Electric Field Sweeping Concept for High Power Gyrotron Collectors

Benjamin Ell, Chuanren Wu, Gerd Gantenbein, Stefan Illy, Moritz Misko,
Ioannis Gr. Pagonakis, Manfred Thumm, John Jelonnek

Introduction to Gyrotron and Traditional Collector Beam Sweeping Systems

Institute for Pulsed Power and Microwave Technology

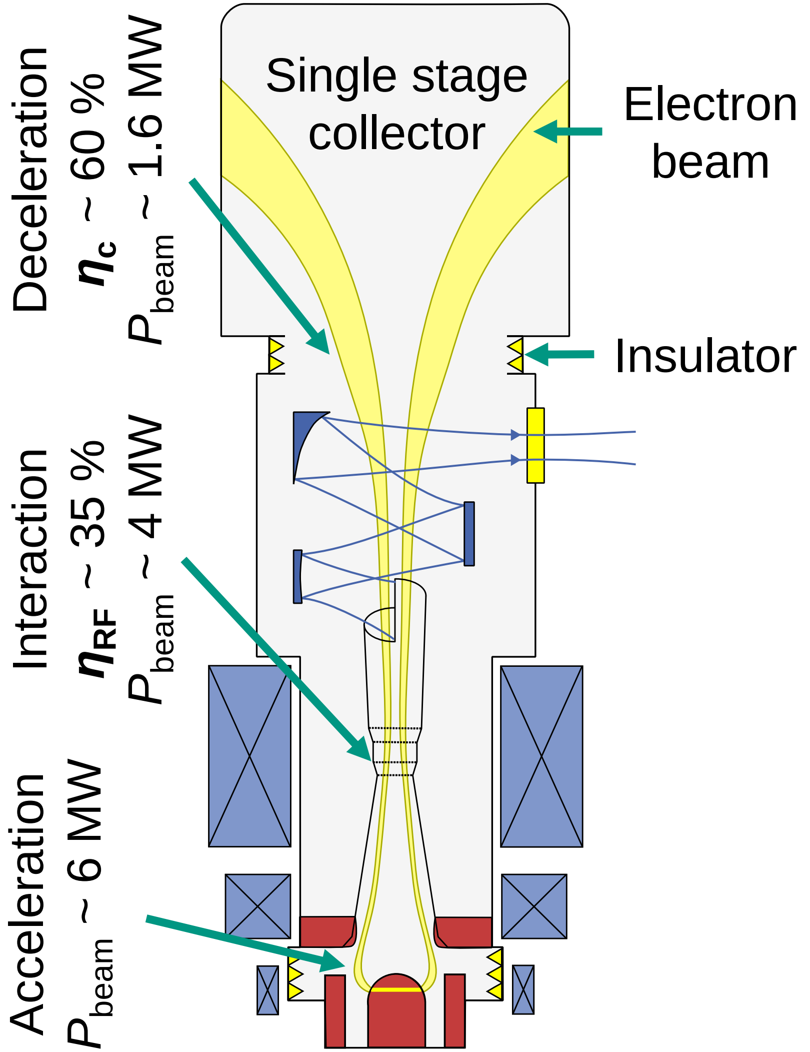
Gyrotrons for ECRH&CD in Nuclear Fusion

State of the Art

- 140 GHz, 1.5 MW continuous wave (W7-X upgrade)
- 170 GHz, 1 MW continuous wave (ITER)
- **170 GHz, 2 MW short pulse (DEMO prototype)**
- Gyrotron efficiency: $\eta_{tot} \sim 50\ \%$

High thermal loading on some components

- Cavity: high power loading density → static load
- Collector: high absolute power loading



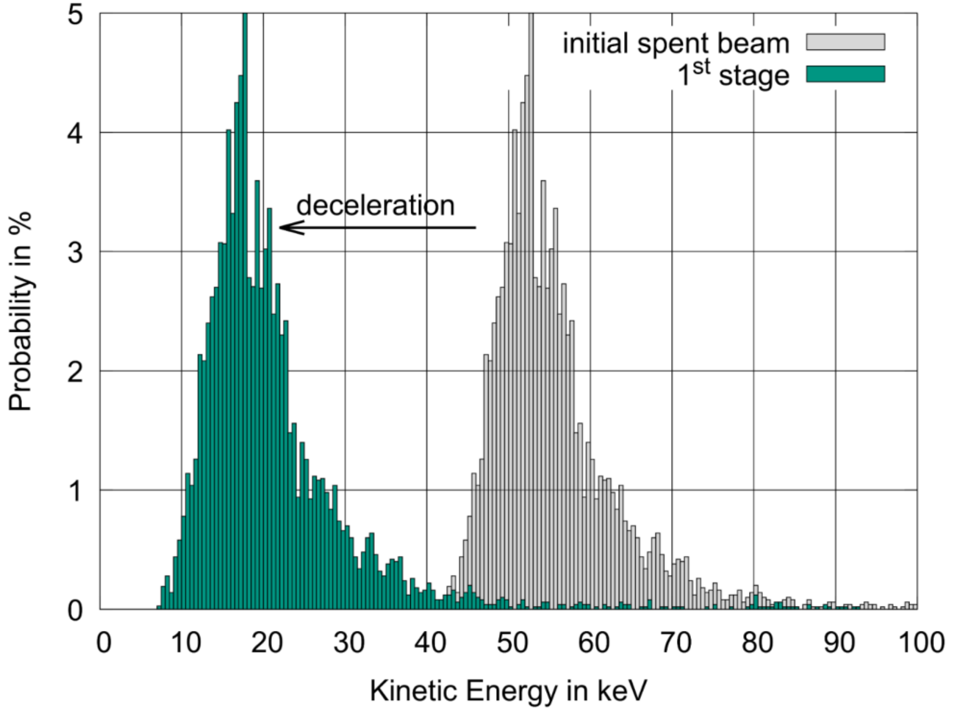
Institute for Pulsed Power and Microwave Technology

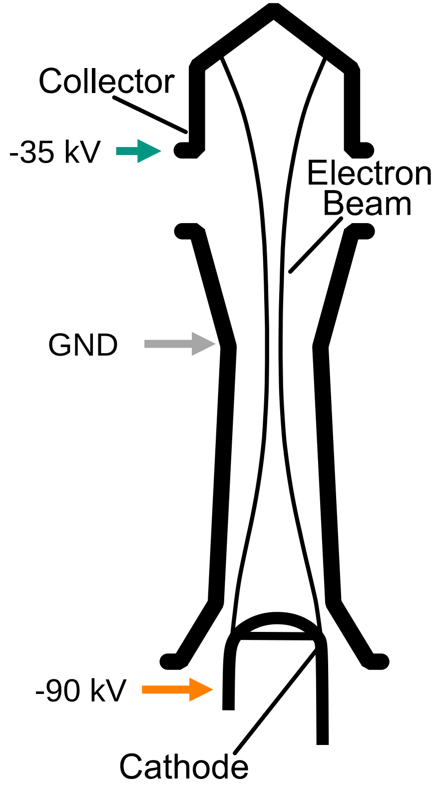
Principle of Single-Stage Depressed Collector (SDC)

- Collector efficiency is limited to η_c ~ 60%
  - Slowest electron
  - Widely spread energy spectrum

- Electron beam confined by strong magnetic field
  - Thin profile at collector wall
  - Very high power loading density

➡ Sweeping system





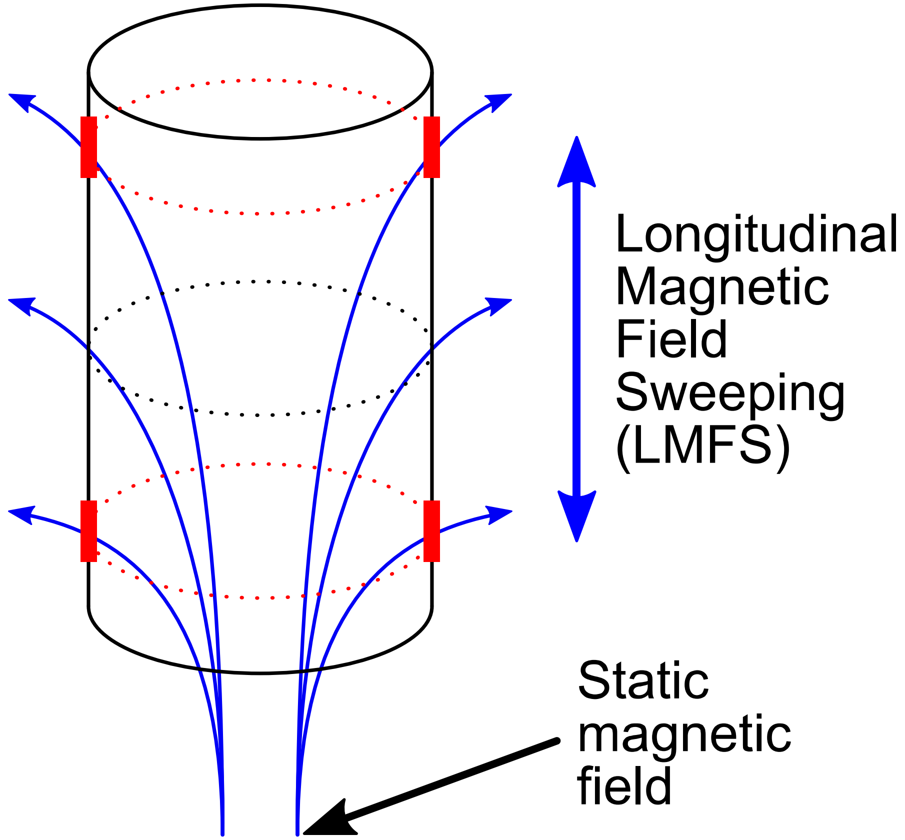
M. Thumm, Fusion Engineering and Design 2003

Longitudinal Magnetic Field Sweeping (LMFS)

Karlsruhe Institute of Technology

- Electron beam swept in axial direction
  - Modification of axial magnetic field
  - Coil required around copper electrode
  - Alternating current in coil

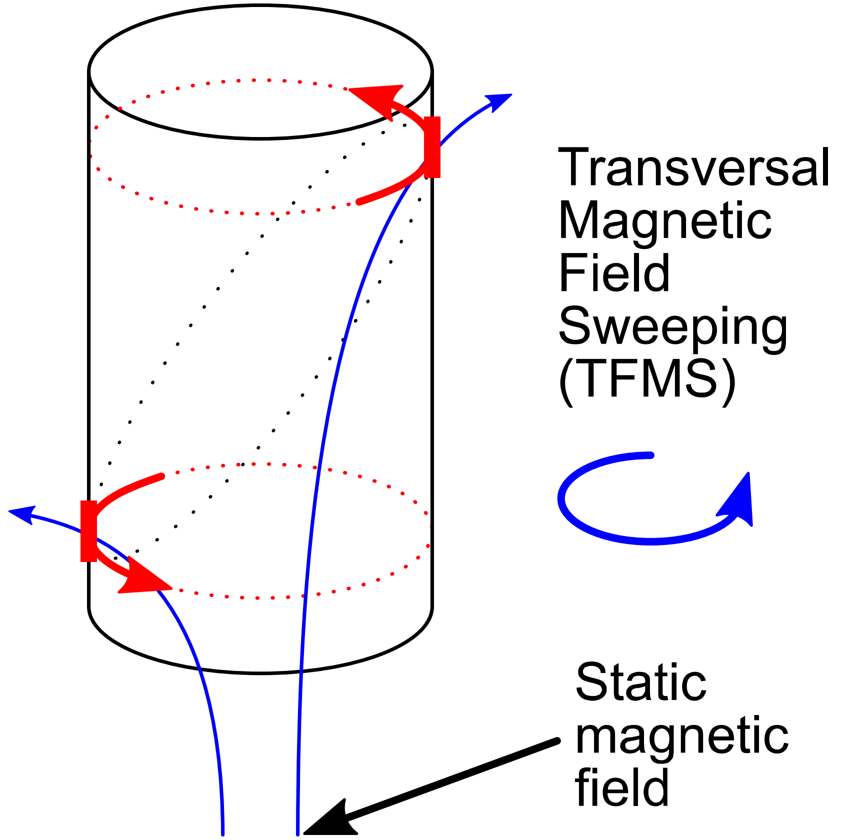
- Sweeping frequency is limited to 7-10 Hz
  - Strong eddy currents induced in copper
  - Magnetic field inside the collector is shielded



Transversal Magnetic Field Sweeping (TMFS)

Karlsruhe Institute of Technology

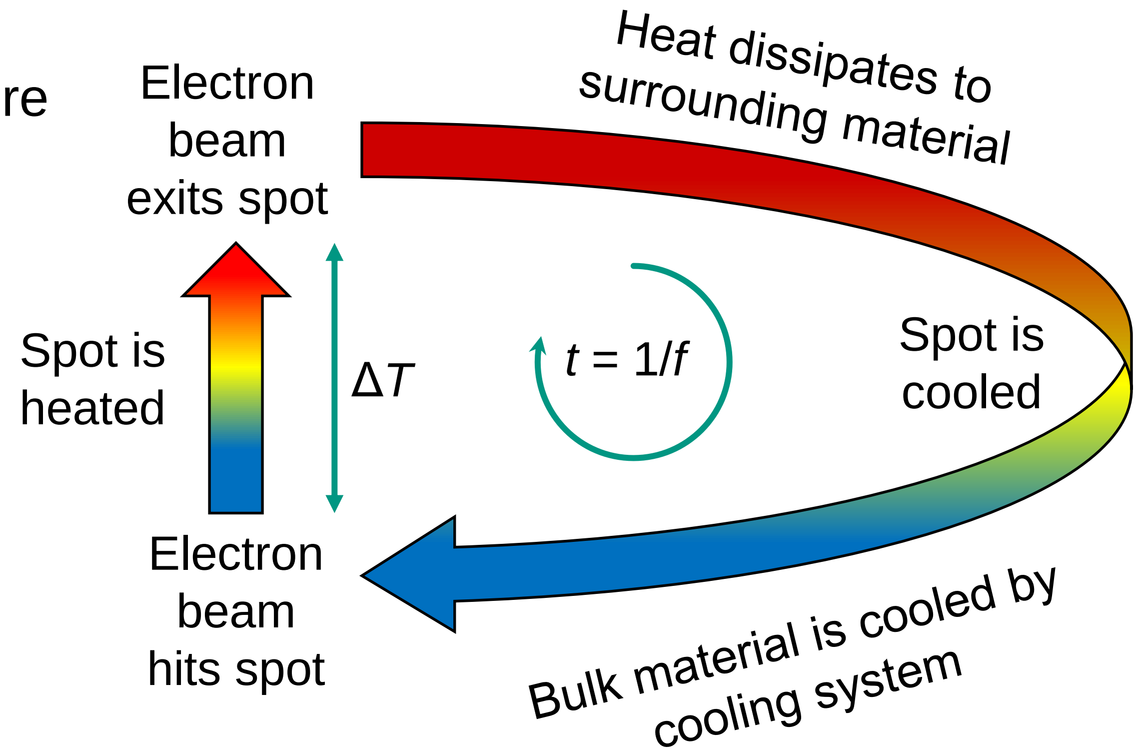
- Electron beam tilted and rotated in transversal direction
  - Modification of radial magnetic field
  - Usually six coils with 60° phase offset
  - Coils mounted below copper electrode around a stainless steel section
  - Sinusoidal current in coil
- Sweeping frequency is limited to around 50 Hz
- Can be combined with LMFS



Limitation of a Low Sweeping Frequency

- Periodic temperature variation
  - With high amplitude
  - Average temperature << maximal temperature
  - Less effective cooling system
- Cyclic fatigue
  - Limited lifetime of the collector
  - Cracks and plastic deformation

➡ Collector size must be increased



Challenges with a High Sweeping Frequency

- Electron trajectories must be modified

- Periodic variation of electric or magnetic fields
  - Magnetic field from outside → low sweeping frequency
  - Magnetic field from inside
  - Electric field from outside
  - Electric field from inside

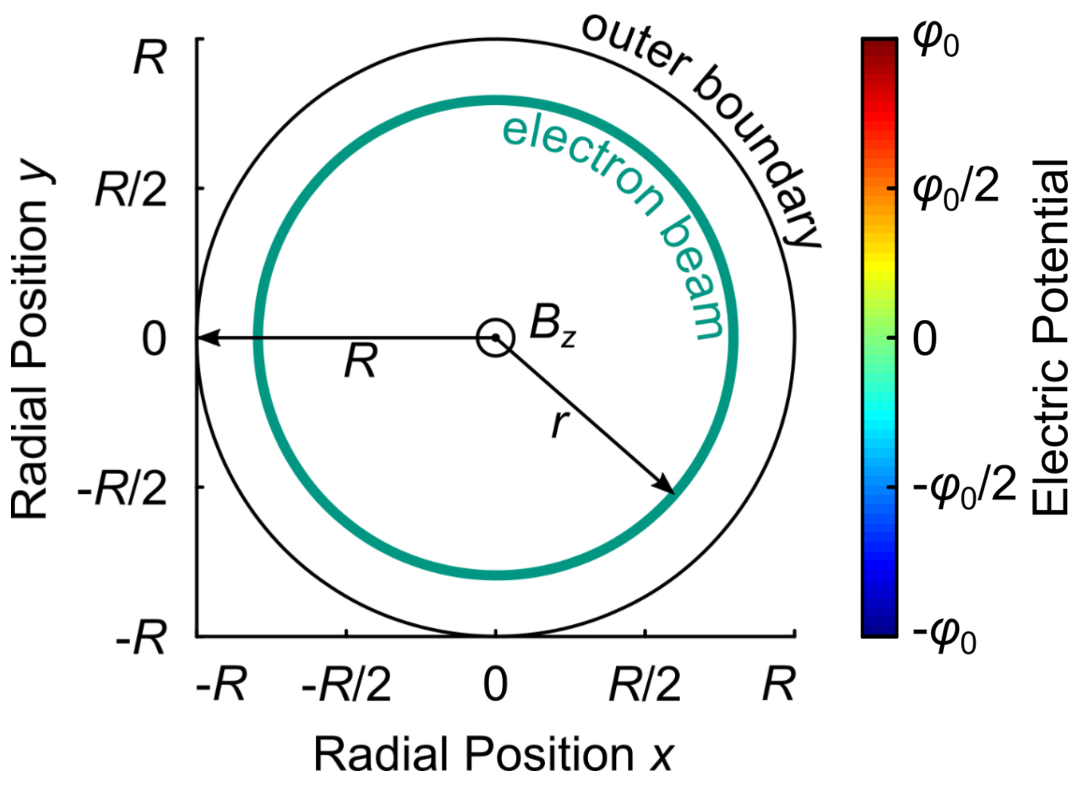
- Electron beam is confined by strong magnetic field
  - Electric field must create an electron drift → $E \times B$
  - Radial electron drift → azimuthal electric field
  - No azimuthal symmetry due to Faradays law

2D Analytical Model with Infinite Electrodes

Analytical Model 2D Cross-Section

- Axial magnetic field $B_z = B_0 \cdot \vec{z}$
- Circular hollow electron beam @ $r < R$
- Outer boundary with infinite electrodes @ $r = R$

- Electric potential at the angular position θ of the boundary is defined to
  - $\varphi(\theta, t) = \varphi_0 \cdot \sin\left(n \cdot \theta + 2\pi \cdot \frac{t}{T}\right)$
  - With amplitude φ_0, azimuthal periodic factor n, time t and period length T



Institute for Pulsed Power and Microwave Technology

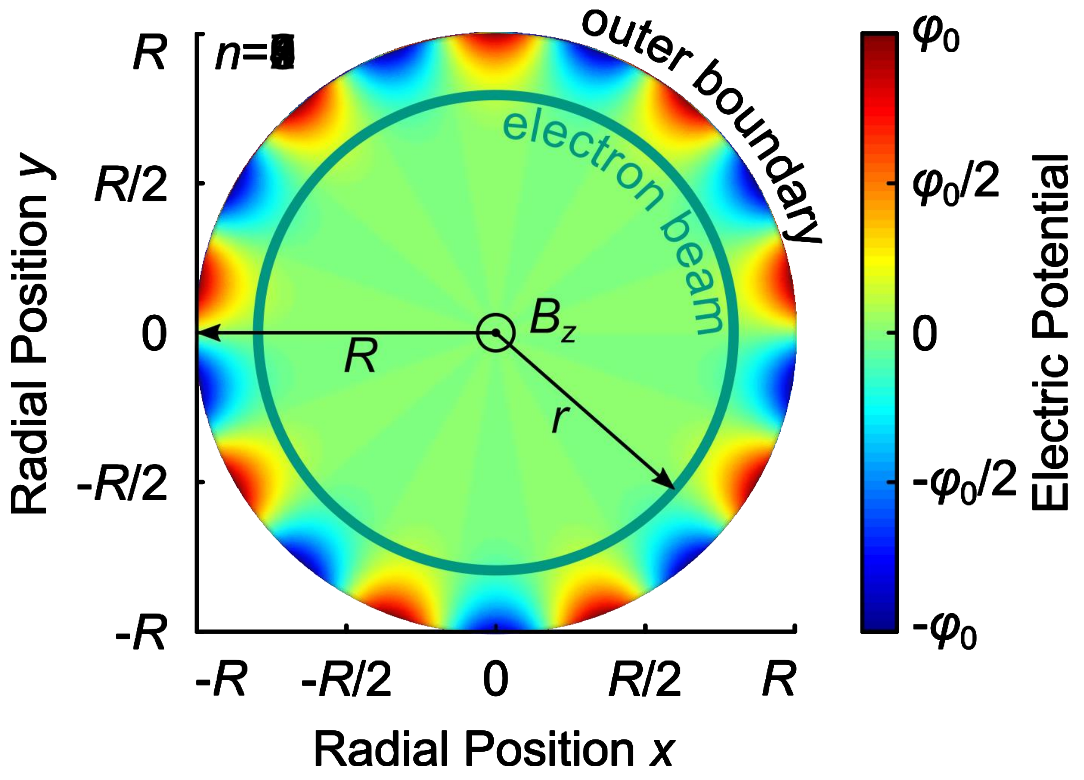
Analytical Model 2D Cross-Section

- Electric potential in the cross-section is calculated by Laplace equation to

$$\varphi(r,\theta,t) = \frac{r^n}{R^n}\cdot\varphi_0\cdot\sin\left(n\cdot\theta + 2\pi\cdot\frac{t}{T}\right)$$

- The electric field is $\vec{E} = -\vec{\nabla}\varphi$
- The drift velocity is $\vec{v_\mathrm{d}} = \vec{E}\times\vec{B}/\left|\vec{B}\right|^2$

$$\vec{v_\mathrm{d}}(r,\theta,t) = -\frac{n\cdot r^{n-1}}{B_0\cdot R^n}\cdot\varphi_0\begin{bmatrix}\cos\left(n\cdot\theta + 2\pi\cdot\frac{t}{T}\right)\\ \sin\left(n\cdot\theta + 2\pi\cdot\frac{t}{T}\right)\end{bmatrix}^T\cdot\begin{bmatrix}\vec{r}\\ \vec{\theta}\end{bmatrix}$$



Analytical Model 2D Cross-Section

- Radial drift distance is proportional to

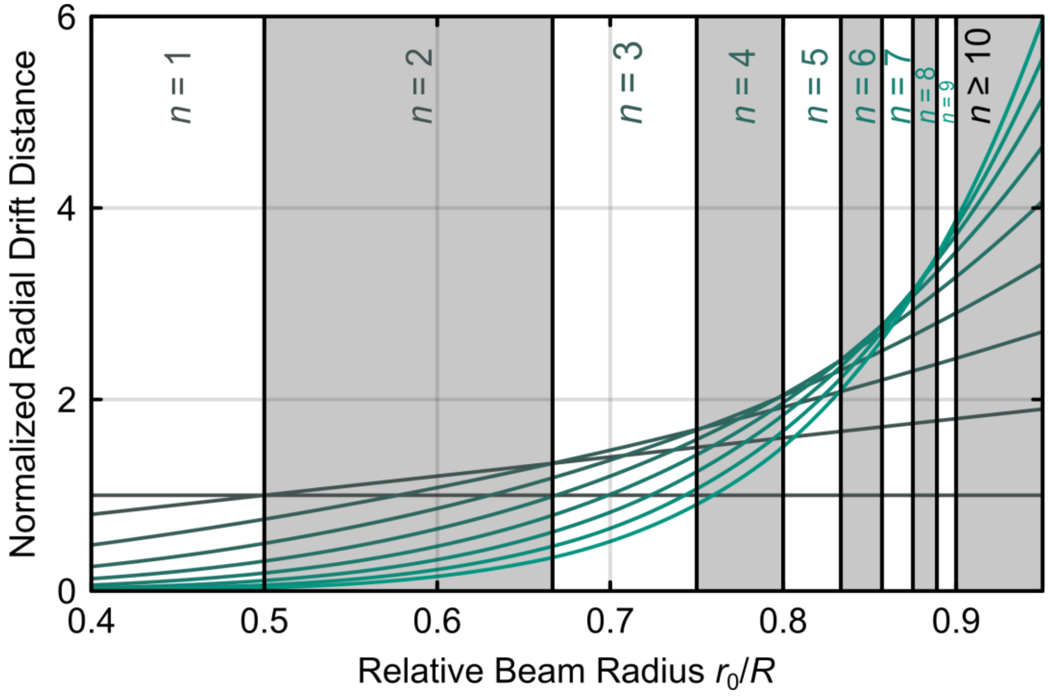
$$\Delta r \propto n \cdot \tau \cdot \left(\frac{r_0}{R}\right)^{n-1}$$

with the characteristic time τ

- Optimal azimuthal periodic factor n for a given relative beam radius

- Maximum relative beam radius $r_0/R := 0.85$

➡ $n <= 6$



2D Analytical Model with Discrete Electrodes

Institute for Pulsed Power and Microwave Technology

Analytical Model – Limited Number of Potentials

Karlsruhe Institute of Technology

- Number of electrodes is limited in a realistic system
- Discrete electrodes at angular position

$$\theta(i) = \frac{2\pi}{n} \cdot \left(\frac{i}{p} - \frac{1}{4}\right)$$

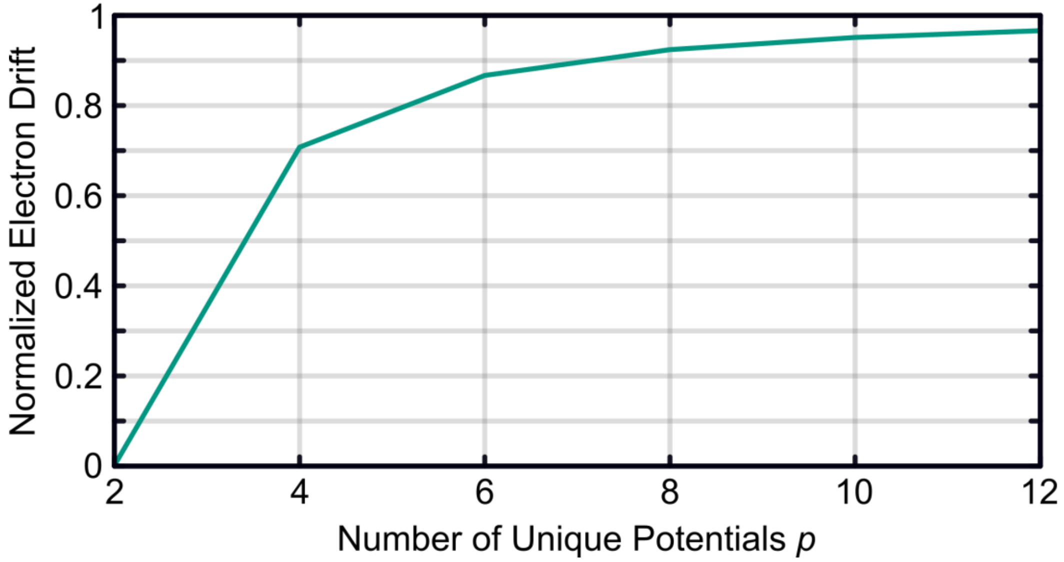
with the number of unique potentials *p* for *i* = 1 to *p*·*n*

- The electric potential between the electrodes *i* and *j*

$$|\varphi(i,j,t)| \leq \left|\frac{\varphi(\theta(i),t) + \varphi(\theta(j),t)}{2}\right|$$

$$= \varphi_0 \cdot \cos\left(\frac{\pi}{p}\right) \cdot \left|\sin\left(\pi \cdot \left(\frac{i+j}{p} - \frac{1}{2}\right) + 2\pi \cdot \frac{t}{T}\right)\right|$$

- Maximum potential between two electrodes is limited

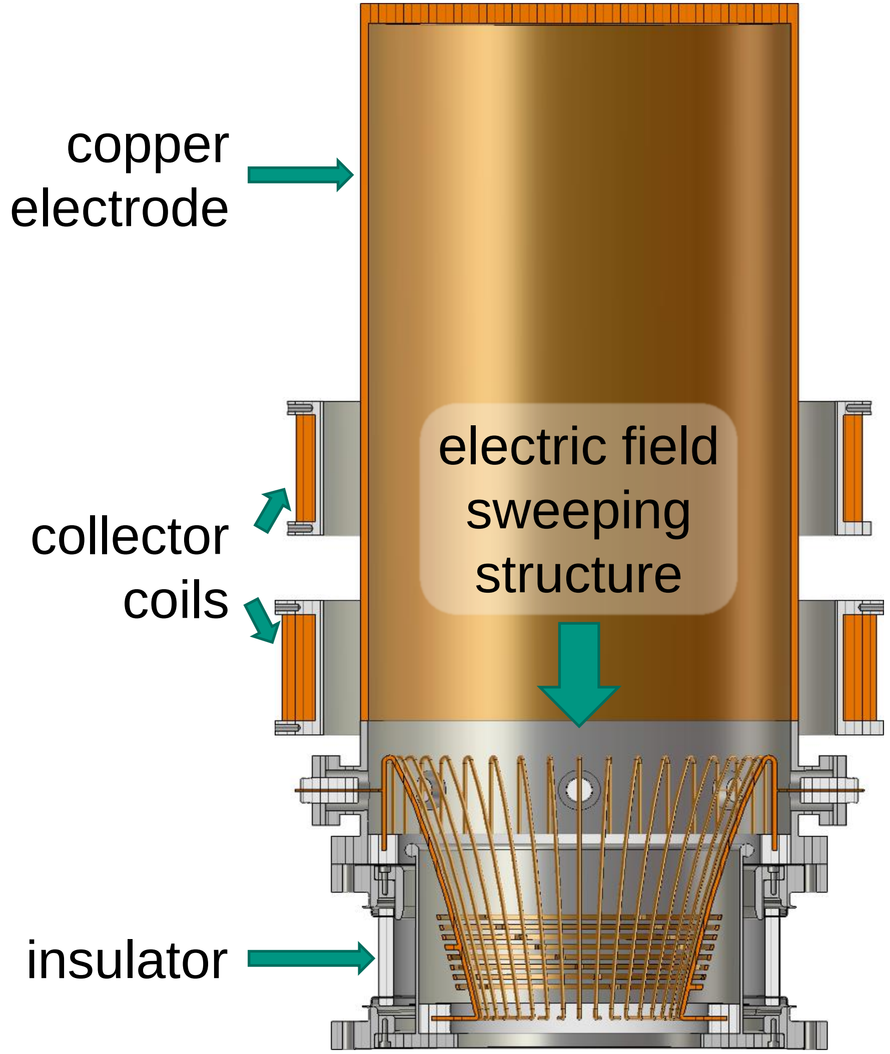


Karlsruhe Institute of Technology

3D Conceptual Design

Overview of Conceptual Design

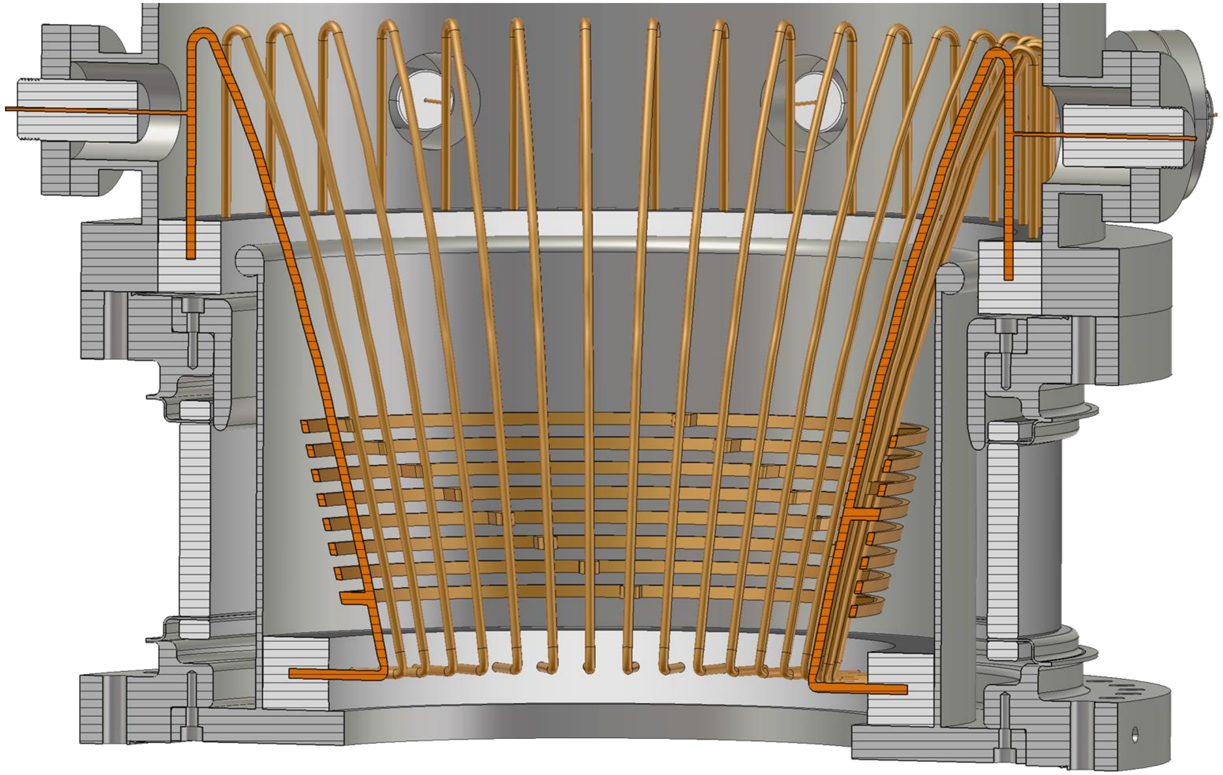
- Electric field sweeping structure at collector entrance
  - Large radius for reduced electric field
  - Low magnetic field (40 – 120 mT)
  - Space to place electrodes
- Large ceramic for depression potential
- Two DC collector coils
- Inner collector radius: 200 mm
- Length of copper section: 700 mm



Detailed Overview of Conceptual Design

- Azimuthal periodic factor $n = 5$
  - Optimal for $r_0/R = 0.8 – 0.8\bar{3}$
  - Maximum $r_0/R := 0.85$
  - Minimum $r_0/R \approx 0.67 – 0.81$
- Unique potentials $p = 8$
  - 45° phase difference
  - 8 high voltage feedthroughs
  - Oscillating between body and depression potential ➡ maximum potential difference
- 40 electrodes in 9° angle steps
- Internal potential distribution
- Two internal ceramic rings for mechanical support

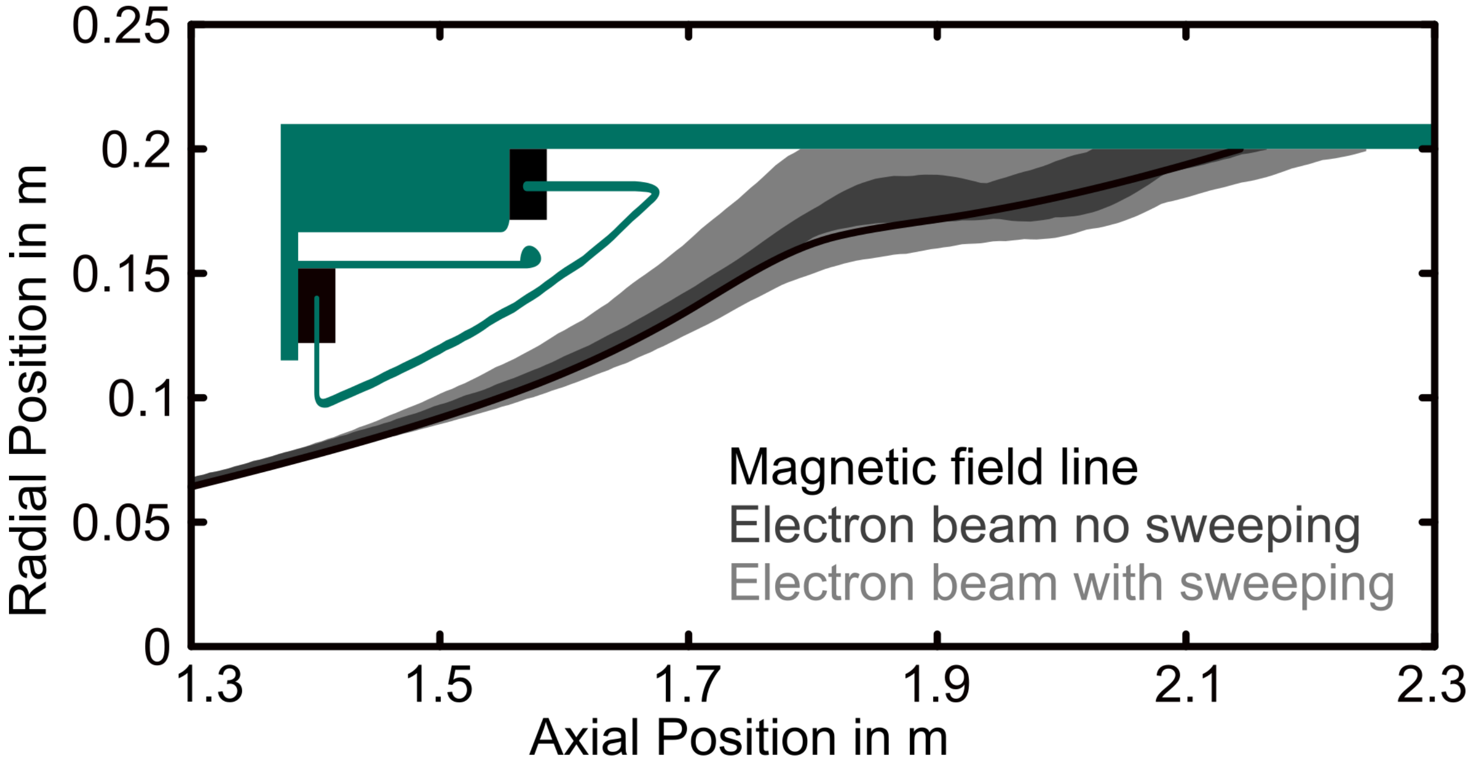
electric field sweeping structure



Magnetic Field of Conceptual Design

- Constant magnetic field is adjusted
- Shallower incident angle at wall
- Non adiabatic transition for increased beam thickness

➡ Modification is required



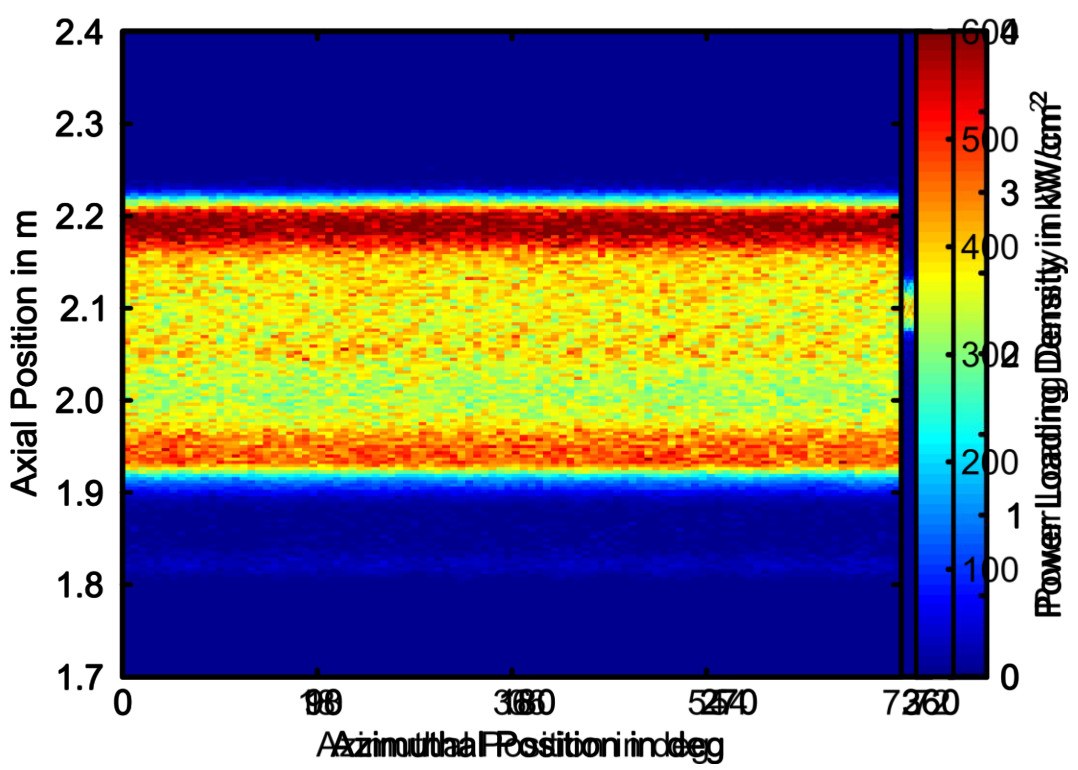
Simulation Results

Wall Loading of Conceptual Design

- Instantaneous wall loading
  - Traditional collector of same size: ~ 6 kW/cm²
  - Here without sweeping potential: ~3 kW/cm²

- Electric field sweeping is applied
  - Axial position of the beam on the wall is varied
  - 72° symmetry (*n* = 5)
  - Instantaneous wall loading: ~4 kW/cm²

- Time average
  - Homogeneous power loading distribution
  - Maximum average wall loading: ~600 W/cm²



Influence of Sweeping Frequency

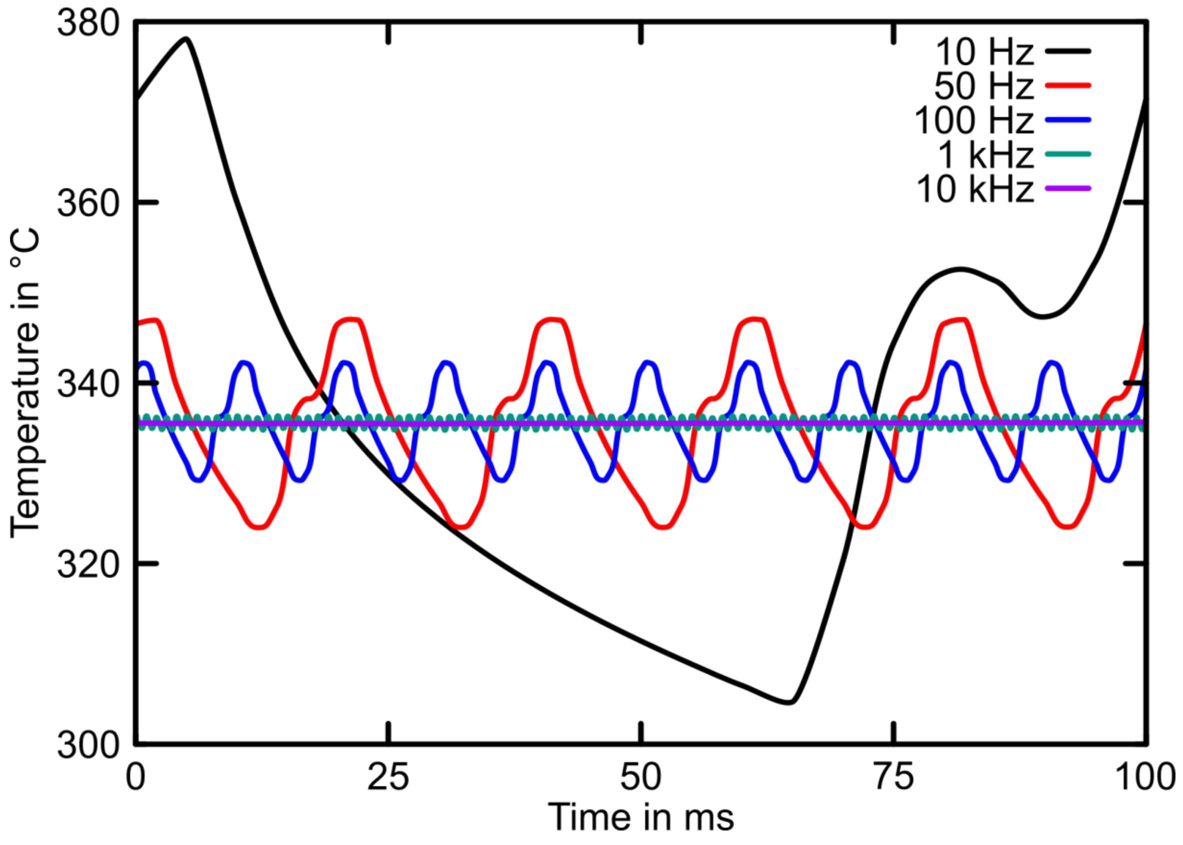
- Temperature variation Δ*T* is reduced with increasing sweeping frequency

Frequency	Δ*T*
10 Hz	73.5 K
50 Hz	23.0 K
100 Hz	12.9 K
1 kHz	1.6 K
10 kHz	0.2 K

- Average temperature not influenced

➔ Less cyclic fatigue

Temperature over time at a sample point



Conclusion

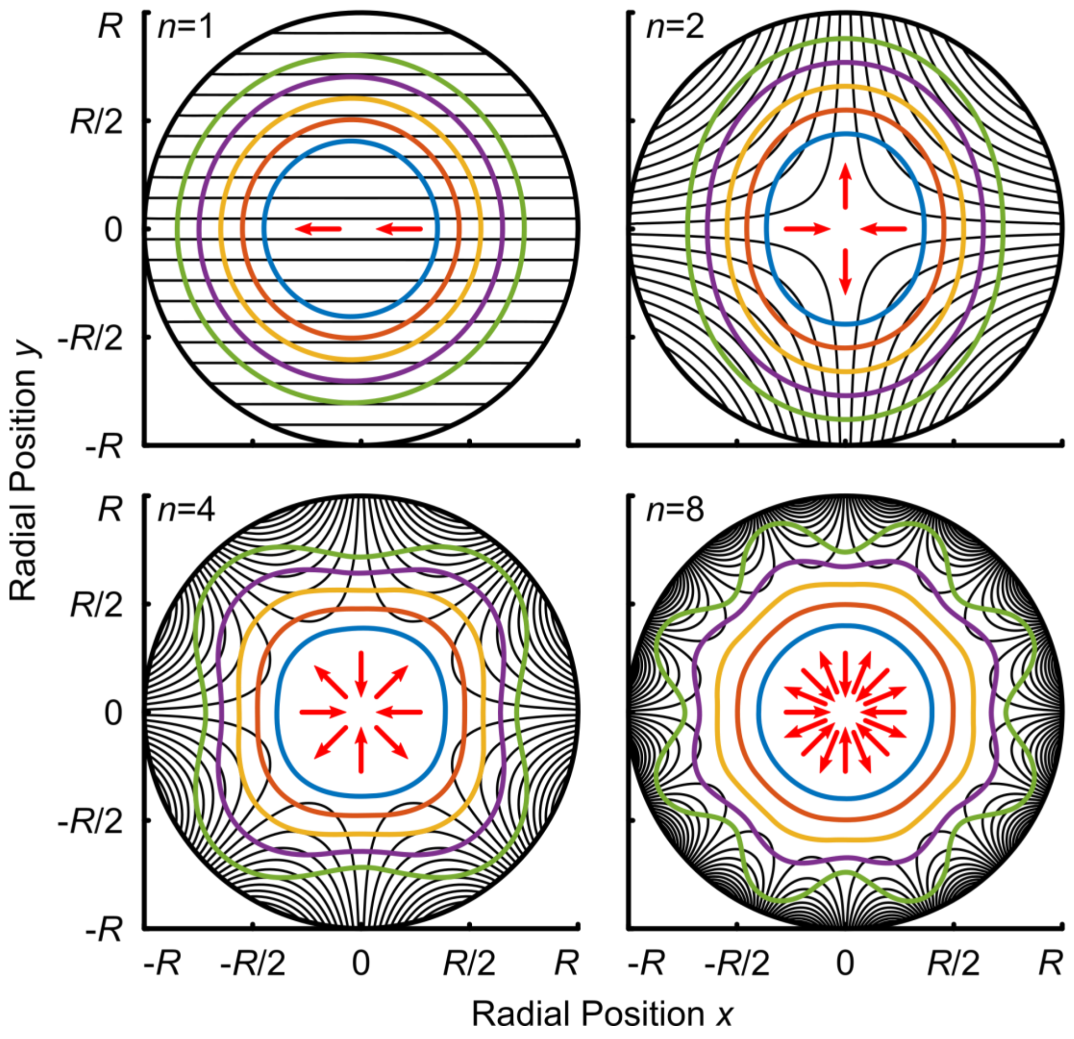
- An electric field sweeping system for a high power gyrotron was designed and analytically optimized
- Achieved strong $E \times B$ drift in radial direction
- Optimized static magnetic field for amplified effect in axial direction
- Temperature variation is significantly reduced with increasing sweeping frequency

Analytical Model 2D Cross-Section

- Radial drift distance is proportional to

$$\Delta r \propto n \cdot \tau \cdot \left(\frac{r_0}{R}\right)^{n-1}$$

with the characteristic time τ



Karlsruhe Institute of Technology

Cutoff Frequency of Sweeping System

- Cutoff frequency for TE mode

$$f_{c_{nm}} = \frac{k_c}{2\pi\sqrt{\mu\epsilon}} = \frac{p'_{nm}}{2\pi a\sqrt{\mu\epsilon}}$$

- Radius a = 200 mm
  - $f_{c1,1}$ = 439 MHz
  - $f_{c2,1}$ = 729 MHz
  - $f_{c3,1}$ = 1.00 GHz
  - $f_{c4,1}$ = 1.27 GHz
  - $f_{c5,1}$ = 1.53 GHz
  - $f_{c6,1}$ = 1.79 GHz

n	m = 1
1	1.8412
2	3.0542
3	4.2012
4	5.3175
5	6.4156
6	7.5013
7	8.5778
8	9.6474