# Review of WAMSDO 2011workshop: Superconductors in LHC Upgrade (HiLumi LHC)


**René Flükiger, Gijs DeRijk**

**CERN**
**TE- SC-SCD**

# Scope of the meeting

- Attempts to characterize the HL-LHC radiation environment for the cables (superconductor and insulator) of the most exposed magnets: **the quadrupoles of the final focus triplet**
- These quadrupoles are most exposed to the collision debris, for a target integrated luminosity of **3'000 $fb^{-1}$ at 14 TeV** center-of-mass energy

# WAMSDO Workshop Program

## I. Irradiation of superconductors

* *$Nb_3Sn$, Coated Conductors (magnets)*
* *$MgB_2$ (LINK current leads)*
* *Superconducting and mechanical properties*

## II. Calculations

* *Modern models/codes including Coulomb elastic scattering, nuclear interactions and DPA model parameters*
* *FLUKA an MARS results on energy deposition and DPA values*

## III. Irradiation of Insulators

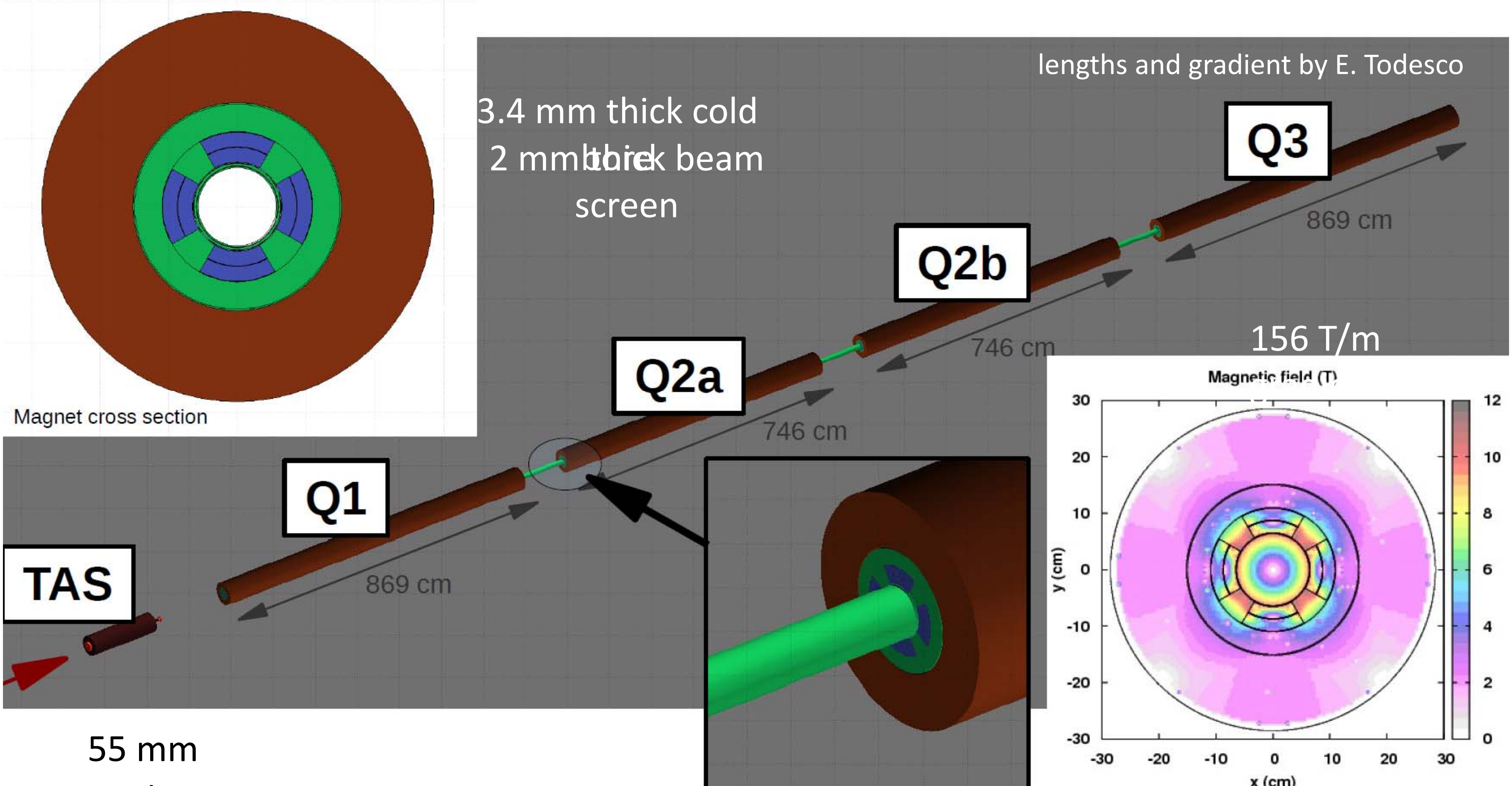
* *Radiation effects on fusion magnet components*
* *Mechanical properties of insulators (including EuCard data)*

*will be discussed by M. Eisterer*

# HL-LHC: The basis for model calculations

Francesco Cerutti, CERN

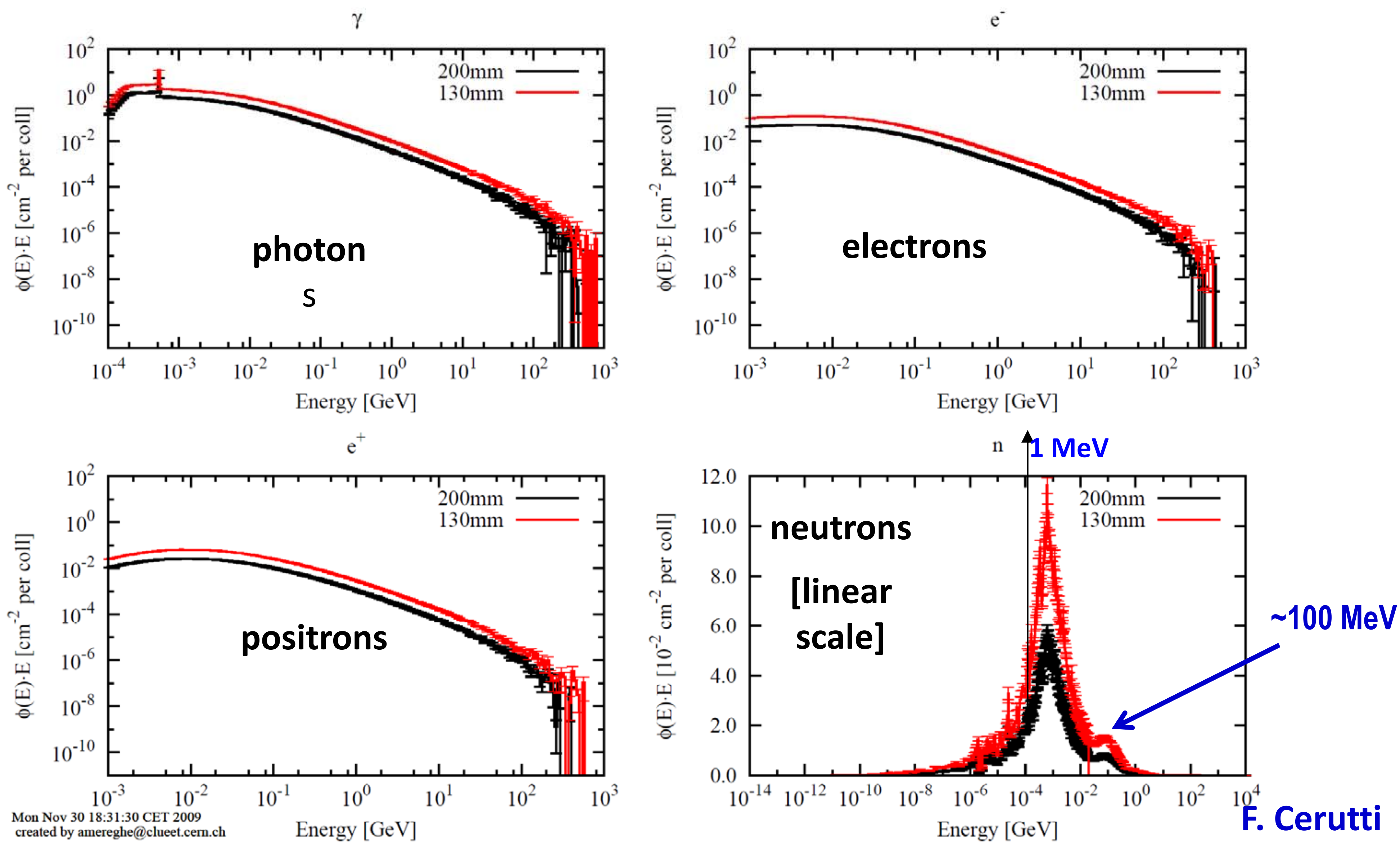
**130 mm aperture** **$Nb_3Sn$ cables (implemented an average coil material including copper and insulator)**




55 mm aperture

# Particle spectra in the coils

Particle spectra in the inner coil (upper coil) in Q2a (at peak location, i.e. 15 cm from magnet beginning)



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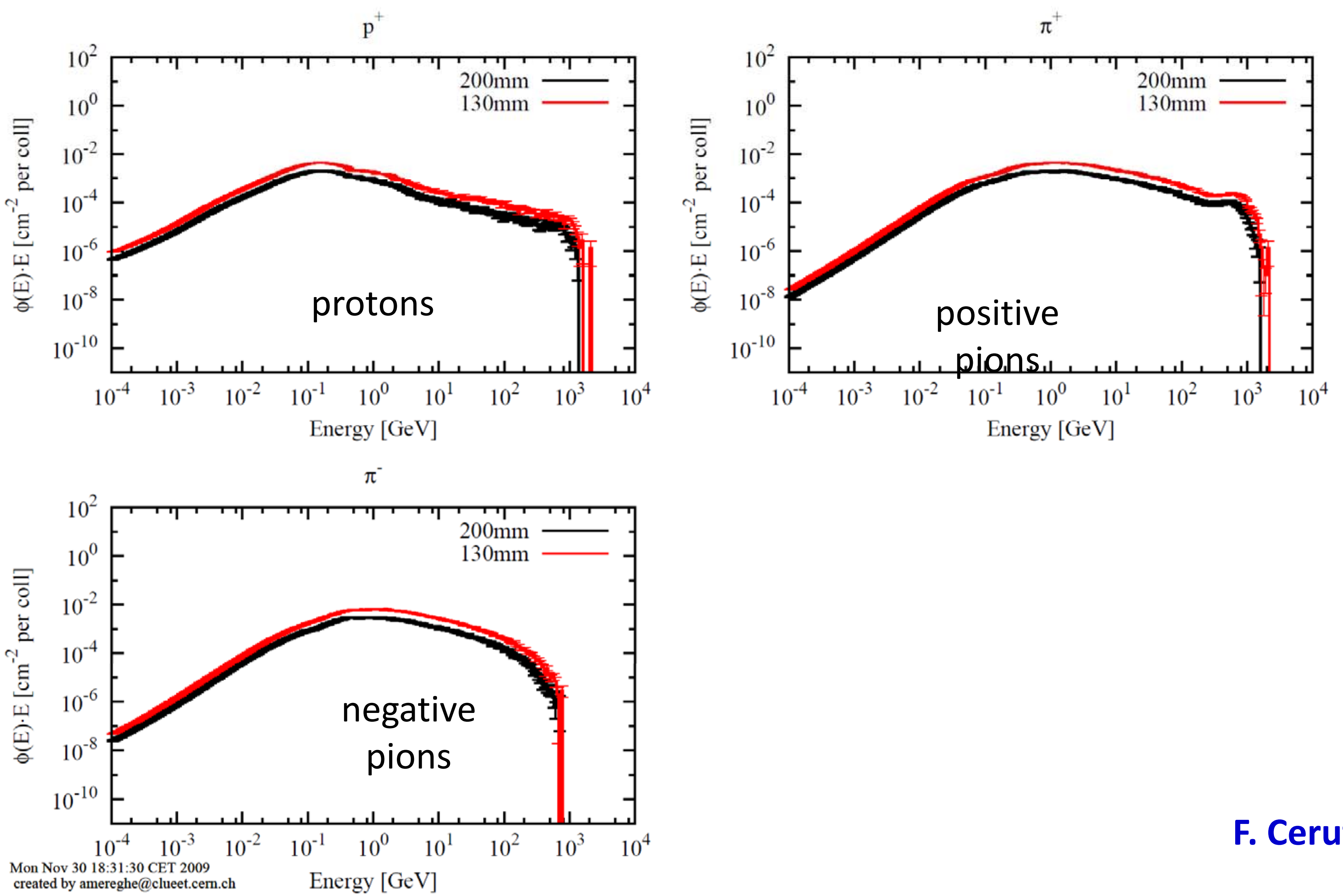
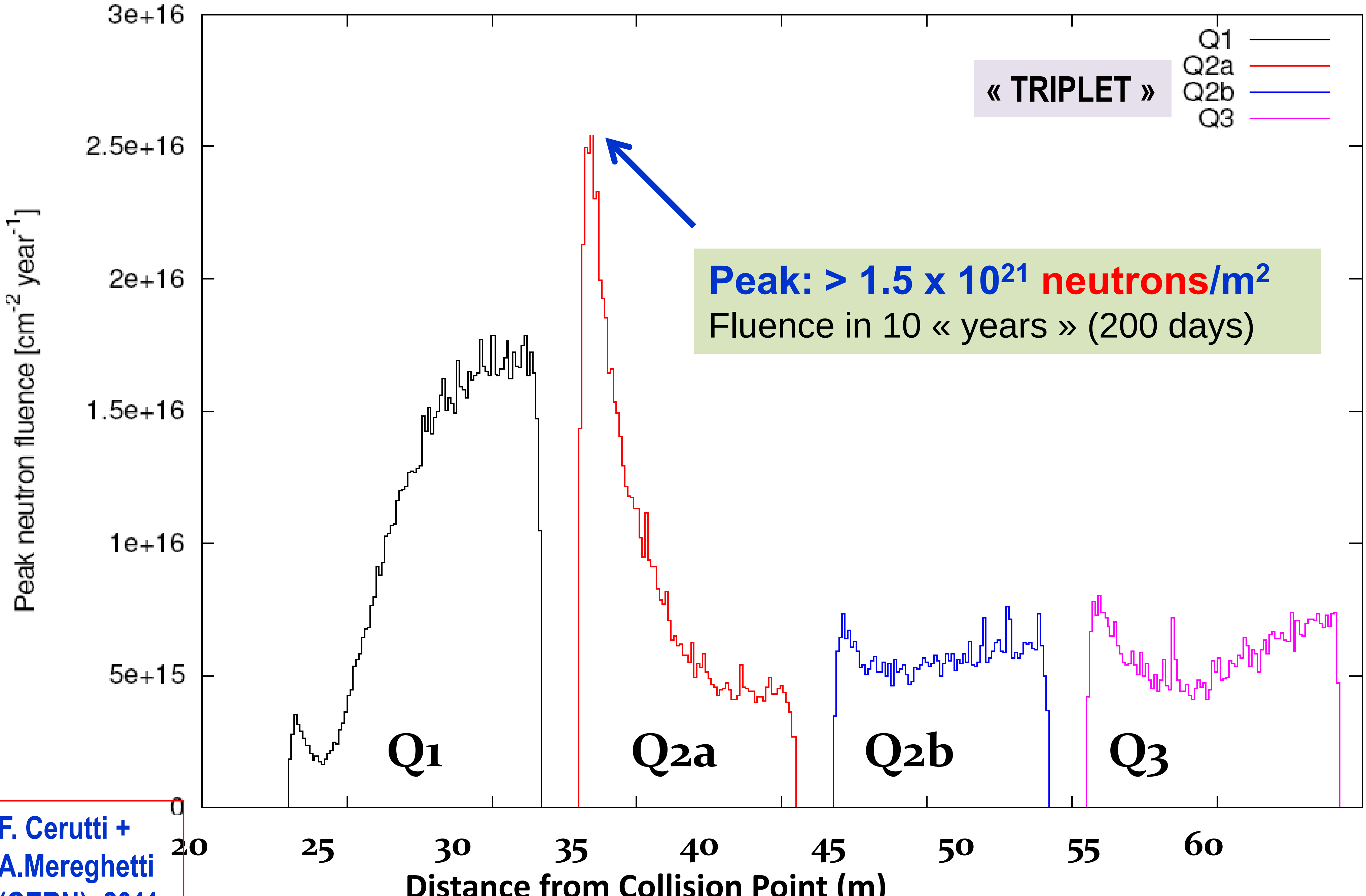



F. Cerutti

# Neutron fluence in the inner winding of Quadrupoles (LHC Upgrade)




F. Cerutti + A.Mereghetti (CERN), 2011

# Preliminary FLUKA calculations (without cold shielding)

Francesco Cerutti

| Track length fraction [ % ] | |
|---|---|
| photons | 88 |
| electrons / positrons | 7 |
| neutrons | 4 |
| pions | 0.45 |
| protons | 0.15 |

Over the HL-LHC target integrated luminosity **(3000 fb$^{-1}$)**,
triplet quadrupole cables and insulators will undergo the following radiation peak values:

**~ 100 MGy (dose)**

**~ $10^{-4}$ (DPA),**

**~ 1.5 x $10^{17}$ neutrons/cm$^2$**

**~ $10^{16}$ pions/cm$^2$**

**F. Cerutti**

# I. Irradiation of superconductors

| | |
|---|---|
| Radiation effects on superconductors in ITER | Harald Weber |
| Irradiation of $MgB_2$ | Marina Putti |
| Irradiation experiments at BNL | Peter Wanderer |
| Neutron Irradiation Measurements for Superconducting Magnet Materials at Low Temperatures | Tatsuchi Nakamoto |
| What do we need? | René Flükiger |

# Neutron Irradiation of superconductors

**Radiation will affect**

⌧ TRANSITION TEMPERATURE $T_c$

- through disorder:
  - ☞ unlikely in alloys
  - ☞ effective in metals and ordered compounds

⌧ NORMAL STATE RESISTIVITY $\rho_n$

- through the introduction of additional scattering centers
  - ☞ very small in alloys
  - ☞ significant in metals and ordered compounds

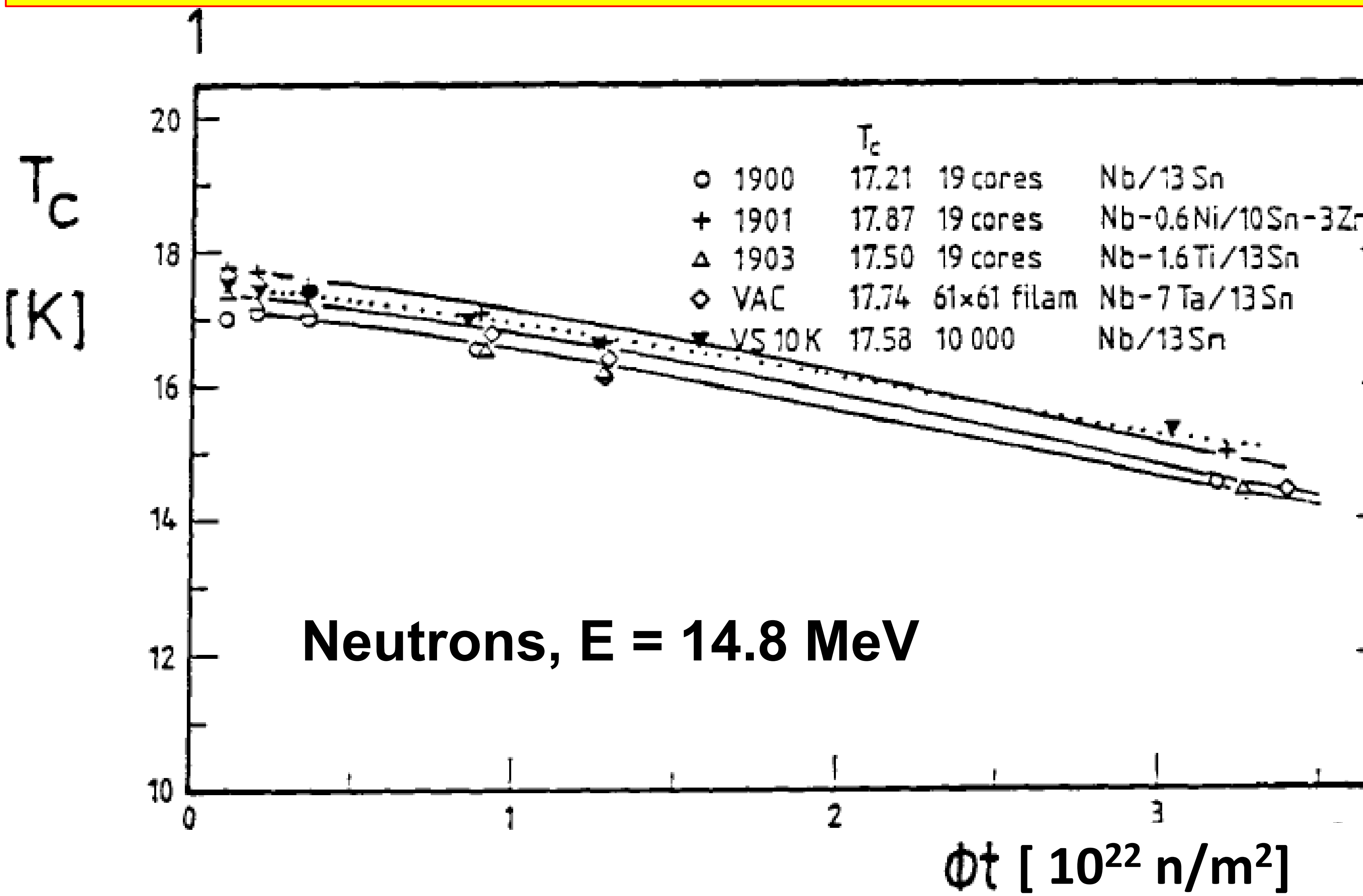
⌧ UPPER CRITICAL FIELD $H_{c2}$

- through the same mechanism: $\rho_n \propto 1/\ell \propto \kappa \propto H_{c2}$

⌧ CRITICAL CURRENT DENSITY $J_c$

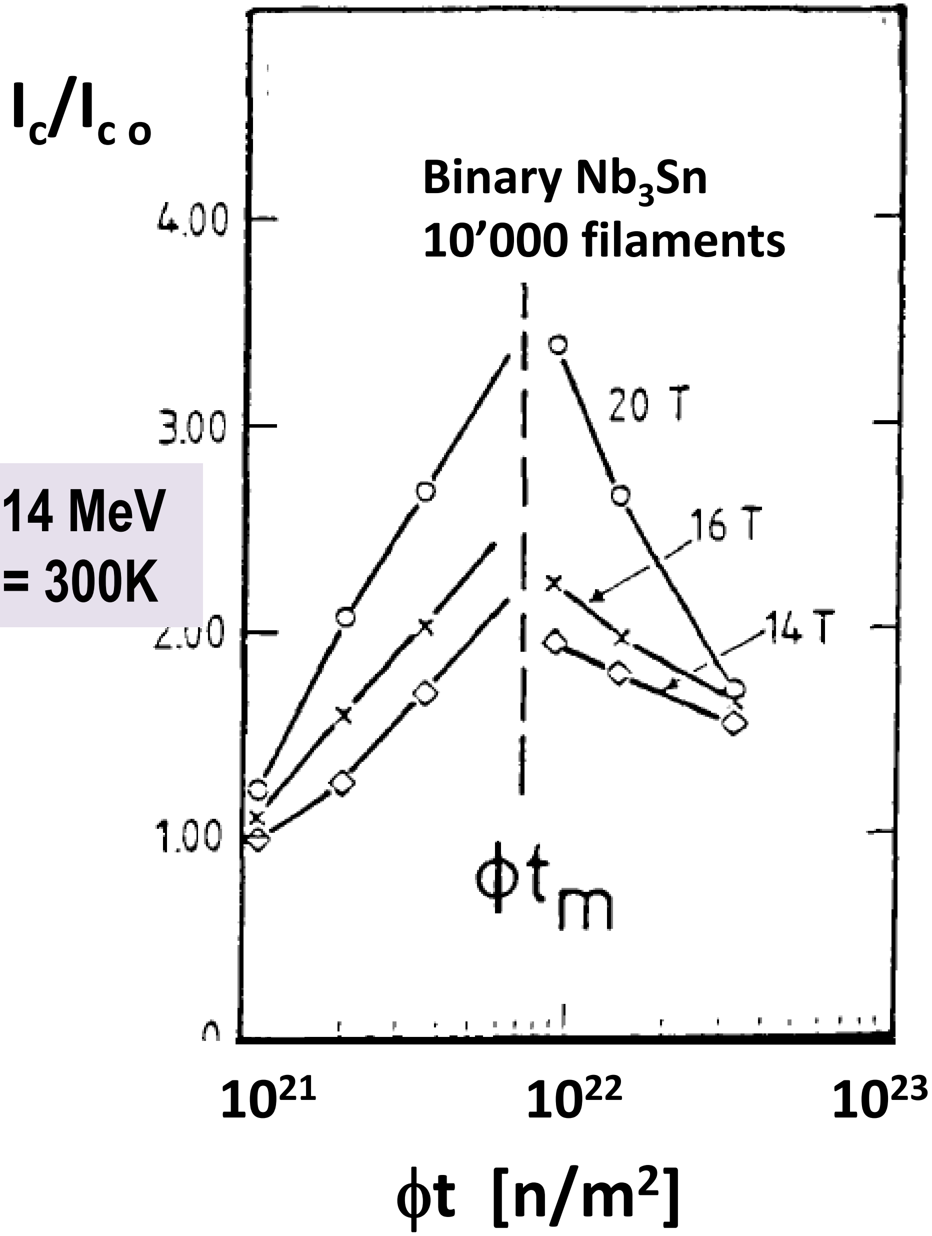
- through the production of pinning centers

# Variation of $T_c$ in neutron irradiated multifilamentary $Nb_3Sn$ wires

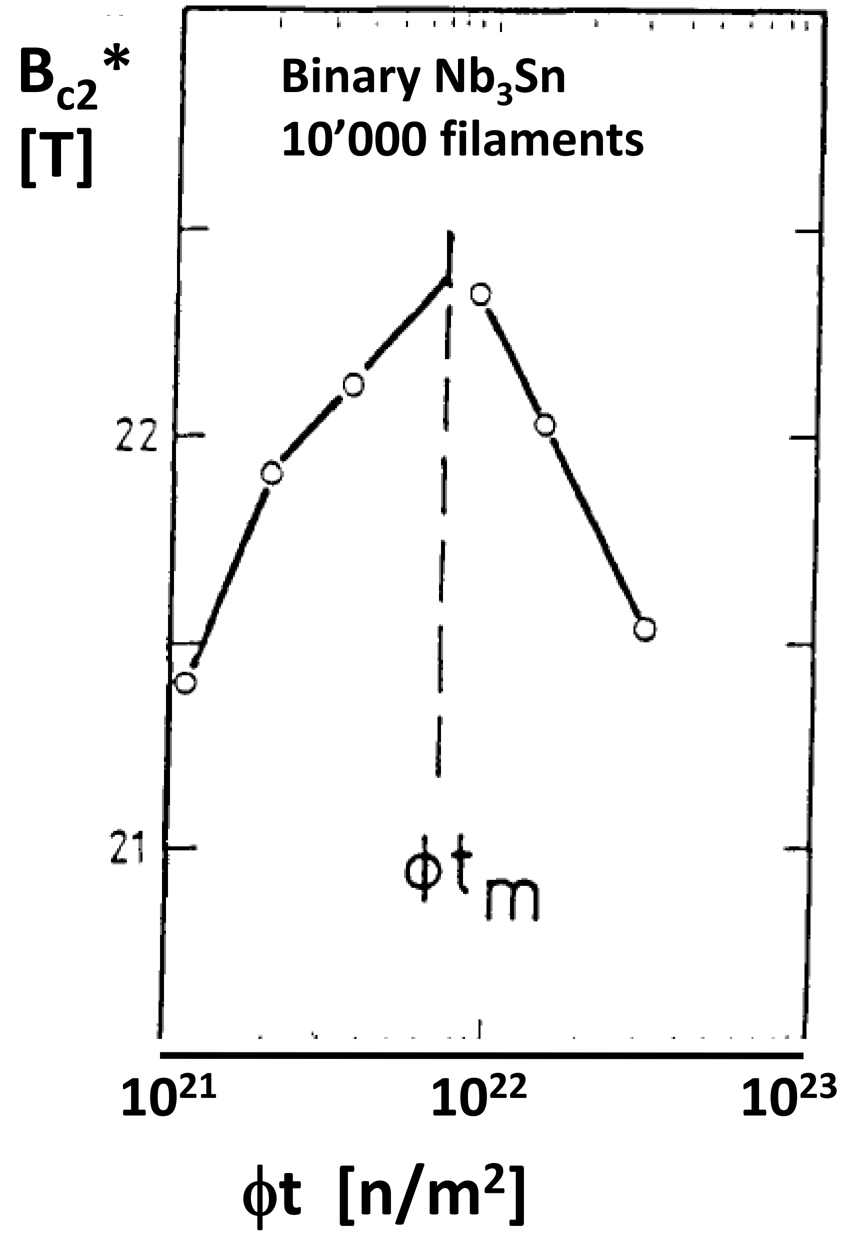



F. Weiss, R. Flükiger, W. Maurer, IEEE Trans. Magn., MAG-23(1987)976

# Binary $Nb_3Sn$ wire (10'000 filaments)



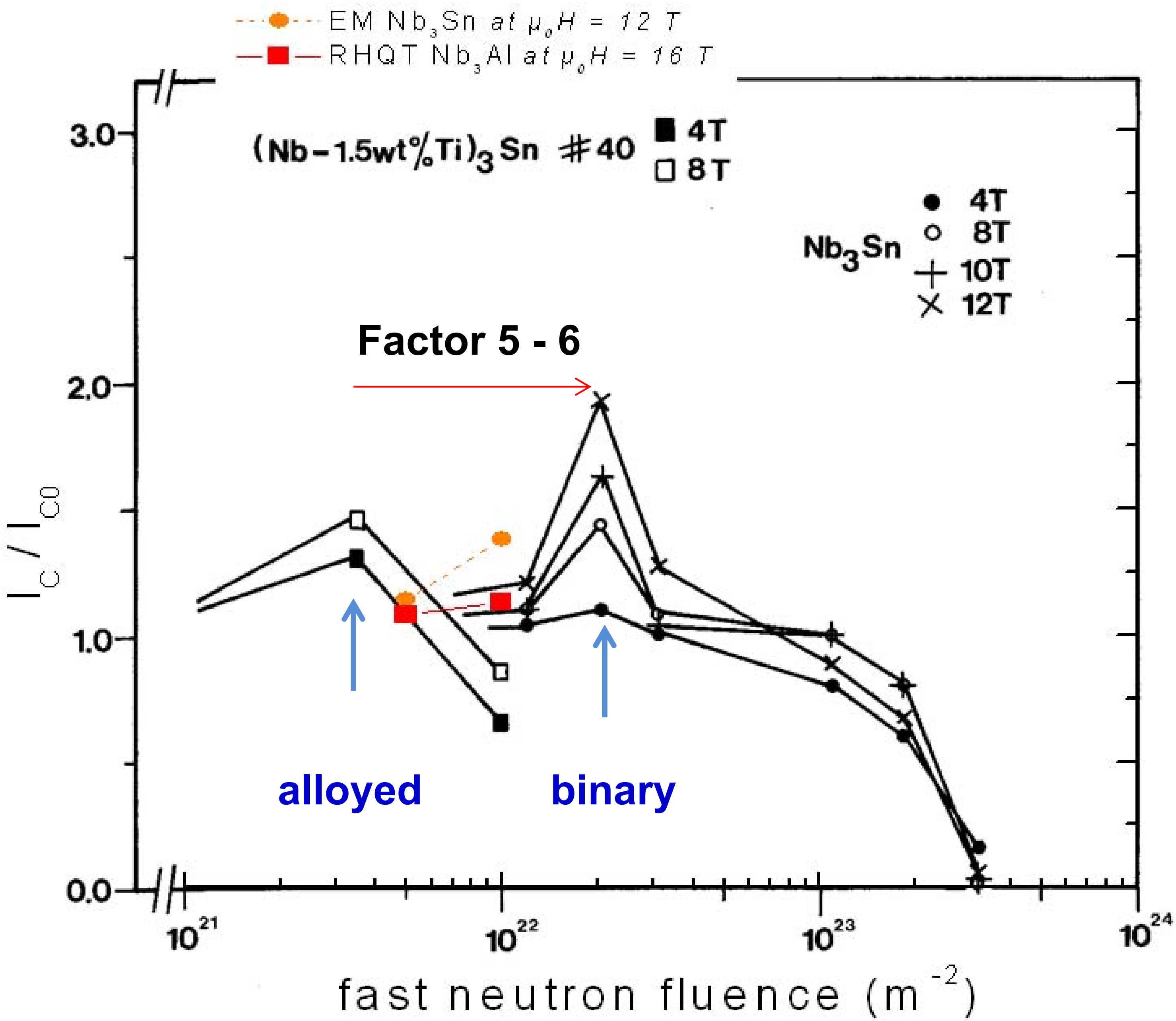

E =14 MeV
$T_{irr}$ = 300K






F. Weiss et al. IEEE Trans. Magn., MAG-23(1987)976

# Binary and ternary alloyed $Nb_3Sn$ wires (bronze route)




**H. Weber at al. 1986**

# Alloyed $Nb_3Sn$ wires: $J_c$ more sensitive to irradiation

1) Maximum $I_c/I_{co}$ and $B_{c2}$ for alloyed $Nb_3Sn$ wires:
   ≈ 5 - 6 x lower fluence than for binary wires

| Wire | $\phi t_{maximum}$ |
|---|---|
| Binary $Nb_3Sn$ wire | 8 x $10^{17}$ n/cm$^2$ |
| Ti alloyed $Nb_3Sn$ wire | 1.5 x $10^{17}$ n/cm$^2$ |
| Ta alloyed $Nb_3Sn$ wire | 1.5 x $10^{17}$ n/cm$^{25}$ |

2) At $\phi t_m$ the increase $\Delta(I_c/I_{co})$ and $\Delta(B_{c2})$ is lower for alloyed $Nb_3Sn$ wires

3) At $\phi t$ = 5 x $10^{17}$ n/cm$^2$:
   $I_c/I_{co}$ for binary $Nb_3Sn$ wire higher than before irradiation
   but:
   $I_c/I_{co}$ for alloyed $Nb_3Sn$ wires similar than before irradiation

# Neutron Irradiation at KUR Kyoto Univ. Reactor)

Tatsuchi Nakamoto

- 5MW max. thermal power
- Irradiation cryostat close to reactor core
- Sample cool down by He gas loop: 10K – 20K
- Fast neutron flux (En>0.1MeV): $1.4 \times 10^{15}$ n/m$^2$/s@1MW

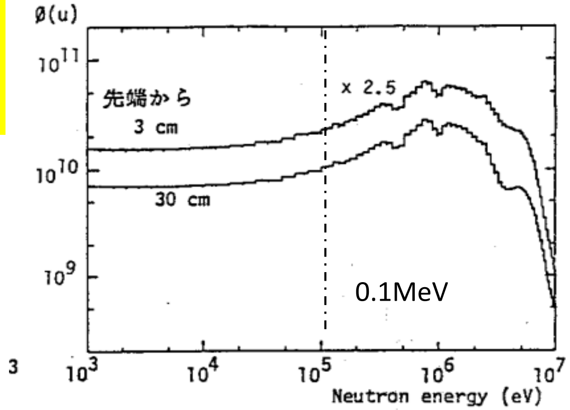
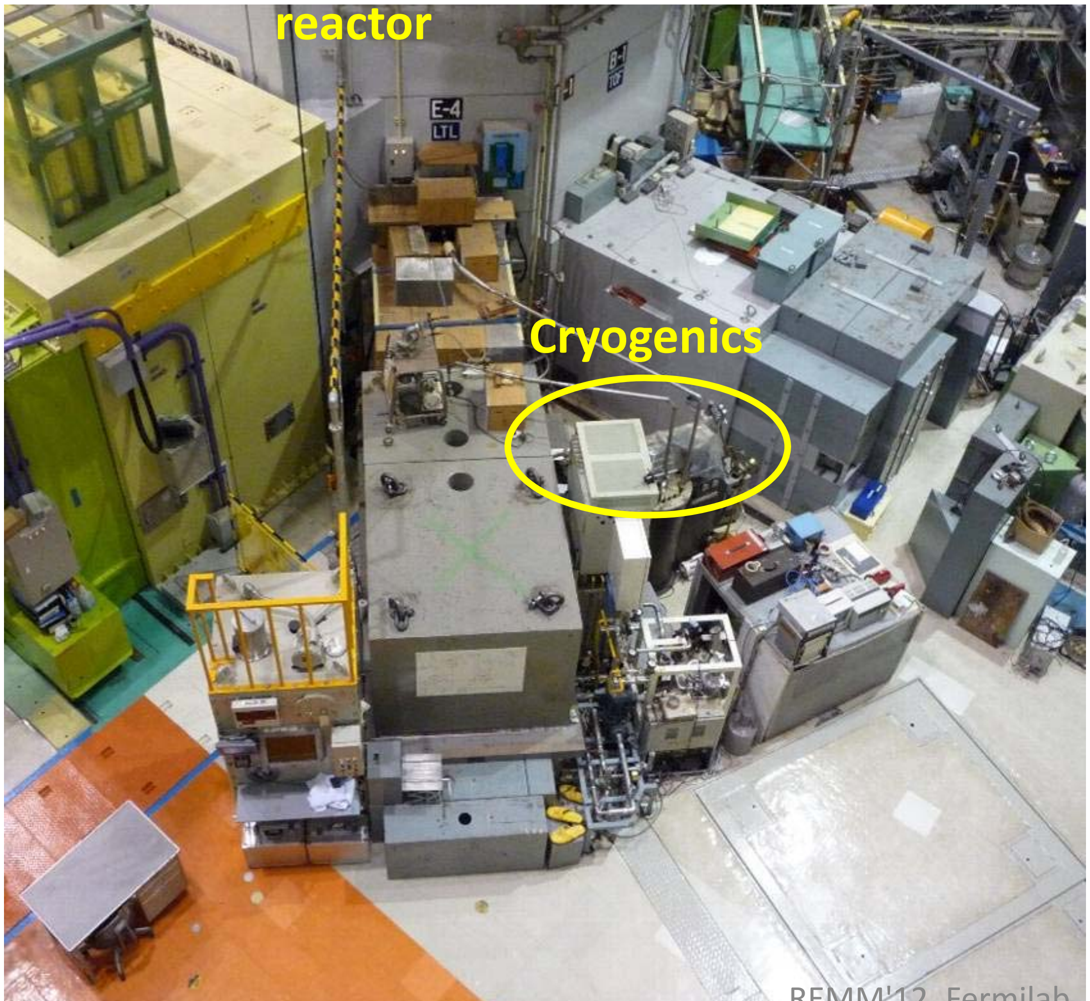
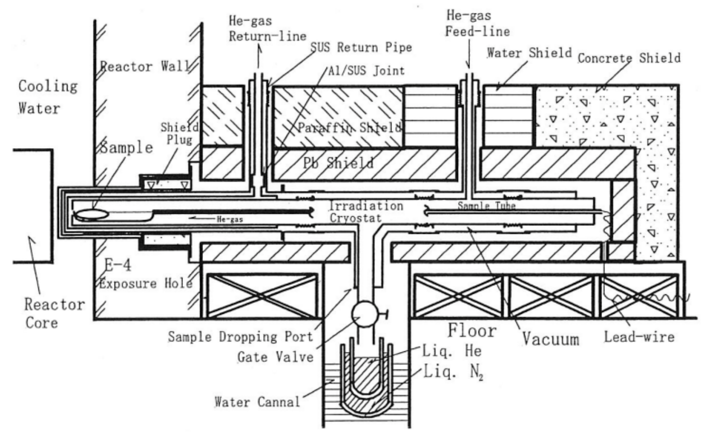



Fig. 15 Neutron energy spectrum in LTL of KUR for ordinary core (above 1000 eV) KUR-TR287 (1987)

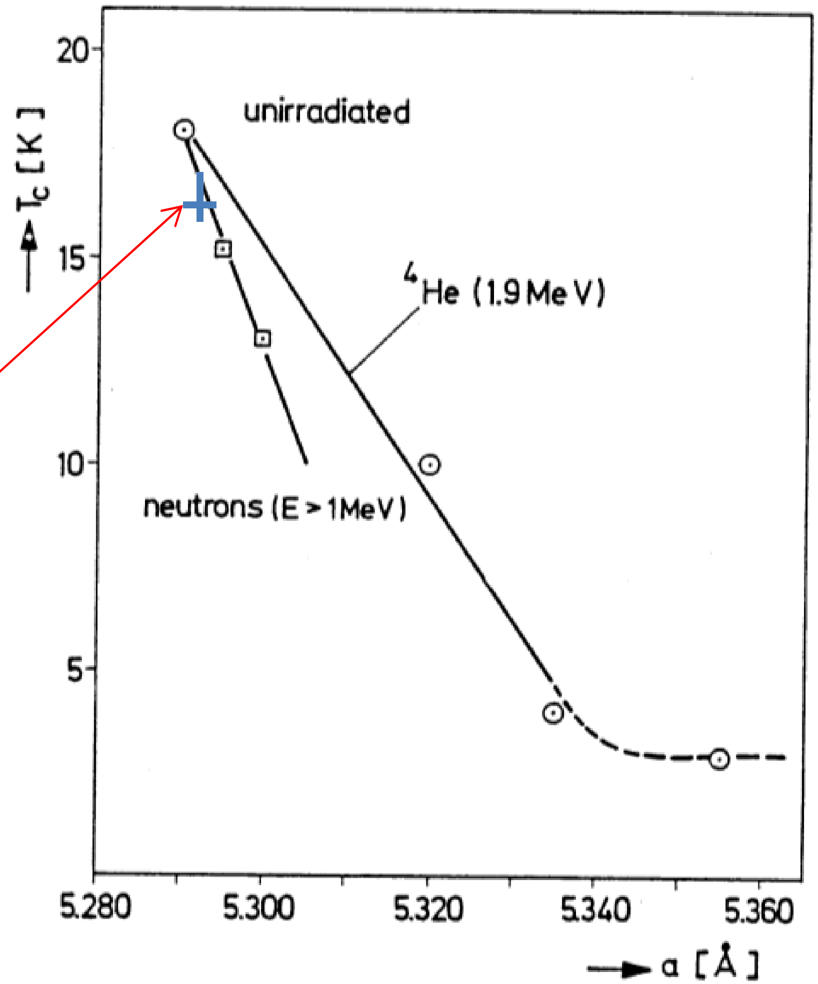



M. Okada et al., NIM A463 (2001) pp213-219




# Volume expansion of irradiated $Nb_3Sn$

# Volume expansion in irradiated $Nb_3Sn$




**0.5 x $10^{22}$ n/m²**

**$\Delta a \approx 0.02\%$**

**Scaling law between various sources not yet investigated**

**At 5 x $10^{21}$ n/m², close to the maximum of $J_c$ vs. $\Phi t$, the volume expansion of $Nb_3Sn$ is ≈ 0.5%. Does this have effects on the internal stresses, and thus on $J_c$, the wires being encapsulated?**

# Effect of irradiation on Cu stabilizer

Normal state resistivity essential for stabilization and quench protection

In-field resistivity experiments on copper

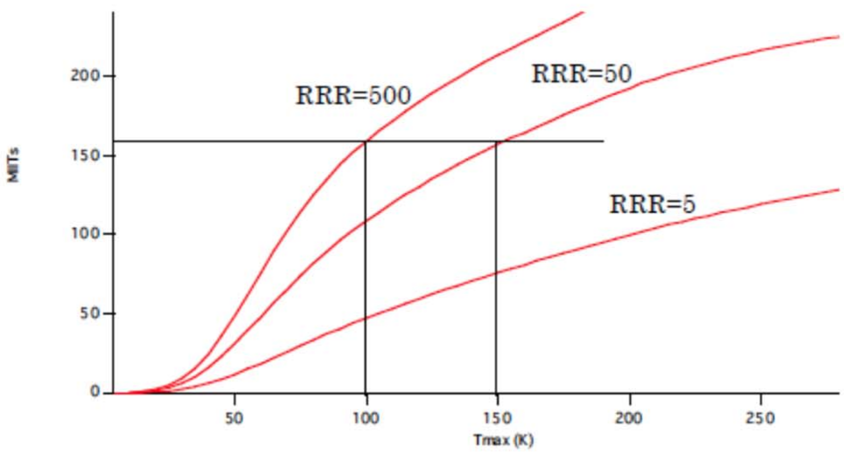
Irradiation *must* be done at low temperature (~ 5 K) due to substantial annealing

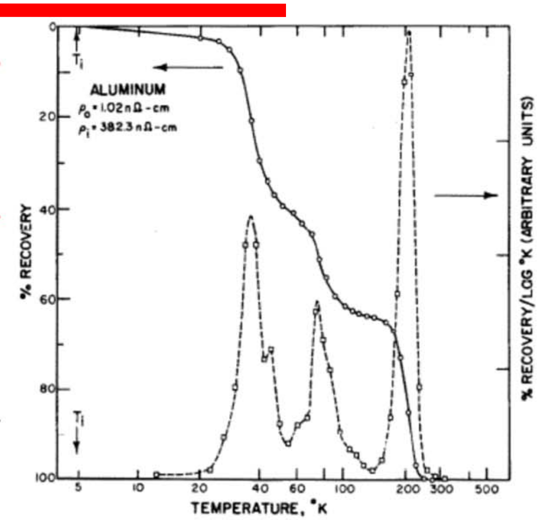
(most low temperature irradiation facilities have been shut down, only one 14 MeV source available in Japan)

# Why is ρ of Stabilizer Important?

**>> very concerned with quench protection.**

- MIITs: $\int_{t_{quench}}^{t_{end}} I^2 dt = \int_{T_0}^{T_{max}} \frac{C_p A}{\rho / A} dT$
- ρ increase ➔ temperature increase



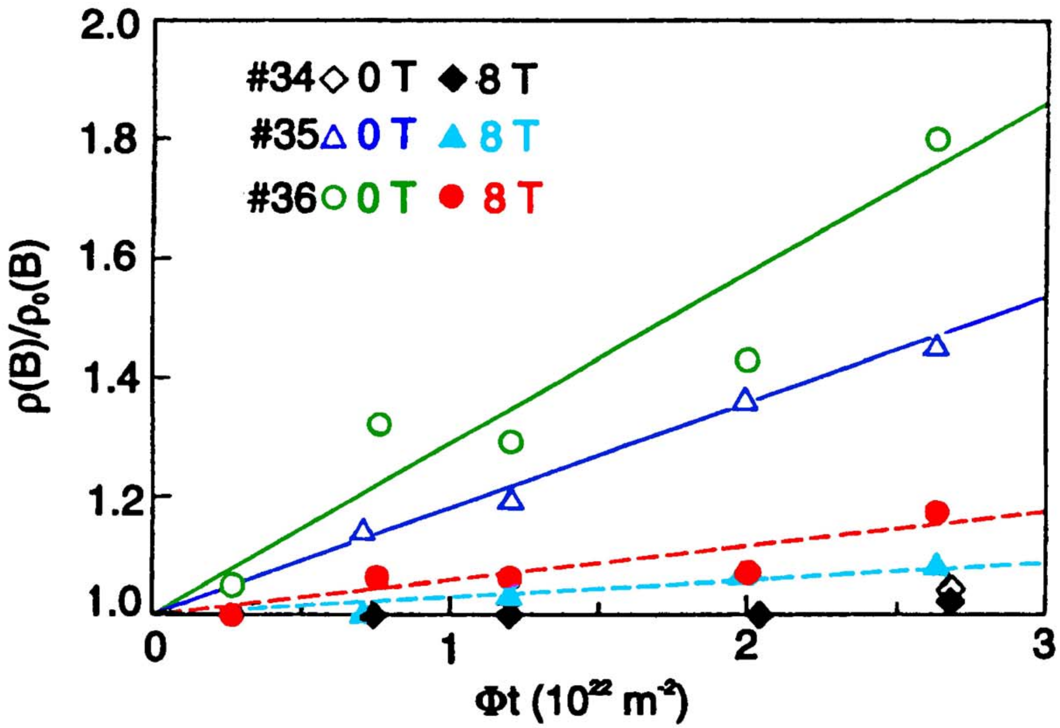

**Neutron irradiation test for stabilizers (copper, aluminum) is undoubtedly necessary.**

minimum fluence to start of degradation

anneal effect on recovery

R&D of witness sample for the operation

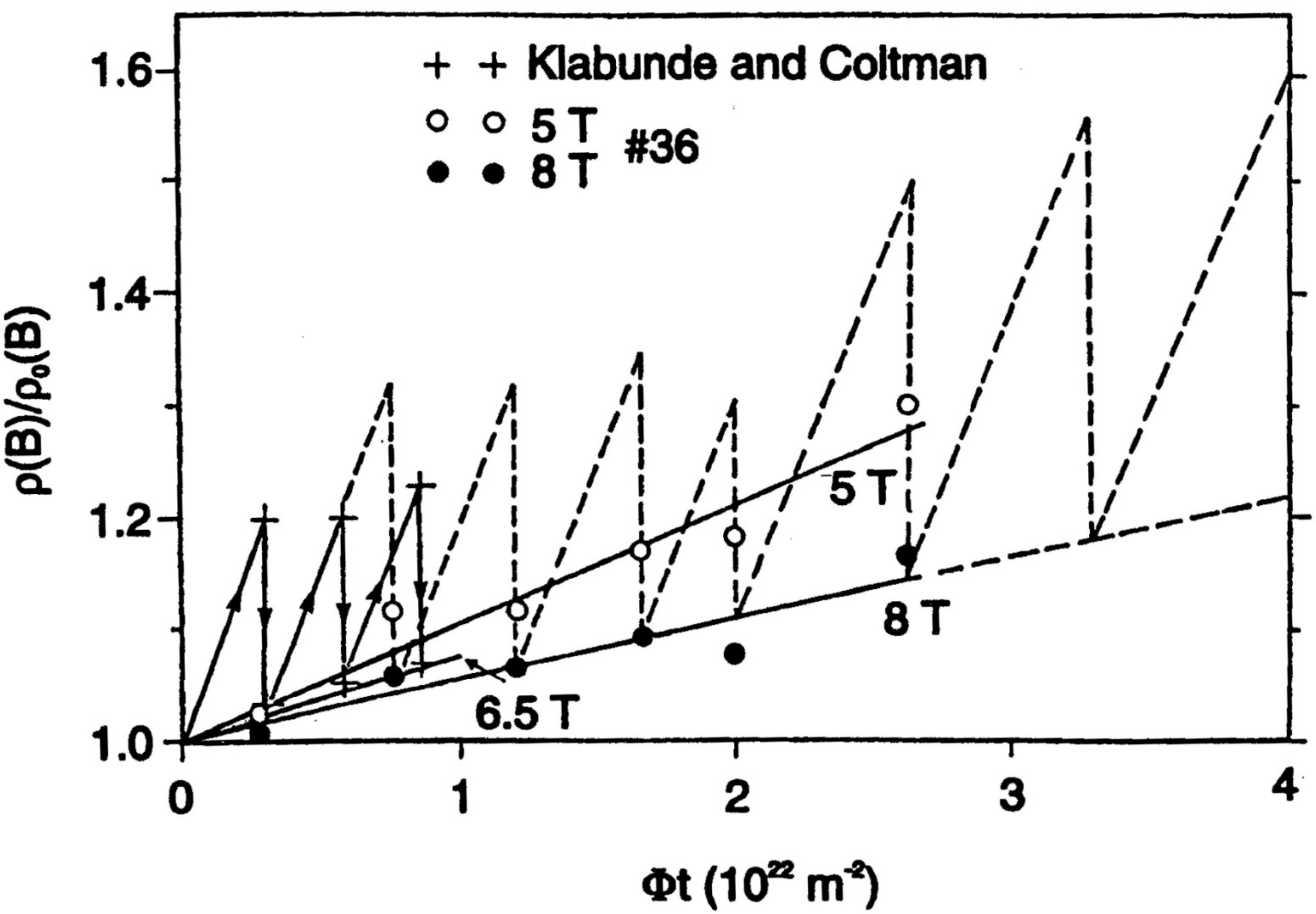
- **Resistivity measurement at 10 K**
- **Neutron irradiation at the IPNS spallation source at 5 K**
- **Warm-up cycle to RT**
- **Resistivity measurement at 10 K**




Multifilamentary NbTi-conductors

#34: RRR ~ 60
#35: RRR ~ 120
#36: RRR ~ 120

**Resistivity increase : factor ~1.3 at 1 x $10^{22}$ n/$m^2$**




**Resistivity increase : factor ~1.3 at 1 x $10^{22}$ n/$m^2$**

T. Nakamoto

| Materials | Aluminum | | | | Copper | | |
|---|---|---|---|---|---|---|---|
| | Horak | Guinan | Present | Present | Horak | Guinan | Present |
| RRR | 2286 | 74 | 450 | 3007 | 2280 | 172 | 319 |
| $T_{irr}$ (K) | 4.5 | 4.2 | 12 | 14 | 4.5 | 4.2 | 14 |
| Netutron Source | Reactor | 14 MeV | Reactor | Reactor | Reactor | 14 MeV | Reactor |
| $\Phi_{tot}$ ($n/m^2$) (>0.1MeV) | 2 x $10^{22}$ | 1-2 x $10^{21}$ | 2.3 x $10^{20}$ | 2.7 x $10^{20}$ | 2 x $10^{22}$ | 1-2 x $10^{21}$ | 2.7 x $10^{20}$ |
| $\Delta\rho_{irr}/\ \Phi_{tot}$ x$10^{-31}$($\Omega m^3$) | 1.9 | 4.09 | 2.4 | 2.4 | 0.58 | 2.29 | 0.82 |
| Recovery by thermal cycle | 100% | 100% | 100% | TBD | 90% | 80% | TBD |

- Degradation rate ($\Delta\rho_{irr}/\ \Phi_{tot}$) seems to be higher in 14 MeV neutron irradiation. Evaluation using a common index such as DPA would be necessary.
- Present work shows that difference in RRR of Al doesn't influence the degradation rate.
- For copper, degradation rates ($\Delta\rho_{irr}/\ \Phi_{tot}$) are ranged from 0.58 to 2.29 $10^{-31}$ $\Omega m^3$. What if SC cables with the initial RRR of 200 are irradiated to $10^{20}$ or $10^{21}$ $n/m^2$?
  - $10^{20}$ $n/m^2$ : RRR of 160 – 190
  - $10^{21}$ $n/m^2$ : RRR of 50 – 120
- Recovery by annealing in copper sample and its multiple irradiation are planned in 2012.

## Superconductors for operation at higher temperatures and/or higher magnetic fields

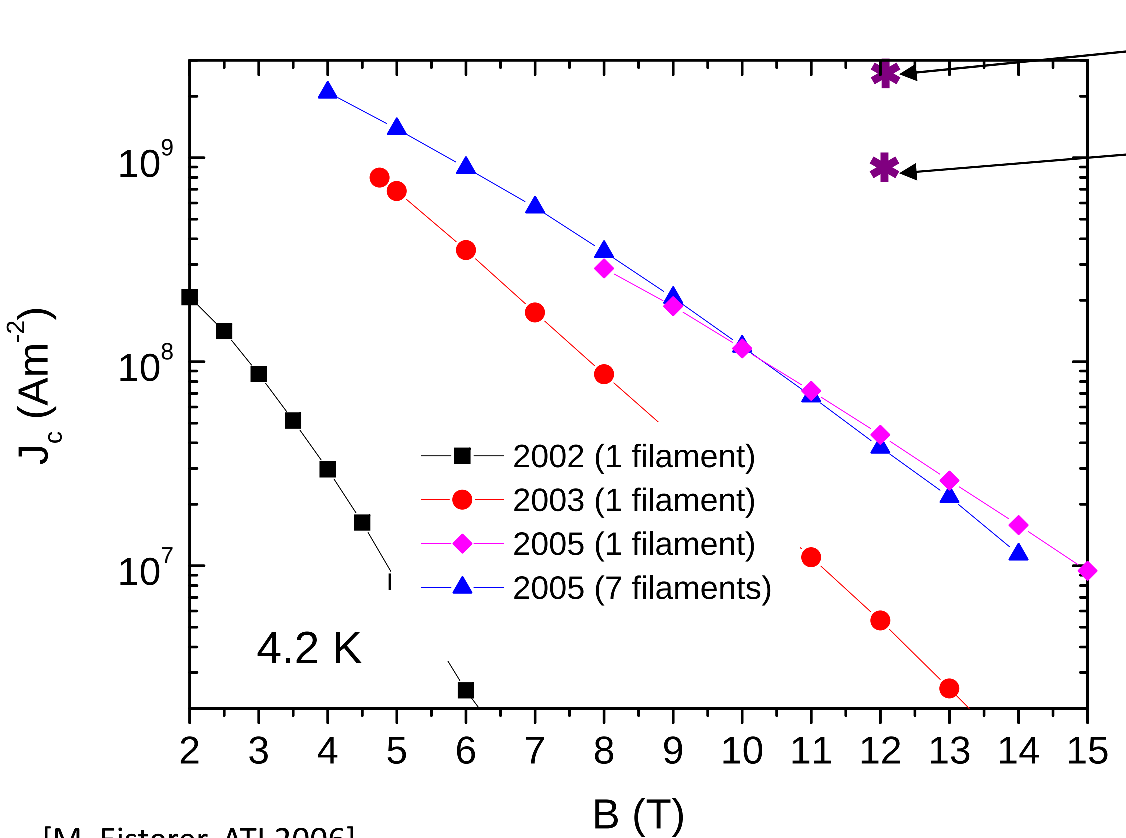
1) **$MgB_2$ ($T_c$ ~39 K):**
   Low temperature (10 – 20 K) and intermediate field (< 10 T) application
   Possibly: LINK Current leads for HL-LHC

2) **Bi-2212 ($T_c$ ~87 K):**
   Fields up to 25 K at ≤ 4.2K
   Only HTS conductor with round cross section
   Difficult fabrication: needs to be improved

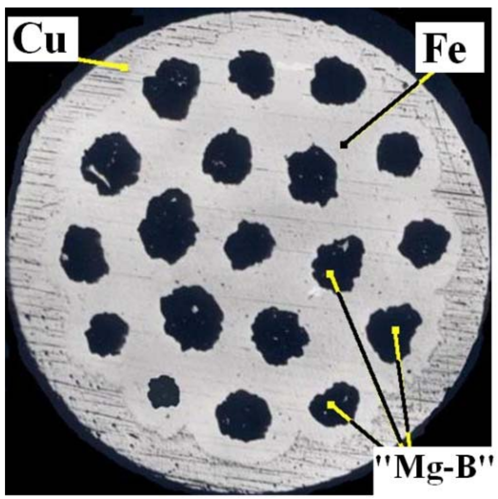
3) **RE-123 ($T_c$ ~92 K):**
   Fields > 25 T at 4.2K possible
   Very high costs, cables applicable in quadrupoles?

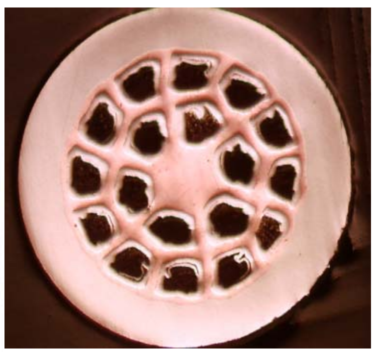
# $MgB_2$ wires

- **Higher field applications only at lower T**
- **Production of ~1 km long wires: ex-situ ok, in-situ improving, many suppliers**



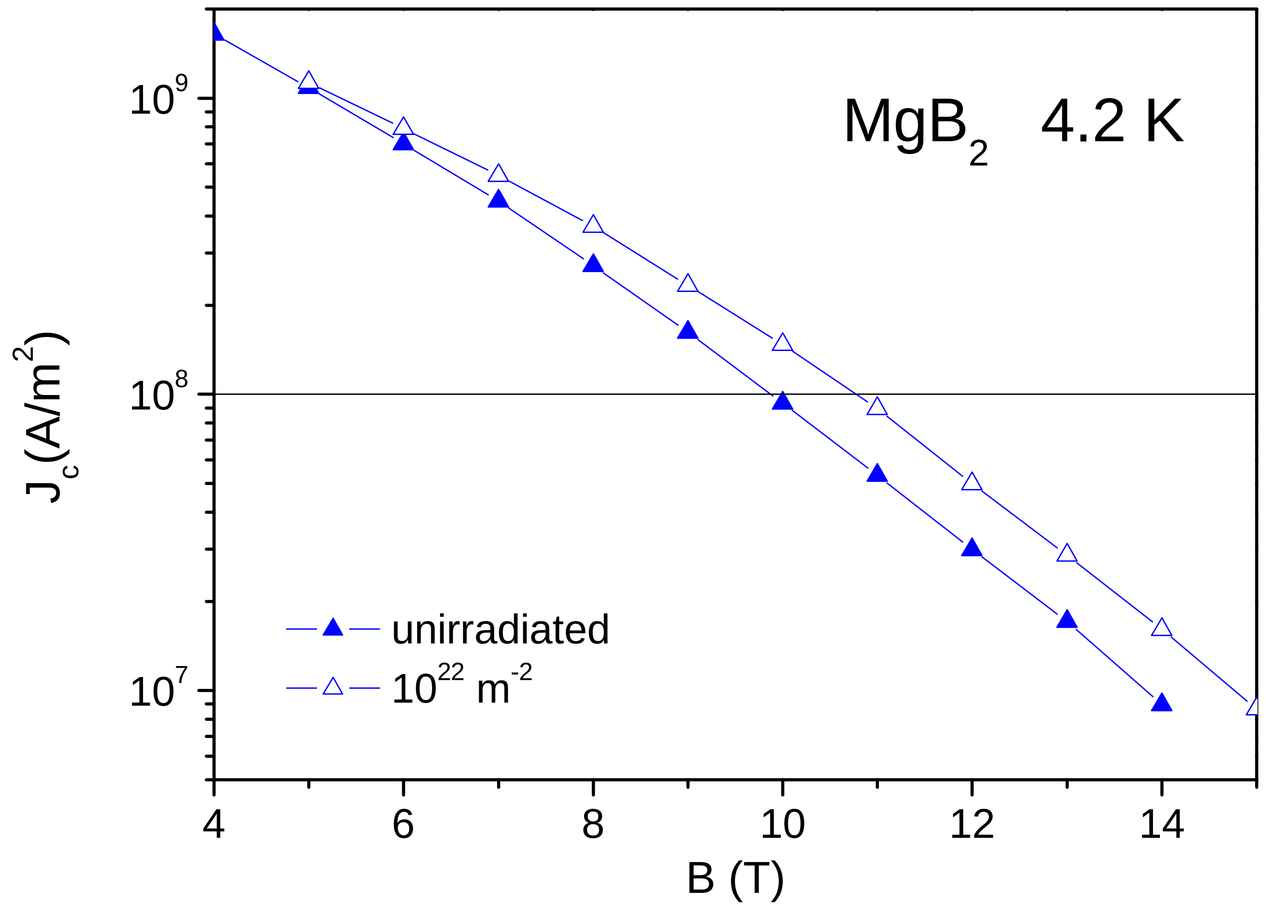

[M. Eisterer, ATI 2006]



**Columbus** **HyperTech**

# Critical Current Densities of $MgB_2$ at 4.2 K




Fluence: $10^{22}$ $m^{-2}$

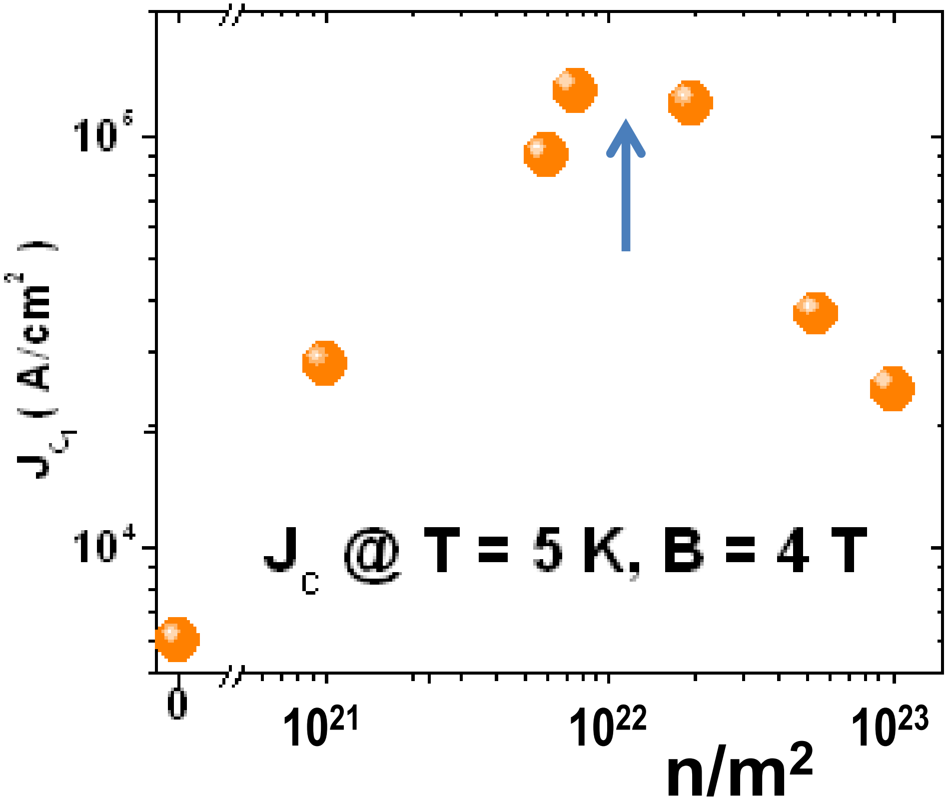
**M. Eisterer, ATI 2007**

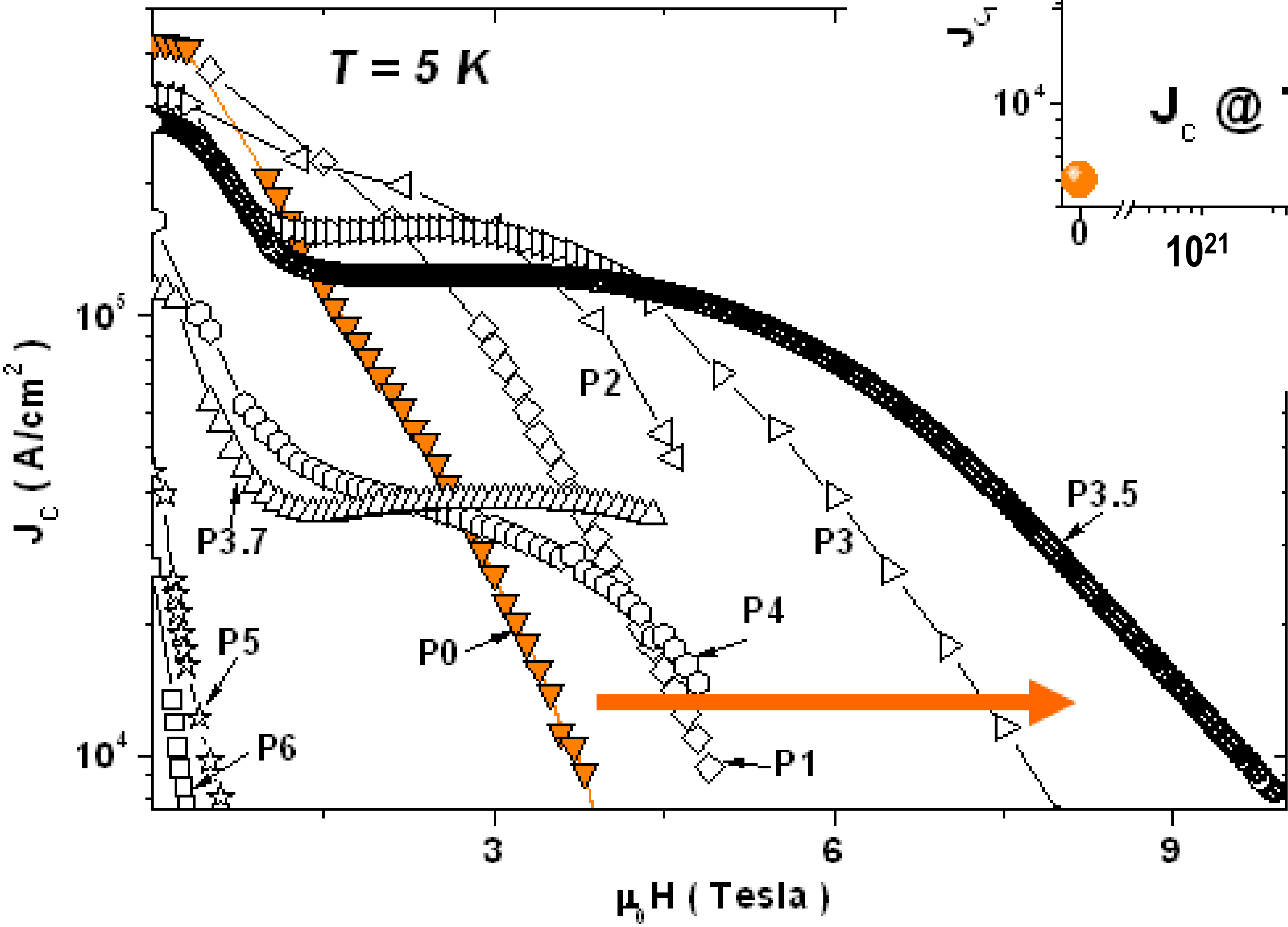
Sufficient current densities only at fields below ~ 10 T

Envisaged for LINK high current leads in HL-LHC

Low cost alternative at low temperatures (< 10 K, PF coils) ?

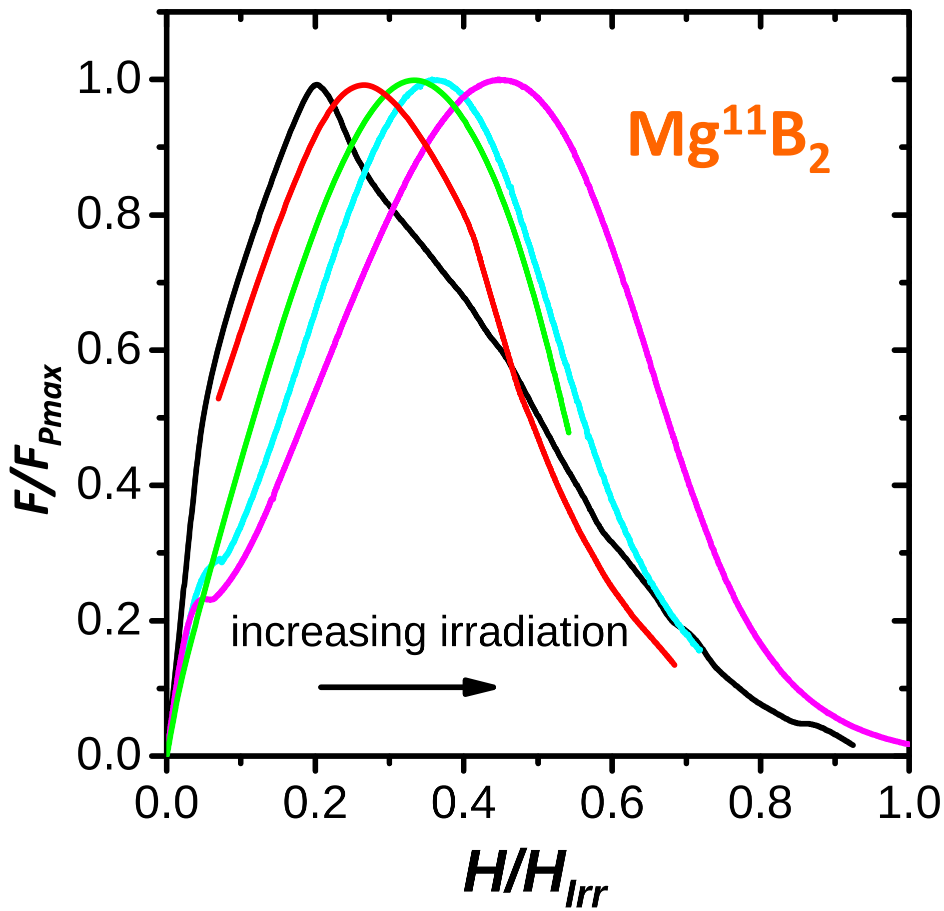
# Neutron irradiated $MgB_2$

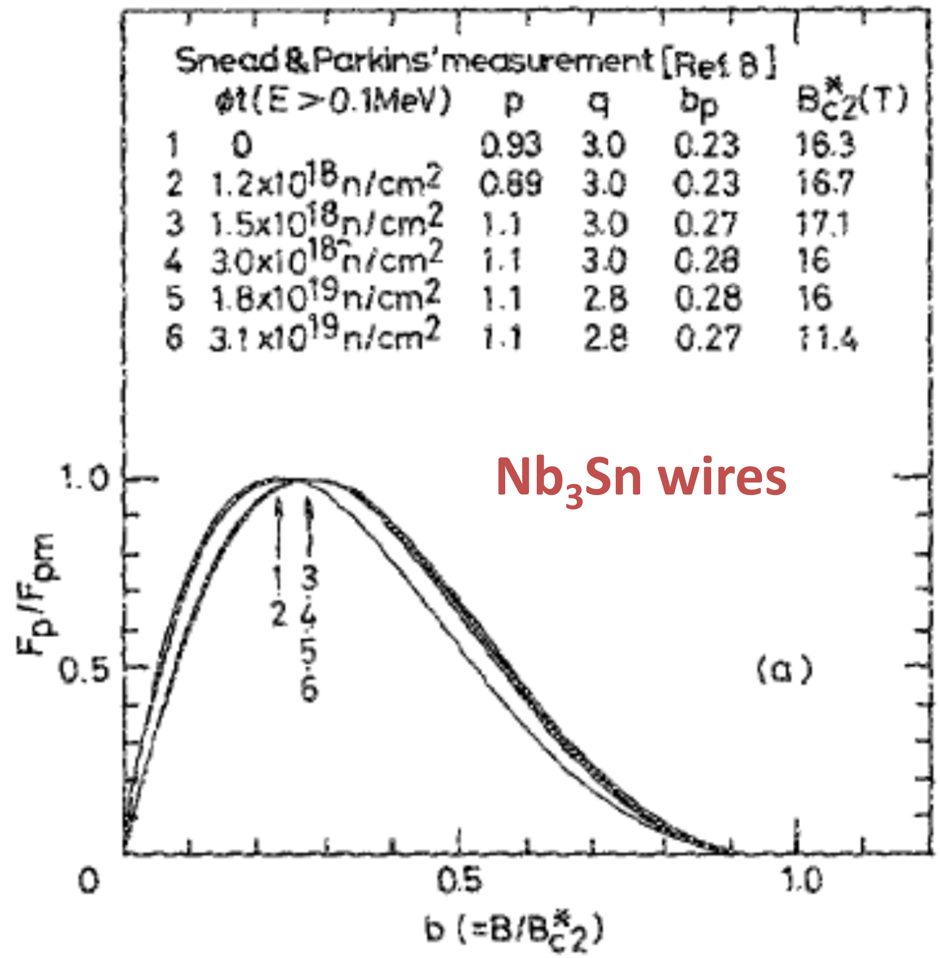



M. Putti, 2011

# Pinning mechanism

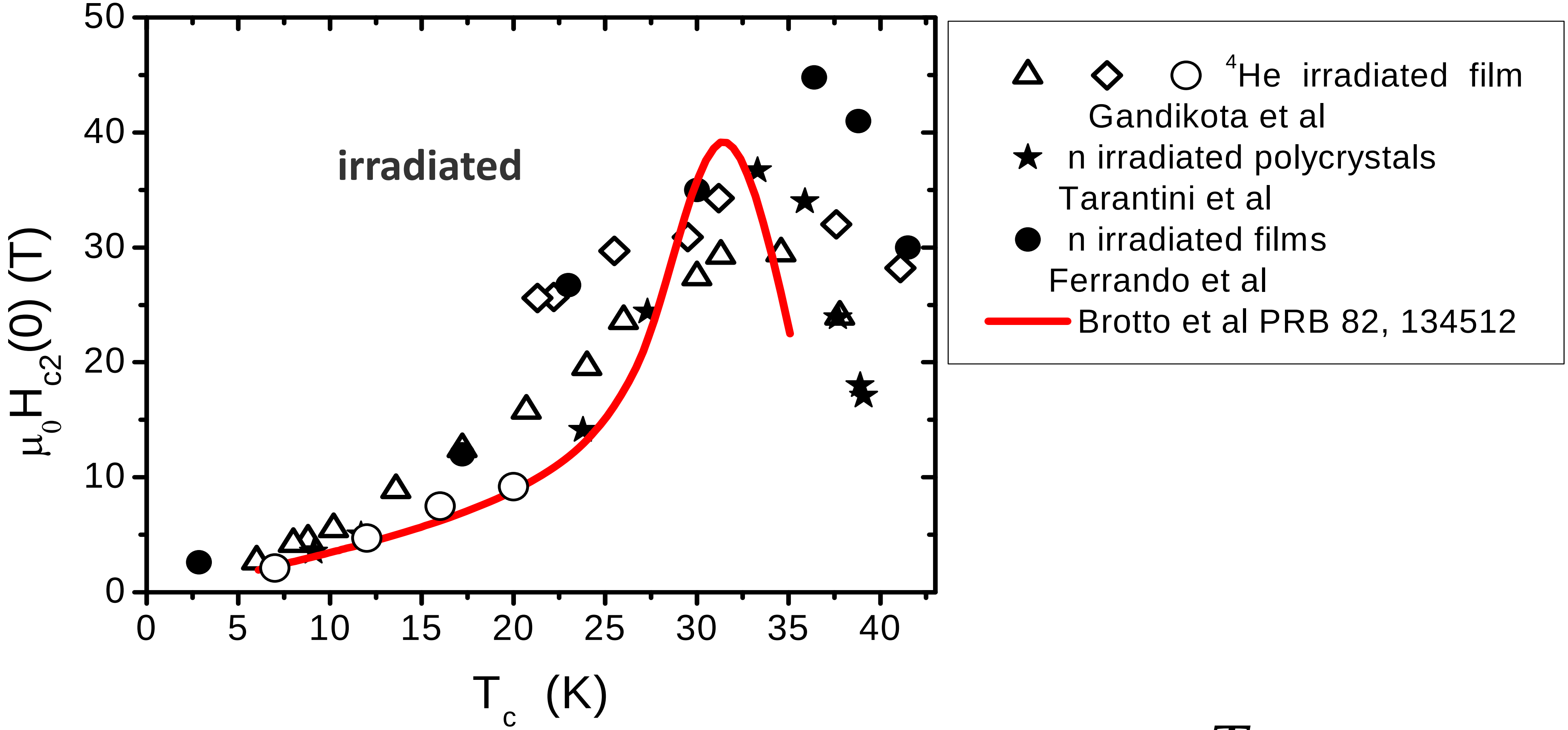



➲ The shift of the $F_P$ peak means that a new pinning mechanisms is working

➲ Similar behaviour was observed in $Nb_3Sn$ wires

# $H_{c2}$ in neutron irradiated $MgB_2$

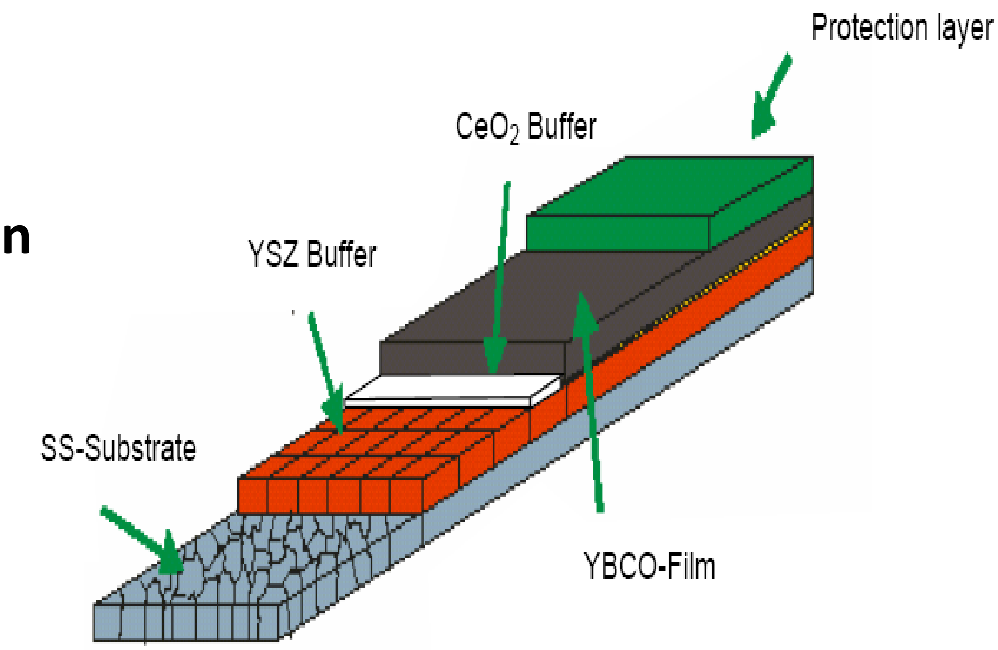



$$H_{C2} \propto T_c \cdot \rho_0$$

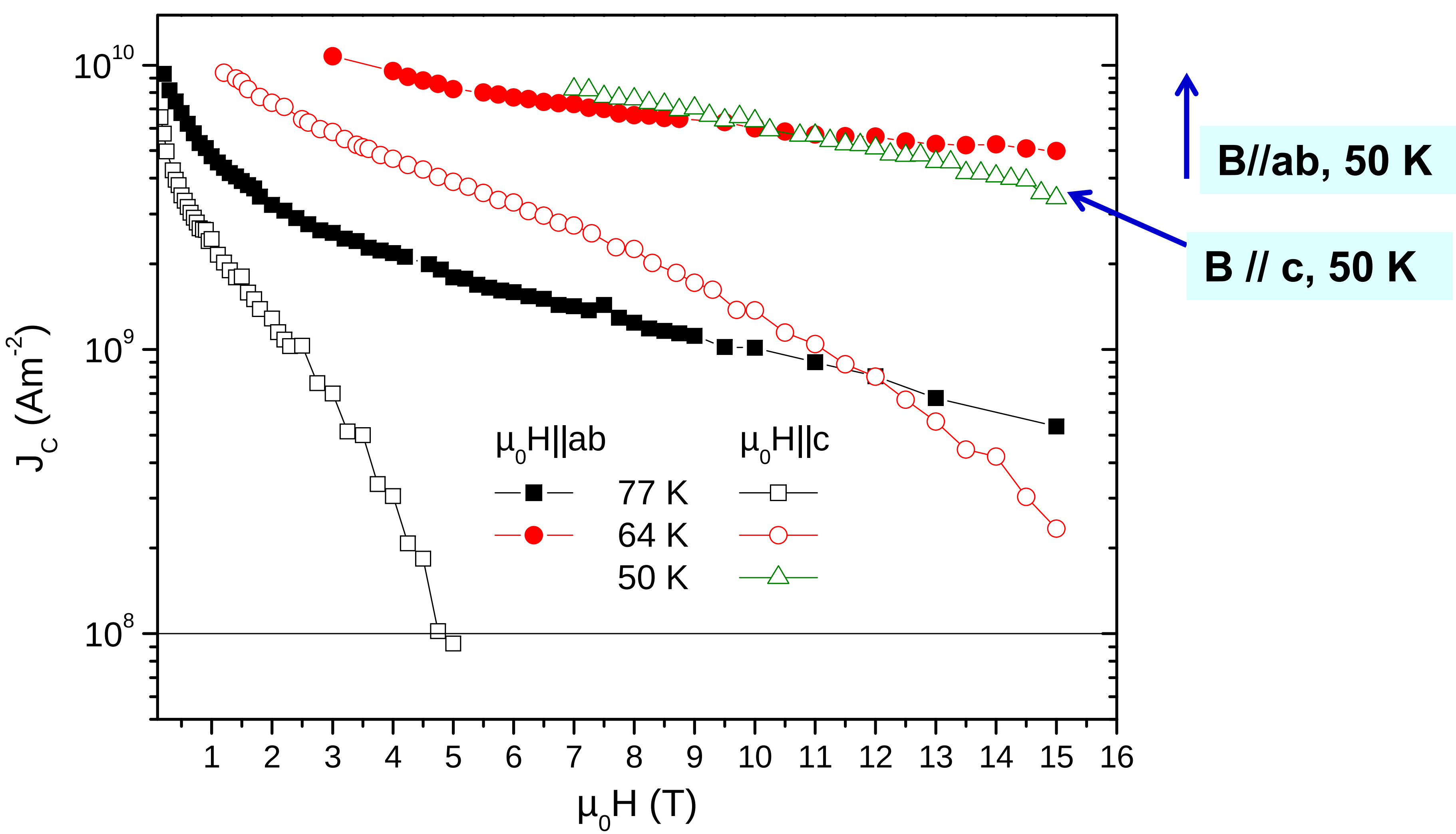
# HTS Superconductors

## Coated Conductors by (EHTS)

- Substrate: Cr-Ni stainless steel
- Buffer stack: $Y_2O_3$/YSZ/$CeO_2$
  - YSZ: Ion beam assisted deposition (IBAD)
- YBCO (2.5 µm)
  - Pulsed-laser-deposition (PLD)
- Silver or gold protection layer
  - Vapor deposition
- Stabilization: Copper ( ~ 17 µm)
  - Galvanic plating process
- Total thickness: 0.120 mm → $J_c/J_e = 50$



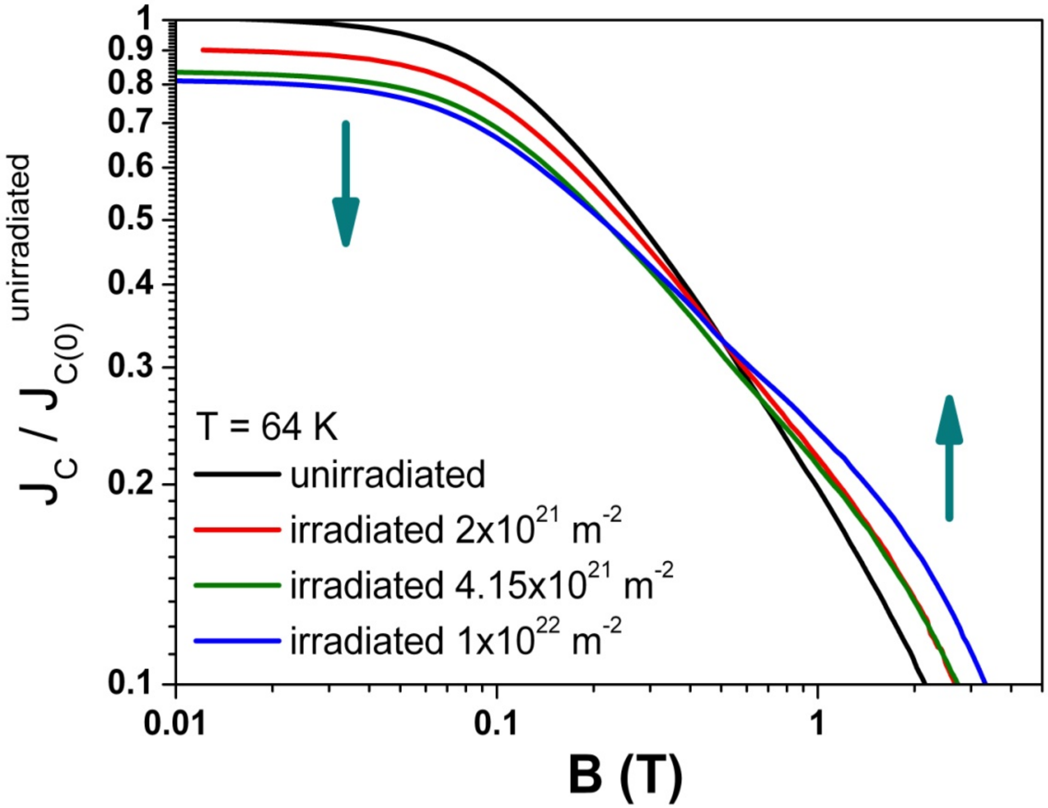
# Coated Conductors: Critical Current Densities

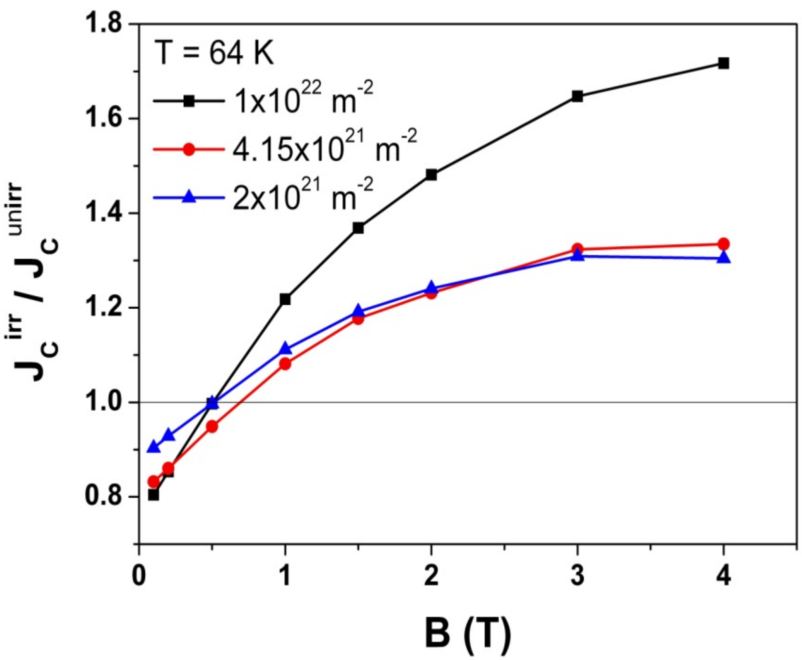



**H. Weber, M. Eisterer**

# Neutron irradiation effects on $J_c$ for fields // c: AMSC

- Decrease of $J_C$ at low fields
- Increase of $J_C$ at higher field
- The crossover indicates a change in flux pinning




| Crossover field (mT) | $2x10^{21}$ $m^{-2}$ | $4x10^{21}$ $m^{-2}$ | $1x10^{22}$ $m^{-2}$ |
|---|---|---|---|
| 77 K | 244 | 382 | 630 |
| 64 K | 114 | 219 | 440 |
| 50 K | 130 | 195 | 334 |

H. Weber, M. Eisterer

# Conclusions for neutron irradiated materials

- **LT Superconductors:**
  **No problems regarding radiation effects expected in HL-LHC**
- **Stabilizer:**
  **Degradation must be kept in mind**
- **HTS:**
  **Substantial R&D still required**
  **Problems: Bending of roebled HTS cables**
  **High costs**

# Effect of various radiation sources on superconductors

**From the present knowledge:**

**Neutrons :** Strong source of damage for superconductors

**Protons:** From known data, even stronger effect (charge)

**Pions:** Nothing is known yet. Effects expected to be comparable to those of protons (charges +/-)

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**Electrons:** Very little is known. Much smaller effects expected
More data needed

**Photons:** Nothing is known. Much smaller effects expected.
(in contrast to insulators). Data needed

## Keep in mind:

* all high energy sources act simultaneously

* there is no experience on a combined effect of several high energy sources

→ * subsequent irradiations with different sources should be carried out on selected samples

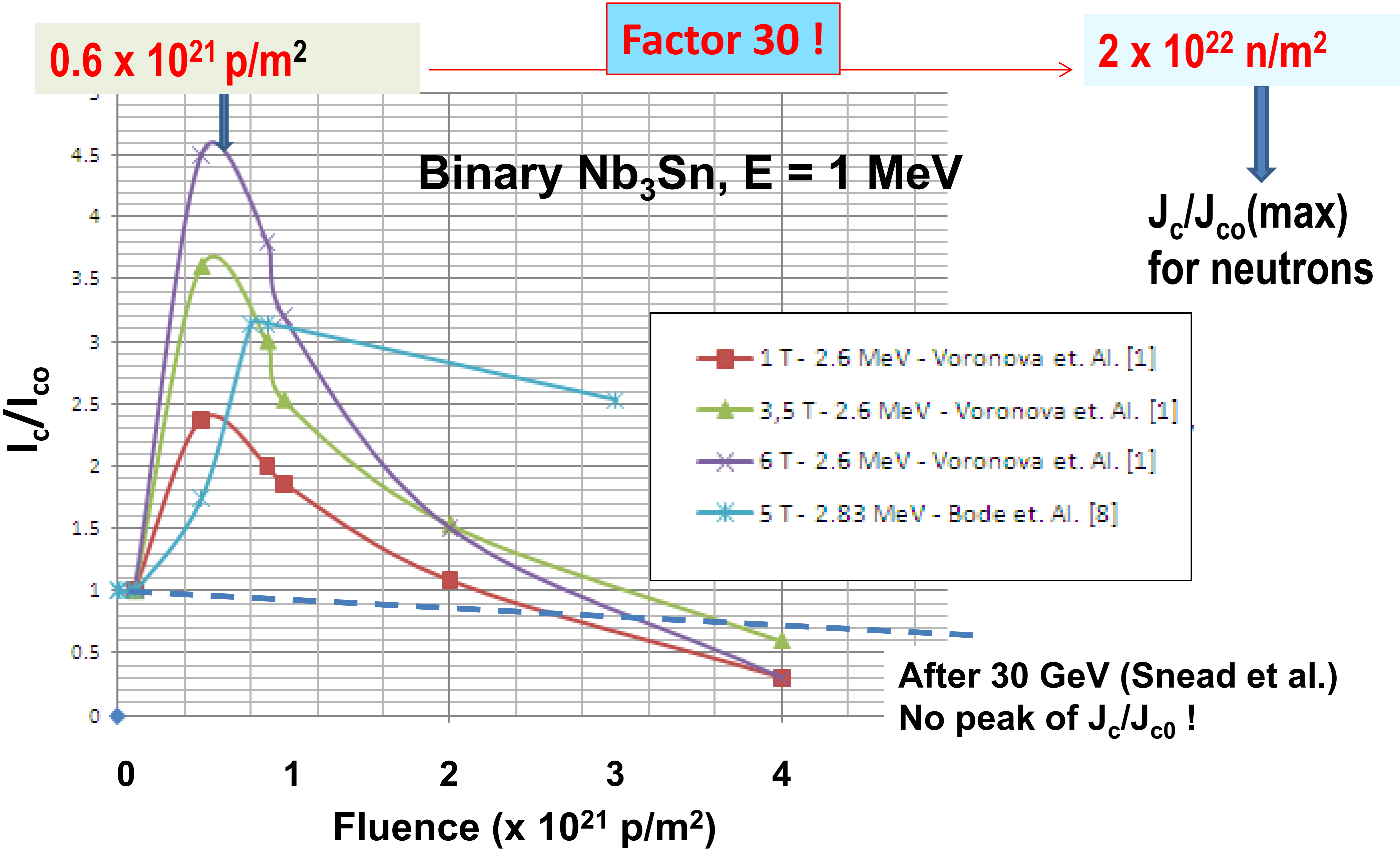
* calculations must be carried out to study combined irradiations
(taking into account the small values of DPA ($\sim 10^{-4}$ ), this may be reasonable)

# The effect of proton irradiation on $Nb_3Sn$ (thin films)

**Pion irradiations: fluxes presently not sufficient for reaching $J_c/J_{co}(max)$ In reasonable times**

**→ Calculations!**

# Maximum of $I_c$ after proton irradiation



## Binary $Nb_3Sn$ wires (and films):

**Maximum of $I_c$:** neutrons: $2 \times 10^{22}$ n/m$^2$

protons: $6 \times 10^{20}$ p/m $^2$

## Ternary alloyed $Nb_3Sn$ wires:

**Maximum of $I_c$:** neutrons: $3 \times 10^{21}$ n/m$^2$

protons: ?

**Still necessary to know behavior after proton irradiation, in spite of 4% fluence with respect to neutrons !**

**Even more necessary: behavior under pion irradiation. Total damage of protons + pions is expected to be comparable or higher to that caused by neutrons**

# Ongoing proton irradiations at Kurchatov Institute:

| | |
|---|---|
| Duration : | 24 months |
| Proton energy: | 35 MeV |
| Temperature: | 300K (+ heating due to proton impact) |
| Maximum fluence: | $1x\ 10^{22}$ p/m$^2$ |
| Tasks on irradiated wires: | $J_c$ by magnetization measurements*)**)<br>Electrical resistivity vs. T<br>$T_c$<br>TEM<br>Lattice parameters |
| Tasks on irradiated bulks: | Long range atomic order parameter*) |
| Calculations: | dpa calculations for proton irradiation |

*) Measurements will be performed at CERN
**) Transport $J_c$ on proton irradiated wires: will be done later

# Also presented at WAMSDO2011:

## II. Calculations

Particle Fluences on LHC magnets — Francesco Cerutti

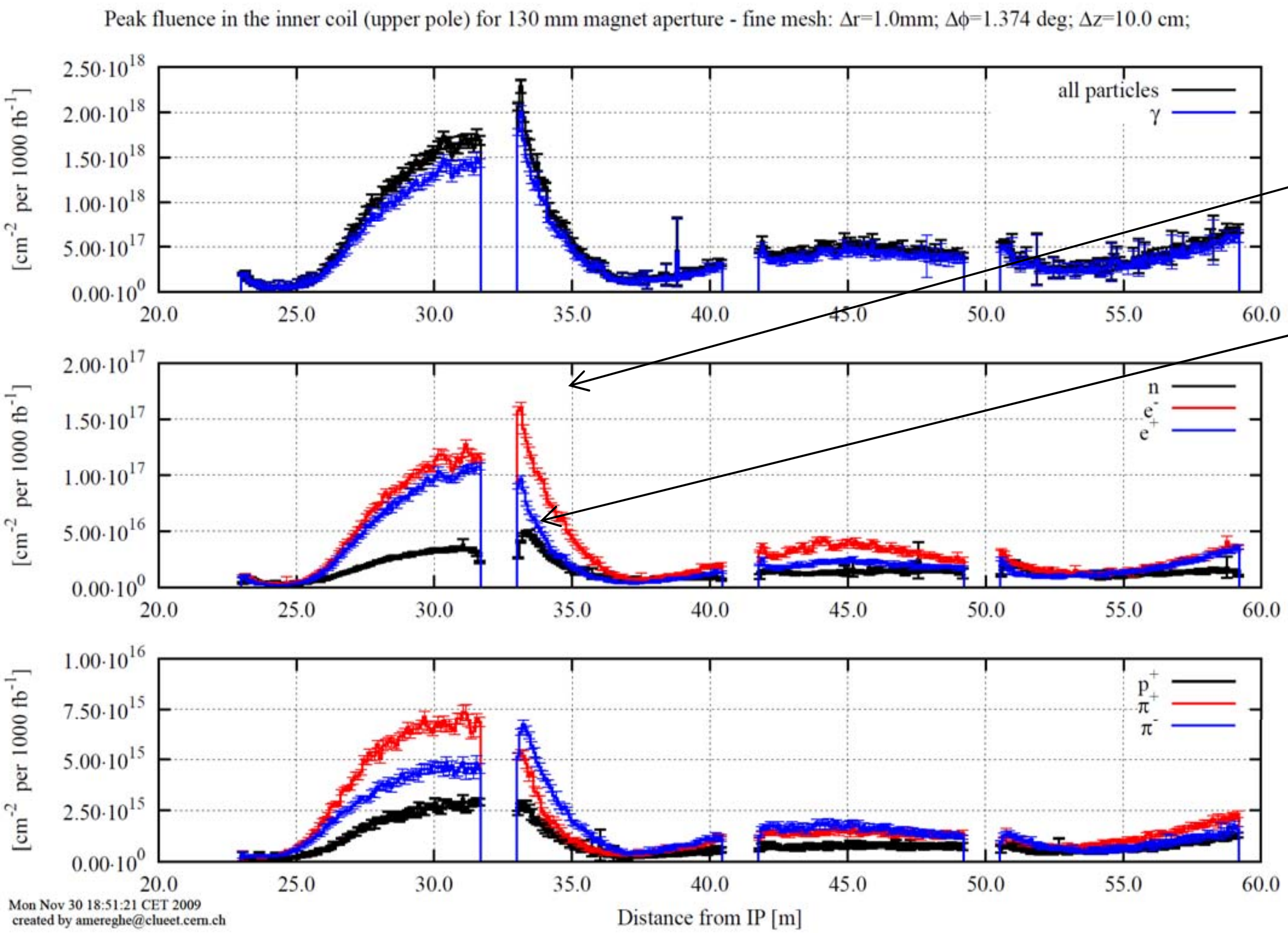
Exploring Parameter Space for Radiation Effects in SC Magnets — Nikolai Mokhov

# Peak fluence in the coils

in the inner cable

x 3

[cm$^{-2}$ per **1000 fb$^{-1}$**]




At 3'000 fb$^{-1}$: peak of

1.5 x $10^{21}$ n/m$^2$ /3000 fb$^{-1}$

and

a few $10^{20}$ pions/m$^2$/ 3000 fb$^{-1}$

| Track length fraction [ % ] | |
|---|---|
| photons | 88 |
| electrons / positrons | 7 |
| neutrons | 4 |
| pions | 0.45 |
| protons | 0.15 |

F. Cerutti

# Preliminary FLUKA calculations (without cold shielding)

Francesco Cerutti
(at the beginning of this talk)

| Track length fraction [ % ] | |
|---|---|
| photons | 88 |
| electrons / positrons | 7 |
| neutrons | 4 |
| pions | 0.45 |
| protons | 0.15 |

Over the HL-LHC target integrated luminosity (3000 $fb^{-1}$), triplet quadrupole cables and insulators will undergo the following radiation peak values:

**~ 100 MGy (dose)**

**~ $10^{-4}$ (DPA),**

**~ 1.5 x $10^{21}$ neutrons/$m^2$**

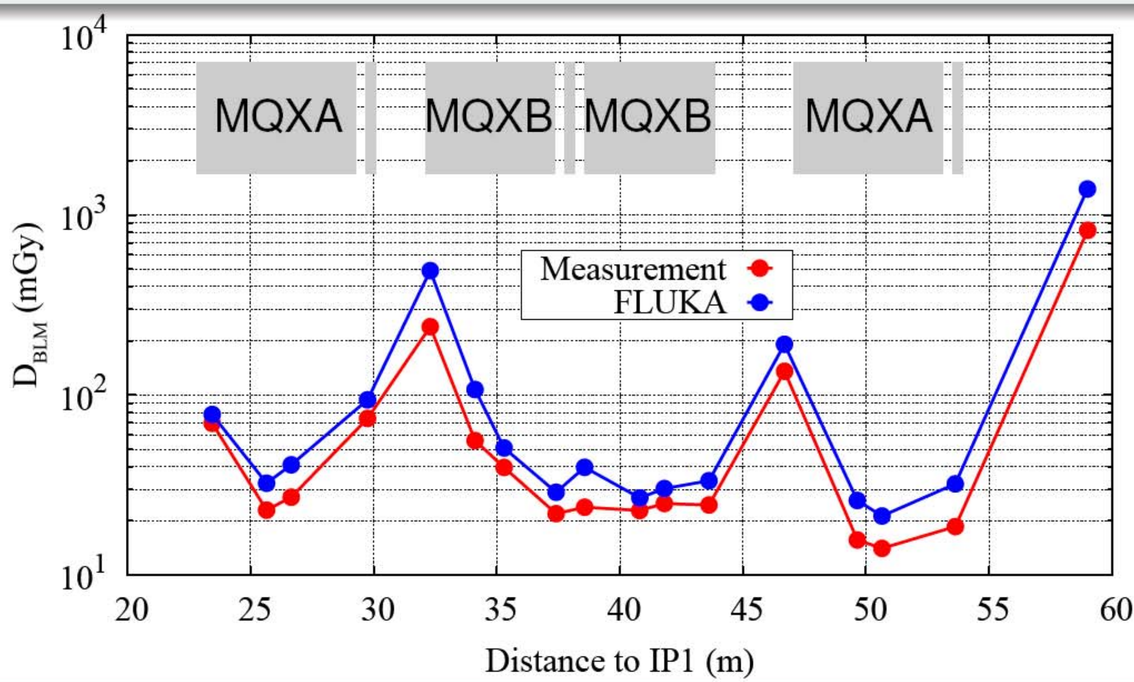
**~ $10^{20}$ pions/$m^2$**

# BENCHMARKING VS FIRST LHC EXPERIENCE [II]

stable collisions in **P1** at 7 TeV center-of-mass *on 2010 Oct 28*

## Time-integrated dose in BLMs

Measurement vs FLUKA (for an integrated luminosity of 6255.71 $nb^{-1}$):




- Relative pattern well reproduced, some discrepancies can be ascribed to missing geometry details (lessons learned from wire scanner simulations)
- **Systematic offset to be understood**, possible source of differences could be normalization (luminosity, total cross section), ...

**F. Cerutti**

# Calculation of DPA and NIEL

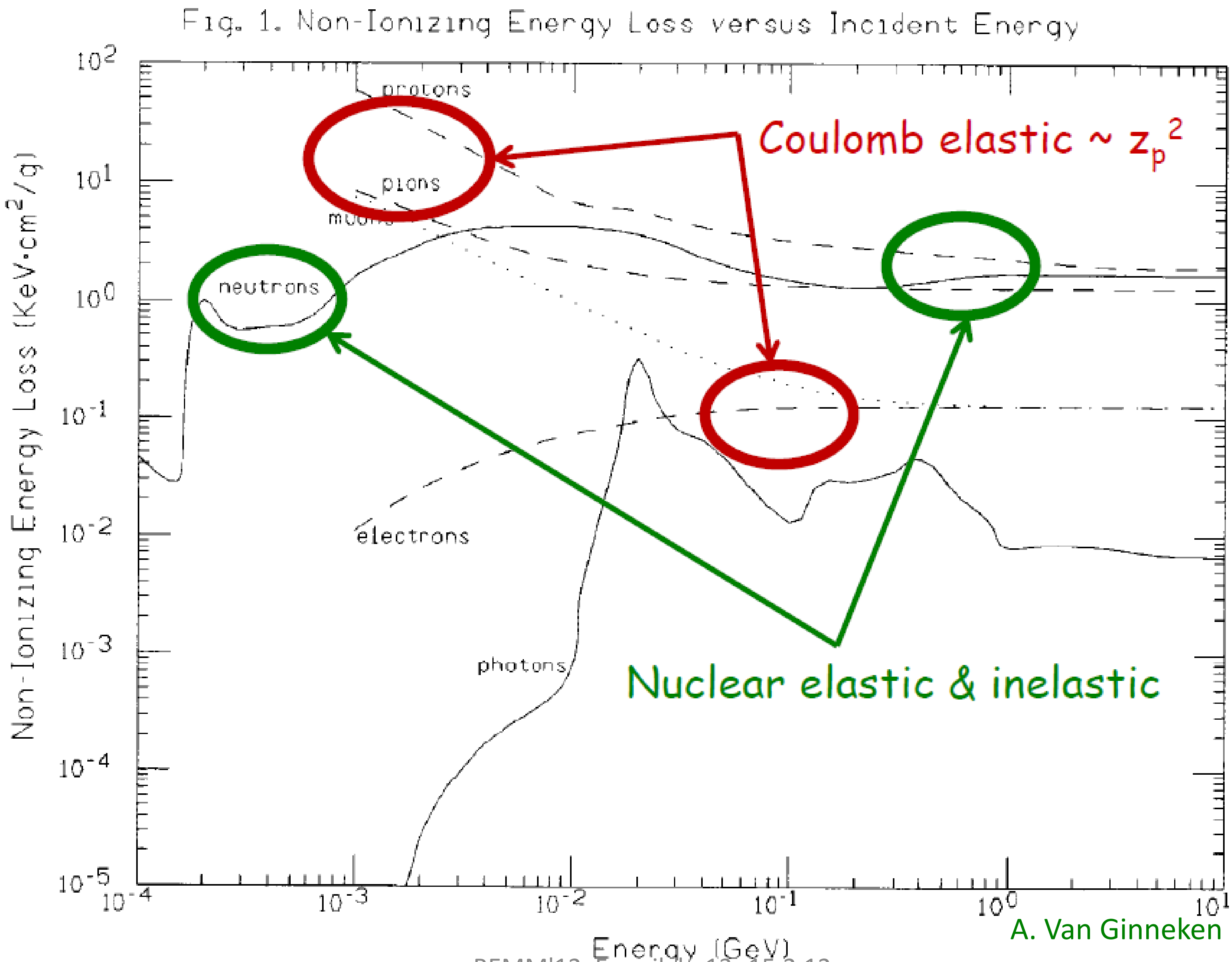
## Displacement per atom (DTA)

**Deterioration of critical properties of crystalline materials under irradiation is usually analyzed as a function of displacements per atom (DPA). The latter is a strong function of projectile type, energy and charge as well as material properties including its temperature.**

## Non-ionizing energy loss (NIEL)

**The non-ionizing energy loss (NIEL) is a quantity that describes the rate of energy loss due to atomic displacements as a particle traverses a material.**
**The product of the NIEL and the particle fluence (time integrated flux) gives the displacement damage energy deposition per unit mass of material.**

# DPA/NIEL vs Particle Type & Energy in Si



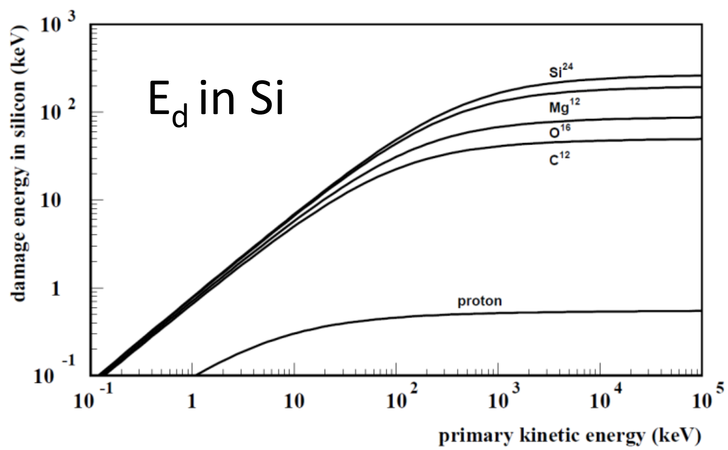

A. Van Ginneken

# DPA Model in MARS15 (in one slide)

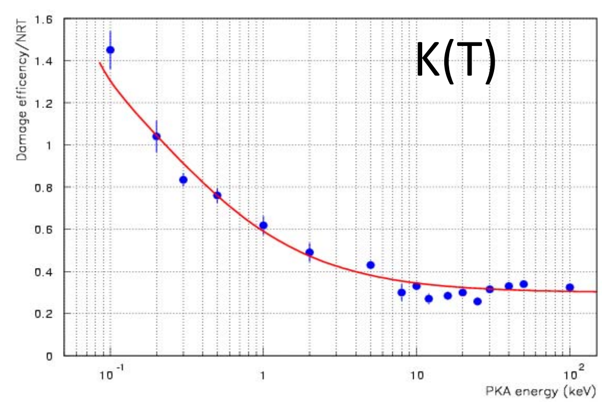
Norgett, Robinson, Torrens (NRT) model for atomic displacements per target atom (DPA) caused by primary knock-on atoms (PKA), created in elastic particle-nucleus collisions, with sequent cascades of atomic displacements (via modified Kinchin-Pease damage function **ν(T)**), displacement energy $\mathbf{T_d}$ (irregular function of atomic number) and displacement efficiency **K(T)**.

$$\sigma_d(E) = \int_{T_d}^{T_{\max}} \frac{d\sigma(E,T)}{dT} \nu(T) dT$$

$$\nu(T) = \begin{cases} 0 & T < T_d \\ 1 & T_d \le T < 2.5T_d \\ k(T)E_d / 2T_d & 2.5T_d \le T \end{cases}$$



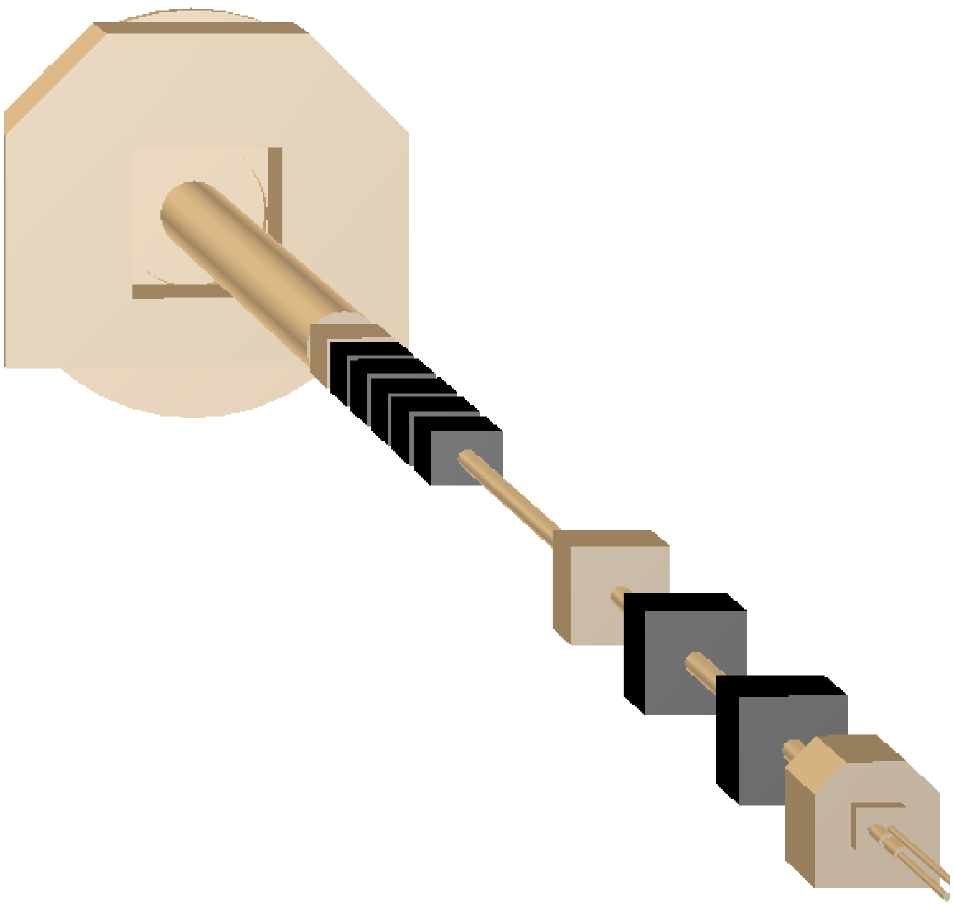

M. Robinson (1970)

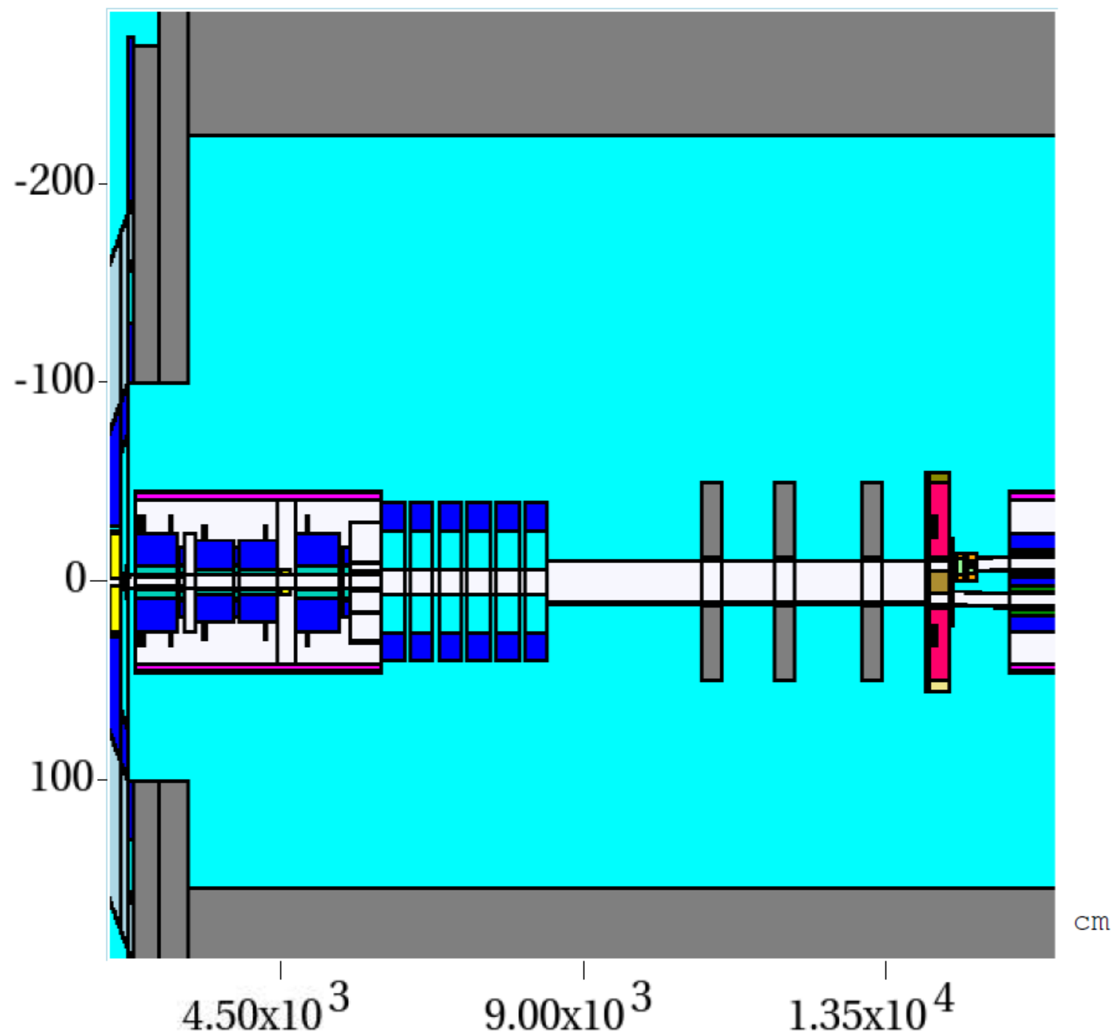



R. Stoller (2000), G. Smirnov

All products of elastic and inelastic nuclear interactions as well as Coulomb elastic scattering of transported charged particles (hadrons, electrons, muons and heavy ions) from 1 keV to 10 TeV. Coulomb scattering: Rutherford cross-section with Mott corrections and **nuclear form factors for projectile and target** (important for high-Z projectiles and targets, see next two slides).

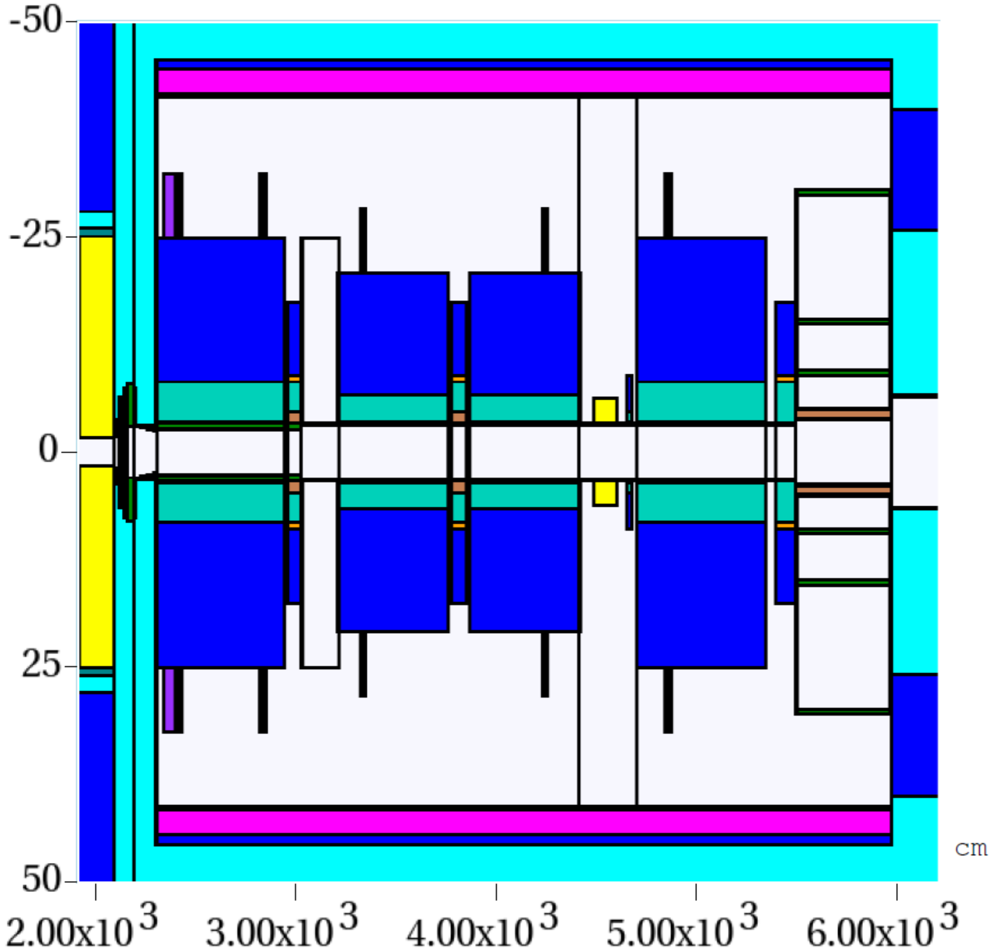
# LHC IR5 MARS15 Model

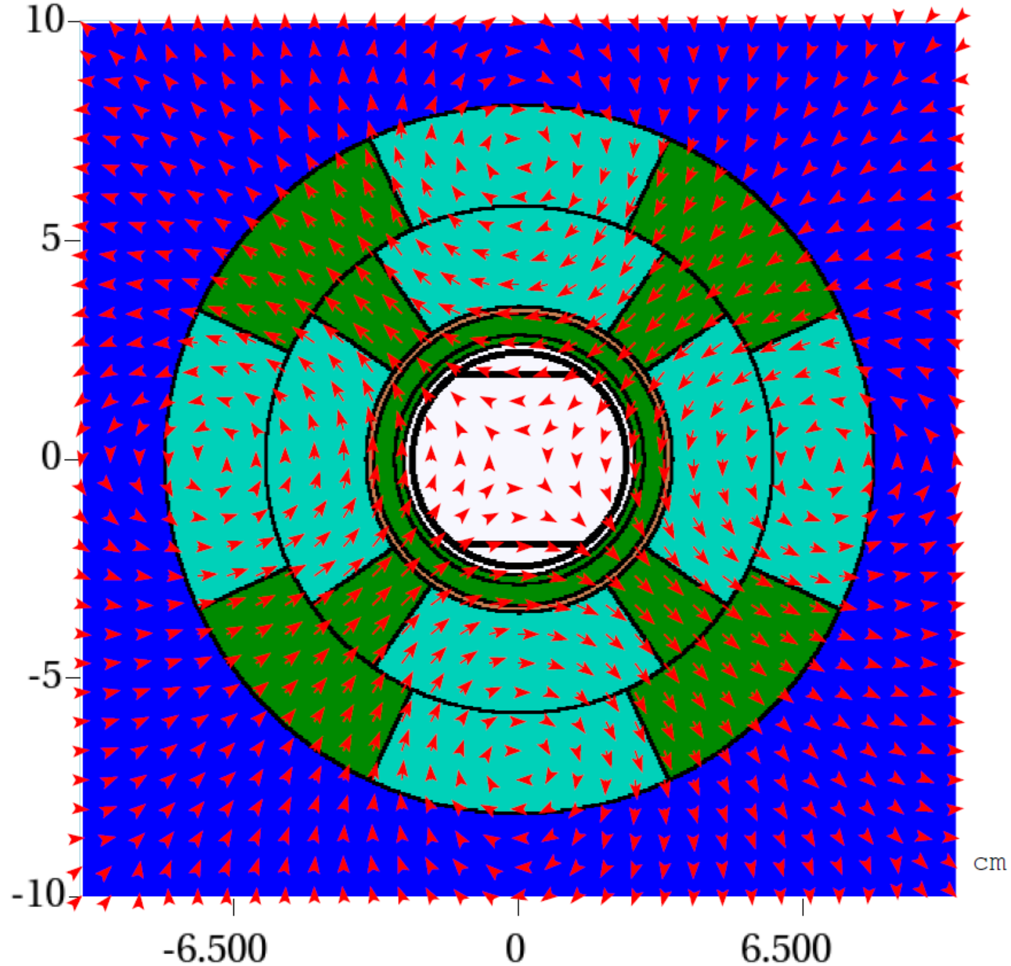





N. Mokhov

# Triplet MARS15 Model




**N. Mokhov**

# FLUKA 2006.3 and MARS15 (2007): Intercomparison

Total heat loads in the insertion region elements (W) for upgrade luminosity L=10*L0

| | FLUKA | +/- (%) | MARS | +/- (%) | Ratio FLUKA/MARS |
|---|---|---|---|---|---|
| TAS | 1853.7 | 0.5 | 1827.3 | 0.1 | 1.01 |
| Beam pipe | 89.1 | 1.0 | 97.9 | 0.4 | 0.91 |
| Q1 cable | 158.0 | 0.6 | 159.1 | 0.2 | 0.99 |
| yoke | 96.3 | 0.9 | 78.5 | 0.4 | 1.23 |
| aluminium layer | 2.3 | 0.6 | 2.4 | 0.5 | 0.98 |
| mylar insulation | 19.5 | 0.8 | 20.4 | 0.3 | 0.96 |
| stainless steel vessel | 16.8 | 0.8 | 17.3 | 0.3 | 0.97 |

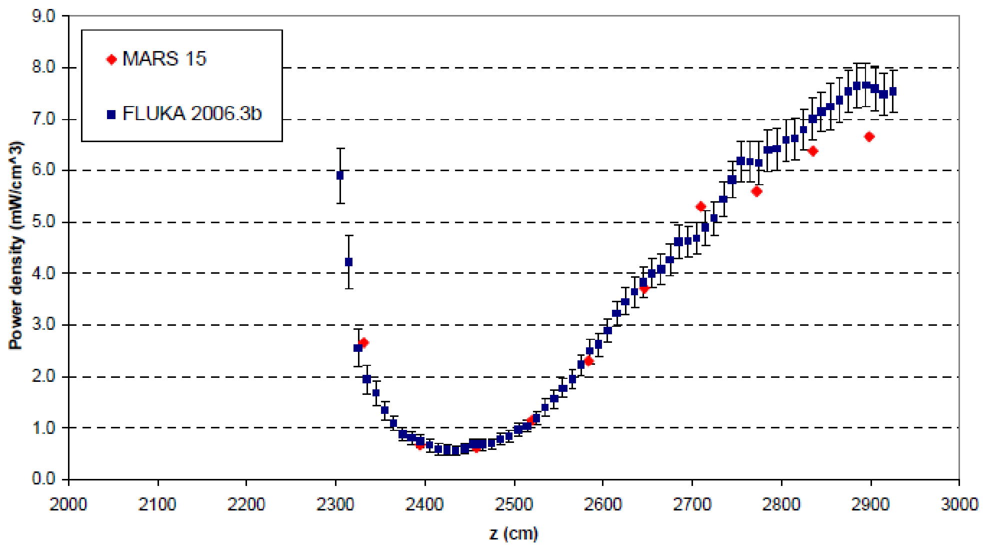



Figure 8: Azimuthal averaged power density in cable1 along Q1

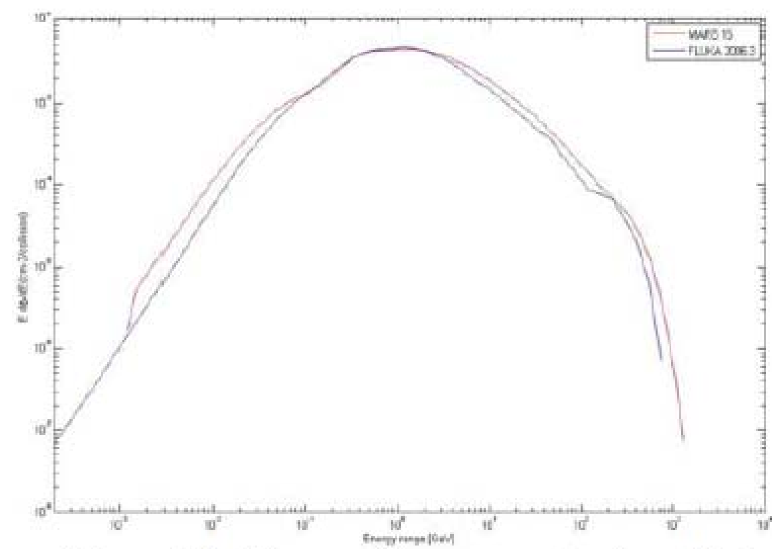
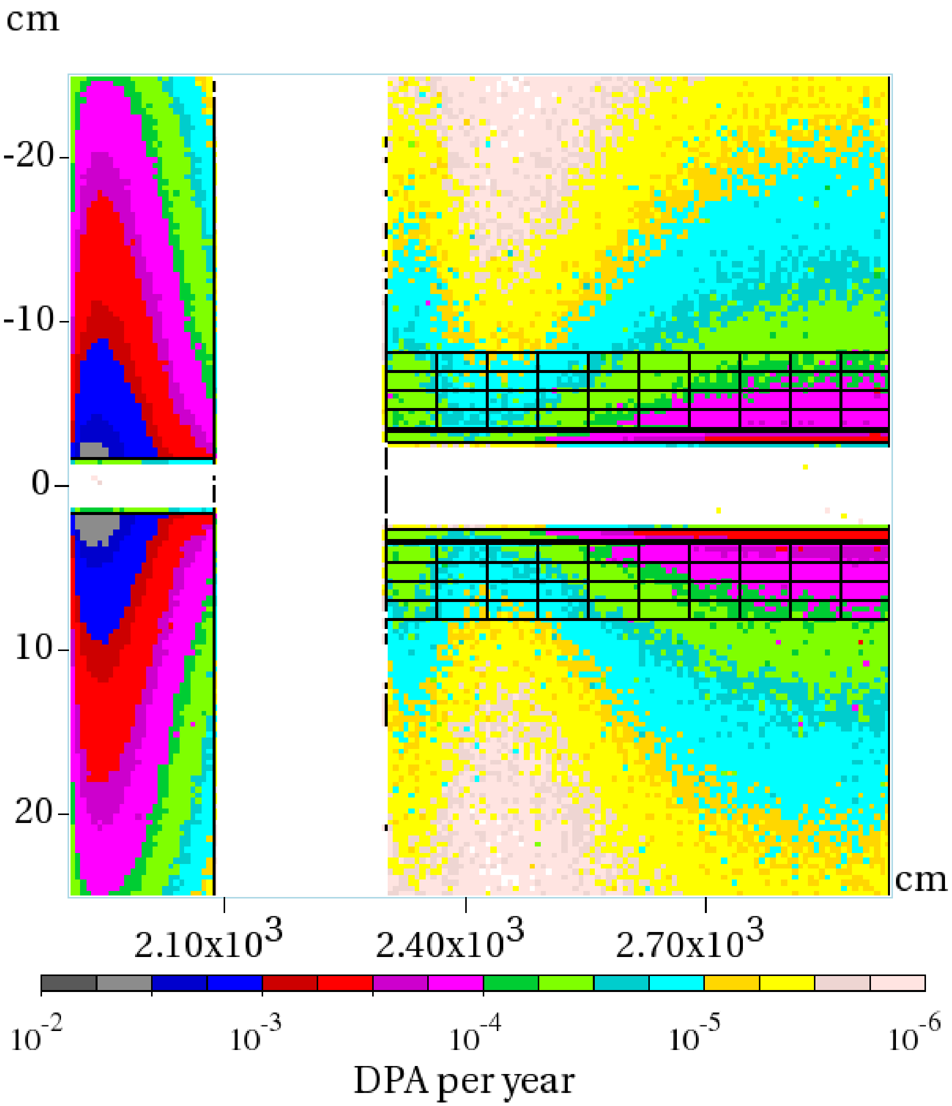
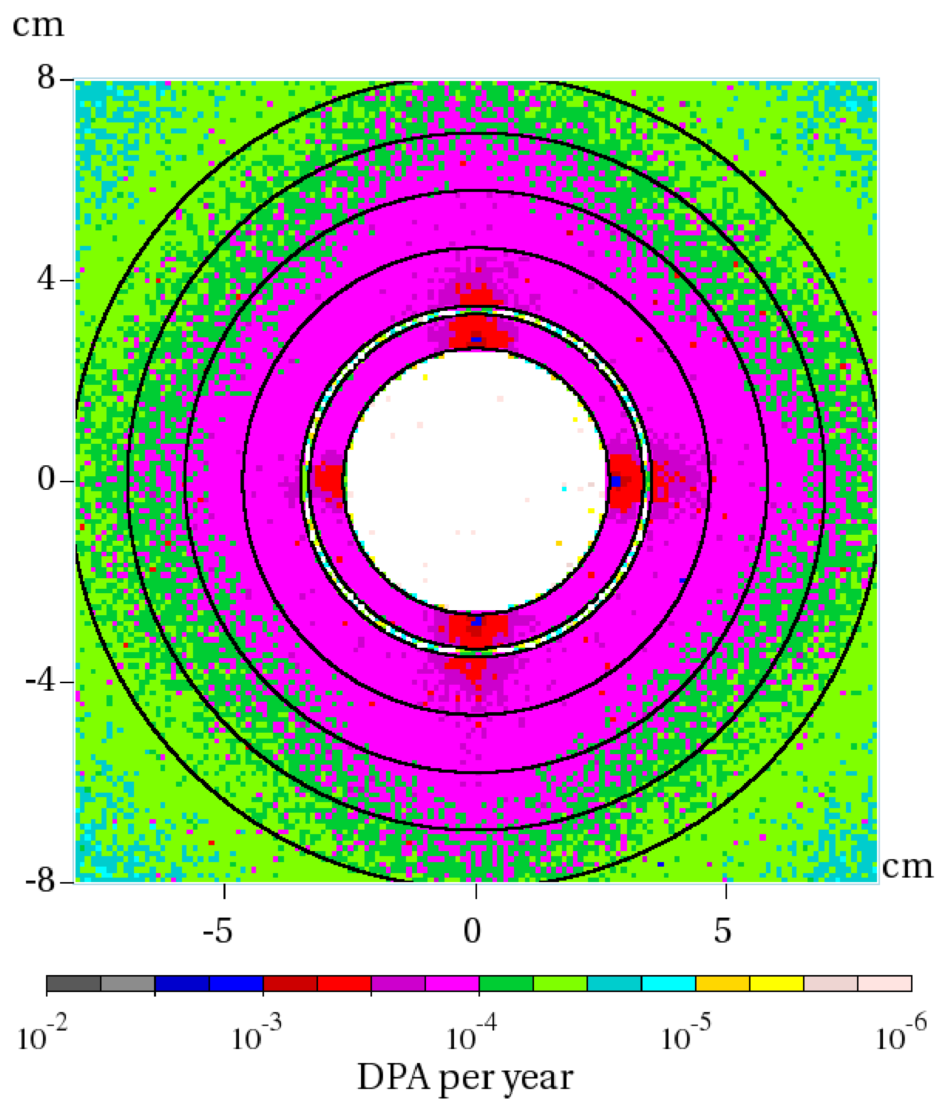


Figure 12: Pion and kaon spectra in cable1

**N. Mokhov**

# DPA


cm
-20
-10
0
10
20
cm
2.10x10^3
2.40x10^3
2.70x10^3
10^-2
10^-3
10^-4
10^-5
10^-6
DPA per year


cm
8
4
0
-4
-8
cm
-5
0
5
10^-2
10^-3
10^-4
10^-5
10^-6
DPA per year

N. Mokhov

# Mean Energy, Flux and DPA averaged over 4 Hot Spots (L, R, T, B)

| Particle j | <E> (GeV) | RMS (GeV) | Flux ($cm^{-2}s^{-1}$) | DPA/yr | DPA (%) |
|---|---|---|---|---|---|
| p | 2.93 | 10.7 | 1.3e8 | 1.75e-5 | 5 |
| n | 0.22 | 3.7 | 2.3e9 | 8.24e-5 | 26 |
| p, K | 13.8 | 41.6 | 5.4e8 | 4.78e-5 | 15 |
| m | 11.3 | 19.7 | 6.3e5 | 1.70e-9 | - |
| g | 0.018 | 0.35 | 8.6e10 | ~2.e-5 | 6 |
| e | 0.077 | 0.5 | 9.8e9 | 2.47e-5 | 8 |
| Sub-thresh. | | | | | 40 |

Sub-thresh.: particles with E<100 keV + all fragments

N. Mokhov

# Summary (calculations)

- Independent FLUKA and MARS results on energy deposition (mostly from EMS) for inner triplet coils are in agreement within a few %, therefore one can predict dose in insulator with same accuracy.

- Uncertainties on DPA predictions in superconductors can be as high as a factor of 2 to 3.

- MARS15 results are obtained on composition of particle flux and DPA in the hottest spots of the final focus quadrupole superconducting coils.

- The major contributors to DPA are sub-threshold particles (40%), neutrons > 100 keV (26%) and pions (15%).

# Estimated total peak fluence in LHC (3'000 $fb^{-1}$)

**Taking into account**

- the calculations
- the observed difference between neutron and proton irradiation effects (factor ≤ 30 between fluences at $J_c/J_{co}$ for 1 MeV)
- the smaller, but not negligible effect of electrons and photons (which have considerable DPA)

→ **Estimated total peak fluence, comprising neutrons and charged particles (protons and pions) is equivalent to the known effects of neutron fluence between 3x$10^{21}$neutrons/$m^2$ and >5x$10^{21}$ neutrons/$m^2$**

→ **Reduction of lifetime of quadrupoles**