The Nuts and Bolts Affecting Accelerator Reliability

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Accelerator Reliability Workshop 2017

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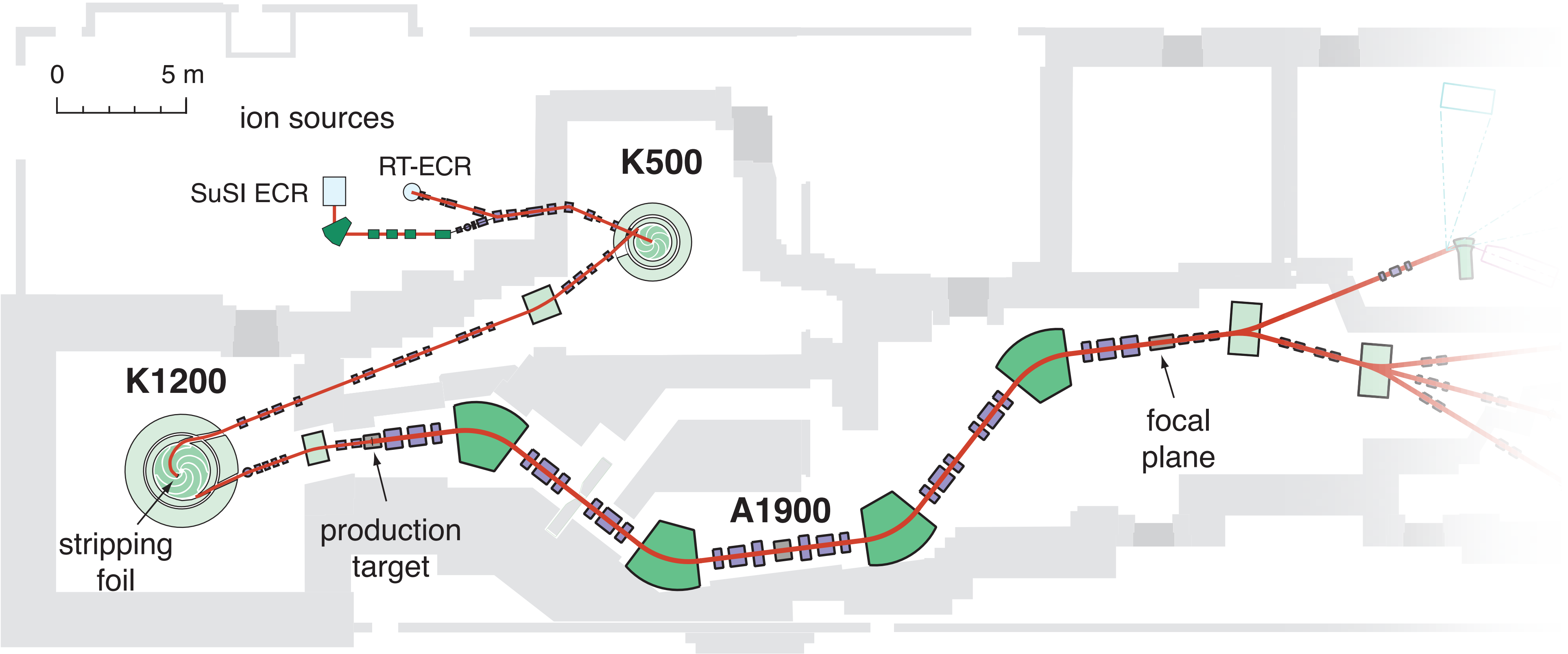
National Superconducting Cyclotron Laboratory

- Located at Michigan State University in East Lansing, Michigan, USA
- National user facility for rare isotope research and education in nuclear science, astro-nuclear physics, accelerator physics, and societal applications
- One of the three nuclear-science flagship facilities in the US: RHIC at BNL, CEBAF at JLAB, NSCL at MSU [2007 NSAC Long Rane Plan]
- Largest university-based nuclear physics laboratory in the United States: 10% of U.S. nuclear science Ph.D.s
- Over 500 employees (NSCL+FRIB), incl. 103 graduate students, and 45 faculty – user group with 1350 members
- Graduate program in nuclear physics ranked 1st [U.S. News and World Report]
- NSCL provides accelerated beams of heavy ions from oxygen to uranium, including rare isotope beams
- Michigan State University has been selected to establish FRIB, the Facility for Rare Isotope Beams

Coupled Cyclotron Facility at NSCL



2 ECR ion sources
2 coupled cyclotrons: K500 + K1200
primary beams: oxygen to uranium
K500: 8 - 14 MeV/u, 2-8 eμA
K1200: 100 - 170 MeV/u, up to 2 kW

A1900 fragment separator
to produce rare isotope beams
by projectile fragmentation

power limit beam dump in first dipole: 4kW

NSCL Primary Beam List

Primary beam list intensities are based on operational experience and serve as planning basis for experiments.

Usually, beam intensities above these values are provided to the experiment.

Beam power for Ca-48: 540 W

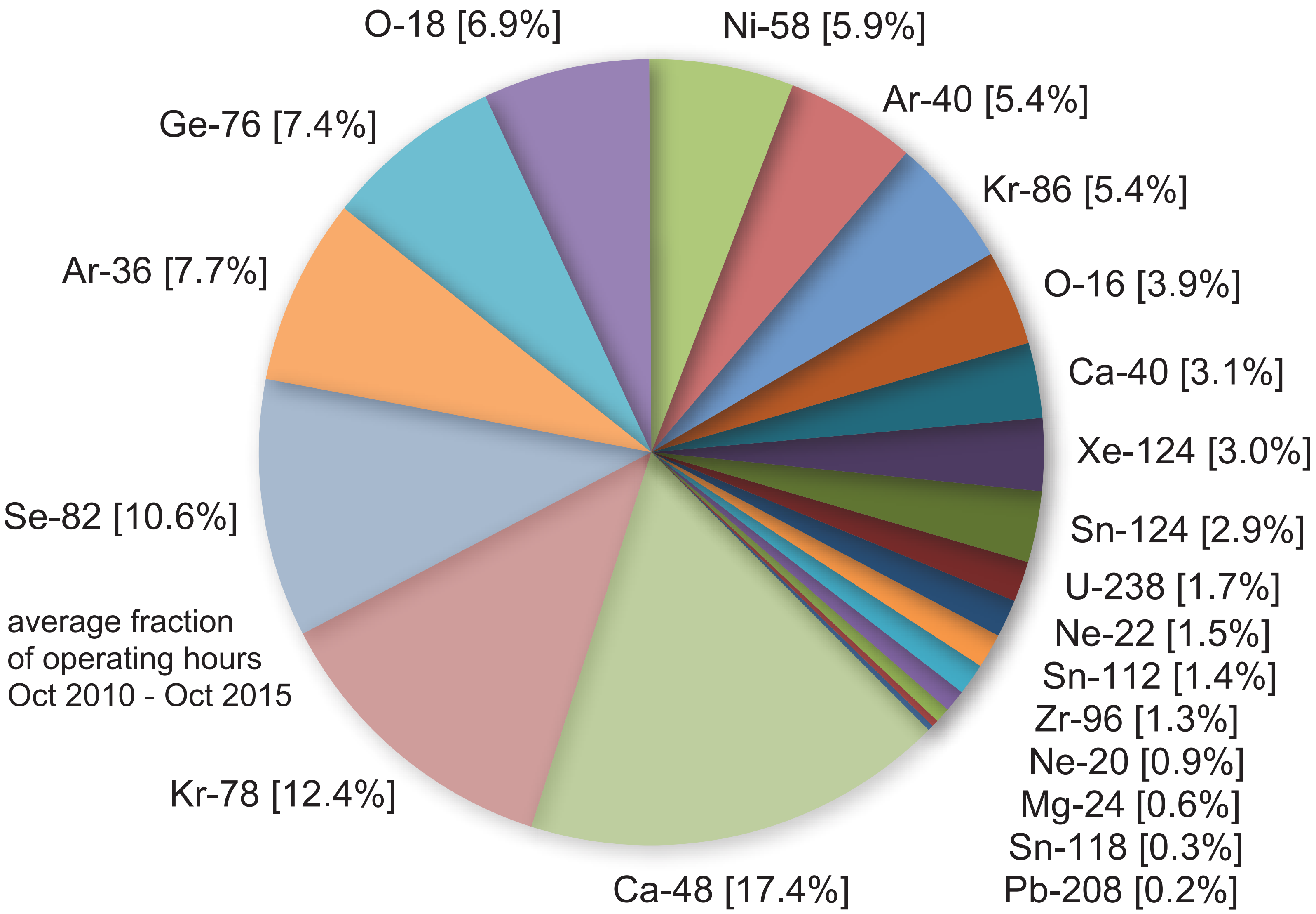
Isotope	Energy [MeV/u]	Intensity [pnA]		Isotope	Energy [MeV/u]	Intensity [pnA]
^{16}O	150	175		^{82}Se	140	35
^{18}O	120	150		^{78}Kr	150	25
^{20}Ne	170	80		^{86}Kr	100	15
^{22}Ne	120	80		^{86}Kr	140	25
^{22}Ne	150	100		^{96}Zr	120	1.5
^{24}Mg	170	60		^{112}Sn	120	4
^{36}Ar	150	75		^{118}Sn	120	1.5
^{40}Ar	140	75		^{124}Sn	120	1.5
^{40}Ca	140	50		^{124}Xe	140	10
^{48}Ca	90	15		^{136}Xe	120	2
^{48}Ca	140	80		^{208}Pb	85	1.5
^{58}Ni	160	20		^{209}Bi	80	1
^{64}Ni	140	7		^{238}U	45	0.1
^{76}Ge	130	25		^{238}U	80	0.2

NSCL Primary Beam Statistics

Coupled Cyclotron Facility (CCF) delivers a different primary beam every 5 to 7 days, typically 30 beam changes per year.

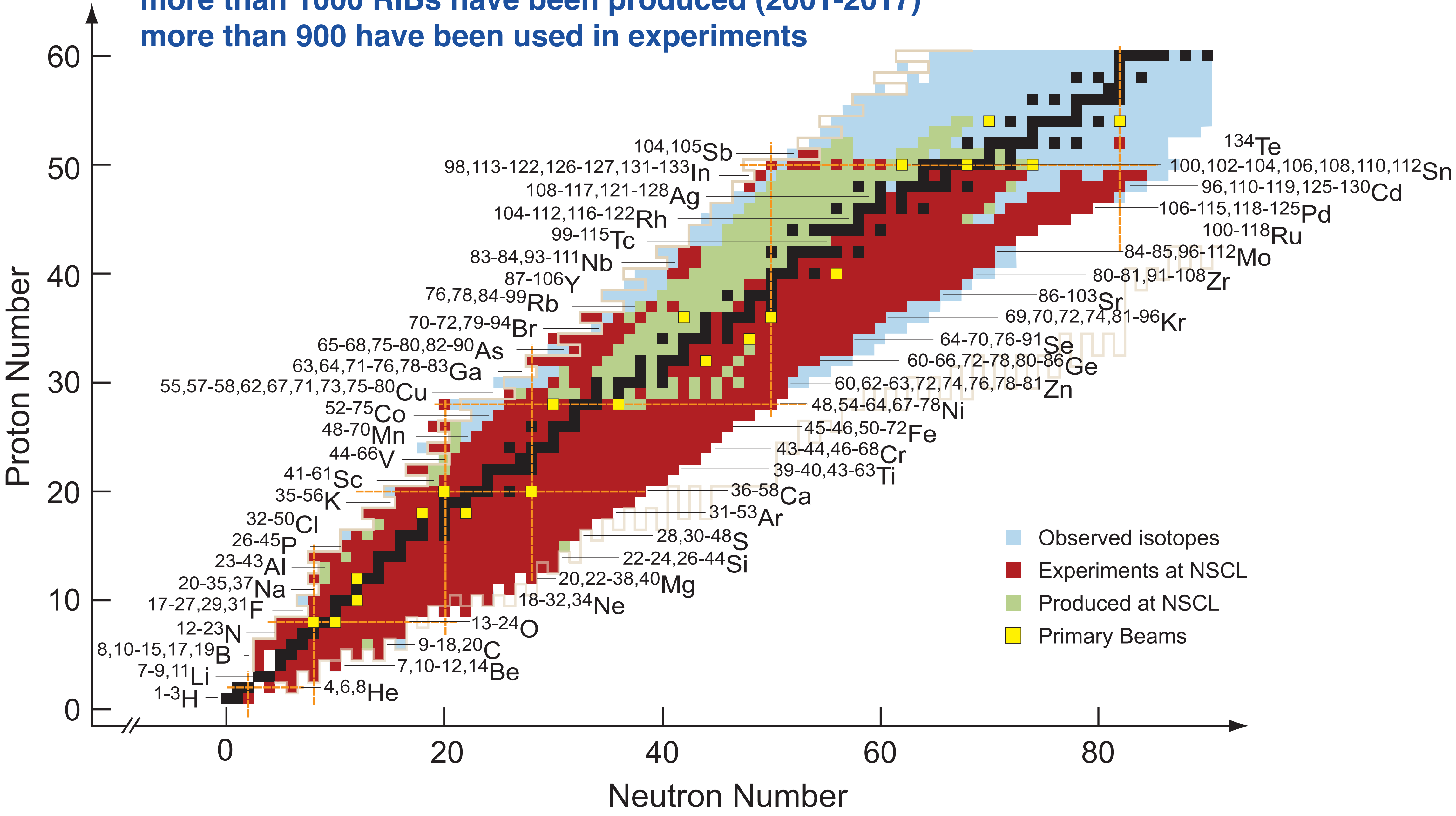
The development of new primary beams (isotope and energy) is driven by user demand.

CCF Primary Beam Isotope Statistics

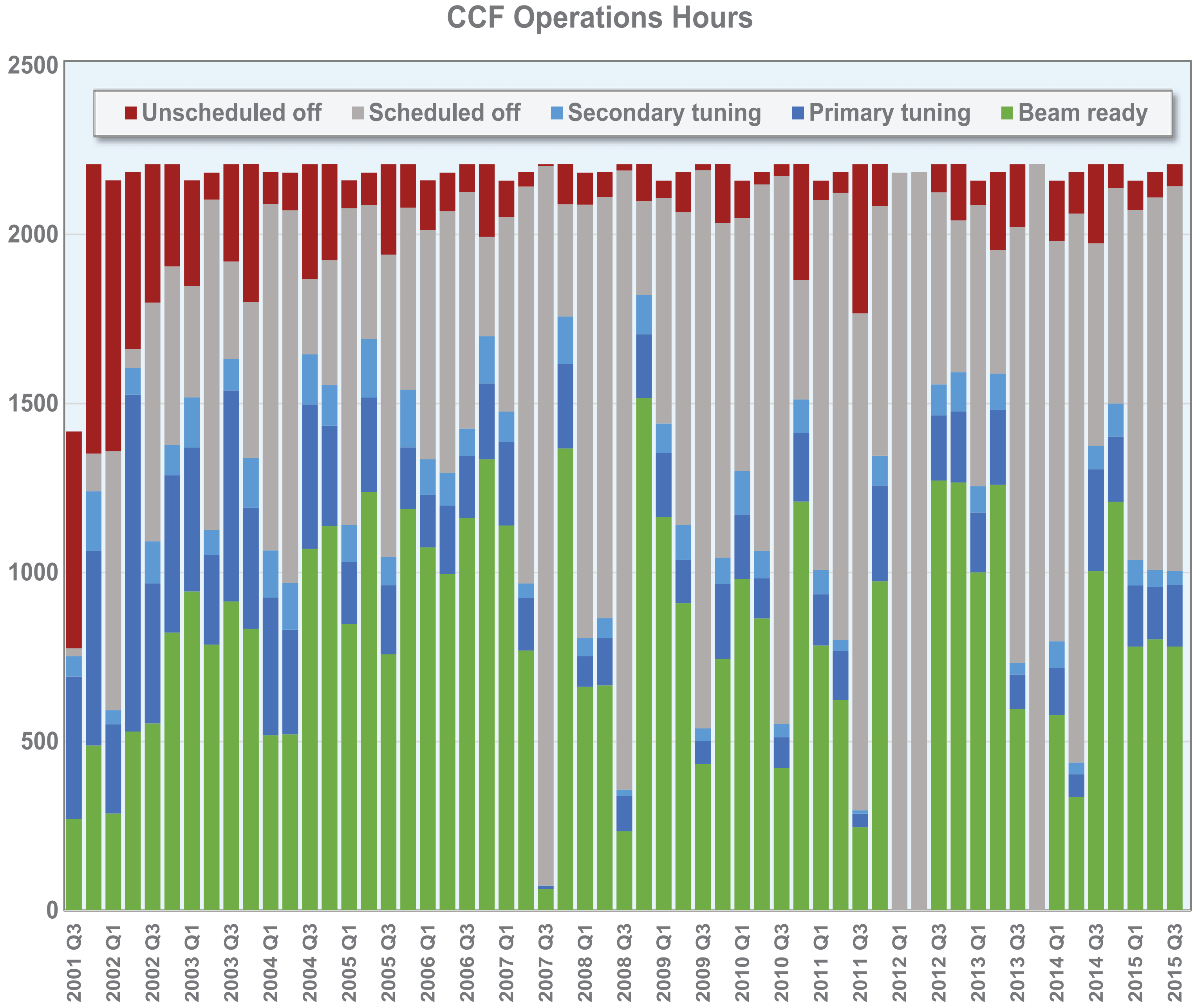


Rare Isotope Beams produced at NSCL

more than 1000 RIBs have been produced (2001-2017)
more than 900 have been used in experiments



CCF Operations Statistics



NSCL operations hours: typically: 4500 hours/year

up to 6000 hours/year possible

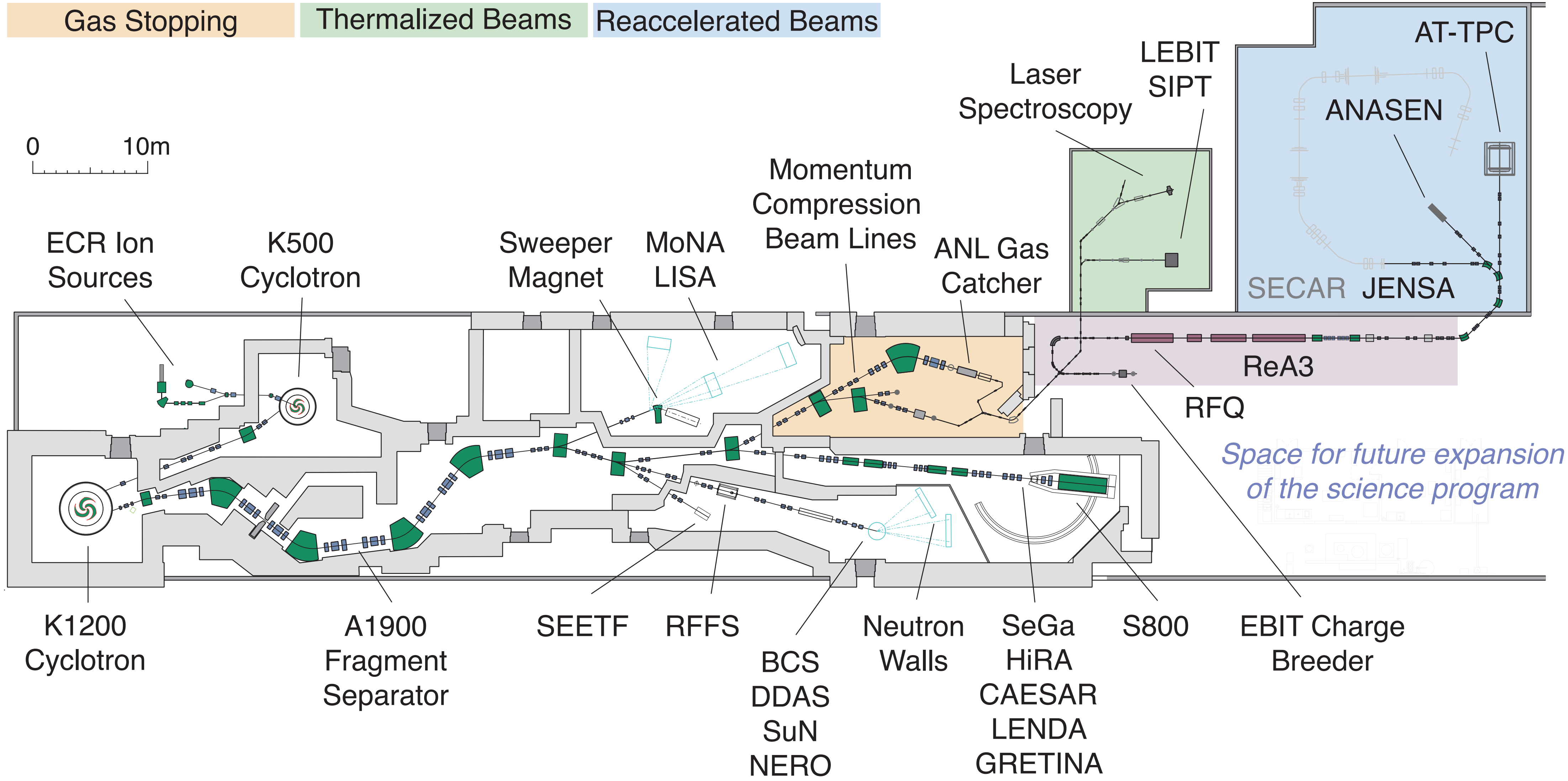
During scheduled facility operations NSCL operates on a 24/7 schedule.

Facility availability of more than 90% allows for reliable schedule and high user satisfaction

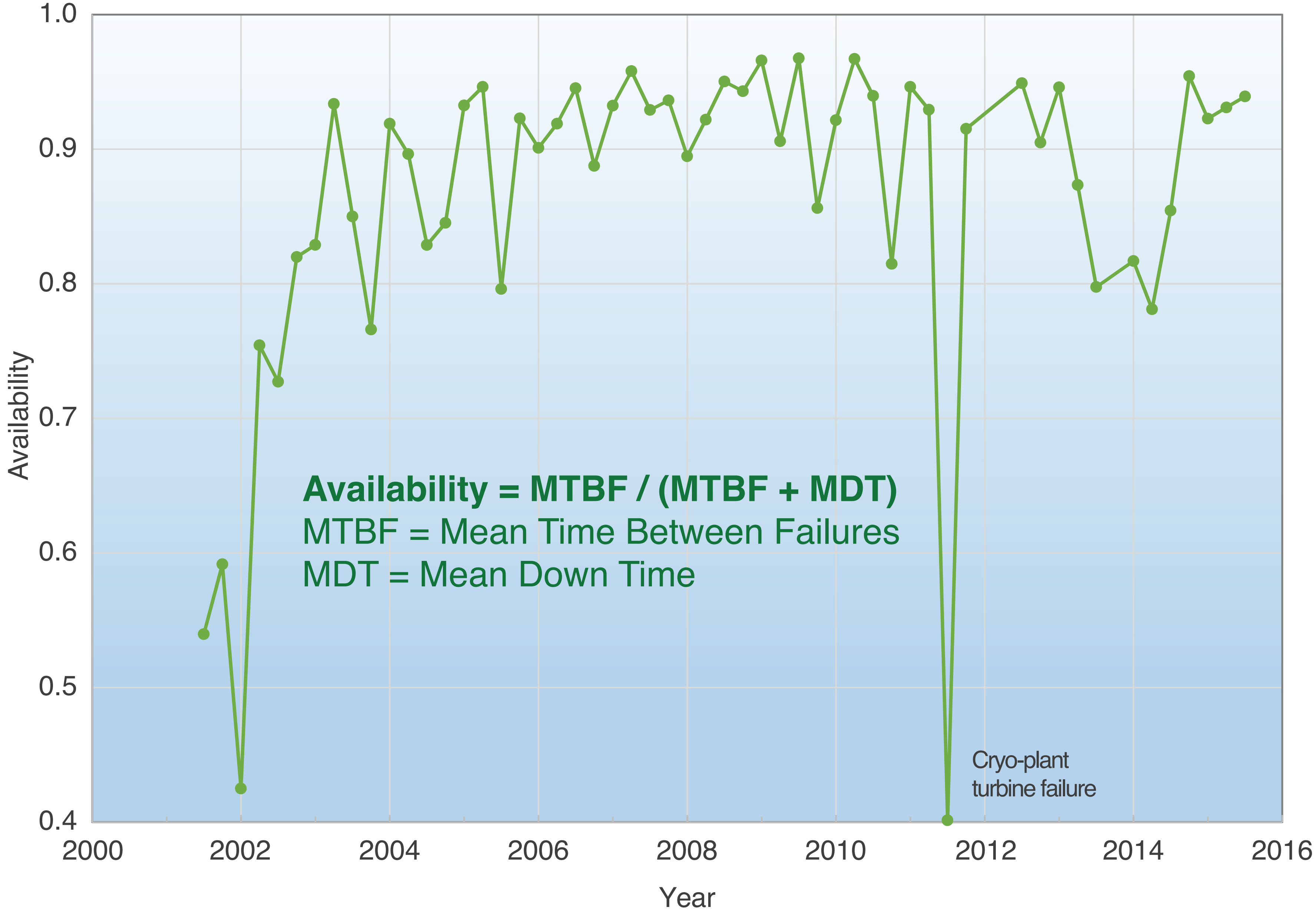
NSCL operations is certified according to ISO 9001, ISO14001, and ISO 18001

NSCL's Experimental Facility Plan

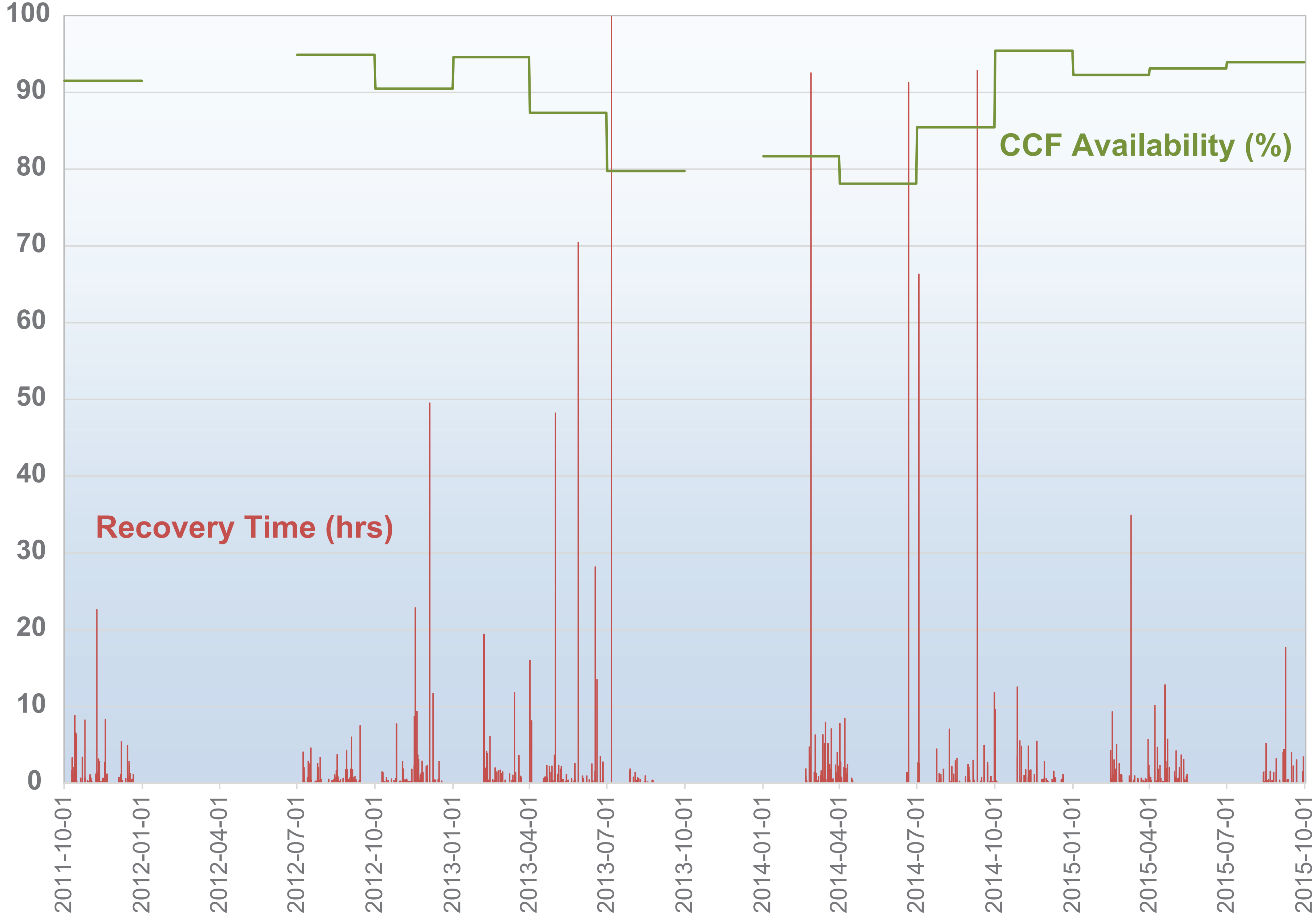
NSCL is the only facility in the world that can provide fast, thermalized, and reaccelerated beams of rare isotope.



CCF Operations Availability



CCF Operations Availability



Learning Opportunities, not a just a Breakdown...

"All men make mistakes, but only wise men learn from their mistakes."

Winston Churchill

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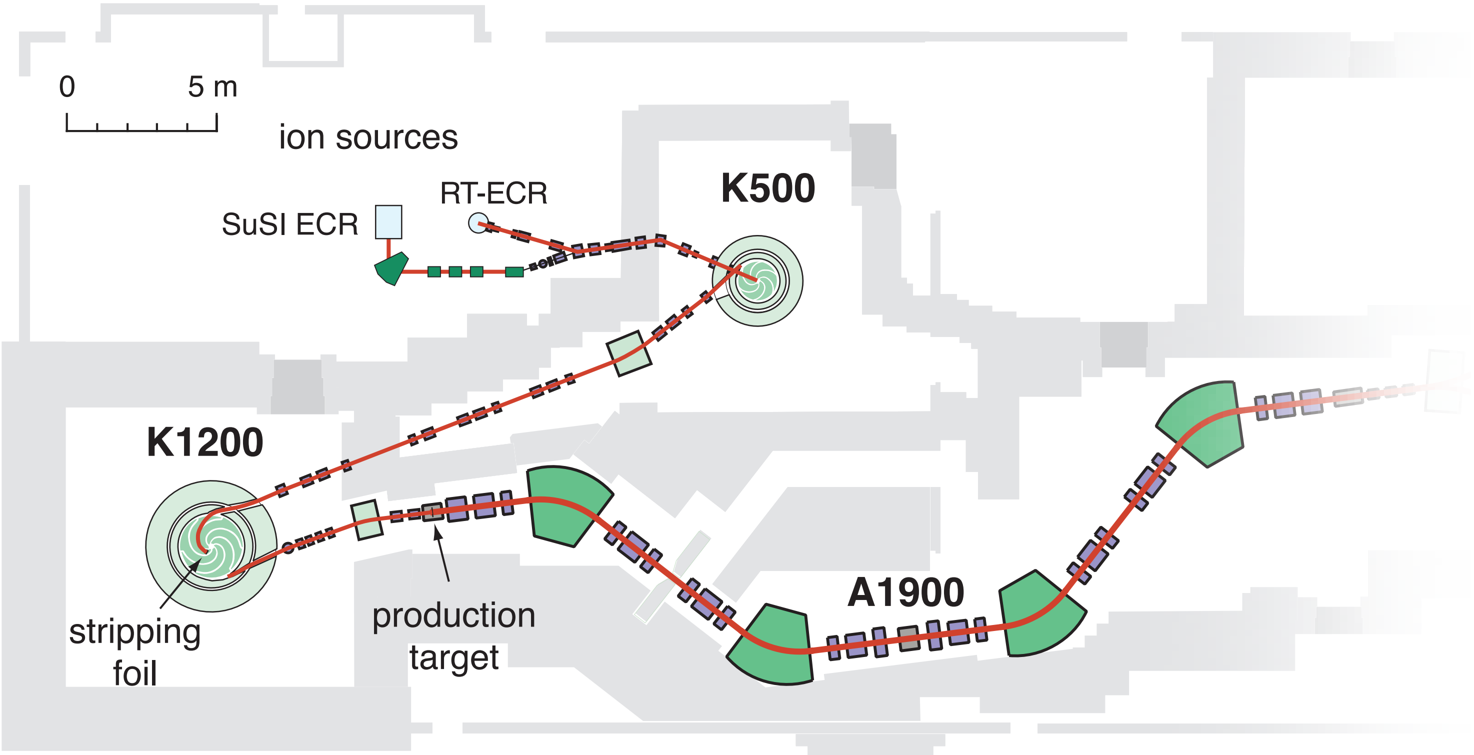
Winston Churchill

"We don't have the time to learn from our own mistakes, we need to learn from other people's mistakes."

Thomas Glasmacher
(my big boss)

Dipole Magnets in the A1900 Fragment Separator



A1900 fragment separator
to produce rare isotope beams
by projectile fragmentation

Superconducting Dipole Magnets
maximum current: 160 Amps
maximum field: 2 Tesla
Inductance: 45 Henry @ 100 Amps
maximum stored energy: 500 kJ
weight: 50 tons

A1900 Dipole Magnet 3 Failure

Electronic LogBook

galbrait, 11/3/15, 3:01 pm
Z071DS is out of LHe. Cryo is filling. Magnet Group is adjusting lead gas.

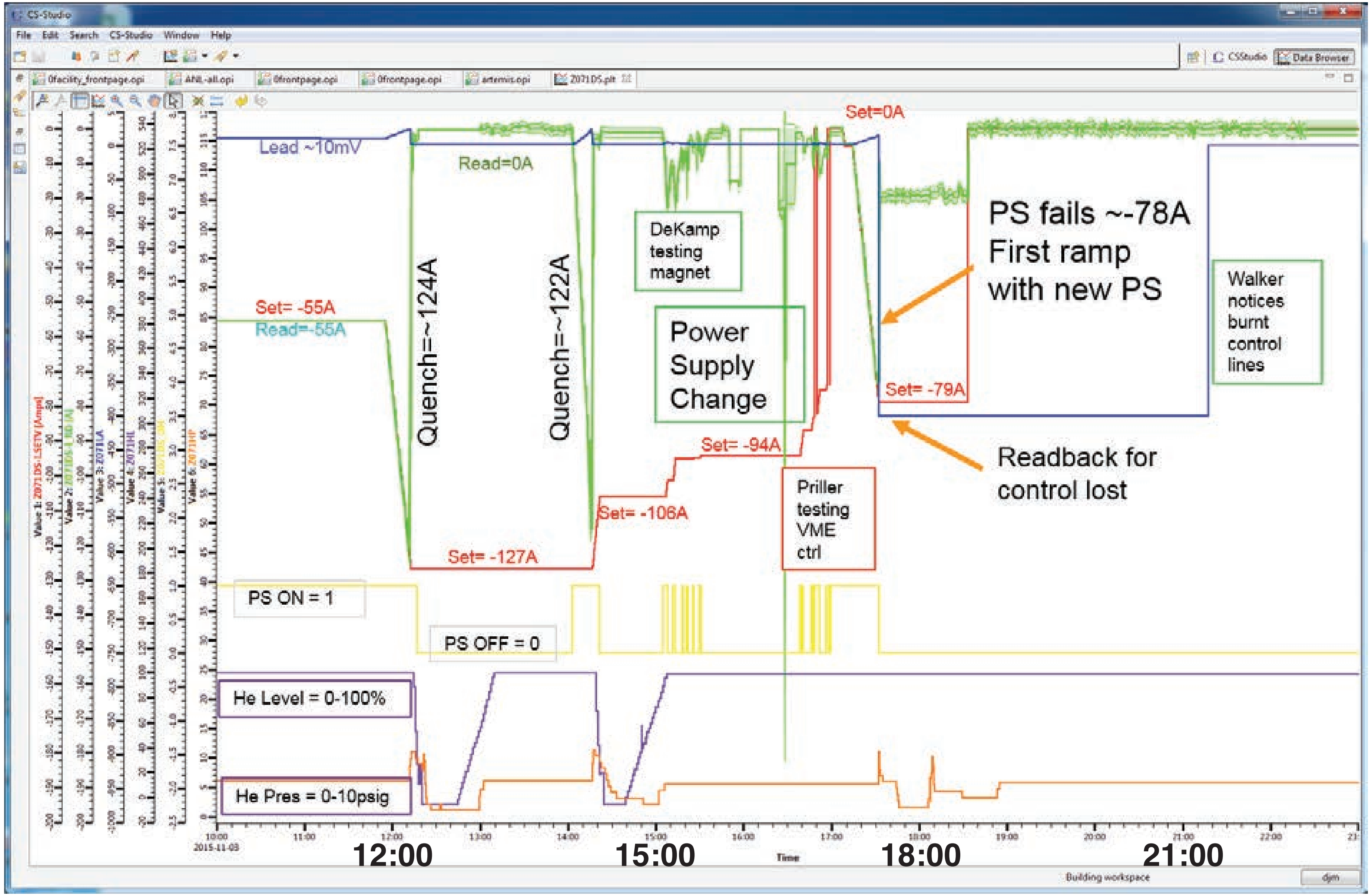
ginter, 11/3/15, 5:25 pm
We have been having trouble with Z071DS -- it quenched twice today.

ginter, 11/3/15, 5:39 pm
Z071DS has tripped again. This time it did not manage to ramp up to 110 A

beal, 11/3/15, 9:21 pm
Problems with Z071DS continue. John DeCamp and Robin Walker now feel the need to access the magnet's power supply.

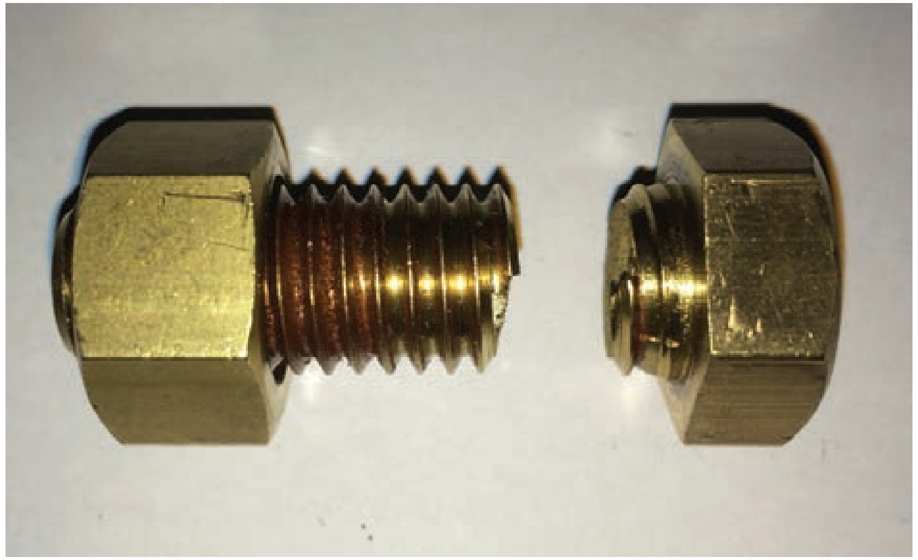
rencsok, 11/3/15, 10:23 pm
General update regarding Z071DS. When power supply cabinet was opened for Z071DS we found one lead off it's connection.

bonofigl, 11/3/15, 11:13 pm
After further analysis, it appears there is damage to the magnet. Will schedule a repair team meeting for tomorrow morning to assess.



A1900 Dipole Magnet 3 Failure - Power Supply

Back of the power supply

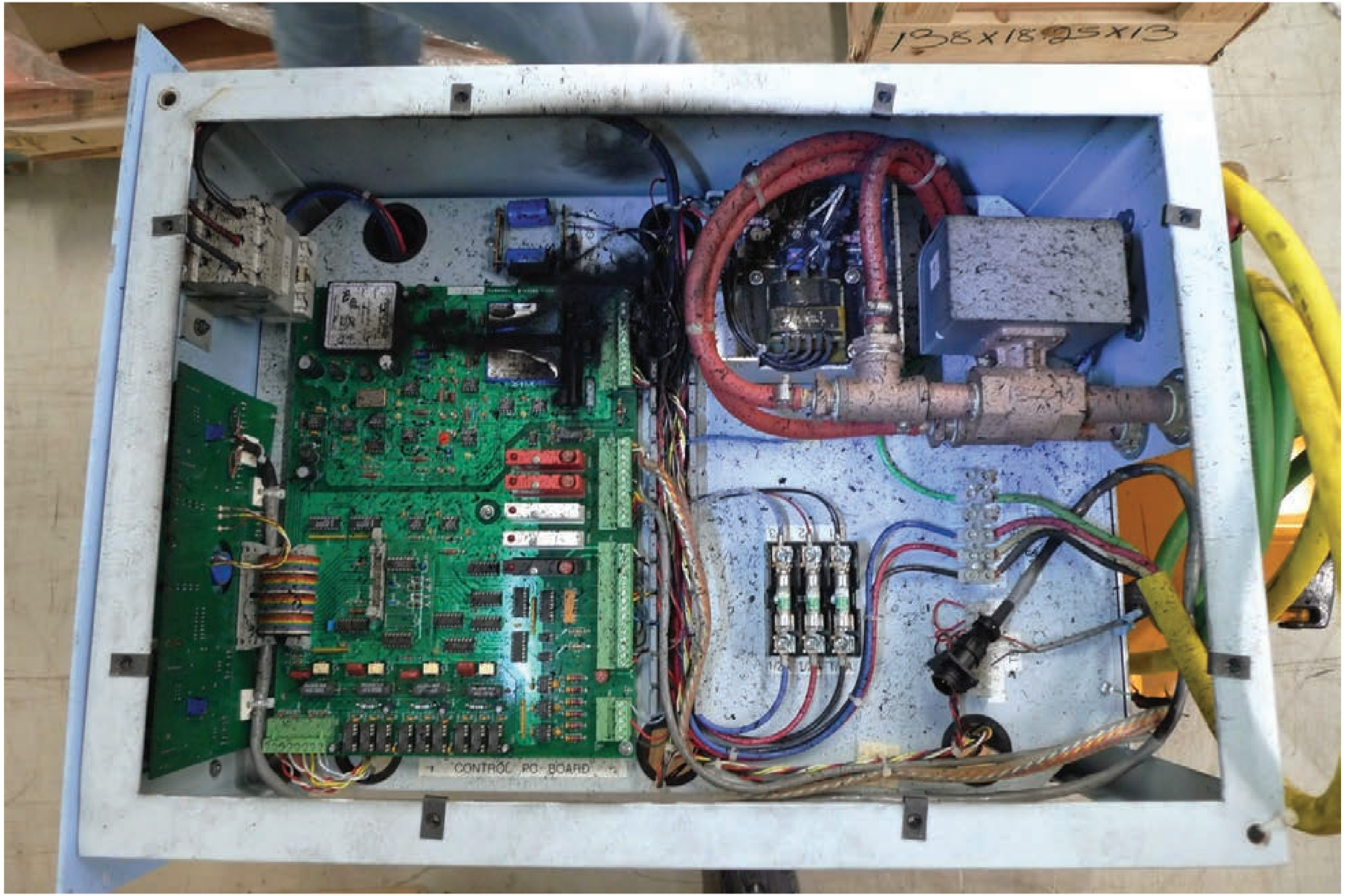


During power supply replacement original stainless steel bolt was replaced with brass bolt in order to increase conductivity.

This bolt was found broken inside the power supply rack.

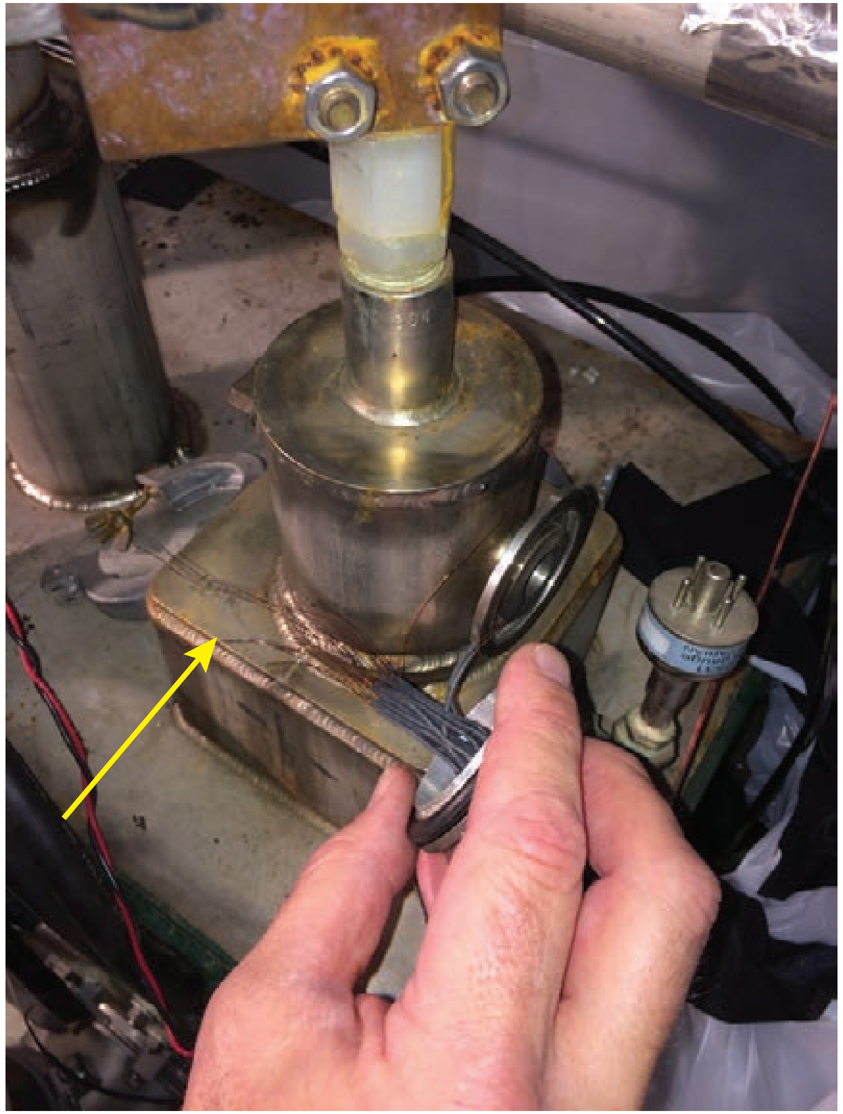
Stored energy in magnet: 137 kJ

A1900 Dipole Magnet 3 Failure - Power Supply



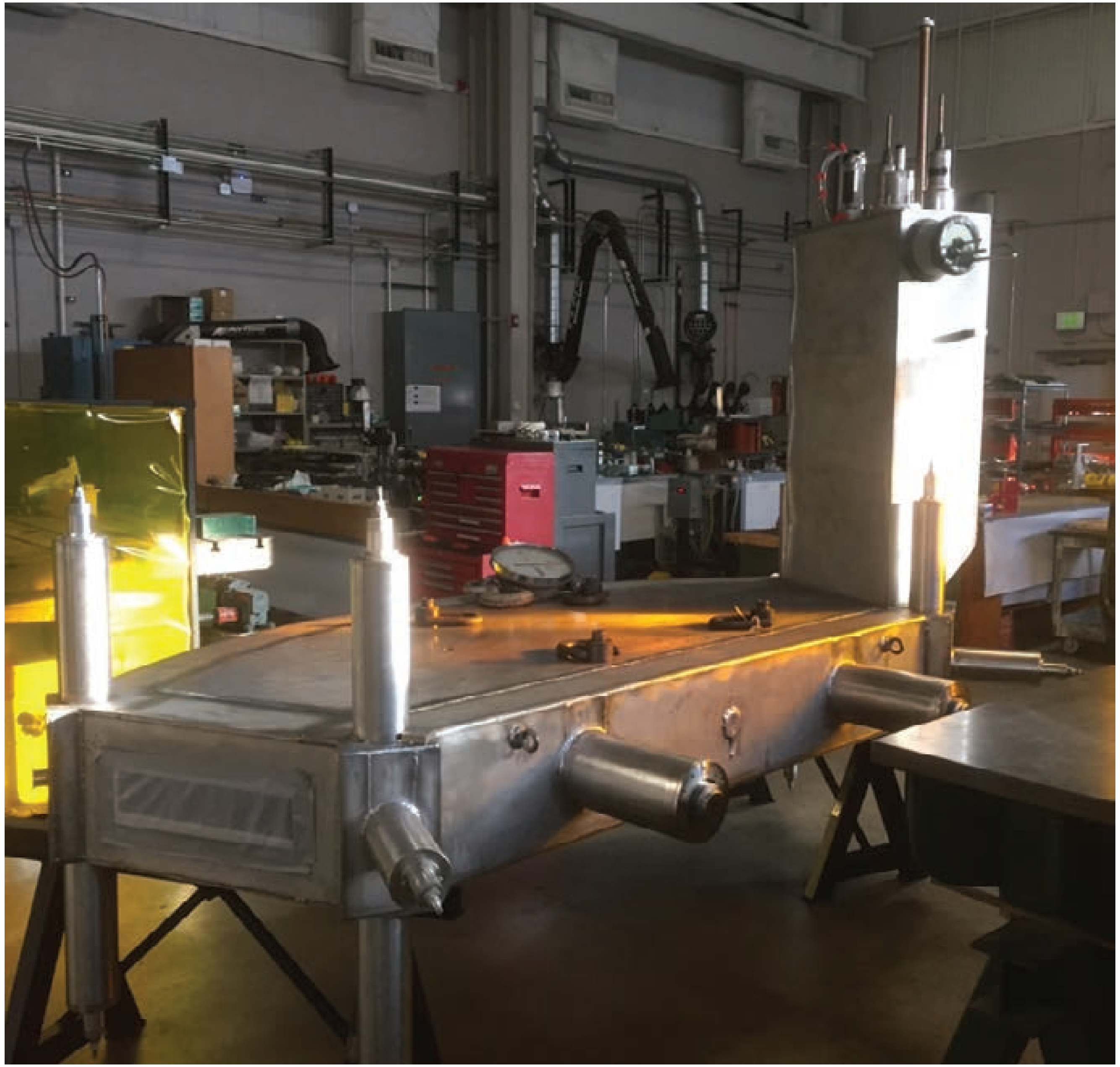
A1900 Dipole Magnet 3 Failure - Magnet Leads

Broken diagnostic wires



After removing the lead can it became obvious that superconducting lead wires were significantly damaged.

Magnet Leads Damaged beyond Repair



Spare dipole coil package just finished

Damaged coil package was replaced with spare one.

Dipole replacement takes 4 week:

- warm-up superconducting magnet
- remove concrete roof beam shielding
- dissamble 40 ton iron yoke
- replace coil package
- assembly 40 ton iron yoke
- align magnet
- install concrete roof beam shielding
- cool-down magnet

A1900 Dipole Magnet 3 Repair

Time Line

76 days

11/03/2015	Magnet failure
11/04/2015	Extent of damage realized, decision to warm up magnet Decision to turn off all superconducting magnets to inspect bolt connections
11/05/2015	Project plan with two options: Magnet Repair / Magnet Replacement
11/06/2015	Decision to start winter maintenance shutdown 5 weeks early
11/09/2015	Decision to replace magnet
11/25/2015	Old magnet removed, new coil package and iron yoke installed
12/10/2015	Cryo-welding completed
12/29/2015	Magnet filled with liquid Helium
01/05/2016	Magnet tested at 160 Amps
01/18/2016	Magnet tested with beam, rho calibration

NSCL

Identifying the Root Cause

This bolt was used

"Ornamental" Brass Bolt

Unknown material property

This bolt should have been used

Silicon-Bronze Hex cap bolt
Alloy 651 silicon bronze
(98.5% copper, 1.5% silicon)

Minimum tensile strength tested according ASTM F468 to 50,000 psi.

Root Cause

Inadequate quality control of power supply lead connections.

No documented work instructions or training material available to workers.

Head markings

Alloy Grade

Manufacturer Identification

Written Procedure for Electric Lead Connections

- **Use only silicon bronze or stainless steel bolts for copper to copper connections**
- **Use lubricant and anti-seize components** (e.g. moly disulphide for stainless steel)
- **Use a calibrated torque wrench, torque to specification for hardware used and mark**
- **Test the joint with milli-Ohm meter**

Bolt Size Inches or #	Threads Per Inch	Standard Dry Torque in Inch-Pounds					
		18-8 Stainless Steel	Brass	Silicon Bronze	2024-T4 Aluminum	316 Stainless Steel	Monel
1/4	20	75.2	61.5	68.8	45.6	78.8	85.3
	28	94.0	77.0	87.0	57.0	99.0	106.0
5/16	18	132	107	123	80	138	149
	24	142	116	131	86	147	160
3/8	16	236	192	219	143	247	266
	24	259	212	240	157	271	294
7/16	14	376	317	349	228	393	427
	20	400	327	371	242	418	451
1/2	13	517	422	480	313	542	584
	20	541	443	502	328	565	613

Facility for Rare Isotope Beams FRIB-T31209-PR-000380-R002
Procedure for Tightening Hardware for Power Supply and Magnet Connections Issued 24 March 2016

Procedure for Tightening Hardware for Power Supply and Magnet Connections

FRIB-T31209-PR-000380-R002

Issued 24 March 2016

Inspection of all Electrical Lead Connections

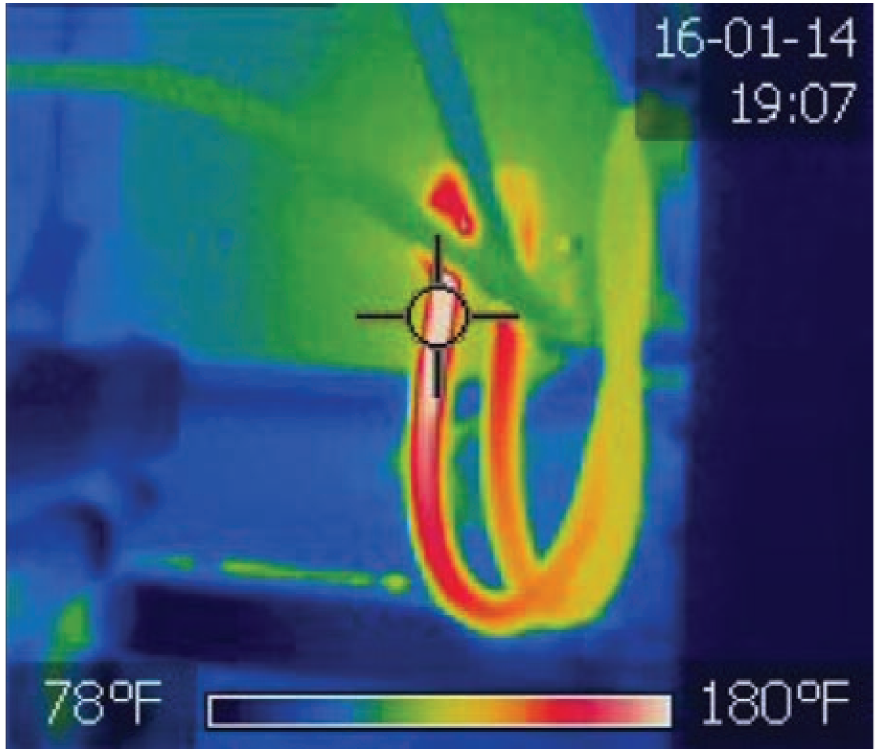
Before start of operations:

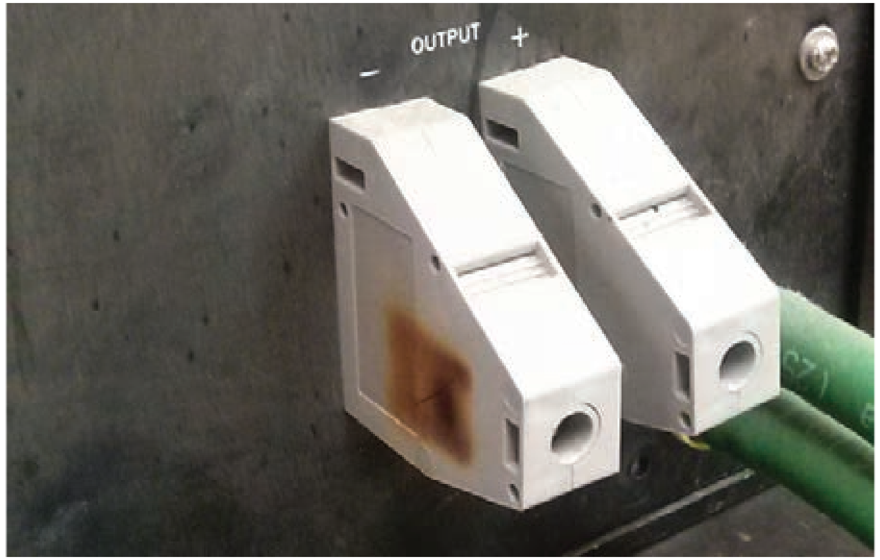
Test all electrical lead connections between magnets and power supplies at the Laboratory (459 supercon-ducting and room temperature magnets)

- **Visual Inspection**
  (you can see a lot by just looking)

- **Measurement of resistance with milli-Ohm meter**

- **Thermal imaging with infrared imaging system**
  (operate magnet at high current and inspect
  temperatures of electric connections)





Summary

Failure of a bolt in an electric lead connection can lead to catastrophic results (particularly with super-conductive magnets)

- **Prepare written instructions for electric connections**
- **Buy quality hardware from reputable vendor**
- **Train your employees**
- **Inspect your connections on a regular basis**

$5

$500000