Los Alamos
NATIONAL LABORATORY

Formation of Field-Reversed Configuration plasma for Magnetized Target Fusion in FRX-L

S. Y. Zhang, G. A. Wurden, T. P. Intrator, W. J. Waganaar, R. Renneke, J. M. Taccetti, I. Furno, S. C. Hsu, E. M. Tejero

(Los Alamos National Laboratory, Los Alamos, NM 87545)

C. Grabowski, E. L. Ruden

(Air Force Research Laboratory, Albuquerque, NM 87117)

Outline

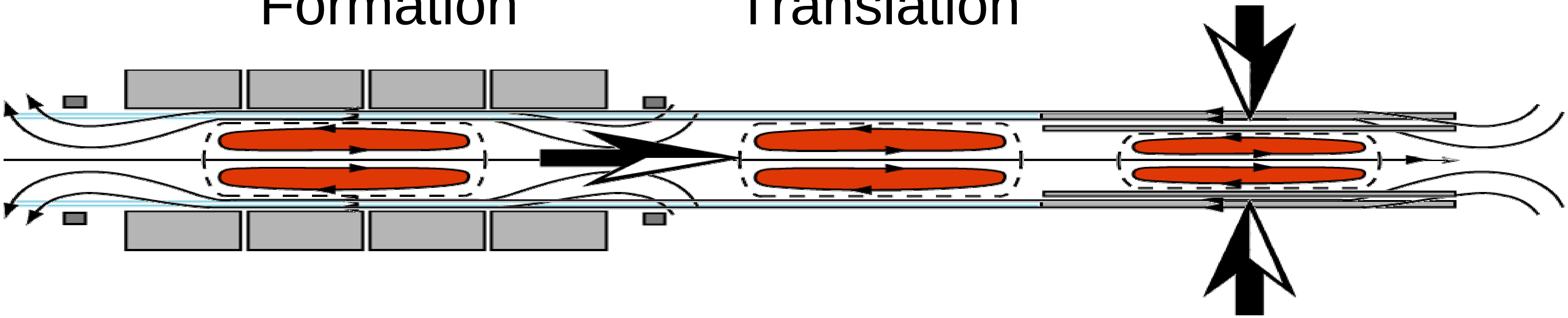
- FRX-L device and its diagnostics
- Examine the typical high density FRC that are within factors of 2-3 from target FRC
- Show that the high density FRC can be reproduced at high reproducibility at FRX-L
- Try to identify some factors that mostly affect the FRC formation and performances
- Discussions and summary

FRC-MTF: an alternative way to fusion
— Currently pursuing FRC parameters

Phase 1: Formation

Phase 2: Translation

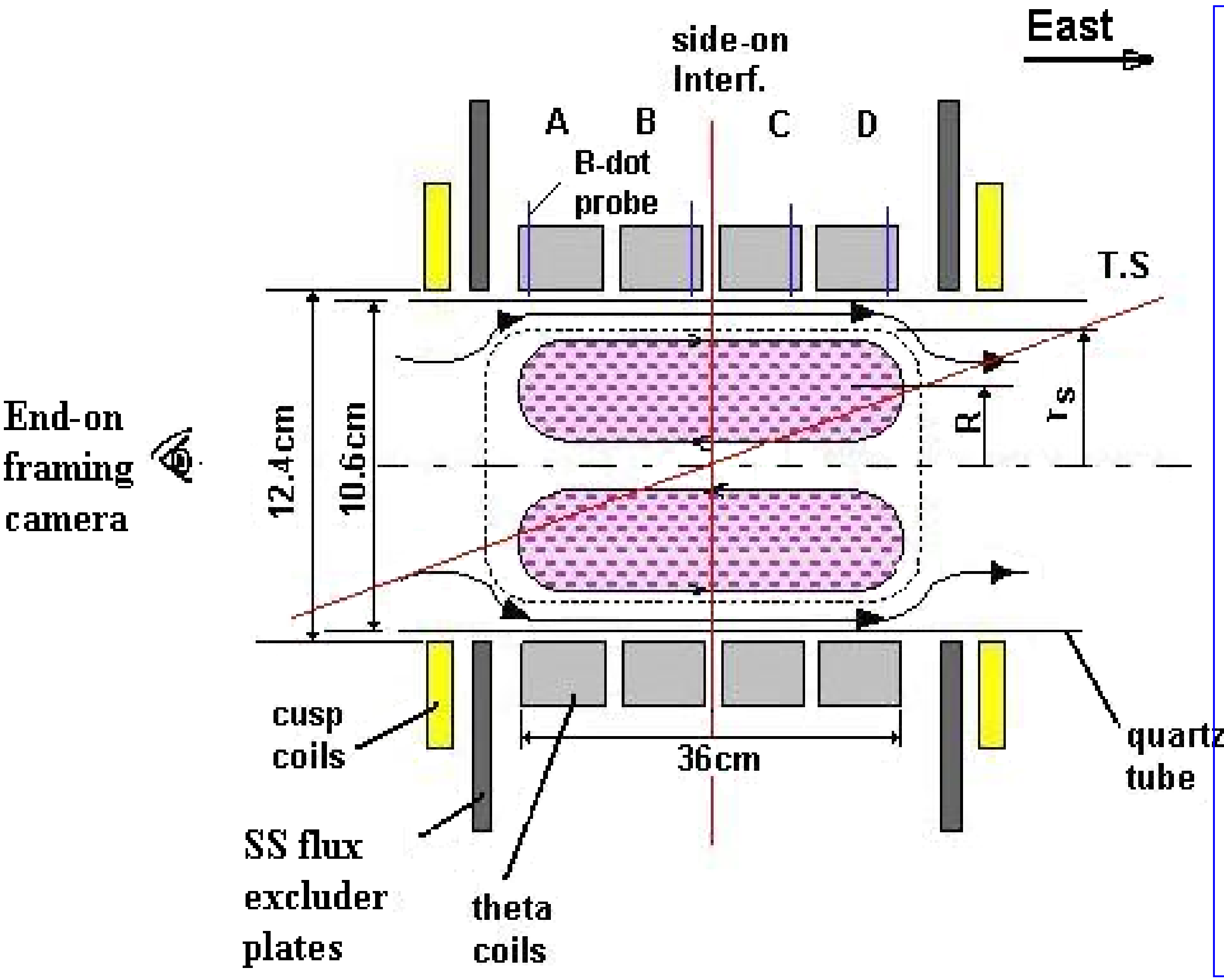
Phase 3: Compression



Density ~ 10^{23} m^{-3}
T ~ 150-300 eV
FRC lifetime ~ 20 μs
Highly reproducible

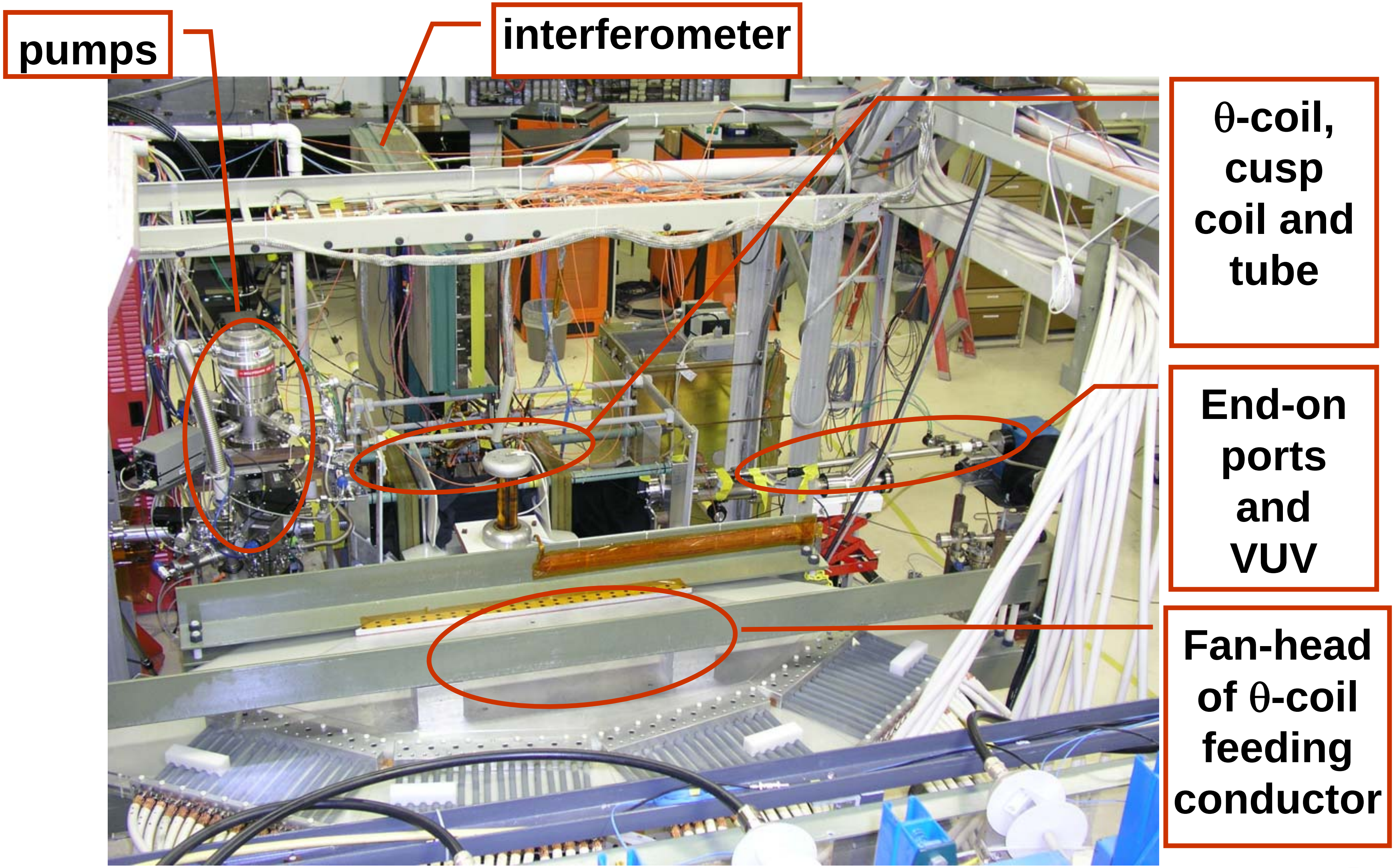
Adiabatic compression by very strong pulsed electromagnetic forces to reach fusion-relative conditions

FRX-L: dimensions and diagnostics

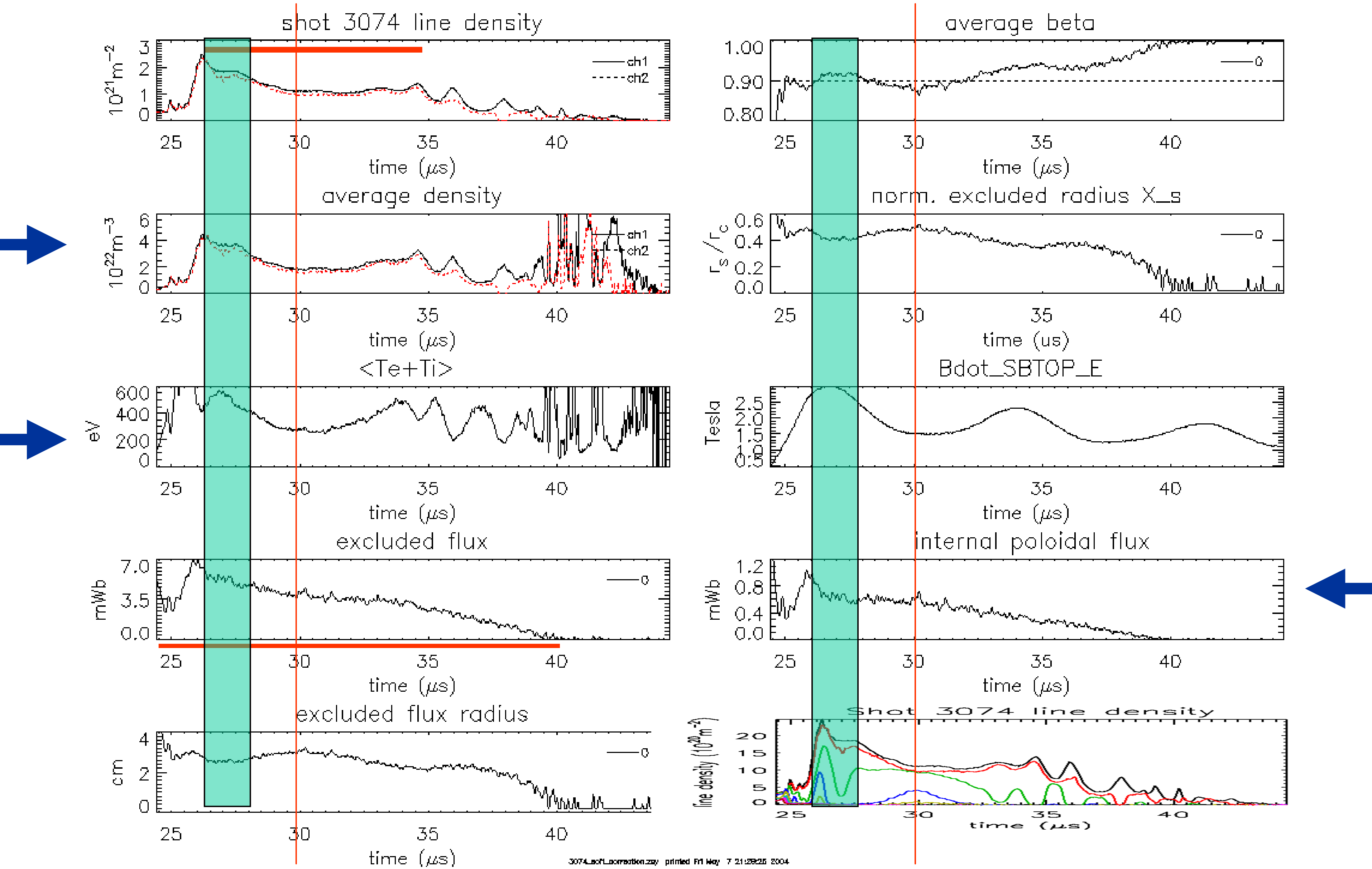


- 8 chs He-Ne laser interferometer
- External B-probes (>20)
- Single turn flux loop wires at A, B, C, D
- OMA1, OMA2
- Optical arrays
- Framing camera
- Spectrometers
- Thomson Scattering
- Bolometer

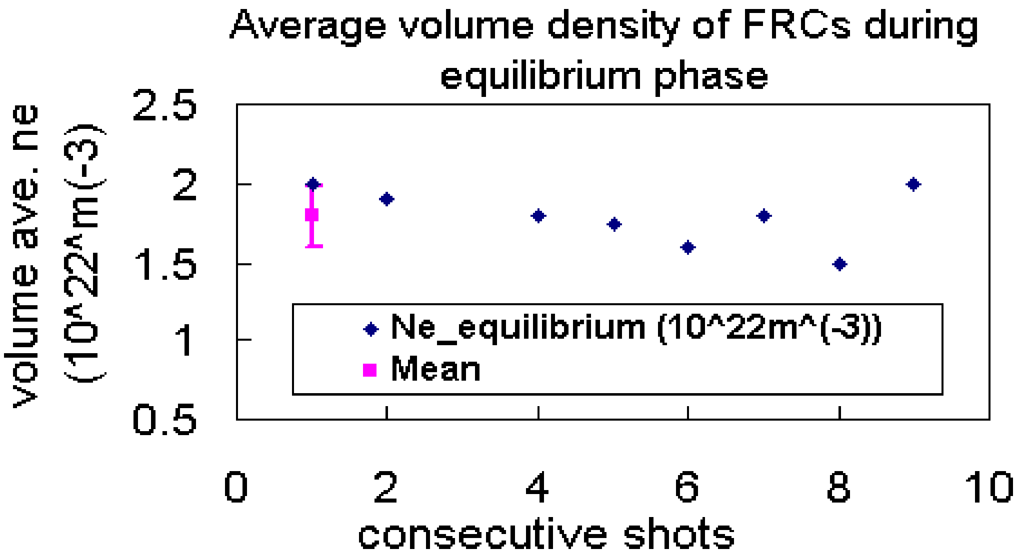
FRX-L at LANL

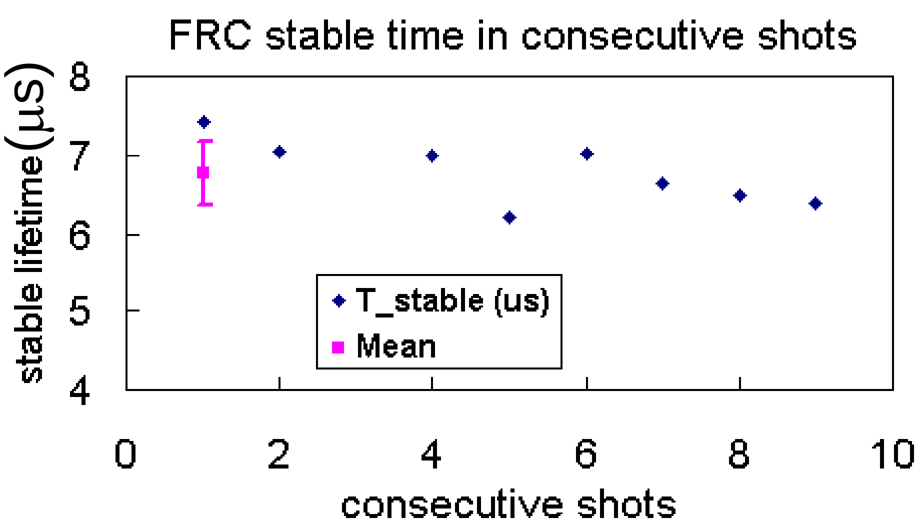

pumps
interferometer
θ-coil, cusp coil and tube
End-on ports and VUV
Fan-head of θ-coil feeding conductor

Typical High density FRC at 50 mTorr



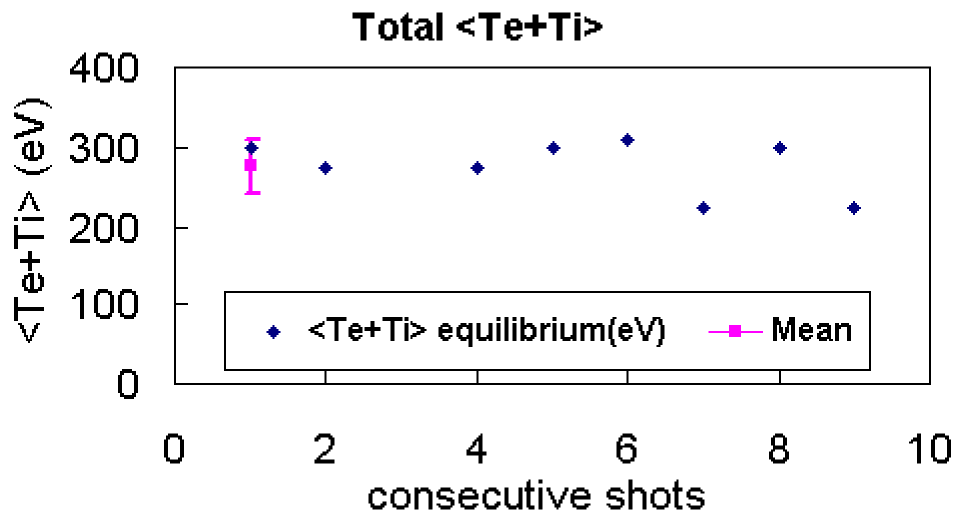
Reproducible high density FRCs (I)

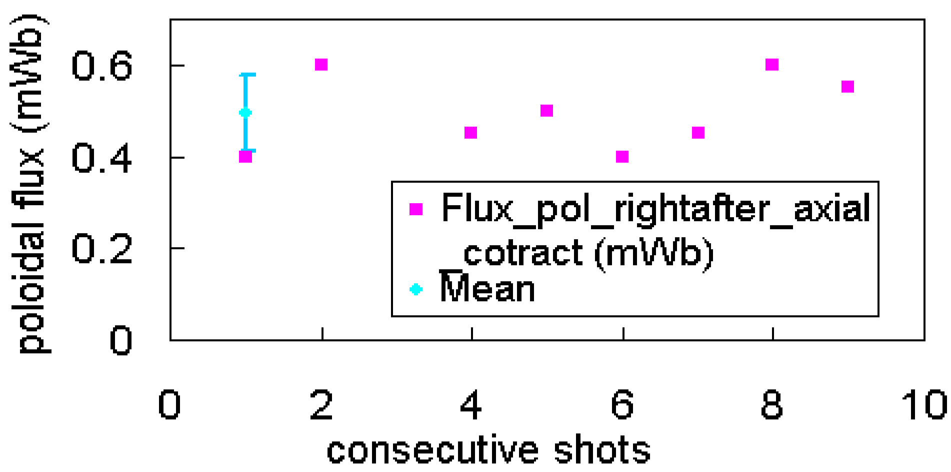




- Volume averaged $n_e \sim 1.8\times10^{22}$ m^{-3}; the STDEV is ±10% of the mean in the 9 consecutive shots.
- FRC stable time 6.8 μs; STDEV is ~ 6% of the mean.
- FRC lifetime is ~ 17 μs for well formed FRCs.

Reproducible high density FRCs (II)





- P_0= 50 mTorr, D_2
- Net bias B_0 ~ 2kG
- Green-Newton B* ~ 3.25 kG
- Lift-off B_{LO} ~ 1.67 kG
- G_{LO} ~ 0.5;
- B_{LO}/B_0 ~ 0.84
- STDEV are within ~10% of mean.

Compare the FRC's flux retention rate with other experiments

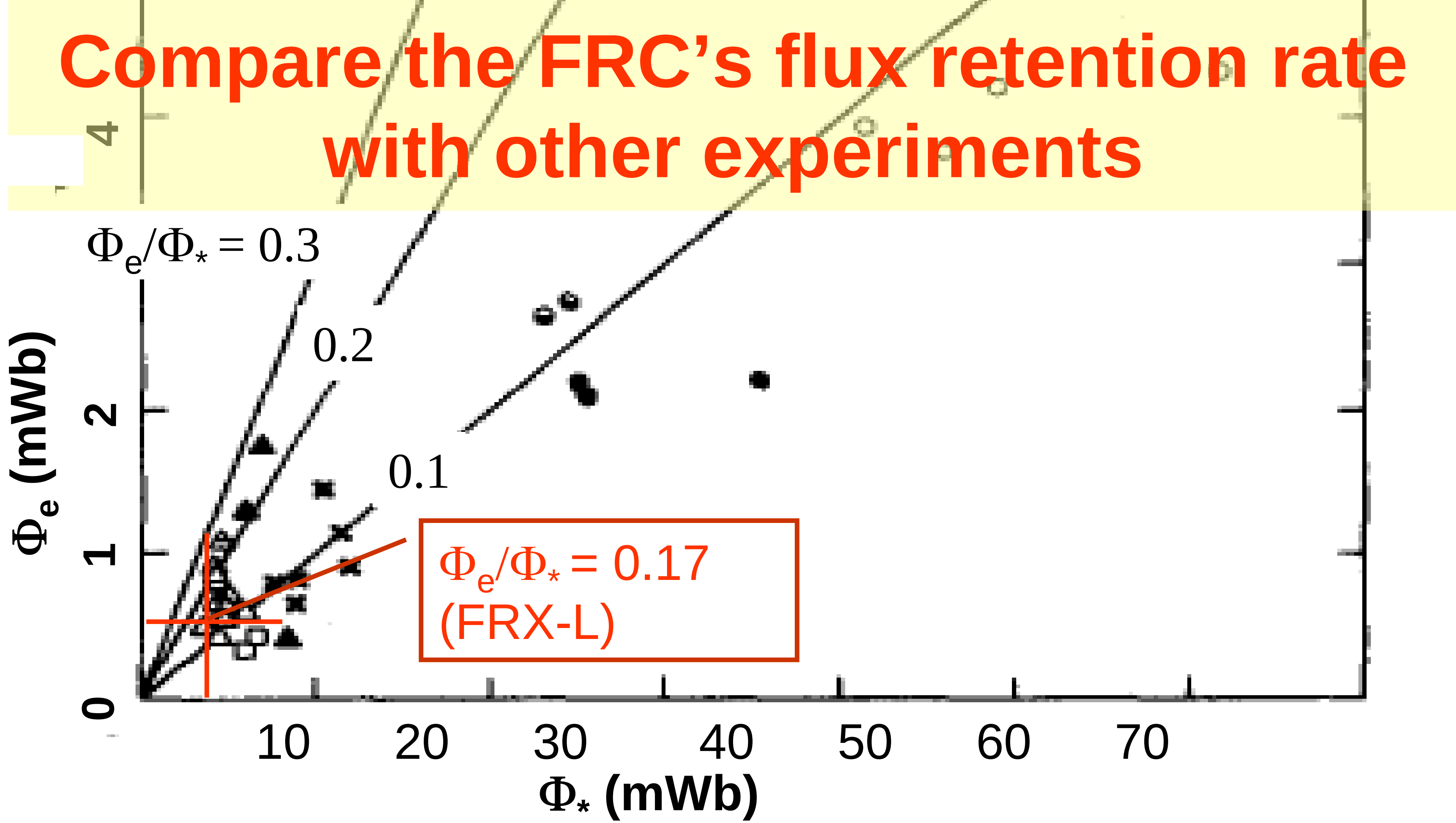
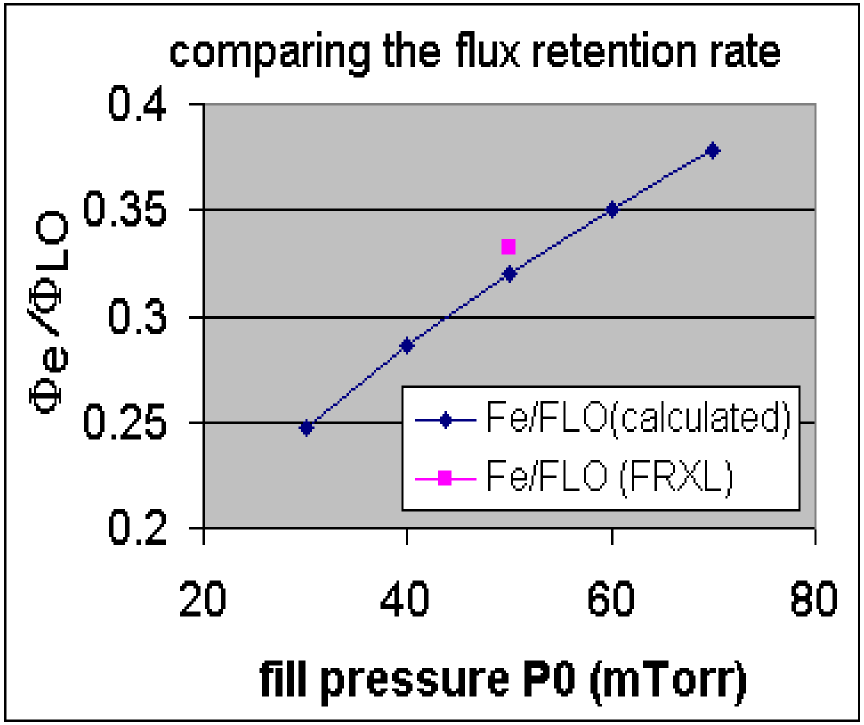


FIG. 3. Experimental values of equilibrium flux just after formation for long-lived FRC's from various devices. Symbols: □, FRX-A; ×, FRX-B; ▲, TRX-I; △, TRX-2; ●, FRX-C; ○, LSM; symbols for reduced B_c: ◬, TRX-2; ◒, FRX-C; ⊖, LSM.

Φ_e/Φ_{LO} conforms with empirical law



$\Phi_e/\Phi_{LO} = 0.85\, r_t(m)\, P_0^{\,½}\,(mTorr)$

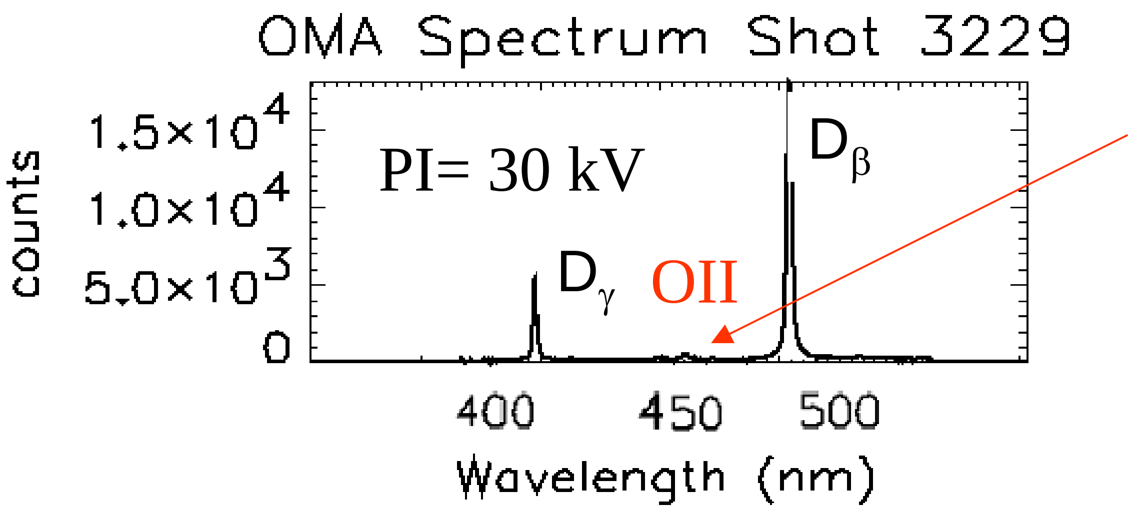
- $\Phi_e/\Phi_{LO} \approx 0.33$ conforms with empirical law
- $\tau_s \sim 6.8\ \mu s$, $\tau_N \sim \tau_\Phi \sim 8 - 13\ \mu s$
- τ_s is ~ 2.5 times less than previous mid-large devices' scaling law
- Suggests much high particle loss and flux loss rate in FRX-L.

Factors that govern FRC formation in FRX-L

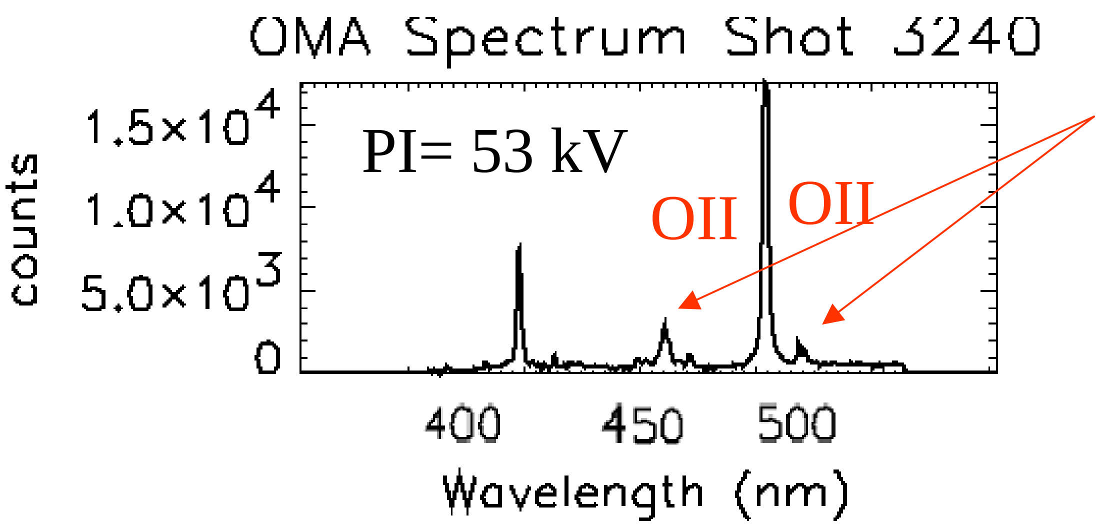
- Cusp locations at the θ - coil ends.
- Fill pressure
- Net bias field inside the θ-coil confinement region
- Main field modulation after being crowbarred.
- **Impurity level in the PI plasma**
- **Timing of main field relative to PI ringing cycles**

An optimal ensemble of all the above settings may lead to reproducible high performance FRCs.

Minimize PI can reduce plasma interaction with quartz tube wall

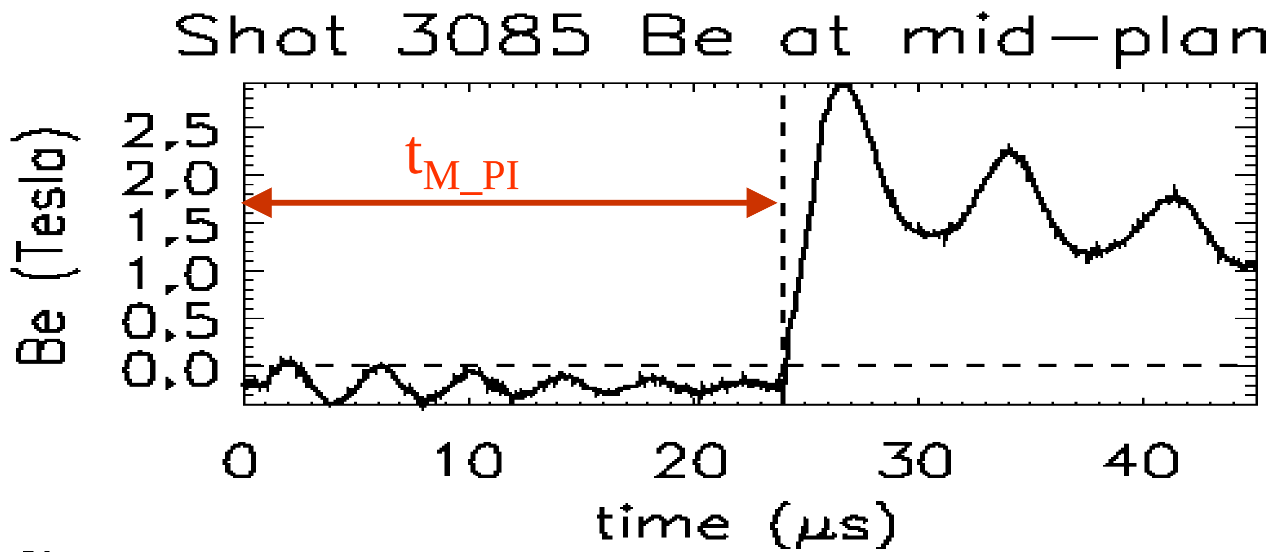


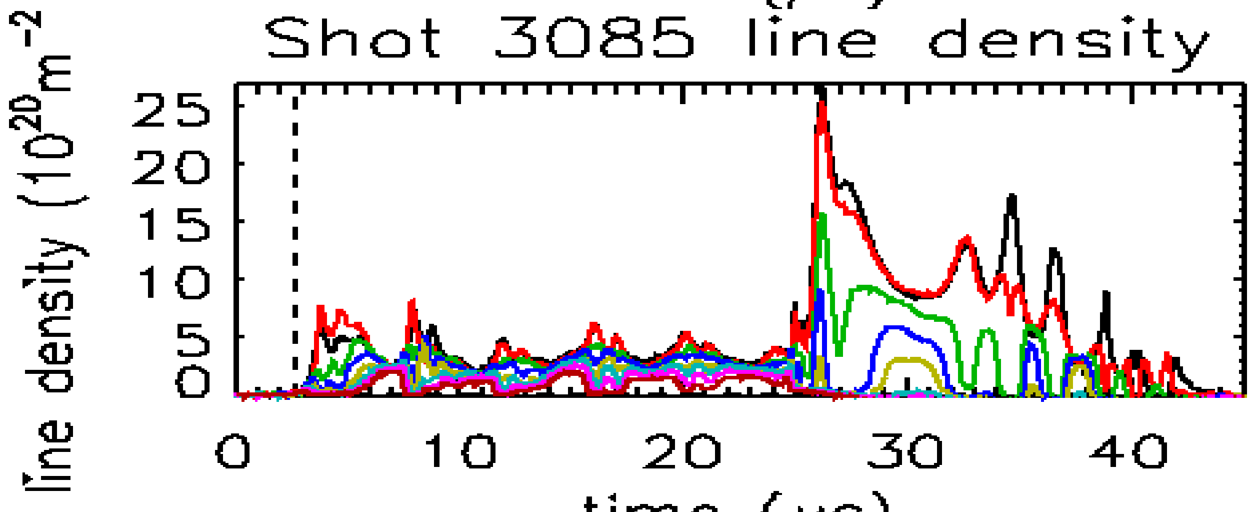
- PI= 30 kV, OMA showed small OII impurity lines.



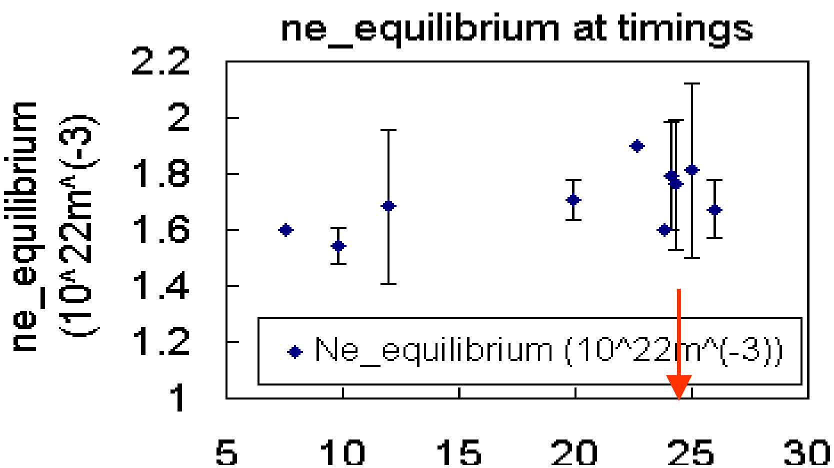
- PI= 53kV, OMA showed much stronger impurity lines of OII.

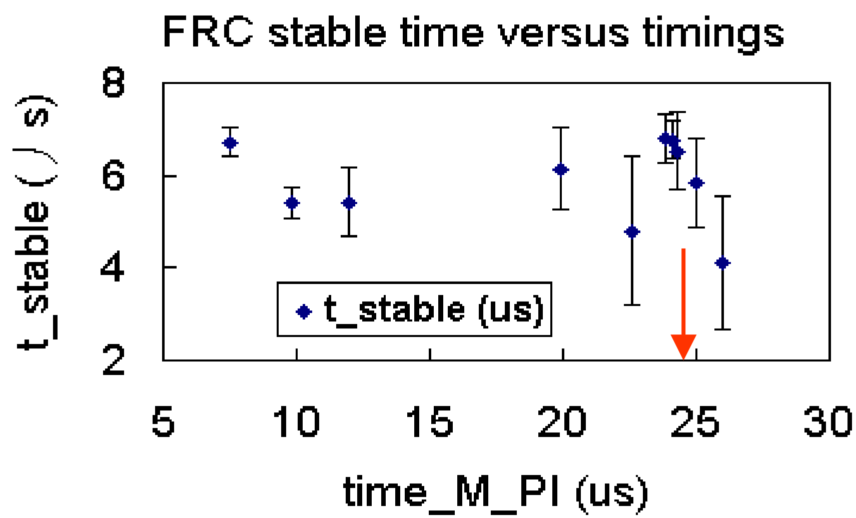
Timing between t_{MAIN} and t_{PI} is the key to reproduce good FRCs in FRX-L

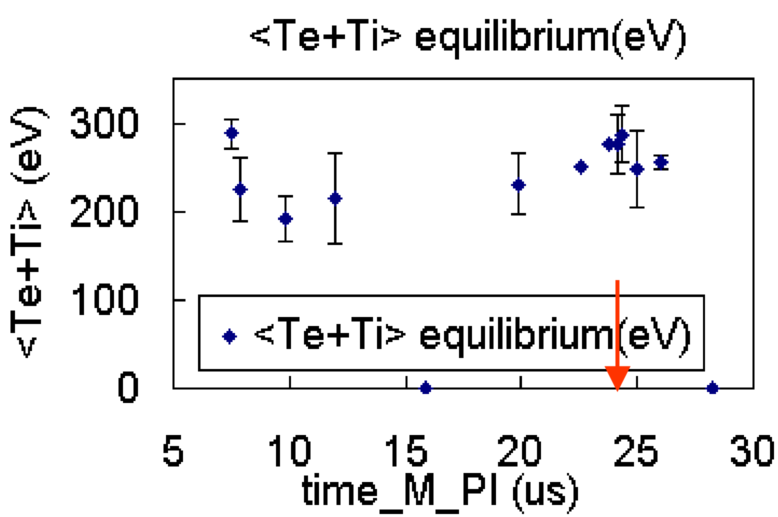




FRCs formed at later timings are mostly better than earlier ones

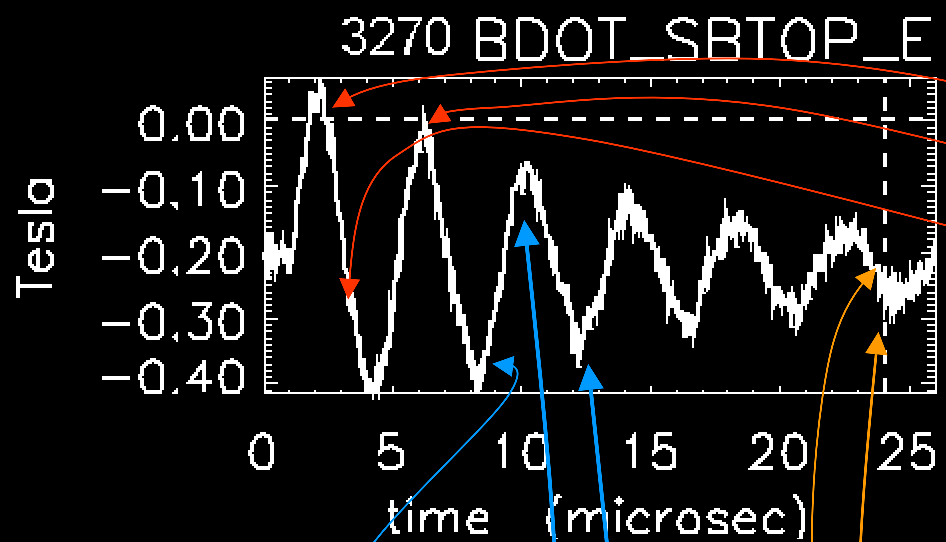




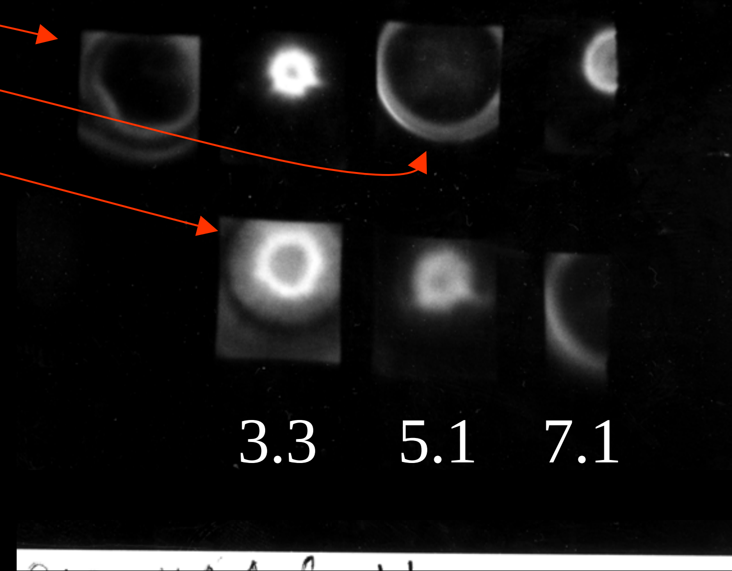


- **Criteria: Looking for high mean, low STDEV error bar for all the key parameters**
- **The best: 24.1± 0.2 μs**
- **best only at this set of control settings.**

Asymmetry in PI plasma dies away in later PI cycles



2.3 4.1 6.1 8.1



3.3 5.1 7.1

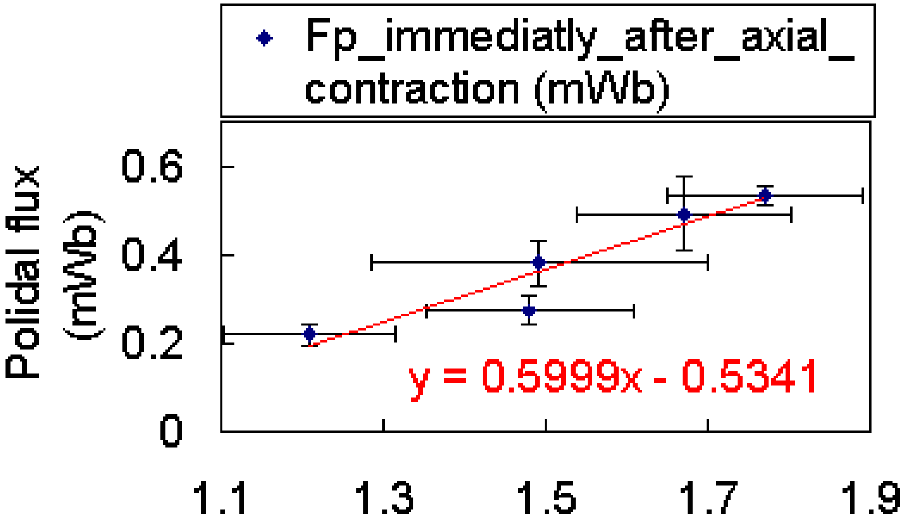
8.3 10.1 12.1

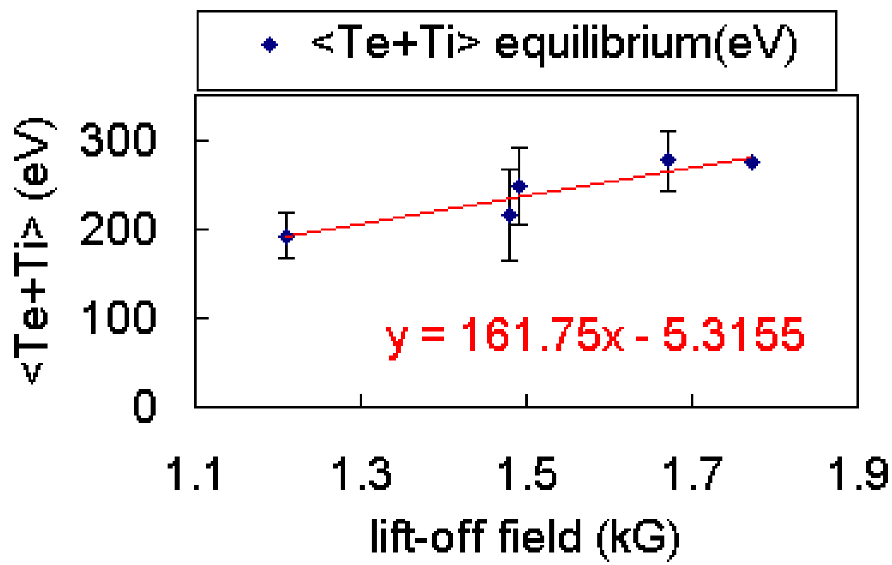
24.1 25.9 27.9 29.7

7.3 9.3 11.1

23.1 25.1 26.9 28.9

How to further improve FRC density and temperature performance?





- In well-formed FRCs, poloidal flux, <T> tend to increase with the lift-off field.
- $\Rightarrow$Increase B_0, P_0 and optimize control settings hopefully will lead us to the desired n_e <T> .
- In FRX-L, simply improving main field crowbar behavior will probably double n_e, and may increase τ_Φ, τ_N.

Can we get longer FRC stable time τ_s ?

- Contradiction may exist between scaling laws and one of the theoretical inferring:
  - Either τ_s, τ_ϕ, $\tau_N \propto R^2/\rho_i$

$$\Rightarrow \tau \propto r_c^{2/3} r_t p_0^{1/3} B_c^{+1/3}$$

  - Or $\tau_s \propto B_\infty^{-1} \psi_p^{-1}$ for strong viscous FRC. **(L. C. Steinhauer, Phys. Fluids, 24(2), 328(1981))**

  - **$\tau \propto$ f (FRX-L, P_0, B_0, cusp locations, t_{Main_PI}, impurity, …)**

- In FRX-L, the capability to scan higher density (n_e: $10^{22}m^{-3} \sim 10^{23}\ m^{-3}$, $P_0 \geq 50$ mTorr) at net $B_0 > 2$kG may provide data facts to find out how τ_s is affected by engineering parameters.

Summary

- In FRX-L, FRCs are produced with very good reproducibility by employing FRTP method, $n_e \sim 2\times10^{22}$ m^{-3}, T ~ 300 eV, FRC stable time of ~ 7 μs, $\tau_{lifetime}$ ~15 μs.
- Firing main bank at later PI cycles provides more chances to get highly reproducible good FRCs, when other factors are constrained; the reason is very likely due to the dying out asymmetries in the PI plasma in later PI cycles.
- The formation techniques developed in FRX-L made progress in getting reproducible high n_e FRCs for MTF; and thus showed FRTP is somewhat controllable than just a trial-and-error method that may have bothered quite a few experimentalists in old days.
- Dataset of FRX-L provides possibility to examine the rightness of extrapolating existing scaling laws to higher density regime FRCs.