Disruption mitigation in tokamak reactor via reducing the seed electrons of avalanche

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Outline

1. Novel approach to disruption mitigation in ITER using tungsten projectile injection after TQ
2. Scenario of mitigation
3. Choice of the projectile material
4. Plasma-projectile interaction
5. Options of the approach realization
6. Conclusions

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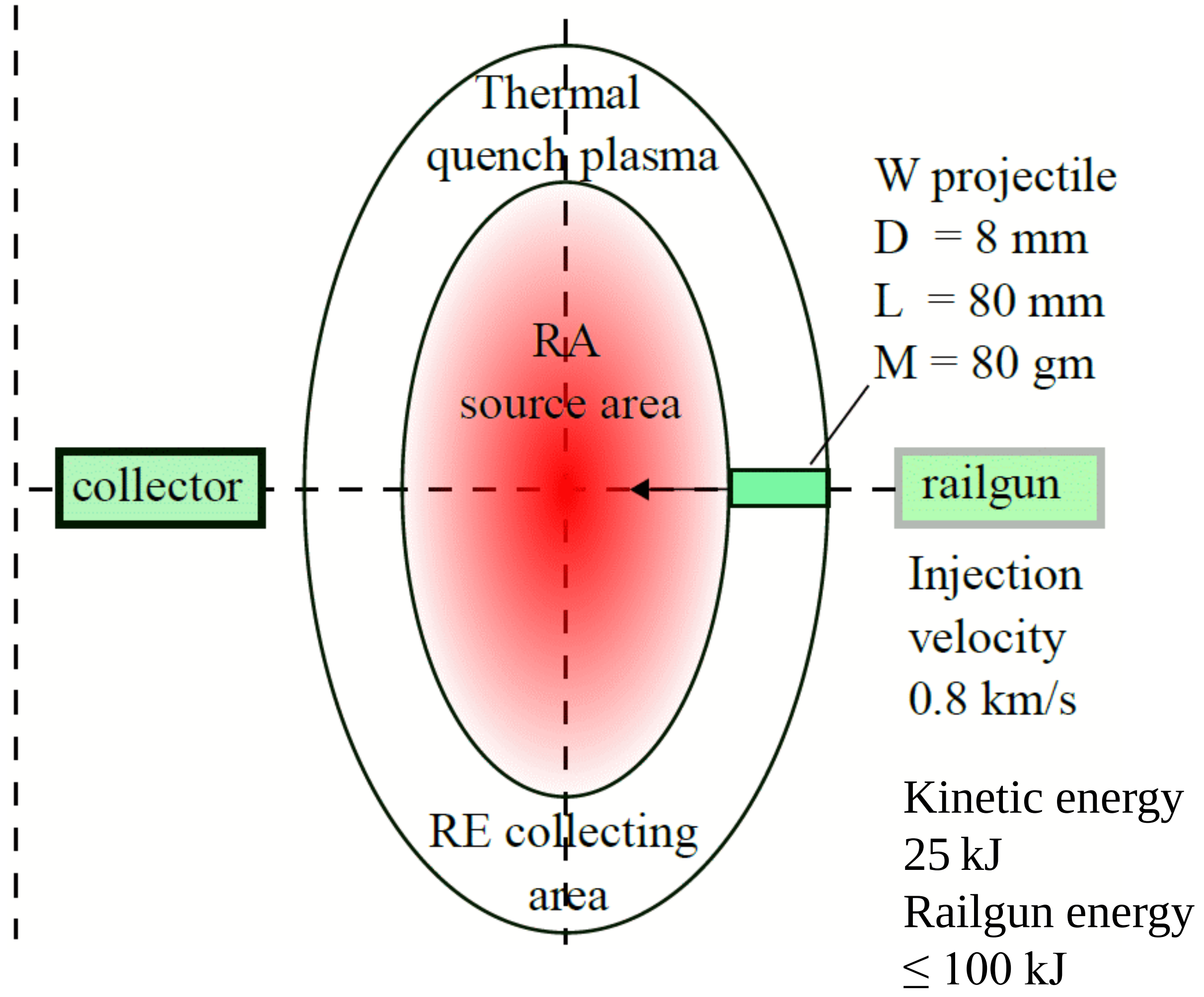
Introduction

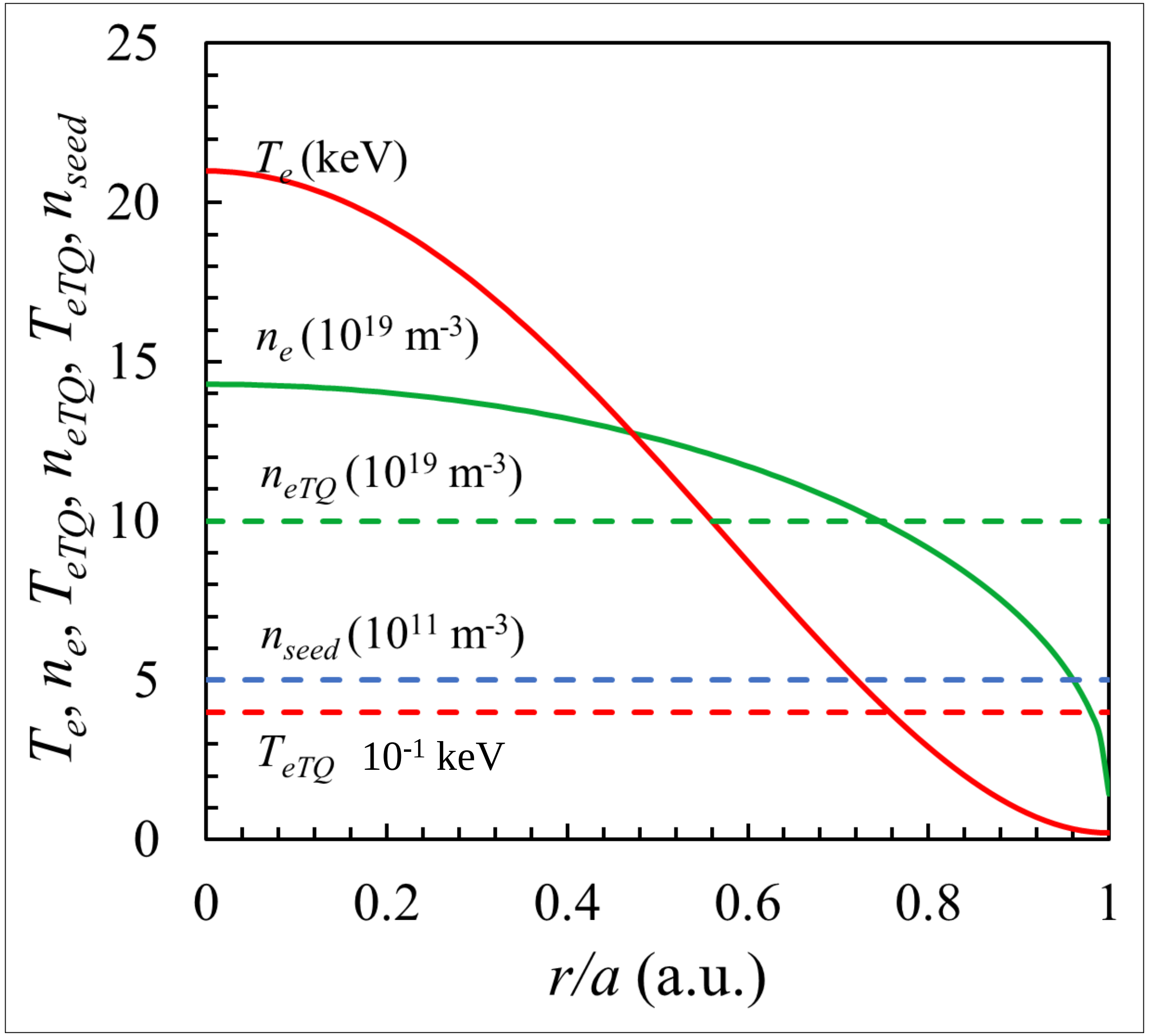
- Effective disruption mitigation technology remains the key issue of safe and reliable operation in future large tokamaks including ITER (M. Lehnen, ITER Tech.Rep. 2018; B. Breizman, NF 2019).
- Several approaches have been proposed and experimentally tested in contemporary devices, which demonstrated opportunities of massive gas, pellets, dust and liquid jets injection in preventing the runaway avalanche as the most dangerous mechanism of the breeding runaway electrons.
- Physics of the avalanche (Yu. Sokolov, JETP 1979) is governed by runaway seeds and a very high electric field generated in tokamak at the final stage of the thermal quench that provides conversion of the plasma current from thermal electrons to runaways. It was shown that effective tool for the runaway avalanche mitigation is a fast growth of the plasma density above so called Rosenbluth density via techniques mentioned in (M. Rosenbluth, NF 1997). This density value is 100~1000 times higher than the plasma operation density. The mass of injected matter being in a kilogram range negatively affects technology systems sited the in-vessel and requires long-term recovery of the tokamak device in the created conditions.
- Here, we analyze a novel approach aiming at an essential reduction of seeds causing the avalanche runaway electron generation after the thermal quench but does not use injection into the device vacuum vessel a large mass of gas, liquid or solid/dust matter.

Schematic diagram of the approach



- Tungsten projectile injected by railgun collects hot-tail seeds after TQ
- The 80 mm length and the 0.8 km/s speed of the projectile were chosen to provide existence of the shadow at the each magnetic surface by ∅ 8 mm projectile.
- ~800 toroidal transits needed to collect runaways during their within 1/4 of the minor radius where the main source of seeds is expected.
- Runaway electrons within the 1~25 MeV energy range are terminated by the W projectile with the 8 mm dimension along the magnetic field.
- Projectile crosses the magnetic surfaces twice which provides sequential cleaning with the efficiency squared (10^{-2}x10^{-2})
- 4 crosses of the magnetic surface are also possible during 15 ms time interval.

Plasma profiles before and after TQ

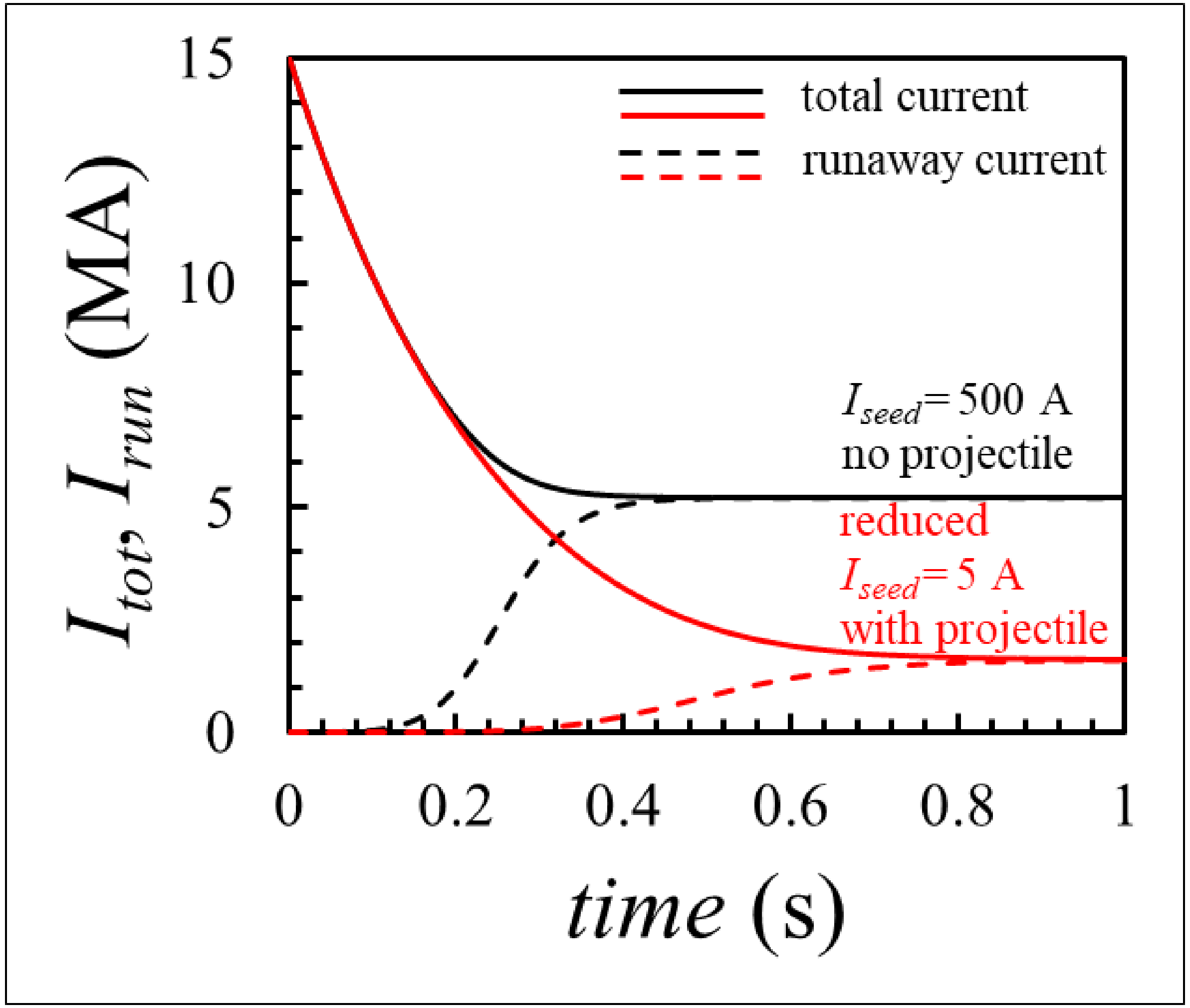


⇐

- Fast reconnection during TQ
  - flattens the plasma parameters
  - drops the temperature creates hot-tail seeds
  - Density and impurity (Z_{eff}) prior TQ
  - O-D analysis is acceptable

- Further development is includes:
  - adding impurities from the wall
  - enhancing plasma radiation
  - increasing plasma density
  - wall current incorporation
  - plasma current jump after TQ

Evolution of currents during CQ (I_0=15 MA)



- Preliminary analysis of the RA development according to evaluation of RA from (M. Lehnen, JNM 2014)
- Avalanche current is simulated assuming large E/E_{CH} values during CQ
- Seed hot-tail current 500 A is evaluated from (H. Smith, PoP 2008)
- Reduction of seeds by factor of 100 delays the avalanche development accordingly and transfers the discharge in an acceptable state with reasonable runaway current less than 2 MA.
- Reducing seeds by factor of 1000 decreases RA current below 0.5 MA.

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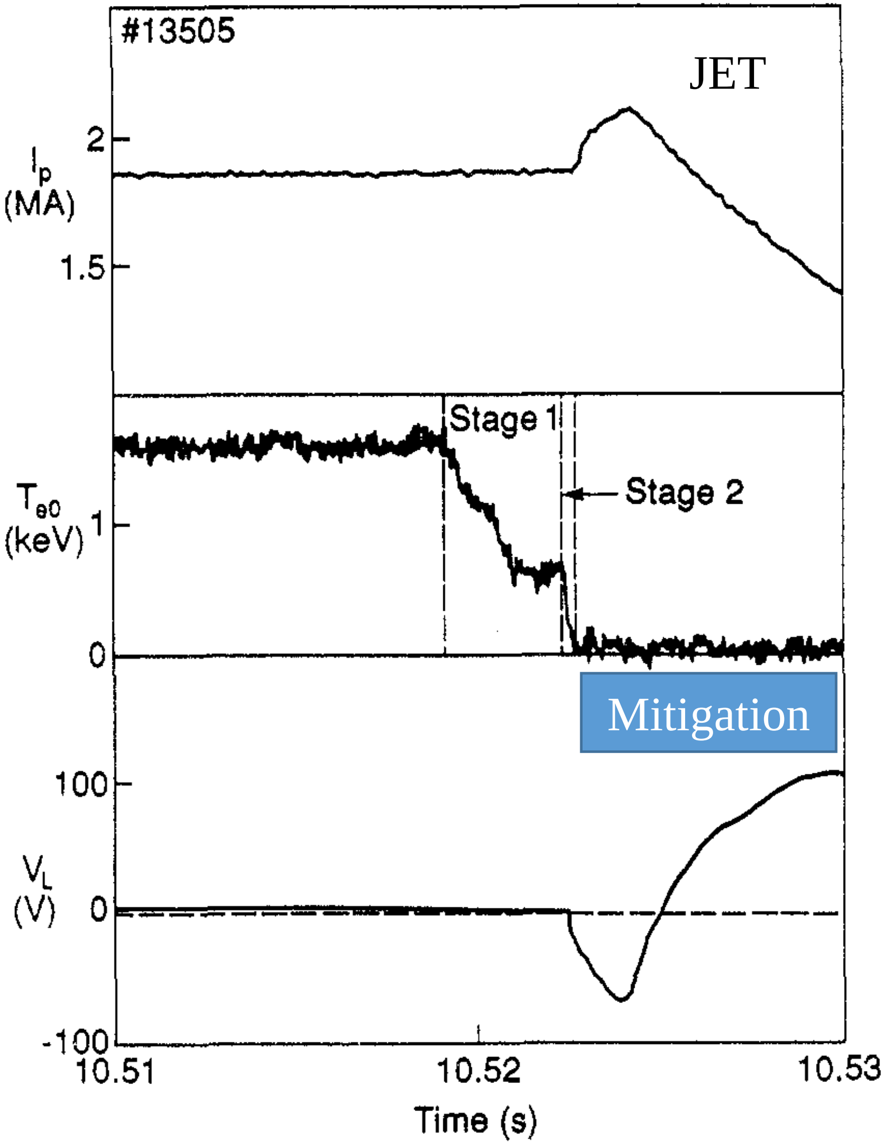
Scenario of disruption at JET and ITER



(D. Ward, NF 1992)

- Natural (unintended) disruption at JET
- Negative voltage spike is used as the trigger for the railgun shot

- Spatial and time scales for the projectile in ITER

Distance to plasma	~1 m
Acceleration time	+1.25 ms
Time to plasma	+1.25 ms
Time at plasma center	+2.50 ms
Time at inner wall	+2.50 ms
Total time	7.50 ms

Scenario of projectile mitigation in ITER

Pre-mitigation conditions:

- Natural (unintended) disruption conditions seem optimal, however deviations are possible with additional impurity injection
- Plasma temperature drop after TQ: 40~200 eV is expected maintained by anomalous (stochastic) electron transport, plasma-wall interaction and enhanced radiation
- Plasma density increase is expected: 2~5 of electron content during disruption TQ

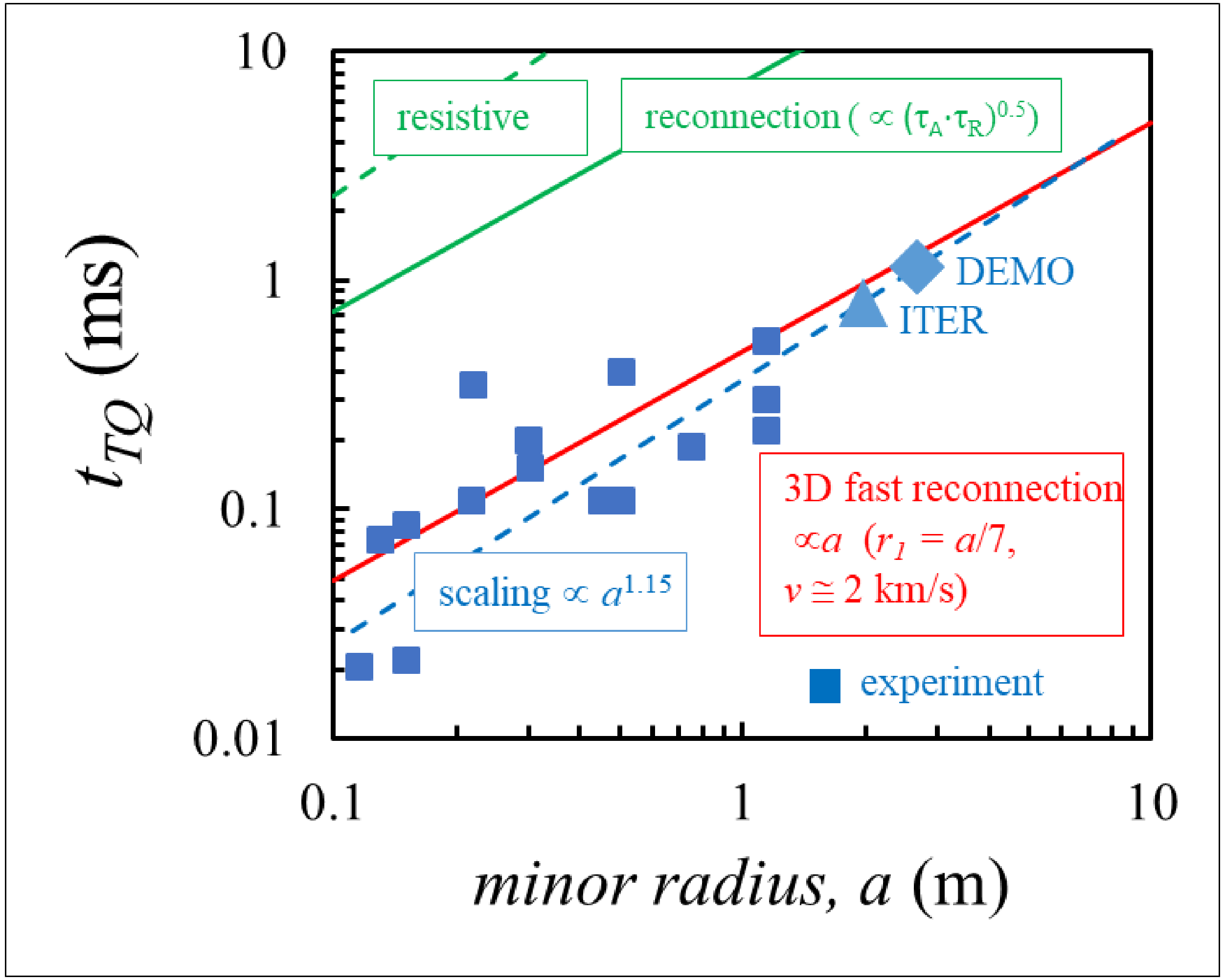
Mitigation stage

- Negative voltage spike triggers the railgun operation
- W projectile injection into plasma by railgun within ~2.5 ms after the fast TQ start
- Collecting RA seeds with $E \leq 25$ MeV by W projectile (cleaning factor $10^{-(2\sim5)}$)
- At velocity 800 m/s interaction of the projectile with plasma takes ~5 ms
- After plasma crossing the projectile is directed to the collector outside by guide tube.

Fast thermal quench duration

- Fast thermal quench stage is most important for ITER
  - Particle velocity during TQ is of 2 km/s
    - Linear dependence on minor radius provided by burst of non-ionized materials (D. Ward, NF 1992)
    - fast reconnection with Alfven time (J. Wesson, Tokamaks 2004; A. Boozer, Pl. Phys. 2018; E. Zweibel, Annu. Rev. Astron. Astrophys. 2009)

$$\tau \sim \frac{\tau_A}{\left(\tau_A/\tau_R + (c/r_1\omega_p)^2\,(1 + (\beta_e/(m_e/m_i))^{1/2})\right)^{1/2}}$$



- TQ duration is the critical parameter for RE generation via hot-tail formation

Hot-tail seeds breeding in avalanche

- Generation of hot-tail seeds during the second fast TQ stage is estimated using model (H. Smith, PoP 2008). It dominates in ITER over Dreicer, tritium decay and other mechanisms:

$$n_{seed}^{hot-tail} = n_0 \cdot \frac{2}{\sqrt{\pi}} \cdot u_{c,min} \cdot e^{-u_{c,min}^2}, \qquad T(t) = T_0 \cdot e^{-\frac{t}{t_0}}$$

- For $n_0 = 10^{20}$ m^{-3}, $T_0 = 8.8$ keV and $t_0 = 1$ ms, $n_{seed} = 5 \cdot 10^{11}$ m^{-3} $\Rightarrow I_{seed} \cong 0.5$ kA.

- For $n_0 = 10^{20}$ m^{-3}, $T_0 = 5$ keV and $t_0 = 1$ ms, $n_{seed} = 5.5 \cdot 10^{6}$ m^{-3} $\Rightarrow I_{seed} \cong 5$ mA.
- Conversion time of seeds to runaway is $\tau \cong m_e c/eE \cong 1$ ms.
- The RA characteristic time is $\tau \cdot ln\Lambda \cong 20$ ms.
- Reducing seeds by 10^2 times delays the RA by $20 \cdot \ln 10^2 \cong 92$ ms.
- Reducing seeds by 10^5 times delays the RA by $20 \cdot \ln 10^5 \cong 230$ ms.

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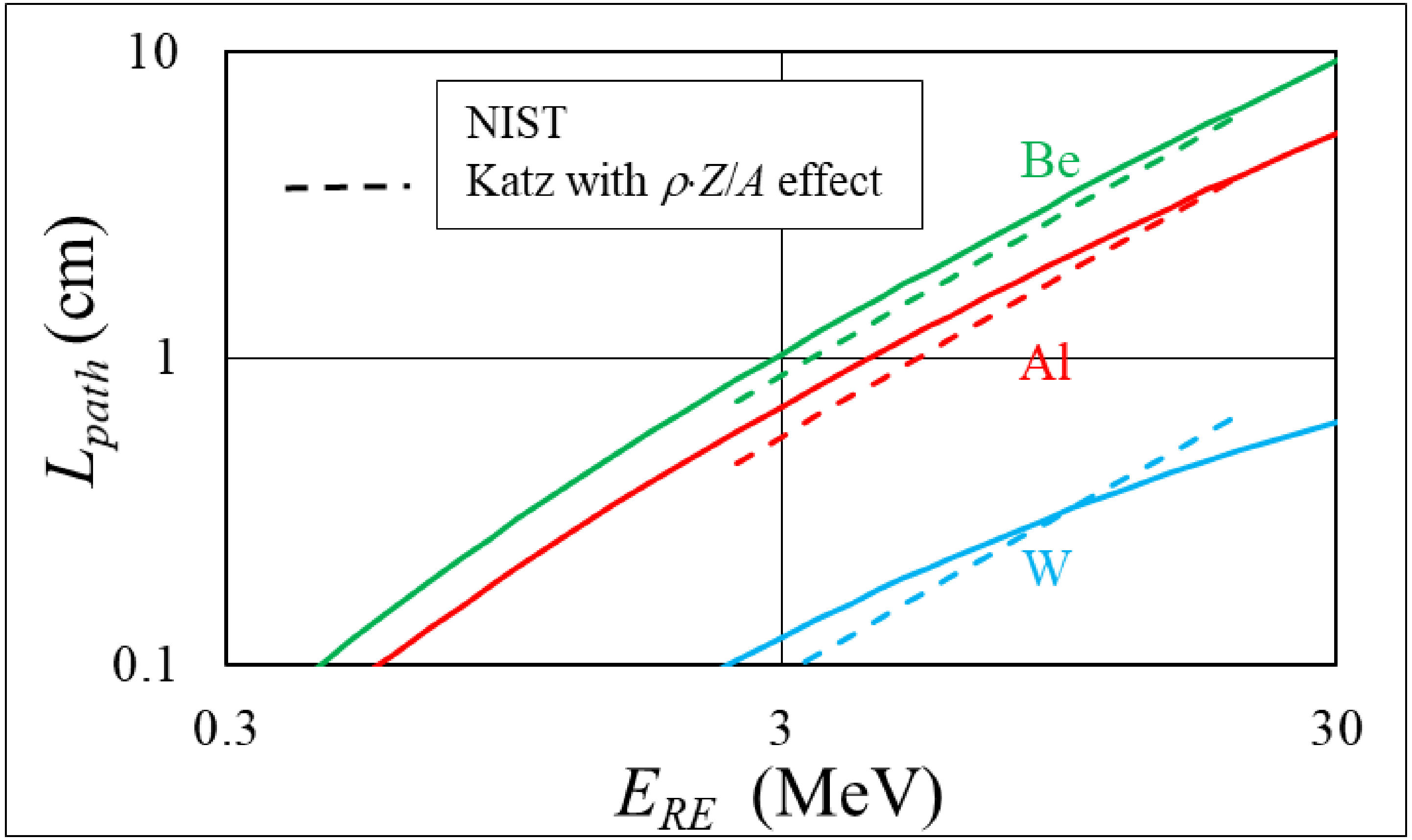
Choice of projectile materials

Material	**Properties**						
	Z a.u.	A a.u.	ρ kg/m^3	Z/A a.u.	$\rho{\cdot}Z/A$ kg/m^3	T_{melt} K	T_{subl} K
Berillium	4	9.012	1848	0.4438	820.2	1551	3243
Boron	5	10.81	2340	0.4627	1083	2348	4138
Carbon	6	12.01	2250	0.4996	1124	4350	4350
Aluminium	13	26.98	2699	0.4818	1300	933	2792
Tungsten	74	183.8	1.94E+04	0.4025	7789	3695	5828
Uranium	92	238.1	1.91E+04	0.3865	7362	1406	4018

- Tungsten has the best physical properties and the shortest length of RE Stopping Power

- The projectile material must have specific physical properties, providing
  - high efficiency of the RE deceleration
  - high melting and evaporation temperatures
  - high combination of properties ($\rho{\cdot}Z/A$) (maximal stopping power)
- Candidates considered (Be, B, C, Al, W, U)

W with 8 mm thickness stops 25 MeV



- Katz's formula (L. Katz, Rev.Mod. Phys. 1952) for RE path length L_{path} approximates the NIST data (M. Berger, NIST 2017) on RE path length versus RE energy E_{RE}
- Tungsten is effective for RE deceleration and absorption

$$L_{path}(E_{RE}, \rho, Z, A) = \frac{4.82 \cdot A \cdot (0.53 \cdot E_{RE}[\mathrm{MeV}] - 0.106)}{\rho[\mathrm{kg} \cdot \mathrm{m}^{-3}] \cdot Z}[\mathrm{m}]$$

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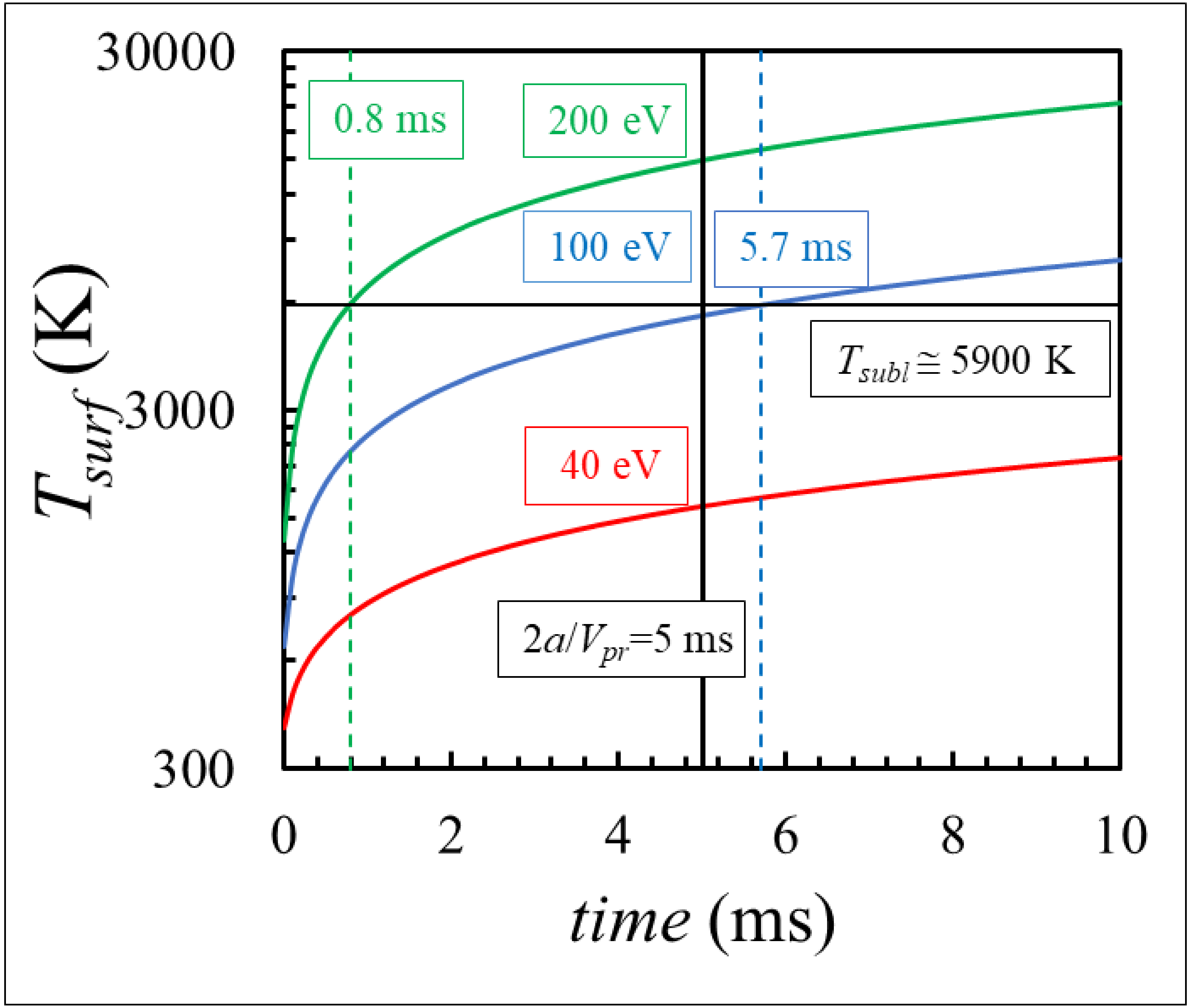
Heating and erosion of W projectile

- Heating by plasma forms different conditions for W ablation
- Projectile temperature:
  - overcomes W sublimation threshold very quickly (<1 ms) at 200 eV
  - reaches it right after the exit projectile from the plasma at 100 eV
  - remains far from the sublimation at 40 eV



Efficiency of seed collecting by projectile

- Toroidal transits of RE on the projectile

$$\tau_{res} = \frac{L}{V} = \frac{80\ mm}{800\ \ m/s} = 0.1\ ms\ \Rightarrow N = \frac{\tau_{res}\cdot c}{2\pi R} = \frac{0.1\ ms\cdot\ 3\cdot 10^{8}\ m/s}{2\pi\cdot 6.2\ m} \approx 770\ transits$$

$$N\cdot D \cong 6.16\ m\ > 2\pi\frac{a}{4}\sqrt{\frac{1+k^2}{2}} \cong 5.34\ m$$

- Isotropic seed current on the projectile

$$F_{seed} = \frac{I_{seed}\cdot S_W}{\pi a^2 k\cdot e} = 3\cdot 10^{17}\frac{1}{sec},\ N_{seed} = \frac{I_{seed}\cdot 2\pi R\pi a^2 k}{\pi a^2 k\cdot e\cdot c} = 4\cdot 10^{14} \Rightarrow \tau_{seed} = \frac{N_{seed}}{F_{seed}} \cong 1.3\ ms$$

$$\frac{N_{seed}(0)}{N_{seed}\left(\frac{2\cdot a}{V}\right)} = e^{\frac{2\cdot a}{V\cdot\tau_{seed}}} = e^{\frac{5\ ms}{1.3\ ms}} \cong 45$$

- Both options evaluate the seed cleaning factor 10^{-1}~10^{-2}

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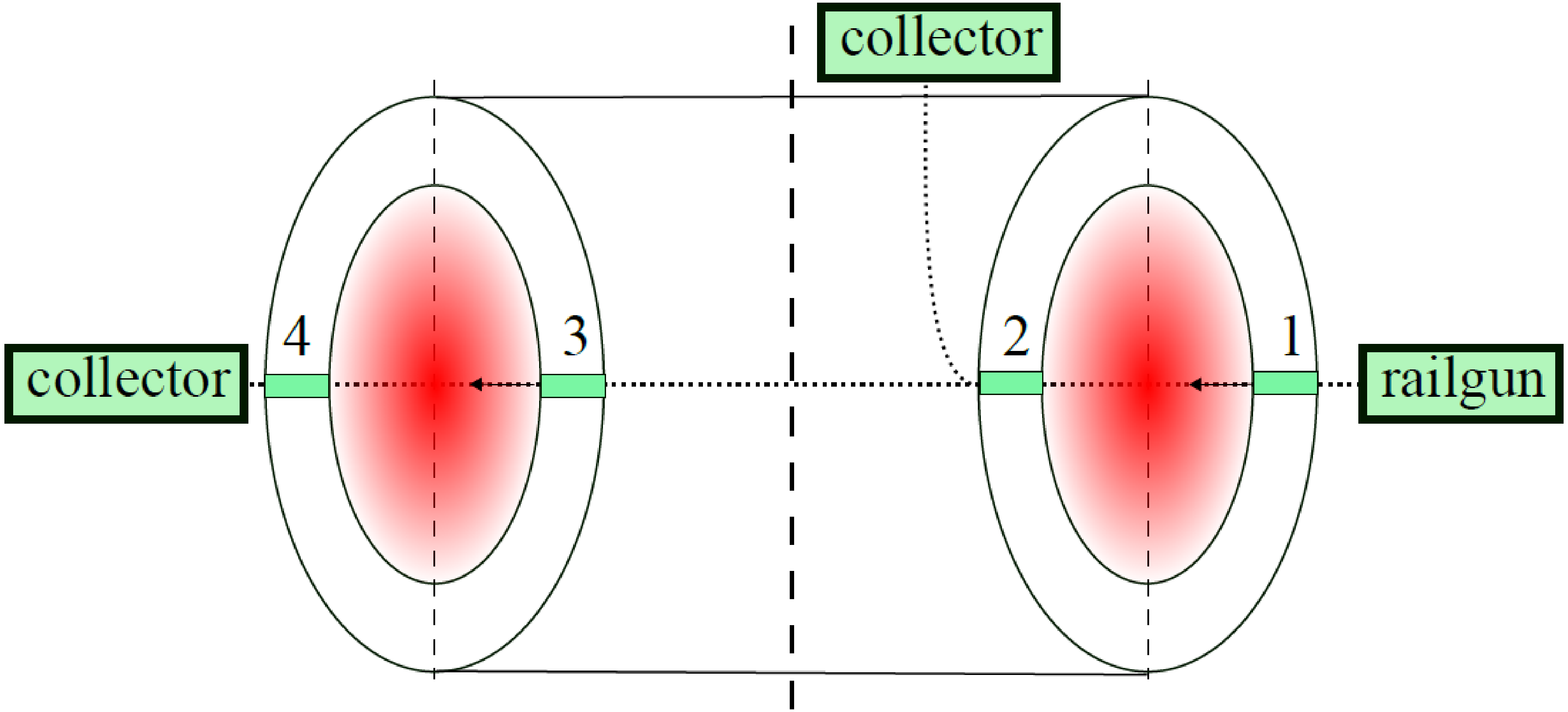
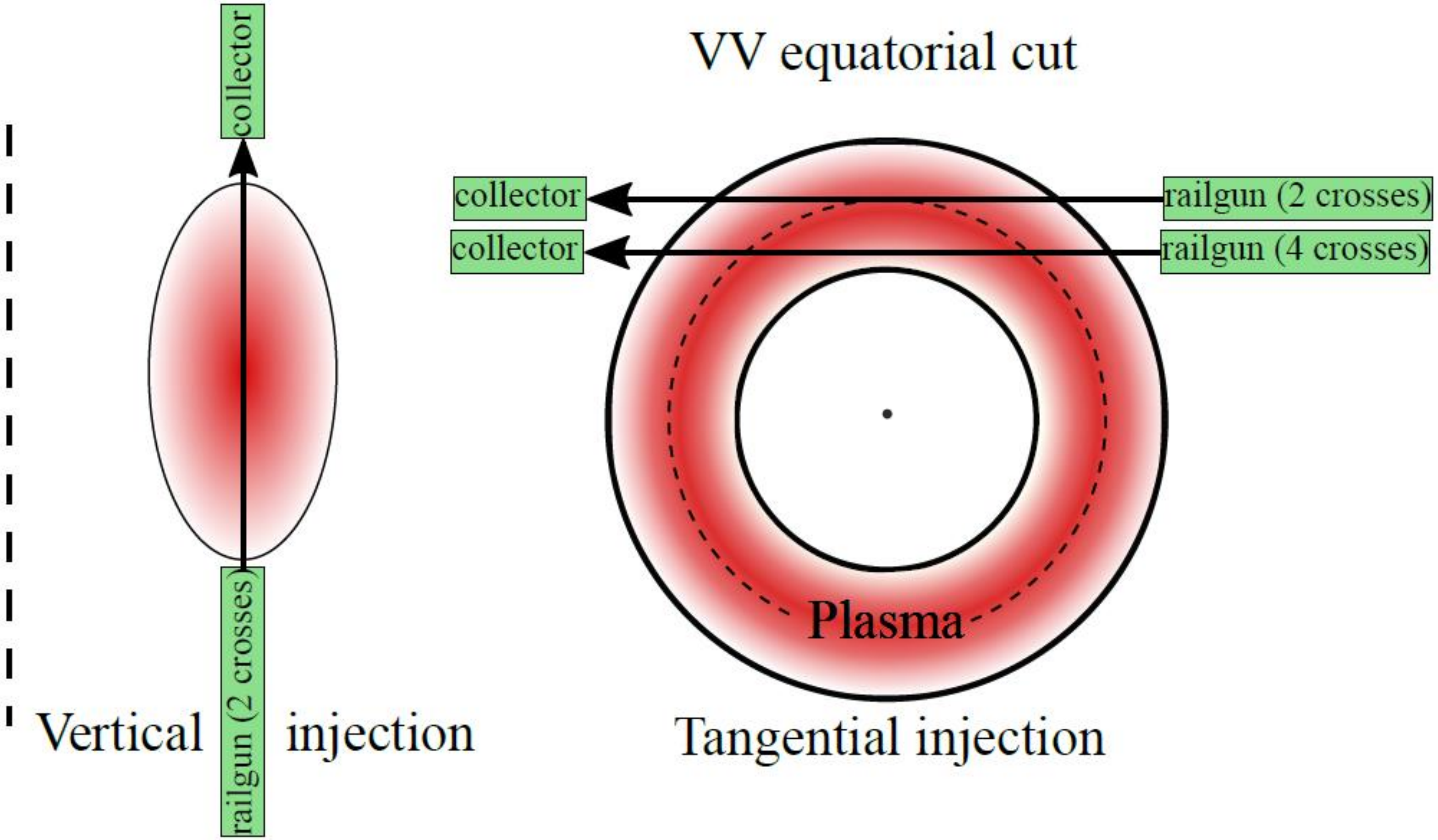
Technical realization on tokamak



- Projectile exists at every magnetic surface 80 mm/800 m/s ~100 microseconds
- Projectile penetrates the plasma cross-section once or twice
- Collecting capability depends on the number of crossing the magnetic surface by the projectile

Projectile injection options



- ➢ Tangential injection is attractive
  - Equatorial region seems optimal
  - 4 crosses of magnetic surfaces
  - Smaller interaction time
  - Simpler technical realization using existing equatorial ports
  - Reasonable interaction time ~15 ms < 20 ms for avalanche e-fold time

- ➢ Vertical injection is possible but it may miss a part of seeds.
  - Disposing in divertor zone is problematic

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➢Advantages of the approach proposed

Direct impact on RE seeds	Reduction of seeds at the start of avalanche
No high pressure gases in V-vessel	Lower loading on P&F, Control and Heating system
Fast reaction time	Pure electro-technique
FW-material	Small impact on FW and divertor
Wide RE energy affected	1-25 MeV effectively terminated
Compactness of railgun	Dimensions are in decimeters range
Neutron environment	Compatible
High RAMI level of injection technology	Research railguns
Reduced n_e, higher T_e after TQ	Lower both convective loadings and electric field
Multiple penetration	4 plasma radius crossings of magnetic surface

➢Problems

Acceleration in vacuum railgun	Fragments of rails and projectile produced by arcs
Collecting technology	Energy of the projectile is in bullet range
Rotational stabilization of projectile	May be required for fine flight stabilization

Further development and experimental testing of the approach are needed!