Perspective on Reversed Field Pinch (RFP) Fusion Research

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"Innovative Confinement Concept" research yields multiple benefits

- Three synergistic elements of ICC research:
  - Invent solutions to fusion's scientific and technical challenges
  - Grow predictive science for fusion plasma systems
  - Advance basic plasma science, especially experimental

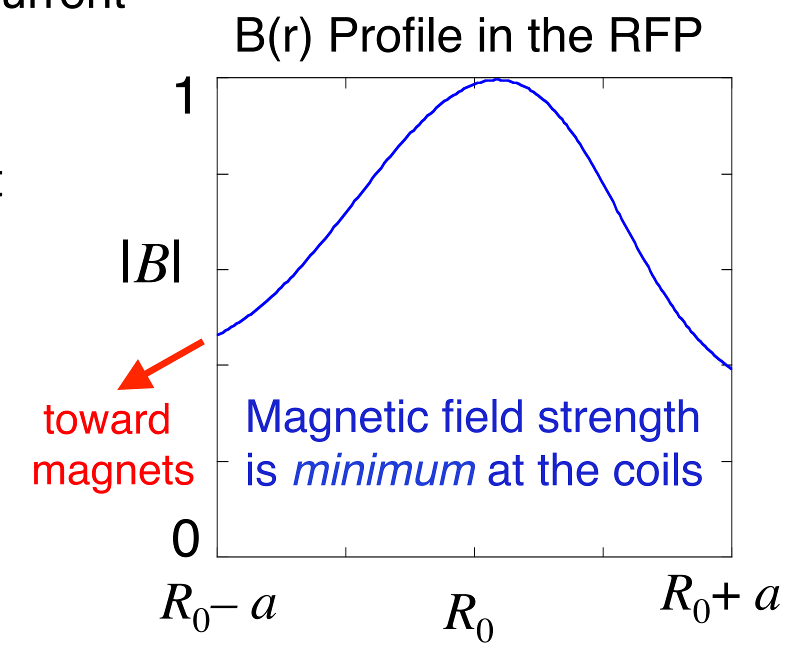
- Represents a significant portion of experimental high temperature plasma research at universities/colleges. On-site experiments remain very attractive to students and deans.

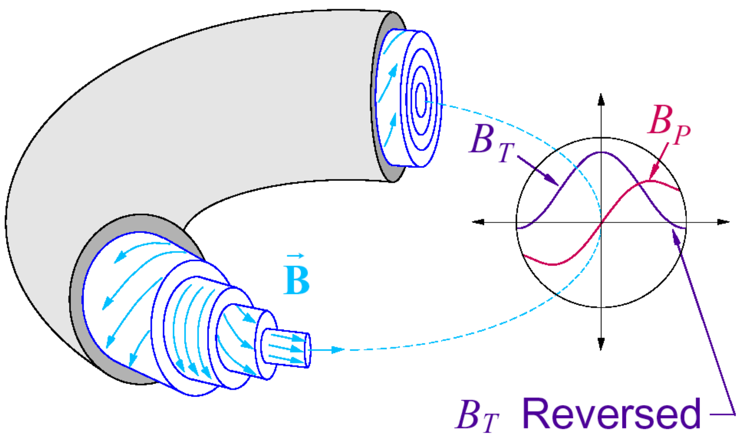
- The ICC community is discussing how to strengthen its role, e.g.,
  - Expanding scope to include areas like HEDLP and materials research experiments
  - New organizational title instead of "Innovative Confinement Concepts"
  - Turnover of the annual workshop program committee, including a new chair (Mike Brown, Swarthmore)
  - Suggestion for NRC-sponsored workshop on basic plasma science

The RFP's distinguishing features could greatly facilitate the reliability and maintainability of a fusion power core

- Magnetic field generated primarily by plasma current
- Small field at the magnet coils
- Possibility for ohmic heating to ignition, without auxiliary heating apparatus facing the plasma
- High beta and high density limits

- Key scientific issues:
  - Confinement at high current
  - Current drive (steady-state or attractive pulsed scenario)
  - Self-consistent plasma-boundary interface
  - Plasma termination dynamics





The RFP's distinguishing features could greatly facilitate the reliability and maintainability of a fusion power core

Why might this be important?

Example: What if RF antennas struggle adjacent to a steady-state 2.5 GW fusion plasma?

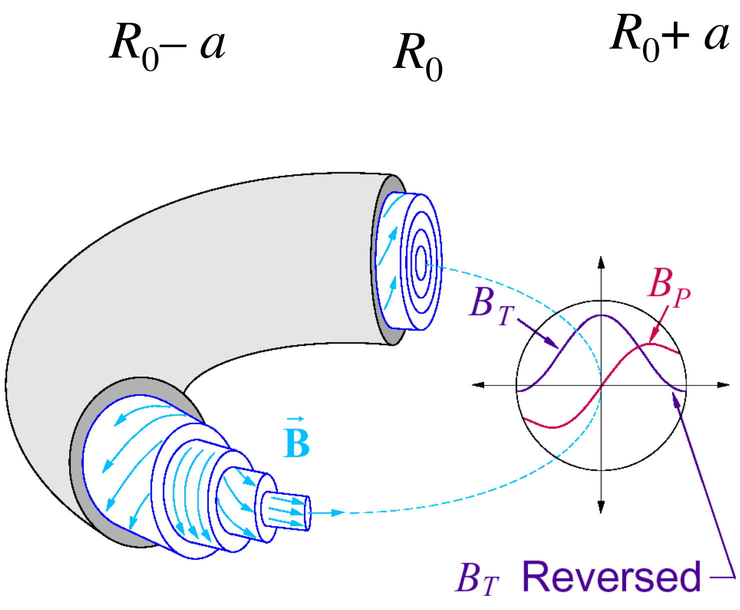
Ohmic heating is efficient and nearly invisibly crosses smooth material boundaries. It's available in large quantity at low safety factor, $q \sim B_t / I_p$ (which the RFP explores)

– Confinement at high current

– Current drive (steady-state or attractive pulsed scenario)

– Self-consistent plasma-boundary interface

– Plasma termination dynamics

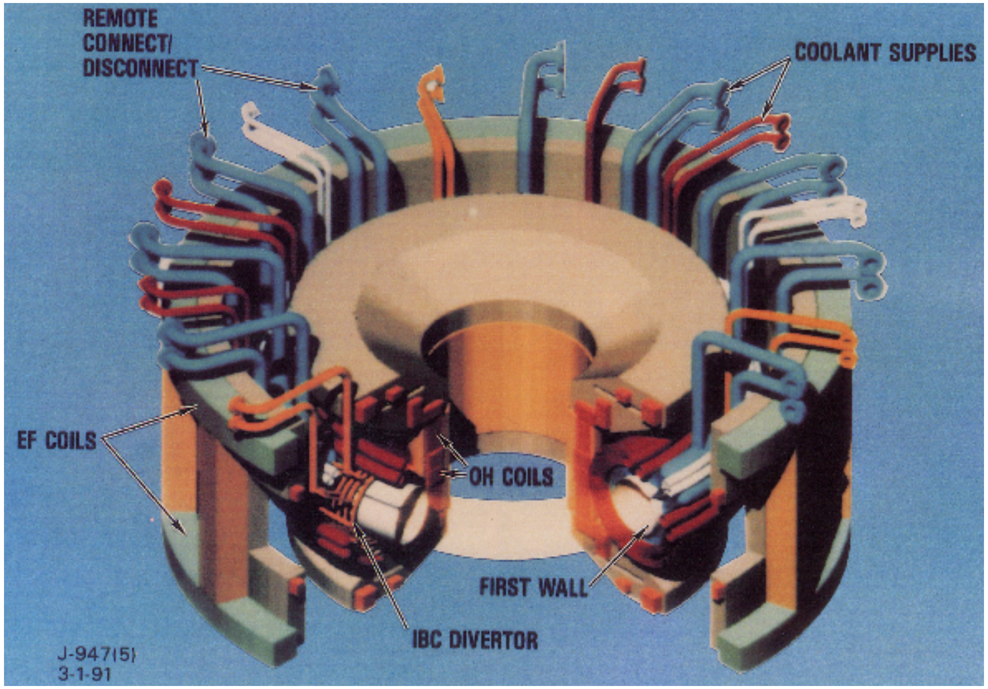


Since 1990, the TITAN reactor study has defined the RFP fusion vision, but it more generically represents the compact limit

- There is nothing fundamental about the RFP that demands compactness
- TITAN exercise lends credence to several attractive features, e.g,
  - Steady-state induction, via oscillating field current drive
  - Ohmic ignition
  - Single-piece maintenance
  - Low cost-of-electricity

TITAN Parameters

- a = 0.6 m, R = 3.9 m
- I = 18 MA
- β_θ = 23%
- 2300 MW fusion
- 18 MW/m^2 neutrons
- 4.6 MW/m^2 radiation



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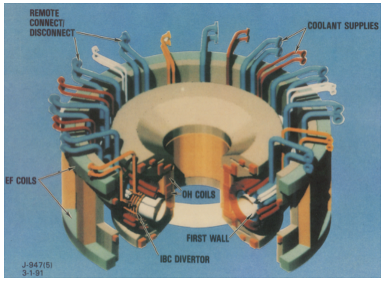
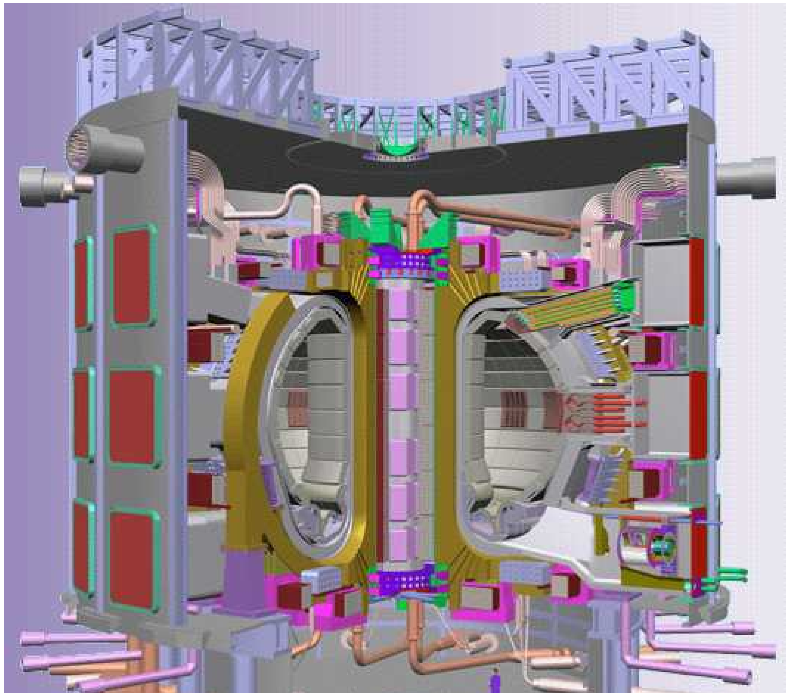
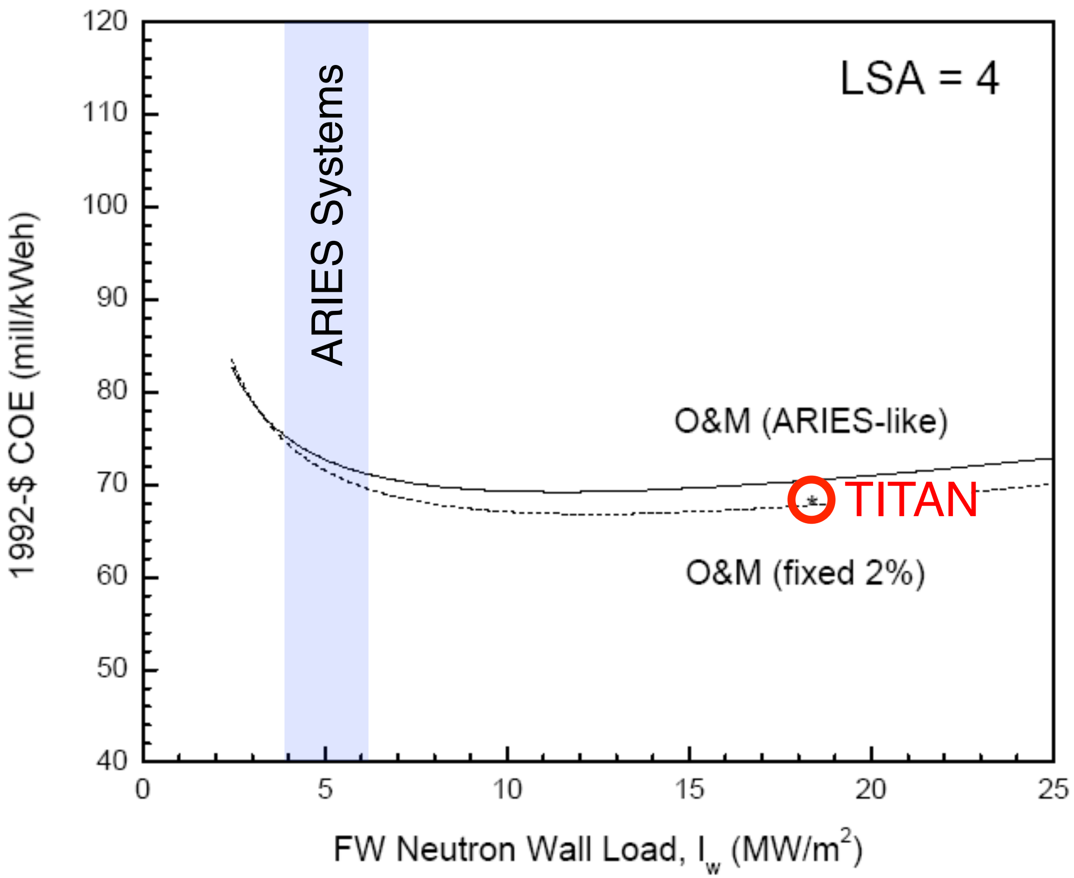




TITAN analysis indicates cost-of-electricity varies weakly above a threshold wall loading $P_n / A \sim 5$ MW/m^2

- Threshold in COE understood to be the point where the plasma minor radius is comparable to the blanket thickness



For “bottom line,” the RFP does not need to be so compact

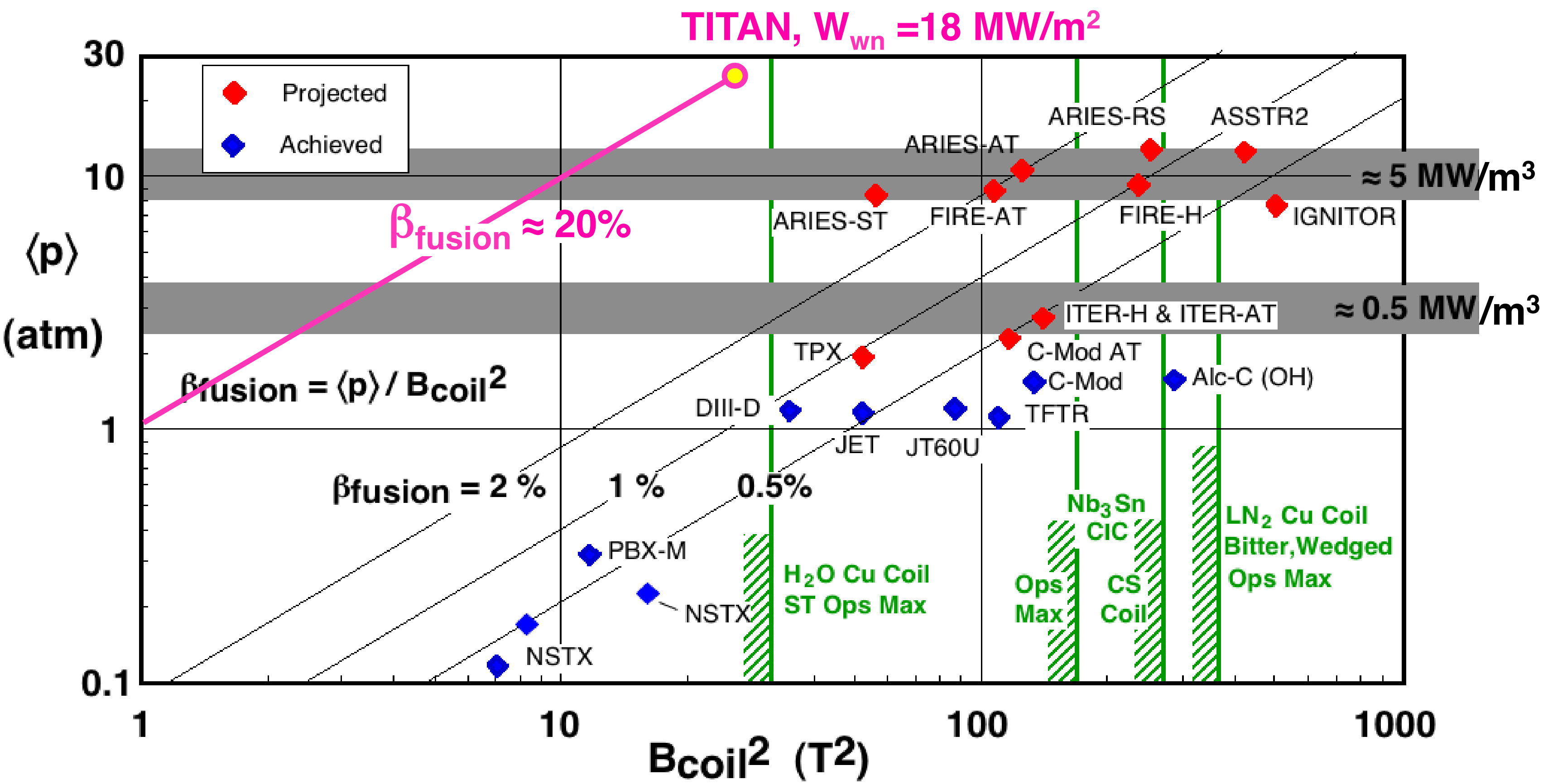
Physics and engineering requirements tend to be less demanding for a larger plasma

Update by Ron Miller, Decysive Systems

Low applied field for the RFP allows shielded copper magnets, if beneficial for reliability and maintainability

- Low B_T configurations have naturally large fusion beta $\beta_{fusion} \sim \langle p \rangle / B_{coil}^2$

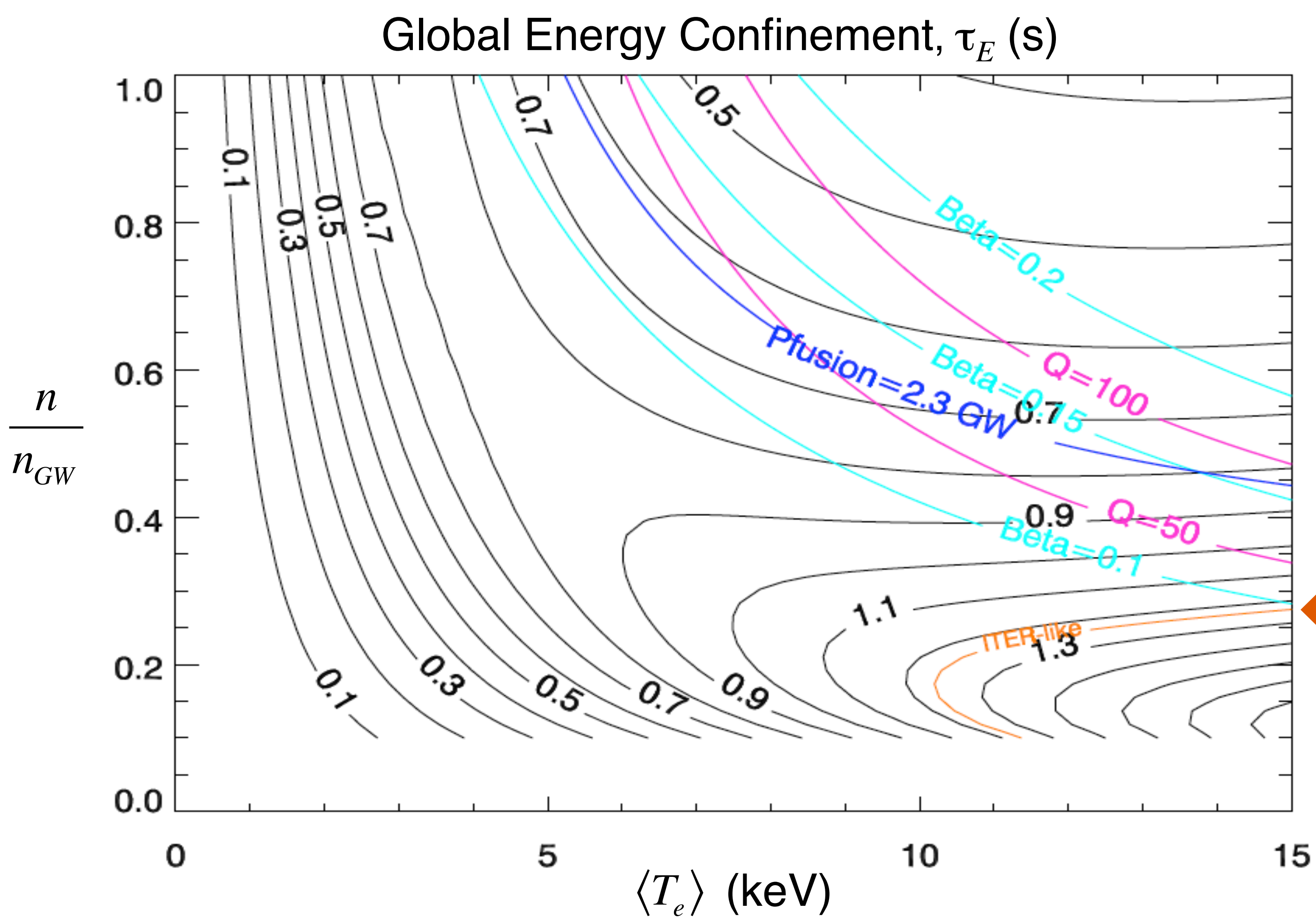
$\langle B \rangle \sim \frac{(P_{fusion}/A)^{1/4}}{\langle \beta \rangle^{1/2}}$ comparable to an advanced tokamak, but $\frac{B_{coil}}{\langle B \rangle} \sim \frac{1}{2}$ for the RFP



From FESAC “Priorities, Gaps and Opportunities: Towards a Long-Range Strategic Plan for MFE”

Lawson-like analysis indicates ohmic ignition is possible if energy confinement is similar to that in a tokamak

- Example: a =1.5 m, R/a=4, I_p = 30 MA, $\langle B \rangle$=5.6 T, B_{coil} ~ 3 T, P_n/A ~ 5 MW/m^2
- 1D profiles similar to present-day RFP assumed



"ITER-like" means scaled as $\tau_E \sim \kappa a^2$

Physics-based scaling for transport in a stochastic magnetic field

- Test particle expectation for parallel streaming in a stochastic field

$$\chi \sim v_{th} D_m \sim \sqrt{T}\, L \left(\tilde{B}/B\right)^2$$

- Magnetic fluctuations in the RFP originate from MHD tearing instability, for which the Lundquist number, $S = \tau_R / \tau_A$, is the key dimensionless parameter

Anticipate a scaling $\tilde{B}/B \sim S^{-\alpha} \longrightarrow \chi \sim T^{1/2} a\, S^{-2\alpha}$

- Zero-D power balance for ohmic heating: $T \sim a^{\frac{1+2\alpha}{3-3\alpha}} I_p^{\frac{1+\alpha}{3-3\alpha}} (n/n_{GW})^{\frac{-(1+\alpha)}{3-3\alpha}}$

- MST and RFX trends for standard confinement (excl. improved via profile control)

$T_e(0) \sim I_p^{0.67} (n/n_{GW})^{-0.5}$ (MST)

$T_e(0) \sim I_p^{0.69} (n/n_{GW})^{-0.31}$ (RFX)

$T_e(0) \sim I_p^{0.93} (n/n_{GW})^{-0.35}$ (RFX-Mod w/CMC)

$$T \sim a^{5/6} I_p^{2/3} (n/n_{GW})^{-2/3}$$

for α = 1/3

(see also measured $\tilde{B}$ and MHD computation)

Ohmic ignition in the RFP does not demand complete suppression of stochastic transport

- Example: a =1.5 m, R/a=4, I_p = 30 MA, $\langle B \rangle$=5.6 T, B_{coil} ~ 3 T, P_n/A ~ 5 MW/m^2
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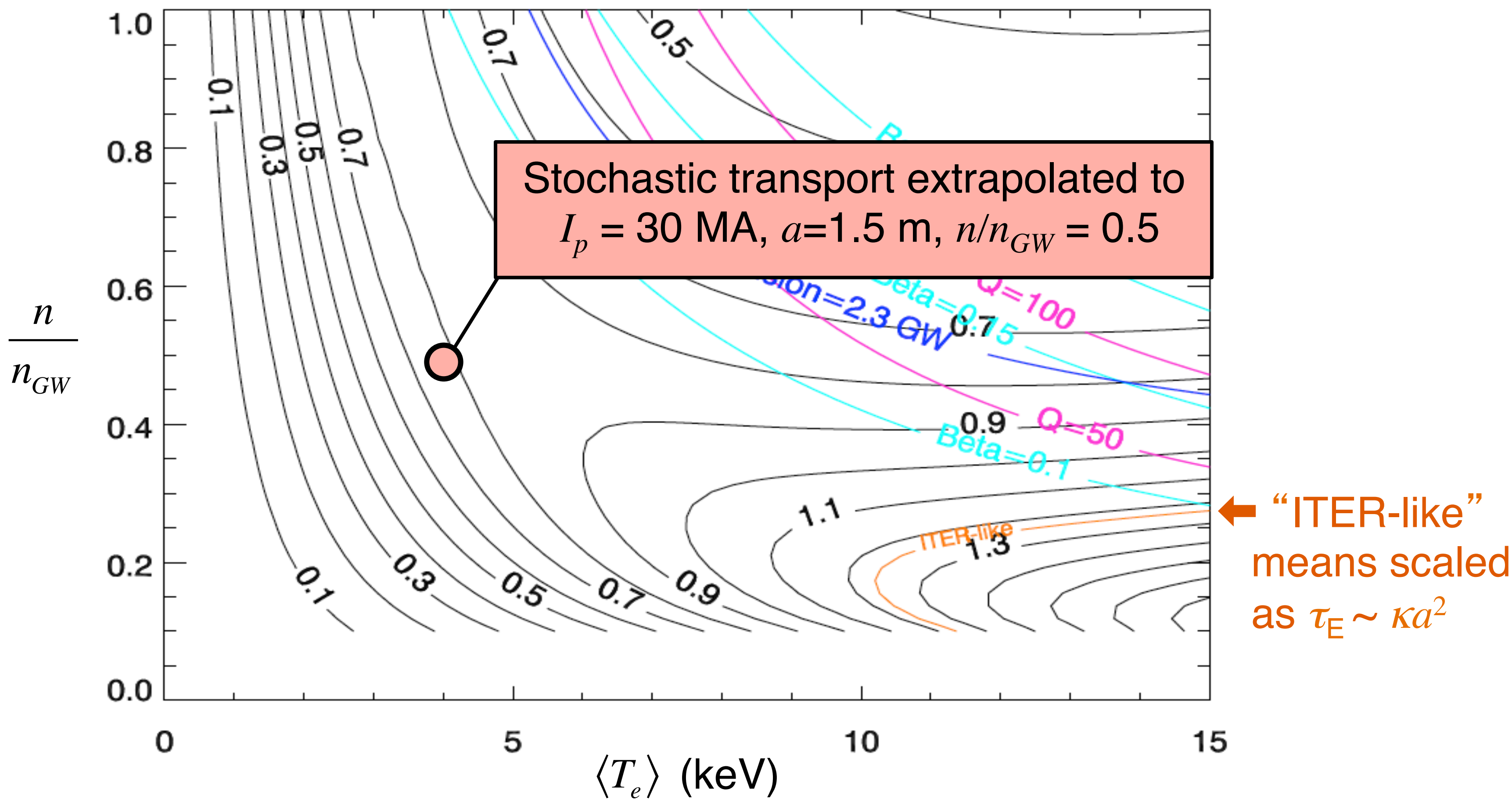
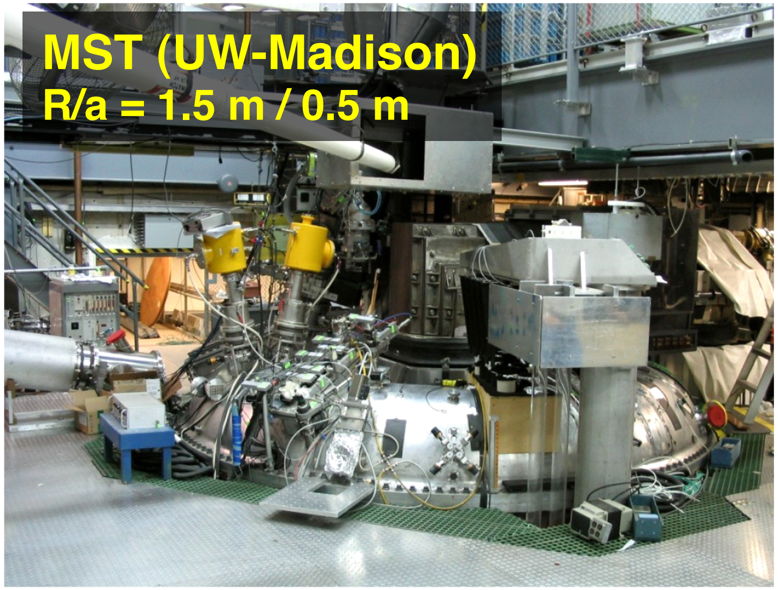
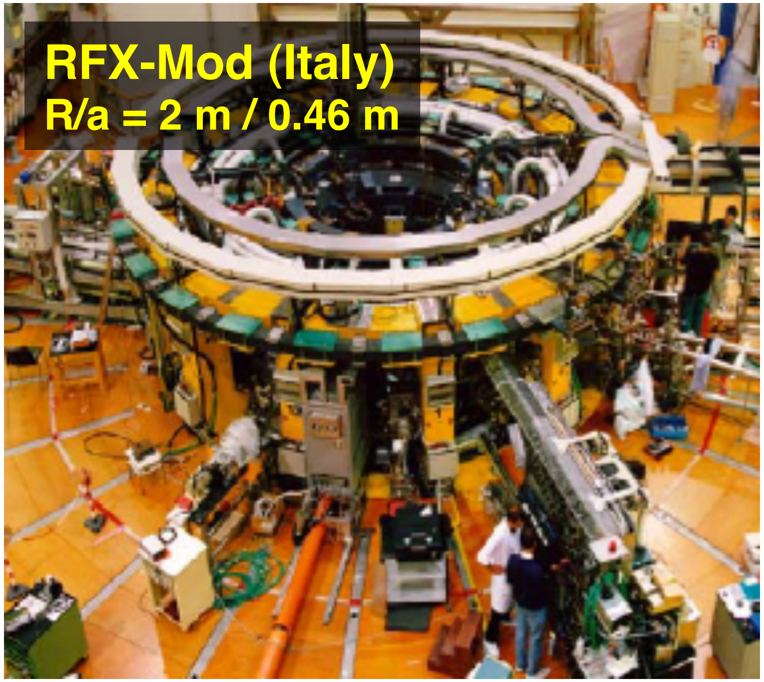
Global Energy Confinement, τ_E (s)

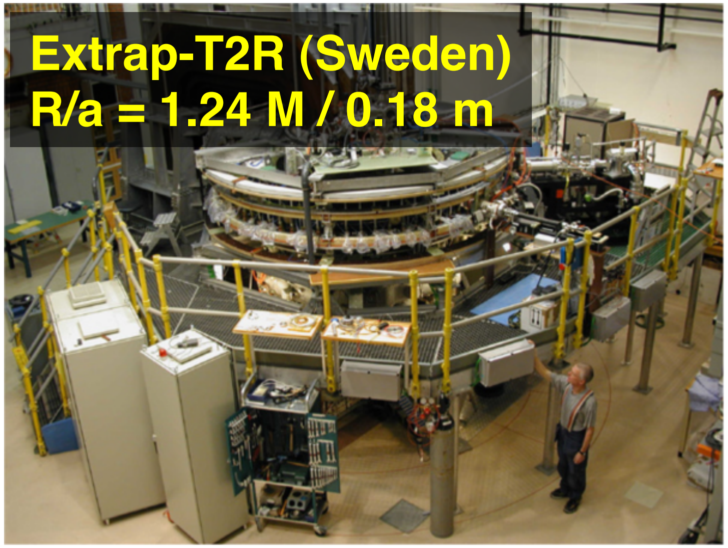


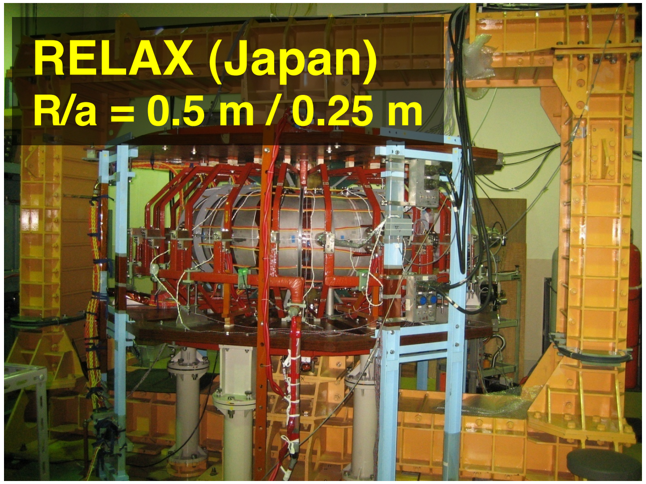
Some recent RFP results

Present RFP experiments







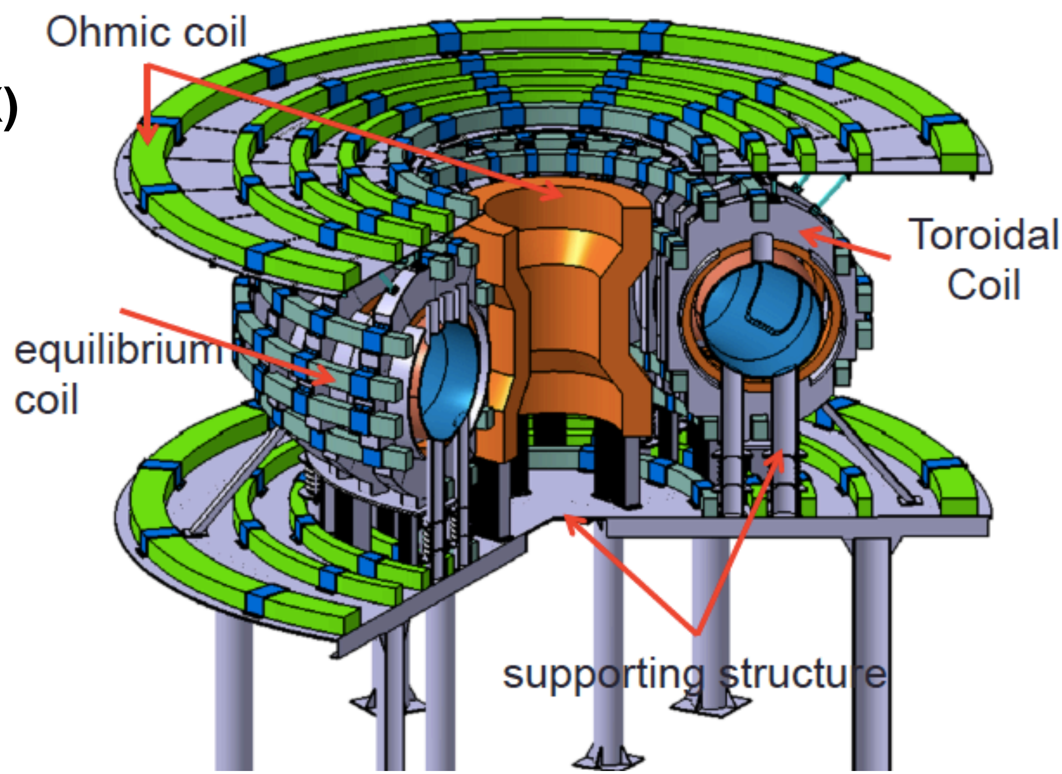


A new RFP program in China established this year at the University of Science and Technology, Hefei

- Shell system suitable for plasma-boundary studies, e.g., lithium
- Advanced active mode control (Phase 2)
- Advanced inductive current drive and 3D physics in helical state
- Collaboration with EAST team on the design and construction
- Goal for 1st plasma in 3 years

Keda Toroidal Experiment (KTX)

R = 1.4 m
a = 0.4 m
I_p = 0.5-1 MA



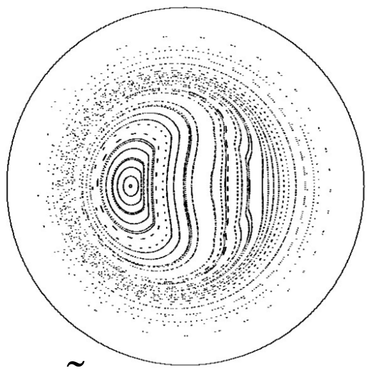
Spontaneous helical equilibrium creates stellarator-like plasmas in RFP experiments

- Growing collaborations with the stellarator community, e.g., opportunity to develop 3D equilibrium reconstruction methods and tools
- MST/RFX diagnostic sets well-suited for this: interferometry/Faraday rotation, MSE, 2-color SXR, Thomson scattering, etc

Magnetic Island

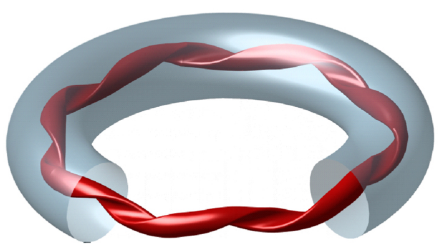
$$\frac{\tilde{B}_{helical}}{B} = 2\%$$

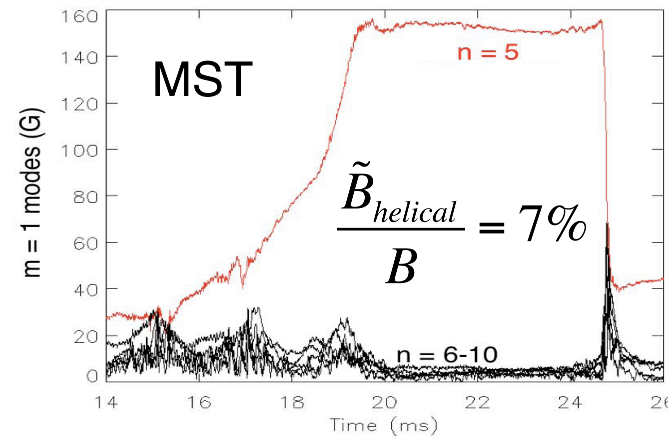
Helical Equilibrium



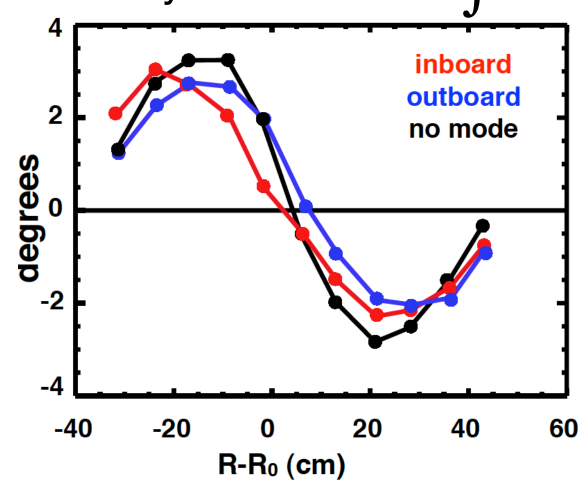
$$\frac{\tilde{B}_{helical}}{B} = 5\%$$

RFX





Faraday Rotation $\Psi^{\circ} \sim \int n\mathbf{B}\cdot\mathbf{dl}$



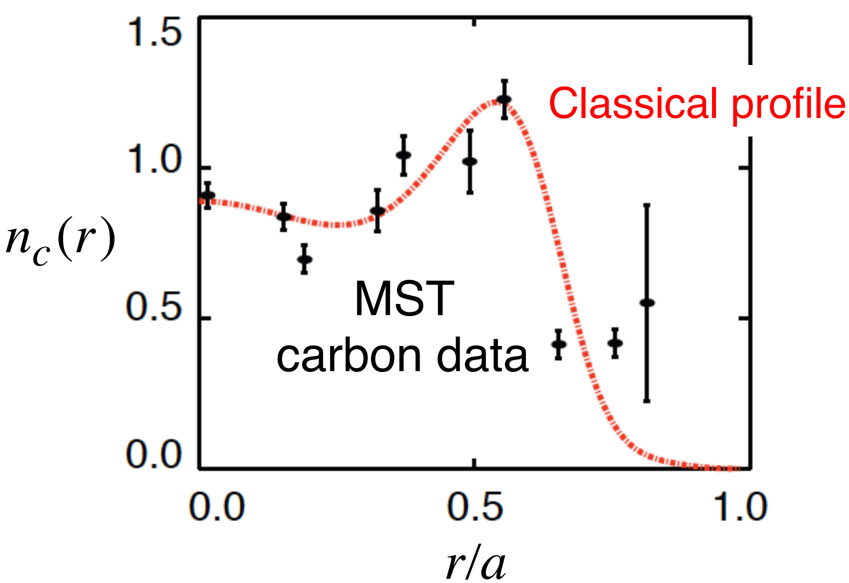
Classical confinement of impurity ions in MST plasmas

- The "neoclassical" enhancement of perpendicular transport is small in the RFP, e.g., the banana orbit width is less the the gyro-radius
- Energetic ions also behave classically (with new 1 MW neutral beam injector)
- Explores basic physics of toroidal magnetic confinement

Classical Transport

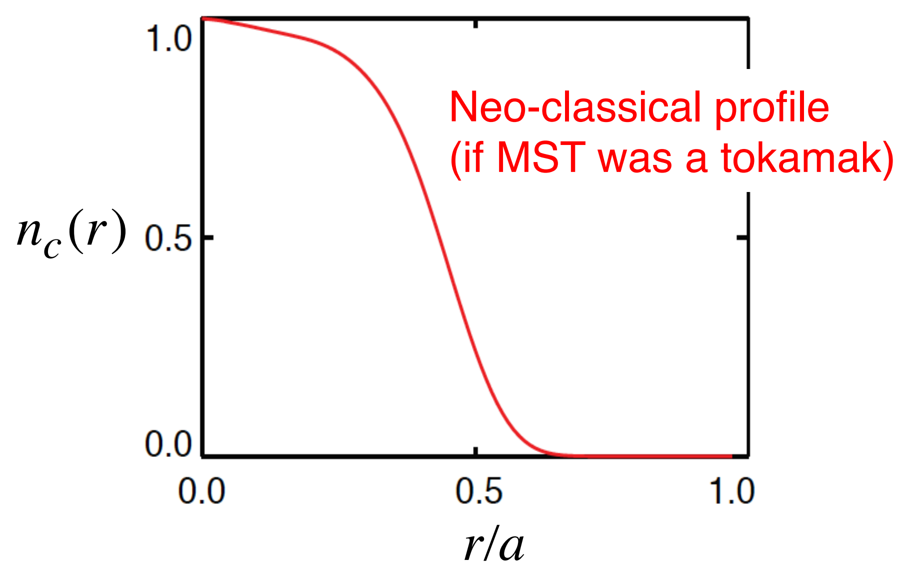
$$\frac{n_Z(r)}{n_Z(0)} = \left[\frac{n_i(r)}{n_i(0)}\right]^Z \left[\frac{T_i(r)}{T_i(0)}\right]^{-0.5Z-1}$$

"temperature screening"



Neo-classical Transport

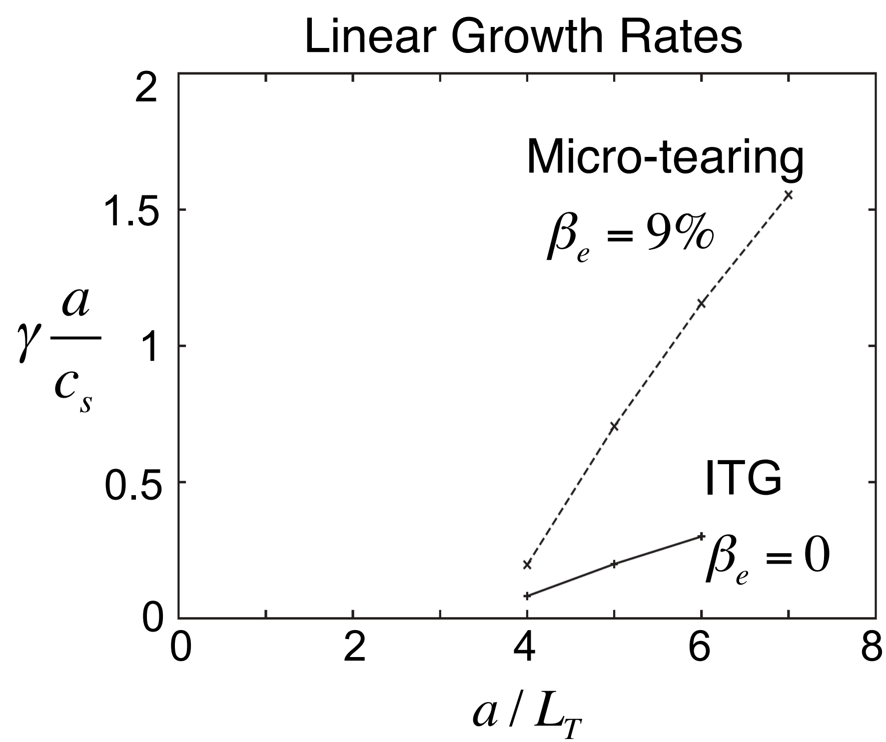
$$\frac{n_Z(r)}{n_Z(0)} = \left[\frac{n_i(r)}{n_i(0)}\right]^Z \left[\frac{T_i(r)}{T_i(0)}\right]^{1.5Z}$$



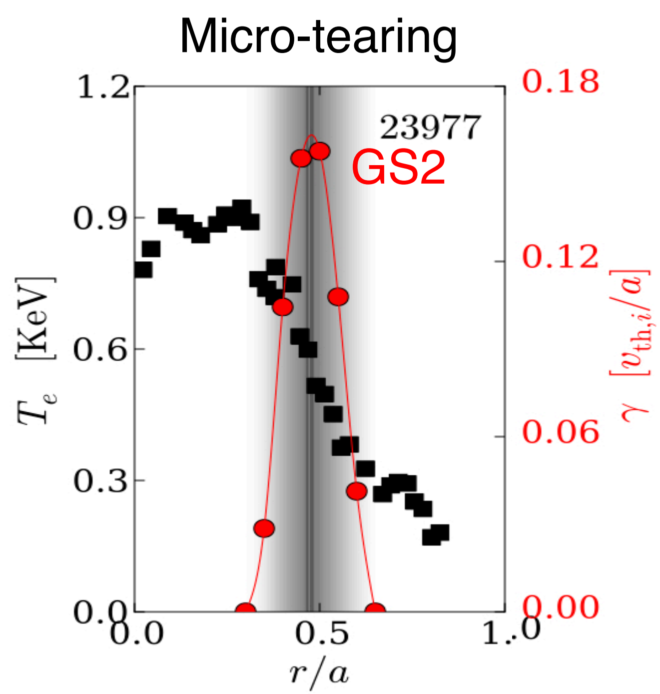
S.T.A. Kumar et al

Micro-turbulence in the RFP an emerging story

- Differences relative to high B_T equilibria:
  - Larger critical gradient, scales with minor radius
  - Mode structure not localized to outboard side of torus (less ballooning)
- Micro-tearing at high beta similar to recent analysis for the spherical tokamak



GYRO, Carmody, Terry

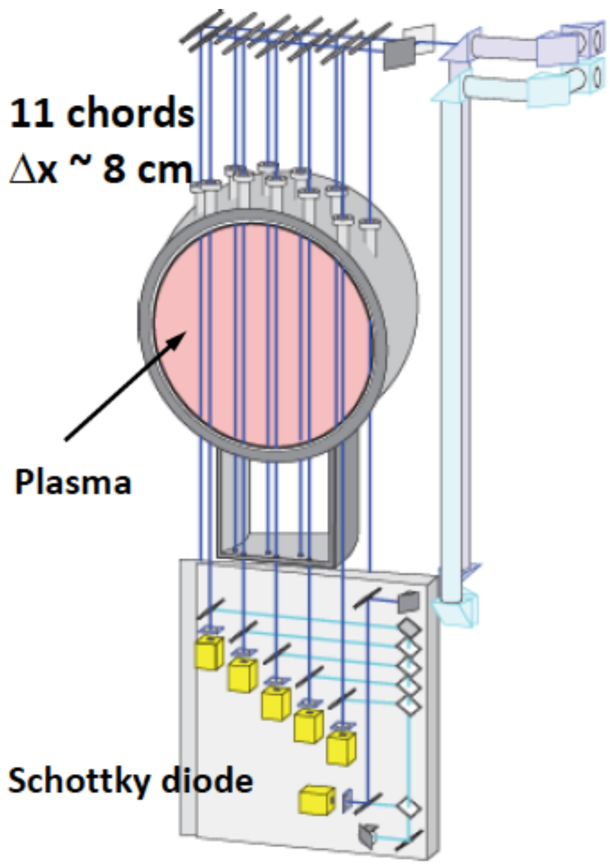


RFX

GS2, Predebon et al

MST's advanced diagnostics offer great potential for measurements of micro-turbulence

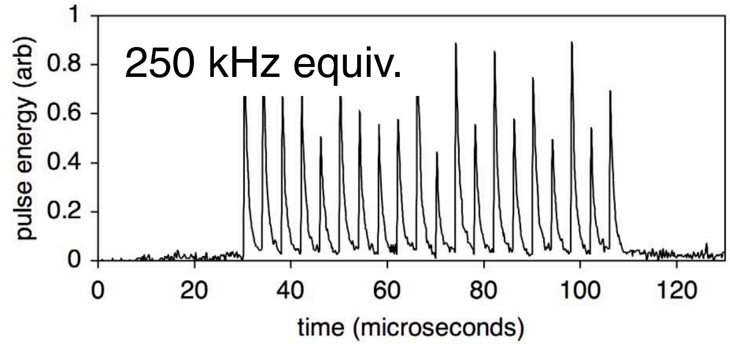
FIR Interferometer/Polarimeter/Scattering (UCLA)



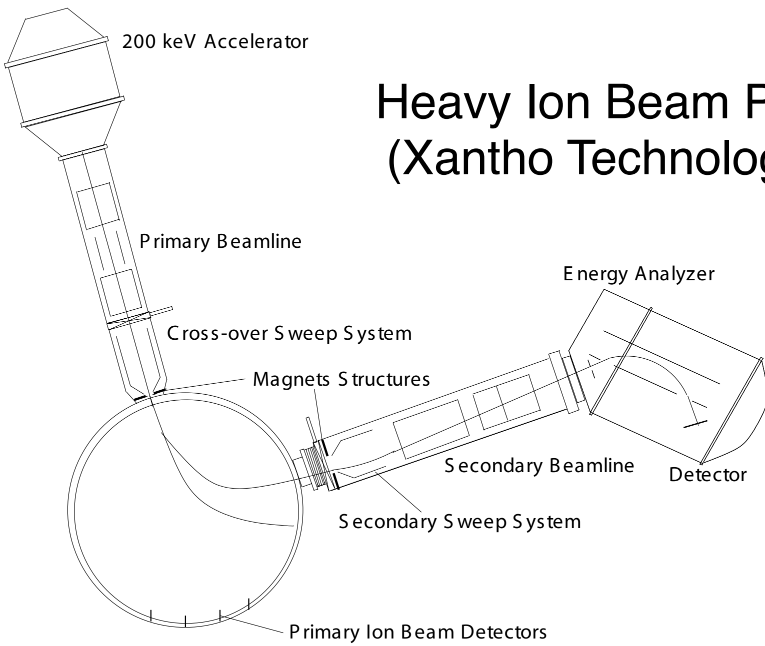
phase noise ~ 0.01°

time response ~ 1 MHz

Fast Thomson Scattering



Heavy Ion Beam Probe (Xantho Technologies)



Summary

- The RFP remains a viable candidate to address key issues for magnetic fusion, while making valuable contributions to the development of fusion science
- Low external magnetic field and ohmic ignition could benefit the maintainability and reliability of a fusion power core
- Growing and validating predictive fusion science benefits from the expanded parameter space of major variables that define various magnetic configurations