Alternative SRF materials: Potential, challenges, and most promising directions for R&D

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GARD RF Roadmap Update - SRF

CLASSE
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U.S. DEPARTMENT OF ENERGY

Outline

- Nb: How do fundamental limits constrain R&D aspirations?
- Nb_3Sn: What have we learned from decades of experience?
- Alternative Materials: What has been explored so far?
- Most promising directions: Focusing on 4.2K applications, what pathways exist toward operating conditions inaccessible with Nb or Nb_3Sn?

Fundamental limits of Nb

- BCS Resistance
  - Originates from superconducting gap, which can't* be modified
  - Forces a difficult choice: accept low-Q, or operate at 2K?
    - Low-Q at 4.2K - limited E_{acc} to manage heating
    - 2K operation - huge cryo costs

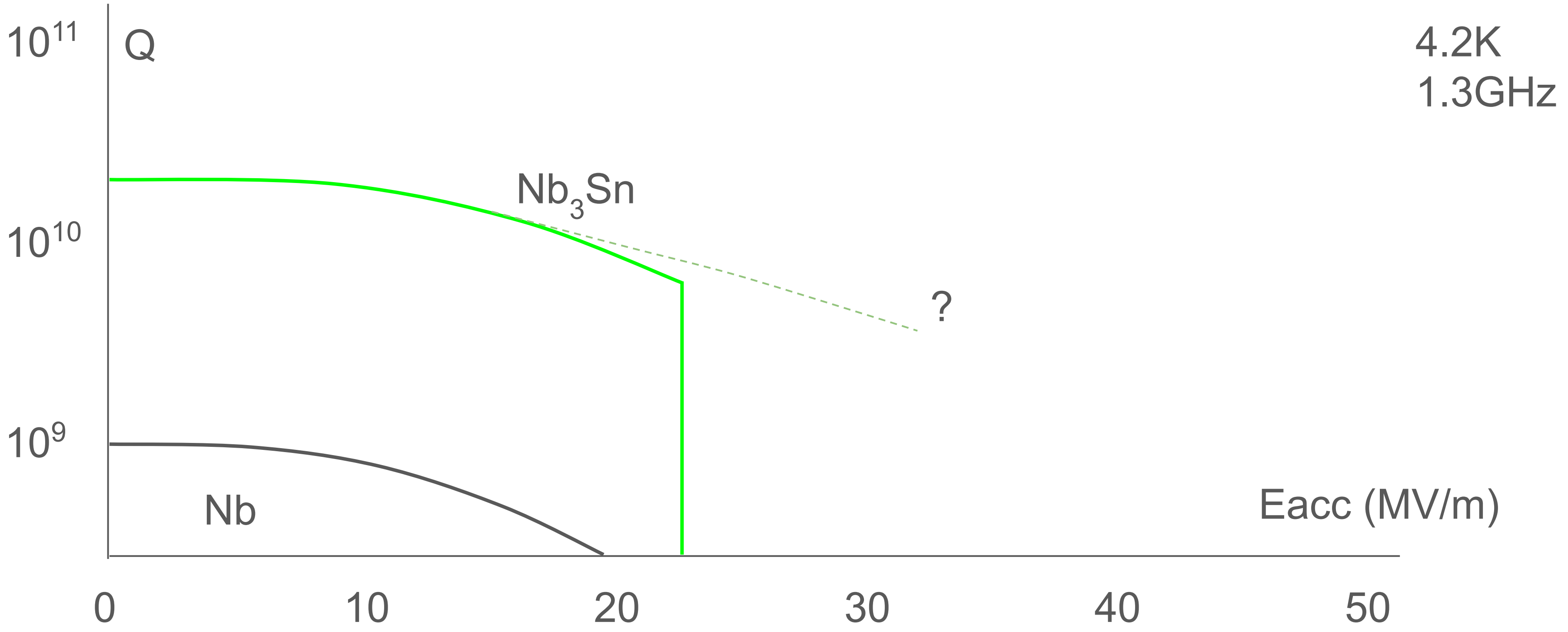
- Superheating field
  - Can't exceed ~50MV/m
    - Limitation especially relevant for pulsed applications
    - Cold copper can go to higher gradients, but only for *very* short pulses

*Anti-Q-slope physics does some interesting things, but there's probably a limit to what we can gain from these effects

Experience from Nb_3Sn

- Lessons learned
  - Getting to high Q, high E_{acc} depends on managing defects, not just max Tc
    - More complicated phase diagram -> more potential defects
      - What low-Tc phases can occur in conjunction with the desired high-Tc phase?
      - How can we minimize low-Tc or normal-conducting phases near the RF surface?
    - Small coherence length -> smaller defects are relevant
      - Grain boundary properties may be important
  - Thermal conductivity is important
    - Compounds vs. pure metals
      - Compounds generally have smaller grains, more point defects
      - Mesoscale defects that are thermally stable on an Nb surface may be thermally unstable on a compound-superconductor surface
    - Larger penetration depth
      - As films get thinner, properties of substrate interface matter more!

Experience from Nb_3Sn



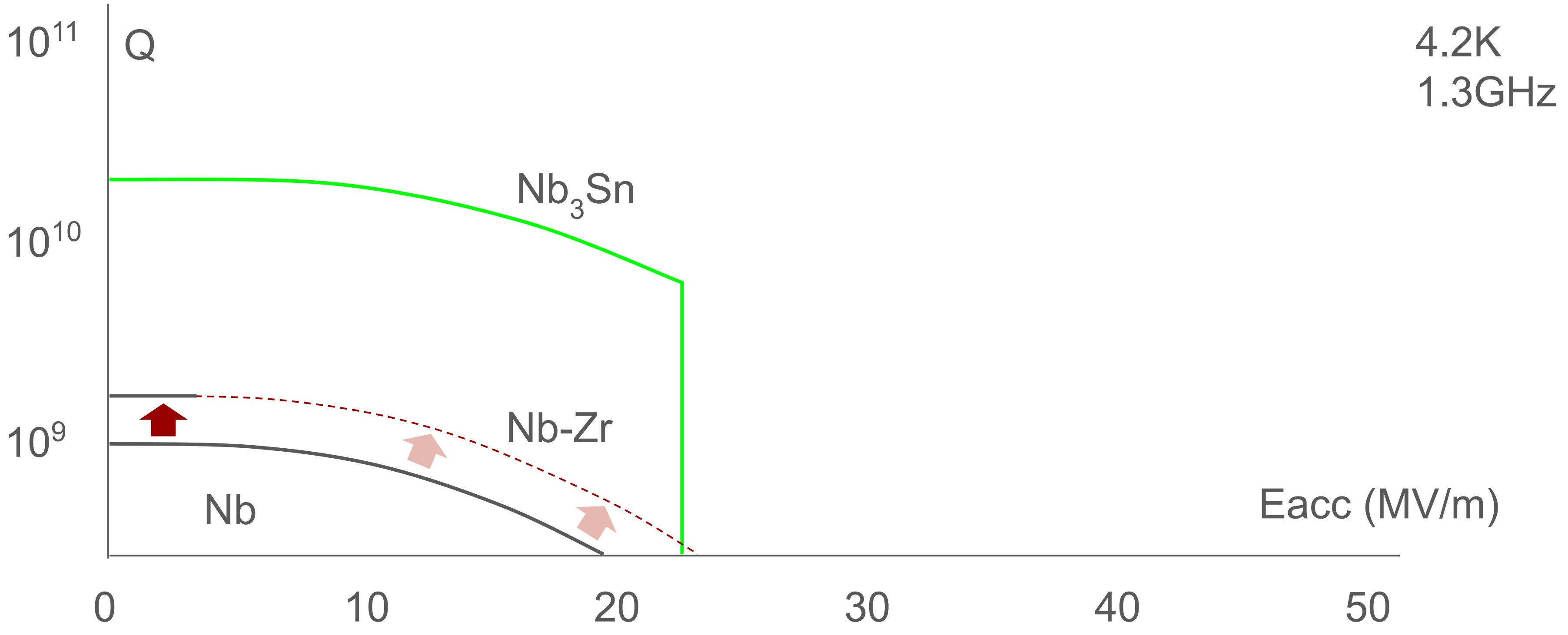
Alternative Materials: Nb-Zr Alloy

- Pros
  - Small “doping effect” perturbation on Nb
    - Longest coherence length, smallest penetration depth of alternative materials
    - Tc increases monotonically from 9.2K for Zr concentrations up to 25%

- Cons
  - Difficult to achieve Tc enhancement of more than 1-2K
  - Zr is more reactive than Nb -> more risk of carbides, hydrides, etc

- Status (Cornell)
  - Demonstrated enhanced Tc
  - Some low-field RF results
  - Q drops rapidly at increasing fields
  - Predominant defects are carbides, which may be responsible for Q-slope

Experience from Nb_3Sn



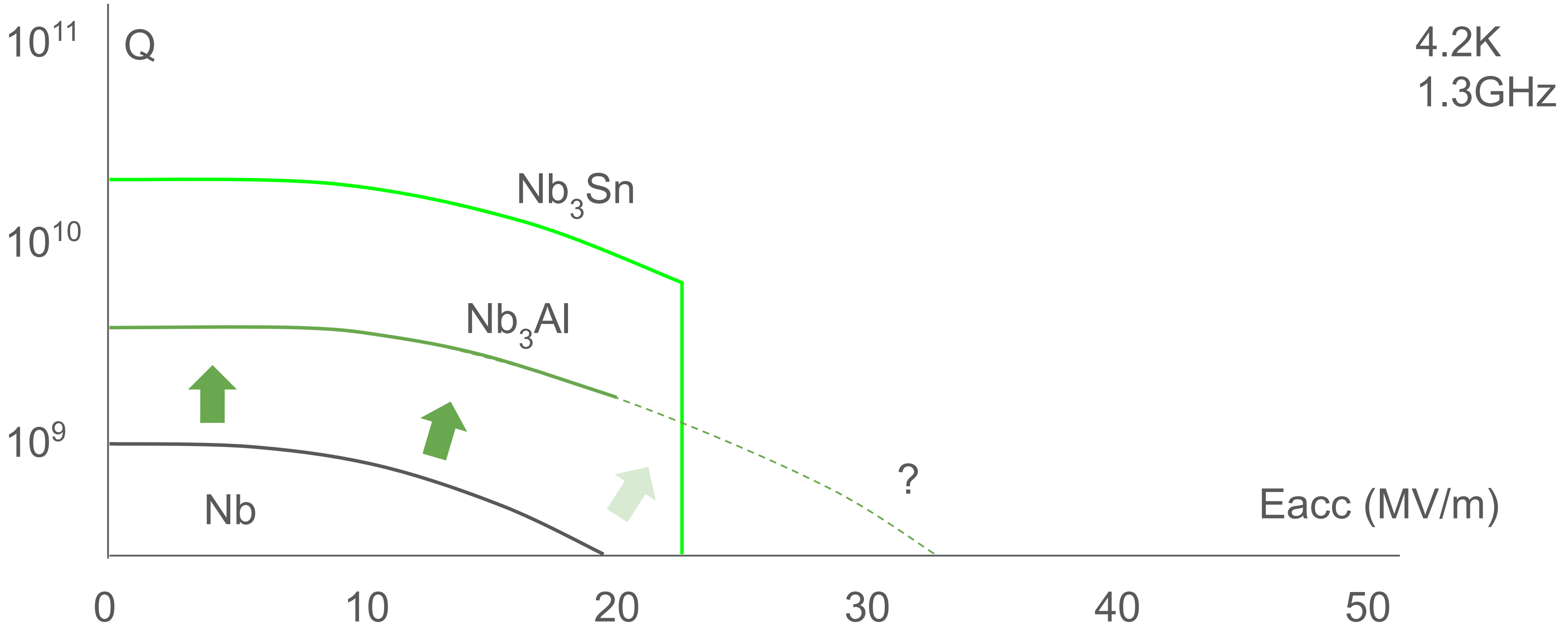
Alternative Materials: Nb_3Al

- Pros
  - Most similar to Nb_3Sn
    - Demonstrated usefulness as a more-robust alternative to Nb_3Sn for wires (DC)
    - Unlike Nb_3Sn, Tc increases monotonically from 9.2K for Al concentrations up to 25%

- Cons
  - Difficult to achieve Tc enhancement of more than 5-6K
  - Al oxidizes more readily than Sn

- Status (Cornell)
  - Demonstrated enhanced Tc
  - Stable operation up to ~80mT
  - Higher residual than Nb_3Sn
  - Predominant defects seem to be oxides, which may be responsible for high residual

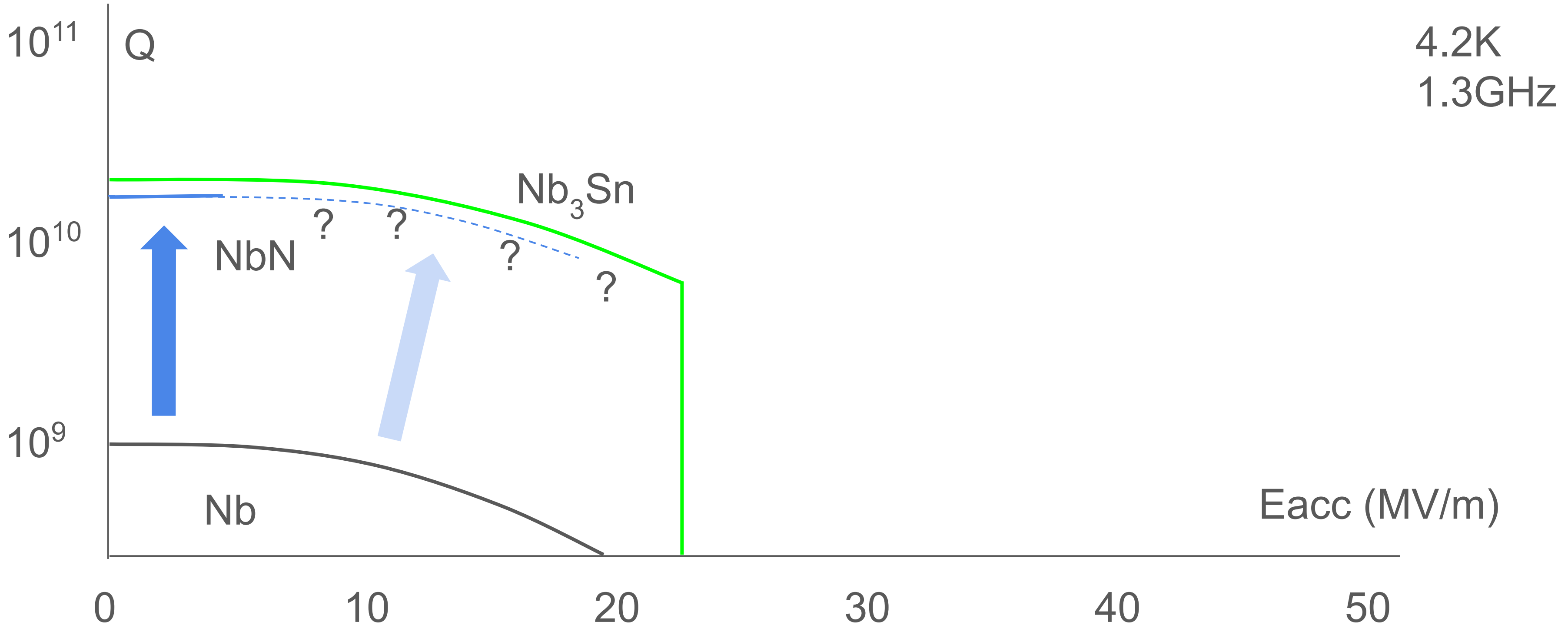
Experience from Nb_3Sn



Alternative Materials: NbN, NbTiN

- Pros
  - Tc similar to Nb_3Sn
    - Potential for major breakthrough if successful
- Cons
  - Low-Tc and normal-conducting phases hard to avoid
  - Hard to avoid side-reaction with oxygen
  - Hard to avoid competing phases at NbTiN-substrate interface
- Status (Saclay, JLab)
  - Demonstrated enhanced Tc
  - Some low-field RF results
  - Q drops rapidly at increasing fields
  - Defects include oxygen-rich phases and competing nitride phases

Experience from Nb_3Sn

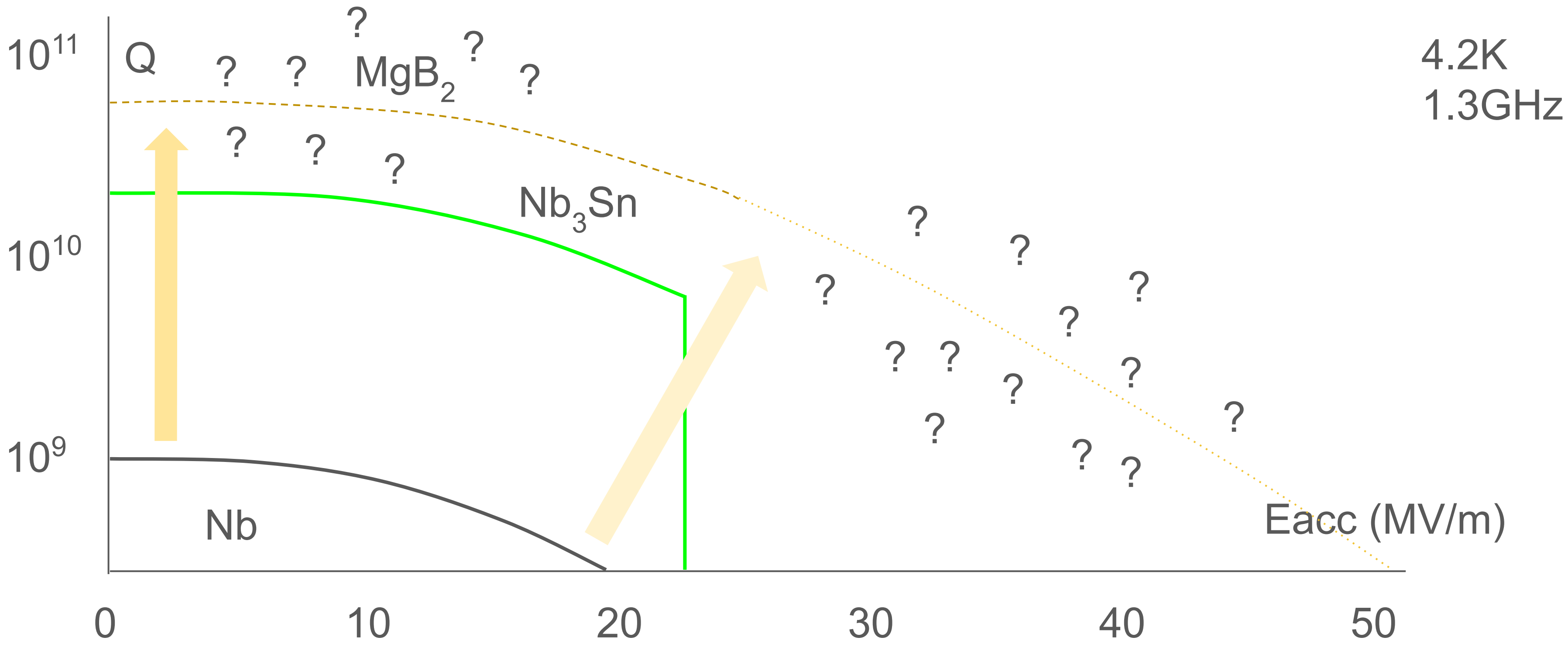


Alternative Materials: MgB_2

- Pros
  - Tc much higher than Nb_3Sn
    - Potential for revolutionary impact if successful
  - Potential for higher fields, higher-T operation than Nb_3Sn for low-field or pulsed operation

- Cons
  - Theoretical questions: unconventional/anisotropic superconductor
  - Vulnerable to side-reactions with C, O
  - Sensitive to moisture: likely requires capping layer
- Status (JLab/Argonne/Temple)
  - Demonstrated greatly enhanced Tc (JLab/Argonne/Temple)
  - Very limited RF results
  - Defects include oxygen and carbon-rich phases, surface degradation

Experience from Nb_3Sn



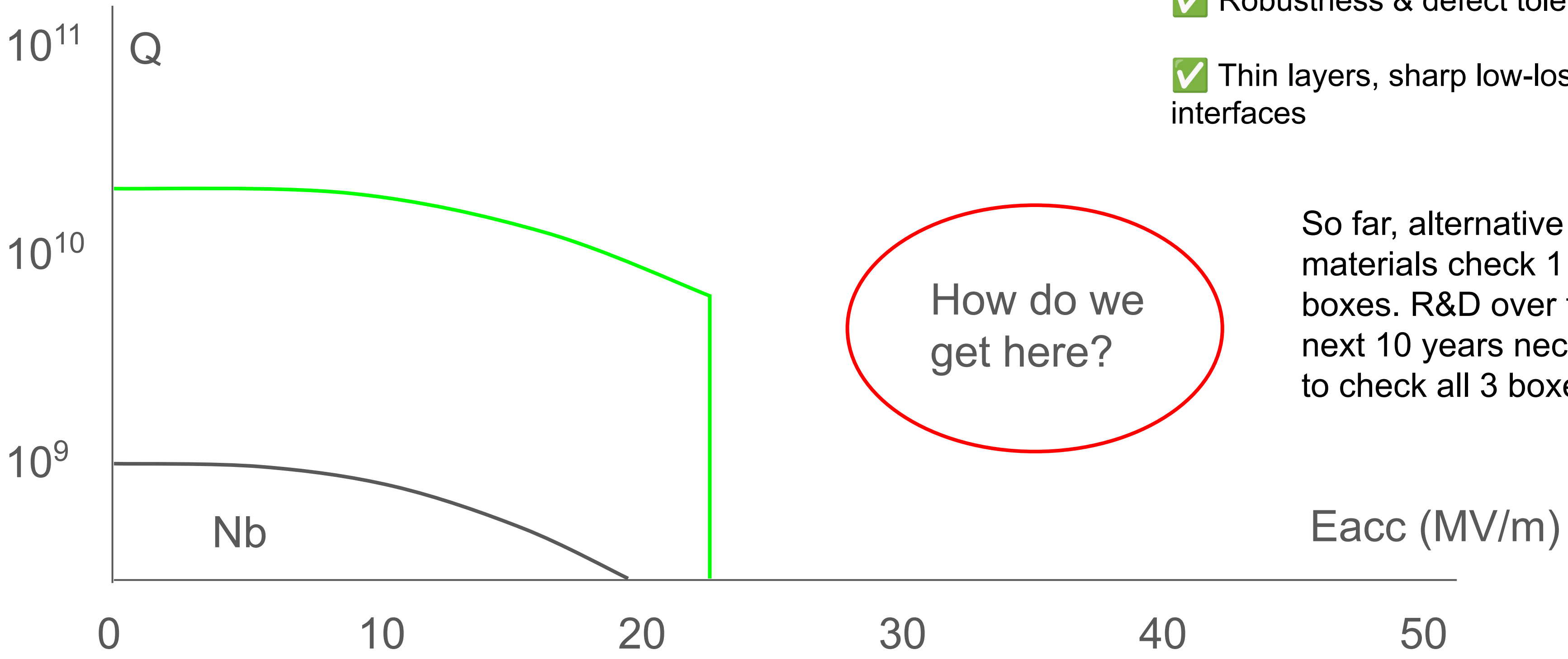
Most Promising Directions (CW)

- High Tc: Easy
- High Q at low fields: Easy(ish)
- Minimizing defect concentration: Hard
  - Took decades of R&D for Nb, Nb_3Sn to perfect this and minimize residual resistance
- Complete elimination of defects: Impossible!
  - On cavity scale, there will *always* be a nonzero number of nanoscale (~10nm+) defects

- R&D efforts very productive toward minimizing defect concentration

- Focus on systems with potential to tolerate *some* defects at high fields
  - Thin layers necessary!
  - Low-loss interface with Nb substrate (and/or barrier layer) necessary!

Experience from Nb_3Sn



✅ High Tc comparable to Nb_3Sn

✅ Robustness & defect tolerance

✅ Thin layers, sharp low-loss interfaces

So far, alternative materials check 1 or 2 boxes. R&D over the next 10 years necessary to check all 3 boxes!

Most Promising Directions (Pulsed)

- Recent results show Nb_3Sn has potential for ~100MV/m pulsed operation
- Can we verify the potential of MgB2 to surpass this value?
- Could even higher Tc superconductors in the vortex state be useful?