Development of a Compact Fusion Device based on the Flow Z-Pinch

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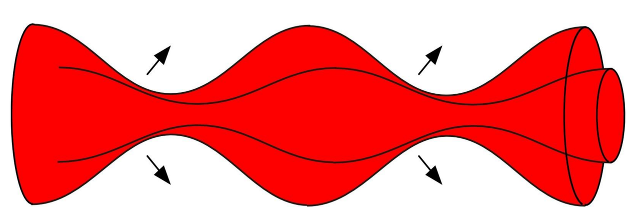
Background

Controlled thermonuclear fusion energy requires positively-charged nuclei to overcome electrostatic repulsion and approach each other to small enough distances to fuse via the nuclear strong force. These close approaches require high temperatures, and the high energy plasma must be confined and sustained in this state for a prolonged period for sufficient fusion energy output. Conventional approaches use massive magnetic field coils to form large toroidal plasma, increasing the energy input cost and complexity of the device.

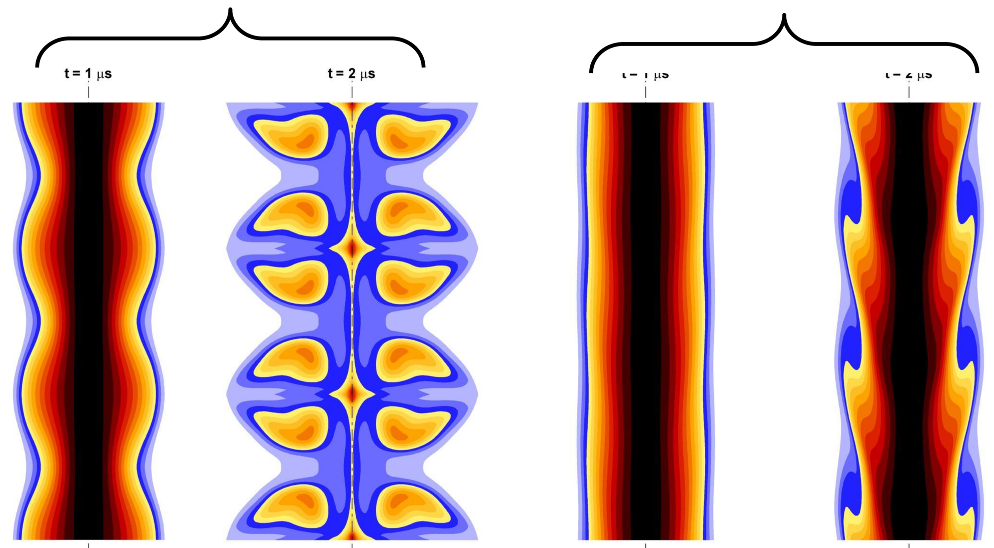
Crushed lightning rod

The Z-pinch eliminates magnetic field coils, increases fusion gain with decreasing plasma radius, and offers a compact configuration. However, it is classically unstable.

$$\frac{B_\theta}{\mu_o r}\frac{d(rB_\theta)}{dr}+\frac{dp}{dr}=0$$



Sheared-flows have been demonstrated to stabilize the Z-pinch.[1] The effect is a phase mixing of the perturbation at different pinch radii.

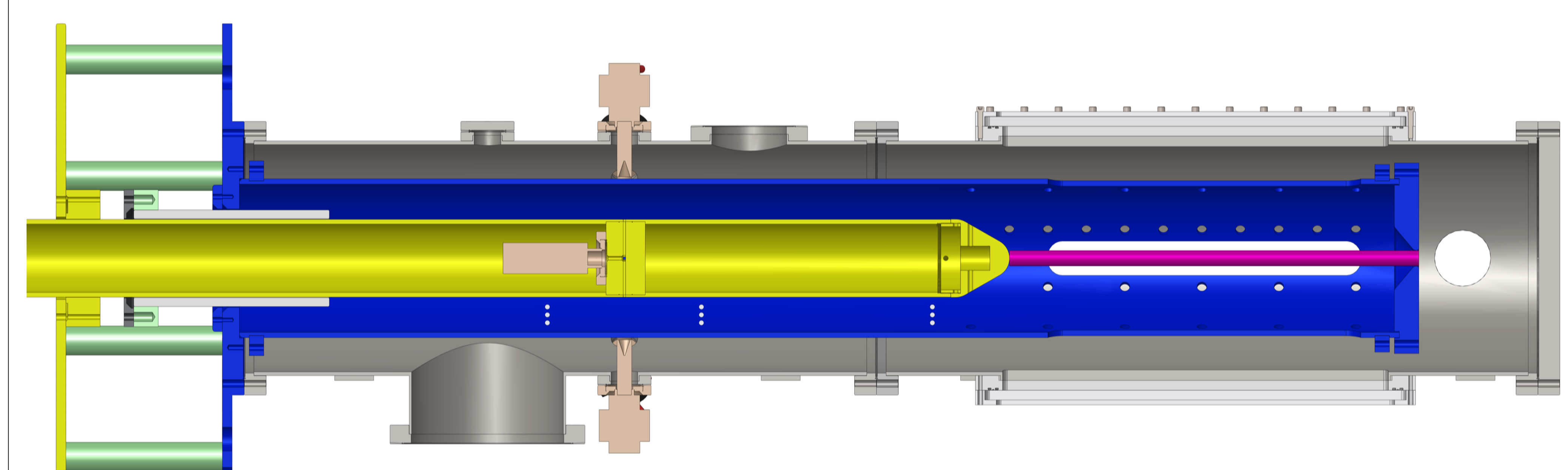


[1]Shumlak & Hartman, PRL (1995)

Overview

Zap Energy Inc., the University of Washington, and Lawrence Livermore National Laboratory are advancing the shear-flow stabilized Z-pinch concept and assessing its potential for scaling to fusion conditions and a practical path to a compact, low-cost fusion reactor. The Z-pinch is a geometrically simple and elegant approach to fusion, utilizing an electric current to simultaneously magnetically confine, compress, and heat a cylinder of plasma. However, the traditional Z-pinch is known to be plagued by instabilities that prevent attainment of conditions required for net fusion energy output. Sheared axial flows have been shown to stabilize disruptive Z-pinch instabilities at modest plasma conditions. Through experimental and computational studies, the team has successfully scaled this concept over the past four years from 50 kA to >300 kA of pinch current with a final goal in the *present device* of >400 kA. The primary goal for Zap Energy Inc.'s *next step device* is to achieve 600 kA of plasma current where plasma density and temperature are predicted to approach conditions of scientific breakeven, *i.e.* fusion power would exceed power input to the pinch were it fueled with a 50-50 mix of deuterium-tritium.

Fusion Z-pinch Experiment: FuZE

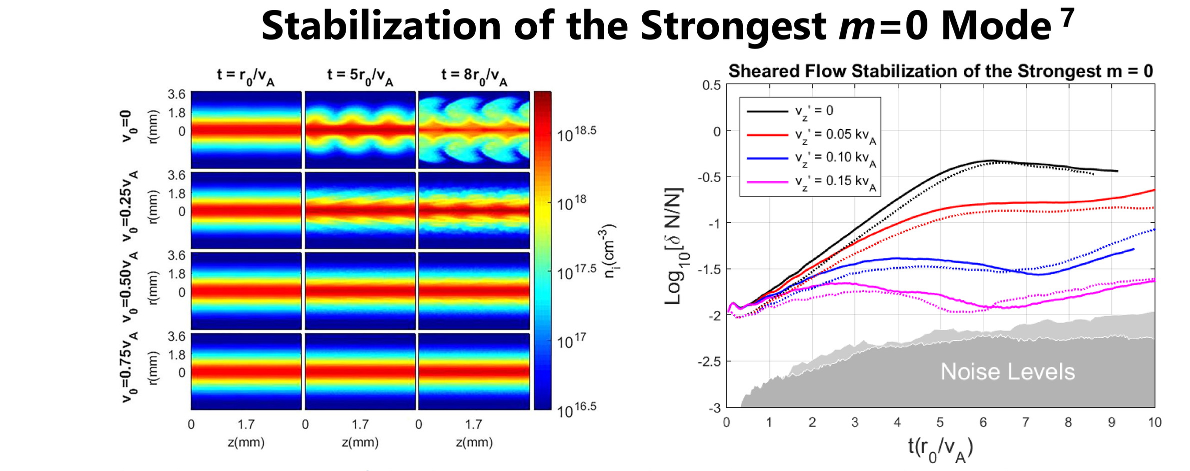


Simulations Show Kinetic Stability

Detailed computational simulations using high fidelity models guide the experimental design and interpretation of the results.

- Fluid plasma models include MHD, two-fluid, and multi-fluid simulated using MACH2[4], MACH3, WARPX[5], & WARPXM.
- Particle plasma model is simulated using LSP/Chicago.[6]

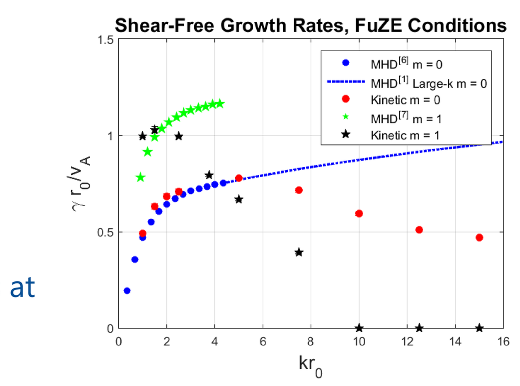
Stabilization of the Strongest *m*=0 Mode[7]



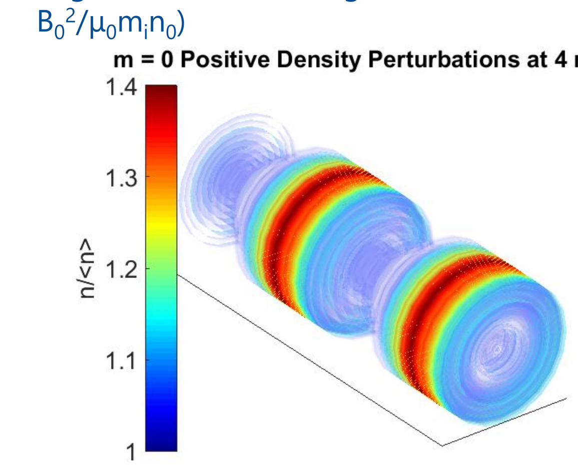
Ion density contours of the kr_0=5, *m*=0 mode under FuZE conditions show improved stability and confinement with sheared-flows (left). Sheared flows cause mode damping in FuZE (right, solid) and reactor (right, dashed) conditions.

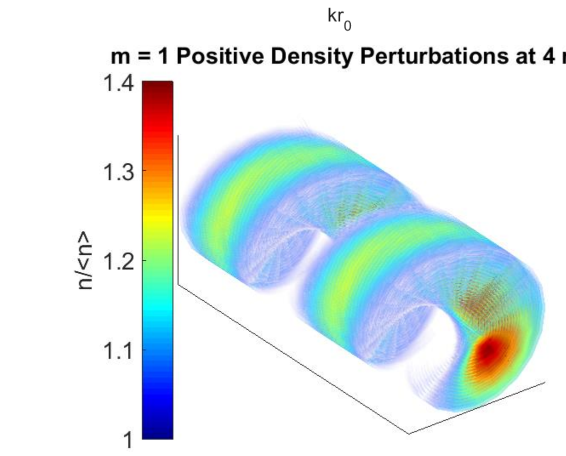
Projected FuZE Parameters

$n_0 = 4.2\times10^{24}$ m^{-3},
B_0 = 33 T, $T = 1.3\times10^7$ K,
I_{tot} = 300 kA



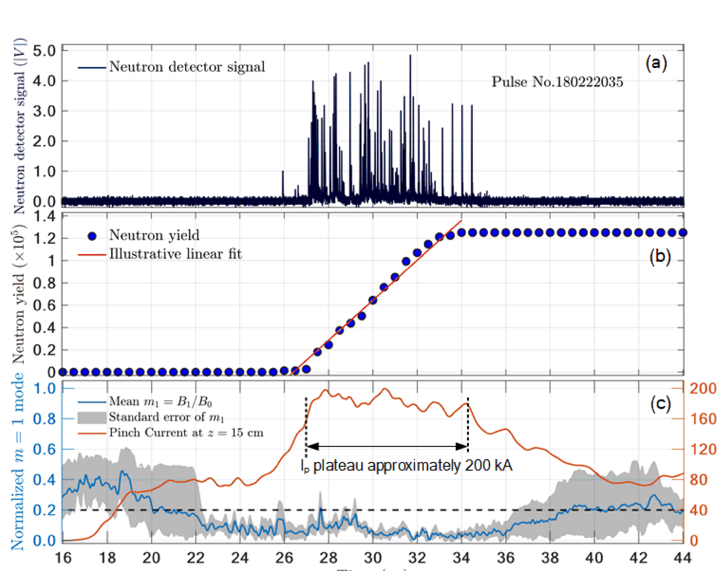
Profiles of *m*=0 (bottom left) and *m*=1 (bottom right) instabilities. Growth rates in kinetic simulations (top right) show lower growth rates at large-k (small scale length) than MHD. ($v_A^2 = B_0^2/\mu_0 m_i n_0$)



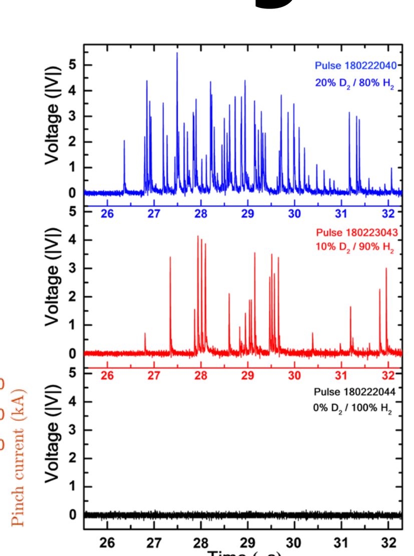


[4]Peterkin *et al.*, JCP (1998); [5]Shumlak *et al.*, CPC (2011); [6]Schmidt *et al.*, PRL (2012); [7]Tummel *et al.*, PoP (2019)

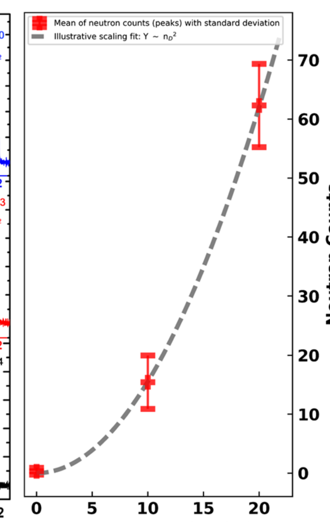
FuZE is Producing D-D Fusion Reactions



Neutron emission occurs over a 5 µs period; greater than 5000 instability growth times[2]

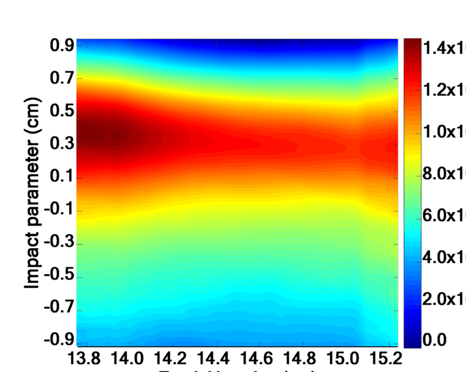


Neutron emission depends on D_2 fraction (0%, 10%, 20%)

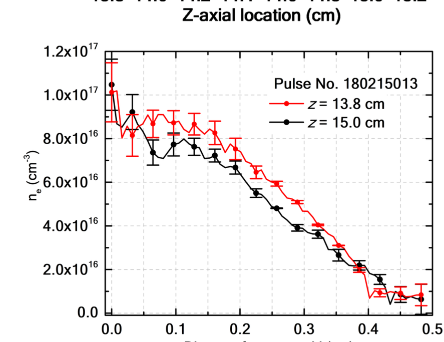


Neutron counts proportional to n_D^2

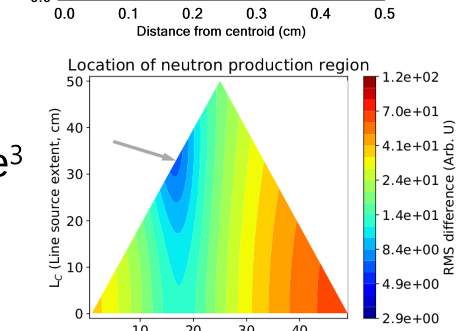
Digital Holographic Interferometry (DHI) shows a pinch structure



Deconvolving DHI data yields a radius of *a*=0.3 cm and density of *n*=10^{17} cm^{-3}



Neutron production is from ~34 cm column, starting at the nose cone[3]



Present Yield: ~5 x 10^5 neutrons / pulse for 20% D_2, I_p = 200 kA, n=10^{17} cm^{-3}, Ti=1-2 keV
Yield Goal: ~10^8 neutrons / pulse for 100% D_2, I_p = 400 kA, n=10^{18} cm^{-3}, Ti>2 keV

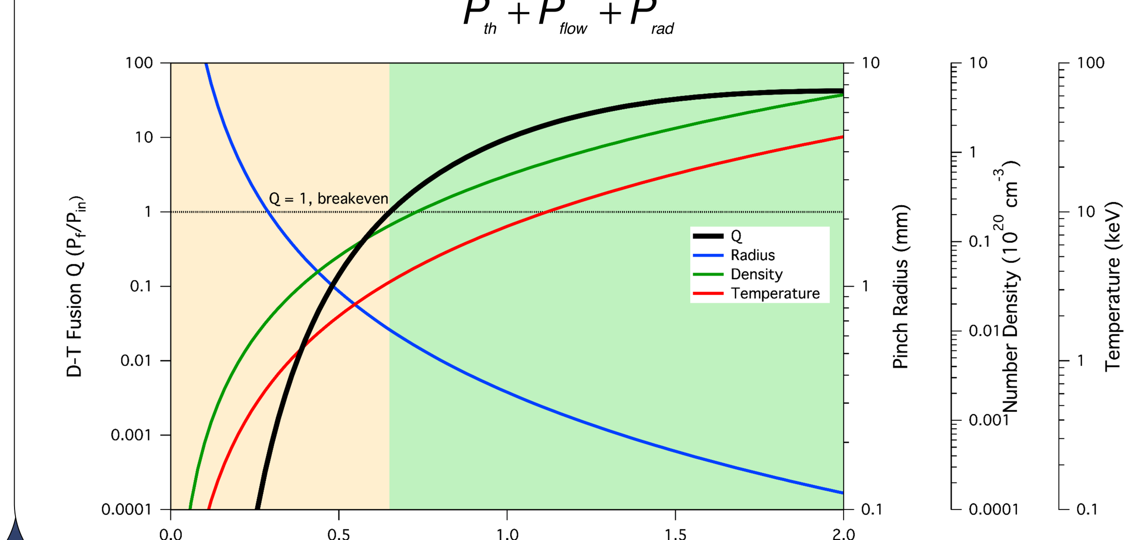
[2]Zhang *et al.*, PRL (2019); [3]Mitrani *et al.*, NIMA (final review 2019)

SFS Z-pinch Favorably Scales to Reactor

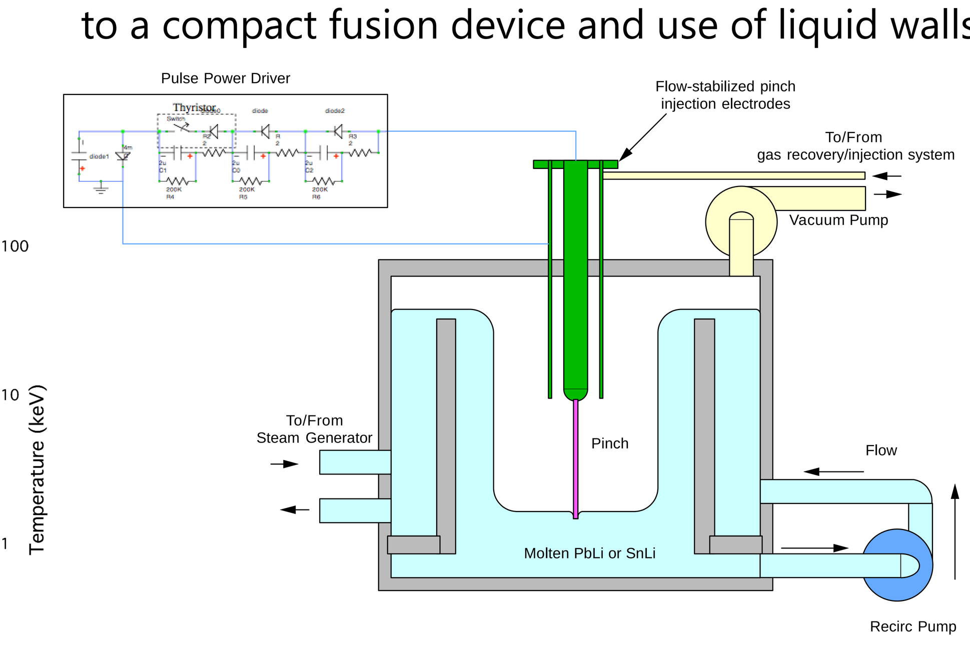
Flow-stabilization theory of a Z-pinch has no additional limitations as the plasma parameters are increased. Experimental results and computational simulations have supported the theory. The Z-pinch scales to high performance conditions by increasing the current or decreasing the plasma mass, which decrease the plasma radius and increases the fusion gain.[8]

$$\frac{a_2}{a_1}=\sqrt{\frac{n_1 N_2}{n_2 N_1}}=\left(\frac{I_1}{I_2}\right)^{\frac{1}{\gamma-1}}\left(\frac{N_2}{N_1}\right)^{\frac{\gamma}{2(\gamma-1)}} \qquad \frac{n_2}{n_1}=\left(\frac{T_2}{T_1}\right)^{\frac{1}{\gamma-1}}=\left(\frac{I_2}{I_1}\right)^{\frac{2}{\gamma-1}}\left(\frac{N_1}{N_2}\right)^{\frac{1}{\gamma-1}}$$

$$Q\equiv\frac{P_f}{P_{th}+P_{flow}+P_{rad}}$$

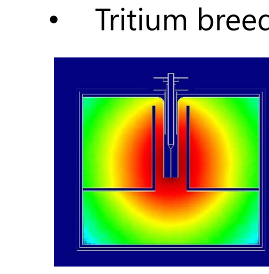


The sheared-flow stabilized Z-pinch naturally leads to a compact fusion device and use of liquid walls.[9]



Liquid metal performs multiple functions:

- Protects walls from neutrons and heat
- Acts as one of the electrodes
- Serves as heat transfer fluid
- Tritium breeding



MCNP calculation of local tritium breeding ratio (TBR/vol)
Total TBR ~1.1

[8]Shumlak *et al.*, FST (2012); [9]Forbes *et al.*, FST (2019)