RHIC Commissioning Experience

Facility Overview

Chronology

Magnet Interconnection

Vacuum

Cryogenics

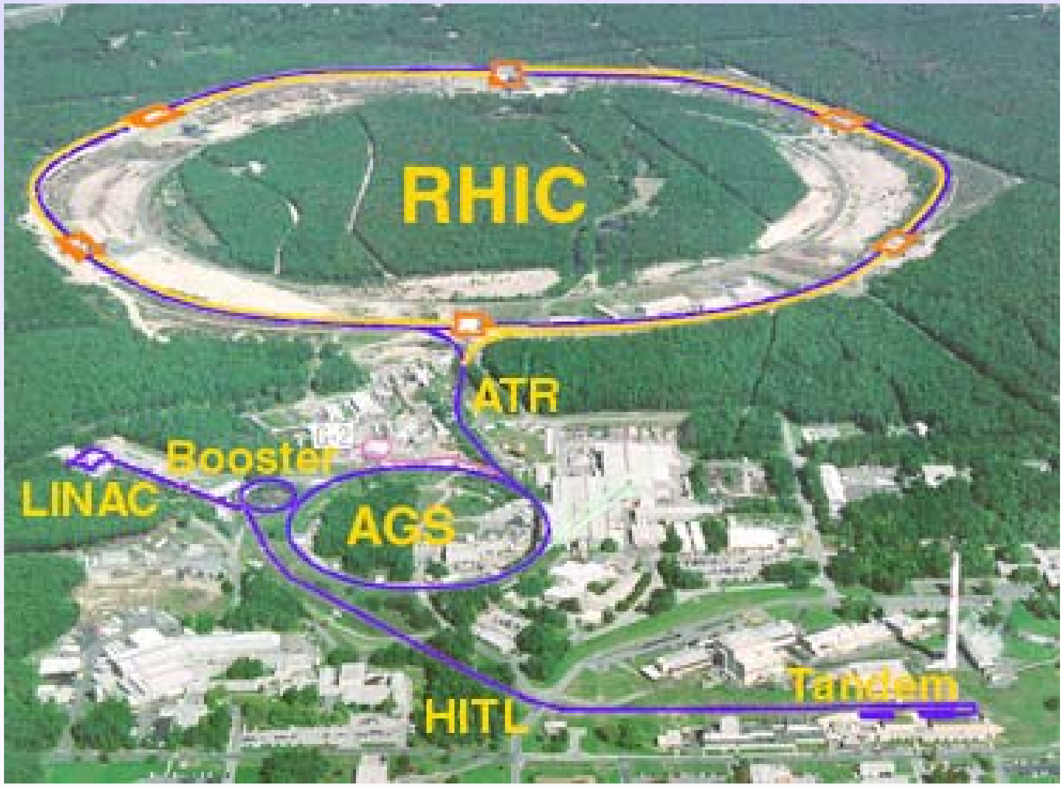
Power Converters

Beam

I'll focus on basic commissioning activities of the type required for collisions at energy i.e. LHC 2007/8. No luminosity related topics (intensity, diagnostics, MPS, collimation, lo-beta etc…)

RHIC Commissioning - Facility Overview

- Gold ions at 100 Gev/u, protons to 250 Gev
- two independent rings
- 4km circumference
- 300 dipoles, 400 quad packages, 8cm aperture
- field strength 3.5T, 72 T/m
- 120 large aperture IR magnets (10, 13, 18 cm)
- 6 identical IR's (dipole first)



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RHIC Commissioning - Chronology

- Construction project 1991 -> 1999
- Nov 1993 Cell test - finalize arc magnet design
- Jan 1997 major systems test - beam through 1 sextant
- last magnet delivered to the ring - Nov 98
- mechanical installation complete - Jan 99
- pump down, leak checking & vacuum certification - Feb/Mar 99. Bellows repair.
- cooldown start - April 99. Blue ring cold end of May 99, Yellow ring July 99. Forced warm up during May. Power supply testing.
- permission to operate - end of June 99.
- Circulating beam in Blue Ring - July 99

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RHIC Magnet Interconnections (the non-IP elements)

- 864 “standard” 8 cm magnet interconnects
  12 joints per interface
  25,000 in situ welds, 10km weld length

- Many electrical splices, two 5KA circuits per ring

- All work performed by Project manpower

- First sextant started 5/95
  - First Sextant closed (all elements) 12/97

- Last RHIC 8cm interconnect closed 4/98

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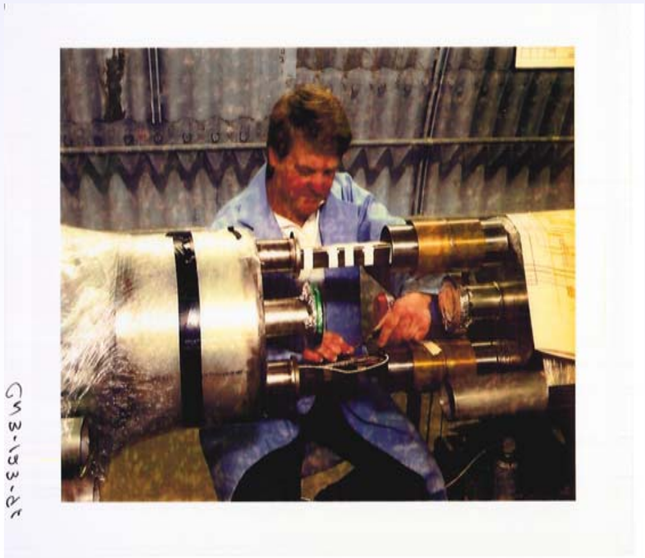
RHIC Magnet Interconnections

- Magnet delivered to tunnel.
- Surveyed into place.
- “Rolled flanges welded on magnet lines (4 places). cryogenic lines measured.
- Electrical interconnection, testing of string (14 interconnects maximum).



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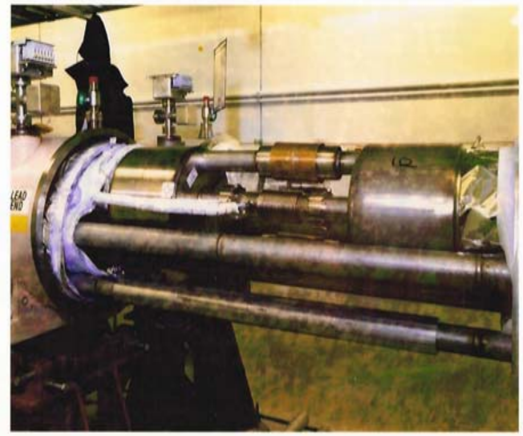
RHIC Magnet Interconnections

- Weld & leak check magnet lines / cryogenic process lines
- Install cold bore vacuum components & BPM cables.
- Install cold mass cage. Wrap cold mass and cryogenic lines in MLI
- Install & weld lower heatshield



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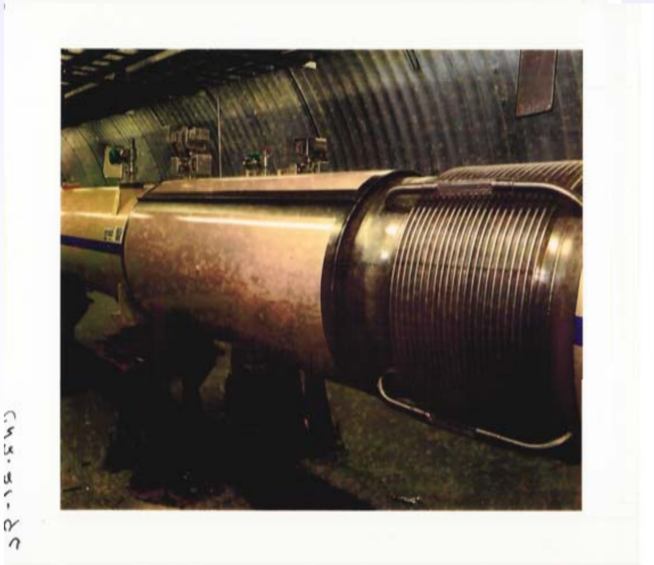
RHIC Magnet Interconnections

- Install & weld upper heatshield
- Wrap heatshield with MLI
- Mount & weld outer shell of vacuum vessel.
- Leak check string



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RHIC Magnet Interconnections

- Technical Staff (at steady state):
  - 1 Technical Supervisor
  - 6 Mechanical Technicians
  - 4 Electrical Technicians
  - 2 Vacuum Technicians
  - 4 Welders
  - 4 Survey Technicians

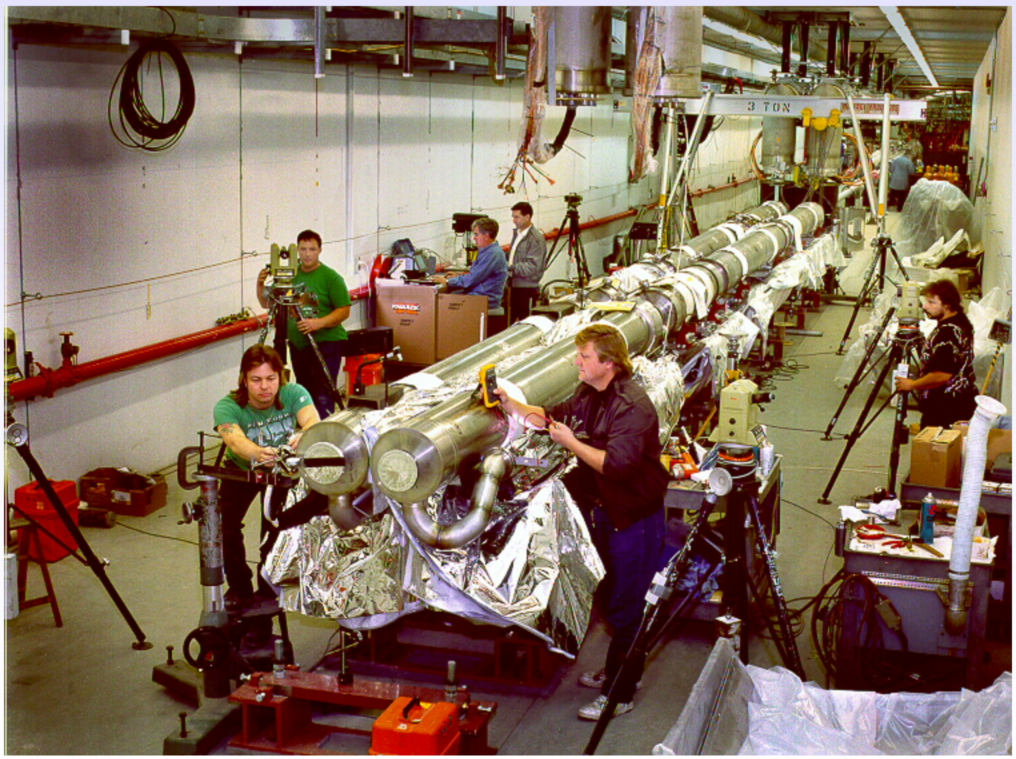
- Other tunnel work simultaneously in progress: Magnet Placement, IP Triplets & dipoles & W-t-C Transition Installations

RHIC Magnet Interconnections

- Work flow:
  - Developed a 10 day Work flow
    - 6 major components with different levels of effort
      - Each completed on a 10 workday schedule.
      - Each with a team dedicated to that task component.
        - » Gaining expertise & specific fixes / solutions
      - Each team must complete on time to allow next team to move in to area. Multiple serial efforts.
      - Schedule included time for electrical & leak/pressure testing.
      - Aggressive survey progress yielded work flexibility.
  - Initially (First Sextant), low interconnection efficiency
  - Improved throughout RHIC installation to ~2 interconnects closed/day

Mechanical Installation - IR's

- automatic welding wherever possible.
- Final focus cryostat assembled in situ. Hand welds in triplets.



RHIC Magnet Interconnections

- First Sextant
  - 2 Arc regions, 144 interconnects
  - Over 16 month effort
    - Issues:
      - Magnet availability/placement in the tunnel non optimal (not in a row)
      - Modifications to interconnect MLI blankets *in-situ*
      - Learning curve / finding & solving installation problems
      - Eliminating time (tasks) to "make" schedule

- Essentially everything we did the first time became an issue, essentially everything the second time was O.K.

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RHIC Magnet Interconnection

- Lessons Learned
  - Maintain hot spares for all essential tools:
    - Working spares and establish quick vendor repair turnaround.
  - Automatic welding machines have tight alignment tolerances. We allowed welders to visually inspect all welds and "wash over" questionable areas (~20%).
  - Risk/benefit of all testing activities
    - Eliminated thermal shock testing
      - From >25,000 welds, 2 leaks that may have been from thermal shock.
  - As confidence builds, extend string length for electrical and vacuum / pressure testing (4 magnets -> 20 magnets).
  - Preserve momentum. If process problems develop & require repair, isolate & solve, but continue forward progress to keep schedule. Affect the repair later as resources become available after completing the ring.
  - Verify all welding machine ground connections to avoid damage to electronics.

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RHIC Magnet Interconnection

- Lessons Learned (cont)
  - Initial installation & leak check procedures/some components modified after first sextant review
  - After the initial learning curve the repetitive mechanical installation was very predictable (both arcs & IR's)
  - Understand safety requirements at the design stage
    - bellows failure in a single component (D5I) of the inner ring during high pressure safety certification
    - RF fingers displaced by bellows motion in non-magnet cryostats resulted in aperture problems in several locations (again high pressure safety certification)

RHIC Commissioning - Vacuum System

- Insulating vacuum: <10^{-5} Torr
  - 12 Arc cryostats, 500m, 150m3 volume
  - 12 IR cryostats, 25m, 50m3 volume
  - 4 small cryostats in the injection region
  - No internal vacuum barriers in the insulating vacuum
  - 1 permanent turbo pump on each insulating vacuum region
- Beam tube
  - ~10^{-9} torr warm,
  - <10^{-10} cold (cryopumped)
- No helium to bore tube welds

RHIC Commissioning - Leak Checking

- After interconnection
  - Sniff around the welds with 2 atm He $> 10^{-4}$ std cc/sec
  - Pump on the 4 cryogenic lines $< 10^{-8}$ std cc/sec
  - Found ~40 large leaks ($> 10^{-4}$ std cc/sec to very large leaks)
- After completing and pumping on the cryostats we had a He background of $> 10^{-7}$ std cc/sec from helium in the MLI
  - Pressurize sextants to 3 atm He
  - Pressurize rings to 10 atm He
  - Located and repaired ~15 leaks of $>10^{-5}$ std cc/sec using He pressure gradients
- 12 out of 28 cryostat volumes had a He background of 10^{-4}- 10^{-6} std cc/sec at 10 atm warm.
  - These have been gradually repaired as opportunity presented itself
- No cold leaks
- No beam tube leaks

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RHIC Commissioning - Pumpdown and repair times

- Pump-down of the insulating vacuum
  - 1-2 days to get to ~1 torr without air large leaks on roughing pumps
  - Check for air leaks with ultra-sonic detectors
  - 10^{-2} torr with mechanical pump station
  - Repeated (3-5) bleed-ups for repair of air leaks (big leaks mask smaller ones)
  - ~ 6-10 days per vacuum section to locate and fix air leaks
- Locate and repair He leaks of > 10^{-5} std cc/sec warm
  - ~ 1 day to locate the interconnect and the offending cryogenic line
  - ~ 2 days to cut open the cryostat and repair
  - ~ 1 day to close up
  - ~ 1-2 days to certify
- Leaks < 10^{-5} (warm) locate and pump using mobile turbo pumps. At times we have had up to 9 additional turbo pumps at various locations

RHIC Commissioning - Cryogenic System

- 1 refrigerator (20 kW at 4K) with built in (parallel) redundancy. 75% nominal overcapacity.
- High pressure (< 15 atmos) super-critical He as coolant with distributed heat exchangers
- Sextant flow and isolation controlled by valve boxes at IR's

Experience

- Water contamination and air required unanticipated refrigerator warm- up during initial cooldown
- Measured heat load in good agreement with design
  - Primary 4K: design 4.3 kW, measured 4.05kW (one ring).
  - Primary 4K from leads: design 2.15kW, measured 2.3 kW.
  - Secondary 50K heat shield : design 31kW, measured 36 kW.

Cryogenic Valve Boxes - 1 per ring per sextant

- Cryogenic control for a sextant and power leads for the IR circuits
- Cryo-loop termination point
- The biggest cryogenic problem
- Difficult to test unless *in-situ*

- Internal bellows & vale stem leaks from un-removed solder flux - difficult to repair
- Lifetime effects on the power lead ceramic-metal joints

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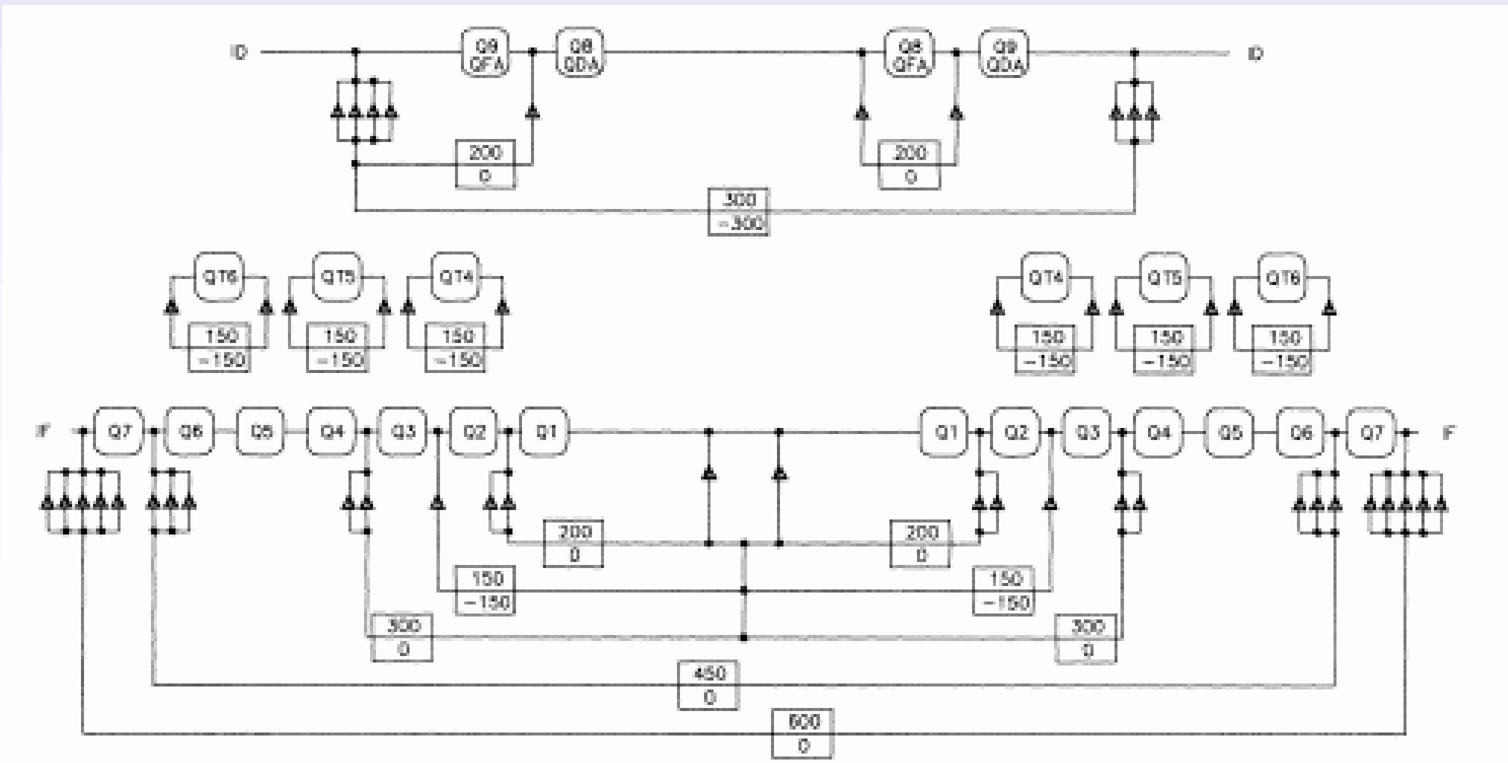
RHIC Commissioning - Power Converters

- 4 Main supplies (5kA), 239 IR supplies (150A-> 600A), 668 tunnel supplies
- All IR buss work superconducting, conventional power leads
- 75% of IR supplies are nested loops
- Active quench detection (resistive voltages) on ring wide link, cold diodes for quench protection



RHIC Commissioning - Power Converters (IR's)

- Initially all power converter testing was performed on resistive (short circuit) loads. This addressed basic power supply operation
  - Typically 40 power converters in an IR + (4 main supplies at 4 o'clock)
  - The team consisted of an engineer and 2 techs.
  - Each IR took ~ 2 weeks to commission on the resistive loads in the service buildings
  - Power converters were operated through the control system (ON/OFF/RAMPING/STATUS)
  - primitive diagnostics (no post mortem or interlock timing resolver)
  - Two parallel teams

- Cold operation the required the commissioning of the nested loops
  - An additional ~10 days per IR per team to complete current regulation on the inductive loads and integrate into the quench detections system

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RHIC Commissioning - Power Converters (ARC's)

- Initially all power converter testing was performed on resistive (short circuit) loads.
  - Each ARC alcove took ~ 3 days to commission on the resistive loads in the service buildings
  - Typically 40 power converters in an ARC alcove (dipole correctors, higher order corrector, sextupoles, no nested supplies)
  - The team consisted of an engineer and 2 techs.
  - One team
  - Power converters were operated through the control system (ON/OFF/RAMPING/STATUS)
  - primitive diagnostics (no post mortem or interlock timing resolver)
- No real issues going from warm to cold
  - 1 day to demonstrate all power converters

RHIC Commissioning - Power Converters (Main supplies)

- Initially all 4 5KA main converter testing was performed on resistive (short circuit) loads.
  - All 4 main supplies took ~ 3 months to commission on the resistive loads in the service buildings
  - Single engineer + 2 techs
  - Power converters were operated through the control system (ON/OFF/RAMPING/STATUS)
  - primitive diagnostics (no post mortem or interlock timing resolver)
- Cold operation
  - ~ one week for all 4 supplies for initial operation. Good enough to perform ramp and quench testing but not good enough for beam
  - An additional month to get to 'beam' conditions. Dynamic tracking of dipole/quad circuits.
  - No major noise problems (high inductance, low voltage)

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RHIC Commissioning - Power Converters (Quench protection)

- Main circuits have dump resistors with SCR switches (mechanical back-up)
- IR supplies IGBT switches for isolation with current limiting resistors
- Corrector supplies trip on over-voltage
- Single active quench heater on the IR crossing dipole
- All supplies on the quenched circuit are shut off
- Dedicated 'MPS style' quench link for power converter interlock. One for each ring.
- Distributed digital quench detection on all converter circuits (18 systems with multiple inputs) except the dipole correctors
  - Initial quench detector check-out warm with 0.1 A and check for correct voltage. Many problems were uncovered in this way (polarity reversals, mis-wiring, bad channels etc..). This was a CRITICAL step.
  - 1 team consisting of 1 eng + 1 tech would manage ~ 1 system per day.

RHIC Commissioning - Power Converters (Quench protection continued)

- SCR switches and dump resistors (12 elements) on the main supplies not much possible warm (ON/OFF/STATUS)
- Cold check-out took about ~ 1 week for all circuits. 1 eng + 1 tech.
- IGBT switches on the IR supplies (239) included in the power converter turn-on
- Quench detection cold check-out and final system integration
  - 3 eng + 4 tech
  - ~ 1 month to get to the point where (slow 5A/s) ramps were possible and initial beam operation at flat bottom
- All cold check out was performed in parallel in about 1 month. Total team of 8 engineers + 15 techs

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RHIC Commissioning - Power Converters major issues

- Systematic problems with a particular style of connector in the interlock link (transient problem, link dropped for 'no' reason, took a long time to eventually track this down).
- Systematic problems in some aspects of the power converters design (no lifetime testing)
- Noise on the controls circuit on the corrector supplies causing interlock trips
- Insufficient building cooling and environmental control (moisture, dust due to summer operation)
- Lack of suitable software resulted in very inefficient fault diagnosis with corresponding impact on beam operation.

RHIC Beam Commissioning - Chronology

- Rings cold June 99
- Blue ring circulating beam in July 99
- Circulating beam in yellow ring, accelerated beam in blue ring - Aug 99
- Rings ramped to 50% of operating current
- Sept 99 - Jan 00 shutdown
  - Power converter installation/modifications
  - Refrigerator valve replacement
  - Cryogenic valve box repairs
  - Beam pipe aperture restrictions
- Jan 00 - Cooldown start
- Feb 00 - Rings cold, power converter testing
- Mar 00 - beam operation- first 'physics' operation
- End of run Sept 00
- Achieved design luminosity in 02
- Operations Au-Au, d-Au, p-p (polarized, ~50% during store to date), Cu-Cu, various energies, 5th physics runs in progress.

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RHIC Commissioning - Initial Beam Results

- Optics fixed at β^*=3m (inj=10m) by power converter availability
- Beam emittances as design, bunch intensity down by factor of 5 (as requested)
- Under these conditions the magnets are cryo stable
- Ramp rate limited to 1 A/s for beam operation

Experience

- Beam optics looked good (1 quad shunt wired backwards)
  - Tunes within 0.01 (as built magnets in the data base)
  - ΔQ_{min} 0.03 without correction (magnet alignment)
  - Orbit correction in arcs worked fine, IR's not local
  - Bump around obstacle (RF finger) needed to circulate beam

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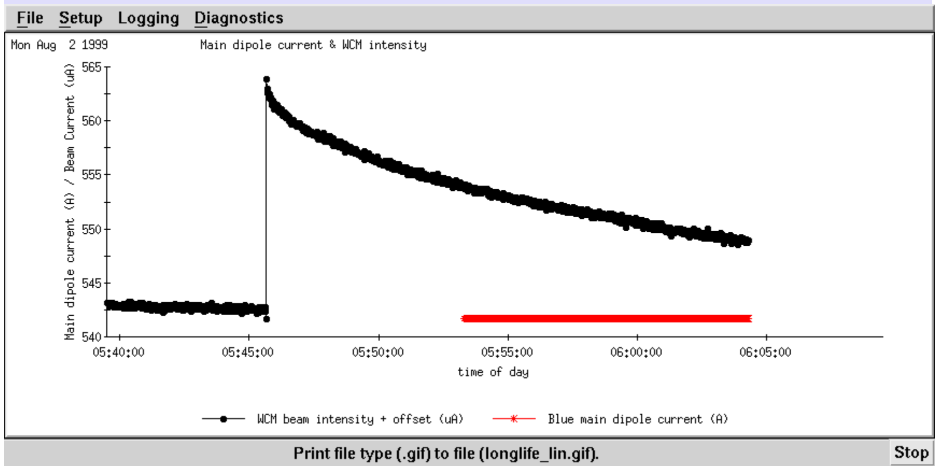
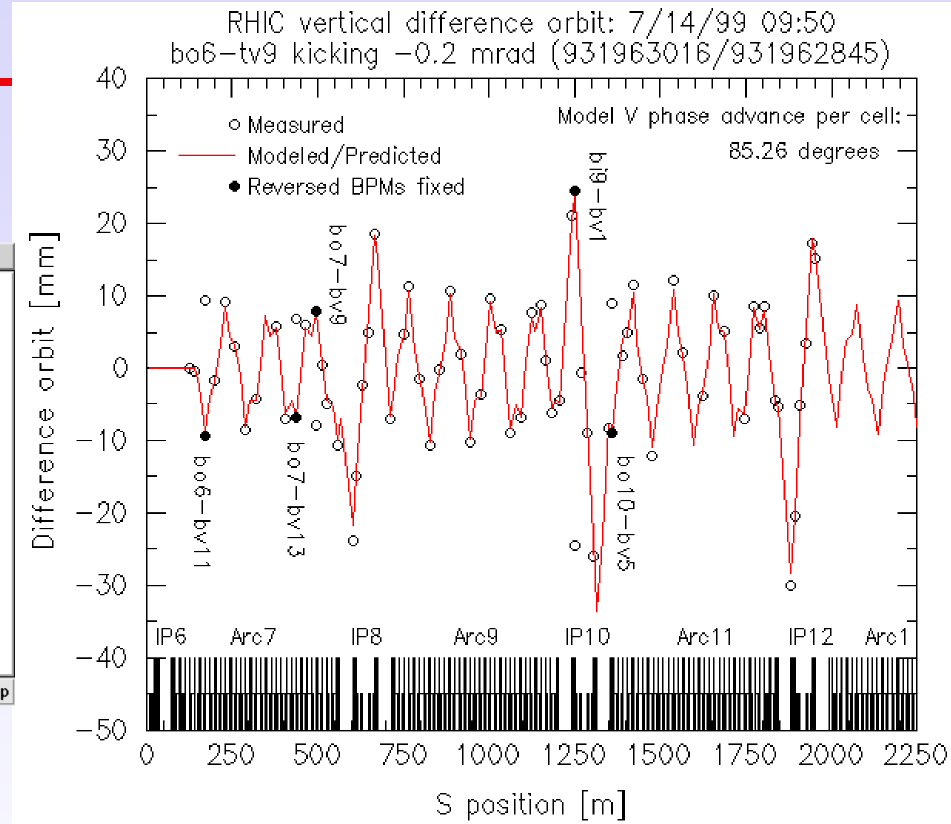
RHIC Commissioning - Beam Results

DC Beam



Injected beam lifetimes of several tens of minutes in spite of limited aperture (radial aperture ± 2mm)



Vertical difference orbit

Lattice defined by online model

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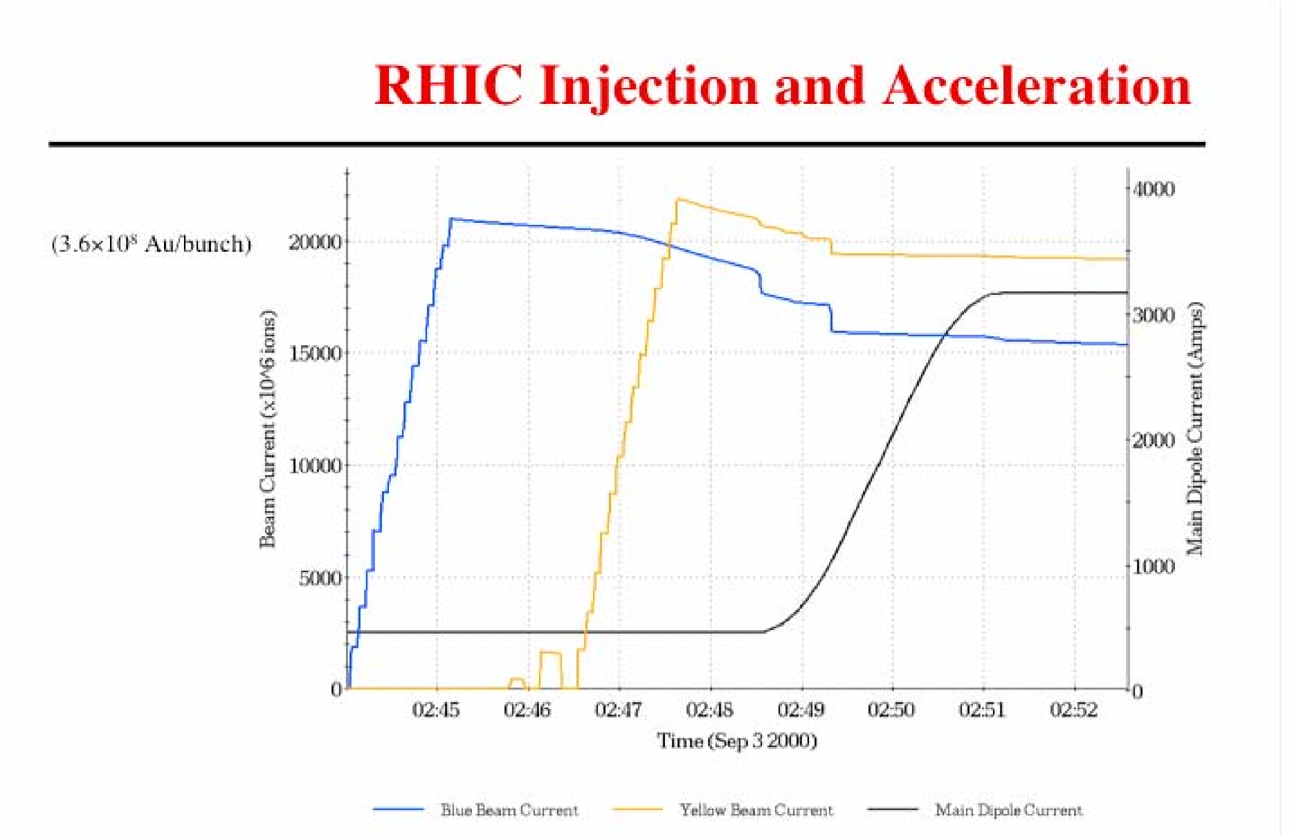
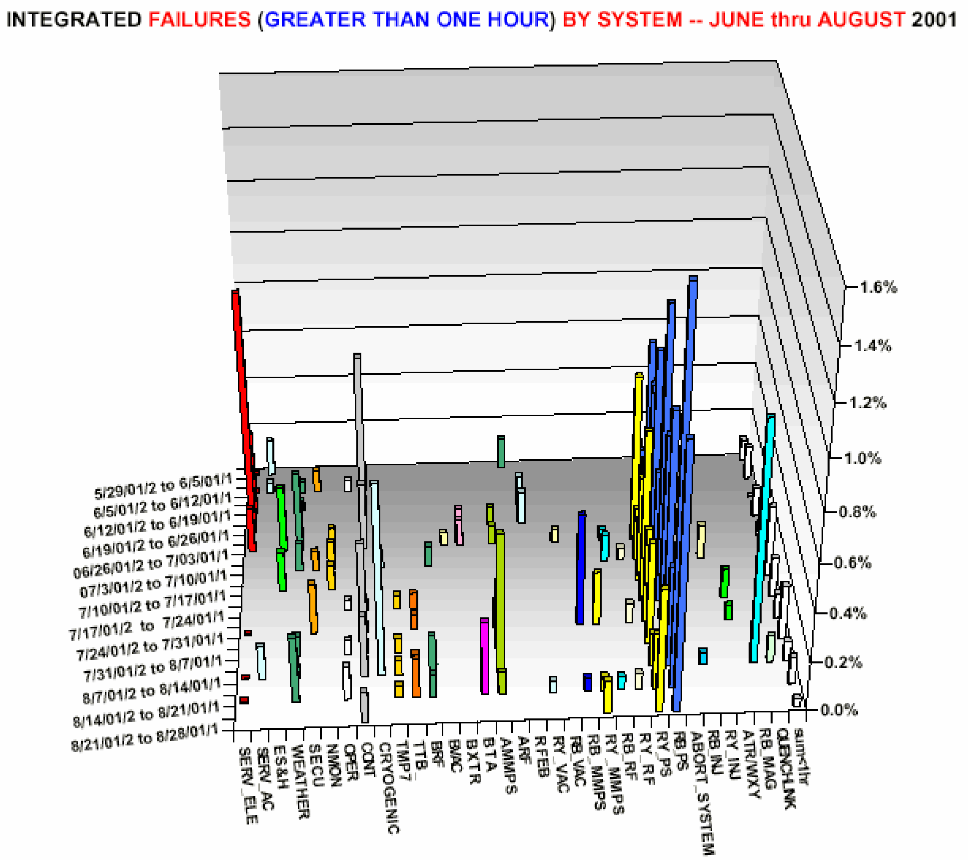
RHIC Commissioning - Second Running period



3 months into the first physics run still seeing 10-20% beam loss in the usual places

- Injection lifetime
- Long range beam-beam
- Snap back
- Transition

Early Operational Downtime - 2nd physics run



Downtime dominated by power converters.

- Many elements
- Operationally complex
- Quench protection system picks up 'all' glitches - twitchier than the machine protection system
- Took until the third running period before the power converters were not the major downtime component

Why power converters ? Unlike the MPS you can't desensitize the quench protection link. No 'safe beam' option.

RHIC Commissioning - Conclusions for LHC

- A significant amount of work can be accomplished with a warm, partially completed machine.

- Make sure that the octant test exercises as much of the sub- systems as possible. The integrated system test is a major effort which will disrupt progress in other areas. Always pressures to cut it short to get on with the balance of the work and 'maintain schedule'. In the long run this is counter productive.

- It is difficult to over emphasize the importance of diagnostic capability. The most disruptive problems will be the unexpected ones.

- It proved difficult at RHIC to predict/maintain a schedule during the commissioning phase. Try and remain flexible during this period.

Never forget: Adversity makes you strong !

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