Plasma Formation in Spherical Tokamaks

Mikhail Gryaznevich and Alan Sykes
Euratom/UKAEA Fusion Association


This work was jointly funded by the UK Engineering & Physical Sciences Research Council and Euratom

M Gryaznevich, Formation in STs, IAEA TM on ST, St Petersburg 3-6 Oct 2005
Main methods of plasma formation in STs:

1. Inductive methods (with or without use of the central solenoid flux):
   - conventional formation using central solenoid flux
   - formation without use of the central solenoid flux (non-solenoid formation)
   - use of external electrodes: CHI, arcs, plasma guns etc.

2. Non-inductive methods:
   - pure non-inductive plasma formation using RF
   - inductive formation assisted by ECR, EBW, NBI or other pre-ionisation and current formation methods

Prospects for future STs
START and MAST Parameters

<table>
<thead>
<tr>
<th></th>
<th>MAST</th>
<th>START</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R, m$</td>
<td>0.9</td>
<td>0.35</td>
</tr>
<tr>
<td>$a, m$</td>
<td>0.7</td>
<td>0.27</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>3 (2.7)</td>
<td>1.5-3</td>
</tr>
<tr>
<td>$I_{p, MA}$</td>
<td>2 (1.35)</td>
<td>0.31</td>
</tr>
<tr>
<td>$B_{t, T}$</td>
<td>0.4-0.7</td>
<td>0.2-0.6</td>
</tr>
<tr>
<td>$Y_{sol, Vs}$</td>
<td>0.9 (0.8)</td>
<td>0.08</td>
</tr>
<tr>
<td>$P_{NBI, MW}$</td>
<td>5 (3.3)</td>
<td>1</td>
</tr>
<tr>
<td>$P_{RF, MW}$</td>
<td>1.5 (0.9)</td>
<td>0.2</td>
</tr>
<tr>
<td>$\beta_N$</td>
<td>5.3</td>
<td>6</td>
</tr>
<tr>
<td>$\beta_t, %$</td>
<td>16</td>
<td>40</td>
</tr>
<tr>
<td>$\tau_p, s$</td>
<td>5 (0.7)</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Red – achieved

Formation methods used:
- merging-compression
- direct induction
- double null merging
- formation in outer multiple null

Pre-ionisation methods and tools used:
- ECR pre-ionisation
- EBW current formation
- NBI pre-ionisation
- UV lamp, TS laser, hot filaments
- combination of these

M Gryaznevich, *Formation in STs*, IAEA TM on ST, St Petersburg 3-6 Oct 2005
Objectives of Formation Studies in STs

Three key elements:

- Provide reliable breakdown and current formation
- Minimise use of the central solenoid flux (save solenoid volt seconds) and maximise use of flux from external coils (i.e. $B_V$ ramp-up)
- Explore non-solenoid formation (as most of CTF and STPP designs have no central solenoid)
Inductive Methods:

- conventional formation using central solenoid flux ("direct induction")
- formation without use of the central solenoid flux (non-solenoid formation)
- use of external electrodes: CHI, arcs, plasma guns etc.
Inductive Methods of Formation

Comparison of M/C (breakdown around P3 coils and formation at midplane multiple null):

with Direct Induction (DI, no proper null):

with ‘hybrid’ induction (formation at off-midplane nulls):
“Direct Induction” Formation

- Direct induction is unlikely to be feasible in future STs, as it requires the presence of a central solenoid. However most present STs use direct induction as the main formation method.

- The advantage of direct induction in STs is that a high electric field can be created with low loop voltage due to the very small inner radius of an ST vessel.

- The breakdown zone, which is the inner midplane area in the ST, is the region of highest TF and also typically has low error field (as it is far from many of the EF sources). These improve b/d conditions.

- Due to low volt-second consumption of STs, direct induction in STs can be quite effective. On MAST, it has provided low \( I_i \) plasmas with high elongation from the formation phase.
“Direct Induction” Formation

- However, M/C allows to increase flat-top duration compared to Direct Induction as it allows very fast plasma current formation.

\[ 0.290 \text{Vs} \quad 0.070 \text{Vs} \]

\[ \text{Direct Induction} \]
“Direct Induction” Formation, MAST

Results of Direct induction breakdown studies on MAST

In breakdown studies:

Only TF and solenoid have been pulsed.

However, due to image currents in PF cases stray vertical field was not optimal for breakdown. This explains relatively high (compared with START) breakdown voltages.

\[ D_\alpha \text{ and line integrated density vs } U_{\text{loop}}. \text{ Triangles represent shots with 8\% less TF} \]
“Direct Induction” Formation, START

Very high $I_p$ ramp-up speeds (up to 17MA/s), low $I_i$ and elongation $\kappa \sim 2.7$ have been achieved on MAST using DI.

However, the breakdown phase has not been optimised on MAST.

Optimisation has been done on START:

- breakdown strongly depends on filling pressure

\[ H_\alpha \text{ emission vs filling pressure at } U_{loop} = 0.3V \]

\[ H_\alpha \text{ emission vs } U_{bd} \text{ at filling pressure } = 0.5 \times 10^{-5}\text{torr and } 1.5 \times 10^{-5}\text{torr} \]
Inductive Methods:

- conventional formation using central solenoid flux ("direct induction")
- formation without use of the central solenoid flux (non-solenoid formation)
- use of external electrodes: CHI, arcs, plasma guns etc.
Formation at High Order Null or Nulls

It is easier to get breakdown at poloidal field null:

\[ j(a) \sim m^2 A_m a^{-2} \]

here \( a \) - maximum radius of current channel
\( m \) - “multiplicity” number
\( A_m \) - vector-potential of multiple field (i.e. field value)

from Zakharov, Shafranov, VTP, v.11, p 190

Various nulls can be used for breakdown:

- formation in high order null at midplane (“merging-compression” or “induction-compression”)
- “outer null formation” attempted on START, MAST, NSTX, TST-2
- “Double Null Merging” (DNM)
Merging-compression studies in STs

- Plasma formed around internal “induction” coils, merged at midplane and compressed to form spherical plasma
- m/c was the main formation method during first years of START, before a small central solenoid was installed

Was also used on FBX-II, Waseda Univ., Japan:

MAST shot #2482
Merging-compression studies on MAST

With standard use of solenoid (blue curves) M/C produces up to 540kA plasma
With zero solenoid (red curves) M/C produces up to 430kA plasma current, discharge lasts ~0.5sec

- Merging-compression minimises use of solenoid flux during start-up
- Reliably used in most START and MAST regimes
- Good target for non-solenoid current ramp
M/C performance:

- Plasma current increases linearly with $I_{P3}$
- Plasma energy increases $\sim (R_{P3} I_{P3})^2$
- Plasma current increases with TF

Difference in $W_e$ and $W_{tot}$ could be partly attributed to ion heating

M Gryaznevich, *Formation in STs*, IAEA TM on ST, St Petersburg 3-6 Oct 2005
Formation at High Order Null or Nulls

- “outer null formation” attempted on START (up to 40kA), MAST, NSTX (20kA), TST-2 (with null outside vessel) and on other STs.

MAST, other null options:

- Problems in STs:
  - TF is low at big radius
  - difficult to provide enough flux and loop voltage simultaneously

M Gryaznevich, Formation in STs, IAEA TM on ST, St Petersburg 3-6 Oct 2005
“Outer Null” Formation

- “outer null formation” demonstrated on START (up to 40kA)

“OH”, bvi and bvo coils in START

First spike on plasma current – formation around “OH” coil (not shown in CCD picture)

CCD pictures show formation at null, t=22.3ms (left) and spherical plasma formation after compression t = 22.5ms (right), $I_{pl} \sim 30kA$
“Double Null Merging” Formation

- "outer null formation" is complicated as breakdown position is too far from outer PF coils (too low $E_{bd}$) or situated at very low TF (poor b/d conditions)

- can we bring breakdown position to higher TF and closer to PF coils?
- these lead to an idea of the “Double Null Merging”, or DNM

First used on START:

- Two rings formed between PF coil and central post
- They merge at midplane without losing any current, producing high elongated plasma

M Gryaznevich, *Formation in STs*, IAEA TM on ST, St Petersburg 3-6 Oct 2005
“Double Null Merging” Formation

Double-Null Merging Modelling for MAST by Frascati team:

more: P Micozzi et al, this meeting

\[ t=15\text{ms} \quad I_p = 150 \text{ kA} \]

\[ t=21\text{ms} \quad I_p = 250 \text{ kA} \]

\[ t=45\text{ms} \quad I_p = 450 \text{ kA} \]

\[ t=60\text{ms} \quad I_p = 600 \text{ kA} \]

\[ t=75\text{ms} \quad I_p = 600 \text{ kA} \]
“Double Null Merging” Formation

- First results of DNM on MAST are very encouraging:
  - merging of two plasma rings formed in low-order nulls between poloidal field coils
  - current ramp using flux from vertical field coils
  - central solenoid was disconnected in these experiments
“Double Null Merging” Formation

Results from MAST: CCD pictures of divertor region confirm plasma ring formation between P3 and P2 coils

Plasma from an upper port, looking at divertor region
No plasma surrounding P3, as P3 support is clear

plasma ring between P3 and P2 clearly seen
“Double Null Merging” Formation

After some optimisation, plasma current up to 340kA formed and plasma sustained for 0.3sec with zero current in central solenoid.

Plasma is hot ( ~ 0.5keV) and dense (9x10^{19}m^{-3}).
“Double Null Merging” Formation

- Studies of plasma merging on TS-3&4 (Tokyo) and MRX (Princeton), suggest strong ion heating due to reconnection.
- On MAST, measurement of $T_i$ by Charge Exchange shows thermal ion and electron temperatures just after merging are comparable.

For DNM plasma current appears to be independent of $I_{P3}$ while for m/c it is linear with $I_{P3}$:

$I_{pl} \times R_0$ vs $P3$ flux

TS profiles for these $I_{p3}$ values: $T_e$, $n_e$, $P_e$

$W_e$ does not depend on $I_{P3}$
“Double Null Merging” Formation

Similar scheme was proposed by the TS-3/4 team:

Here, the 2 initial rings are formed in the null between two external coils. Hence, good flux input; no contact with coil cases

Also: P Micozzi et al, Y Ono et al, this meeting
Non-solenoid start-up and current ramp:

- Plasma current can be ramped-up using only flux from $B_V$ coils during NB heating

After non-solenoid formation, plasma current can be ramped-up non-inductively, or using $B_V$ ramp-up, or combination

green dots – ramp-up in H-mode
blue triangles – ASTRA simulations

- If sufficient NBI power is provided, plasma current can be ramped-up without use of the solenoid flux (ASTRA simulations)
Inductive Methods:

- conventional formation using central solenoid flux (“direct induction”)
- formation without use of the central solenoid flux (non-solenoid formation)
- use of external electrodes: CHI, arcs, plasma guns etc.
Other methods: CHI, arcs, plasma guns, etc

Different other methods have been investigated:

Plasma formation with helical arc (Pegasus)

More: G Garstka, this meeting

CHI on NSTX

More: R Raman, this meeting
Non-Inductive Methods:

- pure non-inductive plasma formation
- inductive formation assisted by ECR, EBW, NBI or other pre-ionisation and current formation methods
“direct induction”, i.e. formation without proper null

Also: Y Takase et al, T Maekawa et al, Y He et al, this meeting
ECRH/EBW plasma current formation

Pure toroidal field: b/d occurs, but no current measured

ECRH pulse of 60 GHz, 0-20 ms (0.3 MW), O-mode polarisation.

With 5 mT vertical magnetic field: current up to 10 kA.

MAST experiment: CCD and magnetics

Schematic of current generation

EC Resonance
RF Plasma
Plasma Drift
$B_{\text{tor}} \nabla B$

M Gryaznevich, Formation in STs, IAEA TM on ST, St Petersburg 3-6 Oct 2005
ECRH/EBW plasma current formation

- ECR current generation during formation stage in present STs has similar efficiency to that observed previously (C Forest)

RF-generated plasma current in different tokamaks

RF frequency:
- DIII-D, MAST: 60GHz
- TST-2: 8.2GHz
- CDX-U, LATE, SUNIST: 2.45 GHz

Plasma current up to 35kA obtained on MAST using combination of EBW and BV ramp-up (#11313 – 0.8MW, #11312 – no RF, U_{loop}=0)
ECRH Breakdown in TF and BV at higher RF power

- Plasma Size in Start-up Phase:

  MAST, # 11603

  RF power, MW
  Loop voltage, V
  \( <n_e> \), \( 10^{18} \text{ m}^{-2} \)
  \( D_\alpha \), a.u.

- possible formation of two plasma rings: inner (bright) and outer (shallow), seen at CCD pictures:

- two plasmas seen by linear CCD

M Gryaznevich, *Formation in STs*, IAEA TM on ST, St Petersburg 3-6 Oct 2005
Non-Inductive Methods:

- pure non-inductive plasma formation
- inductive formation assisted by ECR, EBW, NBI or other pre-ionisation and current formation methods
  “direct induction”, i.e. formation without proper null
- inductive formation can be efficiently assisted by ECRF, EBW, NBI or other pre-ionisation and current formation methods

[B.Lloyd at al., Nucl. Fus. 31 (1991) p.2031]
ECRF breakdown studies on START

- During first START experiments no solenoid was available and ECRF preionisation was used to assist b/d at midplane null
- When solenoid was installed, ECRF preionisation was used to assist “direct induction” formation

- **Three different RF sources have been used:**
  - **2.45GHz**, 1.4 kW magnetron with a low field side (LFS) ordinary (OM) and extraordinary (XM) launch and pulse duration ~ 3.5ms, in hydrogen
  - **14.3GHz**, 0.45 - 2 kW klystron with a low field side *ordinary* launch and pulse duration ~ 10ms in hydrogen
  - **60 GHz**, 160kW gyrotron with the ordinary, extraordinary and 45° LFS and HFS (vertical) launch and pulse duration ~ 20ms, in deuterium.
ECRF breakdown studies on START

- **2.45GHz** experiments (no central solenoid, b/d in pure TF) ~1.0 kW
  OM and XM LFS launch used. Both fundamental and 2nd harmonics
  \((2\omega_{ce})\) breakdown observed

\[\begin{align*}
0.0 & 0.5 & 1.0 & 1.5 & 2.0 & 2.5 \\
0 & 50 & 100
\end{align*}\]

\[\begin{align*}
0.0 & 0.5 & 1.0 & 1.5 & 2.0 & 2.5 \\
0 & 50 & 100
\end{align*}\]

- For the XM launch, the \(H_\alpha\) emission for the fundamental resonance breakdown
  was nearly 2 times lower in the whole pressure range.

- No such difference has been observed for the OM launch.
  
  *similar to CLEO results B. Lloyd et al, 13th EPS, Schliersee, 1986*

- Quadruple null b/d: clear advance up to 0.3ms and increase in the \(H_\alpha\)
  emission by a factor of 10-15 has been observed with the ECRF assist

M Gryaznevich, *Formation in STs*, IAEA TM on ST, St Petersburg 3-6 Oct 2005
ECRF breakdown studies on START

- **14.3 GHz experiments (b/d in pure TF and “direct induction”)**

- ECRF breakdown has been achieved in pure toroidal field at the fundamental resonance.

- By using ~0.45kW of ECRF power it was possible to obtain current formation and ramp-up at 1.5V and filling pressure of ~ 10^{-5} Torr (which is ~ 5 times lower than in m/c formation), at \( \text{TF}_{20\text{cm}} = 0.45\text{T} \).

- No plasma current above the noise level has been observed at lower loop voltage. However, no attempt to optimise breakdown conditions was made.

- Additional vertical field was then applied and plasma current of 25kA was produced. CCD picture showed formation of a low aspect ratio plasma with \( R = 28\text{cm}, A = 1.2 \) and elongation \( k \sim 1.4 \).
ECRF breakdown studies on START

• **60 GHz** experiments ("direct induction" formation). Vertical and LFS launch. OM, XM and 45°

  - No ECRF breakdown has been observed in pure toroidal field at the 2nd harmonic ($2\omega_{ce}$) with $\sim$150kW even after field and pressure optimisation.

  - After optimisation, b/d was produced at loop voltage below 0.3V

  - ECRF preionisation allowed to reduce b/d voltage by $\sim$ 10% and increase the b/d pressure range

  - The range of the breakdown pressures was 0.3 - 1.2 x $10^{-5}$ torr in the 60 GHz case comparing with 0.1 - 4 x $10^{-4}$ torr in the 2.45GHz case.
ECRF breakdown studies on START

60-140 kW of 60GHz \(2\omega_{ce}\) ECRF preionisation, helped to reduce breakdown voltage and increase the range of filling pressures

- Breakdown pressure range for \(U_{bd} = 0.3\) V
- Reduction in \(U_{bd}\) and increase in \(H_{\alpha}\) at filling pressure 0.5x10^{-5} Torr and 1.5x10^{-5} Torr

M Gryaznevich, *Formation in STs*, IAEA TM on ST, St Petersburg 3-6 Oct 2005
Ruby laser pulse (7J) and NBI have been used to assist plasma breakdown on MAST.

- When NBI was applied at t = 0ms or earlier, the moment of b/d was determined by optimum field conditions.
- When laser was used, b/d happened with 2–10ms delay.
- b/d was more delayed without pre-ionisation.

- Delay in breakdown reduces with loop voltage.
- Breakdown delay was calculated as the difference between appearance of first electrons (reflectometer) and gas ionisation (midplane $D_{\alpha}$).

M Gryaznevich, *Formation in STs*, IAEA TM on ST, St Petersburg 3-6 Oct 2005
Conclusions

• Although many STs have demonstrated effective plasma formation with and without use of the central solenoid flux, more systematic studies are needed to make suggestions for plasma formation schemes in future STs:

  • Fully non-solenoid plasma formation and current ramp up to MA level should be demonstrated on MAST and NSTX
  • More formation studies should be done on other STs, in particular on DNM, RF and novel formation methods
Plasma Formation in CTF

No central solenoid in CTF concept design requires alternative formation schemes:

On MAST, both the M/C and the new DNM schemes produced substantial initial plasma currents $> 0.4$MA without using the central solenoid.

M Gryaznevich, *Formation in STs*, IAEA TM on ST, St Petersburg 3-6 Oct 2005
Plasma Formation in CTF

No central solenoid in CTF concept design requires alternative approaches:

Ferritic steel shielding of the central post can provide some flux conservation for breakdown and initial current formation

‘Ideal’ RF start-up Scenario

- Plasma is produced by RF pre-ionisation with O-mode (~28 GHz) at fundamental EC resonance provided by toroidal magnetic field (many tokamaks)
- Small vertical field is applied to initiate pressure driven current (PDC) (CDX-U, DIII-D, MAST, LATE)
- PDC provides initial confinement allowing formation of closed flux surfaces and electron temperature exceeding 10 eV (DIII-D, LATE)
- EBW is excited within the plasma by the X-mode (~28 GHz) launched from the HFS (COMPASS-D)
- EBW CD improves confinement and enhances plasma current up to a few hundred kA at relatively low density so that $\omega_{RF} > \omega_{pe}$ (COMPASS-D)
- O-mode of lower frequency (~18 GHz), so that $\omega_{RF} < \omega_{pe}$, is injected from the LFS at the launch angle providing efficient O-X-B coupling and co-EBW CD (W7-AS)
- Since O-X-B EBW CD is activated the plasma current and density can be increased to required values (limited by RF power only) and sustained indefinitely (W7-AS)
Pressure Driven Current Evolution

- ECRH is applied at 50 ms
- Closed flux surfaces are formed only ~100 ms later
- Maximum PDC is obtained with closed flux surfaces
- In MAST ECRH pulse duration was limited by 20 ms
- Plasma density exceeded the O-mode cut-off
- PDC scheme can generate a target plasma for EBW CD based on O-X-B conversion

FIG. 4. The evolution of poloidal flux contours on DIII-D during bootstrap start-up for a 22 kA discharge. The ECH begins at 50 ms. The final equilibrium shape has $R=169$ cm and $a=48$ cm, with $\rho_95=35$. 

M Gryaznevich, *Formation in STs*, IAEA TM on ST, St Petersburg 3-6 Oct 2005
Start-up Experiments on LATE

FIG. 1: Discharge waveform. The times noted by (a)-(h) correspond those in Fig. 2.

FIG. 4: (a) Plasma current and radial position of current center versus decay index of the external vertical field, and (b) outermost flux surfaces for various decay indices.

FIG. 5: (a) Waveform of 4.15 kA discharge and (b) magnetic field line on the outermost surface at $I_p = 4.15$ kA.

M Gryaznevich, Formation in STs, IAEA TM on ST, St Petersburg 3-6 Oct 2005
Validity of the Ejima scaling at low-aspect ratio

- Addition of low-aspect ratio data to the database shows an apparent variation of Ejima-Wesley parameter \( C_{EW} = \frac{\Delta \psi_{surf}}{\mu_0 I_{pl} R} \) with aspect ratio

- Decrease in \( C_{EW} \) at low-aspect ratio is connected with natural increase in elongation and decrease in \( I_i \), which reduce the inductive flux, and the reduction of resistive losses due to increased current ramp speed

Data for ITER, CIT, MAST, NSTX and USTX taken from simulations (TSC and other codes), all other data is from published experimental results, ITER database and private communications (CDX-U and MEDUSA)
TS preionisation

• Laser radiation can efficiently produce ionization of excited atoms in plasma if the photon energy exceeds the ionization potential of level of interest

• Photon energy of Nd laser (1.17eV) is enough to ionize atoms for the levels \( n \geq 4 \) (\( I_p \leq 0.85eV \)), ruby laser (1.79eV) - for the levels \( n \geq 3 \) (\( I_p \leq 1.51eV \)).

• During the laser pulse, the excited atoms will be ionized but will not emit radiation. So, the selfemission will be suppressed and in the limit of high laser intensity (ionization rate exceeds relaxation one, resulting in the utmost level depletion) the local plasma line emission should go to zero.

\[ S \text{ Tolstyakov, Phys Meet. Nov 2004} \]

• However, these applies for ionized gas, i.e. when we have excited atoms

• Neutral gas ionisation is possible, but at high pressures

• Another preionisation mechanism is photo-effect from laser-dump interaction (acts similar to hot filament)