TARGET, HORN AND ENERGY DEPOSITION STUDIES FOR SPL-SUPERBEAM

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WP2

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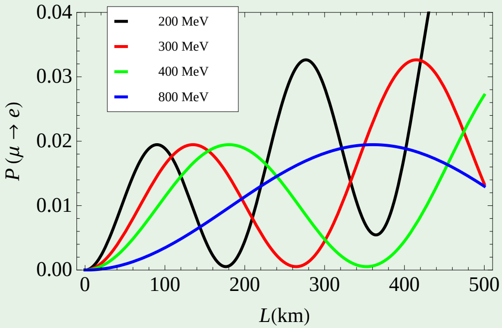
Outline

- Introduction – SPL Superbeam basic parameters
- Target studies – low- and high-Z materials
  $\Rightarrow$ particle types and multiplicities
  $\Rightarrow$ particle distributions
  $\Rightarrow$ energy deposition
- Horn studies
  $\Rightarrow$ physics optimisation
  $\Rightarrow$ some results
  $\Rightarrow$ other options - Miniboone, Bi-conic, integrated target
- Energy deposition studies
  $\Rightarrow$ experimental setup
- Conclusion

SPL Superbeam setup - parameters

- ν_μ disappearance $P_{\mu\to x} \sim \cos^4\theta_{13}\ \sin^2(2\theta_{23})\ \sin^2(\Delta m^2_{32} L/4E_\nu)$
  $\rightarrow \mu \Leftrightarrow \tau$ mixing maximal?
- ν_e appearance $P_{\mu\to e}(\theta_{13,23}, \delta_{CP}, \Delta m^2_{21,31}, \sqrt{2}G_F n_e)$
  $\rightarrow$ exact $\theta_{13} = 0$?
  $\rightarrow$ CP violation $\delta_{CP} \neq 0$?
  $\rightarrow$ normal or inverted mass hierarchy? (for long baseline only)

OSCILLATION PROBABILITY $\nu_\mu \to \nu_e$ VS. BASELINE L FOR $E_\nu \sim (200 - 800)$ MEV

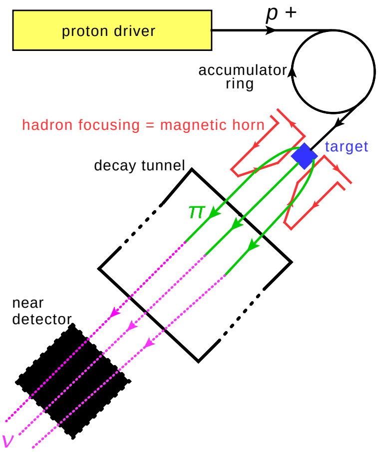


- $\Delta m^2_{21} = 7.59 \times 10^{-5} eV^2$,
  $\Delta m^2_{31} = 2.51 \times 10^{-3} eV^2$
- $\theta_{12} = 34.4^\circ$,
  $\theta_{23} = 42.3^\circ$
- $\theta_{13} = 5.7^\circ$
  $\Leftrightarrow \sin^2(2\theta_{13}) \leq 0.04$
- $\delta_{CP} = 0^\circ$

SPL SUPERBEAM – PARAMETERS

conventional accelerator experiment: ν_μ ($\bar{\nu}_\mu$) beam from $\pi^\pm$ decay

p^+-BEAM	@ CERN, power: 4 MW, pulse frequency: 50 Hz, kin. beam energy: $\sim$ 5 GeV, pulse duration: $\lesssim 5\,\mu$s profile: preferably uniform
TARGET	solid low-Z material (Be, C, Al, ...)
HORN	current: $I \sim 300$ kA
DECAY TUN	$L = 40$ m, $R = 2$ m
FAR DET	@ Fréjus, base line: 130 km, 440 kt (fiducial mass) Water-Cherenkov



Target studies

Target studies – choice of materials

A comparative study of low- and high-Z^{tg} target materials

Z^{tg}	ρ $[g/cm^3]$	λ_I $[g/cm^2]$	λ_I/ρ $[cm]$
Be	1.85	77.8	42.1
C	1.85	85.8	46.4
Al	2.7	107.2	39.7
AlBeMet$^{*)}$	2.1		
Ta	16.69	191.0	11.4
W	19.25	191.9	10.0
Hg	13.546	197.5	14.6

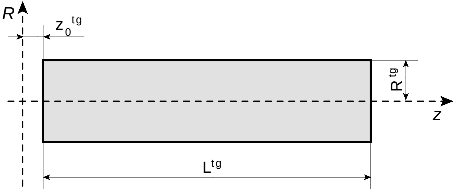
$^{*)}$ AlBeMet = 61% Be, 38% Al, 1% O (mass fraction)

Simulations with FLUKA

- using FLUKA (Oct. 2009) - default parameter set
- scoring of secondary particles at target surface (ID, number, pos, mom)

CYLINDRICAL TARGET

- Z^{tg} ... target material
- $L^{\mathrm{tg}}[cm]$ ... target length
- $R^{\mathrm{tg}}[cm]$ ... target radius



p^+-BEAM PARAMETERS

- $E_{kin}^{\mathrm{bm}}[GeV]$ ... kinetic energy
- $\sigma^{\mathrm{bm}}[cm]$ ... width of gaussian beam profile

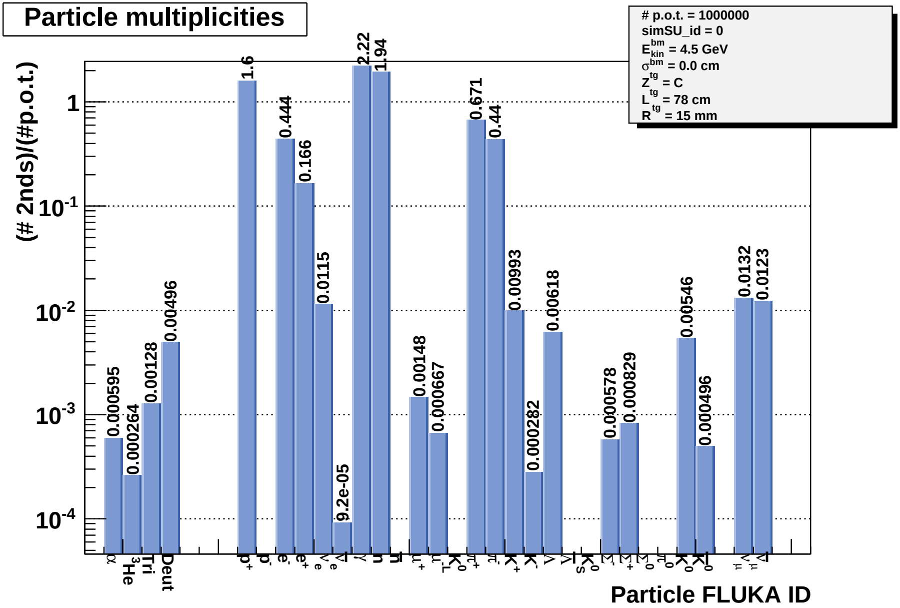
REFERENCE TARGET

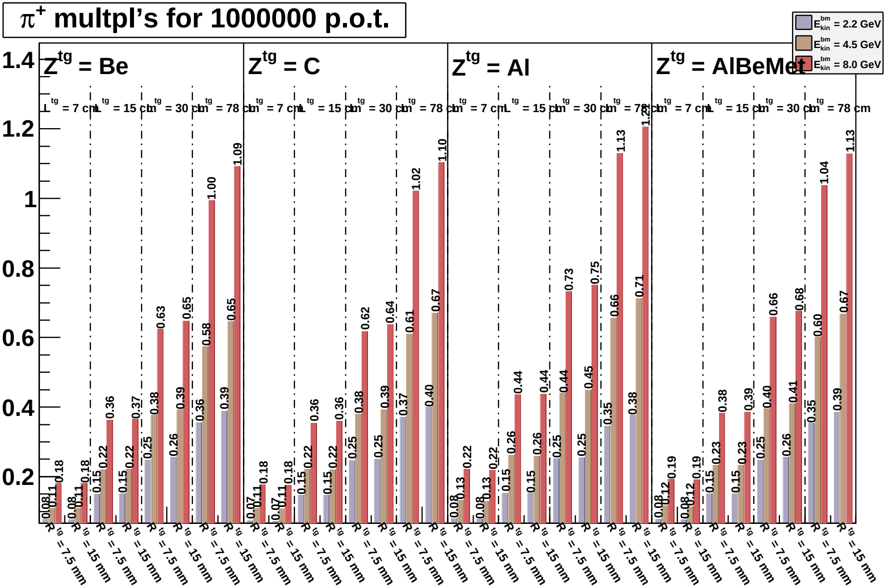
$$Z^{\mathrm{tg}} = \mathrm{C},\ L^{\mathrm{tg}} = 78\,cm,$$

$$R^{\mathrm{tg}} = 1.5\,cm,$$

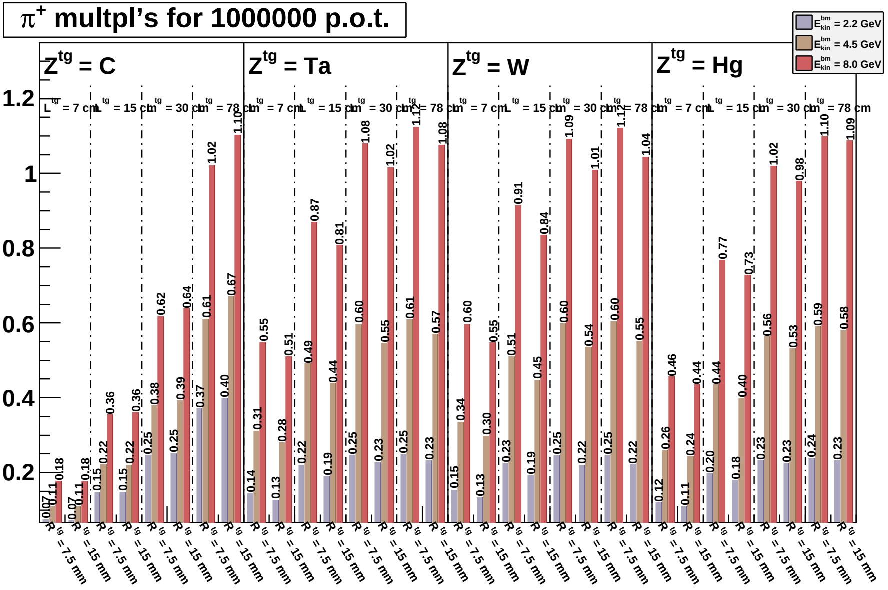
$$E_{kin}^{\mathrm{bm}} = 4.5\,GeV,\ \sigma^{\mathrm{bm}} = 0.0\,cm$$

$$\text{particle multiplicity of type } j = \frac{\#\text{ of 2ndy particles oftype } j}{\#\text{ of p.o.t}}$$

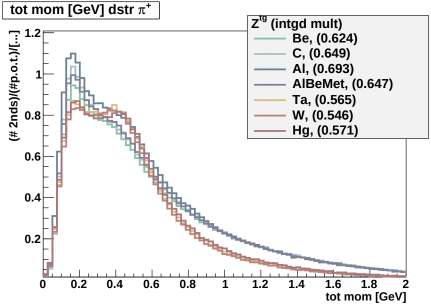

Particle multiplicities
# p.o.t. = 1000000
simSU_id = 0
E^{bm}_{kin} = 4.5 GeV
σ^{bm} = 0.0 cm
Z^{tg} = C
L^{tg} = 78 cm
R^{tg} = 15 mm
(# 2nds)/(#p.o.t.)
Particle FLUKA ID
0.000595
0.000264
0.00128
0.00496
1.6
0.444
0.166
0.0115
9.2e-05
2.22
1.94
0.00148
0.000667
0.671
0.44
0.00993
0.000282
0.00618
0.000578
0.000829
0.00546
0.000496
0.0132
0.0123

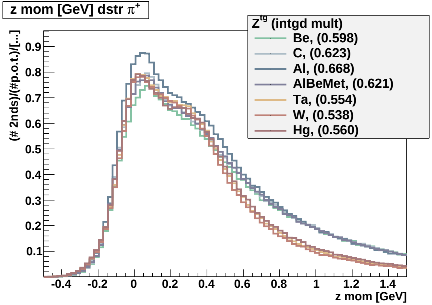

π+ multpl's for 1000000 p.o.t.
E_kin^bm = 2.2 GeV
E_kin^bm = 4.5 GeV
E_kin^bm = 8.0 GeV
Z^tg = Be
Z^tg = C
Z^tg = Al
Z^tg = AlBeMet
L^tg = 7 cm
L^tg = 15 cm
L^tg = 30 cm
L^tg = 78 cm
R^tg = 7.5 mm
R^tg = 15 mm
1.4
1.2
1
0.8
0.6
0.4
0.2
0.08 0.11 0.18 0.08 0.11 0.18 0.15 0.22 0.36 0.15 0.22 0.37 0.25 0.38 0.63 0.26 0.39 0.65 0.36 0.58 1.00 0.39 0.65 1.09
0.07 0.11 0.18 0.07 0.11 0.18 0.15 0.22 0.36 0.15 0.22 0.36 0.25 0.38 0.62 0.25 0.39 0.64 0.37 0.61 1.02 0.40 0.67 1.10
0.08 0.13 0.22 0.08 0.13 0.22 0.15 0.26 0.44 0.15 0.26 0.44 0.25 0.44 0.73 0.25 0.45 0.75 0.35 0.66 1.13 0.38 0.71
0.08 0.12 0.19 0.08 0.12 0.19 0.15 0.23 0.38 0.15 0.23 0.39 0.25 0.40 0.66 0.26 0.41 0.68 0.35 0.60 1.04 0.39 0.67 1.13

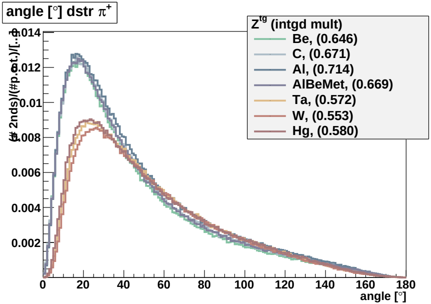
TARGET STUDIES – HIGH $Z^{tg} = \{\mathrm{Ta}, \mathrm{W}, \mathrm{Hg}\}$

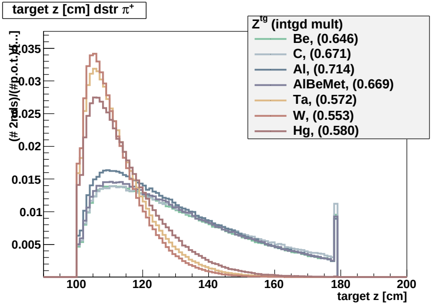


Target studies – π^+ diff. multipls - ref. target

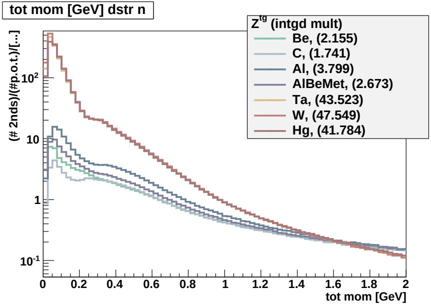


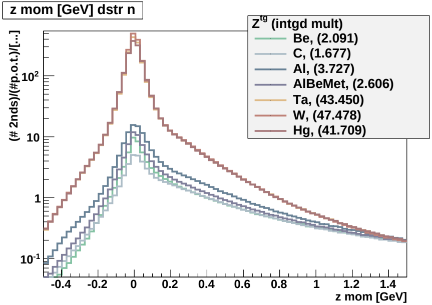


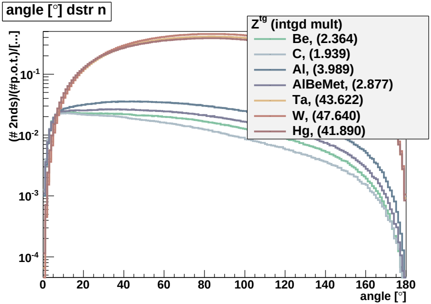


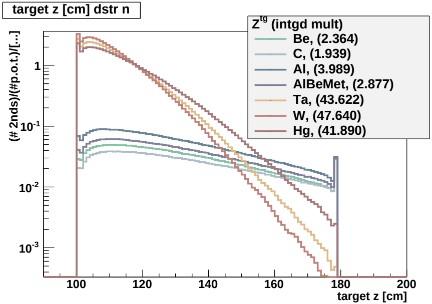


TARGET STUDIES – NEUTRON DIFF. MULTIPLS - REF. TARGET

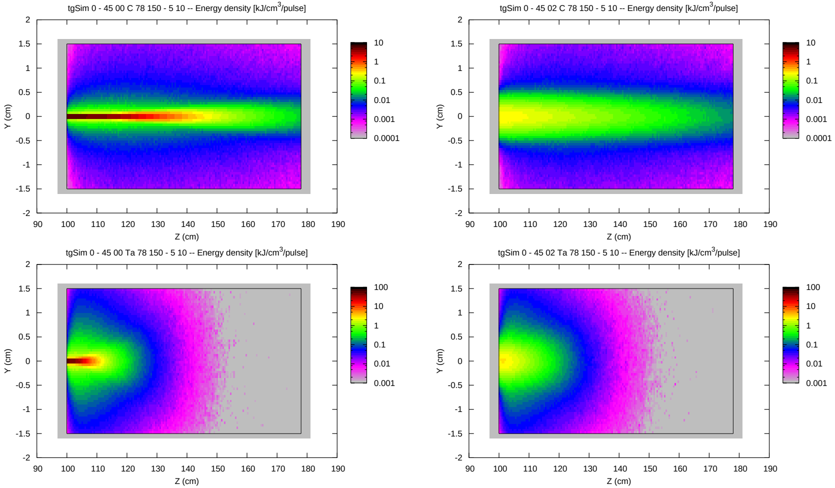








Target studies – Energy deposition: C [upper] vs. Ta [lower]



Ref. Target for beam width $\sigma^{\rm bm} = 0.0\,cm$ [left] and $\sigma^{\rm bm} = 0.2\,cm$ [right]

One order higher in Ta (high-Z) compared to C (low-Z)!

ENERGY DEPOSITION – DIFFERENT BEAM WIDTH σ^{bm}

Assuming continious energy deposition of proton beam @ 4 MW and $E_{\rm kin}^{bm} = 4.5$ GeV.

material	σ^{bm} [mm]	max value power density [kW/cm^3]	total power [kW]	(+ I, - I)
Be	2	11.65	168.7	(+6 %, +4%)
	4	3.25	165.3	(+6 %, +4%)
	6	1.53	153.2	(+12 %, +4%)
C	2	13.22	200.0	(+6 %, +5%)
	4	3.57	196.5	(+7 %, +4%)
	6	1.72	182.2	(+12 %, +4%)
Al	2	19.26	285.6	(+8 %, +6%)
	4	5.36	279.1	(+8 %, +6%)
	6	2.73	257.4	(+14 %, +6%)
AlBeMet	2	14.11	204.4	(+7 %, +5%)
	4	3.92	200.1	(+7 %, +5%)
	6	1.86	185.2	(+13 %, +5%)

(Magnetic field only important if very close to target $\rightarrow$ Assumption: due to horn current directly at target surface: $I = \pm 300$ kA $\rightarrow$ $B = 4$ Tesla @ $R = 1.5$ cm)

With magnetic field: For "+" focusing $(6 - 14)$ % and for "-" focusing $(4 - 6)$ % increased total power due to focusing of charged particles, BUT maximal value of power density stays the same!

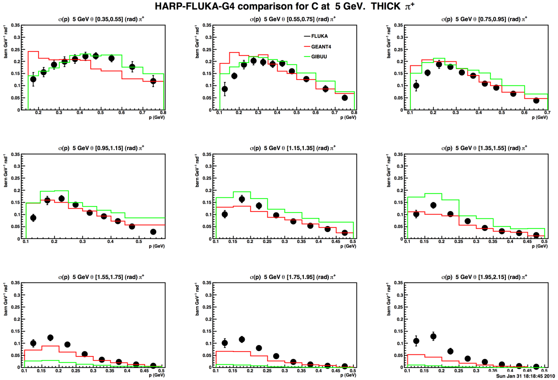
	low-Z	high-Z
$L \sim 2\lambda_I$	(80 - 90) cm	(20 - 30) cm
pi^+	0.65 - 0.71	0.55 - 0.58
pi^-	0.44 - 0.49	0.47 - 0.50
pi^-/pi^+	0.66 - 0.72	0.85
$pi^+ \in [0.5, 0.8]$ GeV	0.13 - 0.15	0.13 - 0.14
$pi^- \in [0.5, 0.8]$ GeV	0.09 - 0.11	0.11 - 0.12
pi^-/pi^+	0.66 - 0.72	0.86 - 0.88
n	1.9 - 4.0	42 - 48
γ	1.9 - 5.7	50 - 54
deposited power$^{*)}$	$(170 - 290)\,kW$	$(1000 - 1300)\,kW$

$^{*)}$ for reference target at 4 MW beam power

TARGET STUDIES – HARP AND NA61-SHINE DATA

Measurements of $\pi^{\pm}$ production cross sections from HARP and recently NA61-SHINE
$\Rightarrow$ validate Monte Carlo codes with real data in region of interest

- thick targets ($L = 100\%\lambda_I$) for C, Ta and Pb (at p^+ momenta $\{5, 8, 12\}$ GeV)
- thin targets ($L = 5\%\lambda_I$) for Be, C, Al, Cu, Sn, Ta and Pb (at p^+ momenta $\{3, 5, 8, 12\}$ GeV)
- coverage $\theta \in [0.35, 2.15]$ rad and $p \in [0.1, 0.8]$ GeV
- also small angle data



[A.Longhin]

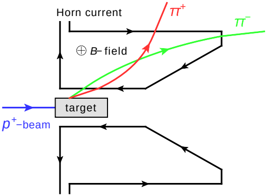
comparison for FLUKA also done

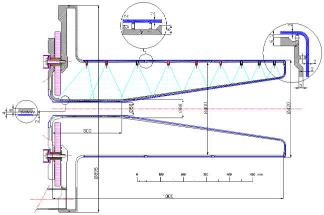
Results of distribution of energy deposition serve as input for cooling and stress studies of the target $\rightarrow$

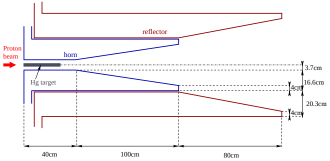
more details by Benjamin Lepers

Horn shape optimisation

HORN – PRINCIPLE AND PREVIOUS STUDIES







- $\pi^{\pm}$ focusing using toroidal magn. field
- "+" and "-" focusing mode depending on current direction
- pulsed horn current to save energy $\longrightarrow$ requires pulsed p^+ beam

- first design for NuFact @ CERN (CERN-NUFACT-Note 042 (2000)) single-conic, target inside
- optimised for $E_{\rm kin}^{bm} = 2.2$ GeV and 30 cm liquid Hg target
- operation at current of: 30 kA, 1 Hz, 100 μs pulses
- mechanical and acoustic frequency measur., laser vibrometer
- test of cooling system
- power supply

- Campagne/Cazes [hep-ex/0411062] - simulation
- 30 cm liquid Hg target
- optimised for $\pi^{\pm}$'s with $p = 600$ MeV
- inner + outer horn with currents: 300/600 kA
- decay tunnel: $L = 40$ m, $R = 2$ m
- baseline: CERN - Fréjus
- 440 kt Water Cherenkov detector
- see also [hep-ph/0603172]

Horn – Shape optimisation criteria

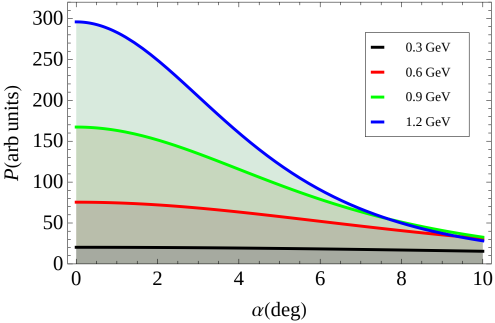
Problem: π distribution broad (momentum and angle) and target long
$\rightarrow$ no analytic approximation of horn focusing
$\rightarrow$ numerical optimisation using simulation, variation of key parameters

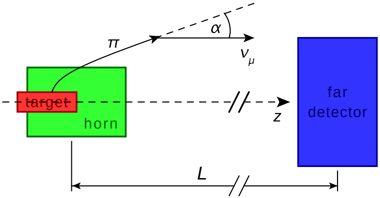
Stages of optimisation

- sensitivity to physics parameters θ_{13}, δ_{CP}
  $\rightarrow$ requires full simulation including details of detector
- optimise ν spectrum in solid angle of detector
  $\rightarrow$ requires full simulation of target, horn, decay tunnel and beam dump
- optimise π spectrum at horn exit
  $\rightarrow$ requires only initial π spectrum at target exit and horn geometry

. . . optimise π spectrum at horn exit

- using simple numerical Euler-integr. for fast π tracking through magnetic field
- checked agreement with FLUKA, accuracy depends on stepwidth = compromise for shorter CPU time
- can be improved using symplectic integration algorithm





$$P(\alpha,\beta) = \frac{1}{4\pi}\frac{A}{L^2}\frac{1-\beta^2}{(1-\beta\cos\alpha)^2}$$

for dim(decay tunnel) $\ll L$

Probability of ν_μ hitting detector depends on

- π-momentum $\{0.3, 0.6, 0.9, 1.2\}$ GeV
- angle α of π with beam-detector axis

$\rightarrow$ more important to focus π's with large momentum

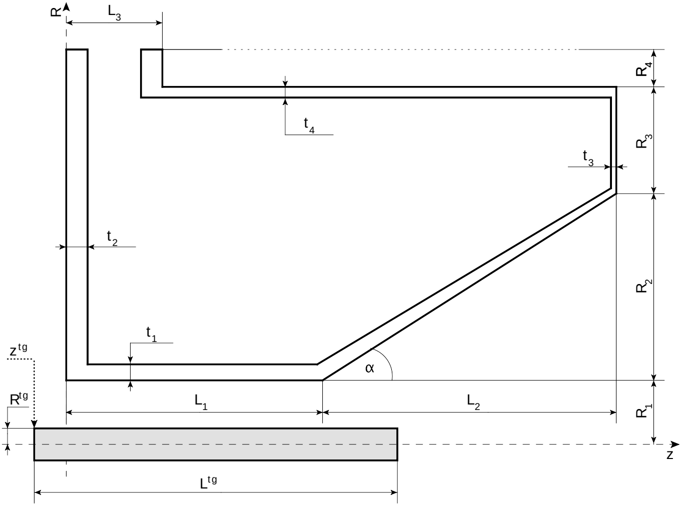
"good" focused π, if α such that $P(\alpha,\beta) > \frac{1}{2}P(0,\beta)$

- using π sample generated with FLUKA for C-target 10^6 pot
  yielding 759914 π^+ and 498397 π^- at target exit (position, momentum)
- optimise horn for π^- focusing, since background suppression
  more important for $\bar{\nu}_\mu$-run
- look for optimal ratio

  $R(\pi^-/\pi^+) =$ (# of "good" π^- with $p \in [0.5, 0.7]$ GeV)/(# of "background" π^+)

  π's are counted when exiting the horn within a circular plane of $R = 1$ m
- sample contains 116689 π^+ and 77392 π^- with $p \in [0.5, 0.7]$ GeV

- optimizing for longer Carbon target $L^{tg} = 78$ cm (previous Hg $L^{tg} = 30$ cm)
- removing reflector with current $I = 600$ kA introduced by Campagne/Cazes



keeping fixed:

$E^{kin} = 4.5$ GeV

$L^{tg} = 78$ cm
$R^{tg} = 1.2$ cm

$z_0^{hn} = 0$ cm
$L_3 = 3$ cm
$R_4 = 4$ cm
$t_2 = 10$ mm, $t_{1,3,4} = 3$ mm

varying:

$z_0^{tg} \in [-20, 20]$ cm,

$L_1 \in [50, 150]$ cm,
$L_2 \in [50, 150]$ cm,
$R_1 \in [1.2, 6.0]$ cm,
$\alpha \in [2, 30]^\circ$,
$R_3 \in [4, 10]$ cm,
$I \in [100, 300]$ kA

Campagne/Cazes:

$L_1 = 40$ cm,
$L_2 = 100$ cm,
$R_1 = 3.7$ cm,
$R_2 = 12.6$ cm,
$R_3 = 4$ cm

HORN – "BEST" 13 HORNS - MATERIAL EFFECT

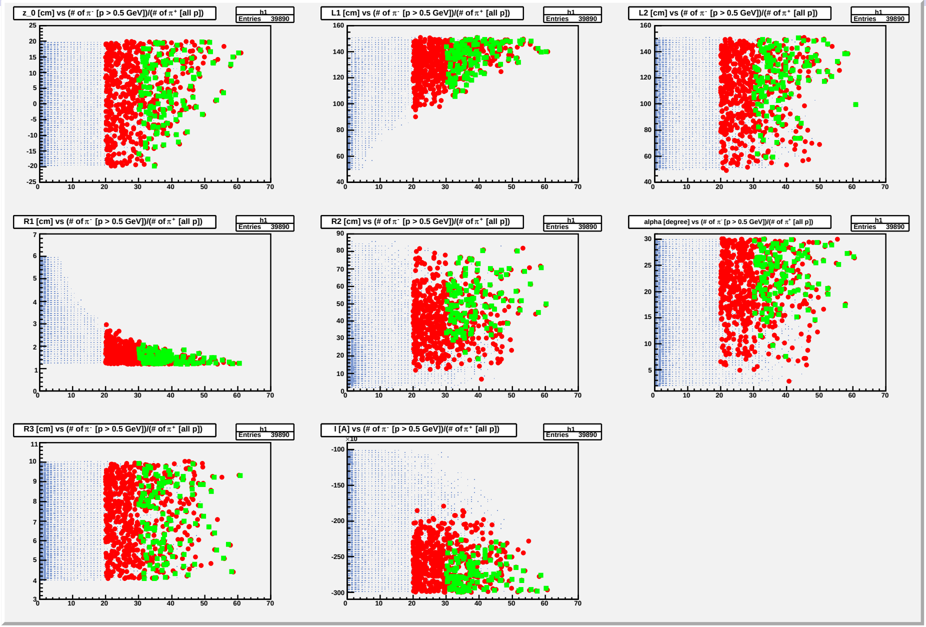
z_0^{tg} [cm]	L_1 [cm]	L_2 [cm]	R_1 [cm]	R_2 [cm]	R_3 [cm]	I [kA]	$R(\pi^-/\pi^+)$	# of π^-	# of π^+
-9.5	132.9	148.9	1.22	38.8	8.9	-290	48.1 (12.3)	20832	433
-16.6	149.5	136.2	1.60	65.6	7.8	-260	48.5 (14.2)	20849	430
-19.8	140.4	125.0	1.45	70.4	8.8	-285	49.3 (16.4)	20359	413
3.17	147.0	133.0	1.20	51.8	7.3	-252	49.7 (13.6)	21316	429
-16.8	135.6	148.2	1.37	80.7	6.7	-298	51.1 (——)	21277	416
-19.5	132.5	118.4	1.23	57.6	8.5	-265	51.9 (13.7)	20147	388
-13.0	149.5	124.4	1.46	46.4	9.2	-285	52.2 (13.6)	21002	402
-13.1	145.7	145.3	1.43	52.0	6.4	-296	52.3 (14.6)	21667	414
-1.31	148.9	122.2	1.24	68.5	5.5	-270	54.0 (16.5)	21269	394
-4.21	147.2	131.4	1.31	61.7	5.1	-294	55.0 (15.2)	22608	411
-12.6	142.4	139.2	1.22	43.9	5.8	-298	57.8 (12.6)	20984	363
-15.0	140.4	138.3	1.20	71.6	4.4	-278	58.9 (16.3)	21142	359
-15.8	141.0	98.34	1.22	49.3	9.3	-297	60.2 (16.1)	21369	355
0.0	40.0	100.0	3.70	12.6	4.0	-300	—— (2.63)	—	—
0.0	40.0	100.0	3.70	12.6	4.0	0	—— (0.09)	—	—

last lines: Campagne/Cazes (no reflector), opt. for $p = 600$ MeV and with Hg target $L = 30$ cm

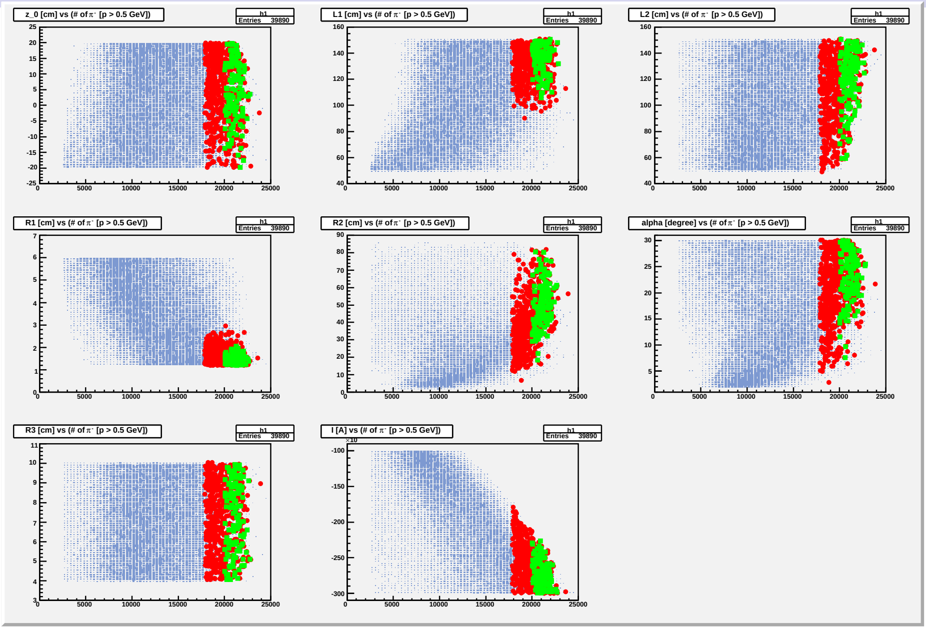
Material effect with FLUKA:

$t_{1,2,3,4} = 3$ mm Aluminium horn skin decreases $R(\pi^-/\pi^+)$ by about factor 4 due to more π^+

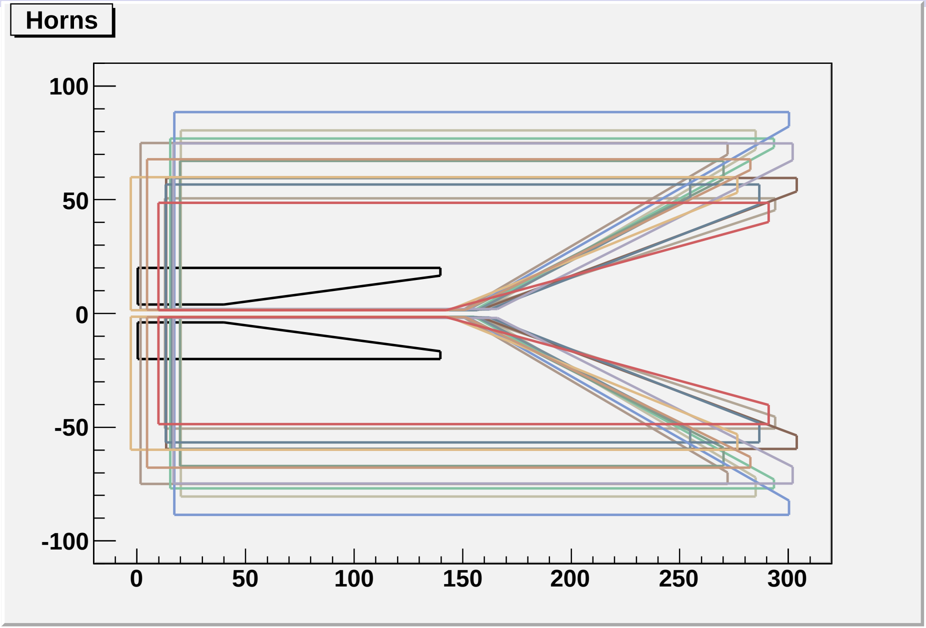
HORN – PARAMETERS VS $R(\pi^-/\pi^+)$



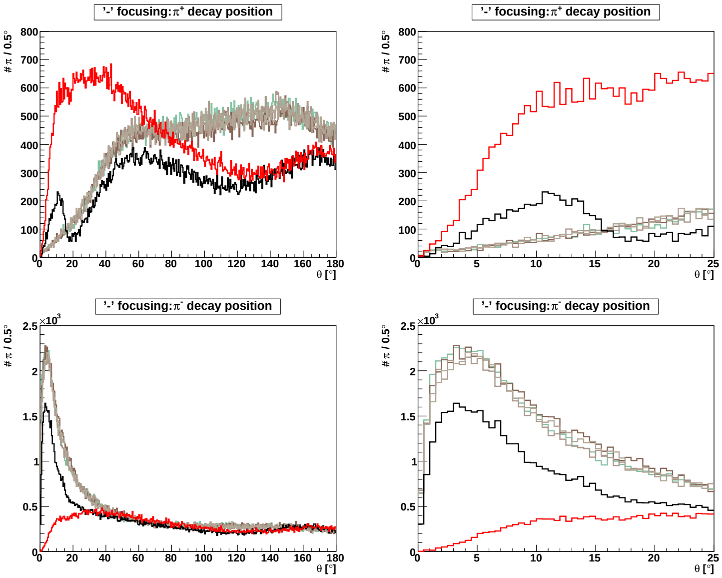
Horn – Parameters vs (# of "good" π^-)



HORN – "BEST" 13 HORNS



HORN – π POLAR ANGLE AT DECAY POSITIONS

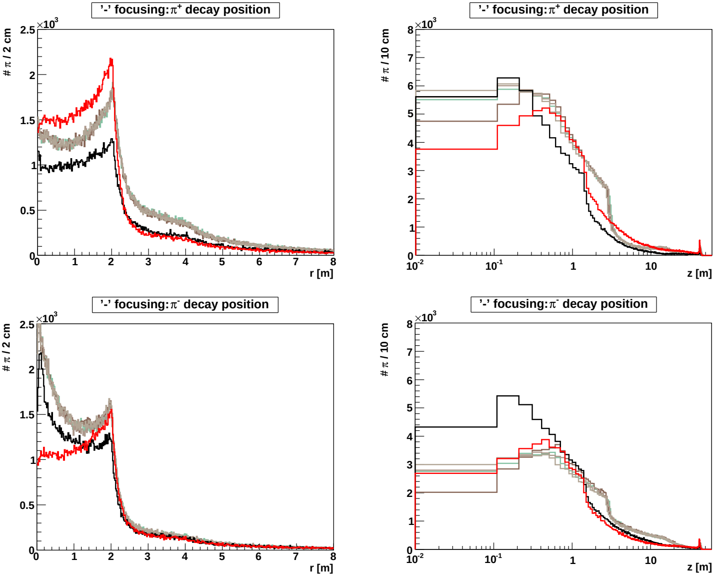


no magn. field

Campagne/Cazes
no reflector

4 best of

HORN – π DECAY POSITIONS r AND z



no magn. field

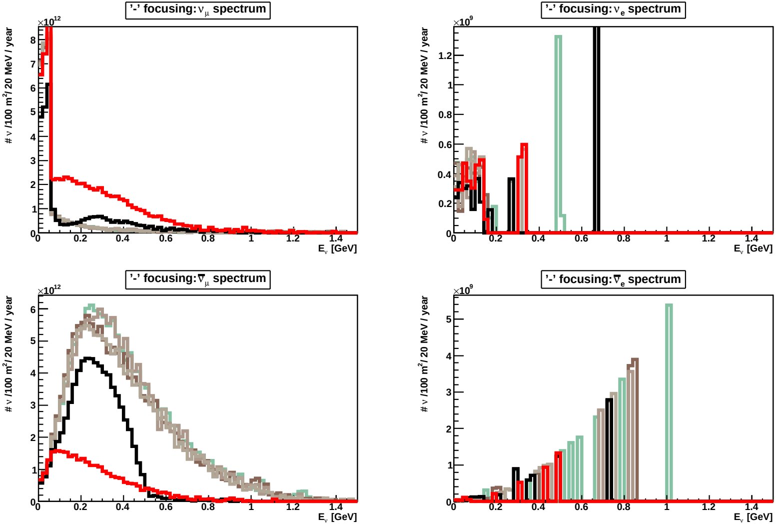
Campagne/Cazes
no reflector

4 best of

decay tunnel

$R = 2$ m,
$L = 40$ m

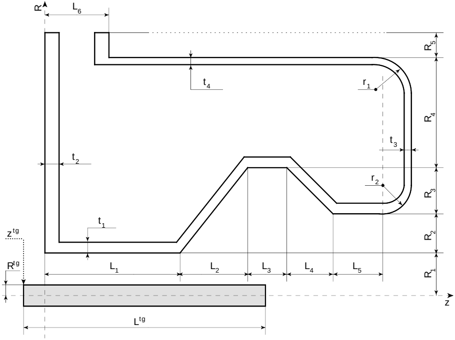
HORN – $\bar{\nu}_\mu$ SPECTRUM FROM $\pi^- \to \mu^- + \bar{\nu}_\mu$



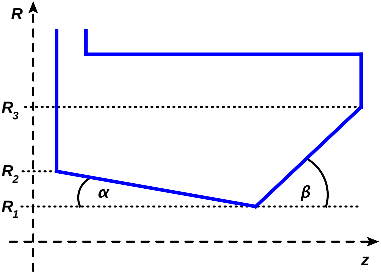
$\bar{\nu}_\mu$ spectrum in detector (100 m^2) from $\pi^- \to \mu^- + \bar{\nu}_\mu$ 2-body decays

need to add 3-body decays for ν_e, $\bar{\nu}_e$ spectra + final sensitivities θ_{13} and δ_{CP}

Miniboone-like horn:



Bi-conic horn



forward closing section serves to
defocus wrong-sign π's
optimised by A.Longhin

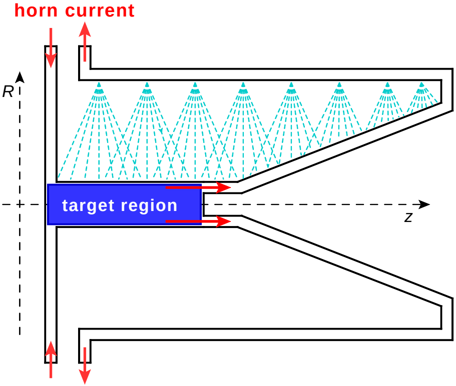
most pions decay after 4 m distance - a second horn (reflector) should follow closely to the first one, if at all

HORN – INTEGRATED TARGET

Idea:

Physics performance prefers small inner radius

→ Integrate the target as inner conductor inside the horn



Requirement

- conducting target material

Advantages

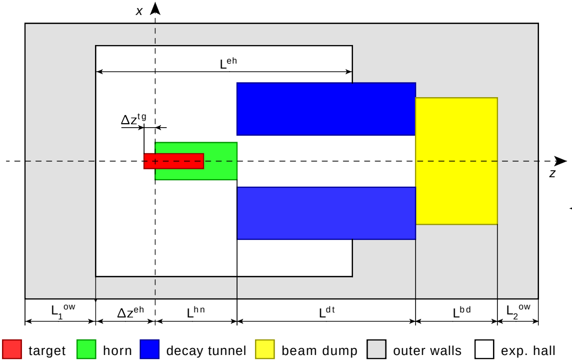
- lower inner radius → higher magnetic field or lower horn current
- can use water cooling of inner horn conductor also for target cooling

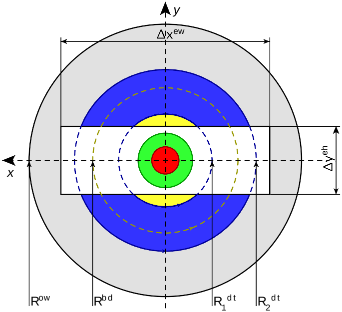
Disadvantages

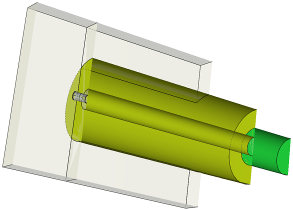
- lower inner radius → higher Joule effect due to horn current in target region

Energy deposition

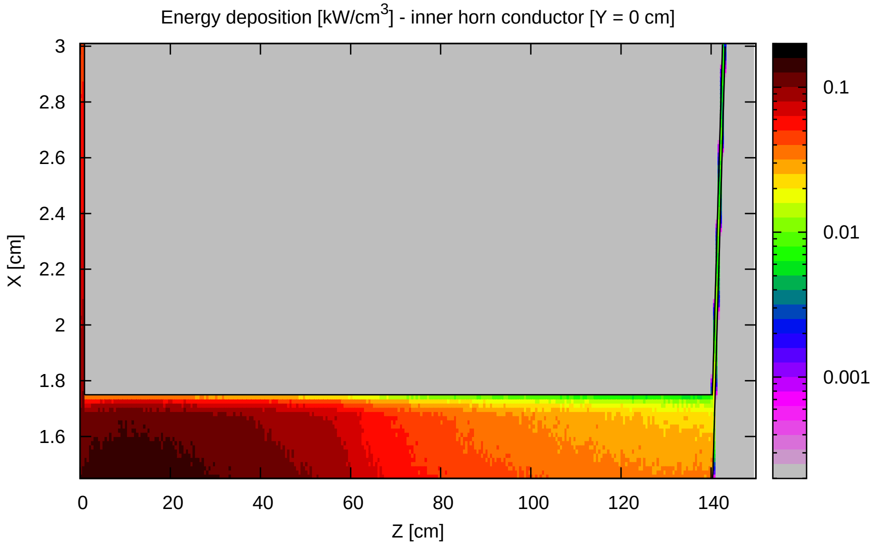
ENERGY DEPOSITION – EXPERIMENTAL SETUP







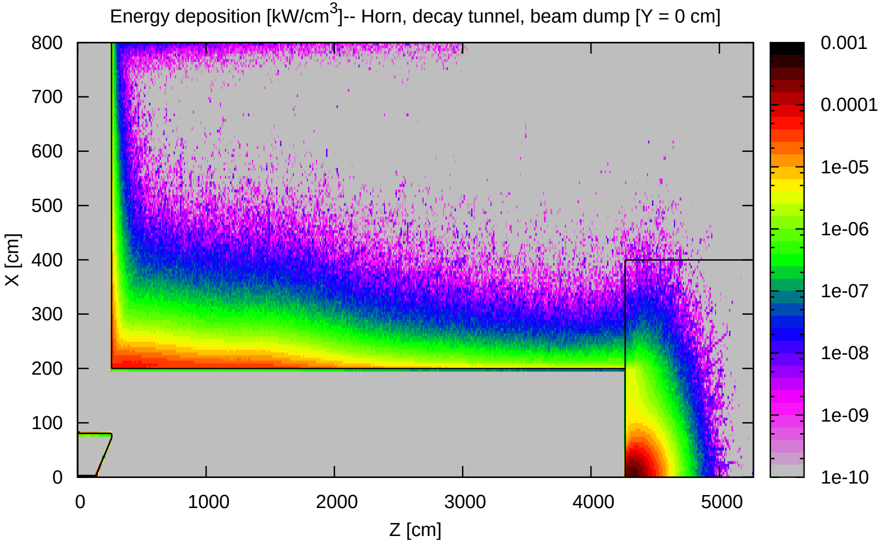
Energy deposition – Inner Horn Conductor



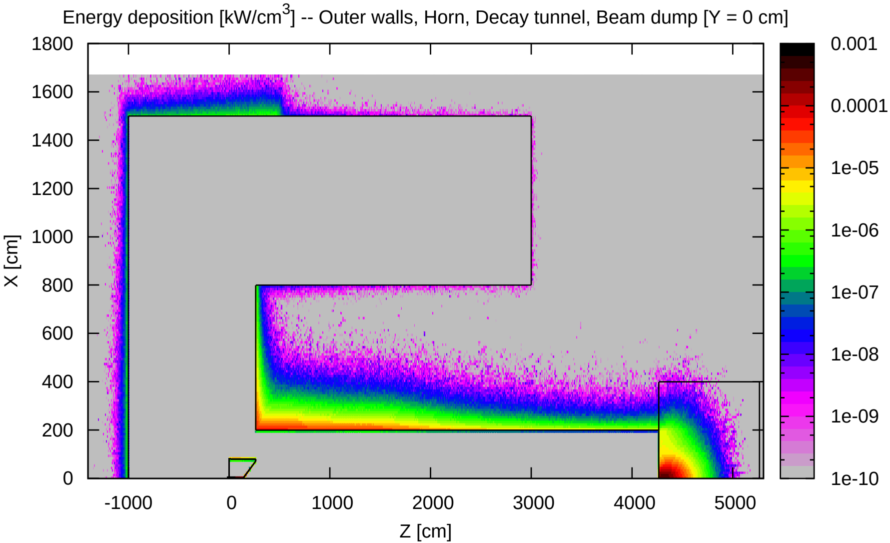
target radius $R^{\text{tg}} = 1.2cm$,

horn inner radius $R_1^{\text{hn}} = 1.45$ cm, thickness $t_1 = 3$ mm

ENERGY DEPOSITION – HORN – DECAY TUNNEL – BEAM DUMP



ENERGY DEPOSITION – ALL



... introduce some additional shielding for target/horn service and exchange area's

region	deposited power
target $R^{\text{tg}} = 1.2$ cm	188 kW
horn $t_2 = 10$ mm, $t_{1,3,4} = 3$ mm	65 kW
decay tunnel walls	2560 kW
beam dump	390 kW
outer walls – behind	15 kW
outer walls – side	166 kW
beyond outer walls	129 kW
missing in FLUKA energy budget	488 kW
sum	4001 kW
horn $t_2 = 10$ mm, $t_{1,3,4} = 10$ mm	160 kW

... activation studies to follow

CONCLUSION

Target

- π-yields of low-Z^{tg} material comparable to high-Z^{tg}
- less n, γ release $\rightarrow$ radiation safety
- less energy deposition $\rightarrow$ cooling, mechanical stress

Horn

- single-conic horn and Miniboone-like horn (A.Longhin) without reflector
- prefered lower inner and larger outer radius, longer inner section
- physics performances comparable to previous studies
- 4-horn scheme
- ... re-iteration with engineering studies to follow

Energy deposition

- energy deposition from secondary particles in experimental environement
- implement more details for service area's
- ... activation studies to follow
- ... re-iteration with engineering studies to follow