Plasma Physics and Fusion Energy Research

Plasma Data Analysis Group:

Paddy Mc Carthy (Group Leader)

Graduate Student:

Sean Knott (PhD) (Co-supervisor: Andy Ruth)

Recent graduates:

Diarmuid Curran (PhD, 2015)
Cormac McAuliffe (MSc, 2014)
Mike Dunne (PhD, 2013)

Funders: EuroFusion Consortium, Max Planck Institut für Plasmaphysik

Activity and Projects:

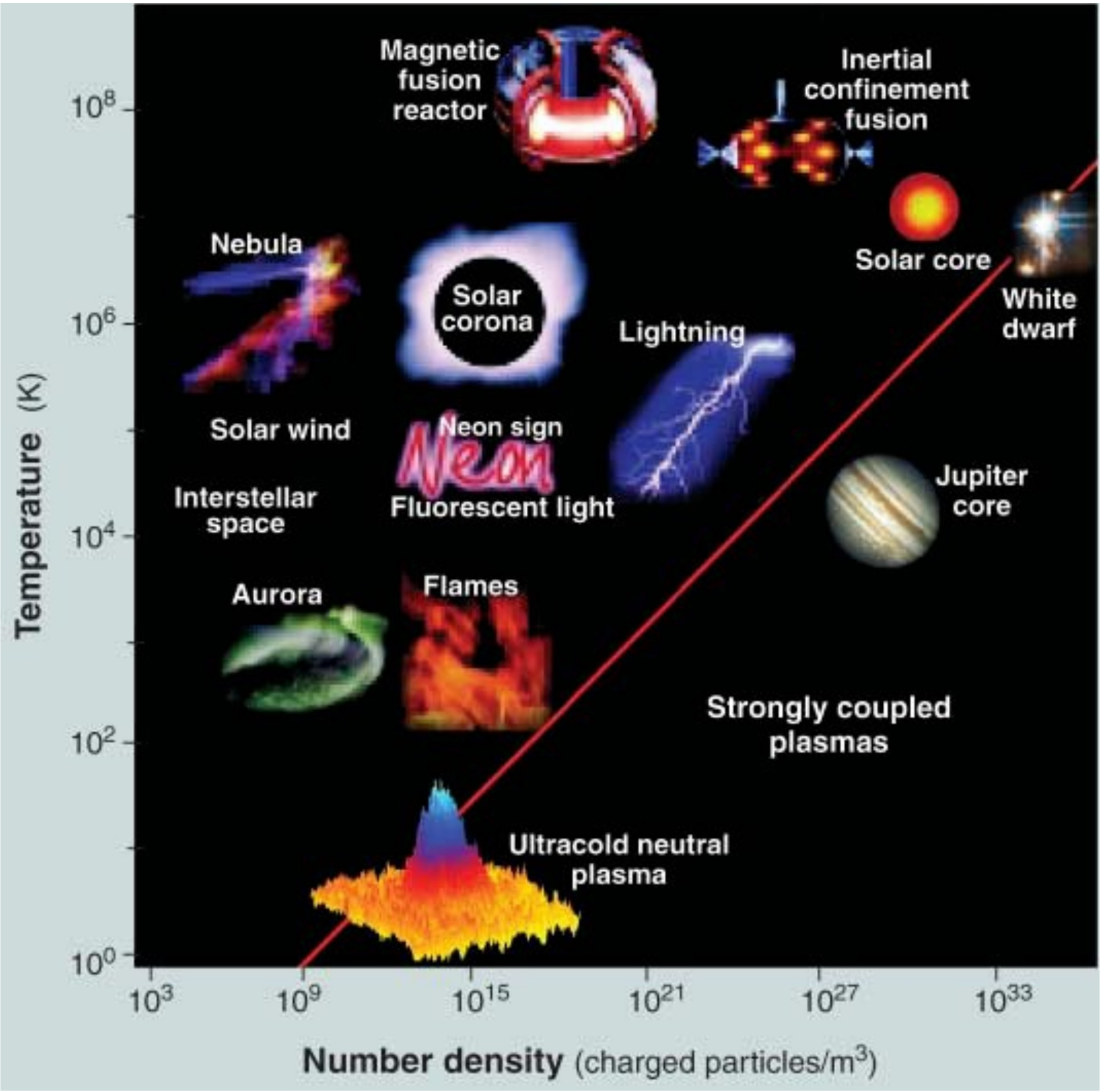
- MHD Equilibrium reconstruction from tokamak and stellarator diagnostic data
- Development of temperature and density diagnostic for MAST Upgrade spherical tokamak
- Monte Carlo generation of large equilibrium databases for predictive equilibrium recovery and diagnostic sensitivity studies
- Double Plasma experiment for student training and He line ratio studies

What is a plasma?

Plasmas are conductive assemblies of charged particles and neutrals whose behaviour is dominated by collective effects.

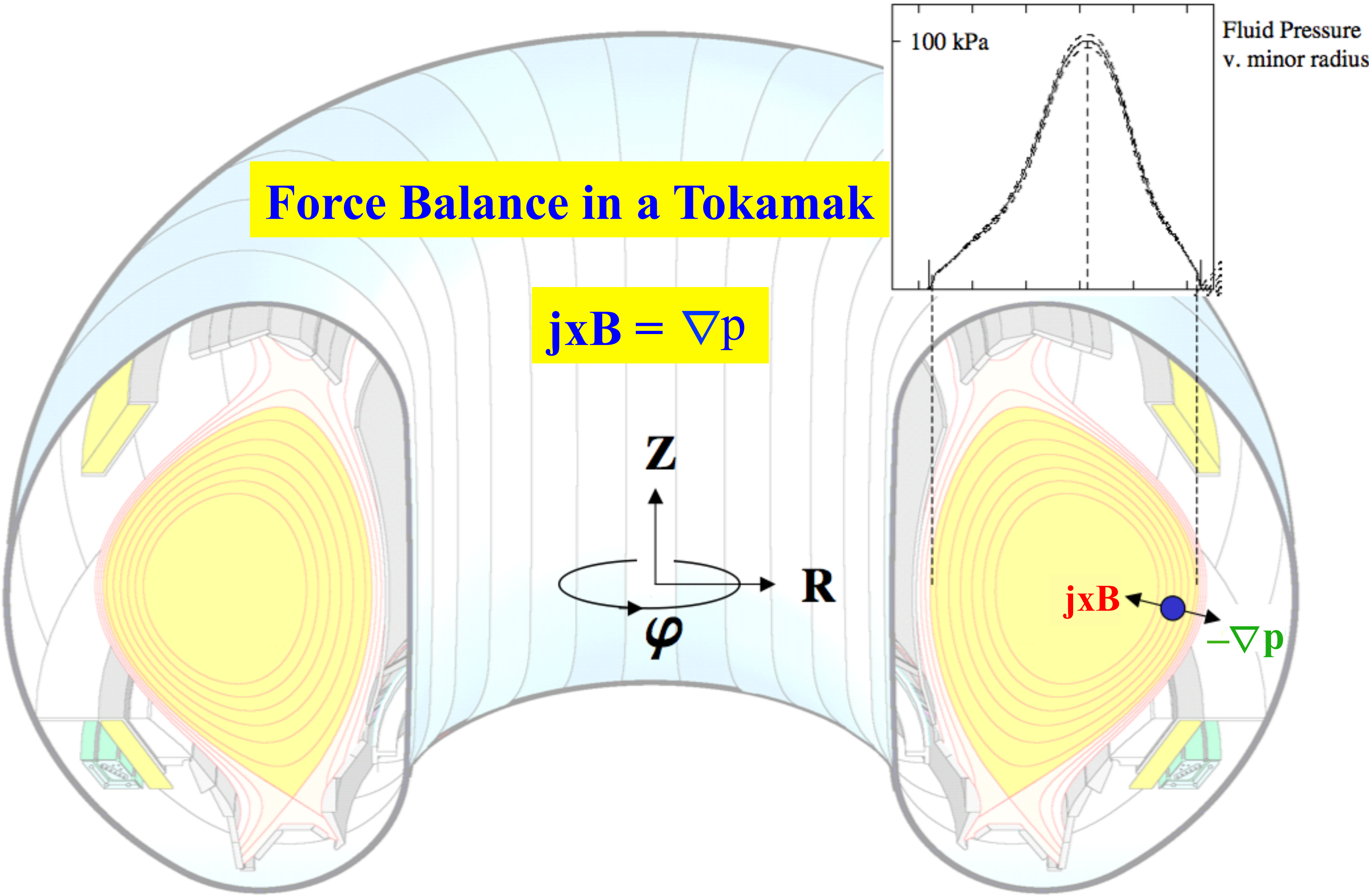
Plasmas carry electrical currents and generate magnetic fields.

Plasmas (dubbed "the fourth state of matter") are the most common form of visible matter, comprising more than 99% of the visible universe.



Why are we interested in plasmas?

- Fusion Energy
  - Potential source of safe, abundant energy.
- Astrophysics
  - Understanding plasmas helps us understand stars and stellar evolution.
- Upper atmospheric dynamics
  - The upper atmosphere is a plasma.
- Plasma Applications
  - Plasmas can be used to build computer chips and to clean up toxic waste.

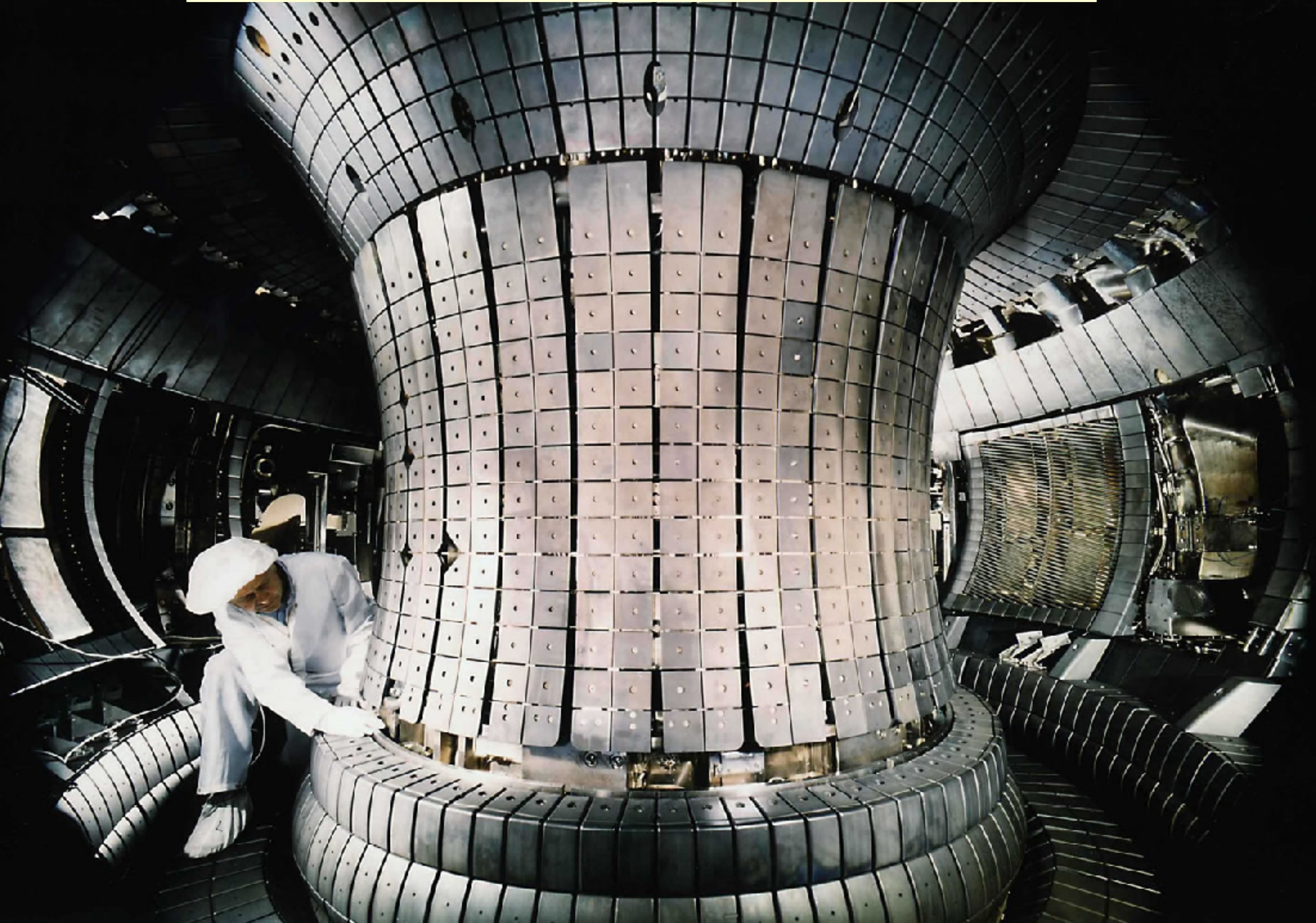


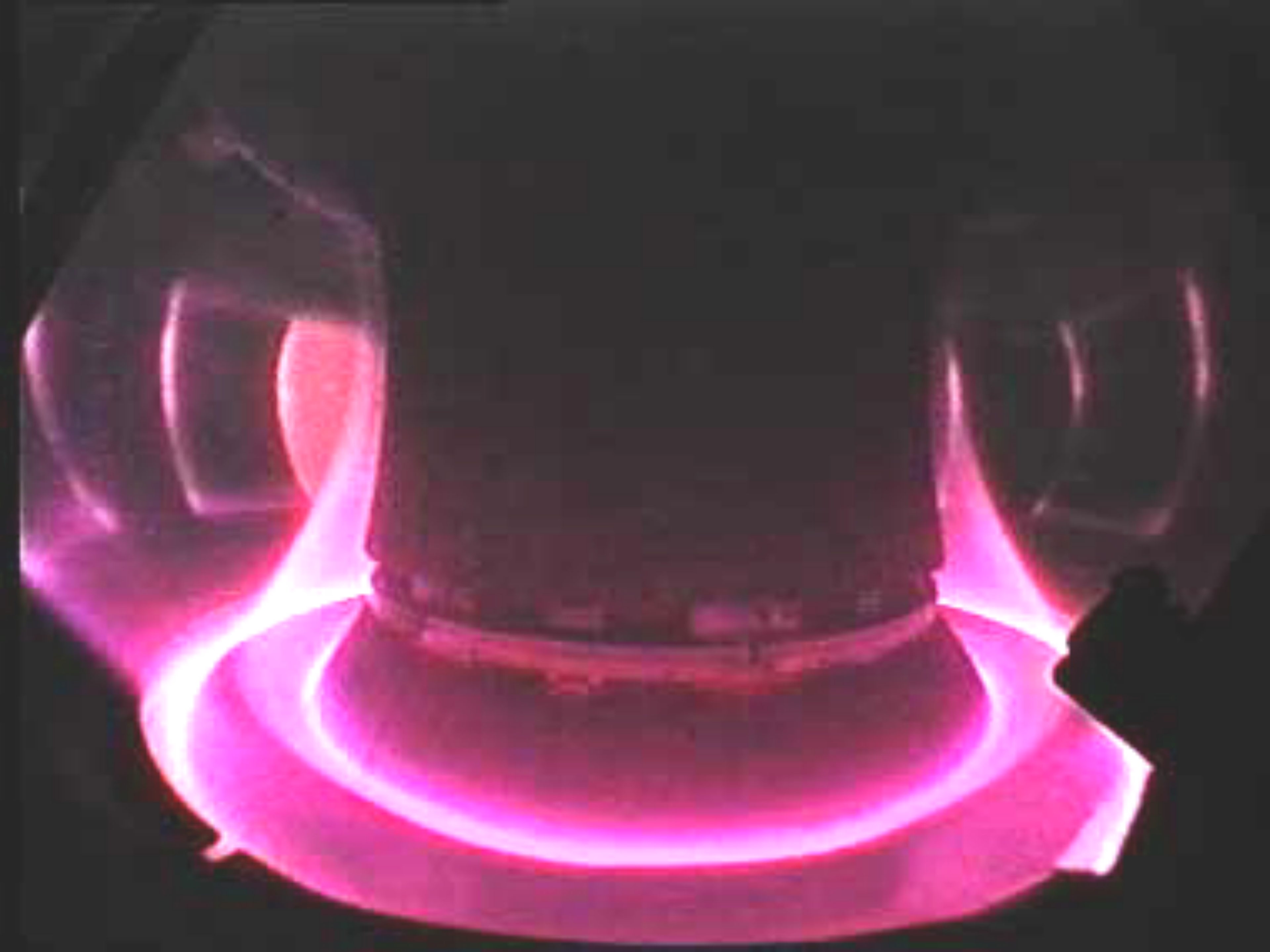
Fluid pressure gradient (outward force/m^3) $-\nabla \mathbf{p}$ balances inward pinch force/m^3: **jxB**

Axisymmetry: **jxB** = ∇p simplifies to: $$-\left(\frac{\partial^2\psi}{\partial R^2} - \frac{1}{R}\frac{\partial\psi}{\partial R} + \frac{\partial^2\psi}{\partial Z^2}\right) = \mu_0 R^2 p'(\psi) + FF'(\psi) \equiv \mu_0 R\, j_\phi$$

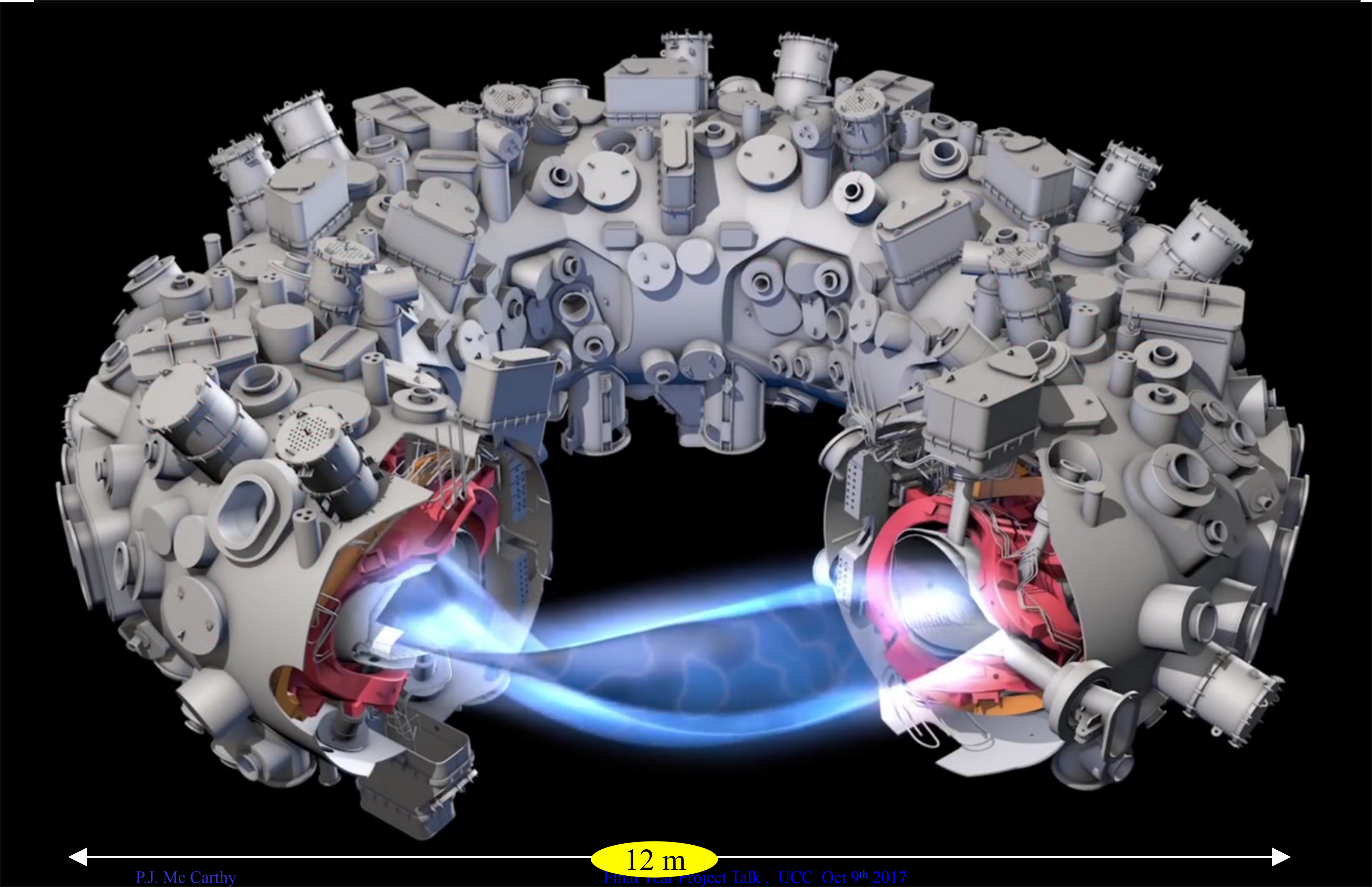
Magnetohydrodynamic equilibrium: Grad-Shafranov equation: scalar, weakly nonlinear PDE

Blick in das Plasmagefäß von ASDEX Upgrade



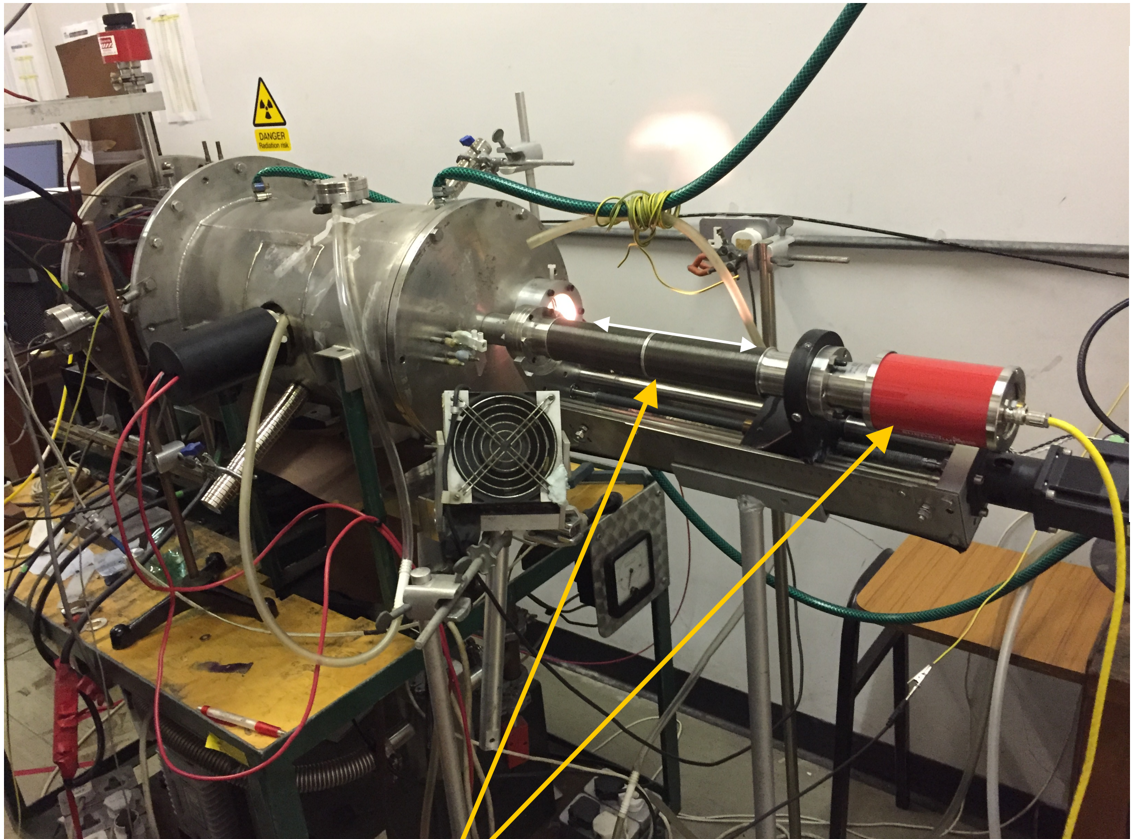


The Wendelstein 7-X Stellarator, Greifswald, Germany
In operation since December 2015

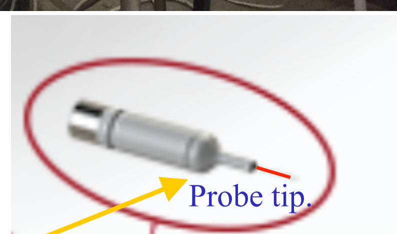


Double Plasma Experiment (Physics Dept. UCC)

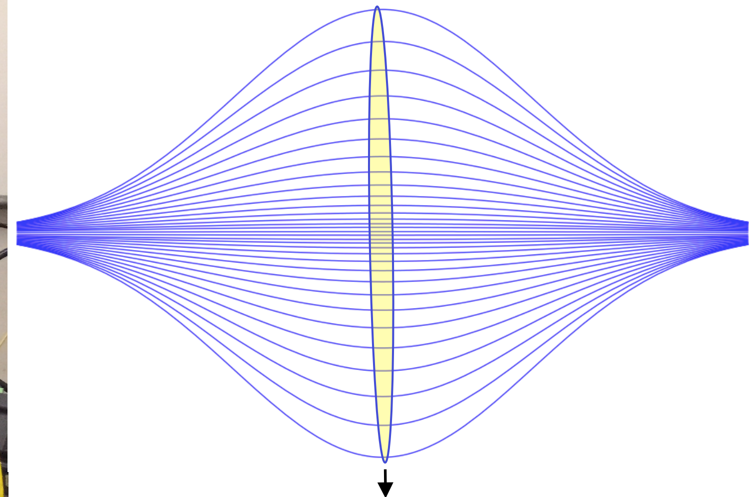
Axisymmetric Magnetic Mirror Configuration

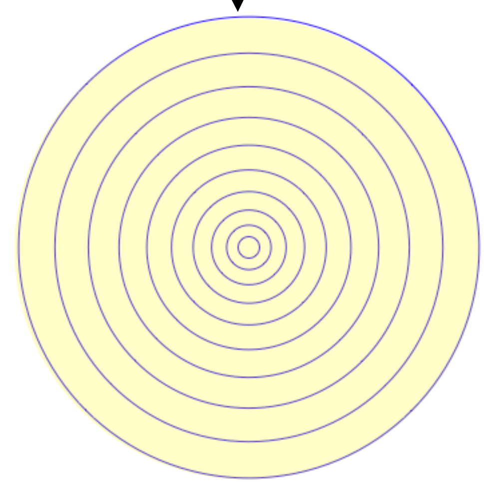


Movable Langmuir Probe system.



Magnetic field lines





Cross-section showing contours of constant magnetic flux.

Double Plasma Experiment (Physics Dept. UCC)

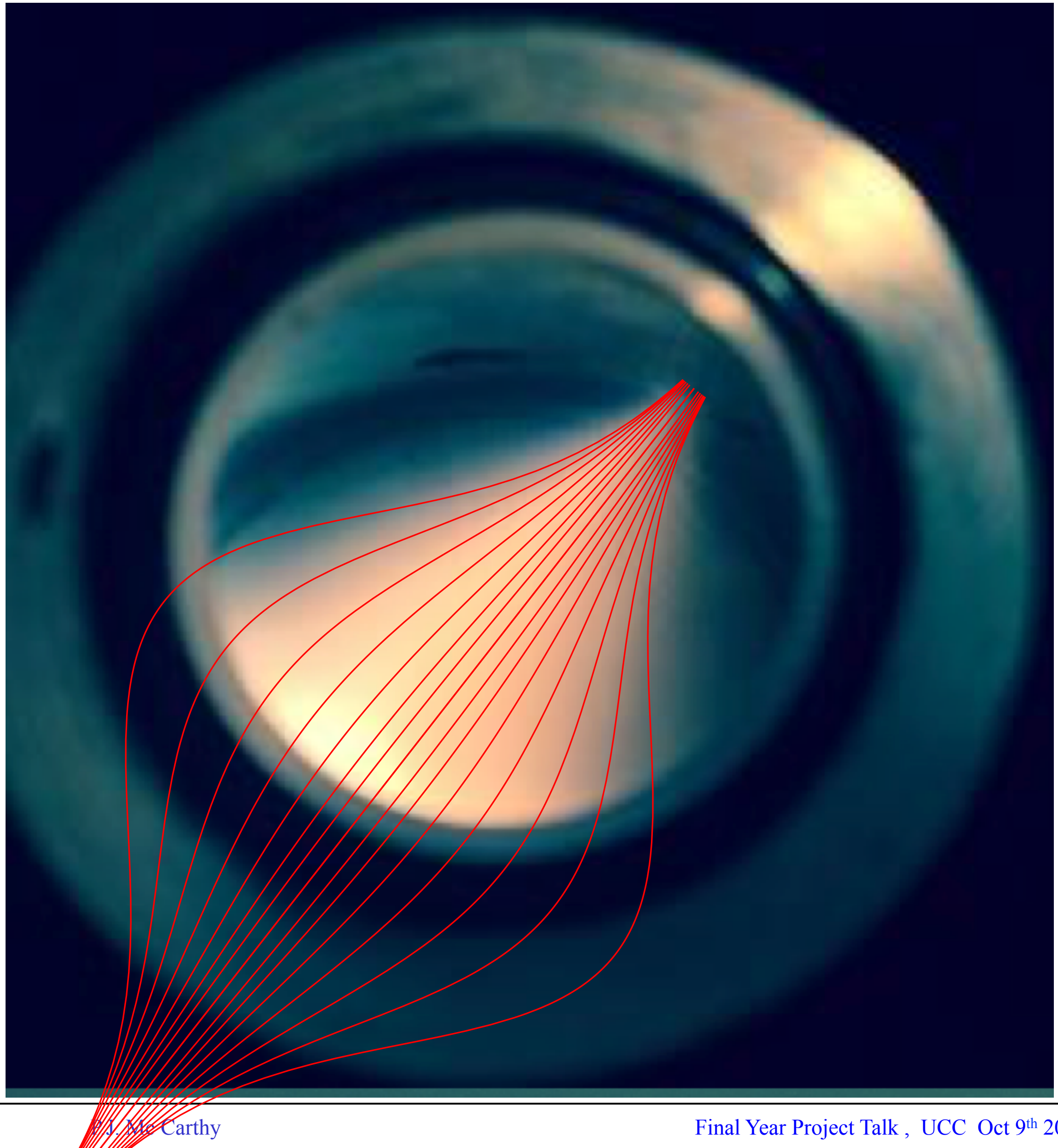
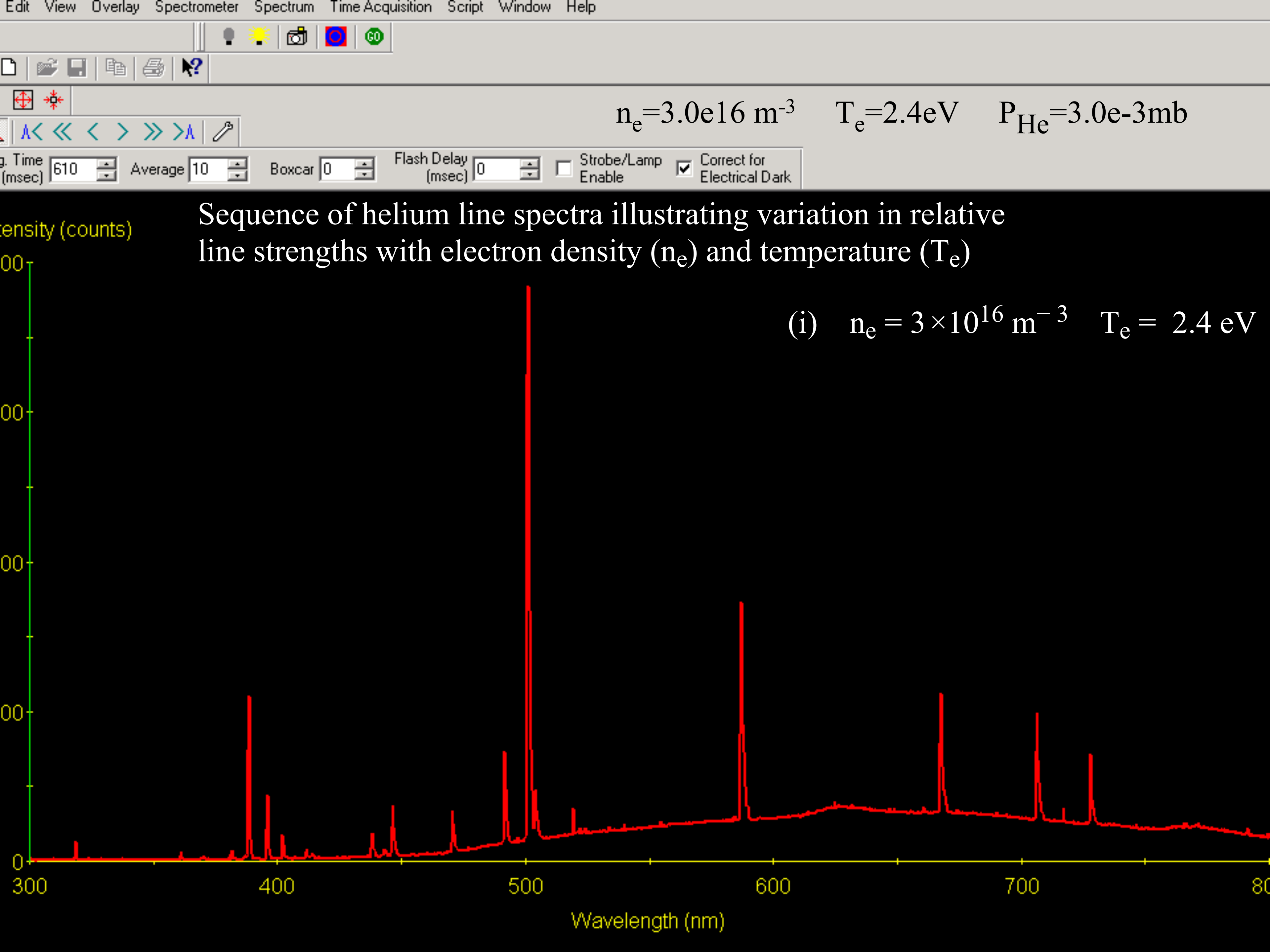
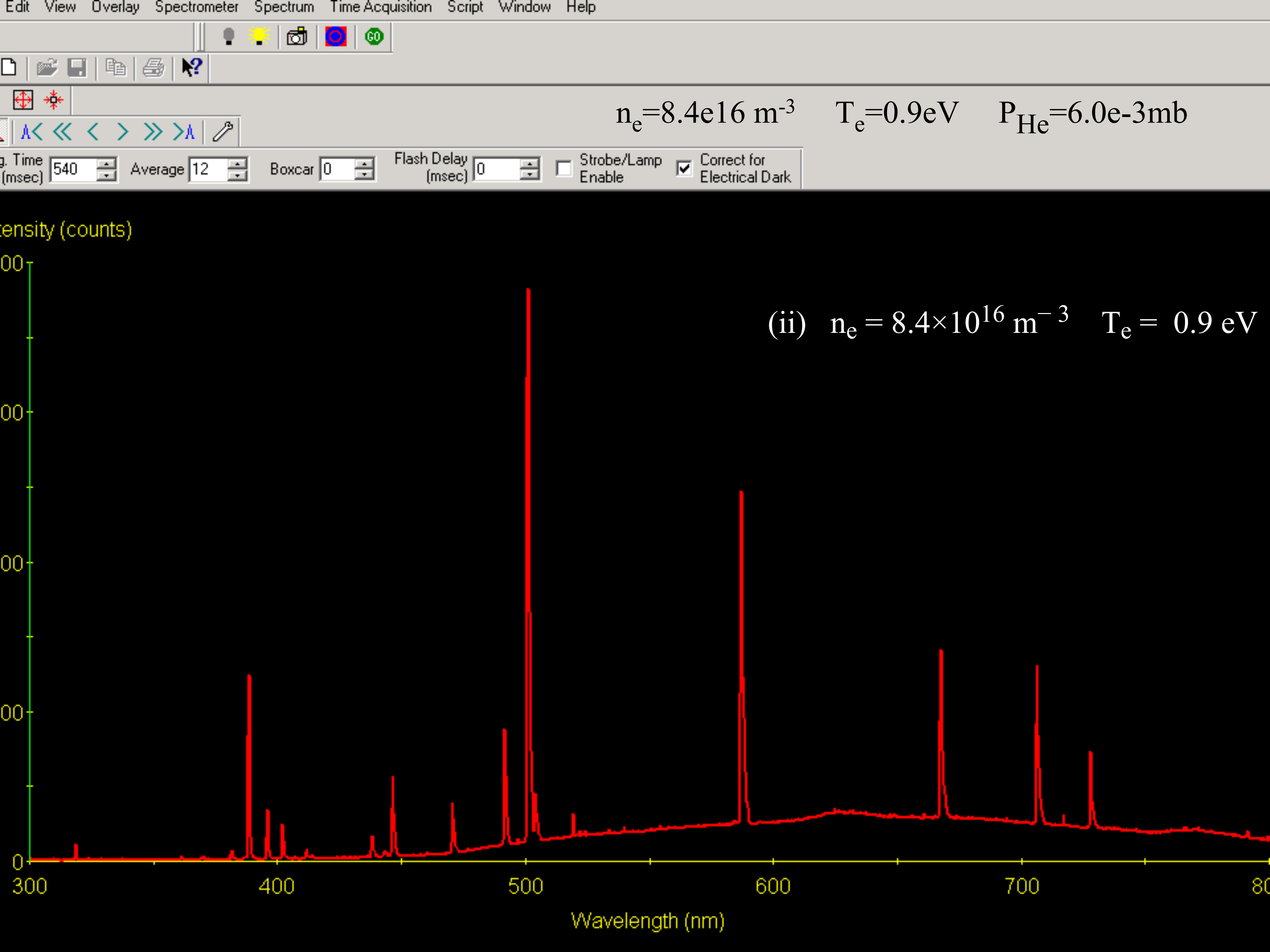


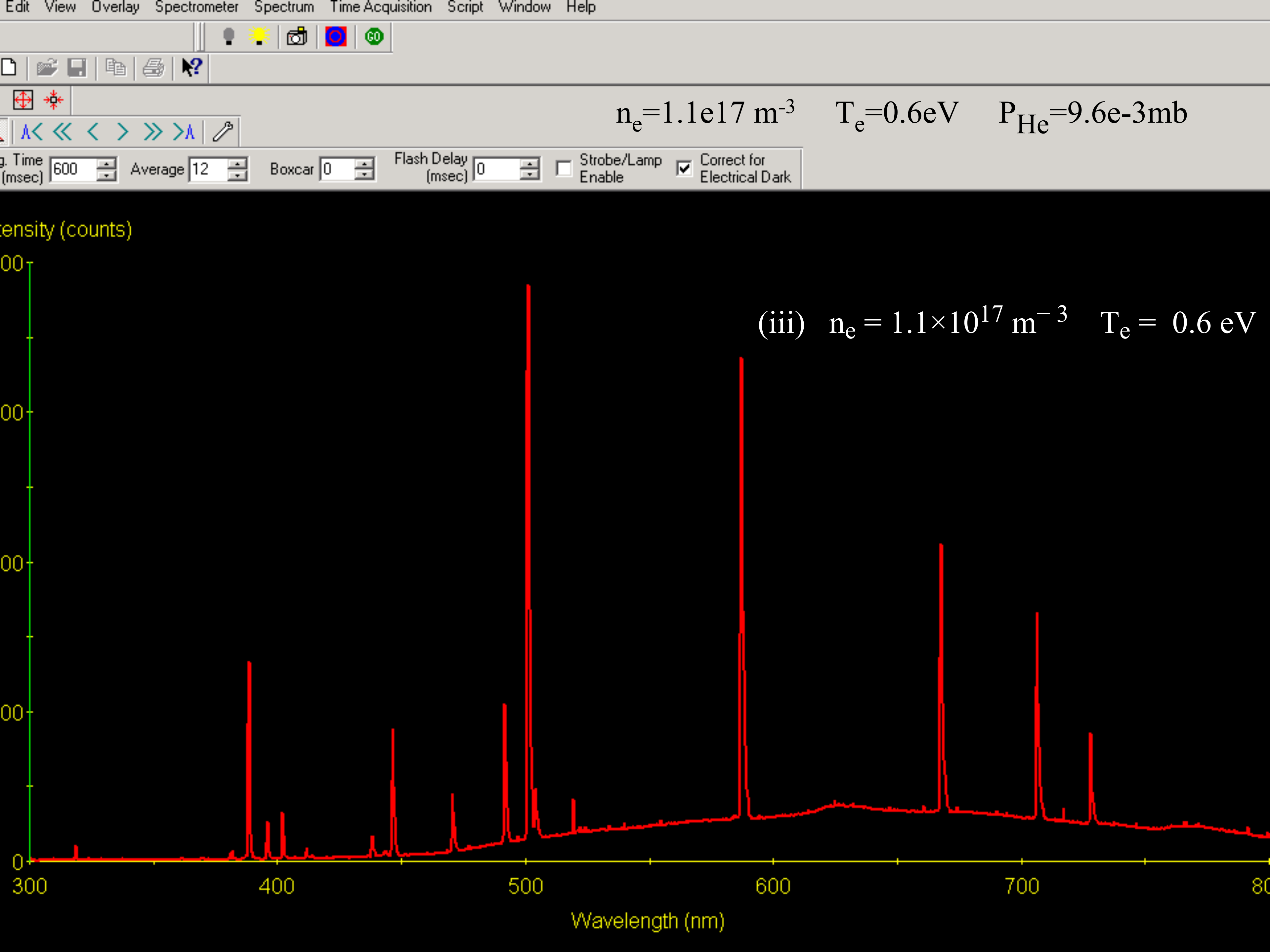
Image of plasma light from magnetic mirror configuration with magnetic field line structure superimposed.

Sequence of helium line spectra illustrating variation in relative line strengths with electron density (n_e) and temperature (T_e)





Edit View Overlay Spectrometer Spectrum Time Acquisition Script Window Help
n_e=8.4e16 m^{-3} T_e=0.9eV P_{He}=6.0e-3mb
Time (msec) 540
Average 12
Boxcar 0
Flash Delay (msec) 0
Strobe/Lamp Enable
Correct for Electrical Dark
ensity (counts)
(ii) $n_e = 8.4\times10^{16}\ m^{-3}$ T_e = 0.9 eV
300
400
500
600
700
80
Wavelength (nm)



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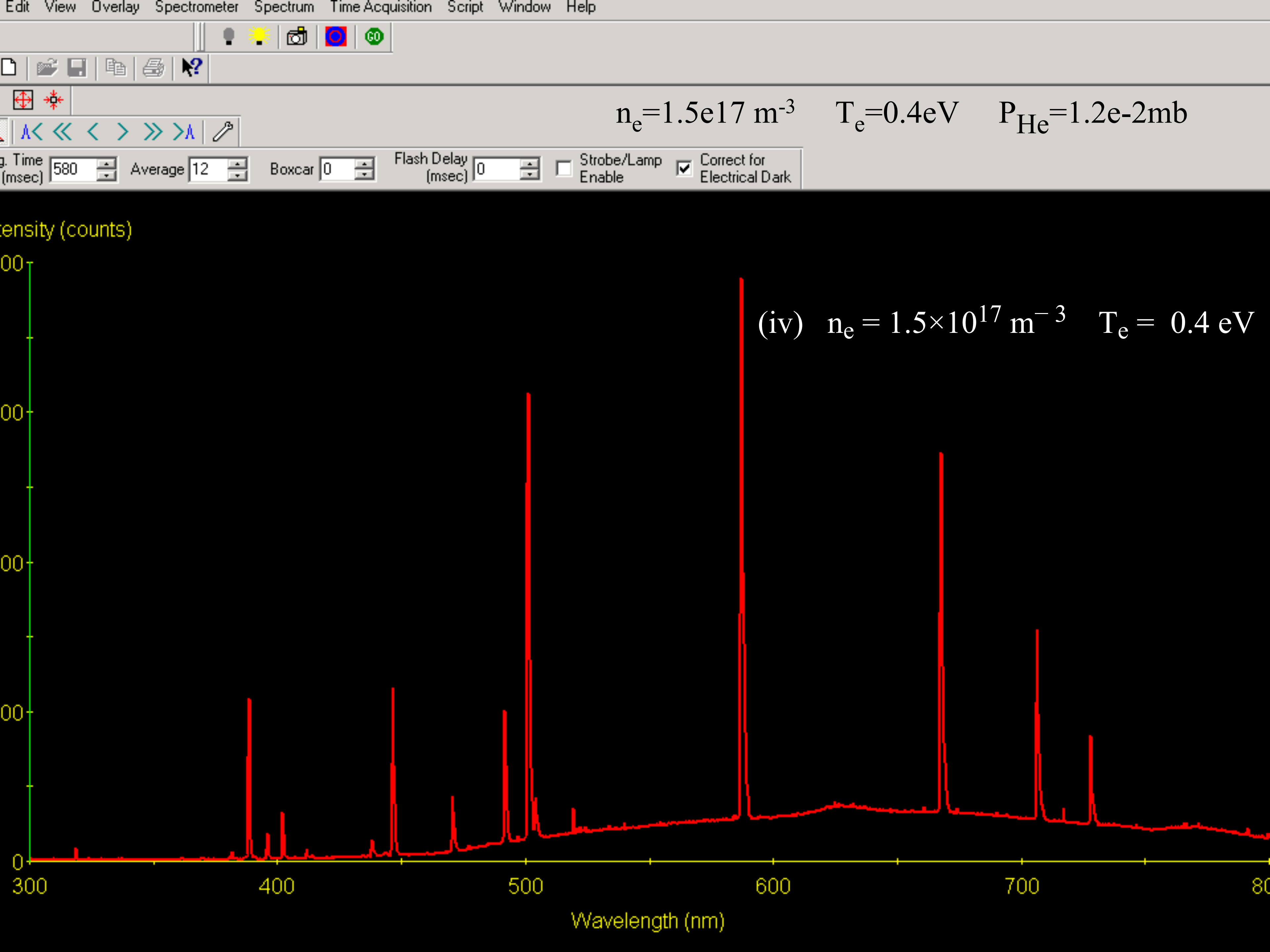
ne=1.1e17 m-3 Te=0.6eV PHe=9.6e-3mb
Time (msec) 600
Average 12
Boxcar 0
Flash Delay (msec) 0
Strobe/Lamp Enable
Correct for Electrical Dark
ensity (counts)
(iii) ne = 1.1×1017 m− 3 Te = 0.6 eV
0
300
400
500
600
700
Wavelength (nm)


Edit View Overlay Spectrometer Spectrum Time Acquisition Script Window Help
n_e=1.5e17 m^{-3} T_e=0.4eV P_{He}=1.2e-2mb
Time (msec) 580
Average 12
Boxcar 0
Flash Delay (msec) 0
Strobe/Lamp Enable
Correct for Electrical Dark
Intensity (counts)
(iv) $n_e = 1.5\times10^{17}\ m^{-3}$ $T_e = 0.4\ eV$
0
300
400
500
600
700
Wavelength (nm)

Ion temperature from Doppler Spectroscopy

Doppler shift: $f = f_0 \sqrt{\frac{1+\mathrm{v}/c}{1-\mathrm{v}/c}} \approx f_0(1+\mathrm{v}/c); \; \mathrm{v}/c << 1$

For thermal (random) motion of excited ions* in a plasma, this leads to a *Doppler* or *thermal broadening* of the emission line. The full width at half max (FWHM) of the thermally broadened line of Gaussian shape is given by

$$\frac{\delta f}{f} = \frac{\delta\lambda}{\lambda} = \sqrt{\frac{8kT\ln 2}{mc^2}} = 7.71\times10^{-5}\sqrt{\frac{T}{\mu}}$$ (T in eV, the ion mass μ in amu)

For the prominent singly ionized helium (He II) line at 468.6 nm for an expected ion temperature of T = 1 eV = 11600 K this gives (with μ=4):

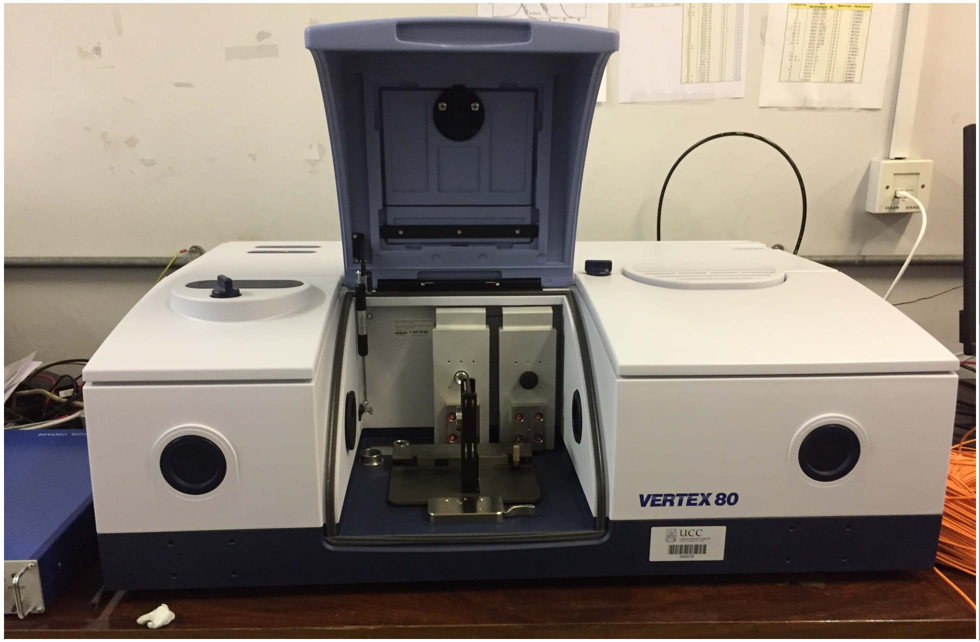
$$\delta\lambda = 7.71\times10^{-5}\times0.5\times468.6 = 0.018\,\mathrm{nm} \quad \text{or} \quad \delta f = 7.71\times10^{-5}\times0.5\times c/\lambda = 24.7\,\mathrm{GHz}$$

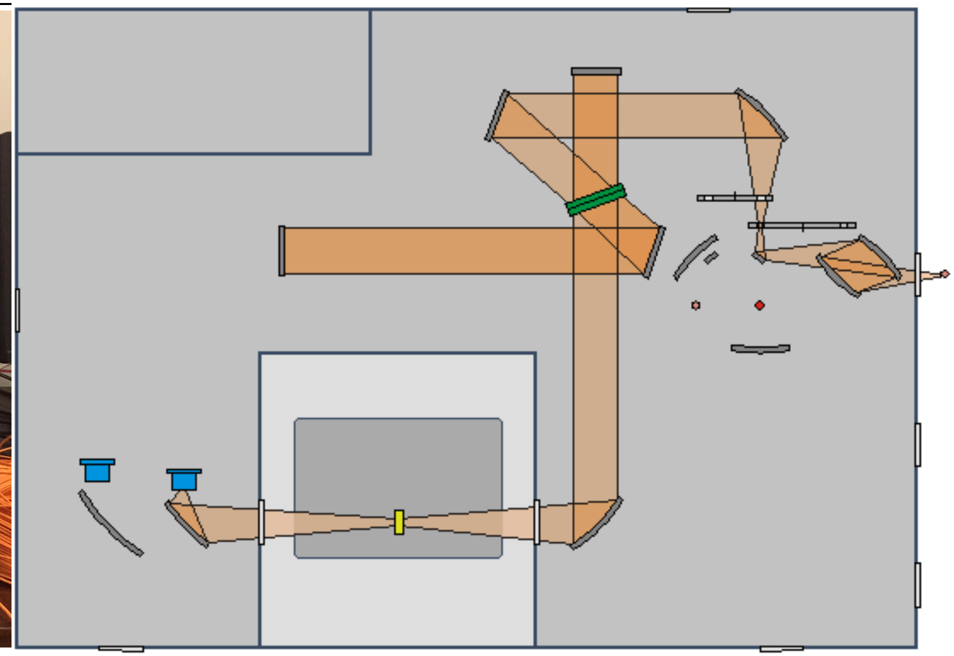
The corresponding $\delta E = h\,\delta f = 1\times10^{-4}\,\mathrm{eV}$ >> natural linewidth $\approx \hbar/2\tau \approx 5\times10^{-8}\,\mathrm{eV}$

Also for working electron densities $n_e < 10^{19}\ \mathrm{m^{-3}}$ and neutral pressures $p < 0.02$ torr collisional/pressure broadening is weak in comparison to thermal broadening.

*also neutral species, but these being at room-like temperatures cause negligible thermal broadening.

Double Plasma Experiment (Physics Dept. UCC)



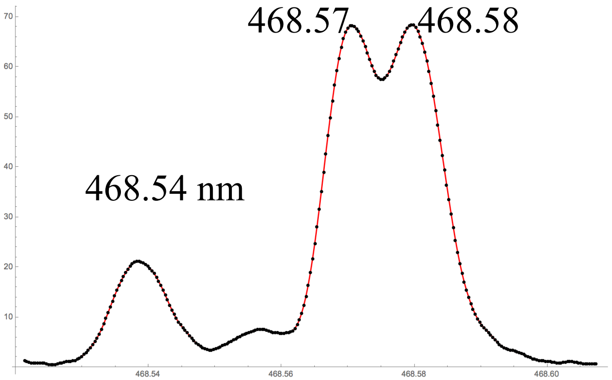


Ultra-high resolution Fourier Transform-based Bruker spectrometer (on loan from Andy Ruth's lab) with signal-boosting photomultiplier tube (PMT).

Best achievable resolution: $\Delta k = 0.075$ inverse cm.

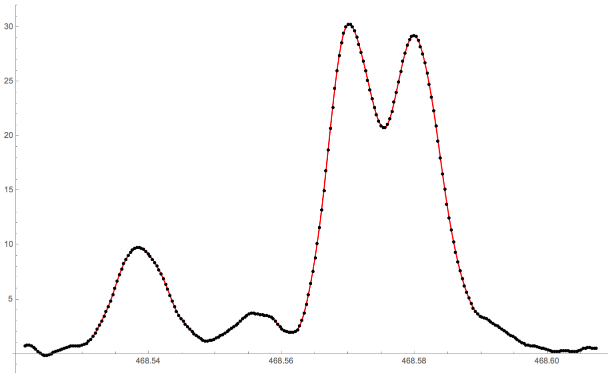
$\Delta \lambda$ @ 468 nm = 1.6 pm !

Use of FTIR spectrometer to measure plasma ion temperatures by Doppler spectroscopy on 468.6 nm HeII line

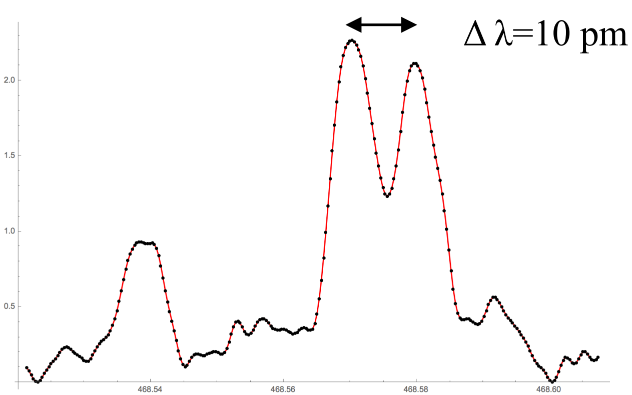


Recent (tentative) first results (S. Knott)

$T_{ion} \approx 0.25$ eV (≈ 3000 K)

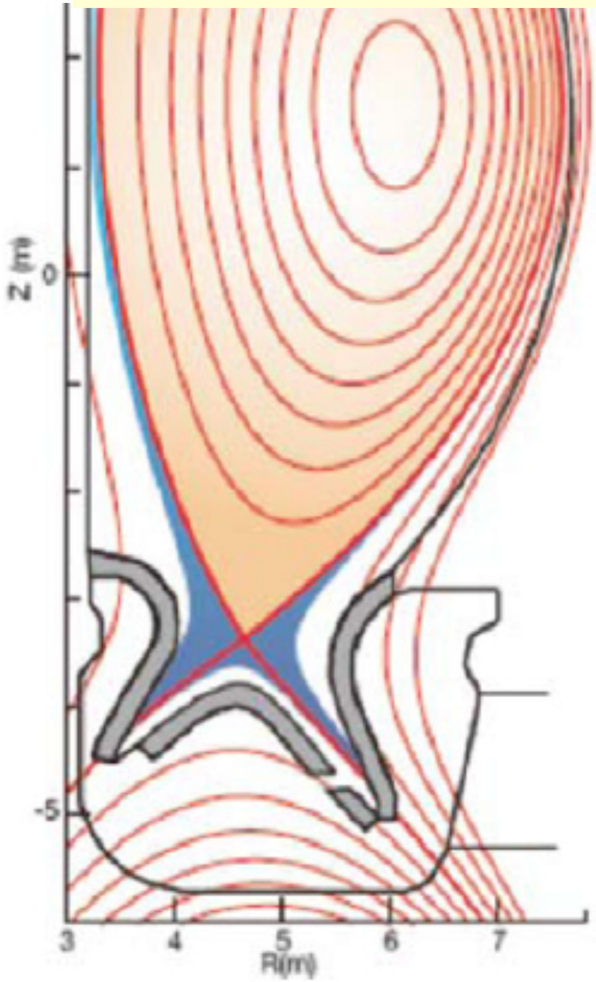


$T_{ion} \approx 0.20$ eV (≈ 2300 K)

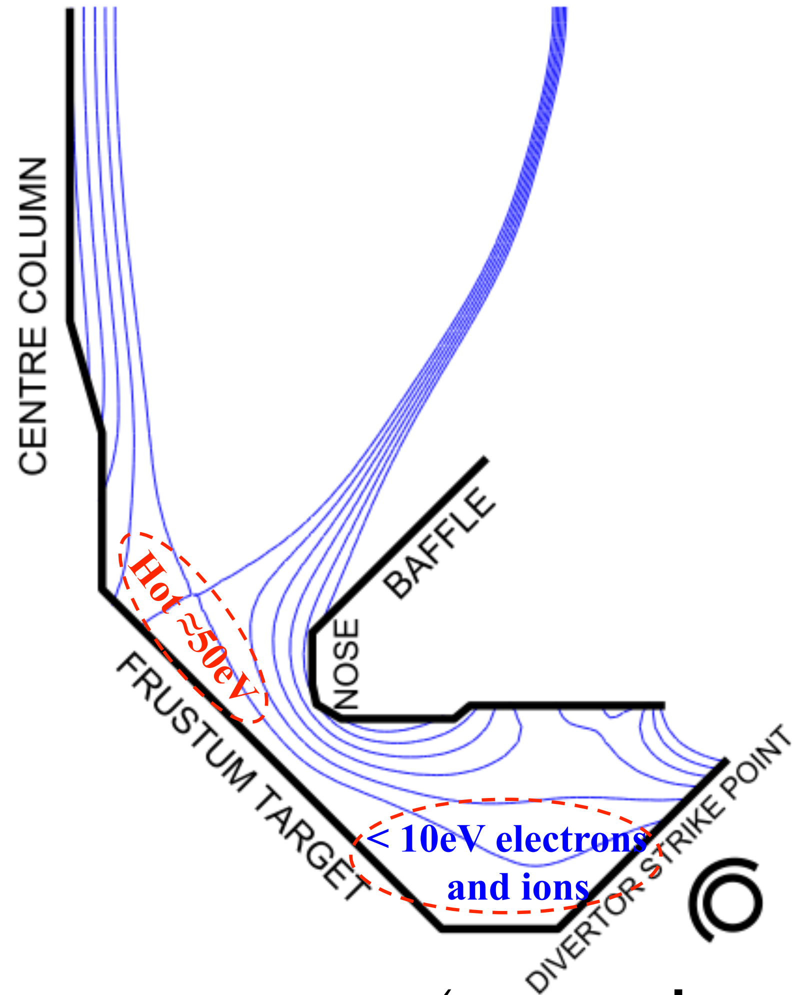


$T_{ion} \approx 0.15$ eV (≈ 1750 K)

Research Goal: Deployment of electron temperature and density diagnostic on MAST Upgrade tokamak (expected to operate from summer 2018)



Conventional divertor design



MAST Upgrade 'Super X' design

Parameterization of ion temperature vs. plasma parameters

Using the mirror plasma experiment in the plasma physics laboratory, the student will become familiar with basic plasma measurement techniques and explore the plasma parameters achievable in a magnetic mirror configuration.

468.6 nm He II lines will be recorded for a wide variety of plasma parameters. The student will learn the concept of Tikhonov regularization for optimal information retrieval from noisy or incomplete data and hence obtain the best possible parameterization of T_{ion} vs. plasma parameters (plasma current, heating power, helium pressure, electron density, electron temperature) from his/her experimental data. These results will form an important component of an ongoing project to develop an electron temperature and density diagnostic based on He I line ratios in the divertor leg region of the Mega Ampere Spherical Tokamak (MAST) Upgrade experiment which is planned to start operating in summer 2018 at the Culham Centre for Fusion Energy, Oxfordshire.

If there is sufficient interest, a second computational project may be offered based on statistical analysis of a database of magnetohydrodynamic equilibrium states.