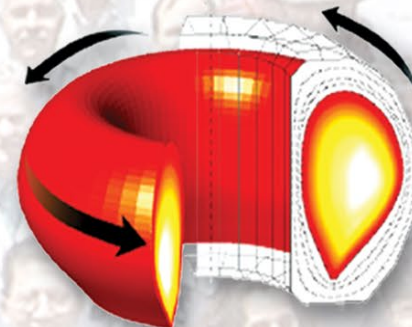
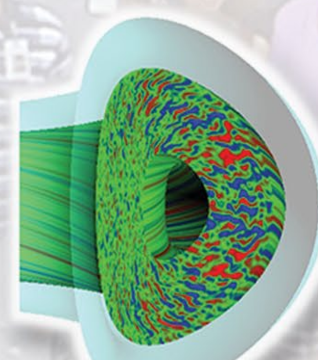
The electromagnetic spectrum: its origin and its importance in understanding the universe

Or, how do we know what we know about 100,000,000 K plasma?





Presented by
Rick Lee
Chief Operator, DIII-D Operations
Manager, Fusion Education Program
General Atomics
San Diego, CA

Demonstrations

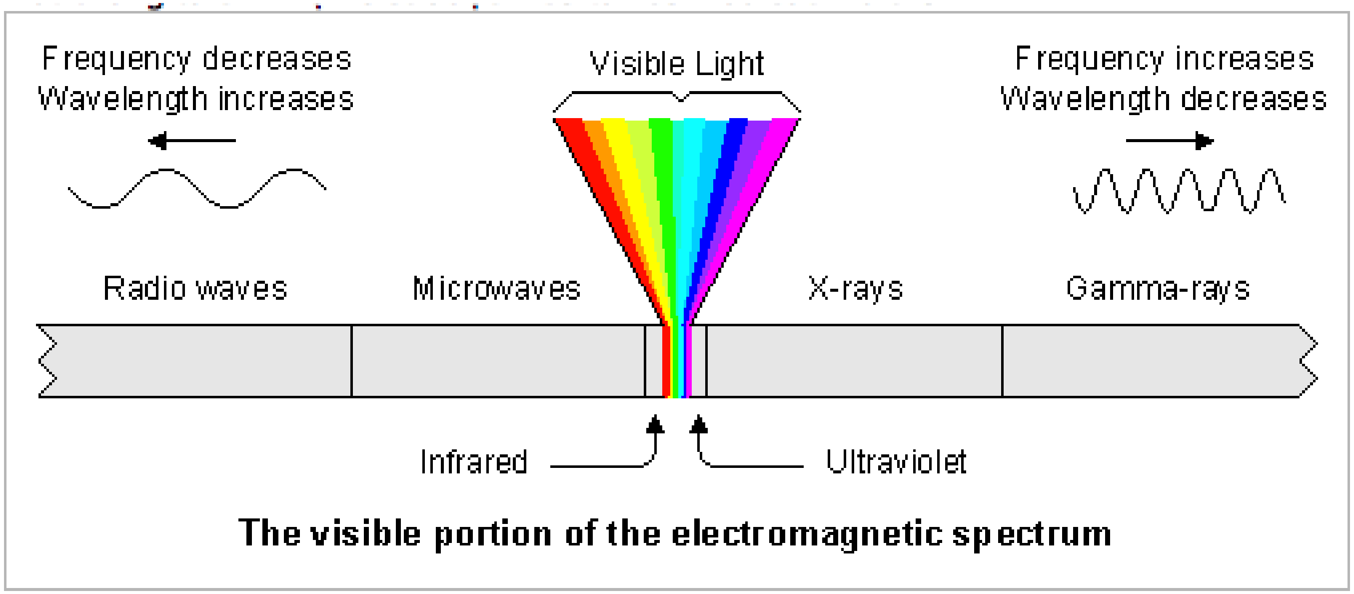
- **Definition of EM radiation**
- EM energy originates from accelerated charged particles (electrons, ions)
  - Demo: Different plasma discharge tubes
  - Human modeling of EM energy – Poynting vector, photons
- **Simple observations & basic tools based on natural phenomena**
  - Your eyes
  - Radio, IR camera: Windows & walls (transmission, absorption, reflection)
  - Spectroscopy, polarization (demos: diff grating, polarizer)
  - ~~Scattering (milky water and flashlight)~~
- **Detection & Interpretation- origin of information**
  - General discussion about detectors
- **Sum it all up with a game of 'Jeopardy'**

Electromagnetic spectrum – general definition

- **Electromagnetic energy** is energy that can move through space – a medium is not necessary, and can be modeled using waves that describe both E, B behavior or particles (photons).

- **The EM spectrum** encompasses a continuum of ‘long’ wavelength (power, tv, radio) through ‘short’ wavelength (gamma rays) energy

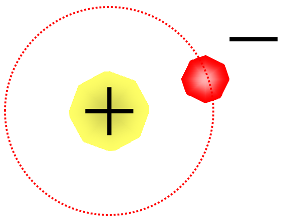
Generalized perpetuated view of EM spectrum



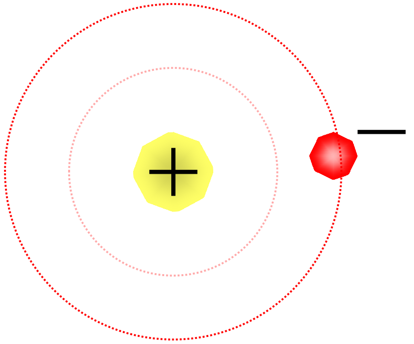
- Continuum, described as waves
- Titled regions are historical and not symmetric
- All regions follow similar physical rules
- Different regions interact differently with matter

A review of simple atomic states

Ground state (neutral)



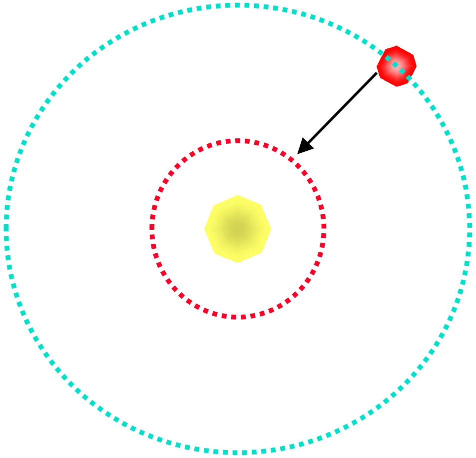
Excited state (neutral)



Ionized state (plasma)

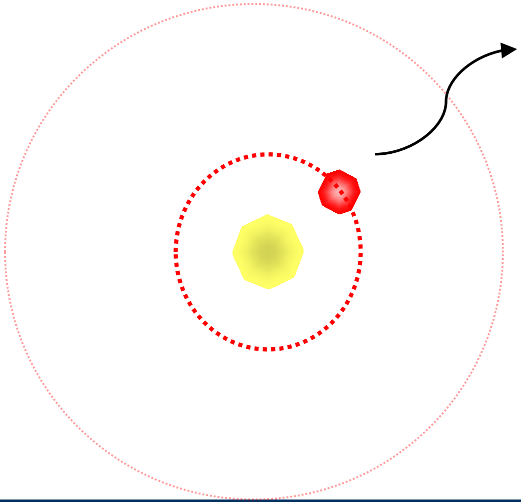
Spontaneous emission of electromagnetic energy

Some high energy (excited OR ionized) state



e^- falls to lower energy level

Lower energy state



Electromagnetic energy (“light”) is emitted

Origin of electromagnetic energy

- **Acceleration of charges**
  - Changes in electronic energy levels
  - Bond vibrations
  - A(de)ccelerating charges due to electric field and/or magnetic field
    - charges have spiral trajectory in magnetic field
    - charges have linear trajectory in electric field

Demo 1: Use of HV source to excite and ionize gas atoms and molecules

- Let's use a hand held HV coil to:
  - **Excite** the gas atoms within a tube
  - Then, **ionize** them to the plasma state

- What to observe:
  - Light emission (how does this relate to excitation or ionization?)
  - Smiles (how do these relate to learning and remembering the experience?)

Tools and Observations in Science

- Science is learning something about an environment, object, or phenomenon by measuring, discovering trends, and using models to simplify and predict outcomes
- In the case of understanding fusion-relevant plasma discharges, we can't simply use touch, smell, sight, hearing, or taste!

- **Measuring tools used in plasma science include**
  - those based on how charged particles interact with each other
  - those based on how charged particles produce and interact with electromagnetic energy (light, microwaves, etc.)

- **We must use tools based on fundamental scientific principles that are suited for the job**
  - spectroscopy, voltage probes, laser-induced or particle-induced action (scattering or fluorescence), magnetics probes, neutron & gamma ray detectors, infrared detectors, plus others

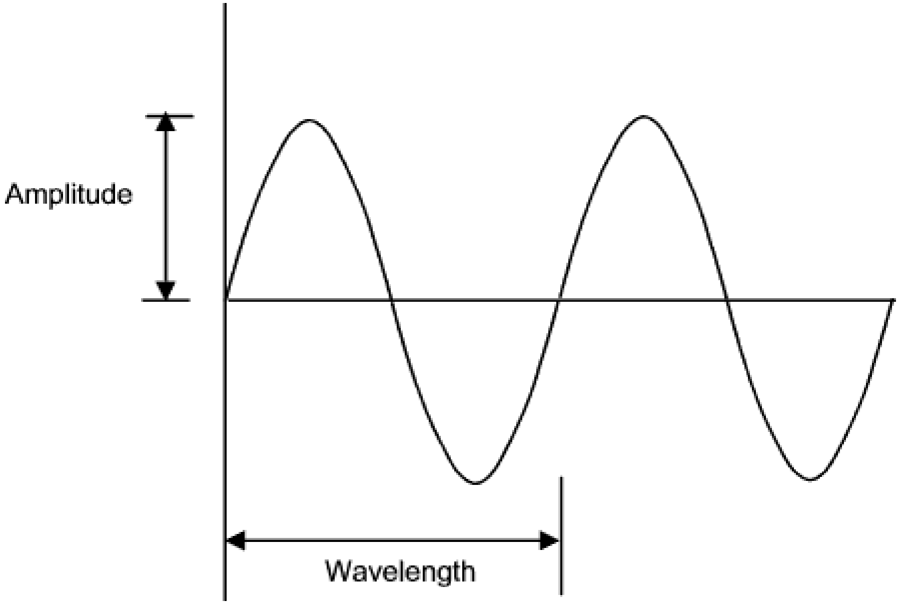
Modeling EM radiation as waves – Maxwell's eqns

- **We can model** EM energy as waves because the equations governing electric and magnetic fields (Maxwell eqns) are solved using sine and cosine functions.

Point Form	Integral Form	
$\nabla \times \vec{H} = \vec{J}_c + \frac{\partial \vec{D}}{\partial t}$	$\oint \vec{H} \cdot d\vec{l} = \int_s (J_c + \frac{\partial \vec{D}}{\partial t}) \cdot d\vec{S}$	(Ampère's law)
$\nabla \times E = -\frac{\partial \vec{B}}{\partial t}$	$\oint \vec{E} \cdot d\vec{l} = \int_s (-\frac{\partial \vec{B}}{\partial T}) \cdot d\vec{S}$	(Faraday's law; S fixed)
$\nabla \cdot \vec{D} = \rho$	$\oint_S \vec{D} \cdot d\vec{S} = \int_v \rho dv$	(Gauss' law)
$\nabla \cdot \vec{B} = 0$	$\oint_S \vec{B} \cdot d\vec{S} = 0$	(nonexistence of monopole)

Modeling EM radiation as waves – what is 'waving'?

- **We commonly** draw a squiggly wave on the board to describe a generic EM wave (light, for example)

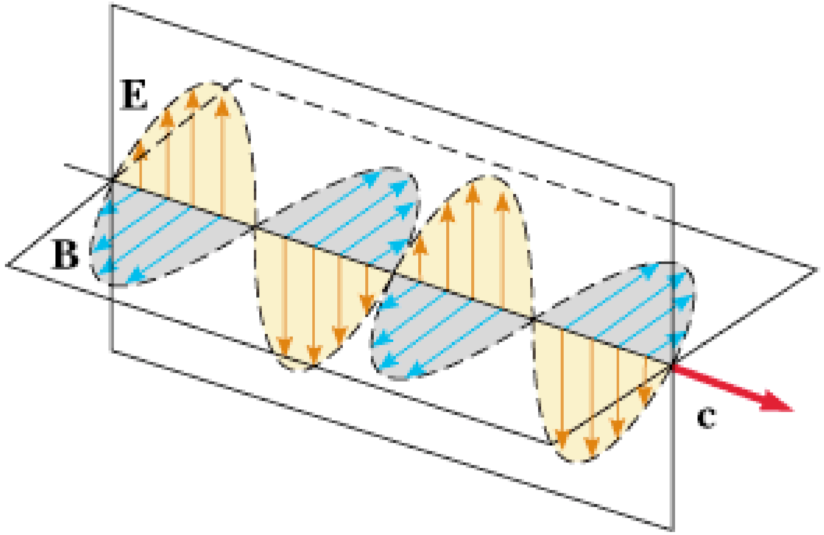


But, what is 'waving' ? EM wave eqn has space and time in it.

Poynting vector – energy flux direction E X B

The sine waves are the tips of the orthogonal electric and magnetic field vectors that make up the term ‘electromagnetic’. The **envelope** of the vector tips of the E vector is what is usually drawn in class.

Poynting vector, S, has units of energy per (area time) = J/(area time), or W/m^2 and direction of the cross product of **E** X **B**.



Serway, Physics for Scientists and Engineers, 5/e Figure 34.3a Harcourt, Inc.

So, why do we draw only a single sine wave?

- Most detectors (including rhodopsin) are sensitive to the electric field vector and produce a voltage
- Magnitude of magnetic field vector set is 1/c that of the E vector set ($B \approx E/c$)
- Ease of construction on 2-d plane – the board

Make your own Poynting vector

- Standard no. 2 pencil
- 3-ring binder hole punch
- Scissors or paper cutter
- E,B vector envelope template (8.5" x 11" paper)
- Copy template onto different colored paper
- Punch, cut, punch, cut as needed to make ≈2 cm wide strips with punched holes
- Weave **correctly** onto pencil; note orientation of E, B vectors follows the right hand rule for energy propagation in direction of E X B.

Origin of EM radiation – energetic matter

name	λ Range (m)	*f* (Hz)	Origin	Comment
electric power	$>10^5$	$< 10^2$	Molecular/electron vibrations	60 Hz house electricity
radio/TV	10^{-1} - 10^4	10^{-1} - 10^4	molecular/electron vibrations	atm can reflect these
microwave	10^{-3} – 10^{-1}	10^9 - 10^4	molecular/electron vibrations	Blocked by metal mesh in ovens
infrared	10^{-7} – 10^{-3}	10^{14} - 10^9	molecular vibs; e- transitions	Emitted from all objects
visible	4 – 7 x 10^{-7}	10^{14}	e- transitions	1/40 of EMR
ultraviolet	10^{-8} – 4 x 10^{-7}	10^{16} - 10^{14}	e- transitions	sunburn cause
x-ray	10^{-11} – 10^{-8}	10^{19} - 10^{16}	e- transitions/ braking	Wavelength size of atom
gamma ray	$< 10^{-11}$	$> 10^{19}$	nuclear transition	Damages tissue; ionization

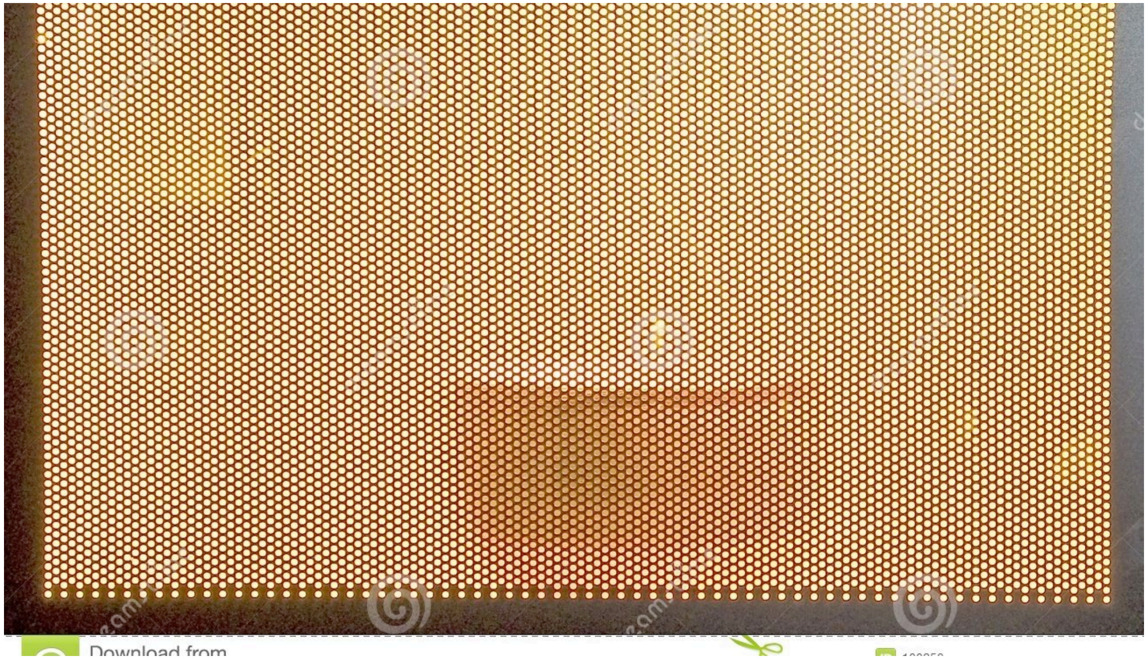
Observational characteristics – windows & walls

- **EM energy** can be transmitted, reflected, scattered, or absorbed
- If EM energy is transmitted – material is a "window"
- If EM energy is not transmitted – material is a "wall"
  - Could be a mirror in a truly reflective case
- We'll use visible light, radio, microwaves, infrared to emphasize different aspects of 'windows and walls'

Microwave oven doors are both a window and a wall

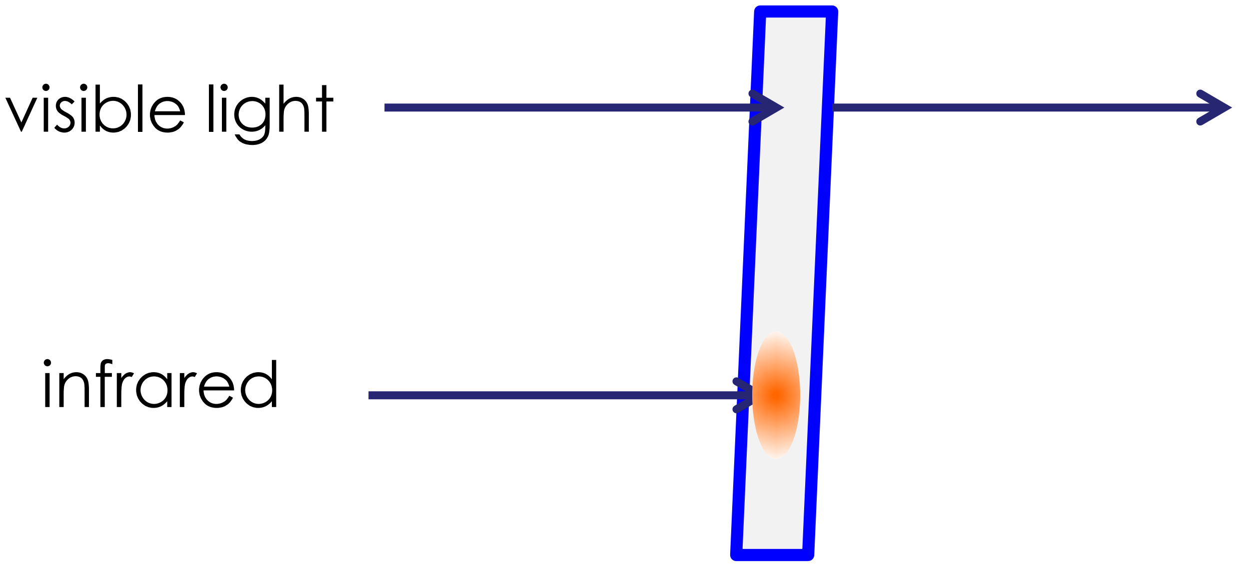
Microwave oven doors allow visible light through, so junior can see his burrito go ‘round and ‘round – **a window**

Microwave oven doors do not allow microwaves through, so junior doesn’t get cooked like his burrito – **a wall**



Glass and plastic windows are a window for visible light and a wall for infrared radiation

Standard glass and plastic windows transmits visible light - a **window** but absorb (block the transmission) infrared energy – a **wall**.



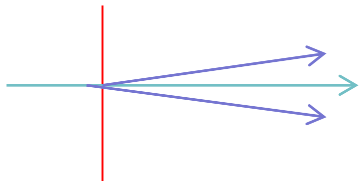
Interference and the diffraction grating

- **Superposition** of waves allows amplitudes from two or more waves to 'add' constructively or destructively
  - Adding e-field vectors (envelopes)
  - Recall sine, cosine waves
  - Diffraction grating uses this concept with many slits

$$n\lambda = d\sin\theta$$

n is order, d is grating dimensions, θ is angle of diffraction

Diffraction grating



- **Many tiny parallel slits**
- **Diffraction grating eqn: $\lambda = d\sin\theta$**
  - d is distance between slits
  - θ (theta) is angle from grating normal where light of wavelength λ will be bright due to constructive interference

Example: suppose d = 1E-6 m (N = 1000slits/mm) and λ is 6500E-10 m (red), then θ is

$$\theta = \sin^{-1}((6.5E\text{-}7)/1E\text{-}6) = 40.6^{\circ}$$

Diffraction grating – viewing multiple wavelength sources

- Use grating to view discharge tubes
- Light having specific wavelengths is observed
- Separated by angle $\Delta\theta$ from central normal
- Closeup of light 'bars' leads to Gaussian structure
- Width of structure due to particle movement
- Doppler shift of whole structure may be present if the velocity between source and observer is great enough.

Detectors – biological, electronic

- **11-cis-retinal within protein opsin (together, called rhodopsin), chlorophylls, photoreceptor flavoproteins**
  - Chemical rxns caused by electromagnetic energy lead to vision, CO2 assimilation, or automatic directional locomotion responses.

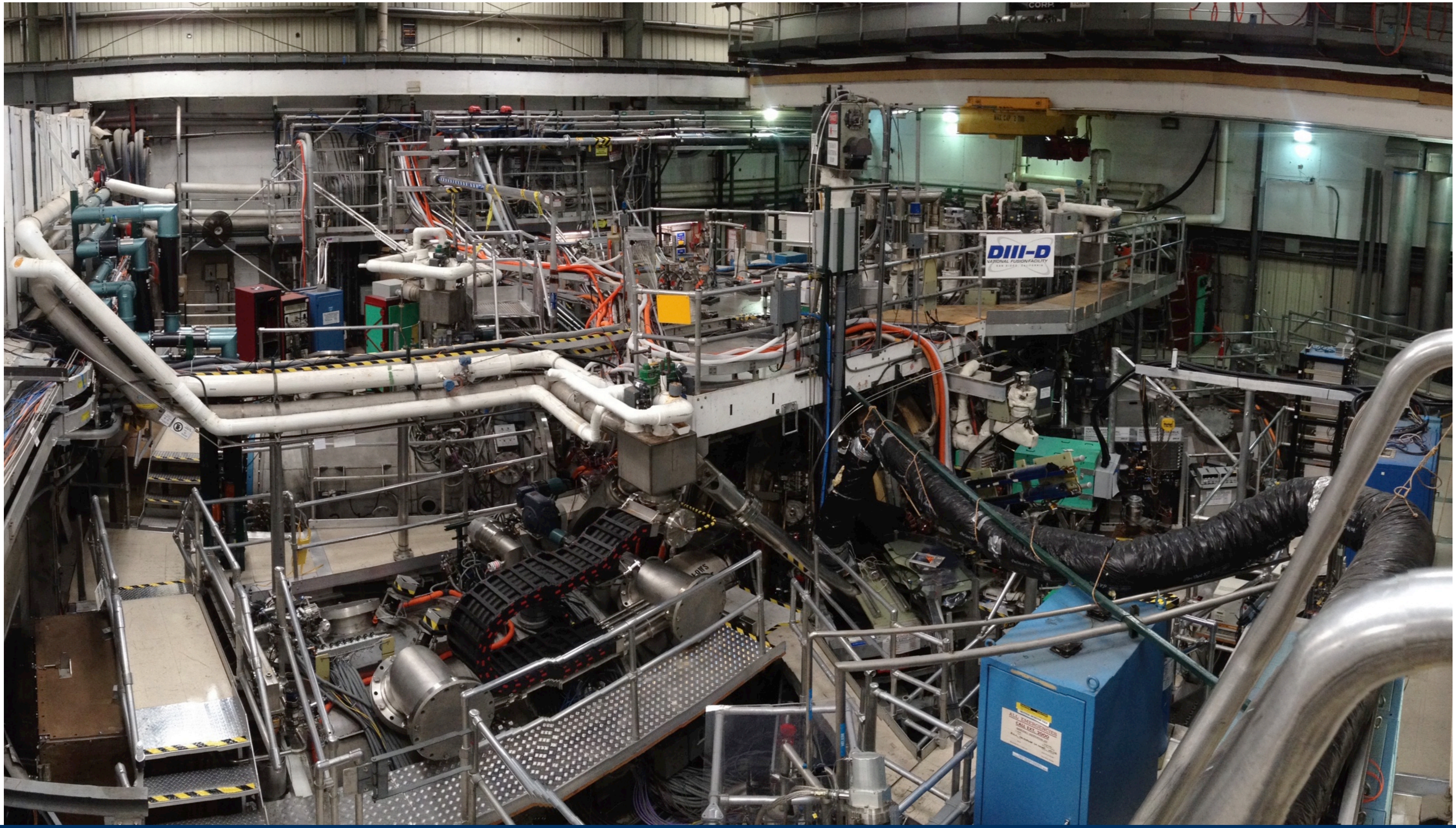
- **Photodiodes, CRT (vidicon), CCDs, thermocouples, etc**
  - Sensitive to visible light, heat, other portions of the em spectrum. EM energy leads to electron transfer to allow voltage production.

Infrared camera as an example

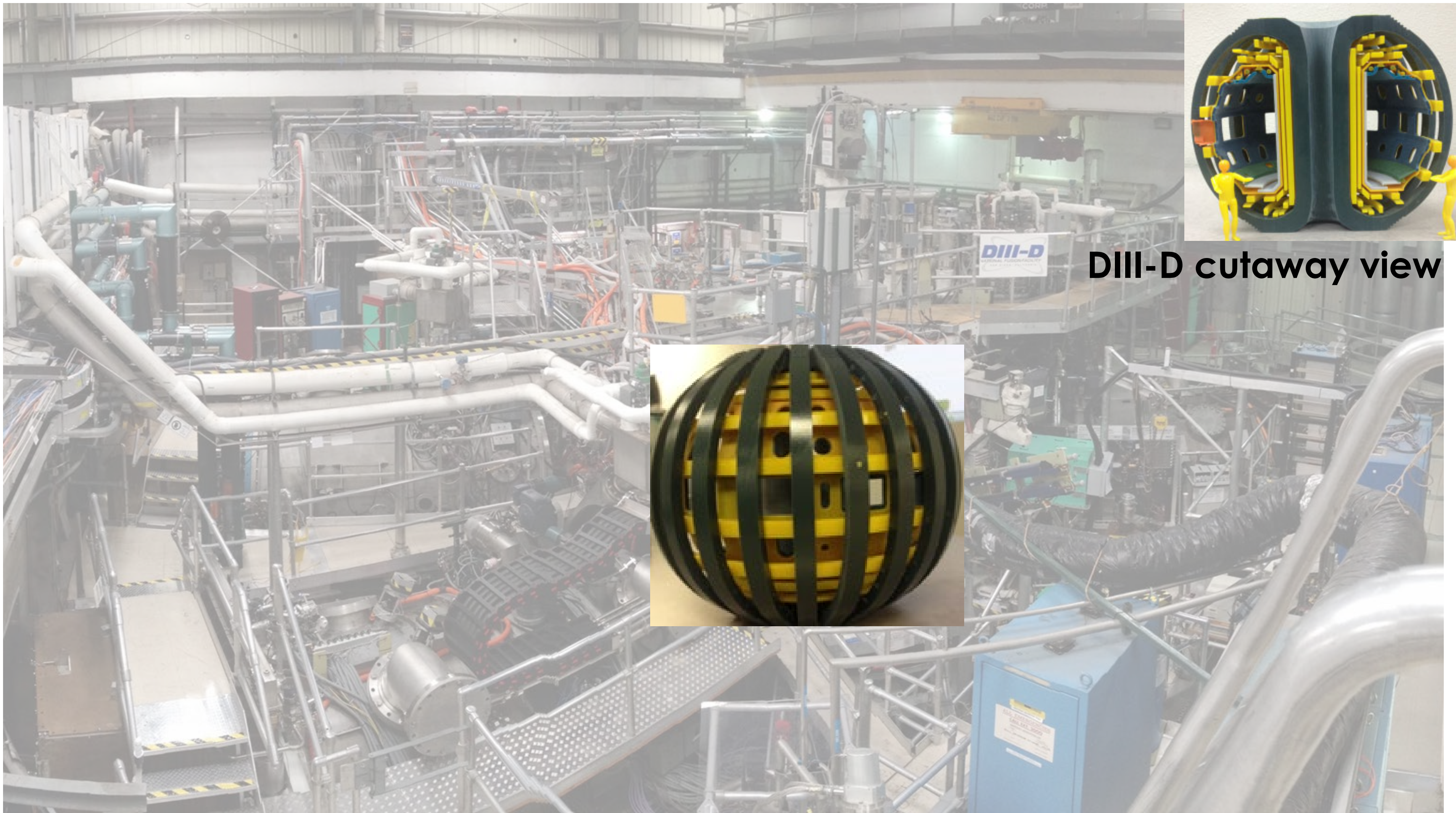
- **Detects ≈ 7 – 14 μm wavelength**
  - Room temp peaks at ≈ 10 μm
  - Warmer objects have shorter peak wavelengths
  - Detector array provides an image

  - Let's 'see'……

DIII-D Tokamak & peripheral systems in San Diego

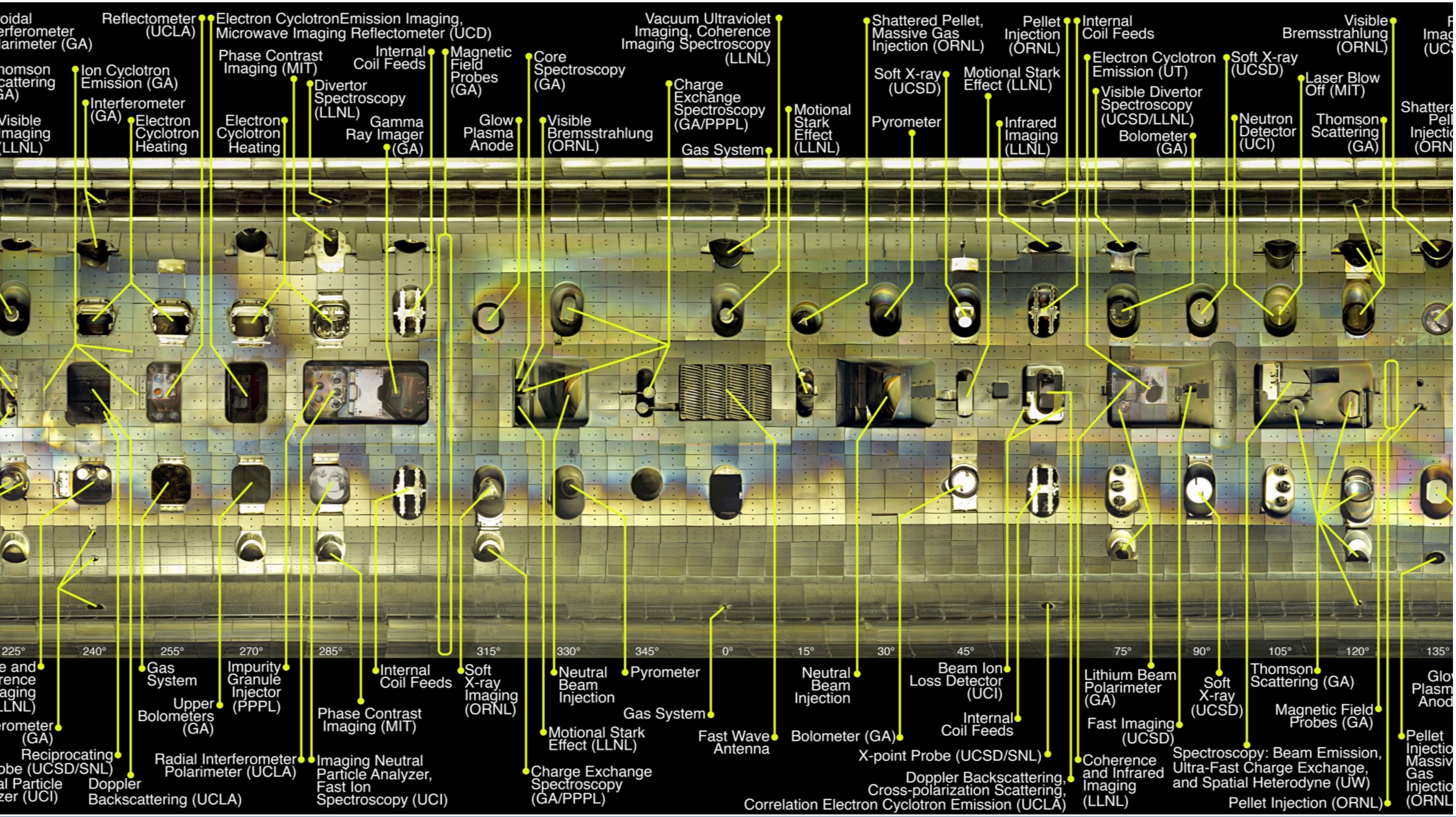


Approximate location of DIII-D Tokamak inside the Machine Hall ("the Pit")



DIII-D cutaway view

Inside view of DIII-D: diagnostics, fueling, vacuum pumping, heating ports



DIII-D NATIONAL FUSION FACILITY

GENERAL ATOMICS

RL

Are you up for a game of Jeopardy?

- Jeopardy