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**Title:** Catching runaway electrons with MCNP: Simulations of runaway electron scattering and attenuation by solid pellets for disruption mitigation in fusion reactors

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Los Alamos NATIONAL LABORATORY

Tokamak Disruption Simulation Center

# Catching runaway electrons with MCNP

*Simulations of runaway electron scattering and attenuation by solid pellets for disruption mitigation in fusion reactors*


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2023 MCNP User Symposium

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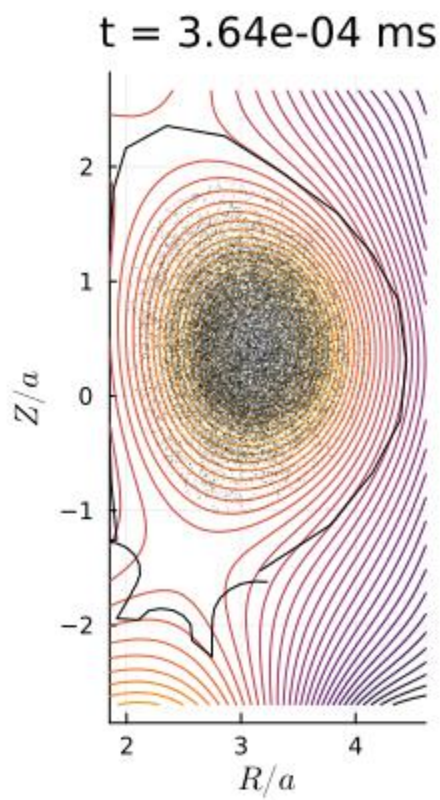
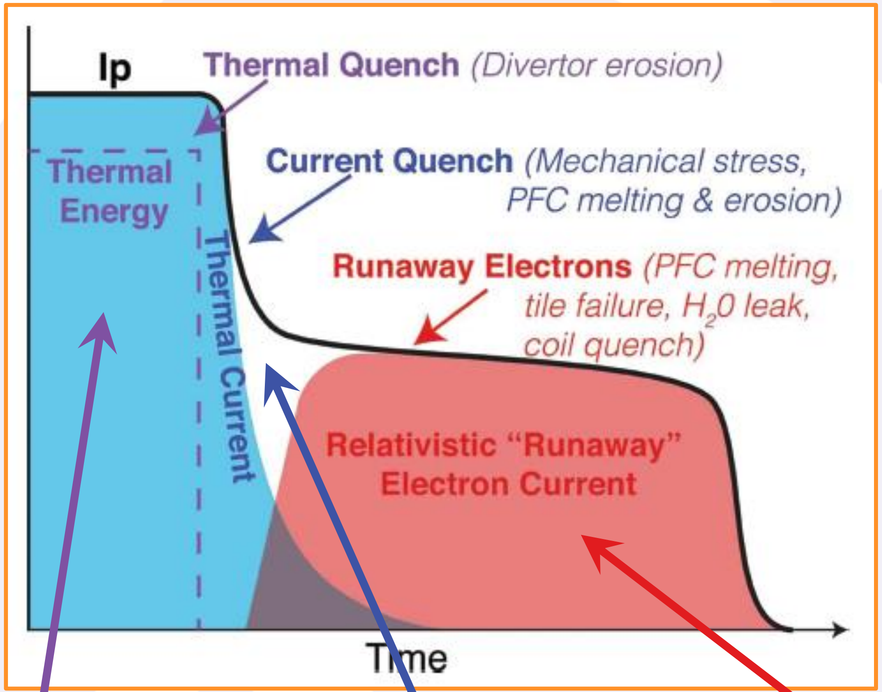
# Executive summary

- Formation and avalanche multiplication of runaway electrons (REs) during a disruption can cause catastrophic damage to a magnetic fusion reactor.
- Using MCNP simulations, we advance a **stand-off runaway termination scheme** to eliminate REs prior to final impact.
- Case 1: Ne shattered pellet injection
  - Already proposed on ITER for other disruption mitigation tasks.
  - Find moderate scattering rates (~20%) but minimal energy absorption, RE elimination.
  - Ne pellet lifetime ~5x RE orbital period → *best* case 49% termination.
  - Ne probably will not solve this problem for us.
- Case 2: W particulate injection
  - Not yet considered but a promising candidate, compatible material for ITER/SPARC.
  - Find elimination rates >99% at all energies, ~20% energy loss per collision.
  - Estimated particulate lifetime ~$10^3$x RE orbital period → *worst* case 98% termination.
  - Gamma radiation is undesirable, but not a problem for RE termination.

# Disruptions in tokamaks and resulting damage to plasma-facing components




*Runaway wall impact during a vertical displacement event (VDE).*




*A.D. Marin et al, Fus. Sci. Technol. (2033).*

Thermal Quench (TQ): Particle and energy loss to divertor and first wall.

Current Quench (CQ): EM energy deposition induces current driven mechanical stresses.

Runaway Electrons (RE): Localized energy loss and catastrophic damage at first wall.

# Shattered pellet injection (SPI) and the ITER disruption mitigation system (DMS)

SPI offers higher density and delivery rate versus MGI, with superior particle assimilation and vessel safety compared to injecting a single large pellet.

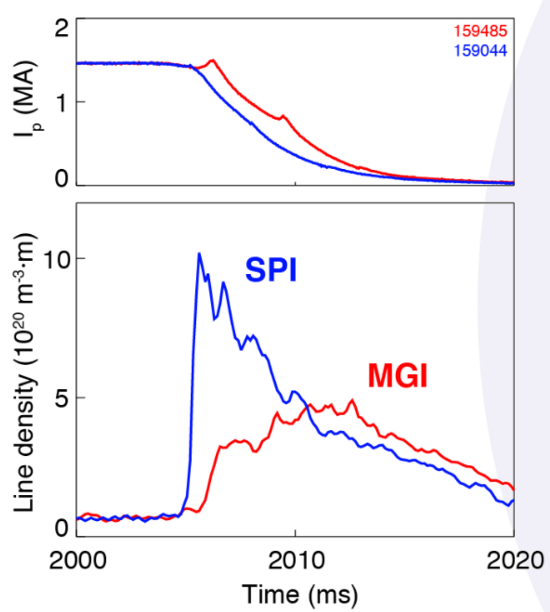
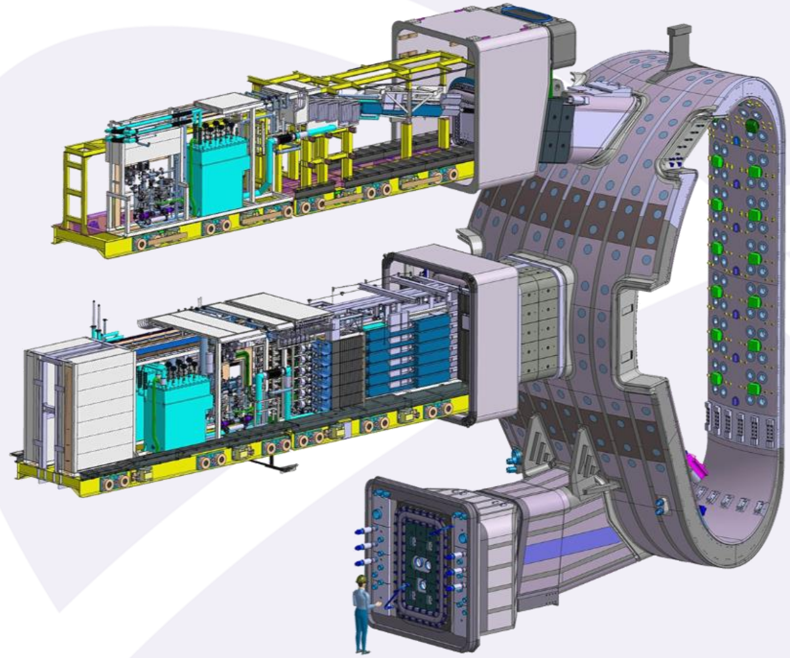
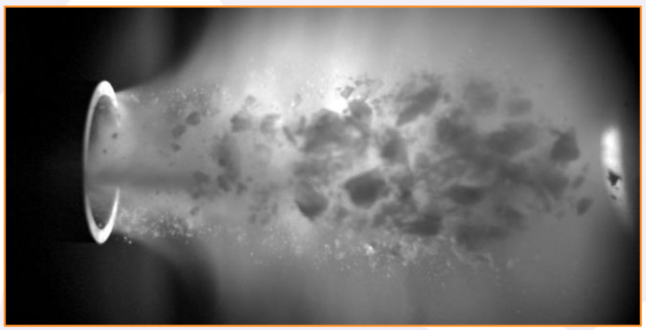



*FIG. 1. Comparison of line integrated densities during the CQ for equivalent neon SPI and MGI injections.*

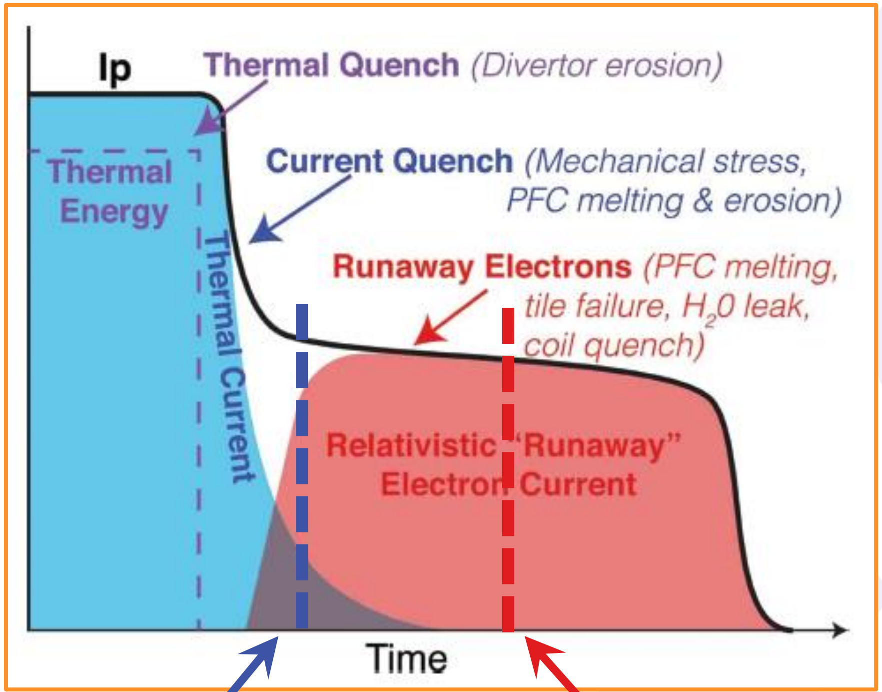
*D. Shiraki, 2019.*





*Cryogenic D-Ne shattered pellet exiting an injection system at 250 m/s (ORNL, 2021).*

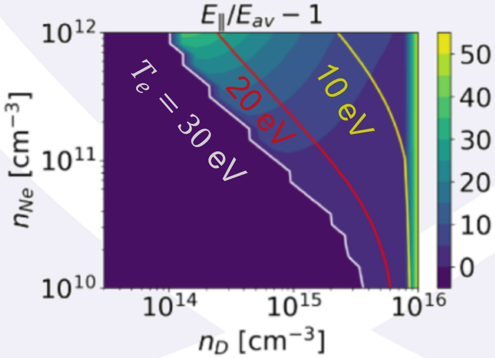
# The problem: constraints on runaway avoidance may be insurmountable for existing mitigation schemes




$t < 50$ ms: Eddy currents from rapid change in EM flux.

$t > 150$ ms: Halo currents as plasma contacts wall and drives wall current.

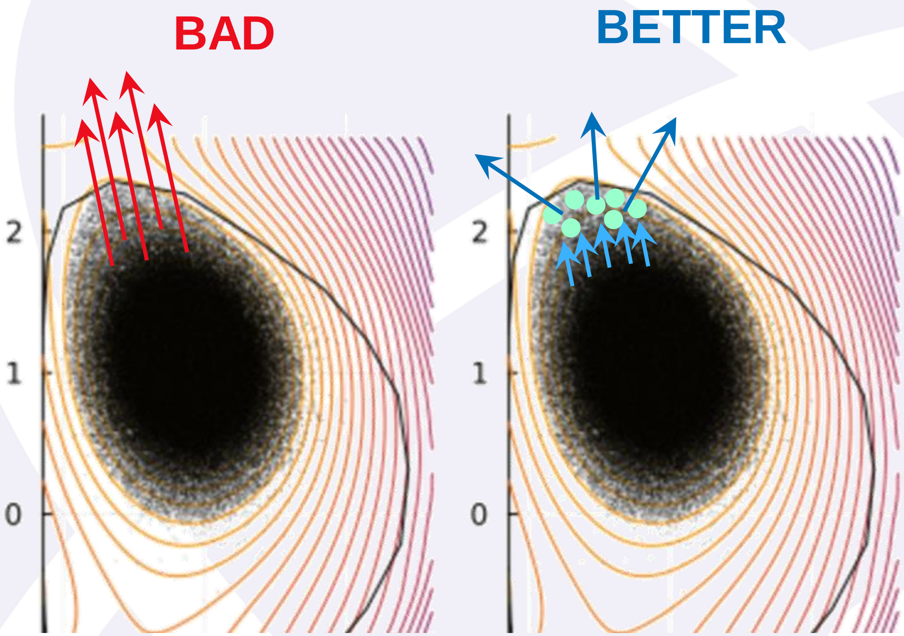
- Runaways are arguably the most dangerous/expensive consequence
  - Can destroy cooling systems, etc.
- Require CQ duration between 50 and 150 ms to prevent damage to VV.
- However, plasma power balance may preclude runaway avoidance!
  - In short: need $E_\| < E_{\rm av}$ to prevent RE avalanche. Since resistivity $\eta \propto T_e^{-3/2}$ this requires reheating the plasma.
  - But higher $T_e$ means longer CQ.



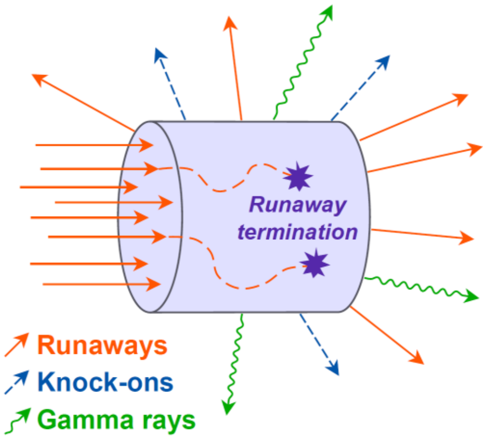

C. McDevitt et al, Nucl. Fusion (2023).

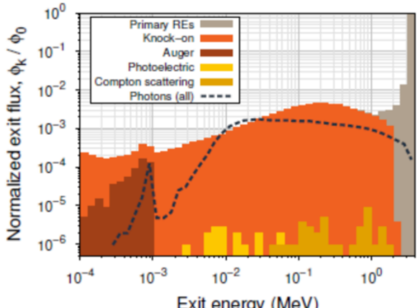
# The solution: Stand-off runaway termination by solid particulate injection

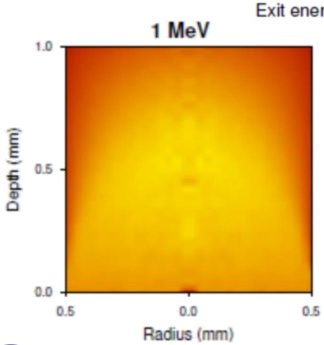
- A last-ditch defense is needed to prevent catastrophic damage from runaway final impact.
- One option: armor or limiter at the predicted impact position.
  - Replacing it every time = $$$$...
- **Better option: particulate injection into the RE path.**
  - Scatter REs across broad surface area or absorb them entirely.
  - Sacrificial particulates are easier to replace than melted wall plates.
  - We already have injectors…
- We compare pellets/particulates of Ne and W using MCNP.



# MCNP simulation setup



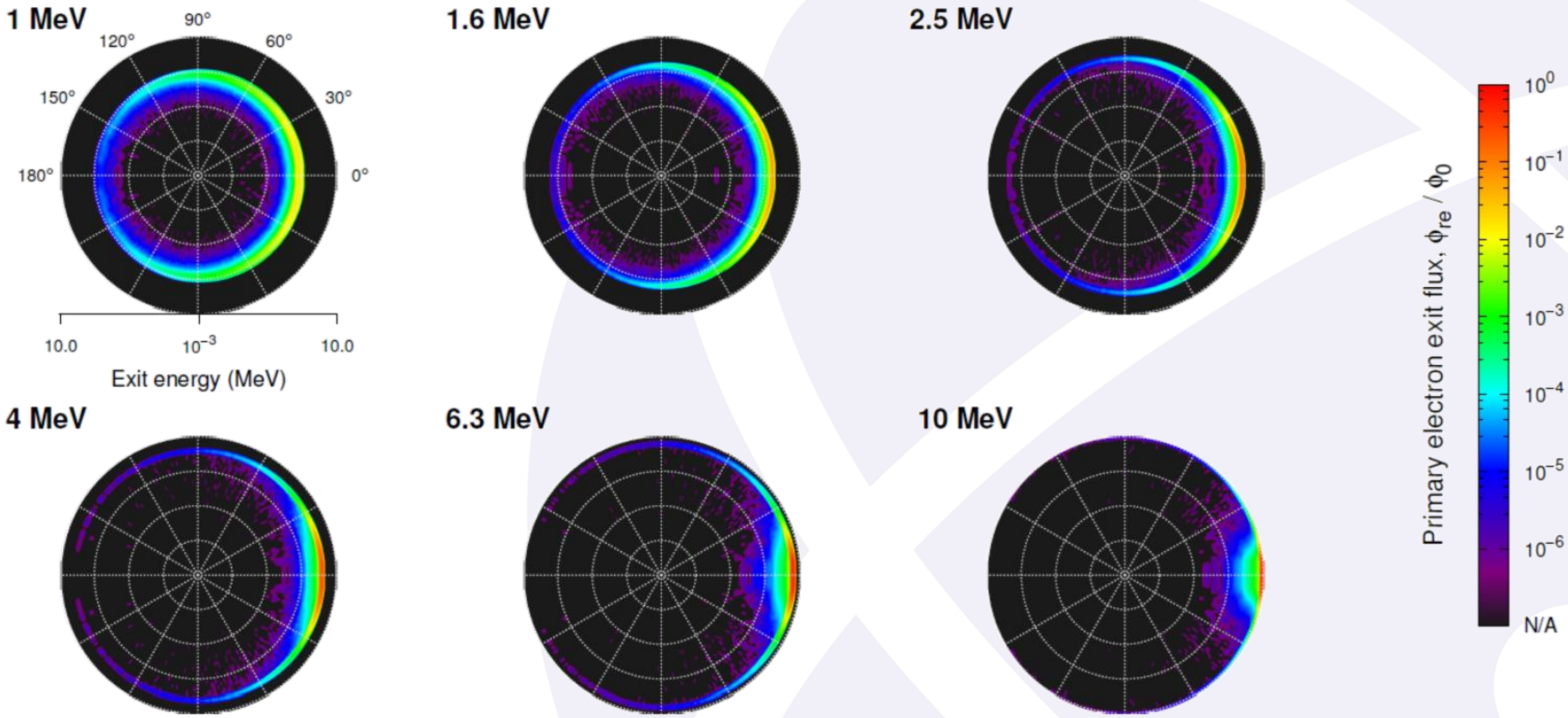




*Examples of output data.*

- Treat particulate geometry as cylinder, $L = D = 1$ mm.
- **`MODE P E`** with EL03 and EPRDATA14 libraries.
- Condensed history method for electrons
  - 10 keV cutoff for electrons to use single-event method.
  - Lower cutoffs 100 eV for electrons, 10 eV for photons.
- Incident energies: 1.0, 1.6, 2.5, 4.0, 6.3, 10.0 MeV.
  - 1,048,576 ($2^{20}$) histories per energy.
- Three types of tallies used:
  1. Flux of electrons exiting the pellet, resolved by cosine, energy, and physical origin (**`FT TAG`**);
     - Energy bins: logarithmic, 10 per decade.
     - Cosine bins: linear, 200 bins in increments of 0.01.
  2. Flux of photons exiting the pellet with same bins; and
  3. Volumetric energy deposition into the pellet fragment as a function of position in cylindrical coordinates, $E_D(r, z)$.
     - Modified code for knock-on and Auger generation to deposit energy at particle origin – WARNING: this increases runtime!

# Primary RE energy/cosine for Ne pellets @ 1-10 MeV




*Energy and angle-resolved exit fluxes of primary/incident runaway electrons colliding with a Ne pellet fragment with indicated initial energy.*

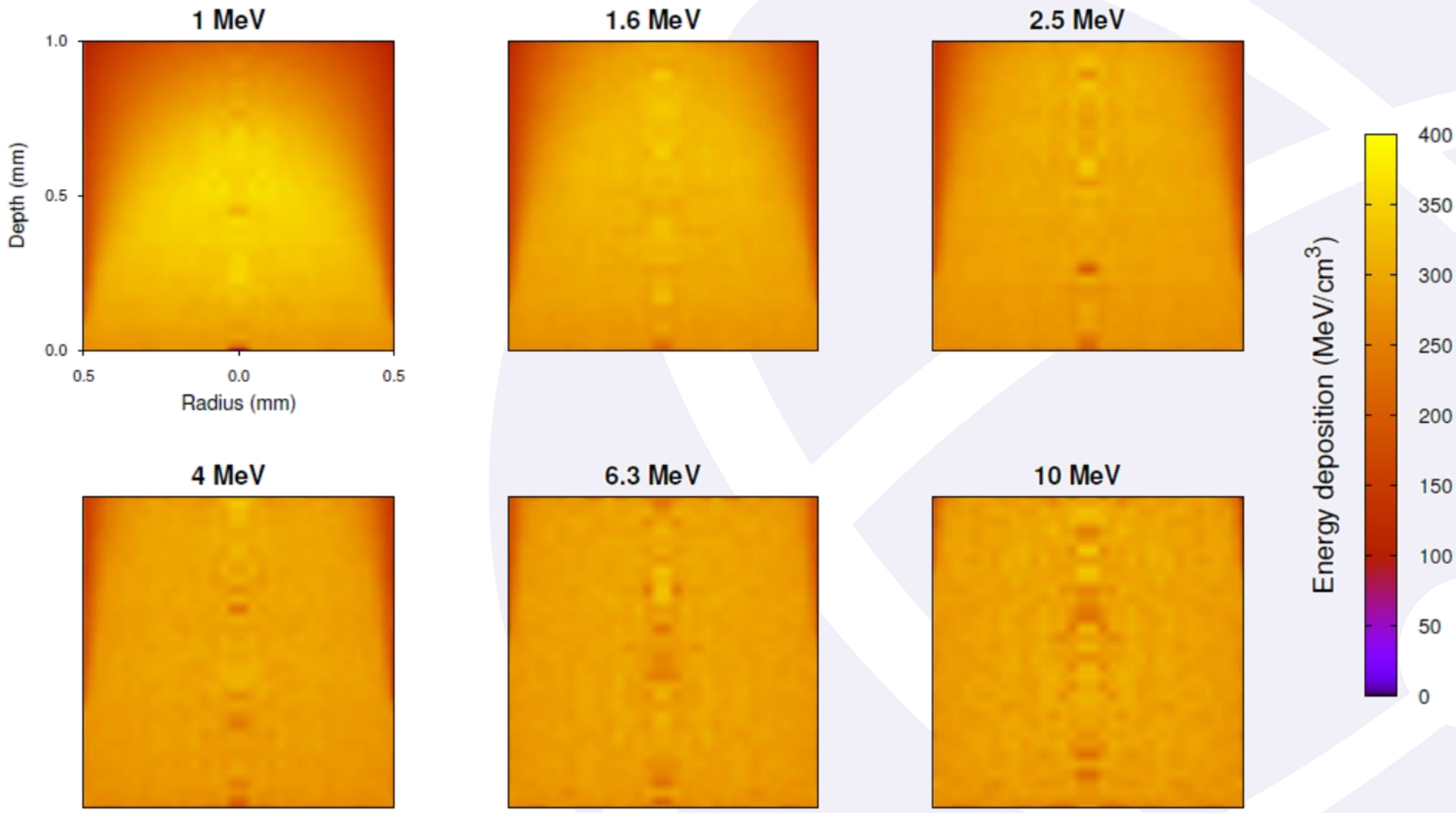
# Trends for energy and angle-resolved exit flux distributions from Ne pellet fragments

*RE energy loss and termination* (arrows to $f_{20}$, $f_{50}$, $f_{90}$, $f_{term}$) — *RE scattering* (arrows to $f_{scat}$, $f_{back}$)

| $E_0$ (MeV) | $f_{20}$ (%) | $f_{50}$ (%) | $f_{90}$ (%) | $f_{term}$ (%) | $f_{scat}$ (%) | $f_{back}$ (%) | $N_{se}/N_{re}$ | $N_{\gamma}/N_{re}$ |
|---|---|---|---|---|---|---|---|---|
| 1.0 | 53.99(9) | 0.171(3) | 0.104(2) | 0.097(2) | 97.02(10) | 4.51(2) | 0.0197(11) | 0.00563(7) |
| 1.6 | 9.58(5) | 0.036(2) | 0.0183(8) | 0.0141(6) | 93.53(10) | 0.758(9) | 0.0334(6) | 0.00853(9) |
| 2.5 | 3.85(3) | 0.0221(12) | 0.0114(6) | 0.0078(2) | 86.46(9) | 0.190(4) | 0.0376(5) | 0.01195(11) |
| 4.0 | 2.02(2) | 0.0253(14) | 0.0083(7) | 0.00299(9) | 72.01(9) | 0.064(2) | 0.0456(4) | 0.01619(12) |
| 6.3 | 1.40(2) | 0.031(2) | 0.0125(10) | 0.00180(6) | 47.06(8) | 0.025(2) | 0.0488(4) | 0.02056(13) |
| 10.0 | 1.06(2) | 0.037(2) | 0.0091(8) | 0.00161(6) | 19.70(6) | 0.0094(9) | 0.0475(4) | 0.02465(15) |

- Ne pellet fragments do not induce significant energy loss from incident REs.
  - 54% of incident REs with $E = 1$ MeV lose 20% or more of their energy.
  - But overall, the energy loss is negligible, and RE termination is nonexistent.
- Ne pellet fragments induce substantial pitch-angle scattering of incident REs.
  - For reference: scattering is defined as $\Delta\theta \geq 5.7°$ (i.e., $\Delta(\cos\theta) \geq 0.01$).
  - Ne is effective at scattering REs out of the beam (i.e., broaden the impact surface).

# Energy deposition distribution for Ne pellets @ 1-10 MeV




*Volumetric energy deposition distributions from incident runaway electrons into Ne pellet fragments with indicated initial energy.*

# Observations and trends for energy deposition distributions into Ne pellet fragments

- Magnitude of $\Delta E_{\mathrm{dep}}$ is nearly constant (~7% change) over the energy range.
  - Stopping power, $-dE/dx$, is nearly constant at these energies.
- Distribution is nearly uniform, rounds off a bit at lower energies.
  - Implies nearly uniform vaporization of Ne pellets rather than outside-in ablation.
- We can *estimate* pellet lifetime, $\tau_{\mathrm{pel}}$, from volume-averaged energy deposition:

$$\tau_{\mathrm{pel}} = \frac{\Phi_{\mathrm{re}}}{\phi_{\mathrm{re}}}, \qquad \Phi_{\mathrm{re}} = \frac{E_{\mathrm{coh}} N L}{\Delta E_{\mathrm{dep}}}, \qquad \phi_{\mathrm{re}} = \frac{j_{\mathrm{re}}}{e}$$

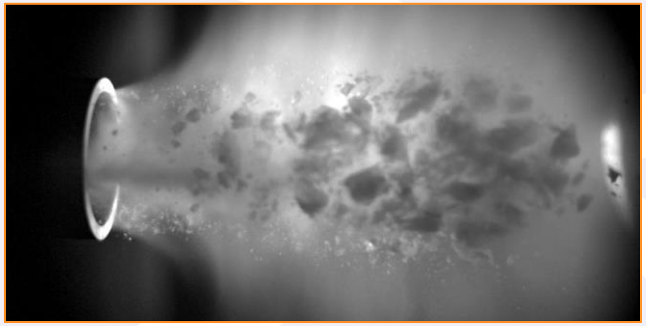
  - For Ne ($E_{\mathrm{coh}} = 0.02$ eV/atom), $\tau_{\mathrm{pel}}$ is on the order of ~0.7 µs.
  - RE orbit time $\tau_{\mathrm{orbit}} \approx (2\pi R_0)/c = 0.13$ µs.
  - Ne pellets survive for about five RE orbits before fully vaporizing.

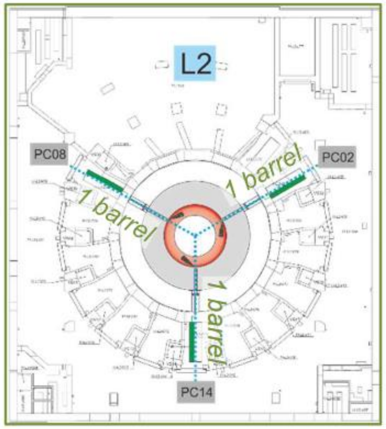
# Discussion: Ne pellet efficacy for RE mitigation

- Consider 10 MeV REs orbiting ITER:
  - 20% of REs incident on pellet scatter out.
  - Estimate ~20% of RE beam area is intersected by SPI fragments in the cloud.
  - 3x upper port barrels at $\Delta\theta_\phi = 120°$ positions.
    - Optimistic assumption: all used for Ne pellets.
  - $\tau_{\mathrm{pel}}/\tau_{\mathrm{orbit}} \sim 5$ RE orbits before vaporization.
  - Thus, each RE will collide with $N_{\mathrm{col}} \sim 3$ Ne pellet fragments before complete vaporization.
    - Neglects numerous details of the ablation process.
- Neglecting multiple-scattering effects:

$$F_{\mathrm{scat}} \approx 1 - (1 - f_{\mathrm{scat}})^{N_{\mathrm{col}}} = 1 - 0.80^3 = 49\%$$

- **<u>Ne SPI is insufficient for stand-off final termination of runaways!</u>**
  - We need a better material.






*Upper port injectors*
∅19 mm x L38mm pellets for post-TQ injection:
- CQ heat load mitg.
- CQ EM load mitg.

*S. Jachmich, 2022*

# What about tungsten?

What are the requirements for injected material for RE final termination?

- High stopping power, usually means high-Z.
  - Higher than Ne ($Z = 10$); $D_2$ injection probably won't cut it.
- Survive long enough to fully terminate RE beam, usually means high $E_{\mathrm{coh}}$.
  - This is a problem for heavier rare gases like Ar, Kr which have higher Z but still have extremely low $E_{\mathrm{coh}}$.
- No materials issues from material deposition at first wall and divertor.
  - No undesirable alloys, defect formation, surface chemistry, oxide formation, precipitates…
  - ITER (and SPARC) will be all-tungsten, so W is a natural choice here as well.

∴ W sounds like a good choice here.

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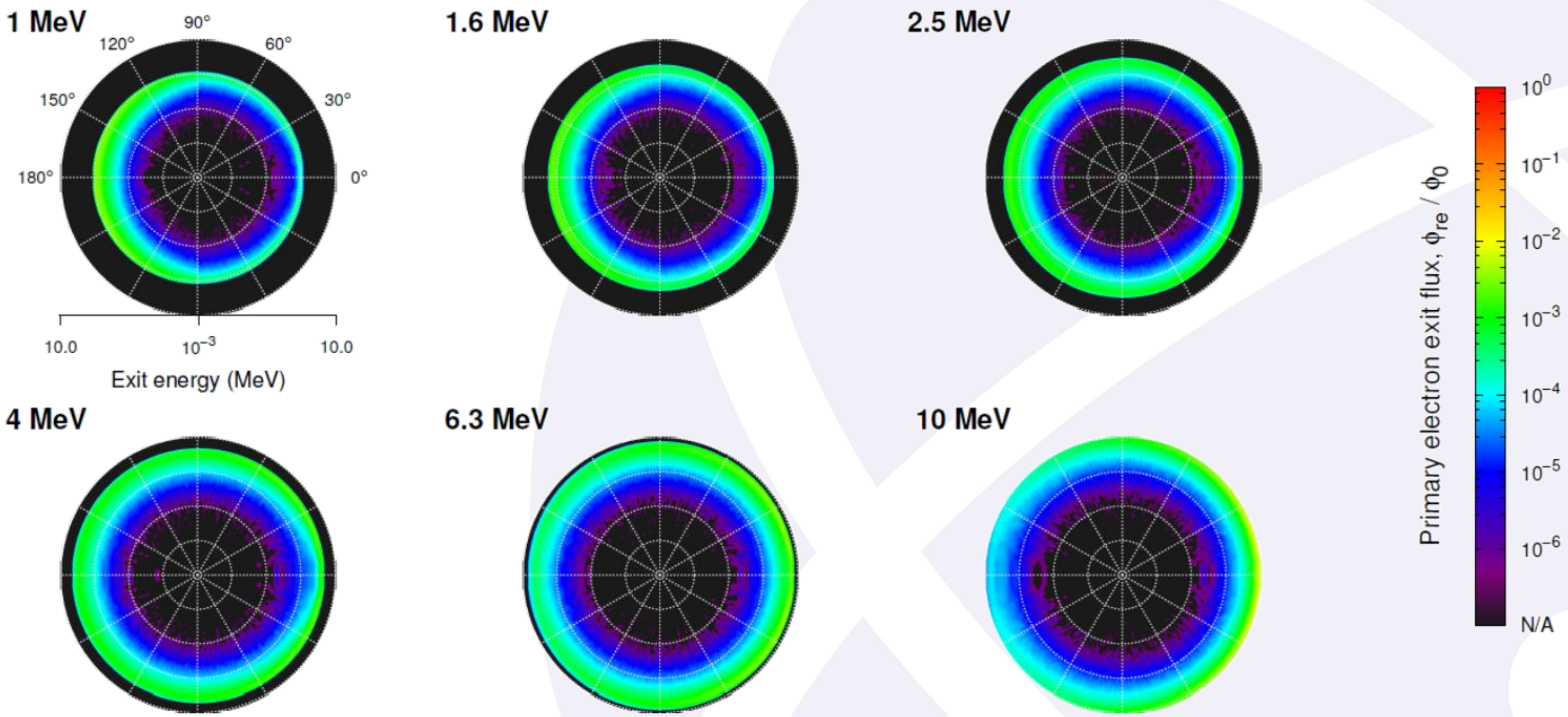
# Primary RE energy/cosine for W pellets @ 1-10 MeV




*Energy and angle-resolved exit fluxes of primary/incident runaway electrons colliding with a W particulate with indicated initial energy.*

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# Trends for energy and angle-resolved exit flux distributions from W pellet fragments

*RE energy loss and termination* ($f_{20}$, $f_{50}$, $f_{90}$, $f_{term}$)

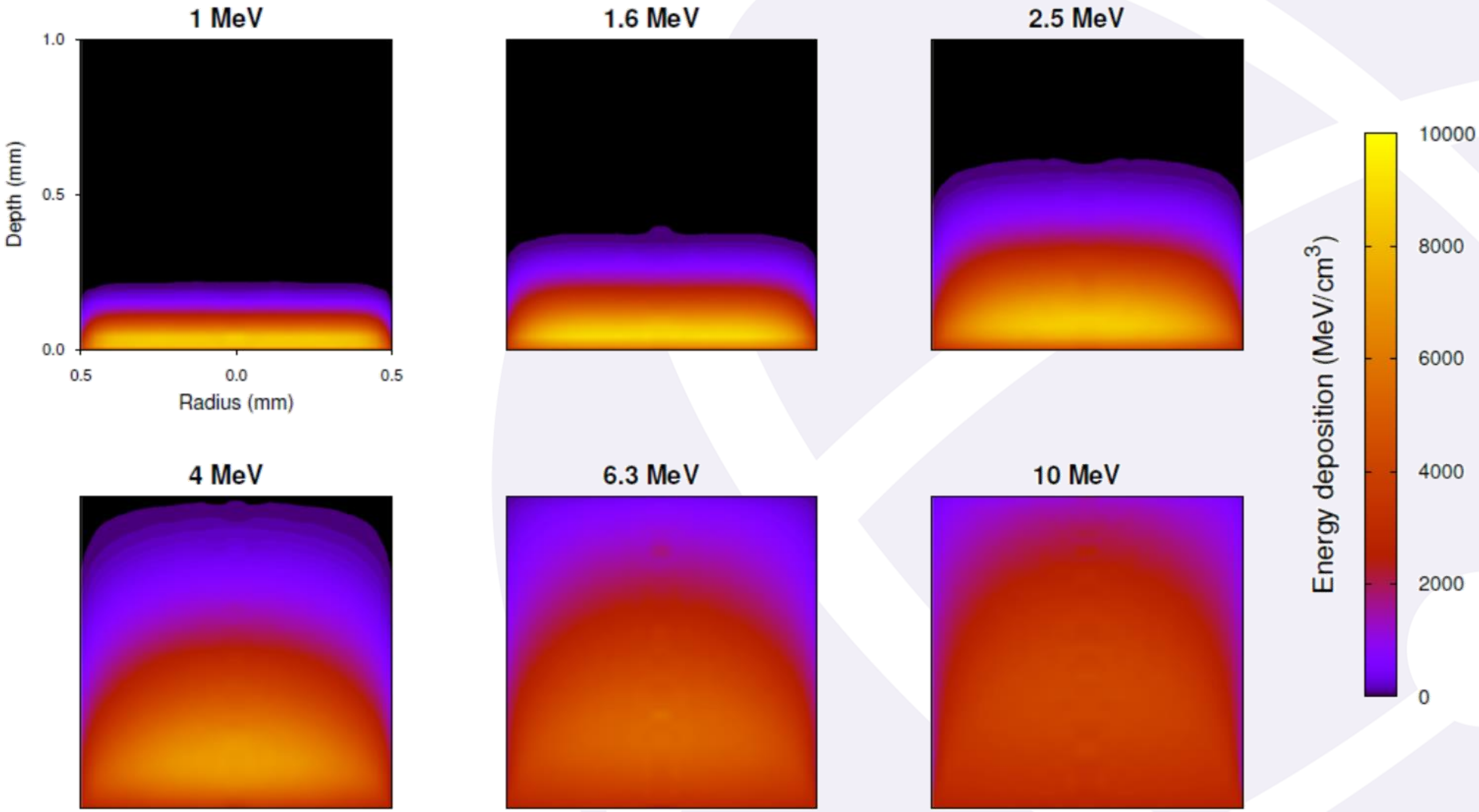
*RE scattering* ($f_{scat}$, $f_{back}$)

**Gamma ray emission!!** ($N_\gamma/N_{re}$)

| $E_0$ (MeV) | $f_{20}$ (%) | $f_{50}$ (%) | $f_{90}$ (%) | $f_{term}$ (%) | $f_{scat}$ (%) | $f_{back}$ (%) | $N_{se}/N_{re}$ | $N_\gamma/N_{re}$ |
|---|---|---|---|---|---|---|---|---|
| 1.0 | 76.20(10) | 49.25(6) | 48.60(6) | 48.53(6) | 51.44(9) | 43.79(6) | 0.0081(9) | 0.0755(3) |
| 1.6 | 76.81(10) | 47.05(6) | 46.21(6) | 46.04(6) | 53.91(9) | 40.17(6) | 0.0128(10) | 0.1563(4) |
| 2.5 | 77.51(10) | 41.92(6) | 40.60(6) | 40.44(6) | 59.47(9) | 36.29(6) | 0.0191(10) | 0.2890(5) |
| 4.0 | 74.06(10) | 31.55(5) | 29.76(5) | 29.31(5) | 70.51(10) | 32.26(6) | 0.0303(11) | 0.4932(7) |
| 6.3 | 70.14(10) | 16.99(4) | 14.77(3) | 14.12(3) | 85.36(10) | 25.96(5) | 0.0456(12) | 0.7201(8) |
| 10.0 | 65.02(10) | 8.62(3) | 6.20(2) | 5.74(2) | 93.85(10) | 14.28(4) | 0.0631(12) | 0.9370(10) |

- W particulates are highly effective in both scattering and termination views.
  - For all incident energies, >99% of REs are either scattered or terminated.
  - Lower-energy REs cannot penetrate through the particulate
    - This is why we see a lot of backscattering, as electron transport approaches a diffusive limit.
- Gamma radiation could pose a challenge.
  - Gamma radiation flux is a factor of ~20-25× that from Ne pellet fragments.
  - Potentially a serious concern as gamma ray interactions could produce more relativistic electrons (runaway reseeding).

# Energy deposition distribution for W pellets @ 1-10 MeV



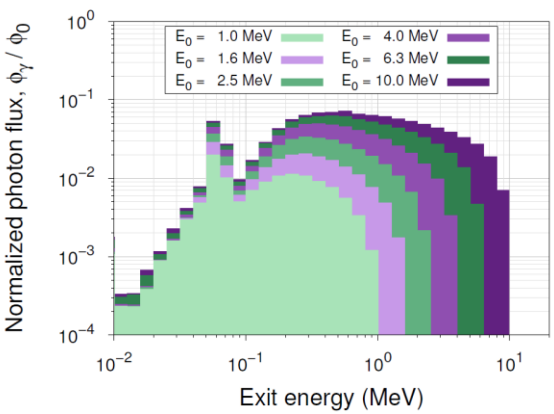

*Volumetric energy deposition distributions from incident runaway electrons into W particulates with indicated initial energy.*

# Observations and trends for energy deposition distributions into W pellet fragments

- Magnitude of energy deposition varies nonlinearly with RE energy.
  - Nearly linear for $E \sim 1$ MeV, approaching asymptote as $E \rightarrow 10$ MeV.
  - Higher-energy REs still leave with a lot of energy.
  - Lower-energy REs terminate near the front of the pellet or backscatter.
- Distribution is rounded at higher energies but becomes flat and shifts toward the front (bottom) of the pellet fragment with lower energies.
  - This implies that W pellets will ablate from front to back under RE flux.
    - We are curious about the possibility of rocket forces…
- For W ($E_{\mathrm{coh}} = 8.90$ eV/atom), we estimate the pellet lifetime $\tau_{\mathrm{pel}}$ to be on the order of ~100 µs.
  - Varying by about a factor of 2 either way with energy.
  - W pellets can survive ~$10^3$ RE orbits before fully ablating.
- This is more than sufficient to fully dissipate the RE beam…
- Need to evaluate the effect of gamma radiation – see next slide!

# Gamma radiation impact on runaway termination

- Gamma rays can re-seed runaways by three mechanisms:
  1. Compton scattering of free plasma electrons to high energies.
     - Completely negligible – mean free path is of order $10^9$ m, far larger than any device size.
  2. Interaction with other nearby W particulates.
     - Most salient effect, order of 1-5% additional runaways under typical conditions.
     - Minimal impact in practice due to broad exit energy and angular distributions.

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| $E_0$ (MeV) | $f_{term}$ (%) | $N'_\gamma/N_\gamma$ | $N_{se}/N_\gamma$ |
|---|---|---|---|
| 1.0 | 3.172(7) | 0.0040(5) | 0.01319(11) |
| 1.6 | 1.812(5) | 0.0133(6) | 0.01736(13) |
| 2.5 | 2.164(5) | 0.0336(6) | 0.0259(2) |
| 4.0 | 3.276(6) | 0.0574(6) | 0.0444(2) |
| 6.3 | 4.734(7) | 0.0770(7) | 0.0745(3) |
| 10.0 | 6.481(8) | 0.0935(7) | 0.1156(3) |

=

About 1-5% additional runaways

  3. Interaction with the first wall.
     - Very negligible – three orders of magnitude ($10^{-3}$) smaller effect than (2).

# Conclusions

- MCNP simulations are a useful and necessary tool to model RE mitigation by pellet or particulate injection in early stages before complete ablation.
- Ne pellet injection looks not quite good enough to mitigate the RE beam even with optimistic estimates.
  - 20% scattering at 10 MeV is not enough for the extremely short pellet lifetime
  - The picture is better at lower energies, but we need to terminate the whole beam.
- W pellet injection is capable of terminating the RE beam by scattering and absorption/termination of REs.
  - High efficiency and long lifetime compared to Ne.
  - High secondary radiation fluxes are not a pressing concern for RE reseeding.

<u>Critical outcomes</u>:

1. "Tungsten shotgun" concept as a viable RE final termination scheme.
2. Establish a radiation-materials interactions basis for future plasma physics simulations (i.e., RE orbits after RE-particulate collision).