

# MST Reversed Field Pinch Development

**Karsten McCollam**  
**University of Wisconsin - Madison, USA**

**A. Almagri, J. Anderson, A. Blair, B. Chapman, D. Craig,  
D. Den Hartog, F. Ebrahimi, G. Fiksel, S. Gangadhara,  
J. Goetz, B. Hudson, S. Prager, R. O'Connell, J. Sarff,  
M. Wyman, and the MST Team -- UW-Madison  
D. Brower, B. Deng, and W. Ding -- UCLA**



# Four Key Plasma Physics Issues in RFP Fusion Path

---



- **Confinement**
- **Normalized thermal pressure (beta)**
- **Current sustainment**
- **Resistive-wall mode stabilization**

# MST Has Made Recent Advances on Three Issues:



- **Confinement**
  - Good for fast ( $E_i > 10$  keV) and thermal ions ( $T_i > 1$  keV)
  - Higher electron temperatures ( $T_e \sim 2$  keV)
- **Normalized thermal pressure (beta)**
  - Improved confinement  $\beta$  nearly doubled to 26% with pellet fueling
- **Current sustainment**
  - ~10% added to plasma current with oscillating field current drive
- **Resistive-wall mode stabilization advanced by other RFP experiments (RFX, Extrap-T2R)**

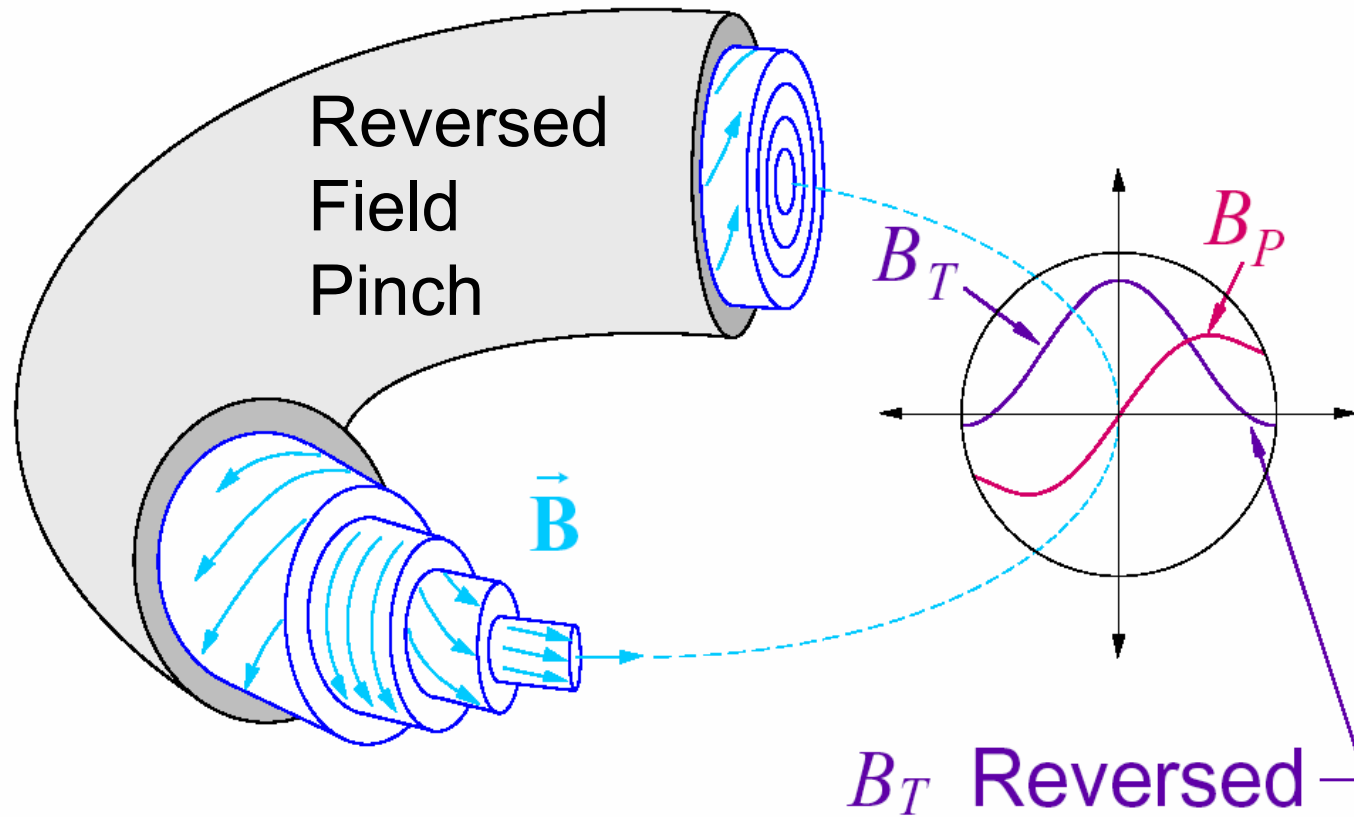
# Outline

---



- Introduction to RFP & MST
- Confinement advances
- Pellet fueling
- Oscillating field current drive
- Conclusion

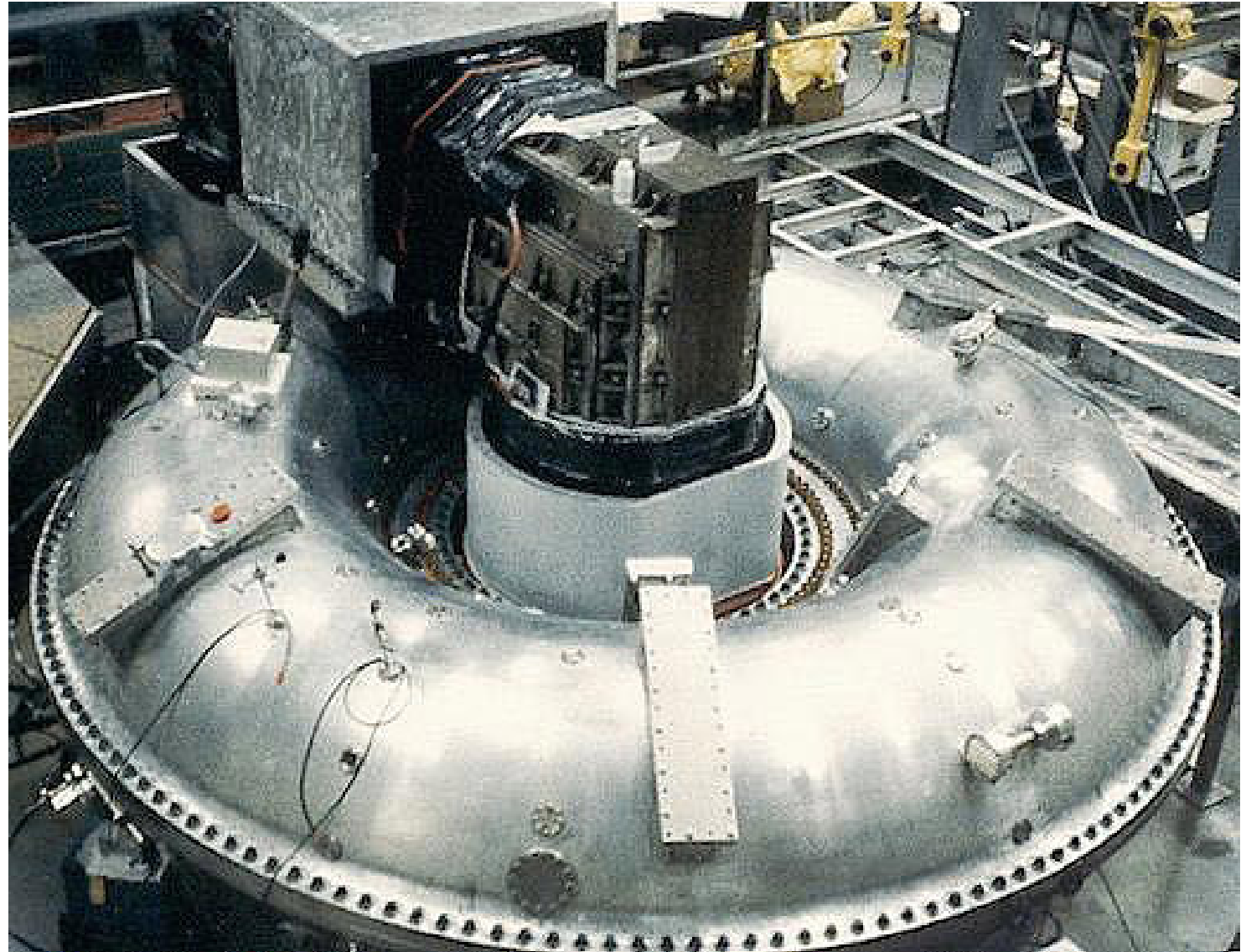
# RFP Magnetic Fields Mostly Due to Plasma Current



- Large magnetic shear
- Large normalized thermal pressure  $\beta \equiv 2\mu_0 \langle p \rangle / B^2(a)$
- Magnetic relaxation and nonlinear coupling important for dynamics of standard RFP
- Magnetic fluctuations dominated by current-driven tearing modes

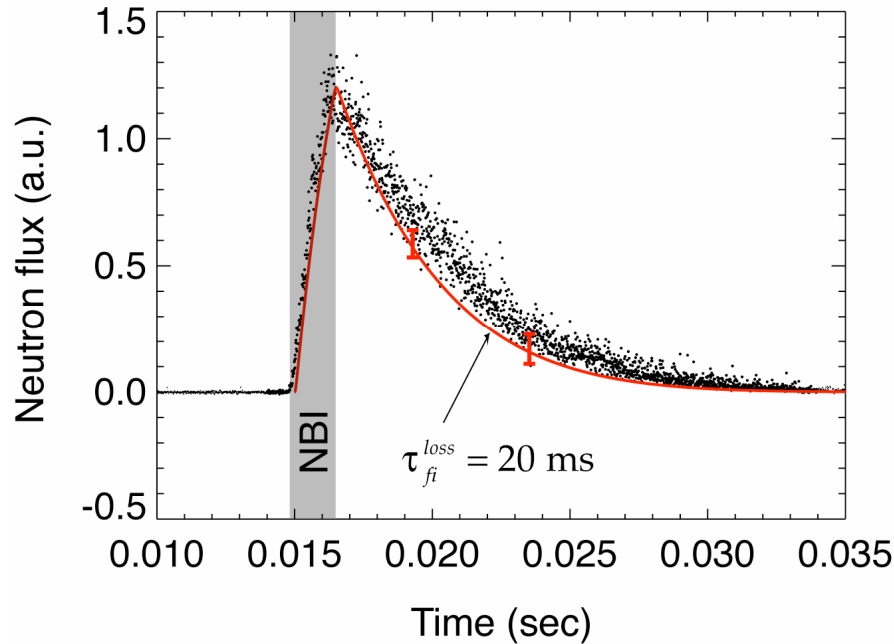
# Madison Symmetric Torus

$R_0$	= 1.5 m
$a$	= 0.5 m
$I_p$	$\leq 0.6$ MA
$B$	$\leq 0.6$ T
$n_e$	$\leq 4 \cdot 10^{19} \text{m}^{-3}$
$T_{e,i}$	$\leq 2$ keV
$\beta$	$\leq 26\%$
$\tau_E$	$\leq 10$ ms
$\tau_{\text{pulse}}$	$\leq 80$ ms

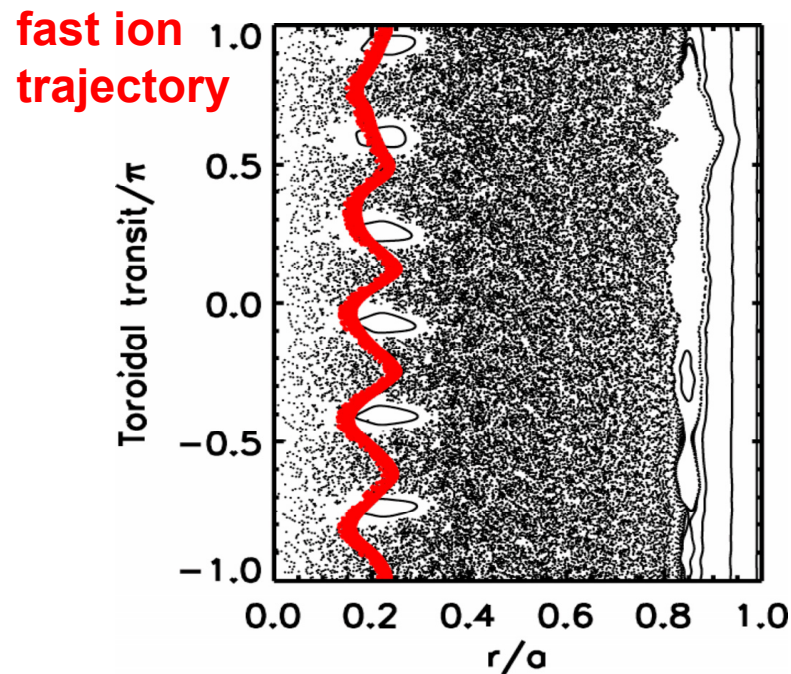


- Introduction to RFP & MST
- **Confinement advances**
- Pellet fueling
- Oscillating field current drive
- Conclusion

# Fast Ions Well Confined in Standard Plasmas



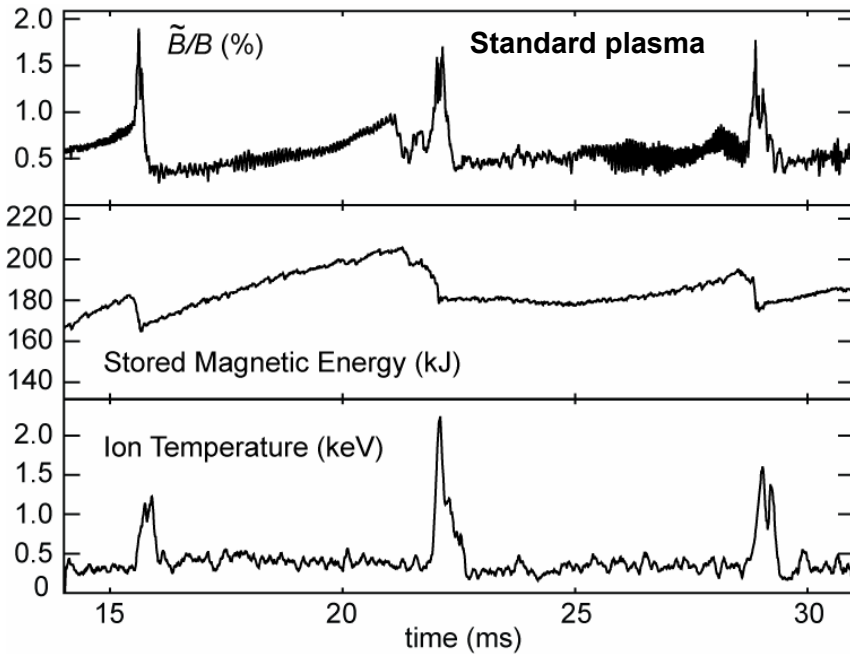
- 25 keV NBI D neutrals ionized in plasma
- DD fusion neutron flux measured
- $\tau_{fast-ion} > 20$  ms despite stochastic magnetic field



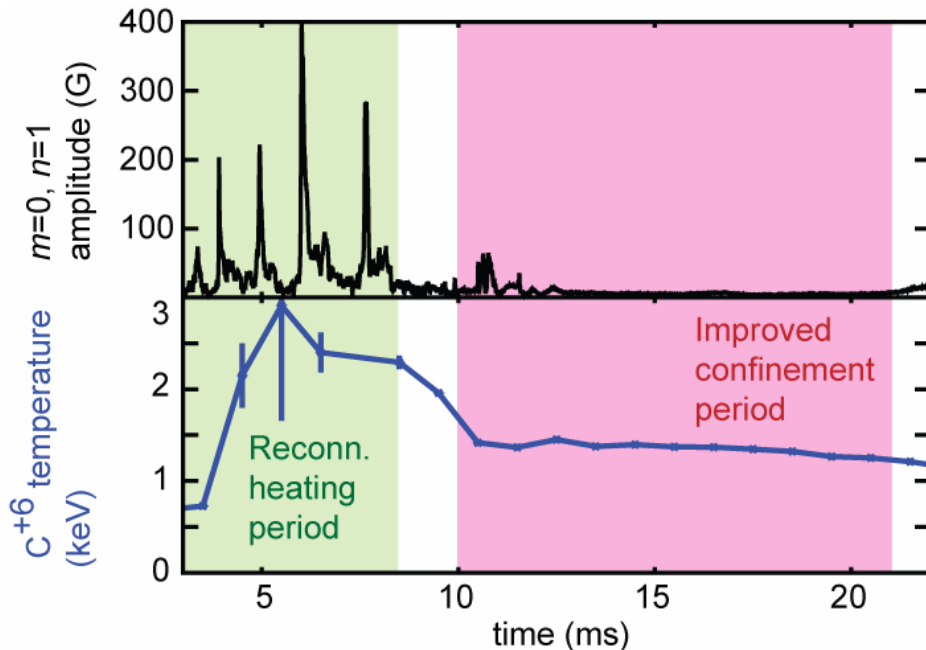
- Fast ion trajectories not stochastic in core
- Encouraging for RFP neutral beam development and alpha heating
- NBI in collaboration with the Budker Institute, Novosibirsk, Russia



# Improved Confinement Captures Ion Heat from Reconnection

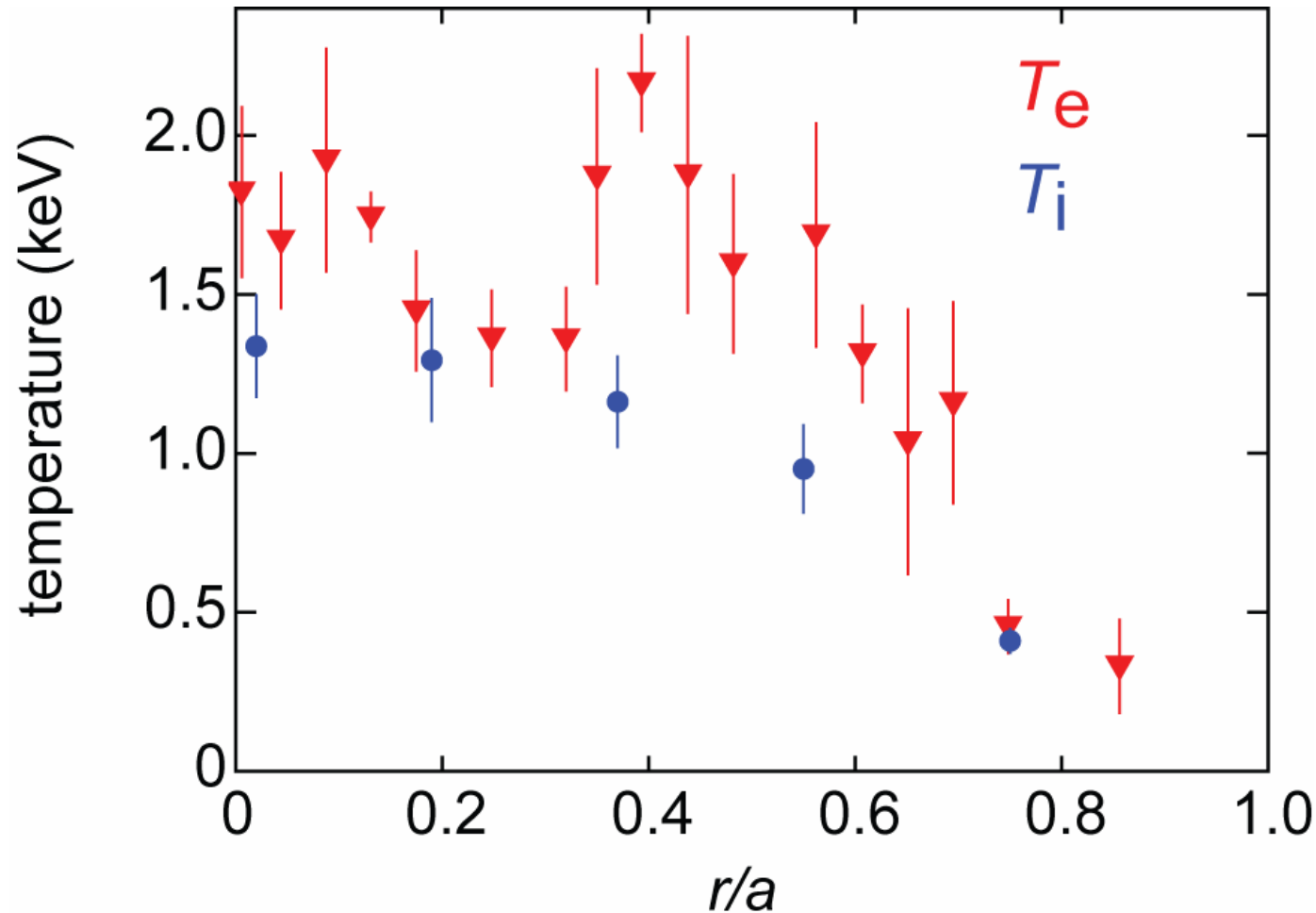


- Large ion heating in sawtooth magnetic reconnection events
- Ion thermal energy increases as stored magnetic energy decreases
- In standard plasma  $T_i$  then quickly drops and ion  $\tau_E \sim 1$  ms



- RFP confinement improved by edge inductive current drive reducing magnetic fluctuations
- Large ion temperature  $T_i > 1$  keV captured
- $\tau_E$  increases to  $\sim 10$  ms

# MST Achieves High $T_e$ and High $T_i$ Simultaneously



- Ion heat captured by improved confinement
- Electrons heated during improved confinement
  - $T_e$  is highest observed in MST to date
- RFP improved confinement similar to tokamak with same plasma current but has  $\sim 10x$  smaller magnetic field

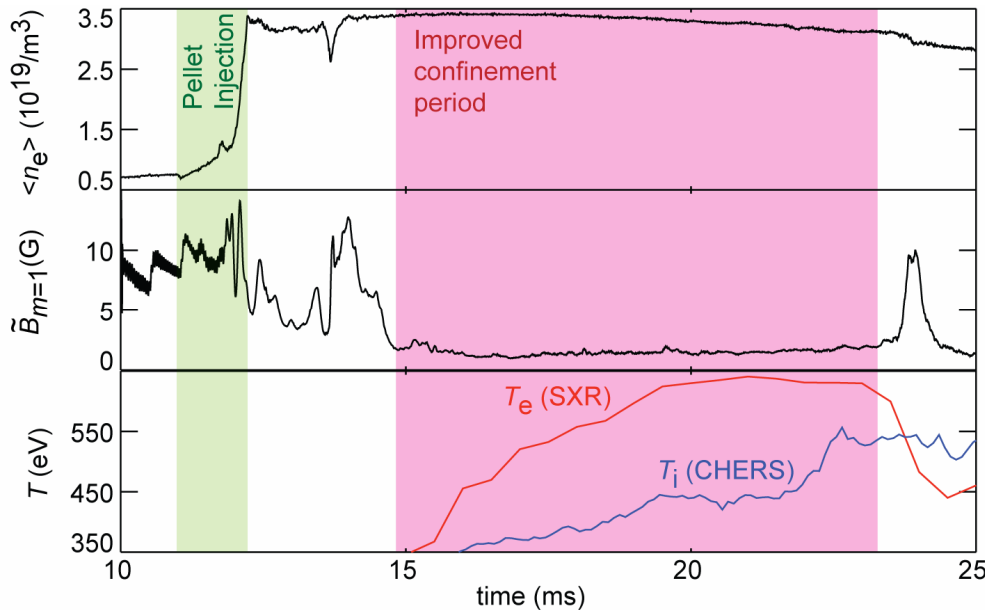
# Outline

---



- Introduction to RFP & MST
- Confinement advances
- **Pellet fueling**
- Oscillating field current drive
- Conclusion

# Pellet Fueling Increases Beta in Improved Confinement



- D<sub>2</sub> pellet fueling in collaboration with ORNL, USA
- Low magnetic fluctuations maintained with high density (unlike edge gas puff case)
- Both  $T_e$  and  $T_i$  increase (unlike low density case)
- SXR in collaboration with RFX, Padua, Italy



	Improved Confinement	Improved Confinement with Pellets
$n_e$	$0.7 \cdot 10^{19}/\text{m}^3$	$2.4 \cdot 10^{19}/\text{m}^3$
$\beta$	$\sim 0.15$	<b>0.26</b>
$\tau_E$	$\sim 10$ ms	<b><math>&gt; 5</math> ms</b>

- Beta roughly doubled from low density case
- Highest betas ever achieved in improved confinement RFP
- No evidence of beta limit observed

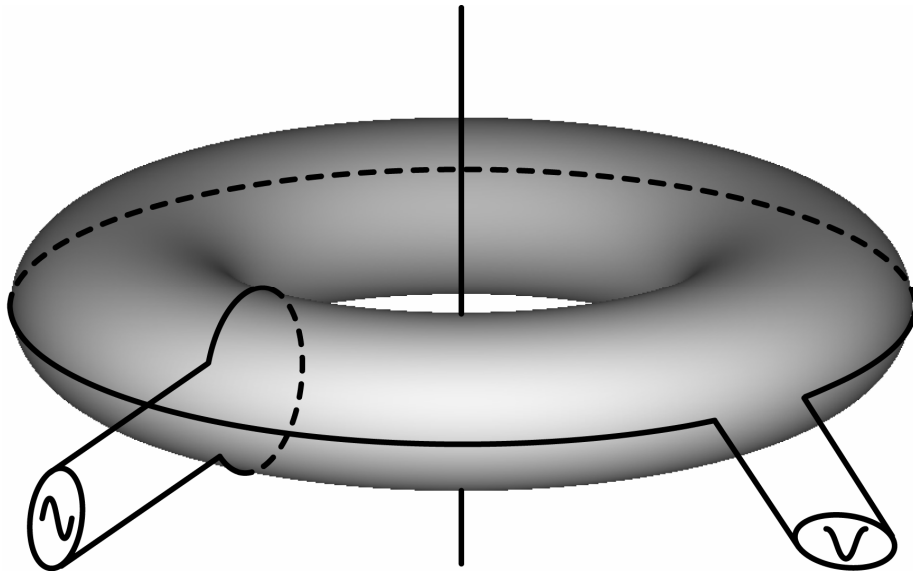
# Outline

---

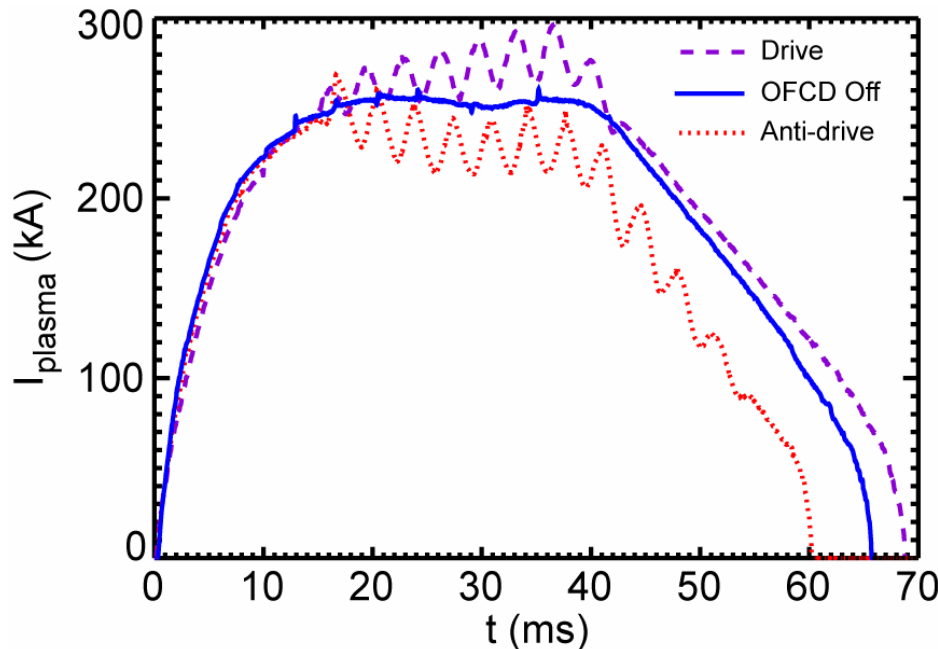


- Introduction to RFP & MST
- Confinement advances
- Pellet fueling
- **Oscillating field current drive**
- Conclusion

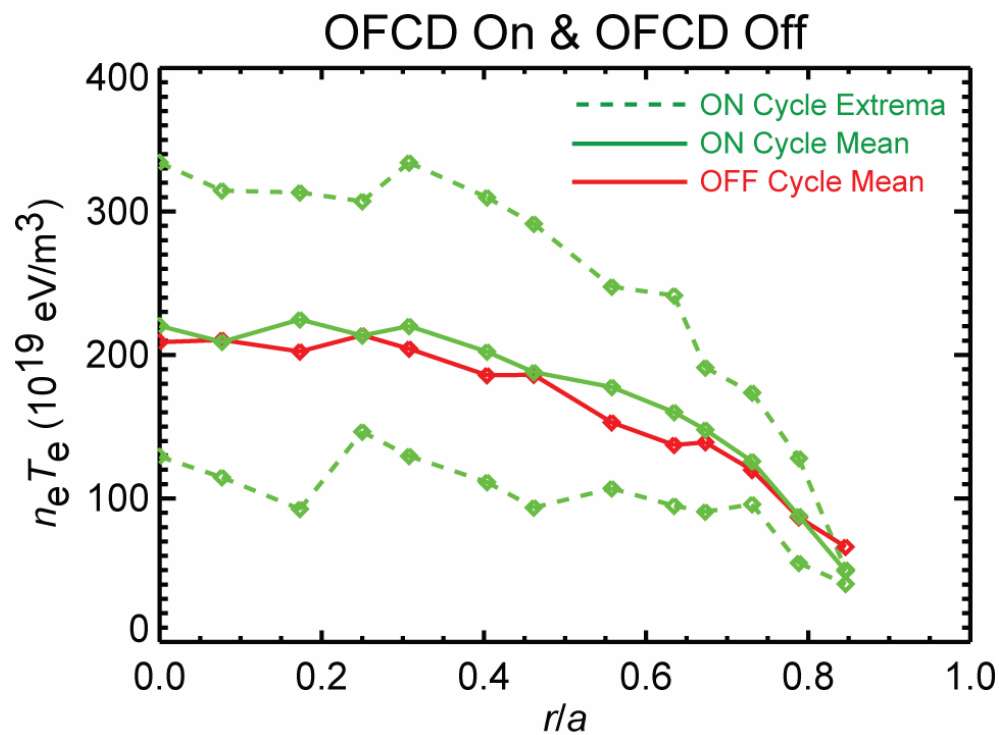
# OFCD a Steady-State, Inductive Sustainment Method



- Oscillating Field Current Drive: poloidal and toroidal AC loop voltages  $V_p \sin(\omega t)$  &  $V_t \sin(\omega t - \delta)$
- Net emf at edge couples to MHD driving DC total plasma current
- Steady-state since  $\langle V \rangle = 0$
- Capable of full RFP sustainment in MHD calculations
- OFCD adds  $\sim 10\%$  to plasma current in MST (for drive phase  $\delta$ )
- CD efficiency is Ohmic



# OFCD Plasma Maintains Standard Net Electron Pressure



- Time-averaged magnetic fluctuations and total input power similar with or without OFCD (in drive phase)
- Time-average pressure profile similar with and without OFCD (for similar plasma currents)
- OFCD at this level consistent with standard RFP confinement and beta
- Power and pulse-length upgrade in progress

# Outline

---



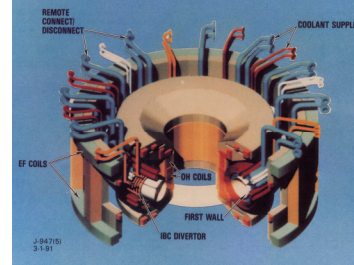
- Introduction to RFP & MST
- Confinement advances
- Pellet fueling
- Oscillating field current drive
- **Conclusion**

# RFP Has Compact Reactor Scenario

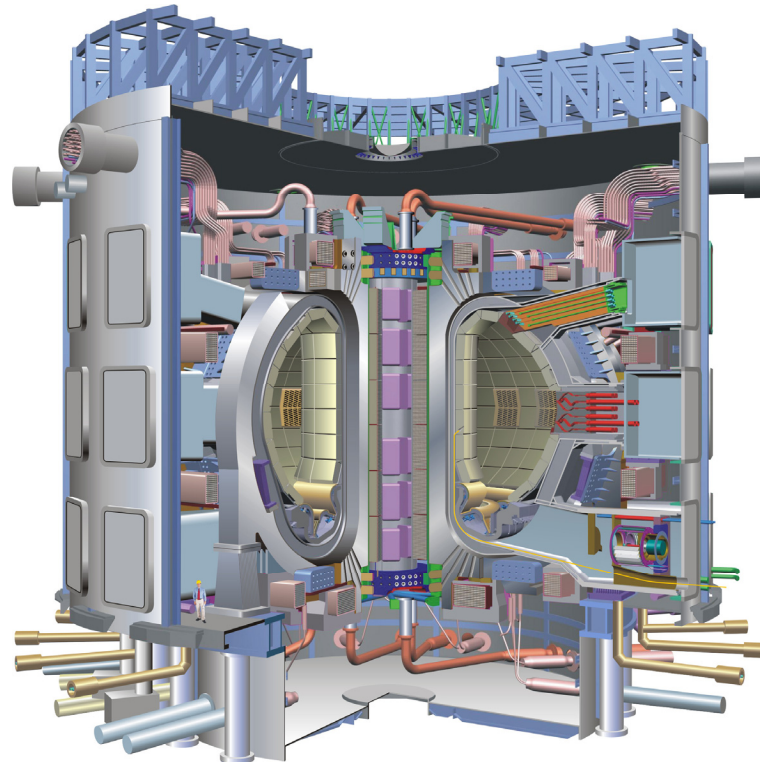
## TITAN

- $R_0 = 3.9$  m,  $a = 0.6$  m
- $I_p = 18$  MA
- $\beta_{pol} = 23\%$ ,  $\tau_E = 0.15$  s
- $\sim 1$  GW electric
- COE  $\sim 4\phi$  / kWh (1990)
  
- Large wall loads:
  - 18 MW/m<sup>2</sup> neutrons
  - 4.6 MW/m<sup>2</sup> radiation
  - But COE shallow with load
  
- Several novel features including OFCD sustainment
  
- Possible features of updated scenarios:
  - Self-similar decay
  - Non-sinusoidal OFCD
  - Updated confinement scaling

## TITAN RFP reactor study (Najmabadi, Conn, *et al.*, 1990)



## ITER tokamak design (same scale)



- **MST research has led to recent advances in confinement, beta, and current sustainment.**
  - **Both fast and thermal ions are well confined.**
  - **Pellet fueling of improved confinement RFP leads to even higher beta.**
  - **Efficient partial OFCD adds to plasma current with similar confinement and beta to standard RFP.**
- **Overall, MST obtains improved confinement for thermal and fast electrons and ions simultaneous with high beta.**
- **A fusion path for the RFP is well defined and is being explored today.**