Plasma start-up at GOLEM

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- **Basic physics of the start-up phase of a tokamak discharge**
- **Results of remote operation of GOLEM from V. N. Karazin Kharkiv National University, The Faculty of Physics and technology**

The GOLEM tokamak

GOLEM is the small tokamak with, which is operational at the Faculty of Nuclear Science and Physical Engineering, Czech Technical University in Prague, http://golem.fjfi.cvut.cz

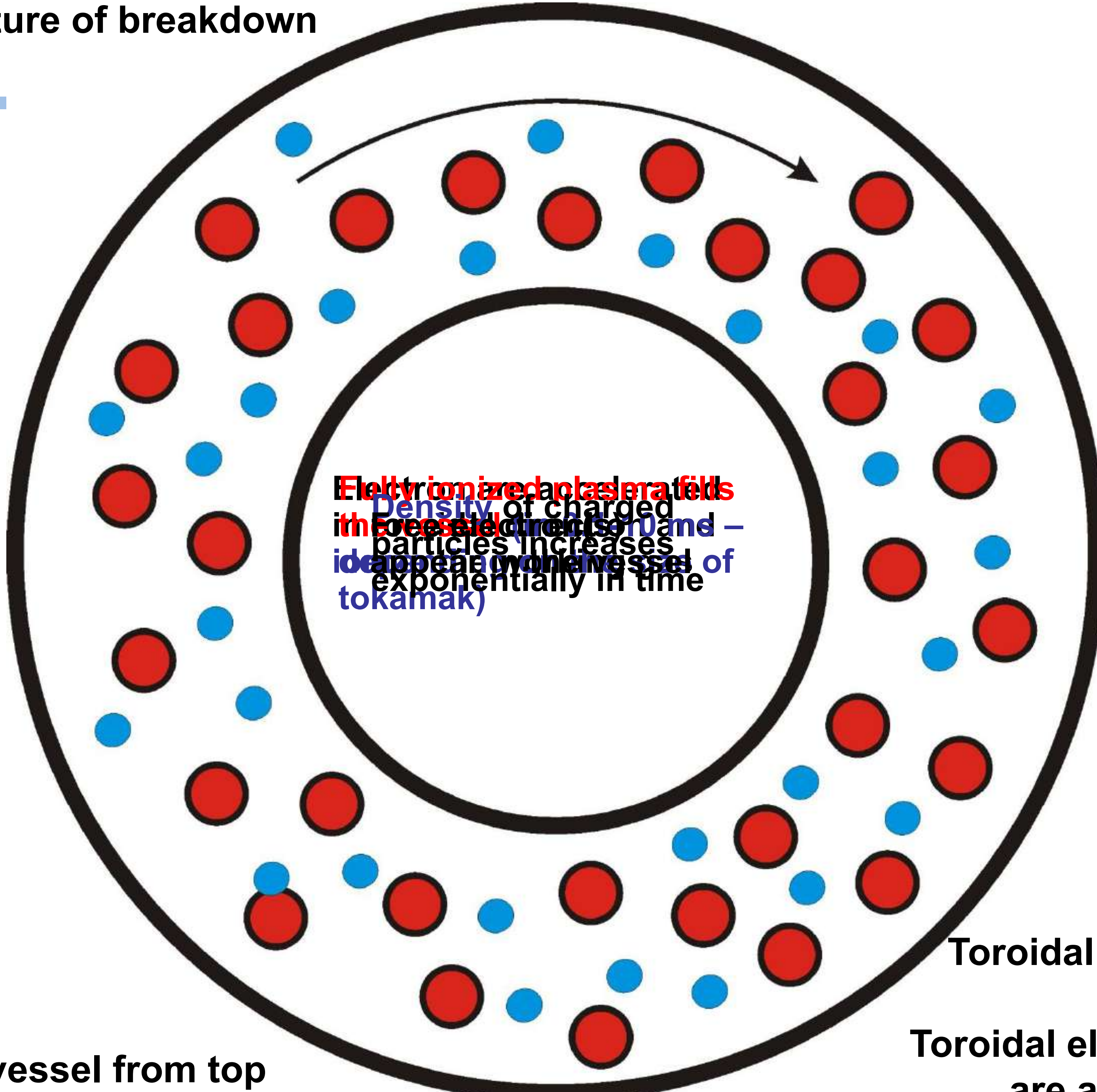
Main features:

- Circular cross section
- Iron core transformer
- Major radius R_0 = 0,4 m
- Minor radius of the conducting vessel b = 0,1 m
- Minor radius of the molybdenum limiter a = 0,085 m
- System of poloidal field coils – out of operation at described experiments
- Power supplies – two capacitor banks

Typically:

- Toroidal magnetic field < 0,5 T
- Plasma current < 8 kA
- Pulse length < 20 ms
- Central electron temperature < 70 eV
- Line average electron density < 10^{19} m^{-3}

Trivial picture of breakdown



Free electrons appear in the vessel

Electrons are accelerated in toroidal direction and ionize neutrals

Density of charged particles increases exponentially in time

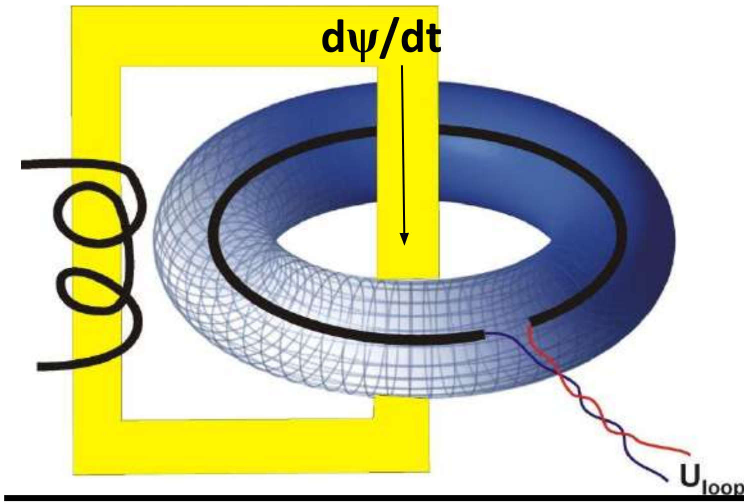
Fully ionized plasma fills the vessel (in 2-10 ms – depending on the size of tokamak)

Tokamak vessel from top

Toroidal magnetic & Toroidal electric fields are applied

Toroidal electric field & plasma current

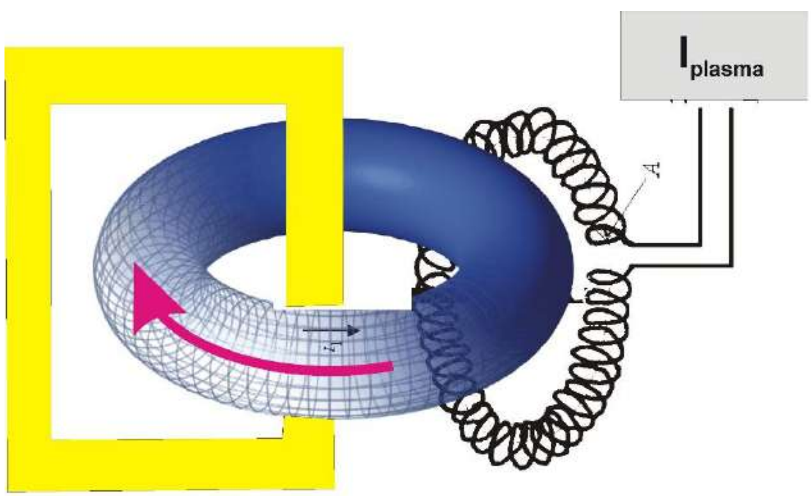
Toroidal electric field E_{tor} is required plasma breakdown in tokamaks and for inductive current drive. E_{tor} is generated by transformer by primary current I(t)



The toroidal electric field is measured by a single loop located along the plasma column

$$E_{tor} = U_{loop}/2\pi R_0$$

Loop voltage $U_{loop} = - d\psi/dt$



Toroidal current I_{rog} is measured by the Rowowski coil, surrounding the vessel

$$I_{rog} = I_{vessel} + I_{plasma}$$

$$I_{vessel} = U_{loop}/ R_{vessel}$$

$$R_{vessel} = 10\ m\Omega$$

Time sequence of plasma start-up at GOLEM

1. **Fill the tokamak vessel (well conditioned) with the working gas (Hydrogen) of requested pressure (p = 5 – 20 mPa) and switch on a preionization**

2. Apply the trigger pulse to start the data acquisition system

⇒ ***Experimental data are collected from t = 0 ms***

3. Apply the trigger pulse to discharge the capacitor bank U_{Bt} at t = 5 ms

⇒ ***Toroidal magnetic field is generated inside the vessel***

4. Wait until a selected value of the toroidal magnetic field is reached. (GOLEM typical time delay 0 - 5 ms

5. Apply the trigger pulse to discharge the capacitor bank U_{oh} to primary winding of the transformer

⇒ ***Time-dependent current in the primary winding generates the toroidal electric field inside the vessel***

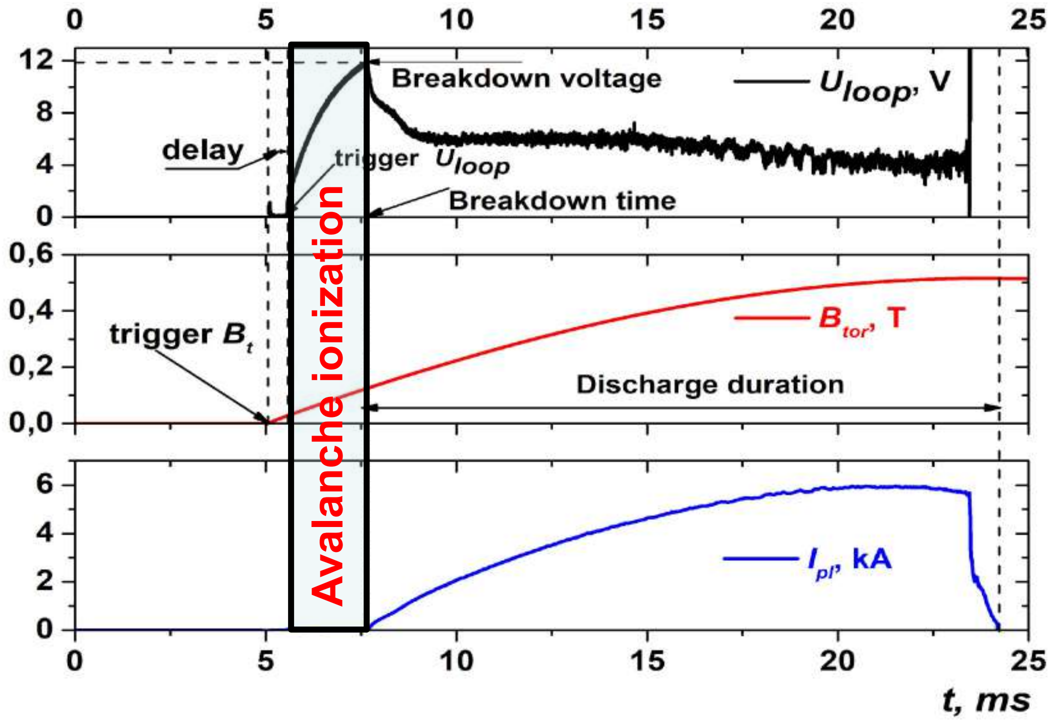
Typical discharge on GOLEM – role of the time delay

#29871 with time delay between triggers of U_{BT} and U_{CD} is 0,5 ms

Loop voltage [V]
U_loop

Tor. mag. field [T]
B_tor

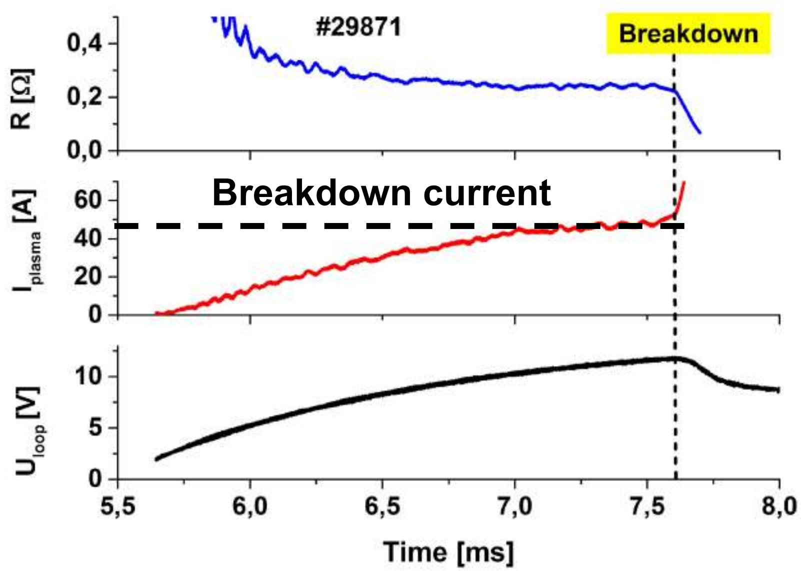
Plasma current
I_plasma

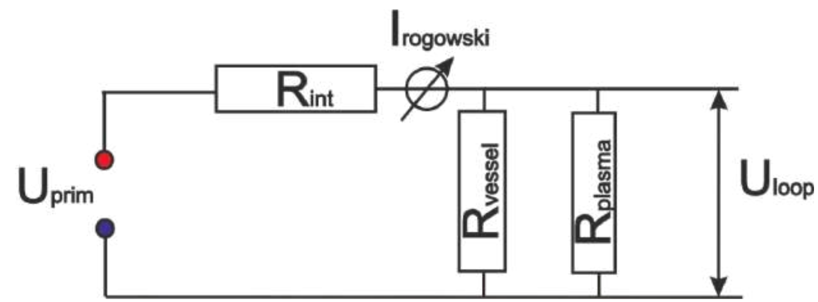


Time [ms]

The time delay between triggers of condenser banks of U_{BT} and U_{CD} determines the toroidal magnetic field at start-up of the avalanche ionization of the working gas

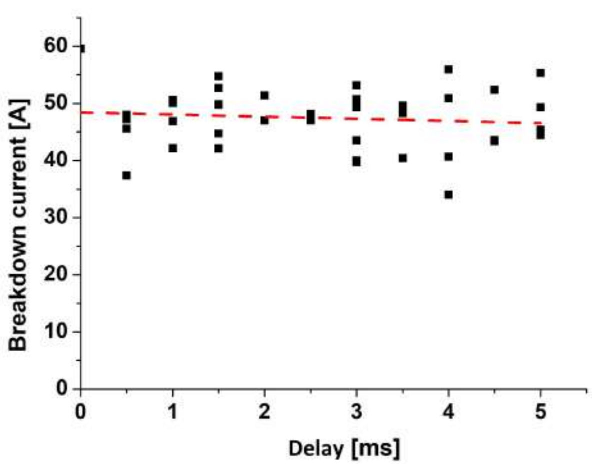
Start up of the GOLEM discharge





Drop of the loop voltage is caused by the drop of the plasma resistivity, because

$$R_{int} \gg R_{vessel}, R_{plasma}$$



At the moment of breakdown, the poloidal magnetic field of the plasma current compensates all particle losses.

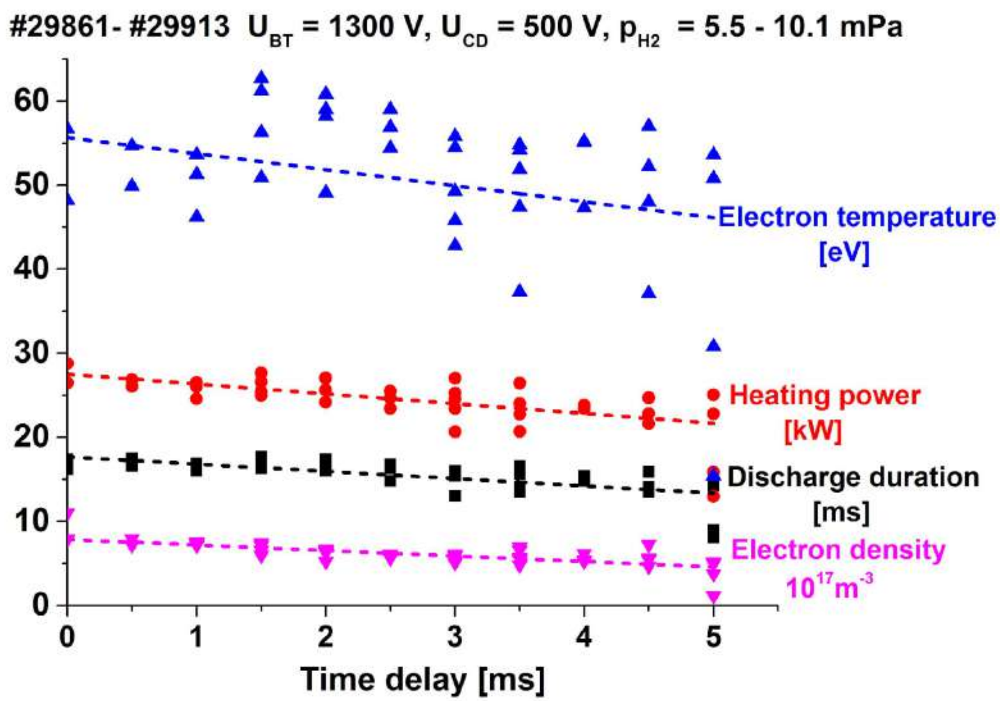
For I_{plasma} at the breakdown I_{BD} ~ 50 A

$$B_{pol} = \frac{\mu_0 I_{BD}}{2\pi a} = \frac{2*10^{-7} I_{BD}}{0,085} = 0.12 \text{ mT}$$

However, the radius of plasma column during the avalanche is not known, and could be (much) lower => B_{pol} >> 0.12 mT

Why to study breakdown at GOLEM?

Main macroscopic discharge parameters noticeably depend on the time delay between triggers of the U_{BT} and U_{CD}, i.e. on the toroidal magnetic field at which the toroidal electric field is applied

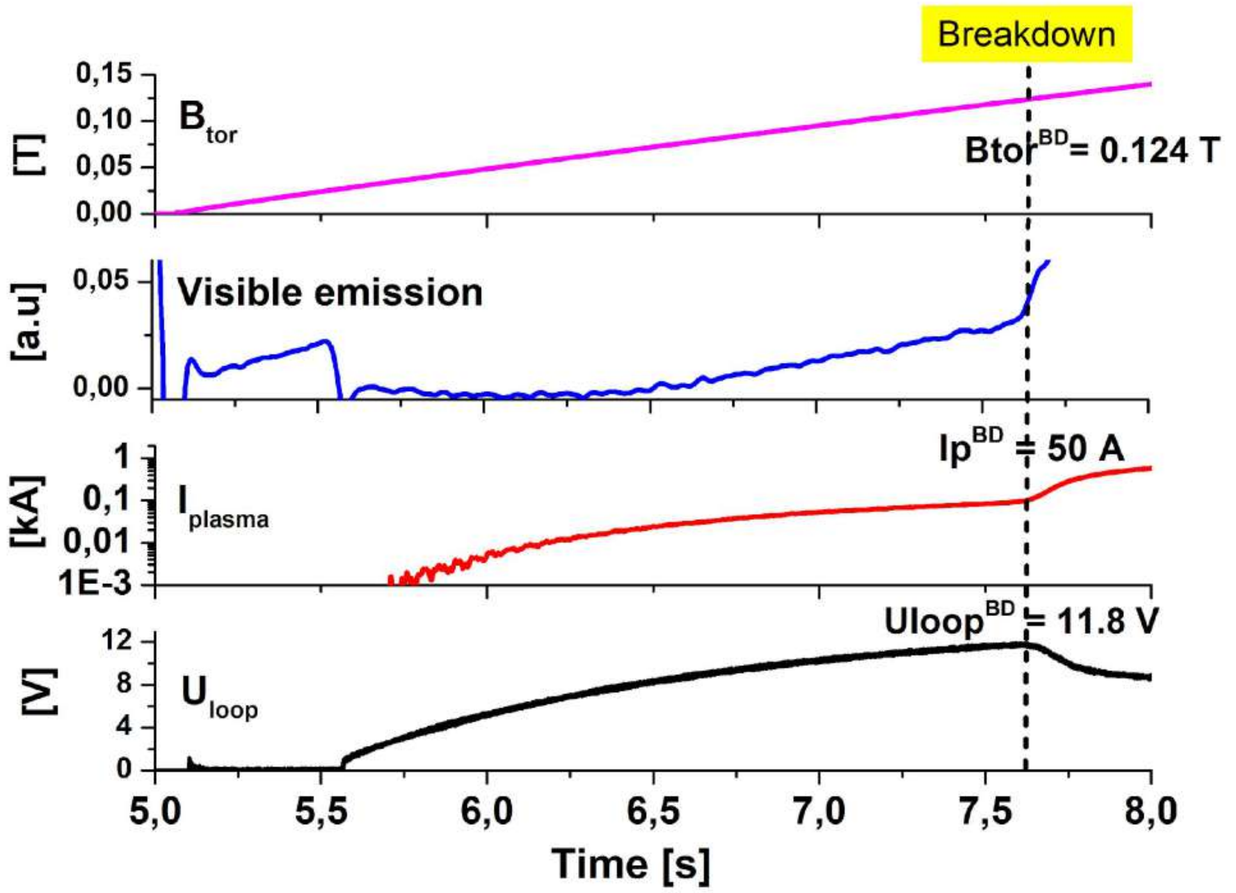


Experimental result of remote GOLEM operation from V. N. Karazin Kharkiv National University, Ukraine

- **Systematic scan: Charging voltage of the capacitor bank for TF is kept constant – UBT = 1300 V**
- **Charging voltage of the capacitor bank for primary winding of transformer is kept constant – UCD = 500 V**
- **Pressure of the working gas is changed from 5 to 10 mPa**

Avalanche phase of a GOLEM discharge

#29871 with time delay 0,5 ms



Toroidal magnetic field

Excitation

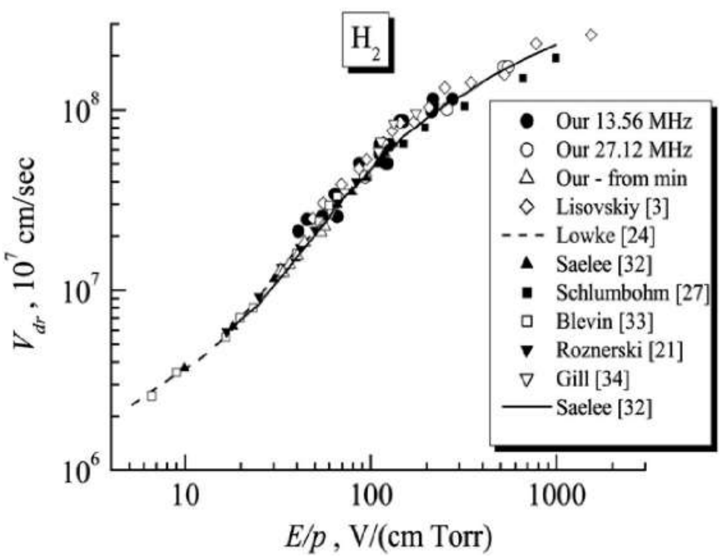
Ionization

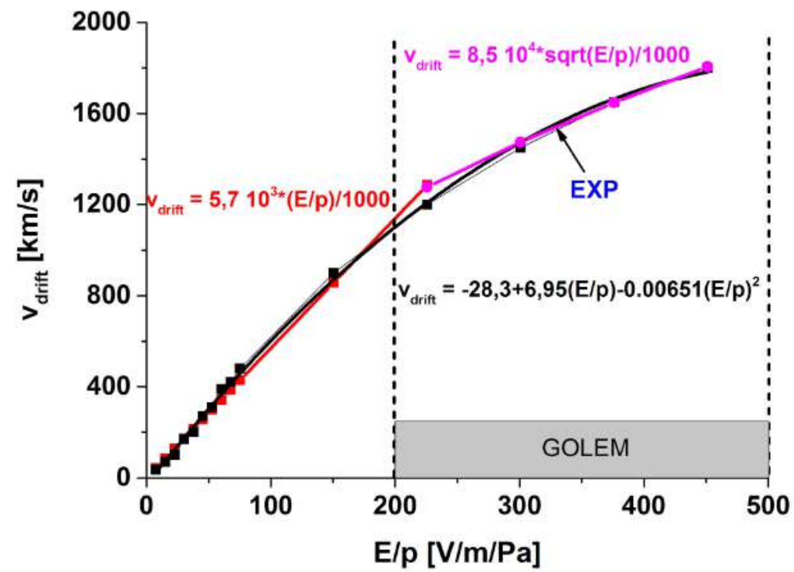
Toroidal electric field

Drift velocity of electrons at the avalanche

Electrons obtain a drift velocity v_d between elastic collisions hydrogen molecules, which depends on the ratio of the toroidal electric field and pressure E/p

p_{H2} = 10 mPa, E ~ 2 - 5 V/m

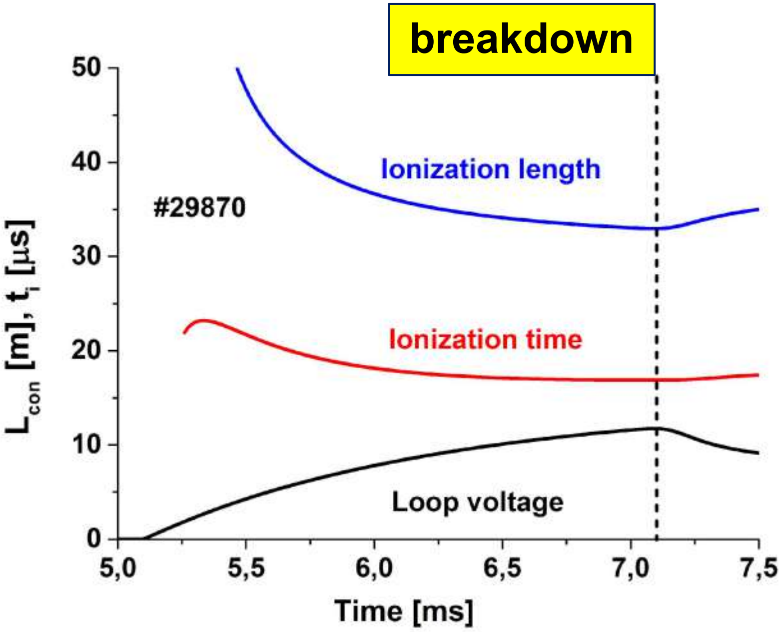




Several approximations of v_d versus E/p are available

-> GOLEM – v_d ~ 1 000 – 2 000 km/s during the avalanche

Ionization length/time at the avalanche



Number of ionizations per unit length is defined by the first Townsend coefficient α

$$\alpha = Ap_0 \exp(-Bp_0 / E)$$

A = 3.75 [Pa/m] B = 93.8 [V, Pa^{-1}, m^{-1}]

Ionization length $L_{ion} = 1/\alpha$

GOLEM – typically 30-40 m

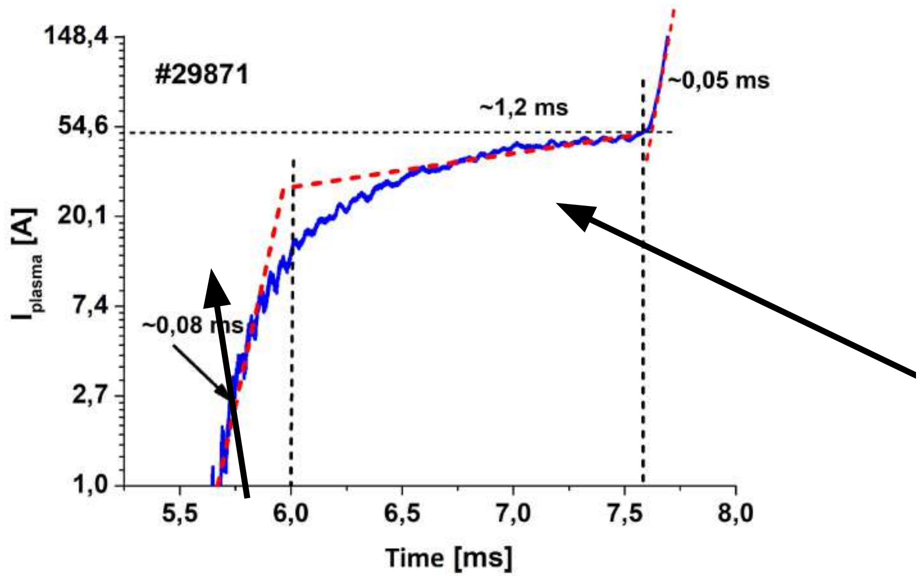
Electrons born during the avalanche have to perform 6-8 circumnavigations around the torus to ionized

Ionization time $\tau_i = L_{ion} / v_d$

Typical ionization time at GOLEM – 15-20 µs

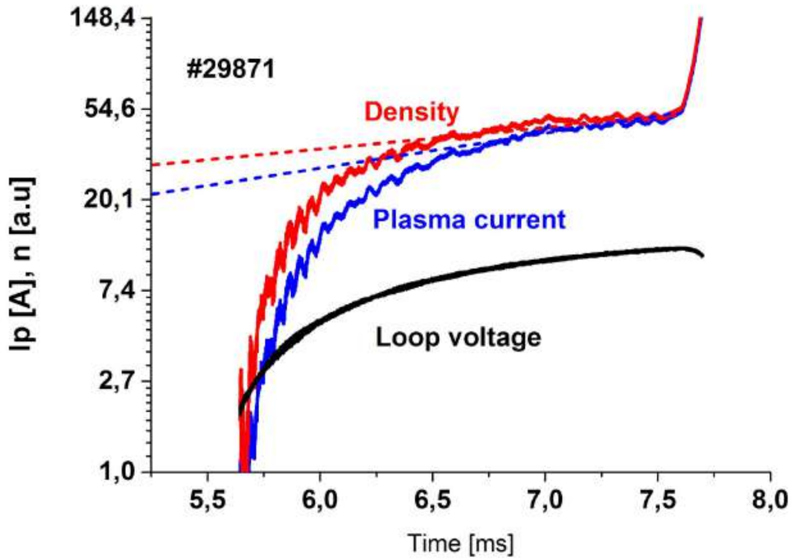
Plasma current/density during the avalanche

#29871 with time delay 0,5 ms



Plasma density during avalanche

$n \sim I_{plasma}/v_{drift}$



Plasma current increases exponentially with a time constant $\tau \sim \tau_i \approx$ 0,04-0,1 ms only the first ~ 0,4 ms after application of the toroidal electric field

Exponential increase of the plasma current / density is much slower in the time interval before breakdown $\tau \sim 1$

Losses of charged particle during the avalanche

$$\frac{n(t)}{n_0} = \exp\left(\frac{1}{t_i} - \frac{1}{t_{loss}}\right)t = \exp\left(\frac{1}{L_i} - \frac{1}{L_{con}}\right)v_D t$$

$$\frac{1}{\tau_{exp}} = \frac{1}{\tau_i} - \frac{1}{\tau_{loss}}$$

Particle loss time τ_{loss}

Example: For $\tau_{exp} \approx 2$ ms and $\tau_i \approx 0.1$ ms, the particle loss time is

$$\tau_{loss} = \tau_i \frac{1}{1 - \tau_i / \tau_{exp}} \approx \tau_i * 1.05$$

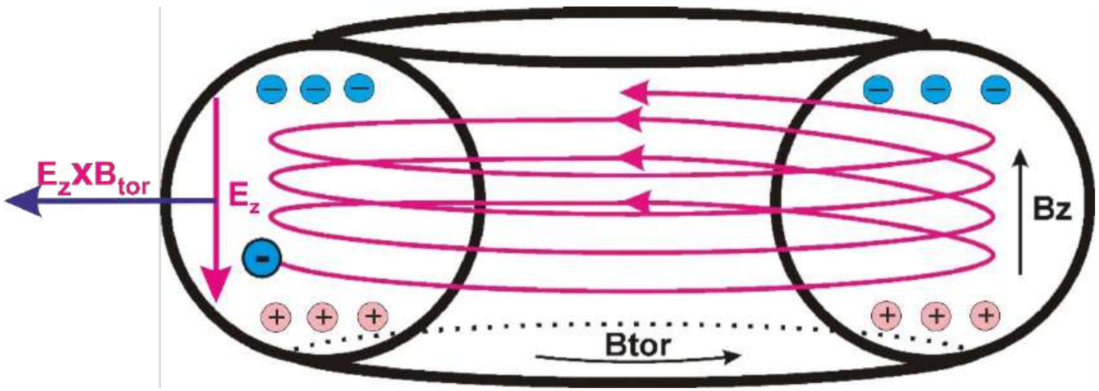
Therefore, the loss time has to prevail the ionization time just by a few percent during the avalanche!
This means that the loss time has to be comparable with the ionization time

Main reason of particle losses during the avalanche phase in tokamaks are
the stray perpendicular magnetic fields $B_{perp} << B_{tor}$

Plasma polarization due to the stray magnetic fields

Mechanism for sufficiently fast particle losses during the avalanche was proposed in the pioneering paper of Martin Valovic in Nuclear fusion, 1987, No.4, pp 599-603.

Perpendicular stray magnetic fields, which are always present in the tokamak vessel cause the drift of charged in perpendicular direction with respect to the toroidal magnetic field.



However, electrons escape much more quickly than ions, which leads to formation of the vertical electric field $E_\perp$ and consequent $E_\perp \times B_{tor}$ drift, followed by particle loses with the characteristic loss time

$$E_\perp \approx \frac{E_{tor} B_{tor}}{B_\perp} \Rightarrow v_{ExB} = E_{perp}/B_{tor} \Rightarrow \tau_{ExB} = a/v_{ExB} \Rightarrow \tau_{ExB} \approx \frac{aB_\perp}{E_{tor}}$$

Plasma polarization on GOLEM

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$$\tau_{ExB} \approx \frac{aB_{\perp}}{E_{tor}}$$

GOLEM: a = 0.085 m and Etor = 4 V/m and assuming the stray magnetic field $B_{\perp} \approx 0.5$ mT (just 0.1% of the toroidal magnetic field). Resulting characteristic loss time

$$\tau_{ExB} \approx \frac{0.085*5\ 10-4}{4} \approx 1.\ 10^{-5}\ [s]$$

Is already comparable with the ionization time.

Main sources of stray magnetic field on GOLEM during avalanche

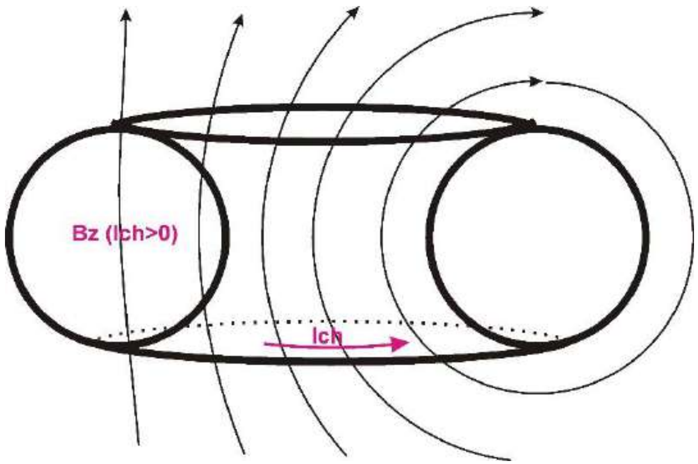
- Current induced in the tokamak vessel
- Stray magnetic field due to imperfect alignment of TF coils and corresponding circuits
- Stray magnetic fields due to the iron core transformer

$$\tau_{ExB} = a/E_{tor}\ (B_{\perp}^{vessel} + B_{\perp}^{TF} + B_{\perp}^{Transf})$$

Let us analyze contributions of individual components of B_{perp} to the total characteristic loss time

Stray magnetic field $B_\perp$ from the vessel current

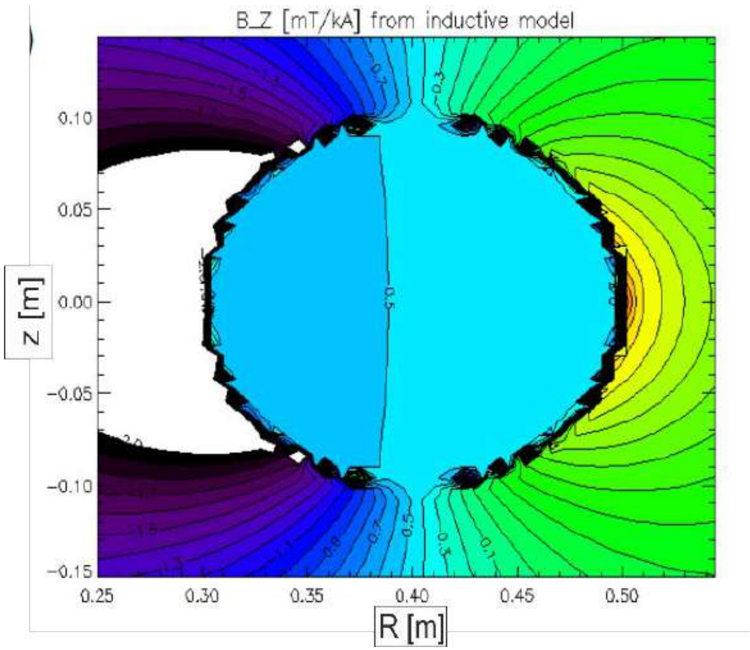
Toroidal current through the tokamak vessel generates a stray vertical magnetic field inside the tokamak vessel



Rough estimate (linear approximation – lower limit):

$$B_z = \frac{\mu_0 I_{vessel}}{2\pi r} = 10^{-7} I / R$$

For $2r = R_0 = 0.8$ m
⇒ B_z ~ 0.25 mT/kA



More precise 3D simulations (Tomas Markovic)
The B_z is almost uniform along the vertical component z, and it mean value is between B_z = 0.4-0.5 mT/kA.

The radial component B_R is much lower (B_R ~ 0. 1 mT/kA) => the vertical component dominates.
The orientation of the B_z component depends on direction of the vessel current.

Loss time resulting from the vessel current

Assume only the vertical component of the stray magnetic field $B_{\perp} \approx B_z$ due to the vessel current $B_z \approx 4.5\ 10^{-7} * I_{vessel} \approx 4.5\ 10^{-7} * V_{loop}/R_{vessel}$

The resistivity of the conducting vessel is $R_{vessel} \approx 0{,}01\ \Omega$ =>
$B_z \approx 4.5\ 10^{-5} * V_{loop}$ [T, V])

The characteristic loss time

$$\tau_{ExB} \approx \frac{2\pi * 4.5\ 10^{-5} a R_0 V_{loop}}{V_{loop}} \approx 1.2\ 10^{-5}\ [\mathrm{s}]$$

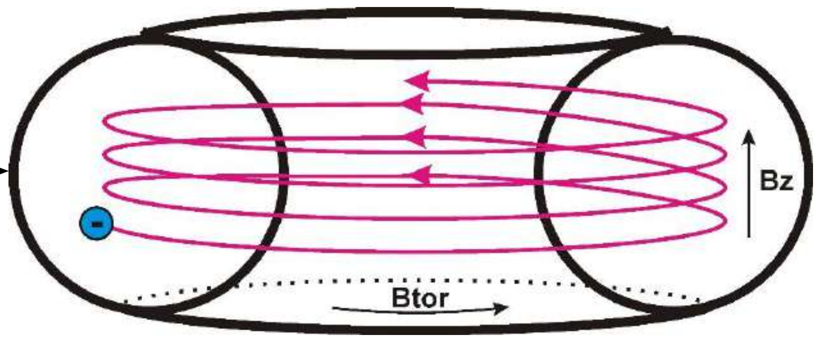
- already comparable with the ionization time

- Plasma losses during the avalanche are independent on the vessel current just a function of the tokamak geometry, if only stray magnetic field from the vessel current is assumed!

Loss time due $B_\perp$ during the avalanche

The trajectories of charged particles during the avalanche

Example $B\perp$ = Bz



The perpendicular drift velocity is

$$v_{perp} = v_d \frac{B_Z}{B_{tor}}$$

v_d ~ 2 000 km/s

The resulting loss time

$$\tau_{BZ} \cong a/v_{perp}$$

GOLEM during the avalanche – $\tau_{Bz} \approx 1$ ms

Particle losses due to B∇B and curvature drift

The guiding drift velocity due to the B∇B and curvature drift

) is the electron cyclotron frequency

Assuming $v_{par} = v_{per} = v_d$ => $v_{B\nabla B} = 3v_d^2/2R_0\omega_{ce}$

$v_{B\nabla B} = 2{,}3\ 10^{-2} * sqrt(E/p) * 1/B$ [m/s, V/m, Pa, T]

$\tau_{B\nabla B} \sim a/v_{B\nabla B}$

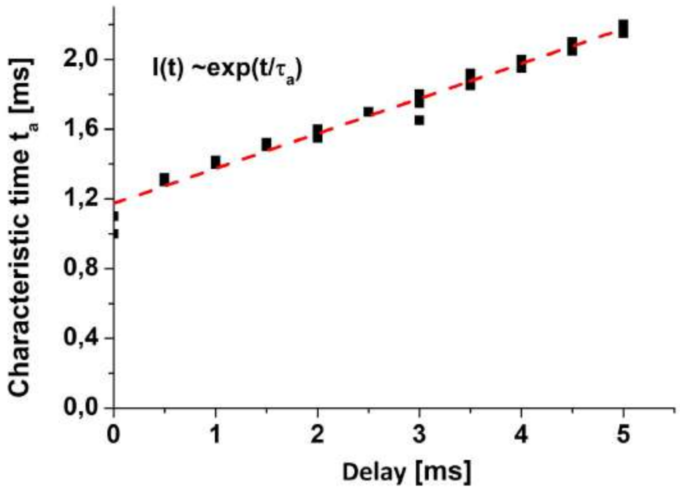
GOLEM during the avalanche => $\tau_{B\nabla B} \sim$ 5-15 ms

Note from previous slide that particle losses due stray magnetic field are much faster than direct losses due the B∇B and curvature drifts

$\tau_{B\nabla B} \approx$ 5-15 ms >> $\tau_{Bz} \approx$ 1 ms >> $\tau_i \approx$ 0,1 ms

- Particle losses caused by stray perpendicular magnetic field must dominate!
- Characteristic times are much higher by two order than the ionization time!

Breakdown versus the toroidal magnetic field



A small fraction of $B_\perp$ exists inside the tokamak vessel because of **imperfect alignment** of TF coils and of the **return conductor**!!

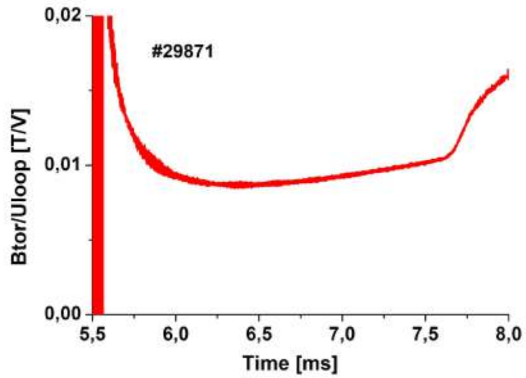
⇒ **There are particle losses during the avalanche proportional to the toroidal magnetic field.**

It is reasonable to assume that this stray field $B_\perp$ is proportional to the to toroidal magnetic field,

$$B_\perp = A*B_{tor} \qquad =>$$

Where A is an unknown constant!

$$\tau_{ExB} \approx \frac{aB_\perp}{E_{tor}} = \frac{2\pi R_0 a\, AB_{tor}}{V_{loop}}$$



$$\tau_{tot} \approx 2\pi R_0 a * (4.5\ 10^{-5} + A * B_{tor}/V_{loop})$$

Conclusions & Outlook

I tried to explain underlying physics of the plasma start-up in GOLEM

- We focus on the avalanche phase
- importance of ionization time and connection lengths
- Importance of stray magnetic fields

The dominant mechanism of particle losses is the plasma polarization caused by stray perpendicular magnetic fields!

Based on pioneering experiment at the CATOR tokamak
M. Valovic, *Convective losses during current initiation in tokamaks*, Nucl Fus 27 599, 1987

However, some features of plasma breakdown at GOLEM are remained still unexplained

In particular, dependence of various parameters on the toroidal magnetic field! => more ideas/experiments on are required to fully understand plasma breakdown on GOLEM

Drift velocity & Ionization time during the avalanche

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Electrons obtain a drift velocity v_d between ionization collisions, which depends on the ratio of the toroidal electric field and pressure of molecular hydrogen E/p . Only approximation of v_d is available for H_2:

Approx. for 70<E/p<1500 [V/m, Pa] $v_D = 6{,}9\times 10^4 \sqrt{(E/p)}$ [m/s, V/m, Pa]

Typically E/p = 80-800 $V_d \sim 0.55 - 2 * 10^6$ m/s

Note: For E/p > 500 , the electron distribution function becomes strongly non-Maxwellian and a significant fraction of electron can run-away!

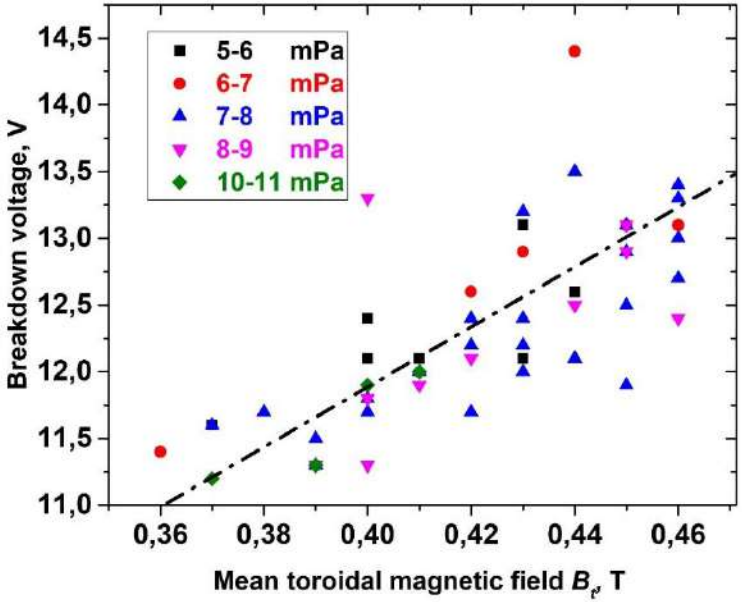
Temporal evolution of plasma density is: $n(t) = n_0 \exp\frac{t}{t_i}$

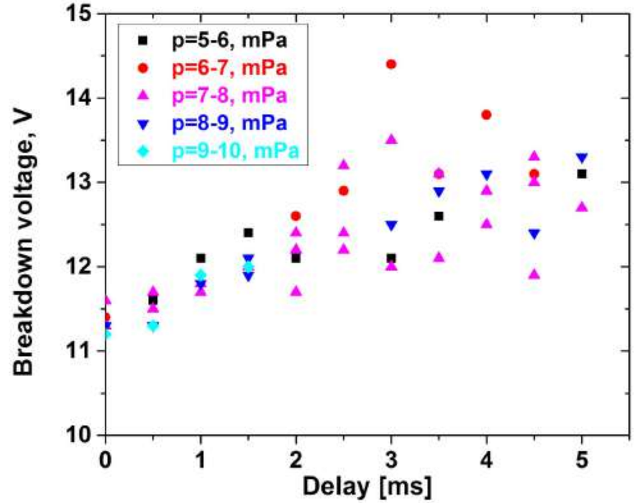
where the ionization time t_i is defined as $t_i \sim L_{ion} / v_d$.
Typically, t_i ~ 20 μs at p_0 ~30 mPa

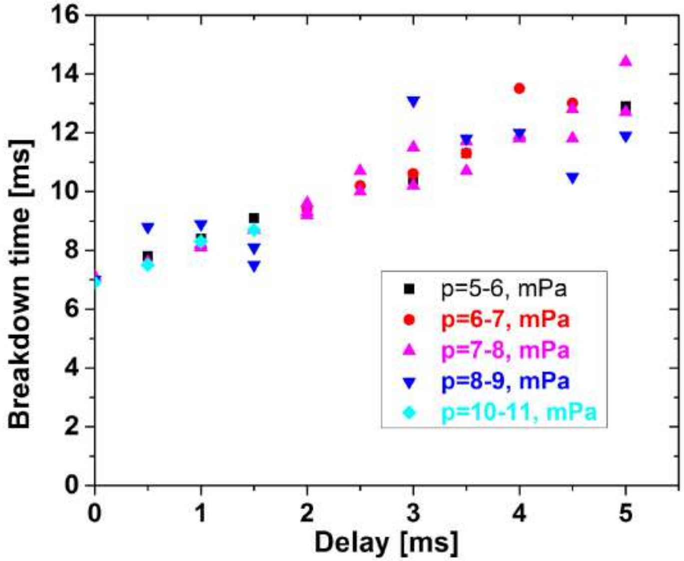
Example: Our final goal is to reach degree of ionization 5%, i.e. the plasma density 5×10^{17} m^{-3} with just a single electron inside the tokamak vessel (n_0=1 m^{-3}).
This occurs during the time interval t = 17 x ln5 x 20 x 10^{-6} ~ 550 μs !!!

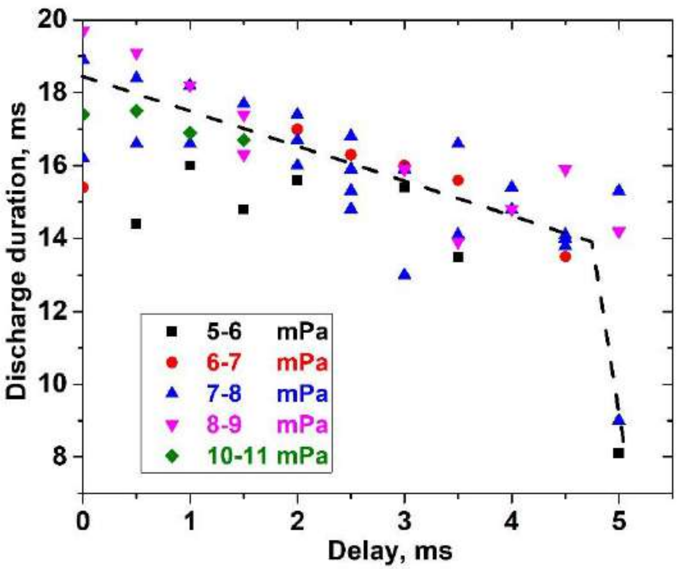
HOWEVER – this appears in an ideal case, when all electrons remain inside the vessel during the avalanche!!!

Why to study breakdown at GOLEM?

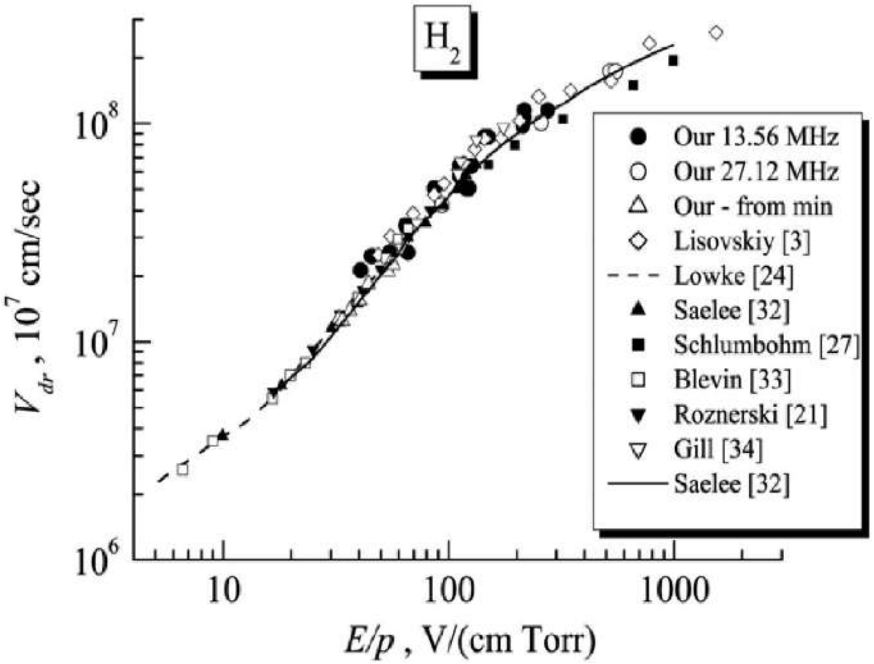


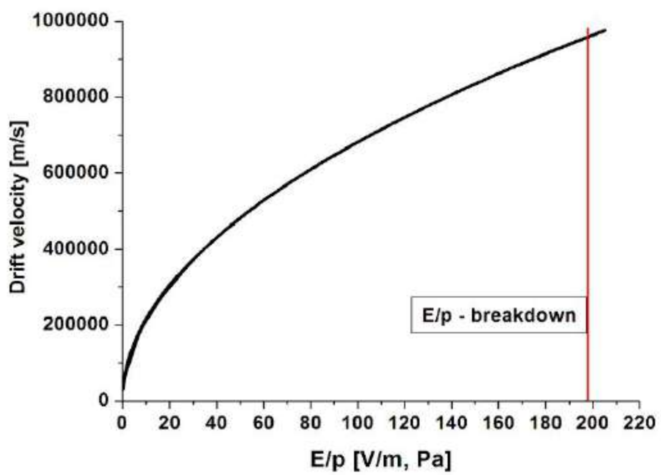






Drift velocity of electrons in molecular hydrogen

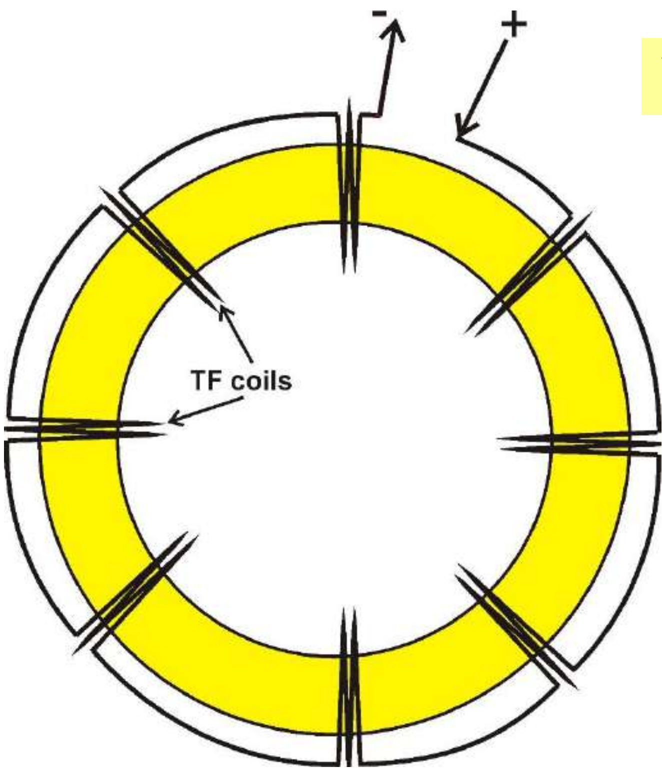




$$v_d = 6.4\ 10^4 * \sqrt{E/p}$$ **[m/s, V/m, Pa]**

Stray magnetic field $B_\perp$ from the Toroidal Field coils

View from the top



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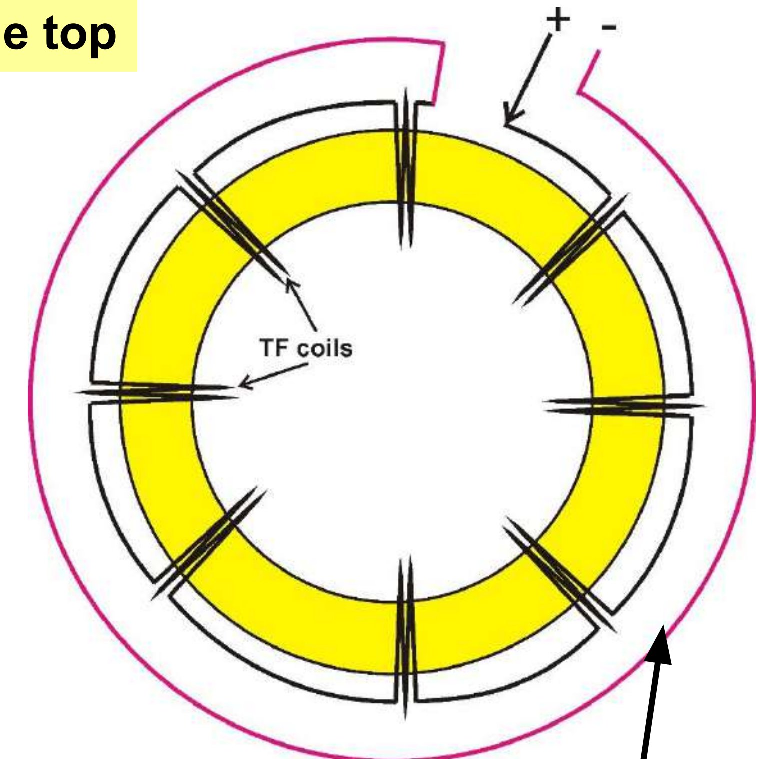

A strong vertical field B_z is created (oriented downwards)

$$B_z = \mu_0 I / 2\pi r$$

I = 1 kA, R = 0.4 m

B_z(center) ~ 0.15 T !!

Installation of Return Current Conductor significantly reduces the Bz field

Nevertheless, a small fraction of Bz (<1 mT) could still exists inside the tokamak vessel because of imperfect alignment of TF coils and the return conductor!!

Avalanche & Coulomb phases of breakdown

Plasma start-up can be divided into two phases with different underlying physics. Therefore, they have to be treated separately.

1. **Avalanche phase** – degree of ionization is low. Collisions between electrons and hydrogen molecules dominate. Electrons obey a drift velocity $v_D \parallel E_{tor}$, which is higher than their thermal velocity. Plasma current is still low, and the rotational transform is negligible.

2. **Coulomb phase** – collisions between charged particles dominate. Plasma current is sufficiently high and magnetic surfaces and the confinement is expected to increase significantly.

Transition between these two phase occurs when

$$\frac{\gamma}{1-\gamma} \approx 5\times10^{-5} T_e^{3/2} \qquad \text{[eV]}$$

where γ is the degree of ionization.

Typically, the transition occurs in tokamaks at 5% ionization at Te ~5 eV