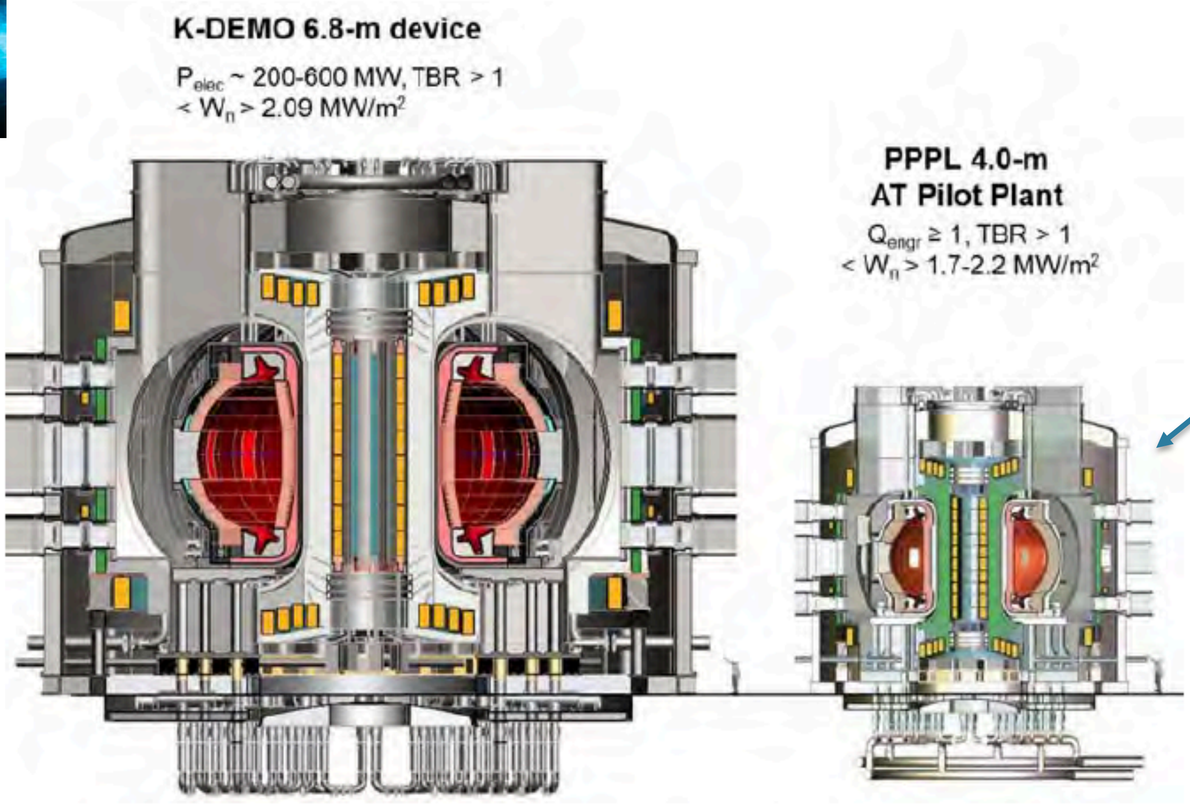
Introduction to Fusion Part 2.

Steve Cowley,
PPPL

National Academy of Sciences calls for Pilot Plant by 2040/50 Community Planning Process 2019-20



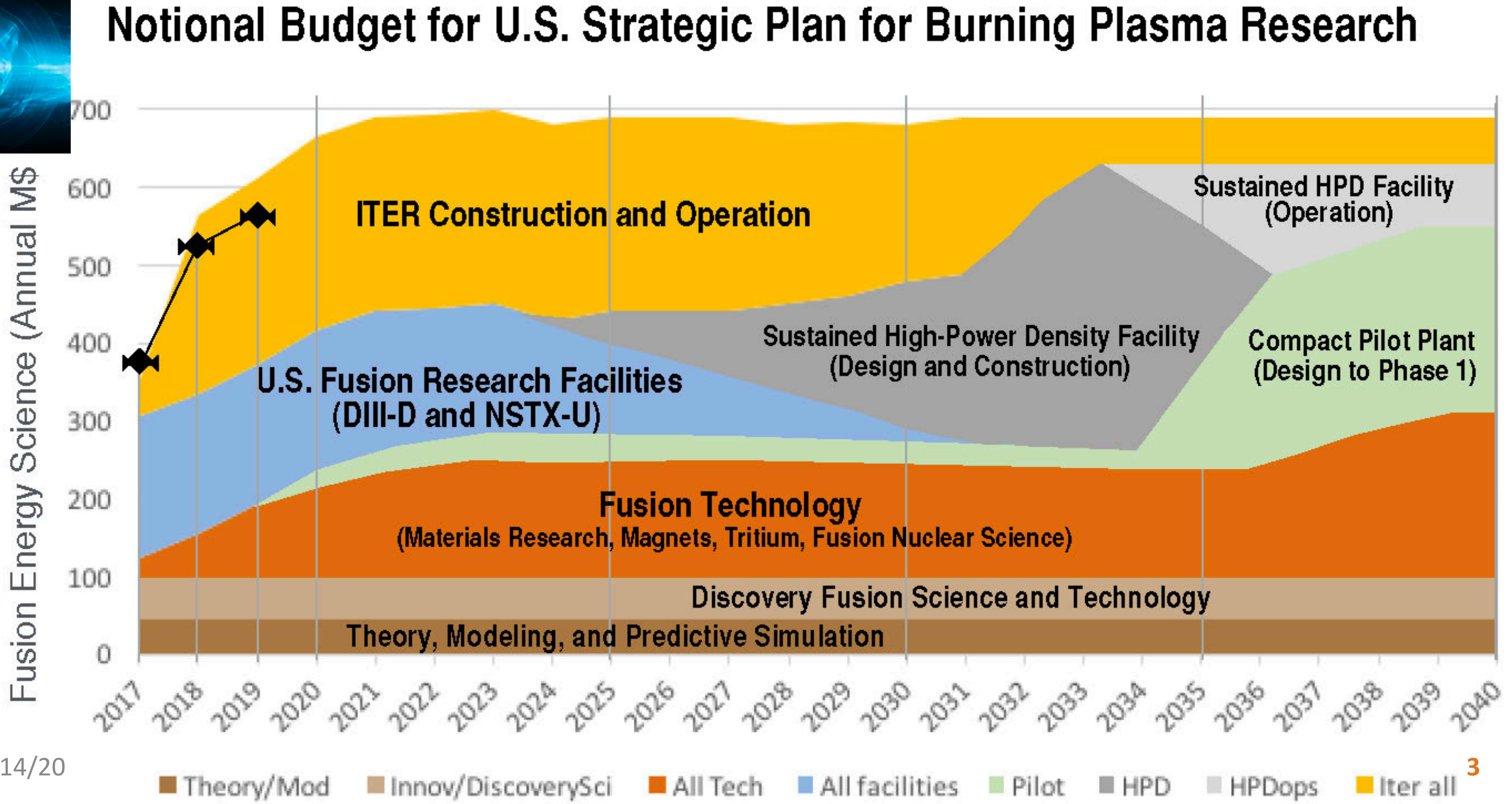
High field compact Designs from **MIT** "SPARC" – "ARC"

And this **Princeton** one shown in NAS report.

High T_c at ~ 20^0 Superconductors ~25T on coil

Tom Brown, Jon Menard PPPL

National Academy Review



Cost of plant – Simplistic Rule of Thumb

Empirical fit to the machines/experiments that have been built

$$\$ \propto R^2(1 + c_1 B + c_2 B^2)$$

Constants?

This formula results from the cost of engineering not the cost of stuff (steel, tungsten, niobium etc.). I think it is misleading. >60% of cost is from coils, power supplies, cryogenics

SIMPLICITY MATTERS

Must add the cost of Balance of Plant – in fission this is > 80% of the cost. It depends critically on the thermal output of the fusion system

Can we make it smaller and cheaper?
What sets the size?

DIII-D Shot 121717

GYRO Simulation

Cray X1E, 256 MSPs

Thanks to Ron Waltz, Geoff Candy

Energy Confinement -- Random walk of heat/particles.

N random turbulent steps to leave machine

Eddy size ρ_i – Larmor radius

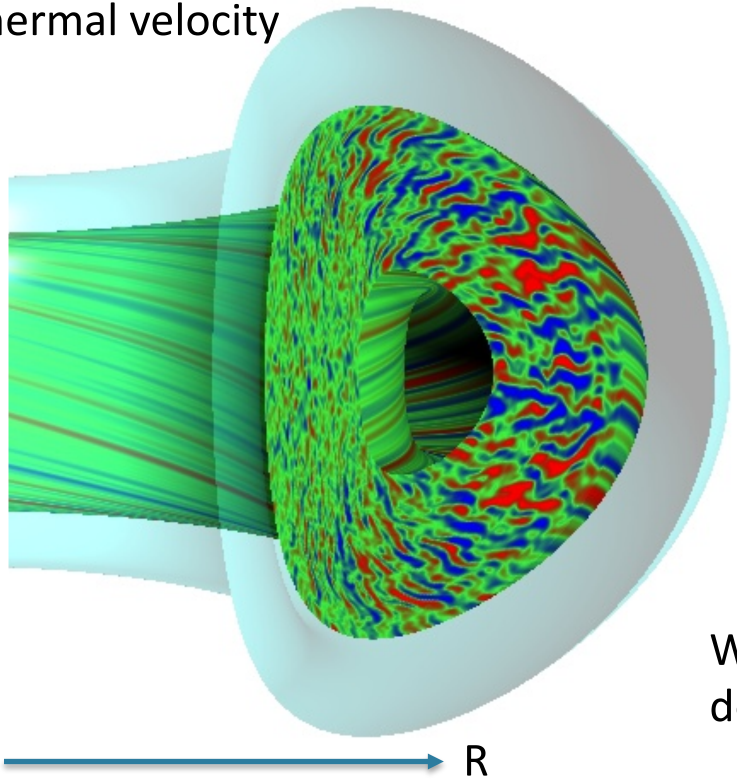
V_{thi} = ion thermal velocity

See Saskia Mordijck's lecture tomorrow

$$R \sim \sqrt{N}\rho_i \rightarrow N \sim (\frac{R}{\rho_i})^2$$

For ITER N ~ 10^6.

Eddy turnover time = $\tau_{eddy} \sim \frac{R}{v_{thi}}$



$$\tau_E = N\tau_{eddy} \propto B^2 R^3 T^{-3/2}$$

Work at constant temperature the community defines an enhancement factor H such that

Ignoring subtleties of the geometry

$$\tau_E \propto H^3 B^2 R^3$$

Burning

$$\mathcal{P}_\alpha = \frac{energy\ \ density}{\tau_E} = \frac{3P}{2\tau_E} \qquad self\ \ heated$$

$0.018P^2$

CONDITION TO BE SELF HEATED

$$P\tau_E > 10(atmopsphere,\ \ s) \quad \text{“}Lawson\ Triple\ Product\text{”}$$

$\tau_E \propto H^3 B^2 R^3$ / $P = 4\beta B^2$

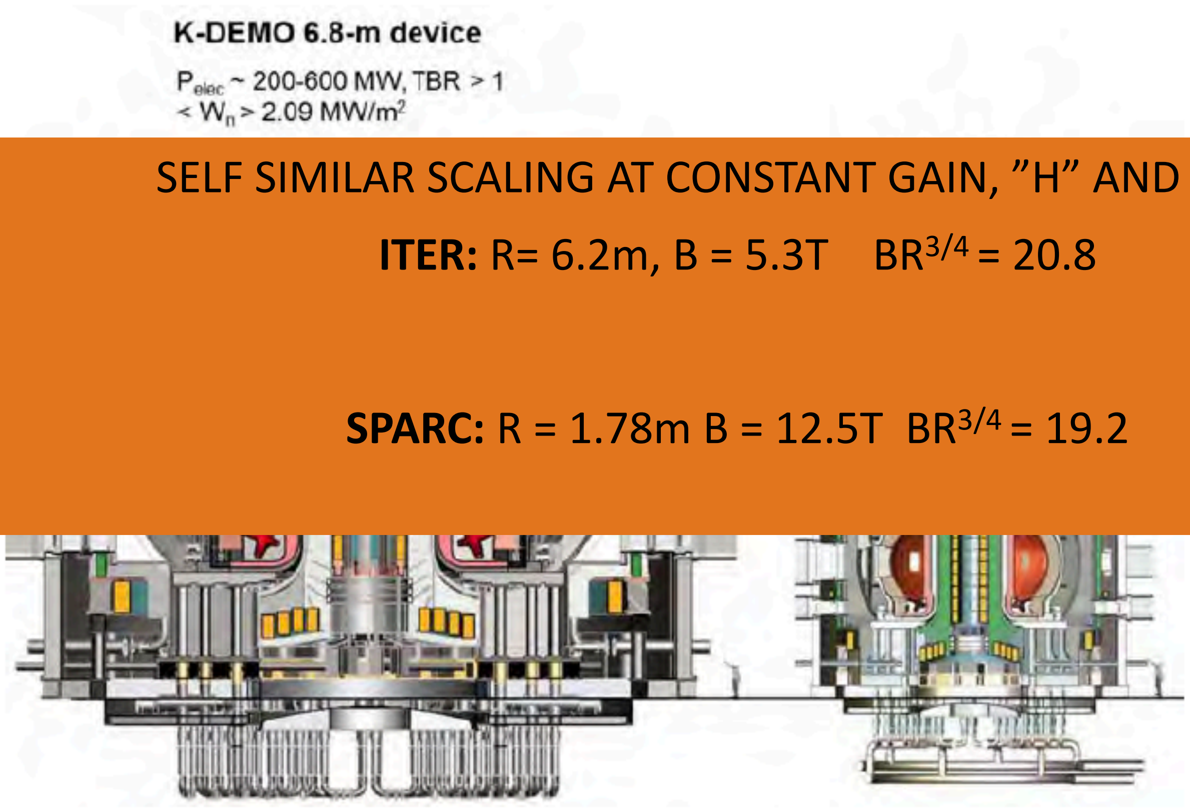
$$\beta H^3 B^4 R^3 \geq constant$$

H and beta depends on shape profiles etc. Physics!

SCALING FOR SELF SIMILAR TOKAMAKS

$$(\beta^{1/4} H^{3/4})\ BR^{3/4} \geq constant$$

National Academy of Sciences calls for Pilot Plant by 2040/50



High field compact

C”

SELF SIMILAR SCALING AT CONSTANT GAIN, ”H” AND SHAPE

ITER: R= 6.2m, B = 5.3T $BR^{3/4}$ = 20.8

SPARC: R = 1.78m B = 12.5T $BR^{3/4}$ = 19.2

High T_c at ~ 20^0
Superconductors
~25T on coil

Tom Brown, Jon Menard PPPL

Self Similar Power and Stored Energy

$$\beta H^3 B^4 R^3 = constant$$ IGNITED DEVICE

FUSION POWER FROM DEVICE = $$\mathcal{P}_{Fusion} \times Volume \propto \beta^2 B^4 R^3 \propto \frac{\beta}{H^3}$$

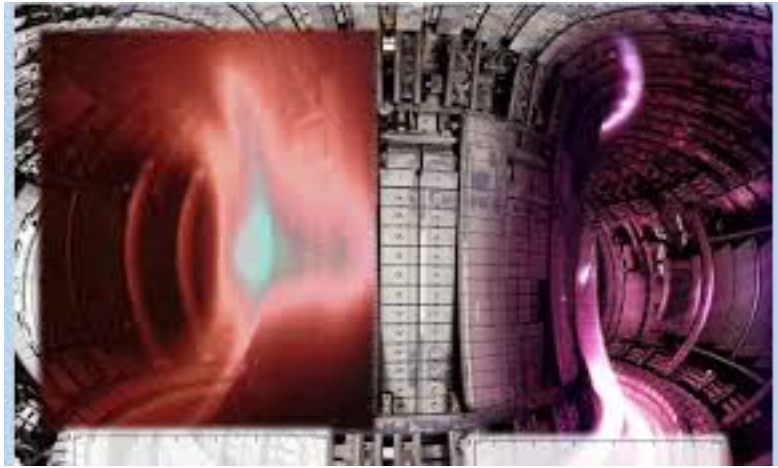
Total power essentially independent of size/field
Small high field devices have large heat fluxes

ENERGY STORED IN PLASMA: $$\mathcal{E}_{Total} = 1.5P \times Volume \propto \beta B^2 R^3 \propto \frac{\beta^{1/2} R^{3/2}}{H^{3/2}}$$

Use scaling

Disruption

Sometimes the plasma becomes unstable and deposits its energy on the wall (often as relativistic electrons) this is called a disruption



Disruption energy per unit area of wall

$$\propto \frac{\beta^{1/2}}{H^{3/2} R^{1/2}}$$

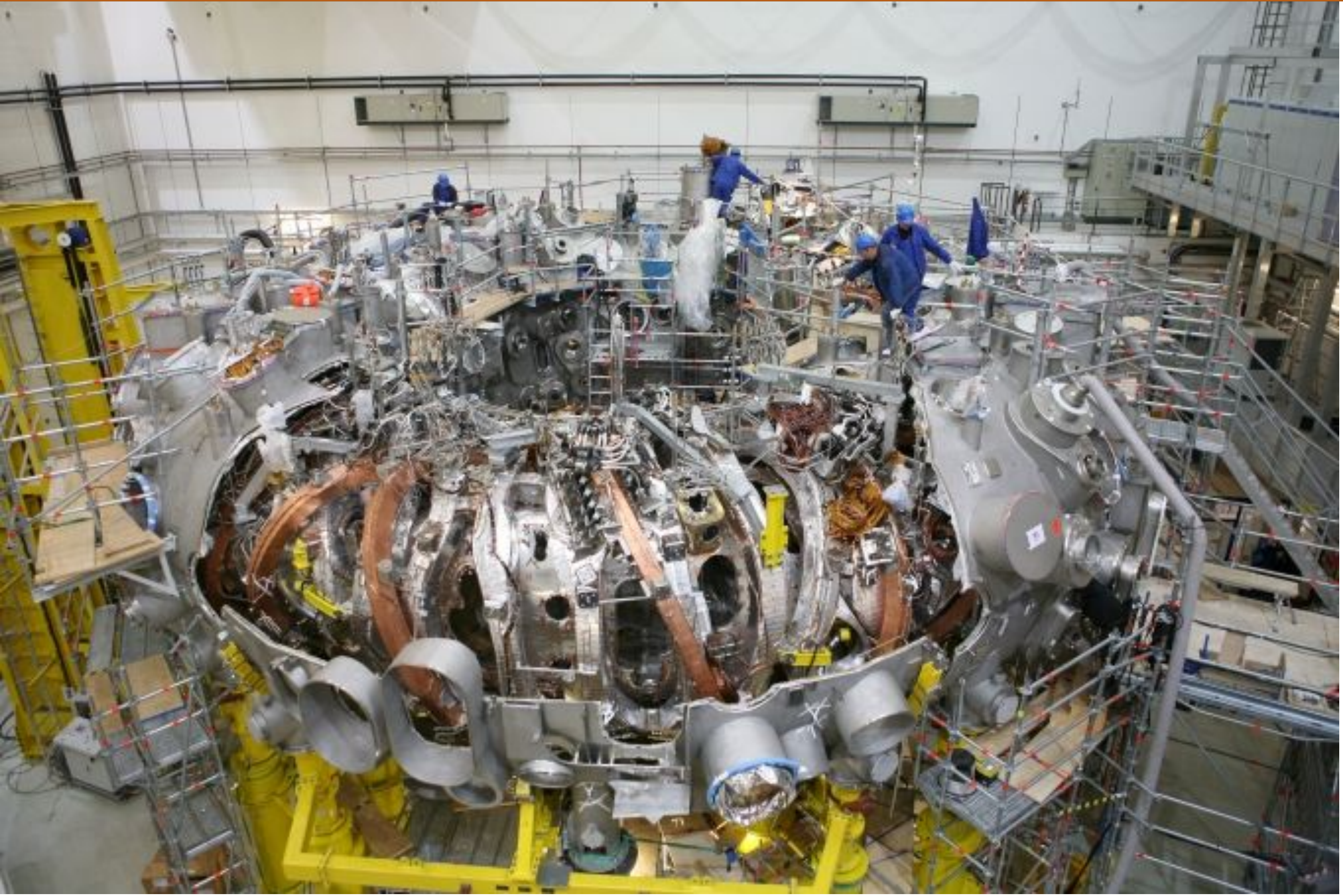
Worse in smaller high field machines

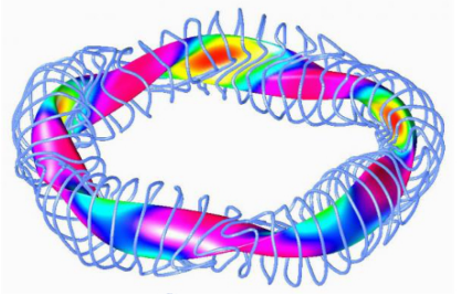
Machine learning being used to predict the Disruption and avoid it.

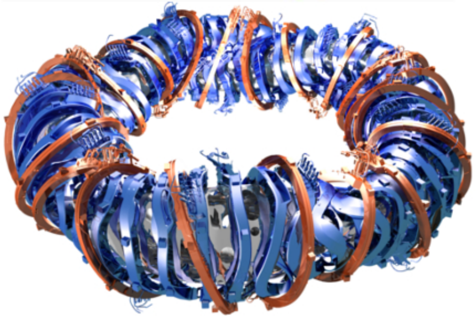
Most disruptions driven by the plasma current.

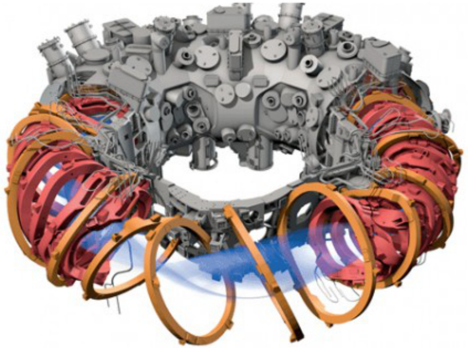
Or 3D? No Plasma Current.

Stellarator – is 3D better?

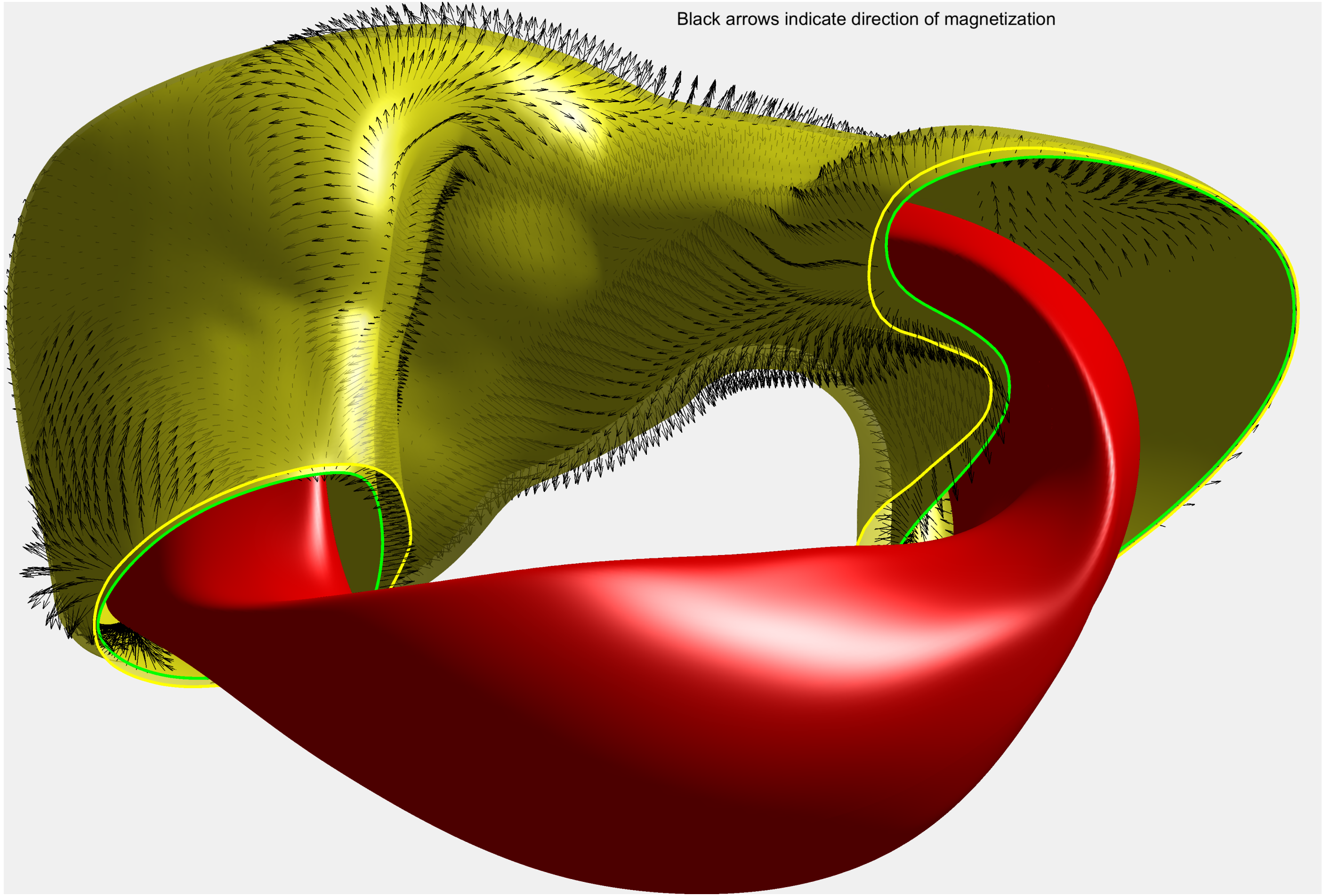








Innovation – permanent magnet stellarator – Gates, Zarnstorff, SC



Perfect Energy?

Safe, no waste legacy, abundant, minimal land use. But……

Development is not optional

We must push down the cost and scale if we are to get to market.

Thank you