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Overview of Russian heavy-ion inertial fusion energy program

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Abstract

The activities overview of Russian laboratories on Heavy-Ion Fusion is presented. The new data on development of the power plant concept based on direct drive of cylindrical DT target by intense 500 MeV/u ion beam in fast ignition mode and two sections wetted liquid wall reactor chamber with lithium–lead blanket are presented. A heavy-ion driver system providing consequent compression and ignition of the cylindrical DT target is described. Data on repetitive energy fluxes generated by the 750 MJ of microfusion explosion are given. The design of the thin liquid wall reactor chamber is specified. The behavior of the liquid film at the first wall and the blanket material under a pulsed energy flux loading is emphasized. The energy conversion thermal scheme and power plant output parameters are presented. The state of the art of the ITEP-TWAC accelerator facility operation and new results of current beam–plasma interaction experiments are discussed. This work has been done under the auspices of the Scientific Council of Russian Academy of Sciences "Analysis of Energy Systems" under the chairmanship of academician V.I. Subbotin.

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1. Introduction

Activities of research groups involved in heavy-ion inertial fusion energy (HIFE) are associated with the availability of powerful heavy-ion accelerators [1–5] pursuing an overall concept proposed in Refs. [2,6–9]. Direct drive of cylindrical DT target by intense 500 MeV/u ion beam in fast ignition mode and wetted liquid wall reactor chamber design with lead–lithium blanket are the basic features of the concept. This approach is characterized by a simple driver–reactor chamber interface and a moderate value of demanded thermonuclear gain. In this paper, new data on the target energy release and the reactor chamber response are given by using newly developed numerical codes. The output parameters of the HIFE power plant for two versions of the DT target designs are specified.

The recent experimental results on the IFE-related beam–plasma interaction and accelerator physics as well as on technology issues performed by using a newly commissioned ITEP-TWAC facility are discussed.

2. Reactor chamber and energy conversion system of the power plan

Thermal scheme of HIFE power plant under consideration is presented in Fig. 1 [8]. The reactor chamber is integrated into an energy conversion system consisting of three loops. The reactor chamber loop is fed by the eutectic $Li_{17}Pb_{83}$ coolant. The coolant of the second loop is sodium. The third loop is a steam turbine cycle. The key parameter of the system is the maximum temperature of coolant eutectic $Li_{17}Pb_{83}$ at the outlet of the reactor chamber taken as 823 K. The inlet temperature is equal to 623 K. The inlet and outlet temperatures of sodium in the intermediate heat exchanger are 573 and 773 K, respectively.

The steam cycle is configured with a reheat. The initial steam temperature and the reheat temperature are equal to 743 K. The temperature of feeding water is computed as 450 K. The efficiency of the steam cycle equals 0.407. Taking into account the driver efficiency, the target gain

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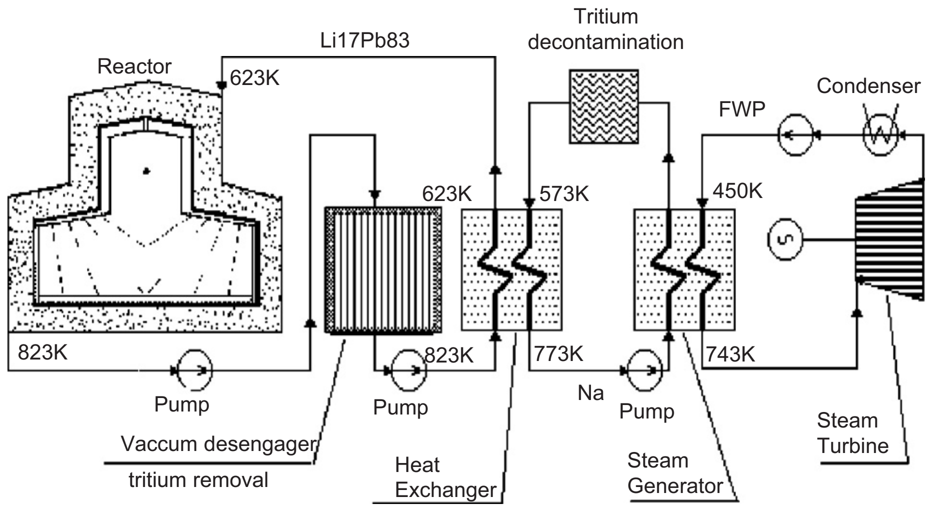

Fig. 1. Thermal cycle for HIFE power plant.

and the blanket multiplication for the fusion power of 1500 MW, we obtain the net efficiency of the plant of 0.373 and net power per reactor of 626 MW.

The general design of the reactor chamber is given in Refs. [2,8,9]. The chamber consists of the two cylindrical sections: the upper smaller section in which the target explosion takes place and the lower section in which sprayed jets of coolant are injected for condensation of evaporated liquid. The diameters of the sections are 8 and 16 m, respectively. Such a configuration prevents an over-pressurization after the microexplosion and provides high rate of vapor condensation on sprayed jets. There are three holes in upper part of the reactor chamber—two holes for guiding the heavy-ion beams for target irradiation and ignition and one for targets injection.

A saturation density of the eutectic $Li_{17}Pb_{83}$ vapor is $10^{18}\,m^{-3}$ before the shot corresponds to the temperature of 823 K, according to Ref. [10]. Under this condition, the ion beam is not deteriorated by the residual gas mixture inside the reactor chamber.

The chamber first wall and the reactor blanket are of conventional design. The liquid film is formed at SiC porous wall. In the blanket, the tubing is made of vanadium alloy. The structural wall is manufactured of HT-9 steel.

3. Accelerator driver

The ground plan of HIFE power plant including schematic view of the accelerator is given in Fig. 2. The length of the main linac is of the order of 10 km. In the case of most complicated target operation version—fast ignition scenario—the driver requires certain complications [8]: ion sources for four Pt isotopes with plus and minus charge states arranged in eight groups of four devices each and a number of storage rings for generation of 0.4 MJ/200 ns ignition pulses. The diameter of storage and compression rings is equal to 1 km.

In the main linac, the final ion energy ends up with ~500 MeV/u. After this the ions with different charges and masses are separated in eight beams, which are compressed into two stages: in storage rings and in exit sections by the time-of-flight method. The final merging of eight beams in an individual transfer line results in a single 0.2-ns bunch delivered to the target in order to provide ignition of precompressed fuel. The precompression of the target is accomplished by the beam which carries Pt^{+}_{192} ions only. This beam is temporally profiled over the duration of 75 ns with a maximum current of 1.6 kA. Repetition rate of FIHIF driver is taken as 8 Hz, which provides two shots per second in each of four reactor chambers. The nominal driver efficiency is equal to 0.25. The operational characteristics of the driver equipment are based on modern developments of accelerator technologies.

4. Target design studies

In the present scenario, because of relatively long ranges (5–10 g/cm^2) of 100 GeV heavy ions, it is natural to use a cylindrical rather than a spherical target. Relatively low efficiency of the cylindrical implosion in comparison with spherical one is partly compensated by using direct drive. High degree of azimuthal uniformity of the ion energy deposition, needed for direct drive, is ensured by fast rotation of the compression beam around the target axis, so that the beam heats a ring area of the lead shell outside the DT/lead interface. As it has been shown in Refs. [11,12], the revolution of the beam at a frequency of 1 GHz during the main pulse should be sufficient to reach the needed radial convergence.

The next step in design optimizations is achieved by implementation of spiral illumination of the target as it is shown in Ref. [9]. The radius of the beam rotation follows in time the absorber shell moving to the center according to computer simulations of the target dynamics. In this case,

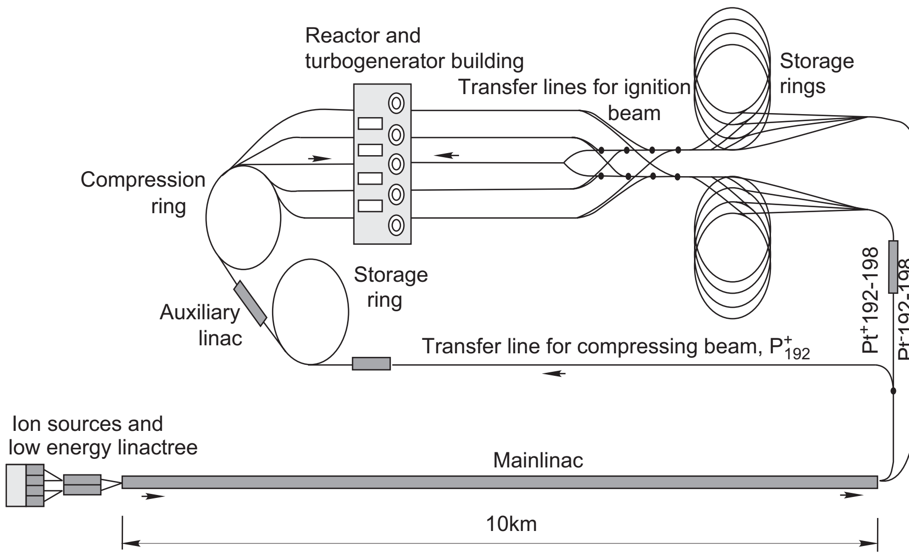

Fig. 2. Ground plan for FIHIF power plant.

the heavy-ion driver may create the best conditions for the energy input in the target at reduced output energy level.

The target consists of a uniform lead tube shell filled with DT fuel ice. The end surface of the shell is axially irradiated by the hollow ion beam formed by a high-frequency rotation of the pointed beam. Target compression and burn are computed by the DEIRA-4 one-dimensional three-temperature Lagrangian code [13], that includes diffusion of radiation in the one-frequency-group approximation and the fast fusion ions, nuclear reaction kinetics, heating rates by neutrons and by fast heavy ions. The equation of state approximates realistic properties of materials in the region of strong coupling. The mathematical model and the algorithm of computations are described in Refs. [8,9].

The target dimensions are chosen as follows: the length is 0.64 cm, the fuel cylinder radius is 0.112 cm and the target radius is 0.4 cm. The masses of the lead shell and the DT fuel are equal to 3.35 g and 5.7 mg, respectively. The total beam energy amounts to 6.4 MJ profiled in 75 ns interval with a maximum of 525 TW for the final stage of the pulse. The fuel burn (~40% burn fraction) delivers 741 MJ fusion energy with the following energy partition: 16 MJ for X-rays, 149 MJ for ion debris and 576 MJ for neutrons.

The fusion burn occurs at approximately 95 ns after the ion beam starts irradiating the target. The fuel burn produces the neutron burst of 100 ps FWHM.

The calculated time dependences of power release is presented in Fig. 3. This target produces relatively high energy of ion debris and moderate energy of X-ray radiation. The X-ray temporary profile is characterized by a sequence of a short intense prepulse and an elongated part from the main X-ray pulse. This substantially mitigates the X-ray impact on the protection film at the first wall.

Innovative target design based on the thermonuclear gain enhancement due to the combined application of DT

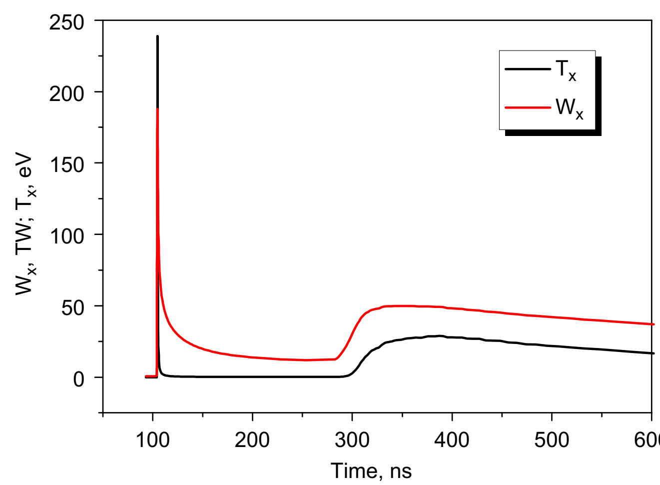

Fig. 3. Time dependence of the X-ray temperature and total power.

fuel and fission layer material is under consideration [14–16]. The concept employs up to 12 MJ heavy-ion driver matched to a directly driven cylindrical target in which the lead pusher is substituted by ^{238}U layer. Since the uranium density differs from that of lead, new hydrodynamic simulations for target compression optimization have been performed [15,17].

According to the results of numerical simulations by using the 2D, 3-temperatures hydrodynamic code H-3T the cylindrical implosion of DT fuel up to ~1000 g/cm^3 and ignition is ensured in course of quasi-isentropic (shock-less) compression process. The 100 GeV heavy-ion beam provides the required level of specific deposition power ~600 TW/g in the absorber layer of cylindrical target. The burst of DT neutrons induces the fission process in the pusher material resulting in better confinement and additional compression of DT fuel.

Ultimately, substantial increase of the burn fraction and of thermonuclear gain is observed for various masses of DT fuel and fission material.

Theoretical and numerical analysis of compression and burn of hybrid target reveal very promising coupling of fusion and fission processes. When compared with a "pure" design in hybrid target, the total energy release doubles even for modest radial compression rates ~30 [17]. As usual for hybrid systems the fast neutrons might be applied to involve ^{238}U into the fuel cycle as well as to transmutation of radioactive waste.

5. Chamber response

The HIFE concept, based on the high-energy ion beams drive of a cylindrical target, is characterized by new features in the reactor chamber response to matter and energy fluxes, generated by DT microexplosions. The HIFE reactor chamber design and performance is determined by deposition of target X-rays, neutrons and ions in the chamber residual gases and structures, vaporization and condensation of the first wall material, generation of dynamic thermal stresses in the blanket walls.

The chamber response starts with the vaporization of thin layer of liquid film under X-ray prepulse radiation. This vapor layer shields the liquid film from the main X-ray pulse absorbing the main part of X-ray radiation delivered by the main X-ray pulse. To describe the liquid film response on X-ray and neutron pulses from the moment of microexplosion to the expansion of ionized vapor over the chamber volume, one-dimensional spherically symmetrical one-temperature hydrodynamic code [18] has been developed. The real equation of state [19] for lead (neglecting lithium contribution to thermodynamic properties of eutectic) has been taken into account as well as ionization process (according to Saha) and radiation heat conductivity in the film (through the radiation Rosseland mean free path for lead plasma). The updated results of the chamber response analysis are presented in Figs. 4 and 5 according to Refs. [20,21].

The impact of X-ray prepulse is demonstrated in Fig. 4, where the pressure distributions are plotted at various times. The pressure wave, generated by the X-ray prepulse, travels across the film. When neutron pulse arrives, the pressure rises being practically uniform in the film.

Fig. 5 illustrates the pressure evolution after the main X-ray pulse starts to be absorbed in the material unloaded by a release wave. It is seen that the amplitude of the emerging pressure wave does not exceed the pressure generated by the neutron pulse (horizontal straight line).

The ion debris are absorbed by the vapor layer as well and the re-radiation from the vapor layer provides the re-vaporization of the liquid film. The computation of the liquid film re-vaporization caused by reheating of vapor by ion debris and subsequent condensation shows that relaxation of atmosphere of the reactor chamber to the initial conditions is fast enough (from 1 to 10 ms) in order not to be a limiting factor for the repetition rate. The fast condensation of vapor is well accomplished, when an array of dispersed jets is employed in the reactor chamber.

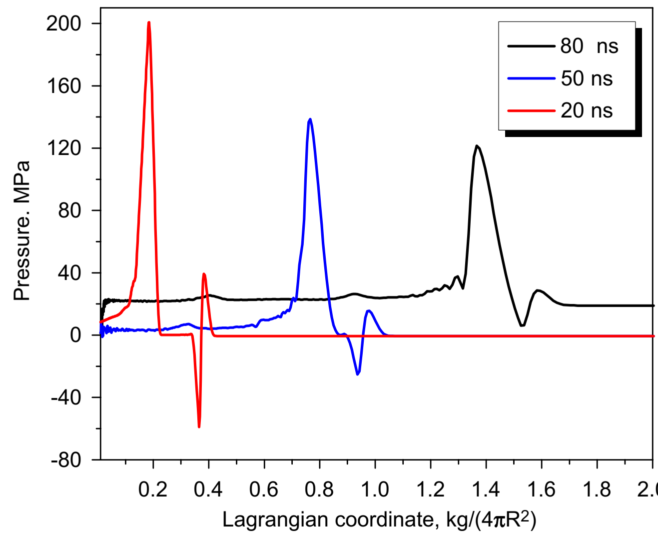

Fig. 4. Pressure profiles in the liquid film at various times for the X-rays prepulse impact, $R = 5$ m.

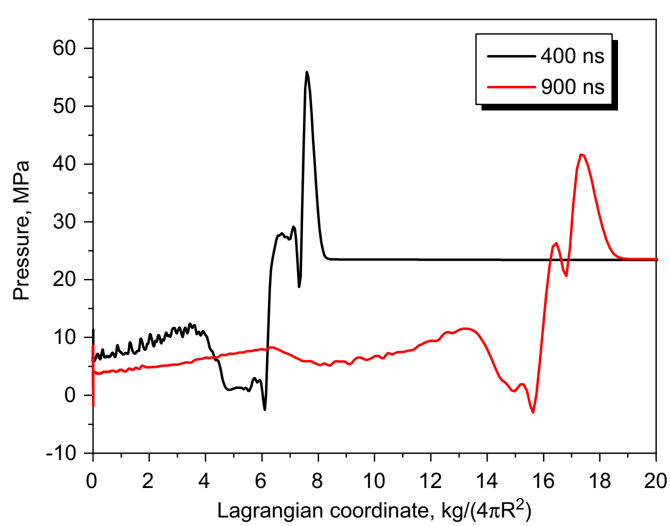

Fig. 5. Pressure profiles in the liquid film at various times for the X-rays main pulse impact, $R = 5$ m.

The neutron transport 2D computations determine the tritium breading ratio (1.112) and blanket energy multiplication factor (1.117) and provide data on thermal energy density distribution inside the blanket.

The numerical simulations of the chamber response show [18] that the pressure in the construction materials does not exceed the elasticity limits, and the relaxation time of the chamber atmosphere is less than a period of target injection.

The design studies of a reactor chamber for heavy-ion IFE performed show that a conservative wetted wall design can be well adopted.

6. Intensity upgrade of ITEP-TWAC facility

The "TeraWatt Accumulator" (ITEP-TWAC) facility at ITEP-Moscow [2,22–24] is in routine operation since 2004 using a non-Liouvillian stripping technique for stacking C^{6+} ion pulses accelerated in the UK booster synchrotron into the U-10 storage ring [23]. Its ultimate goal is to produce a particle beam power of about one TeraWatt with $\sim 10^{13}$ of A ~60 ions in bursts of 100 ns, to be accelerated to nearly 0.7 MeV/u.

Due to the very high particle density aimed at in phase space, many challenges on IFE-related topics in accelerator physics and technology itself are being addressed:

- efficient beam injection into the accelerator chain from an intense ion source capable of producing 10^{10}–10^{11} heavy ions in pulses of some microseconds length at repetition rates of ~1 Hz;
- non-Liouvillian stacking technique is needed to accumulate sufficient ions before extraction to experimental target;
- pulse compression of almost a factor of ten in time has to be mastered just before extraction;
- fast extraction, low-losses beam transport, generation of hollow beams and focusing.

Recent systematic efforts resulted in improvement of the stacking process when the beam current in the accumulator ring increased up to the level of 3×10^{10} in course of 60 cycles accumulation before being saturated. The compression of accumulated coasting beam from 1 μs to ~170 ns (FWHA) has been demonstrated by application of the 10 kV/695 kHz RF bunch rotation technique.

An important issue in intensity upgrade of the whole accelerator-accumulator scheme is the forthcoming commissioning of the new high-current linear injector [25]. The respective RFQ module 1.6 MeV/u 80 MHz undergoes the RF tests now. The subsequent SP RFQ 6 m long sections are in design phase aiming at 16 mA/15 μs, ~7 MeV ion pulses for $z/A = 1/3$. By the end of 2006, a new laser ion source [26] will deliver the ions of Al, Mg and Fe to the accelerator chain.

A 86-m-long new beamline guiding the intense ion beam to the beam–target interaction area is in operation. Focusing elements and the interaction vacuum chamber are manufactured and installed in the experimental area. Experimental activities on beam–target interaction emphasize the development of new specific diagnostic techniques by using a beam focused down to less than ~1.5 mm spot [1,24,27,28].

7. Current experimental activities on high-energy density in matter

The 27 MHz RFQ linac has been upgraded in ITEP [29]. The output energy of accelerated beam was increased up to ~100 keV/nucleon. The accelerator assembly consists of the 150 kV terminal with MEVVA ion source, low-energy beam transport line with two electrostatic lenses, 12-m-long 27 MHz RFQ section and diagnostic station at the output of the accelerator. The linac provides acceleration of ion current ~12 mA with specific mass A/Z up to 60. The MEVVA ion source with Copper cathode is currently used. The beam transport line for multicharged heavy ions from 27 MHz ITEP RFQ accelerator to plasma target have been designed and assembled.

A principle layout of the experimental setup is shown in Fig. 6. A high-quality stopping power value for 101 keV/u Cu^{2+} ions in N_2 gas has been measured experimentally [30]. A strong (by a factor of 5) enhancement of the stopping power of 101 keV/u Cu^{2+} ions in the hydrogen plasma in comparison with the cold H_2 gas has been observed.

Interaction of heavy ions with strongly coupled plasmas and possible non-ideality effects in the density regime up to 10^{22} e-/cm^3 and temperatures between 1 and 10 eV is of interest for basic research in the warm dense matter physics. The shockwave that creates the plasma is driven by the detonation of a high explosive. Experimental investigation of the stopping power of explosively driven plasma have been performed at GSI in close collaboration of the ITEP, GSI and ICP Chernogolovka groups by using UNILAC ion beams at GSI [31].

A new type of plasma target was developed with a one-tube head replacing the 2-stages-type or detonator-driven type. For diagnosing the plasma parameters, the shock-wave velocity was measured. Codes based on spectroscopic data give the plasma free electron density, temperature and the Γ-parameter of non-ideality. The measurements revealed for Ar-plasma free electron densities between 0.26–$1.5 \times 10^{20}\,cm^{-3}$ for initial Ar pressures between 0.2 and 3 bar and Γ-parameters between 0.6 and 1.3.

The measured energy loss for two ion energies, 5.9 MeV/u of ^{12}C ions and 11.4 MeV/u of ^{131}Xe both for plasma and cold gas of the same particle density has been obtained. In the range of the error bars, a slight difference between the energy loss in gas and plasma can be detected. Experimental values for energy losses in plasma up to 10% are greater than those predicted by SRIM code [31].

8. Conclusions

The HIFE concept, based on the high-energy ion beams drive of a cylindrical target, is characterized by new features in the reactor chamber response to matter and energy fluxes, generated by DT microexplosions. Due to increased mass of the target shell, the X-ray radiation has quite long duration of several hundreds of nanoseconds and in turn correspondingly smaller intensity.

The numerical calculations of the chamber response show that the pressure in the construction materials does not exceed the elasticity limits, and the relaxation time of the chamber atmosphere is less than the period of target injection.

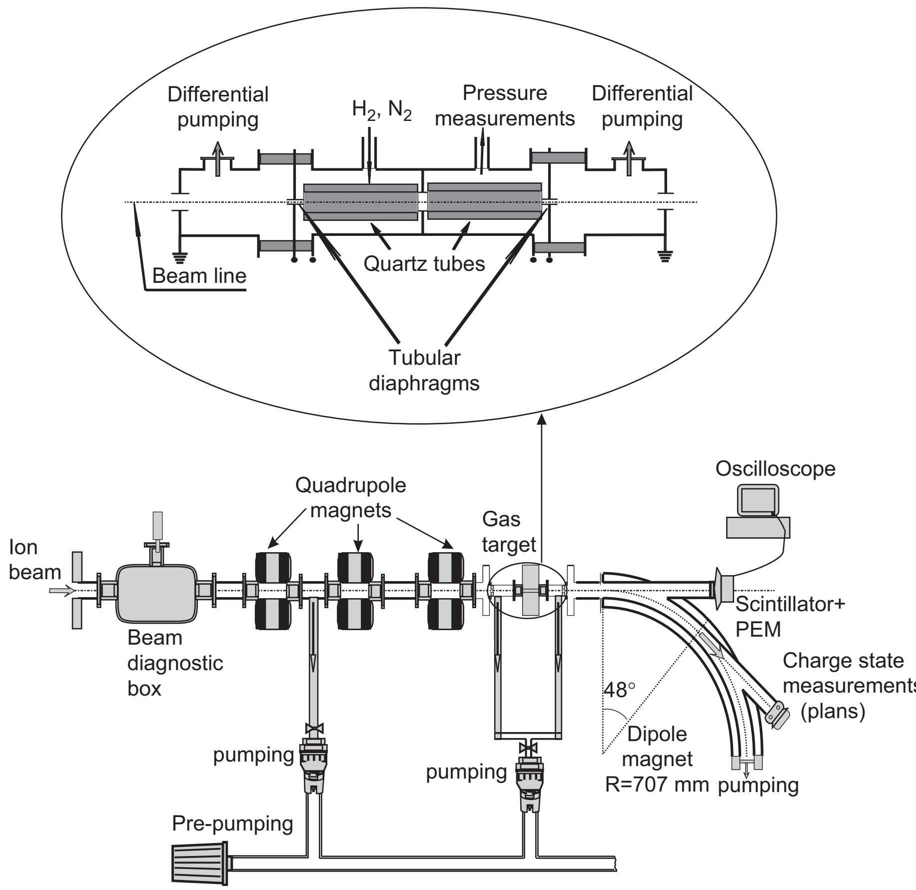

Fig. 6. Experimental setup for measurements of energy losses by low-energy heavy ions in gases and plasmas.

The HIFE massive target produces an elongated X-ray pulse providing moderate mechanical loading of the first wall. The implementation of uranium layer into the lead pusher allows to have additionally fission energy release and enhancement of fusion energy due to more intense compression of DT fuel, although this results in uranium contamination of the coolant.

The major issues of the HIFE technology are synchronization of the target and the beam, confirmation of target ignition and burn by means of more sophisticated physical models, multidimensional simulation of the reactor chamber hydrodynamics and behavior of the blanket construction under conditions of oscillating mechanical load.

TWAC project is well in progress. The accelerator-accumulator facility provides ion beams for increasing experimental activities on beam–plasma interaction physics.

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