Z-pinch Fusion for Commercial Applications

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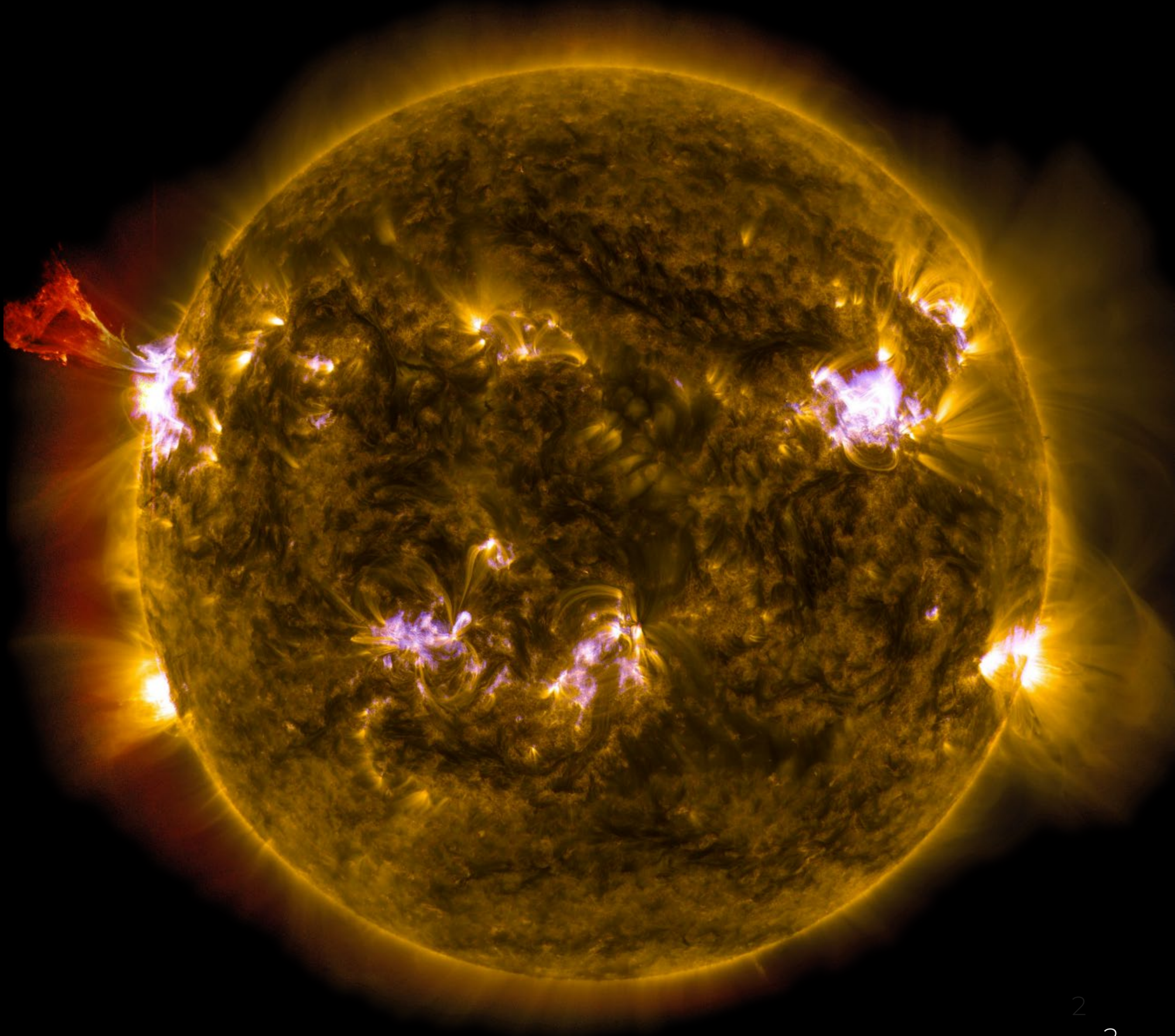
ZAP ENERGY

Fusion — the universe's energy source



Clean: no long-lived waste or harmful emissions

Safe: no risk of meltdown, no major radioactive hazards

On demand: can generate power anywhere, any time

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Fusion Fundamentals

Use the bonds that exist at the heart of the atom instead of along the outside

- 10,000,000x more energy per reaction
- 1 oz of fusion fuel = 25 tons of coal

Fuse together small atoms instead of splitting big ones

Main challenge for fusion energy is to heat and compress the fuel sufficiently

Requirements: hot enough, dense enough, for long enough = triple product

Why fusion?

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	Fossil Fuels	Renewables (Solar and Wind)	Nuclear (Fission)	Fusion
On Demand / Baseload	✓	✗	✓	✓ Capable of high uptime and load balancing
Clean / Carbon-Free	✗	✓	✗	✓ No emissions or long-lived radioactive waste
Fuel Price & Abundance	✗	✓	✗	✓ Fuels are cheap and globally dispersed
Safety	✗	✓	✗	✓ No risk of meltdown or local public health hazards
Land Efficiency	✓	✗	✓	✓ Similar footprint to existing traditional power plants
Public Acceptance	✗	✓	✗	✓ Clean slate, bipartisan support

30 years away? Not a chance.

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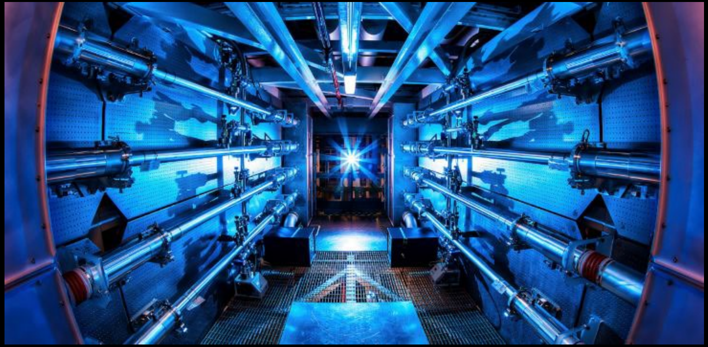
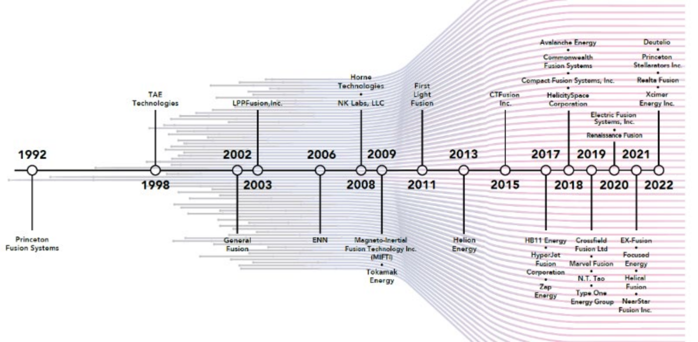
The fusion landscape has fundamentally changed

- Climate change has raised the stakes
- Fusion gain is no longer theoretical
- Multiple decades of progress in fusion is coming to fruition, fusion triple product metric outpaces Moore's Law
- Money and talent is flooding into the industry, fueling faster innovation
- Fusion leadership will be a national imperative and the federal government has begun to step up more broadly to support the nation's competitive position



NIF hit Q=1; who will be next?

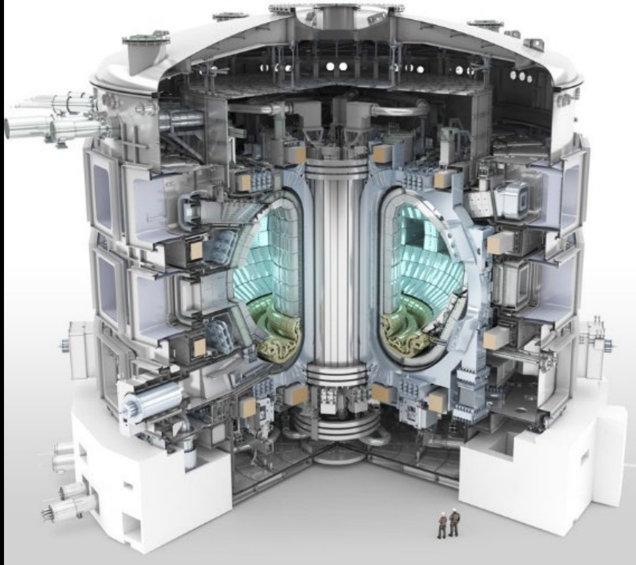


More than 30 private fusion companies have raised over $4.8B to date, mostly in the last few years

Historical approaches to fusion

Magnetic coils:

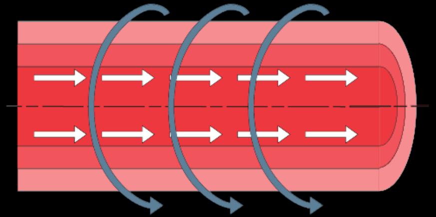
ITER



Inertial confinement:

NIF

Z-pinch fusion: magnetic confinement without magnets

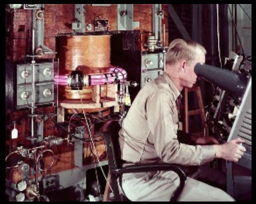


- Electric current moving in "z" direction
- Magnetic field forms around axis
- Field compresses plasma inward (Lorentz force)
- Increasing current increases compression in a compact device without magnetic field coils

Fleming's right-hand rule: thumb points in the direction of current flow, magnetic field squeezes inward

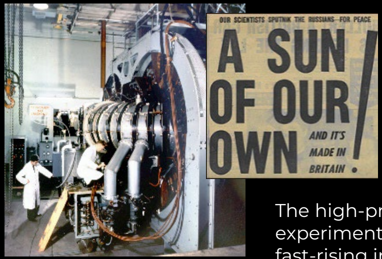
Pollock & Barraclough describe physics of lightning rod crushed by Z pinch

1905



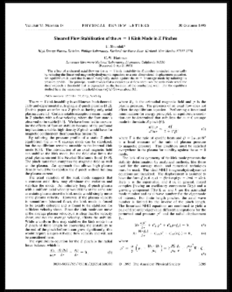
Z pinch is a favored early approach to fusion due to relative simplicity

1950



The high-profile Zeta experiment fails due to fast-rising instabilities

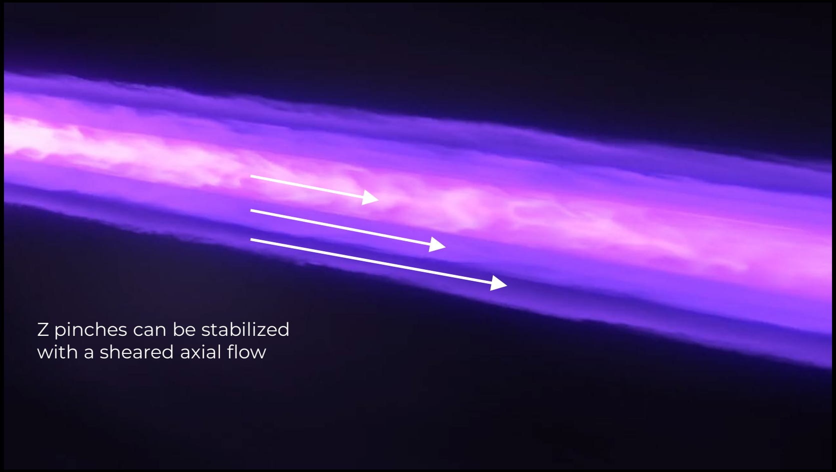
1958

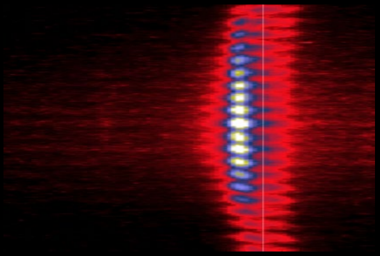


Shumlak's original paper: Sheared Flow Stabilization of the m = 1 Kink Mode in Z Pinches (PRL)

1995

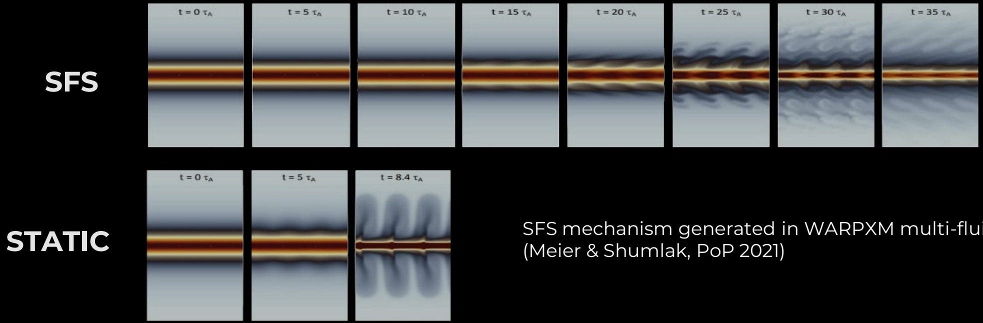
Zap's key innovation: Sheared-flow stabilization





Layers of sheared flow seen via Doppler shift during fusion event (Shumlak et al., PRL 2001)

Sheared flow extends plasma lifetimes manyfold



SFS mechanism generated in WARPXM multi-fluid simulation (Meier & Shumlak, PoP 2021)

Sheared-flow-stabilized Z-pinch fusion has been modeled, experimentally tested and peer reviewed for 27 years.

Recent publications:

- PoP (2019) Tummel et al.
- PRL (2019) Zhang et al.
- FS&T (2019), Forbes et al.
- NIMA (2019), Mitrani et al.
- JoAP (2020), Shumlak
- RSI (2020), Forbes et al.
- PoP (2020), Claveau et al.
- PoP (2020), Stepanov et al.
- PoP (2021), Meier & Shumlak
- PoP (2021), Mitrani et al.
- RSI (2023), Banasek et al.
- FS&T (2023), Thompson et al.

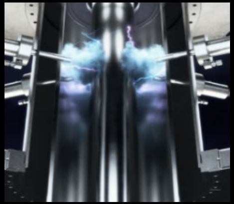
Talks & Presentations:

- Tummel, APS DPP 2018
- Stepanov, APS DPP 2019
- Shumlak, IEEE PPPS 2019
- Mitrani, APS DPP 2020
- Shumlak, JPP 2021
- IAEA 2021
- APS 2021
- EPRI Fusion Forum 2022
- ICOPS 2022

Reactor concept

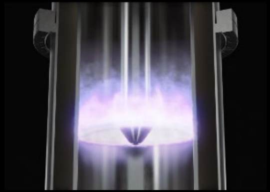
IONIZE

Deuterium–tritium gas injected and ionized into plasma



ACCELERATE

Plasma accelerates down coaxial accelerator

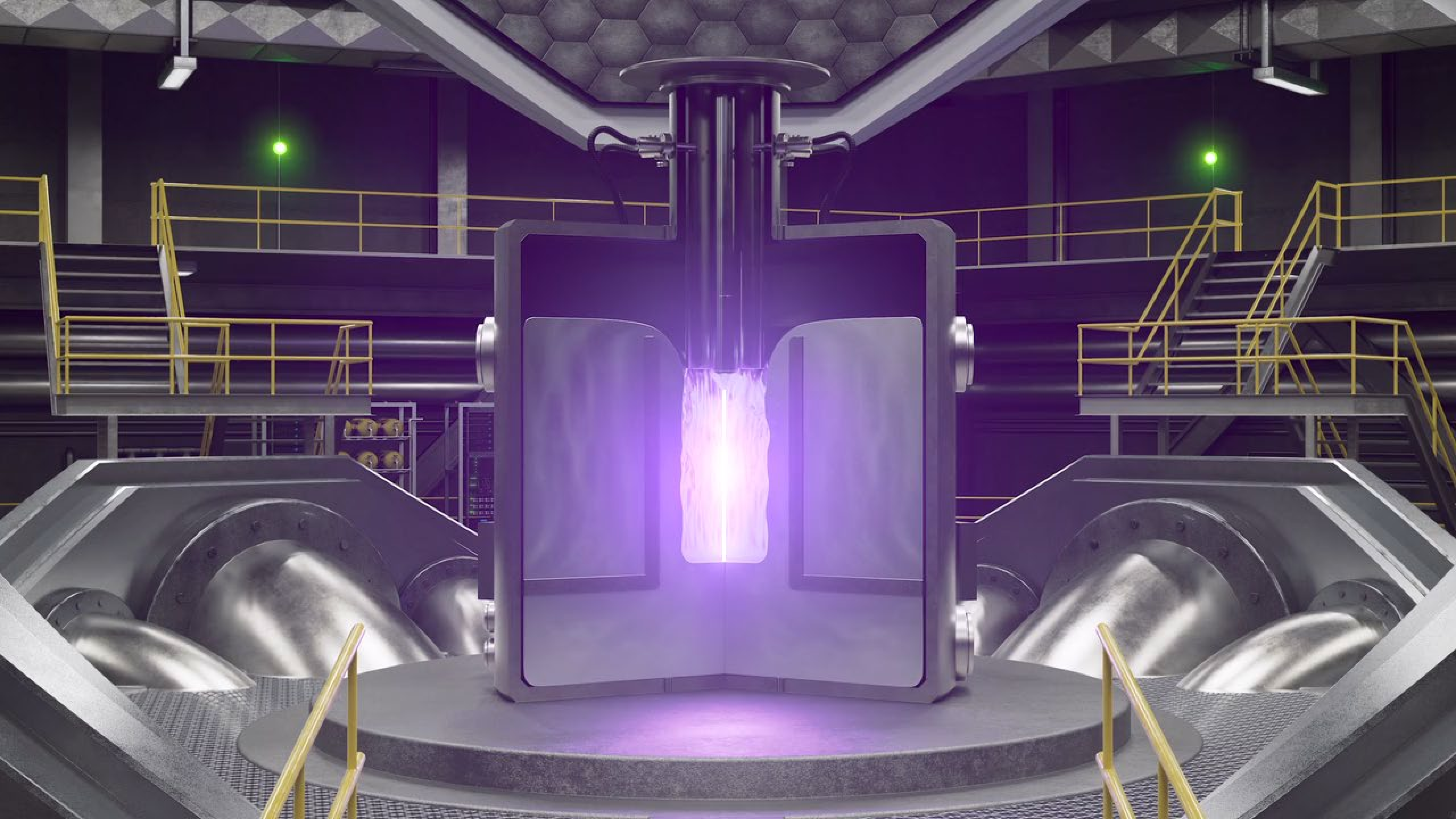


PINCH

Z-pinch plasma column compresses on axis and heats

FUSE

Fusion neutrons (energy) captured in liquid lithium-lead blanket



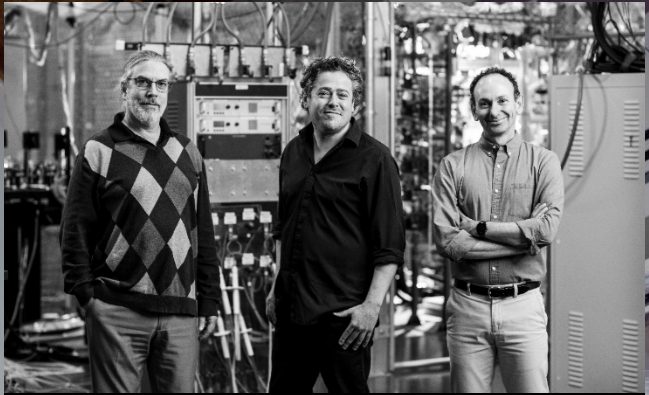
About Zap Energy

- Founded in 2017
- 110 employees with plans to add 40 more this year
- Facilities in Everett and Mukilteo, WA (north of Seattle)
- $200M+ in funding by strategic investors

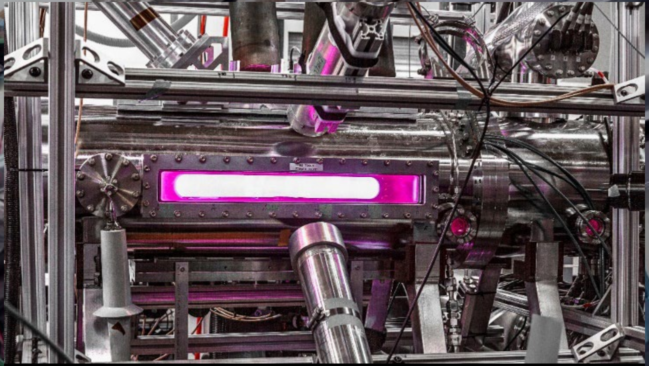
ADDITION — Breakthrough Energy Ventures — LOWERCARBON CAPITAL

Chevron — ENERGY IMPACT PARTNERS — DCVC — VALOR EQUITY PARTNERS — Shell Ventures

- Zap is the only company focused on SFS Z pinch fusion, an approach studied by the University of Washington and Lawrence Livermore National Laboratory dating back to early 1990s



Zap's co-founders (left to right):
Brian A. Nelson, Benj Conway, Uri Shumlak



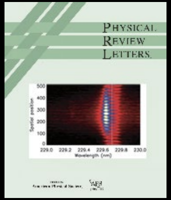
Developing reactor based on a 50-cm filament of plasma

History and milestones

1998

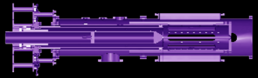
DOE funds initial ZaP experiments at University of Washington ($4.3M)

2001



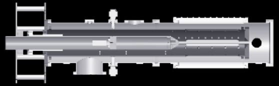
Experiments demonstrate sheared-flow stabilization of a Z-pinch plasma (PRL)

2012



DOE funds 2nd generation ZaP-HD experiments ($1M)

2015



Standout results during ARPA-E funding, 50x performance improvement in 3rd gen FuZE experiments over <4 years

arpa·e

ARPA-E ALPHA program funding ($5.8M)

2017

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Zap Energy is founded by Benj Conway, Uri Shumlak and Brian A. Nelson

2018

arpa·e

ARPA-E OPEN program funding ($6.7M)

2019

Team demonstrates neutron production in a 300kA pinch (PRL)

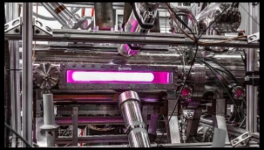
Anchor investor ($2.2M), team moves into facility in Everett, WA

2020

Series A investment led by Chevron ($6.5M)

ARPA-E BETHE program funding ($1M)

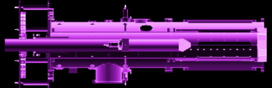
2021



SFS Z pinch thermonuclear fusion confirmed by multiple advanced diagnostics

Series B investment led by Addition ($27.5M), team expands to 2nd facility in Mukilteo, WA

2022

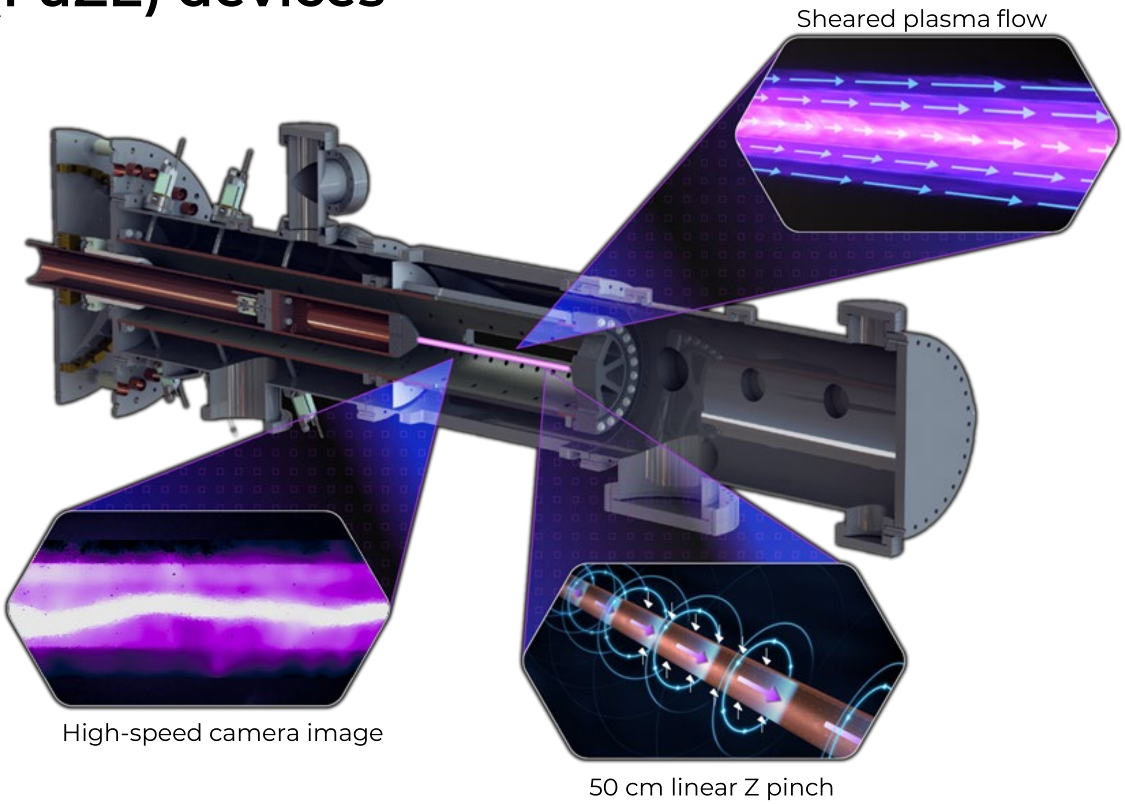


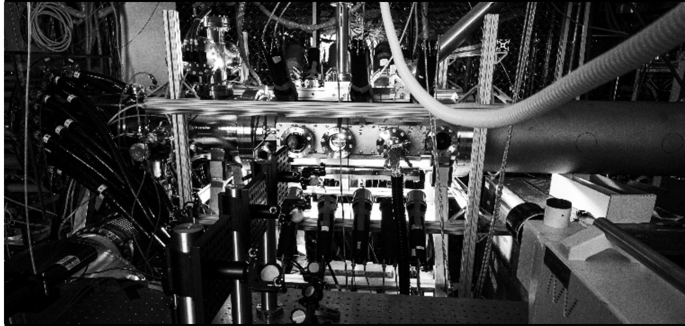
4th gen FuZE-Q turns on:

- First plasmas
- First neutrons
- Commissioned power bank
- Science operations begin!

Series C investment led by Lowercarbon ($160M)

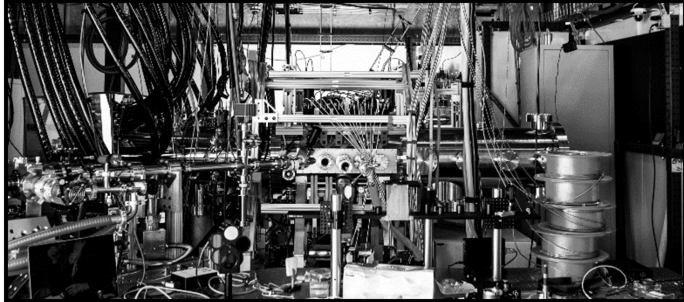
Fusion Z-pinch Experiment (FuZE) devices





FuZE

- Turned on in 2015
- Demonstrated thermonuclear fusion in SFS Z-pinch
- Max current ~ 500 kA
- Upgrading to FuZE-II

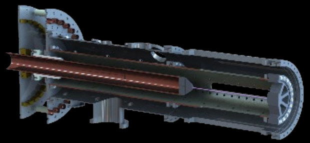


FuZE-Q

- Turned on in 2022
- Custom-built for scientific breakeven (Q=1)
- Advanced power supply, fuel valves, materials, diagnostics
- Max current ~ 1 MA

SFS Z-pinch plasmas lead to better power plant economics

Size of Reactor	~25 m^3 core size
Complexity	No magnets, cryogenics or lasers
Iteration Speed	Single-year cycle
Fuel	Deuterium-tritium
Neutron Damage	No solid first wall, resilient liquid metal design
Plant Design	Modular, factory-built cores

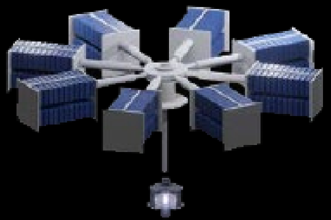


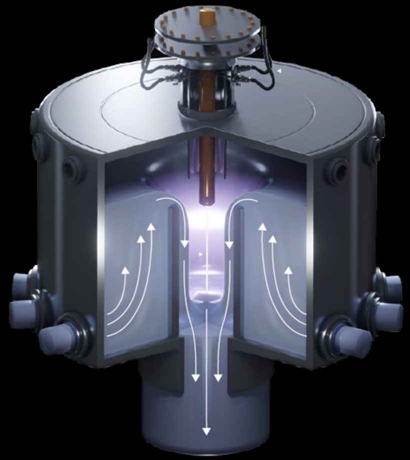
R&D Prototype

System Demonstration

Commercial Reactors

Parallel development underway towards demonstration reactor





HIGH REP-RATE PULSED POWER

- Reactor design based on 10 Hz pulsed power supply
- Each reactor targets 200 MWth, ~40-50 MWe yield
- First-generation advanced power system began operations December 2022

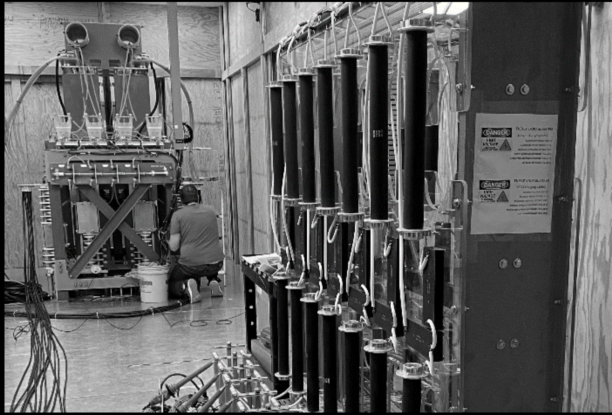
CIRCULATING LIQUID METAL

Resilient lithium-lead metal wall design is durable against extreme conditions, minimizes core maintenance and serves multiple key functions

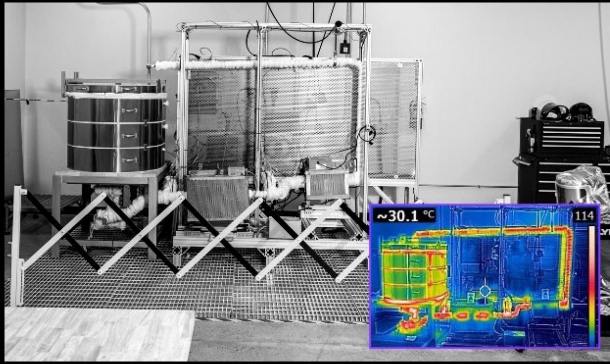
- Heat transfer medium
- Tritium fuel production
- Renewable plasma facing surfaces
- Neutron shielding

SYSTEM INTEGRATION AND PILOT PLANT DESIGN

- Adopt system engineering approach to deal with complexities and uncertainties
- Early design integration is key
- Preliminary plant safety assessments provide guidance to design directions
- Programmatic risk assessments to inform technology maturation priorities

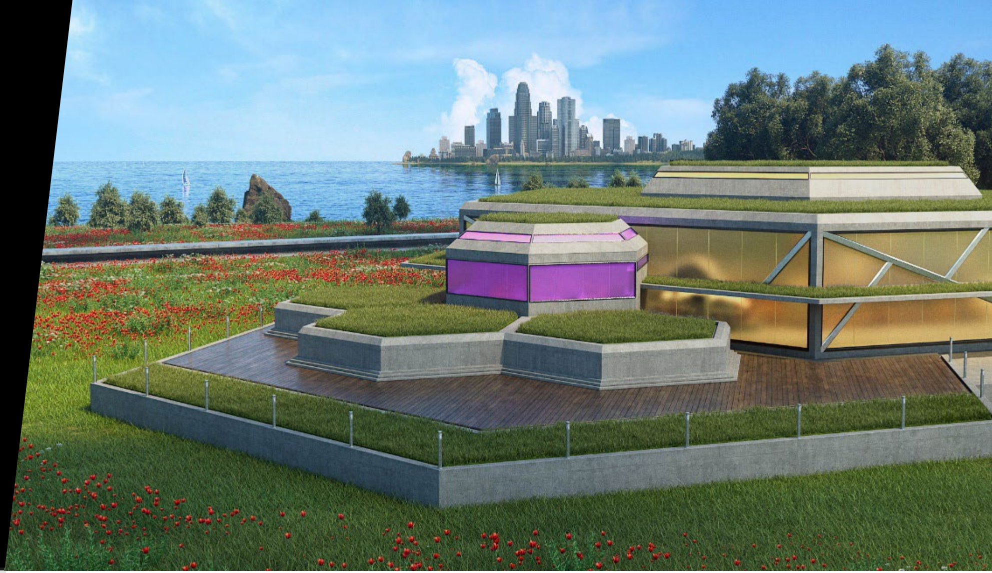


First-gen advanced power source subsystem



Circulating liquid metal test stand

Rapid iteration and de-risking



INTEGRATED DEMONSTRATION

Targets:

- Subsystem integrations
- High repetition rate operations
- Tritium operations
- Reactor-relevant gain
- Heat transfer
- Plasma-materials interactions (erosion / embrittlement)
- Neutron shielding / activation (rad safety)
- Closed tritium cycle (breeding and extraction)

PILOT PLANT

Targets:

- Capital cost estimate for first commercial plant
- Operations cost estimate (skill level of workers, automation and maintenance procedures)
- Manufacturability, operability, reliability, maintainability
- Licensing and hazard management
- Activated material handling and disposal

Retrofitting for fusion?

A landmark Zap-led study, in collaboration with power provider TransAlta, will assess the benefits of siting a Zap fusion energy pilot plant at Washington's only remaining coal power station. In evaluating the feasibility of reusing retired fossil fuel plants for fusion, the project will have three main areas of focus:

CONCEPTUAL DESIGN DRAWINGS

The team will draw up preliminary designs of a fusion plant and subsystems that are integrated and configured in such a way that they match the constraints of the existing site.

ENVIRONMENT & SAFETY SURVEYS

Zap will revisit prior plant safety reviews and assess what information would be needed for fusion plant environment and safety approvals

STAKEHOLDER ENGAGEMENT

The project team will undertake outreach and education efforts with decision-makers, stakeholders and interested community members from Lewis County in order to estimate levels of support or resistance.

Compact scale creates added flexibility for end-uses

Short-transmission, grid-scale power generation

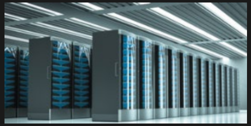
Brownfield power plant conversion

Firm power for load-balancing renewables

Microgrid energy for remote sites and energy resiliency

Industrial process heat supply

Clean hydrogen production



Sustainable and secure data centers

Military installations and other strategic defense applications

Regulatory Landscape and Recent Progress

U.S. NUCLEAR REGULATORY COMMISSION

NRC must ensure the safety and security of commercial fusion energy devices

- NRC staff recommendation is to first regulate fusion energy as byproduct materials (NOT fission plants)
- Similar framework to what is used for particle accelerates and wide-area irradiators

STATE-LEVEL HEALTH AND SAFETY OFFICES

States manage fusion R&D regulations. Zap Energy is licensed for radioactive materials, air emissions and radiation-producing devices.

UNITED KINGDOM

U.K. decided Environment Agency and Health and Safety Executive are the regulators for fusion (NOT the Office for Nuclear Regulation).

INTERNATIONAL ATOMIC ENERGY AGENCY

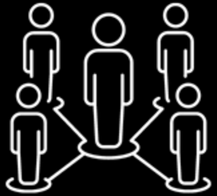
IAEA has begun to develop international fusion safety and security guidance.

AMERICAN SOCIETY OF MECHANICAL ENGINEERS

ASME has begun the process of developing codes and standards for safety components in future fusion plants.

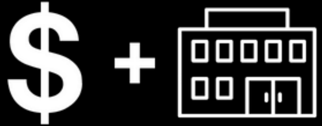
Government Policies & Incentives

Fusion development has the attention of the White House. March 2022 summit announced a “Bold Decadal Vision” to arrive at a fusion pilot plant and recommended $1B for fusion programs in 2024 budget.



U.S. Dept. of Energy established a fusion coordinator who reports to the Under Secretary for Science and Innovation.

Workshop held last June to help formulate a milestone-based public-private partnership program. $50M funding opportunity was released in Sept 2022 (but fusion industry can support a $500M program).

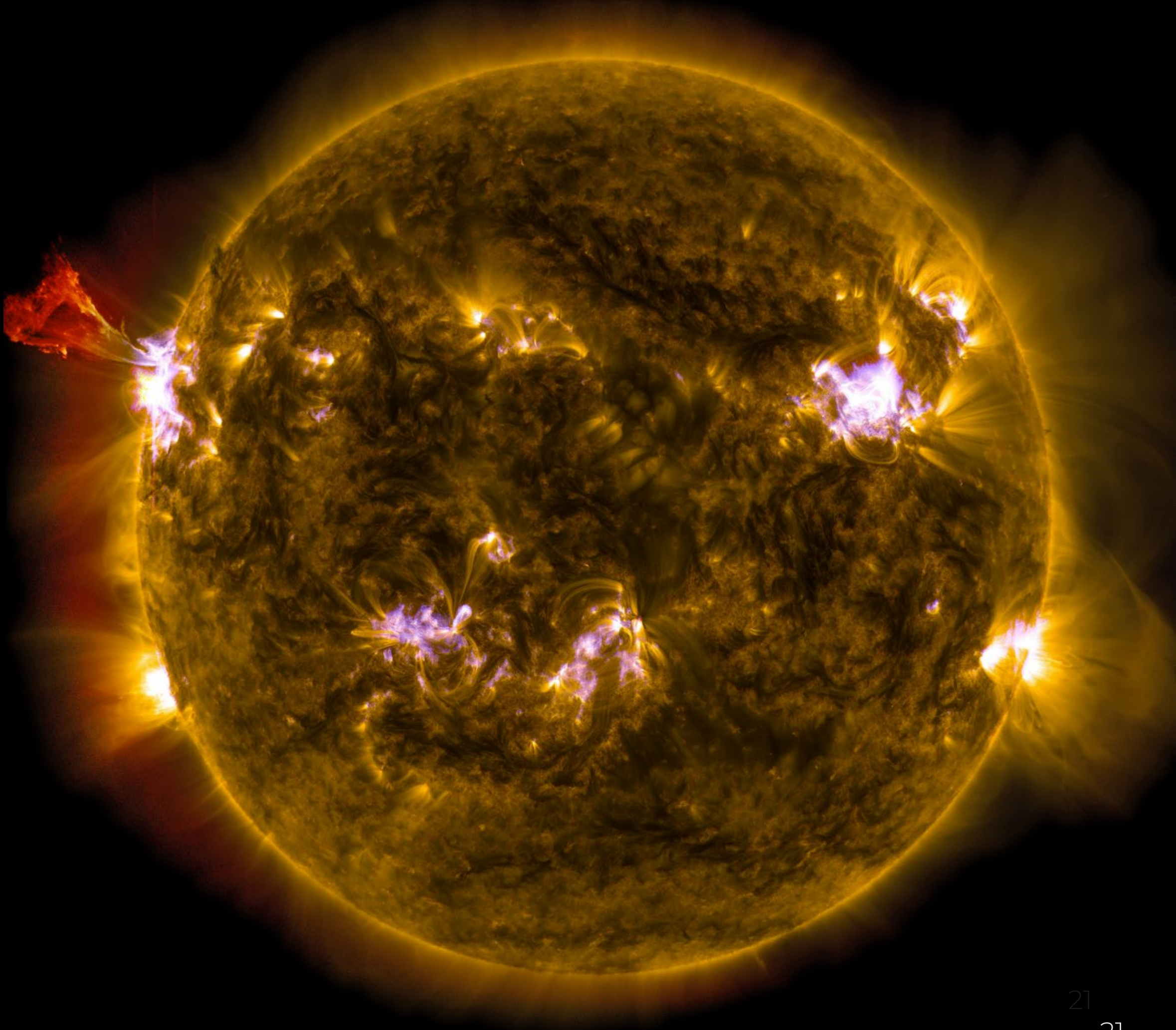


Inflation Reduction Act includes $280M for fusion facilities. Community interest in a Fusion Prototypic Neutron Source to help with materials development.

Inflation Reduction Act includes clean electricity incentives with bonuses for U.S. manufacturing and brownfield siting. Up to $0.0312 / kWh credit for clean electricity production or up to 50% tax credit on upfront capital.

Beyond non-dilutive capital, Zap derives value from government’s power to convene and coordinate.

Summary



Fusion is a necessary part of our future energy supply

Fusion progress is accelerating on both the technology and commercialization fronts

Zap Energy holds promise to be the fastest, cheapest fusion energy

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