An ECRIS Facility for Investigating Nuclear Reactions in Astrophysical Plasmas

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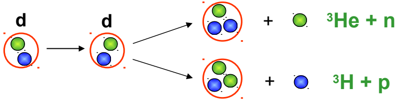
Enhanced electron screening effect

- nuclear fusion reactions at low energies can be strongly enhanced due to screening of the Coulomb barrier by the surrounding electrons
- the enhanced electron screening effect was observed for the first time in the (D-D) reactions in **metallic environments**
  (Czerski K, Huke A, Biller A, Heide P, Hoeft M and Ruprecht G 1998 Europhys. Lett. 54 449)



- could be explained as a result of shielding nuclear charges by surrounding electrons leading to a reduction of the Coulomb barrier in terms of a so-called screening energy U_e
- experimentally screening energies in metals are about a factor of ten larger than those obtained for gas targets
  (Greife U et al 1995 Z. Phys. A 351 107)
  and up to a factor of two larger than the theoretical predictions
  (Czerski K, Huke A, Heide P and Ruprecht G 2004 Europhys. Lett. 68 363)
- an exponential-like increase of experimental reaction cross sections for decreasing projectile energies was measured

Aim of the measurements

- first experimental results have been confirmed by other groups, however there are significant discrepancies between data from different groups
- the strong variation of experimental screening energies arise from the contamination of the target surfaces by carbon and oxygen
  (Huke A, Czerski K and Heide P 2007 Nucl. Instrum. Methods B 256 599, Huke A, Czerski K and Heide P Phys. Rev. C 78 (2008) 015803)
- small amounts of the oxygen contamination is correlated with low and unstable deuteron densities
- new experiments performed under ultra-high vacuum (UHV) conditions at the lowest possible energies with atomically clean targets

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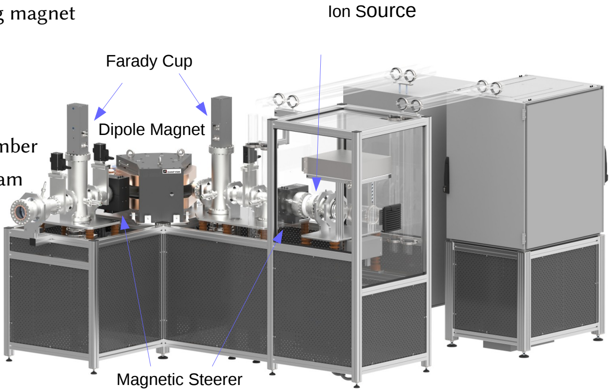
From an experimental point of view, the biggest challenge is to combine a high current ion accelerator system with a differential pumping system to achieve a pressure of 10^{-11} mbar in the target chamber

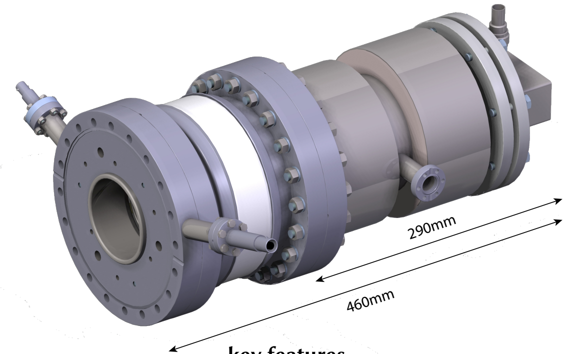
Irradiation facility

key components

- ECR ion source with extraction system (DRESDEN ECRIS-2.45M)
- highly stabilized 20 kV source potential power supply
  the long-term stability achieved for the deuteron energy was about a few eV
- double focussing 90° analysing magnet
- magnetic steerer
- high power Faraday cups
- differential pumping system
- ultra high vacuum target chamber
- einzel lens to focus the ion beam on 5 mm target aperture
- isolated mounted beamline for ion beam deceleration



Dresden ECRIS-2.45M



key features

- 200 W solid state microwave generator, 2.45 GHz
- permanent magnet system
- extraction system with included einzel lens

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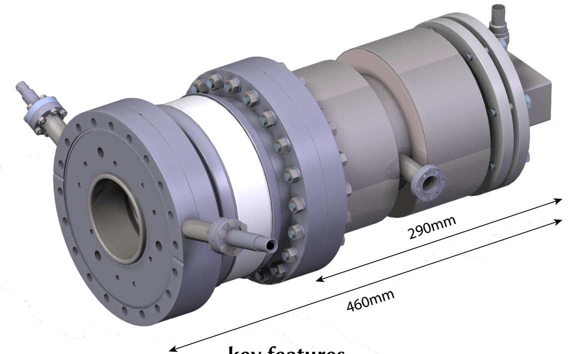

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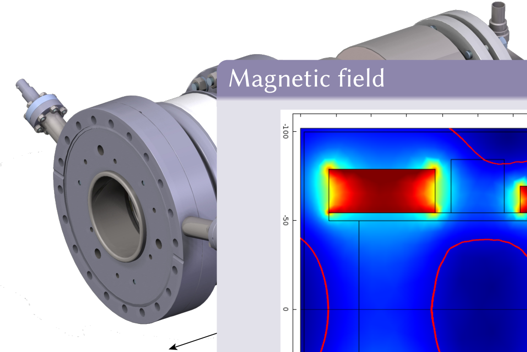
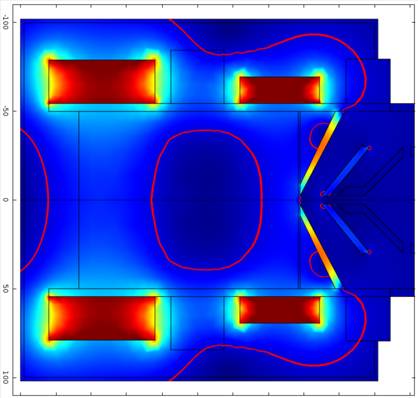


Magnetic field



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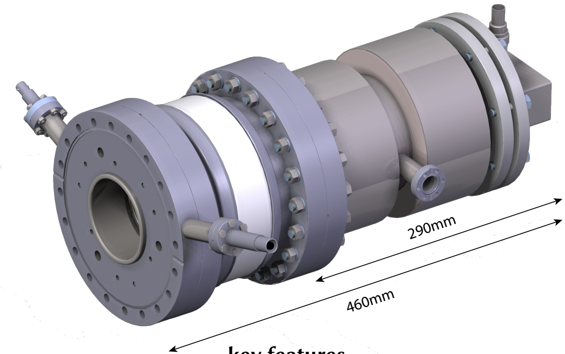

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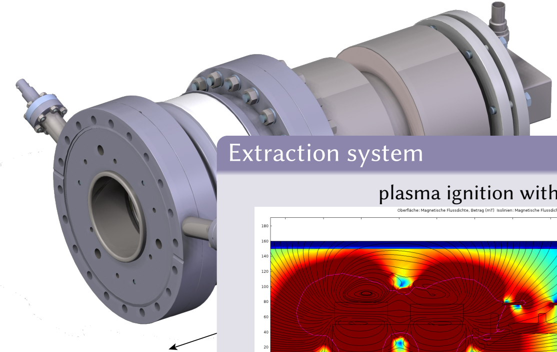
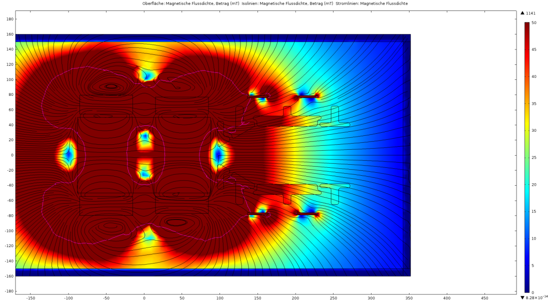


Extraction system

plasma ignition with high gas load



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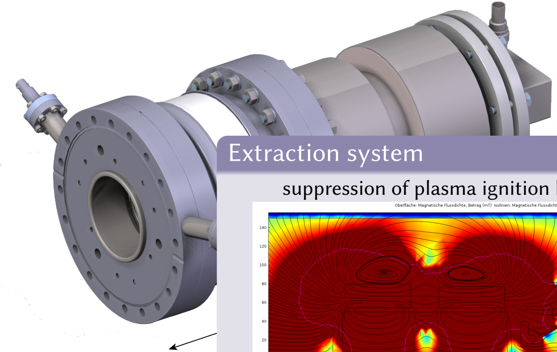
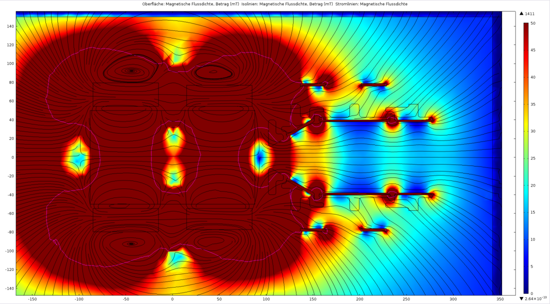


Extraction system

suppression of plasma ignition by iron extraction system



Vacuum system

- strong variation of experimental screening energy arises from target contamination
- ultra-high vacuum conditions necessary

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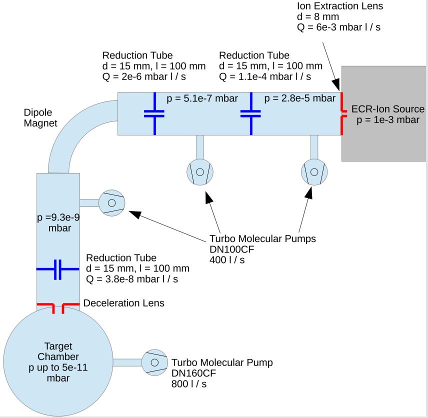
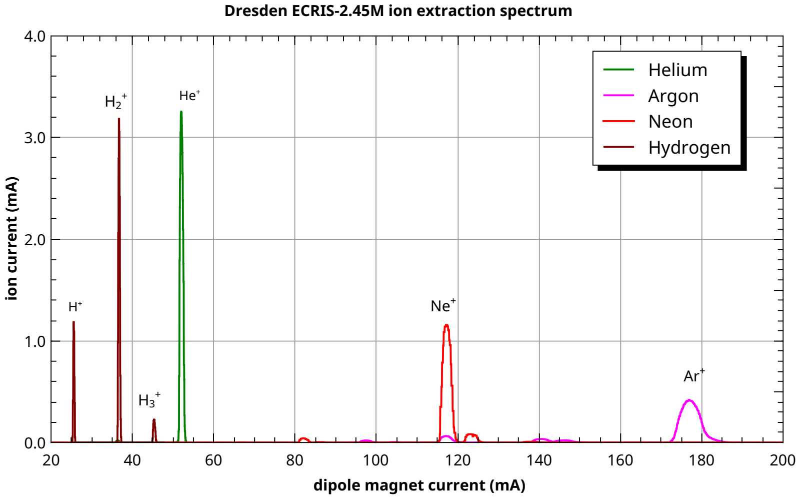
Differentially pumped beamline



Extracted ion currents



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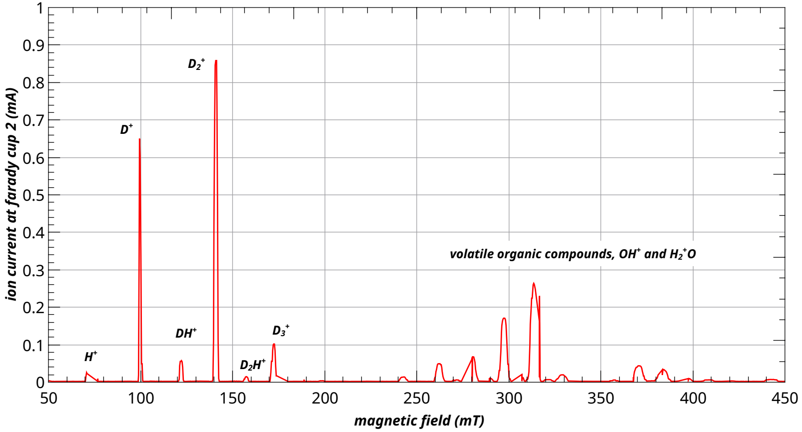
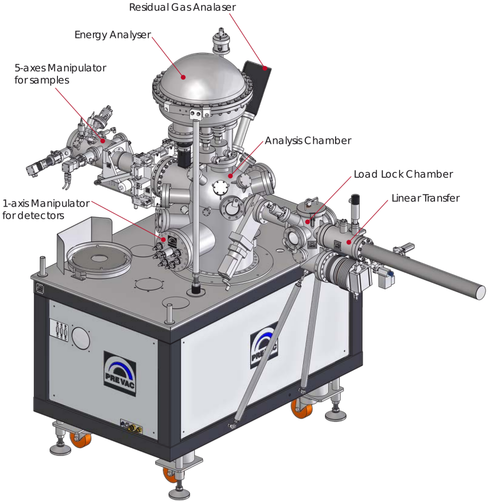


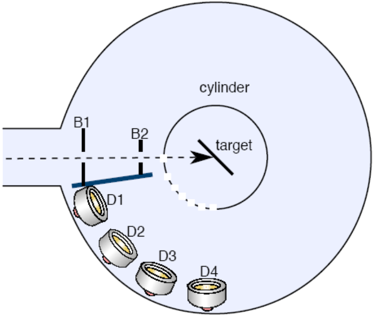
Experimental chamber

- the target surface was cleaned by means of surface sputtering using 10 keV Ar^+ ions
- atomic cleanness of the target surface could be controlled applying Auger electron spectroscopy which is sensitive for a surface contamination smaller than one monolayer
- the beam charge collected was determined by a measurement of the electric current on the target holder



Experimental chamber

- Zr target (1 mm thick foil) was implanted up to the saturation level close to the chemical stoichiometric ratio of about two
- the charged products of the (D-D) reactions (protons, tritium ions and ^{3}He particles) were detected by Si-detectors
- detector position: backward angles 90°, 125° and 150° with respect to the beam, 8 cm distance from target
- Aluminium foils of thickness 150 µg cm^{-2} in front of the detectors prevented elastically scattered deuterons from entering the detector



Experimental results

- experimental results are presented as a total , angle integrated, thick-target yield Y_{scr}

$$Y_{\text{scr}}(E) = \int_{E}^{0} \sigma_{\text{scr}}(E) \left(\frac{dE}{dx} \right)^{-1} dE \tag{1}$$

- it is compared to the theoretical value Y_{bare} based on gas target experiments for which the screening contribution can be neglected

$$Y_{\text{bare}}(E) = \int_{E}^{0} \sigma_{\text{bare}}(E) \left(\frac{dE}{dx} \right)^{-1} dE \tag{2}$$

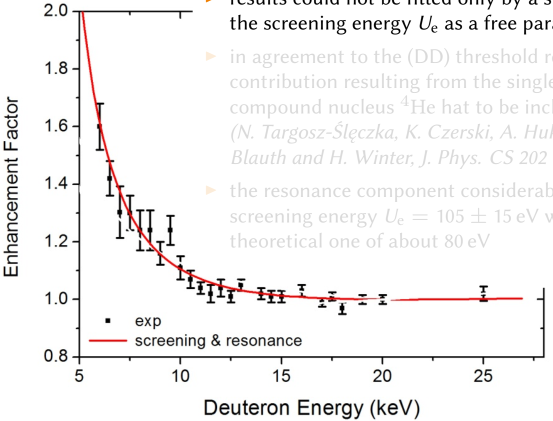
(Brown R E and Jarmie N Phys. Rev. C 41 1391)

- the ratio of both determines the enhancement factor $F(E)$ at different deuteron energies

$$F(E) = \frac{Y_{\text{scr}}(E)}{Y_{\text{bare}}(E)} = \frac{\int_{E}^{0} \sigma_{\text{scr}}(E) \left(\frac{dE}{dx} \right)^{-1} dE}{\int_{E}^{0} \sigma_{\text{bare}}(E) \left(\frac{dE}{dx} \right)^{-1} dE} \tag{3}$$

Experimental results

- due to better vacuum conditions and higher deuteron currents, the new experimental data are much more precise than those obtained previously
- results could not be fitted only by a simple screening curve using solely the screening energy U_e as a free parameter
- in agreement to the (DD) threshold resonance hypothese an additional contribution resulting from the single-particle resonance in the compound nucleus ^{4}He hat to be included
  (N. Targosz-Ślęczka, K. Czerski, A. Huke, L. Martin, P. Heide, A.i. Kilic, D. Blauth and H. Winter, J. Phys. CS 202 (2010) 012041.)
- the resonance component considerably reduced the fitted value of the screening energy $U_e = 105 \pm 15$ eV which is now very close to the theoretical one of about 80 eV



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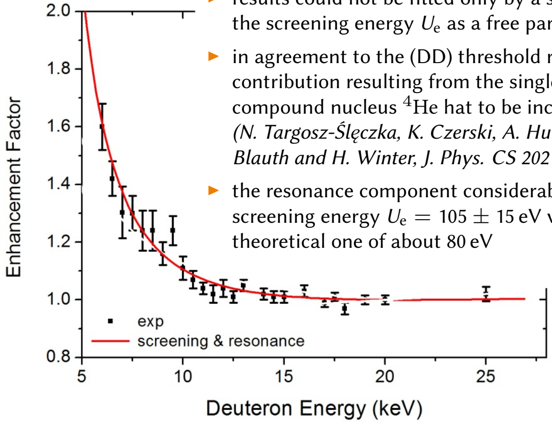

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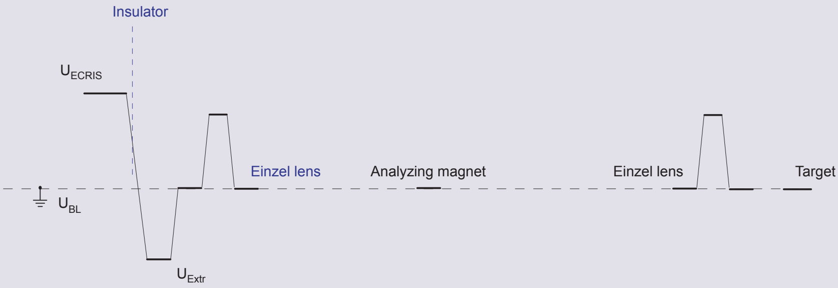
Outlook

- (DD) threshold resonances are of great importance for nuclear astrophysics and applied studies concerning the future energy sources based on fusion reactions
- further experiments performed at even lower deuteron energies are highly required
- it will be possible with an improved accelerator system at the University of Szczecin, Poland

Standard mode



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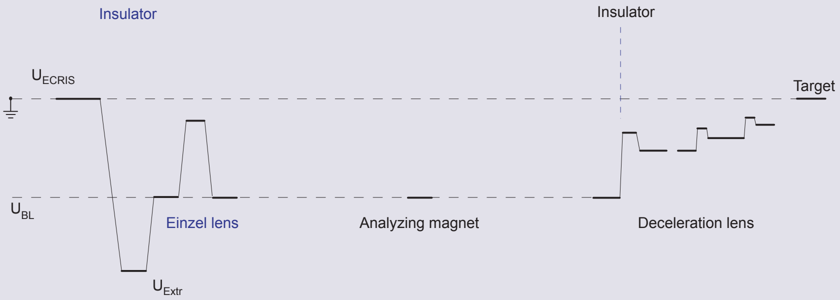
Deceleration mode



Acknowledgements

This project is a cooperation between

- K. Czerski
- M. Kaczmarski
- N. Targosz-Ślęczka

- A. Huke
- G. Ruprecht
- D. Weißbach

- G. Zschornack
- C. Baumgart
- M. Kreller