Auxiliary Heating in Magnetic Confinement Devices

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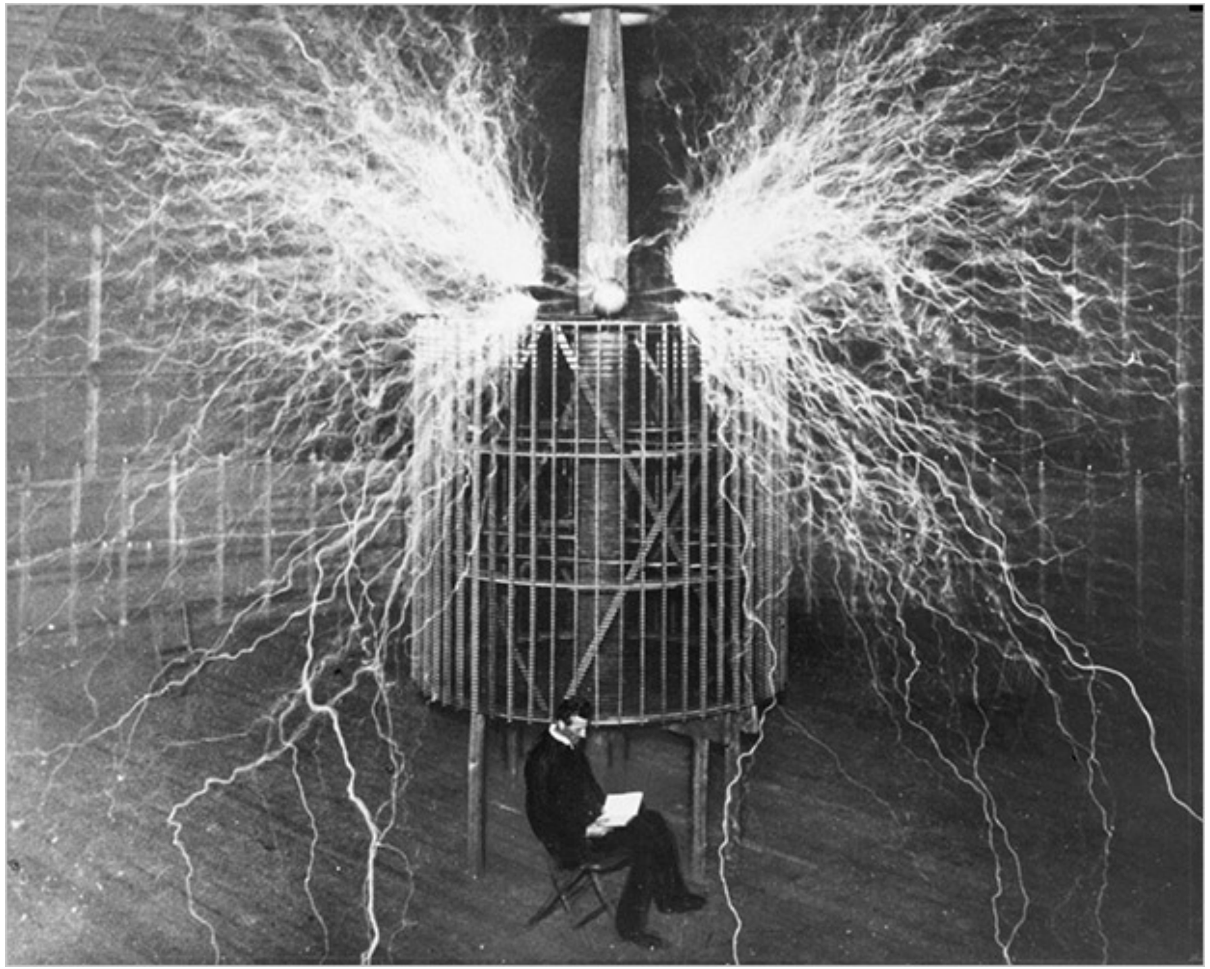
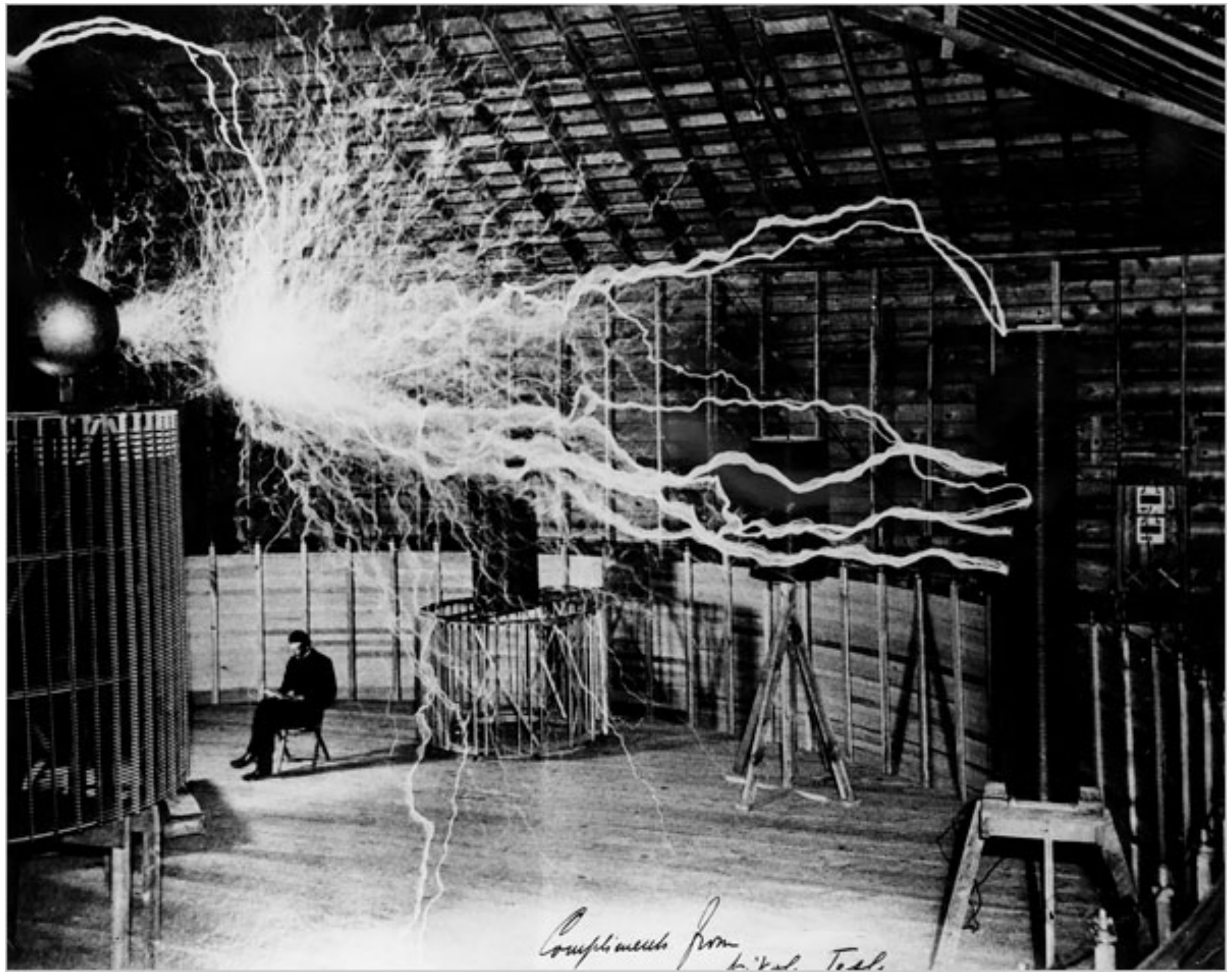
Capsule autobiography – what brought me here?

- I'm from Pittsburgh, PA
- I was interested in science and the space program in the 1960s – my first bath toy was a little Mercury capsule, I remember – and I built all of the plastic models of the Gemini and Apollo spacecraft, LEM, etc.
- I liked all kinds of science, even bacteriology and stuff, in elementary school
- In high school, a friend of mine told me about a hero of his, and I got the only book about the guy that was available at the time:

Nikola Tesla, in his Colorado Springs lab, 1899





So I got interested in sparks and arcs and plasmas

- Built a pretty big Tesla coil with my dad
- Went to MIT for undergraduate, majored in physics and applied math (Course 8 and 18A)
- Got summer internships at Westinghouse Research and Development center after my sophomore and junior years, worked on fluorescent lamps (weakly ionized plasmas)

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Unipolar currents and electrostatic probe characteristics in a gas discharge plasma

Journal of Applied Physics **54**, 1289 (1983); https://doi.org/10.1063/1.332194

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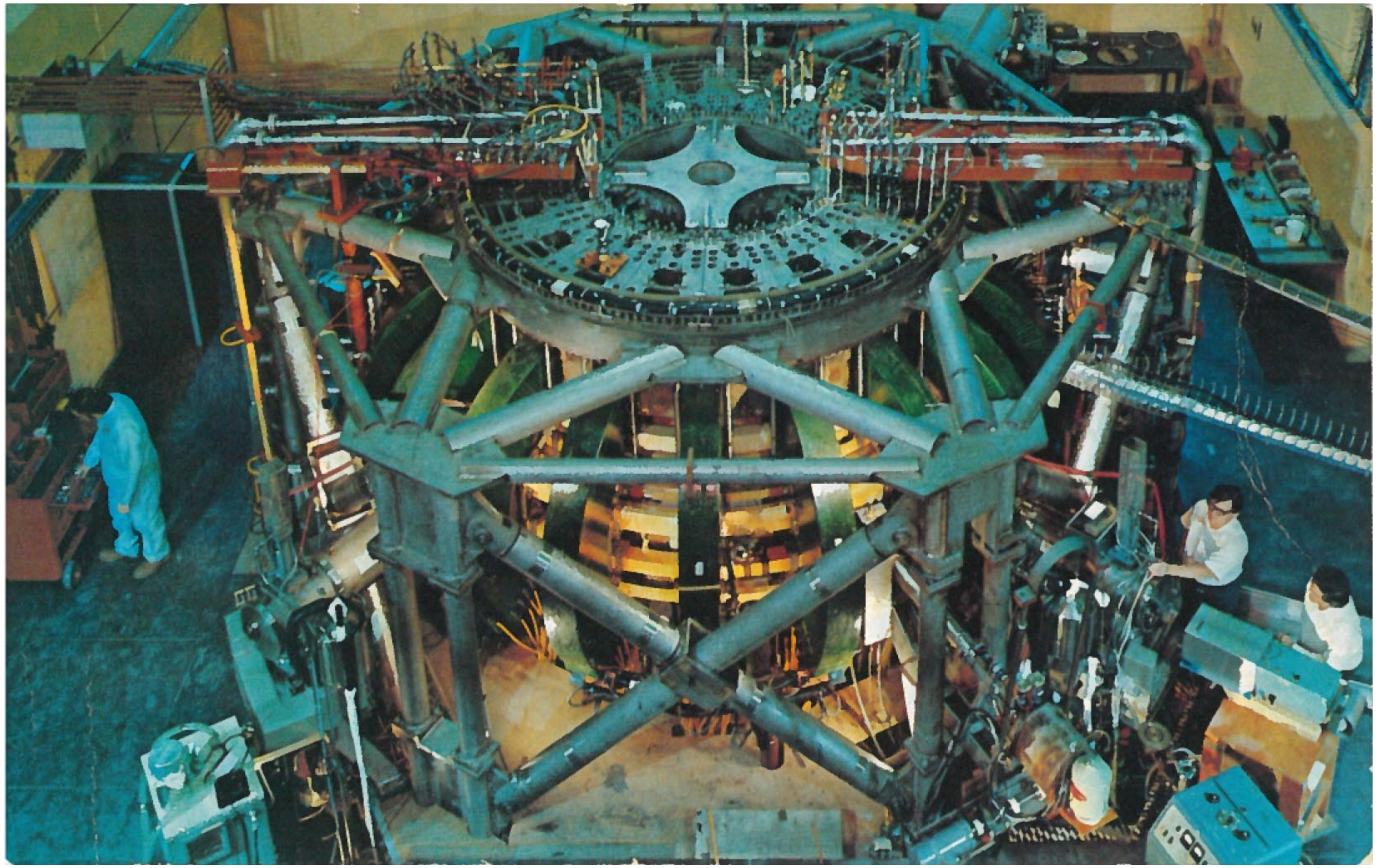
- Did Bachelors thesis experiment in electrical engineering, built a glow discharge apparatus for application in ozone generation
- Applied to grad schools, almost all in non-fusion plasma physics
- But somehow went to Princeton, Dept. of Astrophysical Sciences, Plasma Physics program anyway – in fusion research

Me at PPPL

Me Tim Luce

Steve Cowley Greg Hammett

Me at PPPL

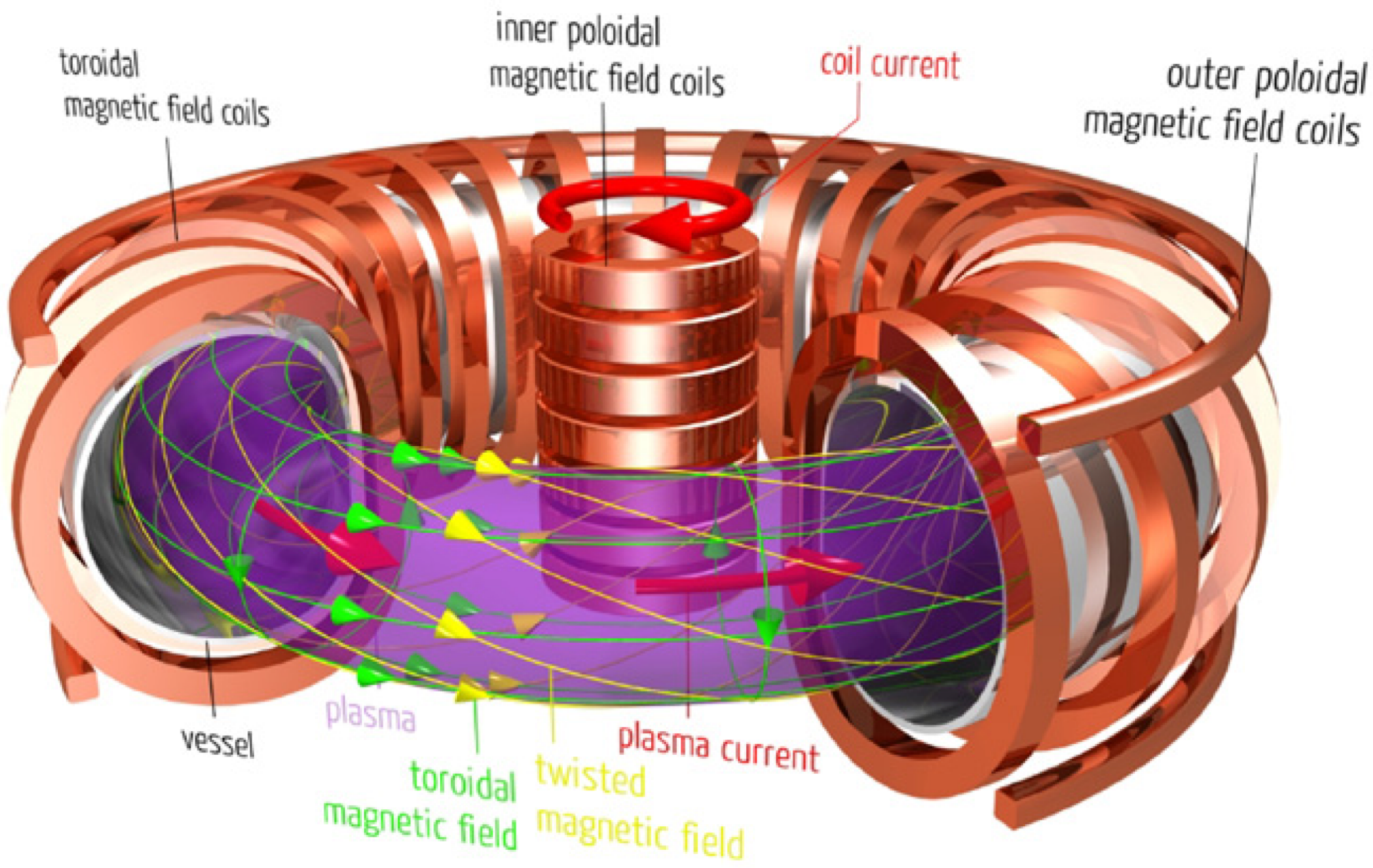


Princeton Large Torus,
before auxiliary heating

Me and Tom Stix, who literally wrote
the book on plasma waves

Let’s talk about tokamaks

- Here’s the picture that has become the standard this year, for ‘conventional tokamaks’
- This picture shows only ohmic heating – nothing else shown



Ohmic heating – the gift of the tokamak

- We've established (see Cowley, Battaglia talks) that axisymmetric toroidal equilibrium must have a toroidal plasma current to generate rotational transform
- With current automatically comes ohmic heating due to the non-zero resistivity of the plasma: heating power $P_\Omega = I_p^2 R$
- In a decent-sized tokamak, Ohmic heating alone heats the plasma to about 0.5 – 1 keV
- At 1 keV, clean hydrogenic plasma has a resistivity similar to copper at room temperature, so the required one-turn loop voltage needed to sustain a plasma current on the order of millions of amps is only a fraction of a volt in a medium-to-large tokamak

Limits of ohmic heating in tokamaks

- Limit: electron temperature scaling of plasma resistance in a fully ionized plasma, due in turn to the basic scaling of electron-ion collision frequency with electron temperature: $\eta \sim T_e^{-3/2}$
- The hotter the plasma gets, the more collisionless and the lower the resistivity, and hence the heating power at a given plasma current
- Hence additional or 'auxiliary' heating is needed to get one more order of magnitude of temperature, from ~1 keV to ~10 keV for D-T fusion

Ways to heat a tokamak plasma

- How do you heat the water in a bathtub?

1. We could run electric current through it (ohmic heating), though that's not usually done
2. We could run waveguide from our microwave oven to the bathroom, and heat it by dissipating microwave power in the water
3. We could add hot water, which is the most popular method

But before we go into the analogous methods, let's talk about heating more generally

0-D model of plasma heating

- First, suppose the plasma is pre-existing with some thermal energy W_0 at time zero, no heating, so thermal energy decays exponentially in time:

$\frac{dW}{dt}$ = (rate of change of stored energy W) = - $\frac{W}{\tau_E}$, which we can integrate:

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$\int_{W=W_0}^{W} \left(\frac{dW}{W}\right)$ = -$\left(\frac{1}{\tau_E}\right) \int_{t=0}^{t} dt$ or $\ln(W/W_0)$ = $-t/\tau_E$ so $W = W_0 e^{-t/\tau_E}$

and you can see why we call τ_E the energy confinement time

0-D model of plasma heating

- Now add heating power (inject some number P of Joules per second, Watts):

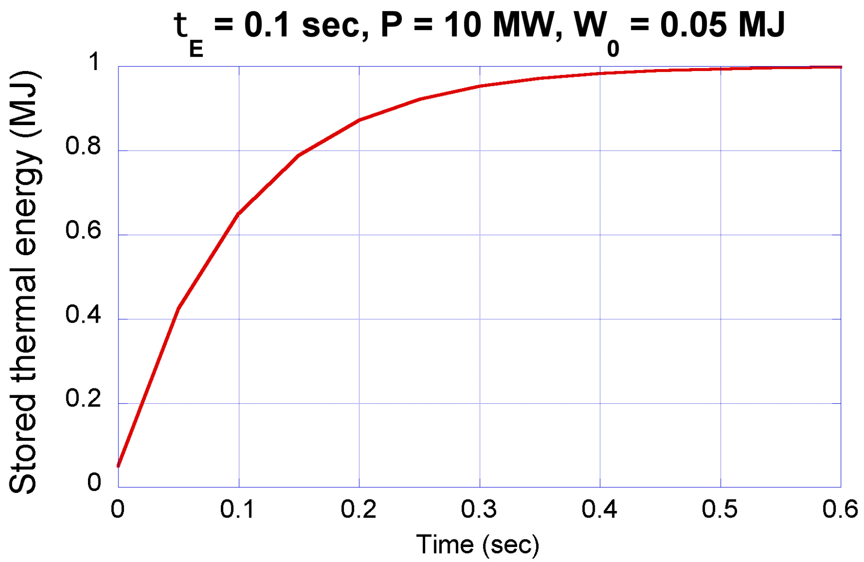
$\frac{dW}{dt}$ = P - (W/τ_E), which we can also integrate (an exercise for the student), obtaining

$$W(t) = e^{-t/\tau_E}\,(W_0 - \tau_E \mathrm{P}) + \tau_E \mathrm{P}$$

Check: at t=0, W=W_0 and for t >> τ_E , W asymptotes to τ_EP.

Note that at large times, then, $\frac{dW}{dt}$ goes to zero, and P = $\frac{W}{\tau_E}$

The confinement time in seconds is just the ratio of the steady-state stored energy W (J) to the heating power P (W=J/sec)

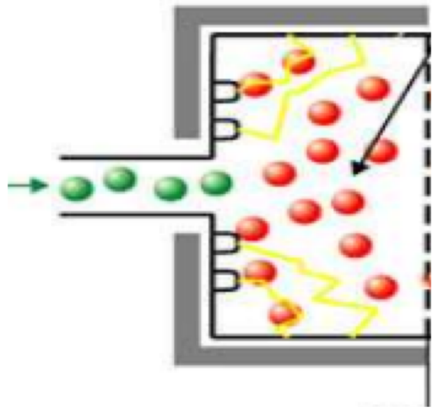


Neutral beam heating: the most successful method to date

- The idea is to inject electrostatically accelerated ions into the plasma, which are then confined by the magnetic field and collisionally slow down on the bulk plasma, transferring the energy to the bulk
- But we cannot inject an ion beam into a magnetic field (why not?)
- Instead we must somehow neutralize the energetic ions and inject energetic neutrals which then ionize again in the plasma and are trapped there
- How to do that??
- Answer is charge exchange!

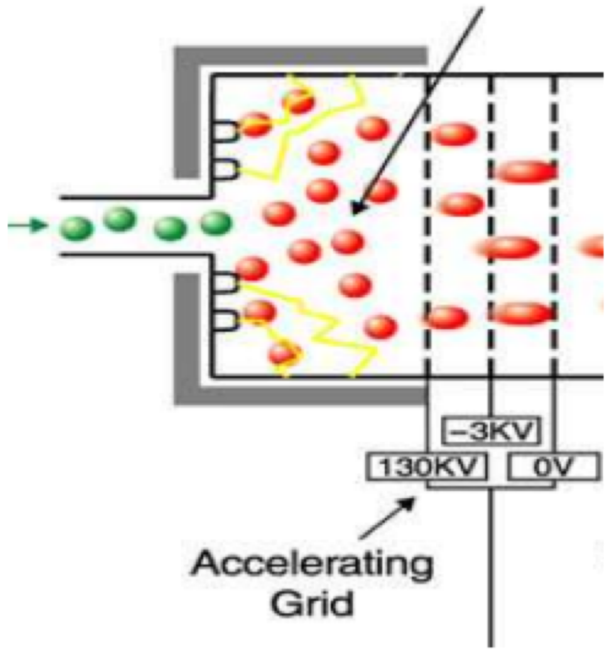
Neutral beam injector is an amazing piece of technology

- First: ion source – filament or rf discharge plasma



Neutral beam injector is an amazing piece of technology

- Second, electrostatically extract ions and accelerate them to ~100 keV



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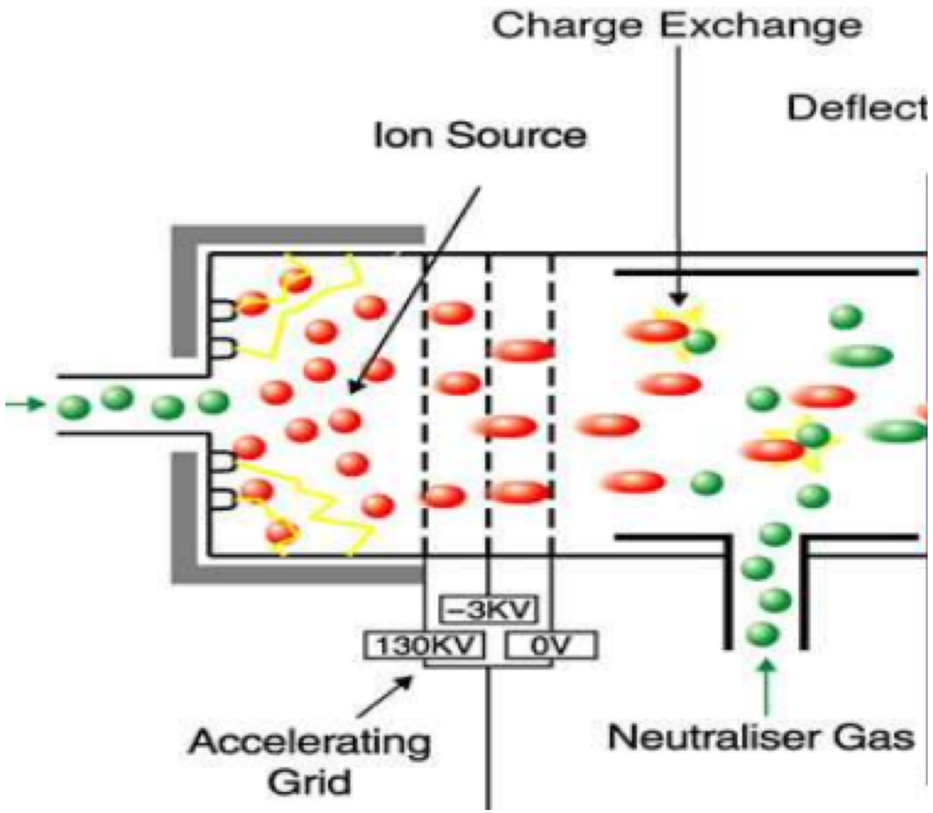
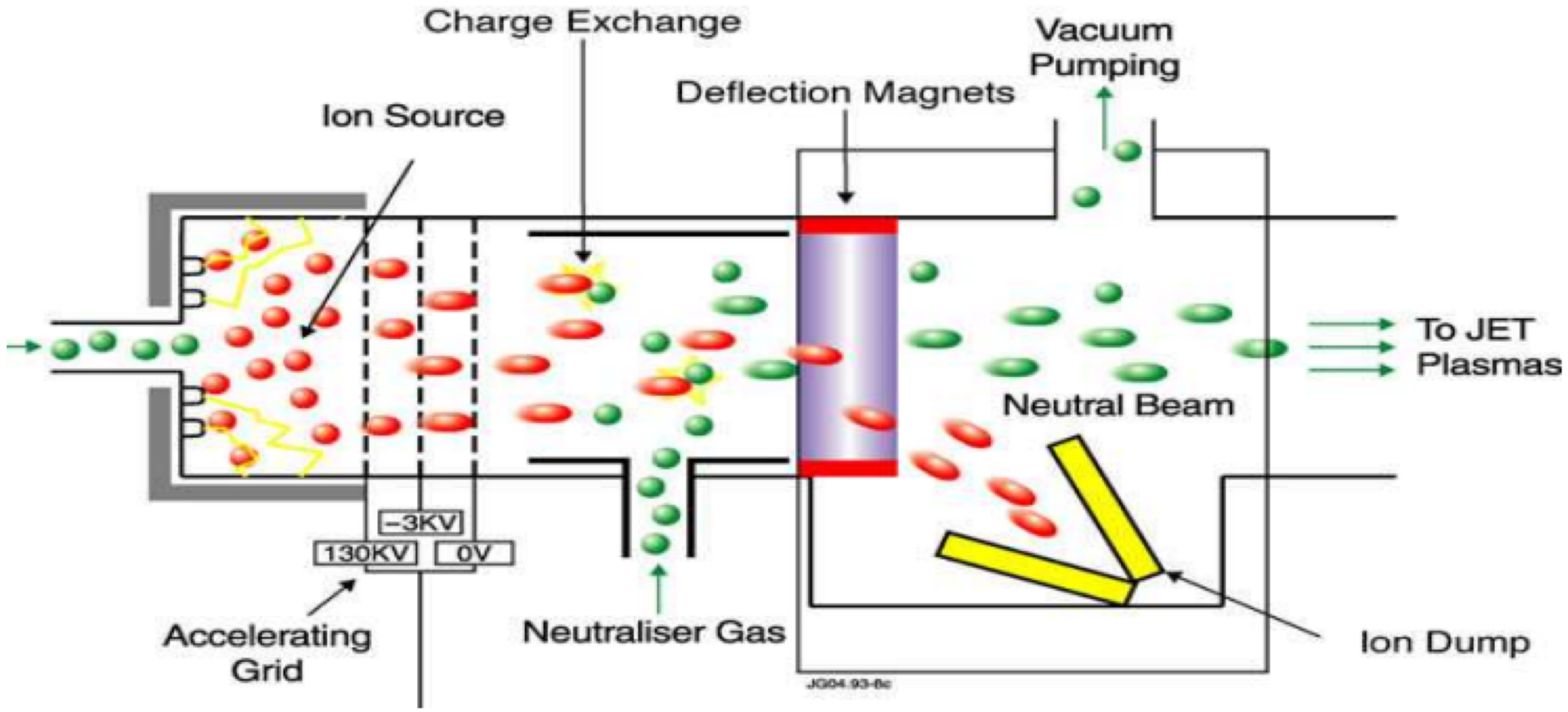


- Neutralizer has gas pressure about two orders of magnitude higher than the tokamak chamber
- Possible only with massive differential pumping (cryopanels)

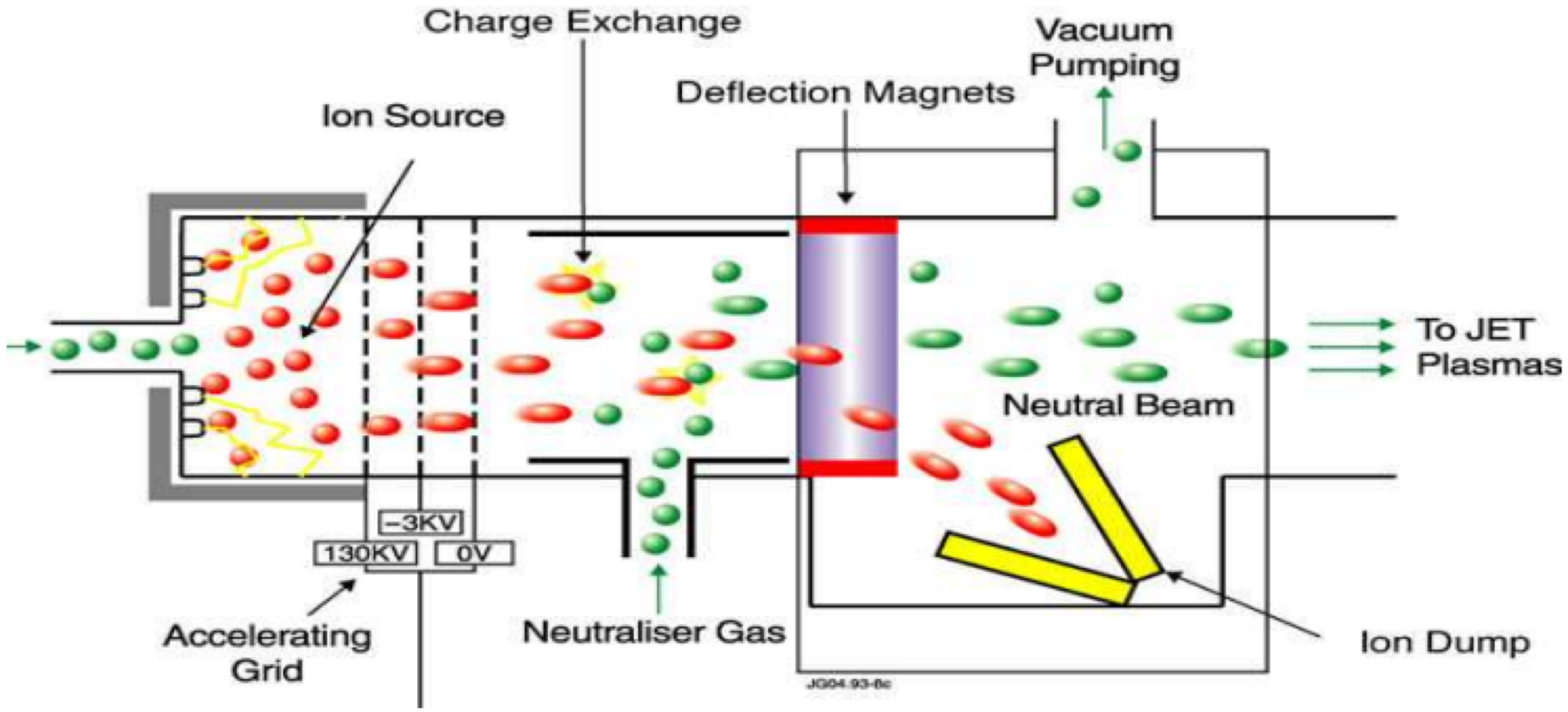
- Charge exchange with neutral deuterium atoms in neutralizer, with efficiency of maybe ~25%

Neutral beam injector is an amazing piece of technology



- Bend unneutralized ions (most of them) out of beam path with magnetic field of ~0.06 T into dump

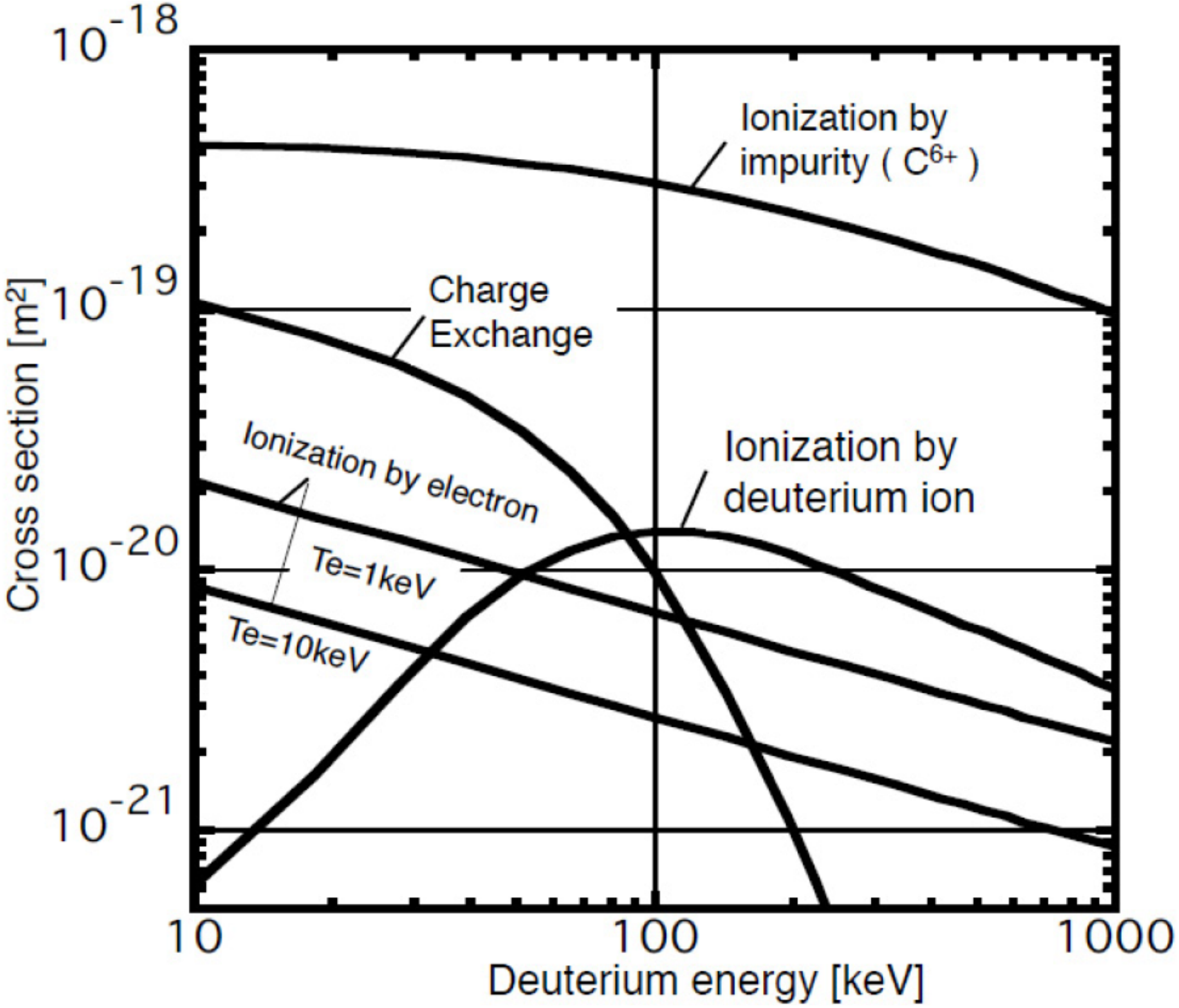
Neutral beam injector is an amazing piece of technology



- Remaining beam of energetic neutrals zips down drift duct, through an open port, and into the plasma

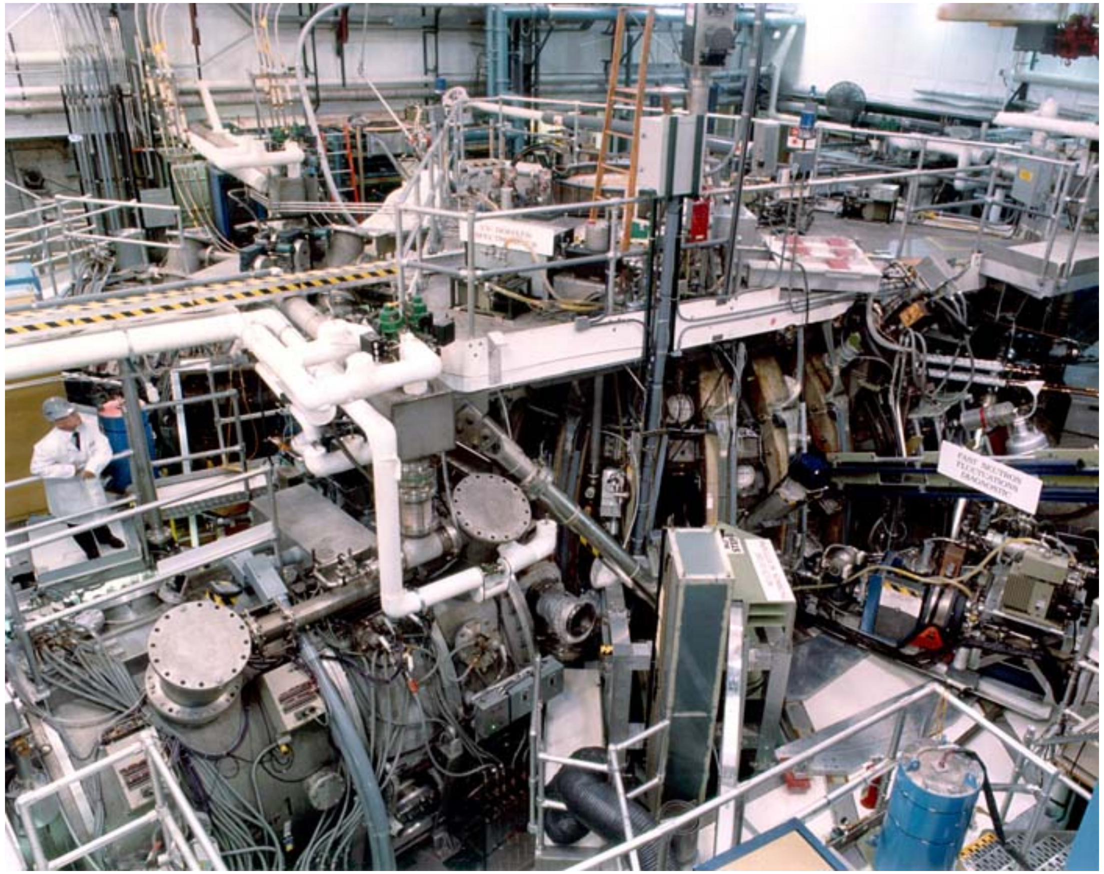
Neutral beam ionized in plasma and heats it by collisional slowing down of resultant fast ion

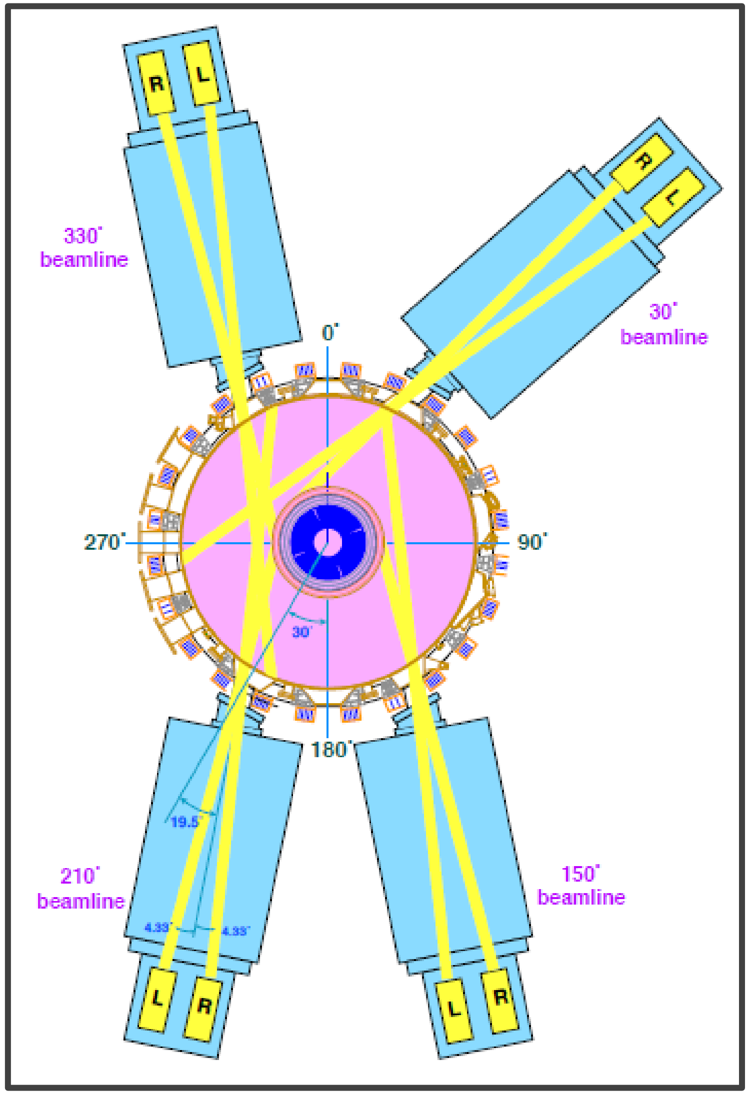
- Neutral beam crosses magnetic field without ‘feeling’ anything, then either is ionized by collisions with impurities or by charge exchange with relatively cold plasma ions



Neutral beam injectors often dwarf the tokamak that they are heating

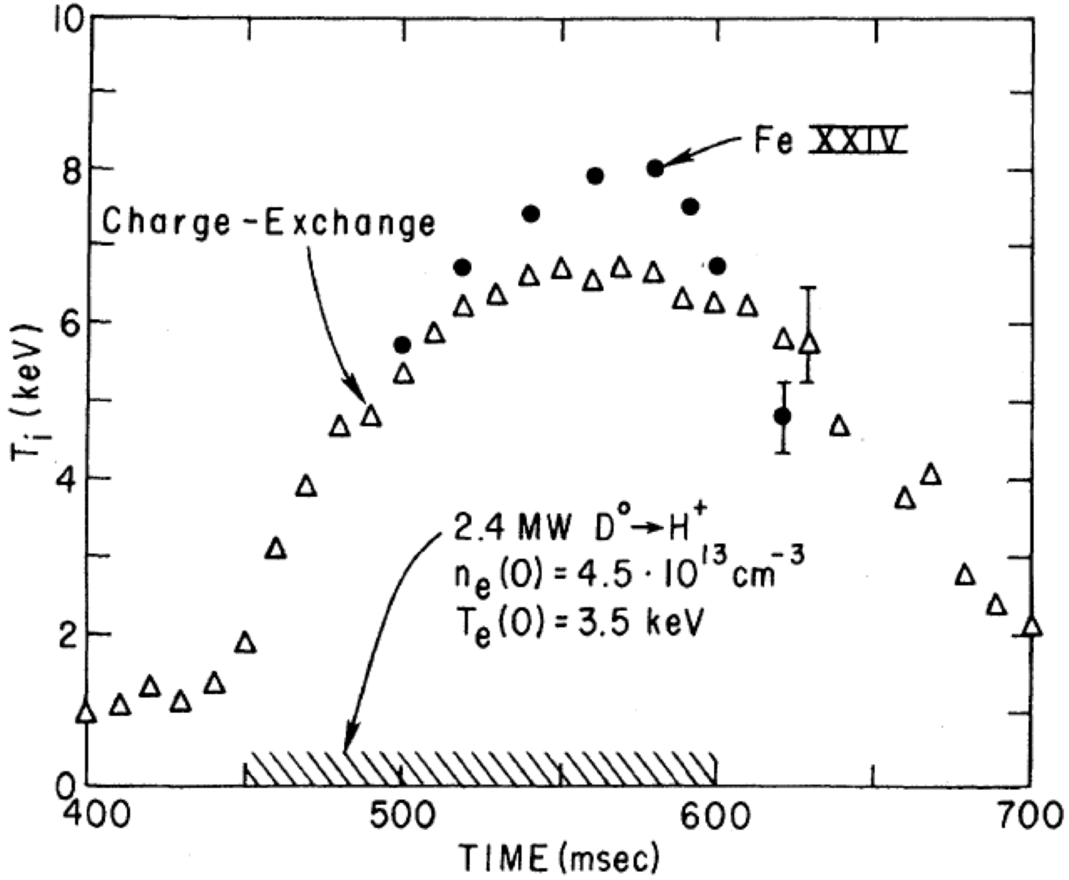
- Example: plan view of DIII-D with 4 beamlines





Most tokamak records for plasma performance were set with NBI

- Highest beta, highest neutron yield, highest Q(D-D), highest Q(D-T), highest $p\tau_E$, highest ion temperature, highest thermal stored energy, . . .



PLT “breakthrough” to thermonuclear regime, 1978

If NBI is so great, why am I still talking?

- Most feel that NBI will not work for a reactor
  - Cannot steer beam or propagate it any distance, so NBI must be immediately adjacent to torus
  - Beam port is big hole in torus wall – neutronics, tritium breeding
  - Beam energy must be very much higher than in present experiments – on the order of 1 MeV or higher, so technology is much more difficult

- What are the alternative methods of auxiliary heating?

Heating with waves: RadioFrequency heating (RF)

- **Difficult to heat gas without collisions; collective effects must take their place**
  Example: limitations of ohmic heating

- **What would we like to do with wave heating?**
  1. **Efficiently couple energy from an external source to a propagating plasma wave**
  2. **Transmit the wave energy to any desired location in the plasma**
  3. **Damp the energy at that location to move particles to a desired location in phase space**

- **Hence, the problem breaks up into several parts:**

  0. Generation of wave energy
  1. Coupling
  2. Propagation
  3. Damping
  4. Thermalization

Collisionless damping mechanisms I: Landau

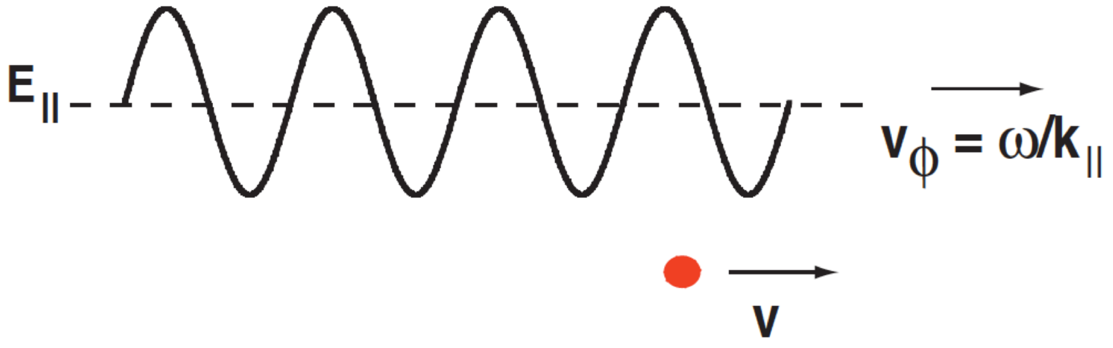
Single charged particle in a wave field: to extract energy from field, particle must see a steady electric field in its rest frame

Hence resonance condition for a particle moving at velocity v and wave with phase velocity v_ϕ is $v = v_\phi = \omega/k$ or in a steady $\vec{B}_0$ field, $v_{||} = v_\phi|_{||} = \omega/k_{||}$

$$\omega - k_{||}v_{||} = 0$$

Laudau resonance

$$\vec{F} = q\,\vec{E}_W$$



Collisionless damping mechanisms II: cyclotron

- Consider a circularly polarized wave, with electric field vector spinning around at some frequency ω
- Interacting with particle gyrating around static magnetic field at gyrofrequency Ω_c
- If handedness and frequency of wave and particle gyration match, then particle experiences a steady electric field in its frame of reference and can take energy from field
- Resonance condition is $\omega=\Omega_c$ (cyclotron resonance)
- Turns out if wave field varies significantly in space across gyroradius, interaction at <u>harmonics</u> $\omega=n\Omega_c$ with n an integer

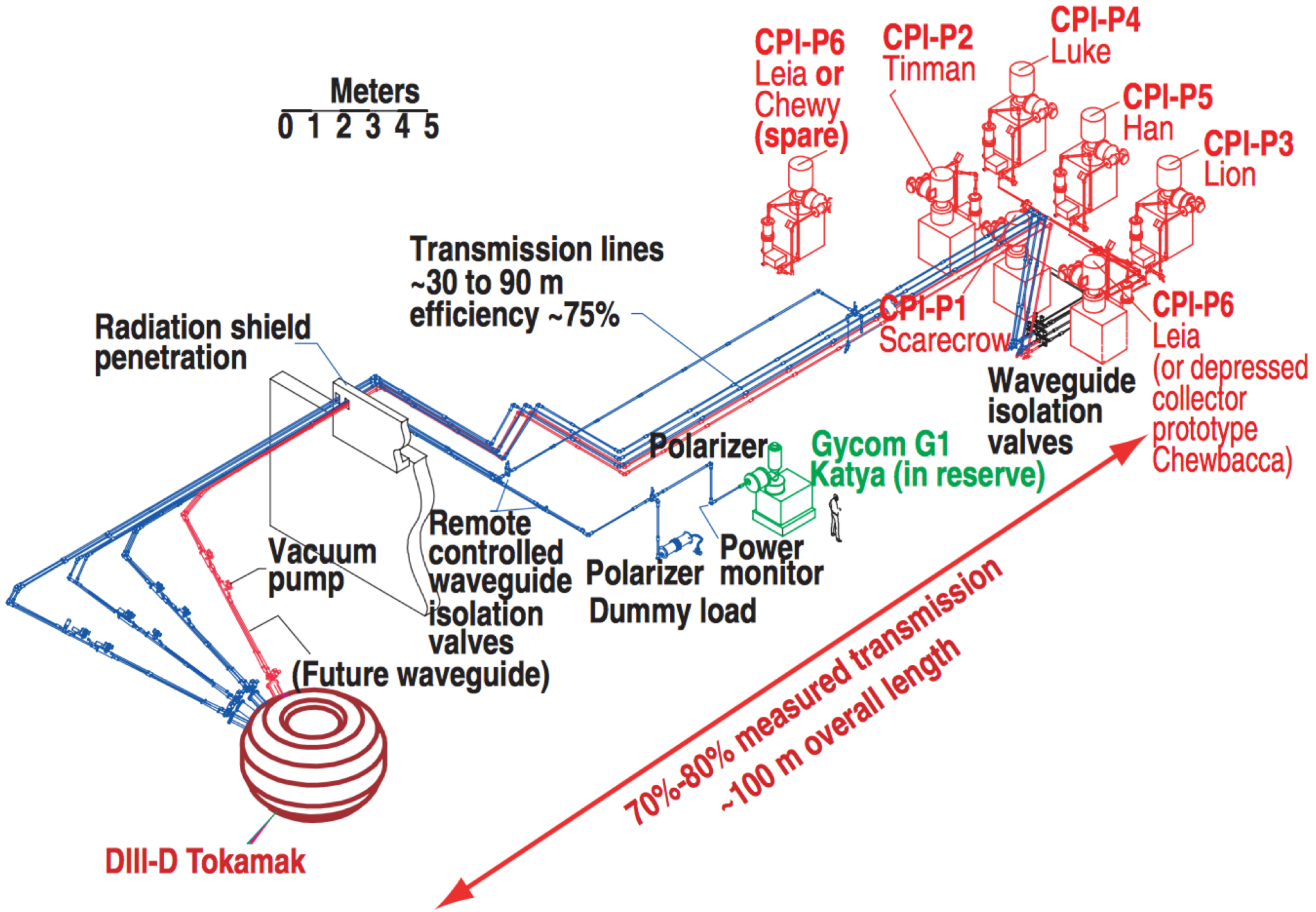
Cyclotron damping works for either ions or electrons, at very different frequencies – consider electrons first

- Numerical value of electron cyclotron frequency is just $f_{ce} = (28\ \mathrm{GHz/T}) \times B_T\ (\mathrm{T})$
- So at the center of DIII-D at 2 T, fundamental electron cyclotron resonance is 56 GHz
- For reasons having to do with wave physics, we use twice this, heating at "2nd harmonic", so we use f=110 GHz or 117.5 GHz at DIII-D for "electron cyclotron heating" (ECH)

ITER 'gyrotron' that produces 1 MW at 170 GHz

Electron Cyclotron Heating (ECH) is nearly the ideal way to heat plasma electrons in a very well-controlled way

- Technology has a lot of important advantages:
  - Gyrotrons can be sited hundreds of m away from torus, in benign, maintainable environment
  - Waves can propagate in vacuum so that launchers do not need to be close to plasma surface
  - Launchers are relatively simple
  - Power deposition can be very well controlled, with 'surgical precision'



Electron Cyclotron Heating (ECH) is nearly the ideal way to heat plasma electrons in a very well-controlled way

- Technology has a lot of important advantages:
  - RF sources can be sited hundreds of m away from torus, in benign, maintainable environment
  - Waves can propagate in vacuum so that launchers do not need to be close to plasma surface
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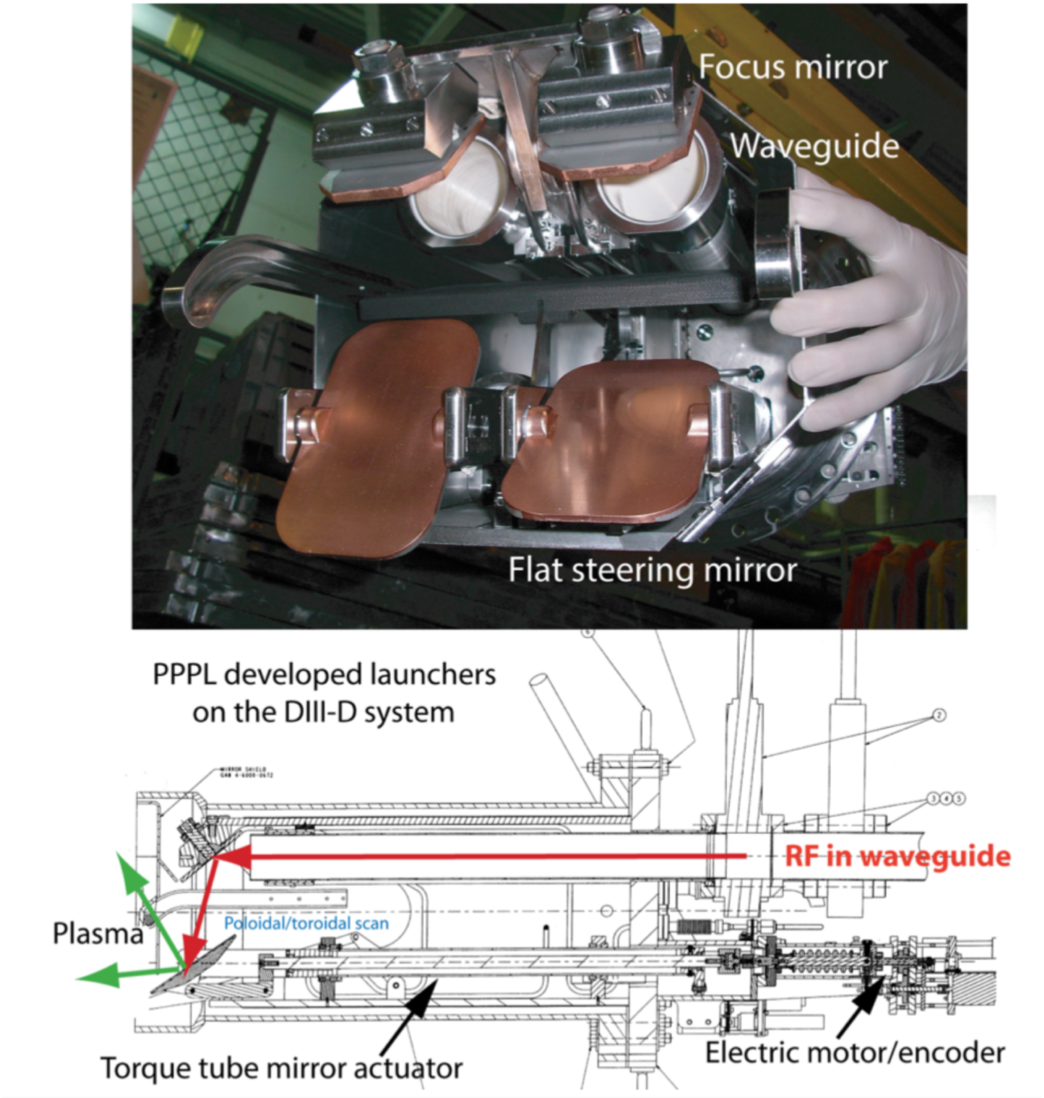
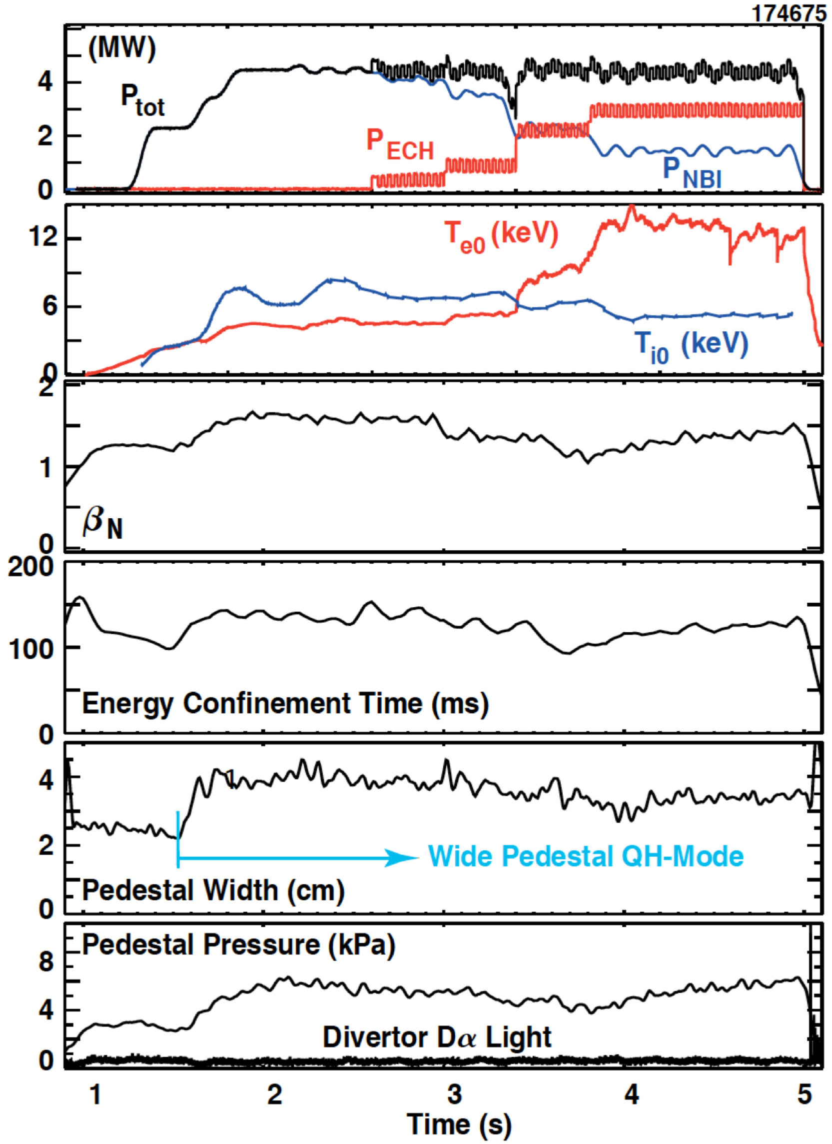


Example of fusion-reactor level electron temperatures in DIII-D achieved with dominant ECH

- Here ~4 MW of NBI is replaced with ~3 MW of ECH, keeping total heating power constant



3 MW 110 GHz ECH +
2 MW 80 keV D NBI

T_e = 12 keV

τ_E ~ 0.14 s

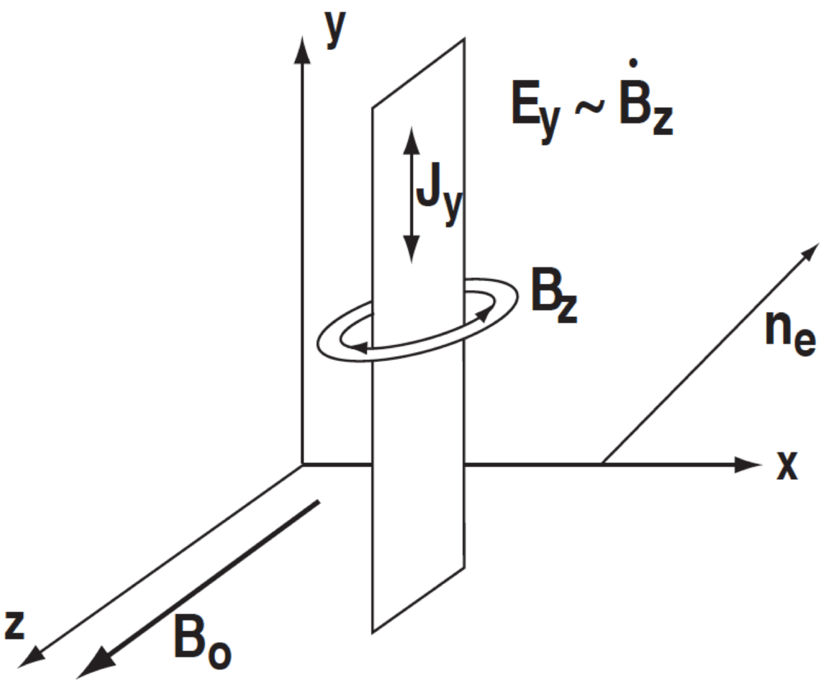
Ion cyclotron heating (ICH) is also a well-established and successful heating method

- Here the cyclotron interaction is with ions gyrating around the field lines, at a much lower frequency than ECH due to the ion mass
- Numerically,
  - $f = f_{ci}$ at $f \simeq 15\ \text{MHz/T} \times B \dfrac{Z_i}{(m_i/m_p)}$

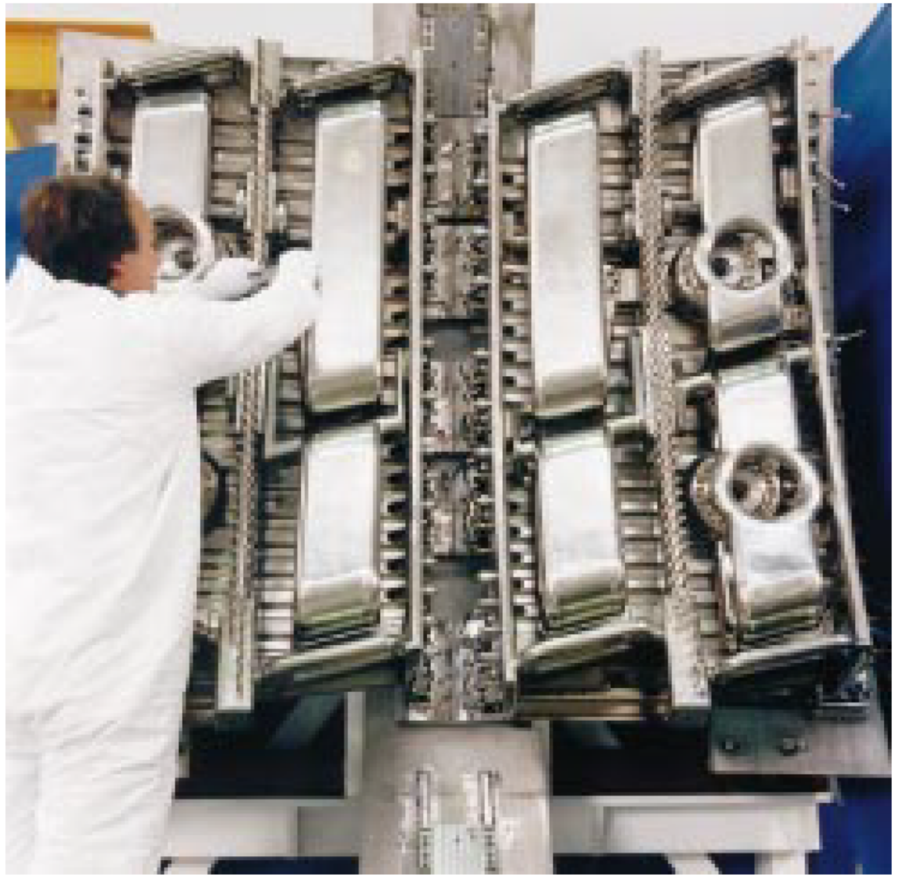
Ion	Z_i	(m_i/m_p)
Proton	1	1
Deuteron	1	2
Triton	1	3
Fully stripped He^4	2	4
Fully stripped He^3	2	3

- So for example if we wish to heat deuterons at their second harmonic, $m_D/m_p = 2$ but n=2, at a magnetic field of 3 T, we would excite waves at f=15 MHz/T x 3 T x (1/2) x 2 = 45 MHz

We excite the waves for ICH inductively with current carrying ‘straps’ near the edge of the plasma



Theorist’s current strap at edge of plasma



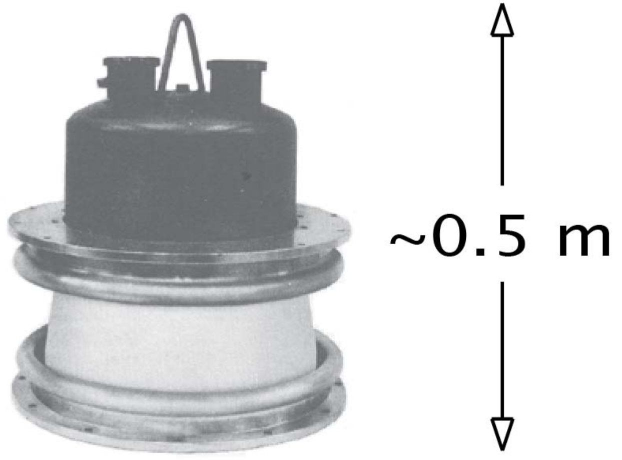
Old JET ICH antennas

RF antenna for launching fast waves in a tokamak

- Antenna oriented to launch fast waves in DIII-D at a very high frequency (not ICH, but Landau damping) of 476 MHz

RF sources and transmission lines for ICH

- Sources used are modified radio transmitters, using a very old type of vacuum tube amplifier called a 'tetrode'
- Transmitters can be very efficient, converting 65% of the prime power to radio waves
- Transmission lines are rigid coaxial lines, so low loss that transmitters do not have to be in the same building as tokamak (see PPPL)

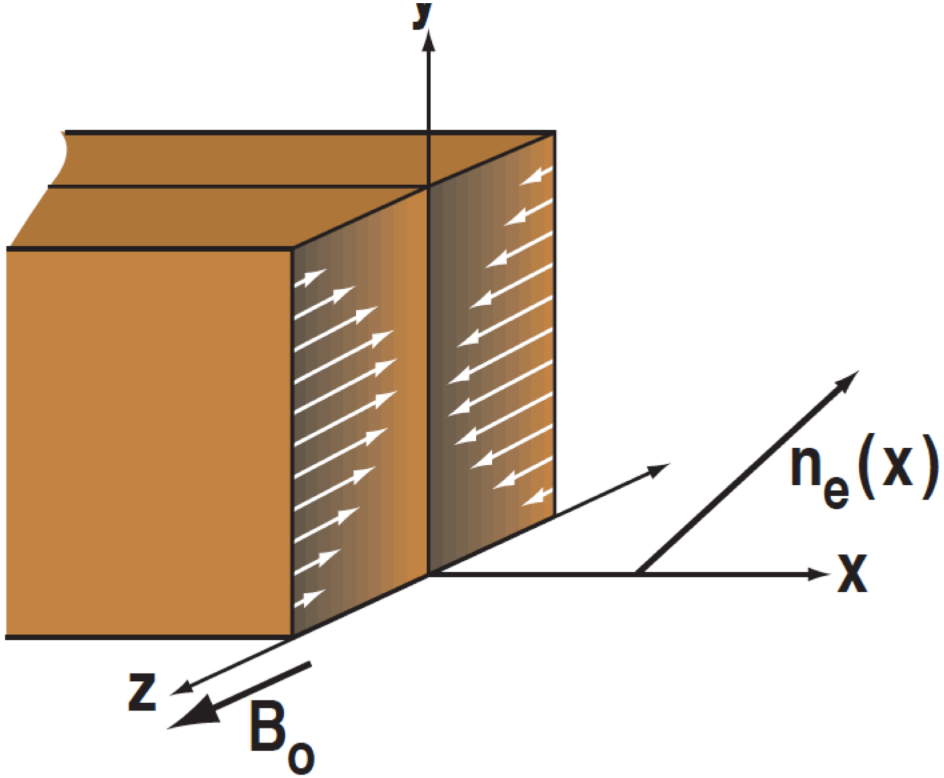


Typical 9" diameter coaxial transmission lines

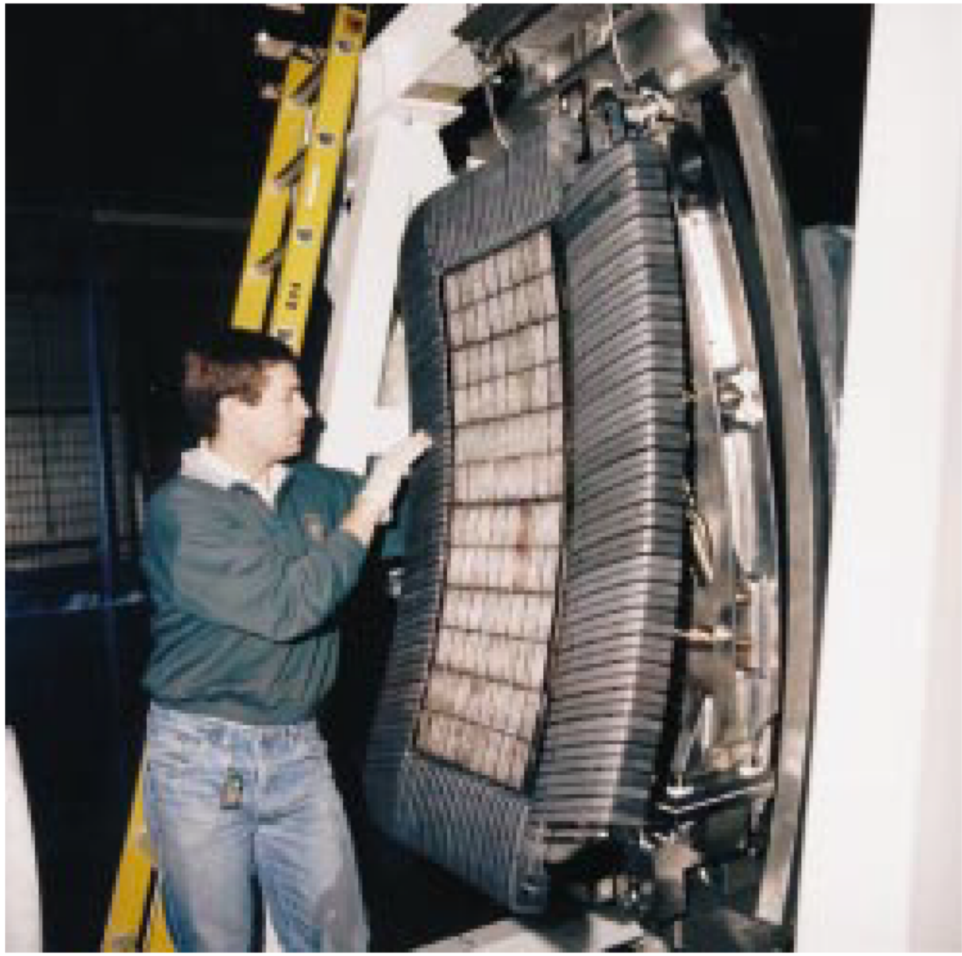
Intermediate frequency waves for electron heating and current drive with Landau damping

- We can also excite waves in the plasma in the range of frequencies near the geometric mean of the electron cyclotron range (hundreds of GHz) and the ion cyclotron range (tens of MHz), around 1 – 5 GHz
- These waves are absorbed when their wavelength along the static magnetic field and their frequency match a few times the electron thermal speed by Landau interaction
- By launching waves mainly propagating in one toroidal direction, we can interact selectively with electrons drifting in that direction, thus driving current non-inductively
- Using waves in this regime called “lower hybrid waves” has proven the most efficient non-inductive current drive method

Lower hybrid waves excited with waveguide array antennas at edge of plasma

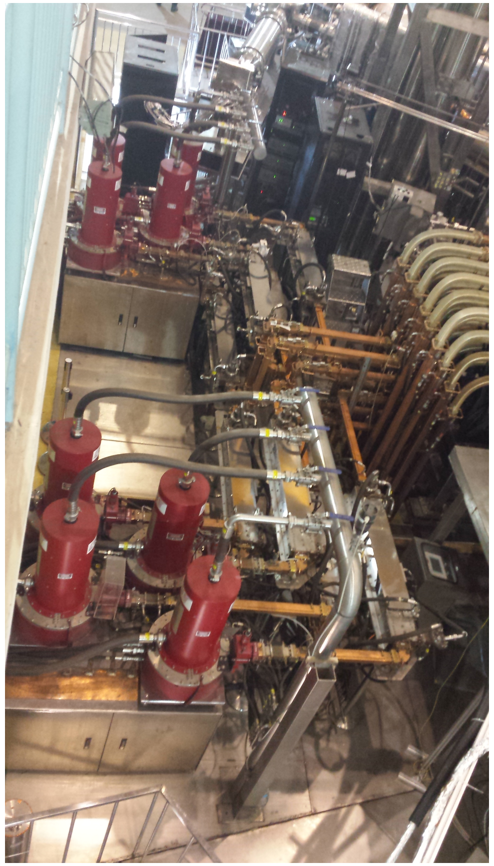


- Theorist's lower hybrid wave launcher at plasma edge

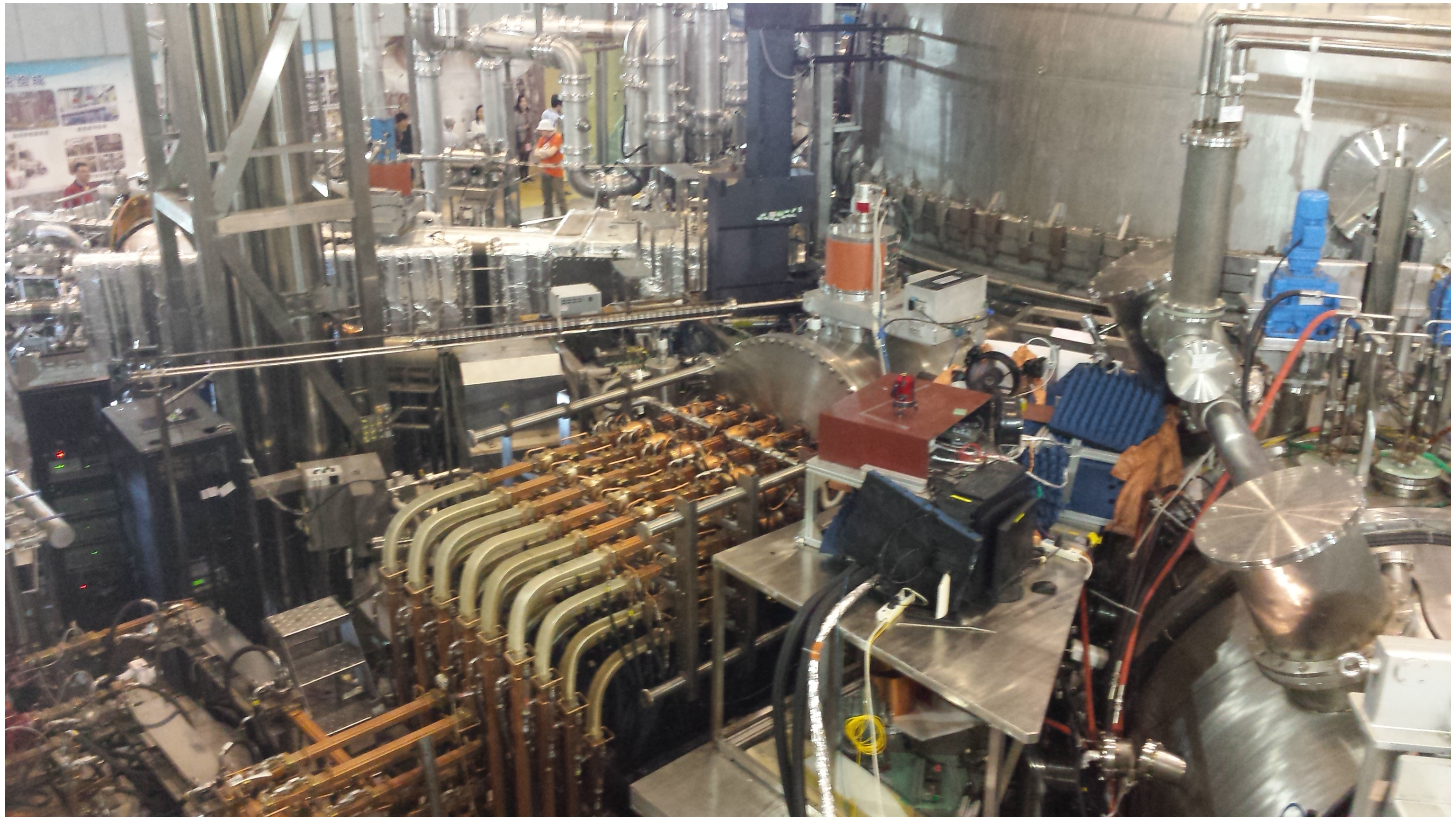


JET LH wave launcher with 384 waveguides

Lower hybrid antennas powered with 'klystron' vacuum tubes, waveguide transmission lines



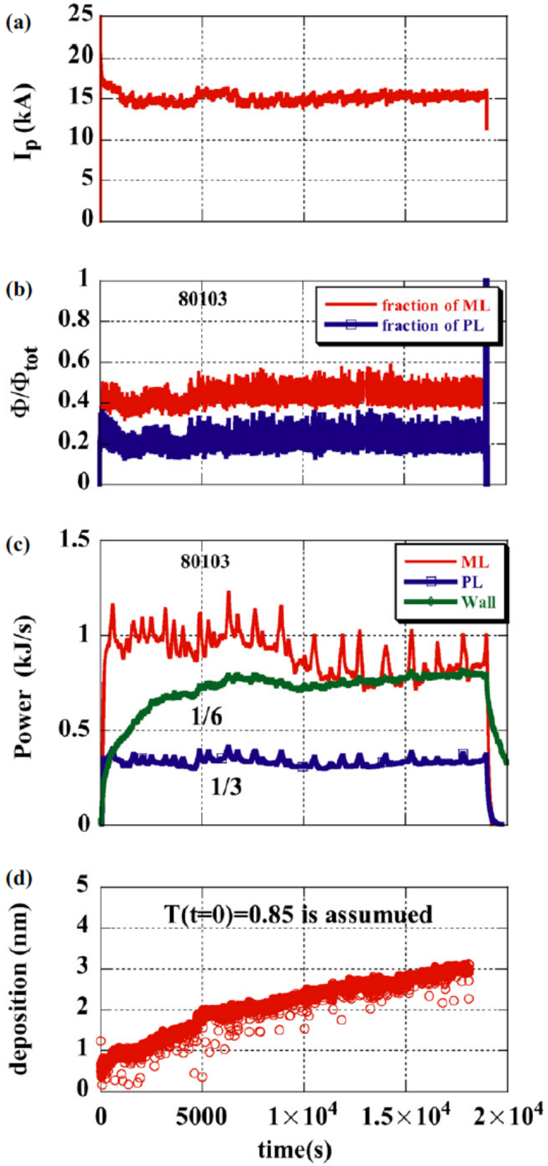
8 x 0.25 MW
4.6 GHz
klystrons



- Installation at EAST, Hefei, China (May 2019)

Longest duration tokamak 'pulse': 5 HOURS, 16 minutes (TRIAM-1M, Japan) with LH current drive

- Low density, low current in 6 T superconducting tokamak, a=12 cm
- Much larger currents have been driven with LH, up to MA levels, in larger machines at shorter durations



Conclusions: auxiliary heating in tokamaks

- Development of high-power auxiliary heating has been essential for most of the advances in tokamak physics since the 1970s
- Techniques using neutral beam injection (NBI) and several forms of radiofrequency (RF) heating have been developed around the world, including
  - Ion cyclotron heating (ICH)
  - Electron cyclotron heating (ECH)
  - Lower hybrid current drive (LHCD)
- Some of these techniques have been used on other MFE concepts:
  - ECH, NBI, ICH on stellarators
  - NBI, ECH on magnetic mirrors
  - NBI on RFPs
- All the techniques other than LHCD are being used at ITER