Particle-In-Cell Simulation Tools for Design and Optimization of High Power CW Gyrotron Oscillators

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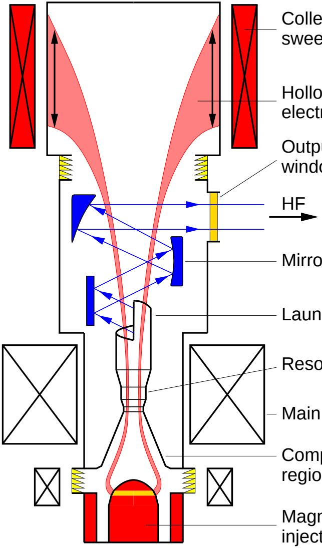
Outline

Introduction

- Numerical simulation tools are indispensable for the design and optimisation of high power CW Gyrotrons
  Examples:
  140 GHz 1 MW Gyrotron for W7-X
  170 GHz 2 MW coaxial Gyrotron for ITER
- The following parts require the use of Particle-in-Cell (PIC) simulation tools:

1. Magnetron Injection Gun (MIG).
   Goal: exact beam parameters (position, velocity ratio), low energy- and velocity spread, no instabilities.
2. Collector.
   Goal: acceptable average and peak power densities on the collector wall. (e.g. 2.4 MW of dissipated power in the case of the 170 GHz 2 MW coaxial Gyrotron)

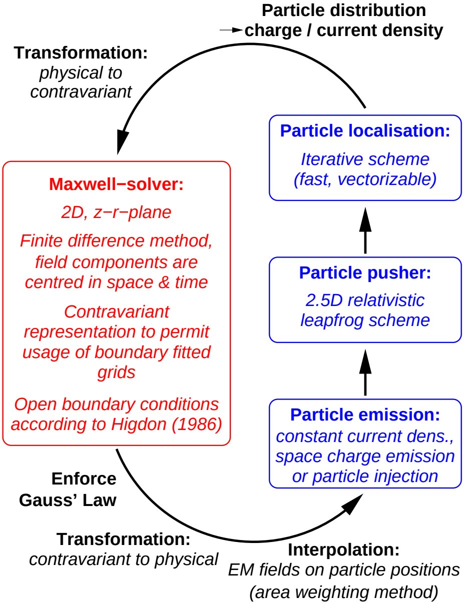


Available PIC codes at FZK

- 2.5D full electromagnetic PIC for simulation of beam instabilities.
- 2.5D electrostatic PIC for gun & collector design (quite slow).
- 2.5D raytracing code for gun & collector design (quite fast).
- 3D raytracing for collector design (with transversal sweeping magnetic field)

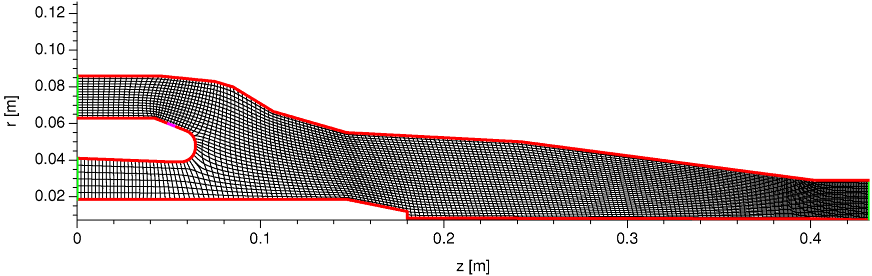
Additional tools:

- Grid generation.
- Calculation of applied magnetic field.
- Visualisation (with interactive GUI)

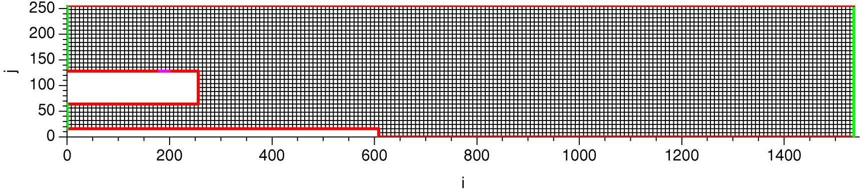


Boundary fitted (non-orthogonal) coordinates

Physical grid (for the 170 GHz, 2 MW coaxial Gyrotron):

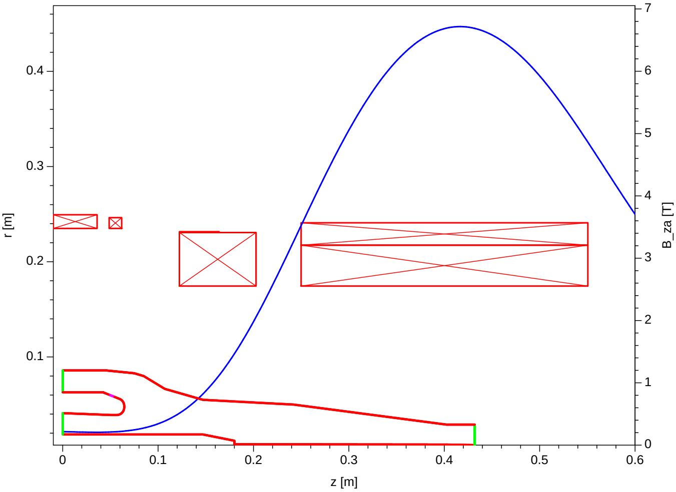


Corresponding logical grid:



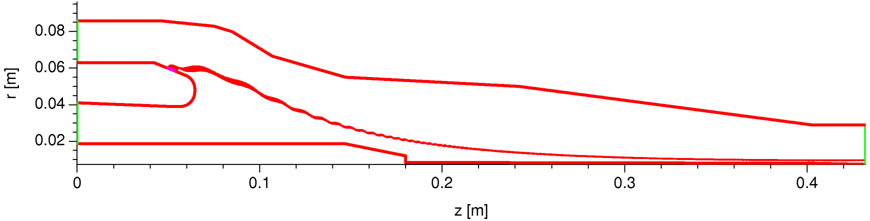
Design of Magnetron Injection Guns

Magnetic system of the 170 GHz, 2 MW coaxial Gyrotron:

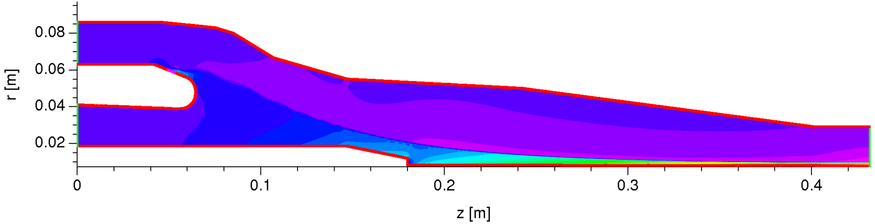


Simulation results

Particle positions:



Self-induced electric field (r-component):



Simulation results (continued)

Typical output of the ESRAY-Module (for $U = 80\,\mathrm{kV}$, $I_{beam} = 75\,\mathrm{A}$):

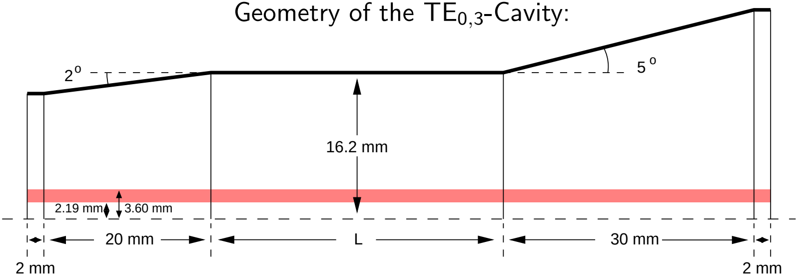
```
------------------------------------------------------------
Convergence reached (Iteration No. 13).
------------------------------------------------------------

Statistics for 144 particle(s) of type ["Electrons"]:
E_kin [keV]:  76.6869   +/- 0.0872929   (0.11383  %),  76.462    .. 76.993
alpha:        1.2936    +/- 0.074269    (5.7412   %),  1.185     .. 1.42
beta_z:       0.302348  +/- 0.0107265   (3.5477   %),  0.28435   .. 0.31828
beta_perp:    0.390321  +/- 0.00844261  (2.163    %),  0.37714   .. 0.40425
u_perp:       0.448898  +/- 0.00974868  (2.1717   %),  0.43357   .. 0.46515
u_z:          0.347721  +/- 0.0123075   (3.5395   %),  0.32701   .. 0.36596
gamma:        1.15007   +/- 0.000170828 (0.014854 %),  1.1496    .. 1.1507
r [m]:        0.0100036 +/- 0.000111635 (1.1159   %),  0.0097675 .. 0.010256
P_total=5.75152e+06W,  q_total=-1.5e-11As,  I_total=-75A.

Dynamic array memory (1D/2D/sum):   1.281M,  34.703M,  35.985M.

Total CPU:                          34.130s     0:00:34  100.000%
Total elapsed (wall clock):         34.179s     0:00:34  100.144%
```

Simulation of the Gyrotron interaction

The simulation of the Gyrotron interaction is a good verification method:

- The Gyrotron interaction is a (wanted) time-dependent instability.
- We have numerical tools to simulate Gyrotron resonators.
- Even the transient behaviour can be calculated with SELFT, a time-dependent multimode code (S. Kern, 1996)

Geometry of the $TE_{0,3}$-Cavity:



Simulation of the Gyrotron interaction: Background

Electrons with relativistic Cyclotron frequency

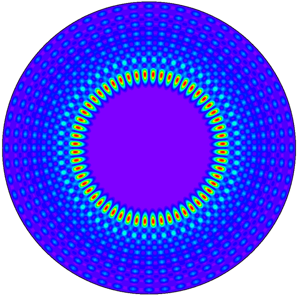
$$\Omega_c = \frac{eB}{m_0\gamma} \approx 2\pi \frac{28\,\mathrm{GHz}\cdot B/\mathrm{T}}{\gamma},$$

$$\gamma = \frac{1}{\sqrt{1-\left(\frac{v_\perp}{c}\right)^2-\left(\frac{v_\parallel}{c}\right)^2}} \approx 1 + \frac{eU}{511\,\mathrm{keV}}$$

are accelerated / decelerated by the E_φ-component of the oscillating $TE_{m,n}$-mode.

Consequence: *azimuthal phase bunching* and energy transfer to the RF-field, if $\Omega_{rf} \gtrsim \Omega_c$.

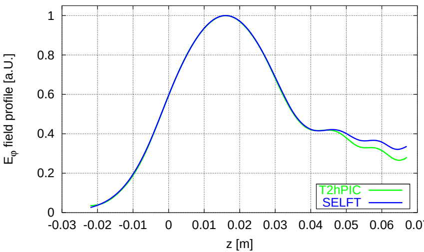
$\mathrm{TE}_{28,8}$-mode:



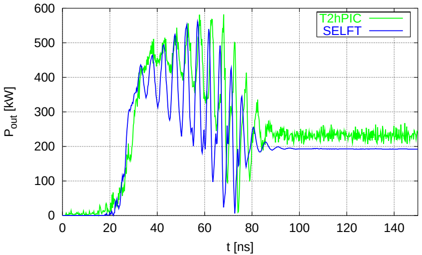
(140 GHz, W7-X Gyrotron)

Simulation of the Gyrotron interaction: Results

Stationary state:
($L = 35\,\text{mm},\ I_b = 15\,\text{A},\ \alpha = 1.5$)



Transient behaviour:
($L = 65\,\text{mm},\ I_b = 20\,\text{A},\ \alpha = 1.0$)



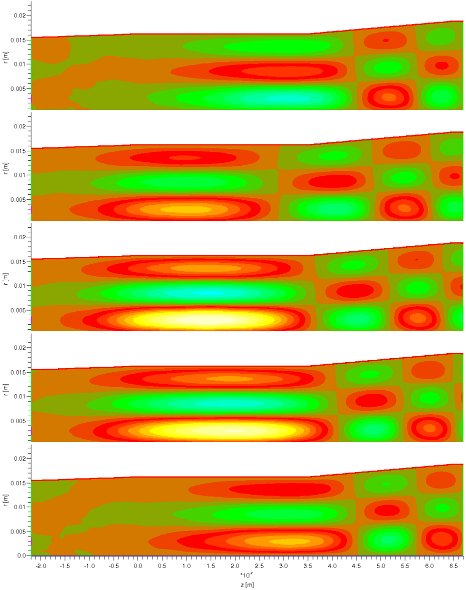
SELFT vs. PIC:
$U_b = 79.0\,\text{kV}$,
$B_R = 1.16\,\text{T}$

$^{*)}$ backward-wave, transient state.
$^{**)}$ forward-wave, transient state.

				SELFT		T2hPIC	
L [mm]	I_b [A]	α	Mode	P_{out} [kW]	f [GHz]	P_{out} [kW]	f [GHz]
35	15	1.5	$TE_{0,3,1}$	583	30.12	**578**	**30.10**
35	20	1.5	$TE_{0,3,1}$	708	30.12	**718**	**30.10**
35	20	1.5	$TE_{0,2}{}^{*}$	57	24.0	**52**	**24.8**
65	20	1.0	$TE_{0,3,1}$	197	30.05	**232**	**30.03**
65	20	1.0	$TE_{0,3,2}{}^{**}$	448	30.27	**466**	**30.25**

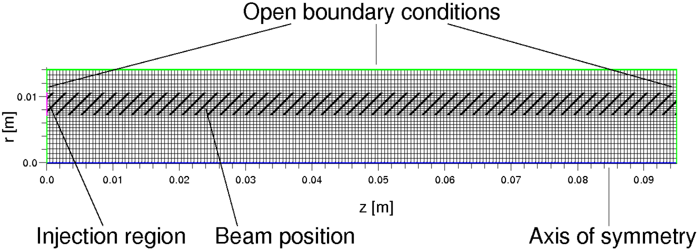
Development of E_φ in steps of $T_{HF}/8$

($L = 35\,\mathrm{mm}$, $I_b = 20\,\mathrm{A}$, $\alpha = 1.5$, $|E_\varphi| < 7.5\,\mathrm{MVm^{-1}}$):



Time dependent simulation of beam instabilities

Structure of the simulation grid
(designed for an applied magnetic field of 1 T)



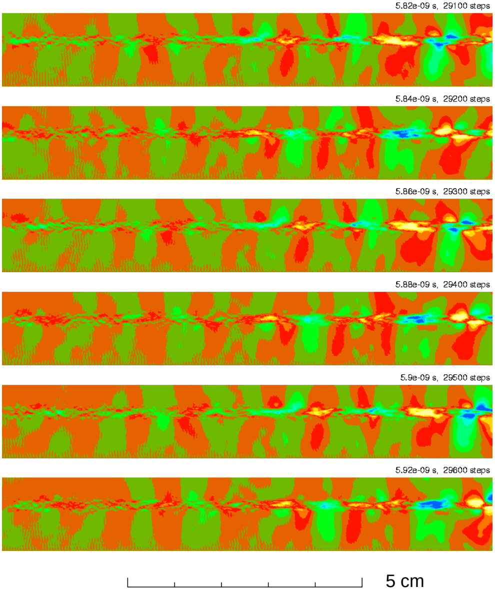
Grid length:	9.5 cm
Number of grid cells:	768×112
Beam radius:	$10.7\, r_L$
Beam thickness:	$4\, r_L$
Time step:	0.2 ps
Number of macro particles:	200 000 . . . 250 000 (6 . . . 8 per cell)

Results of PIC simulation

Development of $E_r(z, r)$ in steps of $20\,\text{ps} \approx T_c/2$

$I = 100\,\text{A}$,
$\alpha = 1.5$,
flat beam profile,
no $E_{r,stat}$,
no TE-polarisation

graphics range: $|E_r| \leq 10^5\,\text{V/m}$



Analytic model of the Electrostatic Cyclotron Instability

Combining Ampères law, Faraday's law and $\vec{j} = \overleftrightarrow{\sigma}\vec{E}$ in Fourier space, we obtain the dispersion relation

$$\vec{k} \times (\vec{k} \times \vec{E}) = -\frac{\omega^2}{c^2} \underbrace{\left(\overleftrightarrow{I} + \frac{i}{\omega \epsilon_0} \overleftrightarrow{\sigma} \right)}_{\overleftrightarrow{\epsilon}} \vec{E}.$$

$\overleftrightarrow{\epsilon}$ is the dielectric tensor of the magnetised relativistic plasma. Example:

$$\epsilon_{xx} = 1 - \frac{2\pi \tilde{\omega}_p^2}{\omega} \int_0^\infty u_\perp du_\perp \int_{-\infty}^{\infty} du_z \cdot \sum_{s=-\infty}^{\infty} \frac{u_\perp \left[(1 - u_z) \frac{\partial \hat{f}_0}{\partial u_\perp} + \frac{k_z u_\perp}{\omega \gamma} \frac{\partial \hat{f}_0}{\partial u_z} \right] \left[\frac{s J_s(k_x r_L)}{k_x r_L} \right]^2}{k_z u_z - \omega \gamma + s \Omega_0}.$$

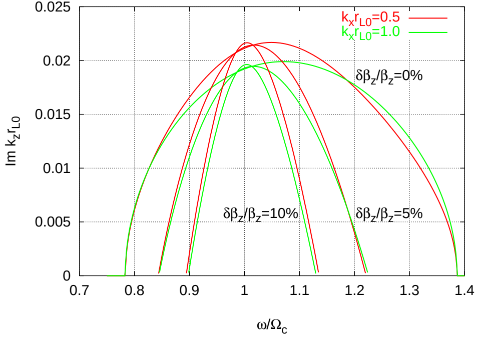
With $\vec{k} = (k_x, 0, k_z)^T$, $E_x \neq 0$ and $E_z \neq 0$ and $E_y = 0$ we obtain

$$k_x^2 \epsilon_{xx} + k_x k_z (\epsilon_{xz} + \epsilon_{zx}) + k_z^2 \epsilon_{zz} - \frac{\omega^2}{c^2} (\epsilon_{xx} \epsilon_{zz} - \epsilon_{xz} \epsilon_{zx}) = 0.$$

Beside other restrictions this dispersion relation is only valid for TM-polarisation (E_x, E_z, B_y), effects of TE-polarisation are ignored.

Comparison analytic model — PIC simulation

Influence of velocity spread (analytic model):



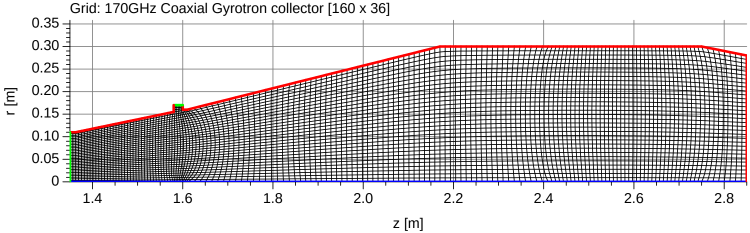
PIC-Results ($I = 100A$, $\alpha = 1.5$) $\longrightarrow$

$\delta\alpha/\alpha_0$=1%

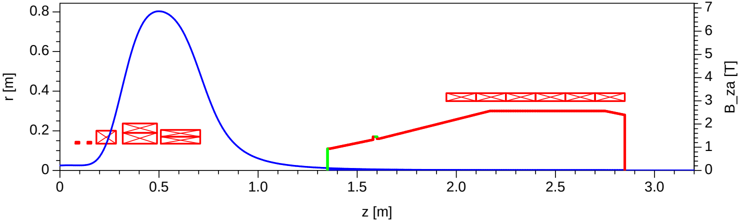
Collector simulation: conventional sweeping

Proposed collector for the 170 GHz, 2 MW Coaxial Gyrotron

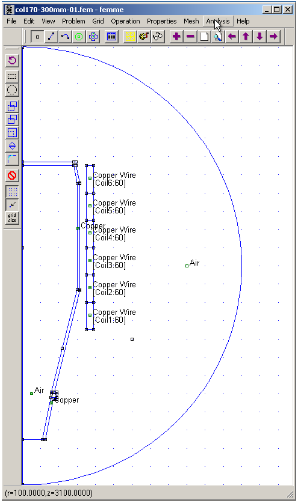
Collector Geometry



Magnetic System



FEMM setup and results

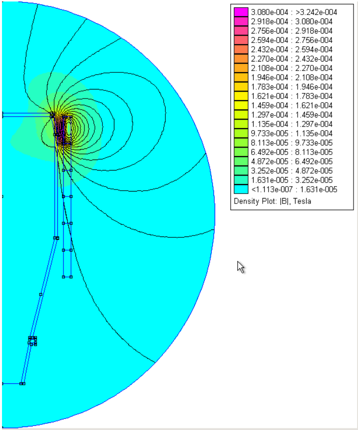


More than 110000 elements are used.

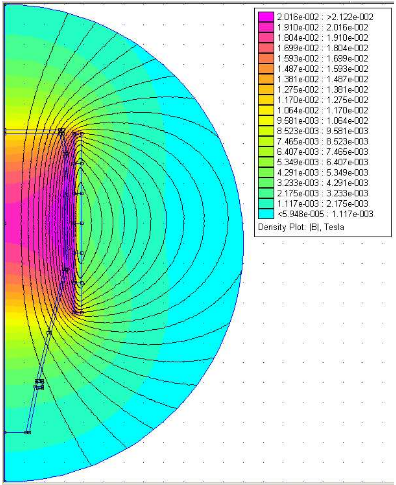
Input Parameters:
Wall thickness:
20mm (top plate),
15mm (rest)

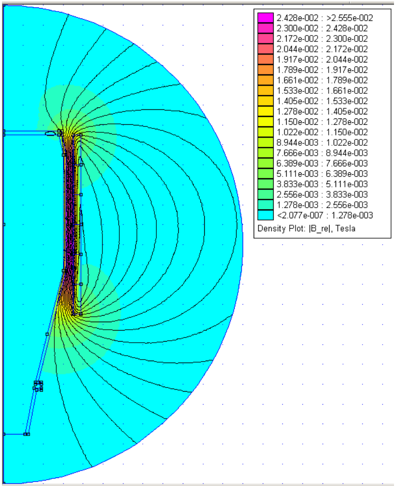
$I_{AC} = 1\,A$,
60 loops per coil

Results show no significant difference to results obtained with ANSYS.



Comparison static vs. harmonic solution (f=7Hz, I=50A)



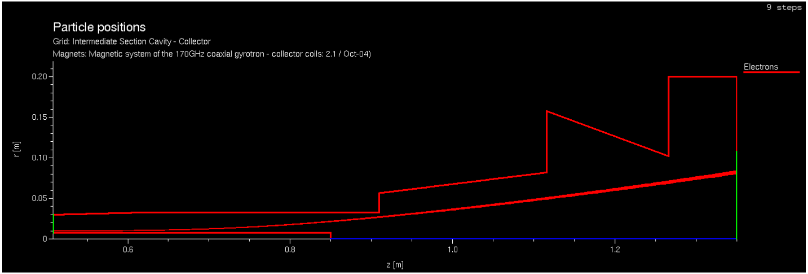


Max. magnetic flux density on axis:

$B_{z,max} = 19.42\,\mathrm{mT}$ (static)

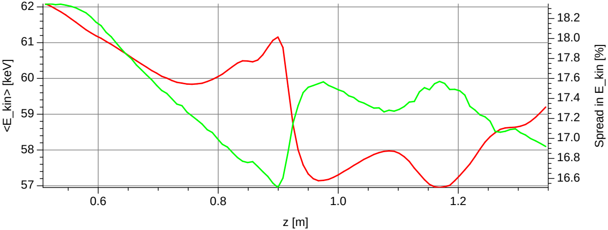
$B_{z,max} = 0.15 - i\,3.24\,\mathrm{mT}$ (harm.)

Modeling of the launcher – mirrorbox section

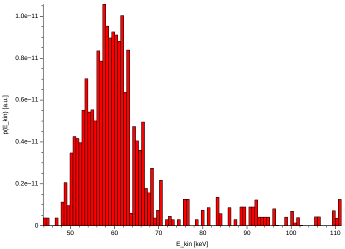


300 input particles from self consistent cavity simulation (mono-mode)
Beam parameters: $E_{kin} = 87.7\,\text{keV}$, $I_b = 80\,\text{A}$
Particles leaving the simulation region will be stored and injected in the collector simulation
→ huge speed-up

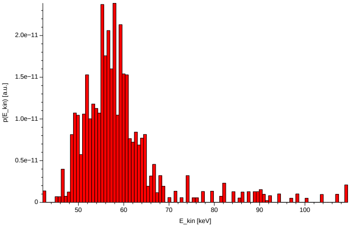
Average of E_{kin} (red) and spread in E_{kin} (green) vs. z



Distribution of E_{kin} at cavity exit



Distribution of E_{kin} at collector entrance

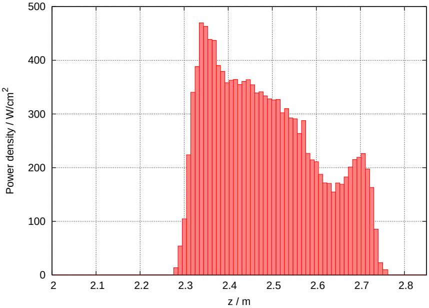


Simulation results (averaged power density on collector wall)

Common parameters: $I_b = 80\,\text{A},\ U_{depr} = 33.1\,\text{kV},\ P_{load} = 2.4\,\text{MW}$

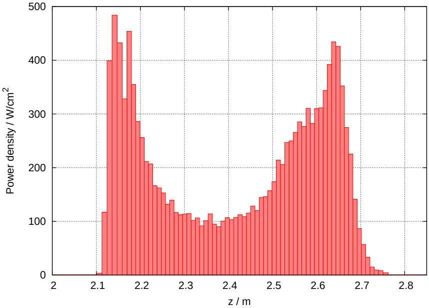
Average of instantaneous power density distributions
for all phases of the applied coil currents $0 \le \Theta < 2\pi$

$f_{sweep} = 7\,\text{Hz}$



$I_{sweep,AC} = [40, 40, 20, 20, 40, 20]\,\text{A}$
$I_{sweep,DC} = 0\,\text{A}$
$T_{peak} = 280\,^\circ\text{C},\ P_{ps} = 0.38\,\text{kW}\ (0.58\,\text{kVA})$

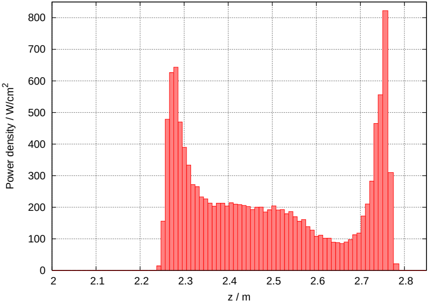
$f_{sweep} = 20\,\text{Hz}$



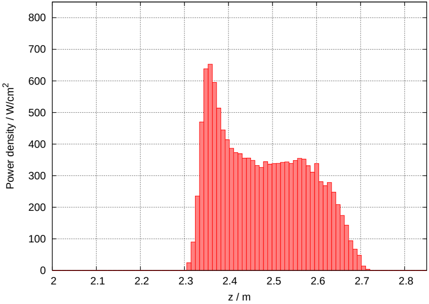
$I_{sweep,AC} = [250, 250, 250, 100, 100, 100]\,\text{A}$
$I_{sweep,DC} = -0.0025\ I_{sweep,AC}$
$T_{peak} = 220\,^\circ\text{C},\ P_{ps} = 15.5\,\text{kW}\ (50.9\,\text{kVA})$

Influence of the hot collector wall

$$T = 150\,^\circ\mathrm{C}, \quad \sigma = 38\,\mathrm{MS/m} \quad (\text{instead of } 58\,\mathrm{MS/m} \text{ at } 20\,^\circ\mathrm{C}), \quad f_{sweep} = 7\,\mathrm{Hz}$$



$I_{sweep,AC} = [40, 40, 20, 20, 40, 20]$ A
$I_{sweep,DC} = 0$ A

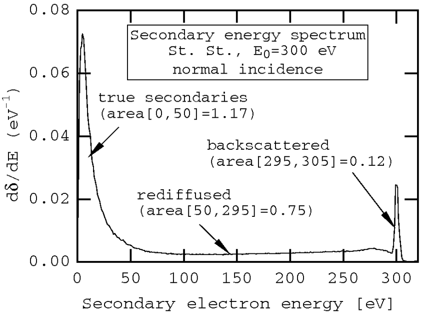


$I_{sweep,AC} = [24, 24, 12, 12, 24, 12]$ A
$I_{sweep,DC} = 0$ A

Modeling of secondary emission

Theoretical models of secondary emission distinguish between three different types of secondaries (where E_0 is the energy of the incident electron):

- So-called "true-secondary electrons" with low kinetic energy (up to $\sim 50\,\mathrm{eV}$) and a yield factor that is relatively high.
- Inelastically backscattered ("rediffused") electrons with a kinetic energy in the range from zero to E_0 and a moderate yield factor.
- Elastically backscattered electrons with high kinetic energy close to E_0 but a relative low yield factor.



Main reference:

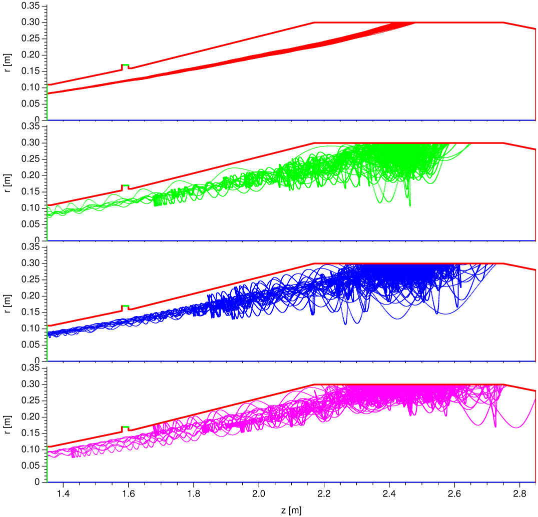
M.A. Furman and M.T.F. Pivi, *"Probabilistic model for the simulation of secondary electron emission"*, Physical Review Special Topics, Accelerators and Beams, Vol. 5, 2002.

Secondary Emission: Simulation results

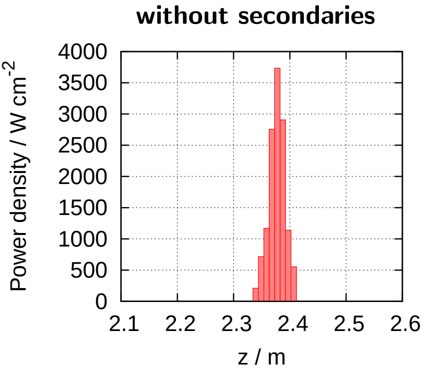
Particle plots of the incident electron beam and generations #1 to #3 of secondary electrons (from top to bottom).

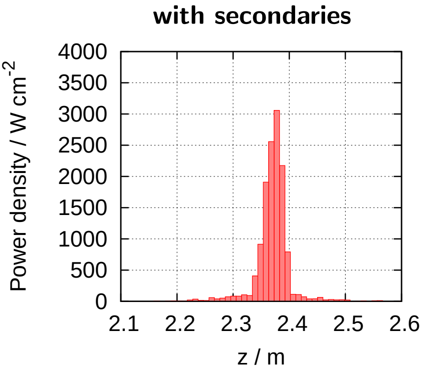
Parameters:

- 80 A beam current
- 33 kV depression voltage
- 2.4 MW power on collector wall
- Sweeping coil currents: 40/40/20/20/40/20 A
- Phase of applied sweeping coil current: 0 deg.



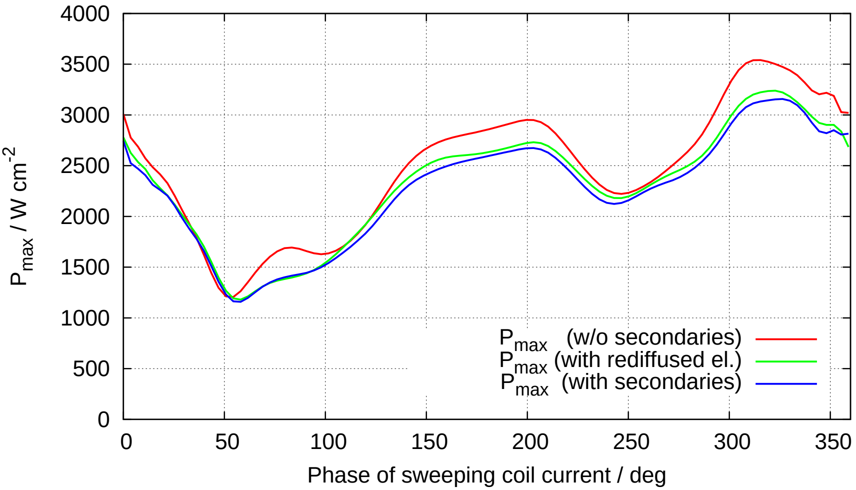
Instantaneous power density on the collector wall





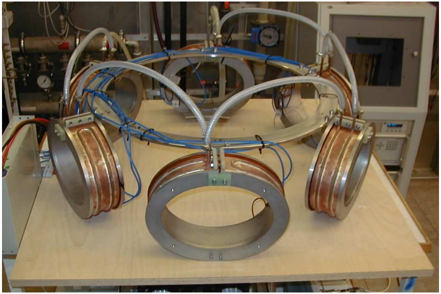
- Maximum instantaneous power density at a sweeping phase of 315°.
- A non-negligible reduction of the instantaneous power density can be observed.

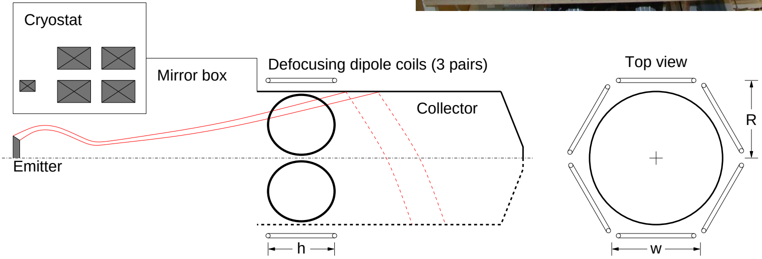
Maximum instantaneous power density vs. sweeping phase



Collector simulation: sweeping with rotating magnetic field

- Uses three pairs of elliptical dipole coils (laterally mounted).
- Geometry of idealised "single loop" coils: $R = 376\,\text{mm}$, $w = 277\,\text{mm}$, $h = 201\,\text{mm}$.
- Excitation currents: sinusoidal, $f = 50\,\text{Hz}$, phase shifted by 60°, $I_{max} = 7\,\text{kA}$.
- Advantages: Smaller influence of eddy currents, higher sweeping frequency, low cost power supply (3-phase transformer)

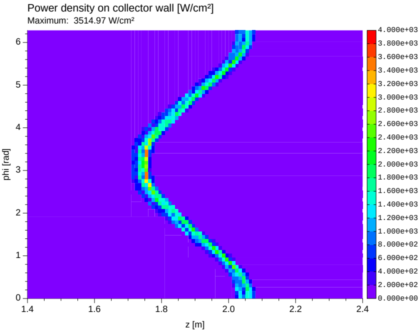




Instantaneous power density on the collector wall

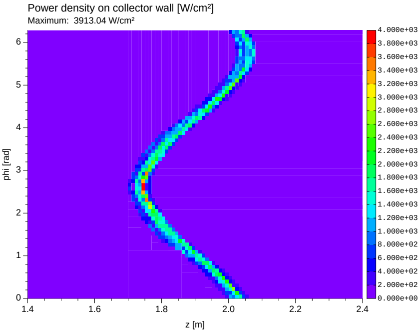
$I_{loop} = 5\,\mathrm{kA}$

$\Theta = 0^\circ$



$P_{max} = 3515\,\mathrm{W/cm^2}$

$\Theta = 30^\circ$



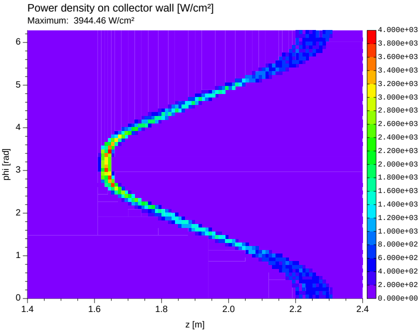
$P_{max} = 3913\,\mathrm{W/cm^2}$

Total power on collector wall: 1 MW

Instantaneous power density on the collector wall

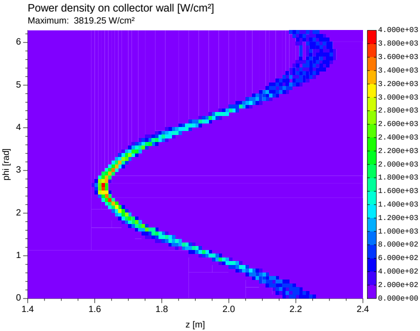
$I_{loop} = 10\,\text{kA}$

$\Theta = 0°$



$P_{max} = 3944\,\text{W/cm}^2$

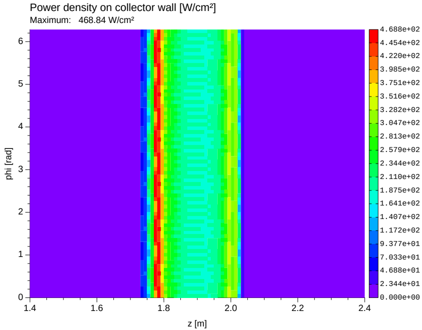
$\Theta = 30°$



$P_{max} = 3819\,\text{W/cm}^2$

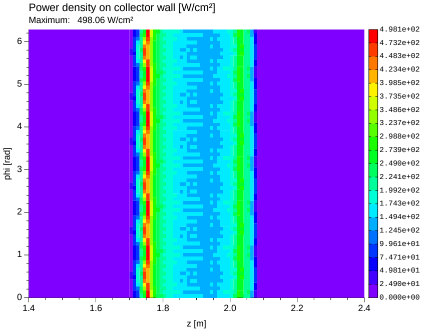
Averaged power density on the collector wall

$I_{loop} = 4\,\mathrm{kA}$



$P_{max} = 469\,\mathrm{W/cm^2}$

$I_{loop} = 5\,\mathrm{kA}$

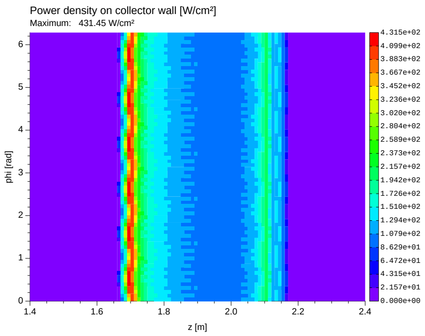


$P_{max} = 498\,\mathrm{W/cm^2}$

P_{max} corresponds to the averaged peak power density obtained in the case of conventional sweeping.

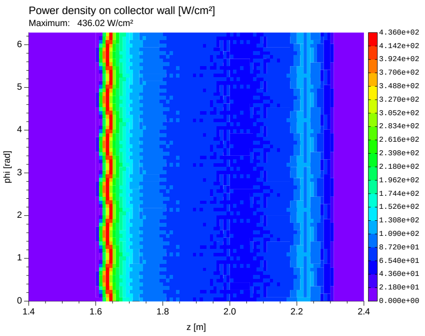
Averaged power density on the collector wall

$I_{loop} = 7\,\mathrm{kA}$



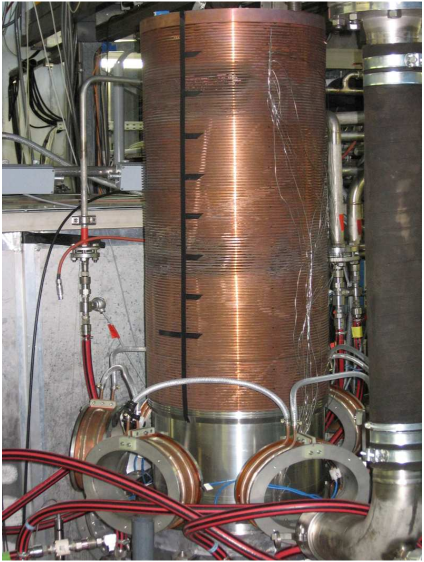
$P_{max} = 431\,\mathrm{W/cm^2}$

$I_{loop} = 10\,\mathrm{kA}$



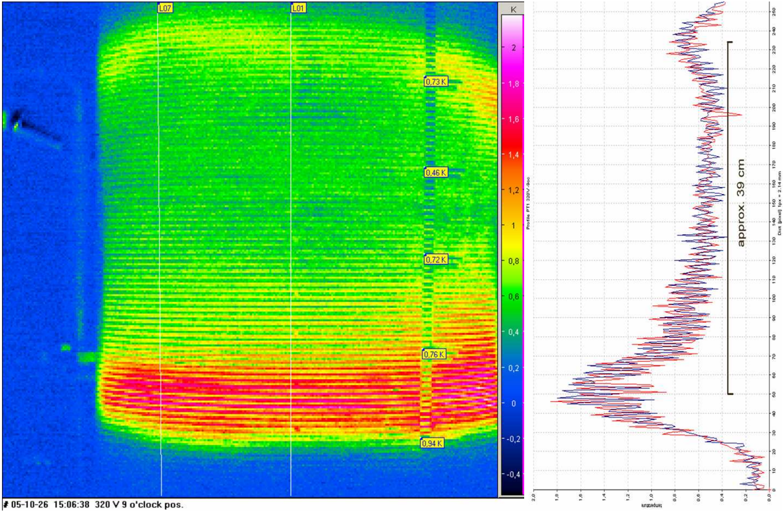
$P_{max} = 436\,\mathrm{W/cm^2}$

W7-X Gyrotron with mounted sweeping coils



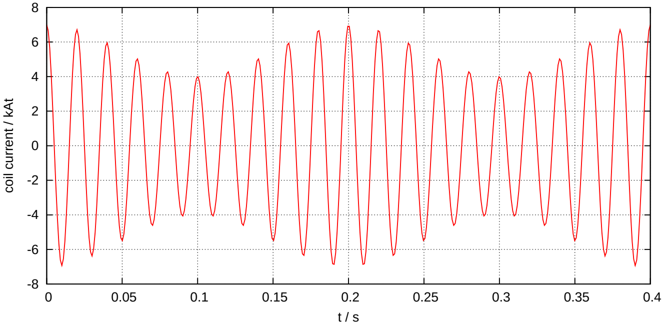
Infrared camera picture (short pulse)

Sweeping current: 7.9 kA · turns



Modulated transversal collector sweeping

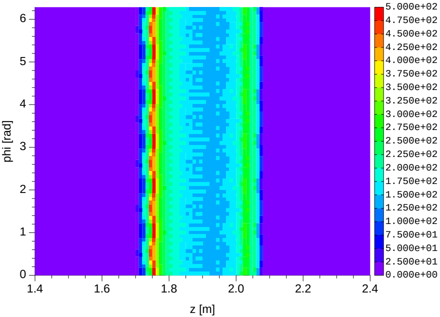
By modulating ("wobbling") the amplitude of the applied 50 Hz three phase current with a lower frequency (5–10 Hz), the critical maxima of the power density distribution will be smeared out.



Example: Amplitude Modulation from 4 kA to 7 kA at 5 Hz.

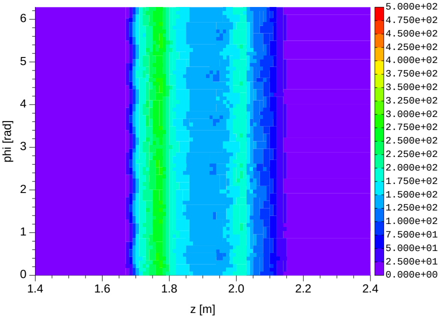
Modulated transversal collector sweeping: Results

$I_{loop} = 5\,\text{kA const.}$



$P_{max} = 498\,\text{W/cm}^2$

$I_{loop} = 4 - 7\,\text{kA, modulated at } 5\,\text{Hz}$



$P_{max} = 283\,\text{W/cm}^2$

At IPP Greifswald experiments with modulated sweeping current already started. Quantitative results obtained with the W7-X Gyrotrons (140 GHz, 1 MW, cw) will be available soon.

Conclusion

In the field of high power CW Gyrotrons Particle-in-Cell codes are an indispensable tool for the ...

- ... design of the Magnetron Injection Gun.
- ... design of the collector shape and magnetic sweeping system.
- ... simulation of beam instabilities that may strongly influence the efficiency of the tube.
- ... verification of numerical tools for cavity design (in limited sense)