Slow Extraction and Spill Control from BNL's AGS and Booster

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BNL

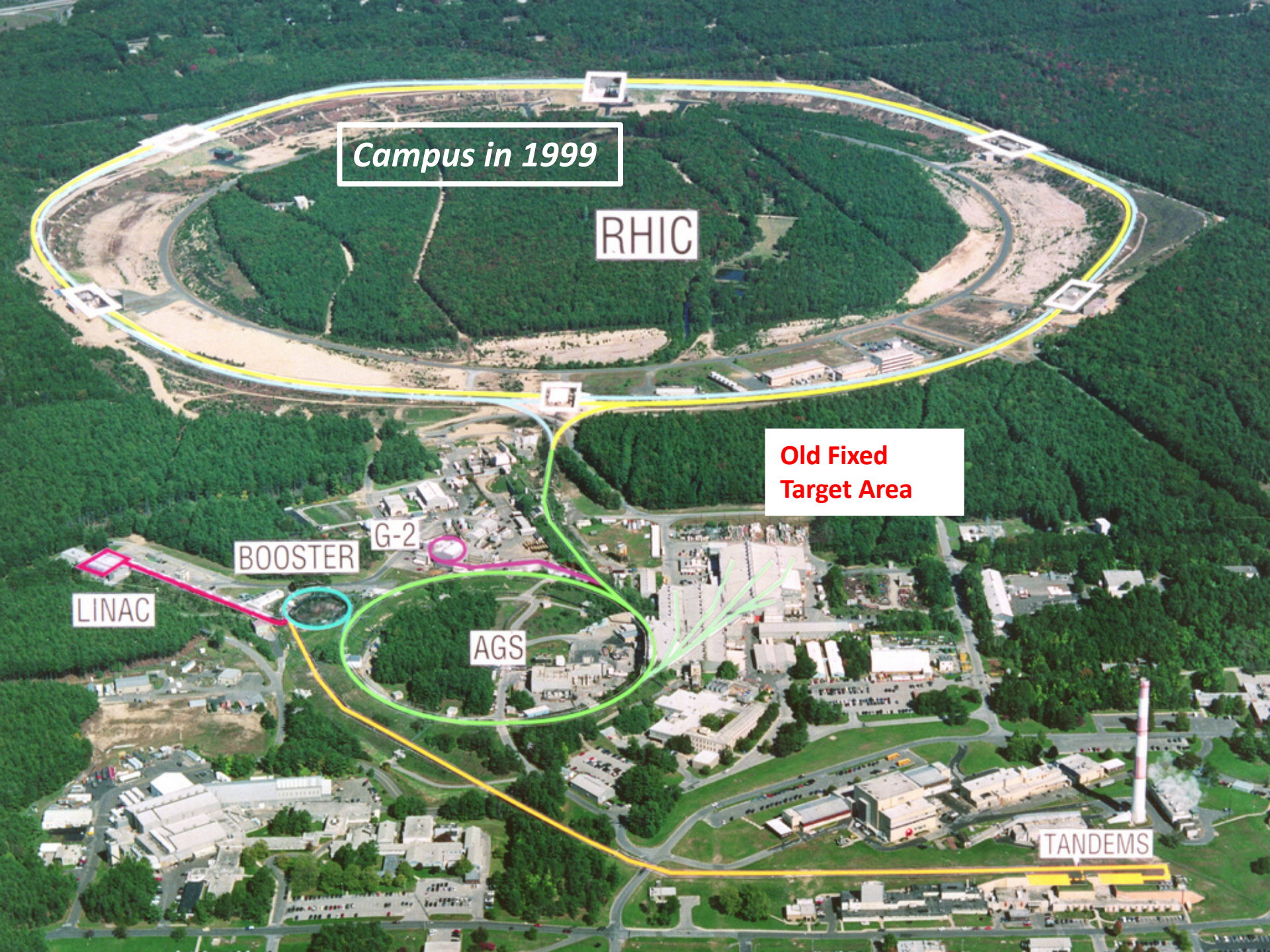
ICFA Mini-Workshop on Slow Extraction, 2019

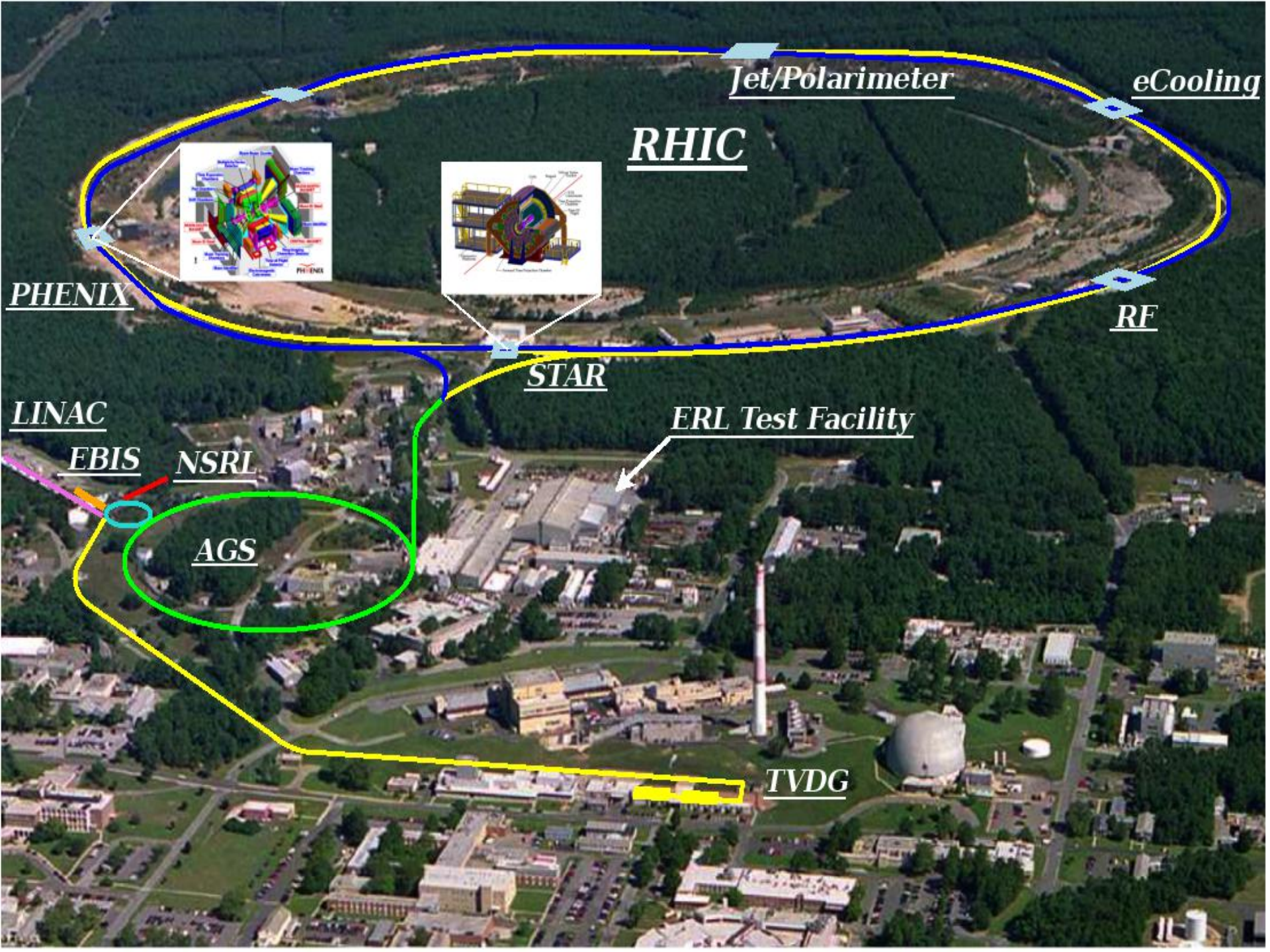
What I have already covered ☺

- 2002, The 10th ICFA mini-workshop on slow extraction
  - Slow extraction of high intensity protons at Brookhaven's AGS
  - http://www.cadops.bnl.gov/ICFA2002/proceedings/AGSSEB.PDF
- 2005, The 14th ICFA mini-workshop on septa devices
  - Septa Requirements for Rare Symmetry Violating Processes (RSVP) Experiments at BNL
  - http://www.cadops.bnl.gov/ICFA2005/proceedings/AGSExtractionSepta.pdf
- 2016, Slow Extraction Workshop at GSI
  - Slow extraction of high intensity beam from the AGS
  - https://indico.gsi.de/event/4496/session/4/contribution/10/material/slides/1.pdf
- 2017, Slow Extraction Workshop at CERN
  - Separatrix folding with multipoles
  - https://indico.cern.ch/event/639766/contributions/2750894/attachments/1555343/2445664/SeparatrixFolding.pdf
  - Spill quality for NASA facility at AGS
  - https://indico.cern.ch/event/639766/contributions/2750927/attachments/1556126/2447208/NSRLatBNL_CSEWSna.pdf

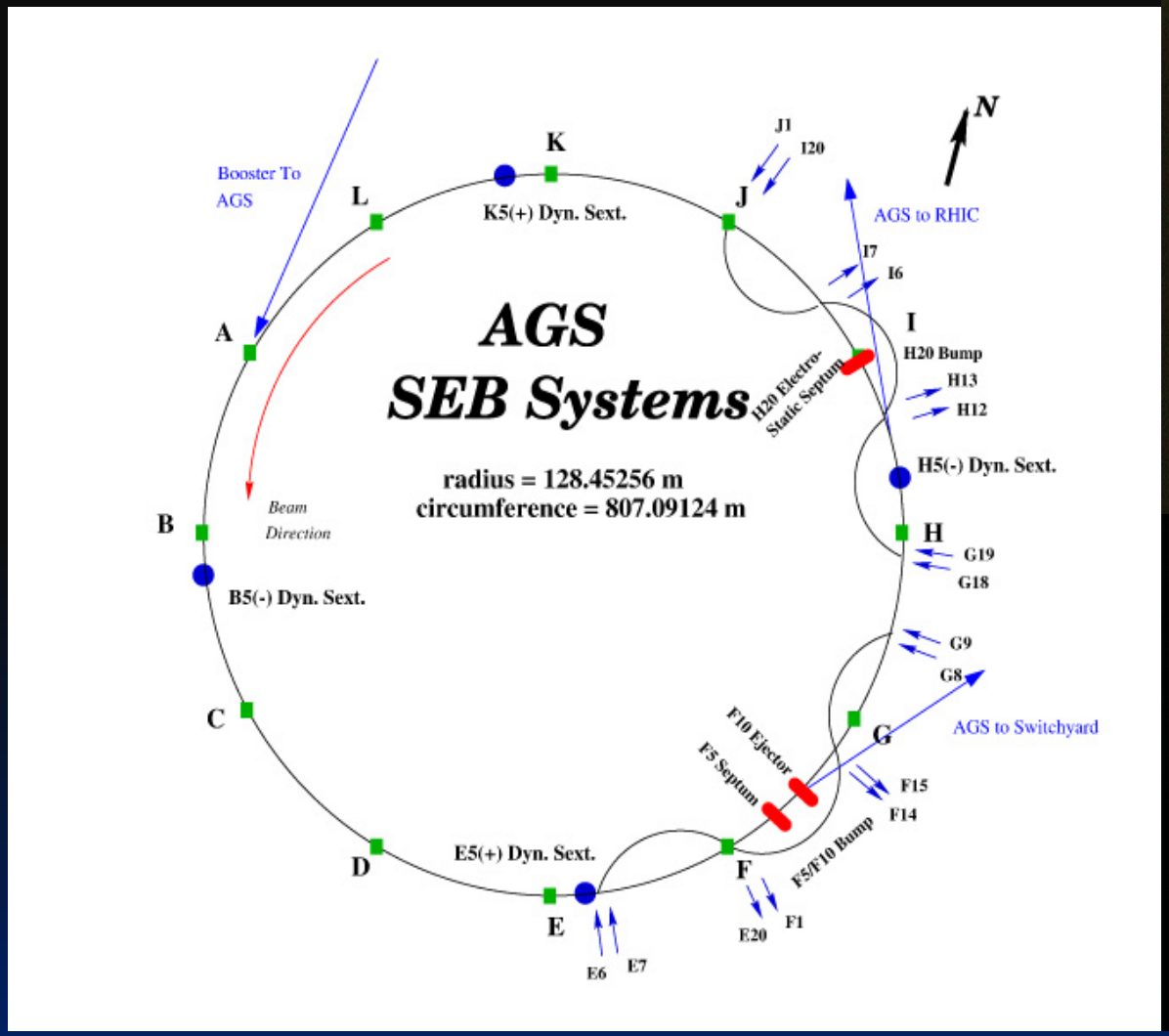
Outline

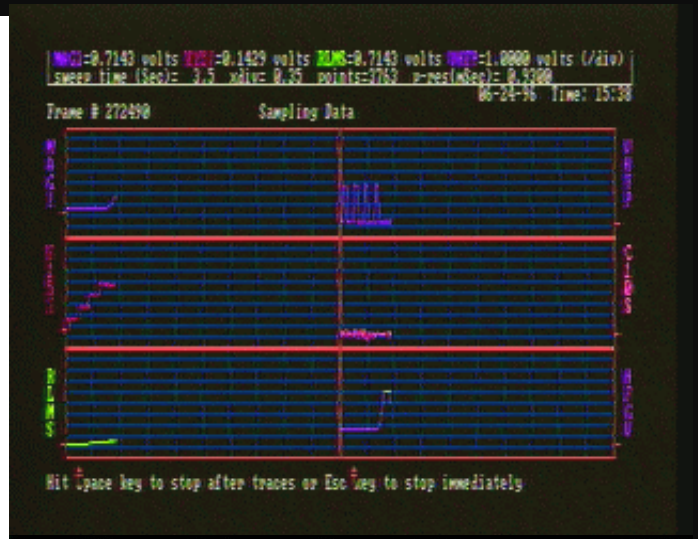
- Review of C-AD Complex
- Review of AGS Slow Extraction
- AGS Spill Control
- Review of NASA Space Radiation Facility (NSRL)
- Booster Slow Extraction
- Solar Particle and Galactic Cosmic Ray Simulators
- Booster Spill
- New NSRL Spill Requirements and Efforts


Campus in 1999
RHIC
Old Fixed
Target Area
G-2
BOOSTER
LINAC
AGS
TANDEMS

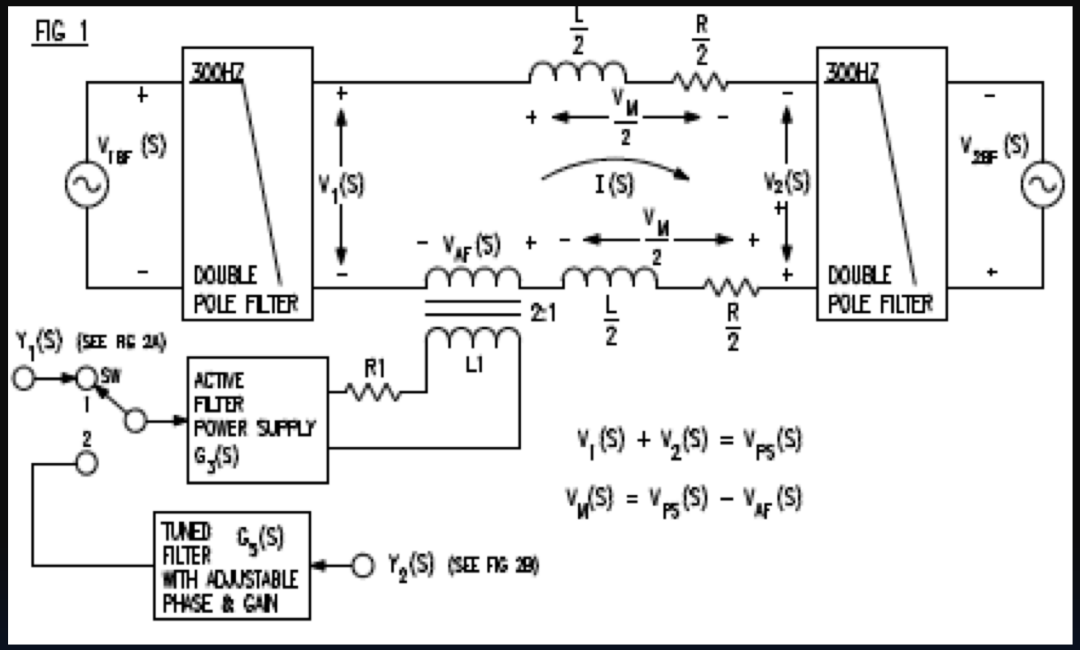

Jet/Polarimeter
eCooling
RHIC
PHENIX
RF
STAR
LINAC
ERL Test Facility
EBIS
NSRL
AGS
TVDG

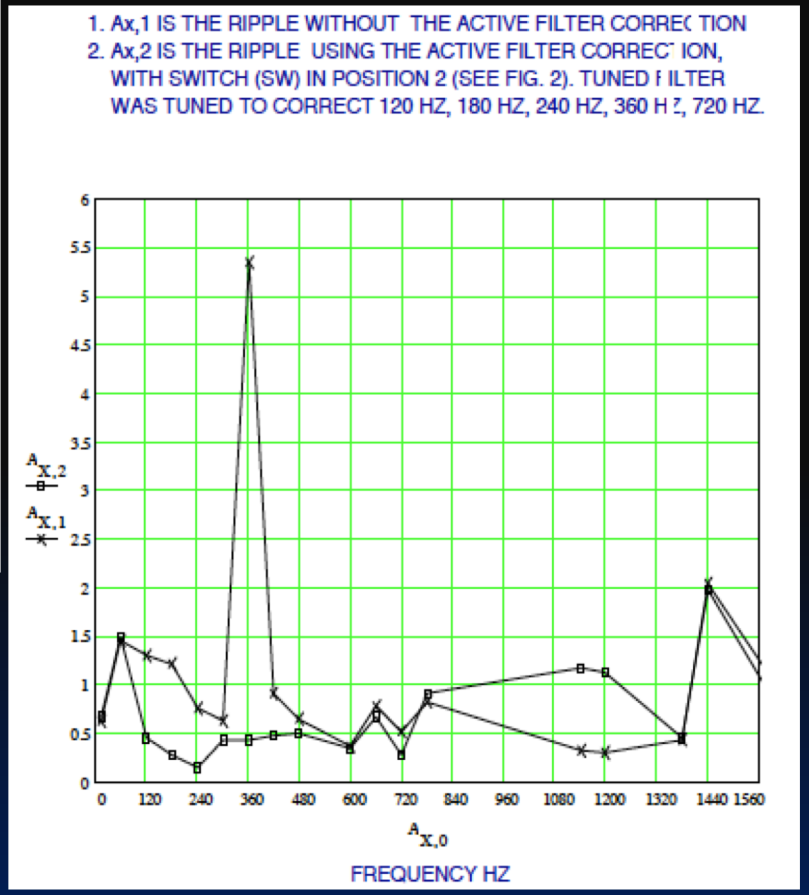
Overview of AGS Slow Extraction



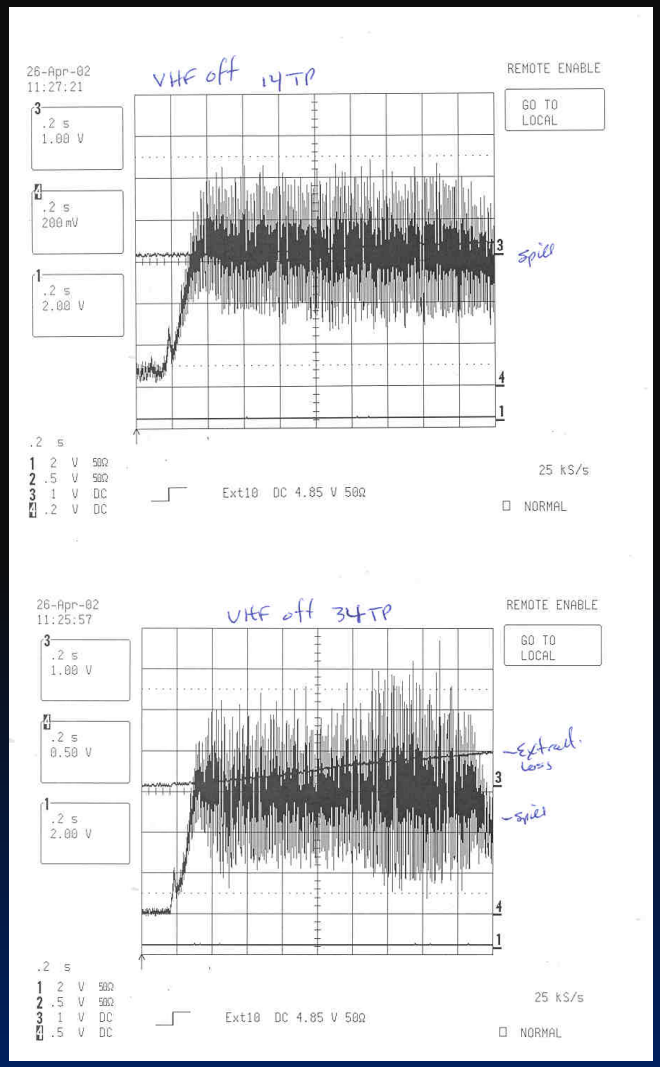


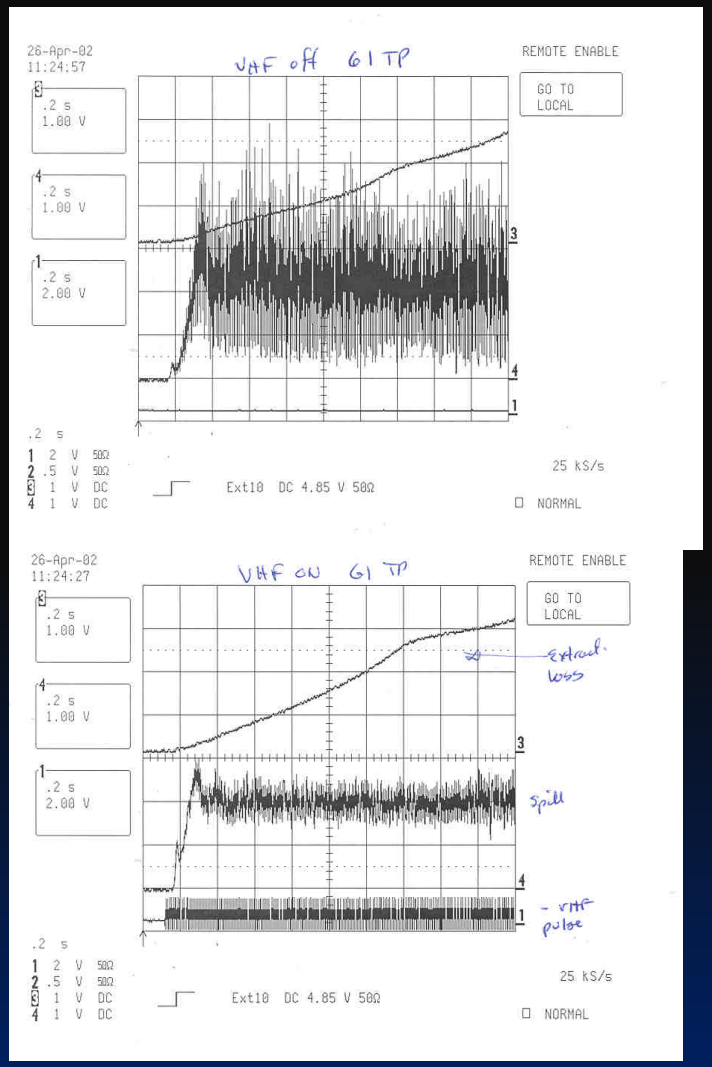
Active Ripple Filter



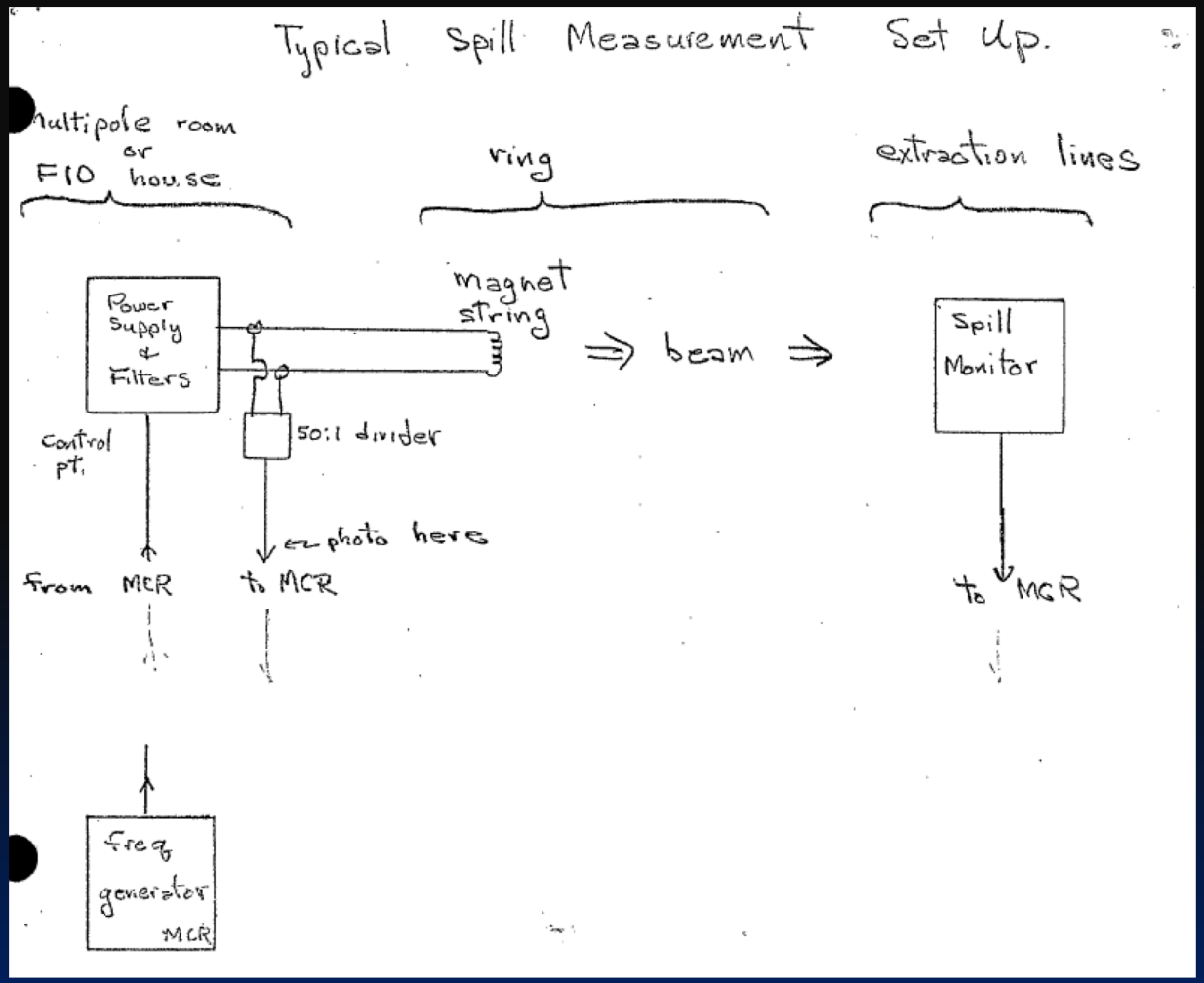


Spill and Ripple

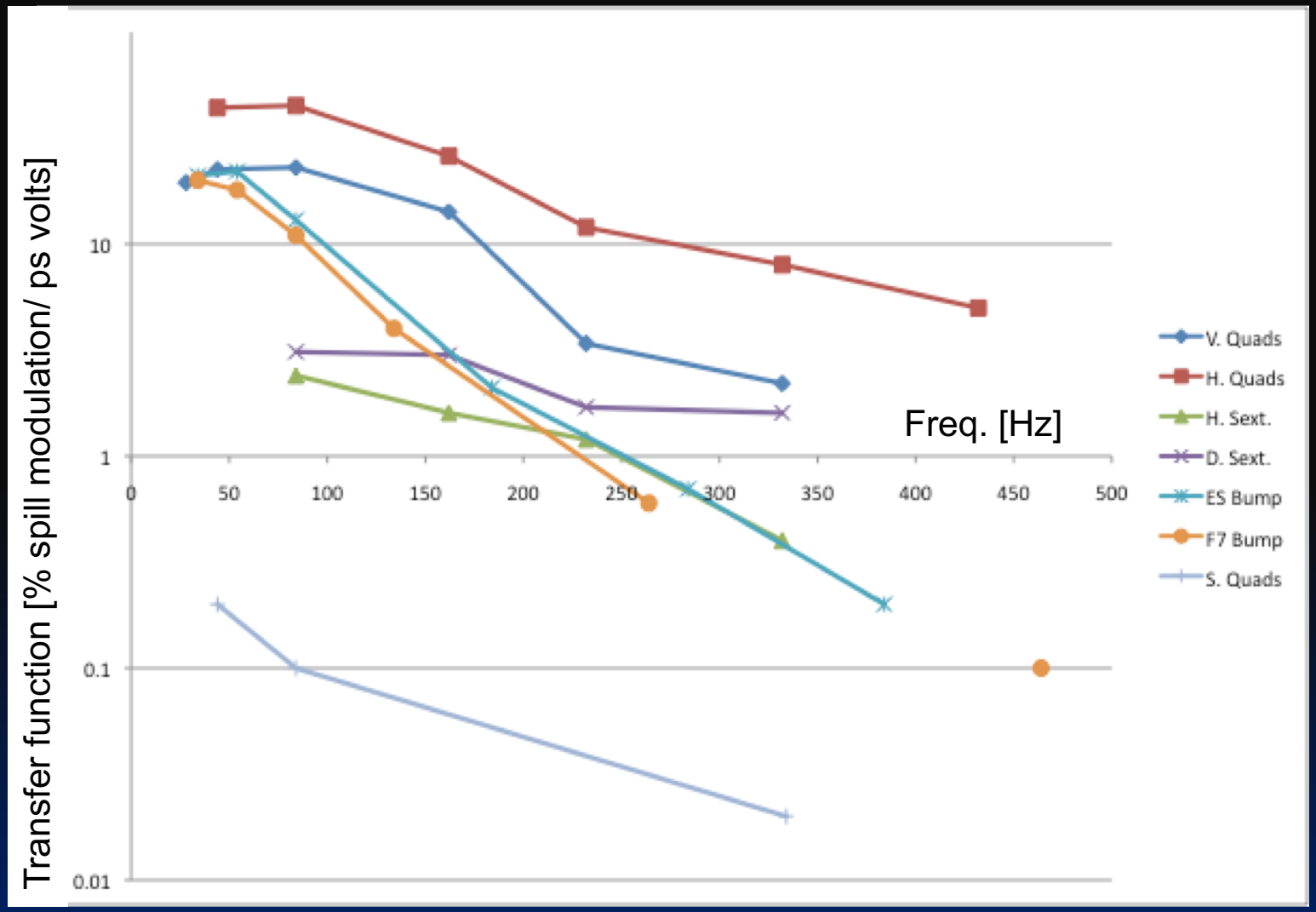


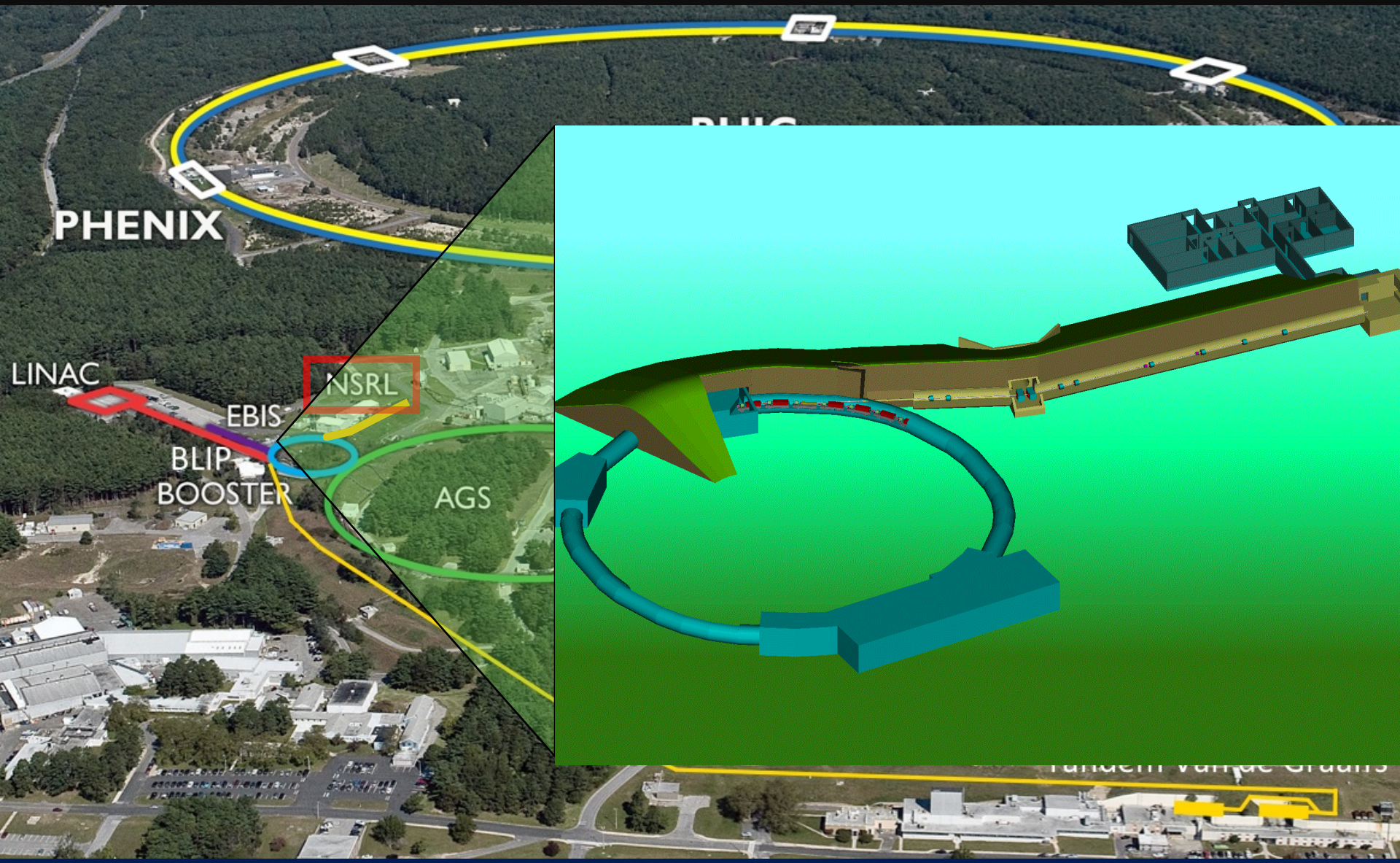


Transfer Function Measurements



Transfer Function Measurements




PHENIX
LINAC
EBIS
BLIP
BOOSTER
NSRL
AGS

Heavy Ions

- Charged
- Ionizing Radiation
- Outer-Space is full of them

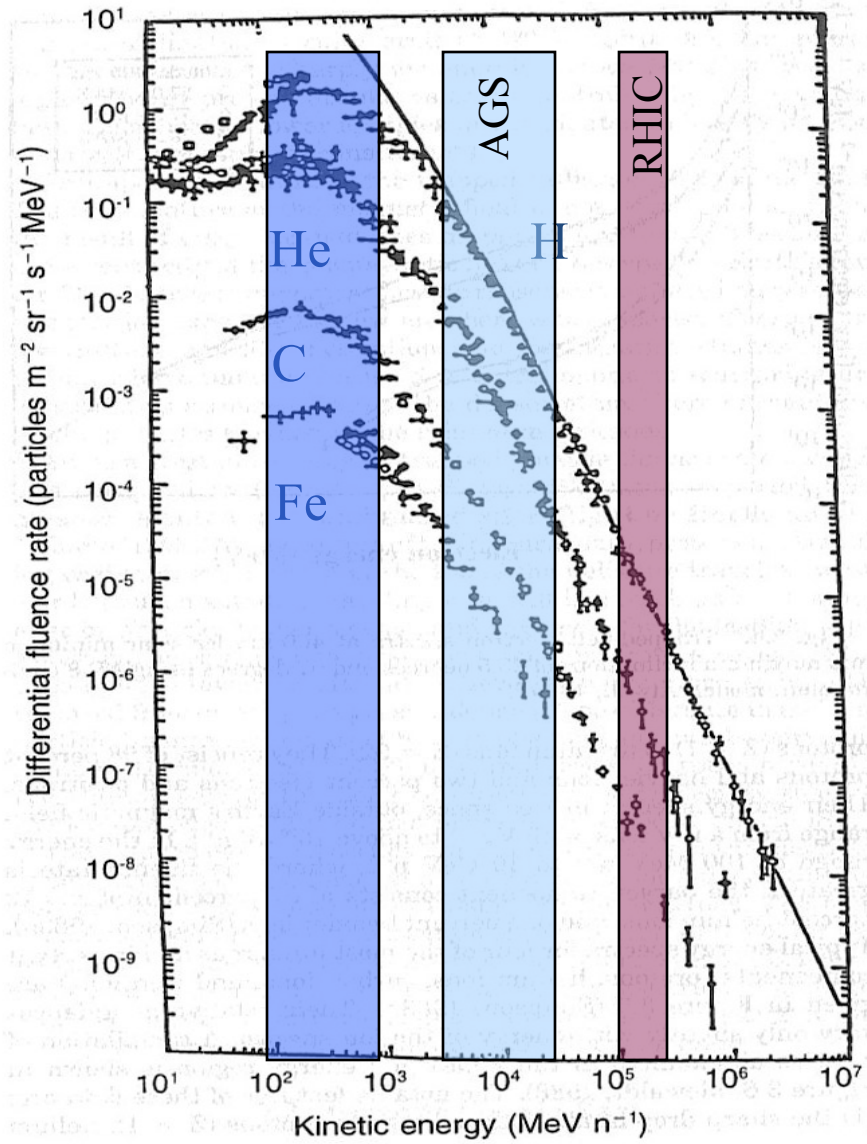
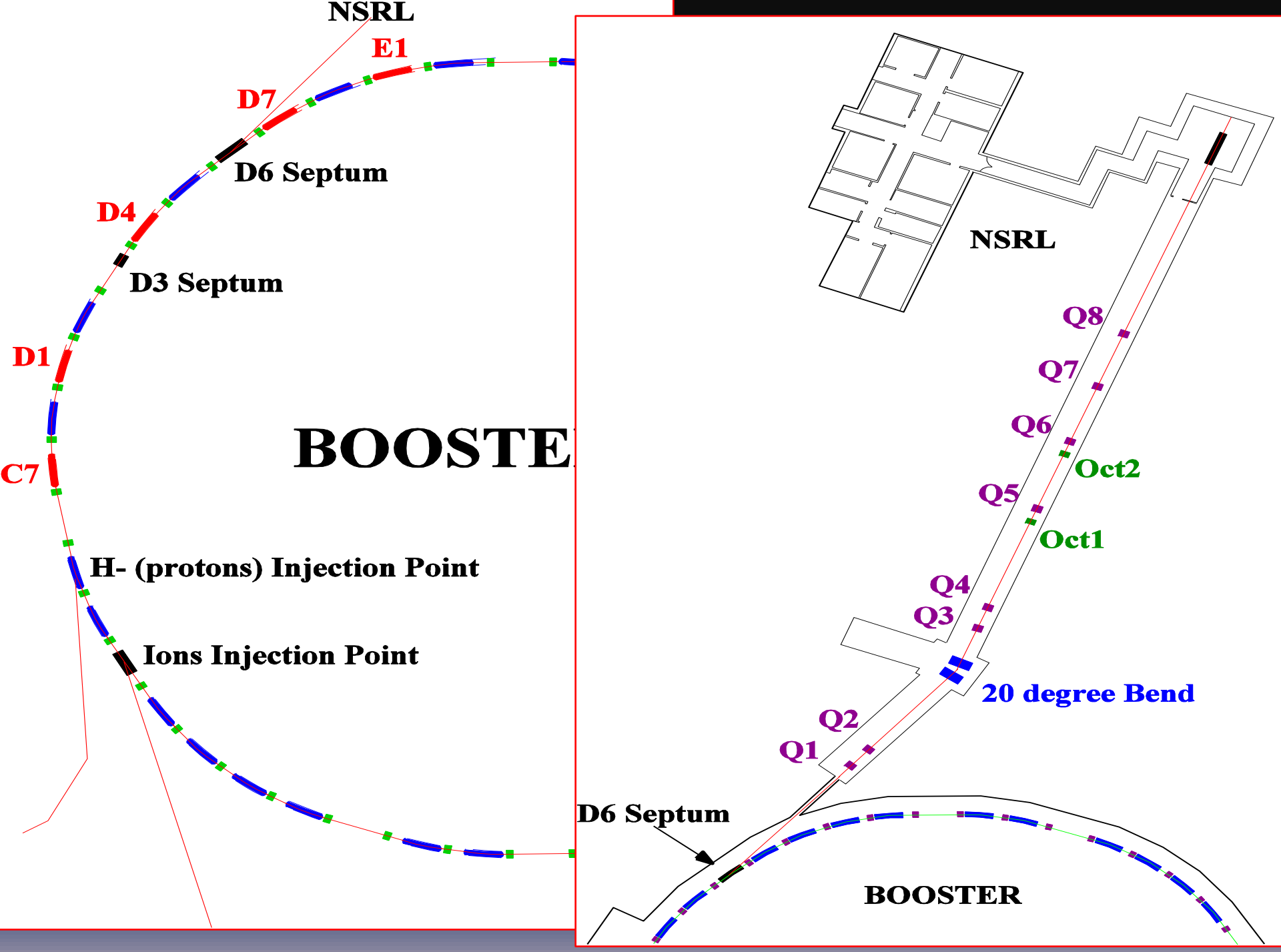
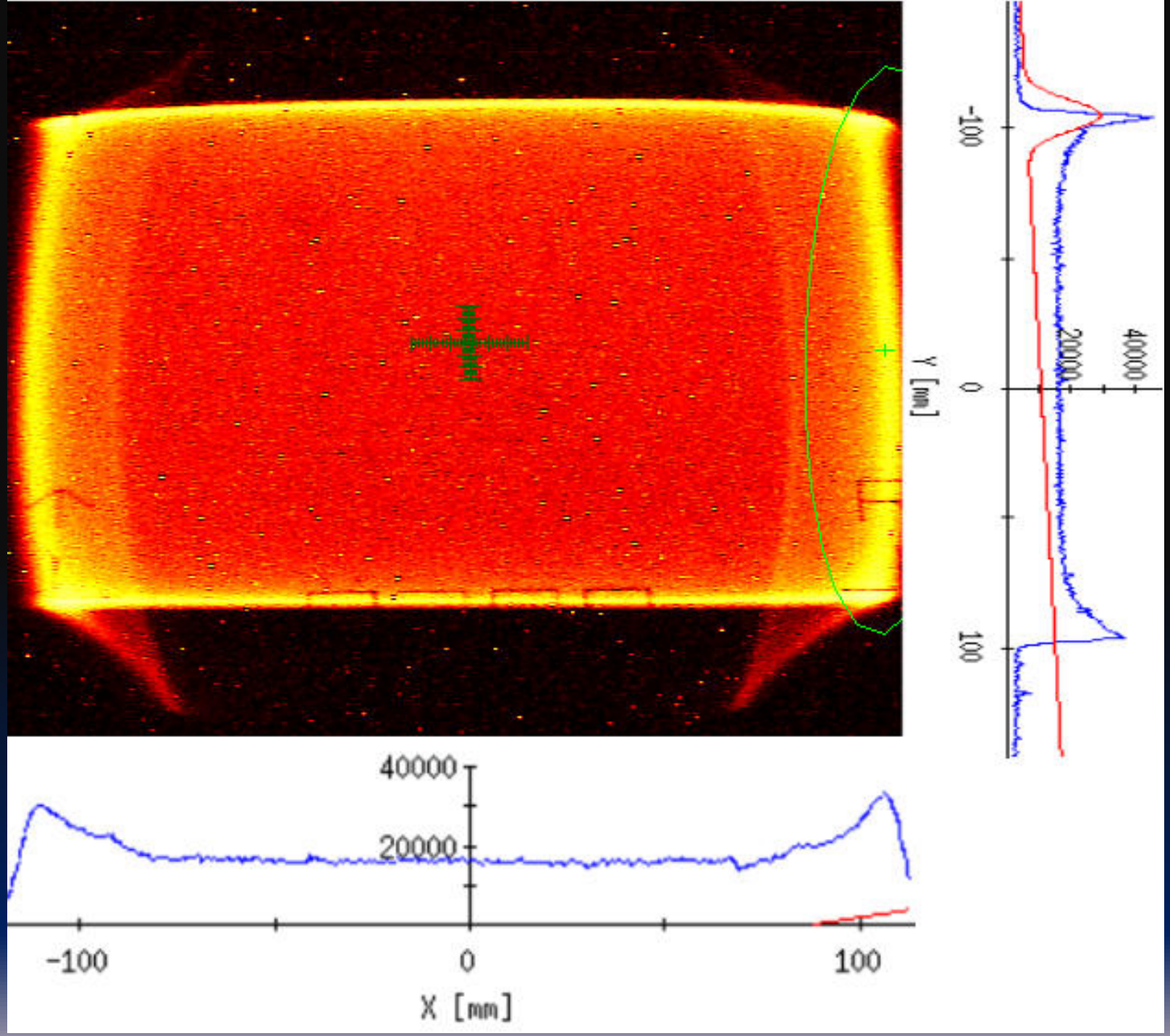


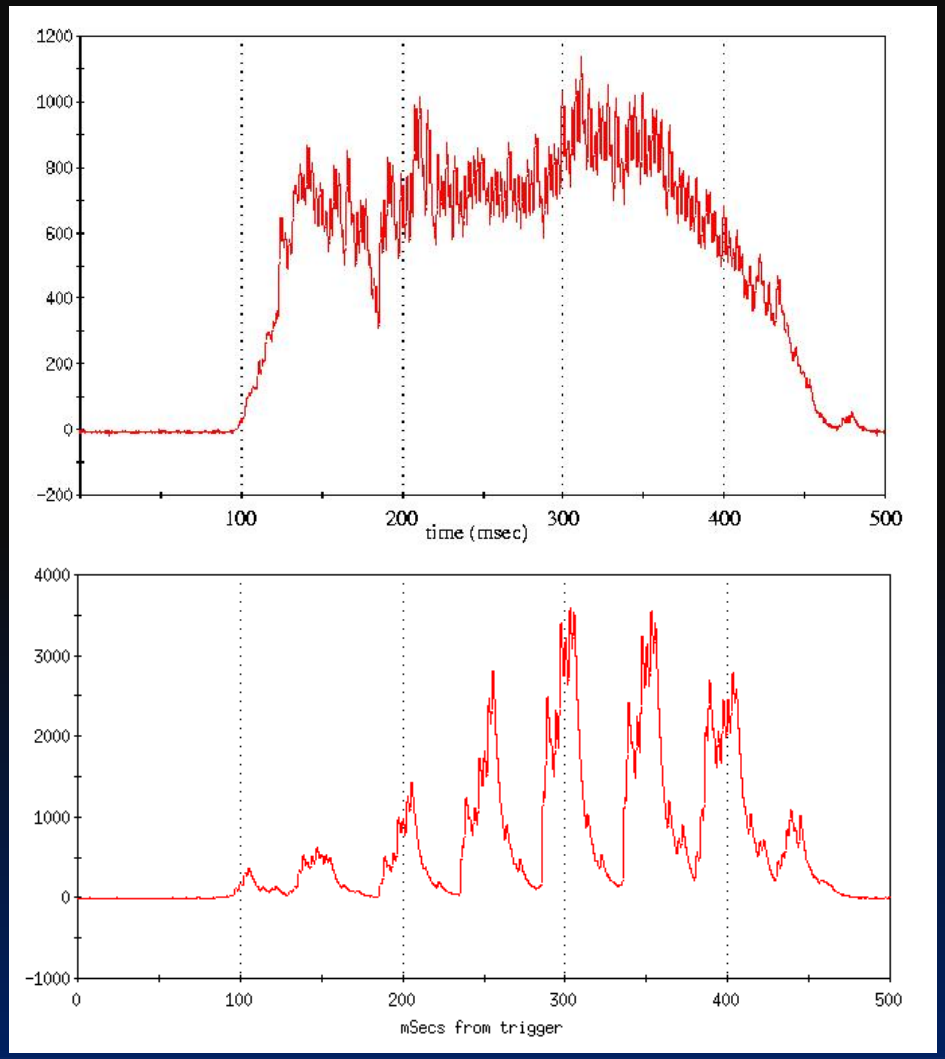
Fig. 3.5. Typical energy spectra for protons, helium ions, carbon ions, and iron ions from "top to bottom," respectively, at solar minimum. The solid line is the local interstellar spectrum (Simpson, 1983a).

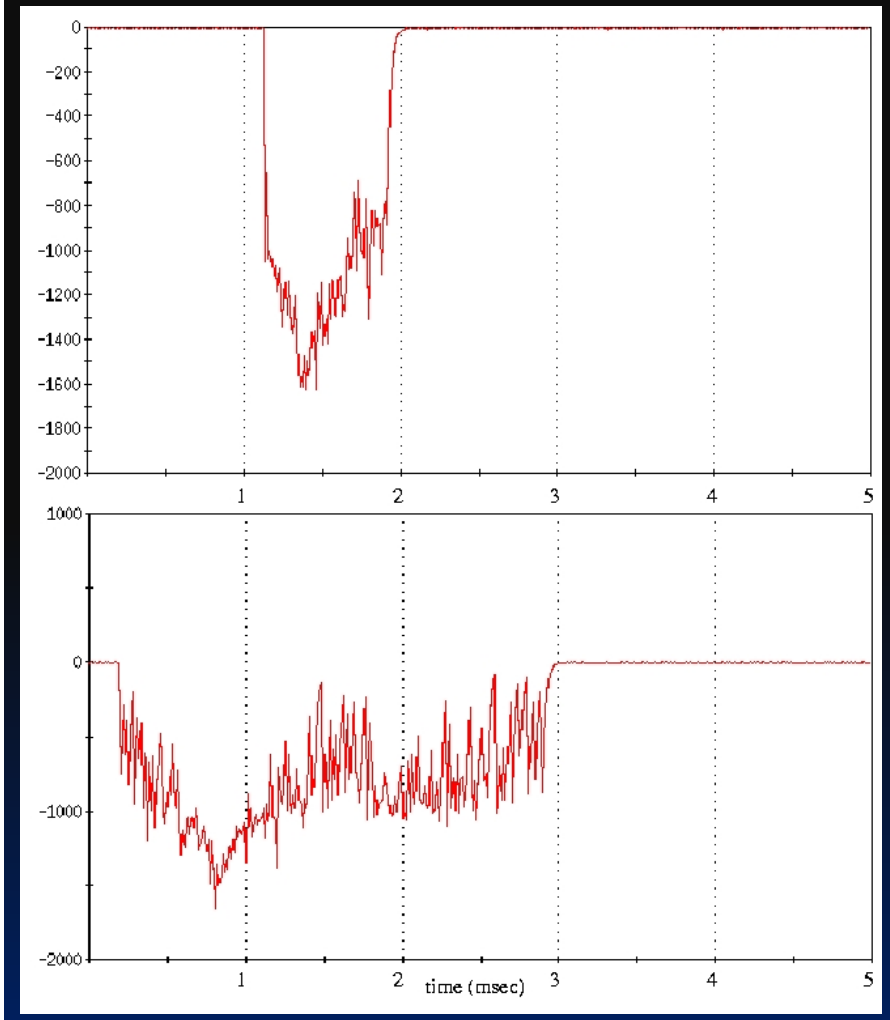

NSRL
E1
D7
D6 Septum
D4
D3 Septum
D1
C7
BOOSTE
H- (protons) Injection Point
Ions Injection Point
NSRL
Q8
Q7
Q6
Oct2
Q5
Oct1
Q4
Q3
20 degree Bend
Q2
Q1
D6 Septum
BOOSTER


40000
20000
-100
0
100
X [mm]
40000
20000
-100
0
100
Y [mm]

Beam Spills Delivered

[Also, have delivered fast extracted beams.]

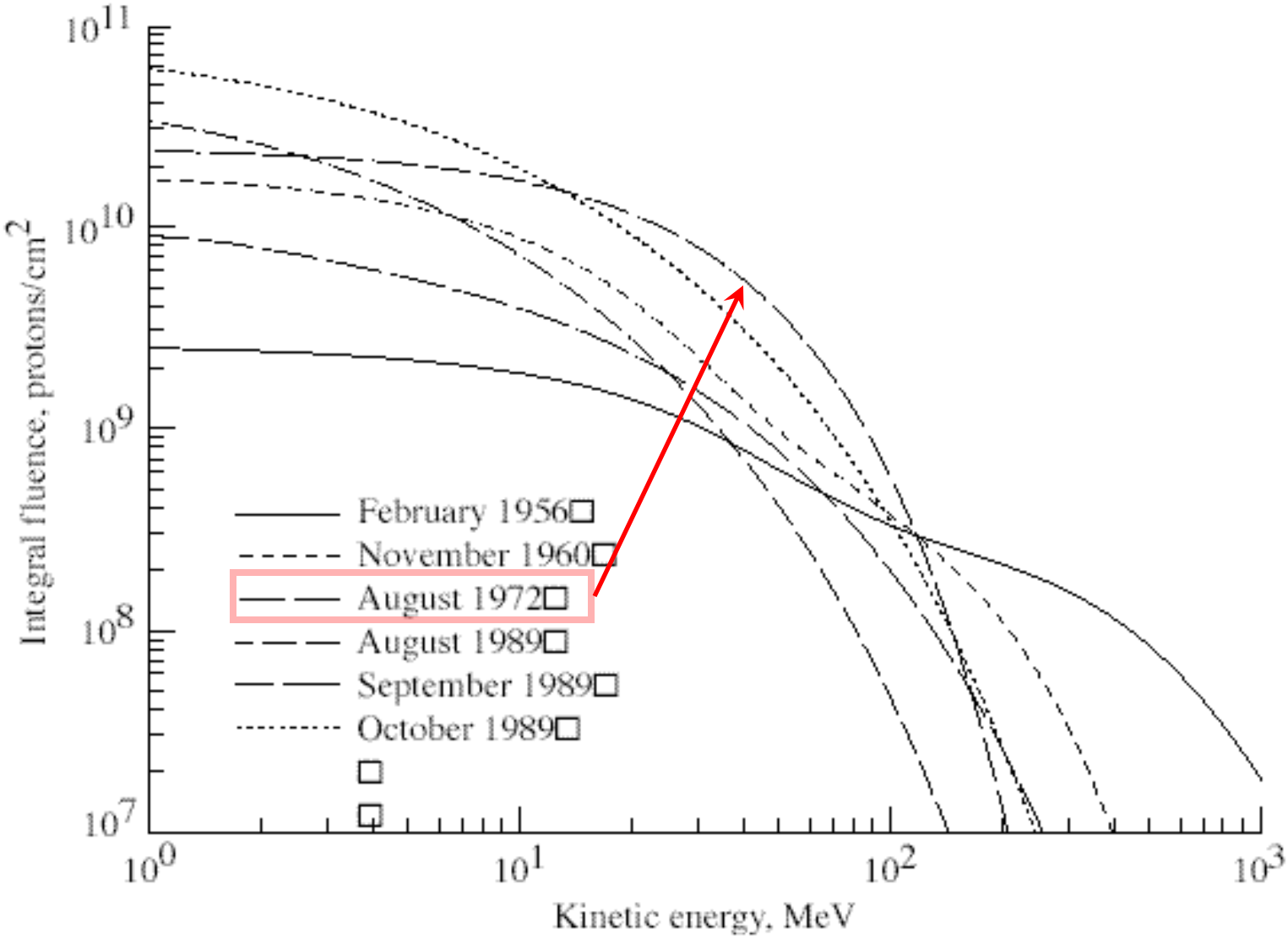




Solar Particle & Galactic Cosmic Ray Simulators

- SPE
  - The main goal is to reproduce the energy spectra from solar events (mostly protons).
- GCR
  - The main goal is to reproduce the energy spectra (& ion species) from the cosmic ray environment in space (mostly ions > He).
- NSRL Ground rules
  - *Need to irradiate a single sample over defined spectrum within as little as a 1 hour period or as long as one day.*
  - *Need a clean beam, as clean as any current NSRL experiment now receives.*
  - *Need to know the energy and ion species of the beam as well as any current NSRL experiment.*
  - *Need to know the dose as well as any current NSRL experiment.*

Solar Proton Events



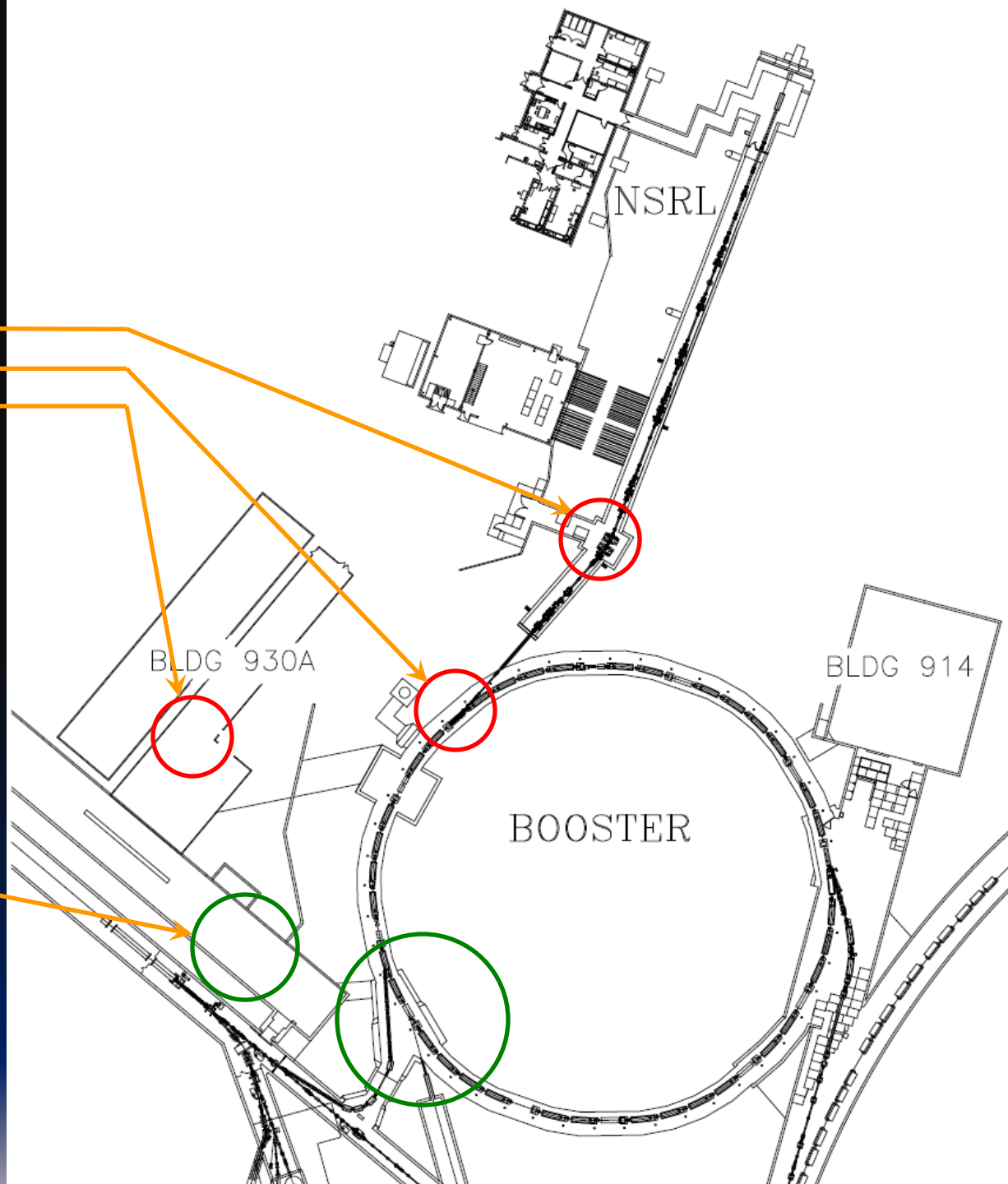
. Large solar proton event integral fluence spectra at 1 AU.

1.5 GeV/n Beam

- Additional bend magnet in R-line
- New D6 septum magnet
- New power supply for said magnet

Fast, multi-ion selector

- EBIS setup
- RF modifications
- Controls
  - Super cycle
  - Beam line
  - NSRL dosimetry



Basis for methods of spill harmonics correction

Spill is created by transforming the particle distribution in tune space into a continuous constant stream of particles.

$$S(t) = \frac{dN}{dQ}\frac{dQ}{dt}$$

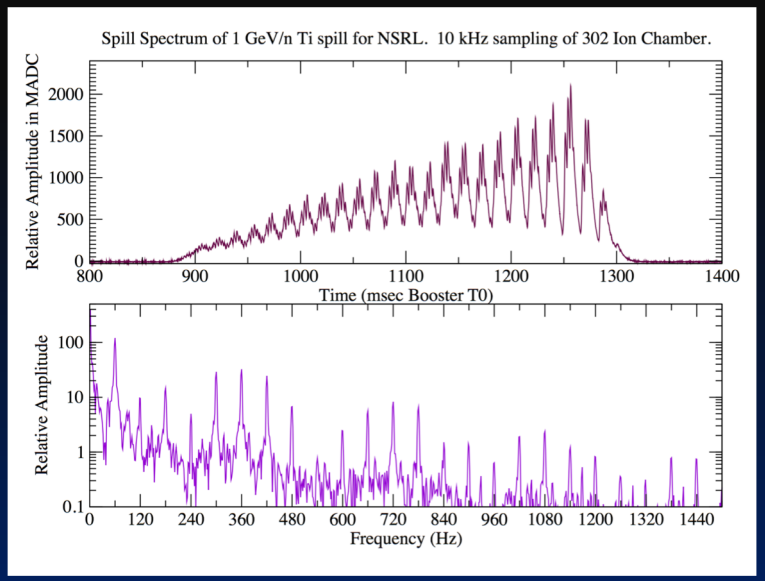
In purely linear terms, given a Gaussian distribution, this transformation simply is an error function (Gaussian to DC transformation).

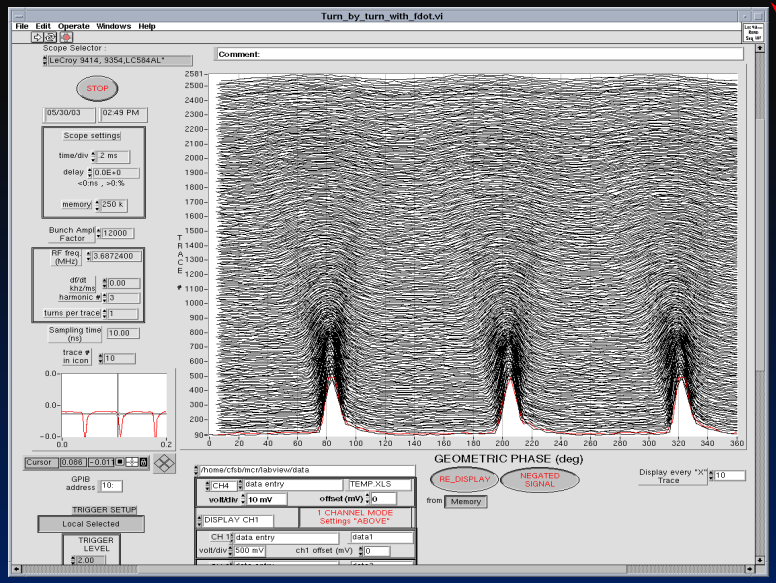
But, the variations in tune, due to power supply harmonics, is what gives the spill its characteristic micro-structure.

Note that the structure is function of the rate. The faster the spill is driven through the resonance, the smaller the micro-structure. This is how many systems make a simple improvement in spill. They just make dQ as big as possible by going to large chromaticity and increase dp/p.

More on spill

- The process is extremely slow, relatively speaking
  - Bunches start ~100 nsec long, with dp/p ~ 1% (after phase back increasing), and dQ/Q ~ 0.1 - 0.2
  - After debunching (RF off), the thin ribbon of DC beam is extracted, taking up to 1 million revolutions to be slowly sliced by septa and peeled out to the transfer line to a target station





Spill correction: 2 methods (there are more)

- Increase rate of particle passage through resonance
  - Increase dp/p
  - Use RF empty buckets (RF Phase Displacement)
- Modify rate by modulating tune
  - Active filter
  - Air core or dedicated quadrupole feedback system
  - Real time feed-forward correction (J-PARC, R. Muto talk tomorrow)

If there is ripple on the magnet power supplies;

$$S(t) = \frac{dN}{dQ}(\dot{Q}_0 + \dot{Q}_v)$$

where $\dot{Q}_0$ is the rate at which particles move into resonance.

$$\dot{Q}_0 = \frac{Q\xi}{I_m}\frac{dI_m}{dt}$$

where $\dot{Q}_v$ is the variations in the rate at which particles move into resonance.

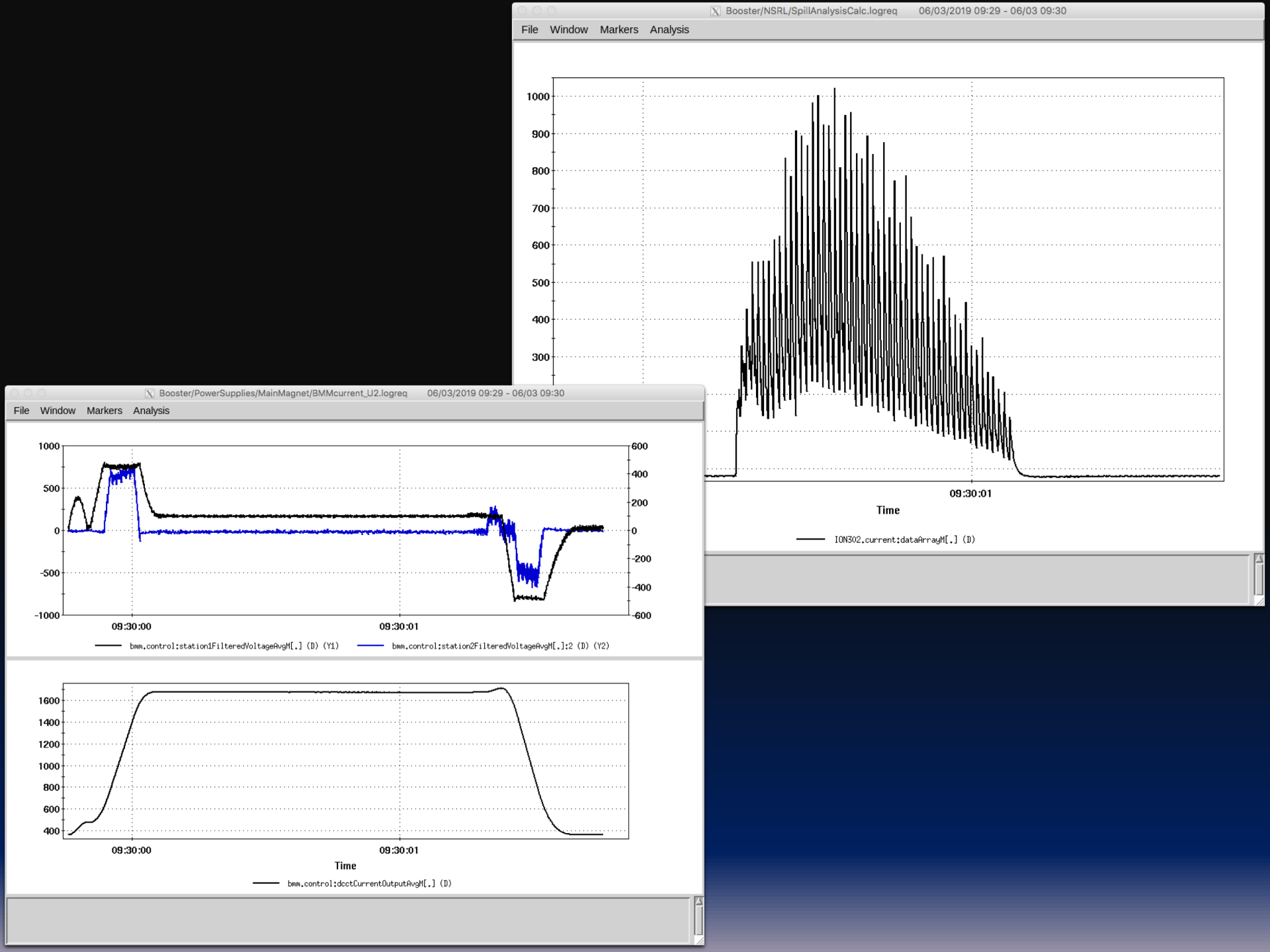
$$\dot{Q}_v = \frac{Q\xi}{I_m L_m}\sum_h V_h$$

L_m is the total inductance of the main dipoles and quads and V_h is the sum of the 60 Hz harmonics amplitudes (in volts).

Tune Modulation, other approaches

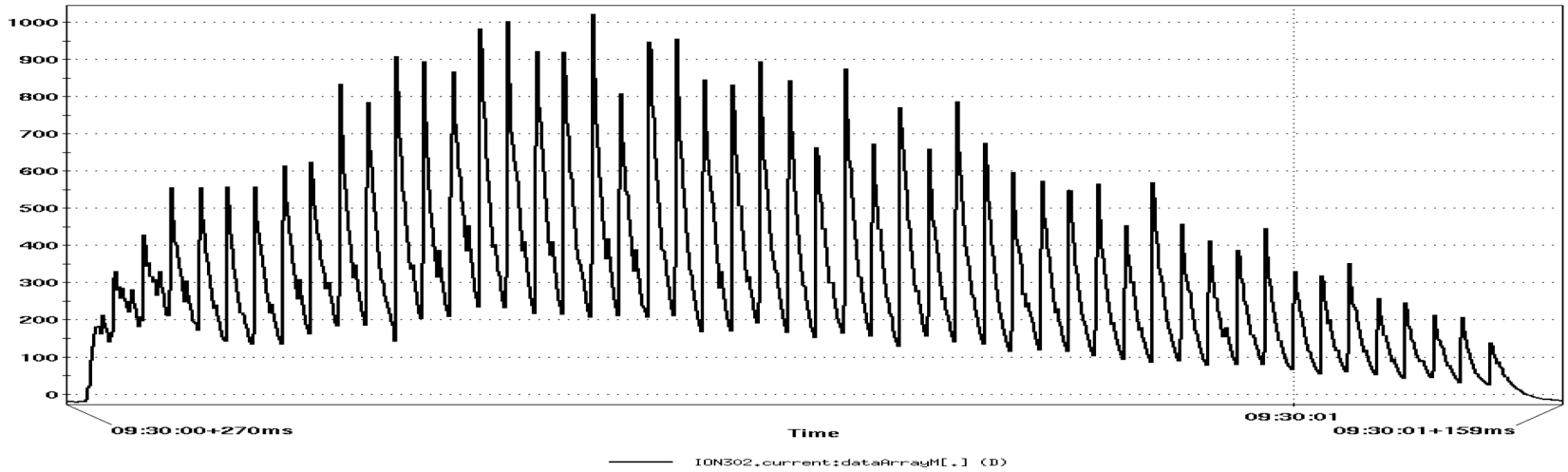
- Tune modulation requires knowledge of harmonics in spill
- Classical ‘approach’:
  - measure FFT (keep both real & imaginary parts)
  - Apply gain and phase factors to real and imaginary components
  - Inverse FFT to use as correction
- Problem:
  - Measured FFT only gives the average of the harmonics and phases

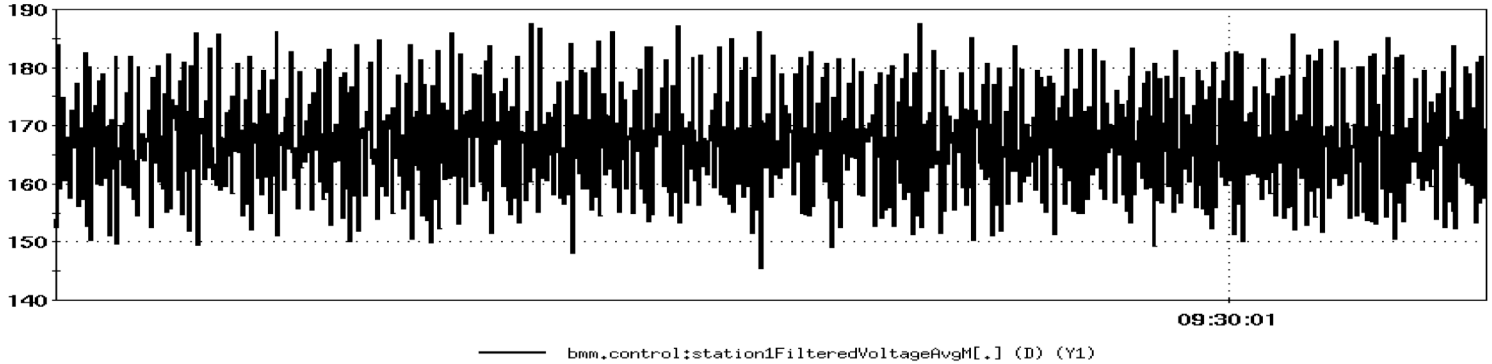
- To beat the average, need a real-time correction.
  - But need to make sense of the real data - not easy

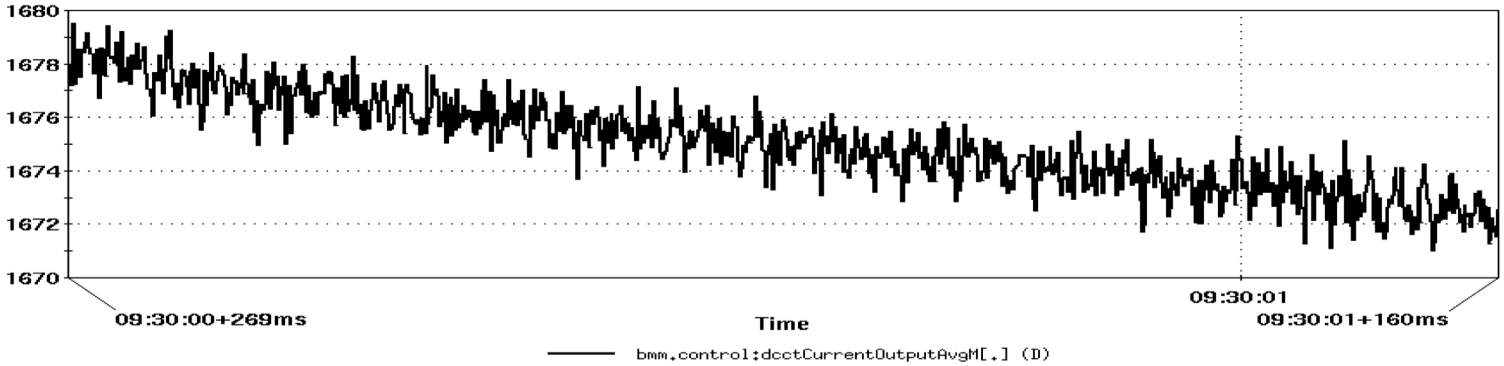

Booster/NSRL/SpillAnalysisCalc.logreq 06/03/2019 09:29 - 06/03 09:30
File Window Markers Analysis
1000
900
800
700
600
500
400
300
09:30:01
Time
ION302.current:dataArrayM[.] (D)
Booster/PowerSupplies/MainMagnet/BMMcurrent_U2.logreq 06/03/2019 09:29 - 06/03 09:30
File Window Markers Analysis
1000
500
0
-500
-1000
600
400
200
0
-200
-400
-600
09:30:00
09:30:01
bmm.control:station1FilteredVoltageAvgM[.] (D) (Y1)
bmm.control:station2FilteredVoltageAvgM[.]:2 (D) (Y2)
1600
1400
1200
1000
800
600
400
09:30:00
09:30:01
Time
bmm.control:dcctCurrentOutputAvgM[.] (D)

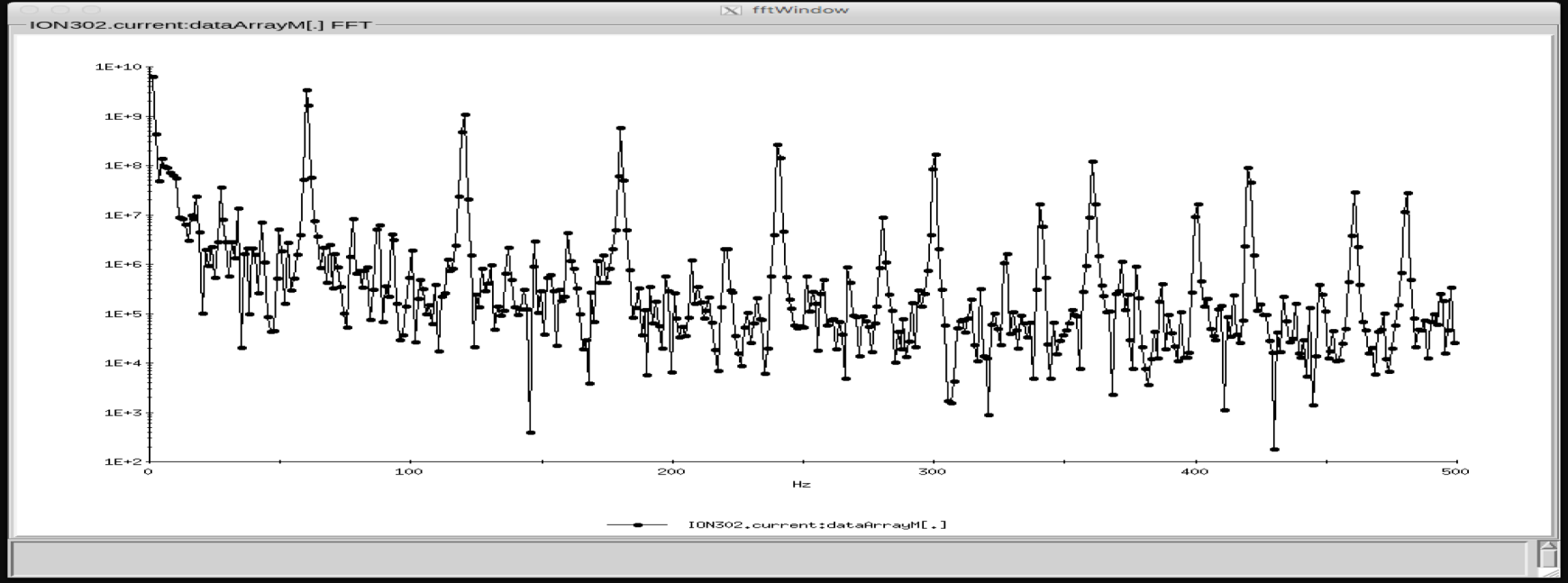
Booster/NSRL/SpillAnalysisCalc.logreq 06/03/2019 09:30 - 06/03 09:30

File Window Markers Analysis








fftWindow
ION302.current:dataArrayM[.] FFT
1E+10
1E+9
1E+8
1E+7
1E+6
1E+5
1E+4
1E+3
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0
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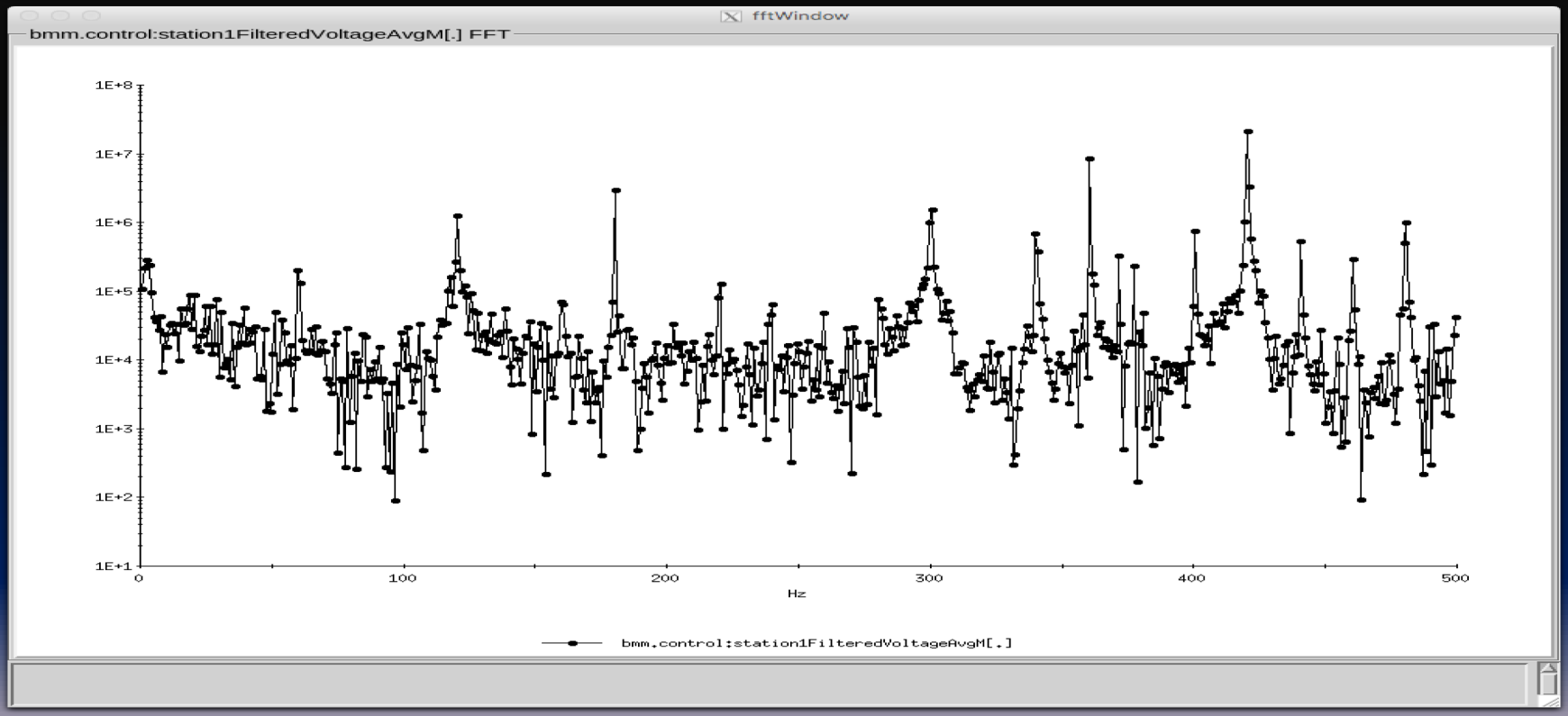
Hz
ION302.current:dataArrayM[.]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1E+7
1E+6
1E+5
1E+4
1E+3
1E+2
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0
100
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Hz
bmm.control:station1FilteredVoltageAvgM[.]

What to do?

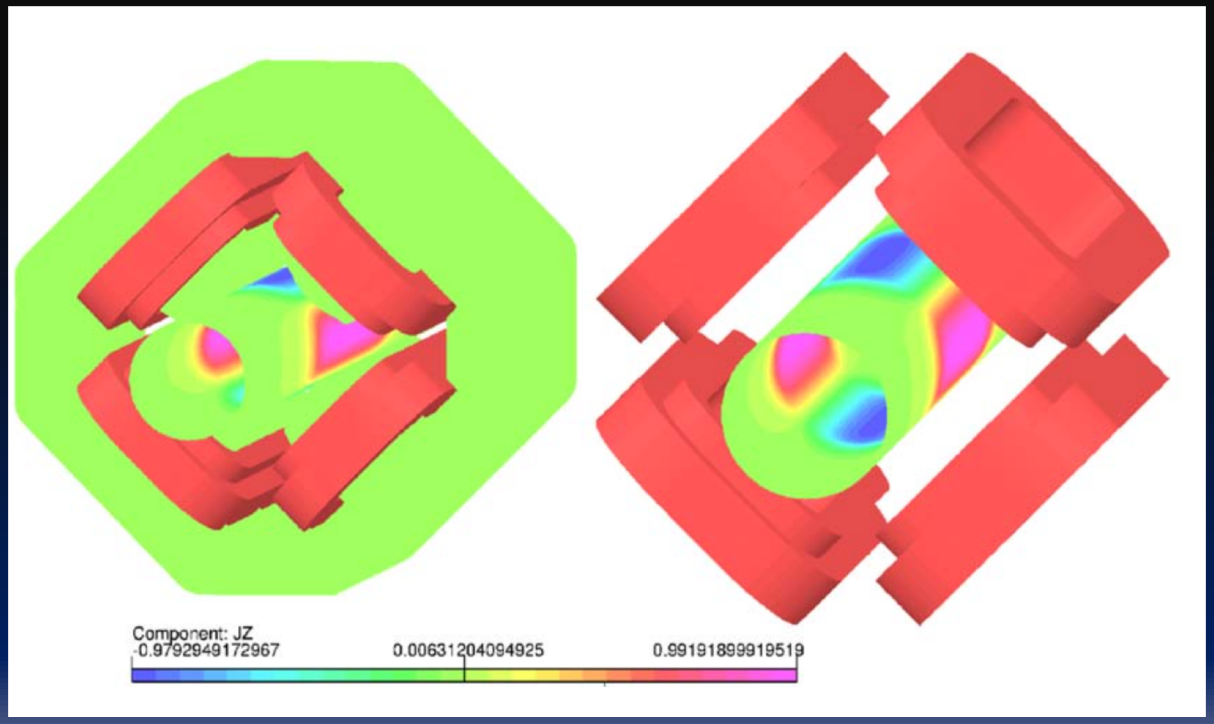
- See Ryotaro Muto's talk - that is one (nice) approach
- The measured voltage is what is across the load, but is not what the beam see's. The higher frequency components are attenuated in the chamber.
- So we need a probe that measures the field variations that the beam see's.

Reference Quadrupole for the Booster

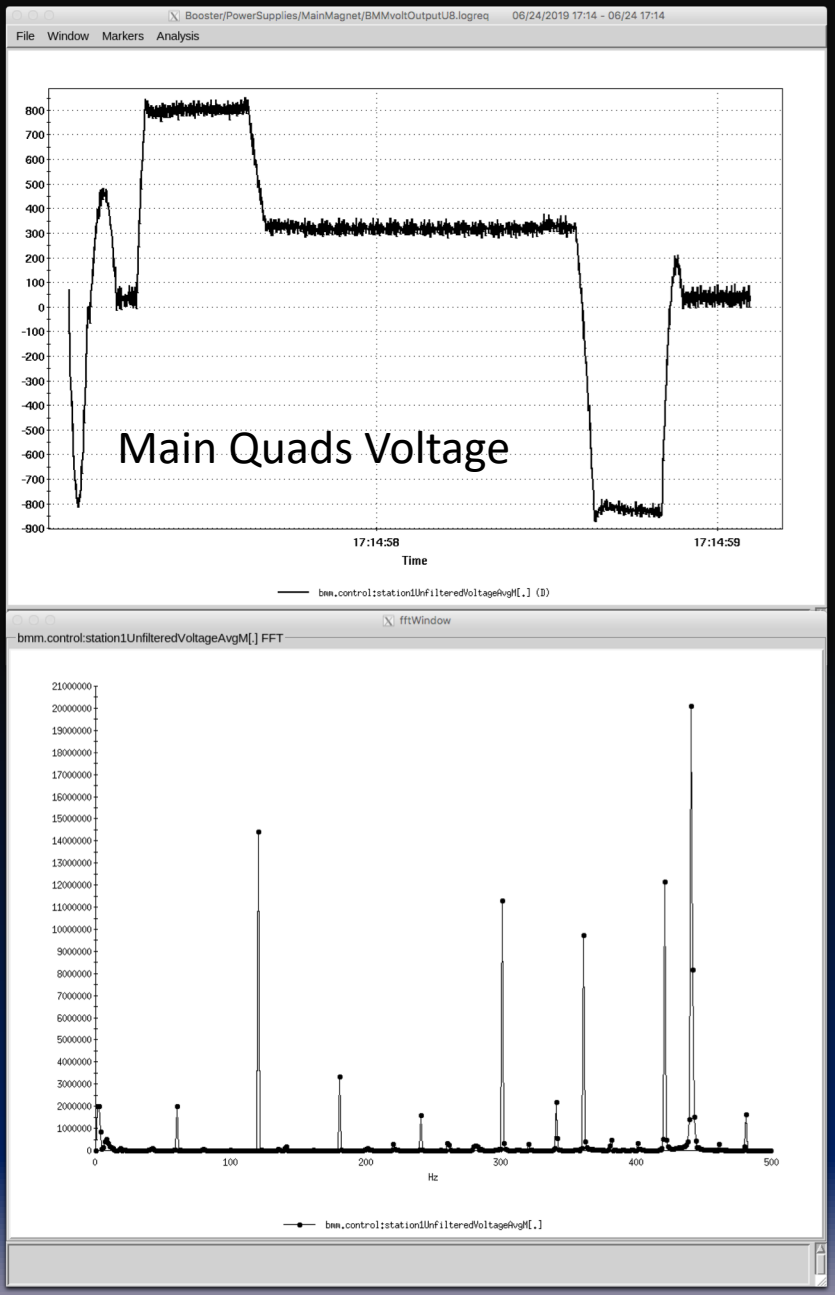
- A reference coil in the quadrupole will measure the change in the field (dB/dt), where the ripple measured from the pickup is

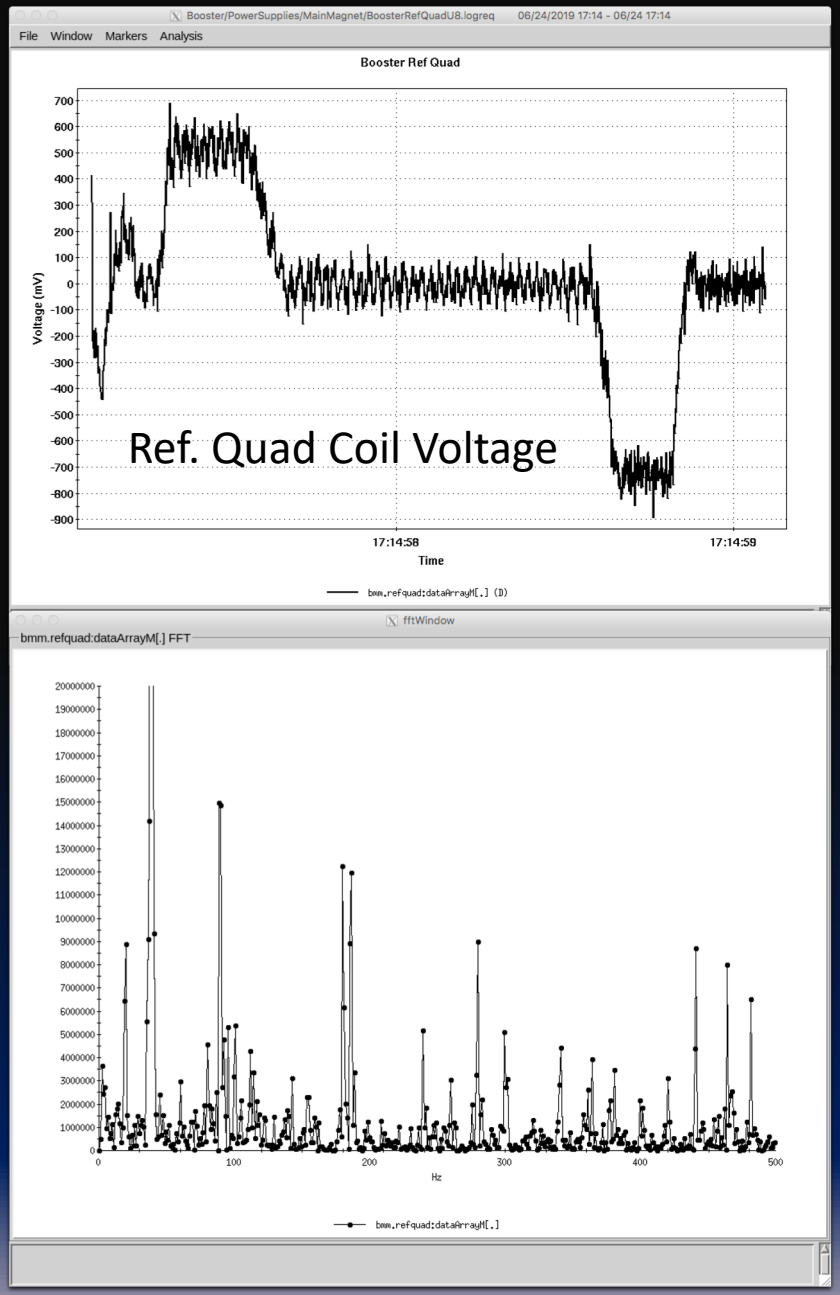
$$V_c = f(g(m), h(c), a_{eddy}) \sum_n \omega_n V_n \cos(\omega_n t + \varphi_n)$$

- A correction can be built by using this signal in real time to modulate the tune
- Problem = the signal needs to be extremely good, since the V_n *'s are tiny.*



Not a good example



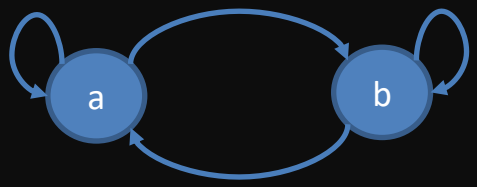


Summary

- AGS slow extraction was a simple robust design that was able to deliver very intense beams
- AGS slow extraction beam quality was extremely good and met the requirements of dozen of diverse experiment's. Spill modulation was routinely at the level of 20%.
- Booster slow extraction was designed for NASA experiments with focus mostly on ions and low intensity beams.
- Booster slow extraction beam quality meets the requirements, delivering highly uniform beams (3D)
- Booster SPE and GCR simulator systems allow unprecedented flexibility in the delivery of different ions and different energies
- New requirements from NASA Physics experiments are looking for high quality spills without the high frequency RF microstructure used to create uniform spills
- Real time spill correction is a very promising technique that we plan to employ to delivery uniform spills for NASA physics experiments

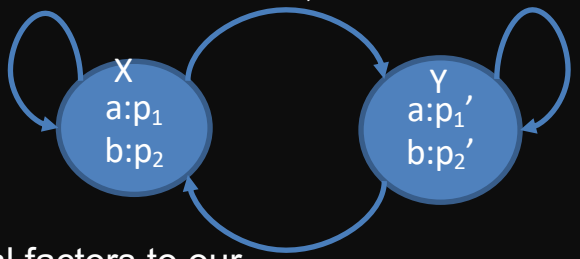
Additional Info & Backup Slides

Hidden Markov Models

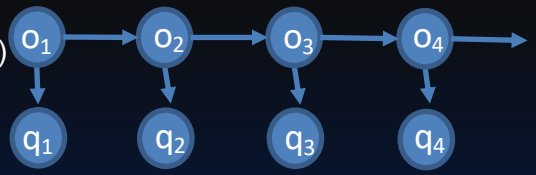


- Markov assumption:
  - When predicting the future, the past doesn't matter, only the present
  - $P(q_i = a|q_1 \ldots q_{i-1}) = P(q_i = a|q_{i-1})$

- Markov Chains
  - A model that tells us something about the probabilities of sequences of random variables, or
  - States
  - Useful to compute the probability for a sequence of observable events



- Hidden Markov Models
  - States + observations
  - What happens when events are hidden? Hidden events that are causal factors to our probability.
    - $Q = q_1 q_2 \ldots q_N$ set of N states
    - $A = a_{11} \ldots a_{ij} \ldots a_{NN}$ transition probability matrix (probability of moving from state i to state j)
    - $O = o_1 o_2 \ldots o_T$ a sequence of T observations
    - $B = b_i(o_t)$ a sequence of observation likelihoods, also called emission probabilities
    - $\pi = \pi_1, \pi_2, \ldots, \pi_N$ an initial probability distribution over states

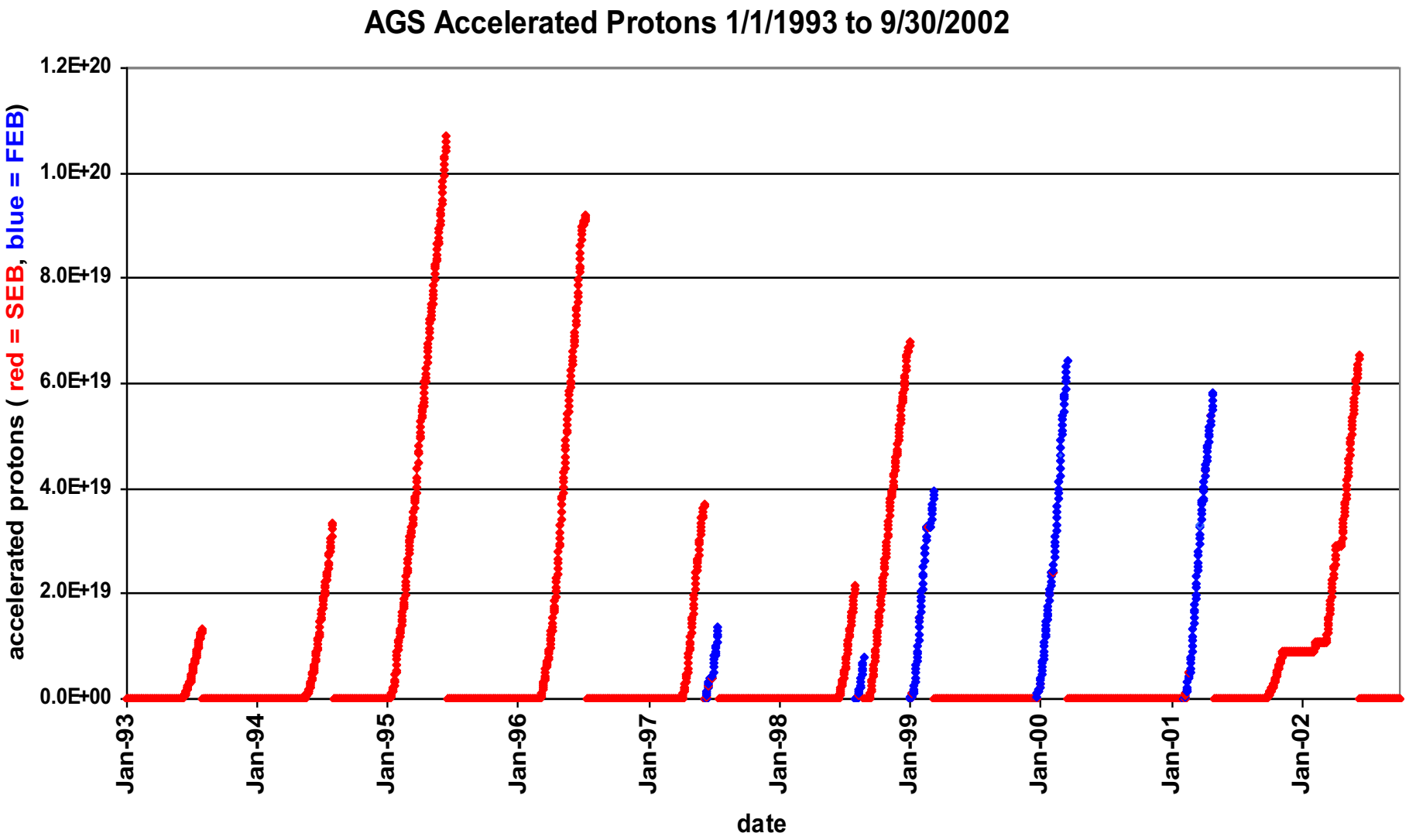


  - the probability of a particular state depends only on the previous state
    - Markov Assumption: $P(q_i|q_1 \ldots q_{i-1}) = P(q_i|q_{i-1})$
  - the probability of an output observation o_i depends only on the state that produced the observation q_i and not on any other states or any other observations
    - Output Independence: $P(o_i|q_1 \ldots q_i, \ldots, q_T, o_1, \ldots, o_i, \ldots, o_T) = P(o_i|q_i)$

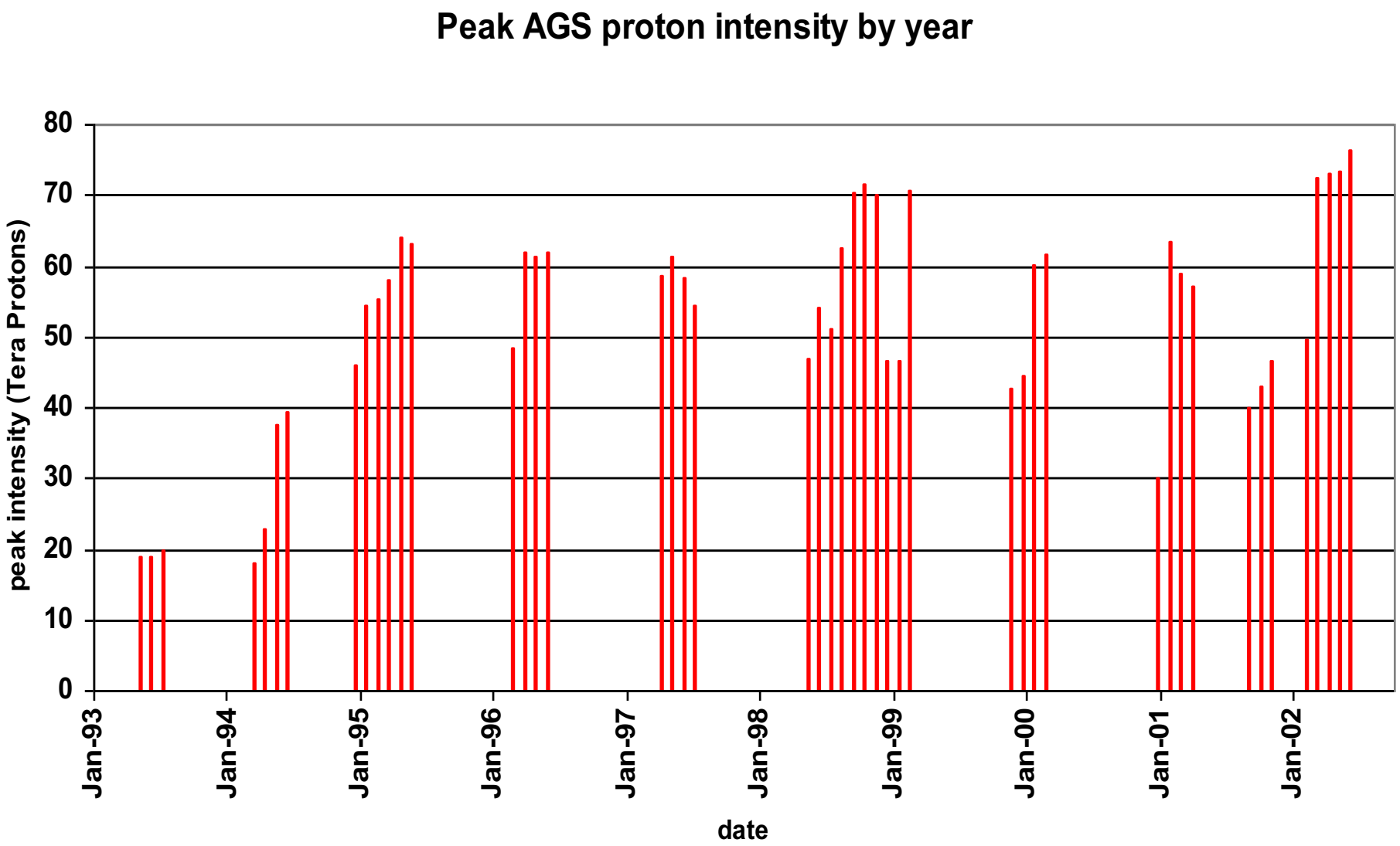
A progression from MM: Averaging the past

- We KNOW our signal is a combination of noise and systematic behavior that must repeat over time.
- Now, instead of taking just the ‘present’ state to predict the future, take an average of the past ‘few’ states, to reduce the influence of random effects from systematic effects
- This process is a simple ML method. We are now using knowledge of the past (the real time average) to predict the future
  - Only care about the systematic effects, so this is okay

Integrated Intensity per Run



Peak Intensities by Year



Booster & AGS Performance: SEB

Imposed limits to lost beam power to maintain hands-on maintenance (ALARA).

•AGS SEB operation, 5.4 s AGS cycle time, 6 Booster cycles.

Achieved **19.6 Tp/sec, Booster Late** & **<u>13.7 Tp/second, AGS Late</u>**.

Table: SEB 10 Pulse Ave. Data (best performance)

	Intensity (Tp/cycle)*	Efficiency (%)	Beam Loss (Tp/cycle)	ALARA (Tp/cycle)	Loss (kW)	Loss/m (W/m)
Linac	177	-	-	-	-	
Booster Injected	125	71	52	54	0.31	1.5
Booster Extracted	106	86	18	18	0.5	2.5
AGS Injected	78	74	28	31.5	1.62	2.0**
Transition	76	98	2	3	0.26	0.3
After Transition	73	95	3	4.5	0.63	0.8
AGS Late	73	100	0	1.5	0	0

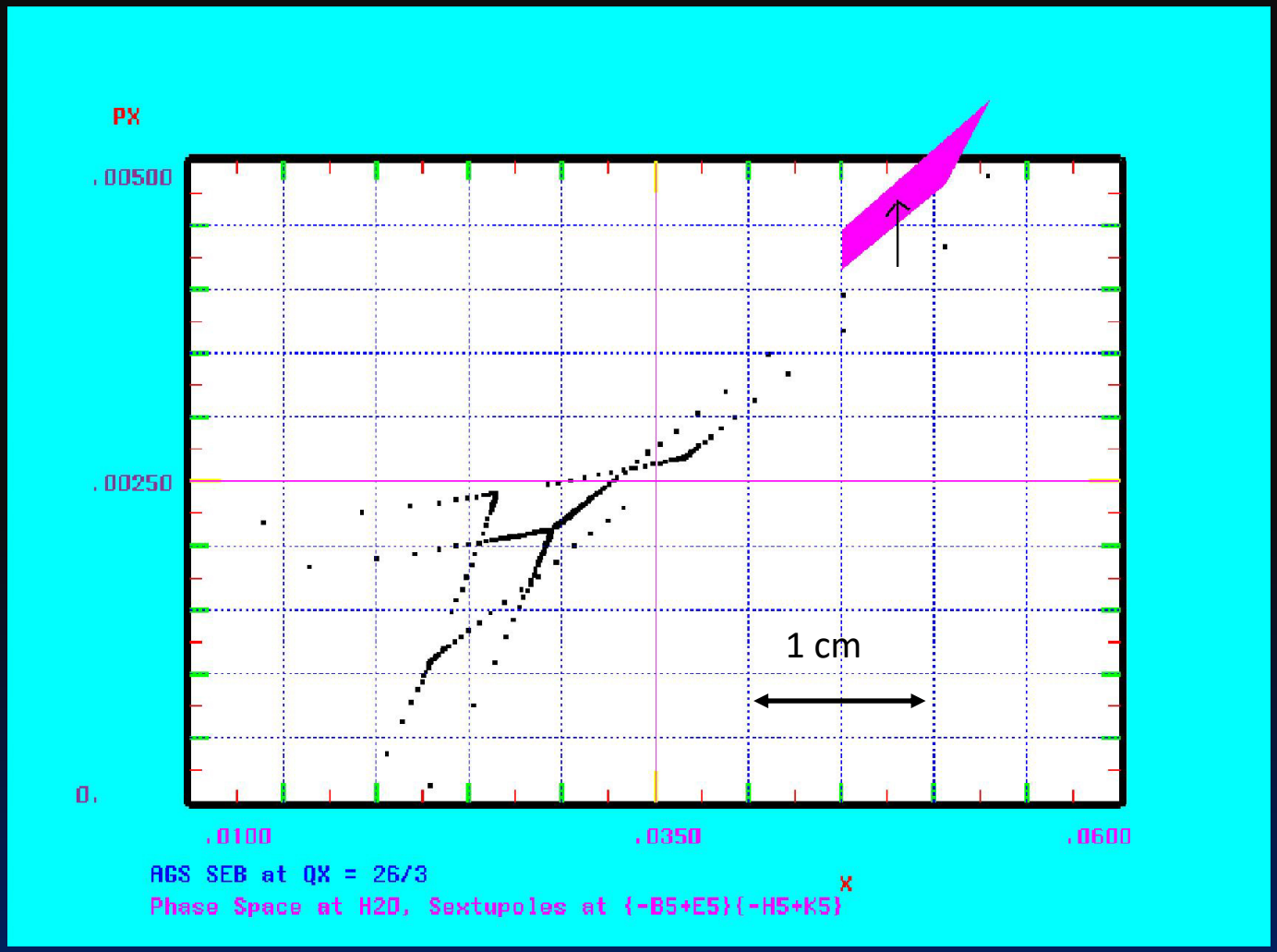
* 1 Tp = 1×10^{12} protons

** assumed lost in AGS

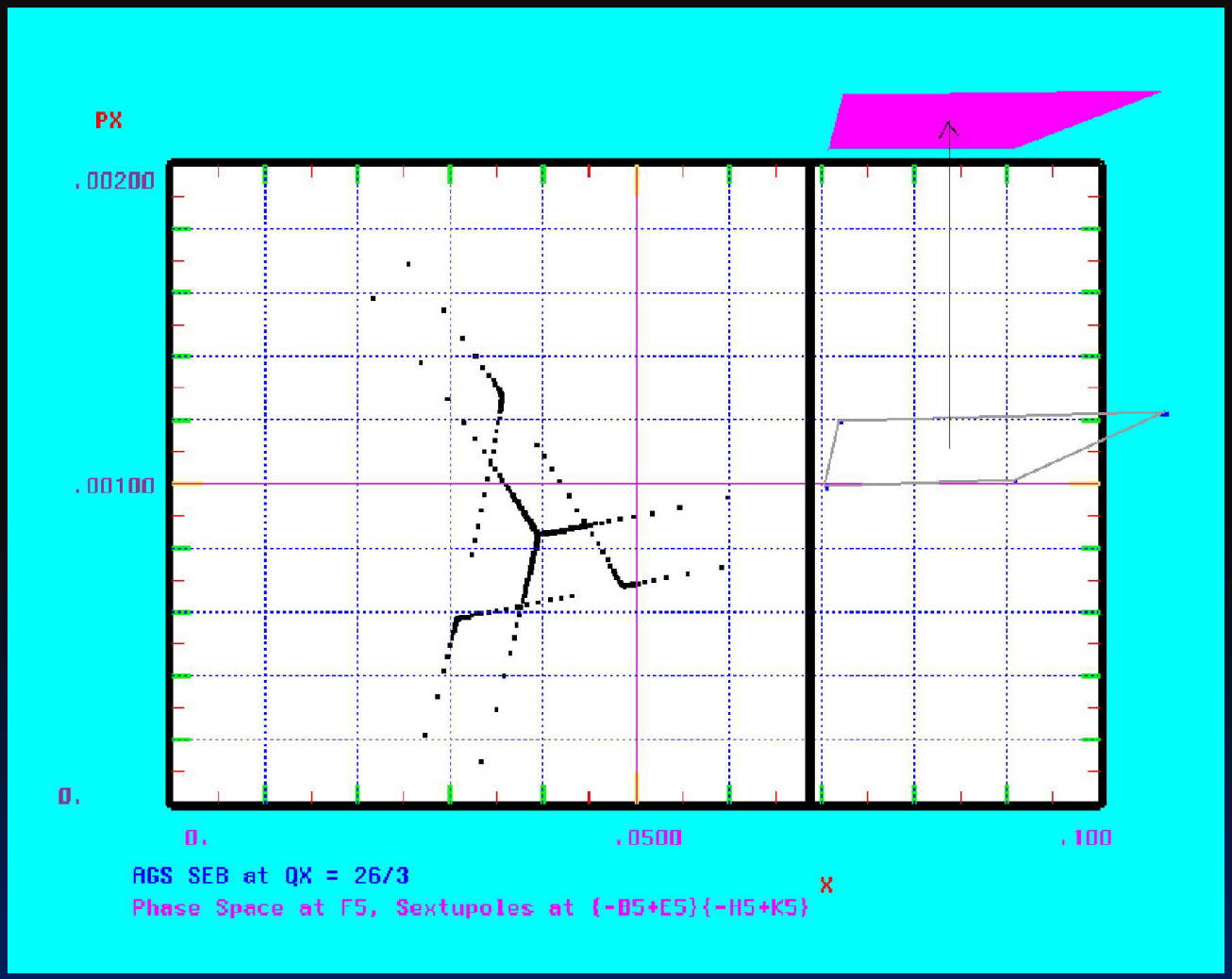
Slow Extraction Parameters

Parameter	Value	Units
Peak Intensity	76.0	10^{12} protons/pulse
Extraction Efficiency	97-98	%
Rep Period/Flattop Length	4-8/2-6	Seconds
Spill Lengths	1.8 – 5.8	Seconds
Working Point	8.667 / 8.78	Horiz./Vert. Tune
Chromaticity	-2.5 / 0.05	Horiz./Vert. Chrom.
Extraction Momentum	25.5	GeV/c

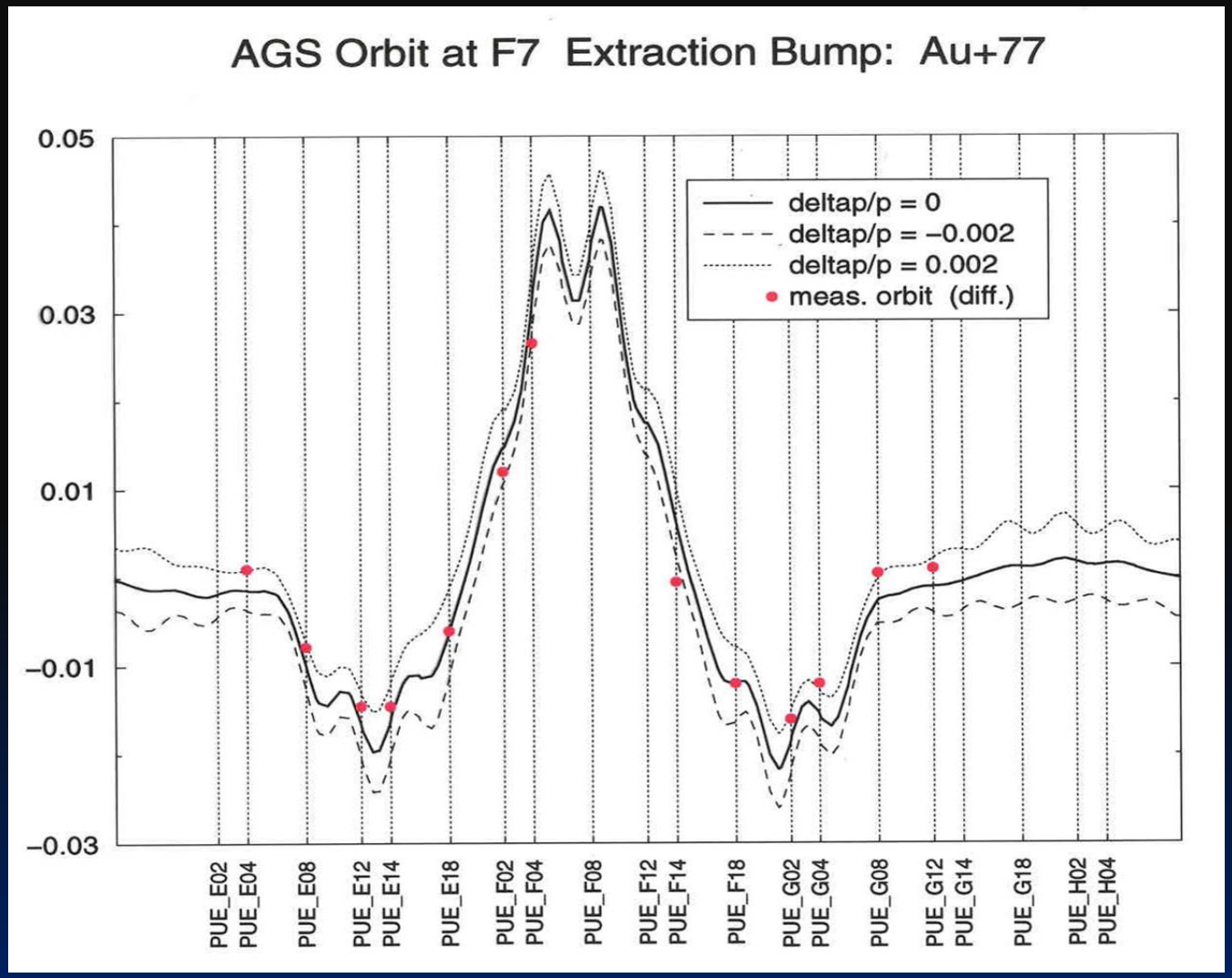
Slow Extraction: ES Phase Space



Slow Extraction: Thin MS Phase Space



Overview of AGS Slow Extraction

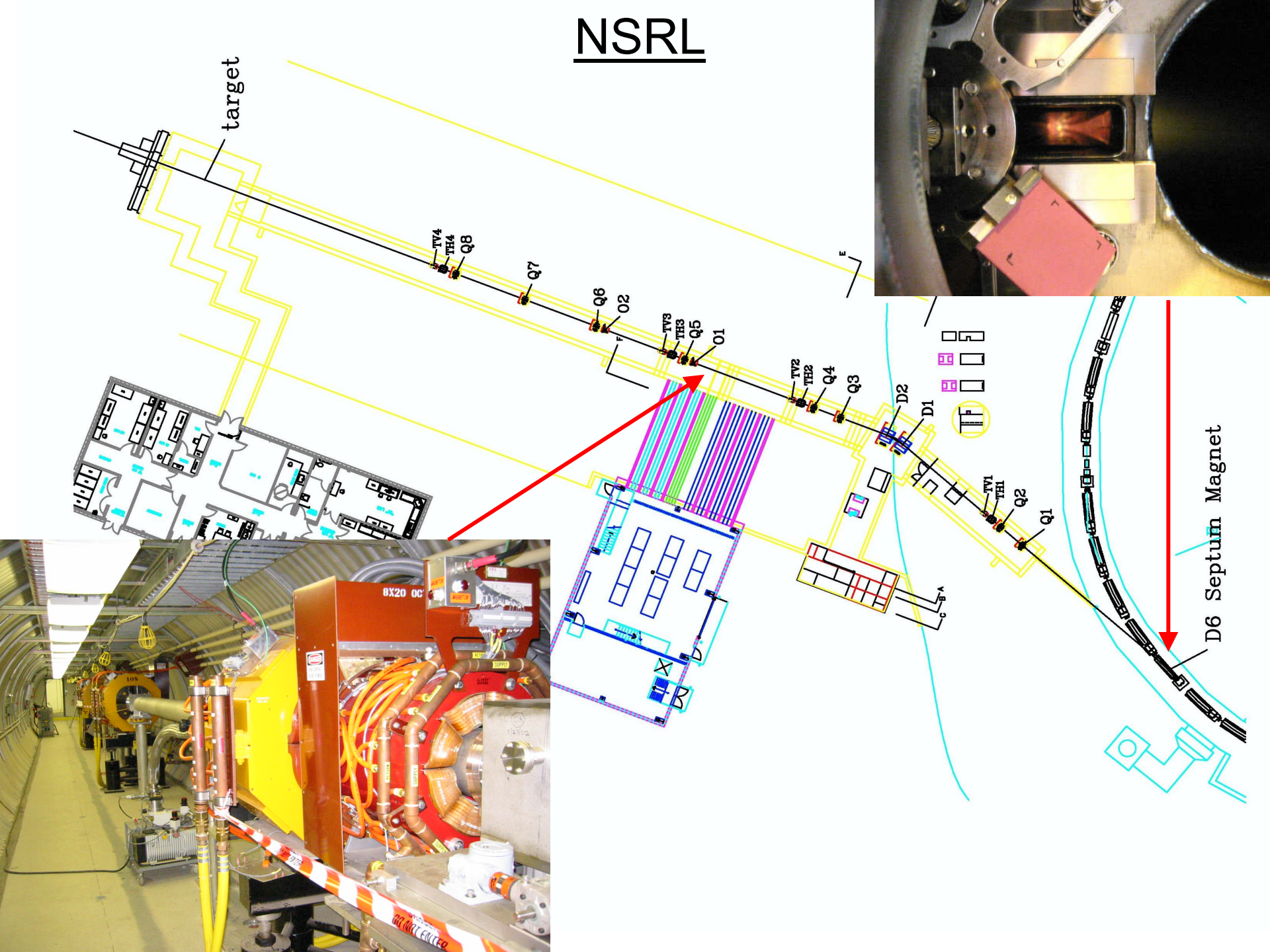


The NASA/BNL Space Radiation Program

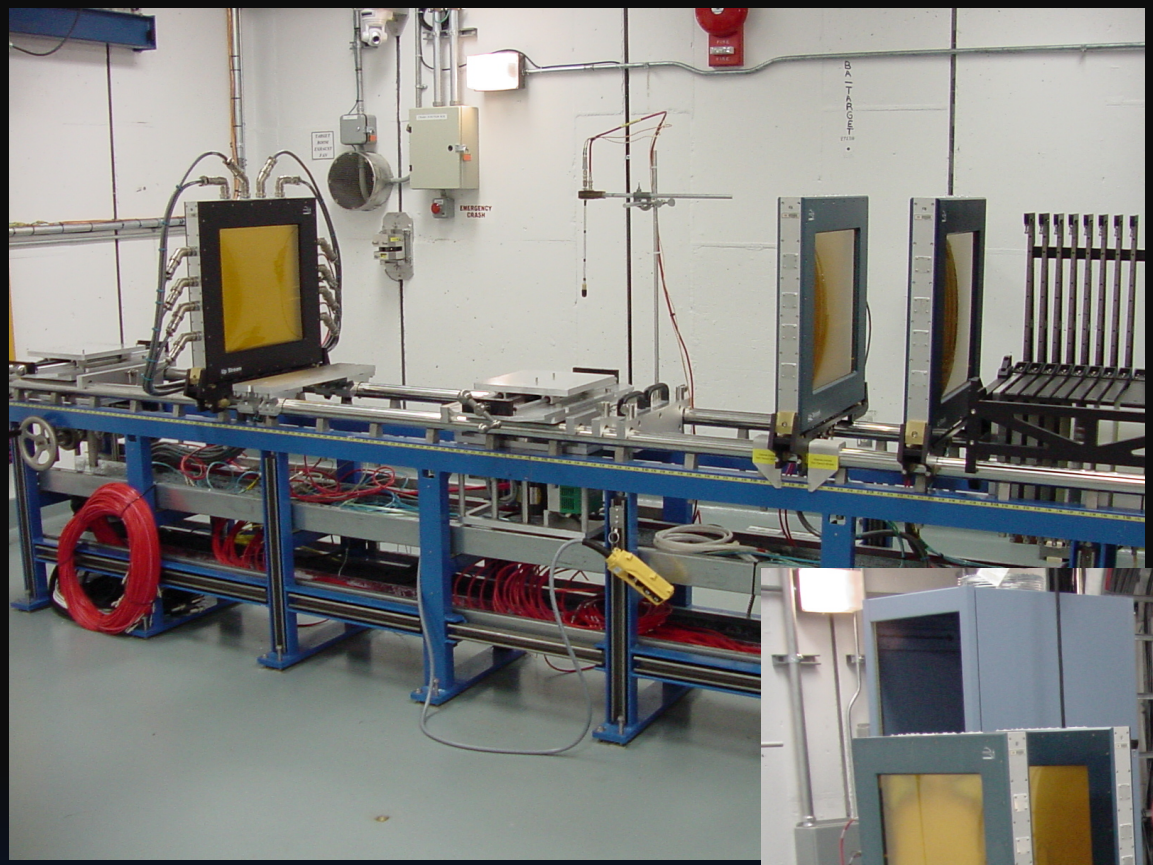
"As the National Aeronautics and Space Administration (NASA) prepares for future missions to the Moon and Mars, many of the health risks of cosmic radiation are still uncertain. Before humans can travel for extended periods outside Earth's atmosphere, scientists must learn more about the risks posed by cosmic radiation. To better understand these risks, NASA has teamed with the U.S. Department of Energy's (DOE) Office of Science to establish the NASA Space Radiation Laboratory (NSRL) at DOE's Brookhaven National Laboratory. There, scientists use beams of ions to simulate cosmic rays and assess the risks of space radiation to human space travelers and equipment."

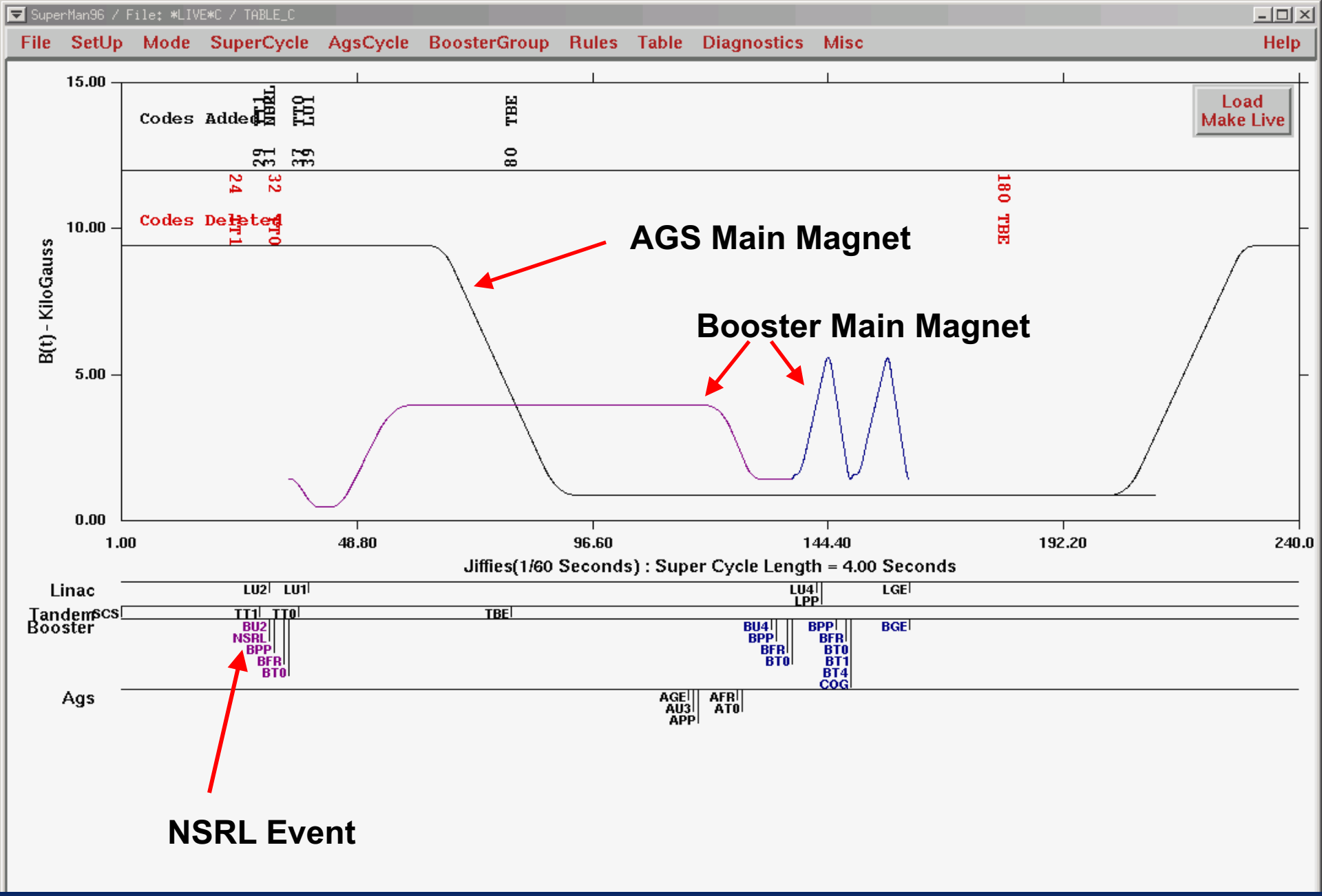
https://www.bnl.gov/nsrl/about.php

NSRL

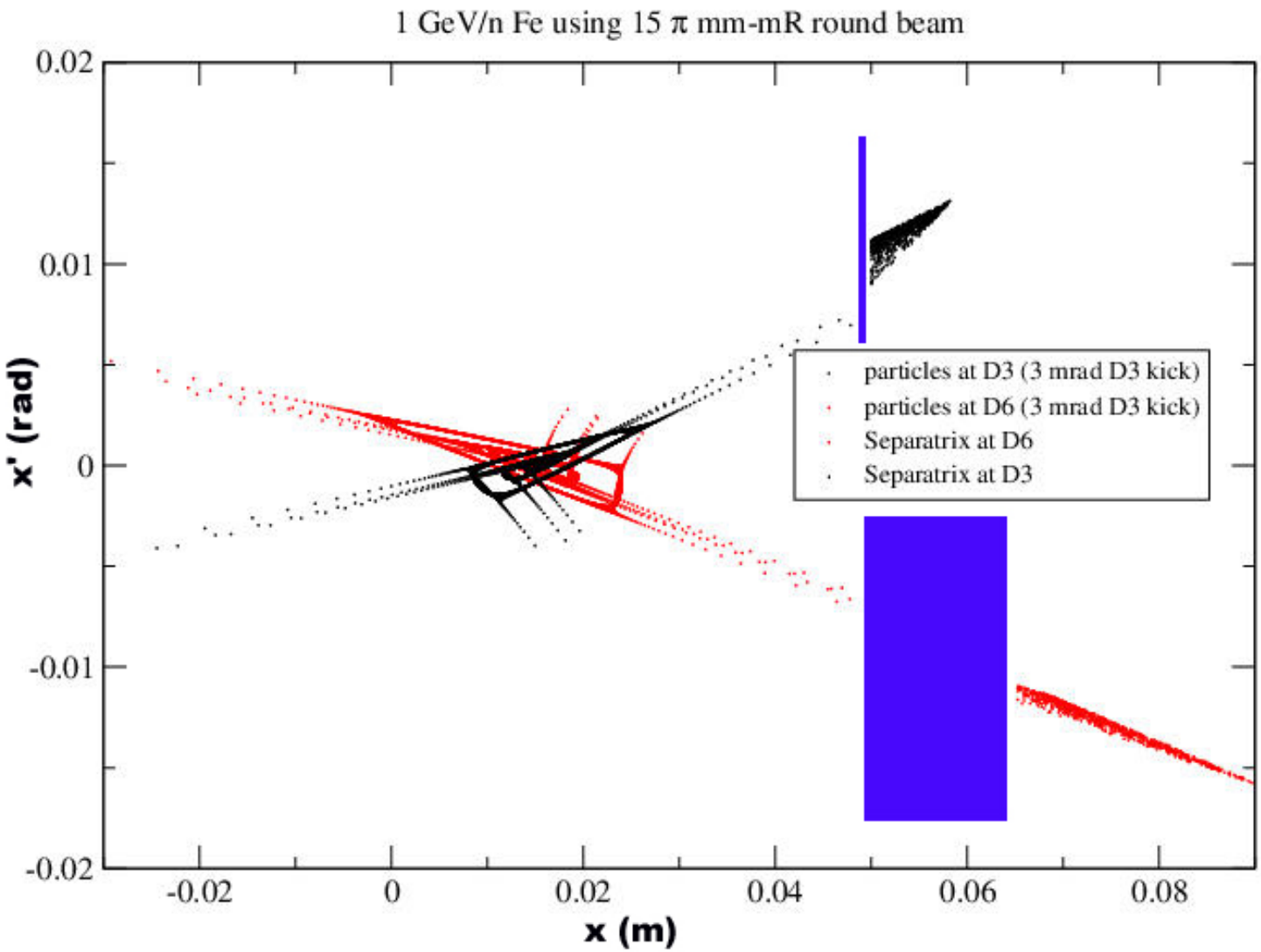

target
TV4
TH4
Q8
Q7
Q6
O2
TV3
TH3
Q5
O1
TV2
TH2
Q4
Q3
D2
D1
TV1
TH1
Q2
Q1
D6 Septum Magnet

NSRL Target Room

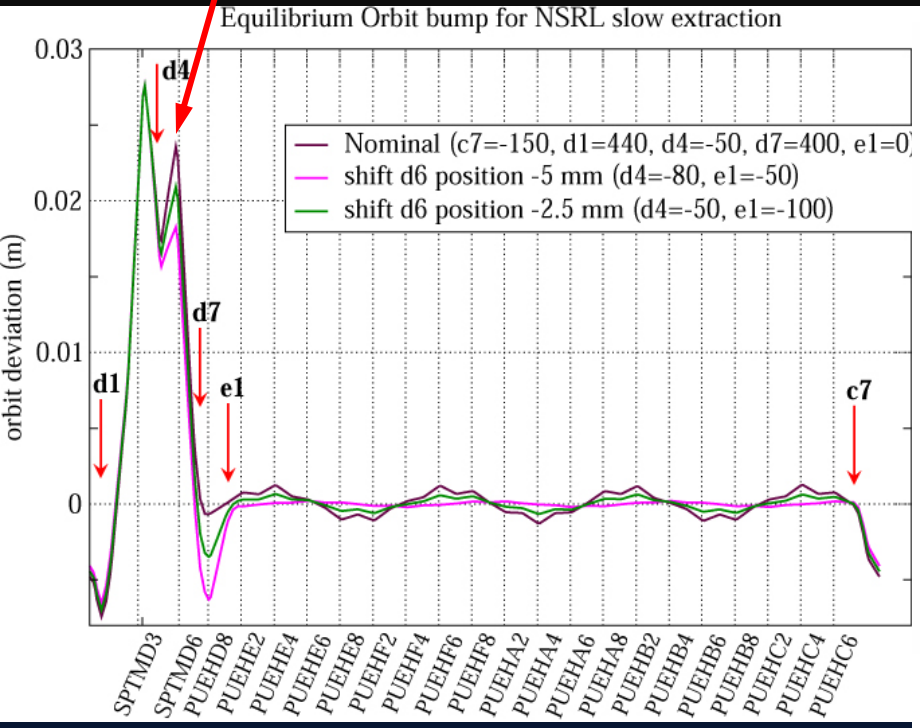


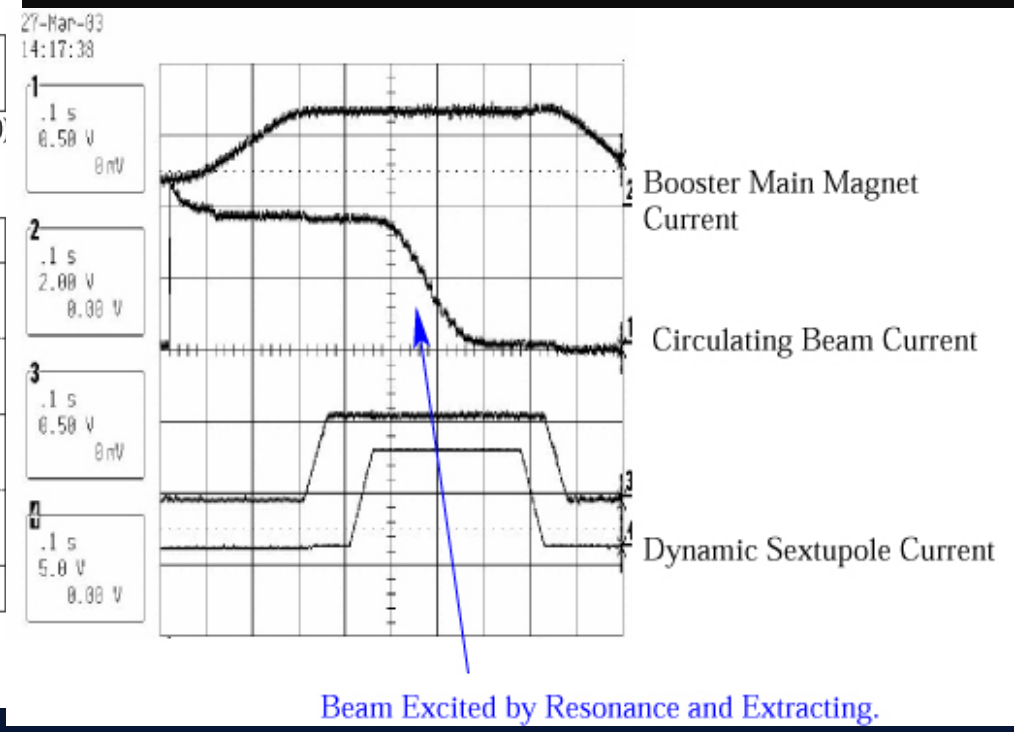

SuperMan96 / File: *LIVE*C / TABLE_C
File
SetUp
Mode
SuperCycle
AgsCycle
BoosterGroup
Rules
Table
Diagnostics
Misc
Help
Load
Make Live
Codes Added
Codes Deleted
AGS Main Magnet
Booster Main Magnet
B(t) - KiloGauss
15.00
10.00
5.00
0.00
1.00
48.80
96.60
144.40
192.20
240.0
Jiffies(1/60 Seconds) : Super Cycle Length = 4.00 Seconds
Linac
Tandem
Booster
Ags
NSRL Event

Booster Resonant/Slow Extraction



Extraction Point

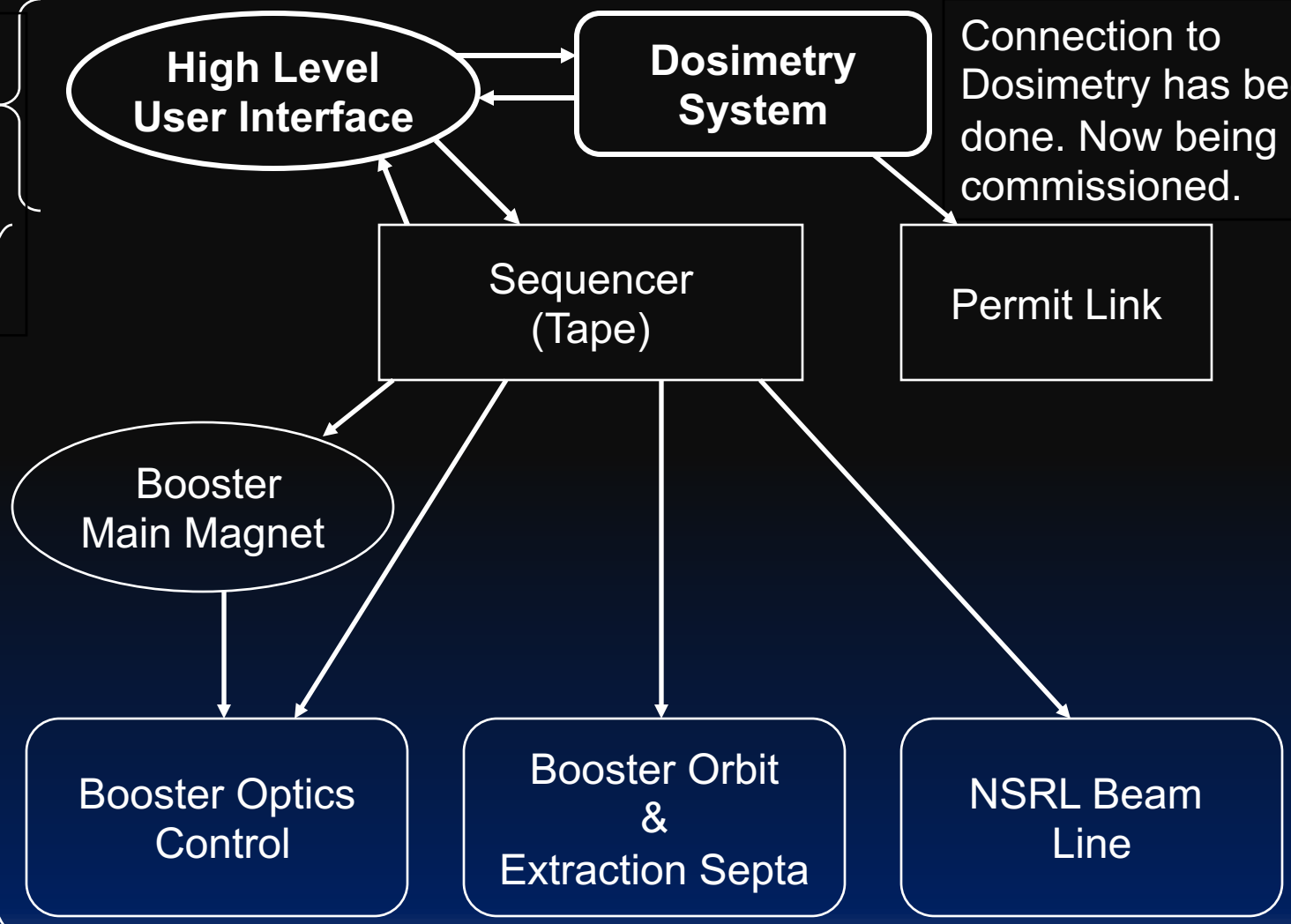




Actively Changing Energy at NSRL

A high level interface has been designed and constructed. Is now being commissioned.

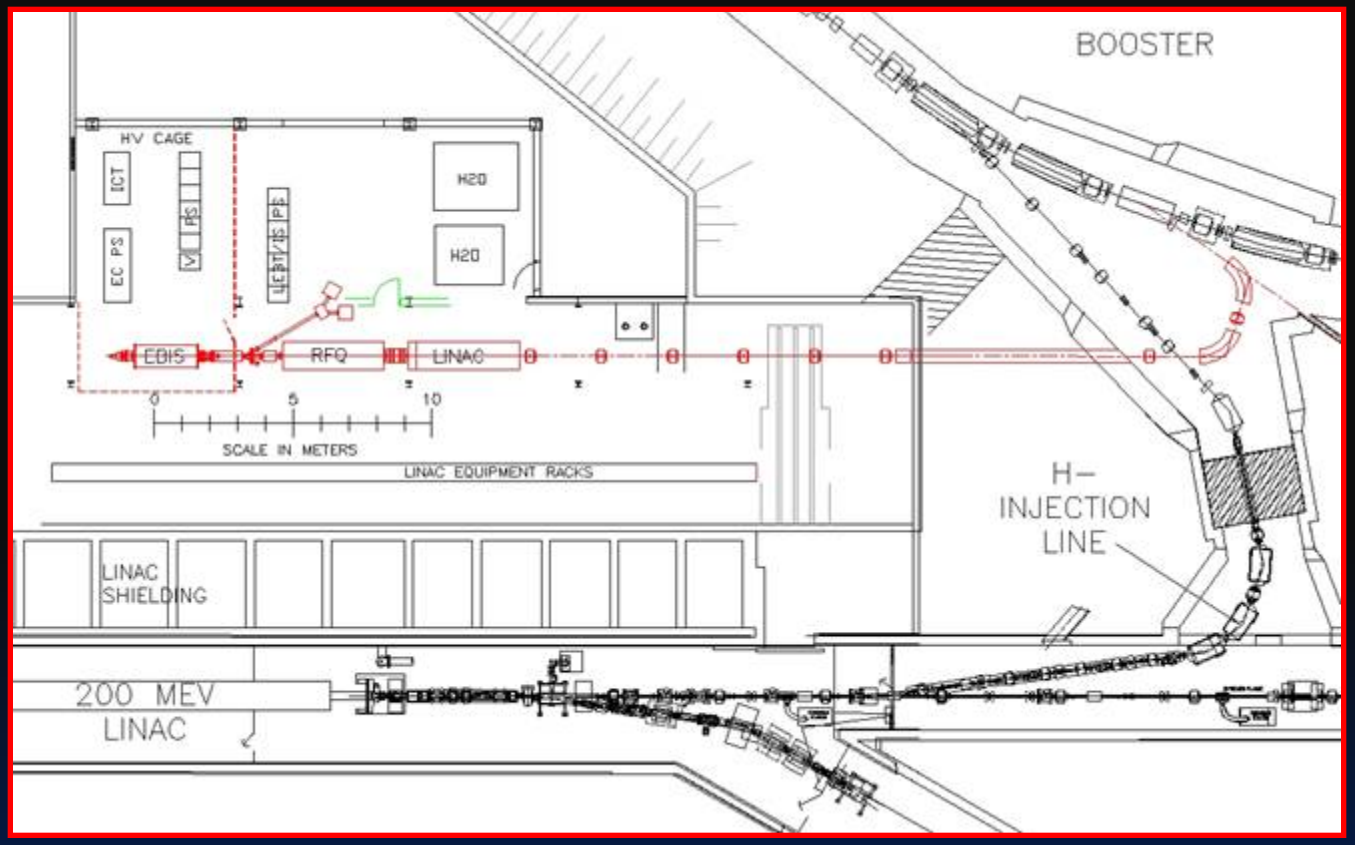
Theses parts are working well and are commissioned.



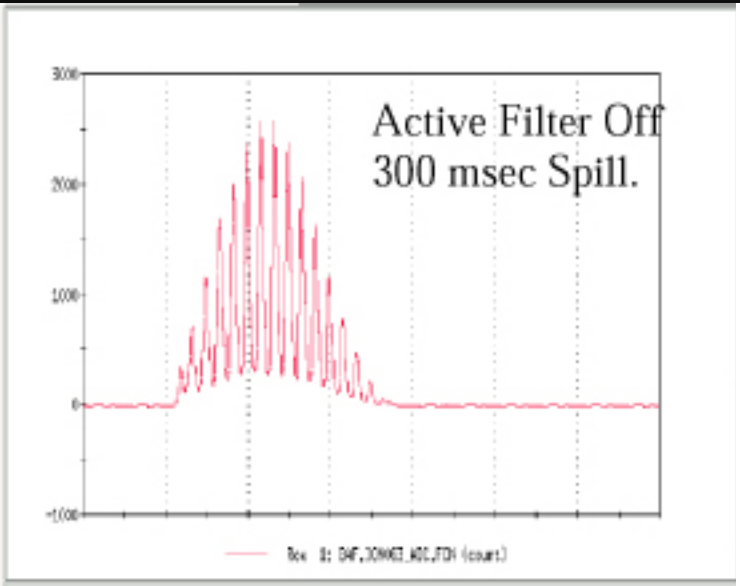
Connection to Dosimetry has been done. Now being commissioned.

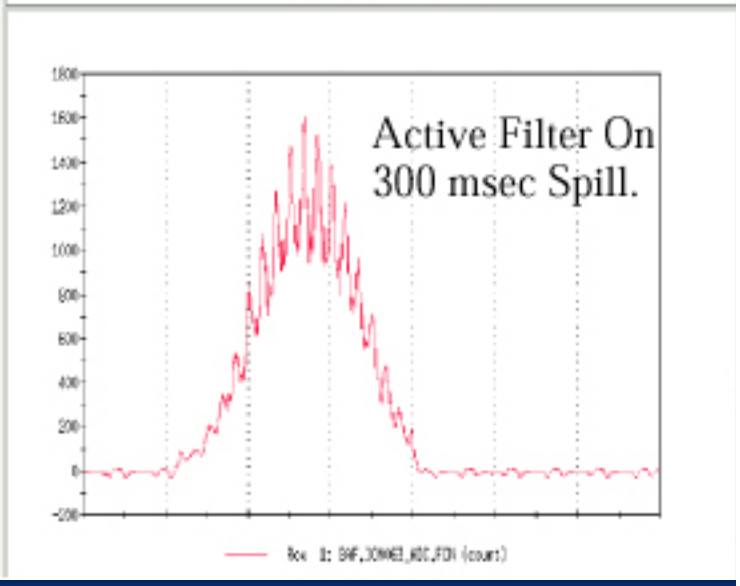
GCR Project

- Source, LINAC, ETB beam line and Booster all change rapidly (~1 minute) between several ion species.
- NSRL remains at one rigidity for several ions, then changes to next setting (2-3 minutes)


BOOSTER
HV CAGE
ICT
EC PS
PS
LIEBT/IS PS
H2O
H2O
EBIS
RFQ
LINAC
0
5
10
SCALE IN METERS
LINAC EQUIPMENT RACKS
LINAC
SHIELDING
H−
INJECTION
LINE
200 MEV
LINAC

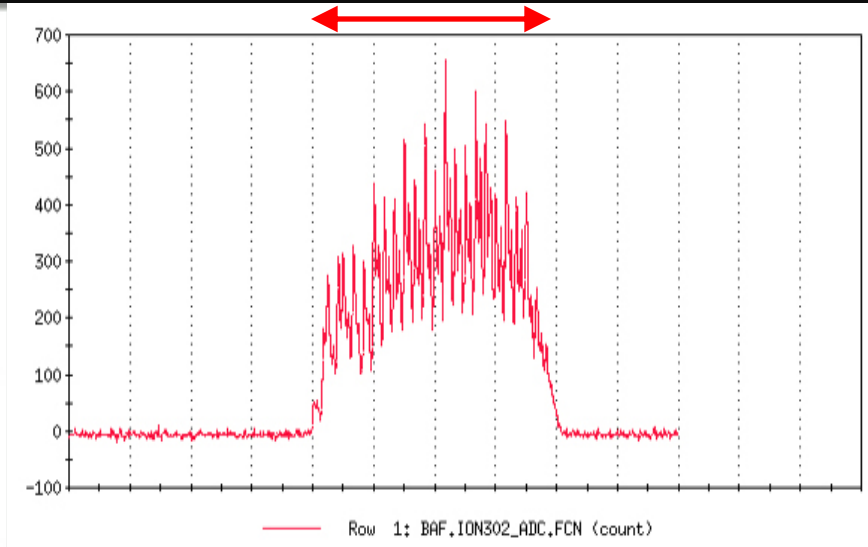
2 GeV Protons



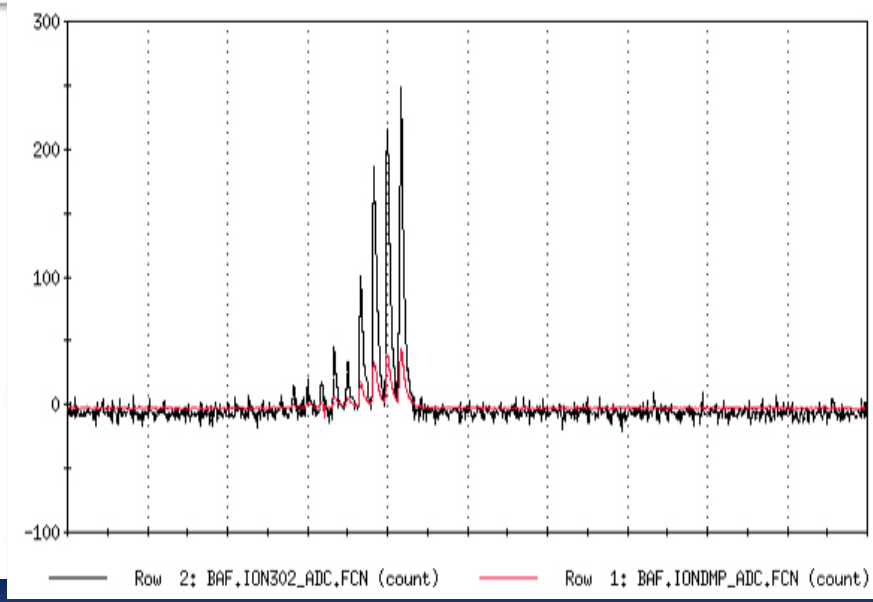


300 MeV/n Carbon

400 ms



Spill Servo And Active Filter On.



Dosimetry Beam Cutoff

SPE and GCR Status

- Both systems are in routine use.
- There are detailed issues to work on
  - Vertical orbit correction needs automating
  - Spill reproducibility needs improvement
  - Time to switch from one energy or one ion species to the next, for short exposures, needs to be faster (in a 1 hour set of 20 exposures, 45 minutes is spent switching)
- More ‘physics’ experiments (non-biology, so counter based, not dose based exposures), which demand smooth spills without RF microstructure.

Motivation for smoother spills

- Low fluence (single particle) exposure
  - Rates need to be reduced to avoid double counts
- Rate limited counter detectors for electronics testing
- Low dose calibrations
- New detector development, keeping signal processing in linear dynamic range
- Strong motivation is to remove high frequency structure (Booster RF) while still keeping smooth low frequency structure (PS 60 Hz Harmonics)