Simulation of Gyrotron Multistage Depressed Collectors using Beam-Shape Transform and E×B Drift

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Outline

- Motivation
- Overview of Concepts
- New Idea: the ***E***×***B*** MDC
  - Electric and Magnetic Fields
  - Electron Beam Trajectory Simulation
  - Discussion of Secondary Electrons
- Conclusion

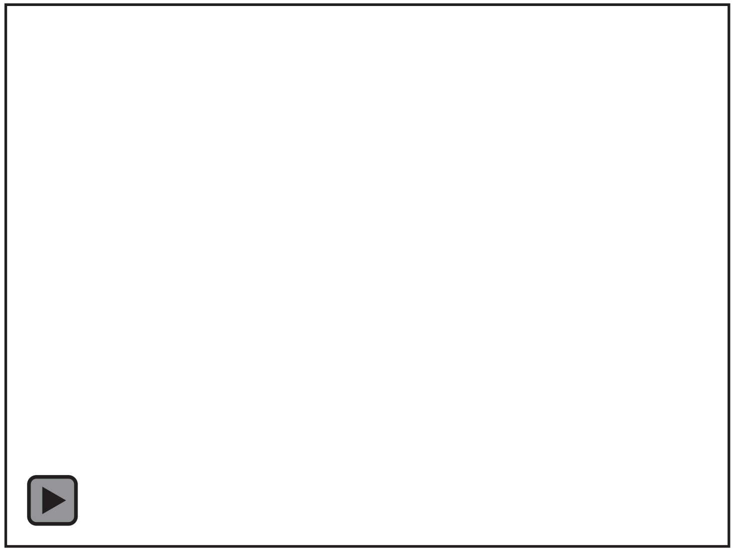
Motivation of MDCs for Gyrotrons

- Sort spent electrons and apply different decelerations to each category.
  - Reduce power consumption.
  - Save operation cost.
  - Reduce thermal loading and cooling / pumping requirement.
  - Increase life-time (due to reduced stress and fatigue effects).

- Comparable to the sorting of balls,
  However, with more challenges.

- State-of-the-art for CW gyrotrons
  $\eta_{total} \approx 50\ \%$ ($\eta_{collector} = 50 – 60\ \%$)

- Goal: $\eta_{total} > 60\ \%$,
  i.e. $\eta_{collector} > 74\ \%$.



Quality sorting of table tennis balls. *source: youtube*

Concepts of MDCs for Gyrotrons

both $\vec{A}$ and φ are rotationally **symmetric**

- Trajectories overlap each other, referred to Busch's theorem
- Can be modelled by the effective potential

at least one of the potentials is **asymmetric**

- Trajectories fully separable using the ***E*×*B*** drift
- Can be easily analyzed

Challenges for the Symmetric Concept 1

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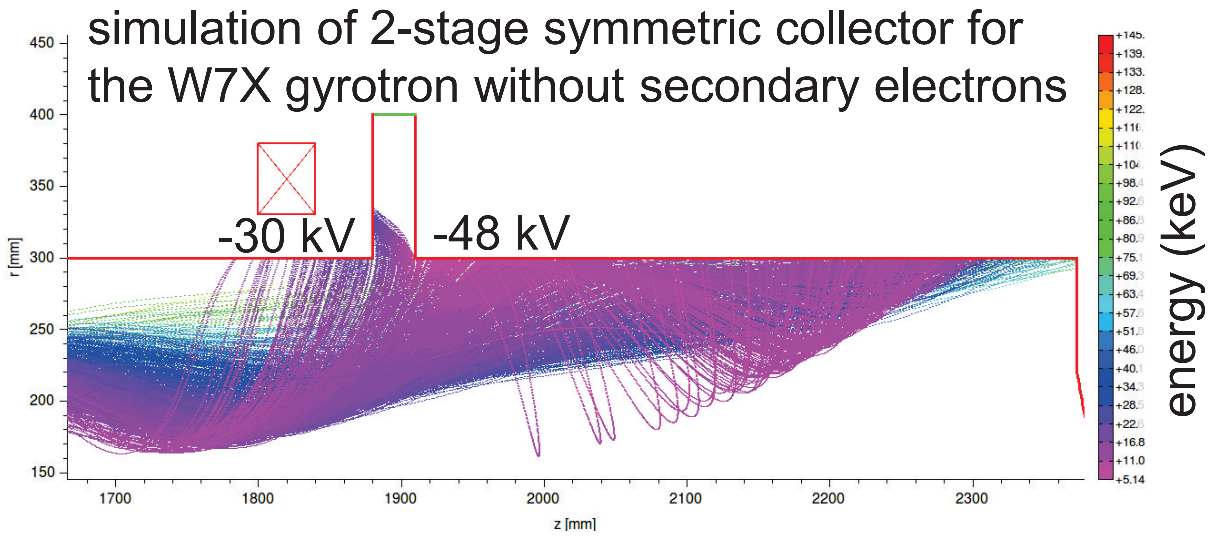
Strong stray field from the super-conducting gyrotron magnet

- B > 0.1 T at the entrance of a collector.
- Still > 10 mT on 1 m axial offset to the entrance.
- Effective magnetic potential: $\varphi_m = \frac{1}{2\,m}\left(\frac{P_\theta - qr\,A_\theta}{r}\right)^2$

φ_m of the stray magnetic field in the collector

- "Tennis Ball" model: Electrons are confined in the narrow potential valley.
- **Solution:** compensate and reduce the stray field.

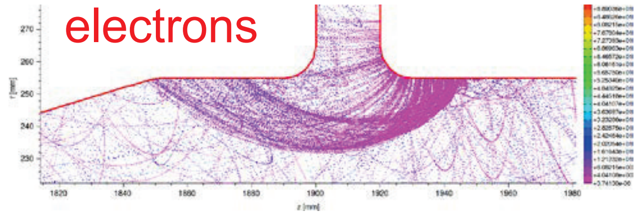
Challenges for the Symmetric Concept 2



- $73.3\ \%\ \eta_{\mathrm{col}}$
  $\hat{=}\ 60.17\ \%\ \eta_{\mathrm{total}}$
- space-charge considered
- no returned electrons
- max. wall loading $435\ \mathrm{W/cm^2}$

- By using compensation coils, the MDC concept may work.
- However, secondary electrons will reduce η a lot.

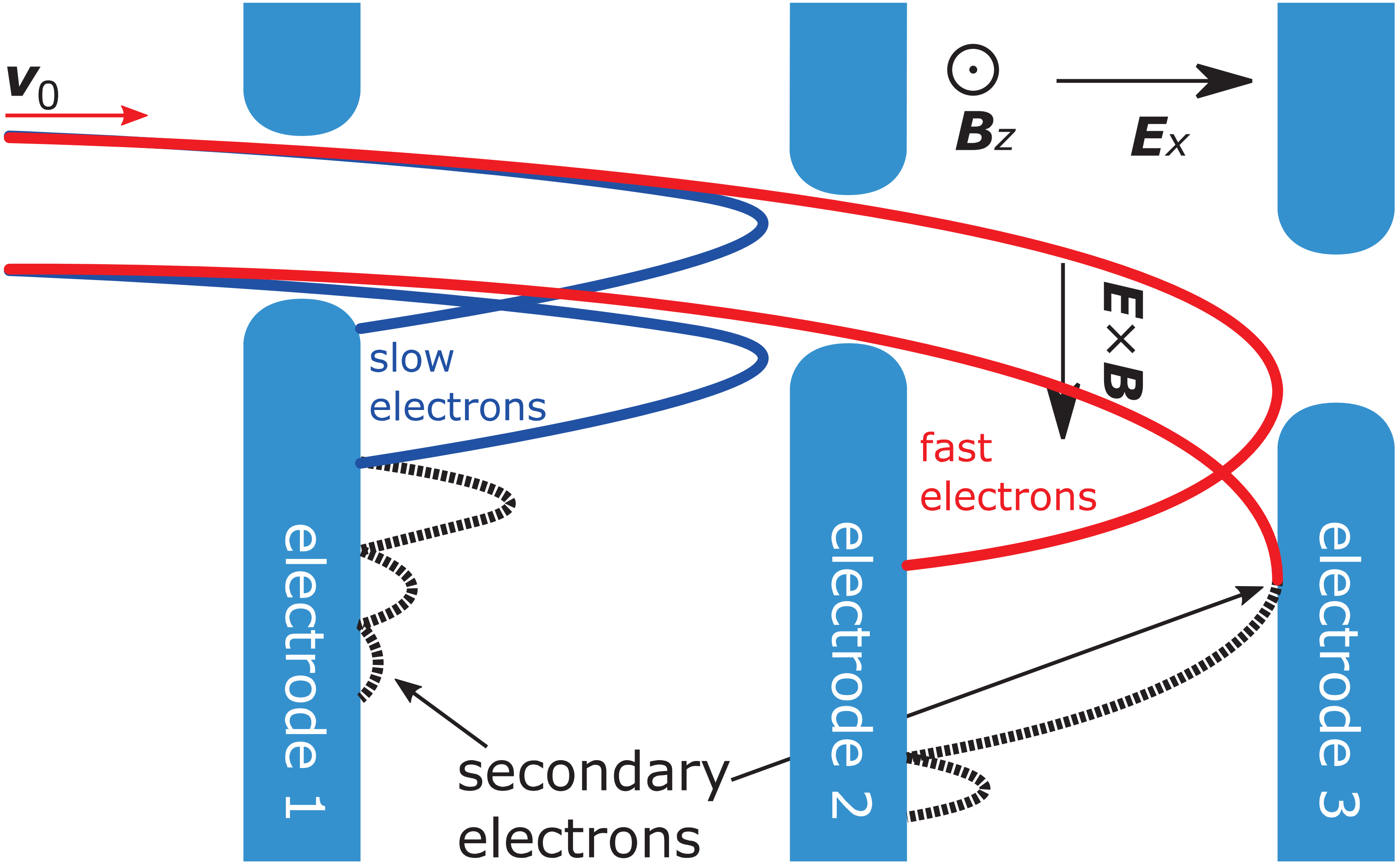
the alternative approach is very promising to handle secondary electrons



Concepts of MDCs for Gyrotrons

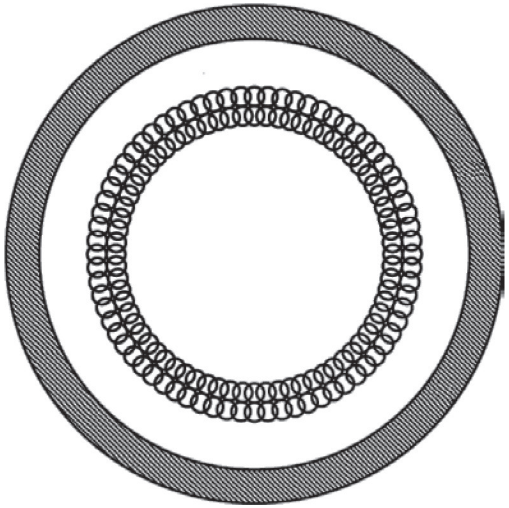
both $\vec{A}$ and φ are rotationally **symmetric**	at least one of the potentials is **asymmetric**
Trajectories overlap each other, referred to Busch's theorem	Trajectories fully separable using the ***E***×***B*** drift
Can be modelled by the effective potential	Can be easily analyzed
Weak magnetic field	**Proper magnetic field**
S.E. affect η enormous	**η is robust to S.E.**

MDC based on $E\times B$ Drift



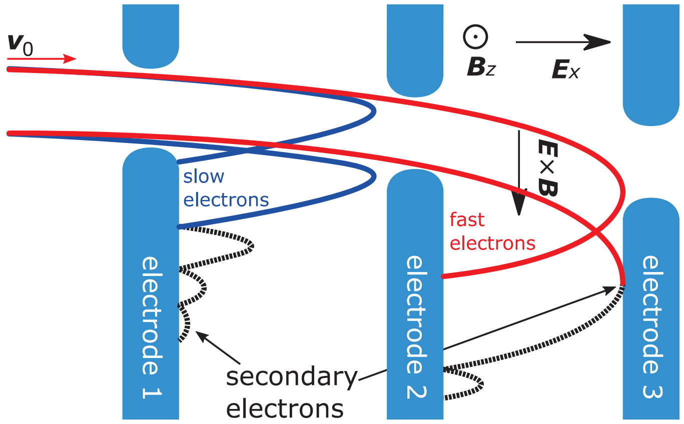
Transform the Electron Beam

hollow electron beam
at the entrance

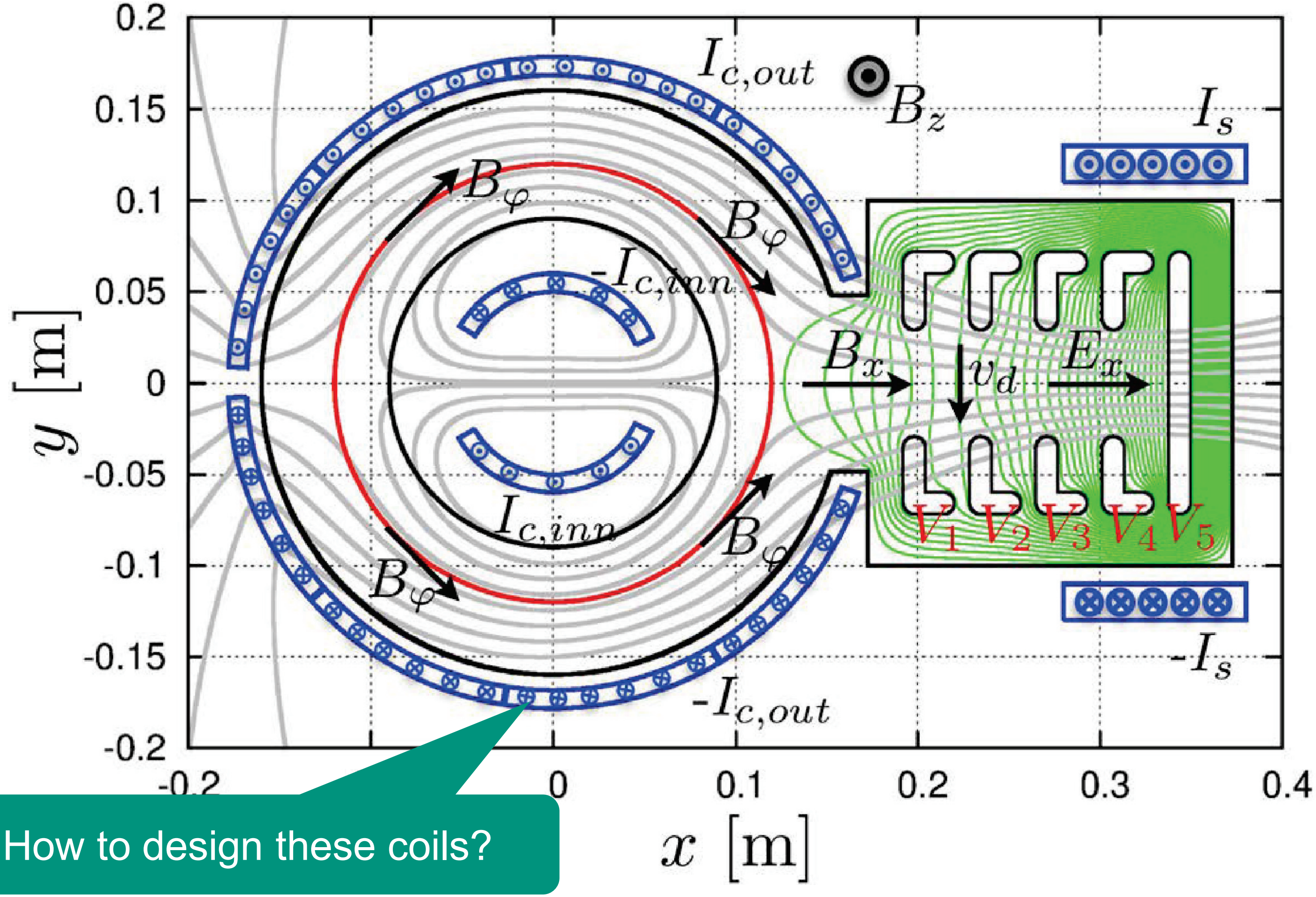


source: Dohler, Int. J. Electronics,1983

thin electron beam
for the collection



Transform the Electron Beam



How to design these coils?

2D Projection of Transversal Magnetic Field

- Flux coordinates α and β for $\boldsymbol{B} = \nabla\alpha \times \nabla\beta$

  (D´haeseleer; Flux Coordinates and Magnetic Field Structure; *Springer*)
  - Points with either α or β constant are on a magnetic field surface
  - Points with both α and β constant are on a magnetic field line

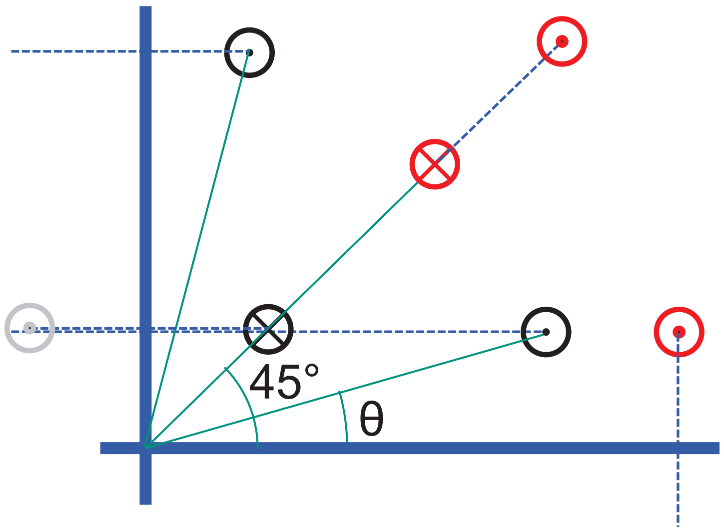
- For a 2D plane with infinitely long current $\boldsymbol{J}$ perpendicular to the plane:

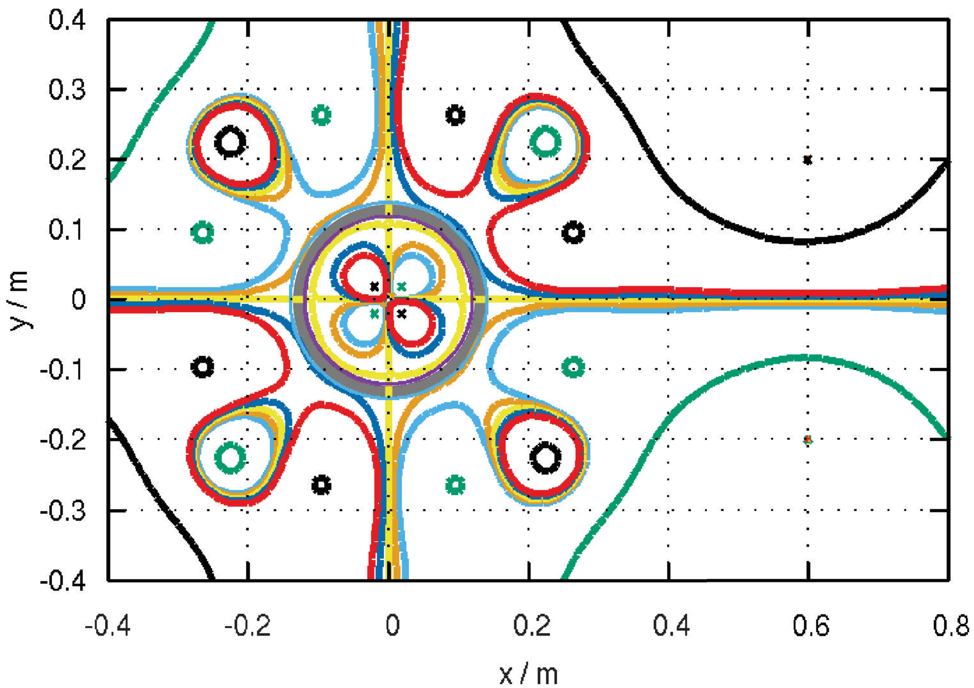
$$\boxed{\nabla^2 \alpha = -J}$$

- Has a simple Green's function solution.

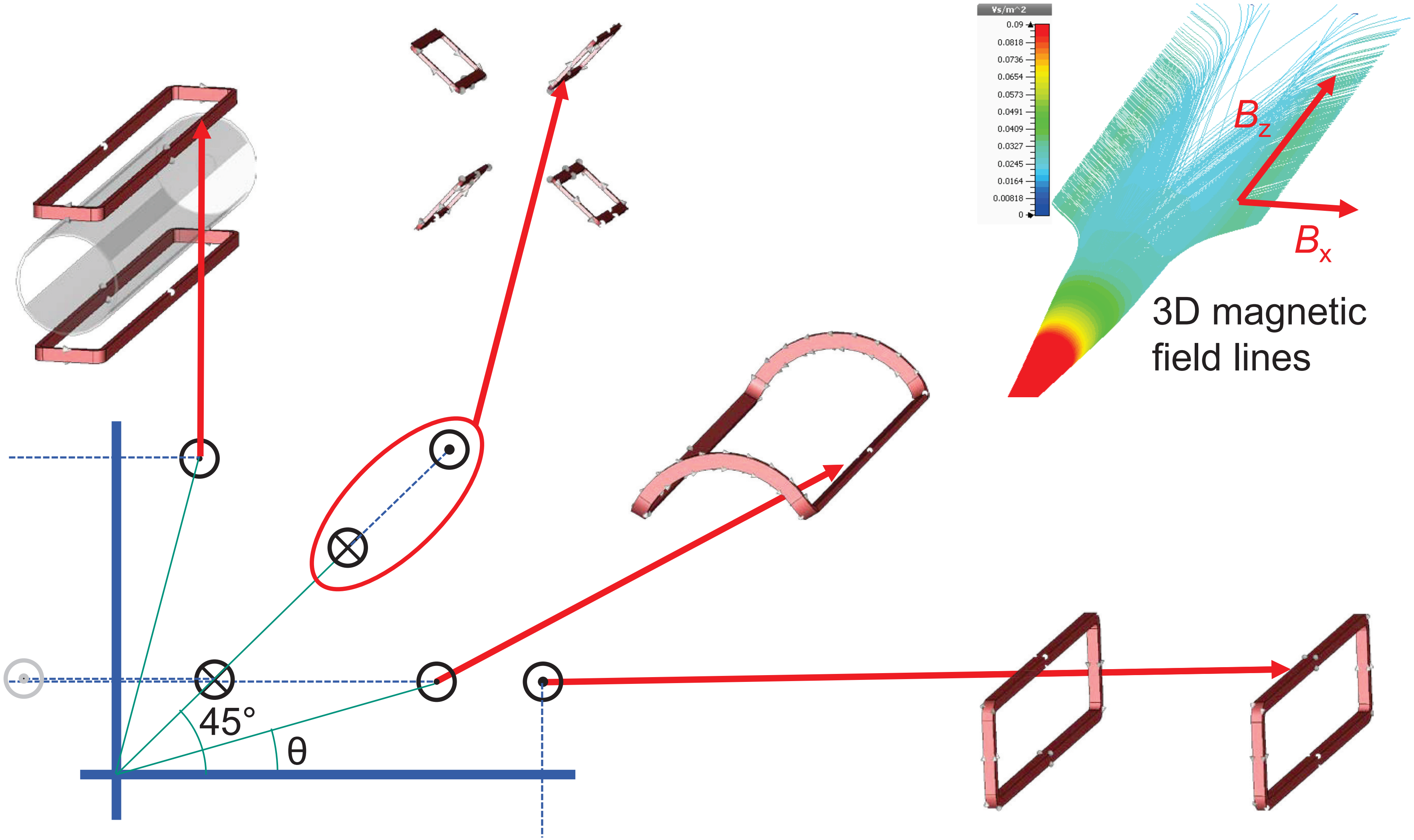
2D Projection of Transversal Magnetic Field

- Symmetric currents perpendicular to xy-plane in four quadrants
- Hollow electron beam are transformed to very thin sheet beams
- A little complicated, but this is only a **conceptual proof design**





3D View of Coils and the Magnetic Field



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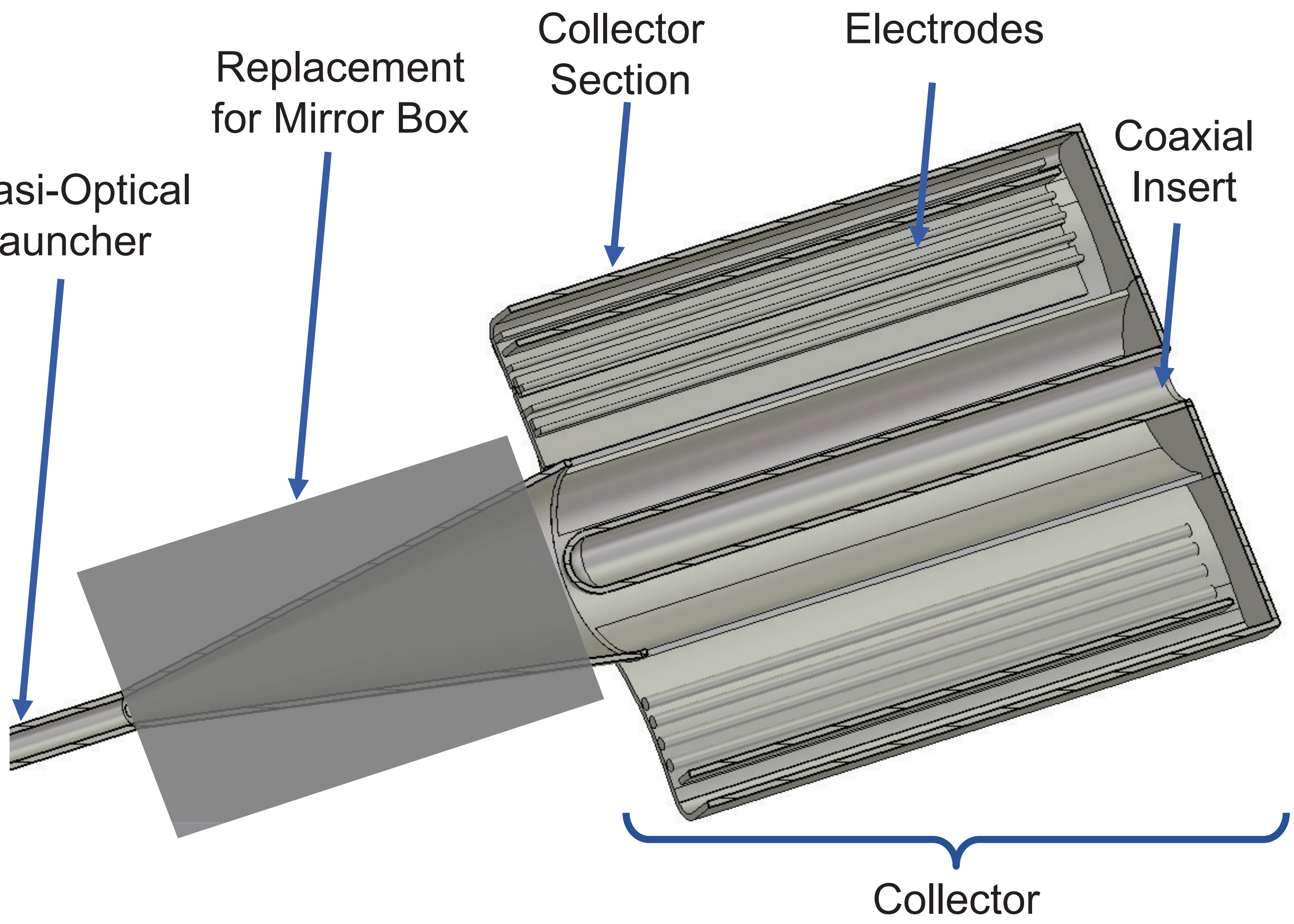
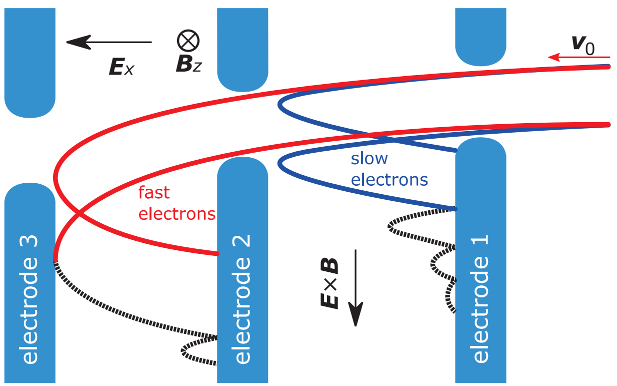
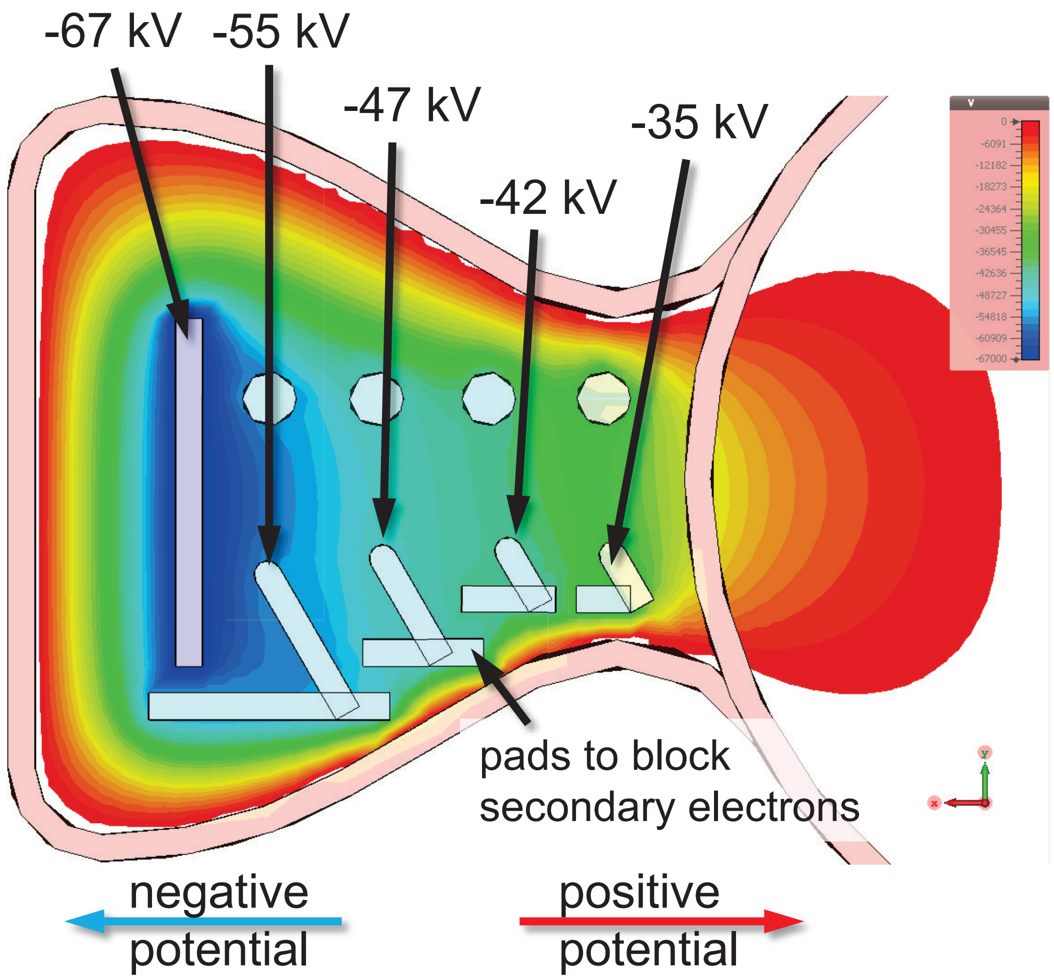
3D Perspective Cut View of the Geometry



Electrodes and Voltages

- Five stages
- Depression voltages are based on the optimal voltages for a zero-thickness beam
- Maximal field strength is far below breakdown





Simulation Example

- A 5-stage collector with η = 86 – 88 %
- Secondary electrons will be taken into account later

Secondary Electrons

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- Shapes of electrodes are adjusted for secondary electrons
- Even with copper (high SEY material), η is reduced from 86 % to 82 %
- Has to be further investigated to minimize the affect

Conclusion

- Concepts are compared
  - Rotationally symmetric MDCs are intuitive, but S. E. reduce η enormous
  - Asymmetric ***E*×*B*** MDC can work robustly with S. E.
- ***E*×*B*** MDC requires thin beam ➔ transform hollow beam to sheet beam
- **Conceptual validation** of the electron beam transform and ***E*×*B*** MDC using CST
  - Gyrotron magnet, plus several realistic normal-conducting trim coils
  - Realistic spent electron beam
  - Secondary electrons
- Preliminary simulation of a 5-stage collector
  - η_{col} = 86 % w/o secondary electrons
  - η_{col} = 82 % for copper, with secondary electrons (η_{total} > 67 %)
- Alternative types ***E*×*B*** collectors are under investigation

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Backup Slides

Create a Homogeneous Magnetic Field

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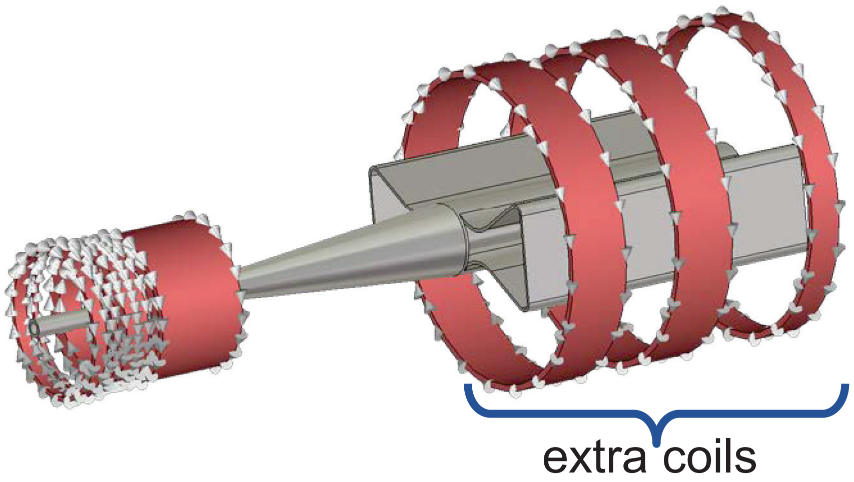
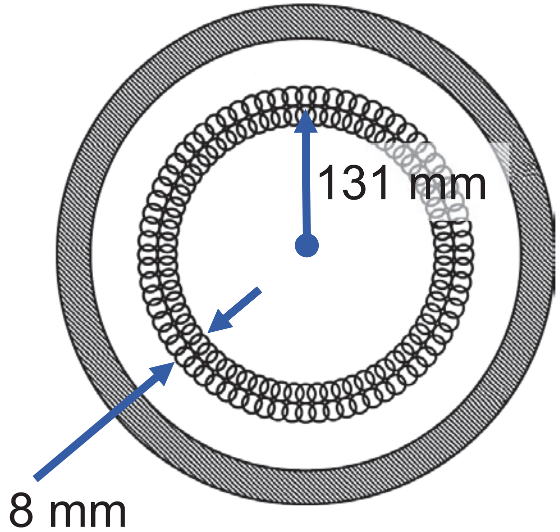
- Create a field homogeneous field (B = 35.6 mT) in the collector region using additional coils regarding the stray field of gyrotron main magnet
- Electron beam at the collector entrance has the radius of 131 ± 4 mm (Compromise between collector size and amplitude of drift velocity)





2D Projection of Transversal Magnetic Field 1

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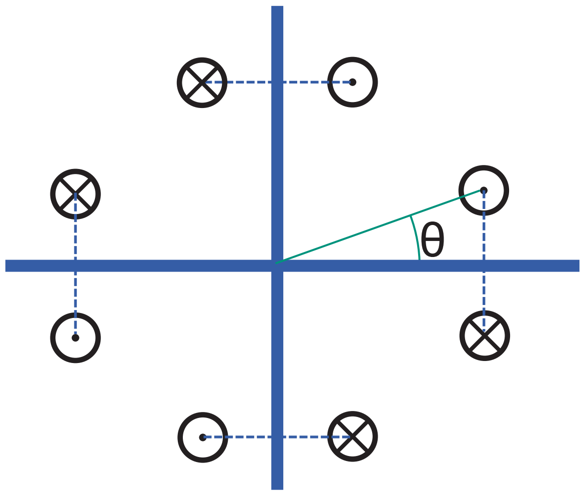
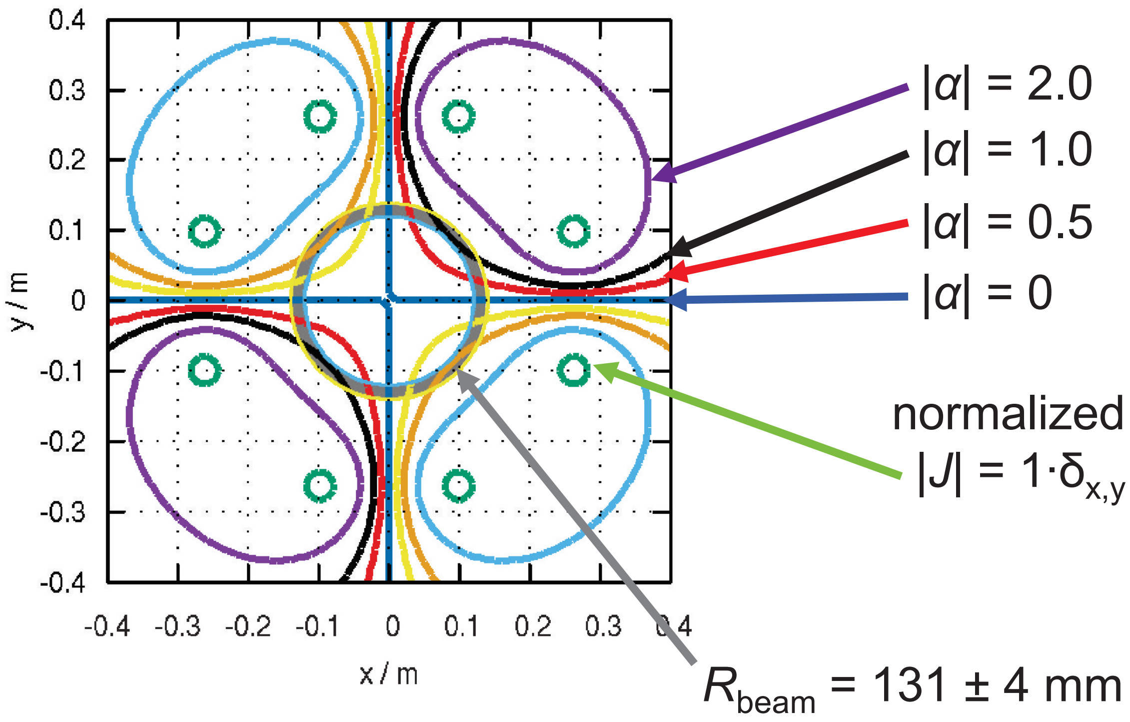
Starting from a long **quadrupole**

- × and · stand for the sign of current
- Inter-connected by dashed lines

Basic considerations

- Quadrants-mirrored
- Diagonally symmetric

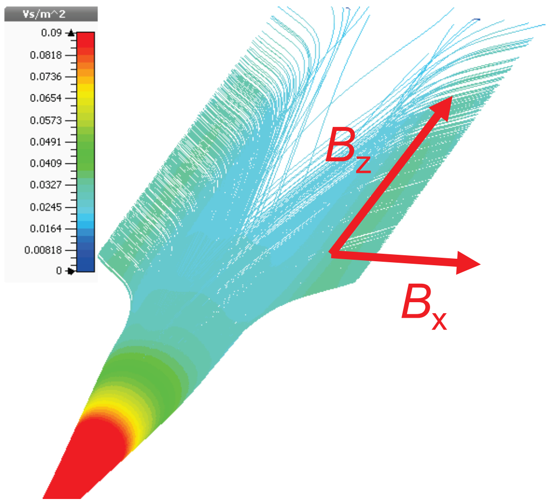


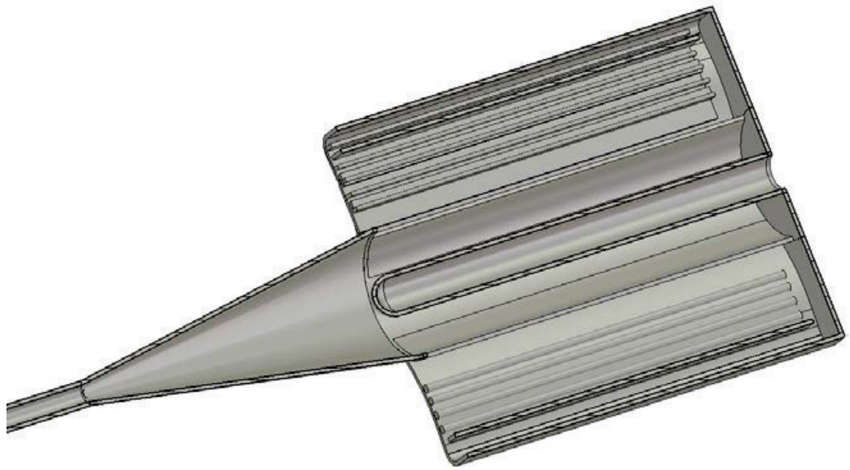


Heat Loading

Very low heat loading because

- Multiple stages already recuperates the most (88 %) energy.
- Heat is loaded on the total long structure along ***z***.





Energy of Imported Spent Electron Beam