Hyper-Velocity High-Density C_{60}-Fullerene Plasma Jets for HEDLP, MIF, and Disruption Mitigation*

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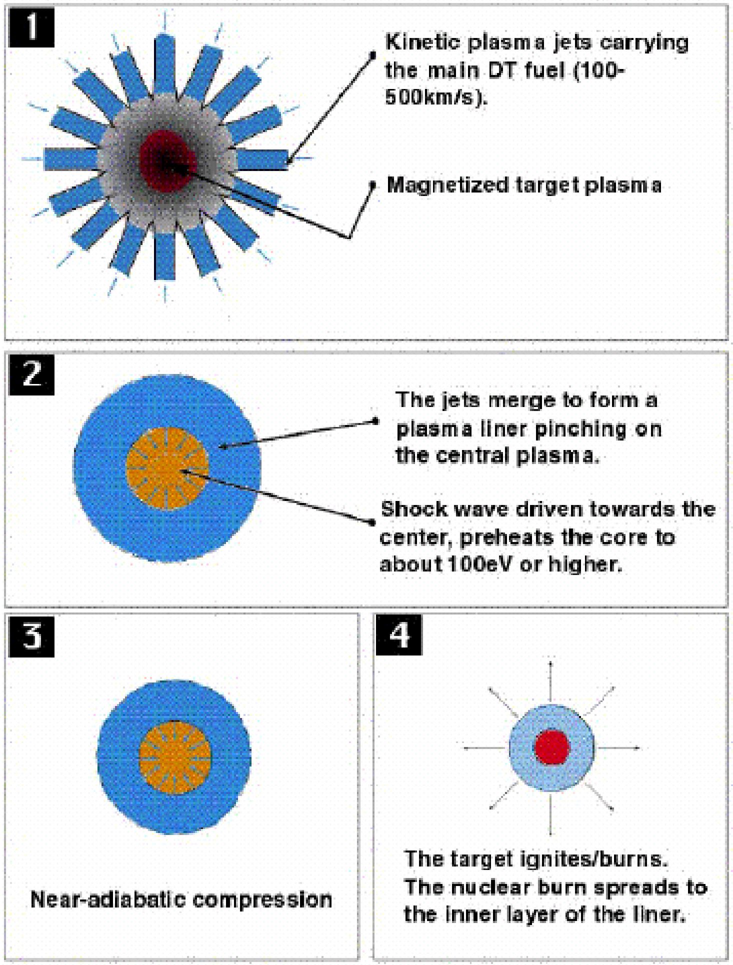
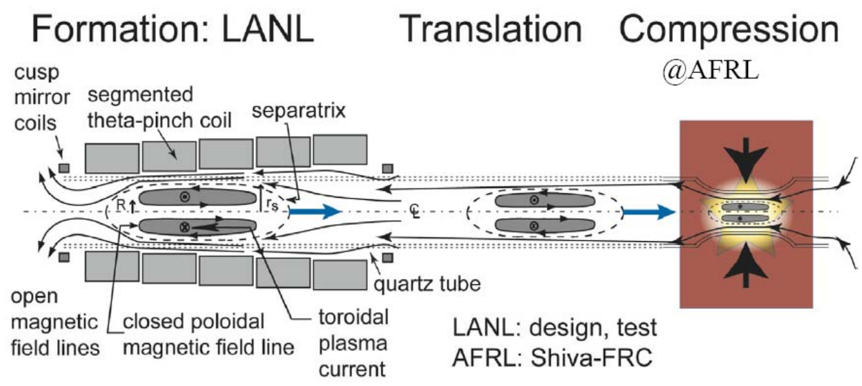
MTF must use inertial compression of D-T fuel by a plasma/metallic liner





K. F. Schoenberg, R. E. Siemon, et al. "*Magnetized Target Fusion: A Proof of Principle Proposal*" submitted to the OFES on May 19, 1998.

G. A. Wurden, "*Magnetized Target Fusion: Plans & Prospects*", for LLNL Seminar, June 26, 2007, LA-UR-07-4608

T. P. Intrator, R. E. Siemon, P. E. Sieck, "*Applications of predictions for FRC translation*", to be submitted to POP, Sept. 2007.

http://fusionenergy.lanl.gov/Physics/magnetized_target_fusion.htm

$$r_0 \cong 5\,cm,\ l \cong 30\,cm$$

$$n \sim (2-4)\times 10^{16}\,cm^{-3}$$

$$T \cong 300-500\,eV$$

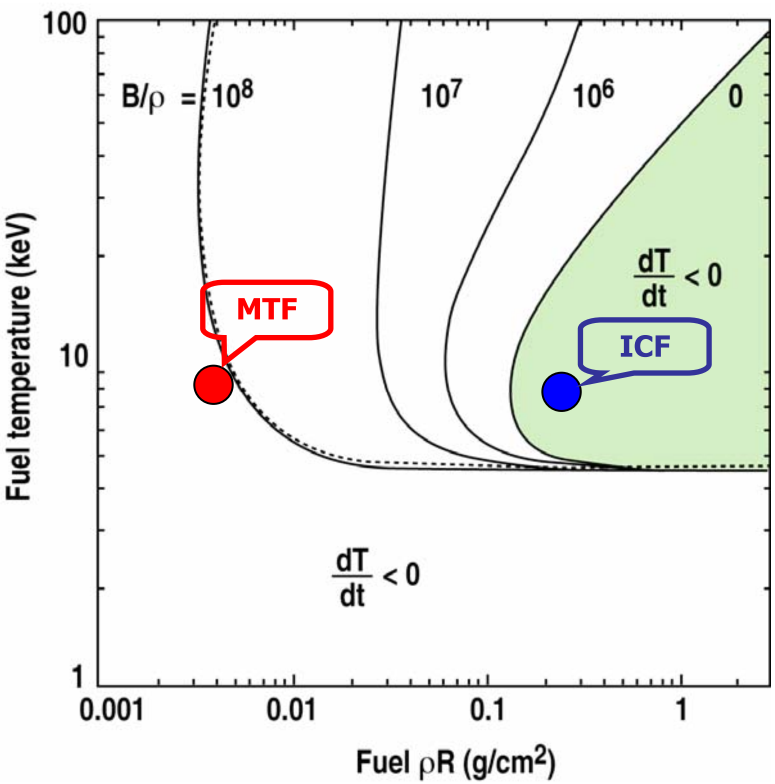
$$\tau_{life} \cong 10-20\,\mu s$$

$$B \approx 2.5T$$

$$\tau_{comp} \sim 25\,\mu s$$

Y. C. F. Thio, E. Panarella, R. C. Kirkpatrick, C. E. Knapp, F. Wysocki, P. Parks, G. Schmidt, *"Magnetized Target Fusion in a Spheroidal Geometry With Standoff Drivers"*, published in *Current Trend in International Fusion Research – Proceedings of the Second International Symposium.* Ed. E. Panarella. Published by the National Research Council of Canada, Ottawa, Canada, 1999.

Ignition criteria in magnetized cylindrical targets relaxes the ICF condition $\rho_s r_s$ > 0.2-0.3 g/cm^2 but requires MG magnetic fields



$$\boldsymbol{T = 7 - 10\,keV}$$

$$\boldsymbol{B_s r_s \geq (0.65 - 0.45) \times 10^6\, G \cdot cm}$$

in uniform DT cylinder with axial magnetic field

$$r_s = 0.5\,cm \Rightarrow B_s \geq (0.9 - 1.3) \times 10^6\, G$$

$$n_s \sim 1.6 \times 10^{21}\, cm^{-3},\ \overline{A}_{DT} = 2.5$$

$$\rho_s \sim 0.0066\, g/cm^3$$

$$\rho_s r_s \sim 0.0033\, g/cm^2$$

$$B_s/\rho_s \sim 166 \times 10^6\, G \cdot cm^3/g$$

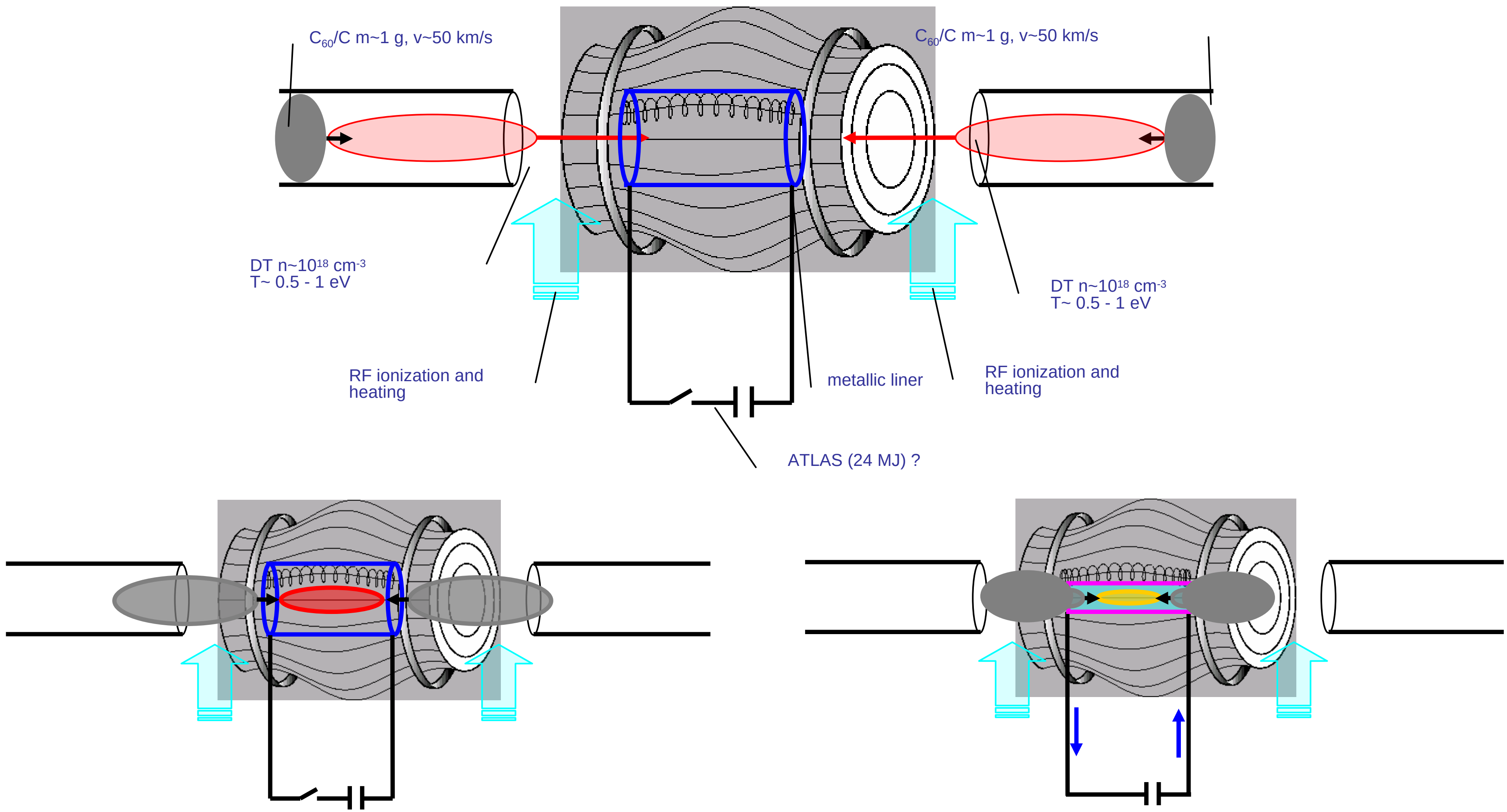
$$(nkT)\tau_E \geq 5\, atm \cdot s$$

$$nkT \sim 20\, Mbar$$

$$\tau_E \geq 0.25\, \mu s$$

M.M. Basko, A.J. Kemp, J. Meyer-ter-Vehn, Nucl. Fusion 40, 59 (2000).
P. B. Parks, Y.C.F. Thio, ICC2006 Workshop Austin, TX, February 13-16, 2006.

Two C_{60}/C-DT plasma jets head-on colliding, stagnating, trapped in pulsed magnetic mirror, and radially and axially compressed

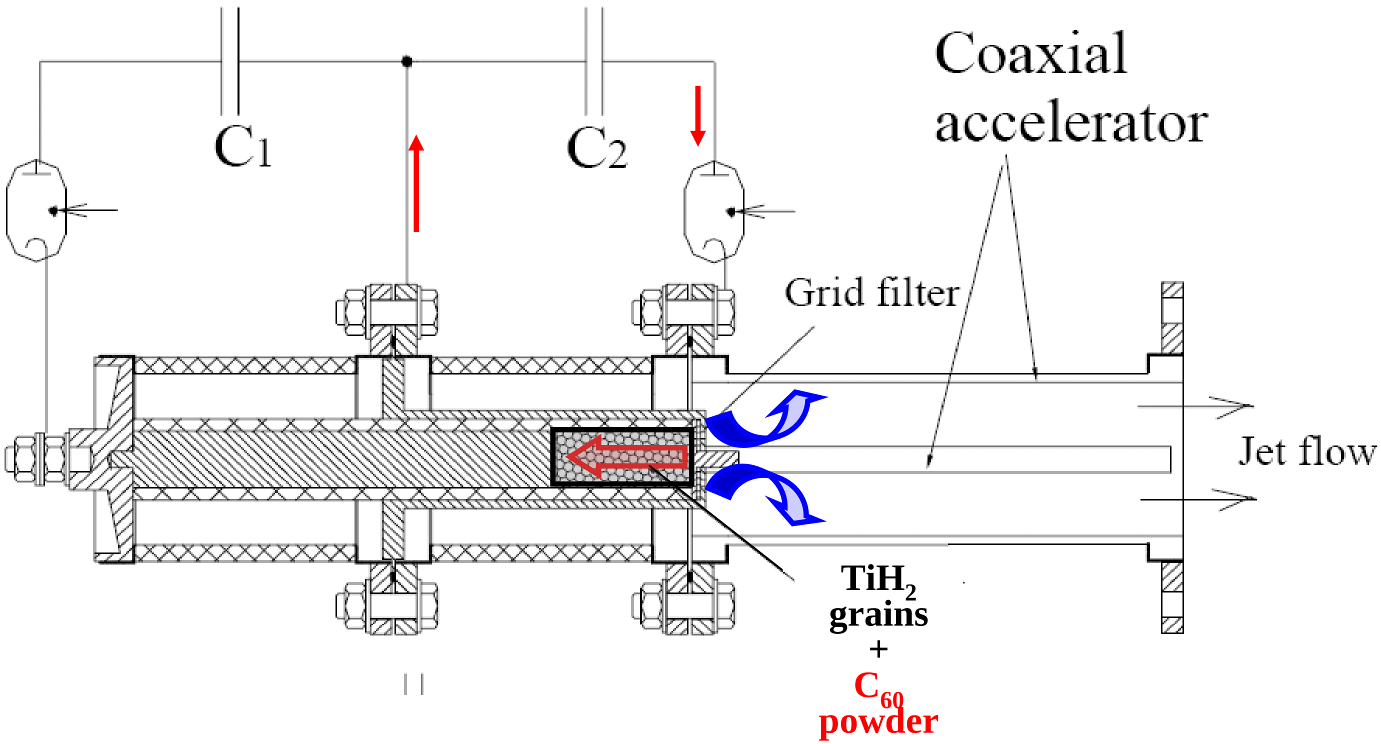


The proposed scheme achieves the required compression of both plasma and magnetic field to ultrahigh values (~ 2-5 MG): in radial direction by Z-pinch of metallic liner and in axial direction by hyper-velocity high-density C_{60}/C plasma jets

Two-jet head-on collision and stagnation in axial magnetic field of the mirror may create the magnetized D-T cylinder plasma

- Only two jets
- D-T fuel mass is relatively large (~ 4 mg) and adjustable from the pulsed source parameters
- Shock front from head-on collision at mid-distance on mirror axis increases the initial plasma jet density (n ~ 10^{17}-10^{18} cm^{-3}) and temperature (~ 1 - 5 eV)
- Axial injection in pulsed magnetic mirror field provides
  - (i) radial confinement of outgoing plasma streams (from stagnation point) by increasing transverse (axial) B-field
  - (ii) adiabatic heating by magnetic compression (B_{max}~ 1.2 - 2.4 T) of shock heated stagnating plasma to T ~ 300 - 500 eV prior to liner compression
  - (iii) magnetization of plasma as B-field penetrates the plasma faster than in a diffusion process
- Magnetized target is created at the compression place - no need to transport it
- Mirror B-field lines topology is favorable to compression by z-pinch metallic liner
- Dense heavy liner (C_{60}/C) of plasma jet axially injected reduces the detrimental effect of loss cone of magnetic mirror and possibly even compresses (better than end-plugs)
- Relatively reduced cost of a pulse power TiH_2/C_{60} technology with good potential also for HEDLP, disruption mitigation, re-fueling, ELM control, and space propulsion

Explosive sublimation of C_{60} heated by TiH_2 grains "oven" can provide fast injection of high-density large mass of H_2 and C_{60} gas



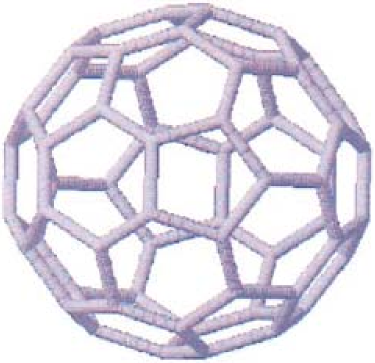
a. Driving a pulsed current through TiH_2 grains transiently heats them to the sublimation temperature of C_{60} (800 K)

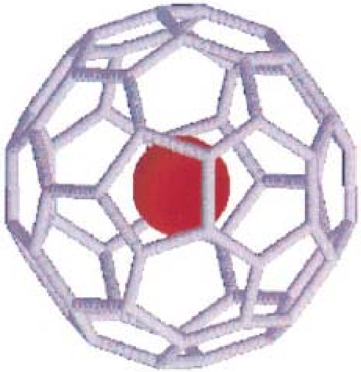
b. During the heat pulse H_2 is released from TiH_2 beginning at 573 K and is complete at 873 K, while C_{60} micron size powder/coating sublimates and becomes a heavy molecular gas

c. TiH_2 can release 448 cm^3 H_2/g or a total number of 1.2×10^{22} molecules H_2/g allowing for scaling up the source volume to sublimate also a larger mass of C_{60} (~0.3 to 1 g)

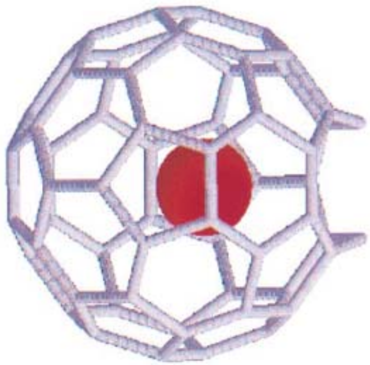
d. Due to the high pressure the C_{60}-H_2 mixture is injected at high velocity through a micro Laval nozzle grid filter into the coaxial gun in a very short burst (<0.15 ms)

Identical C_{60}-fullerenes with large mass form plasma slug heavy ion component (w/o caged atoms) -> efficient acceleration

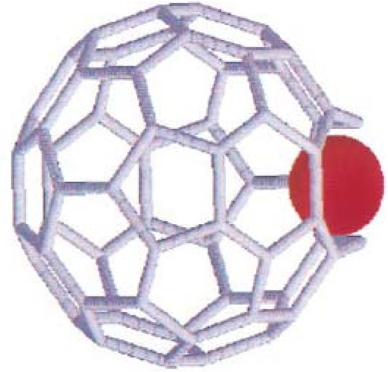




C_{60} with a noble gas atom (He, Ne, Ar, Kr, or Xe) inside
A=724 to 851
$m_{X@C60}$ = 1.20 to 1.41 x 10^{-21} g



C_{60} with a noble gas atom inside and bond broken (open window)



Noble gas atom moving out through the window and released

C_{60} - fullerene

A = 720

m_{C60}= 1.19 x 10^{-21} g

$Ø_{mean\ ball}$ = 6.83 Å

$Ø_{inner\ ball}$ = 3.48 Å

ρ_{mass} = 1.72 g/cm^3

1st $E_{ionization}$ = 7.58 eV

2nd $E_{ionization}$ = 11.5 eV

η_{el} = 1014 ohms m

Sublimes at 800 K

Carbon dust of usual dusty-plasma

$Ø_d$ ~ 1 - 50 μm

ρ_d ~ 1.9 - 2.3 g/cm^3

m_d ~ 10^{-12} - 10^{-7} g

ambient plasma flow must drag negatively charged dust grains

Sublimes at 4000 K

- http://xbeams.chem.yale.edu/~cross/fullerene.html
- M. Saunders et al., *"Noble Gas Atoms Inside Fullerenes"*, *Science* **271**, 1693 (1996).
- H. A. Jiménez-Vázquez and R. J. Cross, *"Equilibrium Constants for Noble-Gas Fullerene Compounds"*, *J. Chem. Phys.* **104**, 5589 (1996).
- R. Shimshi et al. *"Release of Noble Gas Atoms from Inside Fullerenes"*, *Tetrahedron*, **52**, 5143 (1996).
- L. Becker, R. J. Poreda and T.E. Bunch, *"Fullerenes: An extraterrestrial carbon carrier phase for noble gases"*, PNAS (2000) **97**, 2979-2983;

C_{60}-fullerenes have excellent properties for creating a high-density plasma slug accelerated to hyper-velocity

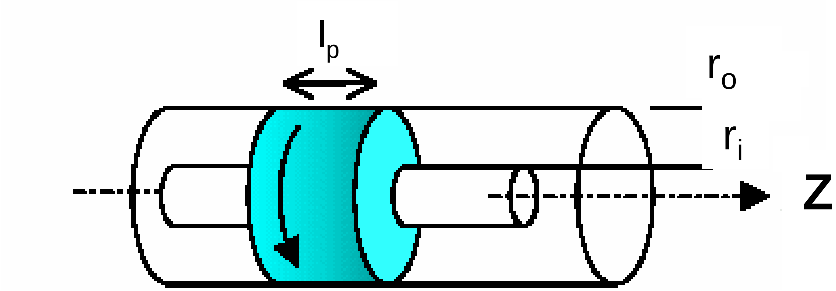
	Mass A (amu)	Normalized charge (Q/e)	Specific charge (Q/e/A)	Sublimation temperature T_s (K)	Sublimation heat λ_s (kJ/mole)
Deuteron	2	+1	0.5	-	-
Carbon	12	+1 (to +6)	0.08 (to 0.5)	4000	715
C_{60} fullerene	**720**	**±1 (to ±4)**	**$\pm 1.4\times10^{-3}$ (to $\pm 5.4\times10^{-3}$)**	**800**	**163±21[†] (159[‡])**
C dust grain	$\sim 6\times10^{11}$ to $\sim 6\times10^{16}$	-10^5 to -10^4	-1.7×10^{-8} to -1.7×10^{-7}	4000	715

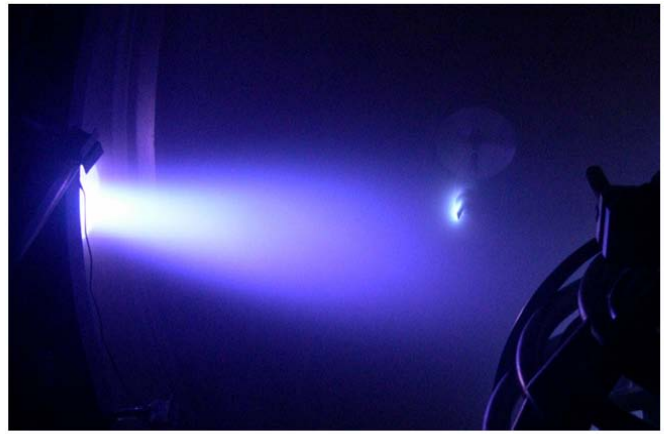
- **Identical mass <-> C dust grain mass is spread over a wide range**
- **Relatively low sublimation temperature**
- **C_{60} can form the high-density plasma slug -> efficient acceleration <-> C dust grains must be dragged by ambient plasma flow**
- **C_{60} has pretty high stability**
  - **is produced in high pressure arcs ($n \sim 10^{16}$ - 10^{18} cm^{-3} and $T \sim 0.5$ - 1 eV)**
  - **C-C bond strength is ~3 times higher than sublimation heat λ_S**

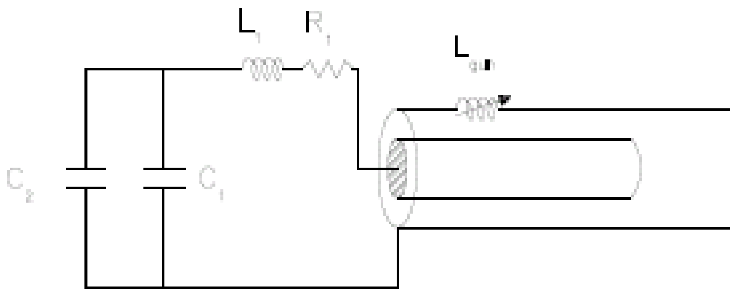
[†] M. Moalem et al., J. Phys. Chem. 99, 16736 (1995)

[‡] A. L. Smith, "Chemical Properties of Fullerenes" ADA282730 (1993)

Small TiH_2 pulsed source has good density-mass yield for a plasma jet accelerated in a coaxial plasma gun







$$\rho_{jet} = 3.3\times10^{-5}\ \boldsymbol{kg/m^3}, \quad \boldsymbol{B} = 0.4\boldsymbol{T}$$

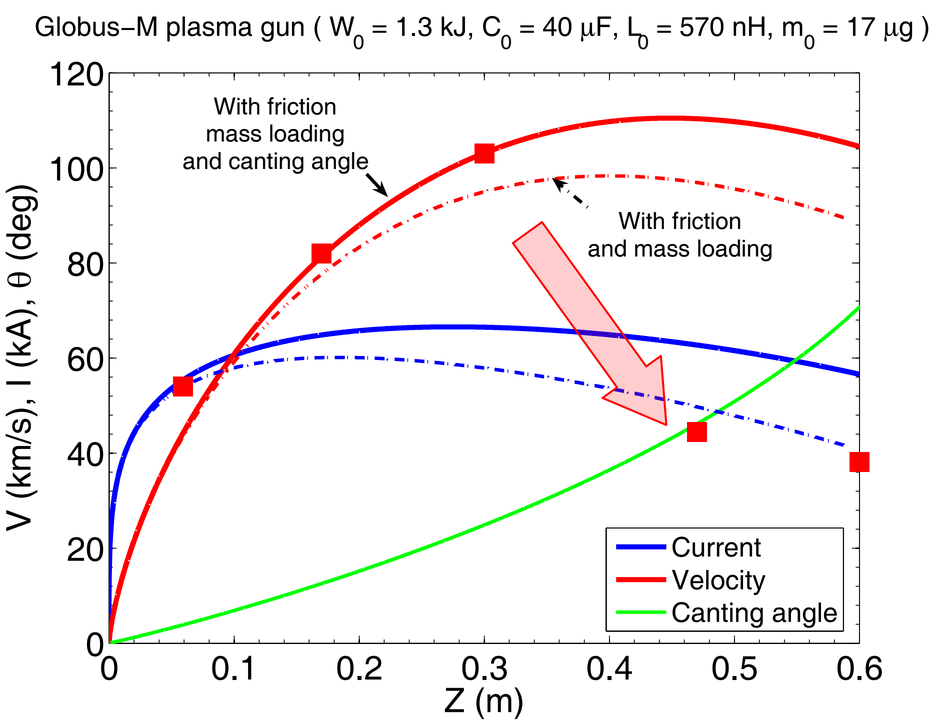
$$\left.\begin{aligned} &\frac{\rho_{jet} v_{jet}^2}{2} = 3.3\times10^5\ \boldsymbol{Pa} \\ &\boldsymbol{p}_{mag} = 3.98\times10^5 \boldsymbol{B}^2 = 6.4\times10^4\ \boldsymbol{Pa} \end{aligned}\right\} \Rightarrow \frac{\rho_{jet} v_{jet}^2}{2} \cong 5\times \boldsymbol{p}_{mag}$$

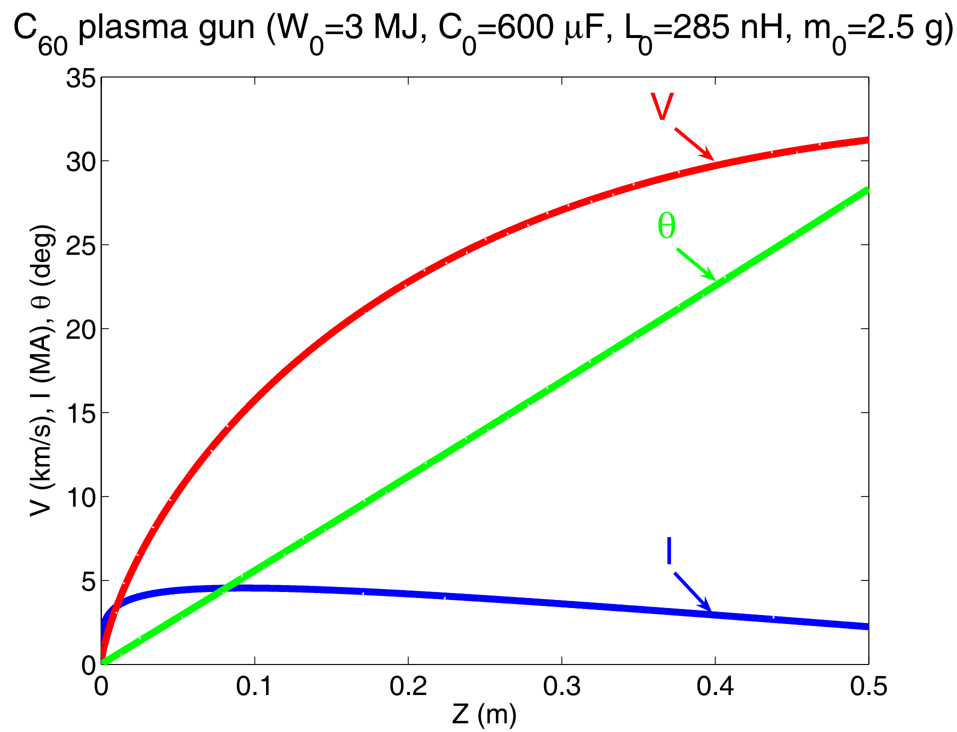
Perpendicular view to the axis of hydrogen plasma jet from the plasma gun on Globus-M spherical tokamak

Vol_{TiH2}=3 cm^3	$m_{plasma\ jet}$=17 μg
$v_{gas\ jet}$ ~ 2 to 7 km/s	$V_{plasma\ jet}$ ~ 110 - 140 km/sec
l_{gun}=0.3 m	n_{jet} ~ 2x10^{16} cm^{-3}
W_0=1.3 kJ	T_{jet} ~ 1 eV
I~60 kA	L_{jet} ~ 30 cm

A.V.Voronin, et al., 33rd EPS Conference (2006); A.V. Voronin, et al., IAEA (2006); A.V. Voronin, et al., Nucl. Fusion, **45**, 1039 (2005); V. K. Gusev et al., 11th ST Workshop (2006).

Plasma slug model agrees of with experimental data for H and predicts that 2.5 g of C_{60} can reach ~30 km/s with a 3 MJ driver





Experimental data: plasma gun of Globus-M tokamak, Voronin A. V., et al., Nucl. Fusion, **45**, 1039 (2005).

Modeling results: I. N. Bogatu et al., 48th APS DPP: Philadelphia, PA, 2006: APS Meeting: Bull. Am. Phys. Soc. **51**, p.269 (2006).

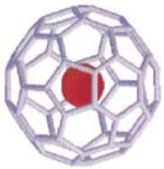
Electrode optimization shape: S. A. Galkin et al., 48th APS DPP: Philadelphia, PA, 2006: APS Meeting: Bull. Am. Phys. Soc. **51**, p.352 (2006).

Application for a reliable disruption mitigation technique with real-time capability on ITER

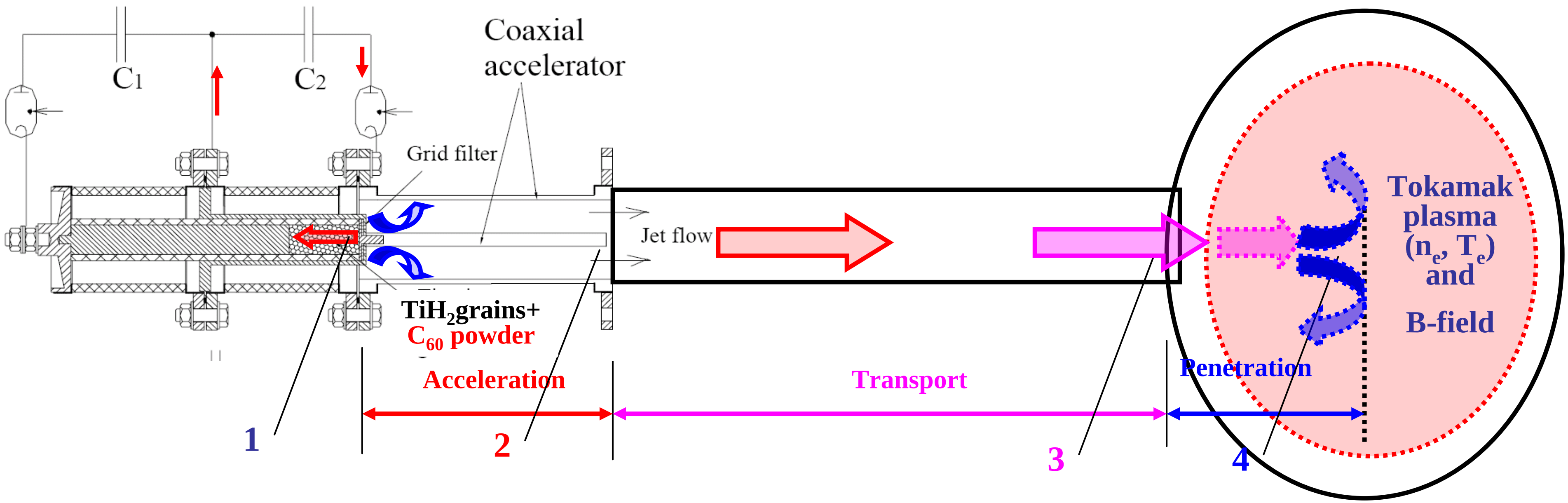
- Basic solution : Impurity injection
  - convert plasma energy density (~1 GJ/840 m^3) in τ~1 ms into radiation power
  - suppress runaway electrons (REs) by increasing electron (free/bound) density by ~100 all over the plasma cross section

- Impurity injection requires proper balance of
  - necessary mass (~ 30 g, for ITER)
  - acceptable atomic number Z
  - suitable density-velocity to penetrate/deliver it in the core plasma on the fast disruption time scale

- Proposed injection method
  - Hyper-velocity high-density C_{60}-fullerene (encaging noble gases, if necessary) plasma jets from a set of plasma guns
  - Penetration to half minor radius of ITER plasma by a 2.5 g C_{60} plasma jet of 30 km/s can be achieved with plasma gun and ~3 to 6 MJ capacitive driver



Disruption mitigation with C_{60} jet accelerated by a coaxial plasma gun



1. **Fast** (<0.15 ms) production of **large impurity mass** (~0.3 - 2.5 g) **as neutral gas at high-density** (~10^{17} - 10^{18} cm^{-3}) and **injection at high-velocity** (~0.4 km/s) into coaxial gun
2. Breakdown, formation of a **high-density compact plasma slug**, and **acceleration to hyper-velocity** (~10 - 40 km/s)
3. **Transport of jet** to tokamak port (advantage of in-flight 3-body recombination)
4. **Injection** of **hyper-velocity high-density quasi-neutral jet** into magnetic field and tokamak plasma, heating, expansion, **ionization, deceleration of jet, penetration to half minor radius** (~a/2) and deliver of impurity mass in the core

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System parameter estimations

	ITER	ITER	DIII-D
Total mass of jets, m (g)	30	15	0.3
Number of jets, N_{jets}	12	6	1
Jet mass, m_{jet}(g)	2.5	2.5	0.3
Gas source mass, m_{TiH2}/m_{C60} (g)	625/250	625/250	75/30
Gas source current, I(kA)	(~730)	(~730)	~90
Plasma jet velocity, v_{jet} (km/s)	10	30	40
Plasma jet density, n_{jet} (cm^{-3})	4.5×10^{17}	4.5×10^{17}	1×10^{17}
Total kinetic energy, E_{kin} (MJ)	1.5	6.75	0.24
Driver efficiency, $\eta = E_{kin}/W_0$	10%	20%	10%
Driver(s) capacitive energy, W_0 (MJ)	15	~34	2.4
Number of driver units, N_{drv}	12	6	1
Driver unit energy, w_0 (MJ)	1.25	5.7	2.4
Jet penetration time to a/2, τ_p (ms)	0.1	0.033	0.0075

<ins>World's largest, most advanced capacitor bank (2006)</ins>

- designed and installed by Rheinmetall Waffe Munition at High Magnetic Field Laboratory Dresden at the Rossendorf Research Centre (FZR) (Building cost: ~€24.5M)
- Stored energy: 50 MJ   Cost: ~€10M
- Peak current: several hundred kA to generate a magnetic field of 100 Tesla

Summary

- Explosive sublimation of C_{60} powder in $TiH_2/D_2/T_2$ grains "oven" -> enough DT fuel-liner mass - high-velocity gas burst injected into coaxial gun -> compact high-density plasma slug
- Acceleration with optimized electrode shape, delay of blow-by instability, and improved efficiency of driver -> hyper-velocity (v_{jet} ~ 10 - 50 km/s) high density (n_{jet} ~ 10^{17} - 10^{18} cm^{-3})
- MTF/HEDLP: two-jet head-on collision and stagnation in the axial magnetic mirror field may provide the magnetized cylindrical DT plasma column to be compressed by z-pinch of a metallic liner as for FRC
- Disruption mitigation: deliver enough impurity mass in deep penetration and fast rise time in electron density all over the tokamak plasma cross section
- At FAR-TECH, Inc. we are working on further developing the concept, physical models, and technology
- A patent application for TiH_2/C_{60} pulsed source has been submitted by FAR-TECH, Inc.

Appendix: Drastic change in the expansion of plasma jet happens already at B=0.4 T when plasma is confined into a narrow jet of higher density

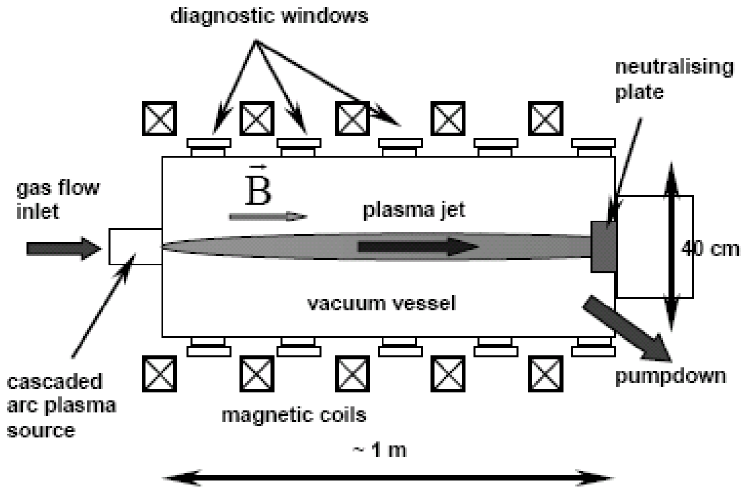
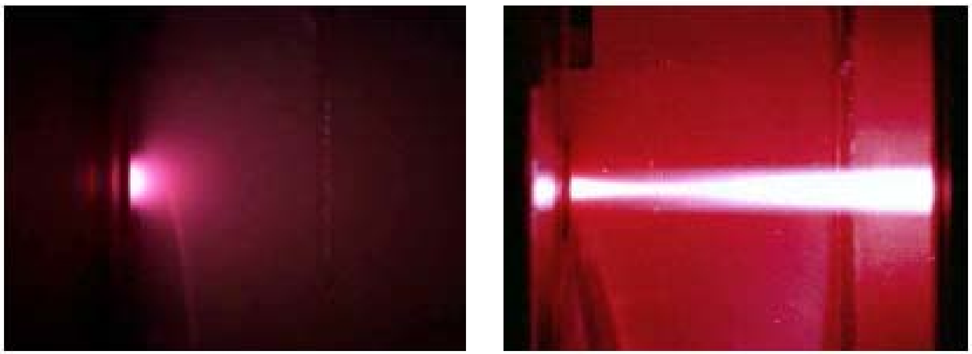


Figure 2.1: Schematic drawing of the experimental setup Pilot-PSI.

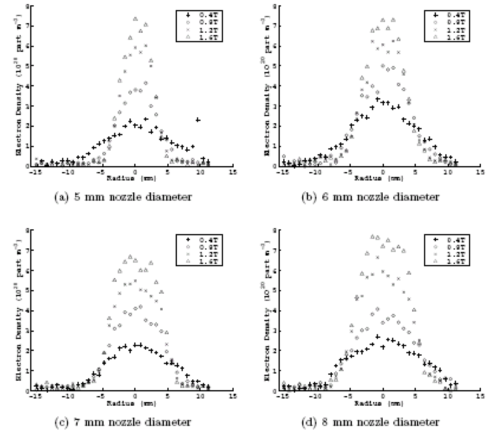


(a) (b)

Figure 4.1: In comparison with a faint expanding plasma without a magnetic field (a) plasma in a magnetic field of 0.4 T (b) is a confined narrow bright jet.

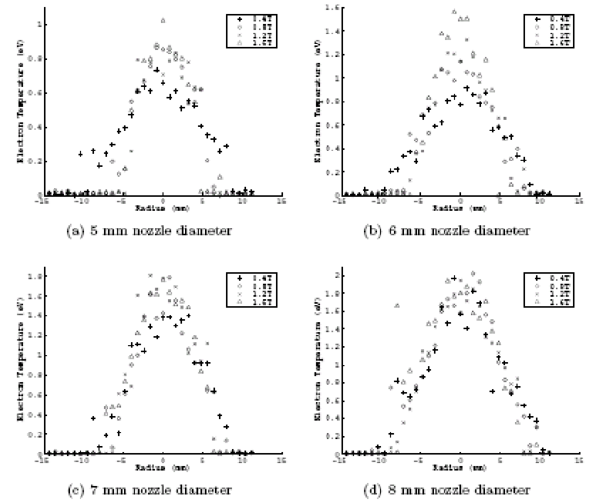
n_e~ 7.5x10^{14} cm^{-3}, T_e~ 1.9 eV, v_z~ 3 km/s, B~0.4 - 1.6 T

V. P. Veremiyenko, *An ITER-relevant Magnetised Hydrogen Plasma Jet, PhD Thesis,* Technische Universiteit Einhoven, 2006.



Electron density

Figure 4.4: The electron density profiles in Hydrogen plasma in a magnetic field of 0.4, 0.8, 1.2 and 1.6 T for nozzle opening diameters of 5 (a), 6 (b), 7 (c) and 8 mm (d). The peak density does not depend on the nozzle diameter but scales only with the magnetic field. The broadening and flattening of the plasma density profile is seen at increasing nozzle diameter.



Electron temperature

Figure 4.5: The T_e profiles in hydrogen plasma for B = 0.4, 0.8, 1.2 and 1.6 T and for nozzle opening diameters of 5 (a), 6 (b), 7 (c) and 8 mm (d). T_e grows significantly at the transition from approximately 6 to 7 mm. The difference in T_e for different magnetic fields is insignificant.