Status of the Gyrotron Multistage Depressed Collector Development at KIT

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Institute for Pulsed Power and Microwave Technology

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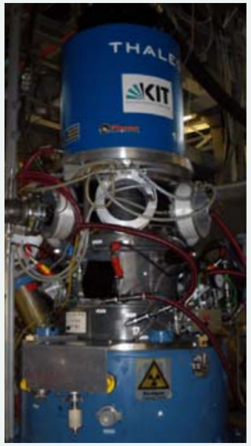
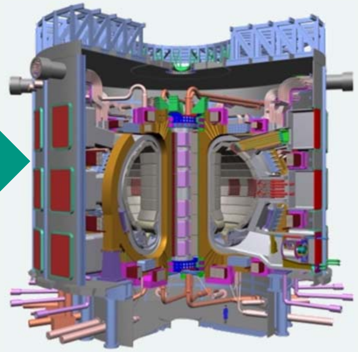
Motivation

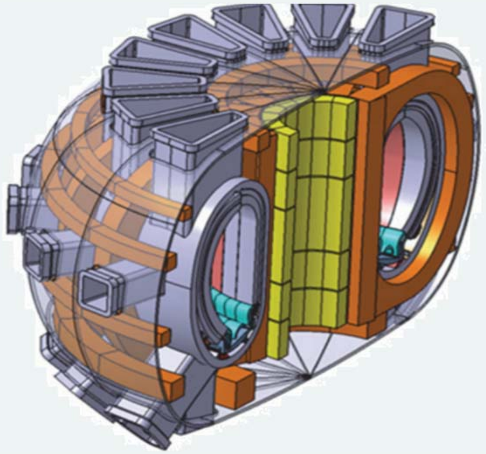
Today: ITER





- f = 170 GHz, P_{RF} = 1 MW
- Gyrotron η_{total} = 50 %

Future: DEMO



- f = 170 / 204 GHz, P_{RF} = 2 MW
- Requires gyrotron η_{total} > 60 %

For a 50 MW ECRH system, increase η from 50 % to 63 %

➔ **Saves 20 MW input power** ➔ increases fusion gain factor

Introduction: Gyrotron Efficiency

Definition of the gyrotron overall efficiency: $$\eta_{\text{total}} = \frac{\text{Output RF power}}{\text{Input DC power}}$$

Introduction: Gyrotron Efficiency

Interaction efficiency
$\eta_{int} \approx 35\ \%$

RF efficiency
$\eta_{RF} \approx 90\ \%$

Collector efficiency
$\eta_{col} \approx 60\ \%$ (single stage)

$$\eta_{total} = \frac{\text{Output RF power}}{\text{Input DC power}}$$

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Overall efficiency

$$\eta_{total} = \frac{\eta_{int}\ \eta_{RF}}{1 - (1 - \eta_{int})\ \eta_{col}}$$

Introduction: Gyrotron Efficiency

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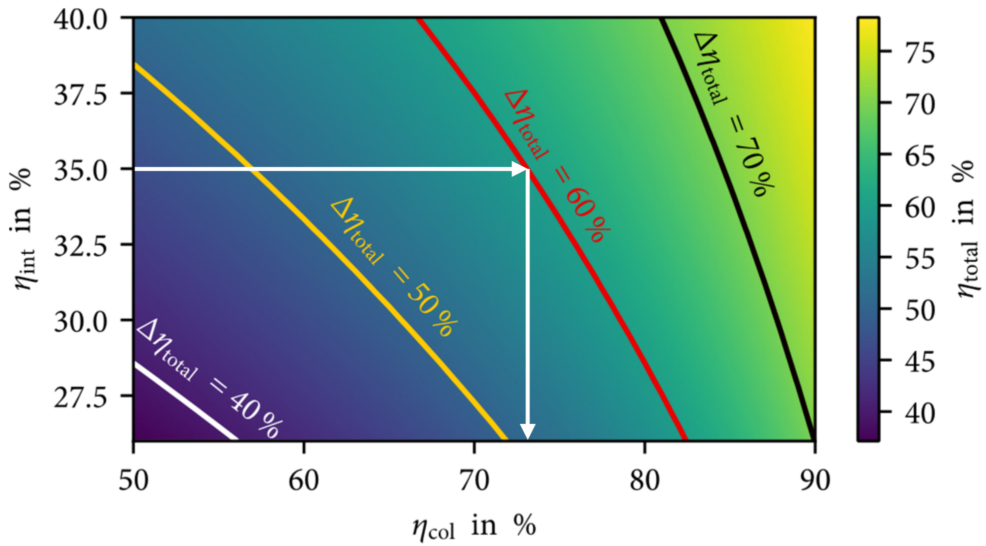
Overall efficiency

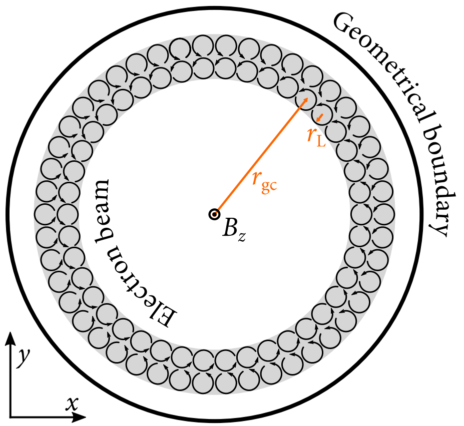
$$\eta_{total} = \frac{\eta_{int}\ \eta_{RF}}{1 - (1 - \eta_{int})\ \eta_{col}}$$

➔A collector efficiency of 74 % is required



Introduction: Spent Electron Beam

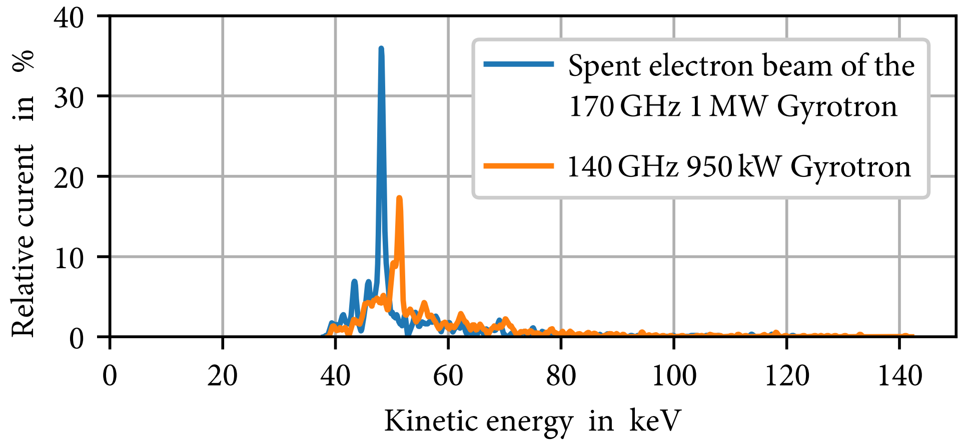
- The small-orbit hollow spent electron beam in gyrotron



- 45 A, 2.5 MW in the 170 GHz 1 MW gyrotron
- Magnetic field confines the electron beam
- At the end of the gyrotron cavity
  - $r_{\mathrm{gc}} \approx 9.9$ mm, $r_{\mathrm{L}} \approx 0.1$ mm , $B \approx 6.2$ T

  ➔ **High magnetic flux** (conserved in the most situations)

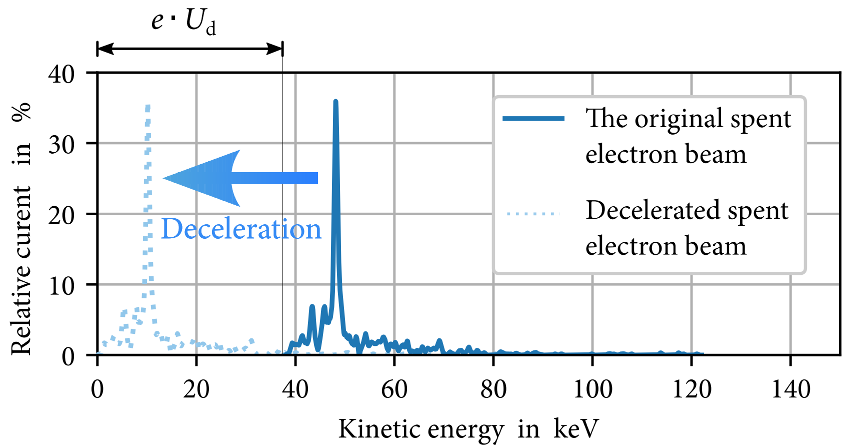
- Distribution of the electron kinetic energy



$$\eta_{\mathrm{col}} = \frac{\text{Recovered beam power}}{\text{Total beam power}}$$

Introduction: Depressed Collectors

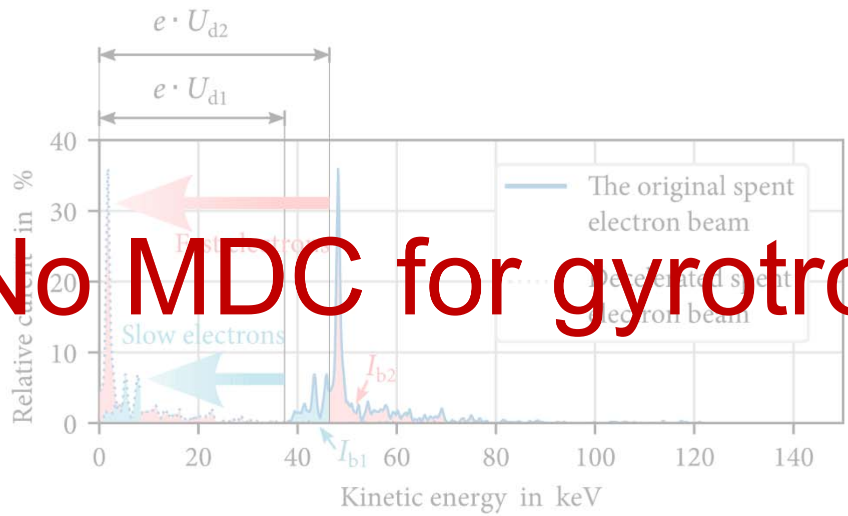
Single-stage **D**epressed **C**ollector (SDC)



Recovered beam power

$$P_{rec,SDC} = U_d \cdot I_b$$
$$= U_{d1} \cdot I_{b1} + U_{d1} \cdot I_{b2}$$

Multistage **D**epressed **C**ollector (MDC)



$$P_{rec,MDC} = U_{d1} \cdot I_{b1} + U_{d2} \cdot I_{b2}$$

$U_{d2} > U_{d1}$: An MDC recovers more power than the SDC.

➔ An MDC can further improve the efficiency

No MDC for gyrotrons exist

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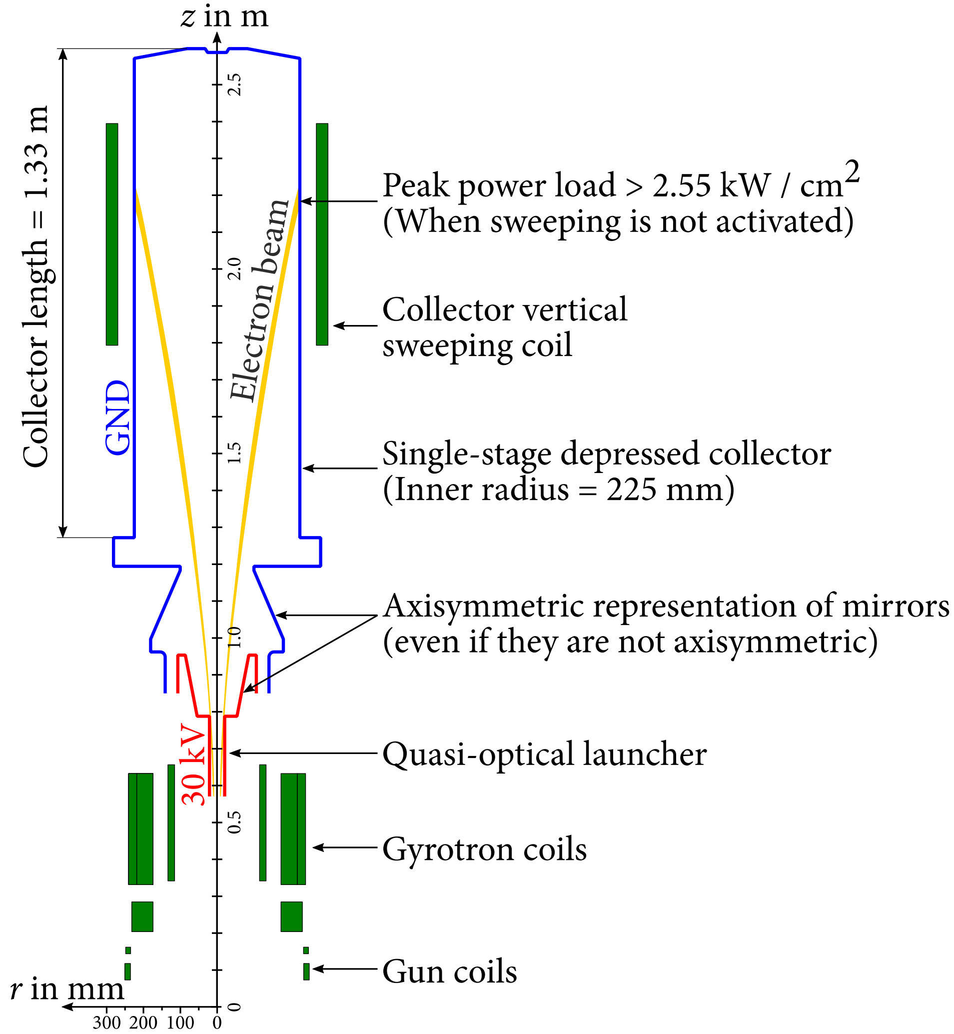
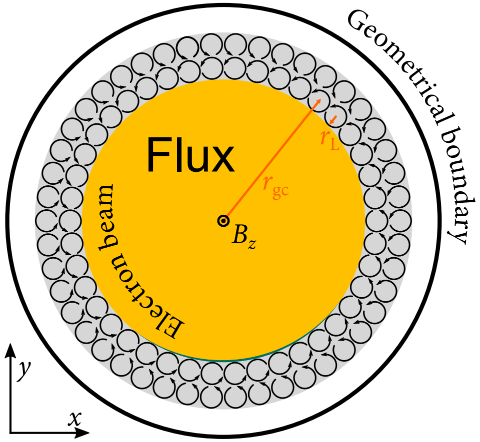
The Reference SDC

- Final target:
  170 GHz / 204 GHz, 2 MW coaxial gyrotron for DEMO
- However, taking the SDC of the 170 GHz 1 MW gyrotron as reference
  - 30 kV depression voltage
  - *L* = 1.33 m
  - *R* = 255 mm
  - Time-averaged power load (beam sweeping) < 500 W/cm²
- Extrapolation for the DEMO gyrotron will be discussed



Challenges for the Gyrotron MDC Concept

- Moderate magnetic field in gyrotron collector
  - B = 100 mT at the collector entrance,
    B = 10 mT at 1 m axial distance away from the entrance
  - ➔ concepts for TWT MDCs (require $B \ll$ 1mT) do not work
- Small orbits electron beam enclosing a high magnetic flux



Example: reducing the B field to 1 mT requires a radius of

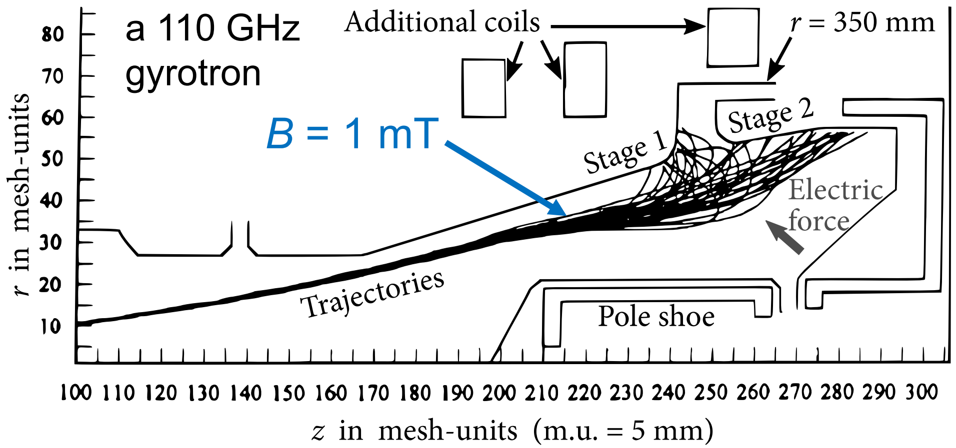
$$R = \frac{\pi\,(9.9\ \text{mm})^2\ 6.2\ \text{T}}{\pi\ 0.1\ \text{mT}} = 0.78\ \text{m}$$

➔ Results in a large collector size

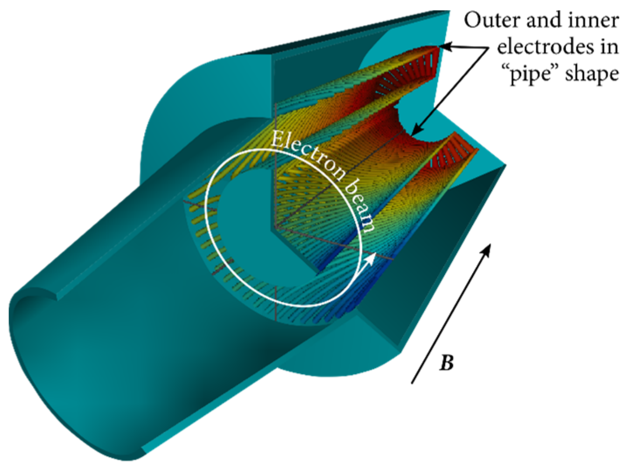
- Busch's theorem indicates that the sorting of orbits is not possible in an axisymmetric system with moderate magnetic field
- In addition, there is a high beam power

Proposals Prior to This Work

There were two kinds of design proposals prior to this work



[Singh 1999 IEEE Plasma Sci.]



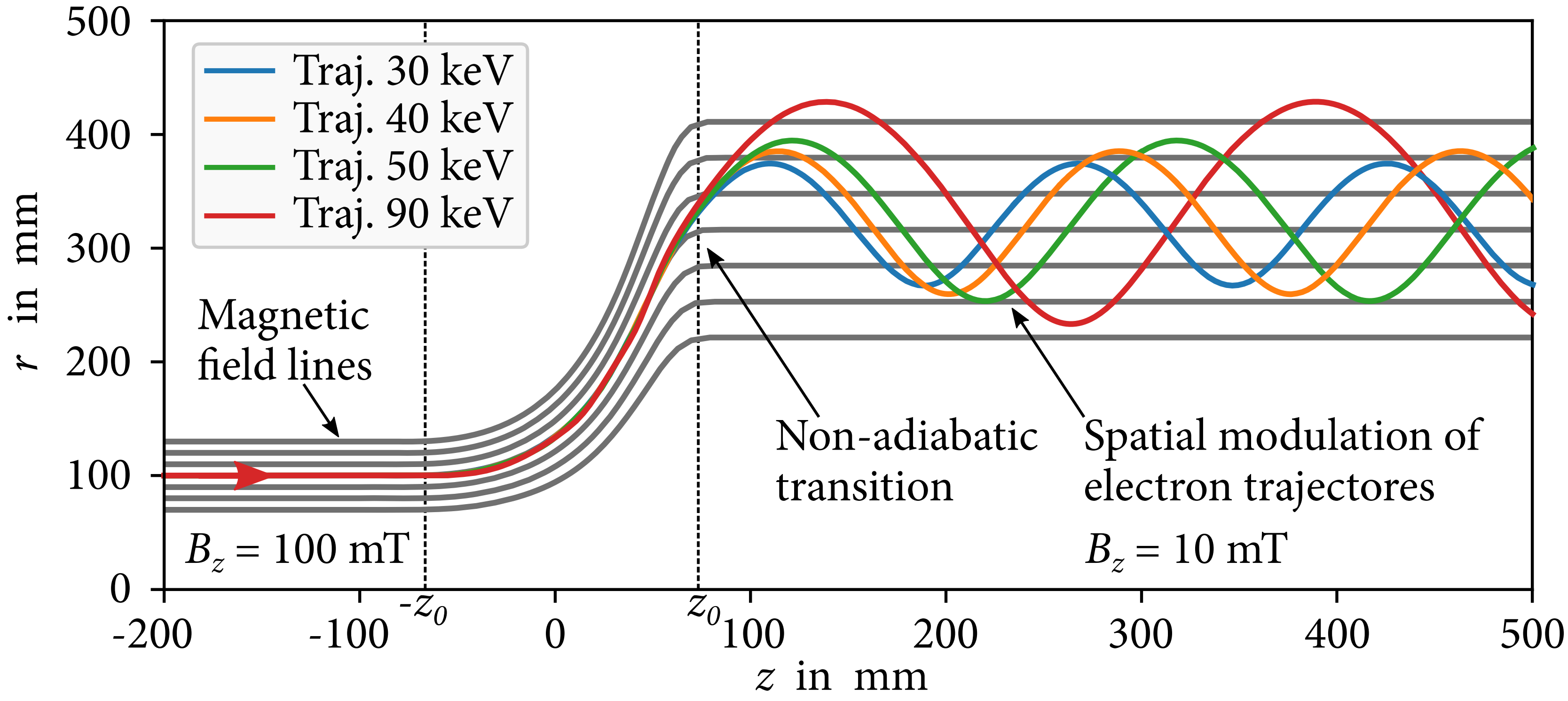
[Pagonakis 2008 IEEE Plasma Sci.]

- Axisymmetric (2D)
- B < 1 mT
- Electric field dominates the sorting
- Hard to scale to a higher frequency

- Non-axisymmetric (3D)
- B = 26 mT
- Use $E \times B$ drift to sort electrons
- Lack of 3D simulation possibility at that time, therefore infinite stages

MDC Type 1: the Axisymmetric Concept

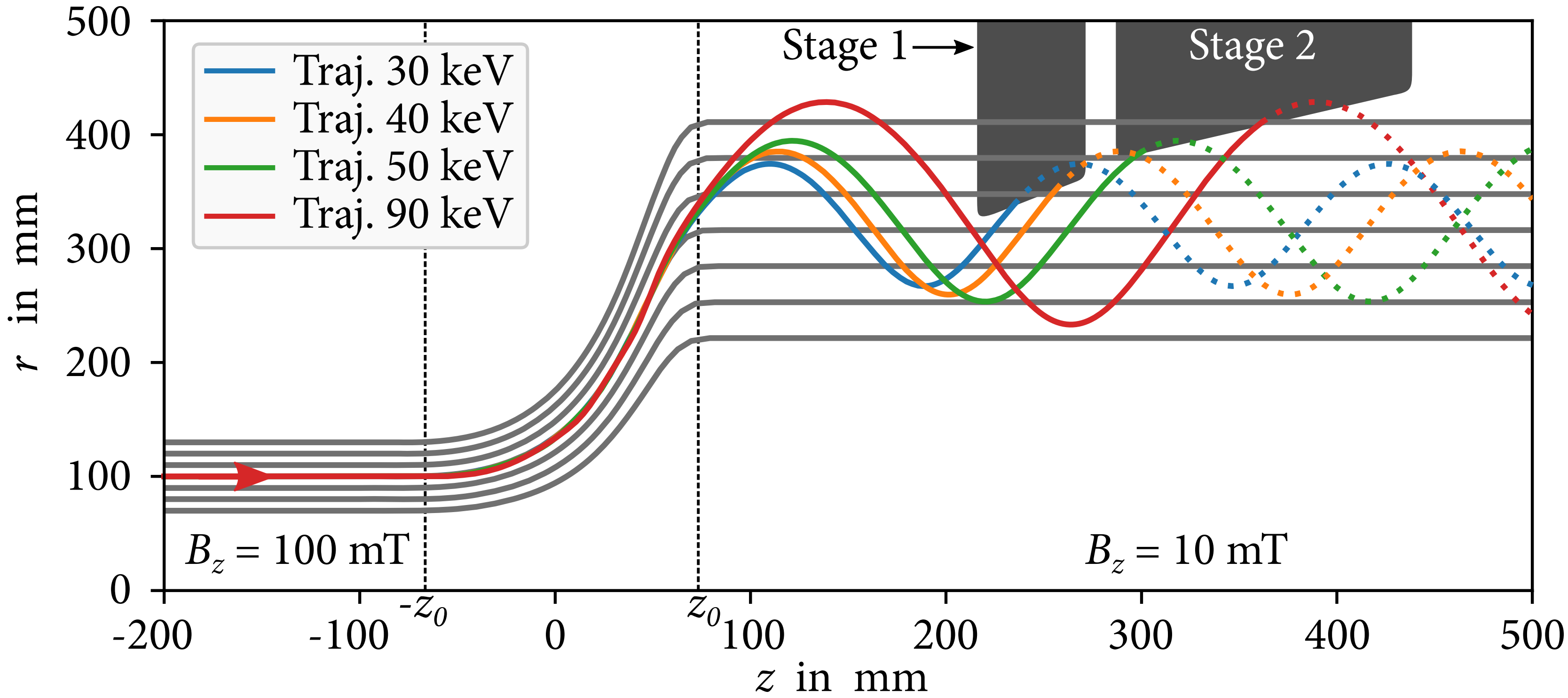
Example: an ideal non-adiabatic transition of magnetic field



- Transition from a uniform B = 100 mT to B = 10 mT
- Electron with energy from 30 keV to 90 keV

MDC Type 1: the Axisymmetric Concept

Example: an ideal non-adiabatic transition of magnetic field



- Electrodes collect the beam electrons at the proper positions

MDC Type 1: the Axisymmetric Concept

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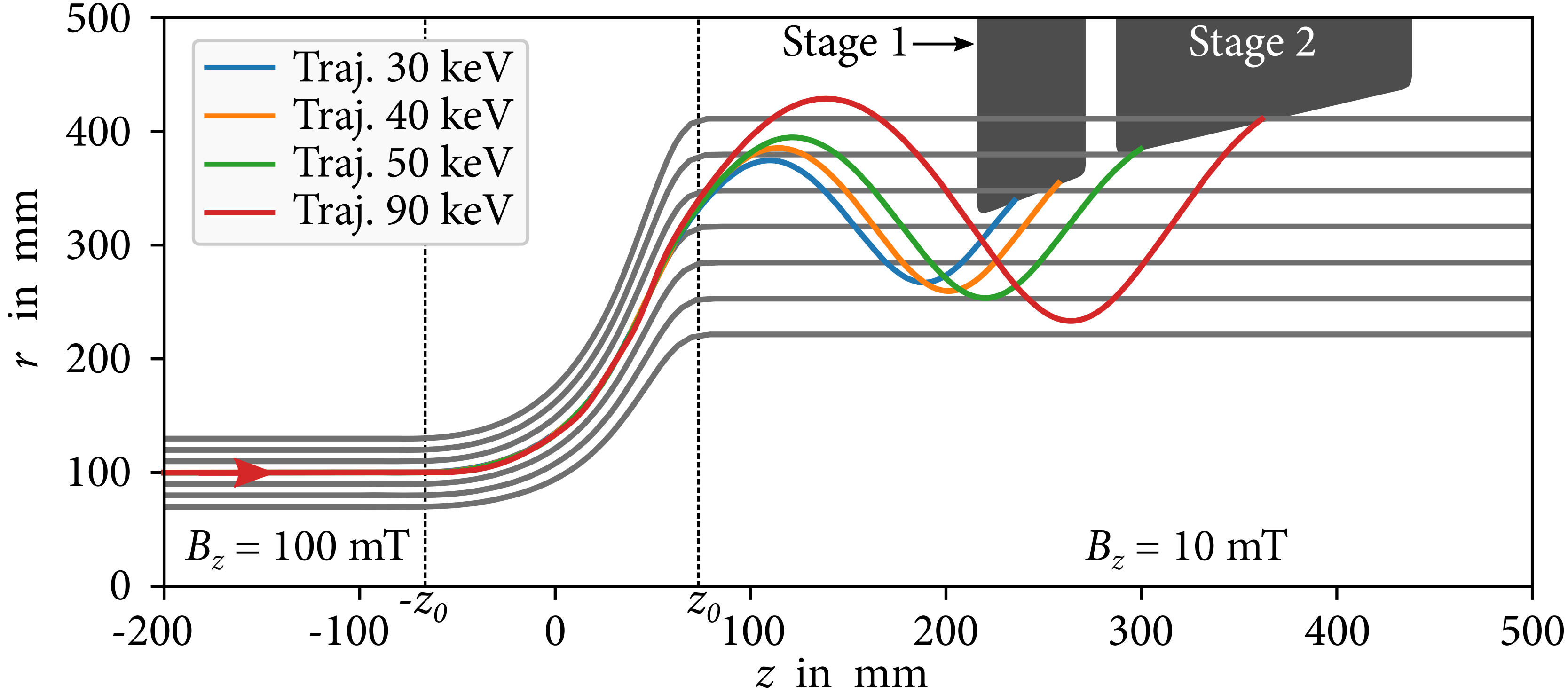
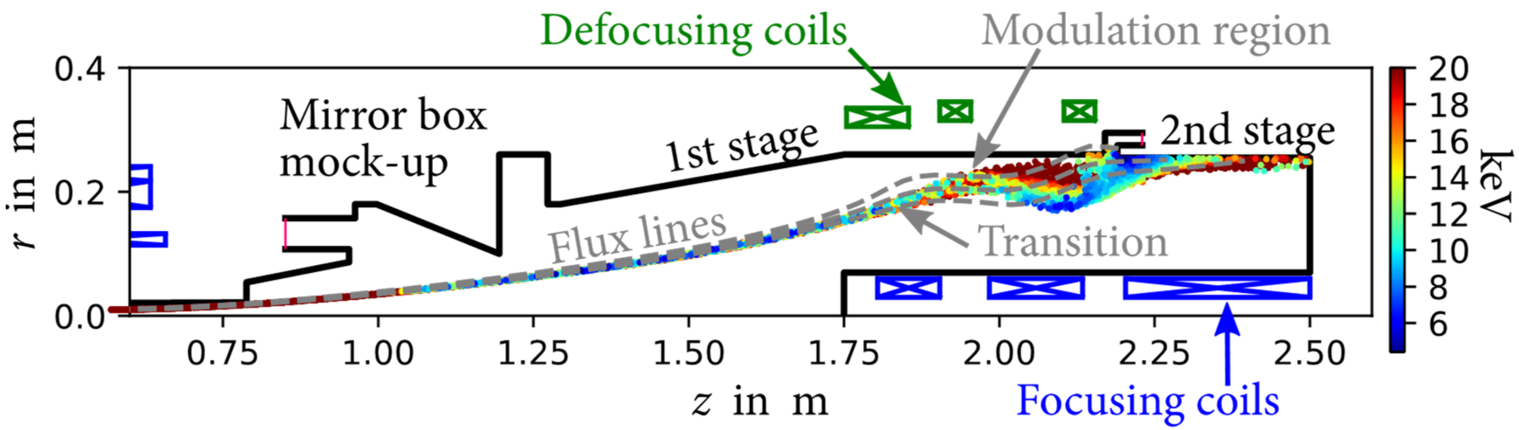


- Electrodes collect the beam electrons at the proper positions

MDC Type 1: the Axisymmetric Concept

- Conceptual design according to this principle, similar size as the SDC



- η_{col} = 73 % w/o secondary electrons, reduced to 65 % with s.e.
- Power density < 500 W/cm^2 w/o secondary electrons
- η_{col} may be reduced by 10 %, if there is an external *B* or misalignment

The efficiency cannot be further improved, since

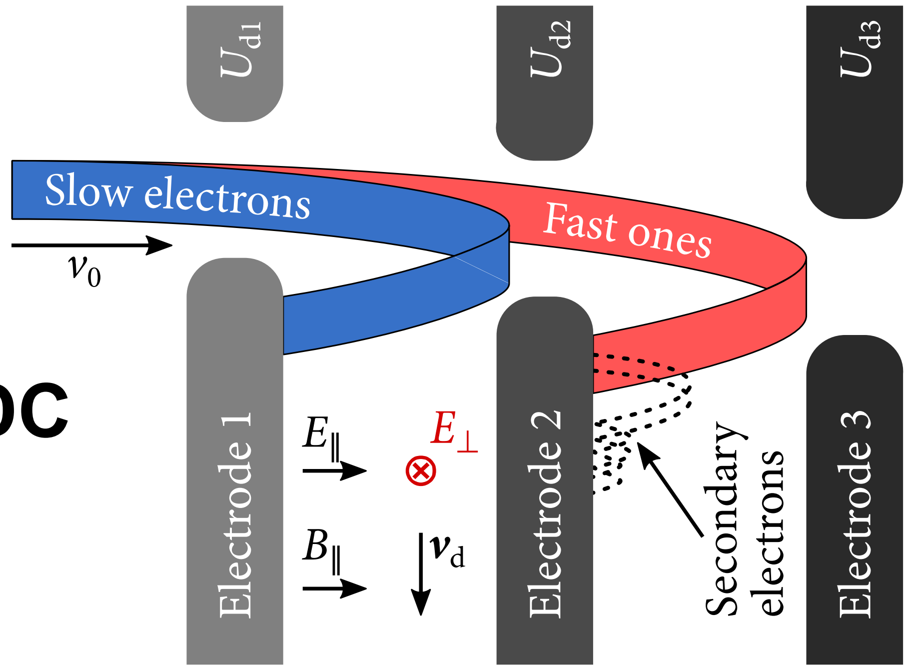
There is no separation of orbits

MDC Type 2: the Concept Using *E*×*B* drift

The electric field causes a charged particle to drift

- The drift velocity $\boldsymbol{v}_\mathrm{d} = \boldsymbol{E}\times\boldsymbol{B} / B^2$
- Independent of mass, velocity and charge
- Can be used to sort and even **separate** the electron orbits

Principle of an E×B MDC



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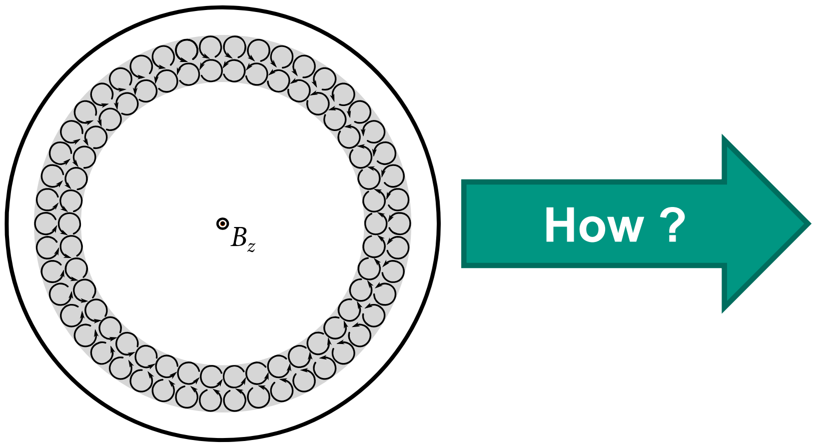
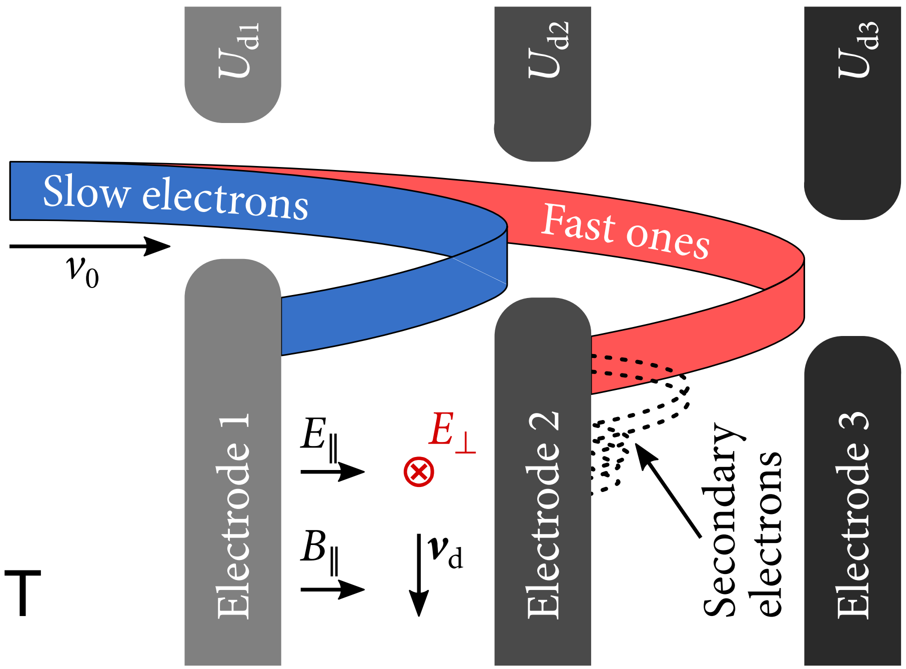
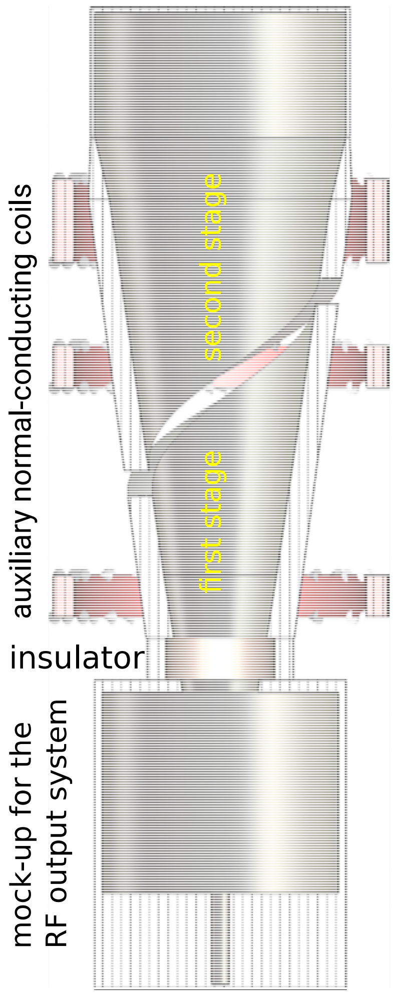
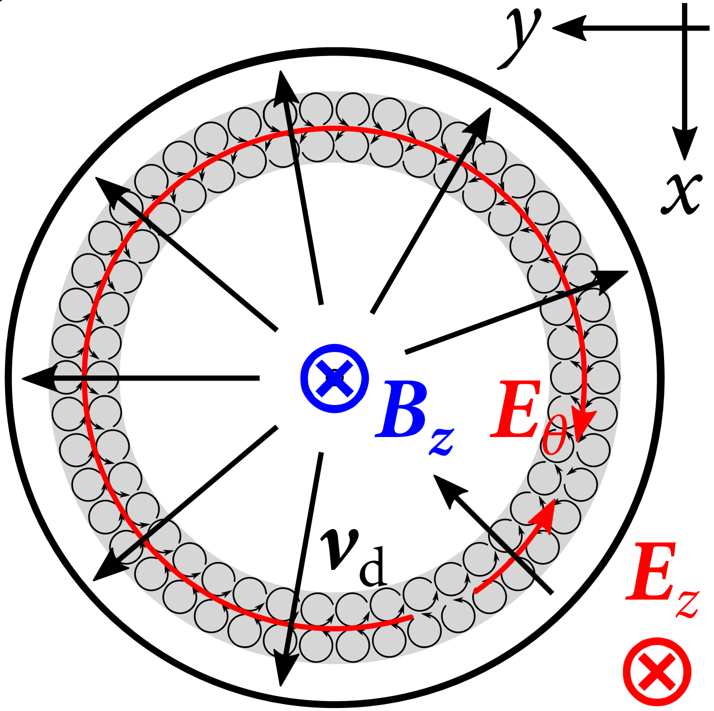




Numerous design proposals have been investigated at KIT

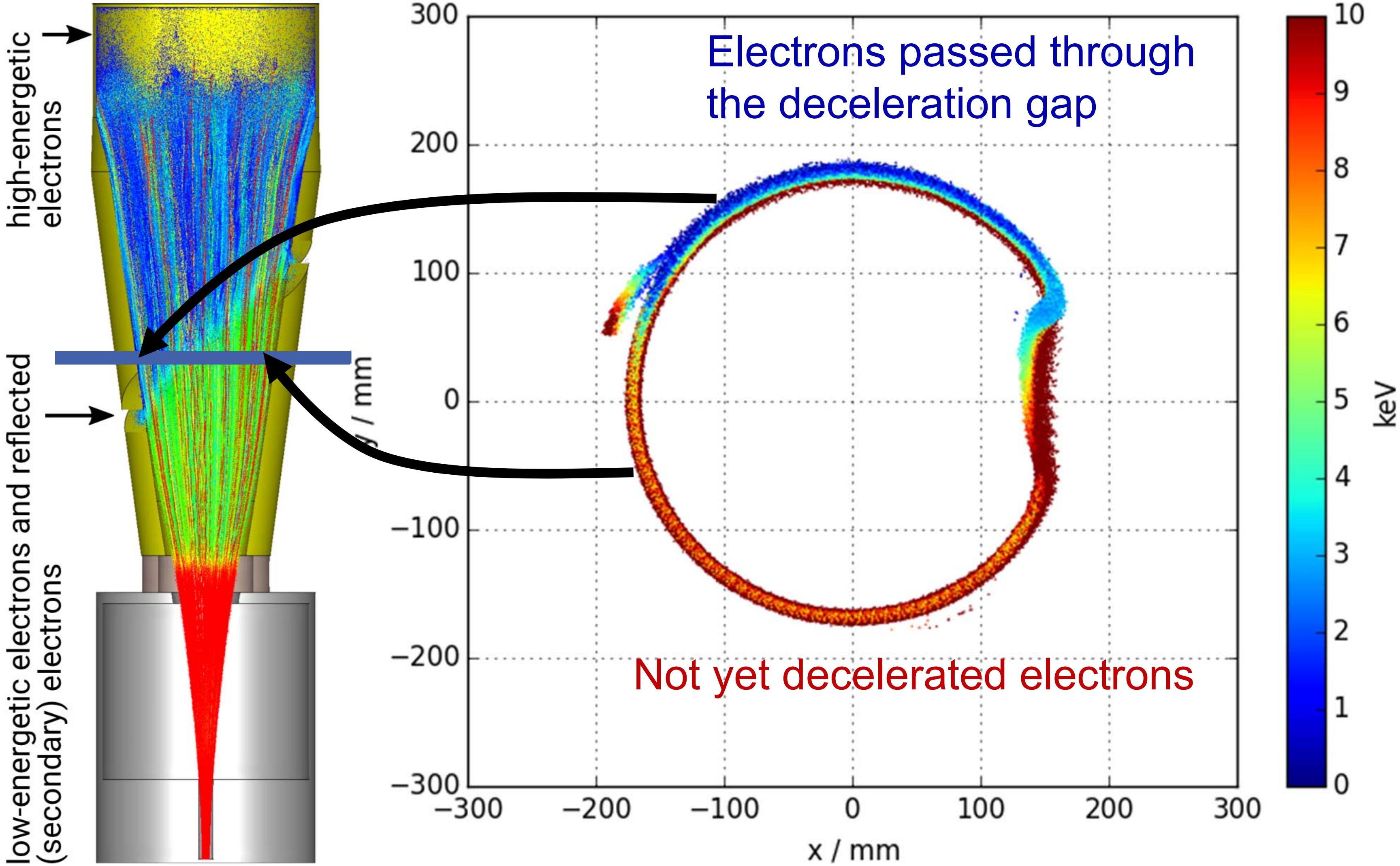
Design Proposal Using Helical Electrodes





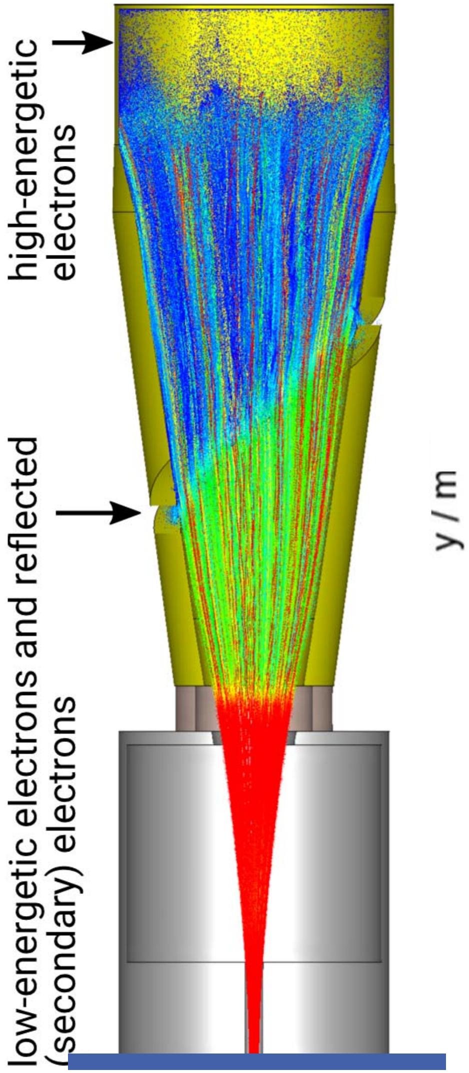
- Azimuthal ***E***-field component ➔ Radial drift
- Two-stage, but extendable if necessary
- Requires 3 tuning coils (ΔB < 20 mT)

Principle



high-energetic electrons
low-energetic electrons and reflected (secondary) electrons
Electrons passed through the deceleration gap
Not yet decelerated electrons
y / mm
x / mm
keV
300
200
100
0
−100
−200
−300
10
9
8
7
6
5
4
3
2
1
0

Principle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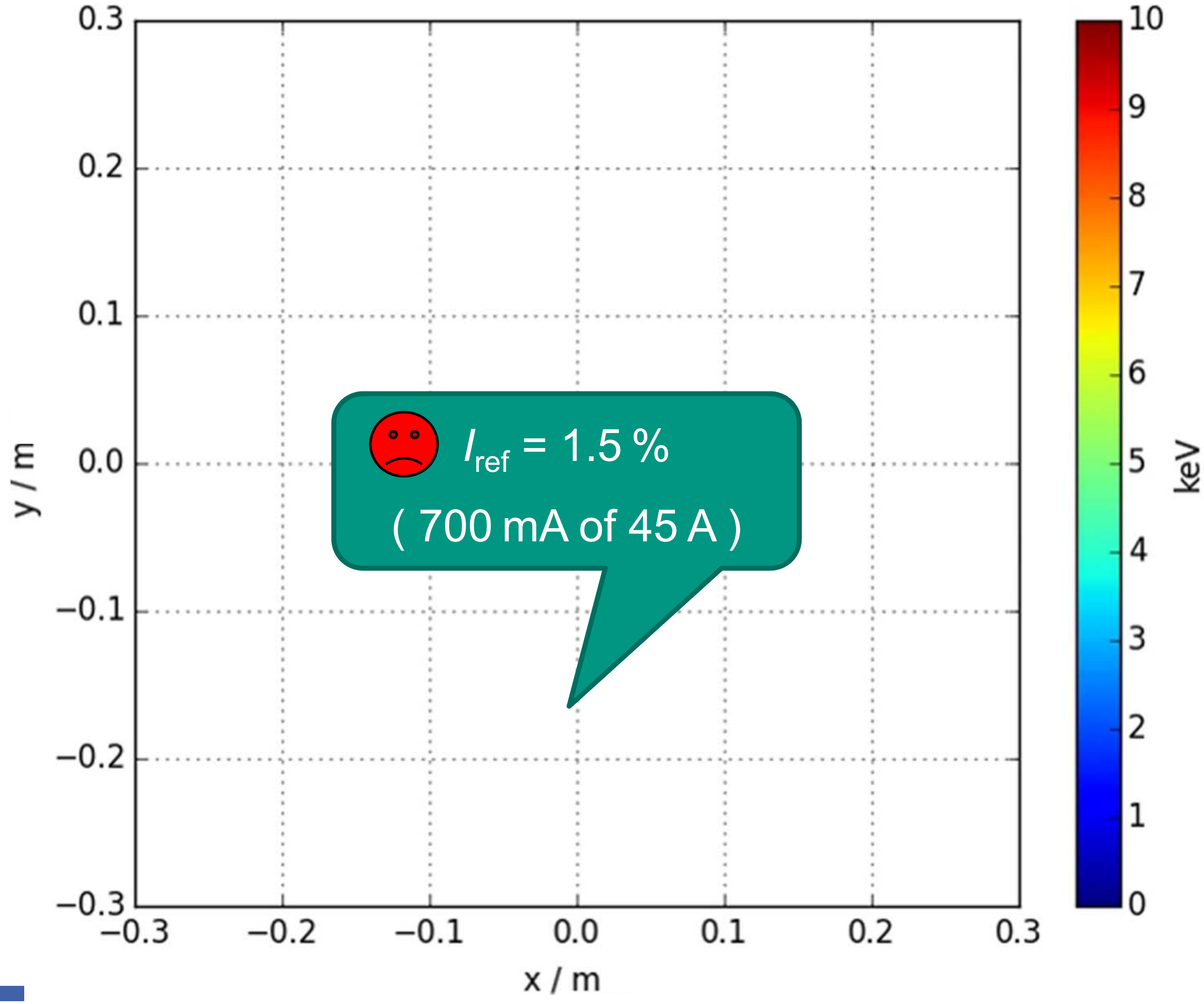
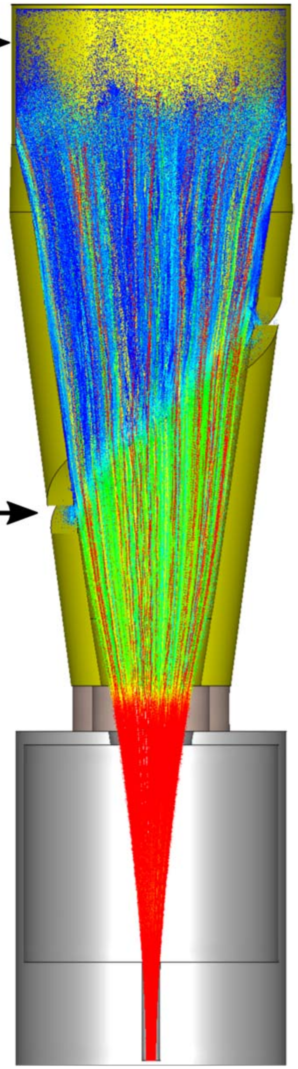

0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
y / m
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
x / m
I_{ref} = 1.5 %
(700 mA of 45 A)
10
9
8
7
6
5
4
3
2
1
0
keV

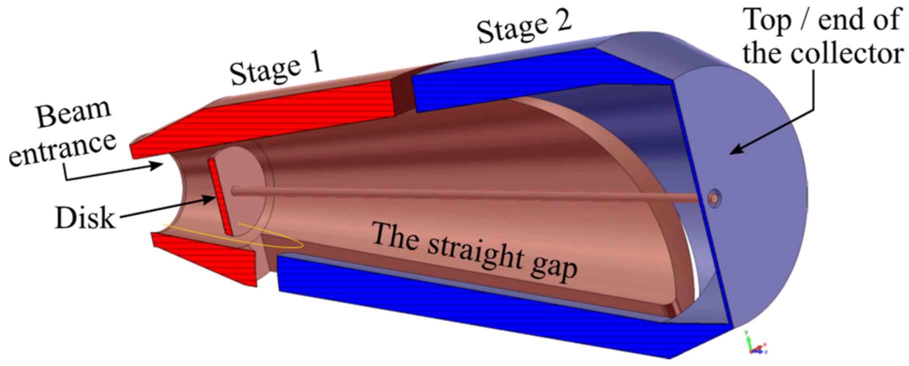
Properties of This Proposal



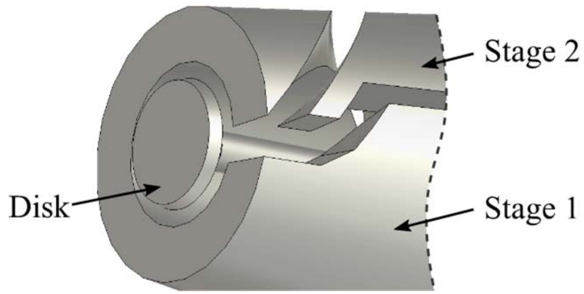
- The simplest collector coil system among all designs
- η_{col} = 76 % (incl. secondary electrons)
  - Well handling of secondary electron ($\Delta\eta_{col}$ = 1 %)
  - η_{col} is insensitive to external *B* field and misalignment
- Power Load density for the 1 MW gyrotron
  - 1^{st} stage: 300 W/cm^2
  - 2^{nd} stage: 700 W/cm^2 ➔ sweep

  Will be doubled for DEMO
  sweeping mandatory
- Compared to the SDC: length -10 %, width +30 %
- 700 mA back-stream current (incl. secondary elect.)

Upgrade 1: Suppress the Back-Stream Current



Proposal 1: disk to collect the reflection

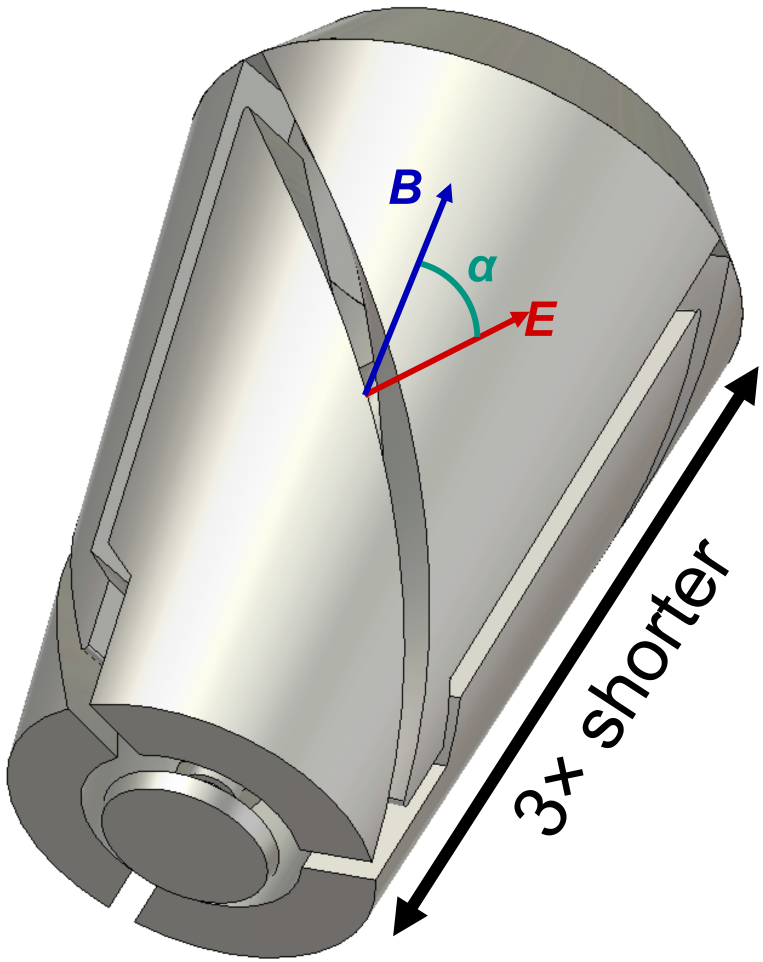


Proposal 2, based on p.1

➔Back-stream current can be reduce from 700 mA to 22.5 mA (incl. secondary electrons)

Upgrade 2: Multiple Helical Electrodes

- *N* helices to separate stages, instead of one
- Helix length is reduced to $1/N$, while the drift velocity $\boldsymbol{v}_\mathrm{d} = \boldsymbol{E}\times\boldsymbol{B} / B^2 = E\,B\,\sin(\alpha)$ keeps constant
- Simulation shows for $N = 3$
  - Same η as with only one helix
  - 45 mA with secondary electrons
  - $P_\mathrm{disk} = 400$ W (the 1 MW gyrotron)



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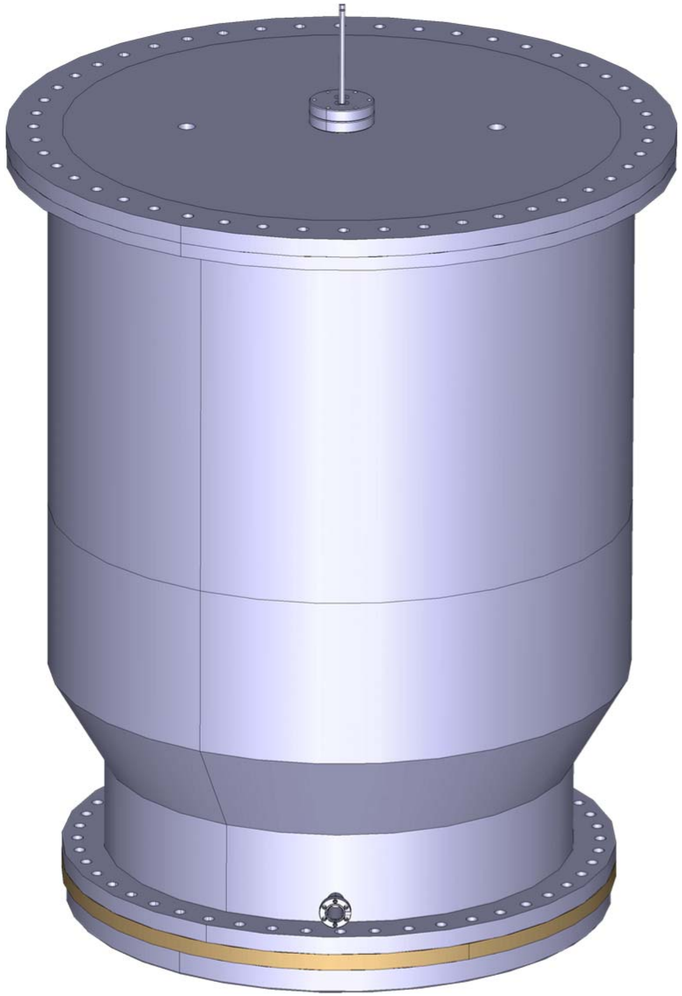
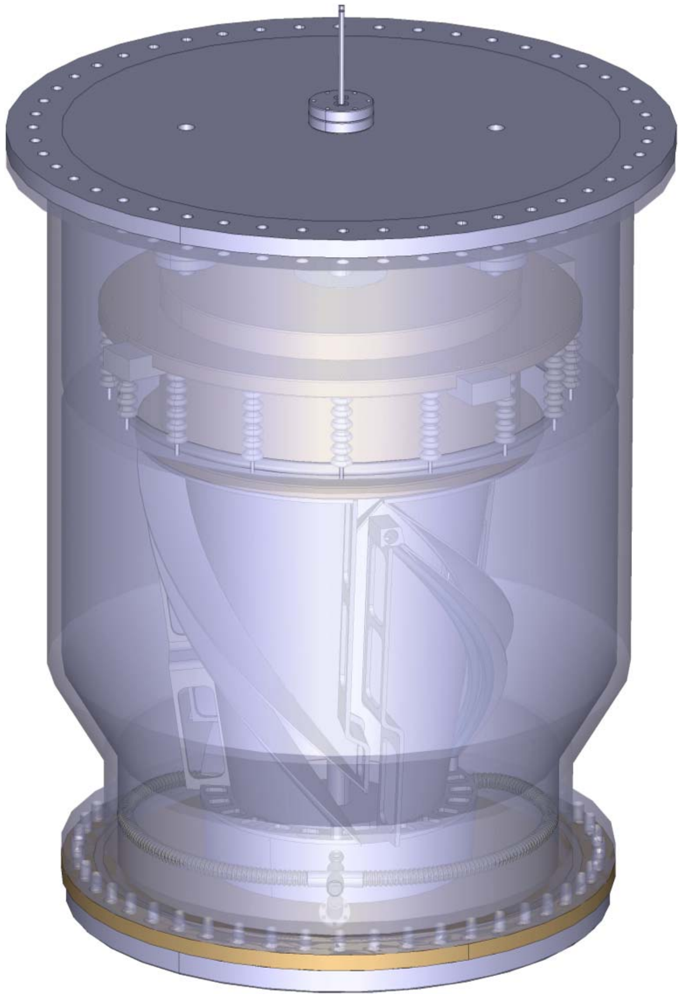
Engineering Design of a Short-Pulse Prototype



- +30 kV at gyrotron body (cavity)
- Ground potential at the
  - vacuum envelope
  - 1^{st} stage
  - gyrotron mirror box
- -12 kV at the second stage
- Approximately 300 kg
  - 30 % shorter than the ref. SDC
  - totally 60 % wider than the SDC

Engineering Design of a Short-Pulse Prototype



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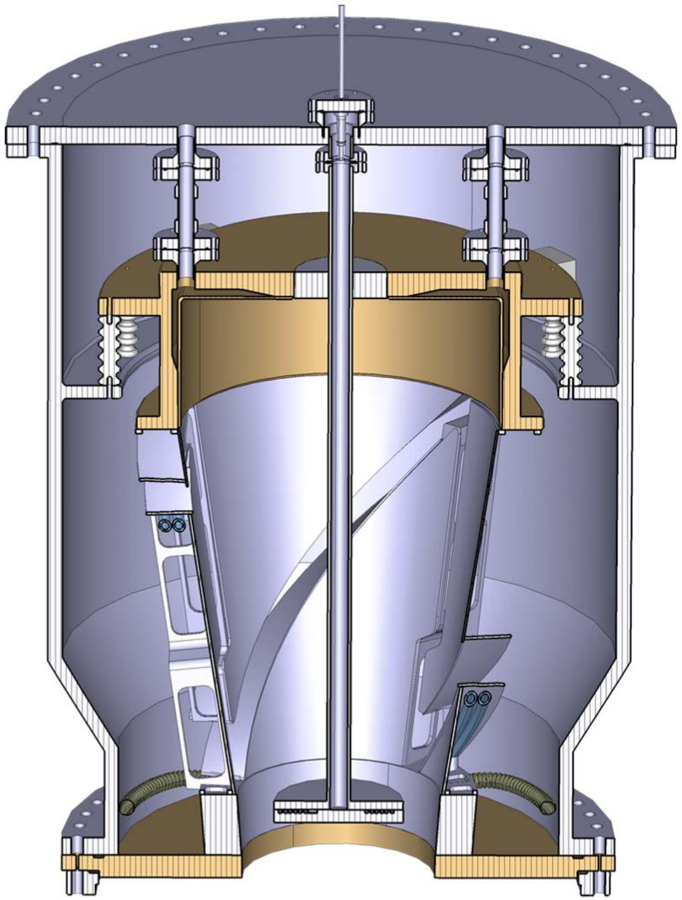

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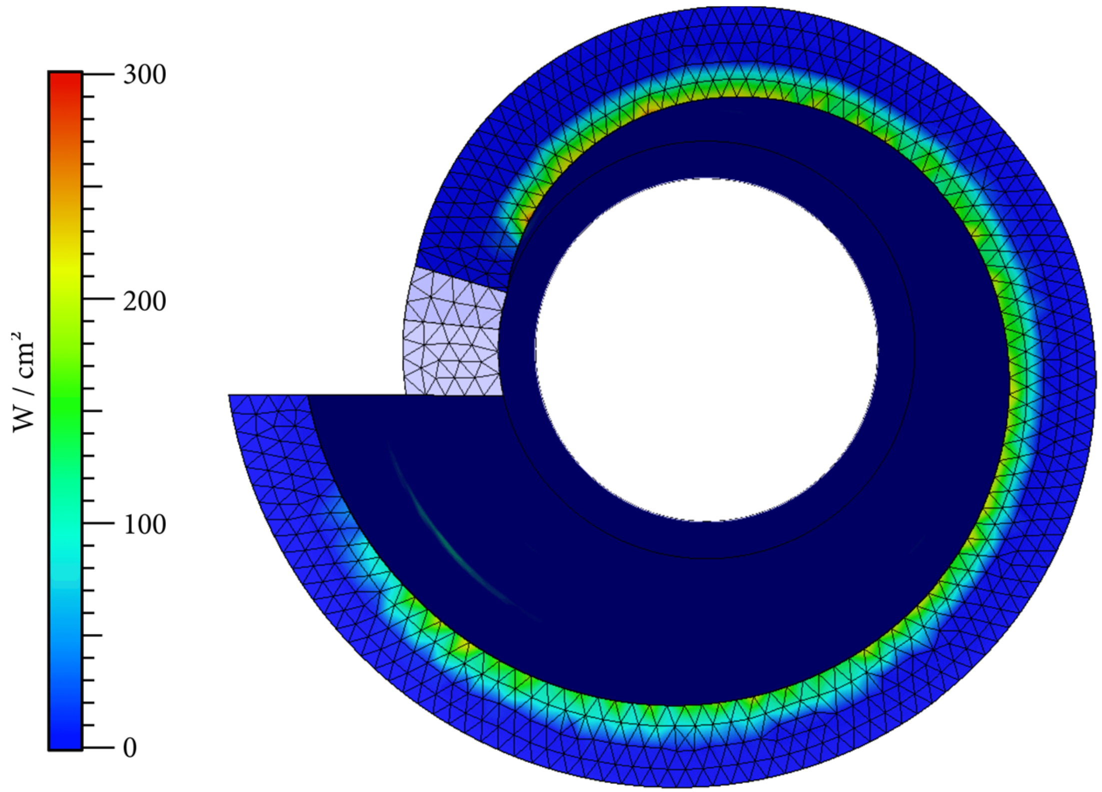
Conclusion

- $\eta_{col} > 74$ % is required for DEMO
- Two fundamentally different concepts
  - Axisymmetic geometry and fields ← no separation of cyclotron orbits
  - Using the ***E***×***B*** drift (breaks the axisymmetry) ← more promising
- Numerous design proposed for the ***E***×***B*** drift concept
  The proposal using helical electrodes (azimuthal ***E***) is promising
  - η_{col} is expected to be 76 %
  - Upgrades of the basic design should be considered
  - Engineering design is presented
- Extrapolation to the DEMO 2 MW gyrotron
  - Doubled back-stream beam current (might be > 90 mA)
  - Doubled load, especially at the 2nd stage: sweeping required

BACKUP SLIDES

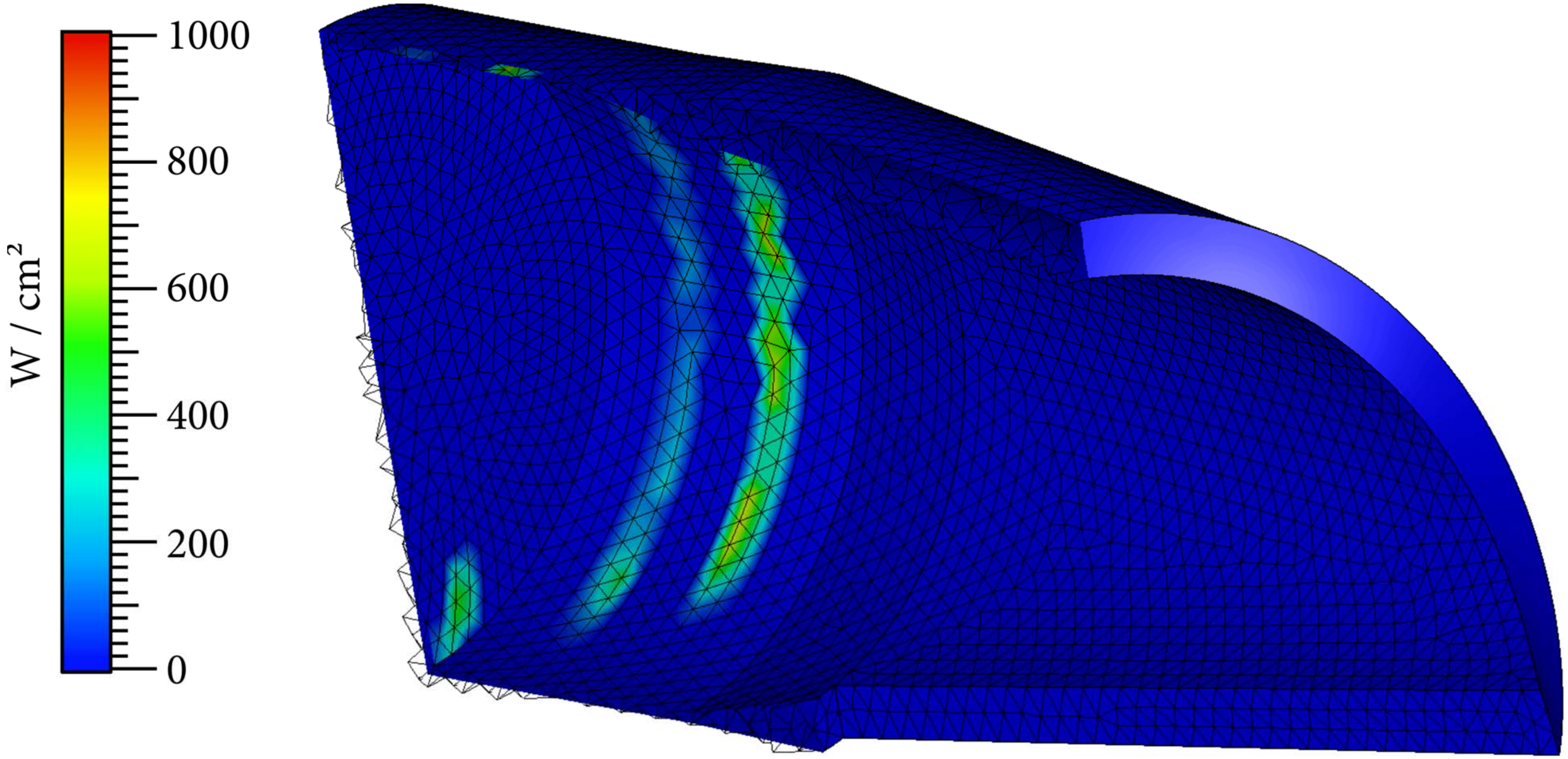
Power Load Density 1st Stage

- Top view of the first stage
- 170GHz, 1MW gyrotron as reference
  - I_{beam} = 45 A
  - P_{beam} = 2.5 kW
- Peak load < 300 W/cm²



Power Load Density 2nd Stage

- Peak load 700 W/cm^2 > 500 W/cm^2 ➔ electron beam might be swept
- Extrapolation for a 2 MW gyrotron: 1.4 kW/cm^2 ➔ sweeping necessary



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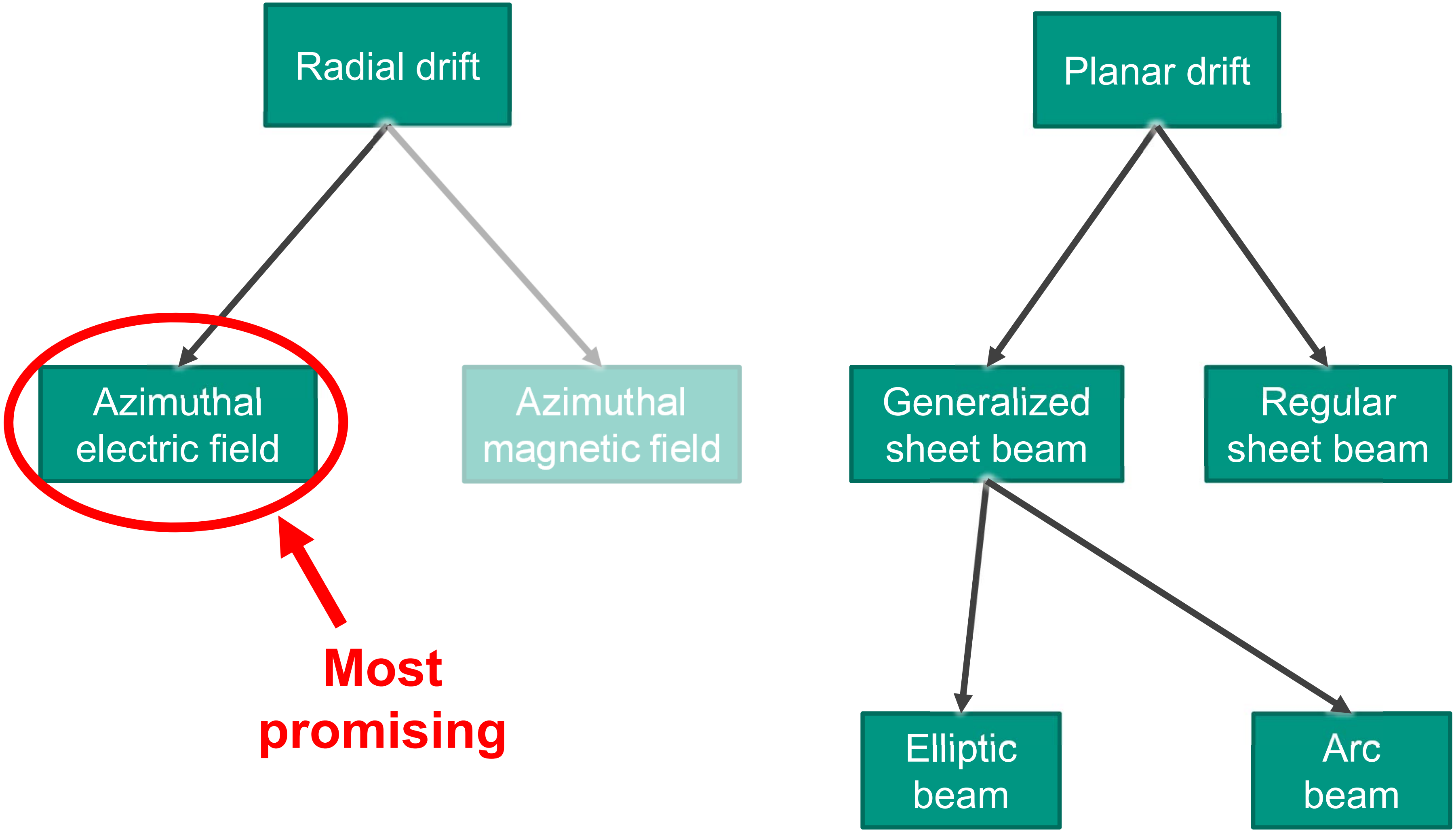
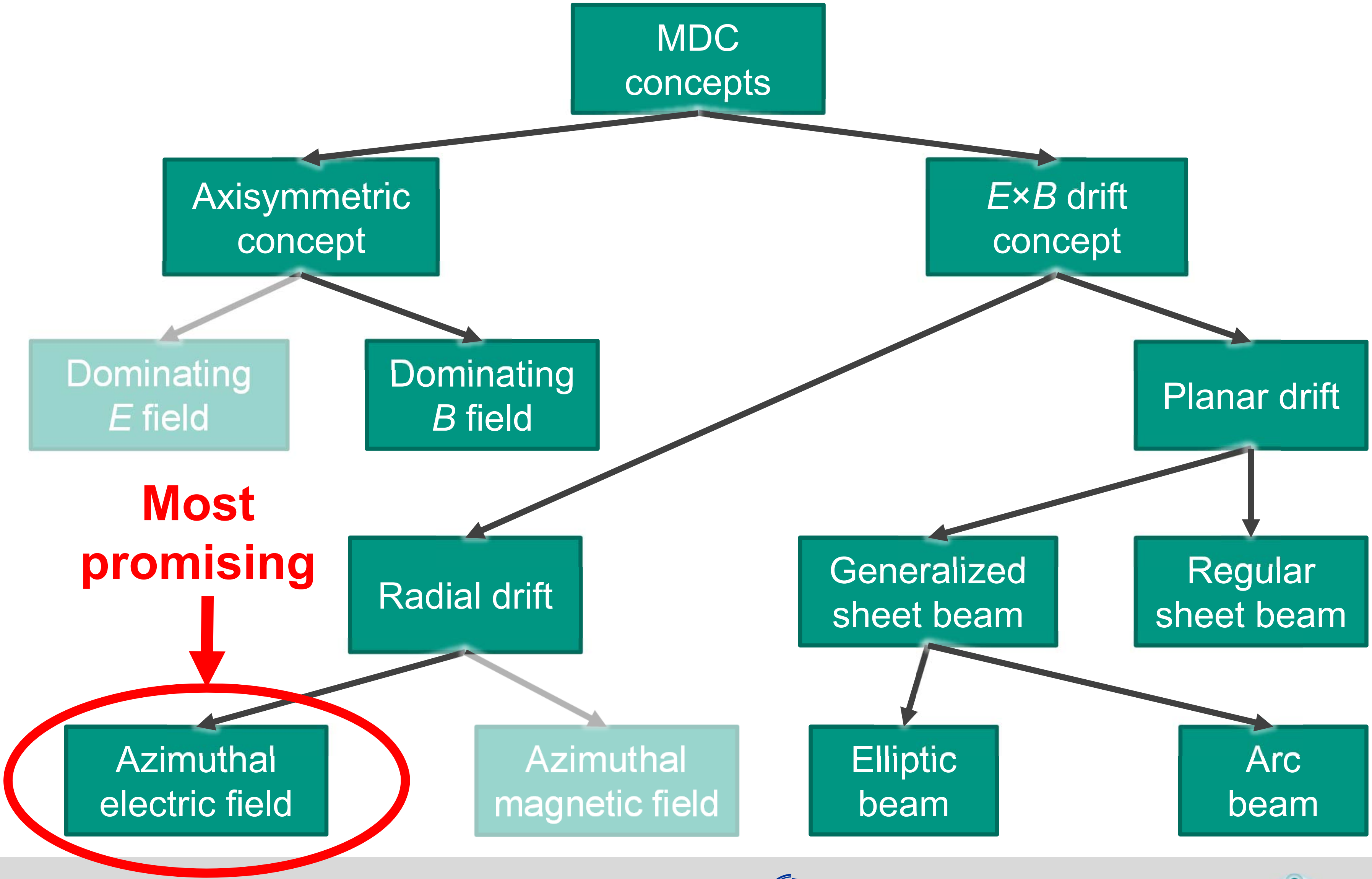
Possibilities to Produce *E*×*B* Drifts



Proposals Investigated at KIT



Influence of electron beam displacement

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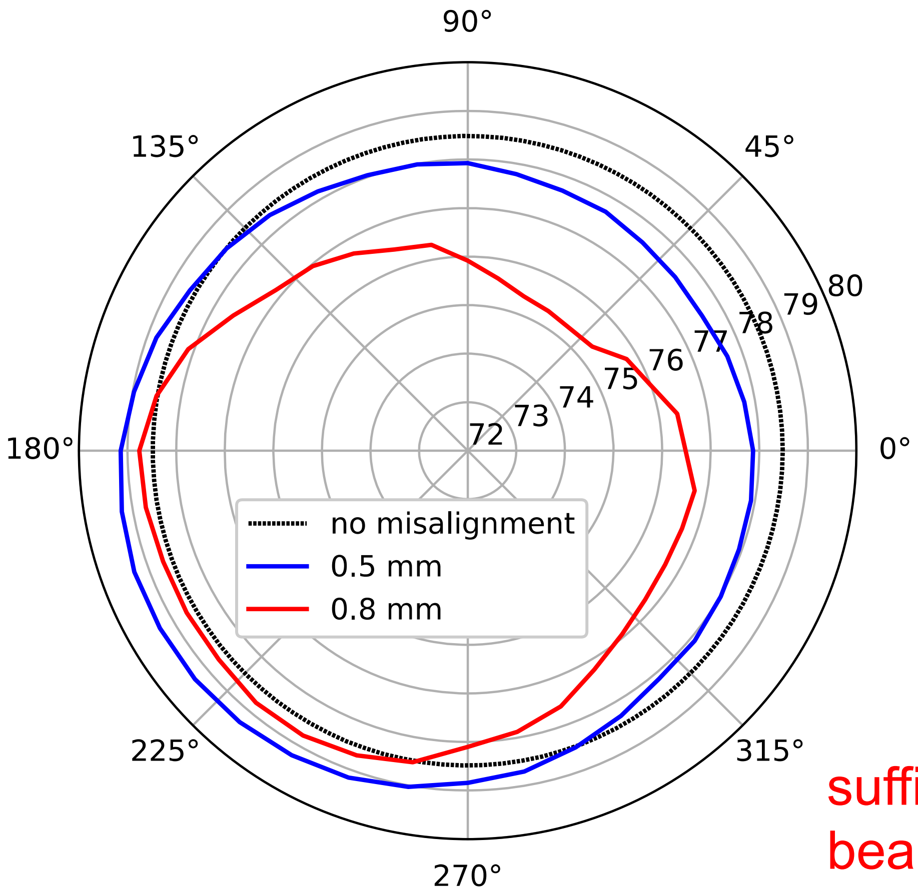
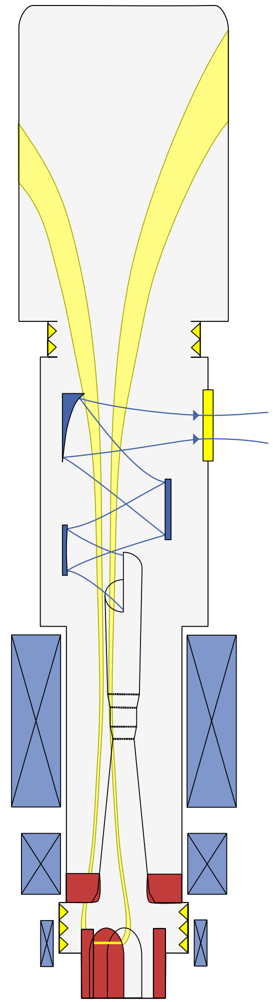
- Electron beam can be misaligned up to 0.8 mm **in cavity**

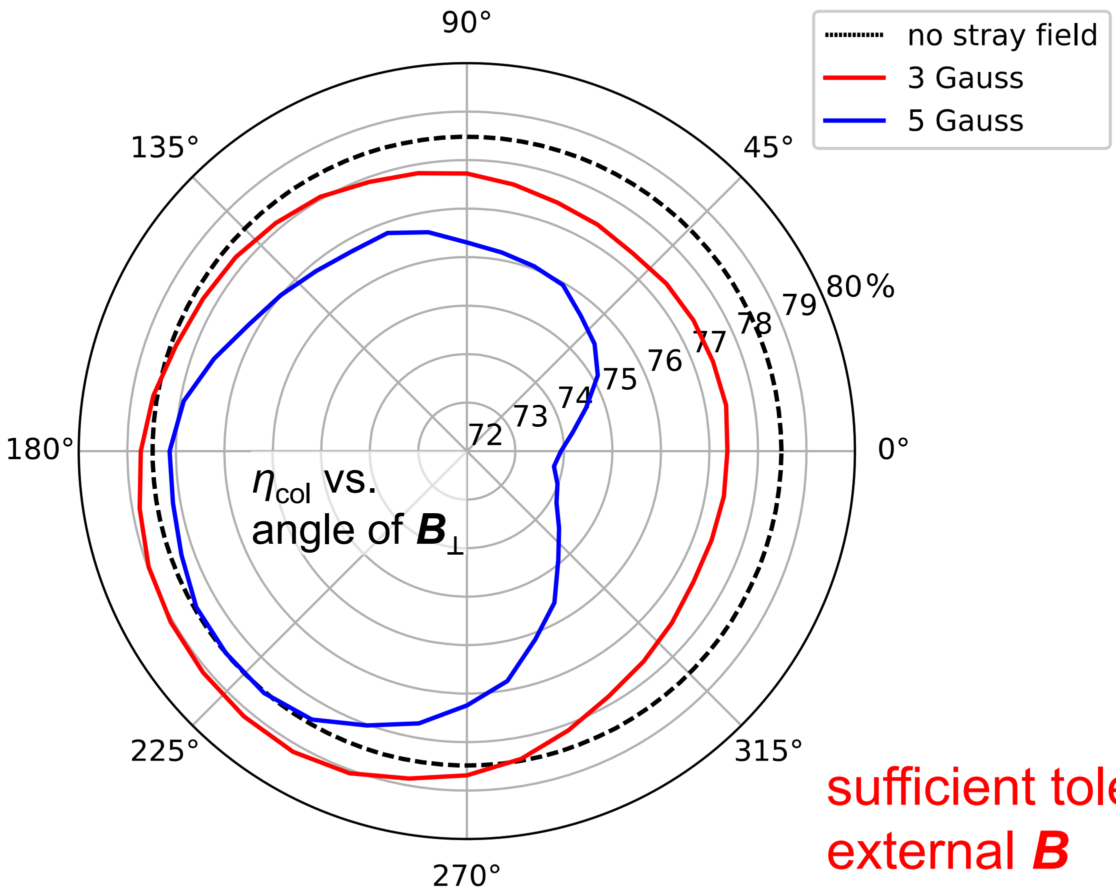


sufficient tolerance to beam misalignment

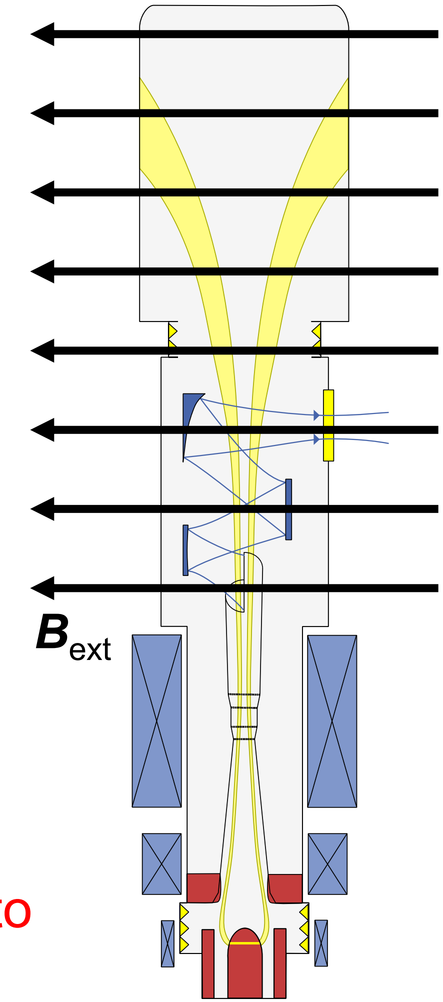


Influence of external magnetic field

- Transversal stray field of the Tokamak up to 5 Gs

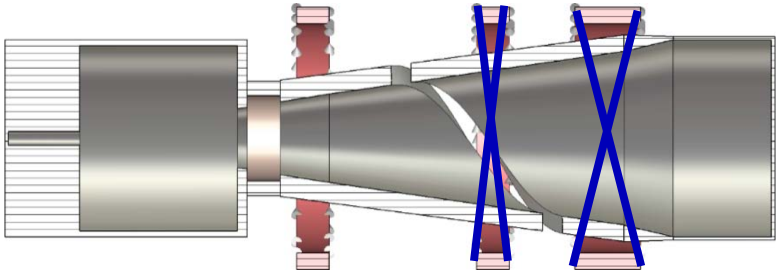


sufficient tolerance to external ***B***

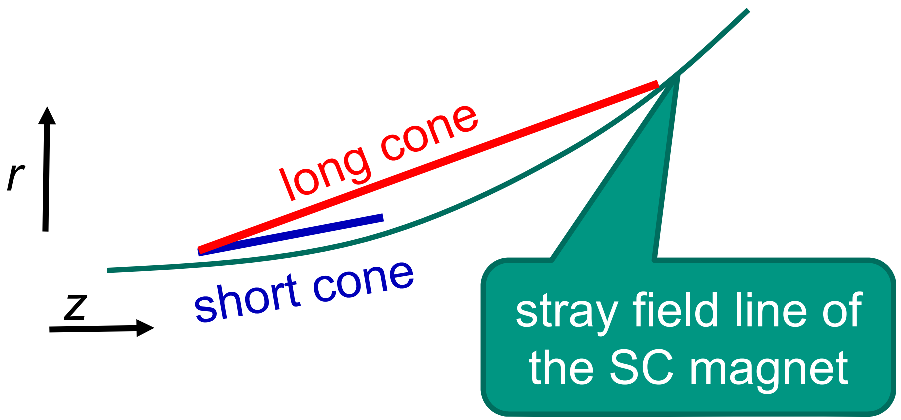


Other advantages

- Shrink the length of magnetic recondition ➔ reduce # of coils



- Further simplify the magnet system



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