APS Storage Ring Power Supply Reliability

7th Workshop on Power Converters for Particle Accelerators

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APS storage ring shut down midnight April 24, 2023.
A new storage ring is being constructed!

Outline

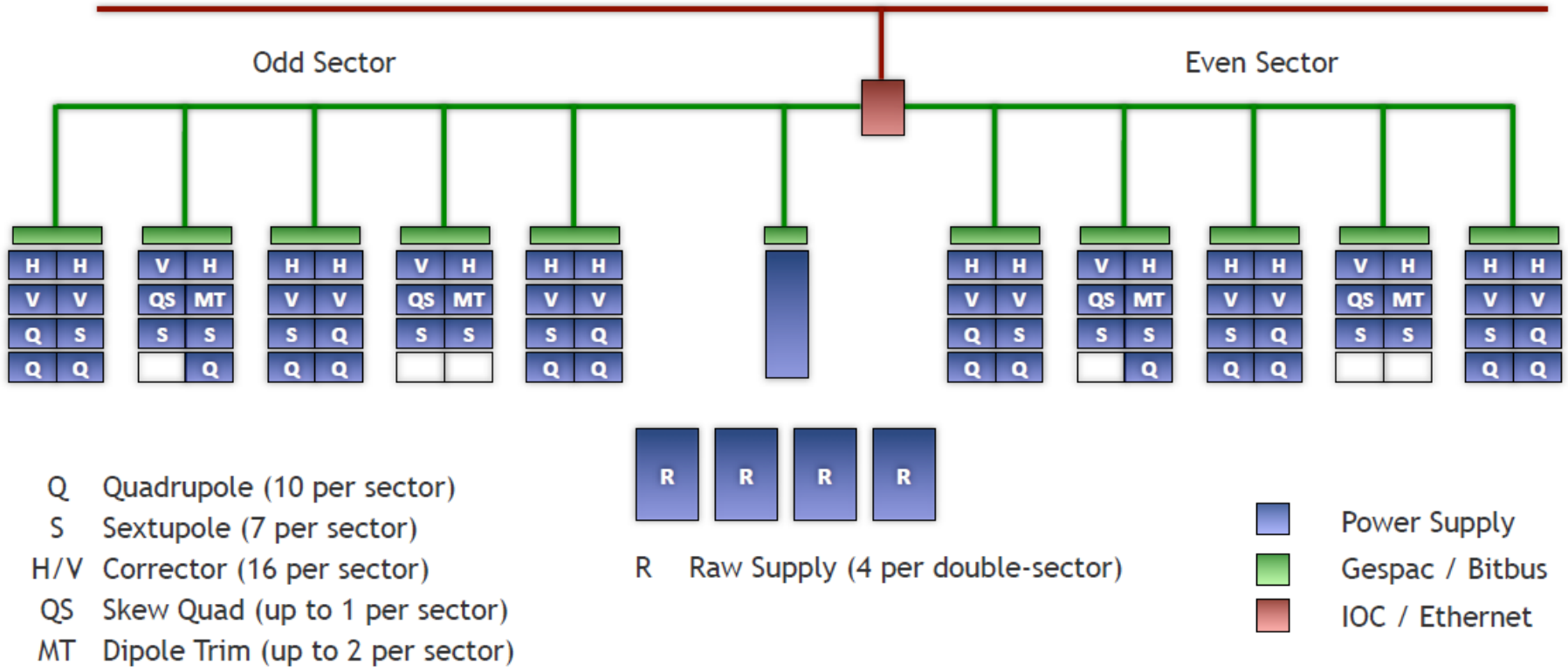
- Brief introduction of APS storage power supplies
- Power supply lifetime stability
- Major upgrades to improve the reliability
- Preventive maintenance
- Summary

APS Storage Ring Power Supplies

- 1500+ power supplies in the storage ring
  - **1 dipole supply, 1,500V, 500A**
  - **636 corrector supplies, ±150A**
  - **400 quadrupole supplies, 460A**
  - **280 sextupole supplies, 250A**
  - 59 skew quad supplies, 10A
  - 12 trim supplies, ±20A
  - **80 raw supplies for DC bus, 40V/62/V**
  - 2 pulsed septum supplies, 2kV
  - 5 kicker supplies, 15kV
  - 20+ supplies for canting beam lines
- **200 power supply controllers**
- A single malfunction of power supply or controller may cause a beam loss

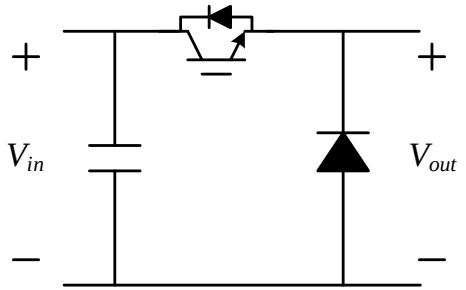
APS Storage Ring Power Supply Configuration

- Double sector configuration repeats twenty times



DC/DC Converters – Simple Design

- A basic buck converter design for quads and sexts, a simple H bridge for correctors
- Very few power components – no input filter and no output filter
- A simple analog P-I regulation loop – no digital PWM
- Interlocks on IGBT case temperature, capacitor temperature, magnet thermal switch, IGBT control power, etc.
- Open chassis – can see inside easily



	Input DC Voltage	Max Op. Current	Capacitor Rating	IGBT Ratings
Quad.	62 V	460 A	150 V	600 V/400* A
Sext.	62 V	250 A	150 V	600 V/400 A
Corr.	40 V	135 A	150 V	600 V/300 A

* Upgraded to 600 V/600 A

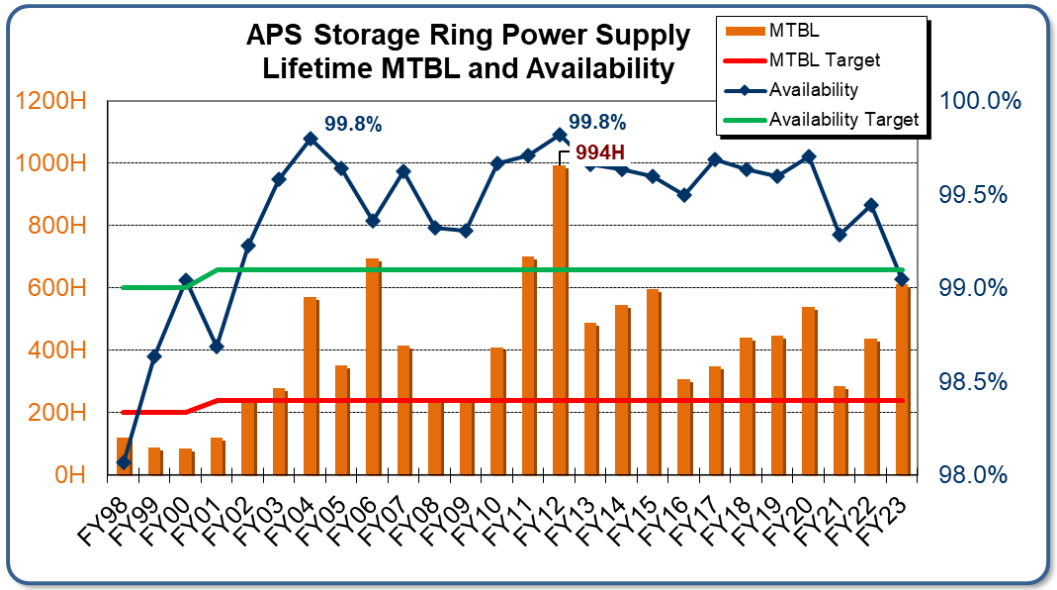
APS Storage Ring Power Supply Lifetime Reliability

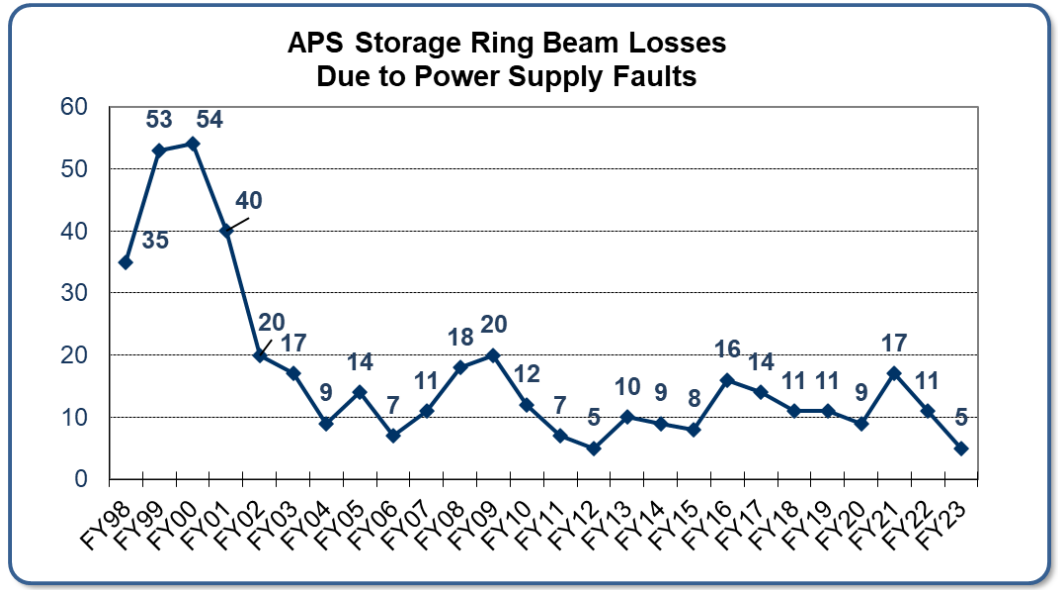
Operation Schedule

- 5000 hours of user beam time a year
- Six days user beam and one day machine intervention
- Three months of user beam and one month shutdown maintenance

Power Supply Reliability

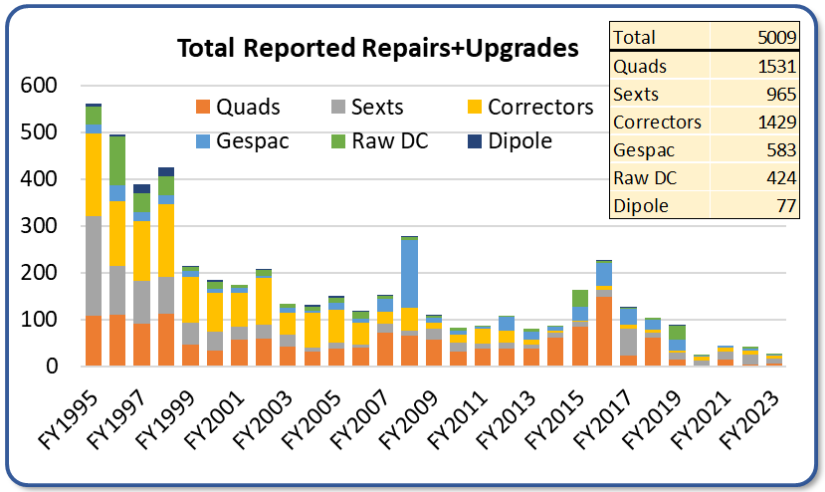
- Consistently exceeded goal of 99.1% availability and 240 hours MTBL
- Average availability greater than 99.4%
- Best year with 5 beam losses due to power supply faults, i.e., 1,000 hours MTBL



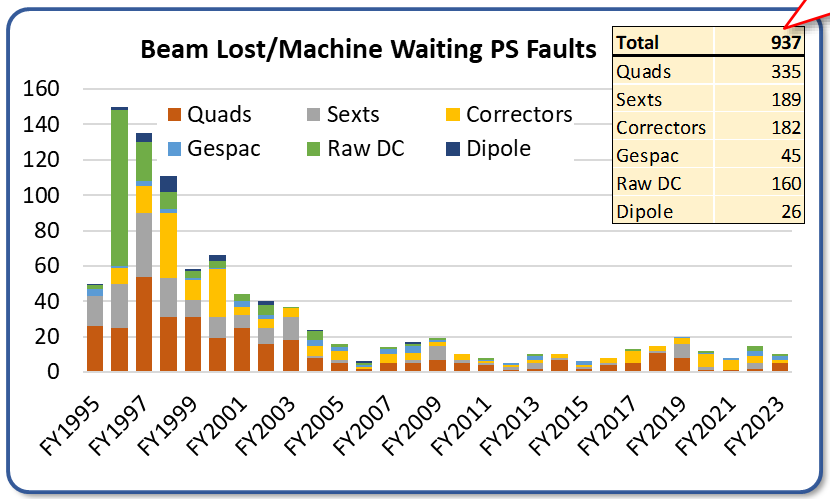


Number of Faults and Services of Lifetime

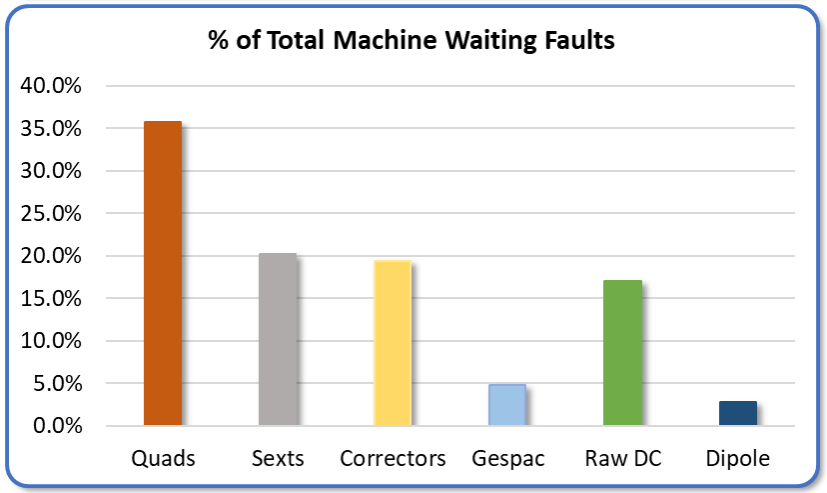
Since FY98,
- 602 machine waiting reports
- 443 beam losses, 73.6%

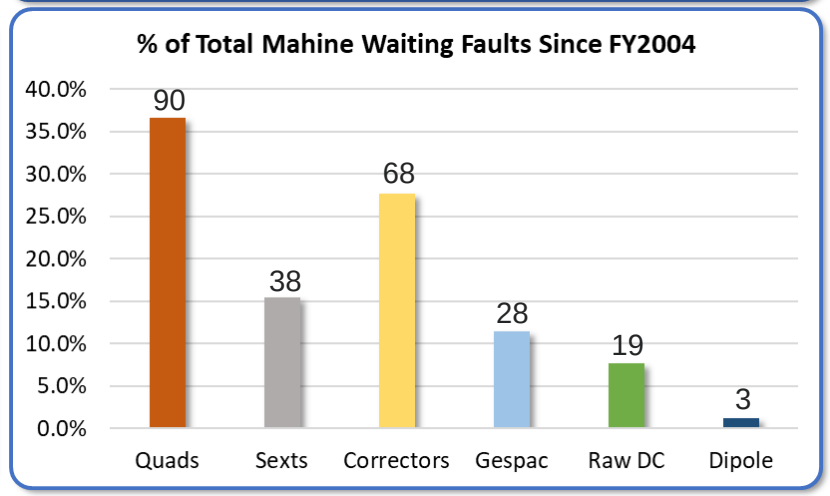


Total	5009
Quads	1531
Sexts	965
Correctors	1429
Gespac	583
Raw DC	424
Dipole	77



Total	937
Quads	335
Sexts	189
Correctors	182
Gespac	45
Raw DC	160
Dipole	26

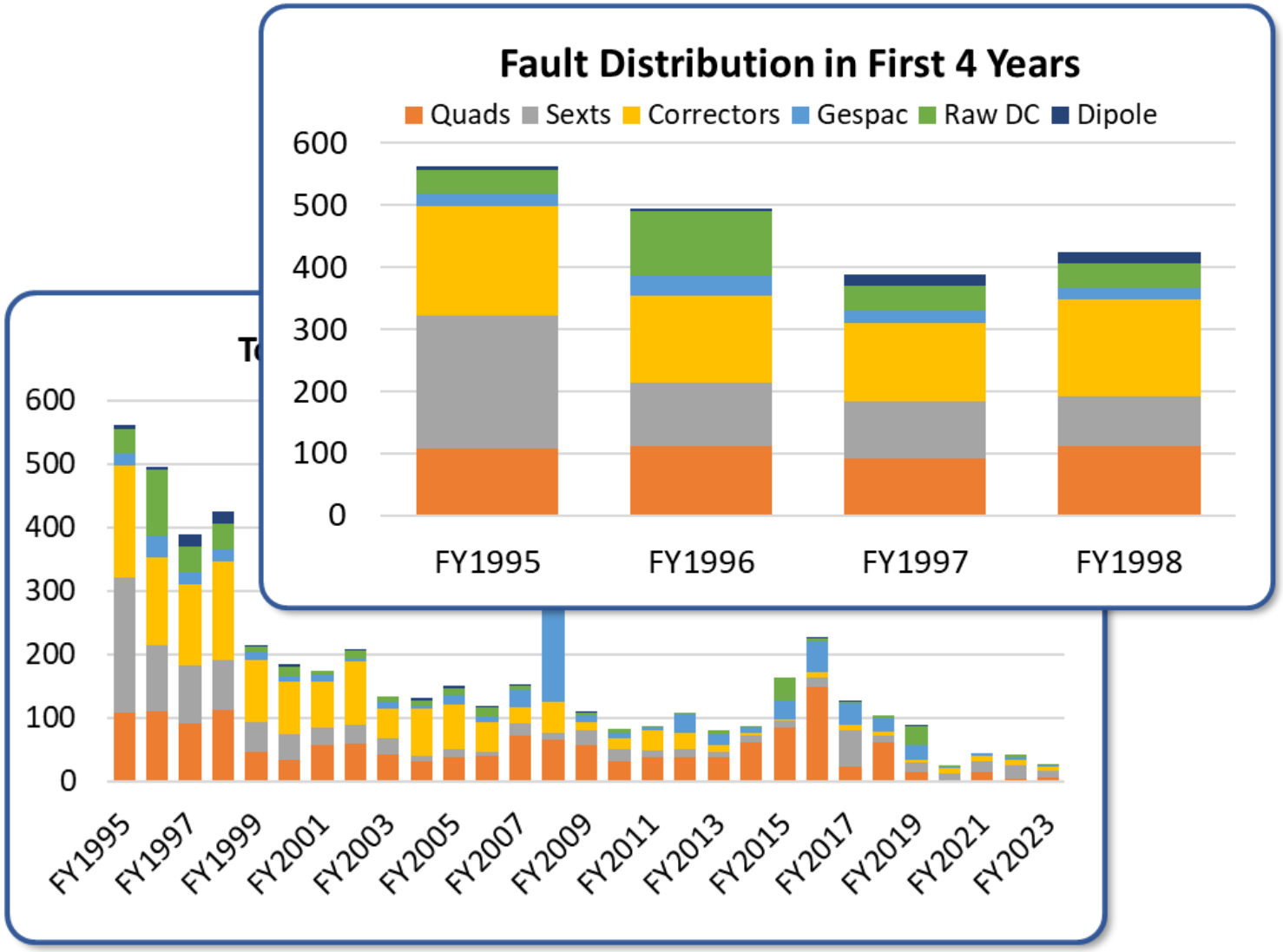




<u>For 1,397 power supplies and 200 PS controllers, there are</u>

- 5,009 repairs + upgrades over the lifetime of 28 years
  - 3.1 repairs or upgrades/unit or 178.9 per year
- 936 beam lost or machine waiting reports over 28 years
  - 0.59 report/unit and 33.4 repairs per year
  - 443 beam lost report since FY98
  - 17 beam losses per year on average
- **11.2 beam loss/year over last 20 years, best 5 beam losses in FY2012**

Faults in Early Years

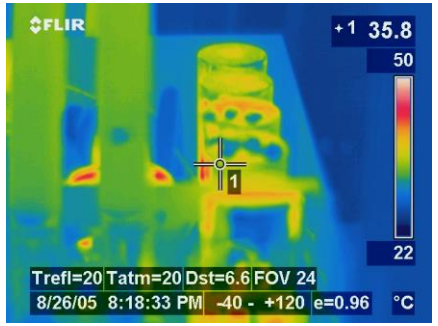


Systems took 4 yours to become mature and stable. The main issues were in DC/DC converters

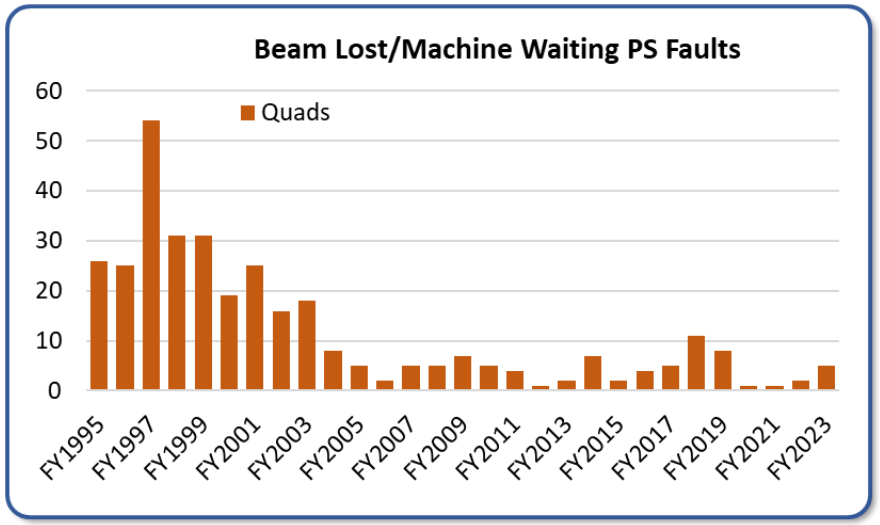
1. Weakness in designs
   - Leaking shunts
   - Control power modules
   - EMI issues in main circuit and control power circuit
2. Quality issues
   - Loose connections
   - Bad soldering joints
   - Low quality electronic assemblies
3. Infant mortality
   - IGBT and drive circuit
   - Components in control power modules

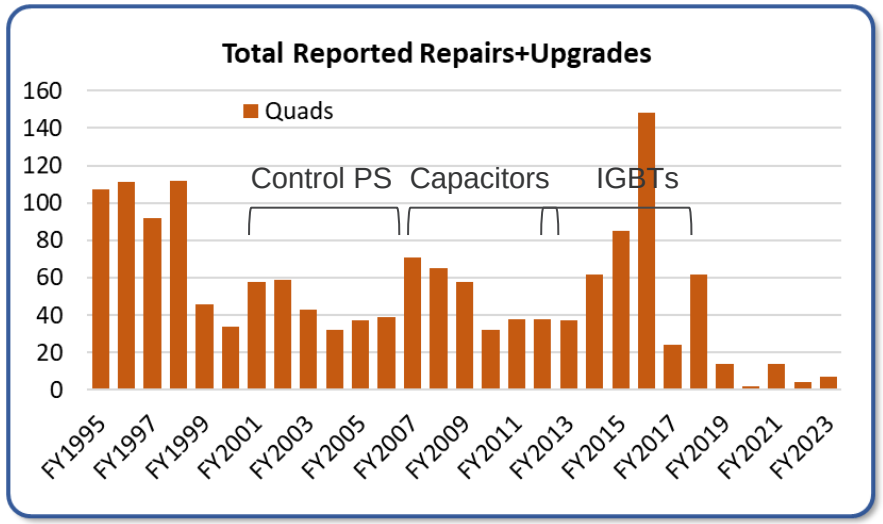
Operations and Hardware Improvement

- **Operations**
  - Swapped out converters after first trip – no reset allowed
  - Thoroughly tested all converters before each user run
  - Developed a QA program following IPC-610 class 2 standard
- **Hardware improvement/upgrade**
  - Replaced inhouse-designed control power with commercial supplies
  - Replaced water-cooled shunts with LEMs
  - Increased speed of DC bus discharge after power outage to protect IGBTs
  - Replaced in quads 400A IGBTs with 600A IGBTs
  - Redesigned and replaced regulation electronics in correctors
- **Preventive maintenance**
  - Thermal scan input capacitor banks before each shutdown maintenance period, replaced caps in all quad converters, replaced caps in others as needed
  - Replace IGBTs when case T is in upper 50°Cs
  - Replaced power modules in PS controllers, continued to check ±12V and 5V sources for excessive ripples, replaced power modules when excessive ripples were found

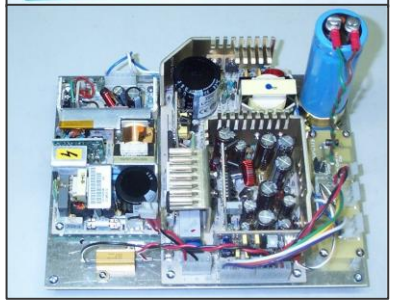


Upgrade in Quad Converters





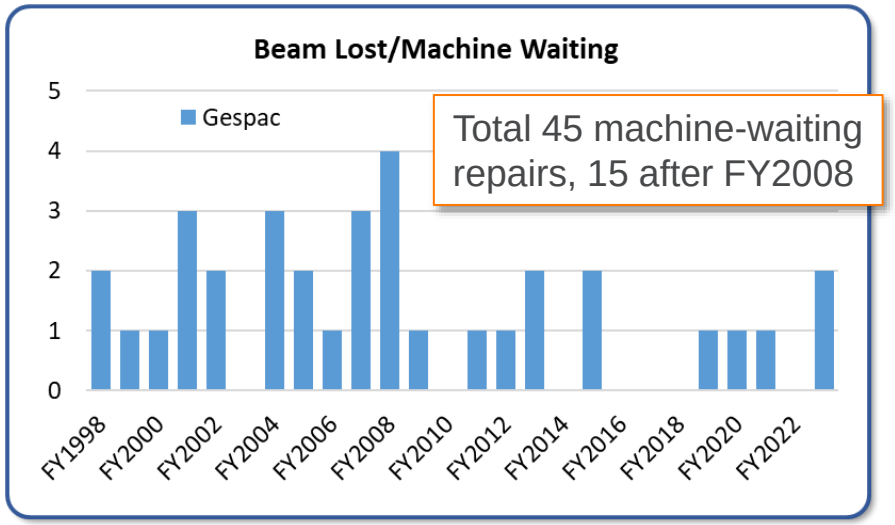
- Increased DC input fuse from 250A to 300A
- Replaced in-house design control power to commercial power supplies
- Increased IGBT size from 400A to 600A
- Replaced input capacitor banks
- Each upgrade took multiple years to complete because time limitation from user operations.

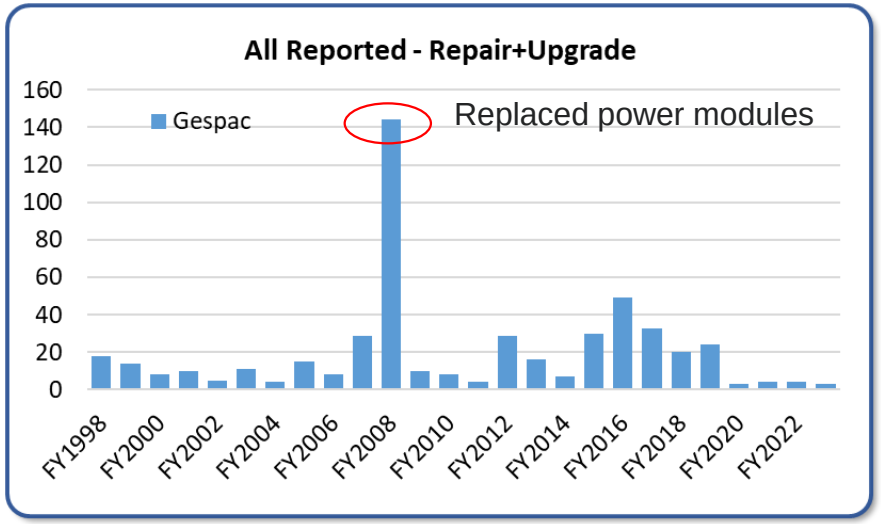


CM400HA-12H
Single IGBTMOD™ H-Series Module
400 Amperes/600 Volts

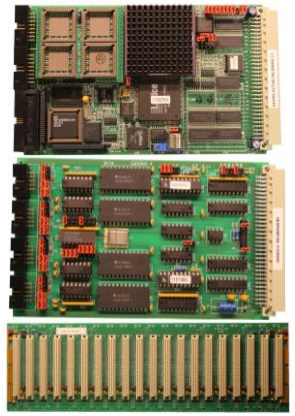
CM600HU-12F
Trench Gate Design Single IGBTMOD™
600 Amperes/600 Volts

Preventive Maintenance – Gespac (PS Controller)

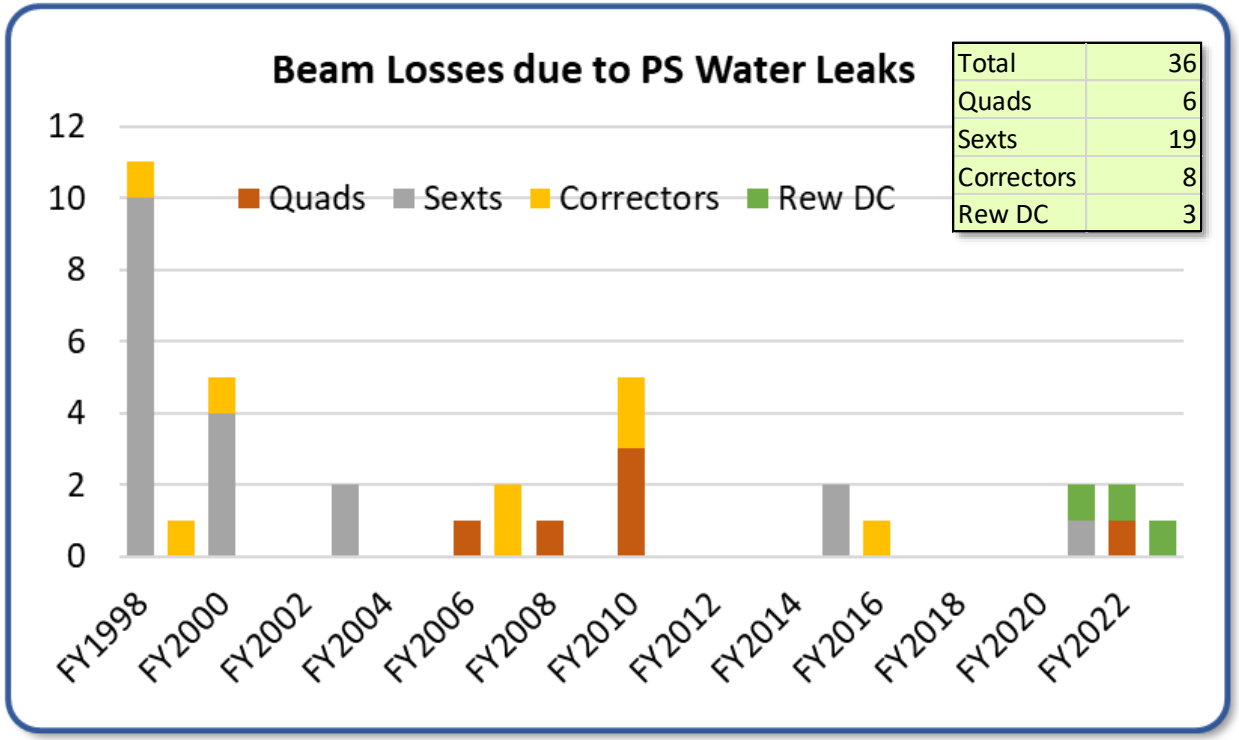




- Industrial computer contained with multiple plug-in cards
  - Bitbus communication
  - CPU card
  - Analog and digital I/O cards
  - Timer card for PWM clocks
  - Press-mount backplane
- Fault peaked in 2008
  - OME power modules either died or had excessive voltage ripples
- Replaced power modules in 2008
- Continued scoping for voltage ripples and replaced as needed



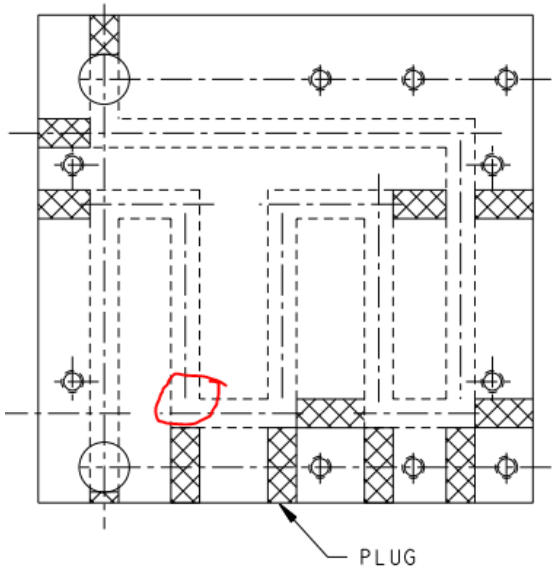
Power Supply Water Leaks



Water-cooled Shunt

LEM

IGBT Heatsink



Water leaks at 90° turns

- Water-cooled shunts in sexts and correctors leaked at beginning, replaced with LEM
- Pin holes in IGBT heatsinks
- Water leak in raw supply quick disconnect started in recent years
- Few water leaks from barb fittings, clamp or push-on types

Summary

- APS storage ring power supplies were in operation for more than 28 years
- Achieved an average of 406 hours between beam losses (MTBL) and an availability of 99.4%
- 20-year average is better than 484 MTBL and 99.5% availability,
  - Highest 994 hours of MTBL and 99.82% availability
  - Two user runs with zero power supply caused beam losses
- Maintaining high MTBL and availability requires continuous hardware upgrades and a preventive maintenance program
- It’s not cheap, cost $ and manpower