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Beam Focusing in Satcom TWTs Including Thermal Electrons

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P.Birtel, J. Wegener, J.-F. David

Security and mobility in a networked world.

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Overview

- **Motivation**
- **Basics of electron beam focusing in a TWT**
- **Modeling of thermal electrons in gun and delay line**
- **Case study: Satcom TWT**
  - Beam focusing including thermal electrons
  - Effects on other TWT parameters (Gain, RF power etc.)
- **Conclusions**

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DLR

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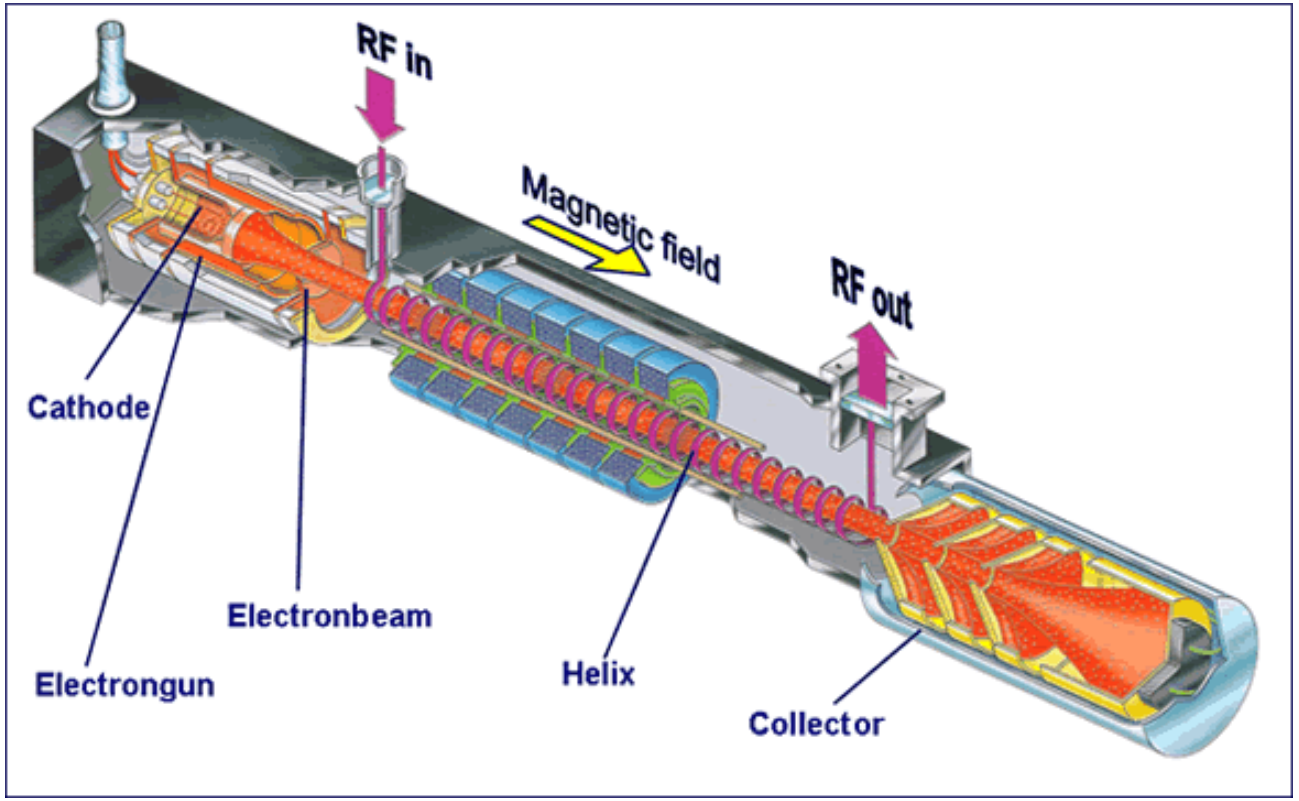
Motivation



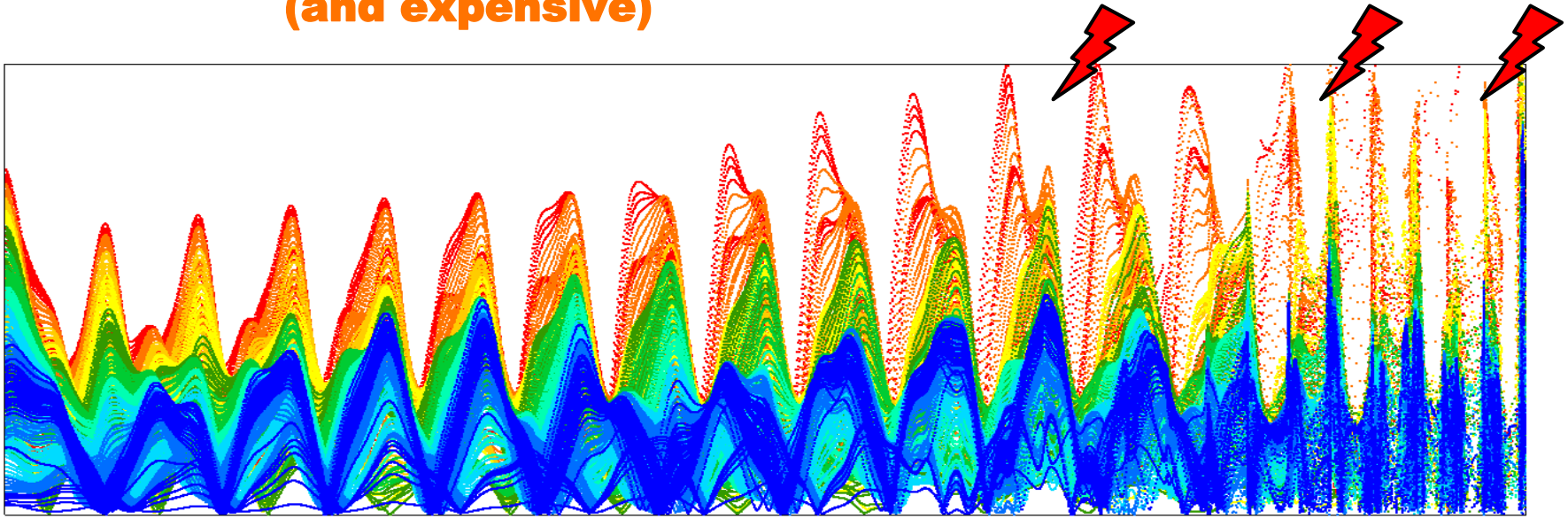
Satcom Traveling Wave Tube

Motivation

Beam focusing critical!

(and expensive)

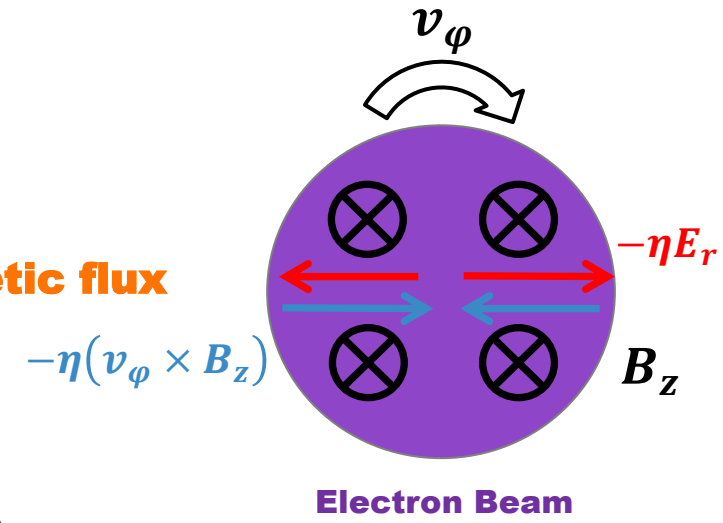
Thermal problems
Efficiency degradation



Simulated electron trajectories in the delay line with RF drive

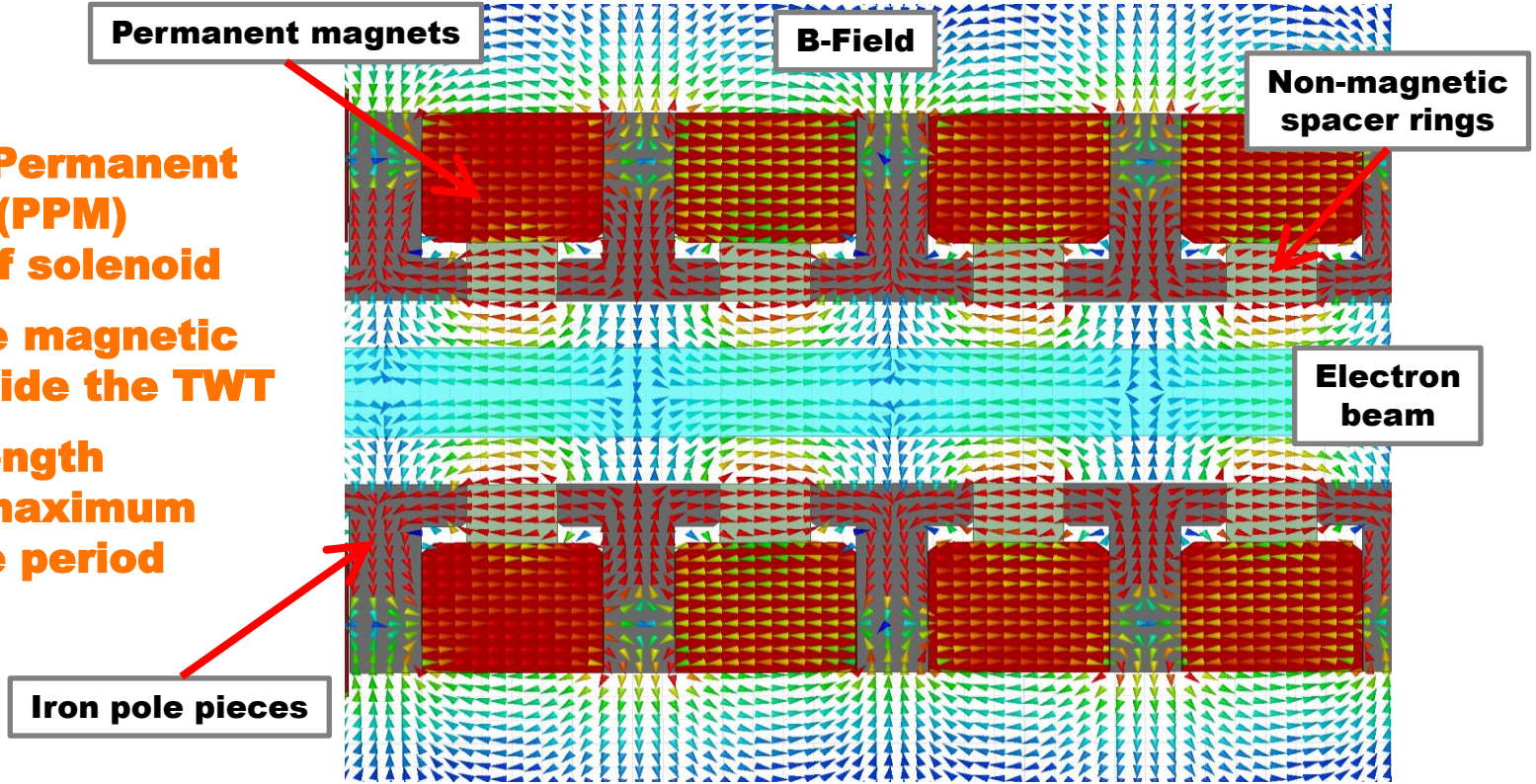
Magnetic beam focusing

- **Beam focused by its *rotation***
  - $\dot{v}_r = -\eta\left(E_r + v_\varphi \times B_z\right)$; B_z axial magnetic field
- **Beam rotation created by change in magnetic flux (Busch's theorem)**
  - $\frac{v_\varphi}{r} = \frac{\eta}{2}\left(B_z - B_C\left(\frac{r_c}{r}\right)^2\right)$;
    B_C magnetic field on cathode, r_c cathode radius, r beam radius
- **Equilibrium between focusing and de-focusing:**
  - $B_z^2 = \frac{2}{r}\sqrt{\frac{I}{2\pi\varepsilon\eta v}} + B_c^2\frac{r_c^4}{r^4} = B_B^2 + B_c^2\frac{r_c^4}{r^4}$; B_B Brillouin field

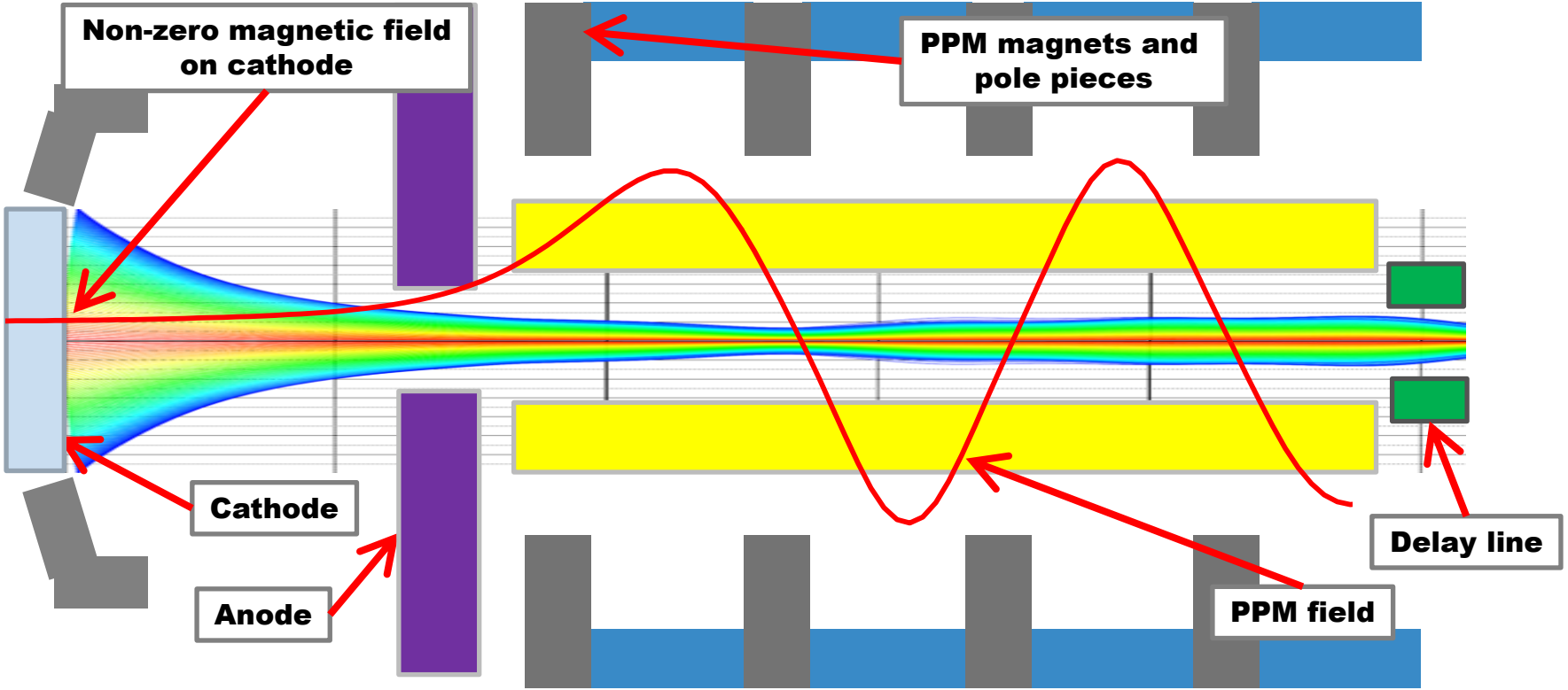


PPM focusing stack

- Periodic Permanent Magnets (PPM) instead of solenoid
- Only little magnetic field outside the TWT
- Field strength limited, maximum allowable period

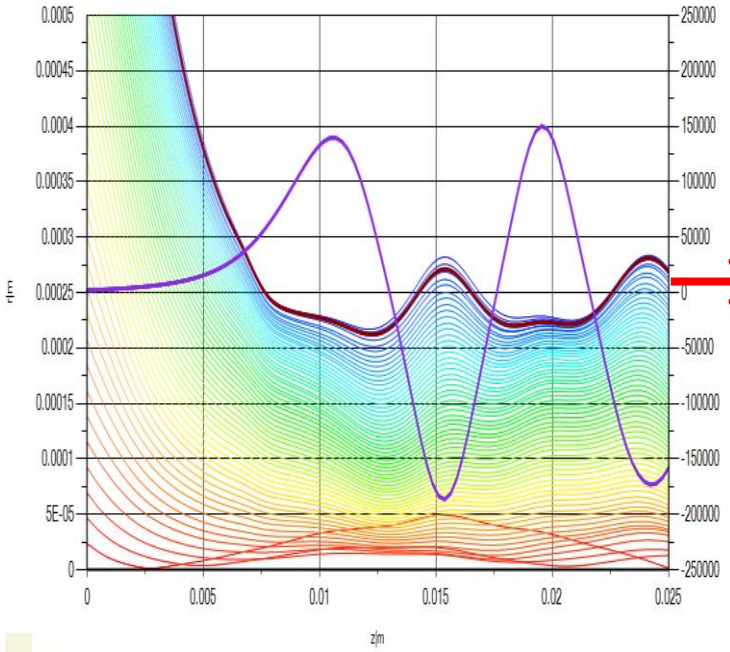


Beam injection

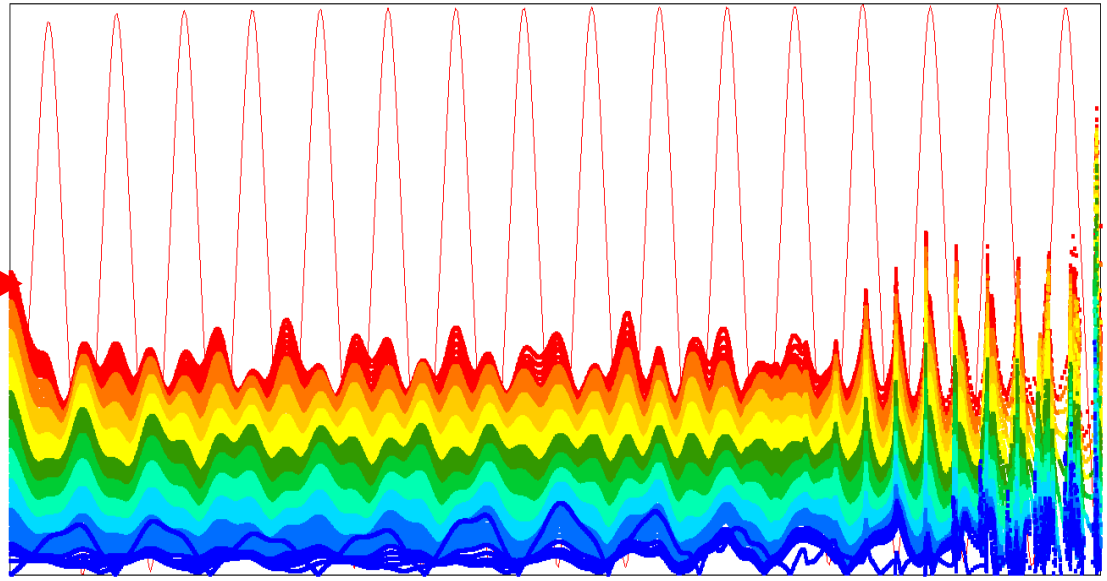


Design codes

- **Gun2 (Thales)**
  - 2.5D Gun optics, no RF



- **MVTRAD (Thales)**
  - 2.5D beam-wave interaction



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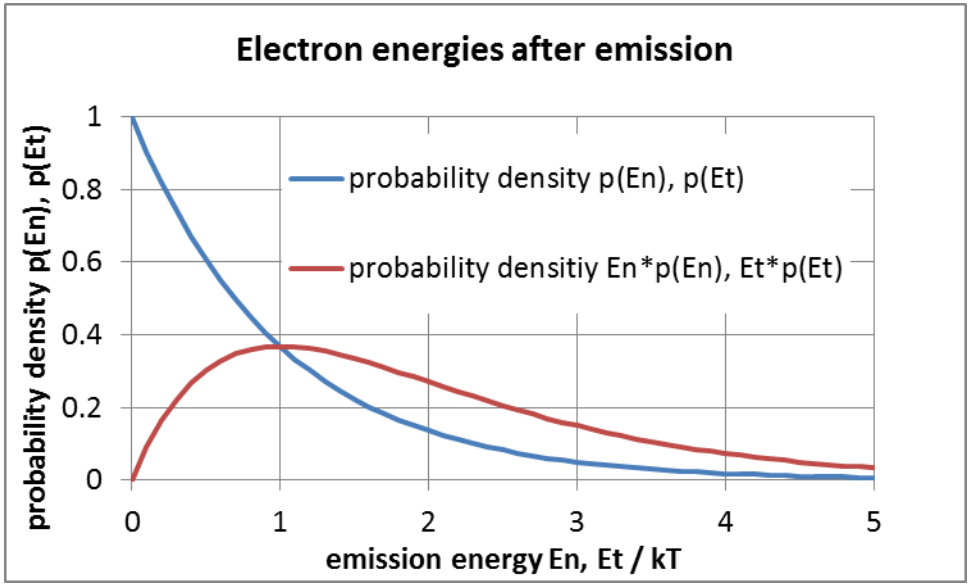
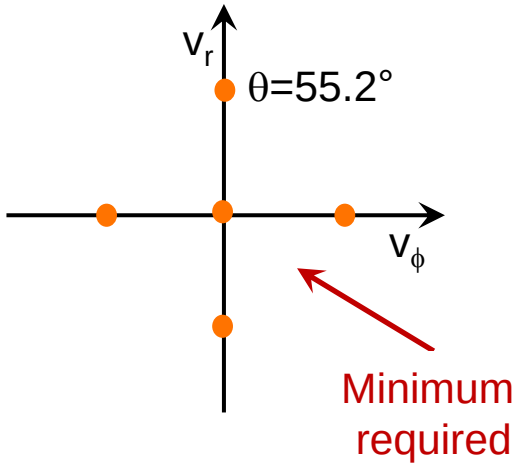
Thermal electrons

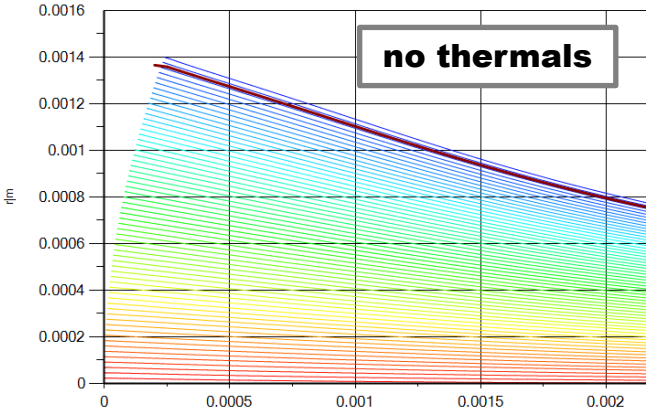
- **Non-zero initial kinetic energy of electrons (cathode normal and transversal)**
  - $\overline{E_n} = \overline{E_t} = kT$
  - $\overline{E_n + E_t} = 2kT\ (ca.0.2eV)$
- **Current density distribution according to Lambert's Law**
  - $J(\theta) = J_0 \frac{\cos\theta}{\pi}$

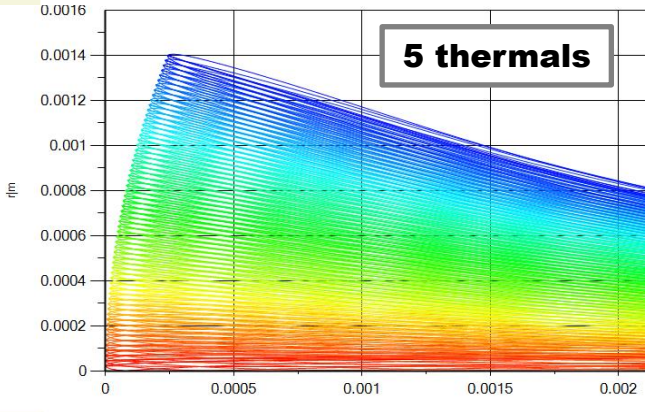


Discretization of emission energies

- **Multiple emitted particles per emission point (e.g. 5)**
- **Equal emission energy (2kT) and equal charge per particle**
- **Varying angles with respect to cathode normal, constrained by Lambert's Law**







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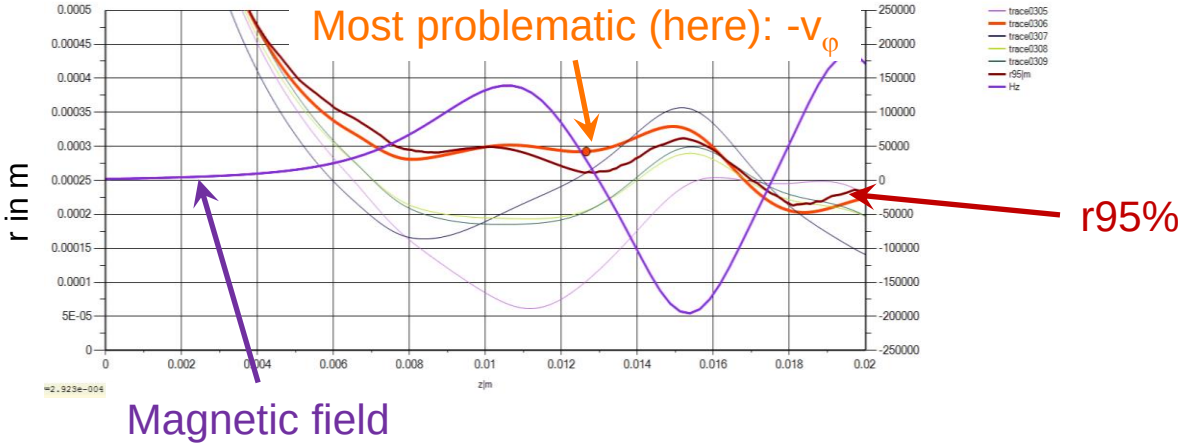
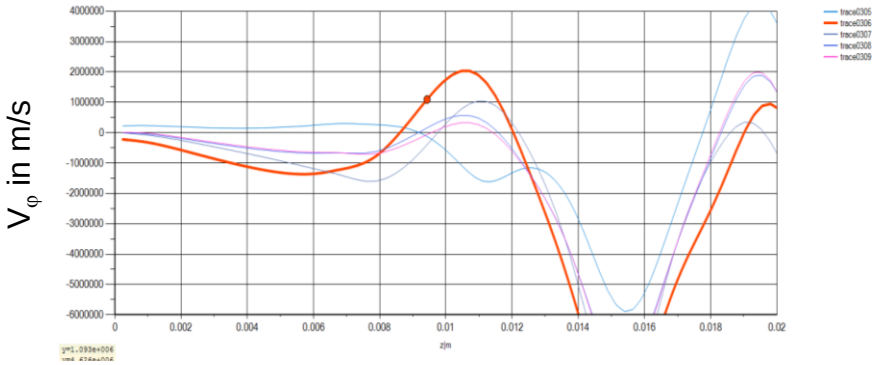
Case study

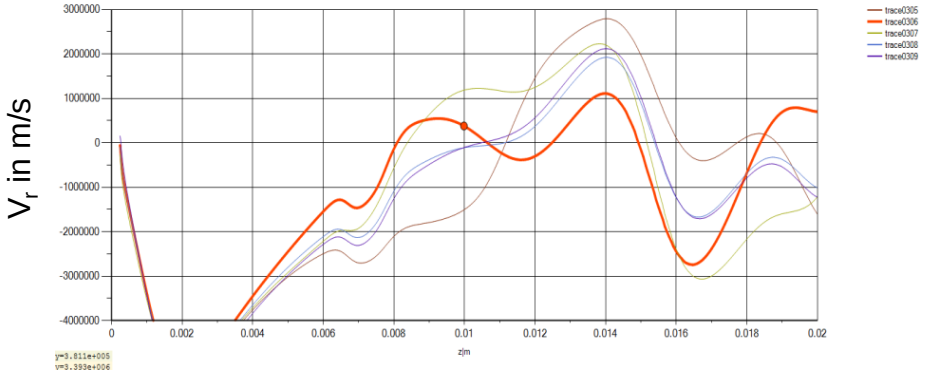
- **Satellite communication TWT design study**
- **CW tube (no gridded gun)**
- **Beam area compression ~50**
- **Beam efficiency ~32% (high linearity)**
- **Target beam fill factor 40%**
- **PPM peak field ~0.3T**

Inhomogeneous thermal beam

- **Very different conditions at first magnet for different electron „classes“ (+/- v_r, v_φ)**
- **No common perfect solution**







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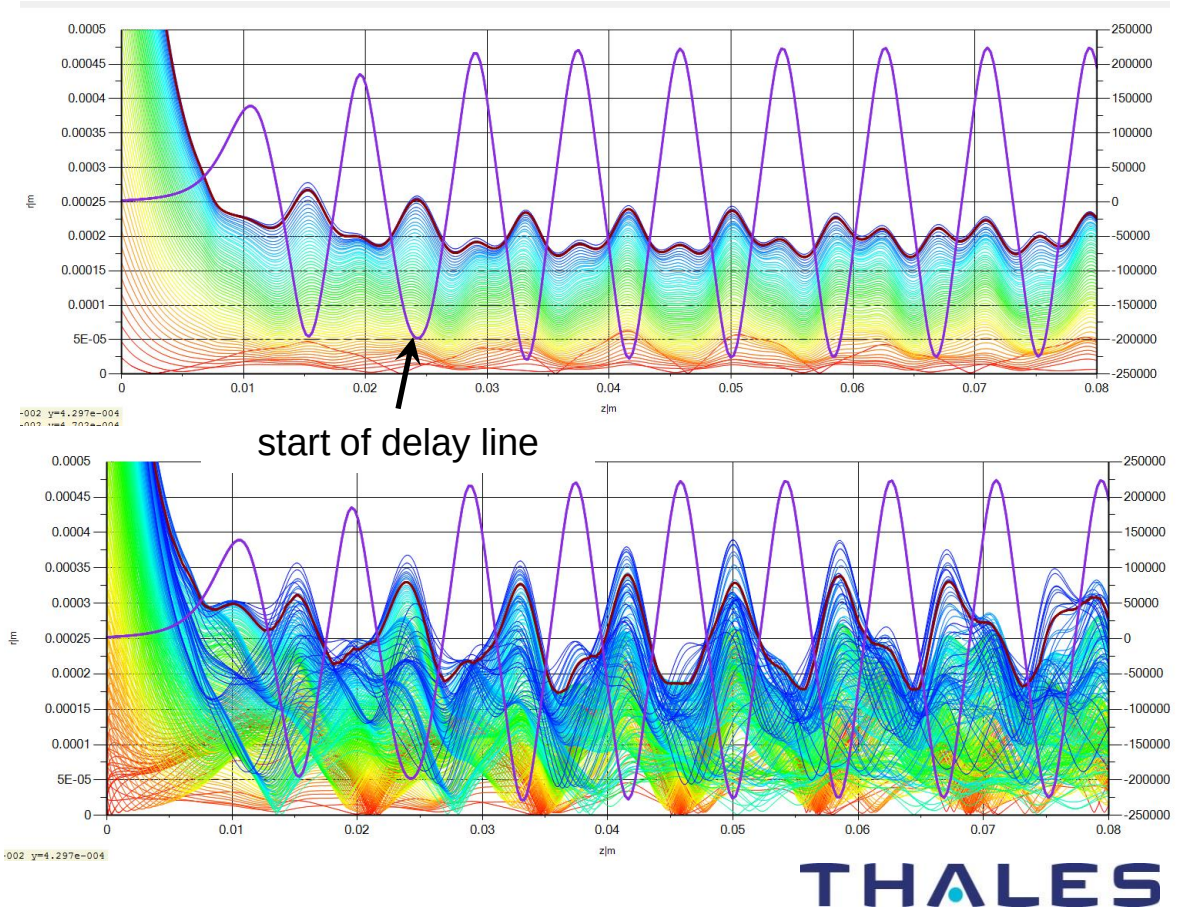
Effect of thermal electrons on beam diameter

- **Non-thermal beam well focused**
- **Beam diameter significantly increased by thermal electrons**



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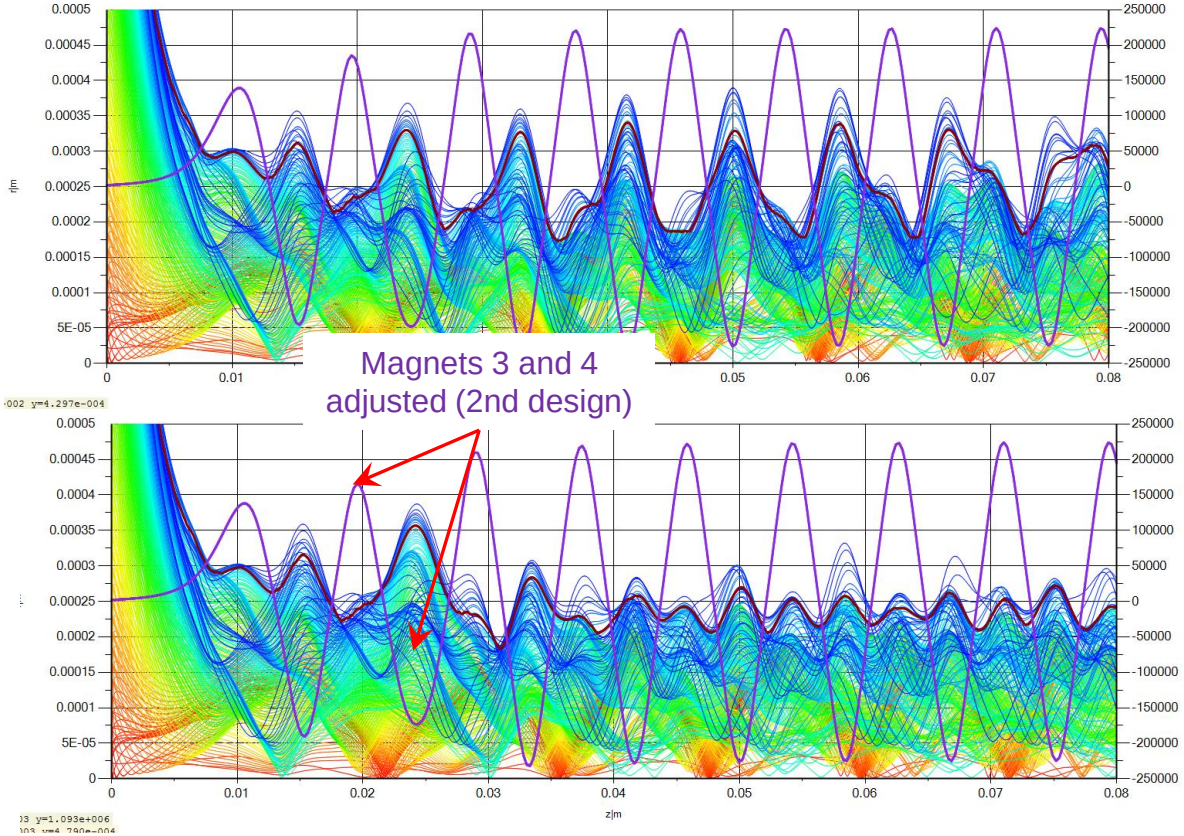
Thermal balancing in zero drive

- **Goal: similar focusing for all „classes“**
- **If possible, keep cathode field and PPM strength unchanged**
- **Trial-and-error process**
- **Quality of non-thermal and thermal focusing only loosely correlated**



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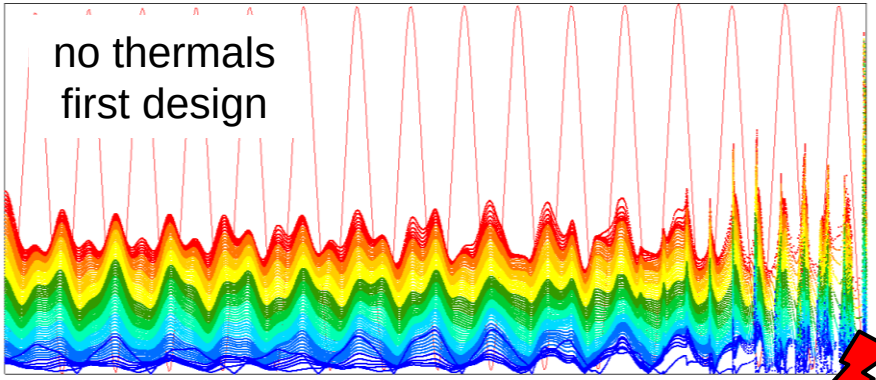
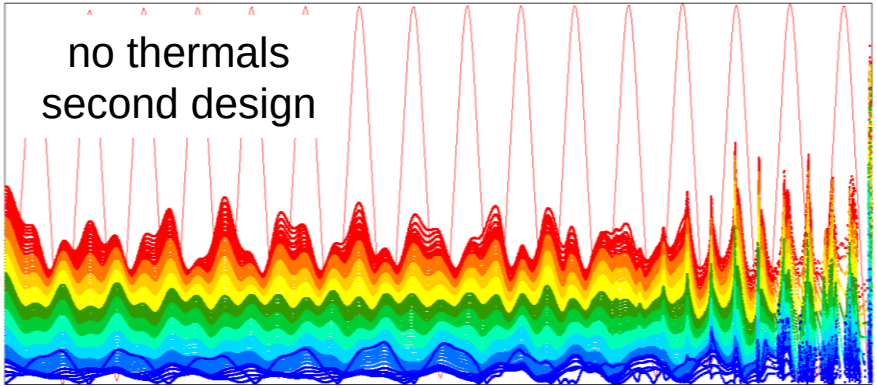
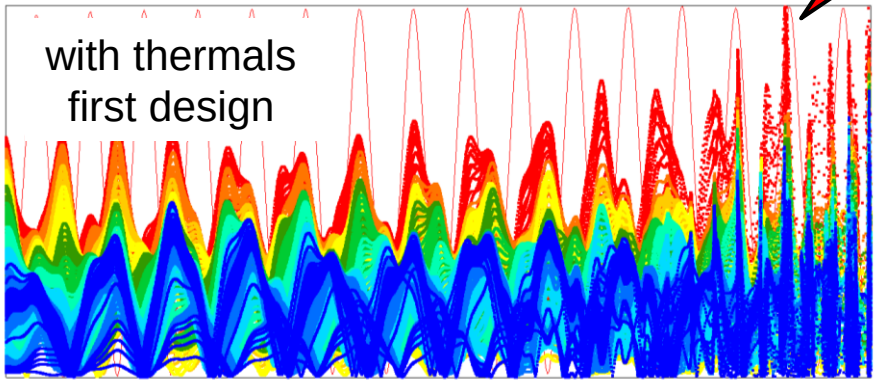
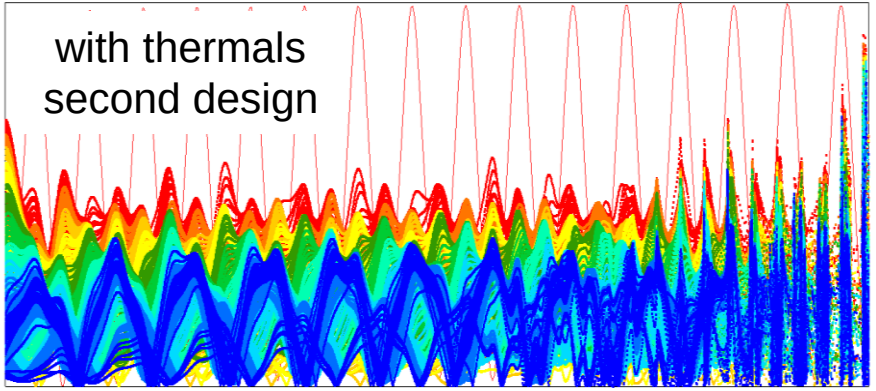
Behavior with rf drive



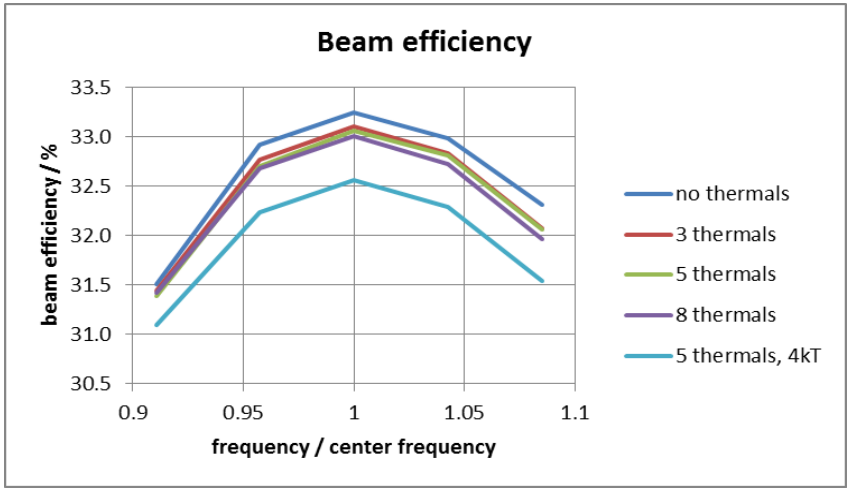


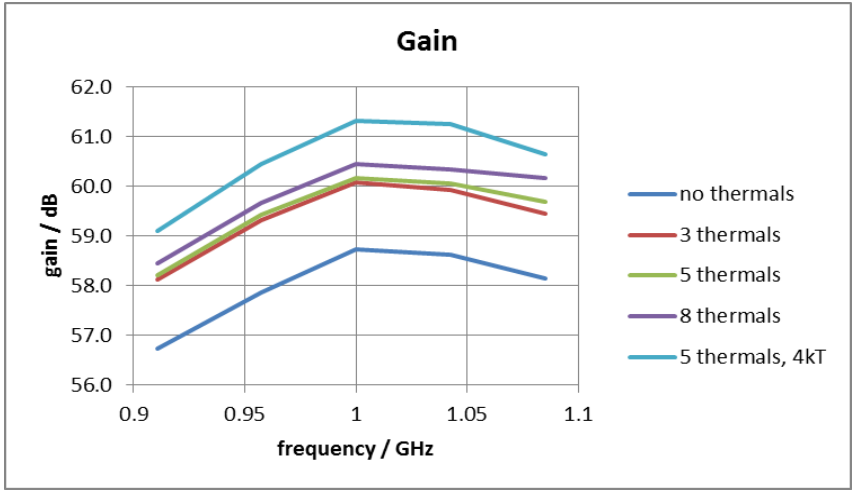




Sensitivity of tube parameters to thermals

- **Negligible effect on beam efficiency**
- **Small effect on gain (~1.5dB)**





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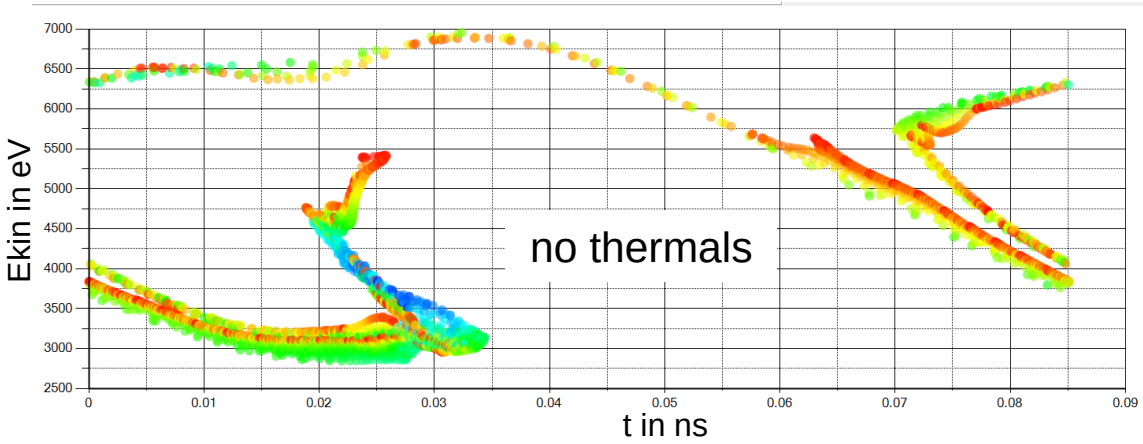
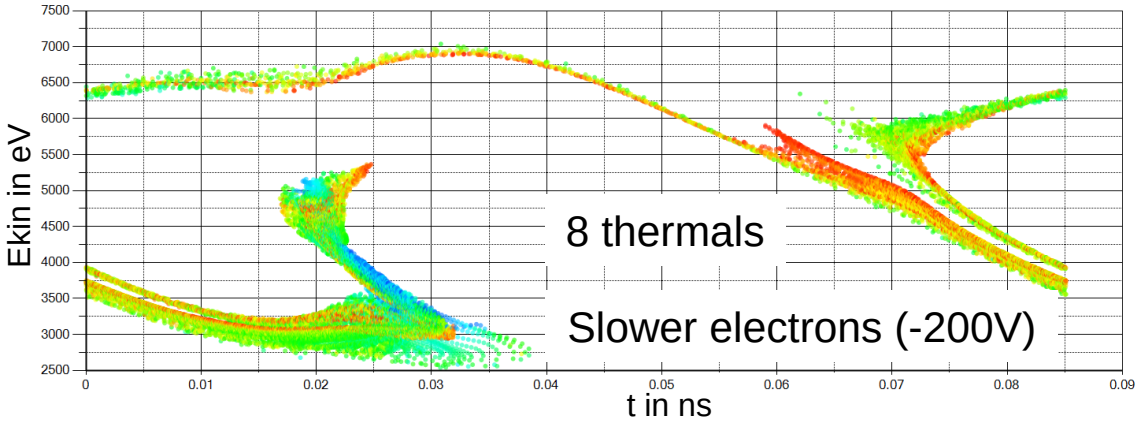
Sensitivity of tube parameters to thermals

- **Little effect on the electron velocity spectrum at output**
- **Spectrum slightly widens (ca. 200V)**





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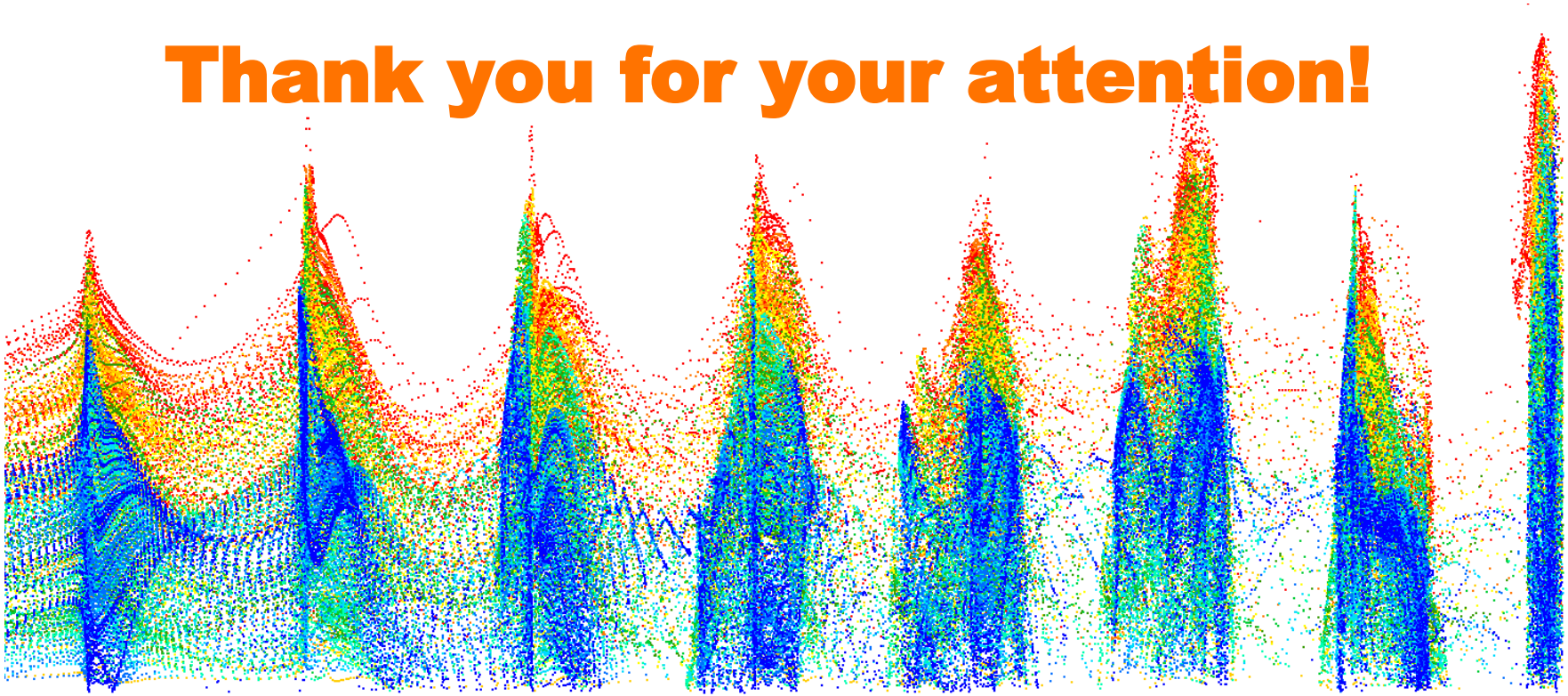
Conclusions

- **Accurate prediction of beam focusing requires chaining of Gun and interaction simulation tools**
- **Predictive value of the simulation significantly improved by adding thermal electrons**
- **Thermal focusing very sensitive to the first PPM magnets**

Thank you for your attention!



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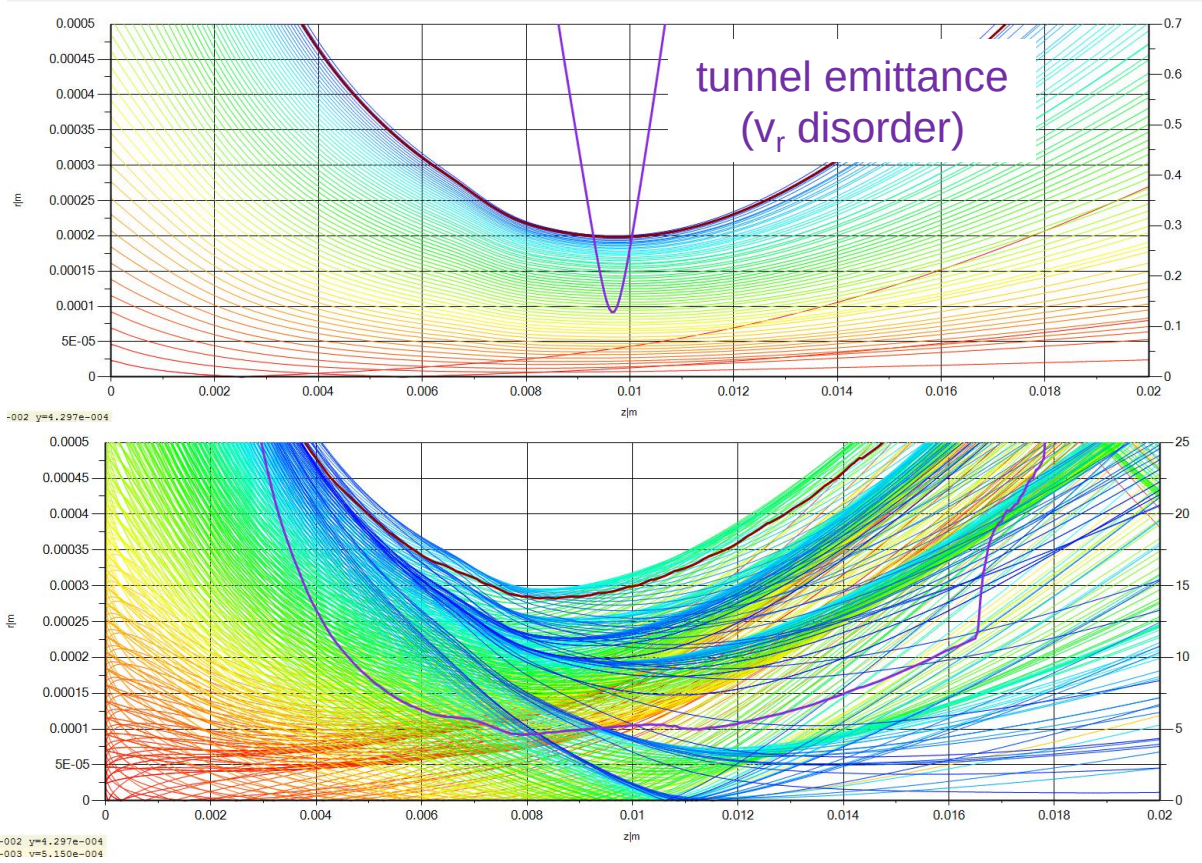
Design of focusing system

- **Zero-drive**
  - Choice of beam radius, overall focusing field, cathode field
  - Gun optics code (Gun2) for beam injection design
- **Beam extension under drive**
  - Beam-wave interaction code (MVTRAD)
  - Ideal beam, or chaining with gun code
- **Inclusion of thermal electrons**
  - Initial transverse velocities in gun code
  - Chaining with interaction code

Thermal electrons without focusing field

- **No focusing field**
- **5 particles per point (5 „classes)**
- **Radial and azimuthal velocity components at beam waist**
- **Disparate starting conditions for PPM focusing**
- **Effects depend on beam area compression**



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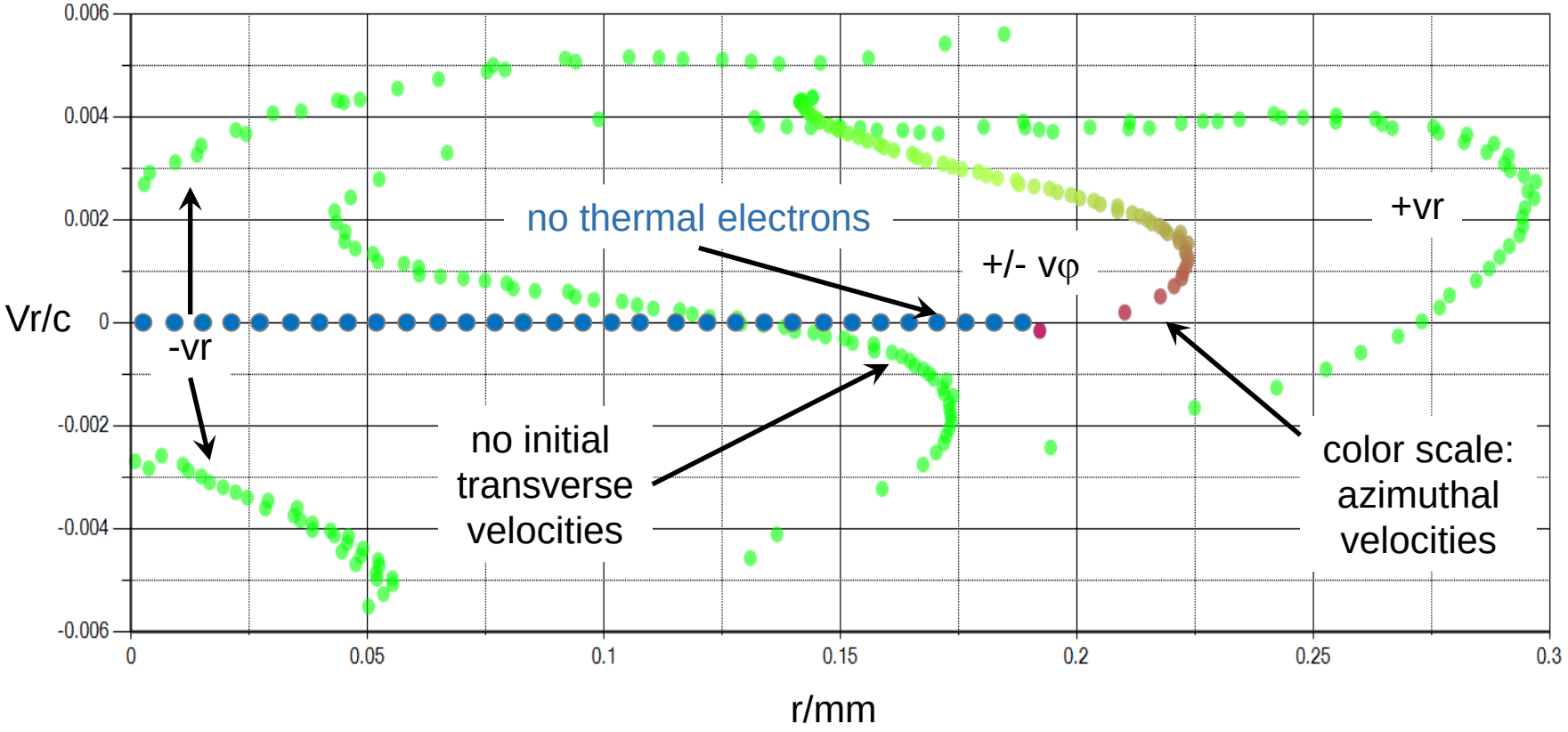
Velocities at beam waist, no focusing field

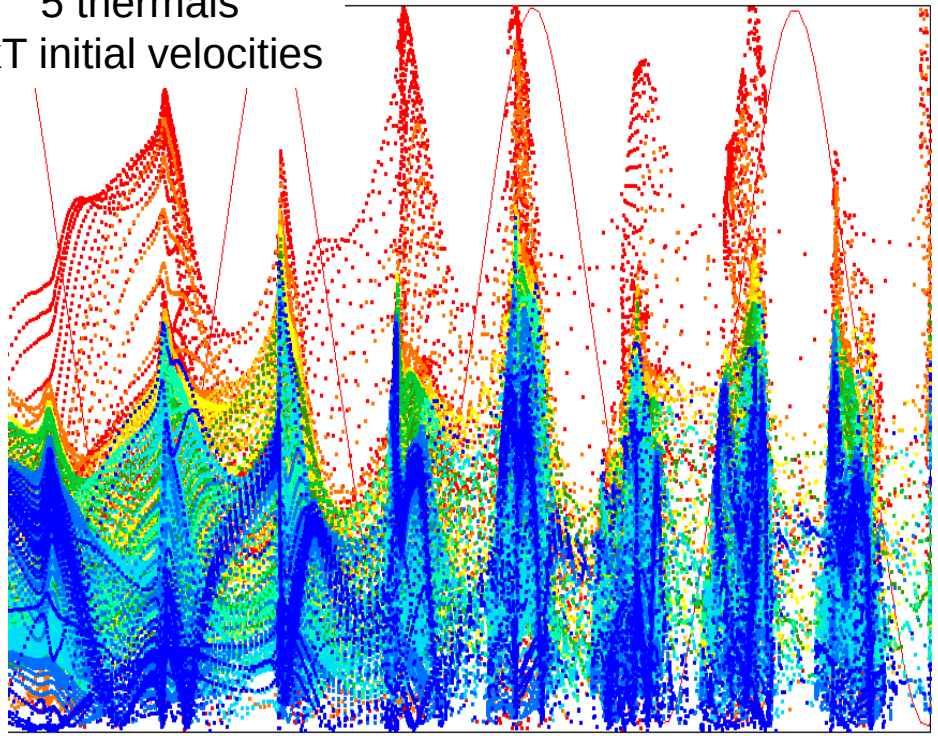


Sensitivity of body current to thermal discretization

- **First design (significant body current)**
- **5 thermals seem sufficient**

Discretization	Body current / %
No thermals	0
3 thermals	1.14
5 thermals	1.49
8 thermals	1.55
5 thermals, 4kT	3.22

5 thermals
4kT initial velocities



Design considerations

- **Focusing critically dependent on beam injection design**
- **Focusing sensitive to accurate modeling of magnetic field in beam injection area**
- **Field on cathode helpful to focus electrons with initial v_r, strong beam rotation in gun helpful with initial v_φ**
- **Non-thermal beam quality and thermal beam quality only loosely correlated…**
- **… but zero drive and RF drive beam quality strongly correlated**

Design codes

- **Gun2 (Thales): Electron gun optics, zero-drive focusing**
  - 2.5D Gun optics, self-consistent static particle trajectory solver
  - Space-charge limited emission model (Child-Langmuir)
  - Finite-difference space charge field calculation, fixed-point iteration
- **MVTRAD (Thales): Focusing with RF drive**
  - 2.5D self-consistent beam-wave interaction
  - Electric field: Superposition of delay line field and space charge field
  - Frequency domain, finite-element, particle-in-cell solver
- **Auxiliary tools (e.g. magnetostatic field computation)**