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Title: Imploding Plasma Liners as a Standoff Driver for Magneto-Inertial Fusion

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IMPLODING PLASMA LINERS AS A STANDOFF DRIVER FOR MAGNETO-INERTIAL FUSION

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By enabling a fusion ignition regime with plasma density intermediate between that of MFE and ICF, magneto-inertial fusion (MIF) offers the potential for a low-cost development path to fusion energy.[1] A *standoff driver*[2] that eliminates repetitive destruction of solid materials (*e.g.*, metal liners or transmission lines) further improves the attractiveness of MIF. With the Plasma Liner Experiment (PLX) starting experimental operation at LANL, we are exploring the feasibility of forming imploding *plasma liners* using an array of spherically convergent dense plasma jets. PLX is focused on the investigation (at modest pulsed power energies ≤1.5 MJ) of scientific issues such as jet propagation/merging and plasma liner formation, convergence, and stagnation, including the validation of simulations that are needed to help guide experimental campaigns, interpret PLX data, and design future experiments. In the near term, PLX will focus on the generation of cm/μs-scale plasmas in the Mbar range for fundamental HEDLP science. There are proposed plans to introduce magnetic fields via laser generated beat wave current drive and to field astrophysical jet and collisionless shock related experiments. Initial 1D radiation-hydrodynamic simulations indicate that a ~375 kJ imploding plasma liner (assumed to be formed by 30 Ar plasma jets each initially with $n \sim 10^{17}$ cm^{-3}, v~50 km/s, E~12 kJ) results in peak stagnation pressure of ~1.3 Mbar with sustained pressure ~0.1 Mbar for over ~4 μs. The simulations also show that an MIF-relevant pressure of ~50 Mbar sustained for ~0.6 μs may be achieved with v~150 km/s and liner kinetic energy of ~50 MJ. Inclusion of additional physics, *e.g.*, 3d effects, will undoubtedly increase the liner and stored energy requirements, which nevertheless ought to remain relatively modest. Furthermore, theoretical analysis indicates that the dwell time can be significantly increased with proper liner profile shaping, adding versatility to the plasma liner concept. This presentation will provide a concept-level description of plasma liner driven MIF, an overview of PLX status/plans, and a summary of the initial theoretical/modeling results.

1. I.R. Lindemuth and R.E. Siemon, *Am. J. Phys.* **77**, 407 (2009); 2. Y.C.F. Thio et al., in *Current Trends in International Fusion Research*, ed. E. Panarella (NRC Canada, Ottawa, 1999).

Imploding Plasma Liners as a Standoff Driver for Magneto-Inertial Fusion

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F. Douglas Witherspoon, Sam Brockington, Andrew Case, Sarah Messer, David van Doren (HyperV Technologies Corp.)

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Acknowledgments: collaborators at Far-Tech, Voss Scientific, Prism Computational Sciences, Tech X Corp., U.C., Davis, Univ. Chicago, and Y.C.F. Thio (DOE)

ICOPS, Chicago, IL, June 28, 2011

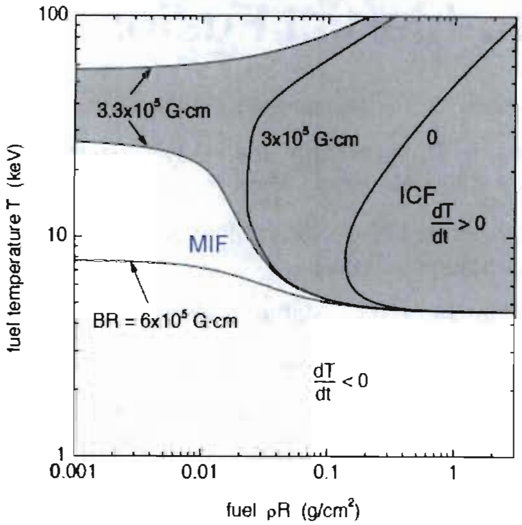
LA-UR-11-xxxx

Funded by DOE Fusion Energy Sciences as part of the SC/NNSA Joint Program in HEDLP

Outline

- Brief introduction to magneto-inertial fusion (MIF)
- Conceptual overview of plasma liner driven MIF
- Plasma Liner Experiment (PLX) project goals & status
- 1D rad-hydro and preliminary 3d ideal hydro simulation results
- Potential advantages of liner profile shaping
- Summary

Magneto-inertial fusion (MIF): Pulsed fusion approach with a magnetic field in the compressed fusion fuel

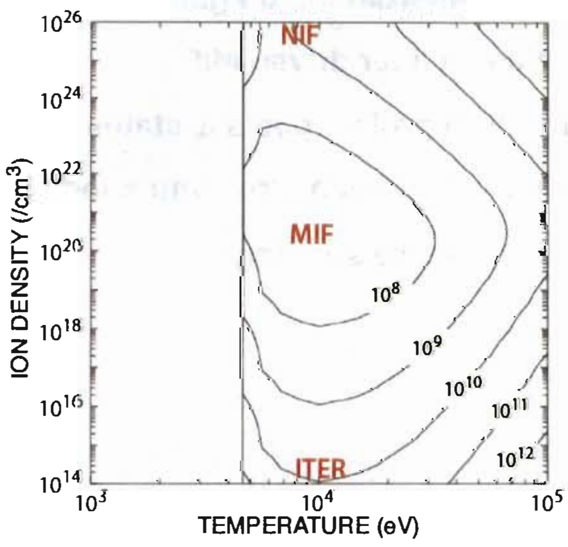


*Basko et al., Nucl. Fusion (2000) cylindrical geometry

- Magnetic field:
  - reduces thermal transport
  - enhances α-particle deposition within burning fuel
  - Lowers *pr* ignition threshold
- Lower required implosion velocities (1–100 km/s) compared to ICF (350 km/s)
- Allows use of more efficient & cheaper pulsed power (few $/J)
- MIF energy concepts aim for $\eta G \sim 0.5\times20$ rather than $\eta G \sim 0.1\times100$ as for ICF
- Several approaches being studied: solid liner MTF (LANL/AFRL), MagLIF (Sandia), magnetized ICF (Rochester), plasma liner driven MIF (LANL)

MIF at intermediate ion densities: A sweet spot in thermonuclear fusion parameter space

Facility cost in $US versus fusion parameter space:



Breakeven facility would cost ~$100M, and they already exist: ZR or ATLAS!

Please see talk SO4A-5 by Irv Lindemuth on Thursday morning for details

Adapted from Lindemuth & Siemon, AJP (2009).

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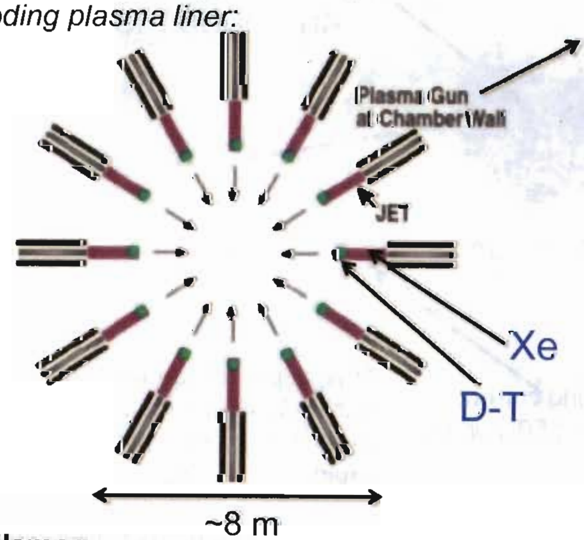
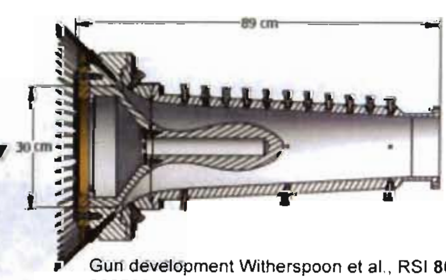
Plasma liner driven MIF aims for standoff and versatility in optimizing implosion and burn

Spherical array of economic, efficient plasma guns launch "composite" plasma jets forming imploding plasma liner:



Concept reference Thio et al., JFE **20**, 1 (2002).



Gun development Witherspoon et al., RSI **80**, 083506 (2009).

V_{gun} ~ 50 kV, I_{gun} ~ 1 MA

τ_{rise} ~ few μs

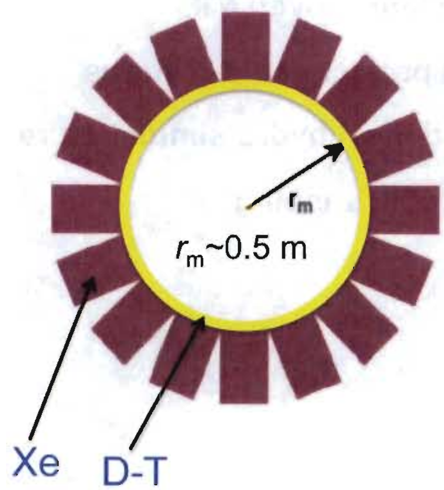
$\langle n_{jet} \rangle$ ~ $10^{17\text{-}18}$ cm^{-3}

T_{jet} ~ 2 eV

M_{jet} ~ 20 mg

E_{jet} ~ 64 kJ

Jets merge to form imploding spherical plasma "liner"



U_{liner} ~ 80 km/s (8 cm/μs)

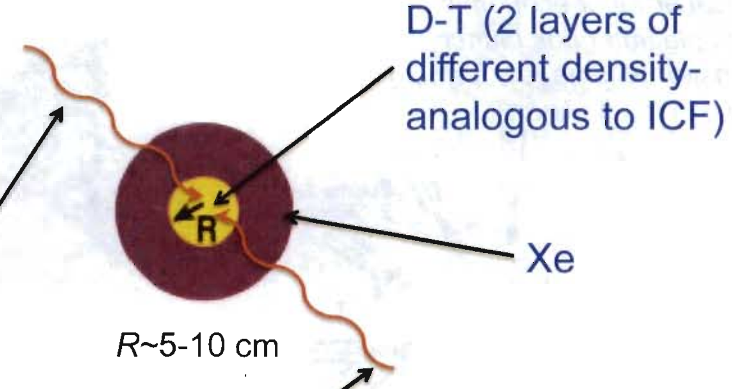
M_{liner} ~ 4 g

E_{liner} ~ 13 MJ

N_{jet}~200

$\tau_{transit}$ ~ 10's of μs

Shortly before reaching peak compression, inner DT portion of plasma liner is magnetized to few Tesla level



One possible method: Fire lasers for driving current (via beat wave resonance) and magnetizing DT portion of liner (IR, kJ, TW class lasers needed)

Advantage: allows for better control of plasma beta and magnetic geometry compared to using pre-formed compact toroids

Rogers & Hwang, PRL **68**, 3877 (1992); F. Liu et al., Proc. 38th EPS (2011).

Final compression amplifies B field to ~50-100 T and heats inner DT layer to fusion temperature (~10 keV)

R~0.5 cm

- Inner DT layer burns (w/goal of ~10% burn-up)
- Aim is to heat and partially burn the denser outer DT layer ("afterburner") by α's and outgoing shock, amplifying the yield
- Xe layer would reduce radiation losses and enhance the energy confinement time (~1 μs)

Reference case (based on 1D hydro liner simulations with analytic burn calculation):

DT fusion yield ~ 300 MJ

Total liner energy ~ 13 MJ

Energy gain > 20

Wall plug efficiency ~ 0.5

Gain-efficiency product > 10

At 1 Hz ➔ ~300 MW average power (~100 MW electric)

Aims to use liquid first wall

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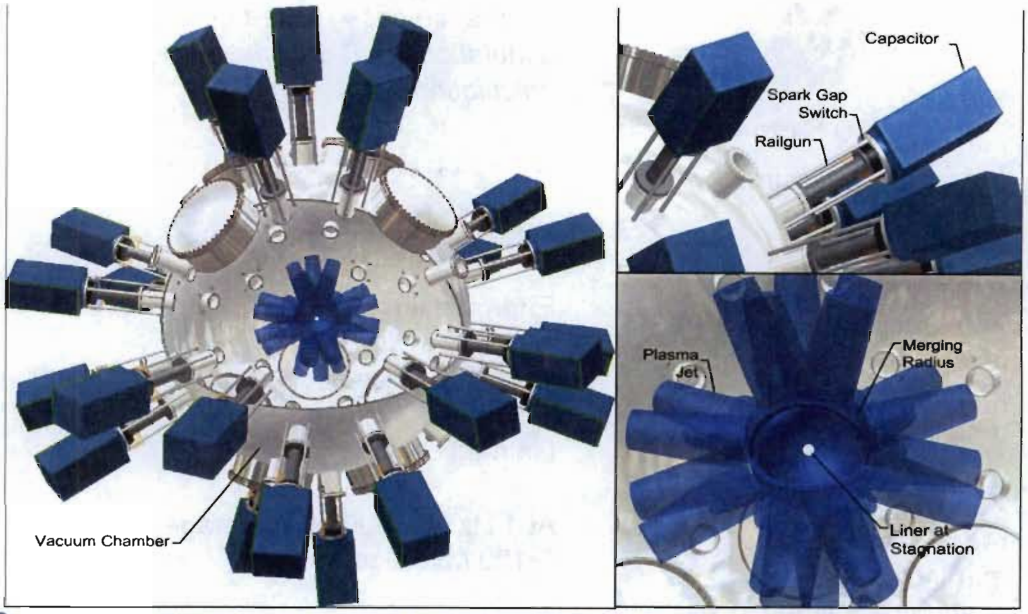
Plasma Liner Experiment (PLX) plans to merge 30 high Mach number plasma jets in spherically convergent geometry to investigate plasma liner formation/implosion at modest energies



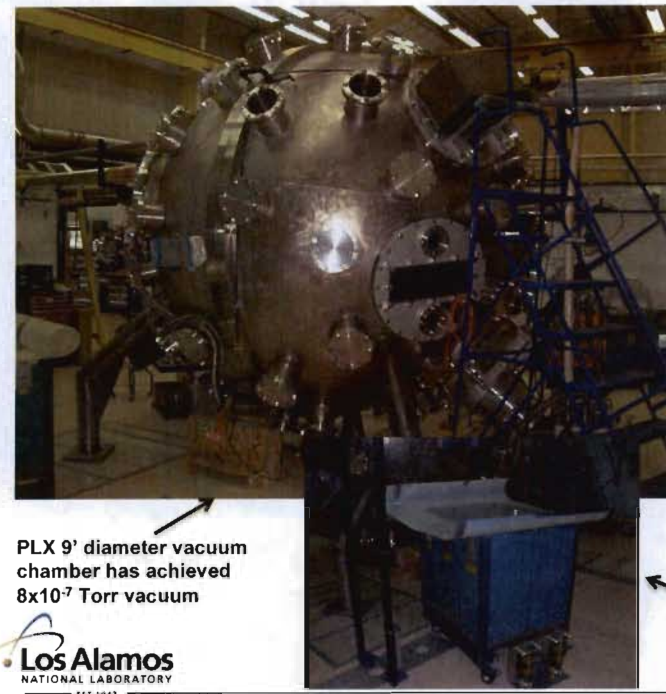
Project goal: generate/characterize μs/cm-scale imploded liners with 0.1–1 Mbar peak pressure using ~1.5 MJ of initial stored energy

Figure by David van Doren (HyperV Technologies)

PLX has three key science & technology objectives in the next few years

1. **Form dense high Mach number high Z (Ar, Xe) plasma jets with required density (~10^{17} cm^{-3}), mass (~few mg), and velocity (>50 km/s)**
2. **Demonstrate imploding plasma liner formation and predictive physics understanding of underlying steps:**
   - *jet evolution from chamber wall to "merging" radius* r_m
   - *liner formation via jet merging (plasma inter-penetration, shock dynamics, uniformity)*
   - *liner convergence (pressure amplification, atomic physics effects, liner stability)*
   - *stagnation (peak pressure scaling, conversion of liner kinetic energy to thermal/radiation energy, confinement time)*
3. **Standoff magnetization via laser generated beat wave current drive**

PLX construction phase 1 nearing completion with first experiments starting in July/August 2011



PLX 9' diameter vacuum chamber has achieved $8x10^{-7}$ Torr vacuum

60kV, 39μF capacitor bank for first gun

Phase 1 objectives (FY11-FY12):

- Two plasma guns each with ~70 kJ stored energy
- Multi-chord interferometry, visible/ IR spectroscopy, and schlieren imaging
- Single jet propagation and two jet merging physics studies

Phase 2 (FY12-FY13):

- Increase to 30 guns and ~1.5 MJ total stored energy
- Addition of VUV spectroscopy, soft x-ray bolometry
- Liner formation, implosion, and stagnation physics studies

Latest generation of plasma railguns with 1" square bore and 2" diameter cylindrical nozzle are being supplied by HyperV Technologies Corp.*

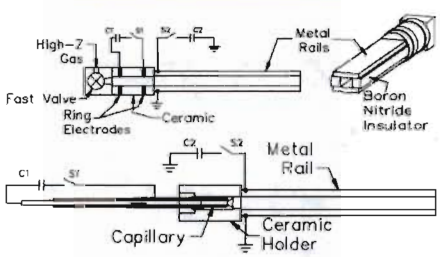


Figure 12 Railgun with two versions of plasma injector. (top) ceramic capillary with fast valve gas injection, (bottom) polyethylene ablative capillary. The dimensions of the railgun relative to the injectors are not quite to scale here.

Latest measurements show:

- Peak electron density ~ 10^{17} cm^{-3}
- Peak velocities > 50 km/s
- Total argon mass up to 4 mg

*F. D. Witherspoon et al. (2011)

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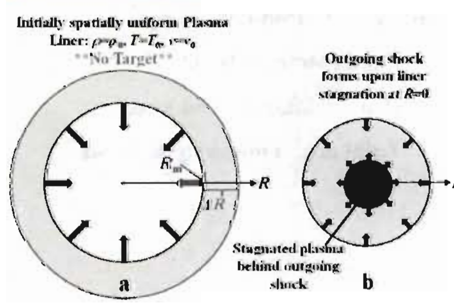
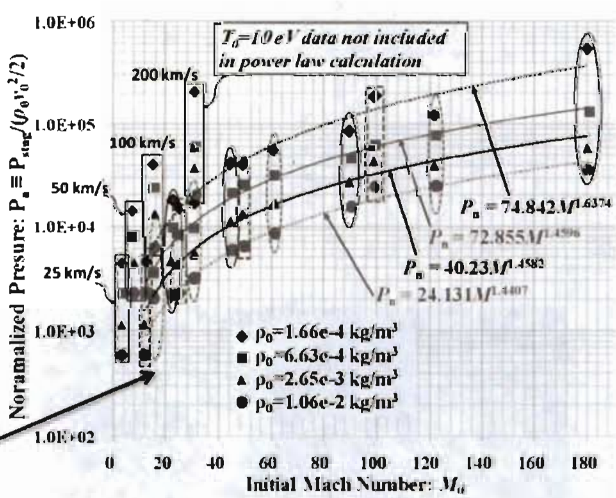
1D rad-hydro (RAVEN) simulations have increased our physical understanding of imploding plasma liner dynamics and scaling*





Key results:

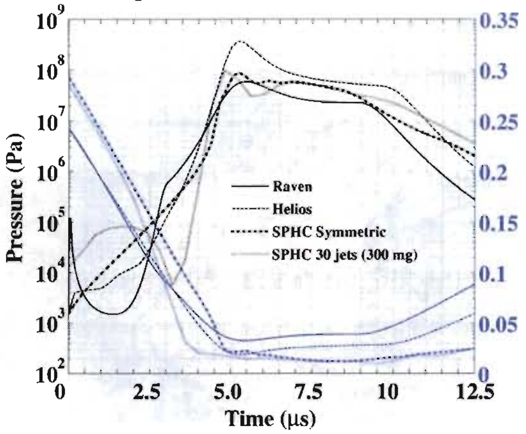
- cm/μs/Mbar-scale plasmas can be generated with PLX-relevant parameters
- Post-shock pressures P_{stag} sustained for $\sim \Delta R_0/v_0$
- $P_{stag} \sim n_0^{1/2}$ and $\sim v_0^{15/4}$
- $P_{stag}/\rho_0 v_0^2 \sim M_0^{3/2}$

Results are based on ideal gas EOS; ongoing work is utilizing state-of-the-art NLTE EOS tables from Prism Computational Sciences.

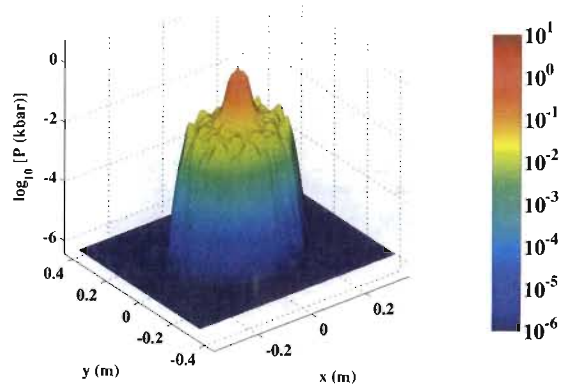
*T. J. Awe et al., submitted to *Phys. Plasmas* (2011).

Preliminary 3D ideal hydrodynamic (SPHC) simulations using discrete plasma jets compare favorably with equivalent 1D results*

Peak pressure magnitude and duration roughly equal to those of equivalent 1D runs using SPHC, RAVEN, HELIOS:



Jet asymmetries get smeared out as liner approaches origin:



*J. T. Cassibry et al., manuscript in preparation (2011)

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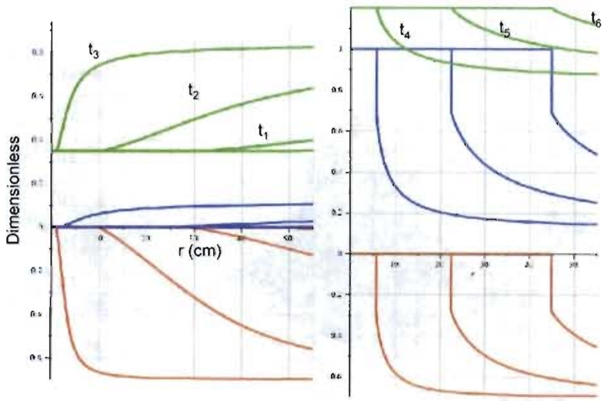
Liner profile shaping provides a way to optimize dwell time and energy gain* and also recommends the use of an "afterburner"

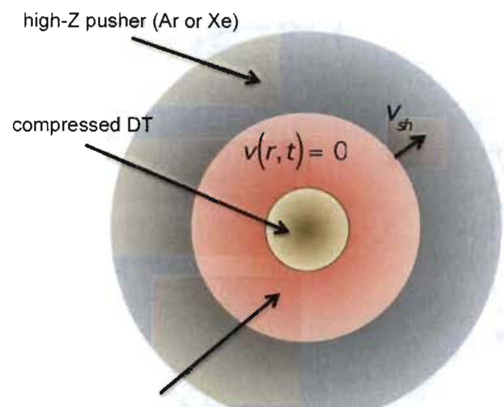
Self-similar solution to 1D ideal hydrodynamics equations admits a "bounce-free implosion":



incoming liner profiles   sustained peak pressure

green=sound speed; blue=pressure; red=velocity

Offers the potential for burning additional fuel layer (afterburner) to amplify energy gain:



DT afterburner shock-heated by outgoing shock to same pressure as compressed core

*G. Kagan et al., manuscript in preparation (2011)

Summary

- **MIF is a pulsed fusion approach using magnetic field in the compressed fuel, and is potentially a sweet spot in fusion parameter space in terms of capital cost**
- **Plasma liner driven MIF is an MIF embodiment that seeks standoff, versatility, and the use of a liquid first wall**
- **Plasma Liner Experiment (PLX), a multi-institution collaboration, will explore/ demonstrate imploding liner formation/implosion/stagnation via merging plasma jets at modest energies**
- **1D rad-hydro simulations have improved our understanding of liner implosion & scaling, and preliminary 3D ideal hydro simulation results are promising**
- **There is much room for optimization including liner profile shaping and use of "afterburners"**