Fusion-Enabled Comprehensive Exploration of the Heliosphere

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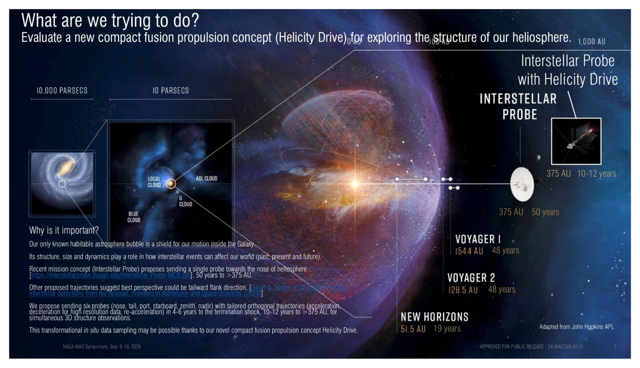
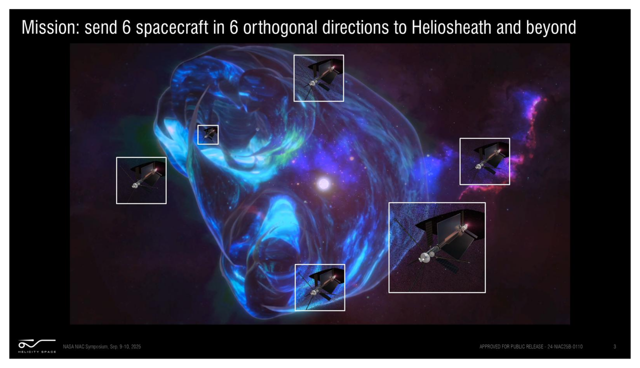
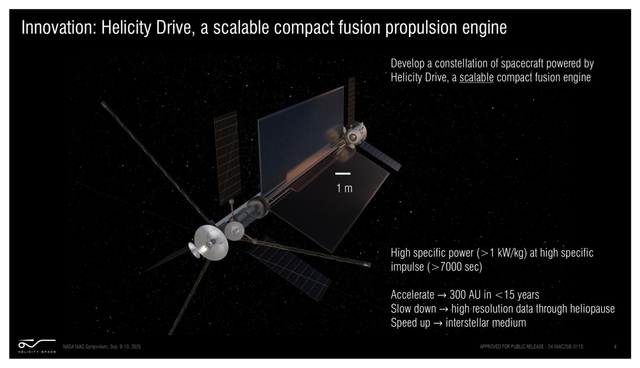
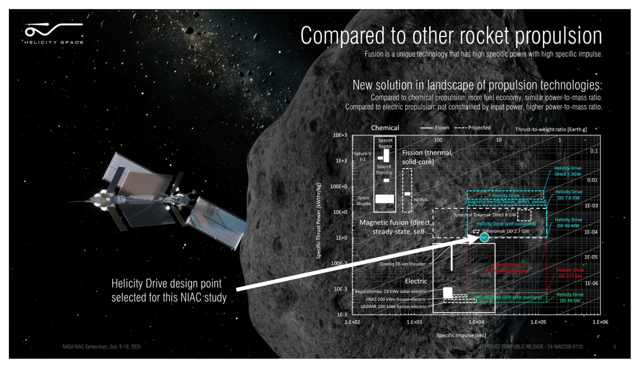
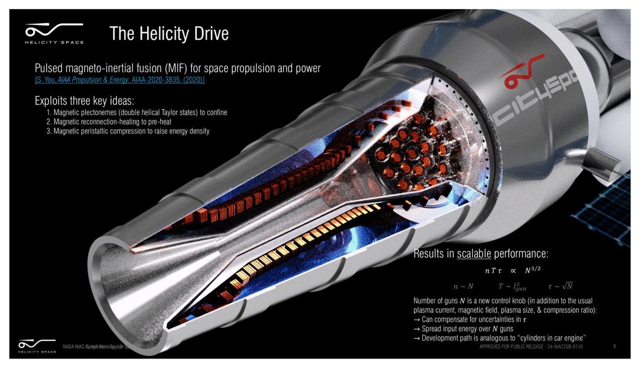
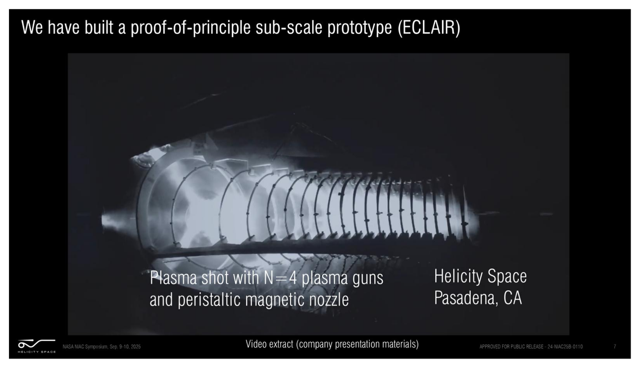
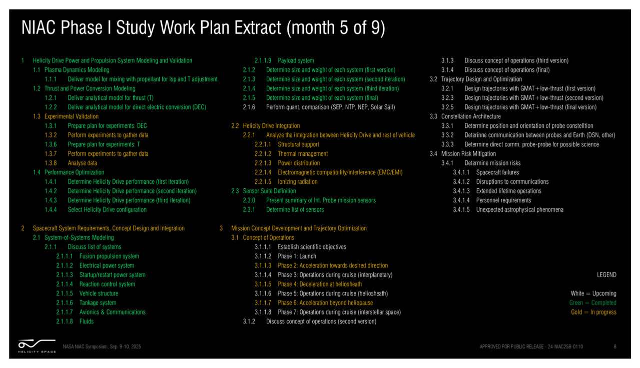
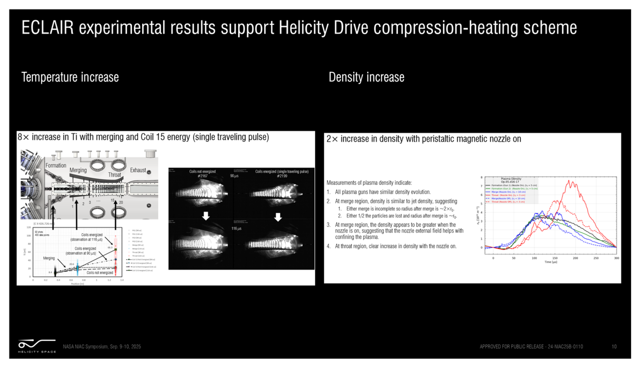
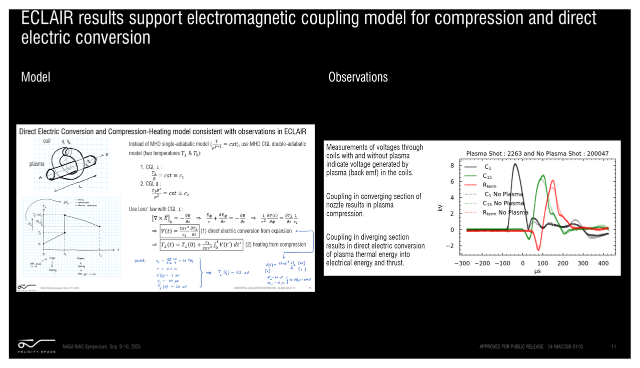
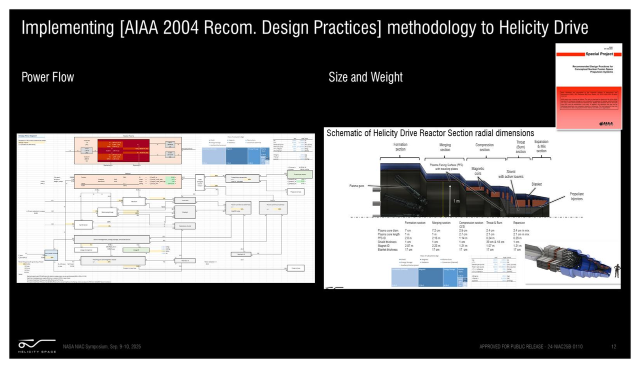
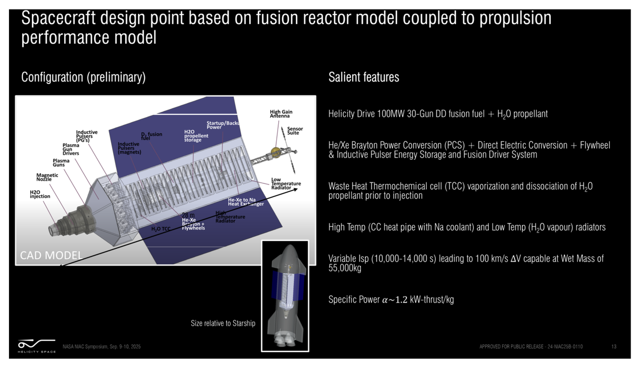
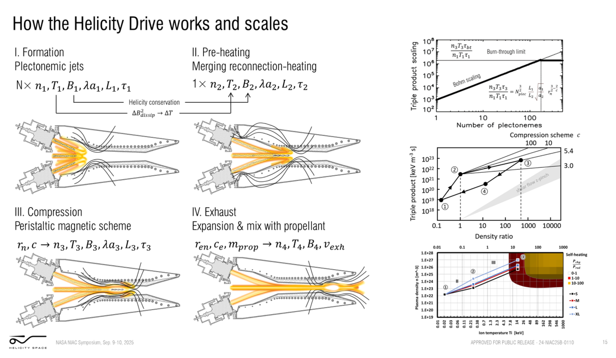
Overview

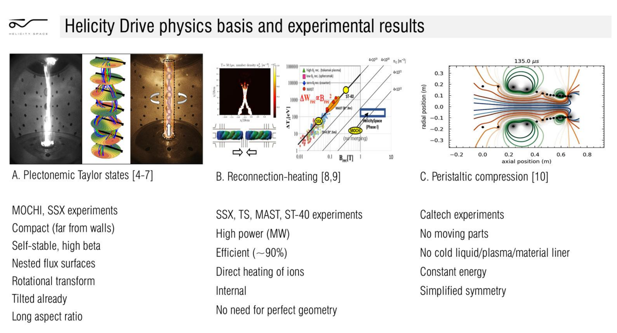








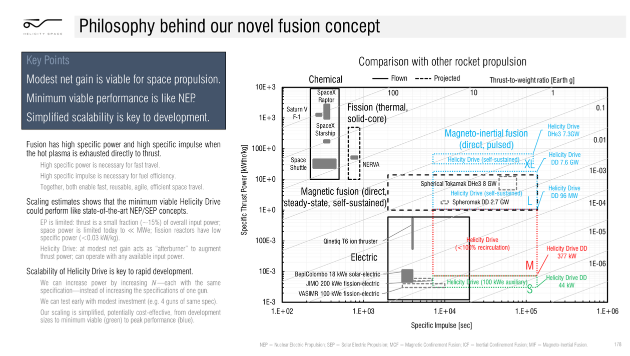
Innovation: Helicity Drive



USE NEW PLASMA HEATING TECHNIQUES FOR FUSION
Leverages recent breakthroughs in magnetic reconnection heating to achieve a scalable, efficient, and more compact fusion solution compared to traditional methods.

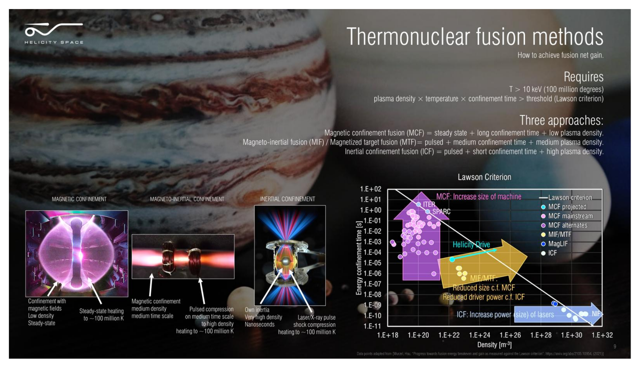
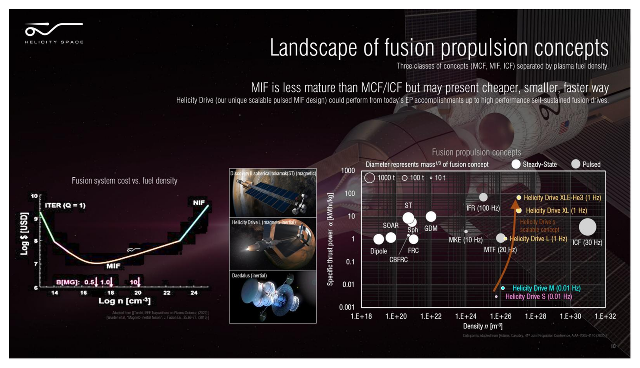


PLECTONEMIC MAGNETIC CONFINEMENT: This recently discovered, stable magnetic configuration provides inherent plasma confinement without requiring solid walls. Its robustness to translation and merging capabilities, combined with reconnection heating, offer a unique pathway to achieving fusion conditions

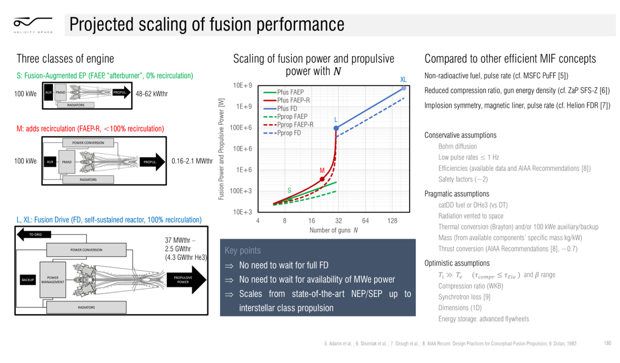


MAGNETIC RECONNECTION HEATING: Directly heats ions, eliminates the need for complex plasma shaping, and enables rapid temperature increases with feasible magnetic field strengths

PERISTALTIC MAGNETIC COMPRESSION: passive arrangement of magnetic coils to compress the plasma in 3D without dynamic material liners at a constant magnetic field energy4

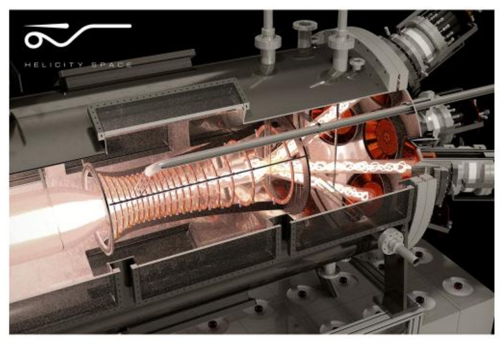



COMPACTNESS & SIMPLICITY: By preheating plasma with reconnection and merging multiple plectonemes, the Helicity Drive reduces the compression ratio and engineering complexities associated with traditional MIF concepts, achieving a mass power density and volumetric power density at least 10x higher than other Nuclear Fission, Fission-Fusion, and CW magnetic confinement fusion approaches5.

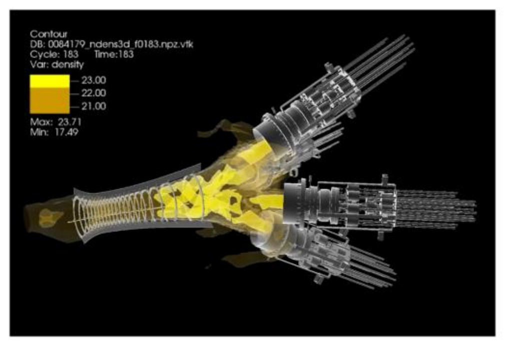


HIGH POWER DENSITY LEADS TO EXTREME DELTA-V's
Spacecraft high-speed capability allows the constellation spacecraft to reach transit velocities quickly, slow down at targets, and reaccelerate to maximize scientific return.

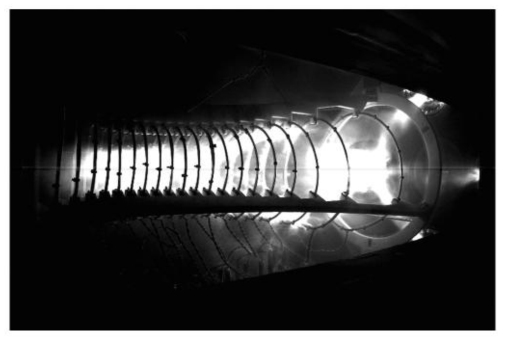
ECLAIR: sub-scale proof-of-principle prototype of Helicity Drive



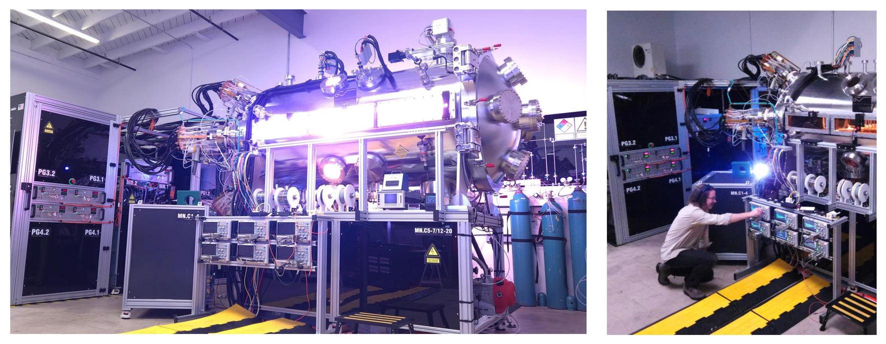
Schematic of ECLAIR experiment showing salient features: 4 plasma guns forming plectonemic plasma jets merging at the inlet of the peristaltic magnetic nozzle. Reconnection-heated plasma is compressed in the diverging section to peak conditions at the throat for further expansion in the diverging section.



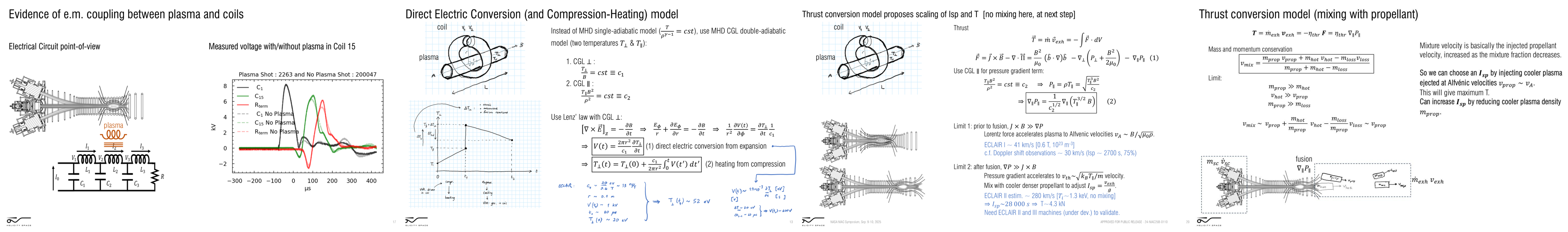
3D MHD simulations performed on the LA-COMPASS supercomputer simulation inc collaboration with Los Alamos National Laboratory, with the support of the DOE INFUSE program. The simulations show merging and braiding of the four plasma jets in the magnetic nozzle (passive, non-peristaltic in this run).



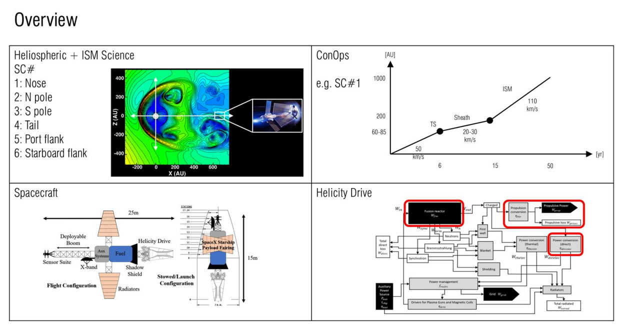
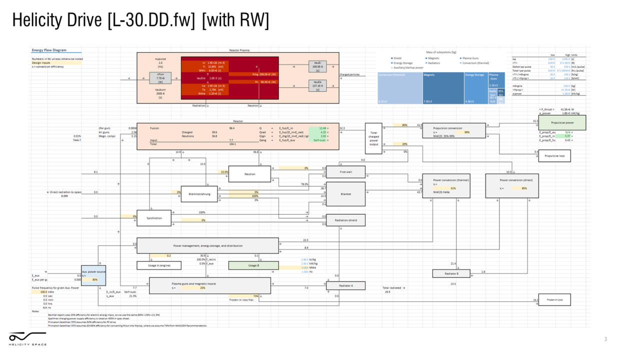
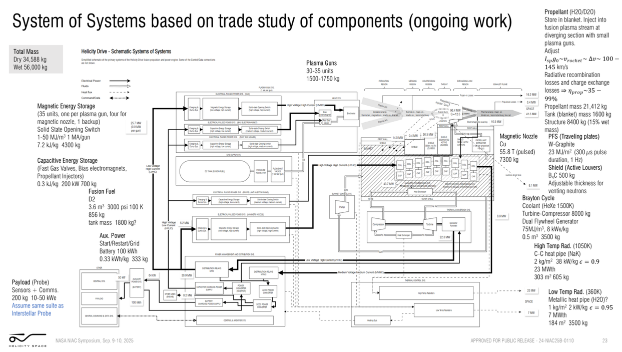
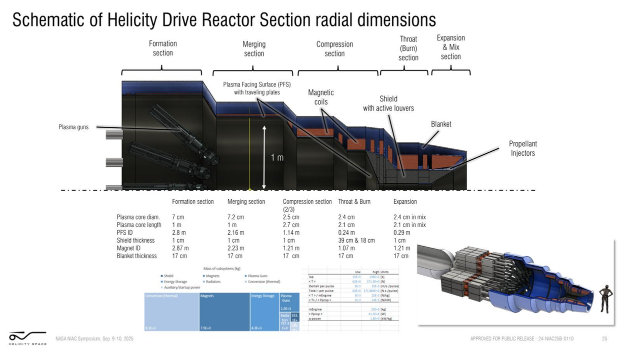
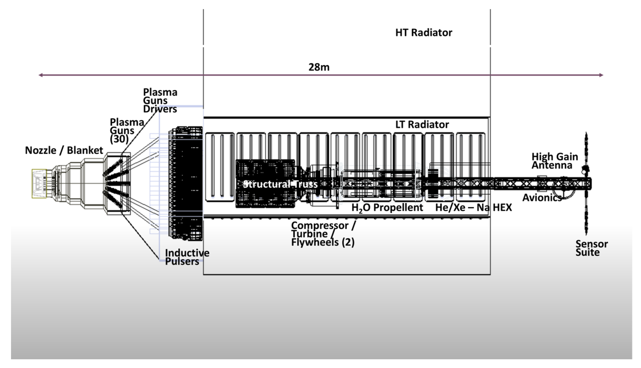
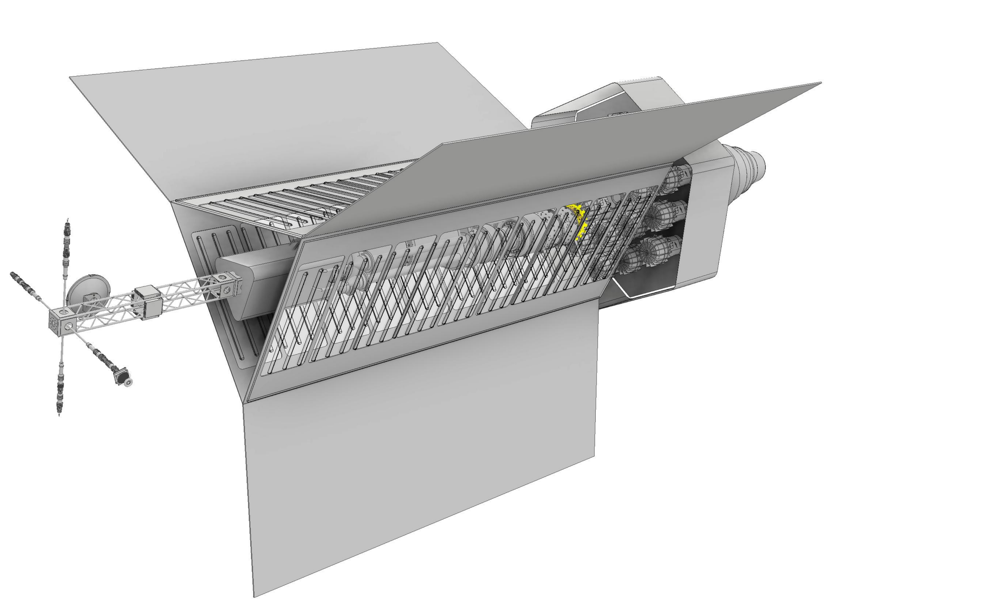
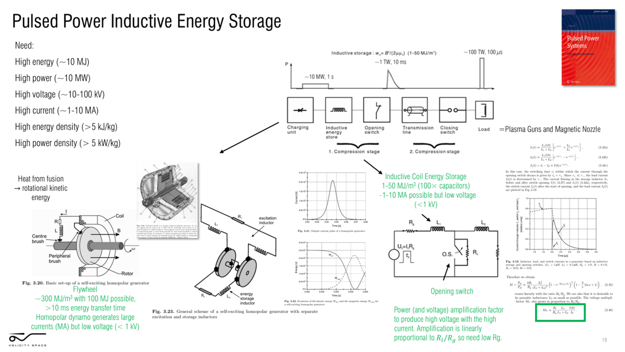
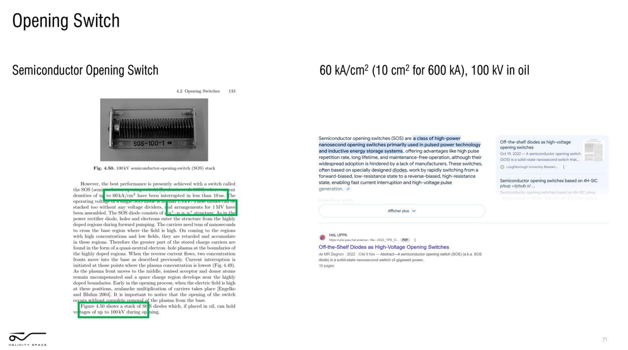
Single frame from a high speed (5M frames per second) camera showing typical plasma shot with four collimated jets merging and travelling inside the peristaltic magnetic nozzle of ECLAIR.



ECLAIR experiment (April 2025) as seen during a plasma shot with a phone camera and with operator.



Design Point for Heliosphere Spacecrafts

Propellant Mix Model

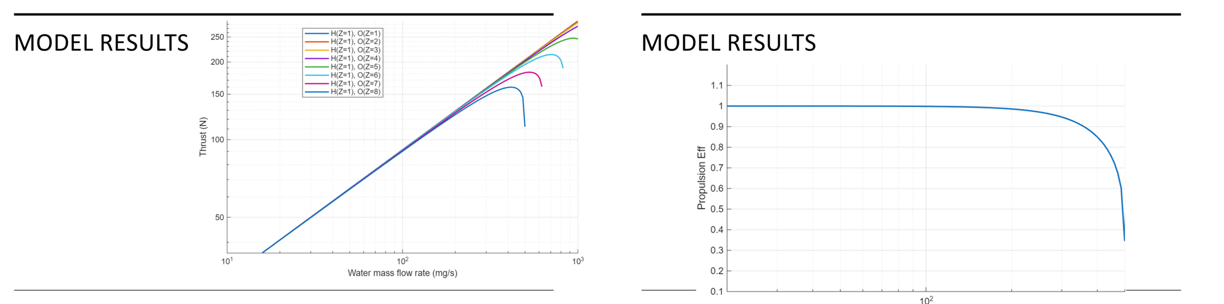
PERFORMANCE MODEL

- Matlab model varies H_2O aux propellent injection rate
- Calculates plasma temperature (w/ radiative and recombination losses) for various ionization states
- Calculates subsystem mass based on aux propellent flow rate (e.g. TCC mass proportional to H_2O mass flow rate)
- Calculates propulsion performance based on thrust efficiency → delta-V calculation based on mass fraction and ISP

ASSUMPTIONS

```
% --- BRAYTON CYCLE PARAMETERS (PHYSICALLY VIABLE) ---
power.T_hot = 1800; % Turbine Inlet Temperature (K)
power.pressure_ratio = 6; % Brayton cycle pressure ratio
power.gamma_HeXe = 1.66; % Heat capacity ratio for He-Xe mixture
power.eta_compressor = 0.94; % Isentropic compressor efficiency
power.eta_turbine = 0.95; % Isentropic turbine efficiency
power.eta_plasmaguns = 0.25; % electrical efficiency of plasma guns for Helicity Drive
power.frozen_in_frac = 0.7; %fraction of PG energy frozen into plasma
% --- Thermochemical Cycle (TCC) Parameters ---
power.eta_tcc = 0.4; % 40% efficiency for converting waste heat to dissociation energy
power.alpha_tcc = 40.0; % 40.0 kg/kW, specific mass of the TCC hardware
% --- Radiator Parameters ---
radiator.areal_massHT = 2.0; % kg/m^2 ,
radiator.areal_massLT = 1.0; % kg/m^2
radiator.emissivityHT = 0.9;
radiator.emissivityLT = 0.95;
radiator.lowtempK = 800; % maximum radiator temperature (low temp coolant)
```

MODEL RESULTS



MODEL RESULTS

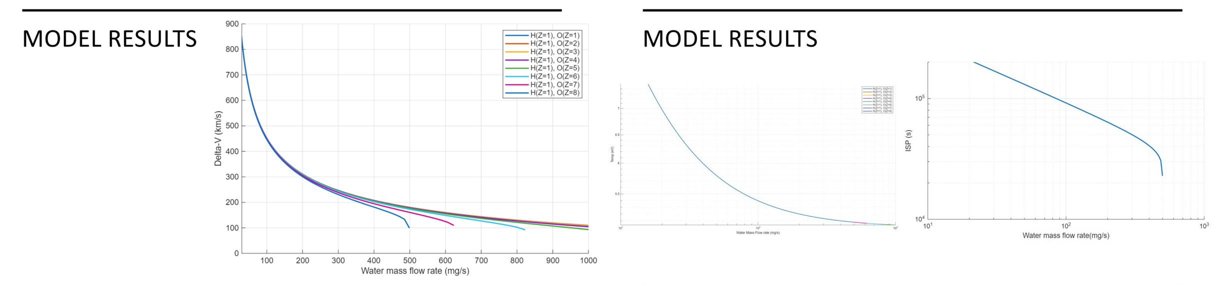
ASSUMPTIONS

```
% --- Mission & Spacecraft Parameters ---
mission.m_wet_max = 56000;                  % Maximum total initial mass (wet mass) in kg
mission.m_engine_payload = 13700;           % Mass of the fusion engine and payload in kg (magnets, shield, PGs, Energy storage, startup power)
mission.f_structure = 0.15;                 % Structural mass as a fraction of total wet mass
%mission.eta_thrust = 0.7;                  % Thrust conversion efficiency (nozzle efficiency)
% --- Fusion & Power System Parameters ---
power.fusion_DD_power = 104.1E6;            % 104.1MW of total fusion power
power.neutron_fraction = 0.38;              % Fraction of power emitted as neutrons
P_recirc_electric = 30.9E6;                 % Required electrical power input to plasma guns
power.alpha_pcs = 0.36;                     % kg/kW, for power conversion system [williams 1998]
P_charged = 52.3E6;                         % from HelicityL-30-DD calculations
P_DEC_frac = 0.2;                           % direct energy conversion from charged particles in fusion plasma expansion
P_charged_thrust = P_charged*(1-P_DEC_frac); % from HelicityL-30-DD calculations
DEC_eff = 0.85;
P_DEC = P_charged*P_DEC_frac*DEC_eff;
```

ASSUMPTIONS

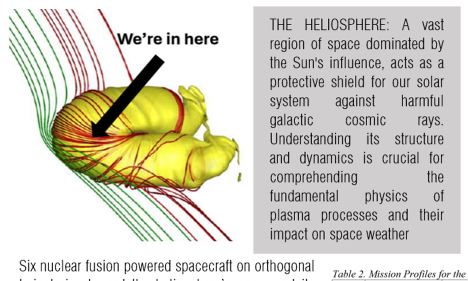
```
% --- Propellant Parameters (Water) ---
propellant.Name = 'Water';
propellant.Formula = {'H', 2; 'O', 1};
propellant.Atoms = struct(...
'H', struct('MolarMass', 1.008, 'IonizationEnergies', [1312.0], 'AtomicNumber', 1),...
'O', struct('MolarMass', 16.00, 'IonizationEnergies', [1313.9, 3388.3, 5300.5, 7469.2, 10989.5, 13326, 71330, 84080], 'AtomicNumber', 8));
propellant.VaporizationEnergy = 2260e3; % J/kg
propellant.DissociationEnergy = 51066e3; % J/kg
propellant.TankMassEfficiency = 10;
% --- Engine Geometry & Analysis Range ---
plasma_geom.volume = .044;
plasma_geom.nozzle_diameter = 0.6;
analysis.max_oxygen_Z = 8;
analysis.m_dot_vector = logspace(-4.8, -3, 150); %m dot range in kg/s
% --- Physical Constants ---
constants.g0 = 9.80665; constants.k_B = 1.380649e-23; constants.e = 1.602e-19;
constants.me = 9.1094e-31; constants.c = 2.99792458e8; constants.N_A = 6.02214076e23;
constants.sigma_sb = 5.670374e-8; %stephan boltzmann constant (W/m2K4)
```

MODEL RESULTS

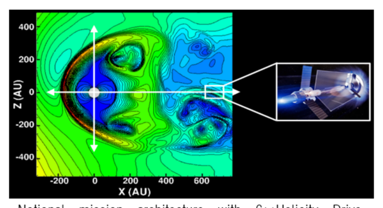


MODEL RESULTS

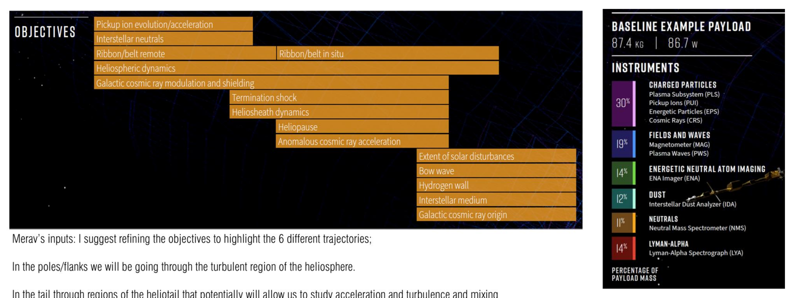
Mission



THE HELIOSPHERE: A vast region of space dominated by the Sun's influence, acts as a protective shield for our solar system against harmful galactic cosmic rays. Understanding its structure and dynamics is crucial for comprehending the fundamental physics of plasma processes and their impact on space weather



Notional mission architecture with 6×Helicity Drive spacecraft with transiting the heliosphere. Adapted from [6].



Six nuclear fusion powered spacecraft on orthogonal trajectories toward the heliosphere's nose, and its north, south, east, and west flanks. Each spacecraft carries a suite of scientific instruments to comprehensively measure plasma wave properties, magnetic fields, heliospheric and interstellar dust properties, and energetic particle distributions.

*Table 2. Mission Profiles for the (6) Heliosphere Explorers. **Bold** = start of heliosphere scientific data collection*

Craft	Mission Profile	Distance to TS	Time to TS	Delta-V to TS (km/s)	Sheath Thickness	Sheath Transit Duration (yrs)	Dist. at 50yrs
#1	Nose	60-85 AU	**6 yr**	50	30 AU	5-9 [21-33km/s slowdown]	1,000 AU
#2-3	N & S Poles	115 AU	**5.75 yr**	95	100 AU	5 [no slowdown]	1,450 AU
#4	Tail	145 AU	**4.6 yr**	150	300 AU	10 [no slowdown]	1,600 AU
#5	Port Flank	105 AU	**5.5 yr**	90	80 AU	5 [14km/s slowdown]	1,200 AU
#6	Starboard Flank	115 AU	**5.75 yr**	95	100 AU	5 [no slowdown]	1,450 AU

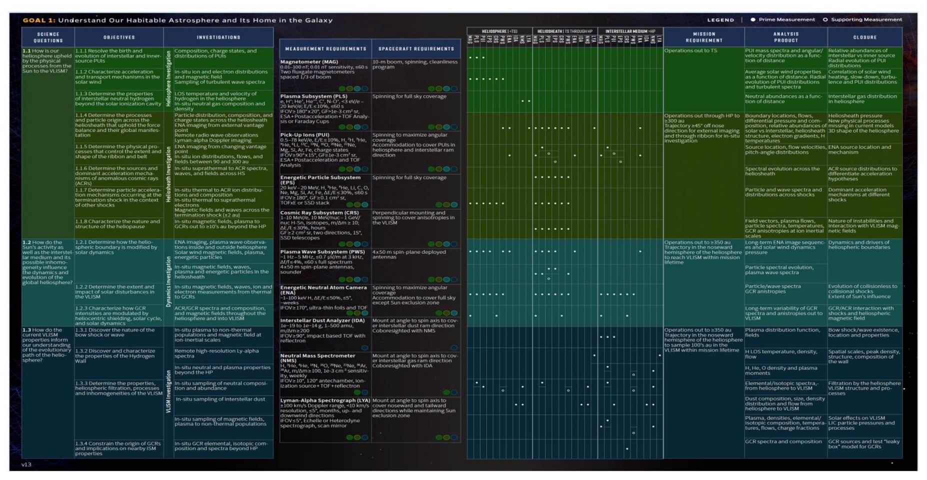
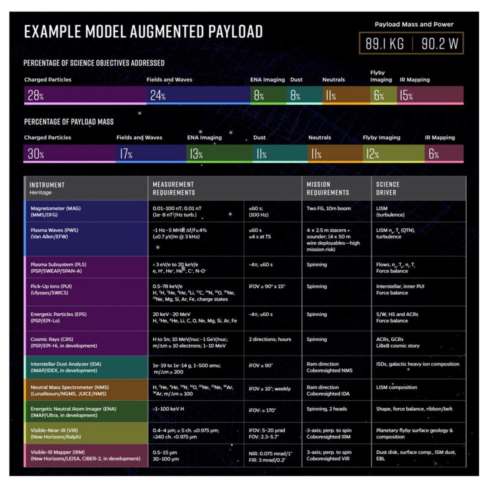
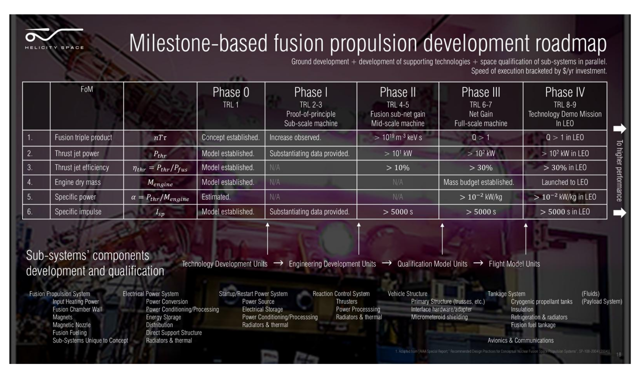
[6] Opher, Merav, et al. "Solar wind with Hydrogen Ion charge Exchange and Large-Scale Dynamics (SHIELD) DRIVE Science Center." Frontiers in Astronomy and Space Sciences 10 (2023): 1143909

We need to go farther, and we need to go faster, and we need to probe in multiple dimensions of the heliosphere simultaneously to resolve the key attributes of the heliosphere. Among these mysteries are –

- the width of the heliosheath
- the nature of the heliopause
- the source of anomalous cosmic rays
- the turbulent nature of the heliospheric tail

Voyager and New Horizons have provided invaluable data, but modern instrumentation can now fully capture key phenomena like pickup ions and weak magnetic fields. Other information comes from Earth-based line-of-sight observations.
This region is starved for in situ observational data.

INITIAL PAYLOAD CONSIDERATION
Based on the Helio Decadal Interstellar Probe Study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5 Cassibry, Jason, et al. "Case and development path for fusion propulsion." Journal of Spacecraft and Rockets 52.2 (2015): 595-612.
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7 Lapointe, M. R., et al. Gradient Field Imploding Liner Fusion Propulsion System: NASA Innovative Advanced Concepts Phase I Final Report. No. M-1471. 2018

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