ANTIPROTON-CATALYZED MICROFISSION/FUSION PROPULSION SYSTEMS FOR EXPLORATION OF THE OUTER SOLAR SYSTEM AND BEYOND

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ABSTRACT

Production and trapping of small numbers of antiprotons for space applications are reviewed, setting the stage for antiproton-catalyzed microfission/fusion (ACMF) reactions as a source of propulsive power. A spacecraft designed around an ACMF engine has been designed. Details, including Isp, thrust, structural features, power systems, radiation shields, ion drivers, payload and system masses, are reviewed. Staging of the spacecraft in space, including requisite propulsion and trajectory parameters and scientific goals for aggressive (Isp=13,000 sec, thrust=180 kN, ΔV=100 km/sec) outer solar system and extraplanetary missions, is discussed.

ANTIPROTON-CATALYZED MICROFISSION/FUSION

In 1992 large fission and neutron yields from antiproton annihilation at rest in a natural uranium target were observed by our group.[1] Calculations indicate that short bursts of antiprotons could induce temperatures of several keV in a small compressed pellet.[2] These conditions are appropriate for ignition of a hydrogen fusion burn within the microsphere. Targets with yields up to 302 GJ have been considered, with compression provided by light ion beams or lasers. Baseline parameters for ignition are: antiproton energy, 1.2 MeV; number, 10^{11}; pulse length, 2 ns; and deposition volume, 1 mm^3. An experiment at the Phillips Laboratory to demonstrate subcritical antiproton-catalyzed microfission is in progress.[3-7]

Most of the energy from the microfission/fusion process is in the form of radiation and hot (35 keV average temperature) plasma. Energy is produced in a target consisting of about 3.0 g of nuclear fuel. The nuclear fuel is in a molar ratio of 9:1 of DT:U(235). Initially, the proportions of energy produced in the target are 83% radiation, 15% neutron kinetic energy, and 2% random ion and electron kinetic energy.

Since most of the energy is in the form of high energy radiation, a high Z material (WLS) is desired to absorb and reradiate at lower frequencies (temperatures). The purpose of this is to optimize ablation of a thruster shell exposed to this radiation. The WLS is a spherical shell of 200 g of lead, which has a K-shell absorption edge near the peak of 115 keV for a spectrum with an average temperature of 35 keV. Of the 302 GJ of energy generated in the target, 247 GJ is absorbed by the WLS. This energy is distributed over the WLS volume according to a stellar photosphere model,[8] initially 5.6 keV at the center and 2.3 keV at the surface. Since only a thin skin on the surface of the shell radiates, most of the lead is near the 5.6 KeV temperature, which corresponds to an ionization level of Z*=75. This temperature is not high enough to remove inner shell electrons, thus enabling continuing K-shell absorption of radiation. Energy distributions of photons radiated from the photosphere around the WLS show a very significant shift of radiation down to a mean value of about 1 keV energy (204 GJ), which greatly enhances the absorption of this radiation in the ablative thrust shell used in the ICAN-II spacecraft.

ICAN-II PROPULSION SYSTEM

The basic premise of the explosion concept is that a spacecraft equipped with an adequate shock absorbing apparatus and a means of safely intercepting debris from a nuclear explosion could use the explosion energy to propel the craft at both high thrust and high Isp. Historically, the first serious effort at this type of propulsion was the ORION pusher-plate system. A more sophisticated system employing a polyethlyene canopy tethered to a winch (MEDUSA) has been proposed by J. Solem.[9-10]

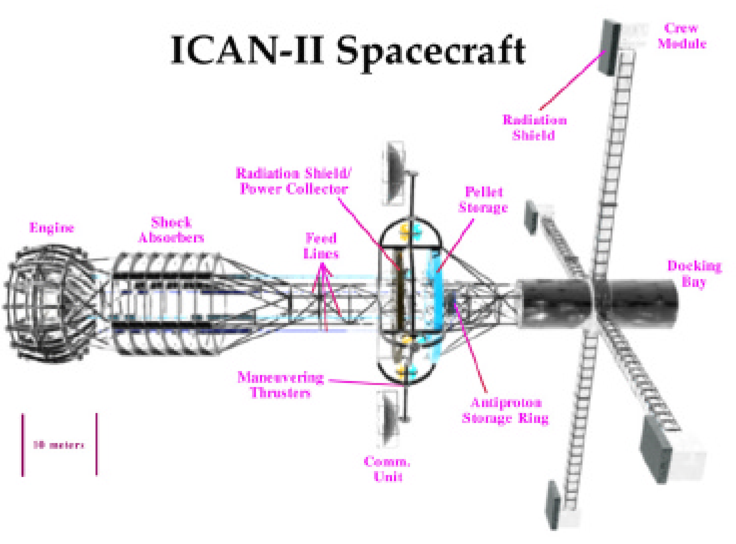


Figure 1. ICAN-II Spacecraft.

In the current version of the ICAN-II concept, a sector of a spherical silicon carbide (SiC) shell of 4 m radius is used to intercept radiation from the explosion. This radiation heats the inner surface of the shell to keV temperatures, and the resultant expanding plasma produces thrust. A schematic version of the ICAN-II spacecraft, including the engine at the aft end, is shown in Figure 1. Estimates of component masses for a 120 day, ΔV = 100 km/s Mars mission (RT) are given in Table 1.

Table 1. Estimate of ICAN-II Vehicle Masses for 120 day, ΔV = 100 km/s Mars Mission (RT).

Component	Mass (metric tons)
Ion Driver	100
Engine Structure	27
Spacecraft Structure	30
Antiproton Traps	5
Neutron Shielding	45
Power Processing	58
Payload on ICAN	20
Mars Lander/Surface Payload	53
Mars Mission Ascent Vehicle	9
Total Dry Mass	345
Mass of Silicon Carbide Thrust Shell	362
Total Mass of ICAN	707

OTHER FEATURES OF ICAN II

Additional major systems and performance characteristics of ICAN-II are reviewed below:

Radiation Control and Power Systems

Figure 2 shows a schematic diagram of the ICAN-II radiation and power systems. Radiation damage to the ICAN-II vehicle can result from neutrons, which pose a threat to the stored targets, antiprotons, and the crew of the vehicle. In order to prevent this, 1.2 meters of lithium hydride shielding (Power Shield) is required. In addition, 2.2 meters of shielding

(Crew Shield) is needed to limit crew exposure to ~ 30 rem over the duration of a mission.

Finally, part of the intense blast of neutrons from the pellet ignition is absorbed by the Power Shield to drive a 10 MW electric generator, which provides power for the ion drivers and other systems on the spacecraft. A liquid droplet radiator (Figure 3) has been designed for expelling the excess 60 MW of heat from the Power Shield into space.

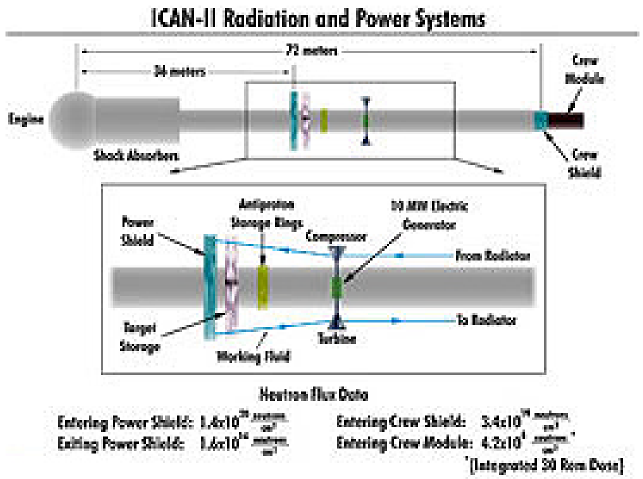


Figure 2

Thrust and Isp

Figure 4 shows the thrust and Isp for a 1 Hz firing rate. For a ΔV of 100 km/sec and an Isp of 13,500 seconds (200 g WLS), 362 metric tonnes of propellant are required for a 345 metric tonne ICAN II dry mass (see Table 1). With a 200 g WLS, the thrust is about 100 kN, which accelerates the outbound craft to a 25 km/sec ΔV in 3 days. For 800 g of ejected mass, about 30 ng of antiprotons are required. Hence, ICAN-II could be fueled with one year's production of antiprotons at Fermilab, estimated by ourselves to be approximately 140 ng by the year 2000.

Energy Utilization

It is interesting to investigate how energy from the exploding pellet is productively utilized in ICAN-II, or more generally in a fusion-driven spacecraft with ablative thrusters. The results are given in Table 2, where 7.1 GJ (7.1 GW @ 1 Hz) energy is imparted to actual forward kinetic energy of the spacecraft.

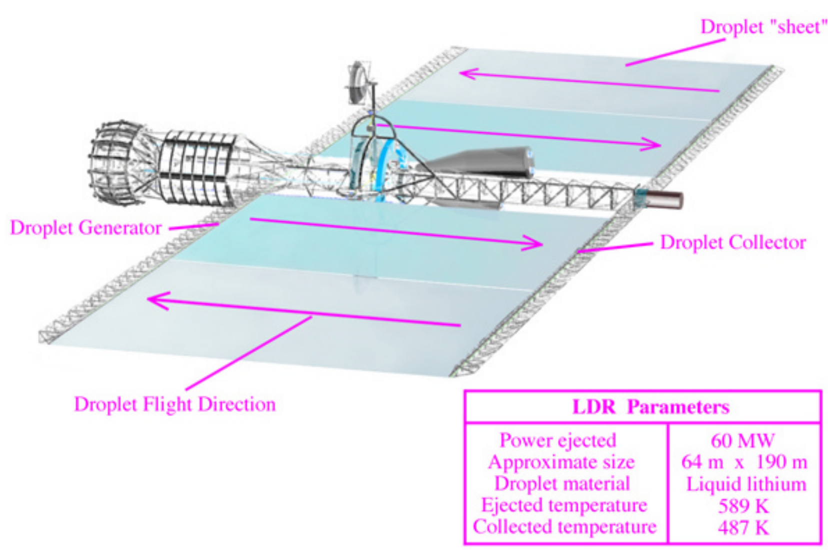


Figure 3. ICAN-II with Liquid Droplet Radiator Deployed.

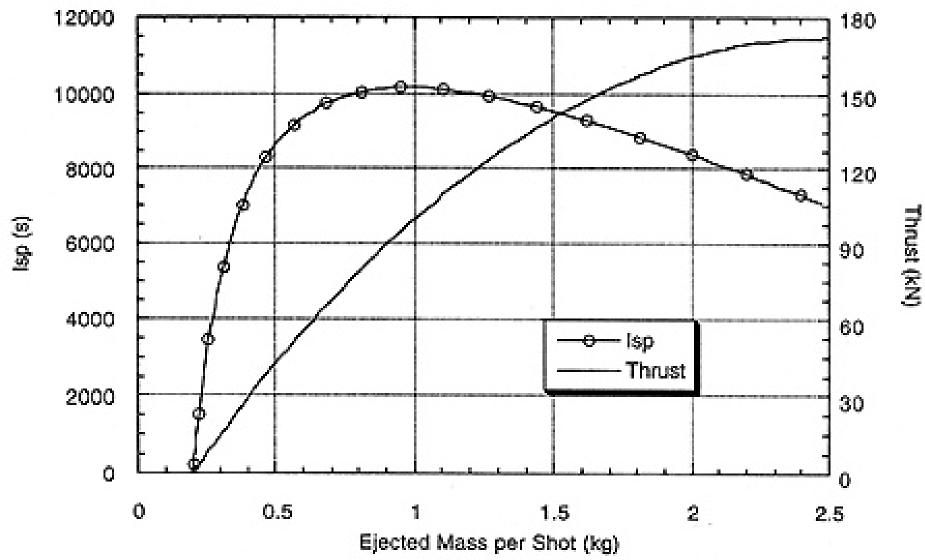


Figure 4. Thrust and Isp Versus Propellant at 1 Hz.

Table 2. ICAN-II Energy Utilization Using Silicon Carbide as Propellant (120 day Mars Mission - ΔV=100 km/s).

Parameters	Energy (GJ)	Remaining Energy (GJ)
Target Energy	302.0	302.0
Neutrons*	54.7	247.3
Hard Xrays	1.3	246.0
Energy Not Absorbed by Thrust Shell	198.7	47.3
Thrust Shell		
Thermal Energy	18.4	28.9
Kinetic Energy	3.6	25.3
Ablated Material		
Thermal Energy	9.2	16.1
Kinetic Energy	16.1	
Transverse	9.0	7.1
Axial	7.1	

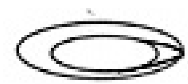
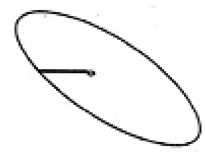
*Includes all onboard power.

EXAMPLES OF INTERPLANETARY AND EXTRAPLANETARY MISSIONS

Utilizing vehicle performance parameters presented above, three potential ICAN-II missions were analyzed. As an intermediate step to a full non-impulsive analysis, simulations of vehicle trajectories within planetary gravitational spheres of influence were performed by modeling vehicle thrust and solar gravity as perturbations. The results indicate that the majority of the ΔV was gained within the planetary spheres of influence, permitting the design of interplanetary trajectories using impulsive maneuvers at the endpoints. Missions to Mars, Jupiter and Pluto were investigated, and the results are presented in Table 3. The short transfer times significantly alleviate psychological and physical dangers to the crew. A total ΔV requirement of 120 km/s was stipulated to provide a large launch window every two years, although the mission can be completed with as little as 70 km/s if departure is timed correctly.

Table 3. Examples of ICAN-II Mission Capabilities.

A mission to the solar gravitational lens[11] point was also examined using the ICAN-II baseline design. After a continuous engine firing of 10 days, a 120 meter diameter radio telescope would be transported to a distance of 550 AU in 18 years, providing a means of observing radio signals from the galactic center with unparalleled sensitivity and resolution. In Figure 5 we show an analysis of detection sensitivity for weak sources with the telescope centered on the Sun. Estimates for solar and galactic continuum noise are indicated, along with their sum. The sensitivity is illustrated for point signal sources with a strength of 1 nanoJansky (nJy) at various frequencies (1 Jy = 10^{-26} W/m^2–Hz). For reference, we note that signals detected on Earth of Cygnus X-3 by radiotelescopes have a strength of approximated 1 Jy. The analysis indicates that small signals from distant sources near the center of the galaxy would be readily detected (with spatial resolution at the center of the galaxy of about one-eighth A.U.) at frequencies above 1GHz.

Mission	Δ (km/s)	Window	Trajectory
Earth-Mars -Round Trip -30 day Stay -120 day Total	120 km/s	~3 mos. every 2 yrs.	
Earth-Jupiter -Round Trip -90 day Stay -18 months Total	100 km/s	~1.5 mos. every year	
Earth-Pluto -One way -3 years	80 km/s	~2.5 mos. every year	

PRODUCTION OF ANTIPROTONS

Antiproton sources exist worldwide at two sources, CERN in Geneva, Switzerland and Fermilab, in Batavia, Illinois. These two laboratories utilize high energy proton synchrotron accelerators, with accumulator storage rings attached to collect antiprotons produced by collisions of protons on targets. Presently, Fermilab collects 6×10^{10} antiprotons per hour in its Accumulator. This means that in one year of dedicated production, it could produce a maximum of 0.85 ng of antiprotons. A new and funded facility, called the Main Injector, will turn on in 1999, with a maximum annual production capacity of 14 ng. A new Recycler Ring presently under construction and located inside the Main Injector ring will increase the collection rate by another factor of 10. This would place Fermilab in the 100 ng range, making it attractive for future space applications.

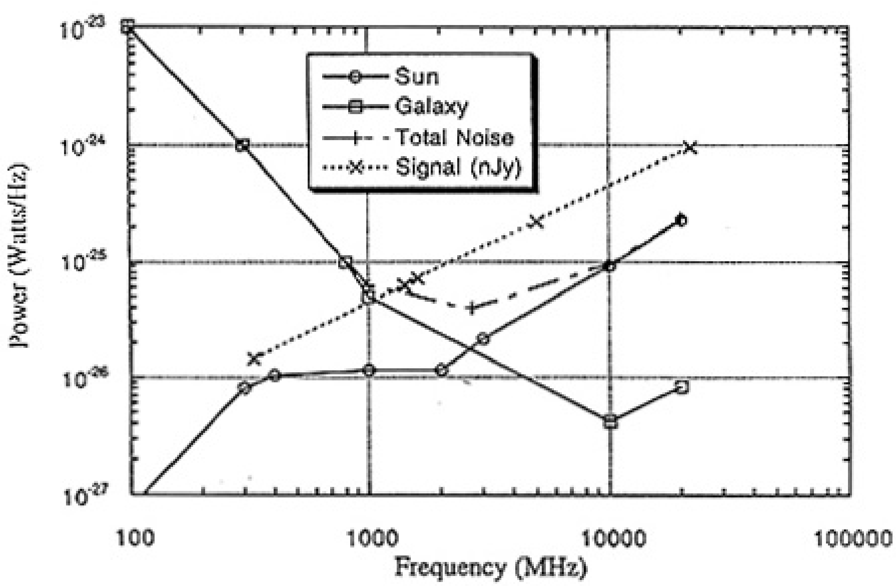


Figure 5. Sensitivity of 120-m Radiotelescope on ICAN-II to Signals from the Center of the Galaxy.

TRAPPING ANTIPROTONS

Antiproton trapping work has been done at the Low Energy Antiproton Ring (LEAR) at CERN.[12] LEAR has provided low energy antiproton beams, presently not available at Fermilab. The 5.9 MeV antiproton beam is degraded down to an energy of 10-30 keV and injected into a large Penning trap. The antiprotons are trapped radially by the magnetic field, and axially by the two confining electrostatic potentials. The harmonic frequencies of these two motions are about 50 and 5 MHz respectively. A third harmonic "magnetron" motion is also present. This precession around the direction of the E x B vector is at a rate of about 80 kHz. Measurement of the actual number of antiprotons trapped is done by lowering the potential of the far electrode, allowing the antiprotons to spill out of the trap and annihilate into charged pions. Observed linear correlations between the number of pion counts and the number of antiprotons injected into the trap show that at least 10^6 antiprotons per injection shot from LEAR have been trapped.

Electron cooling then permits collection of successive shots from LEAR, for example 10 successive shots would yield 10^7 antiprotons in the trap. Electron cooling is done by injecting electrons into the trap, where by collisions they absorb energy from the antiprotons. This energy is released by the electrons as they spin around the magnetic field in the form of synchrotron radiation. The data demonstrate lifetimes of up to several hours, corresponding to vacua of less than 10^{-11} Torr.

TRANSPORTING ANTIPROTONS TO SPACE

For space propulsion applications, 140 ng of antiprotons corresponds to about 10^{17} antiprotons. One possible scenario therefore would be to transport 10^3 traps into space, each holding 10^{14} antiprotons. It is likely that these 10^3 traps would be integrated into a common cryogenic system. Scale-up from traps holding 10^7 antiprotons to 10^{14} antiprotons will not be trivial. Traps presently in use have a Brillouin limit of about 10^{11} antiprotons/cc. Therefore, a trap with a volume of 1 liter can hold the required number of antiprotons.

We are presently building a portable antiproton trap.[13] It is designed to carry up to 10^9 antiprotons for 4-10 days. A schematic drawing of the trap is shown in Figure 6. It is a prototype for a trap capable of carrying 10^{14} antiprotons for up to 120 days (duration of a round trip mission to Mars). The portable trap is one meter tall, 30 cm across, and weighs 125 kg. It operates at 4K temperature, supported by cryogenic nitrogen and helium reservoirs, and has a unique feature that the confining magnet is made of permanently magnetic SmCo materials, which should prove to be robust.

Test results to date are very encouraging. Up to 40 million electrons have been trapped for sixteen hours. H_2 gas (~ 1 μmole) has been injected and the electron gun turned on. Bombardment of the gas by the electrons produces various charged ion species, including small numbers of H^+ ions. The storage lifetime has been measured by extraction into a channeltron detector (Fig. 7). Lifetimes of up to 10^3 seconds have been observed. The electron and H^+ lifetime results are consistent with a vacuum in the inner trap of 10^{-10} Torr.

We are currently installing a high current H^+ injector to permit storage of 10^6 ions. When tests of the system operating on a stand-alone battery system are completed, a portability test of H^+ ions will be made. We estimate that vacuums presently achieved correspond to an antiproton lifetime of 14 hours. We foresee improvements of vacuum by a factor of five, arriving at a 4 day storage time in the near term.

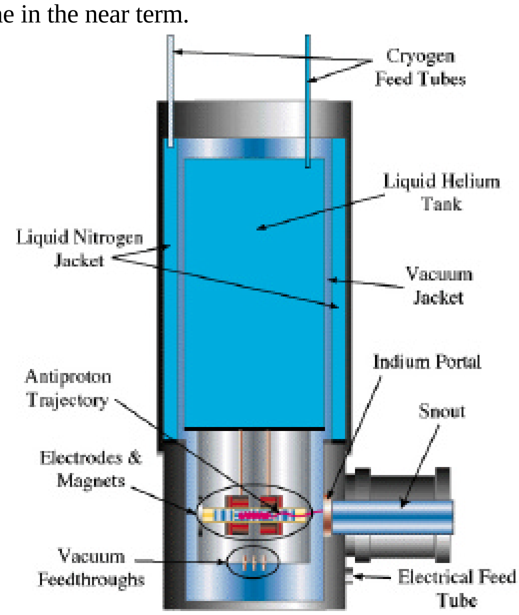


Figure 6. Portable Antiproton Trap.

SYNTHESIZING AND CONFINING ANTIHYDROGEN

Instabilities set in when the charged antiproton Coulomb energy density exceeds the magnetic (Penning trap) energy densities. Since there are practical limits to fields that can be supported, the next step is to prepare accumulations of large numbers of antiprotons in the form of electrically neutral atoms, such as atomic antihydrogen. Within the next two years these atoms will be synthesized at CERN by injecting positronium atoms, bound electron-positron pairs, into a trap filled with antiprotons. Initially we hope to form and confine thousands of antihydrogen atoms in a Pritchard-Ioffe trap, consisting of a vacuum cylinder within a quadrupole magnet, augmented with confining pinch coils at each end. Confinement is provided by the interaction of the atomic magnetic moment with the inhomogeneous magnetic field. This technology is currently available from laboratories studying atomic hydrogen where densities of $>10^{14}$ atoms/cc have been achieved. Although these densities are much higher than allowed by Penning traps, instabilities exist which prohibit their use at high densities for long term accumulation. The next step therefore involves forming condensates of electrically neutral molecular antihydrogen, either in liquid or solid form, which would provide densities approaching 10^{23} atoms/cc; 140 ng of antihydrogen would constitute a spherical volume of about 60 micrometers radius.

Confinement of antimatter has been the subject of extensive studies.[14] Since liquid or solid antihydrogen is diamagnetic, levitation within a confining vessel could be provided by a magnet of modest size.[15] Serious technical issues include annihilation of surface atoms with residual gas in the confining vessel, and sublimation of surface atoms with resultant annihilation on the walls of the confining vessel. In the latter case, the annihilation could eject matter from the walls, which in turn annihilates with the antihydrogen, starting a chain reaction.[16-17]

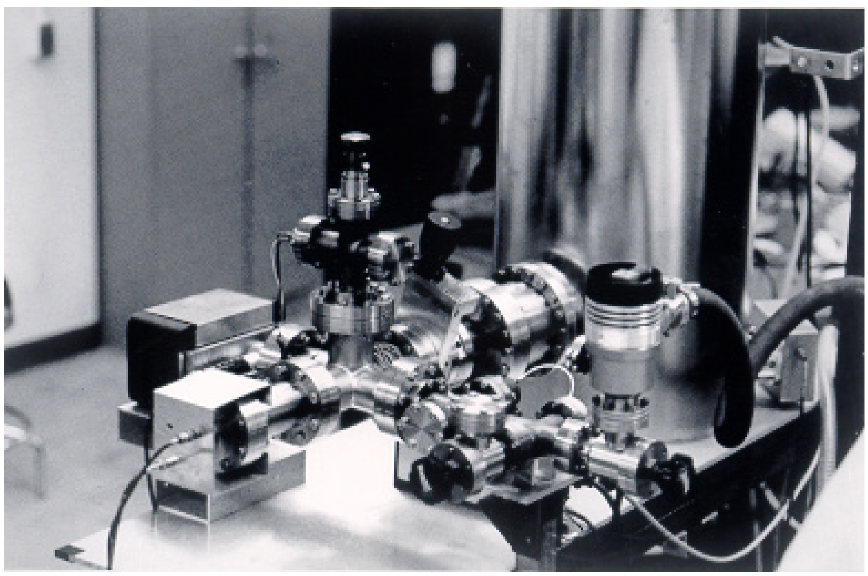


Figure 7. Portable trap (upper-right), including extraction line with electron gun (center-left), turbopump (center-right), ion-pump (center-left), and channeltron detector (lower-left).

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