# *WG III: TARGETS AND BEAMLIINES*

HOW TO HANDLE INTENSE BEAMS AND TARGET THEM SAFELY

LIQUID VS SOLID TARGETS

THICK VS THIN SOLID TARGETS

# Target Development for the SINQ high-power Neutron Spallation Source

presented by

Werner Wagner

Paul-Scherrer-Institute, Villigen PSI, Switzerland

# Outline:

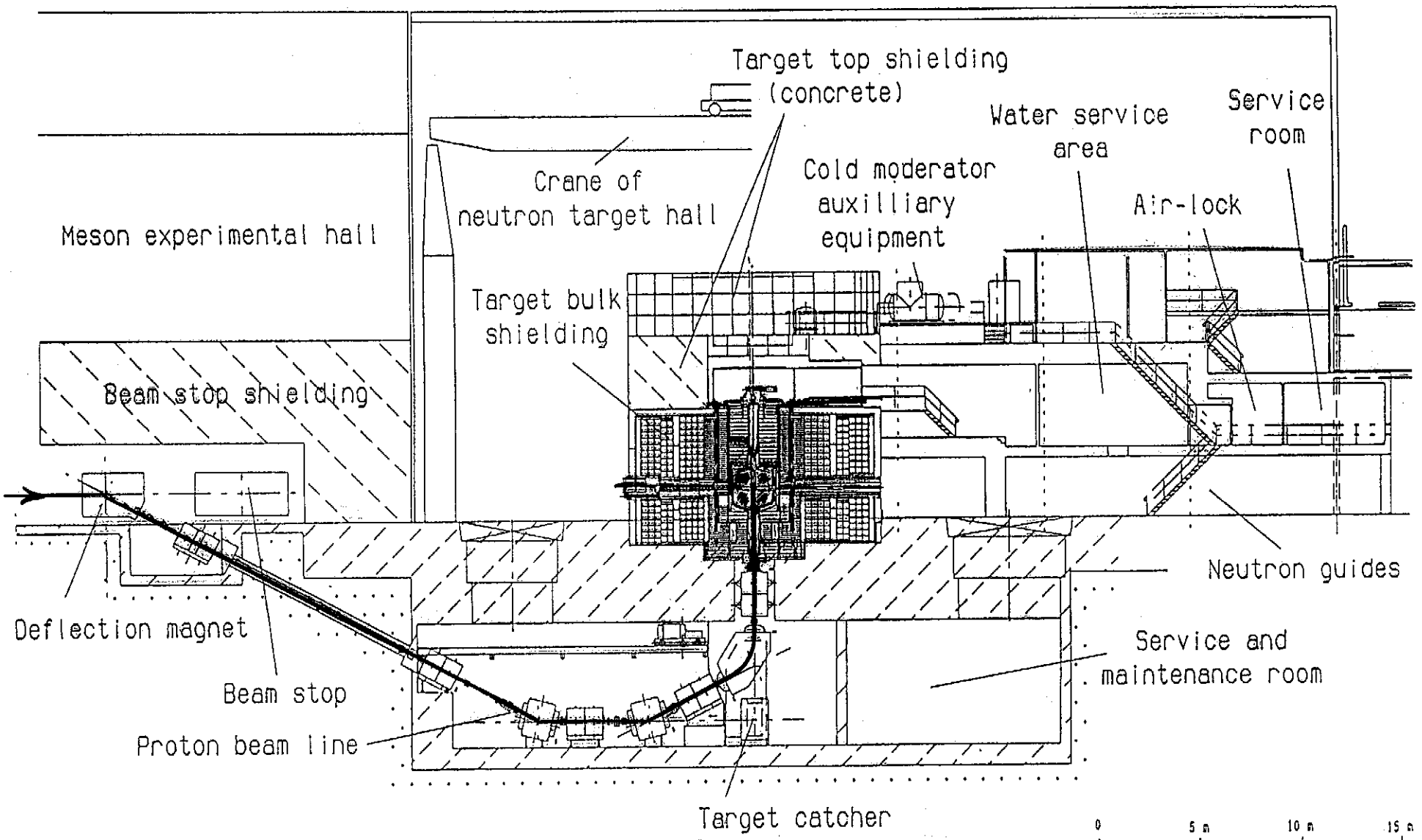
## The SINQ neutron spallation source:

- **Layout, Operation, Applications**

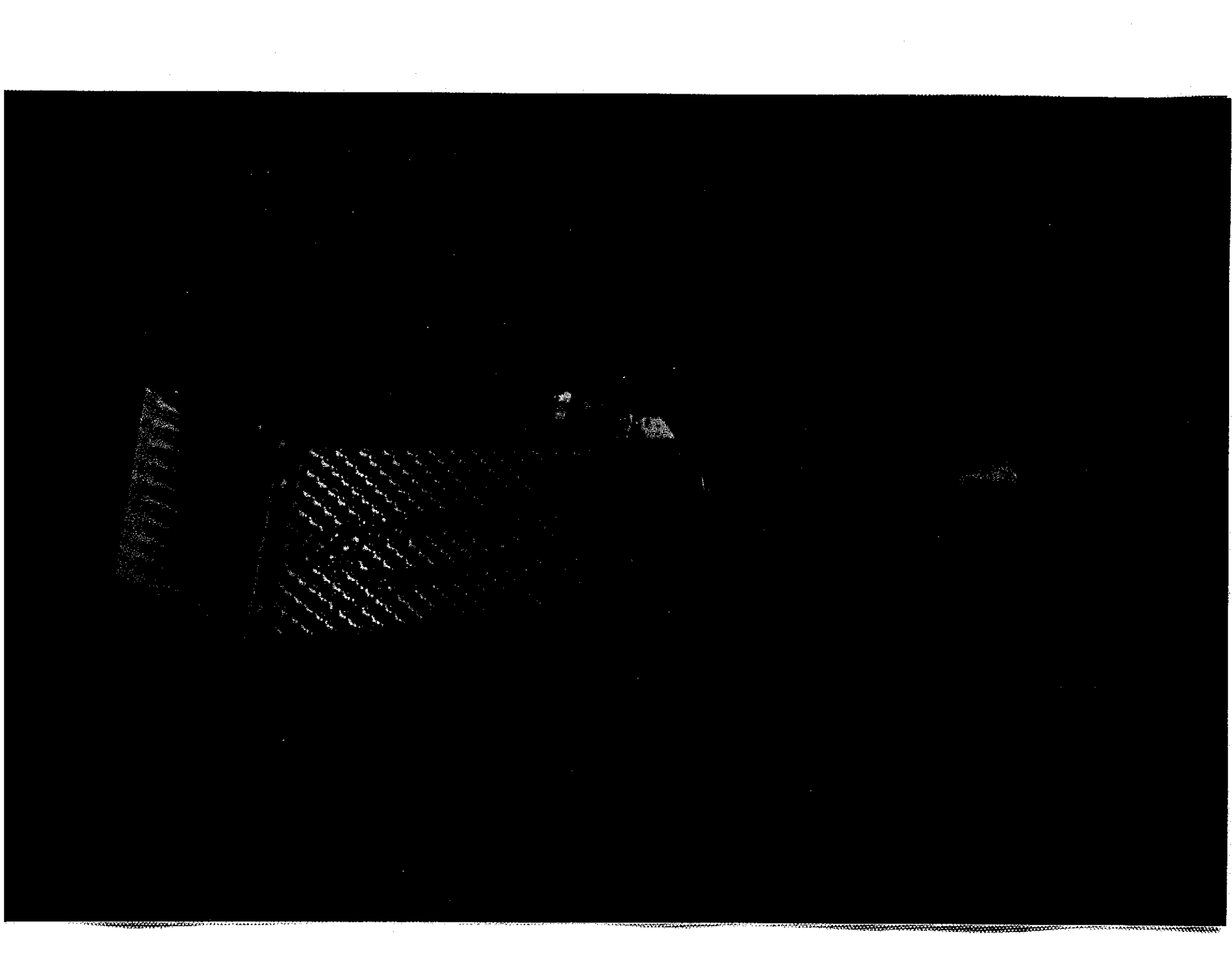
## R&D for higher power:

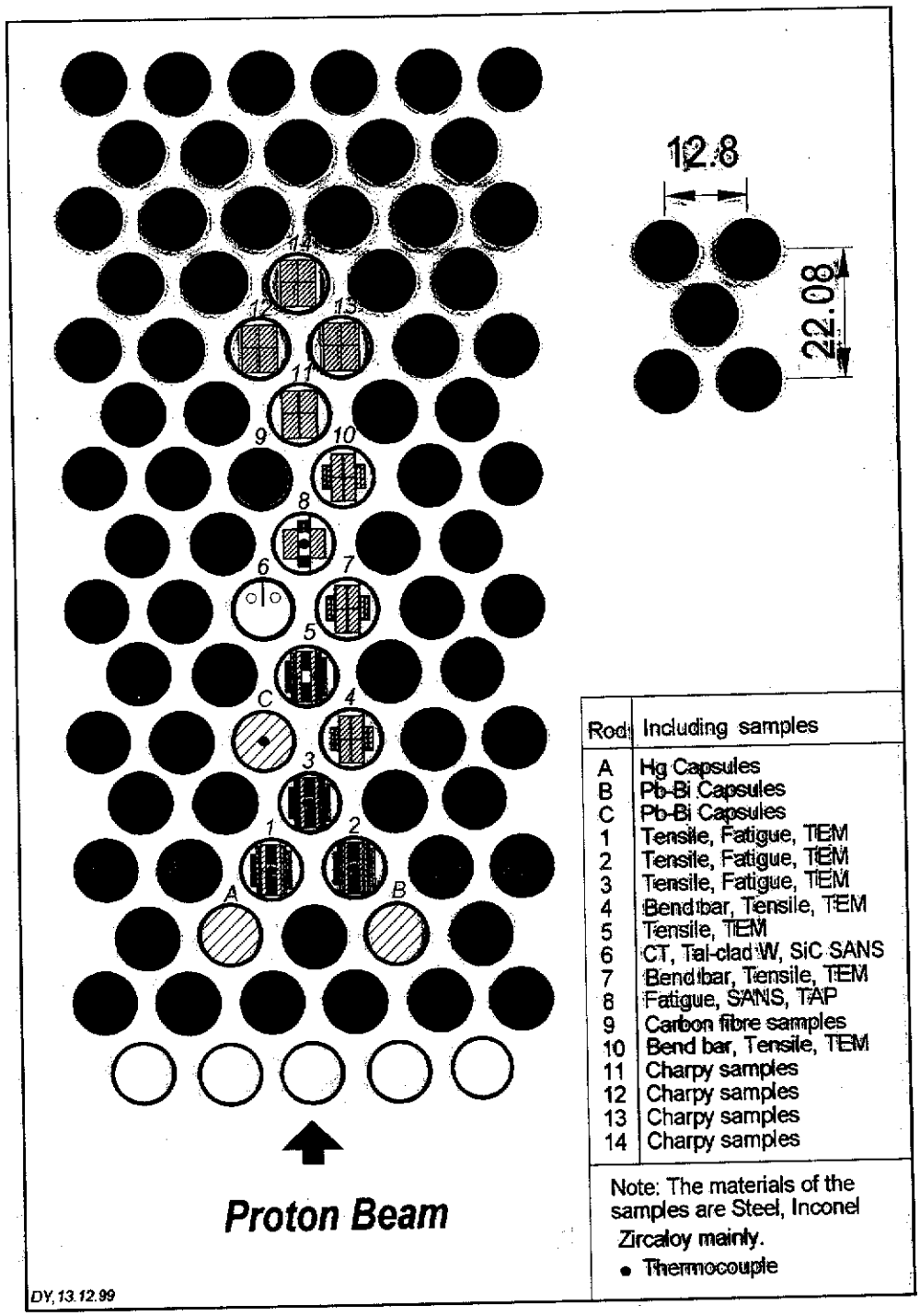
### The target development program

- **STIP**: SINQ Target Irradiation Program
- **LiSoR**: Liquid-metal Solid-metal Reactions
- **MEGAPIE**: Megawatt Pilot target Experiment




The SINQ facility






**A sketch illustrating the arrangement of the 17 specimen rods in the target Mark-3. Temperatures during irradiation are monitored with a total of 10 thermocouples**

# MEGAPIE MEgawatt PIlot Experiment

International collaboration to develop a liquid lead-bismuth spallation target for a beam power level of 1 MW to be operated at SINQ for one year (6000 mAh) in 2005 aiming to

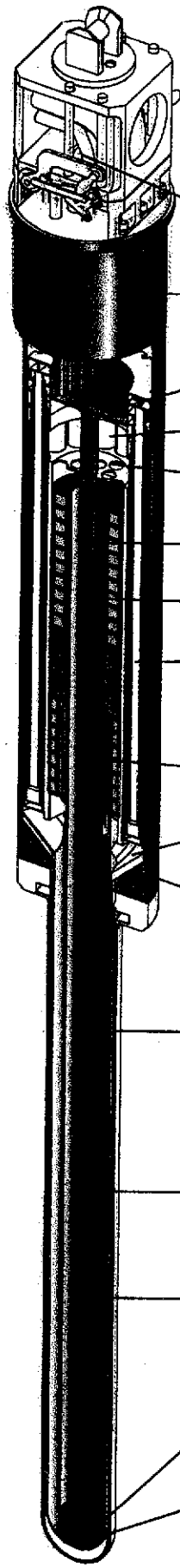
- demonstrate the feasibility for future ADS development
- increase neutron flux for SINQ

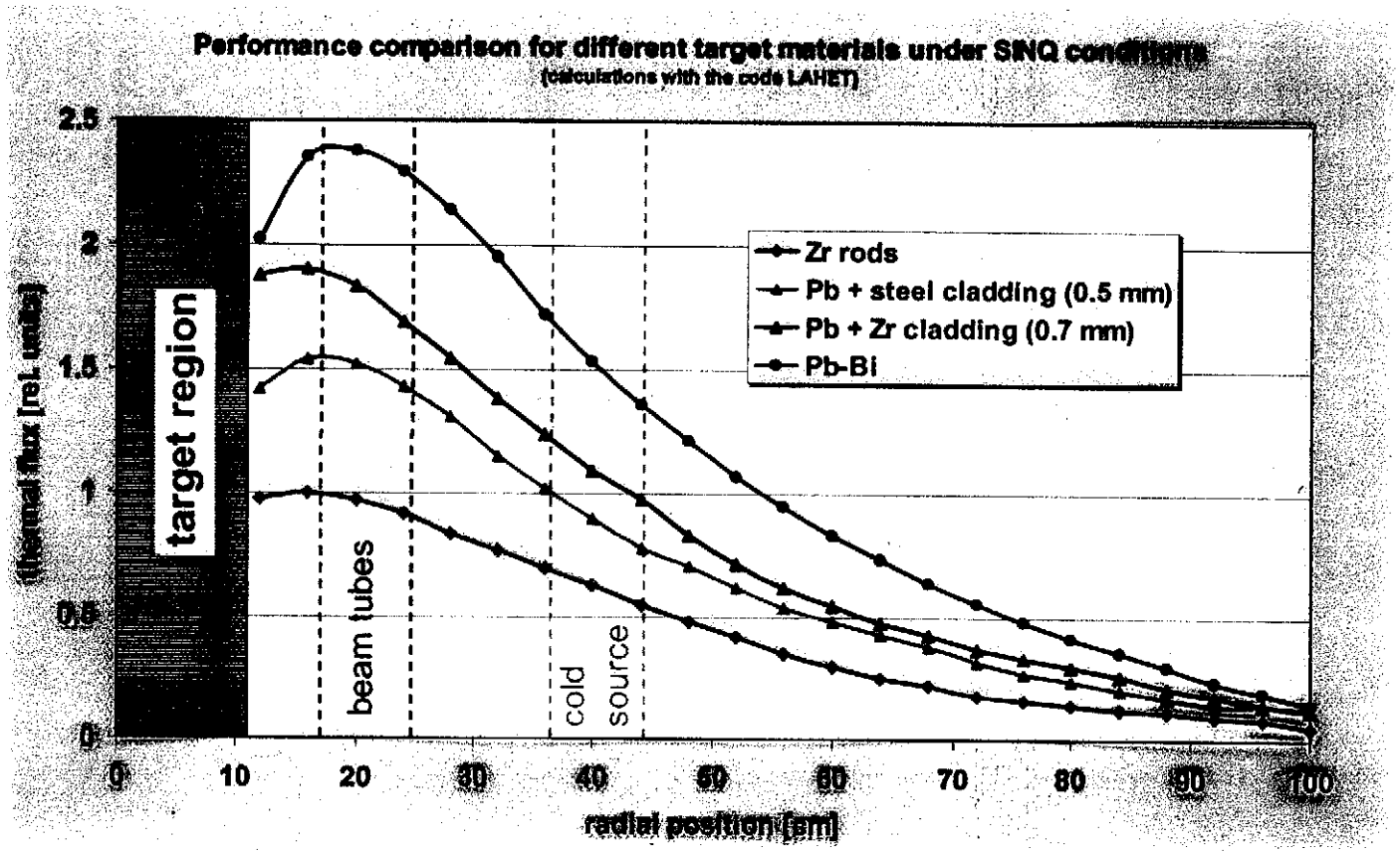
**Project Partners:**

Korea Atomic Energy Research Institute

Department of Energy

# The MEGAPIE Target
## Conceptual Design






Expected increase in neutron flux by 50% compared to Mark II target LAHET calculations (A. Dementjev, E. Lehmann)

# CARBON and BERYLLIUM TARGETS

and

# BEAM WINDOWS

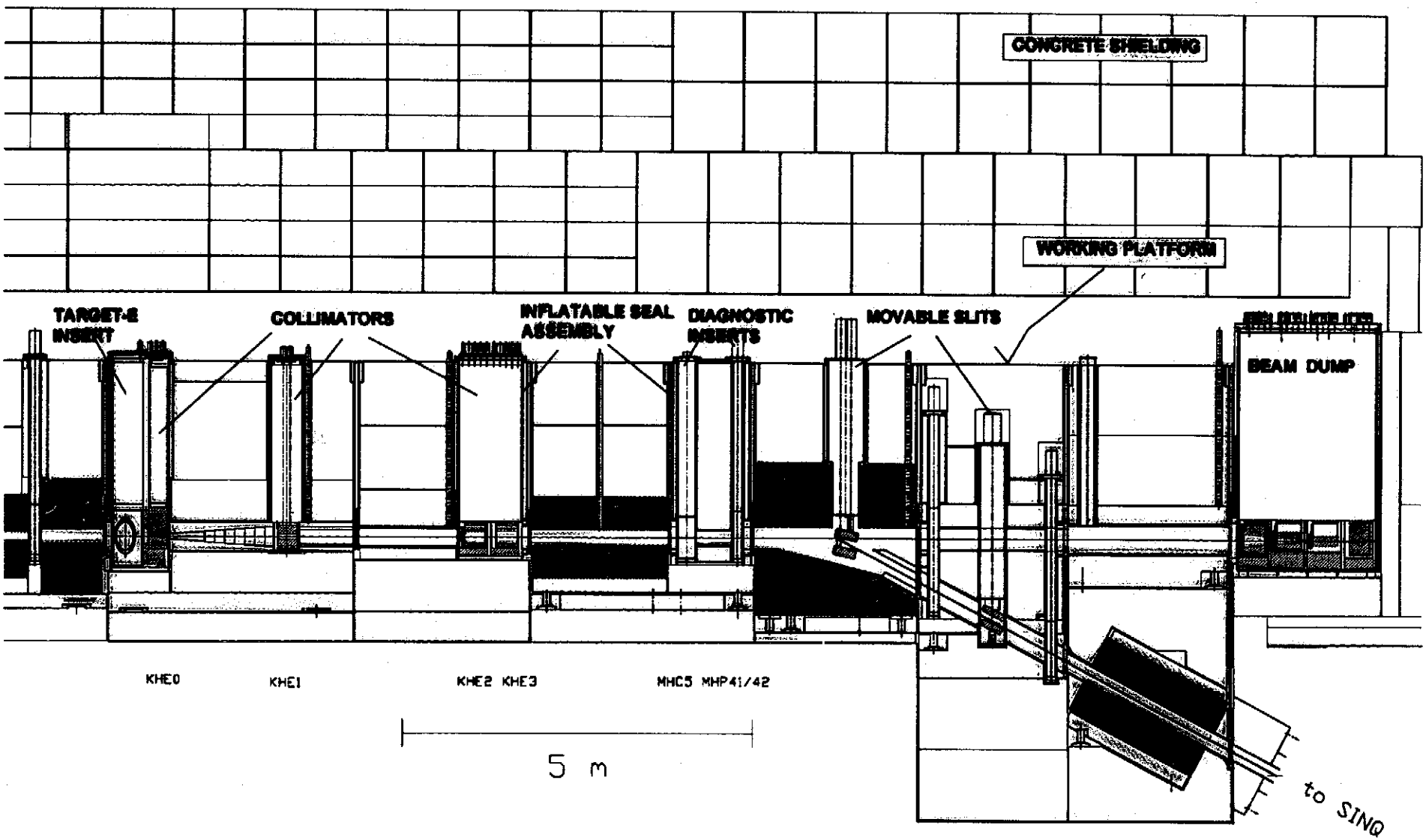
at PSI

Gerd Heidenreich

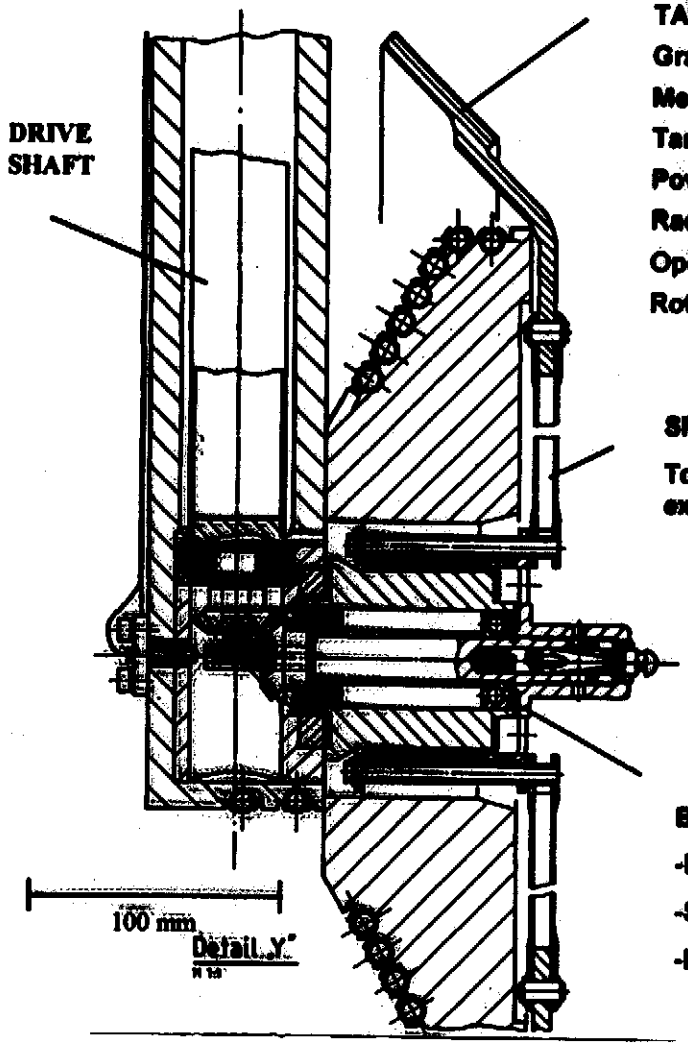
Paul Scherrer Institut (PSI)

Switzerland

# DESIGN OF THE PROTON CHANNEL BETWEEN TARGET-E AND THE BEAM DUMP



# TARGET - E




**TARGET CONE**

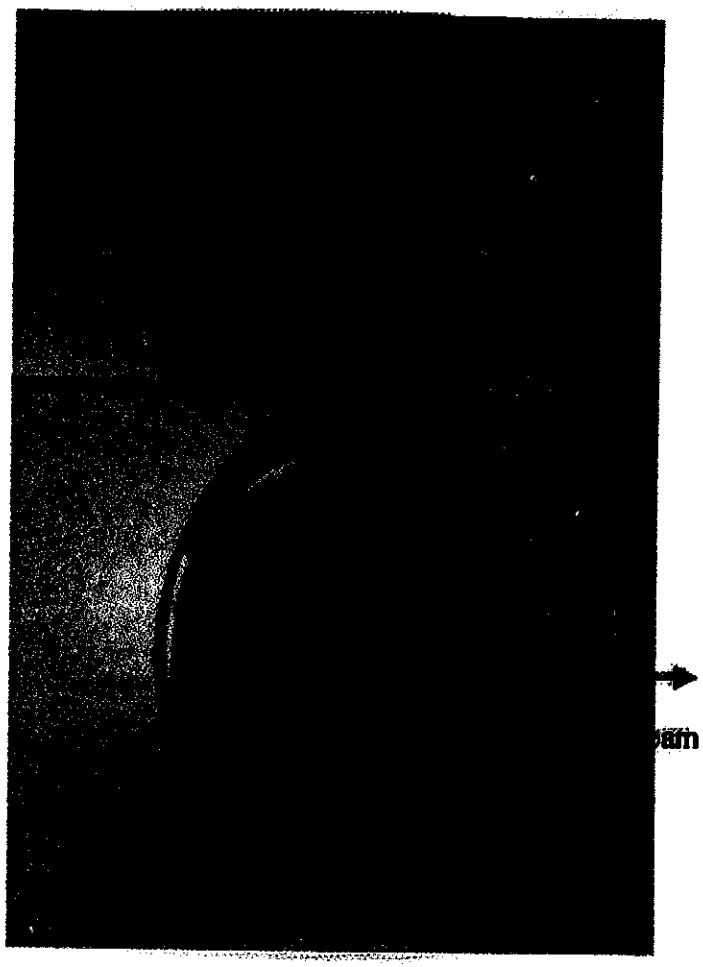
| | |
|---|---|
| Graphite density: | 1.8 g/cm³ |
| Mean Diameter: | 450 mm |
| Target length: | 60 mm |
| Power deposition: | 60 kW |
| Radiation damage rate: | 0.1 dpa/Ah |
| Operating temperature: | 1700 K |
| Rotation speed: | 1 turn/s |

**SPOKES**

To enable the thermal expansion of the target cone

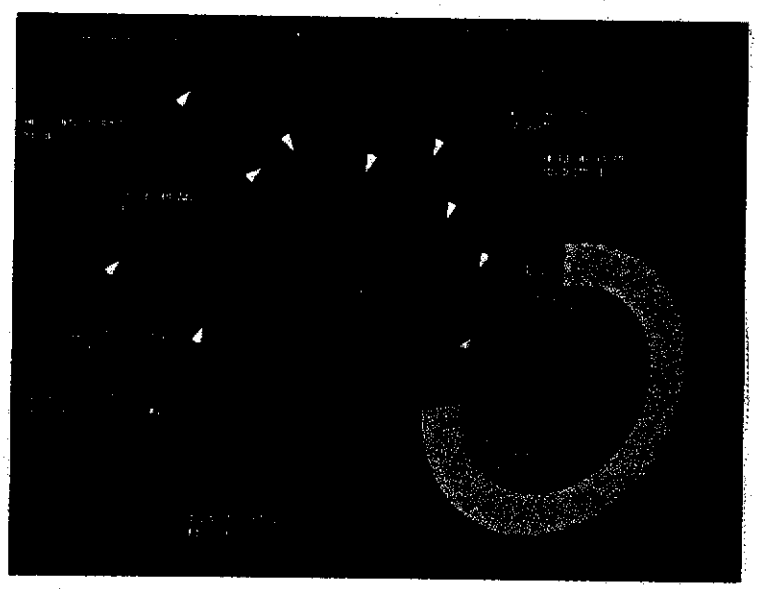
**BALL BEARINGS**

- Rings and cage silver coated
- Silicon nitride balls
- Lifetime ~3000 h



# Carbon and Mercury Targets for Neutrino Beams and a Muon Collider Source

## (BNL E951)



K.T. McDonald

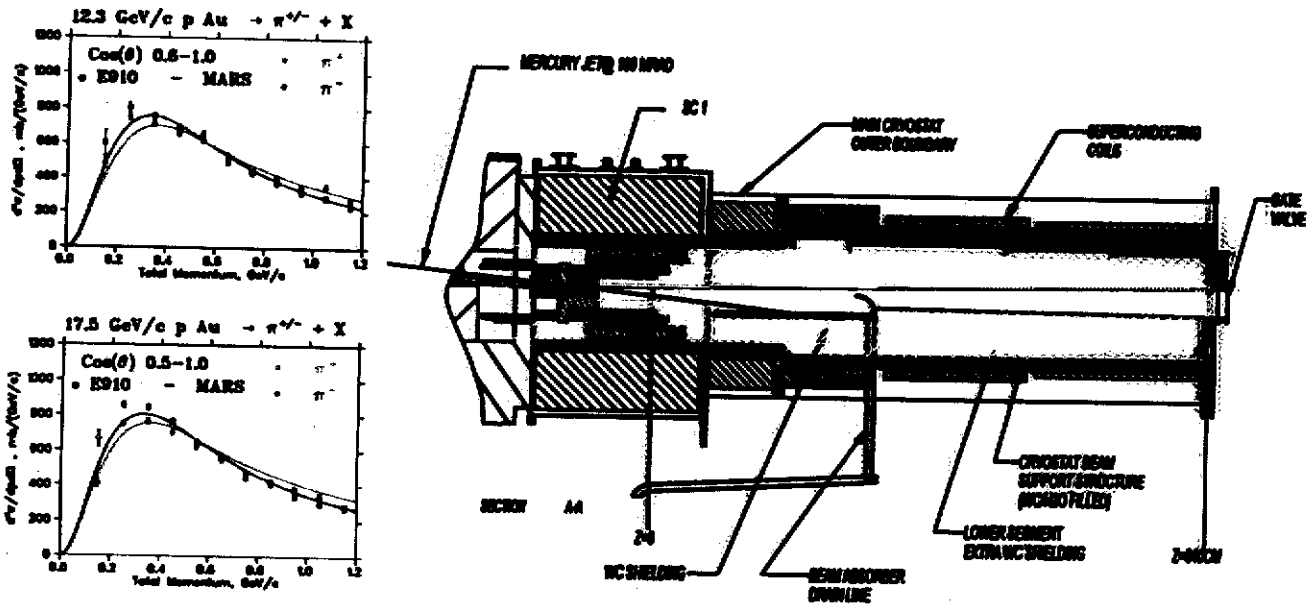
*Princeton U.*

*ICFA Workshop, Fermilab, Apr. 9, 2002*

**http://puhep1.princeton.edu/mumu/target/**

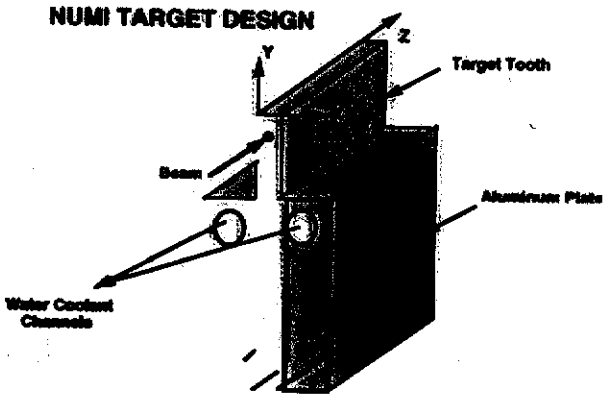
# Challenges

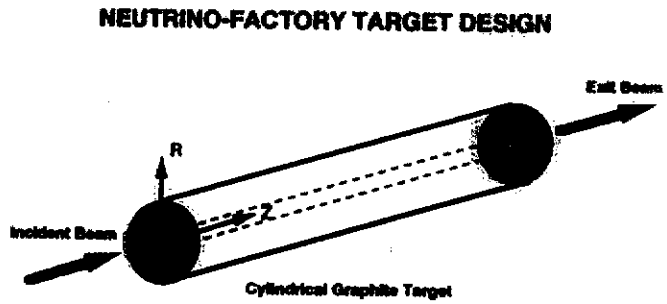
- Maximal production of soft pions → muons in a megawatt proton beam.
- Capture pions in a 20-T solenoid, followed by a 1.25-T decay channel.




- A carbon target is feasible for 1.5-MW proton beam power.
- 
- Static high-$Z$ target would melt, ⇒ Moving target.
- A free mercury jet target is feasible for beam power of 4 MW (and more).

# A Carbon Target is Feasible at 1-MW Beam Power



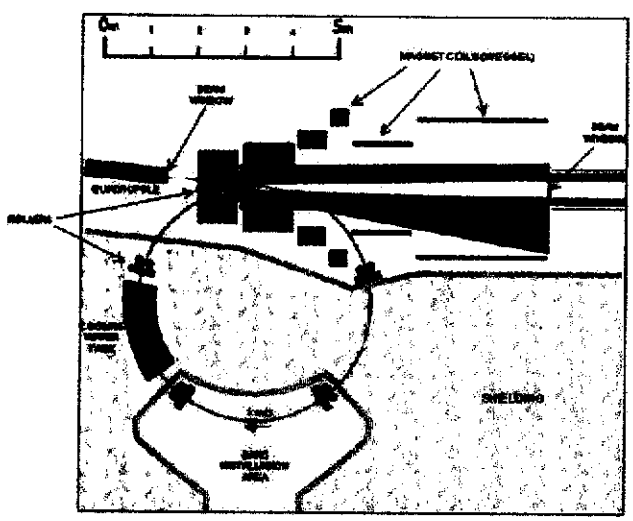

HASSANEIN (ANL)

- A carbon-carbon composite with near-zero thermal expansion is largely immune to beam-induced pressure waves.

Sublimation of carbon is negligible in a helium atmosphere.

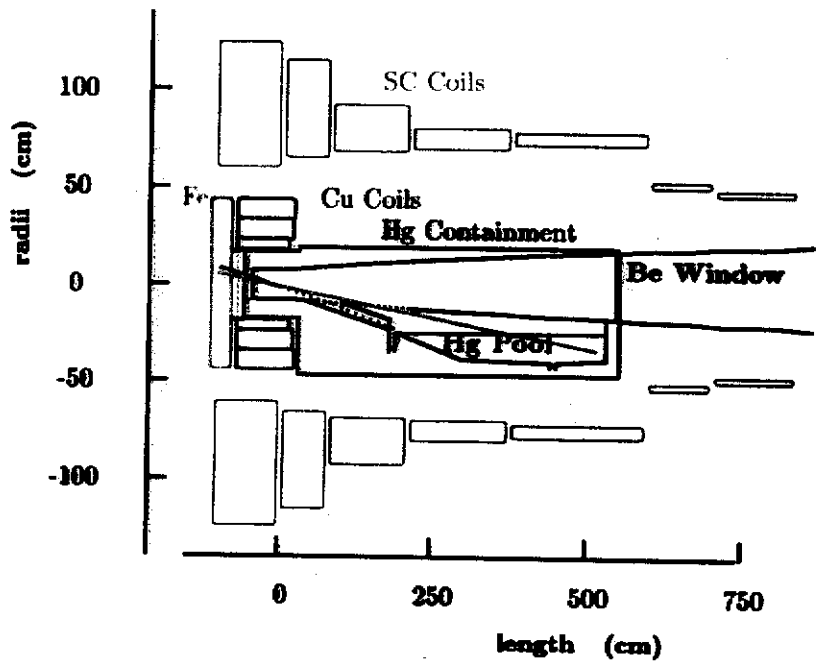
Radiation damage is limiting factor: $\approx$ 12 weeks at 1 MW.

A rotating band target is another option:

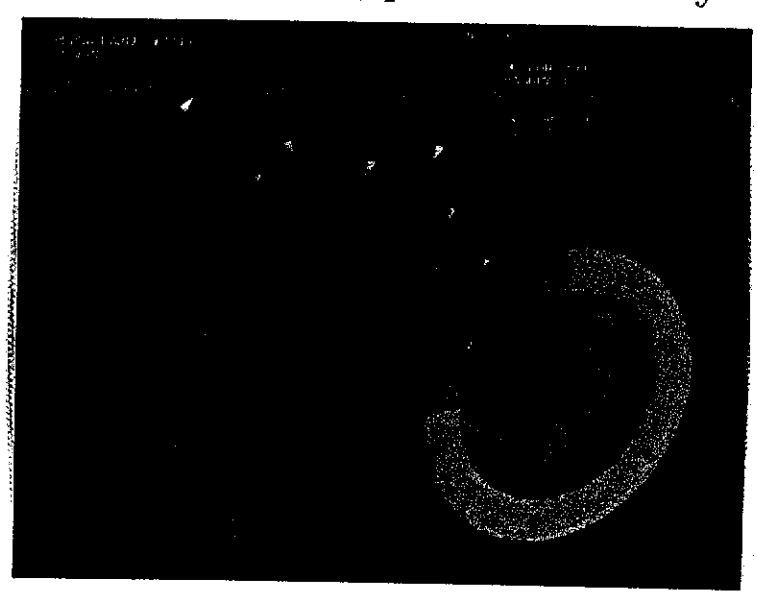


# Target System Layout

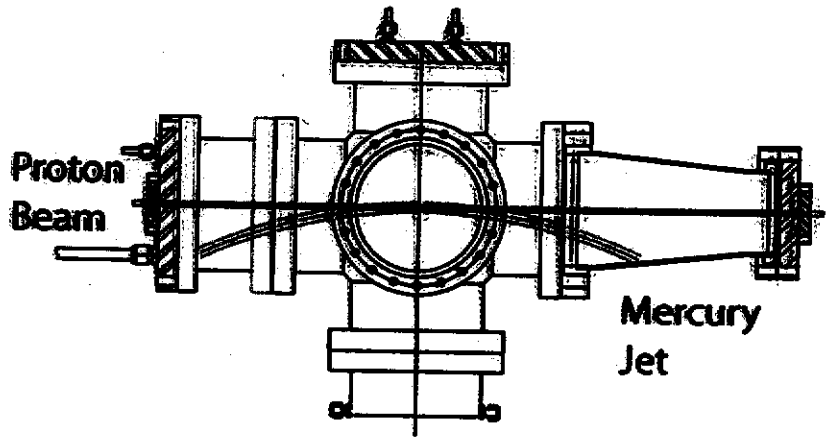
- Mercury jet target inside a magnetic bottle: 20-T around target, dropping to 1.25 T in the pion decay channel.



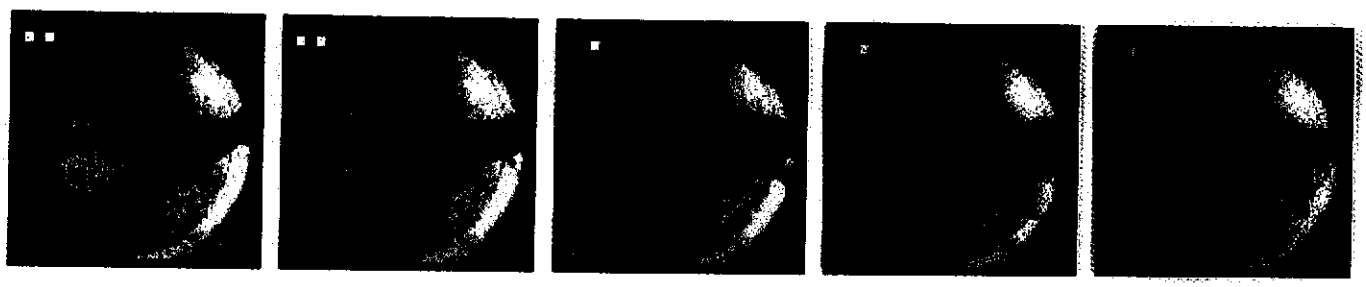

Mercury jet tilted by 100 mrad, proton beam by 67 mrad.



# Studies of Proton Beam + Mercury Jet




1-cm-diameter Hg jet in 2e12 protons at $t = 0, 0.75, 2, 7, 18$ ms.



Model: $$v_{\text{dispersal}} = \frac{\Delta r}{\Delta t} = \frac{r\alpha\Delta T}{r/v_{\text{sound}}} = \frac{\alpha U}{C} v_{\text{sound}} \approx 50 \text{ m/s}$$

for $U \approx 100$ J/g.

Data: $v_{\text{dispersal}} \approx 10$ m/s for $U \approx 25$ J/g.

$v_{\text{dispersal}}$ appears to scale with proton intensity.

The dispersal is not destructive.

# Summary of Targetry Activities Through FY01

- A target system based on a mercury jet in a 20-T capture solenoid is feasible at 1-4 MW beam power.
- Solid target alternatives include graphite rods or a rotating nickel band.
- An early upgrade to 4-MW may be the quickest path to higher neutrino fluxes.
- Continued R&D is needed. The next step is a combined test of a mercury jet in a proton beam and in a 20-T pulsed magnet (BNL E951 phase 2).

# NuMI target



IHEP Protvino design team

V.Garkusha, V.Zarucheisky

F.Novoskoltsev, S.Filippov, A.Ryabov, P.Galkin, V.Gres, V.Gurov, V.Lapygin, A.Shalunov, A.Abramov, N.Galyaev, A.Kharlamov, E.Lomakin, V.Zapolsky

FNAL design team

J.Hylen, K.Anderson

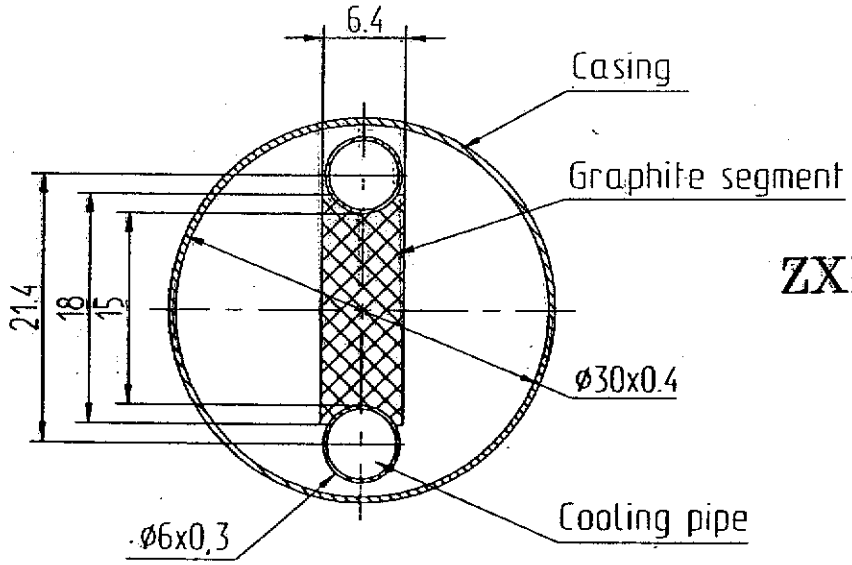
FNAL beam test

J.Morgan, H.Le, Alex Kulik, P. Lucas, G. Koizumi

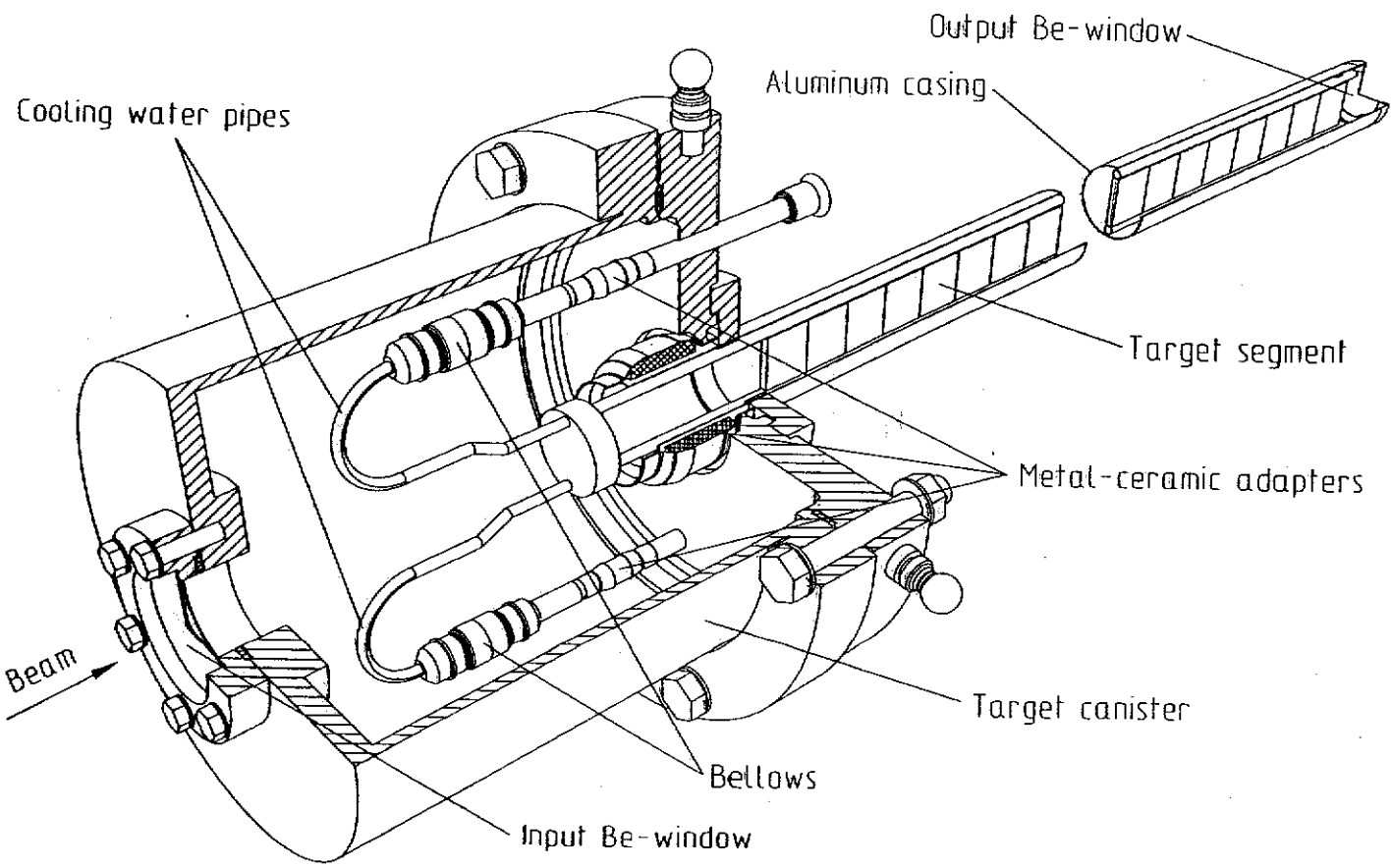
*Target construction done at IHEP*

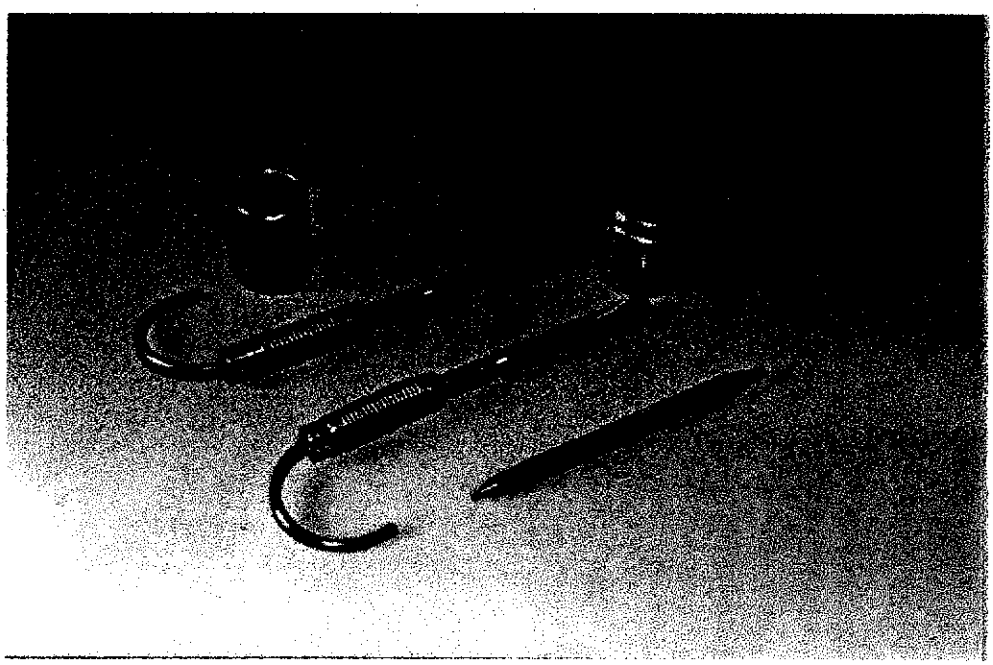
# NuMI Low Energy Target

## 3 GeV $\nu$ from 0.4 MW proton beam



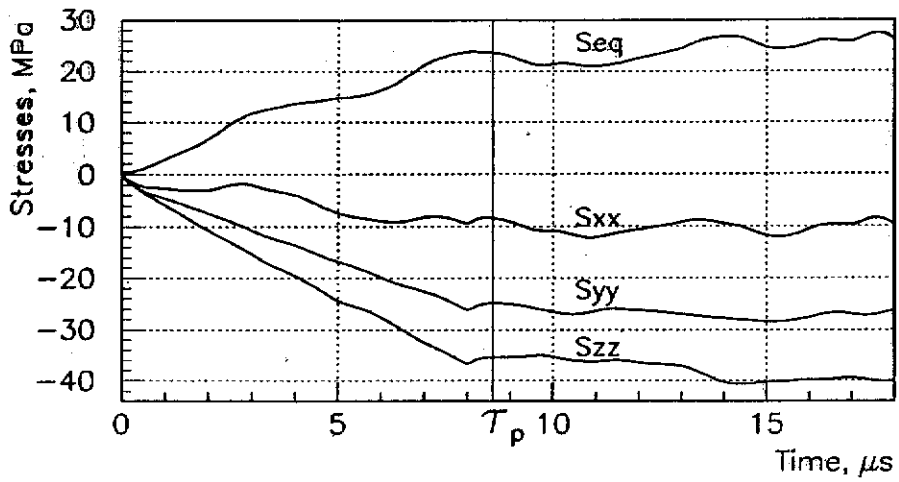

**ZXF-5Q graphite**

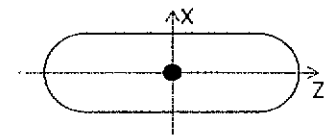




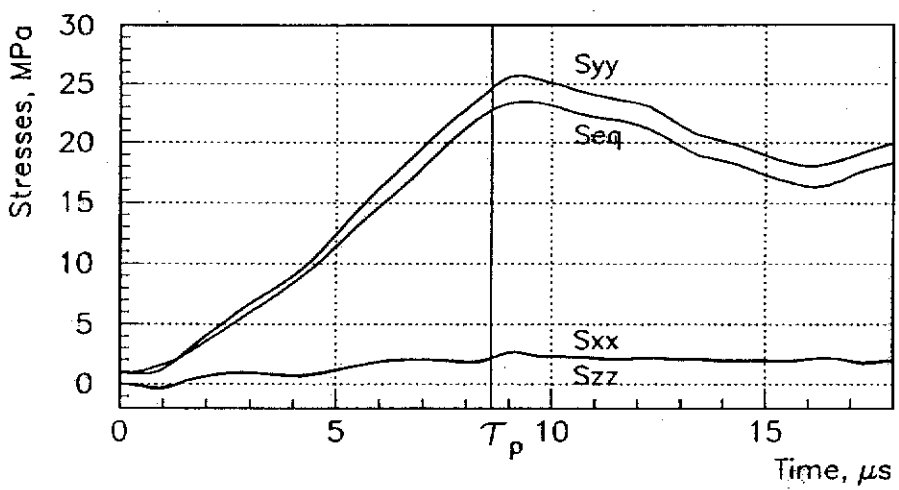
For the target segments with the highest energy deposition density (~0.095 GeV/cm$^3$/p):

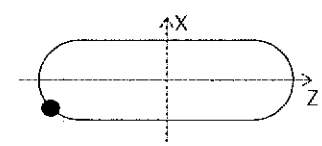
| | |
|---|---|
| Temperature before beam spill | 58.2°C |
| Temperature rise | 272°C |
| Temperature after beam spill | 330°C |




$(S_{eq})_{max} = 27.4$ MPa



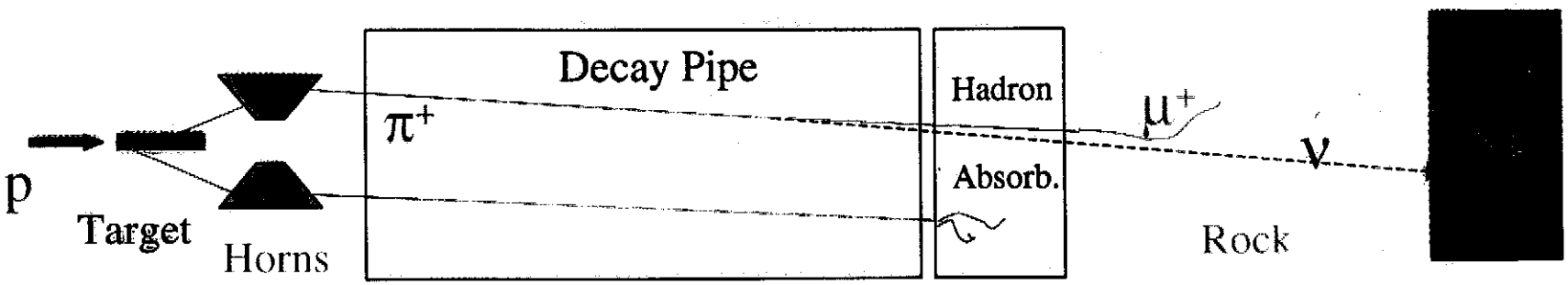

$(S_{eq})_{max} = 23.5$ MPa

ZXF-5Q (1.81 g/cm$^3$): Compressive Strength 210 MPa
Tensile Strength 95 MPa

The high cycle fatigue endurance limit of graphite is 0.5–0.6
The safety factor is $\frac{(0.5-0.6)\times 95}{23.5} \sim 2.2$

# Neutrino Beam Production

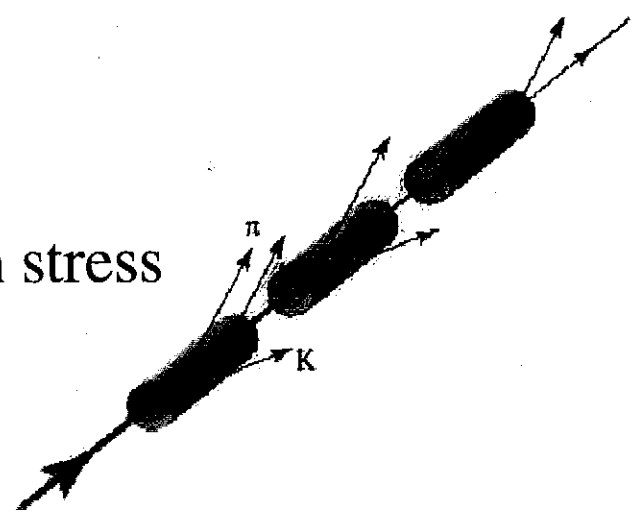
120 GeV protons hit target produce $\pi^+$ which decay to $\mu^+\nu$



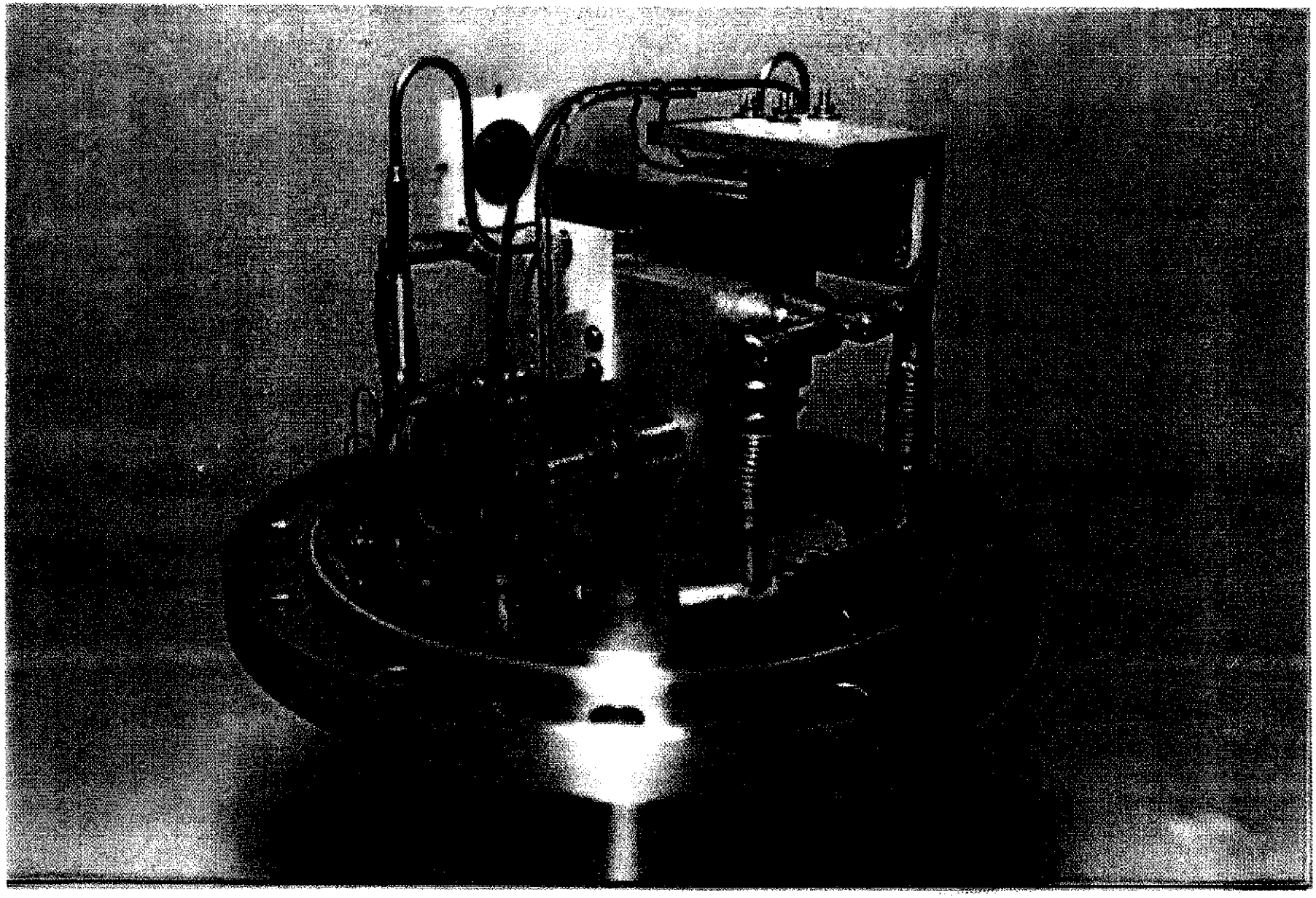

Narrow target lets $\pi$ escape out sides

*but*

Small p-beam spot size -> high stress



# NuMI Prototype Target for Beam Test

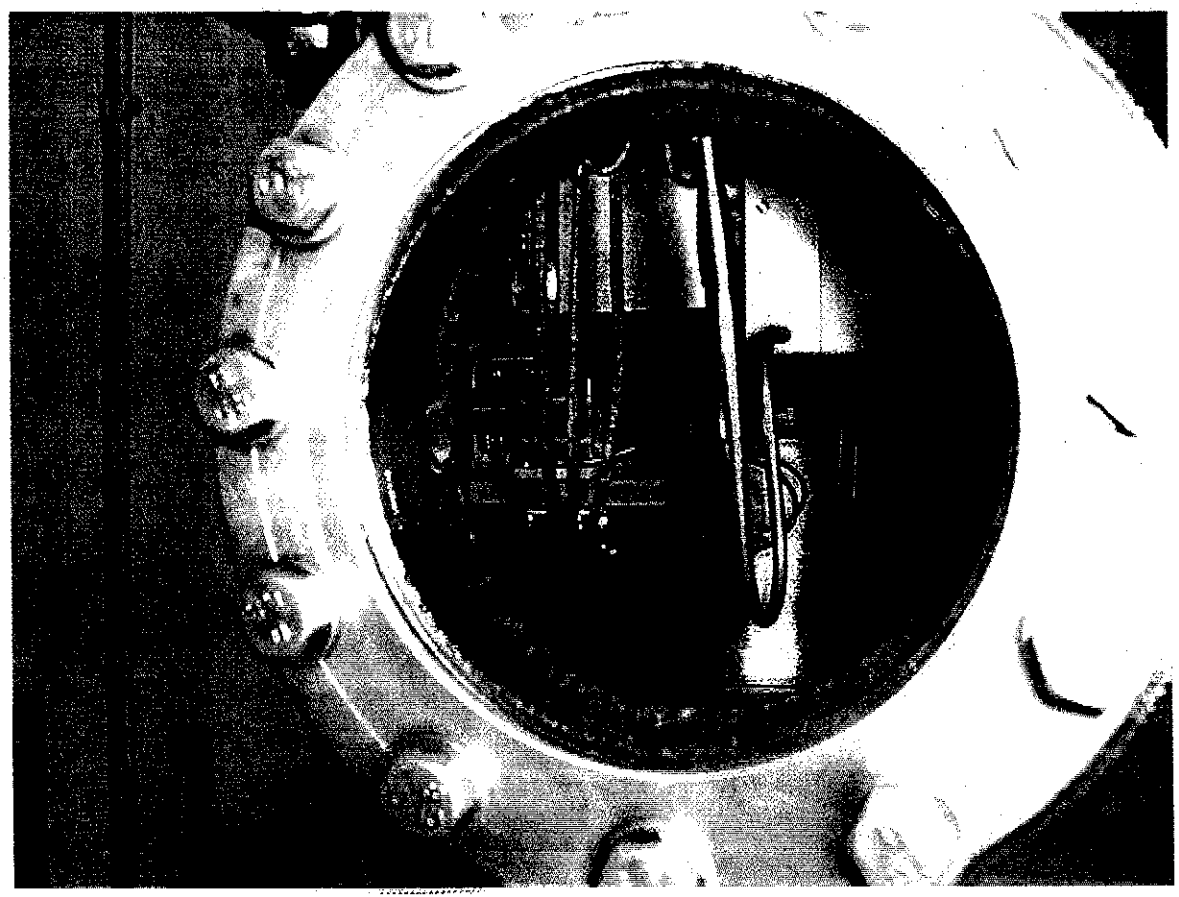


# Prototype Target Test



Target teeth show no damage after
$7 \times 10^{17}$ protons

$3 \times 10^{5}$ pulses
$2 \times 10^{18}$ protons/mm$^2$
( about 1 NuMI
design week )



Max. stress pulses:
$1 \times 10^{13}$/pulse
0.2 mm RMS spot

( NuMI Design:
$4 \times 10^{13}$/pulse
0.9 mm RMS spot )

# Targetry issues for the Fermilab 2 MW neutrino superbeam

Mikhail Kostin, Valeri Balbekov,
Nikolai Mokhov
Fermilab

# Criteria for target



1) Survives one spill

2) Steady state temperature is low

3) Life time > 6 months

4) In the case of multiple choice for target candidates will optimize the pion yeild in the energy interval of our interests.

$$E_\nu = \frac{0.43\ E_\pi}{1+\gamma^2\theta^2}$$

- On-axis experiment $E_\pi$ =5.8-8.2 GeV
- Off-axis experiment $E_\pi$ =5.8-20 GeV

# First trial: Target



- 120 GeV p beam

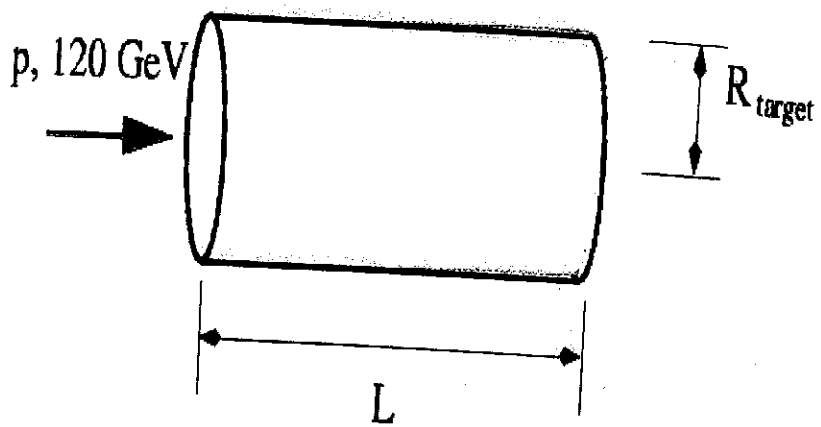
  $\sigma(x) = \sigma(y) = 1.0$ mm

  No angle diversions

- Rod target

  $R_{target} = 2.5$ mm

  $L = 2\,\lambda(\mathrm{Int})$




- Repetition period 1.9 sec.

- $I = 2*10^{14}$ protons/spill = 5 * NuMI beam intensity

# First trial: What material ?

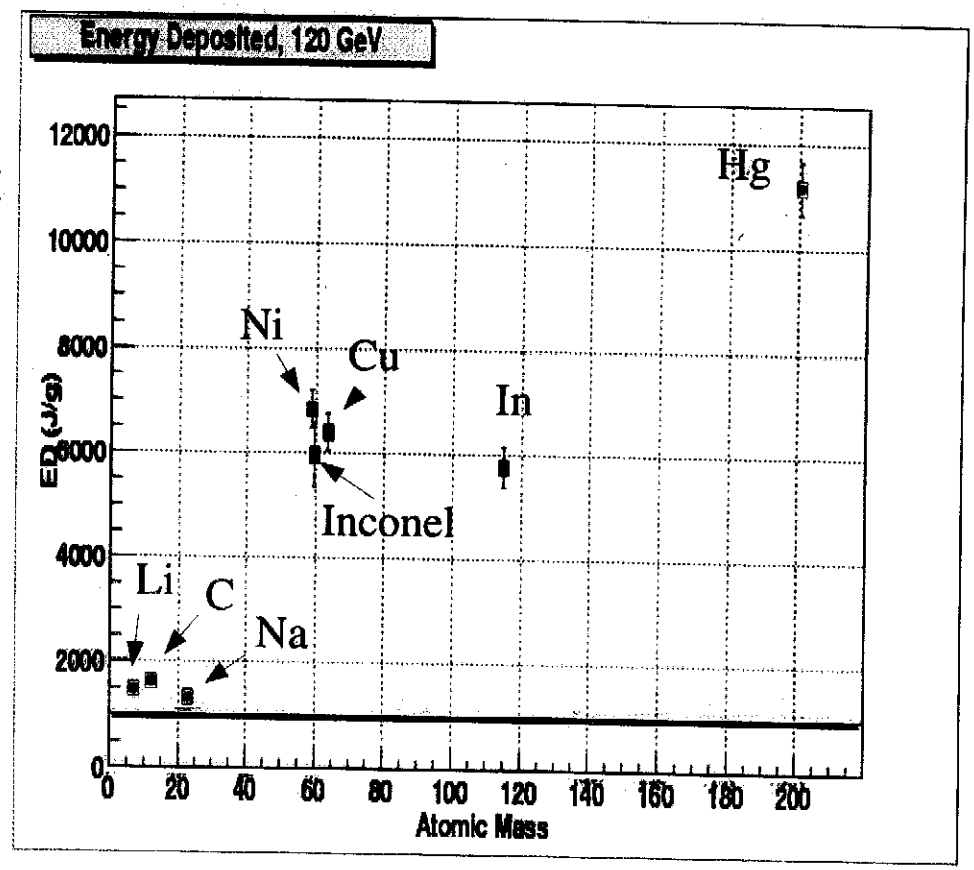


ED limit (C) ~ 1000 J/g
ED limit (Cu) ~ 600 J/g
ED limit (Inconel) ~1000 J/g

**Results:**

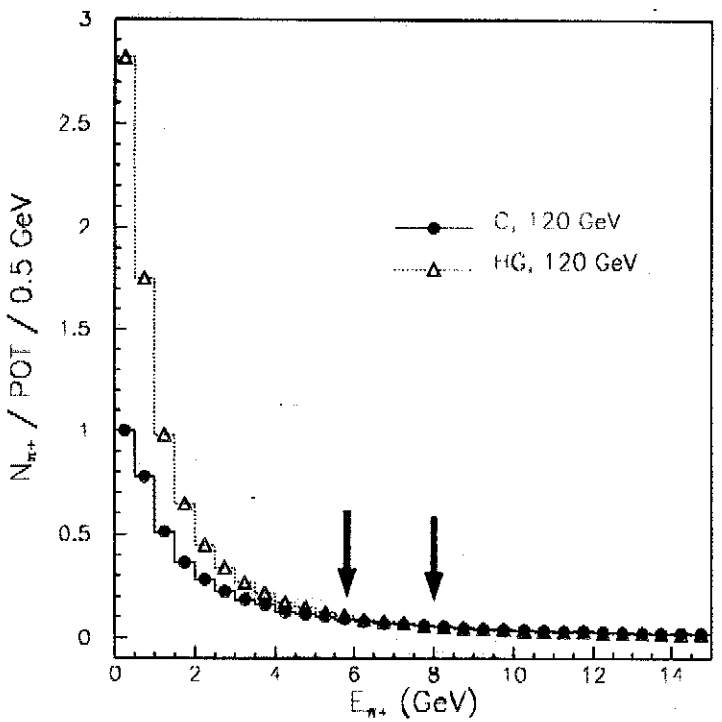
- ED is too high
- $\Delta$ T is very high

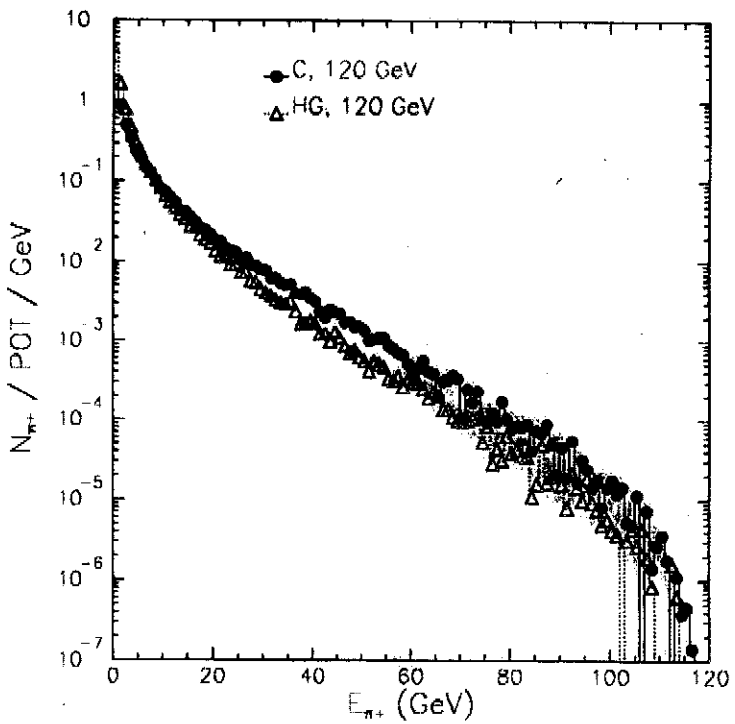
None of materials survives



# First trial: C or Hg ?





# First trial: C or Hg ?



Assume that can focus all pions

- For on-axis beam Hg is not much (any?) better than C
- For off-axis beam C might work even better

# How to survive 2 MW ?

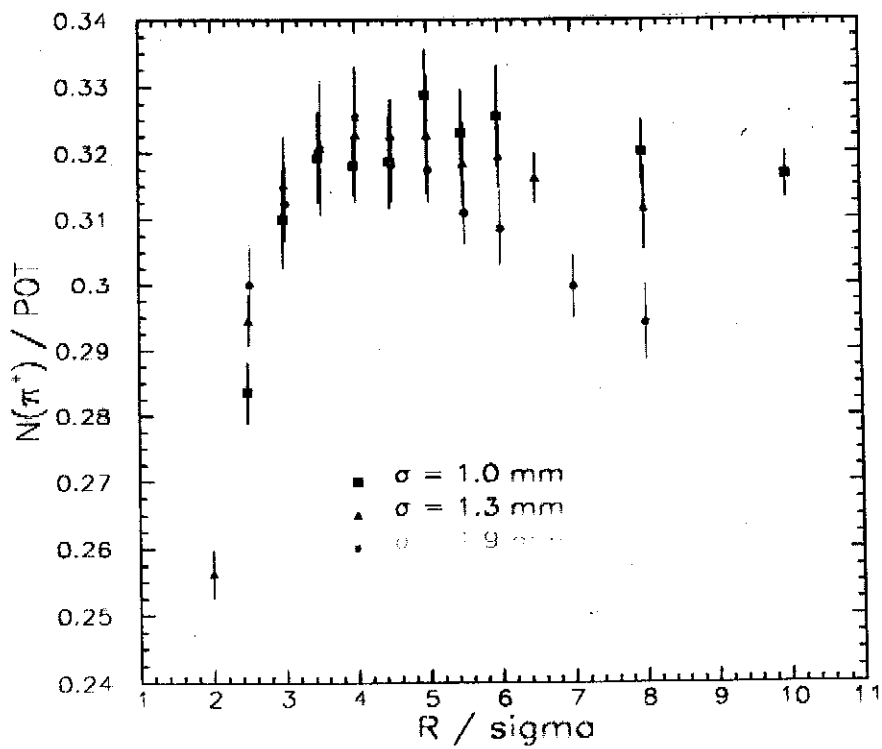


- Beam sweeping
- Extraction of one bunch at a time
- Increase beam size and target size
- ...

# Increased beam/target size for C

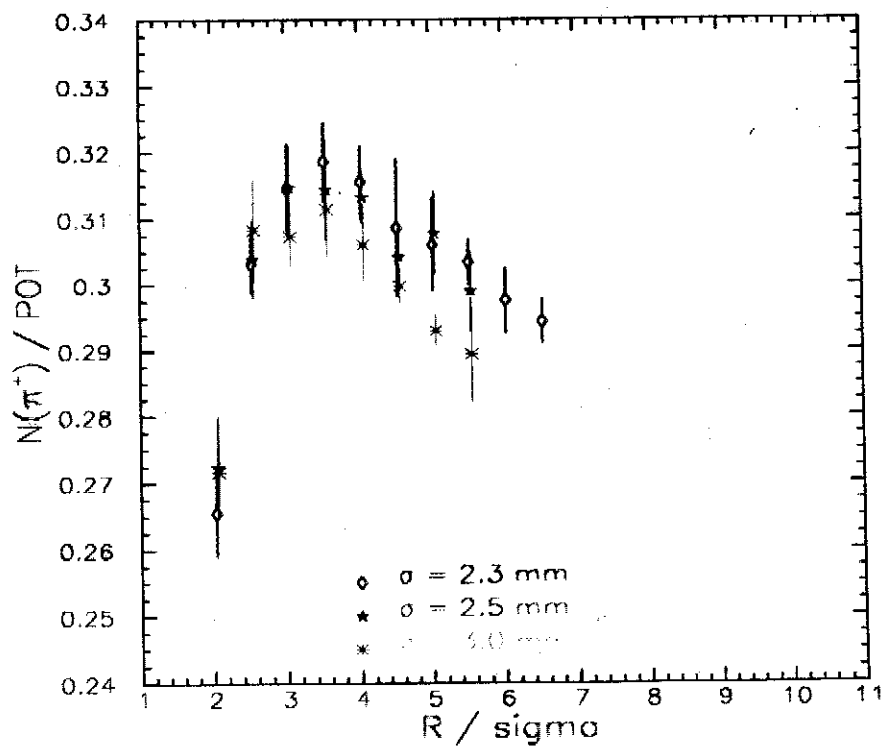


- C rod target
- 40 π emittance
- 120 GeV protons



# Increased beam/target size for C





# Conclusions

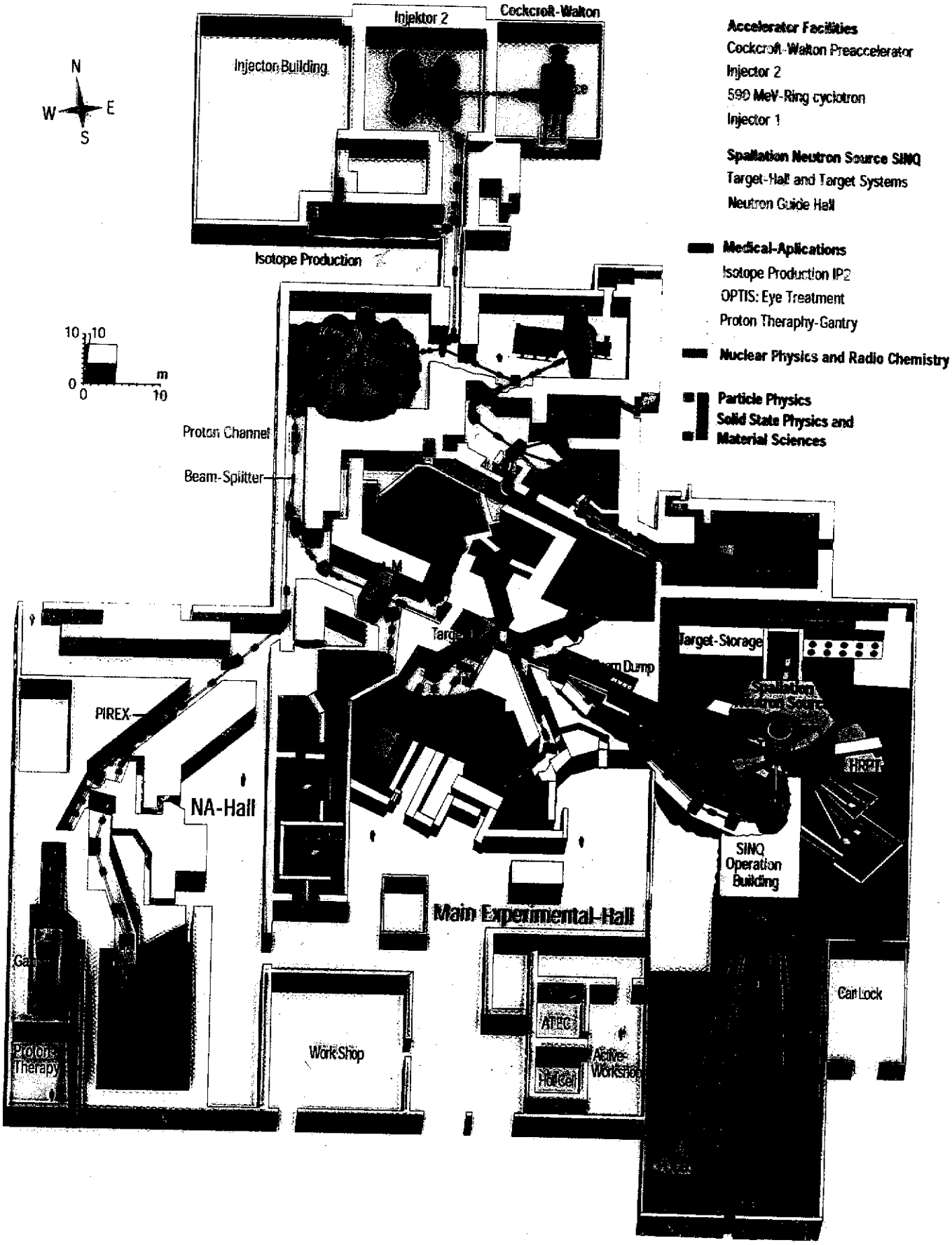
- Wide graphite target and wide beam is OK for a 2 MW facility.
  - Survives one spill
  - Believe the steady state T is low (ANSYS is under way)
  - Life time ~ 5.6 years ( 10 months of operation per year)
  - Pion yeild is quite optimal

# SNS Transfer Lines

D. Raparia, YY Lee, J. Wei

April 8-12, 2002

# Proton Accelerator Facilities of the Paul Scherrer Institute



# ISSUES

- VERY HIGH PROTON POWER
- UNPRECEDENTED NUMBER OF PROTON ACCUMULATION 2 X $10^{14}$
  - LOSS AND COLLIMATION
- HANDS ON MAINTENANCE
  - LIMIT LOSS TO < 1 WATT / m ($10^{-4}$ LOSS)
- STRICT PROTON DISTRIBUTION REQUIREMENTS AT THE TARGET
  - INJECTION PAINTING
- RELIABILITY, AVAILABILITY AND MAINTAINABILITY

# Requirements For HEBT

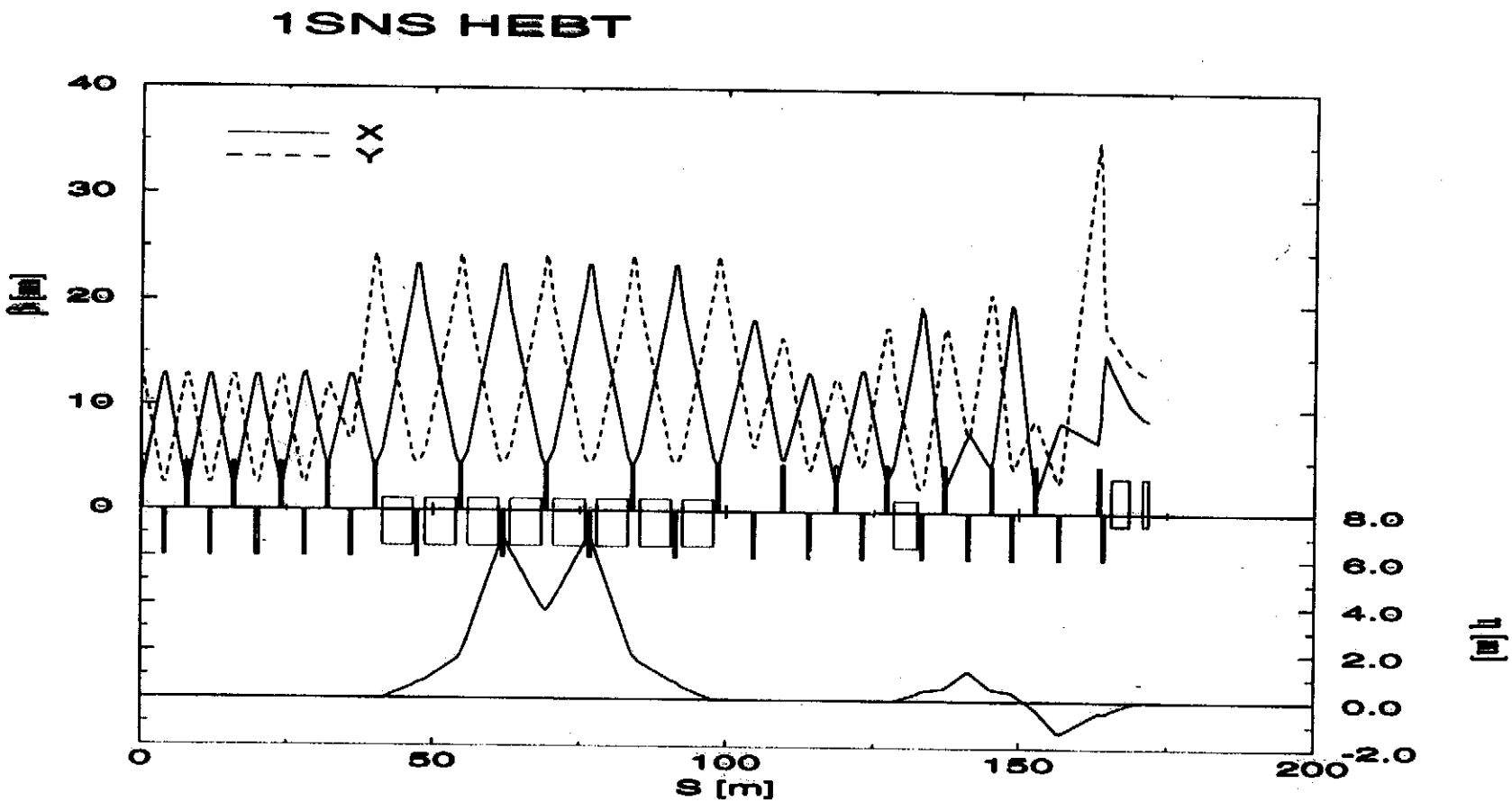
- Matching from Linac to Ring
- Low Uncontrolled Beam Losses (<nA/m)
- Beam Characterization
- Detect Fault Conditions to Protect Ring

| | Linac | Ring | |
|---|---|---|---|
| Transverse Emit.(rms, Nor) | <0.5 | <0.5 | pi mm mr |
| Energy Centroid Error | +- 1.5 | <0.2 | MeV |
| Energy Spread | +- 0.3(rms) | +- 4 (Full) | MeV |
| Beam Chopper Gap | <1.0E-4 | <1.0E-4 | |

# Functions of HEBT
# More Than a Transfer Line !

- Optical and Dispersion Matching to Ring
- Linac Energy Jitter Correction
- Increase Energy Spread (ARMS)
- Characterization of the Linac Beam( L-Dump )
- Cleans Halo, Protect Ring Injection
- Cleans momentum tail from linac
- Diagnostics

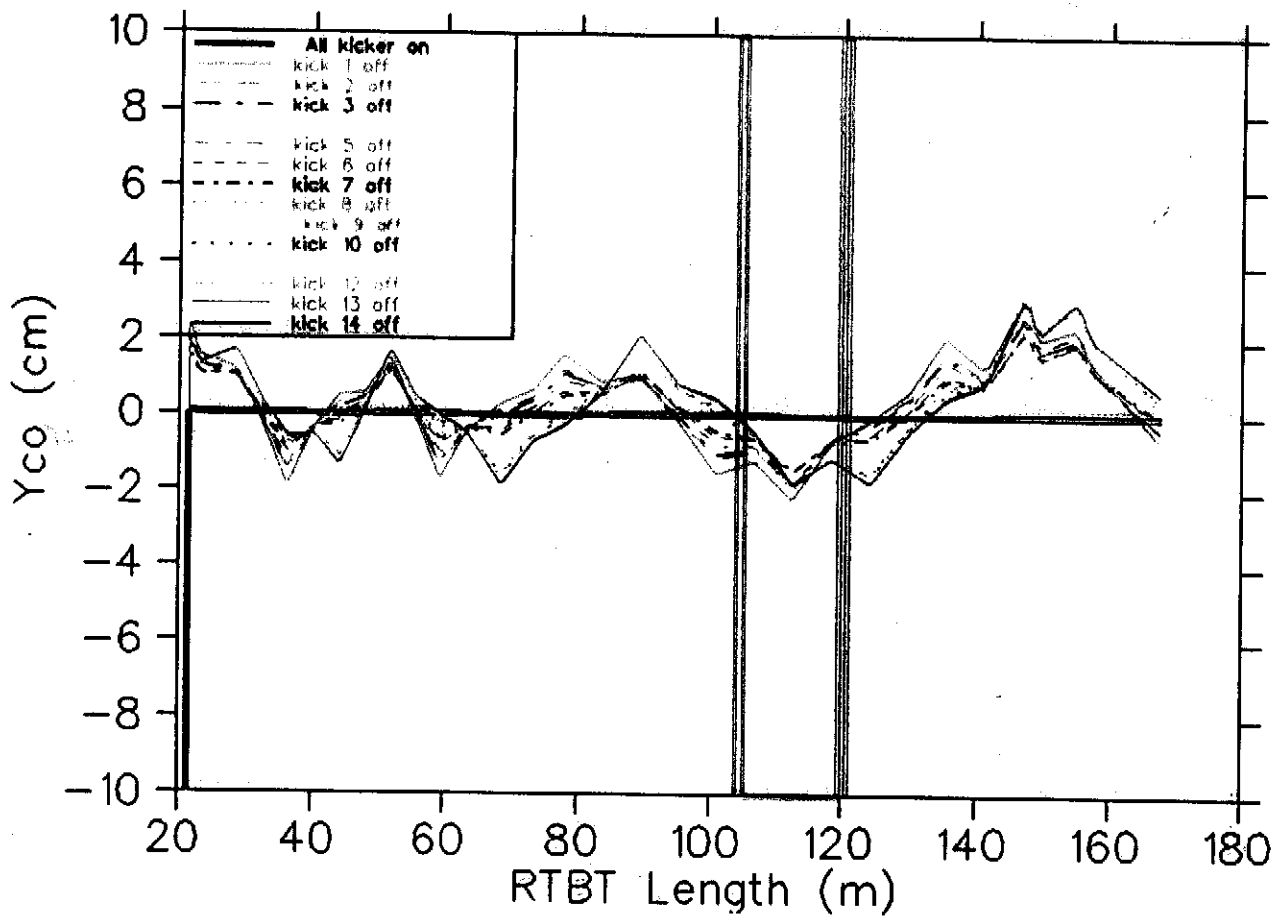
# Transport Output for HEBT



# Functions of RTBT

- Extraction (6 cells, 90°/cell)
- Extraction Beam Dump (Two quads )
- Transport (6 cells/ 90°/cell)
- Beam Spreader ( Last 5 quads)
- Minimize the Beam motion on the target in case of one or two kickers fails
- Diagnostics

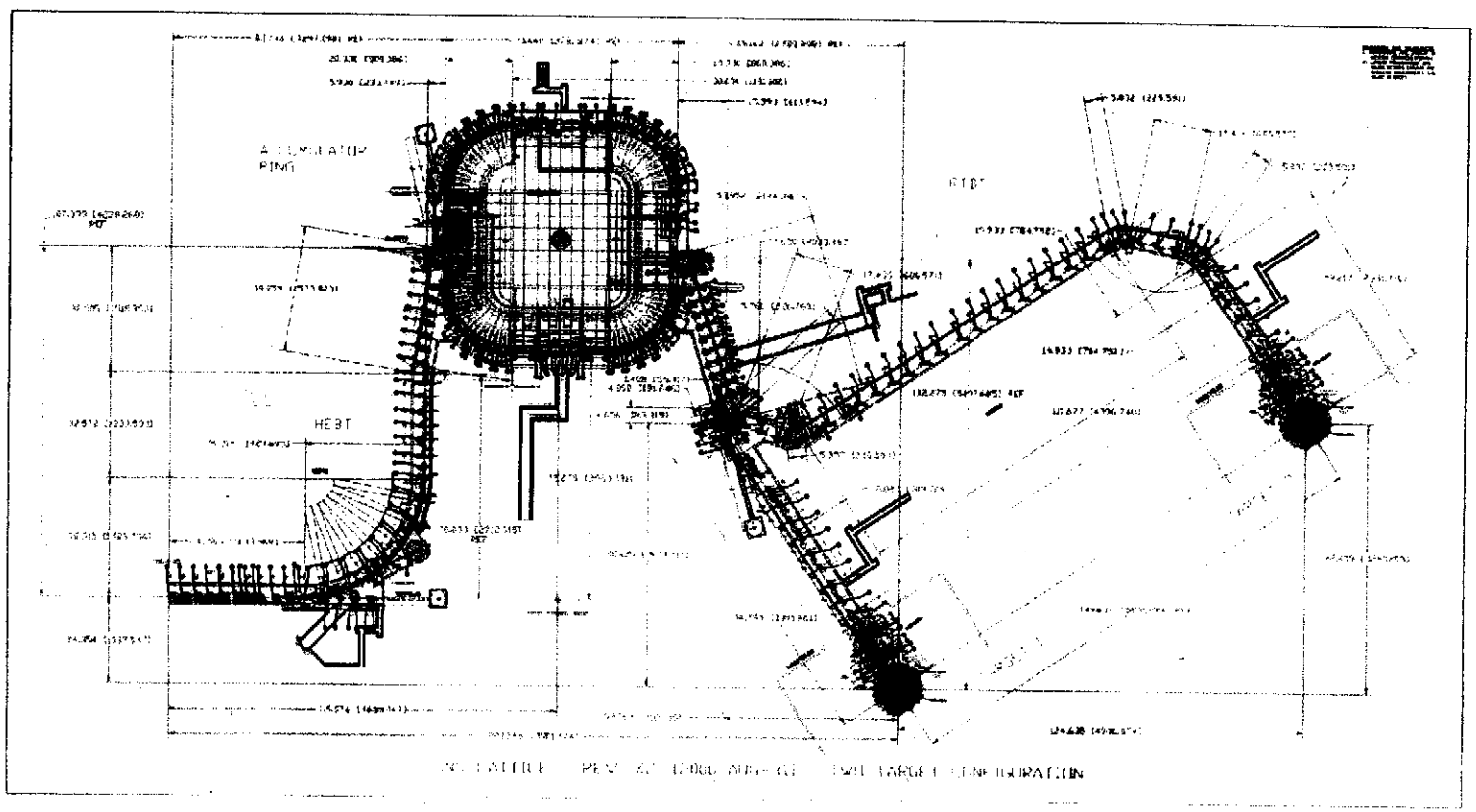
# Target Beam Position Immune to Kicker Failure



# Summary

- Linac/Ring Interface:
  - No major concerns
  - Collimation, energy correction and energy spread are the unique feature of this line
- RTBT/Target Interface:
  - The beam position on the target is immune to case one or two kickers failure
  - Compromise between beam spread on target and low losses in the ring are still under study

# Transfer Lines & Ring



# BOOSTER INTEGRATED INTENSITY

| YEAR | INTENSITY (1E19 PROTONS) |
|---|---|
| 1973 | |
| 1974 | 1.48 |
| 1975 | 1.95 |
| 1976 | 2.33 |
| 1977 | 3.00 |
| 1978 | 2.51 |
| 1979 | 3.25 |
| 1980 | 1.36 |
| 1981 | 2.00 |
| 1982 | 2.24 |
| 1983 | .00307 |
| 1984 | .131 |
| 1985 | .608 |
| 1986 | .152 |
| 1987 | 1.31 |
| 1988 | .737 |
| 1989 | .557 |
| 1990 | .501 |
| 1991 | .725 |
| 1992 | 1.07 |
| 1993 | .971 |
| 1994 | 1.36 |
| 1995 | 1.68 |
| 1996 | .871 |
| 1997 | 1.133 |

3.2 E 20

MINOS 4 E 20/yr.

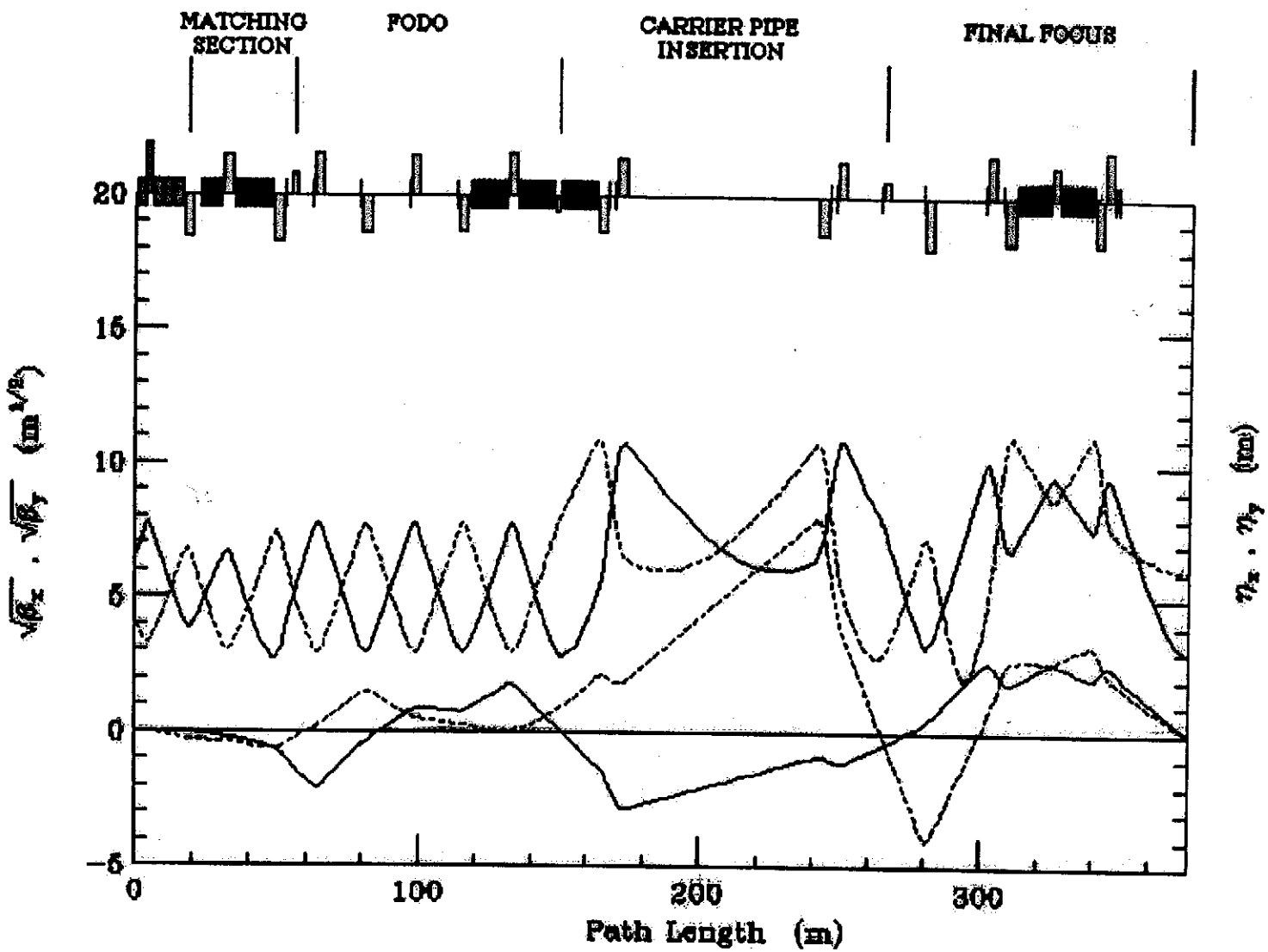
MiniBooNE 5 E 20/yr.

# Tails of beam distribution

D. Jensen, G.M. Koizumi, V. Makeev, A. Marchionni Fermilab
B.C. Choudhary CalTech

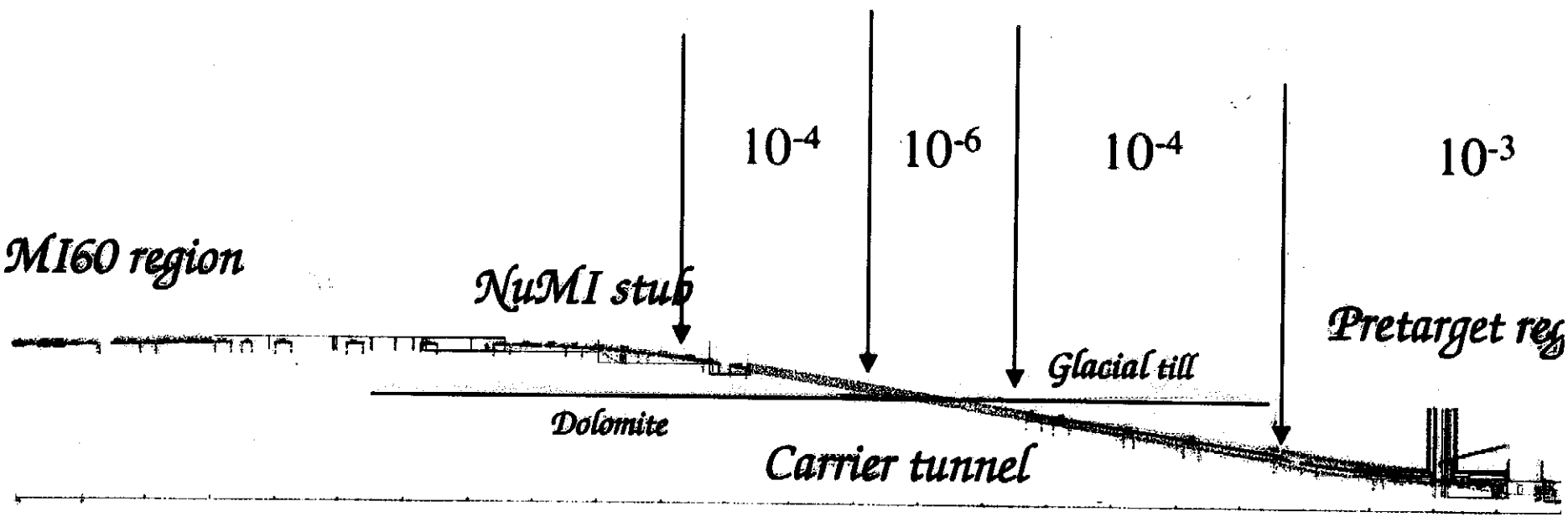
- Need for a measurement of beam tails in the extracted beam from the Main Injector
  - NuMI project
  - primary proton line
- Characterization of MI beam parameters
- Use of the present P1 extraction line to measure transverse tails of the beam and the contribution due to momentum spread

# NuMI primary proton line

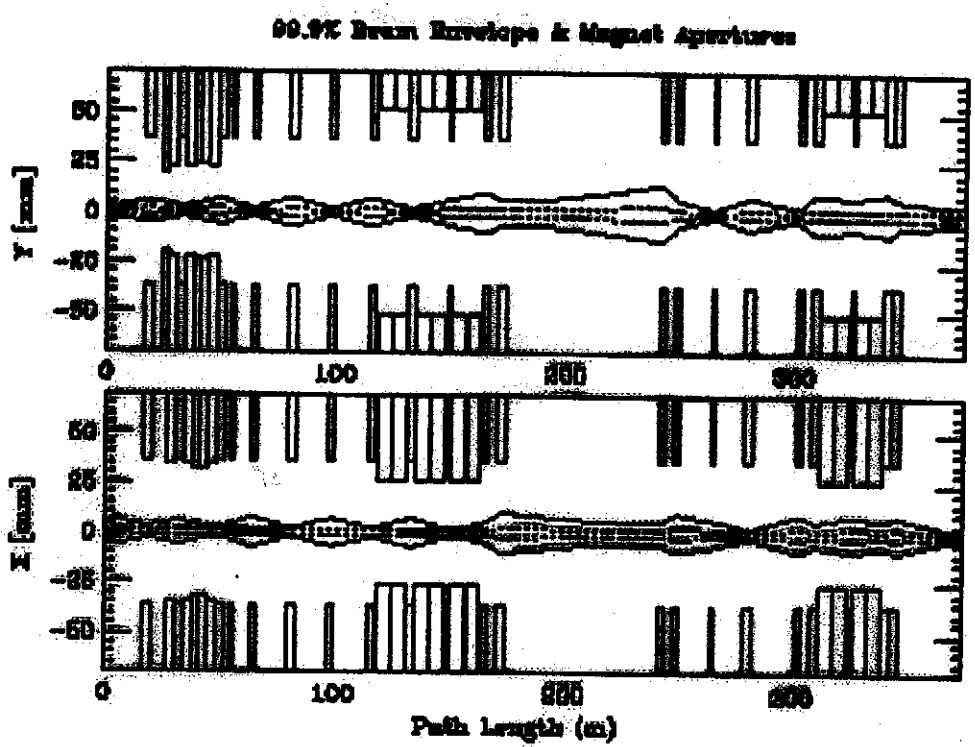


# NuMI primary proton line

Allowable dc fractional proton losses (4 $10^{13}$ ppp) for groundwater protection



# NuMI primary proton line aperture




99.9% beam envelope

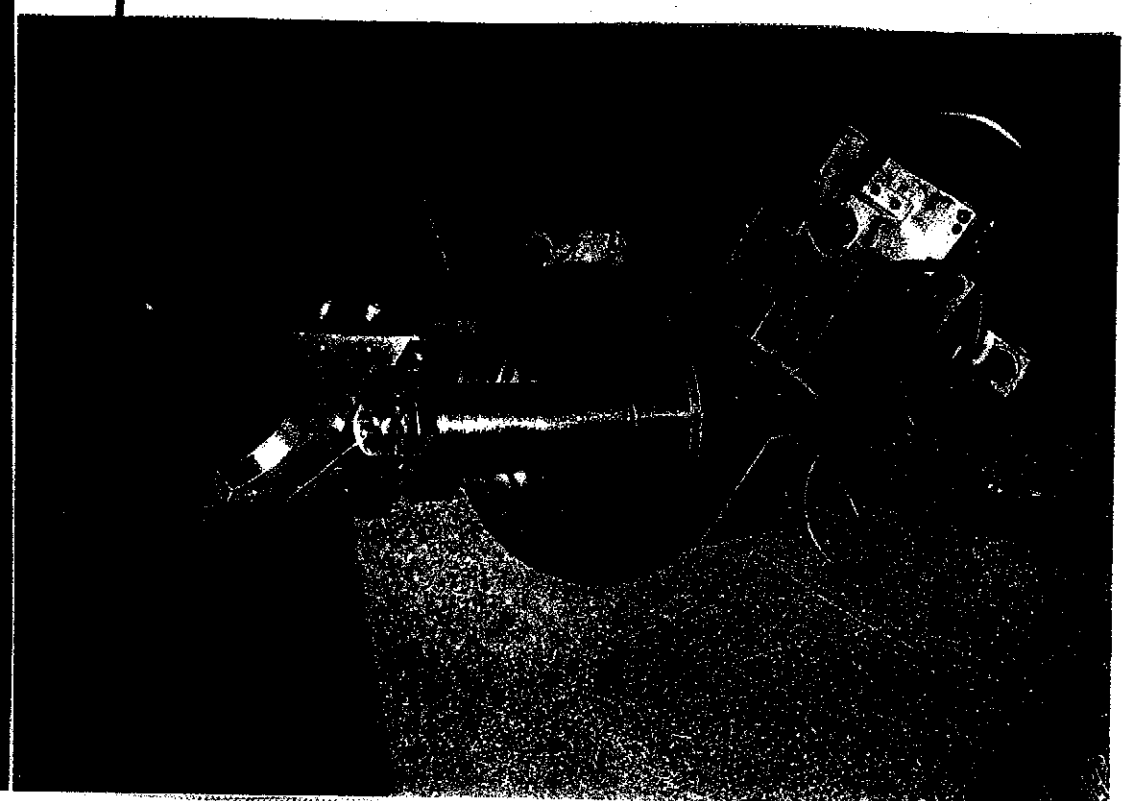
$\varepsilon_{95\%} = 40\ \pi$

$\delta p_{95\%}/p = 7 \times 10^{-4}$

… but what about beam tails ?

# Scanning target

The target: tungsten, 100 μm thick,
1 cm long in the beam direction,
10 cm in the transverse direction



# Conclusions

- MI beam characteristics have been measured, but …
- knowledge of tails of beam distribution is essential for the NuMI project
- Work in progress
  - measurements of beam profiles by scraping beam and recording losses
  - use of 3-bumps and scanning targets
  - compare profiles at locations with small and large dispersion

Fermilab
Beams Division
NuMI Project

# "SOPHISTICATED" BEAM PERMIT SYSTEM

ROBERT J. DUCAR

FERMILAB

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NuMI Department
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# Why?

We Don't Want to Introduce Beam to the Accelerator Complex Unless It Is Wanted (TLG and Operators)

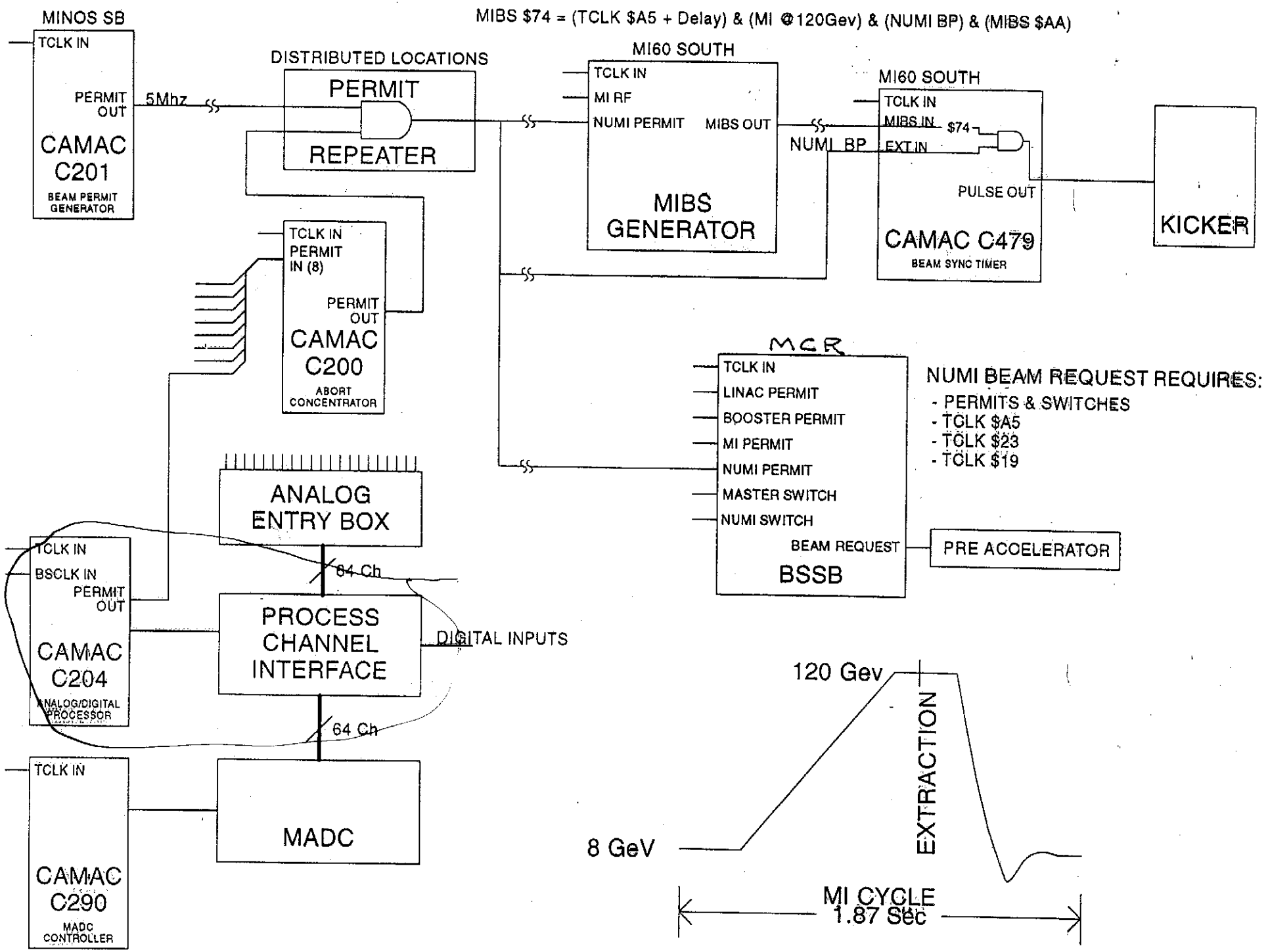
We Don't Want to Introduce Beam Unless the Path to the Destination Is Clear (Beam Permits)

# How?

Beam Switch Sum Box

Accepts TCLK (Scenarios)
Accepts Beam Permits
Accepts Operator Input (Switches)

Sources Pulse Shift Command to Source


MIBS $74 = (TCLK $A5 + Delay) & (MI @120Gev) & (NUMI BP) & (MIBS $AA)
MINOS SB
TCLK IN
PERMIT OUT
CAMAC C201
BEAM PERMIT GENERATOR
5Mhz
DISTRIBUTED LOCATIONS
PERMIT
REPEATER
MI60 SOUTH
TCLK IN
MI RF
NUMI PERMIT
MIBS OUT
MIBS GENERATOR
NUMI BP
MI60 SOUTH
TCLK IN
MIBS IN
$74
EXT IN
PULSE OUT
CAMAC C479
BEAM SYNC TIMER
KICKER
TCLK IN
PERMIT IN (8)
PERMIT OUT
CAMAC C200
ABORT CONCENTRATOR
MCR
TCLK IN
LINAC PERMIT
BOOSTER PERMIT
MI PERMIT
NUMI PERMIT
MASTER SWITCH
NUMI SWITCH
BEAM REQUEST
BSSB
NUMI BEAM REQUEST REQUIRES:
- PERMITS & SWITCHES
- TCLK $A5
- TCLK $23
- TCLK $19
PRE ACCELERATOR
ANALOG ENTRY BOX
64 Ch
TCLK IN
BSCLK IN
PERMIT OUT
CAMAC C204
ANALOG/DIGITAL PROCESSOR
PROCESS CHANNEL INTERFACE
DIGITAL INPUTS
64 Ch
TCLK IN
CAMAC C290
MADC CONTROLLER
MADC
120 Gev
8 GeV
EXTRACTION
MI CYCLE
1.87 Sec

# NuMI BEAM PERMIT INPUTS - SUMMARY SHORT LIST

**4-Sep-01**

| DESCRIPTION | QTY | EXPANDED LIST | COMMENT |
|---|---|---|---|
| Safety System | 1 | NuMI Radiation Safety System | Available at MI-60N |
| Main Injector Performance | 3 | Beam Quality, Bunch Length, No P-Bar Beam | Beam Quality to Include RF and Radial Position As Nominal |
| Special Supplies | 2 | Kicker and Horn | Operational Status and Cap Bank Voltage |
| Bend Supplies | 7 | LAM60, V100, HV101, V104, V105, V109, V110 | Operational Status and Current |
| Quad Supplies | 10 | Q101 thru Q110 | Operational Status and Current |
| Correctors | 12 | HT and VT 102, 103, 105, 107, 108, 110 | Operational Status Only |
| Profile Monitors | 7 | PM103, 104, 105, 107, 108, 110, 111 | Must Not be Between IN and OUT Positions |
| Loss Monitors | 39 | 35 Sealed BLMs and 4 Total Loss Monitors | Test After Extraction and Possibly Before |
| Vacuum | 6 | Beamline and Decay Pipe Pressure, 4 Valve Positions | Pressure Nominal and Valves Open |
| Water Systems | 6 | MI-62 LCW, Target and Baffle RAW, Horn 1 RAW, Horn 2 RAW, Absorber RAW, Decay Pipe RAW | System Operation Nominal |
| Temperature | 5 | Downstream Baffle, Target, Horns and Absorber | Thermocouple Information |

# E-berm

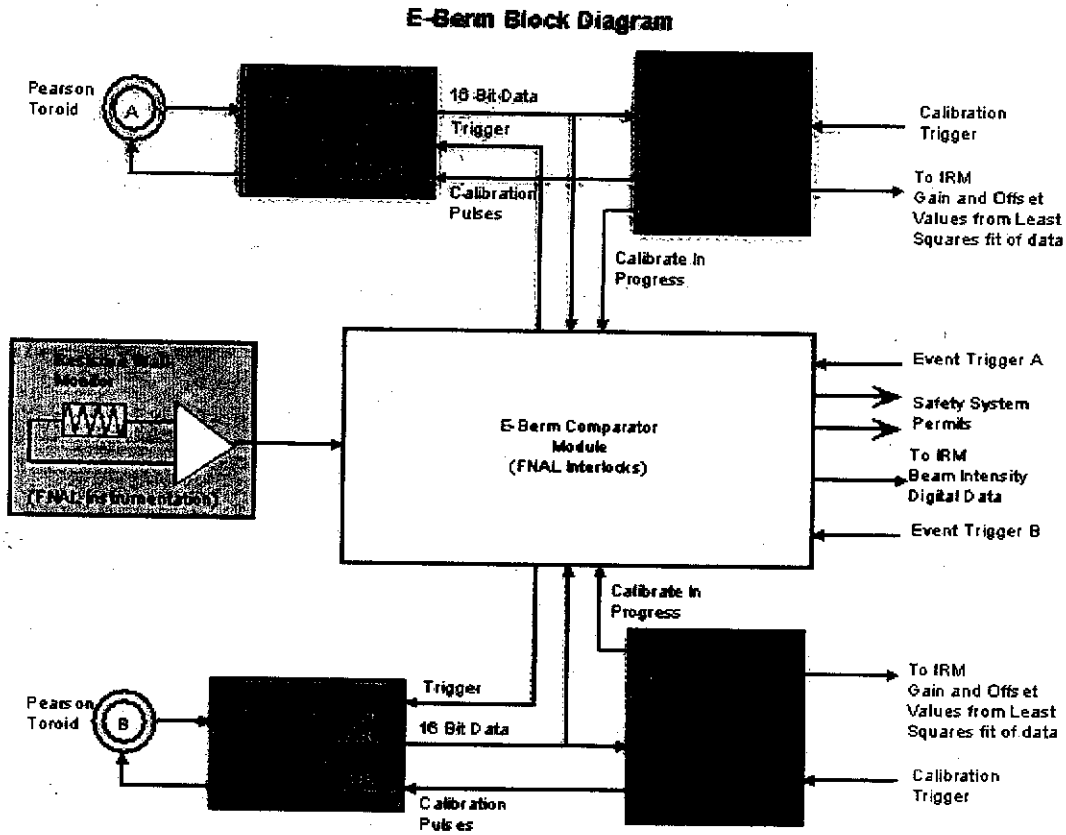
# Electronic Berm Interlock Module

## Functional Description

John Anderson Jr.
Glenn Federwitz
April 10, 2002

**20th ICFA Advanced Beam Dynamics Workshop**
**High Intensity High Brightness Hadron Beams**
**Fermilab**
**April 8 - 12, 2002**

# System Implementation




The diagram above shows a block diagram of the E-berm system. There are four major components to the system; the toroid and integrator electronics, the calibration module, the beam presence detector (resistive wall monitor), and the comparator module. The focus of this document is on the comparator module with a brief description of the other three components.

## Last 10 Sum:

This block adds the current value of the difference engine to a running total and stores the value in a 10 deep by 16-bit shift register. The value that gets shifted out of the memory is then subtracted from the total. Thus generating a sum of the last 10 beam samples to be used for subsequent comparisons.

## Pulse to Pulse Comparison:

The absolute value of the difference between integrator A and integrator B is compared to a set of switches located on the comparator board. The value of the switches for MiniBooNE is set at approximately (~3E11). This equates to 6% of the total pulse-to-pulse beam of (~5E12) per pulse. If the difference value is higher than the switch setting a trip occurs.

## Integrated Loss Comparison:

The value of the sum of the last 10 beam pulse differences is compared to a set of switches again located on the comparator board. The value of the switches for MiniBooNE is set at approximately (~1E12). This equates to approximately a 20% loss of beam for the last 10 beam pulses. Looking at this from a pulse-to-pulse basis yields an average loss of less than 2%. Again, if the value is higher than the switch setting, a trip occurs.

18000 pulses / hr

## Self Test Compare:

Between beam pulses, the integrator is triggered to take a sample with no beam present. The absolute value is then compared to a small positive value to check if the integrator has drifted away from zero. If the value gets too high, the module is tripped. This value is defined inside the EPLD s. At present, the value is set to (2.7E9) and will be defined during the commissioning process after the noise floor for the toroid integrators has been established.

## Beam Presence Detector Compare:

The Beam Presence Detector compare logic is used as a beam coincidence check with the toroid integrator electronics. If either toroid integrator reads more than 1E11 beam, then a pulse indicating beam has passed is required from the beam presence detector. The absence of this pulse, when more than 1E11 beam is detected by either of the integrator electronics, will initiate a system trip.

## Timing:

The timing block takes the ACNET event strobe signals and passes the appropriate signal on to each integrator starting a beam event timing sequence. The event timing sequence requires that the beam pulse from the Beam Presence Detector occur between 2.5us and 8us after the event strobe occurs. Knowing that the Booster extraction pulse is 1.6us guarantees that both integrators were looking for the beam pulse at the correct time. This timing window is defined inside the EPLD's. Additionally a signal from the Beam Presence Detector at anytime outside the beam event will initiate a system trip.

Long-term beam stability can be improved using a simple linear algorithm.

Autotune



TRK
09Apr02

How to do it:

- Change a corrector by a known amount.
- Record how much the beam moves at each BPM downstream of the corrector.
- Do this for all correctors.
- Now we have a simple relationship:

$$\Delta x = R \Delta B$$

- Invert $R$, so you have:

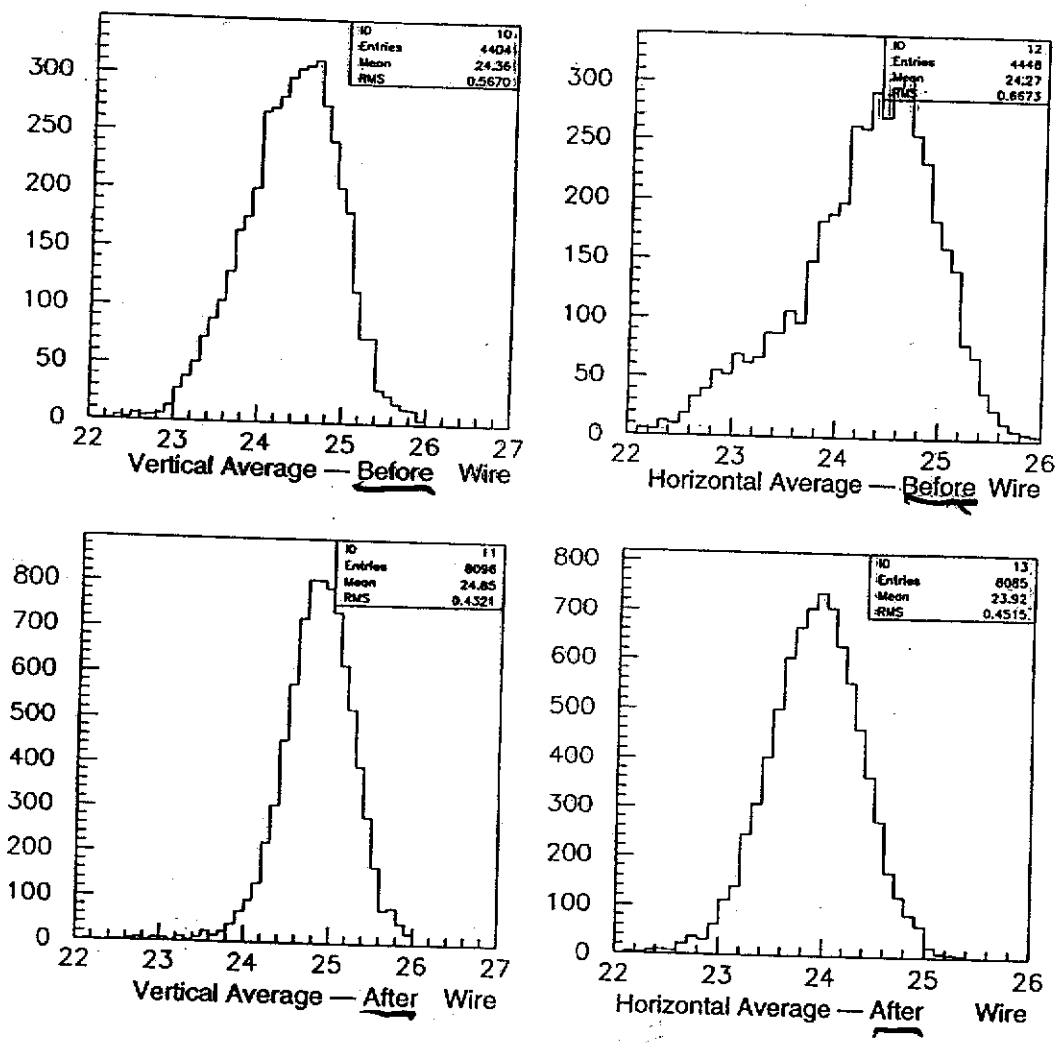
$$\Delta B = R^{-1} \Delta x$$

Important features:

- The correction matrix can be calculated using standard optics programs. Of course, the values should be checked when the beamline is commissioned.
- The correction matrix must be recalculated if any quadrupoles are changed. This can also be done using the standard optics programs.
- The full correction should not be made—pulse-to-pulse variations and noise on the readback introduce errors, guarantying that the correction you calculate is incorrect for the upcomming pulse! However, because the problem is linear, by applying a fraction of the correction it will eventually converge.
- It is important to calculate the corrections in terms of $B$, and then calculate the appropriate current change, taking into account saturation.
- The majority of work goes into checking the state of the beamline. For example, is the beam intensity sufficient to trigger the BPM?

Stale data

From FEMILAB-TM-2037



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09Apr02