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THE SCROUNGE-ATRON: A PHASED APPROACH TO THE ADVANCED HYDROTEST FACILITY UTILIZING PROTON RADIOGRAPHY*

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Abstract

The Department of Energy has initiated its Stockpile Stewardship and Management Program (SSMP) to provide a single, integrated technical program for maintaining the continued safety and reliability of the nation's nuclear weapons stockpile in the absence of nuclear testing. Consistent with the SSMP, the Advanced Hydrotest Facility (AHF) has been conceived to provide improved radiographic imaging with multiple axes and multiple time frames. The AHF would be used to better understand the evolution of nuclear weapon primary implosion shape under normal and accident scenarios. There are three fundamental technologies currently under consideration for use on the AHF. These include linear induction acceleration, inductive-adder pulsed-power technology (both technologies using high current electron beams to produce an intense X-ray beam) and high-energy proton accelerators to produce a proton beam. The Scrounge-atron (a proton synchrotron) was conceived to be a relatively low cost demonstration of the viability of the third technology using bursts of energetic protons, magnetic lenses, and particle detectors to produce the radiographic image. In order for the Scrounge-atron to provide information useful for the AHF technology decision, the accelerator would have to be built as quickly and as economically as possible. These conditions can be met by "scrounging" parts from decommissioned accelerators across the country, especially the Main Ring at Fermilab. The Scrounge-atron is designed to meet the baseline parameters for single axis proton radiography: a 20 GeV proton beam of ten pulses, 10^{11} protons each, spaced 250 ns apart.

1 INTRODUCTION

The Comprehensive Test Ban Treaty does not allow nuclear weapons tests. In order to continue to certify the safety and reliability of the U.S. nuclear weapons stockpile in the absence of nuclear testing, the weapons complex will require a major new radiographic facility, the Advanced Hydrotest Facility (AHF) [1]. This facility is to provide multiple radiographic pulses on multiple axes.

One of the technologies under consideration is a high energy proton beam. Since there is minimal experience with protons as radiographic probes, it would be extremely valuable to perform a series of demonstration experiments to develop the tools, techniques, and understanding that will be required to determine if protons should be the technology of choice for the AHF. The purpose of this research is to determine if it is possible to build a proton synchrotron suitable for the experimental program as quickly and economically as possible. To accomplish this, the machine concept relies heavily on "scrounging" equipment from other decommissioned accelerators. As such, we refer to the accelerator as the "Scrounge-atron" [2].

2 DESIGN PARAMETERS

The design parameters for the Scrounge-atron are set by the experimental program requirements. These parameters are related to image spatial resolution, statistical variance of the image on a pixel-by-pixel basis, number of time frames and duration of frame, and repetition rate of the machine. The design requirements are shown in Table 1.

Table 1: Scrounge-atron Design Requirements

Parameter	Value	Unit
Final Energy	20	GeV
Repetition Period	1	min
Number of Proton Bunches	10	bunches
Bunch Separation	250	ns
Number of Protons / Bunch	10^{11}	protons
Total Number of Protons/pulse	10^{12}	protons

The desired spatial resolution is less than 1 mm full-width at half-maximum (FWHM). This resolution, sufficient to identify image features of interest to the experimental program, is determined by Multiple Coulomb Scattering (MCS) in the beamline window located just downstream of the object. MCS in this window introduces image blur, whereas MCS in the upstream window and in the object do not contribute to this blur.

An assumption of the design is that the windows would mitigate shrapnel and blast shock wave but would not need to guarantee confinement of the experiment. This

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allows aluminum windows to be used, or possibly a composite material like Spectra. Using these materials reduces the required beam momentum needed to achieve a specific image resolution. The beam momentum of the Scrounge-atron is chosen to be 20 GeV/c.

The intensity requirement for a single image is set by the area of the imaging array and the approximate attenuation of the beam pulse through the object and the other material in the beamline. Taking a 10 cm x 10 cm field-of-view and a detector at the image plane with 0.25 mm x 0.25 mm pixels results in 1.6 x 10^5 imaging elements. To obtain a 1% intensity measurement for a pixel requires roughly 1 x 10^4 protons per pixel or 2 x 10^9 protons at the image plane. The proton beam intensity decreases exponentially in passing through material. For the purpose of estimating beam intensities we take the total attenuation of protons through the beamline windows and object to be of order 0.1-0.01. To obtain 2 x 10^9 protons at the image plane would require between 10^{10} to 10^{11} incident protons per beam pulse.

The number of beam pulses required for dynamic radiography can only be chosen based on experimental considerations. Currently no radiography facility provides more than 2 pulses on a microsecond time scale. We choose to provide 10 pulses, spaced 250 ns apart, with a 20 ns pulse width. These parameters are compatible with the AHF requirements. The simplest extraction scheme has the entire beam extracted in one turn, i.e., with 10 pulses equally spaced in time. The 10 pulses would then span roughly 2.5 microseconds. With more complex extraction schemes, a single pulse might be extracted at an arbitrary time allowing a variation in the pulse arrival time format spanning hundreds of microseconds. With 10 pulses, the total intensity required in the Scrounge-atron is roughly 10^{12} protons.

The maximum rate at which the beam should be delivered to the object is set by the detector data-download time which is compatible with 1 cycle per minute.

3 MACHINE DESCRIPTION

Figure 1 shows the Scrounge-atron layout. It consists of a 300 MeV injector linac, the linac-to-ring transfer line (LTRT), the 20 GeV synchrotron, the ring-to-radiography transport line (RTRT), and the radiography beamline. The main Scrounge-atron parameters given in Table 2 are roughly one-tenth the values of the Fermilab Main Ring. Therefore, we should expect that the Scrounge-atron will be scaled to roughly one-tenth of the Main Ring. The synchrotron has a periodicity of two, with a reflection symmetry within the period. Each period contains a long arc, which together account for about 78% of the ring. The arcs are joined together by two insertions, on opposite sides of the ring. Injection equipment, extraction equipment, and the accelerating cavities are in one of the insertions in the transfer enclosure on the linac side of the ring. All accelerator components can be transported into the tunnel enclosure through either the transfer enclosure or through alcoves at the other insertion and in the middle of the arcs. Eight major power supply utility substations are located around the accelerator; six serve the synchrotron proper, one serves the linac/klystron gallery and the other serves the radiography beamline.

The beam is transported to the firing site through the RTRT beamline. At the firing site the beam enters a radiography beamline, consisting of a diffuser, matching lens, intensity measurement station, first imaging lens, blast protection bullnoses around the object location, and two consecutive imaging lenses with collimators and measurement stations. At either end of the firing area, bullnoses protect the upstream and downstream beamline components and enclosures from shock and shrapnel.

The major civil construction consists of the linac enclosure, 100 m long; the ring enclosure, 1030 m long; the transfer line to the firing site, 180 m long; and the radiography beamline at the firing site, 150 m long.

Table 2. Lattice Parameters

Parameter	Value	Units
Lattice		
Periodicity	2	
# Straight Cells "CE"/ Period	6	
# Bend Cells "C"/ Period	20	
Cell Length	19.786	m
Ring Circumference	1028.851	m
B1 Type Dipoles		
Aperture (H x V)	12.70 x 3.81	cm^2
Length	6.071	m
Bending Angle	78.540	mrad
Bending Radius	77.313	m
Sagitta	59.606	mm
Ramp Rate	2.000	kG/s
Number of Dipoles	80	
Q4 Type Quadrupoles		
Aperture (H x V)	12.70 x 5.08	cm^2
Length	1.321	m
$B'' / B\rho$	0.0779	m^{-2}
Ramp Rate	12.045	kG/m s
Number	104	
Drifts		
Short "O"	1.251	m
Long "D"	8.572	m
Accelerator Functions		
Phase Advance / Cell	61.2	°
β_{max}	34.072	m
η_{max}	3.762	m
γ_T	7.387	
Tune		
Q_h - Horizontal Tune	8.84	
Q_v - Vertical Tune	8.82	
ξ_h - Chromaticity	1.107	

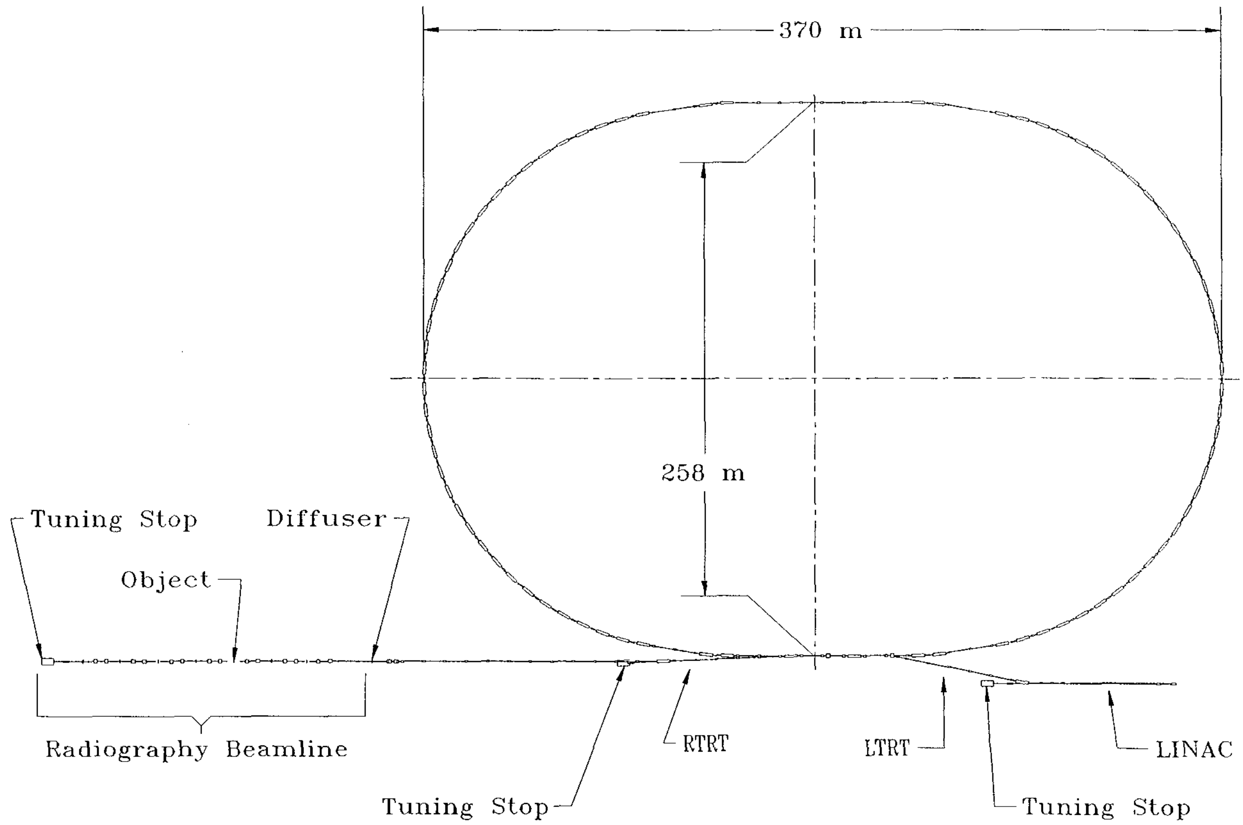

Figure 1. Scrounge-Atron Baseline Lattice

We can meet the schedule and cost goals by the following design procedure: (1) use existing parts where available and appropriate, (2) if parts are not available, use existing designs, and (3) only if these are not available, design and construct the required part. This procedure minimizes the total amount of design for the accelerator. This approach is possible because, for most of the accelerator systems, the characteristics required for radiography are far below the current state-of-the-art used in new accelerators.

Existing and available elements include, from FNAL, 120 B1 dipoles, 30 Q4 quadrupoles, corrector magnets, power supply components, ion pumps, heat exchangers, and Princeton-Pennsylvania Accelerator (PPA) ring .rf cavities; from Lawrence Berkeley National Laboratory, a 5 MeV pre-injector. Designs available include, from Brookhaven National Laboratory, a Drift Tube Linac; from FNAL, a Cavity Coupled Linac.

4 CONCLUSIONS

The result of research on the Scrounge-atron concept as described above is that the machine is technically feasible and can be built within anticipated cost and schedule constraints. In order to accomplish this task, the machine relies heavily on the availability of components from the decommissioned Fermi National Accelerator Laboratory Main Ring. The Scrounge-atron will serve as a test bed and will provide important and timely information to the SSMP which cannot be obtained by any other means.

5 REFERENCES

[1] Final Programmatic Environmental Impact Statement for Stockpile Stewardship and Management, DOE-EIS-0236, U.S. Department of Energy.

[2] O. J. Alford, et. al., "The Scrounge-atron: A Proton Radiography Demonstration Accelerator," UCRL (Lawrence Livermore National Laboratory, in preparation).