# Effects of Fast Neutron Irradiation on State-of-the-Art $Nb_3Sn$ Wires

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# Outline

# Acknowledgments

CERN has been an important partner throughout the past four years and funded the $Nb_3Sn$ irradiation study discussed in this presentation.

Rainer Prokopec provided the presented data on insulating materials.

# Outline

# Technological objective

- Collaboration with CERN
- Examined $Nb_3Sn$ wires are candidates for LHC upgrade
- Replacing the Nb-Ti inner triplets (quadrupole magnet assemblies for focusing) with $Nb_3Sn$ can improve the luminosity
- Intense and complex radiation field near the interaction points (neutrons, protons, pions, . . . )
- What is the life expectancy of a $Nb_3Sn$ inner triplet magnet under these conditions?

# $Nb_3Sn$ wire samples

## Five types of multifilamentary wires

- Ta alloyed RRP

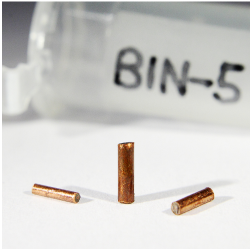
  0.8 mm, 54 sub-elements
- Ti alloyed RRP

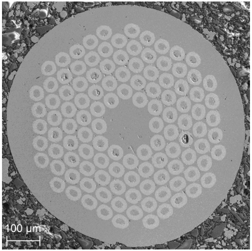
  0.8 mm, 108 sub-elements
- Binary IT

  1.25 mm, 246 sub-elements
- Ta alloyed PIT

  1.0 mm, 192 sub-elements
- Ta alloyed PIT

  0.7 mm, 114 sub-elements



# Expectations

## Effects of radiation damage on $Nb_3Sn$

- Critical temperature $T_c$ decreases

  Explanation: Disorder leads to a reduction of the electronic density of states
- Upper critical field $B_{c2}$ increases

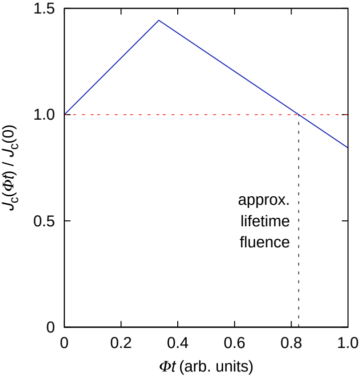
  Explanation: Mean free path of electrons decreases, thus normal state resistivity increases

  $\kappa = \kappa_0 + C\sqrt{\gamma}\,\rho_n, \qquad B_{c2} = \kappa\sqrt{2}\,B_c$
- Critical current density $J_c$ increases up to a certain fluence, then decreases again

  Explanation: Sum of the above effects

# Expectations

## Behavior of $J_c(\Phi t)$




- $J_c$ increases at low fluences
- Usually explained with an increase in $B_{c2}$
- Some reports on changes in flux pinning due to radiation induced pinning centers[1,2]
- $T_c$ degradation dominates at high fluences

[1] M. W. Guinan et al.: *Informal Report, LLNL*, 1984

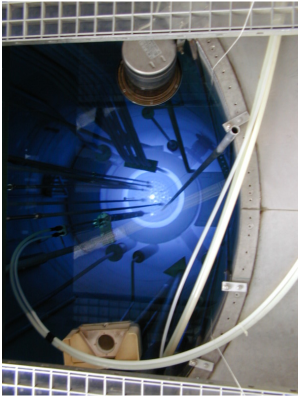
[2] T. Okada et al.: *J. Appl. Phys.* **63** (9), pp. 4580–4585, 1988

# Outline

## 2 Experimental

- Irradiation
- SQUID magnetometry
- Transport measurements
- $B_{c2}(T)$ measurements

# Irradiation



- TRIGA Mark-II reactor in Vienna
- Fast neutron flux density $\Phi_f = 4.1 \cdot 10^{16}\,\mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$ $(E > 0.1\,\mathrm{MeV})$
- Sequential irradiation of short wire samples for magnetometry
- Radioactivity reduced by 2 orders of magnitude relative to transport samples
- Fluence step size: $\sim 2 \cdot 10^{21}\,\mathrm{m}^{-2}$
- Ni samples included for fluence monitoring (reaction threshold $\approx 1\,\mathrm{MeV}$ $\rightarrow$ fast neutrons only)

# SQUID magnetometry

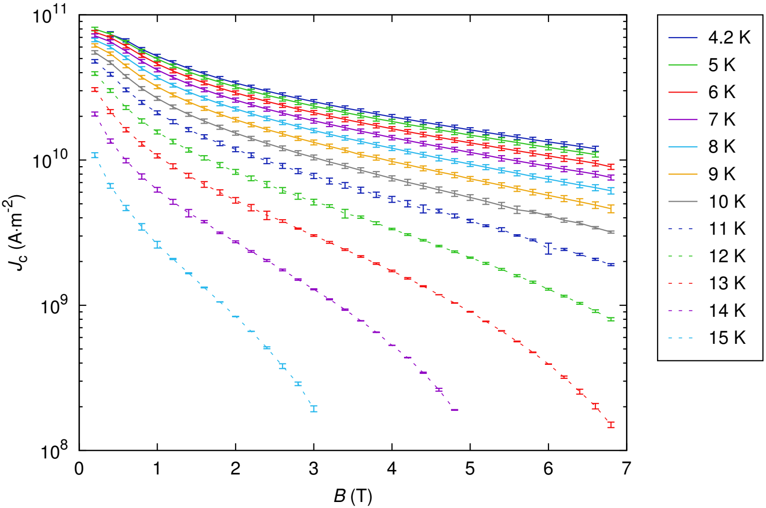
## $J_c$ from magnetization loops

- Quantum Design MPMS XL
  max. field: 7 T
- Irreversible magnetic moment $m_{irr}(B,T)$ obtained from magnetization loops in the temperature range $4.2 - 15$ K
- $J_c(B)$ evaluated at each temperature using $m_{irr}$ and sub-element geometry[3]
- $T_c$ obtained from AC susceptibility measurements

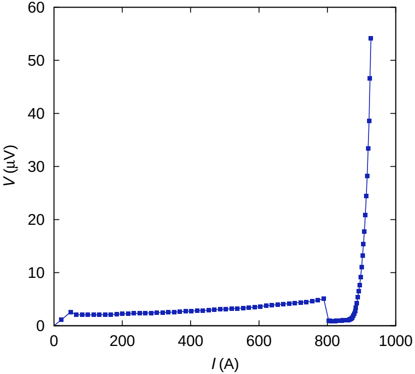
[3] T. Baumgartner et al.: *IEEE Trans. Appl. Supercond.* **22** (3), 6000604, 2012

# SQUID magnetometry

## $J_c$ from magnetization loops



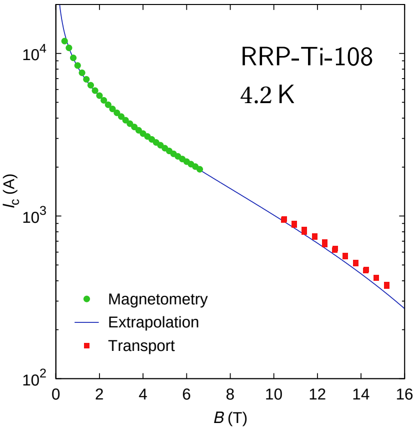
# Transport measurements




- $\sim 0.5$ m of wire on Ti-6Al-4V barrel (mini VAMAS, Ø 23 mm)
- Measurements performed in applied fields of up to 15 T
- Maximum current of 1000 A in liquid helium

# Transport measurements

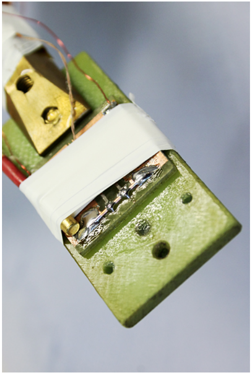
## Comparison with magnetometry results




- Good agreement between magnetometry results and transport critical current measurements
- Less than 15% deviation between extrapolated magnetometry data and transport results

# $B_{c2}(T)$ measurements

- $B_{c2}(T)$ obtained from resistivity measurements (temperature sweep at constant field)
- Direct measurements possible for $T \gtrsim T_c/2$ (15 T max. field)
- Extrapolation to lower temperatures
- Measurements performed on 1 unirradiated sample of each wire type, and 3 irradiated samples



# Outline

## 3 Results

- Critical temperature
- Critical current density
- Upper critical field
- Volume pinning force
- Two-mechanism model

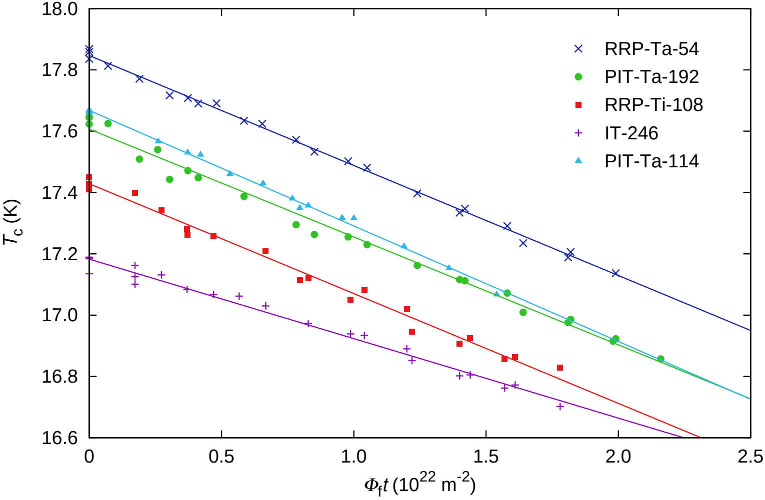
# Critical temperature

- Small $T_c$ degradation within the examined fluence range ($\sim 2\%$ at $\Phi_f t = 10^{22}\,\mathrm{m}^{-2}$)
- Can be described with a linear relationship

  $$T_c(\Phi_f t) = T_c(0) - k_T \Phi_f t$$

- Slope $k_T$ is smaller by about $1/3$ in the binary wire, probably due to a higher initial degree of order

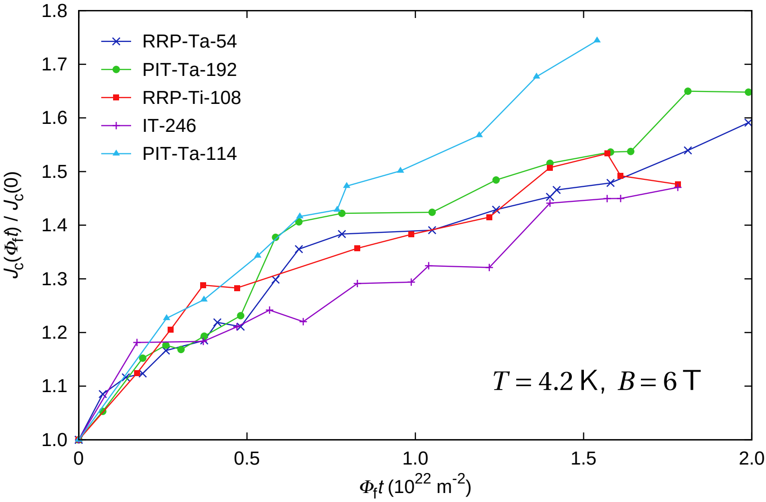
# Critical temperature



# Critical current density

- $J_c(T, B)$ obtained from magnetometry data after each irradiation step
- Data used to assess $J_c(\Phi_f\, t)/J_c(0)$
- 7 T max. applied field ⇒ evaluation at lower field values
- Significant increase found in all examined wire types

# Critical current density

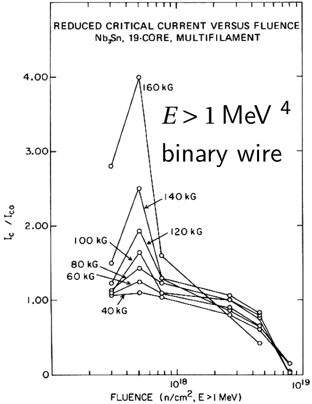


# Critical current density

## “Old” irradiation studies

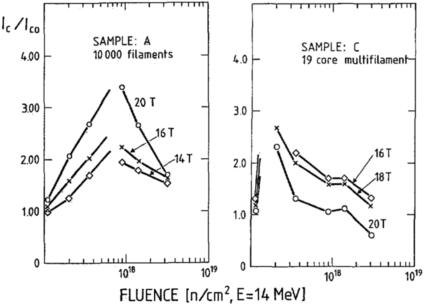
$E > 1$ MeV [4]

binary wire




$E = 14$ MeV [5]

binary wire | Ti alloyed wire




[4] C. L. Snead Jr., D. M. Parkin.: *Nucl. Technol.* **29** (3), pp. 264–267, 1976

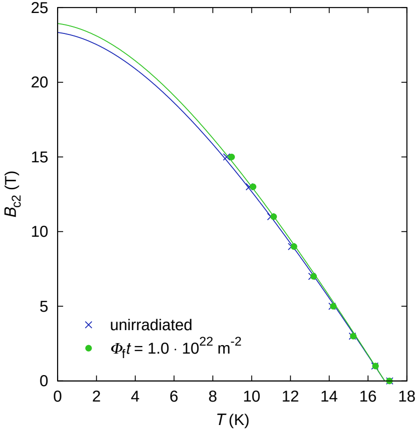
[5] F. Weiss et al.: *IEEE Trans. Mag.* **23** (2), pp. 976–979, 1987

# Upper critical field

- Data obtained at $T \gtrsim T_c/2$ ($15\,\mathrm{T}$ max. field)
- Extrapolation based on the dirty limit WHH function[6]
- Unexpectedly low irradiation induced increase of $B_{c2}$ found in the 3 examined samples

[6] E. Helfand, N. R. Werthamer: *Phys. Rev.* **147** (1), pp. 288–294, 1966

# Upper critical field



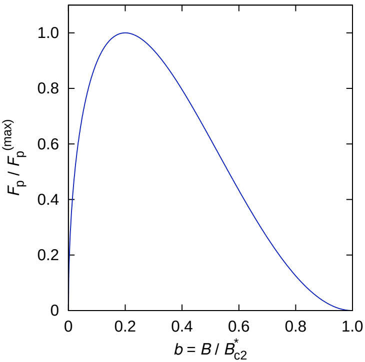

- Binary wire IT-246
- $\Phi_\mathrm{f}\, t = 1.0 \cdot 10^{22}\ \mathrm{m}^{-2}$
- $B_{c2}(T=0)$ increases by $\sim 3\%$ relative to the unirradiated state
- Similar behavior found in RRP-Ti-108 and PIT-Ta-114

# What is going on?

- $J_c$ exhibits a considerable increase as a result of irradiation
- $B_{c2}$ increases only slightly
- Changes in the flux pinning behavior must be responsible for the large $J_c$ increase

# Volume pinning force

## The concept of scaling




- In $Nb_3Sn$ the volume pinning force $F_p = |\vec{J}_c \times \vec{B}|$ exhibits scaling behavior
- Plotting the normalized volume pinning force vs. the reduced field yields the same curve at different temperatures
- $F_p(b) \propto f(b) = b^p (1-b)^q$
- $p = 0.5,\ q = 2$ for pure grain boundary pinning[7]

[7] D. Dew-Hughes: *Phil. Mag.* **30** (2), pp. 293–305, 1974

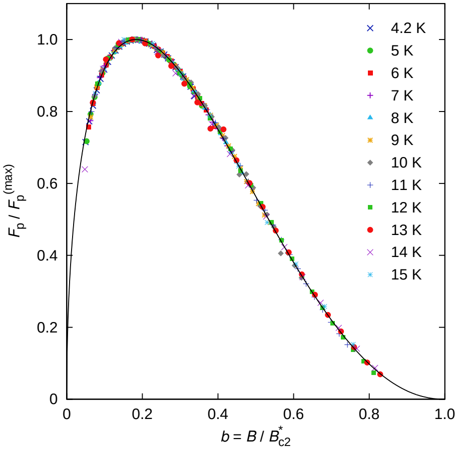
# Volume pinning force

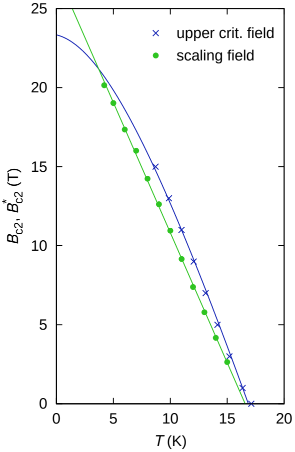
## Analysis of unirradiated samples

- $F_\mathrm{p} = J_\mathrm{c} B$ from magnetometry data normalized at each temperature
- $f(b) = C b^p (1-b)^q$ used as a fit function
- Algorithm finds $p$ and $q$ which minimize the global error (all temperatures included)

# Volume pinning force

## Analysis of unirradiated samples




Binary wire IT-246, unirradiated, $p = 0.49$, $q = 2.16$

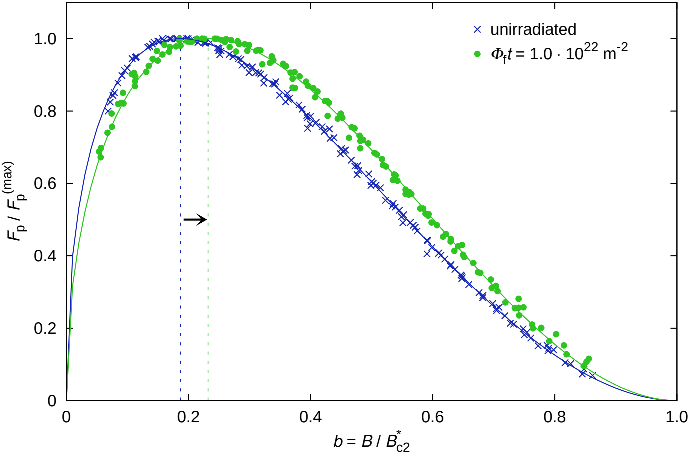
# Volume pinning force

## Analysis of irradiated samples

- Optimal $p$ and $q$ change with fluence
- Peak in the pinning function at $b_{\max} = p/(p+q)$ is shifted to higher values
- Scaling field values changed only slightly, in agreement with the $B_{c2}(T)$ measurements

# Volume pinning force

## Analysis of irradiated samples




Binary wire IT-246, before and after irradiation

# Two-mechanism model

- Observed behavior is inconsistent with grain boundary pinning $(p = 0.5,\ q = 2)$
- Contribution of a second mechanism was investigated [8,9]
  $$f(b) = \alpha\, b^{p_1} (1-b)^{q_1} + \beta\, b^{p_2} (1-b)^{q_2}\,, \quad \alpha + \beta = 1$$
- Second mechanism was identified as pinning by core interaction between vortices and normal conducting point-like structures $(p_2 = 1,\ q_2 = 2)$[7]
- Point-pinning contribution $\beta$ was evaluated as a function of fluence for all samples

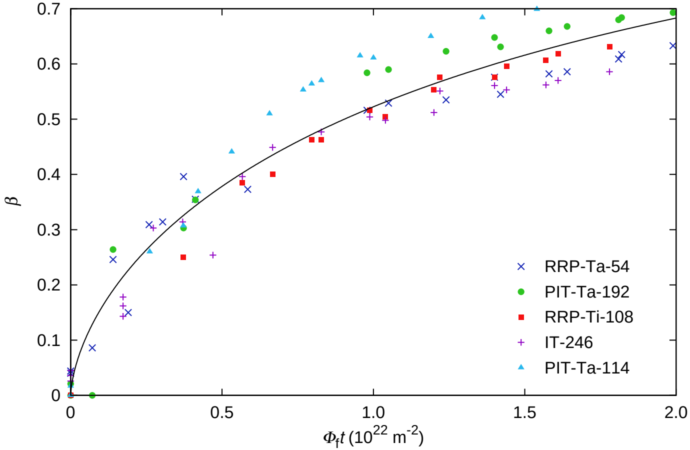
[8] H. Küpfer et al.: *J. Appl. Phys.* **51** (2), pp. 1121–1126, 1980

[9] P. Maier, E. Seibt.: *Appl. Phys. Lett.* **39** (2), pp. 175–177, 1981

[7] D. Dew-Hughes: *Phil. Mag.* **30** (2), pp. 293–305, 1974

# Two-mechanism model

## Point-pinning contribution vs. fluence




$$f(b) = \alpha\, b^{p_1} (1-b)^{q_1} + \beta\, b^{p_2} (1-b)^{q_2}, \quad p_2 = 1,\ q_2 = 2$$

# Outline

## 4 Conclusions

- Summary
- Outlook

# Summary

- Five $Nb_3Sn$ wire types were subjected to sequential fast neutron irradiation up to $\Phi_f t = 2 \cdot 10^{22}\,m^{-2}$
- They appear to be more resilient to radiation than wires used in previous studies
- $T_c$ as a function of fluence shows a linear degradation
- $B_{c2}$ increases only slightly with fluence ⇒ large $J_c$ increase is due to changes in the volume pinning force
- Changes in the pinning behavior can be described with a fluence dependent point-pinning contribution using a two-mechanism model[10]

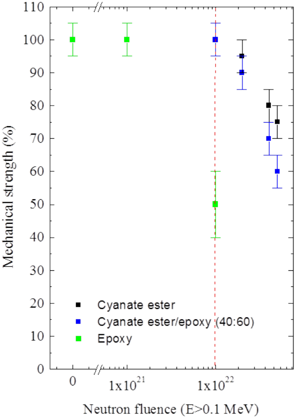
[10] T. Baumgartner et al.: *Supercond. Sci. Technol.* **27** (1), 015005, 2014

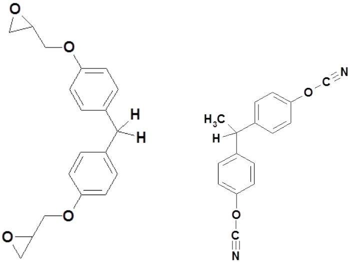
# Outlook

- Maximum in $J_c(\Phi_f t)$ is relevant to life time estimation and comparison with other irradiation studies (different wires or different particles) ⇒ irradiation program will be continued
- Transport samples will be irradiated for comparison with magnetometry results and to obtain more high-field data
- Magnetometry measurements will be attempted in fields of up to $15\,T$ using our self-built vibrating coil magnetometer
- Our group is also active in the field of insulating materials

# Excursus: insulating materials

## Radiation effects on resins



epoxy cyanate ester

- Similar impregnation process
- Costs for CE higher by a factor of up to 10
- CE can be mixed with epoxy to reduce costs

# Excursus: insulating materials

## Qualification of resins for the ITER TF coils[11]

*Demands for ITER:*

- Mixing ratio:
  $40\%$ CE / $60\%$ epoxy
- Long pot life:
  viscosity $< 100\,\mathrm{mPa\cdot s}$
  for more than $100\,\mathrm{h}$
- Maximum curing temperature:
  $160 \pm 10$°C for 24 h

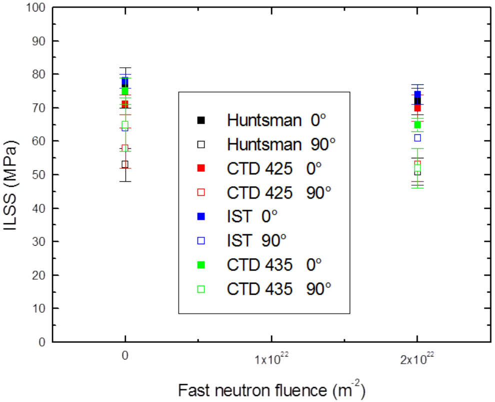
*3 suppliers, 4 resins:*

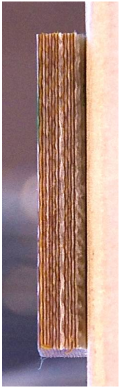
- Huntsman, Switzerland:
  LMB 6653 / LMB 6622-4
- Composite Technologies Development, USA:
  CTD-425
  CTD-435
- Industrial Summit Technology, Japan:
  IST

[11] K. Humer et al.: *Fusion Eng. Des.*, **88** (5), pp. 350–360, 2013

# Excursus: insulating materials

## Mechanical properties before and after irradiation



ITER design fluence: $1.0 \cdot 10^{22}\,\text{m}^{-2}$ ($E > 0.1$ MeV)

# Excursus: insulating materials

## Material tests for CERN

- S-glass fiber reinforced composites
- 3 different types of epoxy resins
- Several irradiations up to a total absorbed dose of 50 MGy
- Glass fibers are wrapped before $Nb_3Sn$ heat treatment
- Possible surface degradation or contamination
- Effects on the resin / fiber / conductor interfaces must be examined

# Thank you for your attention.

*If we knew what it was we were doing,*
*it would not be called research, would it?*

Albert Einstein

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