Plasma Jets for Runaway Electron Beam Suppression*

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Requirements for rapid impurity production and delivery

In ITER runaway electrons are likely to be generated during Current Quench (RE current must be reduced to < 2 MA by collisional suppression with a response time < 10 ms)§

1) Large mass to reach Rosenbluth's electron density over a relatively large fraction of V_{plasma}
2) Prompt response and delivery
3) High injection velocity to reach RE beam in early phase of 'avalanche' at a distance larger than minor radius
4) High ram pressure of ionized injected impurity to penetrate strong confining toroidal field

§ S.Putvinski, *Disruption mitigation in ITER: Physics requirements,* US Disruption Mitigation Workshop, March 12, 2012

Are nanoparticle (NP) plasma jets a solution?

1) Large impurity mass: ← NPs have much larger mass than common gas atoms

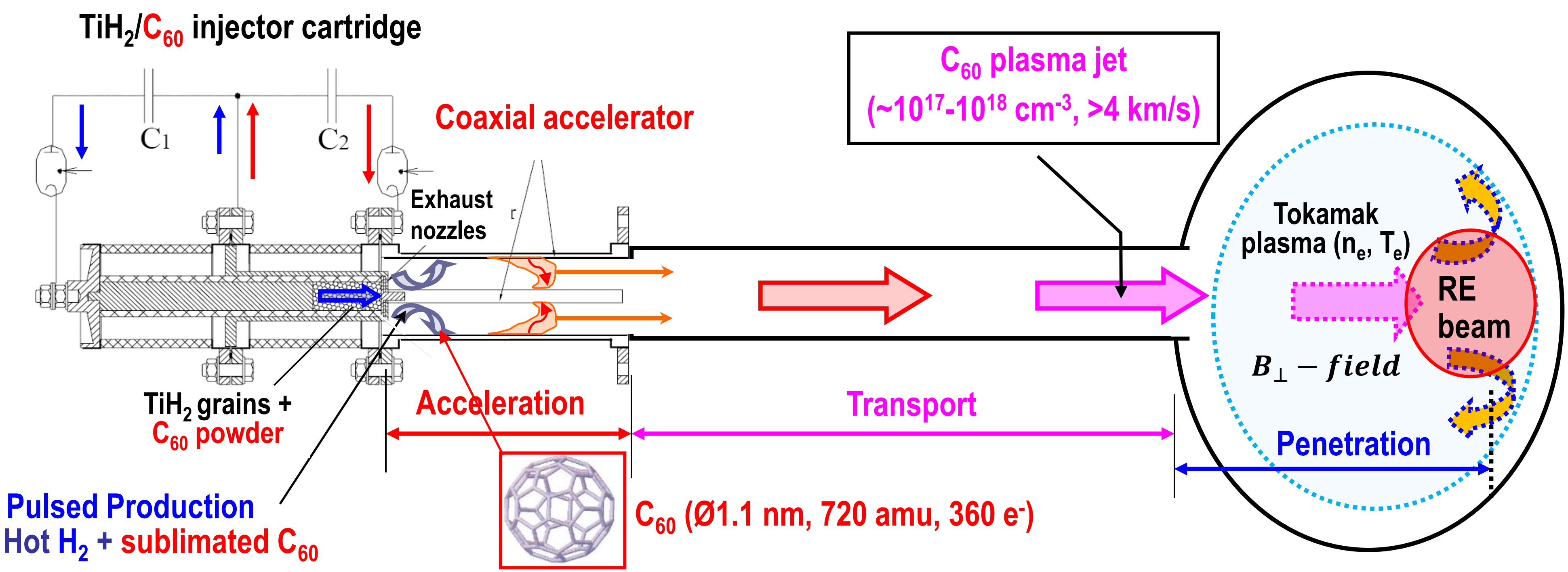
2) High injection velocity, rapid production & delivery: ← NP plasma accelerated to km/s!

3) High ram pressure ($\rho v^2/2$): ← NP plasma jet overcomes confining magnetic field pressure ($B_T^2/2\mu_0$) and penetrates to RE beam

<u>Inherent advantages</u>

- Efficient ablation and assimilation: ← NPs have a large surface to volume ratio
- Enhanced magnetic field penetration: ← NP plasmas have large mass to charge ratio
- Toroidal uniformity improved: ← NP plasma jets expand

C_{60} plasma jet from coaxial gun has injection and delivery potential for RE beam suppression/energy dissipation in DIII-D



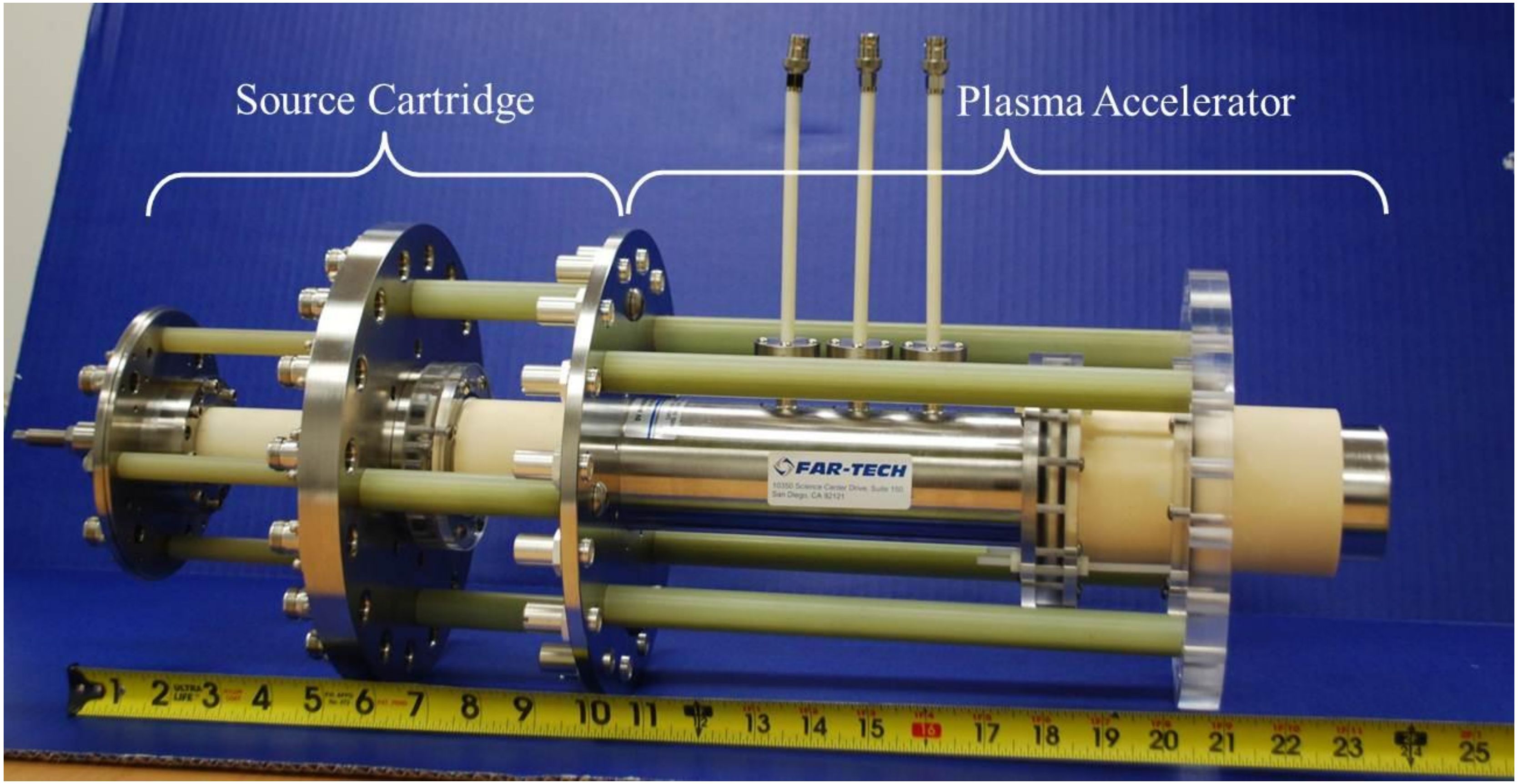
Duration:	$\sim 0.3\ ms$	$\sim 0.02\ ms$	$\sim 0.02 - 0.2\ ms$	$\sim 0.05 - 0.5\ ms$

Overall reaction time, from trigger to the delivery of impurity, is $\sim 1 - 2\ ms$

FAR-TECH's pulsed power system for C_{60}/C plasma jets

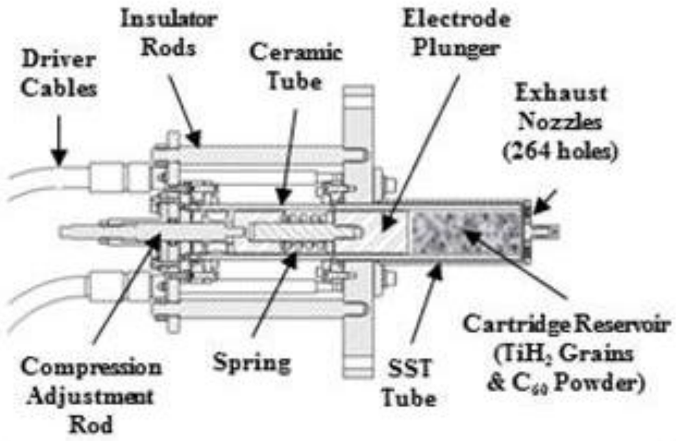
Key components:

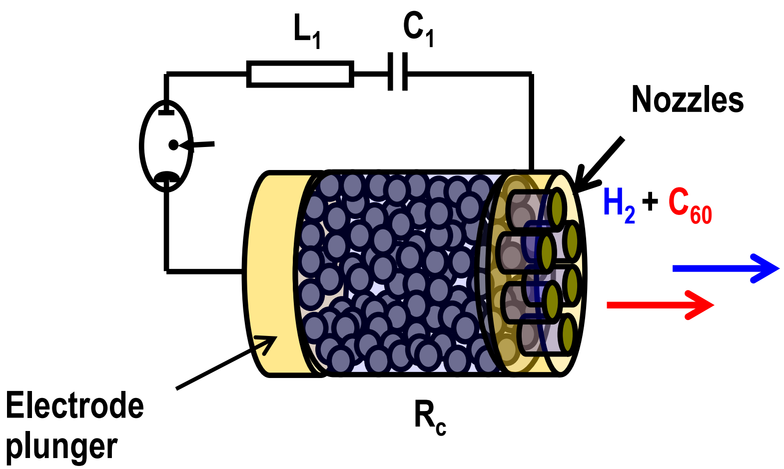
- TiH_2/C_{60} injector cartridge gas source† : $\sim 180\ mg$ C_{60} NP jet $(\sim 5 \times 10^{22}\ electrons)$
- Plasma accelerator: $v_{jet} \geq 4\ \ km/s$

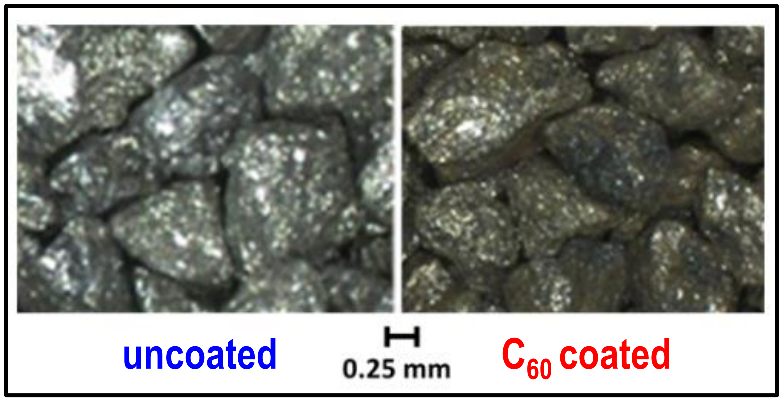


† I.N. BOGATU, *Fullerene/Titanium Hydride Gas Source* (Patent Application No. 12/002,420 submitted in December 2007)

Pulsed power driven TiH_2/C_{60} injector cartridge was characterized in shots with different composition, configuration, and fill length



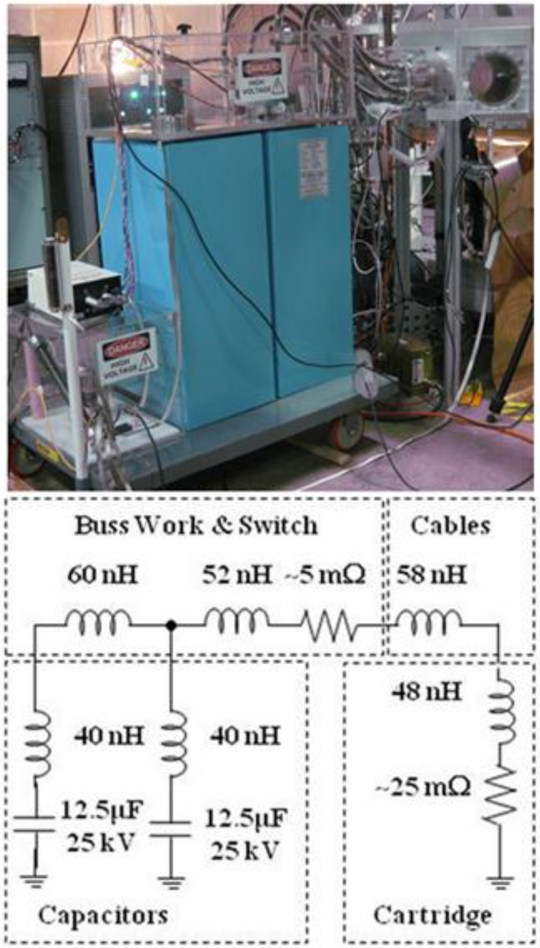




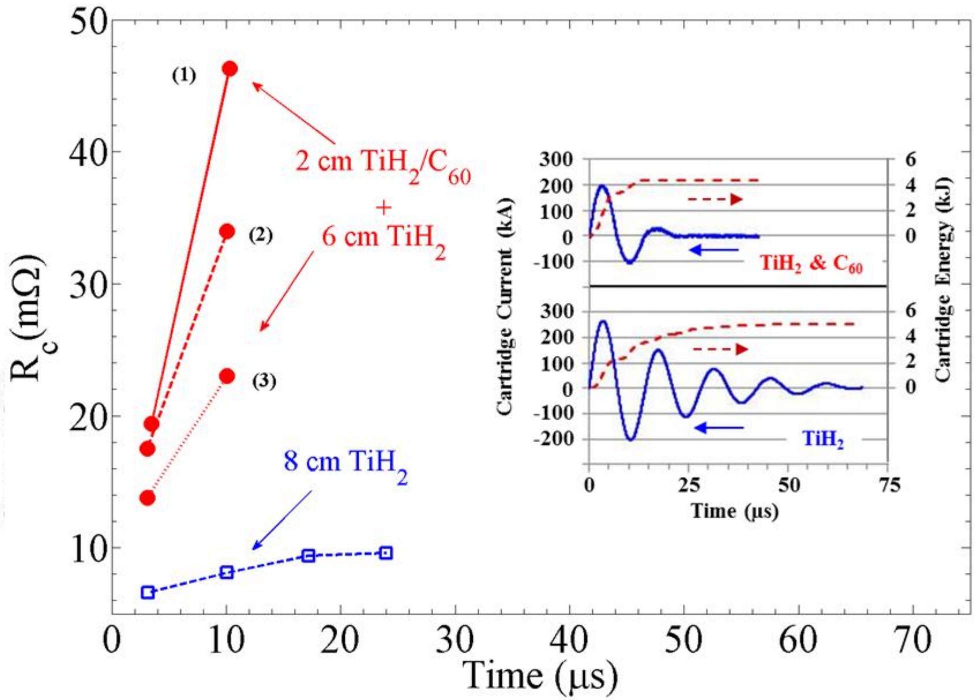
TiH_2 grains (~1 mm)

C_{60} coating increases cartridge resistance and relative energy deposition

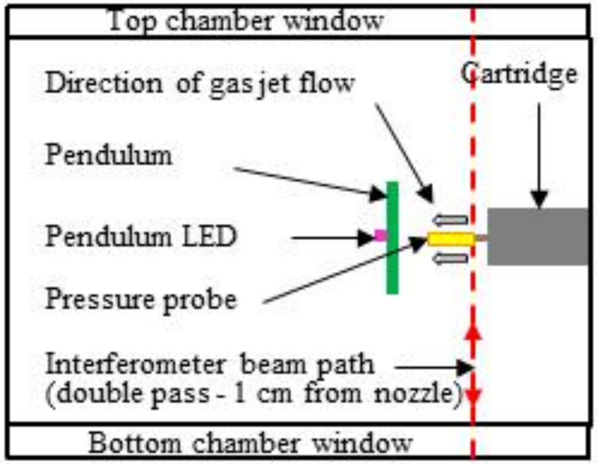
Cartridge capacitive driver and equivalent circuit



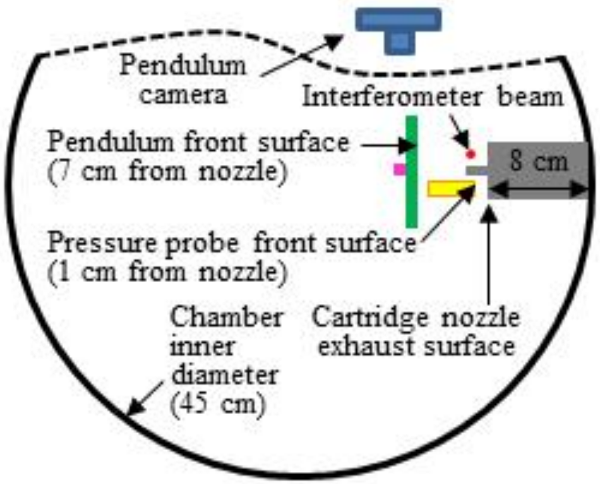
Cartridge resistance variation during the current pulse



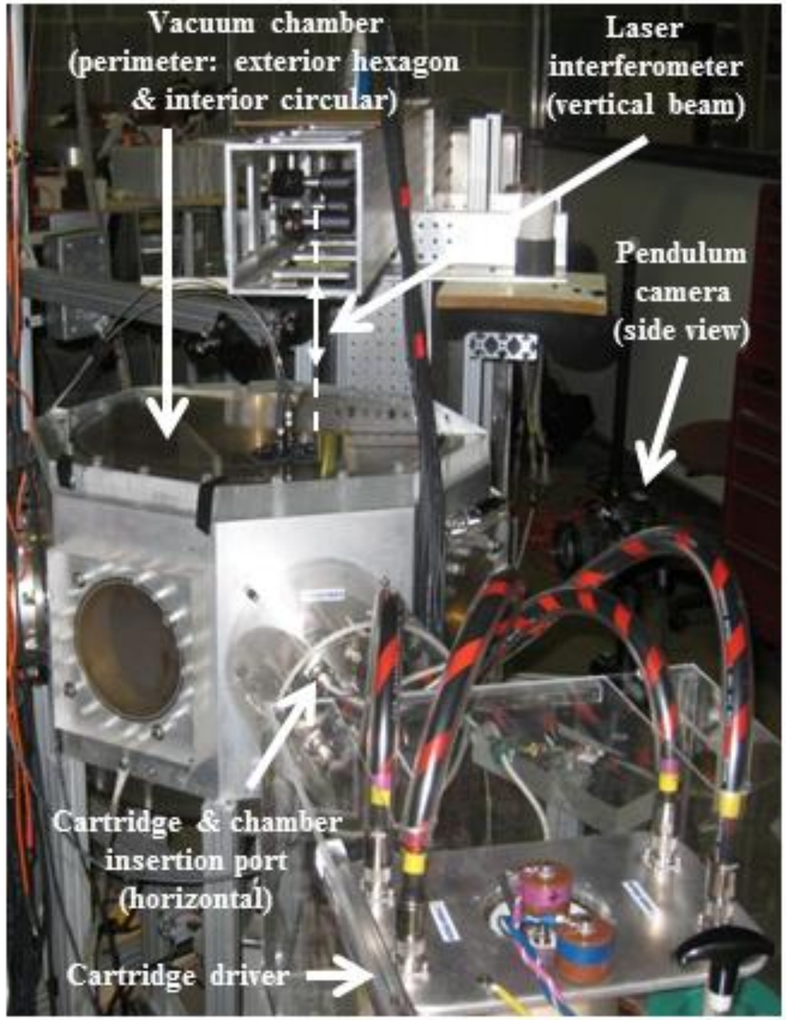
Diagnostics setup for cartridge H_2 and C_{60} molecular gas jets characterization



(a) Side view



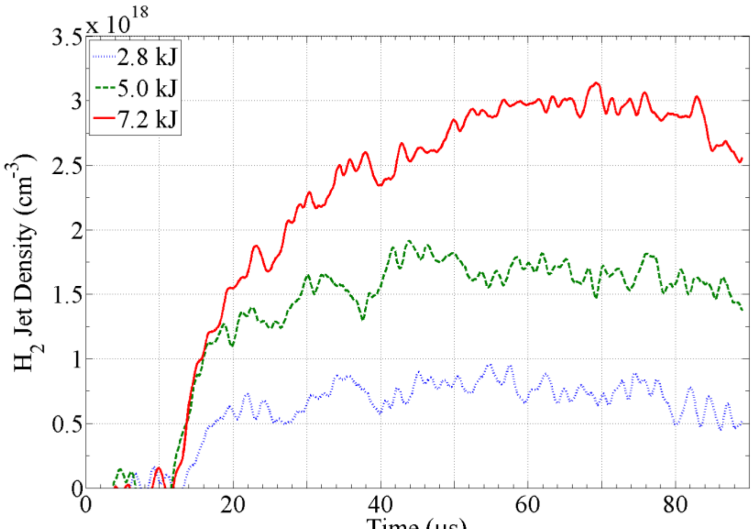
(b) Top view

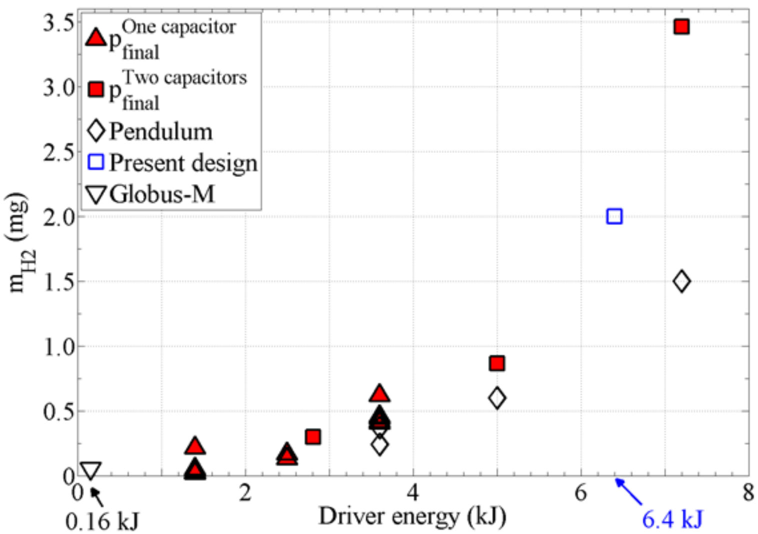


(c) Experimental setup photo

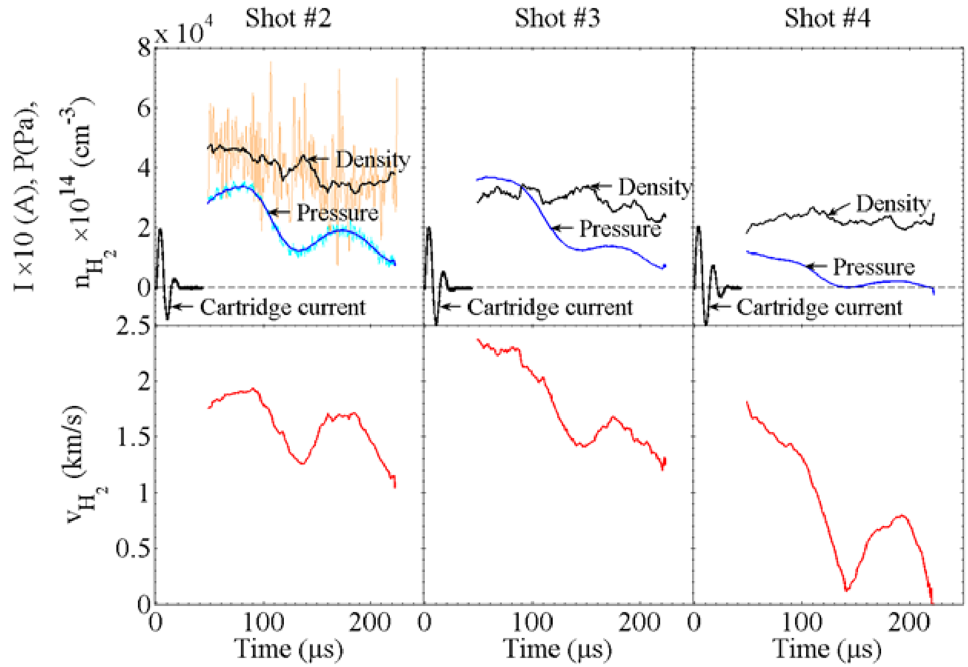
TiH_2/C_{60} cartridge produced in ~300 μs a C_{60} gas mass of ~180 mg with a velocity ~110 m/s

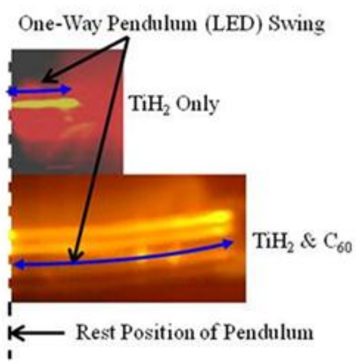
TiH_2 (only)

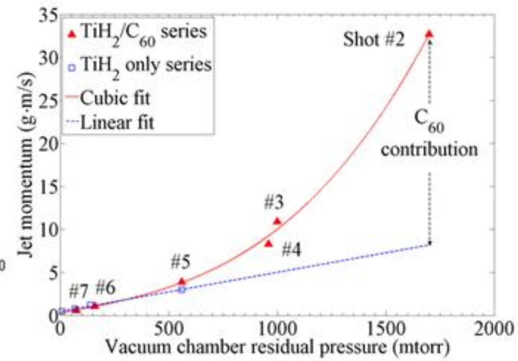




TiH_2/C_{60}

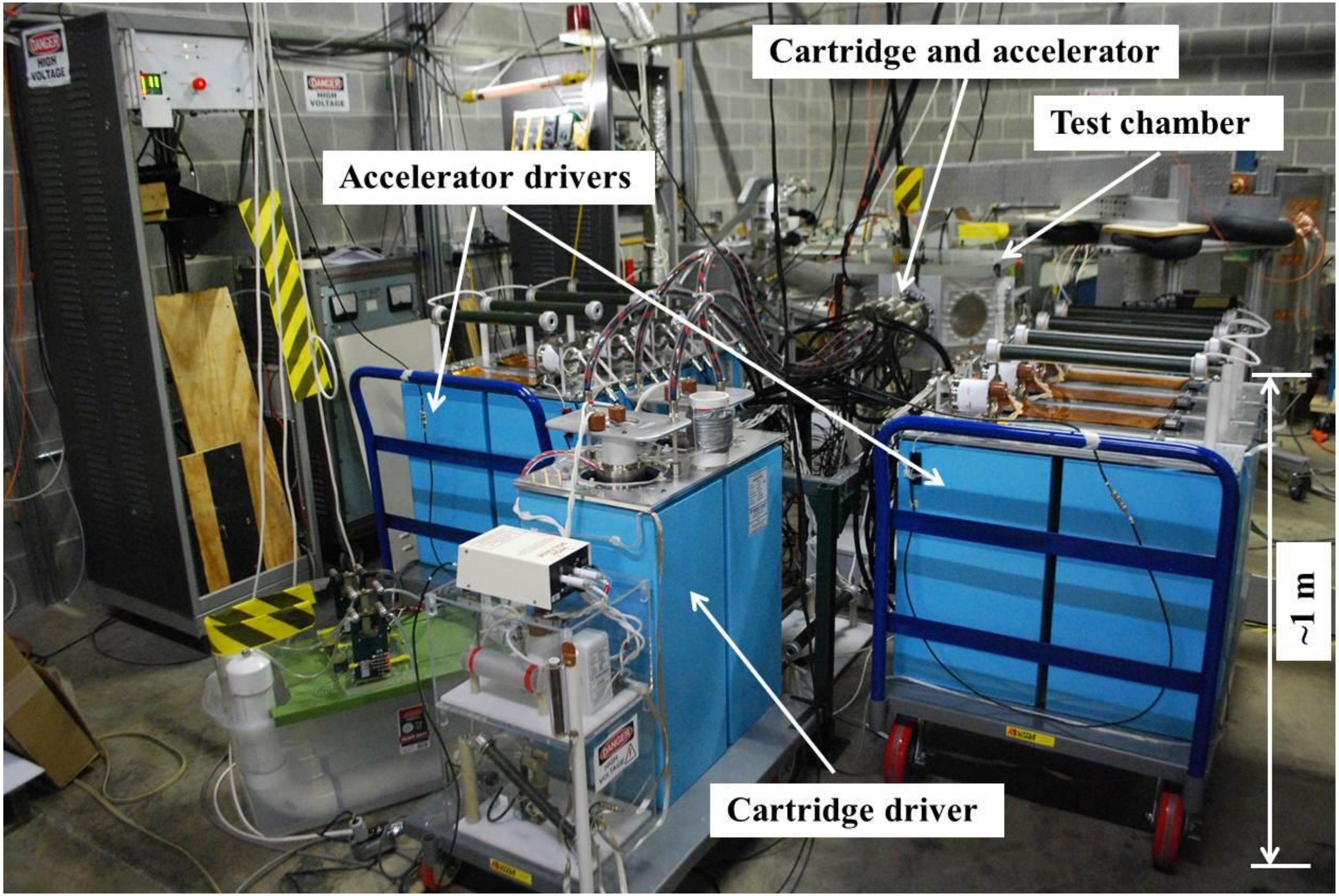




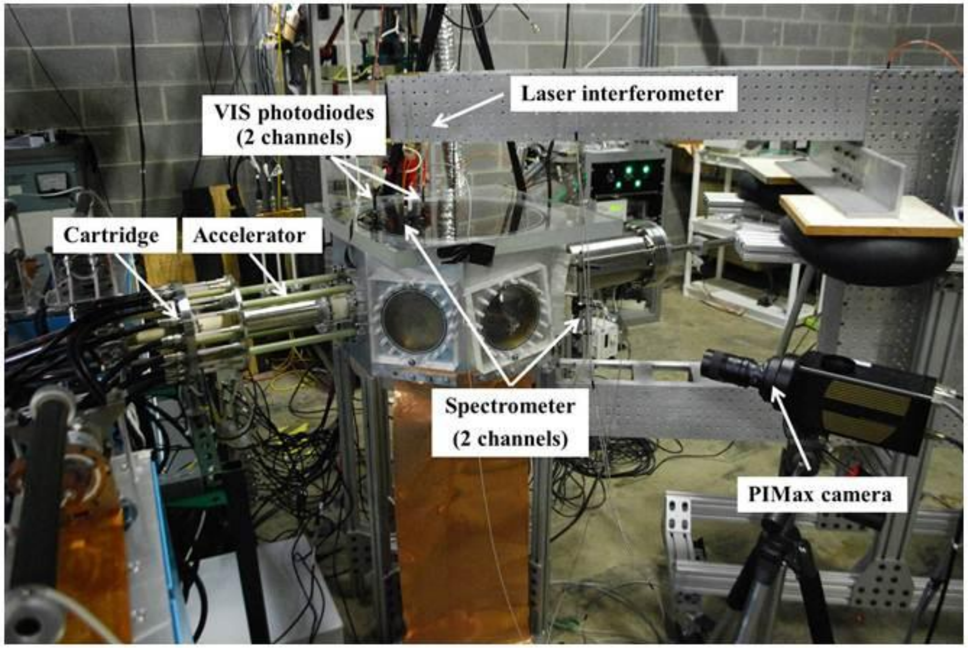


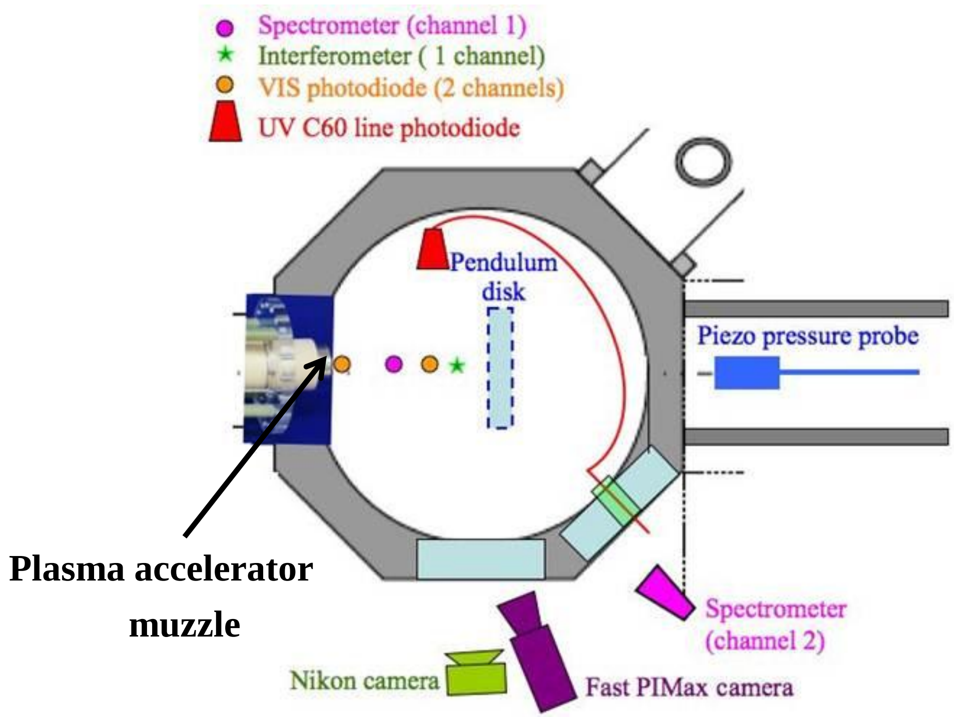
FAR-TECH

FAR-TECH's pulsed power system installed on test chamber at HyperV Technology Corp.



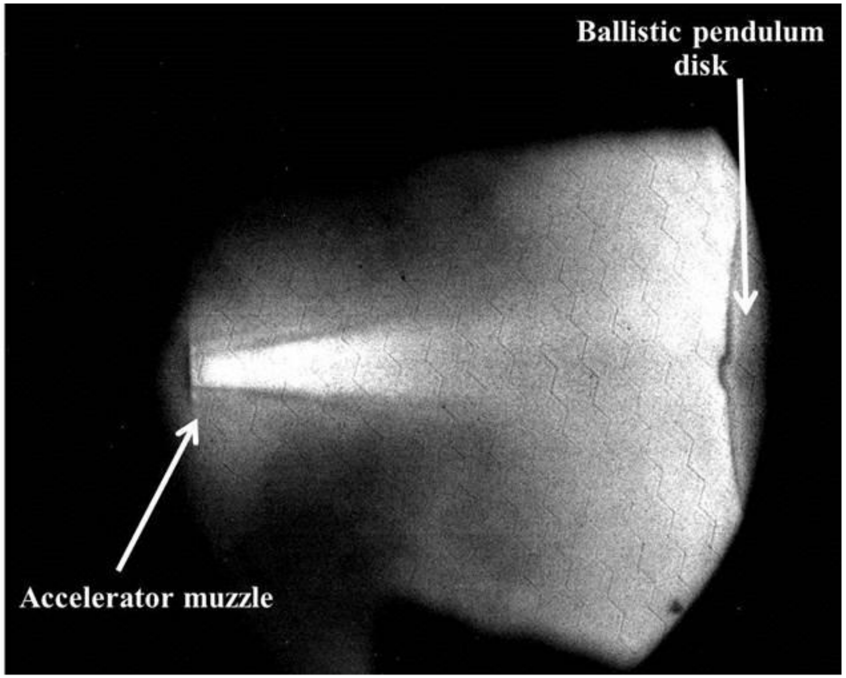
Diagnostics setup used for plasma jet measurements



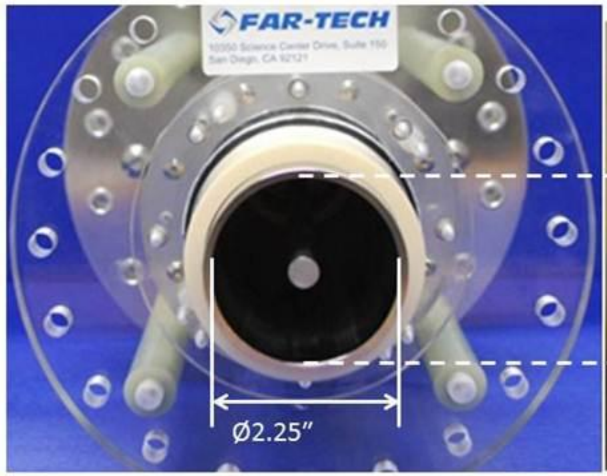


High Mach number C_{60}/C plasma jet shows a high degree of collimation

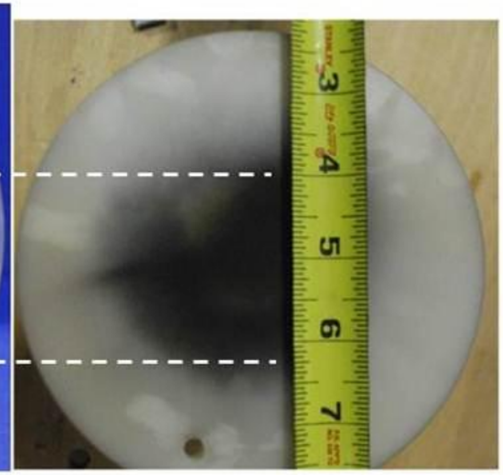
PIMax camera image



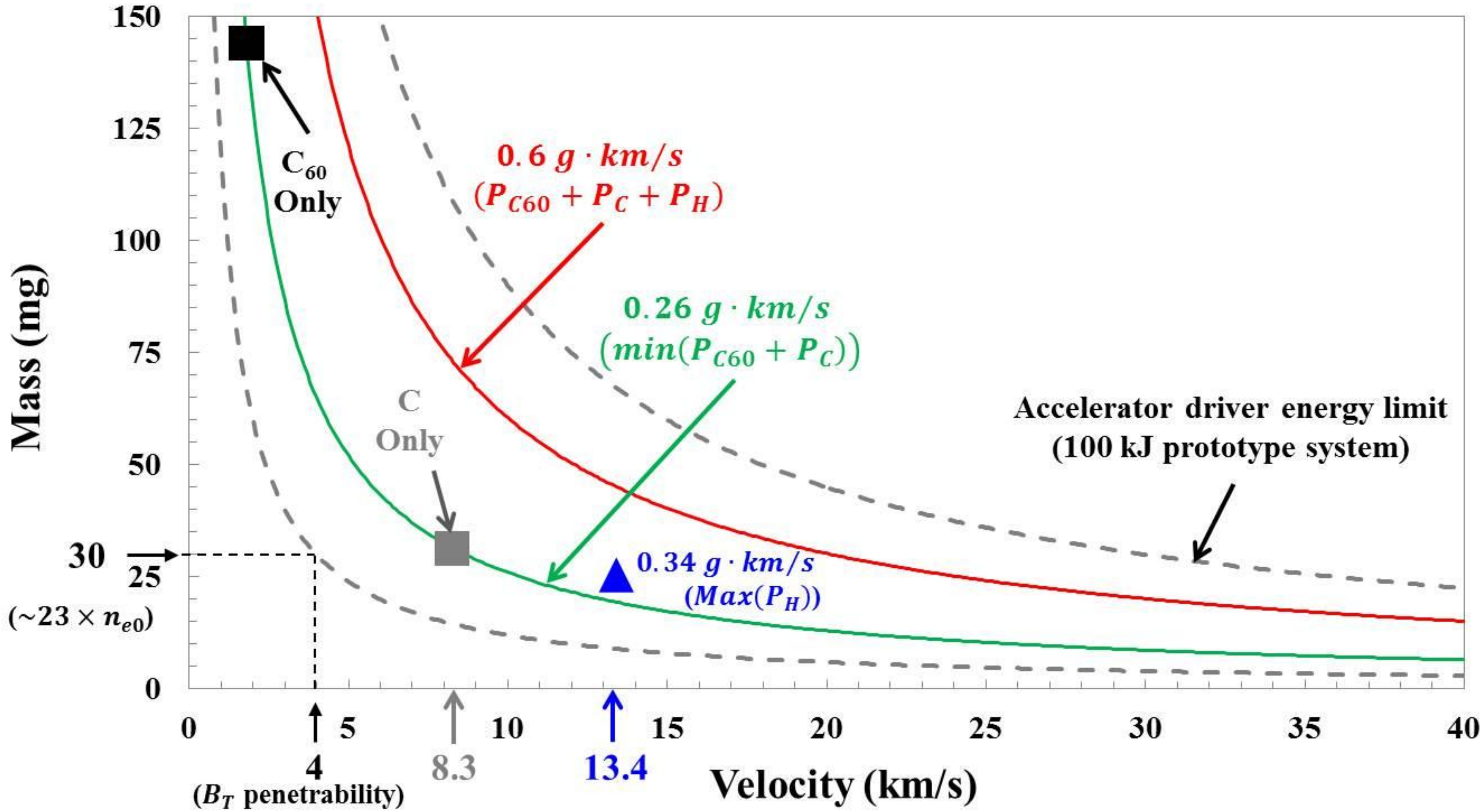
Plasma gun muzzle (front view)



Imprint on ballistic pendulum disk (at 8" from muzzle)



C_{60}/C plasma jet mass and velocity are in the range of several tens of mg with an average velocity of several km/s



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Plasma jet momentum is much larger than gas jet from cartridge injector only as shown by ballistic pendulum data

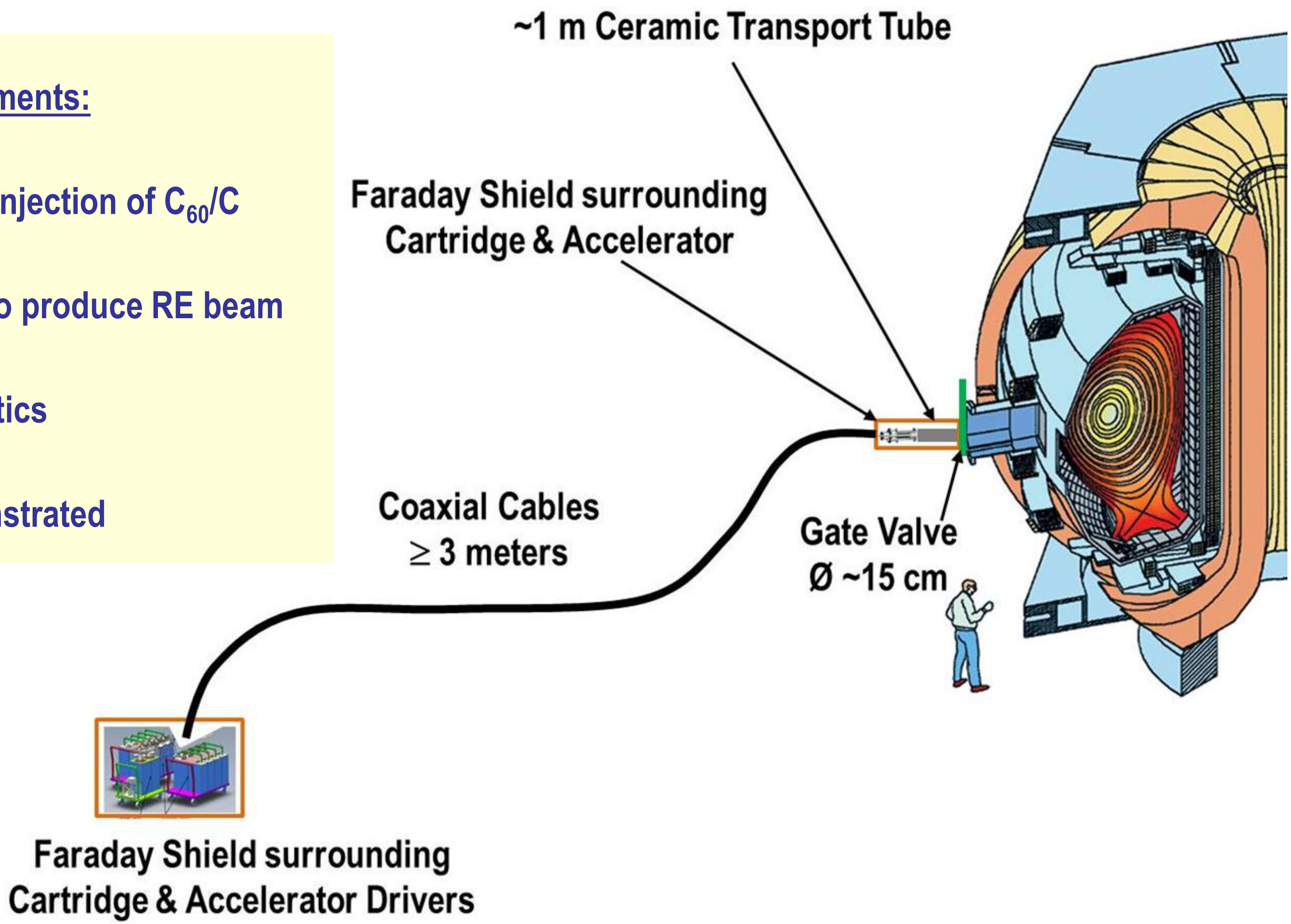
Gas/plasma jet momentum from repetitively firing with the same TiH_2/C_{60} cartridge at 5 kJ driver energy

Shot #	Ballistic pendulum data	
	Gas Jet (2010) $P_{H_2C_{60}}$ $(g \cdot km/s)$	Accelerated Plasma Jet (2012) $P_{H_2C_{60}C}$ $(g \cdot km/s)$
2	**0.033**	no data
3	**0.011**	no data
4	**0.008**	**0.605**
5	no data	**0.282**

C_{60}/C plasma jet implementation proposed for DIII-D†

<u>DIII-D is ideal for RE experiments:</u>

- C tiles compatible with injection of C_{60}/C
- Established technique to produce RE beam
- Broad range of diagnostics
- RE beam control demonstrated



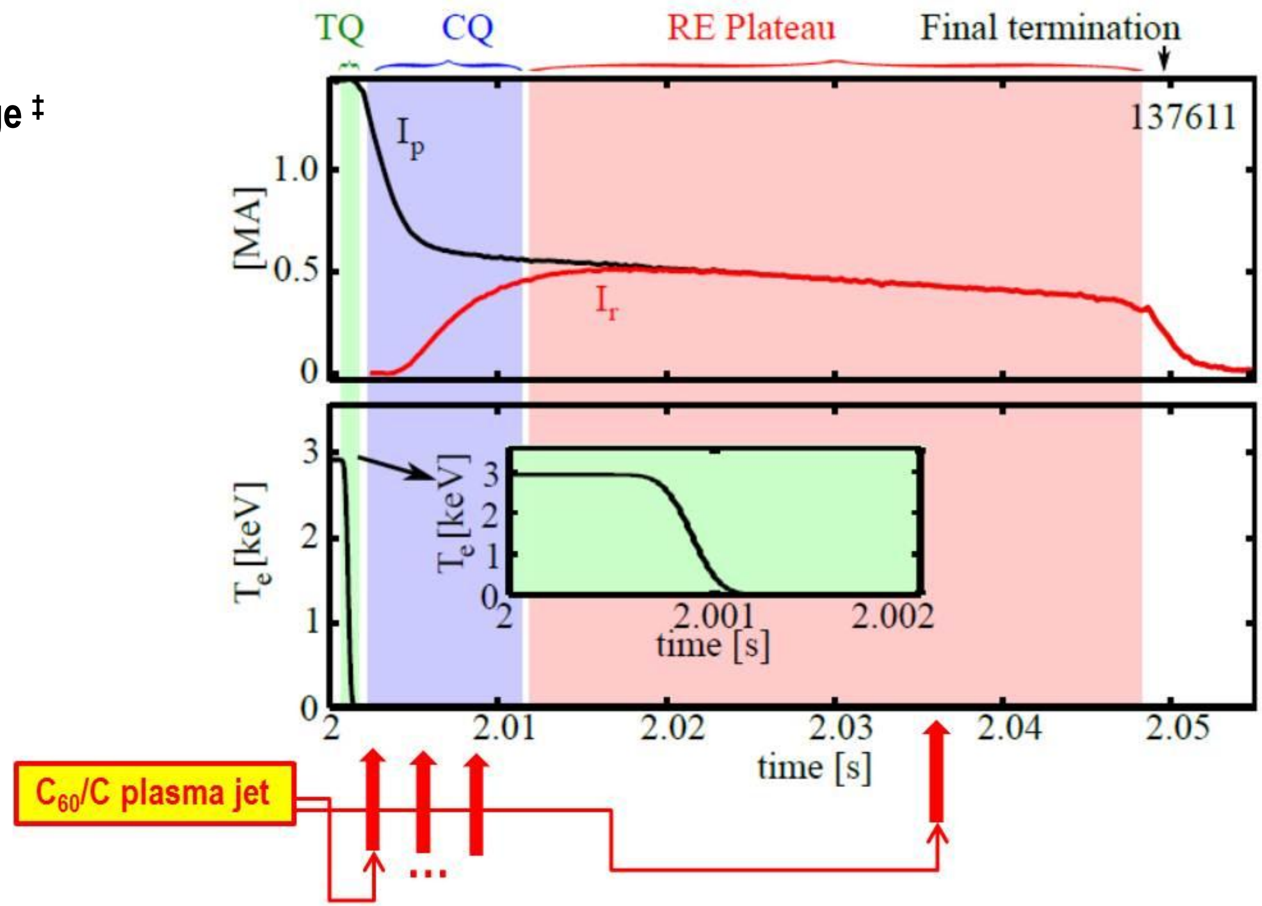
† Proposed for inclusion in the DIII-D Five-Year Plan

I.N. Bogatu, J. R. Thompson, and S. A. Galkin, *Plasma Jets for Runaway Electrons Avalanche Suppression*

Typical evolution of plasma current I_p, RE current I_r, and T_e during thermal quench (TQ), current quench (CQ) and RE Plateau in DIII-D

Pulsed millisecond plasma jet can act during RE current I_r rise (CQ) or on RE Plateau

DIII-D discharge ‡

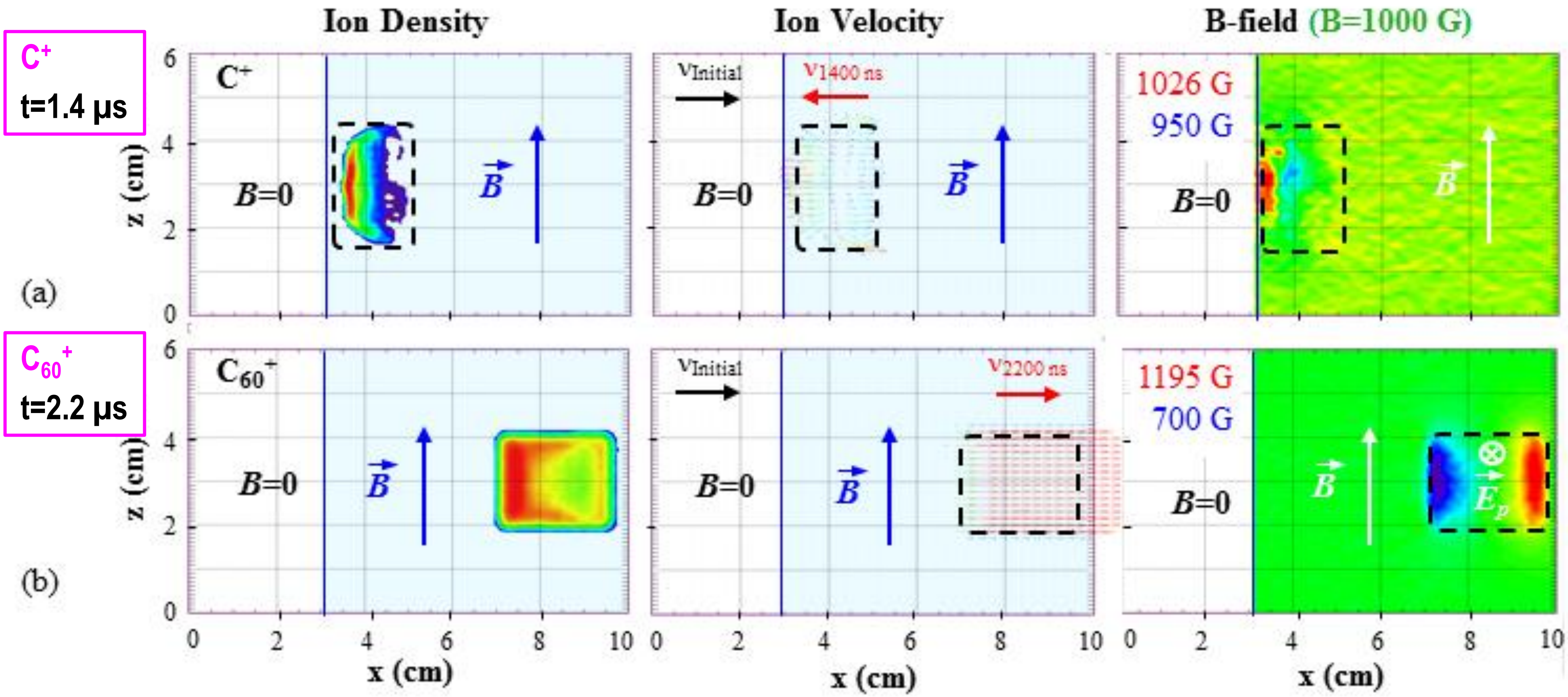


‡ Shot example on DIII-D (from A. N. James, *Investigations of runaway electron generation, transport, and stability in the DIII-D tokamak* 2011 APS-DPP)

Summary

- Hyper-velocity high-density C_{60} plasma jet from coaxial gun has rapid response, injection and delivery potential for RE beam suppression/energy dissipation
- Pulsed power system prototype for C_{60}/C plasma jets has been tested and provided:
  - ✓ ~180 mg C_{60} gas with velocity ~110 m/s from TiH_2/C_{60} cartridge in ~300 μs
  - ✓ Unprecedented momentum of ~0.6 g km/s of Mach number plasma jet
- C_{60}/C plasma jet proof-of-principle experiment proposed for DIII-D
- Pulsed millisecond plasma jet can act during RE current I_r rise (CQ) or on RE plateau suppress/deconfine REs before ‘avalanche’

PIC simulations: C_{60}^+ plasma penetrates $B_\perp$-field barrier as a compact structure by self-polarization



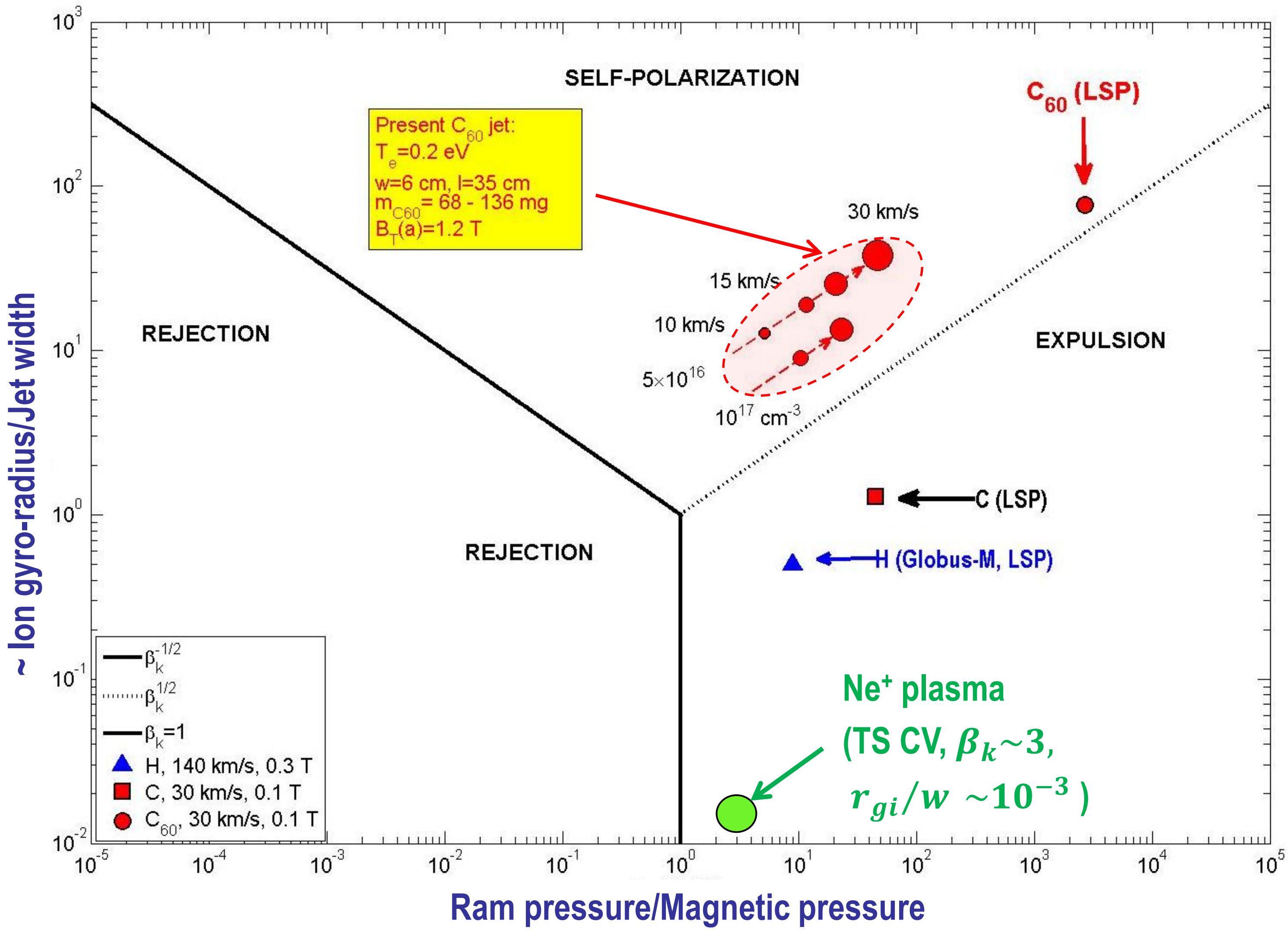
$$\vec{E_p} = -\vec{v} \times \vec{B}$$

LSP PIC code† 3D simulation of C^+ and C_{60}^+ plasmoids ($n=2x10^{16}$ cm^{-3}, T=1 eV, v_0=30 km/s) of penetration depth through transverse B_T magnetic barrier: comparative results

† WELCH, D. R., et al., Nucl. Inst. Meth. Phys. Res. A 464, 134 (2001).

S.A. GALKIN, I.N. Bogatu, and J.S. Kim, *3D Kinetic Simulation of Plasma Jet Penetration in Magnetic Field* (APS DPP 2009).

H, C, and C_{60} plasma jet parameters for LSP PIC code simulations and for present plasma gun



$$\frac{r_{gi}}{w} \frac{1}{2.3\sqrt{\beta_{ith}}}$$

$$r_{gi} = m_i v_0/(qB_\perp)$$

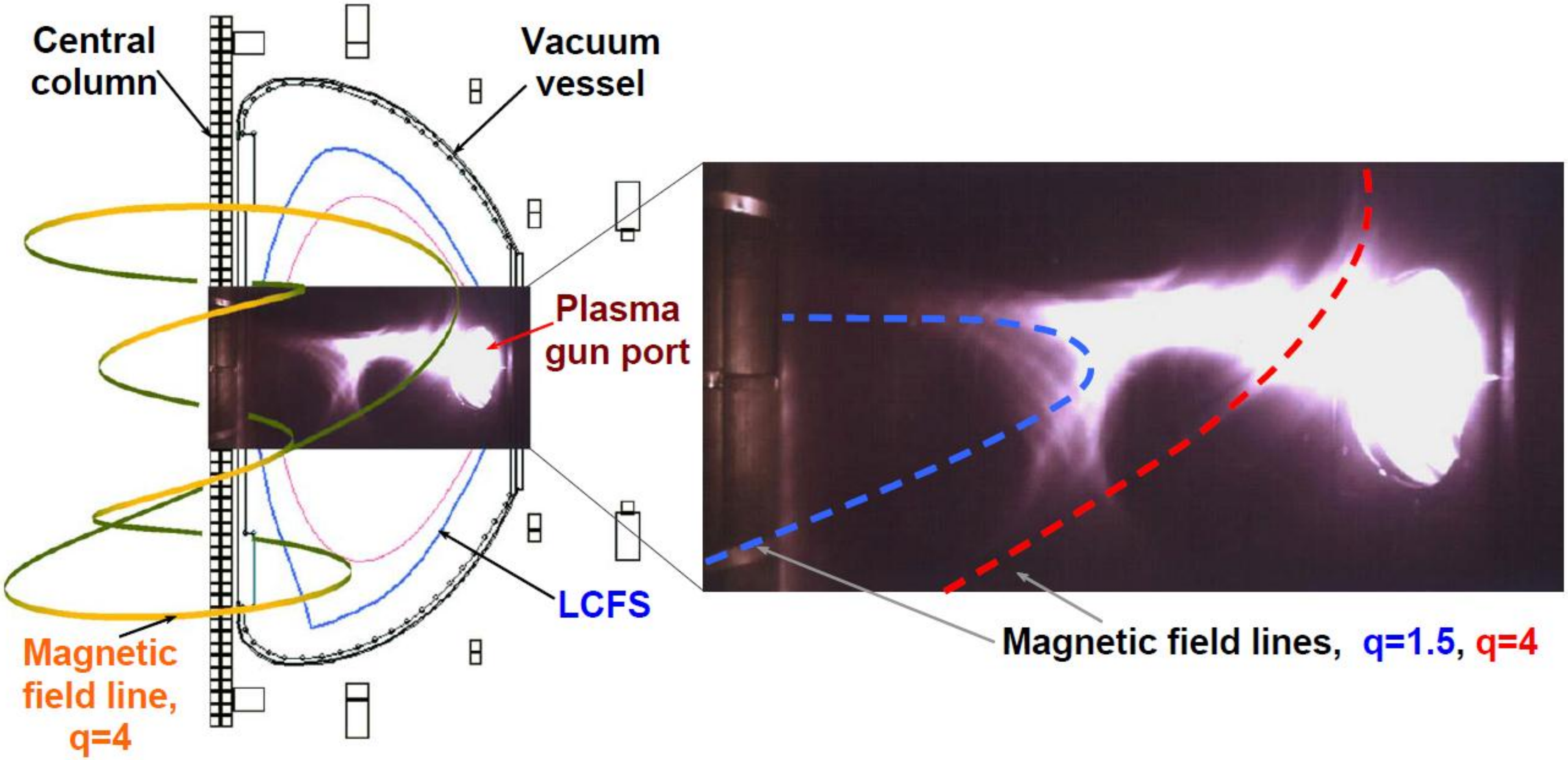
$$W_k/W_B$$

$$W_k = m_i n_{i0} v_0^2/2$$

FAR-TECH

Fast penetration (~50-60 μs) to plasma core of Globus-M tokamak‡ demonstrated by hyper-velocity (~110-140 km/s) H plasma jet

Globus-M tokamak

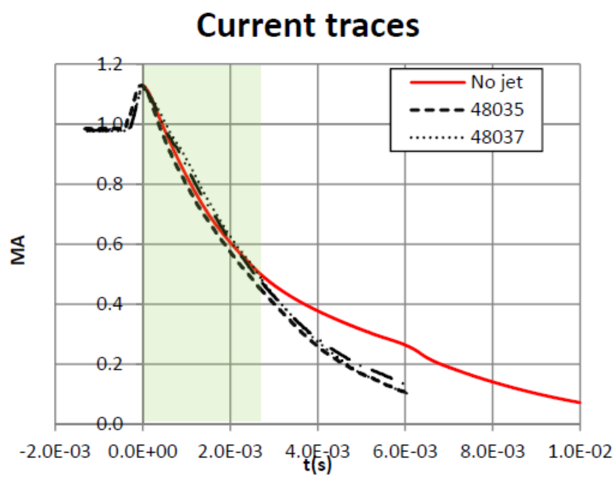


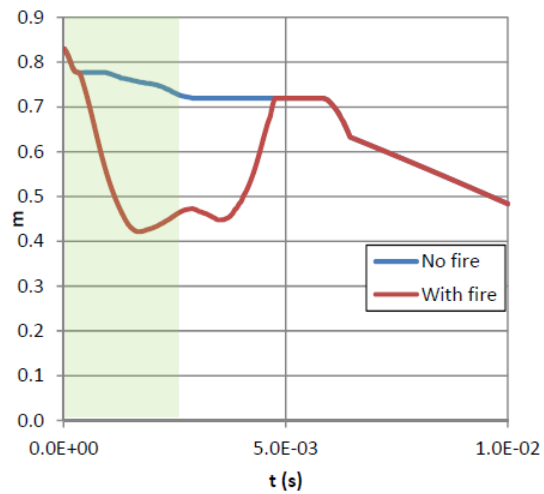
Hyper-velocity NP plasma jets for REs collisional suppression should have similar capability!

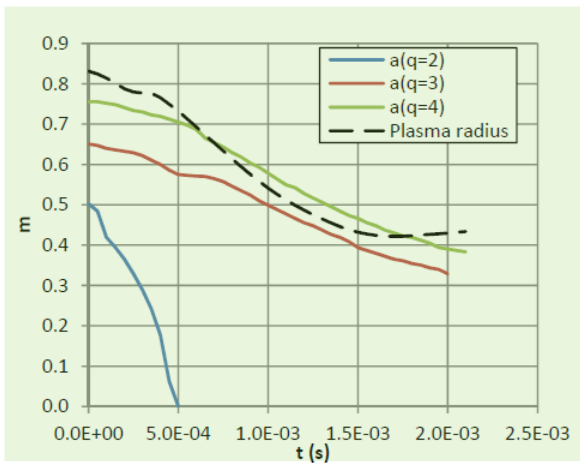
‡ **A.V. Voronin et al.**, ***Double pulse plasma gun for parameter controlling of Globus-M***, *36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, P-5.157 (2009)*

Q: Could C_{60} plasma jet have caught up q=2 (and q=3) surfaces to trigger secondary disruption on Tore Supra[§]?

1D modeling of CQ in shots #48035-37-39







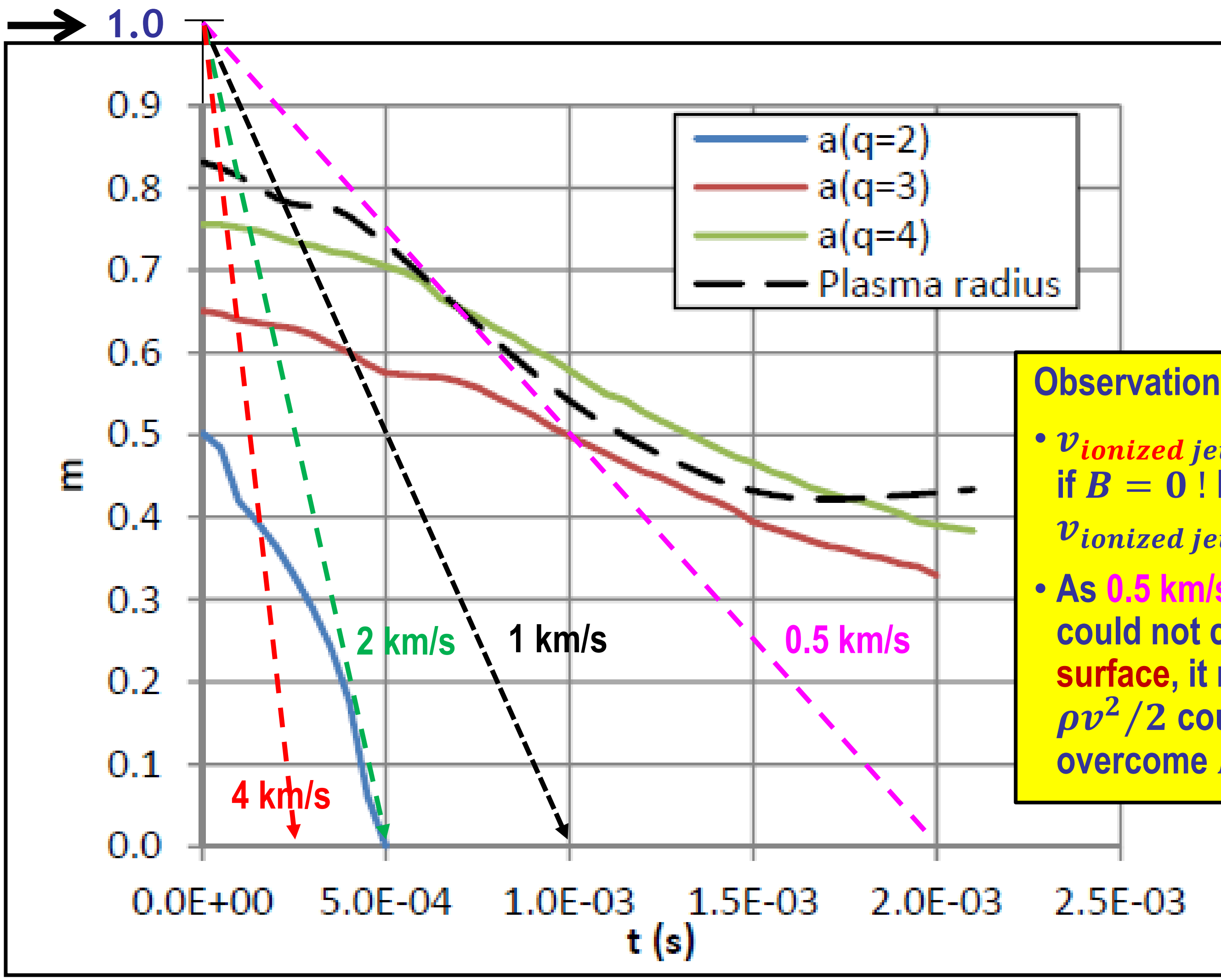
- Gas jet should result in significant contraction of current channel
- However, it can not catch up q=2 and even q=3 surfaces. This would be necessary to trigger secondary disruption

china eu india japan korea russia usa | MHD ITPA, October 2011, ITER_D_6LVR6K | Page 25

[§] S. Putvinski, F. St-Laurent, G. Martin, G.E. Notkin, M. Dremin, B.V. Kuteev,V. Kapralov, *On RE suppression experiments in Tore Supra and T-10,* MHD ITPA, October 2011

A: Likely, as plasma jet has much higher velocity (> 4 km/s)!

Gas (or plasma) injection location (cartridge valve or plasma gun)



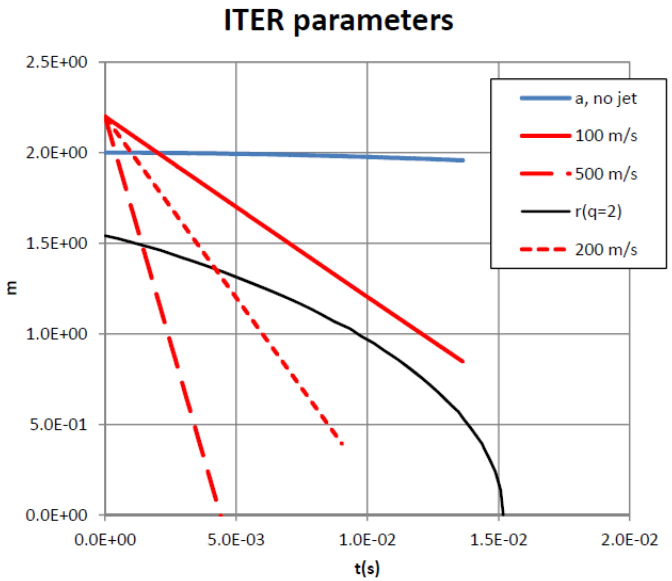
Observations:

- $v_{ionized\ jet} = const.$ only if $B = 0$! In reality $v_{ionized\ jet}$ decreases.
- As 0.5 km/s Ne gas jet could not catch up q=3 surface, it means its $\rho v^2/2$ could no longer overcome $B^2/2\mu_0$

§ S. Putvinski, F. St-Laurent, G. Martin, G.E. Notkin, M. Dremin, B.V. Kuteev,V. Kapralov, *On RE suppression experiments in Tore Supra and T-10,* MHD ITPA, October 2011

Jet distance vs. time (trajectory) is a straight line only for $B = 0$, which is not the real case !

QC in ITER is much slower



- Jet with velocity larger then 200 m/s can catch up the q = 2 surface

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Time to catch up q=2 surface is ~ 10 ms

- jet is ionized, decelerates and stops when

$$\frac{\rho v_{jet}^2}{2} \cong \frac{B_T^2}{2\mu_0}$$

- $\rho = m_i n$ and n decreases due to jet expansion …
- v_{jet} decreases (due deceleration) and v_{jet}^2 even stronger …

$$B_T(r) = \frac{B_T(0)R}{R + r}$$

- magnetic pressure increases by a factor of ~3 for $R = 6.2\ m$ and $a = 2\ m$ at RE beam in-board location

<u>Conclusion:</u> high ram pressure is required - higher initial v_{jet} and ρ !

§ S. Putvinski, F. St-Laurent, G. Martin, G.E. Notkin, M. Dremin, B.V. Kuteev,V. Kapralov, *On RE suppression experiments in Tore Supra and T-10,* MHD ITPA, October 2011

† S. Putvinski, *Disruption mitigation in ITER: Physics requirements,* US Disruption Mitigation Workshop, March 12, 2012

Volume for $E/E_{crit} > 1$ region is smaller than V_{plasma} ¶

Plasma Phys. Control. Fusion **51** (2009) 105004 V A Izzo *et al*

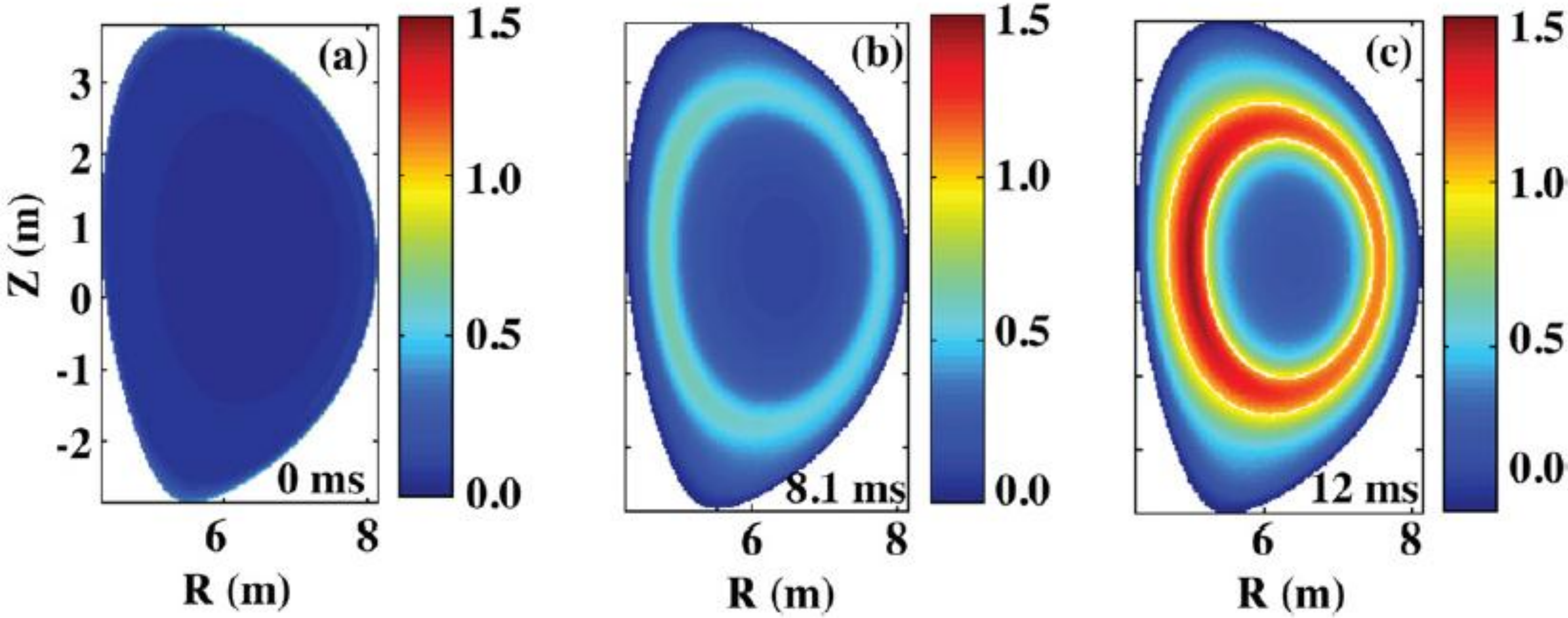

Figure 7. Contours of the Rosenbluth ratio ($E/E_{\mathrm{crit}} = \eta j/0.12\, n_{\mathrm{e},20}$) for the ITER simulation at the three times indicated. The two white lines in the far right frame are the contours $E/E_{\mathrm{crit}} = 1$. With $E/E_{\mathrm{crit}} > 1$, runaway electron avalanching can occur.

¶ V.A. Izzo, P.B. Parks, L.L. Lao, *DIII-D and ITER rapid shutdown with radially uniform deuterium delivery*, Plasma Phys. Control. Fusion 51 (2009) 105004

Potential of C_{60}/C plasma jet on DIII-D

Summary and conclusions

- Cartridge type of DMS valve has been successfully tested in Tore Supra
- High pressure gas jet propagates fast through CQ plasmas and propagates slower in high T plasmas as expected
- Gas jet does not trigger secondary disruption during fast CQs. **The fast CQs are too fast in the present experiments for the gas velocity**
- Gas jet trigger secondary disruption only during slow CQ in T-10
- Gas jet seems does not change current traces (current profile?) in fast CQ. This needs to be explained
- Secondary bump on current profile when occur seems to be a major MHD event with some redistribution of the plasma
- Implication for ITER DMS?

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C_{60} plasma jet !

(~10^{23} m^{-3}, ~100 mg)

- $v_{jet} \geq 4\ km/s$
- **potential to catch up (penetrate to) q=2 surface to trigger secondary disruption**
- **high resistivity (?)**

§ S. Putvinski, F. St-Laurent, G. Martin, G.E. Notkin, M. Dremin, B.V. Kuteev, V. Kapralov, *On RE suppression experiments in Tore Supra and T-10,* MHD ITPA, October 2011

C_{60} plasma jet as a hyper-fast impurity injection for RE suppression/deconfinement at CQ before exponential amplification

24th IAEA Fusion Energy Conference - IAEA CN-197

IAEA International Atomic Energy Agency

Contribution ID : 226

EX/P8-06: Overview of Runaway Electrons Control and Mitigation Experiments on Tore Supra and Lessons Learned in View of ITER

Friday 12 Oct 2012 at 14:00 (04h45')

Primary authors : Dr. SAINT-LAURENT, Francois (CEA)

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Presenter : Mr. SAINT-LAURENT, Francois (France)

Content :

Runaway electrons (RE) generated during disruption are identified as a major issue for ITER. Mitigation techniques are thus mandatory to suppress RE formation or/and reduce their heat loads. Two ways are explored on Tore Supra:

- Suppress the RE beam formation and avalanche amplification by multiple gas jet injections at current quench (CQ).
- Control the RE beam when it is formed and increase the collisionnality to slow down relativistic electrons.

A RE deconfinement at CQ before their exponential amplification might be achieved by ultra-fast supersonic gas injection. Thus a new concept of injector has been developed and tested on Tore Supra. A high pressure gas cartridge (150 bars), is open by rupture of a bursting disk. Neon or helium gas injections (240 Pam3) were triggered at CQ of disruptive plasma. The propagation of the neutral gas burst in the plasma is followed using a fast camera. The cold gas front travels through the plasma and penetrates at half of gas velocity in vacuum. Despite these observations, no robust perturbations on the current decay and on the loop voltage are recorded. The expected RE suppression has not been observed yet. Moreover, neither indication of an increase of MHD activity nor RE destabilization is observed.

RE beams (hundreds of kA) lasting several seconds are observed on Tore Supra. Such a plateau formation is eased with circular plasma in limiter configuration and develops only when the CFC first wall is depleted of deuterium. Mastering the RE plateau regime is a key to deploy mitigation techniques. Associated to a position control, a several hundred milliseconds RE current control was demonstrated on Tore Supra. Massive gas injection (MGI) was triggered on such a controlled RE plateau to increase the electron collisionnality. A subsequent reduction of high electron energy tail is observed, attributed to a beginning of thermalization. These results are very encouraging for mastering the RE beam regime towards a full thermalization.

The suppression of the avalanching process is the only way to guaranty that RE effects are mastered. Because a reliable suppression technique is not available yet and is still an issue for ITER, RE beam control experiments must be pursued. The aim of a collisionnal thermalization of RE seems feasible but is not achieved yet.