Absolute densities of fast H ions in an IEC discharge

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Outline

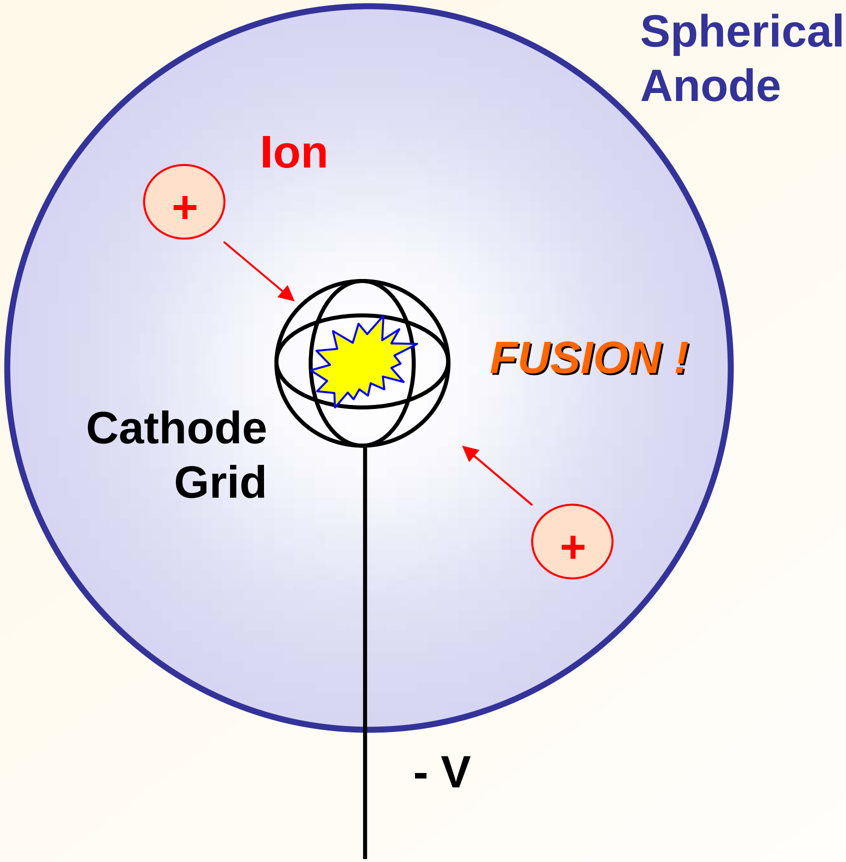
- Background:
  - Inertial Electrostatic Confinement (IEC)

- Optical measure for fast ion densities
  - Theory
  - Results
  - Advantages/limitations

- Plans for future work!

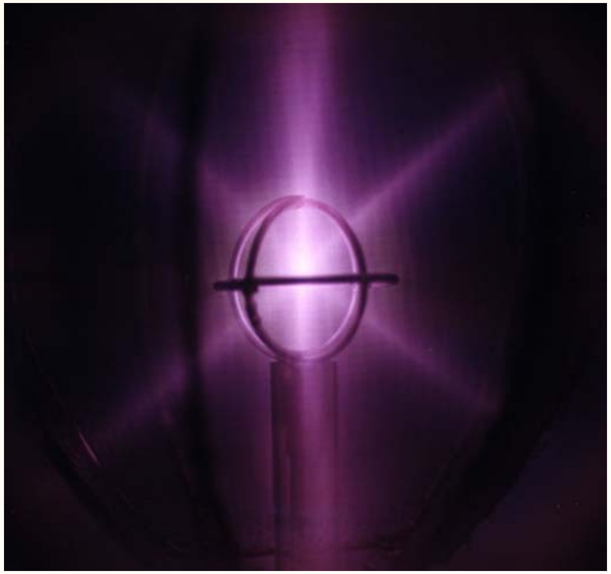
Inertial Electrostatic Confinement (IEC)

- **Aim**: accelerate ions of a D_2 plasma through concentric electrodes (outer radius ~ 30 cm):



Features of a simple IEC device

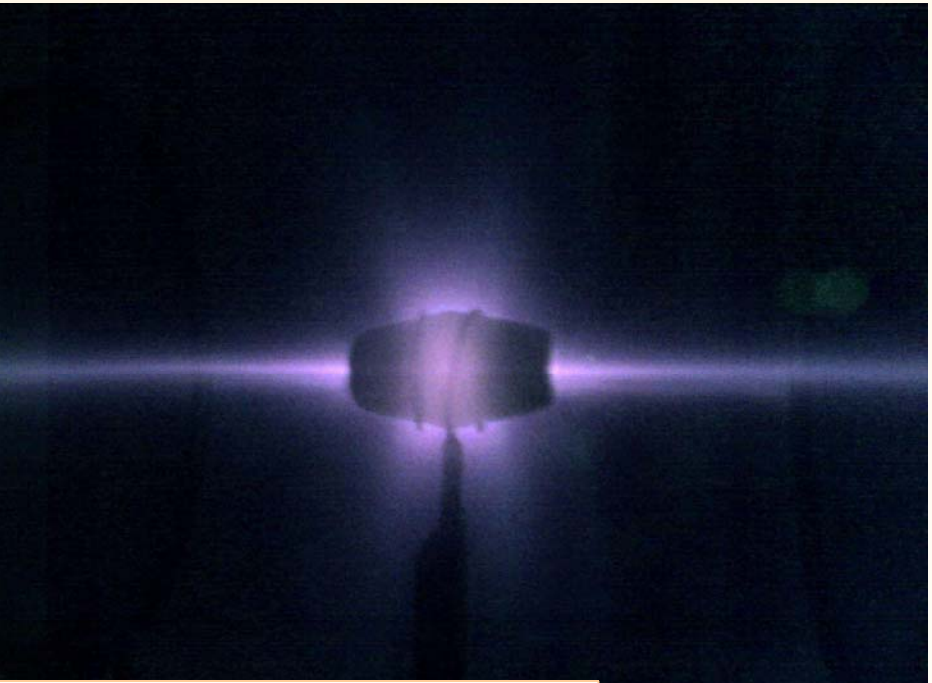
IEC emission channels in hydrogen:

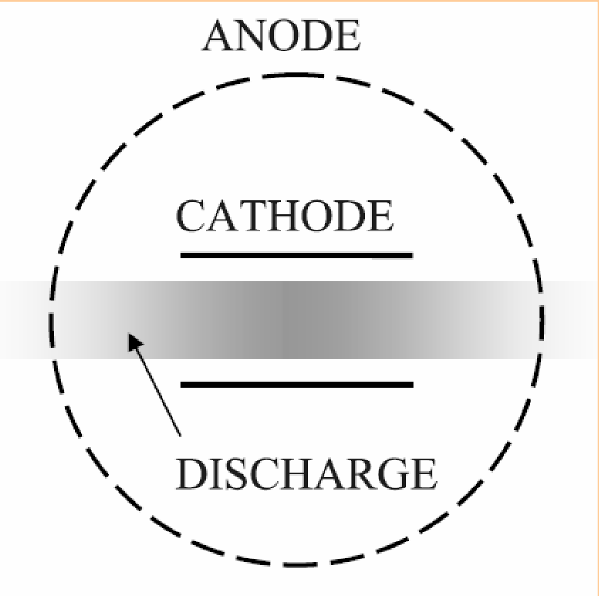


Typical parameters:

Pressure:	$10^{-3} - 10^{-2}$ Torr
Cathode bias:	1 – 10 kV
Current:	1 – 50 mA

‘Abnormal Hollow Cathode’





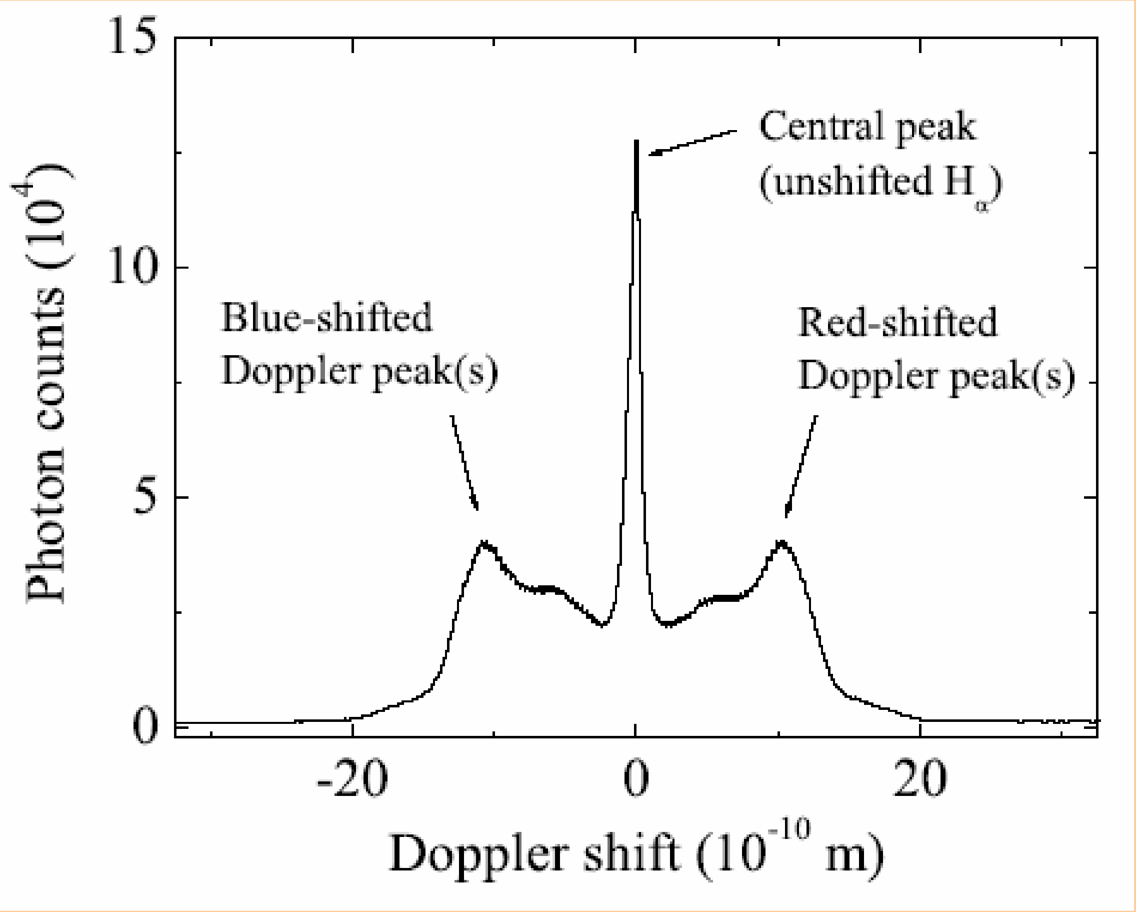
- Dusty plasma experiments:
  (Khachan & Samarian, 2006)
  - → large flux of fast ions emerging from cathode edge.
  - → Fast ion densities of ~ 10^8 cm^{-3}
- cf. Langmuir probe measurements:
  (Khachan, Moore, Bosi, 2003)
  - → Virtual anode in cathode center!

AIM: optical (non-perturbing) diagnostic:

Calculate fast ion densities using a *single* spectrum of the strong H_α ($n = 3 \rightarrow 2$) line…

Typical H_α spectrum:

Central (Lorentzian) peak flanked by Doppler wings:



- Within the cathode, the spectrum is symmetric!

- Kinetic energy *K* of emitting particle:

$$\boxed{K = \frac{m_H c^2 (\Delta\lambda)^2}{2\lambda_0^2 \cos^2\theta},}$$

→ `Fast' H – units/tens of keV

→ `Slow' H – tenths/units of eV

- How to transform photon counts into absolute densities of fast ions?

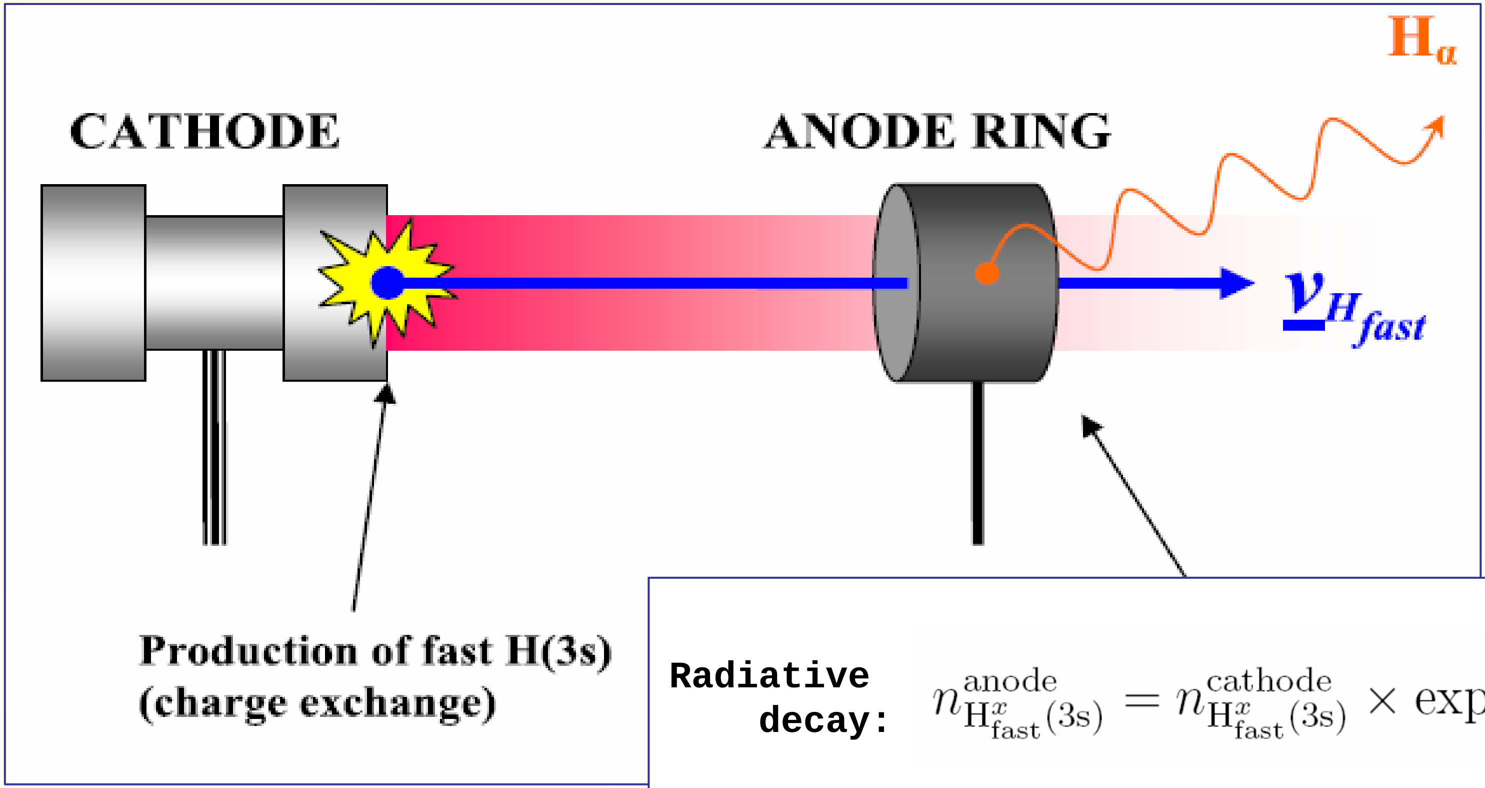
We use the fact that Central / Doppler peaks arise through *distinct processes!*

Theory, Part I: Doppler peaks

(Shrier et al, 2006): **charge exchange** between H_2 and H_x^+ (x = 1,2,3):

$$\begin{aligned} \mathrm{H}^+ + \mathrm{H}_2 &\longrightarrow \mathrm{H}(n,l) + \mathrm{H}_2^+ \\ \mathrm{H}_2^+ + \mathrm{H}_2 &\longrightarrow \mathrm{H}(n,l) + \mathrm{H}(1\mathrm{s}) + \mathrm{H}_2^+ \\ \mathrm{H}_3^+ + \mathrm{H}_2 &\longrightarrow \mathrm{H}(n,l) + \mathrm{H}_2 + \mathrm{H}_2^+ . \end{aligned}$$

(McClure, 1965): Product H(3s) possess trajectory of incident ion, with energy K/x



Radiative decay: $n^{\text{anode}}_{\text{H}^x_{\text{fast}}(3\text{s})} = n^{\text{cathode}}_{\text{H}^x_{\text{fast}}(3\text{s})} \times \exp(-A_{3\text{s}\to 2\text{p}} t_{\text{sep}})$

Theory, Part I: Doppler peaks

- Collisional-radiative model (Fitzgerald et al, 2006):

$$\frac{dn_{H^x_{\mathrm{fast}}(n,l)}}{dt} = n_{H_x^+} n_{H_2} k_x(n,l) - \sum_{\substack{(n',l')<(n,l)\\ \mathrm{allowed}}} A_{(n,l)\to(n',l')} n_{H_{\mathrm{fast}}(n,l)} - k_Q(n,l) n_{H_2} n_{H_{\mathrm{fast}}(n,l)}.$$

→ Can relate Doppler peak intensity to the density of fast H(3s) at the cathode:

$$I_x^{\mathrm{anode}} \propto n^{\mathrm{cathode}}_{H^x_{\mathrm{fast}}(3s)} A_{3s\to 2p} \times \exp(-A_{3s\to 2p} t_{\mathrm{sep}}).$$

… where we have considered steady-state emission through 3s → 2p

  - This transition has a long lifetime (1.6E-7s) and decay length (~10 cm).

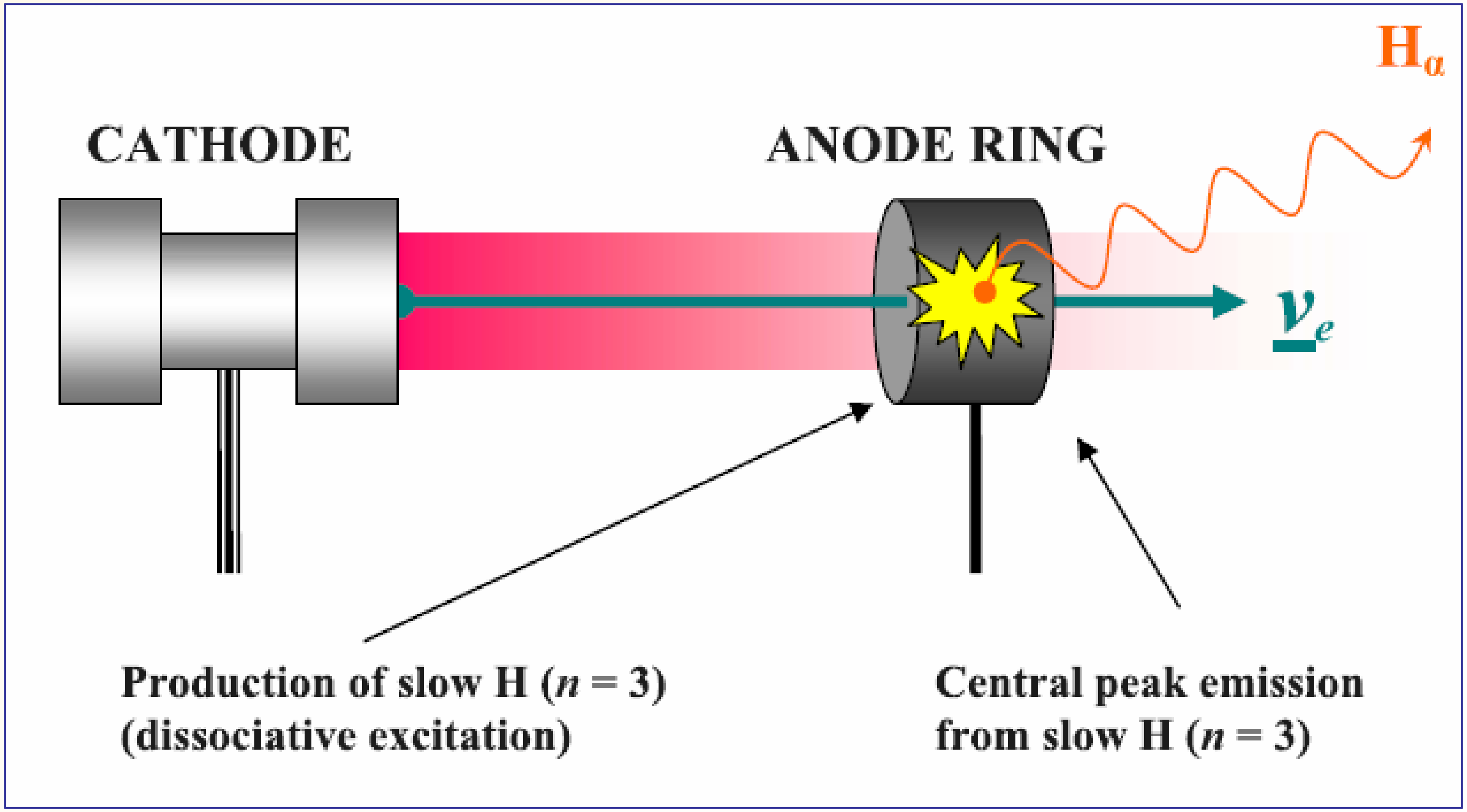
Theory, Part II: the Central peak

(Kipritidis et al, 2007):

Dissociative excitation of H_2 by fast monoenergetic electrons in the keV energy range:

$$e^- + H_2 \rightarrow e^- + H_2^* \rightarrow e^- + H(1,s) + H(n,l).$$

Product H(*n* =3) have relatively *low* energies (0.1-10 eV)



Theory, Part II: the Central peak

- Simplified CR model (cf. Kipritidis et al, 2006):

$$\frac{\mathrm{d}n_{\mathrm{H_{slow}}(n,l)}}{\mathrm{d}t} = k_{\mathrm{D}}(n,l)\,n_{\mathrm{e}^-_{\mathrm{fast}}}\,n_{\mathrm{H_2}} - \sum_{\substack{(n',l')<(n,l)\\ \text{allowed}}} A_{(n,l)\rightarrow(n',l')}\,n_{\mathrm{H_{slow}}(n,l)}$$

→ Can relate central peak intensity to the density of fast electrons at the anode:

$$I^{\mathrm{anode}}_{\mathrm{central}} \propto n^{\mathrm{anode}}_{\mathrm{H_{slow}}(\mathrm{n=3})}\left(0.16\,A_{\mathrm{3s\rightarrow2p}} + 0.44\,A_{\mathrm{3p\rightarrow2s}} + 0.40\,A_{\mathrm{3d\rightarrow2p}}\right)$$

…here we have used branching ratios given by Fujimoto et al (1989).

Theory, Part III: putting it all together!

Since both peaks sampled at same point in space (at the anode)…

→ We can ignore the dependence of intensity on position!

For a single spectrum of H_α observed in the emission channel near the anode:

$$\boxed{n^{(cathode)}_{H^+_x,\,fast} \approx n^{(anode)}_{e^-_{fast}} \left(\frac{I_x^{(anode)}}{I_{Central}^{(anode)}} \right) \times C \left(\frac{\sigma_{diss.exc.}\, v_{e^-_{fast}}}{\sigma_{CX}\, v_{H^+_x,\,fast}} \right) e^{(A_{3s\to 2p}\, t_{c\to a})}.}$$

…where *C* is known.

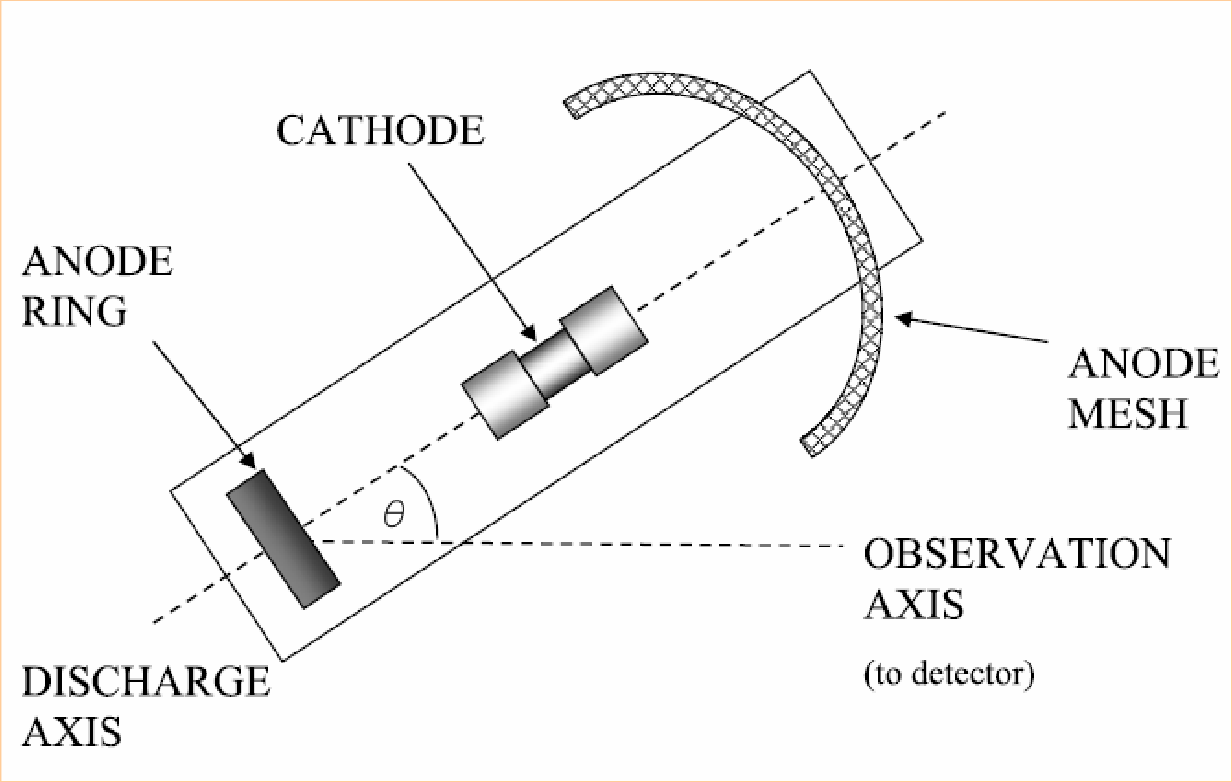
Magnetic deflection of the beam suggests monoenergetic electrons accelerated to the full applied potential → *electron velocities are known!*

$$\boxed{n^{\mathrm{anode}}_{\mathrm{e}^-_{\mathrm{fast}}} = I_{\mathrm{cathode}} / (\pi r^2_{\mathrm{beam}}\, e v^{\mathrm{anode}}_{\mathrm{e}^-_{\mathrm{fast}}})}$$

Experimental Procedure, Part I:

Emission channel is observed through centre of the anode at $\theta = 25$ degrees.

- Cathode bias was kept constant at – 5 kV.
- I changed the cathode current by adjusting pressure.



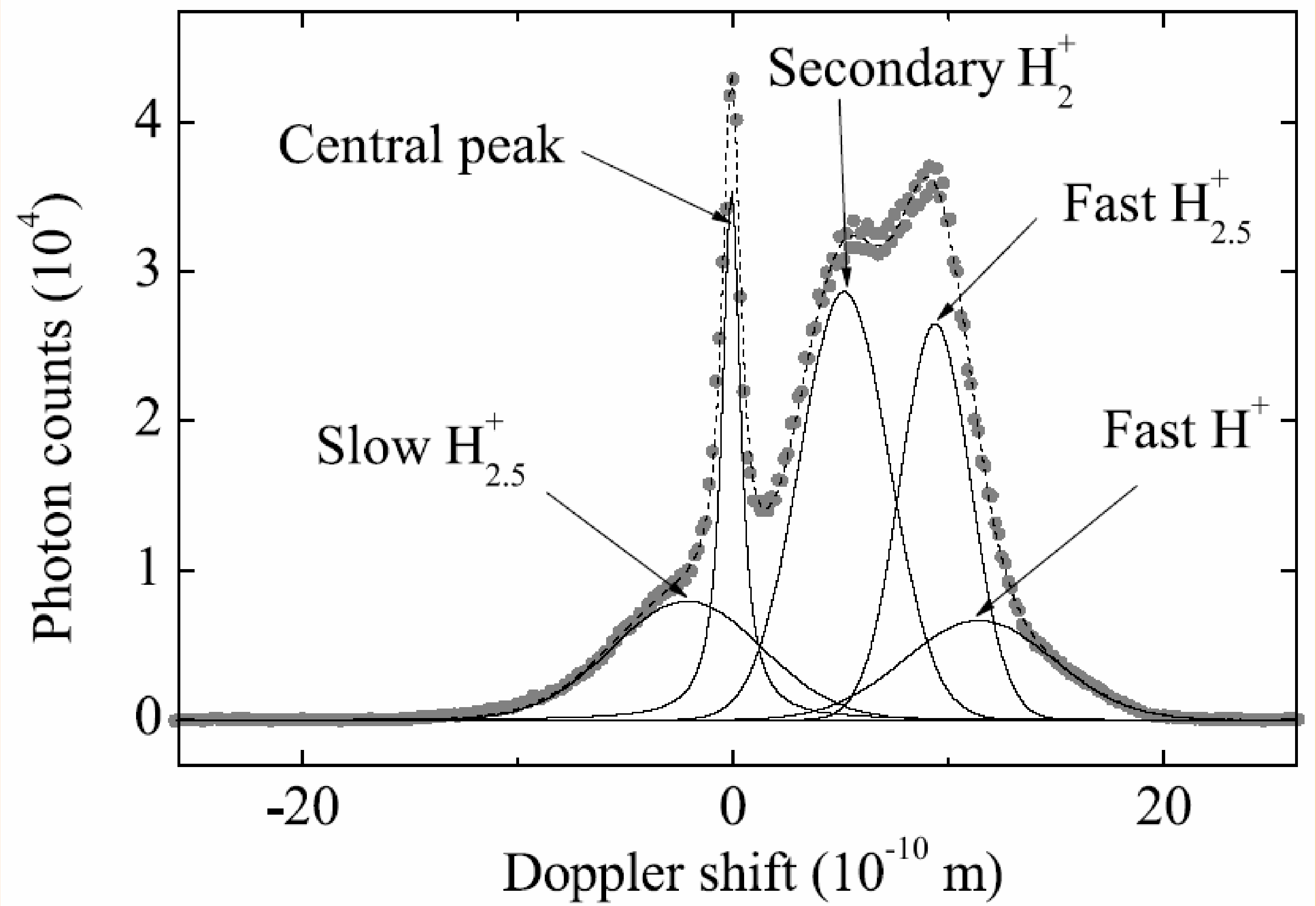
- Detector consists of a <u>monochromator</u> coupled to a <u>linear diode array</u>…

Experimental Procedure, Part II:

Peak fitting (ORIGIN):

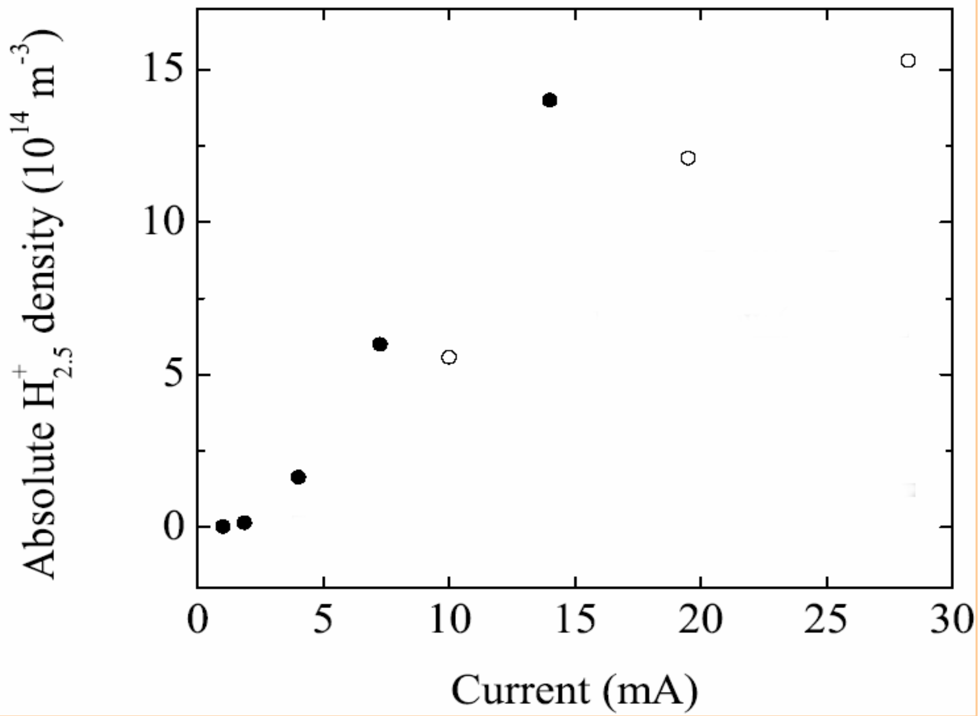
Far from the cathode, spectrum is asymmetric as fast ions are primarily moving away from the cathode / detector…

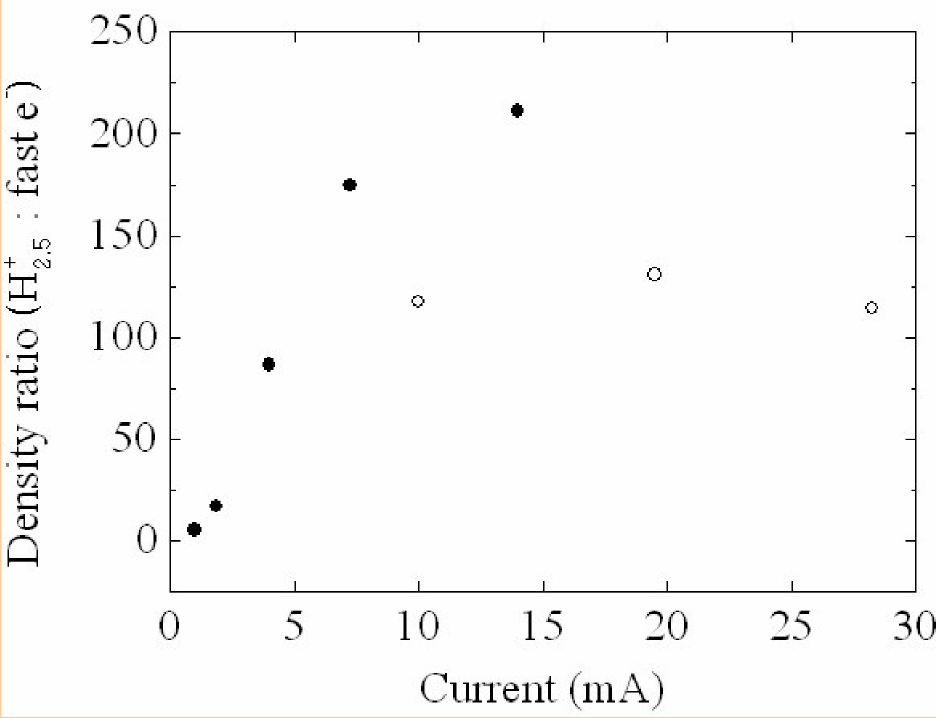
→ we are concerned with the central and red-shifted peaks!



Sample Results, Part I: Absolute densities

- Densities of fast $H_{2.5}^+$ emerging from cathode aperture are ~ $1\text{-}5 \times 10^{14}$ m^{-3}





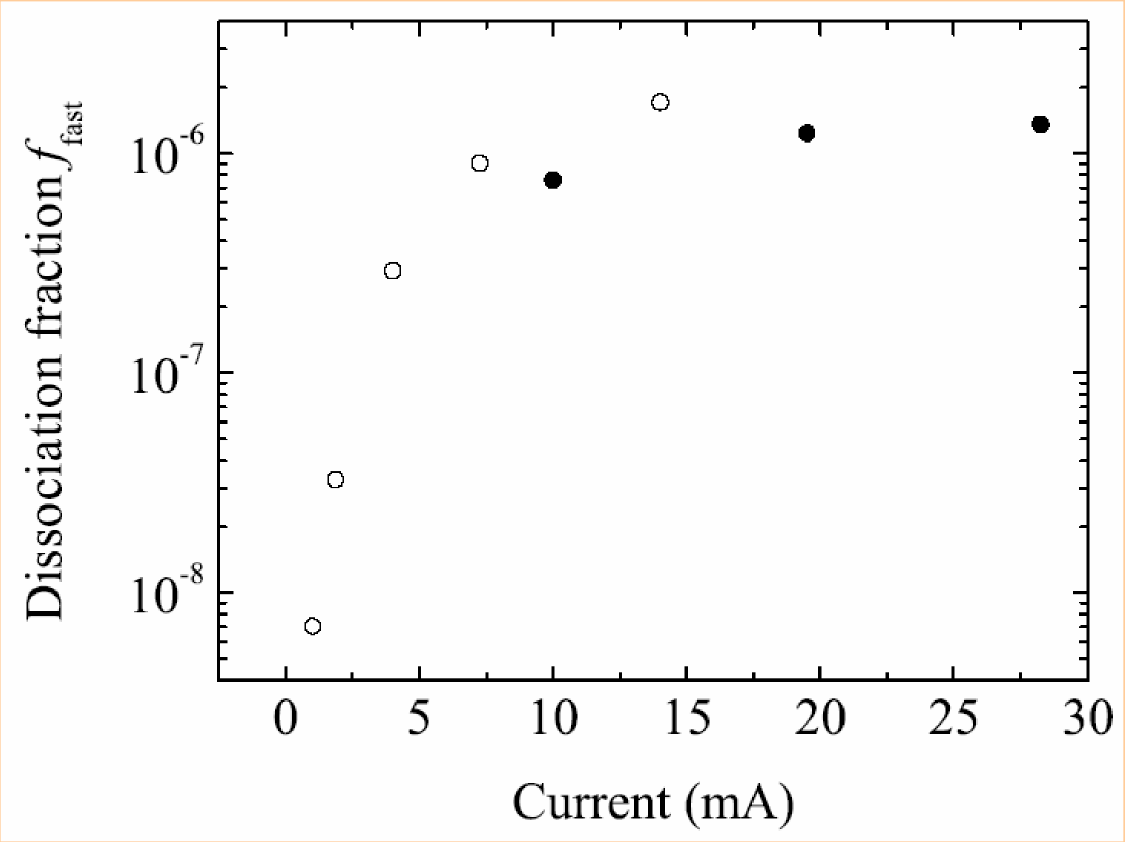
These values are in agreement with previous measurements!

HOWEVER: Spread of ***t_{sep}*** in the exponential term…

→ we have an *order of magnitude* estimate!

Sample Results, Part II: Dissociation fraction

- Can calculate ***f_{fast}***, the fraction of energetic ions/neutrals to background gas!



Could use this to predict fusion rates in a similar discharge of D_2 !

$$\begin{aligned} R_{\mathrm{D-D}} &= n_{\mathrm{D}^+_{\mathrm{fast}}} n_{\mathrm{D}_2} \sigma_{\mathrm{D-D}} v_{\mathrm{D}^+_{\mathrm{fast}}} \\ &= f_{\mathrm{fast}} (n_{\mathrm{D}_2})^2 \sigma_{\mathrm{D-D}} v_{\mathrm{D}^+_{\mathrm{fast}}} \end{aligned}$$

Summary:

Advantages:

- Non-perturbing diagnostic for fast ion densities in a mTorr IEC discharge

- Method requires only two inputs!

- We can infer fusion rates in D_2 without producing neutrons!

- Results are independent of detector slit width / exposure time

Limitations:

- For now, order of magnitude estimates only.

- We ignore any external discharge…
  → Calculated densities are an upper limit!

Present / future work:

Aim: Compare results from optical and nuclear emission spectroscopy!

- We are readying our apparatus for **pulsed** operation
- This should overcome issues of cathode heating for bias > 10 kV
- Extrapolating curves for ***density vs. current*** and ***current vs. bias***…

Neutron production rate: up to 10^9 $m^{-3}s^{-1}$ ***(bias -20 kV, current ~ 200 mA)***

To be continued!

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