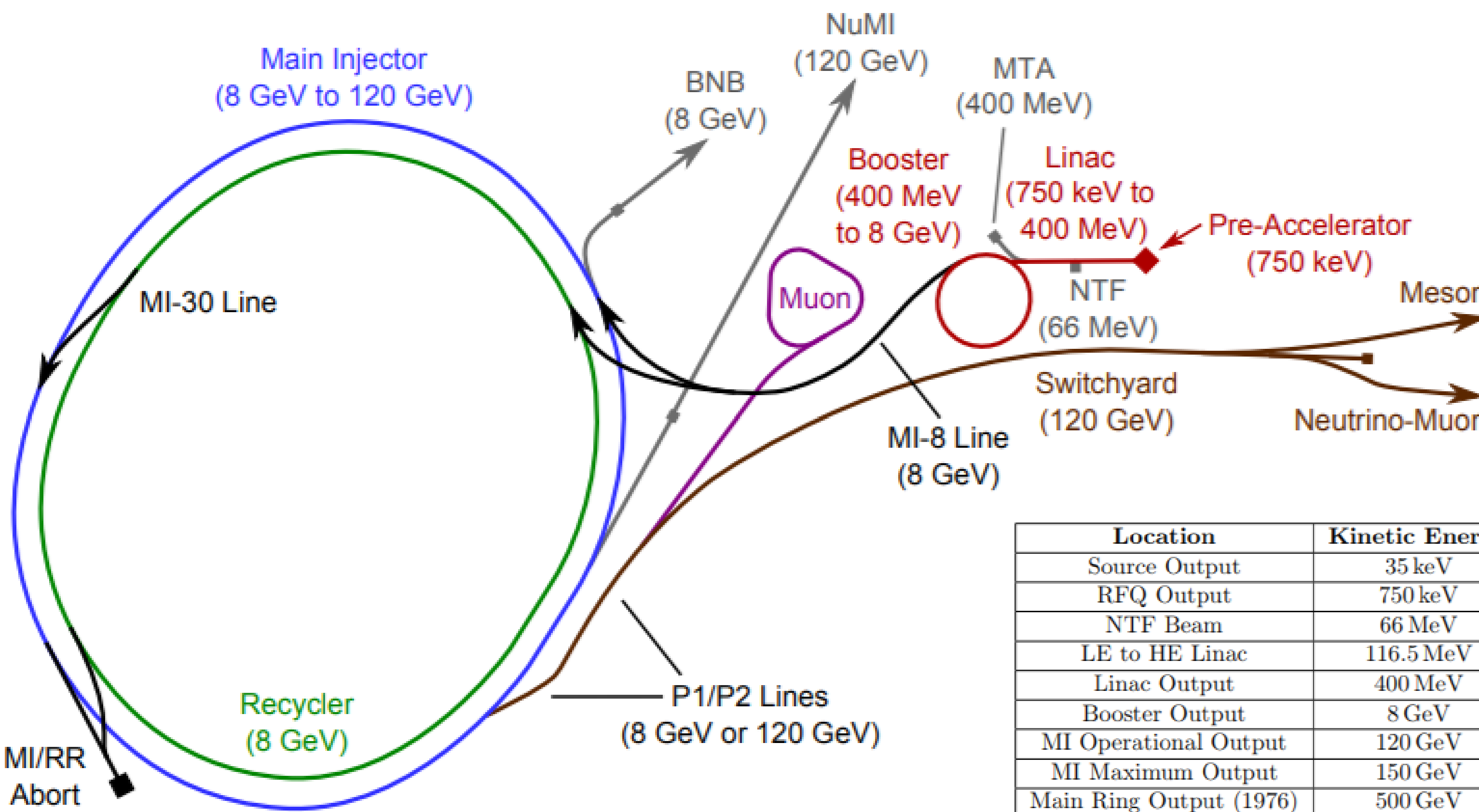
EDIT2018: Where does beam come from?

Adam Watts, Engineering Physicist
Fermilab Accelerator Division
March 2018

Fermilab Accelerators

The Fermilab Accelerator complex consists of a chain of proton particle accelerators and several experimental beamlines. The maximum available beam kinetic energy is 120 GeV, corresponding to protons travelling at 99.997% the speed of light. We deliver beam to a long-baseline neutrino oscillation experimental program (NOvA, MINERvA), a short-baseline neutrino oscillation program (MicroBooNE, SBND, ANNIE), a Nuclear Physics experiment (SeaQuest, E1039) and Test Beam Facility** (Switchyard), and a rare-process Muon experimental program (G-2 and Mu2e experiments).



Location	Kinetic Energy	Velocity (m/s)	Velocity (c)
Source Output	35 keV	2.6E6	0.0086
RFQ Output	750 keV	1.2E7	0.04
NTF Beam	66 MeV	1.07E8	0.357
LE to HE Linac	116.5 MeV	1.37E8	0.457
Linac Output	400 MeV	2.14E8	0.713
Booster Output	8 GeV	2.98E8	0.994
MI Operational Output	120 GeV	2.9978E8	0.999969
MI Maximum Output	150 GeV	2.9978E8	0.999981
Main Ring Output (1976)	500 GeV	2.9979E8	0.9999982
Tevatron[a]	980 GeV	2.9979E8	0.99999954
LHC[b]	8 TeV	2.9979E8	0.9999999931

[a]No longer operational
[b]The Large Hadron Collider is located at CERN in Geneva, Switzerland

**That's you guys.

Particle Accelerators and Beamlines

Particle accelerators increase the kinetic energy of a group of particles (i.e. "beam") and direct those particles to an experiment. Electric field "kicks" from high-frequency electromagnetic resonant structures called "RF Cavities" increase particle kinetic energy. Magnets steer and focus the particles.

Figure 1.3: A simple linear accelerator

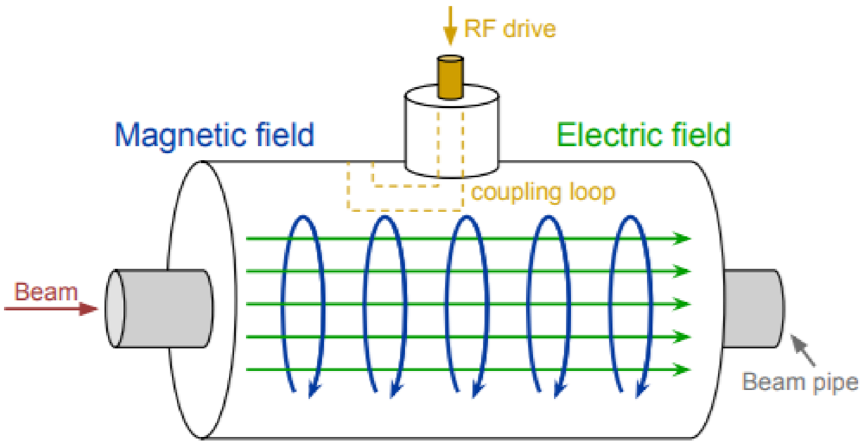


Figure 3.2: Simple "pillbox" RF Cavity.

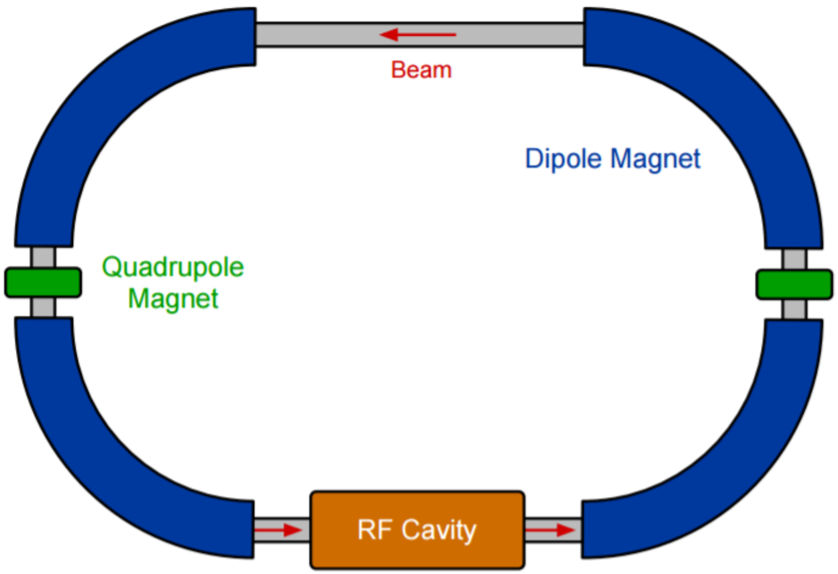


Figure 1.4: A simple synchrotron

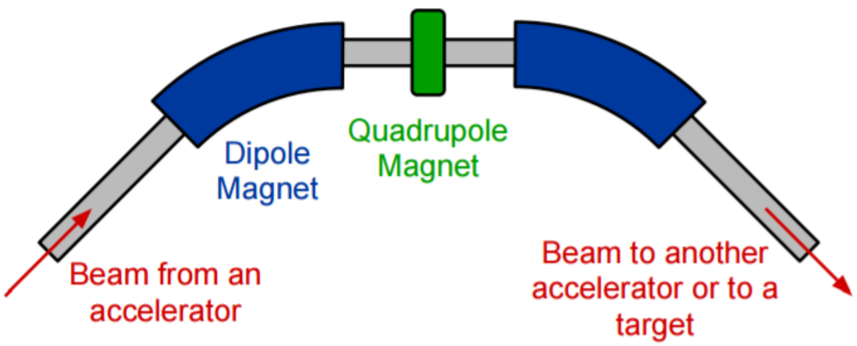
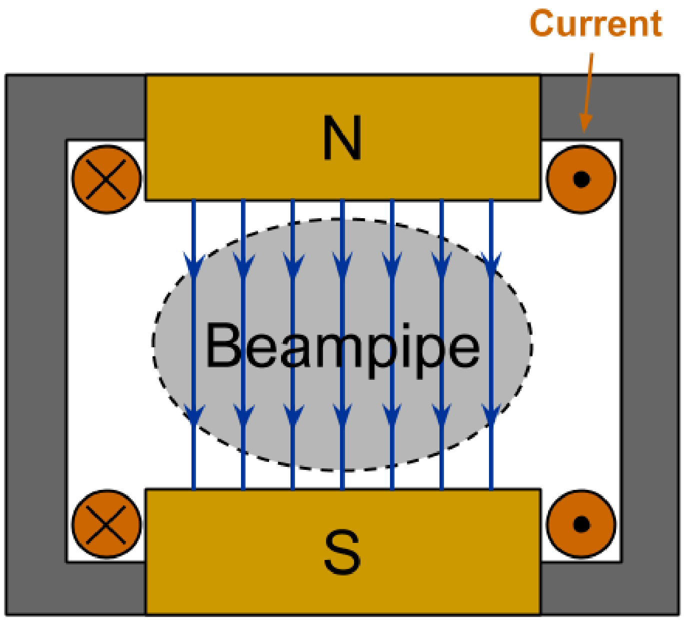
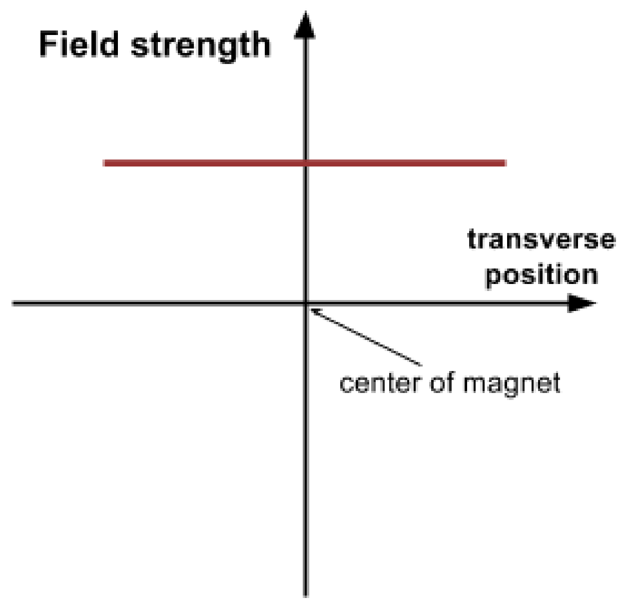


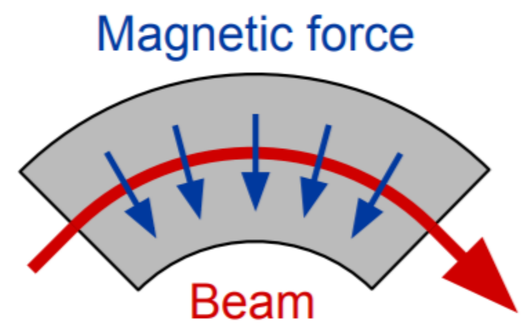
Figure 1.5: A simple beamline

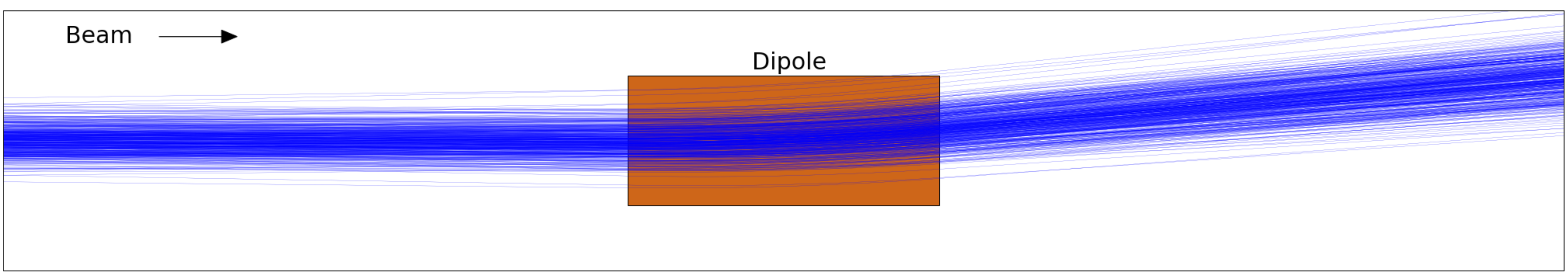
Particle Transport, Dipole Electromagnet

High energy particle beams are typically directed and focused by magnetic fields. Dipole magnets steer the beam trajectory. However, due to non-zero beam divergence (particle angles), beam size increases over distance.



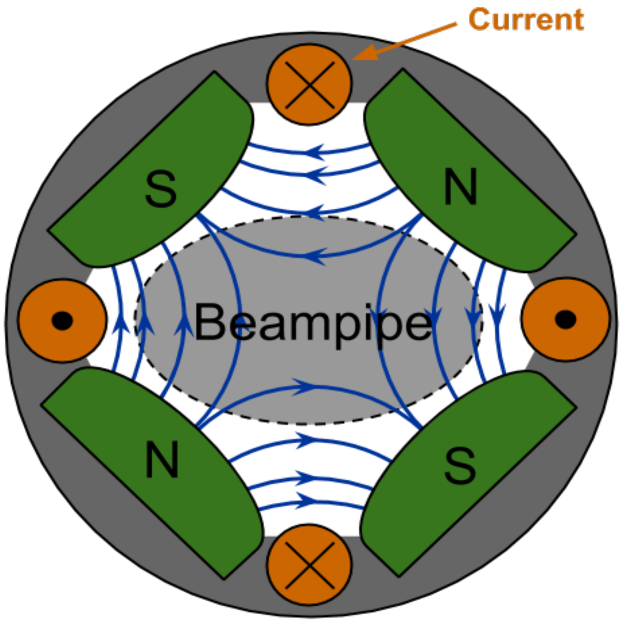


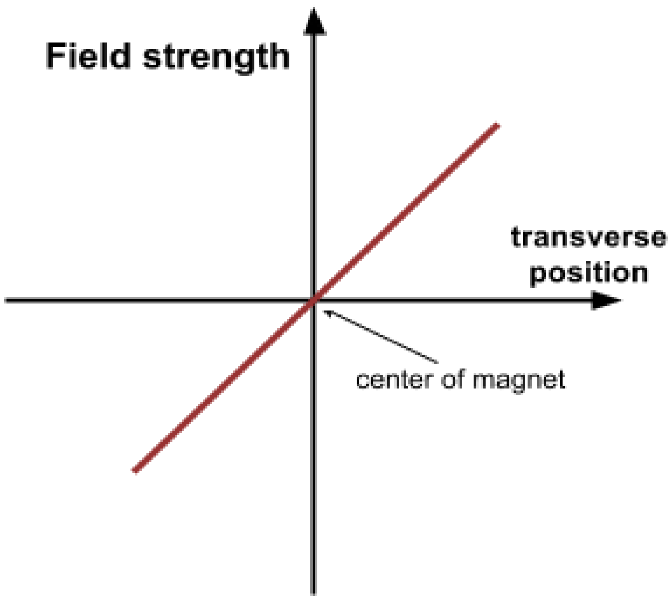


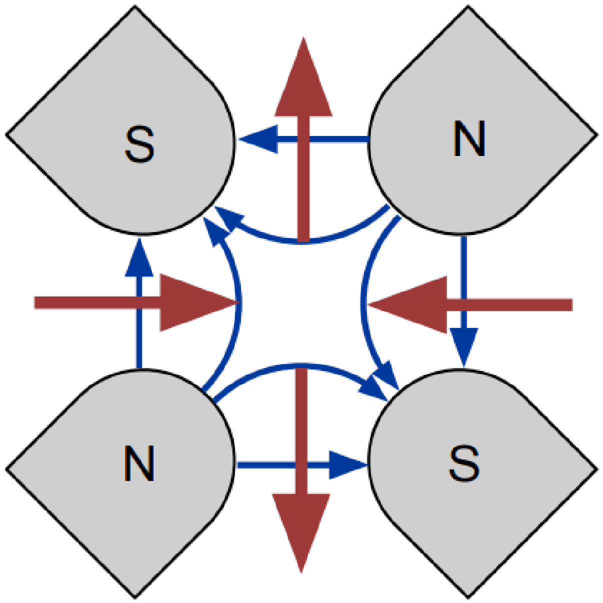


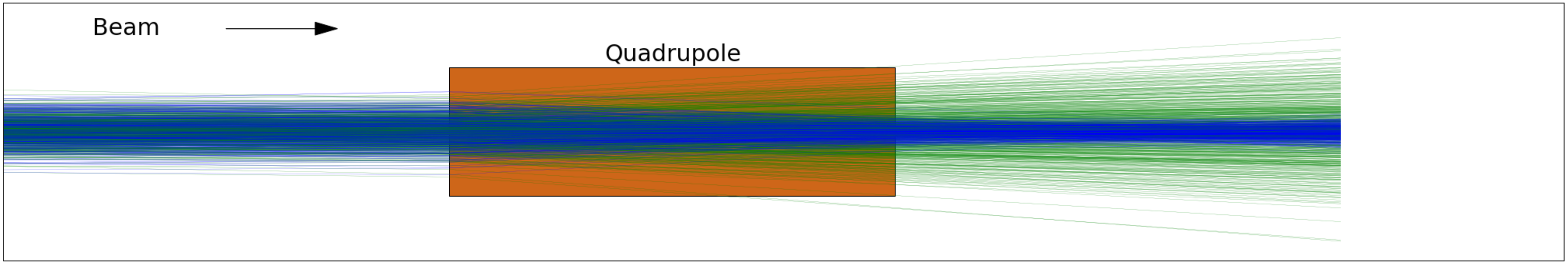
Particle Transport, Quadrupole Electromagnet

To focus the beam, we typically use quadrupole magnets. These provide a linear restoring force toward the center of the magnet, thus acting like a lens; however, a quadrupole always focuses in one plane and de-focuses in the other. (Blue is horizontal beam, green is vertical in bottom diagram)





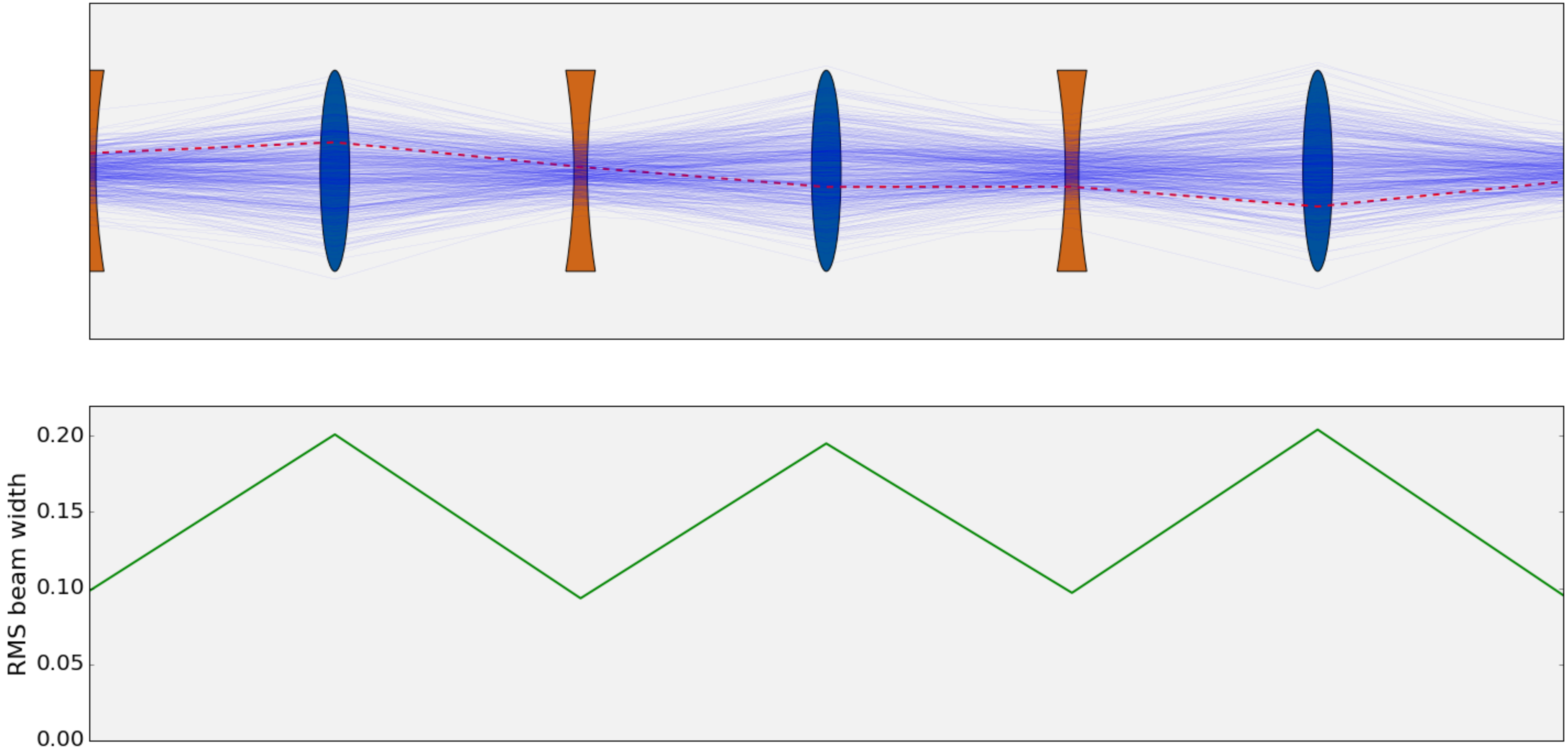




Beam Transport, Strong Focusing

For long-distance beam transport, or to design a stable circular accelerator, it is advantageous to use “Strong Focusing”, or “Alternating Gradient Focusing”. This is a periodic arrangement of quadrupoles that alternate polarity, like stringing doublets together indefinitely. This technique allows for stable transport of beam over arbitrarily-long distances without net increase in the beam size in either plane. Beam size oscillations are known as “betatron oscillations”.

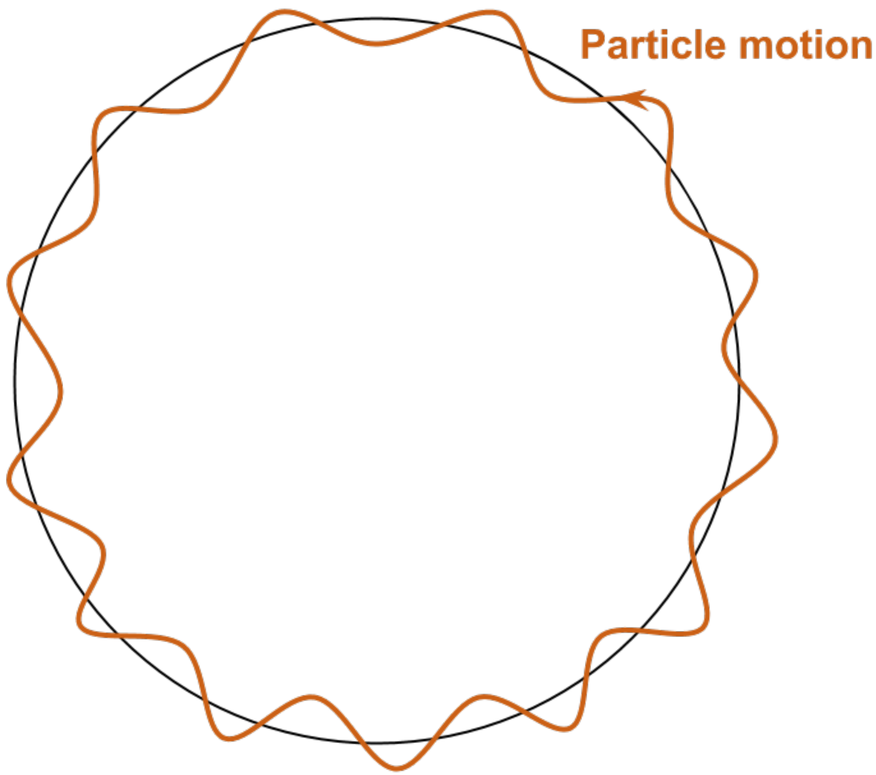
- Christofilos, N. C. (1950). "Focusing System for Ions and Electrons". US Patent No. 2,736,799.
- Courant, E. D.; Snyder, H. S. (Jan 1958). "Theory of the alternating-gradient synchrotron" (PDF). Annals of Physics. 3 (1): 1–48. Bibcode:2000AnPhy.281..360C. doi:10.1006/aphy.2000.6012.

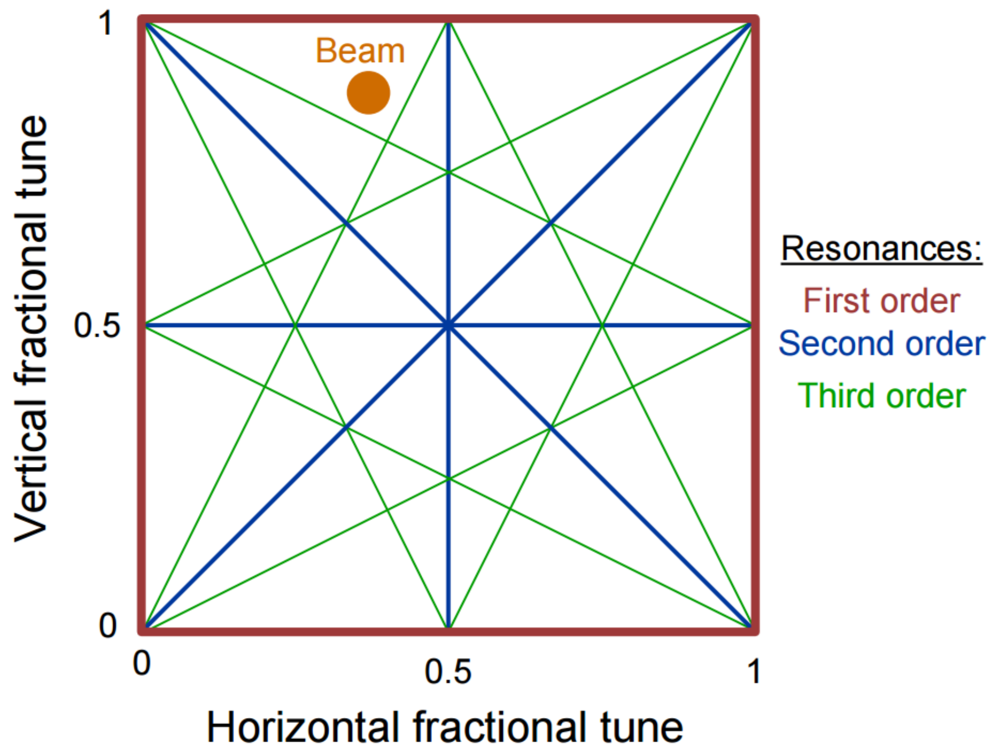


Betatron Oscillations

Alternating focusing/ defocusing pattern ("lattice") in a circular accelerator creates transverse oscillation of particles known as "Betatron motion". The number of oscillations per revolution is called the "tune" ν. .

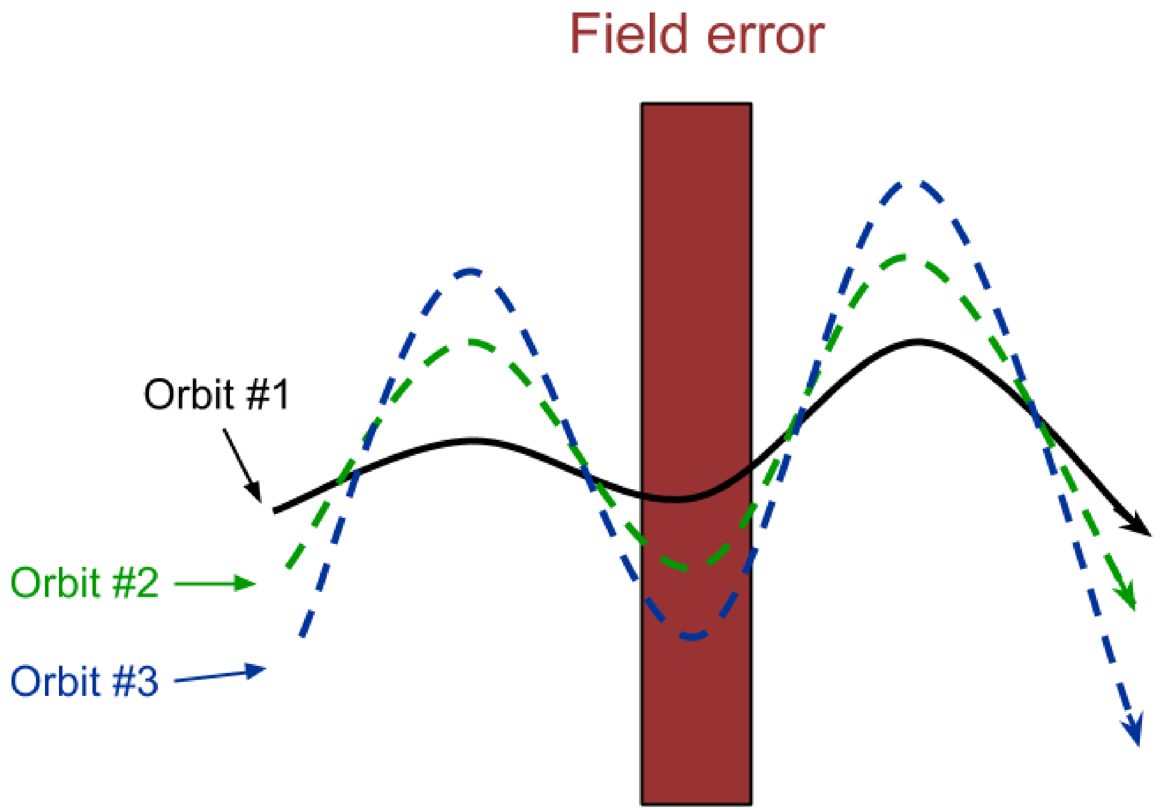
As with any driven oscillation, betatron motion is susceptible to resonance conditions. In particular, fractional-integer tunes allow sensitivity to nonlinear magnet fields in ring; these can be deliberate (sextupoles, octupoles), field imperfections in magnets, or alignment errors.





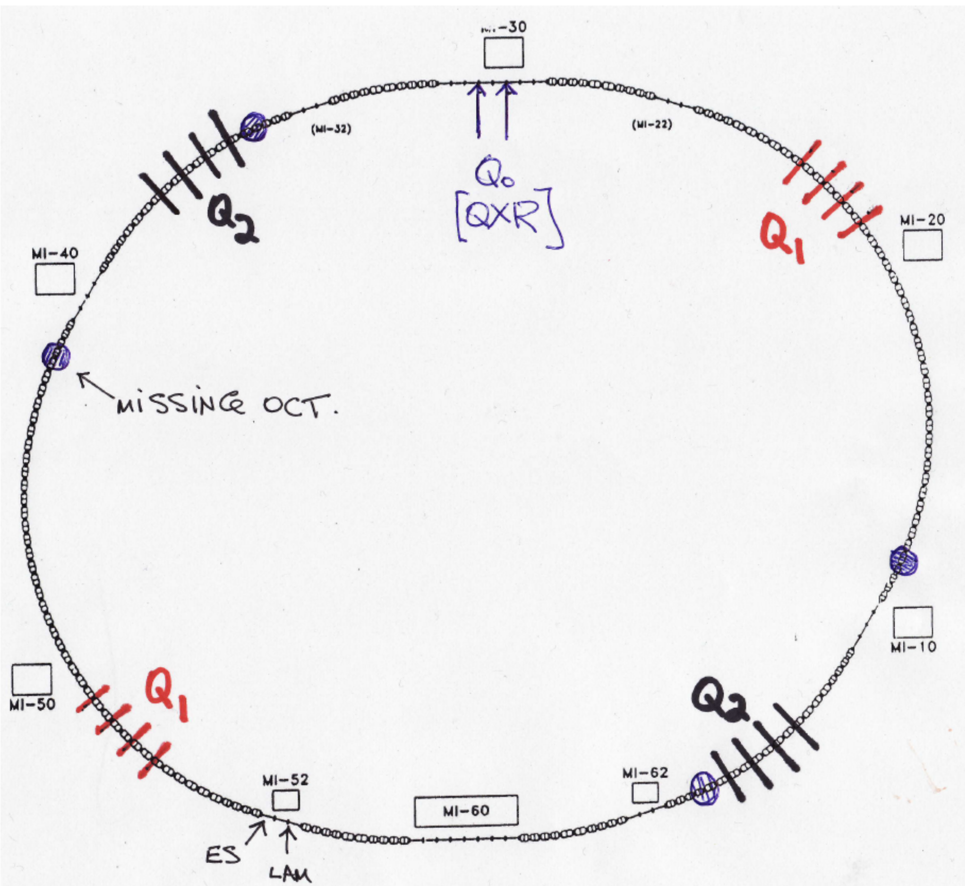
Resonant Extraction

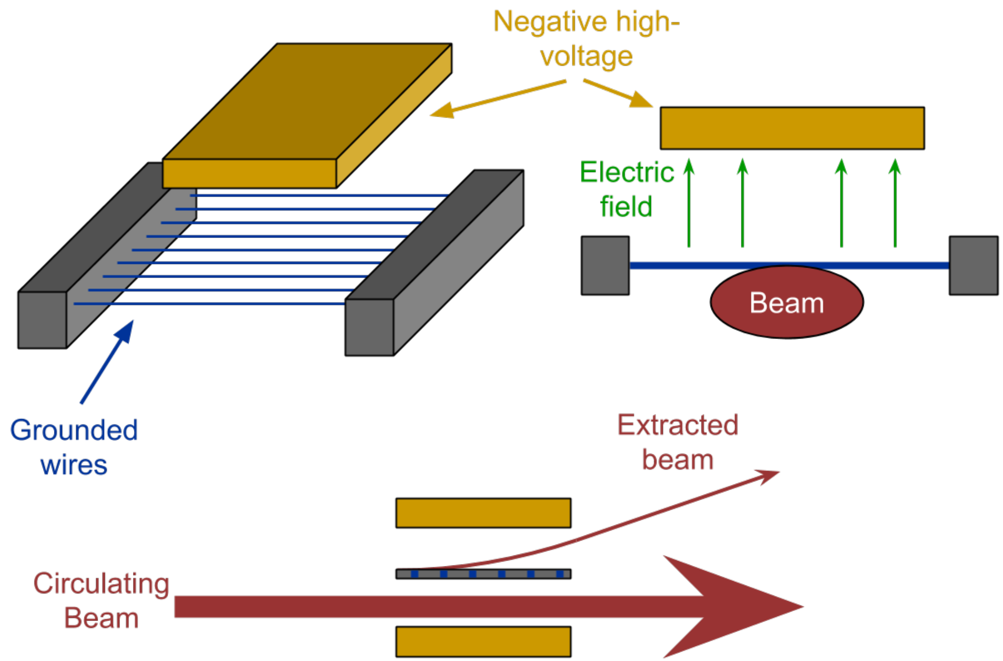
We can leverage betatron resonance to effect a slow extraction out of the synchrotron. In Main Injector, traditional extraction would produce a ~11 μs beam pulse. By causing the beam to undergo betatron resonance and “spill” out of the machine, we can slowly extract the same intensity over 4 s.



MI Half-integer Resonant Extraction

In the Main Injector, we operate with a horizontal tune of 26.5 to increase resonance susceptibility to quadrupole driving forces. Two special-purpose families of “harmonic quadrupoles” drive the half-integer betatron resonance to gradually expand the transverse size of the beam. As particles reach a horizontal orbit deviation threshold (~13mm) at the MI-52 region, an electrostatic septum splits the particles out of the ring and into Switchyard.



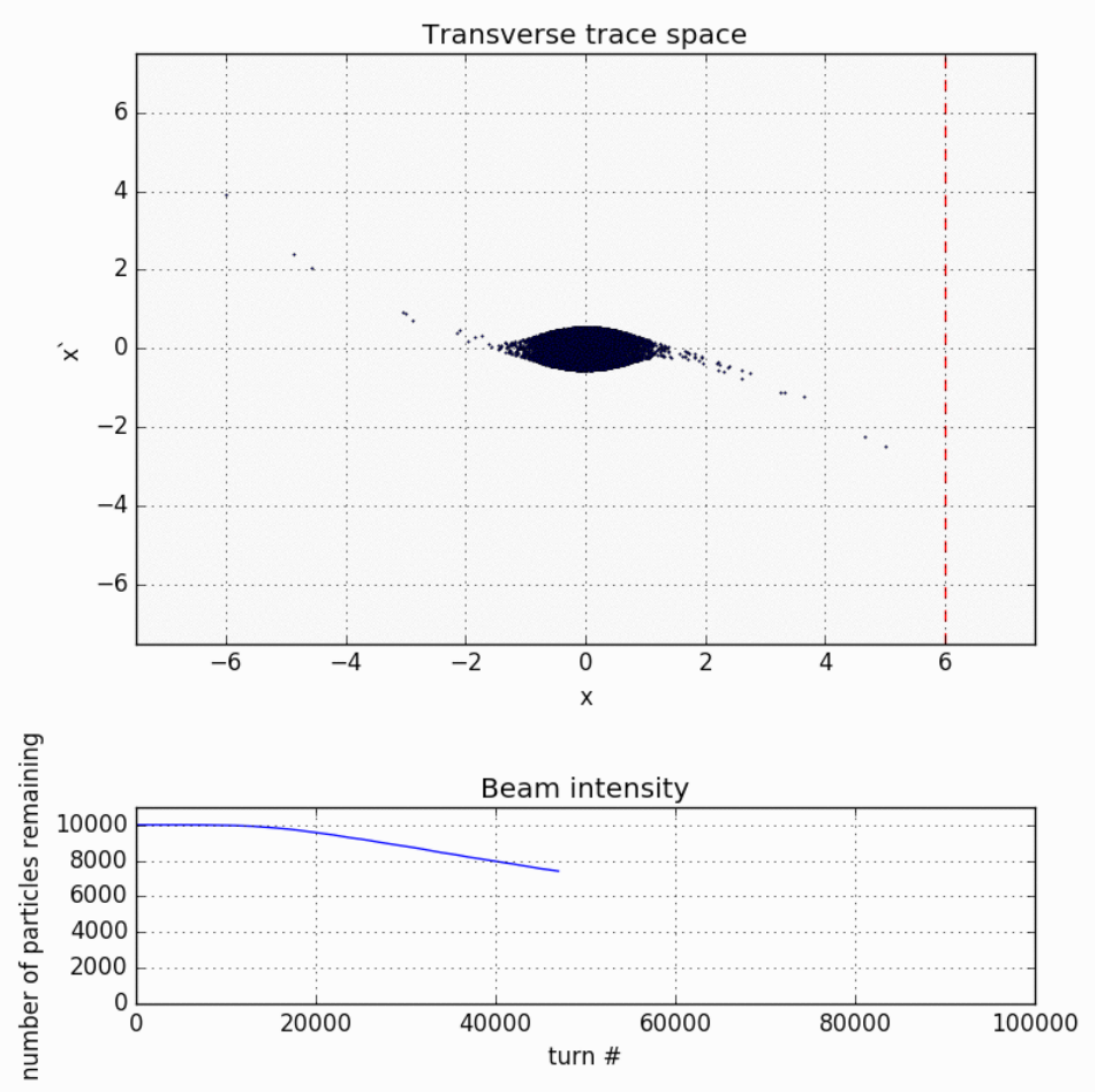


Source: John Johnstone

Fermilab

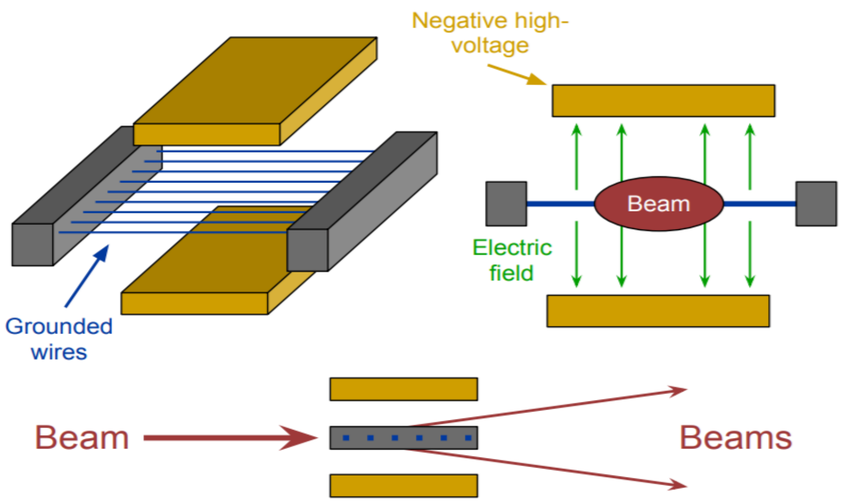
Resonant Extraction

The simulation on the right shows the resonant extraction process in transverse “phase space”, plotting the position x and angle x' for every particle at the location of the first electrostatic septum. Normal linear betatron motion maintains a fixed ellipse; however, non-linear magnets and pushing the tune to the half-integer resonance causes beam to filament into unstable orbits that propagate outward to the septum wires (red dotted line). Particles that cross to the other side of the wires are extract

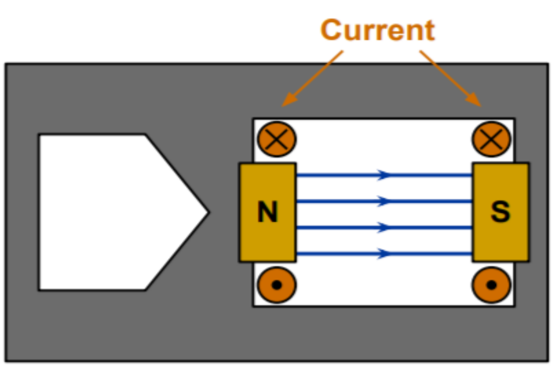


Beam splitting in Switchyard

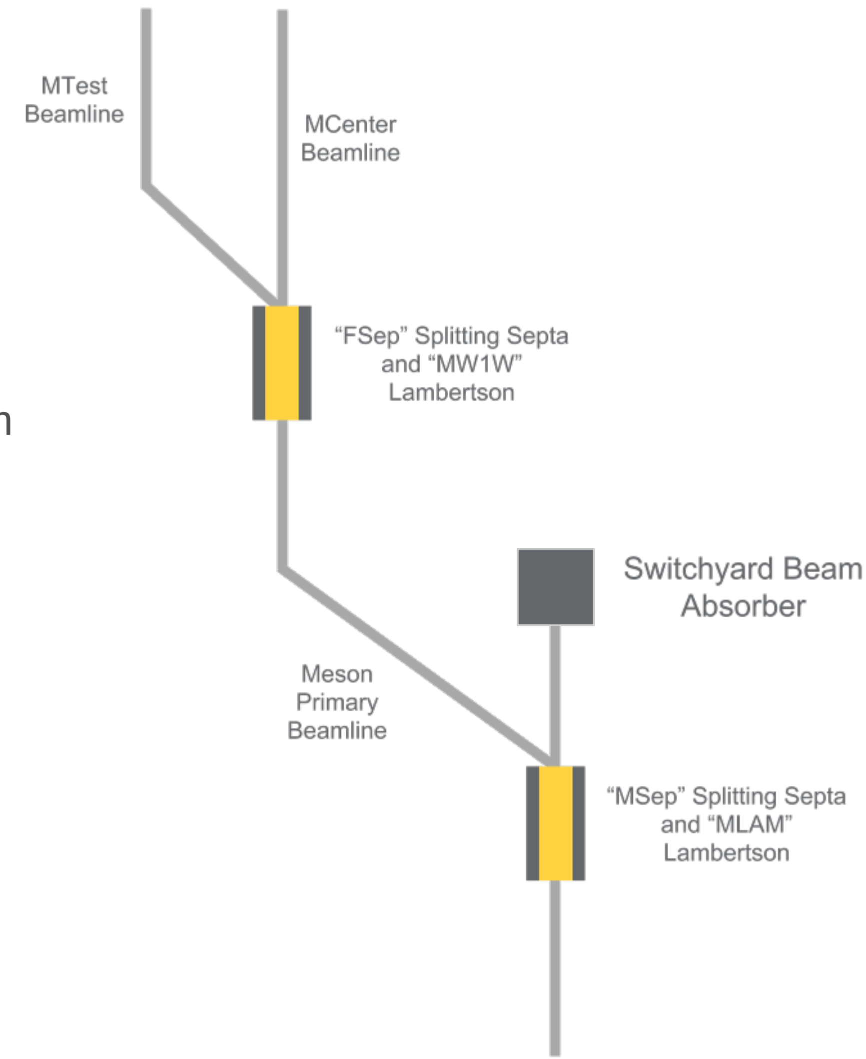
Slow-spill beam is split in Switchyard to supply multiple beamlines simultaneously. Electrostatic splitting septa begin the split with a variable intensity ratio between the two resulting beams, depending on the positioning of the grounded wires with respect to the beam centroid. Multi-aperture “Lambertson” magnets amplify the split into two separate beamlines.



Electrostatic Splitting Septum

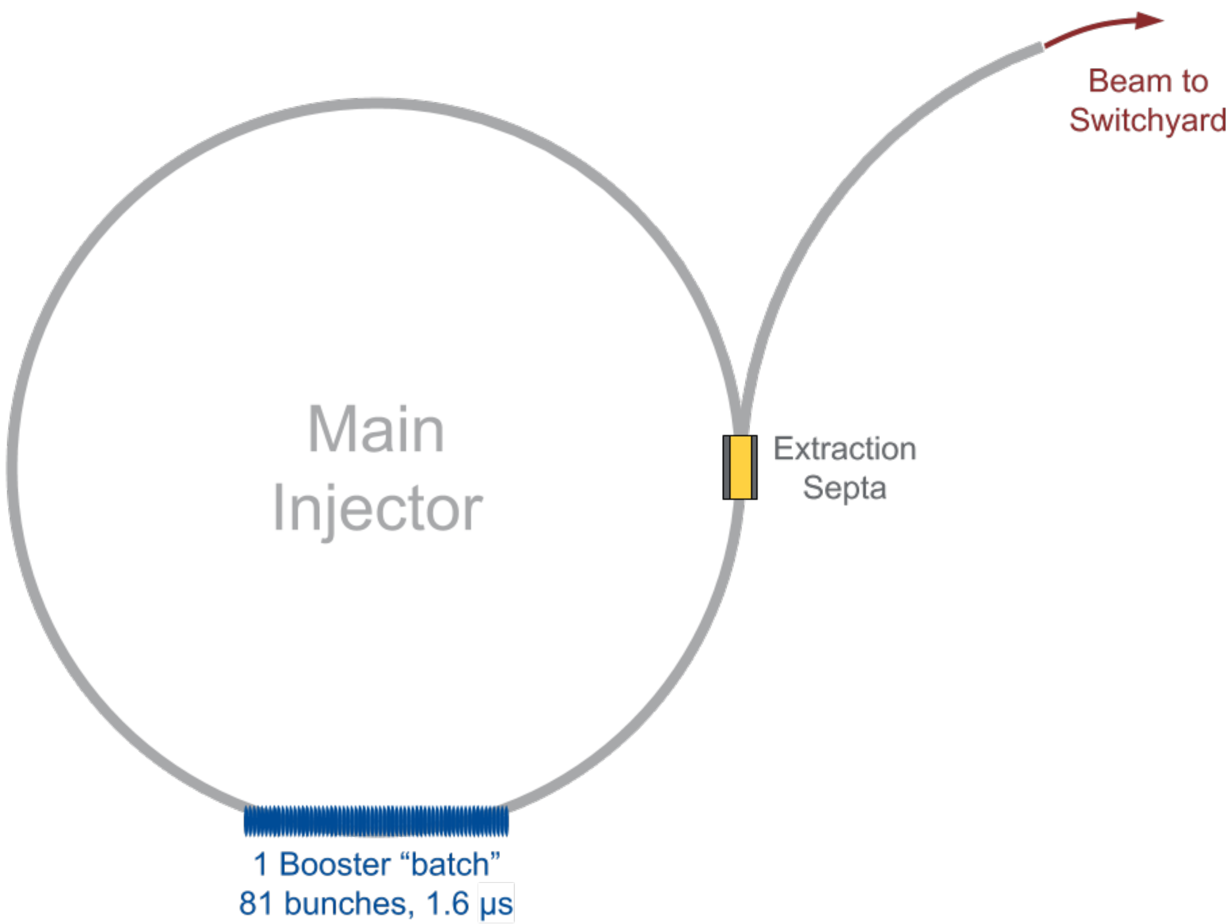


Lambertson Magnet



Beam structure

The most common mode of sending beam to the Test Beam Facility is “single-batch” mode, where the Main Injector is 1/7th full, which is one full Booster “batch”. This beam is extracted over 375,000 Main Injector turns via resonant extraction. The beam as seen by Test Beam experiments consists of ~81 bunches in 93,750 1.6 μs length bursts spaced 11.2 μs apart. Multi-batch mode, where more than one Booster batch fills the Main Injector, is common when higher-intensity beam is needed. Partial-batching, where less than 81 bunches per batch are sent to Main Injector, is rare but possible.



Beam structure

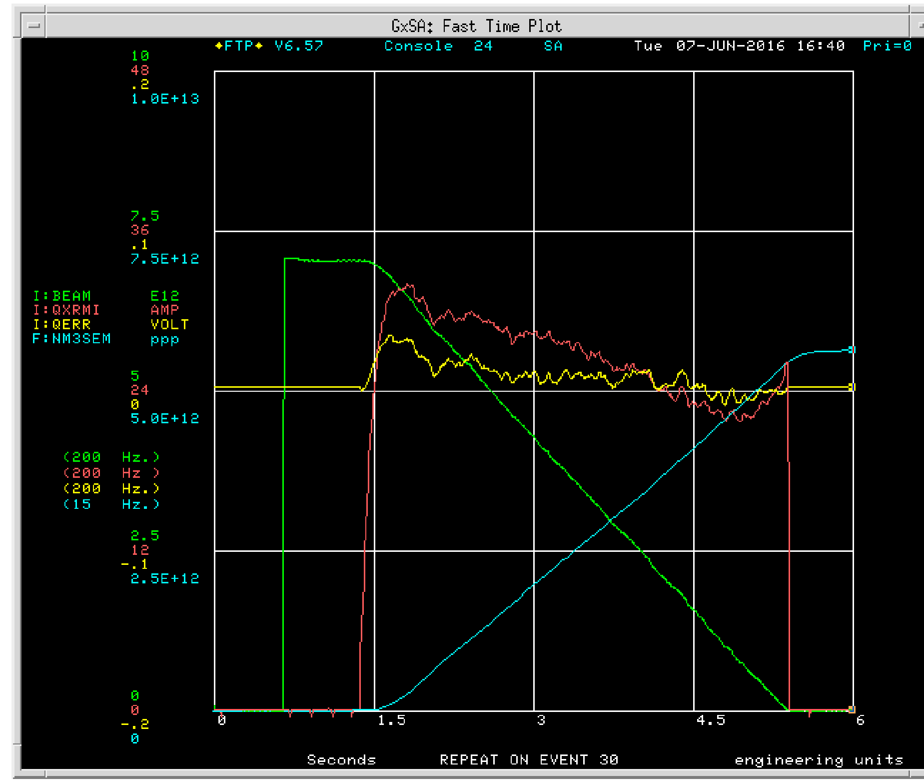
The most common mode of sending beam to the Test Beam Facility is “single-batch” mode, where the Main Injector is 1/7th full, which is one full Booster “batch”. This beam is extracted over 375,000 Main Injector turns via resonant extraction. The beam as seen by Test Beam experiments consists of ~81 bunches @ 53.1 MHz in 93,750 1.6 μs length bursts spaced 11.2 μs apart. Multi-batch mode, where more than one Booster batch fills the Main Injector, is common when higher-intensity beam is needed. Partial-batching, where less than 81 bunches per batch are sent to Main Injector, is rare but possible.

Caveat: the above situation describes the ideal spill. Consider each blue tick in the above image a “bucket”, i.e. one 53 MHz cycle where particles may exist. Due to the chaotic nature of resonant extraction, some buckets may be empty, and others may be over-filled. We can fine-tune the beam to reach up to ~50% evenness in the spill; this requires sending high-intensity beam to the SY dump and splitting off a small amount for the test beams.

Slow-spill Regulation

To provide a spill that is as linear as possible, we use a pair of small quadrupoles to nudge the tune up or down as needed during the spill. This regulation system is known as “QXR”, i.e. “Quadrupole Extraction Regulation”, and employs real-time feedback and feedforward learning to improve spill linearity. In the plot below, the green trace is Main Injector beam intensity, blue is SeaQuest beam intensity, red is the QXR magnet current, and yellow is the error signal for the QXR feedback/feedforward system.

One of the QXR quadrupole magnets that regulates the spill by adjusting the tune

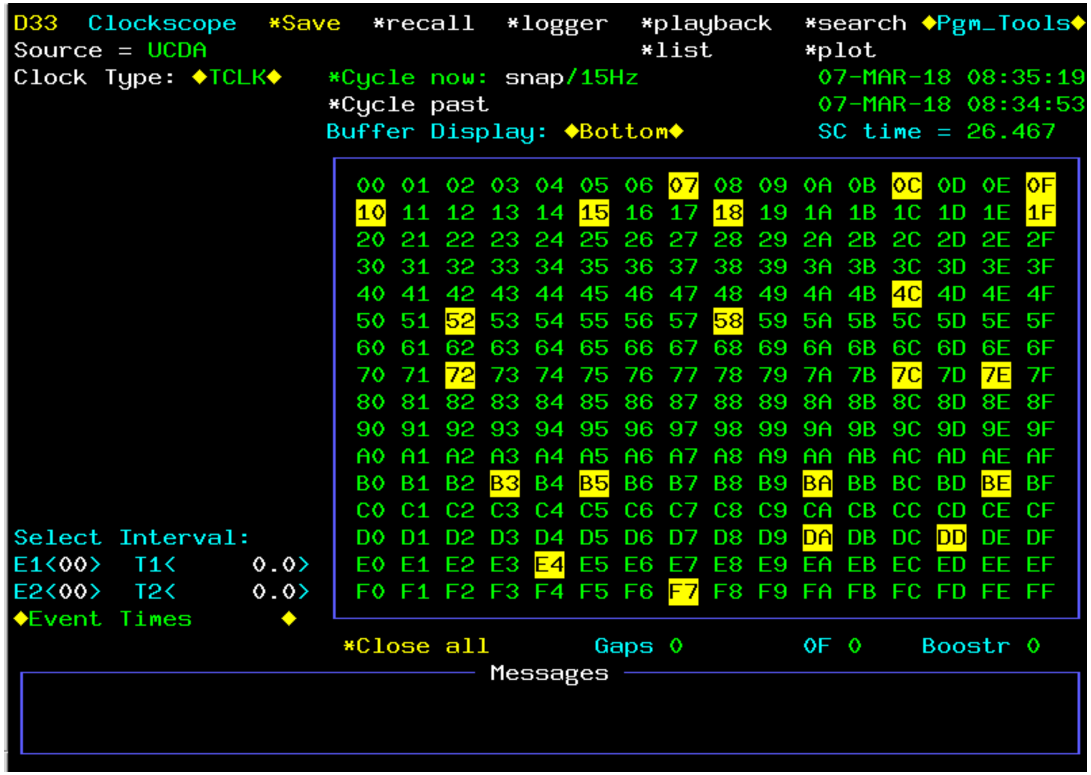


Beam spill to SeaQuest and QXR regulation.

Fermilab

Accelerator Clock System

The entire accelerator complex is synchronized with a lab-wide clock signal link known as “T-Clock”, or simply TCLK. Events on the TCLK link are referred to by hexadecimal indicators, with the first prefix referring to the specific machine: for example, $1x events are for the Booster, $2x events the Main Injector, and $3x events for Switchyard and the associated experimental beamlines. CAMAC modules such as the c377 can decode TCLK events and generate TTL pulses upon event occurrence.



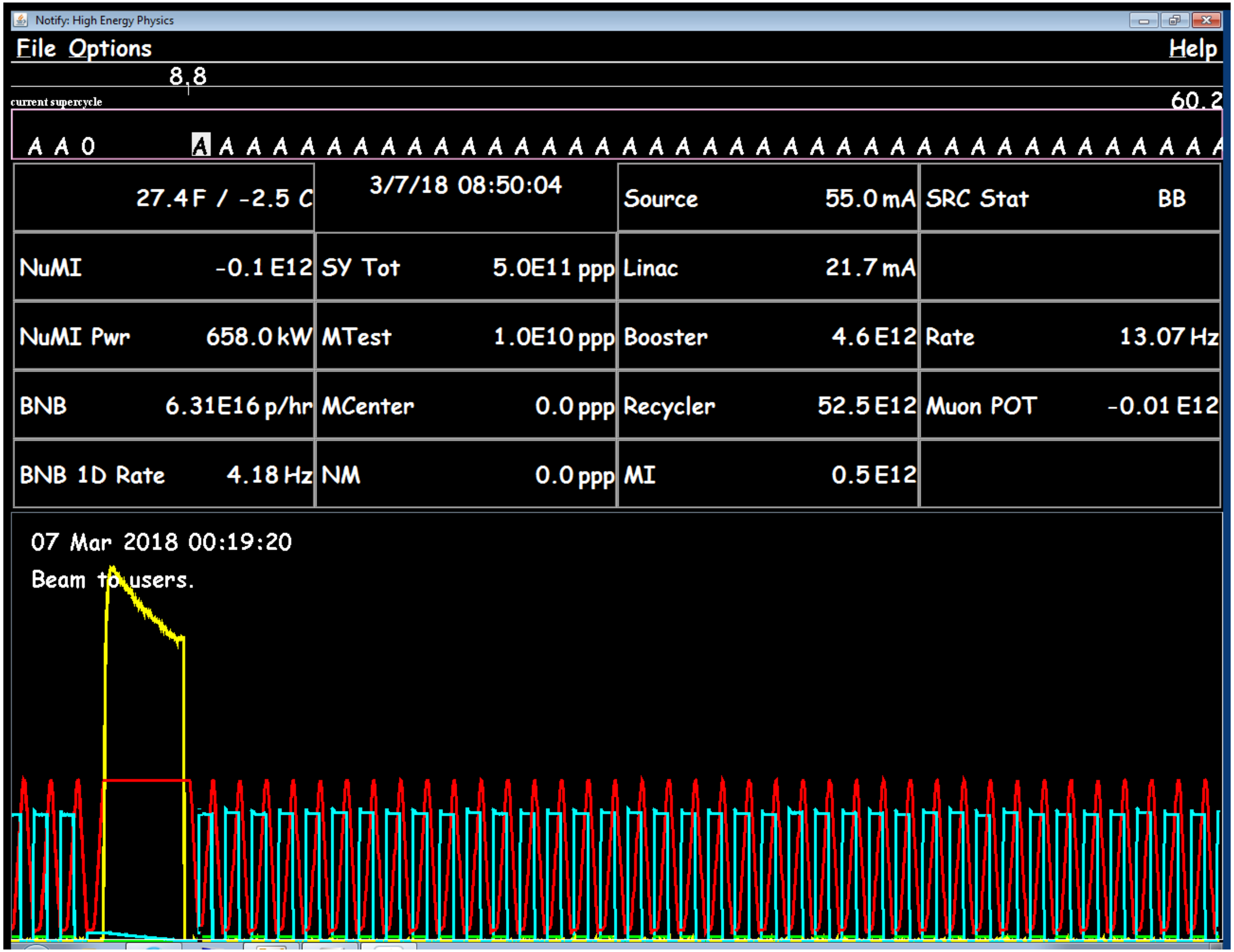
The relevant Switchyard clock events for the Test Beam are as follows:

- $30 represents the start of the entire 6-second beam cycle
- $31 begins the beamline power supply ramp up to full current
- $39 represents the beginning of spill (note that spill may not begin exactly here, but very close)
- $36 is the end of spill marker
- $37 is the post-beam sample time, 1.2 seconds after the end of spill

Accelerator Clock System

Channel 13 shows the real-time sequence of Main Injector events ($2A, $20, etc., the $2 is suppressed). “0” represents beam to Switchyard and “A” beam to NuMI.

The blue trace shows the beam intensity in the Main Injector. If this goes away, then something is wrong and Operators are trying to fix it. Red shows the current in the Main Injector magnets (i.e. the “ramp”), and yellow the current in the QXR spill regulation magnets.



United States Particle Accelerator School

Interested in learning about accelerator physics and technology? Fermilab runs the United States Particle Accelerator School (USPAS, or “yoos-pass”) in cooperation with major U.S. universities. Students can attend specific courses of interest and may attain graduate credit if desired. Many HEP physicists use USPAS as an opportunity to learn about how the accelerators work. Each USPAS session is hosted by a different university every 6 months, and lasts for two weeks.

http://uspas.fnal.gov/index.shtml

Thank you!

awatts@fnal.gov

http://operations.fnal.gov/rookie_books/concepts.pdf