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Impact of Asymmetric Beam Shapes on the Focusing and Oscillation Margin in Helix TWTs

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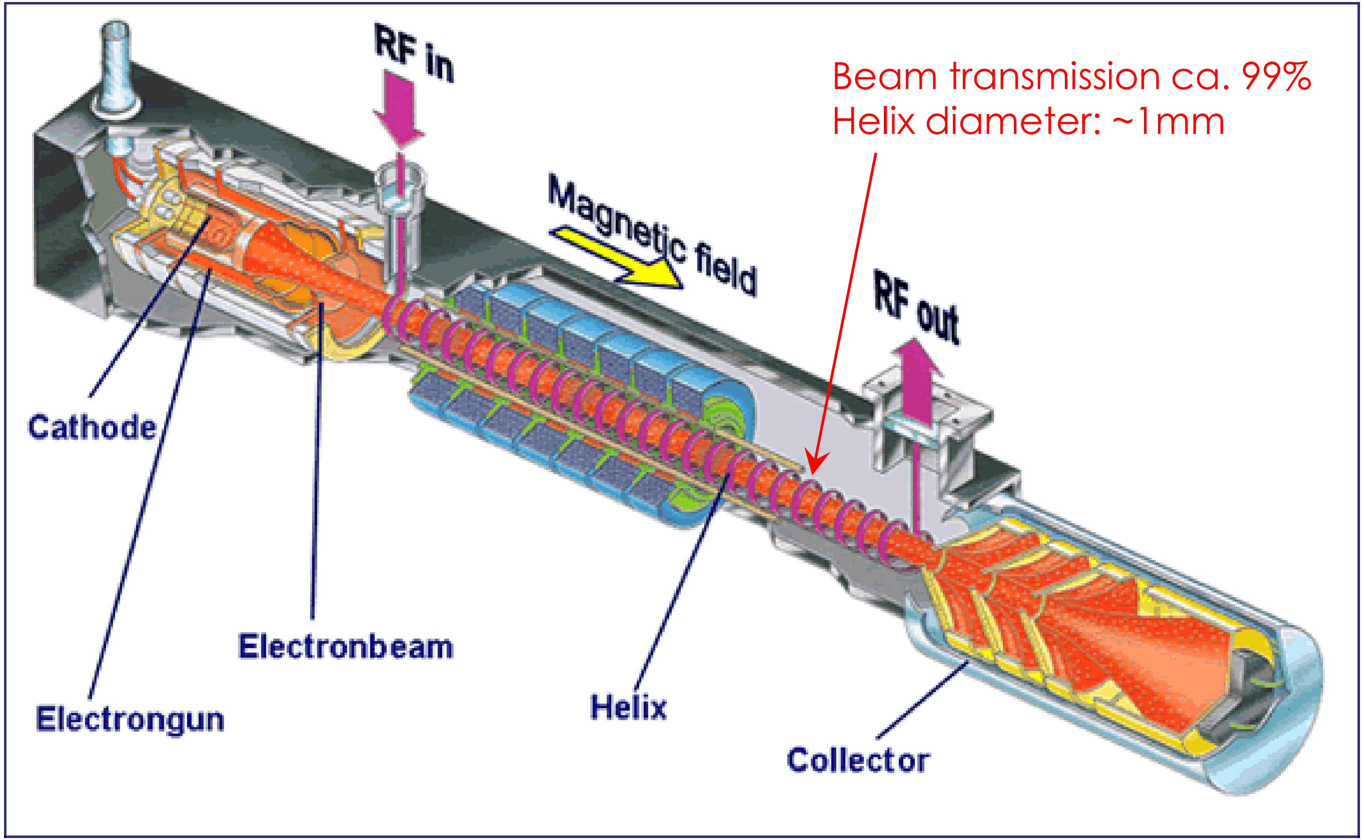
The Traveling Wave Tube



Motivation

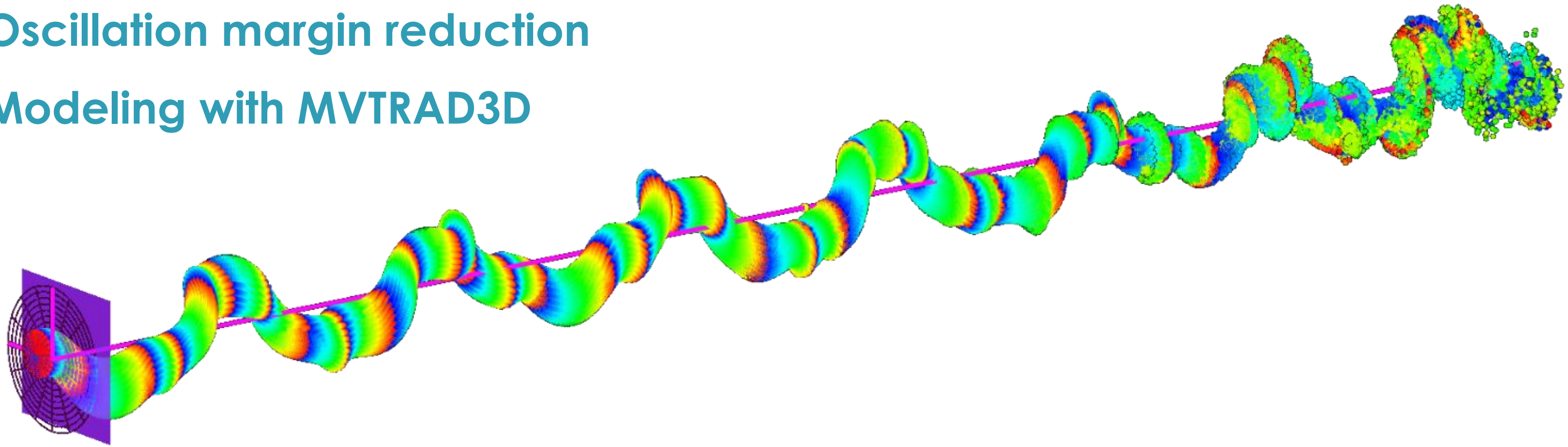
Asymmetric beams

- Geometric asymmetries: tilted/misaligned gun
- Magnetic asymmetries: transversal magnetic fields, tilted magnetization axes

Focusing problems (small signal / nonlinear drive)

Oscillation margin reduction

Modeling with MVTRAD3D



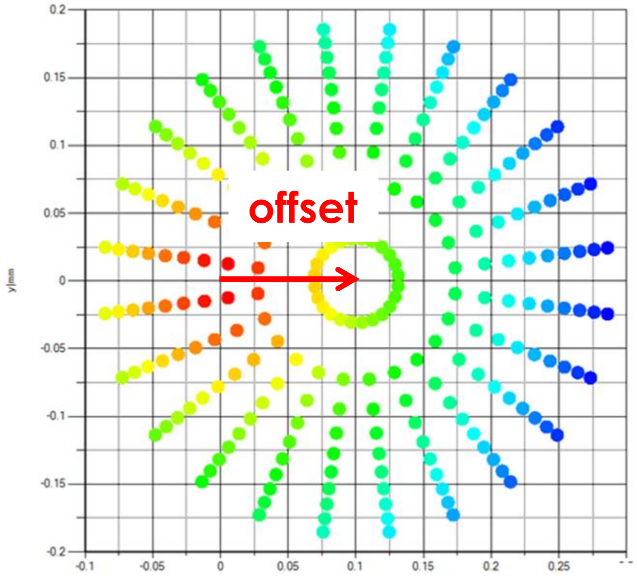
MVTRAD3D

- Proprietary beam-wave interaction tool for helix TWTs
- Particles: Full 3D particle-in-cell model
- EM Fields:
  - **Parametric circuit field** (phase velocity, coupling impedance, attenuation), ~exp(-jωt)
  - Magnetostatic focusing field
  - Space charge field: Poisson's equation
- **Space charge (-field): Fourier series in Θ** (azimuthal coordinate)
  - Multiple 2D solutions instead of a 3D solution
- Time-domain / frequency-domain hybrid

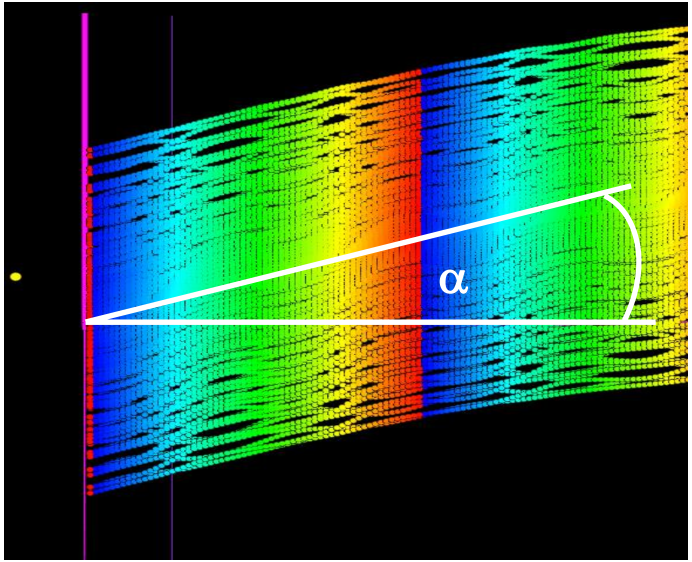
Study Case: Ku-Band TWT

- **150W Ku-Band Satcom TWT**
- **Beam: 6000V / 80mA**
- **Helix diameter ~1mm, target beam fill factor 40%**
- **PPM focusing field: ~0.25T peak, 9mm (full) period**
- **Other examples:**
  - S-Band TWT (5000V / 125mA)
  - Ka-Band TWT (6500V / 80mA) -> BWO
  - Q-Band TWT (12000V / 90mA)

Geometric Asymmetries of the Beam Injection



Transversal beam offset



Beam tilt angle

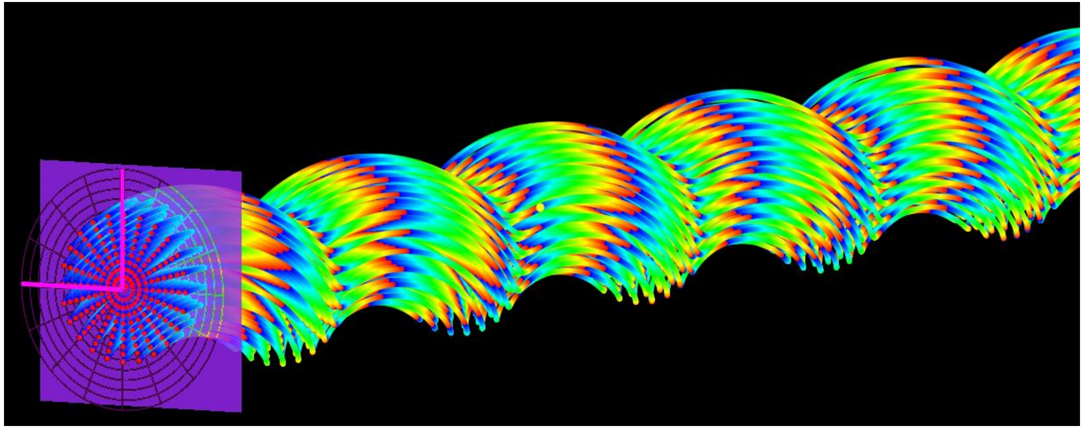
Constant Focusing Field, Tilted Beam

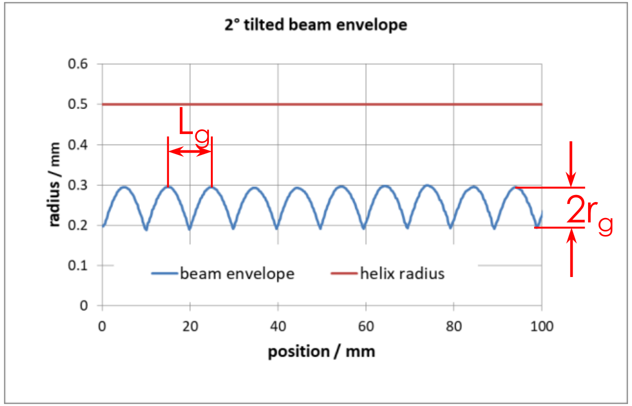
- Tracking of beam axis
- Beam axis rotates around off-center axis, shifted by gyro-radius r_g , with period L_g

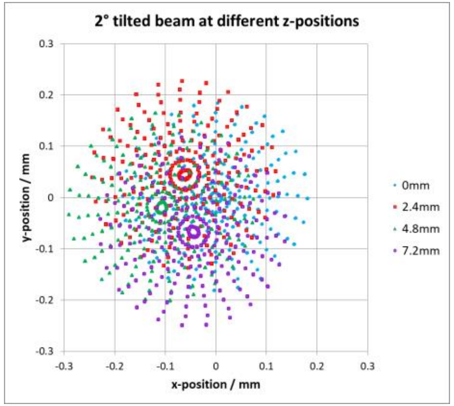
$$r_g = \frac{sin(\alpha)}{B}\sqrt{\frac{2V_b}{\eta}}$$

$$L_g = \frac{2\pi}{B}\sqrt{\frac{2V_b}{\eta}}$$

V_b: beam voltage,
B: focusing field,
η: electron charge-to-mass ratio,
α: tilt angle







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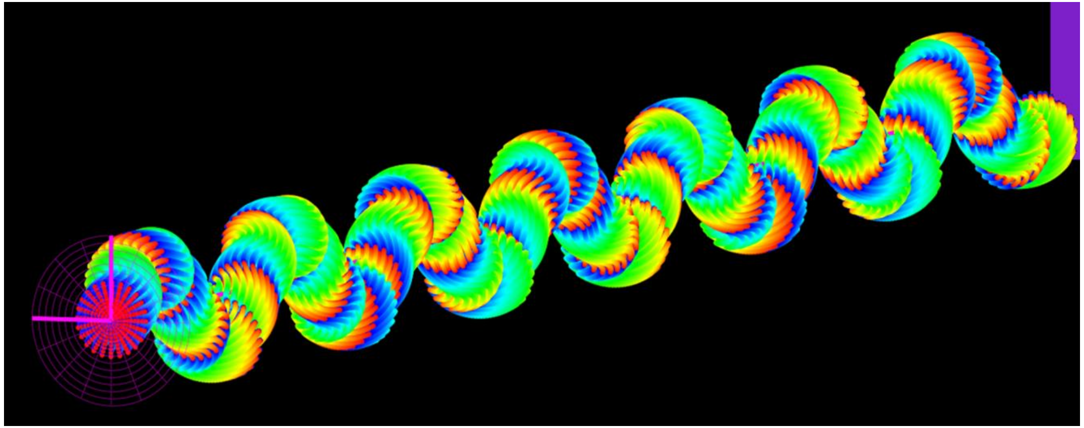
PPM Focusing Field, Tilted Beam

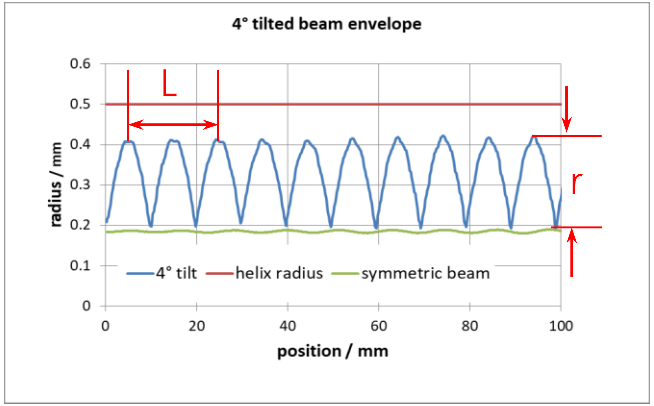
- **Tracking of beam axis**
- **Beam axis oscillates around off-center axis, shifted by radius r, with period L**

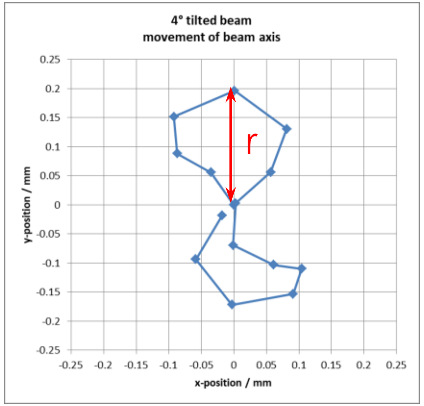
$$r = \frac{2\sin(\alpha)}{B_{peak}/\sqrt{2}}\sqrt{\frac{2V_b}{\eta}}$$

$$L = \frac{4\pi}{B_{peak}/\sqrt{2}}\sqrt{\frac{2V_b}{\eta}}$$

V_b: beam voltage,
B_{peak}: PPM peak value,
η: electron charge-to-mass ratio,
α: tilt angle







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PPM Focusing Field, Tilted Beam

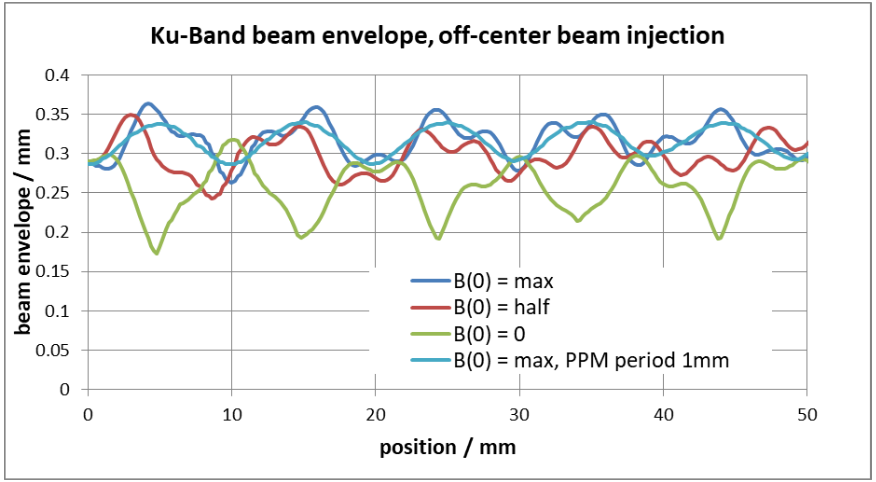
Study case	r (theoretical) / mm	r (observed) / mm	L (theoretical) / mm	L (observed) / mm
Ku-Band 2450G tilt 1°	0.053	0.056	18.9	19.4
Ku-Band 2450G tilt 2°	0.106	0.118	18.9	20.8
Ku-Band 2450G tilt 3°	0.160	0.175	18.9	19.6
Ku-Band 2450G tilt 4°	0.213	0.221	18.9	19.6
Ku-Band 1700G tilt 2°	0.153	0.175	27.3	30.0
Ku-Band 4000G tilt 2°	0.065	0.100	11.6	11.2
Ku-Band 4000G tilt 2° PPM period 2mm	0.065	0.066	11.6	11.2
Q-band 3600G tilt 2°	0.102	0.11	18.0	19
S-Band 1070G tilt 2°	0.226	0.23	40	40

PPM: 9mm

PPM Focusing Field, Off-Center Beam

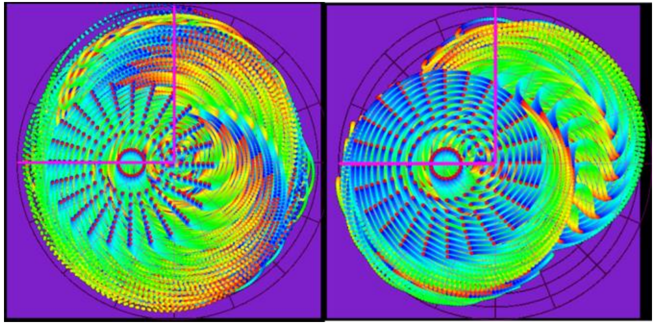
Beam axis rotates/oscillates around axis of PPM field

- Same period L as for the tilted beam
- Amplitude between 1 and 1.5 times initial offset, depending on the phase of the PPM field



Numerical solution (similar to beam border equation)

$$\ddot{r} + r\frac{\eta^2 B_{peak}^2}{4}\left(\cos\left(\frac{\pi\sqrt{2\eta V_b}}{p}t - \Theta_{PPM}\right)\right)^2 - \frac{\eta^2 B_0^2}{4}\frac{d^4}{r^3} = 0$$



V_b: beam voltage, B_{peak}: peak PPM field, p: PPM period, Θ_{PPM}:initial phase of PPM field, B0: cathode field, d: initial beam offset, η: electron charge-to-mass ratio

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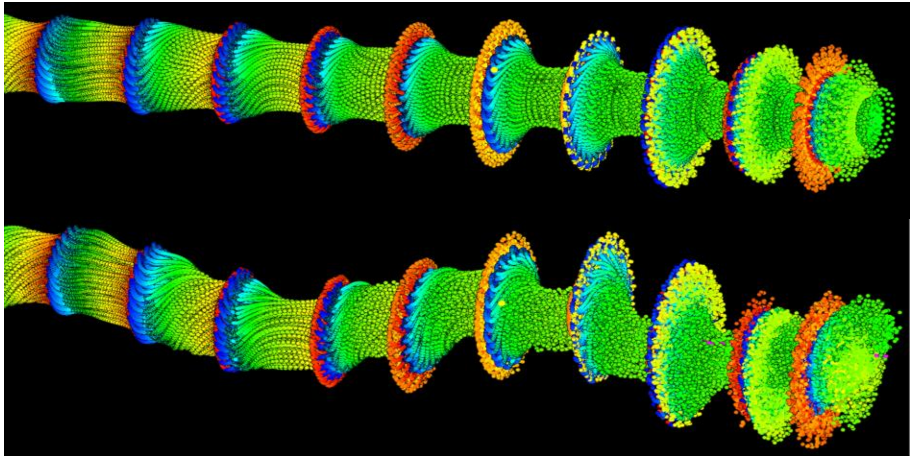
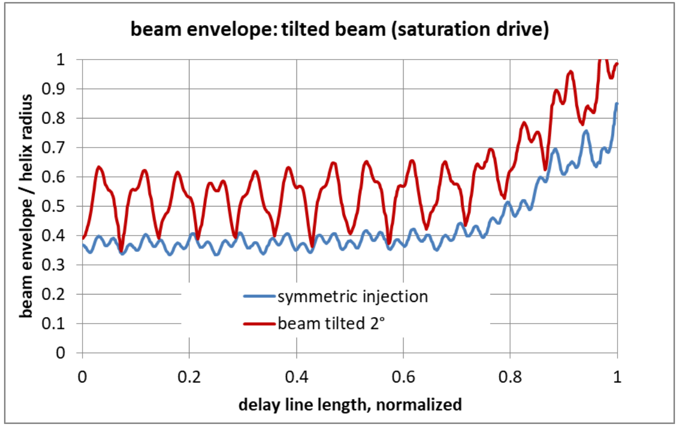
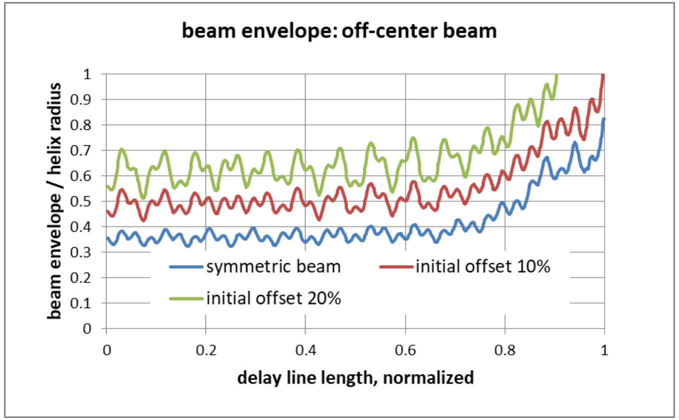
Geometric Asymmetries: Large Signal Drive

- **Small-signal beam envelope extension translates to nonlinear regime**
  - Magnitude approximately equal
- **No significant impact on performance (power, gain, nonlinear phase etc.)**







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Magnetic Asymmetries: Transverse Fields

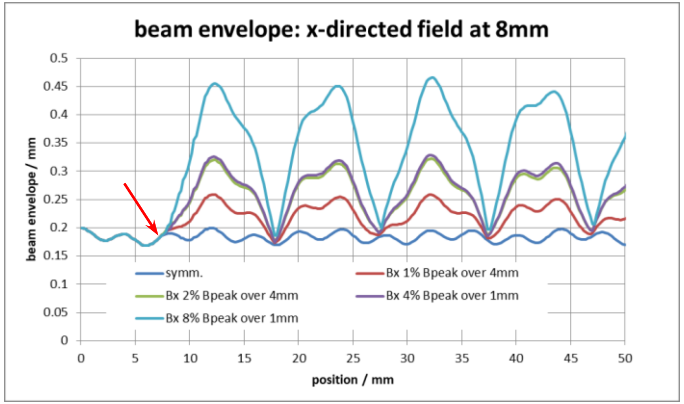
Transverse, non-symmetric magnetic field: effect similar to tilted beam

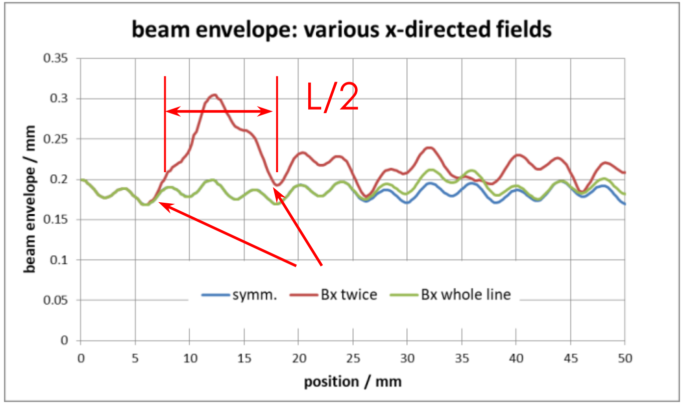
- Effect much less if not l << p (PPM period)

„Repair" through identical Bx after L/2

$$r = \frac{2\sqrt{2}B_x l}{B_{peak}}, L = \frac{4\pi}{B_{peak}/\sqrt{2}}\sqrt{\frac{2V_b}{\eta}}$$

B_x : transverse magnetic field, l: extend of B_x
B_{peak}: PPM peak value,
η: electron charge-to-mass ratio





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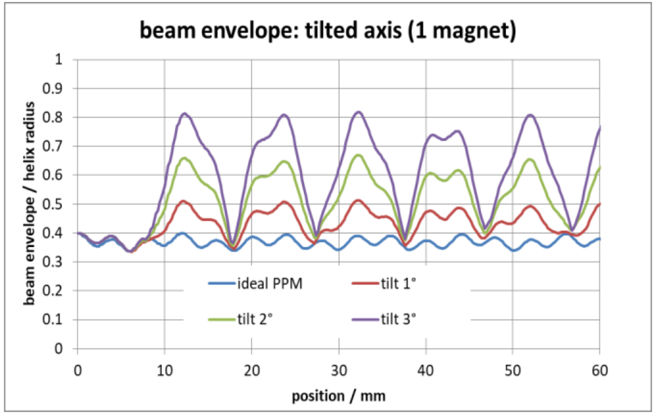
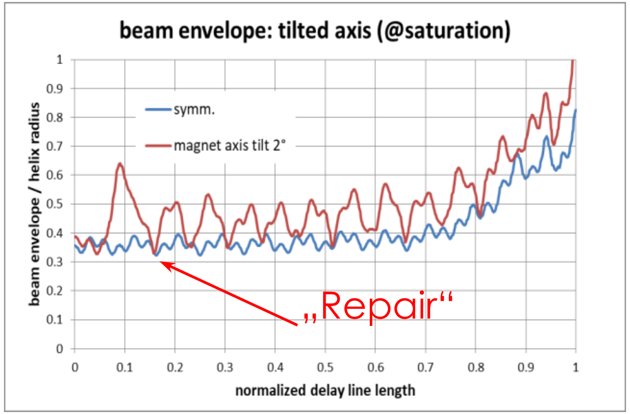
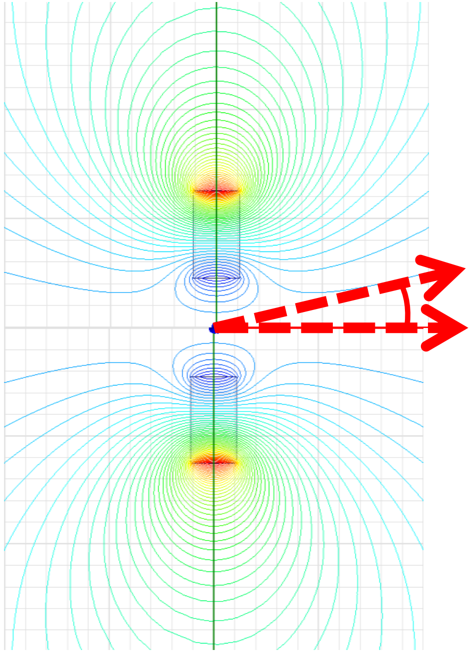
Magnetic Asymmetries: Tilted Magnetization Axis

- PPM magnet axis not perfectly aligned
- NOT compensated by pole pieces
  - Unlike many other magnetic defects
- Very severe effect







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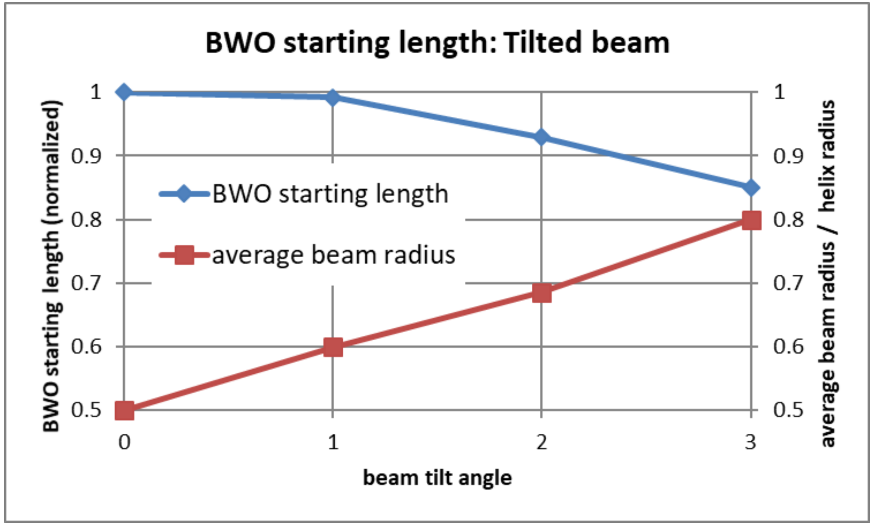
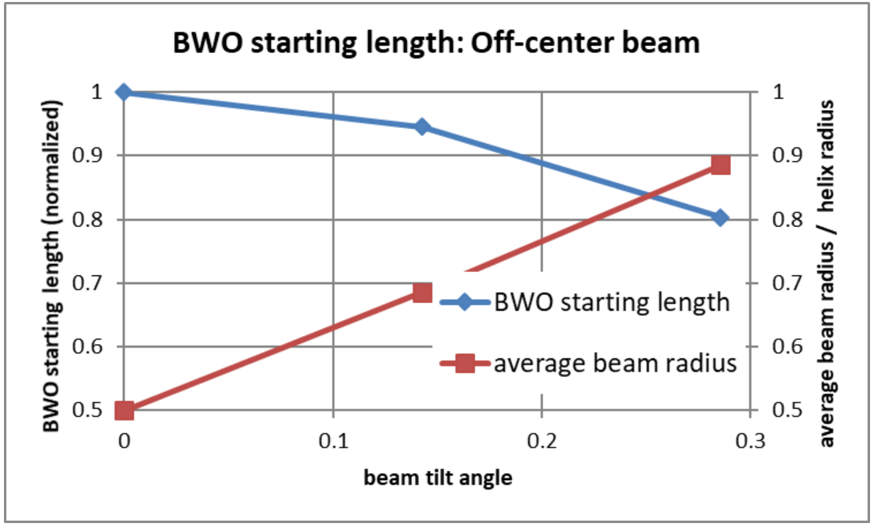
Backward Wave Oscillation Margin

Asymmetric beams (tilted or offset): Decrease of the BWO starting length ~10%

- Equivalent to a decrease in threshold current by ~30%





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Band Edge Oscillation Margin

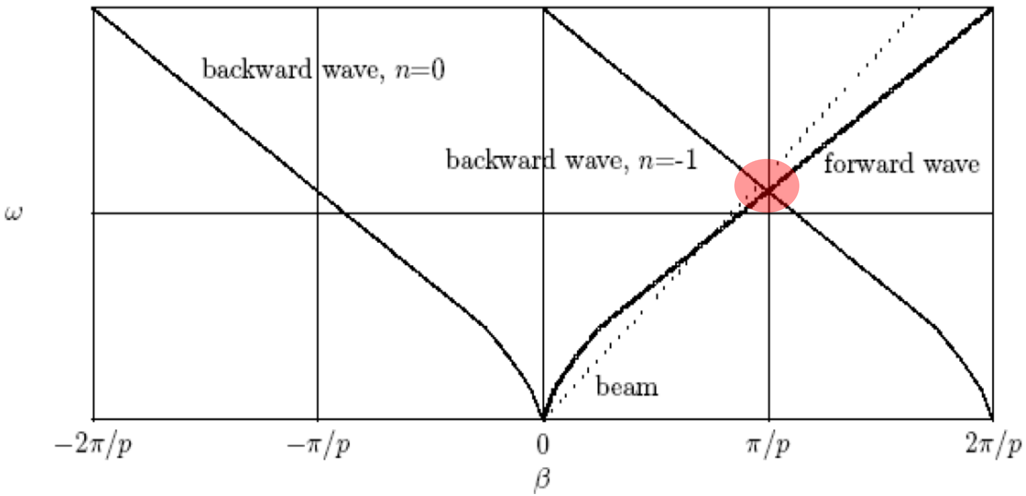
Usually: forward / backward beam modulation orthogonal

- Forward wave: azimuthally constant
- Backward wave: exp(jΘ)

No longer the case for asymmetric beams!

- Coupled forward/backward wave interaction

Bandedge oscillations possible



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Summary

- **3D parametric interaction tool MVTRAD3D has been used to investigate asymmetric beams in helix TWTs**
  - Tilted beam axis
  - Off-center injection
  - Transversal magnetic fields
- **Beam envelope significantly increased even for small asymmetries**
  - Tilted magnetization axes very impactful
- **Small-signal beam envelope increase translates to large signal**
- **Decreased BWO margin due to larger beam envelope**

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Questions?

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