ENSAR/ARES/JYFL-report (2013-2014)

JYVÄSKYLÄN YLIOPISTO

1) Beam transport work (Task 2)
2) Plasma studies (Task 1)
3) Metal ion beam development (Task 3)
4) Project for new 18 GHz ECRIS
5) Future plans

Beam transport: current beam line

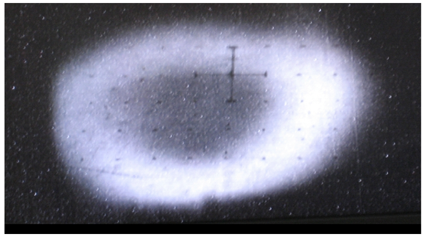
Known issues:

- DJ1 focusing is asymmetric
- Focal point before mass analysis causes emittance growth due to space charge forces from focal points of different species
- Large beam diameter inside DJ1 causes aberrations

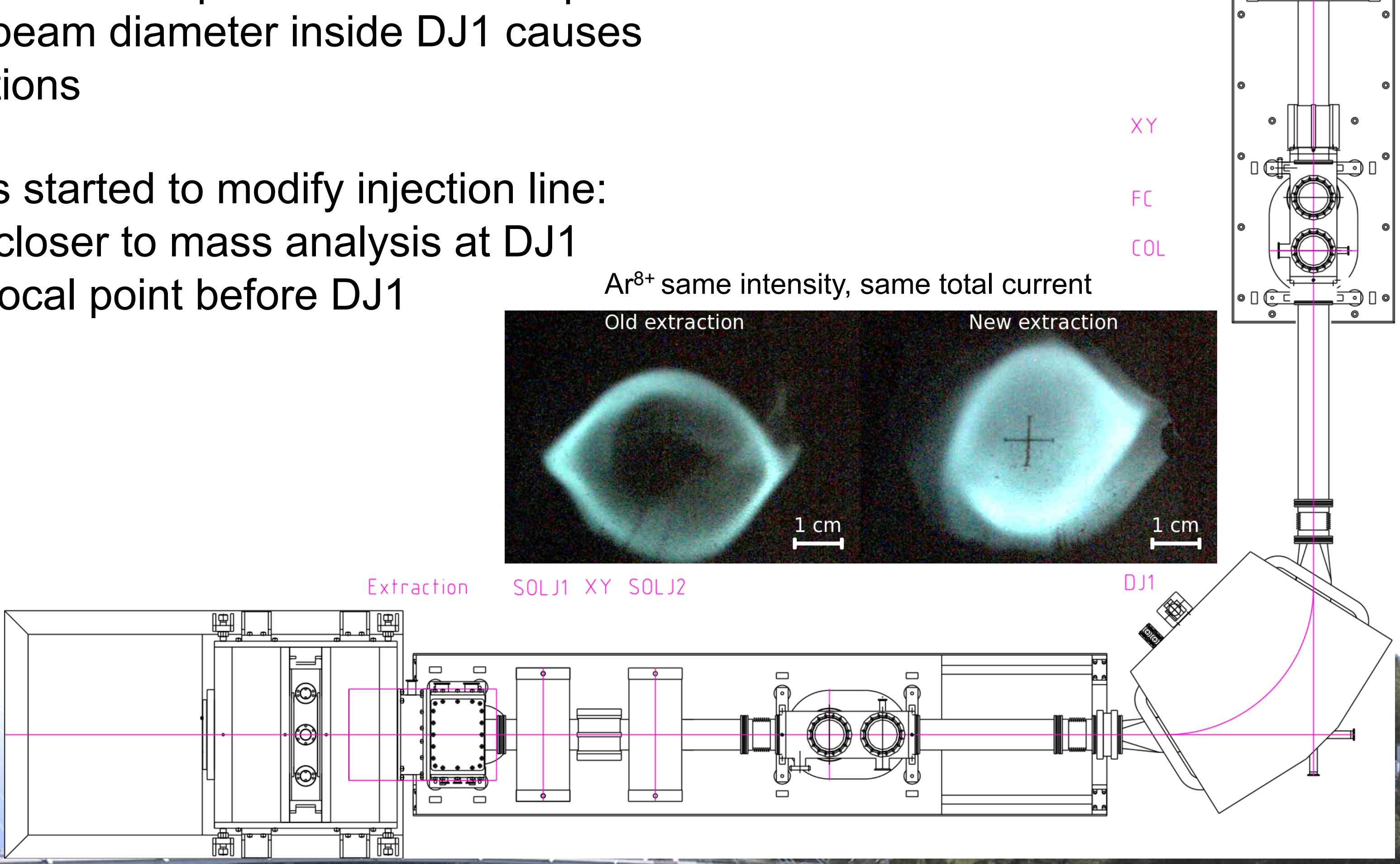
Study was started to modify injection line:

- ECR2 closer to mass analysis at DJ1
- Avoid focal point before DJ1

Ar^{9+} max intensity



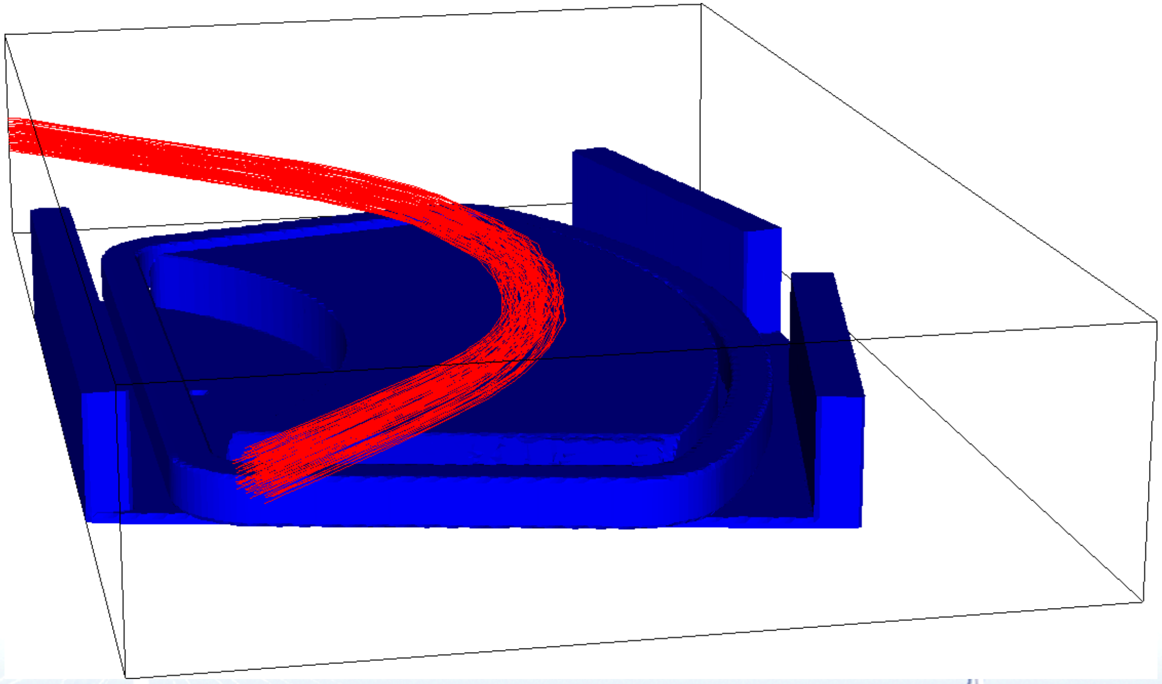
Ar^{8+} same intensity, same total current

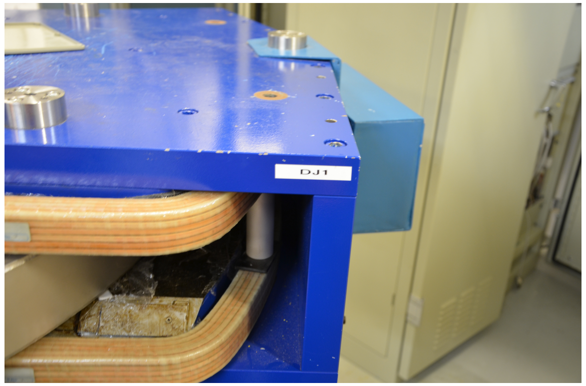


Analysis of 14 GHz ECRIS dipole

- DJ1 has been corrected with iron shims before
- No information about non-linearities exist

- Field model was constructed with Comsol
- Test beam was ray-traced through the magnet
- Linear transport model was constructed

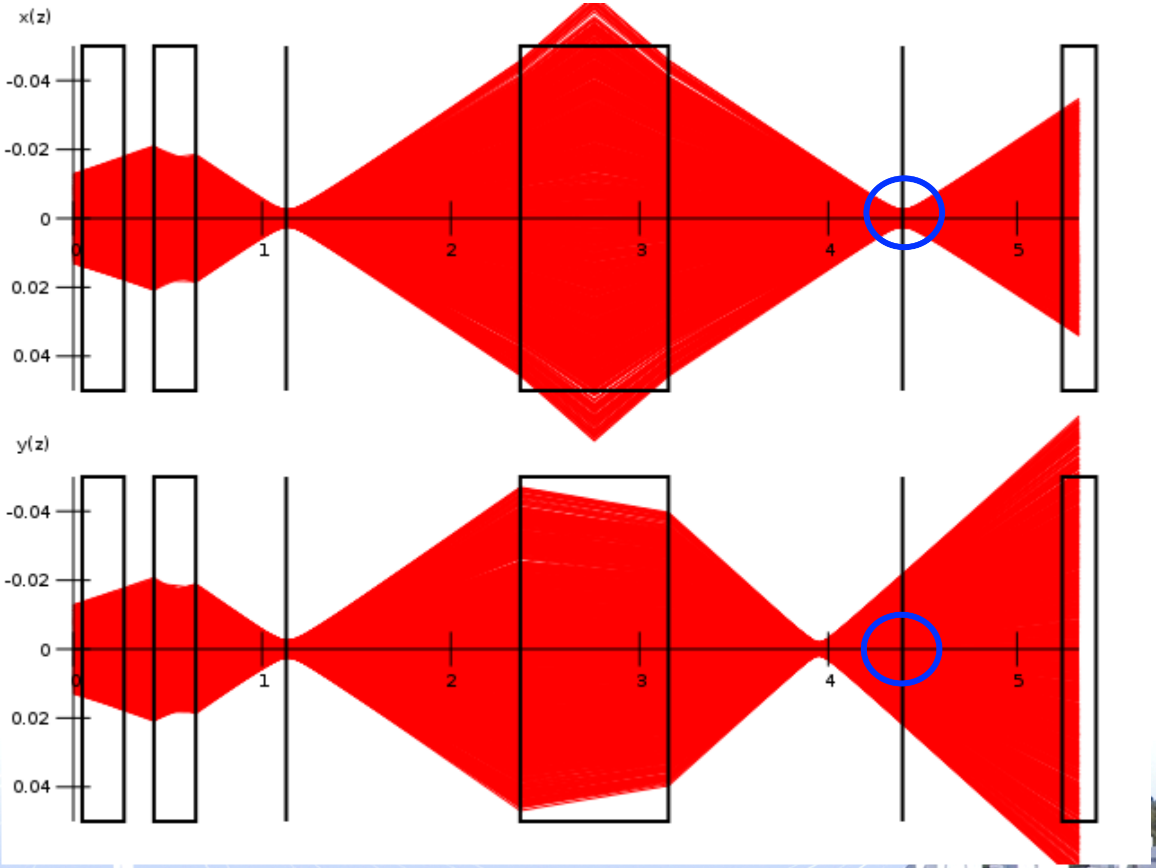




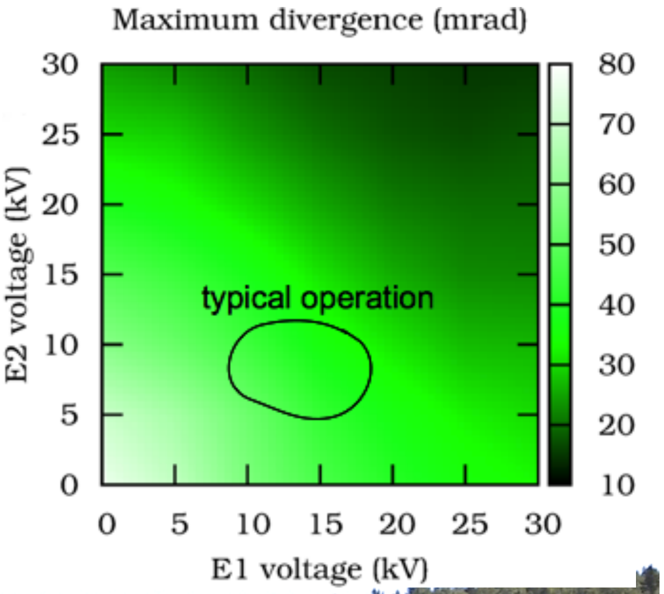
- Mechanical pole angle 32°
- Field angle w/o shims 31.6°
- Field angle w shims 30.8°
- Specification says 29.4°
- Should be 28.3° *assuming same pole shape*

Present beam transport: different focal point after dipole in x/y-plane

- Current optics, 20 mrad divergence, 26 mm diameter, Ar^{8+}
- Beam is cut inside the dipole

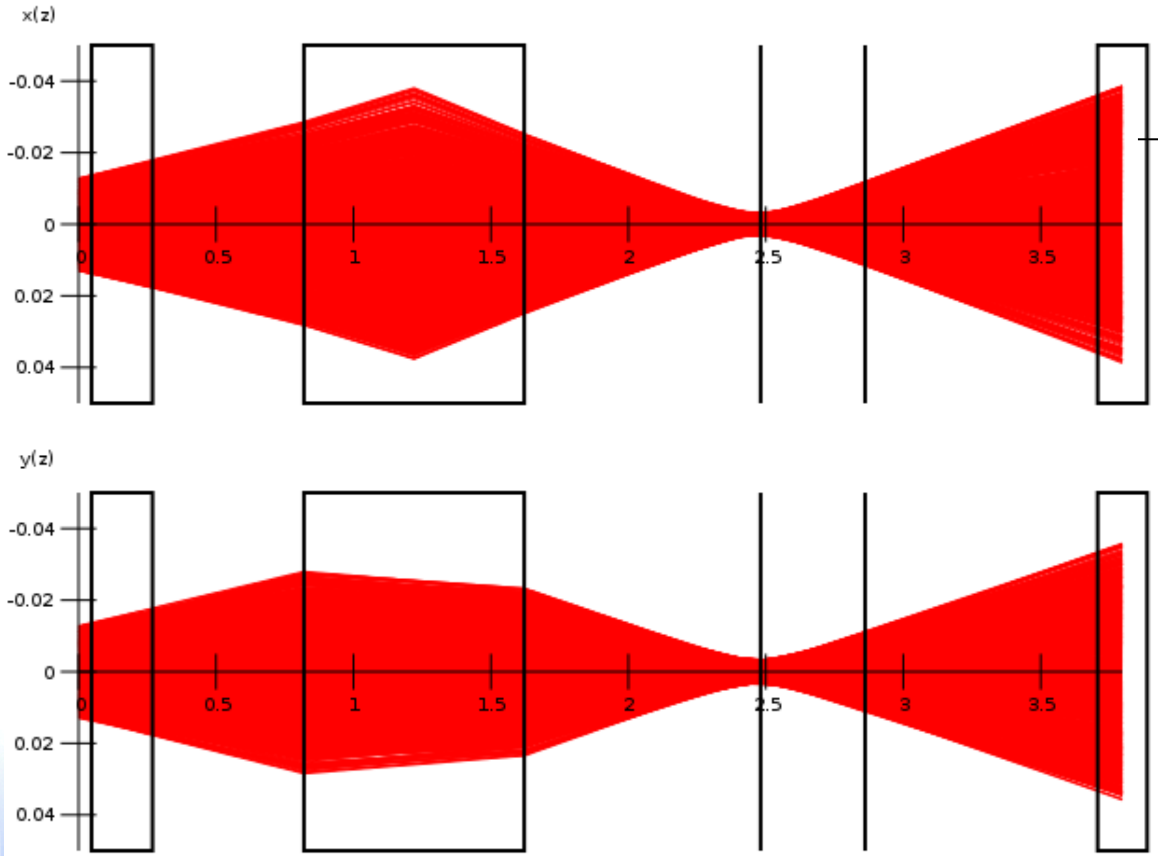


Experimental data from Ville's work: Beam divergence in range of 20-50 mrad.



Proposed solution

1. Direct injection to DJ1 without focal point
2. One solenoid after extraction for adjusting high divergence beam
3. Machine DJ1 pole edges for symmetric focusing

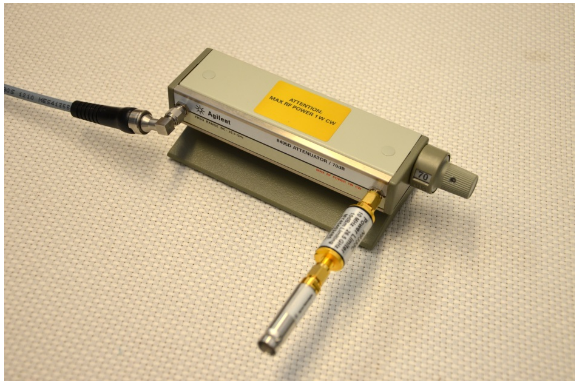


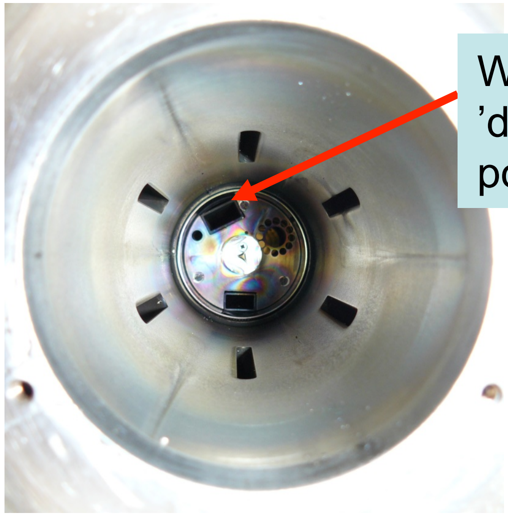
This solenoid will be replaced by two solenoid system

Plasma studies: electron cyclotron instabilities

Experimental setup:

1. 10 MHz – 50 GHz microwave detector diode connected to WR-75 waveguide



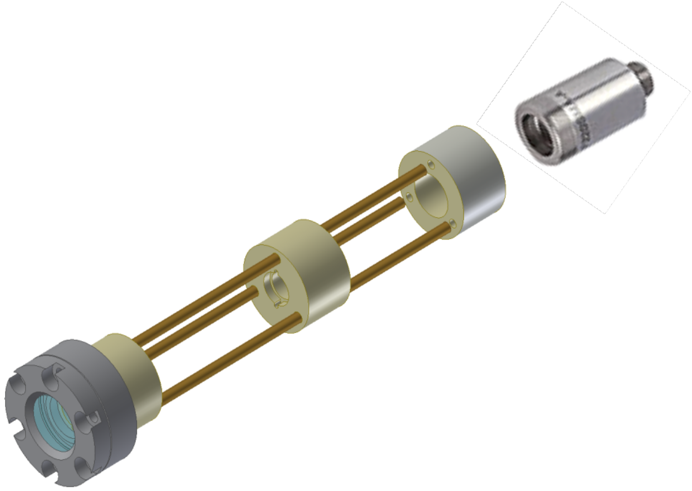


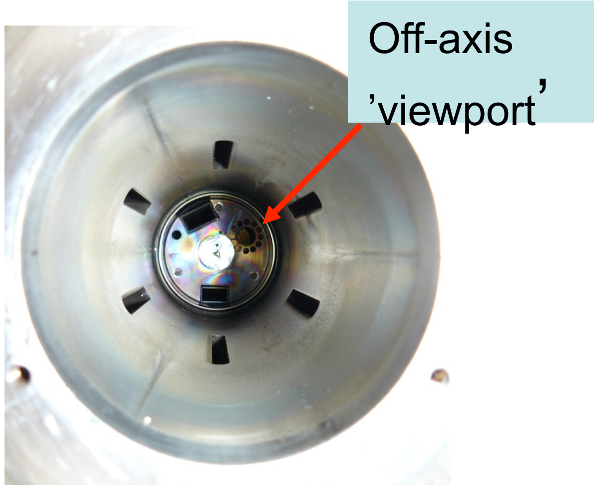
WR-75 ’diagnostics port’

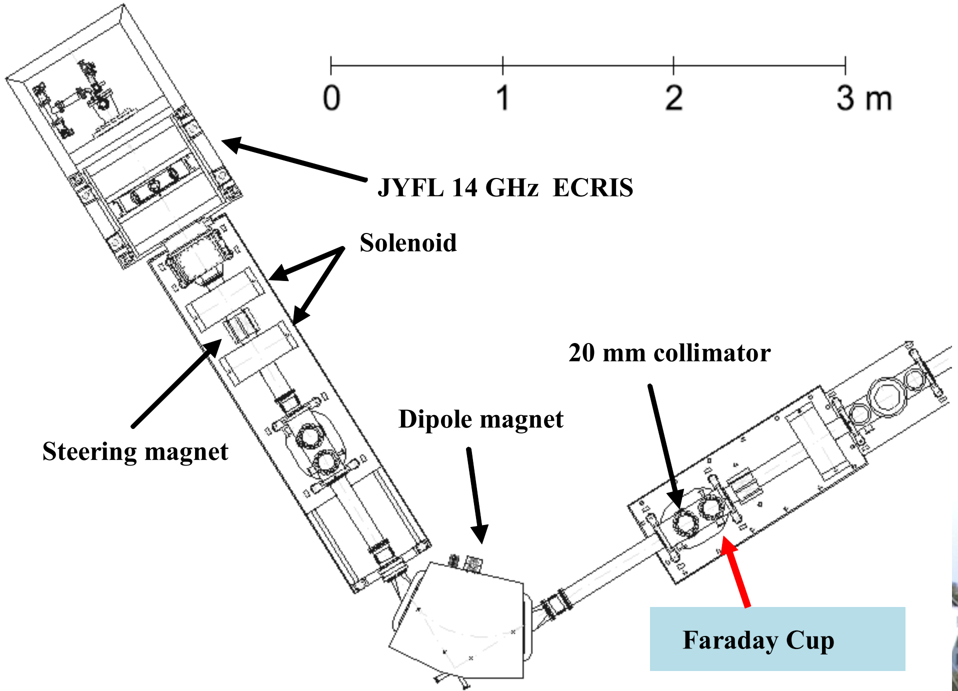
2. Current-mode BGO scintillator + PMT measuring the bremstrahlung power flux

Experimental setup continues…

3. Visible light collector coupled with Na-doped CsI PMT (300-600 nm)

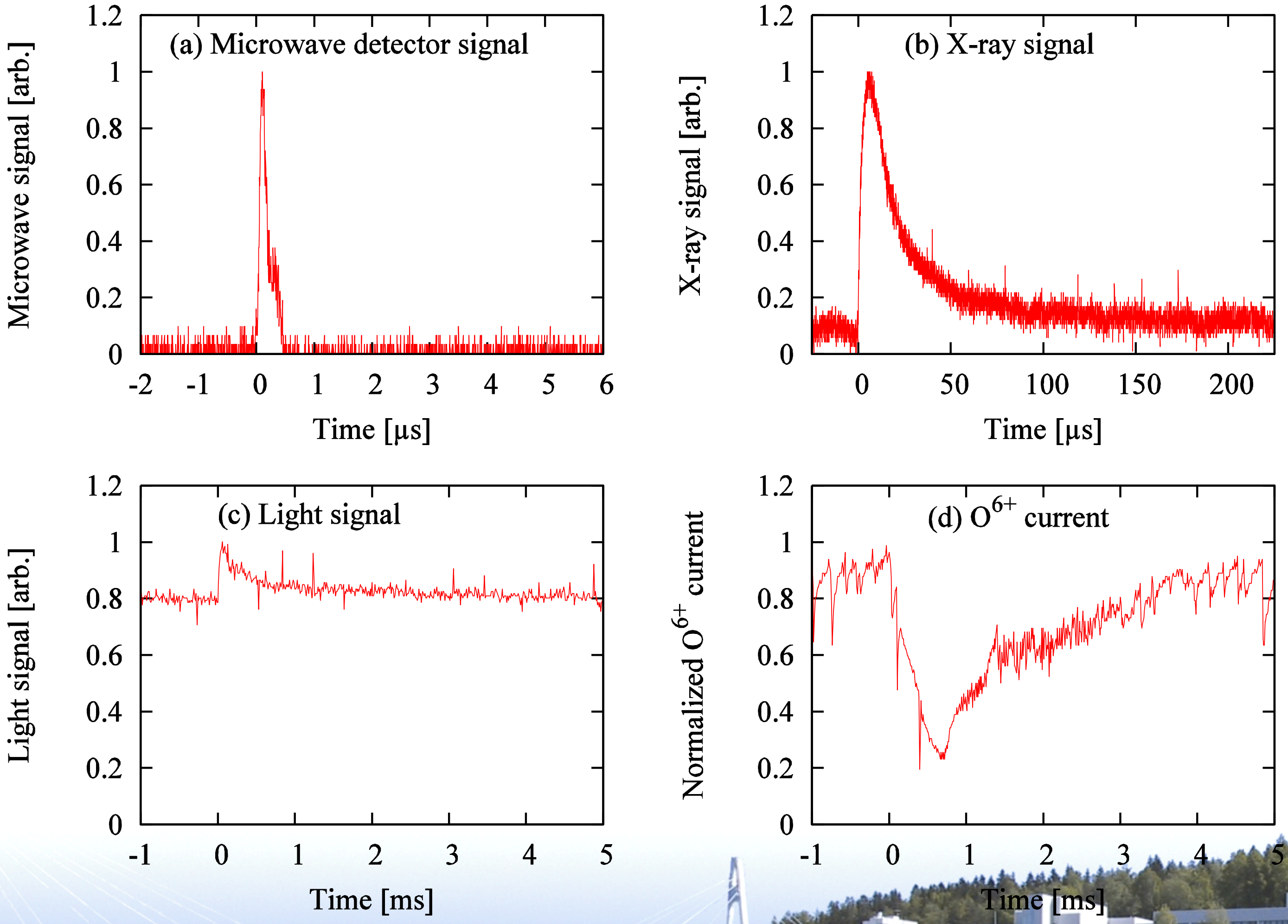






4. Faraday cup ~ 5 m downstream in the beam line

Diagnostics signals: example



Repetition rate (microwave emission)

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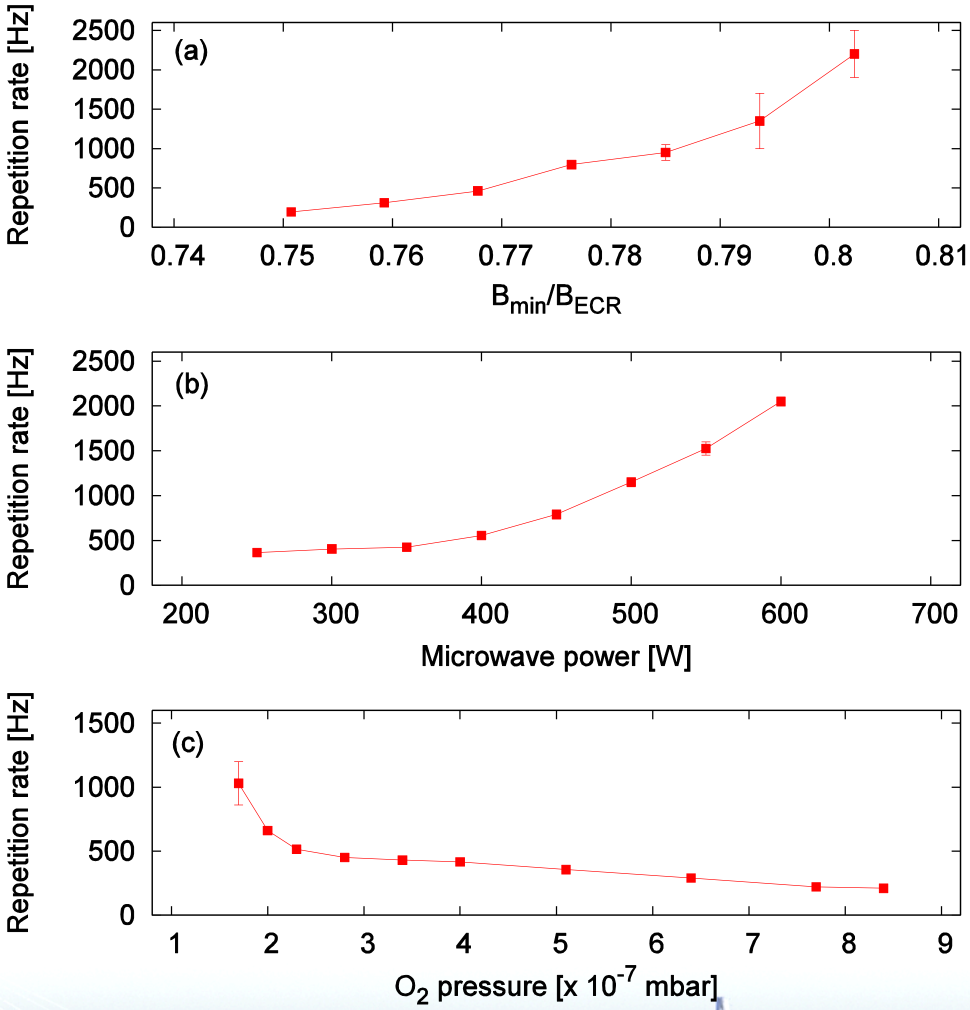
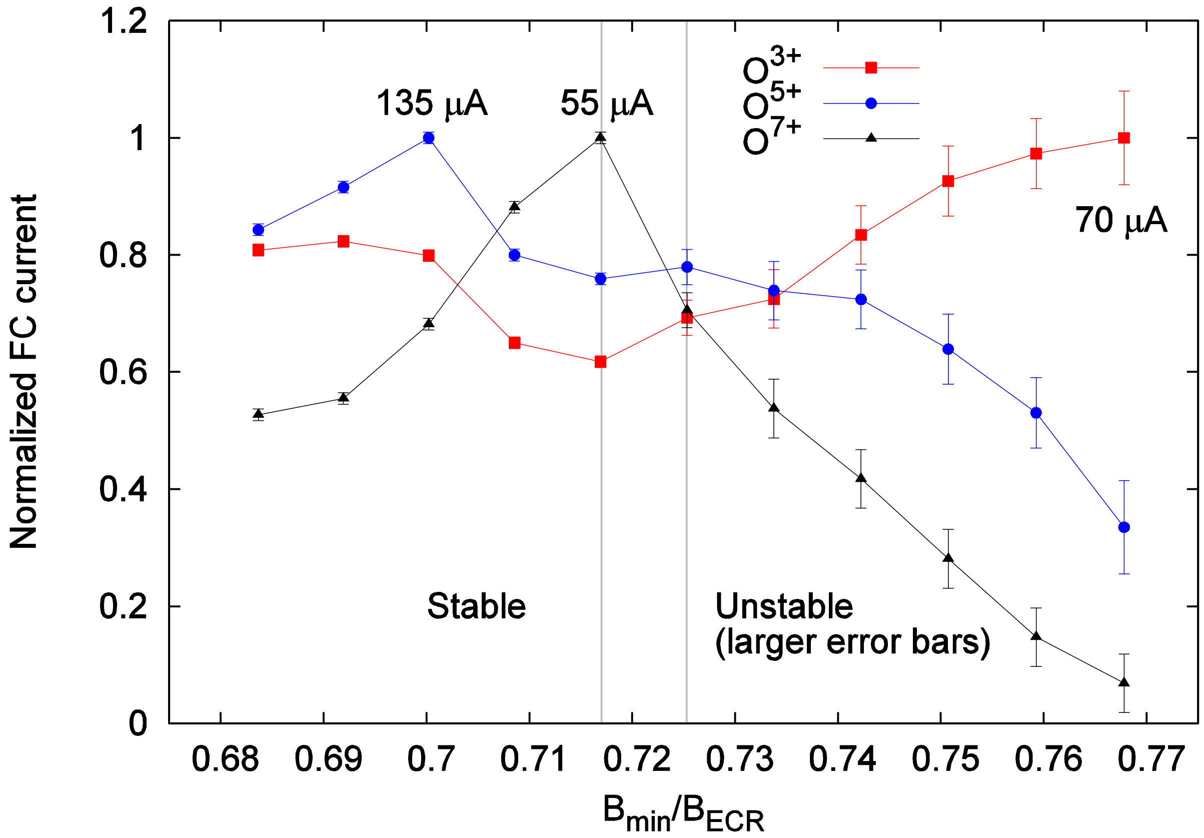
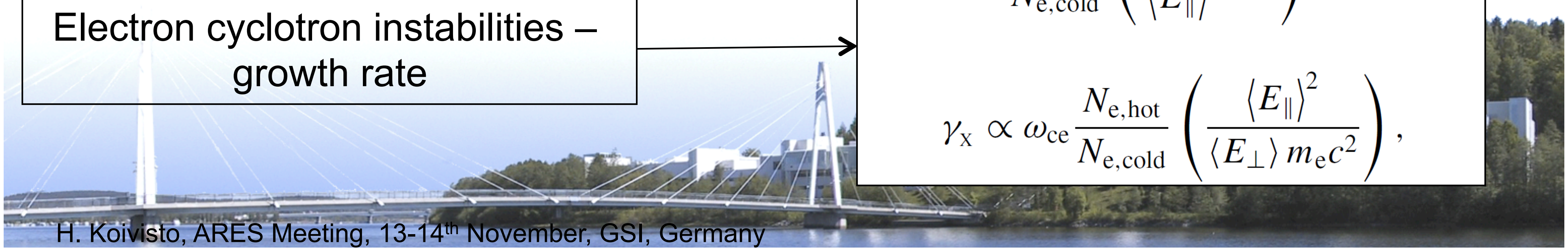


What happens to ion beam intensity and what affects?



$$\frac{\mathrm{d}E_\mu}{\mathrm{d}t} \approx \langle \gamma - \delta \rangle \, E_\mu$$



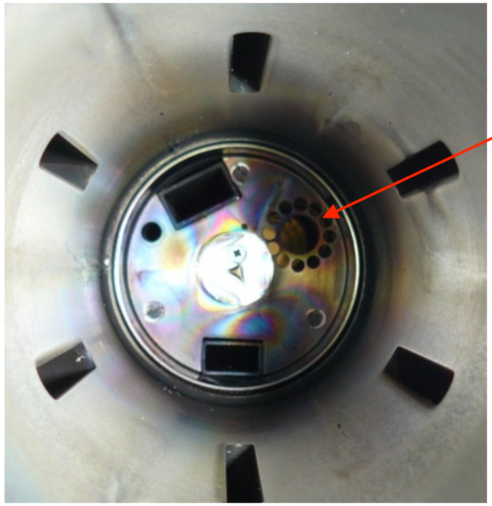
Electron cyclotron instabilities – growth rate

$$\gamma_{\mathrm{w}} \propto \omega_{\mathrm{ce}} \frac{N_{\mathrm{e,hot}}}{N_{\mathrm{e,cold}}} \left(\frac{\langle E_\perp \rangle}{\langle E_\parallel \rangle} - 1 \right) \mathrm{e}^{-\xi \frac{B^2}{\langle E_\parallel \rangle N_{\mathrm{e,cold}}}}$$

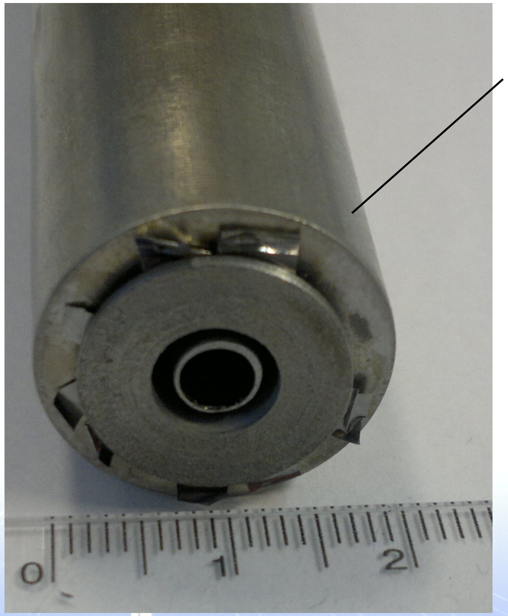
$$\gamma_{\mathrm{X}} \propto \omega_{\mathrm{ce}} \frac{N_{\mathrm{e,hot}}}{N_{\mathrm{e,cold}}} \left(\frac{\langle E_\parallel \rangle^2}{\langle E_\perp \rangle \, m_{\mathrm{e}} c^2} \right),$$

Metal ion beam production: *foil oven*

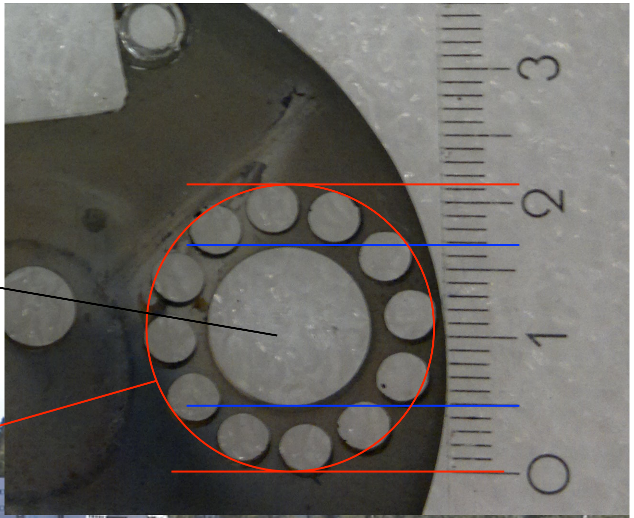
- The original plan was to have tests with the movable oven. This plan was cancelled after the demagnetized permanent magnets (radial sputtering experiments). The reason can be seen from figure (oven very close to the permanent magnets as soon as it is inserted into the plasma chamber).



Port for foil oven



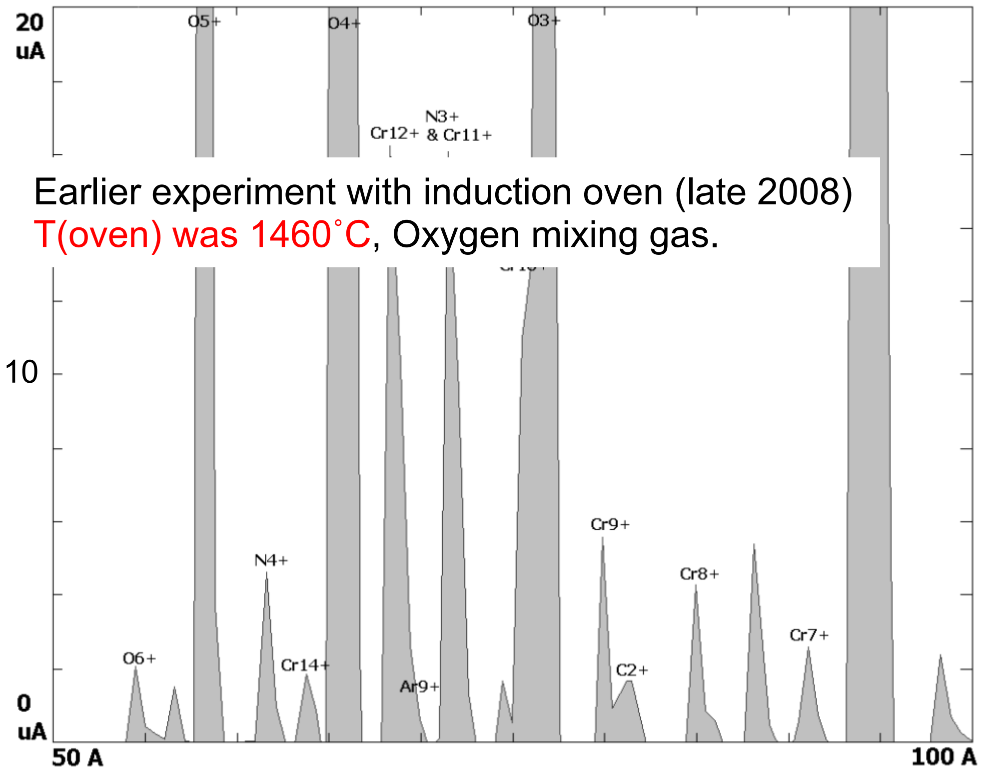
Oven diameter 20 mm



Oven is 1-2 mm behind this plate. Metal vapor comes out tough the aperture (12 mm in diameter).

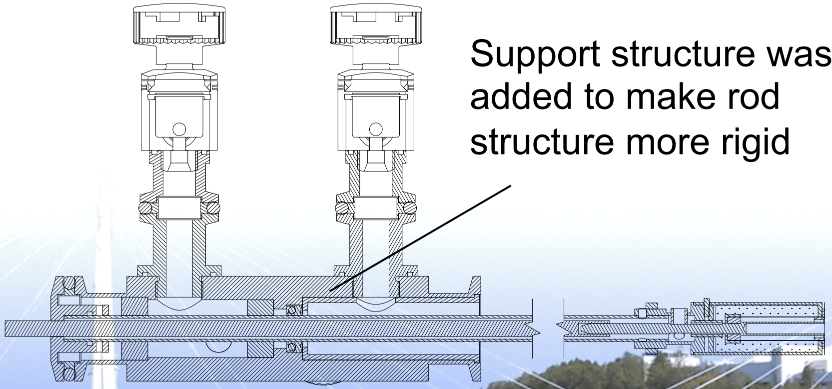
This part was removed to make movable axial sputtering possible

Metal ion beam production: foil oven

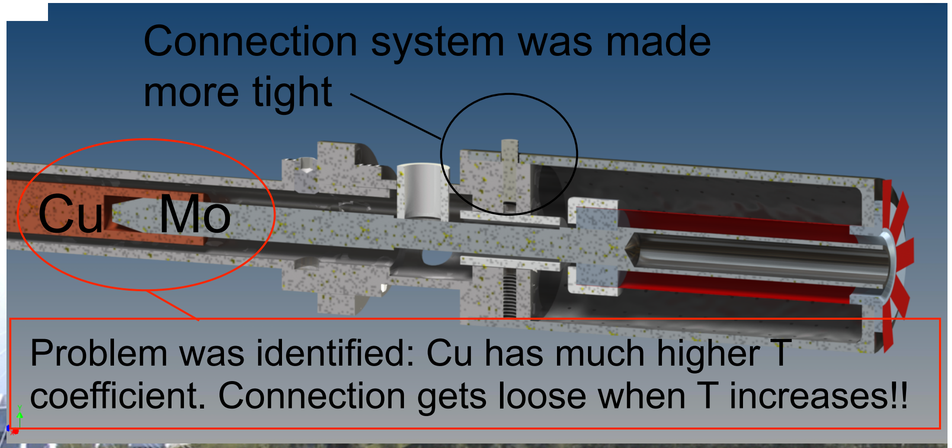


Earlier experiment with induction oven (late 2008)
T(oven) was 1460˚C, Oxygen mixing gas.

During Oct. 2013 – Jan. 2014 foil oven was slightly modified to improve the reliability (not inserted into the chamber). The intensity of 7.6 µA for Cr^{8+} was obtained with the helium mixing (I_{oven} was 59 A). If we trust on the earlier T calibration the oven temperature was slightly above 1500˚C. This oven has potential to go remarkably higher in T.



Support structure was added to make rod structure more rigid

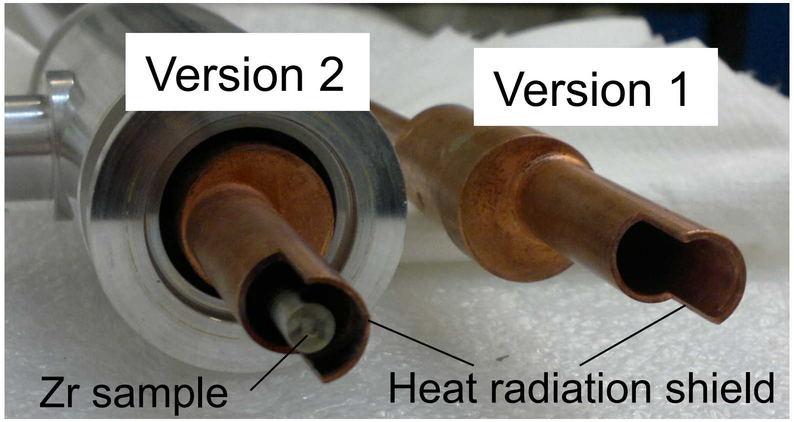


Connection system was made more tight

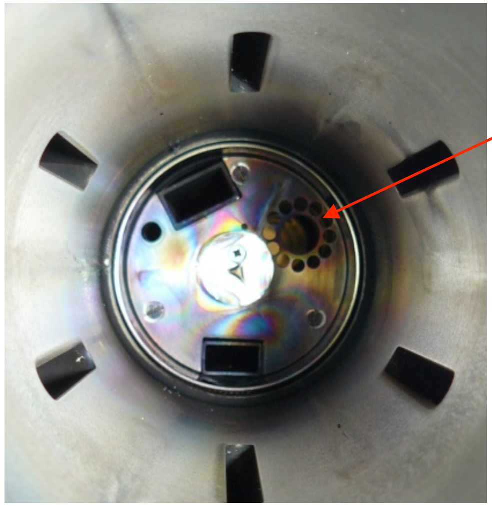
Problem was identified: Cu has much higher T coefficient. Connection gets loose when T increases!!

Metal ion beam production: axial sputtering

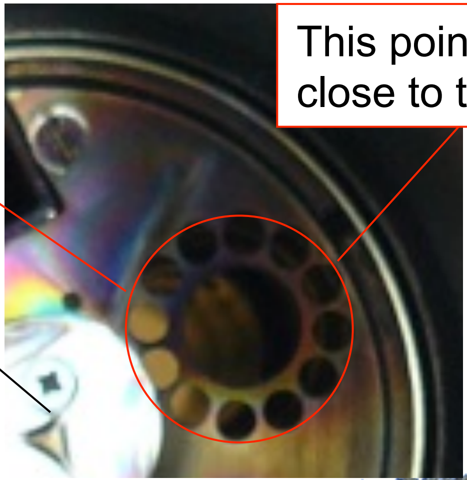
Axial sputtering: two versions, two separate experimental weeks, **not yet successful.**



Version 1: Heat shielding is very close to the wall when sputter sample is inserted into the plasma chamber. To avoid any contact (possibly causes a local heat load on permanent magnet) we decided to limit insertion to 15 mm. We saw some tens of nA of Zr^{12+} beam (without high confidence!)



Port for axial sputtering



This point very close to the wall

This part was removed to make insertion possible

Bias disk

Metal ion beam production: axial sputtering

Version 2: we were able to get up to 0.5 µA of Zr^{12+} beam. During the short time we see more (close to 2 µA) but we were not able to get it back. The intensity is far behind the requested (≈ 20 µA).

Zero level corresponds to inner surface of pc

Poistion [mm]	Sputter voltage [kV]	Sputter current [mA]
-10	3	0.21
-20	3	0.45
-20	4	0.52
-40	4	1.04

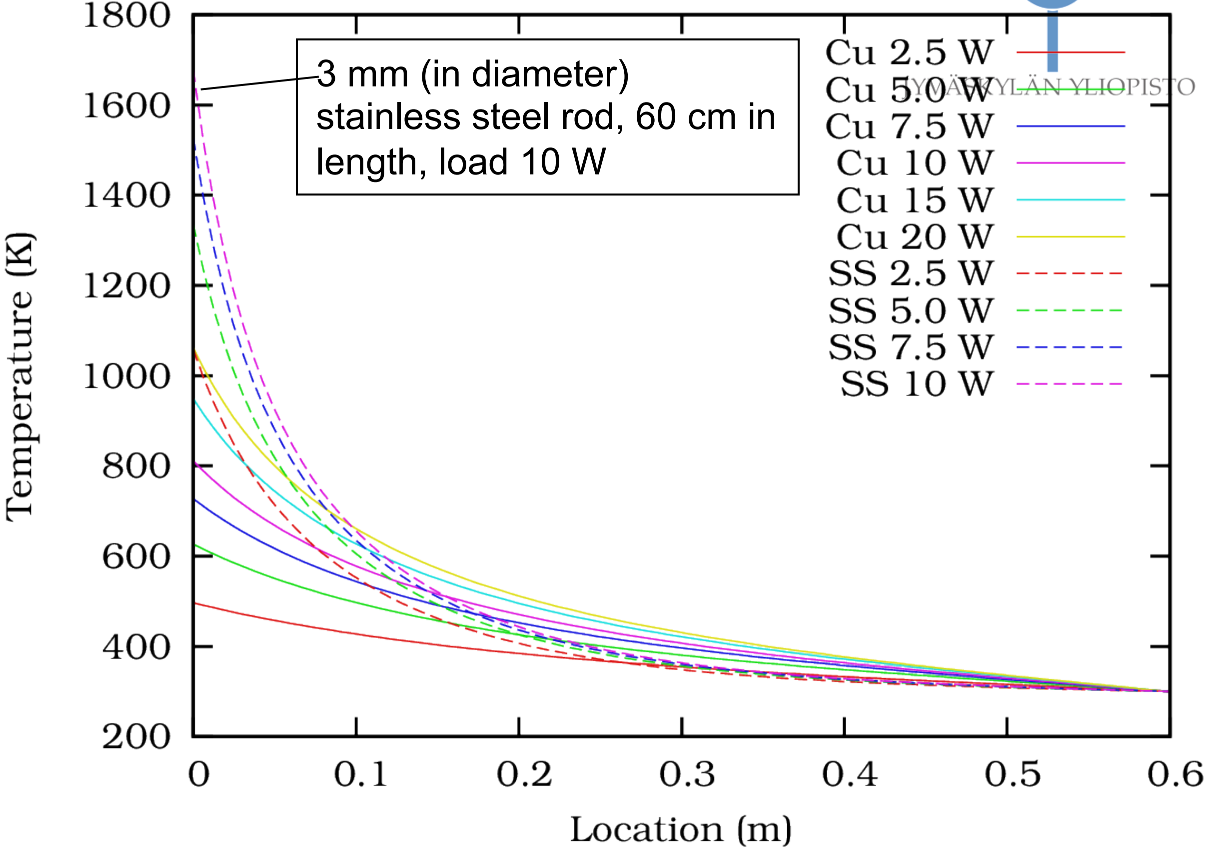
Typical sputter current in the case of radial sputtering is 1-2 mA

Typical sputter voltage in the case of radial sputtering is 1-2 kV

- The insertion had a big effect as is seen from the current of sputter voltage.
- We should have enough sputtering (sputter current high enough)
- Conclusion: sputter products do not reach the plasma.

Spin-off from the axial sputtering work?

During the development work of axial sputtering we realized that even a low power load can result on substantial increase of T if material has a low thermal conductivity. This might be useful when the geometry has been optimized for this idea.

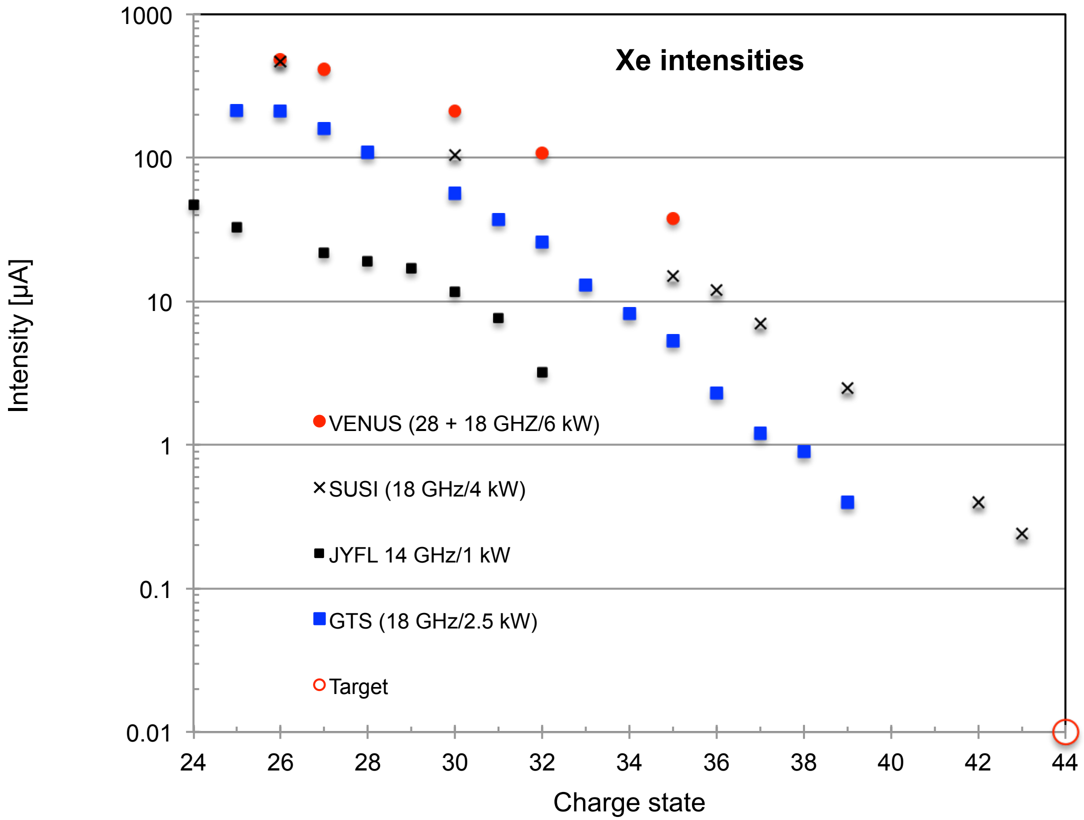


3 mm (in diameter) stainless steel rod, 60 cm in length, load 10 W

	Depends on T		
Material	Thermal conductivity @25˚C [W/m/K]	Melting point [˚C]	Thermal expansion E-6 [1/K]
Ti	21.9	1668	8.6
SS	**16**	1510	15
Cu	400	1084	16.5
Zr	**22.7**	1855	5.7
Mo	139	2623	4.8
Ta	**57**	3017	6.3

- Optimal geometry
- Optimal combination of materials

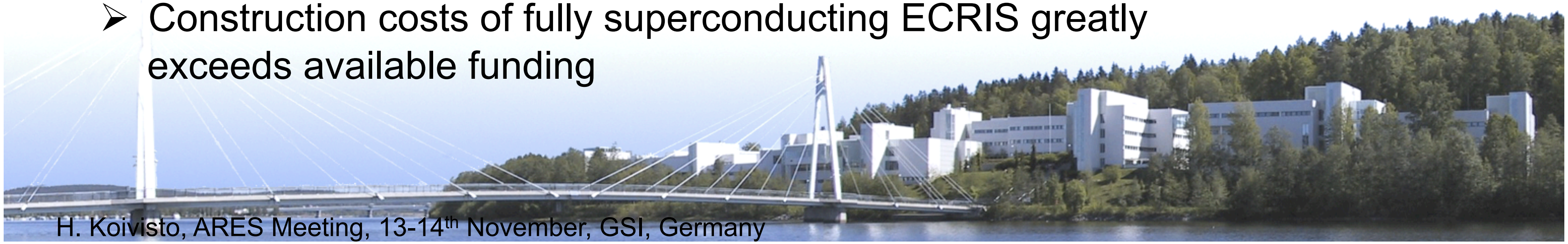
HIISI: new ion source for the JYFL accelerator laboratory



Requirements:

- Nuclear physics: ×5-10 intensity at medium charge states (Ar^{8+}, Xe^{26+}, energy ≥ 5 MeV/u)
- Radiation effects facility: Ion beam cocktail energy increased from current 9.3 MeV/u to 15 MeV/u (Xe^{44+} required)

- SUSI can meet the requirements for example
- Construction costs of fully superconducting ECRIS greatly exceeds available funding



Axial field of HIISI at 18 GHz operation:

SUSI values for comparison

Element	Charge	I (euA)	Power (kW)	Brad (T)	Binj (T)	Bmin (T)	Bext (T)	gradB Inj (T/m)	gradB Ext (T/m)	Plasma Length
129Xe	**35**	**16**	**3,2**	**1,36**	**2,82**	**0,46**	**1,56**	**6,6**	**5,9**	**115**
40Ar	12	730	3,8	1,06	2,55	0,43	1,19	6,8	5,6	142

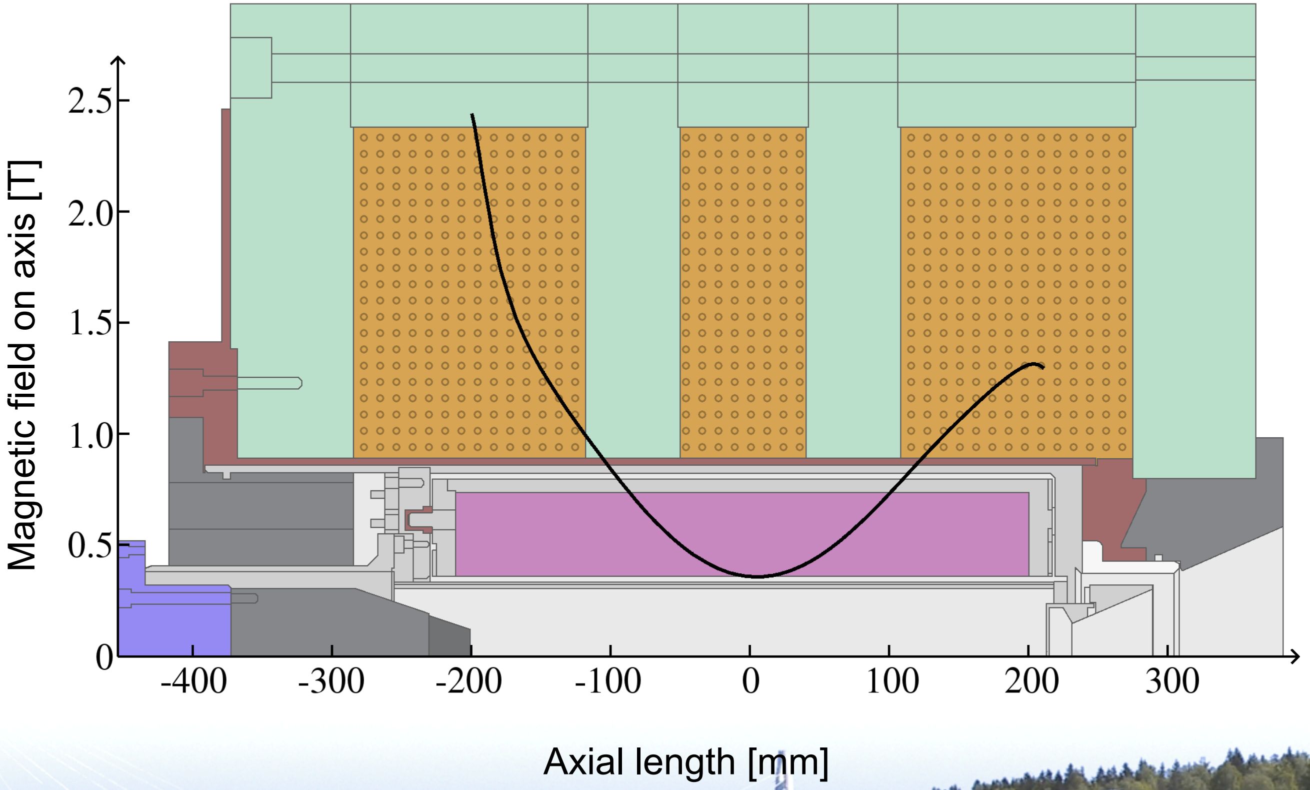
	I_{inj} / P_{inj}	I_{ext} / P_{ext}	I_{mid} / P_{mid}	B_{inj}	B_{ext}	B_{min}	∇B_{inj}	∇B_{exr}	L
216 kW	1050 / 101	1050 / 101	600 / 14	2.63	1.52	0.43 (66 %)	6.3	6.3	132
137 kW	1000 / 92	680 / 43	210 / 1.8	2.48	1.18	0.41 (64 %)	6.2	5.5	157

Small changes might come during the finalization process

Axial B-field configuration of SUSI can be met. Power consumption is 120 - 220 kW in 18 GHz operation mode. **How about B_{rad}?**

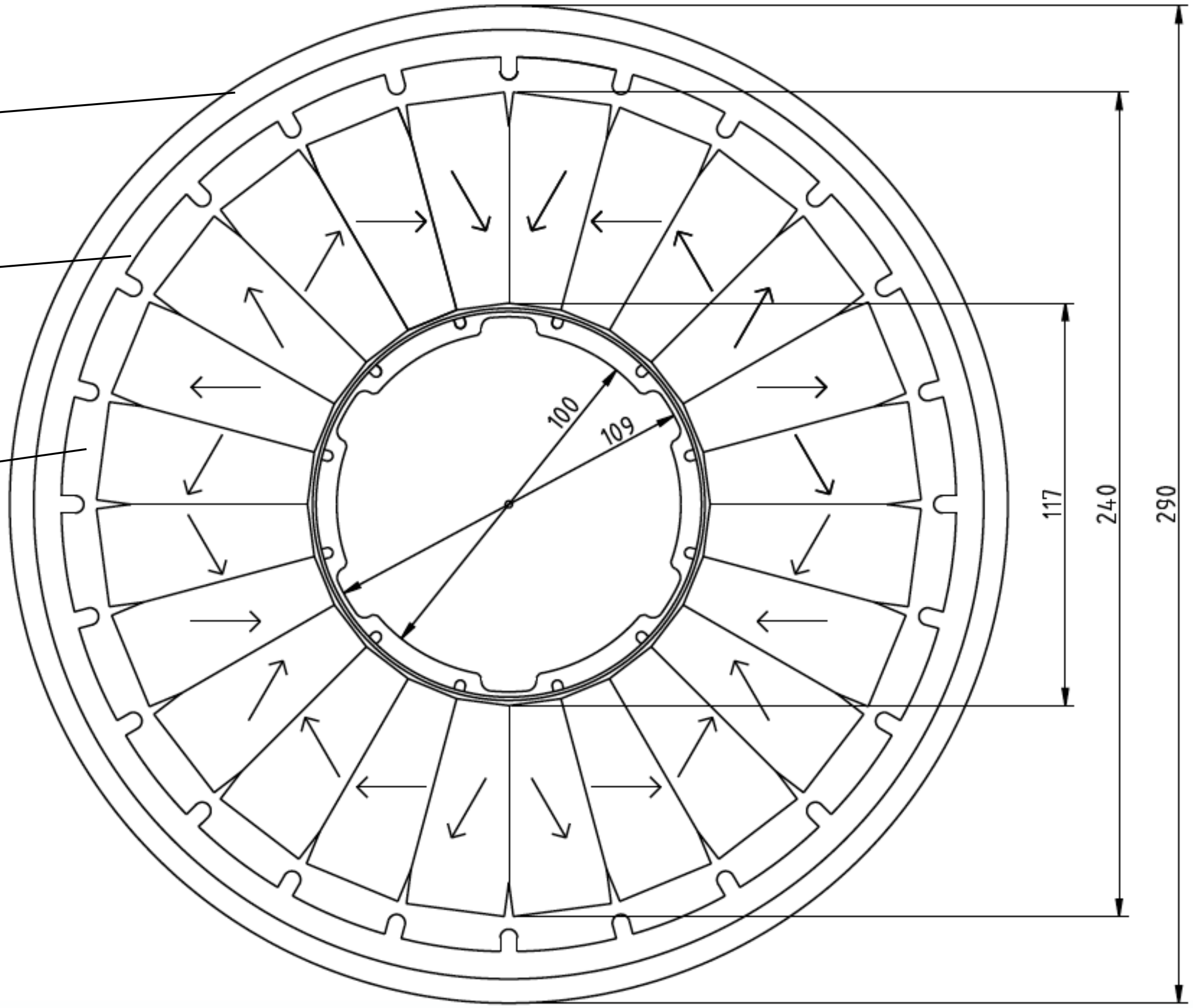
Solenoid field design

- Injection and extraction coils: 7 double wound, double pancakes (20 turns)
- Can be operated also in 14.5 GHz mode, power consumption about 80 kW



Hexapole design

24-segment offset Halbach



Insulator + vacuum pumping chamber

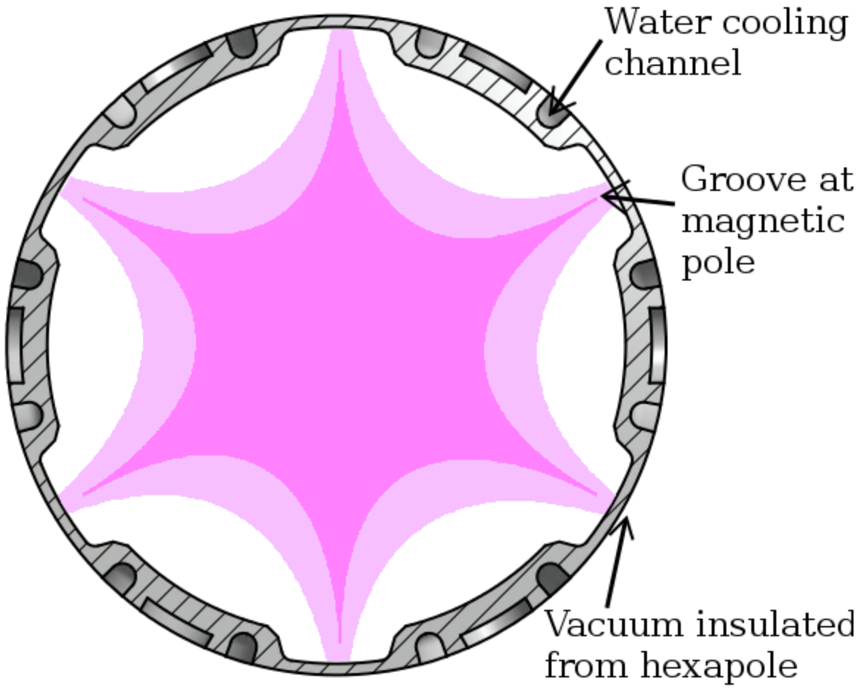
Vacuum gap

Hexapole chamber with cooling lines

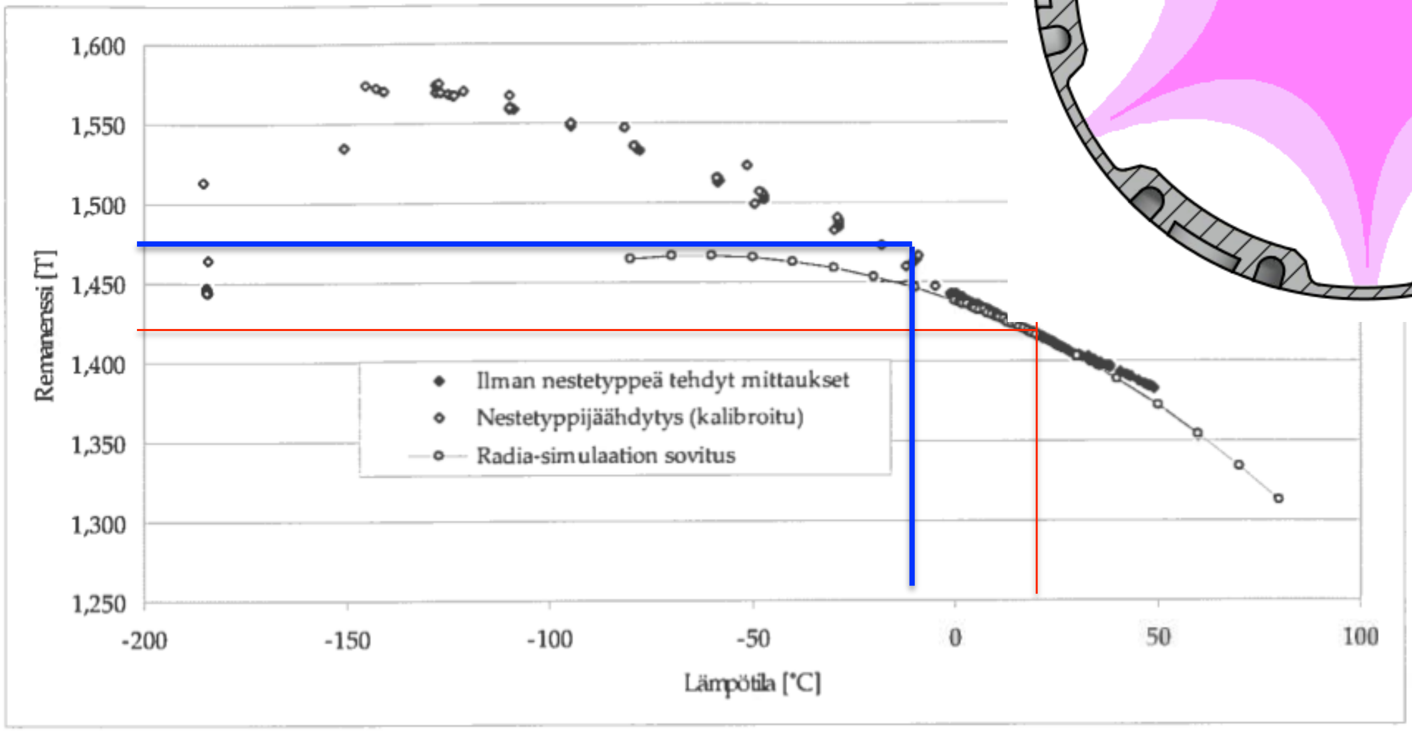
Required hexapole field of 1.36 T is difficult to reach using permanent magnets

Methods to boost the radial field:

1) Minimize the distance between the magnet and plasma on the magnetic pole
2) Cool the magnets (5 % in Br if from 20 °C to -10°C)



Effect of cooling:
Master thesis: P. Frondelius (former team member)



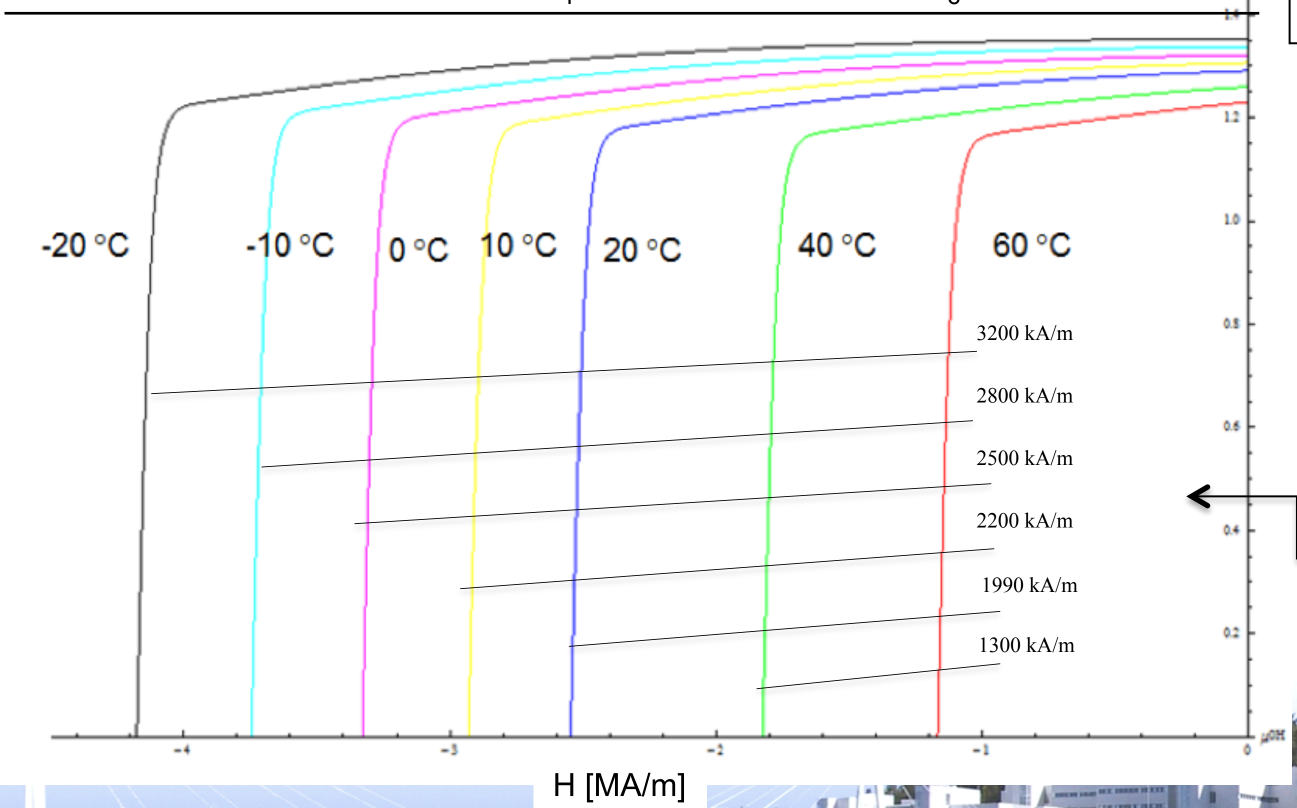
Cooling from 20°C to -10°C: clear improvement on B_{rem} (≈ 5 %). Much bigger effect in coercivity!

Coercivity of magnets vs temperature:

Demagnetization analysis show that macroscopic volume of the magnet is exposed to the field of around 1600 kA/m → grade N40UH, B_{rem}=1.29 T, iH_c=1990 kA/m (at 20 ˚C) might be selected for safety of magnets.

N40UH	B_r = 1.29 T	H_c = 1990 kA/m
N45SH	B_r = 1.35 T	H_c = 1590 kA/m
N48H	B_r = 1.42 T	H_c = 1350 kA/m

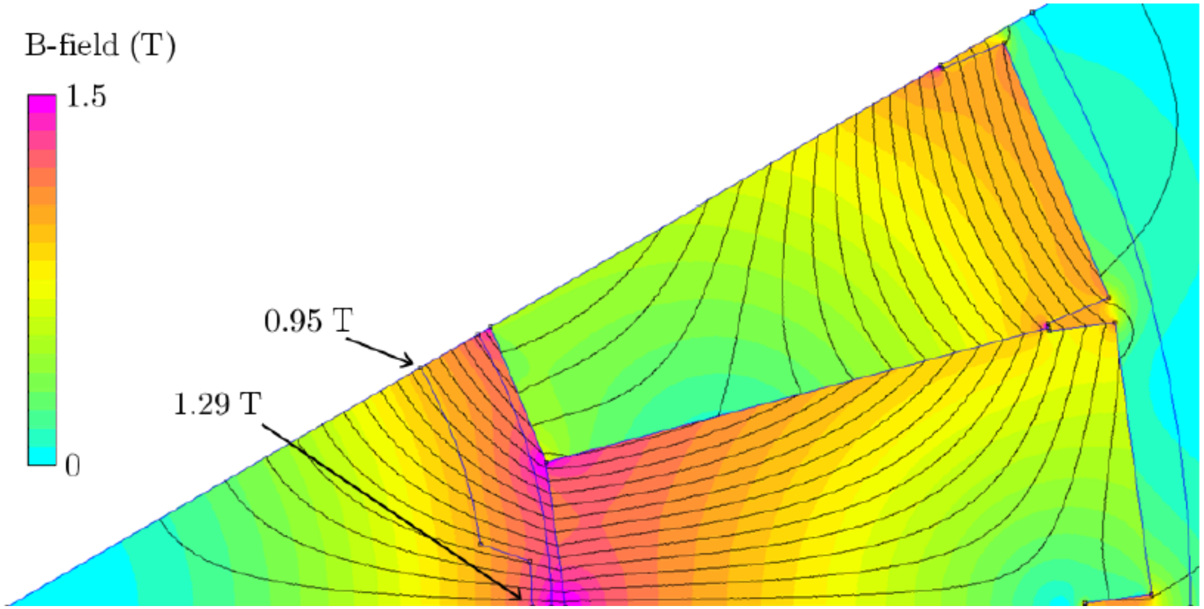
H-field analysis shows small magnet volume is exposed to 1800 kA/m, ok at 20˚C (N40UH).



N40UH

Coercivity value at different T

Hexapole magnetic field



N40UH

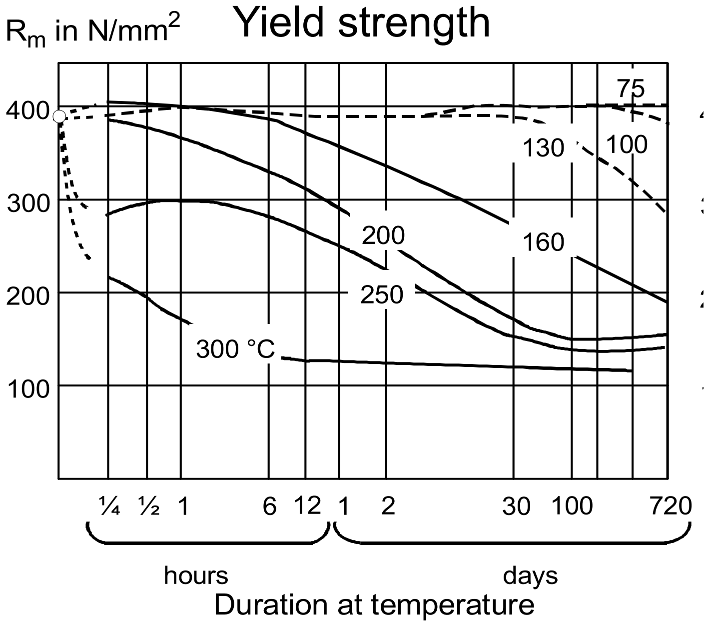
Distance (mm)	Description	B 20°C (T)	B −10°C (T)	B using N48H −10°C / −30°C (T)
3	1 mm gap + 2 mm wall	1.29	1.33	1.46 / 1.49
3.5	1.5 mm gap + 2 mm wall	1.27	1.30	1.44 / 1.47
4	**1.5 mm gap + 2.5 mm wall**	**1.24**	**1.28**	**1.41 / 1.44**
4.5	1.5 mm gap + 3 mm wall	1.22	1.26	1.38 / 1.41
5	1.5 mm gap + 3.5 mm wall	1.20	1.23	1.36 / 1.38

36-segment Halbach for further improvement?

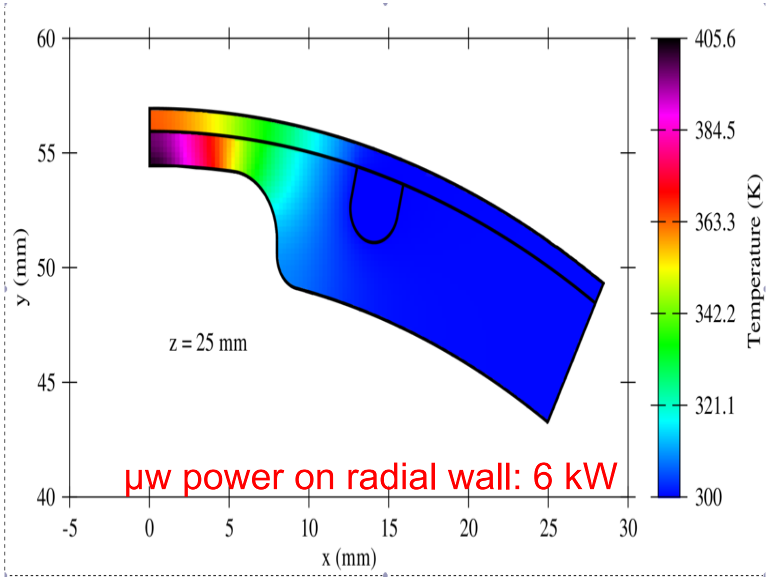
Temperature distribution on the plasma chamber surface

T distrib. information is needed for:

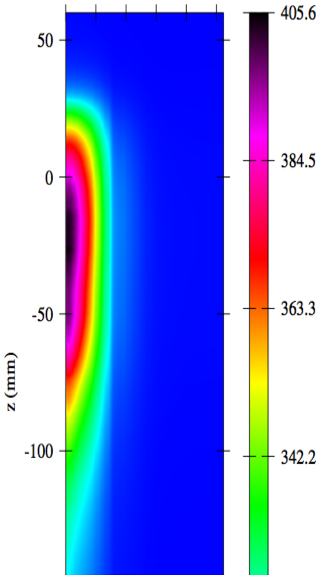
1) Temperature of Al should be kept < 100˚C
2) Heat load on PM-heaxapole



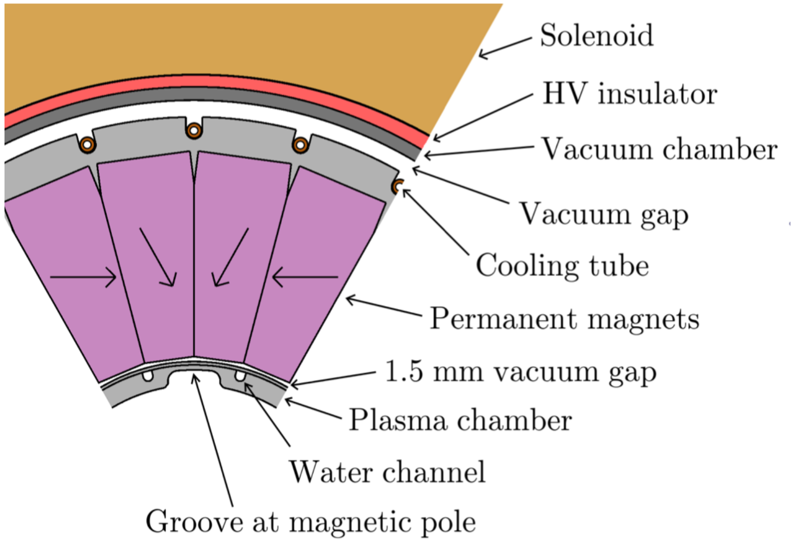
130˚C: too high!



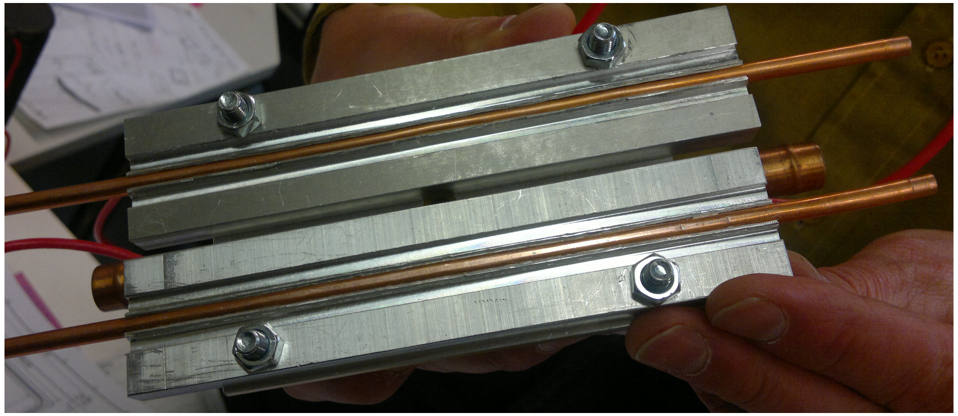
μw power on radial wall: 6 kW



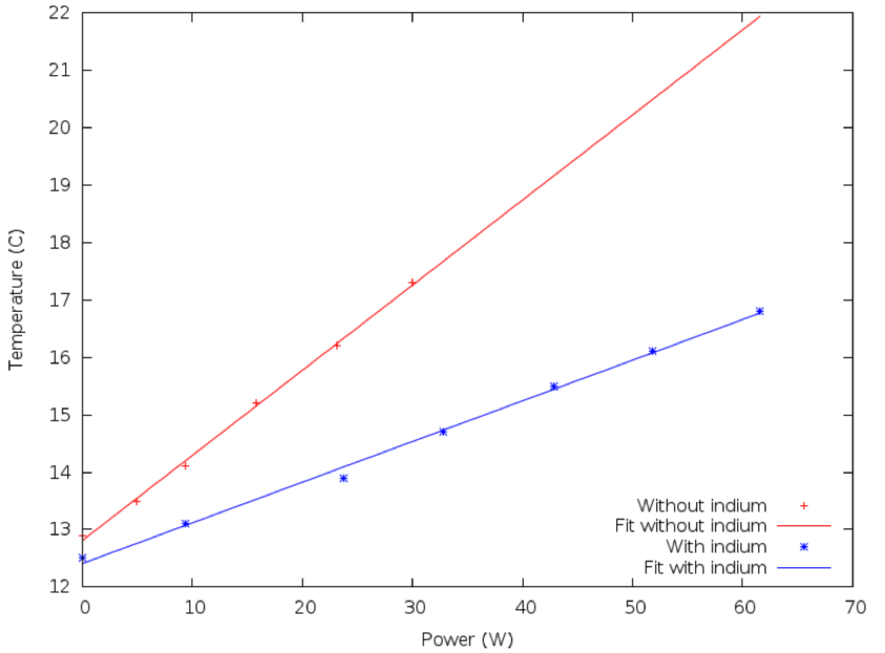
In this case perfect heat transfer between the water surface and metal surface is assumed: **not true!**



Heat transfer from metal to water?



Test 1: mechanical (pressed) contact
Test 2: indium between Al and Cu tube

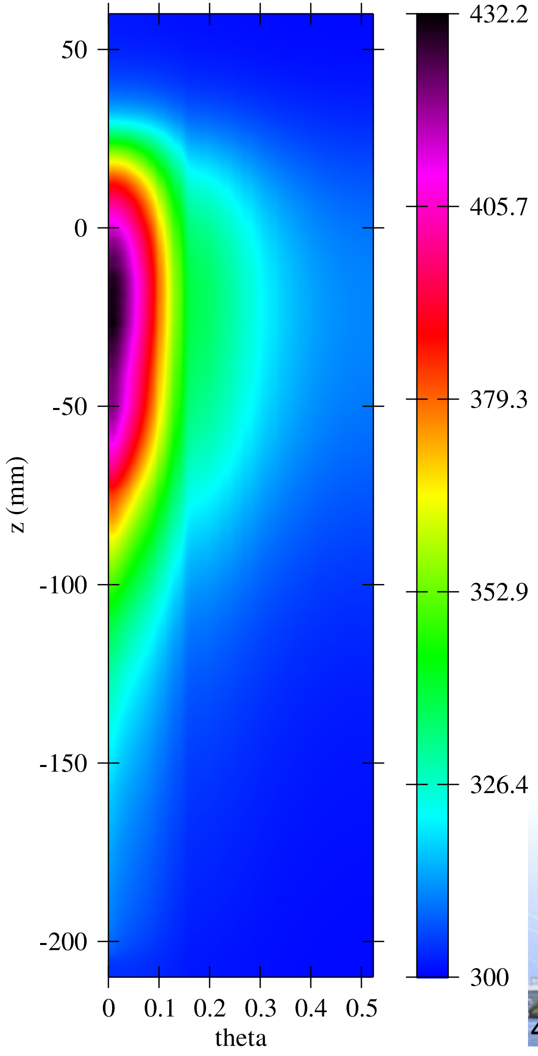


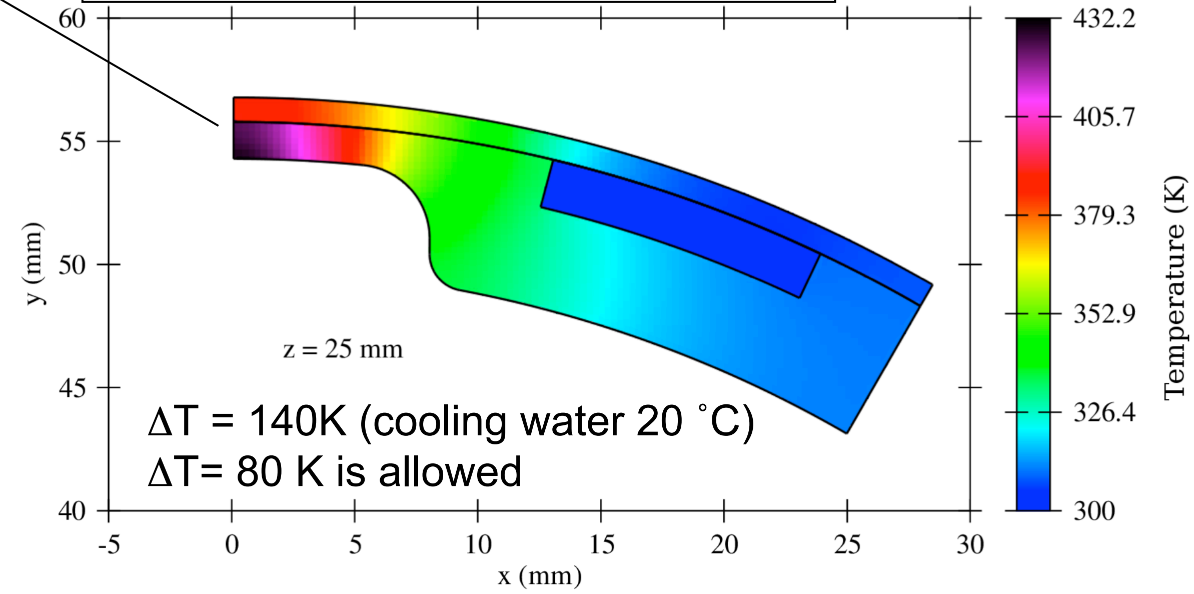
Test 1: 4000 W/m^2/K
Test 2: 8500 W/m^2/K
The latter one was used as an experimentally defined minimum value for the heat transfer between the water-metal interface

Using afore-mentioned heat transfer over water-metal surface:

- 6 kW on wall (not realistic – a lot of safety margin)
- 4000 W/m²/K heat transfer oven metal-metal boundary

Result: T_{max} increased by 30K
→ 160˚C, this is too much!





ΔT = 140K (cooling water 20 ˚C)
ΔT= 80 K is allowed

80/140x 6 kW = 3.4 kW towards the radial walls.

This limits the total µw-power into the pc to 4.3 kW: is ok!

Some theoretical considerations:

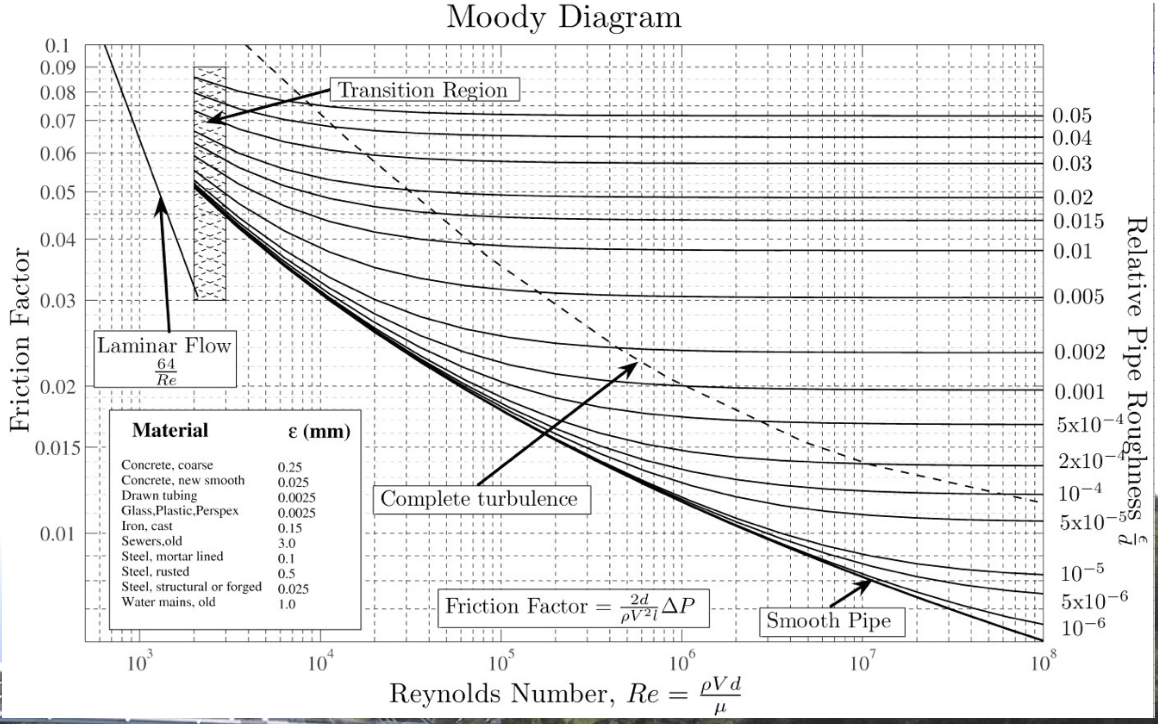
- our 8500 W/m^2/K was obtained with long Cu tube (≈ 5,5 m, ID ≈ 3 mm) and 4 Bar pressure drop.
- Note: water-metal heat transfer depends (for example) on Reynolds number and friction factor…
- This gives the Re number of about 11 000 (clearly turbulent and heat transfer coefficient of 16800 W/m^2/K (quite reasonable because afore-mentioned 8500 includes also metal-metal contact conductance). This was calculated using equation for smooth pipe

$$\text{heat transfer} = \frac{Nu \cdot k}{D_h}$$

$$Nu = 0.0265\,\mathrm{Re}^{0.8}\mathrm{Pr}^{0.3}$$ Nusselt number for smooth pipe

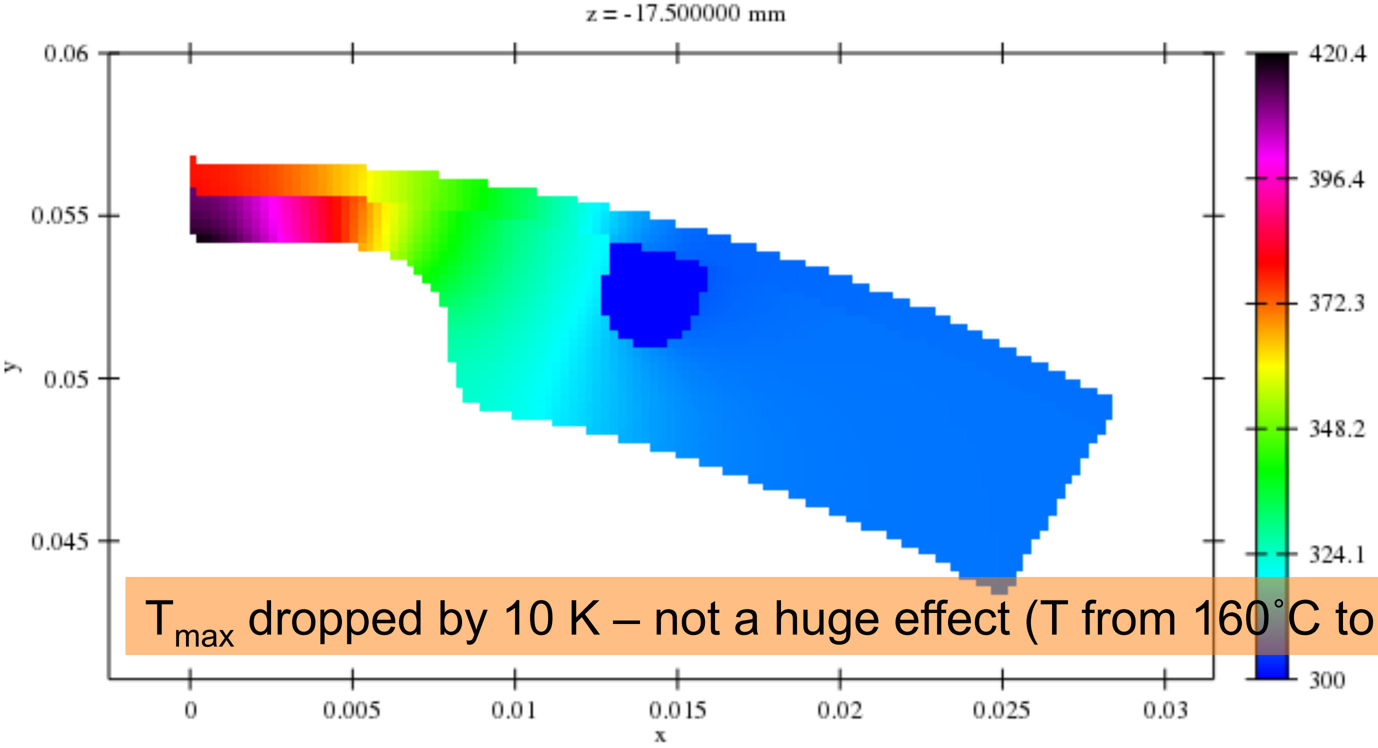
In the case of HIISI plasma chamber we can have 4 mm water channel and 1 mm in length. Our workshop can produce “rough” surface channel. Using this information, equation taking into account the surface friction and using Moody diagram we can get the heat transfer of even as high as 70000 W/m^2/K

$$Nu = \frac{(f/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7(f/8)^{1/2}\left(\mathrm{Pr}^{2/3}-1\right)}$$



Material	**ε (mm)**
Concrete, coarse	0.25
Concrete, new smooth	0.025
Drawn tubing	0.0025
Glass,Plastic,Perspex	0.0025
Iron, cast	0.15
Sewers,old	3.0
Steel, mortar lined	0.1
Steel, rusted	0.5
Steel, structural or forged	0.025
Water mains, old	1.0

Using “conservative” number of 30000 W/m^2/K (should be safe)



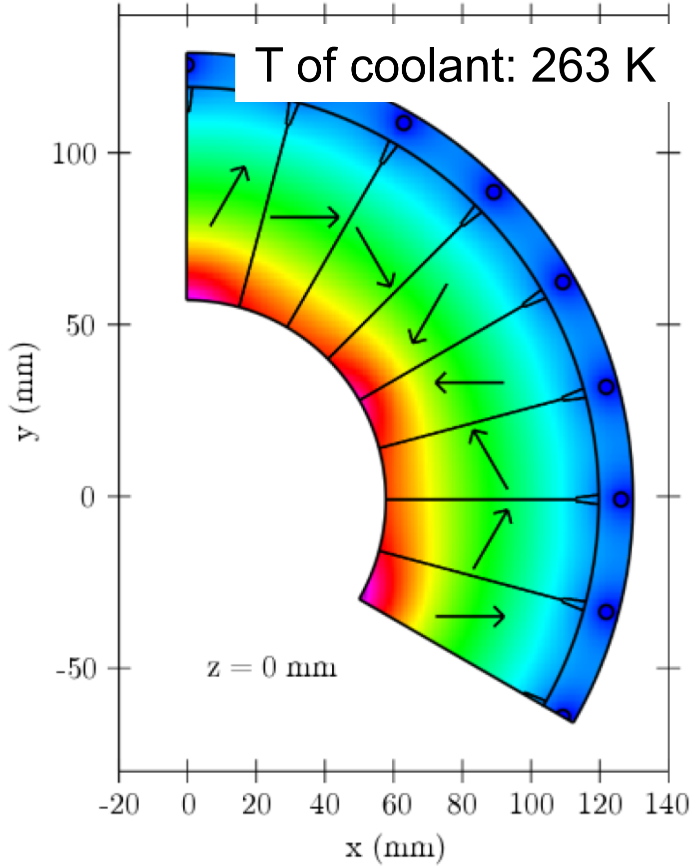
T_{max} dropped by 10 K – not a huge effect (T from 160˚C to 150˚C)

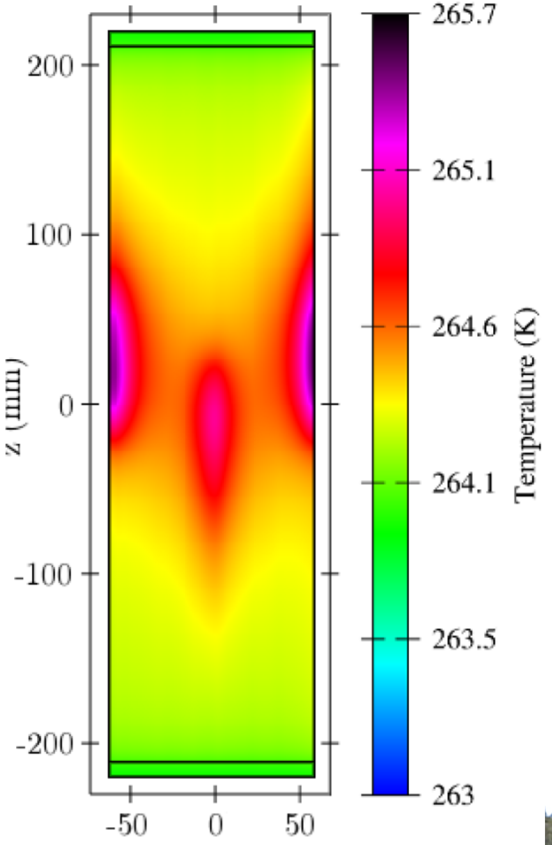
Conclusion: 4 kW microwave power should be feasible!

How about the heat load on permanent magnets?

Heat load from the plasma chamber on permanent magnets

- Earlier shown T distribution has been used (heat radiation from coils is also included)
- Pressure of 10 mbar in the pumping chamber has been used (≤ 1 mbar is our goal)
- Emissivity of 1 is used for safety margin (Al has emissivity of 0.1)
- Thermal conduction through the support structure has been taken into account


T of coolant: 263 K



Using these assumptions: magnets can be cooled down to -10 ˚C
Taking into account the yield point of Al -20˚C is safe. T behavior of magnets might be a problem/challenging?

5) Future plans

1) Movement of 14 GHz ECRIS closer to dipole (dipole modification): April 2015
2) More electron cyclotron instability experiments: during 2015
3) Movement of 6.4 GHz ECRIS: before construction of 18 GHz ECRIS
4) Construction of 18 GHz ECRIS starts: fall 2015
5) First beam from 18 GHz ECRIS: by summer 2016
6) Other plasma studies and metal beam development….always when possible!

5) Future requirements

1) Beam transport efficiency of K130 cyclotron facility has been restored back to > 5 %
2) Beam intensities extracted from the ECRIS has to be increased substantially (factor > 5) for M/q= 5 without compromising the beam quality
3) Substantial improvement in ECRIS performance regarding the super-high charge states (for example in the case of xenon $q>40$)
4) New intensive metal ion beams: Zr, more intensive Ti beam, Mo, …)

Lets try to define specific “targets” and then create networking groups