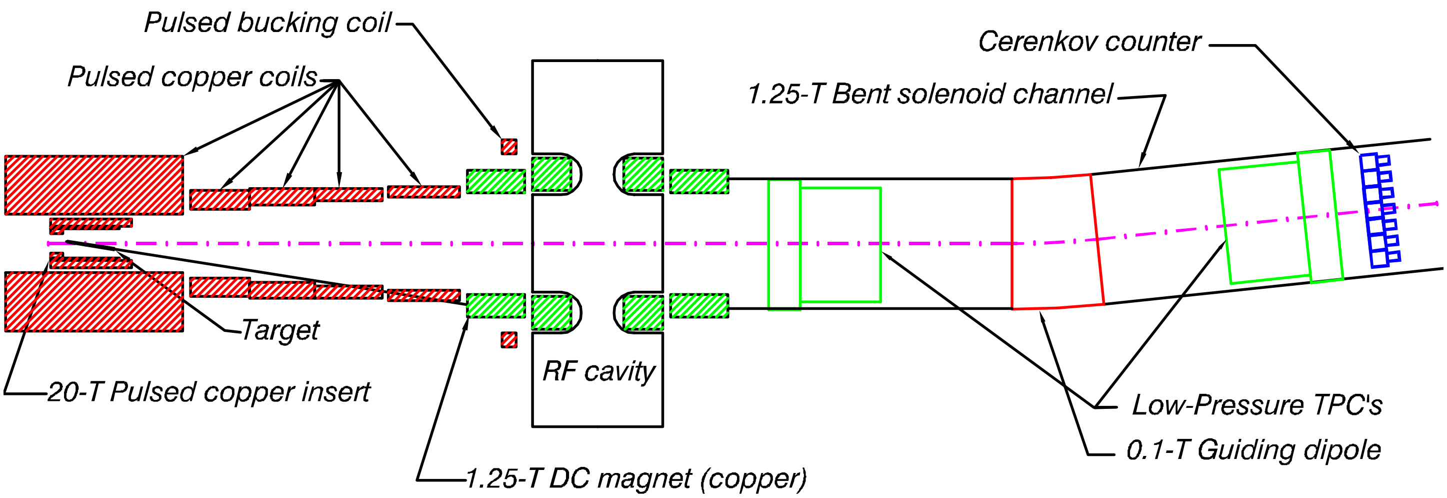
# The R&D Program for Targetry and Capture at a Neutrino Factory and Muon Collider Source

## (BNL E951)

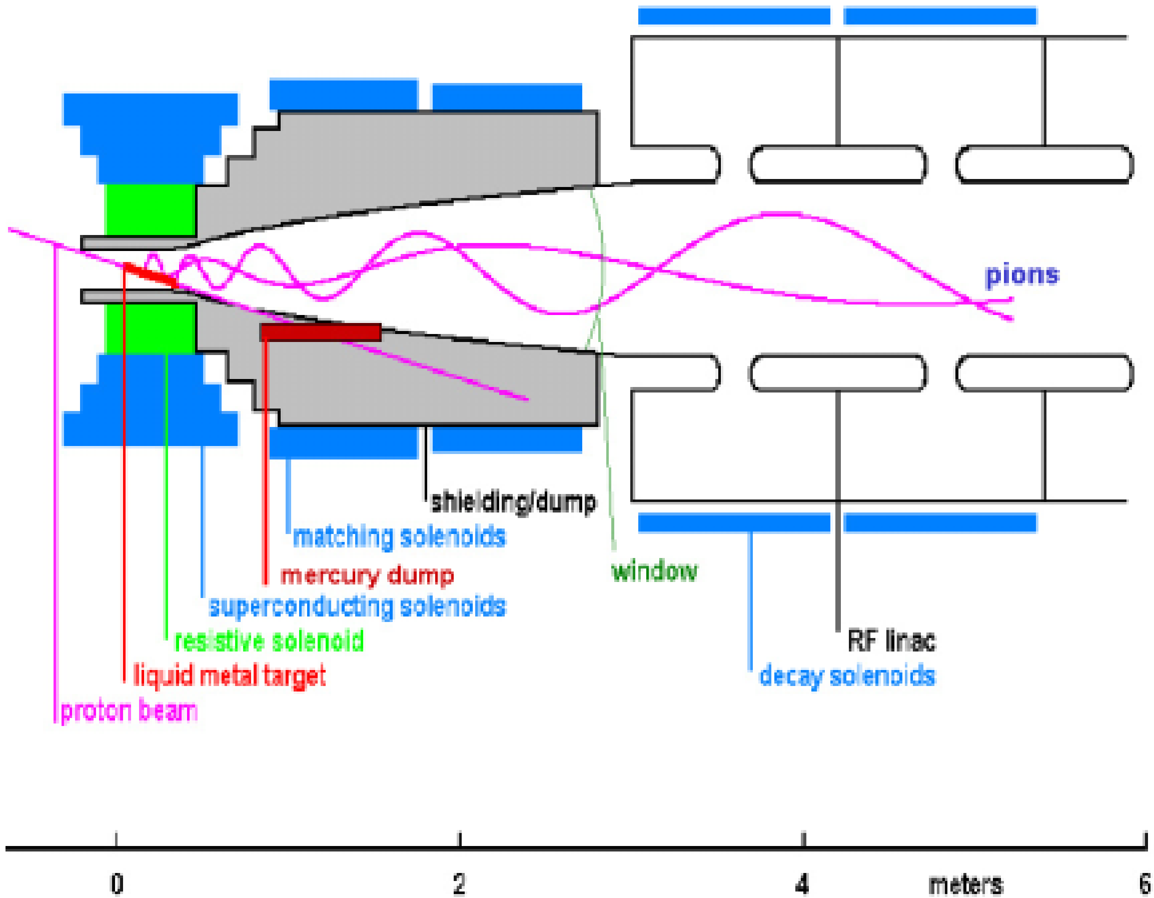



K.T. McDonald
*Princeton U.*

May, 2000

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

# Requirements for Targetry and Capture at a Neutrino Factory/Muon Collider




- $1.2 \times 10^{14}$ $\mu^{\pm}$/s via $\pi$-decay from a 4-MW proton beam.
- Proton pulse $\approx$ 1 ns rms.
- Mercury jet target.
- 20-T capture solenoid followed by a 1.25-T $\pi$-decay channel with phase-rotation via rf (to compress energy of the muon bunch).

## Two Classes of Issues

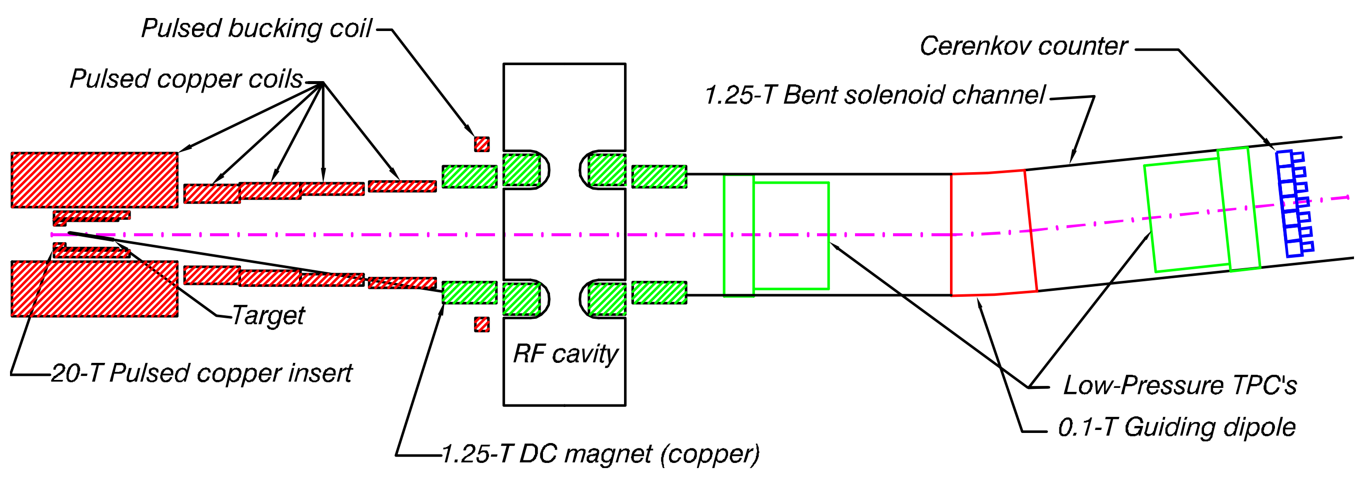
1. Viability of targetry and capture for a single pulse.
2. Long-term viability of the system in a high radiation area.

## E951 Studies the Single Pulse Issues

**Overall Goal:** Test key components of the front-end of a neutrino factory in realistic single-pulse beam conditions.

**Near Term** (1-2 years): Explore viability of a liquid metal jet target in intense, short proton pulses and (separately) in strong magnetic fields.

**Mid Term** (3-4 years): Add 20-T magnet to beam tests;
Test 70-MHz rf cavity (+ 1.25-T magnet) 3 m from target;
Characterize pion yield.



# The 8 Steps in the R&D Program

1. Simple tests of liquid (Ga-Sn, Hg) and solid (C, Ni) targets with AGS Fast Extracted Beam (FEB)of $1.5 \times 10^{13}$ $p$pp.

2. Test of liquid jet entering a 20-T, 20-MW, cw Bitter magnet at the National High Magnetic Field Laboratory).

3. Test of liquid jet and other targets with $10^{14}$ $p$pp via fast extraction of 6 AGS bunches.

4. Add 20-T pulsed magnet (5-MW peak) to target tests with AGS FEB.

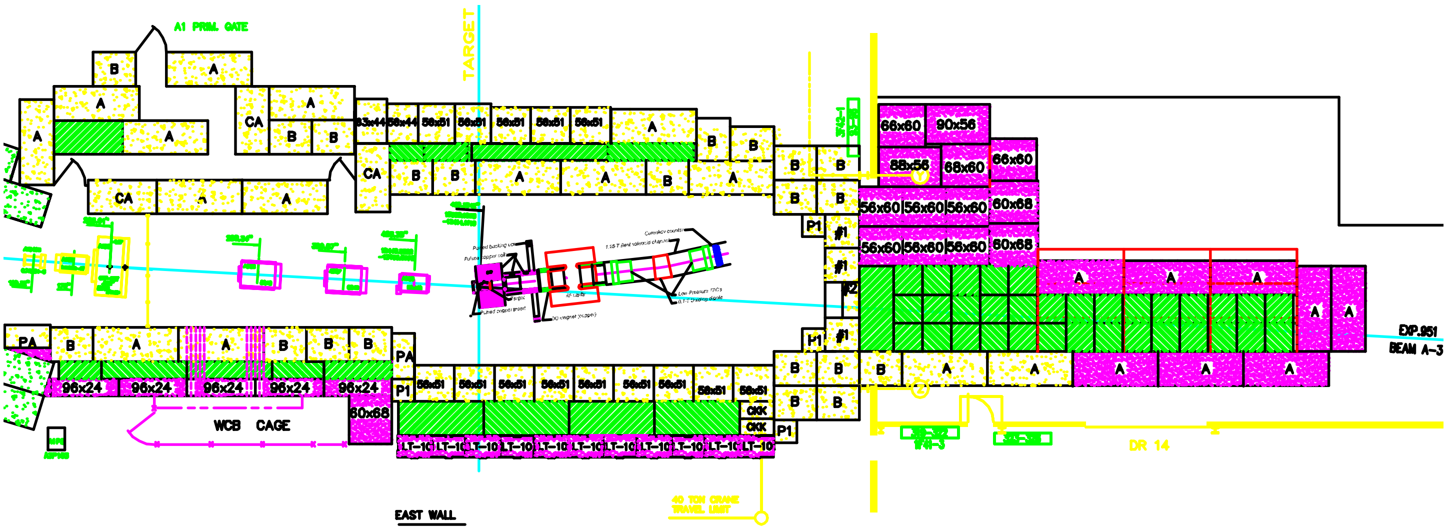
5. Add 70-MHz rf cavity downstream of target in FEB.

6. Surround rf cavity with 1.25-T magnet. At this step we have all essential features of the source.

7. Characterize pion yield from target + magnet system with slow extracted beam (SEB).

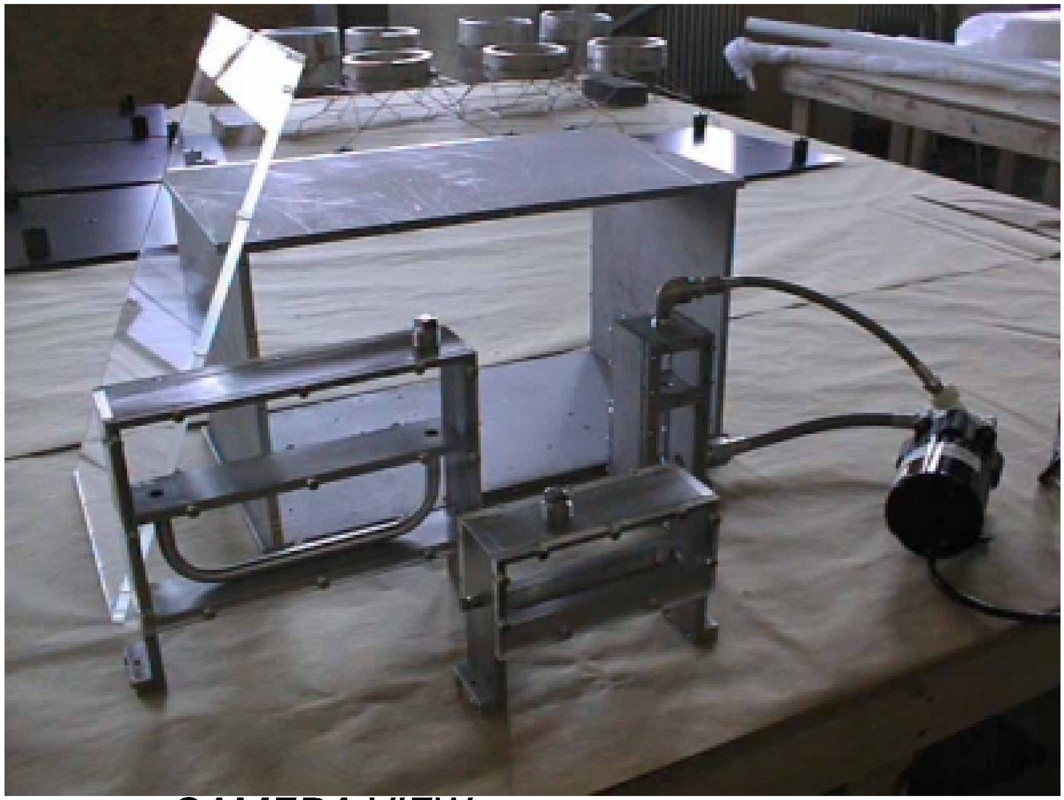
8. Ongoing simulation of the thermal hydraulics of the liquid-metal target systems.

# Construction in the A3 Beamline

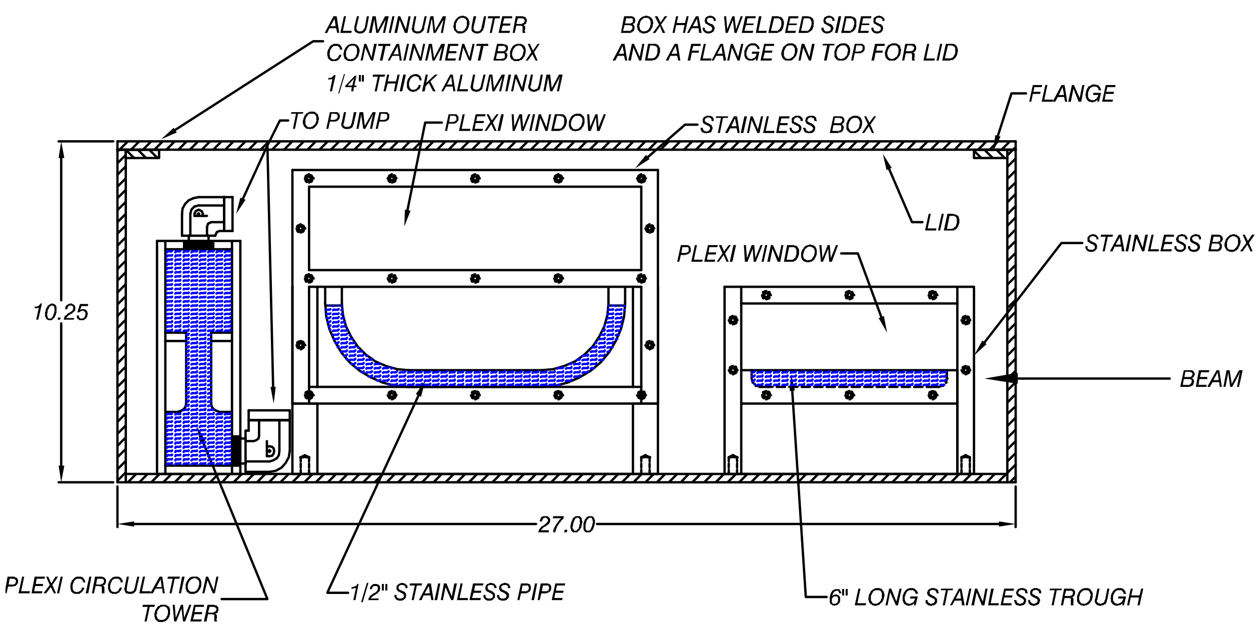


# Simple Target Tests

Simple targets:
Pipe, trough,
waterfall:



CAMERA VIEW



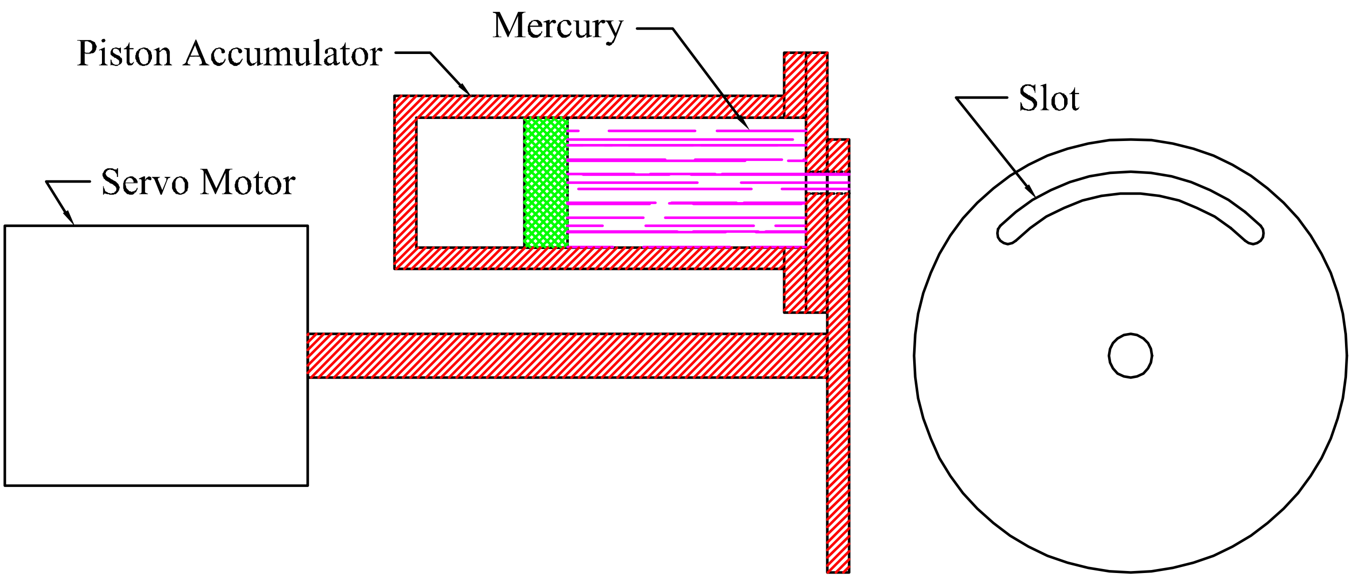

PIPE AND TROUGH ARE FILLED WITH Ga-Sn EUTECTIC LIQUID METAL

Plus: carbon and nickel targets.

# Prototype Mercury Jets

CERN:

Princeton:



# Target Diagnostics

## High-speed digital camera ($10^6$ FPS for 16 frames):


Silicon Mountain Design
EXCELLENCE IN IMAGING

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**SMD 64K1M Camera • 240x240, 1,000,000fps, 12 bits**

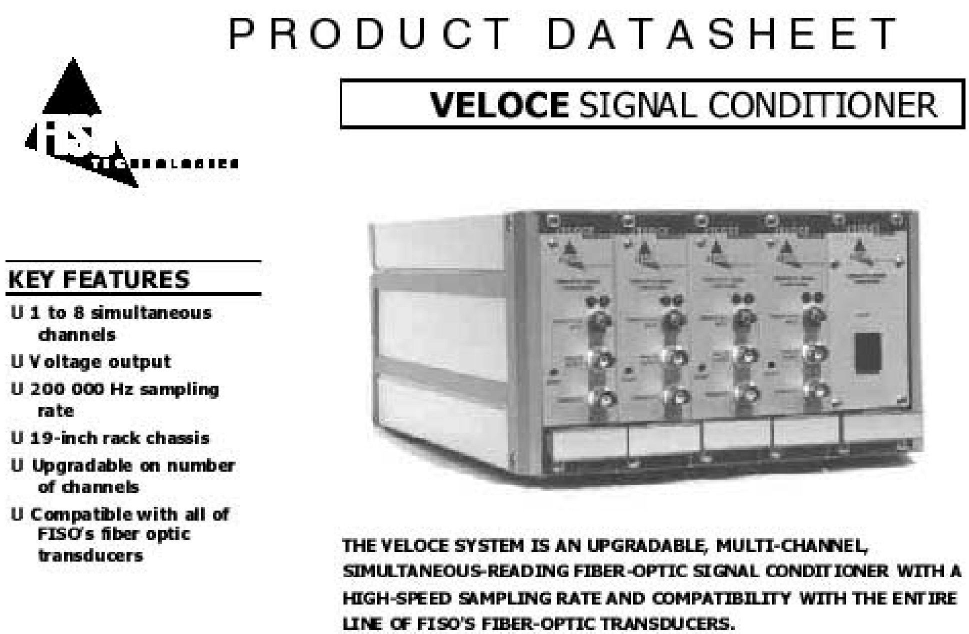
*SMD has solved the problem of real-world interface to hyper-speed cameras*

Contents: Features | Applications | Description | Specifications

**Features**

- Ultra High Frame Rate with Electronic Shutter. Up to one million frames per second at 240x240 resolution from a custom-designed interline transfer sensor.
- High Quality Images. The custom sensor's electronic shutter allows crisp, clear images without smearing, even at maximum frame rate. True 12-bit dynamic range preserves superior image quality, even in low light conditions.
- Flexible Data Readout. The sensors's multiple parallel channels of image data are digitized, buffered, and output through four 12-bit wide ports at 10MHz each. Maximum readout is 15 bursts per second of 17 consecutive frames.
- Compact and lightweight. Small form factor to ease system integration.
- Internal/External Sync. Asynchronous-mode frame capture, externally triggerable to within 250 nanoseconds.
- Extended Spectral Response. Sensitive to UV and near IR wavelengths.

## Fiberoptic strain sensors:


PRODUCT DATASHEET

**VELOCE** SIGNAL CONDITIONER

**KEY FEATURES**

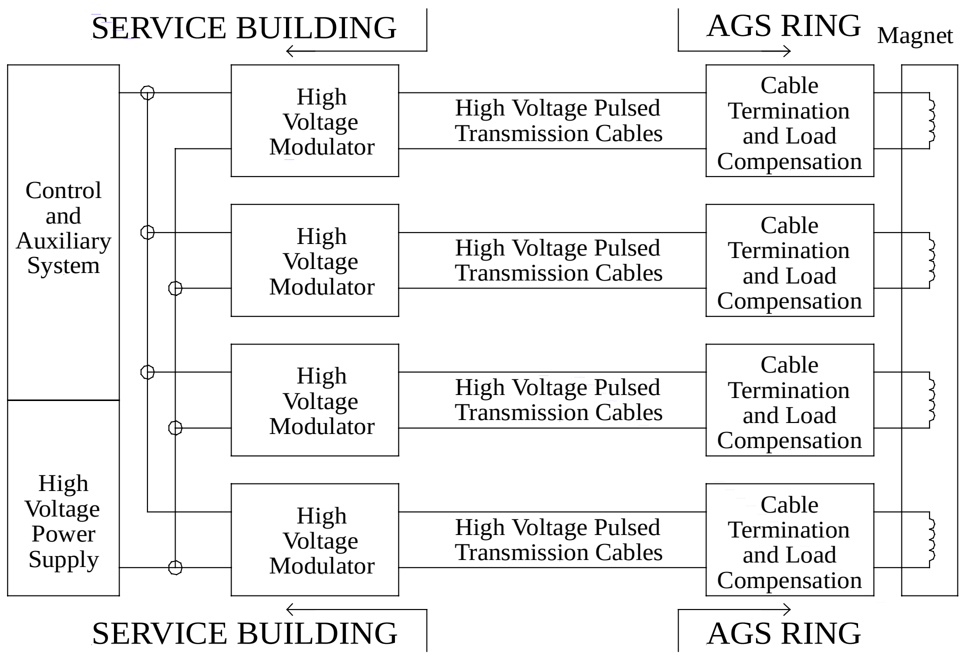
- 1 to 8 simultaneous channels
- Voltage output
- 200 000 Hz sampling rate
- 19-inch rack chassis
- Upgradable on number of channels
- Compatible with all of FISO's fiber optic transducers

THE VELOCE SYSTEM IS AN UPGRADABLE, MULTI-CHANNEL, SIMULTANEOUS-READING FIBER-OPTIC SIGNAL CONDITIONER WITH A HIGH-SPEED SAMPLING RATE AND COMPATIBILITY WITH THE ENTIRE LINE OF FISO'S FIBER-OPTIC TRANSDUCERS.

( Need to improve the frequency response.)

# AGS Full Turn Fast Extraction

- A single AGS proton bunch can have $1.6 \times 10^{13}$ protons.
- Can have 6 bunches in the AGS $\Rightarrow 10^{14}$ protons.
- Must upgrade pulse forming network of the G10 fast kicker to permit single-turn extraction of all 6 bunches.
- Arlene Zhang of the AGS is beginning a design study.

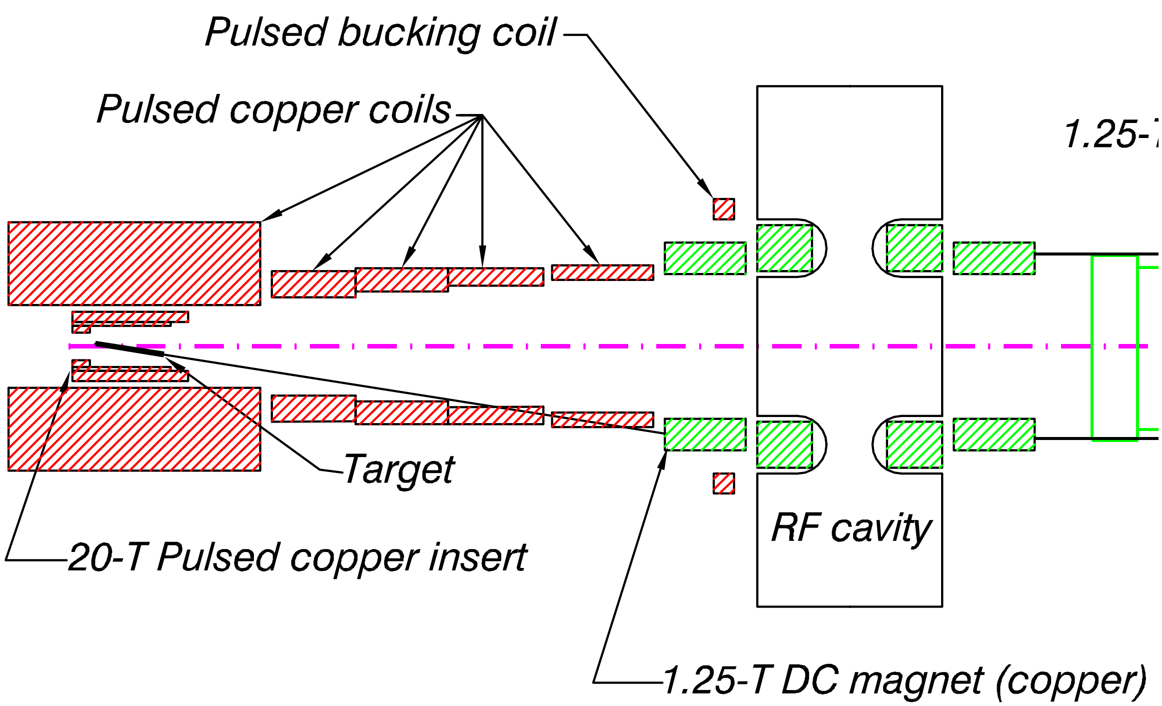



AGS FULL TURN EXTRACTION KICKER SYSTEM

- The LANL Proton Radiography Project also desires the AGS kicker upgrade – and may have a budget for this. However, they want somewhat greater capability than we need, and foresee a longer schedule – completion in FY03.

# 20-T Pulsed Solenoid and 70-MHz RF Cavity

- We now propose to build a new 5-MW pulsed power supply. (J. Sandberg)
- We now propose that the 70 MHz rf cavity have resistive coils within its nosepieces to provide 1.25-T field on axis. (B. Weggel)
- The rf frequency will actually be 71.2 MHz = 16 × AGS frequency for six 24-GeV bunches.
- The rf cavity will provide 6 MeV/m accelerating gradient at 4.5 MW power. (J. Rose)
- The rf power is from six 1.5-MW 8973 tetrodes. (J. Corlett)



# R&D on High Power, Low Frequency RF Sources

Inductive Output Tubes (Marconi, Thomson):

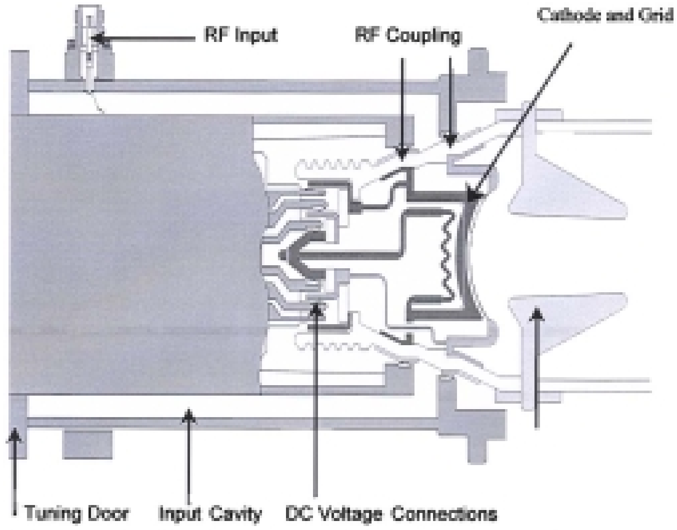
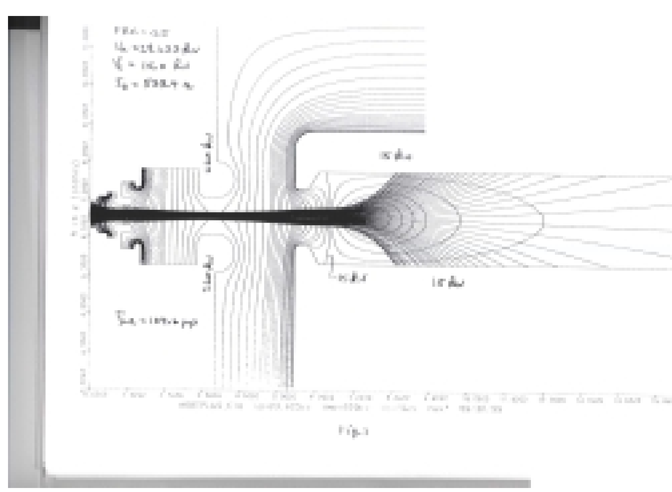



**Figure 3.2** Schematic of how a standard television IOT interfaces with the input cavity.

| IOT Option - 50 MW RF Output Power at 70 MHz | | | | | | |
|---|---|---|---|---|---|---|
| Number of beams | 1 | 6 | 12 | 24 | 36 | 48 |
| Peak Single beam perveance ($\times 10^{-6}$) | 1.3 $AV^{-3/2}$ | 1.3 $AV^{-3/2}$ | 1.0 $AV^{-3/2}$ | 1.0 $AV^{-3/2}$ | 1.0 $AV^{-3/2}$ | 1.0 $AV^{-3/2}$ |
| IOT perveance ($\times 10^{-6}$) | 1.3 $AV^{-3/2}$ | 7.8 $AV^{-3/2}$ | 12. $AV^{-3/2}$ | 24 $AV^{-3/2}$ | 36 $AV^{-3/2}$ | 48 $AV^{-3/2}$ |
| Efficiency | 73 % | 73 % | 73 % | 73 % | 73 % | 73 % |
| Peak DC power | 68.5 MW | 68.5 MW | 68.5 MW | 68.5 MW | 68.5 MW | 68.5 MW |
| Pulsed Cathode voltage | 500 kV | 243 kV | 203 kV | 154 kV | 130 kV | 116 kV |
| Peak tube current | 460 A | 934A | 1098 A | 1450 A | 1687 A | 1896 A |
| Peak cathode current / beam | 460 A | 156 A | 91 A | 60 A | 47 A | 40 A |
| Total current with no RF | 25 A | 54 A | 84 A | 96 A | 126 A | 144 A |
| Idle current per beam with no RF | 25 A | 9 A | 7 A | 4 A | 3.5 A | 3 A |
| Mean current density of M-type cathode | 2.5 $Acm^{-2}$ | 2.5 $Acm^{-2}$ | 2.5 $Acm^{-2}$ | 2.5 $Acm^{-2}$ | 2.5 $Acm^{-2}$ | 2.5 $Acm^{-2}$ |
| Area of emitter | 184 $cm^2$ | 62 $cm^2$ | 37 $cm^2$ | 24 $cm^2$ | 19 $cm^2$ | 15.8 $cm^2$ |
| Cathode diameter | 15 cm | 9 cm | 6.8 cm | 5.5 cm | 4.9 cm | 4.5 cm |
| Gain | 25 dB | 25 dB | 25 dB | 25 dB | 25 dB | 25 dB |
| Drive power | 158 kW | 158 kW | 158 kW | 158 kW | 158 kW | 158 kW |
| Height | 2.5 m | 2.5 m | 2.5 m | 2.5 m | 2.5 m | 2.5 m |
| Diameter | 2 m | 2.0 m | 3 m | 3 m | 3.5 m | 3.5 m |

**Table 1.3** Approximate parameters for single and multiple beam IOTs to deliver 50 MW output power at 70 MHz. (Figures are only indicative).

Hobetron (Litton):



# PROPOSAL FOR
# LOW-FREQUENCY, HIGH-POWER PULSE COMPRESSION BY A THYRATRON SWITCH

Y. Zhao, BNL (April, 2000)

## PRINCIPLE:

A **superconducting storage cavity** is charged by a tetrode. Its output line is a λ/2 line ended with a thyratron, which is open during charging, so that only a little energy leaks out.

Once the thyratron is fired by a trigger pulse, the cavity is coupled to the load and discharged rapidly.

## KEY ISSUE:

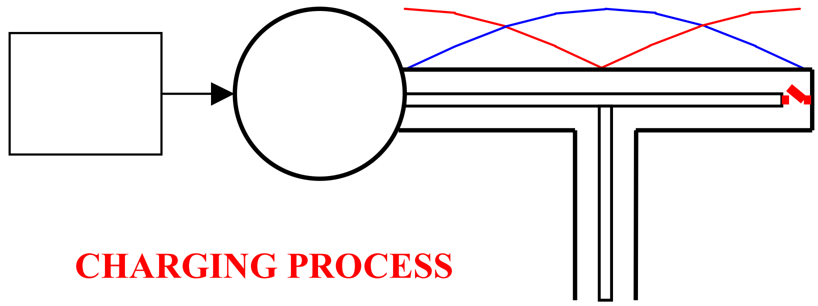
Thyratrons usually work at video frequency, but brief operation at RF frequency is possible before breakdown occurs.

## POWER COMPRESSION RATIO:

Reduced by leakage in the switch and by transmission loss.

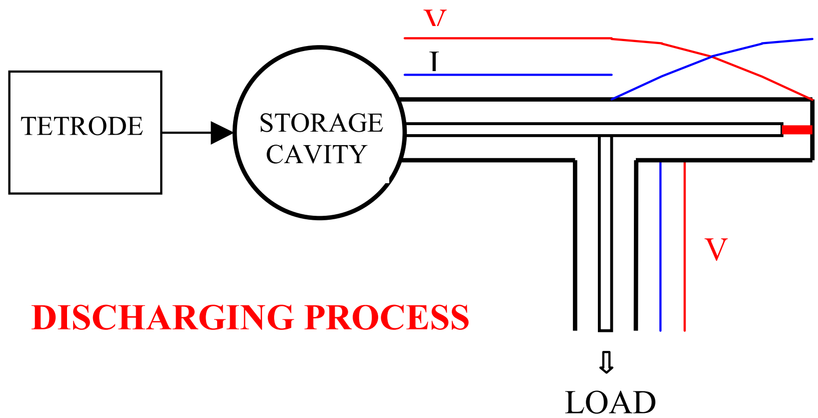
Theoretical analysis indicates a **gain of more than 1000 is possible.**

Initial R&D goal: **power gain of 20** or more.



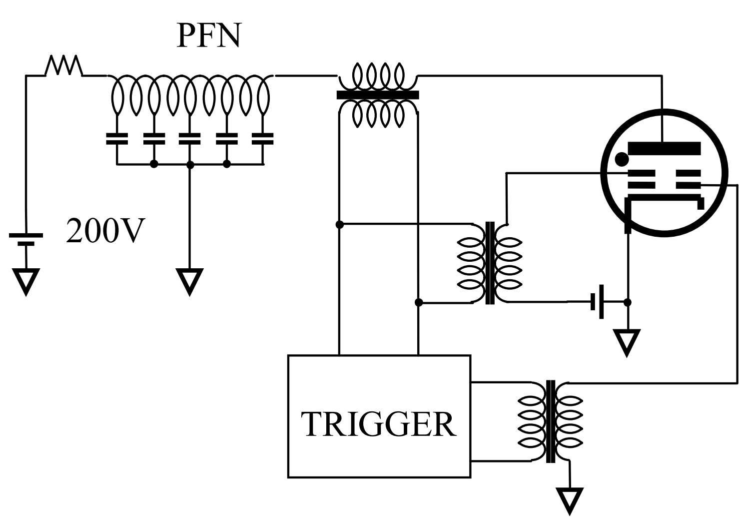
CHARGING PROCESS

**SWITCH CLOSED** --- TOTAL ENERGY TO LOAD




DISCHARGING PROCESS

THYRATRON FIRING CIRCUIT



# Simulations

[Talk by S. Kahn]

1. Pion production: MARS, FLuka. (H. Kirk, N. Mokhov)
2. Pion decay, phase rotation: MARS, GEANT, ICOOL.
   (Y. Fukui, H. Kirk, N. Mokhov, S. Kahn)
3. Neutron doses: MARS, LAHET/MCNP. (N. Mokhov, ...)
4. Radionucleide inventory: LAHET/MNCP
5. Beam-induced pressure waves in targets.
   (A. Hassanein, R. Samulyak, N. Simos)
6. Magnetohydrodynamics of liquid metal jets. (C. Lu)

# Beyond E951

[Talk by P. Spampinato]

- Target station infrastructure (ORNL).
- Radionucleide issues (BNL, ORNL).
- Neutron damage to materials (BNL, MSU, ORNL).
- Large exposure tests of targets at neutron spallation facilities (BNL, LANL, ORNL).

# Neutrino Factory Target R&D Proposal From ORNL

**Near Term R&D Tasks for the Graphite Target (1.5MW Design)**

1. Assess commercially available graphite-composite properties for candidate target materials.

2. Develop a neutronics model for heating distribution (energy distribution) in the target.

3. Develop a neutronics model for heating distribution and multiple scattering effects in the proton beam window.

4. Develop a finite element model for temperature and stress distributions, and deflections.

5. Develop a test plan, design and assemble equipment for sublimation tests under high temperature conditions in a helium environment: assuming that test equipment is available, do benchmark tests in vacuum; exploratory tests would proceed to measure sublimation rate and determine the effect of He pressure and purity.

6. Do thermal shock tests using ATJ graphite; assess material survivability.

7. Develop the design details for the radiatively cooled target, including rod supports, water-cooled support tube, utility connectors, and remote handling approach.

The estimated cost for accomplishing these tasks in FY00 is $64K. There is approximately $20K available at ORNL to support this work; therefore, $44K of additional funding would be required.

**Preliminary List of Additional (Longer Term) R&D Tasks**

1. Develop a full scale mock up of the target region ($-120<Z<140$ cm) using low cost materials; demonstrate access and remote handling for replacing the target and Bitter coil; assess downtime.
   *(Note: Robotic facilities and remote handling equipment in use by SNS are available at ORNL at no cost.).*

2. Develop a proton beam window mock up; demonstrate remote removal of cooling and diagnostic connectors; demonstrate window replacement; assess downtime.
   *(Note: Robotic facilities and remote handling equipment in use by SNS are available at ORNL at no cost.)*

3. Develop a preliminary design of the target beam stop located at $5.5<Z<6.5$ m).

4. Complete the sublimation tests under target operating conditions.

5. If a suitable carbon-carbon composite material is found that has insufficient irradiation data, test for neutron/gamma irradiation survivability at ORNL's High Flux Isotope Reactor.

6. Construct and test a full scale prototype target; assess the geometric integrity of the support structure and the target rod (fabrication and alignment issues); assess support schemes for graphite wire, silicon carbide, …, assess remote handling features.

This is a preliminary list of tasks that support the baseline approach for a radiatively-cooled carbon target design. It should be noted that many of the items in this list would also be recommended for an actively-cooled target, if that became a design option. Furthermore, as the target design evolves, additional R&D tasks may be identified that should be added to this listing.

The estimated cost for this follow-on R&D work is $387K.

# SUPPORT TO MUON COLLIDER TARGETRY

**H. Ludewig, P. Simos, M. Todosow**
**Energy Sciences and Technology Department, BNL**

## METHODS VALIDATION/QUALIFICATION/CONFIRMATION

- Main tool for nuclear design to-date appears to have been the MARS code
- We use the LANL suite of codes: LAHET/MCNP, MCNPX
- Can perform "check" calculations to confirm predictions, help quantify uncertainties, identify deficiencies in modeling and/or data

## TARGET DESIGN

- Can perform all aspects of target design: nuclear, thermal, stress, material damage
- MCNPX in conjunction with the COSY code allows incorporation of magnetic or electric fields in particle transport, including modeling of magnets, etc.

## ENVIRONMENTAL, SAFETY & HEALTH (ES&H)

- Activation/dose analyses for target, surrounding components, environment (air, soil, water), waste characteristics
- Evaluate accident scenarios and consequences; hazards analyses; safety/hazards class
- Suggest and evaluate design features to mitigate

# E951 Schedule

- FY99:
  Prepare A3 area at the AGS (Step 1);
  Begin work on liquid jets, magnet and rf systems (Steps 2, 4-6).

- FY00:
  Complete A3 line (Step 1);
  Continue work on jet, magnet and rf systems (Steps 2, 4-6);
  Begin work on AGS extraction upgrade (Step 3).

- FY01:
  First test of targets in A3 (Step 1);
  Liquid jet test in 20-T magnet at NHMFL (Step 2);
  Continue work on extraction, magnet, and rf systems (Steps 3-6).

- FY02:
  Complete extraction upgrade, magnet, and rf systems (Steps 3-6);
  Test targets with $10^{14}$ $p$pp (Step 3);
  Begin work on pion yield diagnostics (Step 7);
  Option to study mercury dump in vertically pitched beam (Step 3.5).

- FY03:
  Beams tests of target + 20-T pulsed magnet + rf cavity (Steps 4.6);
  Complete pion detectors; test yield with low intensity SEB (Step 7).

# Targetry and Capture Budgets, I

## Yearly Projections (made in 1998)

| Category | FY99 | FY00 | FY01 | FY02 | FY03 | Total |
|---|---|---|---|---|---|---|
| Base Program | $0.5M | $1.5M | $2M | $2M | $1M | $7M |
| AGS Operations | | $0.2M | $0.2M | $0.4M | $0.4M | $1M |
| RF Power Source | $0.05M | $0.5M | $1M | $1M | $1M | $3.5M |

## Targetry FY99, Allocated

| Task | ANL | BNL | LBL | Princeton | Industry | Total |
|---|---|---|---|---|---|---|
| Initial Target Studies | | 20 | | 85 | | 105 |
| AGS Beamline Upgrades | | 100 | | | | 100 |
| Pulsed Solenoid Design | | 50 | | | | 50 |
| RF Systems | | 65 | 75 | | 50 | 190 |
| Simulation Studies | 75 | | | 5 | | 80 |
| Total | 75 | 285 | 75 | 90 | 50 | **$525k** |

# Total Targetry FY00, Allocated

| Task | ANL | BNL | LBL | ORNL | NHMFL | Prin. | MSU | Total |
|---|---|---|---|---|---|---|---|---|
| Initial Target Studies | | 25 | | | | 50 | | 75 |
| AGS Beamline Upgrades | | 1338 | | | | | | 1338 |
| Magnet Systems | | 240 | | | 25 | 40 | | 305 |
| RF Systems | | 295 | 75 | | | | | 370 |
| Simulation Studies | 80 | | | | | 10 | | 90 |
| Target Station | | | | 50 | | | | 50 |
| Radiation Damage | | | | | | | 20 | 20 |
| Carryover | | −100 | | | | | | −100 |
| Total | 80 | 1798 | 75 | 50 | 25 | 100 | 20 | **$2148k** |

# FY00 Targetry Allocation: Details

1. **Initial Target Studies** . . . . . . . . . . . . . . . . . . . . . . . . . . **$75k**
   - Remote positioner for target box (BNL) . . . . . . . . . . . $25k
   - Target box, targets, cameras (Princeton) . . . . . . . . . . . $50k
2. **AGS Beamline Upgrades** . . . . . . . . . . . . . . . . . . . . **$1338k**
   - Labor (11,000 hours, BNL) . . . . . . . . . . . . . . . . . . . . . . . $1100k
   - Beamline Instrumentation (BNL) . . . . . . . . . . . . . . . . . $120k
   - Radiation Safety (BNL) . . . . . . . . . . . . . . . . . . . . . . . . . . $38k
   - 6-Bunch kicker design (BNL) . . . . . . . . . . . . . . . . . . . . . $80k
3. **Magnet Systems** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . **$305k**
   - Mech. engineer (BNL) . . . . . . . . . . . . . . . . . . . . . . . . . . . $170k
   - 1/4 Mech. engineer (Princeton) . . . . . . . . . . . . . . . . . . . $40k
   - 1/6 Mech. engineer (NHMFL) . . . . . . . . . . . . . . . . . . . . $25k
   - Design of 5 MW magnet power supply (BNL) . . . . . . $70k

4. **RF Systems** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . **$370k**

   - Recommissioning of the 8973 power supplies (LBL) . $75k
   - 1 1/2 RF engineer (BNL) . . . . . . . . . . . . . . . . . . . . . . . . . $255k
   - Materials (BNL) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . $40k

5. **Simulation Studies** . . . . . . . . . . . . . . . . . . . . . . . . . . . **$90k**

   - (ANL) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . $80k
   - (Princeton) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . $10k

6. **Target Station Studies (ORNL)** . . . . . . . . . . . . . . **$50k**

7. **Radiation Damage Studies (MSU)** . . . . . . . . . . . **$20k**

8. **Total** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . **$2248k**

# FY01 Targetry Request: Details

1. **Initial Target Studies** ........................ **$200k**
   - Engineering support for A3 target station (BNL) ... $50k
   - Mercury jet for BNL/NHMFL tests (Princeton) .... $50k
   - [Carbon target studies (BNL, ORNL, LANL) ..... $100k]
2. **AGS Operations: 3 weeks, A3 + linac costs $200k**
3. **AGS Beamline Upgrades** ..................... **$900k**
   - Labor (1,000 hours, BNL) ...................... $100k
   - 6-Bunch kicker fabrication (BNL) ................ $800k
4. **Magnet Systems** ............................ **$1200k**
   - Mech. engineer (BNL) ........................... $170k
   - 1/2 Mech. engineer (NHMFL) .................... $80k
   - 1/4 Mech. engineer (Princeton) .................. $40k
   - Designer (BNL) ................................. $110k
   - Fabrication of 5 MW magnet power supply (BNL +) $400k
   - Fabrication of pulsed & DC magnet coils (BNL +) . $400k

5. **RF Systems** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . **$1335k**

- Shipping of 8973 rf gear from LBL to BNL . . . . . . . . . . $20k
- Materials for 8973 power source (BNL) . . . . . . . . . . . $100k
- 1 1/2 RF engineer (BNL) . . . . . . . . . . . . . . . . . . . . . . . . . . . $255k
- Mech. engineer (BNL) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . $160k
- 2 × 1/2 Technician (BNL) . . . . . . . . . . . . . . . . . . . . . . . . . $100k
- Fabrication of the 70 MHz rf cavity . . . . . . . . . . . . . . . . $400k
- [RF switch R&D (BNL) . . . . . . . . . . . . . . . . . . . . . . . . . . . $50k]
- [Industrial development of 10-50 MW power sources $250k]

6. **Simulation Studies** . . . . . . . . . . . . . . . . . . . . . . . . . . **$360k**

- 1/2 FTE (ANL) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . $80k
- 1/2 FTE (BNL) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . $80k
- [1/2 FTE (BNL) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . $80k]
- [1/2 FTE (ORNL) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . $80k]
- 1/4 FTE (Princeton) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . $40k

7. [Target Station Studies (ORNL) . . . . . . . . . . . . . . . . . . . . . . . $100k]

8. **[Neutronics . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . $150k]**

- [Radiation Damage Studies (MSU) . . . . . . . . . . . . . . . . $50k]
- [Neutron dosimetry studies in A3 (BNL+) . . . . . . . . $100k]

9. **Total . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . $4435k**

[Items in brackets are beyond the E951 base program]

[Total for items beyond the base program . . . . . . . . . . . . $810k

# Summary of FY01 Targetry Budget, Requested

| Task | ANL | BNL | ORNL | NHMFL | Prin. | MSU | Ind. | Total |
|---|---|---|---|---|---|---|---|---|
| Initial Target Studies | | 50 | 100 | | 50 | | | 200 |
| AGS Operations | | 200 | | | | | | 200 |
| AGS Beamline Upgrades | | 900 | | | | | | 900 |
| Magnet Systems | | 1080 | | 80 | 40 | | | 1200 |
| RF Systems | | 1085 | | | | | 250 | 1335 |
| Simulation Studies | 80 | 160 | 80 | | 40 | | | 360 |
| Target Station | | | 100 | | | | | 100 |
| Neutronics | | 100 | | | | 50 | | 150 |
| Total | 80 | 3575 | 280 | 80 | 140 | 50 | 250 | **$4435k** |

# Comments on the FY01 Targetry Budget Request

1. Of the \$4435k requested, \$810k are for intiatives beyond the E951 base program.

2. Support for Neutronics may be available from the NSF.

3. Support for AGS Operations may be available from DOE Facilities Operations.

4. Support for the AGS kicker upgrade may be available from the LANL Proton Radiography project.

5. Support for industrial development of rf power sources might be available from DOE BES or elsewhere.

6. Candidates for support by other than DOE Advanced Accelerator Projects total \$1400k.