Target and Capture Simulation Studies

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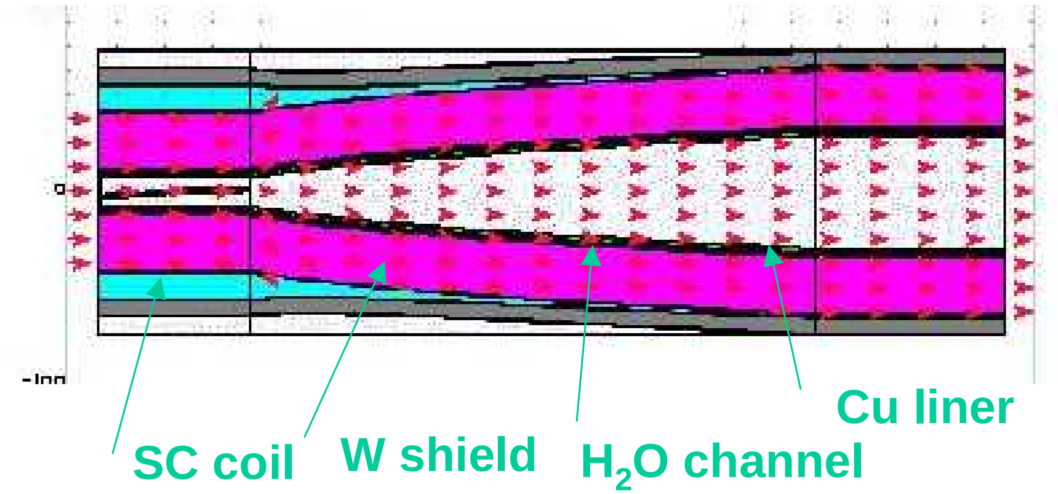
Simulation Topics

- Particle transport simulations:
  - Using MARS (N. Mokhov, H. Kirk)
  - Using GEANT (S. Kahn, Y. Fukui)
- Particle production at target.
- Energy deposition in target and surrounding magnets.
- Thermodynamic aspects of the target.
  - Using ANSYS (N. Simos)
  - Using FronTier (R. Samulyak)
- Hydrodynamics of liquid jet in a magnetic field.
  - Using ANSYS/FLOTRAN (C. Lu)

Mars Target Studies

Beam Parameters	FNAL Values	BNL Values
Energy	16 GeV	24 GeV
$\sigma_x = \sigma_v$	3 mm	1.5 mm
σ_t	3 ns	1 ns
$c\sigma_t$	90 cm	30 cm
$\theta_{incline}$	50 mrad	150 mrad

Parameter	Target Region	Matching Region	Straight Section
Field	20 Tesla	$\frac{20.Tesla}{(1+0.05z)}$	1.25 Tesla
R$_{aperture}$	7.5 cm	$7.5\sqrt{1+0.05z}$ cm	30 cm
Length	C: 80 cm Hg: 30 cm	300 cm	100 cm

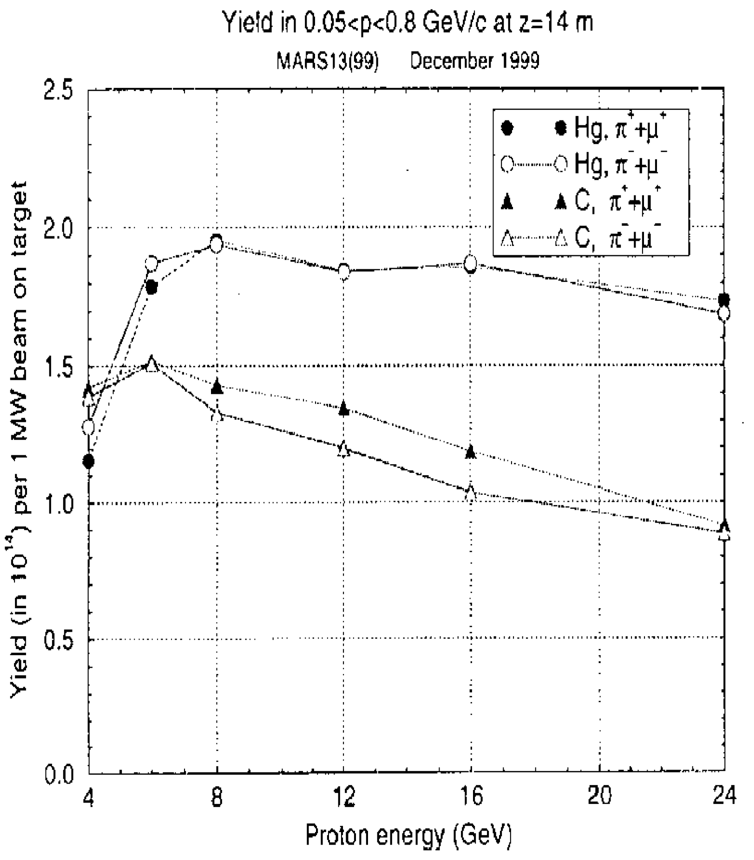


Mars Particle Yields per Incident 16 GeV Proton

Particle	At End of Target (Z=0 cm)		1400 cm Downstream	
	Hg Target	C Target	Hg Target	C Target
π^+, μ^+	0.772	0.471	0.309	0.182
π^-, μ^-	0.803	0.421	0.315	0.153

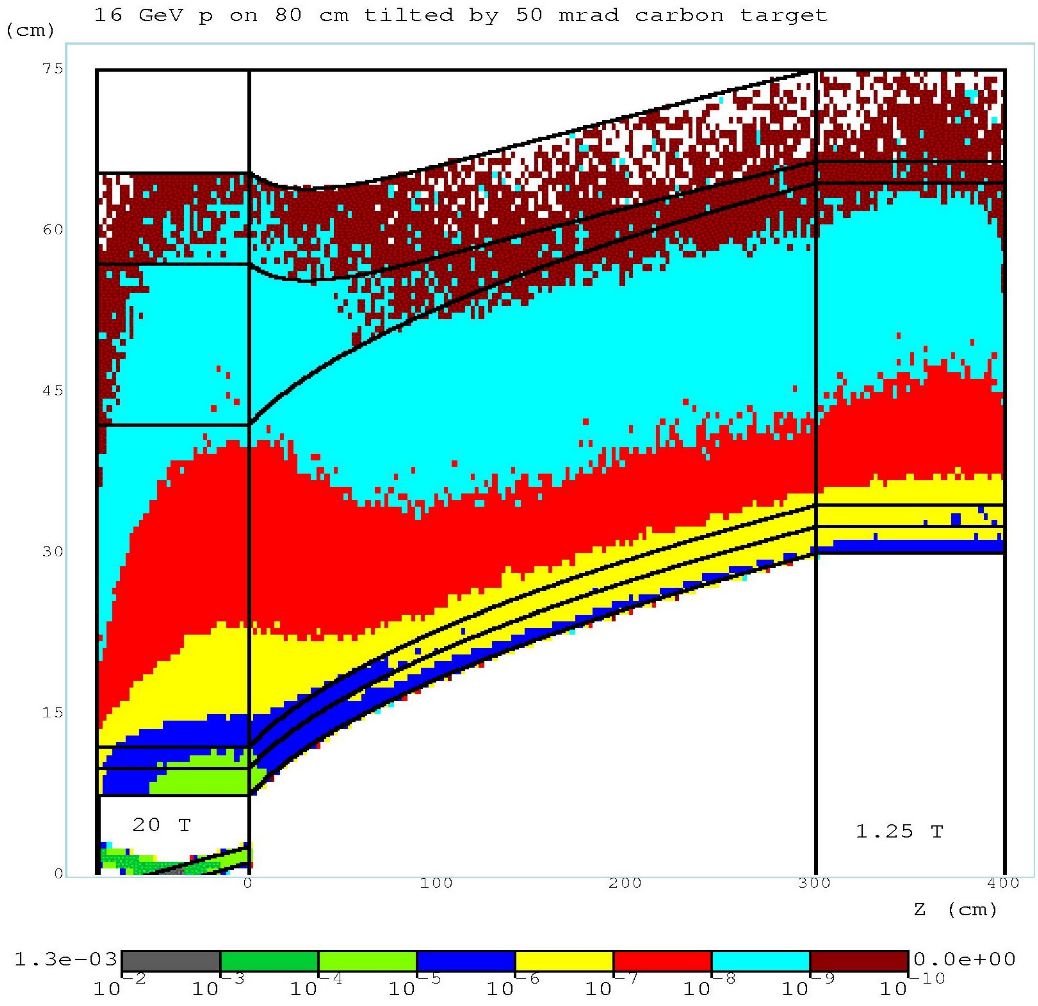
- The relative yield for Hg/C targets is 1.64 (1.91) for positive (negative) mesons* at the end of the target.
- Similar relative yields after 1400 cms is 1.70 (2.06) for positives (negatives).

Meson Yields for Hg and C Targets for 16 GeV Protons

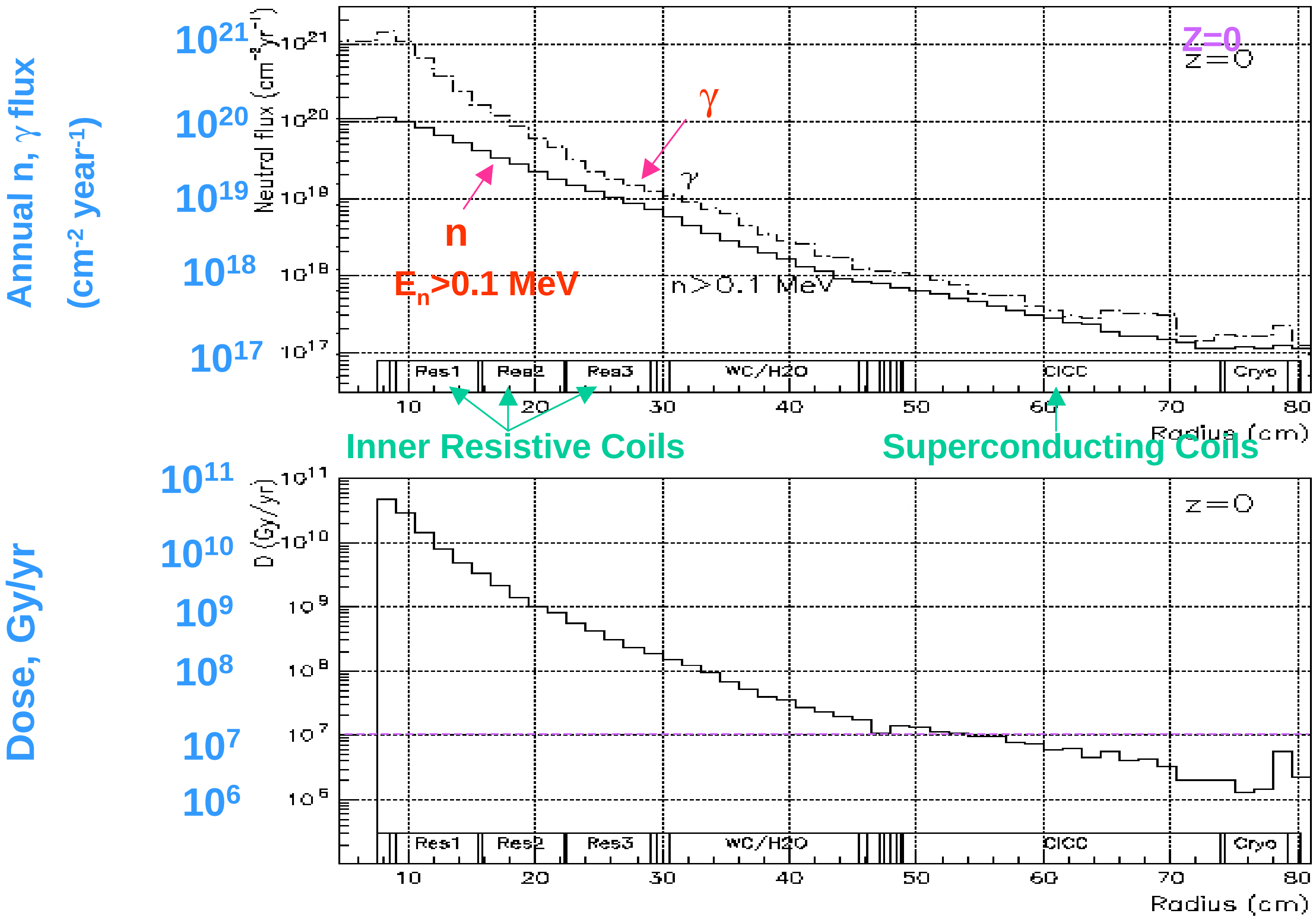


- Yield per beam power:
  - Approx constant for **Hg** target.
  - ~30% falloff for **C** target.
- Yield is ~30% larger for 50 mrad tilted target than no tilt.
- Capture yield saturates at 1.5 λ_{int}. Choose 2 λ_{int} to reduce punch thruough.
- For 16 GeV, 1 MW power:
  - 117 kw in **Hg** target.
  - 24 kw in **C** target.

Energy Deposition Near Target



Radial Distribution of n and γ flux



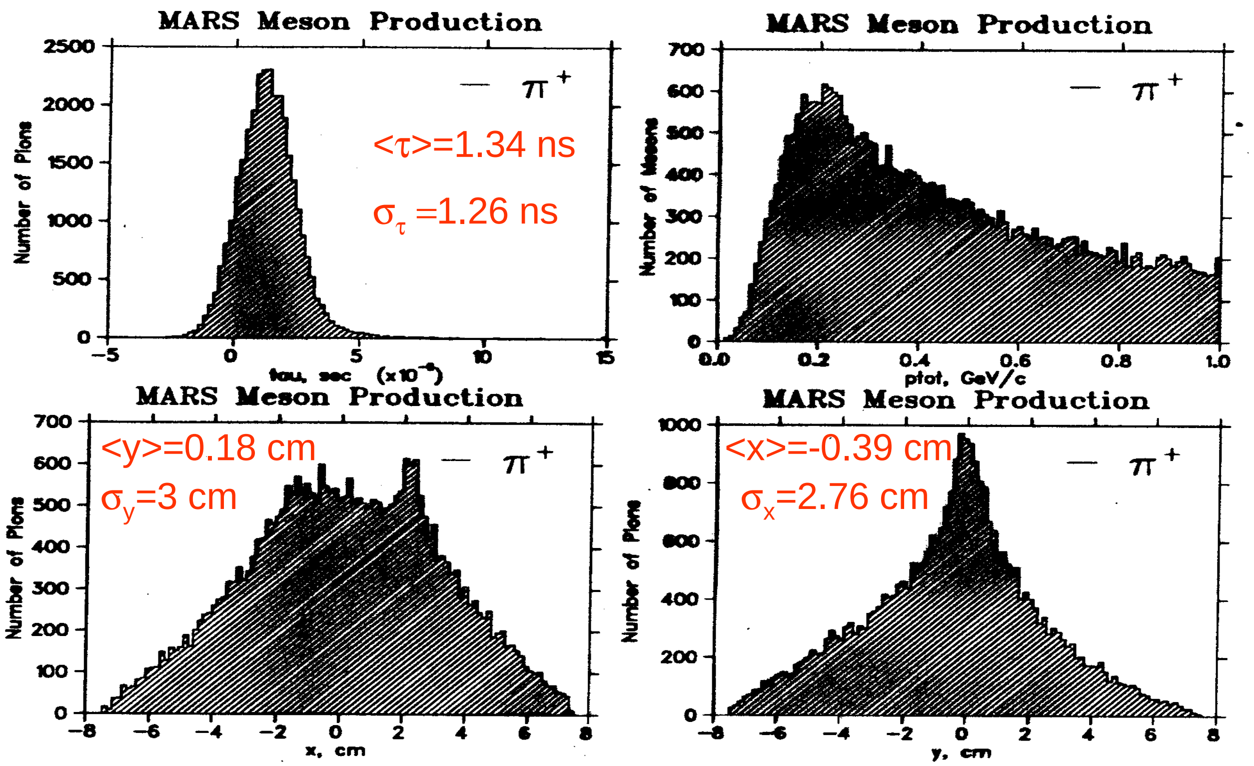
Comments on Radiation Damage

Material	Damage Dose Limit	Comments
Kapton	3×10^7 Gy	Mechanical
Epoxy Resins	$\sim 10^7$ Gy	Mechanical
Copper	3×10^6 Gy	4% increase in ρ
Electronic Components	400 Gy	Neutron damage

- Can not use epoxy insulation in resistive coils.
- Resistive coils to be replaced every 6 months.
- Probably can use kapton as an insulator in SC coils as long as it does not require its tensial strength.

Production Characteristics of 24 GeV Protons on Hg Target

24 GeV p-Hg Meson Production



<τ>=1.34 ns

σ_τ =1.26 ns

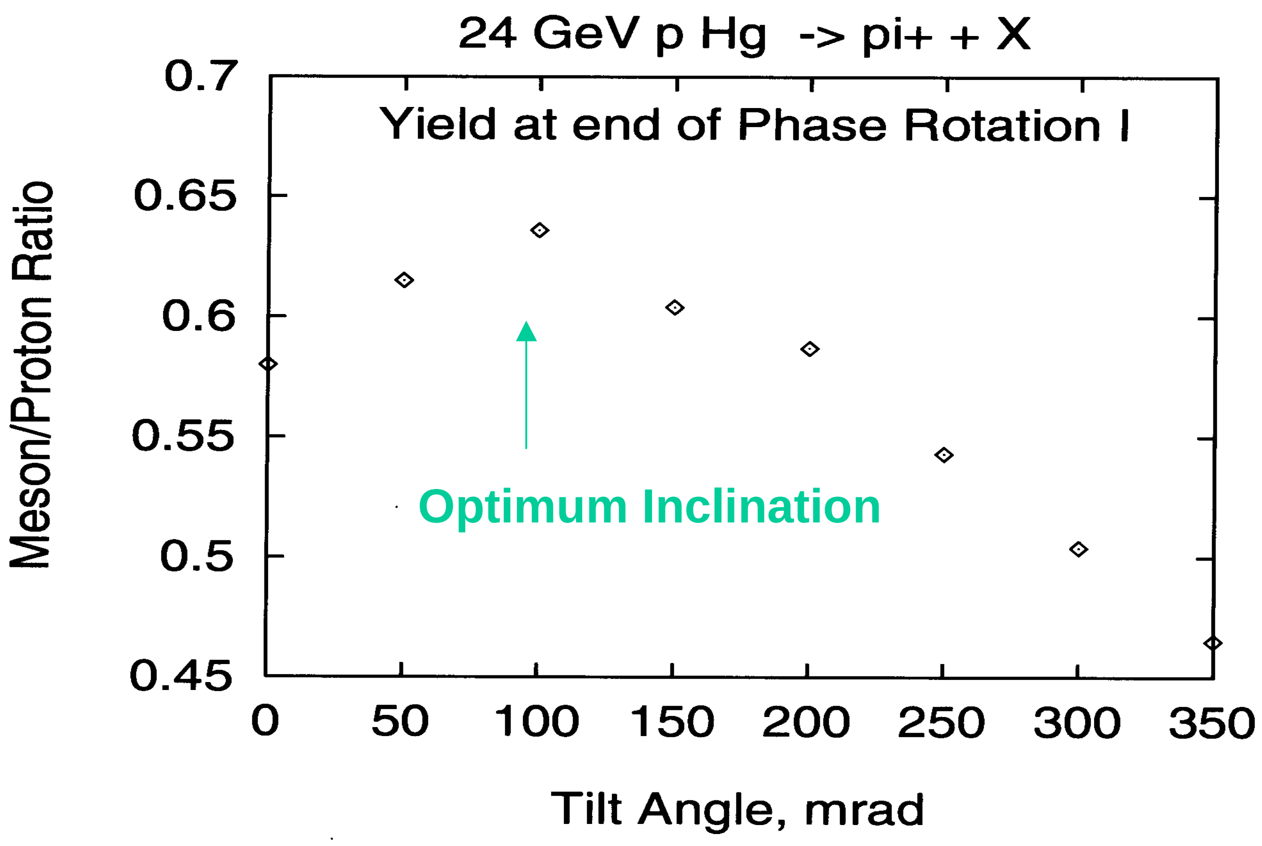
<y>=0.18 cm

σ_y=3 cm

<x>=-0.39 cm

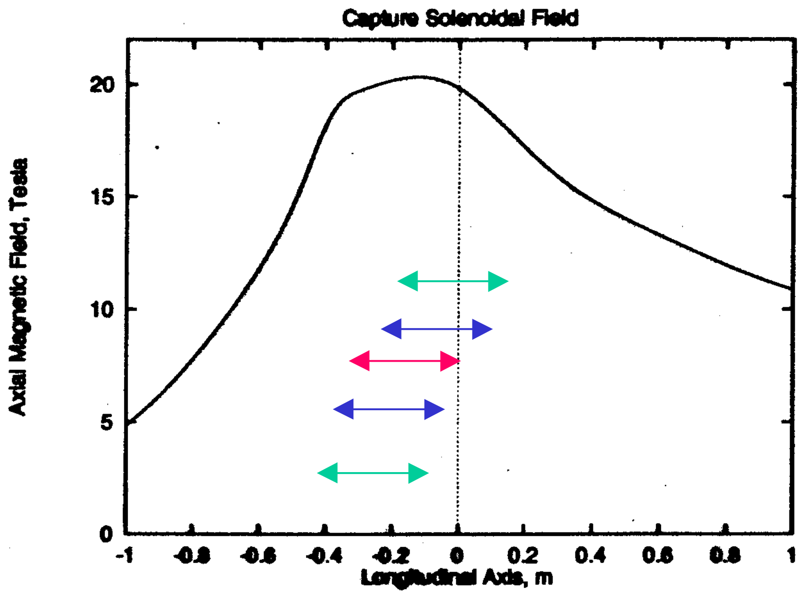
σ_x=2.76 cm

Variation of Target Inclination at 24 GeV



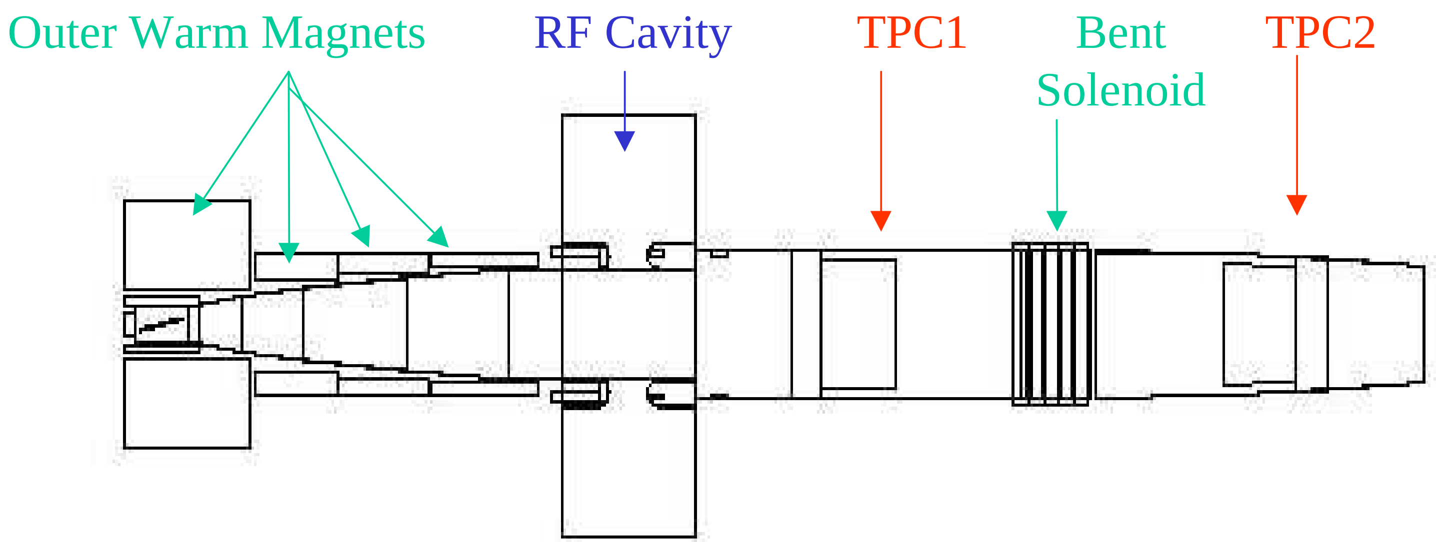
Alignment of Target with Magnetic Field

Target Region Magnetic Field

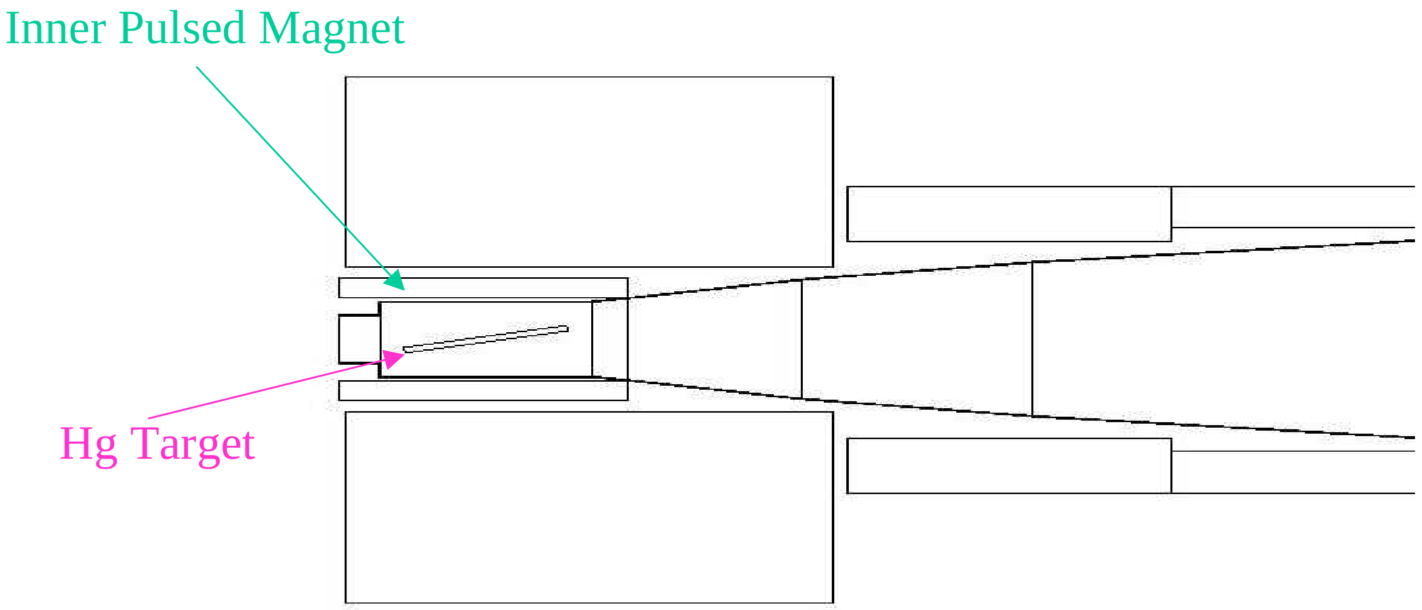


30cm Hg Target Positioning

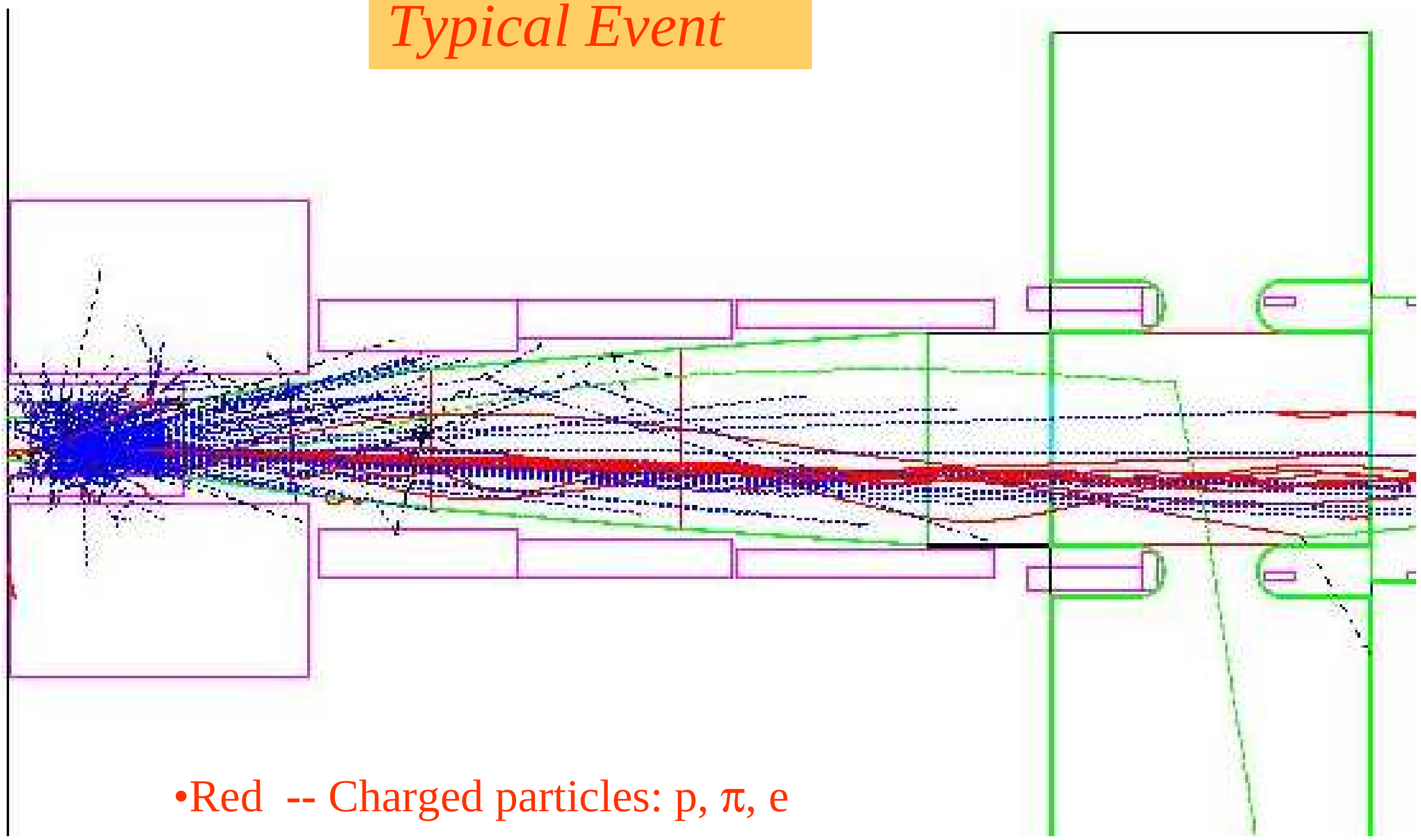
Target Shift cm	B_z T	Meson/Proton Yield End of Target	Meson/Proton Yield End of PR I
10	18.65	1.108	0.573
5	19.30	1.092	0.565
0	19.83	1.139	0.604
-5	20.17	1.035	0.538
-10	20.32	1.030	0.518



GEANT drawing of E951 geometry



Typical Event



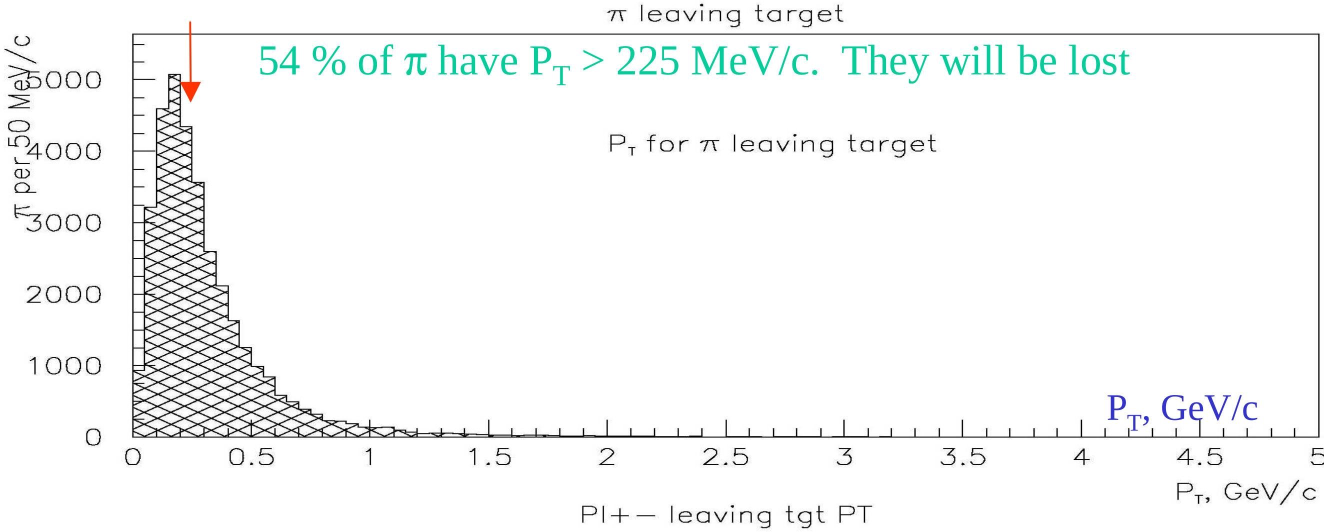
- •Red -- Charged particles: p, π, e
- •Blue -- Photons
- •Black -- Neutral particles: n
- •Green -- Muons

Particles Exiting Target

- 2.0 λ Hg target
- Target inclined 150 mrad to axis
- 24 GeV incident proton beam
- 7 mm target radius
- 20 Tesla solenoid field

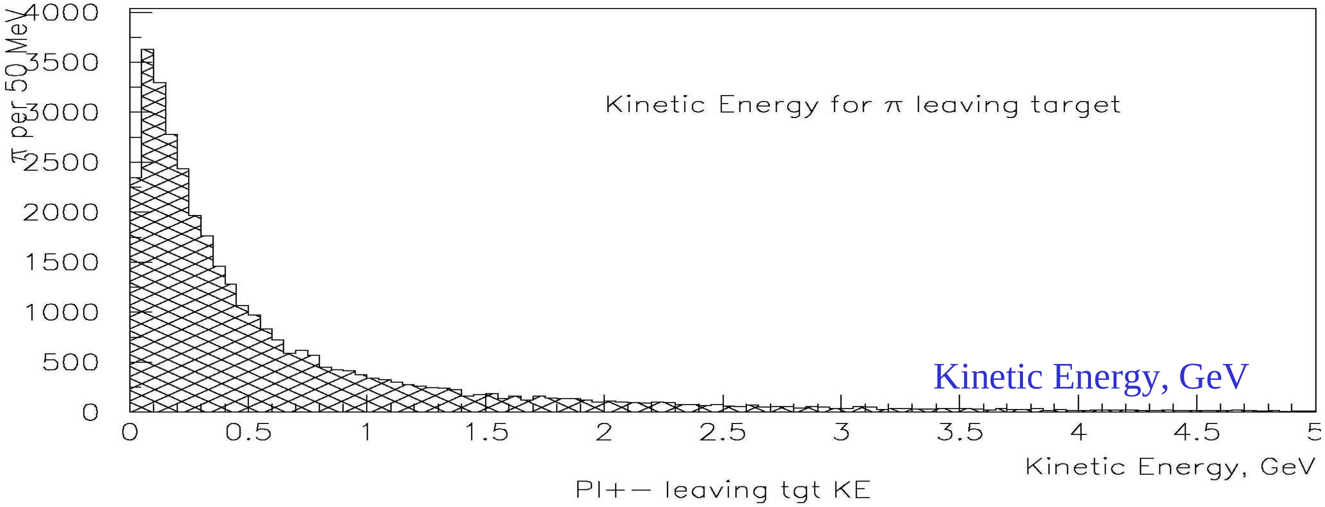
Particle	Hi Energy	All Energies :
gammas	263.4	461.655
$e^{+/--}$	25.38	53.4
ν	1	9.425
$\mu^{+/-}$	0.04	0.105
$\pi^{+/-}$	6.98	21.28
n	50.76	55.13
p	5.5	7.435
Pp cut	0.001	0.0001
Pe cut	0.001	0.0001
Pn cut	0.001	2.15E-12
Pmu cut	0.001	0.0001

π Momentum Distributions Leaving the Target



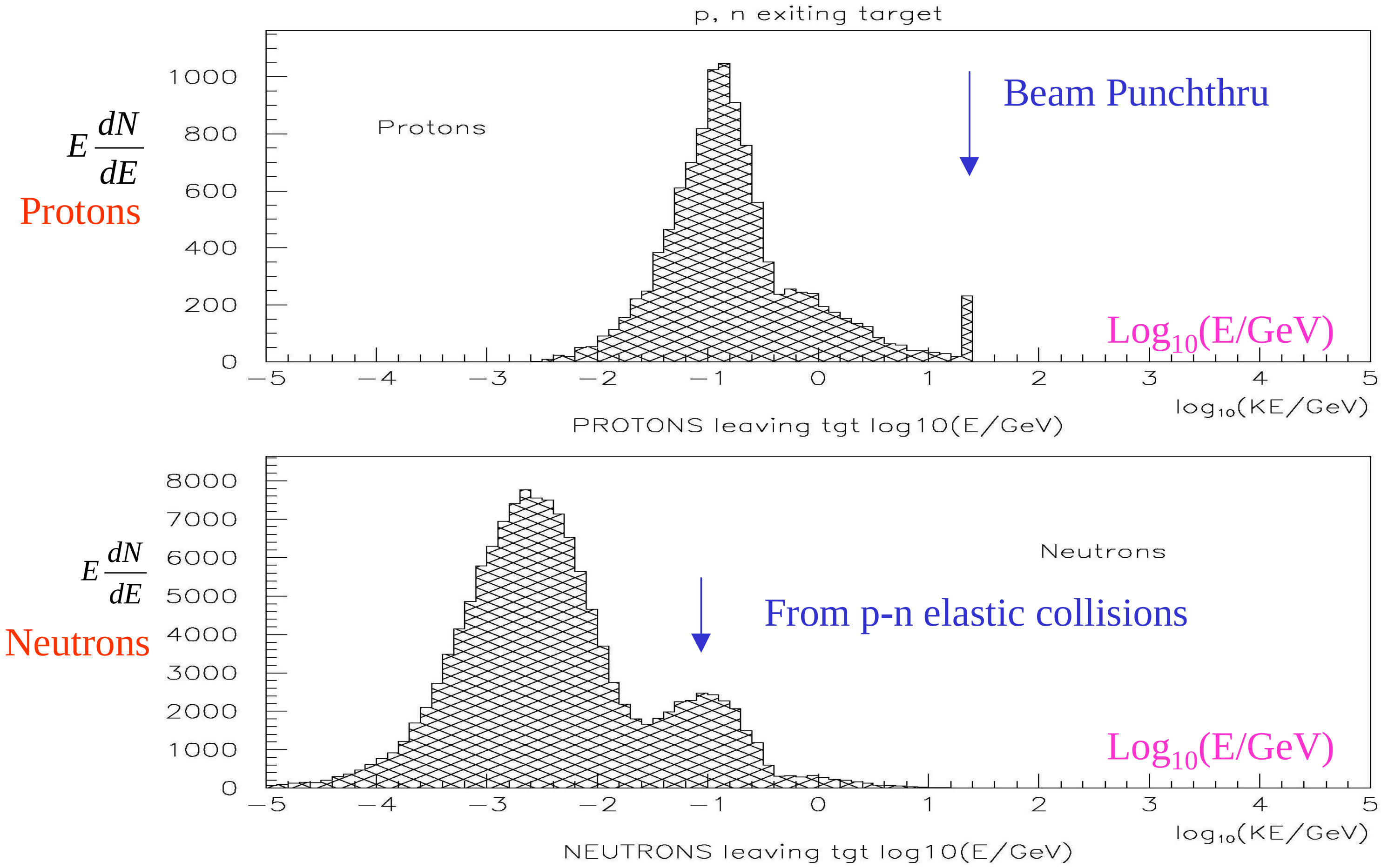
54 % of π have P_T > 225 MeV/c. They will be lost

P_T, GeV/c



Kinetic Energy, GeV

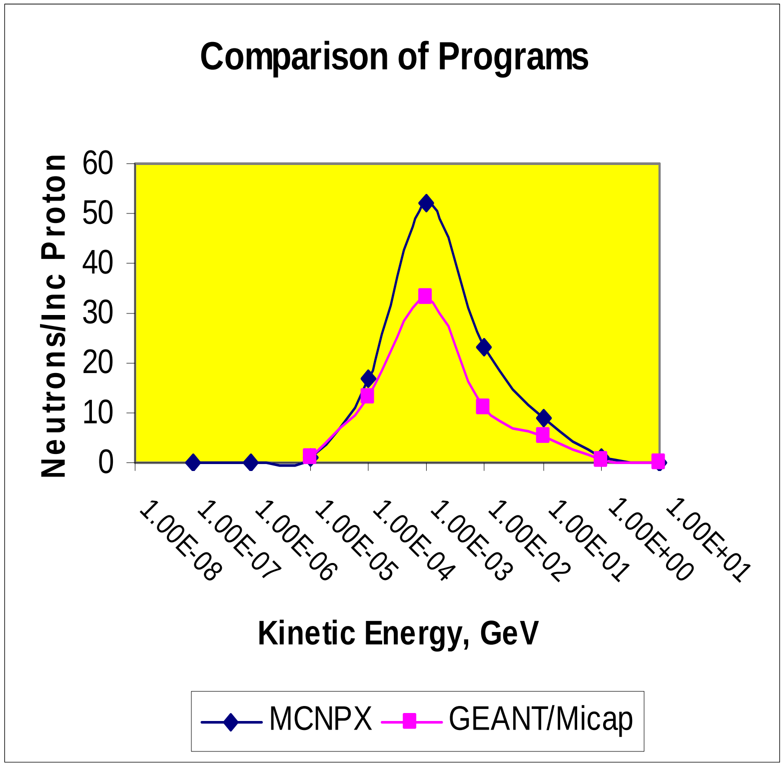
Energies of Neutrons and Protons as They Leave the Target



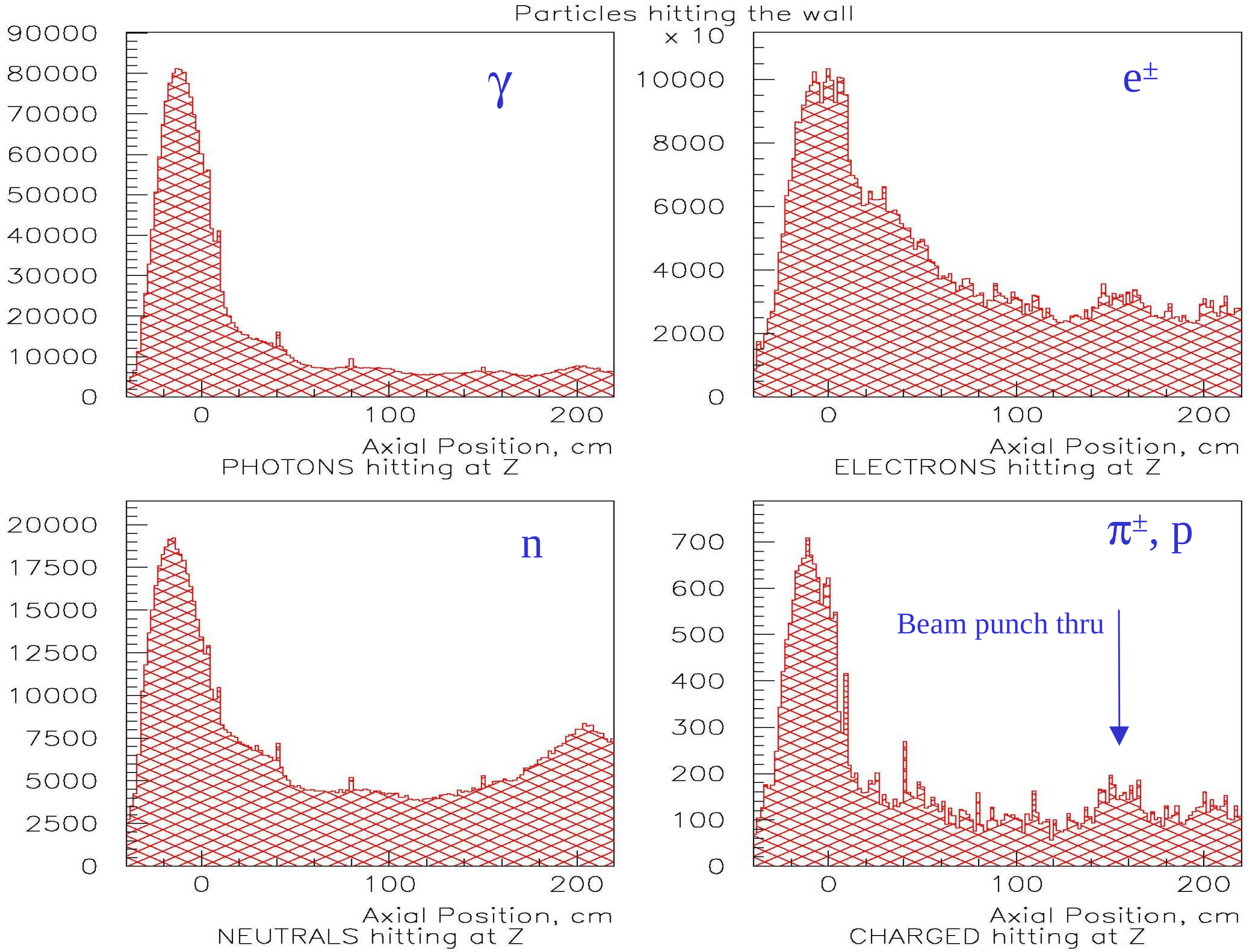
Note: You must divide by E if you want dN/dE

Comparison of MCNPX to GEANT

- As a validity check of the particle production rate, MCNPX was run with a similar geometry.
  - MCNPX show ~50% more neutrons. (It has been subsequently pointed out to me that the current version of MCNPX overestimates neutrons.)
- I am trying to get a e/γ sample for comparison but MCNPX is extremely slow and the job is still running.



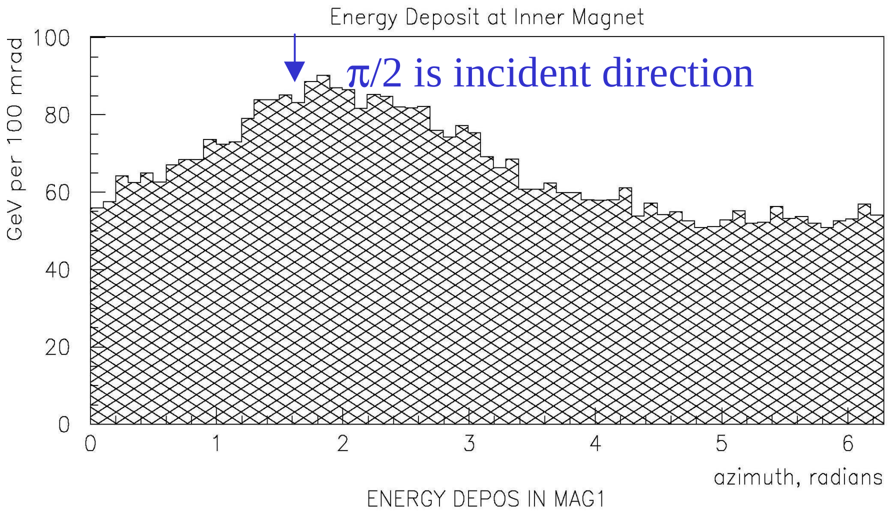
Where Do Particles Hit



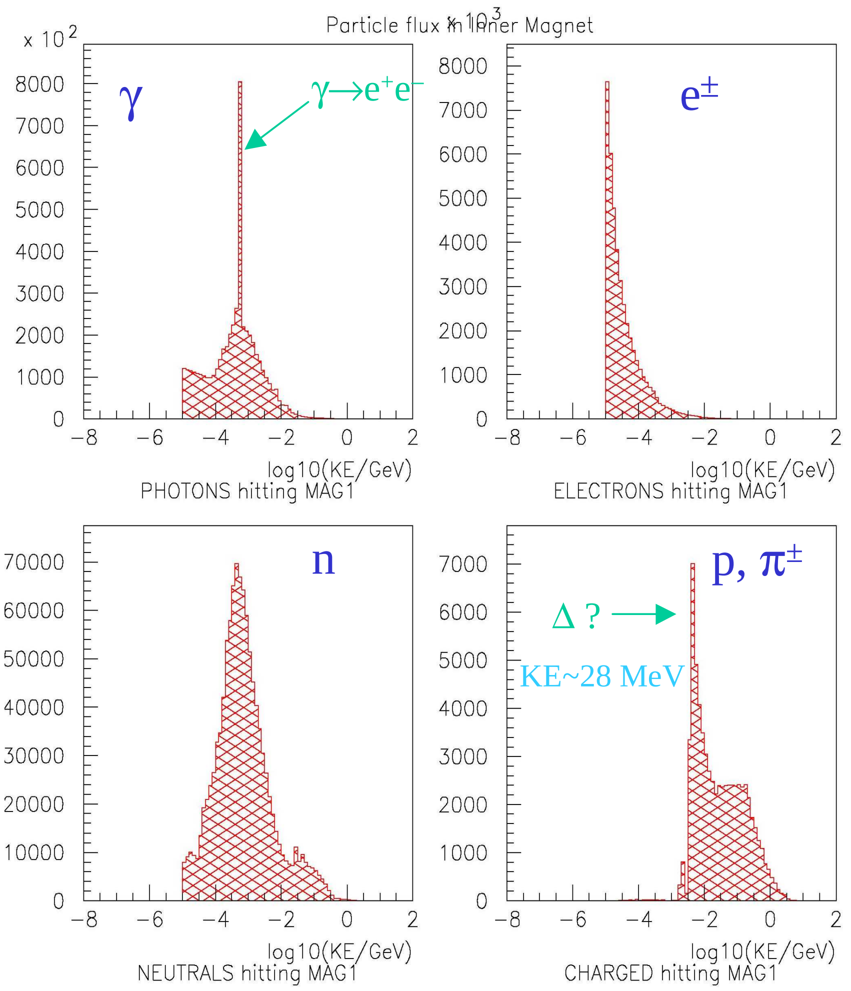
Energy Deposited in Inner Magnet

- Inner coils of solenoid system occupy the radial space 10.7 to 17.8 cm from the axis.
- The inner coils subtend from 27°→153°. That is 89% of the solid angle.
- The table indicates that 8.7% of beam energy is deposited in the *Inner Coils!*
- A 50 TP proton beam will deposit *0.79 joules/cm*^{3} on average.
- ~3 μjoule in *minimum propagating zone* will quench a magnet
  - MPZ is ~1 cm × $(0.75\ \text{mm})^2$

Particle Type	Energy per Incident Proton (GeV)	Energy deposited per pulse (joule/cc)
Photons	0.14535	0.054982
Electrons	1.31295	0.496655
Neutrals	0	0
Chg Hadrns	0.6212	0.234983
Muons	0.00355	0.001343
Heavy Ions	0.0042	0.001589
Total	2.08725	0.7895



Particle Fluxes into Inner Magnet

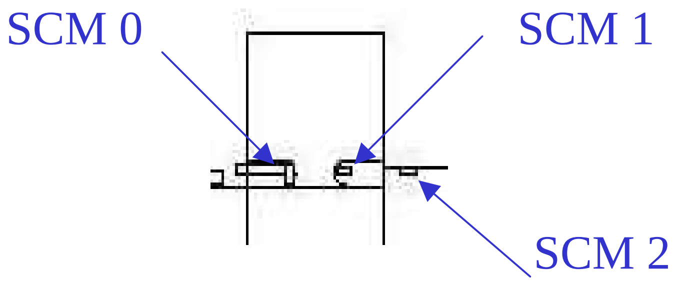


- Figure shows particle fluxes at entrance into inner magnet
- Figure shows $E\frac{dN}{dE}$ vs. $\log_{10}$(E/GeV).
- GEANT does not handle γ, e, and charged hadrons below **10 keV**.
  - The deposited energy may be underestimated since the peak is at the lower edge

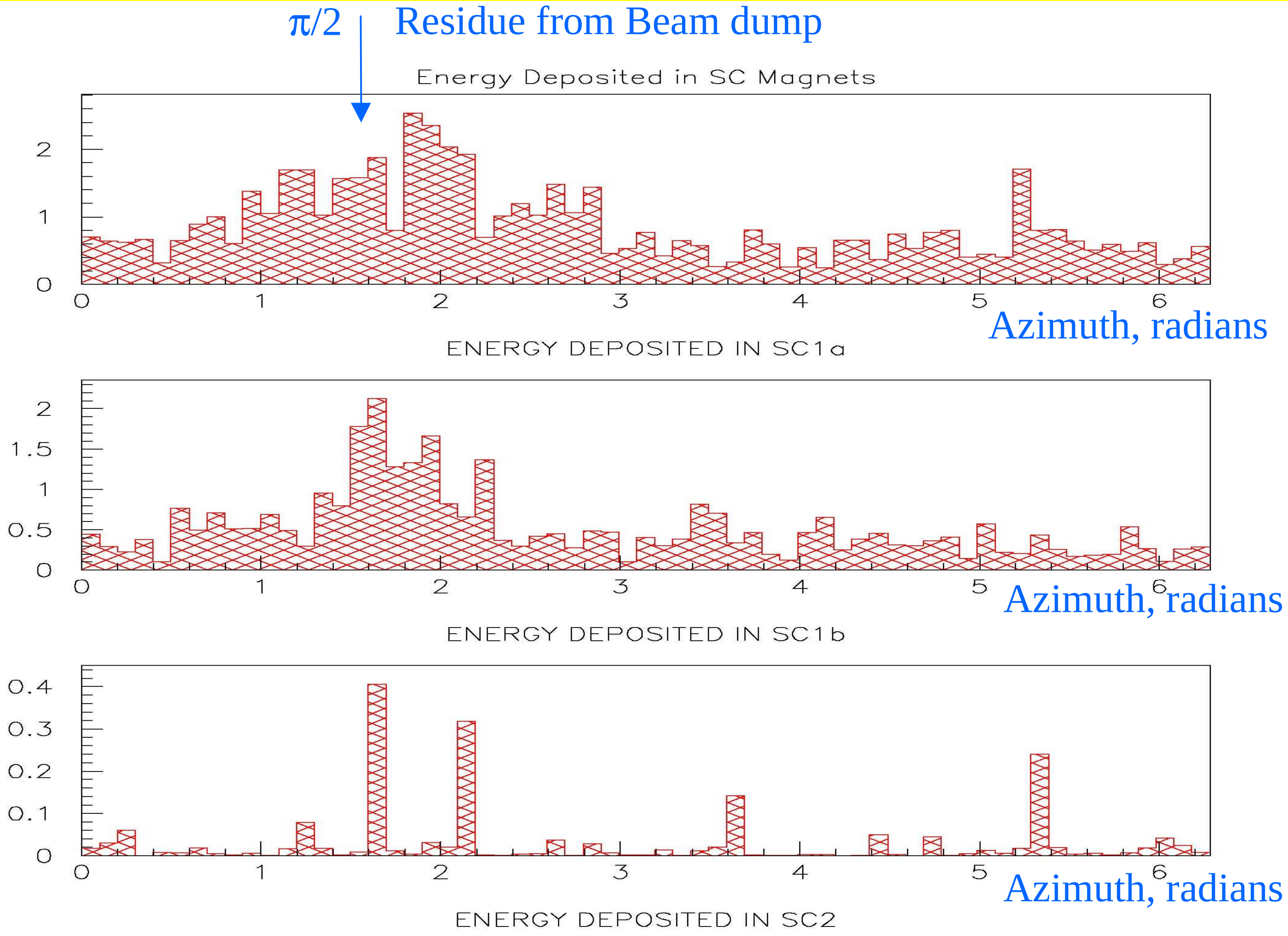
Energy Deposited in Superconducting Coils

- Can we use SC magnets to provide the field at the cavities?
- Adjacent table shows energy deposited near 1st RF cavity.
  - – SCM 0 can’t be SC.
  - – SCM 1 can’t be SC.
  - – SCM 2 is questionable

Magnet	Energy Deposited Per Proton	Energy Deposited Per 50 TP Pulse
	(GeV)	(joules/cm^3)
SCM 0	0.0276	0.0426
SCM 1	0.0164	0.0253
SCM 2	0.00094	0.0012

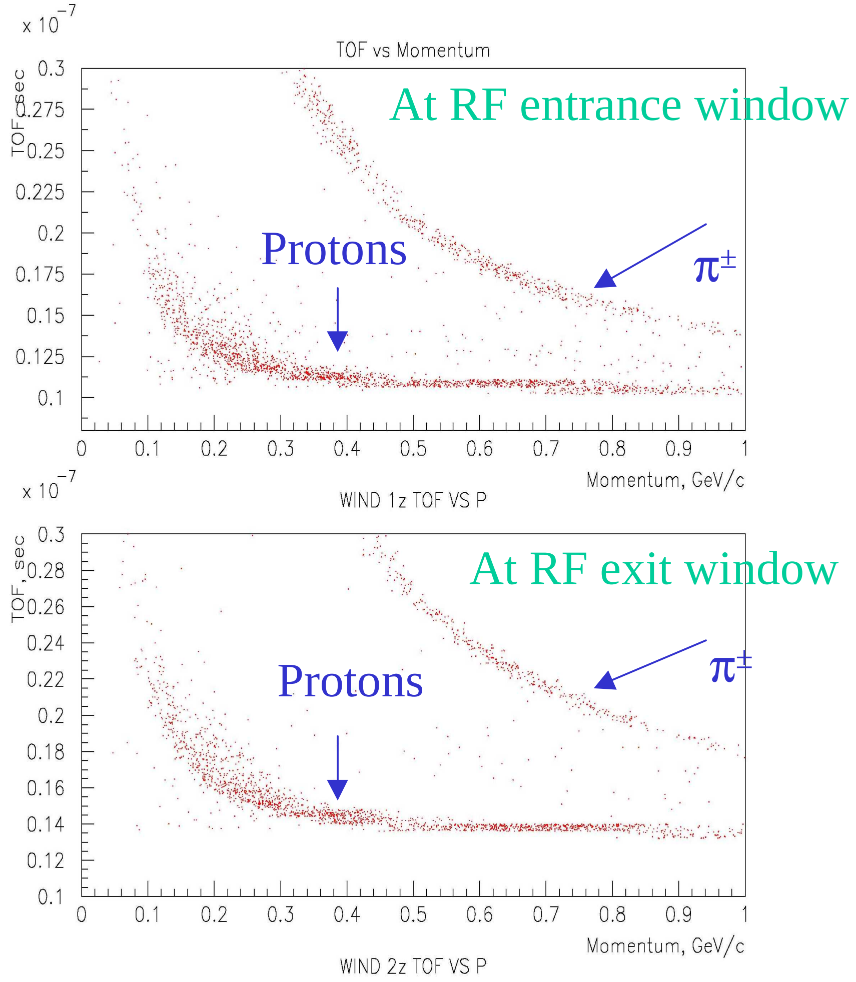


Energy Deposition in Superconducting Coils

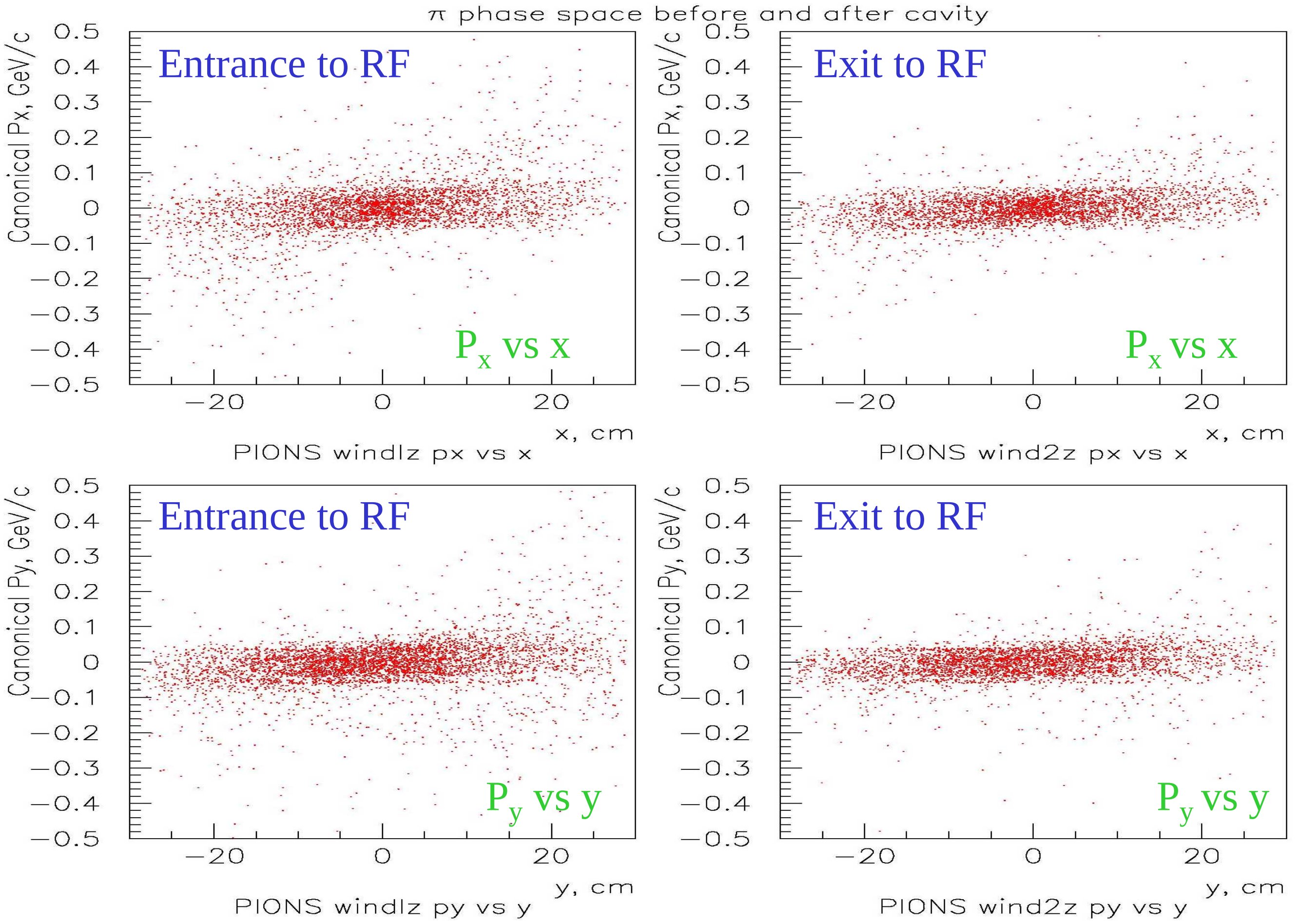


Time of Flight

- Figures show TOF vs. p for charged hadrons at the entrance and exit windows to the RF cavity.
- There appears to be clean separation between π and protons since the protons are slower.
- However I have assumed no longitudinal spread in the incident proton beam!
- Y. Fukui will examine the detection issues in the next talk.



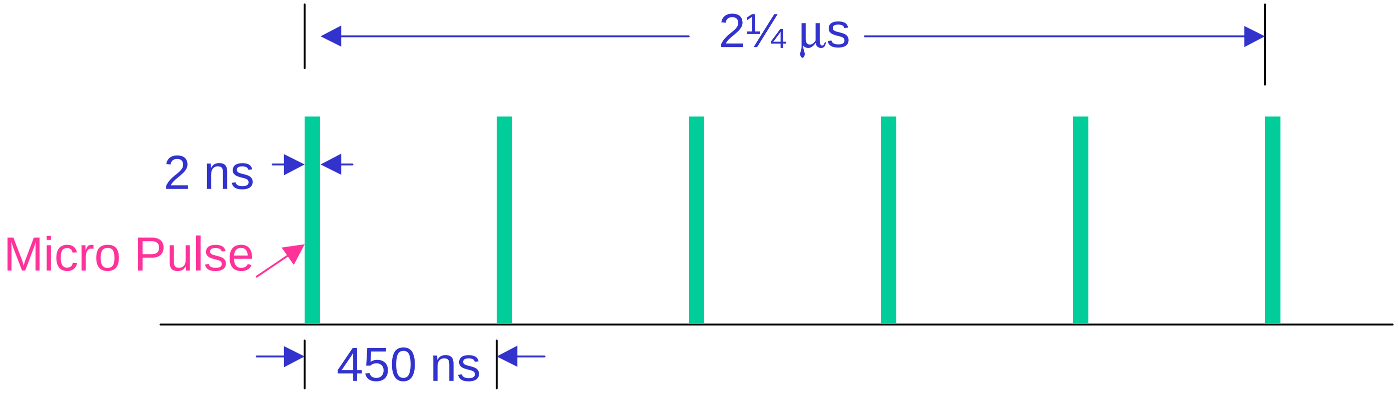
Phase Space Variables at the Entrance and Exit of the RF Cavity



Thermodynamic and Hydrodynamic Issues

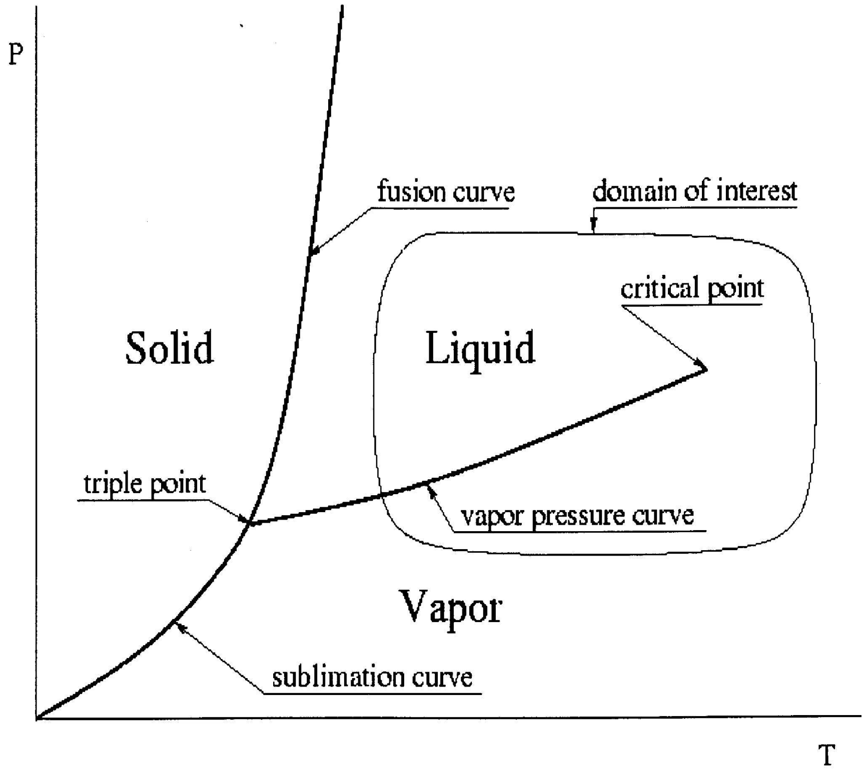
- A liquid jet of 1 cm in diameter with a velocity of **10.0 m/s** enters a magnetic field off axis and is hit with 40 kj.
  - What happens to the jet after the proton beam hits it and strong pressure waves develop?
  - Does the jet break into droplets?
    - Can we estimate the size?
  - Are cavitation bubbles formed?
    - Large negative pressures from reflective pressure wave.
  - How does the jet distort on the way into the magnetic field due to the Eddy currents?
    - Magneto-hydrodynamics?

Time Structure of the AGS Beam



- 50 TP (total) of 24 GeV protons are deposited in 6 micro-pulses.
- Peak energy per micro-pulse is 87.36 joule/gram.

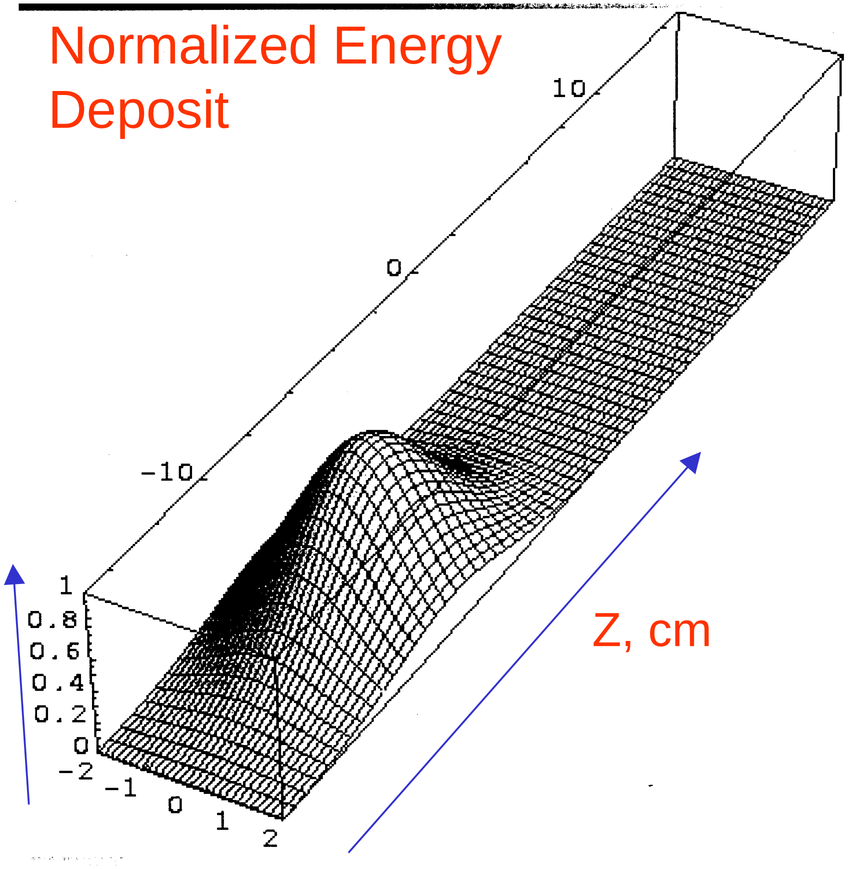
Mercury Phase Diagram



- Critical Point:
  - T_c=1750 K
  - P_c=172 Mpa
  - 43 cm^3/mole
- Boiling Point:
  - T_b=629.84 K
  - P_b= 0.1 Mpa
  - ρ = 13.546 g/cm^3
- Analytical Expression for vapor pressure:
  - $P=133.3\ e^{(18.41-7318/T)}$ in Pa

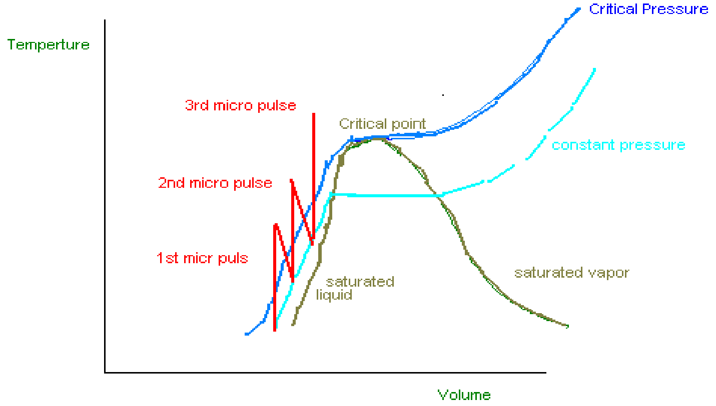
Beam Energy Deposition in Hg Target

- The distribution of energy deposit comes from MARS calculation.
- The distribution is normalized to unity. Peak $E_{deposit}$ is 87.36 j/g for a *micro-pulse.*
- This distribution is used in both ANSYS and FronTier calculations.

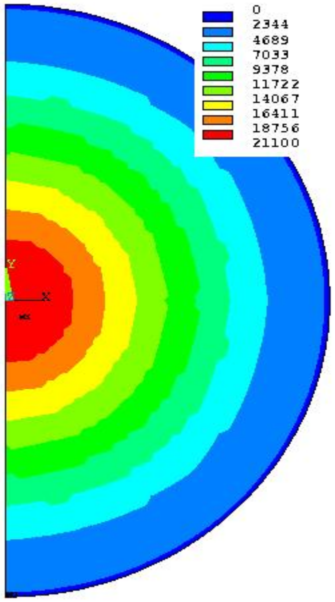


Basic Assumptions

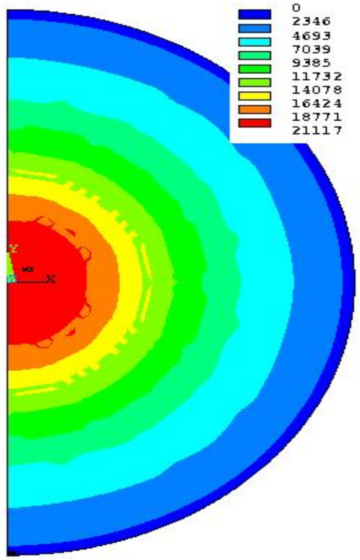
- A single micro-pulse would raise the Hg temperture above boiling *if the Hg could expand.* In the first 2 ns we assume constant volume.
- Between micro-pulses there is a pressure wave expansion at ~v_s=1.45 mm/μs.



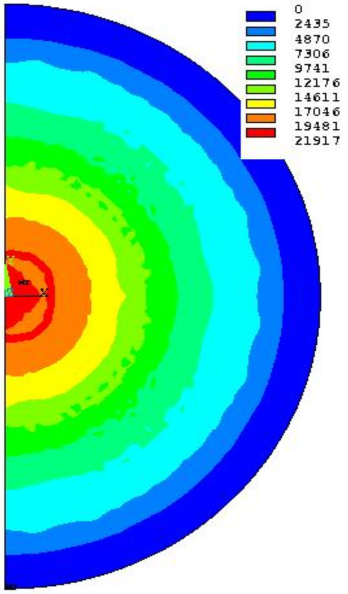
- Temperture is above critical after 3rd micro-pulse.
- Pressure wave will not hit boundary in 2.25 μsec.



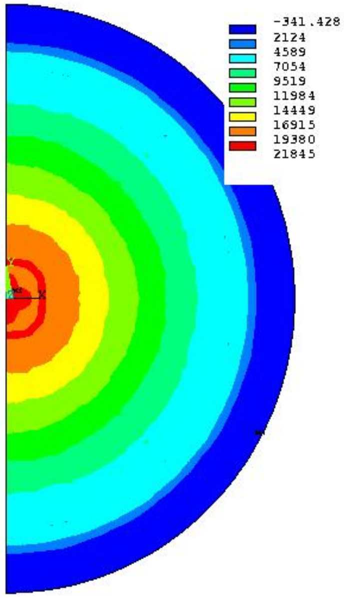
0 sec 1st μpulse



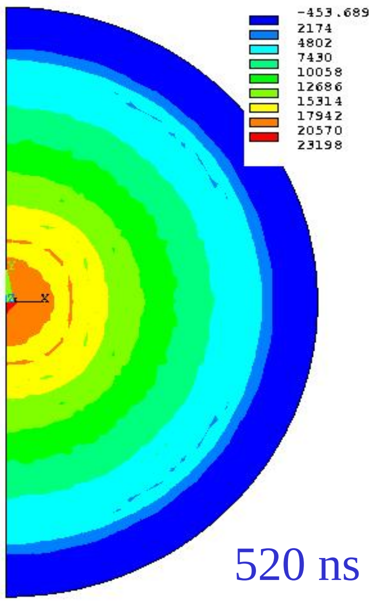
80 ns



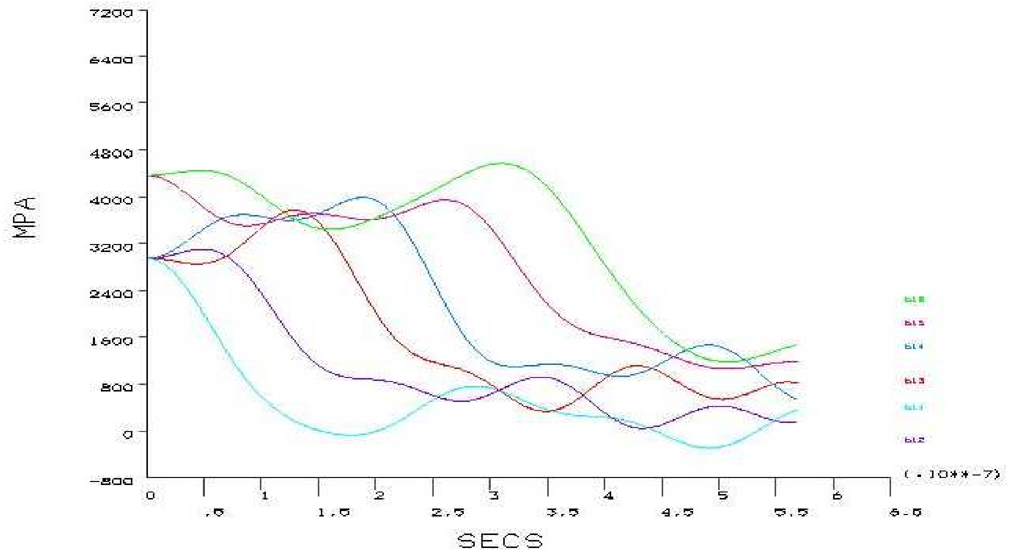
400 ns before
2nd μpulse



460 ns after
2nd μpulse



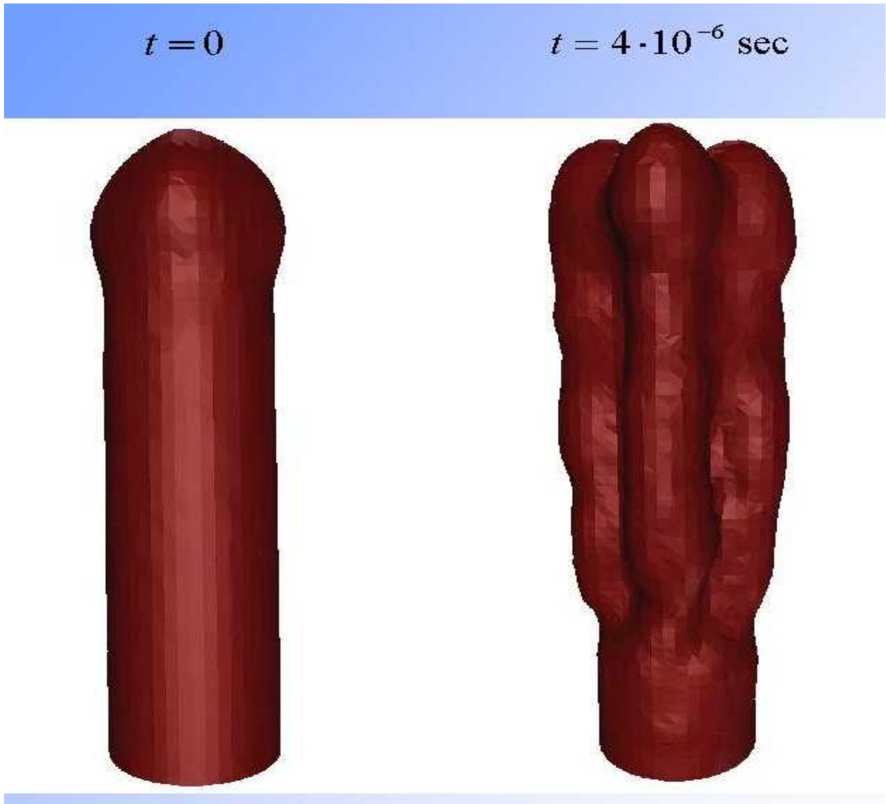
520 ns

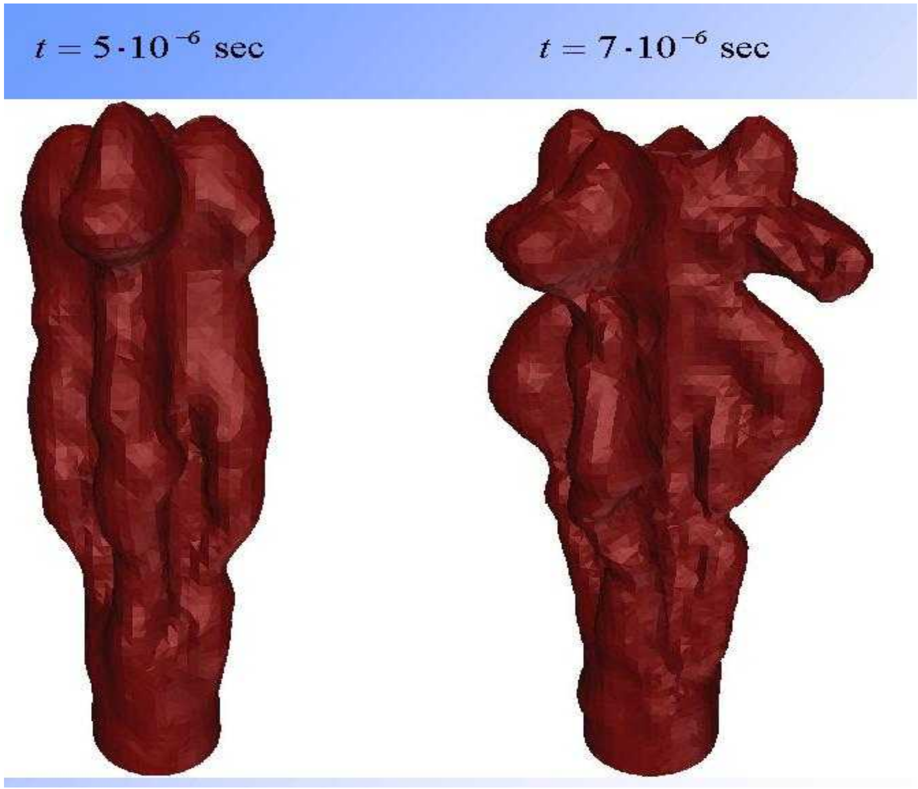


The FronTier Code

- “The *FronTier* code is based on *front tracking*, a numerical method for solving systems of *conservation laws* in which *evolution of discontinuities* is determined through the solution of the *Riemann problem.”*
  - Used to solve thermodynamic Equation of Sate
  - Does not require a highly refined mesh.
  - Ideal for problems where discontinuities are an important feature, such as with two states.
- **SESAME EOS** library from Sandia Lab provide physical and thermodynamic properties for Hg. (Used also in previous Ansys calculation.)

Shape of Hg Target from Interaction with Beam





Before 1st Pulse

Just Before 2nd Pulse

Just After 2nd Pulse

After 2nd Pulse

Roman Samulyak’s Conclusions

- The wave growth rate is

$$\sigma_m^2 = \frac{T}{R^3 \rho} \frac{x \mathrm{I}'_m(x)}{\mathrm{I}_m(x)} \left(1 - x^2 - m^2\right), \qquad x = kR$$

- **For all** $m \neq 0 \quad \sigma_m^2 < 0 \quad \mathbf{for} \ \forall x > 0.$

  Therefore the jet is stable for all non-axisymmetric deformations.

- The most unstable waves correspond to the value

$$\sigma_{0,\max} = 0.3433 \sqrt{T / R^3 \rho} \quad \text{at} \quad x = 0.697 \, .$$

- The characteristic time for the mercury jet breakup (*R*=1 cm) is 0.5sec.

- In the limit of high but finite resistivity we observe that the stabilizing effect of the magnetic field decreases. For the mercury jet (*R* = 1cm) the magnetic field strength of order 10000 Gauss = 1 Tesla will be necessary to stabilize the jet against the varicose deformations of all wavelengths.

Comments on Thermodynamic Studies

- Negative pressures that can cause cavitation are not likely to be caused by smooth distributions of energy deposited over a finite radial extent (~millimeters).
- Negative pressures can come from reflected pressure wave from boundary, however the time scale is after all 6 micro-pulses of the AGS (for example) have passed.
- In the ~½ second required for the Hg jet to break up, it is more likely to hit the wall since it is traveling 10 m/s.
- The magneto-hydrodynamic aspects of these studies should now be emphasized.