# Prospects for He Pumping by Nano-Bubble Formation in Liquid Metals

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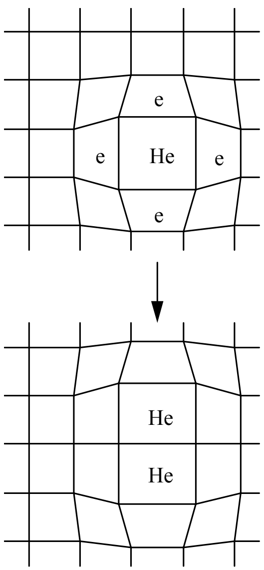
Outline:

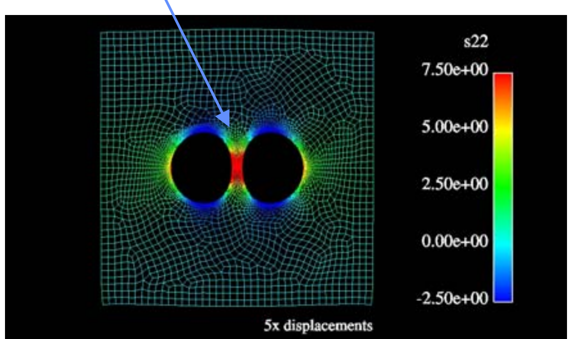
- Sandia's Nano-Bubble Evolution code for He in metals
- Modifications for liquid metals
- Sample calculations for He implantation in liquid Ga, Sn, Li
- Implications for He pumping
- Experimental validation

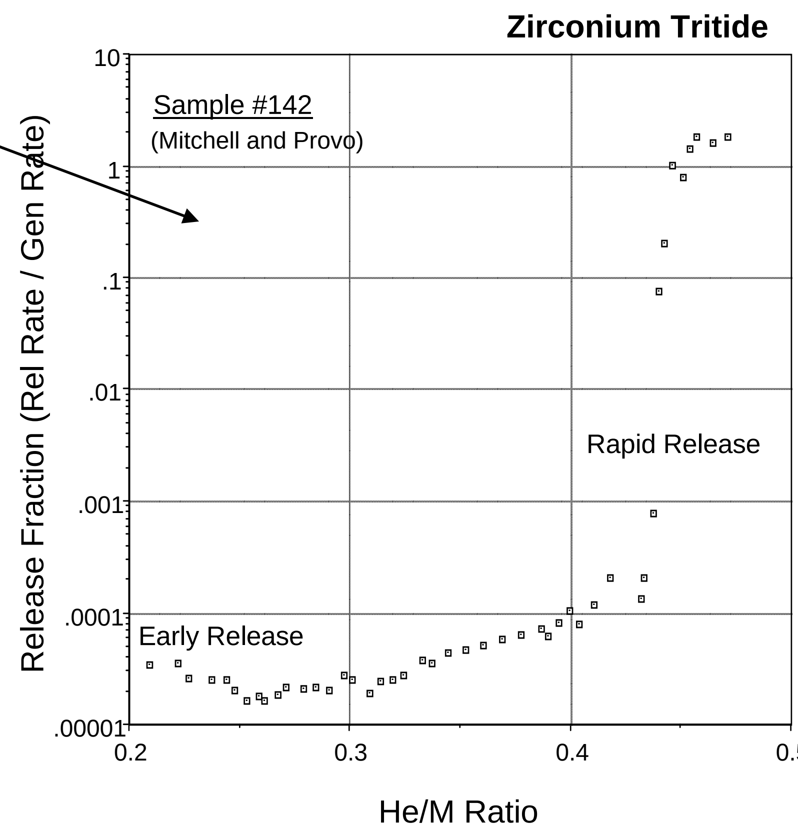
# Sandia's Nano-Bubble Evolution (NBE) code models the retention of He generated in metals.

- The NBE code was developed to model $^3$He retention in aging solid metal tritides.

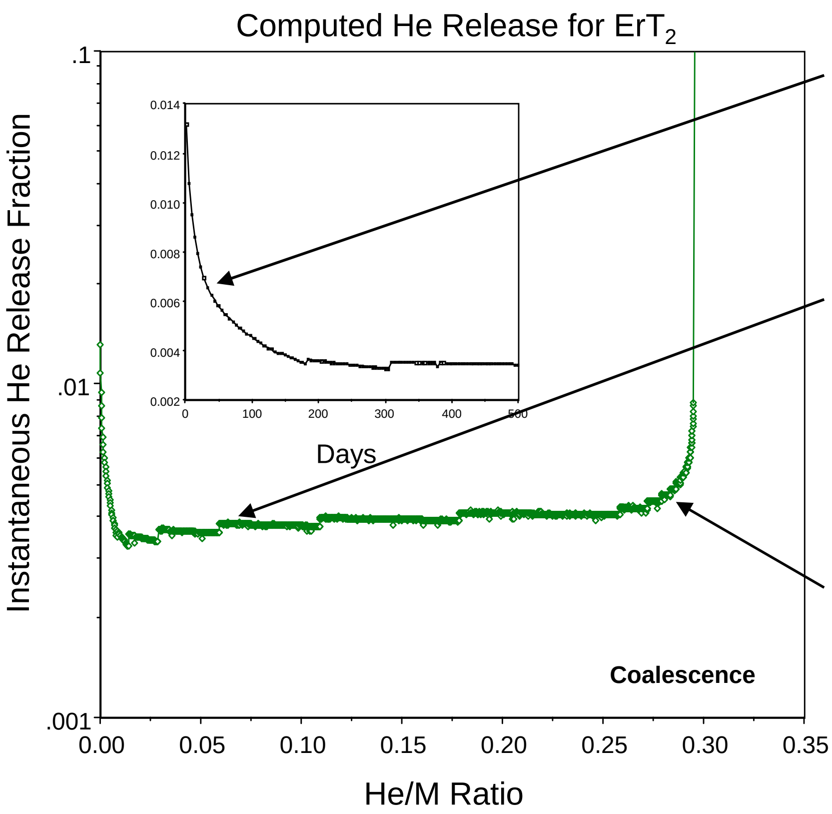



- It follows He bubble nucleation, growth, and release by inter-bubble ligament fracture.



# The computed He release for solid tritides has all the characteristics of observed release.




- Initially, release is high until bubbles become large enough to compete with nearby surfaces or grain boundaries.
- Mobile He near surfaces & GB's produce the Early Release Fraction.
  - which slowly increases with the "breaching" of near-surface bubbles.
- Rapid Release of He occurs when the growing bubble network becomes sufficiently interconnected.

*Model shows how material parameters affect each part of release spectrum.*



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# For Liquid Metals, we modify the conditions for bubble stability and add bubble motion.

• The nano-bubble stability is determined by the liquid metal's surface tension $\gamma$:

$$\text{Binding energy of N-th He, } E_N = 4\pi \left[ (r_{N-1}^2 + r_1^2) - r_N^2 \right] \gamma.$$

• The bubble pressure $p_N$ and radius $r_N$ are related by

$$p_N = 2\gamma / r_N.$$

• We assume spherical bubbles so that

$$V_{bubble} = (4/3)\pi r_N^3 = n\, v_a,$$

where $v_a(p,T)$ is the He atomic volume as determined by the bulk He equation-of-state, corrected for bubble wall curvature effects.

• Nano-bubble migration is included using the Stokes-Einstein equation for diffusion of sub-micron particles:

$$D_N = kT / 6\pi\eta r_N.$$



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# Concentration profiles of diffusing He atoms and n-atom bubbles are computed.

- Coupled differential equations follow He *atom* and *bubble* concentrations as a function of depth and plasma exposure time:

  $dc_n/dt = - D_n\, d^2c_n/dx^2 + (\text{Source terms})_n - (\text{Loss terms})_n$

  where $c_n$ = concentration of bubbles with N atoms.

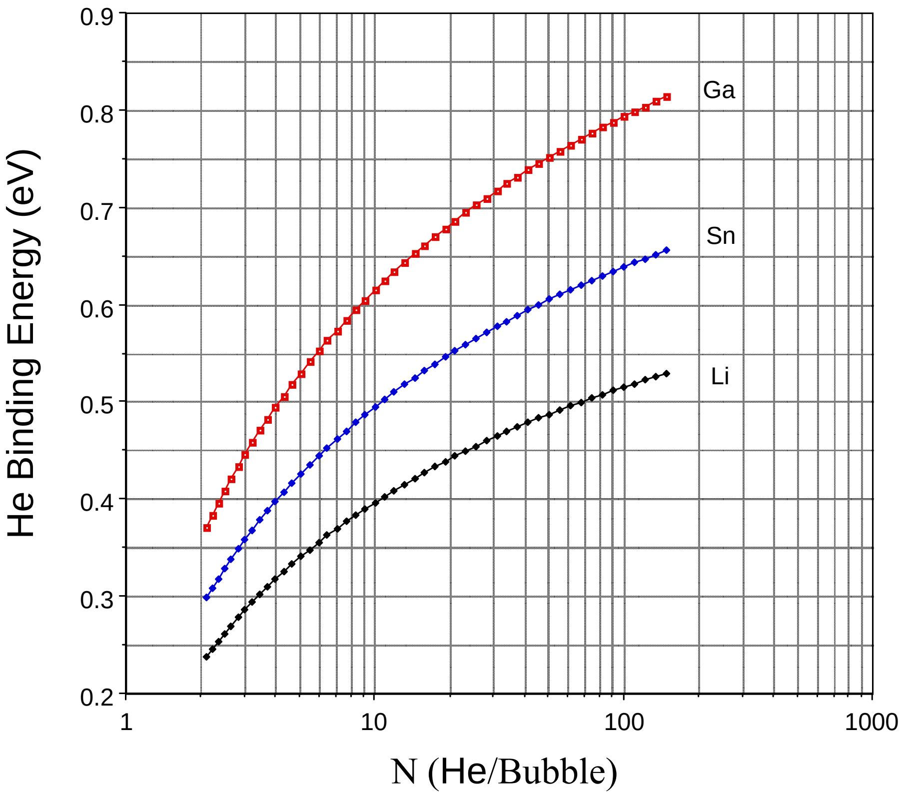
  Source terms: for n=1, implant flux = $ø(x,t)^{TRIM}$
  n-species formation = $c_1c_{n-1}$, $c_mc_{n-m}$, $c_{n+1}\exp(-E_{n+1}/kT)$
  (growth, coalescence, dissociation)

  Loss terms: n-species dissociation factors = $c_n \exp(-E_n/kT)$
  n-species promotion factors = $c_1c_n$, $c_mc_n$

  (Formation and loss rates also involve attempt frequency and bubble size factors.)

- Species bins increase geometrically: N = 1, 2, 4, 8, 16, …, $2^{n-1}$.

# The model shows small bubbles rapidly dissociate due to a low He binding energy to the bubble.




- Generation of large stable bubbles from diffusing atoms requires:

  species promotion > dissociation

  $s_n c_1 > N \exp(-E_N/kT)$,

  $s_n$= bubble surface area
  $c_1$= atomic He concentration.

- At .01 A/cm$^2$, 600 K, $c_1$~10 appm; which requires

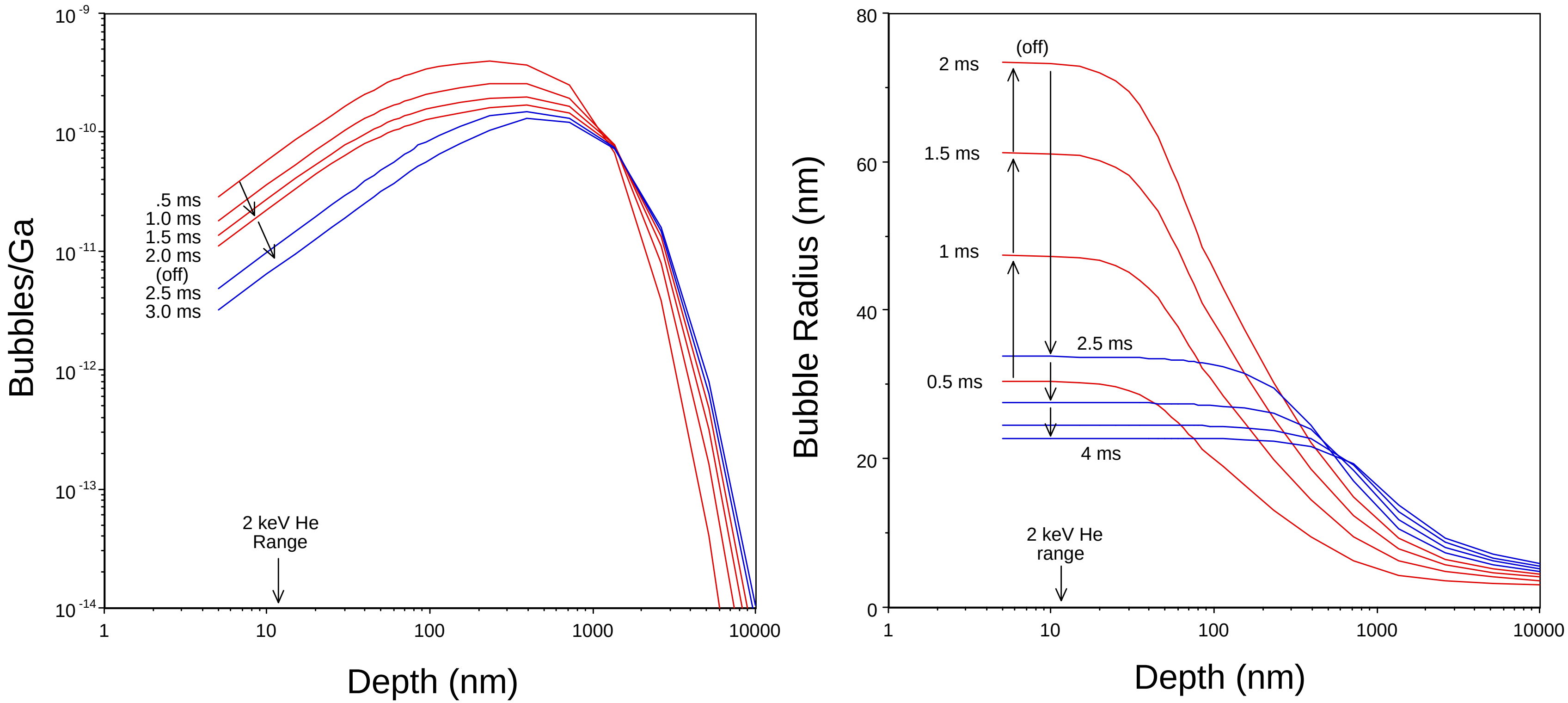
  $E_N \geq 0.4$ eV.

- Bubble promotion in Li requires a large $c_1$ or very high He flux.

*The larger surface tensions for Sn and Ga rapidly produce bigger bubbles.*

# The profiles show bubbles are formed well beyond the He implant range.

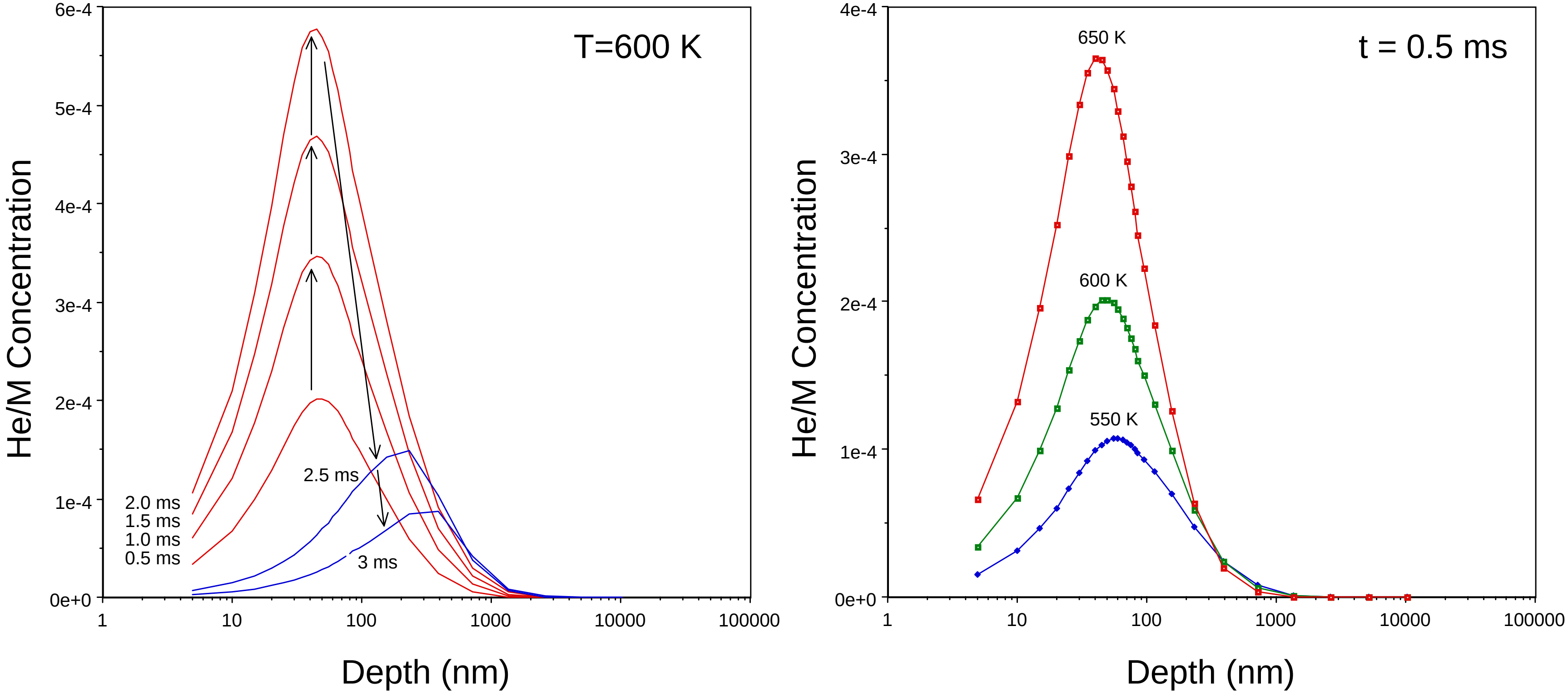
Liquid Ga: 600 K, 2 keV He, 2e18 He/cm$^2$-s, 2 ms implant pulse




• Bubble concentrations drop with time as bubble sizes increase, due to bubble coalescence.

# Most of the He concentration remains within the surface region, and it *increases* with temperature.

Liquid Ga: 2 keV He, 2e18 He/cm$^2$-s, 2 ms implant pulse




- Increasing the mobility promotes bubble growth and coalescence, creating larger bubbles.



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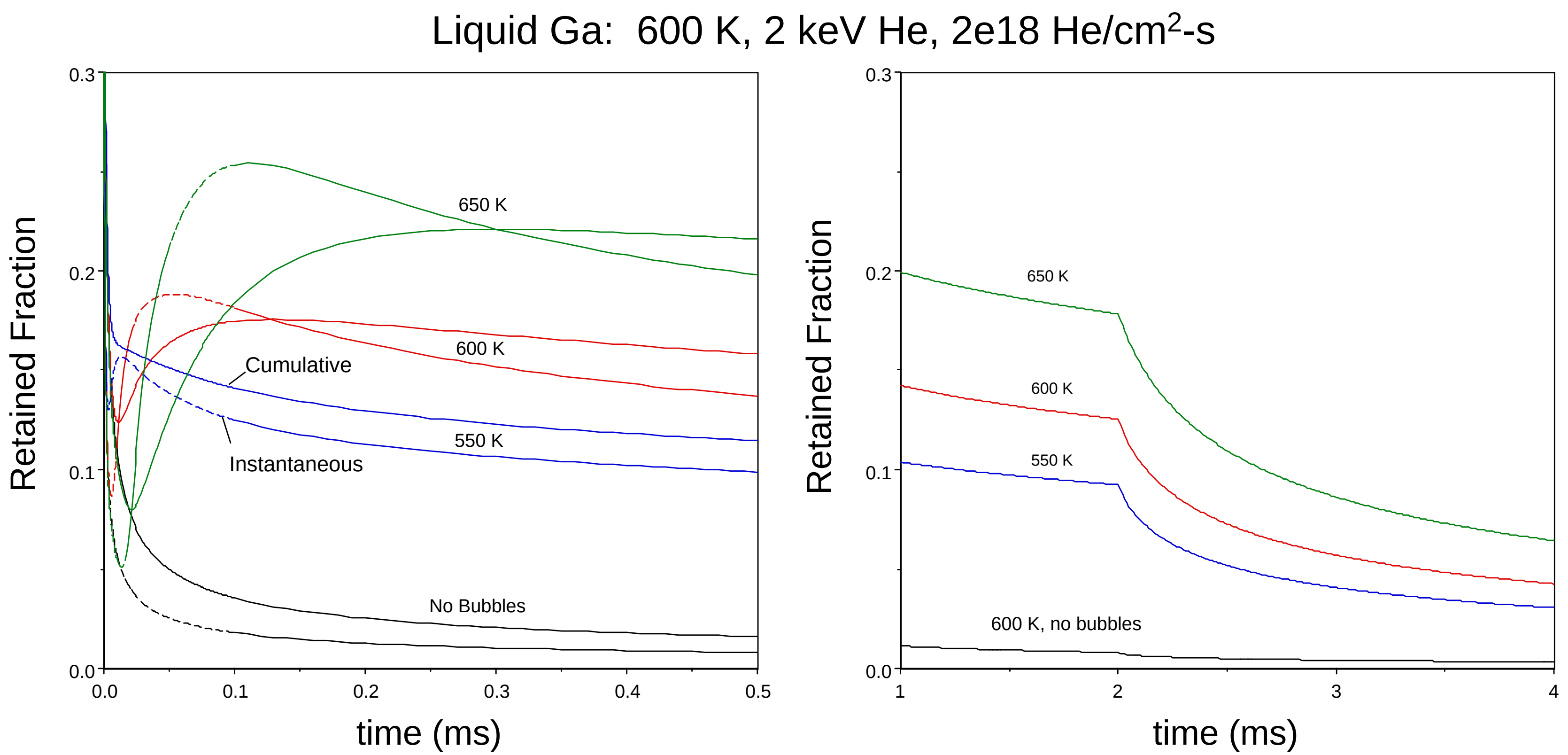
# He retention in Ga reaches 10-20% over a 2 ms exposure pulse, then drops relatively slowly.




• The large quantity of He trapped in large bubbles in flowing Ga provides time for transport well into a capture duct.



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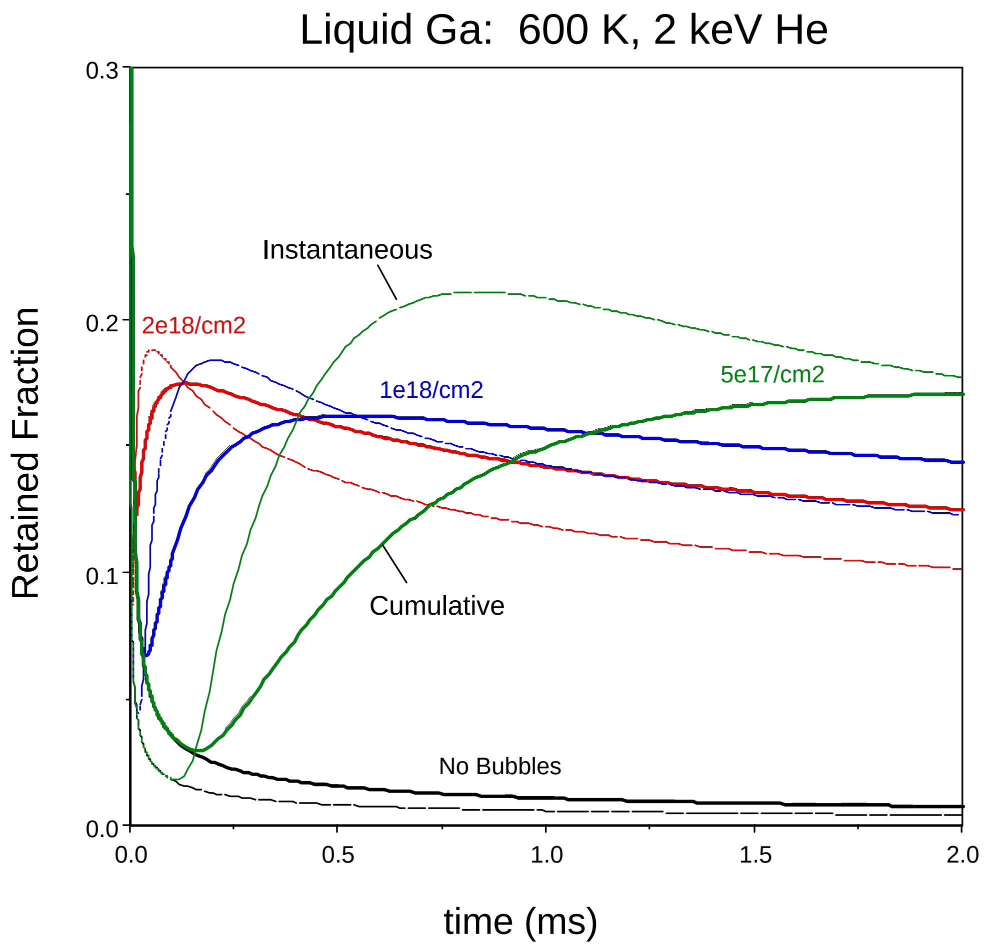
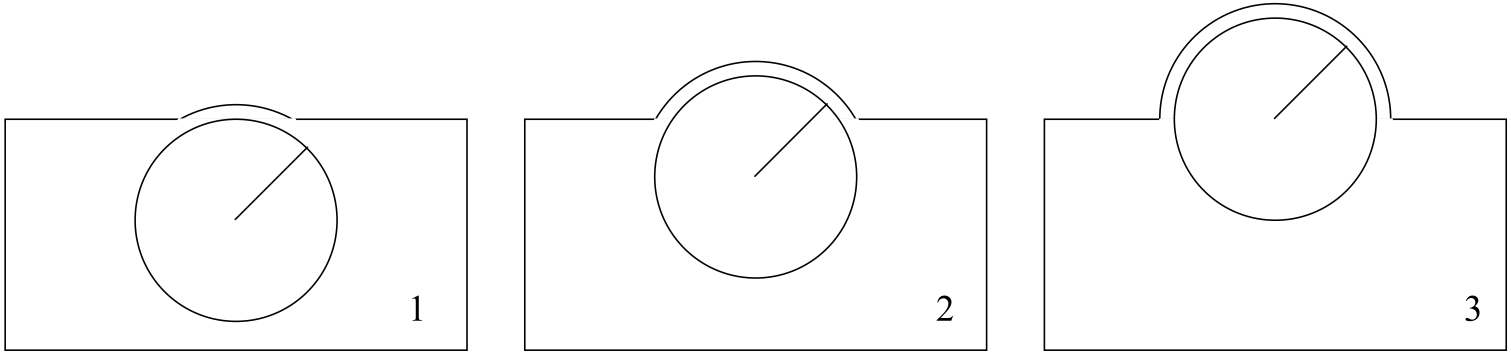
# The retention builds more slowly at lower He flux, but can reach similar levels.

- It takes longer to achieve a high concentration of large bubbles.
- At peak retention, there are increasingly fewer, but larger bubbles.
- For even lower fluxes, the retention drops as µm-mm size bubbles breach by growth.
  - Collapse of the large cavities left behind can produce *undesirable* metal ejection -- *splattering*.



# He released from large bubbles depends on the condition for bubble “breach”.

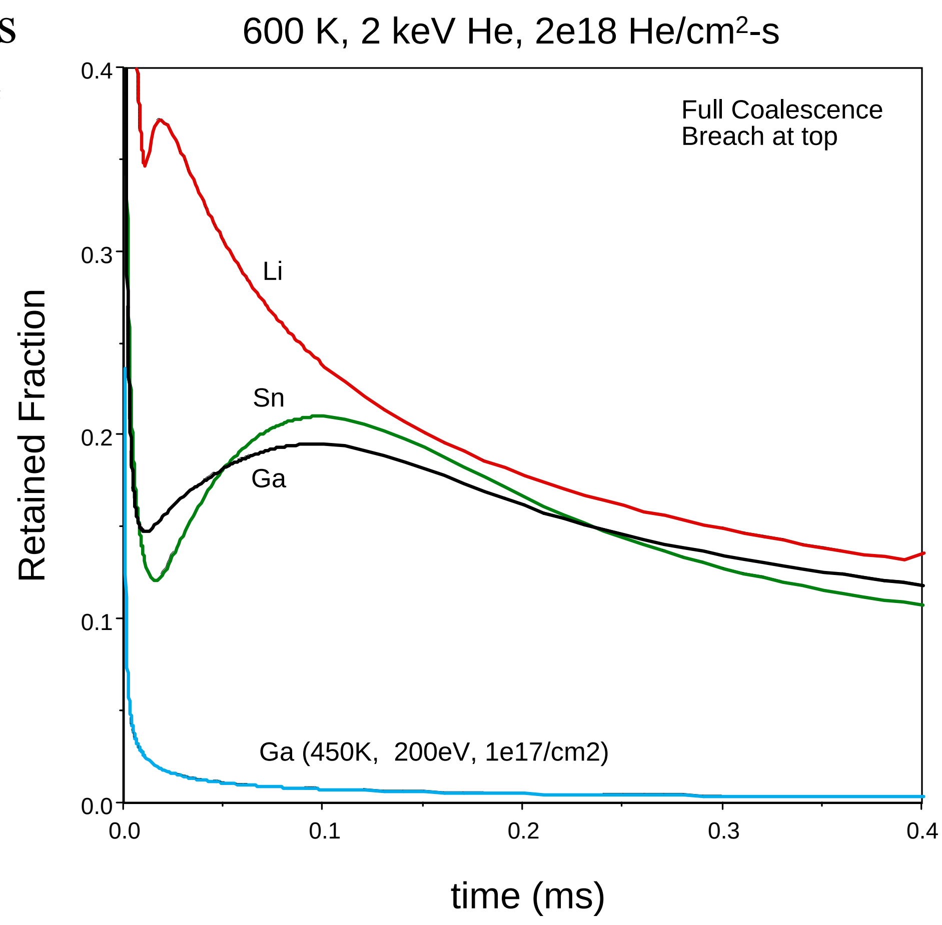



- The previous calculations assume bubble breach at position 3.
- Breach may occur at some intermediate position 2.
  - Surface tension from the additional (outside) surface may shrink the bubble and increase its pressure.
  - Plasma heating of the bubble “skin” may accelerate the breach.
- Breach at position 1 should provide more conservative retention values.
  - Collapse of the resultant, deep cavity may produce metal ejection.
  - Is there a minimum bubble size for this to occur?

# With breach at the bubble top, retention is similar for Ga, Sn, and Li at .1-.2 ms

- For Li, very high concentrations of small bubbles (N≤256) cause early, sustained high retention.
  - He is implanted deeper in Li.
  - The bubbles never get large.
  - Retention *depends strongly* on temperature and flux.

- For Ga and Sn, the retention grows until bubbles breach.
  - Breach of very large bubbles occurs by rapid coalescence -- not by diffusion.
  - Ret. is *less sensitive* to T, φ.



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# In summary, flowing Liquid Metals have potential for pumping He from plasma devices.

Based on very limited number of code runs -

- Retention is 10-20% over 1 ms pulse
  - For a given particle energy, the retention can be optimized using temperature, flux, and fluid flow.
- Best flux ranges:
  - Ga: low-moderate flux (.1-.2 $A/cm^2$)
  - Sn: moderate-high flux (.2-.3 $A/cm^2$)
  - Li: very high flux (>.3 $A/cm^2$)
- Ga and Sn are less sensitive to variations in T, flux.
  - Net retention *increases* with temperature.
- Ga and Sn will provide better retention during transit into the collection duct.
  - But, Ga and Sn may splatter at high flux.

Future computations will examine the full parameter space and look at retention for mixed He-D plasmas.



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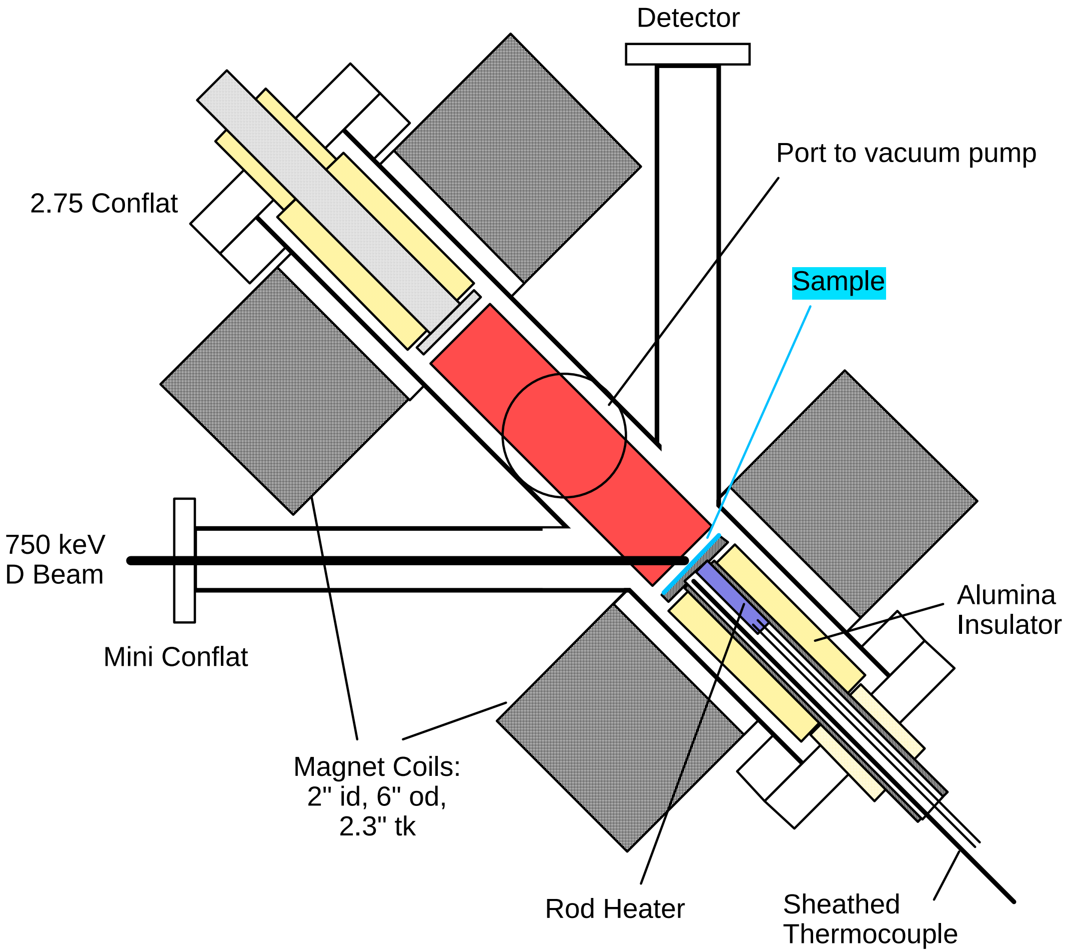
# We hope to set up an experiment to test the model and provide a low flux benchmark of the code.




- Penning trap produces flux of $10^{21}$ He/m$^2$-s at 1 keV.
- Liquid Ga or Sn (1 cm$^2$) covers trap (cathode) plate.
- $^3$He added to plasma is *profiled in LiqM* by d$^+$ beam.
- High steady-state retention will signify bubble formation.
- Low retention (no bubbles) will provide a measurement of effective He diffusivity.