

Recent milestones in the fusion development.

S. O. Makarov

Max-Planck-Institut für Plasmaphysik, Garching, Germany

email: sergei.makarov@ipp.mpg.de

In the last several years, several milestones have been achieved in the fusion development, which drives the interest from the public and private investors. Sixty years have passed since the first serious attempts to make fusion reactions happen was made in the 1960-s. However, the energy, which is delivered to the D-T fuel, have been smaller than the energy, which is gained in the fusion reactions. Recently, a significant milestone in the fusion development was achieved. First in a mankind history, scientific energy breakeven was accomplished, i.e. fusion energy gain factor (Q) was achieved greater than unity. The $Q = P_{\text{fus}}/P_{\text{ext}}$, where fusion power (P_{fus}) is the power produced in a controlled fusion reactions, and external heating power (P_{ext}) is the external power delivered inside the reactor wall. On 5 December 2022, at National Ignition Facility (NIF) 3.15 MJ of fusion energy were produced after delivering 2.05 MJ of laser energy to the fuel target, for an equivalent of steady-

state Q of 1.54. The NIF is based on the inertial confinement fusion (ICF) concept.

Unfortunately, petawatt-class laser drivers needed for the ICF are extremely inefficient. The NIF lasers have around 1% wall-plug efficiency, which means around 322 MJ of electrical power were consumed to conduct this historical experiment.

The comparable to the ICF Q were achieved in the tokamaks, which are based on the magnetic confinement fusion (MCF) approach and does not suffer from the poor laser efficiency. The tokamak concept includes the generation of the plasma current (I_p) in the toroidal direction. Most of the tokamak-reactor concepts involve a steady-state (or long-term) operation. The steady-state tokamak operation requires organization of the, so-called, advanced scenarios and non-inductive current drives systems. The most impressive results were achieved in the EAST tokamak in China on 30 December 2021, where the D plasma of high central temperature electron temperature (T_e) 6keV was successfully confined for 1056s in the, so-called, Super-I mode. On 12 April 2023, the H-mode (high confinement mode) was sustained for 403s in the EAST tokamak with the $T_e=9\text{keV}$. The D-T mixtures are not used in the EAST tokamak. Besides, the EAST plasma parameters are not sufficiently high to achieve the high values of Q . Scientific energy breakeven was not achieved in tokamaks to date. Tokamaks have demonstrated $Q = 0.3$ in a flat-top and $Q = 0.7$ in a transient regimes.

On 21 December 2021 in European JET tokamak $\sim 10\text{MW}$ of fusion power were generated in 5s flat-top D-T plasma with $\sim 30\text{MW}$, generating the record 59MJ of fusion energy.

Superconductors are essential for the tokamak-reactor design. A critical magnetic field for the low-temperature superconductors (LTS), at which the conductor loses the superconductivity, limits toroidal magnetic field (Bt) in the plasma around 6T. Tokamak operational limits and the energy confinement for the given Bt suggest that the high Q can be reached in the large machine. This defines the large scales of ITER device. High-temperature superconductor (HTS) coils, which have been recently developed, have larger critical magnetic field (also critical temperature and critical current density) than LTS. On 5 September 2021, using full-scale HTS coil the magnetic field of 20T was achieved. Potentially, the high Bt, which can be created by HTS conductors, allows to achieve $Q>1$ in a compact machine, without reaching density and beta limits at high densities and temperatures. The SPARC tokamak is supposed to achieve central plasma pressures larger than in ITER (with smaller confinement times). The ITER and SPARC are reactor-scale devices, which are meant to demonstrate fusion-like triple-products and $Q>1$.