Globus-M2 experiments at 0.7 T magnetic field

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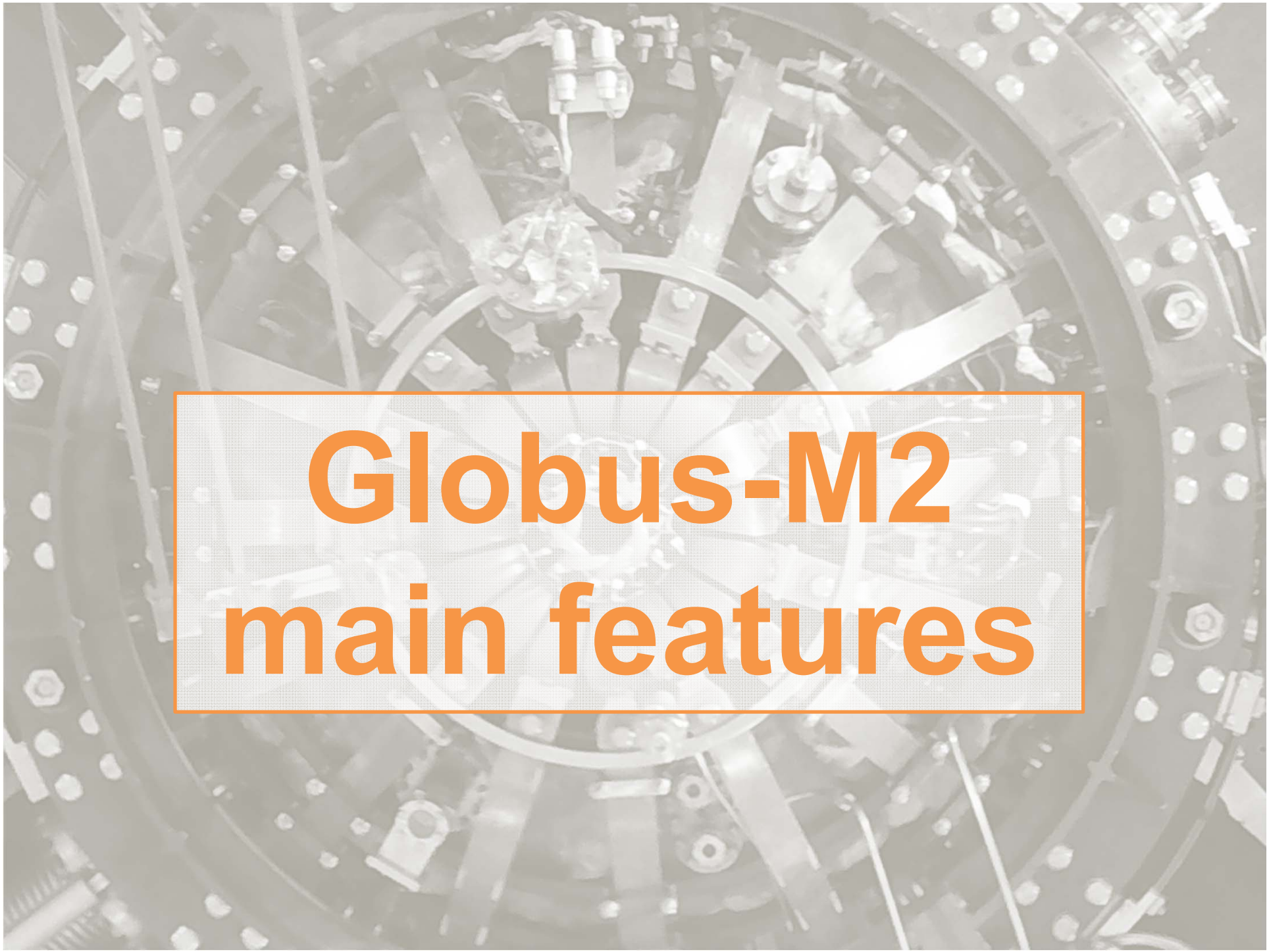
Outline

- Introduction

- Globus-M2
  - Main features
- Results of 0.7 T experimental campaign:
  - Plasma start-up
  - Plasma performance
  - Alfven instabilities
  - NB current drive
  - Lower Hybrid Current drive
  - Energy confinement
- Summary



Globus-M2 main features

Globus-M and Globus-M2

	Globus-M	Globus-M2 (ind / nonind)
B_{tor} (on axis), T	0.4	1.0 / 0.7
I_{pl}, MA	0.2	0.5
Ψ_{pol}, Wb	0.3	0.4
B_{tor}/R, T/m	< 1.1	< 2.7
I_{TC} kA (in each of 16 coils)	50	110
t_{pulse}, s	< 0.15	0.35 / 0.7
NBI [E, keV /P, MW]	30 / 1	40 / 1 + 50 / 1
ICRH [f, MHz / P, MW]	7.5 / 0.3	15.0 / 0.5
LHCD [f, GHz / P, MW]	0.9 / 0.1	2.45 / 0.5

Vacuum vessel, first wall armor, magnetic geometry remain unchanged

Globus-M2 mission

- High temperature– low collisionality regimes
- Noninductive current drive and regimes with “decoupled” heating and CD systems
- Beam-plasma neutrons regime investigation
- Plasma with significant anisotropy, $p_{fast}/p_{thermal}$ ~30%
- Regimes with plasma detached from divertor plates
- SOL physics and boundary layer investigation
- Diagnostics development, materials test

The program is focused on Compact Fusion Neutron Source development

Globus-M demonstrated:

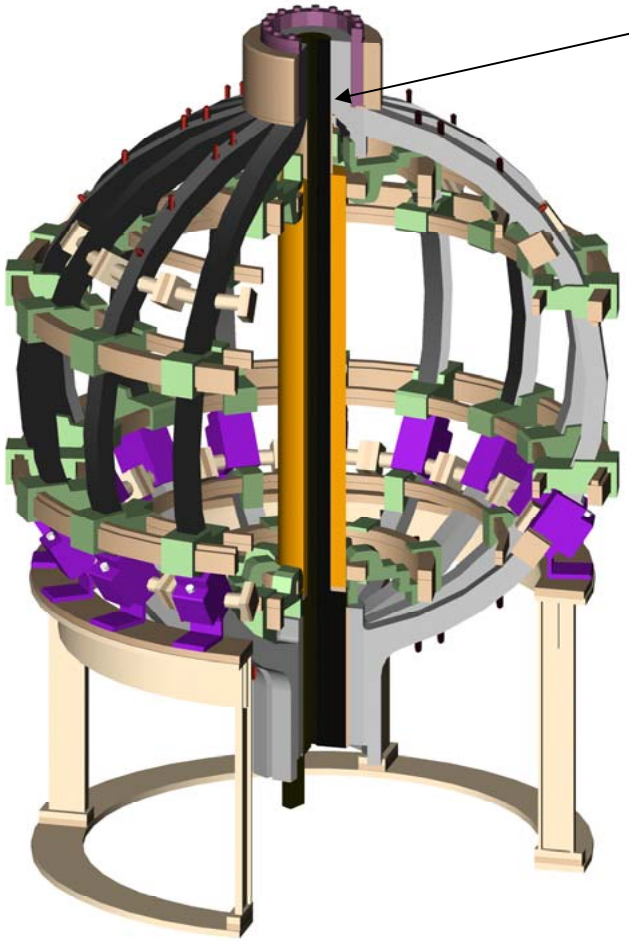
- Big losses of high energy particles - need to increase B_T & I_p
- Plasma temperature is insufficiently hot – neutron yield is low
- ICR heating efficiency is increasing with B_T
- LH CD efficiency is increasing with B_T & I_p
- τ_E increasing with B_T & I_p rise and collissionality descent

$$\tau_E \sim I_p^{0.5} B_T^{1.3} P_{abs}^{-0.5} n_e^{0.7}$$

$$B_T \tau_E \sim \nu^{*-0.44}$$

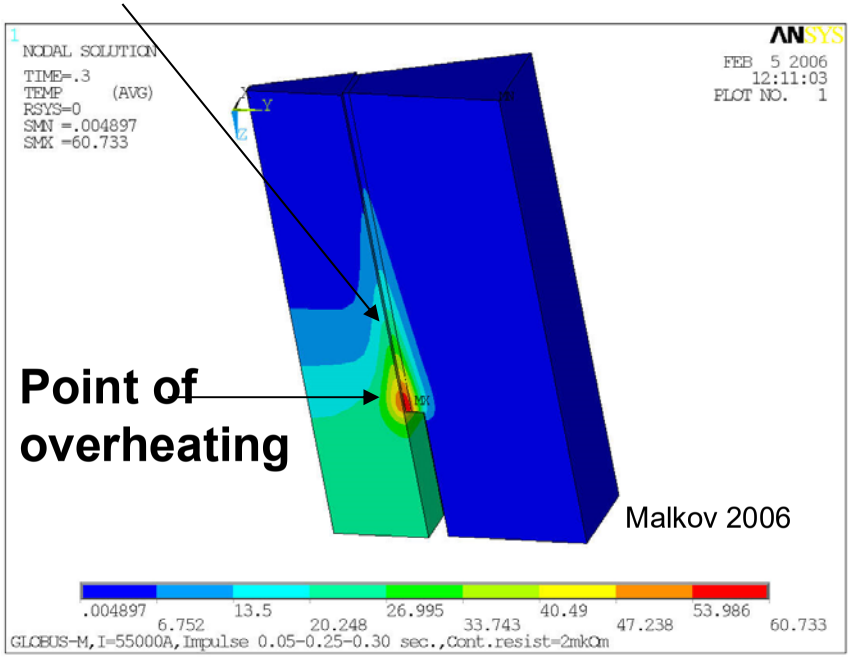
Toroidal magnetic field and plasma current increase is desirable at the lowest cost

Why is was not possible to increase magnetic field in Globus-M?



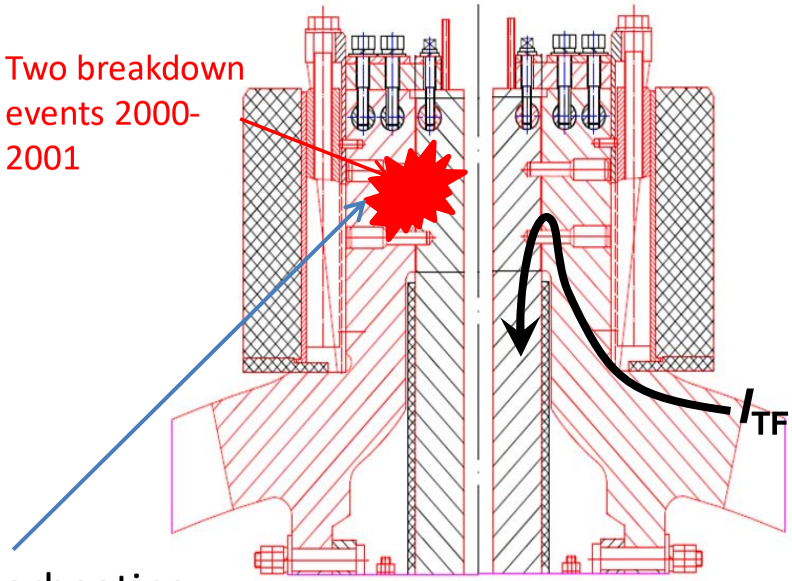
EMS of Globus-M

Upper contact joint of TF coil

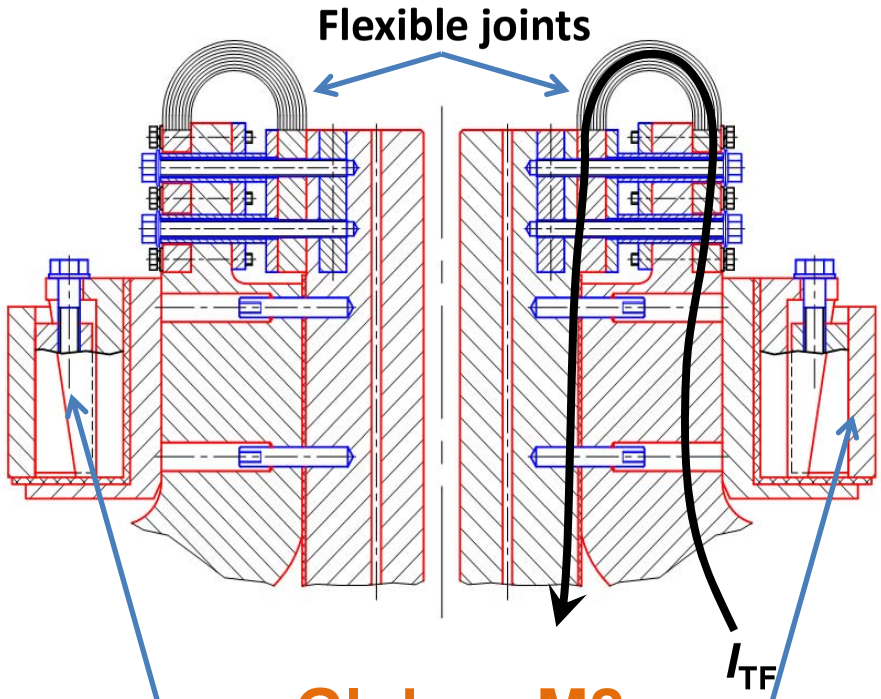


For 1T toroidal field - contact joints area and contact pressure should be increased

Contact area is increased and contacts are placed outside of max stresses zone



Globus-M



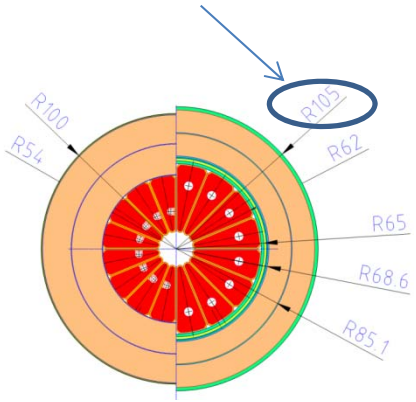
Globus-M2

- **Compression of TF limb with Central Column is provided with Bandage ring and Wedges**
- **Contact pressure is provided with independent bolts.**

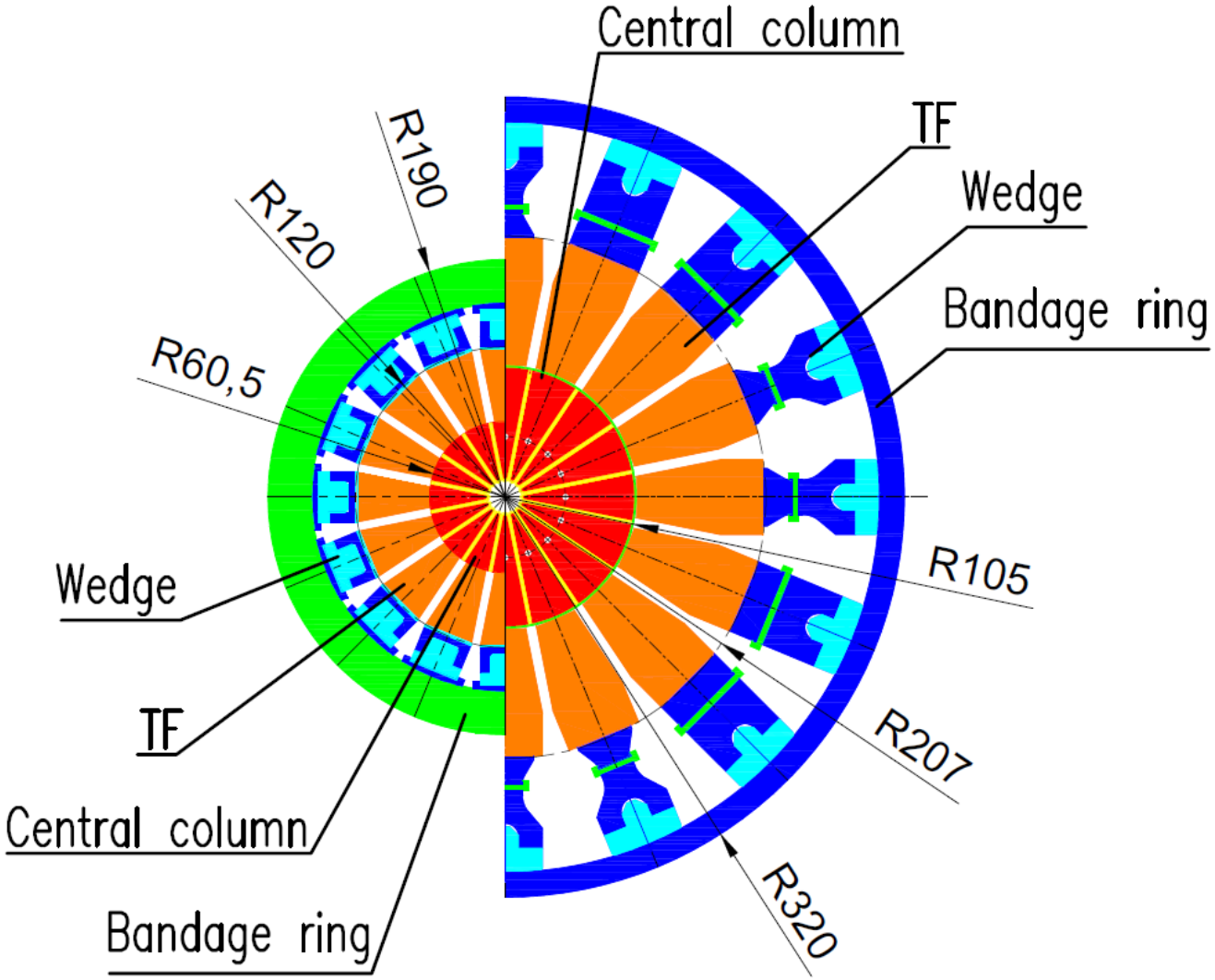
Contact current density < 70 А/мм^2

Contact area is increased but Central Stack became nonseparable

Critical size



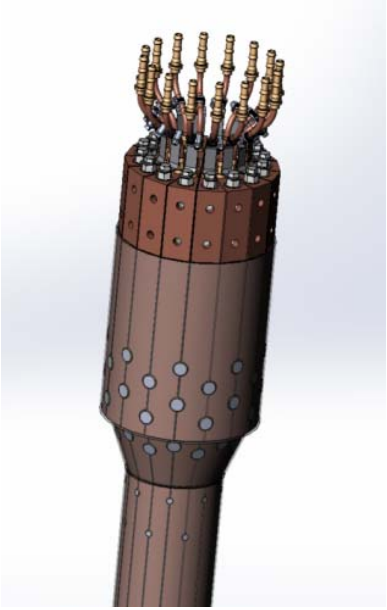
Central Stack Globus-M/Globus-M2. Equatorial plane



Bandage Ring cross-section Globus-M / Globus-M2

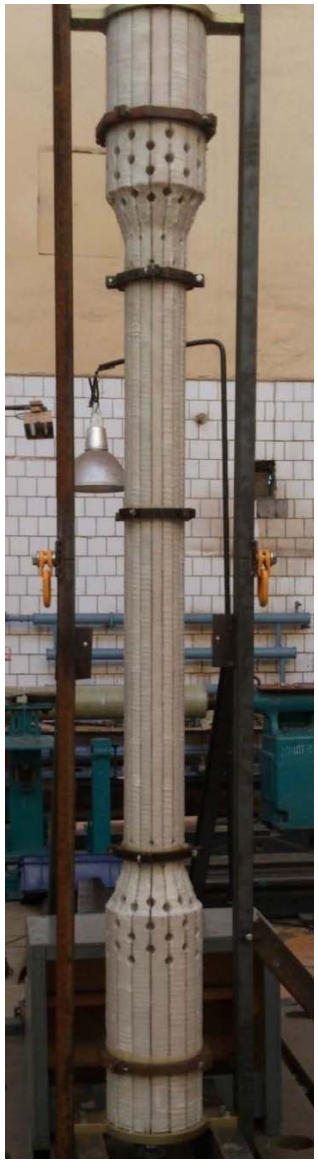
Spool shaped Central Column is assembled from 16 segments of 2.3 m length

CS diameter = 136 mm (middle part), 210 mm (ends)



Material – oxygen free cold extruded silver bearing copper alloy (σ_{02}>240 MPa)

Temperature rises up to ~ 80-90 °C at the end of pulse

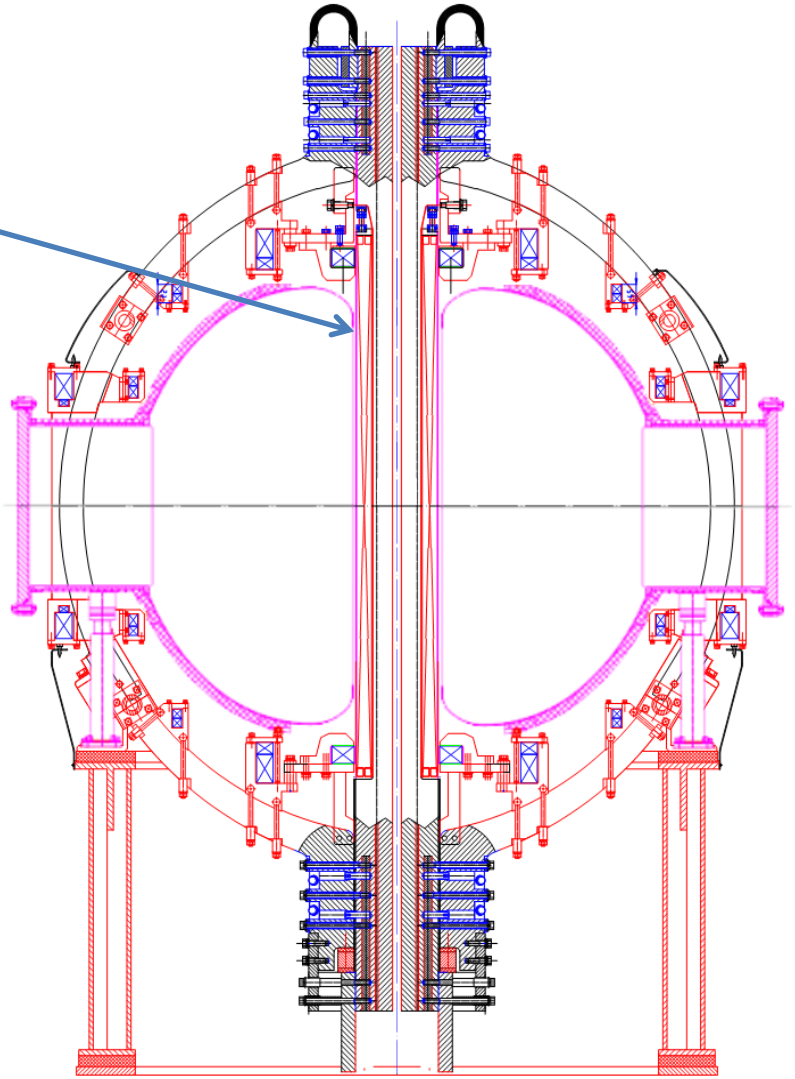


Globus-M2 has a very tight assembly

Central Stack diameter is increased up to possible limit – clearance CS - VV is only 1mm

“Sliding layer” of 1mm separates Central Column from Central Solenoid

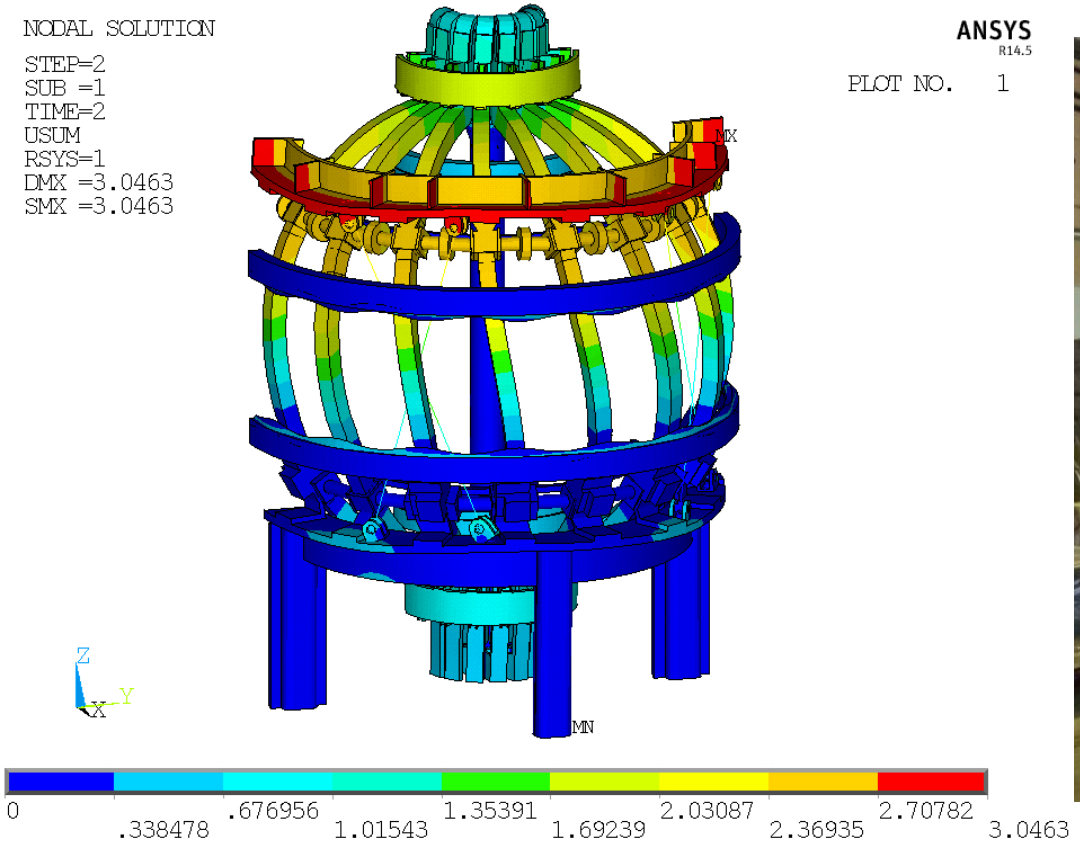
Globus-M2



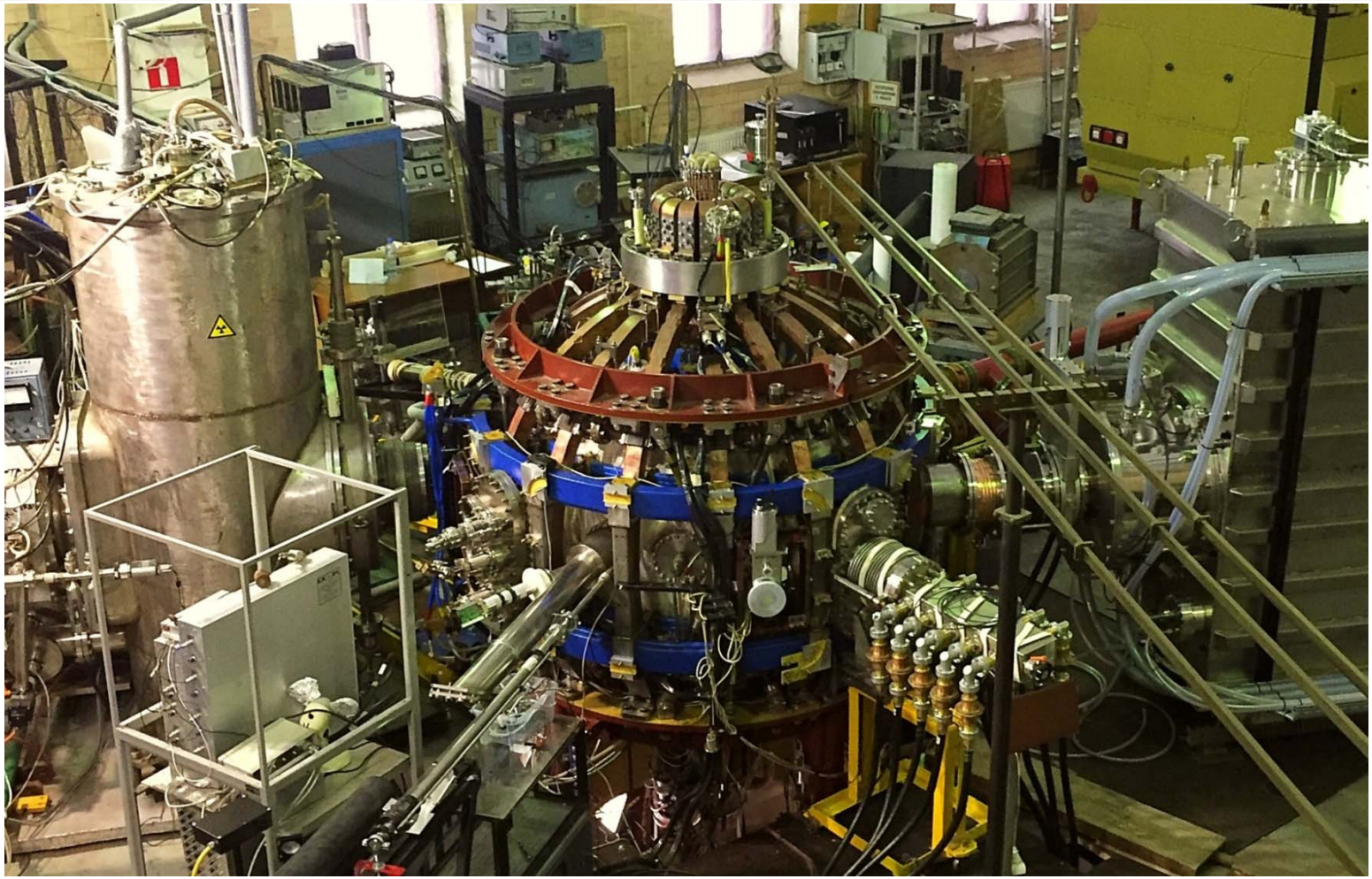
Basic regimes for FE analysis

Engineering parameter	B-max regime B_T = 1.0 T (at R = 0.36 m)	t-max regime B_T = 0.7 T (at R = 0.36m)
Plasma current	0.5 MA (at a=0.24 m)	0.5 MA (at a=0.24 m)
Poloidal flux consumption	0.4 Wb (+/- 0.2 Wb)	0.4 Wb (+/- 0.2 Wb)
Duration of TF flattop	≤ 0.4 s	≤ 0.7 s
Basic regime	Inductive/Noninductive	Noninductive CD
TF field rippling at R=0.6m	≤ 0.4%	≤ 0.4%
Number of working pulses in regime with nominal/maximal load	30000 / 5000	30000 / 10000
Pulse repetition rate	Every 15 min	Every 15 min

EMS pieces displacement under the strain were minimized with crosspieces



Globus-M2 was assembled for the first time in December 2016

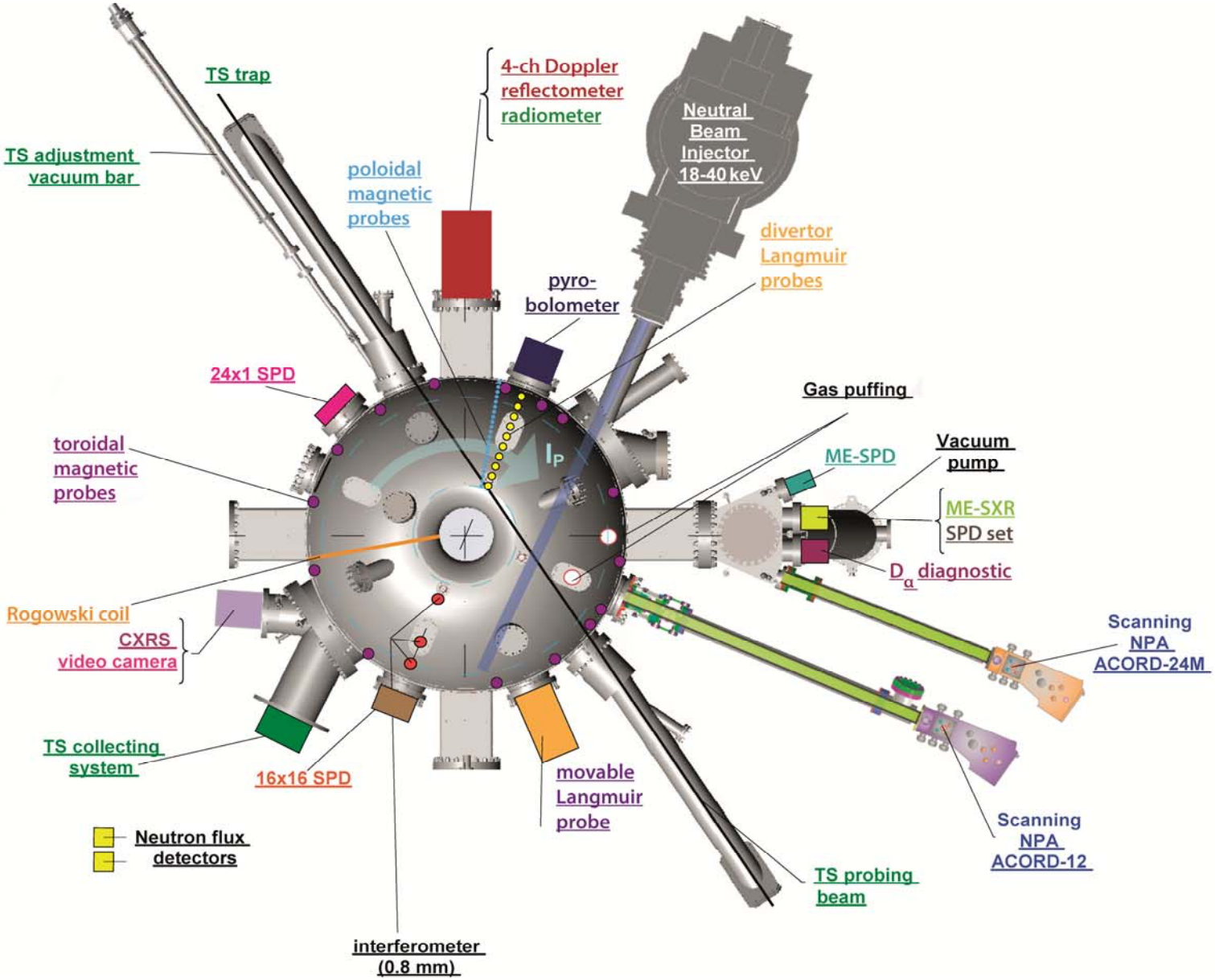


2017 year tests were finished with CS breakdown at 60 kA current.

In May 2017 tokamak was disassembled, CS was repaired and assembled again in January 2018

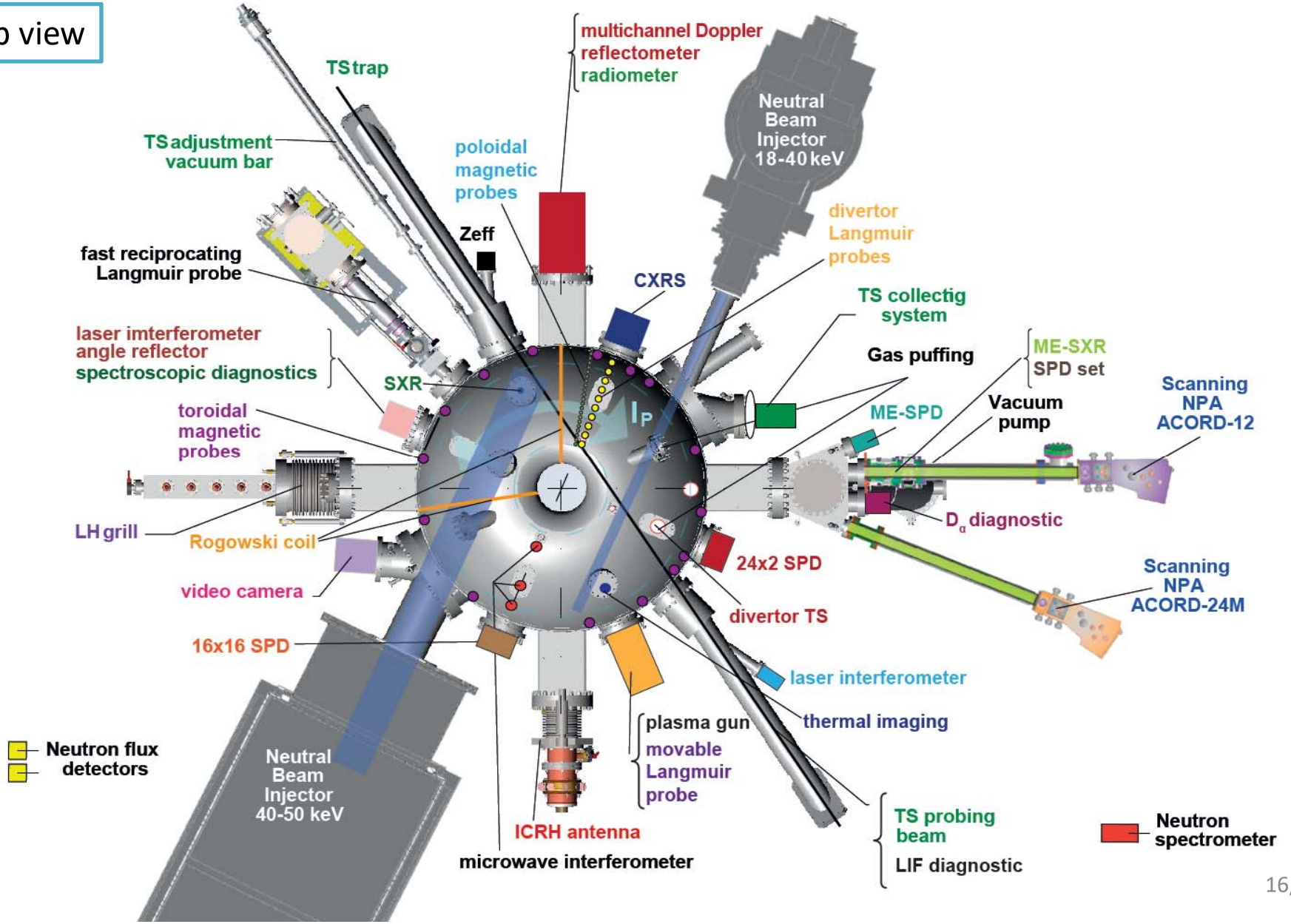
Globus-M

Top view

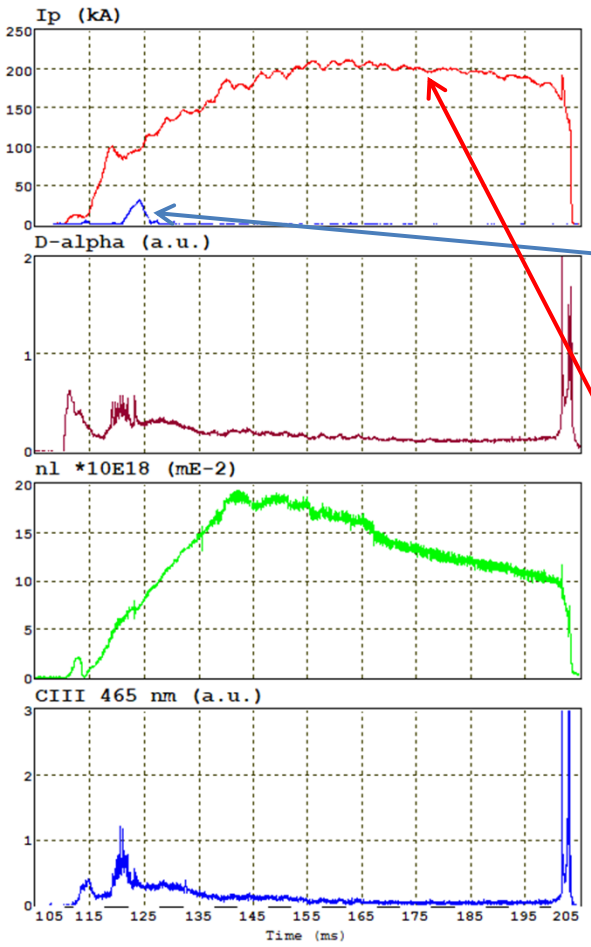


Globus-M2

Top view



Globus-M2 shakedown at 23-april-2018



Globus-M regime imitation

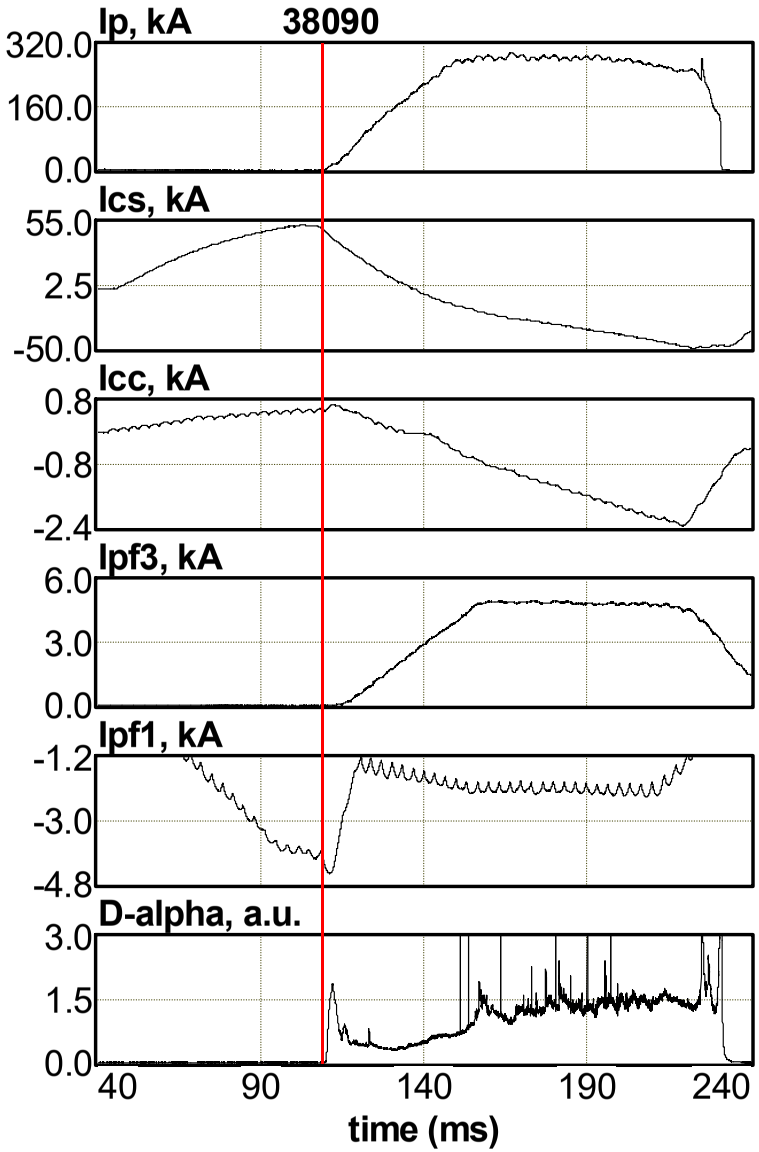
23.04.18 – 21.06.18

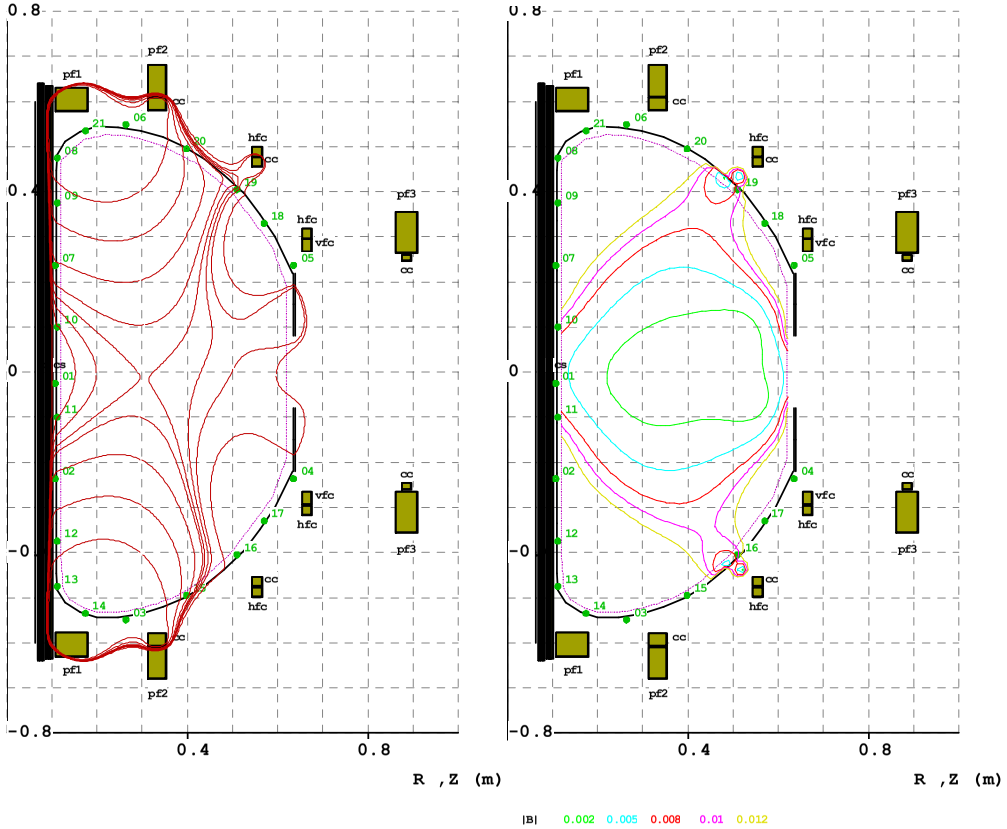
First shot plasma
30 kA, B_T = 0.4 T

Totally 290 shots
170 – OH, 20 – NBI shots
Ip = 200kA,
Pulse duration ~ 90 ms

0.7 T experimental campaign

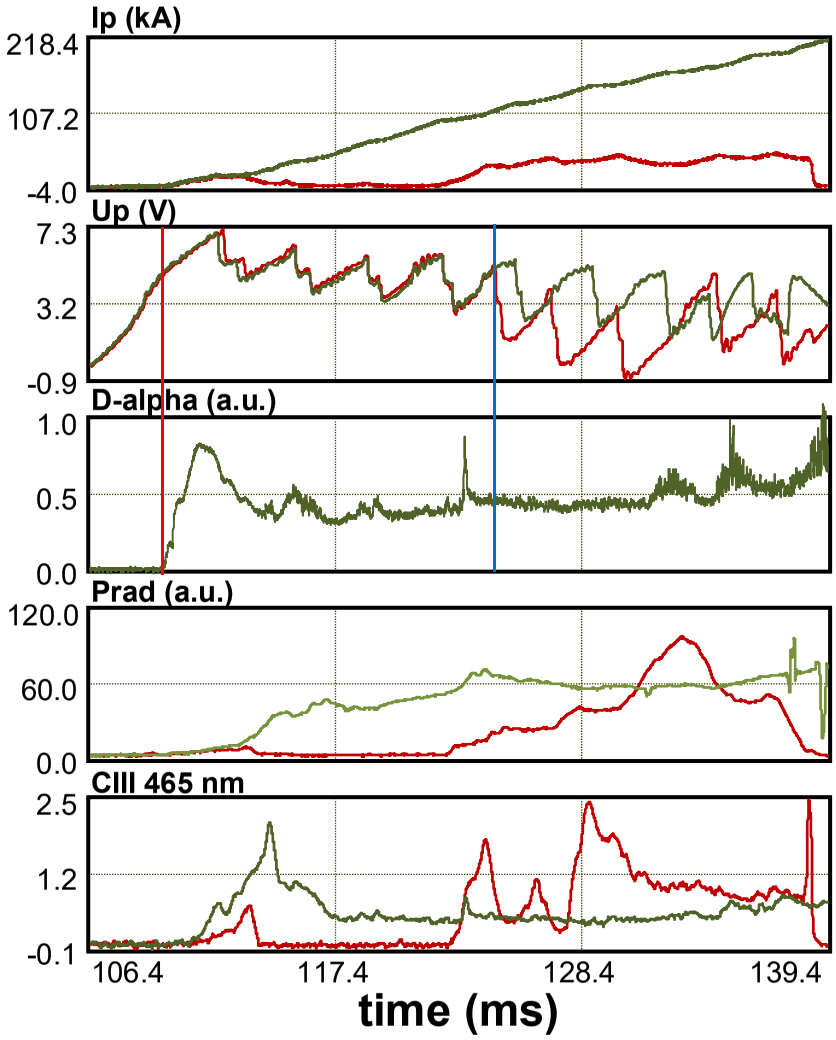
Plasma breakdown magnetic configuration





Breakdown magnetic fields reconstruction – Constant magnetic flux (left) and
Lines of equal poloidal field $|Bp|$ = 0.002, 0.005, 0.008, 0.010, 0.012 T (right) after CS magnetic field compensation.

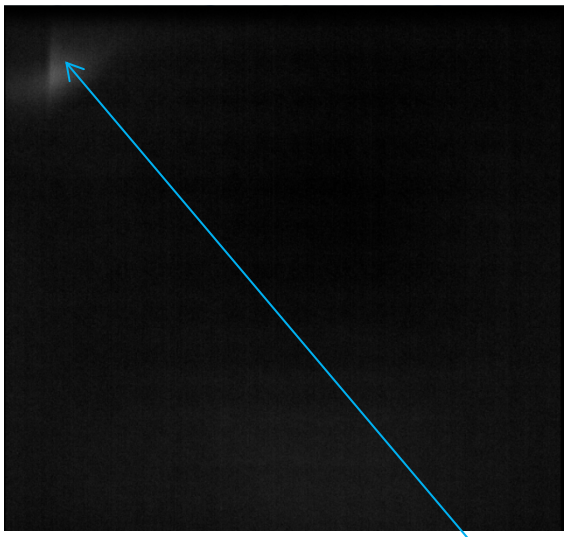
Plasma breakdown and current start-up

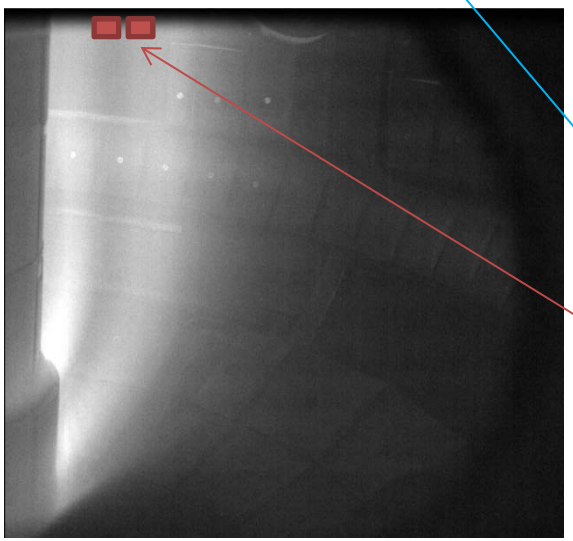


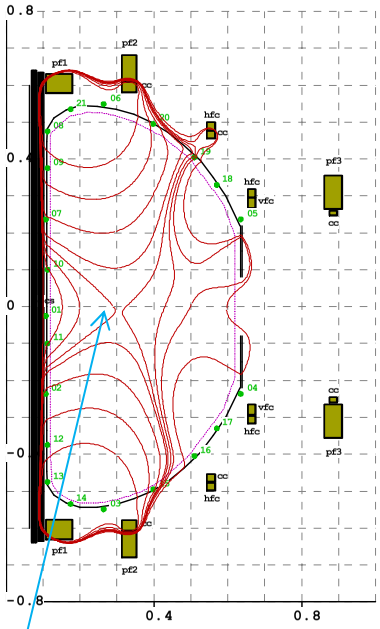
- Breakdown loop voltage U_p= 4.7 V, B_T= 0.7 T
- Hydrogen pressure at breakdown ~ 10^{-5} mm Hg
- Preionization is by ultraviolet bulb radiation
- Carbon is the main impurity

Red line - breakdown
Blue line – plasma current feedback control is on

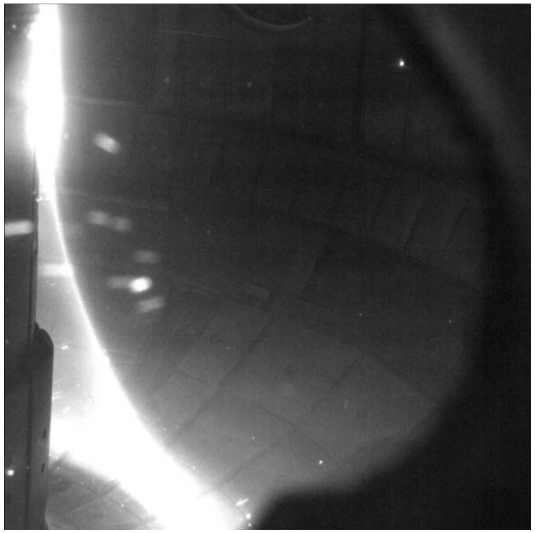
Breakdown and plasma column formation







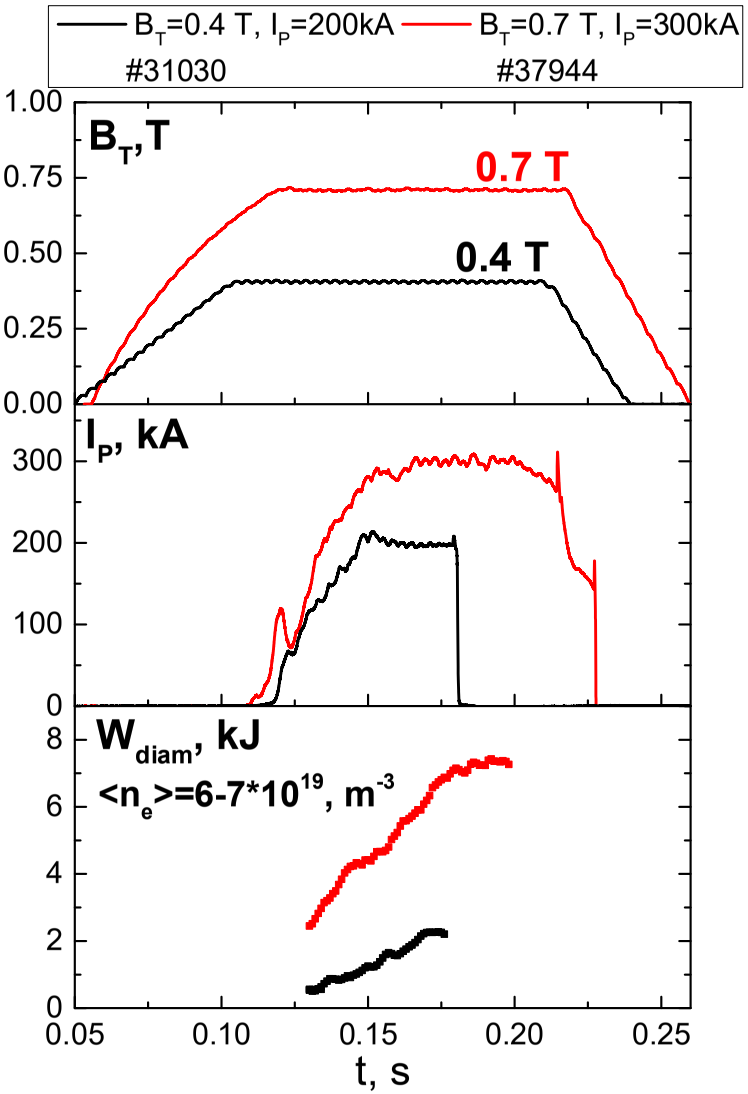
~ 80 ms later
Gas puffing from HFS.
Sharp separatrix indicate H-mode formation



- Breakdown happens at the Central Column surface, not in the field null
- 1ms after breakdown I_p = 7kA
  T_e=8-4 eV, n_e=0.25·10^{19} m^{-3} is measured by TS

Global discharge parameters at 0.7 T

Record stored energy W_p = 7.5 kJ



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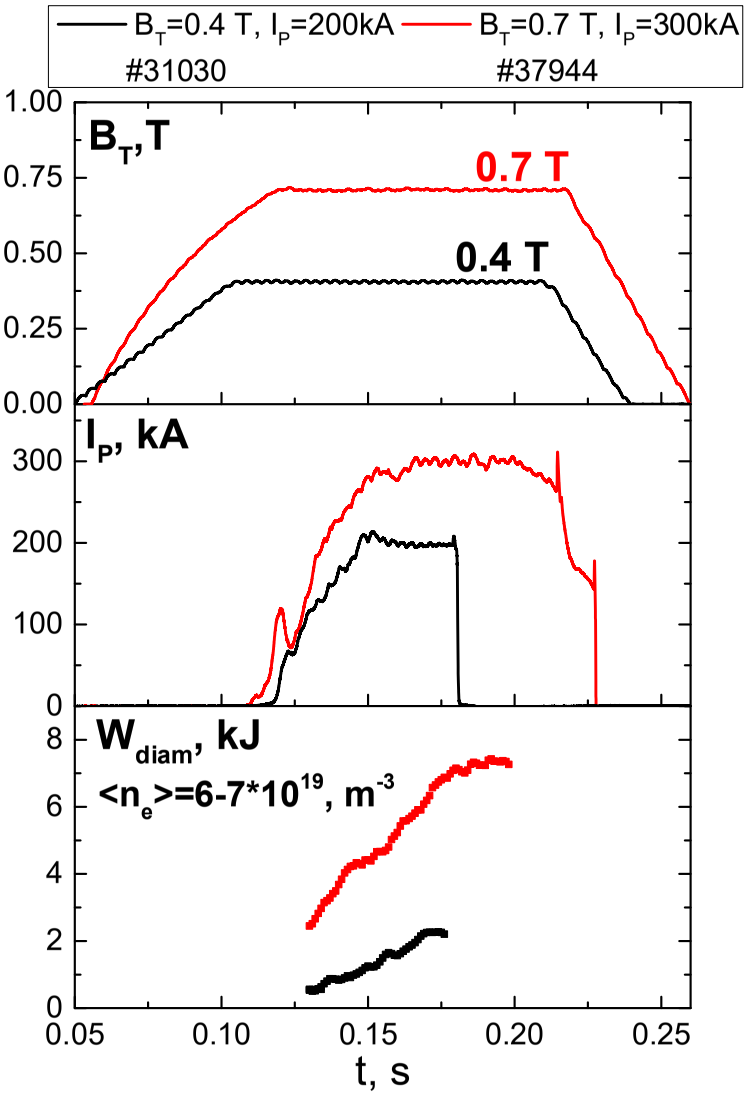
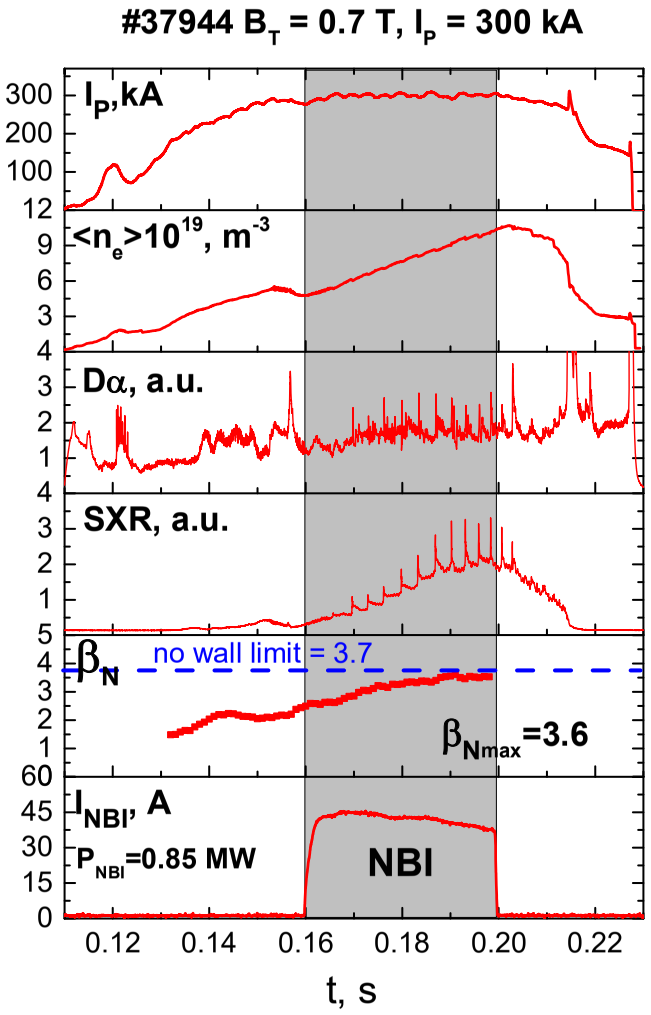
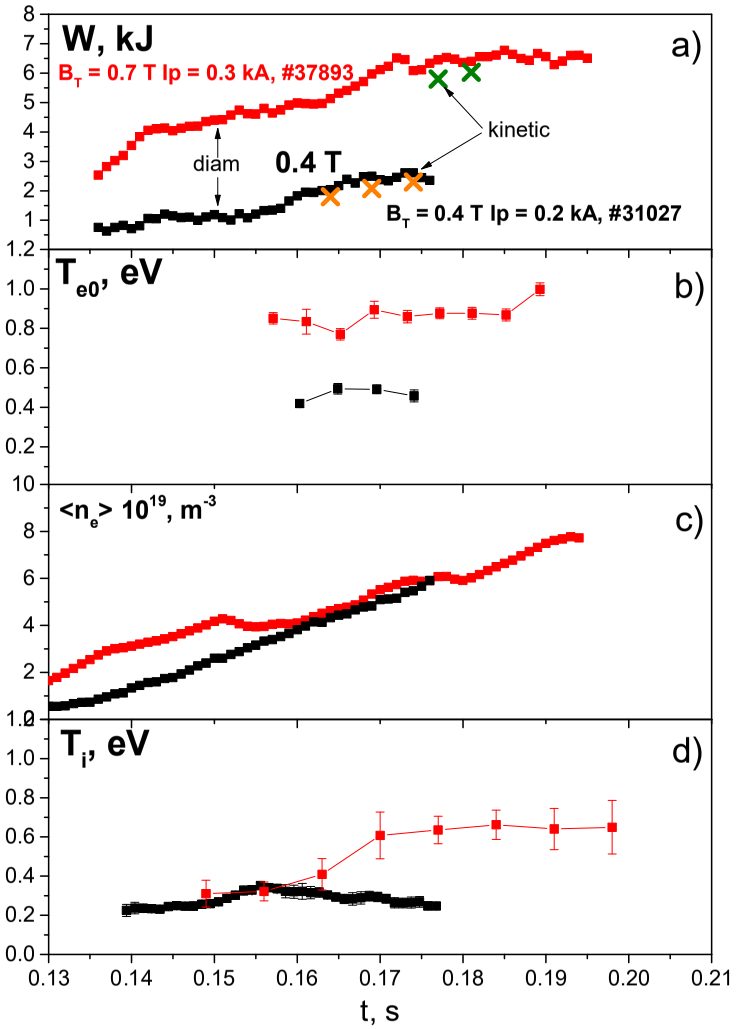
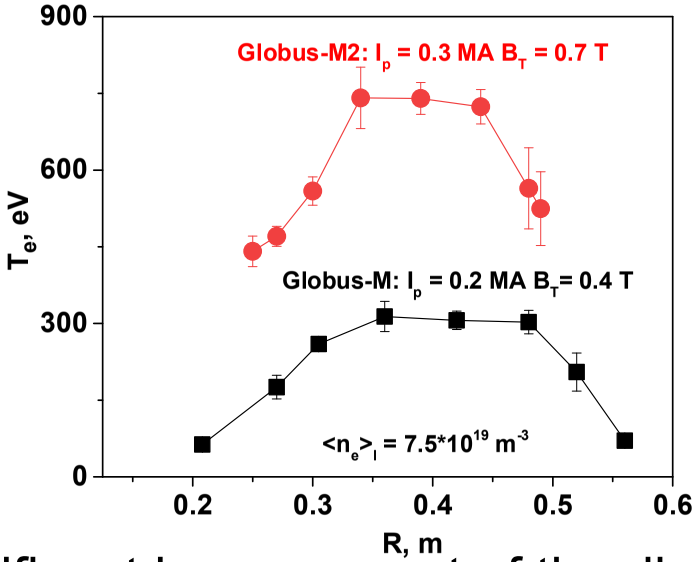


D->D P_NBI=850 kW E_NBI = 28 keV



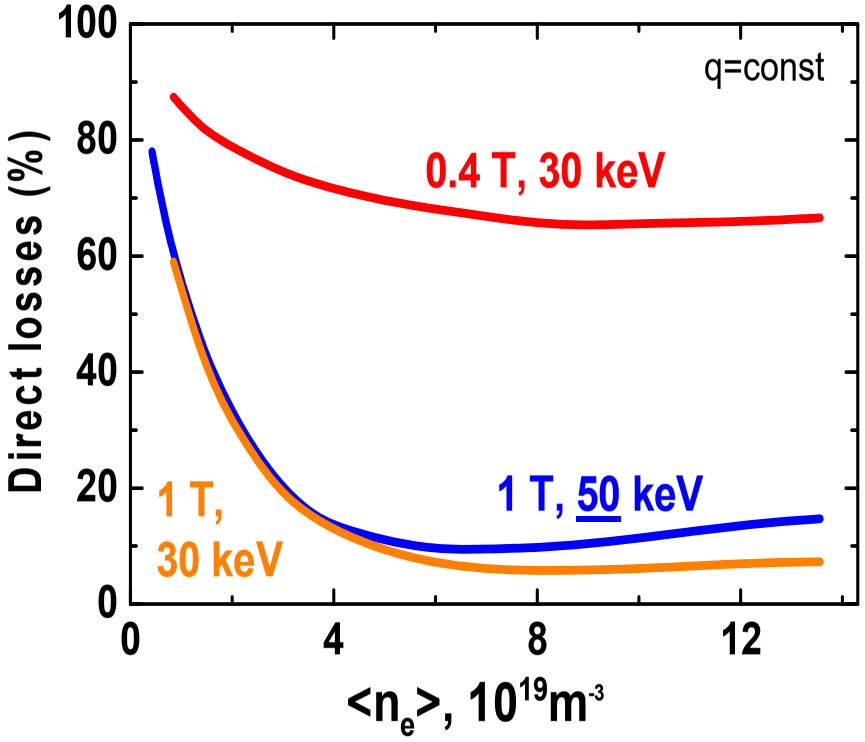
Temporal behavior of plasma parameters

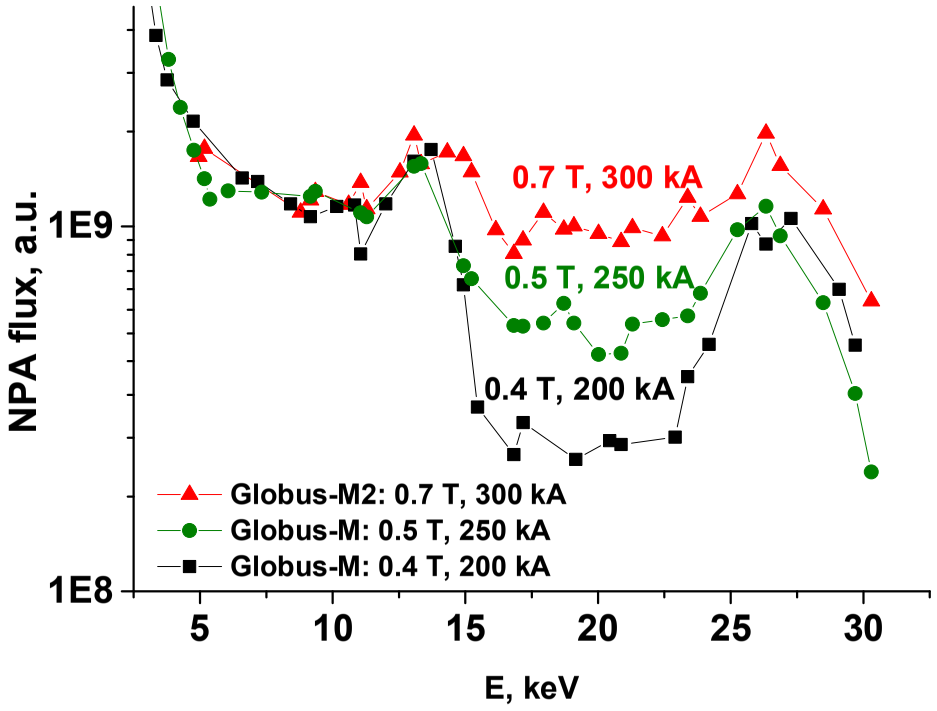




- Significant improvement of the discharge parameters
- Significant Ti, Te and neutron yield growth
- Record stored energy W_p = 7.5 kJ, τ_E~10 ms

Fast particle losses are decreasing

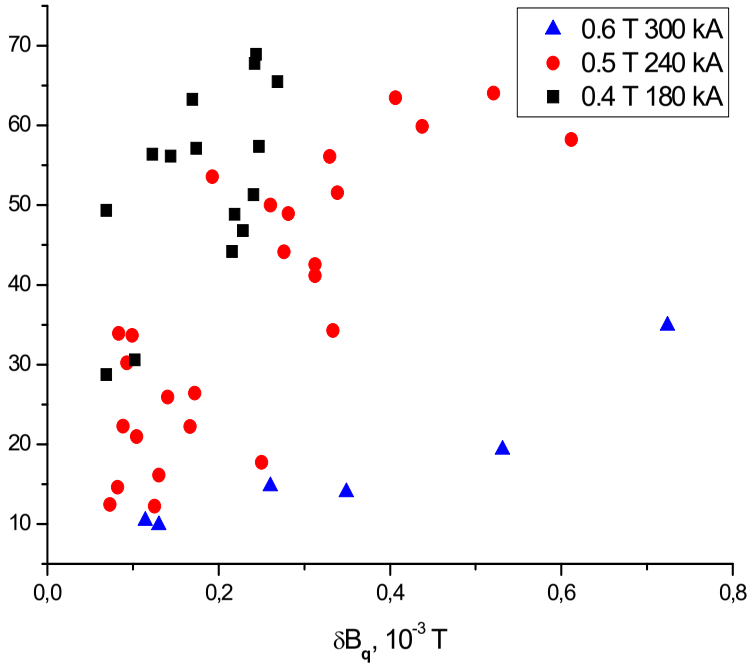




- I_p & B_T rise improving fast ion confinement
- Experiments prove that.
- Ions with energies of 50 keV is confined in Globus-M2

TAE induced fast particle losses are decreasing with B_T rise

Drop of 28.5 keV CX neutral flux (%) on TAE burst intensity

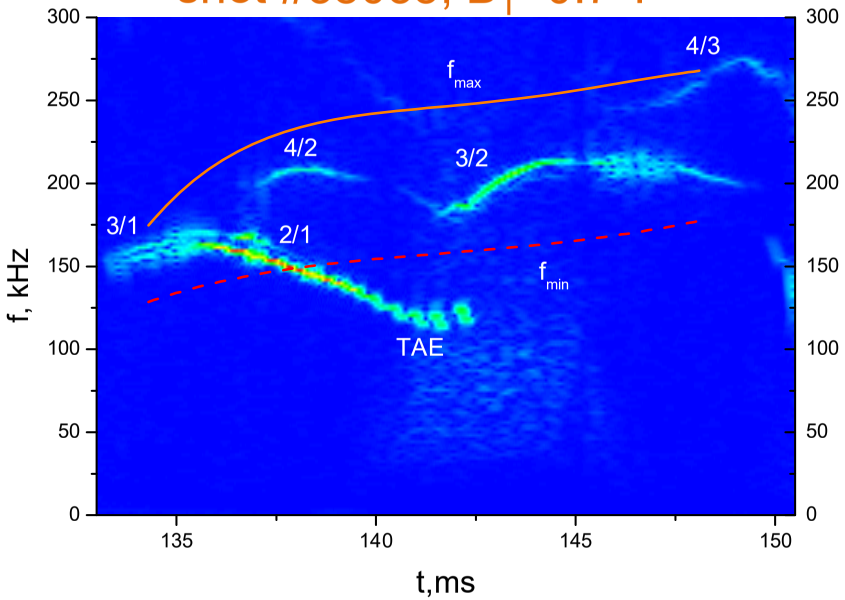


Different combinations of B_T and I_P with q remaining unchanged

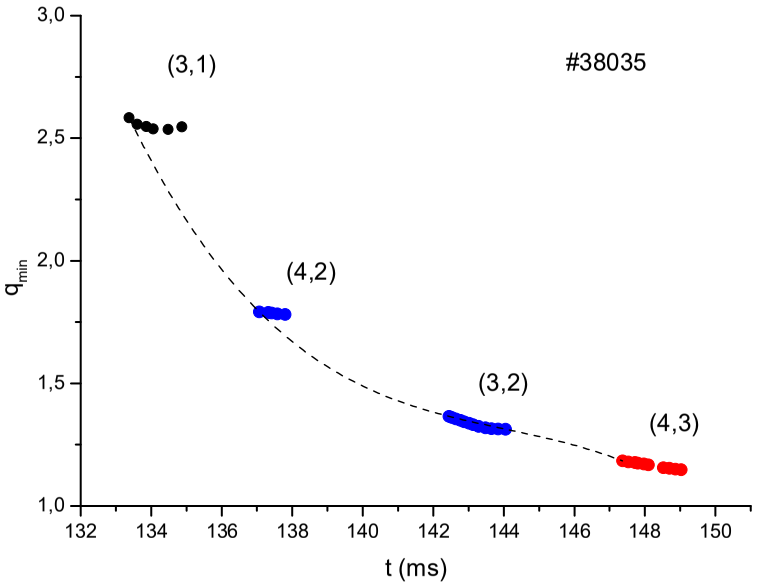
- TAE burst intensity (perturbation of the poloidal magnetic field δB_q) is measured by a Mirnov coil
- Losses decrease with an increase of the B_T and I_P
- Favorable forecast for next-generation spherical tokamaks with higher values of the magnetic field and current

Alfven cascade mode generation provides new diagnostic possibilities

Spectrogram of Mirnov coil signal, shot #38035, B_T=0.7 T

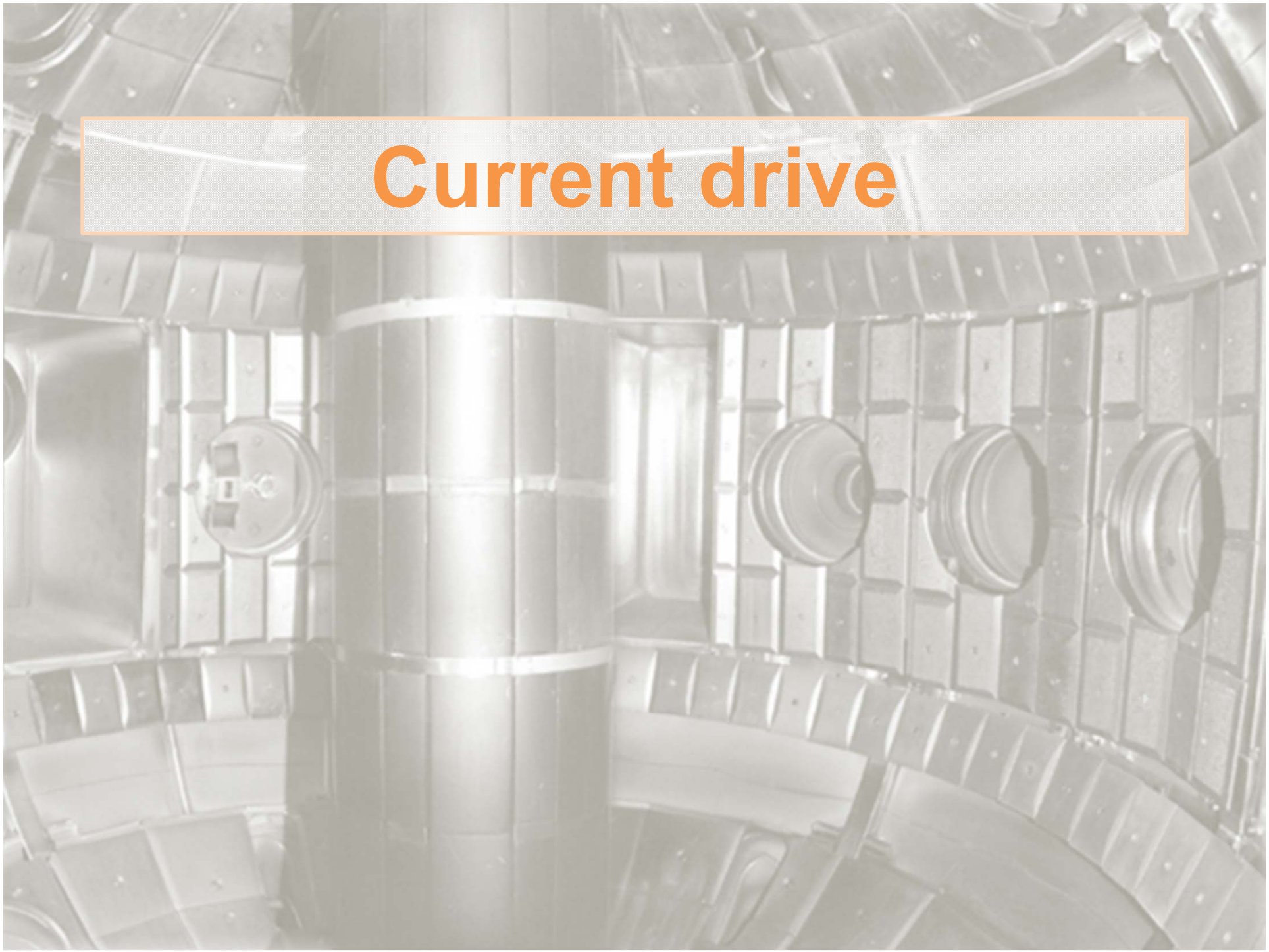


Evolution of q_{min} as deduced from AC



$$\omega_{AC}^2 = [\left(\frac{m}{q_{min}} - n\right)^2 \frac{V_A^2}{R_0^2} + \frac{2T_e}{M_i R_0^2}\left(1 + \frac{7}{4}\frac{T_i}{T_e}\right)]^{1/2}$$

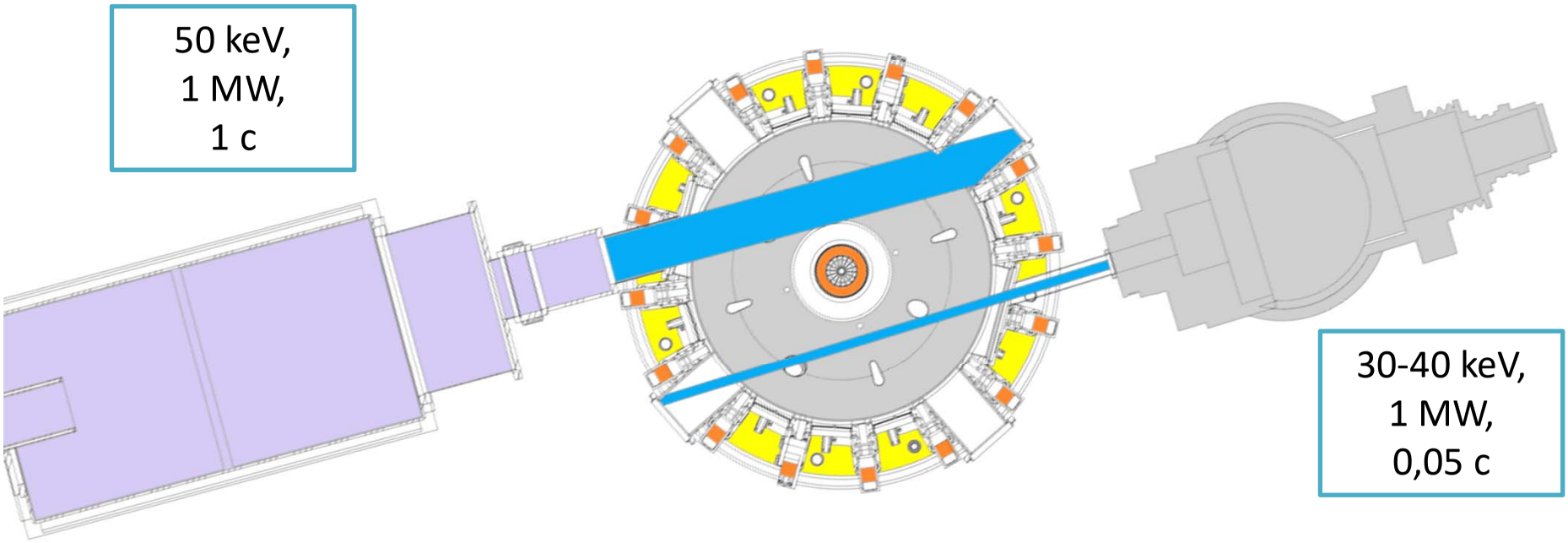
$$q_{min} = \frac{mV_A}{nV_A + R_0(\omega_{AC}^2 - \omega_{min}^2)^{1/2}}$$



Current drive

Pair of injectors on Globus-M2 allow “decoupling” of injector functions

- Current drive
- Plasma heating
- Neutron generation

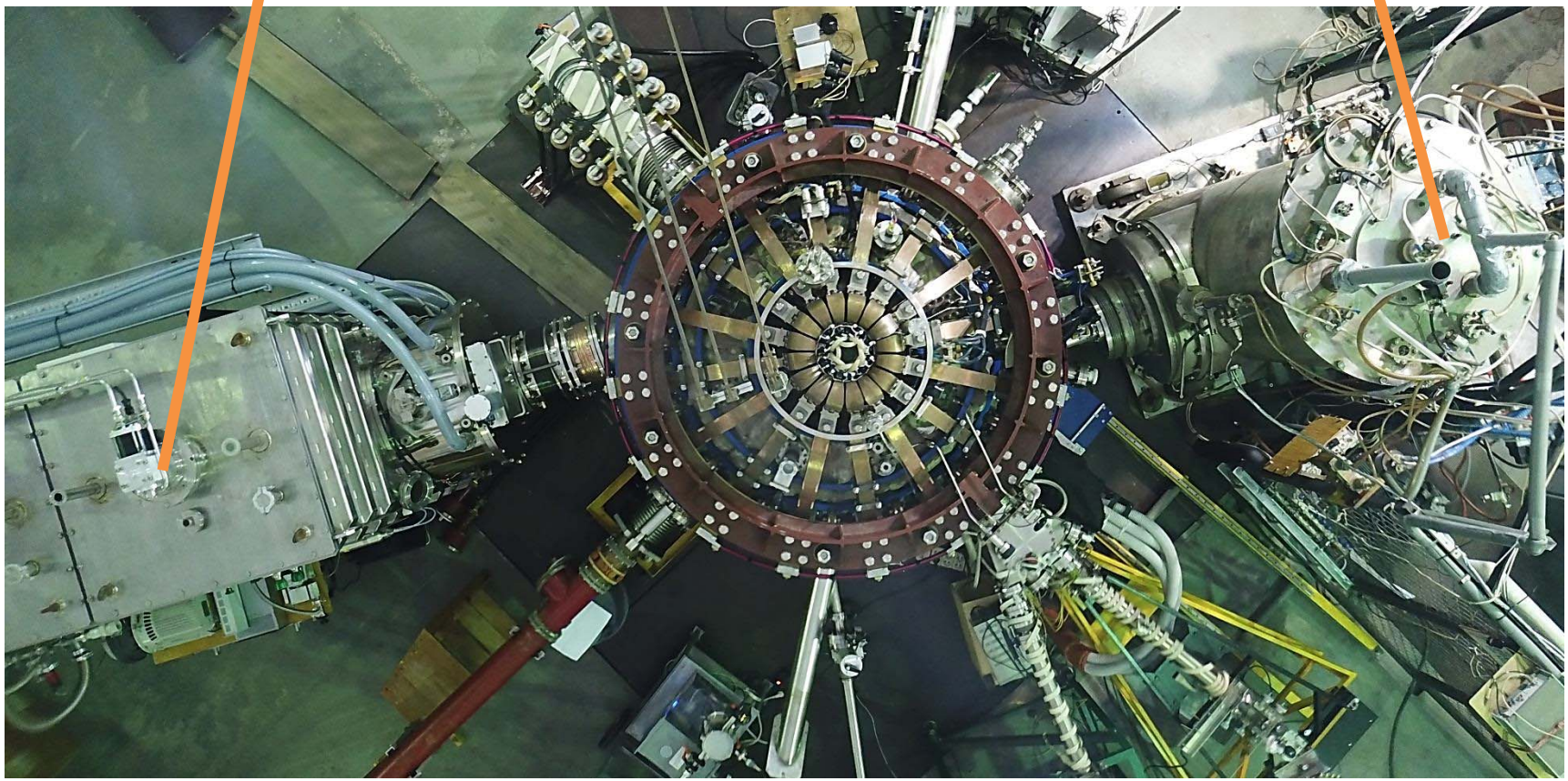


Neutral Beam Injection

Parameter	Globus-M	Globus-M2
NBI	1 MW, 18-30 keV	1 MW, 18-40 keV 1 MW, 40-50 keV **4MW/m^3**

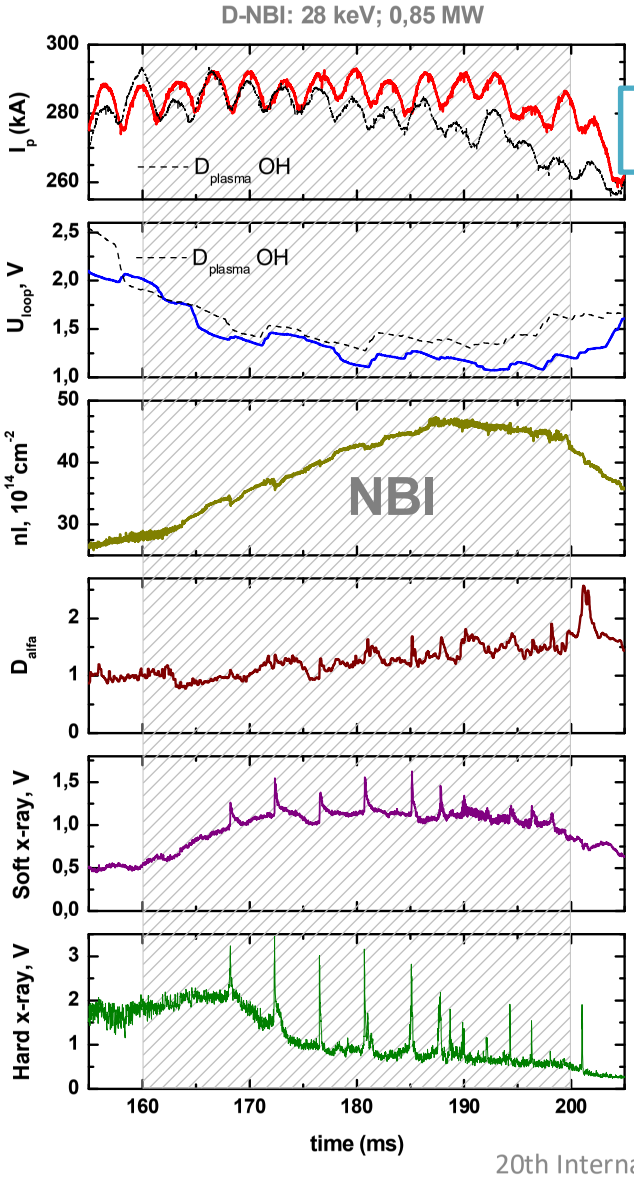
NEW: 1 MW, 40-50 keV

1 MW, 18-40 keV



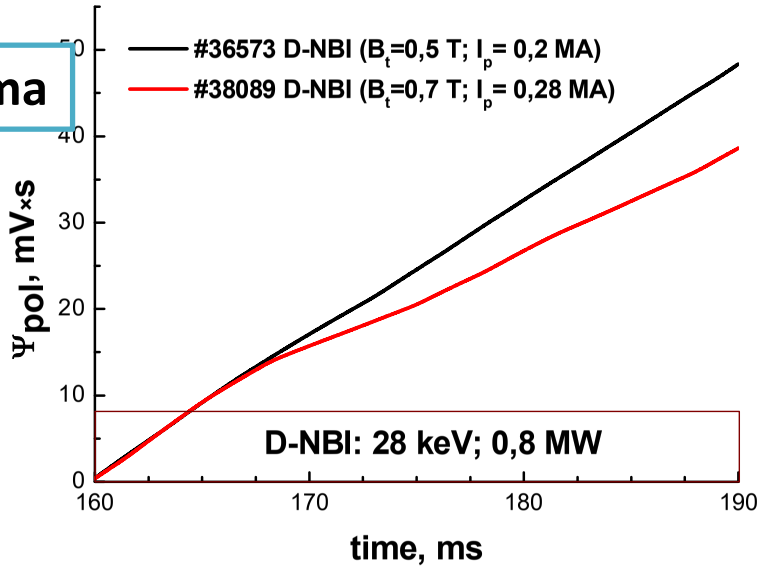
Neutral Beam Current Drive

The first results on neutral beam current drive were obtained on Globus-M2



D-beam → **D-plasma**

28 keV, 0.85 MW



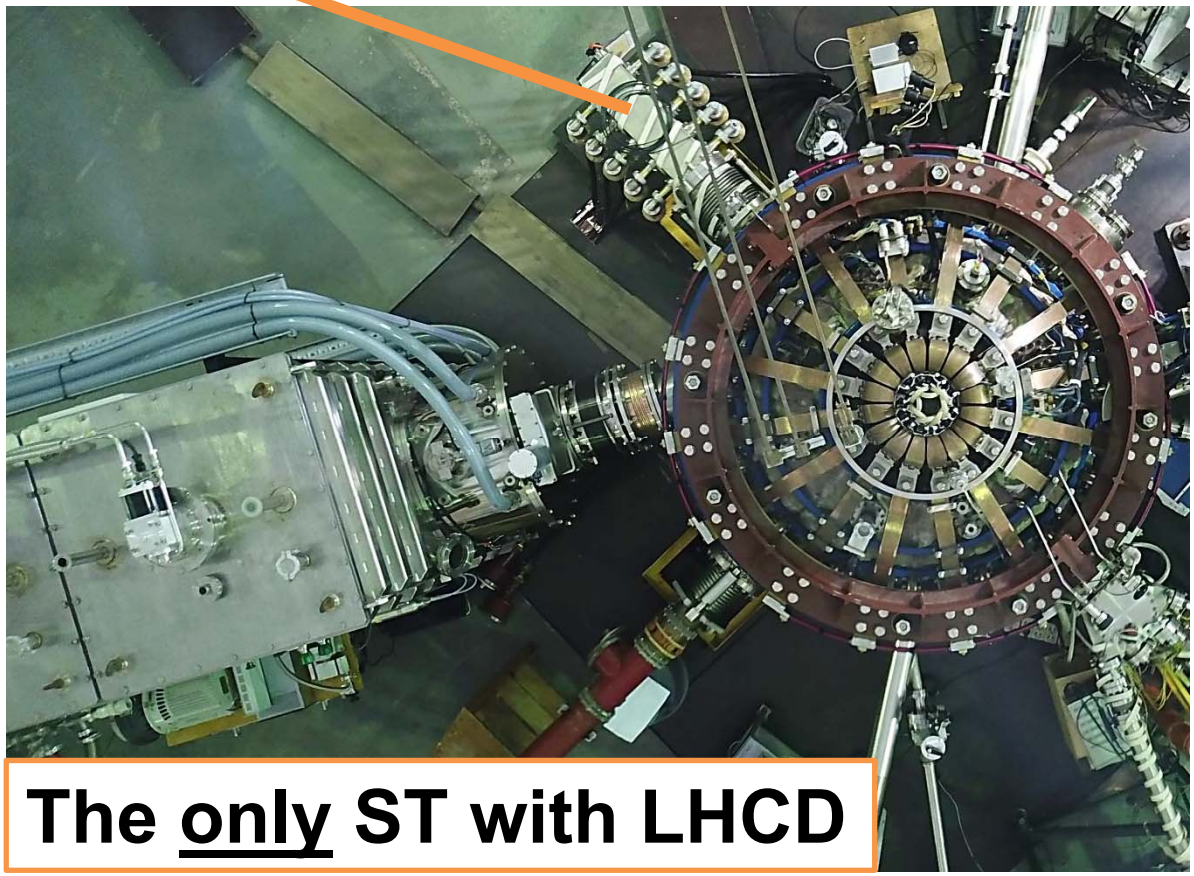
✓ **Toroidal magnetic field rise improves CD efficiency.**

Shchegolev 2019

Lower Hybrid Current Drive

Parameter	Globus-M	Globus-M2
LHCD, kW	100	500

NEW: 500 kW, 2.45 GHz, toroidal and poloidal wave slowing down

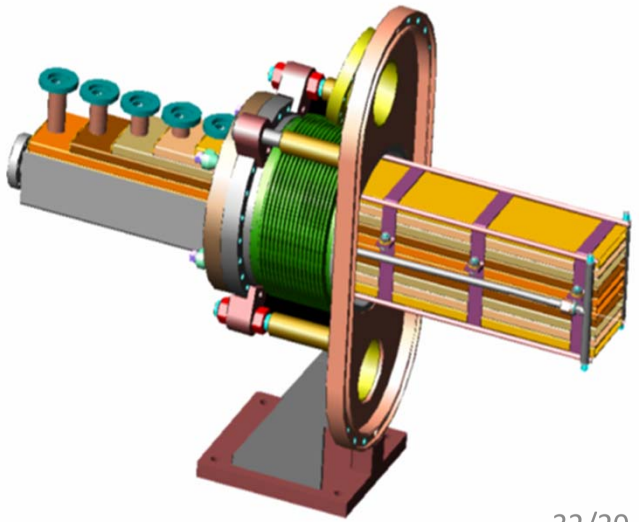


The only ST with LHCD

Rotatable

10-waveguide grill

antennae



Lower Hybrid Current Drive

Globus-M 2.45 GHz **Globus-M2**

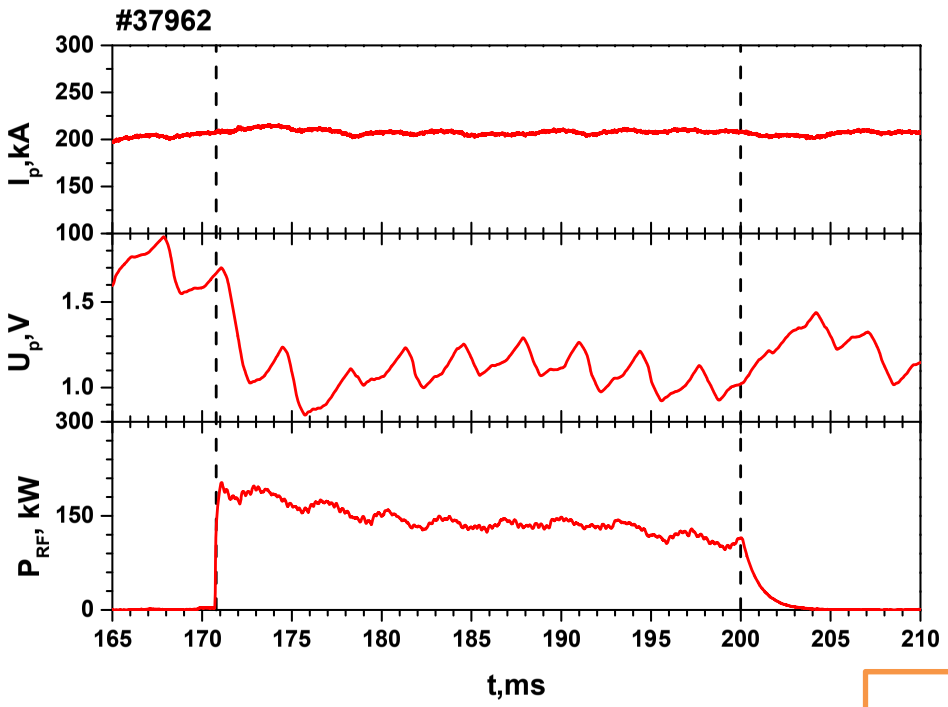
120 kW → **180 kW**

Poloidal wave launch → **Toroidal wave launch**

90°

The <u>only</u> LHCD experiments on ST

Lower Hybrid Current Drive



B_T = 0.7 T

Toroidal grill orientation

2.45 GHz, 180 kW, N_{II} = 3,

Phase shift between neighbor waveguides 120°

n_e=0.5*10^{19} m^{-3}
T_e=450 eV
I_p = 200 kA

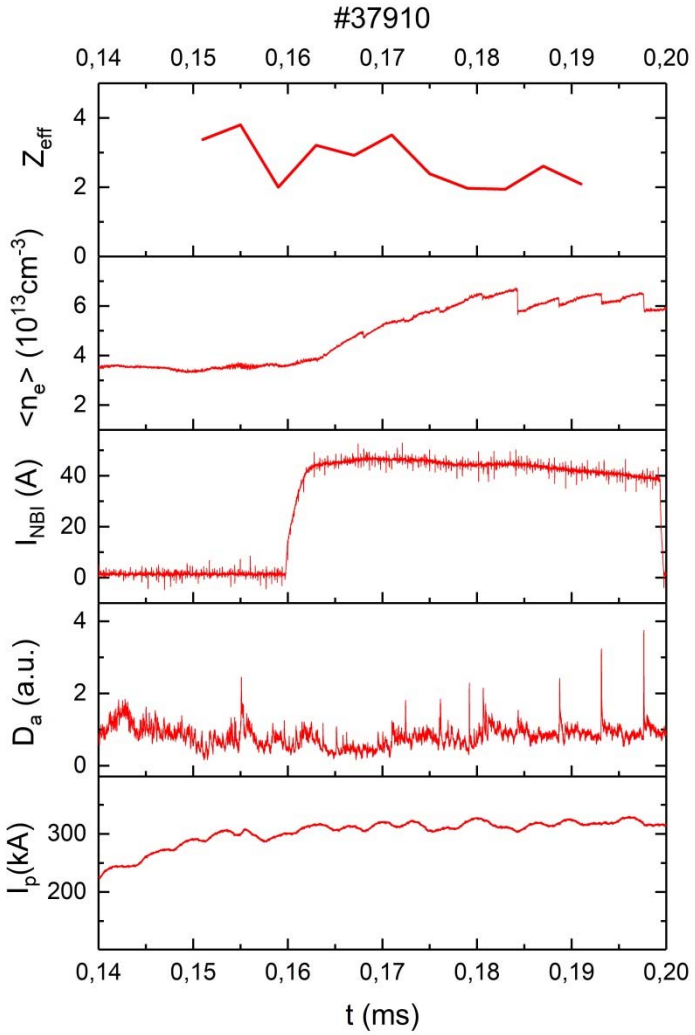
$$\eta = 0.1 \cdot 1019\, A \cdot m^{-2} \cdot W^{-1}$$

~30% of Non-inductive current

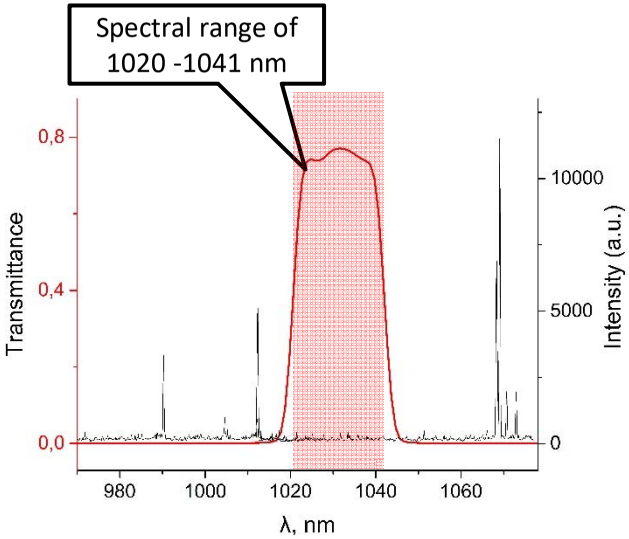
Poloidal slowing down – Dyachenko, 2015

Energy confinement

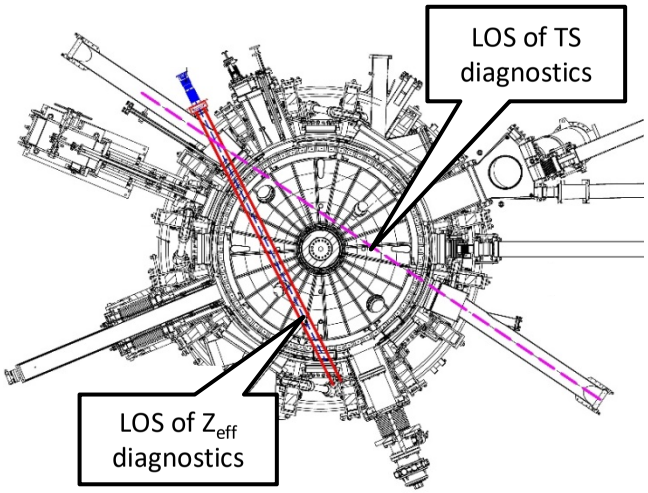
Z_{eff} is measured at tolerable value



Diagnostics is based on the measurements of the bremsstrahlung intensity

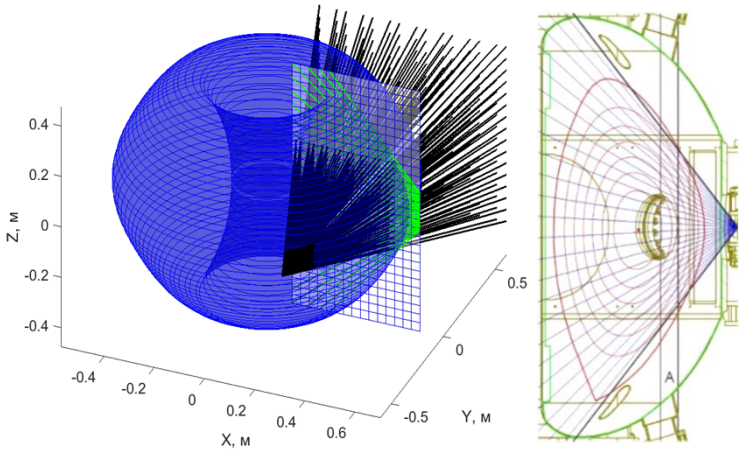


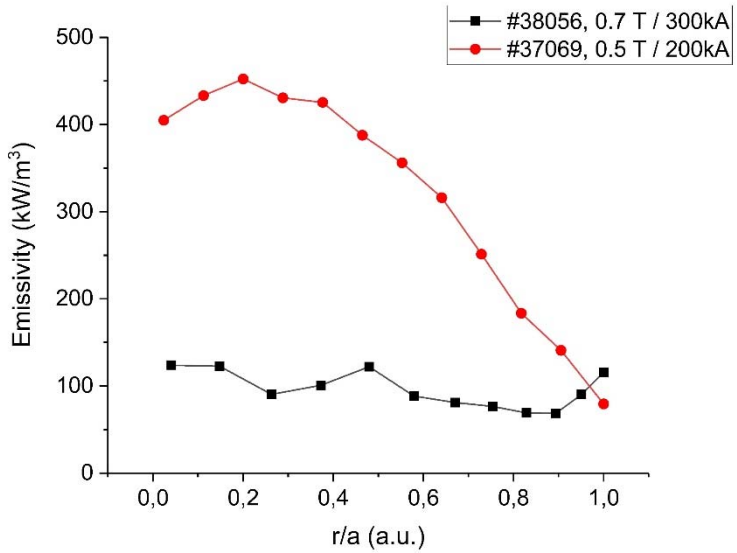
Cylindrical observation volume d = 3 cm along the line-of-sight in the equatorial cross section

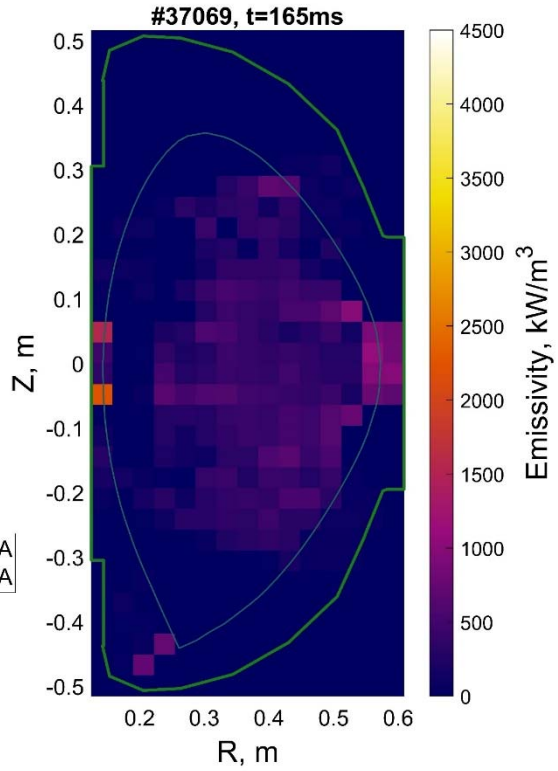


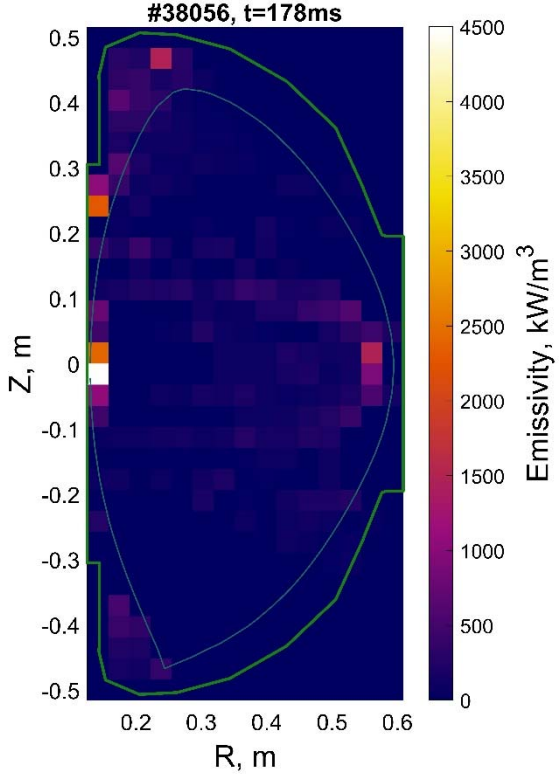
Radiation losses were minimized

LOS of P_{rad} diagnostics









B_T = 0.5 T, I_p = 200 kA

P_{rad} total = 170 kW

(30% P_{heat})

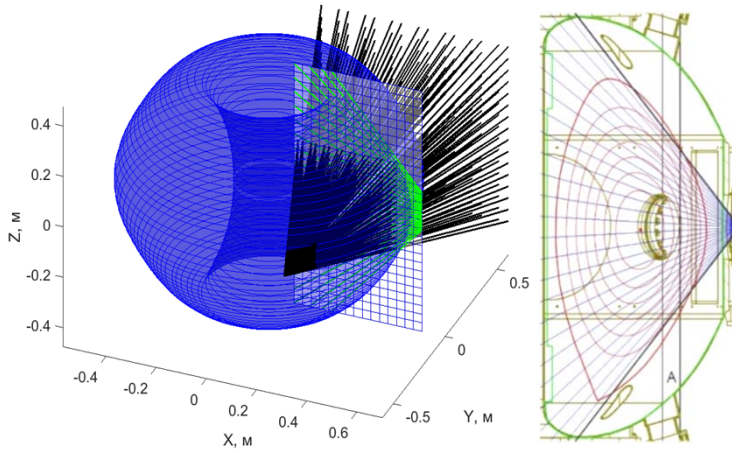
B_T = 0.7 T, I_p = 300 kA

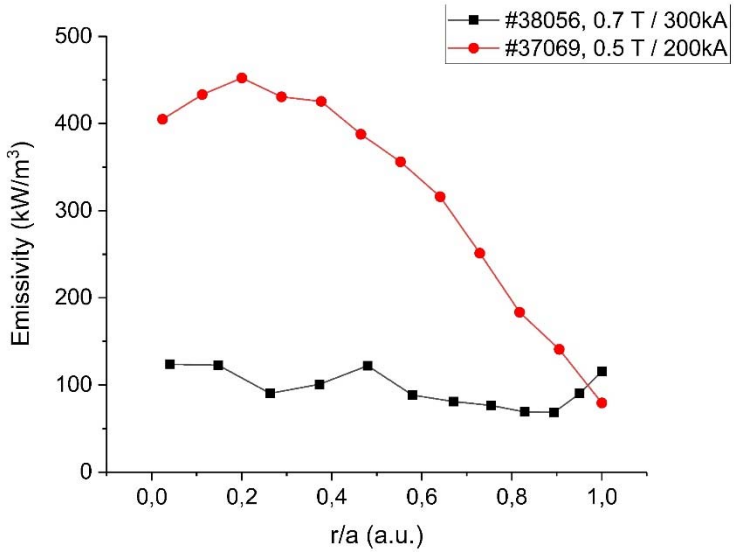
P_{rad} total = 70 kW

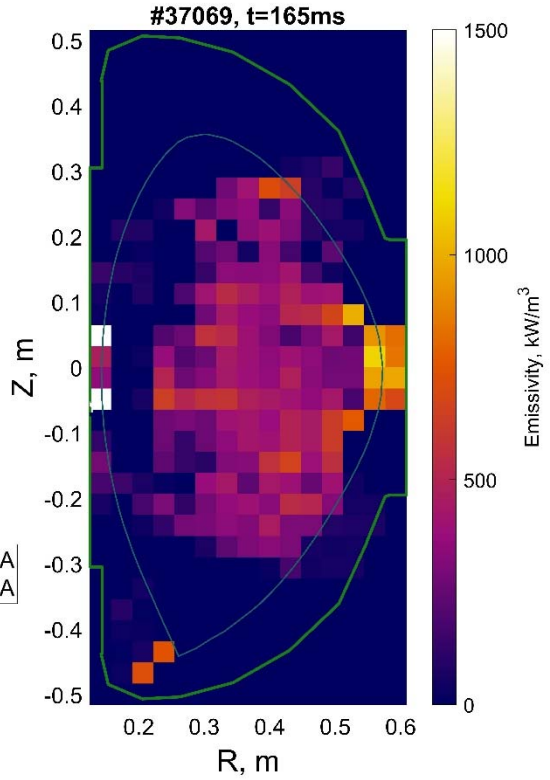
(10% P_{heat})

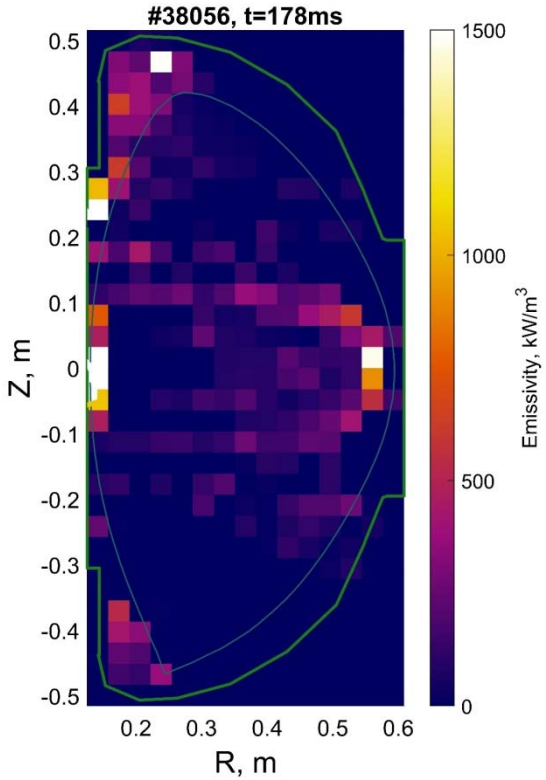
Radiation losses are mainly from inner separatrix region at 0.7 T

LOS of P_{rad} diagnostics









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Energy confinement

Conventional tokamaks

$$\tau_E \sim I_p^{a_{Ip}} B_T^{a_{BT}}$$

Spherical tokamaks

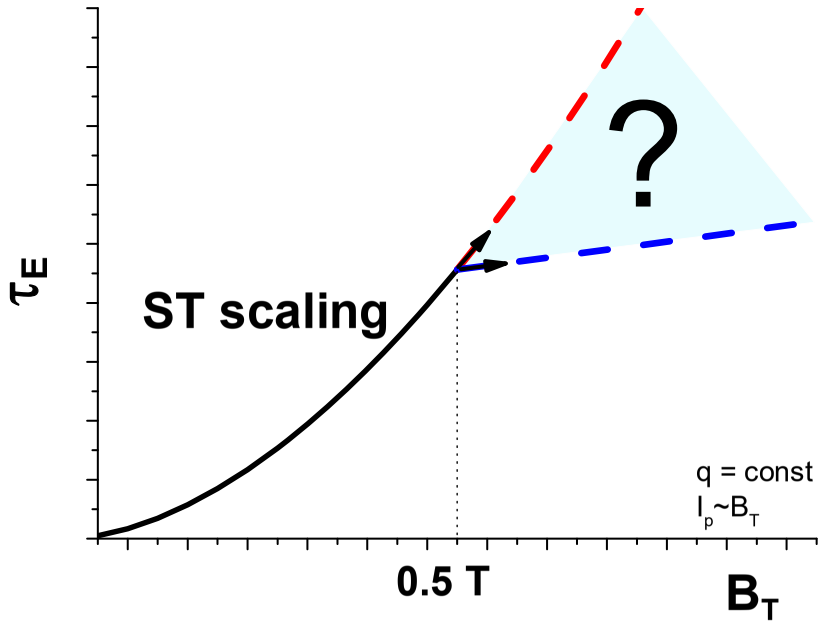
	IPB98(y,2)
a_{Ip}	0.93
a_{BT}	**0.15**

	NSTX	MAST	Globus-M
a_{Ip}	0.57	0.59	0.48
a_{BT}	**1.08**	**1.4**	**1.28**

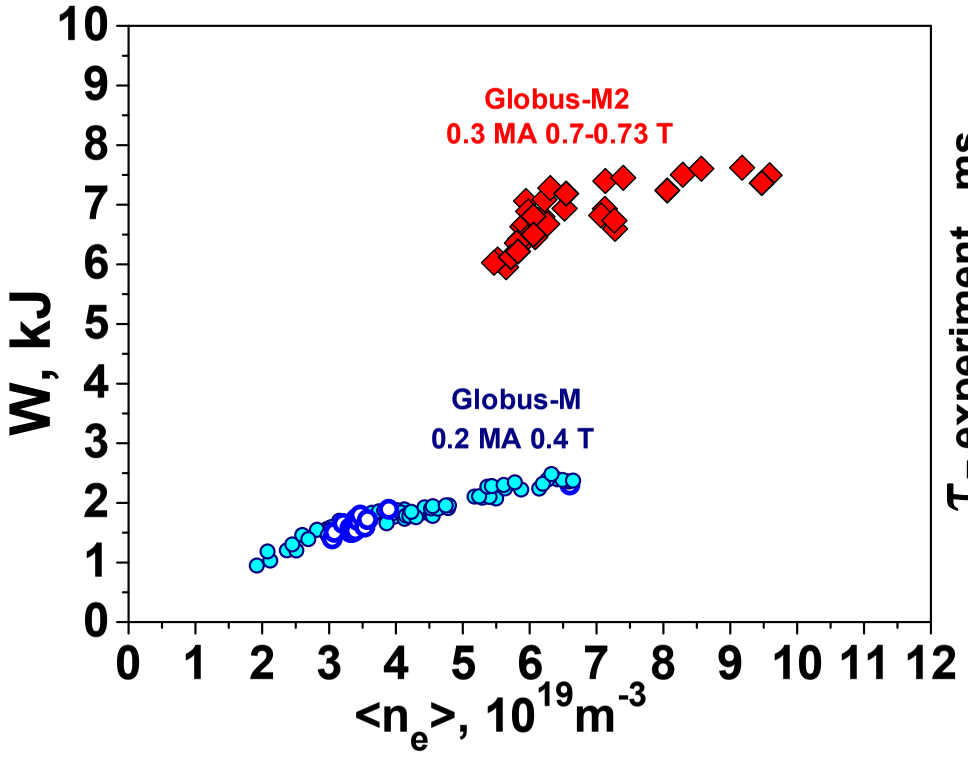
Kaye, 2006
Valovich, 2009
Kurskiev, 2019

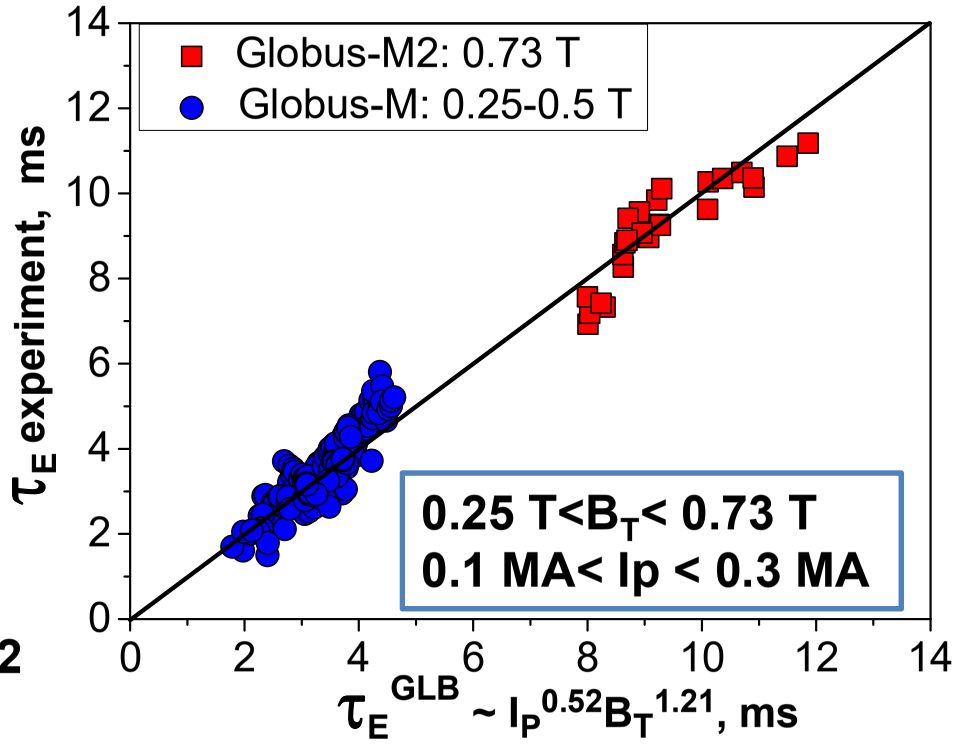
Main ST scalings were obtained at B_T < 0.55 T

Are they valid at higher fields?



Energy confinement scaling is close to Globus-M data





$H_{IPB98(y,2)} = \tau_E^{exp} / \tau_E^{IPB98(y,2)}$: **0.8 -> 1.2**

More in the next report by Kurskiev

Summary

- Globus-M2 was successfully put in operation and first full-scale experimental campaign was held in 2019.
- Toroidal field increasing up to 0.7 T decreases break- down loop voltage and together with higher plasma current (up to 0.33 MA) improves significantly plasma performance - discharge duration and total stored energy and ion and electron temperature growth was achieved
- Non inductive current generation was recorded in NB heated discharge and in the experiment with toroidally slowed down LH waves launch (for the first time in STs)
- Fast particle losses reduction with increase of plasma current and toroidal magnetic field provides conditions for higher efficiency of NB heating (up to 50% of absorbed power) as well as for Alfven cascades generation which is novel phenomena in Globus-M2
- Energy confinement time increasing was higher than predicted by IPB98(y,2) scaling and close to the predictions obtained using dependences on B_T and I_p from spherical tokamaks.