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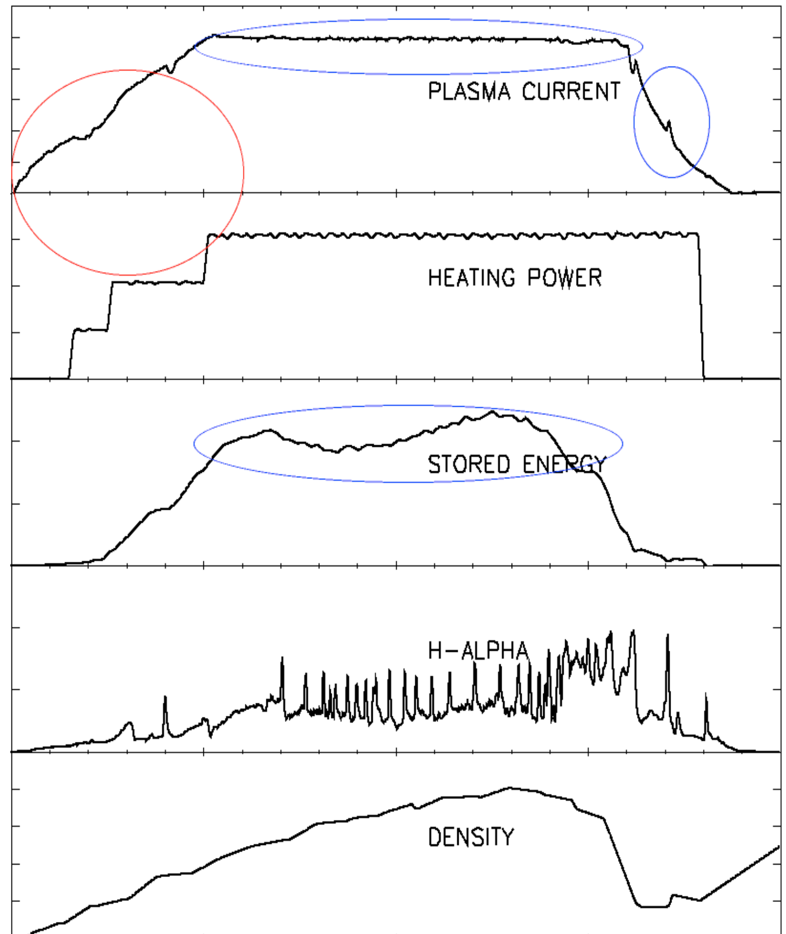
Physics of tokamak plasma start-up

D. Mueller

APS-DPP Meeting, Providence, RI Meeting
October 29 - November 2, 2012

Normal aspect ratio tokamaks have inner coils for inductive start-up, spherical tokamaks have limited space



- Now is the time to plan for start-up in
  - NSTX-U
  - JT60-SA
  - ITER
- Most of the planning revolves around what will happen during the flattop
- Recent start-up experience from
  - EAST and KSTAR, the first fully super-conducting tokamaks
  - JET ITER-like wall
- Long-pulse STs require non central solenoid start-up

Generally focus is on the plasma current flattop, MHD events ELMs and disruptions

Start-up gets attention when it fails

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- Central solenoid inductive start-up and current ramp
  - Breakdown/avalanche
  - Impurity burn-through
  - Electron cyclotron radio-frequency assist
  - Examples from EAST and KSTAR
  - Early stage of plasma current ramp-up
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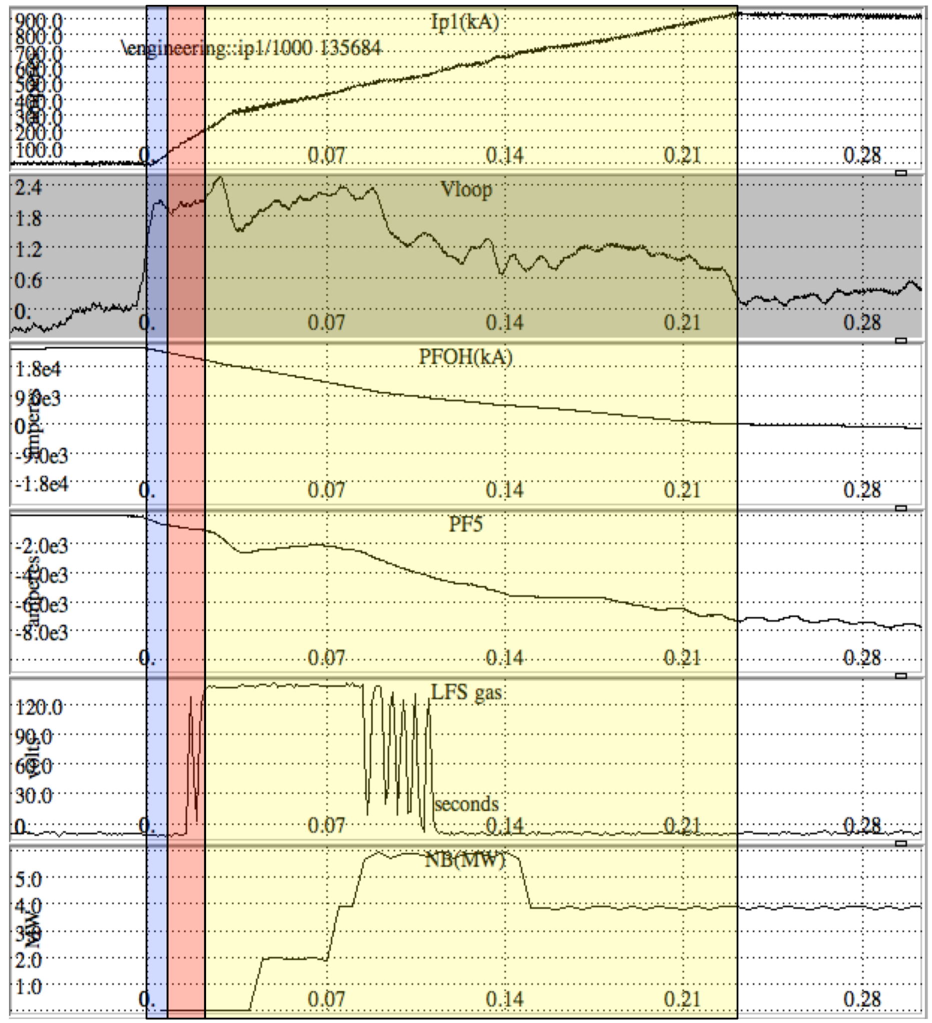
  - Outer PF coil start-up
  - Electron Bernstein Wave start-up
  - Helicity injection
    - Coaxial helicity injection (CHI)
    - Plasma Guns

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)

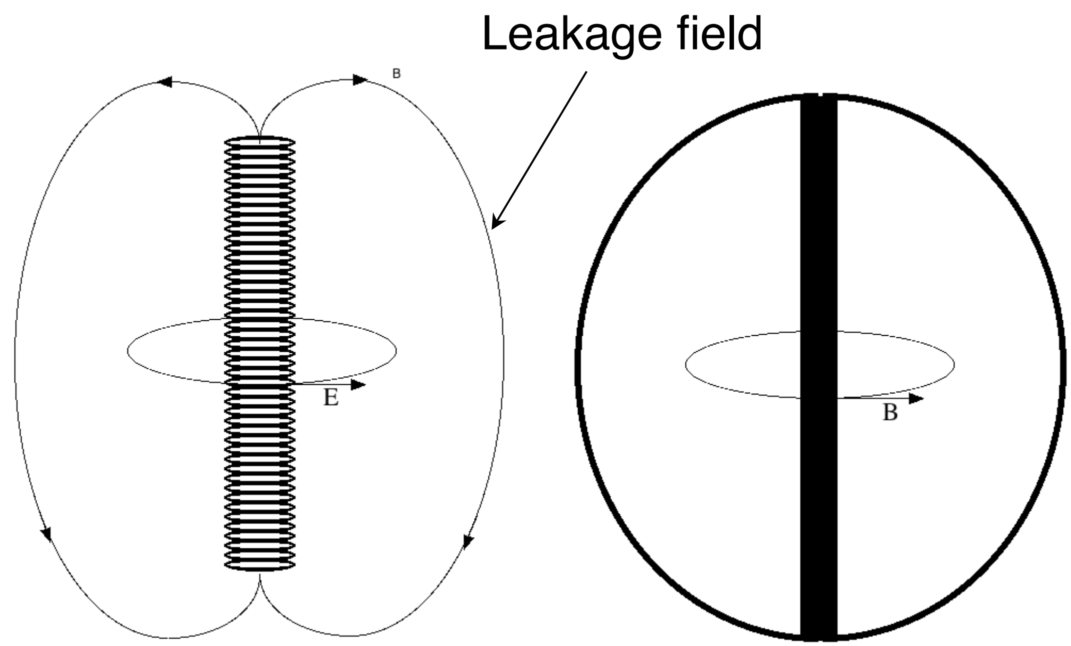
Inductive start-up

- 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

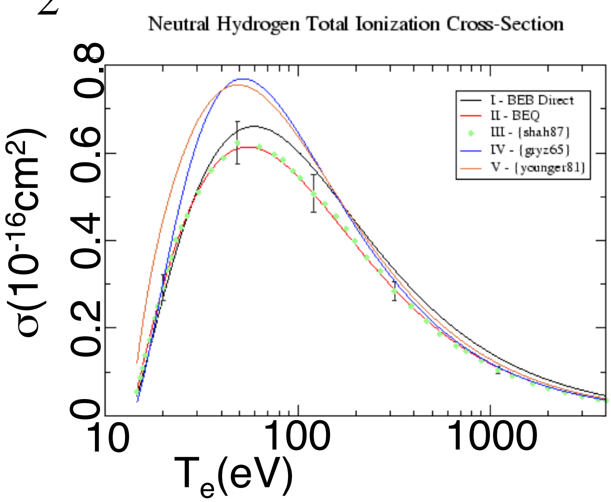
$$F = m\frac{dv}{dt} = qE$$

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

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

$$\text{mean free path } \lambda = 1/n\sigma$$

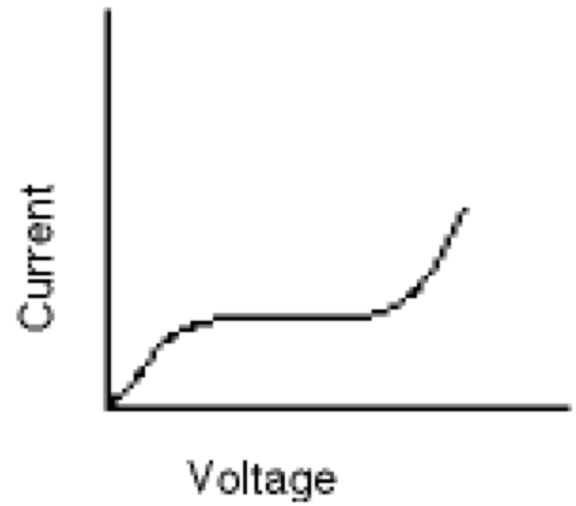
$$\frac{1}{2}mv_{impact}^2 = qE\lambda \geq 13.6eV\,(Hydrogen)$$



- 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



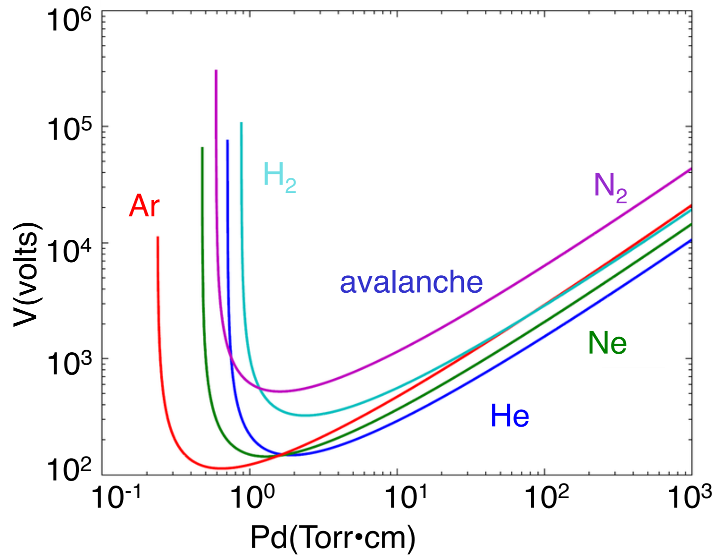
- If an electron produces α new electrons per meter then
- $dn_e = \alpha\, n_e\, dx$
- $n_e = n_e(0)\, e^{\alpha x}$
- α is called the first Townsend coefficient

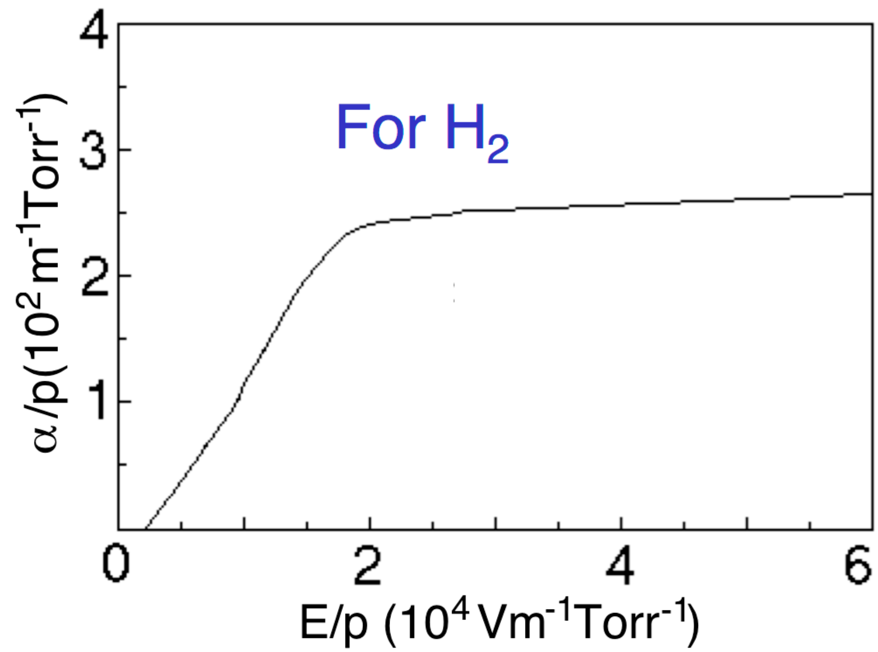
From S.C. Brown, Intro. To Electrical Discharges in Gases, John Wiley and Sons, 1966.

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



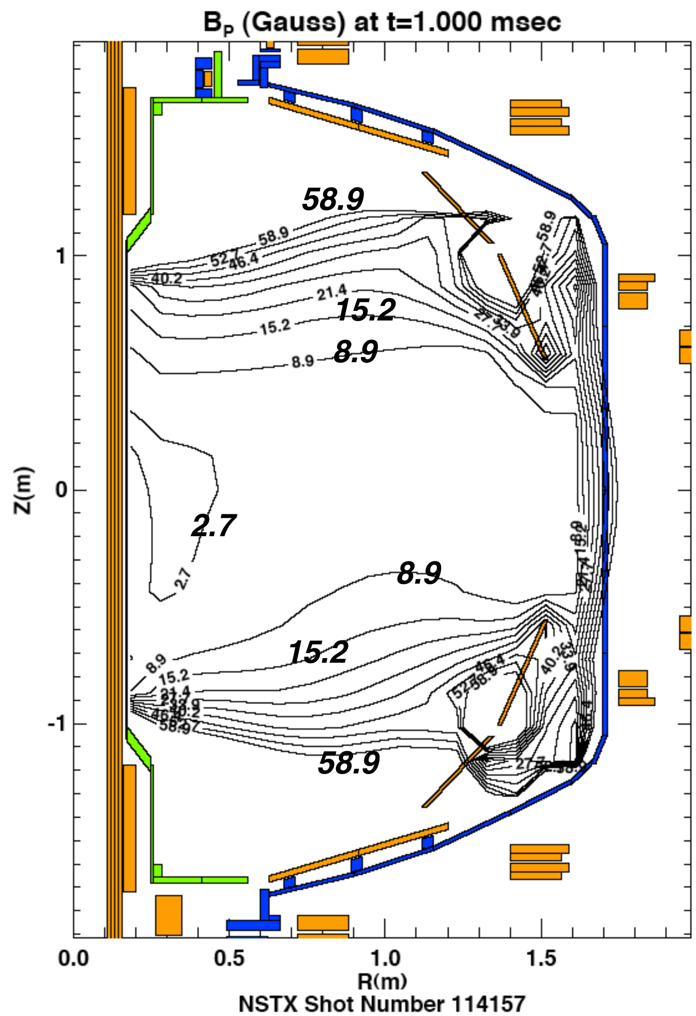


- For NSTX, p ~ 5x 10^{-5} Torr and V_l ~ 2 V/turn
  - For NSTX then $\alpha \sim 10^{-2}$ /m
- Connection length must be > 100 m, many toroidal transits
- For E/p > 5X10^3 V m^{-1} Torr^{-1}, T_e is high enough that thermal ionization is important
- This limits T_e to about 10 eV until ionization of 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 $B_T \sim 4$ 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 the density of neutrals will not be sufficient to provide electrons for the avalanche to continue

- Guiding center drift velocity
  - $v_D = (1/2 v_\perp^2 + v_\parallel^2)/R\omega_{ce}$; $v_\perp^2 \sim v_\parallel^2 \sim 3KT_e/2m$
  - $v_D \sim 4$ 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 $E \bullet B_T/dB_z > 10^3$ V/m*

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

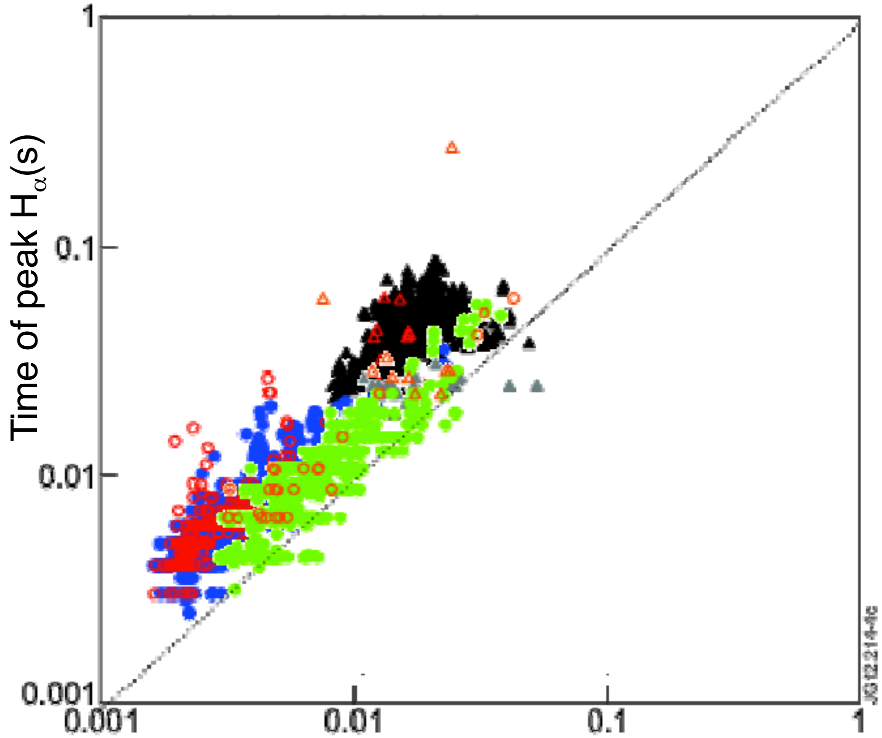
I.H.Hutchinson, J.D.Strachan Nucl. Fusion 14 649(1974)

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

Database from JET show good agreement between Lloyd's estimate of the avalanche time and the peak time of H_α

The JET ITER-like wall is comprised of Tungsten and berrylium



$$\tau^{Lloyd} = 41/(v_{de}(\alpha - L^{-1}))$$

Carbon wall

- ● Mode D ('high voltage')
- ○ Failed mode D
- ▲ Mode B ('low voltage')
- △ Failed mode B

ITER-like wall (ILW)

- ● Mode D ('high voltage')
- ○ Failed mode D
- ▲ Mode B ('low voltage')
- △ Failed mode B

Using the best estimate of L

Failed discharges do not deviate from others during the avalanche

→ failure is generally not in the avalanche process

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

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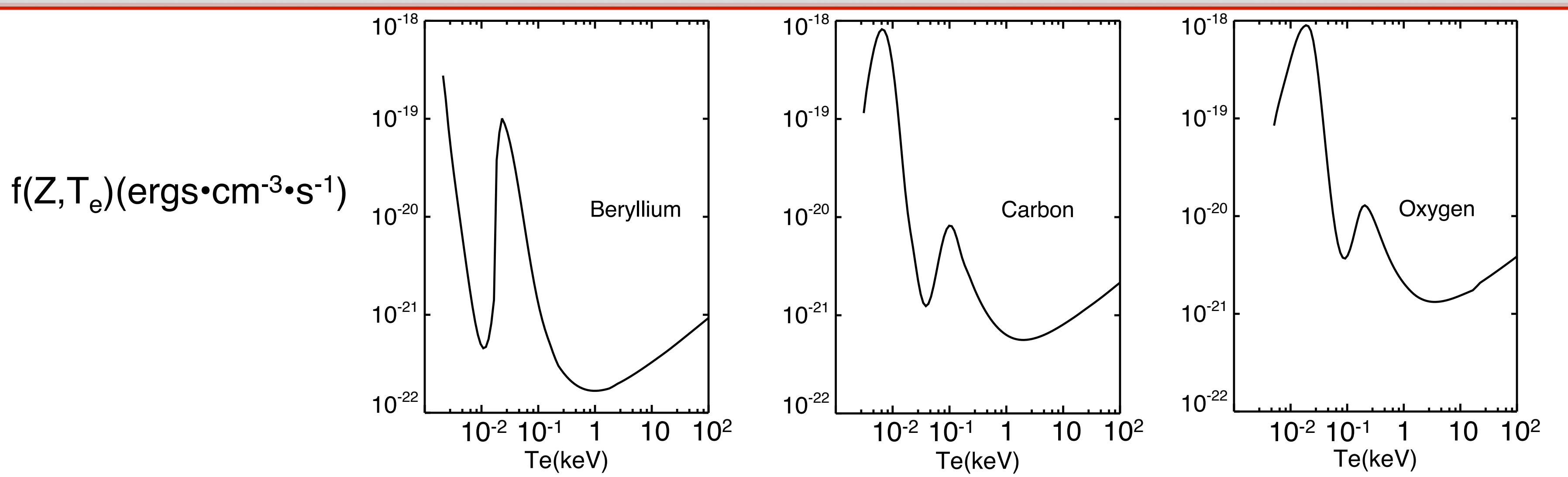
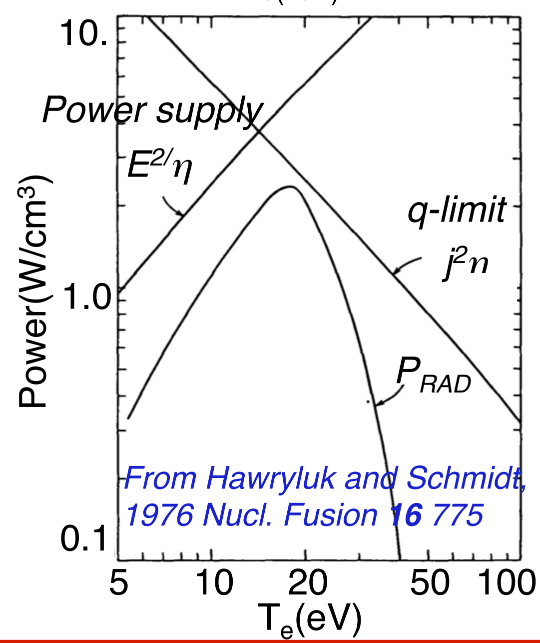
It has been known for a long time that Low Z impurity radiation can cause excessive energy losses at low T_e



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



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

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

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)
  - 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)

- Alternatively auxiliary heating can be employed to burn through the low Z impurities and heat the plasma

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 $(T_e + T_i)^{1/2}/m_D$

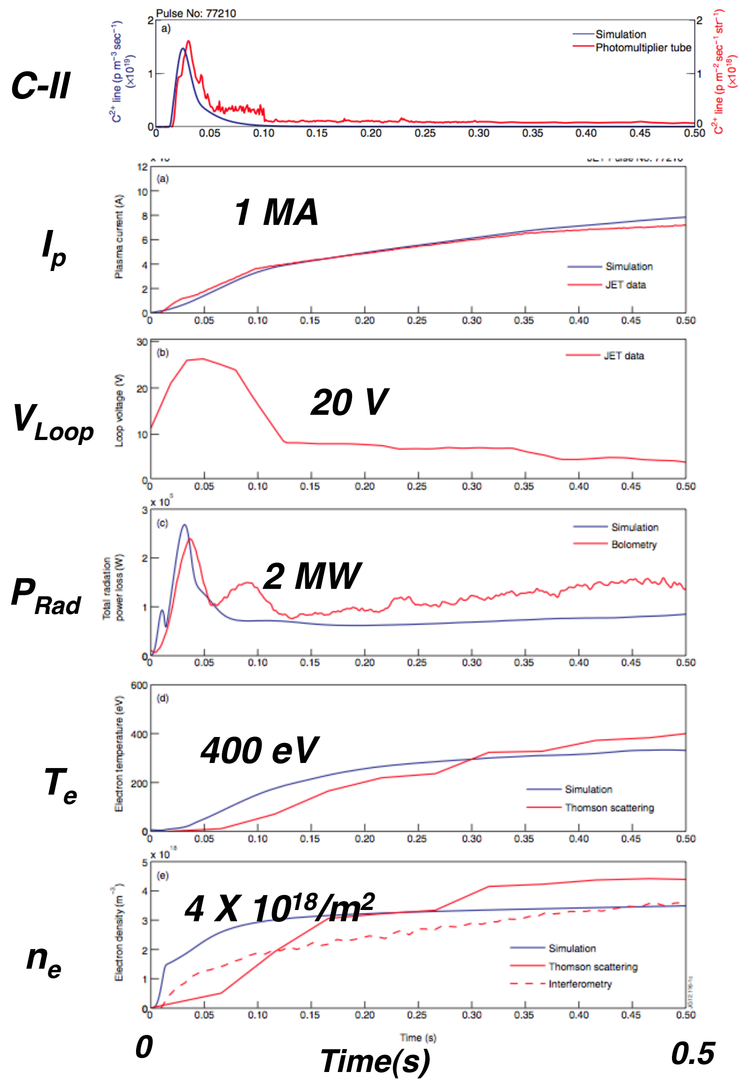
- For Perpendicular transport use Bohm diffusion

- A dynamic recycling coefficient is used for deuterium

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

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

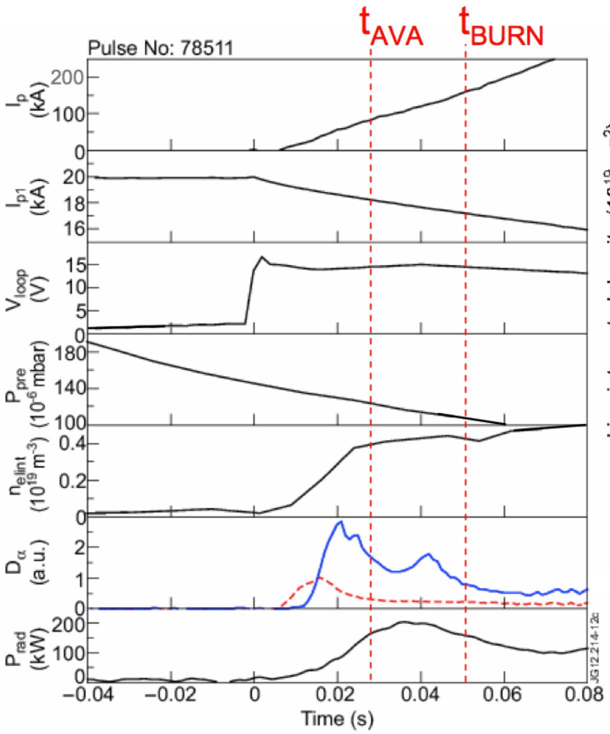


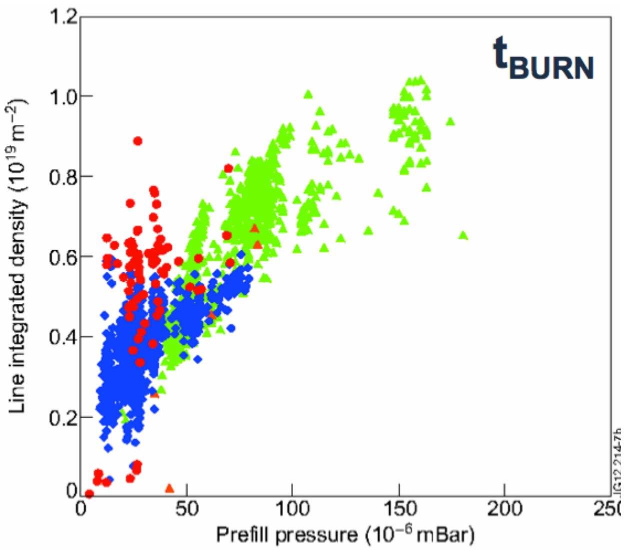
- Blue lines indicate simulation results
- Red curves on the plots are JET data

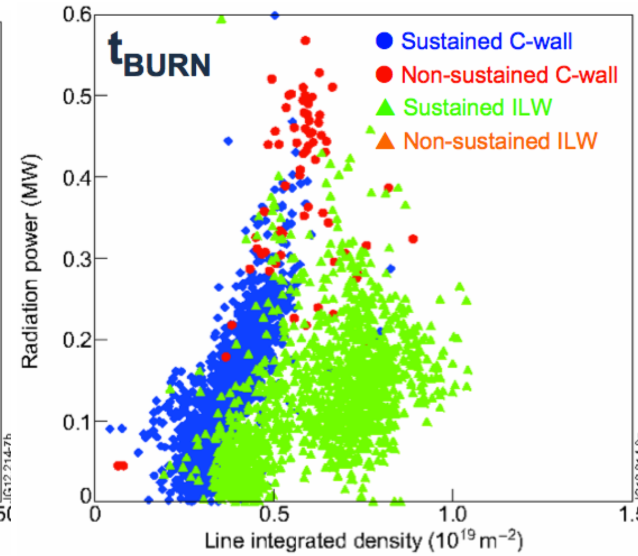
- The temporal agreement for the C-II emission gives confidence that impurities are being well-modeled
- The time evolution of the C charge states in the model indicates from 0.15 s on C is fully ionized
- The early density discrepancies may be due to geometrical effects
- This recent start-up model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

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_{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)

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Superconducting tokamaks have low loop voltage which can be marginal on ITER for breakdown and burn-through

- Power supply cost, eddy current heating in the superconducting coils, vacuum vessel and cryo-stat combine to place limits on the applied electric field
  - For ITER, E ~ 0.3V/m, the low end of successful breakdown
  - EAST and KSTAR insert resistors into the coil circuits to produce higher voltage for breakdown

- All 3 have less ohmic power to heat the plasma and ramp the plasma current than conventional tokamaks
  - Electron Cyclotron Radiofrequency Heating (ECRH) can lower the voltage required for breakdown by a factor of about two
  - ECRH can provide power to heat the plasma
    - This is especially important during burn-through when I_p is low and ohmic power is limited

Lloyd used a 0-D model of power balance during the start-up on ITER to assess the need for additional power

- Electron power balance

$$\frac{3}{2}\frac{d}{dt}\left(n_e K T_e\right) = P_{OH} + P_{RF} - (P_{Dion} + P_{Drad}) - P_{e-i} - P^{e}_{con} - P_{brem} - \sum_{I}\left(P_{ion} + P_{line} + P_{RRE} + P_{DRE}\right)$$

- Ion power balance

$$\frac{3}{2}\frac{d}{dt}\left(n_i K T_i\right) = P_{e-i} - P_{CX} - P^{i}_{con}$$

- Particle balance

$$\frac{dn_D}{dt} = \frac{V_n}{V_p} S n_0 n_e - \frac{n_D}{\tau_p}$$

This 0-D model handles impurities by assuming they are a fixed fraction of the deuterium density

It uses deuterium recycling coefficient R=1.01

B Lloyd, P G Carolan and C D Warric, Plasma Phys. Control. Fusion 38 (1996) 1627–1643.

Conclusions for the 0-D model for start-up is that start-up on ITER will be more robust with additional power

- Zero-dimensional modeling of ITER start-up scenarios indicates that for inductive only start-up:
  - Burn-through with 2% Be impurity is possible for low fill pressure $1.5X10^{17}/m^3$ ($2X10^{-6}$ Torr), post avalanche density < $1.5\ X10^{18}/m^3$
  - However for 5% Be or a higher fill pressure failure is likely

- Addition of auxiliary power in the form of Electron Cyclotron Resonant Heating (ECRH) improves power margin
  - With 2 MW of absorbed ECRH 5% Be impurity is allowable with a post avalanche density of $5\ X10^{18}/m^3$
    - but not for 2% C
  - For 5% C and the same density 5 MW of absorbed ECRH is required for robust start-up

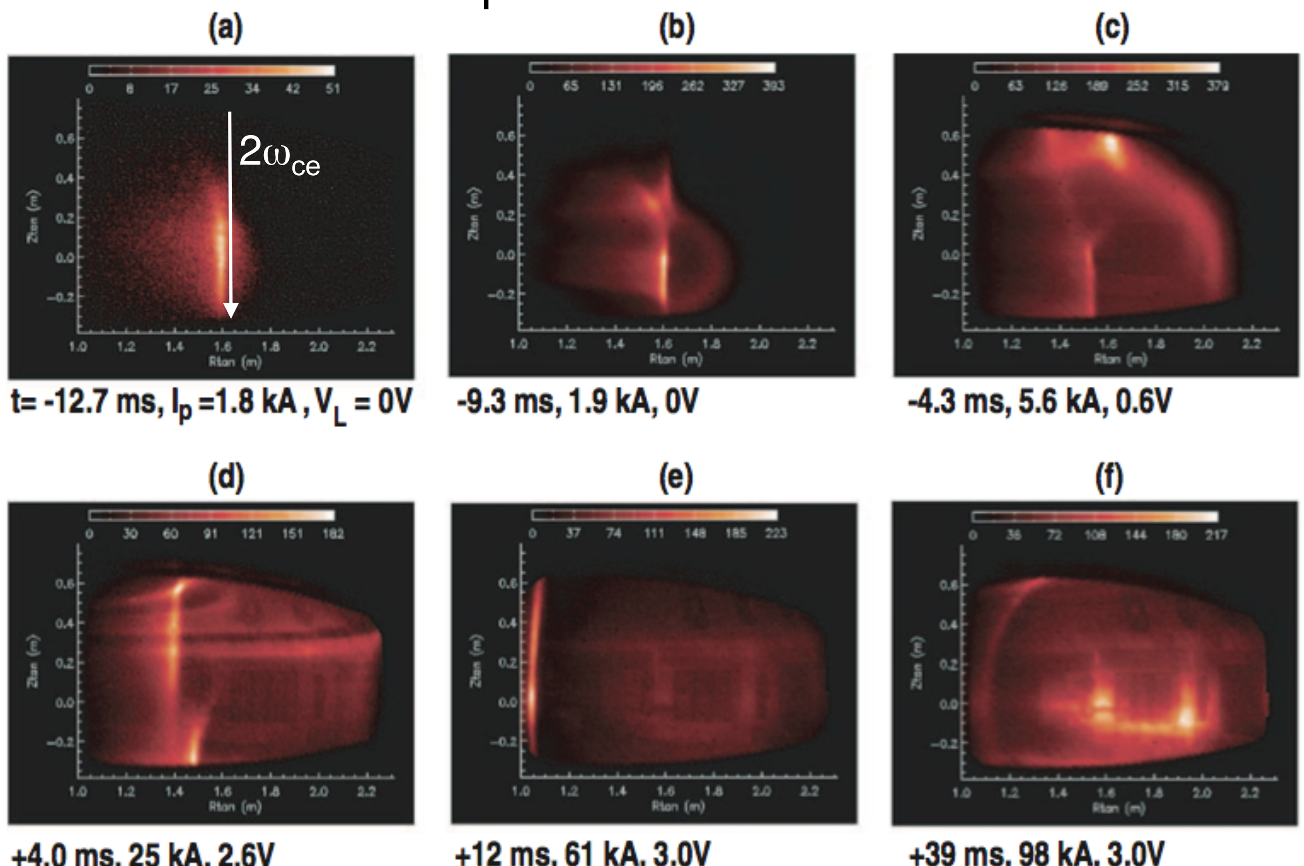
- ITER plans now include several MW of ECRH

- Now we will move on to experience with ECRH and start-up on JET with ITER-like wall which provide useful data for further insight

B Lloyd, P G Carolan and C D Warric, Plasma Phys. Control. Fusion 38 (1996) 1627–1643.

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

- 2^{nd} Harmonic X-Mode ($E \perp B$) 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

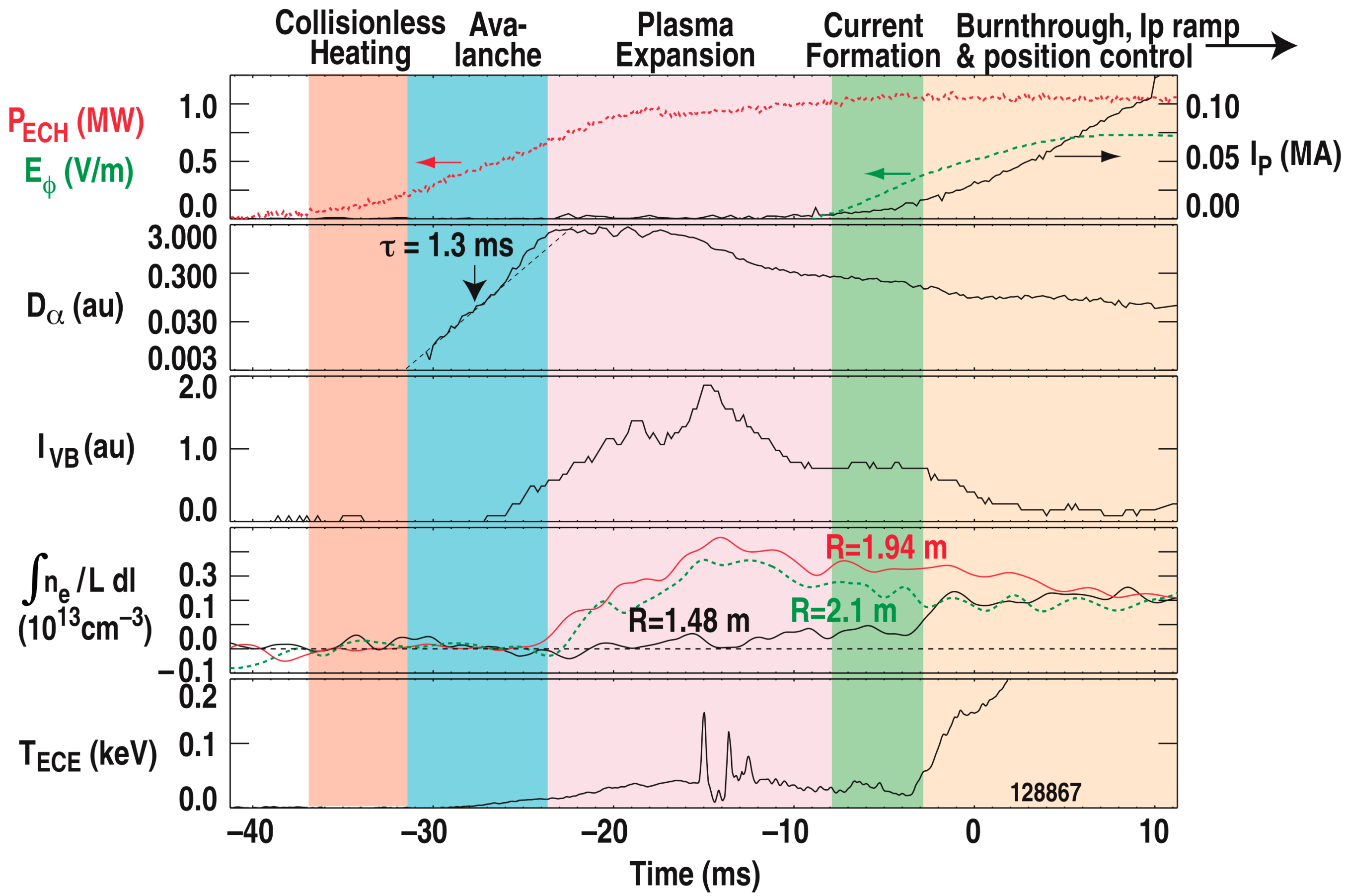


Fast-framing camera of C^{III} emission during 2^{nd} harmonic ECH in DIII-D

G. L. Jackson PhysPlasmas_17_056116 (2010)

Progression of discharge phases during ECRH start-up in DIII-D

- Avalanche and expansion phases have low I_p
- Current channel forms at 20-60 kA evidenced by increase it T_e
- Burn-through follows with additional heat from ECH



Jackson, et al., Fus. Sci & Technol.,**57**(2010)27

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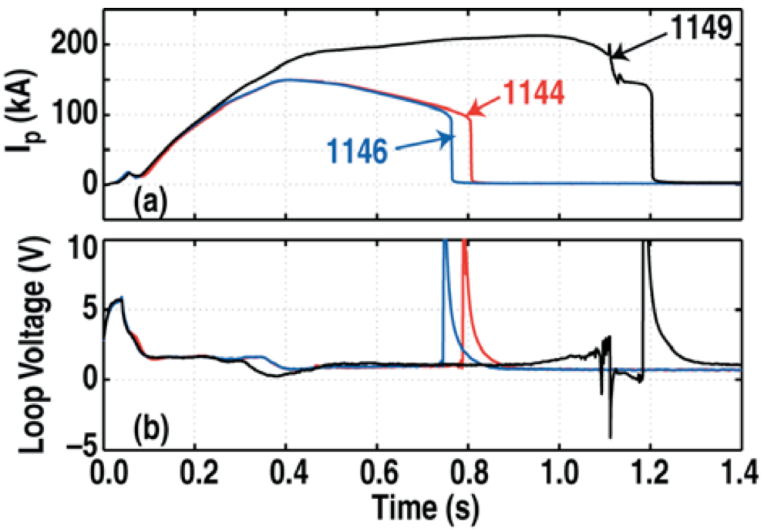
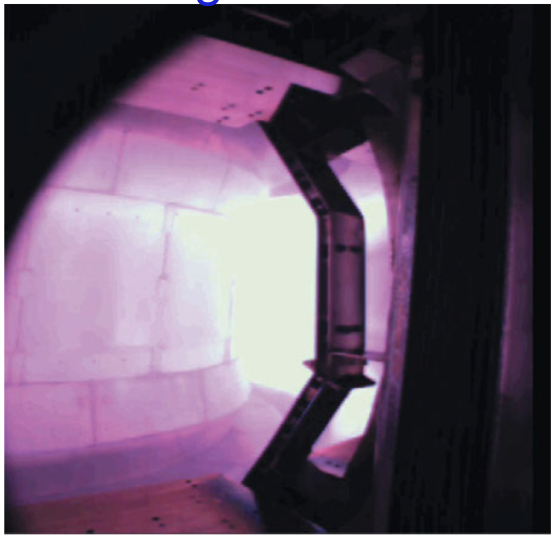
Causes of discharge failure are not always obvious

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 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

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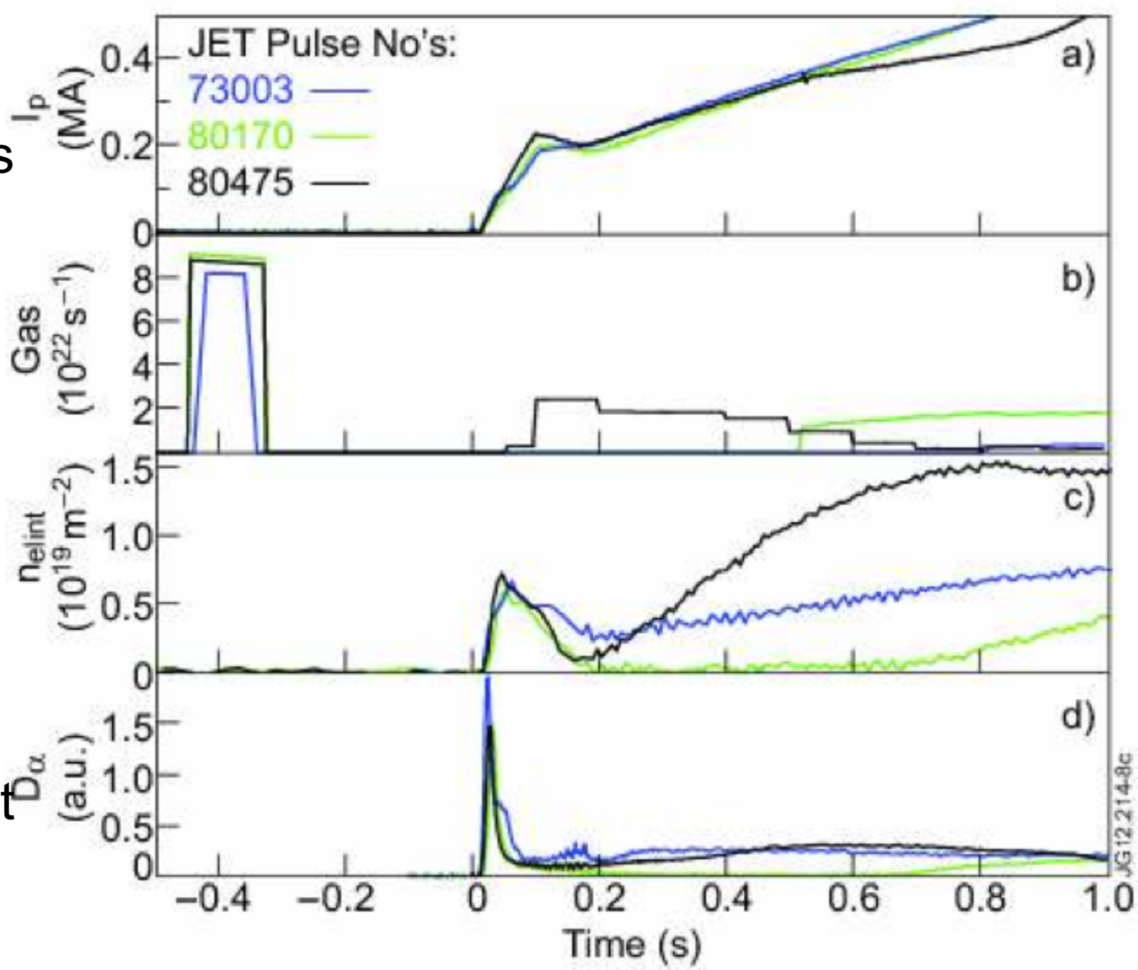
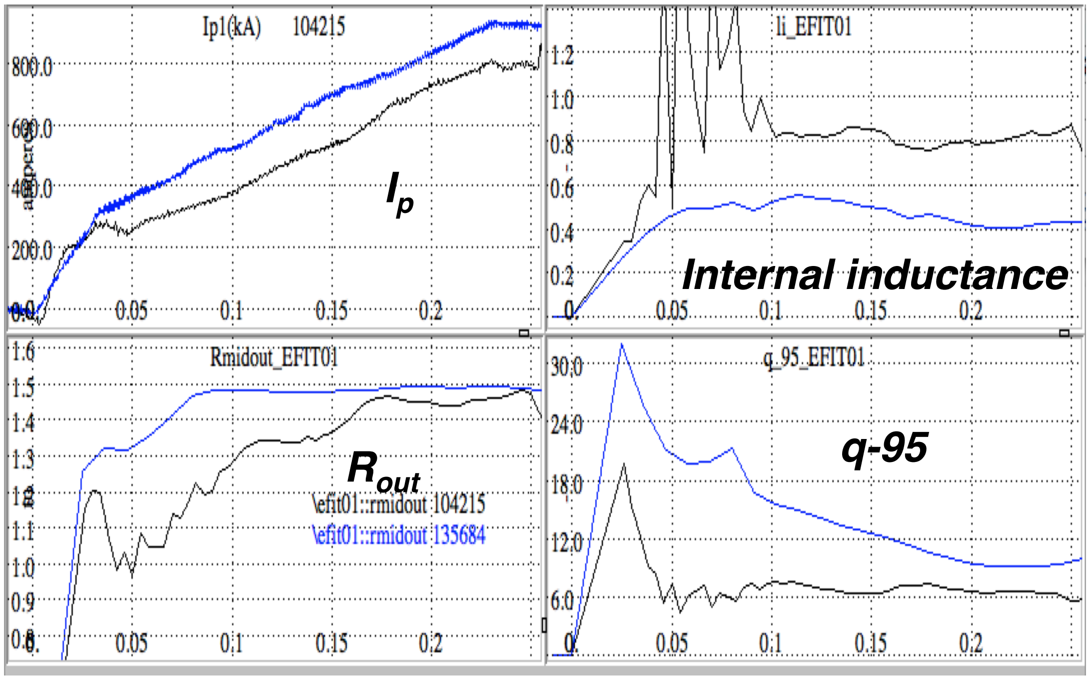
So far neglected a discussion of plasma density except when discussing Kim's and Lloyd's modelling

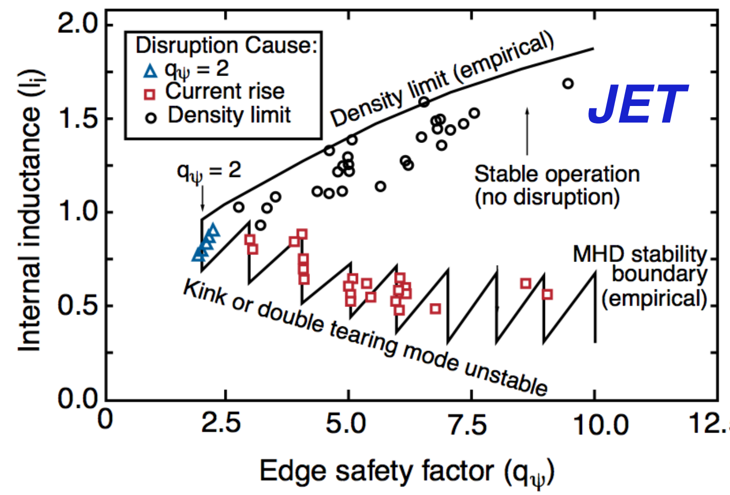
- With graphite wall generally the density rises with Ip, even with no additional fueling (Blue trace)
- With JET-ILW and no additional fueling the density falls (Green trace)
- Lower n_e → higher T_e broader current profiles that result in instability
- Gas puffing is effective to fuel the plasma and target plasmas can be achieved (Black trace)



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

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





•Constant q growth realizes fully evolved j(r) profiles earlier a
internal inductance, l_i

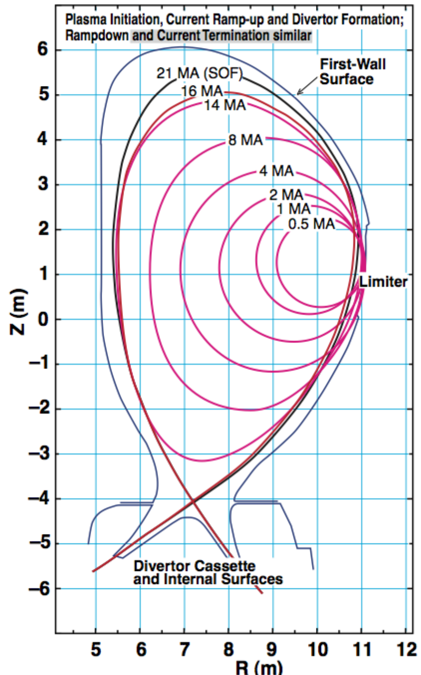
•Full aperture scenario has broader j(r) and minimizes l_i

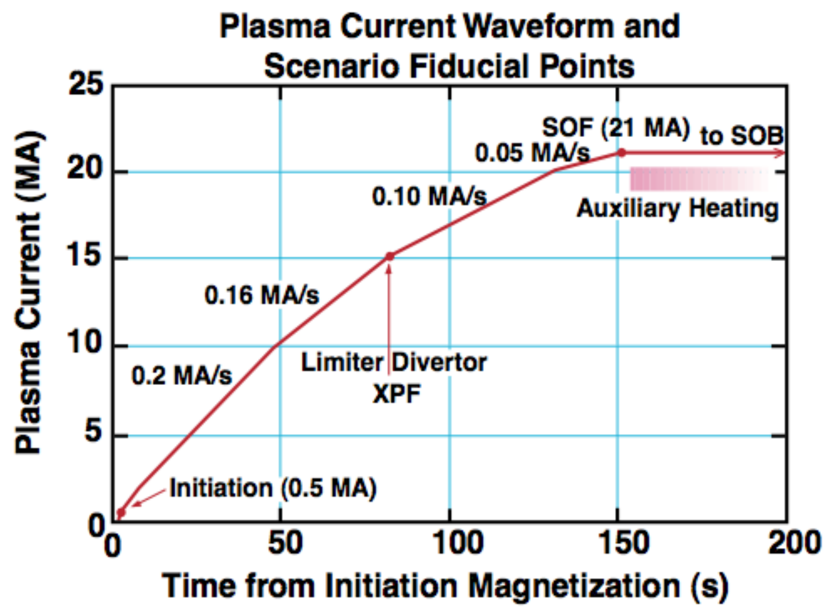
•Each strategy is affected by ramp-rate, impurities and heating power and timing typically, $dI_p/dt < 0.5$ MA/s

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

ITER strategy for plasma growth has evolved from small aperture growth to a large-bore start-up that diverts earlier

Small aperture growth





- Small bore start-up scenario; q ~ constant growth, diverts at high current
  - Long Ip ramp-up time due to low loop voltage
  - Limited on outboard surface – heating issue
  - Facilitates current penetration – early sawteeth
- Large bore plasma that diverts at lower I_p reduces heating of limiter
- Large-bore start-up studies on DIII-D indicate less heating of limiter and l_i closer to ITER target and has now been adopted by ITER

G. Jackson, Nucl. Fusion 48 (2008) 125002

Physics of tokamak plasma start-up

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Central solenoid is well understood and works well, but there are reasons to consider other start-up techniques

- Elimination of a conventional solenoid is required to achieve low aspect ratio at small device size for fusion nuclear applications
- If non-inductive current drive could support a steady state reactor, an alternative start-up technique could support elimination of the solenoid
- Having small or no solenoid could also help reduce conventional tokamak reactor size and cost
- With an iron core the plasma physics is similar, but engineering issues remain

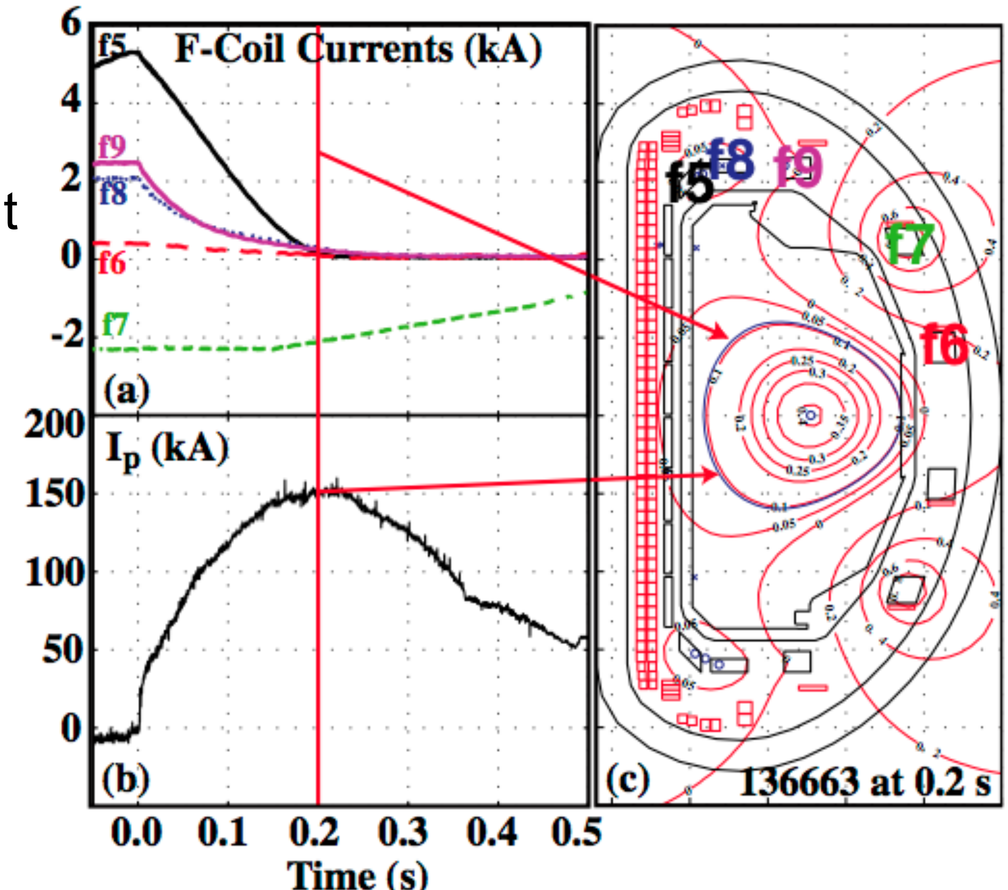
D.A. Gates et al. Fusion Engineering and Design 86 (2011) 41–44

All inductive start-up strategies face the same issues as using a central solenoid, but the emphasis may differ

- DIII-D, JT60, MAST, NSTX and others have demonstrated inductive start-up without use of the central coils
  - A good field null with a stabilizing poloidal field pattern must be provided while at the same time ramping the outer coils to produce flux

<u>Example from DIII-D</u>

- Coil currents and plasma current for outer PF start-up
- Used ECRH for plasma initiation and burn-through
- Only the labeled coils participate
- Diverting plasma requires positive current in divertor coils



From J. Leuer, Nucl. Fusion 51 (2011) 063038

Physics of tokamak plasma start-up

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Of the candidate RF start-up strategies for the ST, so far Electron-Bernstein Wave (EBW) is the most promising

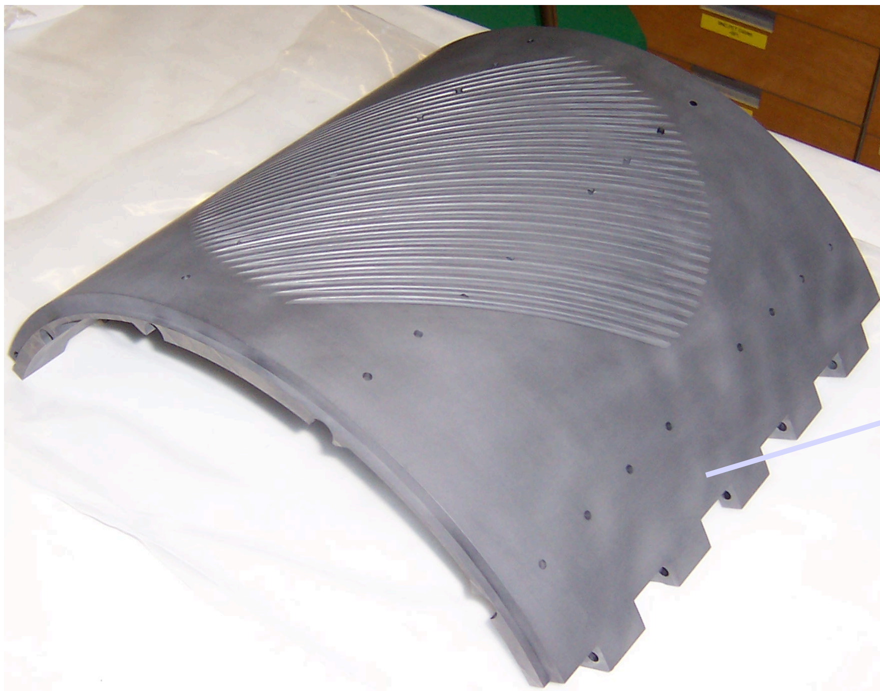
- The acceleration of electrons in a preferential direction by RF waves can be used for start-up

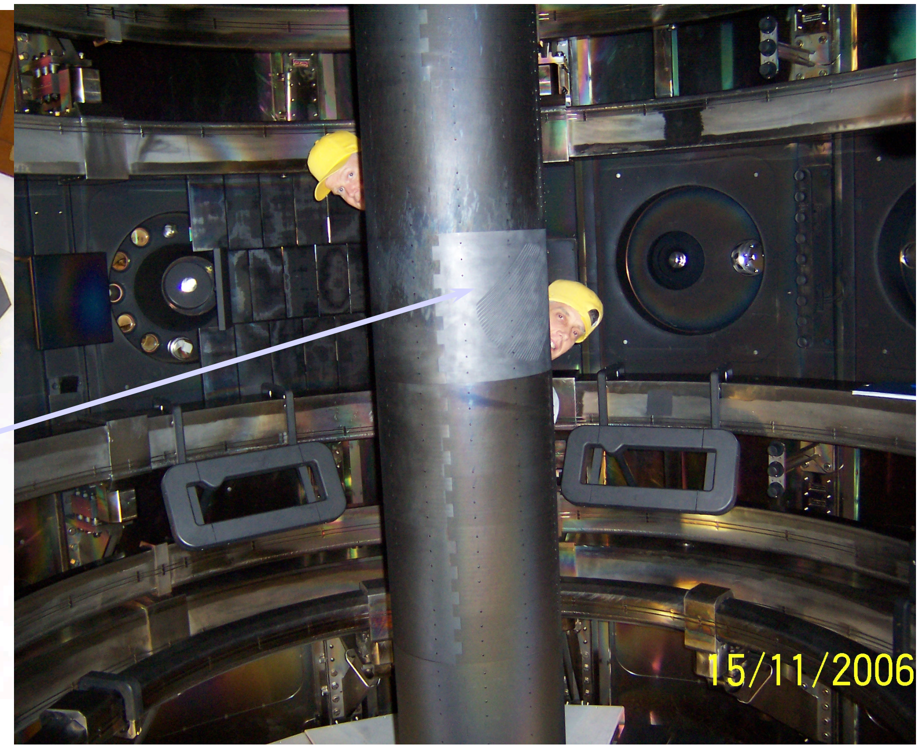
- Lower Hybrid Current Drive start-up to 100 kA was demonstrated on PLT in the early 80s.

- Start-up by ECH on DIII-D, TS2 and LATE

- EBW has been used on MAST to start-up the plasma current to 33 kA using 100 KW
  - EBW is an electrostatic wave that can exist only in a plasma
  - It can be produced by mode-conversion of X-Mode electron-cyclotron frequency waves at the upper hybrid resonance (UHR)

EBW can be produced by mode conversion of X-Mode waves in ECRF launched from the high field side

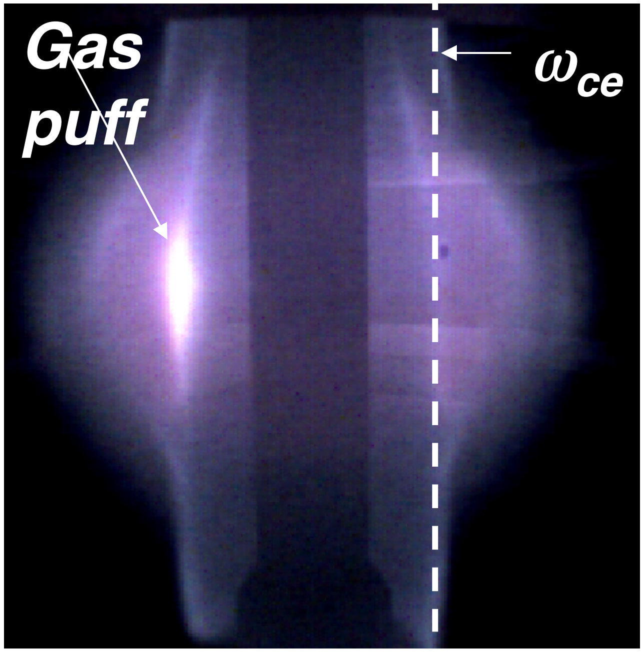




- MAST solution is to launch O-Mode from the low field side (LFS)
  - O-Mode wave at 28 Ghz is not strongly damped (<2% absorption) below the cut off density of about $1X10^{19}/m^3$
  - A grooved reflector (polarizing mirror) cut into the central column converts the O-Mode to X-Mode wave.

From V. Shevchenko, EC-15 Joint Workshop, 2008, Yosemite, CA, USA

28 GHz breakdown with O-Mode launch with toroidal field and 1mT vertical field in MAST, and ray tracing of EBW

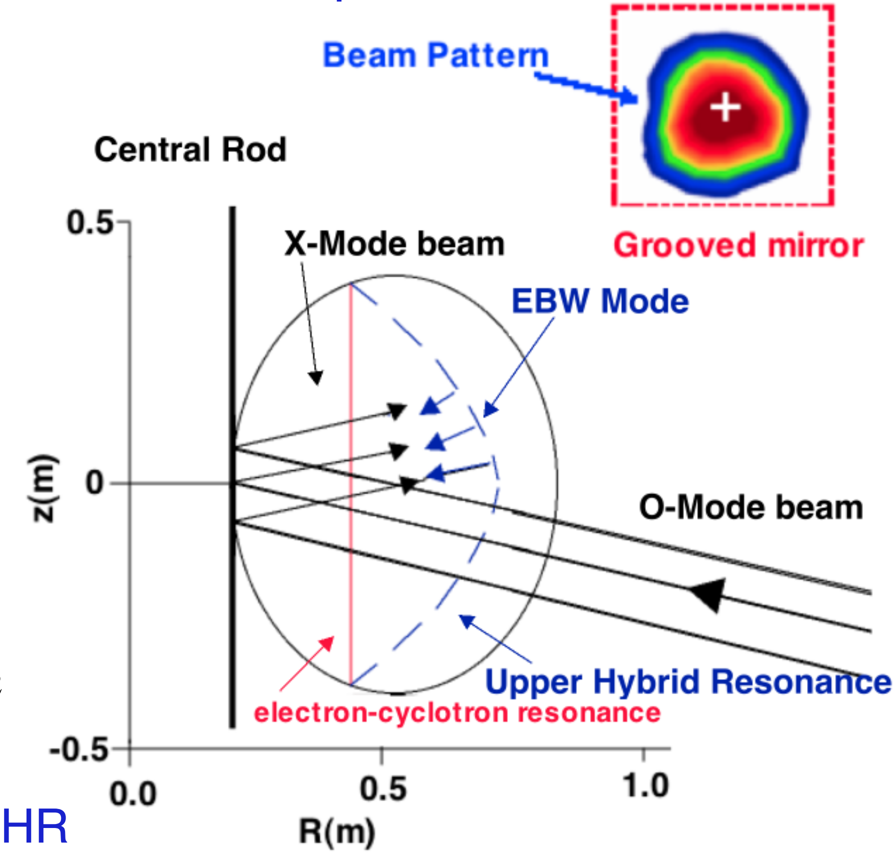


O-mode, $I_p \approx 5$ kA

$$\omega_{ce} = eB/m_e \qquad \omega_p = (n_e e^2/\varepsilon_0 m_e)^{1/2}$$

$$\omega_{UH} = (\omega_p^2 + \omega_{ce}^2)^{1/2}$$

Sketch of ray-tracing modelling of EBW CD plasma initiation



EBW ⊥ UHR

Sign of $n_{||}$ from projection of k along poloidal field (B_p)

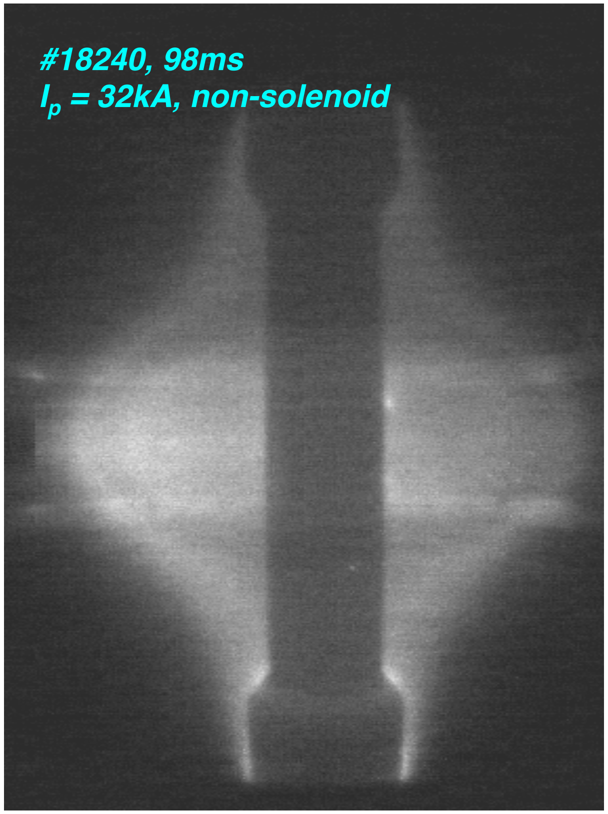
B_p changes sign when closed flux forms

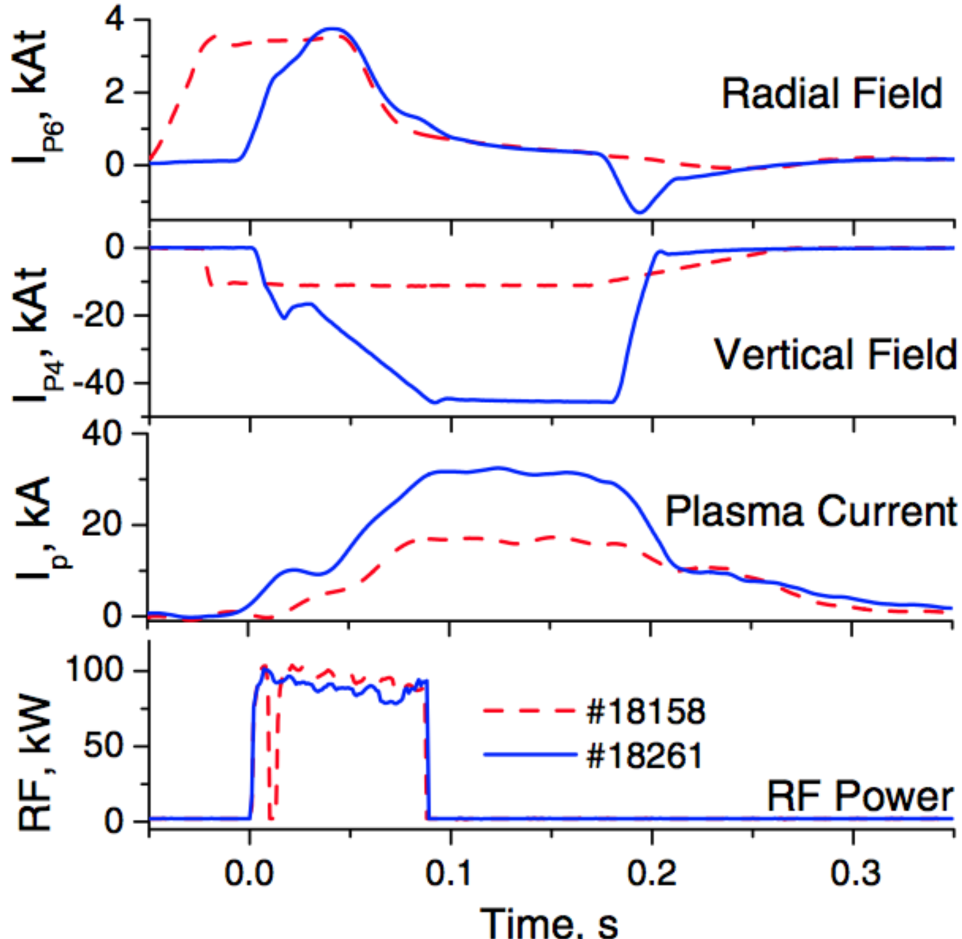
V. Shevchenko, EC-15 Joint Workshop, 2008, Yosemite, CA, USA

See Laqua, Plasma Phys. Control. Fusion 49 (2007) R1–R42

MAST EBW start-up to 33 kA with 100 kW ECRF using vertical shifts to provide co-current in both open- and closed-fields

V.F. Shevchenko et al. Nucl. Fusion 50 (2010) 022004 (5pp)





- Proportion co/counter EBW CD depends on fraction above/below the midplane
- Plasma shifted up during open field line period
- Plasma shifted at the time closed field lines appear to maintain co-current drive

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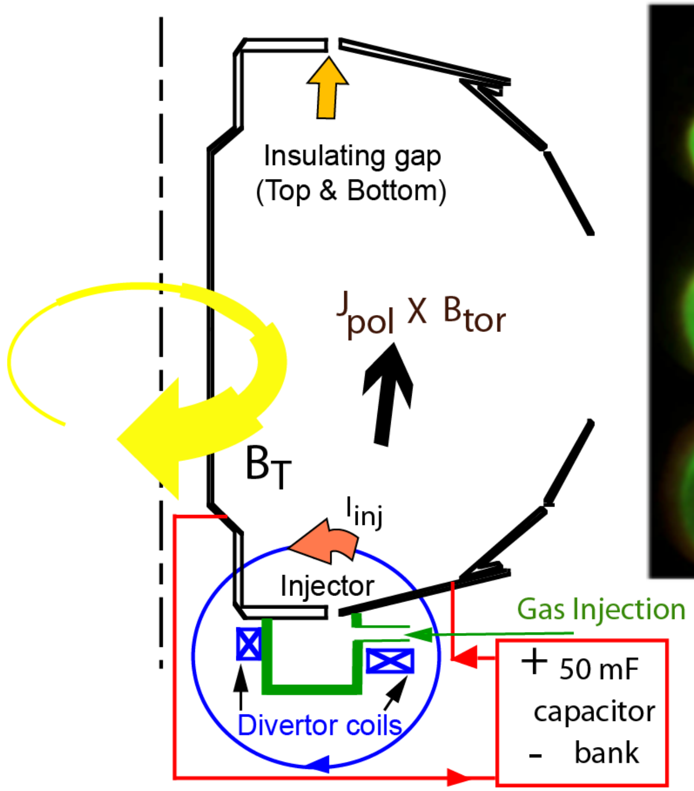
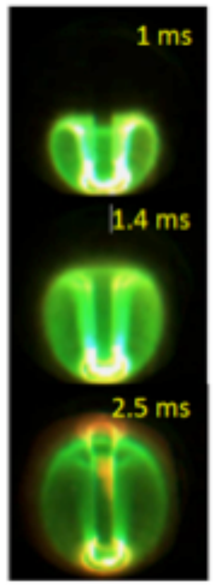
Transient CHI current formation achieved by biasing inner vs. outer vessel to drive expanding helical current channel

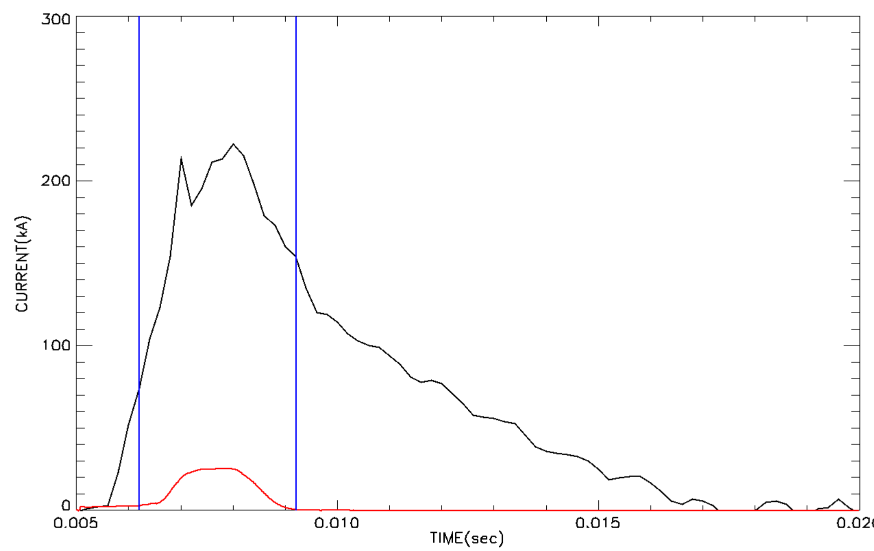
Gas injected at bottom of device, breakdown proceeds via Townsend avalanche along helical field connecting inner and outer vessel with many wraps the toroidal current can be 100 times injector current





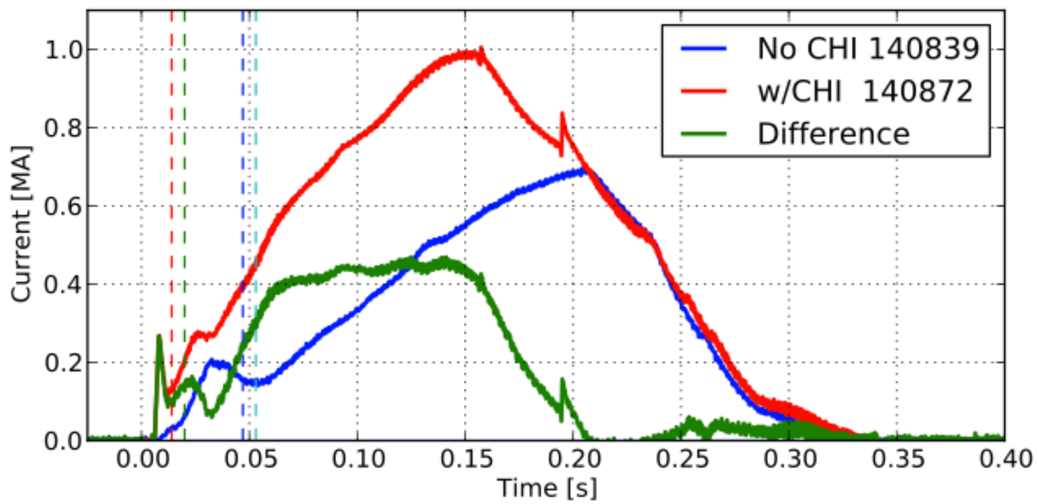
Bubble burst condition: When $I_{inj} > 2\ \psi_{inj}^2/(\mu_0^2 d^2 I_{TF})$ Plasma fills vessel

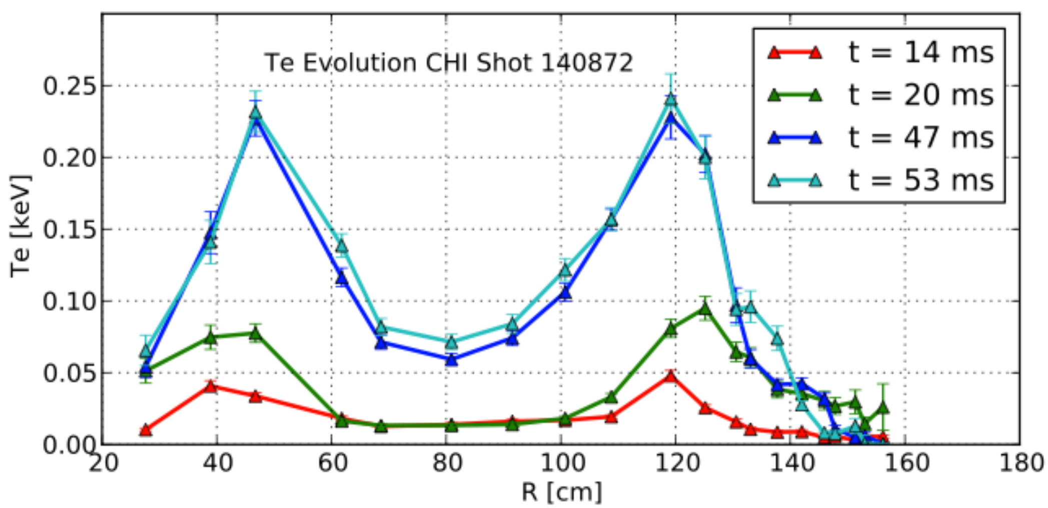
Reconnection occurs when injector current is reduced to zero → closed flux surfaces



R. Raman, Nucl. Fusion 51 (2011) 113018 (8pp)
D. Mueller. Fusion Science and Technol. 52 2007

Transient CHI start-up must be followed by another means of current drive - so far only inductive drive has been available





Comparison of CHI initiated discharge (in red) with only inductive current drive (in blue)

Neutral beam heated L-Mode discharges initiated with CHI use about 40% less inductive flux to reach 1 MA.

Discharges with high T_e early ramp to higher currents

From Nelson, Nucl. Fusion 51 (2011) 063008

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Plasma guns have been employed on PEGASUS to inject helicity and provide start-up plasmas

Relaxation Limit → High I_{inj}, low w

$$\textit{Magnetic Helicity} \quad K = \int \vec{A} \bullet \vec{B}\, dv$$

$$\lambda = \mu_0 I / \Psi \quad \textit{and} \quad I_p \le I_{inj} \frac{\Psi_T}{\Psi_{edge}}$$

$$\textit{where} \quad \Psi_{edge} = 2\pi R_{edge} w B_{z,edge}$$

$$I_p \le f_{Geom} \left(\frac{\varepsilon A_p I_{inj} I_{TF}}{2\pi R_{edge} w} \right)^{1/2} \qquad 1 < f_{Geom} < 3$$

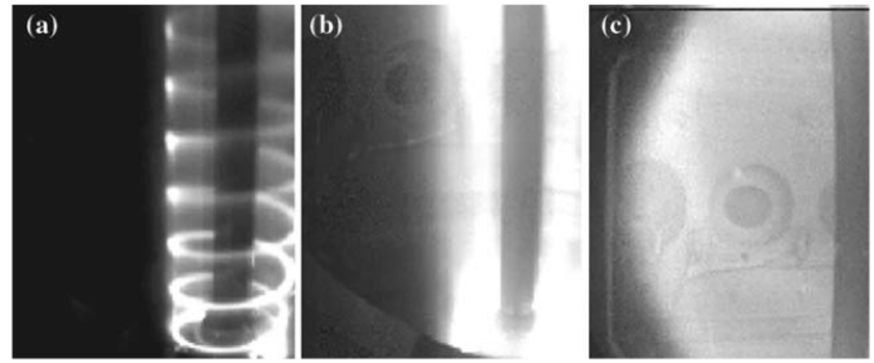
Helicity input rate → High V_{inj}, A_{inj}

$$I < \frac{1}{2\pi \langle \eta \rangle} \left(\frac{A_p V_{ind}}{R_0} + \frac{A_{inj} V_{bias}}{R_{inj}} \right)$$

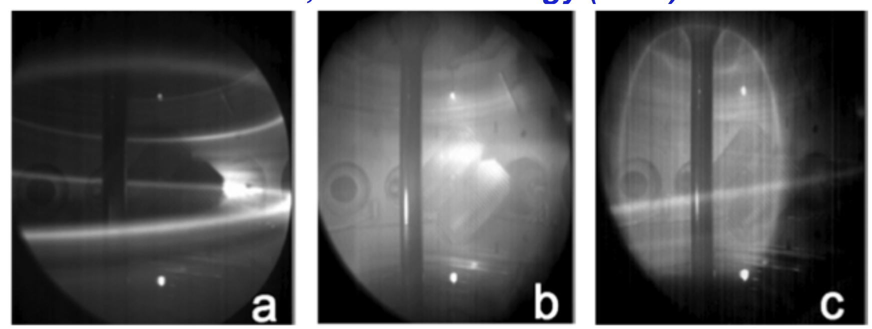
Gun location is flexible

Could be withdrawn after start-up

From Battaglia, J Fusion Energy (2009) 28:140–143



From Eidietis, J. Fusion Energy (2007)26:43-46



From Battaglia, Nucl. Fusion 51 (2011) 073029

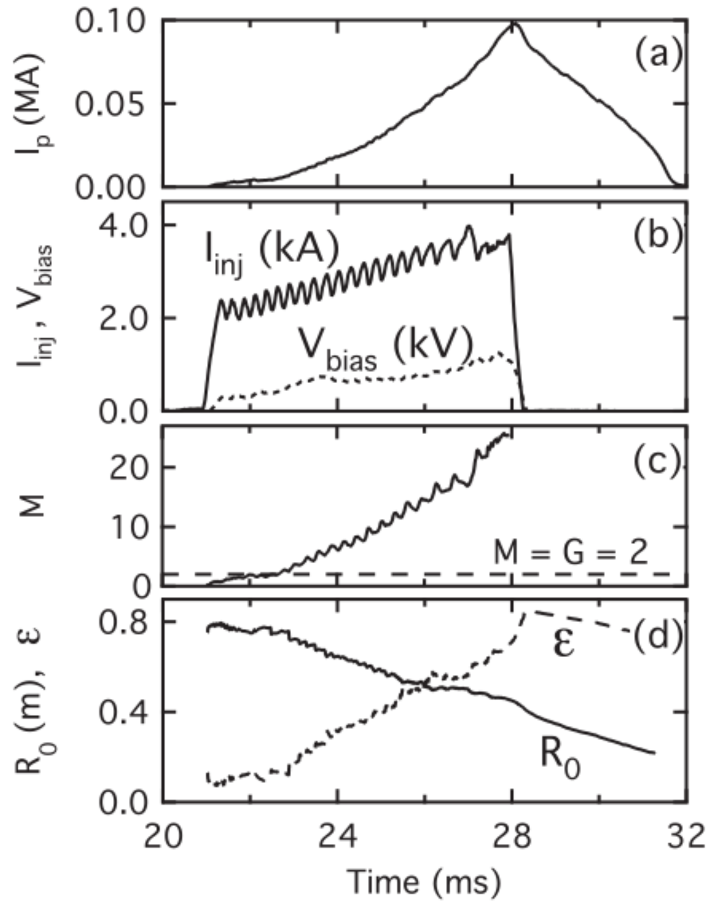
Images of plasma gun startup with gun located near the center (top) and outside (lower) of the Pegasus

a) filaments

b) Merging

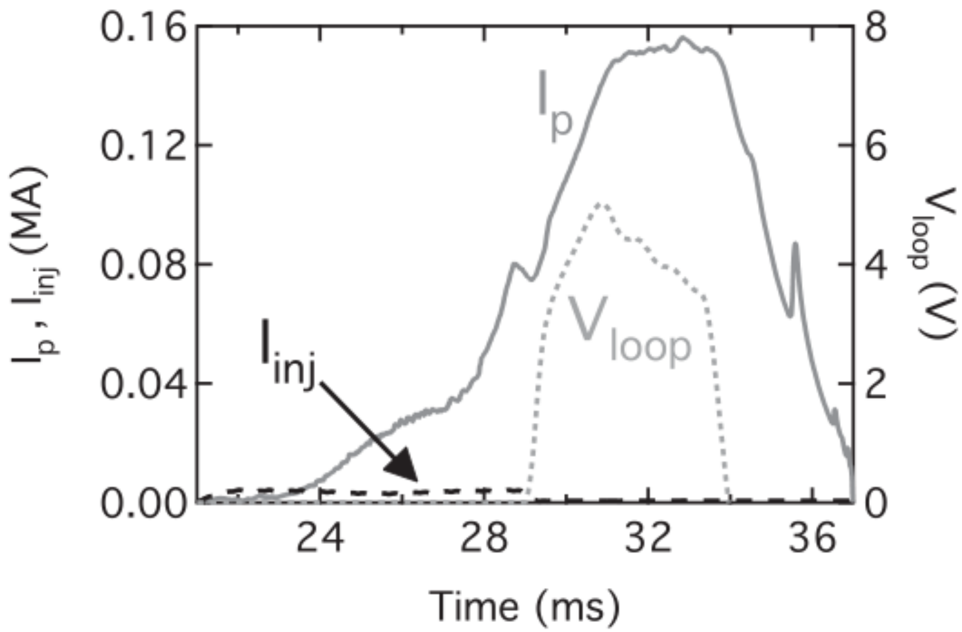
c) Relaxation

Plasmas initiated with plasma guns on PEGASUS have been ramped to over 100 kA with < 4 kA of gun current



- Demonstrated initiation and ramp-up I_p > 100 kA
- Current multiplication >25

Battaglia, PRL 102, 225003 (2009)



- Plasma initiated with plasma guns can be ramped to higher current by induction.
- 150 kA in this example was achieved with half the inductive flux required for a purely inductively driven plasma

Inductive start-up with ECH is well understood and promising non-inductive start-up techniques exist for STs

- Townsend avalanche and burn-through have been modeled self-consistently
- ECRH to both assist the avalanche and heat to burn through low Z impurities
- Low aspect ratio tokamaks have little space for a central solenoid so the usual inductive technique is problematic
- Possible alternatives to solenoidal start-up
  - Outer PF start-up
  - Electron Bernstein Wave
  - Coaxial helicity injection
  - Plasma guns to inject helicity
- Demonstrated start-up from zero to significant current
- Well-positioned for start-up of ITER

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References to illustrative work

- Inductive start-up
  - S.C. Brown, Intro. To Electrical Discharges in Gases, John Wiley and Sons, 1966.
  - R. Papoular, Nucl. Fusion 16 (1976) 37
  - B. Lloyd et al., Nucl. Fusion, Vol.31. No.ll (1991)
  - A. Tanga, et al. in “Tokamak Start-up” H. Knoepfel. Plenum Press, NY (1985)
  - I.H.Hutchinson and J.D.Strachan Nucl. Fusion 14 649(1974)
  - E.A. Lazarus et al. Nucl. Fusion 38 1083 (1998)
  - P. deVries, 25^{th} IAEA,SanDiego, EXD4-2(2012)
  - R. Hawryluk and J. Schmidt, 1976 Nucl. Fusion 16 775
  - From D.E. Post et al., At. Data Nucl. Data Tables 2, 400, 1977
  - Hyun-Tae Kim et al. Nucl. Fusion 52 (2012) 103016
  - J. Kim, Nucl. Fusion 51 (2011) 083034
  - J. Leuer, et al., Fusion Science and Tech.. 57 2010
  - J. Leuer, Nucl. Fusion 51 (2011) 063038
- ECRH
  - B Lloyd, P G Carolan and C D Warric, Plasma Phys. Control. Fusion 38 (1996) 1627–1643.
  - G. L. Jackson et al. Phys. Plasmas_17_056116 (2010)
  - G.L. Jackson et al. Fus. Sci. & Technology 50 (2010) 27
  - T. Yoshinaga et al. PRL 96, 125005 (2006)
  - A. Ejiri et al. Nucl. Fusion 46 (2006) 709–713
- EBW
  - V. Shevchenko, EC-15 Joint Workshop, 2008, Yosemite, CA, USA
  - Laqua, Plasma Phys. Control. Fusion 49 (2007) R1–R42
  - V.F. Shevchenko et al. Nucl. Fusion 50 (2010) 022004 (5pp)
  - C.B. Forrest et al. Phys. Plasma 7, 1352 (2000)
- CHI
  - R. Raman et al. Nucl. Fusion 51 (2011) 113018 (8pp)
  - D. Mueller et al. Fusion Science and Technol. 52 2007
  - B.A. Nelson et al. Nucl. Fusion 51 (2011) 063008
- Plasma guns
  - Battaglia, J Fusion Energy (2009) 28:140–143
  - Battaglia, Nucl. Fusion 51 (2011) 073029
  - Eidietis, J. Fusion Energy (2007)26:43-46
  - Battaglia, PRL 102, 225003 (2009)
- Other
  - F.C. Jobes PRL 52 12, 1005 (1984)
  - F.C. Jobes et al. in , et al. in “Tokamak Start-up” H. Knoepfel. Plenum Press, NY (1985)
  - D.A. Gates et al. Fusion Engineering and Design 86 (2011) 41–44