Pinch Plasma EUV Source with Particle Injection

Malcolm W. McGeoch **mcgeoch@xuv.com**

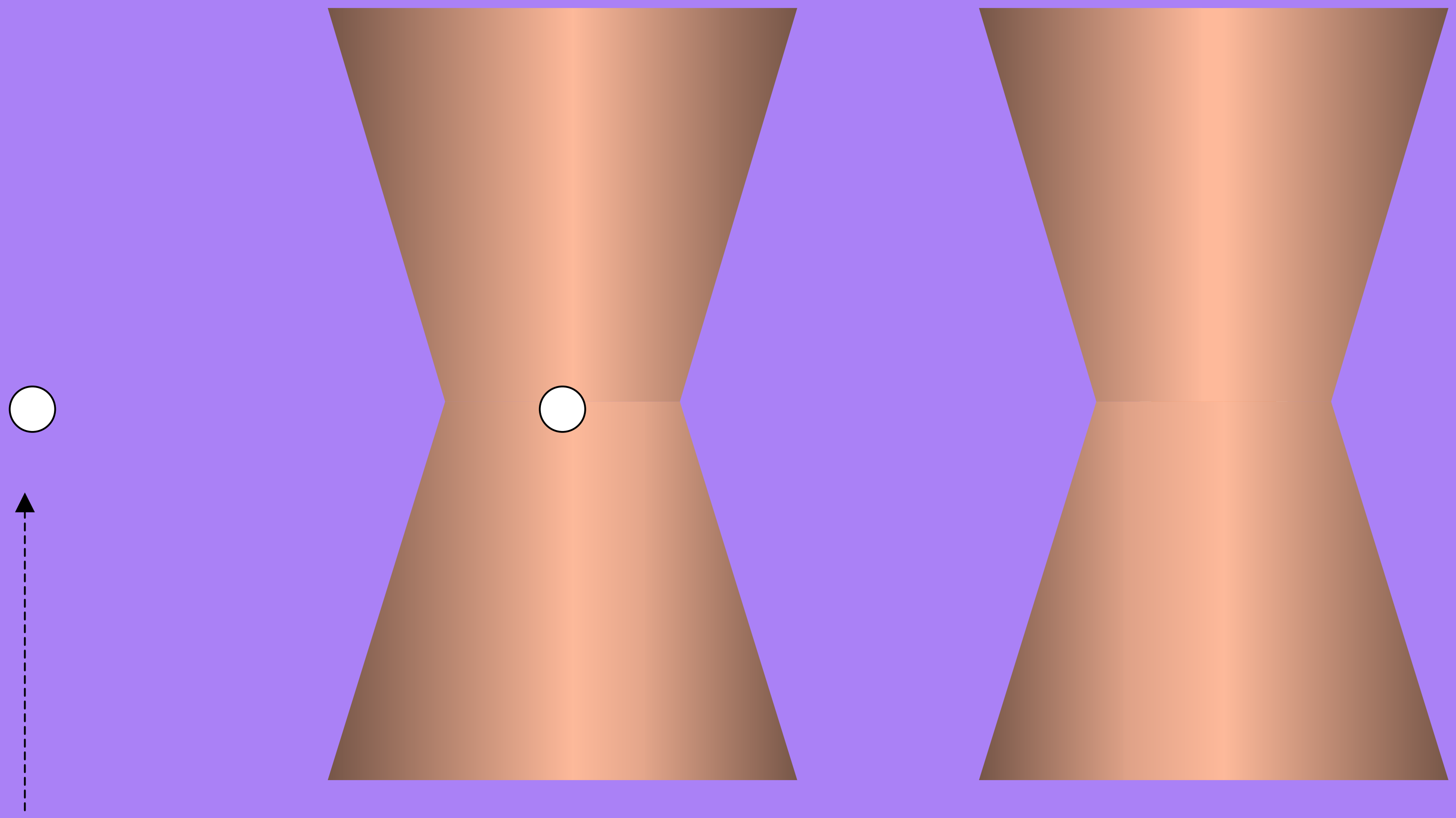
PLEX LLC, 20 Chapel St. C512, Brookline, MA 02446 USA.

ABSTRACT

Injection of tin droplets into an argon or helium pinch discharge can provide high extreme ultraviolet (EUV) generation efficiency together with small plasma size. We calculate the rates of evaporation, ionization and expansion of a spherical solid density target in a gas pinch discharge. It is found that an initial tendency for the particle to become negatively charged reduces electron heat transport from the plasma. Negative charging is counteracted, and electron heat flux enhanced, by the generation of secondary electrons by ion impact on the surface and by photo-emission dependent on the plasma radiation spectrum. When the heat flux exceeds 1GWcm^{-2} the particle can ionize and expand very rapidly to a diameter comparable to that of the pinch plasma. The time required for ionization and the final radius are each estimated as a function of particle size, plasma density and temperature. It is demonstrated that the plasma conditions in the Star Pinch EUV source are suitable for high brightness EUV generation via particle injection. Specifically, a spherical tin plasma of diameter 600μm is predicted from an initial tin droplet of diameter 30μm, leading to a smaller etendue than otherwise possible from a pinch plasma. Experimental progress toward an injection EUV source will be reported.

acknowledgement: Work supported by DARPA Advanced Lithography Program

Principle of Injection Pinch EUV Source



Sn droplet
injected

→

Buffer gas
pinch formed
around droplet

→

Droplet ionizes,
expands, radiates

PLEX LLC

Droplet potential and heat fluxes

Maxwellian electron velocity distribution

$$f_M(\vec{v}) = n\left(\frac{m_e}{2\pi kT_e}\right)^{3/2} \exp\left(\frac{-m_e\vec{v}^2}{2kT_e}\right) \qquad (1)$$

Let droplet potential be V_f

For zero net current $J_i + J_e = 0$ (2)

where J_i and J_e are the ion and electron current densities onto the droplet.

$$J_e = ne\sqrt{\frac{kT_e}{2\pi m_e}}\exp\left(-\frac{eV_f}{kT_e}\right) \qquad (3).$$

$$J_i = \frac{nZ|e|}{Z}\sqrt{\frac{kT_e}{2\pi M_i}} \qquad (4)$$

with ion number density n/Z and ion mass M_i. Inserting (3) and (4) into (2):-

$$\frac{eV_f}{kT_e} = \ln\sqrt{\frac{M_i}{m_e}} \qquad (5).$$

The equilibrium negative droplet potential exceeds the electron temperature by 5.6 times for argon.

Electron heat flux $$W_e = \frac{n}{\sqrt{2\pi m_e}}(kT_e)^{3/2}\exp\left(-\frac{eV_f}{kT_e}\right) \qquad (6).$$

Ion heat flux $$W_i = \frac{n}{\sqrt{2\pi M_i}}(kT_e)^{3/2}\left[\frac{1}{Z} + \frac{eV_f}{kT_e}\right] \qquad (7).$$

Negative droplet potential controls electron and ion heat fluxes. See FIG 1.

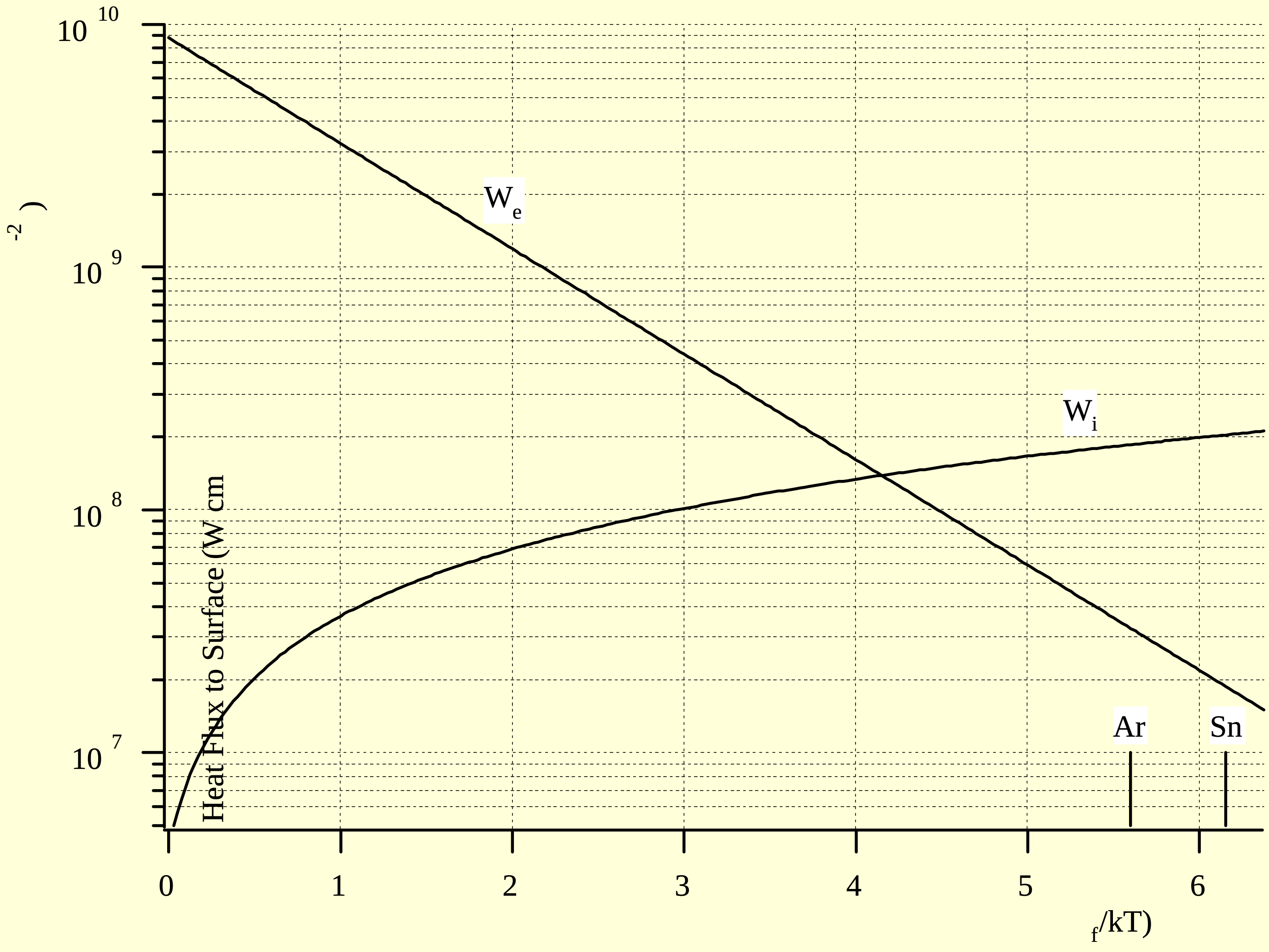


FIG 1. Electron and ion heat fluxes to the droplet surface as a function of the relative droplet potential for the case of a 30eV, $2x10^{19}$ electron cm^{-3} argon plasma with Z=8.

Modifiers of the Droplet Potential

Processes that act to reduce the magnitude of V_f and increase heat flux include:-

a) Secondary electron emission in response to ion bombardment,

b) Thermionic field emission.

c) Photoemission of electrons in response to plasma radiation.

a) Secondary Emission. For secondary electron emission with coefficient γ_{i} electrons per incident ion the equilibrium potential is found from

$$J_i + \gamma_i J_i / Z + J_e = 0 \qquad (8)$$

giving

$$\frac{eV_f}{kT_e} = Ln\left[\sqrt{\frac{M_i}{m_e}}\,\frac{Z}{(Z+\gamma_i)}\right] \qquad (9)$$

Ar^{8+} incident on tin at 170eV could produce as many as 10 secondary electrons, which would modify $eV_f/\mathrm{k}T_e$ downward from 5.6 to approximately 4.8.

c) Thermionic Field Emission. In the present droplet case the sheath thickness of a few times λ_{D}, the Debye length, is only about 30nm, and with voltage $|V_f| = 170V$ across it there can be a surface field of $5\mathrm{x}10^7\mathrm{Vcm}^{-1}$.

The ionic heat flow of $>10^8$ Wcm^{-2} can raise the surface to boiling point (2543K) in only 10nsec, and electron emission can then reach extremely high values via field-enhanced (Schottky) emission. The emission current is

$$J_{th} = \frac{4\pi (kT_S)^2 m_e |e|}{h^3} \exp\left[-\left(\frac{\Phi - \sqrt{e^3 E}}{kT_S}\right)\right] \qquad (10)$$

in which T_{S} is the surface temperature, Φ is the work function and E is the surface electric field. This is evaluated for tin in FIG.2 Some depression of droplet potential, but self-limiting due to reduction of surface field.

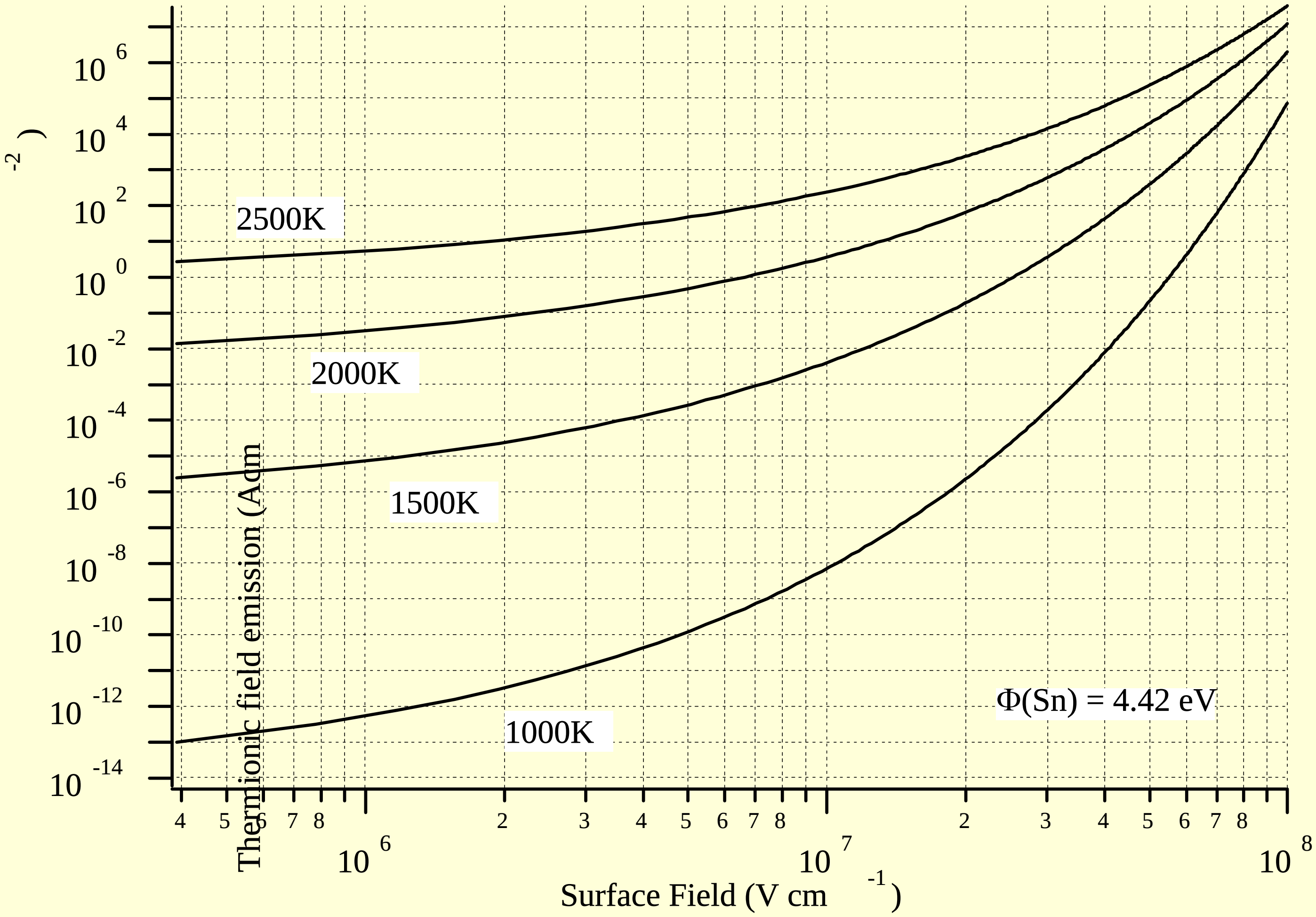


FIG. 2 Thermionic field emission current from tin surface.

c) Photoemission. The pinch plasma radiation field can produce surface photoelectrons and significantly reduce the droplet negative potential V_f. Consider Planck radiation flux

$$I_P(\phi) = 1.6\times 10^4 \frac{\phi^3}{\left(e^{\phi/kT_e}-1\right)} \quad \text{W cm}^{-2}\ \text{eV}^{-1} \tag{11}$$

where ϕ is the photon energy and kT_e is the plasma temperature, both in electron volts.

Consider radiation from UTA at 100eV of width 10eV. The integrated radiation power can be approximated by

$$I_{UTA} = 6\times 10^9 \eta \quad \text{W cm}^{-2} \tag{12}$$

where η = fraction of the Planck intensity reached by the peak of the UTA and we have assumed 100eV photon energy and 30eV plasma temperature.

the photoemission current becomes

$$J_{PE} = 4\times 10^{26}\eta\gamma_{100}|e| = C_{PE}\eta\gamma_{100}|e| \quad \text{cm}^{-2}\ \text{sec}^{-1} \tag{13}$$

where the current units will be Amperes with $|e|$ in Coulombs and γ_{100} is the secondary yield of tin at 100eV. The droplet potential in the presence of radiation is given by

$$J_i + J_{PE} + J_e = 0 \tag{14}$$

leading to

$$\frac{eV_f}{kT_e} = -Ln\left\{\sqrt{\frac{m_e}{M_i}} + \frac{C_{PE}\gamma\eta}{n}\sqrt{\frac{2\pi m_e}{kT_e}}\right\} \tag{15}$$

The potential is shown as a function of η in FIG. 3 and corresponding heat fluxes in FIG. 4.

In this case, depending on the value of γ_{100}, the potential can be depressed to zero when radiation from the UTA reaches the Planck intensity.

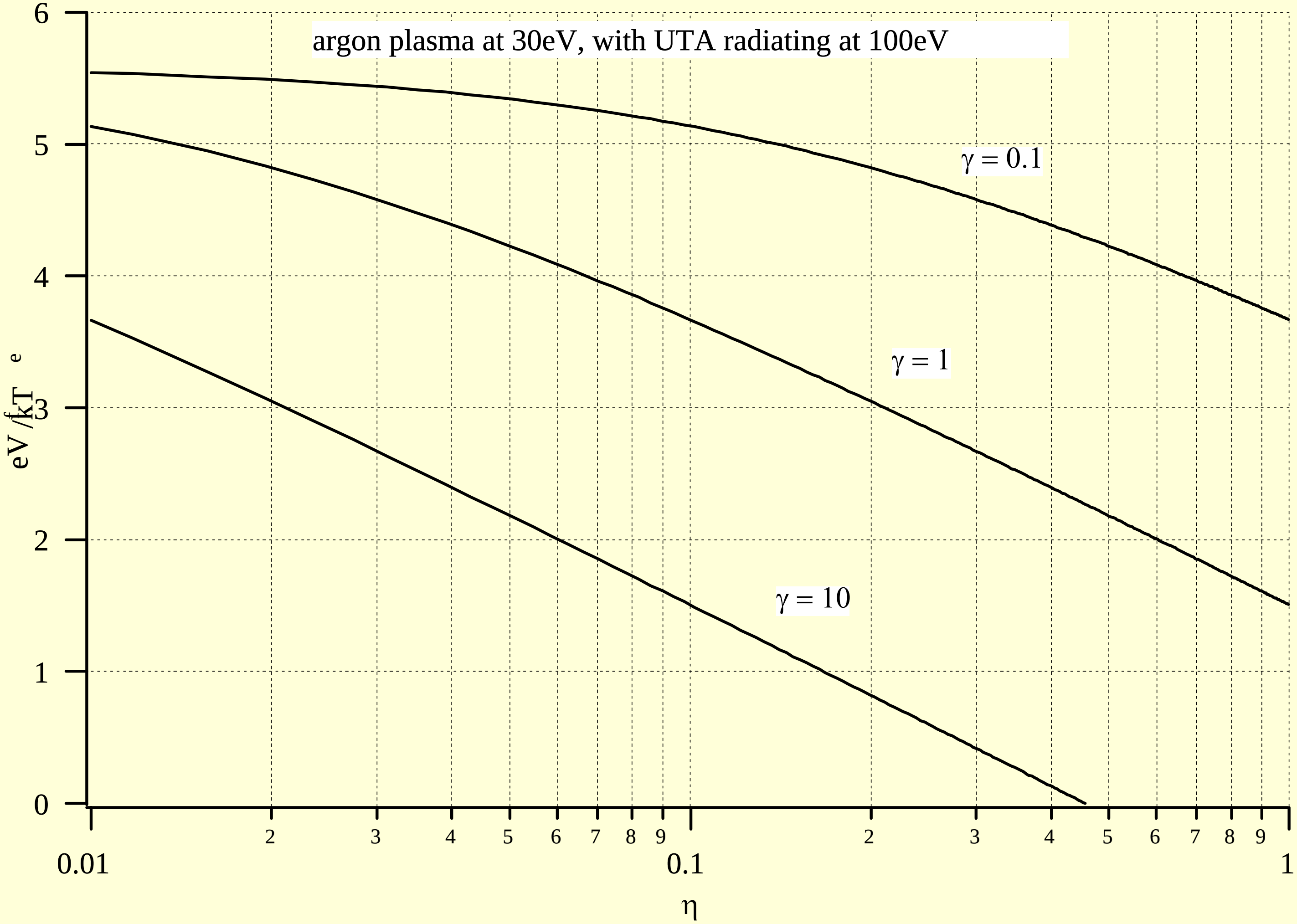


FIG 3. Depression of droplet potential by photoemission with coefficient γ in the presence of an unresolved transition array (UTA) at approximately 100eV with peak intensity η times the Planck intensity for a 30eV plasma.

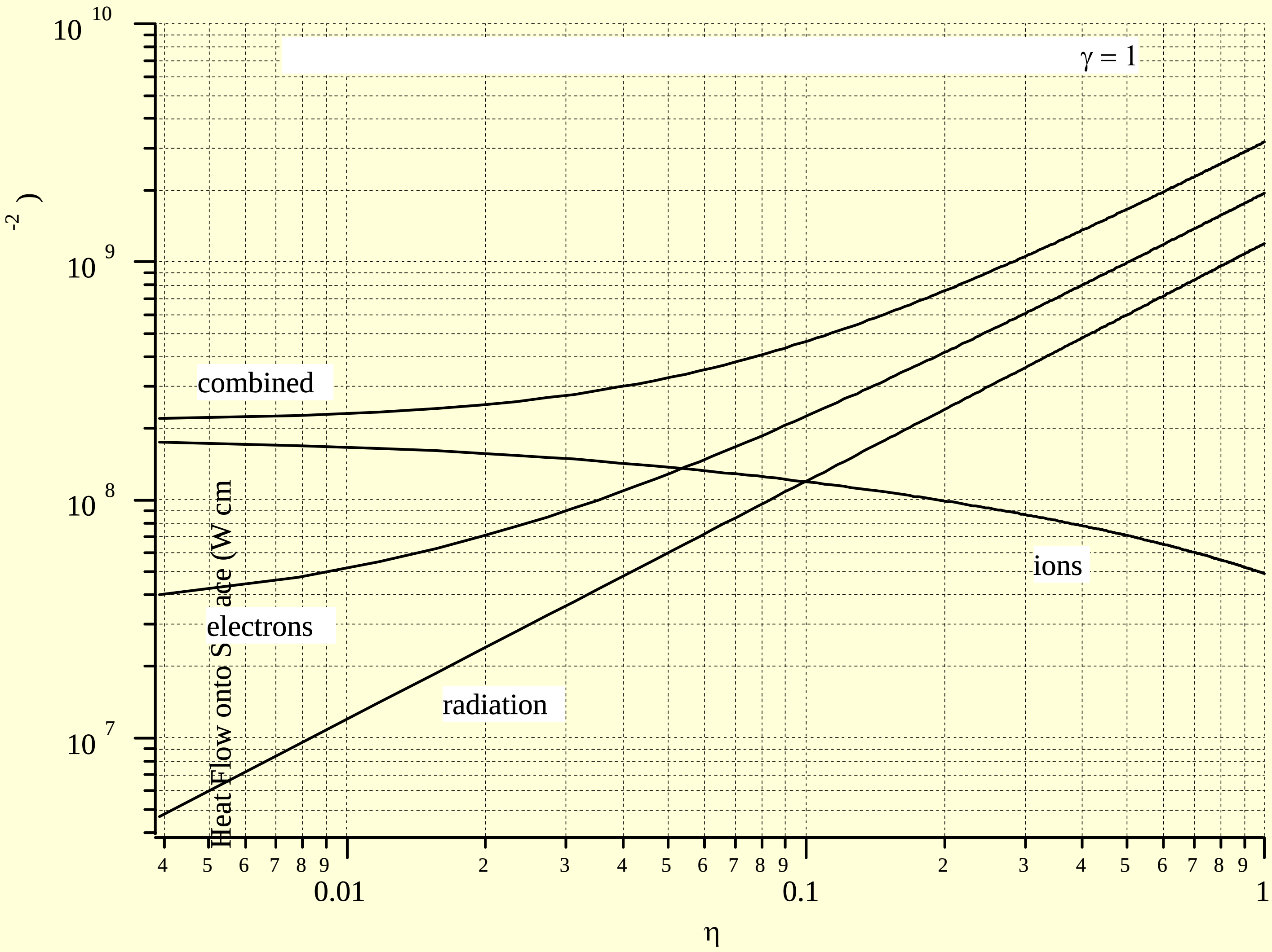


FIG 4. Effect on heat fluxes of potential depression of Fig. 3 due to the presence of an unresolved transition array (UTA) at approximately 100eV with peak intensity η times the Planck intensity for a 30eV plasma.

Model of particle inflation

The droplet expands rapidly in response to the sudden application of a heat flux that can approach 10^{10} Wcm^{-2}. We estimate the rate of expansion and the likely final size of the object when the Sn^{7+} to Sn^{12+} states that emit 13.5nm radiation are accessed. As radiation builds up and lowers the droplet potential the dominant heat flow to the surface becomes that of the plasma electrons. The set of processes that takes control is akin to a laser-plasma interaction with shock propagation into the dense phase followed by greatly enhanced thermal conduction. Shock heating takes place in a time of the order of 10nsec, but the subsequent thermally driven expansion is limited by the rate of heat input.

We make the following assumptions:

a) The droplet surface, coordinate r_s, expands with radial velocity equal to the ion acoustic velocity for the tin plasma, i.e.

$$\frac{dr_s}{dt} = \sqrt{\frac{kT_e Z_{Sn}}{M_{Sn}}} \qquad (16)$$

where T_e is here the electron temperature inside the tin droplet, Z_{Sn} is the average charge of tin ions and M_{Sn} is the ion mass.

b) Heat that enters via the surface is instantly communicated throughout the droplet.

c) The thermal capacity of the tin plasma increases as the average charge state increases.

d) The average charge state increases linearly with temperature (again not exact).

e) The integrated kinetic energy of expansion can be neglected relative to the internal thermal energy.

Exponential tin droplet/plasma growth

We find exponential growth of the droplet radius according to

$$r_s = a_0 \exp(\Gamma t) \qquad (17)$$

where the growth constant is given by

$$\Gamma = \left(\frac{3W_T}{\beta a_0{}^3 \rho_{Sn}} \right)^{\frac{1}{3}} \qquad (18)$$

with

$$\beta = \frac{3(Z_{SnF}+1)}{Z_{SnF}} + \frac{2\sum IP}{kT_F Z_{SnF}} \qquad (19)$$

and W_T = the total surface heat flux from all sources. This is true until the tin plasma temperature begins to approach the temperature of the surrounding buffer gas plasma.

The time t_{exp} taken to reach Z_{SnF}, the final average charge state, at final temperature T_F is

$$t_{\exp} = \Gamma^{-1} \ln\left[\frac{1}{a_0 \Gamma} \sqrt{\frac{Z_{SnF} kT_F}{M_{Sn}}} \right] \qquad (20)$$

and then the radius of the droplet/plasma is

$$r_F = a_0 \exp(\Gamma t_{\exp}) \qquad (21).$$

Assuming that $kT_F = 30eV$ and $Z_{SnF} = 10$ we evaluate typical expansion times and radii in FIG. 5 and FIG. 6

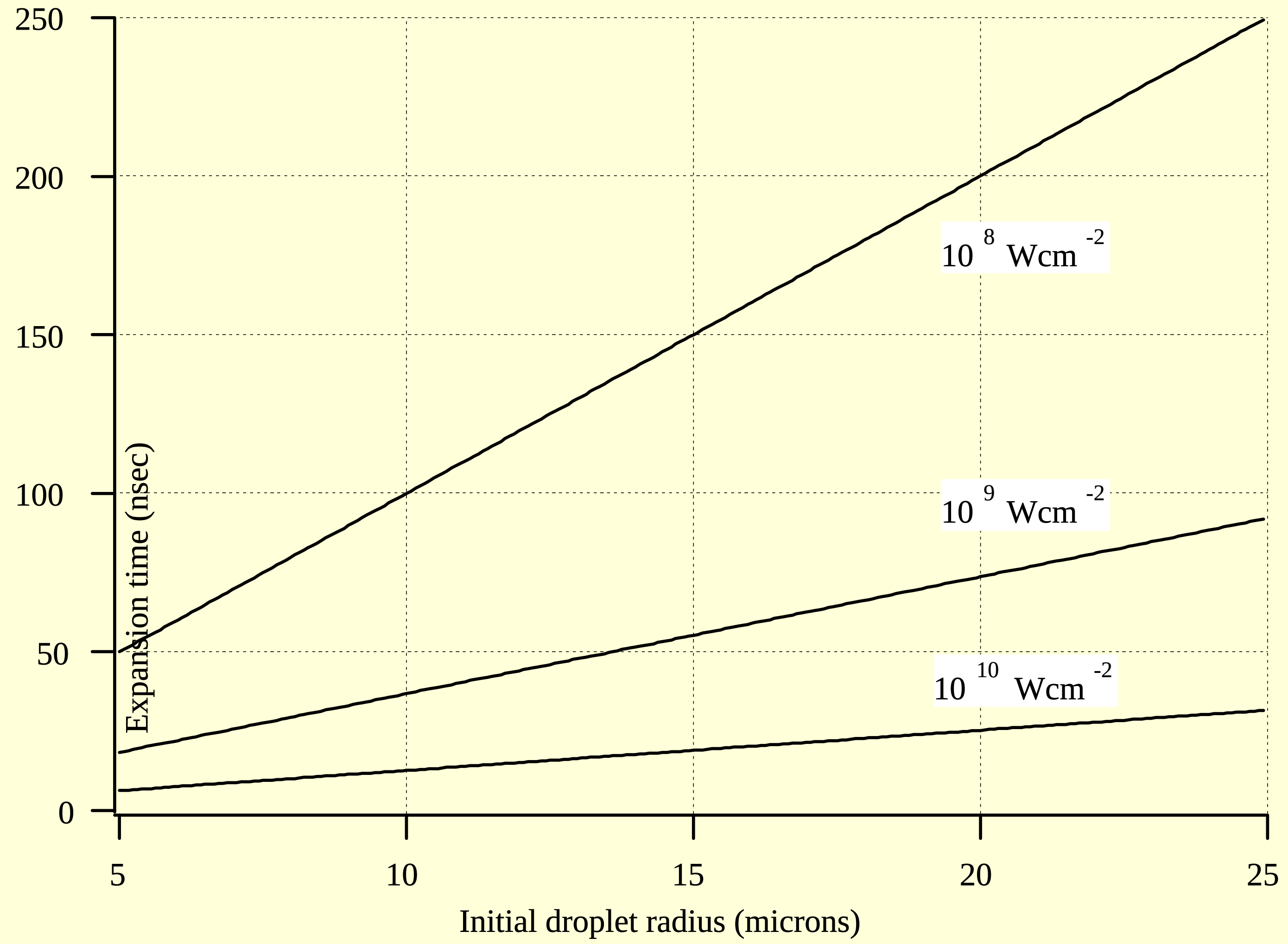


FIG 5. Expansion time to tin plasma temperature of 30eV as a function of initial radius and plasma power flux onto the surface of a tin droplet.

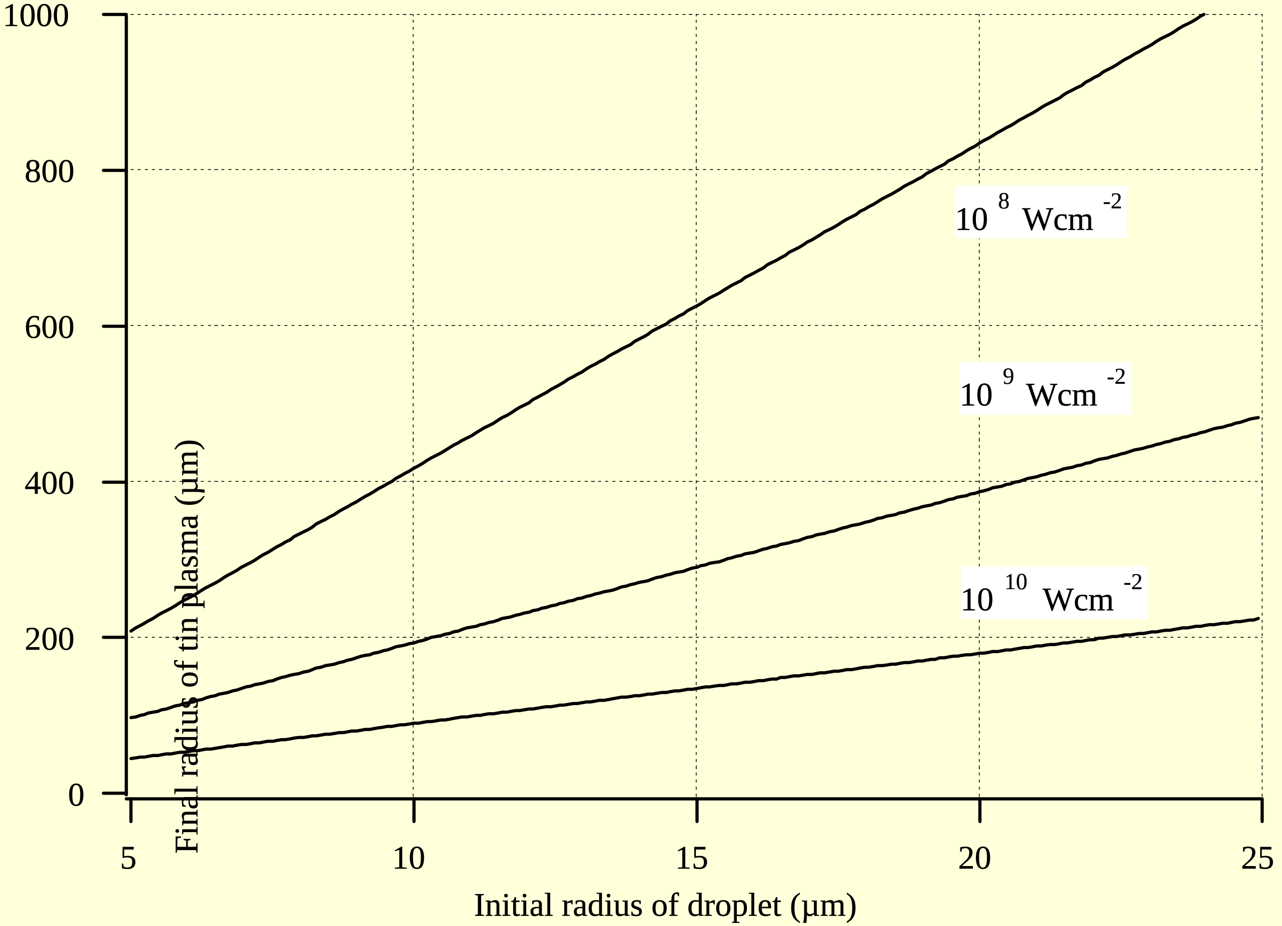
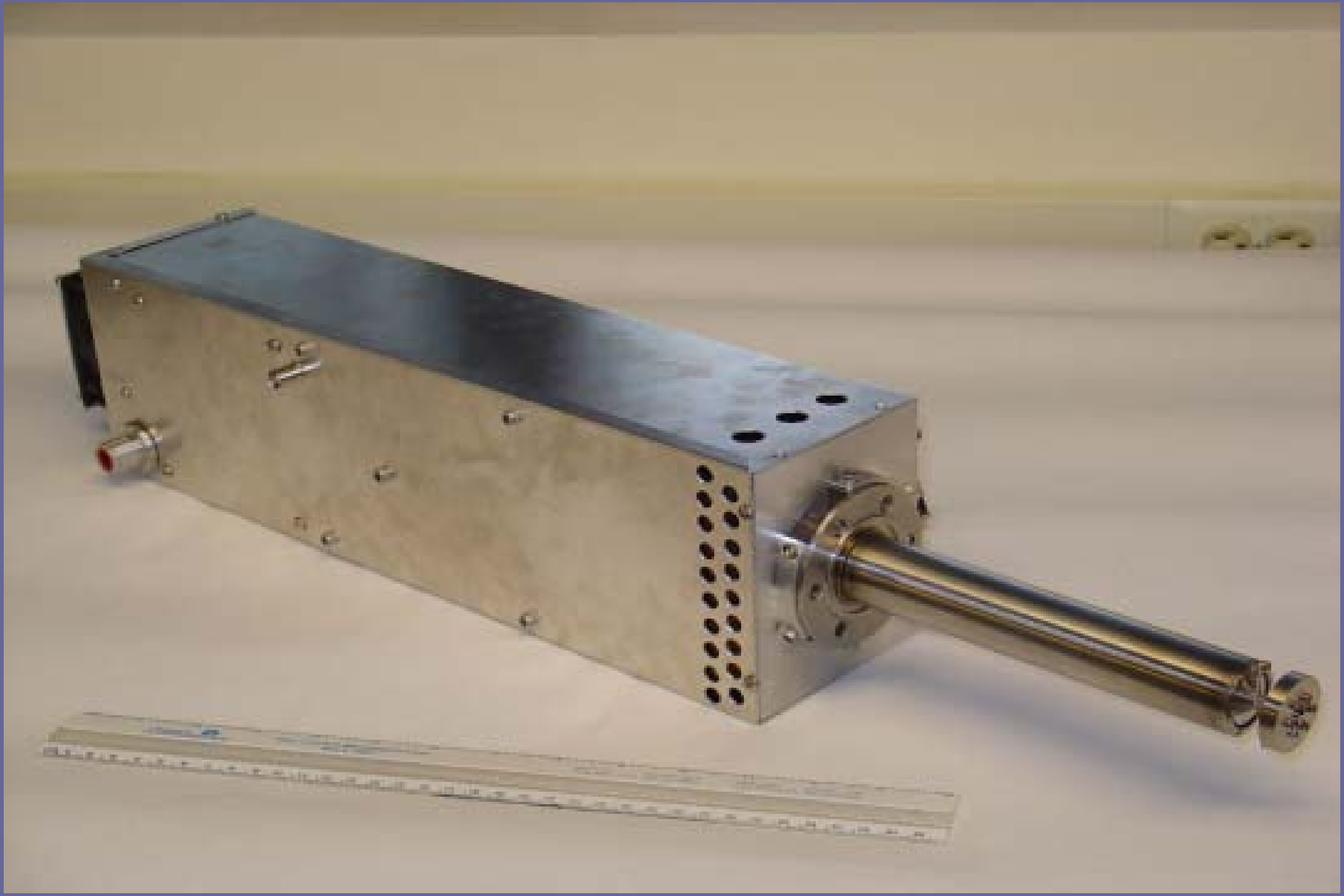


FIG. 6. Radius of tin plasma at temperature of 30eV as a function of initial radius and plasma power flux onto the surface of a tin droplet.

Tin Droplet Specifications

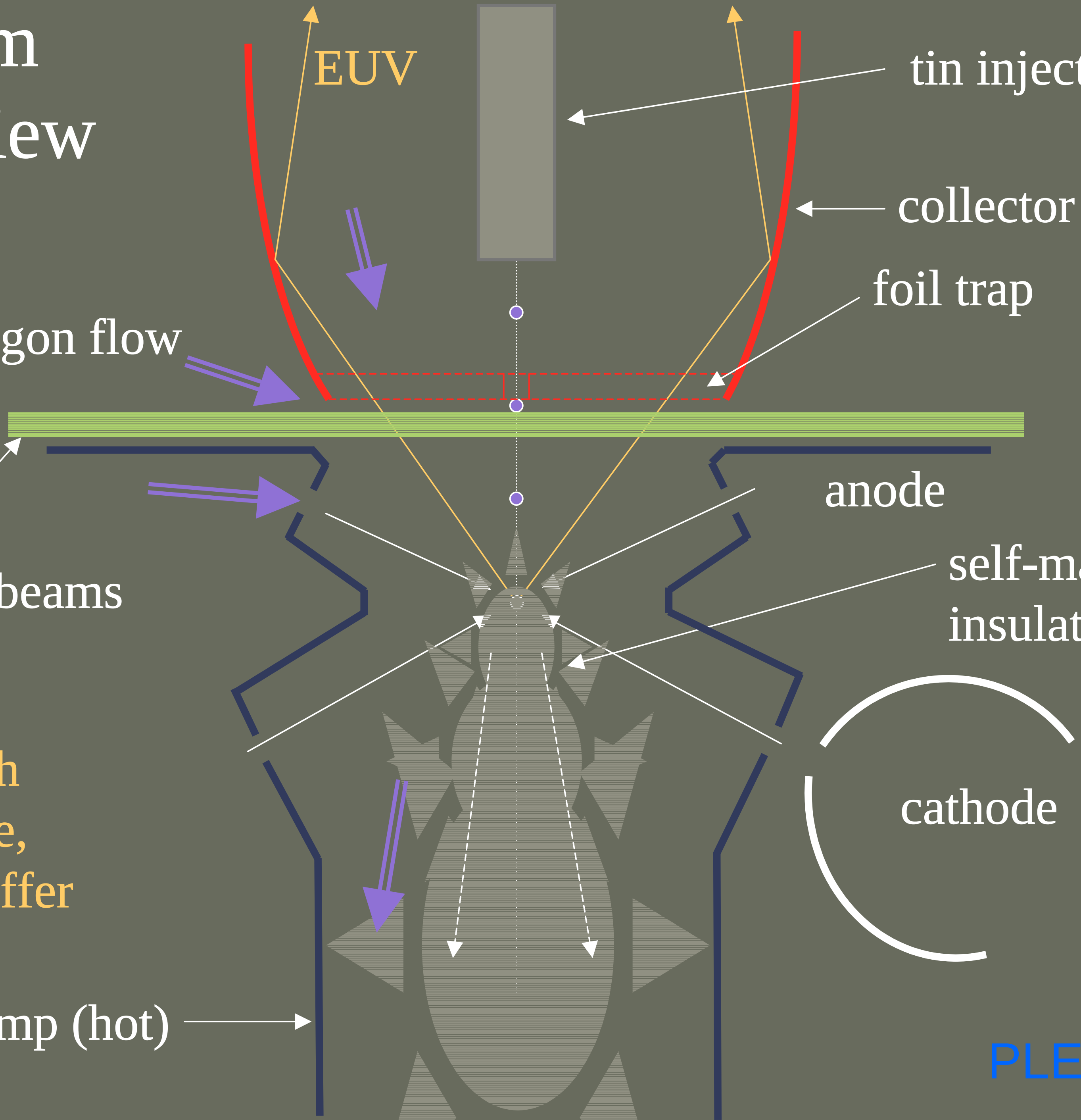
	Size (μm)	Δr (μm)	Δz (μm)	Velocity (m sec^{-1})	Rep.rate (kHz)
DPP (injection pinch)	30	50	50	>20	6
LPP	20	2	2	>30	10
PLEX to date	20-50	2	10	12-46	>0.1

Approach: impulse ejection of liquid tin thru’ nozzle



PLEX tin droplet generator

System Overview



EUV

tin injector

collector

foil trap

argon flow

anode

monitor beams

self-magnetic insulation

star pinch discharge, argon buffer

cathode

beam dump (hot)

PLEX LLC

Injection Pinch Discharge EUV Source

Conclusions and Status:

Star Pinch plasma 30eV, $2x10^{19}$, 100ns
should ionize mass-limited 30µm tin droplet*

13.5nm emission expected from 600µm diameter tin plasma

PLEX has generated tin droplets suitable for injection pinch

Alignment of droplet stream with plasma is a current challenge

**Forthcoming paper in J. Phys. D special issue on EUV sources*