Update from BNL:

Slow Extraction, Extinction, and Spill Control Methods

Kevin Brown

kbrown@bnl.gov

Collider Accelerator Department

BNL

JPARC/FNAL/BNL Collaboration on Slow Extraction,
November 16-November 18, 2020

Topics

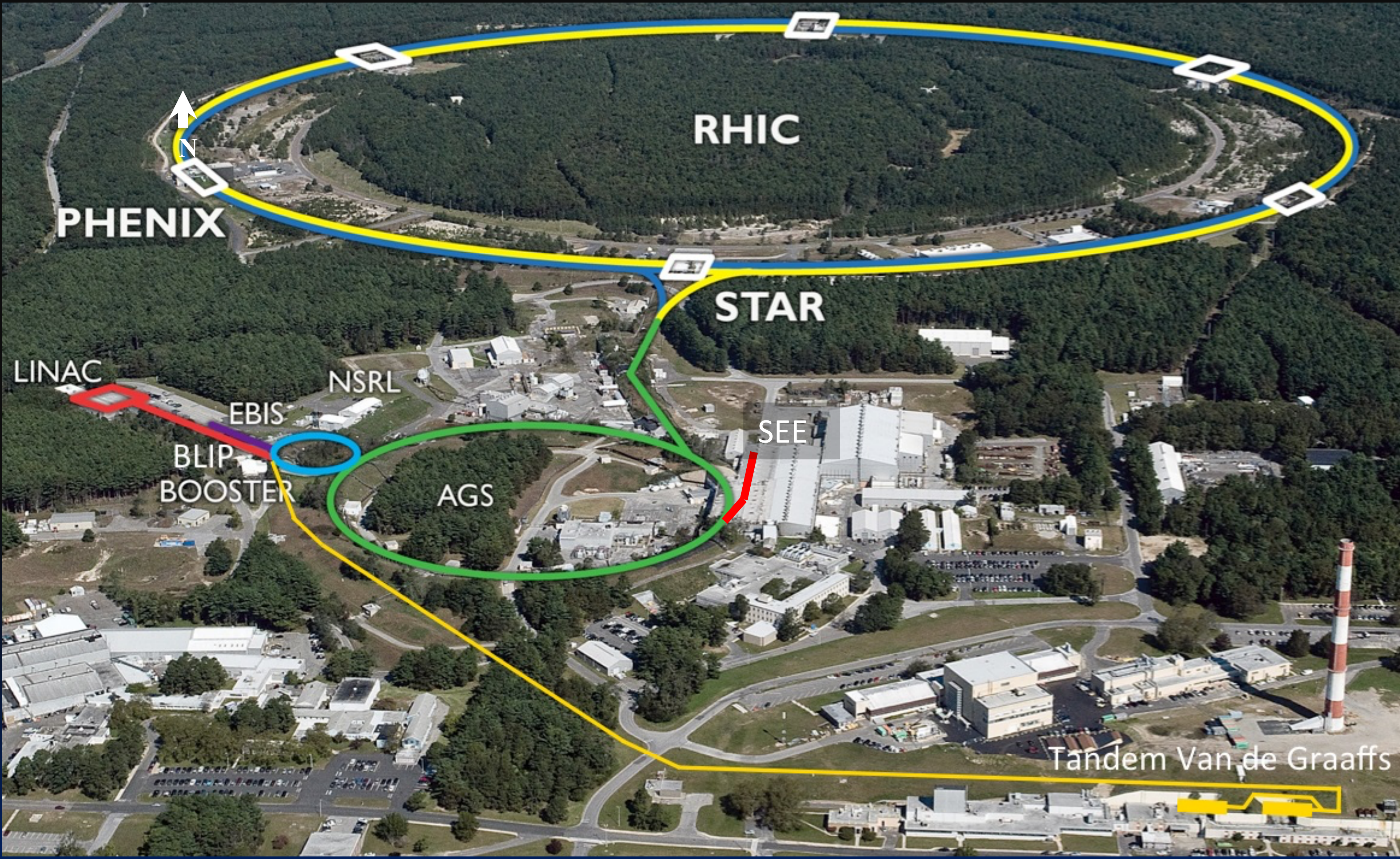
- Impact of COVID-19
- DS/ML/AI efforts at C-AD
- Slow Extraction and Spill Structure insights
- SEE Project for the AGS
- Slow Spill Requirements for SEE
- Publications plans

Impact of COVID-19

- For RHIC and C-AD, operations were suspended March 20, 2020 into a normal full shutdown mode and a bare minimum of personnel remained on site to monitor the facilities. All other personnel remained active through remote working arrangements. BNL overall went into ‘Reduce On-site Operations’ or a ‘Min-Safe’ mode, with only absolutely essential personnel allowed on-site. Some facilities, such as NSLS II continued operations, with focus on COVID-19 related science.
- BNL Began restart of operations June 3, with focus on facilities and laboratory operations (not Science).
- Operations for RHIC and C-AD started ramping up in mid-June, with re-establishment of beam in RHIC on June 19. Most C-AD staff remained working remotely with a minimal staff on site. Only MCR staff were allowed in the MCR. All operations support staff worked either from remote control rooms or from home.

Impact of COVID-19

- Activities since March 20 had to adapt to remote work arrangements. For example, the Controls System hardware lab was shutdown and Controls HW group could only focus on design work, operations support, documentation and training.
- For Japan/US collaboration efforts, progress was impacted on digitizing the spill controls for the Booster.
- In a positive effect - fewer distractions in the remote work arrangements made for improved productivity in some areas (i.e., SEE proposal).


N
RHIC
PHENIX
STAR
LINAC
NSRL
EBIS
SEE
BLIP
BOOSTER
AGS
Tandem Van de Graaffs

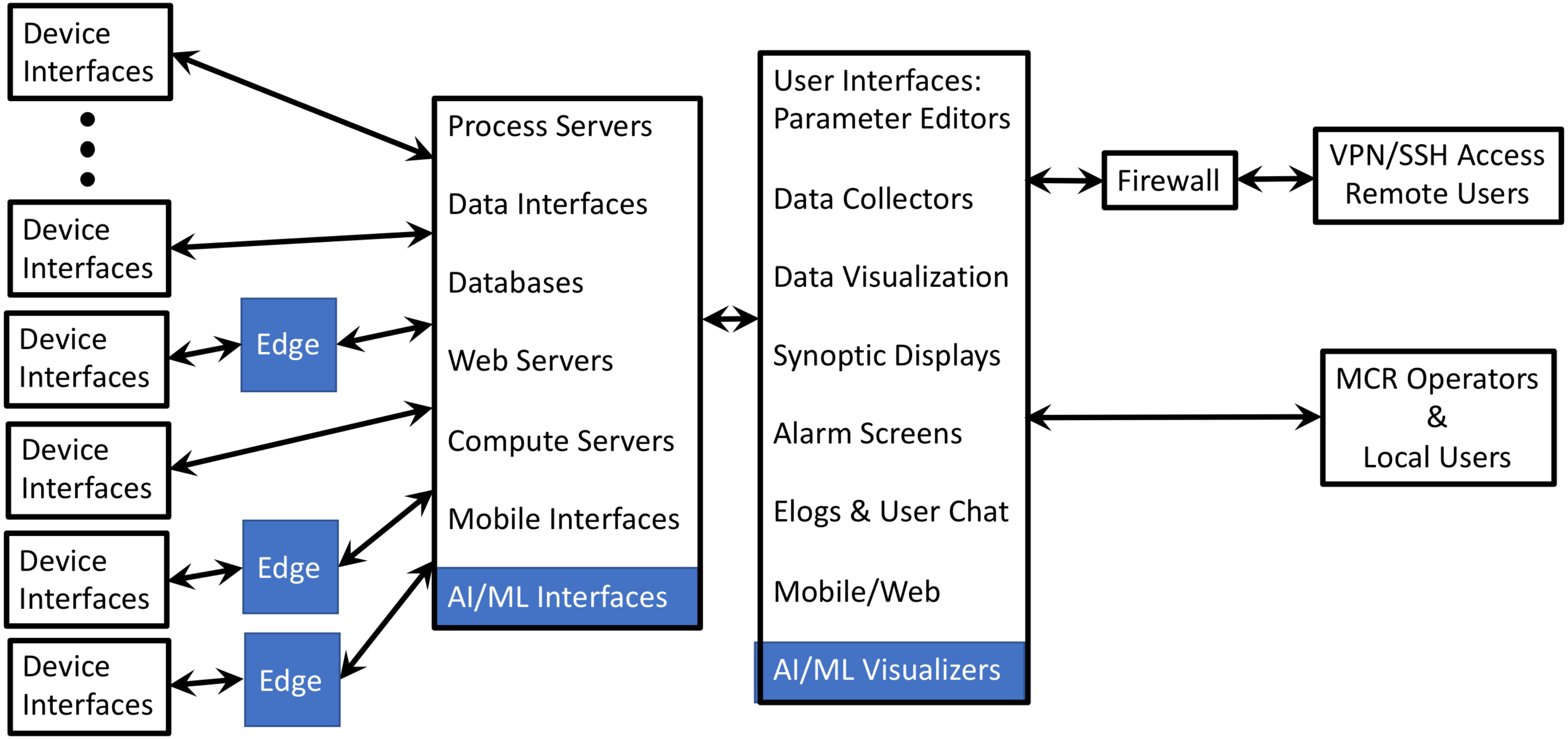
DS/ML/AI efforts at C-AD

- Prognostics
  - Anomaly detection system using neural engine (NuPIC) developed. Working on deployment strategy.
- Data Analysis and Models
  - RadiaSoft Sirepo tools developed under SBIR to do ML with transfer lines (AGS to RHIC as test case)
- Reinforcement learning
  - Q-Learning system developed for LEReC to optimize cooling. Next plan to integrate into controls and test in beam experiments.
- EBIS Fault Prevention
  - Avoid hard crashing of beam by detecting high voltage breakdown and electron beam disruption in the Electron Beam Ion Source
- NSRL Spill Quality
  - Focus on creating Digital Active filter and quadrupole tune compensation electronics. In the design process. Collecting and analyzing data.
- Coordinating with EIC to incorporate AI in new controls.

Global DS/ML/AI efforts

- Many virtual seminars and meetings developed during COVID-19
  - One World charged particLe accElerator (OWLE) Seminar*
  - BNL/Cornell Collaboration on Machine Learning (which became BNL/Cornell/Univ. of Chicago/SLAC over time).
- Development of reinforcement learning system for optimizing Low Energy RHIC electron Cooling
  - Next step is to do beam experiments in FY21
- Development of predictive prognostics using Numenta Platform for Intelligent Computing (NuPIC), based on Hierarchical Temporal Memory, which simulates the neural-cortex of the brain (some may call this sparse deep neural network theory for temporal dependent data)
- Beginnings of investigations into ‘edge’ computing for distributed controls (see next slide)
- AI Strategy for BNL, a plan is being developed labwide

* https://sites.google.com/view/owle/home



Device Interfaces

Device Interfaces

Device Interfaces

Edge

Device Interfaces

Device Interfaces

Edge

Device Interfaces

Edge

Process Servers

Data Interfaces

Databases

Web Servers

Compute Servers

Mobile Interfaces

AI/ML Interfaces

User Interfaces: Parameter Editors

Data Collectors

Data Visualization

Synoptic Displays

Alarm Screens

Elogs & User Chat

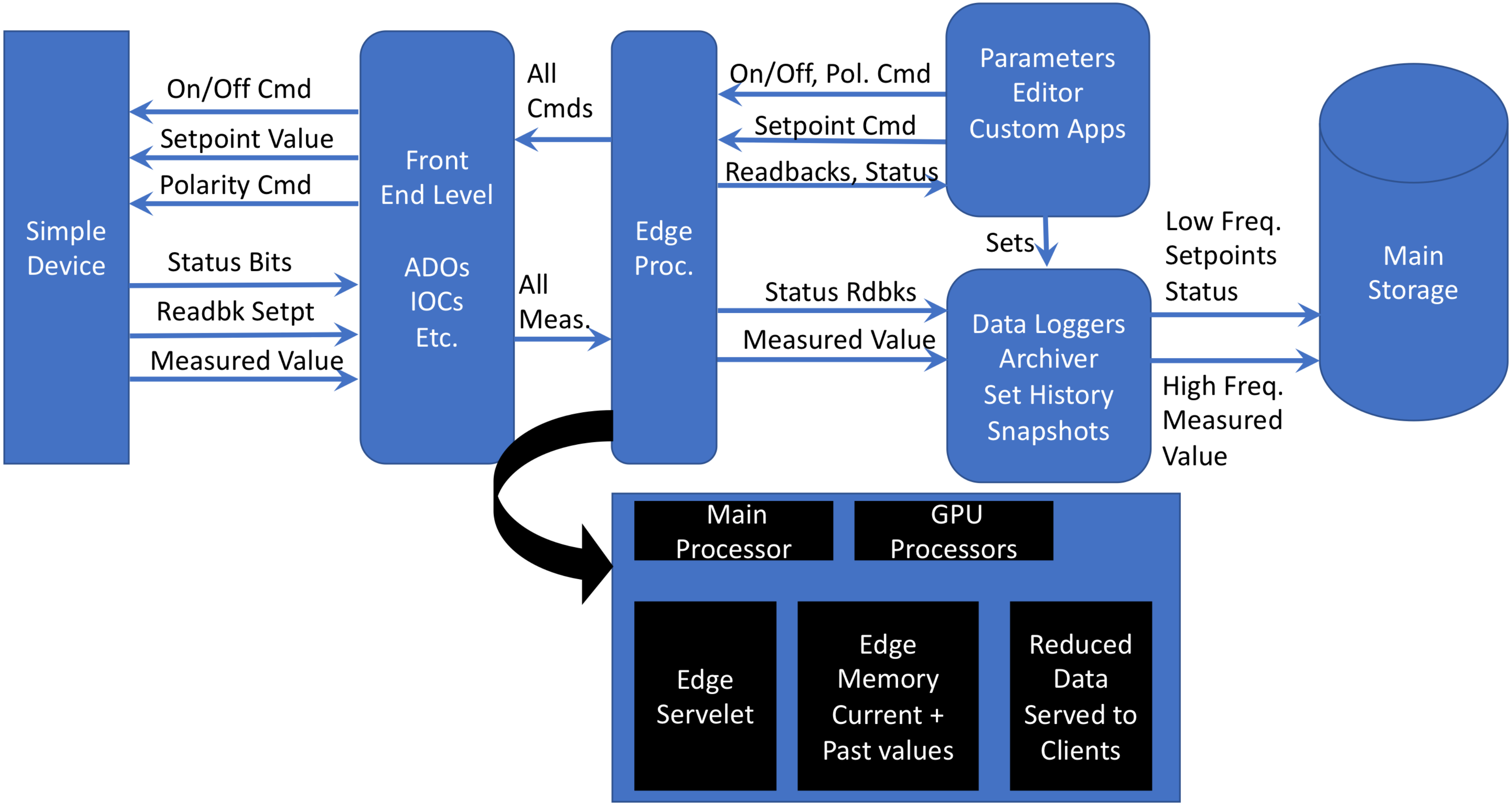
Mobile/Web

AI/ML Visualizers

Firewall

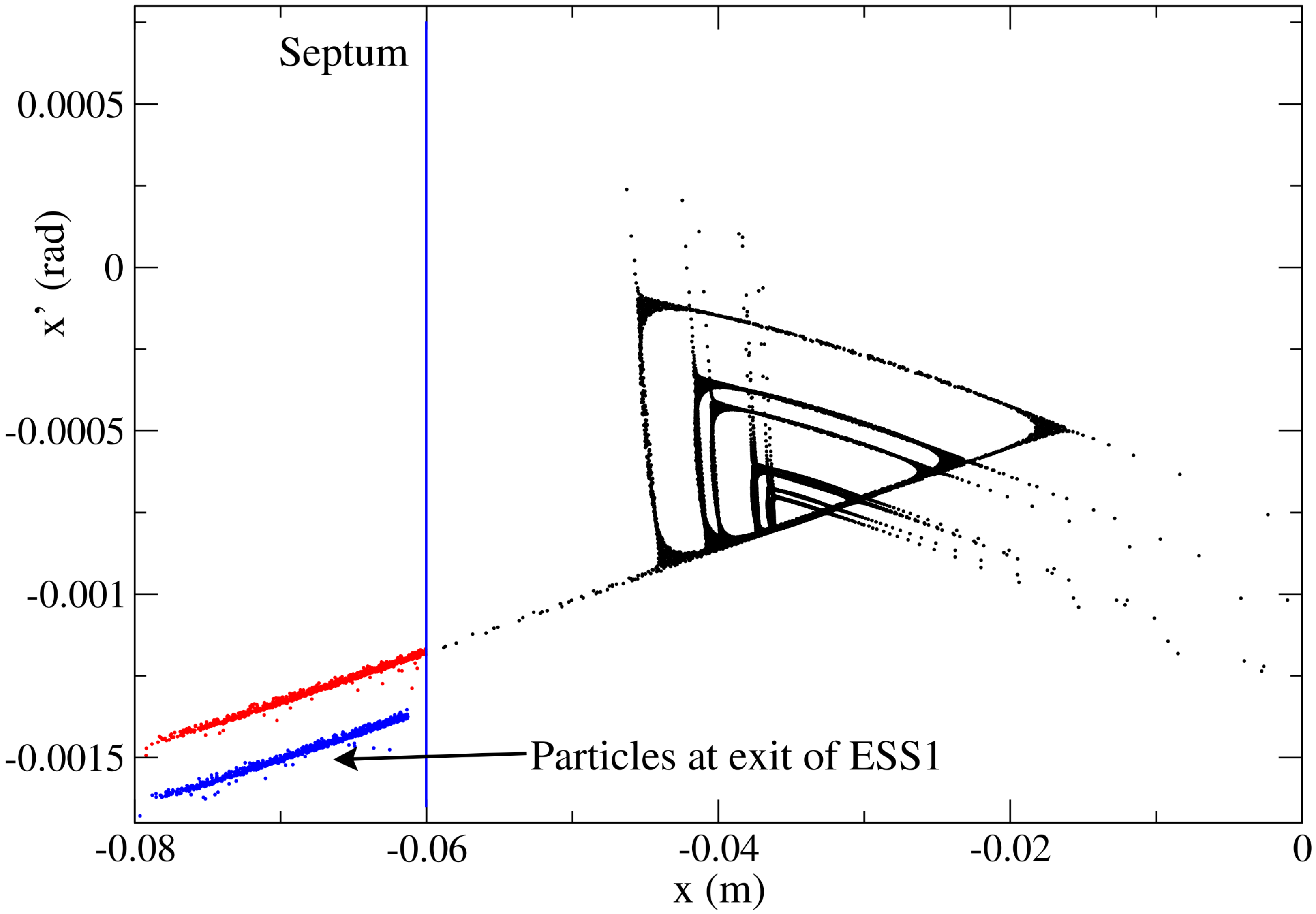
VPN/SSH Access Remote Users

MCR Operators & Local Users

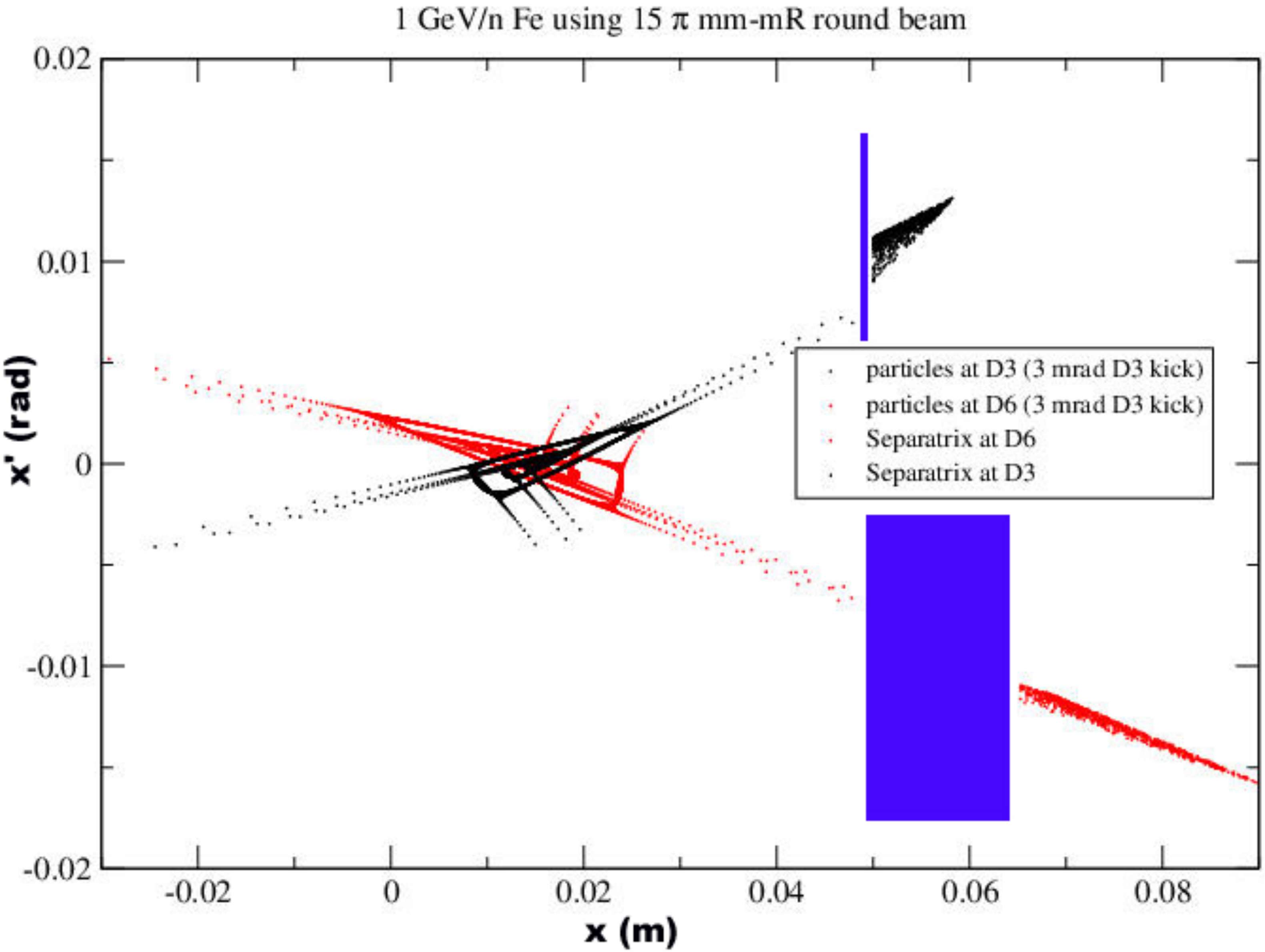


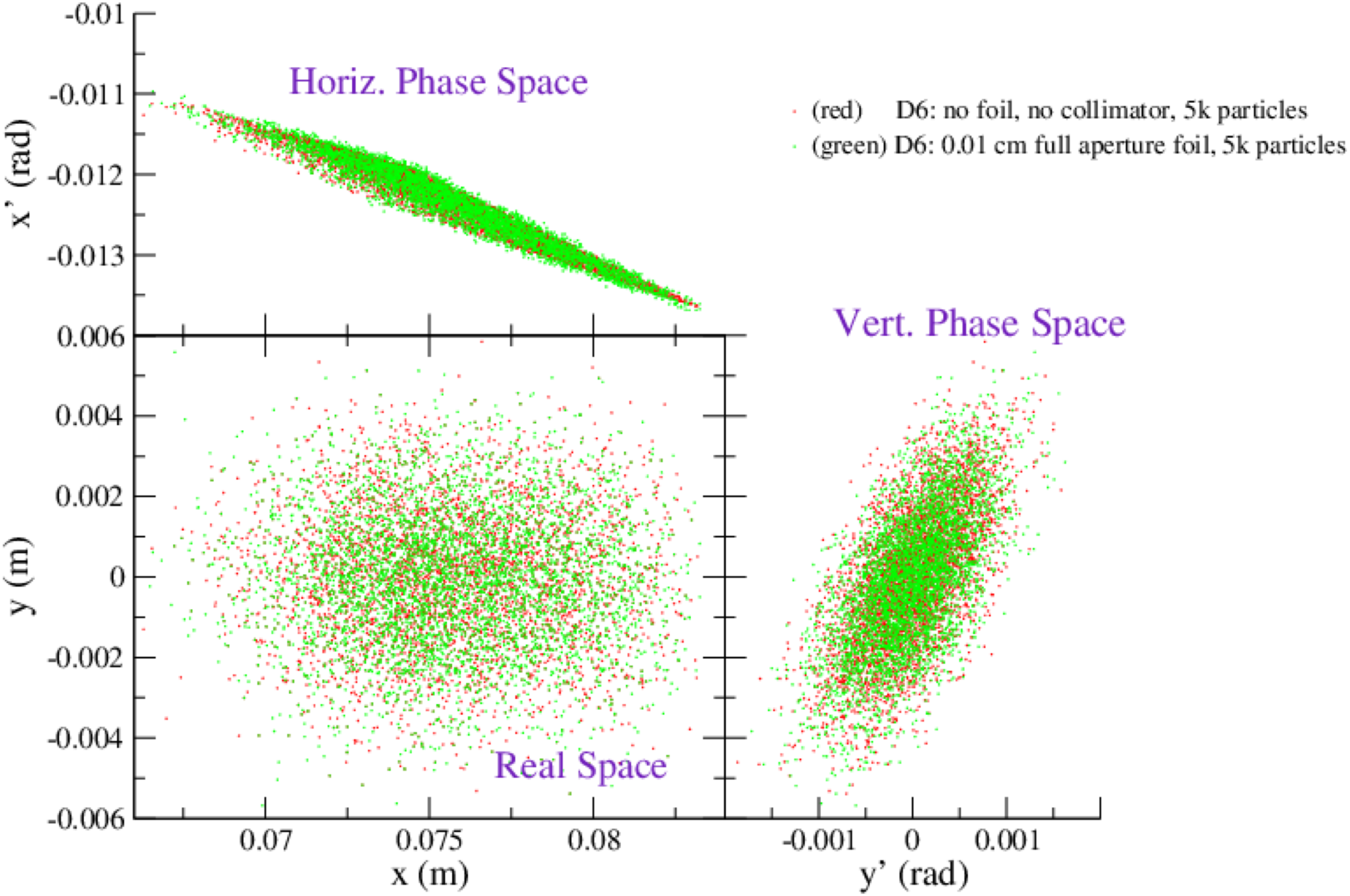
Slow Extraction and Spill Structure insights

J-PARC Slow Extraction Example

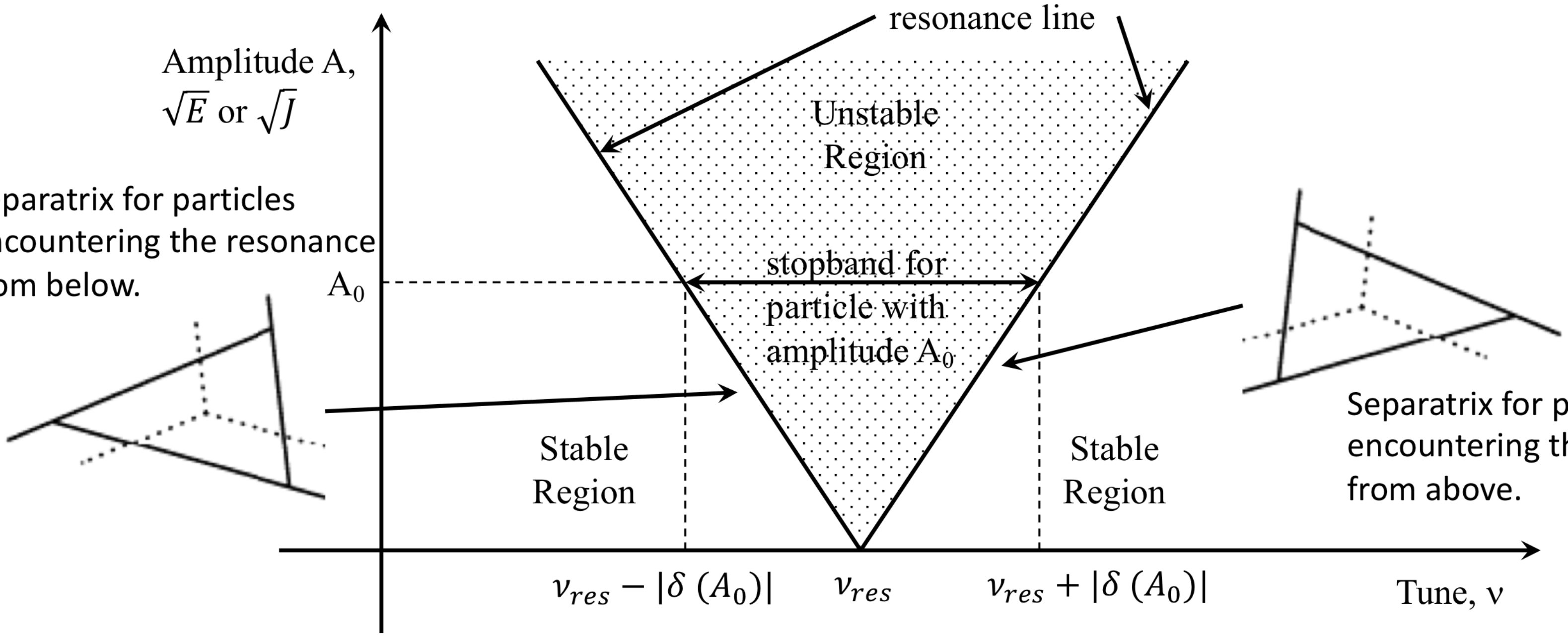


Booster Resonant/Slow Extraction



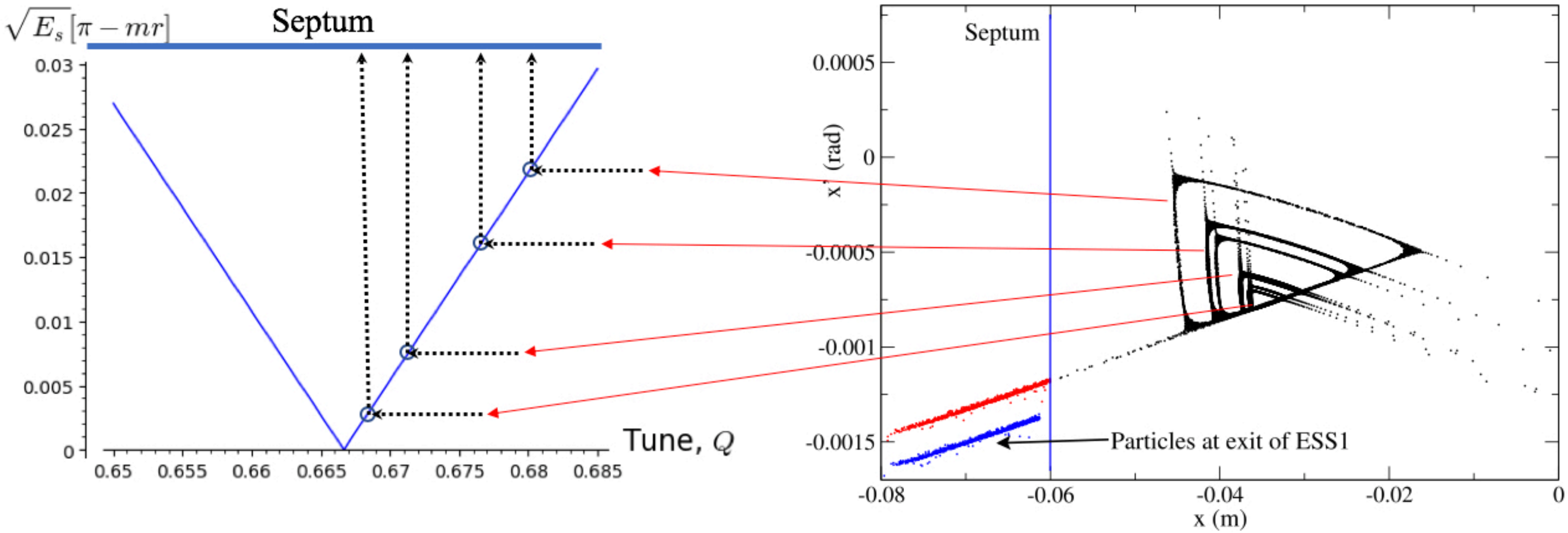

Horiz. Phase Space
Vert. Phase Space
Real Space
· (red) D6: no foil, no collimator, 5k particles
· (green) D6: 0.01 cm full aperture foil, 5k particles
x' (rad)
-0.01
-0.011
-0.012
-0.013
y (m)
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
0.07
0.075
0.08
x (m)
-0.001
0
0.001
y' (rad)

Steinbach Diagram: Tune-Amplitude Space

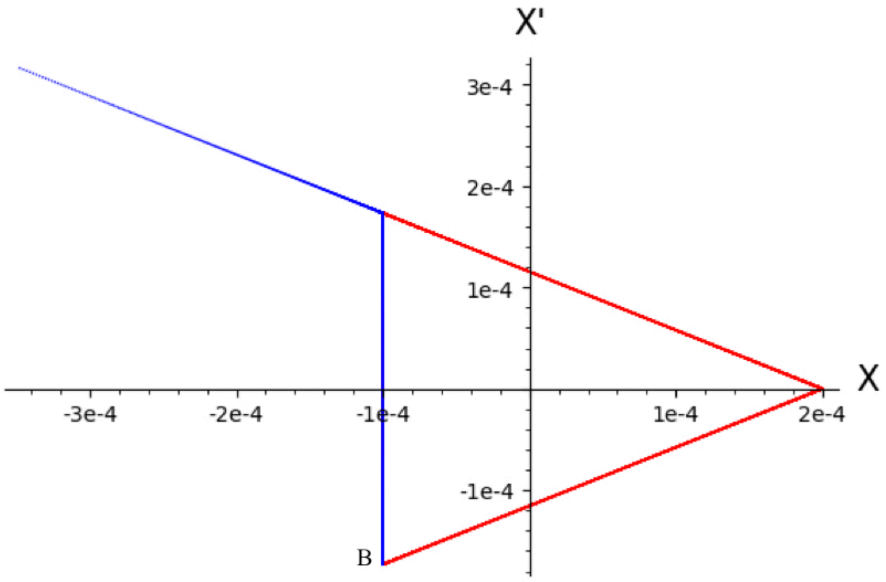


Separatrix for particles encountering the resonance from below.

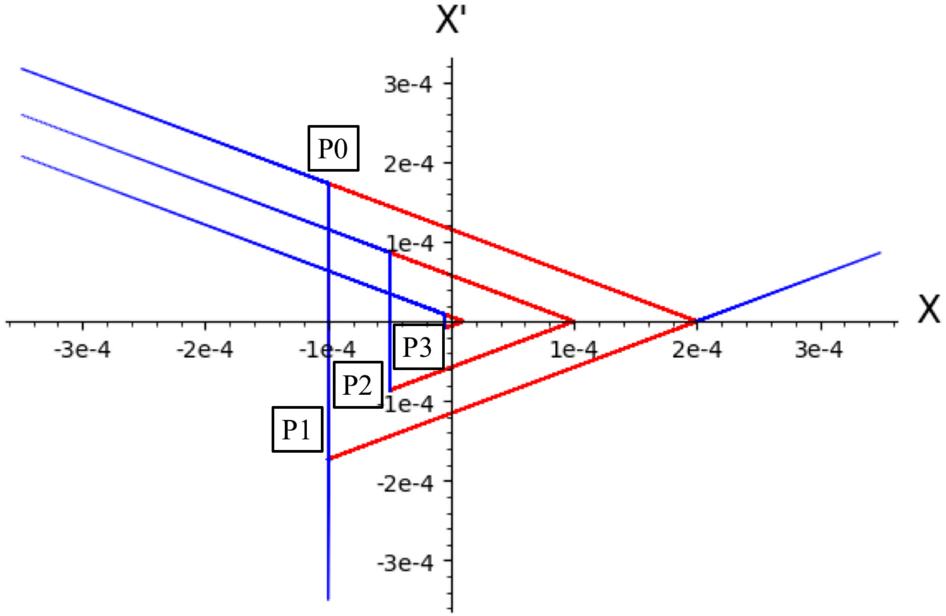
Separatrix for particles encountering the resonance from above.



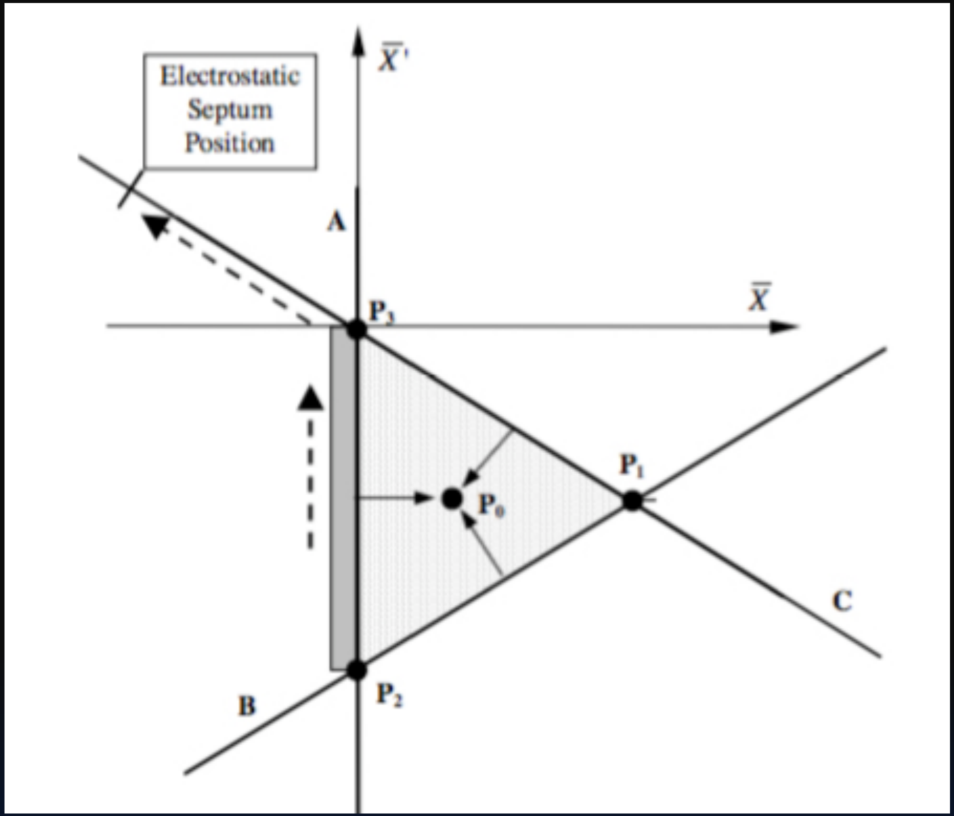
$\sqrt{E_s}[\pi - mr]$
Septum
0.03
0.025
0.02
0.015
0.01
0.005
0
0.65
0.655
0.66
0.665
0.67
0.675
0.68
0.685
Tune, Q
Septum
0.0005
0
-0.0005
-0.001
-0.0015
x' (rad)
Particles at exit of ESS1
-0.08
-0.06
-0.04
-0.02
0
x (m)

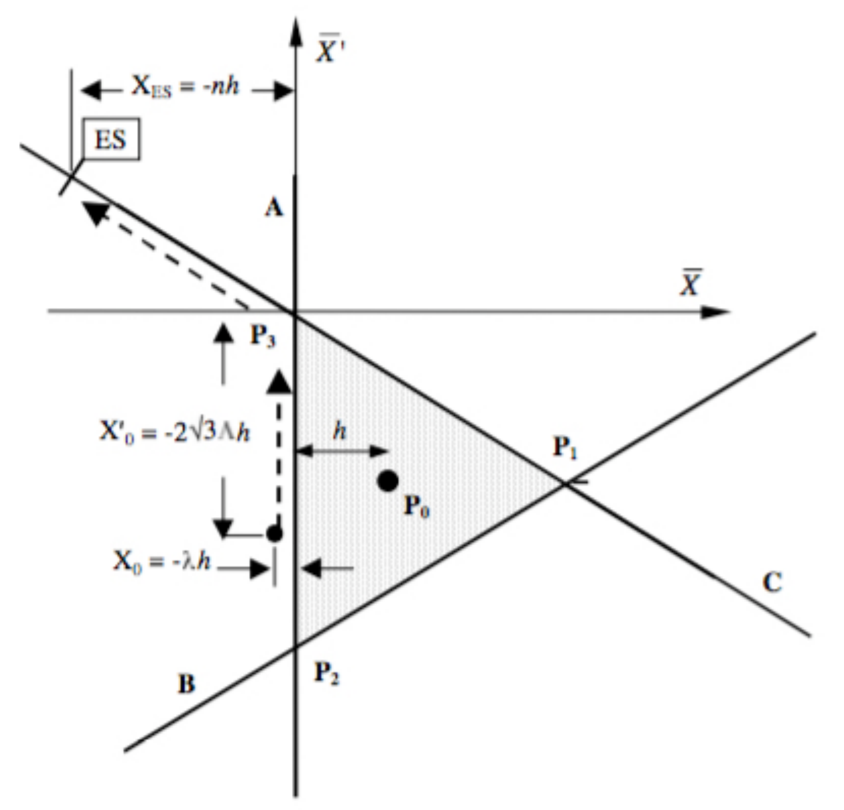


X'
3e-4
2e-4
1e-4
-1e-4
X
-3e-4
-2e-4
-1e-4
1e-4
2e-4
B



X'
3e-4
2e-4
1e-4
-1e-4
-2e-4
-3e-4
X
-3e-4
-2e-4
-1e-4
1e-4
2e-4
3e-4
P0
P1
P2
P3



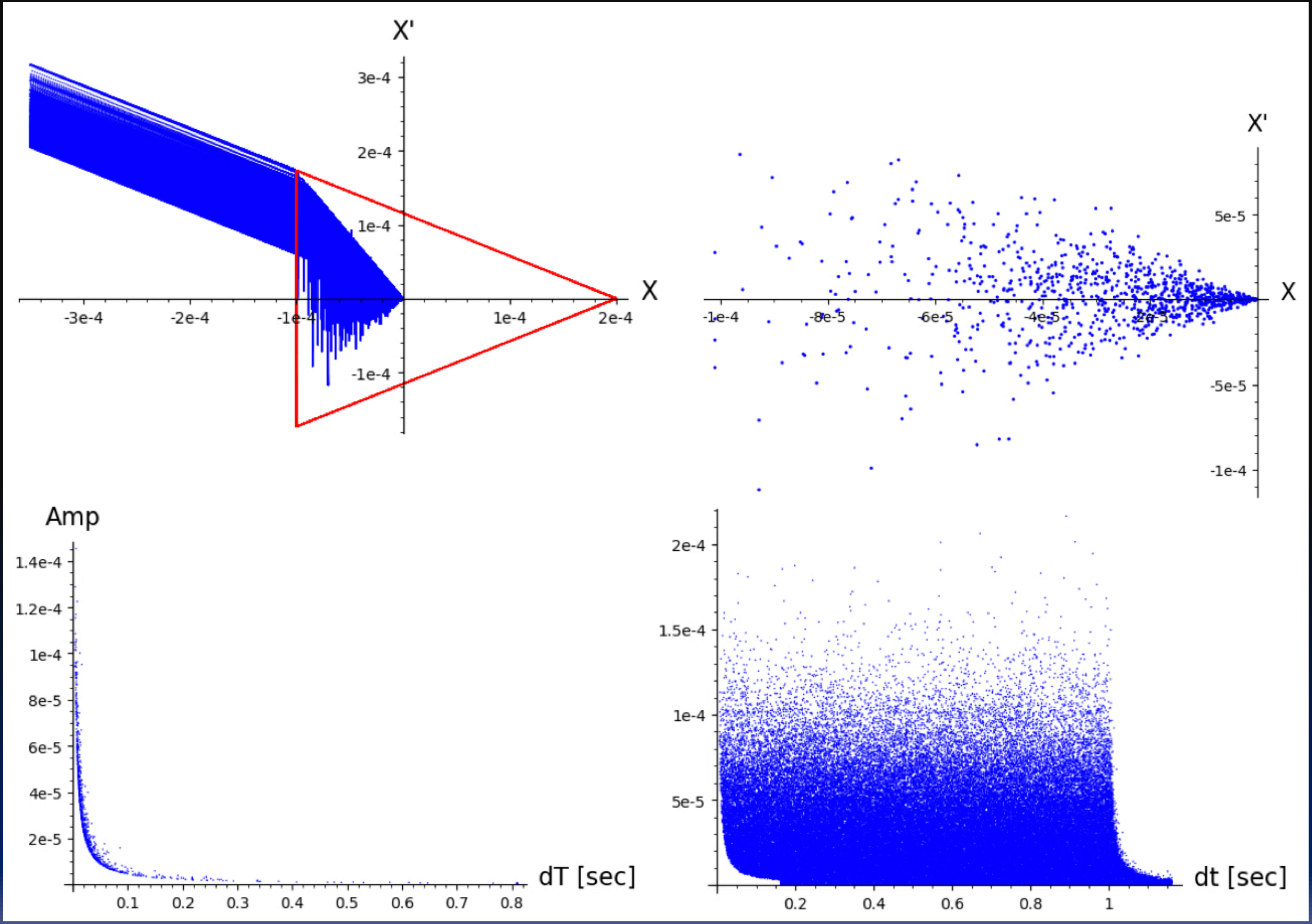


Total Transit time formula

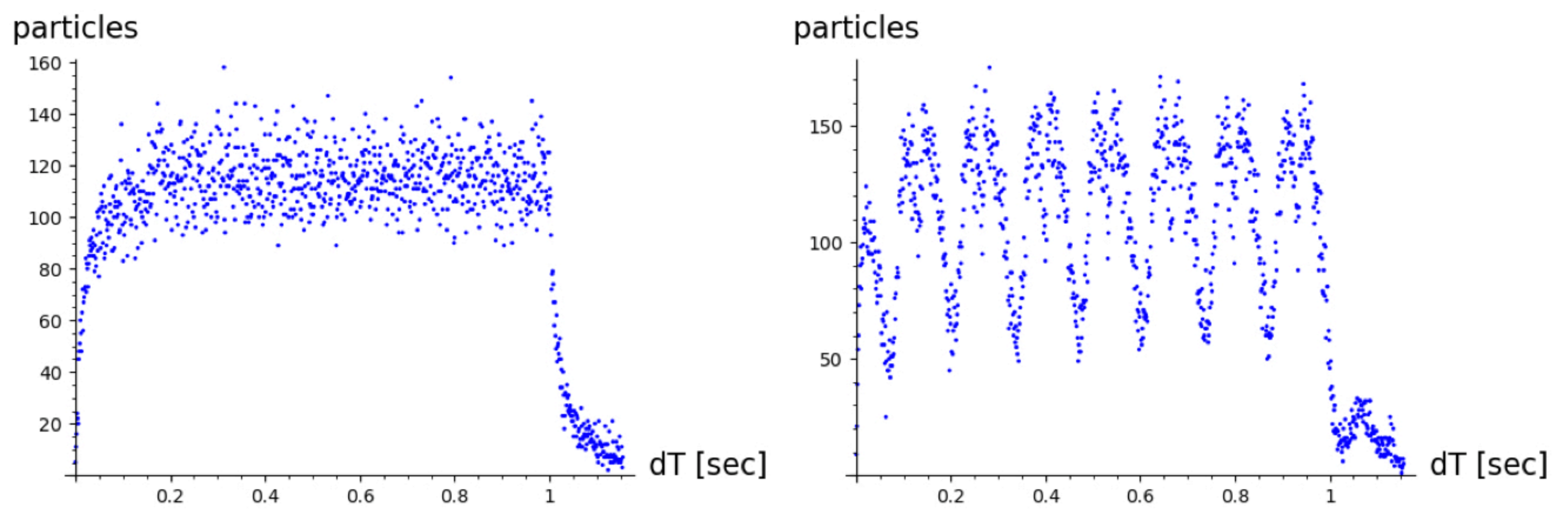
$$T_{TT} = \frac{2}{\sqrt{3}S}\frac{1}{\sqrt{9h^2+4(X_0^2+\sqrt{3}X_0X_0')}}\left[\ln\left|\frac{-2X+3h-\sqrt{9h^2+4(X_0^2+\sqrt{3}X_0X_0')}}{-2X+3h+\sqrt{9h^2+4(X_0^2+\sqrt{3}X_0X_0')}}\right|\right]_{X_0}^{X_{ES}}$$

Diagrams from M. Pullia, PhD Thesis, 1999
Universite´ Claude Bernard - Lyon

Reconstructing a Spill



Simulated Spills



Spill Correction

Active Ripple Filter

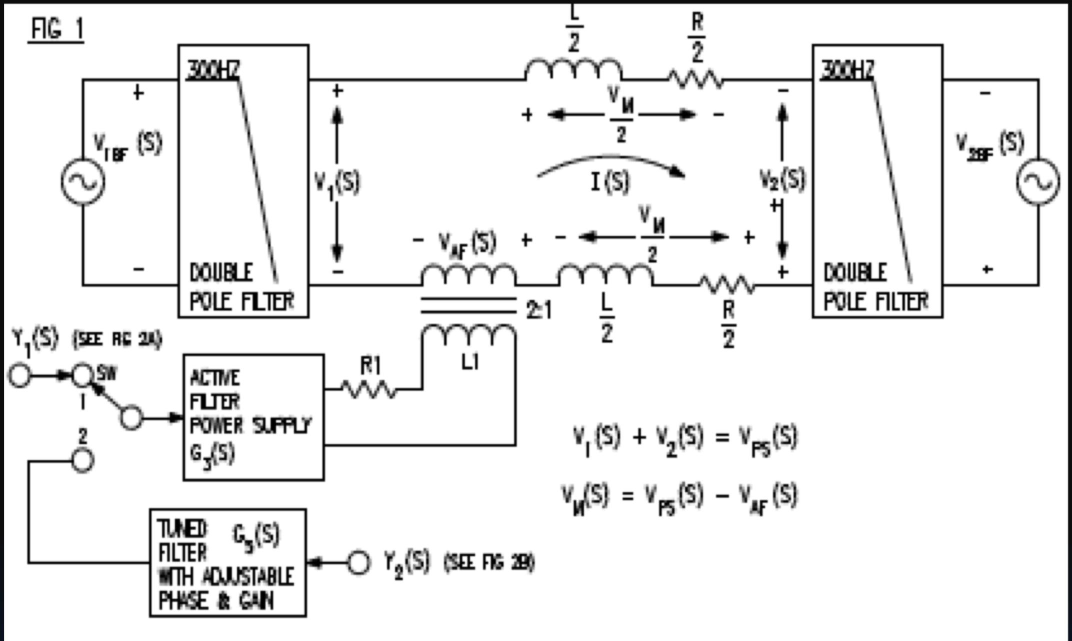
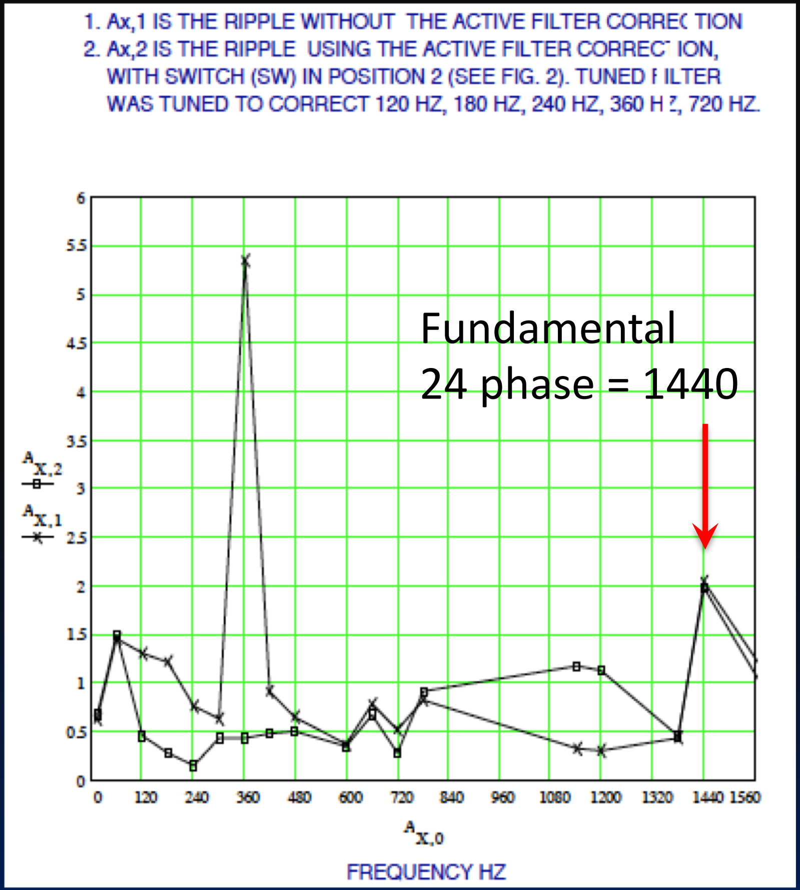


FIG 1

$$V_1(S) + V_2(S) = V_{PS}(S)$$

$$V_M(S) = V_{PS}(S) - V_{AF}(S)$$

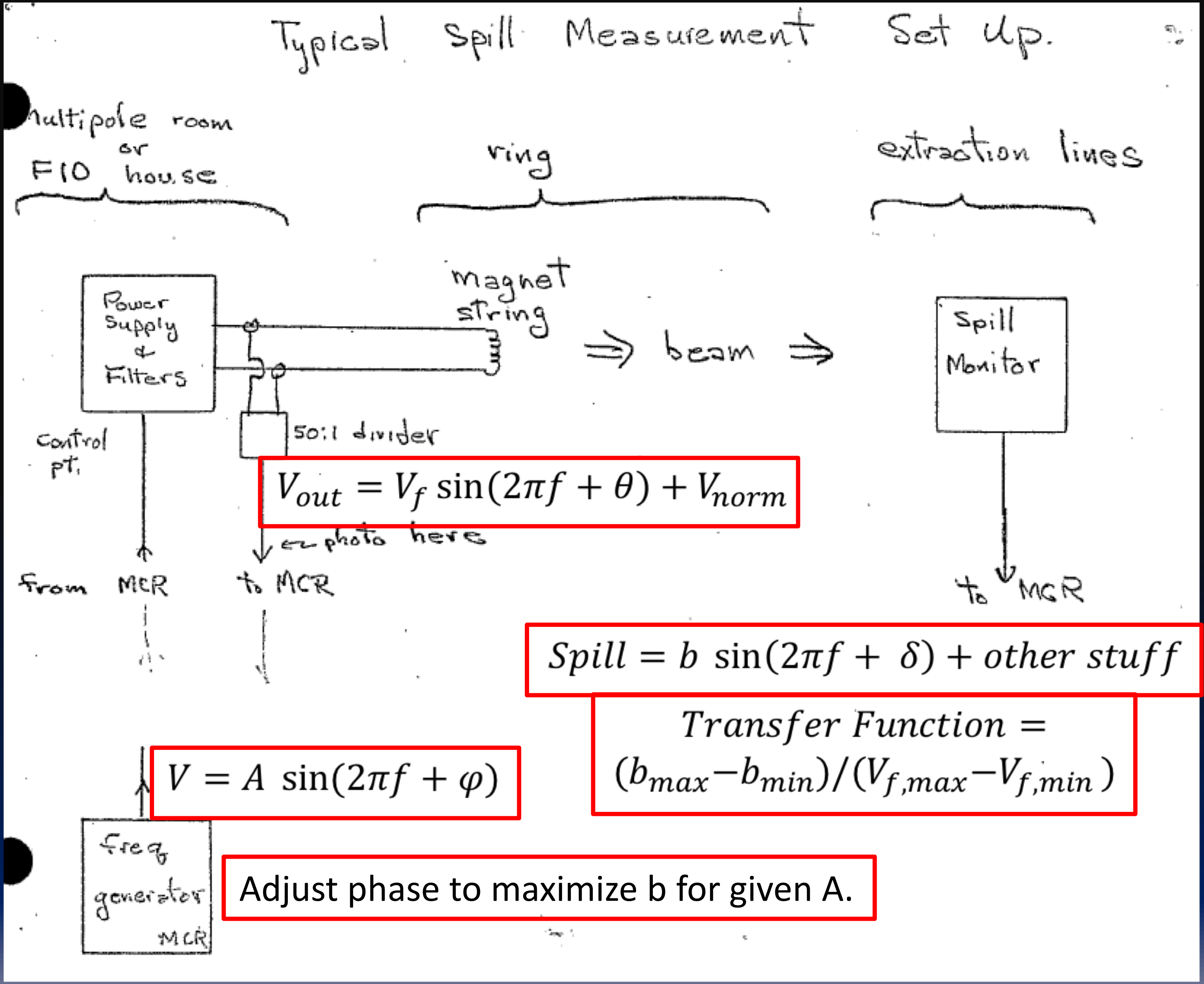


1. Ax,1 IS THE RIPPLE WITHOUT THE ACTIVE FILTER CORRECTION
2. Ax,2 IS THE RIPPLE USING THE ACTIVE FILTER CORRECTION, WITH SWITCH (SW) IN POSITION 2 (SEE FIG. 2). TUNED FILTER WAS TUNED TO CORRECT 120 HZ, 180 HZ, 240 HZ, 360 HZ, 720 HZ.

Fundamental
24 phase = 1440

The tuned filter is basically performing an analog FFT, via bandpass (Butterworth) filters. Each filter stage passes a narrow band around a 60 Hz harmonic. A gain and phase are applied to the output of the filter.
All filter outputs are added together to form a single reference to the Power Supply.

Transfer Function Measurements



$$V_{out} = V_f \sin(2\pi f + \theta) + V_{norm}$$

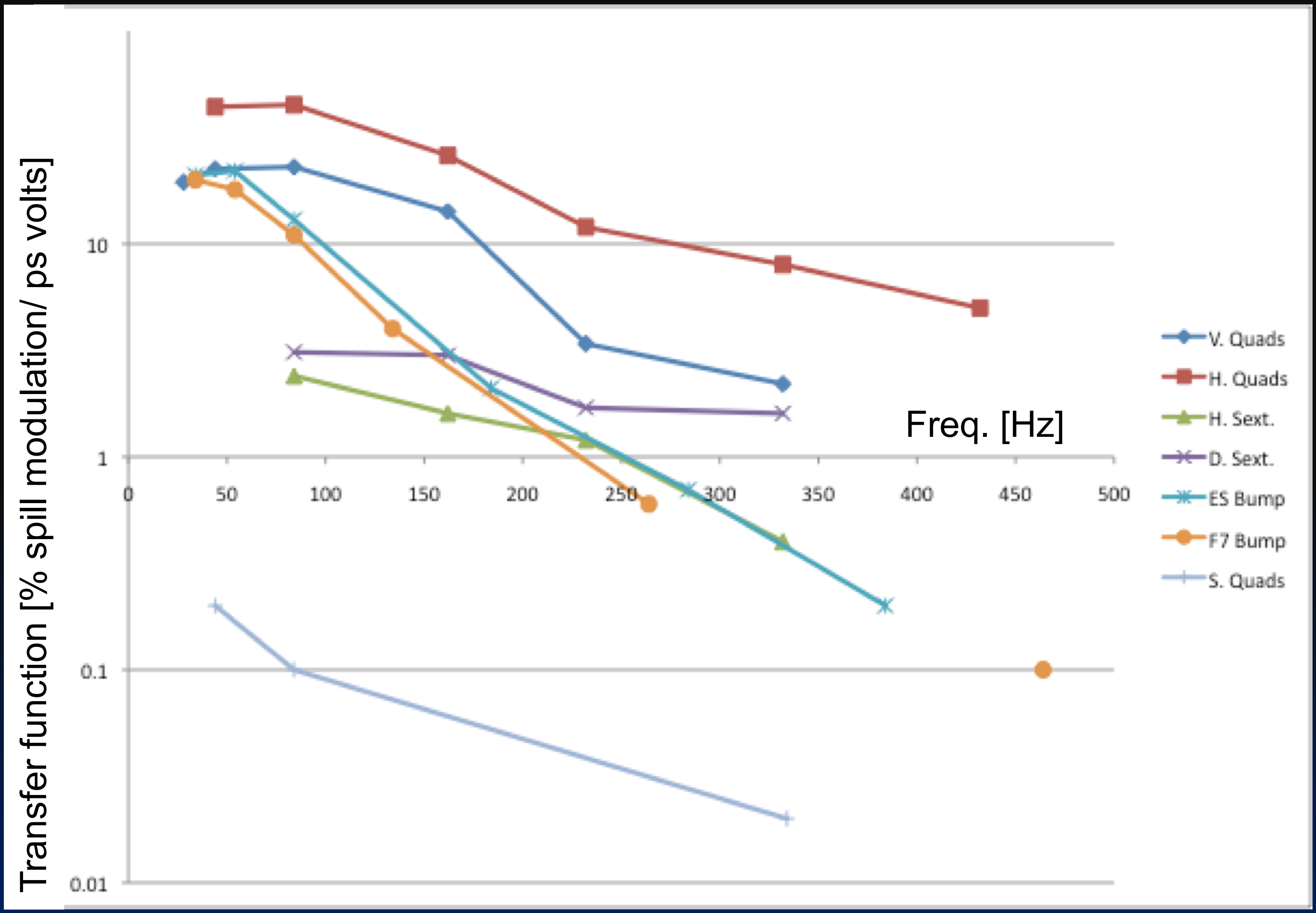
$$Spill = b\ \sin(2\pi f +\ \delta) + other\ stuff$$

$$Transfer\ Function = (b_{max} - b_{min})/(V_{f,max} - V_{f,min})$$

$$V = A\ \sin(2\pi f + \varphi)$$

Adjust phase to maximize b for given A.

Transfer Function Measurements



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.

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

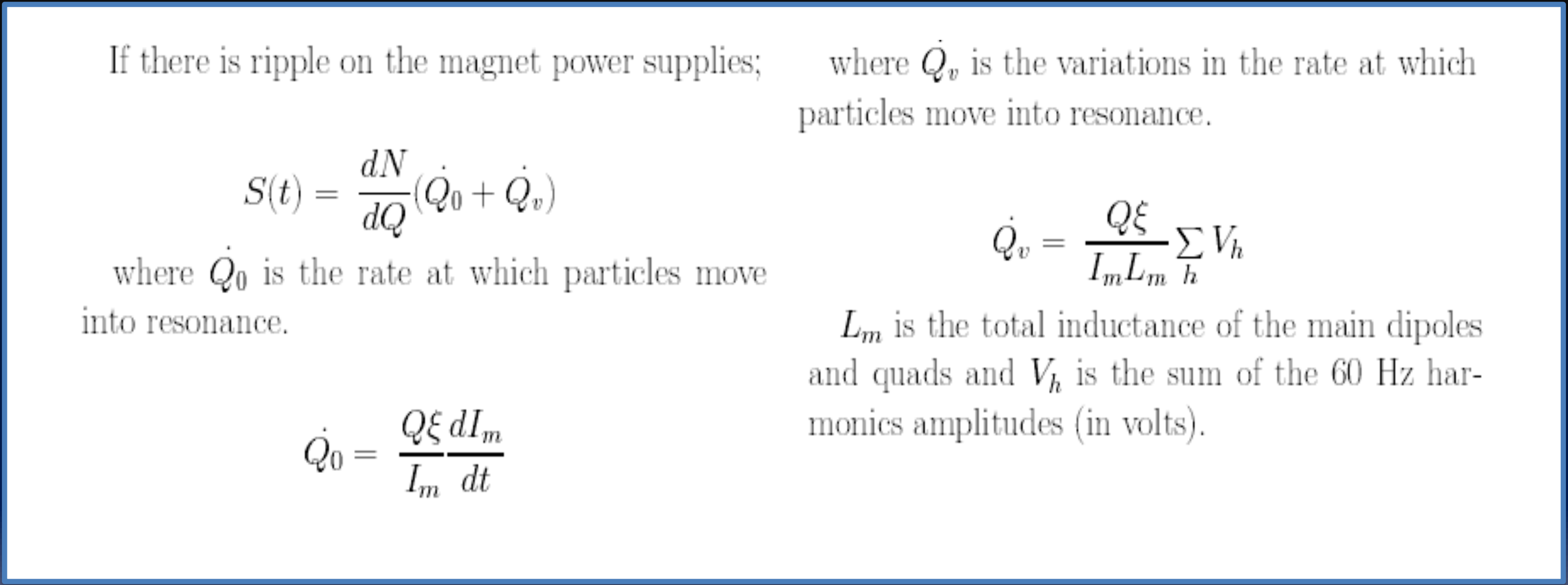
In purely linear terms, given a Gaussian distribution, this transformation simply is an error function (Gaussian to DC transformation).

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.

Spill correction: 2 methods (there are more)

- Increase rate of particle passage through resonance
  - Increase dp/p to increase dQ/dt
  - 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

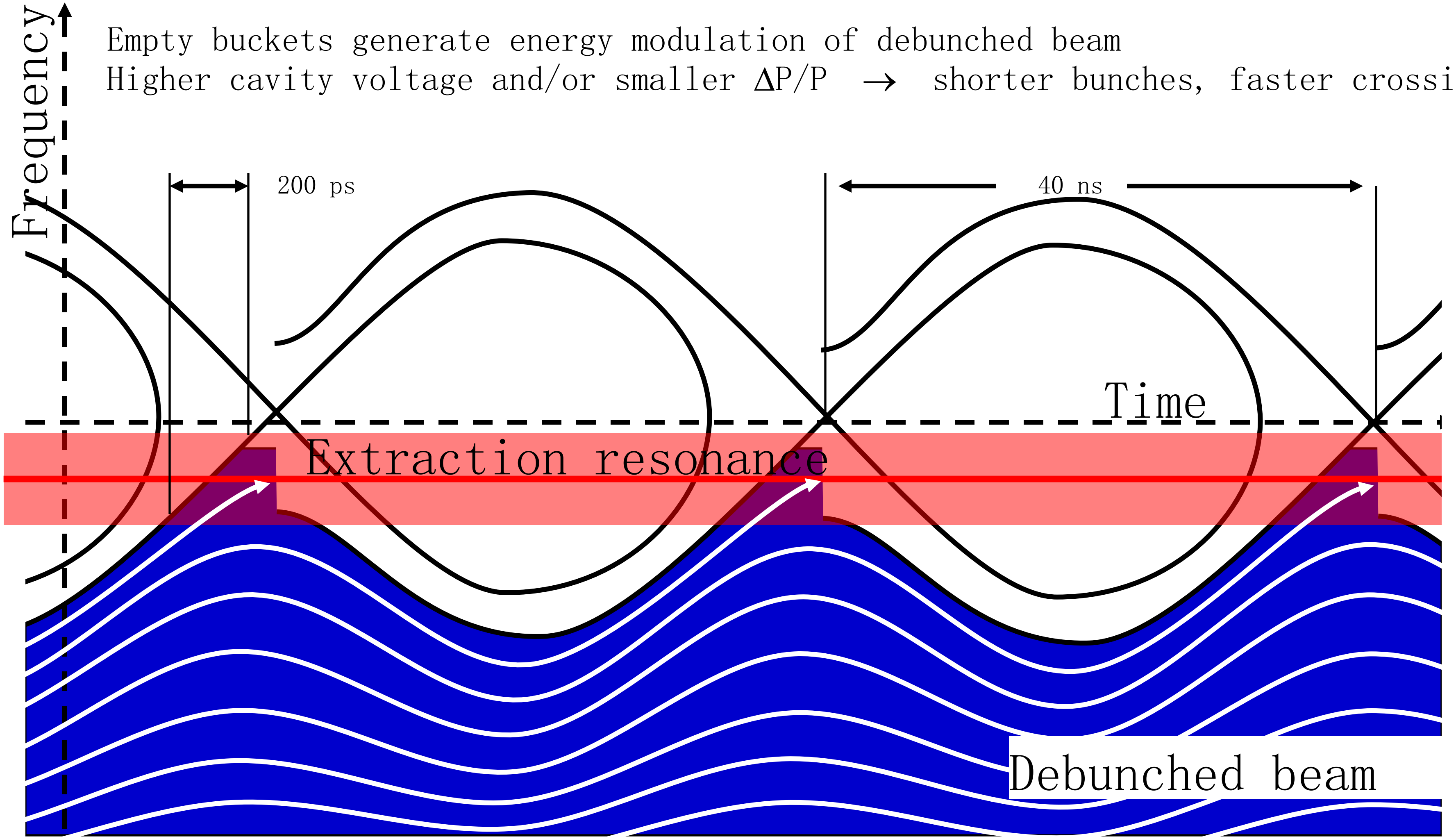
- To beat the average, need a real-time correction.
  - But need to make sense of the real data - not easy

- No matter what we do, we have to do it before particles pass the stability boundary.

RF Phase Displacement Technique

Empty buckets generate energy modulation of debunched beam

Higher cavity voltage and/or smaller ΔP/P → shorter bunches, faster crossing



BROOKHAVEN
NATIONAL LABORATORY

SEE Project for the AGS

SEE = Single Event Effect Facility at the AGS

Design Capabilities

- Large range of beam energies (e.g., 0.1 - 2.0 GeV/n Fe^{56} ions)
- Large number of available ion species (e.g., H to Au and more)
- Fast energy change (minutes)
- Fast switching of ions (minutes)
- Support for both unclassified and classified experiments
- 3D Uniform Beams
- Square uniform beam sizes from 25 cm^2 to 144 cm^2, and larger
- Small beams on the scale of 1 cm rms (and smaller are possible)
- Beam spills from 0.1 - 5.0 seconds
- Fast beam cutoff with insignificant overshoot (e.g., 0.001%)
- Same level of support and service as existing NASA Space Radiation Laboratory (NSRL) that runs from the AGS Booster

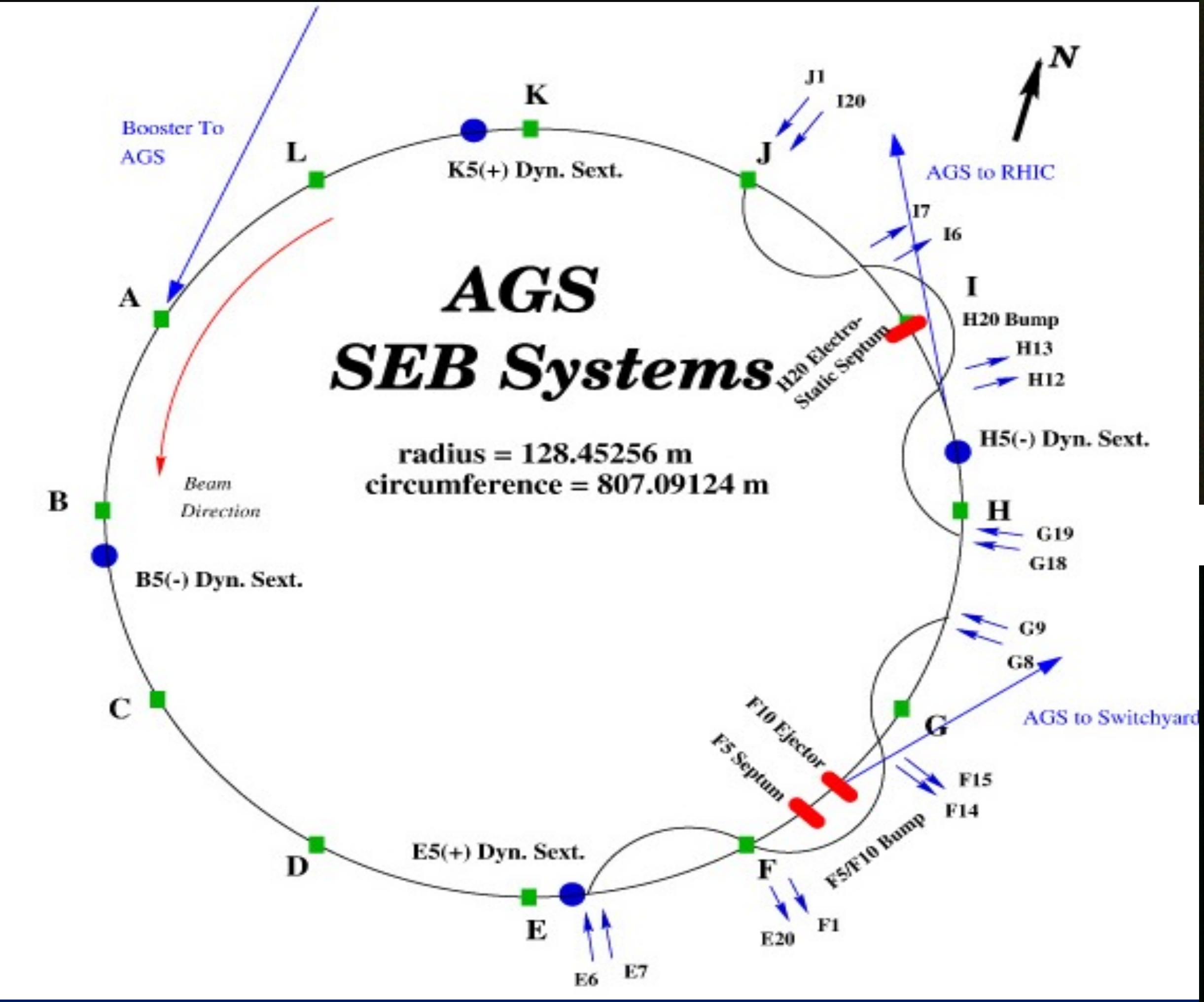
Beam Requirements - Boundary Conditions

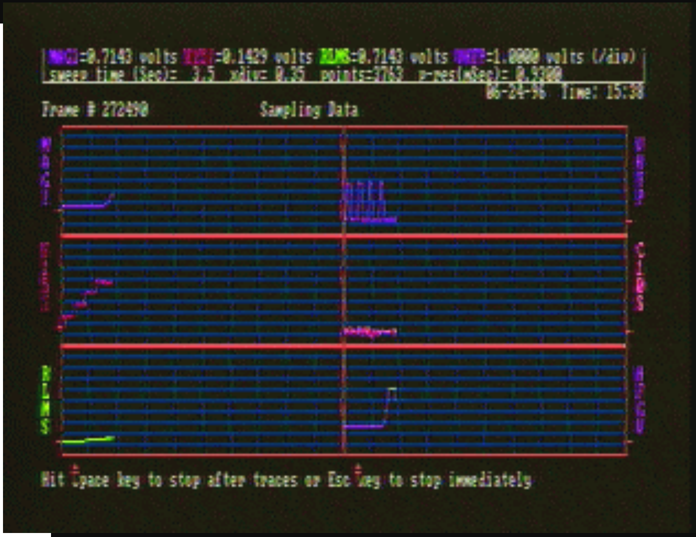
- Beam rigidities up to 24 Tm
  - 0.1 to 2 GeV/n for Fe^{56} ions
  - Up to 7.1 GeV for protons
- Beam characteristics: 3D uniform beams
  - 0.1 - 5 second long spills
  - 5”x5” usable uniform beam spots, same beam sizes as used at NSRL
  - Intensities similar to NSRL
- Beam Cutoff
  - Assume the cutoff will involve a 1 msec overshoot
  - E.g., given 100 or so spills, effect of the overshoot is then only about 0.001%
  - For low dose, at most a few particles overshoot for a 1000 particle irradiation

Slow Extraction at the AGS

- March, 1968: first SE for HEP, $3Q_H=26$
  - Simple system with no ES septum
- 1972: 200 MeV LINAC (previous was 50 MeV), H+ injection to AGS
- 1979: first ES septum installed
- 1979: new multi-hall switchyard (3 lines)
- 1980's: pre-Booster era, H- injection to AGS
  - Intensities 1.0 – 1.6 x 10^{13} protons/pulse
  - Extraction momentum 25-29 GeV/c
  - Spills 1 – 2 sec., repetition periods 2.4 - 4.0 sec.
  - Extraction inefficiency 3 – 5 %
  - Began doing heavy ion experiments (NPP)
- 1990's: post-Booster era
  - Intensities 5.0 – 7.6 x 10^{13} protons/pulse
  - Extraction momentum 25.5 GeV/c (to improve uptime)
  - Similar spills and rep periods, more optimization on duty factor
  - Extraction inefficiency 2 – 3 %
  - NASA Radiobiology program in the A3 beamline
- 2001: slow extraction from Booster, NSRL Line Commissioning
- 2002: AGS SEB program ends. RHIC era.

Overview of AGS Slow Extraction





```
[illegible]=0.7143 volts [illegible]=0.1429 volts RLMS=0.7143 volts [illegible]=1.0000 volts (/div)
sweep time (Sec)=  3.5  xdiv= 0.35  points=3763  x-res(mSec)= 0.9300
                                                        06-24-96  Time: 15:38
Frame # 272490              Sampling Data

Hit Space key to stop after traces or Esc key to stop immediately
```

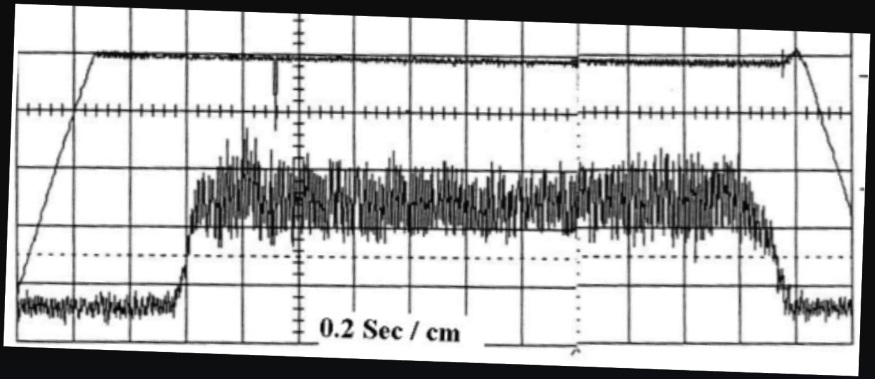
Measured extracted beam emittance with High Intensity Protons

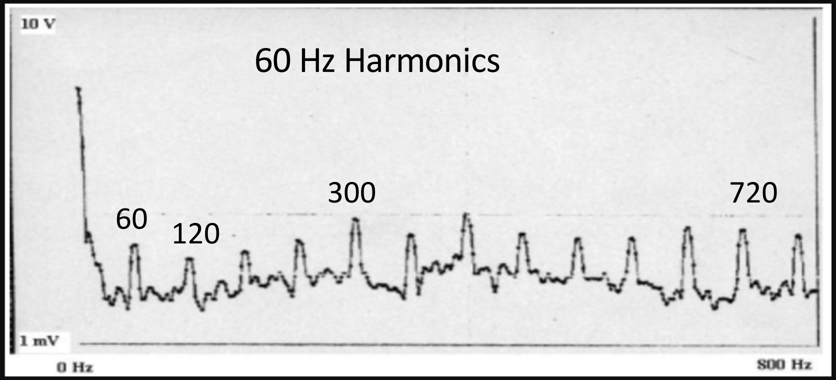
	$\varepsilon_H^{99\%,N}$ (π mm-mrad)	$\varepsilon_V^{99\%,N}$ (π mm-mrad)
Pre-Booster (1980) 200 MeV injection	49	60
Post-Booster (1997) 1.94 GeV injection	99	85

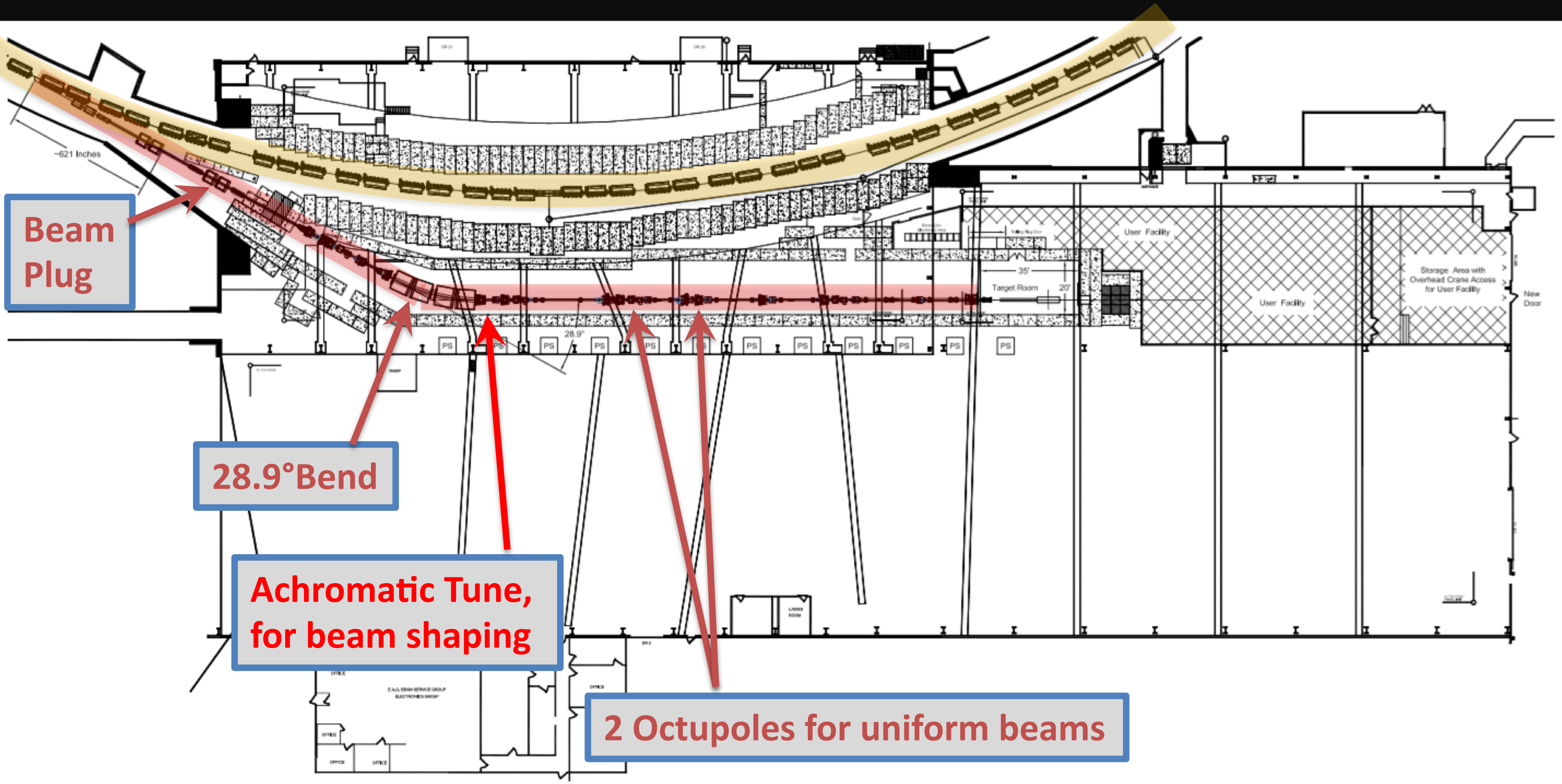
Normal SEB AGS Parameters

Parameter	Value	Units
Peak Intensity	74.0	10^{12} protons/pulse
Extraction Efficiency	97-98	%
Spill Lengths	1.8 – 5.8	Seconds
Working Point	8.667 / 8.78	Horiz./Vert. Tune
Normalized Chromaticity	-2.5 / 0.05	Horiz./Vert. Chrom.
Extraction Momentum	25.5	GeV/c

Spill Structure from AGS SEB







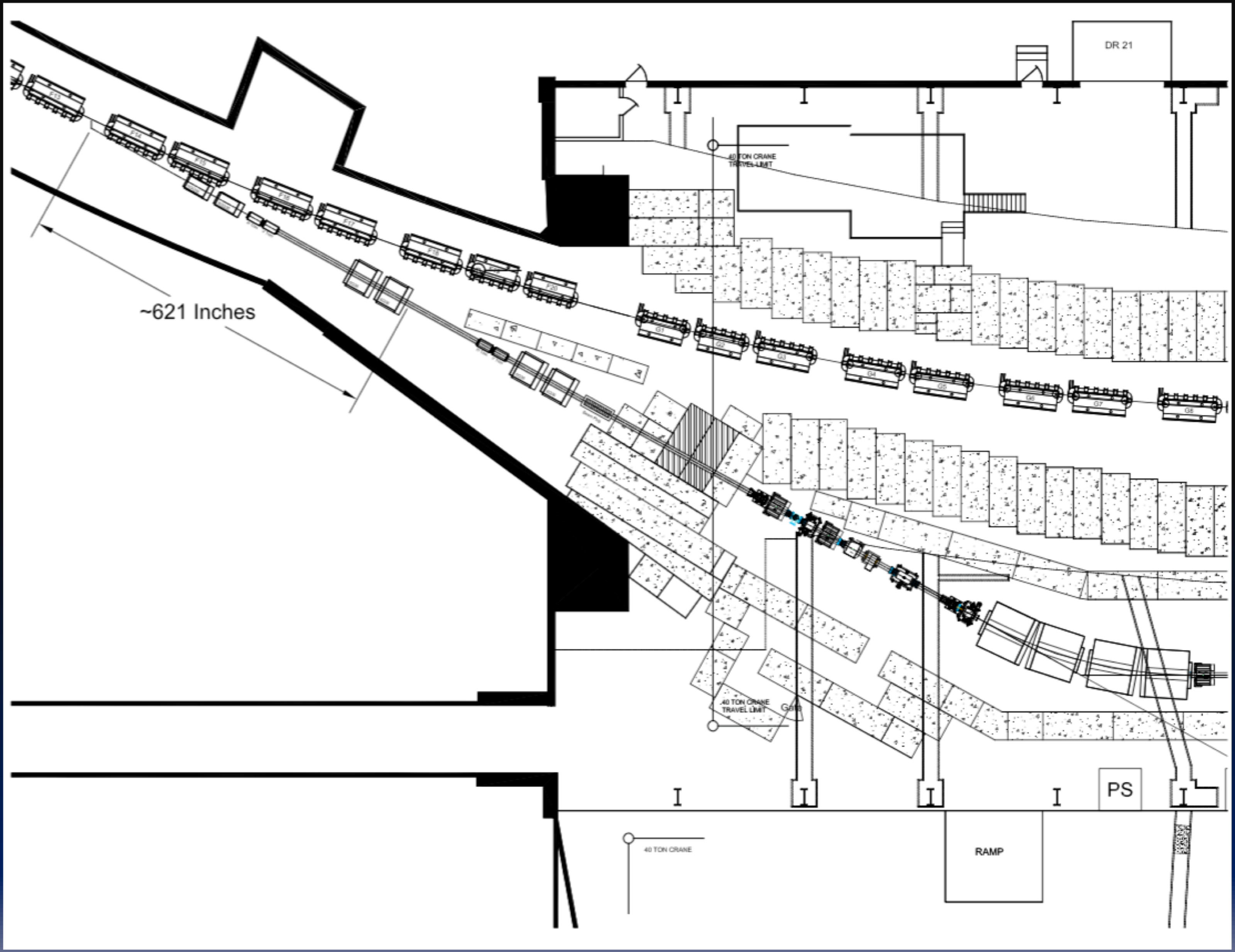
Beam Plug

28.9°Bend

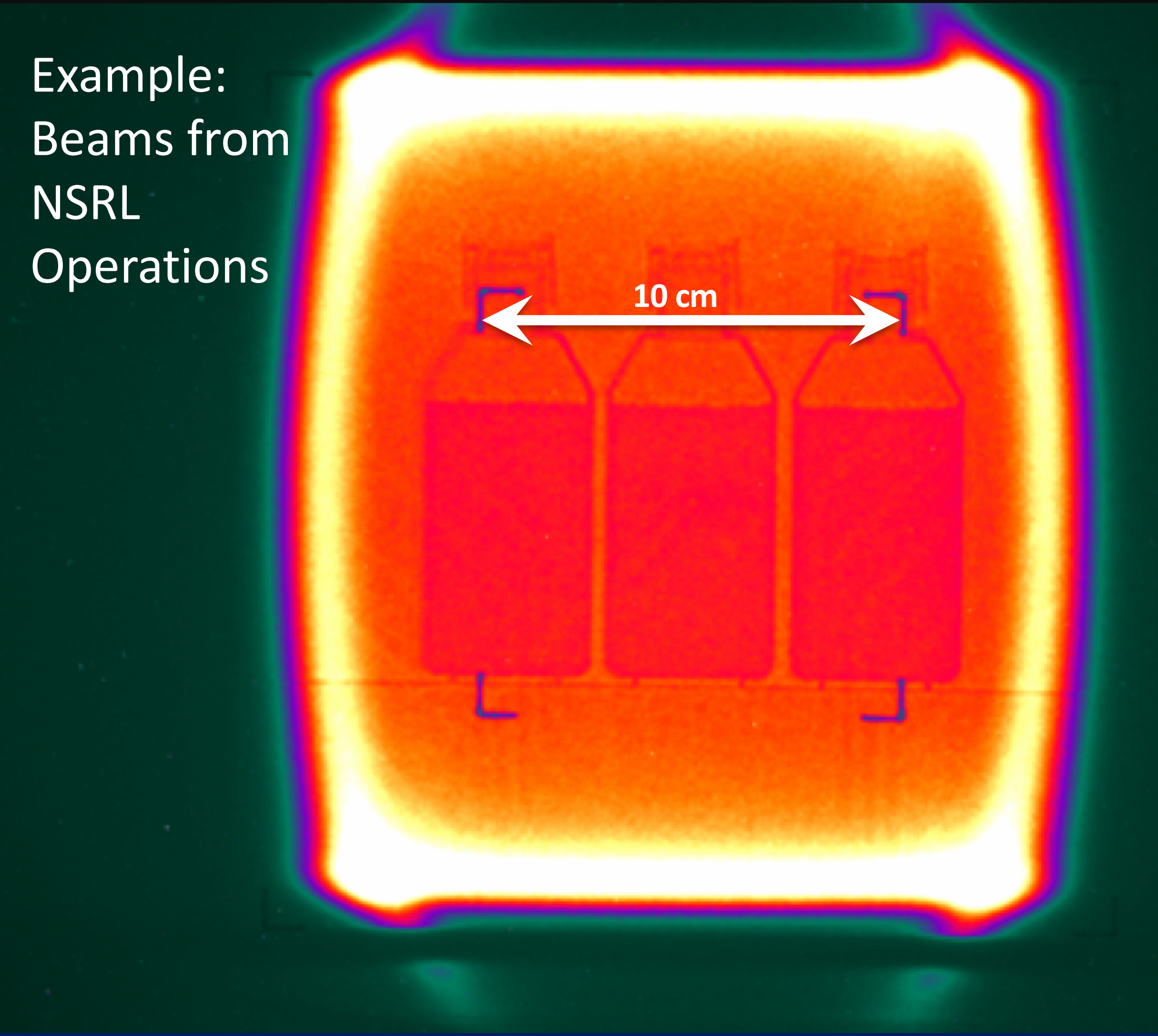
Achromatic Tune, for beam shaping

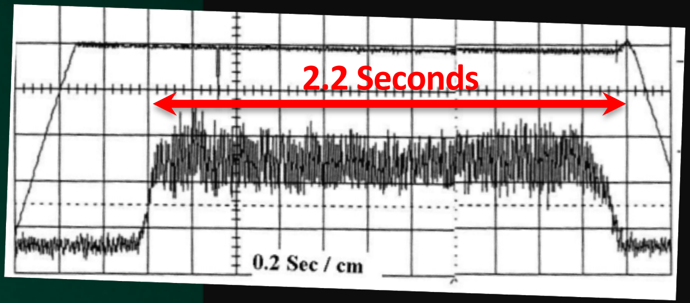
2 Octupoles for uniform beams

Proposed SEE, Upstream Beamline



Example:
Beams from
NSRL
Operations



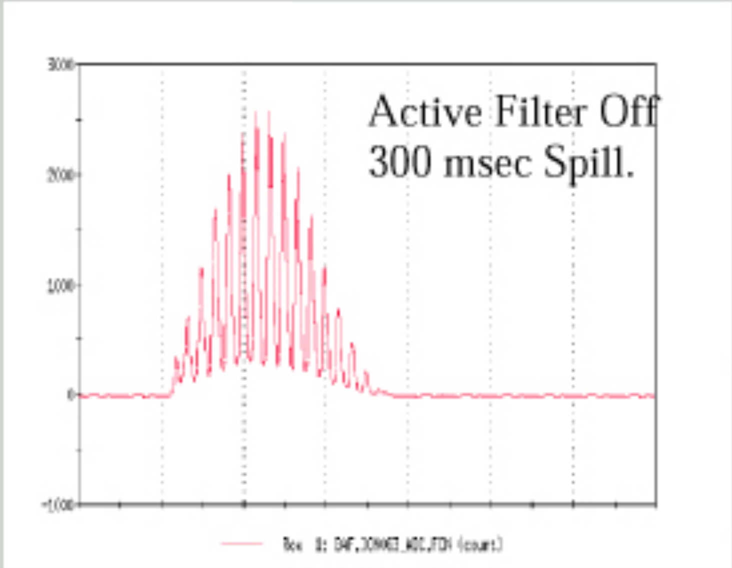


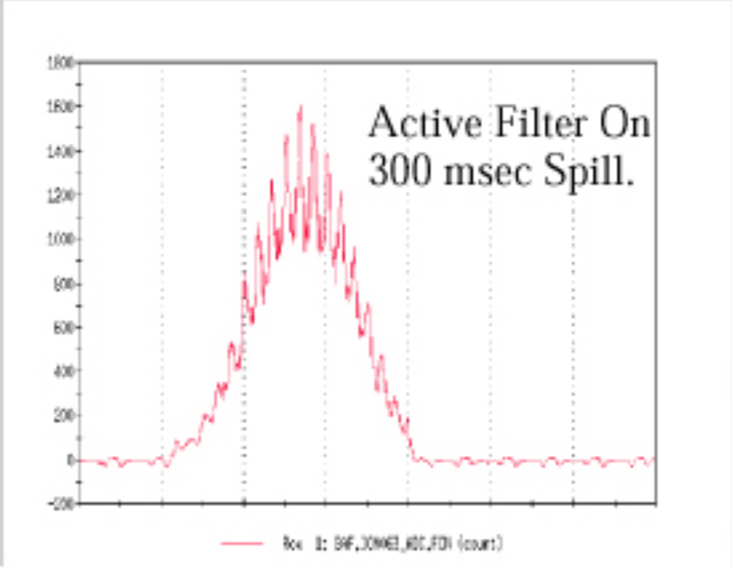
Example of AGS Spill from 1990s

NSRL Target room - model for SEE TR

NSRL Gate to access the NSRL target area

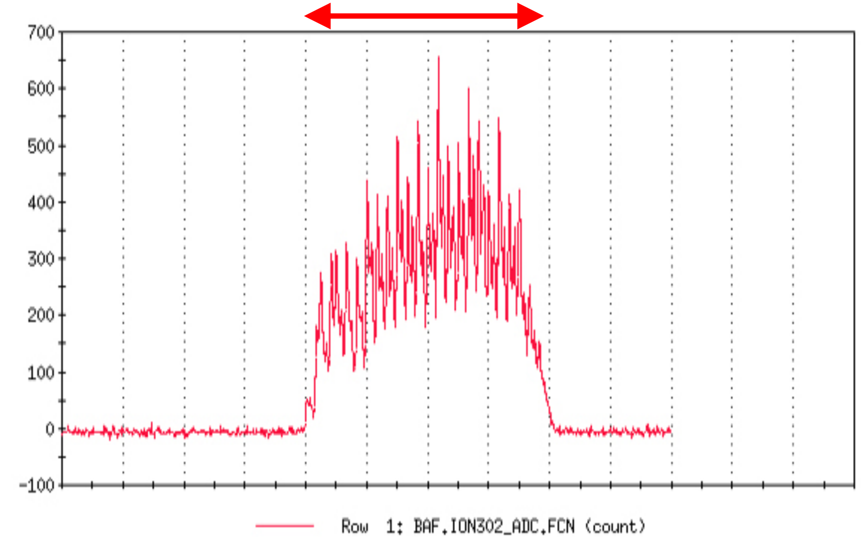
2 GeV Protons


Active Filter Off
300 msec Spill.

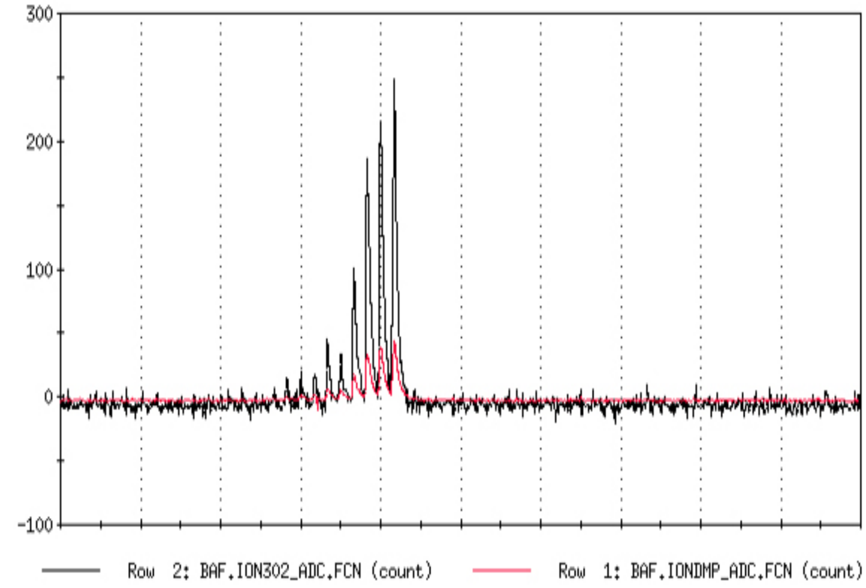

Active Filter On
300 msec Spill.

300 MeV/n Carbon

400 ms



Spill Servo
And Active
Filter On.



Dosimetry
Beam Cutoff

Advantages a BNL Facility offers

- Large range of ions and ion energies
- Large range of spill lengths up to 5 seconds, possibly longer
- Improved well controlled spills and spill structure
  - Steady particle rates with low micro-structure
- Fast energy and ion change
- Ability to go to higher energies in the future (AGS -> 30 GeV)
- Support for classified and unclassified experiments
- No civil construction - Existing floor, shielding, Bldg. 912 with large capacity cranes, etc.

Publications? (things I would contribute to)

- A few interesting papers to think about:
  - Simulation of beam spill
  - Simulation of bunched beam spill
  - Spill correction simulation
  - Comparisons with real data
  - Fast slow extraction (i.e., a few turns to short burst via slow extraction method and well controlled bunch parameters) = note, who wants this?
  - Spill correction using sextupole modulation
  - Spill correction using machine learning in a fast quadrupole compensation system
- Of course, I'm happy to contribute in other areas, if help is desired.