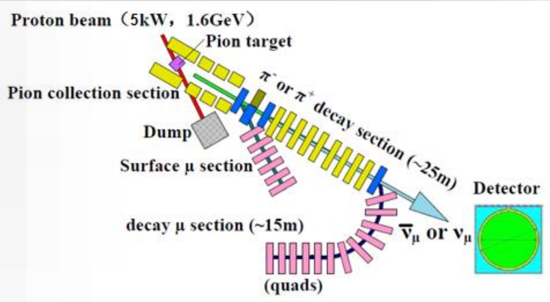
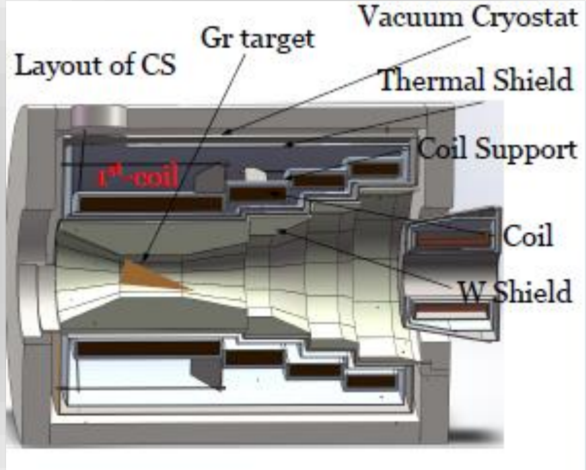
Institute of High Energy Physics
Chinese Academy of Sciences

SNS
CHINESE ACADEMY OF SCIENCES

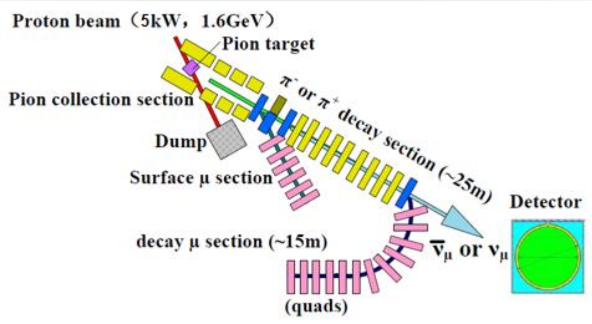
EMuS: Updated Studies for targets, up to 25 kW

Nikos, Y. Yuan IHEP, CAS





layout



EMUS at CSNS

Baby scheme
- layout
- target studies (in terms of rates and polarization)

Baseline scheme
- layout

Target Station
- muon and pion collection with 4-coils/3-steps Superconducting Adiabatic Solenoid
- Graphite conical target, 15^0 tilt angle
- rates and polarizations in terms of adiabatic magnetic fields

Shielding studies for both schemes (presented in Zhao Guang, Nitin Yadav posters)

Aim
- produce a competitive number of muons for μSR applications
- a rate of 10^6 – 10^7 for surface muons per second and higher rates for decay muons under certain emittance selection criteria

CSNS facility as today

IHEP Dongguan Branch

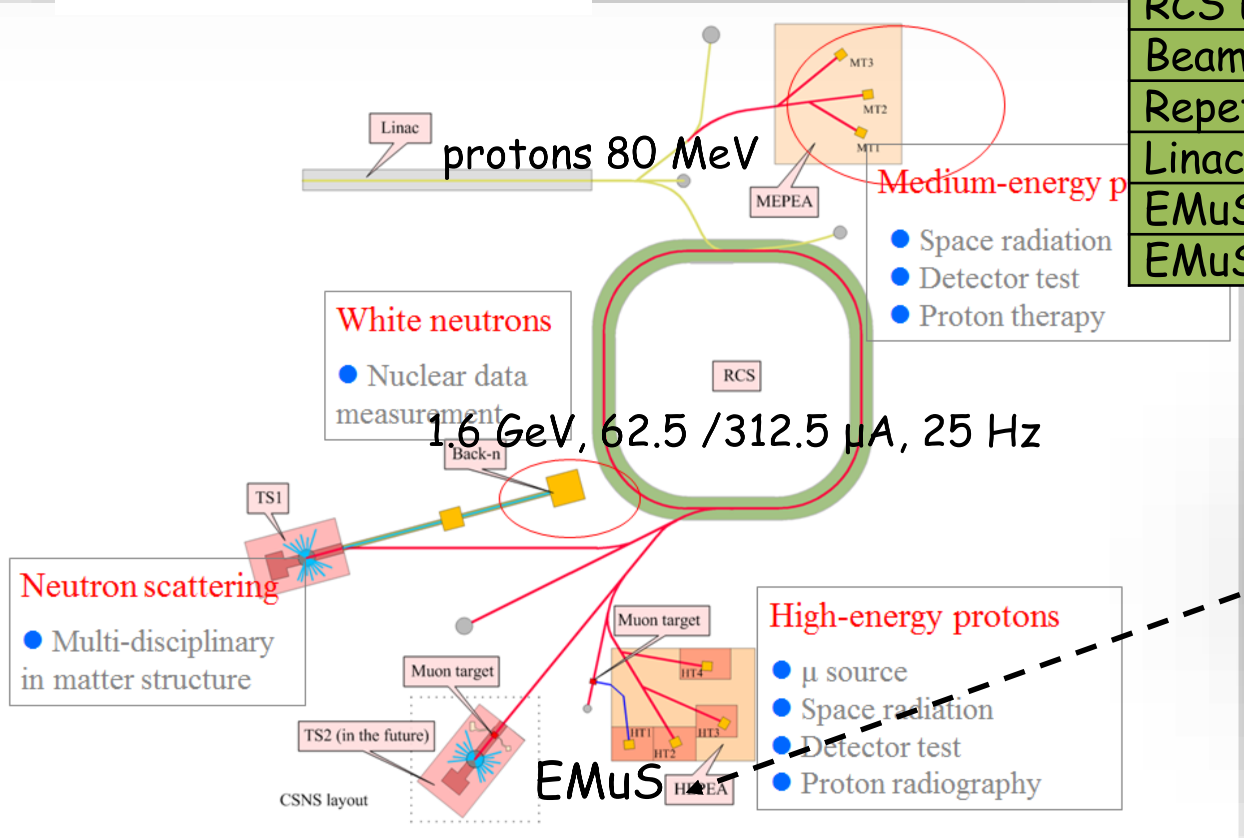
- The site for CSNS is in Dongguan, Guangdong Province
- CSNS is the first large scientific facility in southeastern China, jointly invested by the central government and local government. It will promote advanced researches in the economic developed zone of Guangdong-Hong Kong. Total budget: ~2.3B CNY (or 350M USD)

CSNS and EMuS

CSNS is the only large-scale proton accelerator in China today

- Strong needs from other fields than neutron scattering
- Excellent capability to support multiple platforms
- Phased development from 100 kW (I) -> 500 KW (II)

Schematics for CSNS



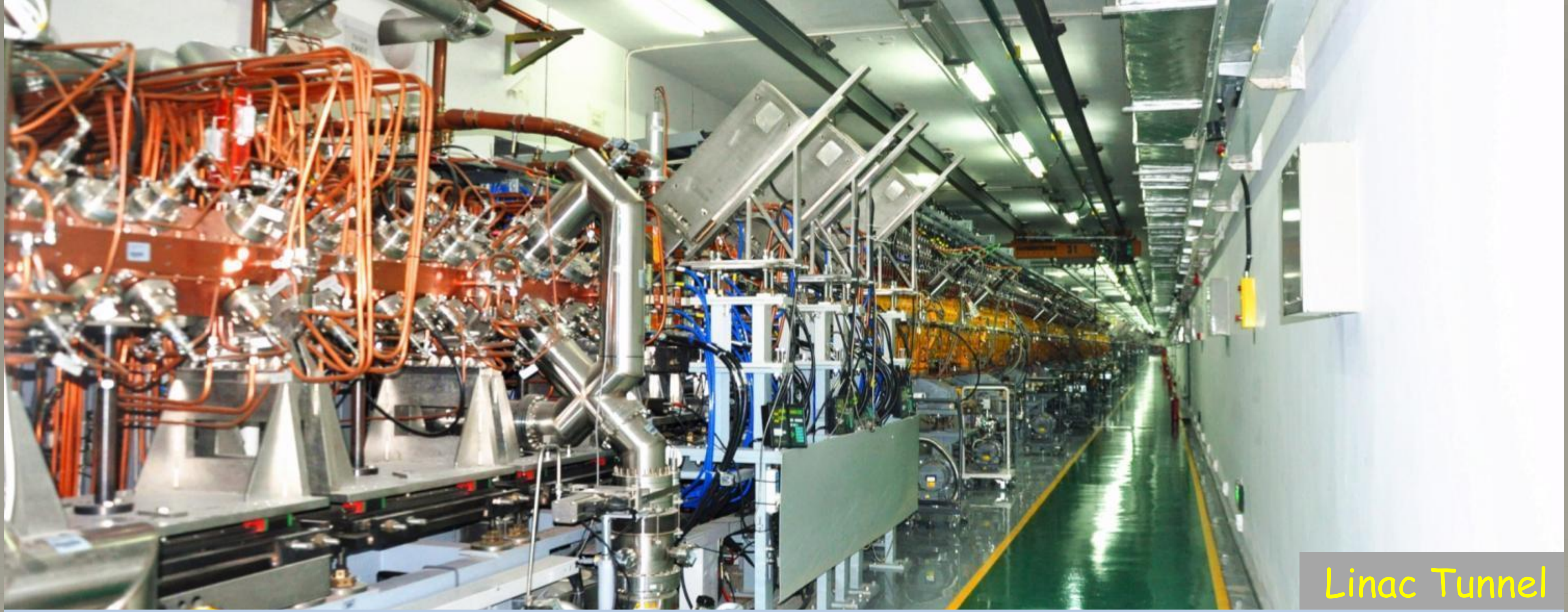
Parameters	CSNS-I	CSNS-II
Beam power (kW)	100	500
RCS Energy (GeV)	1.6	1.6
Beam current (μA)	62.5	312.5
Repetition rate (Hz)	25	25
Linac Energy [MeV]	80	250
EMuS power (kW)	5	25
EMuS repletion rate (Hz)	2.5	2.5

EMuS will be located at the High Energy Proton Application hall

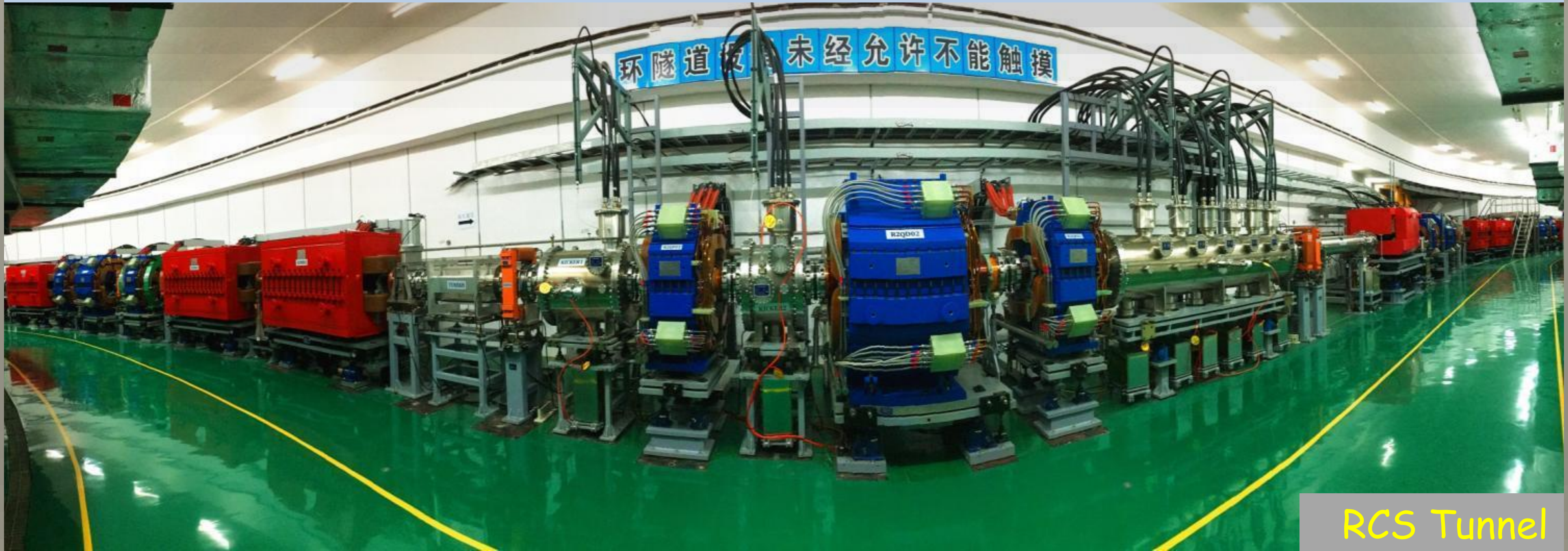

Target and experiment hall


LINAC service building


RCS service building

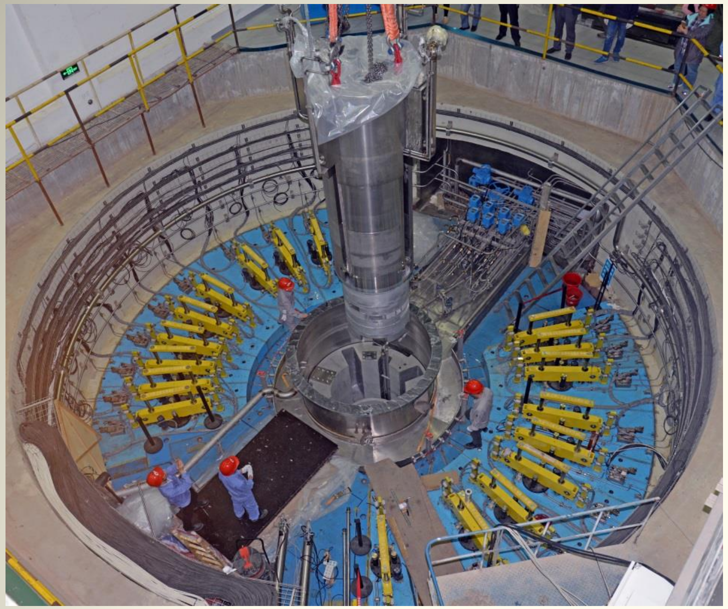


Linac Tunnel



RCS Tunnel

Target Station



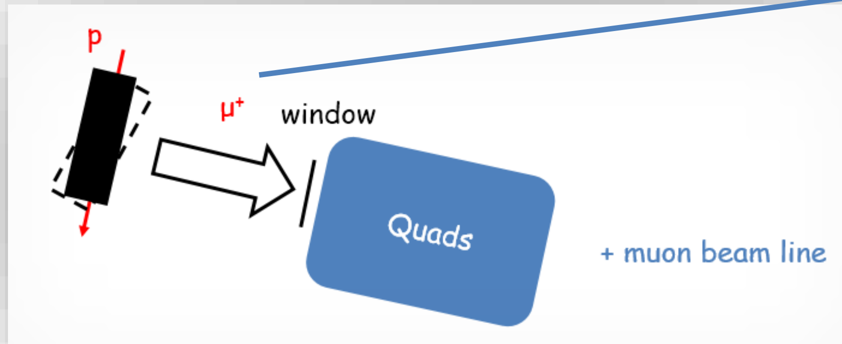
Target in Hot-cell

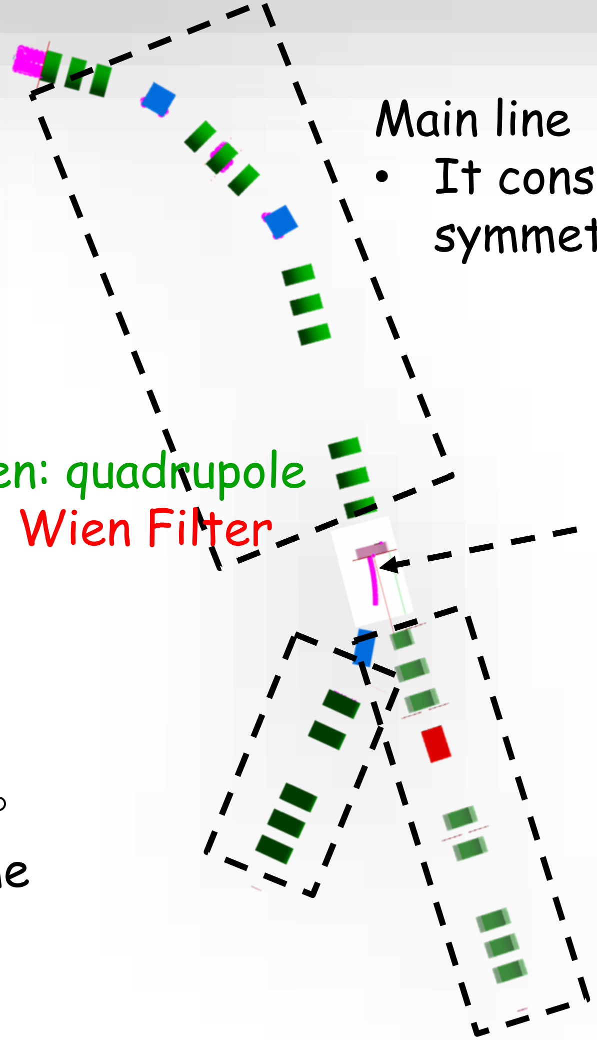
South Exp. Hall

North Exp. Hall

EMuS "Baby" scheme schematics

- Sideway μSR collection at 90^0 with respect to the primary proton beam direction
- Quadrupole system, low acceptance collector





Green: quadrupole
Red: Wien Filter

Main line
- It consists of 4 groups of triplets. Using symmetric achromatic design.

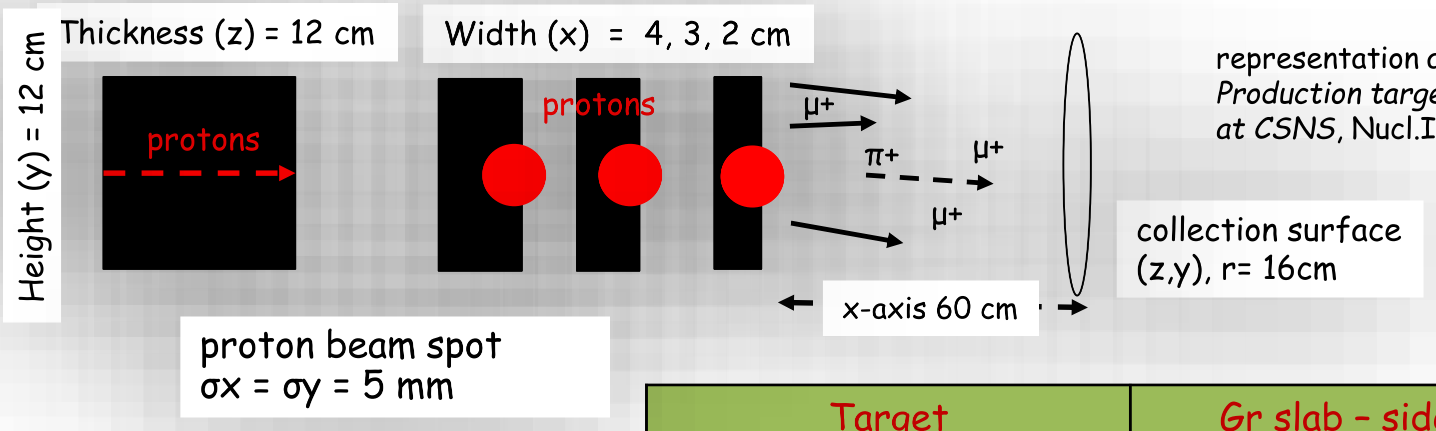
Electrostatic deflection separator
- The beam is divided into 2 parts here

ES line
- Half of the beam passes through the deflector
- Total angle (ES separator + dipole): 41°
- No positron, so both quadrupole-scheme and solenoid-scheme are under development

Straight line
- Half of the beam is unaffected and straight ahead

proton beam and target semi interaction is best target case (from last year)

- proton's Gaussian peak is displaced by 0.5 cm from side (collection) surface
- best target Width = 3 or 2 cm with 4500 π mm mrad selection



representation as discussed in H.T. Jing, C. Meng, J.Y. Tang, B.J. Ye, J.L. Sun, *Production target and muon collection studies for an experimental muon source at CSNS*, Nucl.Instrum.Meth. A684 (2012) 109-116

25 kW

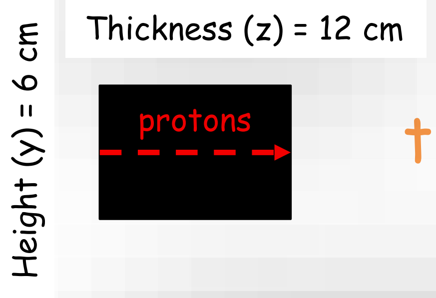
Target	Gr slab – sides : 12x12 cm2		
emittance (π mm mrad)	4500		
momentum	μSR - μ^+ 25 < P < 29.8 MeV/c		
Target's Width (cm)	4	3	2
intensity ($\times 10^6$) μ/sec	16	17.5	17
polarization	-0.96	-0.96	-0.96
surface muon purity (%)	97	97	97
stat. error ~ 3% for intensity, < 1% for polarization			

less mass, less radiation

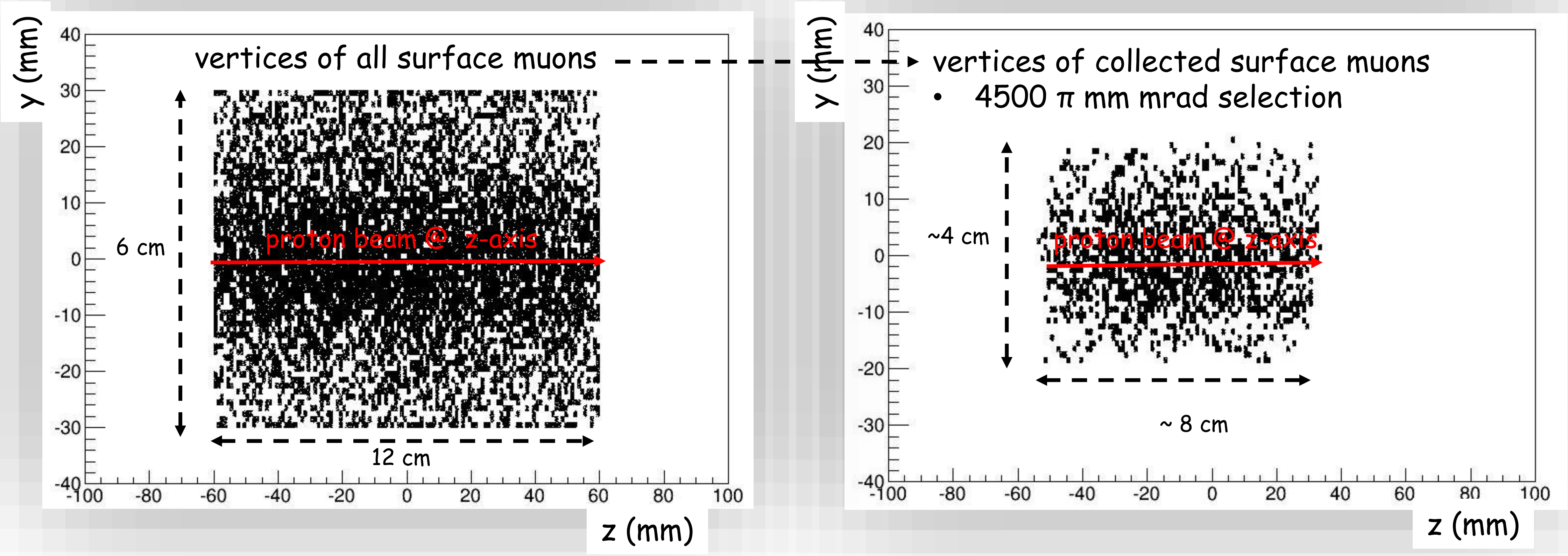
best target-proton configuration compared to singlet-turn, also to doublet and triplet

possibility for a smaller target asked from International Review Committee

- smaller target size for smaller surface muon beam size at sample
- less cloud muons
- less radiation



vertices of all and selected surface muons passing through the collection surface for a smaller target 12x6 cm2

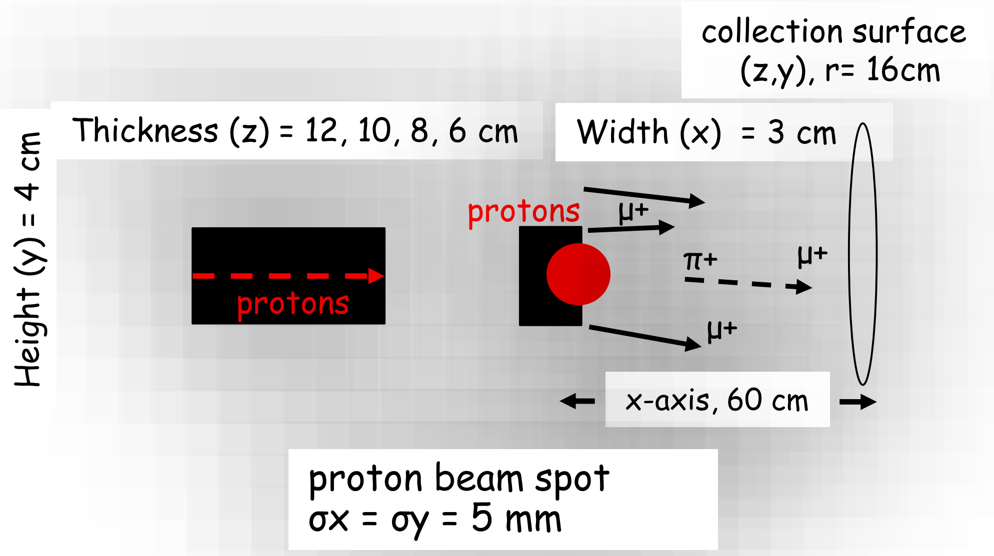


for the given emittance selection target side surface could be reduced

tests of smaller configurations than 12x12 cm2: 12->8 x 4 cm2, 25 kW

singlet slab best case

- proton's Gaussian peak is displaced by 0.5 cm = 1 σ_p from side (collection) surface

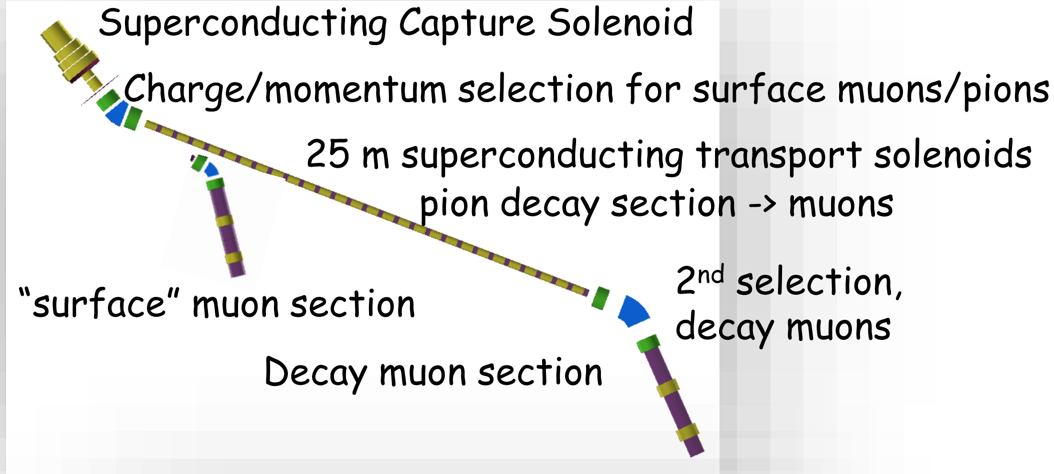


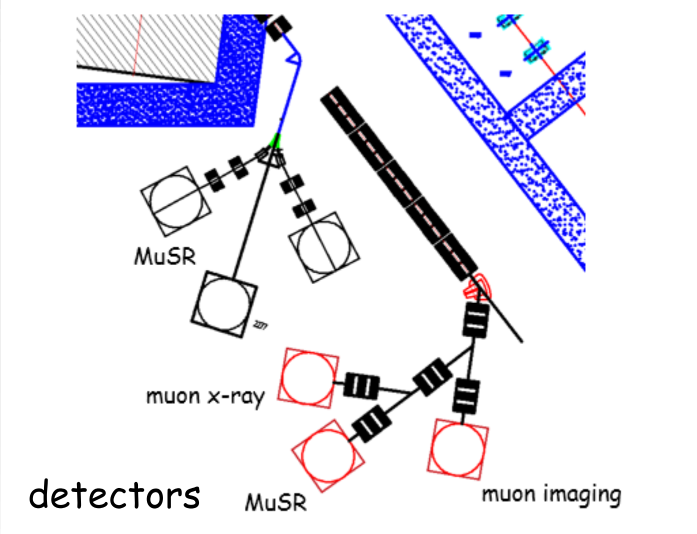
25 kW

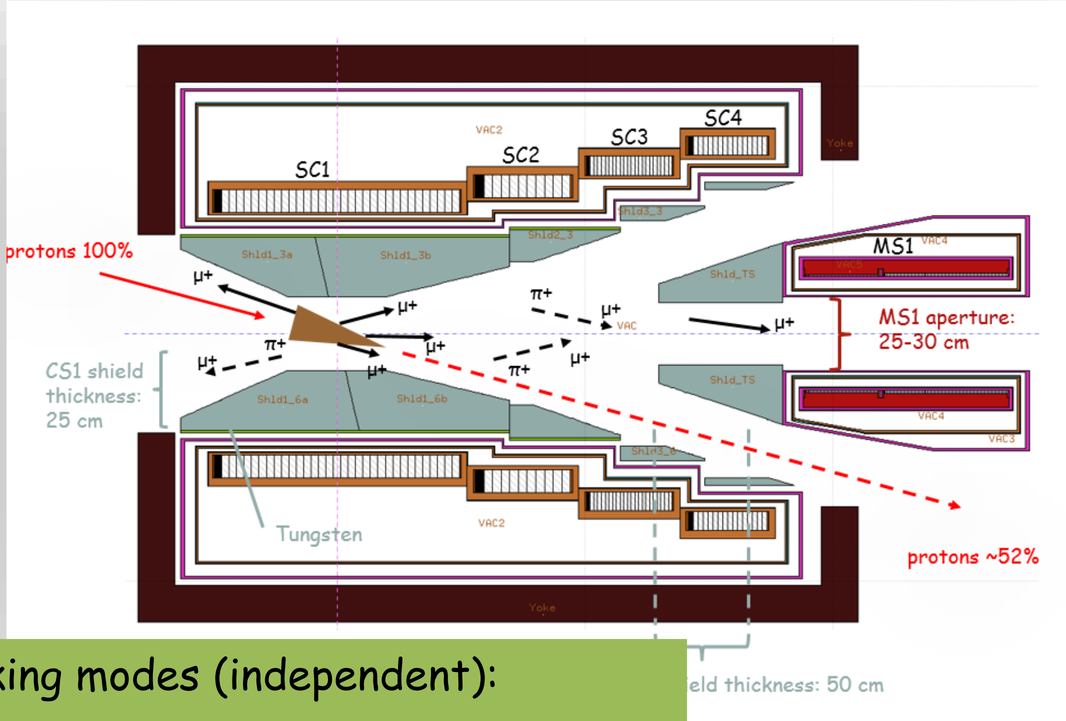
Target	Gr slab – Width = 3 cm				
emittance (π mm mrad)	4500				
momentum	μSR - μ^+ 25 < P < 29.8 MeV/c				
Height x Thickness (cm2)	6x4	8x4	10x4	12x4	12x12
intensity ($\times 10^6$) μ/sec	14	15.5	16	17	17.5
polarization	-0.96	-0.95	-0.95	-0.96	-0.96
surface muon purity (%)	97	97	96	97	97
stat. error ~ 3% for intensity, < 1% for polarization					

- also 8x4 cm2 could be chosen if not matter the -10% in rates

“baseline” Scheme: surface and decay muons





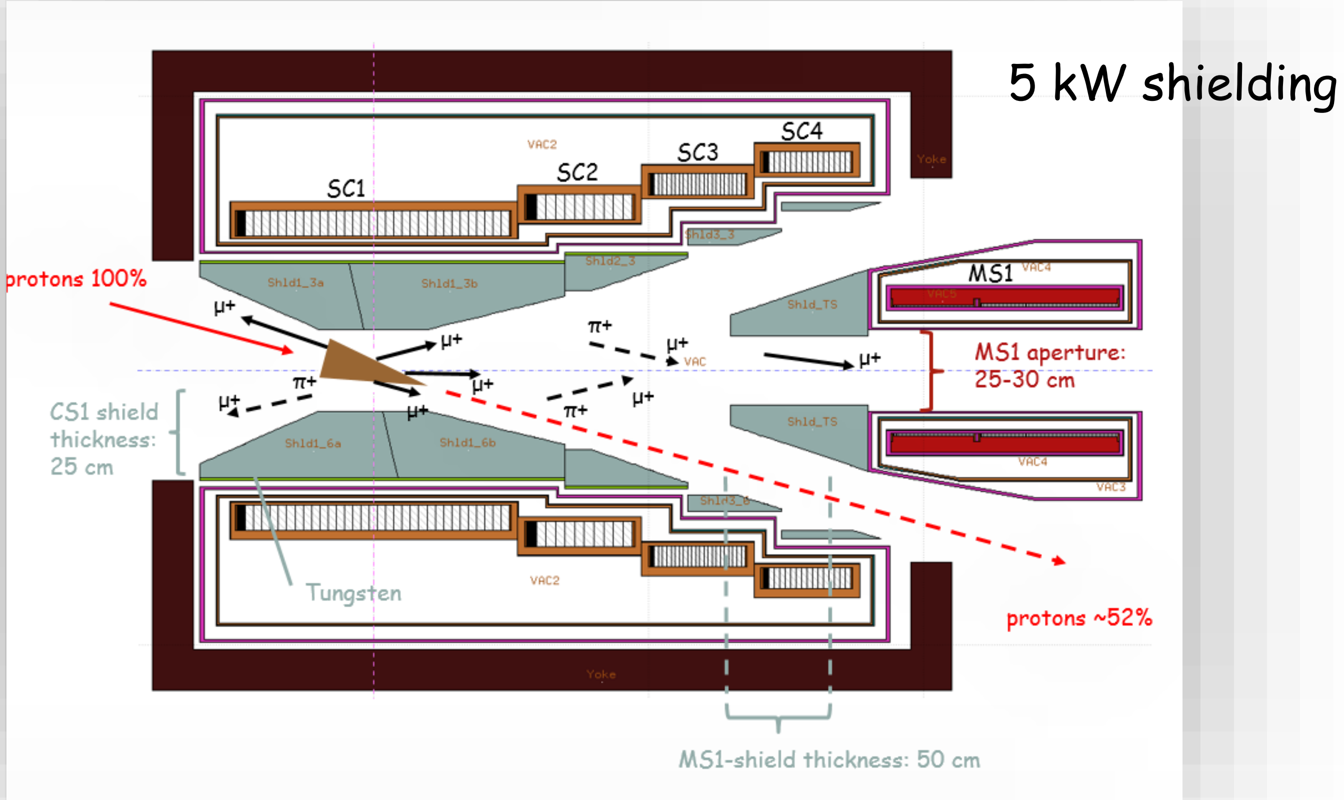


Working modes (independent):

1. Surface μ mode
   a) Δp/p: <±5%
   b) Ref. Pμ=29 MeV/c
2. Decay μSR mode
   a) Δp/p: <± 10%
   b) Ref. Pμ =40-150 MeV/c
3. High-momentum μ mode
   a) μ imaging, neutrinos
   b) Ref. Pπ=200-450 MeV/c

capture using superconducting capture adiabatic solenoid

- Forward spent-proton extraction, proton beam & target tilted in respect to magnetic axis, θp = 15°
- 4-coils/3-steps design, NbTi-Al coils, adiabatic taper



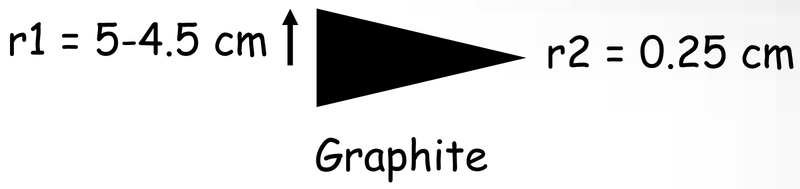
15^0 tilt of protons/target with respect to magnetic field lines:

- facilitate the extraction of spent-protons with a moderate length of 2.5 m of the CS through the Matching Solenoid and capture coils
- lower tilts as 10^0 make the length of CS excessive and costly

primary protons and conical target

target parameters - conical target				
material	radius r1 large / r2 small (cm2)	length (cm)	Z	λ_I (cm)
C (1.82 gr/cm^3)	5-4.5 / 0.25	25 - 30 / ~0.65 λ_I	6	47

use only one target for surface muon and π+ collection

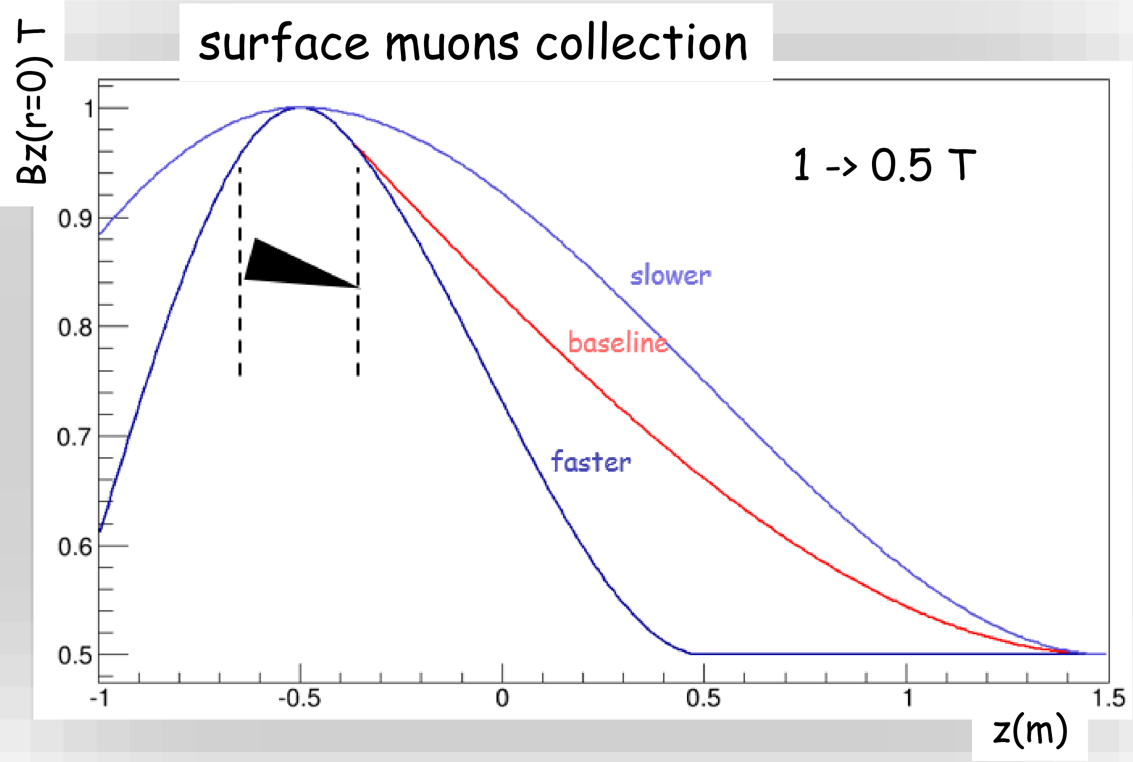


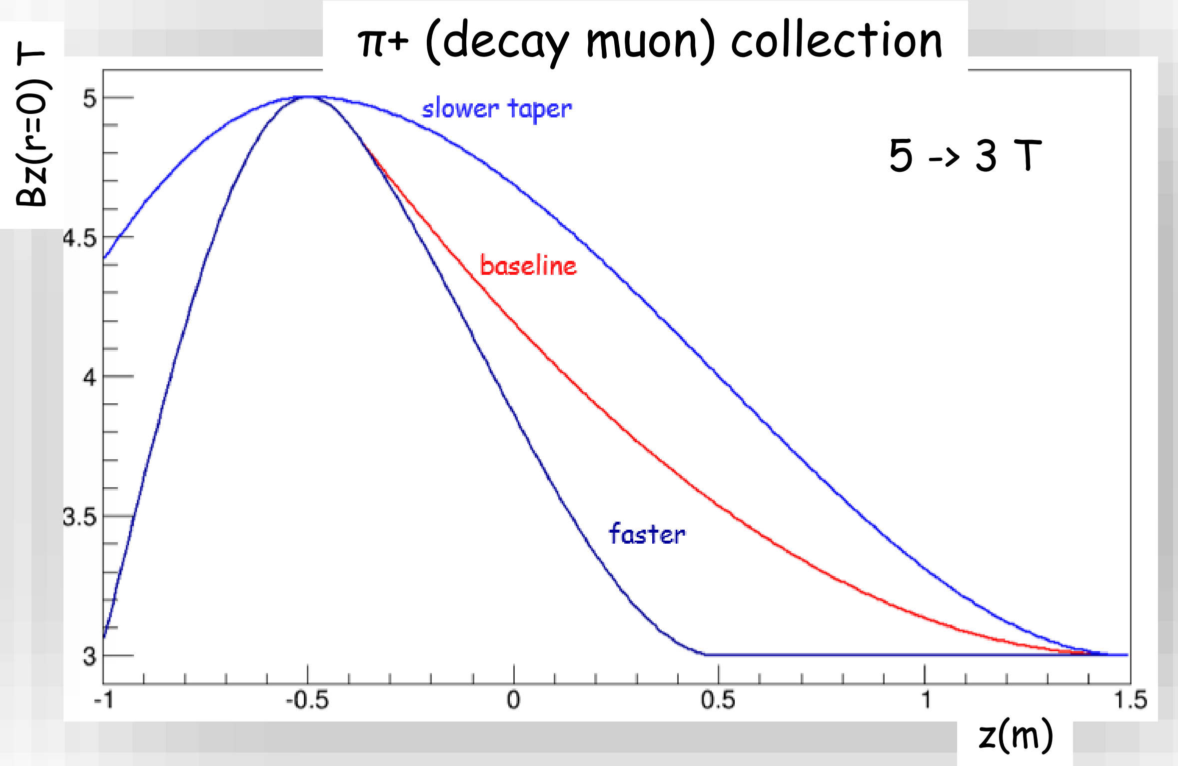
for surface muons
- better surface muon collection than cylindrical shape
- lower power deposition on the SC

for π+ collection at MS1
- similar collection to cylindrical shape

test several adiabatic tapers from combinations of Gaussian and polynomial functions for the surface muons and pions (decay muons) capture

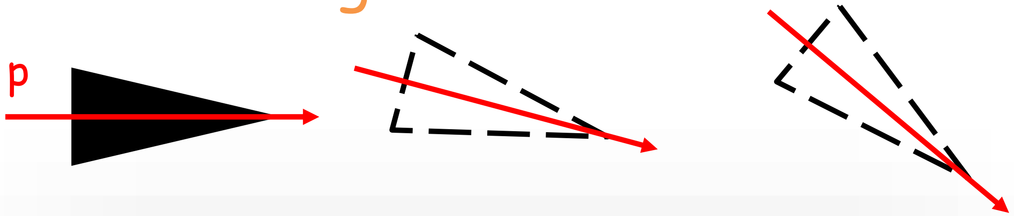
- 1 or 2.5 -> 0.5 T for surface muon mode and high polarization
- 5 -> 3 T for decay muon mode and high rates

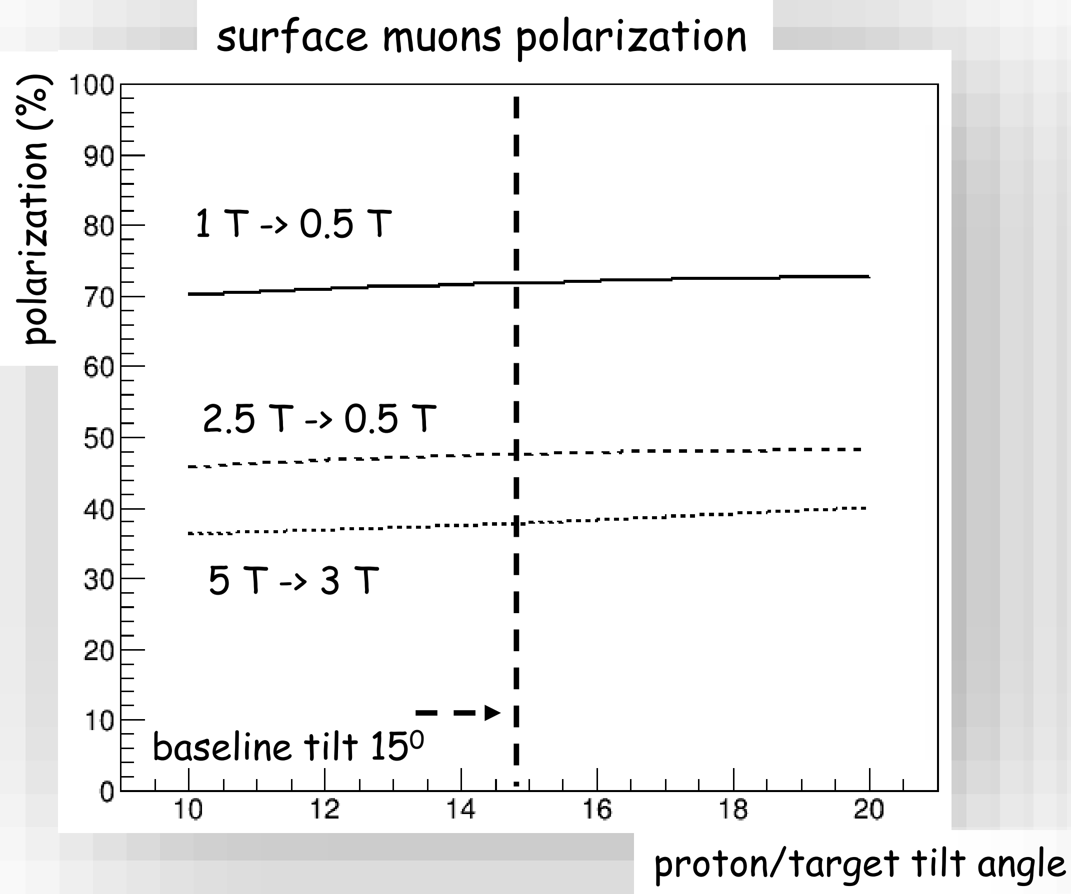


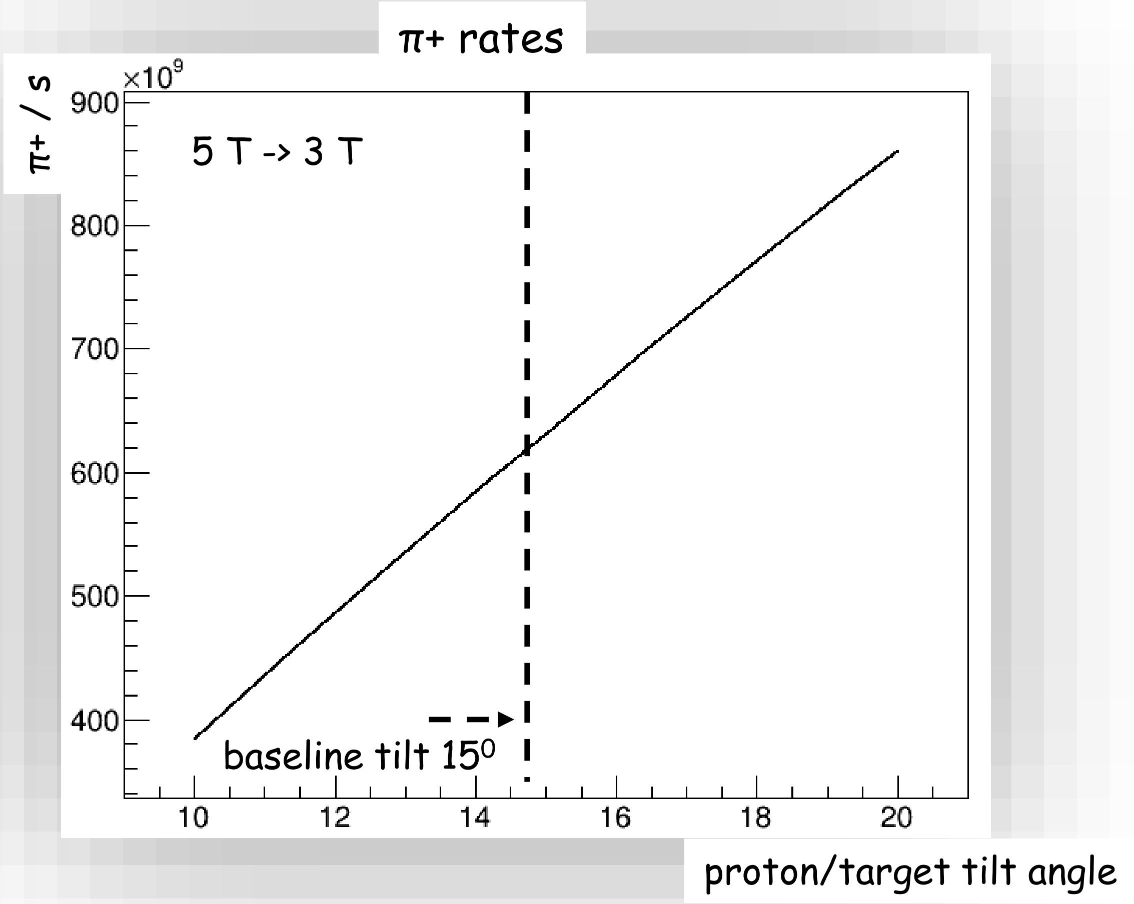


polarization and rates as function of fields and proton/target tilts
1st coil exit, 5 kW shielding

- surface muons: best polarization at 1 T
- tilt benefits surface muons & π+ rates

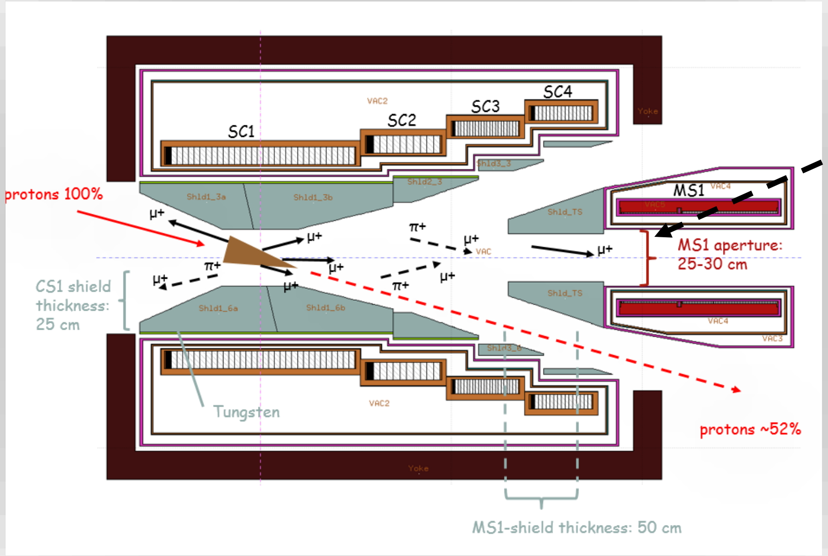






1st coil study – no shielding
no emittance selection

μSR: surface muon collection at MS1 from 1 to 5 T, 5 kW shielding



surface muon sources:

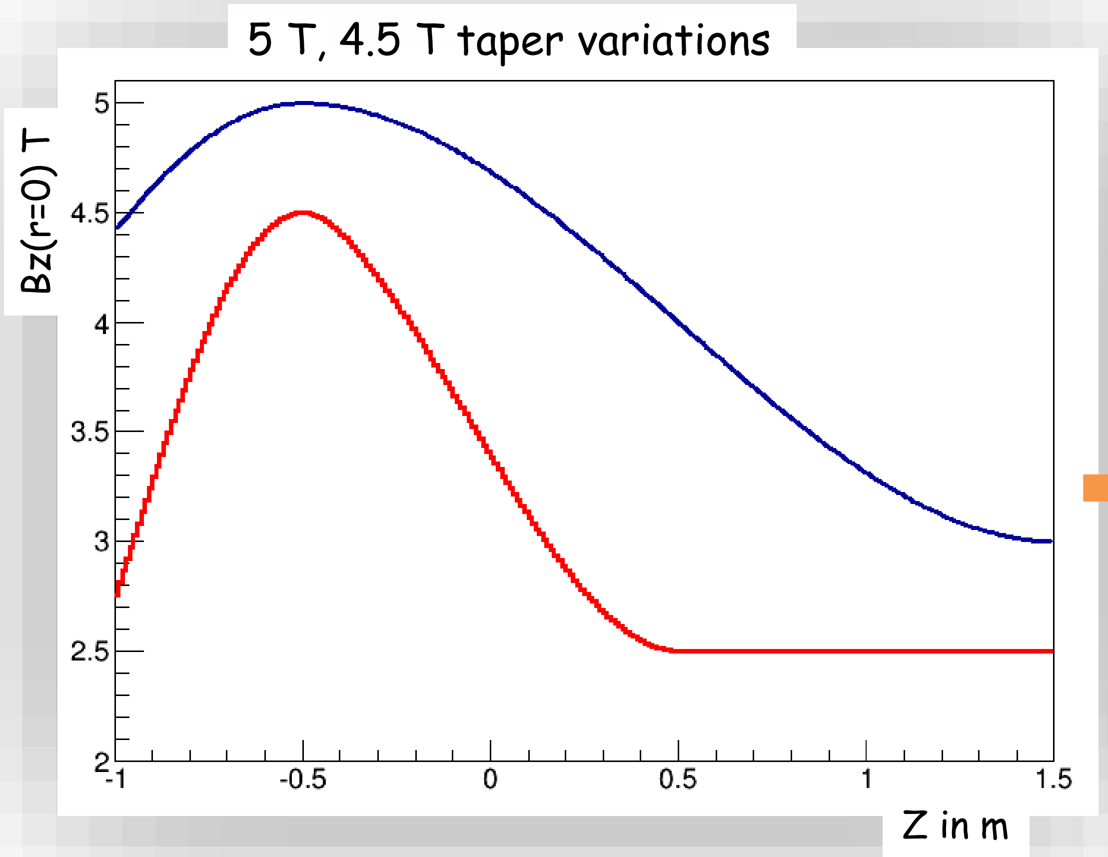
- target
- shielding

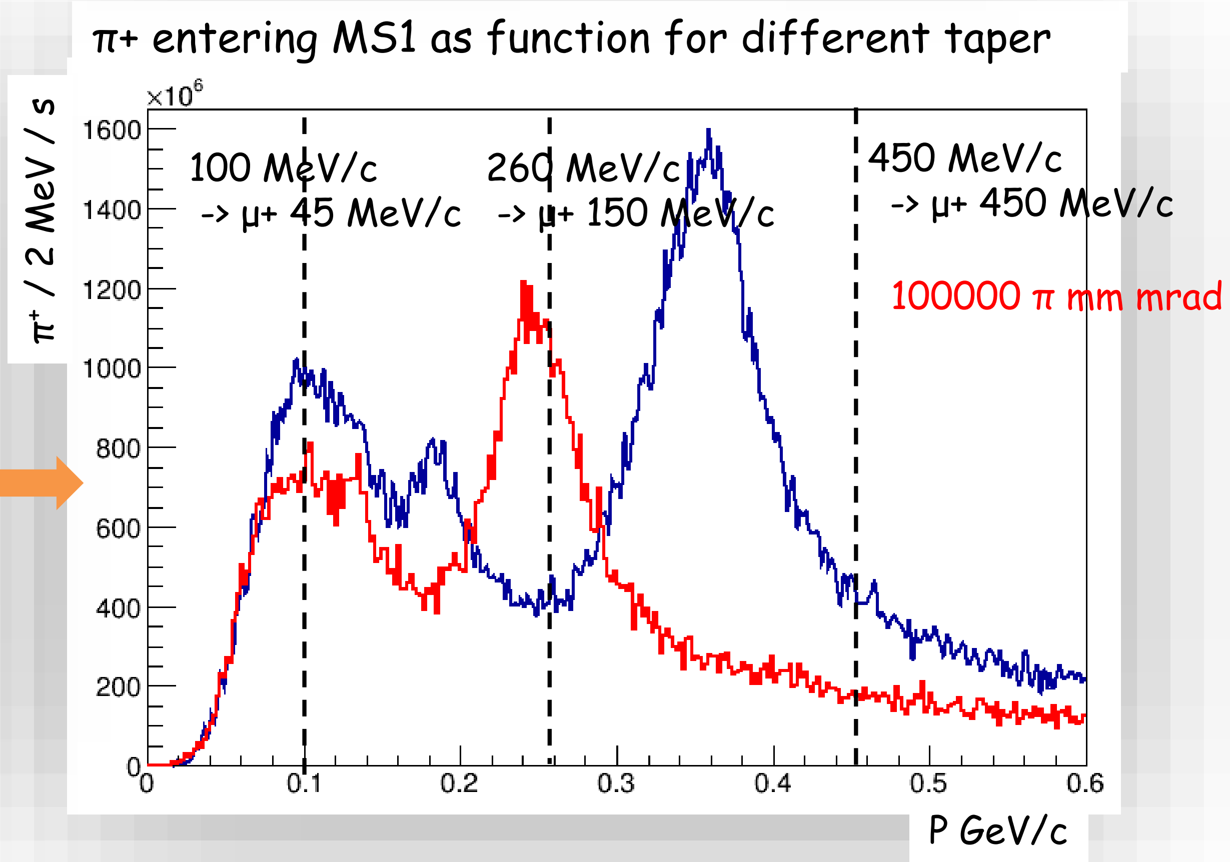
shielding of MS1 act as collimator

emittance (π mm mrad)	10000				
momentum (MeV/c)	μSR - μ^+ 25 < P < 29.8				
field	1 -> 0.5 T	2.5 -> 0.5 T	3 -> 1.5 T	4 -> 2.5 T	5 - > 3 T
intensity ($\times 10^6$) μ/sec	7	18	21	26	32
polarization	-0.83	-0.62	-0.44	-0.38	-0.38
surface muon purity (%)	86	68	55	50	50
stat. errors for both intensity and polarization ~ 5%					

field tuning for π+ collection at MS1 for decay muons, 5 kW shielding

final 5 T and 4.5 T used for π+ collection:

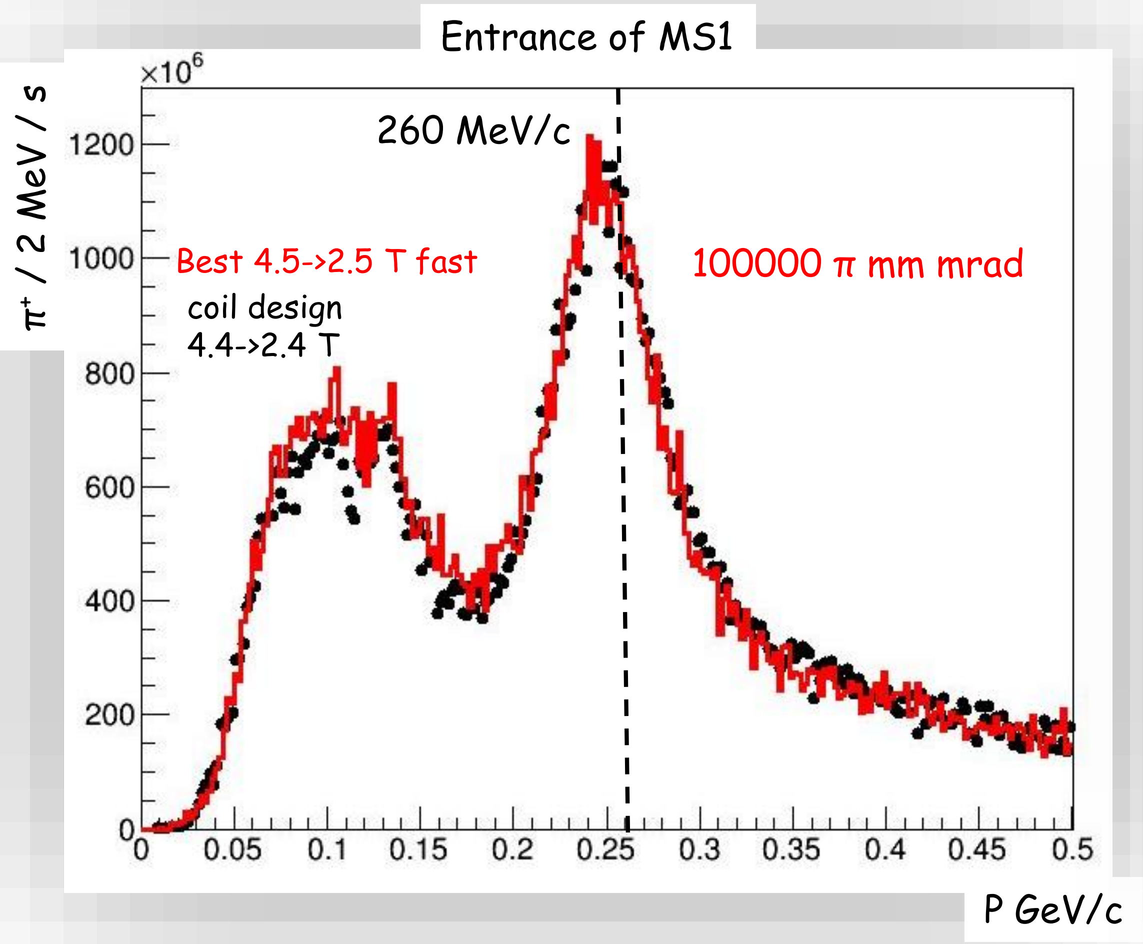


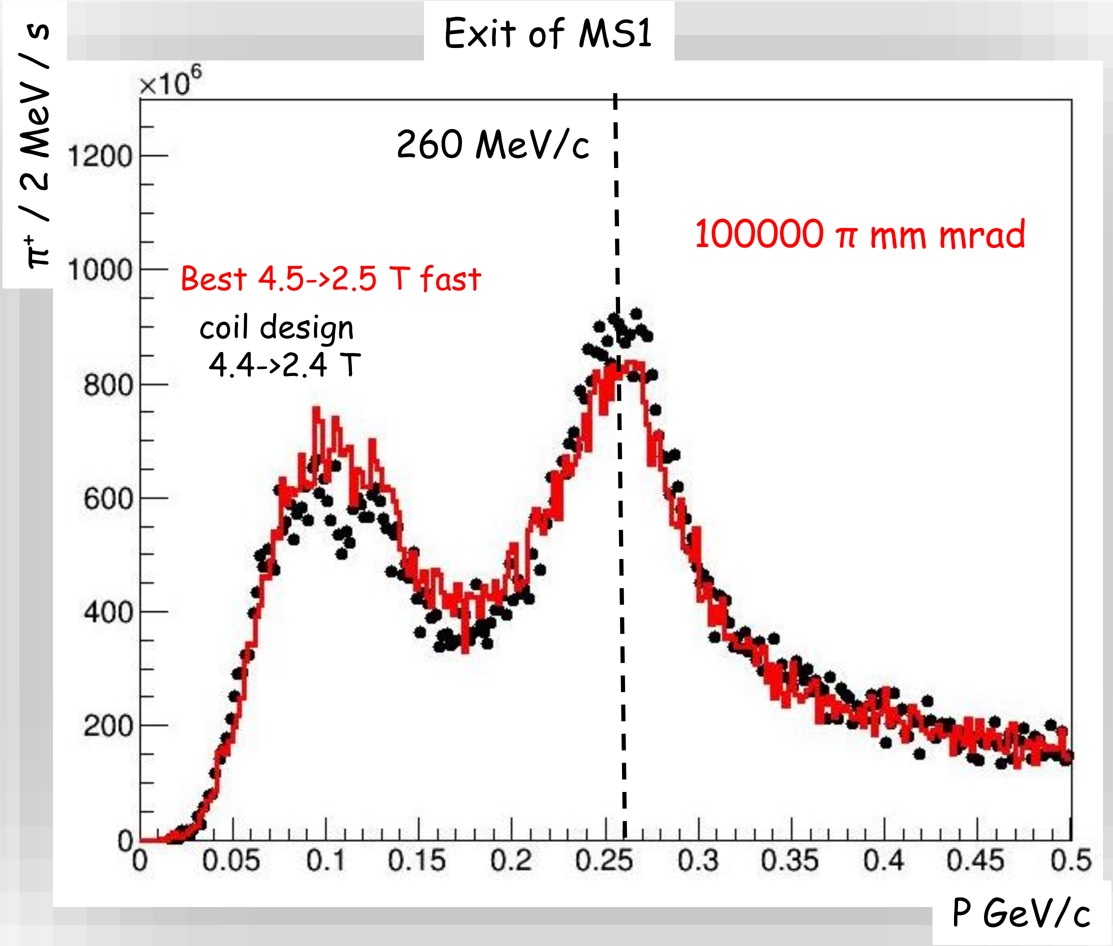


emittance (π mm mrad)	100000		
P (MeV/c) ± 10%	100	260	450
intensity π+ (x10^{10}) μ/sec	1	2.8	2.4
stat. error ~ 1%			

the selected polynomial best fields can be reproduced with realistic coil design, 5 kW shielding

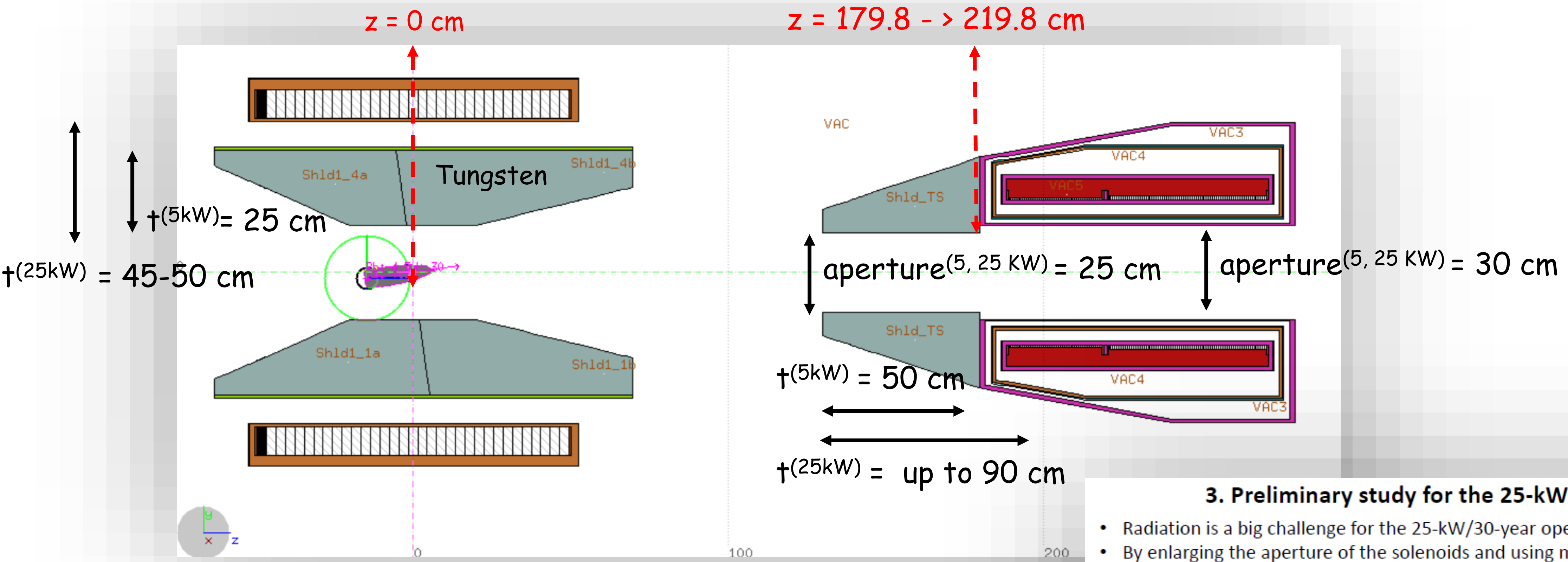
- e.g. π+ collection at 260 MeV/c at MS1 entrance/exit





5 kW -> 25 kW
"baseline" scheme: increased shielding is needed

under study, G. Zhao, N. Yadav posters



aim of the shielding design

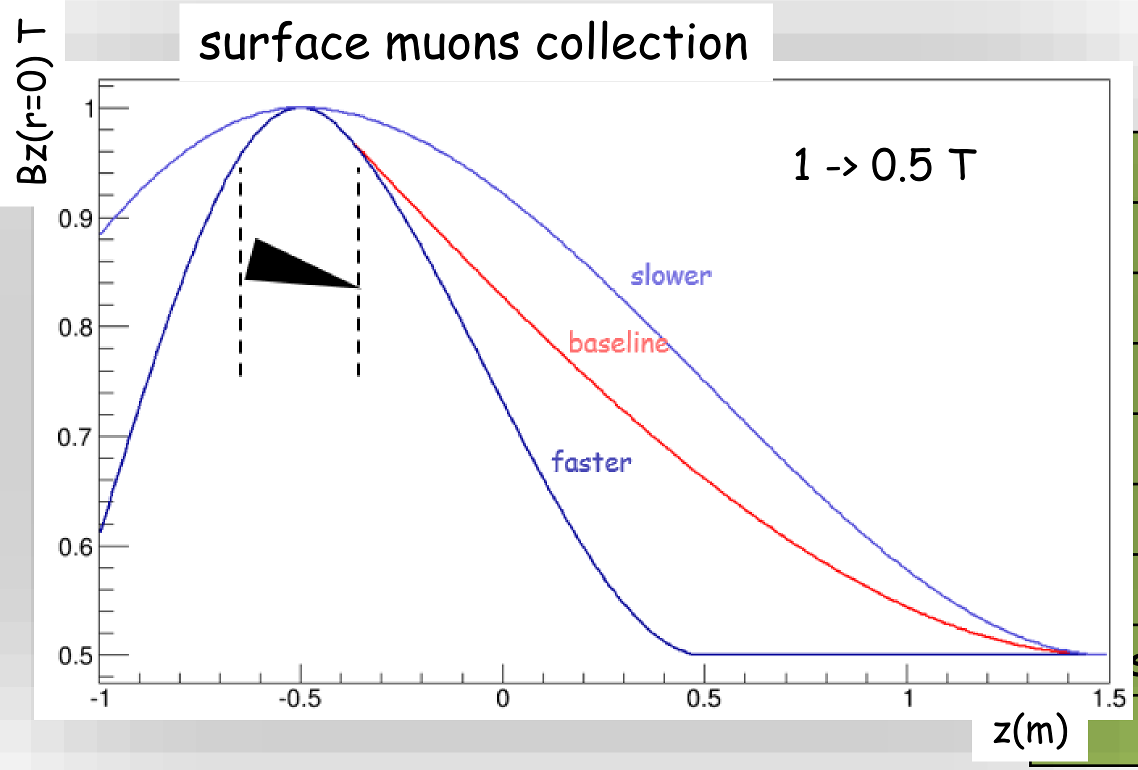
- protect the coils at 25 kW
- produce x 5 the rates of surface muons and pions
- keep the field shape as smooth as possible due to the MS1's displacement downstream

3. Preliminary study for the 25-kW beam

- Radiation is a big challenge for the 25-kW/30-year operation
- By enlarging the aperture of the solenoids and using more shields, we are possible to satisfy the dose limit on epoxy

Peak dose < 0.23 MGy/y

µSR: surface muon collection at MS1, 1 T, 25 kW studies, preliminary

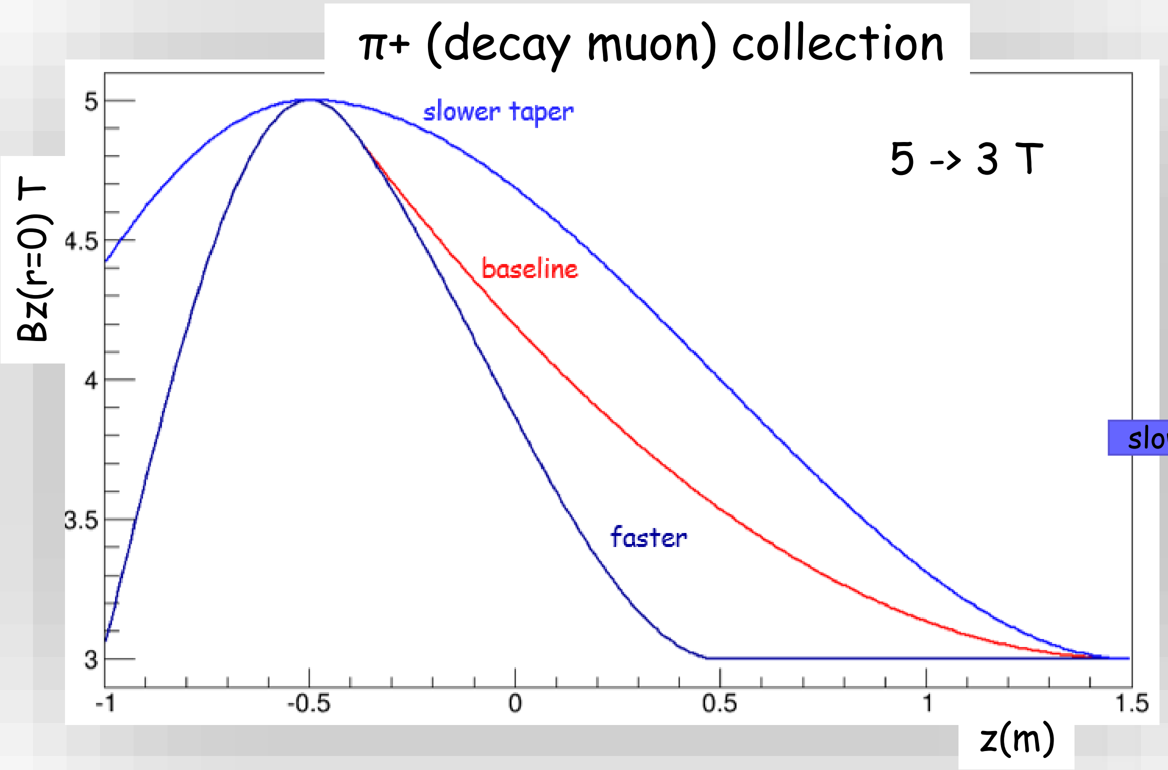


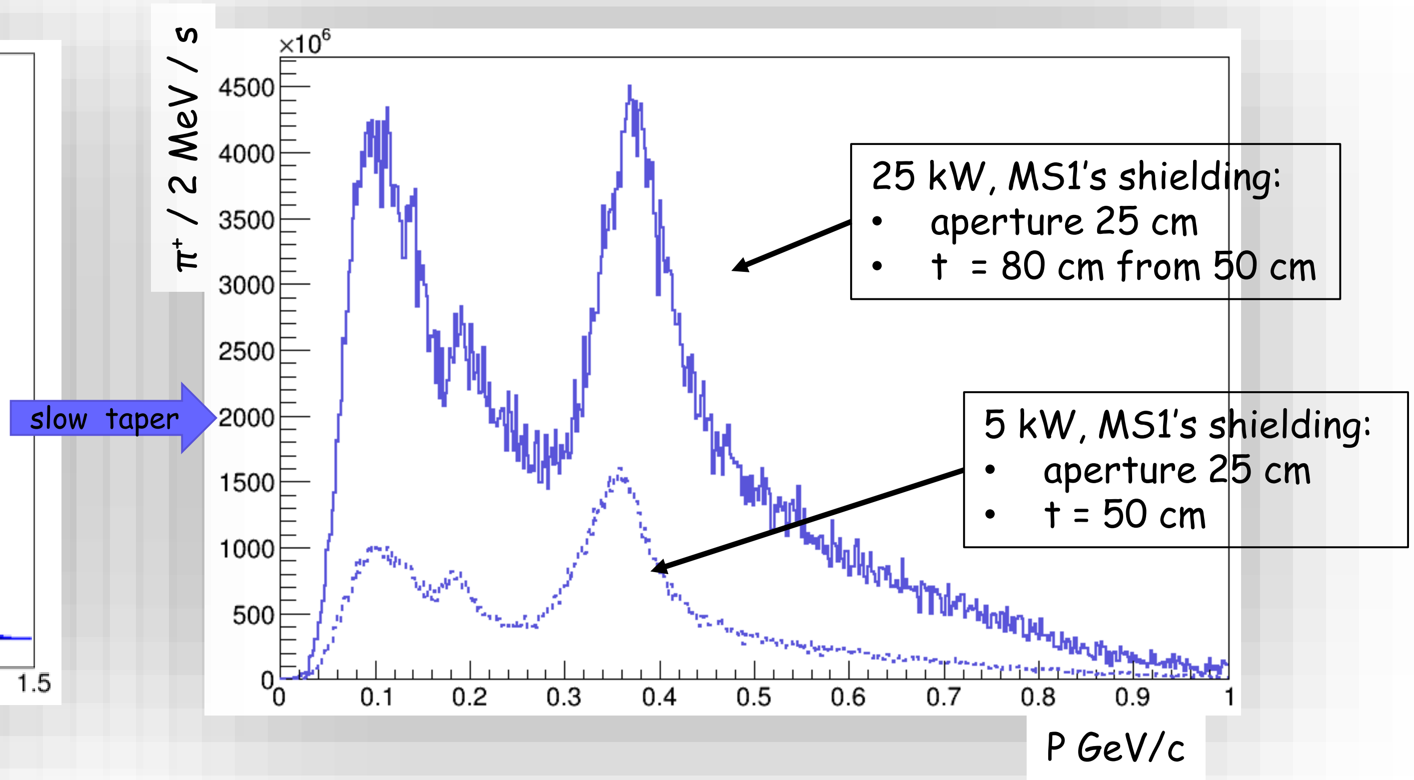
MS1 shielding
- aperture 25 cm
- t = 90 cm from 50 cm

emittance (π mm mrad)	10000		
momentum (MeV/c)	µSR - μ^+ 25 < P < 29.8		
collection	MS1 - entrance		
field	baseline	baseline	faster
power-shielding case	5 kW	25 kW	25 kW
intensity ($\times 10^6$) µ/sec	7	37	26
polarization	-0.83	-0.80	-0.86
surface muon purity (%)	86	83	85
stat. errors for both intensity and polarization ~ 5%			

- rates are increased with same factor of 5 as primary proton beam power
- faster fields increase polarization but decrease rates

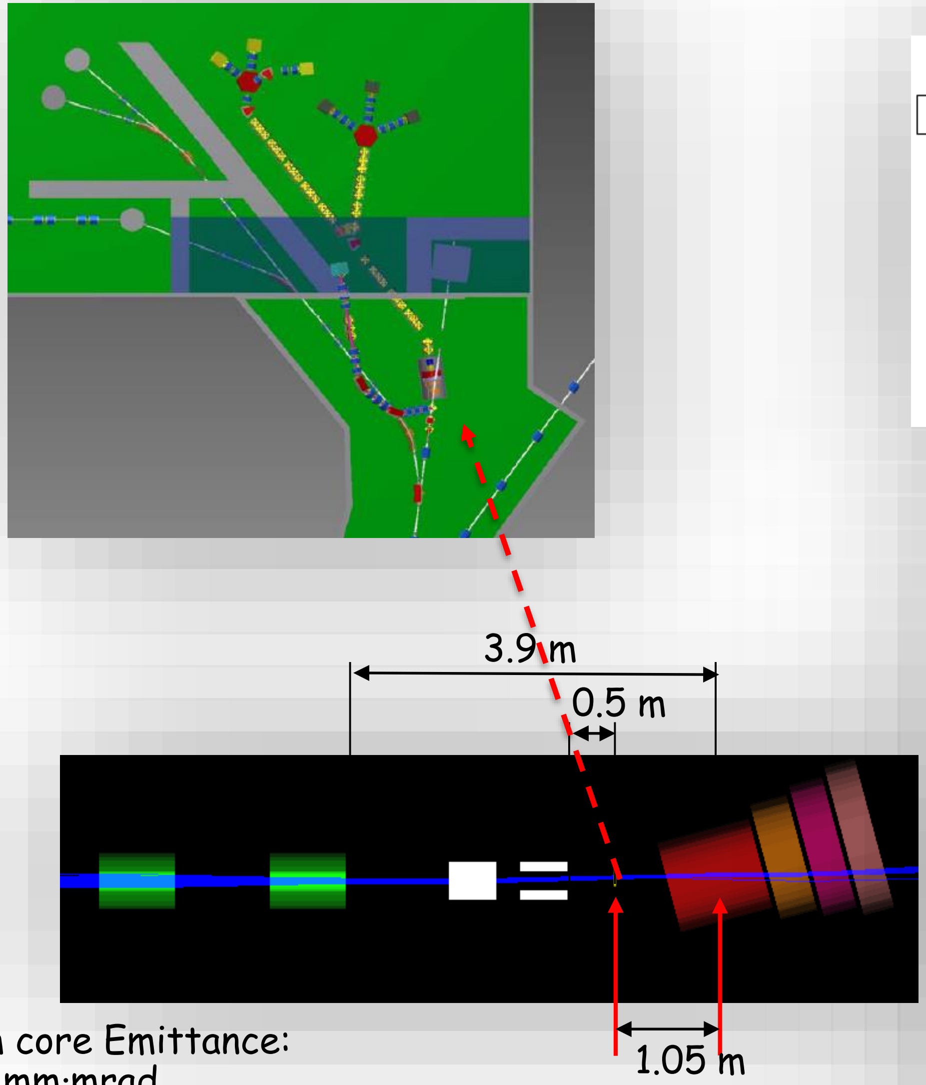
π+ : 5 T, 100000 π mm mrad at MS1, 25 kW, preliminary





MS1's shielding is being optimized with hybrid solutions for shielding in order have the 5x π+ rates per second than 5 kW rates

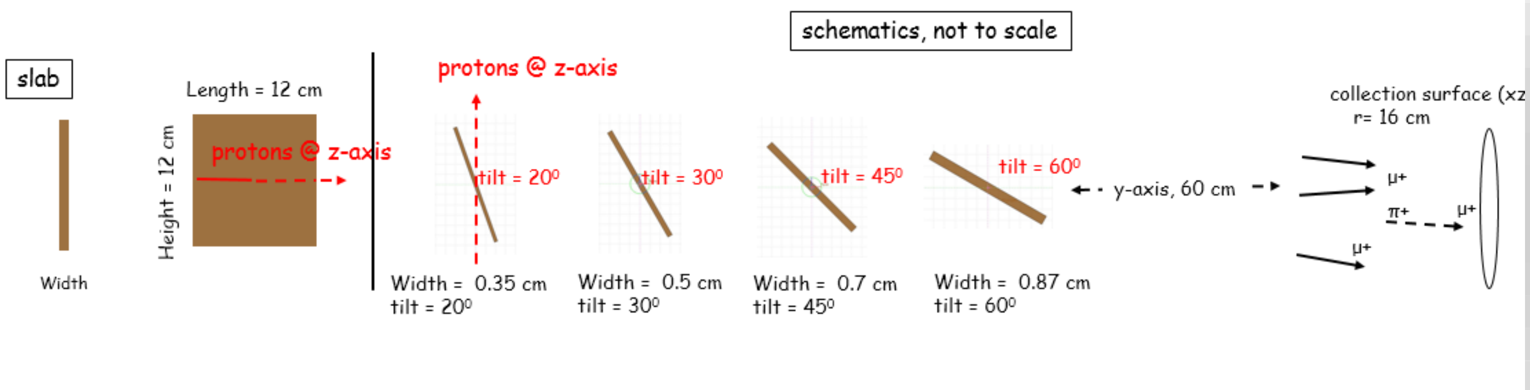
vertical μSR beam line with thin target before superconducting solenoid at "baseline scheme" (under study, 25 kW)



Beam core Emittance:
80 π mm·mrad

Beam spot at thin target
σx = 6 mm
σy = 12 mm

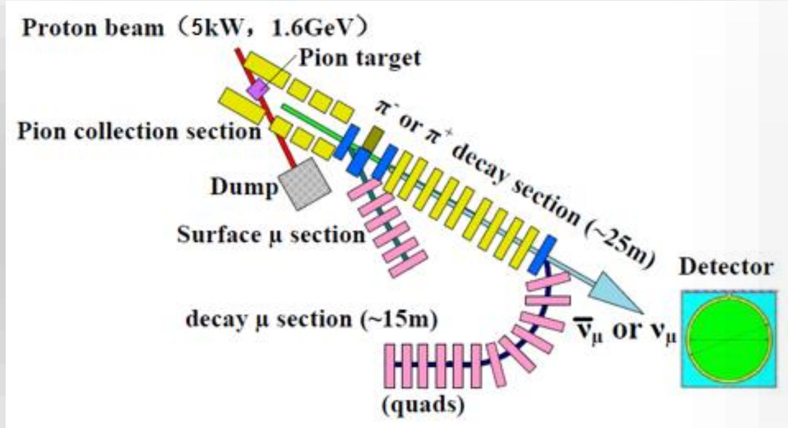
Beam spot at ce
of main target
σx = σy = ~5 mm

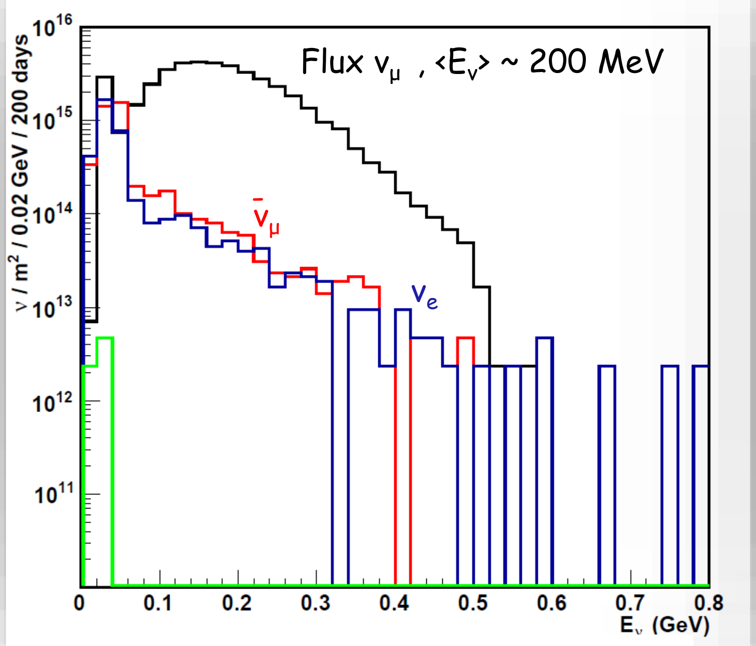


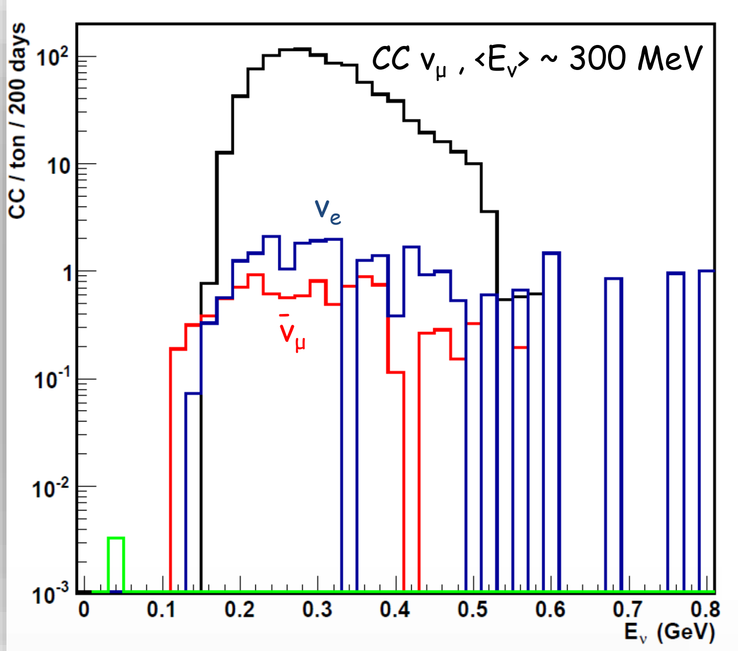
interaction length	1 cm				
beam size	σ_x = 6 mm, σ_y = 12 mm				
emittance (π mm mrad)	4500				
momentum	μSR - μ^+ 25 < P < 29.8 MeV/c				
tilt (degree)	45				
length x height (cm2)	12x12	10x10	8x8	6x6	5x5
intensity ($\times 10^6$) μ/sec	3.55	3.6	3.55	3.4	3.05
polarization	-0.96	-0.95	-0.97	-0.94	-0.94
surface muon purity (%)	97	97	98	96	96
statistical error	~ 5% / 2% on intensity / polarization				

other applications for EMuS

- The neutrino beam is an option under investigation. Motivation of the neutrino beam is the lack of recent cross sections measurements at lower energies







5 kW

1-8% stat. error, FLUKA	N_ν ($\times 10^{16}$) / m^2 / 200 days		CC / ton / 200 days	
	> 53 MeV	%	-	%
$\bar{\nu}_\mu$	3.78	94.5	959	96.5
ν_μ	0.13	3.2	10	1
ν_e	0.09	2.3	25	2.5
$\bar{\nu}_e$	-	-	0.004	-

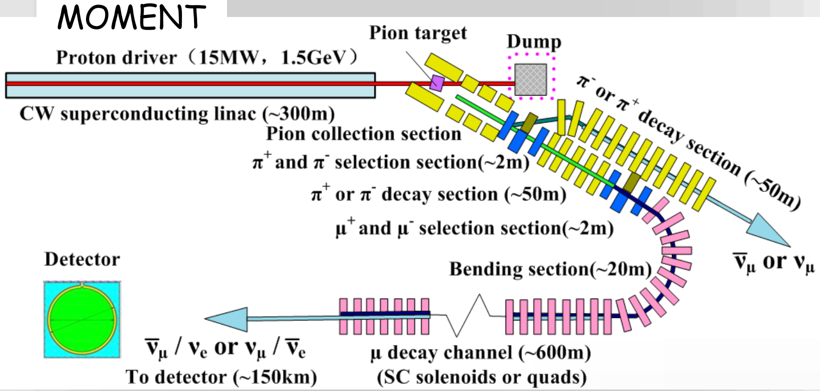
CC ν_μ at $\langle E_\nu \rangle$ = 300 MeV at EMuS

- ~ 1000 CC events / ton / year at 5 kW
- ~ 5000 CC events / ton / year at 25 kW

Other applications for EMuS

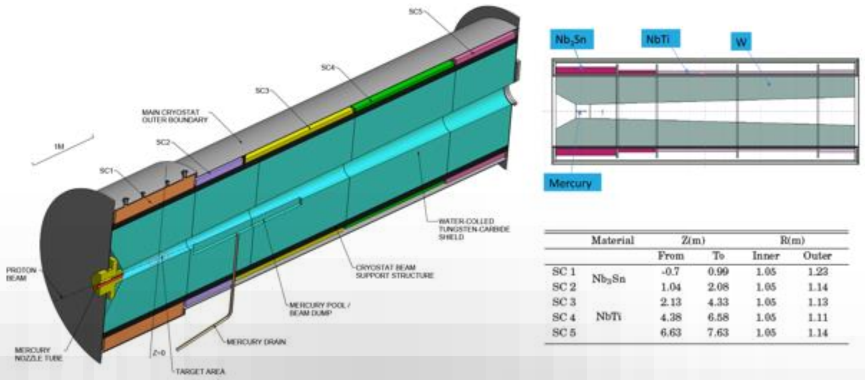
- EMuS could act as a high power targetry and accelerator R&D platform for MOMENT, a future muon-decay medium-baseline neutrino beam facility in China

MOMENT



MOMENT's high-field superconducting solenoid

- Baseline design: super conductive solenoid from ~ 14 T -> 3 T
- 2 first Nb_3Sn coils, 3 last NbTi coils
- 80 -> 60 cm thick W-shielding <-> 15 MW proton beam



	Material	Z(m)		R(m)	
		From	To	Inner	Outer
SC 1	Nb_3Sn	-0.7	0.99	1.05	1.23
SC 2		1.04	2.08	1.05	1.14
SC 3		2.13	4.33	1.05	1.13
SC 4	NbTi	4.38	6.58	1.05	1.11
SC 5		6.63	7.63	1.05	1.14

Novel waterfall granular target

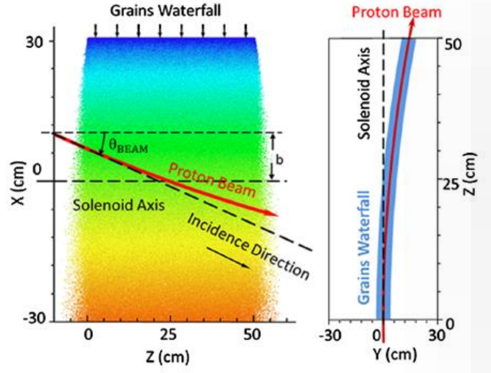


FIG. 15. The beam-target geometry for the waterfall target.

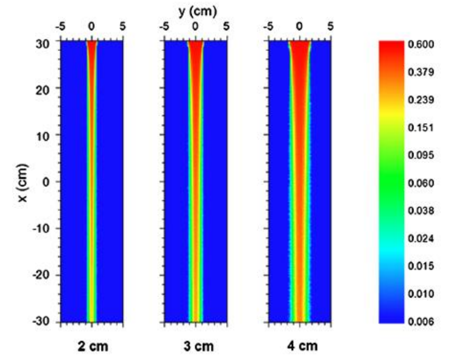
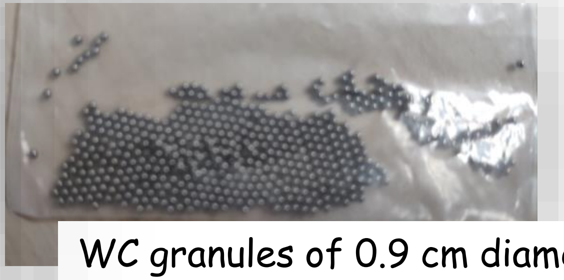


FIG. 6. Medium density (relative factor) distributions (in x-y plane) for the grain waterfalls with 2, 3, and 4 cm target width.



WC granules of 0.9 cm diameter

Thanks

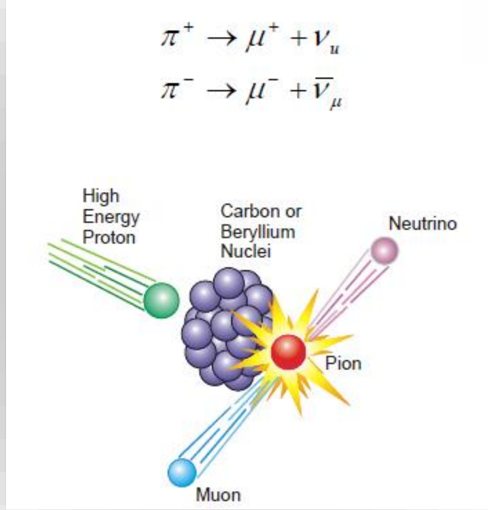
extra

μSR muons for EMuS, the first muon source in China

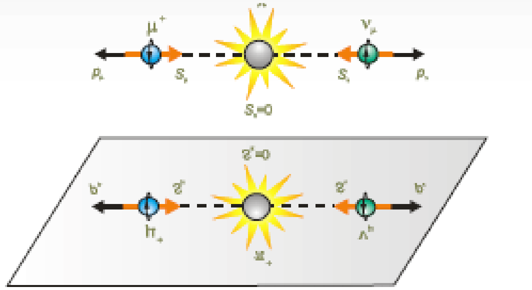
The high intensity muon source project EMuS is foreseen at CSNS and is being optimized for both muon and neutrino experiments

- It is primarily intended for muon science related to μSR techniques in matter physics and chemistry concerning μSR muons:
  - surface muons: μ+ from π+ decaying at rest inside target or at its surface, P ≤ 29.8 MeV/c, 100% polarization
  - cloud muons that are background by causing beam depolarization: any μ+ with P ≤ 29.8 MeV/c produced from π+ decaying in flight in the target station
  - decay muons that are also signal, μ+ from π+ decaying in flight, which can be used also for material science

μSR muons from DAR, produced only at target

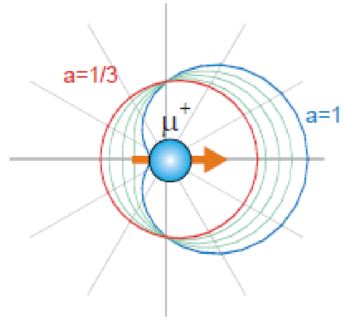


100 % polarisation due to DAR pions



Parity-violating collinear decay of a pion π^+ at rest into a muon μ^+ and a muonic neutrino ν_μ.

Asymmetrical decay due to week interaction

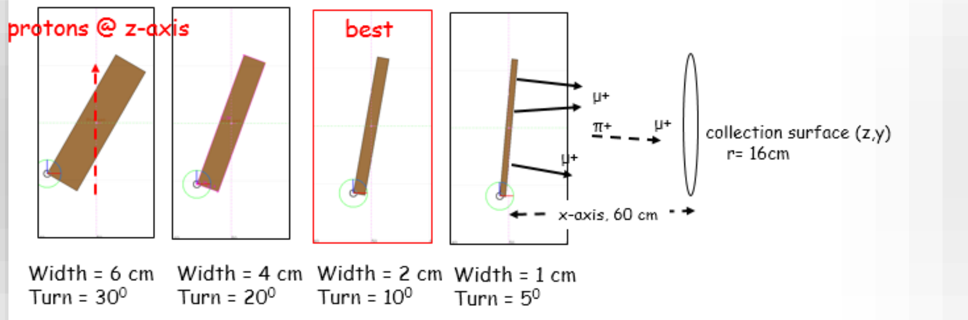


Angular distribution of the positrons from the muon decay: $W(E,\theta) = 1 + a(E)\cos(\theta)$. When all positron energies E are sampled with equal probability the asymmetry parameter has the value $a = 1/3$ (red curve).

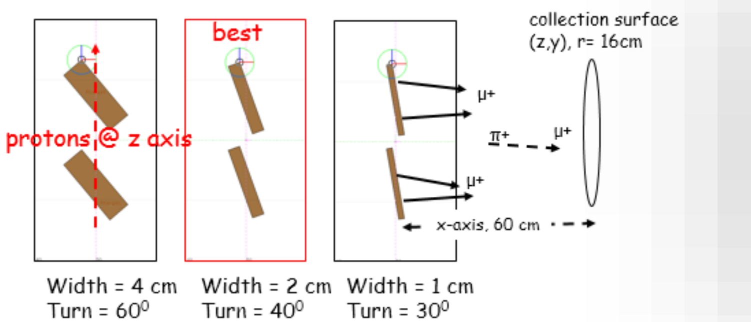
singlet-tilt case and doublets, triplets, 5 kW

- total proton – target interaction always 12 cm

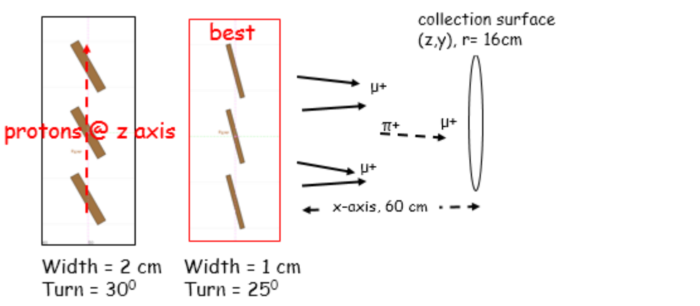
- side-surface Length x Height from 12x12 cm2 -> 24x24 cm2 due to singlet and turn



- side-surface 2 x Length x Height = 12x12 cm2

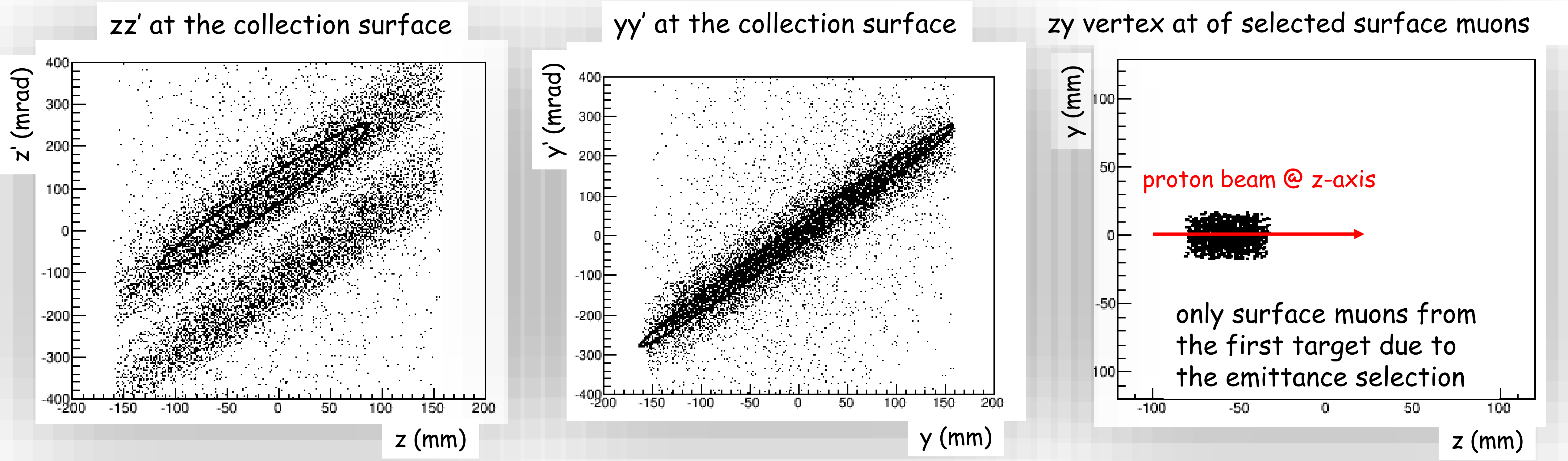


- side-surface 2 x Length x Height = 12x12 cm2



Target	Gr slab			
Selection	μSR - μ^+ 25 < P < 29.8 MeV/c			
target	BEST singlet	singlet-tilt	doublet	triplet
total intensity ($\times 10^6$) μ/sec	24	31	28	31
emittance (π mm mrad)	4500			
intensity ($\times 10^6$) μ/sec	3.5	3.2	2.6	2.2
polarization	-0.95	-0.96	-0.95	-0.97
surface muon purity (%)	97	96	97	98
stat. error ~ 1.5% for intensity / polarization				

zz' phase space is split into two with doublets (three with triplet)



doublet underperformance:

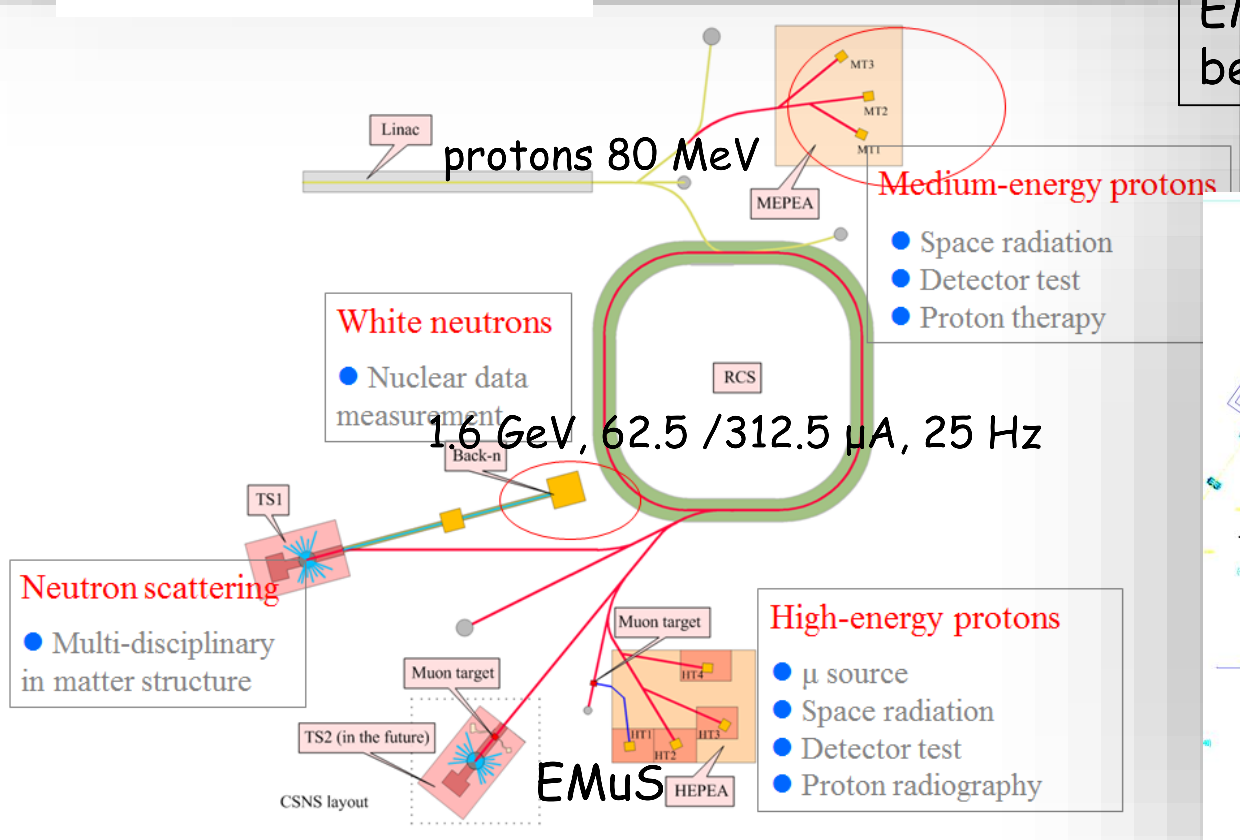
selected μSR μ^+ from only one ellipse at zz′

e_z .and. e_y @ 4500 π mm mrad

CSNS and EMuS

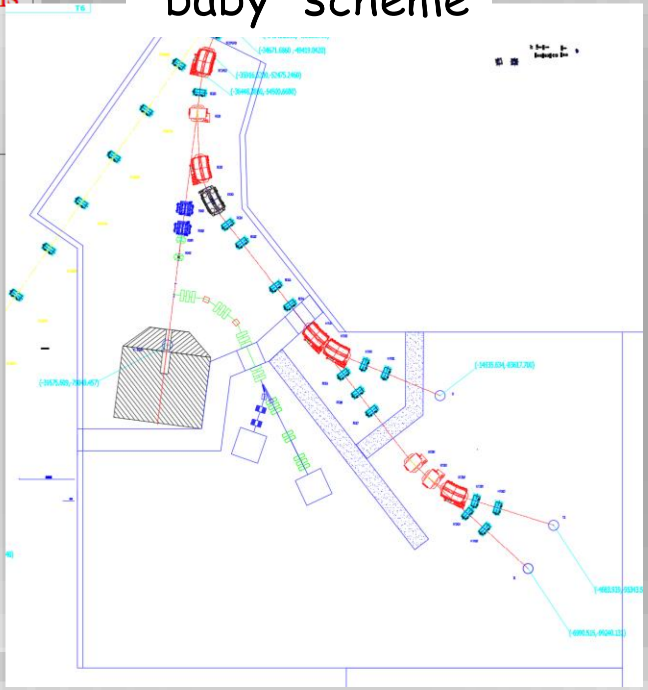
CSNS is the only large-scale proton accelerator in China today
- Strong needs from other fields than neutron scattering
- Excellent capability to support multiple platforms
- Phased development from 100 kW (I) -> 500 KW (II)

Schematics for CSNS

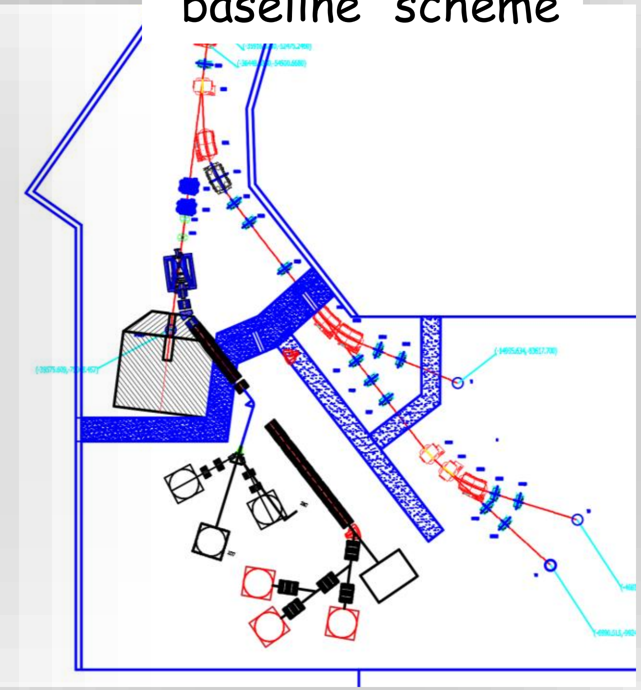


EMuS with 1.6 GeV / 5 kW to 25 kW primary protons will be located at the High Energy Proton Application hall

"baby" scheme



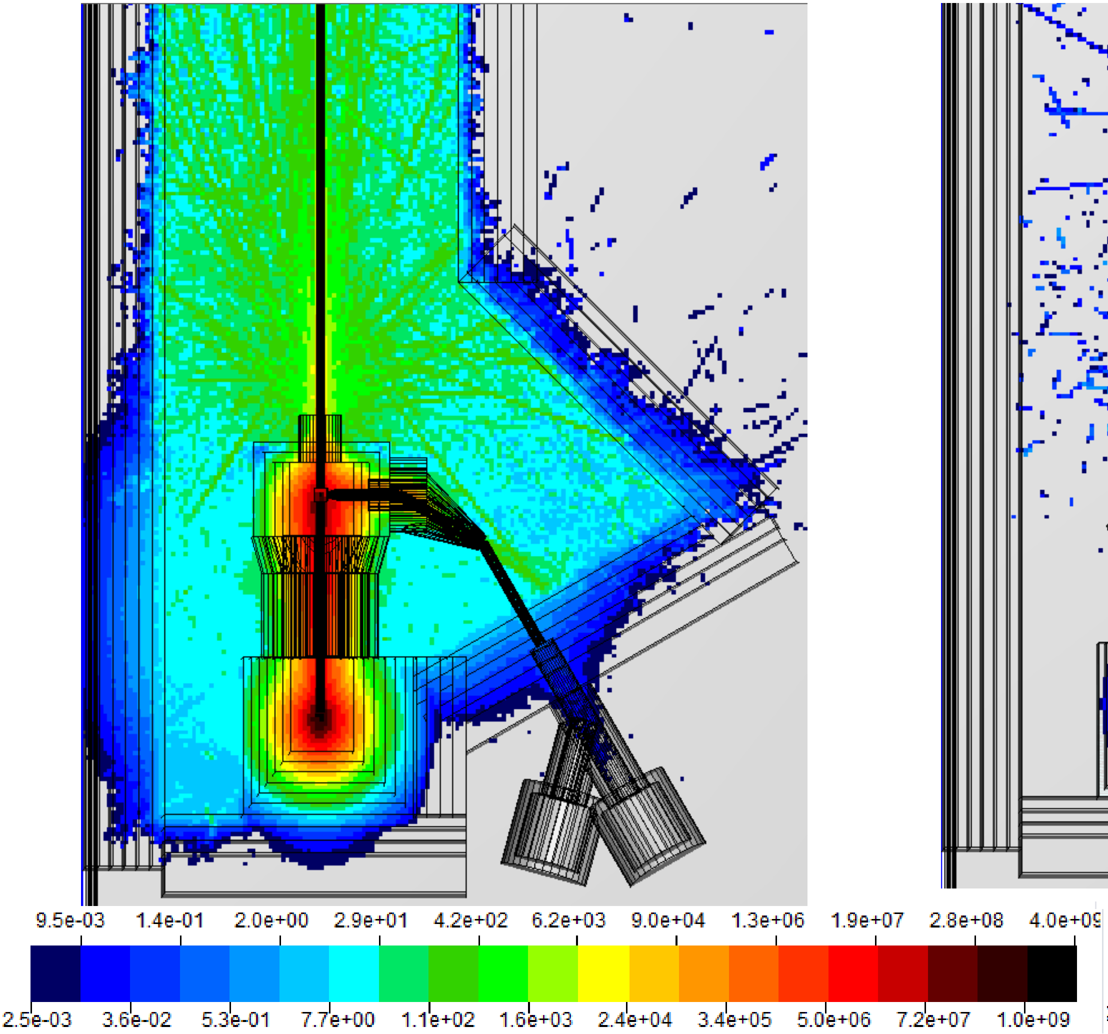
"baseline" scheme



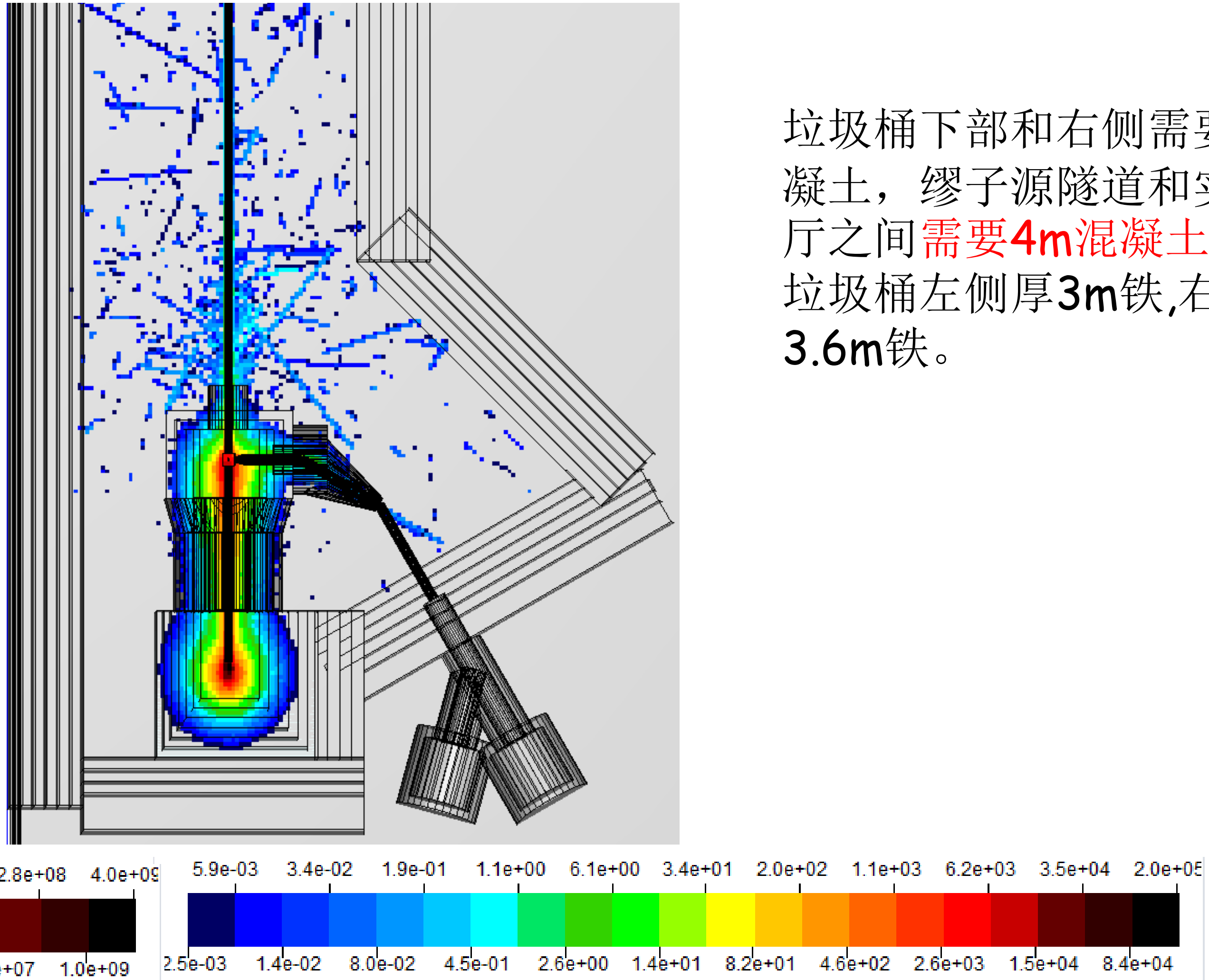
Commissioning and initial operation

- First beam on target: Aug.28, 2017
- Accelerator-target-instruments joint commissioning: November 1-9, 2017
- Accelerator reached the acceptance beam power of 10 kW: Nov. 9, 2017
- Instrument tuning and Day-one experiments: from January to March, 2018
- Initial operation: Since April 2018
- First physics paper including CSNS neutron scattering experiment published: April 17, 2018
- Open to general users: from September 2018
- Present beam power: ~50 kW

屏蔽与防护——baby-scheme方案



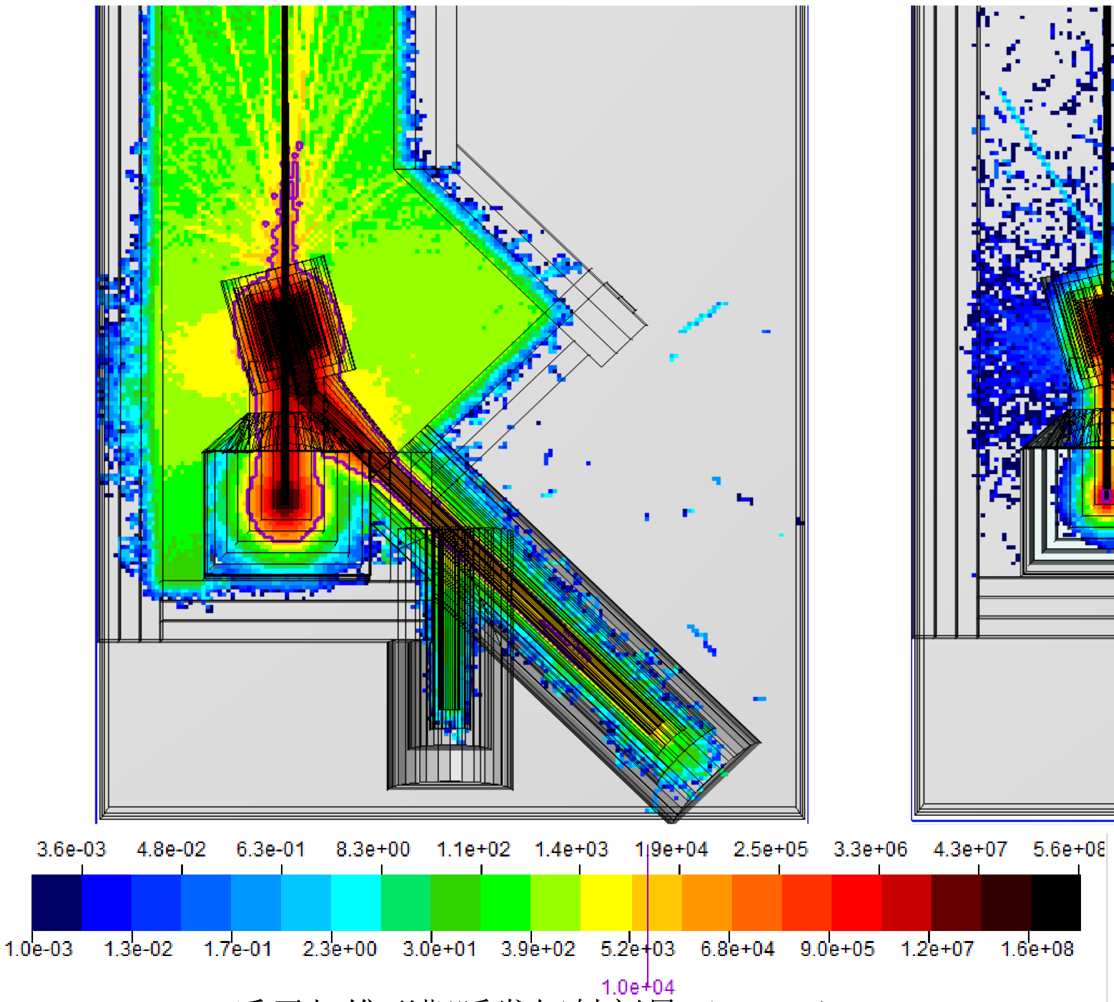
1.6GeV-25kW质子打长方体碳靶瞬发辐射剂量（mSv/h）



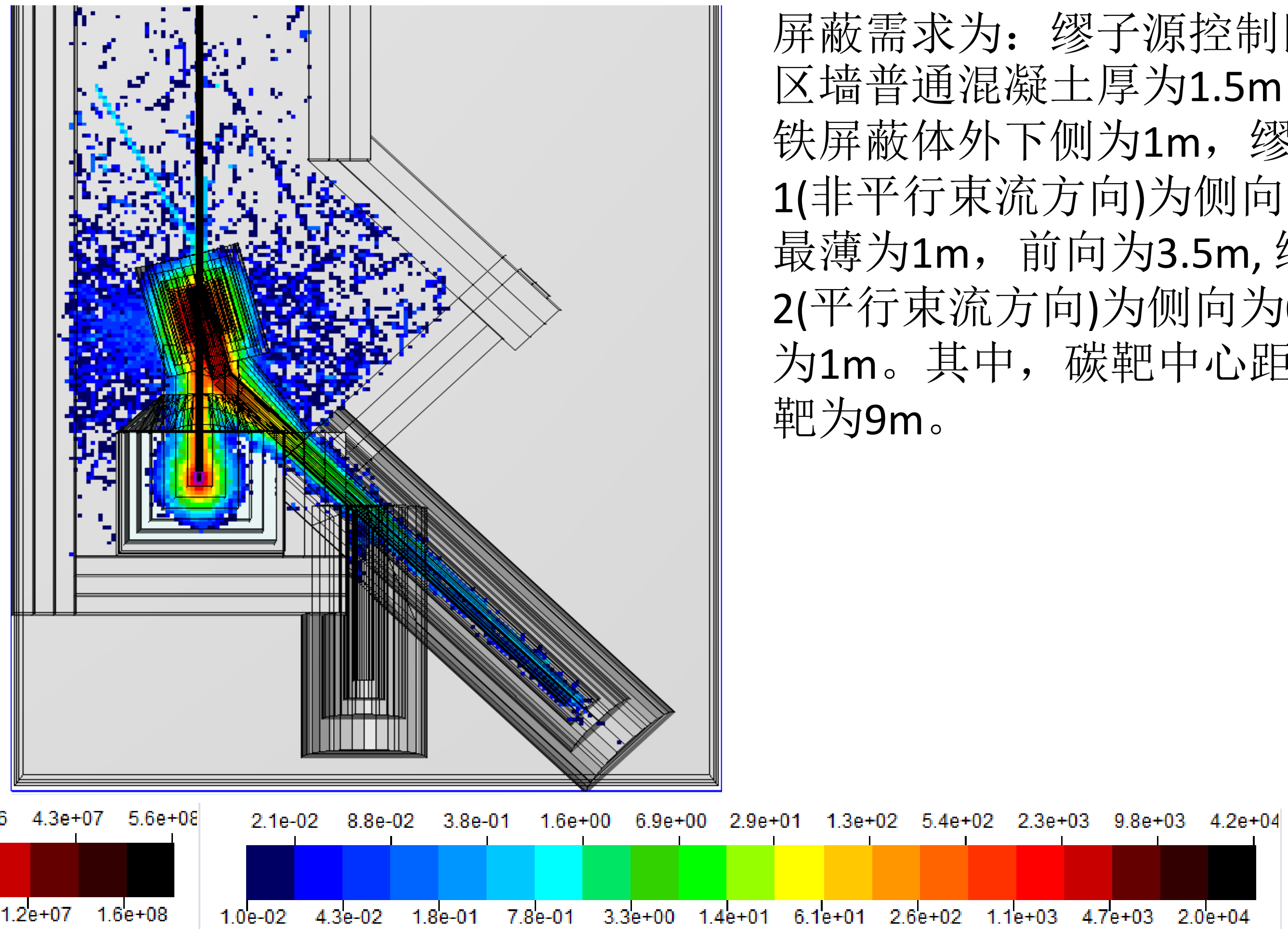
1.6GeV-25kW质子打长方体靶运行100天停机4小时剩余辐射剂量（mSv/h）

垃圾桶下部和右侧需要2m混凝土，缪子源隧道和实验大厅之间需要4m混凝土，其中垃圾桶左侧厚3m铁,右侧厚3.6m铁。

屏蔽与防护——baseline方案



1.6GeV-25kW质子打锥形靶瞬发辐射剂量（mSv/h）



1.6GeV-25kW质子打锥形靶运行100天停机4小时剩余辐射剂量（mSv/h）

屏蔽需求为：缪子源控制区和实验区墙普通混凝土厚为1.5m，垃圾桶铁屏蔽体外下侧为1m，缪子输运线1(非平行束流方向)为侧向最厚为3m，最薄为1m，前向为3.5m, 缪子输运线2(平行束流方向)为侧向为0.5m前向为1m。其中，碳靶中心距离垃圾桶靶为9m。

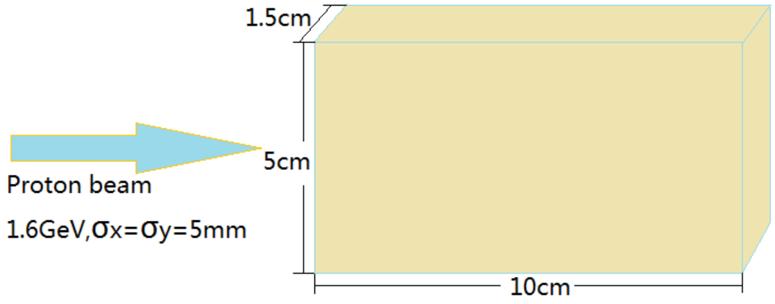
Thermal analysis of Baby target

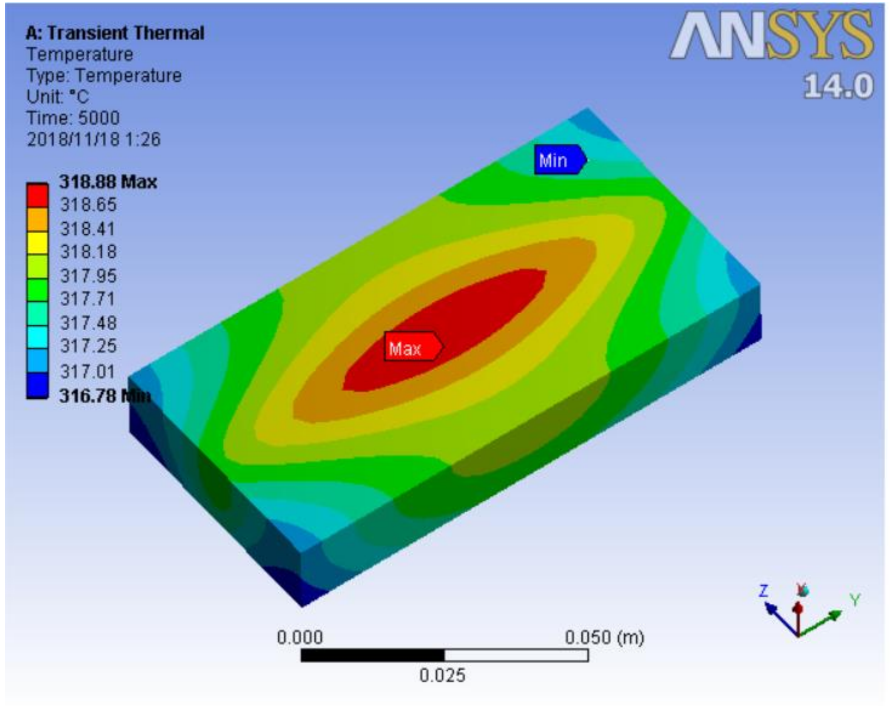
material:C

Heat deposition

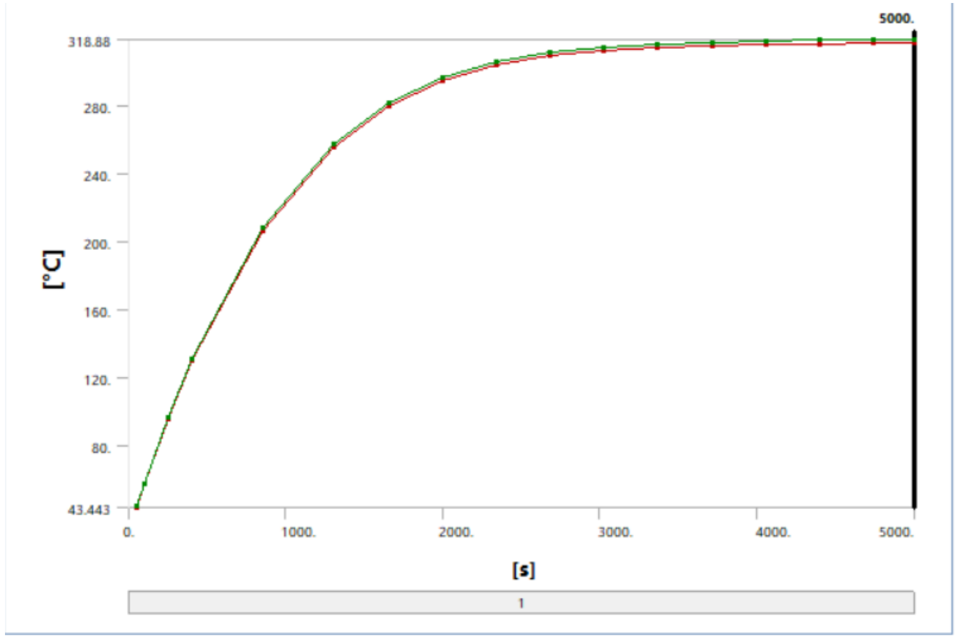
Given for Gaussian distribution in phase space

(Max 0.32W/cm^3,integral 126W for t-100mm,σ_x=5mm,σ_y=5mm)



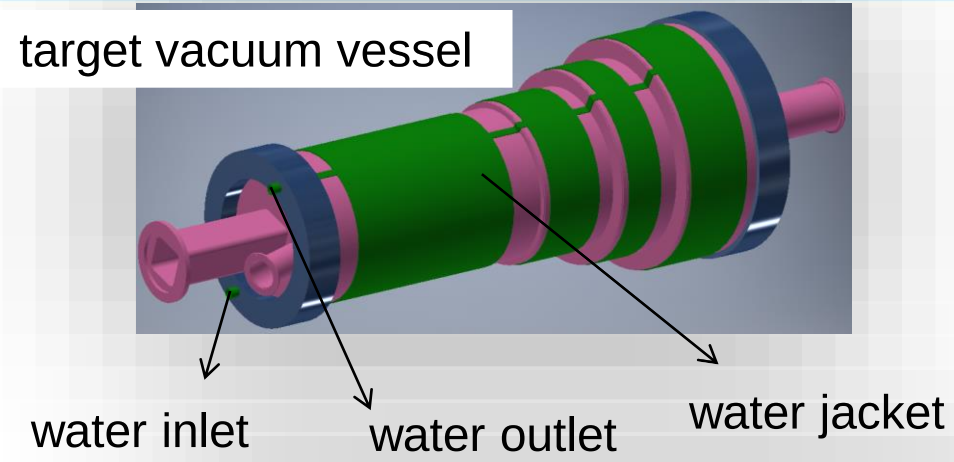


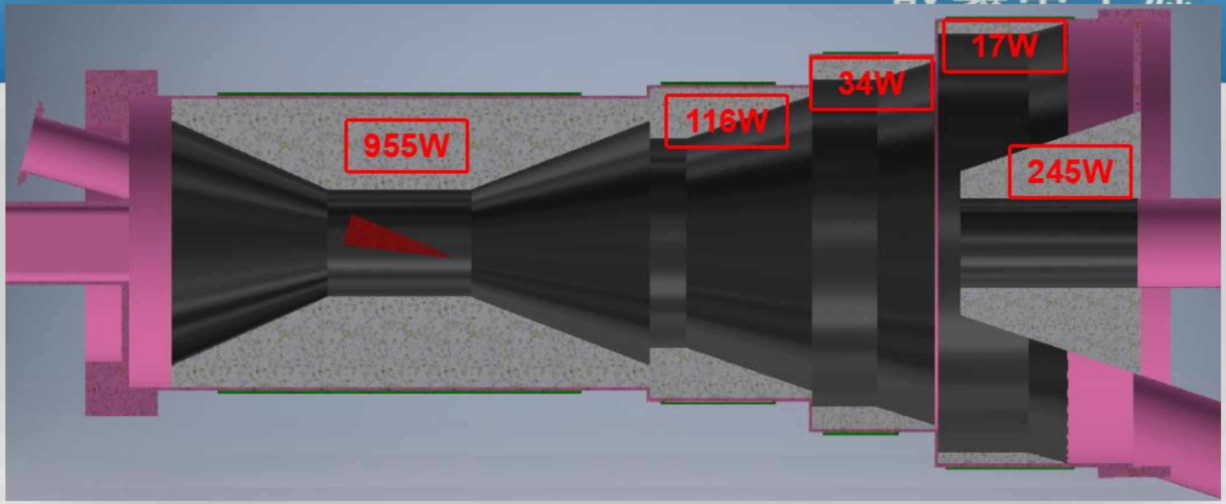
Max temperature 318℃

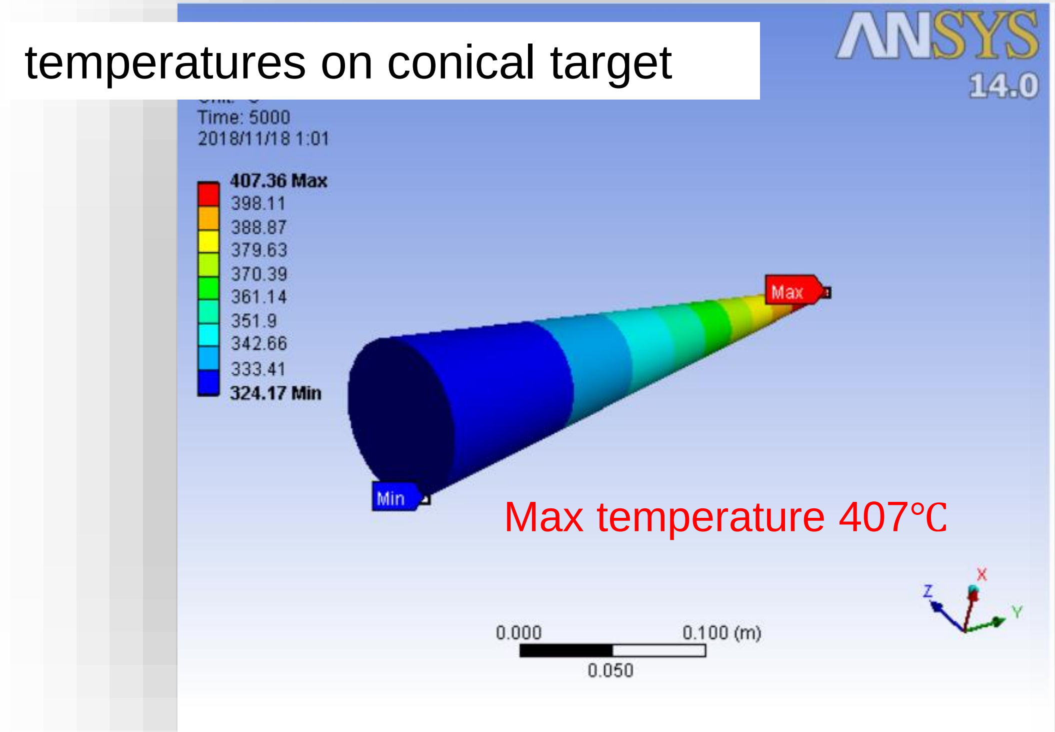


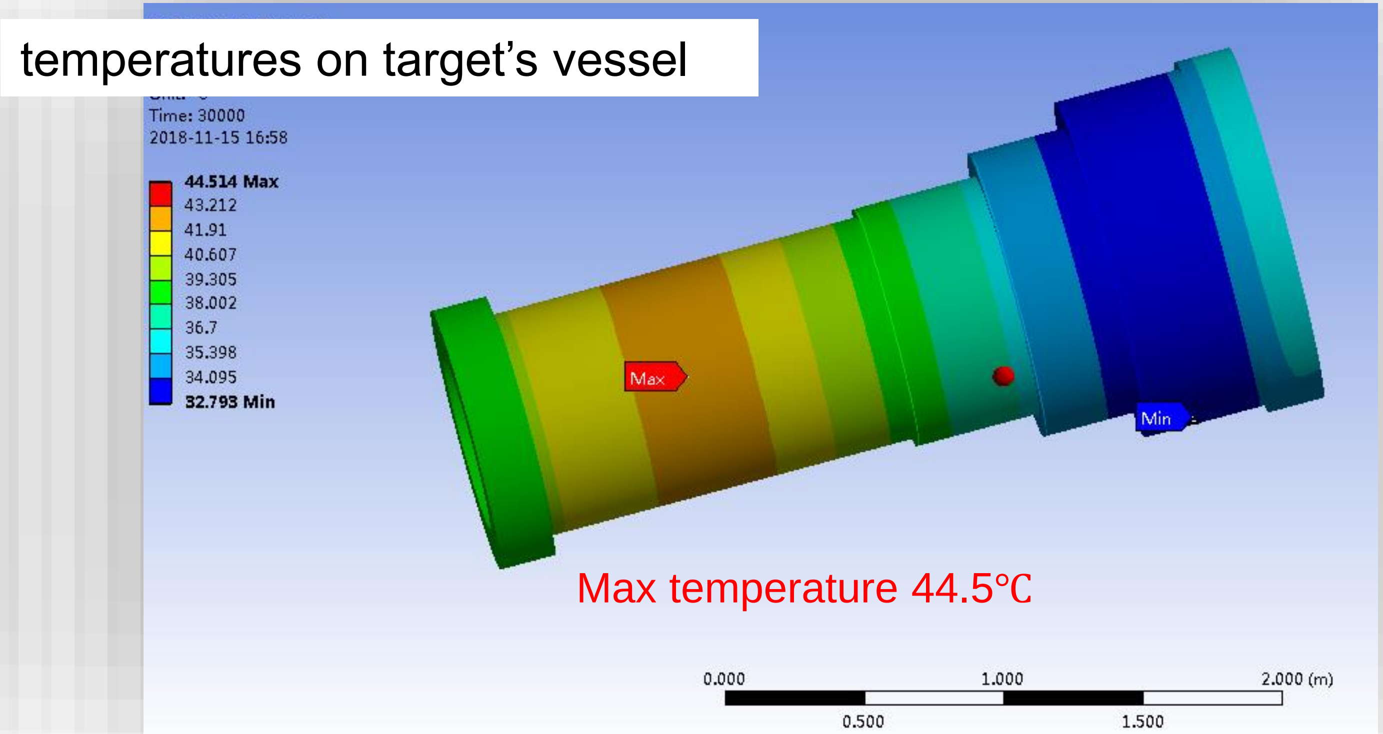
Temperature rise curve

radiation studies, 5 kW shielding

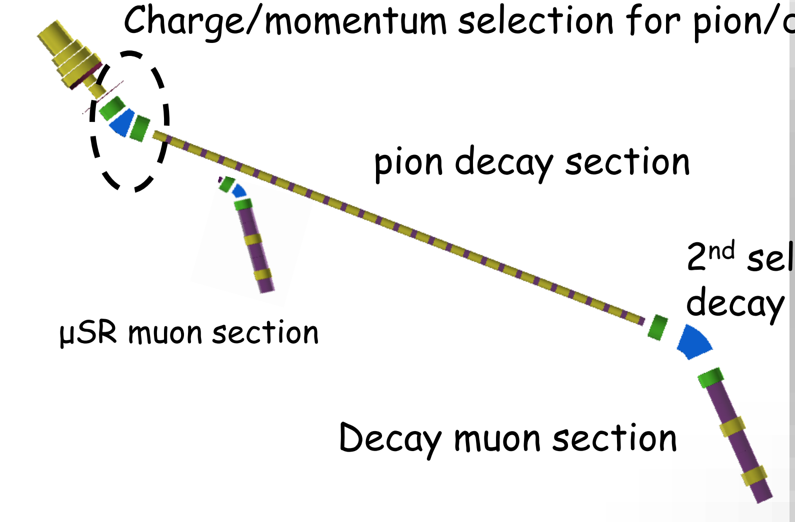


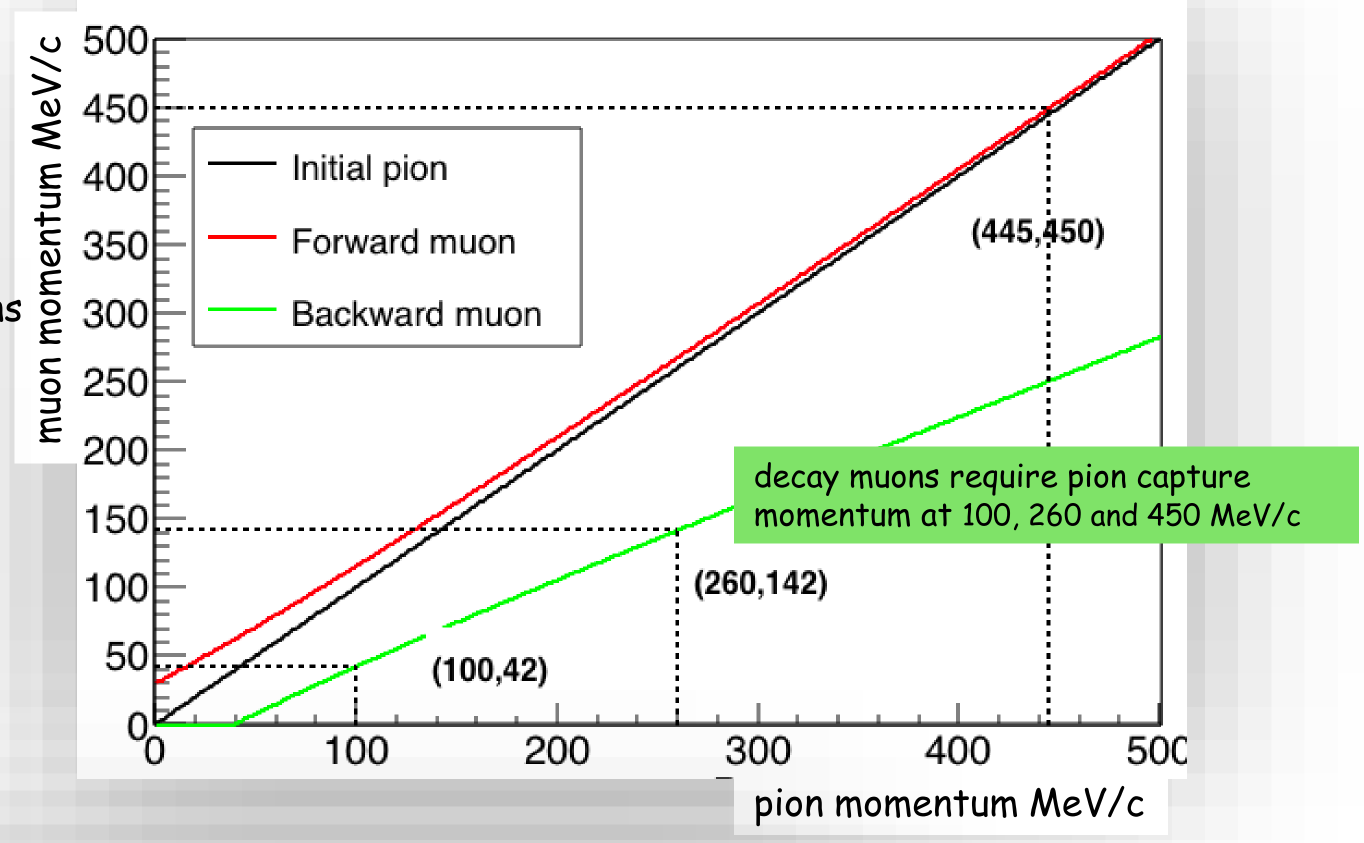






π+ momentum selection for decay muons

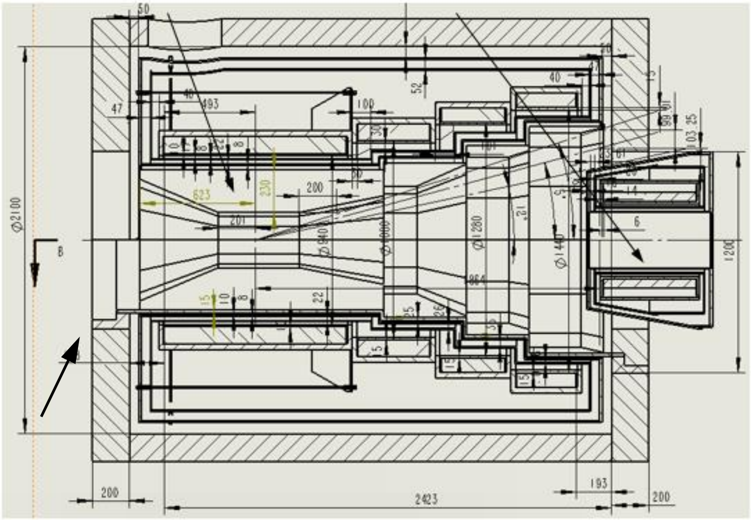


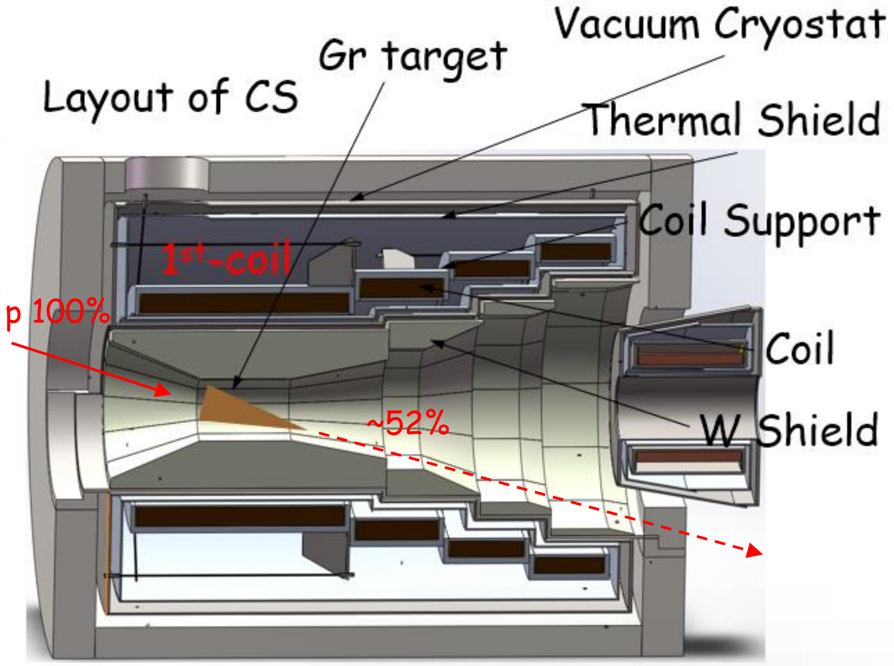


$$p_\mu = \frac{(m_\pi^2 - m_\mu^2)(p_\pi^2 + m_\pi^2 c^2)^{1/2} \pm p_\pi (m_\pi^2 + m_\mu^2)}{2 m_\pi^2}$$

+ or – reflects spin direction of "forward" and "backward" muon

Conceptual Design of
Capture and Matching solenoids



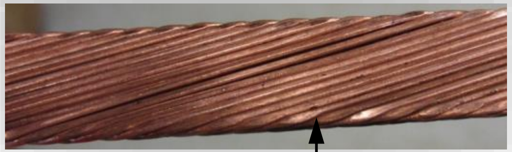


Hou Zhilong/IHEP

Conductor —Aluminum stabilized NbTi Rutherford cable by Chinese industry:

Aluminum | Rutherford cable

Cross section of Rutherford cable



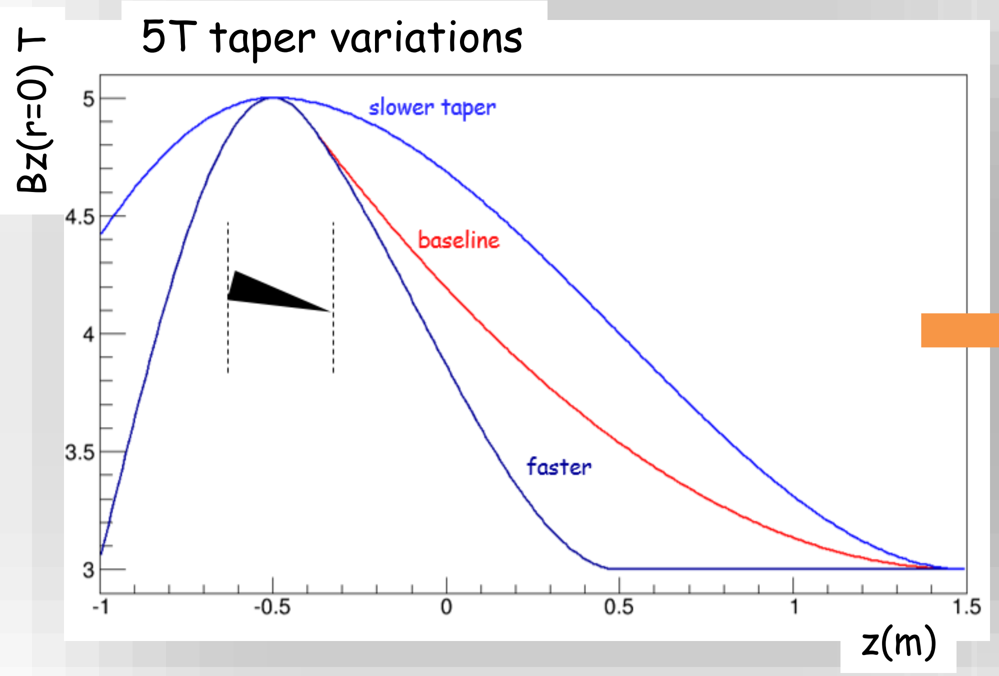
Rutherford cable

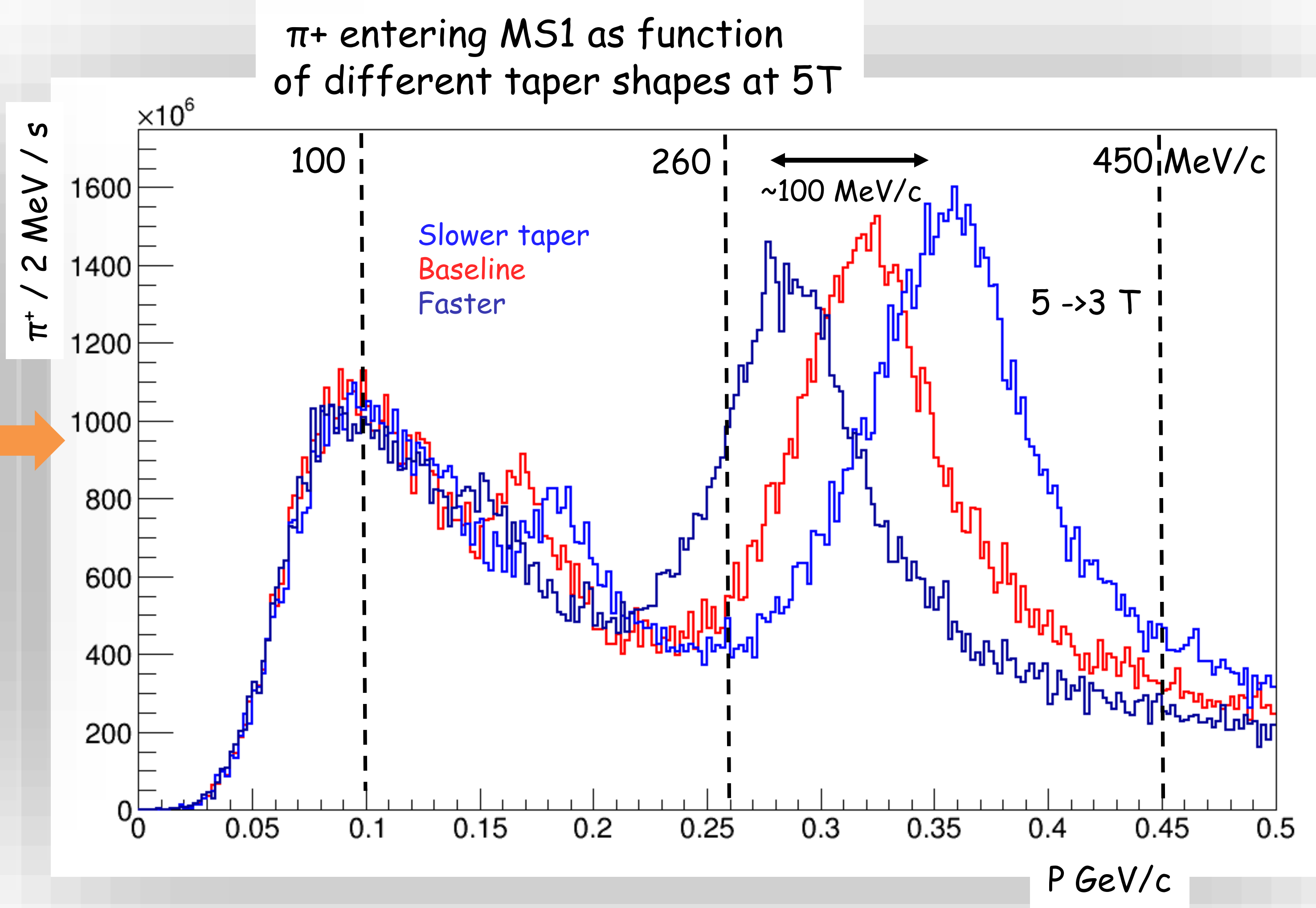
Superconducting Capture Adiabatic Solenoid:

1. Forward spent-proton extraction, proton beam & target tilted in respect to magnetic axis, $\theta p = 15^o$
2. 4-coils/3-steps design, NbTi-Al coils, adiabatic taper
3. Graphite target with conical shape
4. Adiabatic 1 -> 0.5 T for surface muon capture, 5 -> 3 T for pions

different adiabatic tapers <-> different momentum selection

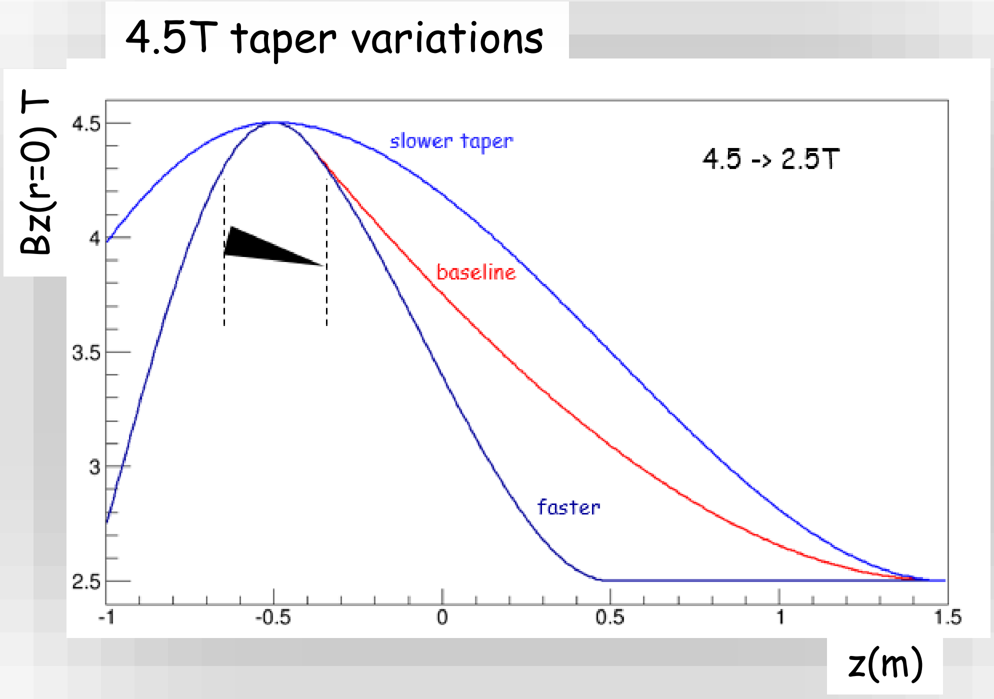
- 5T case
- polynomial representation of tapers

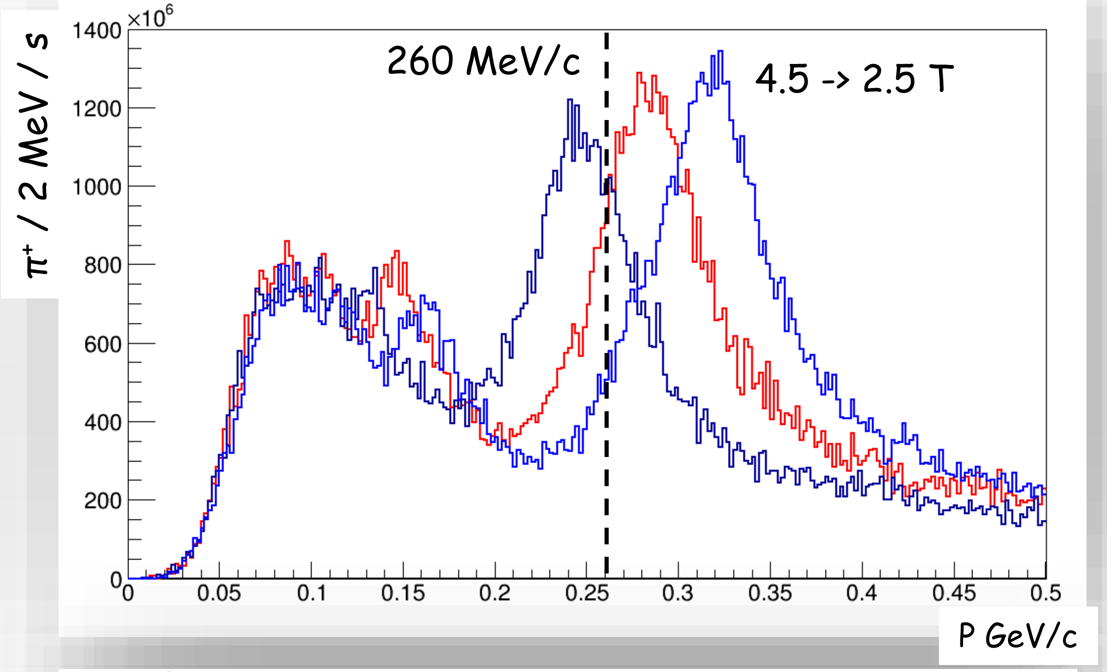


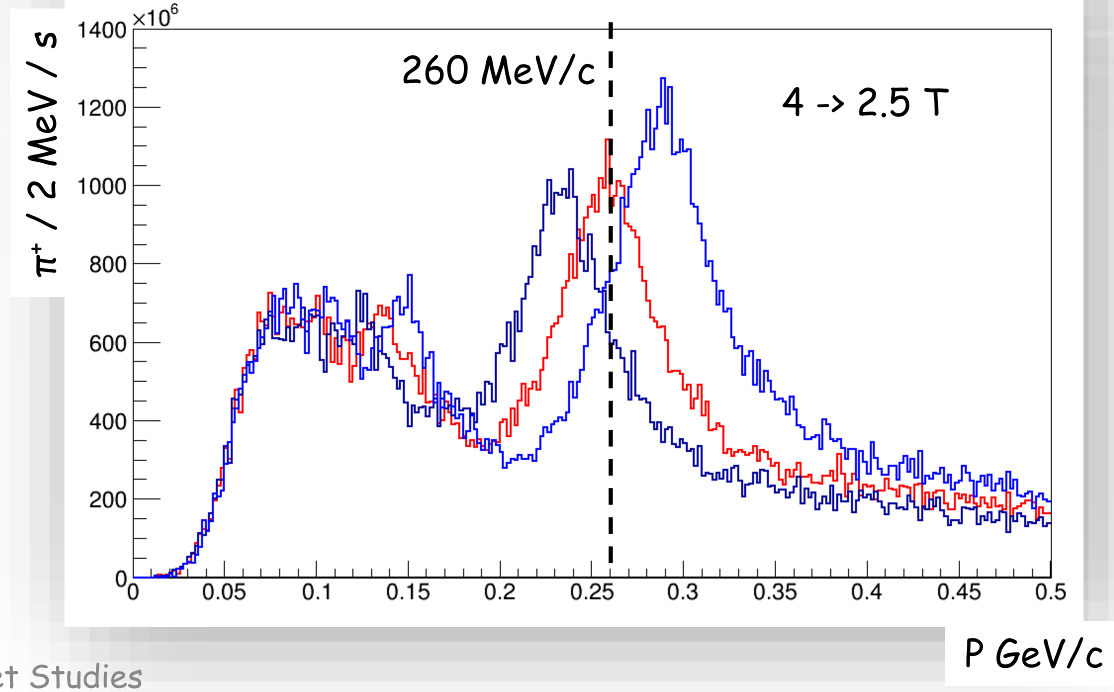


different momentum selection

- 4.5, 4 T cases
- polynomial representation of tapers

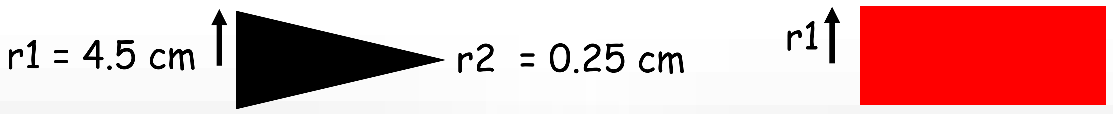




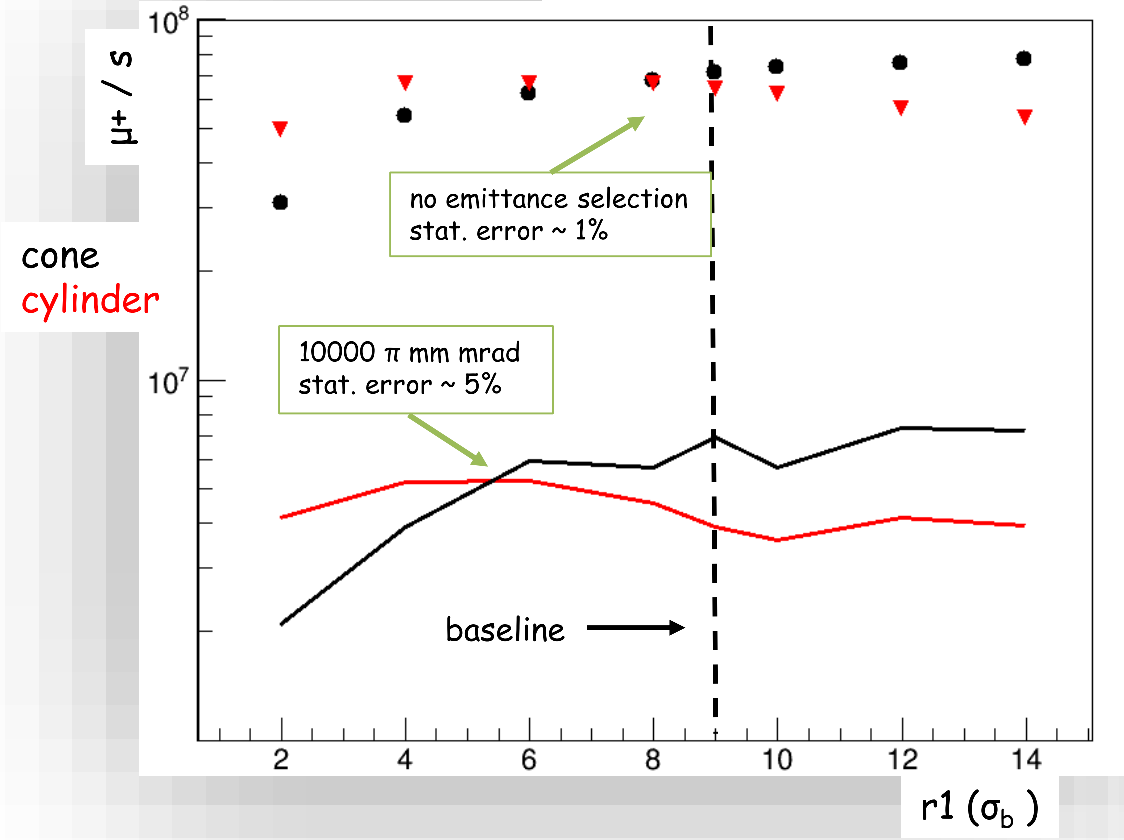


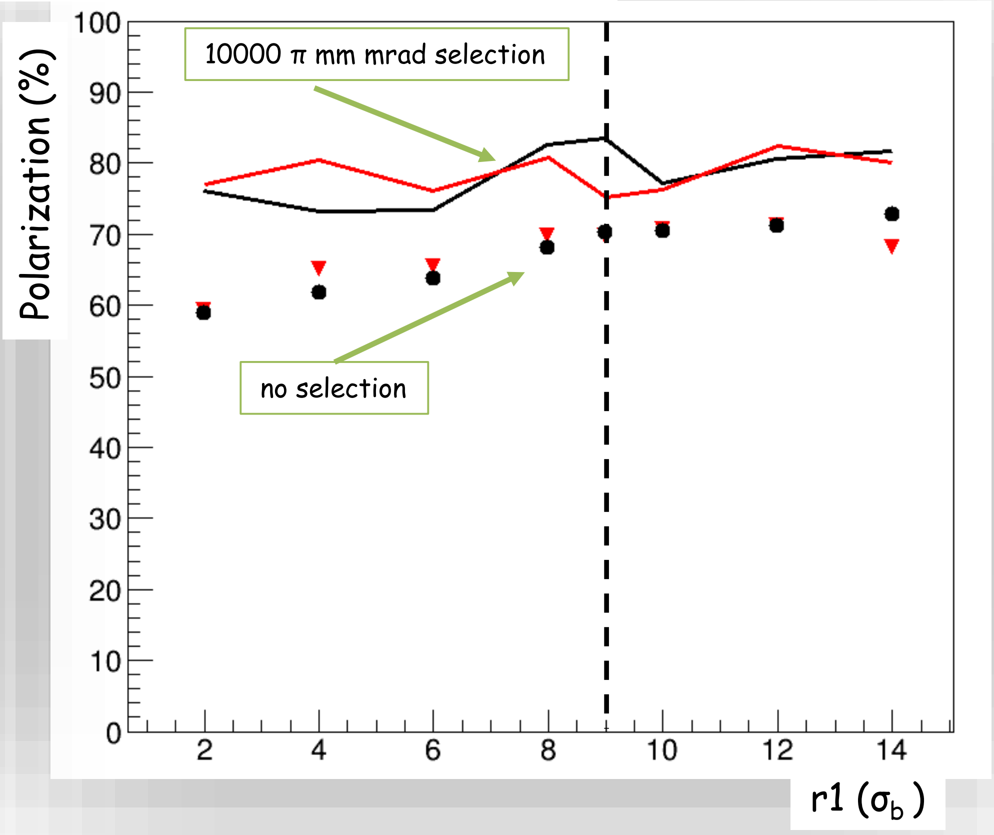
conical target

- better surface muon collection than cylinder
- lower power deposition on the SC
- μ+ with 25 ≤ P (MeV/c) ≤ 29.8
- similar polarization



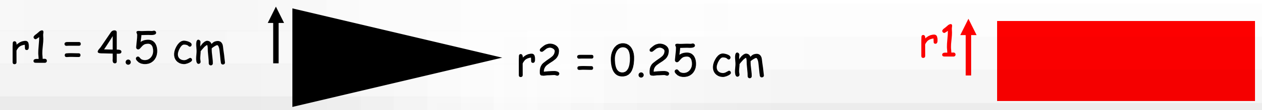
rate and polarization as function of radius r1 (in σ_b = 0.5 cm)



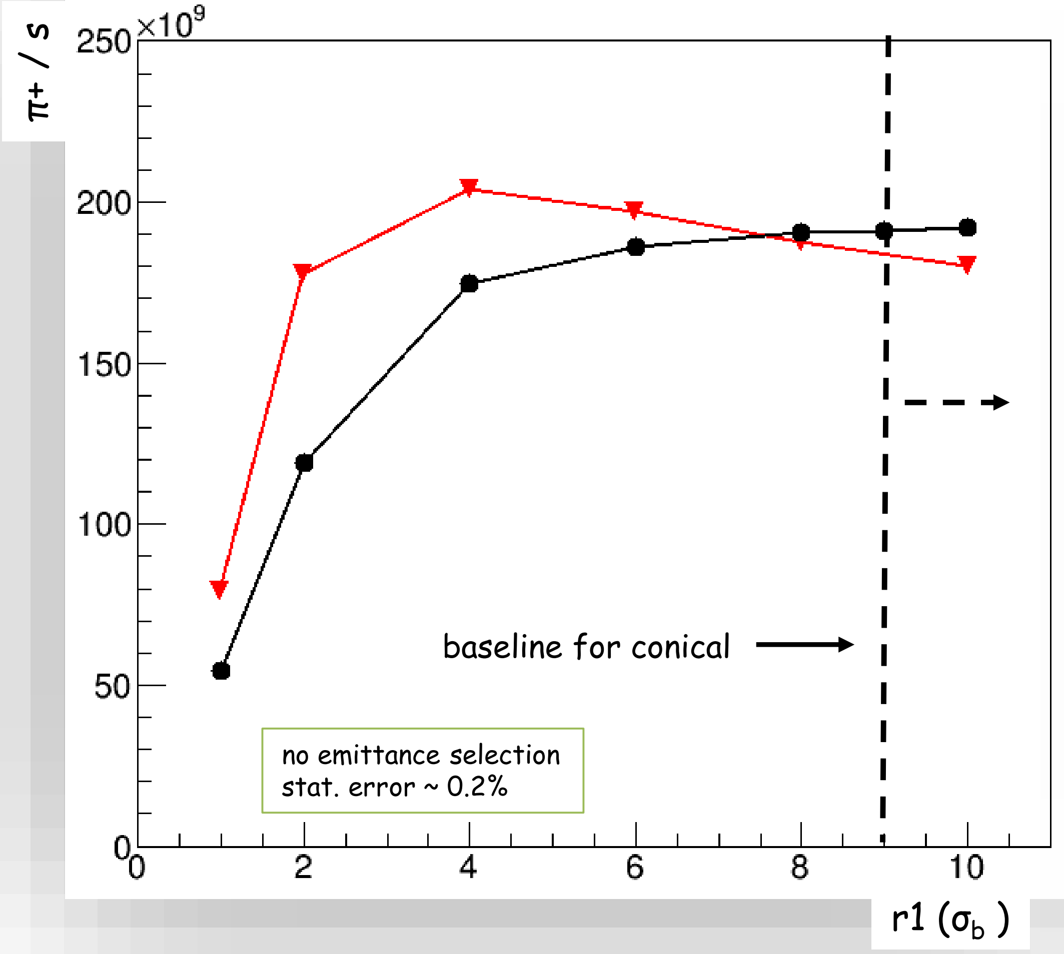


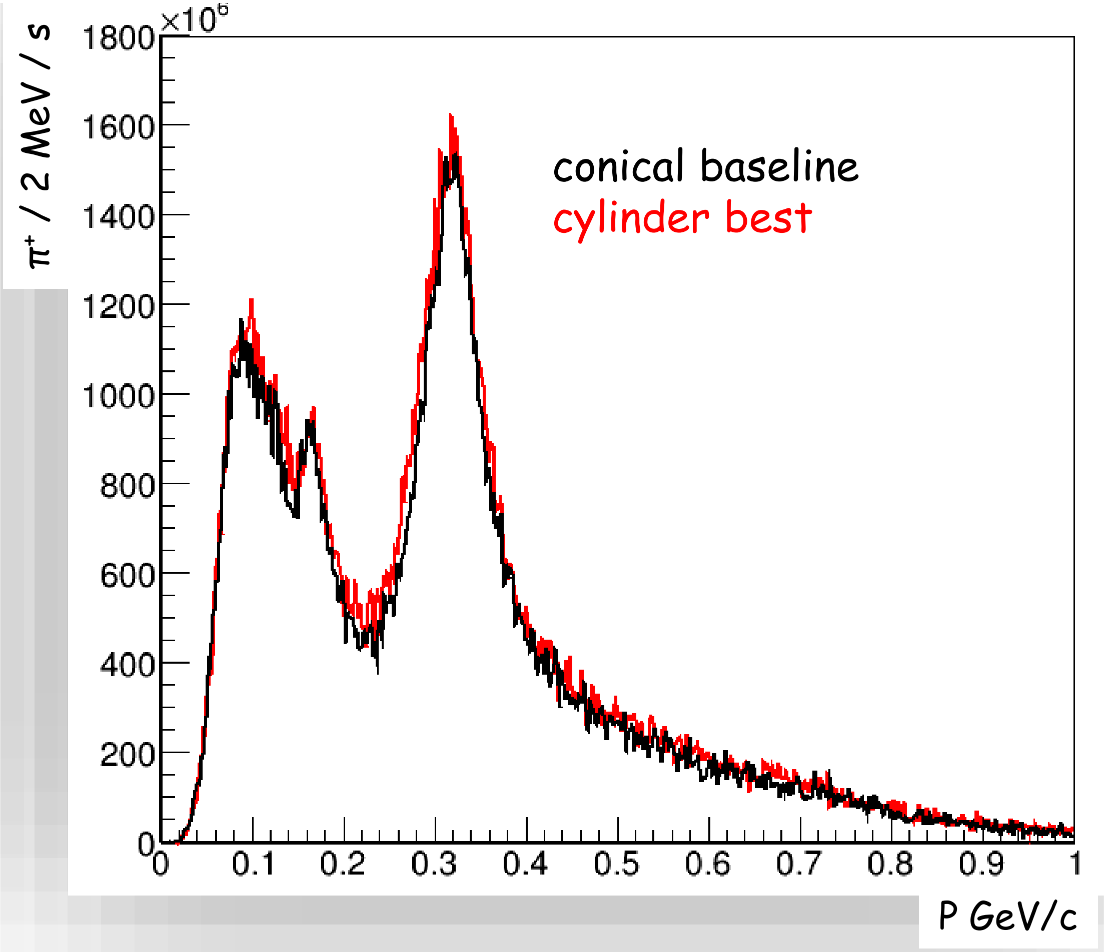
conical target π+ collection at MS1, 5 kW shielding

- similar collection to cylindrical best

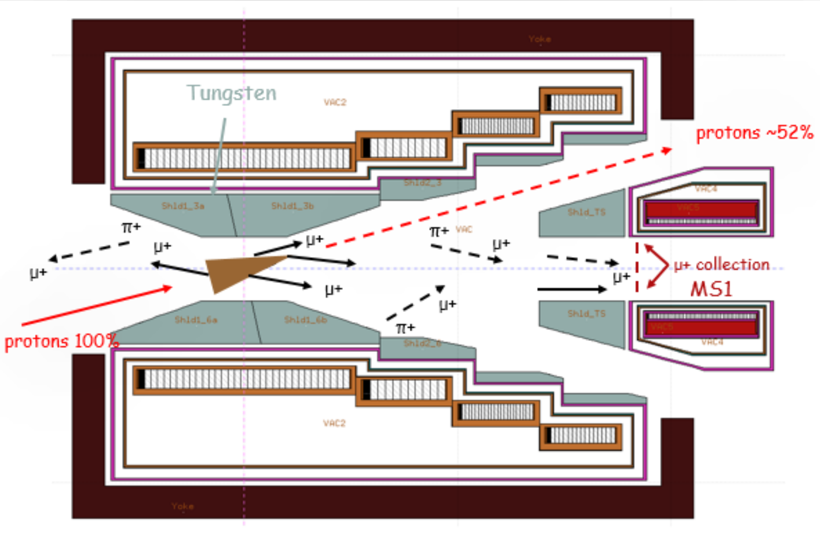


rates as function of radius r1 (in σ_b = 0.5 cm) and momentum distributions

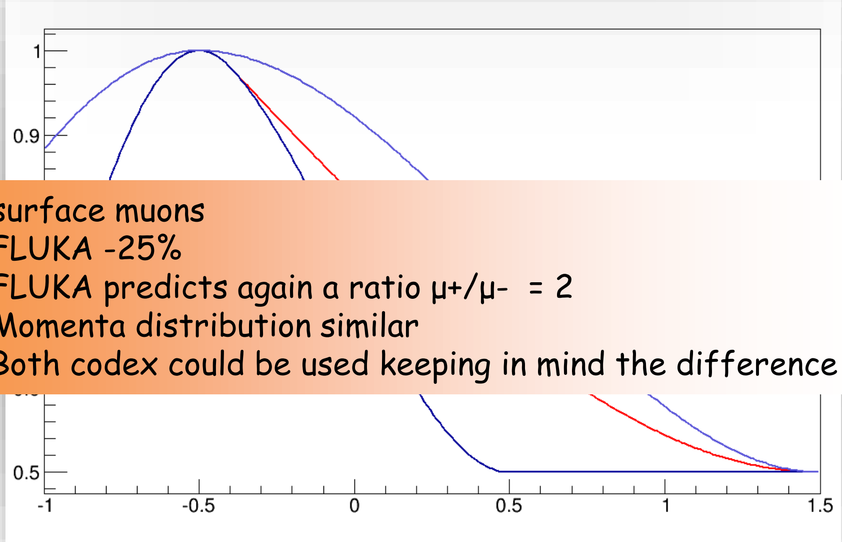




Systematics from monte-carlos: μ+ and μ- with FLUKA and G4 (BERTINI) at MS1, 1 T

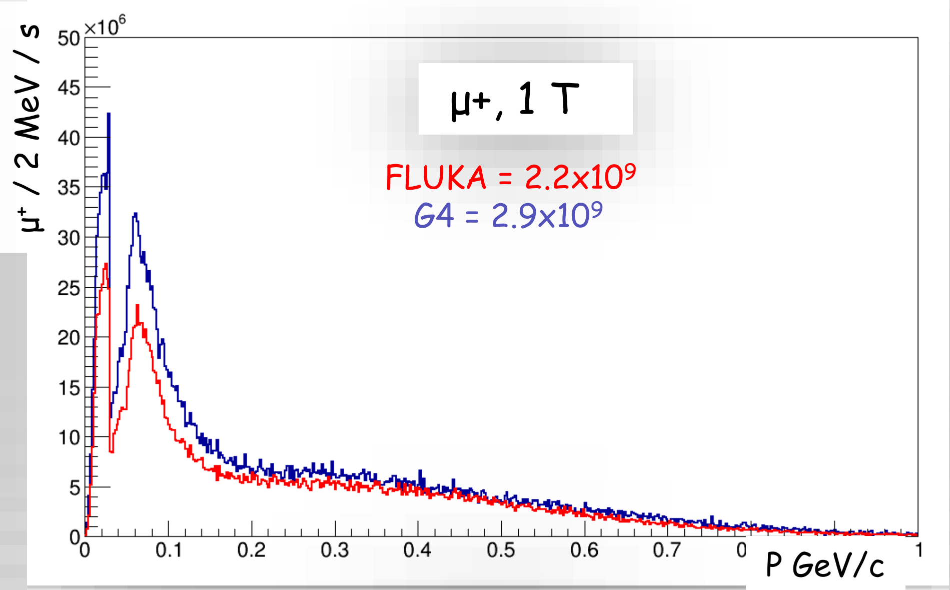


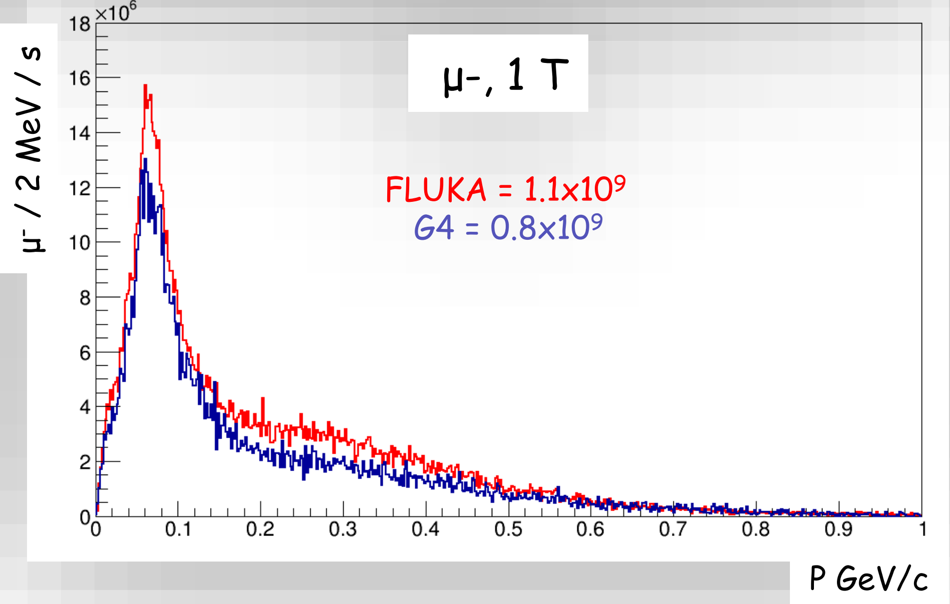
Same baseline 1T taper used on both



For surface muons

- FLUKA -25%
- FLUKA predicts again a ratio μ+/μ- = 2
- Momenta distribution similar
- Both codex could be used keeping in mind the difference



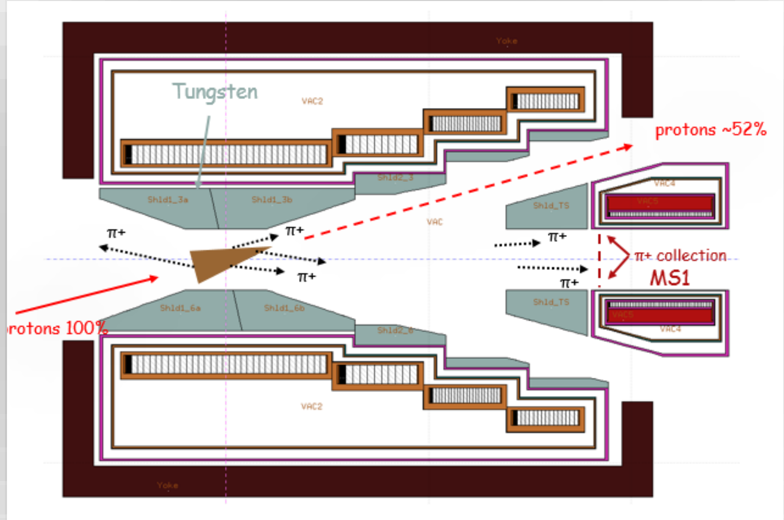


Ratio μ+/μ-

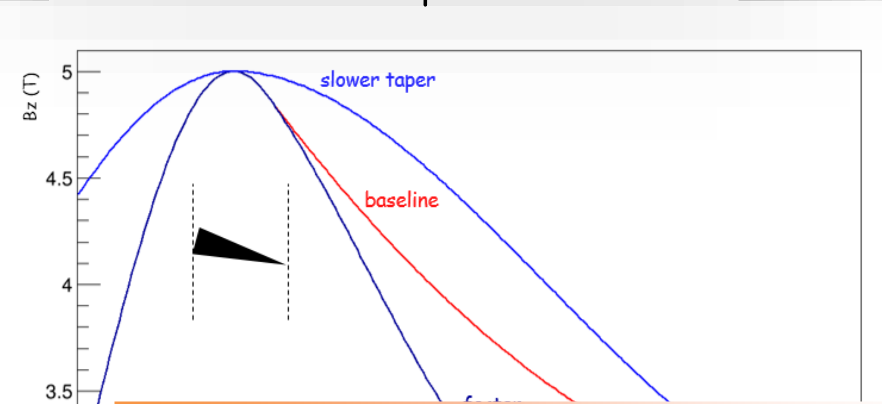
- FL = 2
- G4 = 3.6

G4: Song Yingpeng

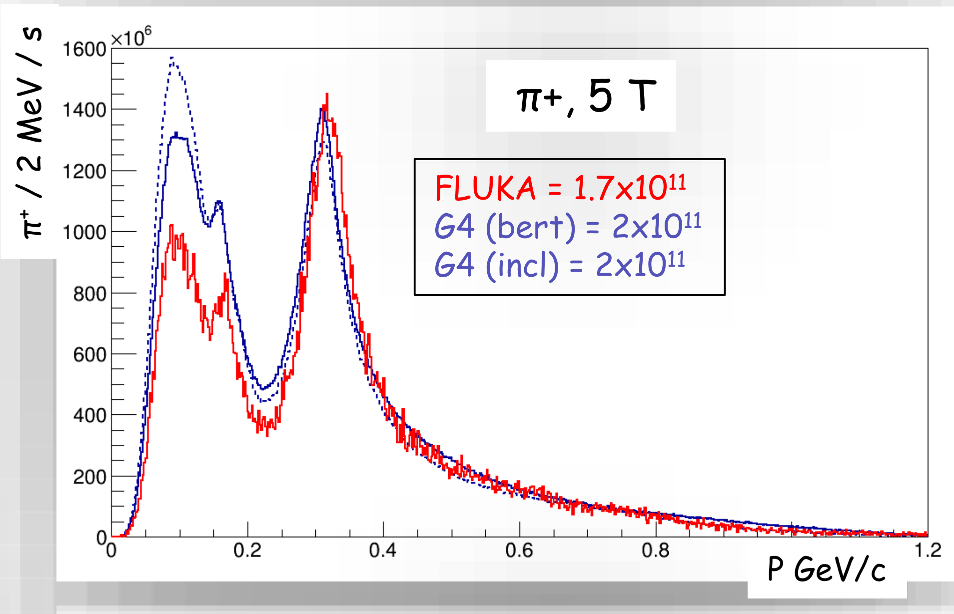
Systematics from monte-carlos: π+ and π- with FLUKA and G4 (BERTINI, INCL) at MS1, 5 T



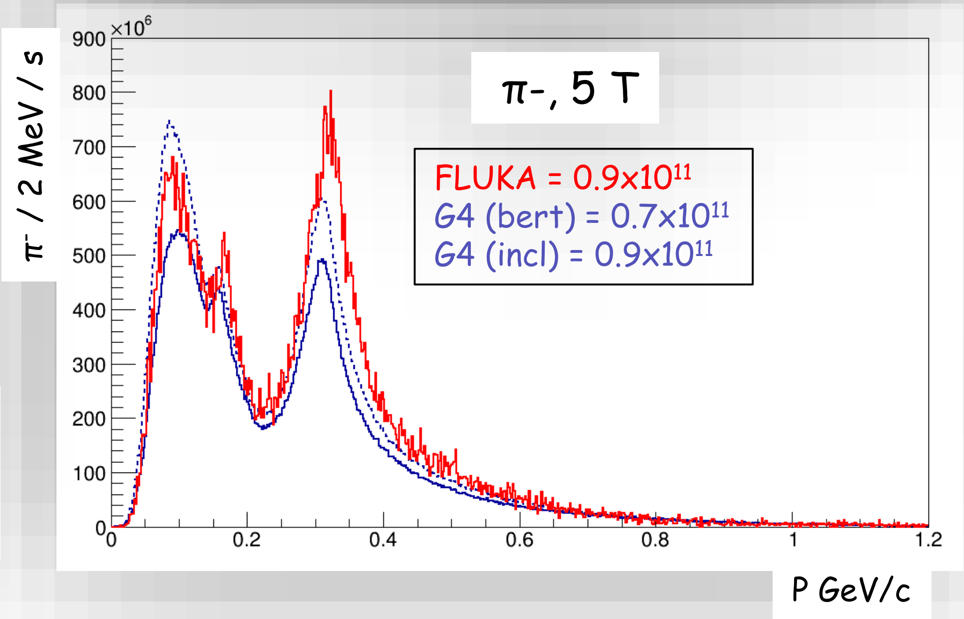
Same baseline 5T taper used on both



- Total pions are similar with FLUKA and G4 (BERTINI)
- G4(INCL) produces more pions
- The distribution at the high momentum peak is similar
- FLUKA predicts a ratio π+/π- = 2



G4 bert
G4incl



Ratio π+/π-:
- FL = 1.9
- G4 (bert) = 2.9
- G4 (incl) = 2.2

G4: Song Yingpeng

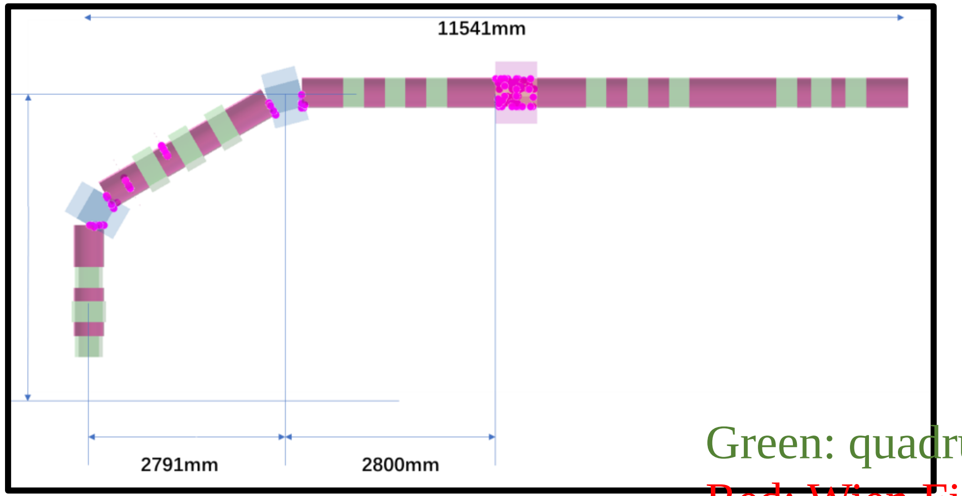
Decay muon beam parameters

	μSR		X-ray analysis		Muon imaging
Ref. mom.	45MeV/c	150MeV/c	45MeV/c	150MeV/c	450MeV/c
Intensity (1E6/s)	0.6	11	0.44	25	13000
PolZ	0.82	0.81	–	–	–
$Spot_{FWHM}$ (mm)	27×30	20×30	30×30	35×37	20×51
dp/p_{FWHM}	6.7%	8.0%	4.4%	9.2%	5%

1. All data is based on the proton beam power of 25kW.
2. The momentum spread for imaging beam is done manually, the intensity usually One order of magnitude higher than done by collimators.

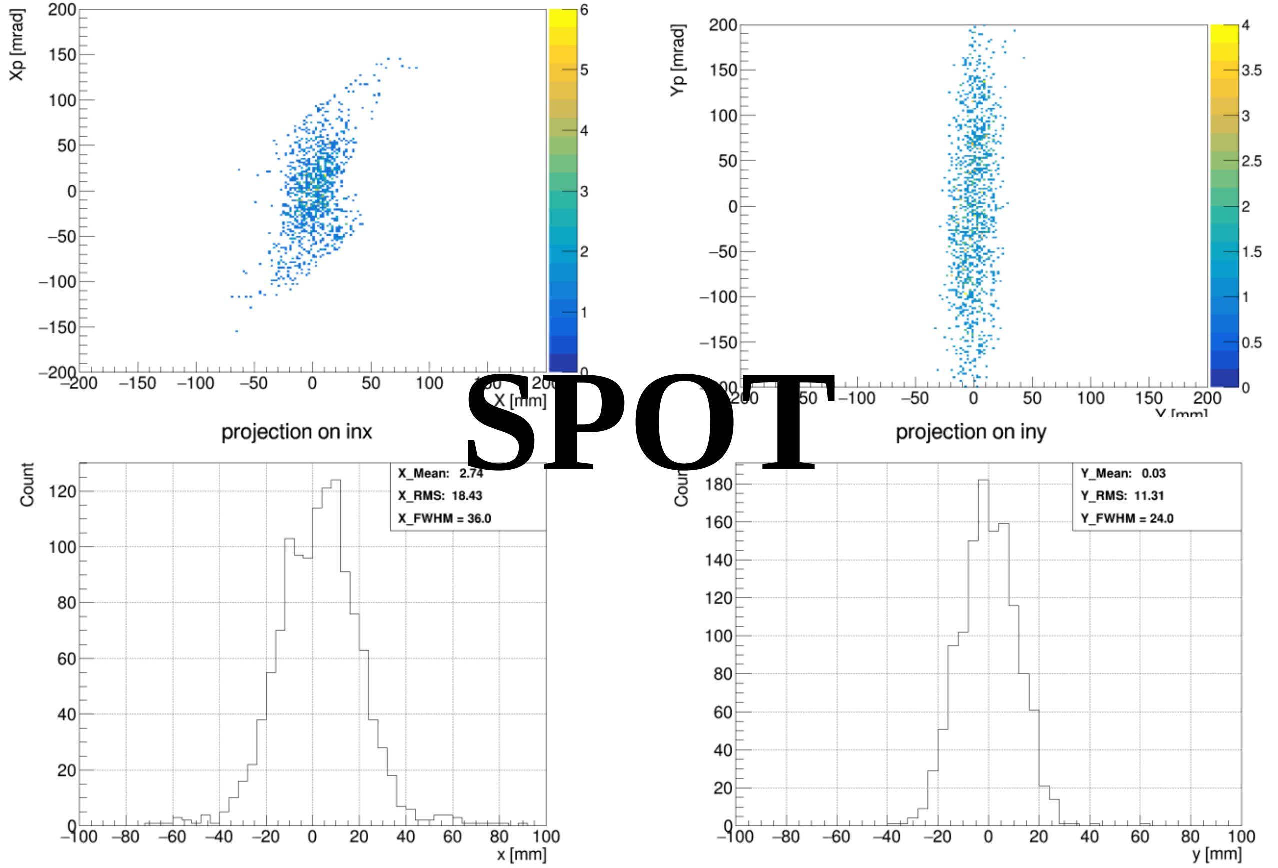
Vertical Beamline of Baseline-scheme

Layout of vertical beamline



Green: quadrupole
Red: Wien Filter
Magenta: Drift

Limited by space, the vertical beamline use a 60°+30° asymmetric achromatic design. The aperture of first triplet is limited (30cm).

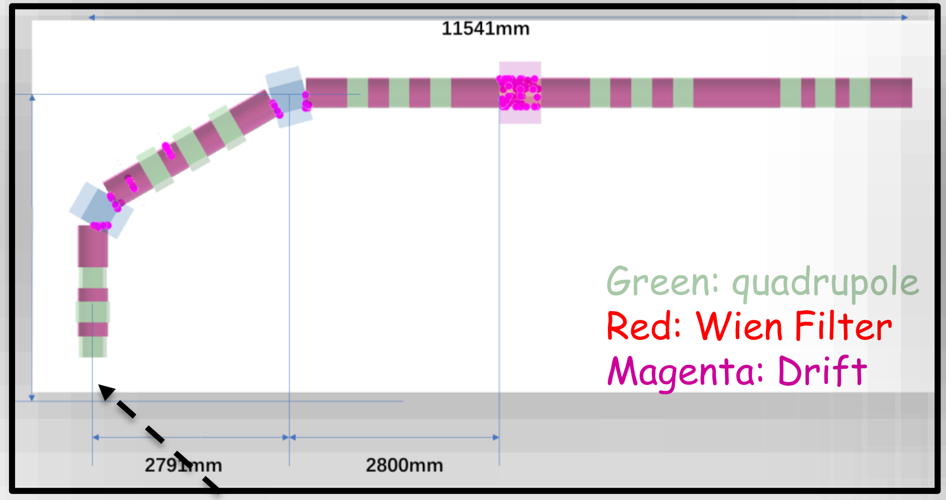


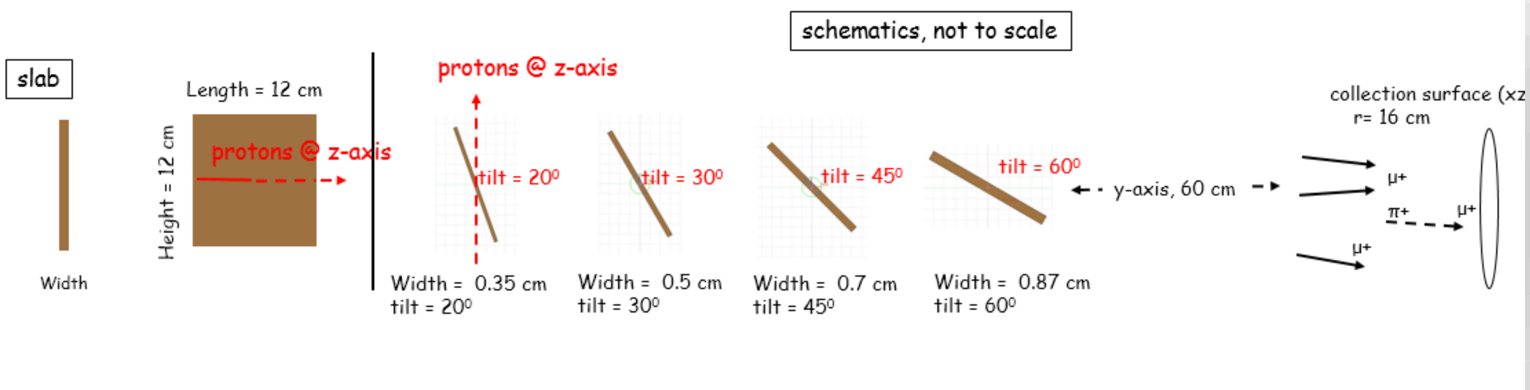
SPOT

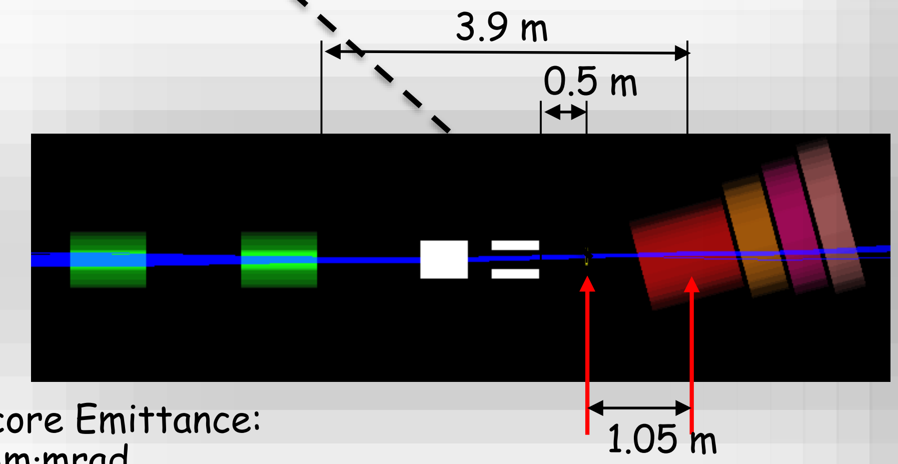
Spot properities of this port:

- **Phi30 Flux: 5.6*10E+05/s**
- **Polz: -0.94 (-0.95 in phi30), purity: 96.2%**
- **RMS Emittance: 743*954 (pi·mm·mrad)**

vertical μSR beam line with thin target before superconducting solenoid at "baseline scheme" (under study)







Beam core Emittance:
80 π mm·mrad

Beam spot at thin target
σx = 6 mm
σy = 12 mm

Beam spot at ce
of main target
σx = σy = ~5 mm

interaction length	1 cm				
beam size	σ_x = 6 mm, σ_y = 12 mm				
emittance (π mm mrad)	4500				
momentum	μSR - μ^+ 25 < P < 29.8 MeV/c				
tilt (degree)	45				
length x height (cm2)	12x12	10x10	8x8	6x6	5x5
intensity ($\times10^6$) μ/sec	0.71	0.72	0.71	0.68	0.61
polarization	-0.96	-0.95	-0.97	-0.94	-0.94
surface muon purity (%)	97	97	98	96	96
statistical error	~ 5% / 2% on intensity / polarization				