Thermal Design of Refridgerated Hexapole 18 GHz ECRIS HIISI

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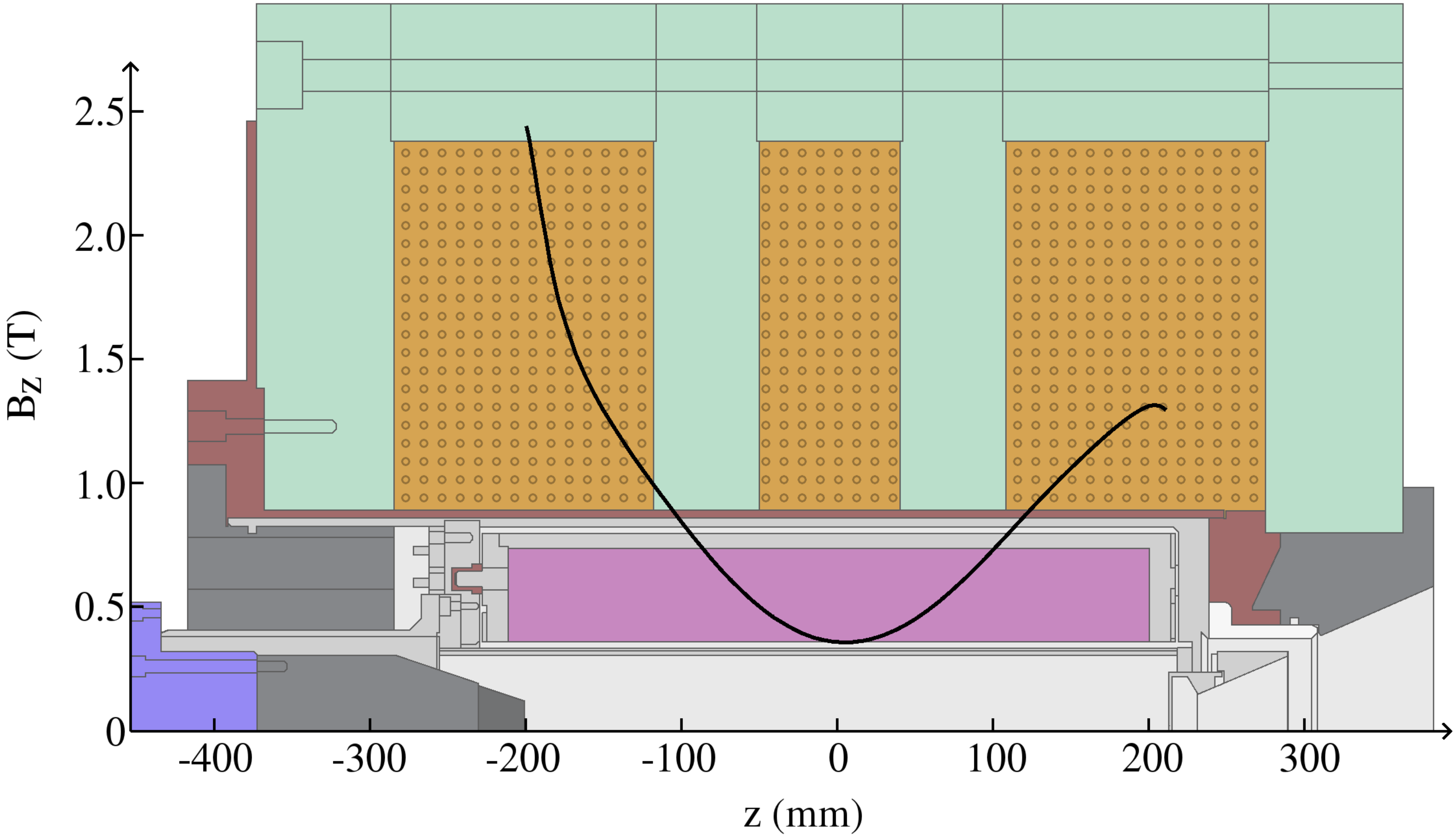
Presentation outline

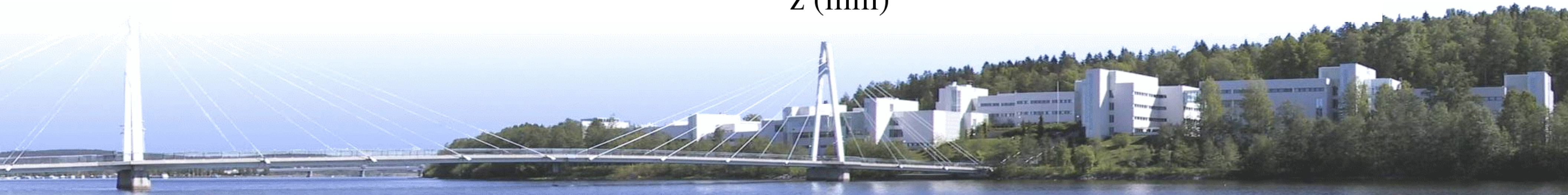
- Review of the 18 GHz ECRIS HIISI design
- Electron trajectory simulations
- Thermal modelling
- H-field analysis

18 GHz ECRIS HIISI

$B_{\mathrm{ecr}} = 0.64$ T

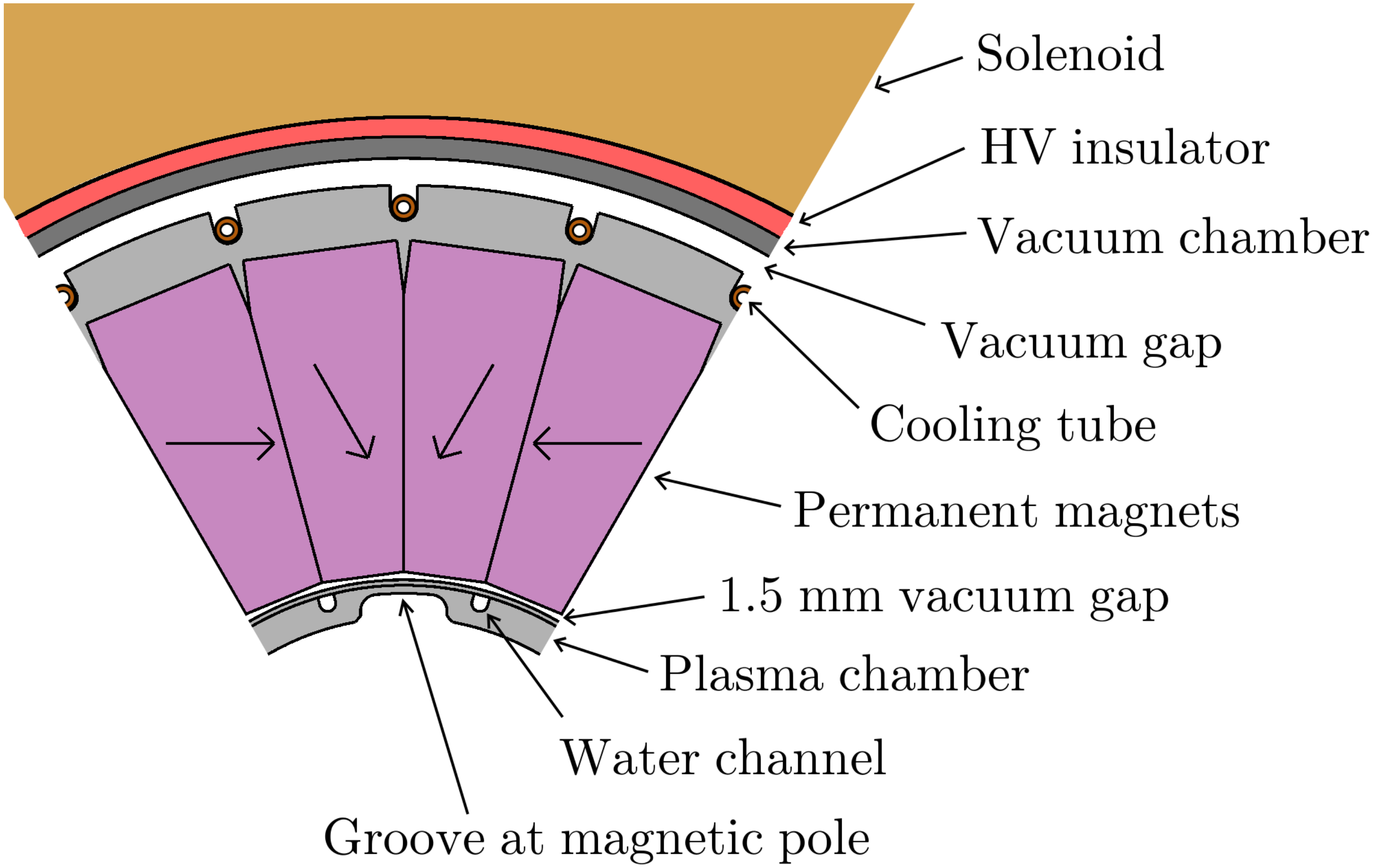
1000 A, -475 A, 820 A: $B_{\min} = 0.36$ T, $B_{\mathrm{inj}} = 2.53$ T, $B_{\mathrm{ext}} = 1.31$ T





18 GHz ECRIS HIISI

Hexapole using N40UH with $B_r = 1.29$ T and $H_c = 1990$ kA/m (at 20°C)



Refridgerated hexapole

The hexapole is going to be cooled nominally to $-10°\mathrm{C}$

- Boosts permanent magnet remanence and coercivity
- Gains demagnetization safety margin
- Makes it possible to use higher remanence, lower coercivity grades:

N40UH	$\boldsymbol{B_r = 1.29\ \mathrm{T}}$	$\boldsymbol{H_c = 1990\ \mathrm{kA/m}}$
N42SH	$B_r = 1.32\ \mathrm{T}$	$H_c = 1600\ \mathrm{kA/m}$
N48H	$B_r = 1.42\ \mathrm{T}$	$H_c = 1350\ \mathrm{kA/m}$

- The plasma chamber and hexapole have to be thermally modelled to verify the design and to find the necessary cooling power.
- Demagnetizing H-field has to be analyzed to find maximum permanent magnet temperature

Electron trajectory simulations

An estimate of the heat flux from plasma is created for thermal modelling:

- Tracking of single electron trajectories in source B-field
- Electrons are launched isotropically from random locations in $B < B_{\mathrm{ecr}}$, where B_{ecr} is for relativistic electrons with E_K
- No E-field, no collisions, energy conserving, relativistic algorithm: Boris leap-frog iterator
- Simulated trajectories can be thought to represent electron trajectories after collision process in the plasma
- If particle is in the loss-cone it will escape within a finite time, if not, it will remain confined in the plasma

Magnetic field model

A smooth and fast model is needed for the 3D magnetic field

- Mesh-based magnetic field map is not an option
- Using analytic formulation for solenoid field in (r, z) and hexapole field in (r, θ) coordinates
- A sixth degree polynomial is fitted to axial solenoid field from FEMM simulation. Expansion is used to produce off-axis fields $B_r(r, z)$ and $B_z(r, z)$.
- A multipole expansion is fitted to FEMM simulation data of the hexapole field for $B_r(r, \theta)$ and $B_\theta(r, \theta)$
- 3D field constructed as a superposition of these 2D fields

Validation of the code

The code was first used to model the JYFL 14 GHz ECRIS at a typical operating point with 520 A solenoid currents.

$$B_{\text{ecr}} = 0.50 \text{ T}, B_{\text{min}} = 0.37 \text{ T}, B_{\text{inj}} = 2.03 \text{ T}, B_{\text{ext}} = 0.94 \text{ T},$$
$$B_{\text{pole}} = 1.08 \text{ T}, B_{\text{btw}} = 0.69 \text{ T}$$

Simulations with monoenergetic electrons $E_K = 10, 100, 200$ keV.

- Time step $\Delta t = 1$ ps is used for trajectory calculation
- Tracking time of 1000 ns is used
- 10^6 particles used for statistics
- Test cases show error in location < 1 mm during this time

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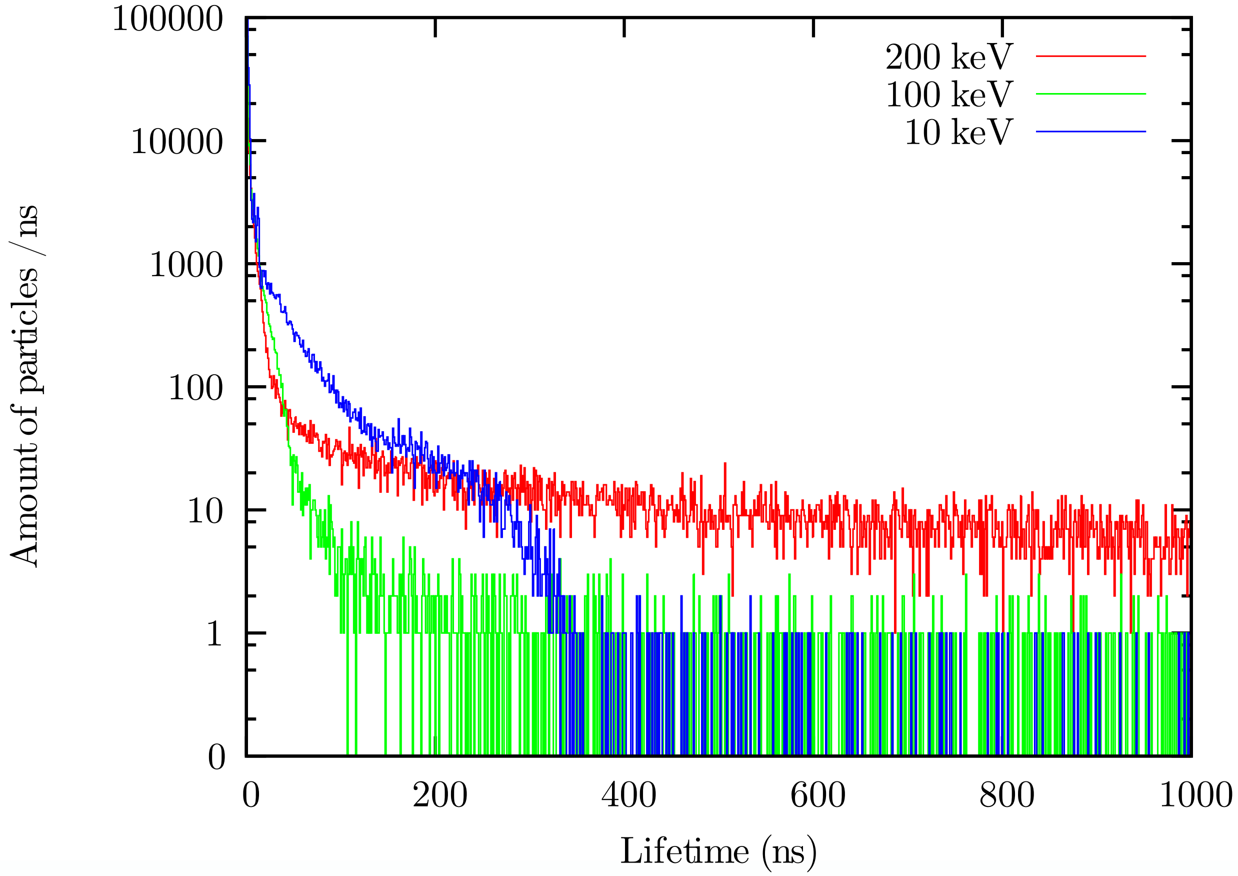
Lifetime of particles in simulation

70 % particles are time-limited. Increasing the tracking time by ×10 decreases the number of time-limited particles by less than 1 %.



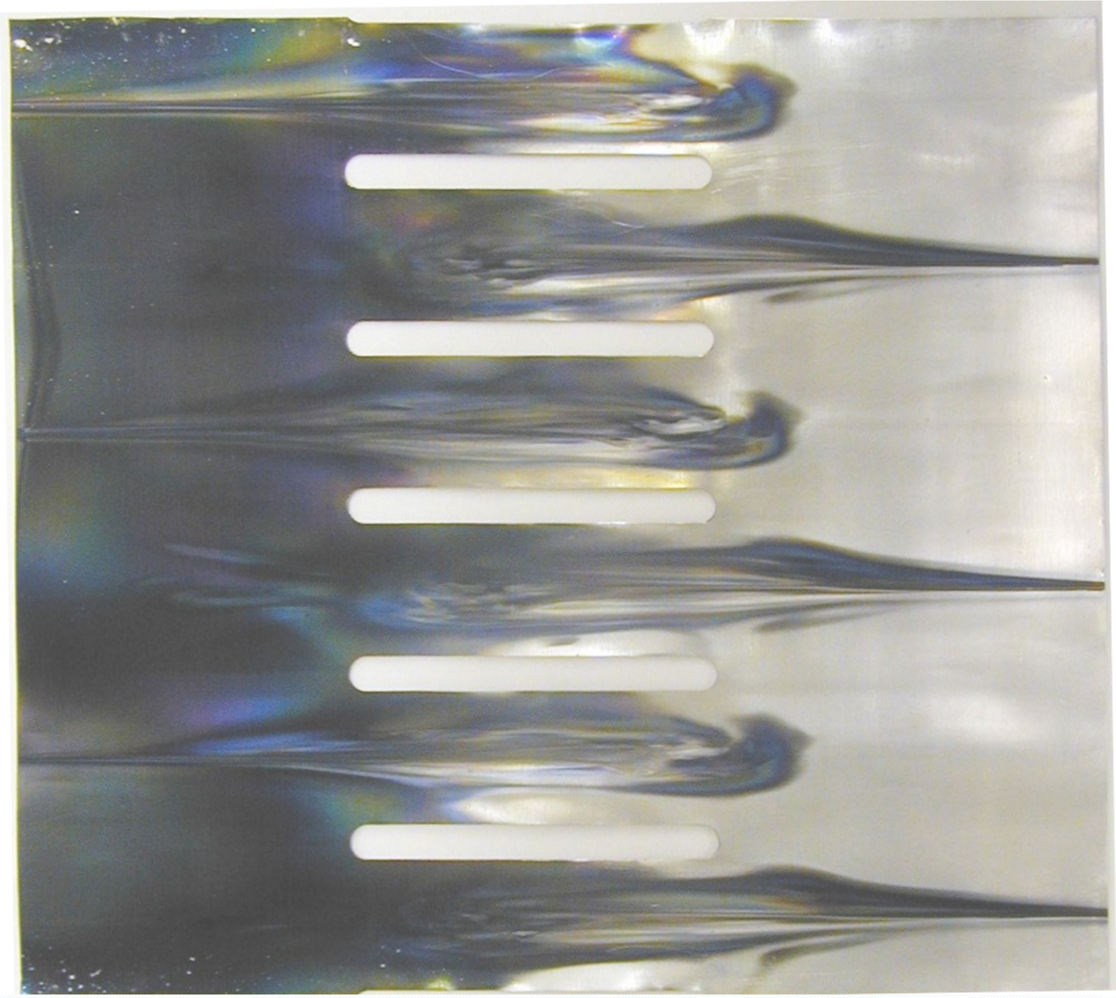
Distribution of electron fluxes

Outgoing electron fluxes in 14 GHz ECRIS simulation

	10 keV	**100 keV**	**200 keV**
Injection flux	8.3 %	6.9 %	5.7 %
Extraction flux	27.1 %	23.5 %	22.6 %
Extraction aperture flux	5.1 %	3.4 %	2.6 %
Radial flux	64.5 %	69.7 %	71.7 %

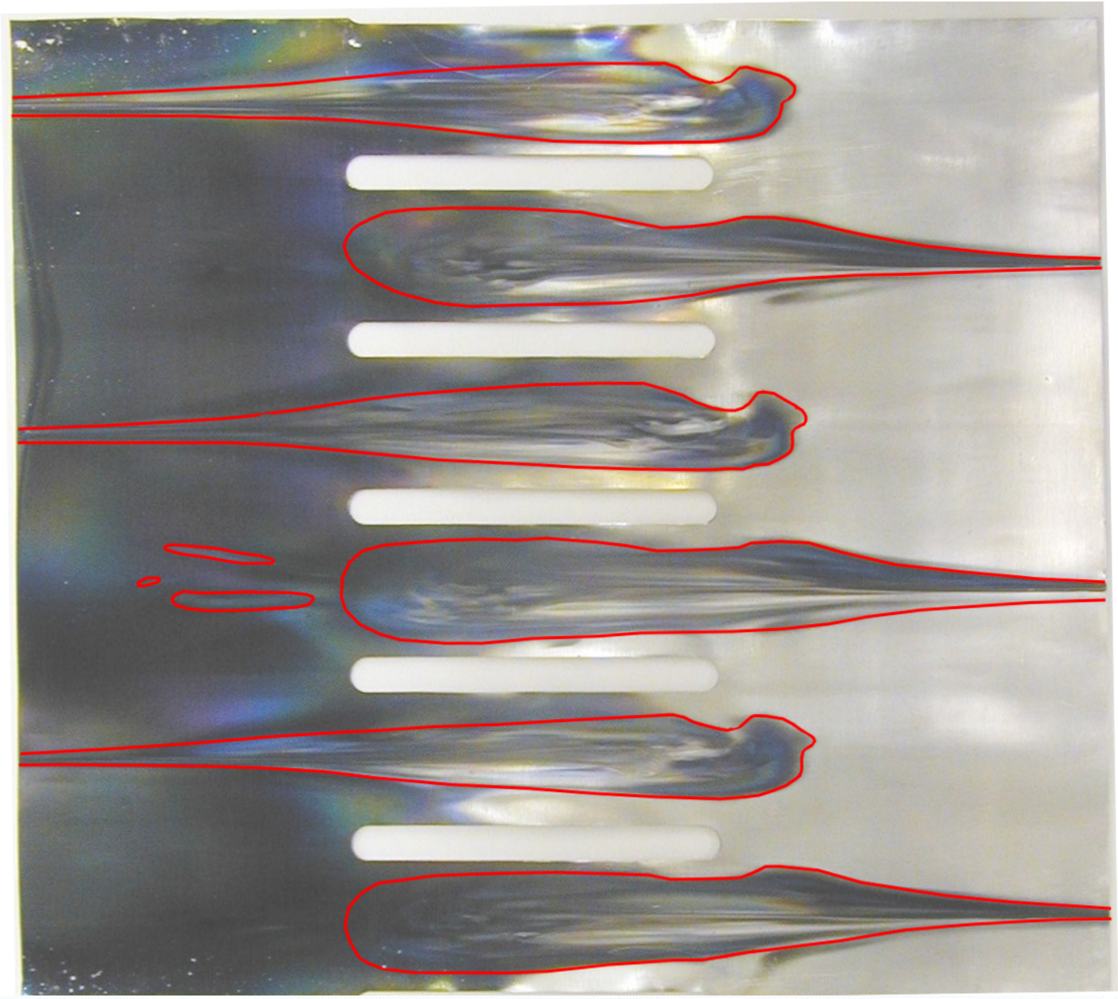
Comparison of electron flux to chamber patterns

Carbon contaminant patterns on 14 GHz ECRIS chamber liner



Comparison of electron flux to chamber patterns

Carbon contaminant patterns on 14 GHz ECRIS chamber liner



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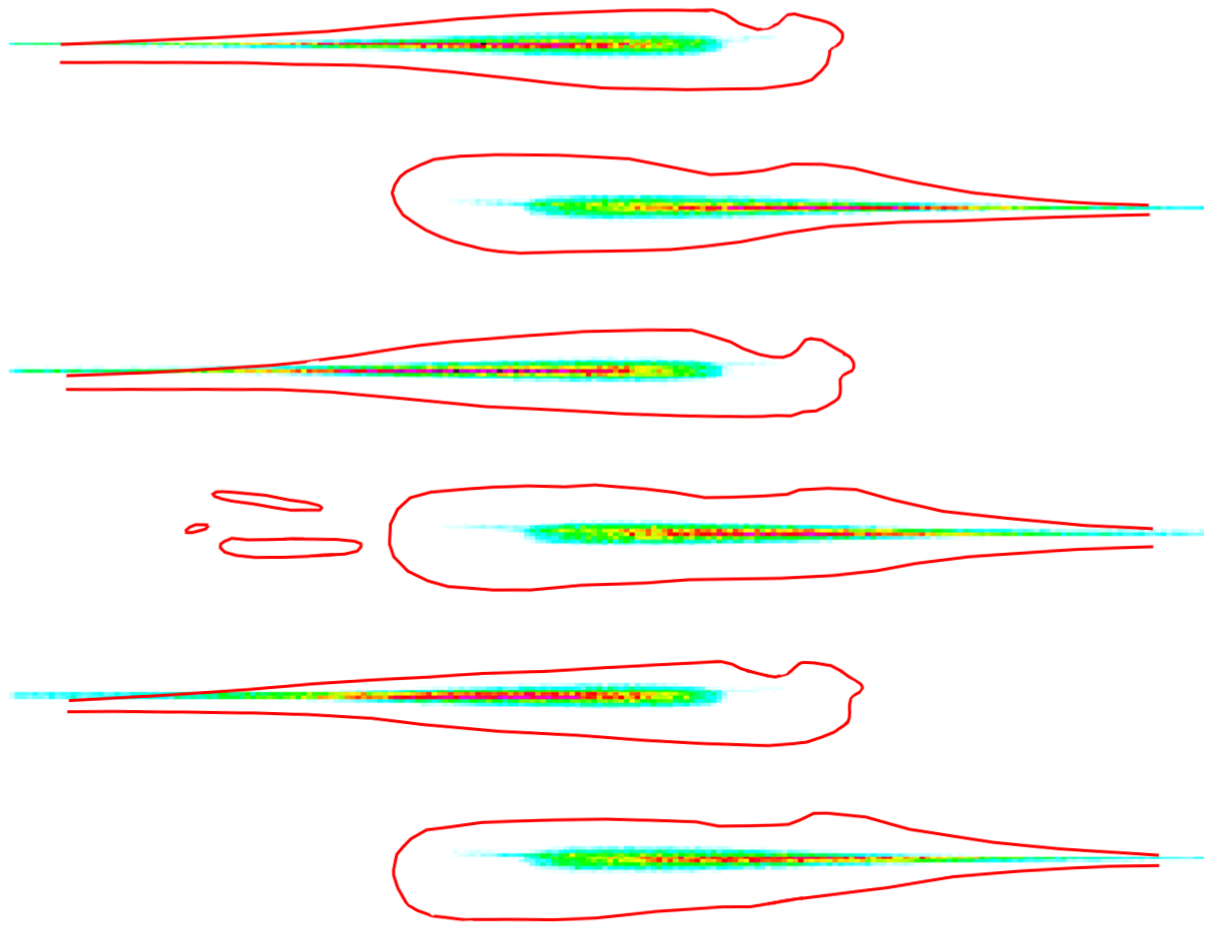
Comparison of electron flux to chamber patterns

Simulation, $E_K = 10\ \text{keV}$

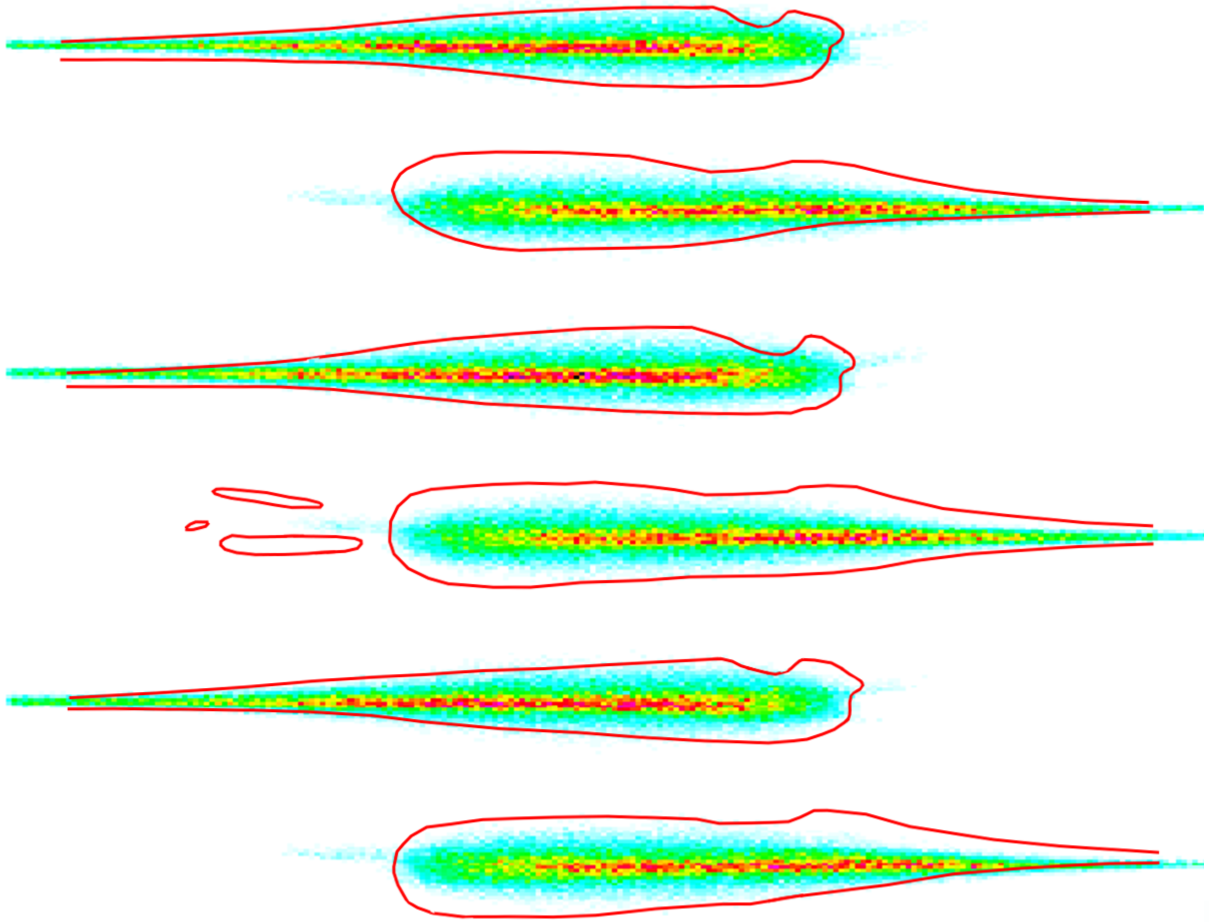


Comparison of electron flux to chamber patterns

Simulation, $E_K = 100$ keV

Comparison of electron flux to chamber patterns

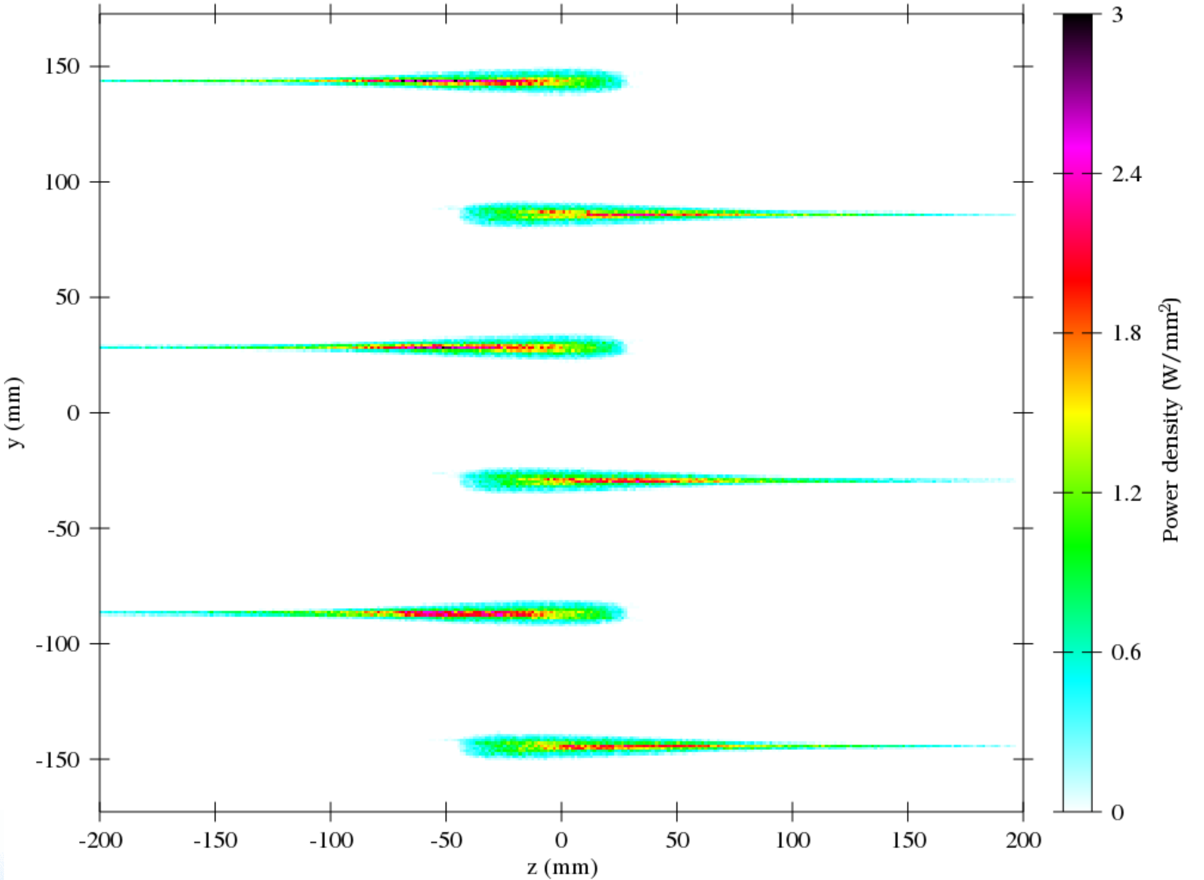
Simulation, $E_K = 200$ keV



Radial flux distribution with 18 GHz ECRIS

After gaining some confidence to simulations, the 18 GHz HIISI was modelled.

Assuming all 6 kW of RF power used to heat the plasma is deposited **radially** to the plasma chamber with distribution from 10 keV electron simulation:



Distribution of electron fluxes

Outgoing electron fluxes in 18 GHz ECRIS simulation

	10 keV	**100 keV**	**200 keV**
Injection flux	6.7 %	5.7 %	5.1 %
Extraction flux	12.4 %	10.4 %	9.1 %
Extraction aperture flux	2.2 %	1.5 %	1.0 %
Radial flux	80.8 %	83.9 %	85.8 %
Radial distribution width	±5.5 mm	±9.4 mm	±12.7 mm

Plasma chamber groove width is ±8 mm

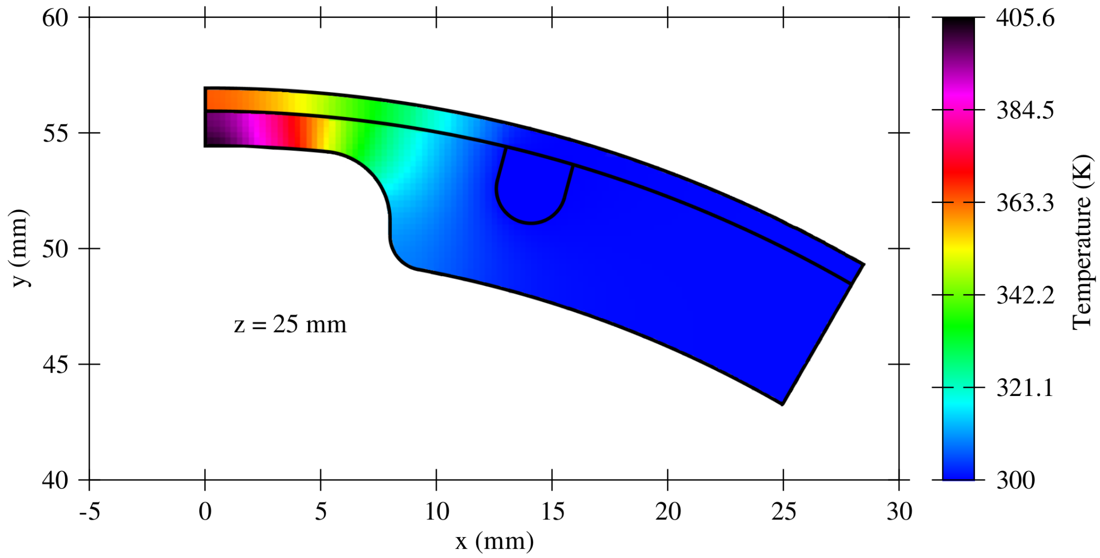
Thermal modelling

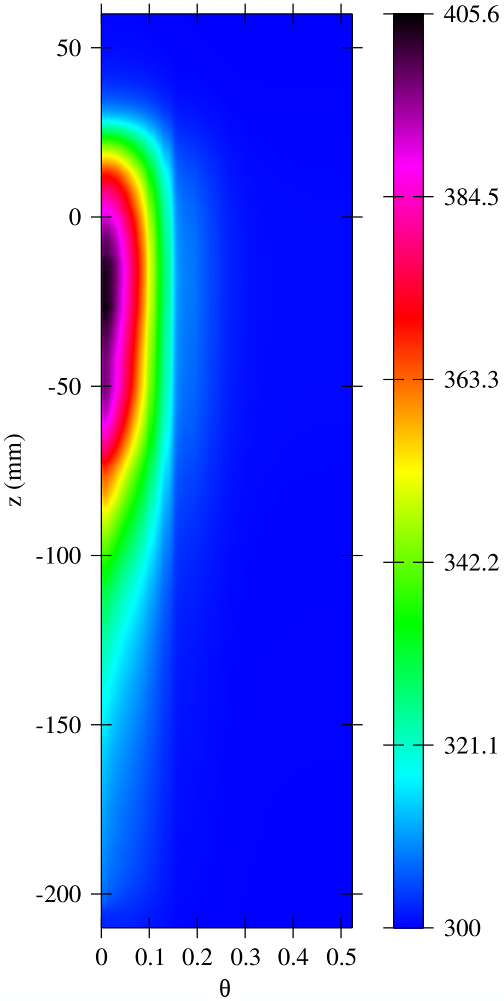
- A 3D code, which solves discretized heat transfer problem in a Cartesian grid with regular step size is used
- Takes in account conductive, radiative and convective processes
- Handles different materials with non-linear properties, emissivities, absorptivities, etc.
- Radiative and convective transfer models assume thin gaps, which allow heat transfer only in the direction of surface normal.

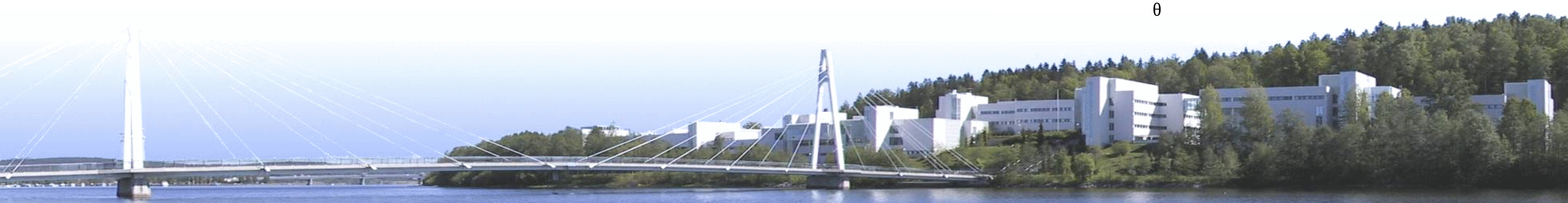
Plasma chamber

Thermal simulation

- 6 kW input power flux from 10 keV electron trajectory simulation
- Heat transfer with hexapole at $-10°\mathrm{C}$

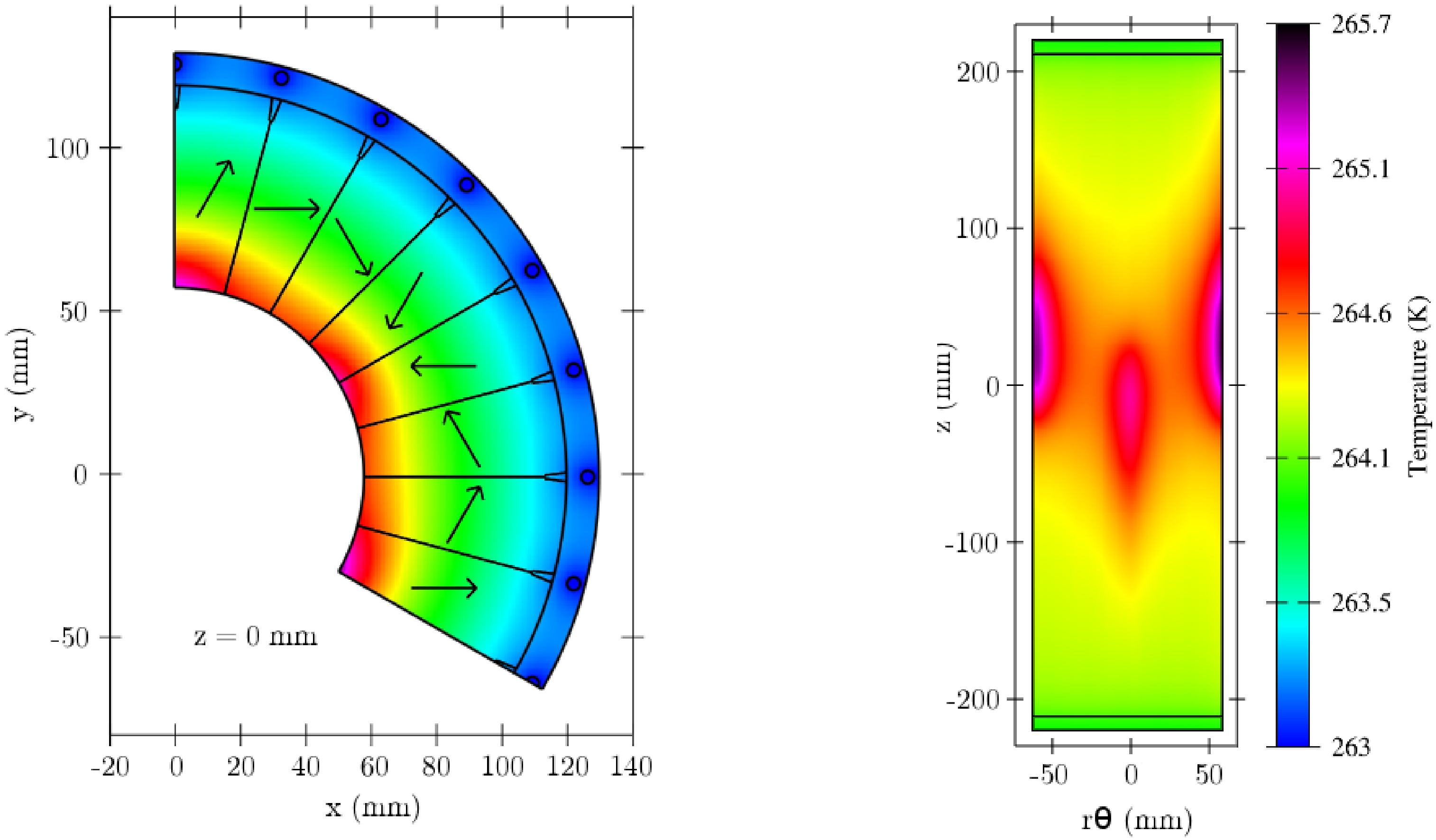






Hexapole temperature distribution

Heat flux from plasma chamber and solenoid at 320 K. Assuming 10.0 Pa pressure in insulating vacuum and 1.0 emissivity (worst case)



Hexapole heat load

Hexapole temperature elevated only by few degrees from cooling fluid temperature.

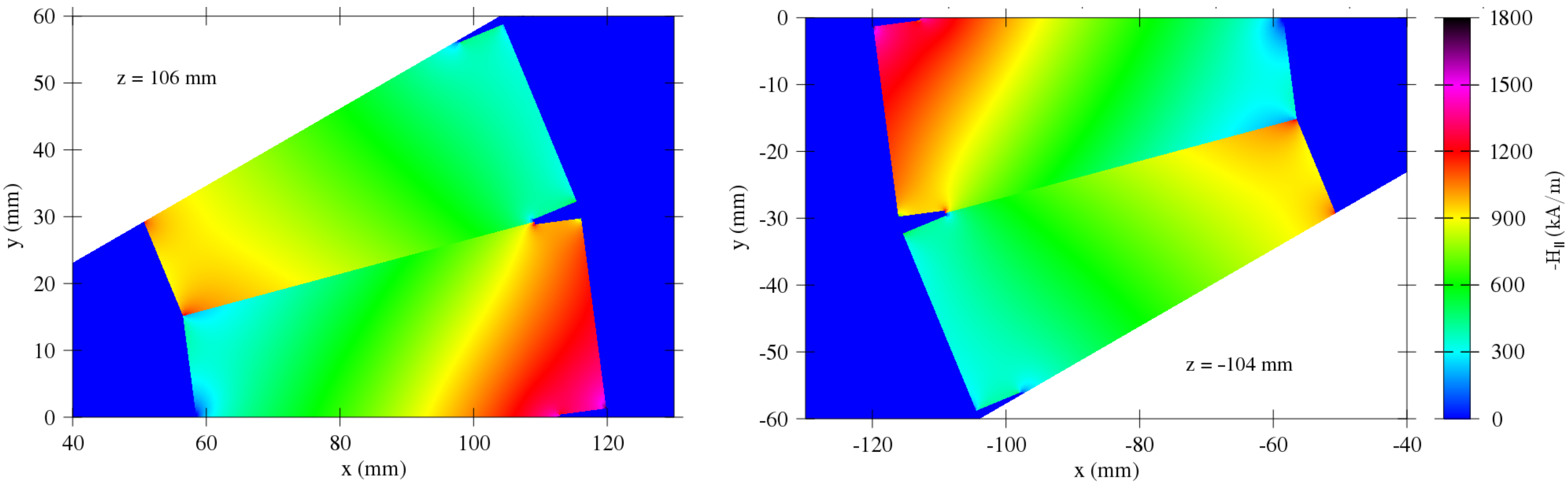
Heat flux is highly dependent on insulating vacuum level and surface emissivity

	$P = 1$ Pa $\epsilon = 0.1$	$P = 1$ Pa $\epsilon = 0.5$	$P = 10$ Pa $\epsilon = 0.1$	$P = 10$ Pa $\epsilon = 0.5$	$P = 10$ Pa $\epsilon = 1.0$
Radiative	19.7 W	98.3 W	19.6 W	98.0 W	195 W
Convective	16.0 W	16.0 W	159 W	159 W	158 W
Conductive	12.0 W	12.0 W	12.0 W	12.0 W	12.0 W
Total	47.7 W	126 W	191 W	268 W	365 W

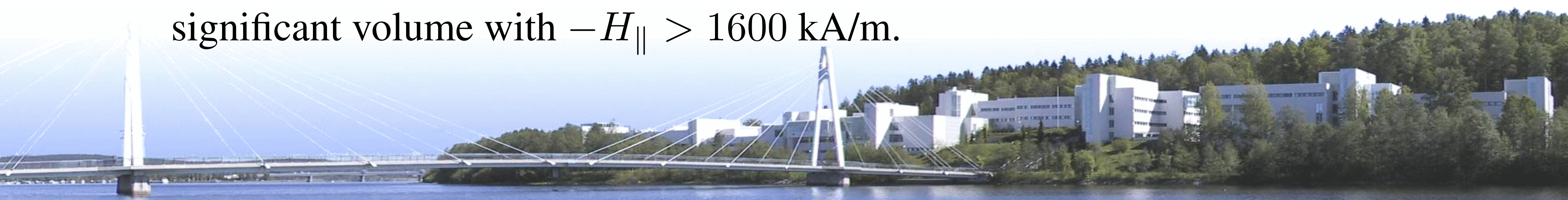
It is expected that a 300 W (at -20°C and 750 W at -10°C) refridgeration unit is sufficient for reaching -20°C.

H-field analysis

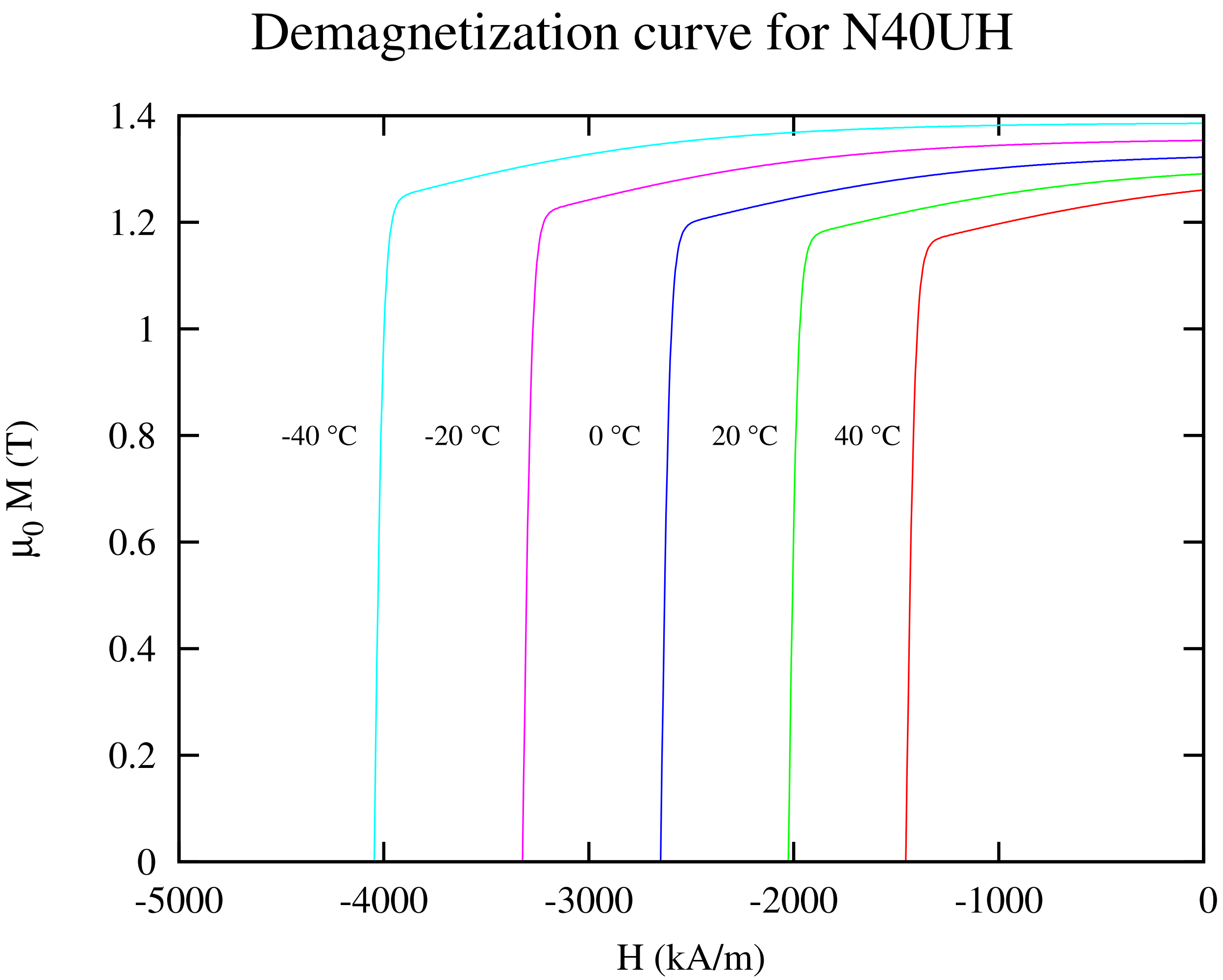
The total H-field of the hexapole and solenoid field is separated to components perpendicular to direction of magnetization $H_\perp$ and parallel to magnetization $H_{||}$.



Miniscule volume with $-H_{||} \sim 1800$ kA/m, significant volume with $-H_{||} > 1600$ kA/m.



H-field analysis



Permanent magnets are safe at $T < 20°\mathrm{C}$.

Conclusion

- 18 GHz normally conducting ECRIS HIISI is being designed
- Innovative grooved plasma chamber and refridgerated hexapole will be used.
- First hexapole will be made using N40UH: 20°C is sufficient
- This hexapole will be used to debug the refridgeration issues
- After development and verification of the refridgeration technology another hexapole can be constructed from higher remanence, lower coercivity grade, which requires refridgeration to sub-zero temperatures.

Thank you for your attention!