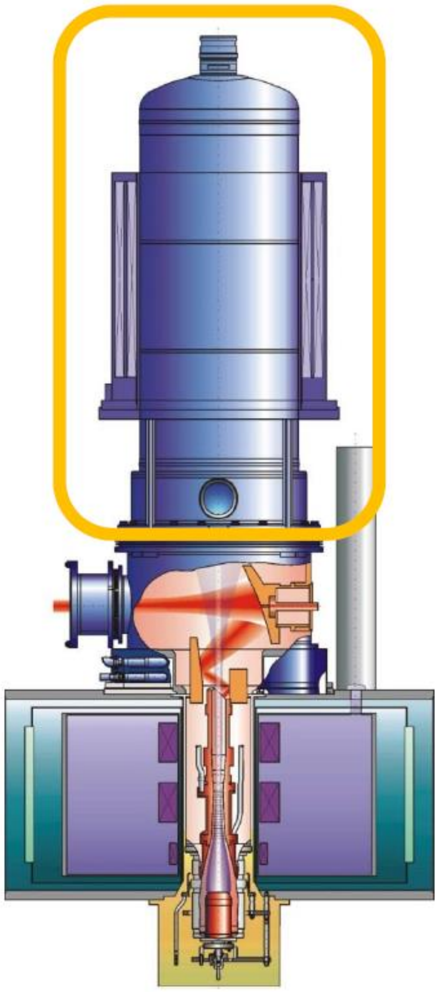
Section 2.2

BASICS OF ELECTRON COLLECTORS



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Collectors

There are two major considerations in the design of collectors for linear beam tubes:

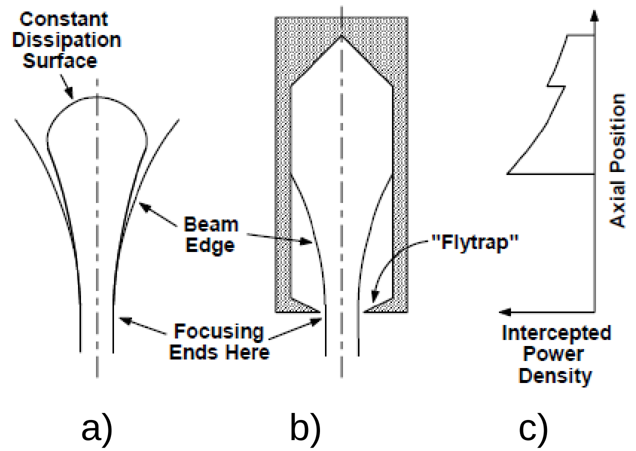
- Energy dissipation
- Energy recovery

- Energy dissipation
  - A simple collector is a single electrode at the voltage of the body (usually ground).
  - These collectors are used for huge devices in applications where energy consumption is not critical problem.
- Energy recovery
  - The collector has several electrodes.
  - To recover energy, the voltages on the electrodes must be negative with respect to the body → the beam is slowed down before it is collected.
  - The energy recovered in slowing the beam is returned to the power supply

    → The heat that must be dissipated by the collector is strongly reduced

Power Dissipation (I)

- Two critical areas of high power dissipation exist:
  - Where the beam first touches the collector wall (dissipation is maximum)
  - At the end of the collector
- Typically, the ratio of average to maximum (where the beam is first intercepted) wall dissipation will vary between 0.25 and 0.5.
- The maximum allowable intercepted power density is affected by:
  - Collector wall material and thickness
  - Method of heat transfer from the wall to the cooling medium
  - Whether the intercepted power is continuous (CW) or pulsed



a) Collector for constant dissipation (ideal)
b) Electron collector (real)
c) Intercepted power density

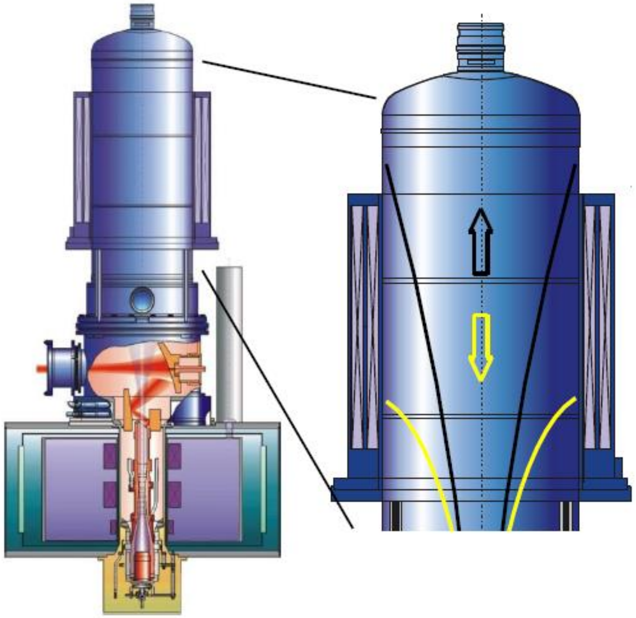
Power Dissipation (II)

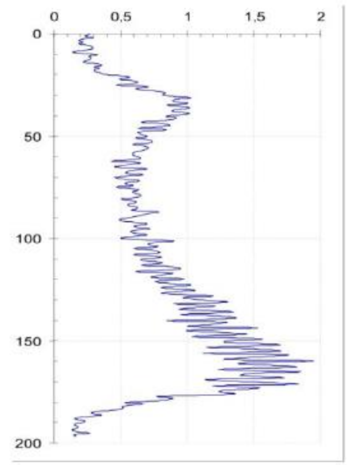
- Collectors for high power tubes are mostly made of cooper (high thermal conductivity)

  But also: Collector material (Cu-OFHC, CuCrZr (PH), GlidCop Al15 (DS))
- For forced-flow water cooling with water channels, the average power dissipation is limited to a value of 1 kW/cm².
- Power dissipation up to 18 kW/cm²
  - Use of laminated wall materials
  - Very small water channels
  - Extremely high water pressures
- During a pulse, the temperature rises to a high value in a very thin surface. Problems may arise:
  - The surface may melt during the pulses
  - Stresses caused by the expansion and contraction during the repeated heating and cooling may destroy the surface.

Prevention of Intercepted Peak Power

With additional coils the electron beam is swept over the collector surface for a uniform heat distribution over the whole surface.





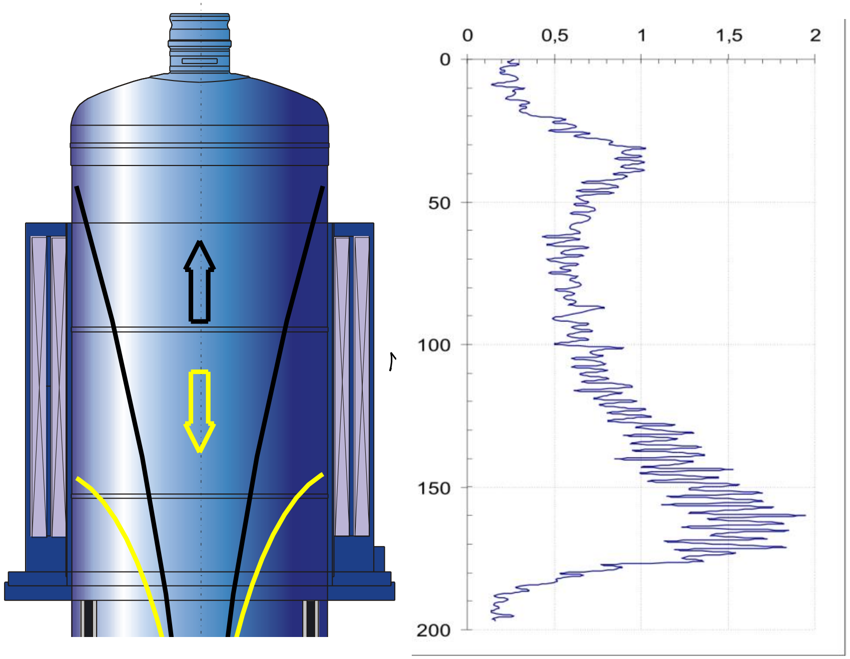
Temperature distribution on collector surface (a.u.)

Slotted surface for efficient water cooling

Longitudinal Field Sweeping

As the electrons follow the magnetic field lines, the position where the electron beam hits the collector surface is given by the field lines.
By additional normal conducting coils at the collector, the position can be moved up and down by applying an alternating magnetic field.

normal-conducting
AC- and DC-coils



Skin effect

→ **low frequency**
only sinusoidal excitation

Disadvantage of sinusoidal excitation:
The rest time at the reversal point is high. This effect is even amplified by the finite length of coils.

Temperature distribution on collector surface: a.u.

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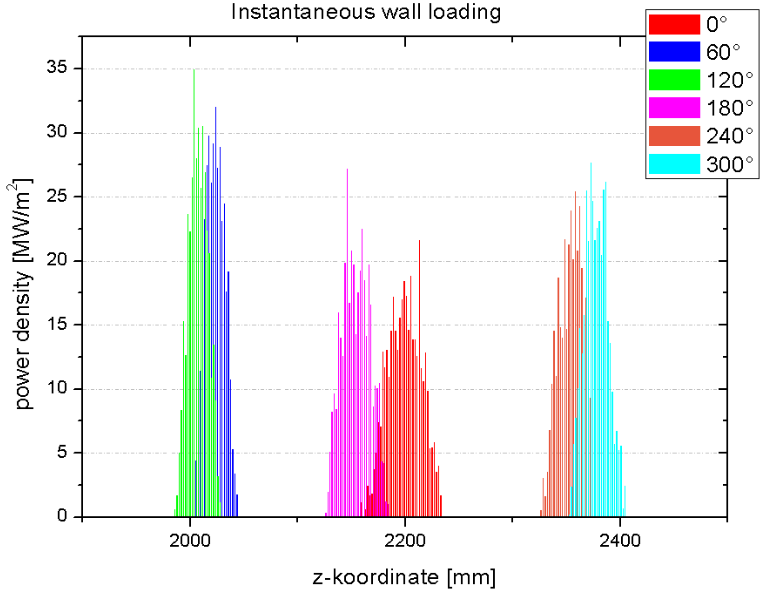
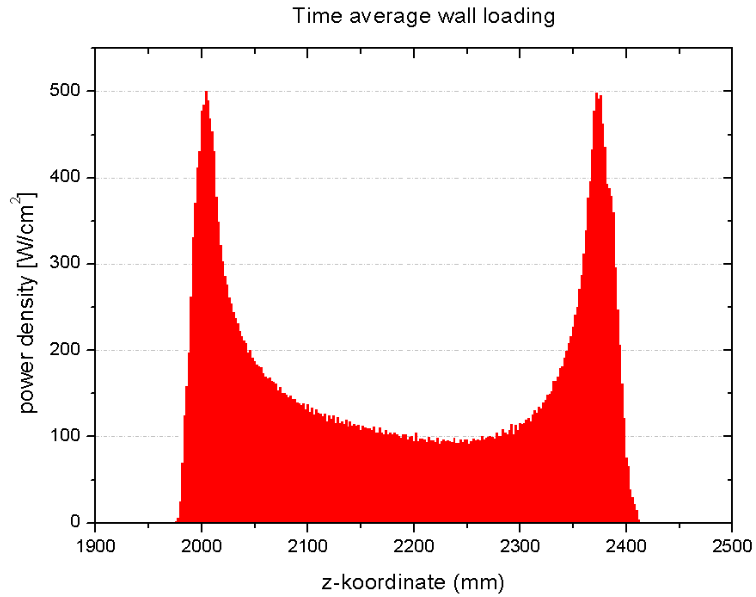
Sweeping Systems – Vertical Magnetic Field Sweeping (VMFS) - Wall Loading





Electron trajectory simulation:

-> Wall sees instantaneous load

-> Two distinct maxima at upper and lower turning point

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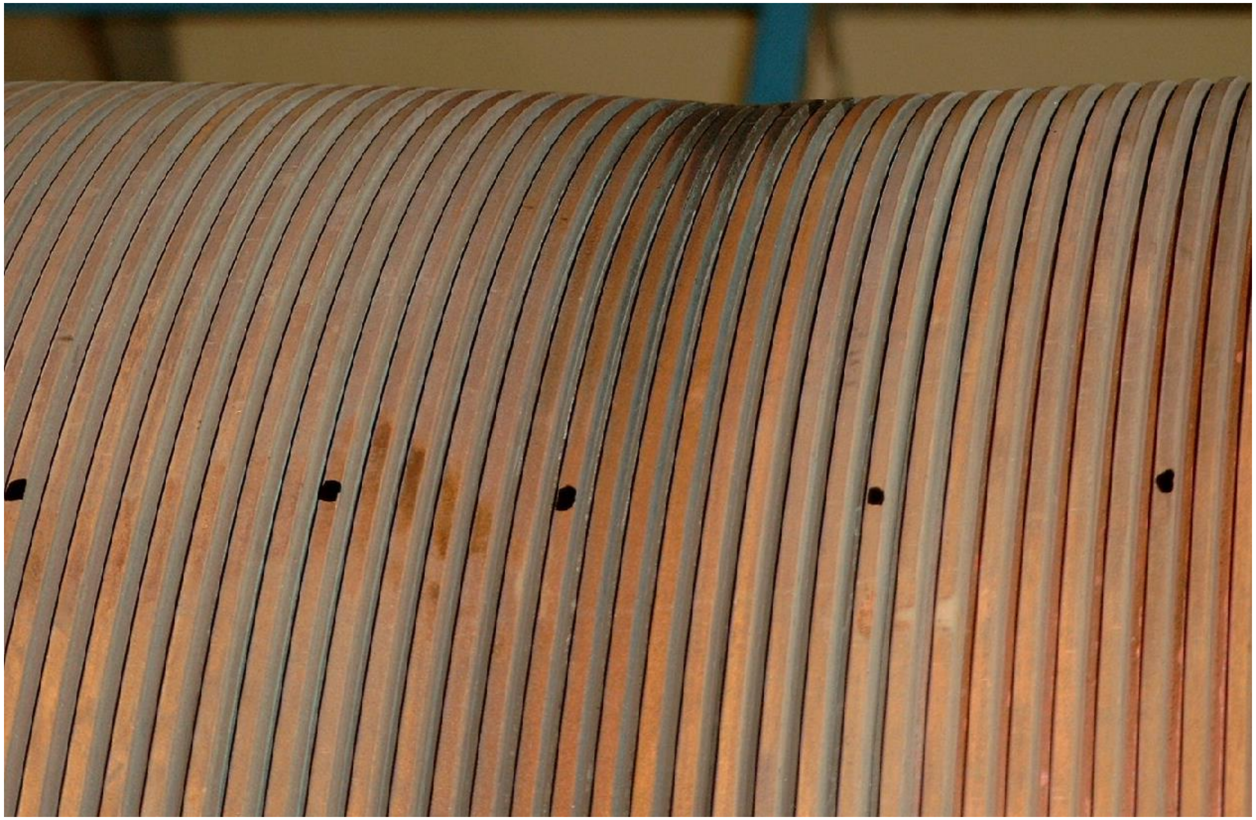
Plastic Deformation of the Collector

In general the frequency is chosen to 7 Hz
(by mistake the sweeping system was operated at 0.7 Hz for a short while)

Material fatigue at the collector is the main limiting factor for gyrotron lifetimes (apart from accidental damages)



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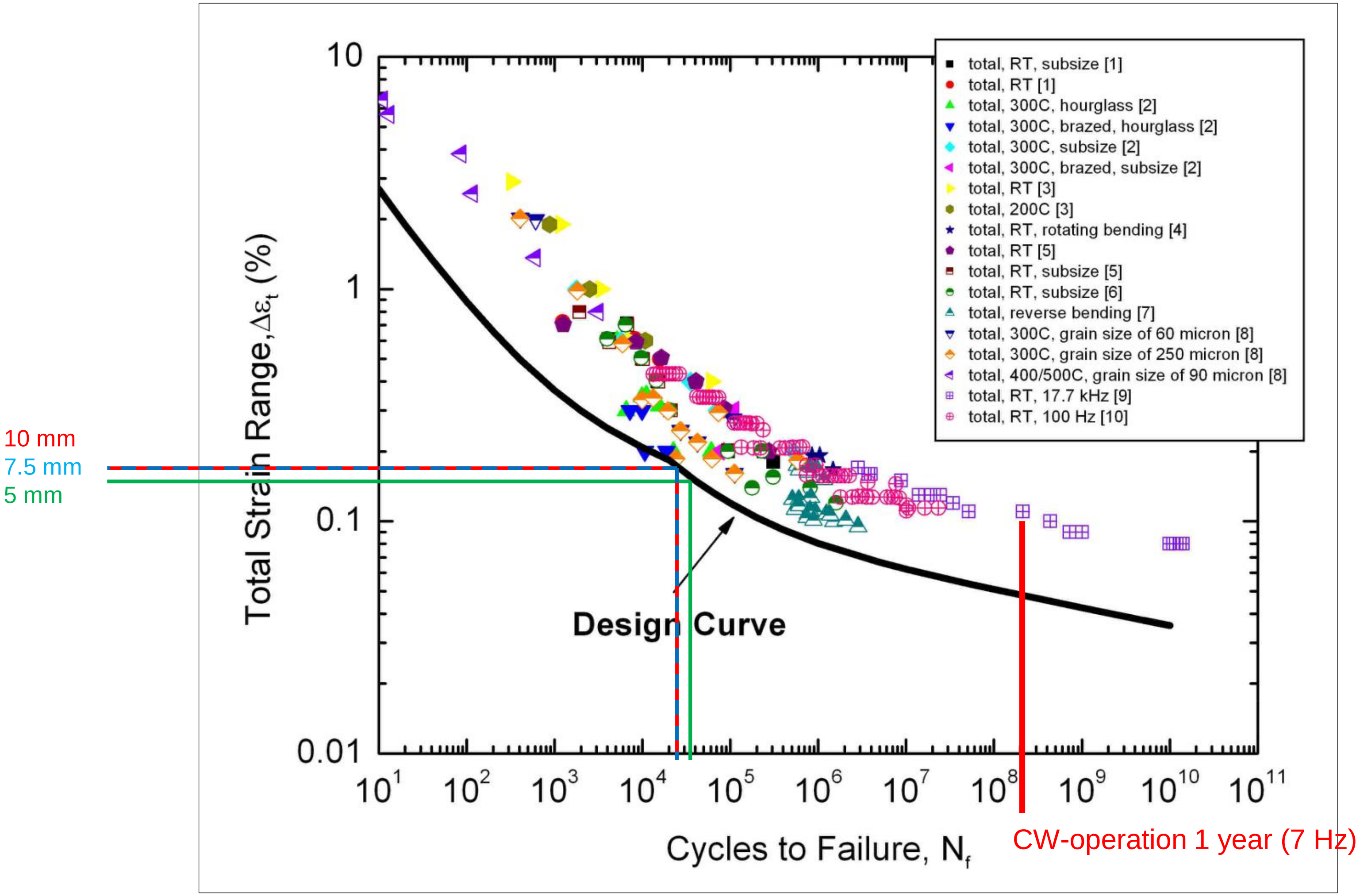
Lifetime Estimation Process – Lifetime Estimation

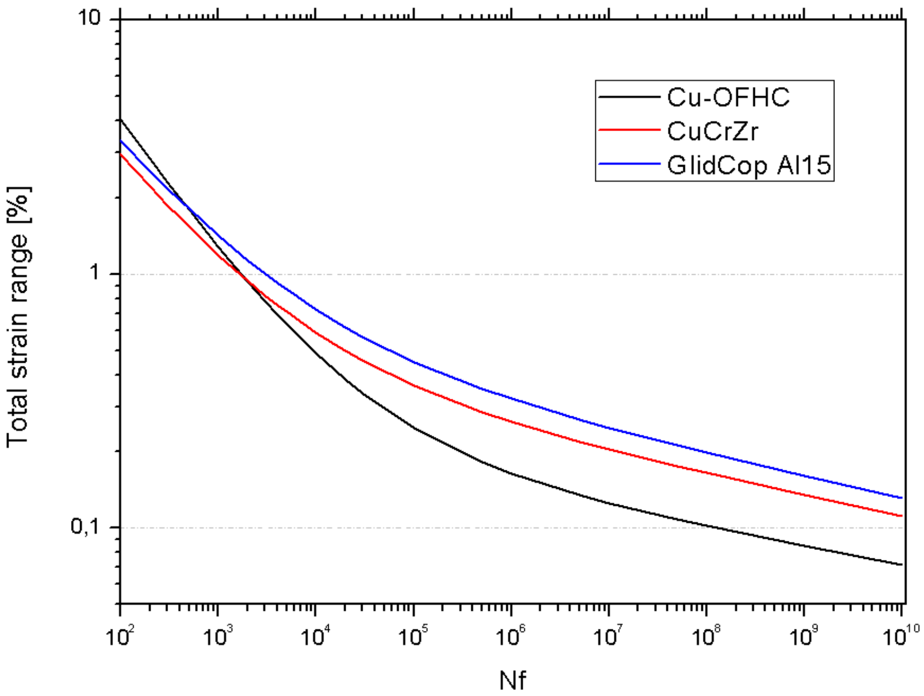
Karlsruher Institut für Technologie



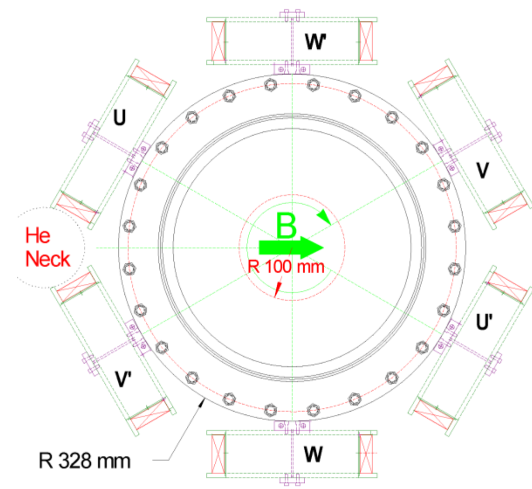
Source: ITER Material Handbook

Simulation and Lifetime Estimation Results

- Strain range determines lifetime
  -> directly connected to the temperature range
- Way to increase lifetime:
  - Reduce temperature range
  - Use material with better fatigue properties



Transverse Field Sweeping (II)



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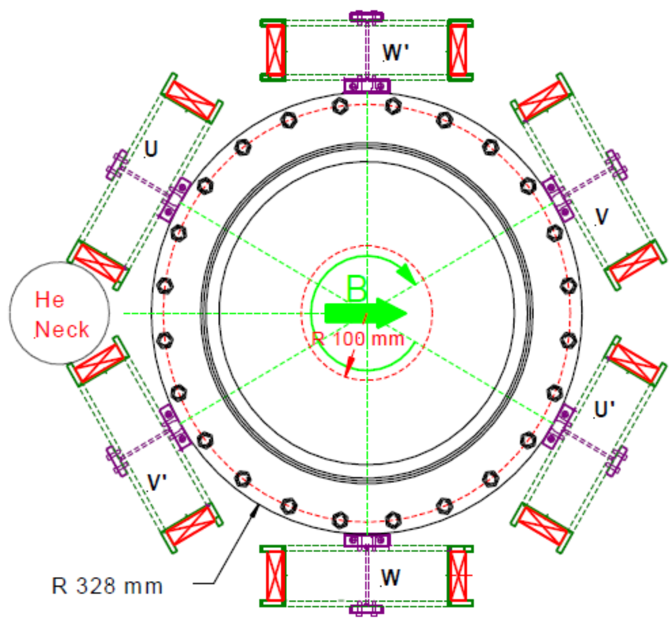
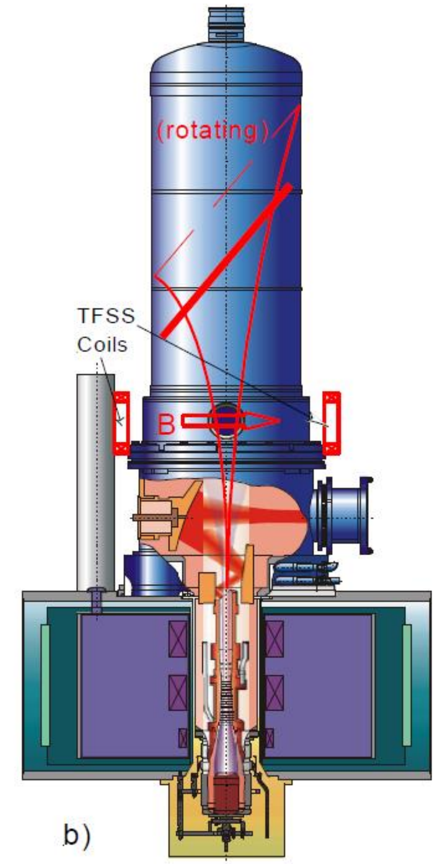
Transverse Field Sweeping (I)

Additional transverse magnetic field decline the field lines and reduce the magnetic fields on one side of the collector. (The strike point of the electron beam on the collector form a tilted rotating ellipse)

By rotation of the magnetic field the ellipse also rotates causing a reduction of the power loading. Rotation by a 3-phase net.

Opposite coils are excited in phase, neighboring coils have a phase shift of 120° (standard 50 Hz 3-phase transformer.)





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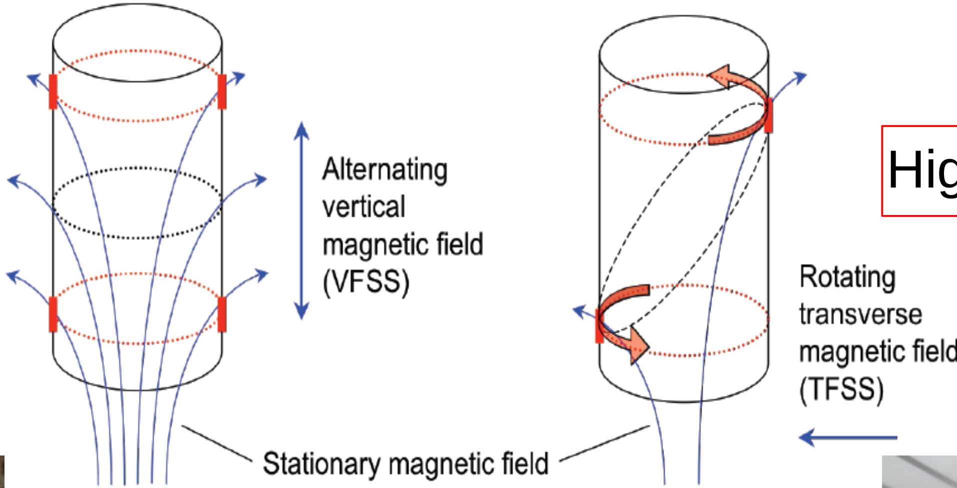
Electron Beam Sweeping Systems – Operation Principles

Low frequencies

High frequencies



Vertical magnetic field sweeping (VMFS) 7 Hz

Transverse magnetic field sweeping (TMFS) 50 Hz

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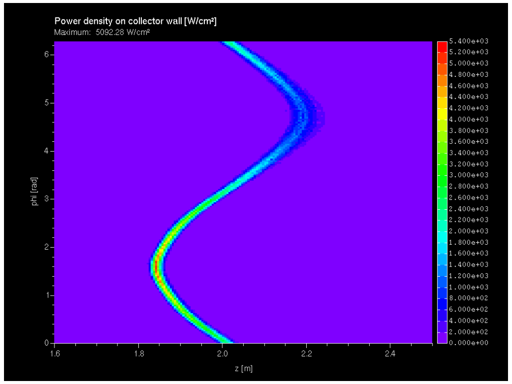
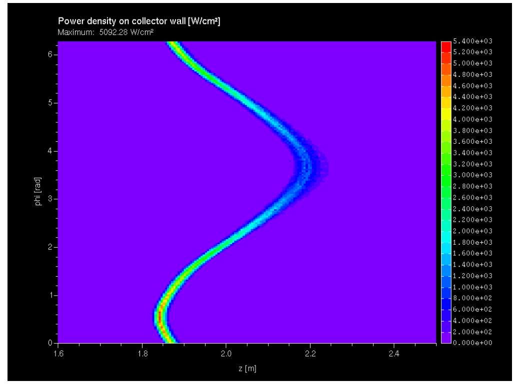
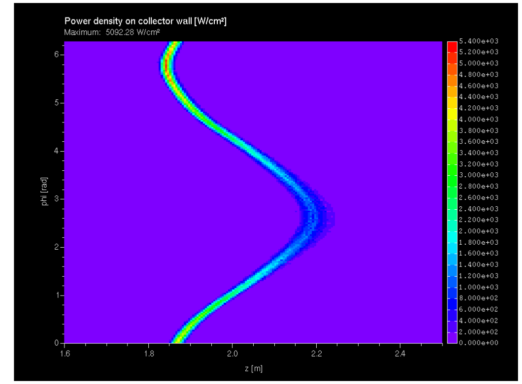
Sweeping Systems – Transverse Magnetic Field Sweeping (TMFS) - Wall Loading



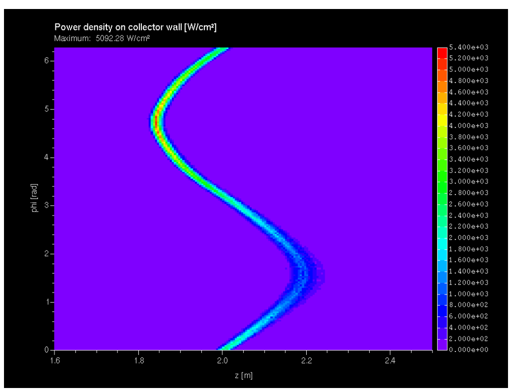
0°



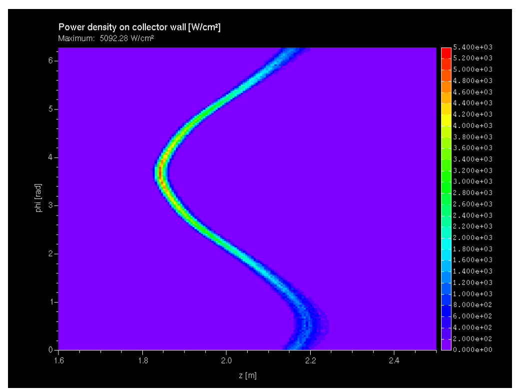
60°



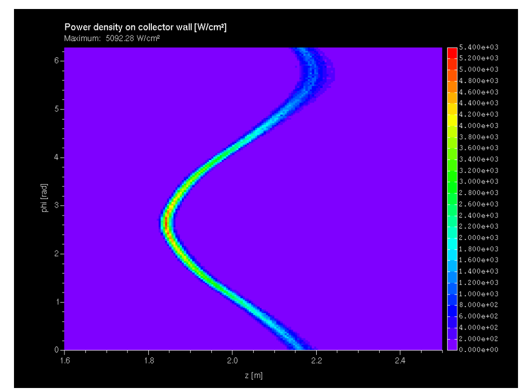
120°



180°



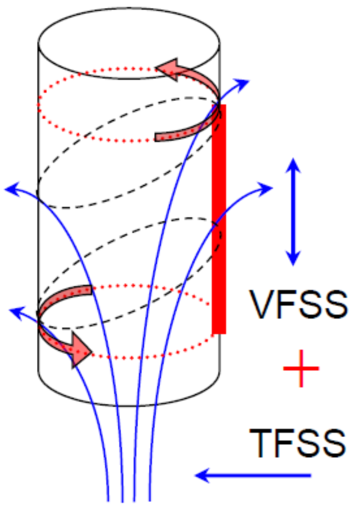
240°

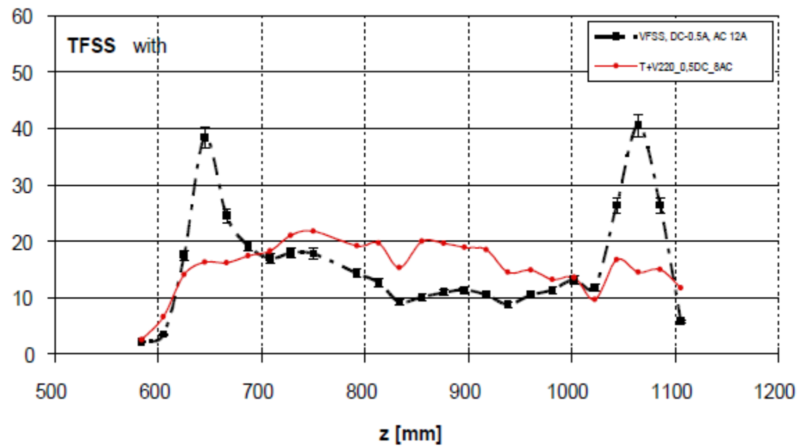


300°

Transverse Field Sweeping (III)

50 Hz rotating field (TFSS) combined with vertical field sweeping (VFSS)





Temperature increase TFSS and VFSS (red) and profile for VFSS only (black).

- TFSS only does not solve the problem completely
  → combine VFSS and TFSS
- Obtain smooth distribution, increase collector capability (factor 1.6 – 2
- Modulated TFSS satisfies the demands for multi-MW gyrotrons)

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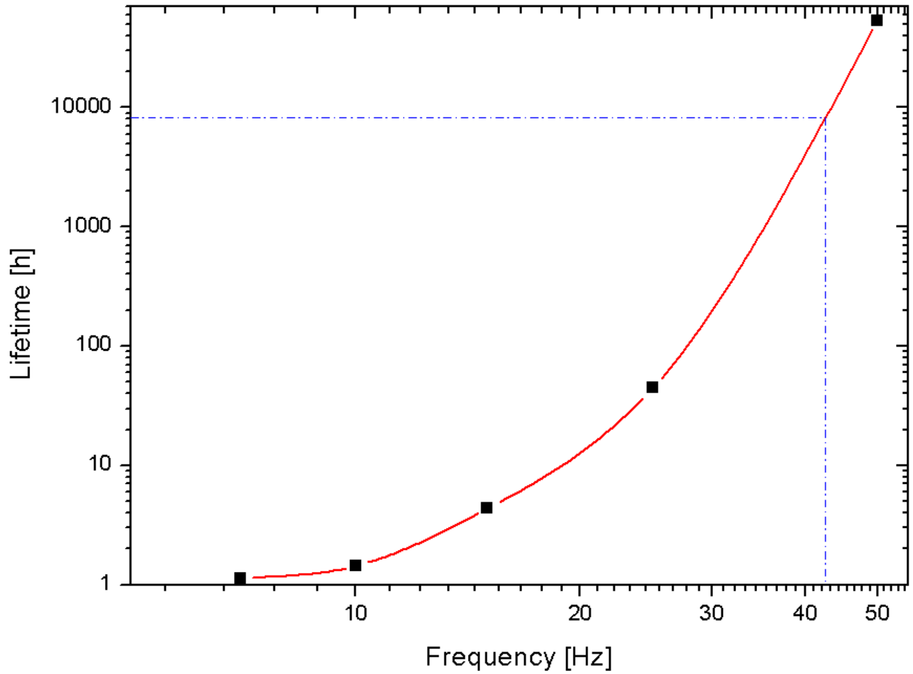
Simulation and Lifetime Estimation Results VMFS - Sweeping Frequency -

Cu-OFHC	7 Hz	10 Hz	15 Hz	25 Hz	50 Hz
T_{max} [°C]	358	344	330	313	300
ΔT [K]	113	97	78	57	31
$\Delta\varepsilon$ [%]	0.17	0.144	0.1043	0.0684	0.0352
$\Delta\sigma$ [MPa]	44	42	38	33	28

Cu-OFHC	Lifetime [h]
7 Hz	1.14
10 Hz	1.44
15 Hz	4.36
25 Hz	44.61
50 Hz	53 800



VMFS is limited to low frequencies

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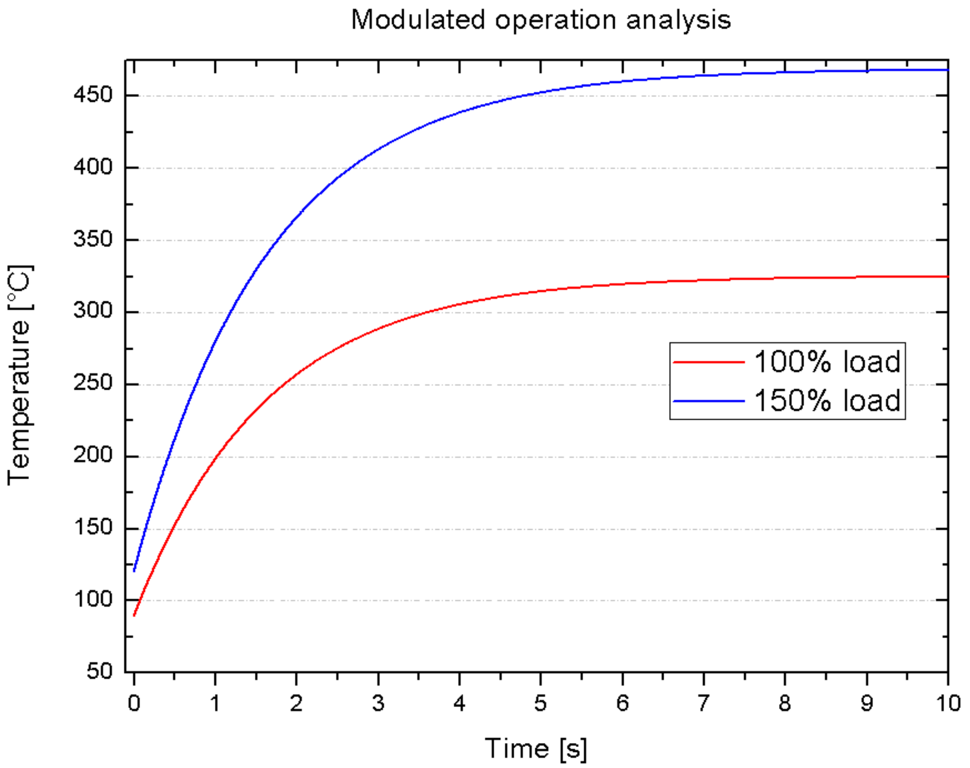
Simulation and Lifetime Estimation Results TMFS (50 Hz)

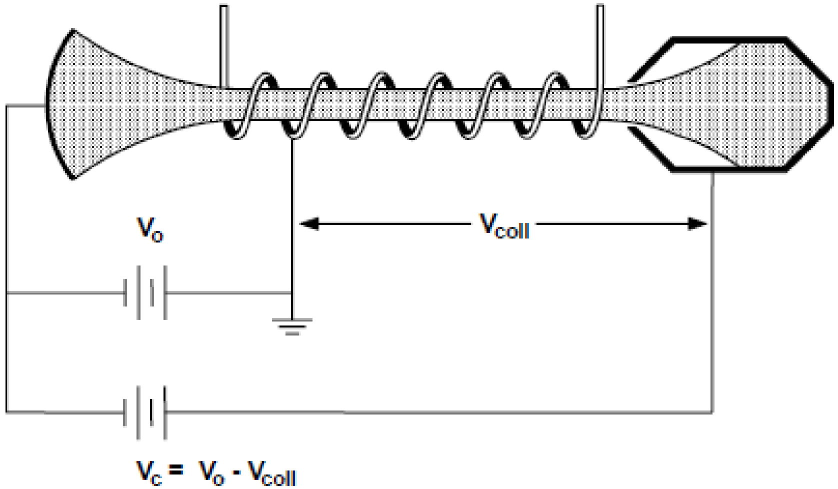
Cu-OFHC	100 % load	150 % load
T_{max} [°C]	315	468
ΔT [K]	17.7	28.3
Δε [%]	0.0291	0.0488
Δσ [MPa]	21	22

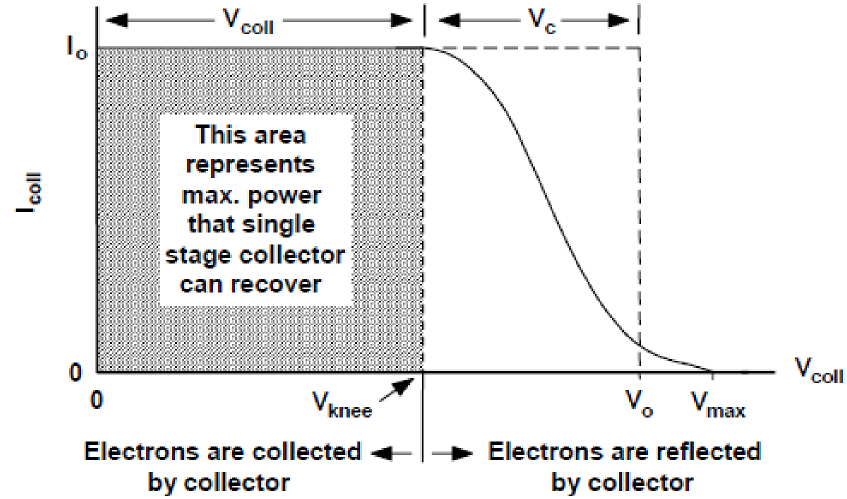
Cu-OFHC	Lifetime [h]
100 % load	550 000
150 % load	811.1



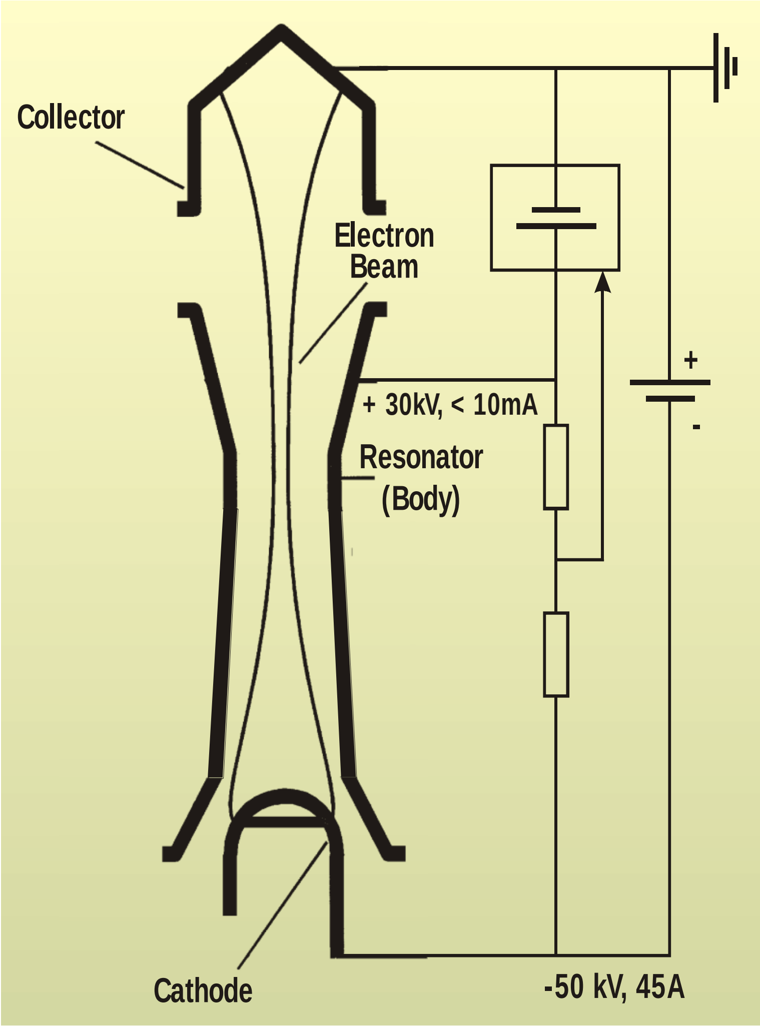
Power Recovery with Single-Stage Depressed Collector

- The maximum depression voltage is limited by the slowest electrons
- If the collector voltage is depressed too much the slower electrons will be reflected → collector current decrease, body current increase
- Excessive body current will damage the RF structure.
- Reflected electrons travelling back through the tube induce noise
- Single-stage depressed collector recover 30% to 40% of the power in the spent beam.
- For recovering a large fraction (over 80 %) without reflected electrons a multi-stage depressed collector is necessary.





Single-Stage Depressed Collector (SDC)



Energy recovery:

- Increased efficiency

Significant cost reduction:

- Power supply system
- Cooling system

Less X-rays

$V_{acc} = V_{cathode} - V_{body}$

$-80\ kV = -50\ kV - 30\ kV$

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Single Stage Collector (170 GHz 1 MW Gyrotron)

State-of-the-art: SDC

- $\eta_{total} \approx 50\ \%$

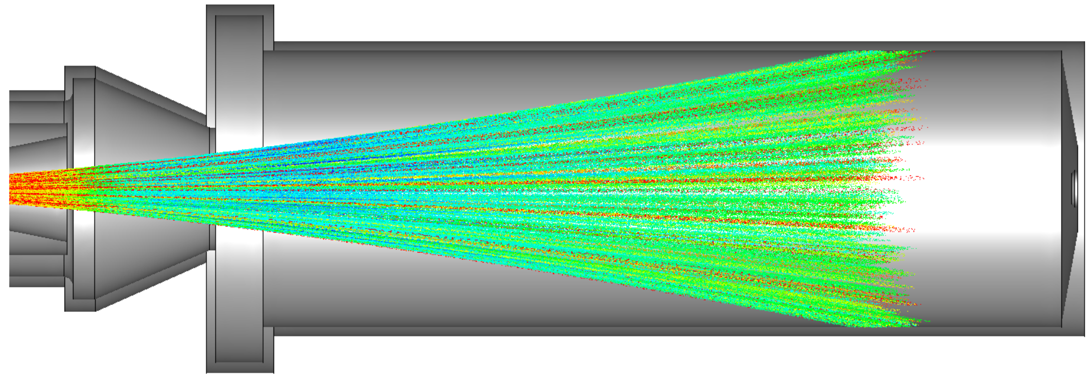
Targeting: $\eta_{total} > 60\ \%$

- MDC required

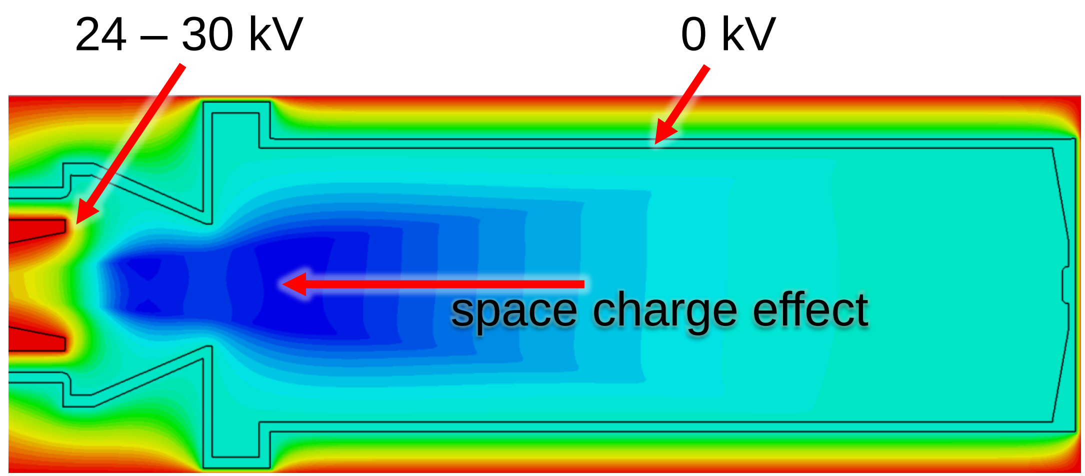
Main difficulty for MDC

- Confinement of the strong magnetic field

MDCs for gyrotrons are still under conceptual investigation



- Electrons (CST Particle-in-Cell simulation)



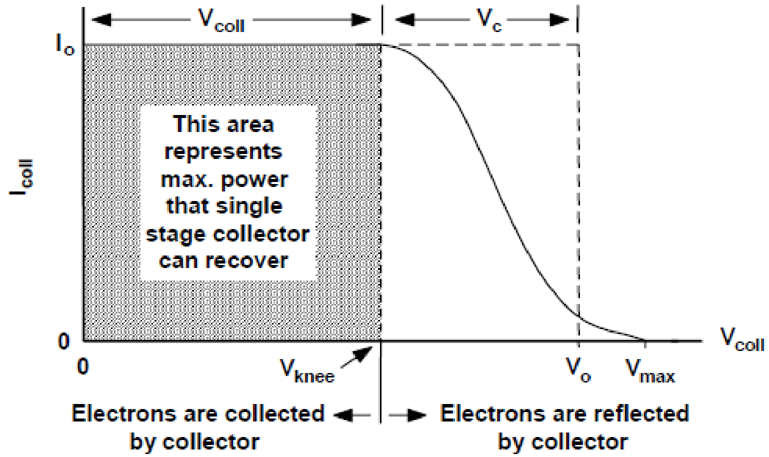
- Electrostatic potential

Power Recovery with Multi-Stage Depressed Collector (MDC)

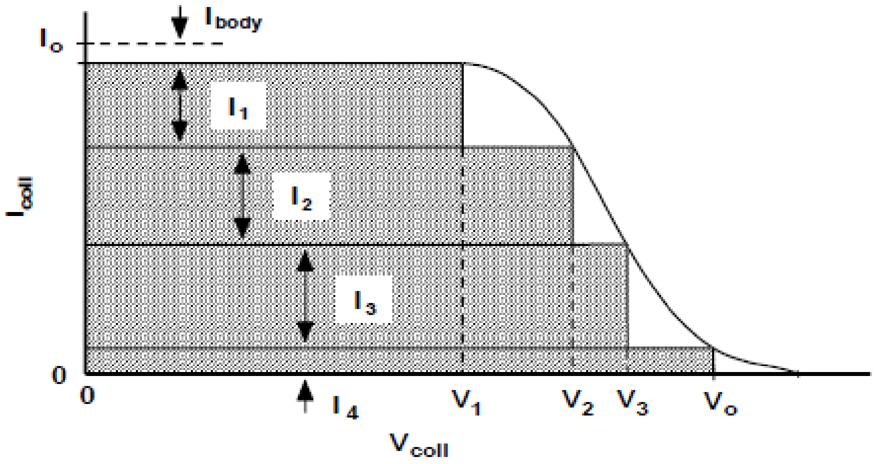
- Basic principle of multistage depressed collector
  - Sorting of electrons according to their energies
  - Avoiding a flow of secondary electrons and reflected electrons
- Sorting Electrons
  - After RF interaction the electrons have a wide energy dispersion (35-140 %)
  - For an efficient collector system, it is necessary to spatially separate the electrons with different energies
  - In conventional microwave tubes, electrostatic or magnetic rfocusing systems are employed in the collector region to sort out the electrons.
- Secondary electrons
  - Secondary electrons are emitted by the impact of primary electrons
  - Creation of a secondary electron flow between the electrodes of the collector → reduction of the efficiency
  - Suppression:
    - Material with low secondary emission coefficient (anti-secondary coating)

Comparison of SDC and MDC

Single-stage depressed collector



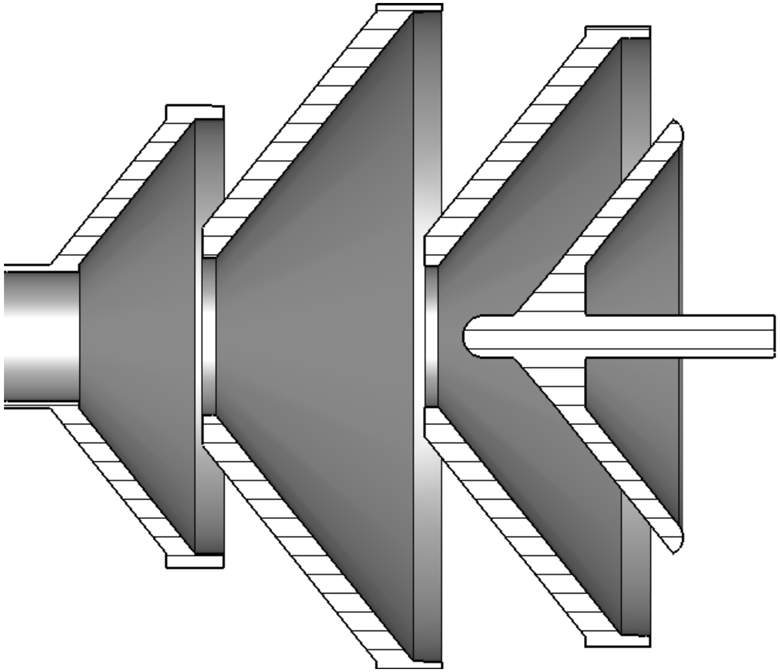
Multi-stage depressed collector



The area under a curve represents the power available for recovery by the collector. To recover a large amount of the electron beam, the collector must be designed to sort the electrons into various energy classes. The electrons in each energy class must be collected on an electrode at a voltage that recovers as much of that energy as possible

Analog to the Quality Sorting of Table Tennis

source: youtube



- Sort by Tennis Quality
- Sort by Electron Energy

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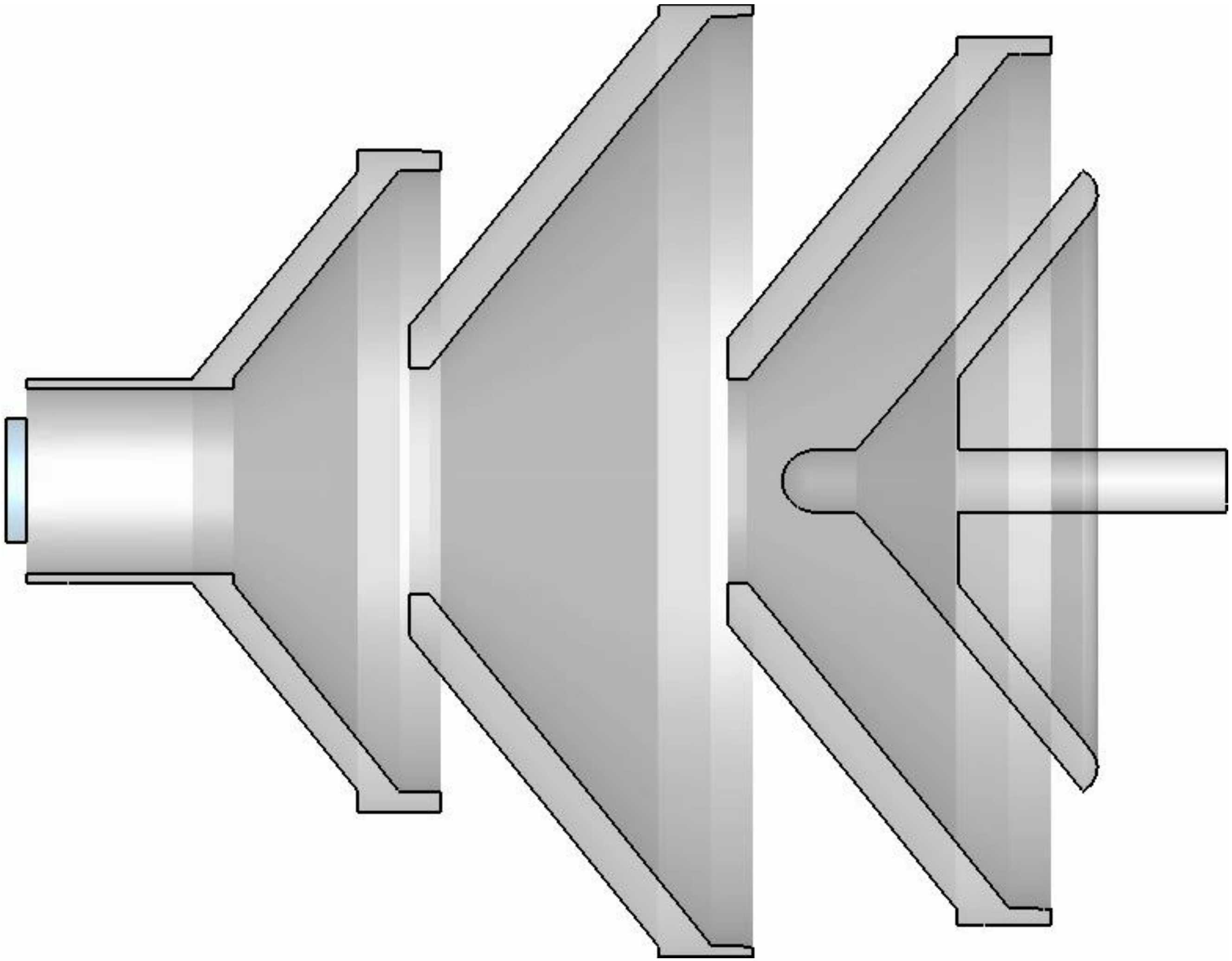
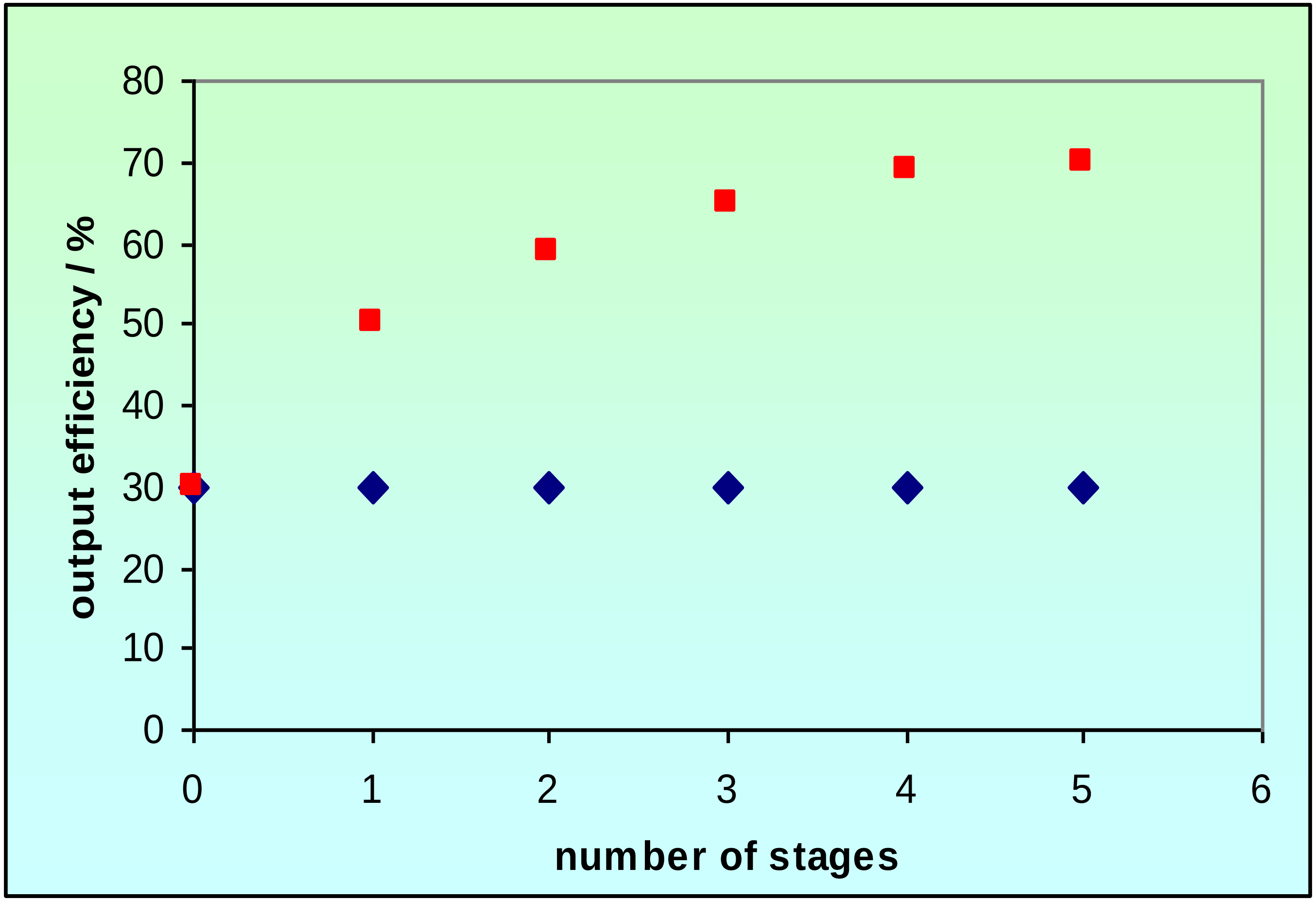
Trajectories in a MDC for Pencil Beam



- Without B-Field
- Potential depends only on position.
- Secondary electrons are
  - Reflected,
  - Bounced to previous electrodes, reducing efficiency.

Efficiency with Multi-Stage Depressed Collectors

Gyrotron parameters: U_c = 80 kV, I_b = 21.5 A, α = 1.24; P_{rf} = 0.635 MW



Internal losses (~ 10%) included.

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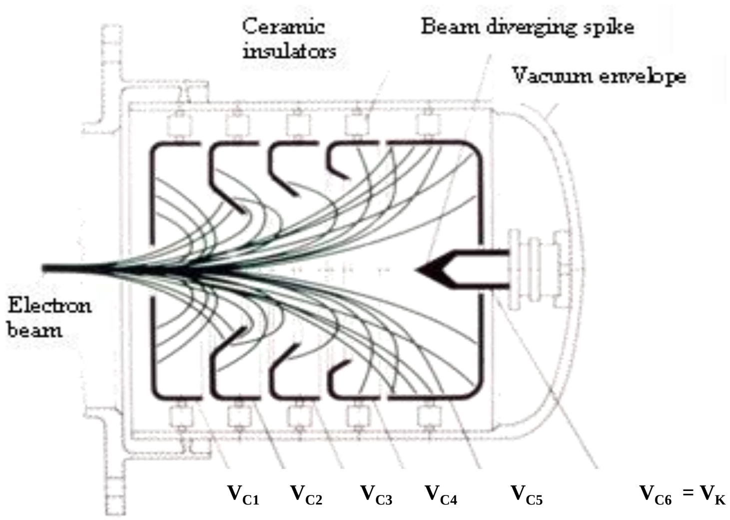
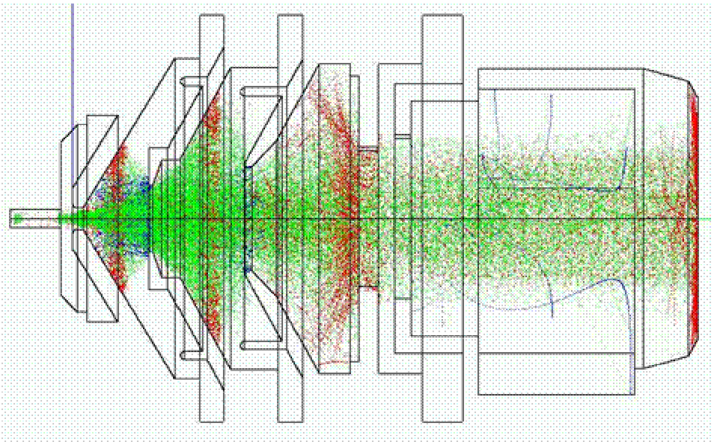
Electrostatic Collectors

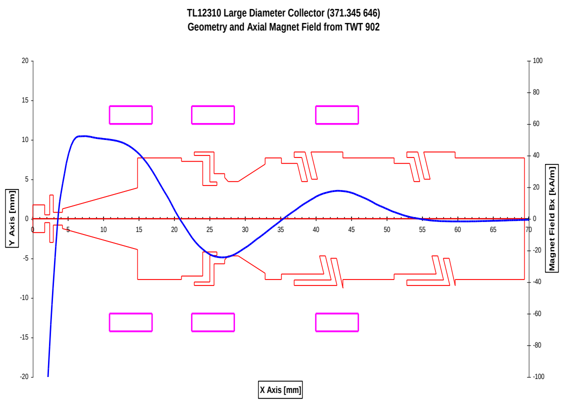


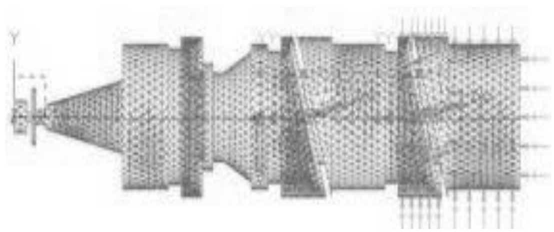
Electron trajectories in a 6-stage (5 stages + 1 spike on cathode potential) collector as it was used in the 1980s for the radiation cooled 250 W space TWT TL 12250. It achieved typically 48% total efficiency.



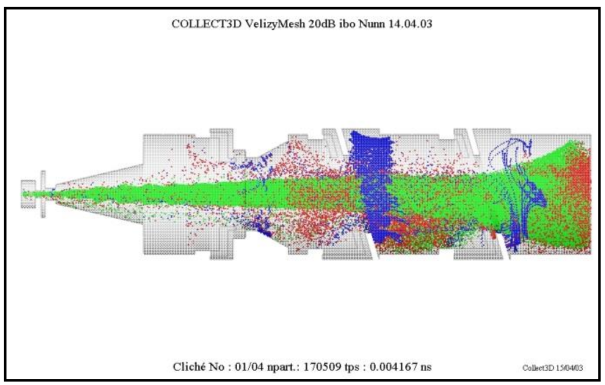
Distribution of primary (green), reflected (blue) and secondary (red) electrons in an electrostatic 4-stage collector simulated with the Thales Electron Devices PIC program Collect 3D for a 150 W Ku-band TWT (68% total efficiency).

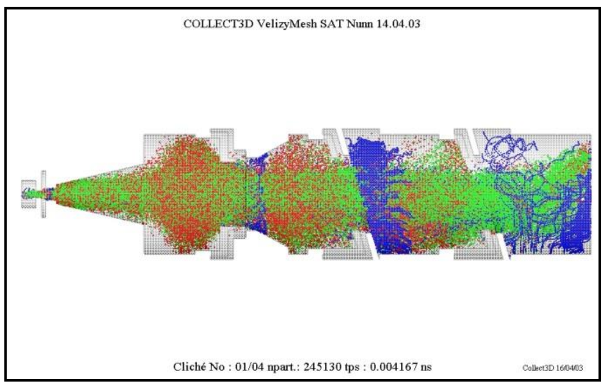
Magnetically Focused Collectors





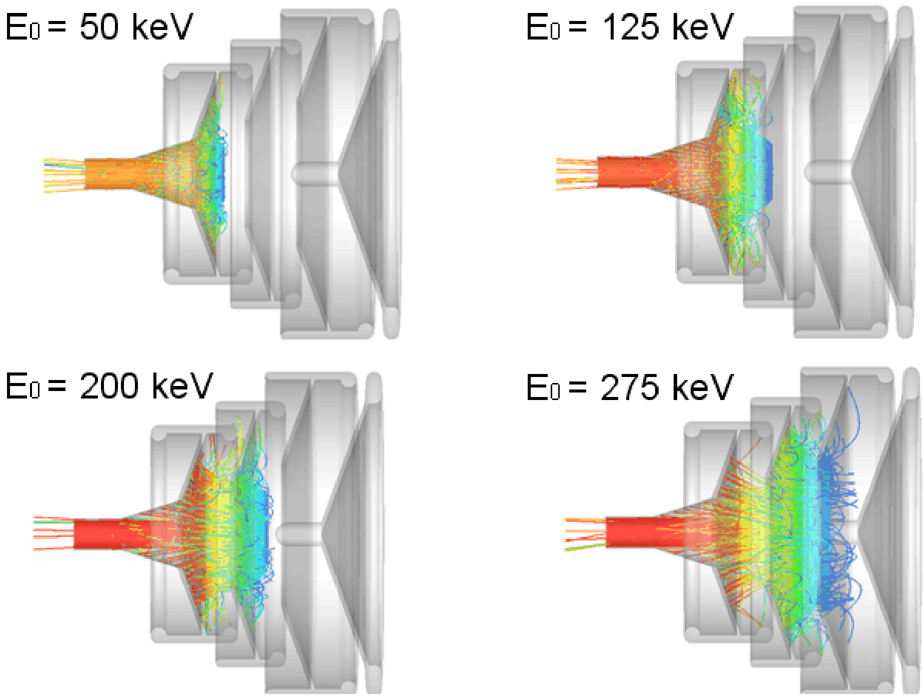
Collector geometry, axial magnetic field and simulation mesh of a magnetically focused 4-stage collector for a 300 W Ku band TWT (the transverse magnetic fields are not shown).





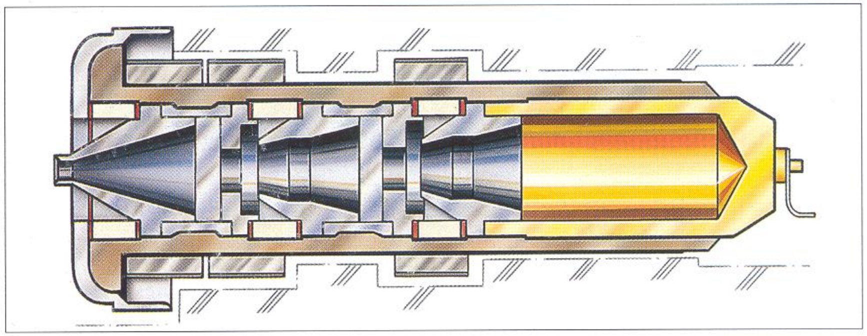
PIC-simulation of electron distribution in the **magnetically focused** 4-stage tilted field collector at zero drive (left) and saturation. Primary (green), reflected (blue) and secondary (red) electrons are simulated with the Thales Electron Devices PIC program Collect 3D.

Multi Stage Depressed Collector

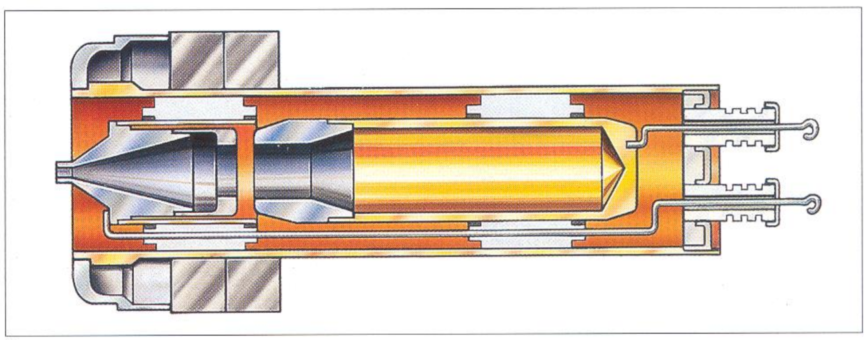


Depressed Collector with four different initial beam energies.

Depressed Collectors



1



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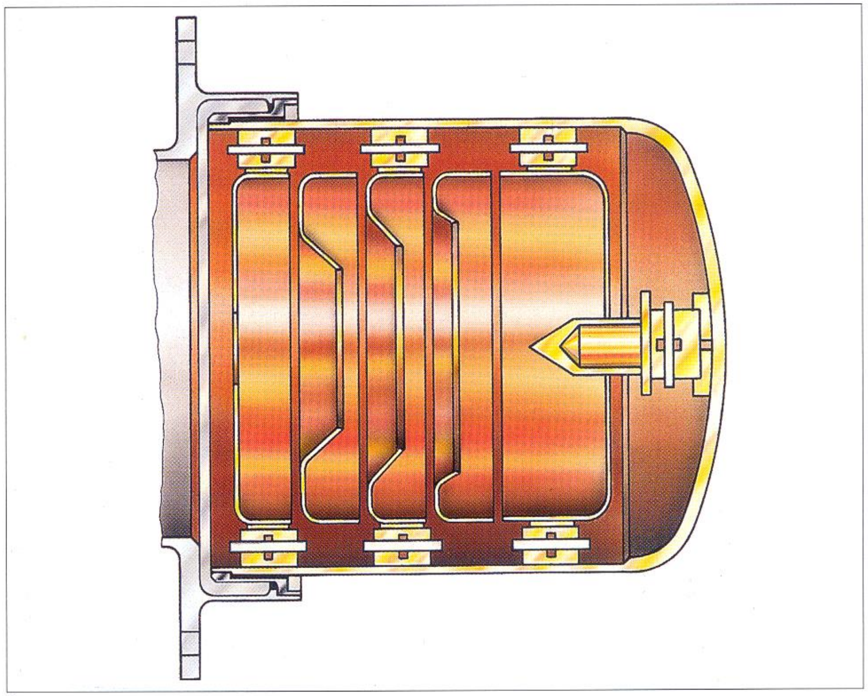
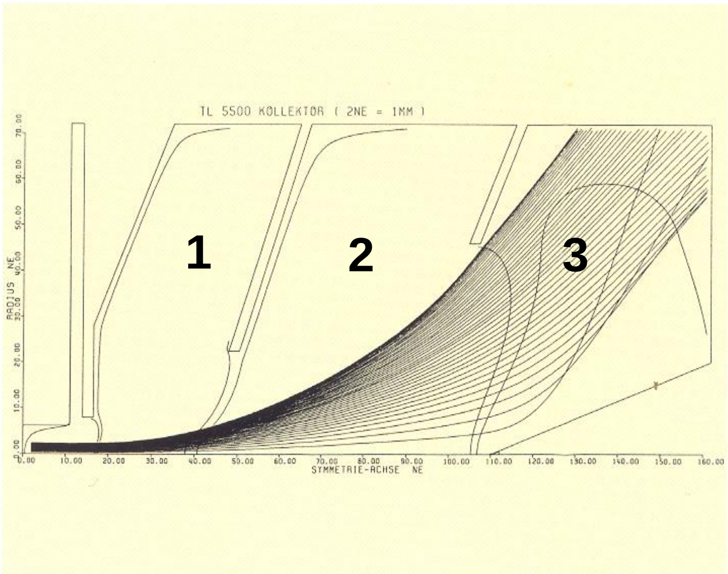
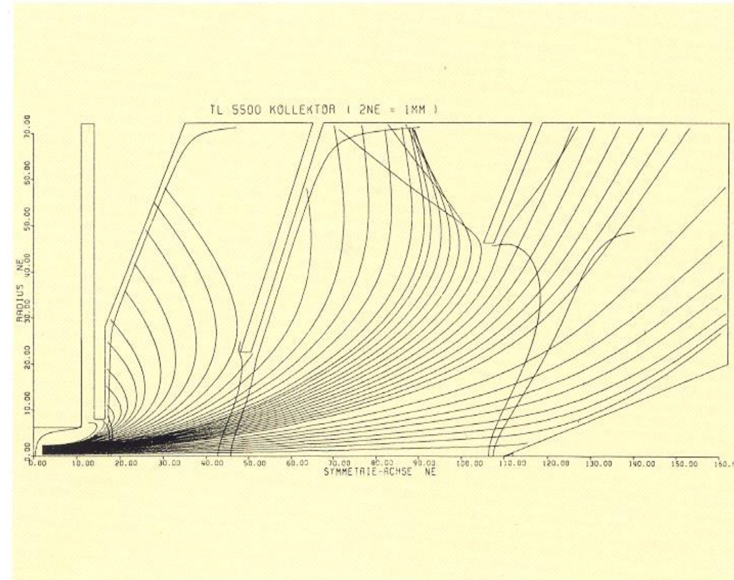


3

$$P_{C,diss} = \sum_i I_{Ci} \cdot V_{Ci} - P_2$$

Simulation Calculations on a 3-Stage Depressed Collector



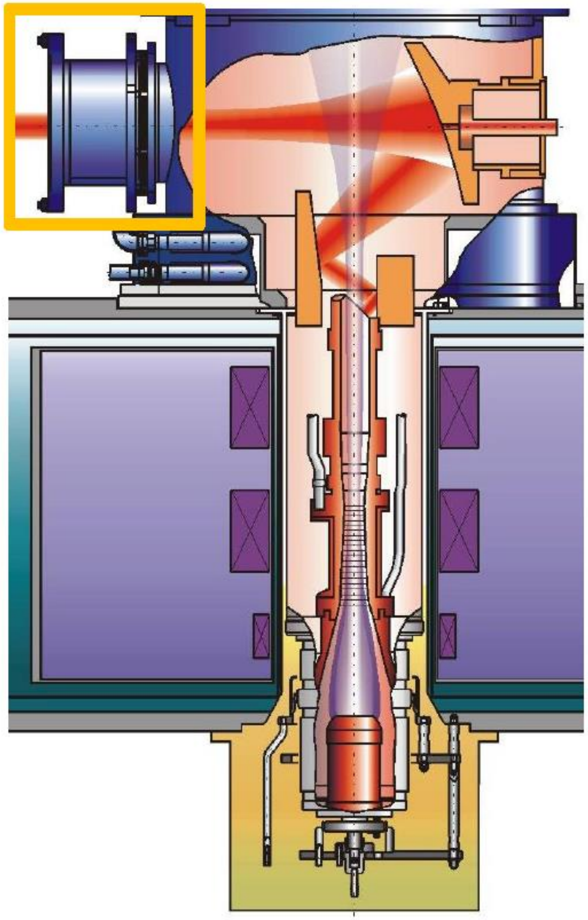


Zero drive: non-modulated e-beam

All electrons reach the 3rd stage

Saturated gain: maximum modulation of e-beam

All 3 stages catch electrons



Section 2.3

BASICS OF VACUUM OUTPUT WINDOWS

Definition

The window acts as a vacuum barrier and exit for the RF-beam and
has to be fabricated from (electrically non-conducting) ceramics.

For high-power long-pulse tubes it has:

- to be low-loss material
- to have very good heat conductivity
- to have high mechanical strength
- to have low temperature dependence of parameters

Window Material Characteristics

Values at room temperature (in brackets those at 77 K)
p.c. = poly-crystalline; s.c. = single-crystalline

Material	Sapphire s.c.	Silicon (s.c.) Au-doped	Diamond (p.c.)	BN (p.c)	SiC (6H)
Thermal Conductivity: W/mK	40 (900)	150 (1300)	**2000 (10000)**	55	330
Thermal Expansion: $10^{-6}K^{-1}$	5.5	2.5	1	3	4.3
Ultimate Bending Strength: MPa	410	1000	450	80	440
Permittivity (145 GHz)	9.4	11.7	5.67	4.7	9.92
Loss Tangent: $\tan(\delta)$ 10^{-5} (145 GHz)	20 (0.57)	0.35 (0.4)	**2 (<1)**	115	7
Specific Heat Capacity c_p [J/g K]	0.8	0.7	0.5	0.8	0.38
Power Capacity (a.u.)	0.09 (71)	106 (907)	106 (441)	0.05	0.63

Despite the costs, modern gyrotrons use synthetic diamond disks (chemical vapor deposition: CVD).

The gyrotrons at CEA (Cadarache) are equipped with LN_2-cooled sapphire disks

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CVD-Diamond Vacuum Windows (1-2 MW)

Commercially available CVD-diamond disks
Element 6 (De Beers), Diamond Materials (FhG-IAF)

diameter $\leq$ 120 mm
thickness $\leq$ 2.5 mm } up to 420 carat

$\tan\delta \approx 2 \cdot 10^{-5}$ = const.
$\varepsilon_r' = 5.67$ = const. } for 300 – 400 K

very small thermal expansion

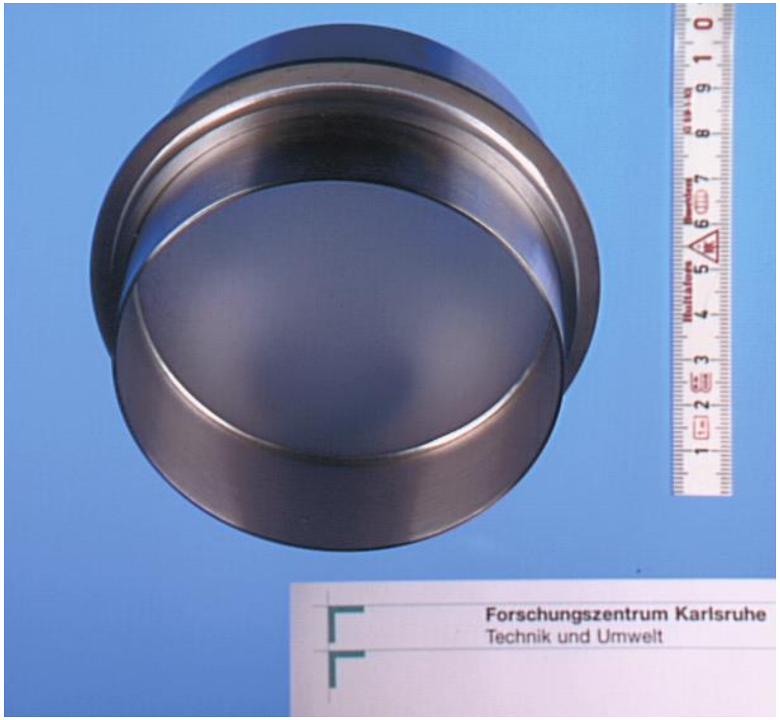
thermal conductivity (T = 300K) $\approx$ 1900 W/m $\cdot$ K

mechanical strength $\sigma_B \approx$ 400 MPa

no influence of neutron irradiation ($< 10^{21}$ n/m^2)

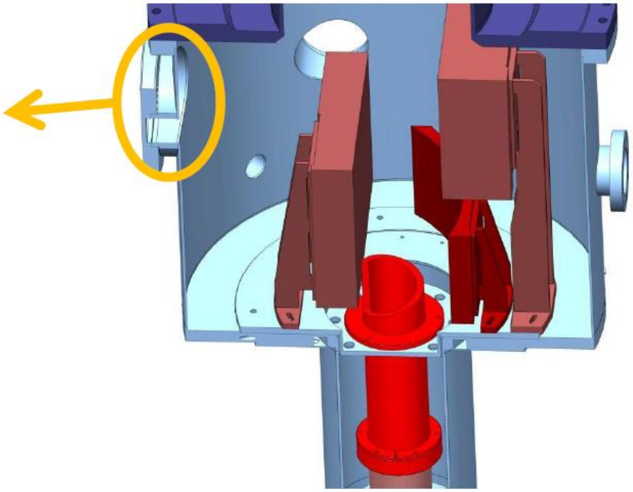
no influence of γ/X-rays (0.8 Gy/s)

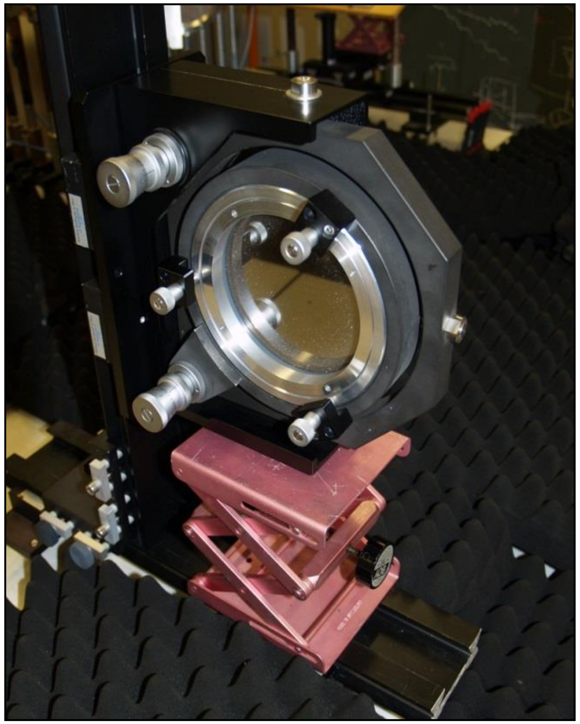
brazing technology available



Single Disk Window

CVD diamond windows are state of the art today
(CVD = chemical vapor deposition)





Diamond Window

$$\varepsilon_r = 5.67$$

$$d = 1.611mm$$

$$\varnothing = 106mm$$

CVD-Diamond Disks for the 10 MW, CW W7-X ECH System (∅ = 106 mm, t = 1.8 mm : 279 carat)

"The Centenary" (274 carat, 247 facets)

July 17, 1986

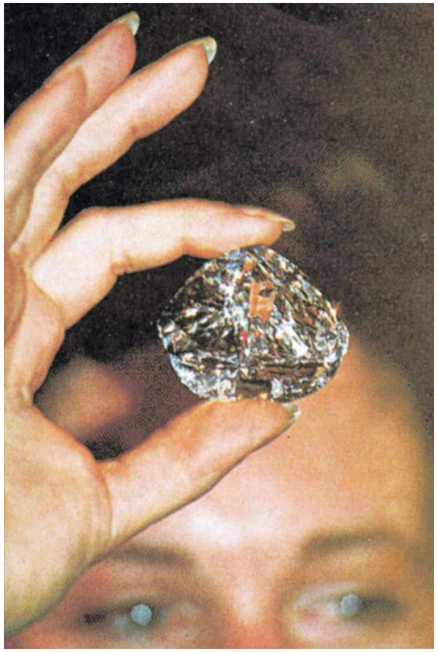
Premier mine in South Africa (DeBeers)

Celebration of the

Company's 100th year in March 1988

Chairman:

Julian Ogilvie Thompson



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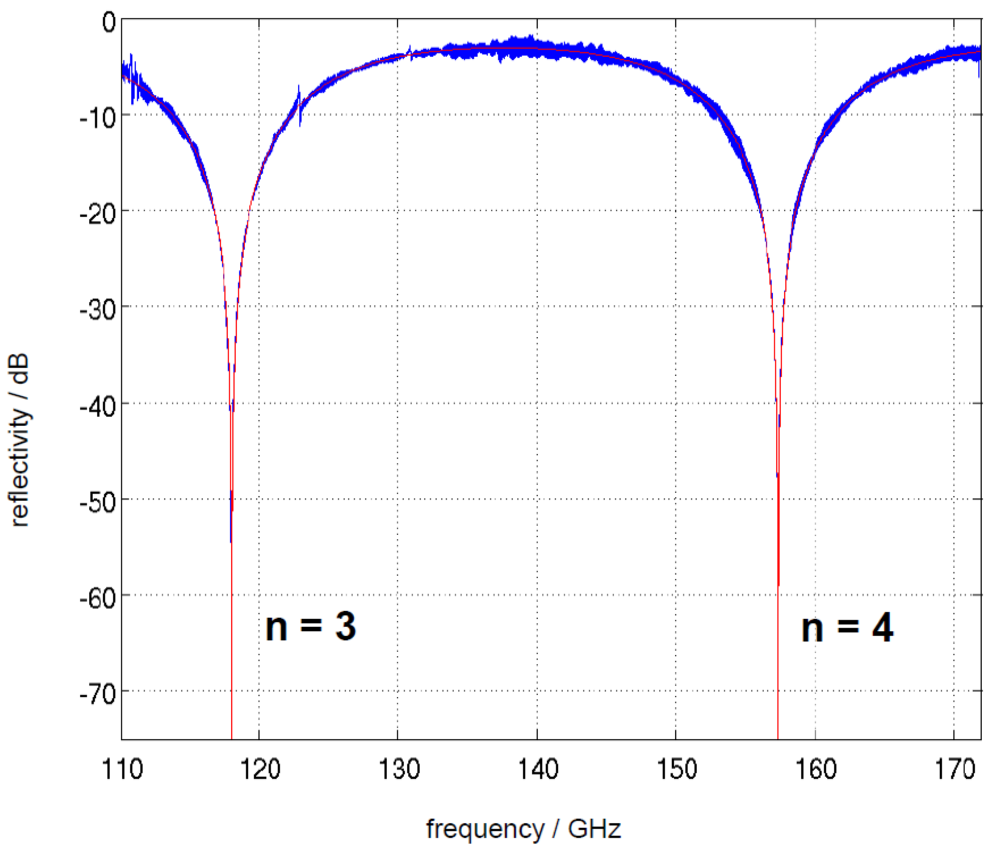
Window Measurement and Simulation (118 GHz)



$$\varepsilon_r = 5.67$$

$$d = 1.611 mm$$

$$\varnothing = 106 mm$$

The window reflection vanishes when the thickness is a multiple of λ/2:

$$f = \frac{n \cdot c}{2d\sqrt{\varepsilon_r}}$$

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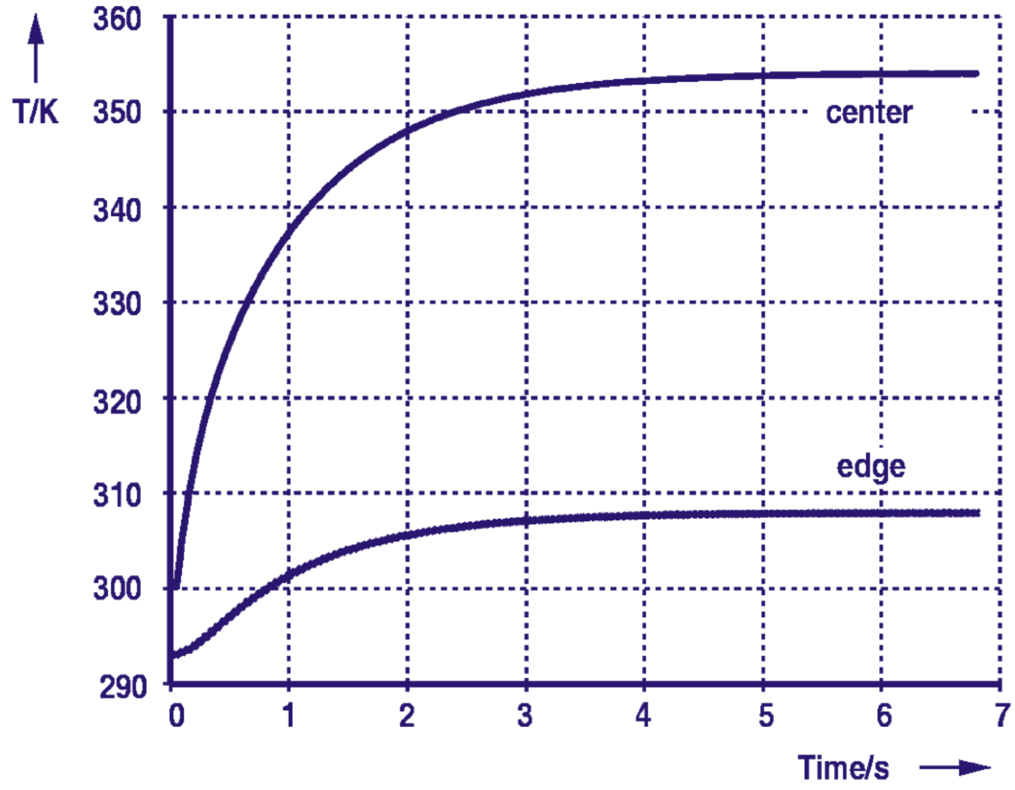
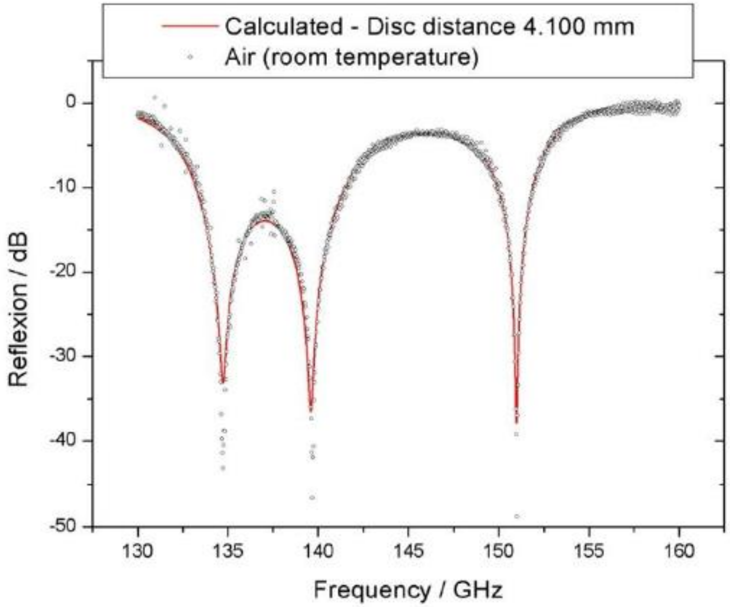
Window Temperature

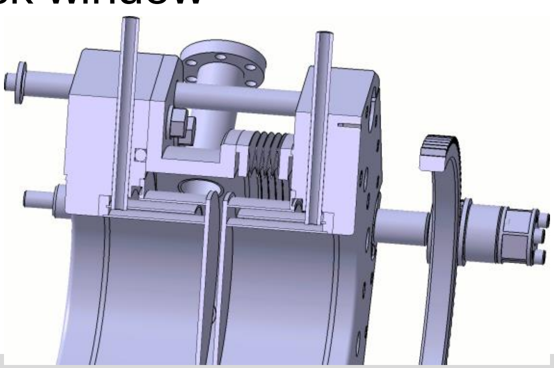
Time dependence of center and edge temperature of CVD-diamond window disk at 1 MW-mm-wave power



Tunable Double Disk Window



Reflection coefficient for a double disk window



Double Disk Matching:

Destructive interference: The wave reflected from one disk must cancel the wave reflected from the other (no phase step).

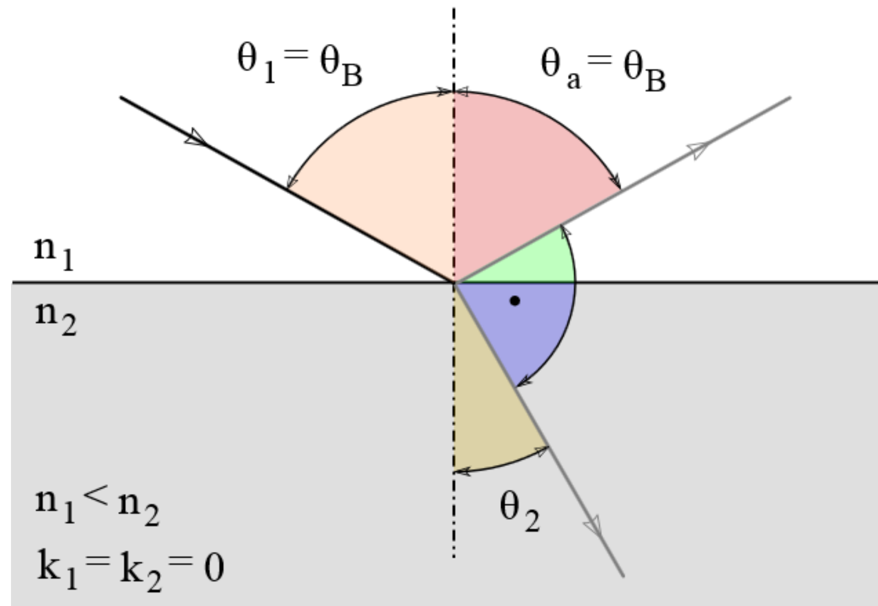
$$\frac{2d}{\lambda_r} + \frac{2d_0}{\lambda_0} = n + \frac{1}{2}$$

d_0: spacing of disks
d : disk thickness

By changing the distance between disks, the frequency can be matched to the window
→ No reflection
(multi-frequency gyrotron)

Brewster Law

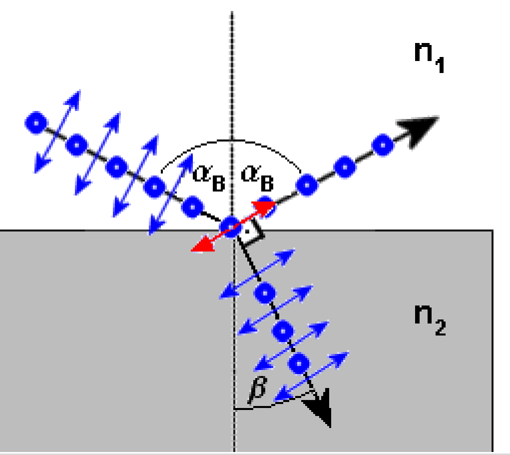
If the refracted and reflected beams are perpendicular to each other, than the reflected power is linearly polarized. The polarization is parallel to the surface. The incident angle is called Brewster-angle.



In other words:

For the Brewster angle, if the input beam does not have a polarization component parallel to the surface the reflection must be zero.

For the Brewster angle, a linearly polarized beam with the polarization perpendicular to the surface no reflections are present.



The Brewster angle is defined by: $\tan(\theta_B) = \epsilon_r^{1/2}$

For Diamond ($\epsilon_r = 5.67$) $\theta_B = 67.2$ degree

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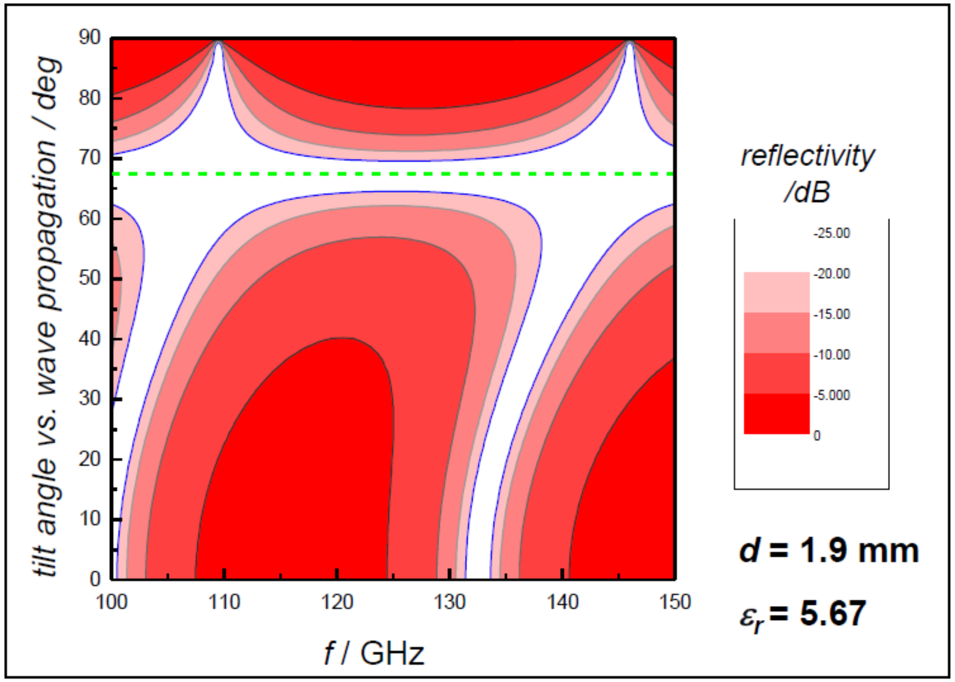
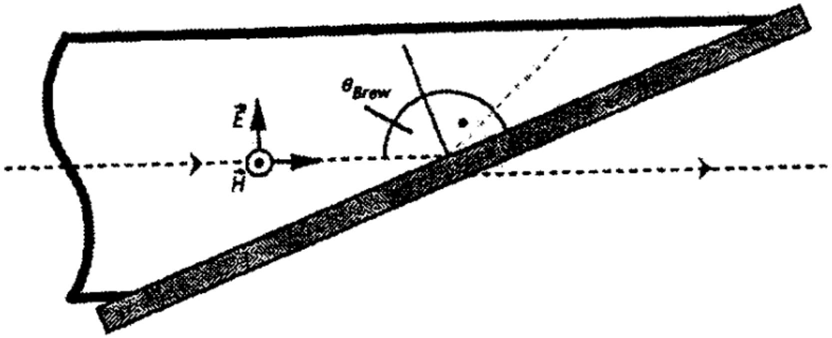
Broadband Brewster Window

The window reflection also vanishes for linearly polarized waves at the Brewster angle:

$$\theta_B = \tan^{-1}\sqrt{\epsilon_r}$$

with $\epsilon_r = 5.67$ and $\theta_B = 67.2$ deg.





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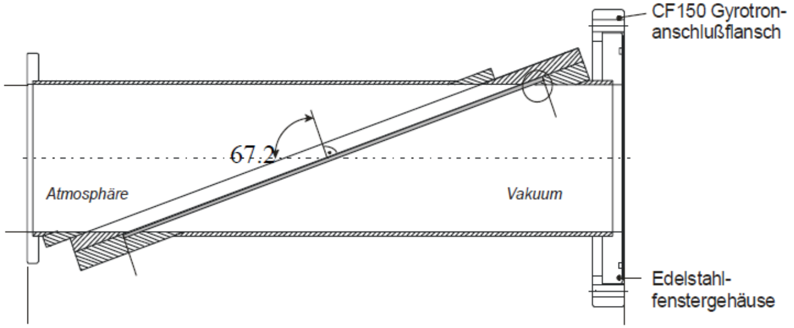
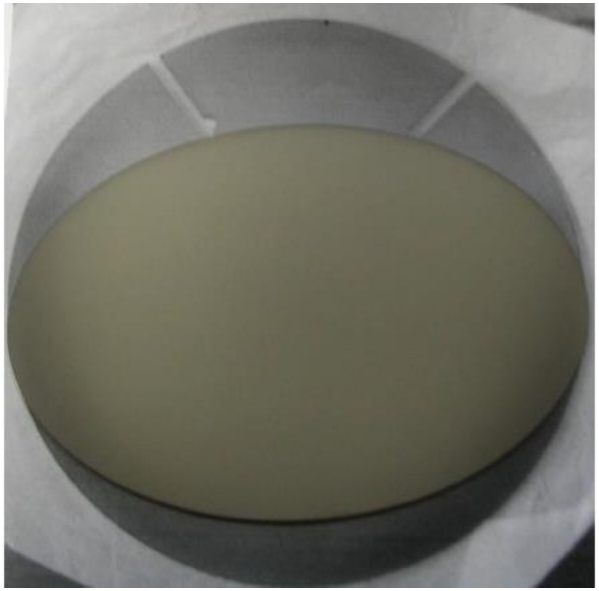
Broadband Brewster Window

For an aperture of 50 mm,
the diameter of 140 mm is needed

Brewster-window



Polarization would be downwards



Ellipse: 139mm x 95mm

A disk with a diameter of 140 mm has been fabricated by element Six (formerly DeBeers):

Thickness: 1.70 mm

Diameter: 140 mm

Due to problems during manufacturing, the disk had teo cracks which were stopped by laser cuts.

Nevertheless, an elliptic disk could be cut.

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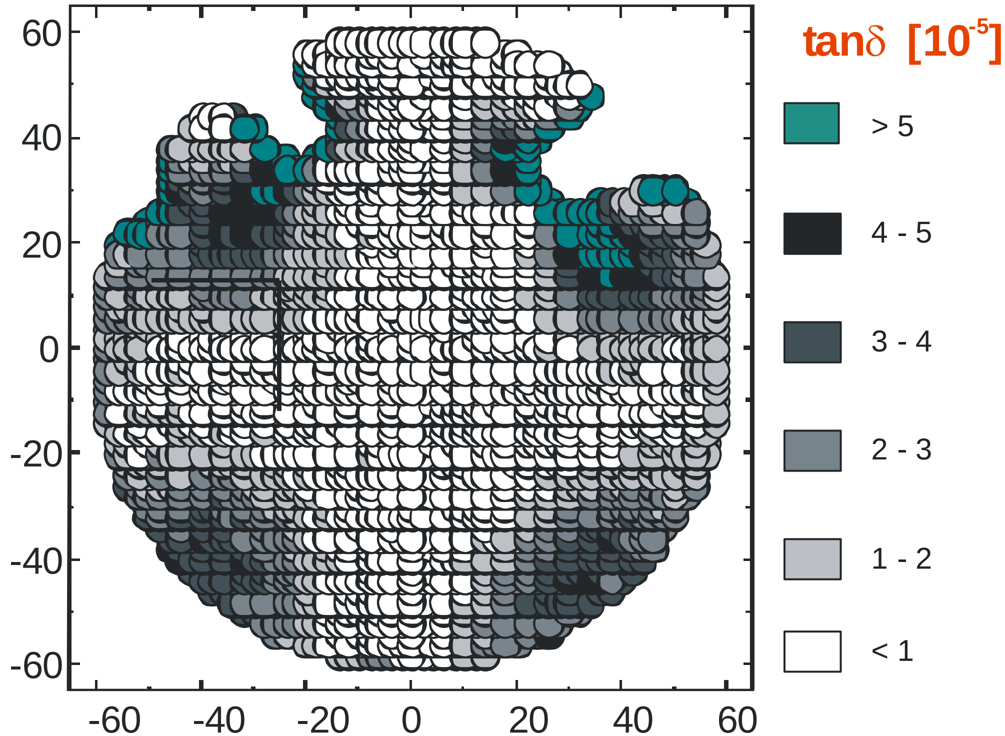
Loss Tangent of Brewster Disk

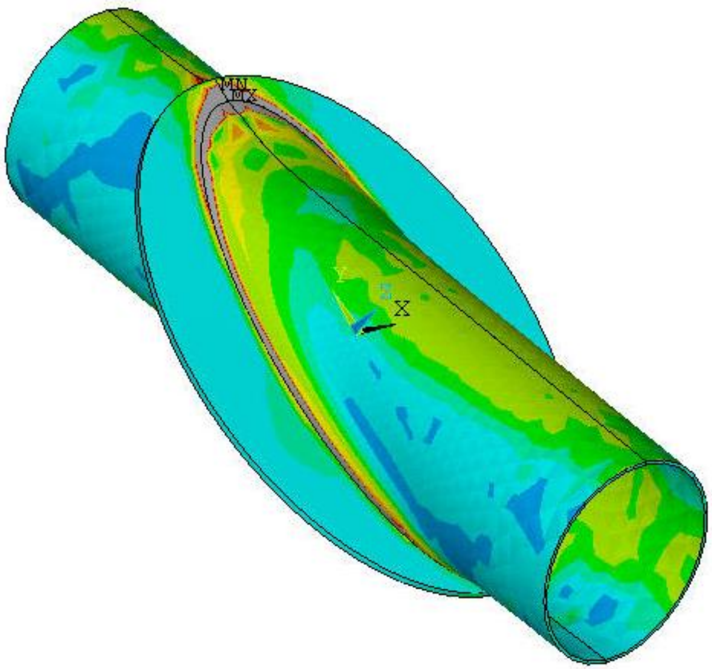


The elliptic part shows very low loss tangent.
The disk can be used for high-power gyrotrons.

Technical Realization of Brewster-Window

Brazing of (circular) diamond disks to copper cuffs is a standard procedure.

What about brazing of elliptical disks ?
Calculation of the stresses during brazing process have been performed (up to twice as high as for circular disks).



Window

- Disk (elliptic): 95 x 139 mm²
- Disk thickness S: **1.7 mm**
- copper pipe diameter (inner): **49 mm**
- copper pipe length: 240 mm
- copper thickness: **0.8 mm**

Problems:
Stresses
Shifts, Tolerances (leak tightness)

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