Experience with AGS High Intenisty Protons Operation

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BROOKHAVEN NATIONAL LABORATORY

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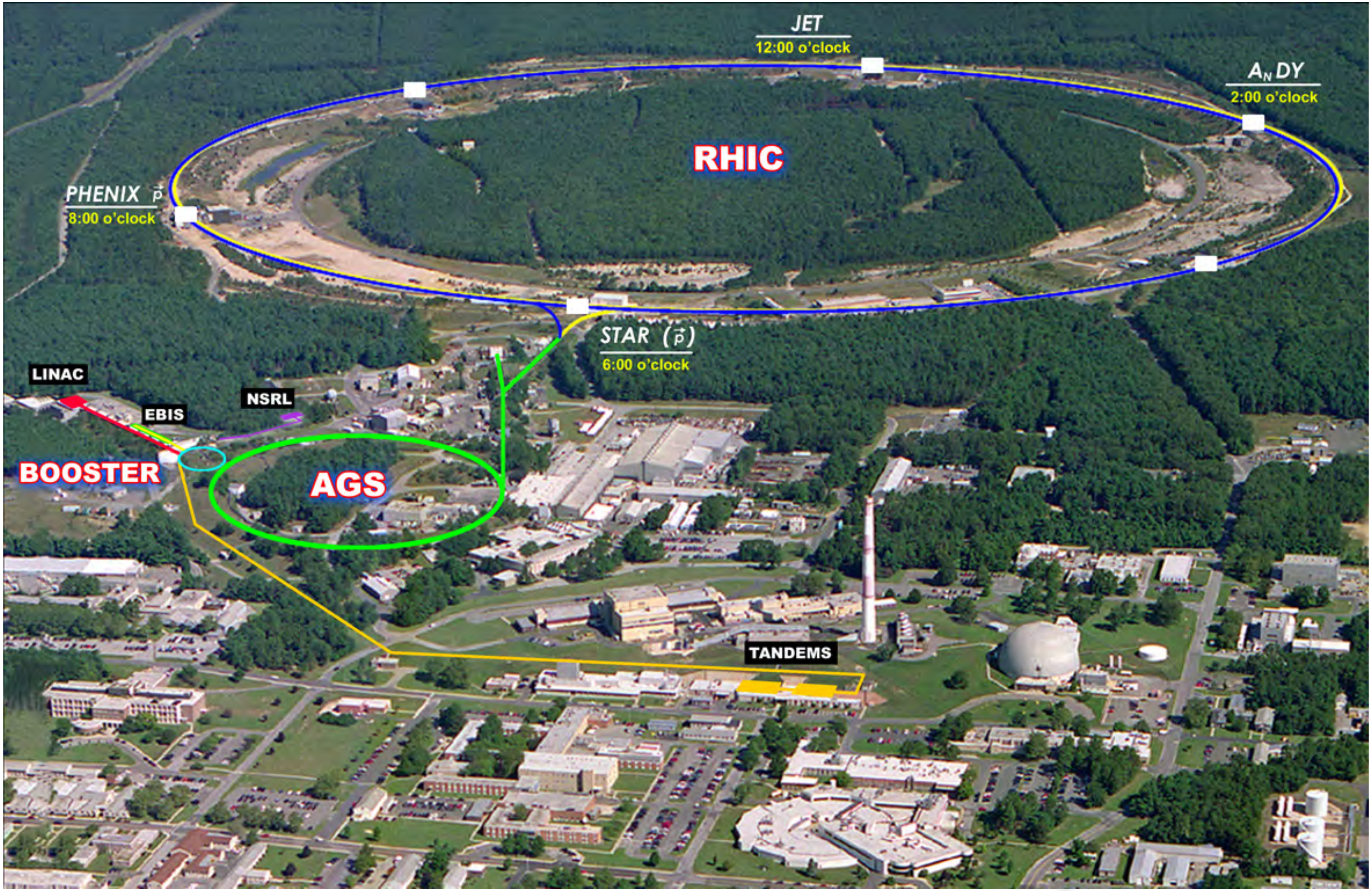
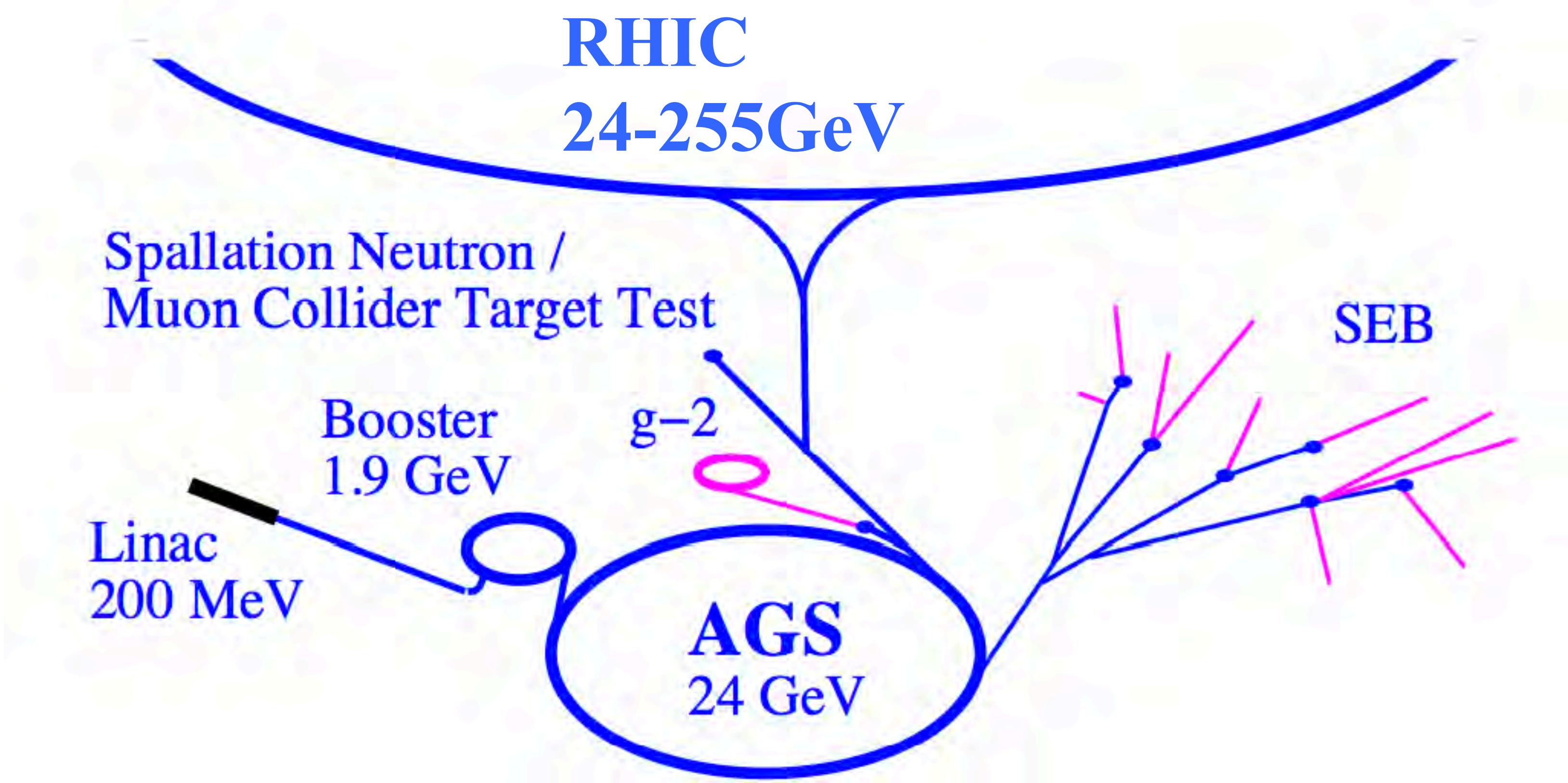
Brookhaven Hadron Accelerator Complex



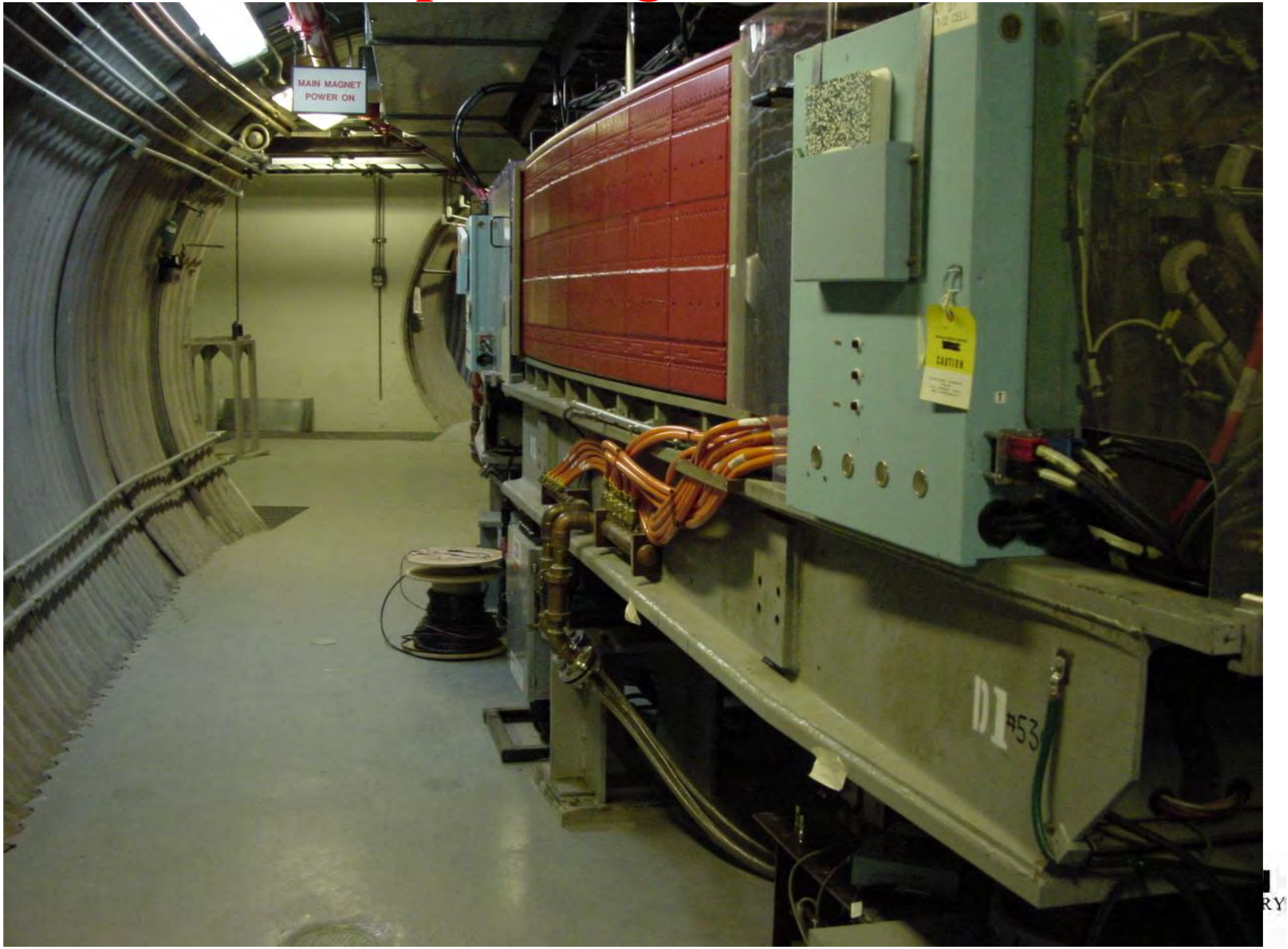
AGS Complex with Beam Lines



Booster Design Goal

1. Increase AGS proton intensity by a factor 4 to $6*10^{13}$.
2. Accelerate heavy ions with mass numbers up to 200 and beyond for RHIC heavy ion operation.
3. The design was a rapid cycling synchrotron which can accelerate proton to 1.5GeV at a 7.5Hz rate.
4. The Booster was first commissioned in 1993 successfully.
5. The high intensity proton operation stopped in year 2000.

Booster C1 Dipole Magnet

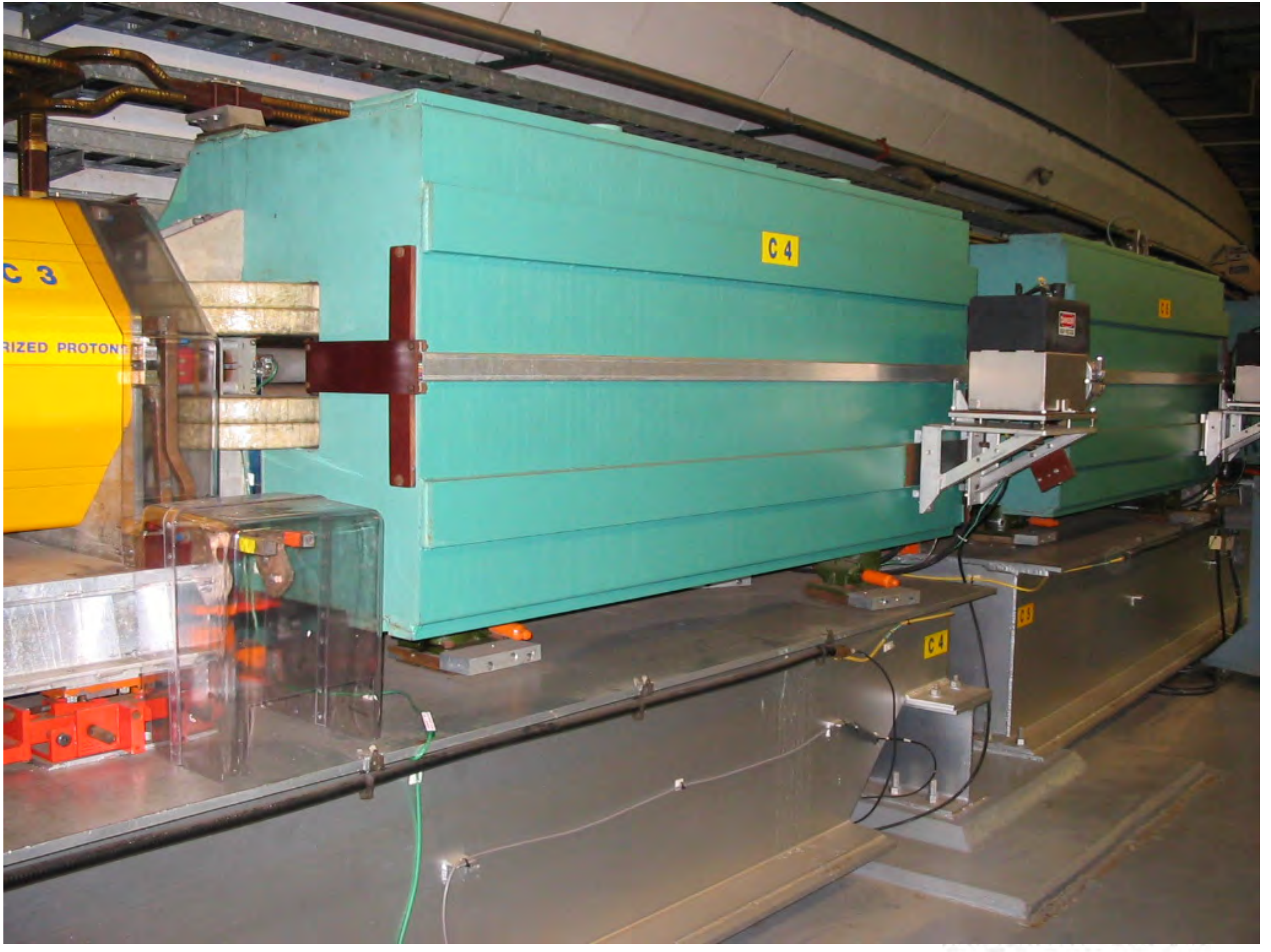


AGS Superperiod

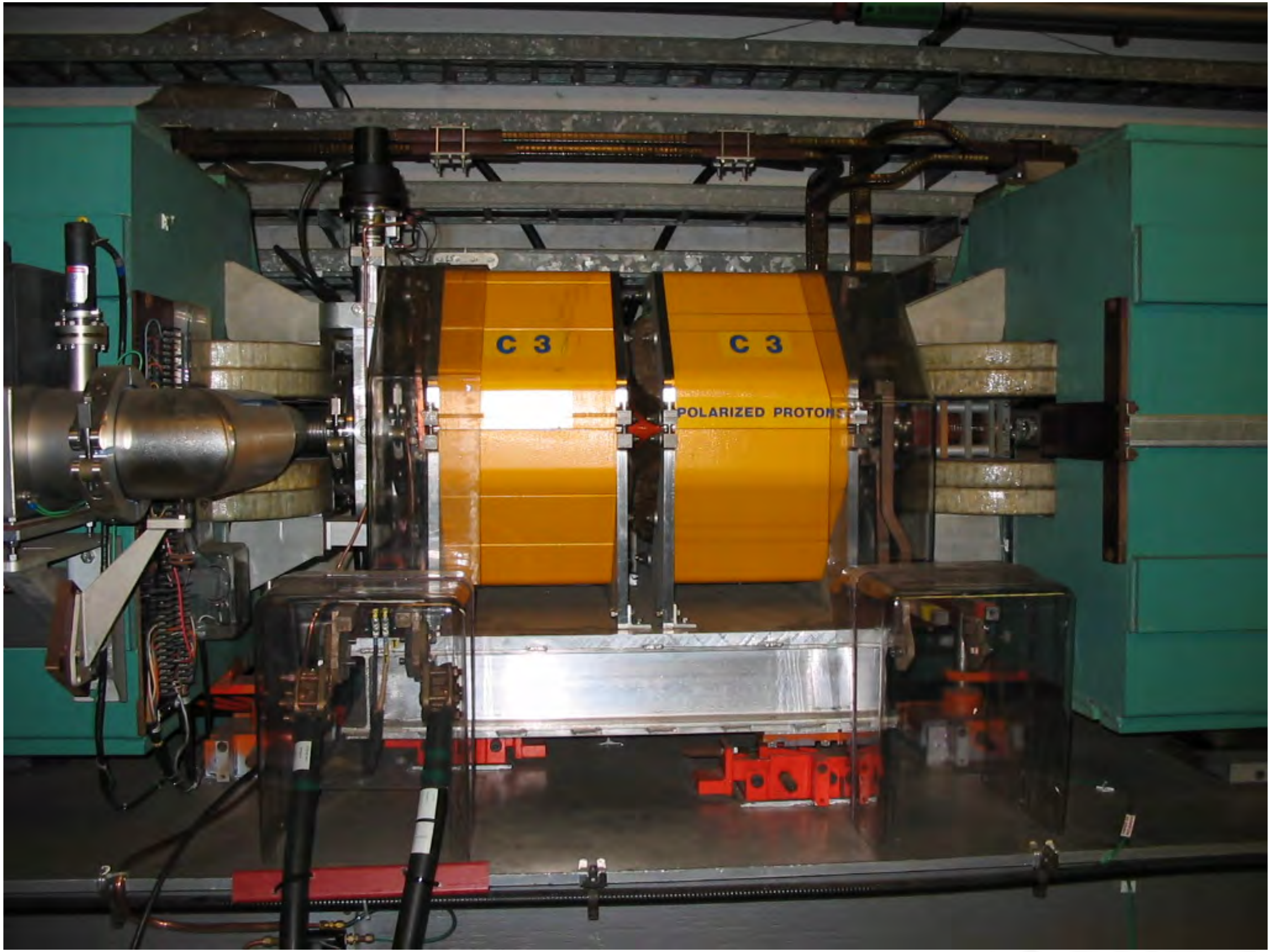
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
h	h	v	v	h	h	v	v	h	h	v	v	h	h	v	v	h	h	v	v
s	s	l	l	l	l	l	l	s	s	s	s	l	l	l	l	l	l	s	s

- The AGS is composed of 12 unit cells or superperiodicity of 12.
- Each superperiod consists of 20 long (l) and short (s) combined dipoles with horizontally(h) and vertically(v) focusing gradients.
- The two tuning quadrupoles are located in sections 3(vertical) and 17(horizontal) in each superperiod. Additional twelve vertical tune quads are in sections 3 for polarized proton operation.
- Sextupoles are in sections 7 and 13.
- Symmetry points of each superperiod are at section 5 and 15.

AGS C4 Dipole Magnet



AGS Quads between C3 and C4 Dipole Magnets



Parameters of the AGS and the Booster

Parameters	AGS	Booster
Circumference	807.07m	201.78m (1/4 of AGS)
Betatron Tune Qx, Qy	8.75, 8.75	4.82, 4.83
Transition γ_{tr}	8.5	4.88
Peak bunch intensity	$1.2*10^{13}$	$1.7*10^{13}$
RF harmonic number	H=12,8,6	H=4,3,2,1
Space charge tune shift	0.2	0.5
Maximum Bdot	2.2T/s	9.5T/s
Superperiod	12	6
Injection Energy (kinetic)	1.41->1.56->1.9	0.2
Extraction Energy(kinetic)	24-29	1.41->1.56->1.9
Beta function β_{max}, β_{min}	22m, 10m	13.7m, 3.6m
Dispersion; max, min	2.2m, 1.5m	2.7m, 0.5m

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Space Charge Tune Shift

Direct tune shift from space charge force is given by:

$$\Delta Q_{\mathrm{dsc}} = -\frac{N_{\mathrm{b}} r_{\mathrm{p}}}{4\pi B \beta \gamma^2 \epsilon_{\mathrm{N}}}$$

To reduce the effect, one can:

1. Raise the injection energy (γ);
2. Reduce the bunch factor(B);
3. Enlarge the emittance (ε_N).

AGS/Booster Scheme

1. LINAC: charge exchange injected into Booster. 200MeV, 300 turns, 33mA H^-. Intensity of $1.2\text{-}1.5*10^{13}$ after H^- injection was introduced in 1983.
2. Booster: accelerated to 1.4-1.9GeV kinetic energy.
3. AGS: take 4-6 Booster transfers, accelerated to 24GeV. Need to cross transition at 8.7.

Development of harmonic numbers and intensity in 1990s

Run Year	Harmonic Numbers		Booster Cycles	Intensity $x10^{12}$
	Booster	AGS		
94	3	12	4	40
95,96, 97	2 & 4	8	4	63
98 SEB	1 & 2	6	6	71
98 g-2	1 & 2	6→1 2	6	58

Beam Loss at Booster Injection

1. The highest loss point, in terms of protons, was at Booster injection.
2. The Linac delivers 35 mA beam current and is capable of maintaining this for pulse widths of 500 μsec and so can totally saturate the Booster capacity. In fact the Booster is routinely delivering 22 Tp/ cycle x 4-6 cycles/ AGS cycle, operating 50% above its "design" intensity of 15 Tp.
3. Space charge driven losses early in the cycle are expected, but pouring more Linac beam in is the obvious source for higher AGS output. Losses at Booster injection vary significantly but are typically 30%.

Fighting Space Charge in the Booster

1. Dual harmonics to change the bunch length and bunching factor.
2. Incoherent tune shift still reach 1 and not sustainable. Ramp injection field and linac energy by 1% during the injection and ramp fast right after.
3. Reduce the harmonic number from 4 to 1 (single bunch). This requires very low RF voltage.
4. Upgrade the Booster ramp rate to very fast: 9T/s, finish a cycle in 75ms. One can run 8 Booster cycle for one AGS cycle.

Beam Loss in the AGS

1. AGS injection losses include both losses in the transfer process, and losses incurred as the four Booster batches are accumulated on the injection porch. A quarter is from Booster and BtA line. A quarter is during the accumulation time at injection, so called "drool" loss. This was reduced by introducing octupoles. Sharp coherence losses can occur during this injection intervals and are controlled by vertical betatron tune adjustments in conjunction with AGS vertical damper. A third quarter of beam loss could be seen on the AGS current transformer on a ms time scale at each of the four transfers. The remaining quarter was not explicitly accounted for either in the loss monitor or wall monitor. It was most likely happened in tens of turns around the machine and also ended in ring locations having low sensitivity in the loss monitors. These losses could be space charge driven.
2. Transition crossing at 8GeV. This loss is potentially serious radiation sources because of the beam energy, but it is usually under 4%. It requires constant attention.

Fighting Space Charge in the AGS

1. Transverse feedback system damps bunch instability during injection.
2. A low impedance RF system allows low voltage at high beam current during accumulation in the AGS.
3. Betatron tune set at 8.9 to avoid non-linear octupole stopband resonance at 8.75.
4. To reduce space charge effect further, the beam bunch are lengthened by purposely mismatching the bucket.
5. Another high frequency (92MHz) dilution cavity to reduce peak current at injection and after transition crossing.

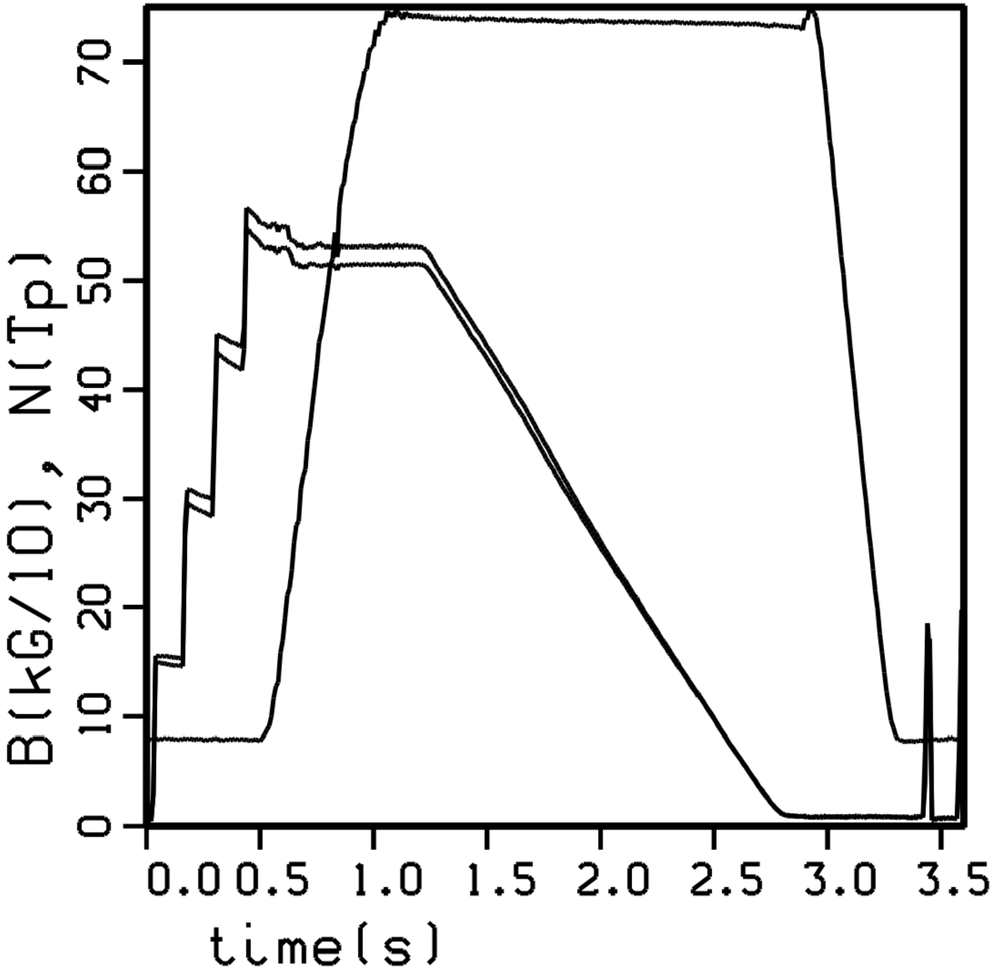
AGS Improvement in 1994

1. Rasised injection energy from 1.41GeV to 1.56GeV.
2. Gamma_tr jump system was commissioned (ramp up in 60ms and jump down in <1ms). The crossing rate was increased by a factor 30 but the byproduct is smaller aperture due to the associated dispersion and beta function changes.
3. The large Dispersion and not centered orbit in quads lead to beam loss. A smaller longitudinal emittance with tune jump makes the beam unstable after transition.
4. Significant slow losses across the front porch have so far been avoided.
5. The final power amplifiers for the 10 cavities were moved into the ring. A fast feedback loop was implemented.
6. A bunch-shaper damper was essential for efficient transition crossing.

AGS Improvement in 1995

1. A higher harmonic dilution cavity (h ≈ 270) which aids filamentation and increases the emittance. Not only a large bunching factor but also adequate momentum spread appear to be necessary for beam survival on the injection porch and that the dilution cavity creates both.
2. Broadband impedance was greatly reduced by: removing the 10 fast ferrite quads (opening the vertical aperture, replacing the ceramic chambers with metal ones reduces beam induced signals; upgrading high pass networks).
3. A vertical survey of the AGS during the summer shutdown of 1994 led to repositioning several combined function magnets. The rms orbit excursions decreased significantly in both planes.
4. Continue commission the transition jump system. Moved the jump quads so that beam centered on the jump quad.
5. Two normal octupoles were added to the AGS lattice.

AGS Beam Intensity with Octupoles on and off

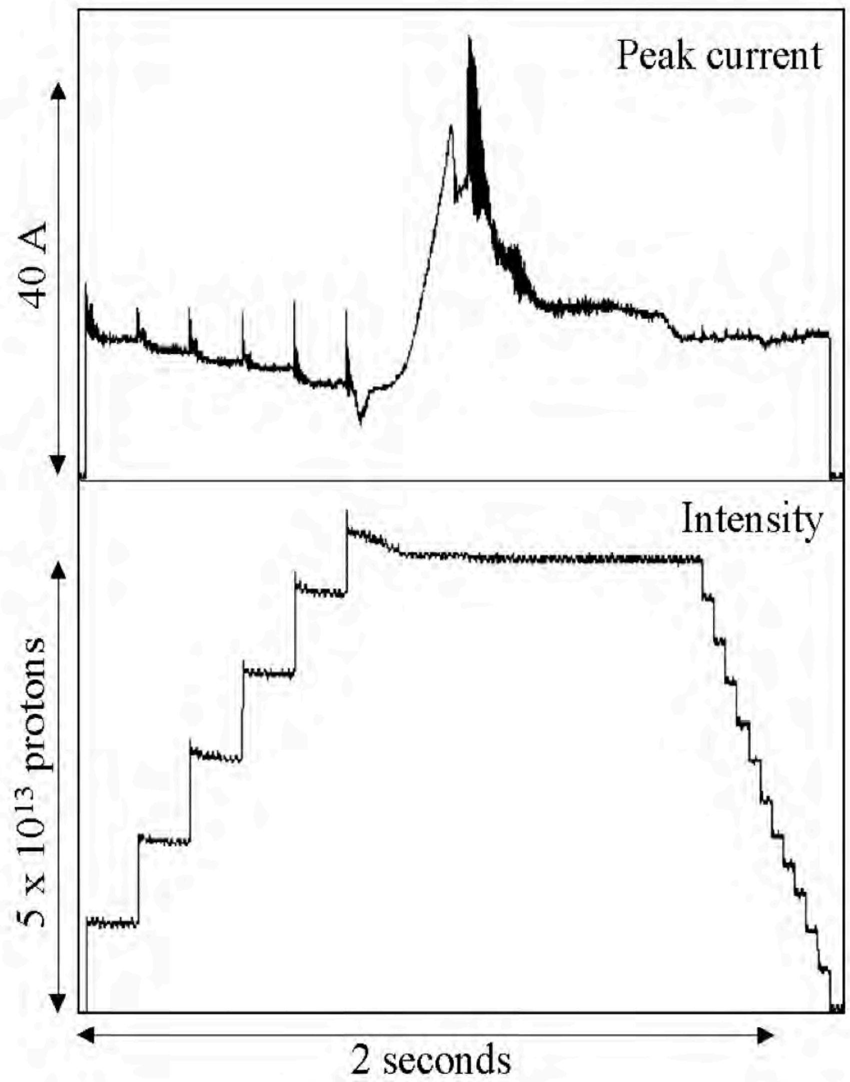


It has been found that losses on the decapole lines going through $Q_x = Q_y = 8.8$ can be largely corrected by the octupoles. In any case, the high intensity coherent tunes at injection were down by ≈ 0.05.

Total Intensity and Peak Current of AGS

To reduce the space charge forces further the beam bunches in the AGS are lengthened by purposely mismatching the bunch-to-bucket transfer from the Booster and then smooth the bunch distribution using a high frequency dilution cavity. The resulting reduction of the peak current helps both coupled bunch instabilities and stopband beam losses.

The right plots were for the case of fast bunch extraction for g-2 experiment.

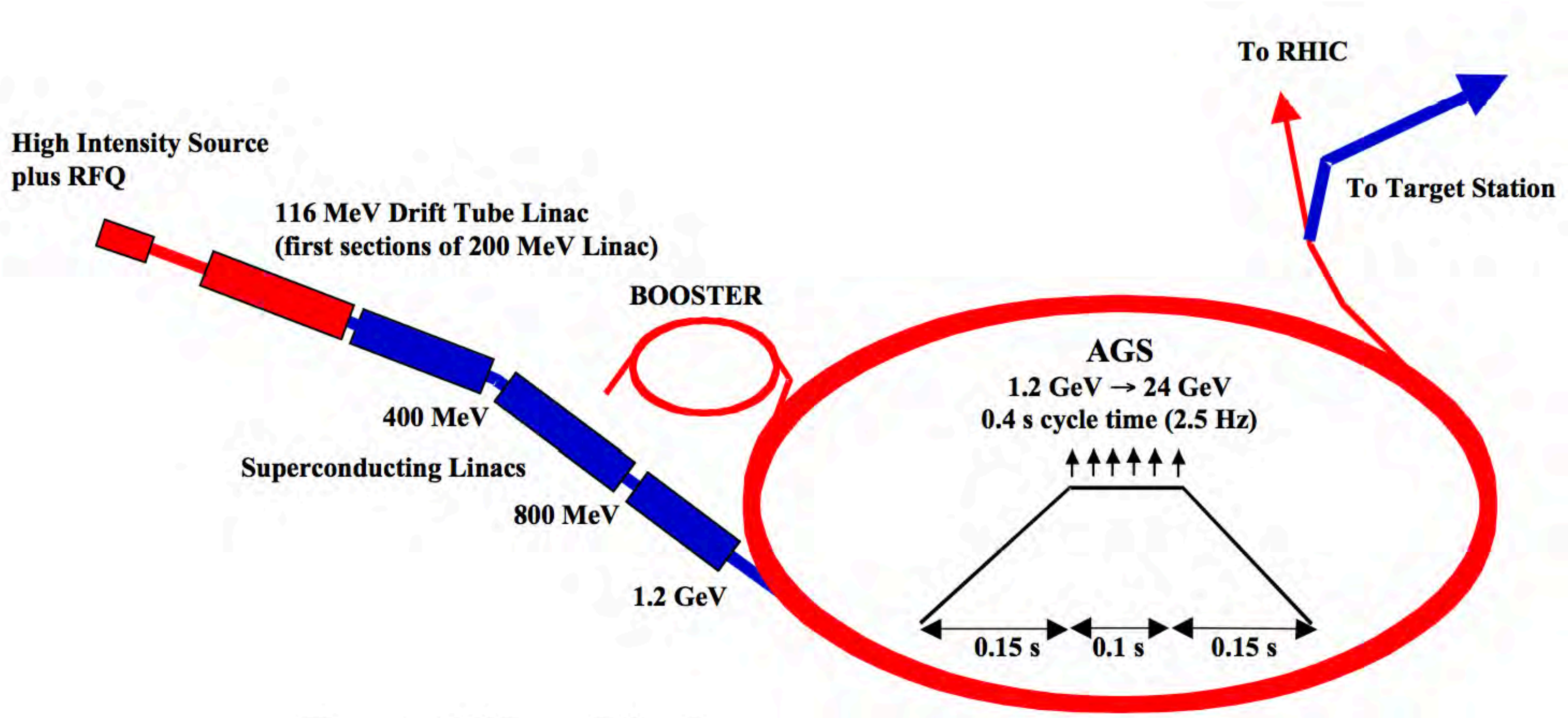


Summary

1. AGS exceeded upgrade (Booster) goal in intensity: $7.1*10^{13}$ vs $6*10^{13}$.
2. The intensity increase came from many factors: Higher Booster extraction energy; Booster injection with ramping field; faster Booster ramp rate; double RF cavities in the Booster and lower harmonic number; Octupoles in the AGS; AGS magnet realignment; new gamma_tr jump system; AGS dilution cavity.
3. As Brookhaven was transformed from high energy physics program to nuclear physics program, the high intensity operation came to the end in 2001.

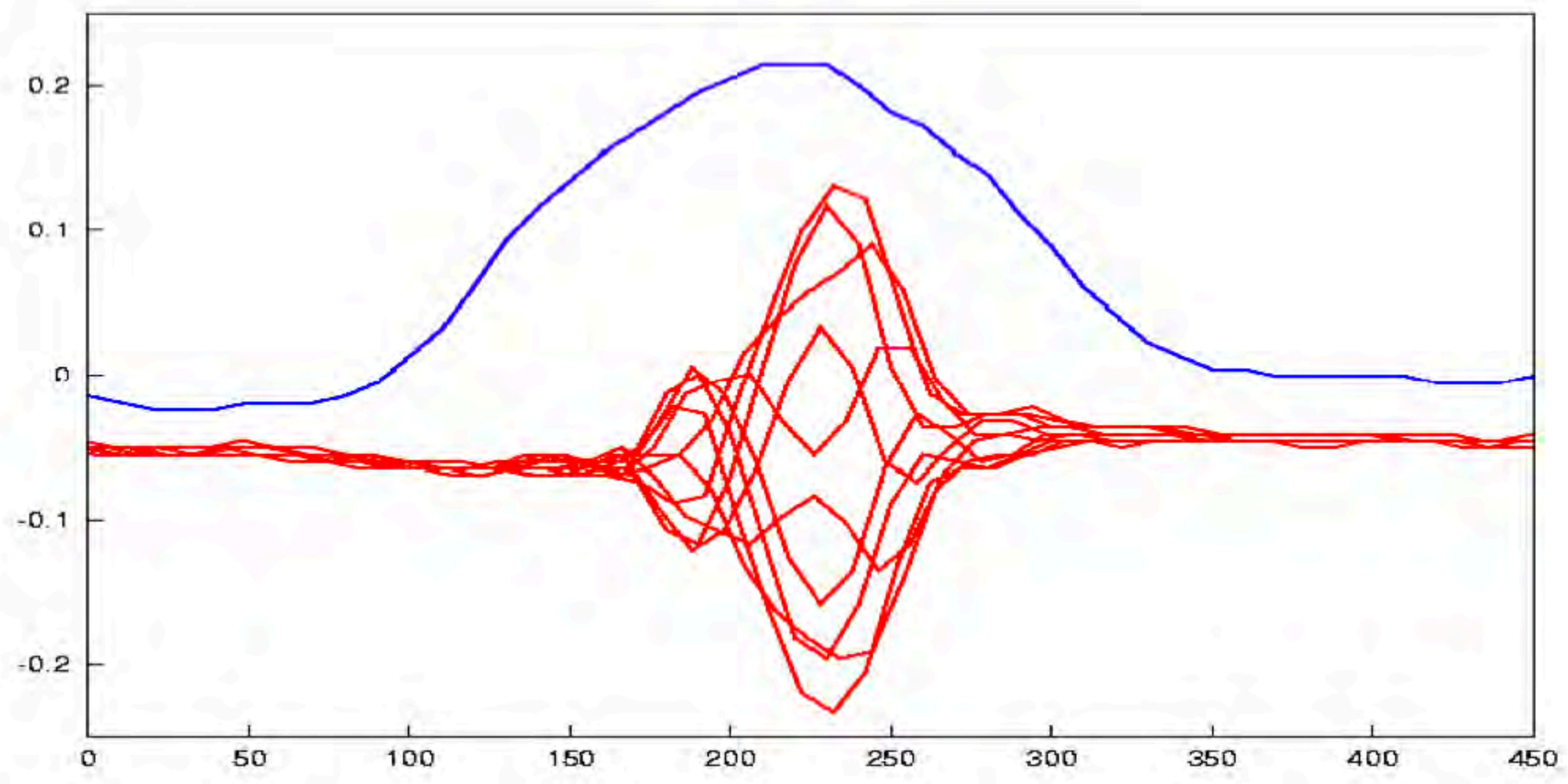
Backup Slides

AGS as a Proton Driver



Increase AGS average beam power from 0.2MW to 1MW. It requires power supply and RF upgrade for faster ramping in additional to the 1.2GeV superconducting linac. This was proposed in early 2000, but never proceeded.

Single Bunch Vertical Instability in the AGS



(ns)

BPM signals: sum (blue) and difference (red).
The instability caused emittance growth and was self limited after some beam loss.