Supported by

Progress in Spherical Torus Research

Roger Raman
University of Washington, Seattle
and the NSTX National Research Team

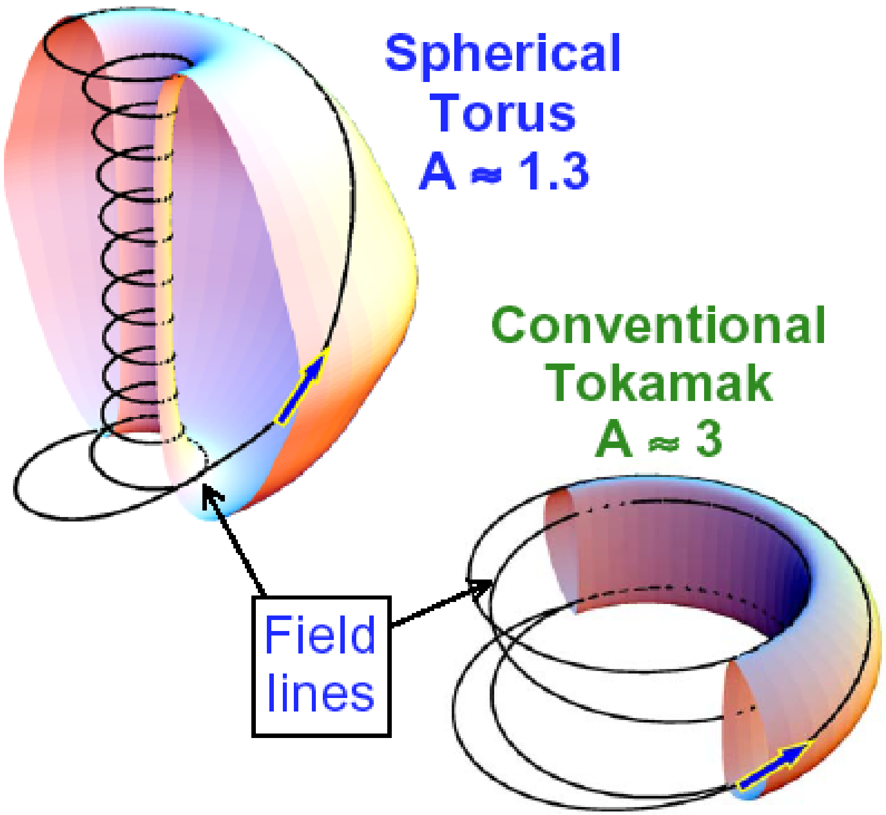
ICC Workshop
28-30 May 2003, Seattle, WA

Acknowledgments

M. Bell, D. Gates, L. Grisham, S.M. Kaye, H.W. Kugel, R. Majeski, M. Redi, E. Synakowski (PPPL)
T.R. Jarboe, B.A. Nelson (Univ. of Washington)
R. Maingi, M. Peng (ORNL)

For presentation material
M.Gryaznevich, A. Sykes (MAST, UK)
R. Fonck, G.D. Garstka (Pegasus)
Y. Takase (TST-2, Japan)
G.O. Ludwig (ETE, Brazil)

STs expand parameter space in Aspect ratio



- Strong toroidicity
  - Good stability
- High edge *q*
  - High Bootstrap current fraction

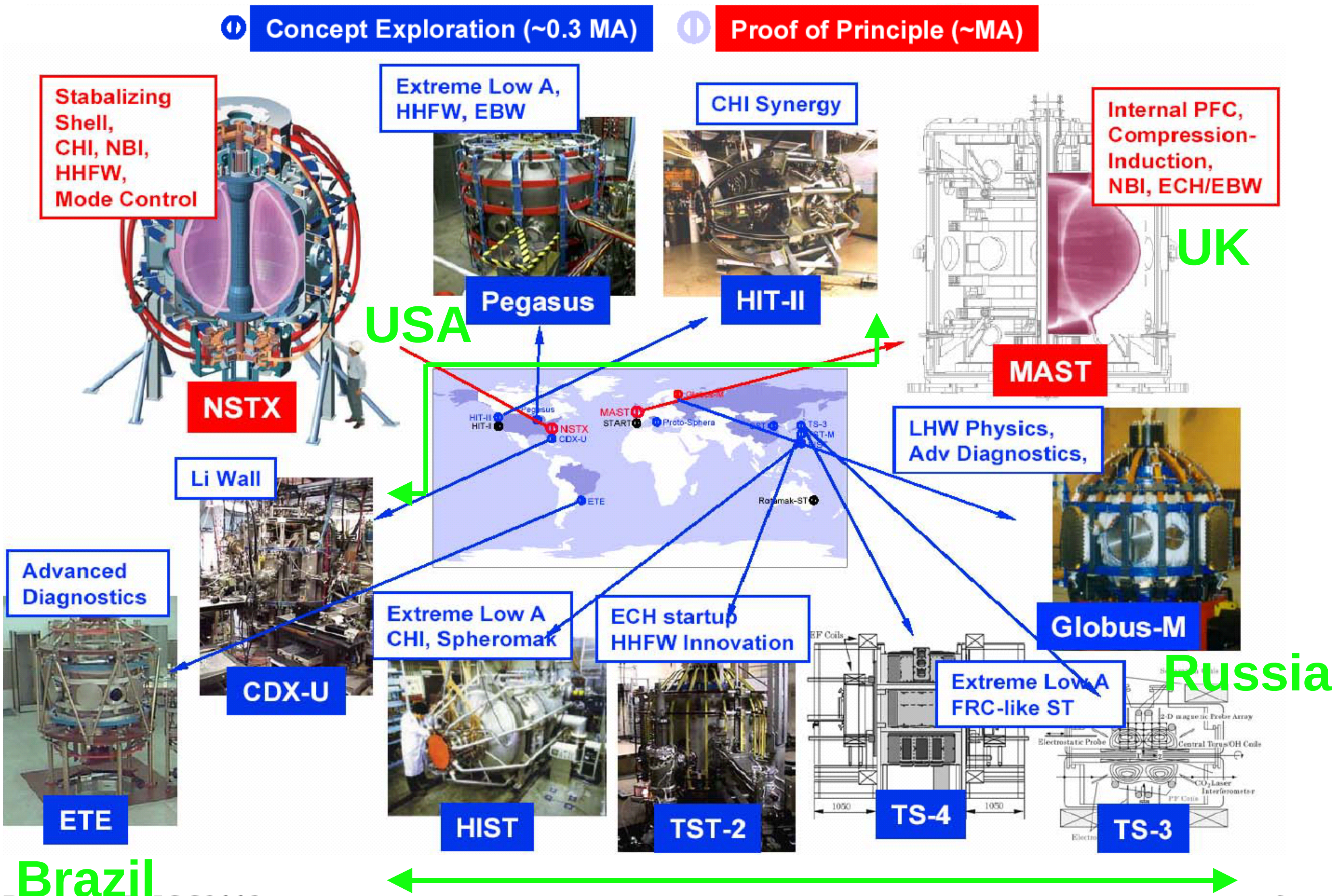
High performance steady-state capability in smaller machines

- Most of the current driven by the plasma
- Small auxiliary current drive needed
- Low values of B_T
  - leads to cheaper machines
  - enables easier demonstration of scientific understanding that allows for extrapolation with confidence

ST Program connects with good confinement tokamak database and with spheromaks

- Medium sized machines
  - NSTX and MAST (1MA, R/a ~ 0.85/0.65)
- Concept exploration machines
  - Pegasus: Very Low Aspect ratio machine, RF current drive for sustainment
  - HIT-II: CHI for startup and sustainment
  - CDX-U: Li-Wall development
  - Other STs also contribute to these studies (TST-2, ETE, Globus-M, HIST)

ST Program is an international effort

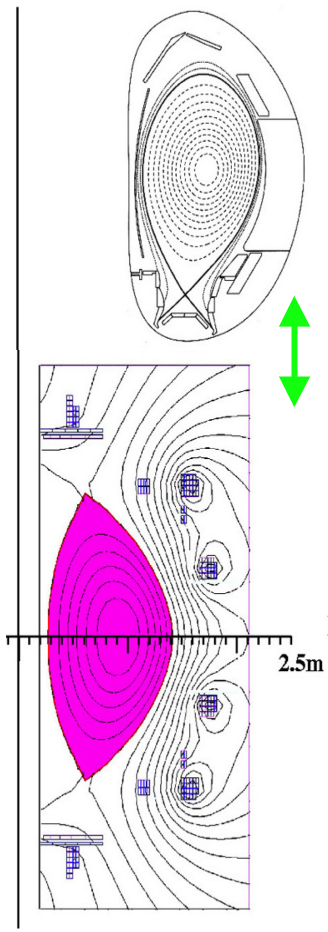


ORNL, PPPL

Medium sized STs study the following physics

- High β and global confinement
- High Bootstrap current fraction
- Solenoid free plasma startup
  - Coaxial Helicity Injection (CHI)
- Non-inductive current sustainment
  - High Harmonic Fast Wave (HHFW)
- Long pulse, high performance
  - Acceptable heat loads
- Other studies in progress
  - Fast particle physics
  - Transport and Turbulence
  - H mode physics

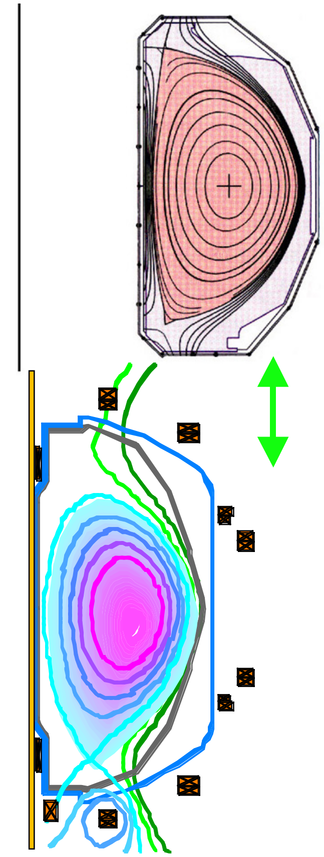
Strong linkages between STs and Tokamaks



MAST and ASDEX-Upgrade in Europe

Red shows design values

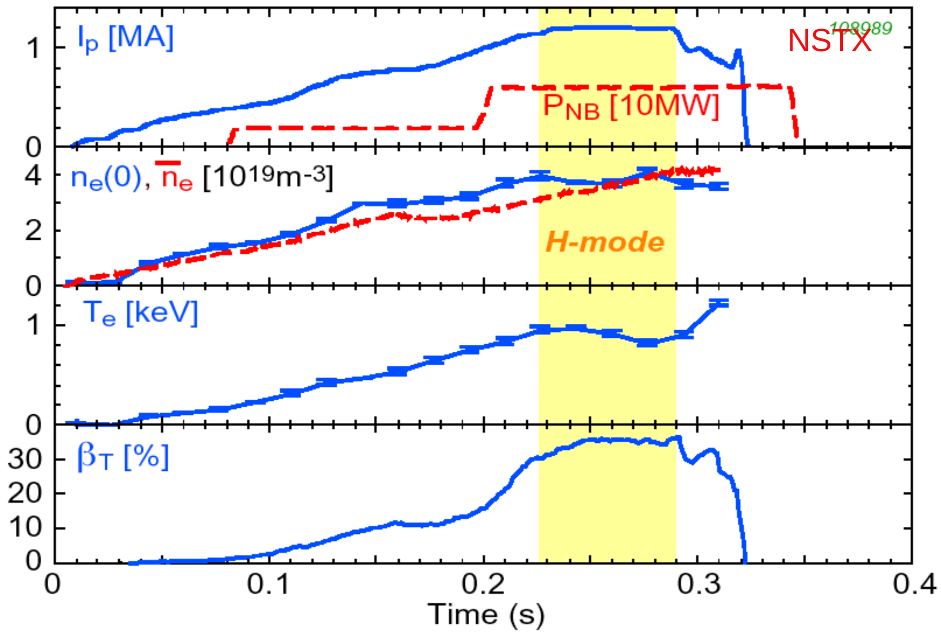
	MAST	NSTX
R (m)	0.85	0.86
a (m)	0.65	0.68
k	2.4 (3)	2.5
I_p (MA)	1.2 (2)	1.5 (1)
B_T (T)	0.5	0.45
P_{AUX} (MW)	3 NBI (5) 1 EC (1.5)	5 NBI (5) 4 FW (6)
T_{pulse} (s)	< 0.65 (5)	0.55 (5)

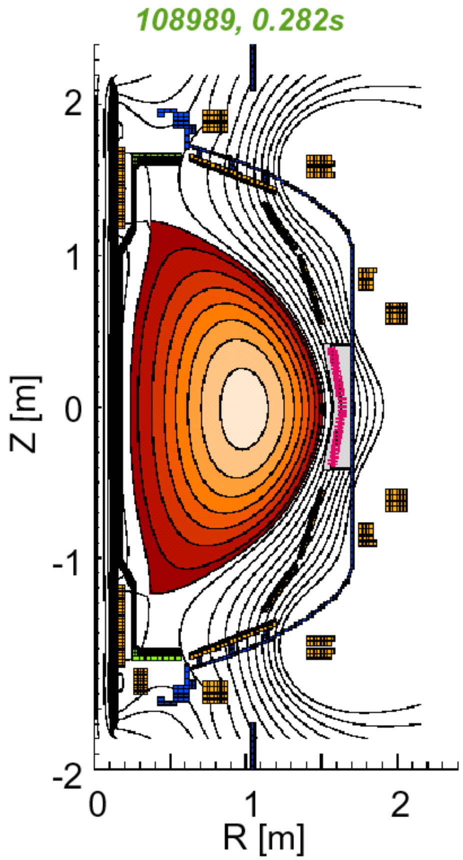


NSTX and DIII-D in USA

- Similarity experiments proposed on MAST/ASDEX-U and NSTX/DIII-D
- NSTX/MAST similarity experiments started

NSTX has shown high β capability at 1 MA

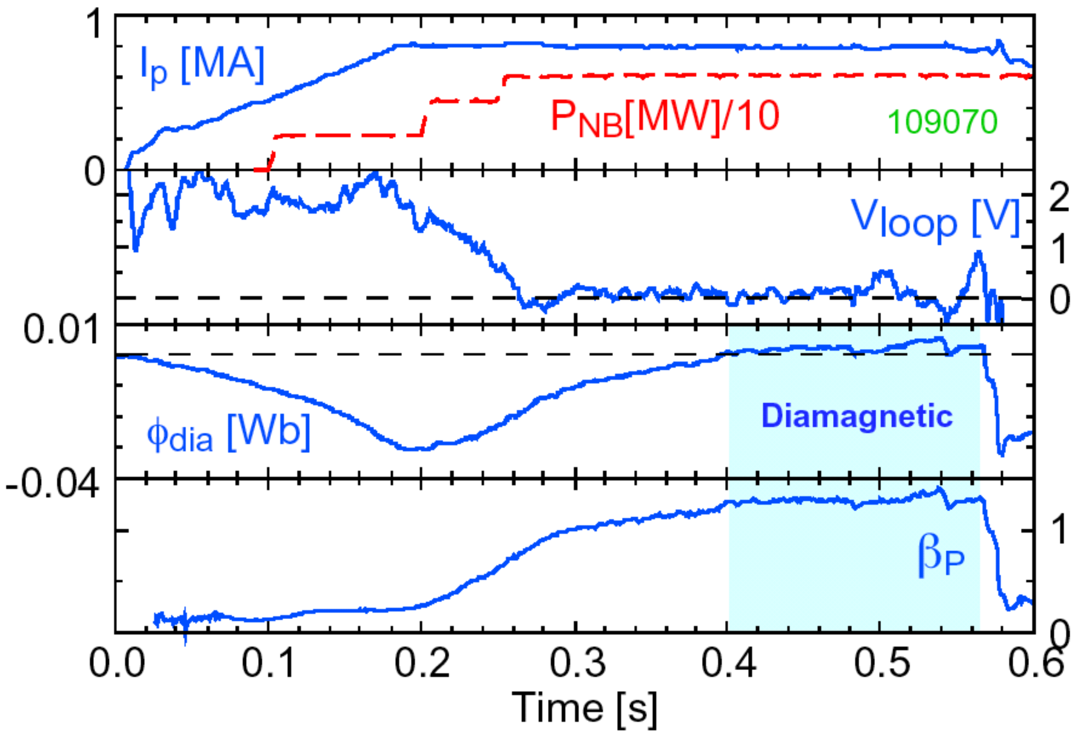




- β_T = 35% determined by magnetic analysis
- B_T = 0.3T, A = 1.4, κ = 2.0, δ = 0.8
- β_T ~ 30% obtained on MAST

Gates & NSTX Team

Substantial bootstrap current fraction achieved in NSTX

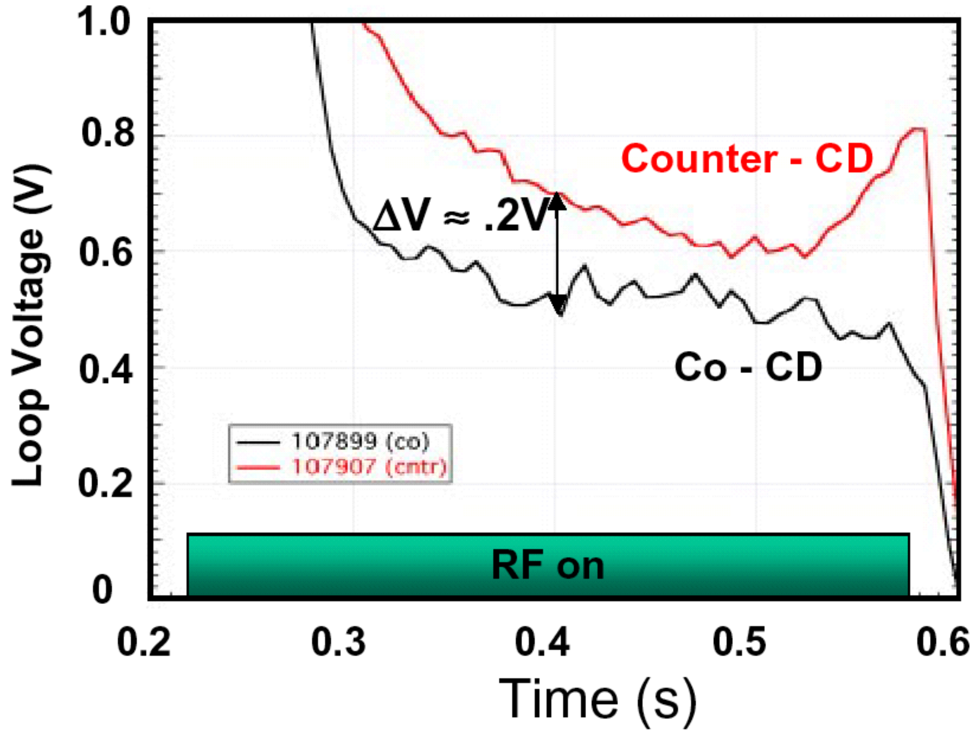


- V_{loop} ~ 0.1V for ~ 0.3s
- I_{NBI}/I_p = 0.18
- $I_{bootstrap}/I_p$ = 0.42
- $I_{non\text{-}ind}/I_p$ = 0.6

- Goal is to control profiles of both pressure & current to maximize stability and bootstrap current contribution

Menard & NSTX Team

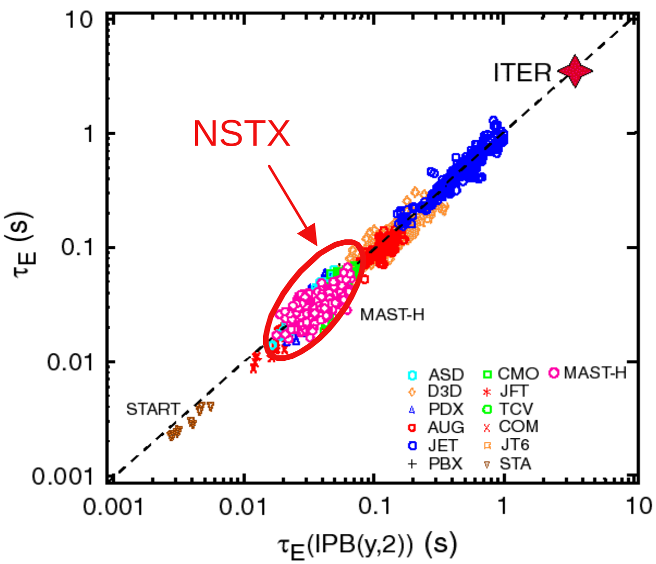
0.1MA of HHFW current drive inferred by circuit analysis

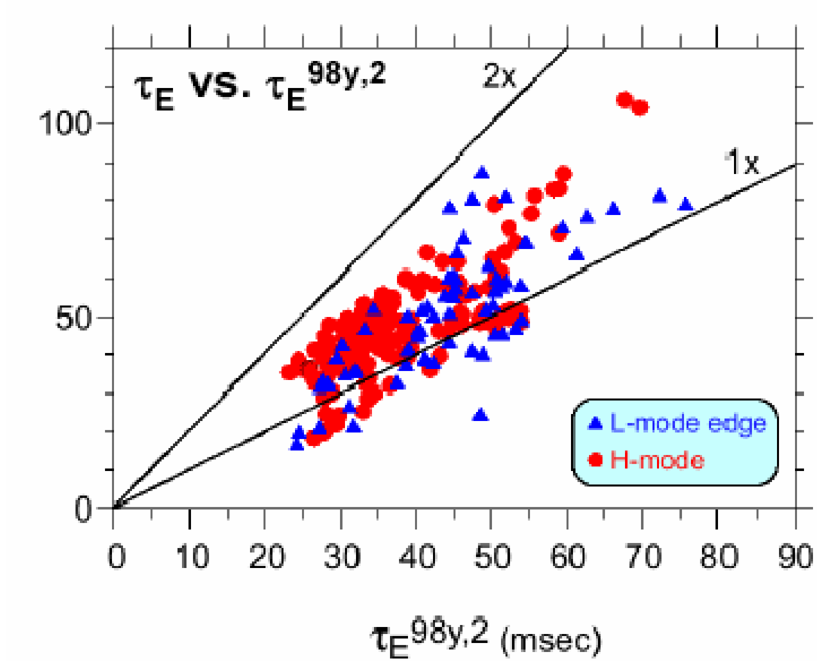


- HHFW are compressional fast Alfvén waves, $\omega \sim k_\perp V_A \sim (6\text{-}12)\ \Omega_D$
- For NSTX $\beta \sim 4\% - 38\%$, choose $\omega / k_{11} \sim V_{te}$

- 2 discharges with similar $n_e(r)$, $T_e(r)$
- ΔV not caused by dI_i/dt

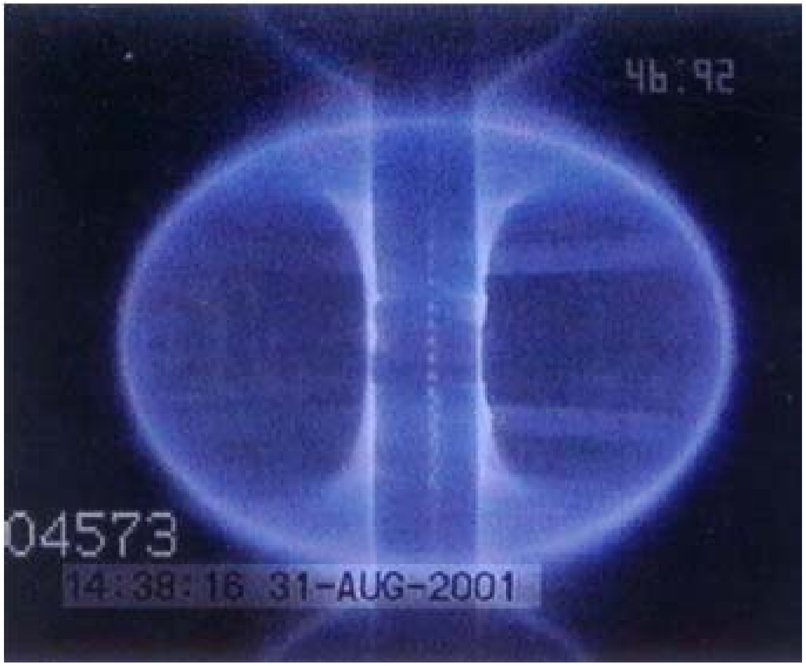
MAST & NSTX show good confinement (τ_E > 100ms)



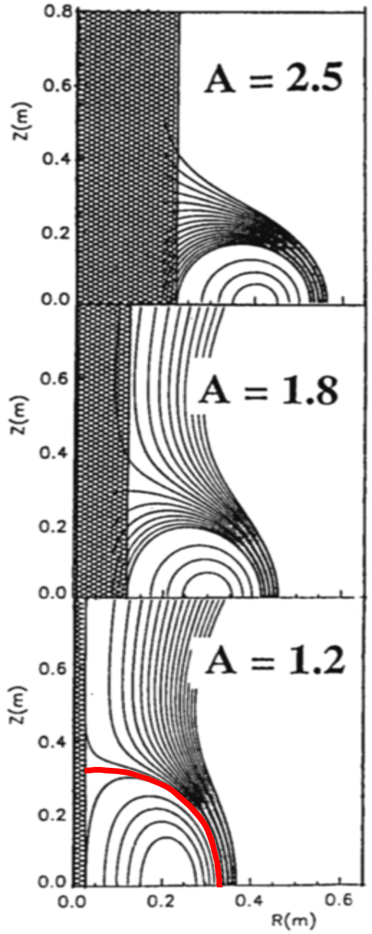


- Little difference in scaling for L and H modes
- In general agreement with IPB98y2 scaling
- Extends the range of R/a in scaling database
- MAST has obtained H-modes in an ohmic plasma

Natural divertor plasmas may offer an alternate configuration for high performance discharges

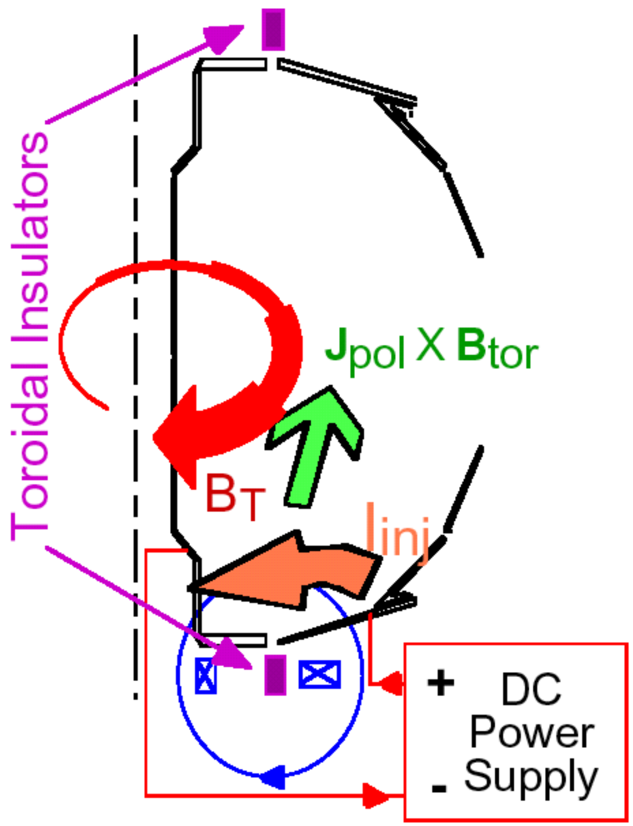


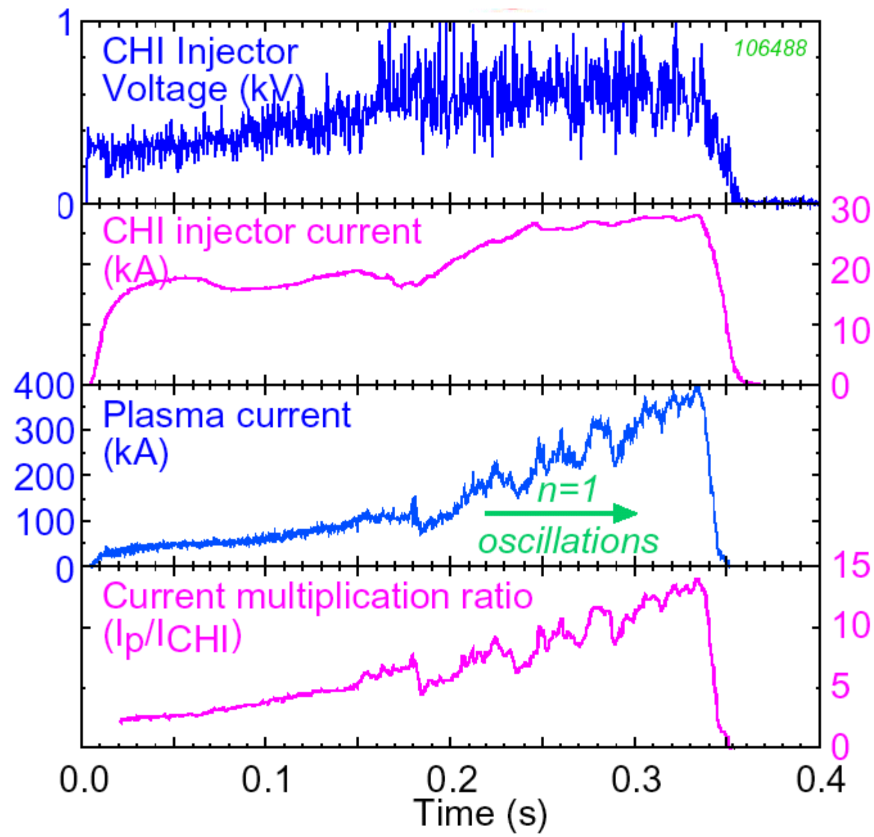
- **Formation of the Natural Divertor at low R/a:**
- *As aspect ratio A decreases, exhaust plume expands*



- Inboard limited plasmas have an **expanded outer SOL**
- Reduced, evenly spread contact on the centre limiter.
- Exhibited H-mode features with ELM-free periods

CHI has generated substantial toroidal current in NSTX



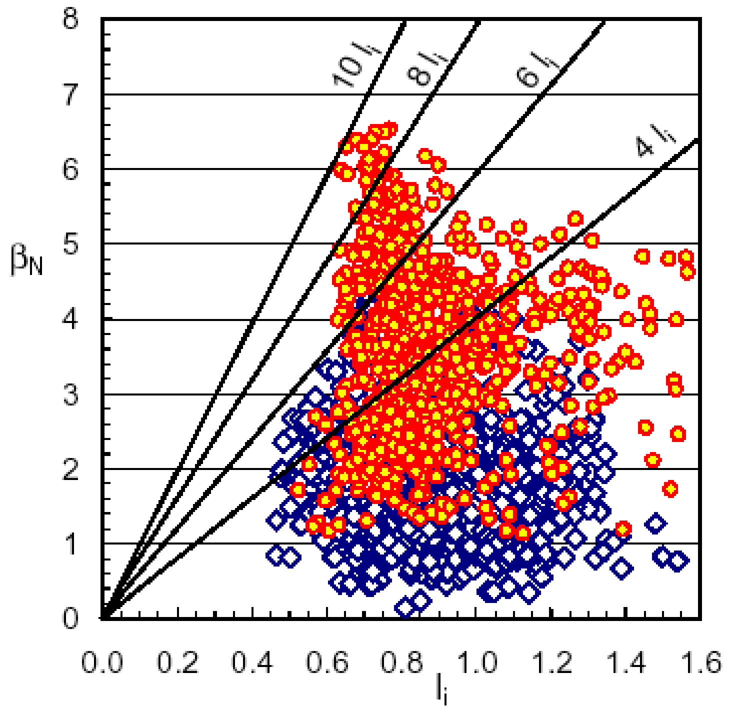


- Goal is to control discharge evolution to promote relaxation of toroidal current into closed flux surfaces

NSTX: ***Univ. of Washington, PPPL***

Other results from medium sized STs

- MAST uses a merging-compression method (outer PF coils) to generate solenoid-free startup current
- Power handling studies on MAST and NSTX indicate most of the heat deposition on outboard divertor legs
- Conventional aspect ratio tokamak empirical scaling of $\beta_N \leq 4l_i$ limit(generally $\sim 2.5l_i$) not seen in STs.

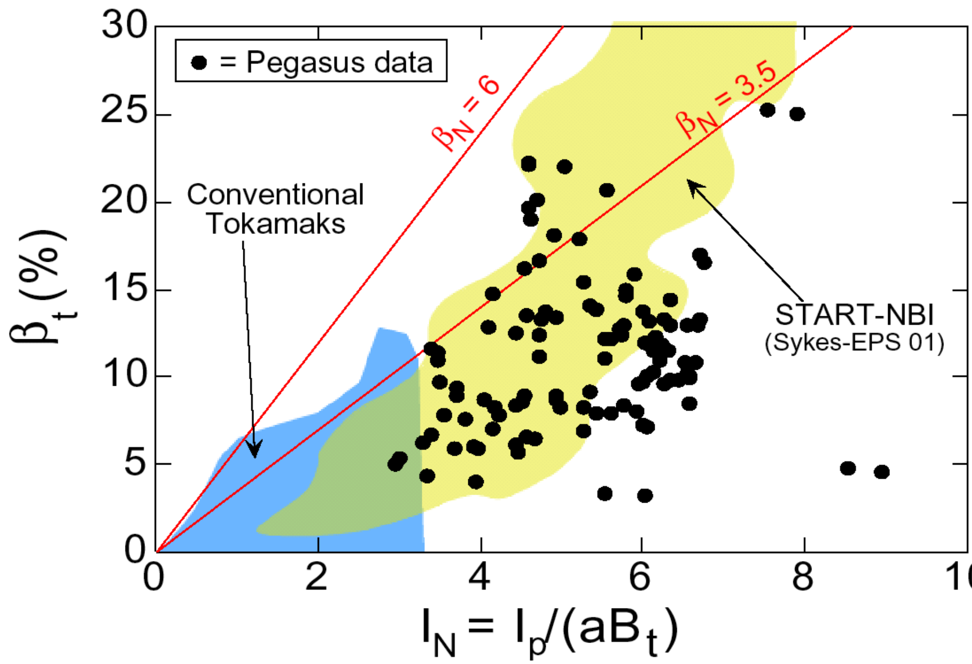


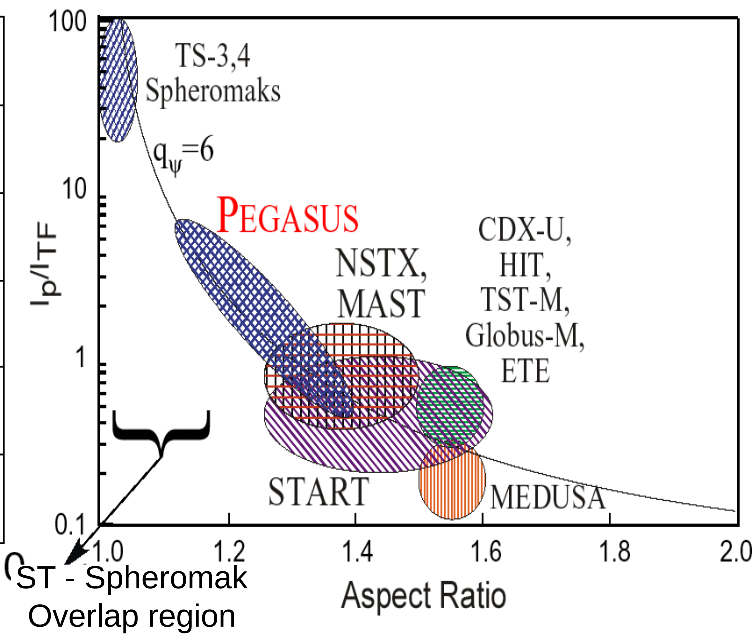
Sabbagh & NSTX Team

Results from the concept exploration STs

	Pegasus	HIT-II	CDX-U	TST-2
R/a (m)	0.45/ 0.4	0.3/ 0.2	0.34/ 0.24	0.36/ 0.23
B_T (T)	0.15	0.5	0.2	0.4
I_p (kA) *(Achieved)*	160	265	70	90

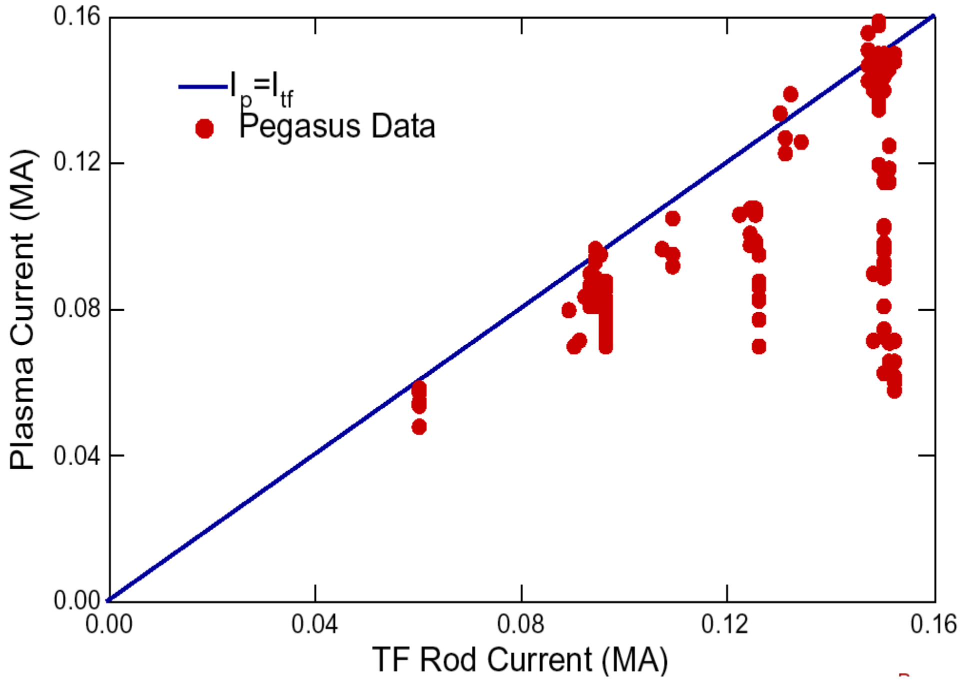
Pegasus explores extremely low-aspect ratio physics in high-β plasmas





- β_t up to 20% and I_N up to 6.5 achieved *ohmically* at A of ~1.2
- Minimize central column
- Maintain good stability and confinement

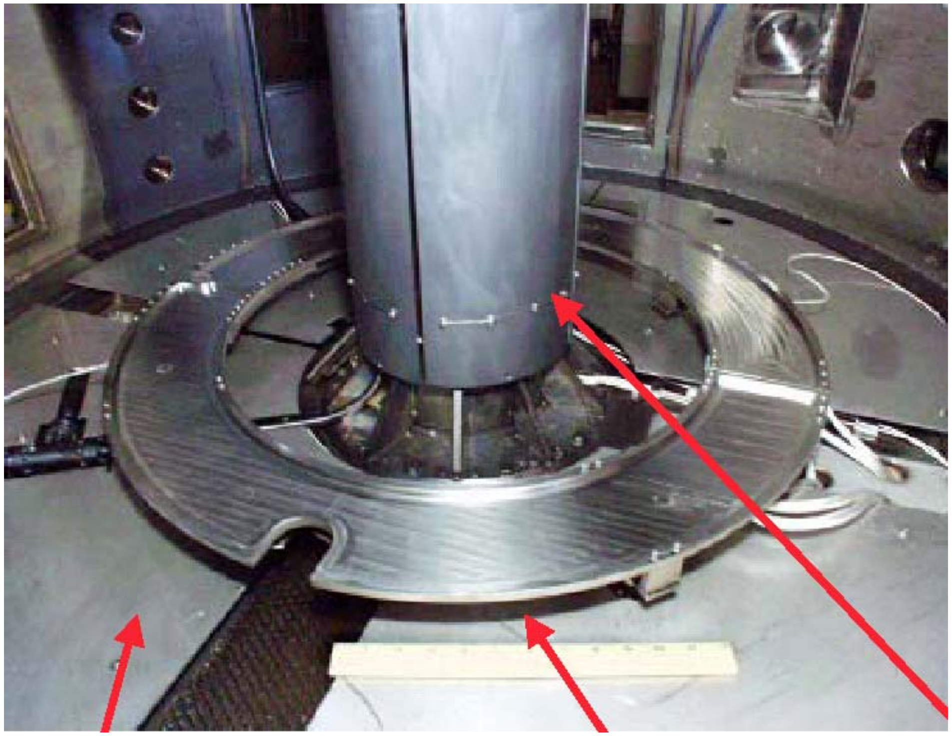
Toroidal field utilization exhibits a “soft limit” around unity



I_P/I_{tf} is a figure of merit for access to low-A physics

- Maximum $I_p \sim I_{tf}$ in almost all cases
- Limit is not disruptive, I_P saturates or rolls over
- Large resistive MHD instabilities degrade plasma as TF decreases
- Reduced available volt-seconds as TF is reduced
- Upgrades now in progress will allow access to larger I_p/I_{TF}

CDX-U studies role of Lithium PFCs on plasma operations and practical implementation issues



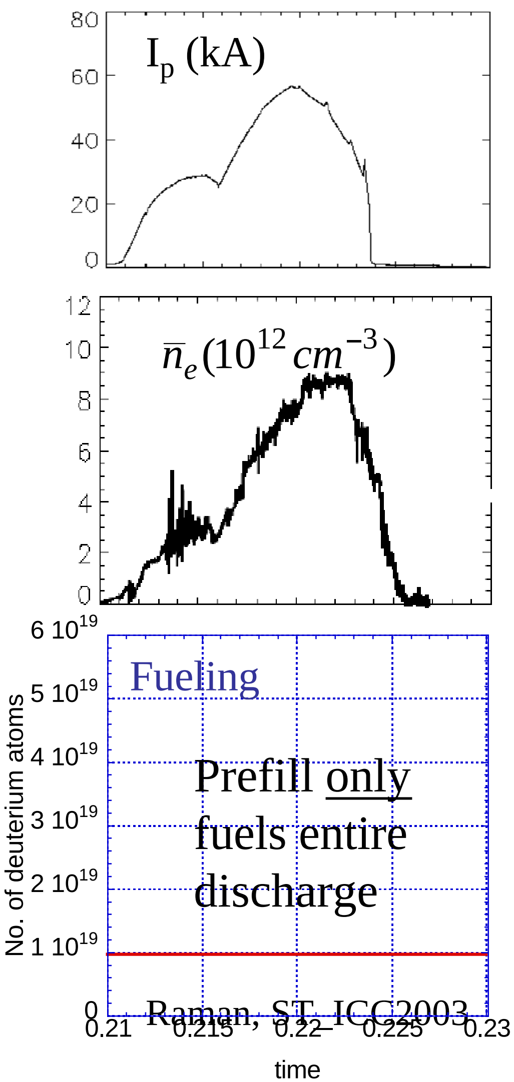
Heat/Li shield   Tray temp. monitored   TiC coated shield on CS

- Recycling & Fueling
- Impurity reduction
- Performance enhancement
- Radiation lossses, core Li accumulation
- Safety issues
- Motion of liquid during PF ramps, disruptions

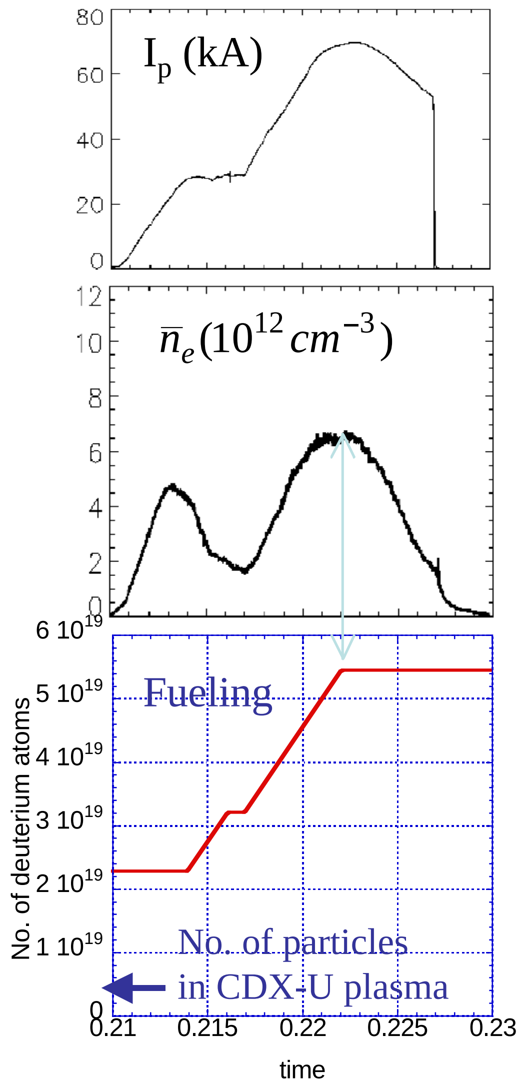
- Tray has a radius of 34cm, width of 10cm, depth of 6mm, Temp. ~ 300C
- Electrical break between two halves, Liquid Li injected into both halves

A new lithium tray has been installed and filled. *Global* recycling greatly reduced by clean lithium

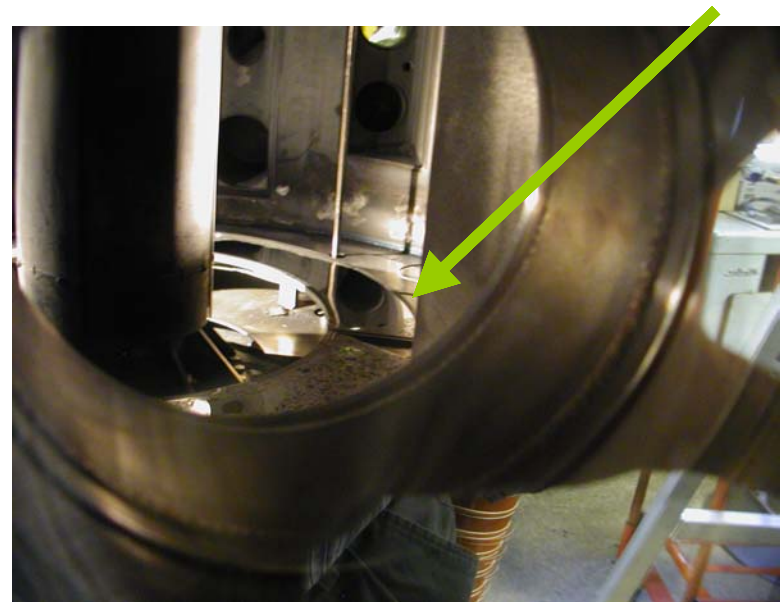
Pre-lithium fueling



Post-lithium fueling



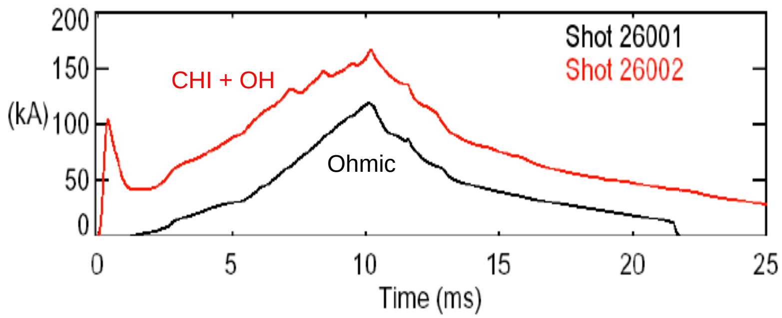
Improved filling technique developed by UCSD - PISCES group
Note reflections in metallic lithium

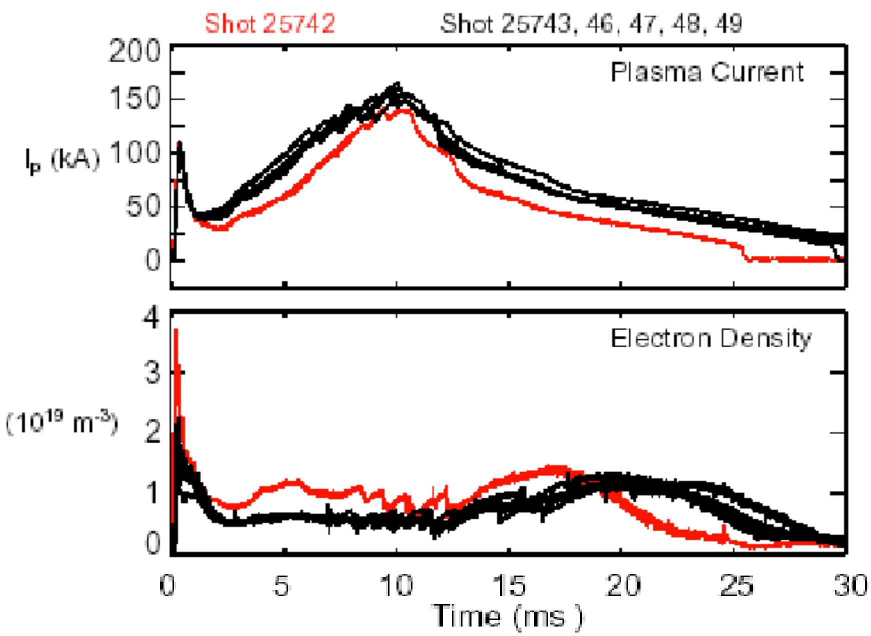


Oxygen, carbon impurities virtually eliminated
Immediate 30% increase in peak plasma current, discharge duration
Loop voltage to sustain current dropped from 2.0 $\Rightarrow$ 0.5V

CDX-U: *PPPL & UCSD*

New method for CHI startup on HIT-II improves performance of inductive discharges





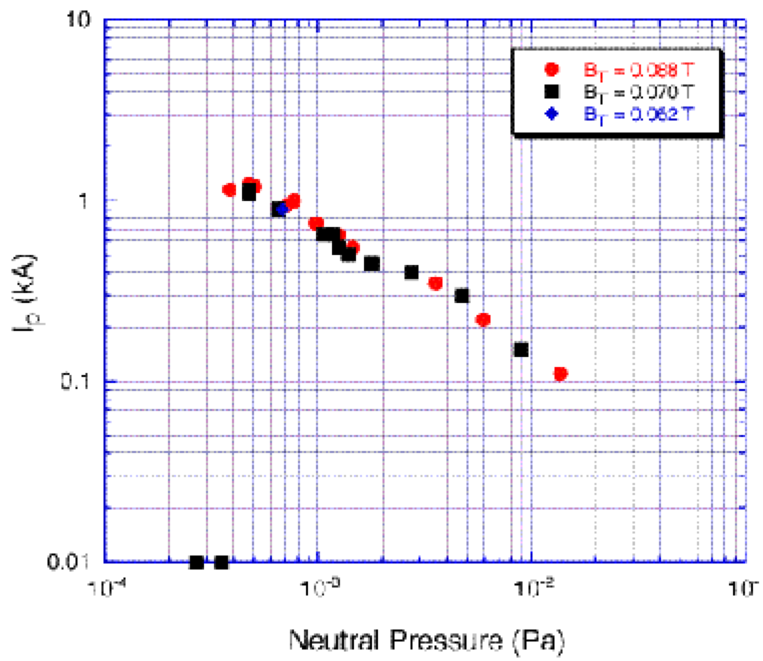
- New method *"Transient CHI startup"* developed
- Record plasma currents of 265kA obtained using CHI startup
- CHI transition current reduces at higher density
  - Indicates need for improved pre-ionization
- Method is applicable to a pre-charged transformer

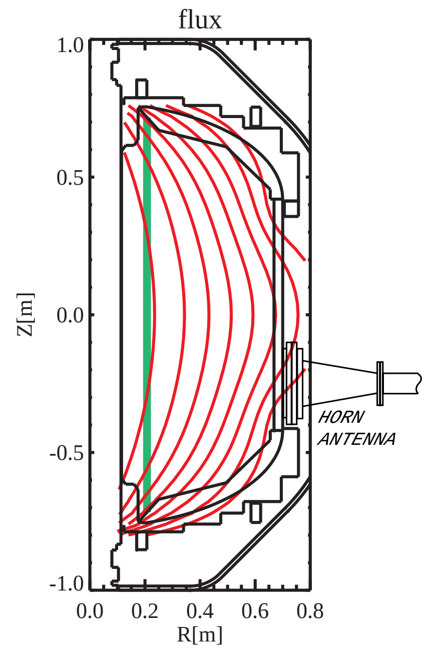
Non-inductive current initiation by ECH in TST-2

Achieved parameters

β_T	5.7% (β_N 2.7)
τ_E	3 ms
I_p	90 kA
B_t	0.2 T

- ECH (2.45 GHz)_ → 1 kA / 1 kW
- Low gas pressures → low collisionality
- Vertical field with positive curvature → trapped electrons





Other results

- During IRE, Impurity temperature increases from ~ 100 to 500 eV

TST-2: *Univ of Tokyo*

Summary

- Remarkable progress in ST physics and technology in just a few years
- MA machines validate important predicted physics
  - β_T ~ 35% achieved on NSTX
  - Good τ_E > 100 ms achieved by NSTX and MAST
  - Good progress with divertor power loading studies
  - Non inductive current drive observed
- Good progress with current initiation studies on HIT-II and TST-2
- Liquid Li experiments on CDX-U showing immediate plasma performance improvement
- Pegasus is upgrading to allow access to larger Ip/I_{TF}