Some study progresses on the EMuS target

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(On behalf of the EMuS Group)

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Outline

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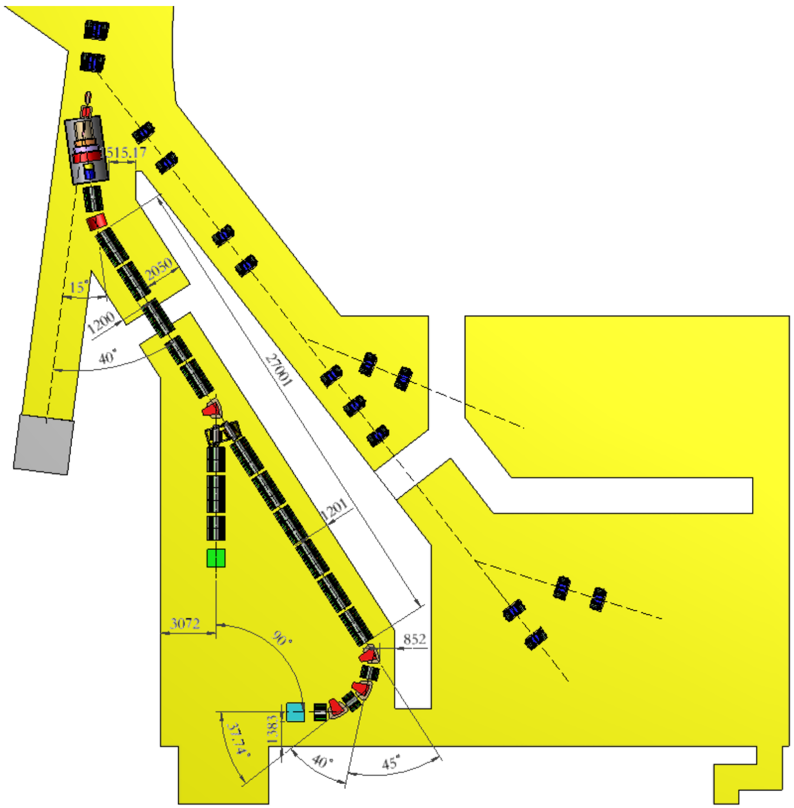
    - ❑ Target
    - ❑ Surface muons
  - ❑ Radiation on solenoids
- ❑ **Summary**



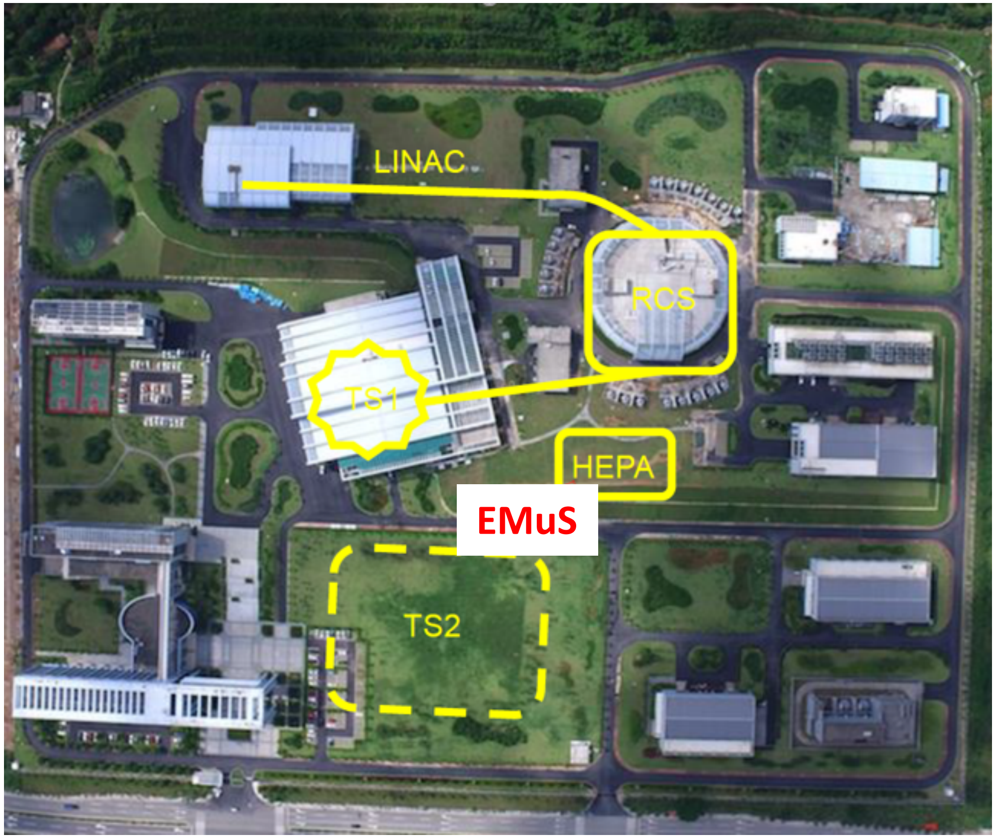
Overview of the EMuS

- **An Experimental Muon Source (EMuS) at China Spallation Neutron Source (CSNS), to carry out or explore**
  - MOMENT R&D (target, muon beamline, etc.)
  - muSR applications
  - Neutrino cross-section measurements
  - Muon physics

- **Design and R&D supported by a NSFC Key Instrument Development project: 2016.1-2020.12**

Layout of the CSNS

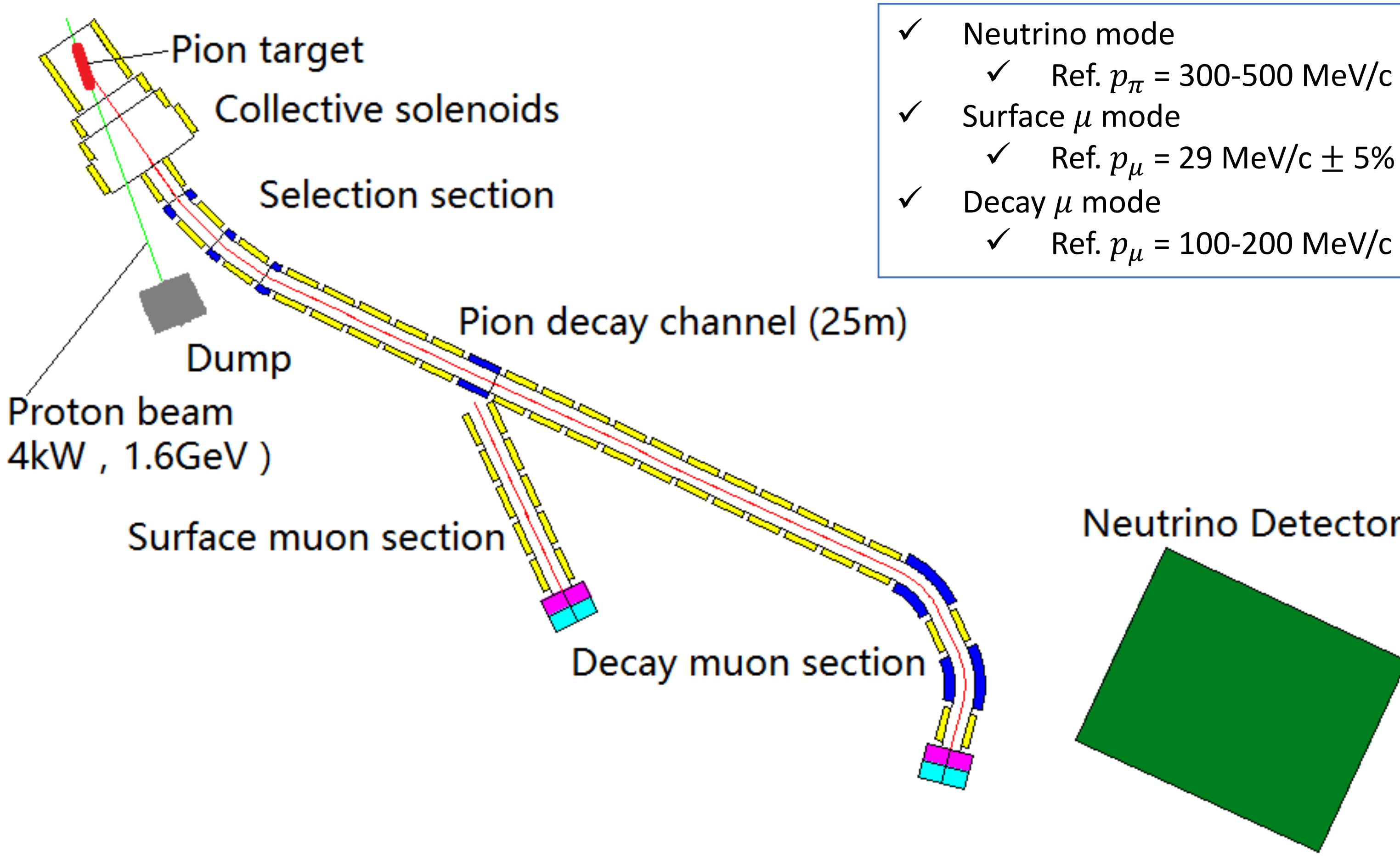
First neutron beam obtained on Aug. 28th



HEPA: High Energy Proton Experimental Area

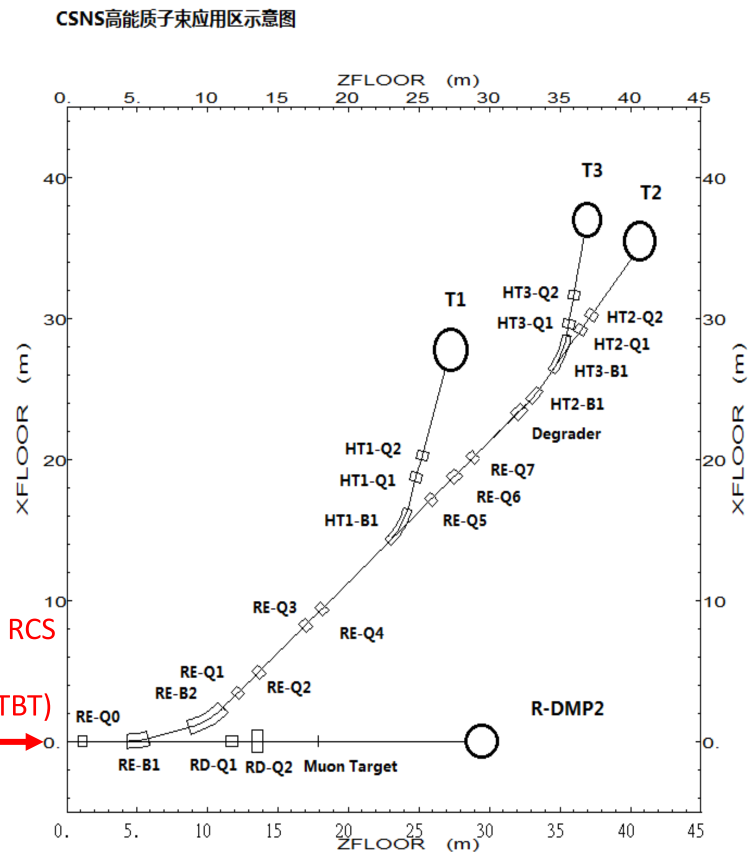
Parameters	CSNS-I	CSNS-II
Linac Energy (MeV)	80	250
RCS Energy (GeV)	1.6	1.6
Power (kW)	100	500
Beam current (μA)	62.5	312.5
Power of EMuS (kW)	4	20
Bunches per pulse	2	2
Length of one bunch (ns)	70	70

Layout of the EMuS

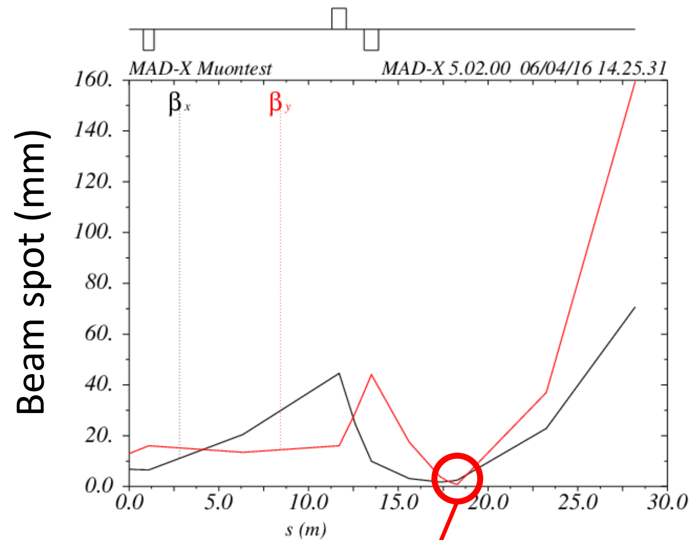


- ✓ Neutrino mode
  - ✓ Ref. p_π = 300-500 MeV/c
- ✓ Surface μ mode
  - ✓ Ref. p_μ = 29 MeV/c $\pm$ 5%
- ✓ Decay μ mode
  - ✓ Ref. p_μ = 100-200 MeV/c $\pm$ 10%

The proton beamline



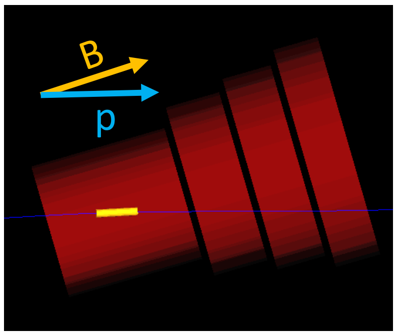
Beam from the RCS to target beam transfer line (RTBT)



Min. beam size @ target: $\sigma_x = \sigma_y = 5.2$ mm

Beam deflection

The proton beam is deflected by the magnetic field in SC



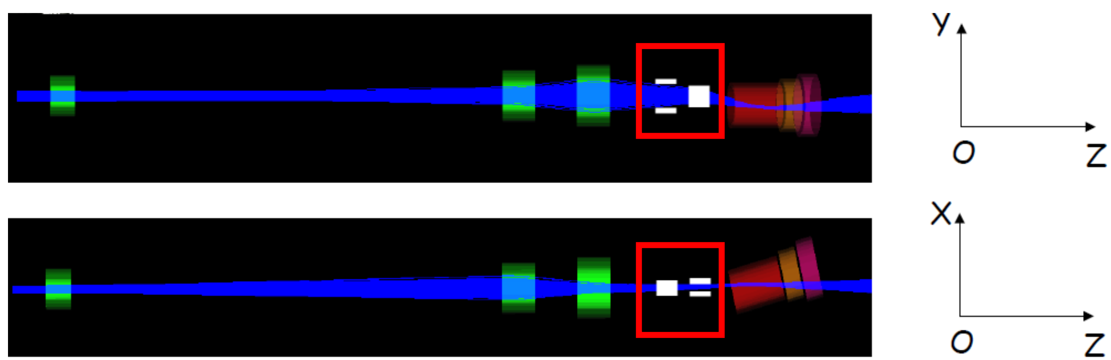
Proton beam is deflected in both horizontal and vertical direction

Angle of the solenoid	Deflection angle in X direction	Deflection angle in Y direction
5°	0.54°	2.24°
10°	1.08°	4.49°
15°	1.61°	6.77°
20°	2.15°	9.09°

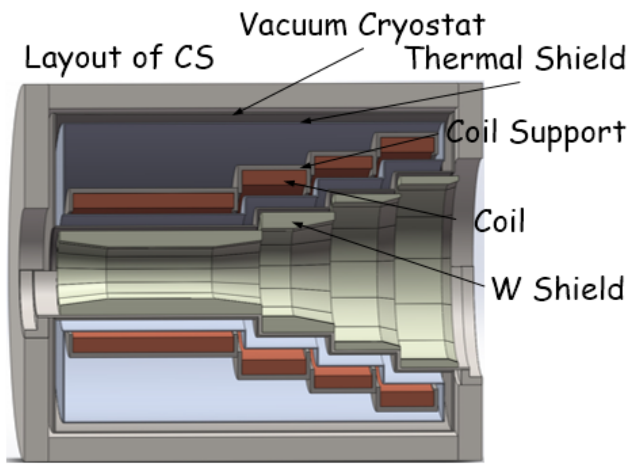
Estimation of deflected angle

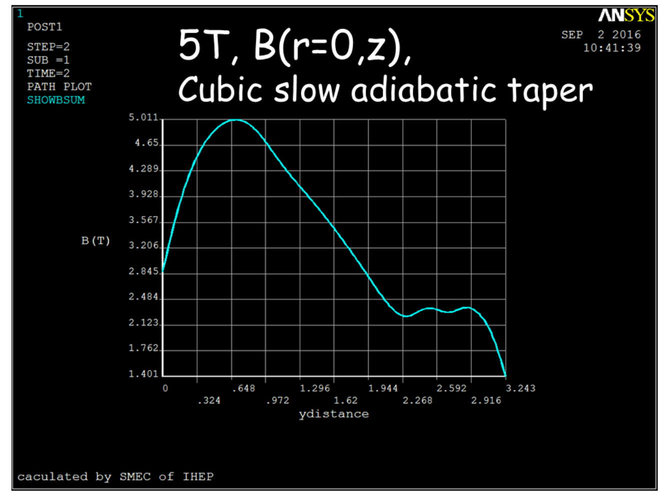
Correct the beam by adding **two dipoles** before the SC

- ✓ L_{dipole}: 0.5 m
- ✓ Bending angle: less than 5 deg
- ✓ Magent field: less than 1.37 T



Target station



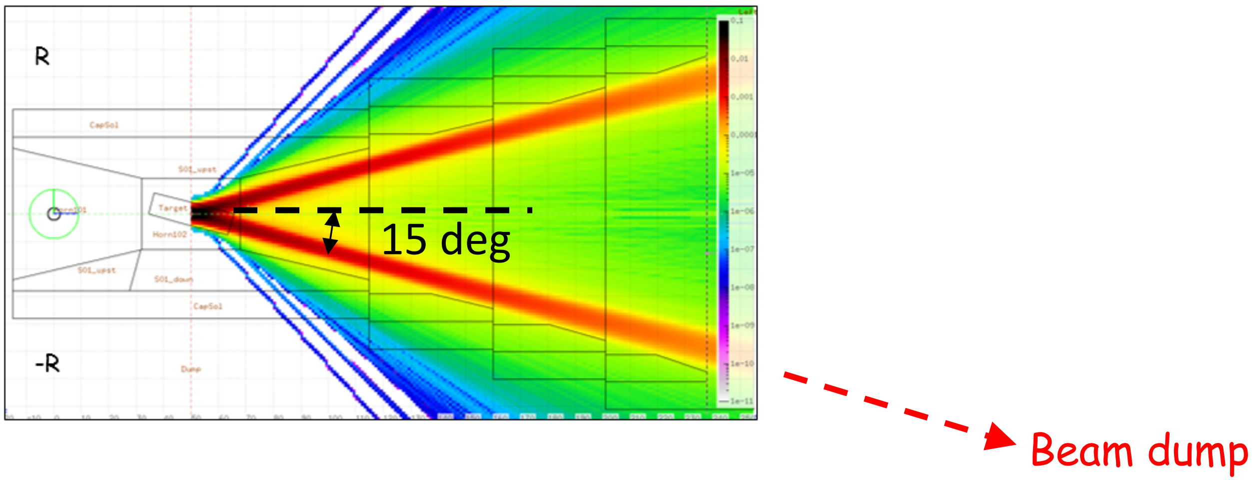


Field pattern by 4 coils, B = 5T→3T cubic, L = 2.5 m, 1st-coil aperture ~ 1 m

- **Baseline: Conductor NbTi/Aluminum stabilized Rutherford cable**
  - Option: Conductor NbTi/Copper Matrix <-> more prone to radiation damage
- **1st-coil aperture**
  - Defines the physical parameters of the whole capture system
  - Cost sensitive, R&D prototype set to 1 m
- **5T→3T slow type adiabatic taper**
  - High field necessary for pion (neutrino) mode
  - Low field for surface muons –> less decay muon contamination <-> higher beam polarization

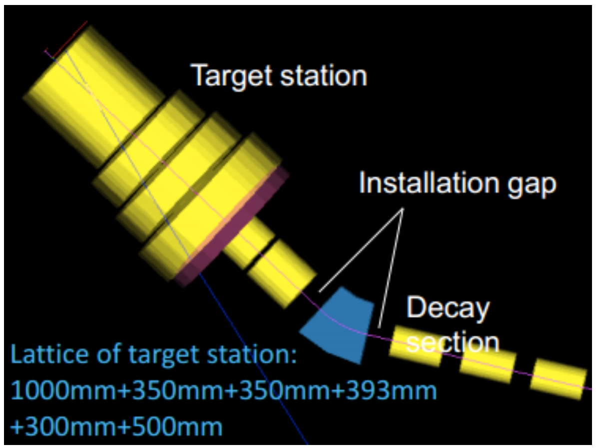
Target station (II)

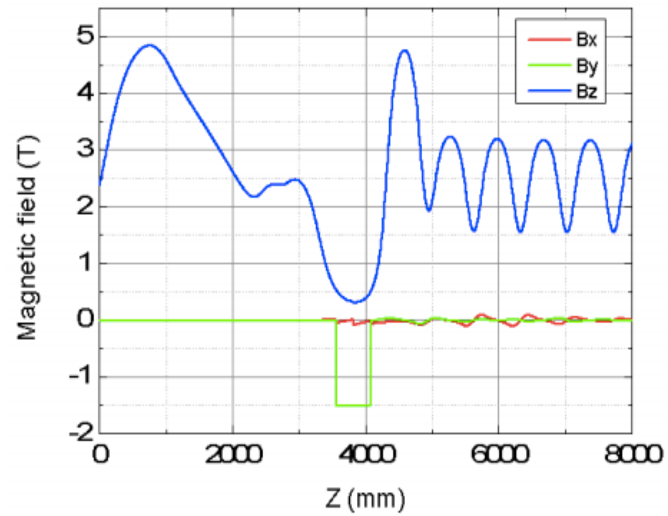
spent protons flux p / cm² / p.o.t.
P > 2 GeV/c



- **Proton beam & target tilted in respect to magnetic axis, $\theta_p = 15^o$**
  - Facilitates the spent proton extraction and separation from muons and pions beams & increases the surface muon flux
  - Limited by 1st-coil aperture
- **Triangle edge shapes defined by spent proton flux contours in FLUKA & G4beamline**
  - Field, no-field accidental case studied for spent protons
  - same polar angle but different azimuthal at exit -> shape triangular all shields over the azimuth
- **W shielding, thickness 15->5 cm -> limited by coils apertures & spent protons direction**

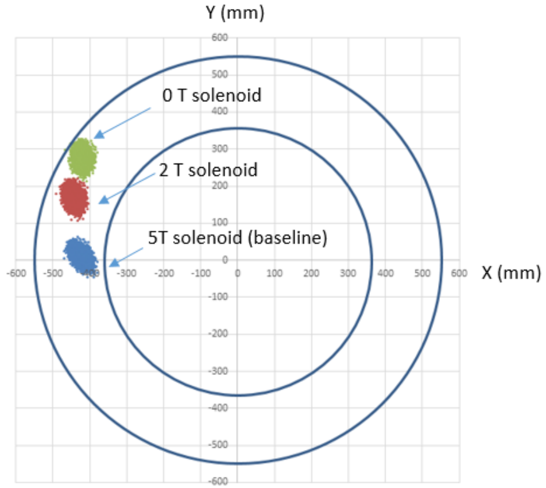
Momentum selection section





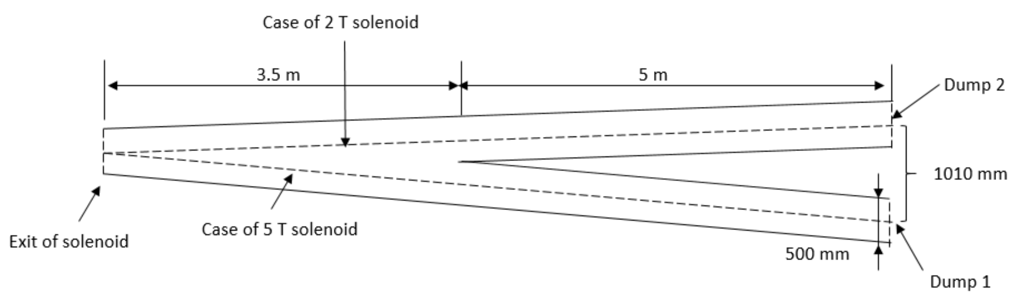
Dipole parameters	Value	Note
Field	-1.5 T	
Height	310mm	
width	310mm	
Radius of curvature	1000mm	
Bending angle	30degree	Length of ref. orbit 523.955mm
installation gap	250mm	
Lattice of decay section	3T	500mm （ solenoid ） +200mm（drift）

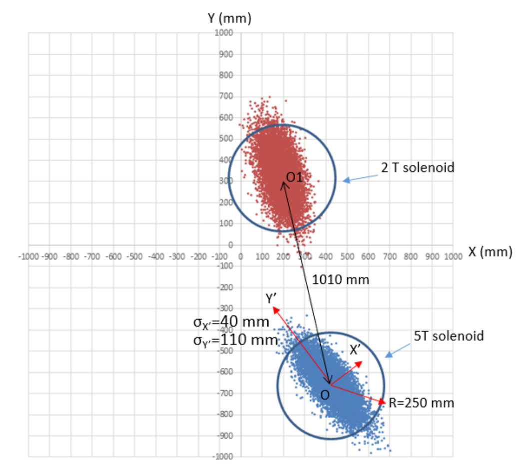
Beam dump



Proton beam distribution at the **Exit of solenoid** (when proton through target)

- ✓ The proton beam distributes differently for 5T/2T mode
- ✓ Need two dump holes @ 8.5 m

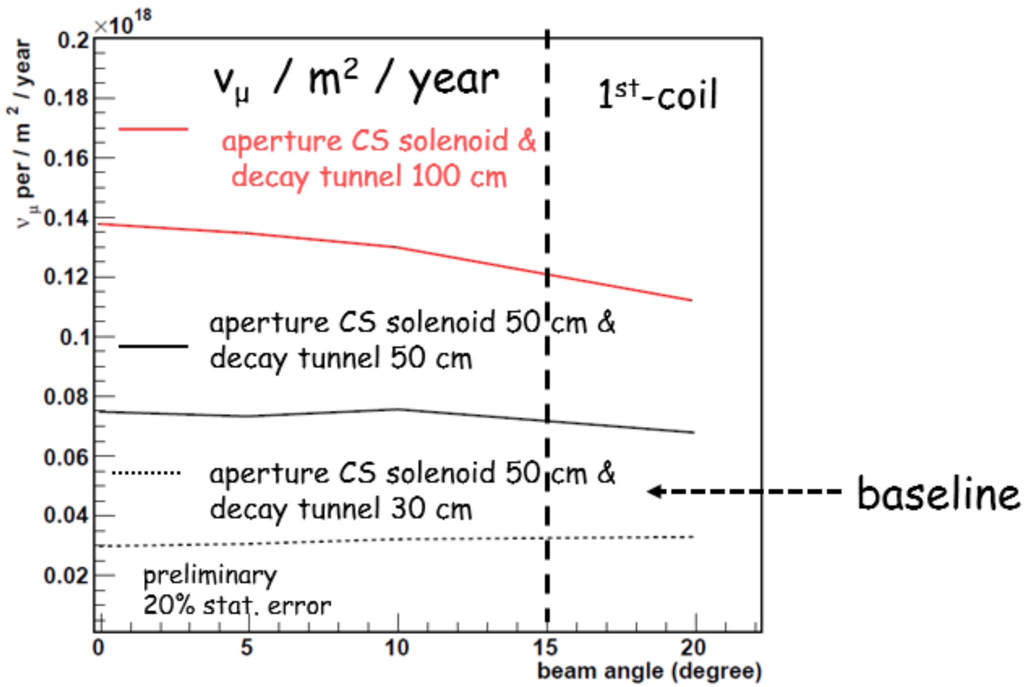




Proton beam distribution at **beam dump** plane (when proton through target)

Neutrino beam

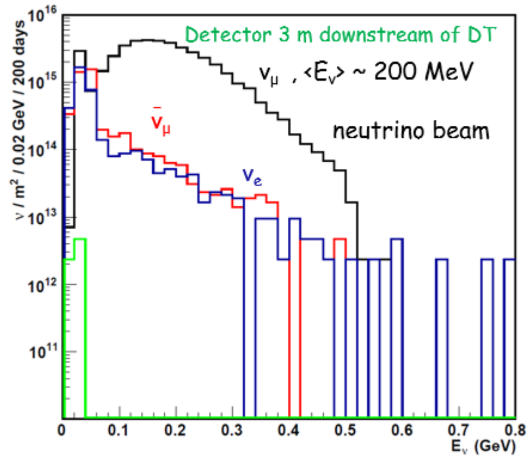
ν_μ / m^2 / year as function of proton beam/target tilt
for different 1st-coil and decay tunnel apertures

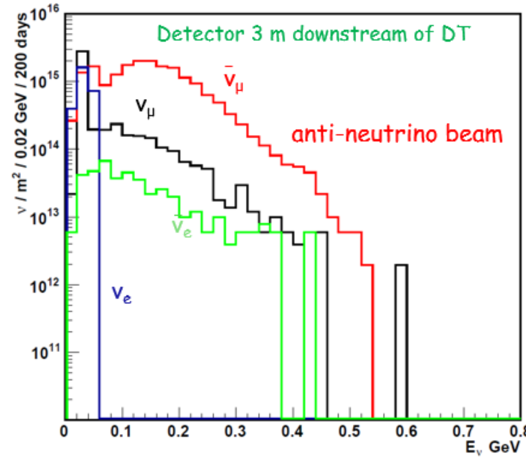


- ✓ > 10^{16} ν_μ / m^2 / year at 3 m upstream of the decay tunnel
- ✓ higher apertures higher fluxes <-> x5 for 100 cm apertures

ν-fluxes at 3 m

Decay Tunnel (L-25 m, aperture - 30 cm)

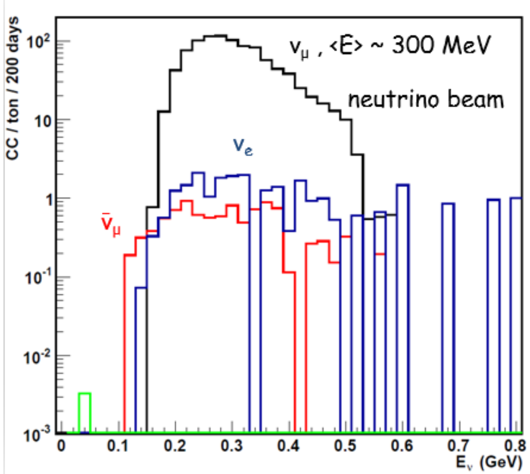


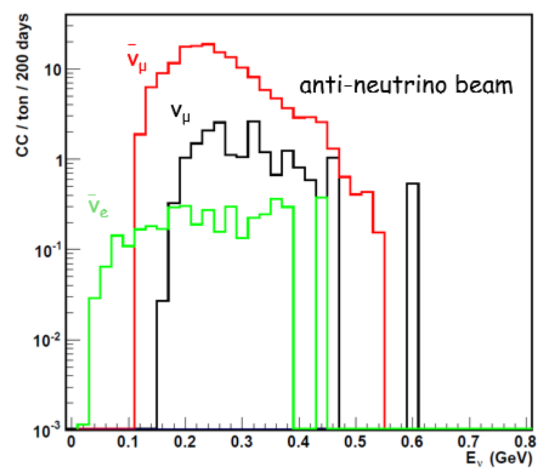


1-8% stat. error, fluka	**neutrino beam**		**anti-neutrino beam**	
	N_ν ($\times 10^{16}$) / m^2 / 200 days		N_ν ($\times 10^{16}$) / m^2 / 200 days	
	> 53 MeV	%	> 53 MeV	%
ν_μ	3.78	94.5	0.15	8.5
$\bar{\nu}_\mu$	0.13	3.2	1.57	89
ν_e	0.09	2.3	-	-
$\bar{\nu}_e$	-	-	0.04	2.5

Charged Current events

xs from water target





1-8% stat. error	**neutrino beam**		**anti-neutrino beam**	
	CC / ton / 200days at 3m	%	CC / ton / 200days at 3m	%
ν_μ	959	96.5	18	10
$\bar{\nu}_\mu$	10	1	155	87.6
ν_e	25	2.5	-	-
$\bar{\nu}_e$	0.004	-	4	2.4

Design optimization

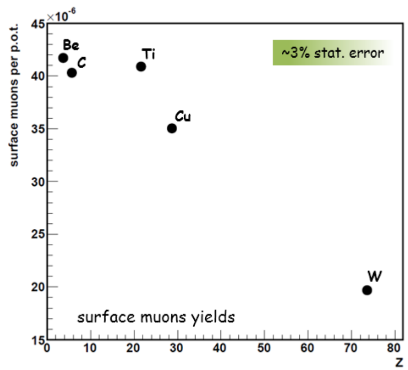
- **Besides the neutrino beam, EMuS is intended to do a lot of things (muSR, nuclear physics, muon rare decays, muon structural detection and imaging etc.)**

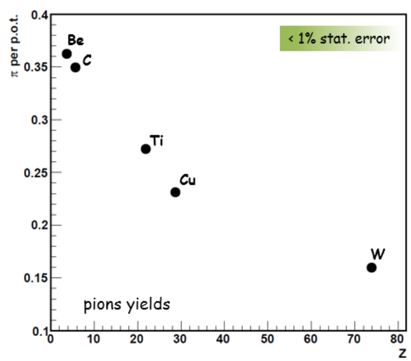
- **Among them, MuSR is one of the most important motivation. MuSR has wide applications in condensed-matter physics, materials science, chemistry, biological macro-molecules etc.**

- **Studies are carried out for muSR optimization**
  - Figures of merit: Intensity x $(\text{Polarization})^2$ with at least 50% polarization for μSR

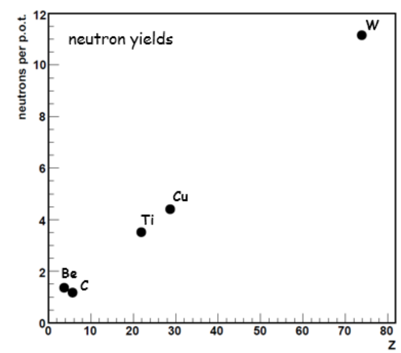
Target optimization (I): Material

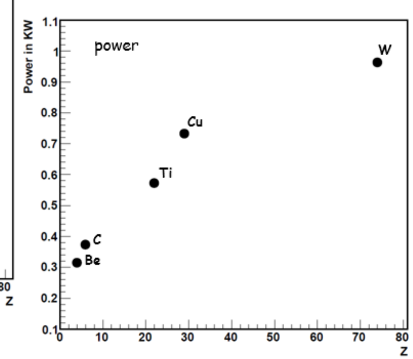
yields as function of Z
for λ_I of different target materiel





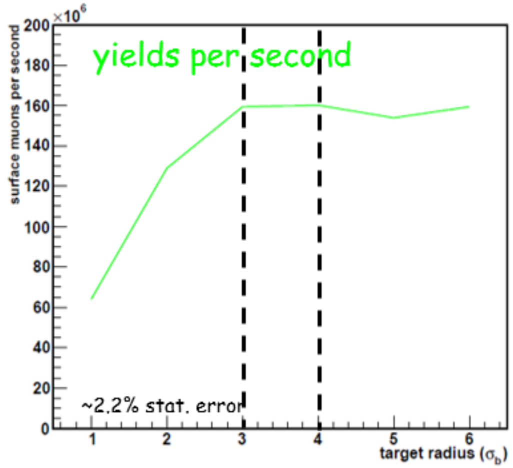
neutron yields & power
for λ_I of different target materiel

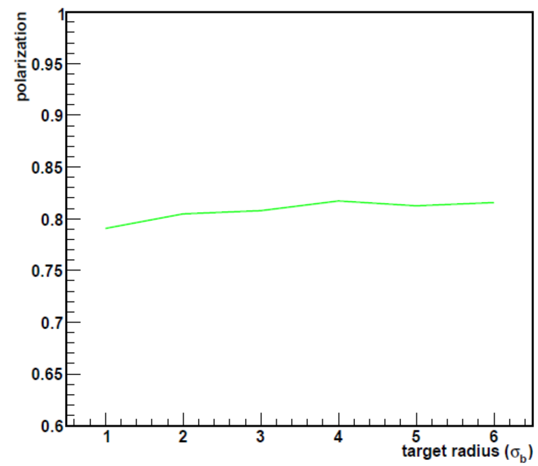




- **Lower Z materials as C, Be have (per nuclear interaction length)**
  - higher yields at 1.6 GeV
  - lower radiation and power densities deposited
  - only reason –if any- is the smaller length/volume → compact solenoid e.g. for W length ~ 20 cm ($2\lambda_I$)

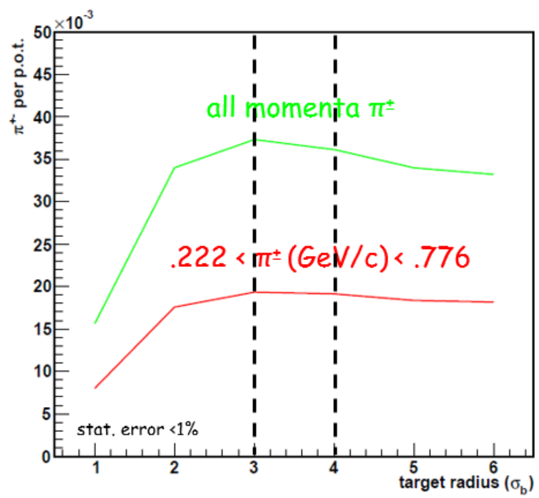
Target optimization (II): Radius





Surface muon yields and polarization

- Yields reach maximum for r = 3-4 σ_b
- Polarization is stable

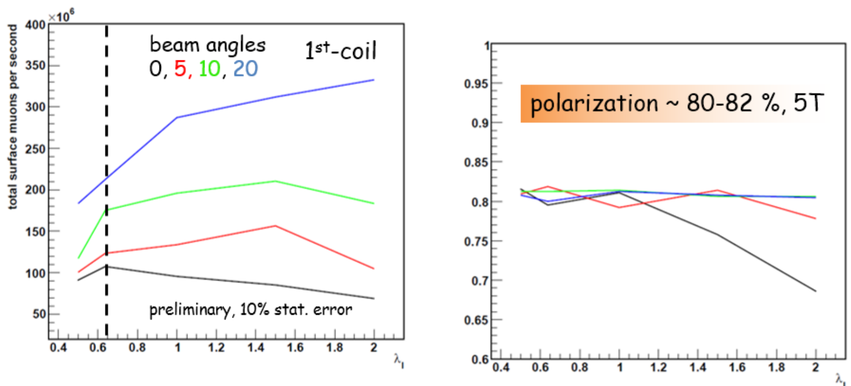


Pion yields

- optimal r = 3-4 σ_b for the pion production

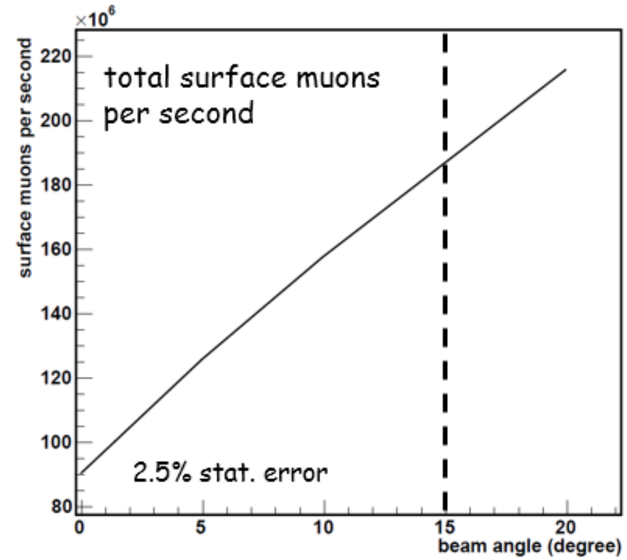
Target optimization (III): Length and tilt

C: total surface muons as function of λ_I (47 cm)
for different beam angles



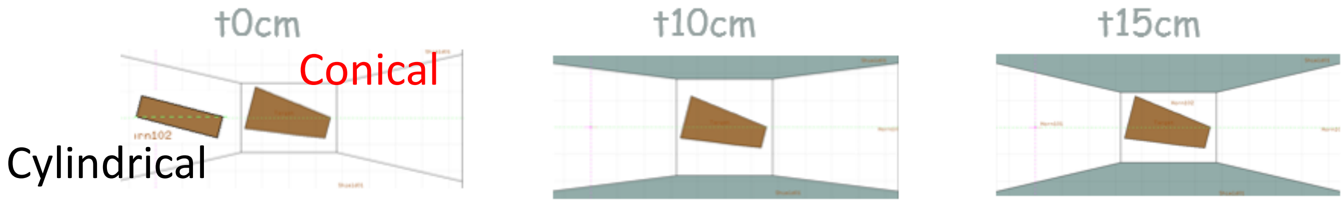
- higher beam angles increase by a good factor the yields
- no-difference in yields to the high aperture solenoid due to the small wavelength and radius of the helix

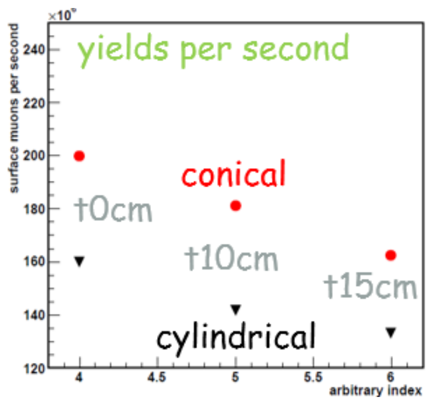
surface muons
(muons from pions decay at rest) :
- P_π = 0 MeV
- μ^+
- 27 MeV/c < $p_{\mu+}$ < 29.8 MeV/c

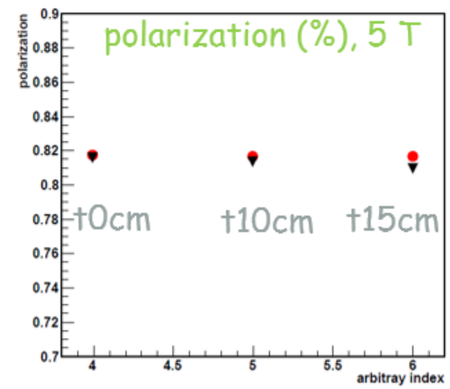


- Length and tilt are limited by the aperture of the coils
- Total surface muons 10^8 / second
- Polarization along beam axis ~ 80-82%

Target optimization (IV): Shape

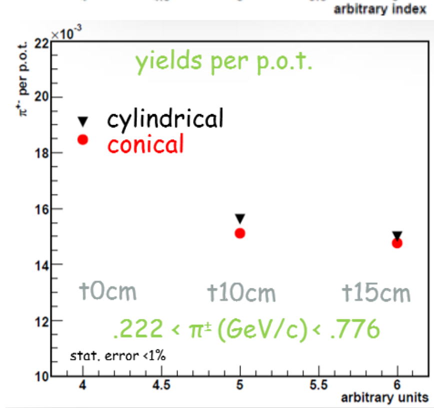


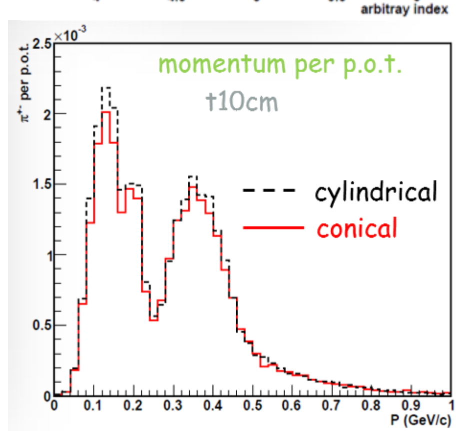




Surface muon yields

- ✓ +25 % with conical shape
- ✓ same polarization at the exit of Capture Solenoid





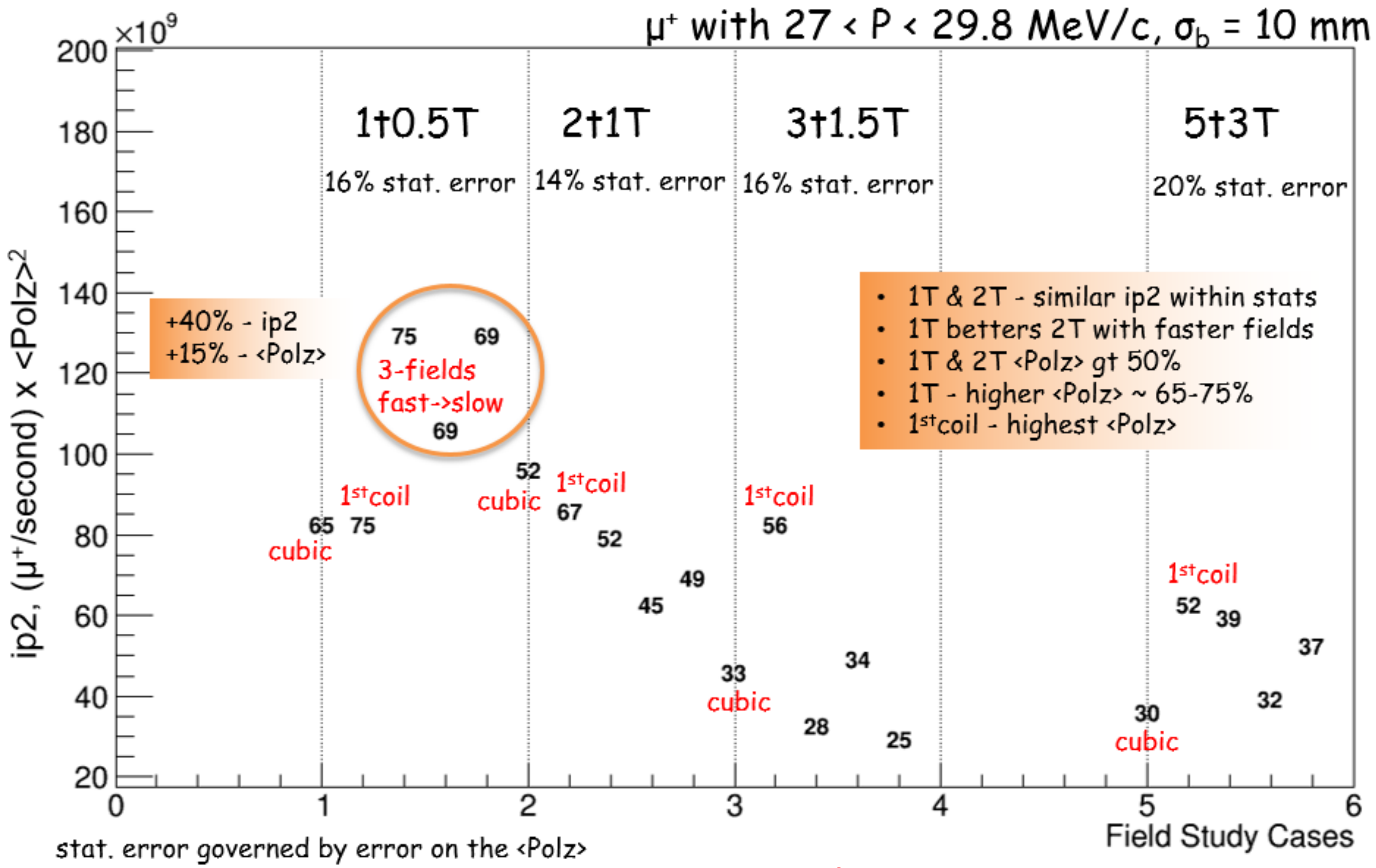
Pion yields

- ✓ similar yields with shielding

Surface muon optimization

- **Low field for surface muons -> less decay muon contamination -> higher beam polarization**
- **5T(5+3T), 2T(2+1T), 1T(1+0.5T) at transport solenoid with 30 cm aperture, also:**
  - situation at exit of 1st coil
  - fields with faster adiabatic reduction but same values
- **Target optimization shows that cone is better than cylinder both for σ_b = 5 or 10 mm**
  - A max cone-radius of 7-8 cm is optimum
- **Remember: max ip2 = 10^{12} for 10^8 muons and 100% polarization**

IP^2 for different field cases



cosz < 300 mrad

Radiation study for the solenoids

- **3 radiation issues**
  - Damage to the superconductor’s Aluminum stabilizer and Copper matrix
  - Maximum local radiation dose to the superconductor insulator over the lifetime of the experiment
  - Local heat load allowed anywhere within the superconducting coils

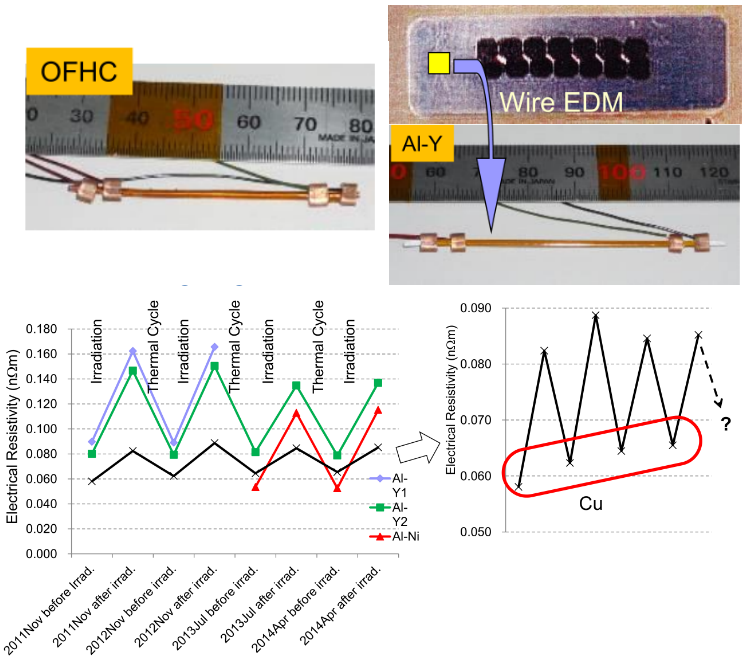
- **Radiation environment around the magnet**
  - 1.6 GeV, 4 kW proton beam
  - Length of 30 cm, radius of 2.28 cm graphite target
  - ~ 3e20 p.o.t. for 200 days in an accelerator year
  - 2.5e7 p.o.t. in simulation stat. error < 5%

RRR in neutron irradiation

- **The Residual Resistivity Ratio (RRR)**
  - the ratio of the electrical resistance at room temperature of a conductor to that at 4.5 K.
- **A given sample's RRR will**
  - decrease in various neutron environment
  - recover while warming to room temperature (order of days)
- **RRR limits**
  - aluminum: initial RRR > 500; limit > 100; 100% recovery ability
  - copper: initial RRR > 100; limit > 50; ~90% recovery ability

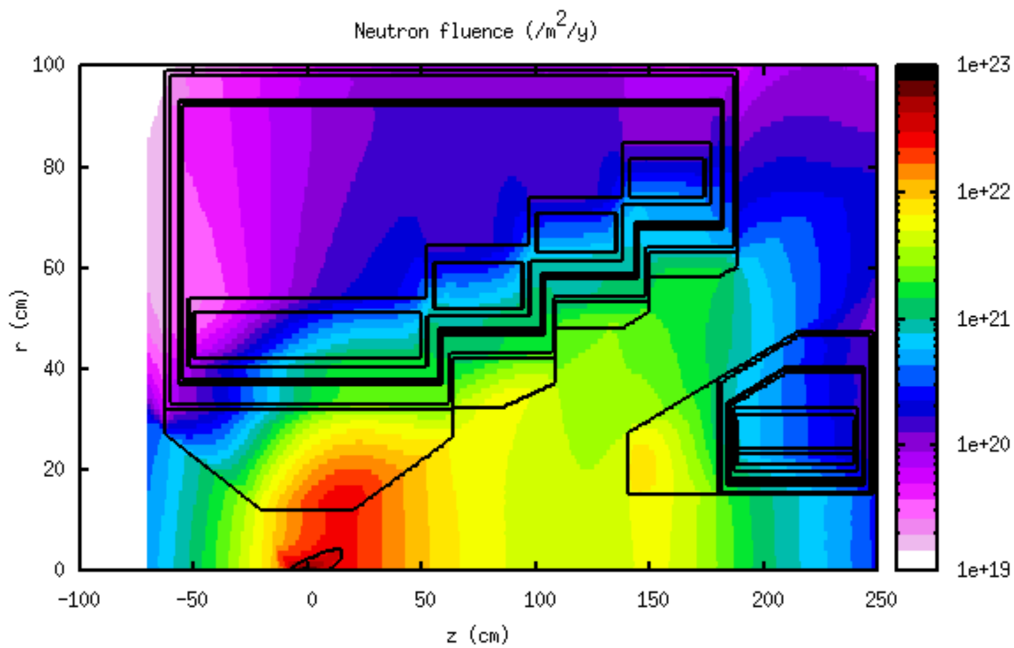
M. Yoshida et al, RESMM14

Neutron irradiation test on KUR



$$\frac{\Delta\rho_{irr}}{\Phi_{tot}} = \begin{cases} 2.5\times10^{-31}\Omega\mathrm{m}^3(\mathrm{Al}) \\ 1.0\times10^{-31}\Omega\mathrm{m}^3(\mathrm{Cu}) \end{cases}$$

Fast neutron fluence (/m²/y)



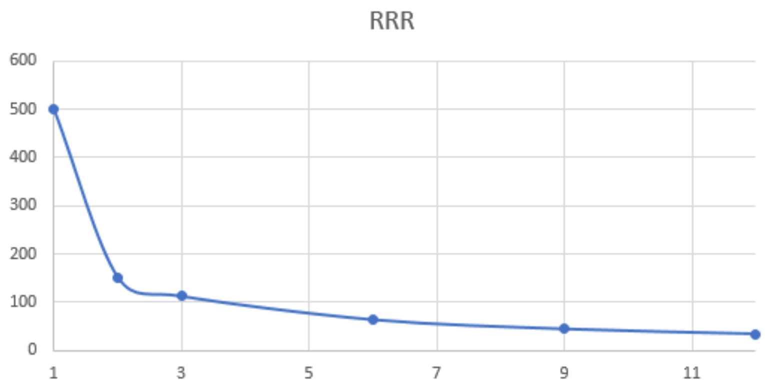
$$RRR = \frac{\rho_{RT}}{\rho_0 + \frac{\Delta\rho_{irr}}{\Phi_{tot}} \times \Phi}$$

- ✓ ρ_{RT}, ρ_0: properties of the stabilizer
- ✓ $\frac{\Delta\rho_{irr}}{\Phi_{tot}}$: KUR measurements
- ✓ Φ: fast neutron fluence

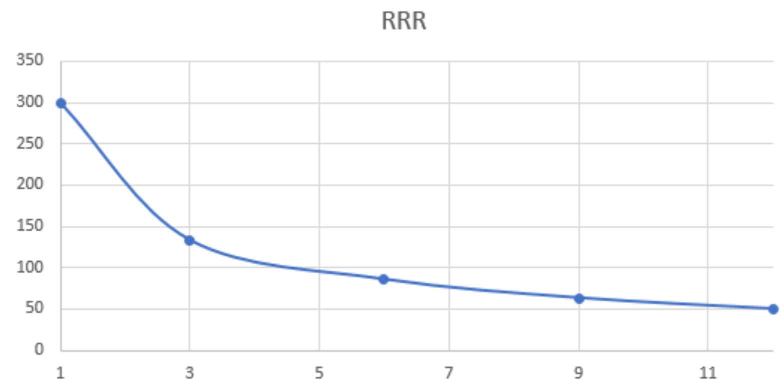
Peak fast neutron fluence in the CS: 3.0e21 m^{-2}/y
Peak fast neutron fluence in the MS: 1.2e21 m^{-2}/y

Degradation of Stabilizer

Aluminum ☺



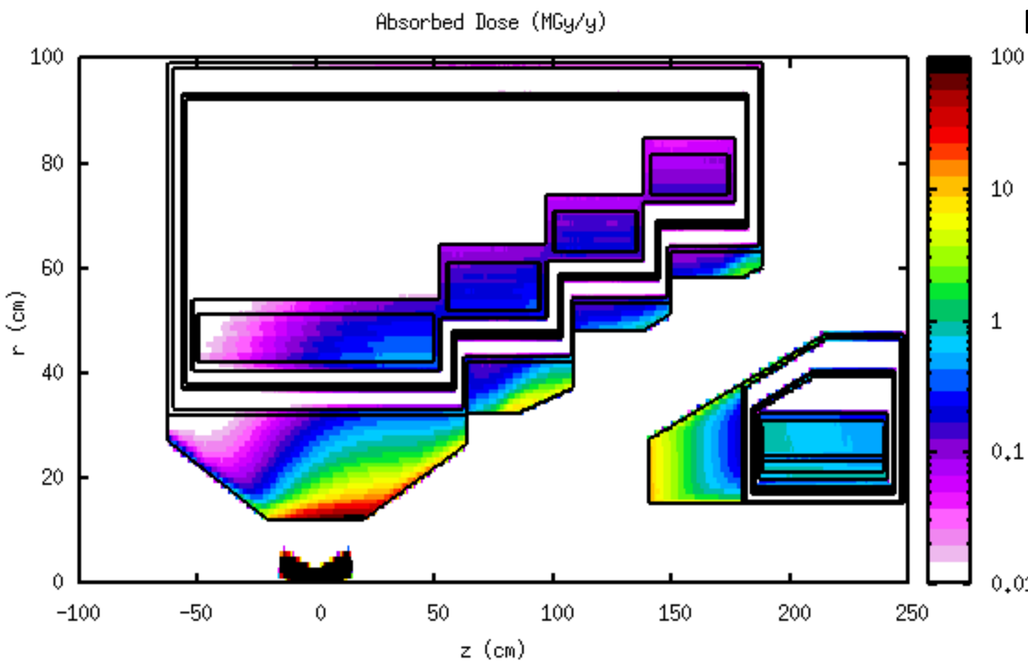
Copper ☹



- ✓ Stabilizer survive in a continuous operation around 3 month
- ✓ Can be fully recovered by thermal cycle

- ✓ Can be run for longer continuous time
- ✓ Can only to partly recovered (i.e. RRR decrease drastically after several thermal cycles)
- ✓ Could be dangerous

Absorbed dose (MGy/y) (Al)



Max dose in CS: 1.0 MGy
Max dose in MS: 1.1 MGy

Radiation Hard Coils, A. Zeller et al, 2003

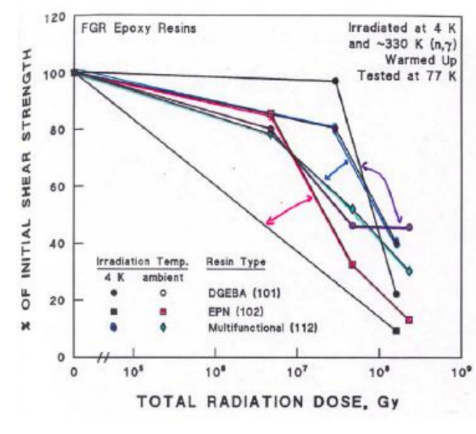
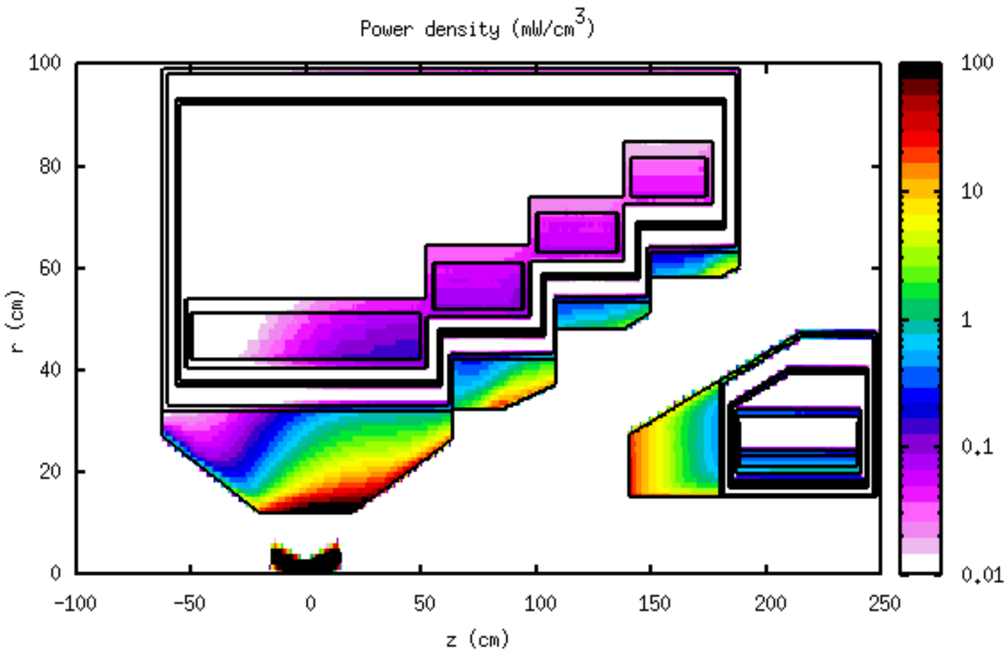


Figure 1.25. A comparison of the shear strengths of three types of reinforced epoxy resins that were reactor-irradiated at both 4 K and at ambient temperature. See text for differences in the fast neutron spectrum in the two reactors. Data from Munshi [1991]. (Supplementary Tables A. 3-3 and A. 8-4.)

The epoxy used to bond the insulation to the superconducting cable can tolerate a maximum of 7 MGy before it experiences a 10% degradation in its shear modulus

Power density (mW/cm^3) (Al)



By A. Zlobin

- ✓ **LHC NbTi:**
  - ✓ 1.6 mW/g (13 mW/cm^3).
  - ✓ Used in design: 0.5 mW/g
- ✓ **HL-LHC Nb_3Sn:**
  - ✓ ~5 mW/g (40 mW/cm^3).
  - ✓ Used in design: 1.7 mW/g

Peak power density in CS: 0.35 mW/cm^3 (~0.06 mW/g)
Peak power density in MS: 1.8 mW/cm3 (~0.3 mW/g)
Much below the LHC limit

Summary

- **Previous Base design**
  - Proton beamline
  - Target station
  - Moment selection section
  - Beam dump
  - Neutrino beam
    - $> 10^{16}$ ν_μ / m^2 / year
    - x50 with 1 m aperture of 1st-coil, 20 kW beam and $2\lambda_I$ target

- **Design optimization**
  - Target
    - Material: graphite; Radius: $4\sigma_b$; Length: $0.64\lambda_I$; Tilt: 15 deg; Shape: conical
  - MuSR beam
    - $IP^2 \sim 10^{11}$ for the lower fields of 2 T or 1 T, 1T with fast adiabatic fields has +40% ip2 and +15% <polz>

- **Radiation study (RRR for stabilizers/dose for insulators/power density for coils)**

Backups

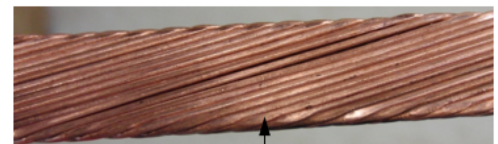
Stabilizers

- Option 1： Conductor ——Aluminum stabilized Rutherford cable

Aluminum

Rutherford cable

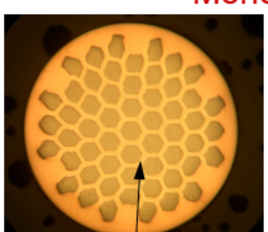
Cross section of Rutherford cable



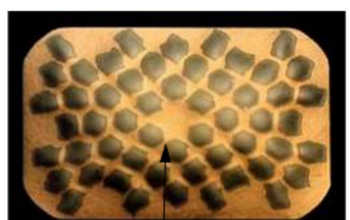
Rutherford cable

- Option 2： Conductor ——Nb-Ti / Copper Matrix Monolith Wire or Wire in channel

Monolith Wire

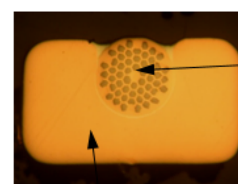


Cross section:Round



Cross section:Rectangle

Wire in channel



Monolith Wire

Copper stablized

Backward case