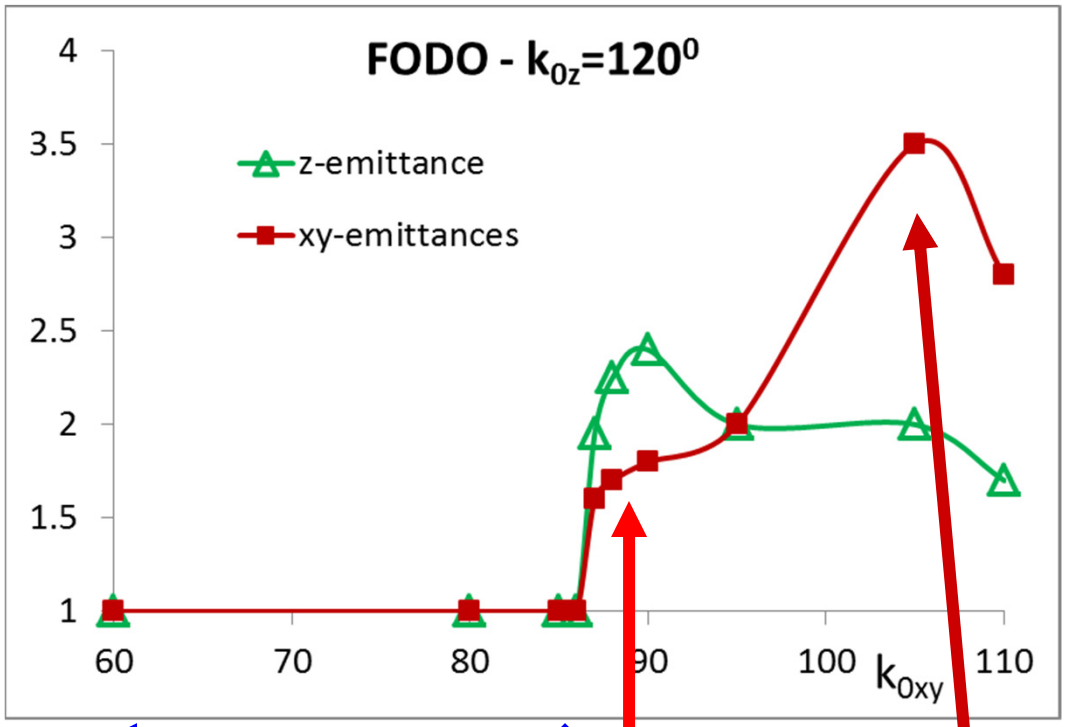
3D Gaussian distribution





Combined stopbands in xy and z

$k_{0z} + k_{0xy} = 180^o + \Delta k_{coh}$ for stopband center
here: $\Delta k_{coh} \sim \Delta k_{incoh,z} \sim 30^0$



safe

sum envelope instability

transv 90^0 envelope instability

Summary

for avoiding the 90^0 and sum mode

Periodic solenoid channel SR-SR-...

- $k_{0xyz} < 90^o$ safe
- no sum mode ($k_{0z} + k_{0xy} < 180^o$)

- Periodic quadrupole channel FRDR-FRDR-...
- $k_{0xy} < 90^o$ safe
- $k_{0z} > 90^o$ also ok, provided that:
- sum mode condition $k_{0xy} + k_{0z} = 180^o + \Delta k_{coh}$ is avoided

Overview

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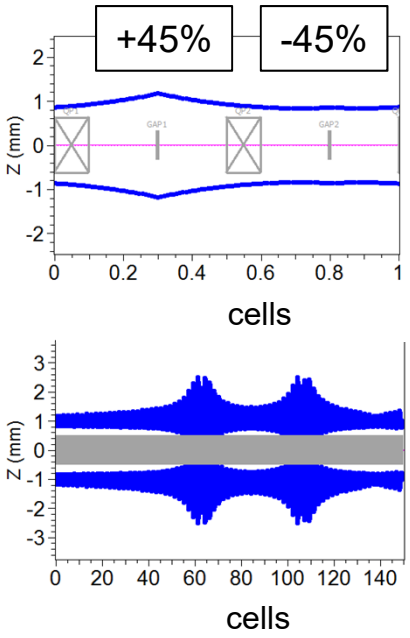
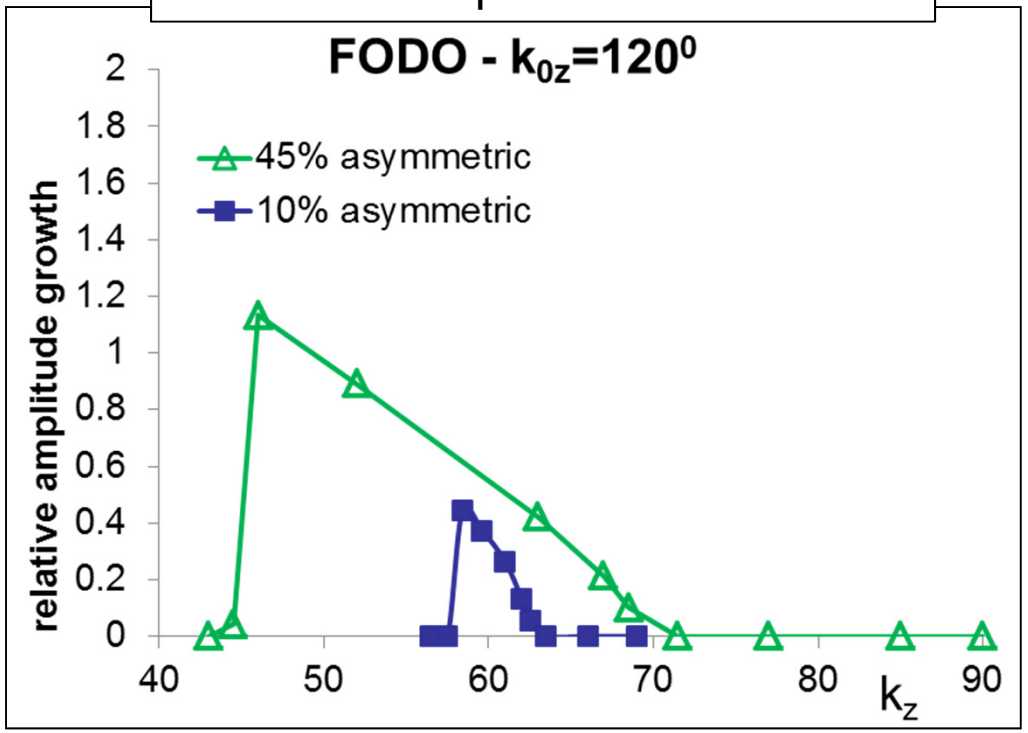
Linacs often not strictly periodic

test case: breaking RF gap strength symmetry

asymmetric gap voltage: 2→1 cell



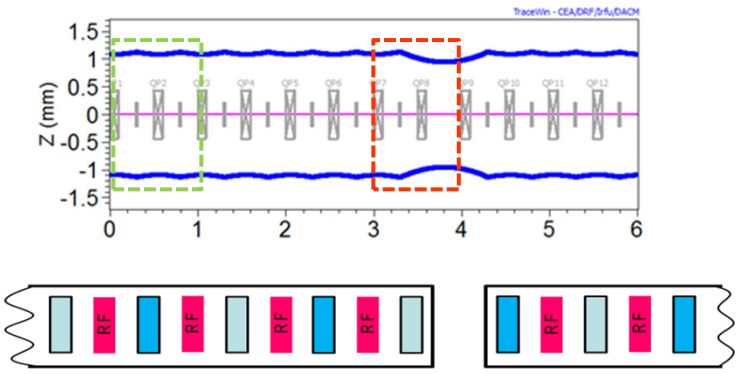
Envelope simulation

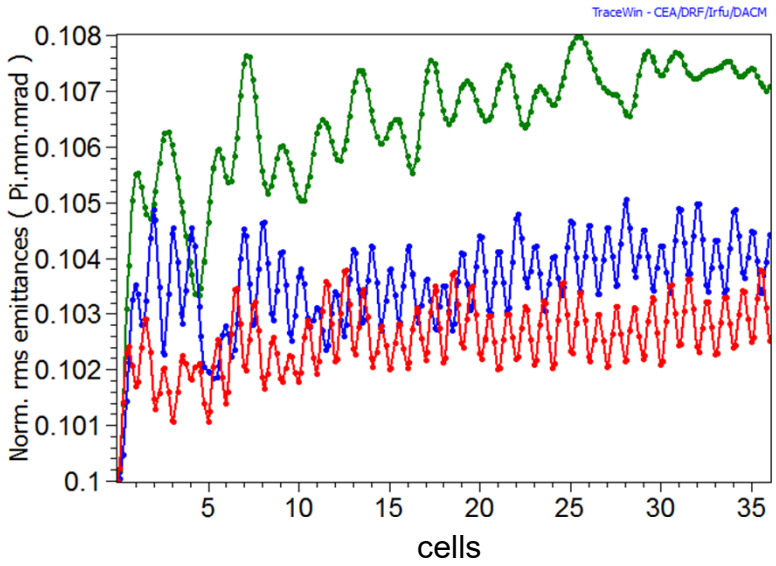


width of stopband ~ asymmetry
→ small asymmetry ignorable

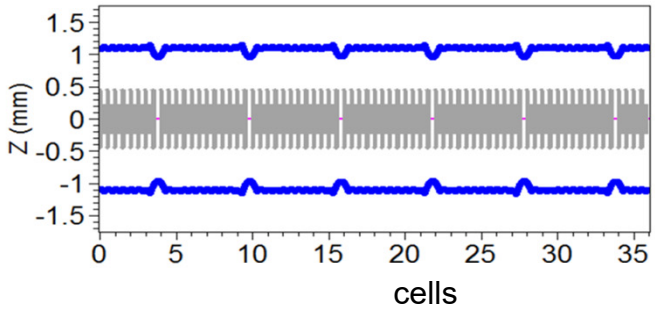
Periodic interruptions – from tank to tank

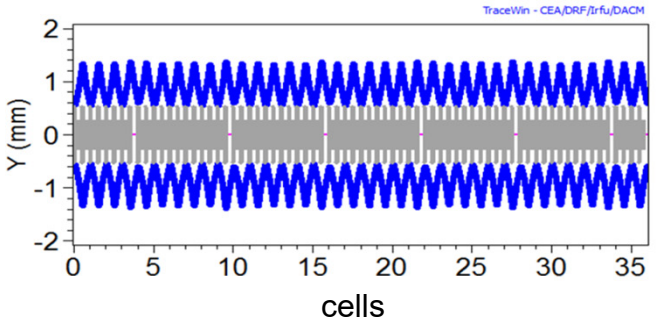
"toy" example: missing every 6th gap (between tanks)





The missing 6th gap generates a space charge harmonic with a period over 2 cells equivalent to a phase advance $2k_{0z} = 120^0$ - but no evidence for envelope instability





Overview

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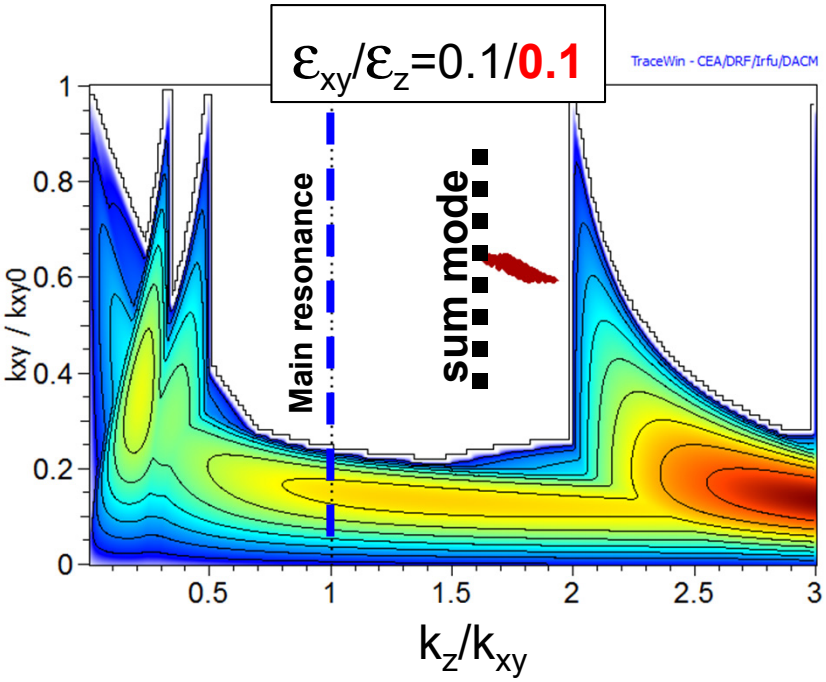
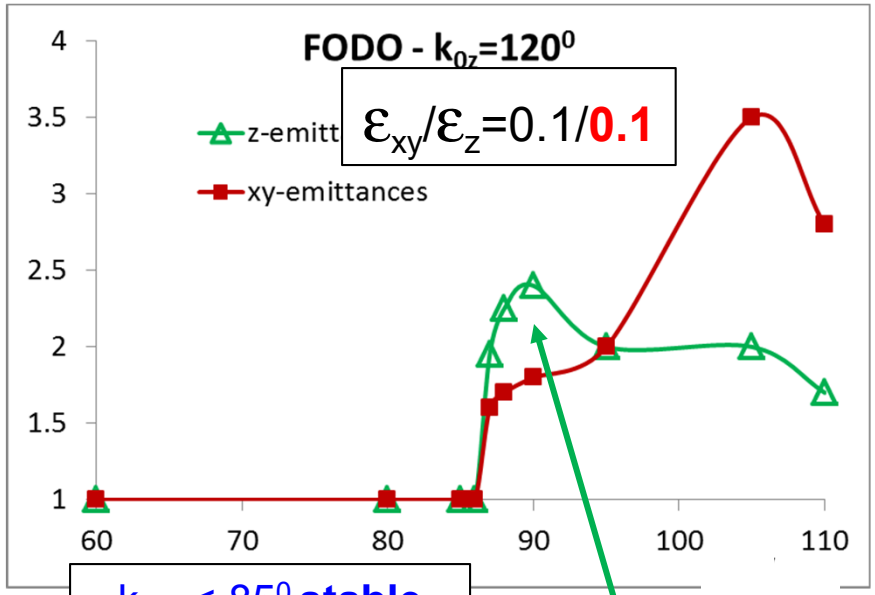
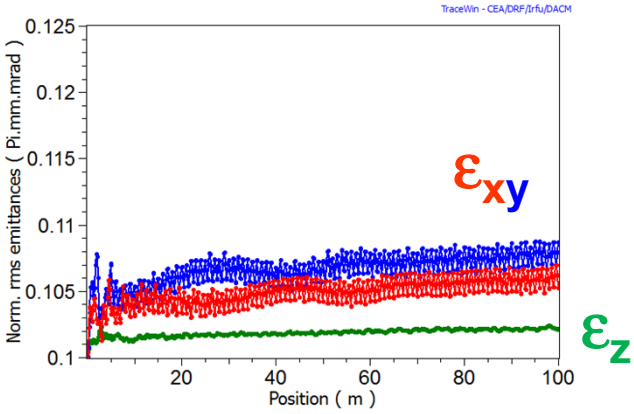
Interference with “stability chart”

enable operation far to the right of “main resonance”



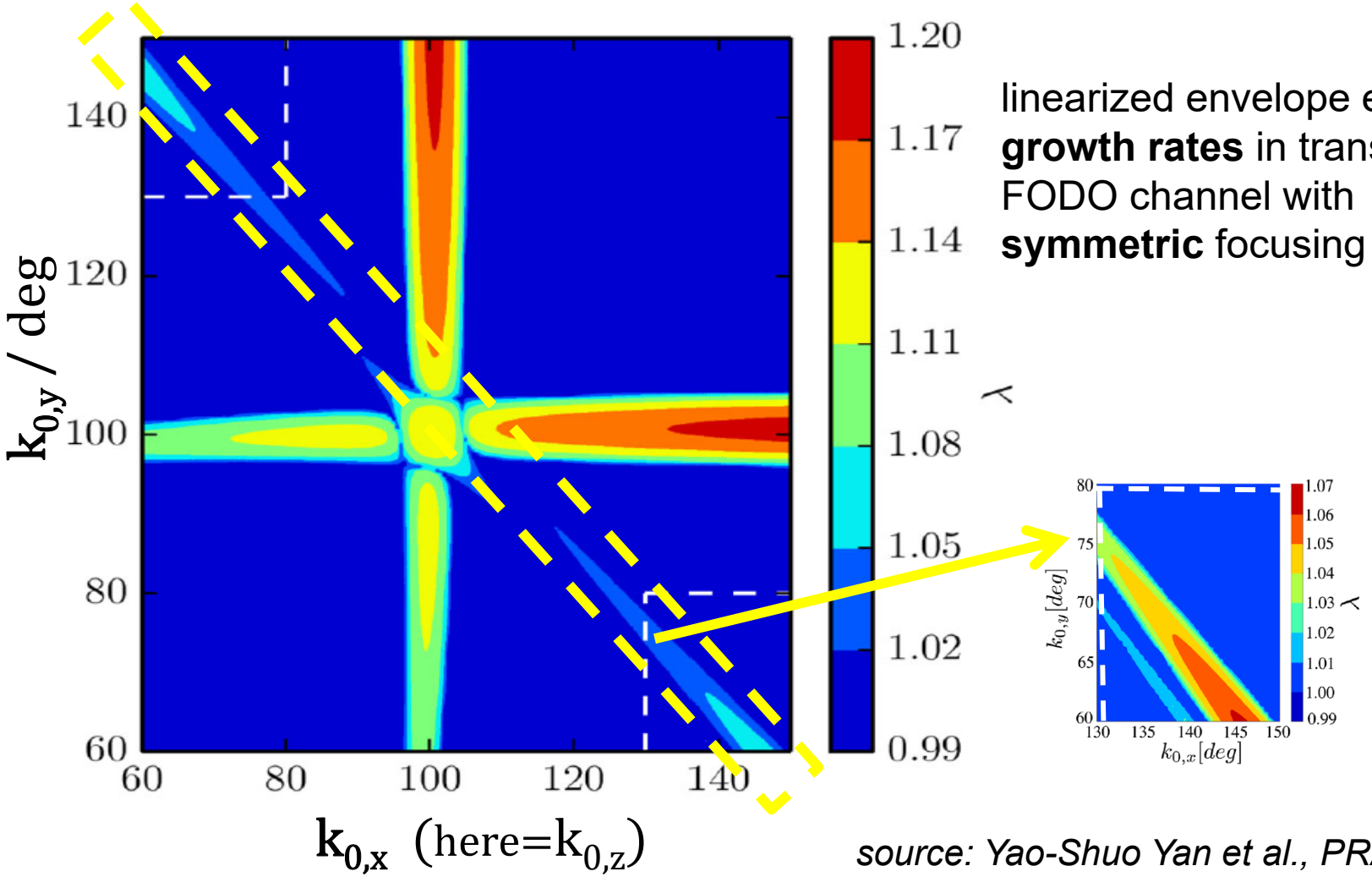


$k_{oxy} < 85^0$ **stable** against sum mode
$k_z + k_{oxy} < 180^0$



k_{oz} =120^0 k_z =100^0
k_{oxy}= 85^0 k_{xy} =54^0

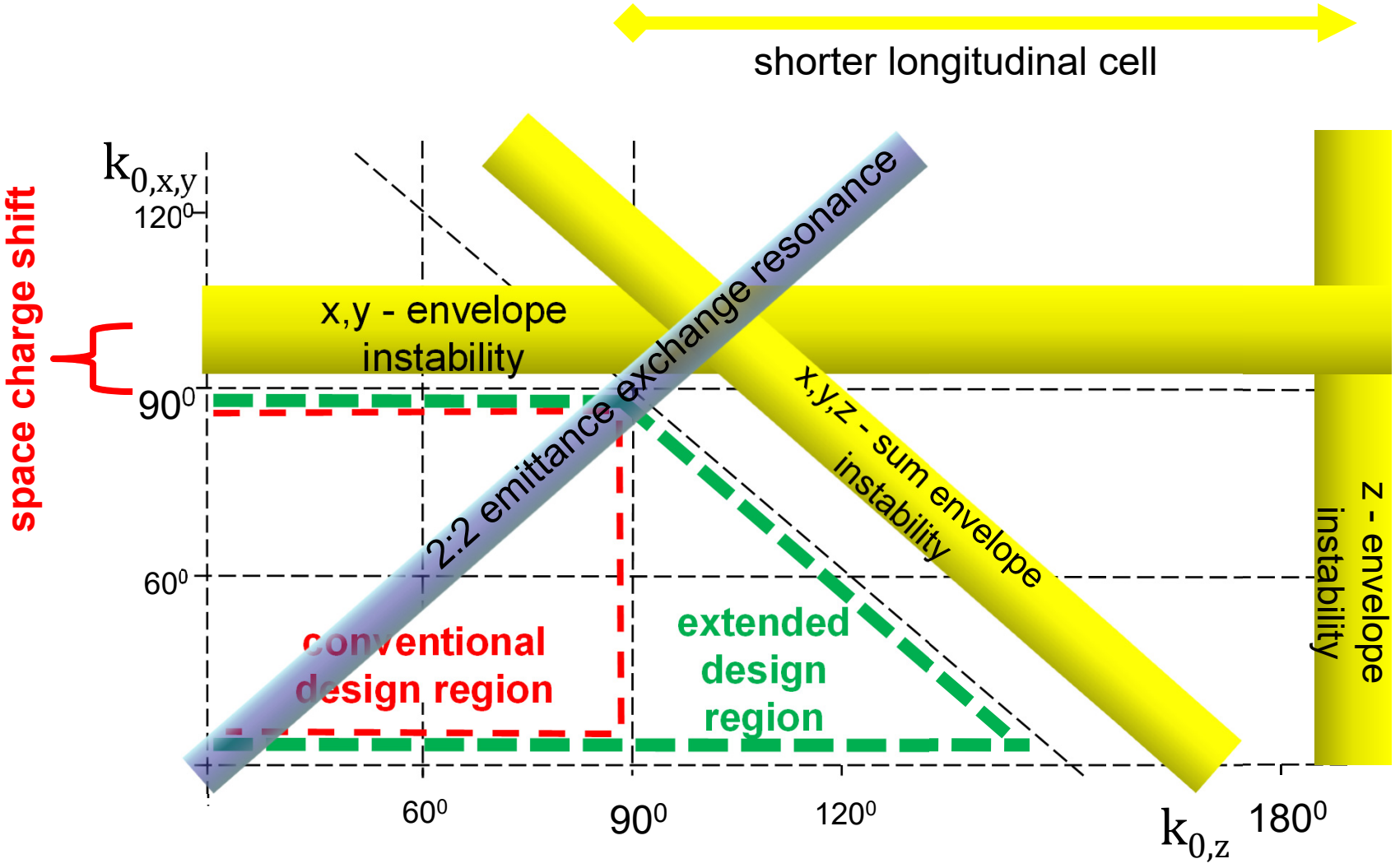
Scan of envelope instabilities in x - y (similar in xy – z)



linearized envelope equation **growth rates** in transverse FODO channel with **symmetric** focusing in x-y

source: Yao-Shuo Yan et al., PRAB 2107

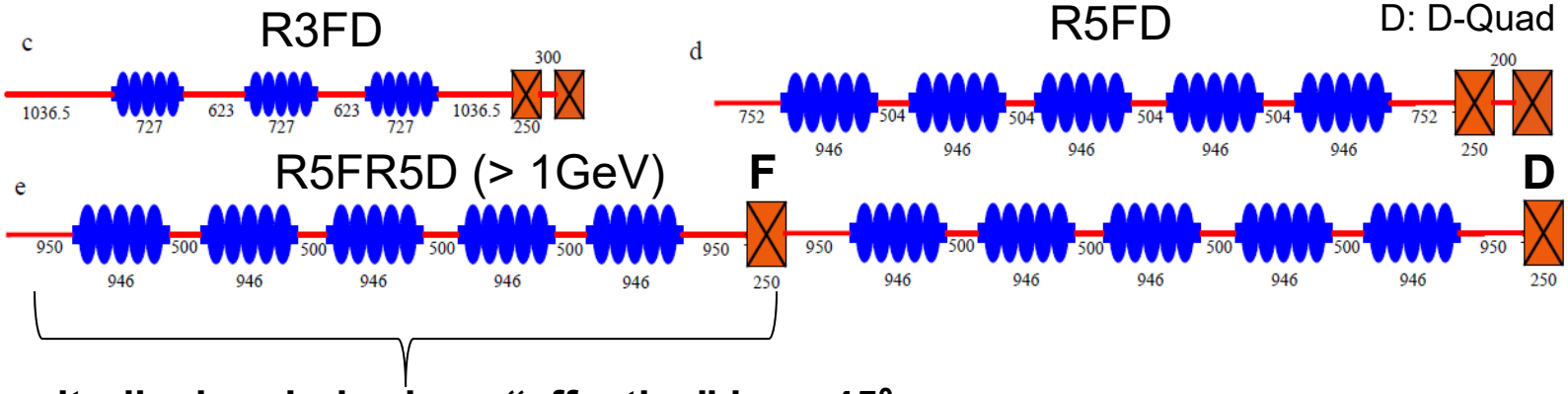
3D chart of structure resonances



Application example

Discussion of CW s.c. linac C-Neutrino Driver (J-Y. Tang)

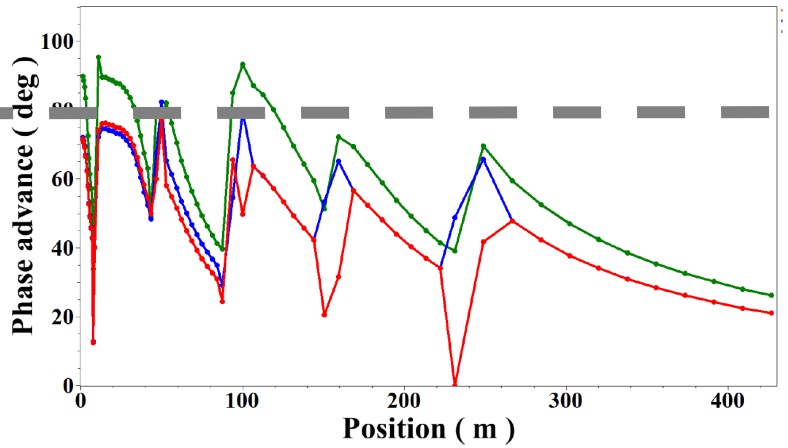
R: Resonator
F: F-Quad
D: D-Quad



1 longitudinal period, where "effective" $k_{0z} < 45^0$
- could be chosen larger!

R5FR5D (> 1GeV)

90^0



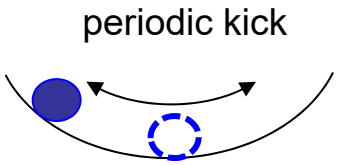
Conclusions

- Retrieved interplay of fourth order and envelope instability in longitudinal plane for Solenoid + RF – similar to transverse 90^0
- Demonstrated that in FODO+RF longitudinal period effectively halved and absence of 90^0 stopband
- Allows longitudinal phase advance (per focusing cell) above 90^0
- Watch additional constraint for $k_{0z}>90^0$: "sum envelope instability"
- No need to replace FODO by shorter solenoid cells
- Added design flexibility in high gradient superconducting linacs
- Expect that full linac studies including high acceleration gradients also shows mitigated 90^0 effects in transverse plane
- → **conventional "under-90-degrees" (longitudinally) is an over-emphasized criterion – needs to be relaxed in number of cases!**

Thank you for your attention!

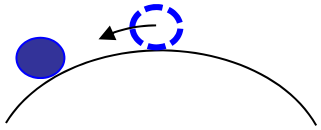
Resonance – Instability

- 2 distinct sources of emittance growth -



resonant excitation

- single particle resonances
- coherent resonances
- in linacs only **structure** resonances
- here: fourth order, driven by space charge



instability

- parametric resonance
- here: envelope instabilities

Beam potential from lattice **and** self-consistent electric field

Sum mode activated by increased ε_z

but only "delayed" growth, if beam well-matched

$k_{oz}=120^0$