Power Scaling of the Tin LPP Source via an Argon Cusp Plasma

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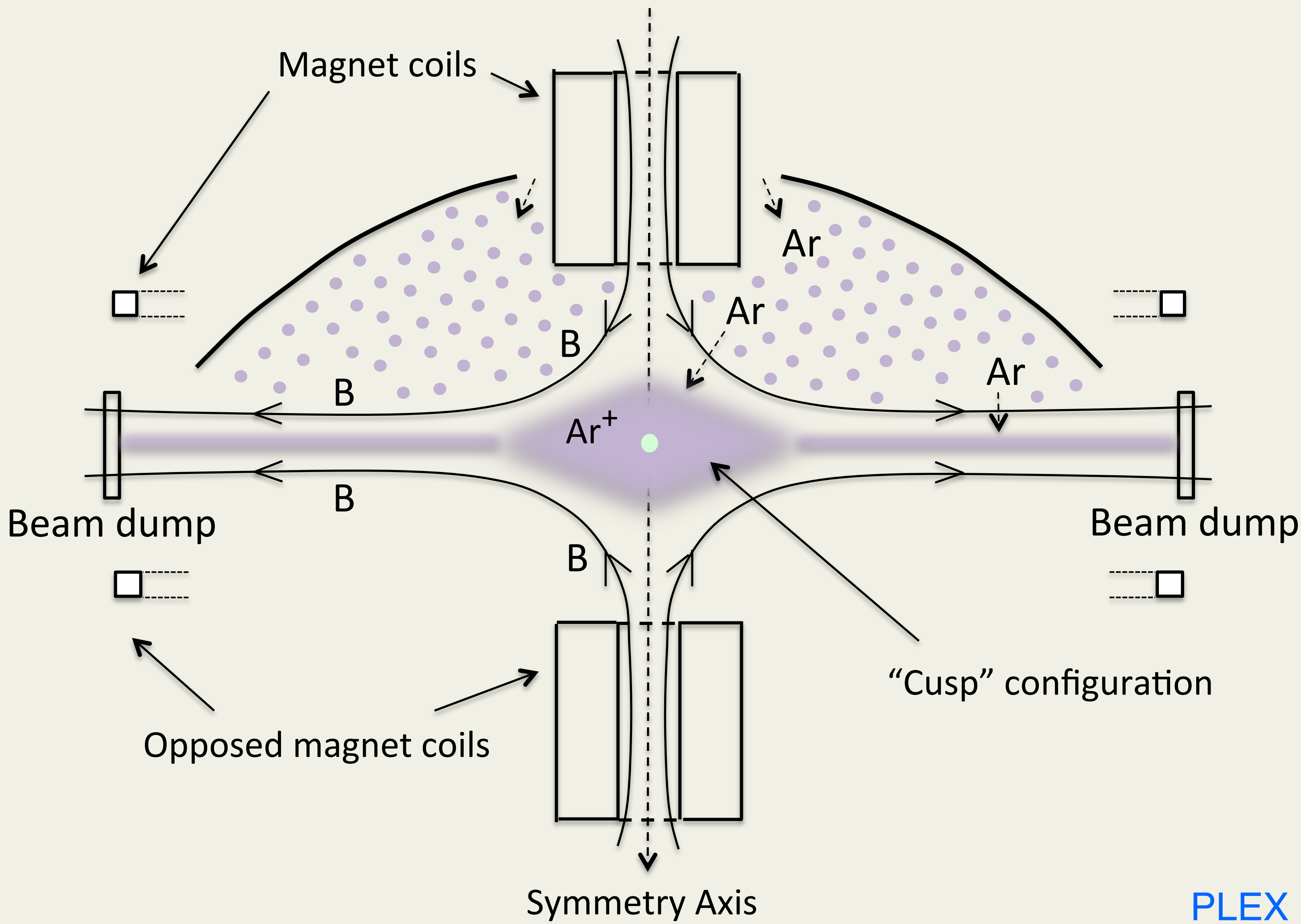
Overview: A new approach to particle and power handling that should scale to 500W



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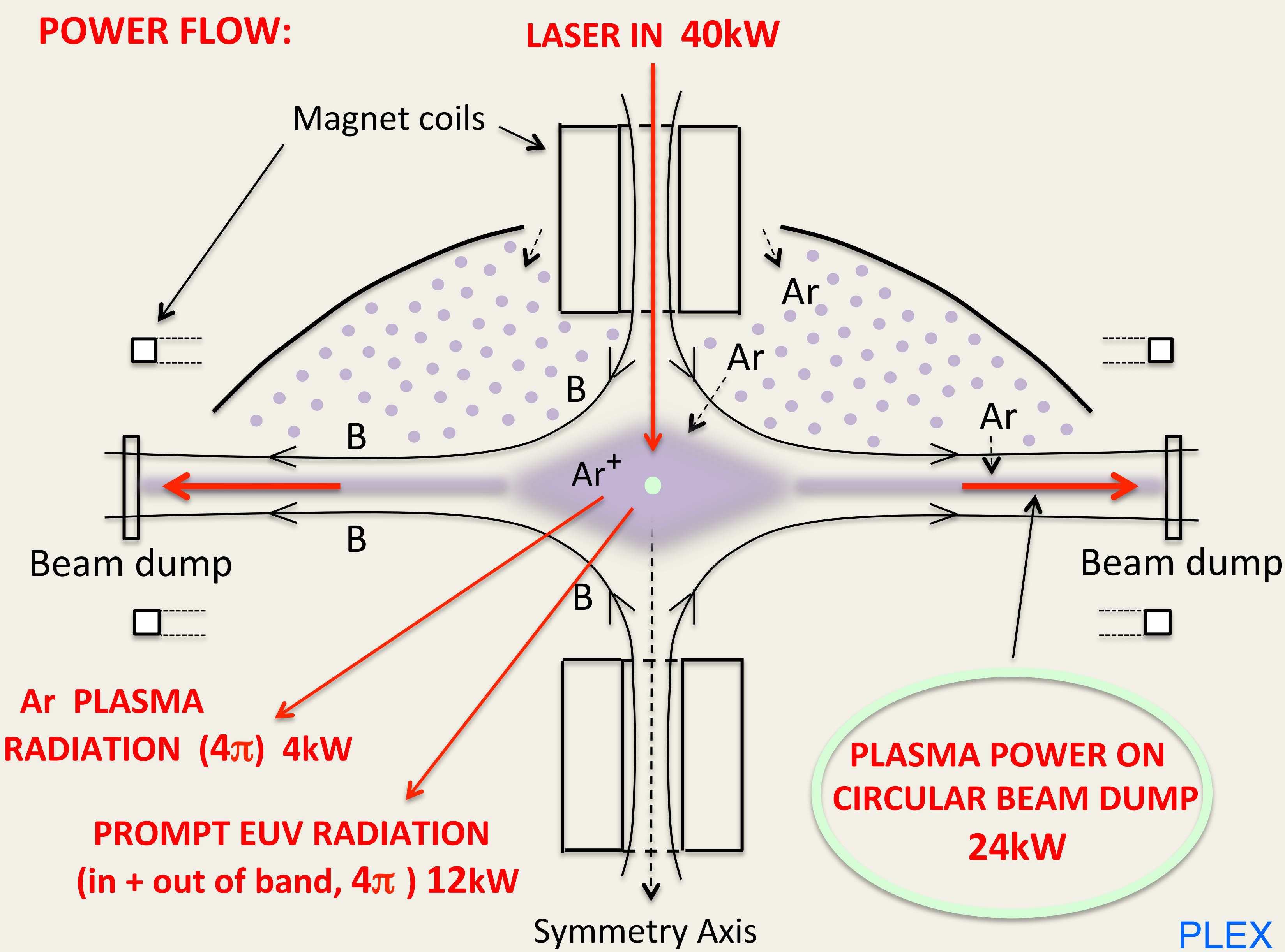
Overview: A new approach to particle and power handling that should scale to 500W



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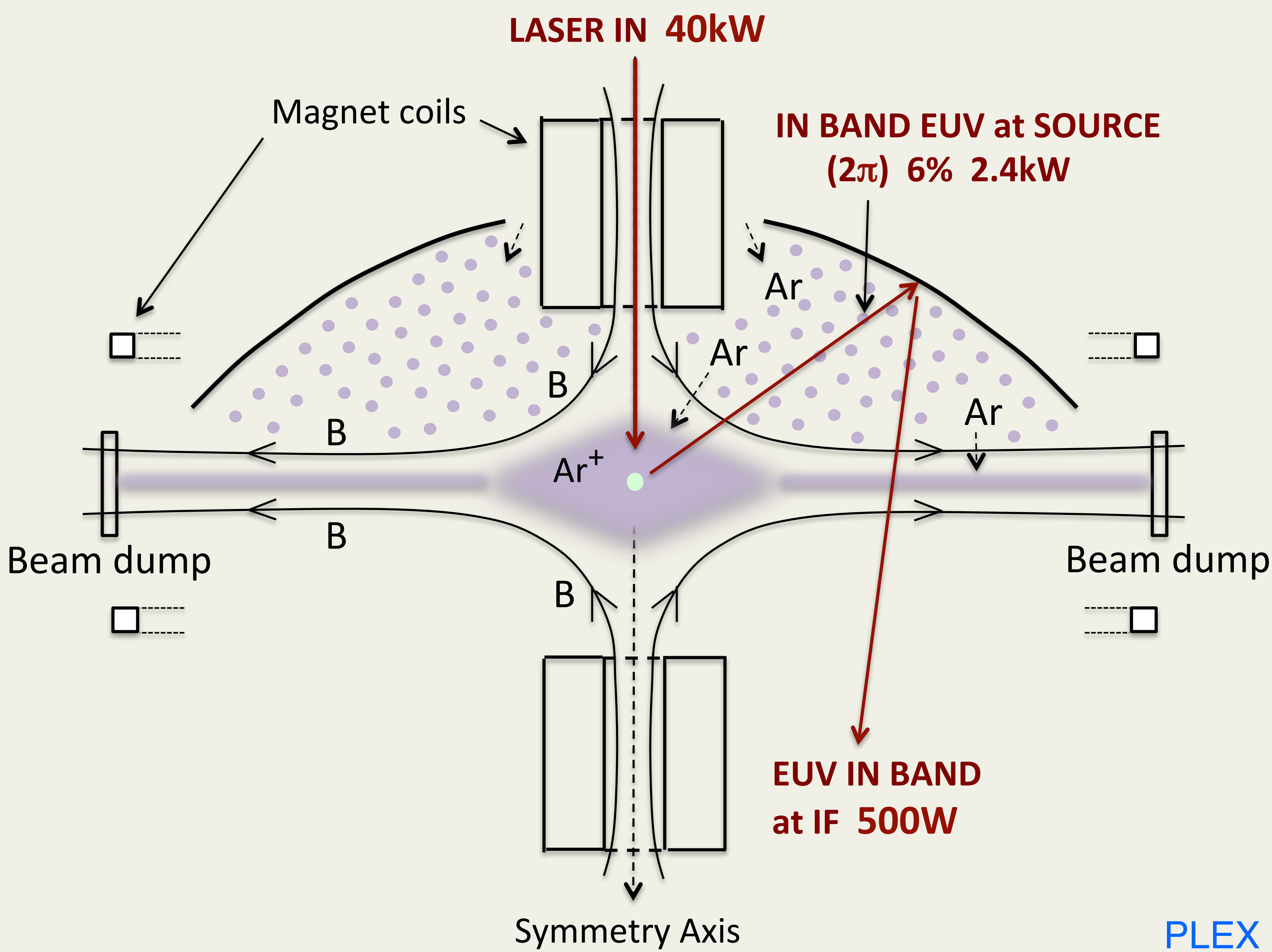
Overview: A new approach to particle and power handling that should scale to 500W



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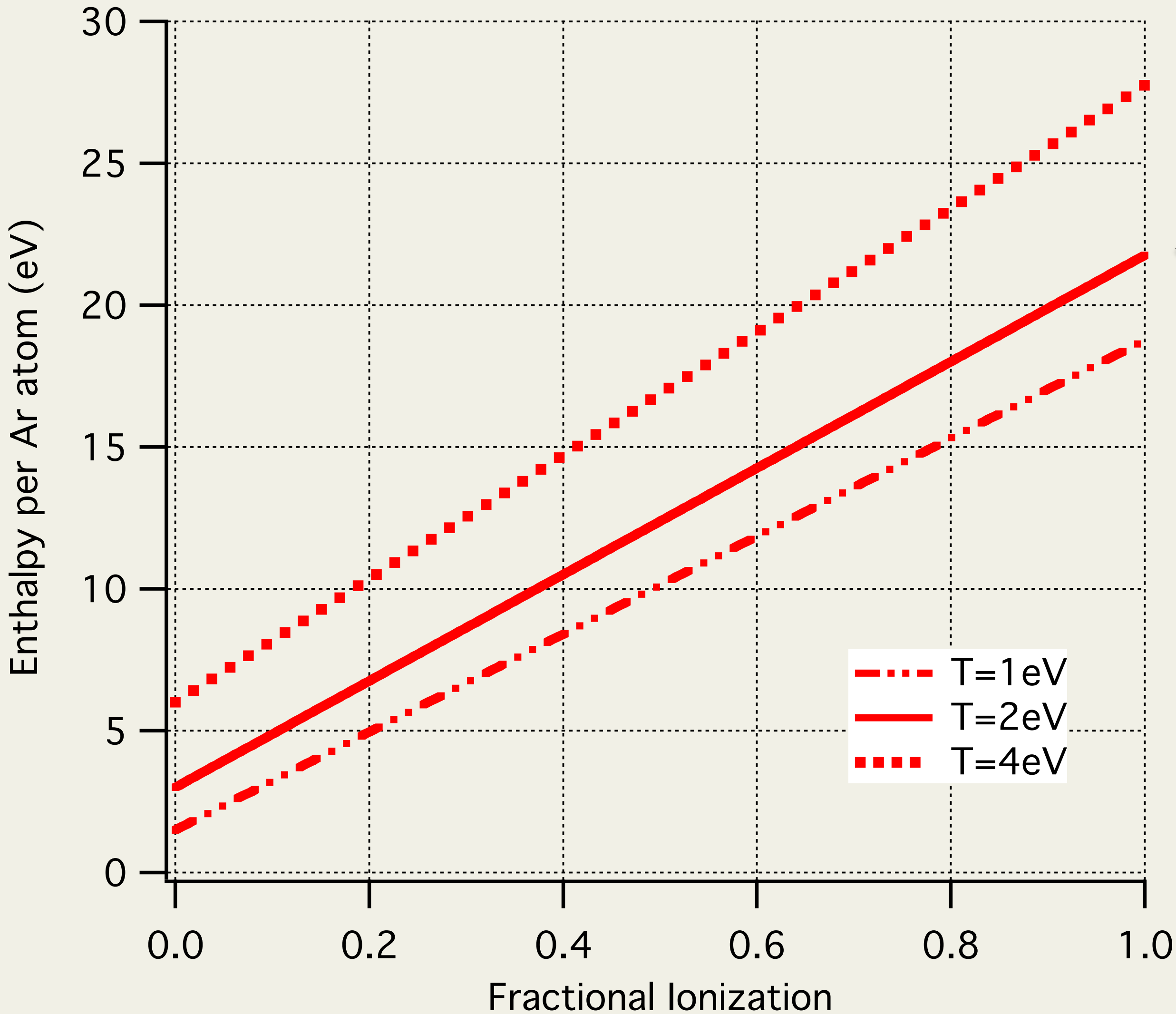
Overview: Excellent coolant



Fully ionized Ar plasma at 2eV has 22eV/atom enthalpy → excellent coolant

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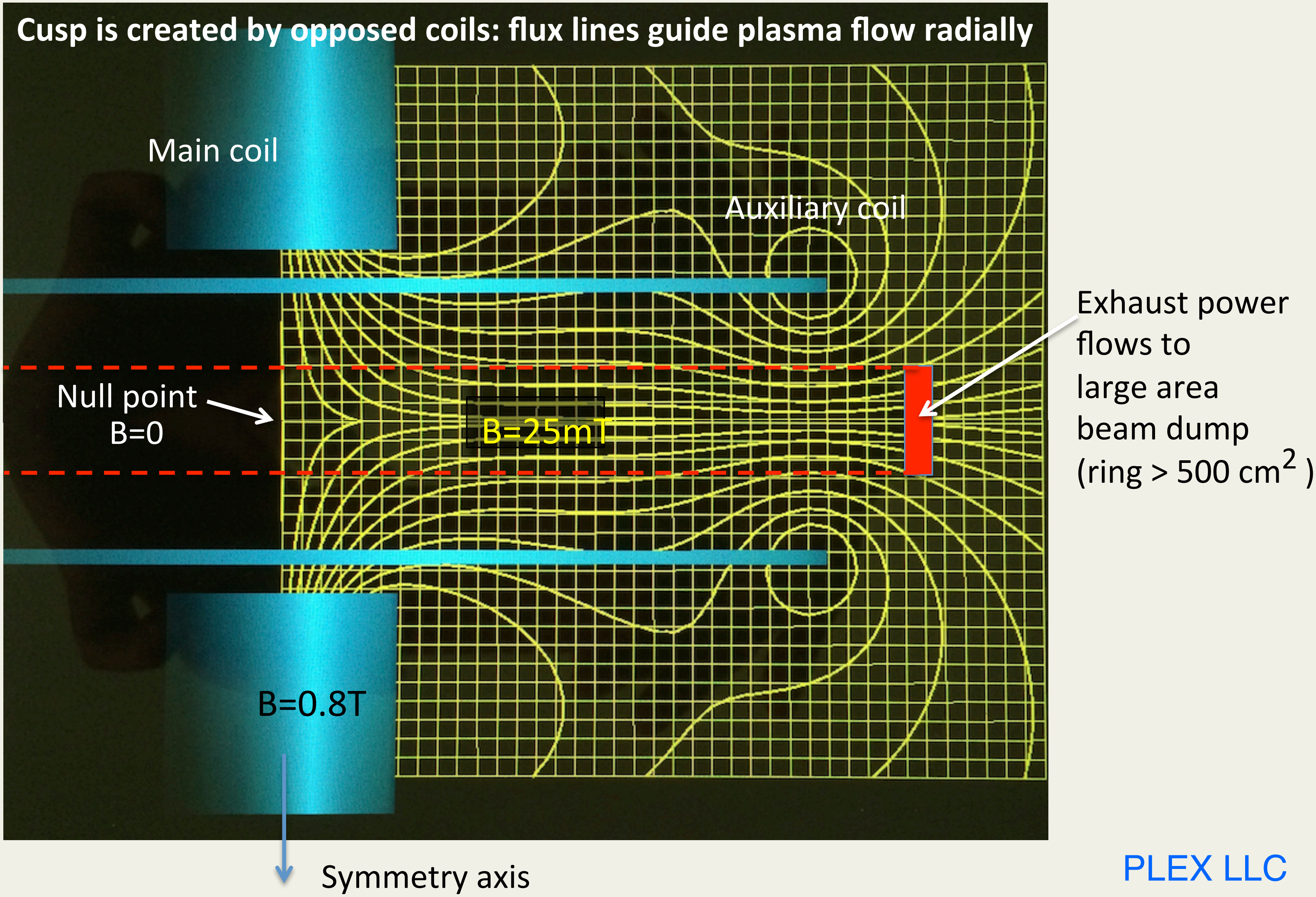
Overview: Low stress, large area beam dump



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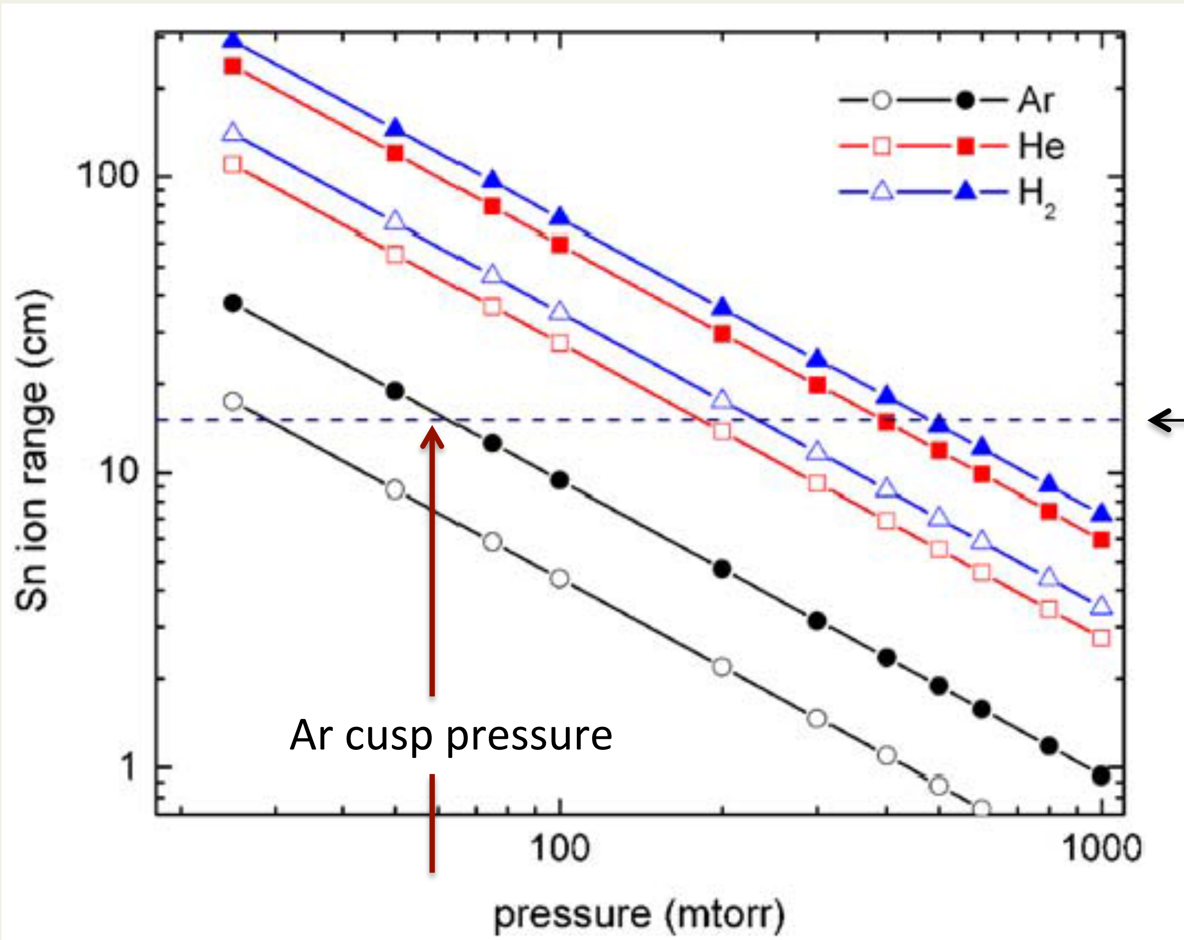
Overview: Good stopping power

Argon has good stopping power with 90% EUV transmission



Open symbols 1keV

Solid symbols 5keV

15 cm range

SRIM ion range calculations from: Harilal et al., Appl. Phys. B 86, 547-553 (2007) PLEX LLC

Overview summary

We are presenting a new route to >500W tin LPP that has:

- **Argon plasma coolant for high enthalpy**
- **500 X dilution of tin by argon**
- **Combined magnetic field and argon buffer to stop tin reaching the collector**
- **A cusp argon plasma to contain and thermalize tin ions**
- **Radial plasma exhaust at low temperature**
- **A gas barrier with entrainment pumping that reduces absorption in the exit path**
- **Uniform power flow onto a large area circular beam dump**

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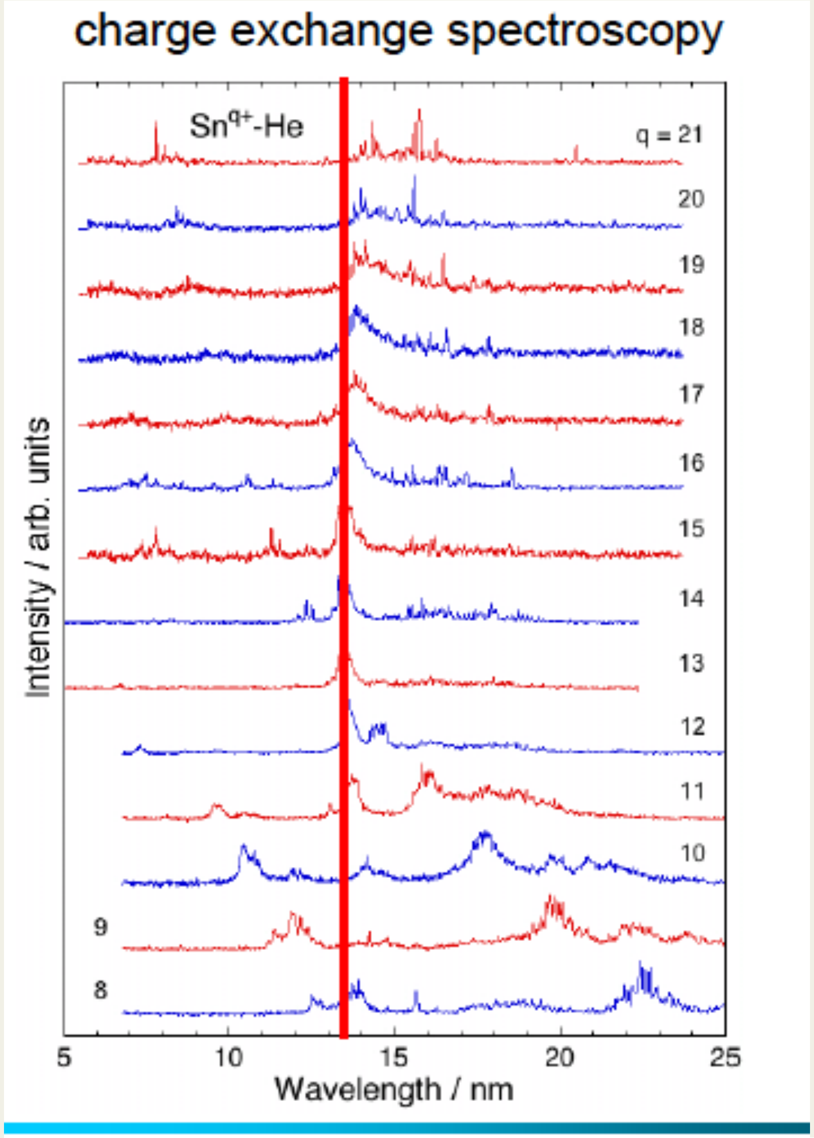
Tin 13.5nm emission is 4d-4f UTA in Sn^{10+} to Sn^{14+} ions from 45eV plasma



H. Tanuma SO-P12, Sapporo EUVL Symposium 2007

"Charge exchange spectroscopy in Sn $^{q+}$ (q=6−15)-He collisions"

H Ohashi, H Tanuma, S Fujioka, H Nishimura, A Sasaki and K Nishihara
J. of Phys. Conf. Series **58** 235 (2007)

"EUV spectra from highly charged tin ions observed in low density plasmas in LHD"

C Suzuki, T Kato, K Sato, N Tamura, D Kato, S Sudo, N Yamamoto, H Tanuma, H Ohashi, S Suda, G O'Sullivan and A Sasaki
J. of Phys. Conf. Series **163** 012019 (2009)

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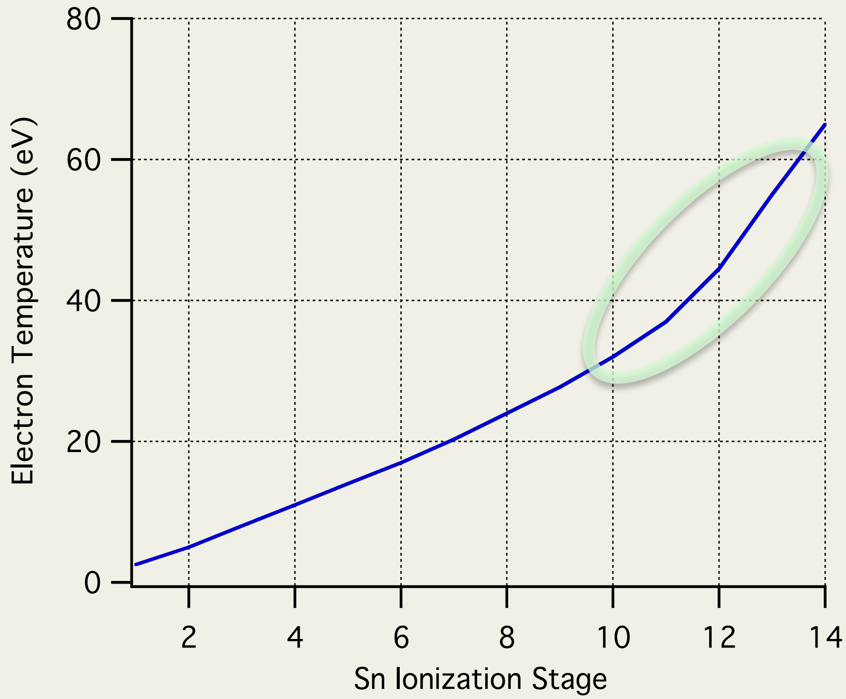
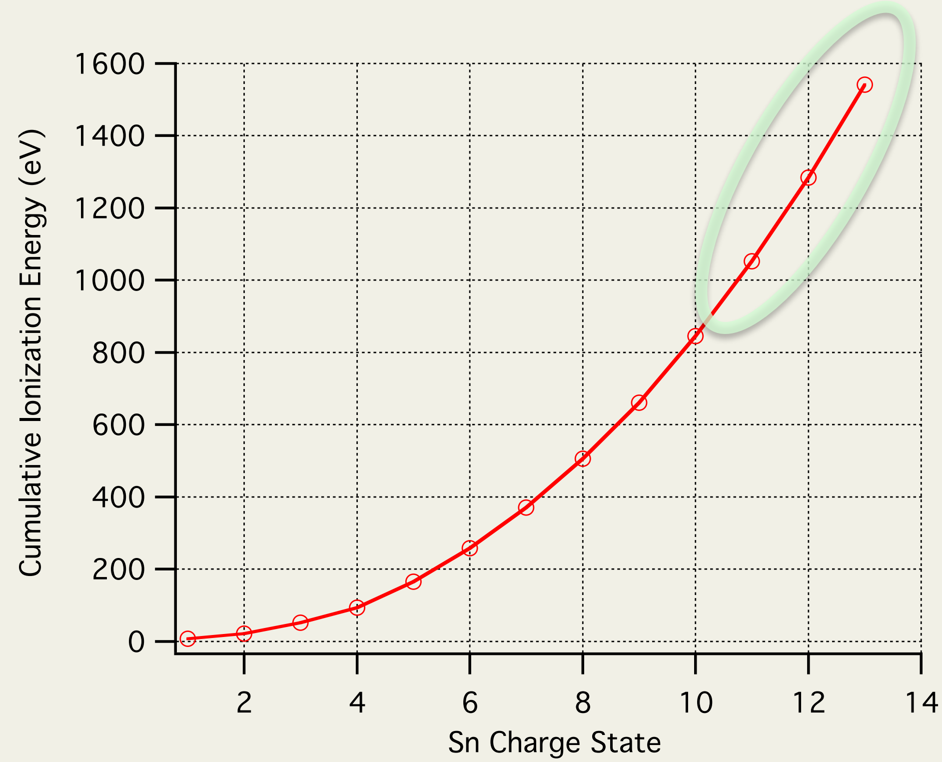
Tin data





45 eV temperature needed

1.4keV/atom invested in ionization

At Z=12 and 45eV, the plasma energy = 1.9keV /tin atom

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Efficiency highest at low plasma density (K. Nishihara et al., Phys. Plasmas 15, 056708 (2008))

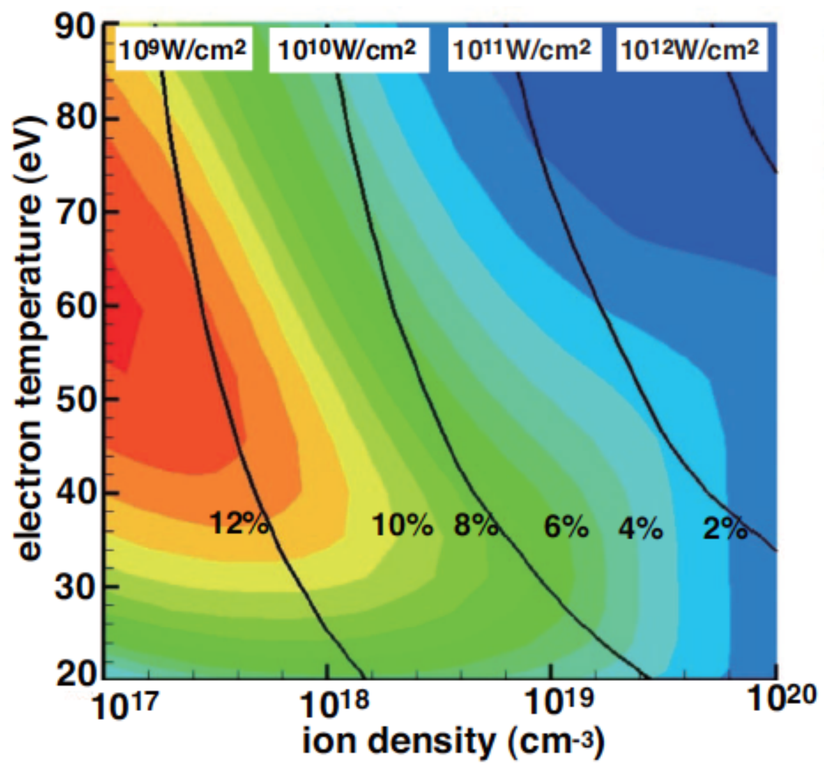

FIG. 2. (Color) Optimum conversion efficiency from 1 to 13% with increment of 1% (color), and absorbed laser intensities 10^9, 10^{10}, 10^{11}, and 10^{12} W/cm^2 from left to right (solid lines), are required to sustain the plasma in (n_i, T_e) plane.

(CE into 4π sterad)

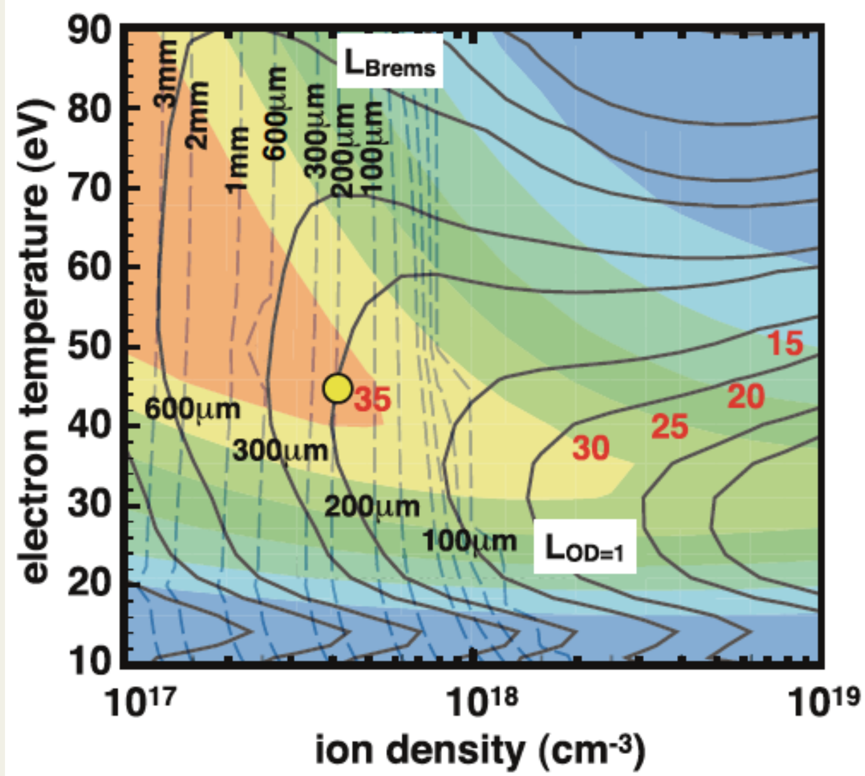

FIG. 6. (Color) Isocontour of spectral efficiency from 10 to 35% with the increment of 5% (color), the ratio of 13.5-nm radiation with 2% bandwidth to total radiation, density scale length for CO_2 laser light to be absorbed (dashed line), and density scale length corresponding to 13.5-nm radiation optical depth of 1 (solid line) in the (n_i, T_e) plane.

Optimum 6% (2π) efficiency at 7×10^{17} ions cm^{-3} matches best density for CO_2 laser absorption

($Z=14 \Longrightarrow 10^{19}$ electrons cm^{-3})

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At 10.6µm efficient laser absorption requires a long scale length plasma (>200µm)

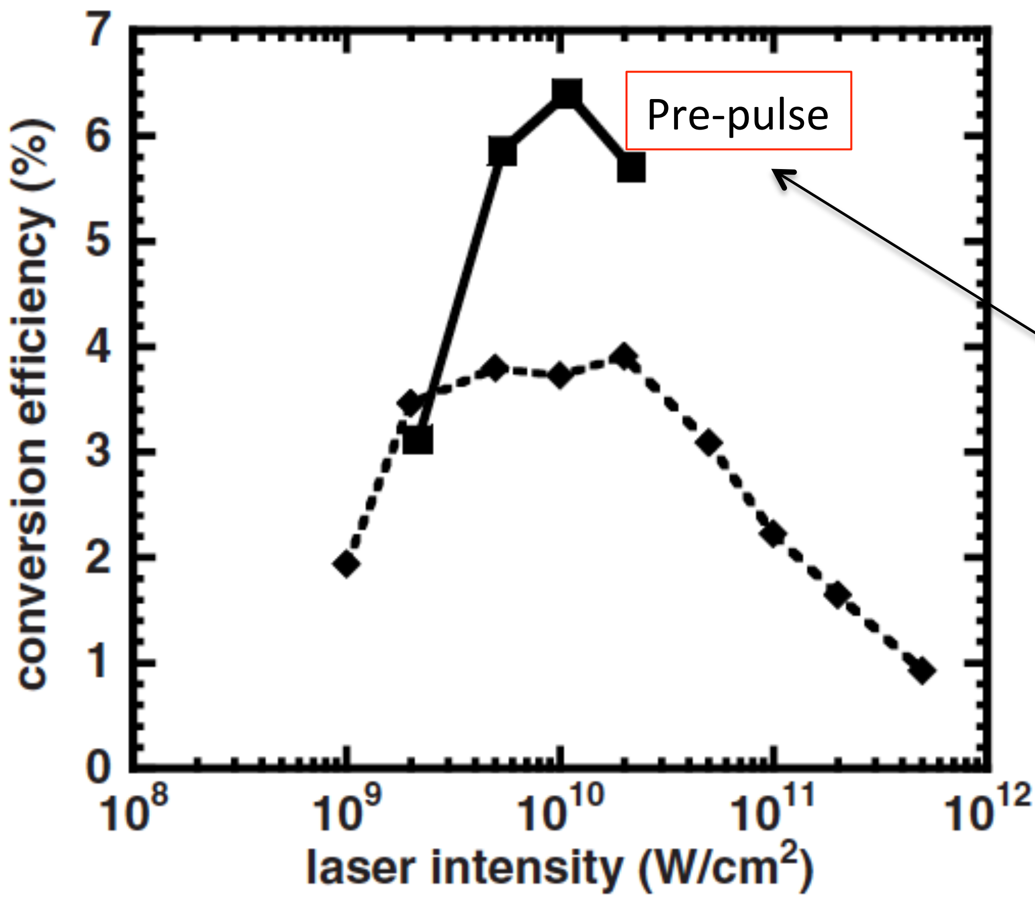

FIG. 9. Conversion efficiency dependence on CO_2 laser intensity for single (dashed) and double (solid) pulse irradiation cases.

Solid tin surface has only about 50% absorption for single pulse CO_2 light (resonance plus some IB)

CO_2 absorption is increased to >90% by enhancing IB absorption length via use of a **pre-pulse**

Fig 9: Calculation from K. Nishihara et al., Phys. Plasmas 15, 056708 (2008)

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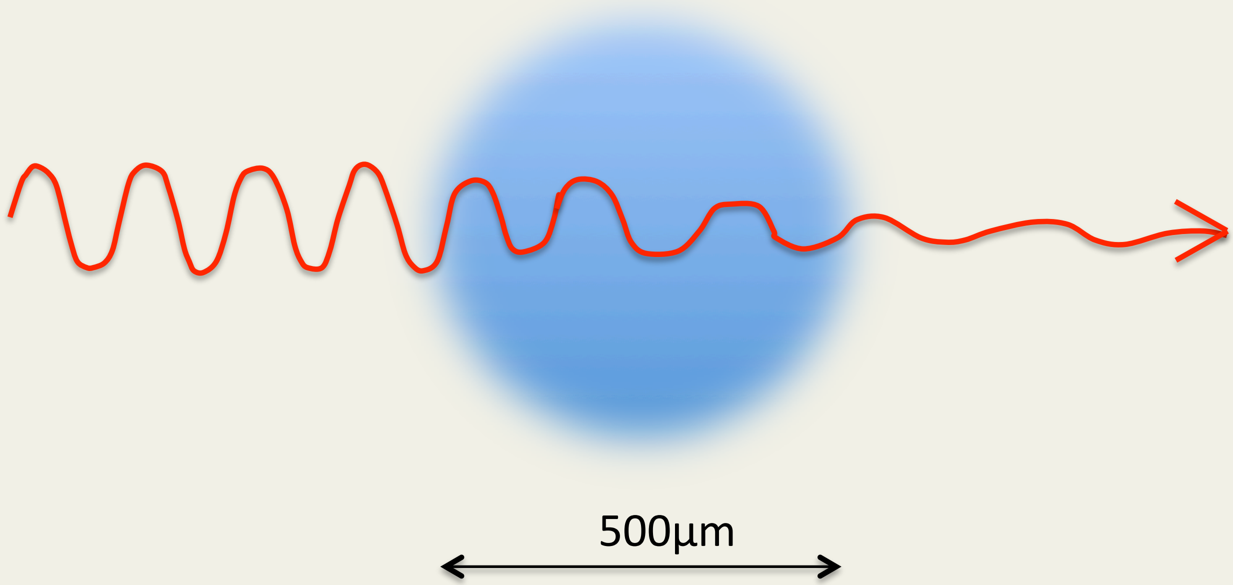
To reduce contamination we wish to use as little tin as possible



Suppose underdense for 6% efficiency and Z=14 to use all emitting ion species

CO_2 laser critical density $n_{CR} = 1x10^{19}$ electrons cm^{-3}

=> Ion density $n_i = 7x10^{17}$ cm^{-3} => initial tin droplet diameter **14µm**

with PERFECT EVAPORATION BY PRE-PULSE

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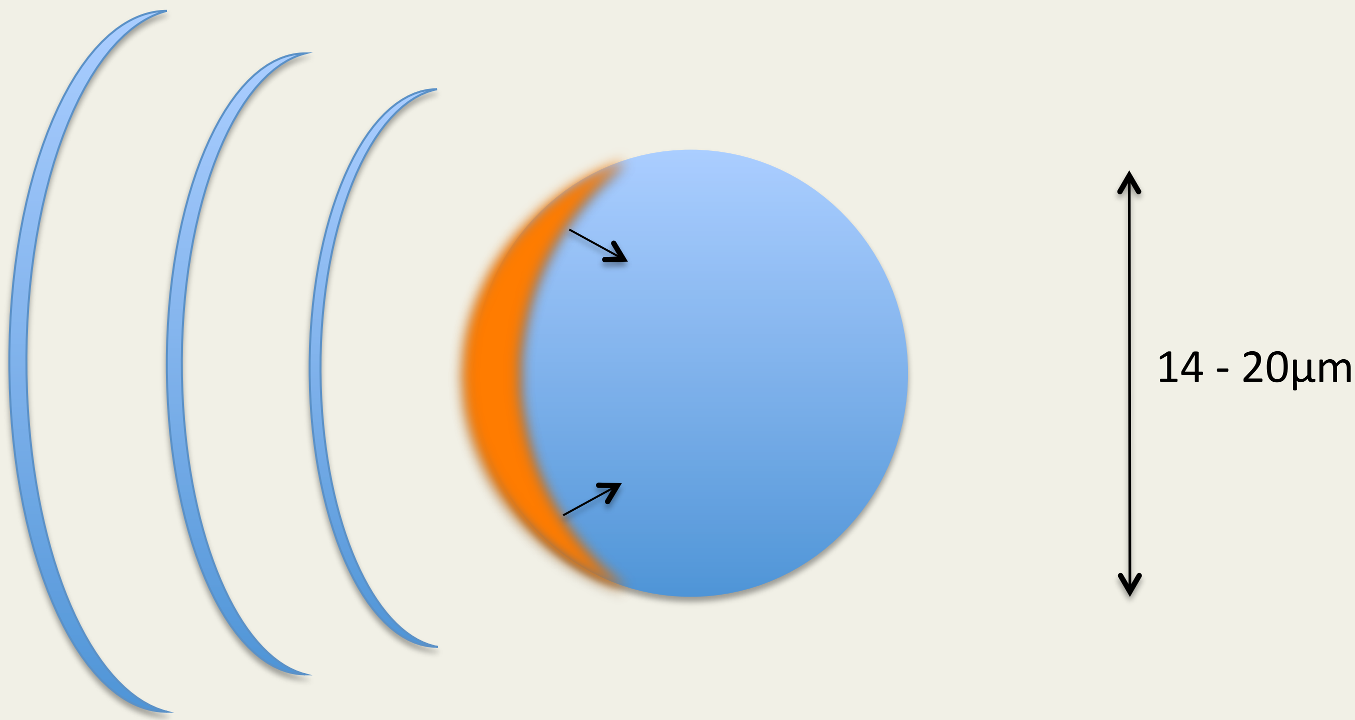
Perfect evaporation requires a short wavelength, very intense pulse



High intensity, short λ => strong shock wave => rapid boiling/ ionization

Picosecond 1.06µm laser gives very fine "mist"   Mizoguchi et al., SPIE 2013…

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Stimulated Brillouin Backscatter from an under-dense plasma limits pulse energy

We need under-dense to achieve 6% efficiency, but a long path in an underdense plasma is the exact recipe for enhanced stimulated Brillouin backscatter with threshold intensity:

$$I_t \approx \frac{7x10^{15}}{L(\mu m)\lambda(\mu m)} \Theta_{keV} \left(\frac{\omega}{\omega_{PE}} \right)^2 W/_{cm^2}$$

Where: L is the path length; λ the laser wavelength, Θ the electron temperature in keV ω and ω_{PE} the laser and plasma (angular) frequencies. Here $\omega \approx \omega_{PE}$.

EXAMPLE: at 0.040 keV, 10.6µm and 400µm path I_t = $7x10^{10}$ Wcm^{-2}

This would limit the energy per pulse, e.g. at 5nsec, 400µm diameter E<0.4J

Any departure from perfect laser beam quality, e.g. transverse or longitudinal mode structure or refraction by mist particles will create intensity "hot spots" reducing safe energy to about **0.3J/pulse**

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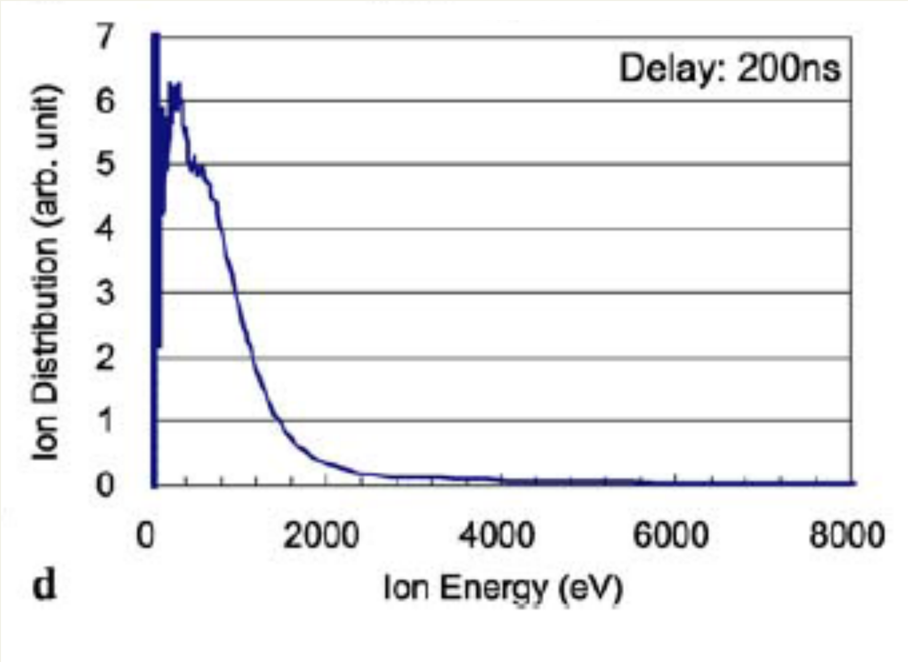
What leaves the interaction region: Sn neutrals, ions, radiation and micro-droplets

Psec pre-pulse at 1.06µm generates very fine micro-droplets, or mainly ions/neutrals

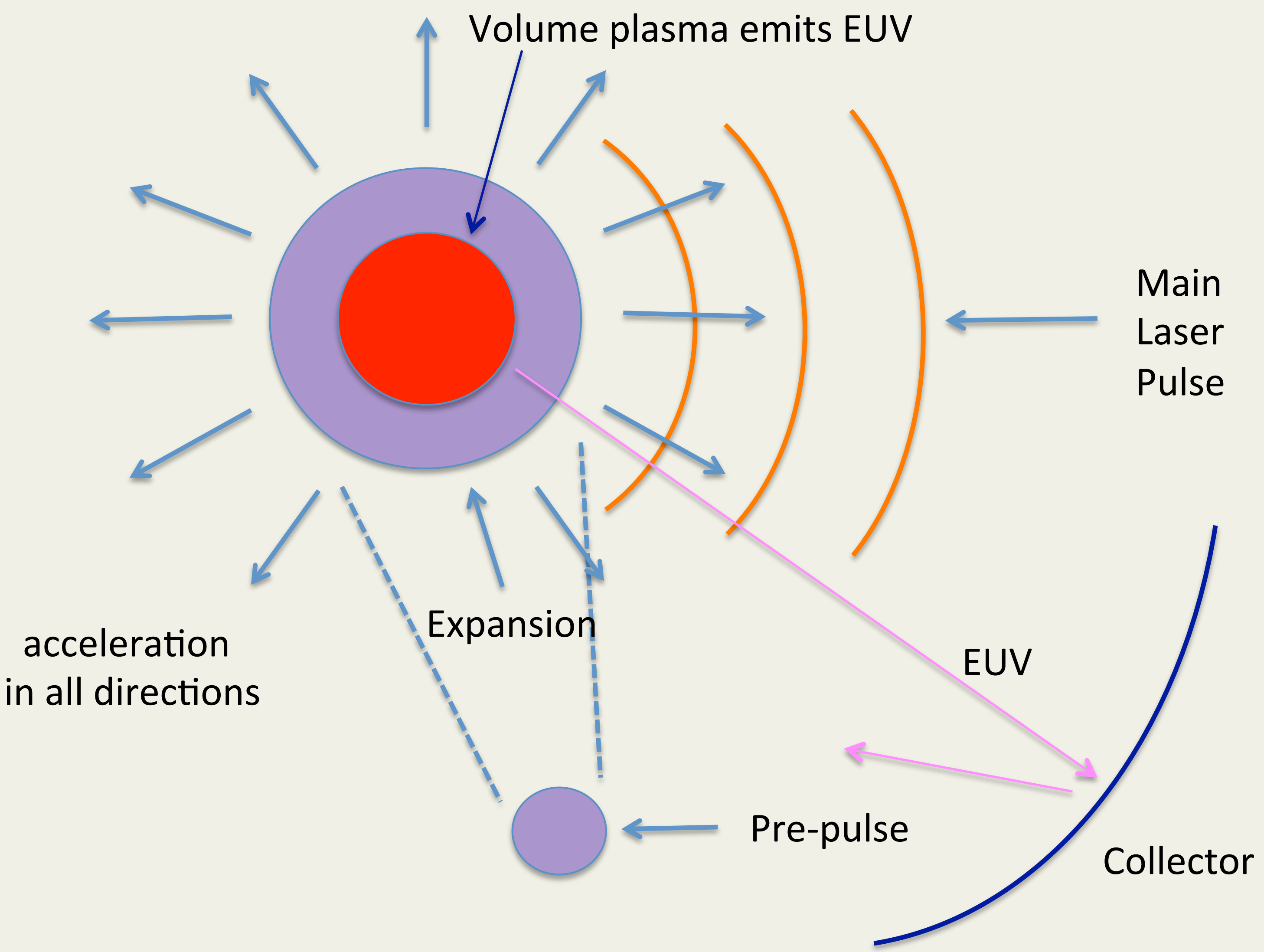
Main CO_2 pulse that follows evaporates all droplets (Gigaphoton SPIE 2013)

Exhaust ion spectrum is "soft" (max 5keV) when there is a pre-pulse and 3D expansion



Ion spectrum with YAG laser pre-pulse then CO_2 laser main pulse in Xenon (like tin) Komori et al. Appl. Phys. B **83**, 213-218 (2006)

Under-dense case : Ions and fragments are accelerated in all directions



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The engineering challenge: Particle and power handling

- Droplet diameter 17-20μm Tin atoms/droplet 1×10^{14} - 1.5×10^{14}
- Droplet expansion to under-dense at 300-400μm dia.
- Repetition frequency 100 – 150kHz
- CO_2 laser pulse energy 0.2J – 0.3J (20-45kW)
- Laser pulse duration 5-10ns
- Max. ion energy 5keV
- Prompt radiation in all bands = 30% of absorbed light

Following from above: **Tin throughput 1×10^{19} - 2×10^{19} sec^{-1}**

Exhaust energy per tin atom 6 keV – 12 keV

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Two well-established approaches to collector protection and heat removal

	Magnetic field	Gas pressure
Gigaphoton	strong	Zero (or small?)
Cymer	zero	high
And now PLEX	moderate	moderate

Disclaimer

The following analysis of the Gigaphoton and Cymer approaches is based on publicly available material. It may be out of date, or only partly correct! In which case, my apologies to those concerned.

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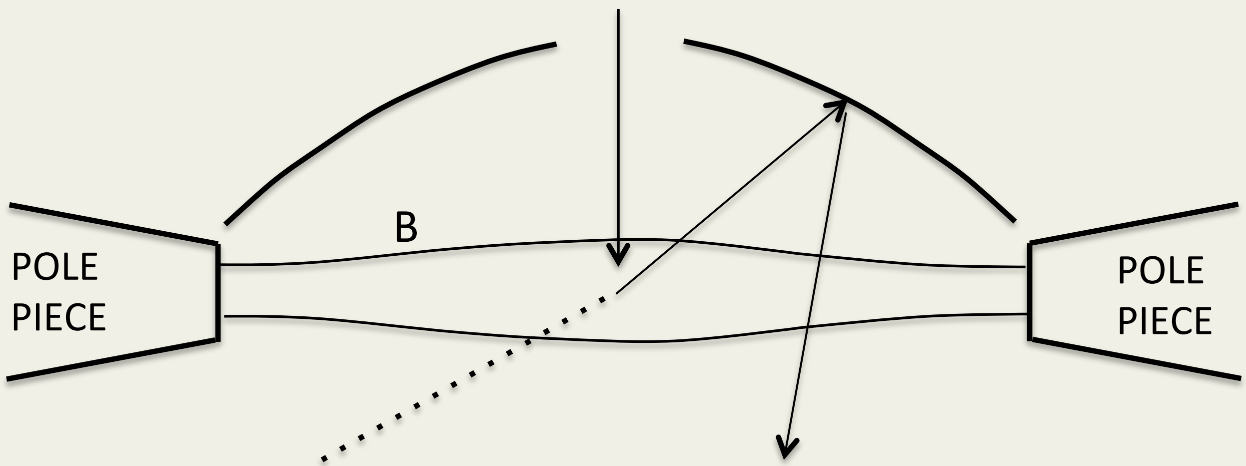
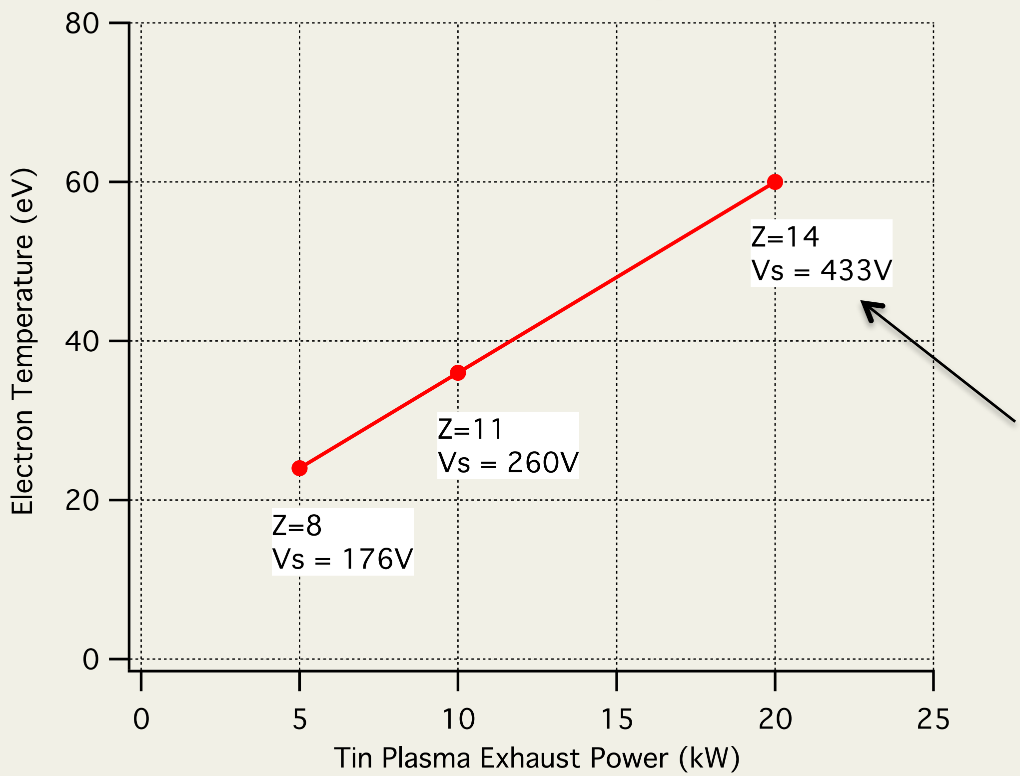
Gigaphoton 1. Particle and heat removal via magnetic field only. No buffer gas





Good exhaust confinement, but

a) High Sn charge states

b) Large sheath potential

c) Up to 6keV ion energy at impact

d) Possible beam dump erosion

e) High local intensity on beam dump

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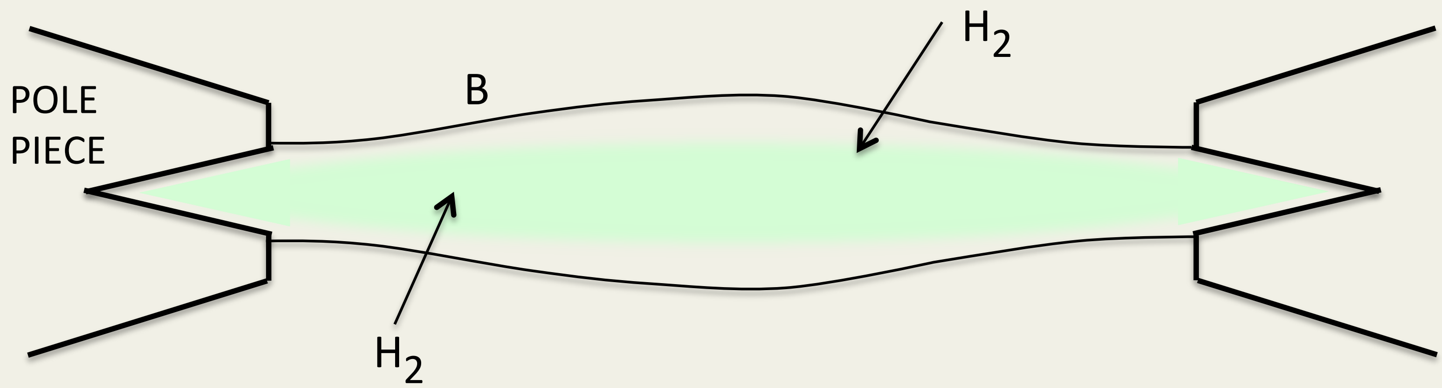
Gigaphoton 2. Low H_2 pressure could moderate ion energies at beam dump



Consider 3Pa ($6x10^{14}$ $\mathbf{H_2}$ cm^{-3}) → kinetic entry rate $2x10^{22}$ sec^{-1}

Calculate: $N_e = 2x10^{15} cm^{-3}$, full dissociation to H^+, Sn^{5+} recombination complete

Sheath potential dominated by hydrogen V_s = 12eV, Sn^{3+} impact only 36eV!

Chemical dissociation cooling 4.478 eV per molecule → 14kW + plasma cooling

BUT:

This H_2 density provides negligible additional protection to the collector

Large plasma volume => efficient (H_2 → H) dissociation reactor. Disposal?

Still has high intensity on the beam dump because of B field geometry

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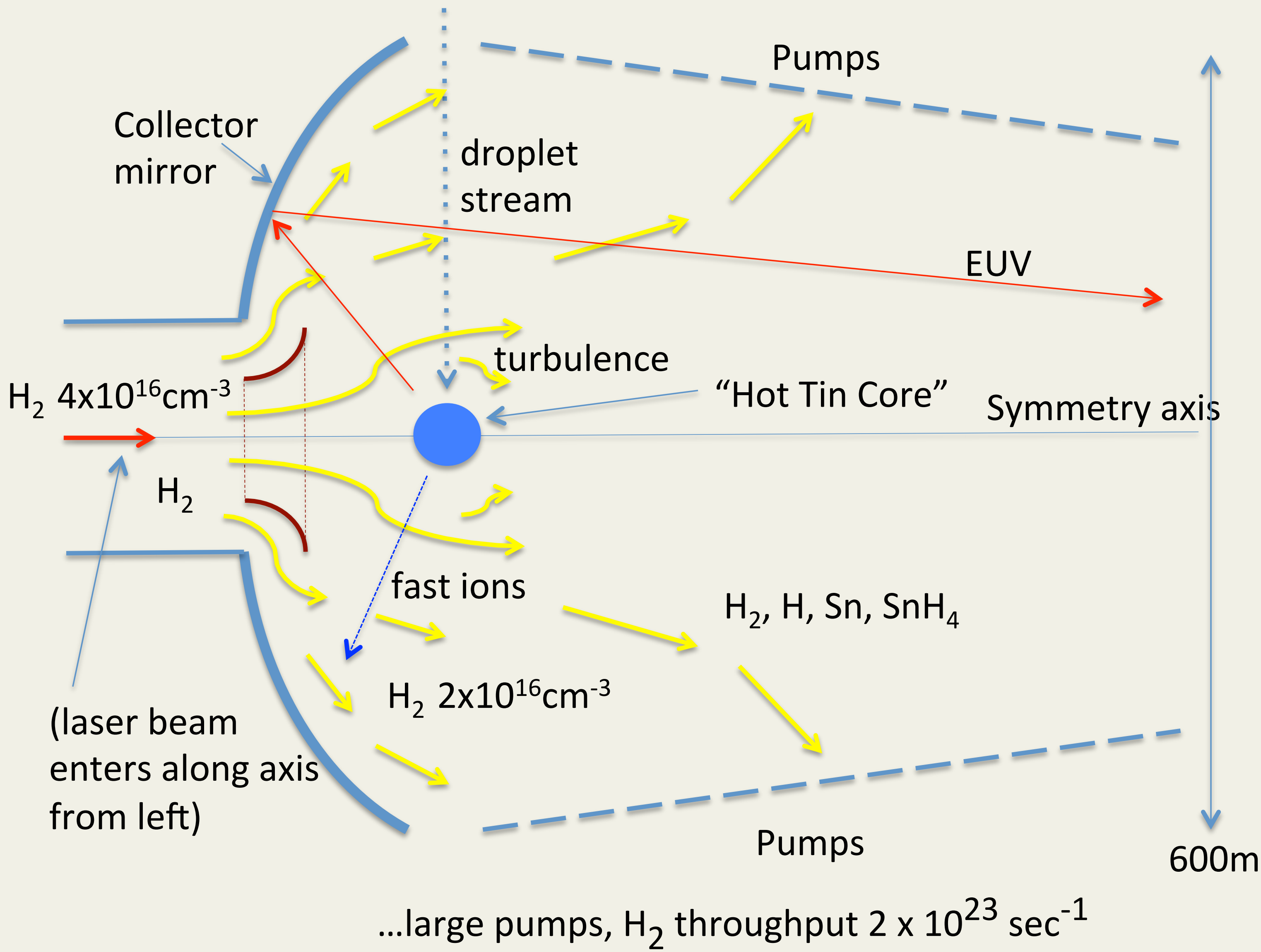
Cymer 1. Hydrogen gas flow clears tin and protects collector. No B field.



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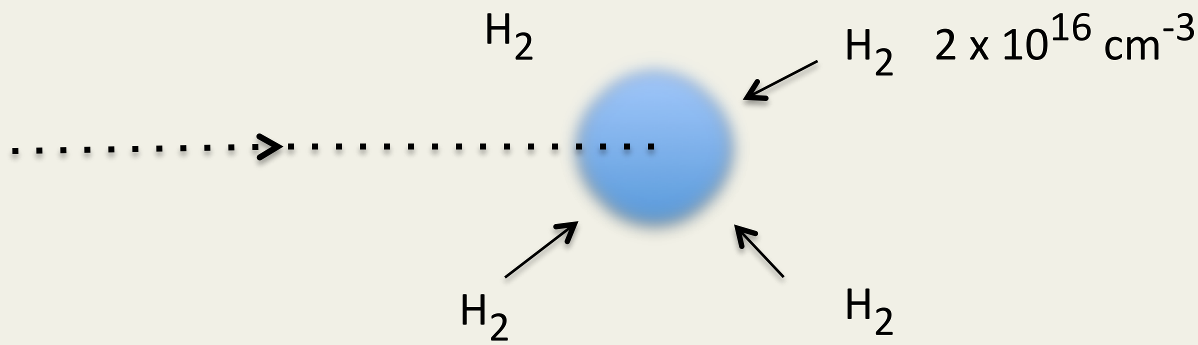
Cymer 2. The "Hot Tin Core" and its radiation



Momentum of expanding tin plasma is balanced by H_2 to establish a hot, dense tin core

Radiation may be strong:

$$Q_R = 4\pi R^2 \varepsilon \sigma T^4$$

R = 2 cm

ε = *0.01*

Temperature (K)	Radiated Power (kW)
4,000	0.73
6,000	3.69
8,000	11.7
10,000	28.5

BUT, no "beam dump" as such and the balance of all power lands on collector and other in-chamber components via radiation.

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Summary of the engineering challenges in current approaches (if assumptions correct)

Common to both

Hydrogen dissociation – needs care to control energy deposition downstream

(assuming Gigaphoton uses a low H_2 flow)

Gigaphoton

Magnetic field design concentrates energy on a small area beam dump

Cymer

Most input power floods the chamber and collector as radiation. No beam dump

Large pump necessary to vent hydrogen

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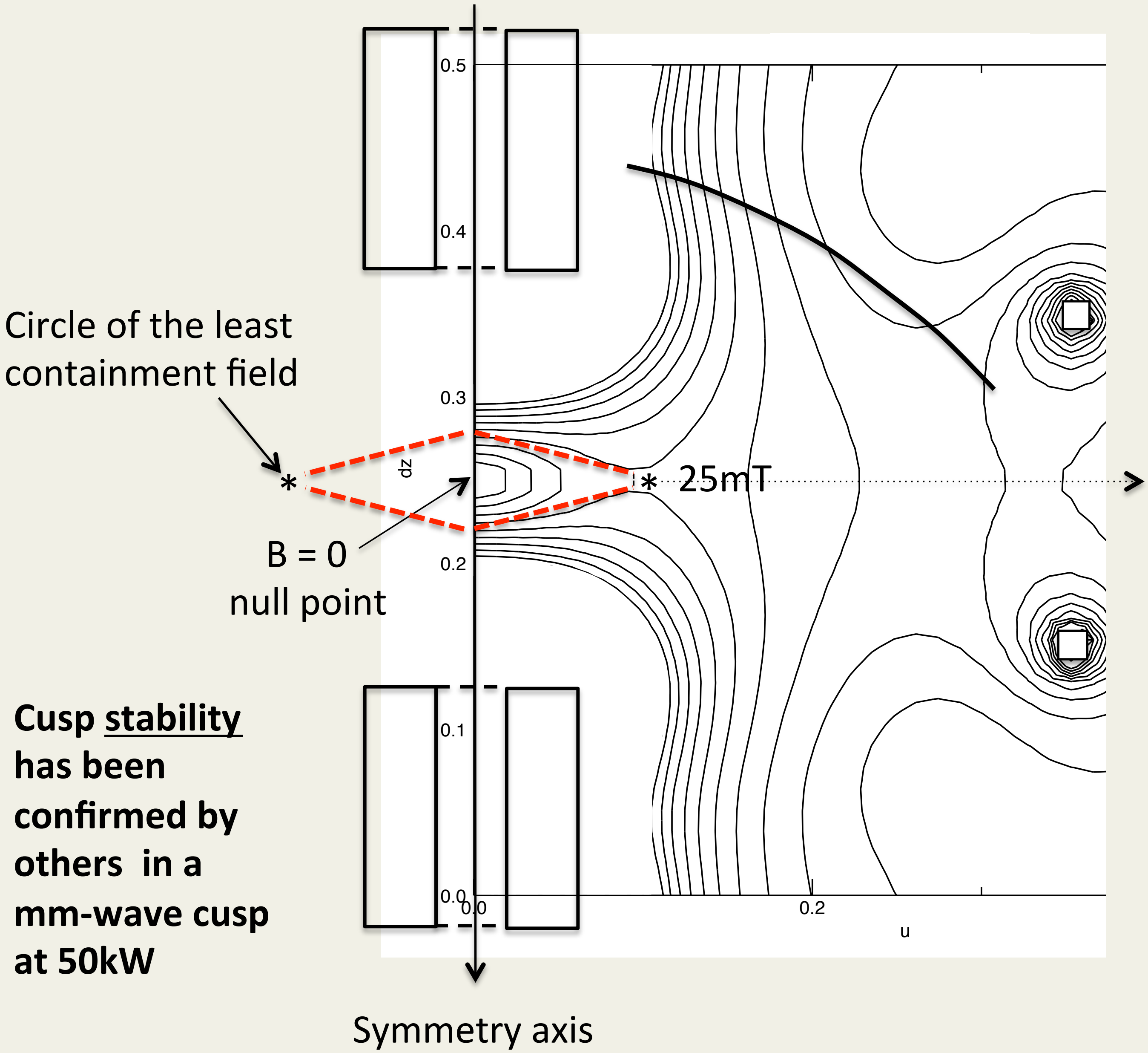
The cusp is a stable magnetic well, shown here in contours of constant B.



Cusp stability has been confirmed by others in a mm-wave cusp at 50kW

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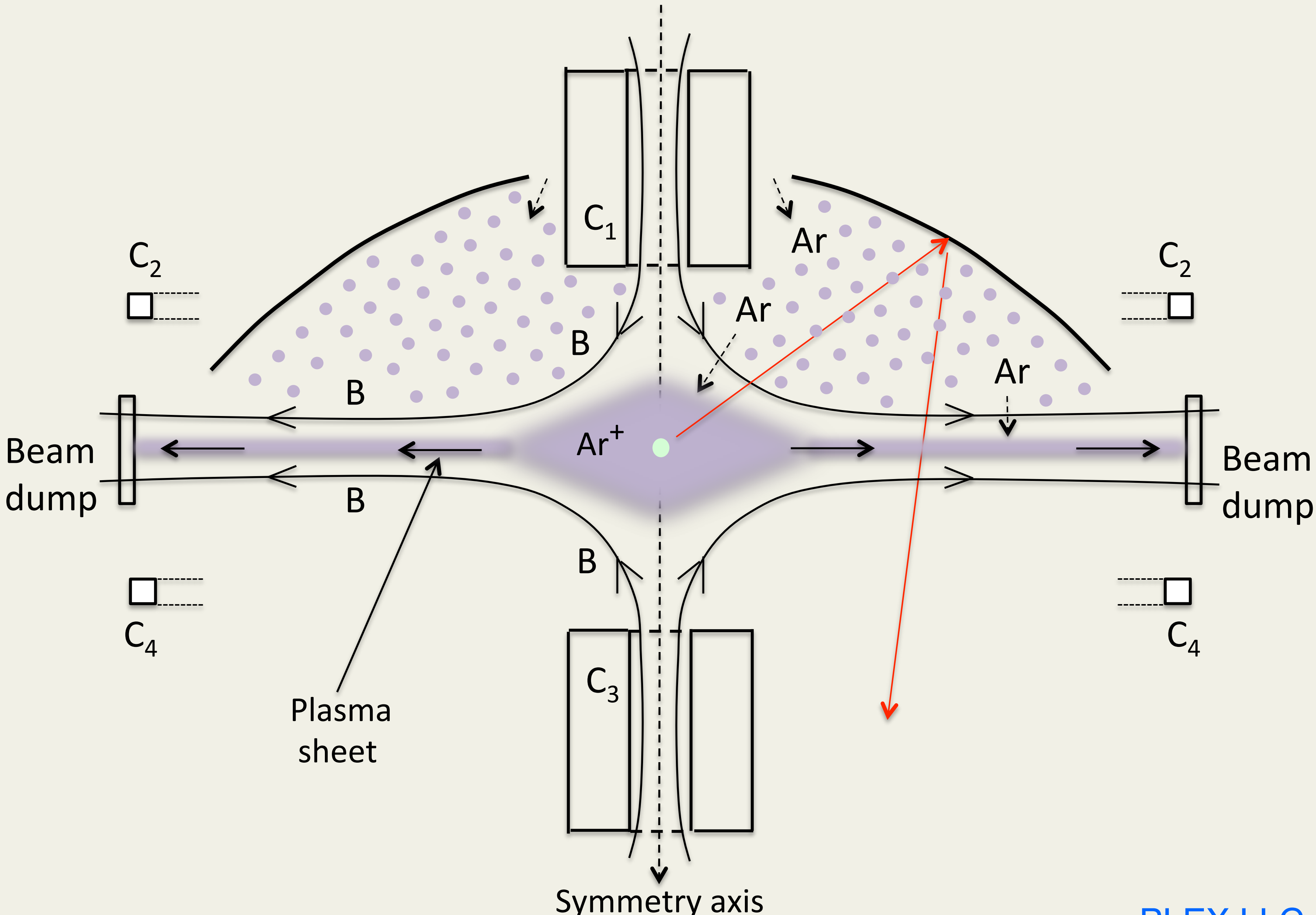
The cusp "exhaust" flows radially in a disc, providing a gas barrier



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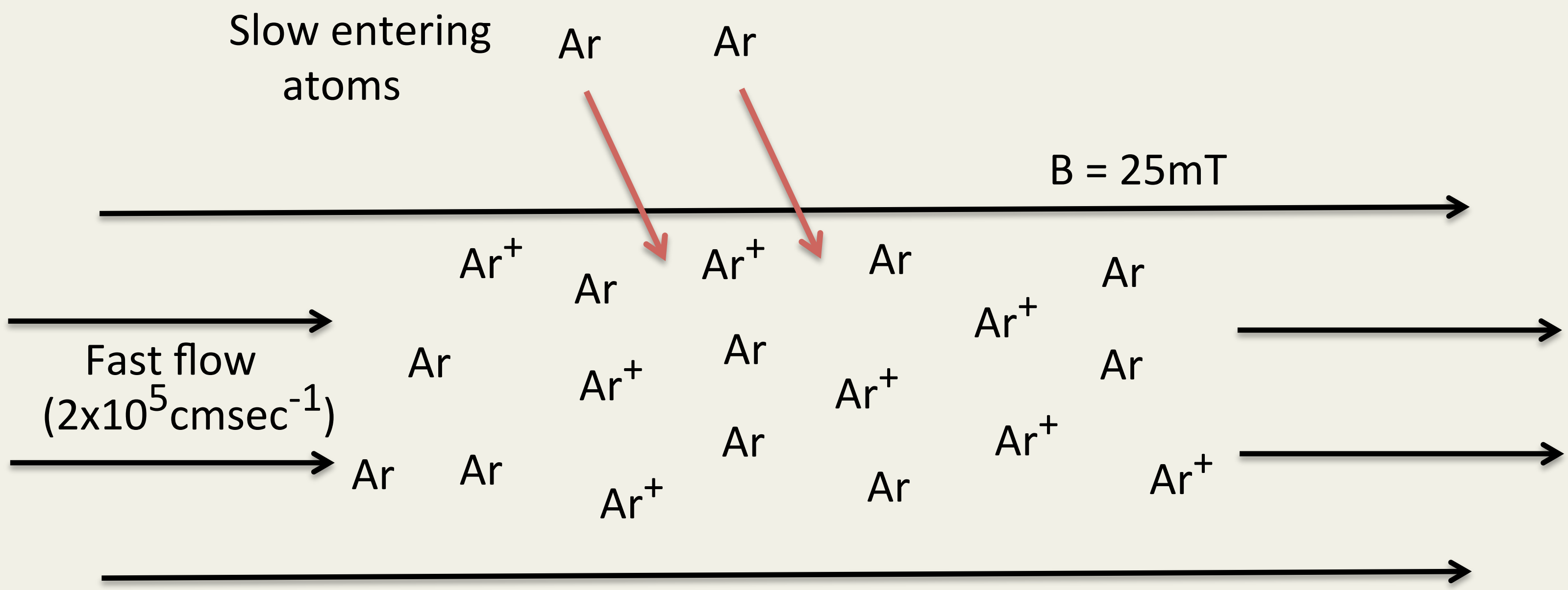
97% of the argon is entrained in the plasma sheet which has a powerful pumping action



Processes (combined entrainment efficiency >97%):

Momentum transfer (MT) $Ar + Ar_{flow} \rightarrow 2Ar_{flow}$ $\sigma_{MT} = 1.0\text{x}10^{-14}\ cm^2$

Charge exchange (CE) $Ar + Ar^{+}_{flow} \rightarrow Ar^{+}_{flow} + Ar_{flow}$ (captured) $\sigma_{CE} = 6\text{x}10^{-15}\ cm^2$

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The power – handling capability of the argon cusp scales to 40kW

$$(1-\xi)P_L = \dot{N}_{Ar}\left[\eta\varepsilon_i + 3(1+\eta)kT/2\right] + P_{RAD}$$

Enthalpy per argon atom (max. 22eV)

Where:

P_L = absorbed laser power

ξ = prompt radiation fraction (0.3)

$\dot{N}_{Ar}$ = argon throughput

η = fractional ionization

ε_i = IP Ar (15.76 eV)

kT = electron temperature

P_{RAD} = argon radiated power (4kW)

Limit to throughput is argon density $2x10^{15}$ cm^{-3} in space near collector

→ $\dot{N}_{Ar} = 7x10^{21}\ \sec^{-1}$

Achievable P_L = 40kW

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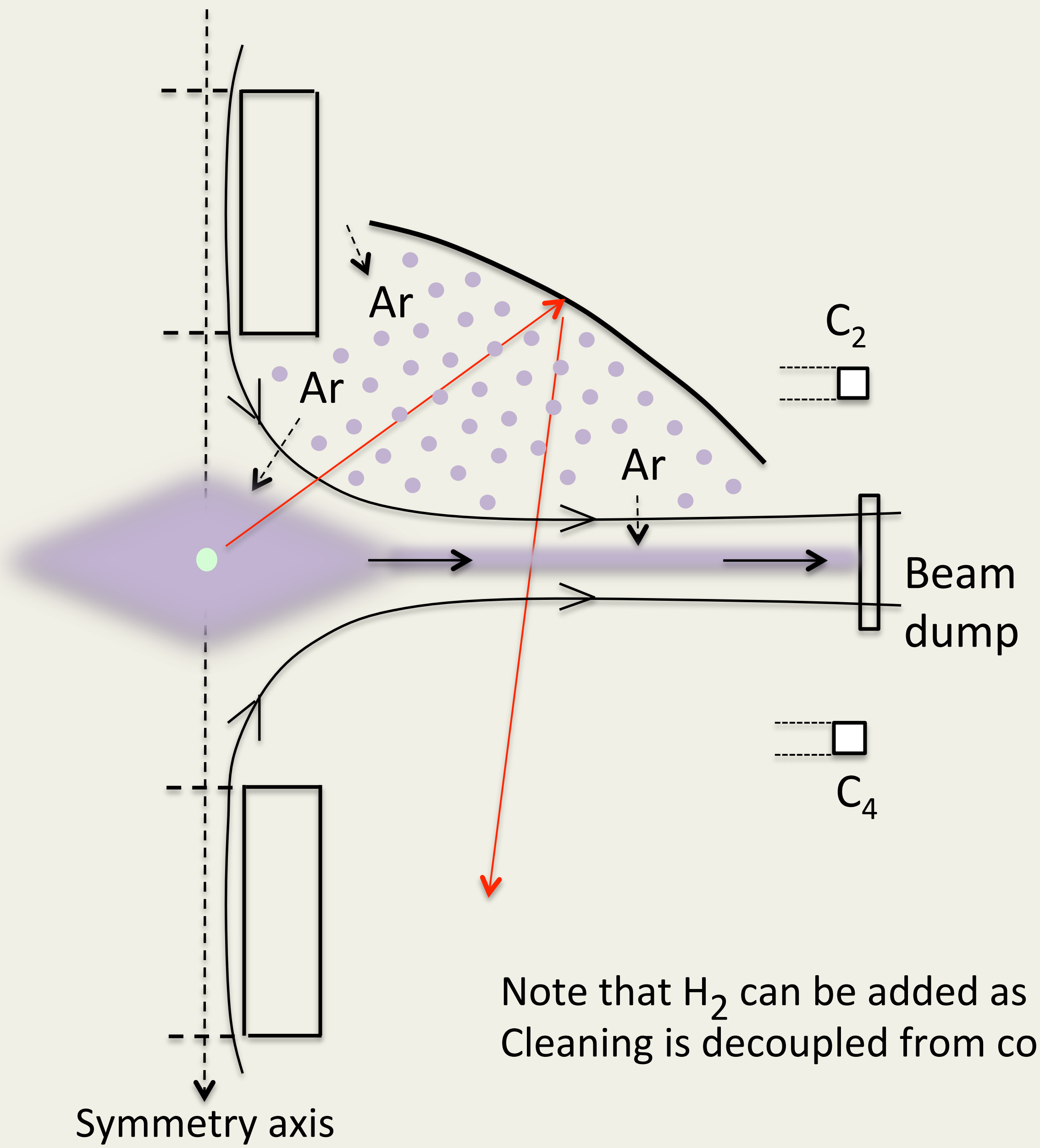
> 500W EUV output is predicted from the argon cusp



Gas path above disc T = 90%

Solid angle 4 sterad

Ave. mirror refl. 50%

Path to IF T= 80%

Laser power absorbed 40 kW

Efficiency 4 - 6%

Usable EUV 360 – 550W

Note that H_2 can be added as minority to clean the collector (as H). Cleaning is decoupled from cooling, so may be optimized separately

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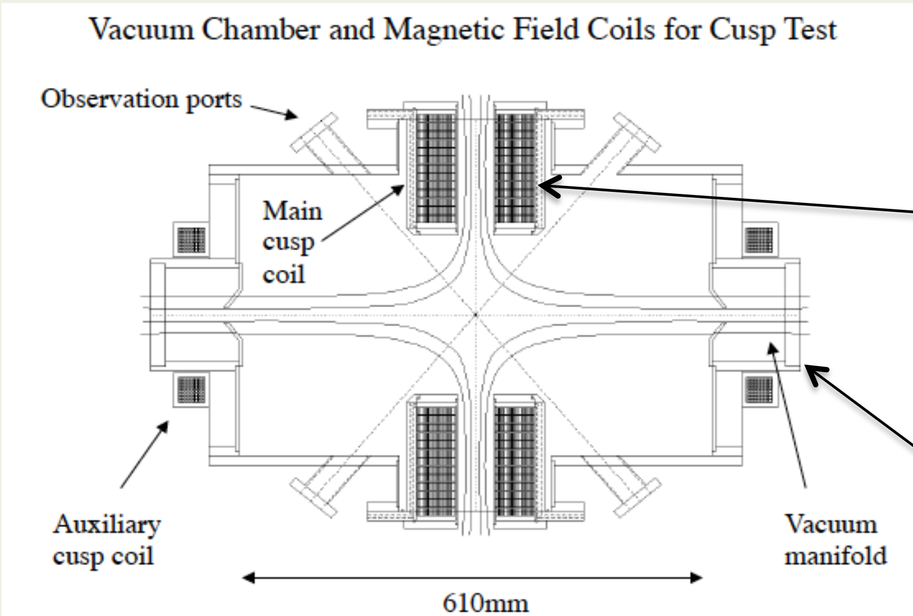
A simple experiment can validate the engineering of the argon cusp EUV source



Chamber due 11-3-14

- At full magnetic field and scale size, argon plasma can be studied
- Plasma size, gas entrainment and pressure differential measured
- Energy flow to the peripheral beam dump will be measured
- Test duration 5-10 sec possible at powers up to 25kW

PLEX is seeking $750K to test this new tin LPP approach

Full scale, 25kW Ar cusp experimental test with substitute energy source (e.g. arc)

Q4 '14 → 6 mo → Q1 '15

YES = stable plasma at temp/density + entrainment/ differential pressure + power flowing to beam dump

Design and test HVM tank for Ar cusp with supercond. magnets (build at supplier + laser + tin + collector)

Q2 '15 → 15 mo → Q3 '16

YES = >200W EUV power at IF + collector long life + smooth start/stop etc.

Supply argon cusp technology in new source shipments

Q4 '16 onwards

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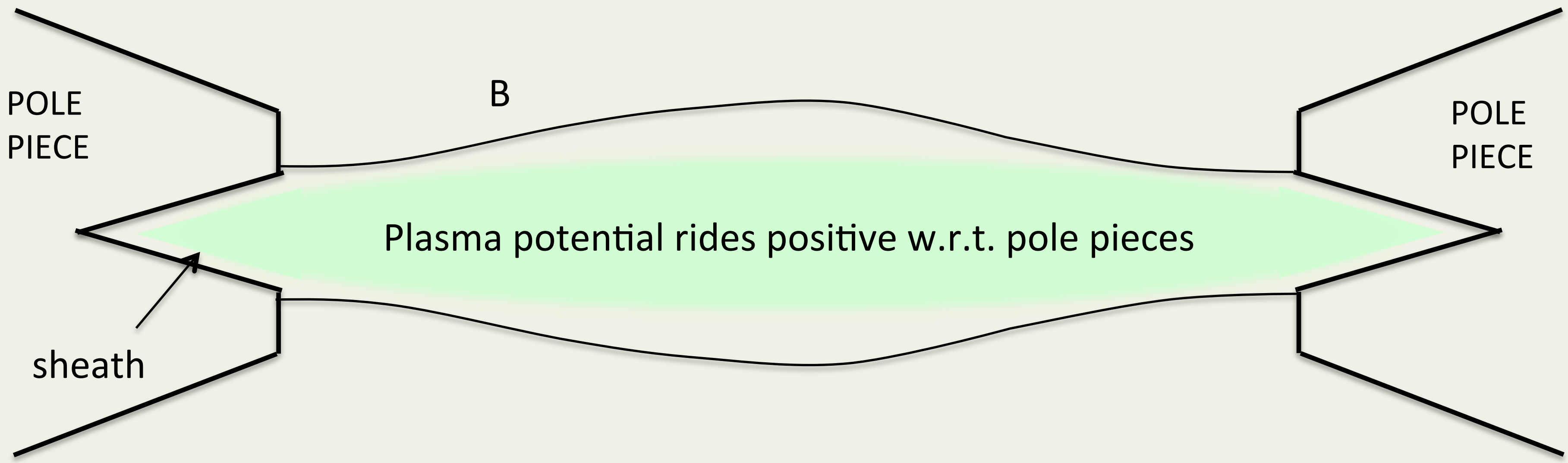
Conclusions

- The argon cusp offers the first clear path for scaling tin LPP to 500W
- It uses existing lasers, tin technology and optics
- Only $750K is needed to perform a "dry" demonstration
- Once demonstrated, engineering for HVM should be straightforward
- It can be in production by Q4 '16, if work starts now
- PLEX LLC wishes to license the argon cusp IP* so this can happen

(*patents applied for)

Supplementary material

Gigaphoton 2. Heat flow from plasma to beam dump when Sn ions only



$$W_T = \left[1 + \frac{1}{Z} + \ln\sqrt{\frac{M_i}{m_e}}\right](Z + \gamma_i)\dot{N}_{Sn}kT_e + \dot{N}_{Sn}\sum_{j=0}^{j=Z-1}\varepsilon_j$$

W_T = total heat flowing from plasma to beam dump surface

Z = average charge of tin ions in plasma (Z>>1 approximation made)

γ_i = secondary electron emission coefficient at beam dump surface

$\dot{N}_{Sn}$ = tin atom throughput

T_e = electron temperature (=T_i)

ε_j = ionization potential of Sn charge state j

Based on results in M McGeoch J Phys. D **37**, 3277-3284 (2004)

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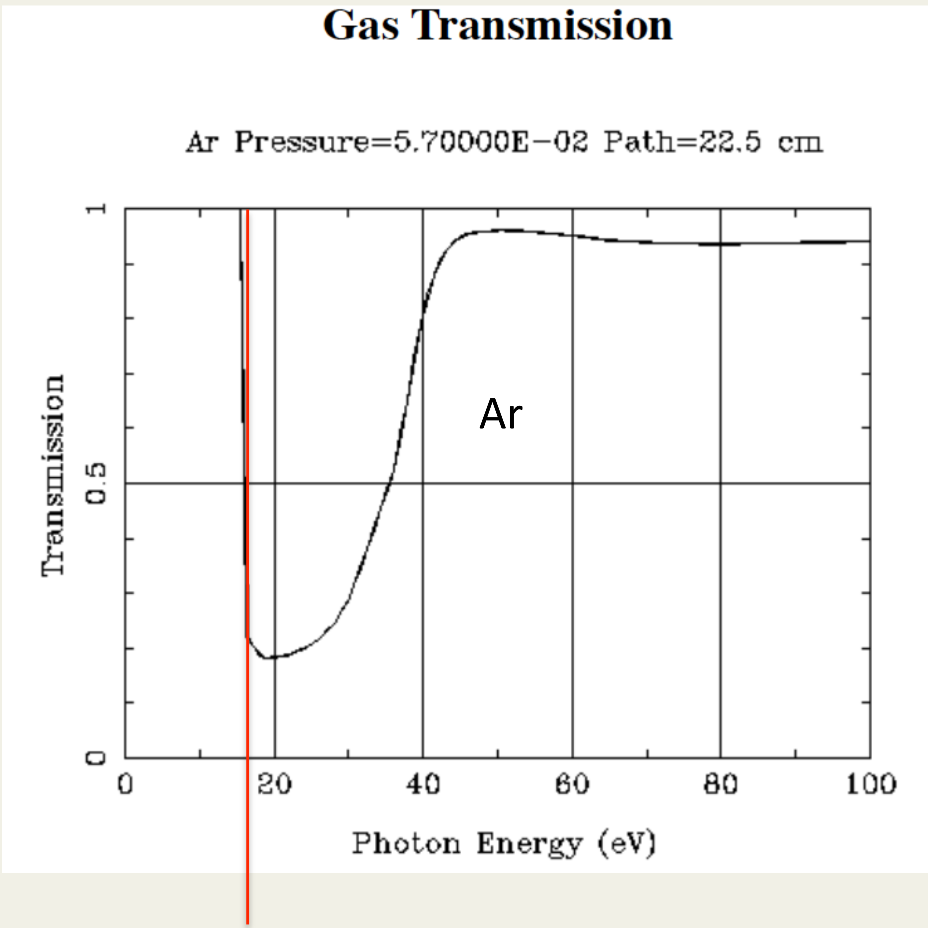
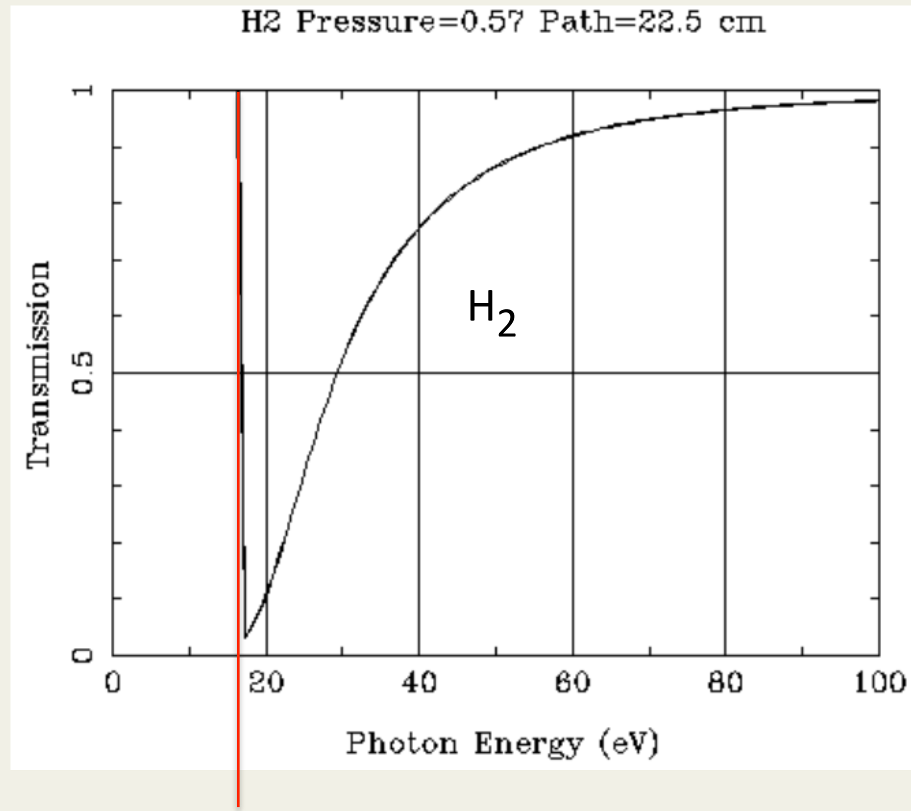
Argon blocks near EUV out-of-band photons better than H_2





Sn^{2+} resonance lines at 16 eV

(typical 22cm path to collector mid-point)