PPPL Graduate Summer School: Introduction to Plasma Diagnostics

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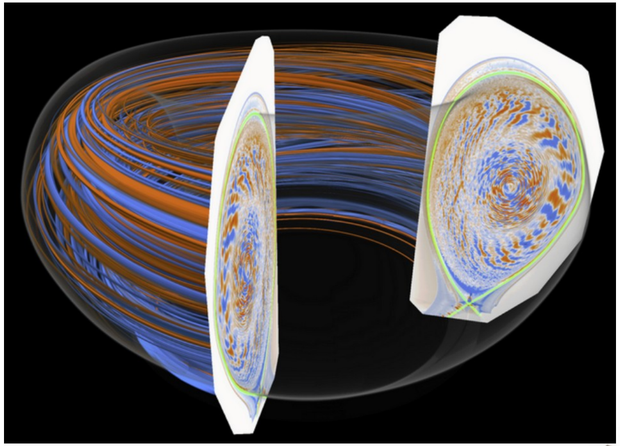
Questions that models can answer:

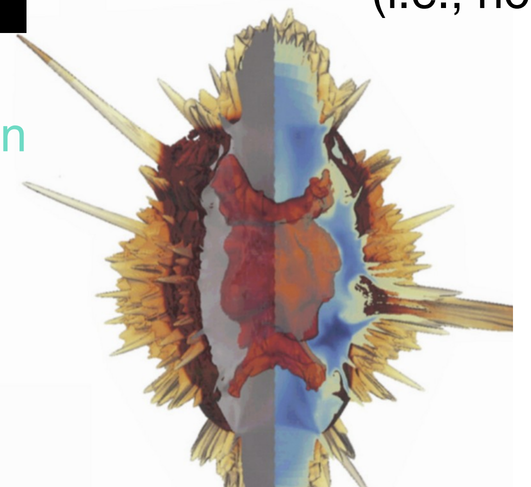


C. S. Chang (PPPL)
XGC1 gyrokinetic simulation
of tokamak plasma

What mechanisms produce a given effect?

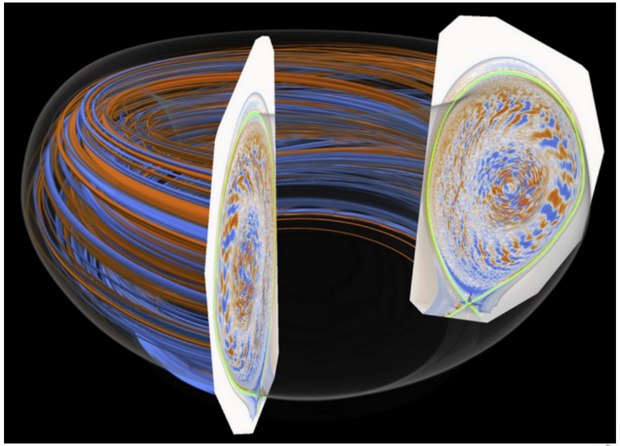
Why is that the case?

How do effects **scale** with different parameters?
(i.e., how can we get more of what we want?)



C. R. Weber et al. (LLNL)
HYDRA radiation-hydrodynamics
simulation of NIF implosion

Questions that models **can't** answer:

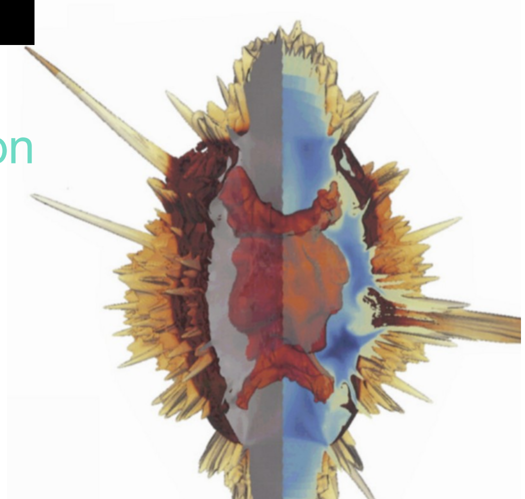


C. S. Chang (PPPL)
XGC1 gyrokinetic simulation
of tokamak plasma

Do these conclusions **matter?**

or

Is any of this **real?**



C. R. Weber et al. (LLNL)
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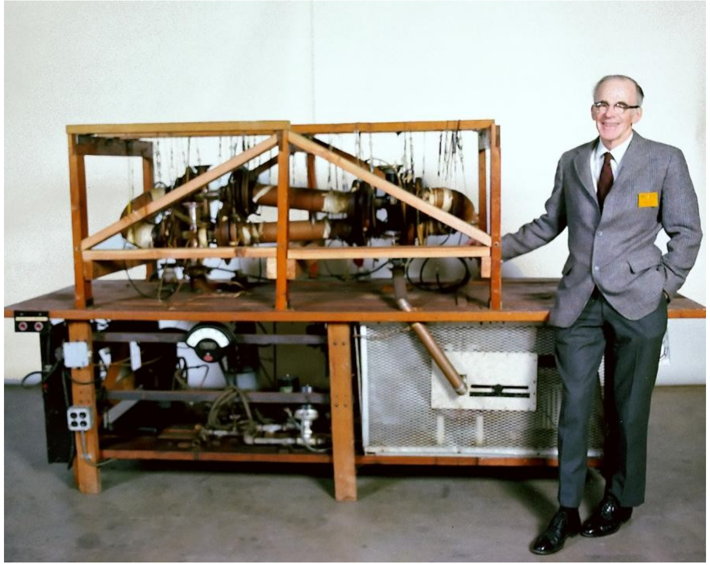
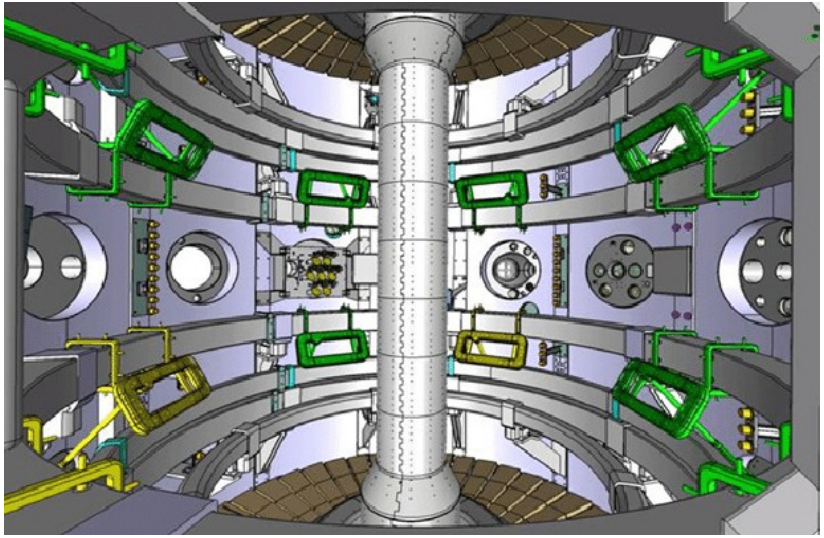
Diagnostics: connecting things we think we understand to *real life*



Lyman Spitzer's Stellarator A (1953)
Hard to see inside

progress



Inside the UK's MAST tokamak
(Gryaznevich et al., Nuclear Fusion 2008)
Literally constructed to see inside

Our goal: tie observables to quantities of interest in the plasma

Plasma does plasma activity

Step 1: Measure it

Step 2: Interpret it

Densities:

n_e, n_i, n_z …

Temperatures:

T_e, T_i, T_{rad}

Plasma flows:

v_e, v_i, j, $v_{toroidal}$, $v_{poloidal}$ …

Fields

E, **B**, particular plasma waves…

Anything else that can be compared to a model

Our goal: tie observables to quantities of interest in the plasma

Plasma does plasma activity

Step 1: Measure it

Step 2: Interpret it

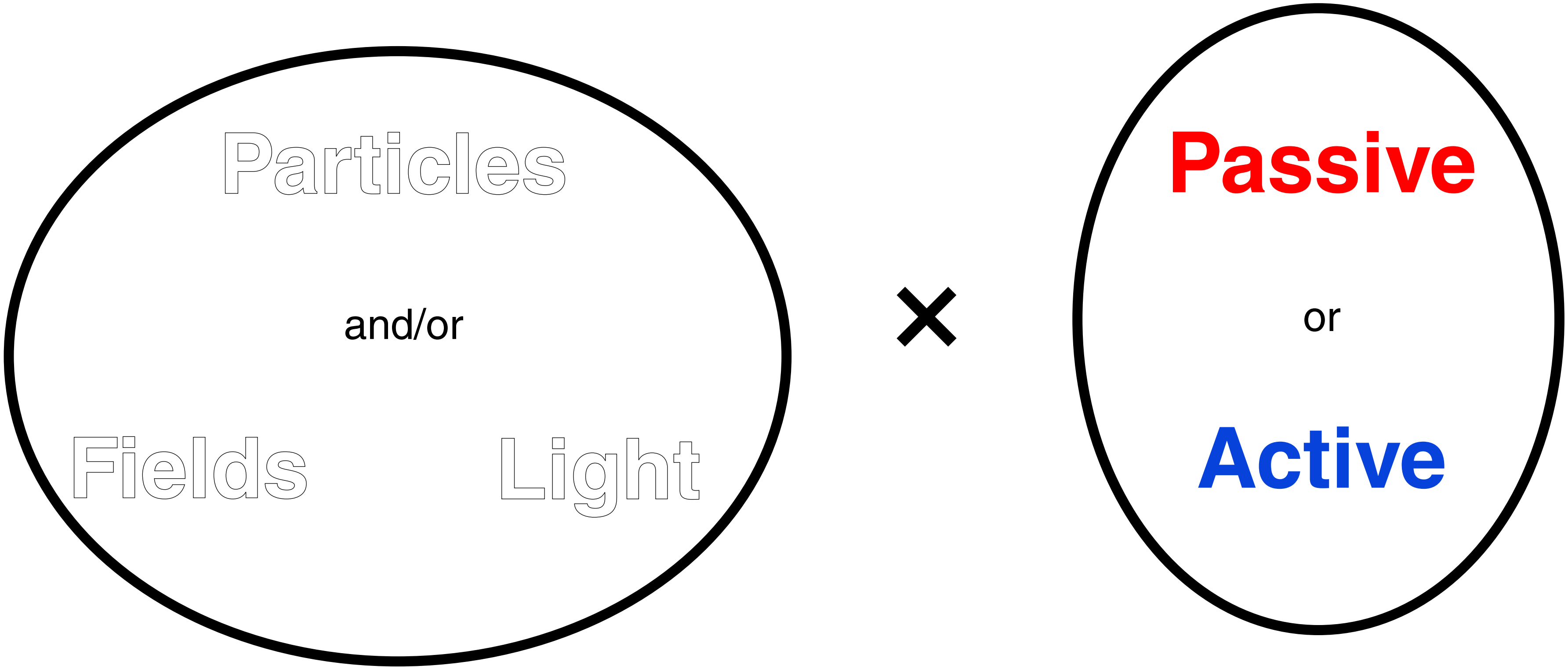
Densiti

…

n be
model

Don't forget:
"Interpretation" involves assumptions!

What are our options?



Passive diagnostics:
use whatever comes out of the plasma

No effect on plasma behavior 😃

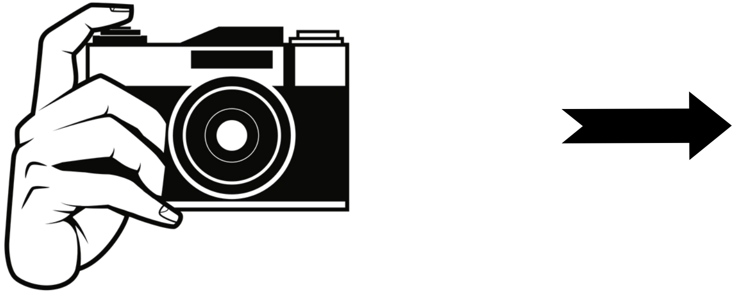
Simpler 😃 (but rarely simple)

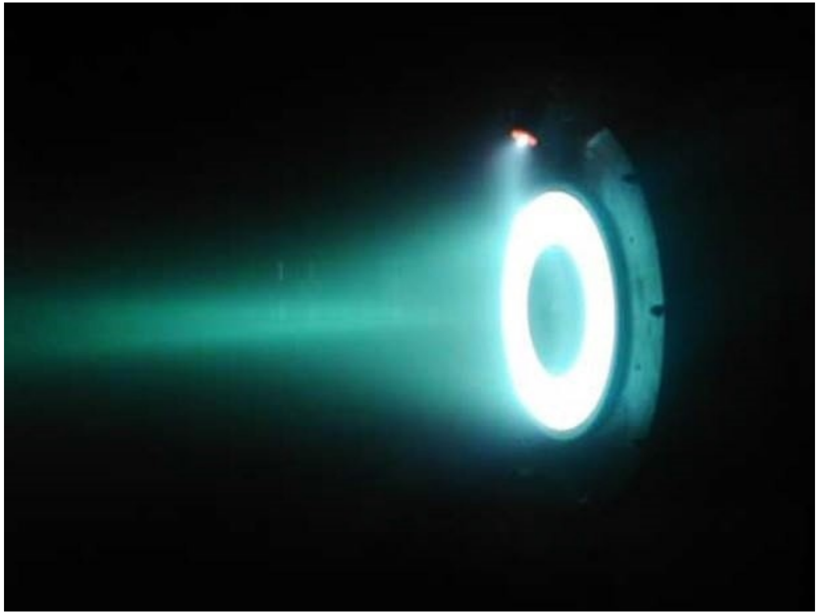
Options are limited →

potentially, less information is accessible 😟

Passive

You are already equipped to make a passive measurement

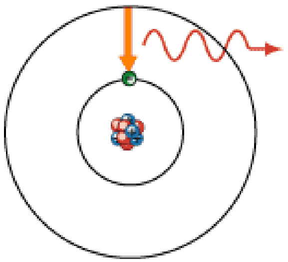




2.0 kW thruster
PPPL Hall Thruster Experiment

You are already equipped to make a passive measurement

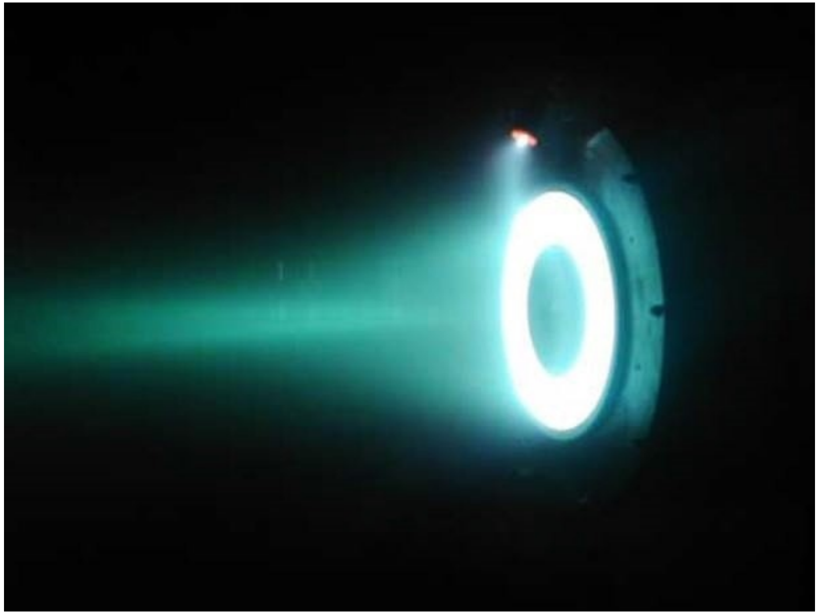
Visible light emission comes from bound-bound atomic transitions



More excited ions → more light

So, brighter spots have higher

- Atom / ion density
- Collisionality with plasma electrons



2.0 kW thruster
PPPL Hall Thruster Experiment

Mileage of photography varies depending on plasma conditions

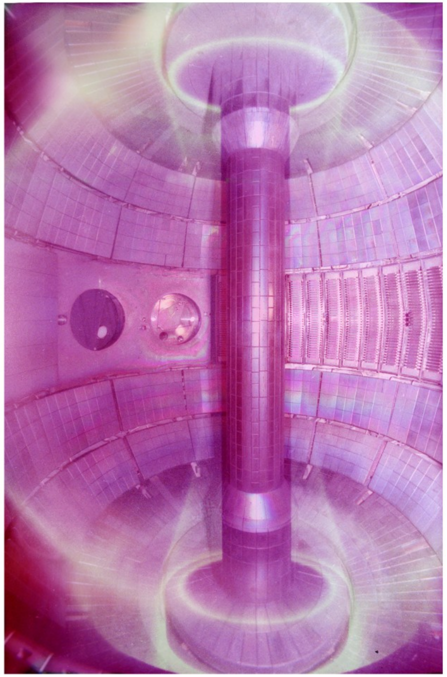


Photo of NSTX-U (UCLA)

Camera integrates over ≲ 1 ms
with great spatial resolution
and spectral resolution within λ ~ 400 – 700 nm
~ 1.5 – 3 eV !

$$E_{photon} = h\nu = \frac{hc}{\lambda} \approx T_e$$

In a tokamak, edge plasma has low T_e with some visible emission…

But the all-important core is invisible!

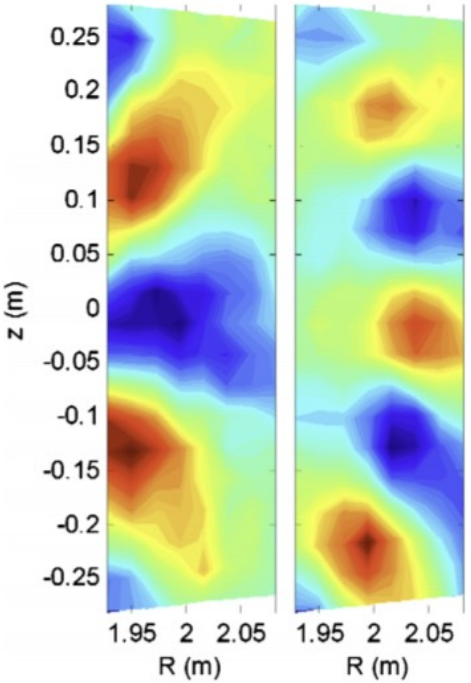
Varying the detected wavelength yields very different information

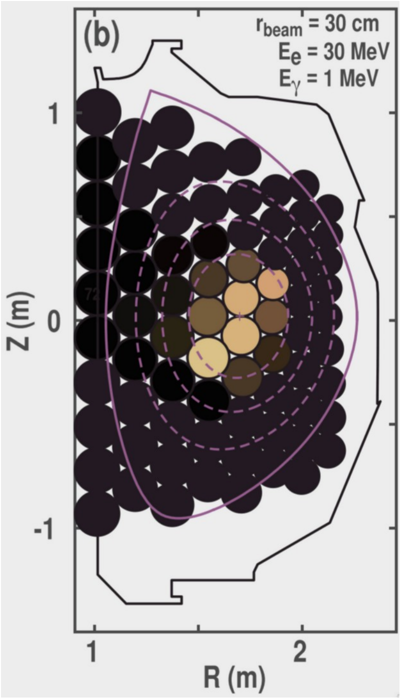
Electron cyclotron emission imaging at DIII-D
(Tobias 2010)

$$\nu = \frac{eB}{2\pi m_e}$$

Near B = 2 T,
E_{photon} < 1 meV

Can measure 0.1% fluctuations in T_e





Gamma Ray Imager
In progress at DIII-D
(C. Paz-Soldan 2018)

Synthetic image, showing array of gamma measurements

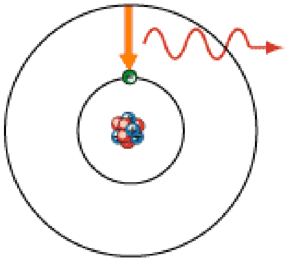
E_{photon} ~ 1 – 30 MeV

→ Info on runaway electrons

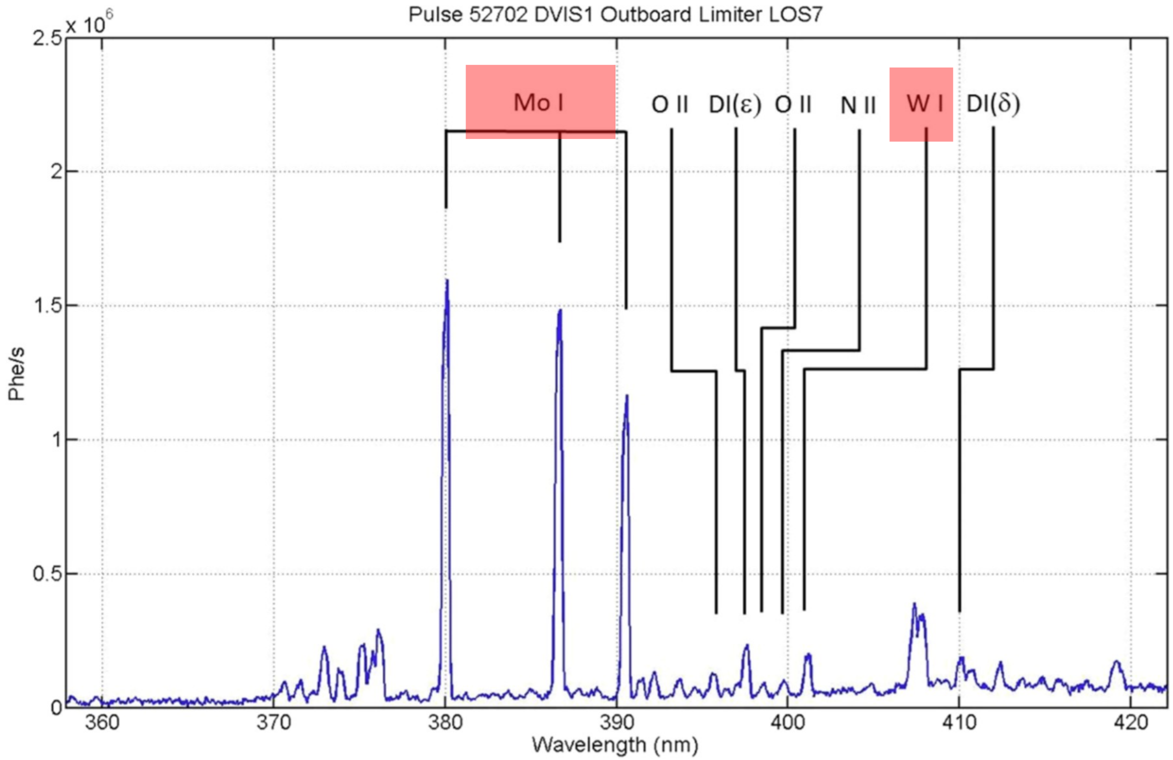
Passive + Light

Fine resolution in λ = spectroscopy

Each element has transitions at precise but unique energies!



Obvious application: detect where and which impurities are present



Near-visible spectroscopy at WEST tokamak (Meyer 2018)

Fine resolution in λ = spectroscopy

Each eler
precise

Obvi
detect
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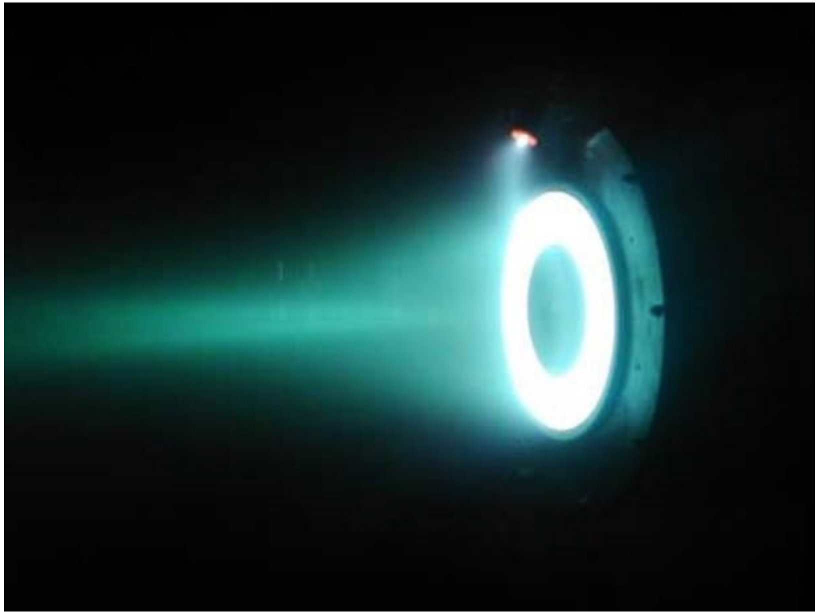
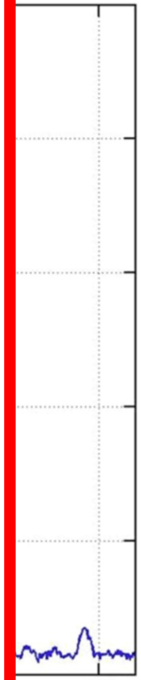


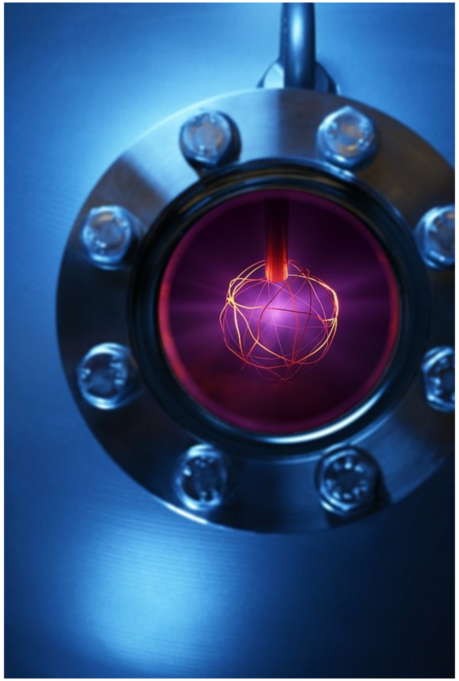
2.0 kW thruster
PPPL Hall Thruster Experiment

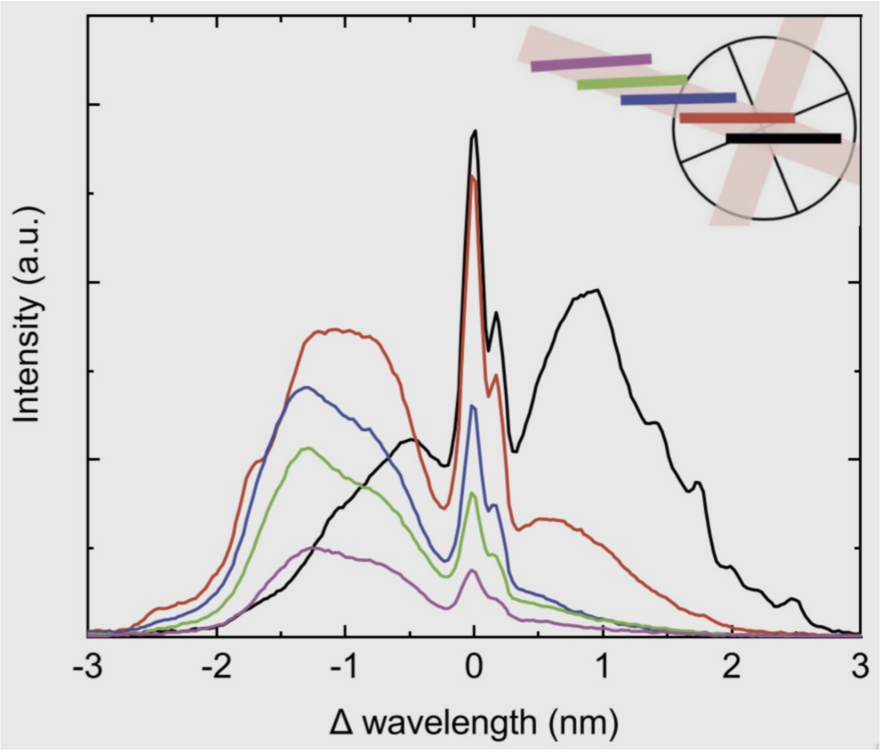
Same idea: the colors in this photo can identify which gas is used in the thruster



Near-visible spectroscopy at WEST tokamak
(Meyer 2018)

Line emission carries a lot more information about plasma behavior





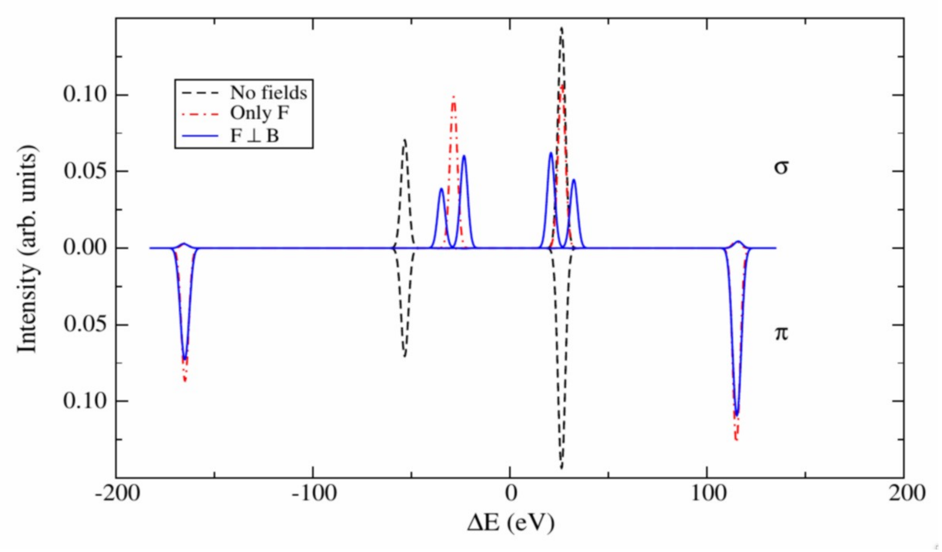
Farnsworth fusor at Eindhoven Inst. Tech.
(Hermens 2019)

Lines **Doppler shift** when plasma flows

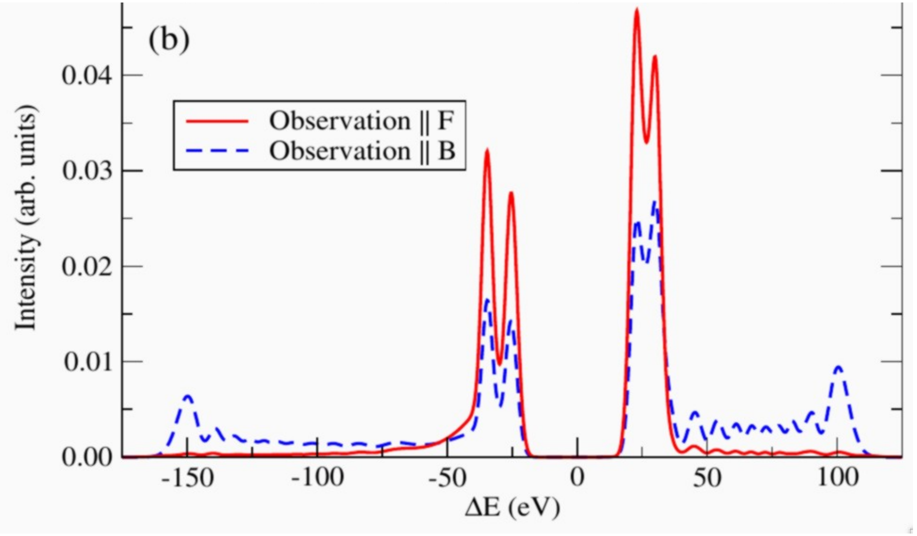
Shifts in D emission imply flows in fusor

(D Balmer-α line, 656.29 nm)

Polarization of light opens other doors



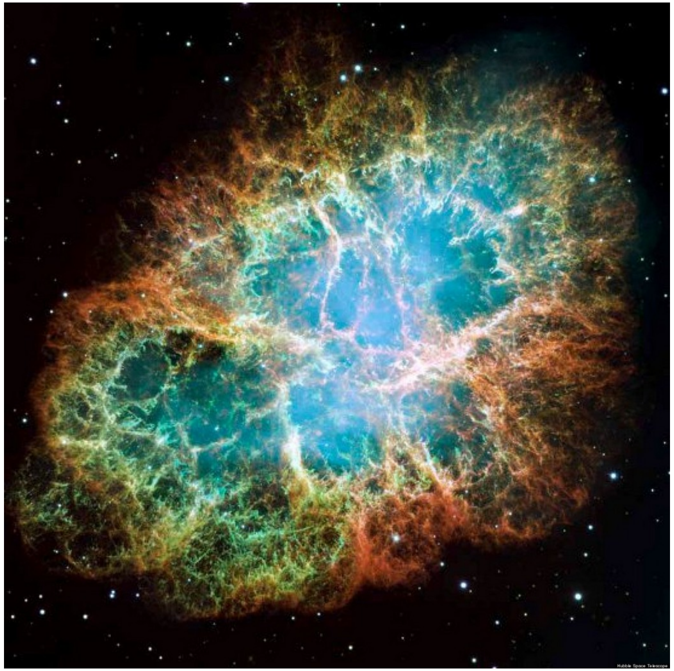
X-rays from H-like Kr are polarized by strong laser fields



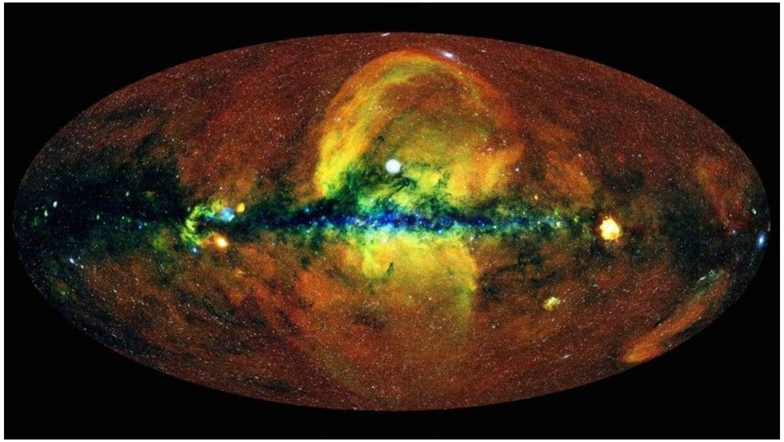
Spectra look very different depending on orientation of laser fields

Theoretical method for measuring laser intensities with x-ray lines (Stambulchik 2014)

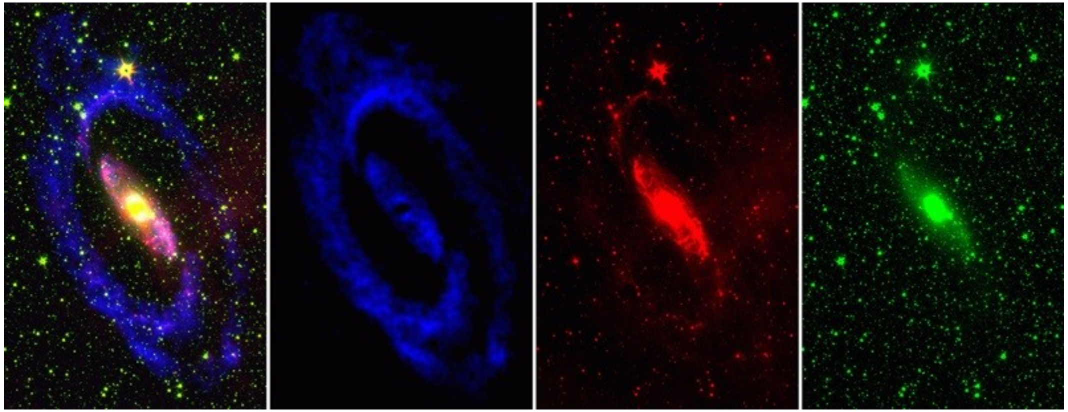
For astronomers, the lecture ends here!



Crab Nebula in the optical
via the Hubble Space Telescope



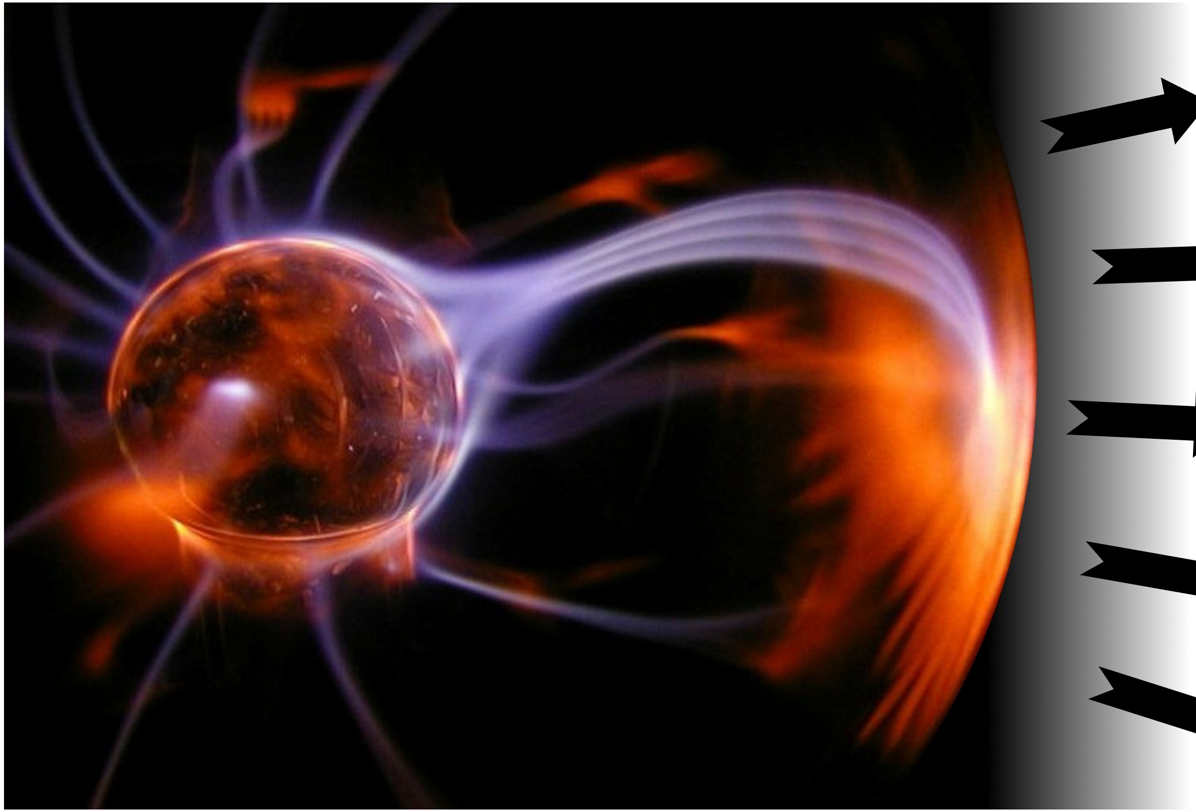
Our view of the universe, in x-rays via eROSITA



The Circinus galaxy in radio and infrared
(For et al. 2012)

Passive + Light... that's all!

Here on Earth, we can observe particles ejected from the plasma



Neutrons

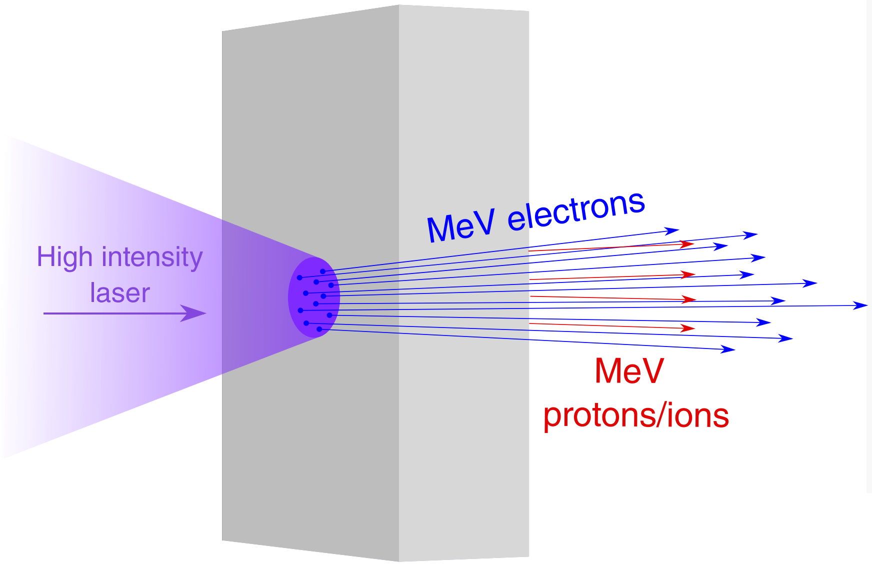
Electrons

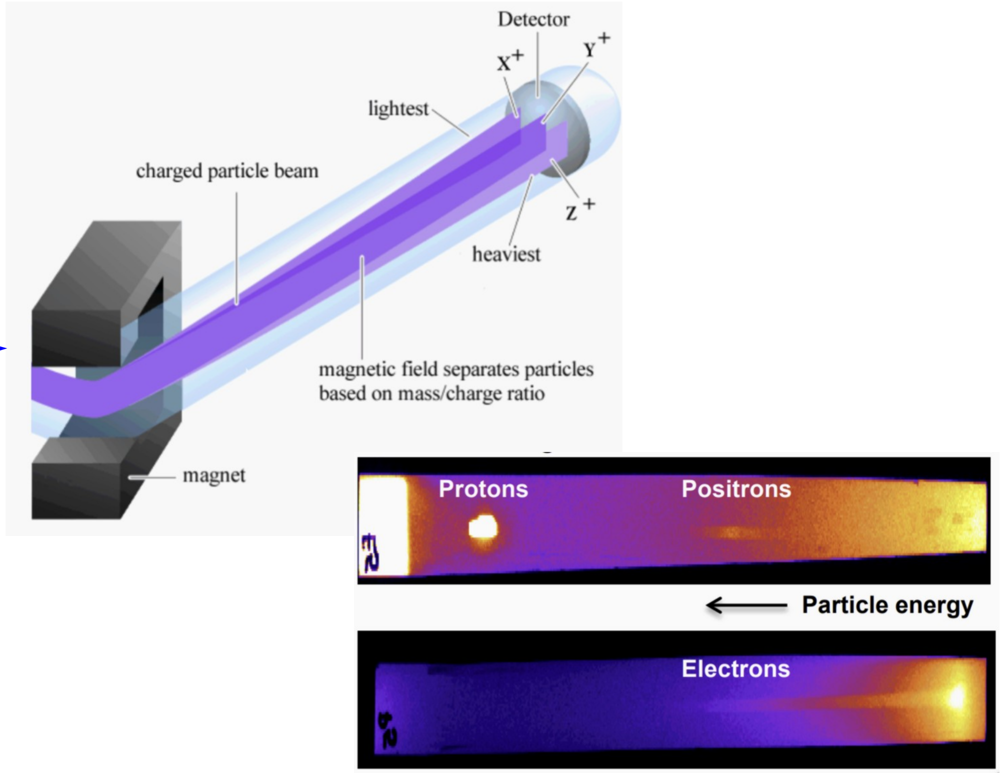
Ions (main or impurities)

Dust / clusters / molecules

Positrons

Many particles are naturally ejected from high-energy-density experiments

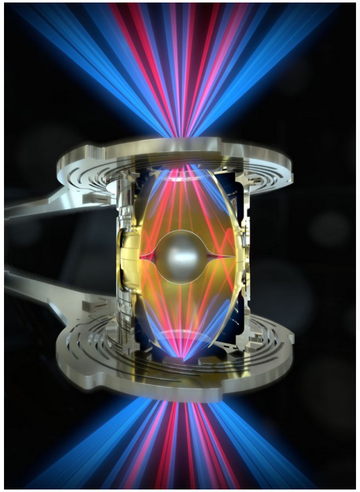


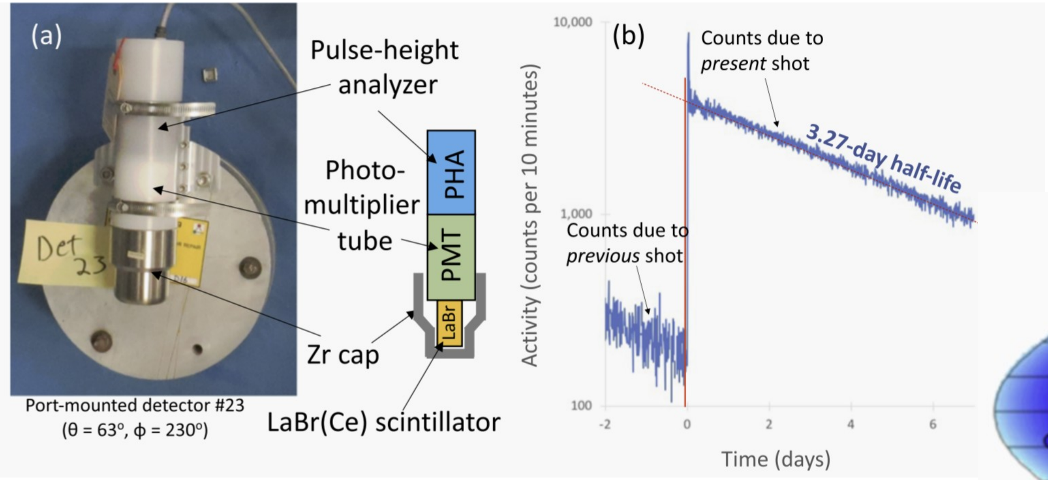


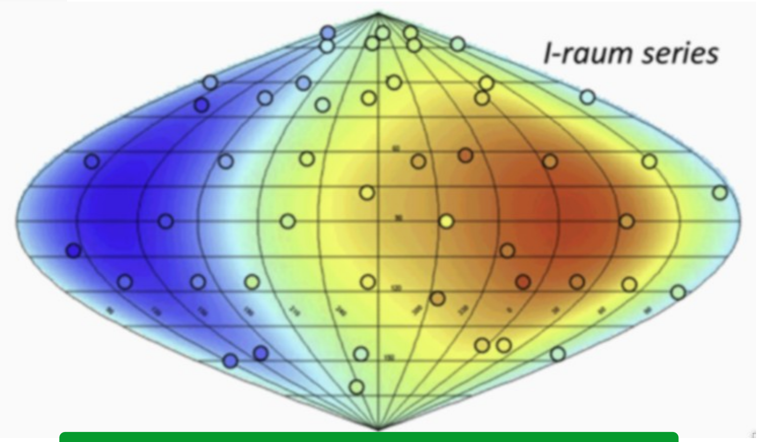
H. Chen
Presentation to NIF/JLF User Group Meeting 2016

Fusion creates unconfined, relativistic neutrons, here used to study NIF shell

Inertial confinement fusion on NIF





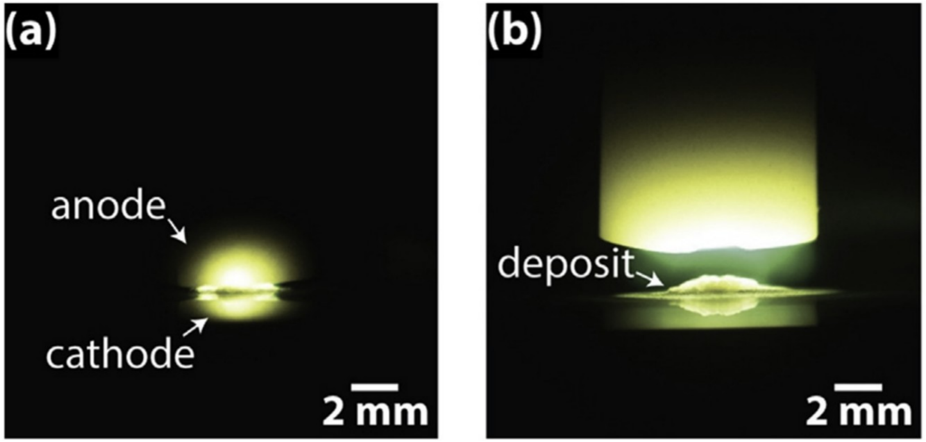


Many detectors around chamber are irradiated by >12 MeV neutrons (all scattered neutrons are lower energy)

Resulting asymmetries show where capsule shell was thickest

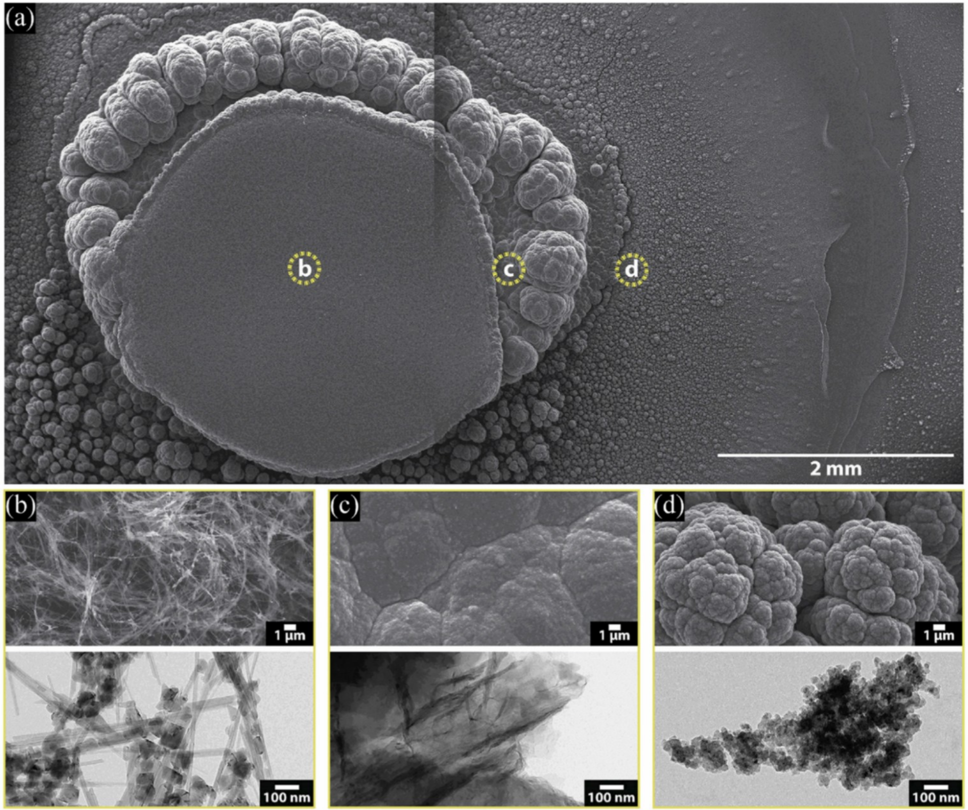
RT-NAD array at NIF (Hahn et al. 2021)

Some low-temperature plasmas generate nanoparticles to image post-discharge



High-voltage carbon arc discharge
Directed by Y. Raitses, PPPL

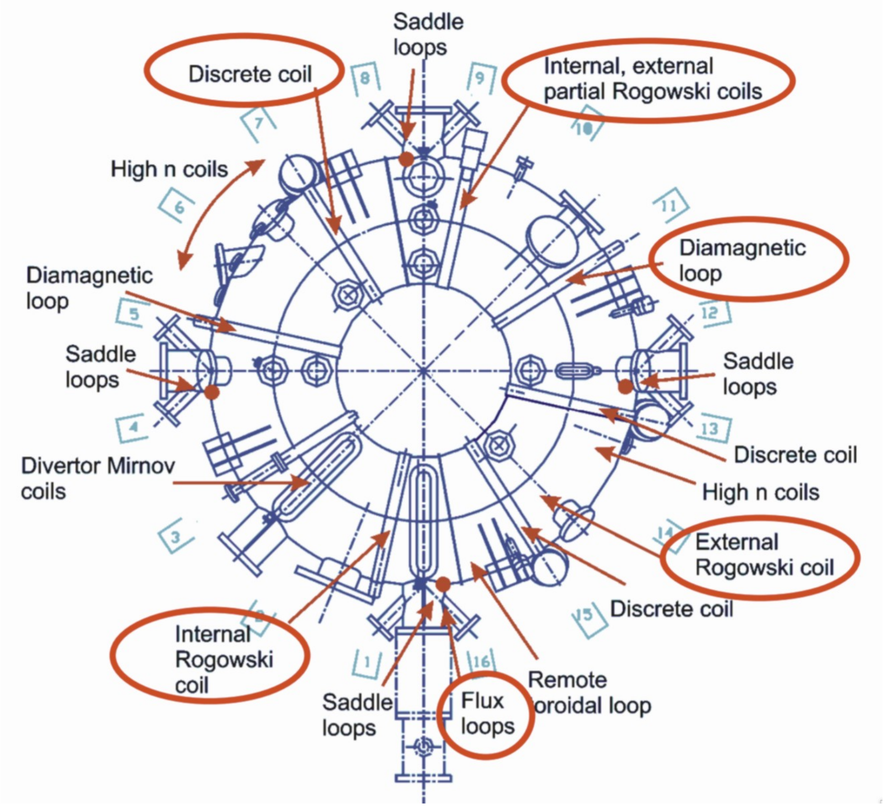
→ creates diversity of carbon nanostructures related to local plasma conditions



(Y. W. Yeh et al. 2016)

Passive + Particles

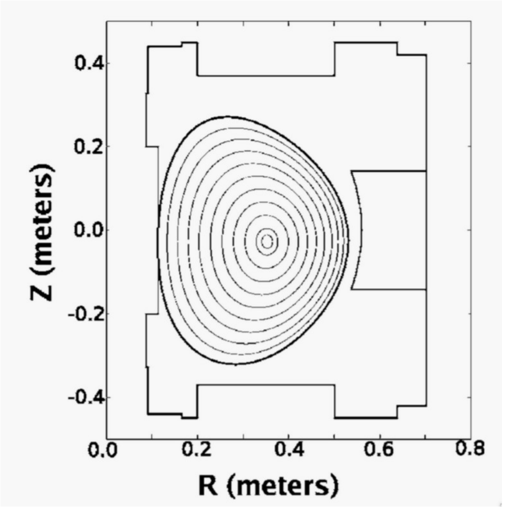
Plasma-induced field effects can be detected remotely



Compass tokamak (Havlicek et al. 2010)

An amazing number of magnetic sensors surround most tokamaks

Combined, their signals map plasma current and flux surfaces

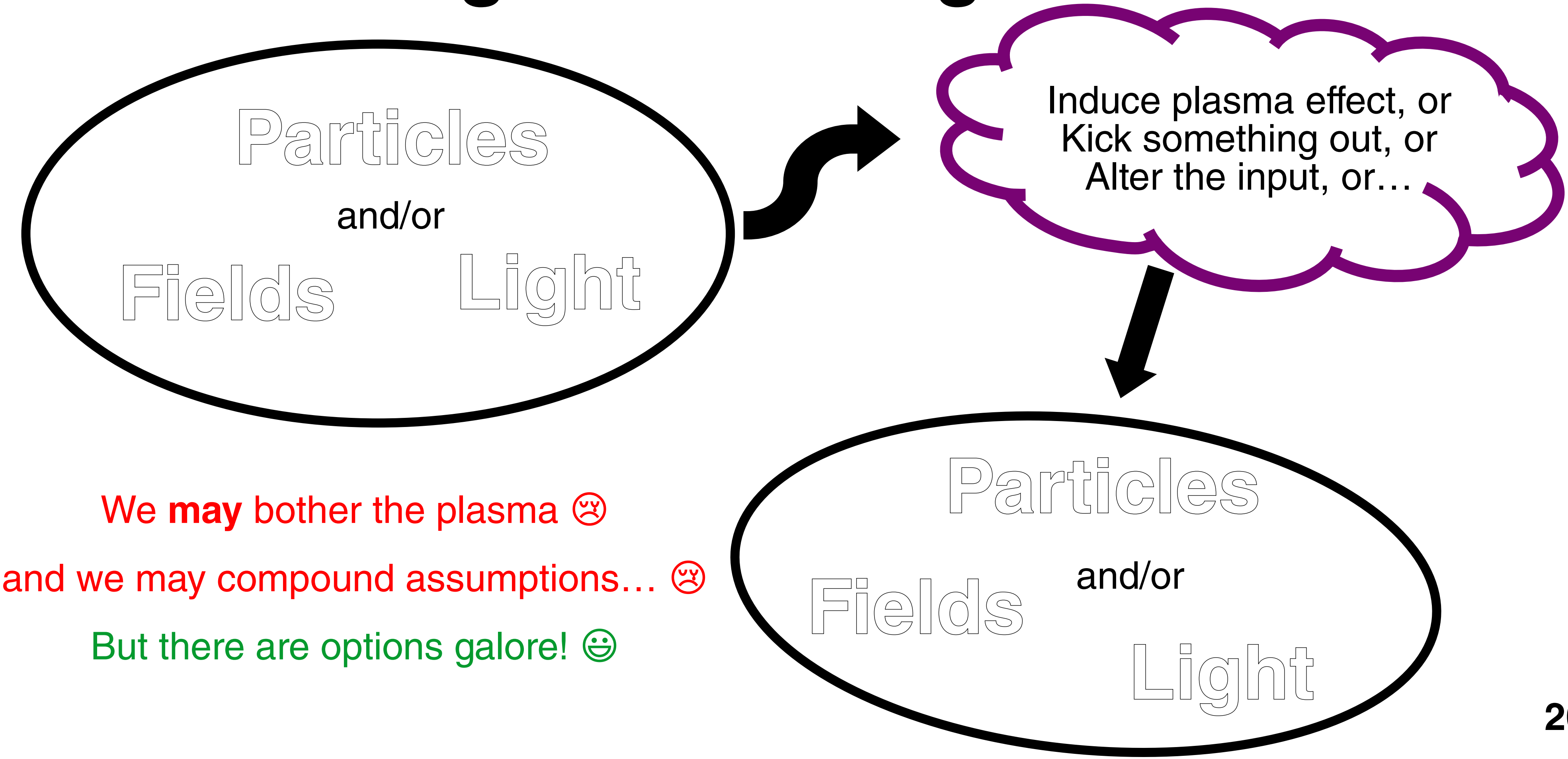


CDX-U tokamak, formerly at PPPL

(Spaleta et al. 2006)

Passive + Fields

Active diagnostics: send something in, get something out

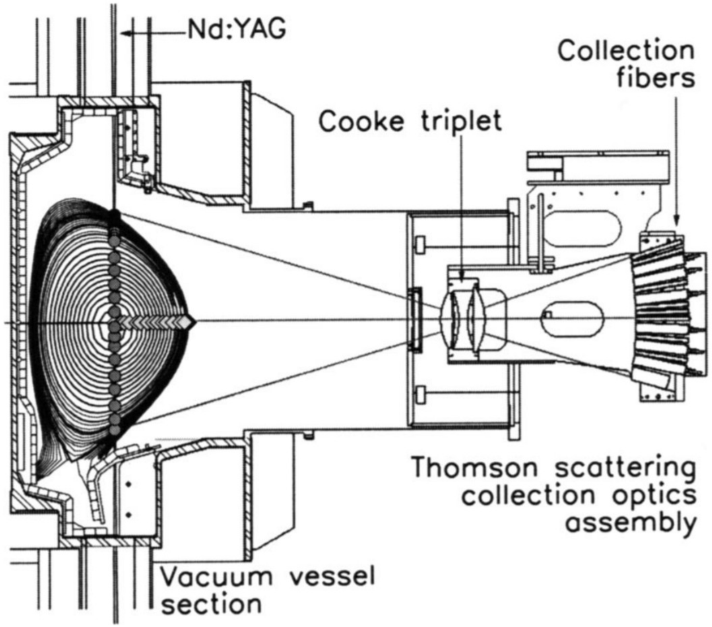


We **may** bother the plasma ☹

and we may compound assumptions… ☹

But there are options galore! ☺

Most obvious: bounce light off of plasma particles



Alcator C-Mod Thomson scattering system
(Hughes 2003)

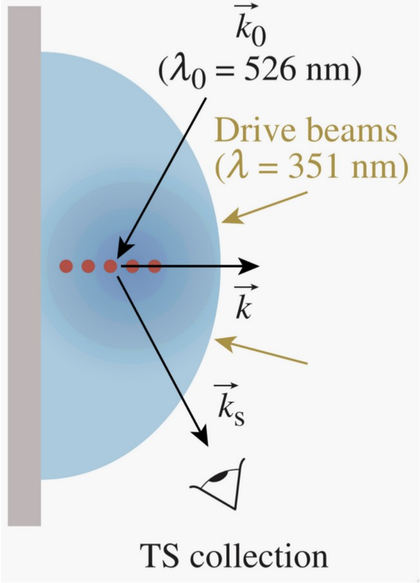
1. Send a laser through the plasma
2. A few photons collide with free electrons
3. A few Thomson scattered photons enter collection optics

# of photons ~ electron density

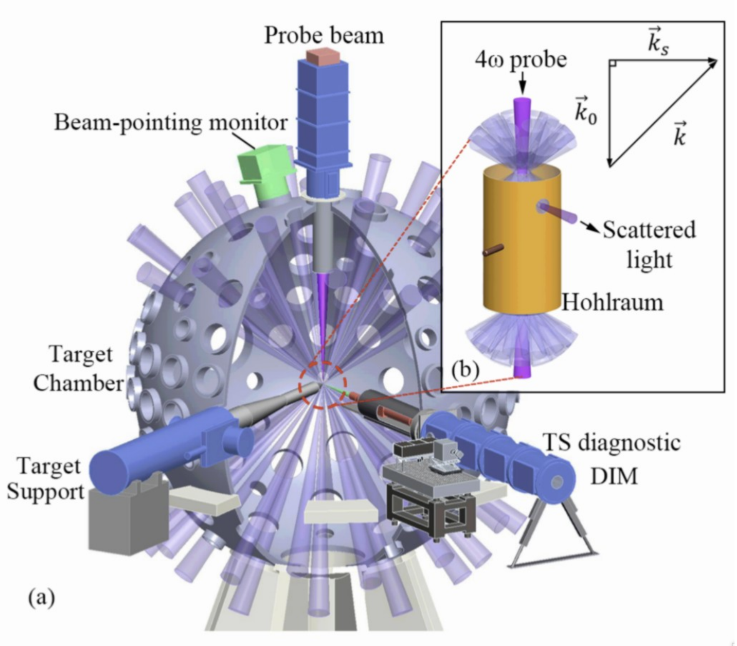
Photon energy spread ~ electron temperature

Laser × Viewing Chord = Spatial Resolution

And if plasma is too dense for laser light? Use higher-energy photons



Thomson scattering at the OMEGA laser (Henchen 2018)



Implementing 4ω beam (Zhao 2018)

Harmonic	λ [nm]	Max n_e [cm^{-3}]
ω	1052	9×10^{20}
2ω	526	3.6×10^{21}
3ω	350	8×10^{21}
4ω	263	1.4×10^{22}
5ω	210	2.2×10^{22}

Active + Light ⇒ Light

Even light that can’t propagate through plasma can tell you something

Waves reflect off the plasma surface where

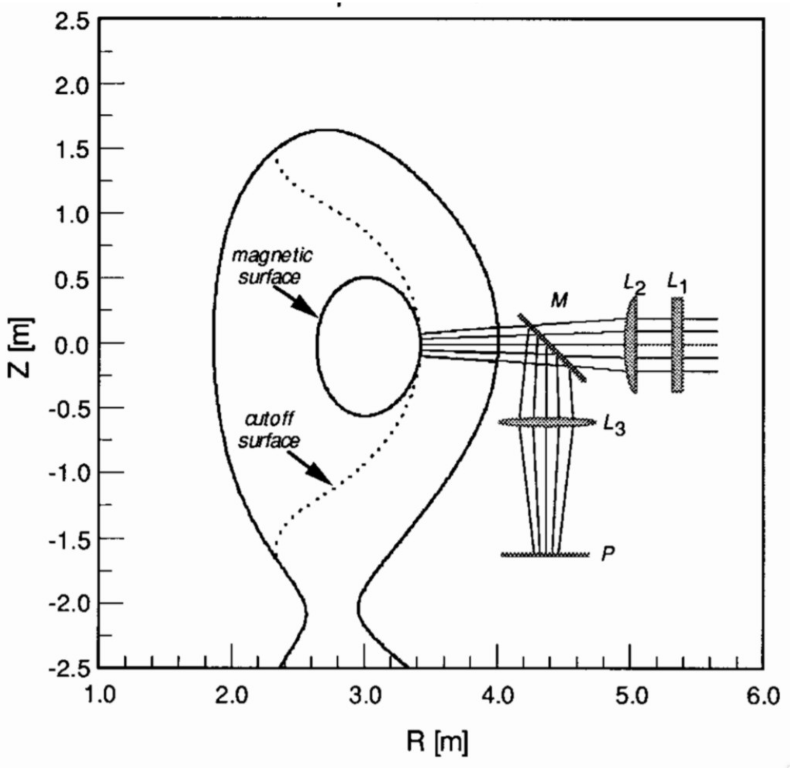
$$\omega_{photon} = \omega_p(n_e)$$

Magnetic fusion plasmas have $\omega_p \sim$ GHz, similar to microwaves

As microwaves approach cutoff, the plasma greatly modifies their phase φ:

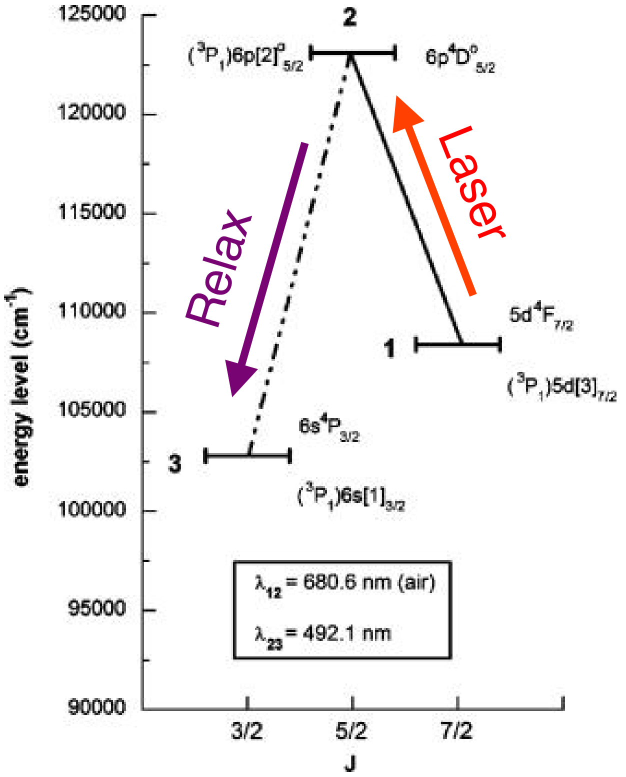
$n_e(x)$ related to $d\varphi/d\omega_{photon}$

Microwave reflectometry measures density profiles & turbulent fluctuations

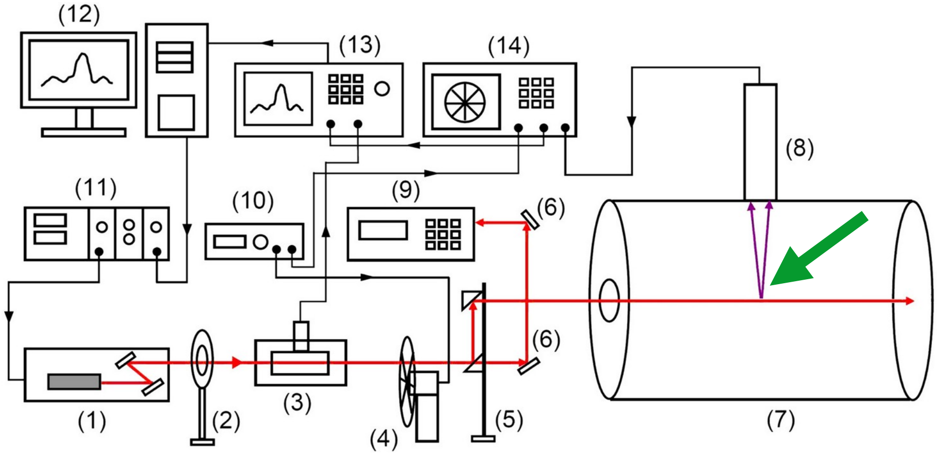


Microwave reflectometry (Mazzucato 1998)

Laser light can spark atomic transitions in specific locations only



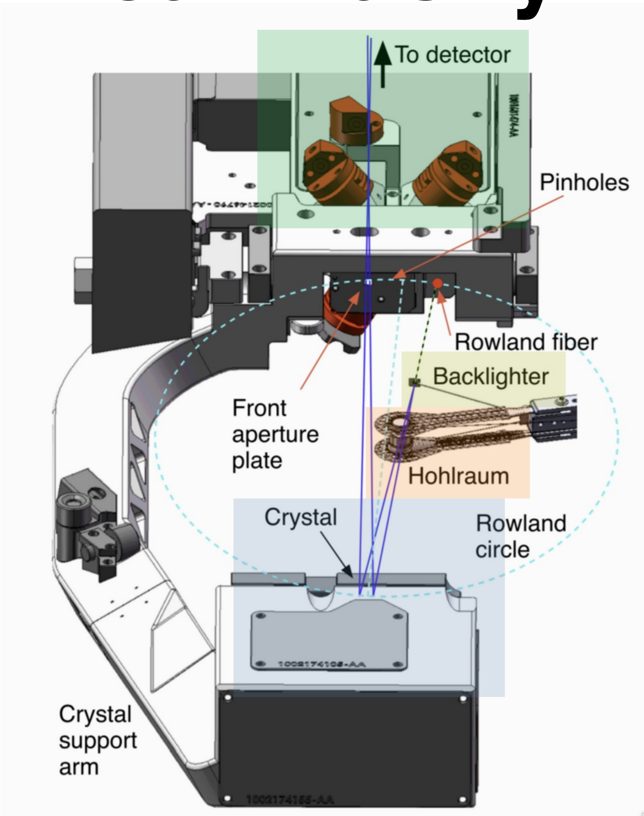
1. Pick an atomic state to excite with a tunable laser
2. Ions/neutrals absorb laser if it resonates *in their frame*
3. View a second transition emitted **from one place**
4. **Get a local velocity distribution of neutrals or ions!**



Laser-induced fluorescence
(Severn 2007)

Active + Light ⇒ Light

Backlighting with a single wavelength can vastly improve signal-to-noise

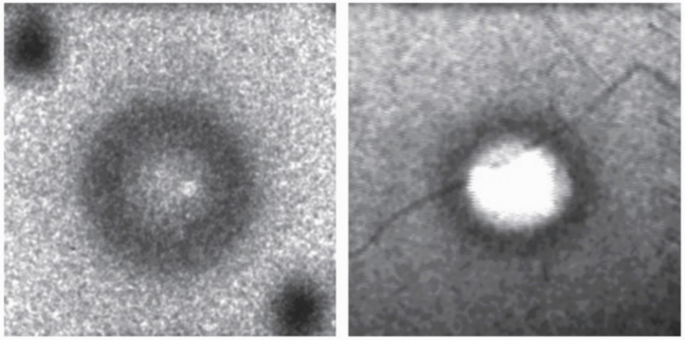


Heat backlighter → generate Se line emission

Se passes through ICF experiment

Crystal imager only diffracts Se line

→ Absorption image of implosion!



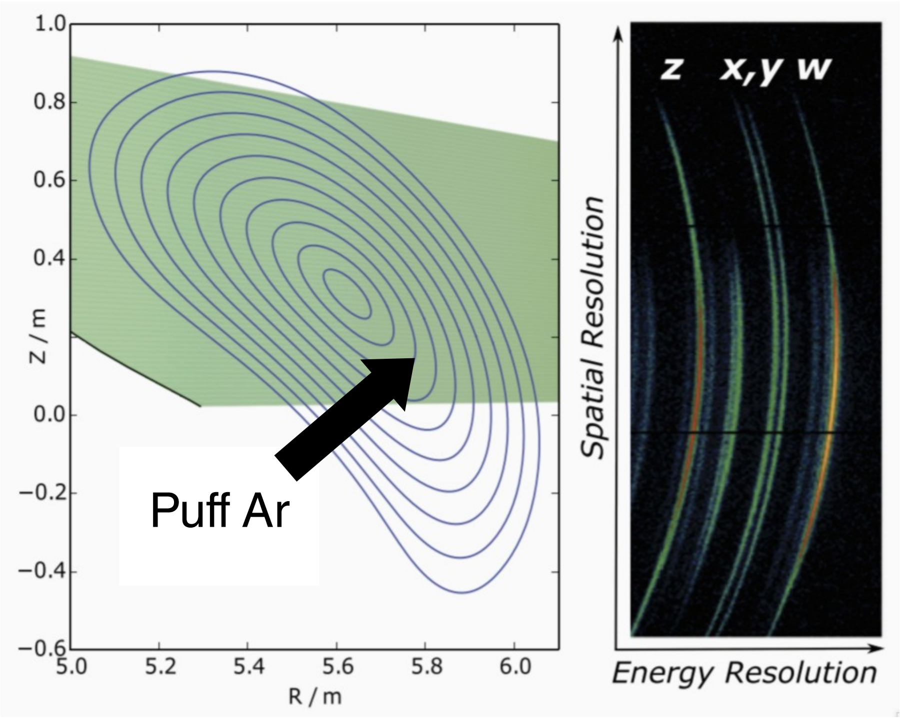
Se x-rays only

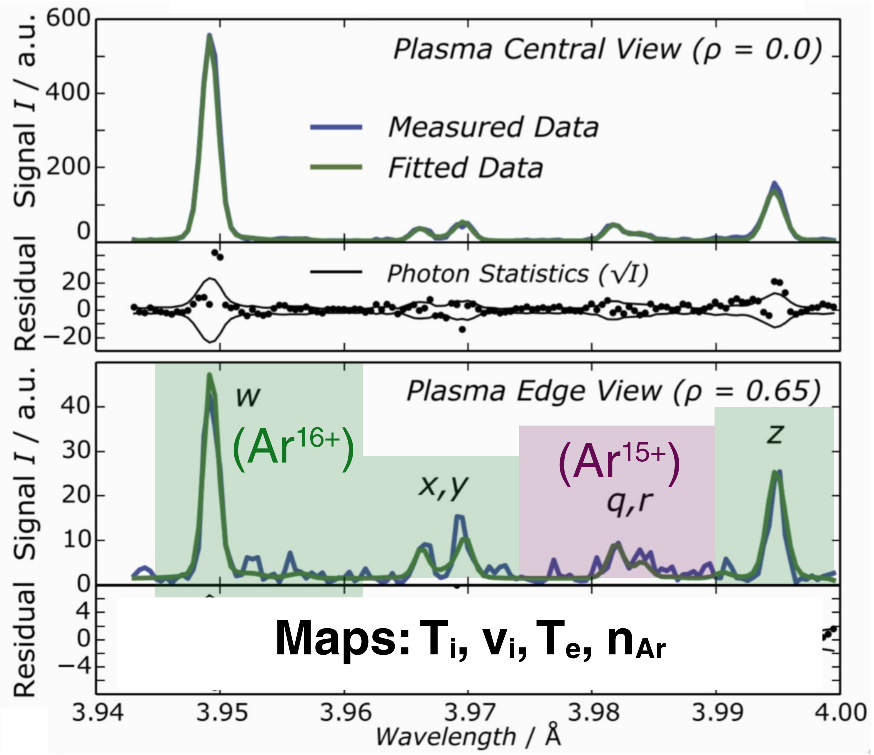
Broadband x-rays

Crystal Backlighter Imager at the National Ignition Facility (Hall 2019)

Active + Light ⇒ Light

Dope plasma with “tracer” material → get detectable emission lines

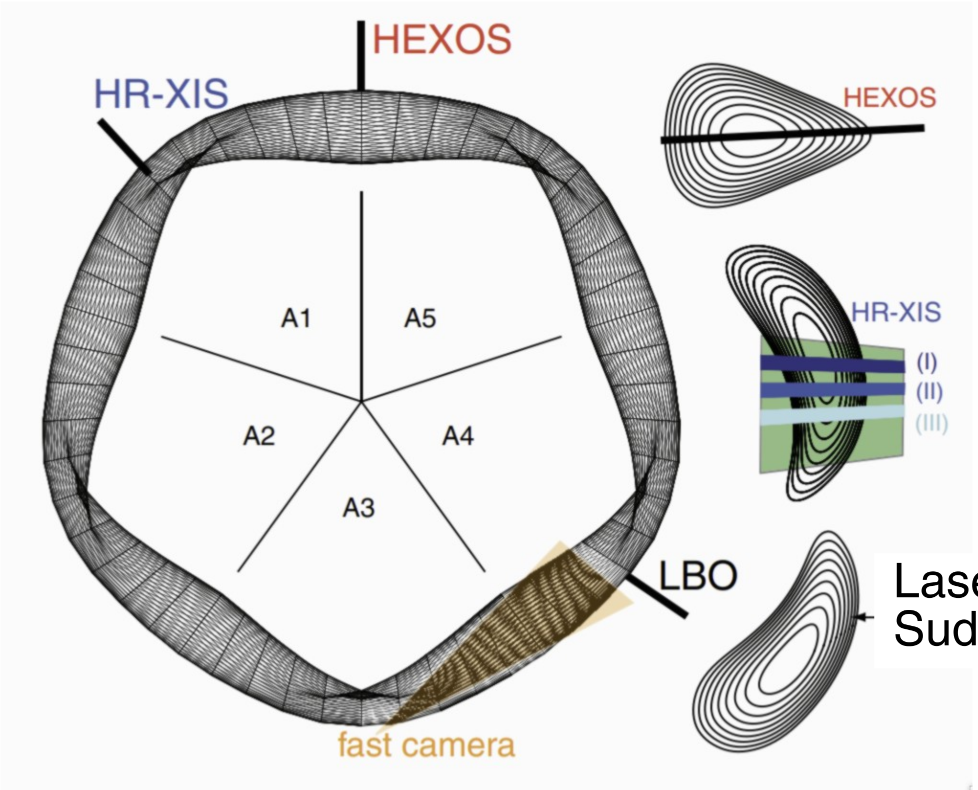


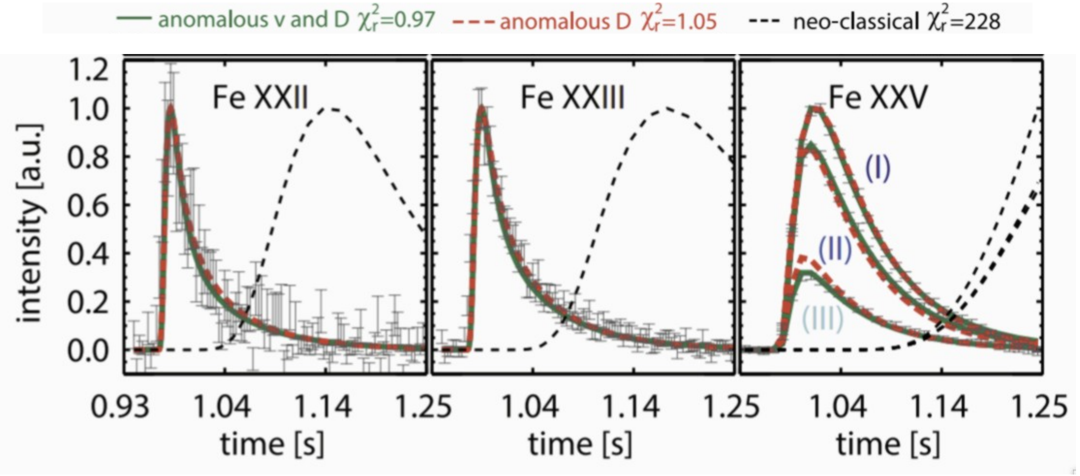


Maps: T_i, v_i, T_e, n_{Ar}

X-ray spectroscopy with Ar^{16+} at W7-X
(Langenberg 2017)

Careful introduction of tracer material allows transport studies

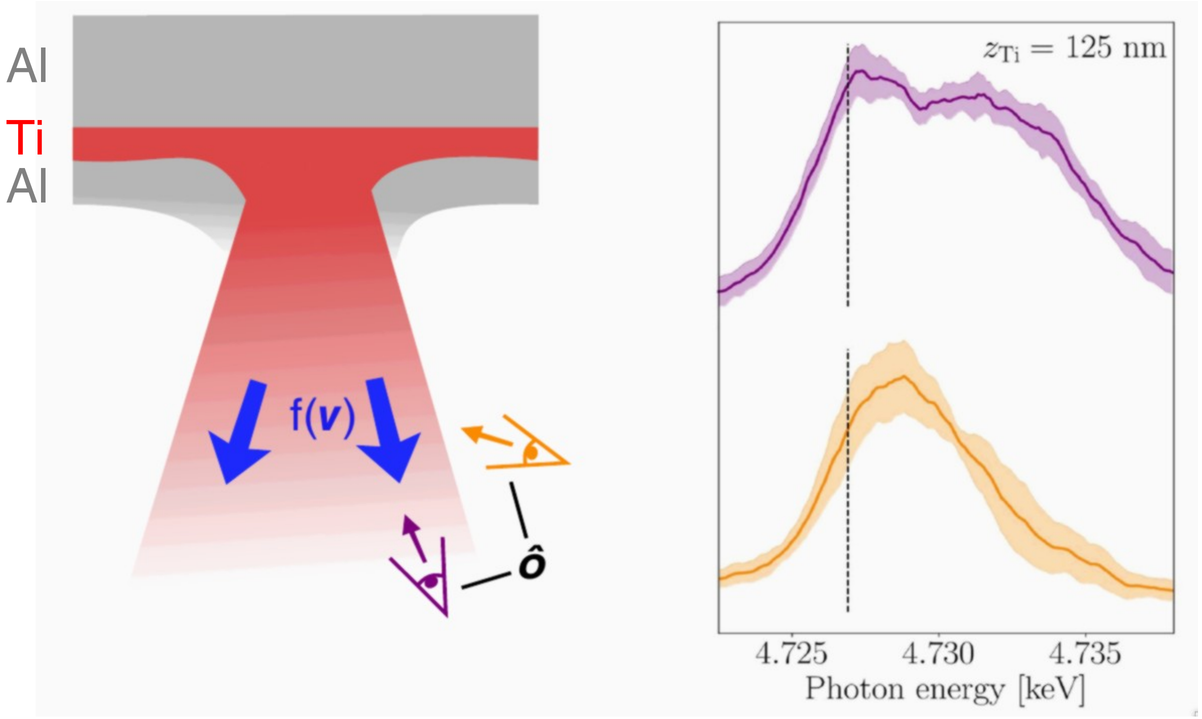




Laser Blow-Off = Sudden Fe injection → Track motion of Fe around W7-X

UV and x-ray spectroscopy of Fe at W7-X (Geiger 2019)

X-rays from tracer material are able to escape high-density plasmas



Spectrometers only see x-rays from Ti layer

High-resolution x-rays are Doppler shifted

View from two directions → get velocity distribution

Solid-density plasma experiments at ALEPH laser (Kraus 2021)

Active + Particles → Light

What if dense material is not hot enough to produce x-rays? Use fluorescence

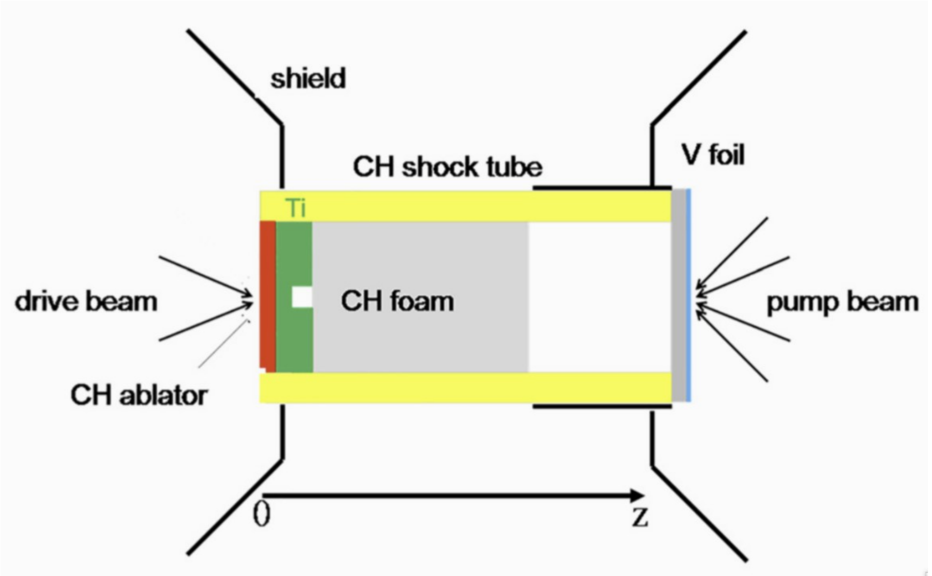
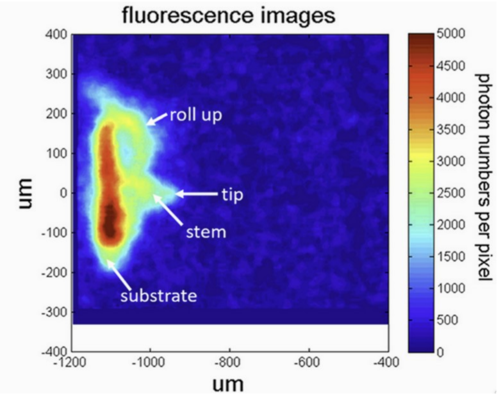


Image specific locations
exactly at time of pump beam!

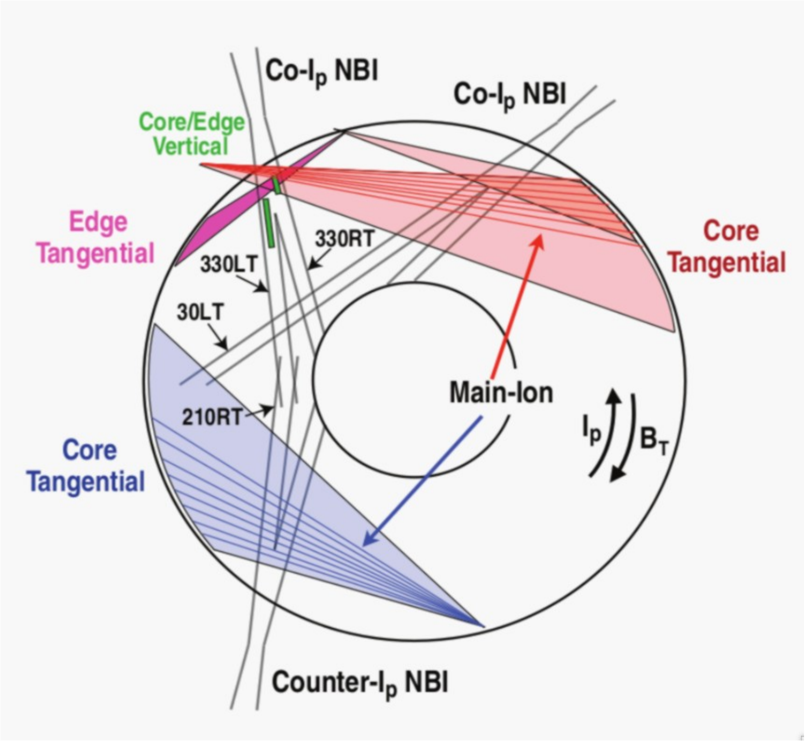
Build in **high-energy x-ray source**
V^{21+} emits ~5 keV x-rays

These excite lower-energy x-rays in material of interest
Cold Ti **fluoresces** at 4.5 keV

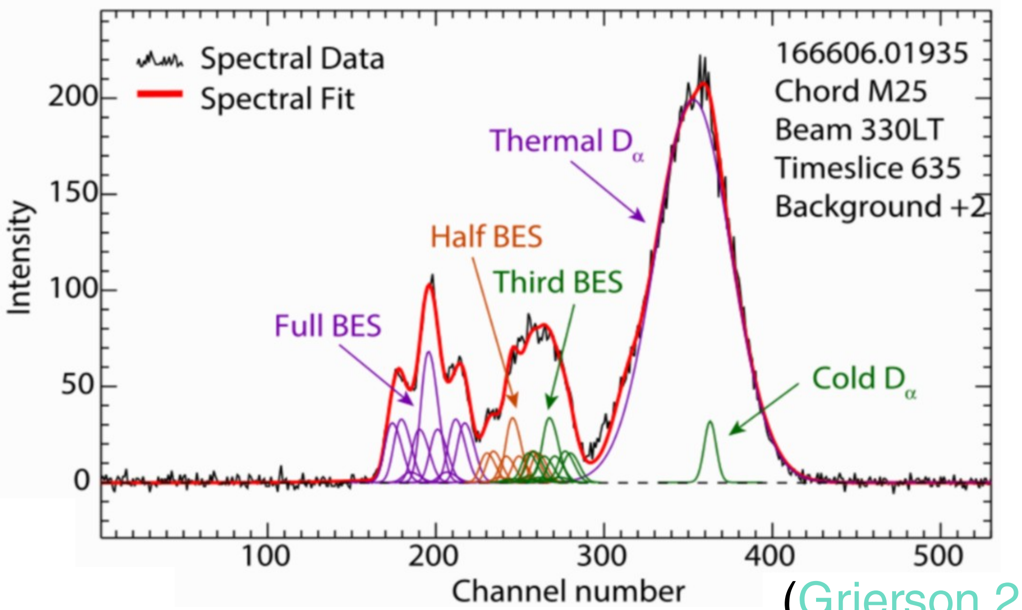


Shock experiments at SG-III laser
(Pu 2019)

Particle injection can also drive specific + traceable line emission



D^+ doesn't have bound electrons to radiate until charge exchange with beam neutrals!

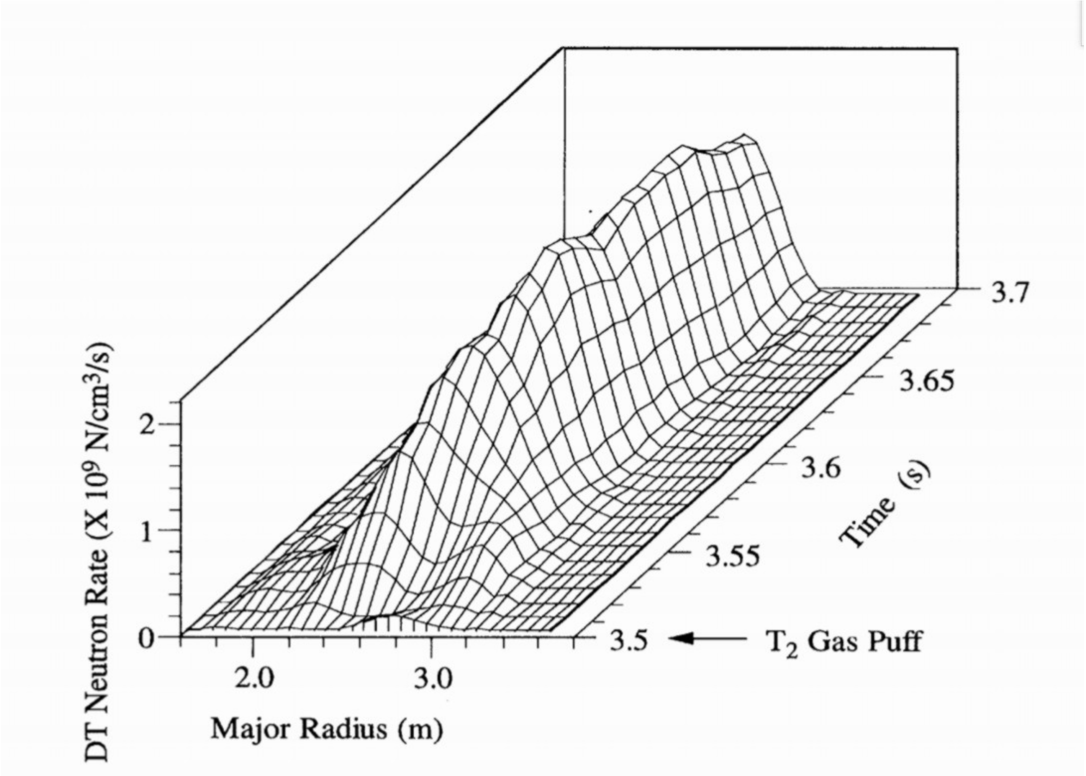


(Grierson 2016)

Dissect D_α spectrum → T_i, v_i of *main ions* localized to beam-sightline intersection!

Active + Particles ⇒ Light

How about sending in particles to fuse? Learn from resulting neutrons



Puff T_2 gas into D^+ plasma

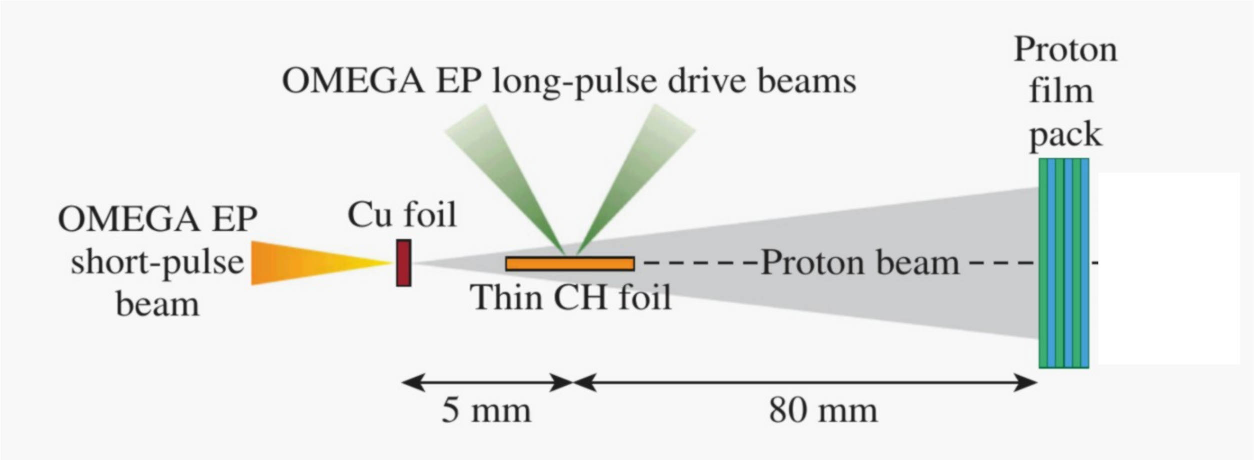
Fusion is dramatically enhanced when T^+ ions reach a location

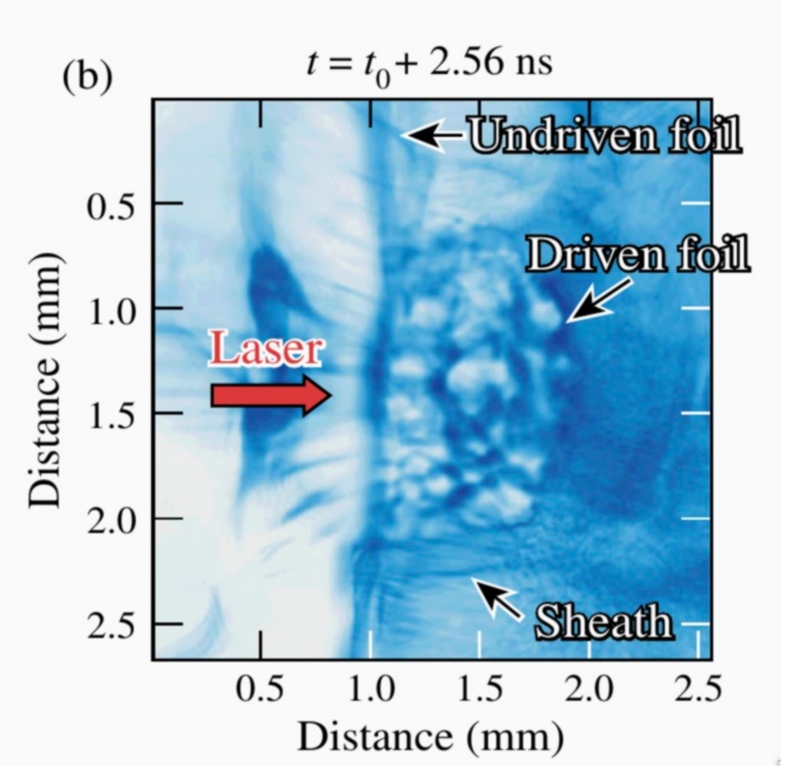
Neutrons escape and are "imaged" in directionally specific detectors

→ Validate transport models of *fusion particles themselves*

(Efthimion 1995)

Send particles through plasma → study all kinds of deflections





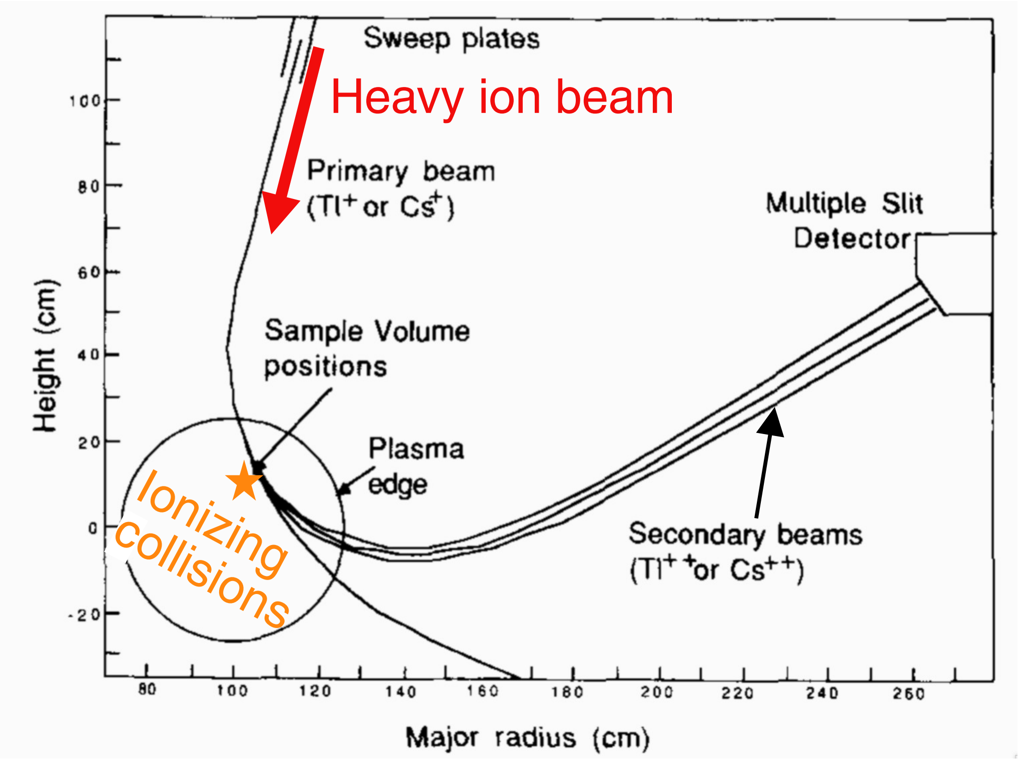
Proton radiography: one laser drives proton source, others drive plasma of interest

Protons pass through and map out **E** and **B** fields

Active + Particles → Particles

(Gao 2012)

Planning for known particle deflection can be an integral part of the diagnostic



Heavy ion beam probe
(Crowley 1994)

Detector captures heavy ions that were re-ionized in a known location

Energy is conserved:

Ionized electron "falls" into plasma potential φ_p, losing potential energy

The heavy ion gains an identical amount of energy

Energy of the detected heavy ion is *directly related to* φ_p

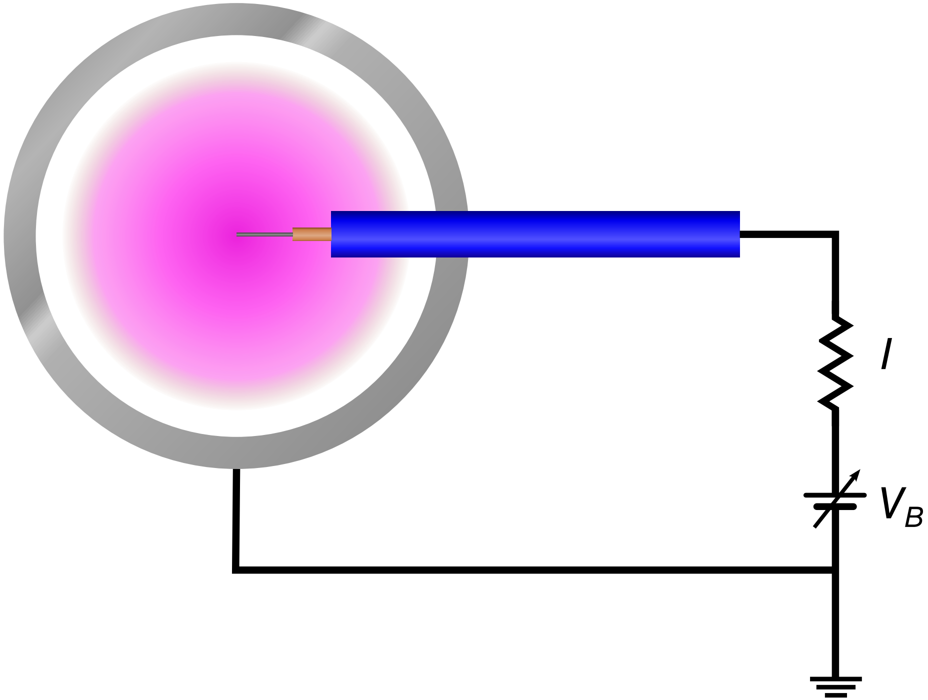
What about fields? Probes are a primary way to get through Debye shielding

Let probe **float** at whatever voltage brings zero current ($I_e = I_i$) → informs T_e

Bias probe negatively to collect ions → get n_i

Bias probe positively to collect electrons → get n_e, maybe melt probe

Sweep probe about the floating potential: only some electrons hit probe, get **electron energy distribution function**



So, how do you measure a plasma?

1. **Decide what you want to know**
   E.g., fluctuations in n_e

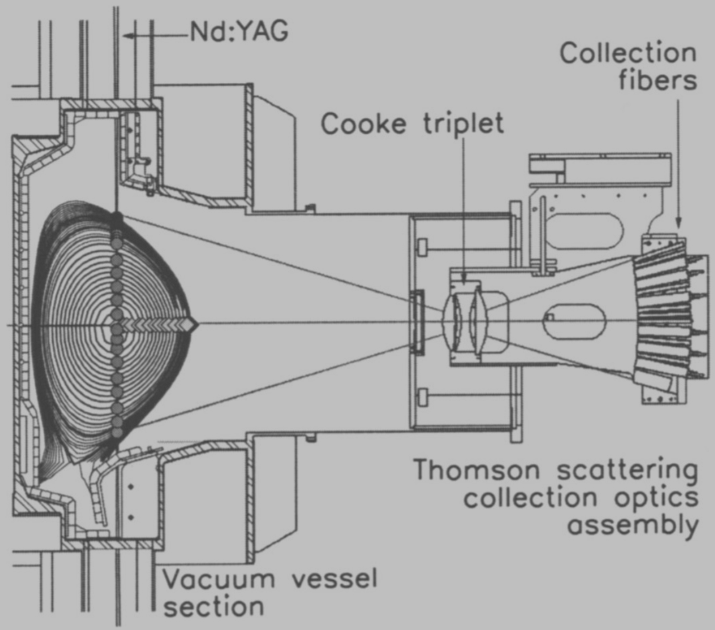
2. **Brainstorm: what does that parameter influence?**
   Local particle flux, brightness, plasma frequency…

3. **How can you obtain related information *in your given plasma*?**
   Probe to collect particles: Will it melt?
   Will it perturb the plasma?
   Camera to collect light: What wavelength will the light be?
   Can that light escape?
   Is emission dependent on n_e only?

   Can either option resolve fluctuations in time? How well?

4. **Pick at least one option, and convince yourself you can account for or neglect all confounding factors**

Most obvious: bounce light off of plasma particles



Alcator C-Mod Thomson scattering system (Hughes 2003)

1. Send a laser through the plasma
2. A few photons collide with free electrons
3. A few Thomson scattered photons enter collection optics

# of photons ~ electron density

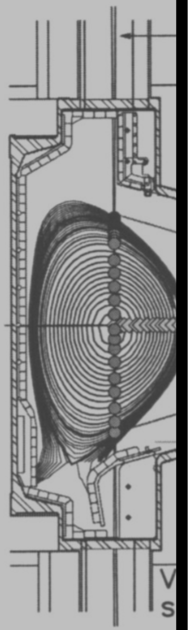
Photon energy spread ~ electron temperature

Laser × Viewing Chord = Spatial Resolution

Most obvious: bounce light off of plasma particles

What might be problematic here?

- Is the laser bright enough to scatter measurable light?
- Do I have to sacrifice time resolution for signal?
- What if we detect light scattered from walls, not electrons?
- How good does spectral resolution need to be to get meaningfully precise T_e?



Alcator C-Mod Thomson scattering system
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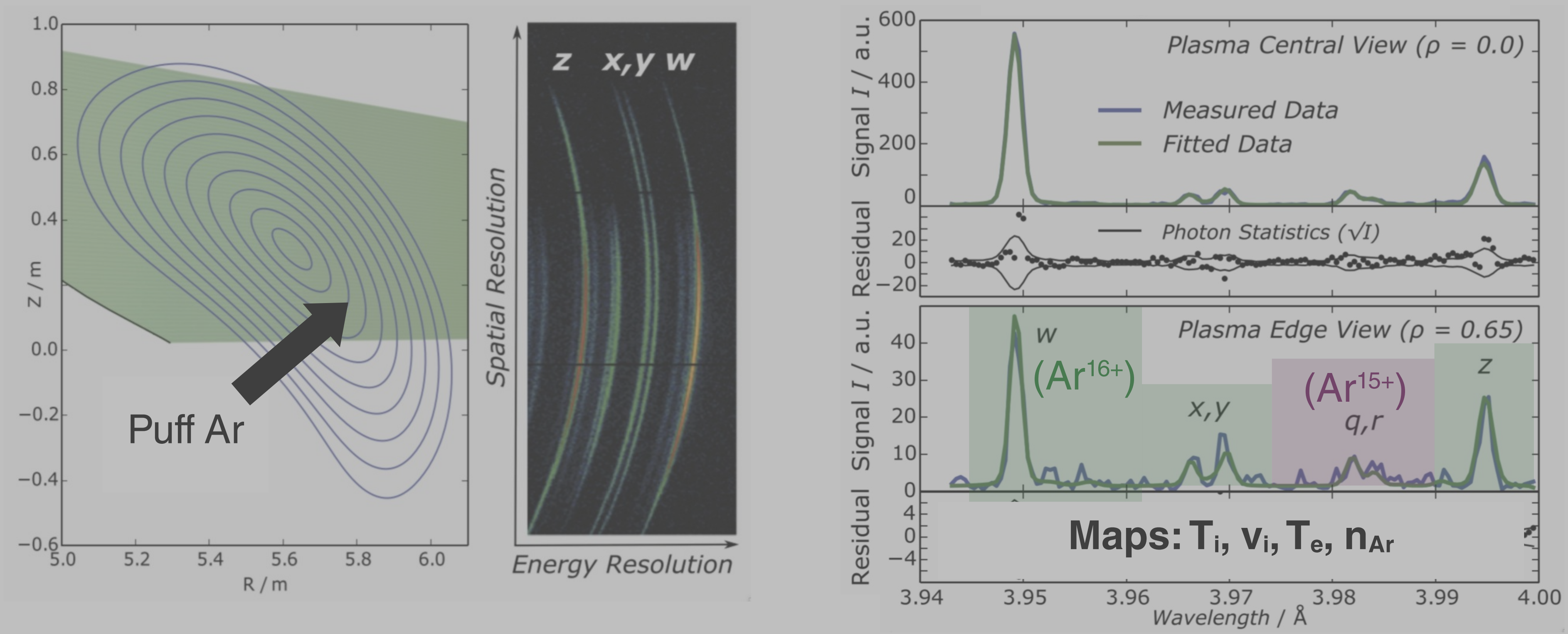
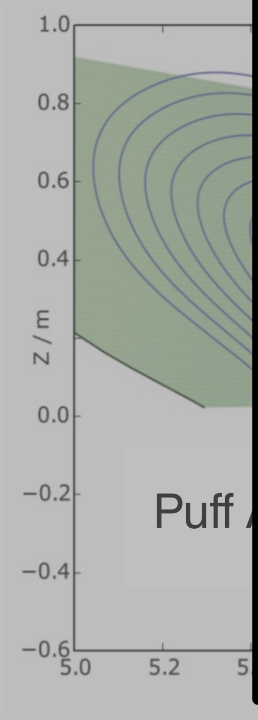
Dope plasma with "tracer" material → get detectable emission lines



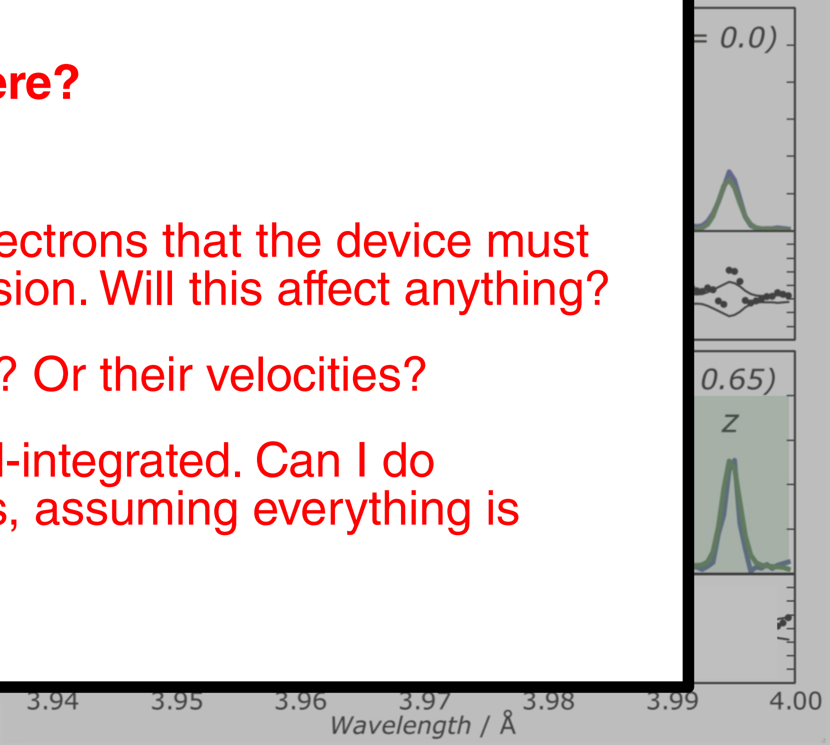
X-ray spectroscopy with Ar^{16+} at W7-X
(Langenberg 2017)

Dope plasma with "tracer" material → get detectable emission lines



What might be problematic here?

- Each Ar^{16+} ion donates 16 electrons that the device must confine with no benefit to fusion. Will this affect anything?
- Are T_i of Ar and D the same? Or their velocities?
- All measurements are chord-integrated. Can I do tomographic reconstructions, assuming everything is constant on a flux surface?



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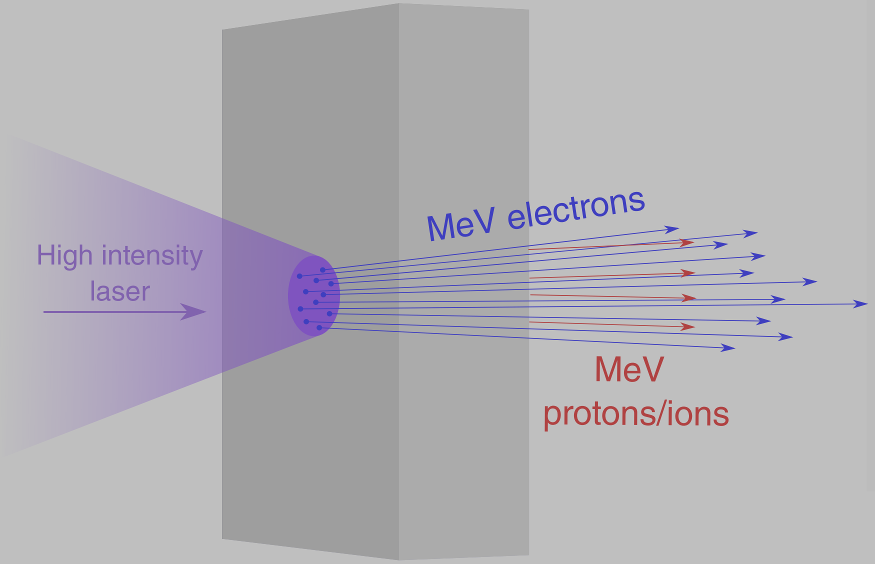
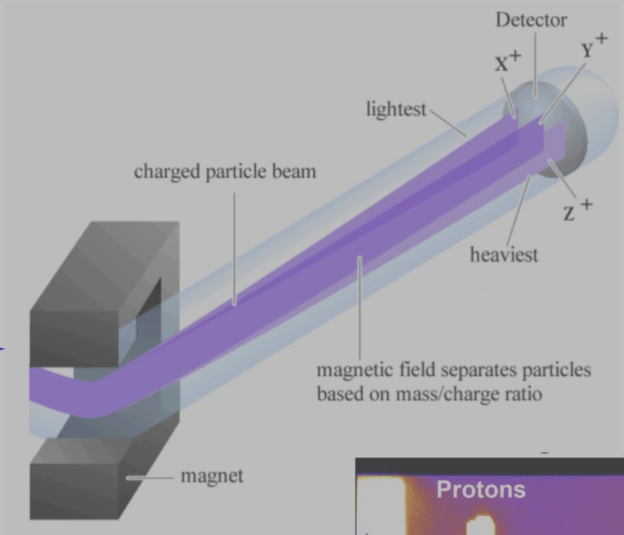
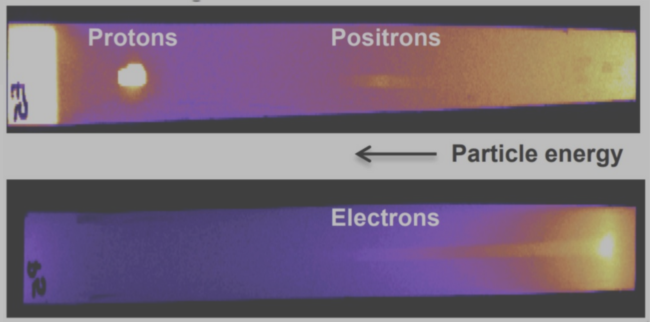
Many particles are naturally ejected from high-energy-density experiments







H. Chen
Presentation to NIF/JLF User Group Meeting 2016

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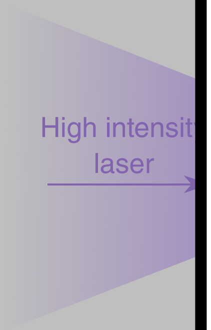
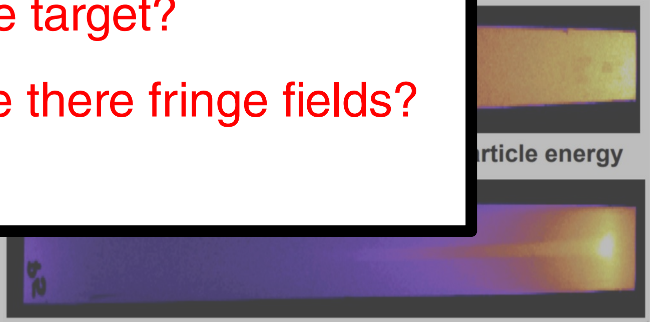


What might be problematic here?

- Is there a detector that can (a) be in the chamber to collect particles and (b) survive strong EMP?
- Do the particles that escape tell you anything about the behavior of material that remains in the target?
- How well calibrated is the magnet? Are there fringe fields?



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So, how do you measure a plasma?

Think critically and acknowledge every assumption you can

Minor differences between plasma systems may demand disproportionately different approaches

Learn about what's specifically been done in the past

- Each example shown here is the result of uncountable person-years of consideration, engineering design, and trial and error
- Collaborate with other groups, or talk to them at conferences like APS-DPP or the High Temperature Plasma Diagnostics conference (which happens every even year)

Remember: any shred of information you can gather is **real!**