Plasma break-down, ramp-up and flux consumption

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Physics Operators' Course
PPPL
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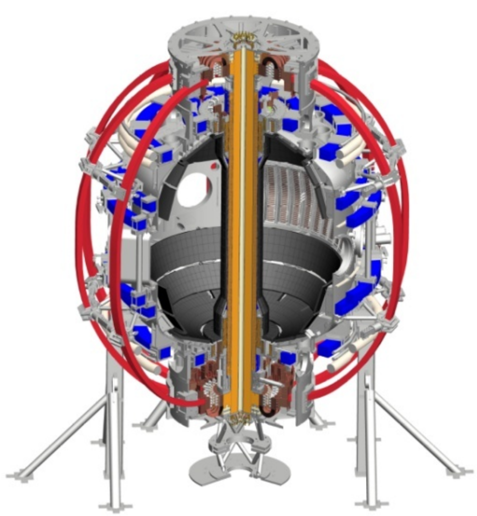


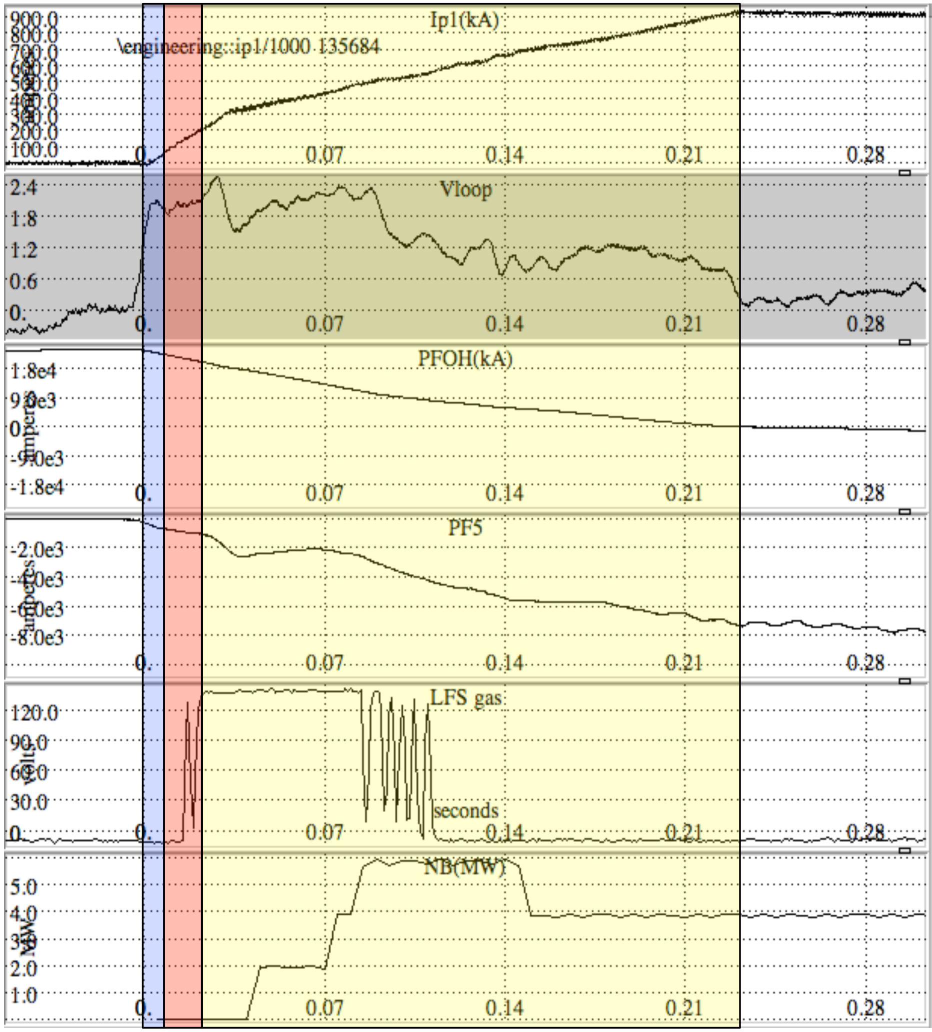
Physics of tokamak plasma start-up

- Central solenoid inductive start-up and current ramp
  - Breakdown/avalanche
  - Impurity burn-through
  - Electron cyclotron radio-frequency assist
  - Examples from EAST, KSTAR, NSTX
  - Early stage of plasma current ramp-up

Inductive start-up can be divided into three phases, break-down/avalanche, burn-through and controlled ramp-up

- Break-down, $T_e < 10$ eV, $j < 35$ kA/m^2, $I_{p(NSTX)} < 35$ kA
- Burn-through, 10 eV $< T_e <$ 100 eV, 30 kA/m^2 $< j <$ 300 kA/m^2
- Controlled ramp-up $I_p > 100$ kA
- Central solenoid provides voltage
- Resistive heating or auxiliary power to heat and ionize low Z impurities
- Vertical field to control plasma radius
- Other Poloidal Field coils - shaping
- Gas puffing for fueling

NSTX



Time (s)

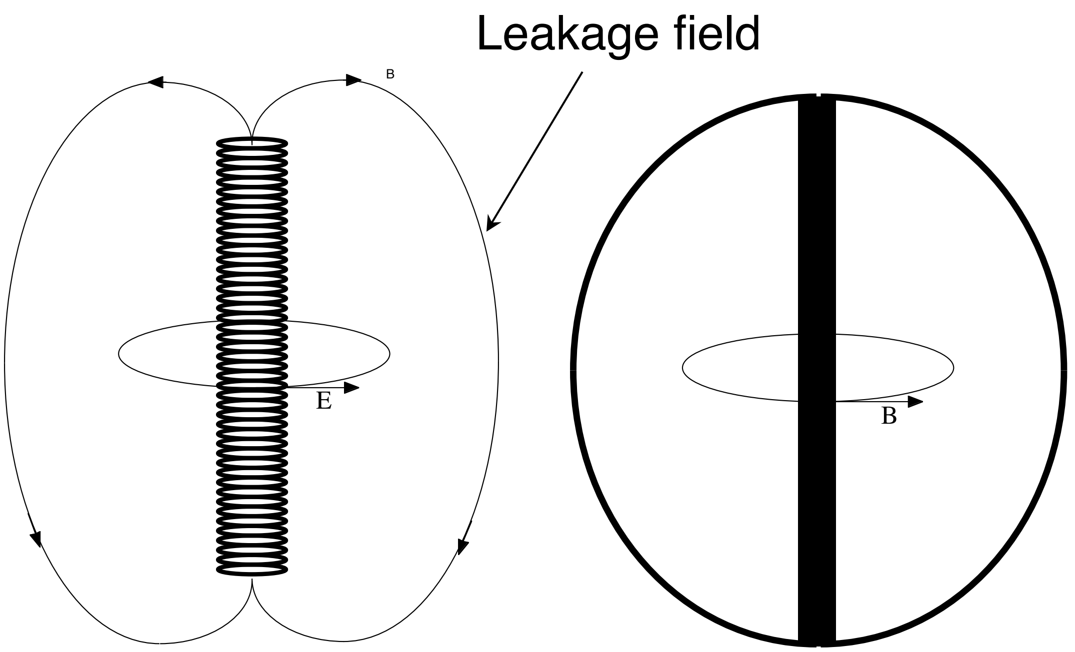
Inductive start-up

- The central solenoid is supplied with a current in the desired direction of the plasma current before t_0
- At t_0, the current is reduced towards zero by action of power supplies (assisted by IR drop)
  - Resistance of coil or for superconducting coils by a resistor inserted into the circuit

$$V_{coil} = V_{ps} - I_{coil} R_{coil+}$$

$$V_{loop} = V_{coil} M / L$$

$$E = V_{loop} / 2\pi R$$



Free electrons are always present, but can be supplemented by ECH, radiation, heated filaments, etc.

Breakdown in a gas, the Townsend avalanche

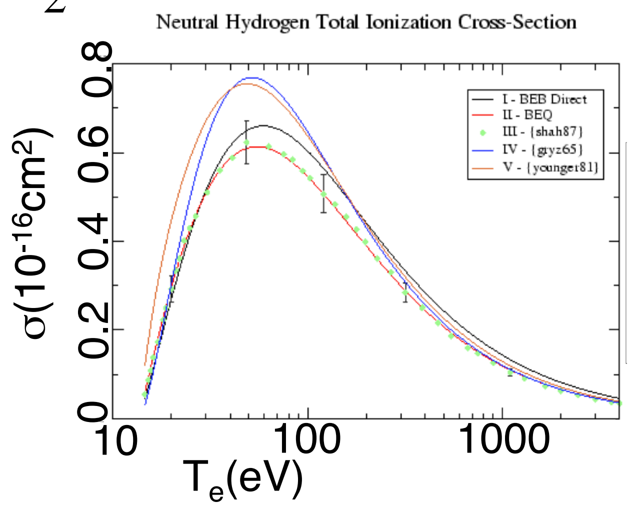
$$F = m\frac{dv}{dt} = qE$$

$$\Rightarrow v_{impact} = \frac{q}{m}Et\Big|_0^{\tau_{coll}} = \frac{qE}{mn\sigma v}$$

$$\tau_{coll} = 1/n\sigma v; \sigma\ ionization\ cross\ section$$

$$mean\ \ free\ \ path\ \lambda = 1/n\sigma$$

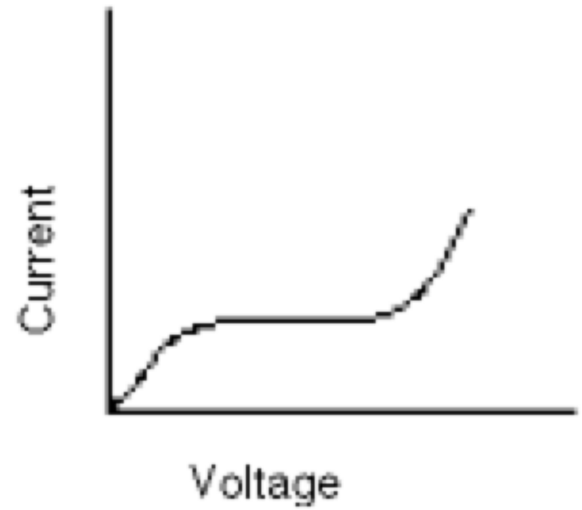
$$\frac{1}{2}mv_{impact}^2 = qE\lambda \geq 13.6eV\,(Hydrogen)$$



• Ionization cross-section peaks at about 50 eV and falls at high energy

From http://physics.nist.gov/cgi-bin/Ionization/ion_data.php?id=HI&ision=I&initial=&total=Y

- For parallel plate electrodes



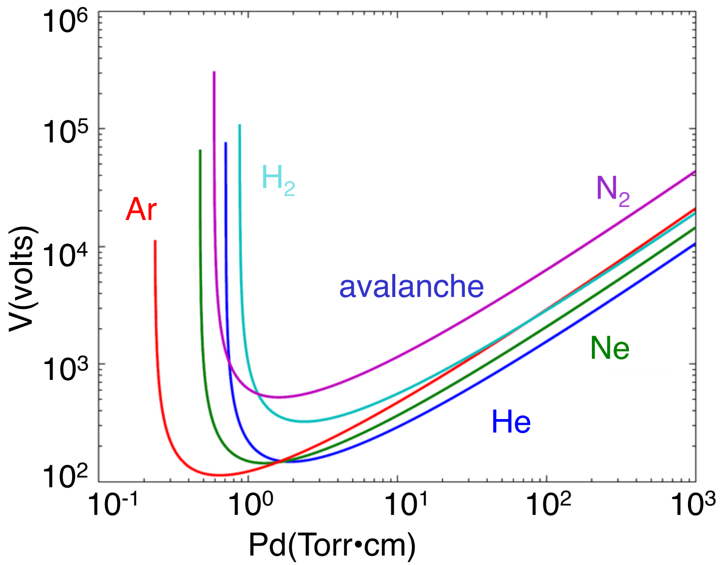
- If an electron produces α new electrons per meter then
- $dn_e = \alpha\, n_e\, dx$
- $n_e = n_e(0)\, e^{\alpha x}$
- α is called the first Townsend coefficient

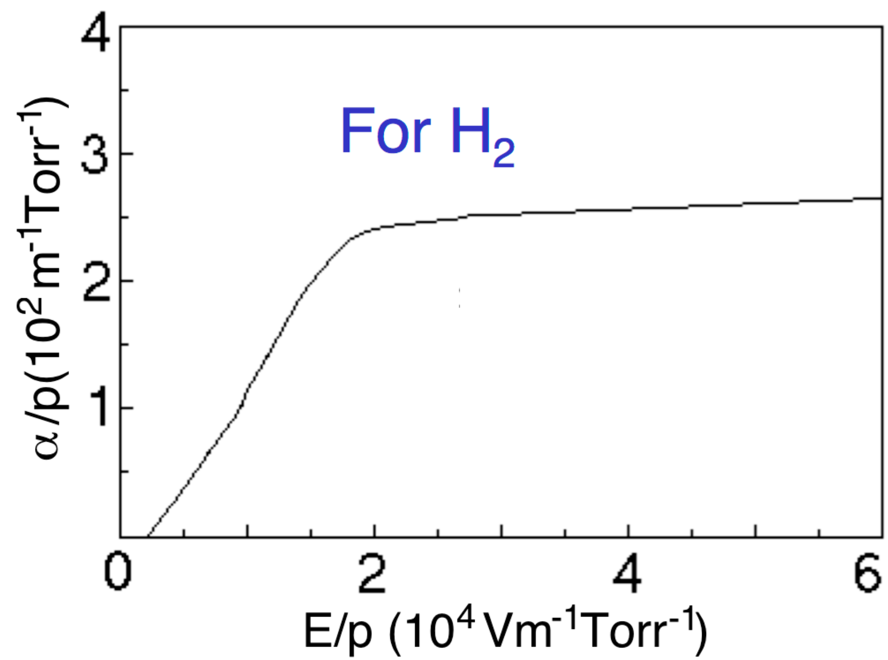
From S.C. Brown, Intro. To Electrical Discharges in Gases, John Wiley and Sons, 1966.

The voltage required for an avalanche depends upon the pressure distance product

The Paschen curve

(from http://ja.wikipedia.org/wiki/ファイル:Paschen_Curves.PNG



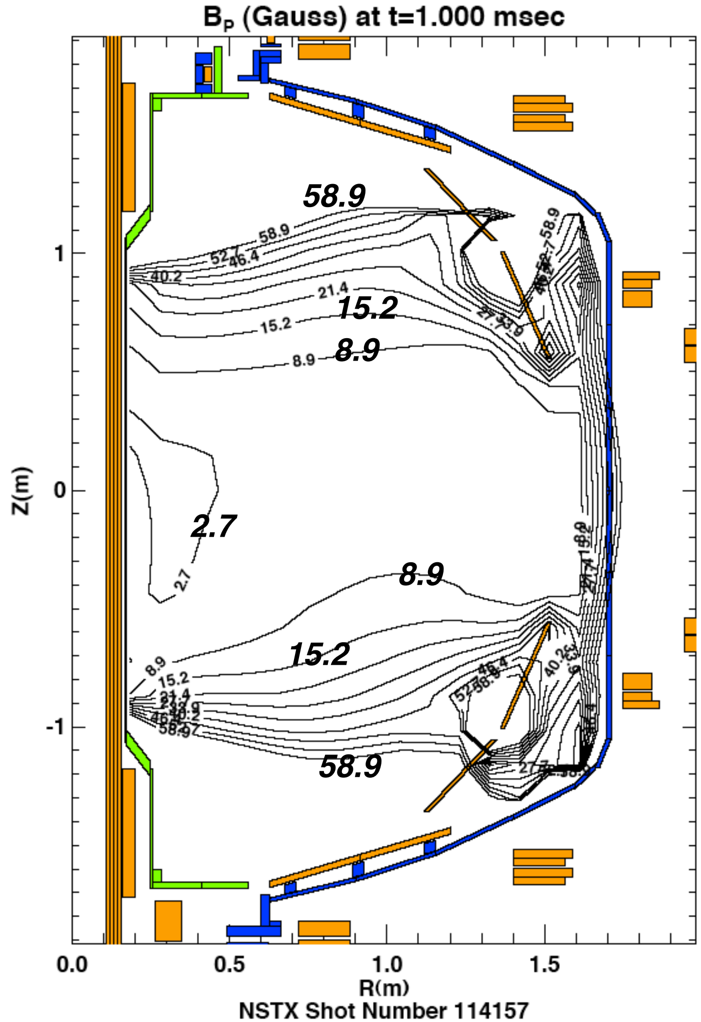


- For NSTX, p ~ 5x 10^{-5} Torr and V_l ~ 2 V/turn
  - For NSTX then α ~ 10^{-2} /m
- Connection length must be > 100 m, many toroidal transits
- For E/p > 5X10^3 V m^{-1} $Torr^{-1}$, T_e is high enough that thermal ionization is important
- This limits T_e to about 10 eV until ionization of the initial gas is nearly complete

R. Papoular, Nuclear Fusion 16 (1976) 37.

Electrons must travel many ionization lengths before being lost if an avalanche is to occur

- Parallel losses
- The stray field connection length, $L \sim h\, B_T/\langle \delta B_z \rangle$ h is the height of the machine $\langle \delta B_z \rangle$ is the average transverse field
  - For NSTX B ~ 4 kG, h ~ 2 m
  - $\langle \delta B_z \rangle \sim 2.5$ to 5.0 G
  - L ~ 3000 m
- The electron drift velocity, v_{de} parallel to the field lines is approximately 35 E/p (m/s)
  - Time to drift to wall ~ 6 ms
  - For ions, v_{di} = 0.9E/p, the time to drift to the wall ~ 150 ms
  - Secondary emission is unimportant
- Lloyd estimates the time to complete the avalanche process as $41/v_{de}(\alpha - L^{-1})$
  - ~ 7 ms



Field null at start-up in NSTX, includes eddy currents
Similar plots can be made for every tokamak

Lloyd et al., Nuclear Fusion, Vol.31. No.II (1991)

Other losses that might stop avalanche from proceeding

- If pressure is too low there will not be enough neutrals to provide electrons for the avalanche to continue

- Guiding center drift velocity
  - $v_D = (1/2v_\perp^2 + v_\|^2)/R\omega_{ce}$; $v_\perp^2 \sim v_\|^2 \sim 3KT_e/2m$
  - $v_D \sim 4$ to 40 m/s
  - Loss time ~ 25 -250 ms > avalanche time

- Taken together for a wide range of devices
  - V_L = 2 to 30 V/turn, E = 0.3 to 2 V/m, with stray fields $B_z/B_T \sim 10^{-3}$ over much of the vessel
  - p = 1-10 x 10^{-5} Torr
  - E/p = .4 to 3 X 10^4 V m^{-1} $Torr^{-1}$
  - Time for avalanche to occur ~ 2 - 50 ms
  - *JET found $E \cdot B_T/dB_z > 10^3$ V/m*

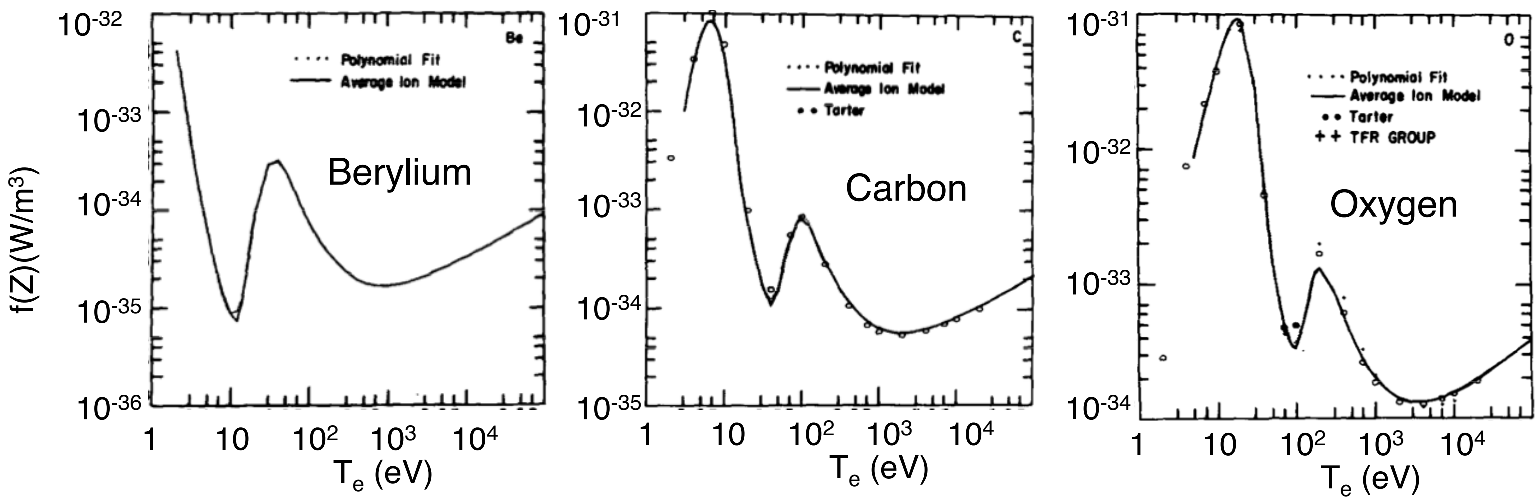
    A. Tanga, et al.in “Tokamak Start-up” H. Knoepfel. Plenum Press, NY (1985)
  - *Consistent with NSTX and DIII-D*

I.H.Hutchinson, J.D.Strachan Nucl. Fusion 14 649(1974)

Avalanche proceeds until electron-ion collisions are the dominate process compared to electron-neutral collisions

- Electron-neutral and electron-ion collision rates equal when $n_e \sim 0.1\ n_0$
- Current density is $j = \gamma\ n_0\ e\ v_d$ where γ is the H or D ionization fraction
  - $j \sim$ 15-40 kA m^{-2}
  - $I_p \sim$ 5 - 10 kA for NSTX, ~ 20 kA for JET
  - For I_p= 10 kA a = 0.5 m, poloidal field $\mu_0 I_p/2\pi a \sim 40$ G
    - Comparable to stray fields
  - At end of avalanche phase, $\gamma \sim 0.5$, Coulomb collisions dominate $j \sim 160$ kA m^{-2} this agrees with $I_p \sim$ 200-400 kA at end of avalanche for JET
- Until ionization is nearly complete, T_e is limited below 10 eV
- Later T_e can be limited by low Z impurity radiation to < 100 eV until the impurities are ionized (latter phase is called burn-through)
  - Burn-through can be a sticking point when either the influx of impurities liberated from the wall or the density is too high
  - For NSTX this can happen at I_p = 100 to 300 kA and limit the current ramp-rate during start-up so discharge fails

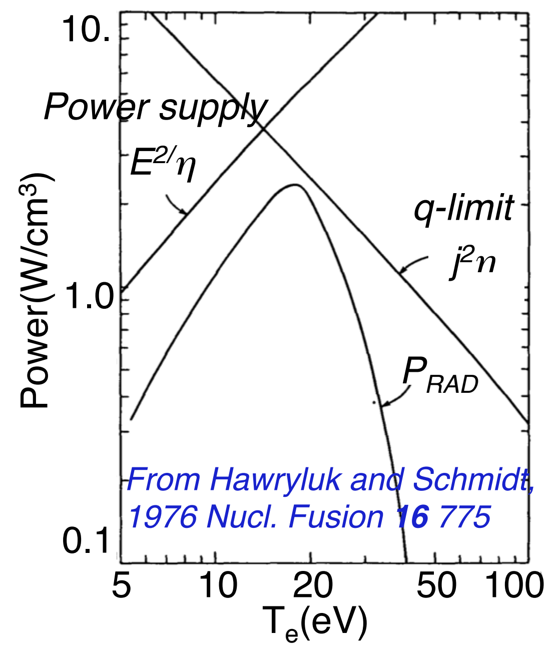
It has been known for a long time that Low Z impurity radiation can cause excessive energy losses at low Te



*From D.E. Post et al., At. Data Nucl. Data Tables **2**, 400, 1977*

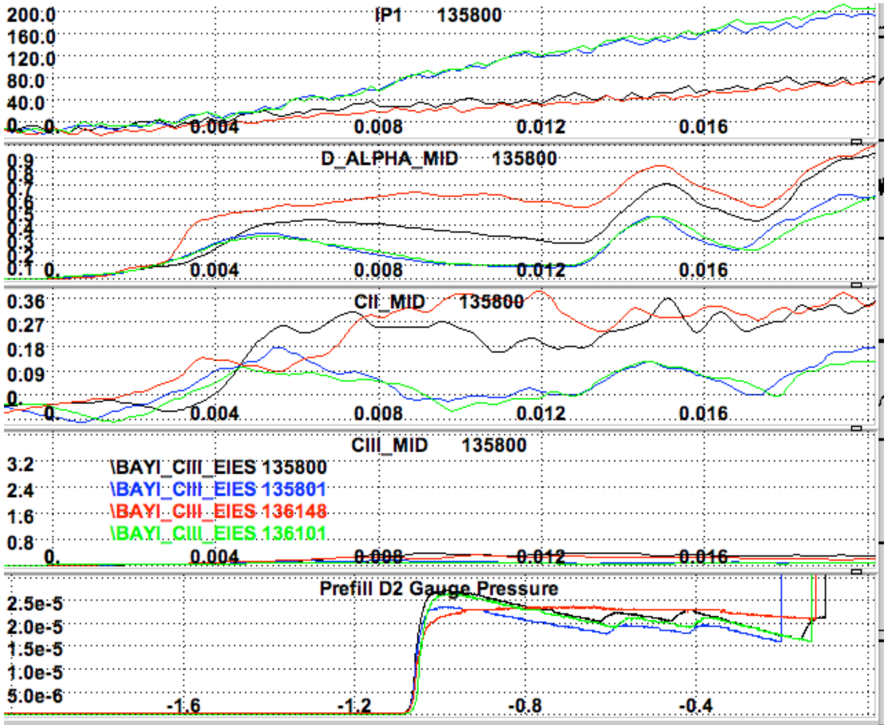
Radiated power $P_{rad} \sim n_e \Sigma n_Z f(Z,T_e)$

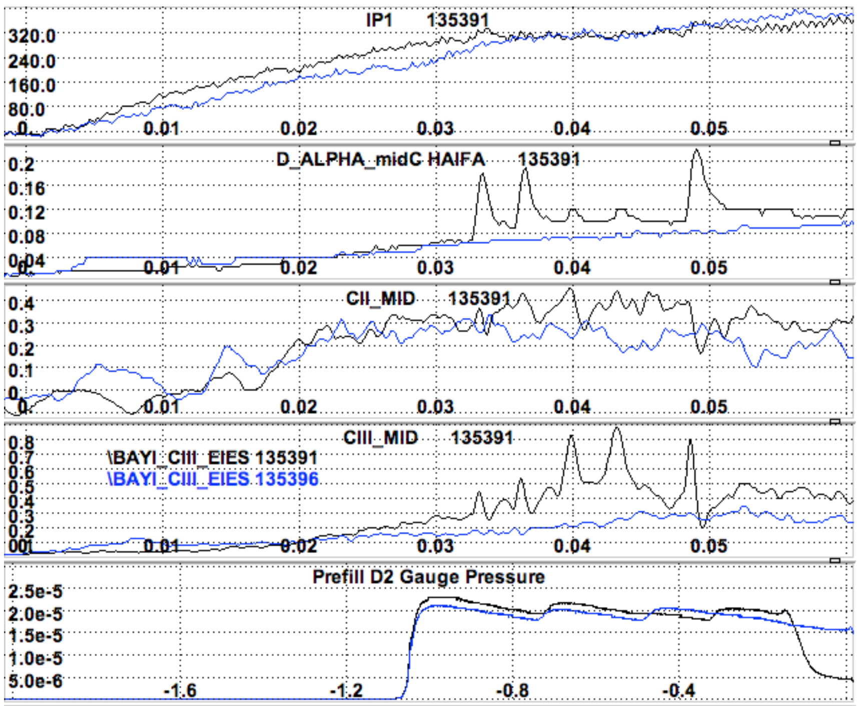
- Coronal equilibrium 3% O with n_e of 3 X 10^{19} m^{-3} V_L (150V)
- *Radiation Barrier: The radiated power must be less than the input power or the discharge will cool and collapse*
- *High Z materials have lower sputtering yields at low T so are less important at start-up*



*From Hawryluk and Schmidt, 1976 Nucl. Fusion **16** 775*

Too high prefill (low E/p) breaks down but fails to start Ip up, too low prefill (or low fueling) gives higher Ip, but instabilities





- *Too high prefill raises Hα and C radiation*
- *Causes I_p to not reach target of 90 kA at 20 ms*

- *Too low prefill does not cause discharge to fail to break-down*
- *2x10^{-6} is enough to make plasma (zero does fail)*
- *Low p has Hα spikes associated with MHD*

Impurity burn through has presented difficulties to most tokamaks, particularly early in the machine's operation

- Solutions employed to minimize impurity influx include
  - High temperature vacuum bake (to 350° to remove water and complex hydrocarbons)
  - Glow discharge cleaning (removes oils and He GDC removes H/D)
  - Boronization (various application techniques, reduces O probably by making volatile compounds with CBH and O)
    - Effect can persist after a vent
  - Lithium coatings (Reduces C, O and H/D)
  - Ti gettering (coats surfaces reduces O, H/D and C)
  - Use of metal walls can limit the source of low Z impurities (ITER plans include Be which radiates significantly less than C or O)
  - More about these on coming slides
- Alternatively auxiliary heating can be employed to burn through the low Z impurities and heat the plasma

Most tokamak experience is with graphite covered walls and limiters and the chemistry of C plays a large role in start-up

Recent exceptions ASDEX-U, C-MOD, JET

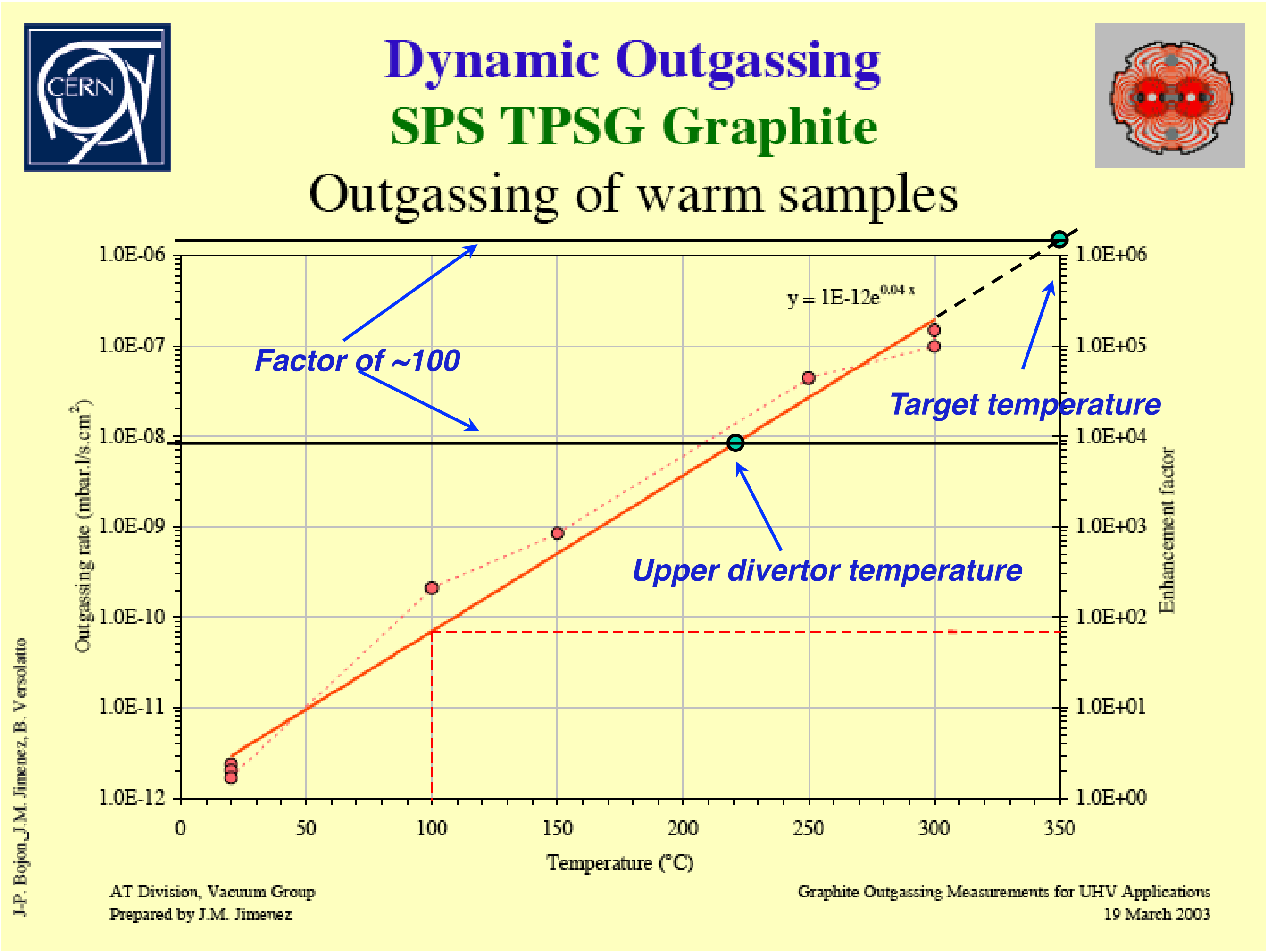
- Graphite can hold about 1 T•l of water per gram
  - About 1 liter of water in a ton of graphite
  - Diffusion rate of water in graphite is very low at room emperature
  - If graphite is not baked the bulk provides a large source of water that will diffuse to the surface when it is heated by the plasma
  - The oxygen in water that comes from the surface can cause a radiation collapse
    - Only surface concentration matters to plasma
    - Diffusion rate increases 10 times for each 60°C rise
    - Experiments indicate 350°C bake in vacuum is needed to remove most of water from graphite*
    - TFTR disruptive discharge cleaning
- Graphite can trap up to about 1 atom of H per atom of C
  - The H is easily sputtered by plasma and sputtered C striking the surface can release multiple H this leads to high density
  - To remove most H from C requires 1000°C bake

**** Bohdanski et al., JNM 162-164 (1998) 861-864.***

Why do we bakeout?

Bakeout raises water outgassing rates from Carbon by an order of magnitude per 60°C

- 1day at 350° = 100 days at 220°C = 1400 years at room temperature

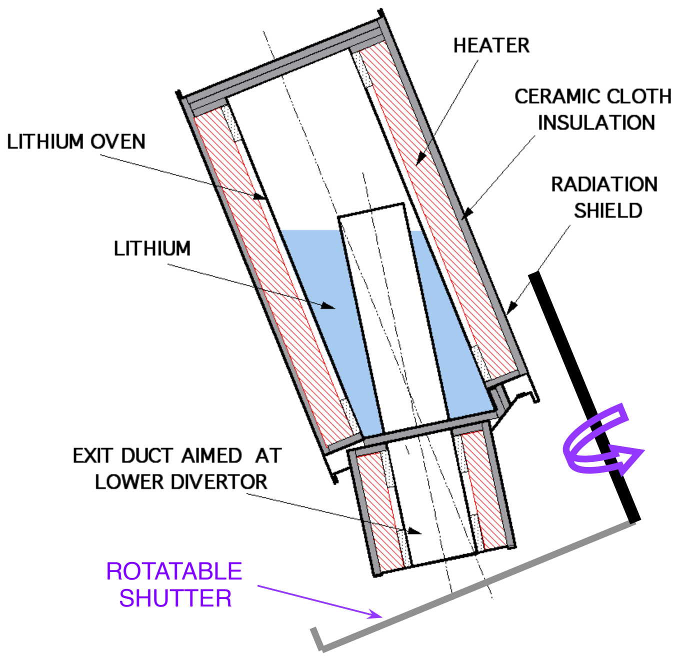


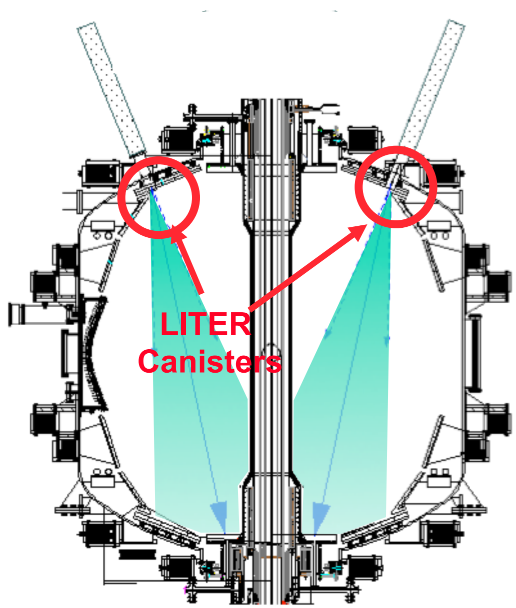
Glow Discharge Cleaning and Boronization

- In past, performed extensive glow-discharge cleaning to remove contaminants and residual plasma constituents from PFCs
  - 2 stainless-steel anodes at Bays G, K on outer VV near midplane
  - ~3 A total current at ~550 V with gas pressure 2 - 5 mTorr
  - Deuterium GDC used to remove oxygen-bearing contaminants at end of bake
  - Helium GDC to remove hydrogenic species
    - After DGDC (~2hr); at start of each run day (30min); between shots (7–15 min)
- More recently, eliminated DGDC and cut back on HeGDC
- Also used "boronization" at end of bake and periodically during each run
  - Run GDC in mixture of 5% deuterated trimethyl boron (TMB - $(CD_3)_3B$), 95% He
  - Generally used half or full bottle containing 10 g TMB over 2 - 3 hours
    - TMB is toxic, pyrophoric, expensive (bottle costs ~$3K)
  - Apply ~1hr pure HeGDC afterwards to deplete D from deposited B/C/D layer
  - B has high affinity for oxygen and sequesters it as borates (or makes it volatile)
  - B layer does not sequester impinging hydrogenic species significantly

Dual LITERs Replenish Lithium Layer on Lower Divertor Between Tokamak Discharges

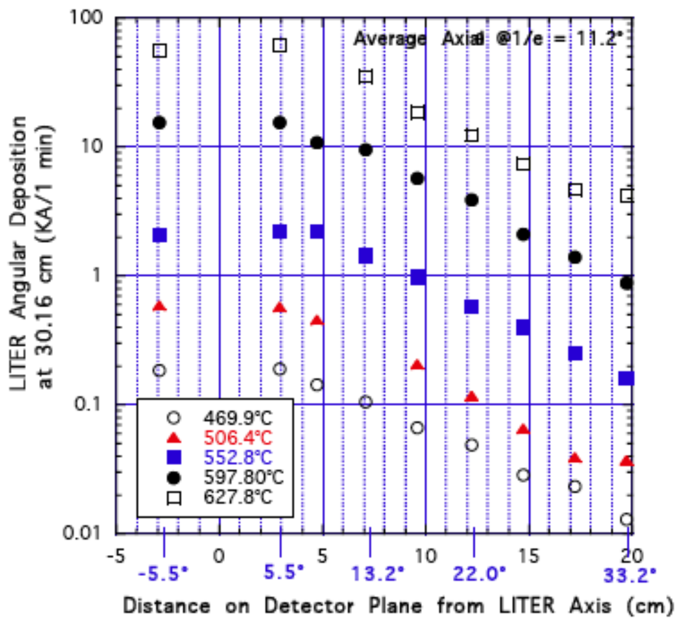
- Electrically-heated stainless-steel canisters with re-entrant exit ducts
- Mounted 150° apart on probes behind gaps between upper divertor plates
- Each evaporates 1 – 40 mg/min with lithium reservoir at 520 – 630°C
- Rotatable shutters interrupt lithium deposition during discharges & HeGDC
- Withdrawn behind airlocks for reloading and initial melting of lithium charge
- Reloaded LITERs 6 times during 2009 run (Mar - Aug): ***~250g on PFCs***



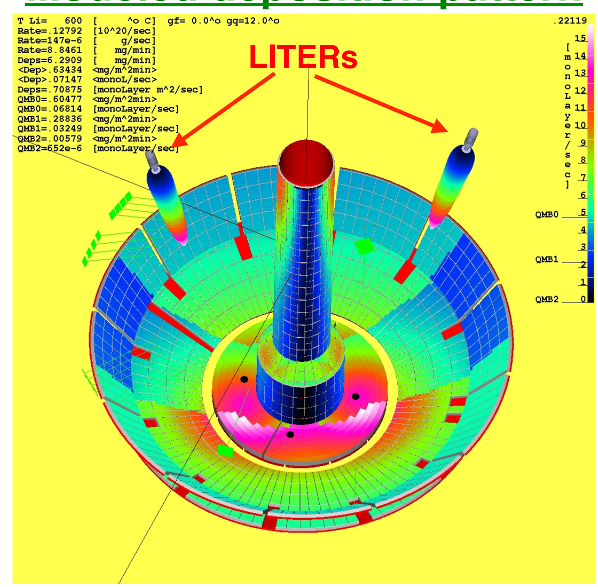


Dual LITERs Deposit Lithium on Lower PFCs Including Divertor Plates

- Measured deposition pattern in laboratory tests with scannable quartz-crystal micro-balance (QMB)
  - Plumes of lithium vapor are roughly Gaussian in angular distribution
  - Good agreement with model based on molecular flow through exit duct
- Lithium applied between discharges typically 20 – 600 mg
  - More than needed to react all injected D_2, typically 5 – 15 mg
- In-situ QMB data implies deposited lithium thickness is 5 – 160 nm on inner divertor plate near strike point of standard NSTX plasmas

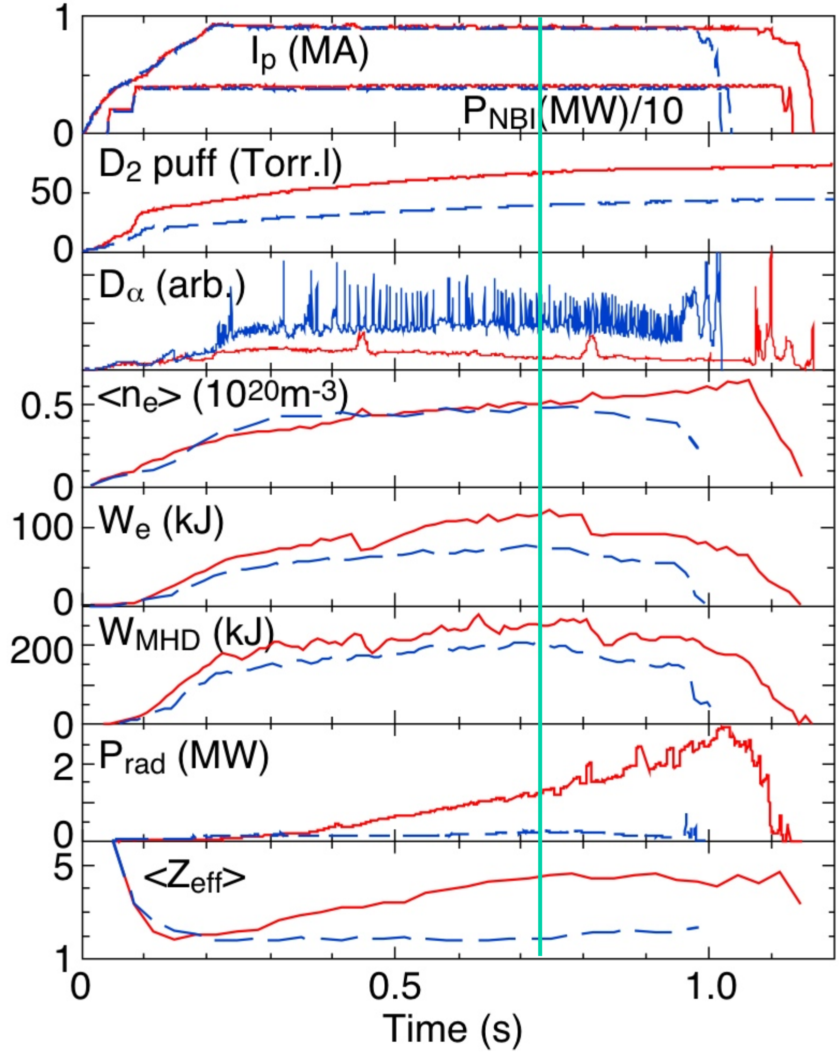


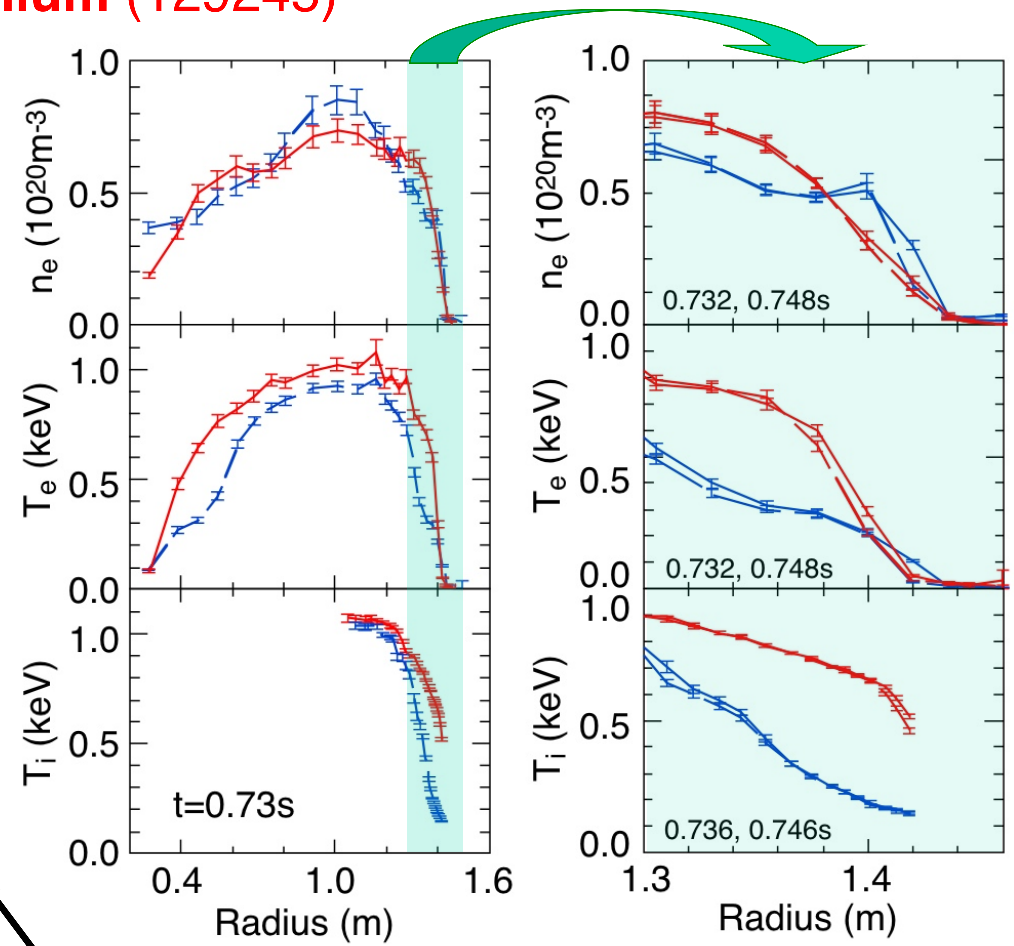
Modeled deposition pattern



Lithium Coating Reduces Deuterium Recycling, Suppresses ELMs, Improves Confinement

No lithium (129239); **260mg lithium** (129245)

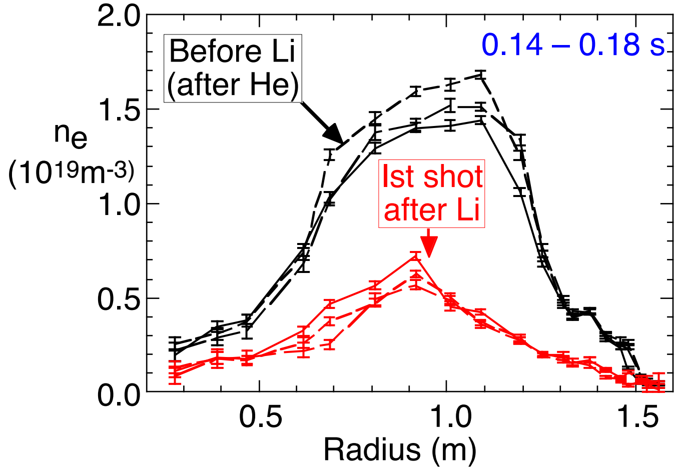




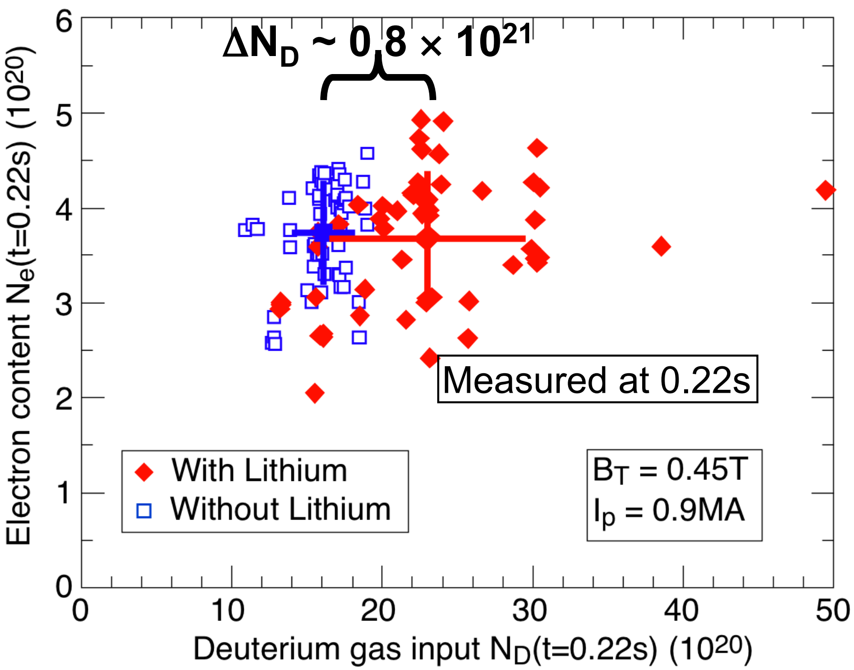
Without ELMs, impurity accumulation increases radiated power and Z_{eff}

Solid Lithium Does Pump Deuterium but Normally We Increase Fueling to Avoid Early Locked Modes

CS Limiter D discharges
(0.9MA, 0.45T, 4MW NBI)
with same gas fueling after
Helium conditioning and
lithium pellets (**~30mg**) injected into
preceding 10 OH He discharges



2008-9 **LSN discharges**
100 – 600 mg fresh Li from LITER
(25 – 160 nm thick at inner divertor)



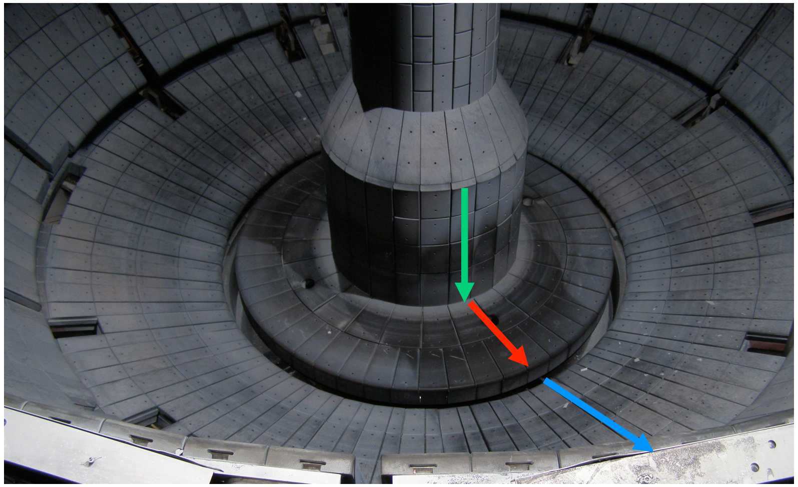
Tangentially viewing camera for edge D_α emission shows greatly reduced neutral D density across outboard midplane with lithium from LITER

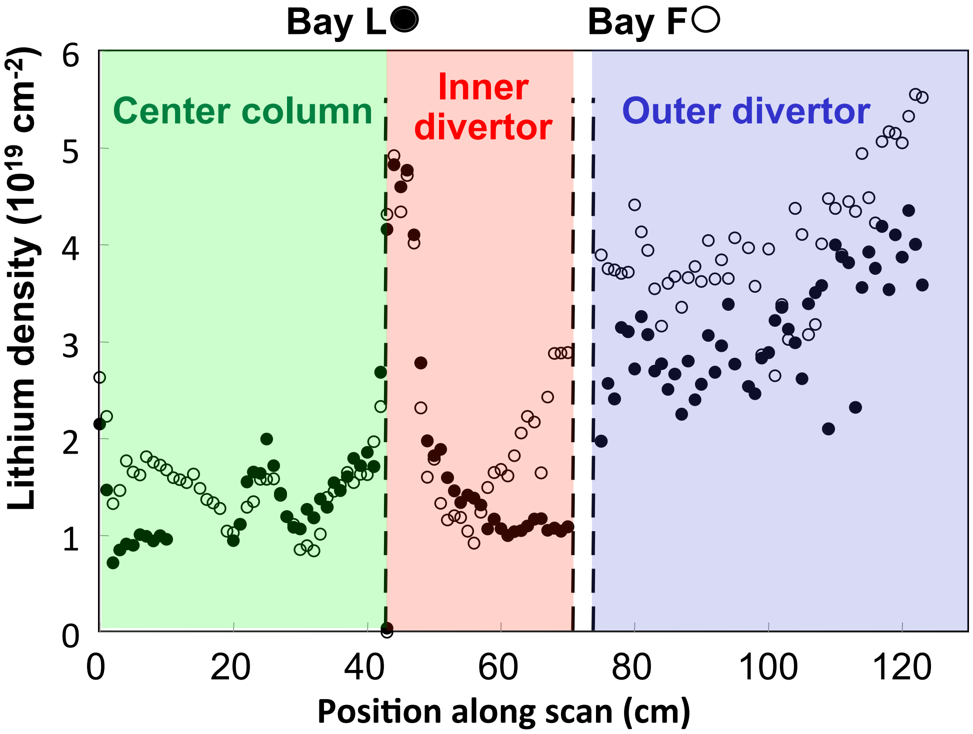
Lower density *is* achievable early in discharges but likelihood of deleterious locked modes increases: *we need to learn to avoid locked-modes to exploit lithium*

Analysis of Carbon Tile Surfaces Confirms Migration of Lithium Under Plasma Fluxes

- Analysis performed on surface of carbon tiles as removed from vessel
- Used ion-beam nuclear-reaction analysis for lithium and deuterium areal density in surface layer

Scan across lower divertor



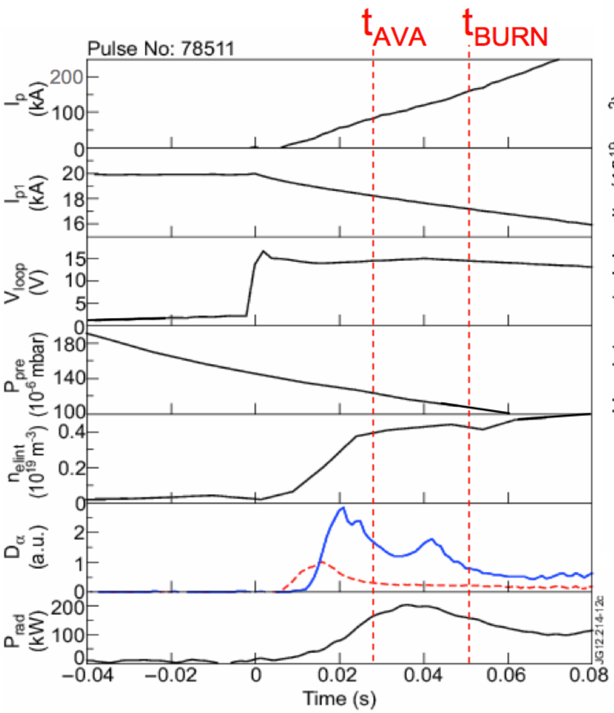


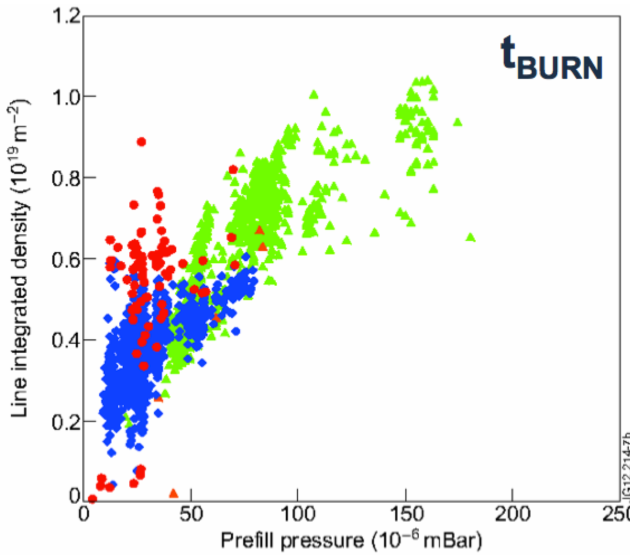
Peak lithium density remaining on inner divertor ~0.6 mg·cm^{-2}

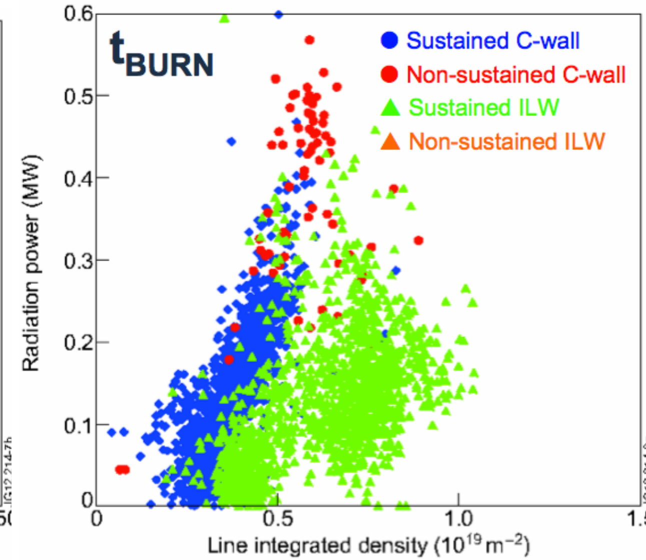
Total deposition there estimated at ~8 mg·cm^{-2}

Less than 1% of deposited lithium remains in high heat flux region

JET ITER-Like Wall: the density at the time of burn-through depends on fill pressure, and the radiated power depends on the wall







- For discharges with similar start-up conditions V_{loop} =12 V, E = 0.8 V/m
- At t_{AVA} the density is prefill pressure for ILW and C-Wall
- At t_{BURN} the density is prefill pressure + some extra for C-Wall
- At t_{BURN} radiated power is a steep function of density for C-Wall
  – No non-sustained breakdowns with ILW due to deconditioning

P. deVries, 25th IAEA, SanDiego, EXD4-2(2012)

Recently H-T Kim developed a model (DYON) that uses a dynamic recycling and sputtering model for JET start-up

- Deuterium confinement time τ_D

  $1/\tau_D = 1/\tau_{D,\parallel} + 1/\tau_{D,\perp}$

- The rotational transform will increase the effective distance to the wall as Ip increases *so*

  $$L(t) \sim (0.25\, a(t)\, B_T/B_z(t)\, \exp(I_p(t)/I_{ref}))$$

  - I_{ref} is chosen so the plasma's poloidal field exceeds the stray field

- The deuterium confinement time due to parallel particle loss is

  $\tau_{D,\parallel} = L(t)/C_s$ where C_s is the sound speed $(T_e + T_i)^{1/2}/m_D$

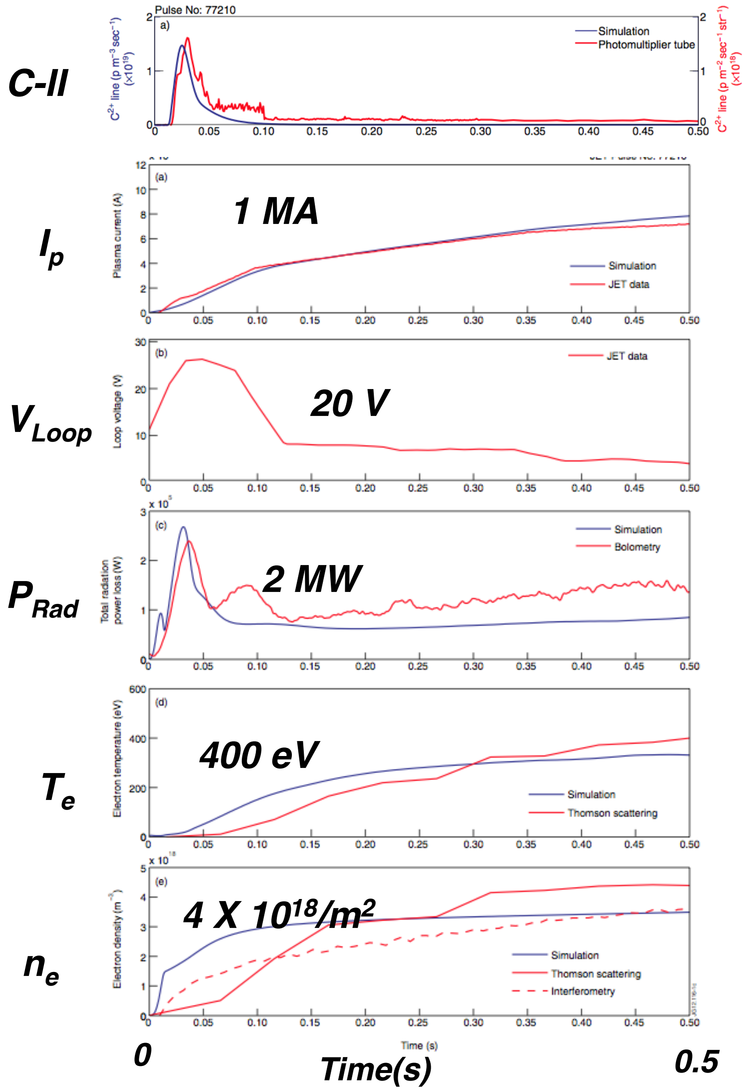
- For Perpendicular transport use Bohm diffusion

- A dynamic recycling coefficient is used for deuterium

- Physical sputtering and a simple chemical sputtering model is used: O→ C+O and C + 4D→ CD_4

Hyun-Tae Kim, W. Fundamenski, A.C.C. Sips et al.Nucl. Fusion 52 (2012) 103016

Model results agree well with experiment and demonstrate the importance of including the parallel loss



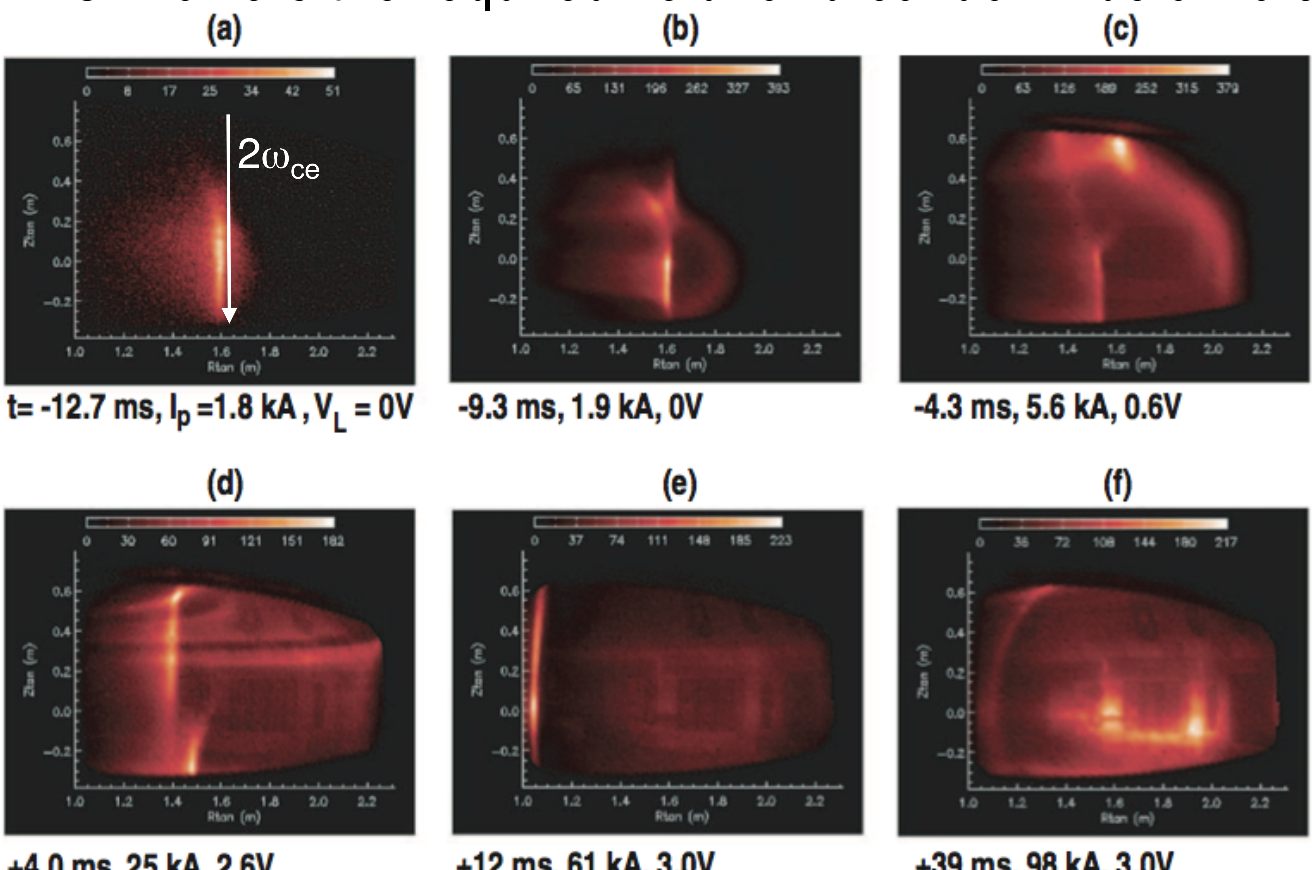
- Blue lines indicate simulation results
- Red curves on the plots are JET data

- The temporal agreement for the C-II emission gives confidence that impurities are being well-modeled
- The time evolution of the C charge states in the model indicates from 0.15 s on C is fully ionized
- The early density discrepancies may be due to geometrical effects
- This recent start-up model is self-consistent and includes the important time evolution of impurities from the wall due to sputtering by plasma ions

Hyun-Tae Kim, W. Fundamenski, A.C.C. Sips et al.Nucl. Fusion 52 (2012) 103016

ECRH has been used on many devices to provide pre-ionization and electron heating during start-up

- 2^{nd} Harmonic X-Mode (E⊥B) and fundamental O-Mode (E||B) launched from the low field side can access the plasma
- Use of ECH lowers the required field for breakdown below 0.3 V/m

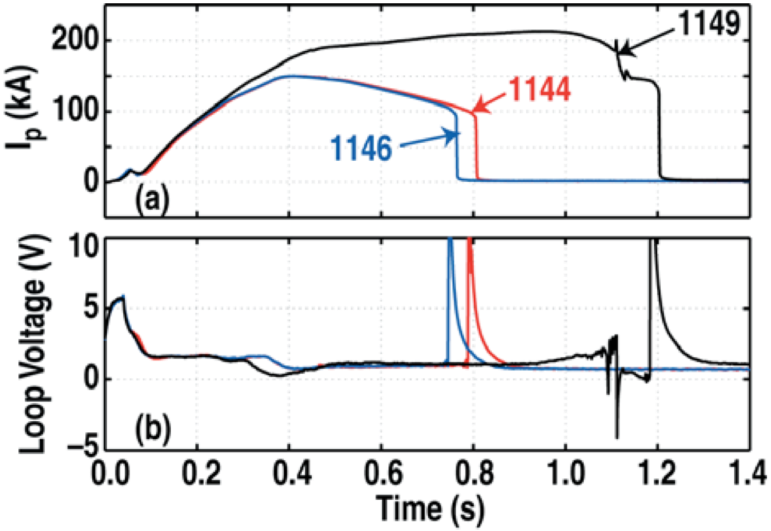


Fast-framing camera of C^{III} emission during 2^{nd} harmonic ECH in DIII-D

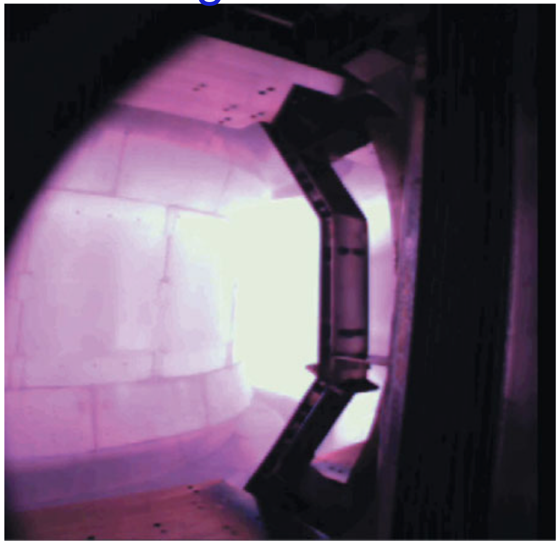
G. L. Jackson PhysPlasmas_17_056116 (2010)

Causes of discharge failure are not always obvious

EAST First Plasma



CCD image just after break-down suggests failure to burn-through



- The start-up of the first plasma on EAST
  - Early attempts disrupted at I_p ~ 35 kA at 70-100 ms, unclear why
  - The breakdown resistors were in the circuit for 100 ms
  - Mutual from central coils exceeded vertical field power supply capability (which have since been upgraded)
- Model predicted more negative vertical field than achieved
- Camera images indicate plasma was at large R
- Failure was due to too small vertical field
- Shortened the breakdown resistor time to 50 ms

*From J. Leuer, et al., Fusion Science and Tech.. **57** 2010*

For all tokamaks it is essential to apply the proper vertical field and to have a vertically and radially stable field pattern

Vertical field (circular plasma)

$$B_z = -\frac{\mu_0 I_p}{4\pi R_0}\left[\ln\left(\frac{8R_0}{a}\right) + \frac{l_i}{2} + \beta_p - \frac{3}{2}\right]$$

$$\beta_p \sim 0.1,\ l_i = \frac{2}{\mu_0^2 R I^2}\int B_p^2 dV \sim 1$$

Radial Field

$$B_r = -n\frac{B_z}{R_0}\left[Z - Z_0\right]$$

Field index n

$$n = -\left(R/B_z\right)\left(\partial B_z/\partial R\right) \Rightarrow 0 < n < 3/2$$

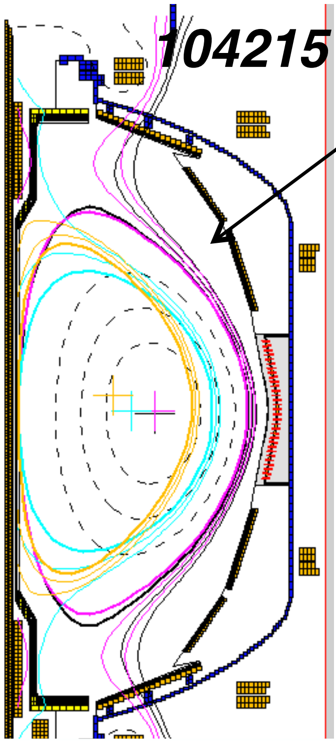
- KSTAR has ferromagnetic material in the coil jackets
- Higher vertical field at small R which increases field index
- Important effect for field null and low B_z
- Plasma start-up variability, particularly smaller R, sometimes resulted in radial instability before the effect of magnetic material was considered
- Modifying the start-up field pattern to account for ferromagnetic effects produced a more stable configuration
- Greatly improved reliability when implemented in 2010 and allowed ohmic start-up without ECH for the first time in KSTAR

J. Kim, Nucl. Fusion 51 (2011) 083034

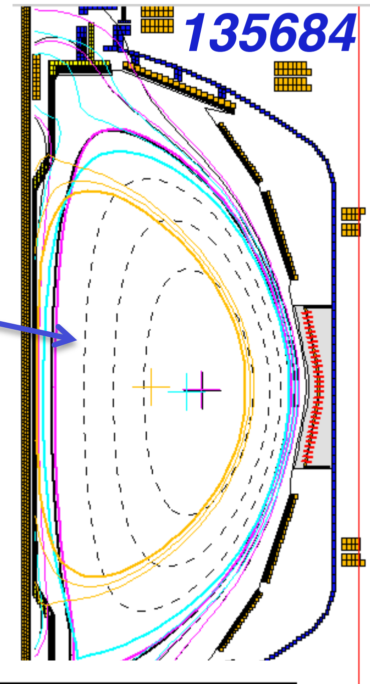
Start-up is dependent upon wall conditions

- NSTX performs HHFW heating experiments, often using He as the working gas (with D prefill) to achieve reliable density and antenna loading
- After a series of He discharges, the D recycling is low and plasma is nearly all He
- This low recycling can result in behavior like with the JET-ILW that requires fueling to increase the density
- On at least two occasions on the first plasma shot following a day of He HHFW experiments, runaway discharges were formed (low n_e, very high T_e)
- The hard X-rays caused by the energetic electrons hitting the wall resulted in damage to electronics in the test cell

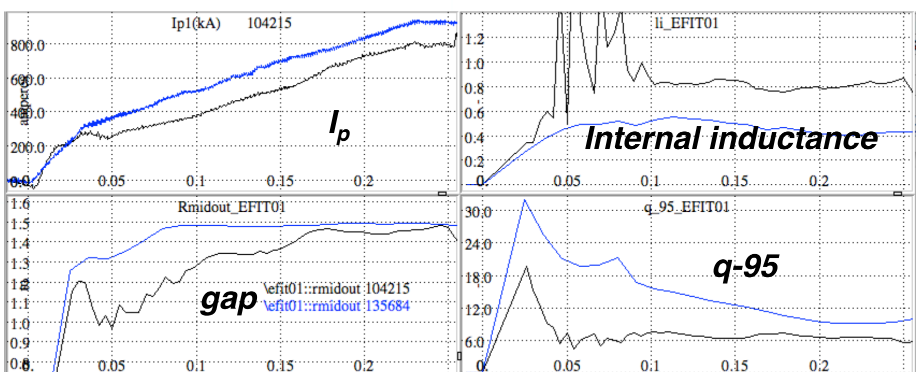
The choice of plasma growth strategy determines the current density profile evolution

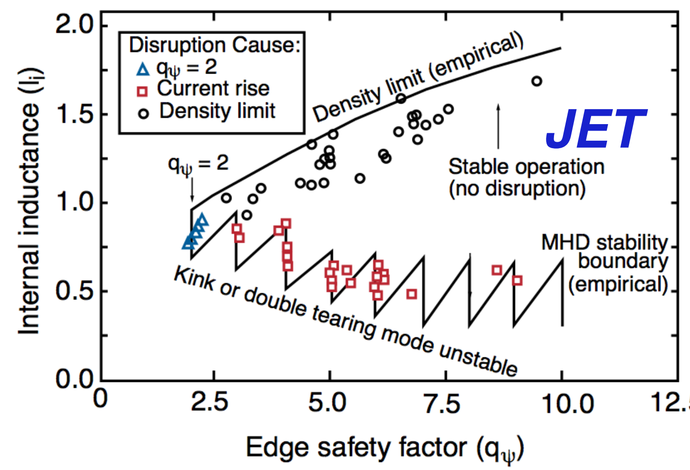


- Constant q growth realizes fully evolved j(r) profiles earlier and has higher internal inductance, l_i
- Full aperture scenario has broader j(r) and minimizes l_i
- Each strategy is affected by ramp-rate, impurities and heating power and timing typically, $dI_p/dt < 0.5$ MA/s



NSTX EFIT at 25 100 175 250 ms





Wesson, J., et al., Nucl. Fusion 29 (1989) 641.

Volt-second (flux) consumption

NSTX seldom runs with no auxiliary power so data for purely inductive flux consumption is sparse

Menard, Nucl. Fus. ***41*** *(2001)* ***summarizes early NSTX results***

Total poloidal flux

$$-\Delta\Phi_S(t) \equiv \int_0^t V_S dt' = \Delta\Phi_I(t) + \Delta\Phi_R(t)$$

where

$$\Delta\Phi_I(t) = \int_0^t \frac{dt'}{I_p} \int \frac{\partial}{\partial t}\left(\frac{B_P^2}{2\mu_0}\right) dV \qquad \Delta\Phi_R(t) = \int_0^t \frac{dt'}{I_p} \int J_\phi E_\phi dV$$

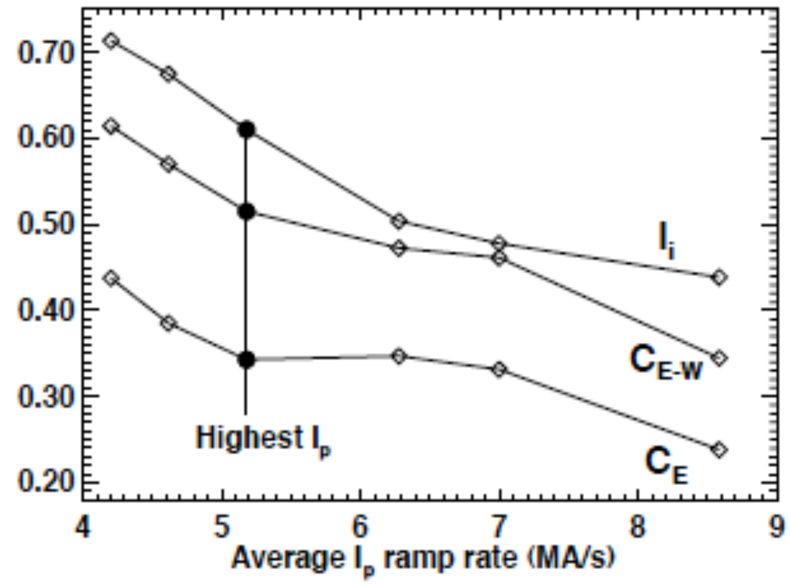
Ejima coefficient

$$C_E \equiv \Delta\Phi_R / \mu_0 R_0 I_p$$

Ejima - Wesley coefficient

$$C_{E-W} \equiv \left(\Delta\Phi_I + \Delta\Phi_R\right) / \mu_0 R_0 I_p$$

Φ *Computed at the end of the I_p ramp*



Summary

- *Scenario with low stray fields over much of vessel volume*
- *Loop voltage of 2V/turn is adequate to break-down prefill gas of 5.5 x 10^{-5} Torr*
- *Low Z impurities or too high prefill prevents I_p ramp-up*
- *Too low gas fueling (low prefill and no early gas puff) leads to MHD or worse*
- *Typical ramp-up has a goal of keeping l_i low*
- *NSTX was starved for V•s but could reach 1 MA ohmically with a short flattop; NSTX-U has 3 X NSTX flux for a substantial flattop at 2 MA*