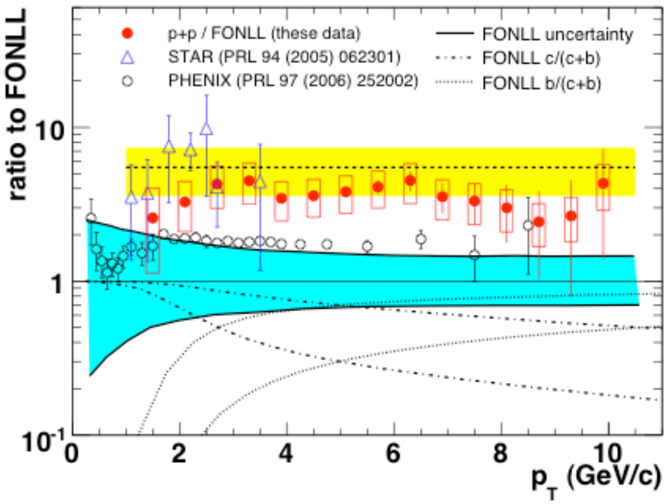
RHIC:
From colliding ions to physics results

Thomas Ullrich

QCD School, Les Houches
Mar 25 - Apr 4, 2008

What my 3 lectures are all about ...

Theorists view of RHIC

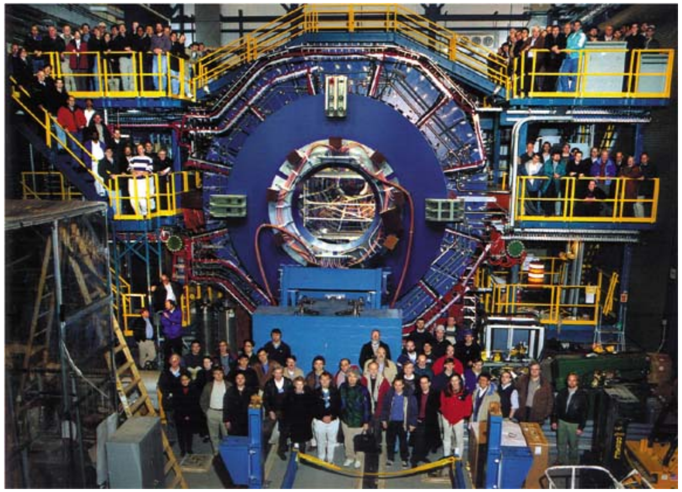


What my 3 lectures are all about ...

Student experimentalist view of RHIC

What my 3 lectures are all about ...

Senior experimentalists view of RHIC



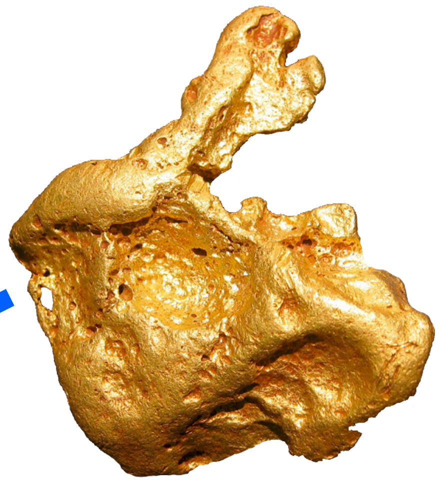
What my 3 lectures are all about ...

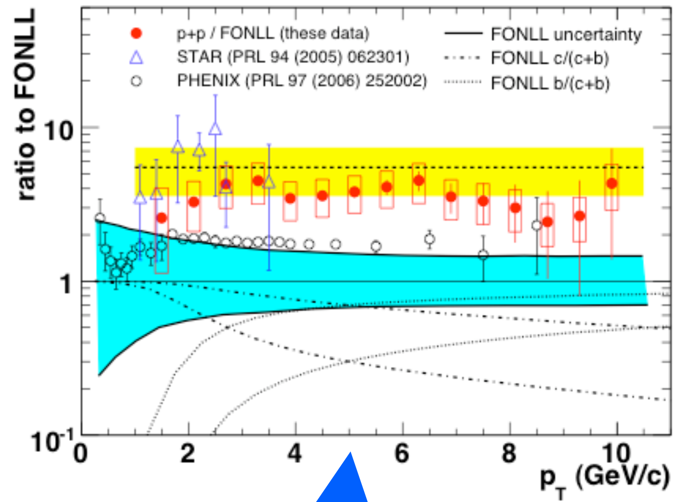
Accelerator Physicist view of RHIC

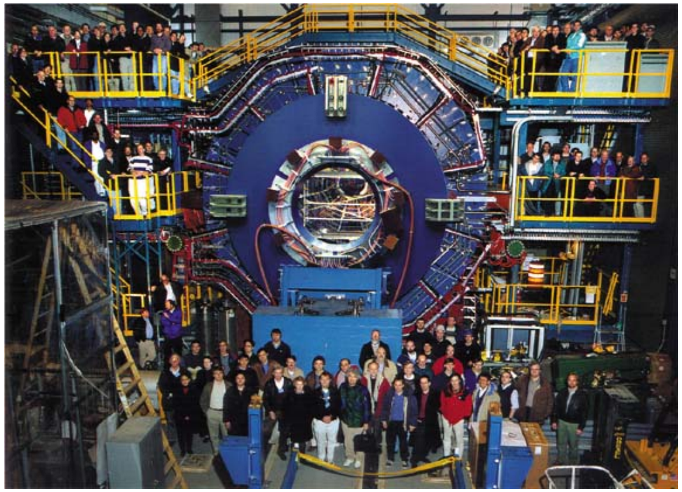
What my 3 lectures are all about ...

Funding agencies view of RHIC

What my 3 lectures are all about ...







RHIC

Part I: The QCD Collider

How it all started (I)

1973: Gross, Wilczek, Politzer: Asymptotic freedom of QCD

1974: Workshop on "BeV/nucleon collisions of heavy ions" at Bear Mountain, New York turning point in bringing heavy ion physics to the forefront as a research tool.

The driving question:
is the vacuum a medium whose properties one could change?

"we should investigate . . . phenomena by distributing high energy or high nucleon density over a relatively large volume."

T.D. Lee

Note: the idea of quark matter as the ultimate state of nuclear matter at high energy density had not taken hold

How it all started (II)

1975: Paper of Collins and Perry:
EoS of matter needed to set an upper limit on the maximum mass of a neutron star

Crucial realization ⇒ ultra-high temperature as well as ultra-high baryon density corresponded to the asymptotic regime of QCD, not a hadronic regime. Ultimate state would be a weakly interacting ”quark soup.”

1978: Eduard Shuryak coined the term “Quark Gluon Plasma”

1979: “first workshop” on ultrarelativistic nuclear collisions at Berkeley

1980: GSI Workshop, Japan seminar at Hakone, theory workshop in Bielefeld

1982: second conference in the Quark Matter series at Bielefeld

1983: Plans for the fixed target heavy ion facilities at the AGS and at CERN were well under way

How RHIC started (I)

1977: Nuclear Science Advisory Committee (NSAC) formed

- Provides official advice to the Department of Energy (DOE) and the National Science Foundation (NSF) on the national program for basic nuclear science research
- Every 5 years NSAC is charged to produce a "Long Range Plan"

The critical events (July-September 1983)

July 1983: NSAC Town Meeting (NSAC) in Aurora, New York

- Recommend the next major construction project to follow the just approved 4 GeV electron accelerator, CEBAF, at the future Jefferson Lab.
- Subcommittee: Baym, Gyulassy, Ludlam, McLerran, Vigdor and others)
  - hadron versus heavy ion machine
  - LAMPF II at Los Alamos vs. VENUS at Berkeley

How RHIC started (II)

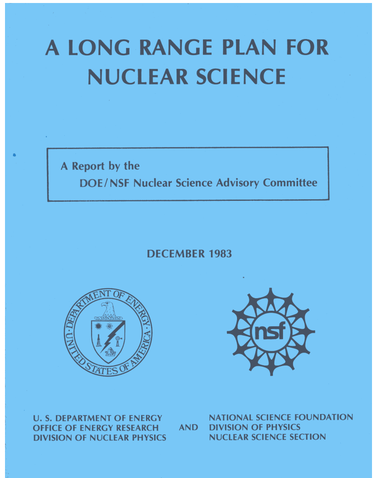
Conclusion: "the highest priority for the field is an ultra-relativistic heavy ion collider of E/A > 30 GeV in the center of mass, with A up to uranium"

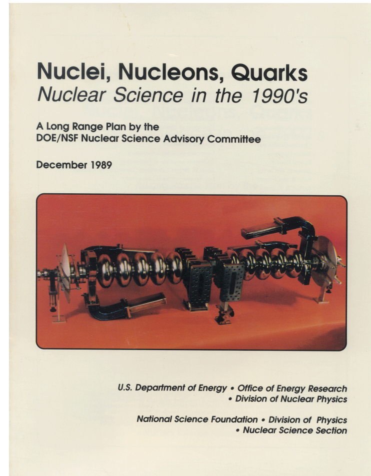
Towards the end of the meeting news broke. HEP Advisory Panel (HEPAP), which advises DOE on high energy facilities, had just decided to abandon the problematic ISABELLE, the 400 GeV on 400 GeV proton collider at Brookhaven – whose construction was well under way – in favor of building the then named Desertron, that eventually became the SSC. This is after spending more than US $200 million on ISABELLE (hint: it was more for the SSC).

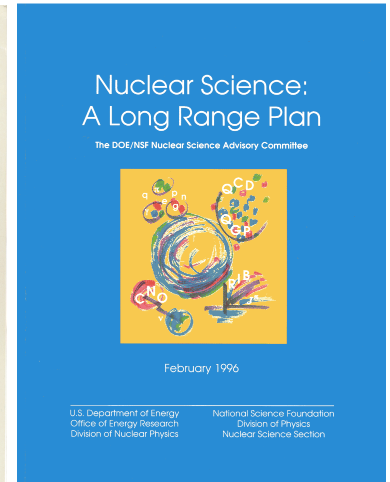
Gordon Baym: build heavy-ion facility in existing tunnel
Final vote: 27 to 11 with one abstention ⇒ RHIC was born !

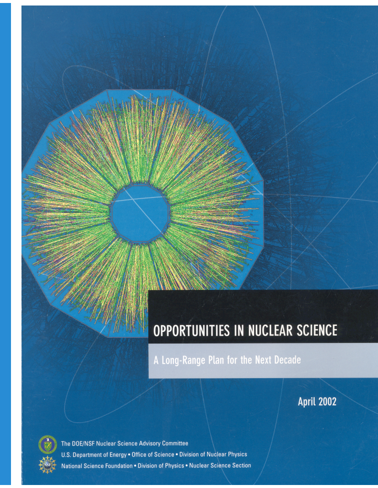
How RHIC started (III)

1979	1983	1989	1996	2002

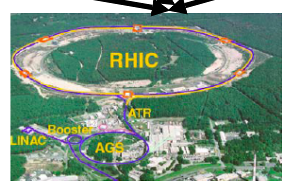






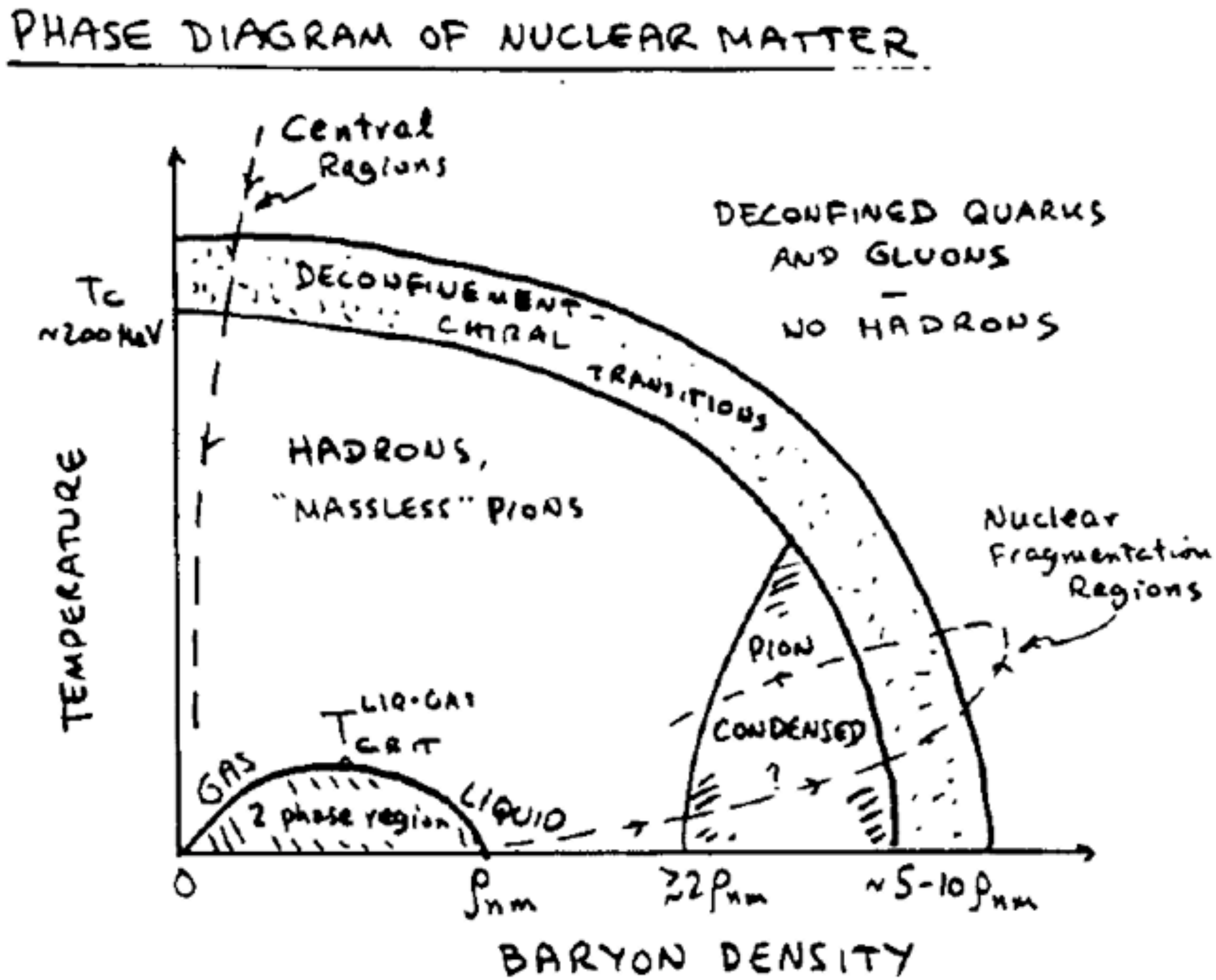


RHIC
1990-1999



At the end RHIC was highest priority in 3 Long Range Plans
Initial estimates: $150-200 M

How RHIC started (IV)



Phase diagram of nuclear matter in equilibrium, and how it can be explored in ultra-relativistic heavy ion collisions, from the 1983 NSAC Long Range Plan.

How RHIC started (V)

August 1983: task force met at BNL

- how to “stuff a collider” into the pre-existing tunnel
- Energy range
  - from 50 GeV/A (ISR)
  - to 100 GeV/A to producing high energy jets, and studying their propagation through the nuclear collision
- recognized the need to be able to run pp, pA, and AA
- at least three intersection regions, with at minimum two large solid angle detectors and one small solid angle experiment.

September 1983: 3rd Quark Matter: build community support

- Gordon Baym: first beams in October 1992

“a sense of enthusiasm, excitement, . . . , a feeling of adventure in the air.”

Allan Bromley

(Science Advisor to President George H. W. Bush)

RHIC Construction Costs (2001 numbers)

Conceptional Design Report: May 1986
KD1: Jan 1991
KD2: Jan 1991
KD3: Jan 1992 ⇒ construction money
CD4: Aug 1999
Total Project Cost = $616.5M

RHIC Spin…Snakes & Polarimetry
Japan (RIKEN) $10.0M

RHIC Computing Facility Equipment
DOE AEE $7.9M

STAR

DOE Funding (Baseline+AEE)	**$52.3M**
NSF Funding (Endcap Calorim.)	**4.2M**
Germany (Frankfurt; MPI Munich)	3.7M
France (Nantes; Strasbourg)	3.0M
CERN/Italy (Bari)	0.5M

PHOBOS

DOE Funding	$6.5M
NSF Funding	0.3M
Poland (Crakow)	1.1M
Taiwan (NCU)	0.2M

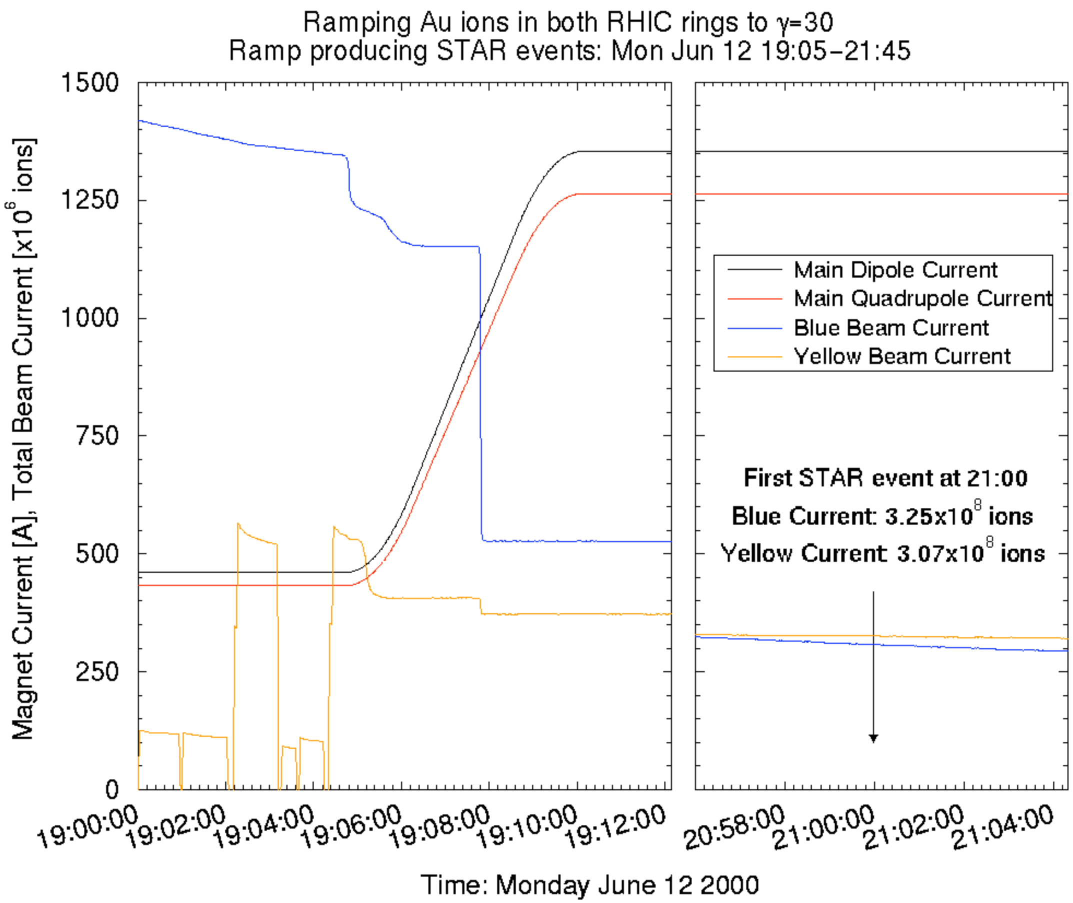
PHENIX

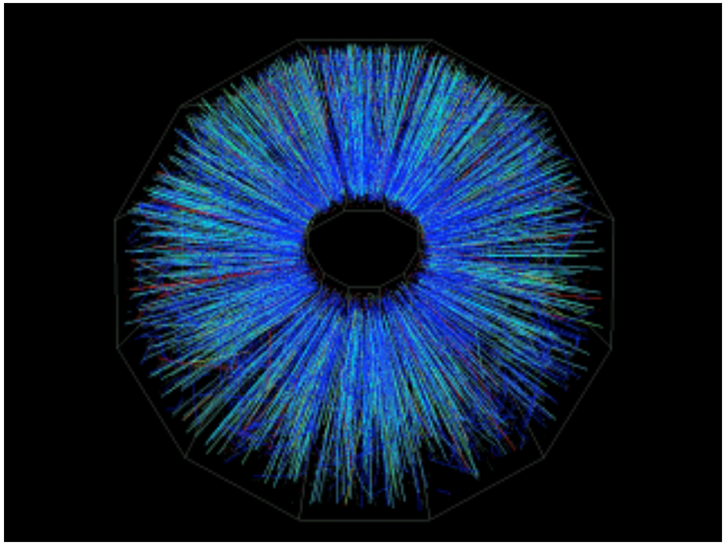
DOE Funding (Baseline+AEE)	**$55.8M**
Russia (IHEP, PNPI)	9.3M
Japan (PHENIX-J)	10.3M
Japan (RIKEN)	10M
Sweden	1.3M
France	0.4M
Canada	0.4M
India (BARC)	0.3M
Germany	6.3M

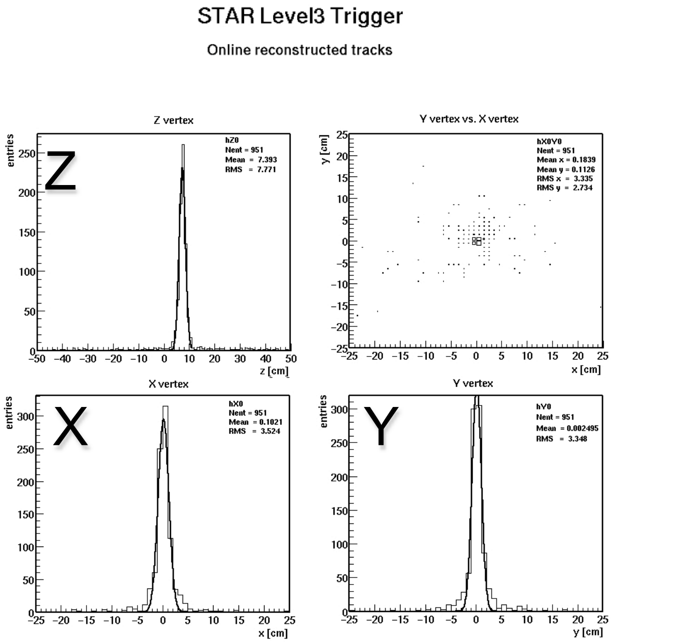
BRAHMS

DOE Funding	$5.5M
Denmark (NBI)	0.5M
France (Strasbourg)	0.2M

First Au+Au Collisions at RHIC (STAR, June 12 '00)



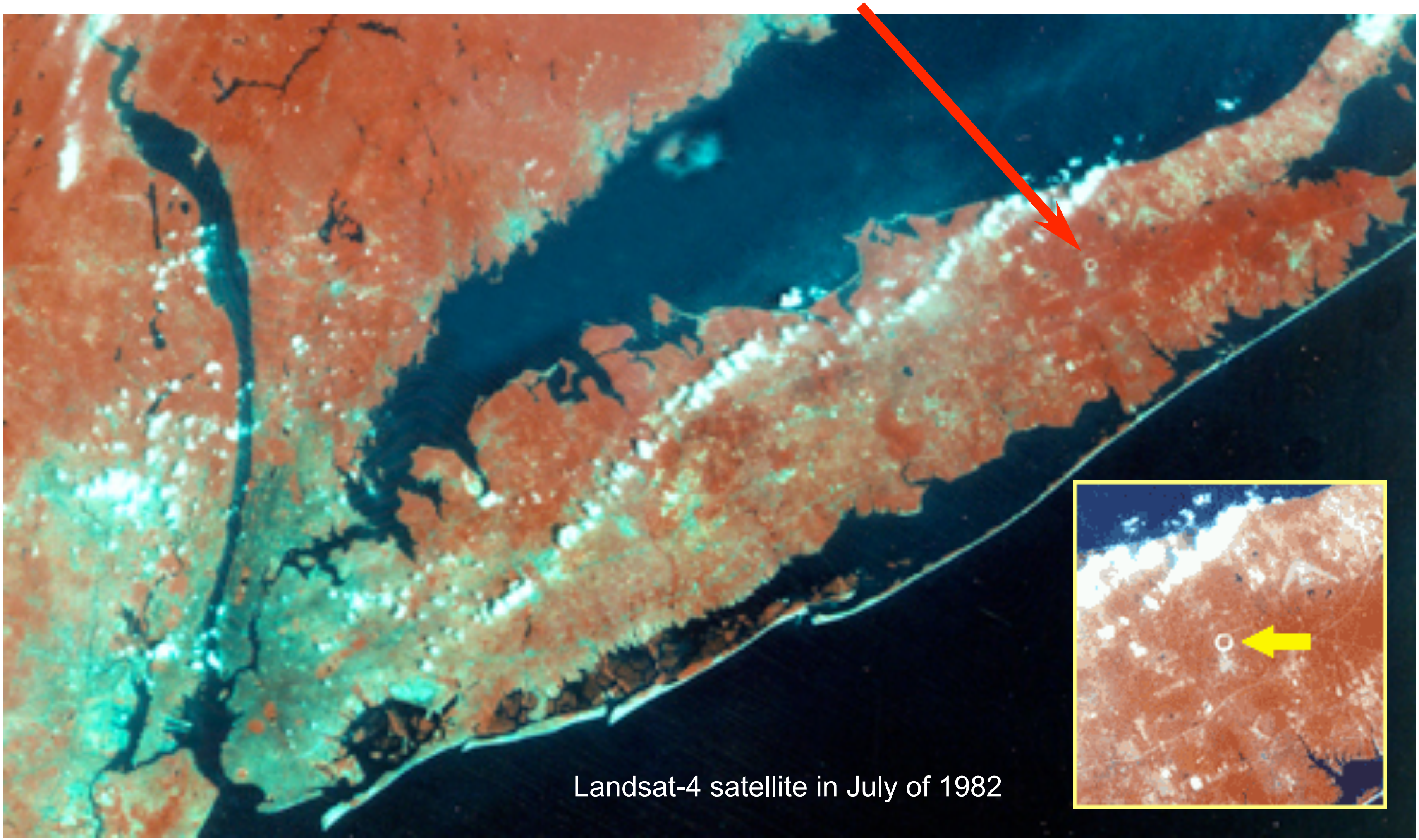




In the STAR Control Room ... that night

BNL and RHIC from space

- RHIC = Relativistic Heavy Ion Collider
- Located at BNL = Brookhaven National Laboratory



How is RHIC different?

It's dedicated to High Energy Heavy Ion Physics

- Heavy ions run 20-30 weeks/year

It's a collider

- Detector systematics independent of $\sqrt{s}$
- (No thick targets!)

It's high energy

- Access to perturbative phenomena
  - Jets (very violent calculable processes in the mix)
  - Non-linear dE/dx

Its detectors are comprehensive

- All final state species measured with a suite of detectors that nonetheless have significant overlap for comparisons

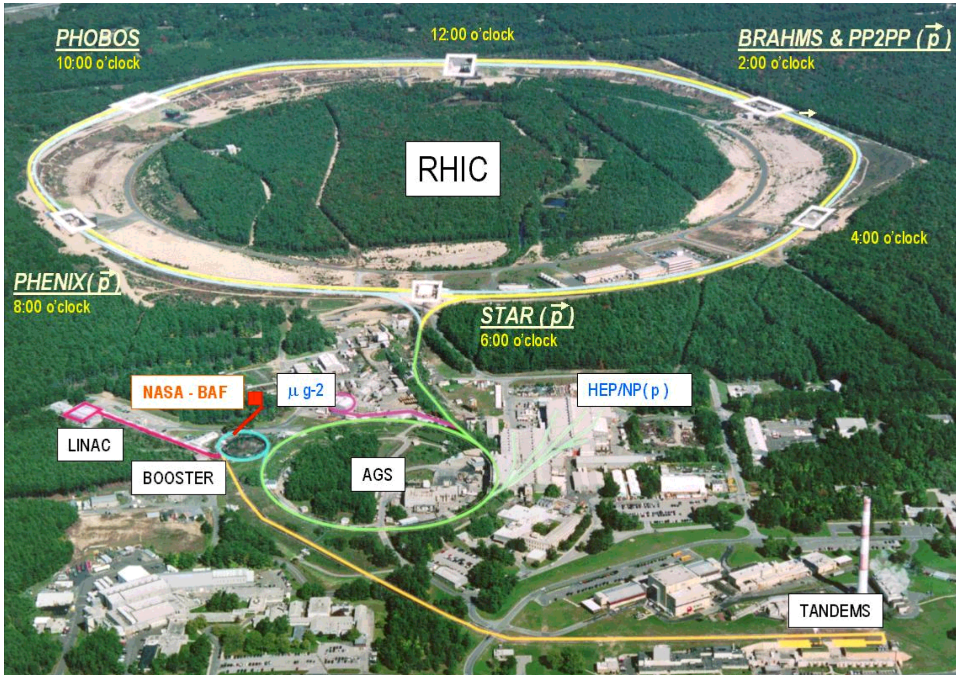
RHIC Main Specifications

RHIC is an intersecting storage ring and particle accelerator.

Two independent rings each 3.834 km circumference

(one is termed yellow the other blue)

Hexagonally shaped rings



Can collide:

any nuclear species on any other:

p+p to Au+Au (U+U)

p beams are polarized !

Max Energy: $\sqrt{s_{NN}} \approx \frac{Z}{A}(500\,\mathrm{GeV})$

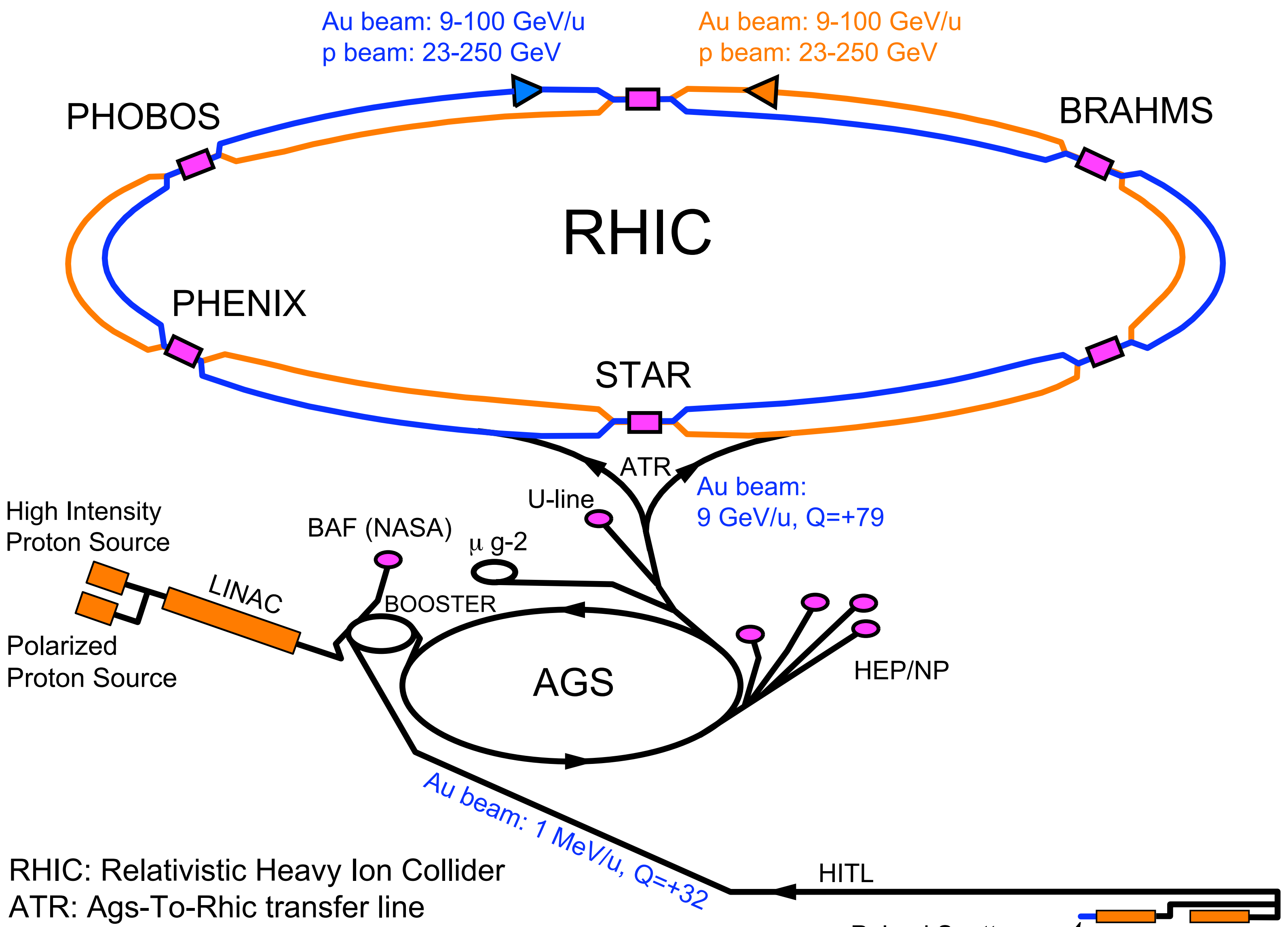
p+p: $\sqrt{s}$ = 500 GeV

Au+Au: $\sqrt{s_{NN}}$ = 200 GeV

Some RHIC facts worth knowing

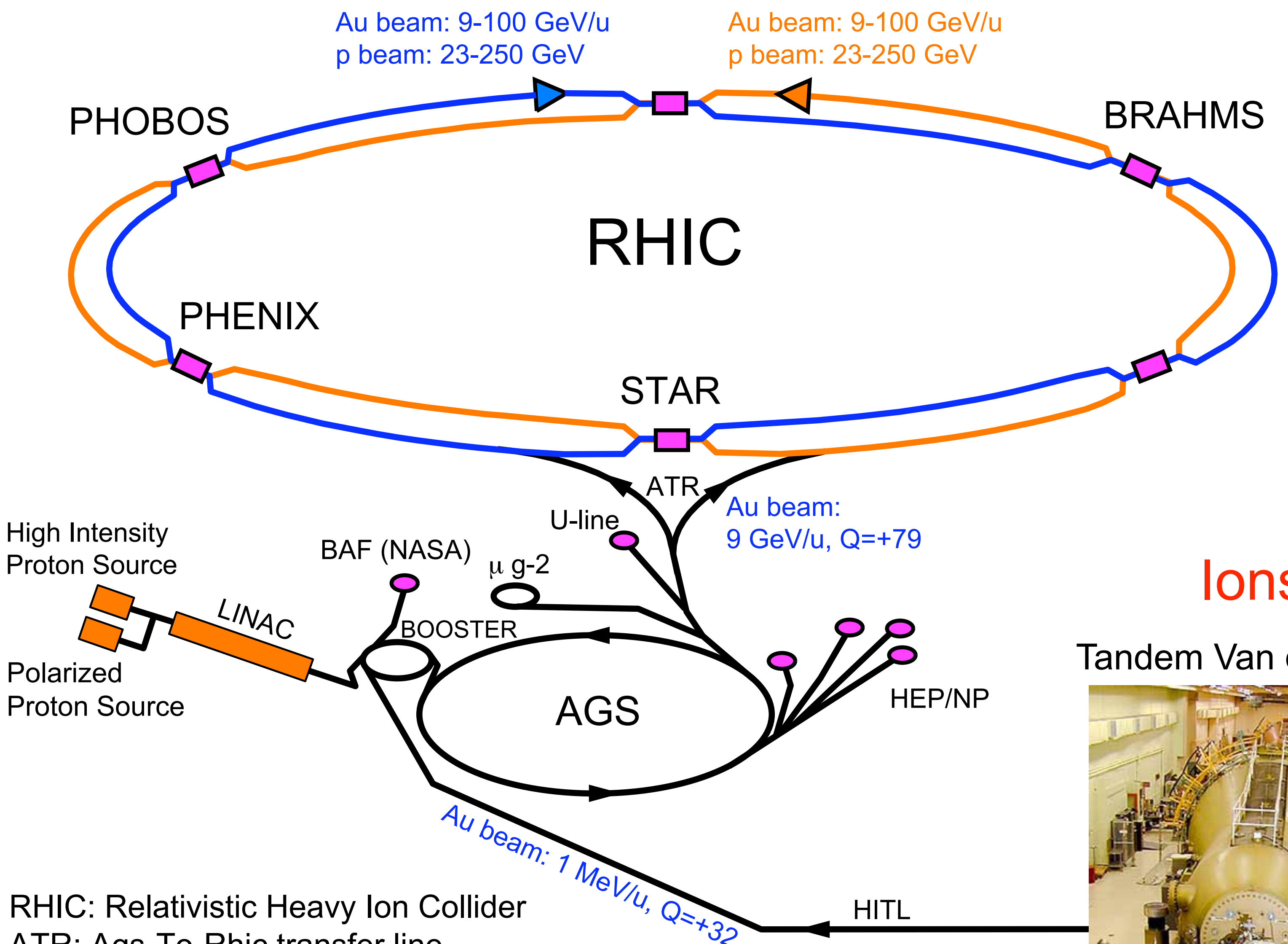
- RHIC's two rings made of 1740 super-conducting magnets are cooled by liquid helium to -269^{o}C
- RHIC contains seven tons of helium
- The refrigerator to cool the helium needs a power of 15 MW (as much as 15000 homes!)
- Over 20 years for the Au beam, less than one gram of gold is used.
- At top energy: stored beam energy is 200kJ per ring
  - the energy 2000 persons get by drinking a single drop of beer each

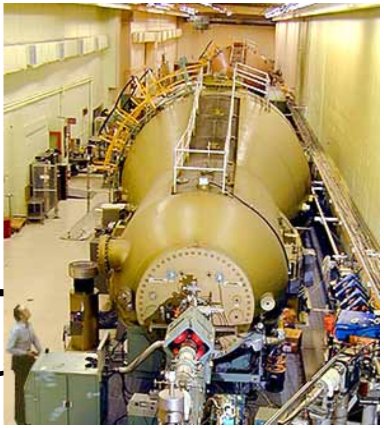
RHIC – a High Luminosity Hadron Collider



RHIC: Relativistic Heavy Ion Collider
ATR: Ags-To-Rhic transfer line
AGS: Alternating Gradient Synchrotron
HITL: Heavy Ion Transfer Line

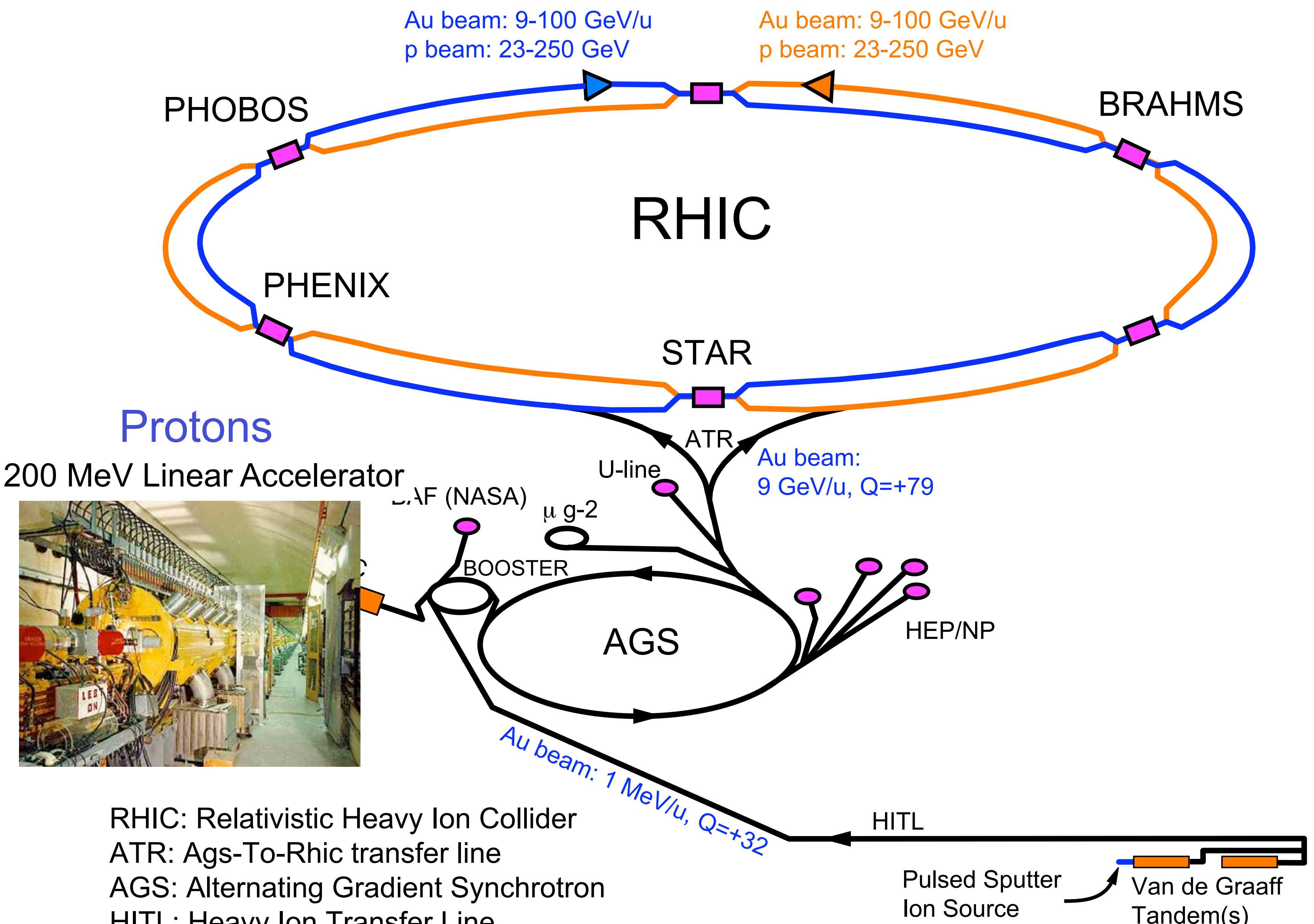
RHIC – a High Luminosity Hadron Collider





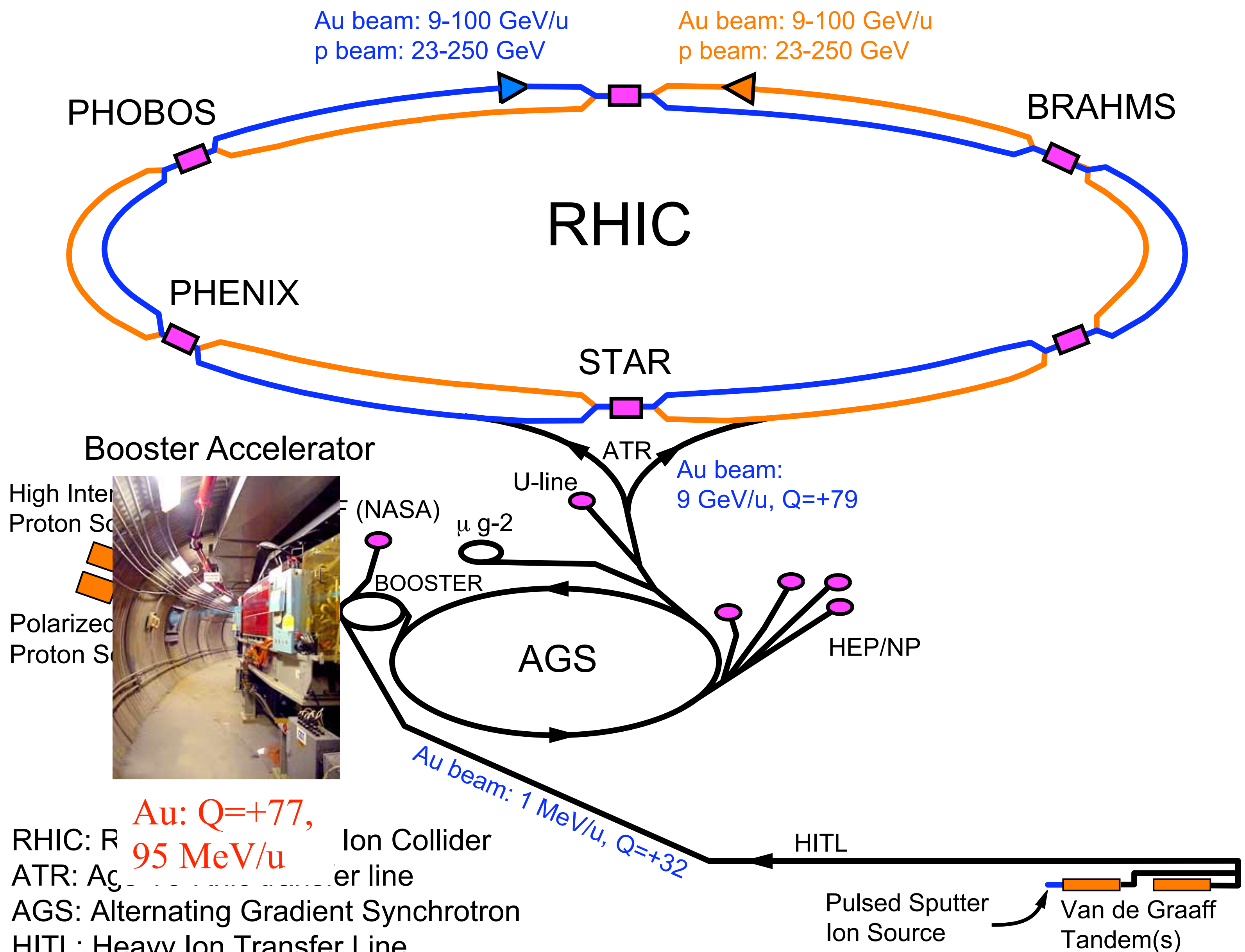
RHIC: Relativistic Heavy Ion Collider
ATR: Ags-To-Rhic transfer line
AGS: Alternating Gradient Synchrotron
HITL: Heavy Ion Transfer Line

RHIC – a High Luminosity Hadron Collider

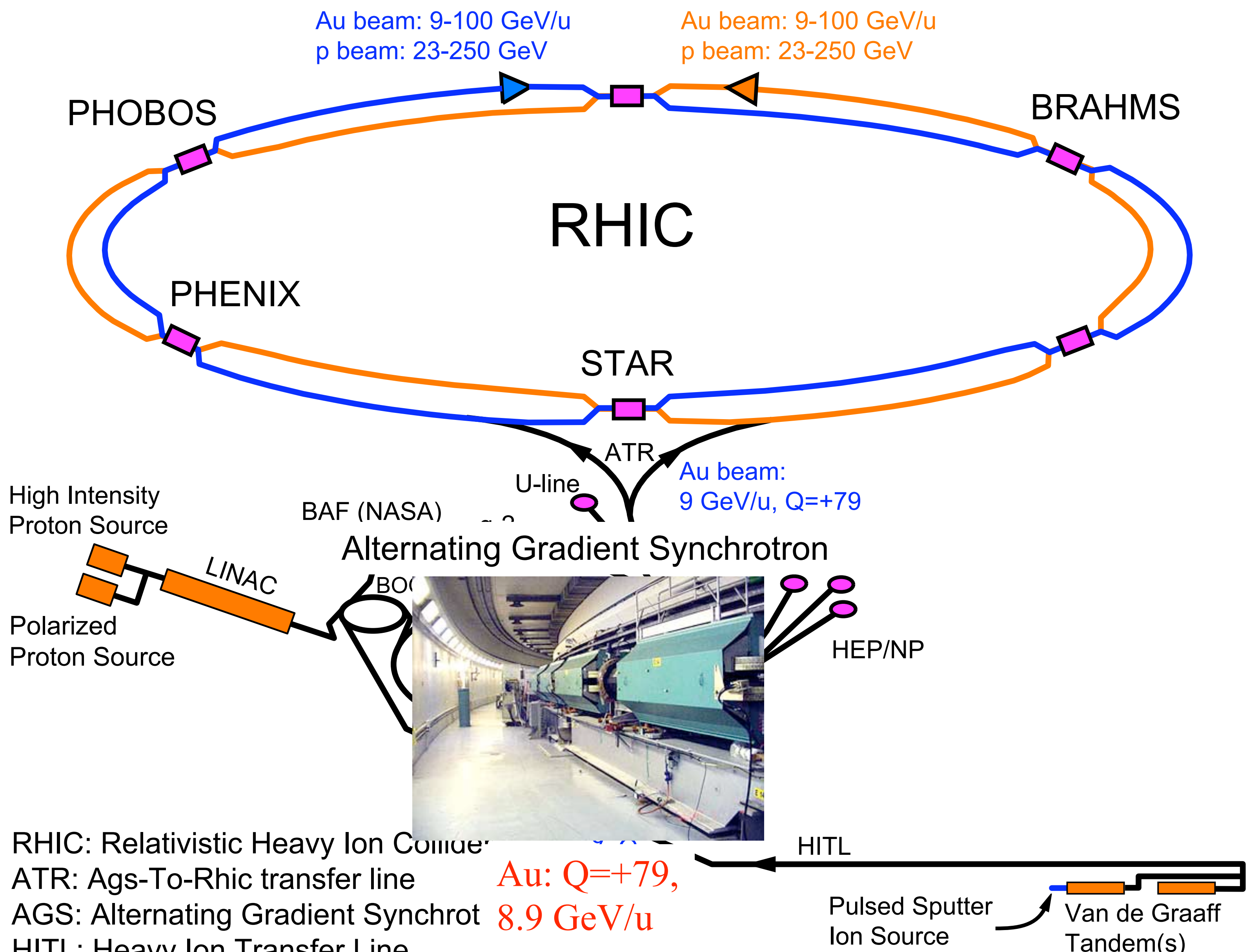


RHIC: Relativistic Heavy Ion Collider
ATR: Ags-To-Rhic transfer line
AGS: Alternating Gradient Synchrotron
HITL: Heavy Ion Transfer Line

RHIC – a High Luminosity Hadron Collider

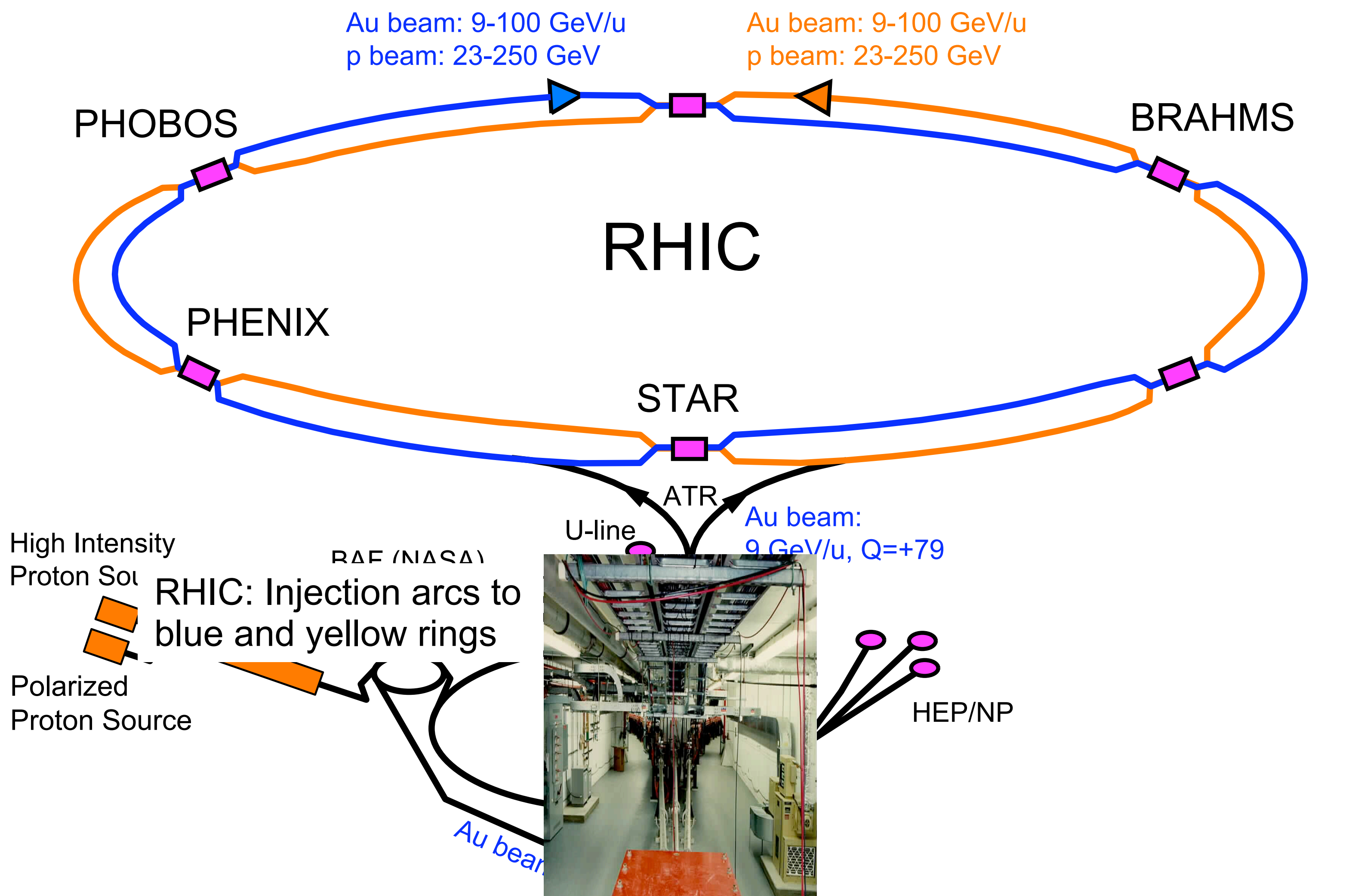


RHIC – a High Luminosity Hadron Collider



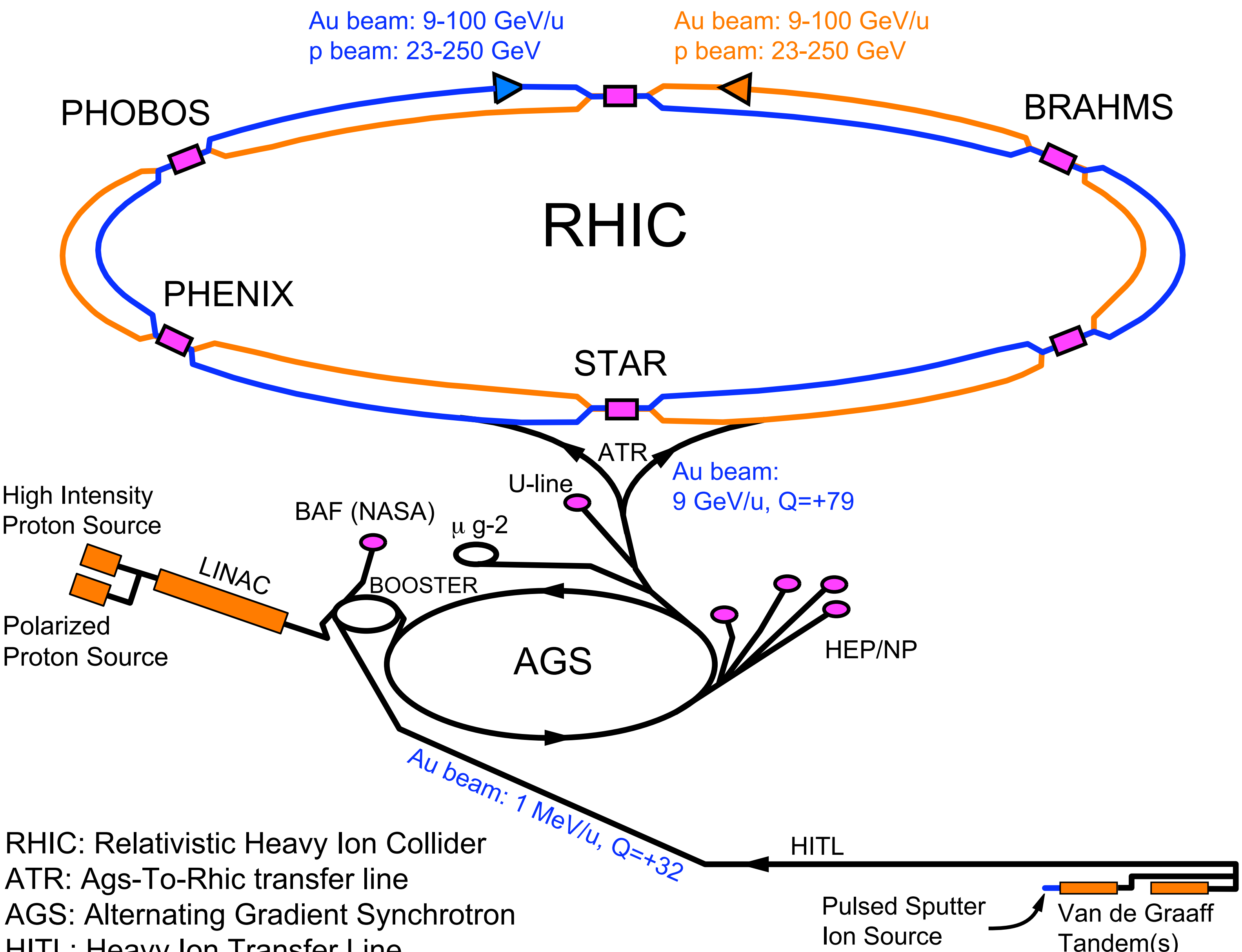
RHIC: Relativistic Heavy Ion Collide
ATR: Ags-To-Rhic transfer line
AGS: Alternating Gradient Synchrot
HITL: Heavy Ion Transfer Line

RHIC – a High Luminosity Hadron Collider



RHIC: Relativistic Heavy Ion Collider
ATR: Ags-To-Rhic transfer line
AGS: Alternating Gradient Synchrotron
HITL: Heavy Ion Transfer Line

RHIC – a High Luminosity Hadron Collider

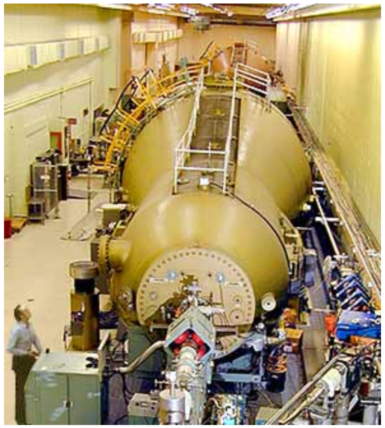


RHIC: Relativistic Heavy Ion Collider
ATR: Ags-To-Rhic transfer line
AGS: Alternating Gradient Synchrotron
HITL: Heavy Ion Transfer Line

RHIC requires a complex of machines

Ions

Tandem Van de Graaff



Au: Q=+32,
1 MeV/u

Booster Accelerator

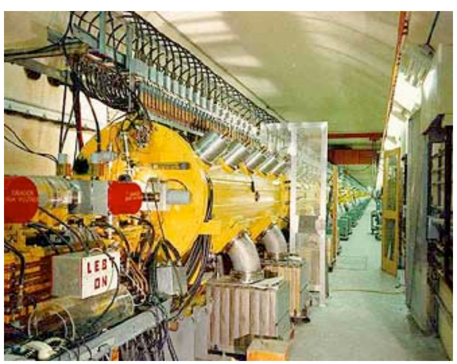
Alternating Gradient
Synchrotron

Au: Q=+77,
95 MeV/u

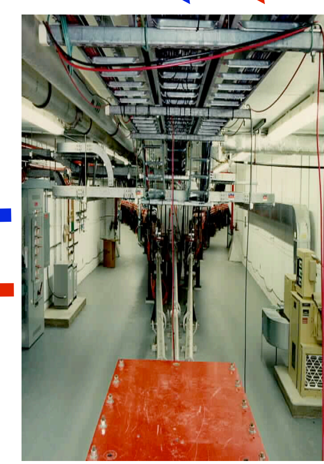
Au: Q=+79,
8.9 GeV/u

Protons

200 MeV Linear Accelerator



RHIC: Injection arcs to
blue and yellow rings

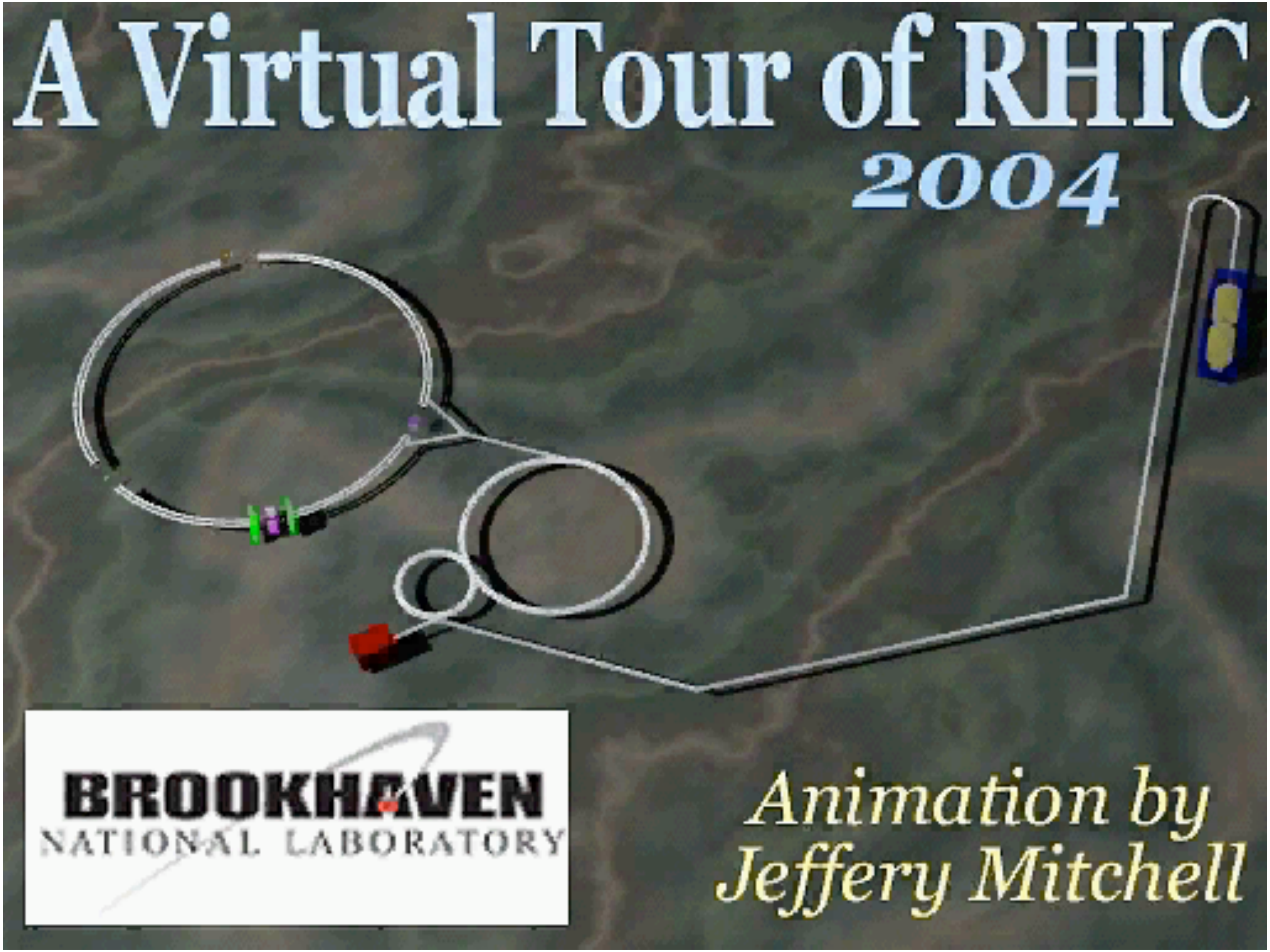


RHIC

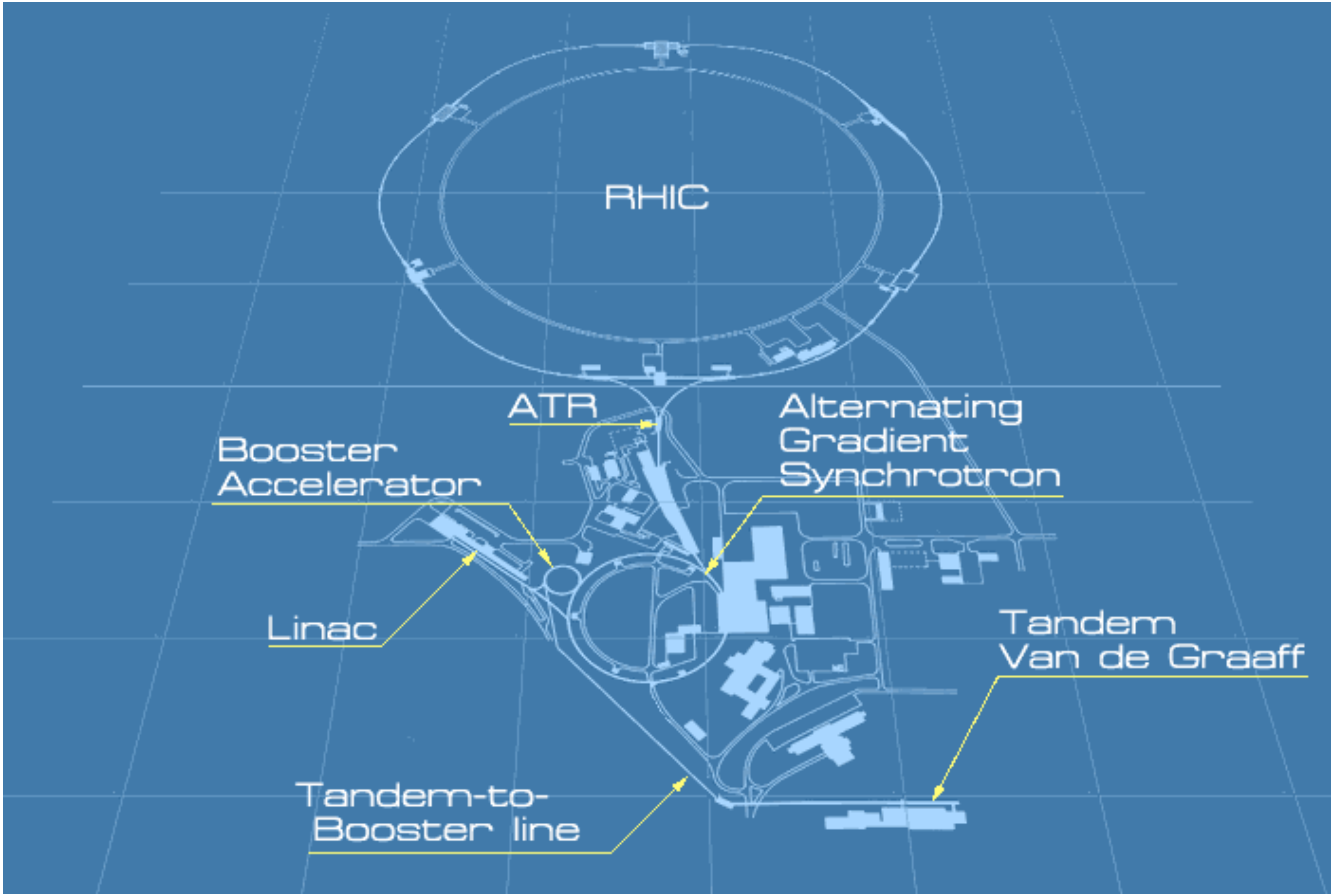
Au: Q=+79, 9-100 GeV/u

RHIC: the movie

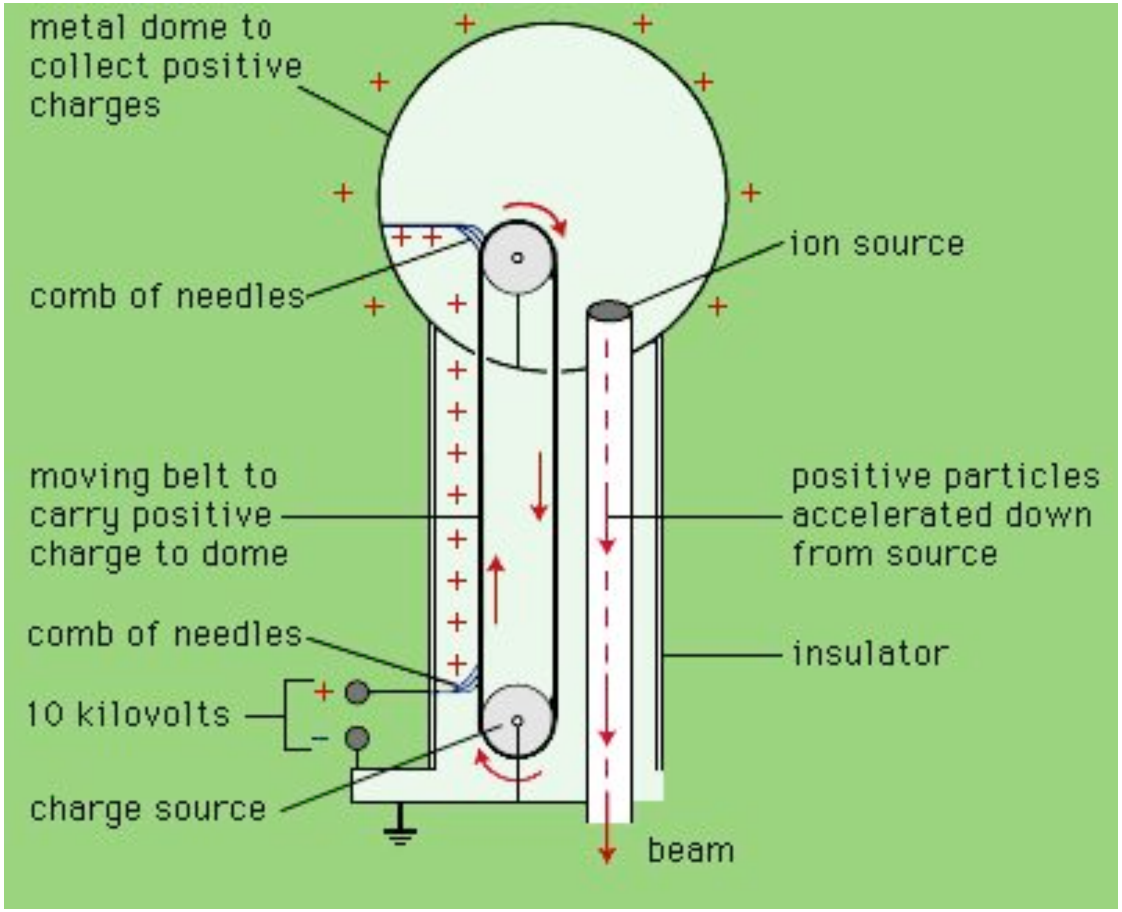
RHIC: the movie



RHIC Complex

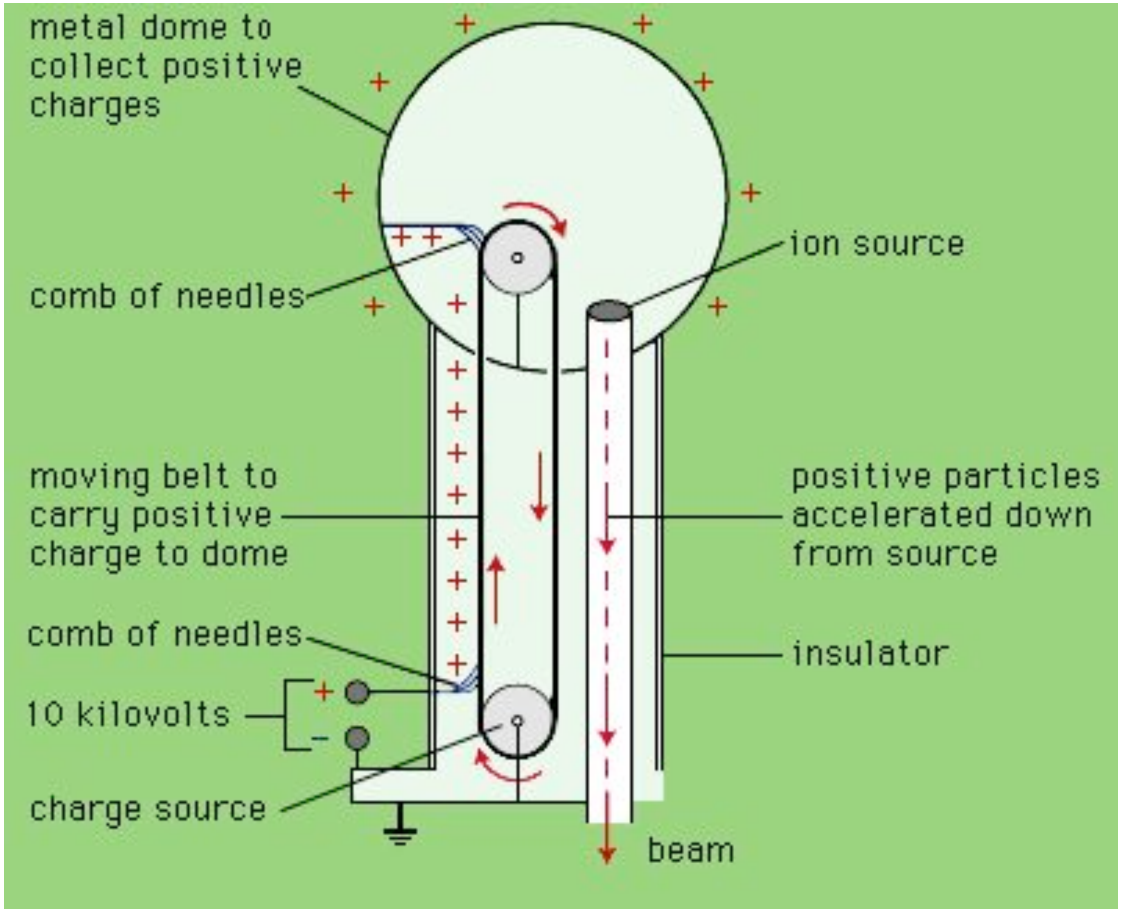


Electrostatic Accelerators: Van de Graaff



- The needle transmits the charge to the belt by glow discharge and/or field emission
- The electric field inside the sphere is zero permitting the passage of the charge from the belt to the sphere

Electrostatic Accelerators: Van de Graaff



- The needle transmits the charge to the belt by glow discharge and/or field emission
- The electric field inside the sphere is zero permitting the passage of the charge from the belt to the sphere

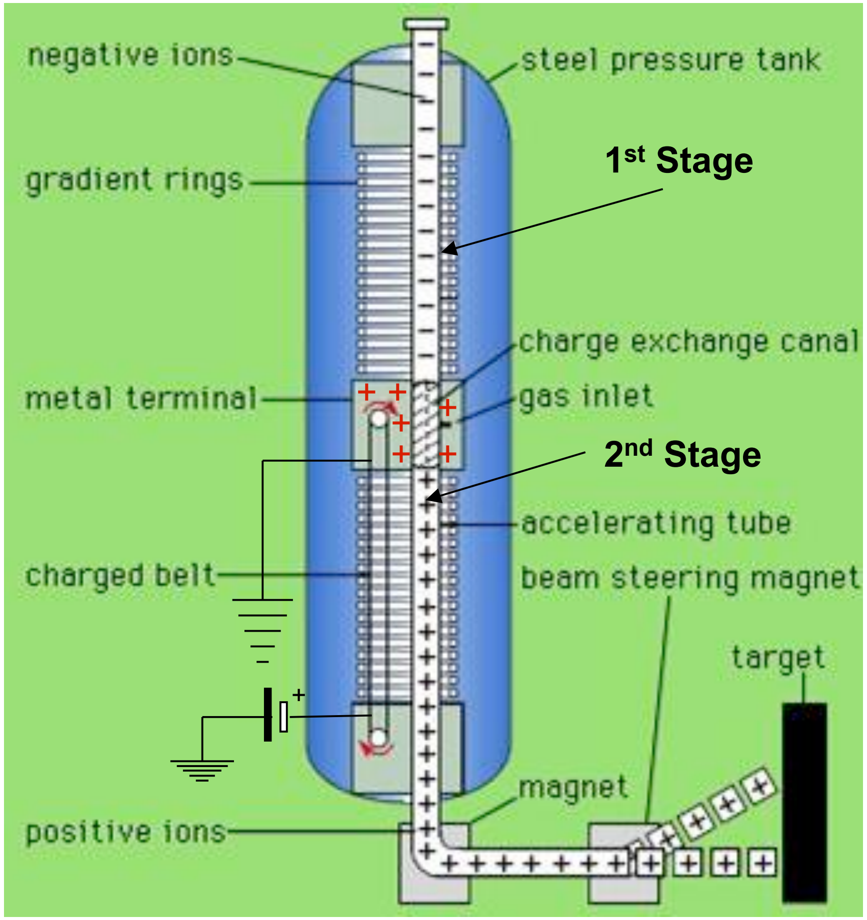
Tandem Van de Graaff

Electrostatic accelerator concept

- Negative ions from sputter ion source (Q=-1)
- Accelerated from ground to +14 MeV potential
- Stripping foil ⇒ +Q
- Accelerated back to ground potential
- E.g. Au: E_{kin} = 1 MeV/u Q=+12

- After VdG ions get further further stripped to Q=+32
- Transfered over 800m long transfer line to *Booster Synchrotron*

Tandem Scheme

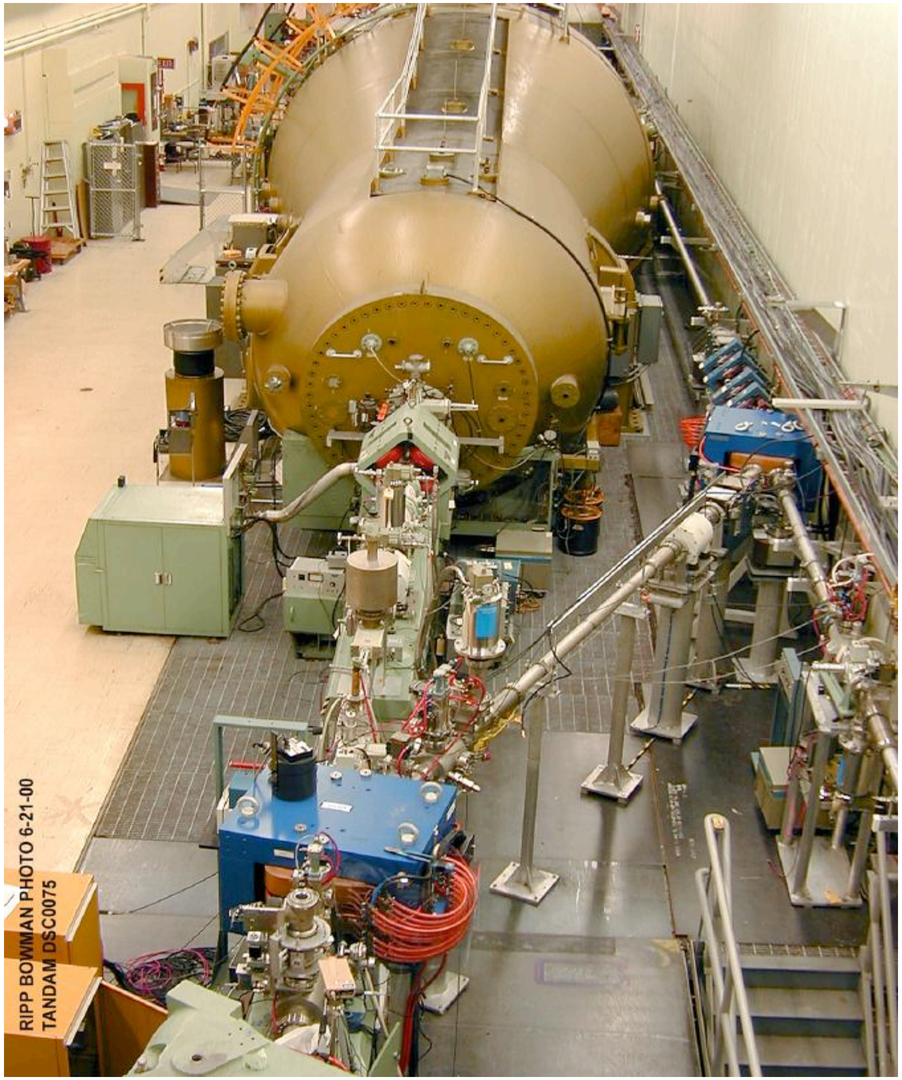


Tandem Van de Graaff

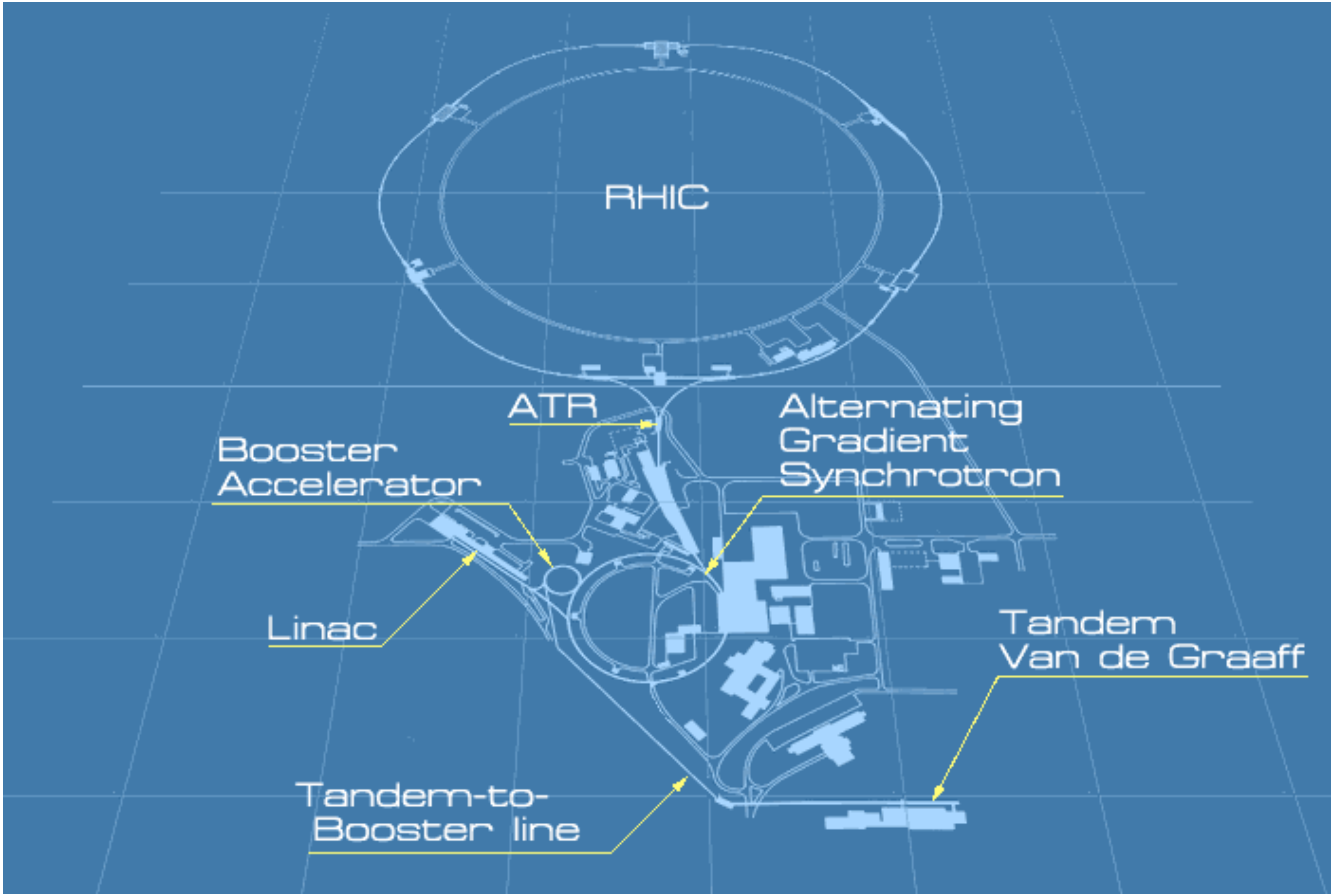
Electrostatic accelerator concept

- Negative ions from sputter ion source (Q=-1)
- Accelerated from ground to +14 MeV potential
- Stripping foil $\Rightarrow$ +Q
- Accelerated back to ground potential
- E.g. Au: E_{kin} = 1 MeV/u Q=+12

- After VdG ions get further further stripped to Q=+32
- Transfered over 800m long transfer line to *Booster Synchrotron*



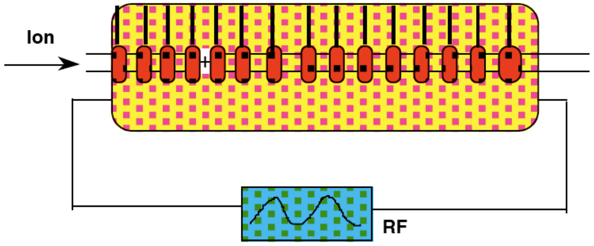
RHIC Complex



p from 200 MeV Linear Accelerator

Linear Accelerator (Linac)

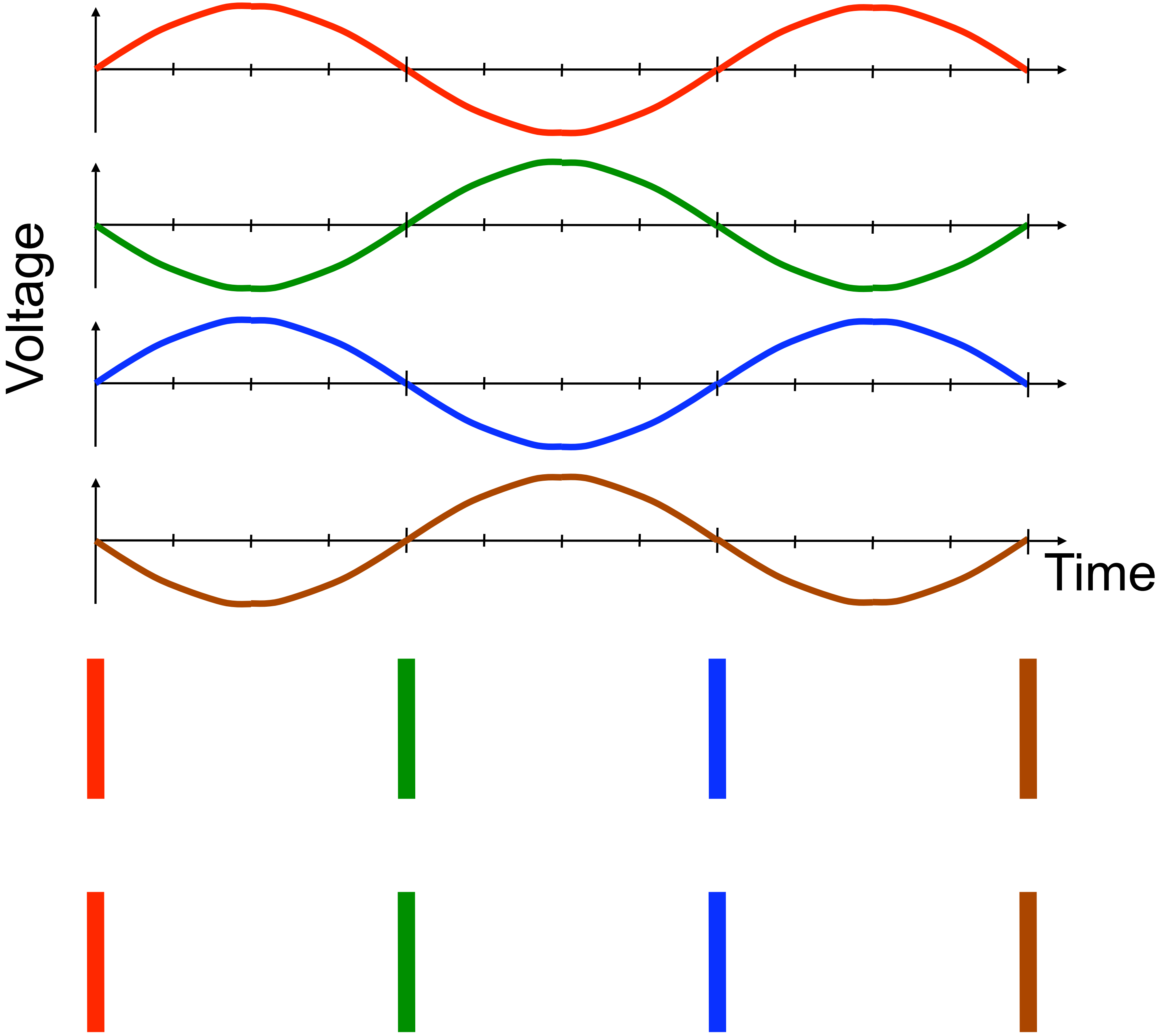
Provide accelerated protons for use at AGS/RHIC

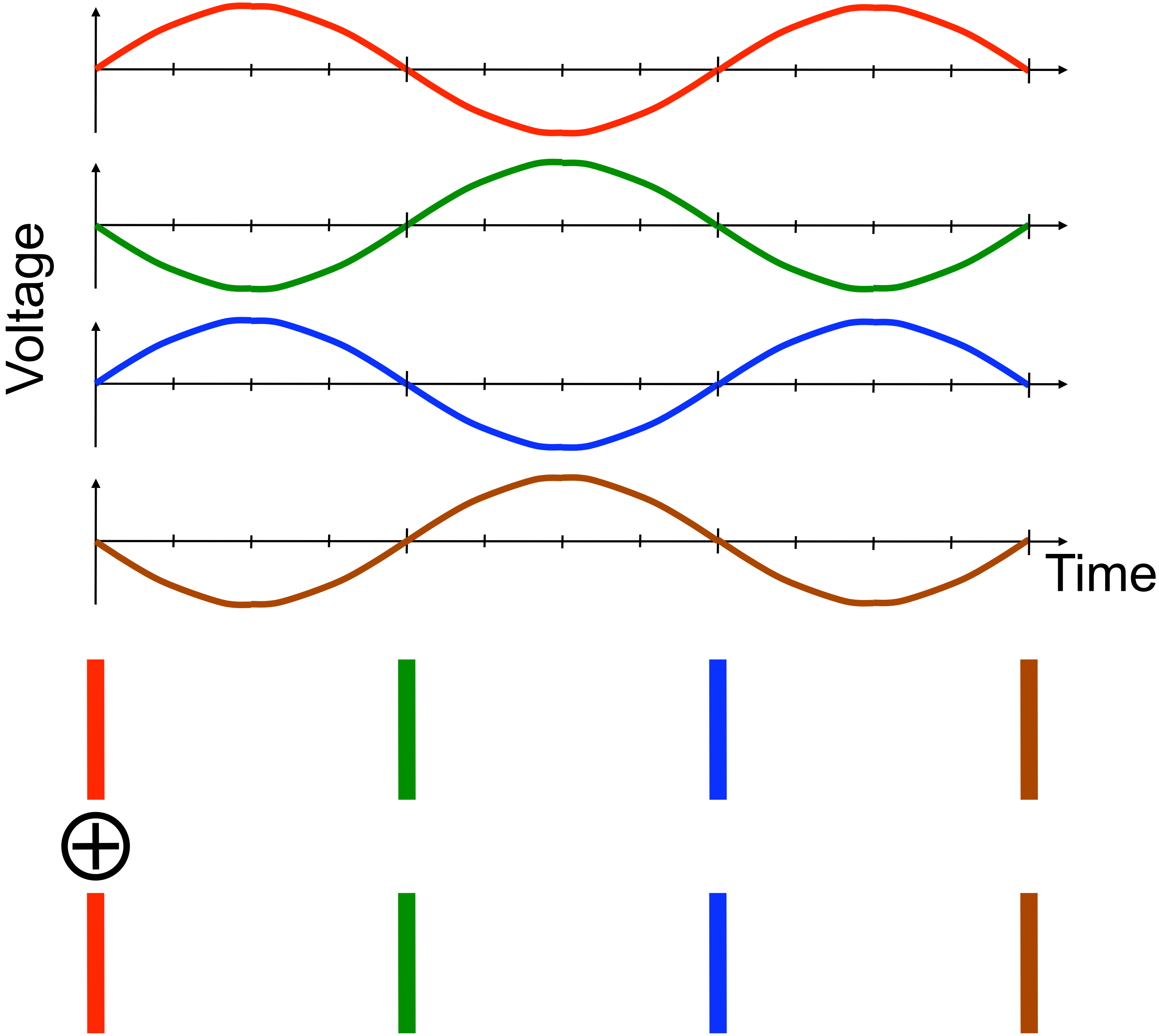


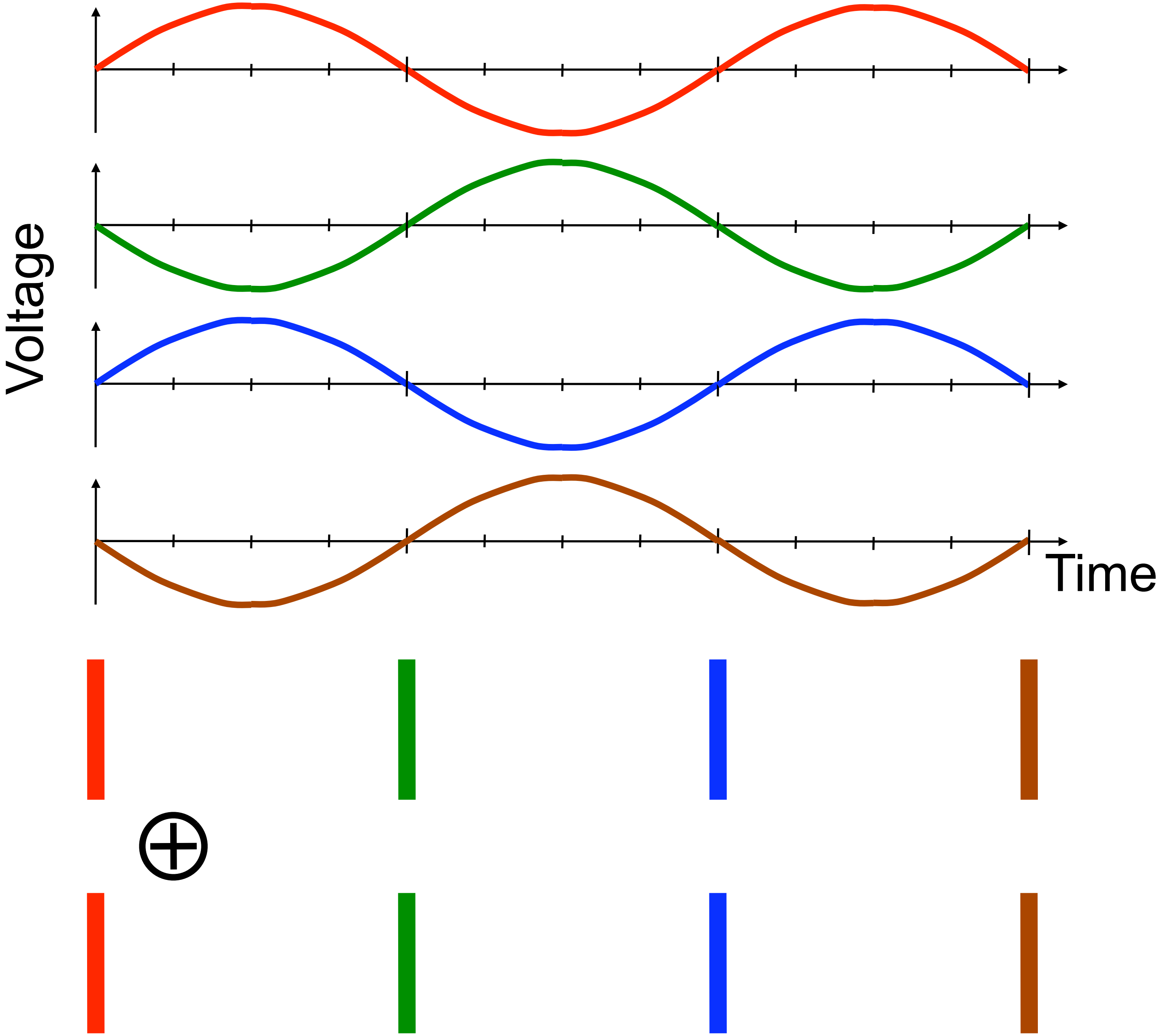
Basic components

- H+ ion sources
- a radiofrequency quadropole pre-injector
- nine accelerator radiofrequency cavities spanning the length of a 140 m tunnel (right).

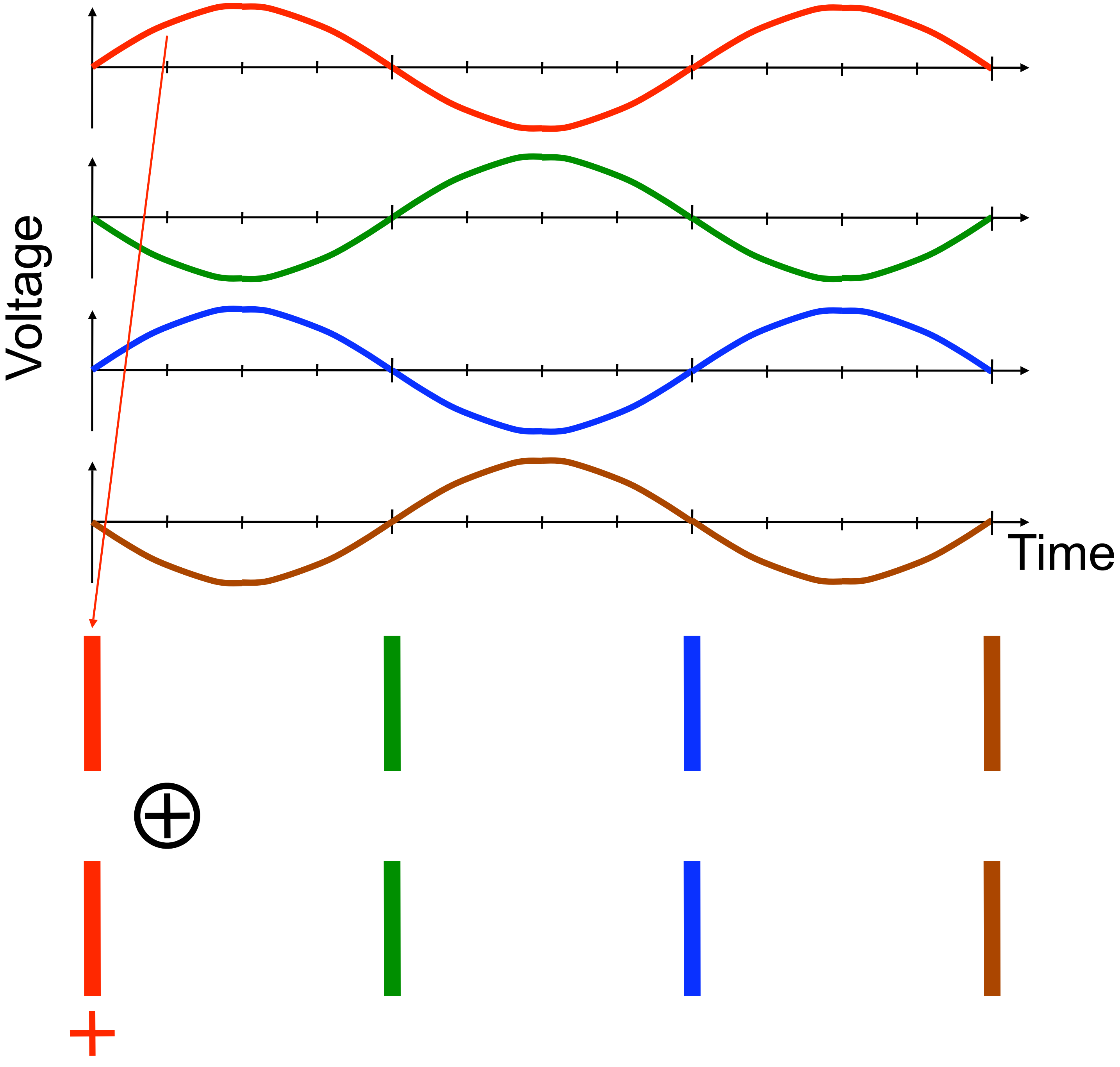
The Linac is capable of producing up to a 35 mA proton beam at energies up to 200 MeV for injection into the AGS Booster


Voltage
Time

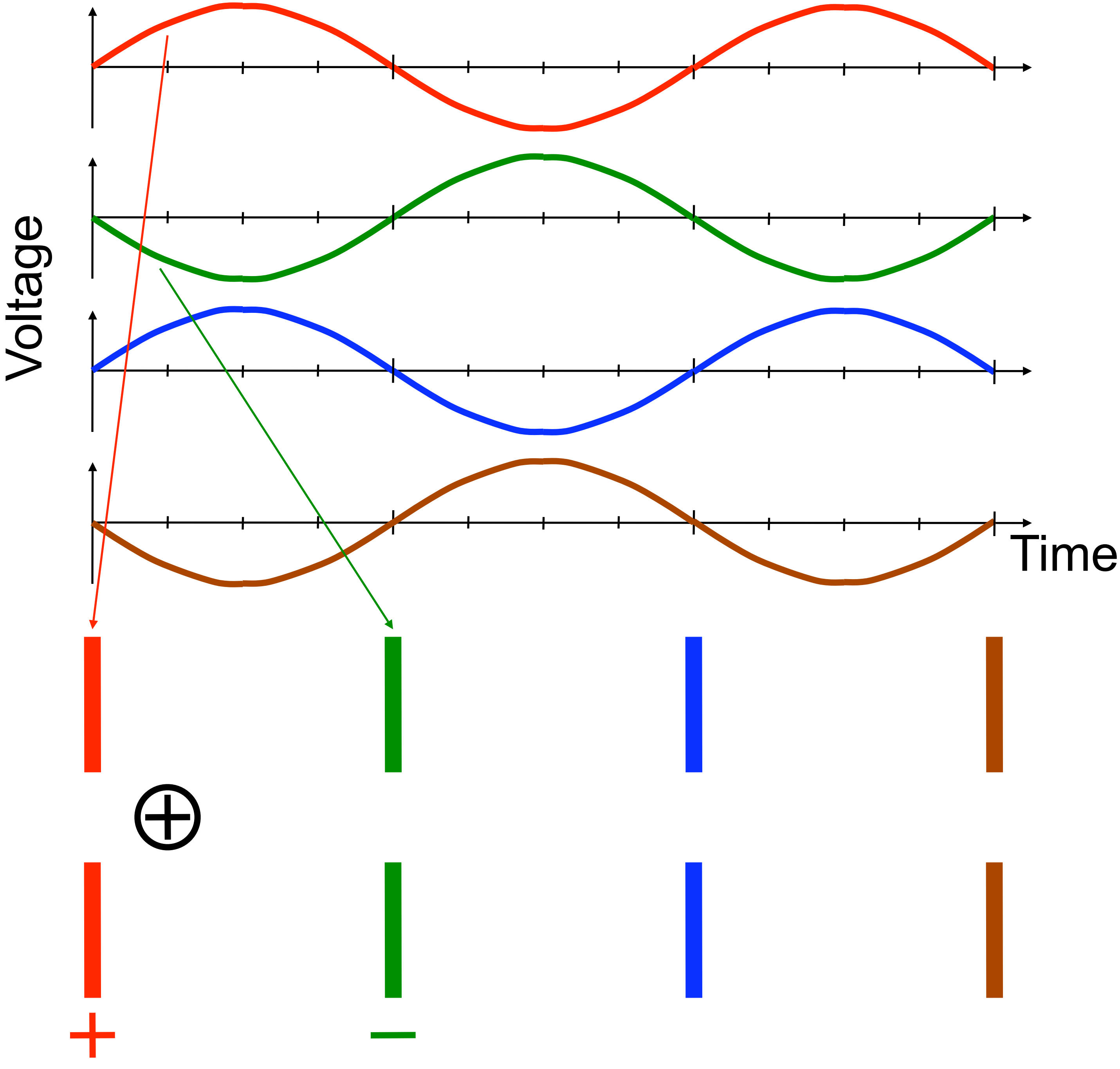

Voltage
Time
⊕



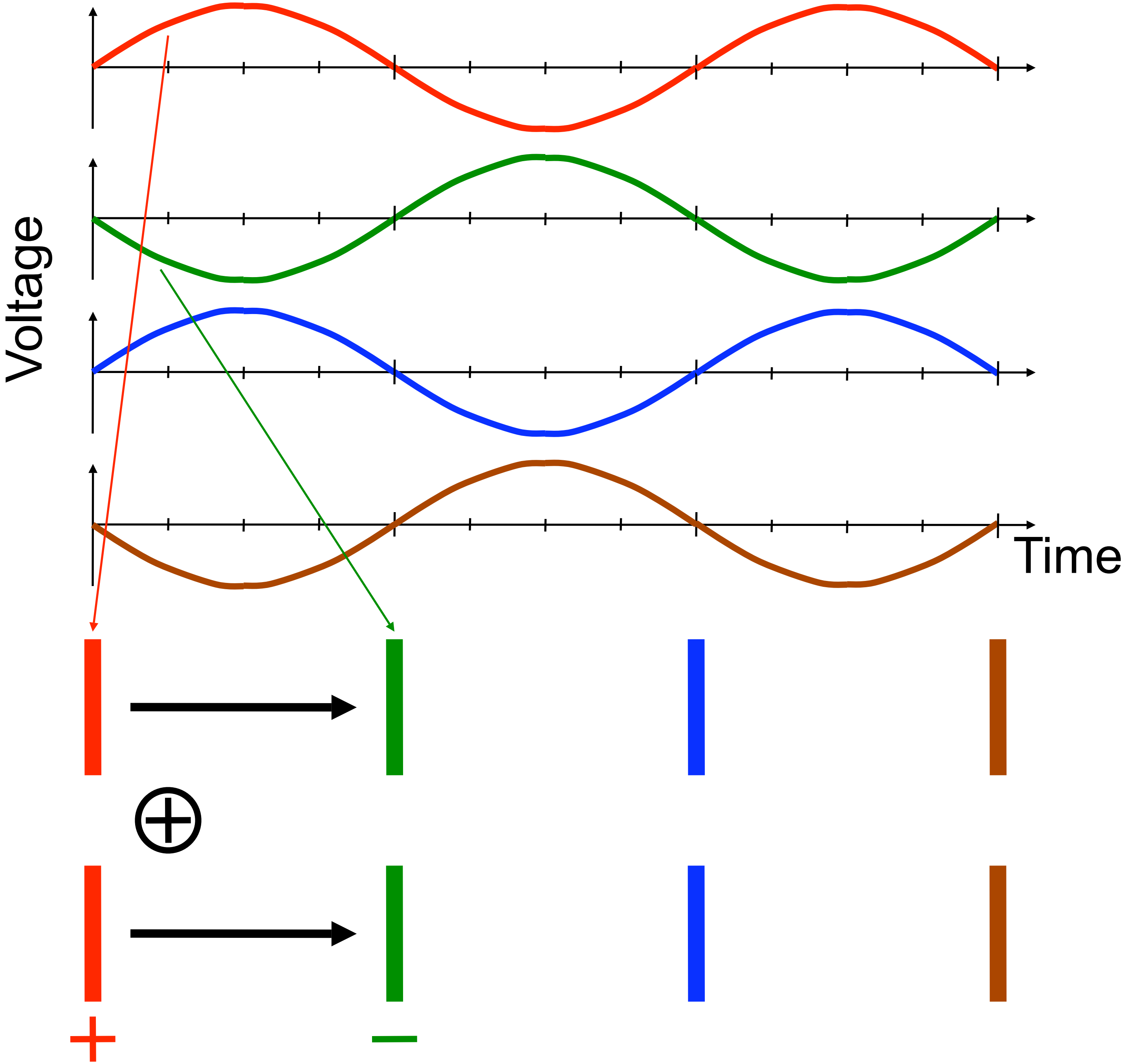
Voltage
Time
⊕

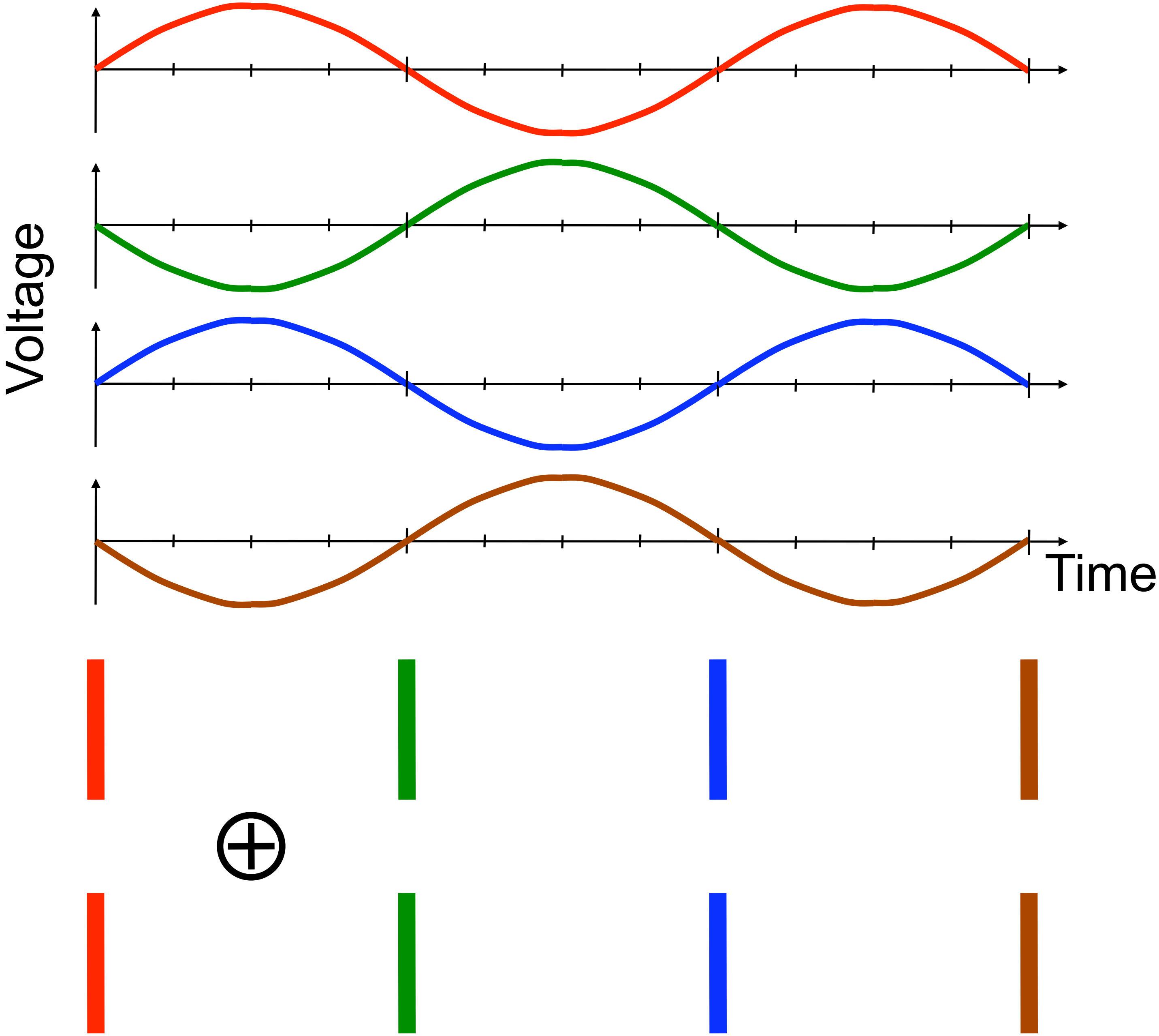


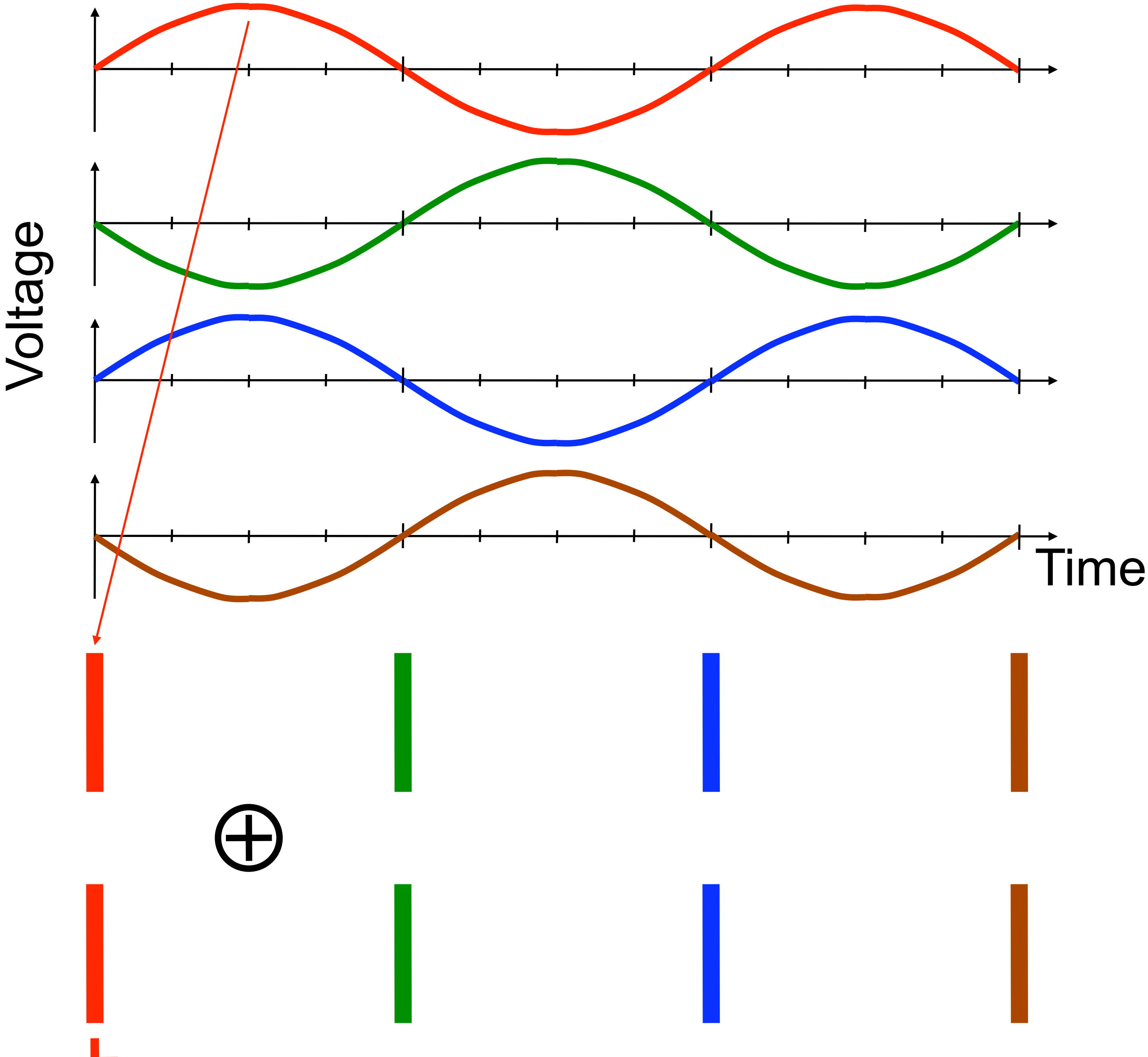
Voltage
Time
⊕
+



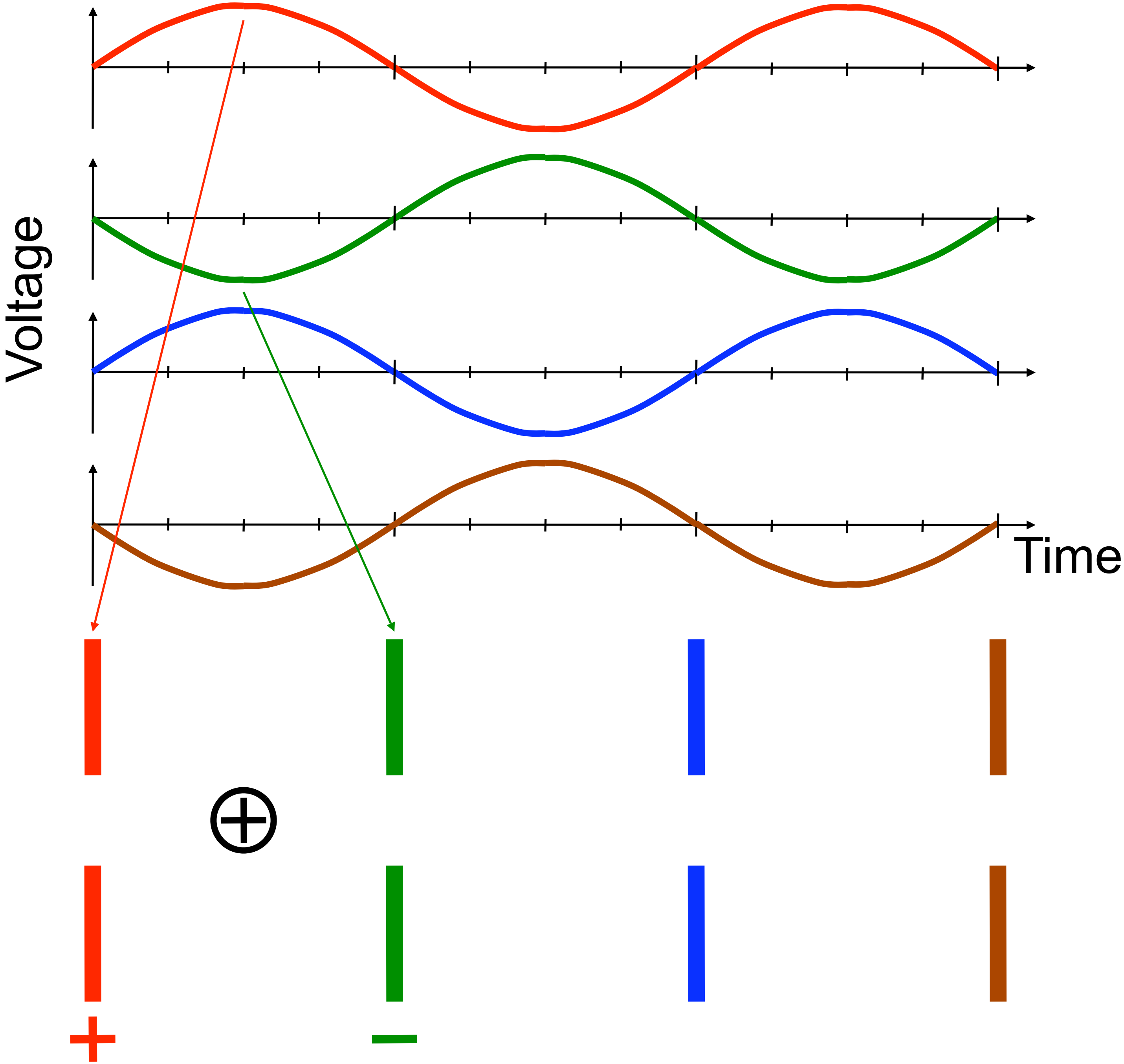
Voltage
Time
⊕
+
−


Voltage
Time
⊕
+
−

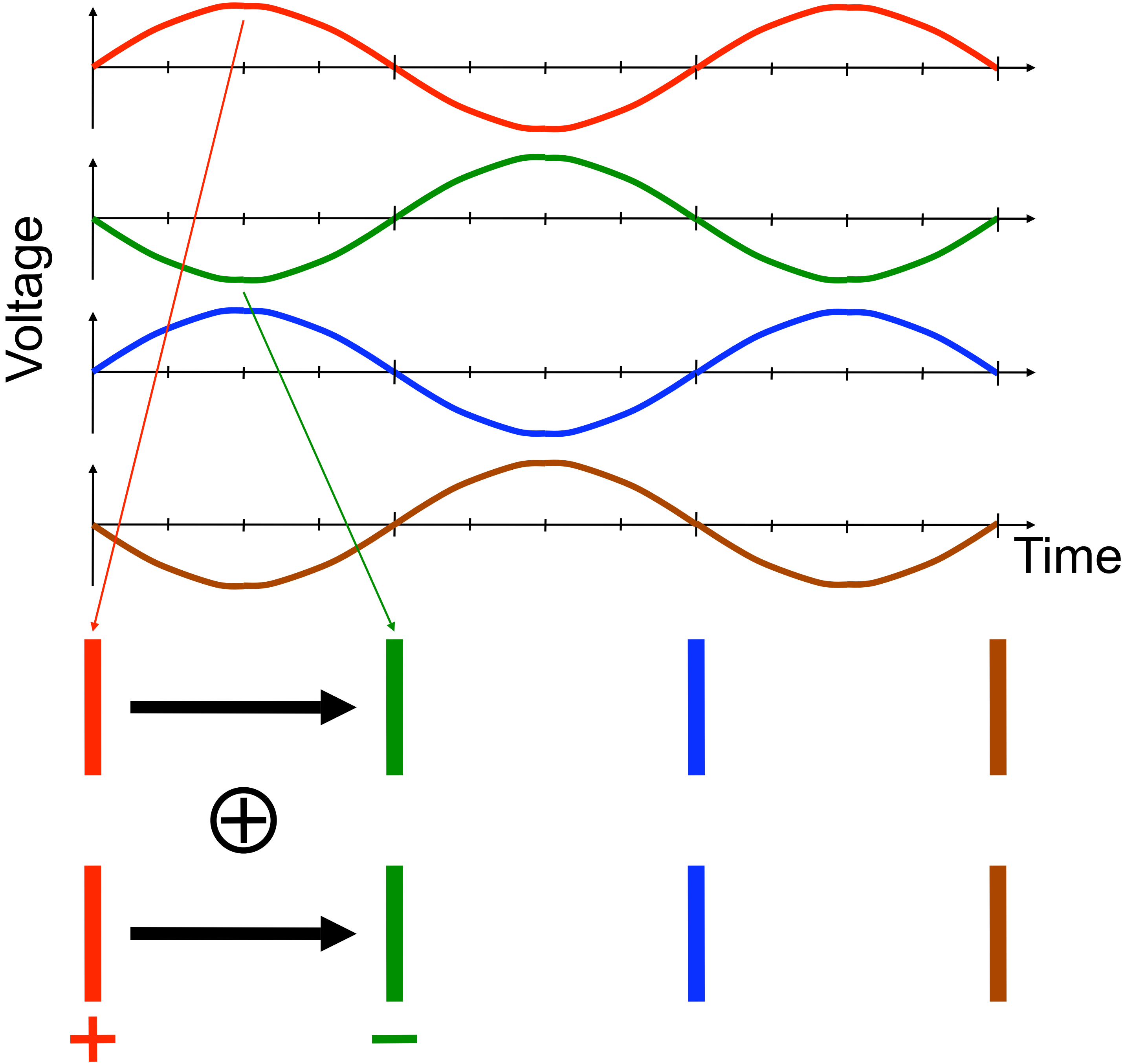

Voltage
Time
⊕

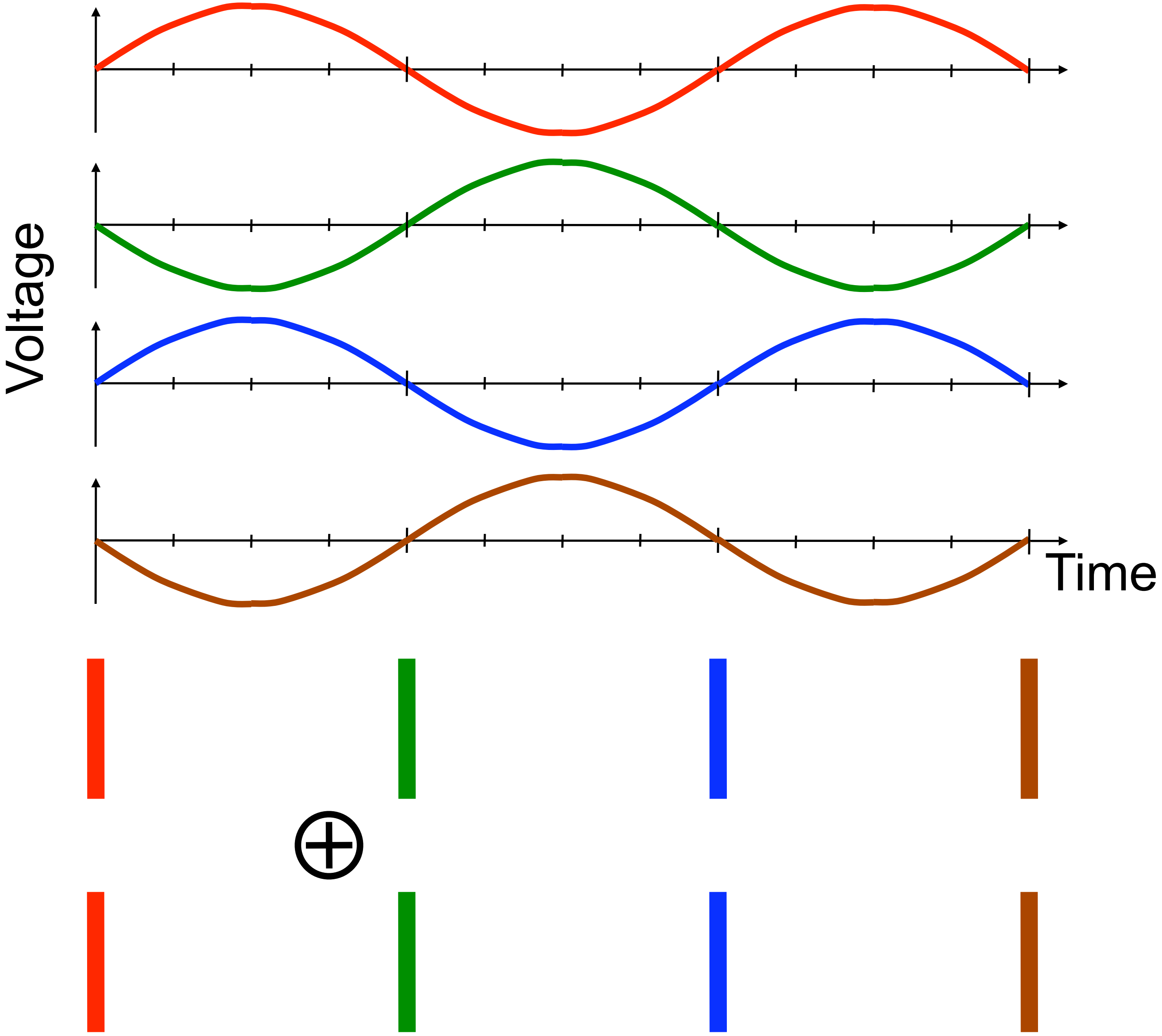


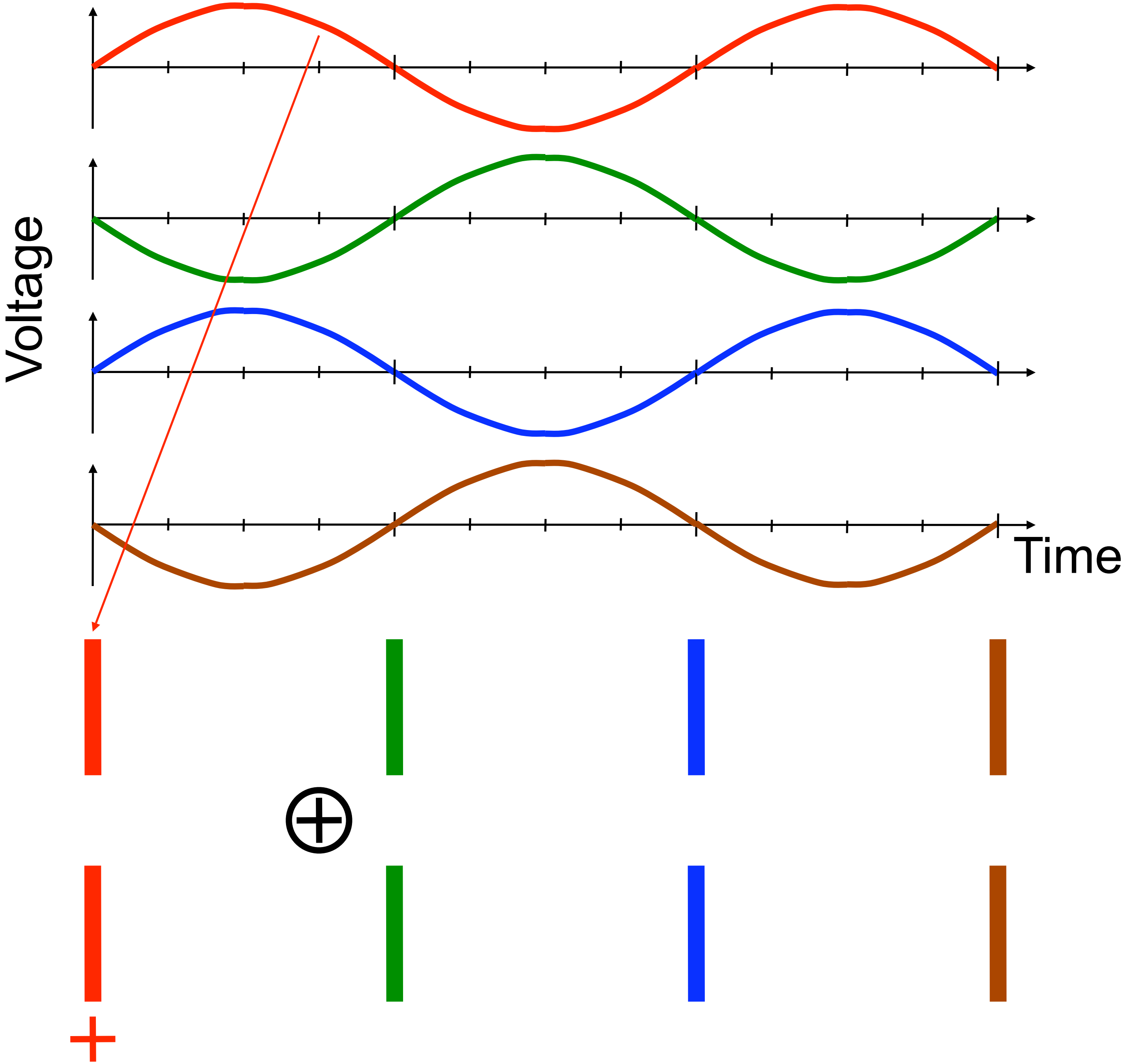
Voltage
Time
⊕
+

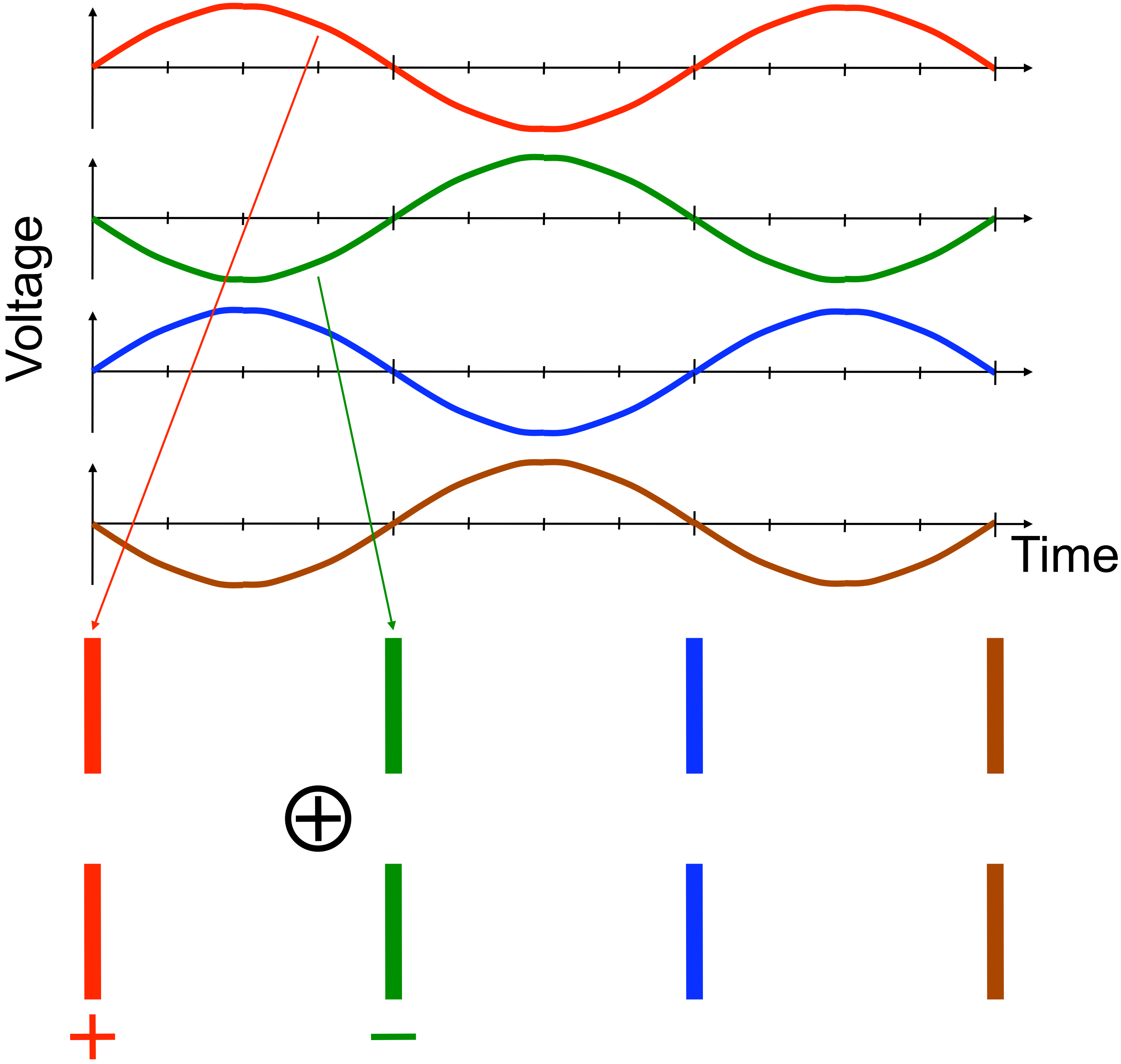


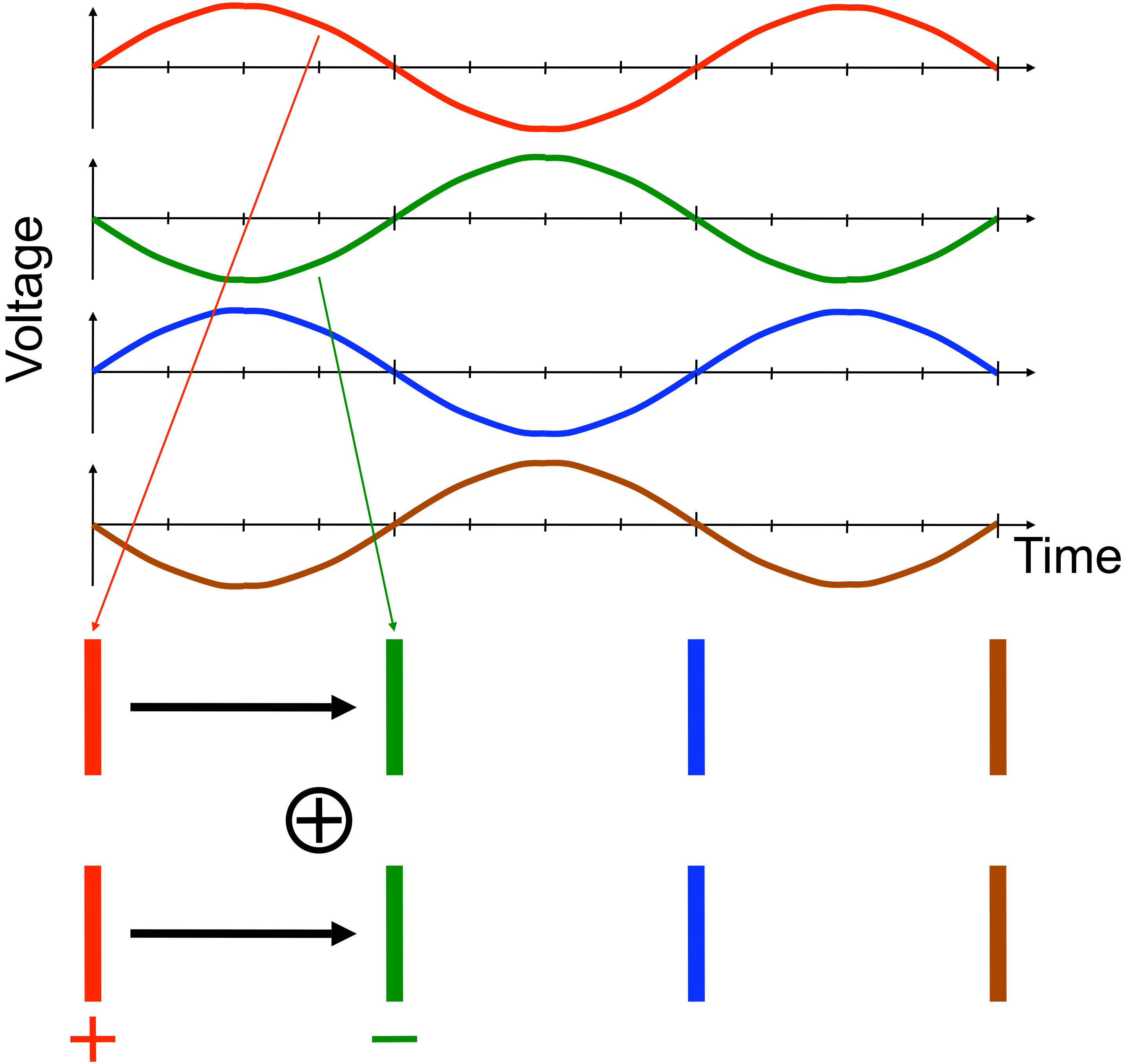
Voltage
Time
⊕
+
−


Voltage
Time
⊕
+
−

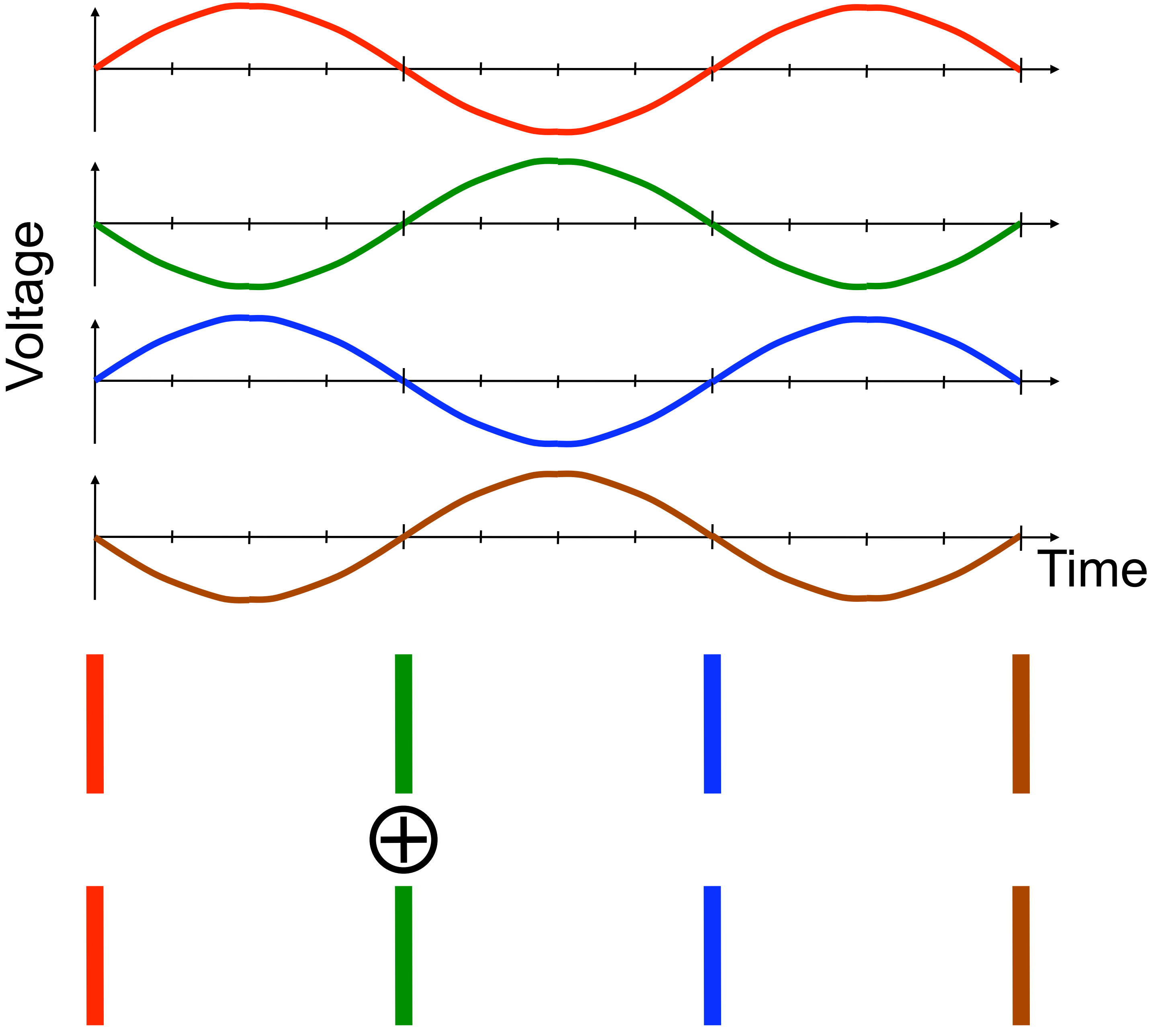

Voltage
Time
⊕

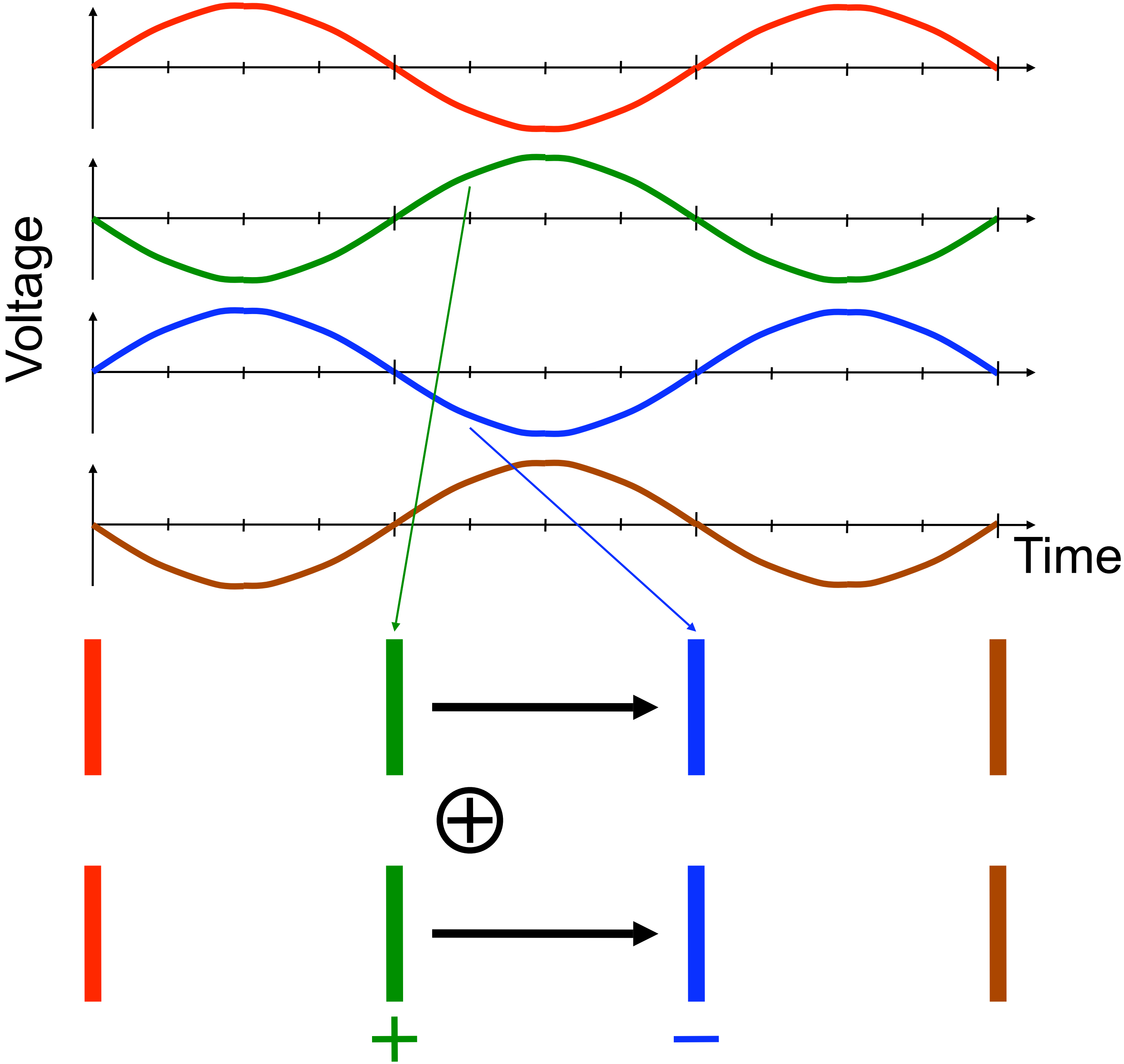

Voltage
Time
⊕
+


Voltage
Time
⊕
+
−

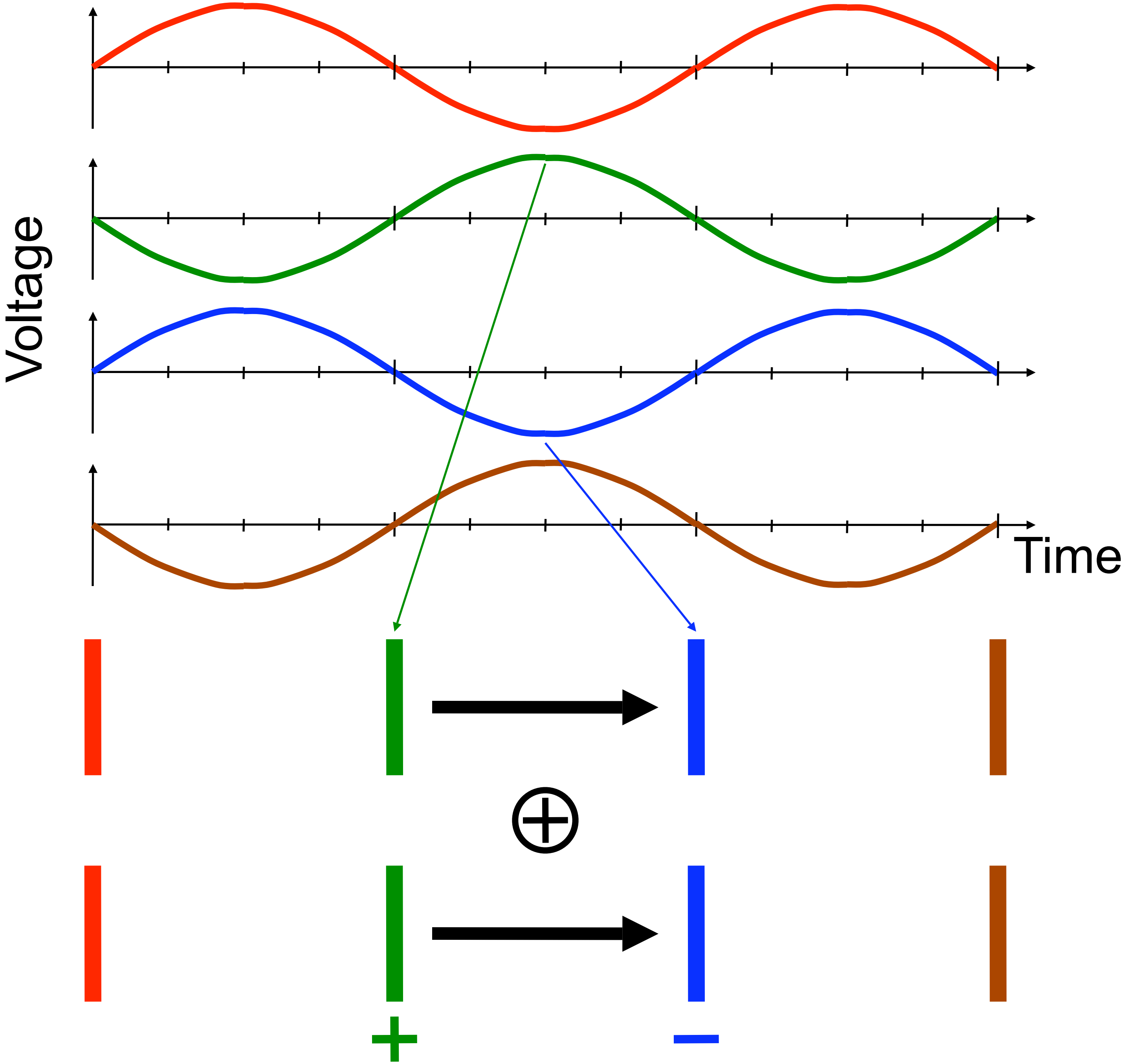


Voltage
Time
+
−

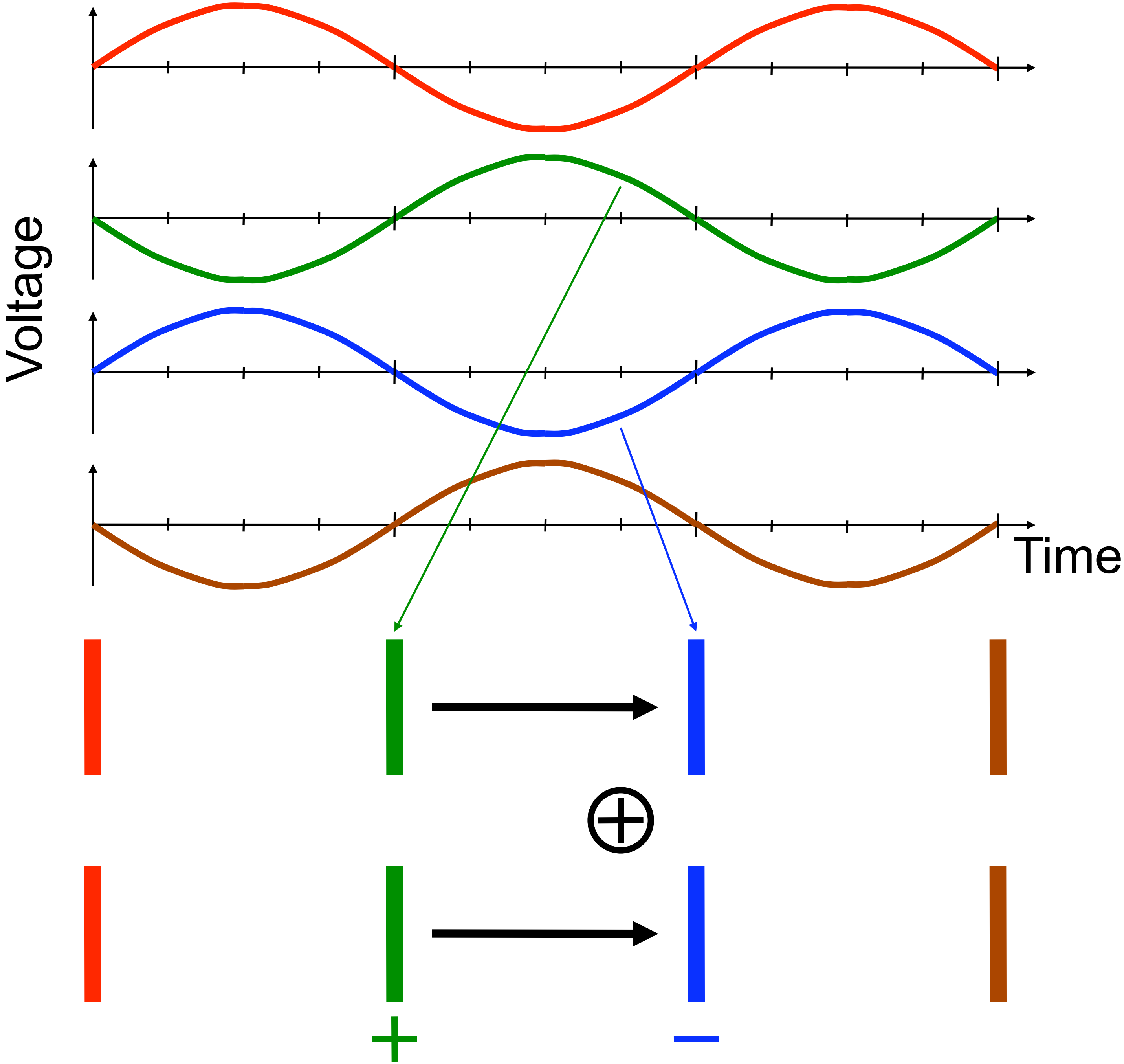

Voltage
Time
⊕

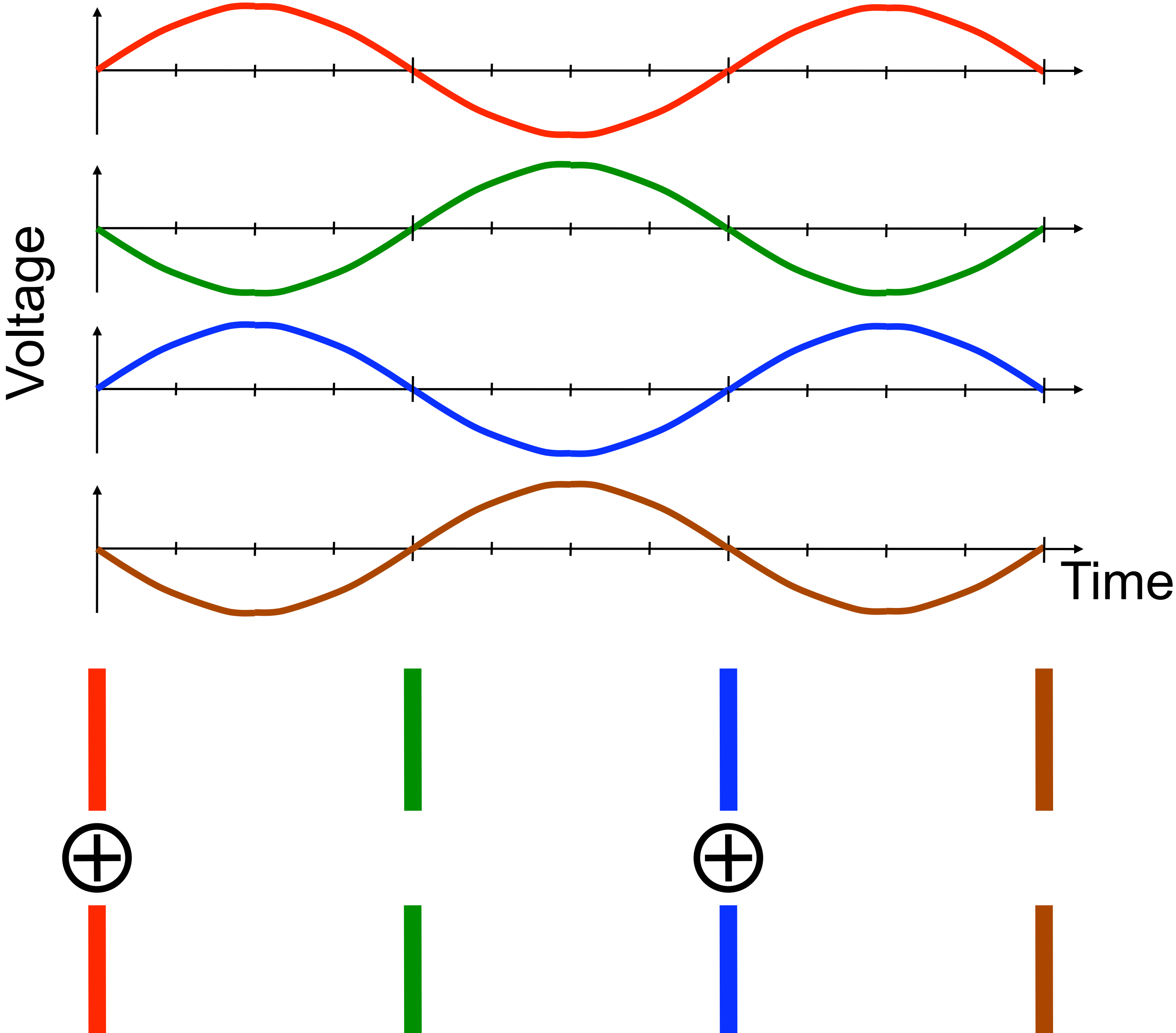


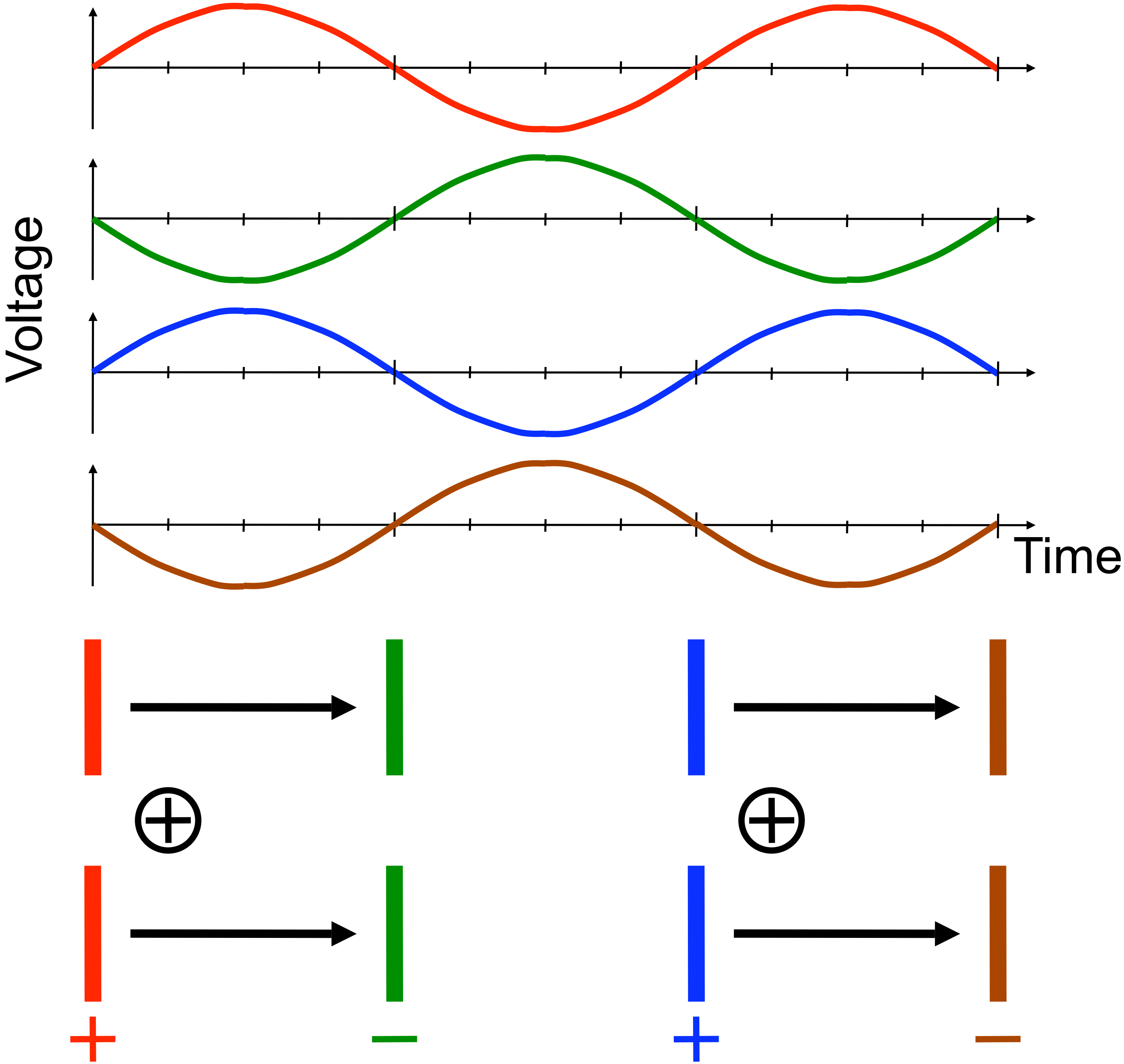
Voltage
Time
⊕
+
−

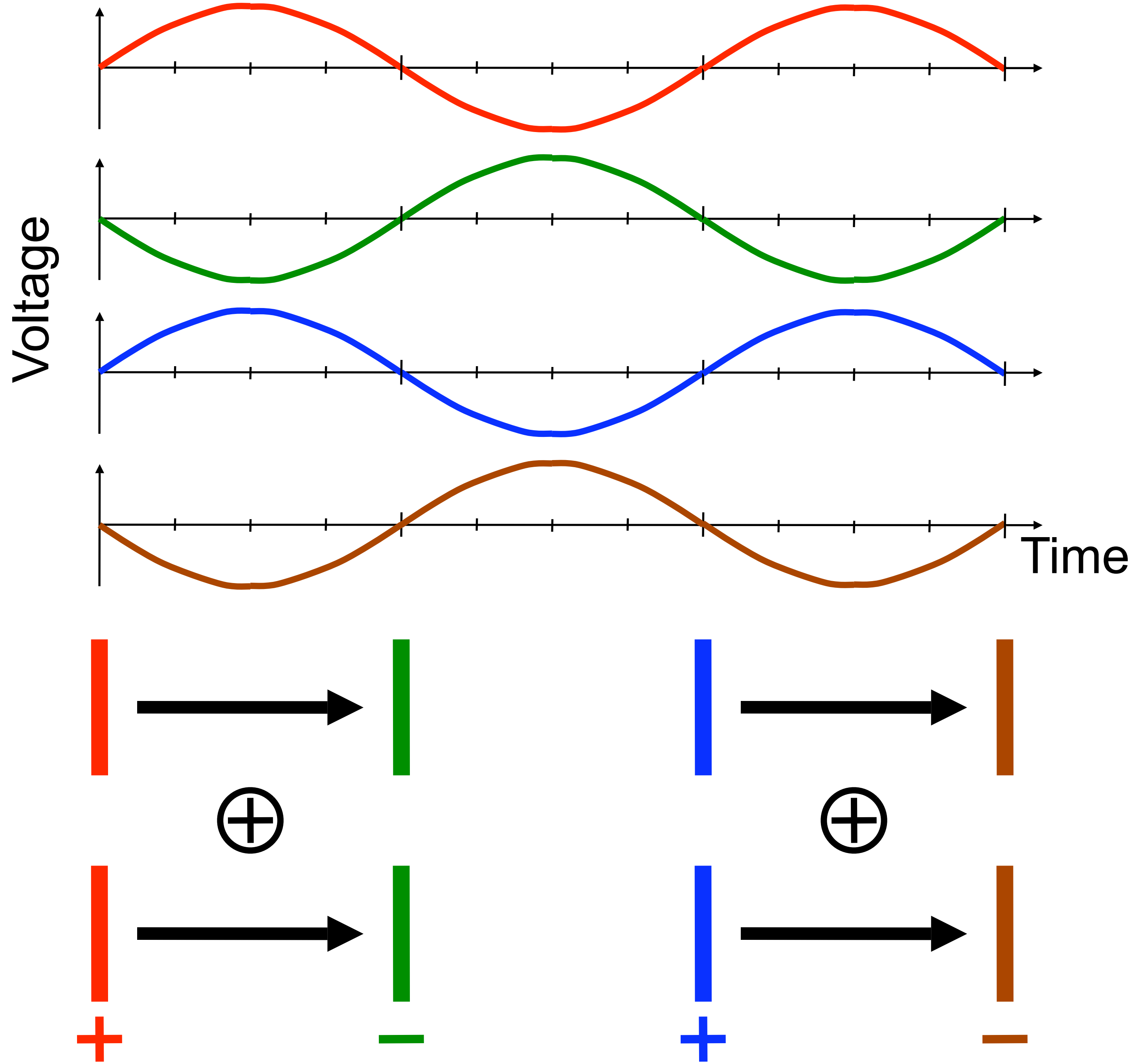


Voltage
Time
⊕
+
−

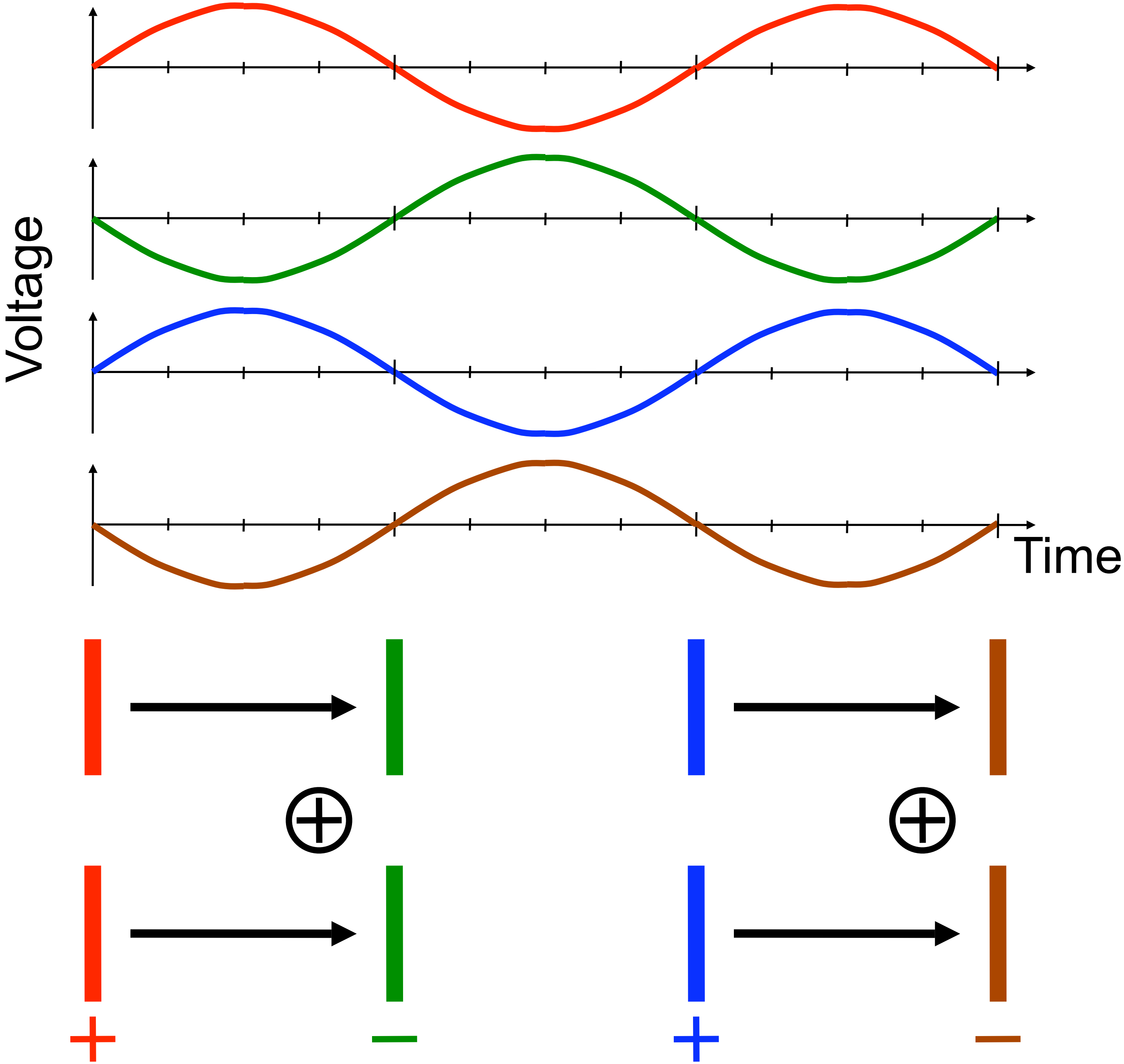

Voltage
Time
⊕
+
−


Voltage
Time
⊕
⊕

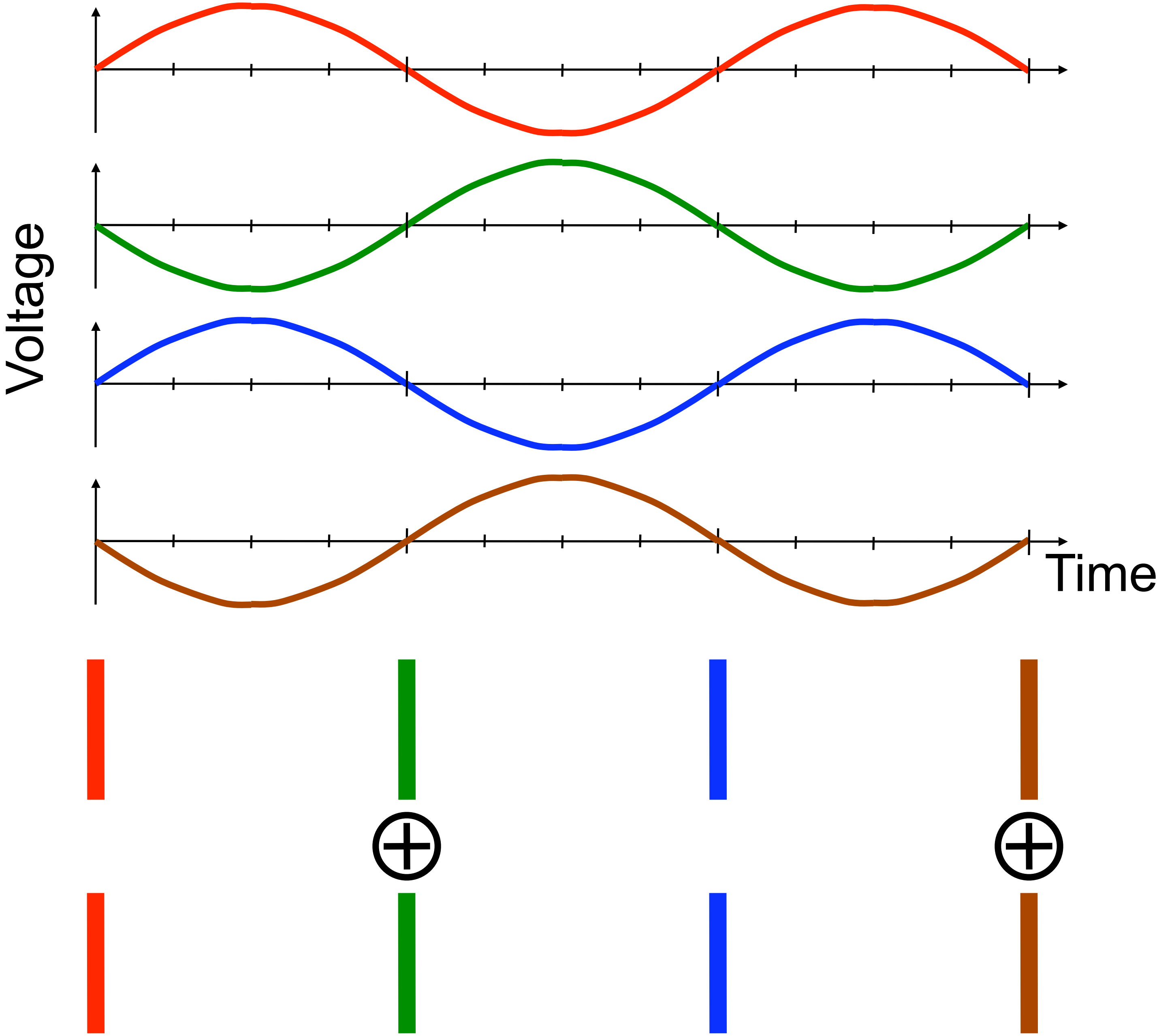

Voltage
Time
⊕
⊕
+
−
+
−

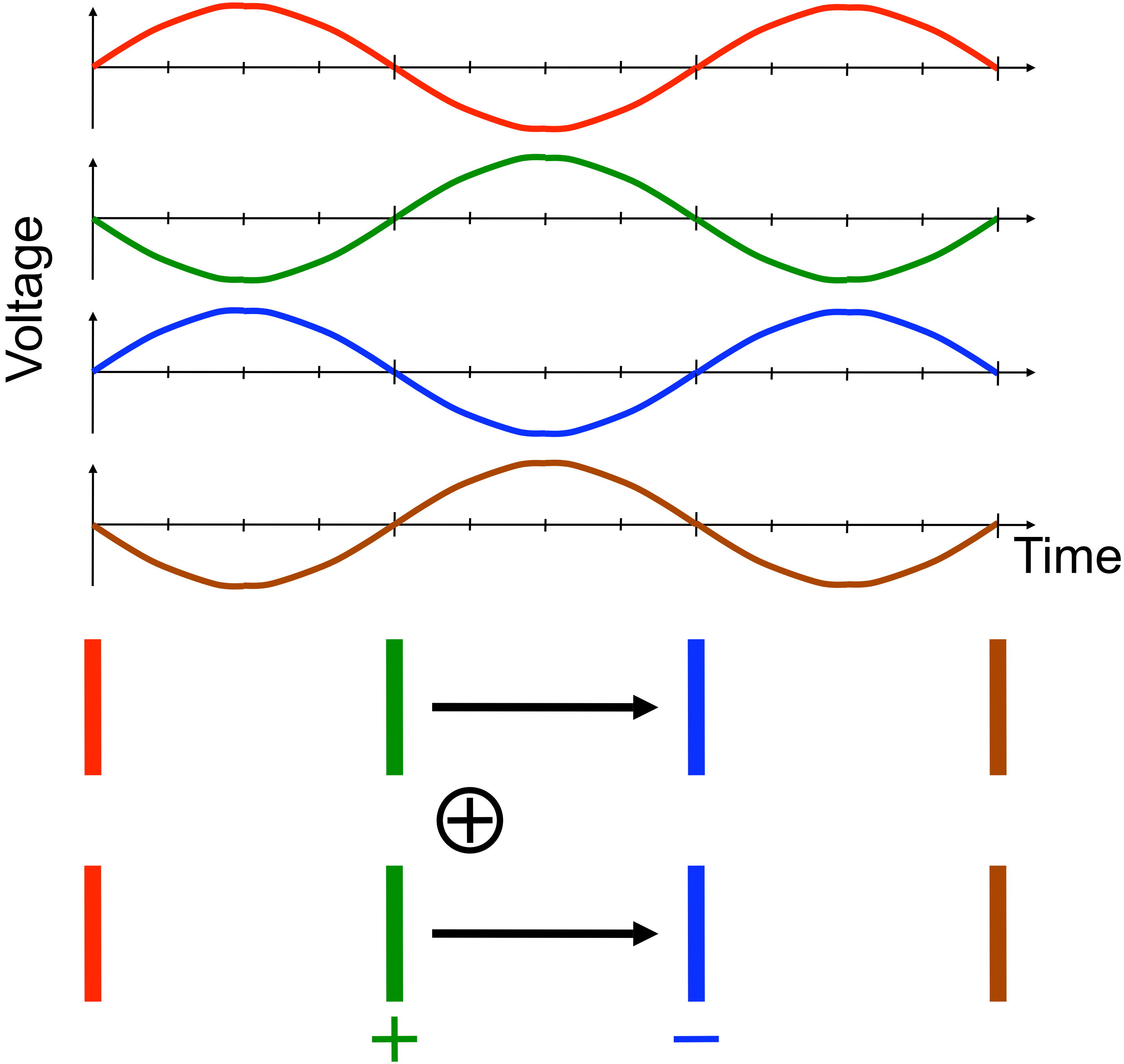


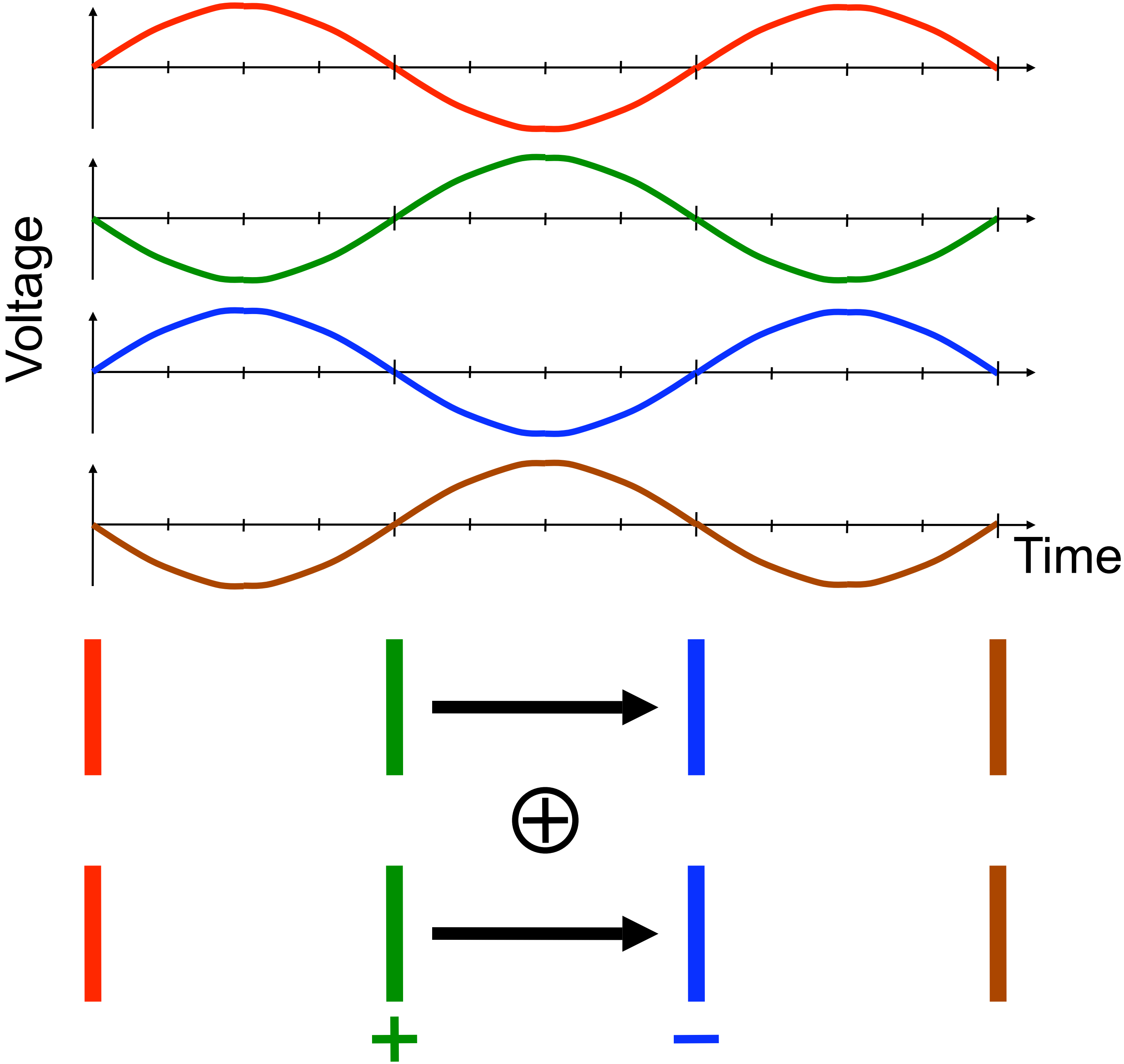
Voltage
Time
+
−
+
−

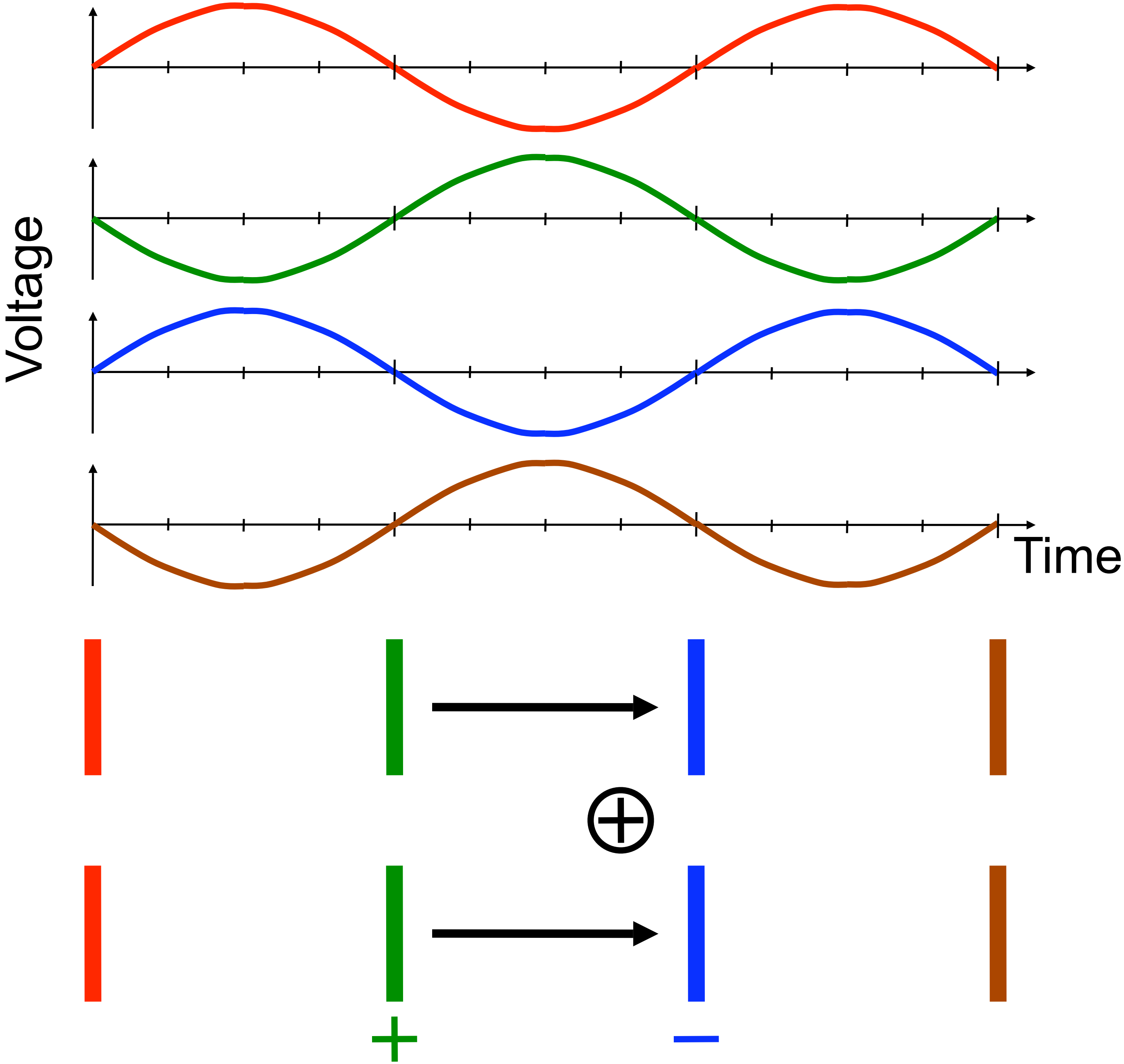


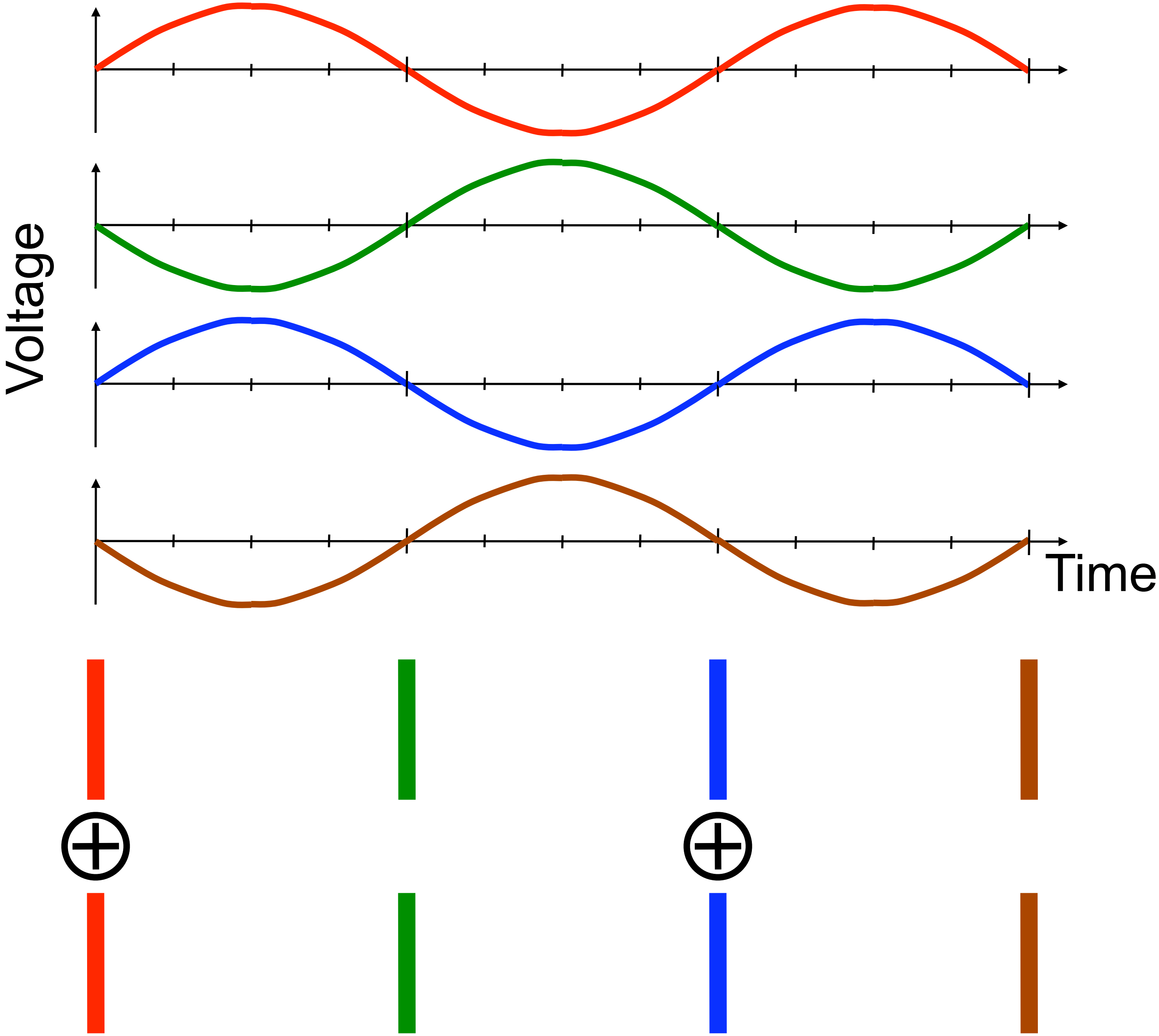
Voltage
Time
+
−
+
−

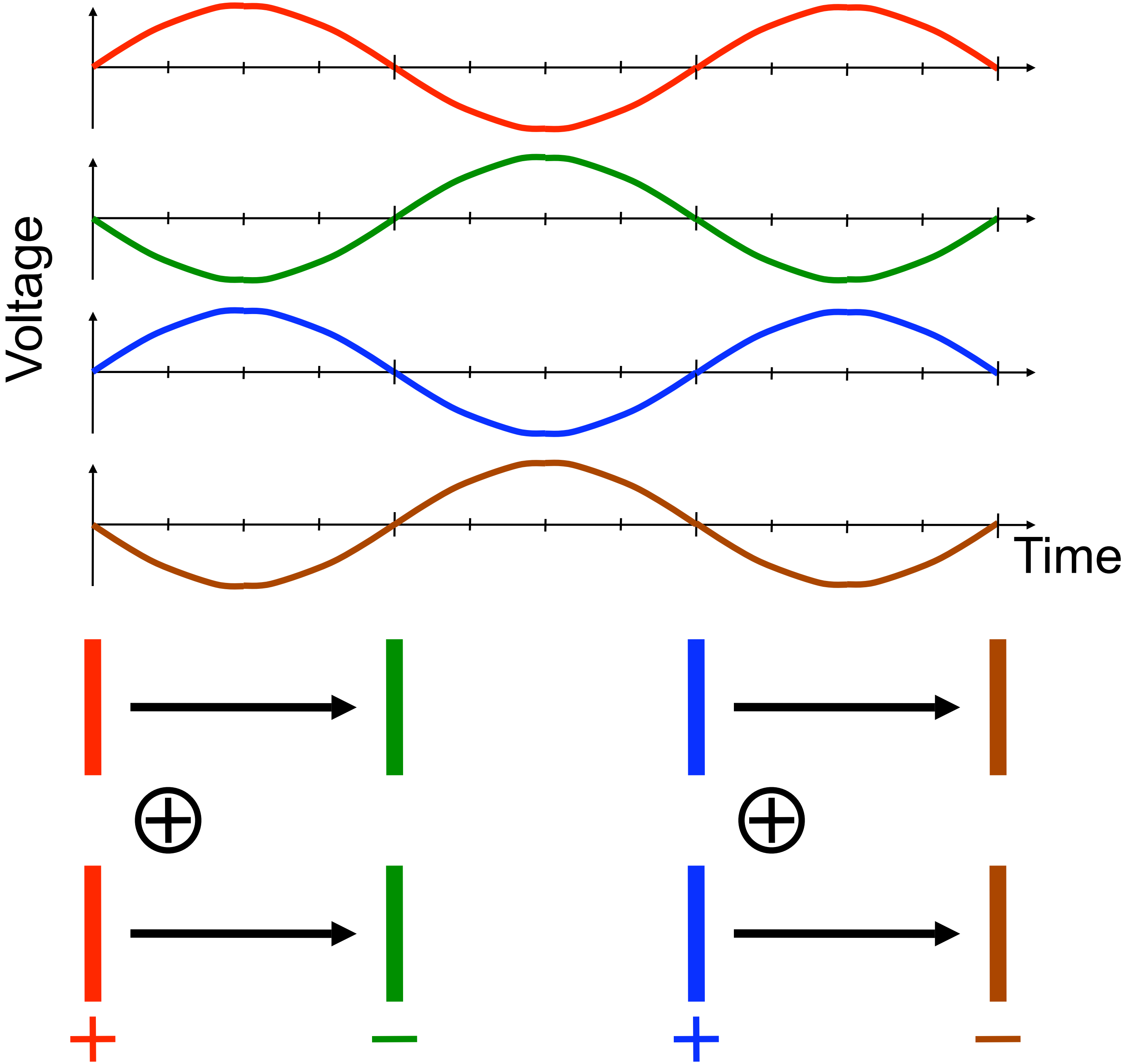

Voltage
Time

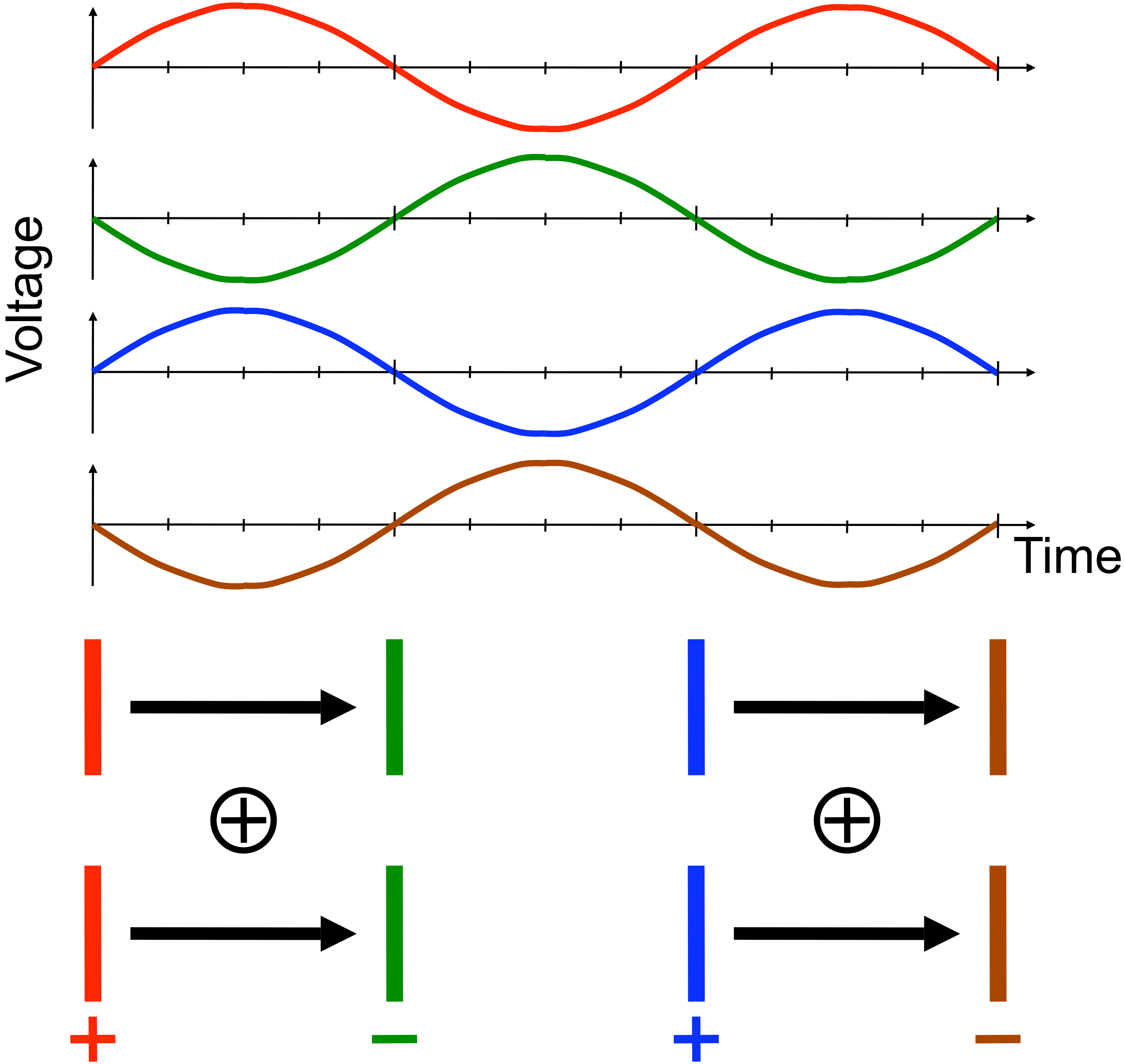

Voltage
Time
⊕
+
−


Voltage
Time
⊕
+
−

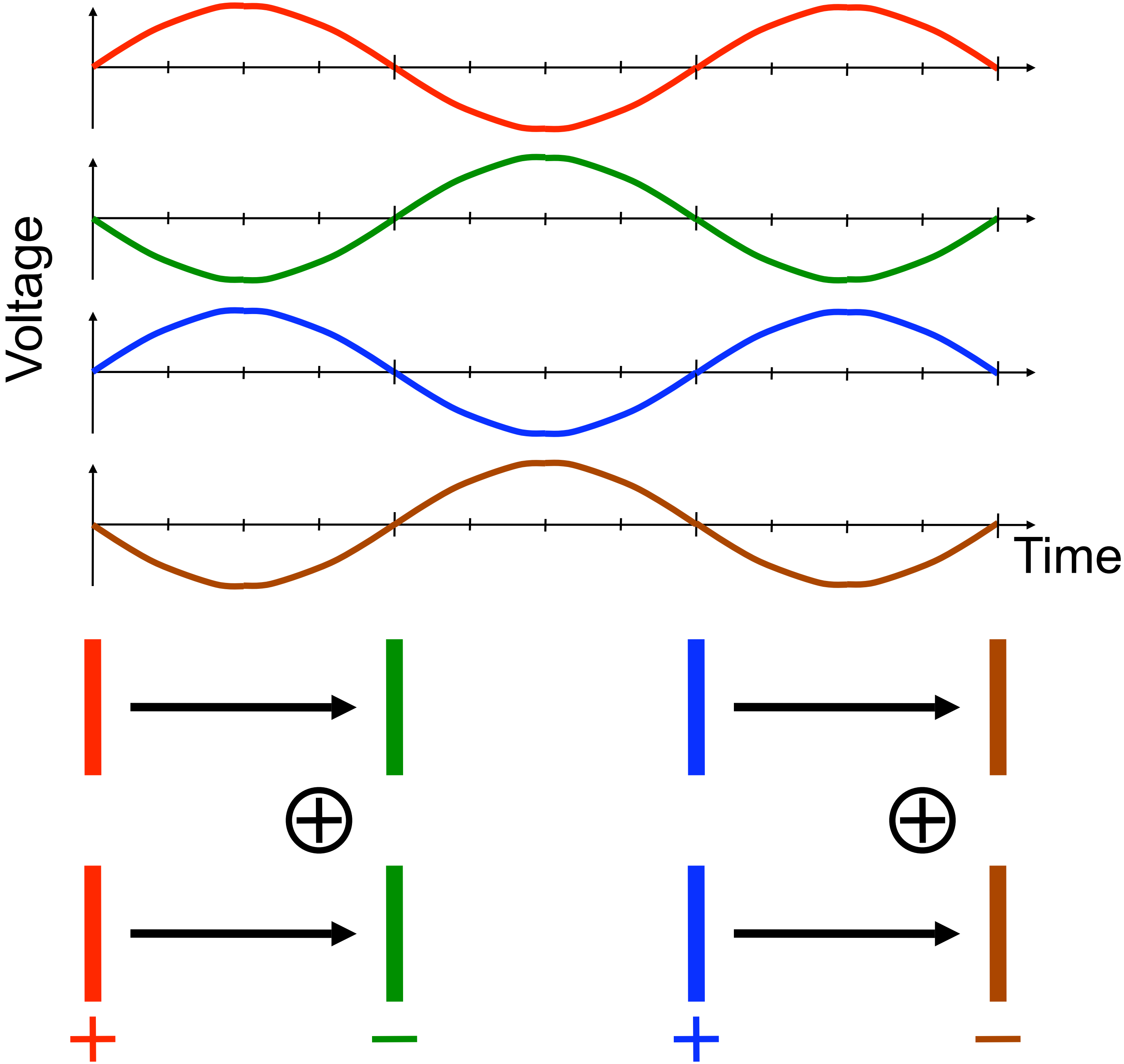

Voltage
Time
⊕
+
−


Voltage
Time

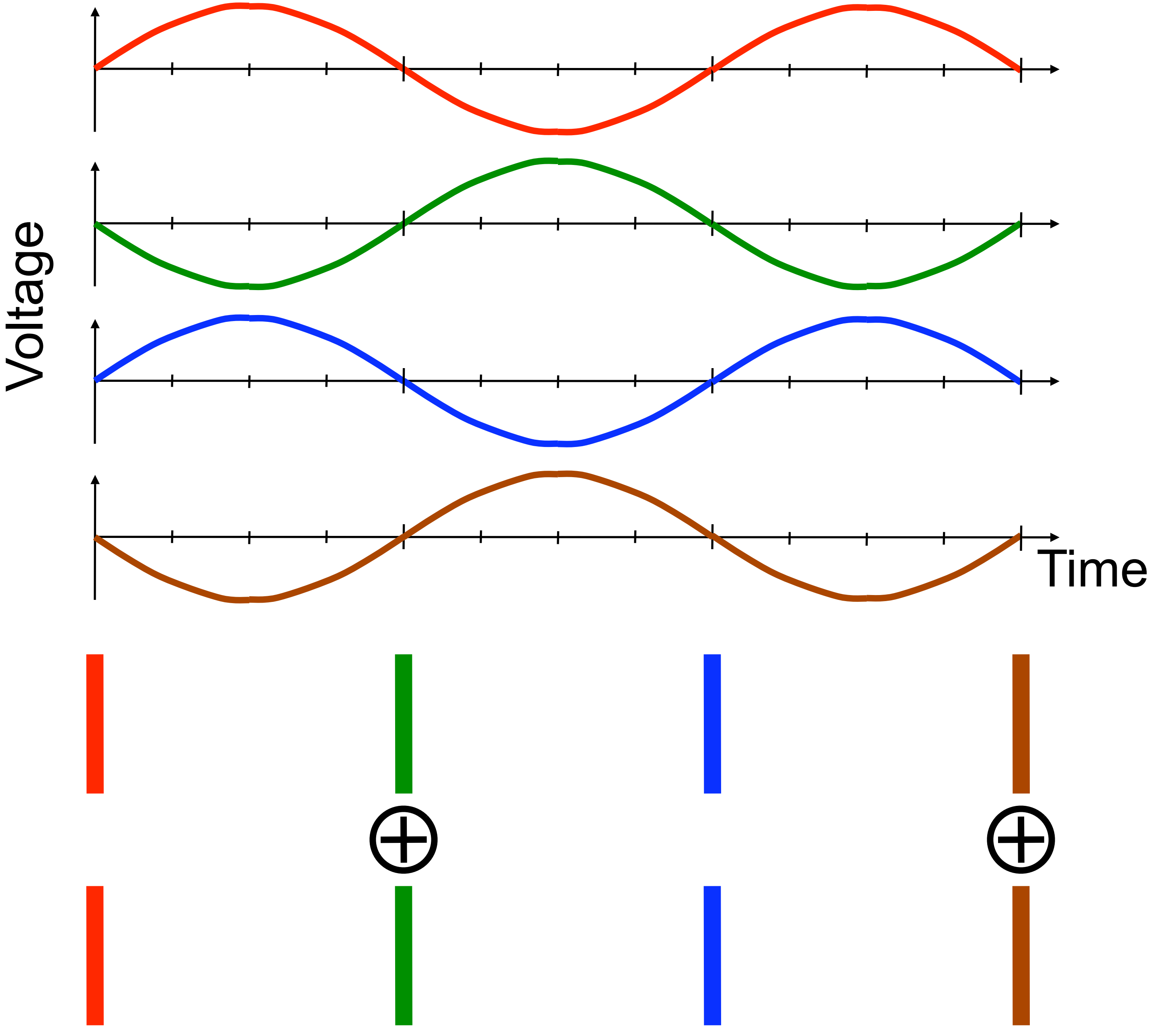

Voltage
Time
+
−
+
−



Voltage
Time
⊕
⊕
+
−
+
−

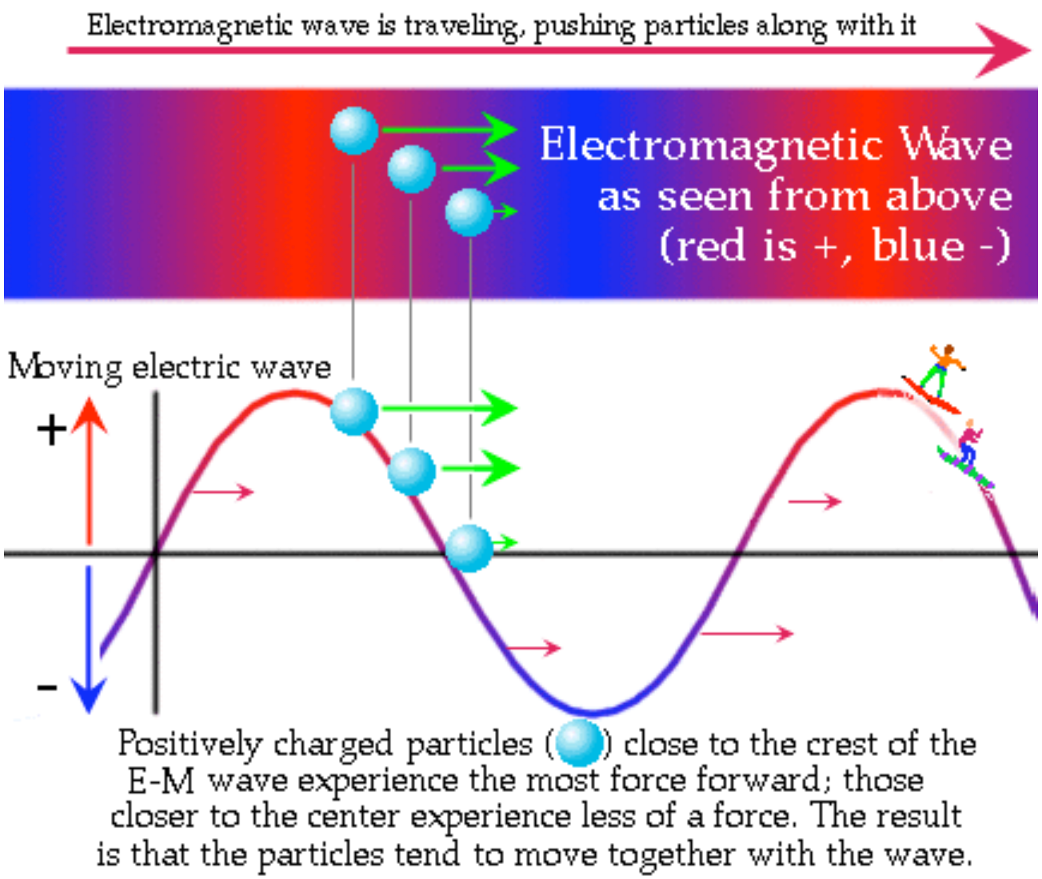


Voltage
Time
+
−
+
−

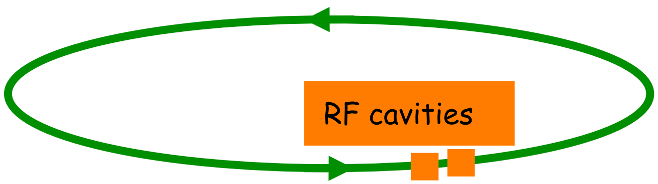

Voltage
Time

Getting Real" How RF Accelerates

Particles are accelerated by riding an electromagnetic wave in RF cavities. These waves also bunch particles together.



- One pass through an RF cavity is not enough to accelerate particles all the way up to these high energies
  - One option: build a long line of many, many RF cavities
    - linear accelerator (such as SLC at SLAC, BNL LINAC)
  - Another option (RHIC) is to build only a few RF cavities, but have particles go through them many times in a storage ring.

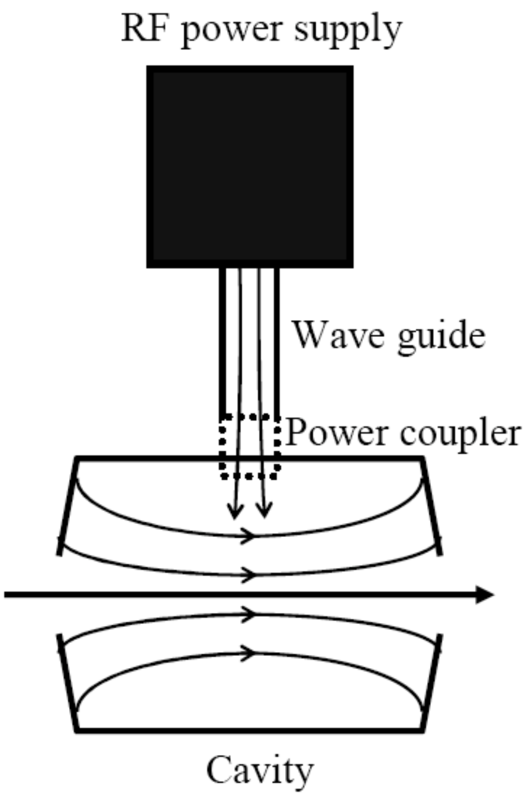


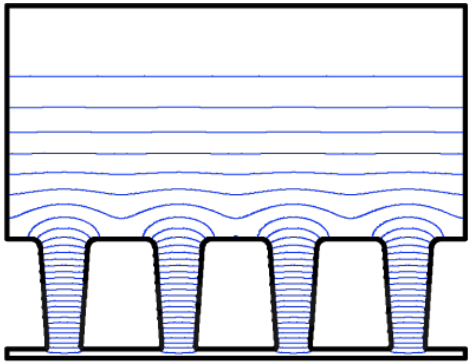
Because v = c, the frequency of these electromagnetic waves needs to be very high, hence RF for "radio frequency". At RHIC 28 MHz.

RF Resonant Cavity

Basic principle

- Conductor enclosing a close volume
- Maxwell equations + boundary conditions allow electromagnetic field E_n/B_n configurations to oscillate with a given frequency f_n : *a resonant mode*. The field is a weighted superposition of these modes.
- The wanted (accelerating) mode is excited at the good frequency and position from a RF power supply through a power coupler.





TM $_{010}$: f=352.2 MHz

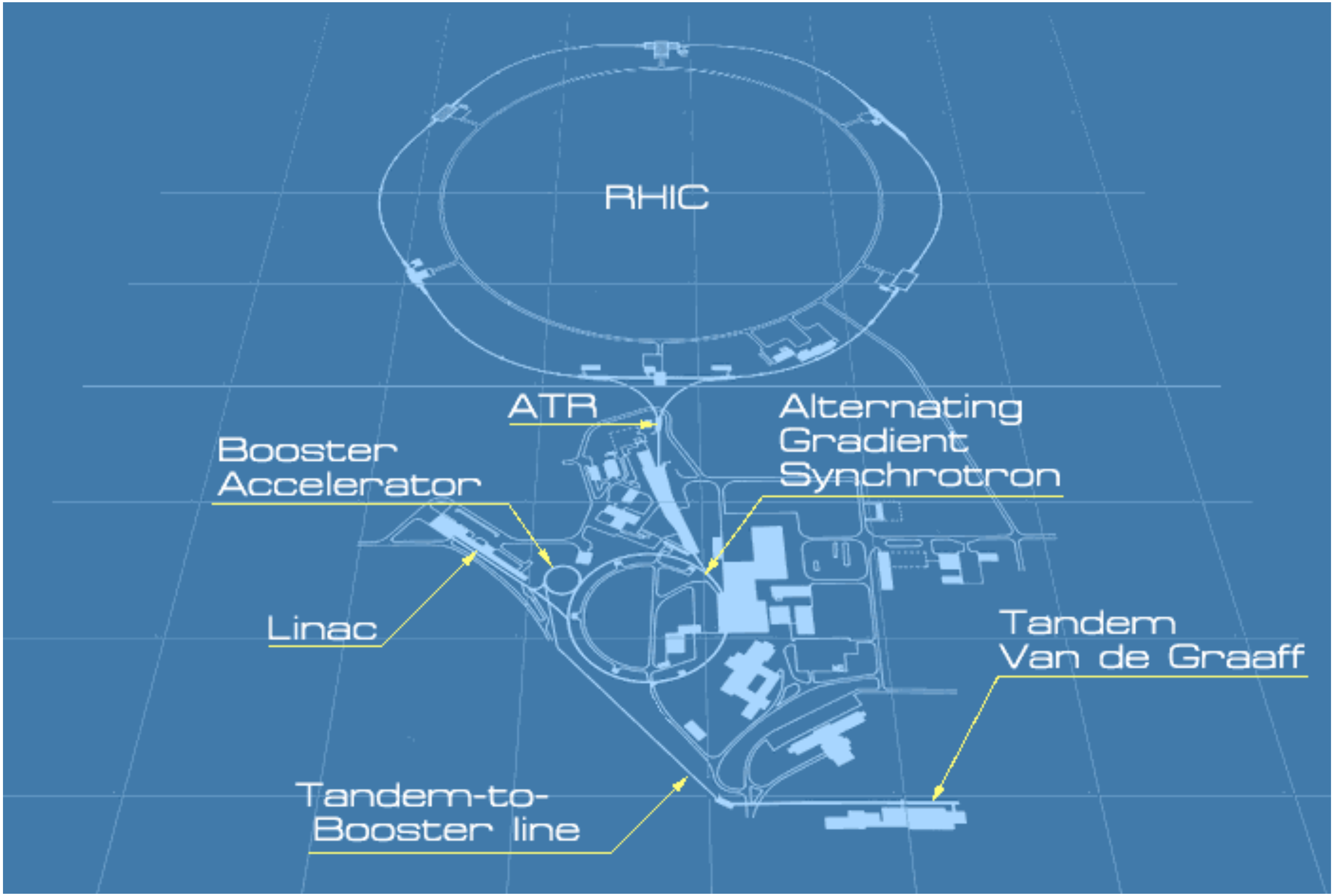
Elements of mode calculation:

Boundary conditions: $\vec{E}_{||} = 0,\ \vec{B}_{\perp} = 0$

Mode calculation: $\nabla^2 \vec{E}_n + \frac{2\pi f_n}{c^2} \cdot \vec{E}_n = 0$

Electrical field: $\vec{E}(\vec{r}, t) = \sum e_n(t) \vec{E}_n(\vec{r})$

RHIC Complex



What's a Synchrotron ?

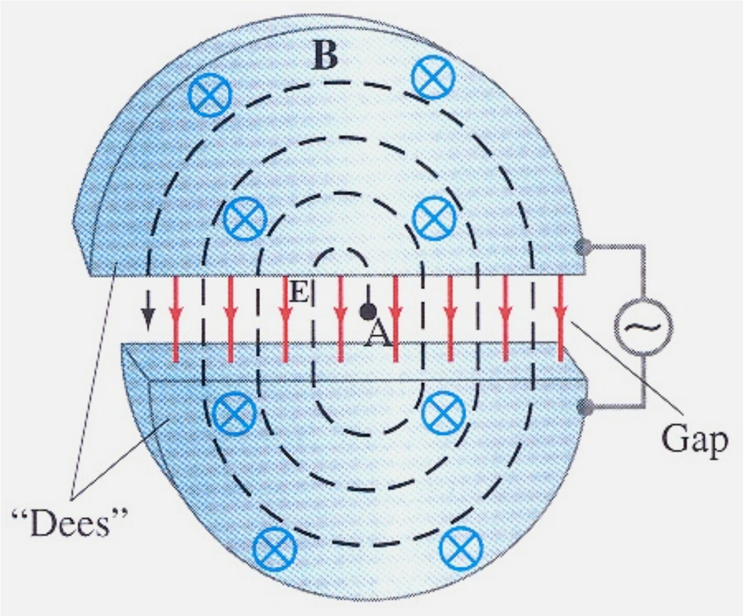
First useful particle accelerator: Cyclotron

Constant magnetic field and a constant-frequency applied electric field (2 'D's)

Pros: Simple

Cons:

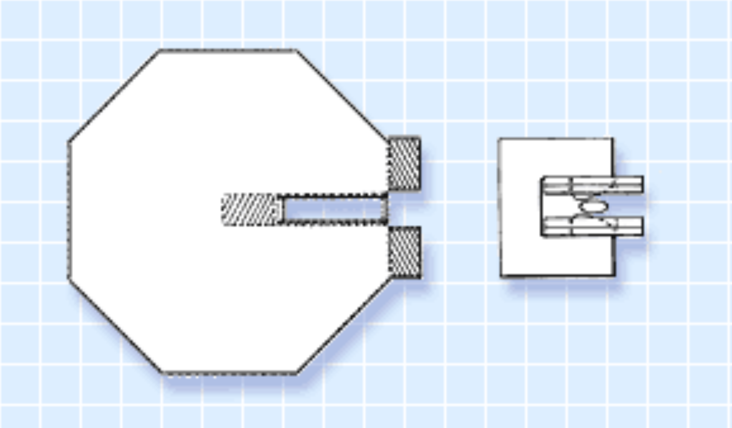
- Lots of iron needed
- B field must be high to get high E at "normal" D sizes
- In an ordinary electromagnet the field strength is limited by the saturation of the core.



Way out: Synchrotron

Narrow beam pipe surrounded by smaller and more tightly focused magnets

Magnetic field and the electric field (to accelerate the particles) are carefully synchronized with the traveling particle beam.



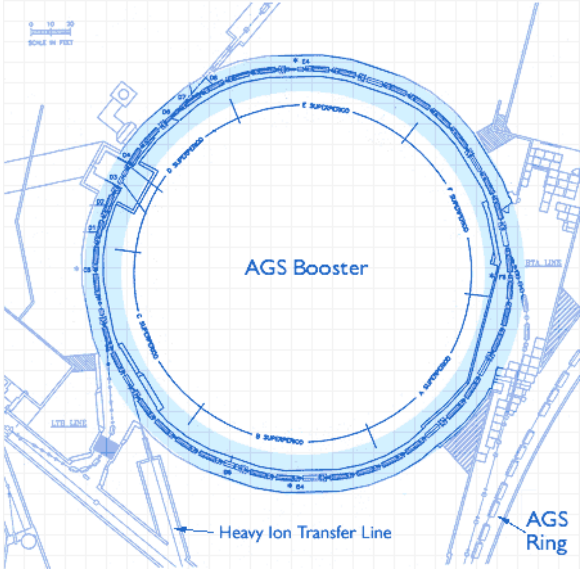
Booster Synchrotron

It is used to pre-accelerate particles entering before the *AGS*

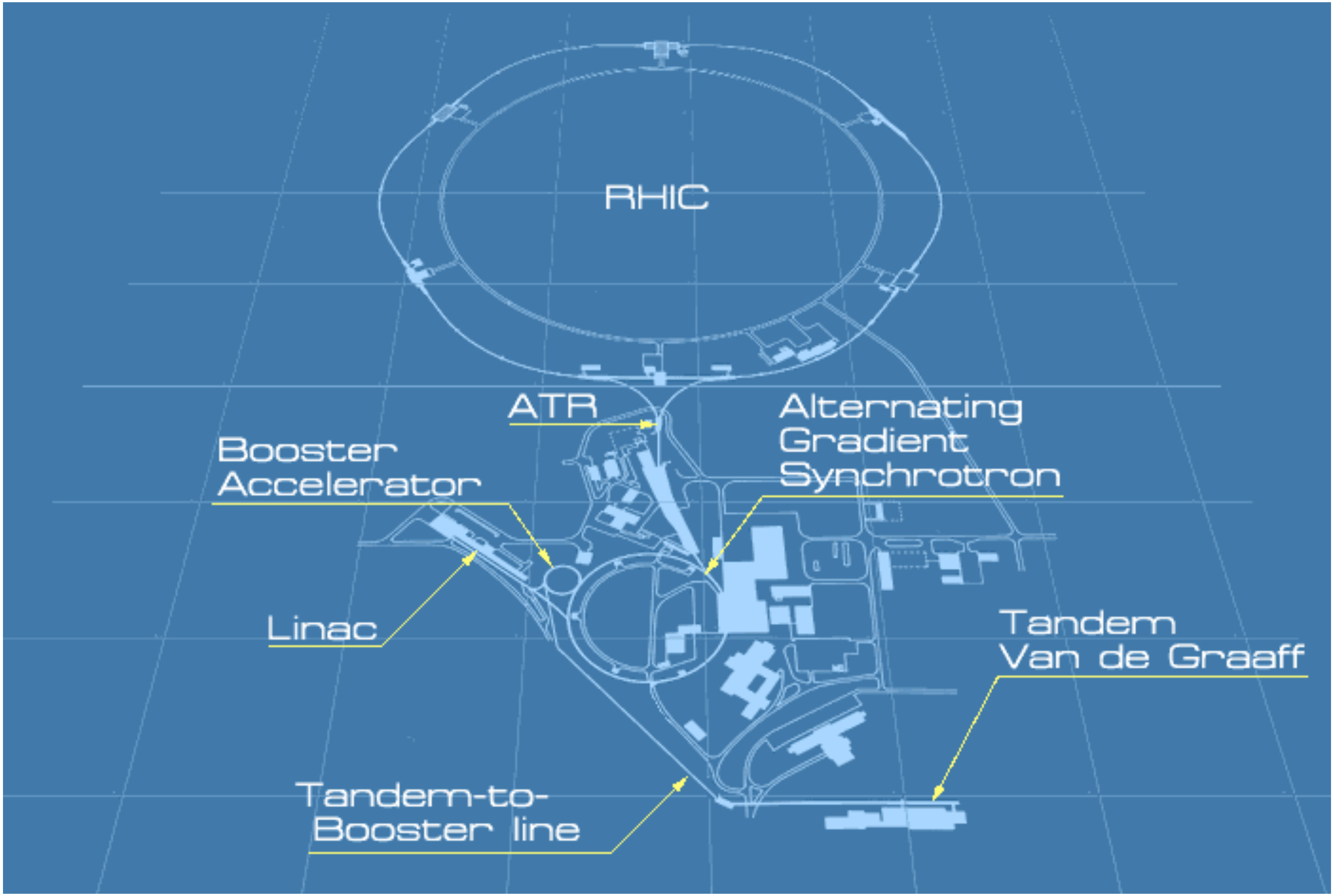
Compact circular accelerator

The 600 μs long ion pulse from tandem multiple times injected into Booster (accumulating intensity!)

- Beams captured in 6 bunches
- Accelerated to 95 MeV/u
- Foil at exit strips all electrons except 2 tightly bound K-shell electrons
- $4.3 \cdot 10^9$ ions from Tandem ⇒ ~ $2 \cdot 10^9$ ions from Booster



RHIC Complex



Alternating Gradients

Synchrotron:

beam focused in the vertical direction

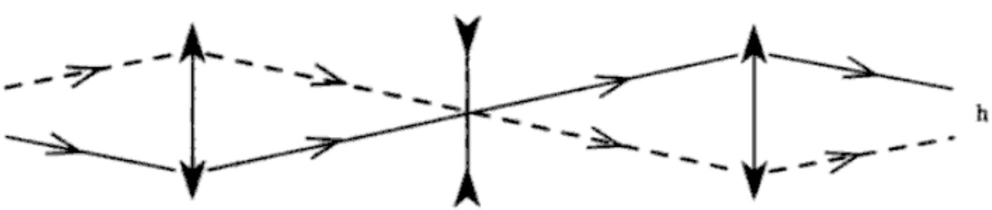
but trajectory unstable in the horizontal direction => leading to beam loss.

This could only be overcome by using more powerful (and far heavier) magnets and drastically increasing the size of the machine.

1958: Courant, Snyder: Discovery of **alternating gradient focusing**

Net effect of alternating the field gradient: vertical and horizontal focusing of protons could be made strong at the same time

Birth of modern accelerator lattice



Optical Analog

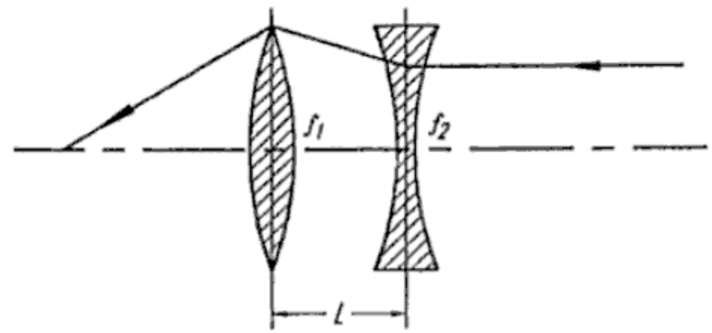


Figure 1 Doublet that is focusing overall

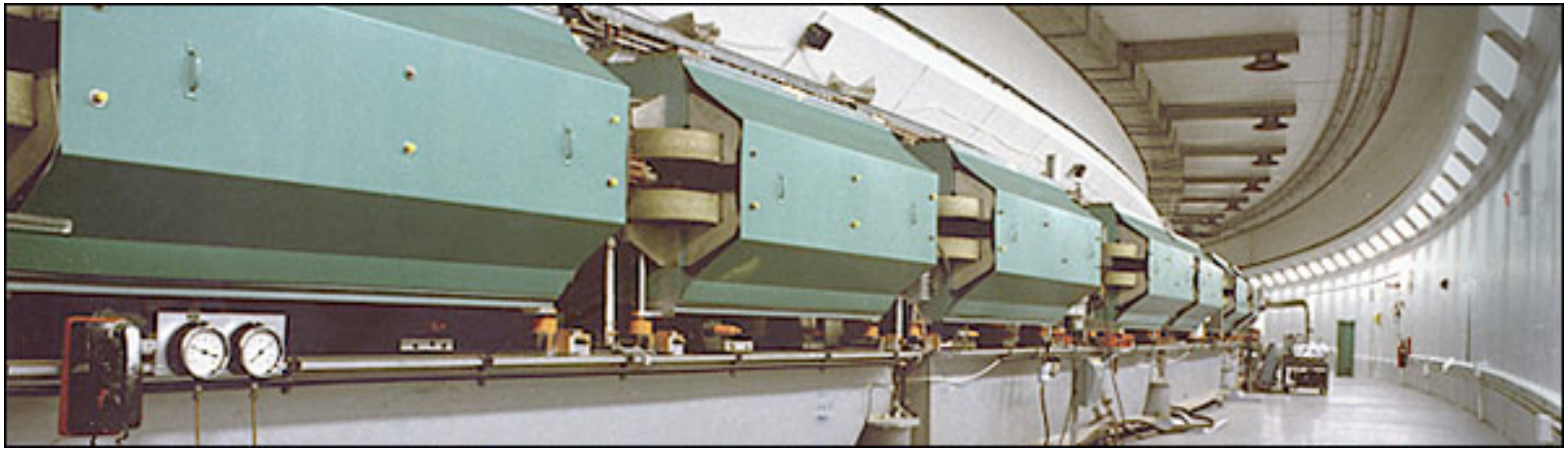
$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{L}{f_1 f_2} .$$

F remains positive over large range even when f_1 and f_2 are not equal but still opposite signs

Intuitively: although beam may be defocused by one lens it arrives at the following lens further from the axis and is then focussed more strongly

Alternating Gradient Synchrotron (AGS)

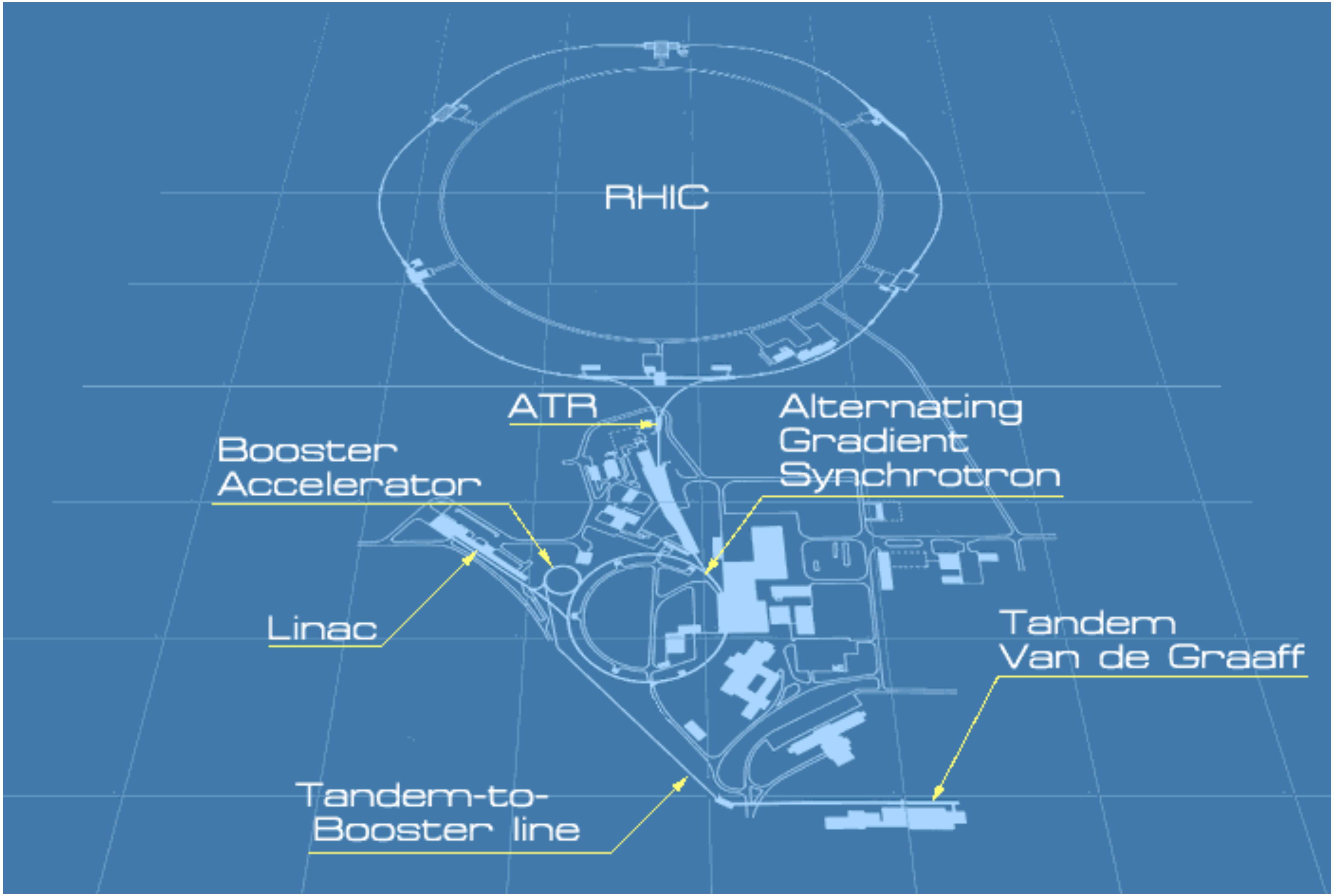
The AGS name is derived from the concept of alternating gradient focusing
Produced 3 Noble prices (J/ψ, CP with K, ν_μ)
240 “warm’” magnets
Luminosity now at 7,600 times the design value



AGS is filled in 4 Booster cycles with 24 bunches

- debunched and rebunched into 4 bunches (1 bunch = 1 Booster filling = (later) 1 RHIC bunch)
- accelerated to 8.86 GeV/u with Q=+77 (Au)
- at exit ions fully stripped
- via AtR beamline to RHIC

RHIC Complex



RHIC Recipe

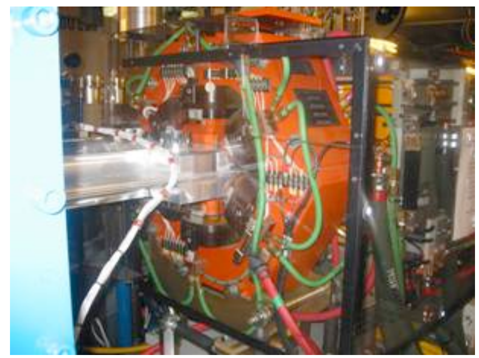
To built a collider you need:

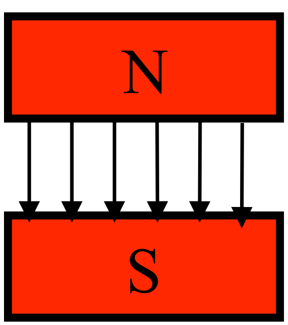
- Ring-shaped beam pipe(s) with good vacuum inside.
- Strong magnets forming a lattice to bend the particle beams and force them to circulate. RHIC magnets are super-conducting.
- Accelerating devices (so called “RF cavities”) to increase the particles energy (or speed) => ramp.
- Maintain high beam currents and small profiles to guarantee high collision rates.

Design and Available Tools ...

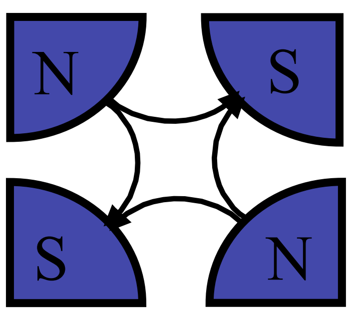
- Given an existing lattice, determine the properties of the beam
  - ➡ in principle straight-forward to solve
- For desired beam properties, determine the design of the lattice.
  - ➡ not straight-forward – a bit of an art



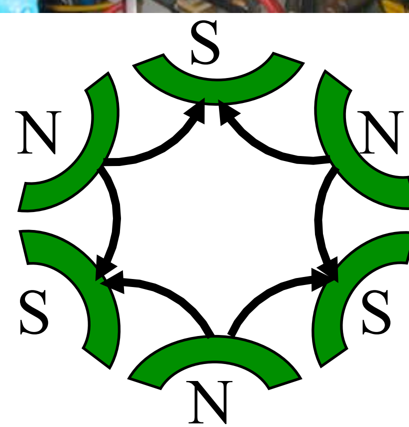




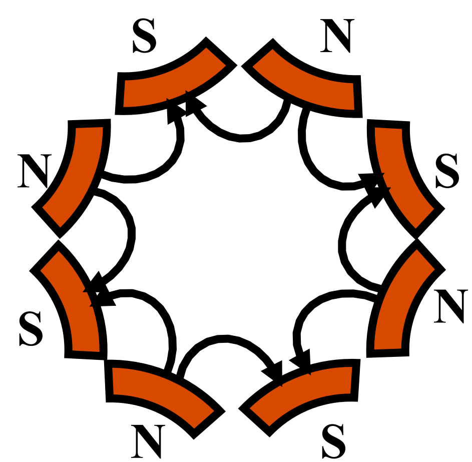
Dipole



Quadrupole



Sextupole



Octupole

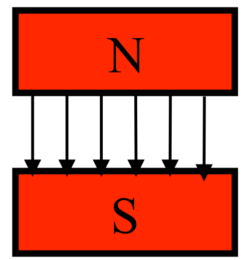
... and Rules

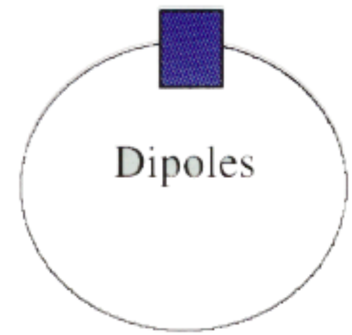
What are the various magnet types for?

Dipoles $\Rightarrow$ guiding

$B_x = 0$

$B_y = B_o$

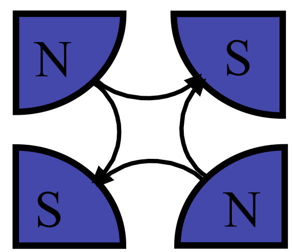


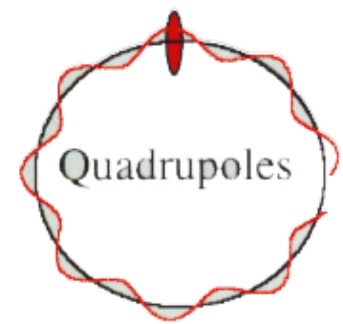


Quadrupoles $\Rightarrow$ focussing

$B_x = Ky$

$B_y = Kx$

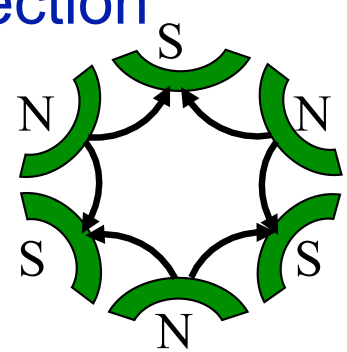




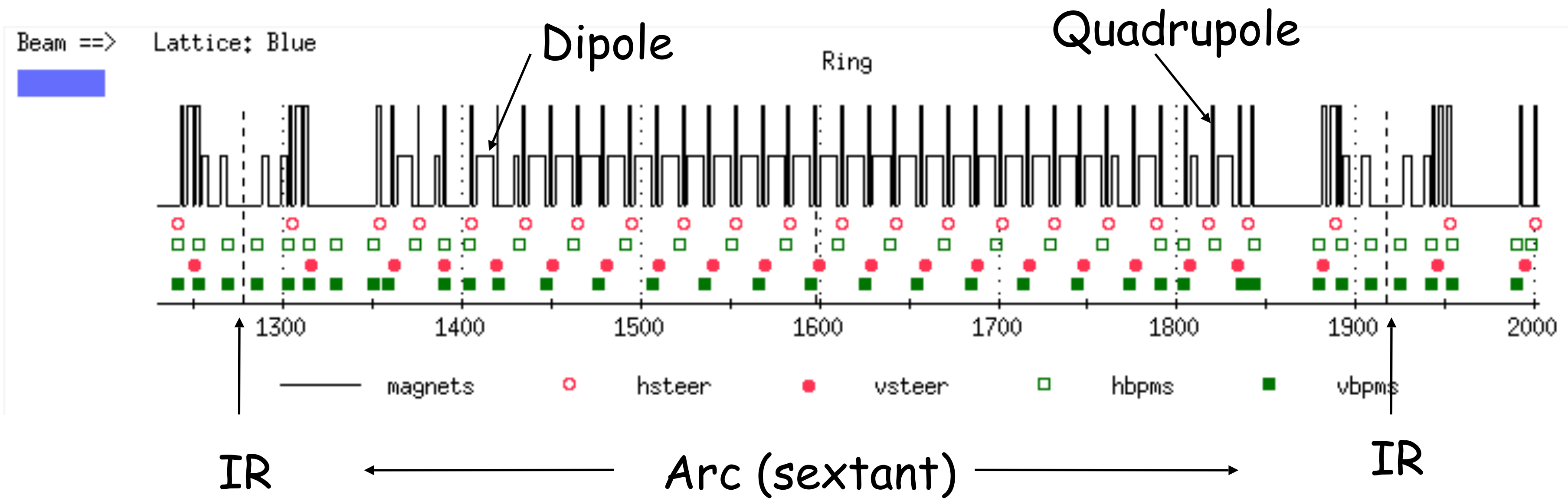
Sextupoles $\Rightarrow$ chromatic correction

$B_x = 2Sxy$

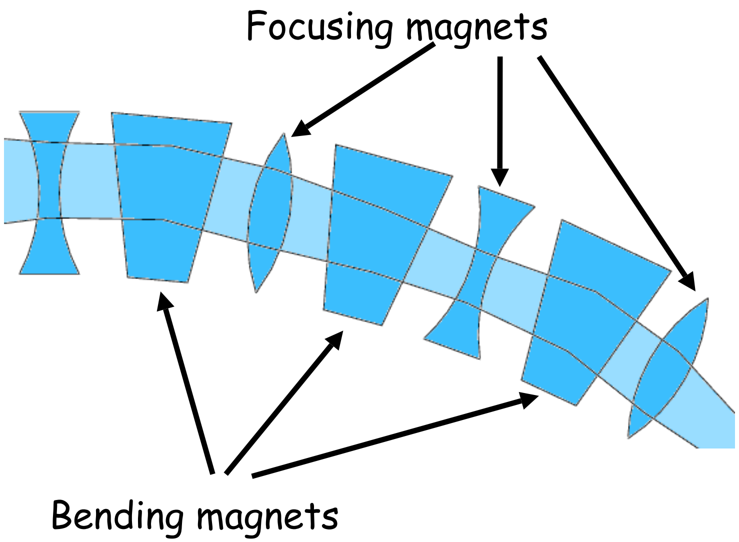
$B_y = S(x^2 - y^2)$



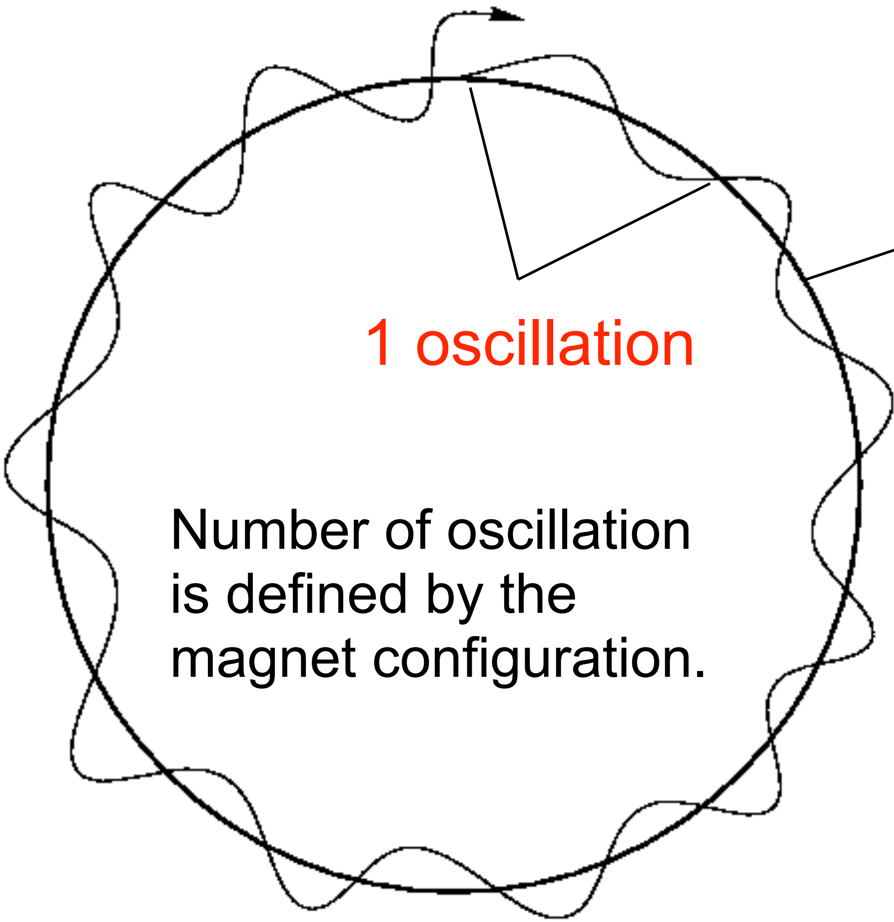
RHIC lattice



- One arc is built of a regular series of dipoles (bend) and quadrupoles (focus).
- RHIC consists of 6 Interaction Regions (IR) and 6 arcs.
- A certain power configuration of those magnets is called a **lattice**.



Circulate: Betatron Motion



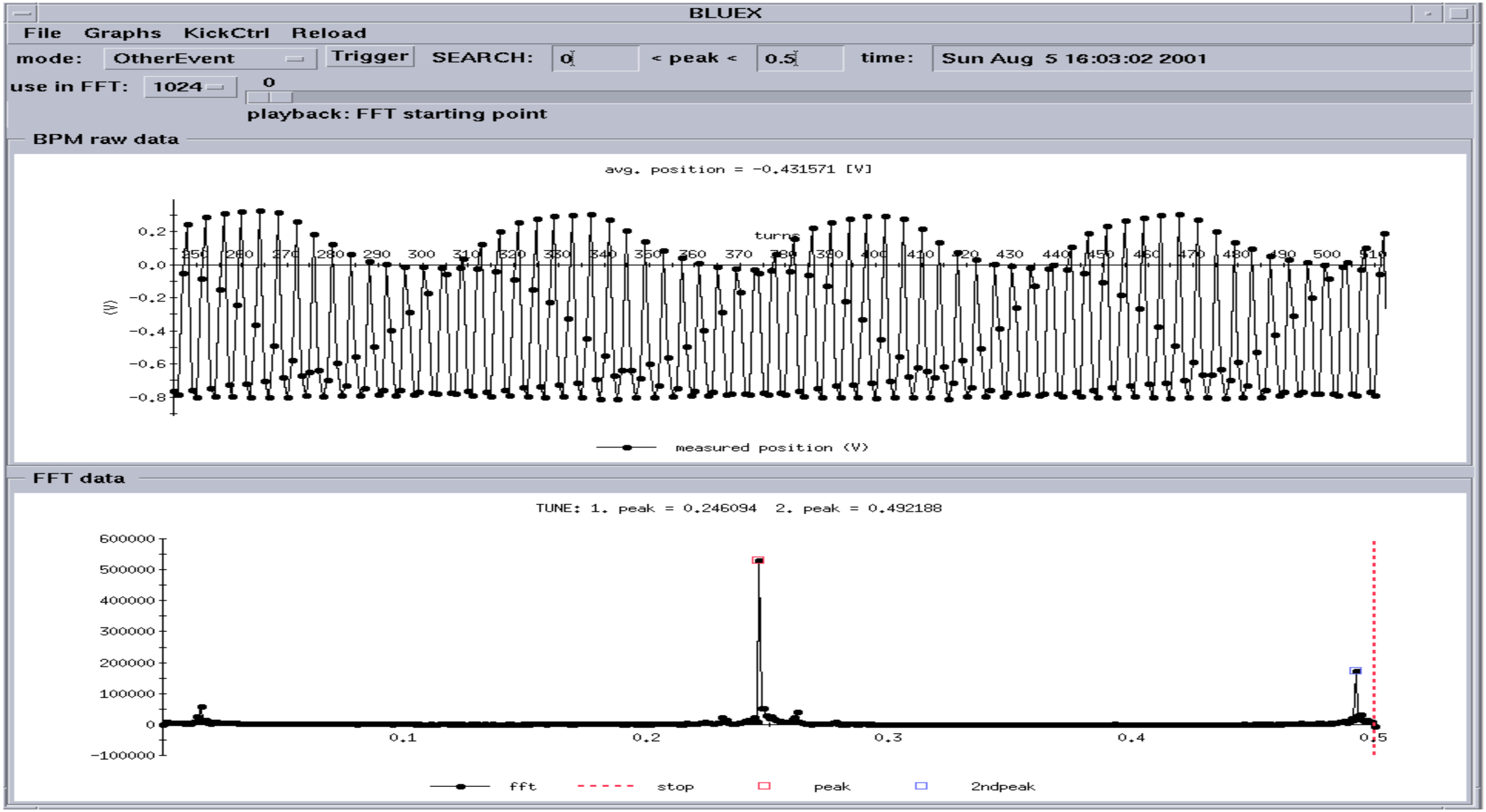
Particles perform oscillations around closed orbit.

The number of oscillations per revolution is called the "tune".

Integer and 1/2 , 1/3, 1/4 … tunes would cause magnetic imperfections to be repetitive and resonant => beam loss

This example: tune = 11.27

Betatron Motion: The Tune



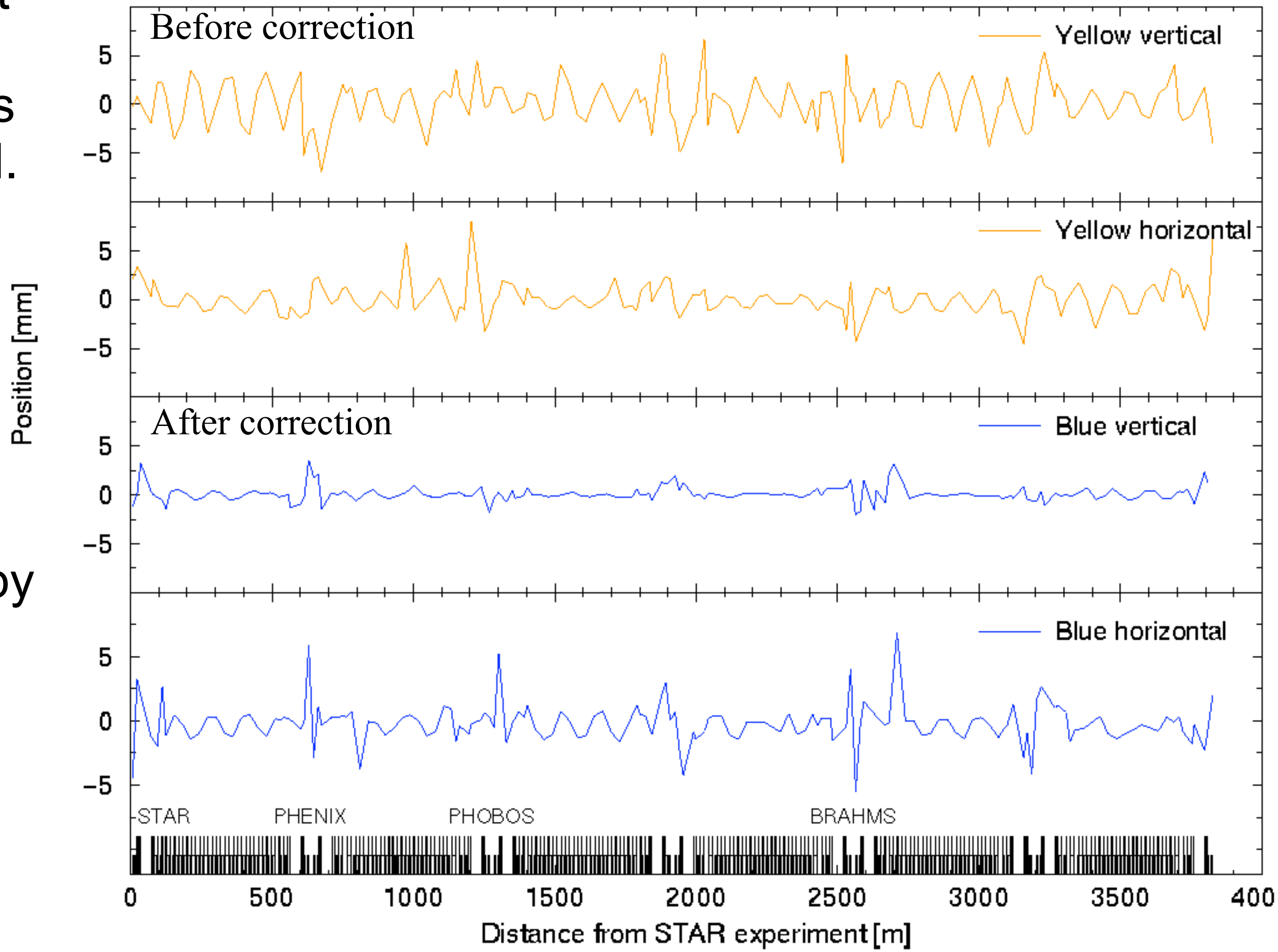
Upper plot: beam displacement from closed orbit as function of turn number

Lower plot: frequency analysis (FFT) of above data to determine the number of oscillation per turn = tune

Typical closed orbits:

The closed orbit is the average path all particles oscillate around.

It is measured by hundreds of beam position monitors (BPM) along the two beam pipes.



Accelerate

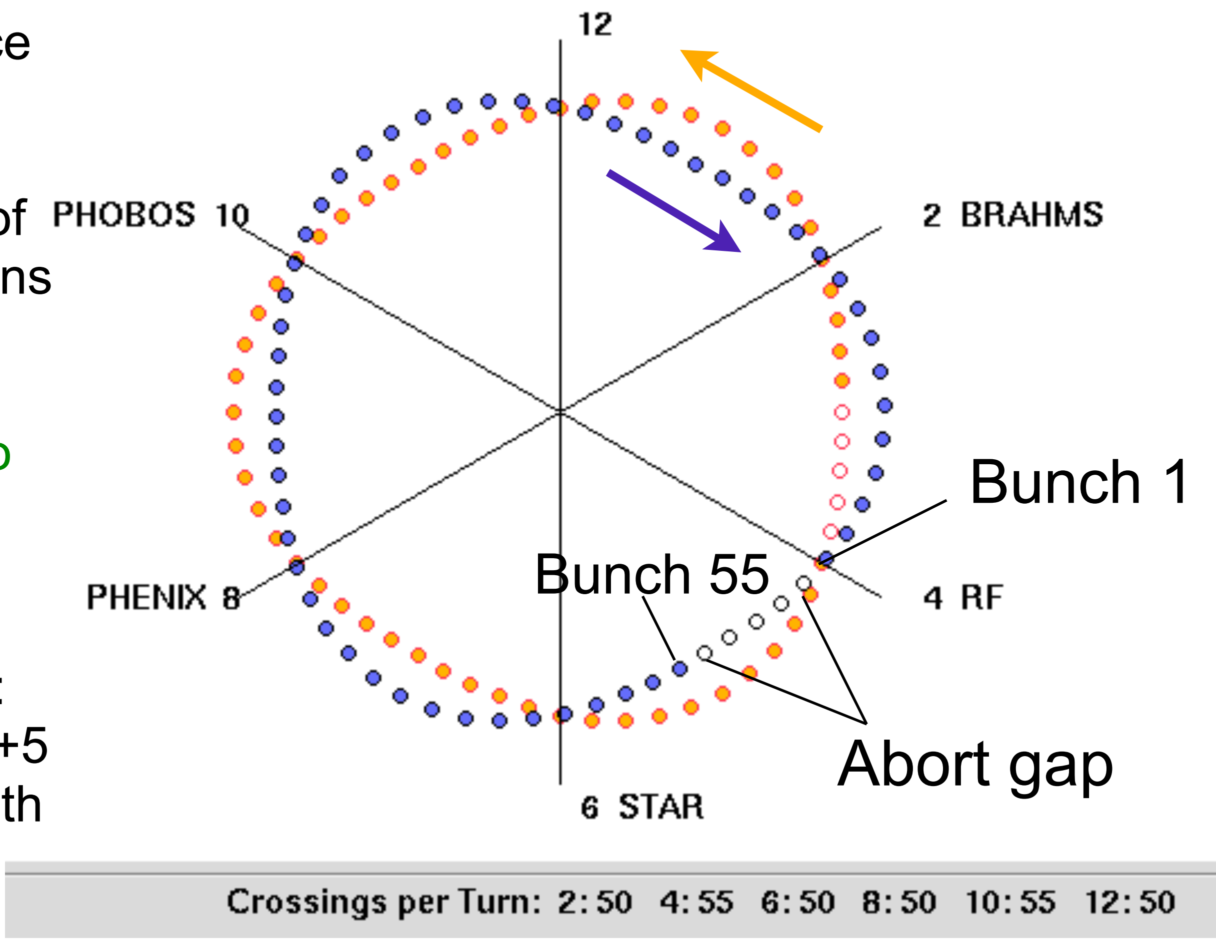
Beam is accelerated by Radio Frequency (RF) cavities:
28 MHz for acceleration
200 MHz for storage to reduce bunch length

28 MHz defines the number of “buckets” = 360, length is 35 ns each (or ~10.7 m)

Note: a continuous beam (no bunch structure), cannot be accelerated

Bunched (or captured) beam: every 6th (3rd) bucket, i.e. 55+5 (110+10) bunches per ring with 10^9 ions

Example: total of 55 bunches per ring

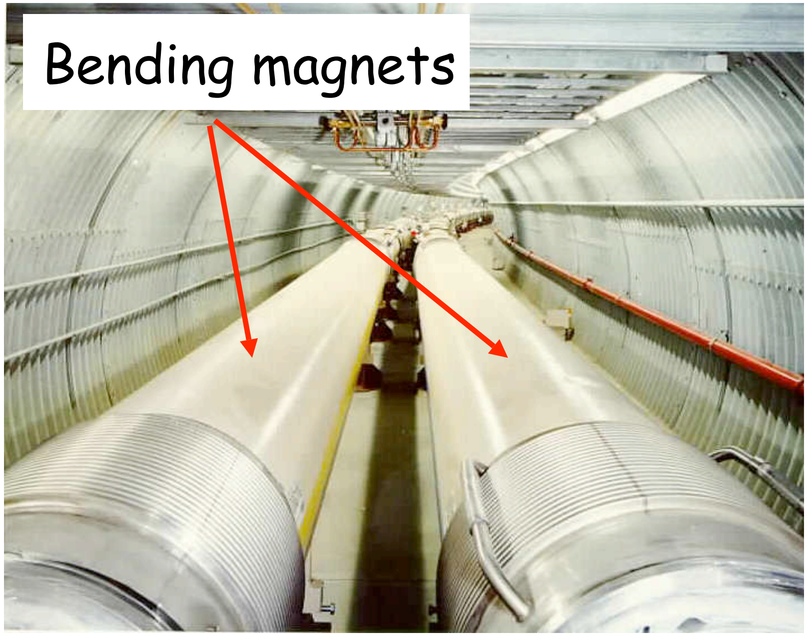


RHIC is now using 110+10 bunches

RHIC Pictures

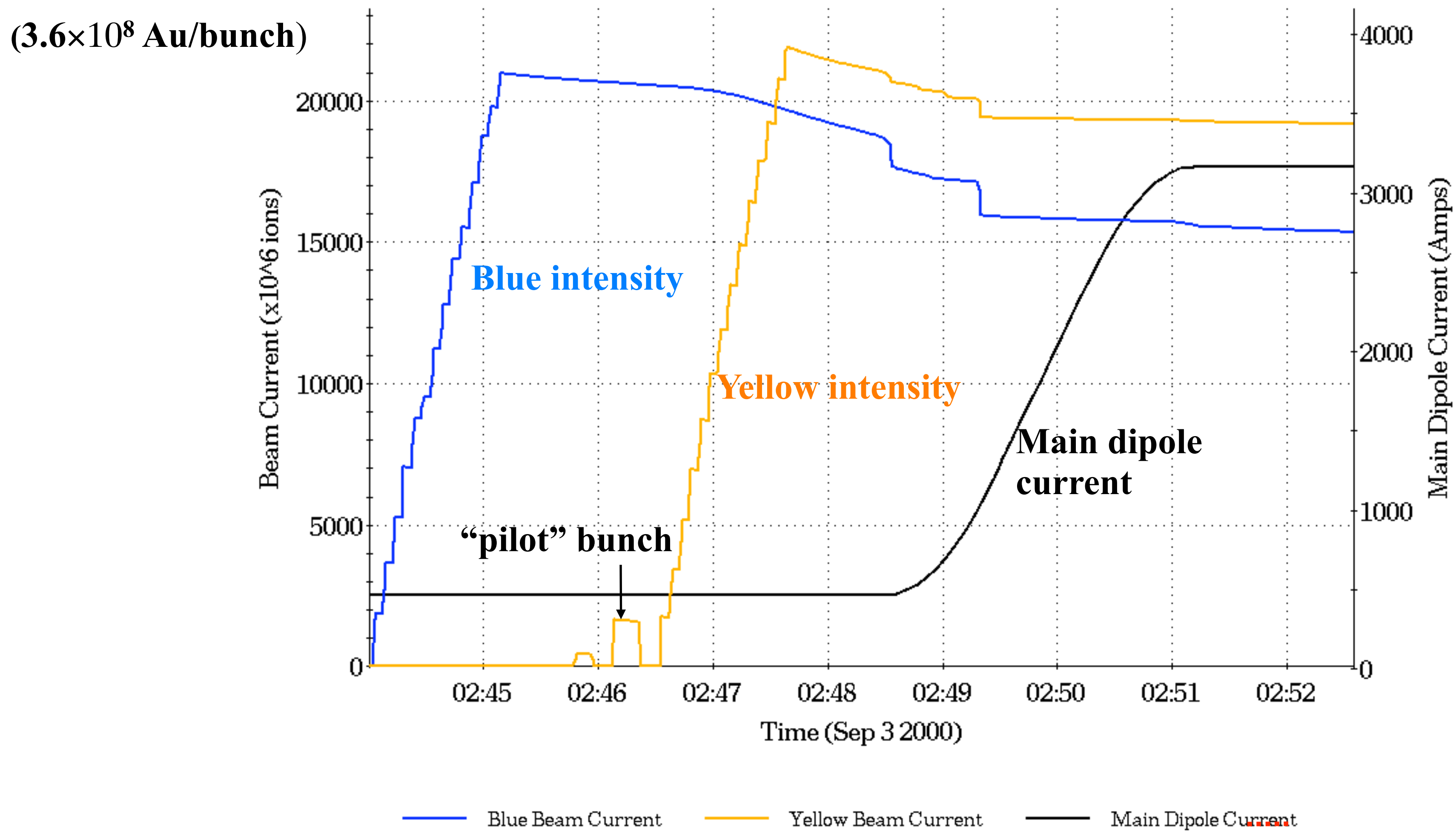
RHIC dipole magnet

RF storage cavities



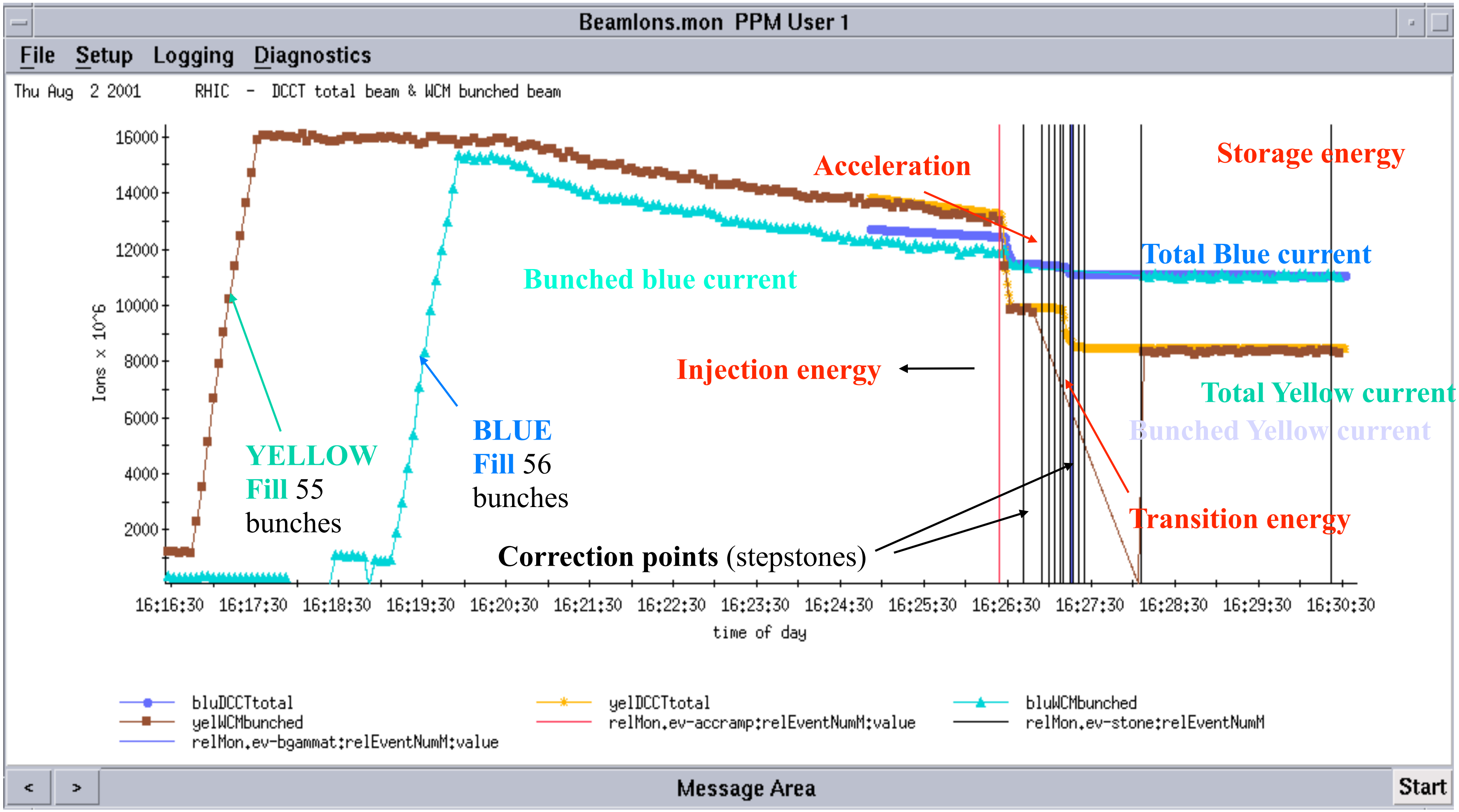
Blue and
yellow rings

RHIC Injection and Acceleration



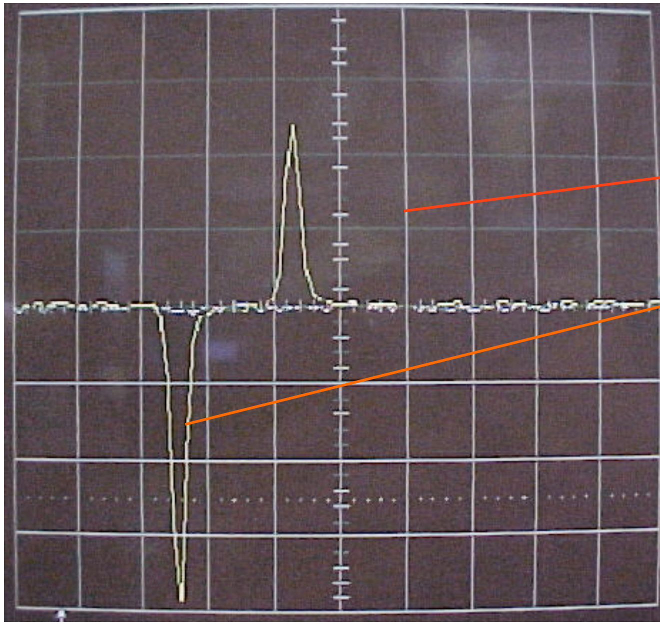
The beam is accelerated from Injection Energy (10 GeV) to Storage Energy (100 GeV). The acceleration process is called "ramp".

RHIC ramp with 56 bunches in detail



The beam is accelerated from Injection Energy (10 GeV) to Storage Energy (100 GeV). The acceleration process is called “ramp”.

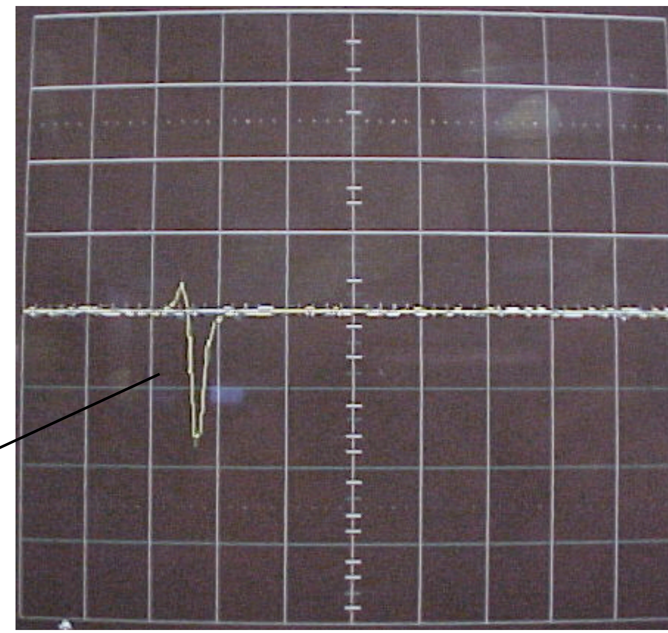
Bringing beams into collision (cogging)



Beam in blue ring

Beam in yellow ring

200 ns (60 m)



Beams in collision at the interaction regions

200 ns (60 m)

Dispersion

Beam particles are not mono-energetic, they have a momentum spread $p_0+\Delta p$

Dispersion function D(s,p) relates horizontal displacement with momentum deviation:

$$x(s) = D(p,s)\frac{\Delta p}{p_0}$$

Particles with different momenta will follow closed orbits of differing length => shift in arrival time

$$\text{momentum compaction} : \alpha = \frac{dR/R}{dp/p}$$

$$\frac{dT}{T} = -\frac{d\omega}{\omega} = \left(\alpha - \frac{1}{\gamma^2}\right)\frac{dp}{p}$$

$$\frac{dT}{T} = -|A|\frac{dp}{p} \quad \text{for} \quad \beta \approx 0$$

$$\frac{dT}{T} = |A|\frac{dp}{p} \quad \text{for} \quad \beta \approx 1$$

Particle has critical energy at transition when $\alpha=1/\gamma^2$

Typical:

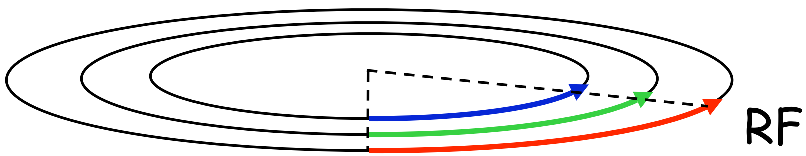
$\alpha=10^{-1}$ ... 10^{-3}

$\gamma=3$ ... 30

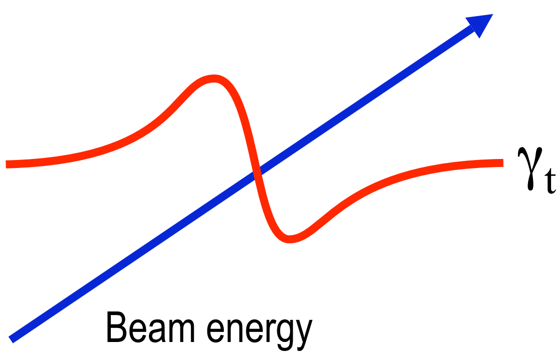
E_p = 3 ... 30 GeV

Transition energy crossing

RHIC is the first super conducting, slow ramping accelerator to cross transition energy (~ 23 GeV):



Cross unstable transition energy γ_t by rapidly changing transition energy (2001) using special quadrupoles:



Avoids beam loss and longitudinal emittance blow-up

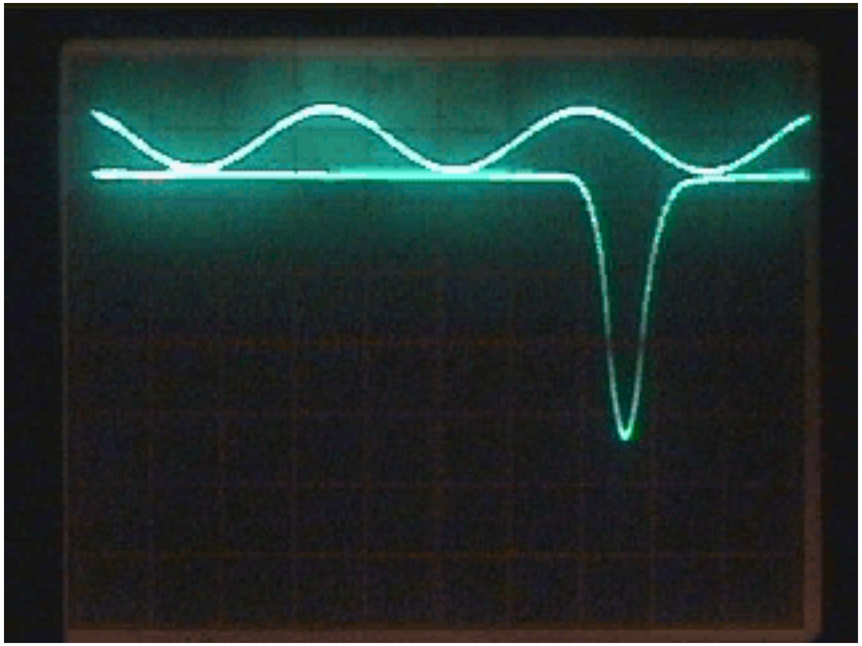
What is "transition" ?

- ⇨ below transition fast particles arrive early at the RF
- ⇨ with increasing energy fast particles go more and more to the outside (Dispersion!)
- ⇨ above transition fast particles arrive late at the RF
- ⇨ at transition all particles arrive at the same time: short and unstable bunches!

Transition Crossing - Movie

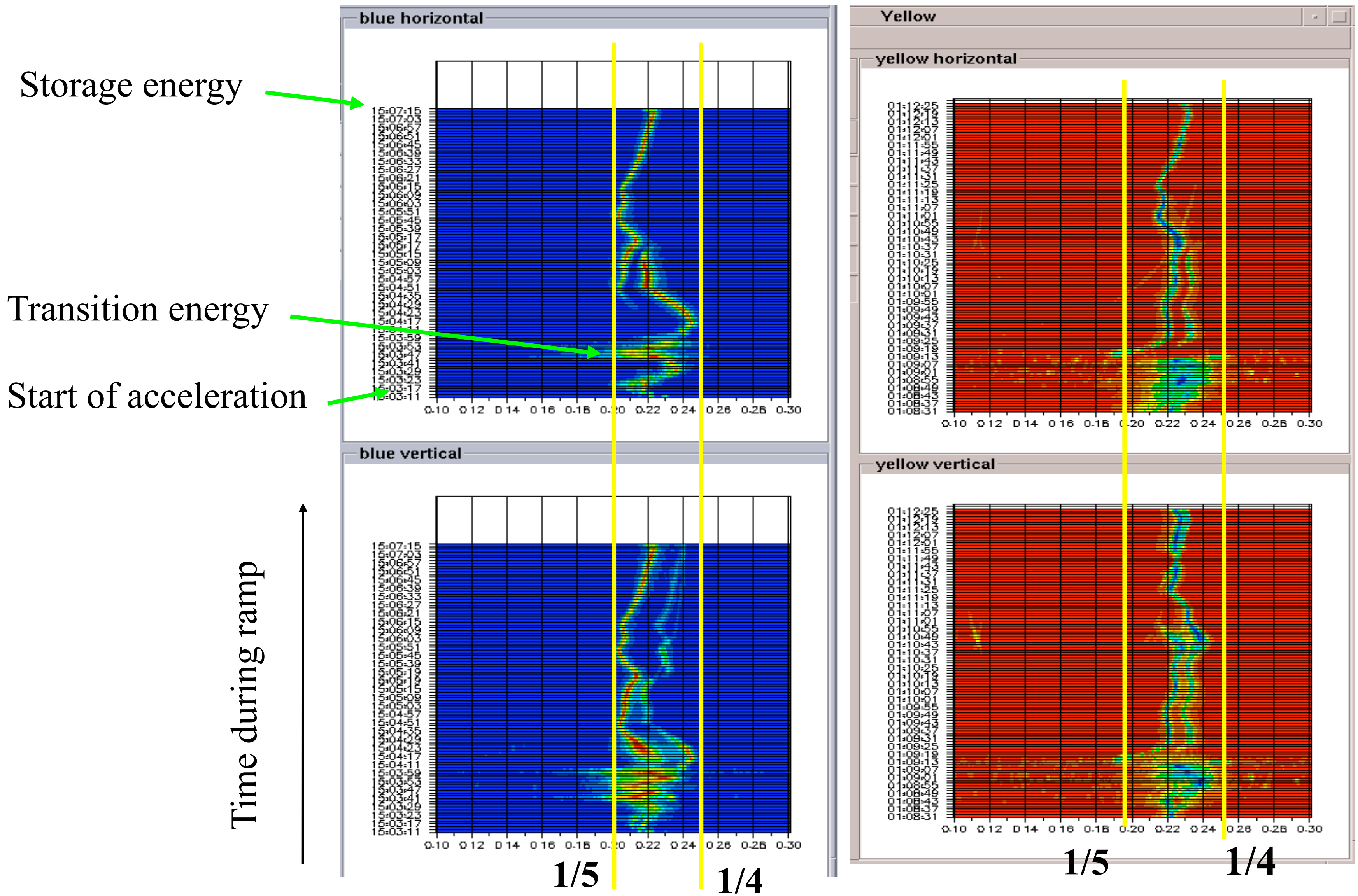
Upper trace: 28 MHz f_{RF}

Lower trace: 1 bunch, longitudinal distribution



Transition: Watch for phase jump and very narrow bunch distribution.

Tune measurements during acceleration ramp



Beam is lost when the tunes cross 1/5 or 1/4 resonances.

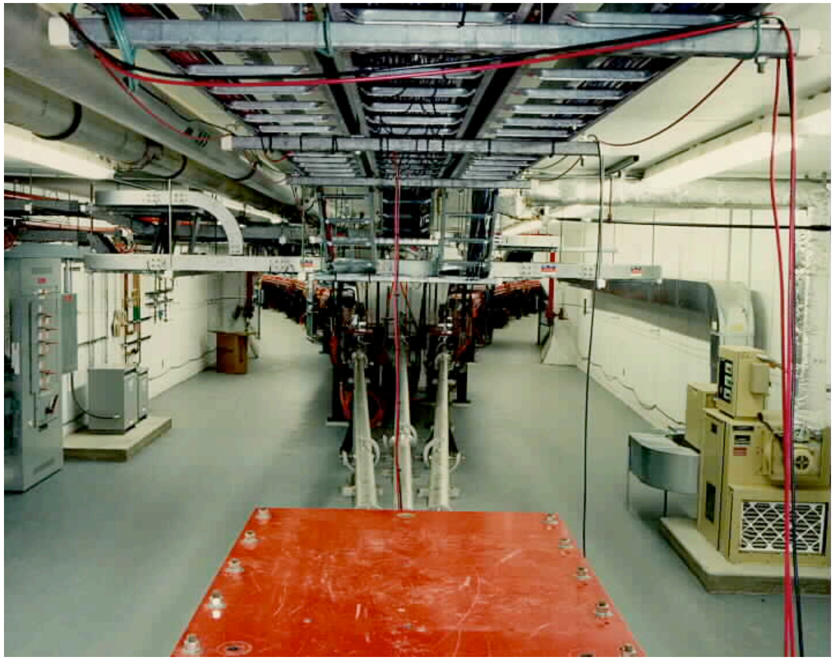
How the ions get into RHIC .... and out

AtR -> RHIC: vertical pitching magnets

Beam injection: box-car fashion one bunch at a time

AGS cycle is repeated 14 times for 56 RHIC bunches

Filling is done RF bucket wise (360 RF buckets)



Injection arcs (AtR) to blue and yellow rings (switching magnet)

Beam is “disposed” (dumped) after ~4-6h (Au+Au), ~8h (p+p) in a single turn (12 μs) via abort kickers into a mix of graphite, steel and marble
Note: 200kJ/12 μs ~ 17 GW

Number of Merit: Luminosity

Luminosity L: measure for delivered intensity (number of merit)

$N = L \cdot \sigma$ where

N is the reaction rate of specific process

σ is the cross-section for this process

Units: $s^{-1}\ cm^{-2}$

A more practical units would be (but is never used):

$\Rightarrow 1\ s^{-1}\ cm^{-2} = 10^{-24}\ s^{-1}\ b^{-1} = 10^{-21}\ s^{-1}\ mb^{-1}$ (since 1 barn = $10^{-28}\ m^2$)

Some typical cross-sections at $\sqrt{s}$ = 200 GeV (approx.):

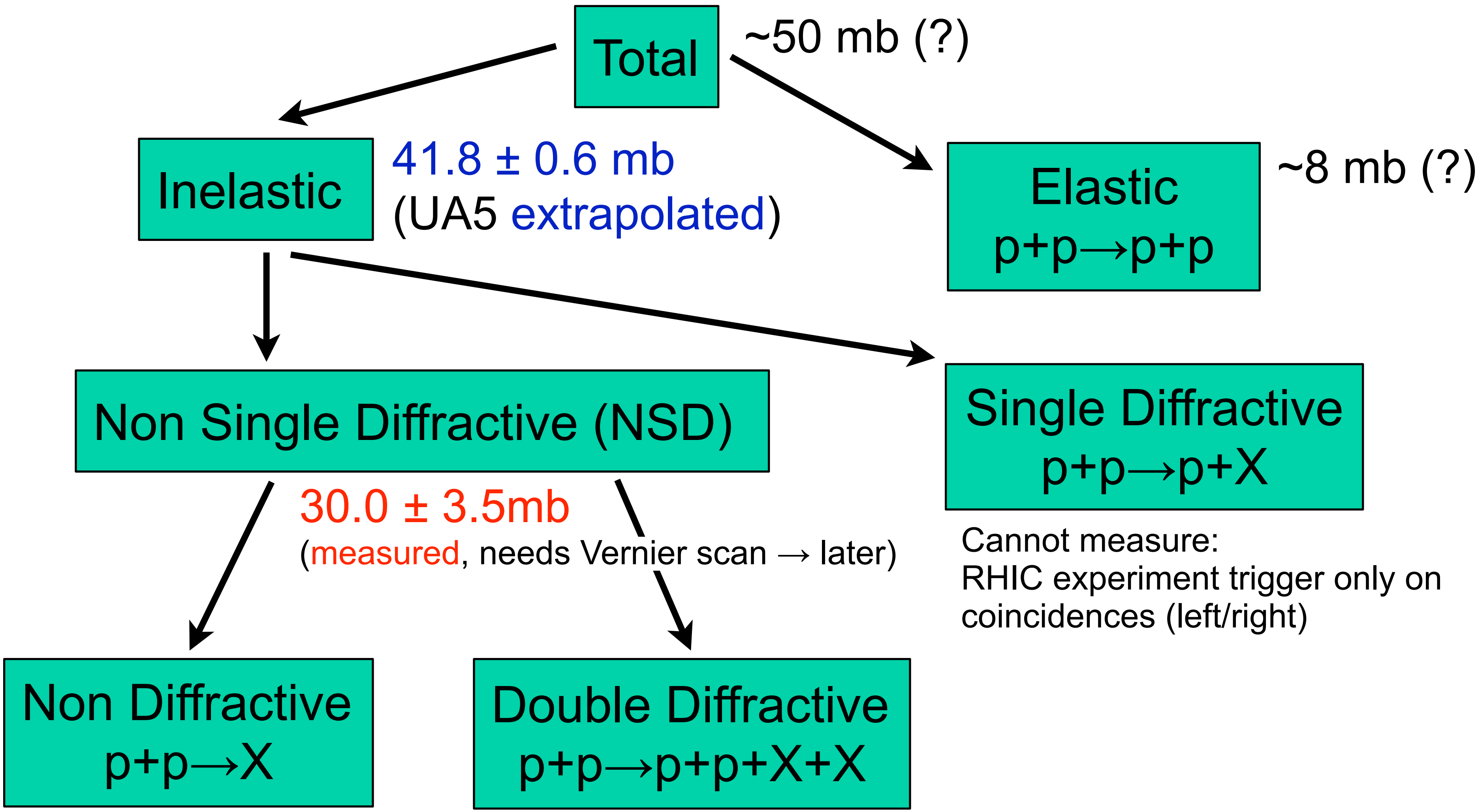
p+p total cross-section: σ_{tot} = 42 mb

J/ψ production cross-section: $\sigma_{J/\psi}$ = 3 μb

Au+Au total cross-section: σ_{abs} ~ 10 b $\sigma_{hadronic}$ ~ 7 b

N.B.: p+p collisions and cross-sections

People get this wrong quite often therefore ($\sqrt{s}$=200 GeV):



What we measure σ_{NSD} ⊗ trigger efficiency ~ 26 mb

N.B.: Au+Au collisions and cross-sections

A bit murky ...

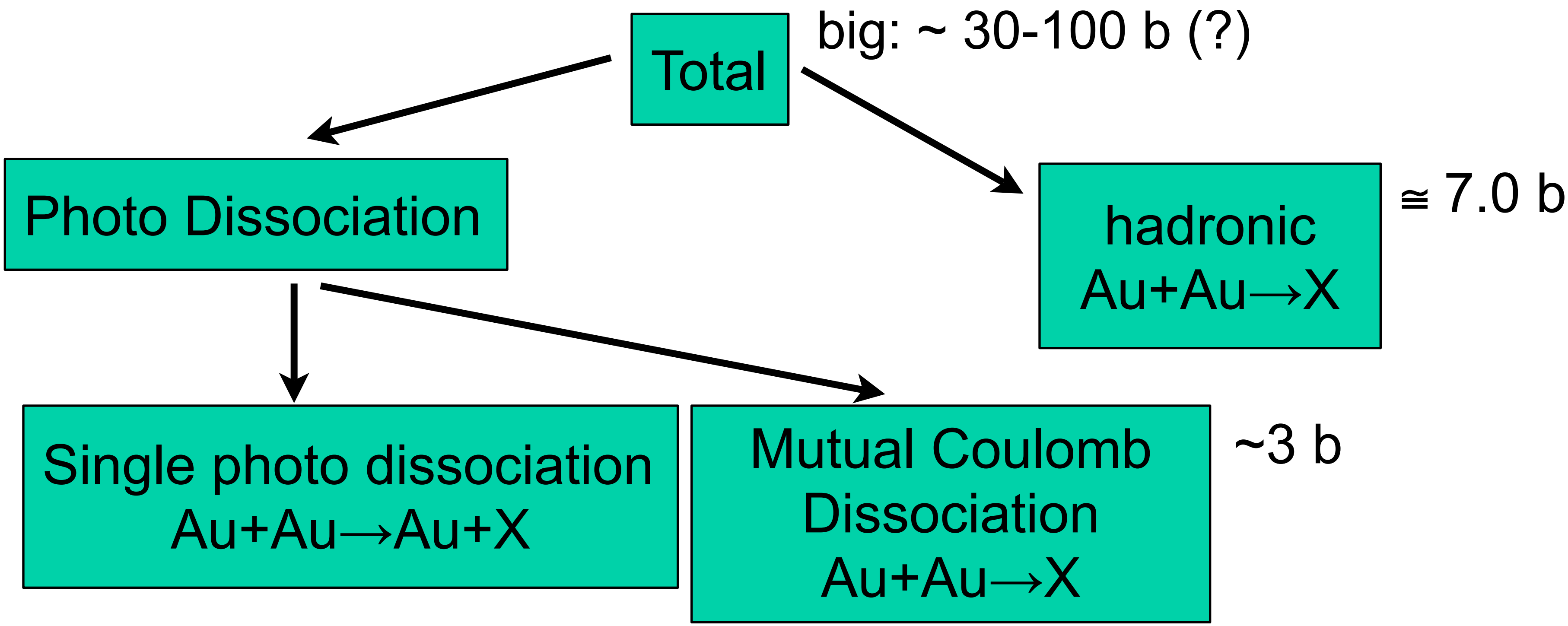


Photo Dissociation:
Coulomb fields (Z^2) → Giant Dipole Resonance → breakup

Common term: hadronic + mutual coulomb diss. is called σ_{abs} (~10b) because in neither case the Au survives and we end up with final state hadrons

RHIC Luminosity

$$L = \frac{3 f_{rev}\gamma}{2}\frac{N_B N^2}{\varepsilon\beta^*}$$

Other high luminosity hadron colliders:

	achieved	goal	scaled to 200 GeV
Tevatron (2 TeV)	128×10^{30}	200×10^{30}	20×10^{30}
LHC (14 TeV)		10000×10^{30}	140×10^{30}

RHIC Design (store average):

Au+Au: 2×10^{26} s^{-1} cm^{-2}

p+p: 4×10^{30} s^{-1} cm^{-2}

Achieved so far:

Au+Au: 12×10^{26} s^{-1} cm^{-2}

p+p: 20×10^{30} s^{-1} cm^{-2}

Note on total yields/run:

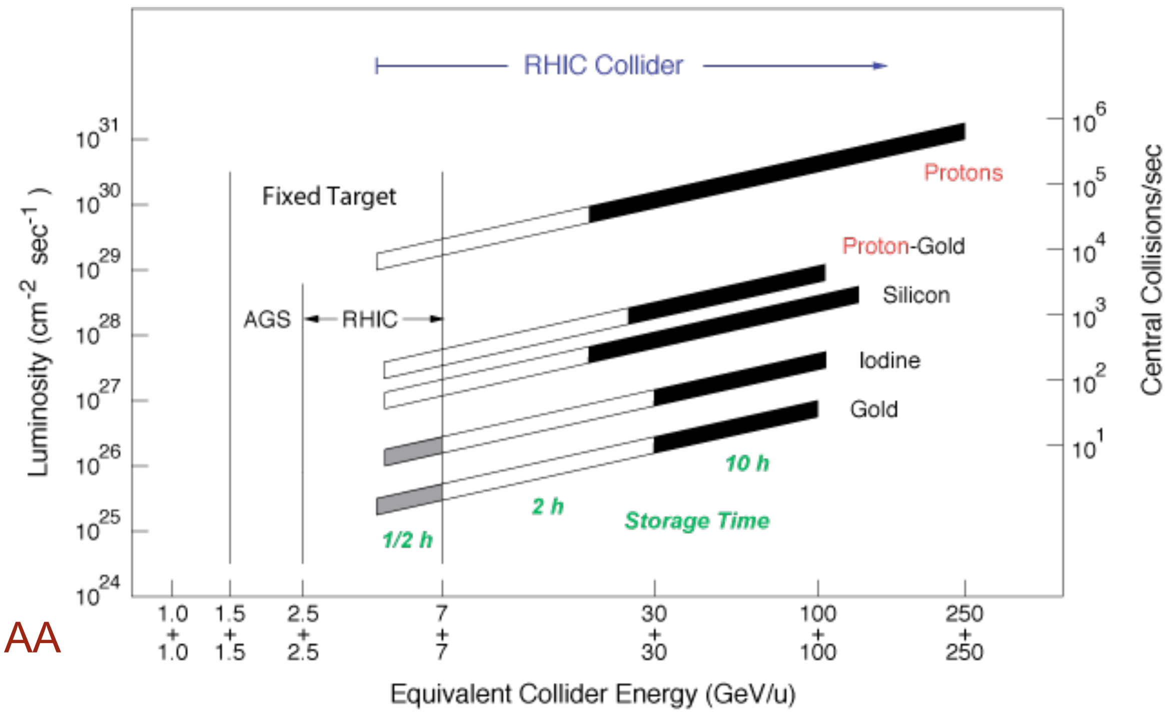
$\sigma_{AA} = \sigma_{pp}\times A\times A$

$N_{pp} = L\times\sigma_{pp}$

$N_{AA} = L\times\sigma_{pp}\times A\times A$

$L/(A\times A) \sim \text{const} \Rightarrow N_{pp} \approx N_{AA}$

RHIC (Design Values):



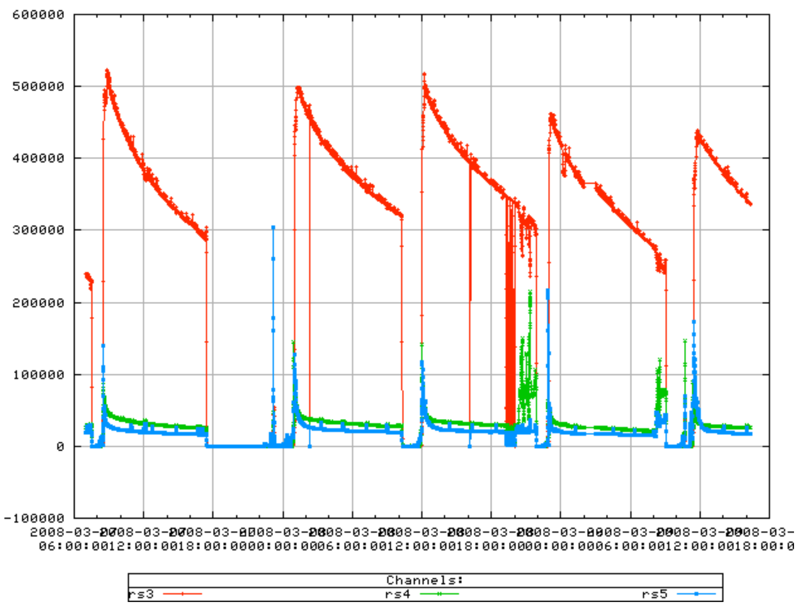
RHIC Efficiency

Probability(things break) > 0

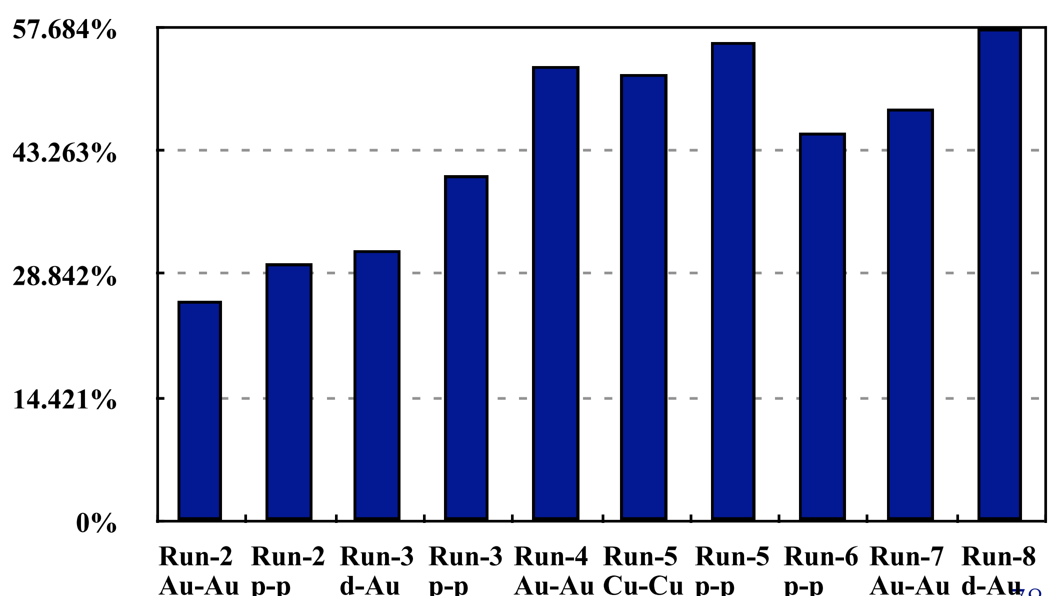
- magnet quench
- power supply problems
- beam loss limits measures

Most problems occur when filling/ramping

Big question: running with low rate and keeping beams to the very end or refilling and risk delays.



RHIC time in store



Optimizing RHIC Running

What counts at the end is integrated luminosity ∫Ldt

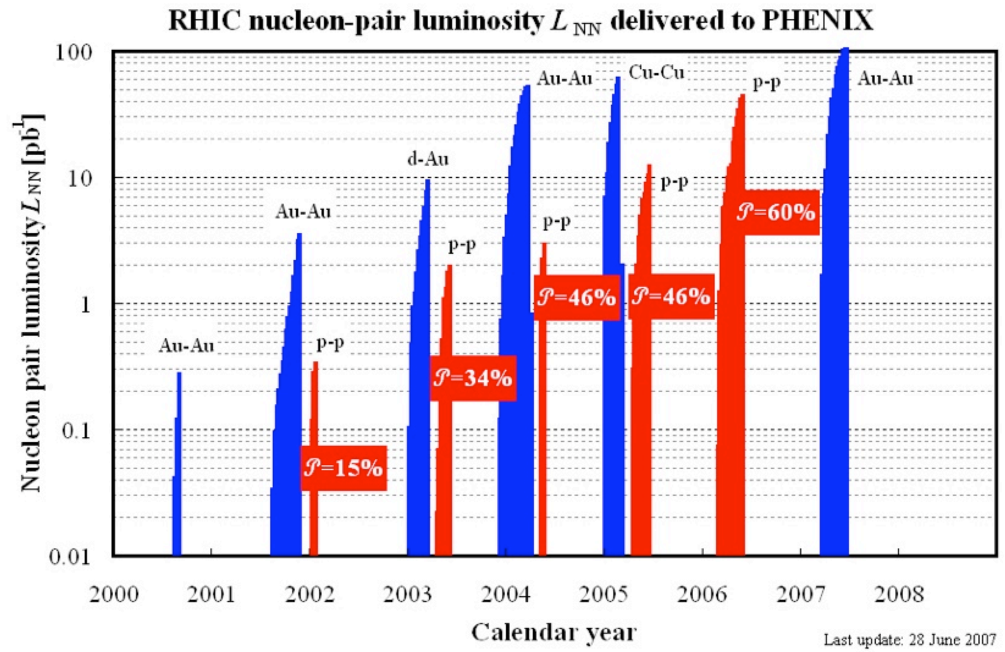
Rel. stat. err. ~ $(\int L dt)^{1/2}$

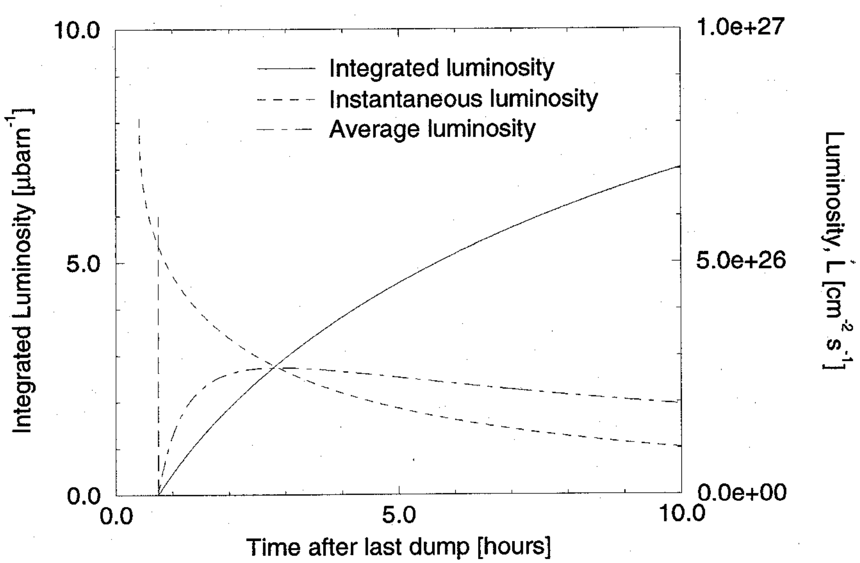
Nontrivial optimization process (experiment dependent)

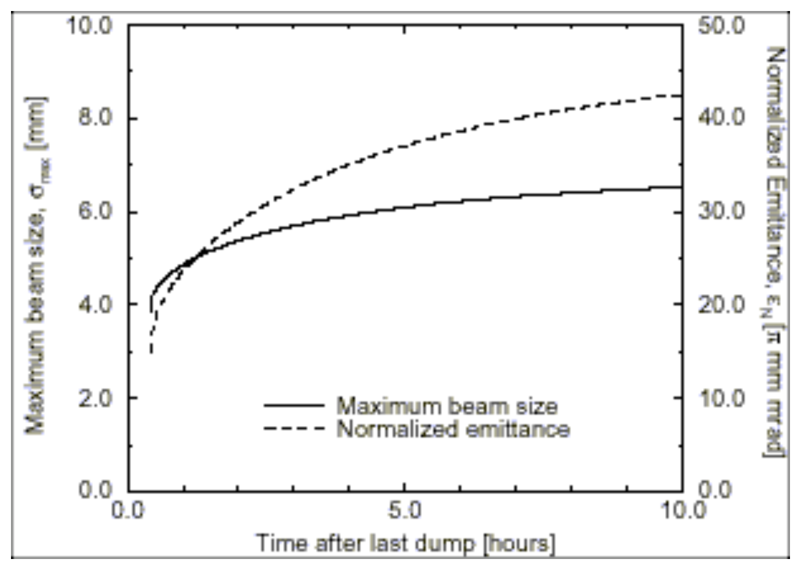
Schemes used:

Online voting (until 2005)

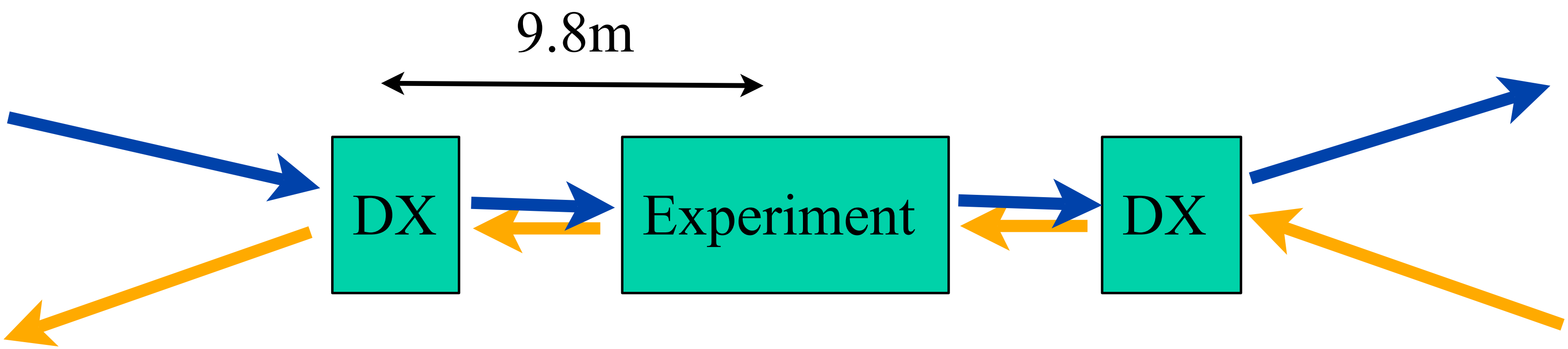
Fix fill time (2006/7/8)





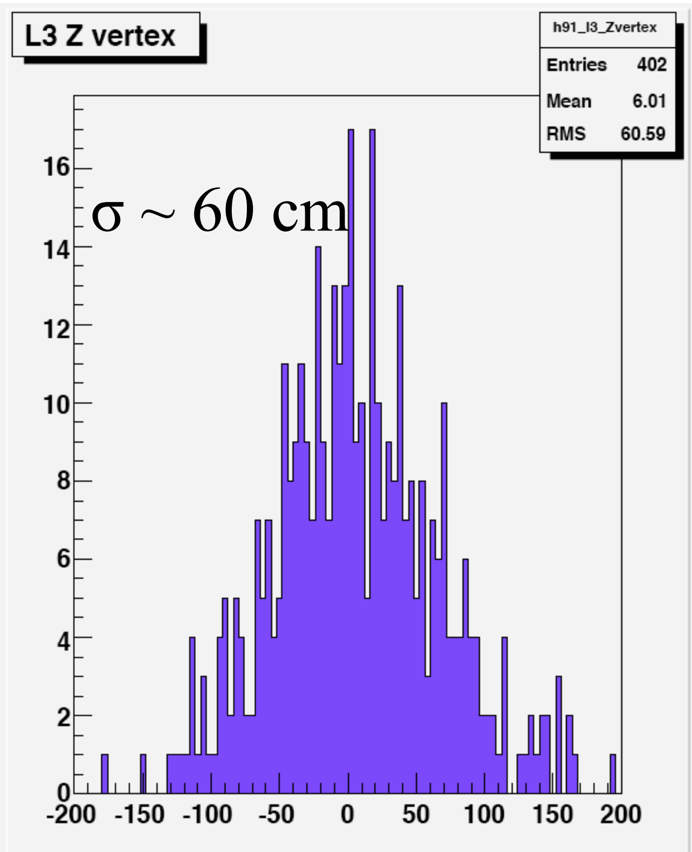


What else experimenters care about: vertices



- DX magnets ~ 9.8 m away from Interaction Region (IR)
- Note: there's no diamond as at ISR. The beams collide frontal with 0°
- the size of the vertex is given by the bunch length and its profile

... and it is unfortunate large



RHIC's future: RHIC-II

1. New ion source (EBIS)

Objectives

- Allow for U+U collisions, polarized ^3He
- Get rid of Tandem Van De Graaff (reduce costs)

2. Beam cooling (ions only)

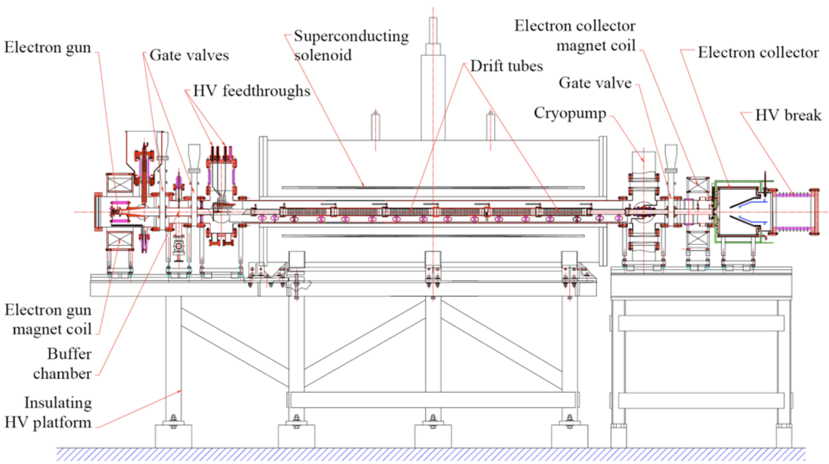
Objectives

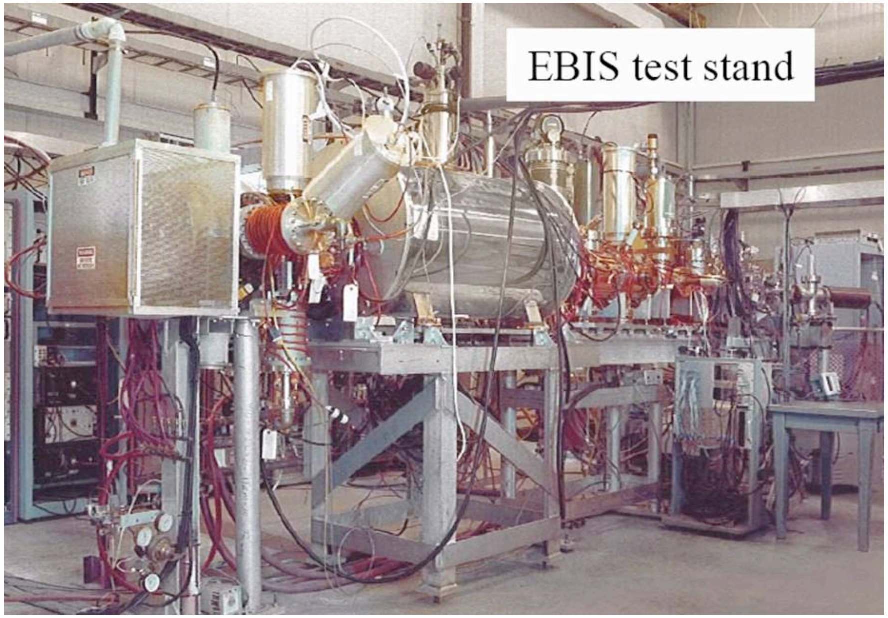
- Increase RHIC luminosity: For Au-Au at 100 GeV/A by 5-10
- Reduce background due to beam loss
- Allow smaller vertex

RHIC-II: EBIS Ion Source

New Ion Source:

- New high brightness, high charge-state pulsed ion source
- Replaces 35 year old Tandem Van de Graafs
- Improved reliability, lower operations costs
- Enables new beams: noble gas ions, Uranium, polarized 3He
- Construction schedule: FY2006 –10

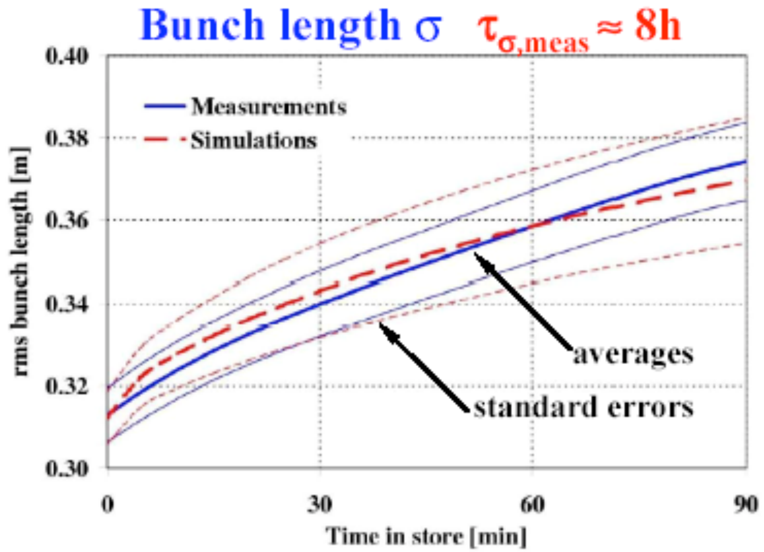


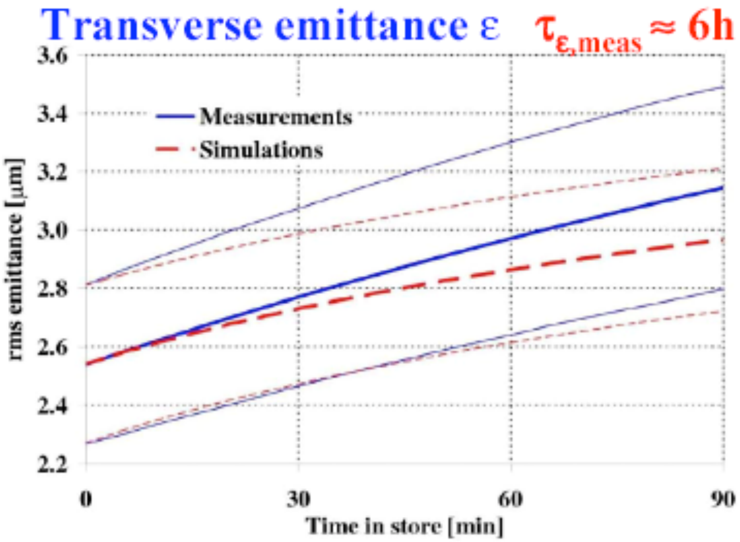


Intra-Beam Scattering (IBS) in RHIC

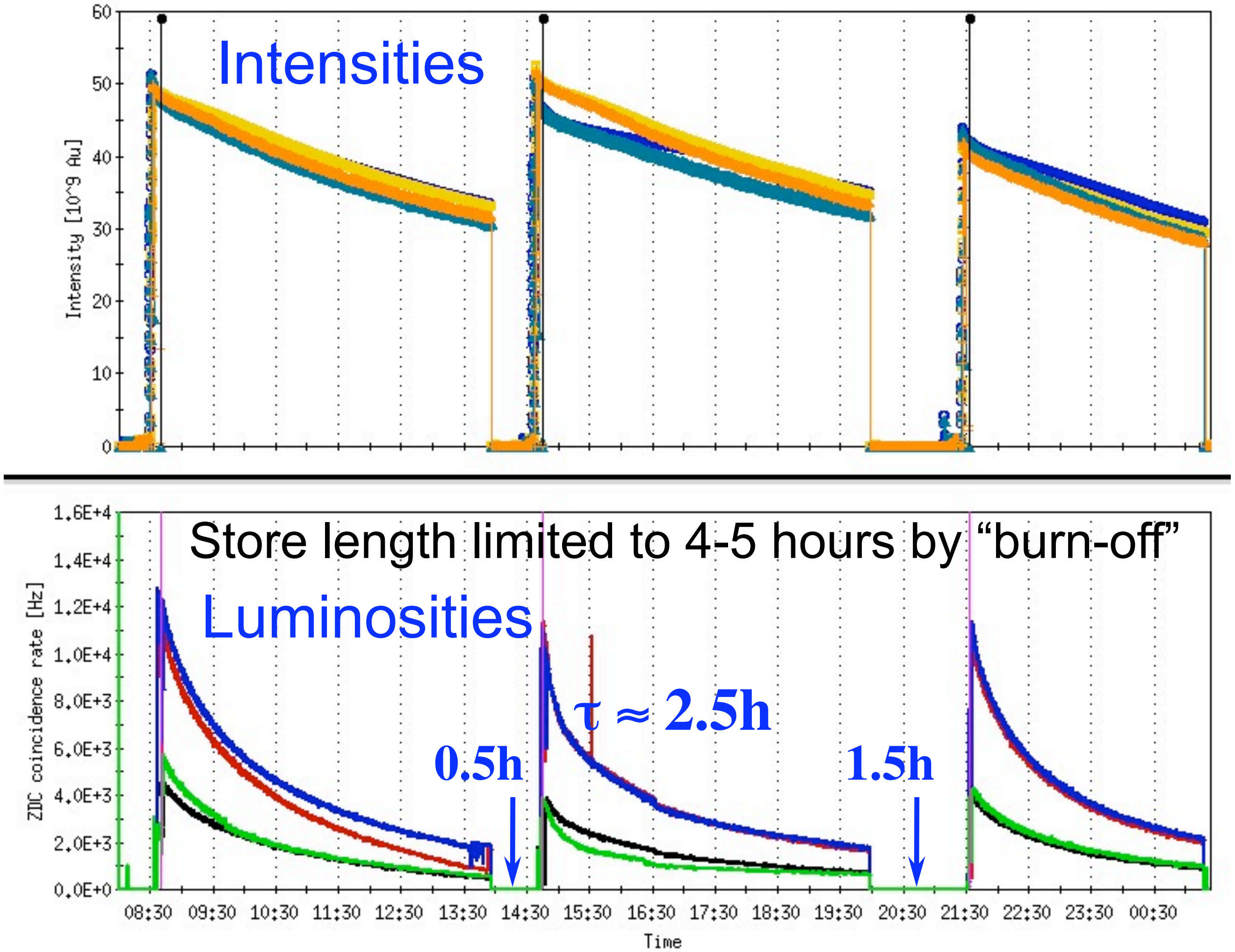
Intra-Beam Scattering:

The ions collide with each other, leading to accumulation of random energy (heat) derived from the guide fields and the beam's energy.





Luminosity Limit – Intra-Beam Scattering

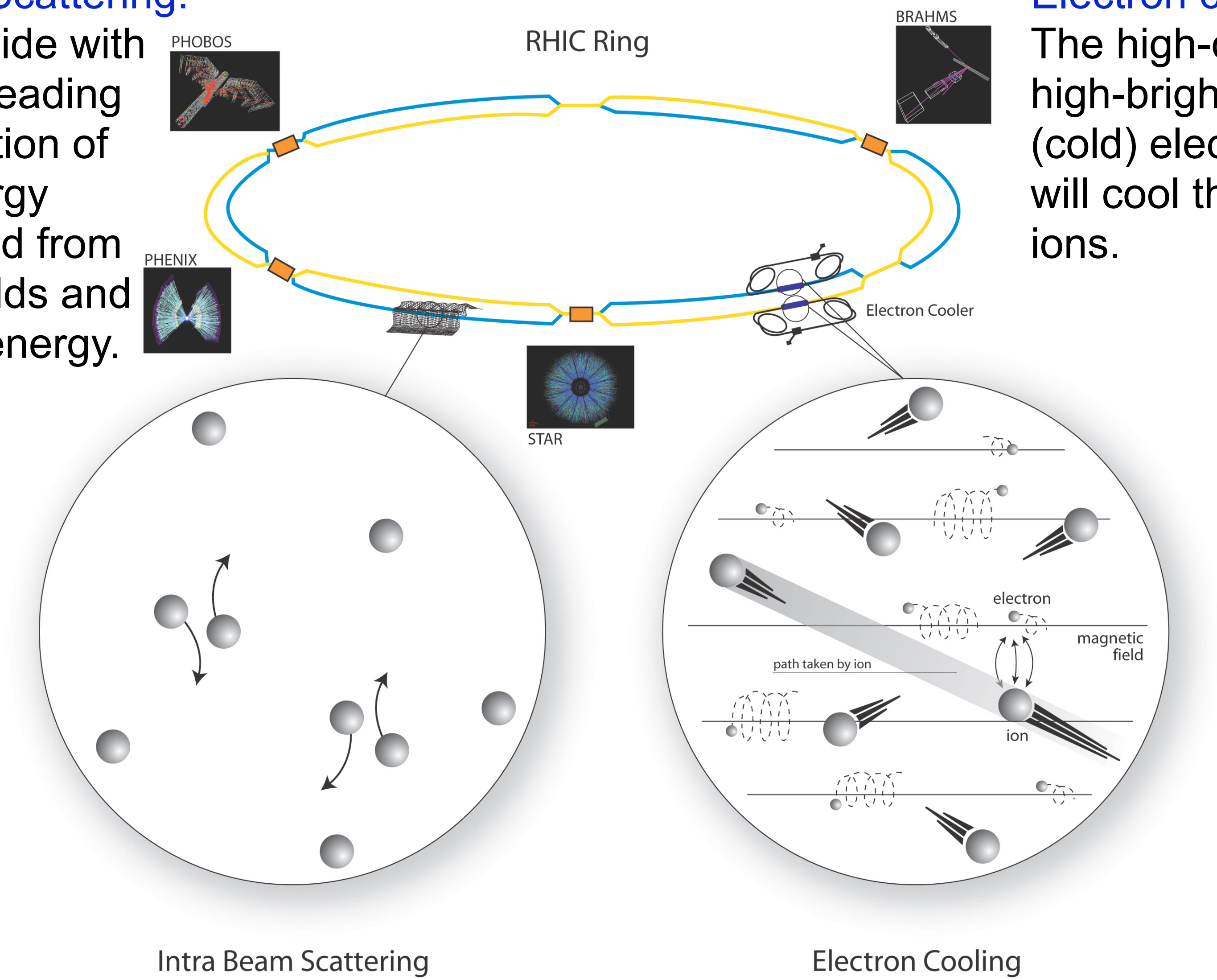


- Debunching requires continuous gap cleaning (tune meter)
- Luminosity lifetime requires frequent refills
- Ultimately need cooling at full energy

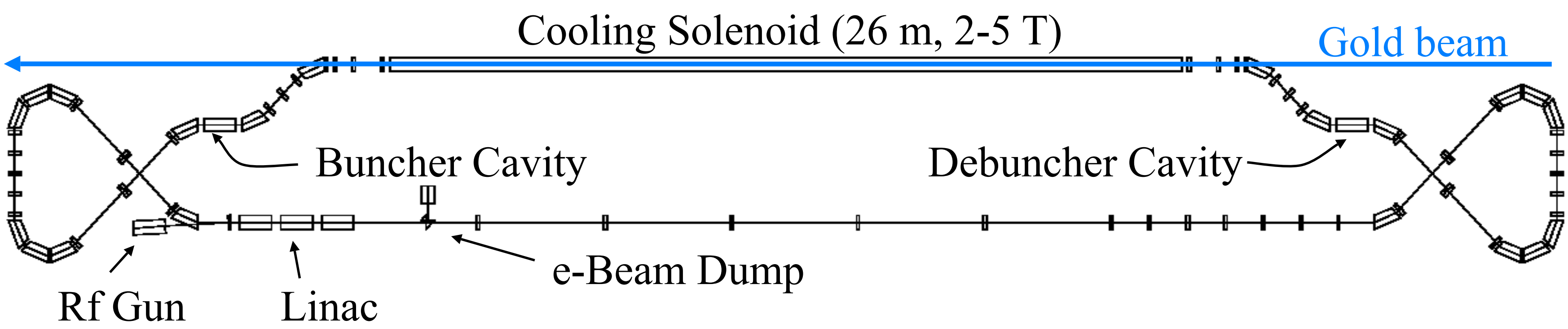
Electron cooling and IBS

Intra-Beam Scattering:
The ions collide with each other, leading to accumulation of random energy (heat) derived from the guide fields and the beam's energy.

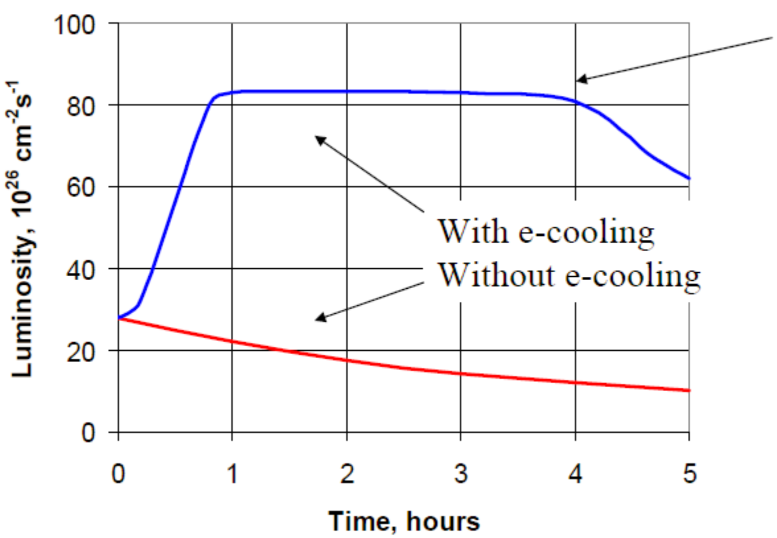
Electron cooling:
The high-current high-brightness (cold) electron beam will cool the RHIC ions.



RHIC-II: Electron Cooling



Gold collisions (100 GeV/n x 100 GeV/n):	w/o e-cooling	with e-cooling
Ave. store luminosity [10^{26} cm^{-2} s^{-1}]	8 (12)	70
Pol. Proton Collision (250 GeV x 250 GeV):		
Ave. store luminosity [10^{32} cm^{-2} s^{-1}]	1.5	5.0



The high-current high-brightness (cold) electron beam will cool the RHIC ions.

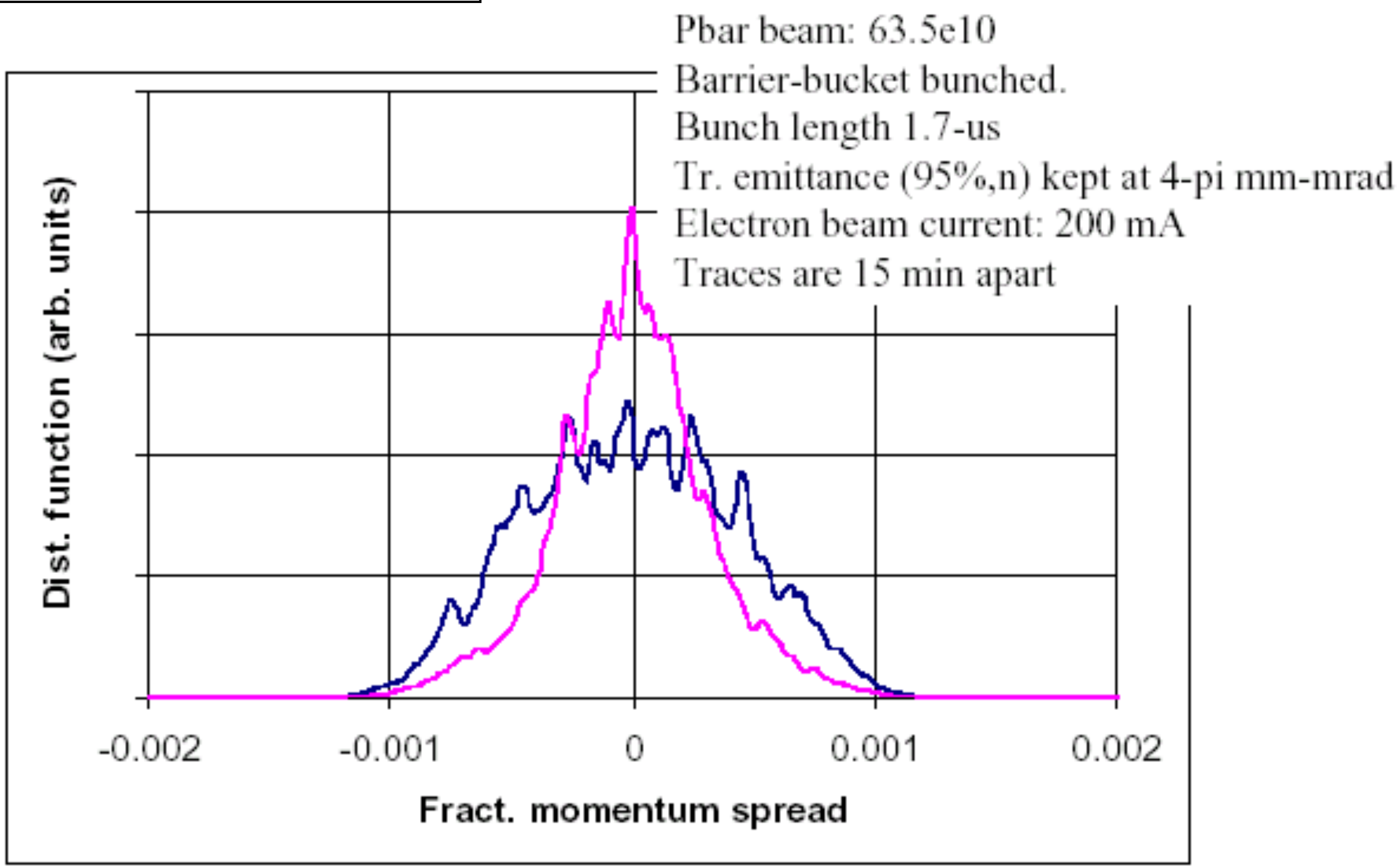
Reduces the inter-beam Coulomb scattering and reduces the size of the beam at the IP

Luminosity leveling through continuously adjusted cooling

Store length limited to 4 hours by "burn-off"

First e-cooling demonstration at FNAL (2005)

S. Nagaitsev et al.

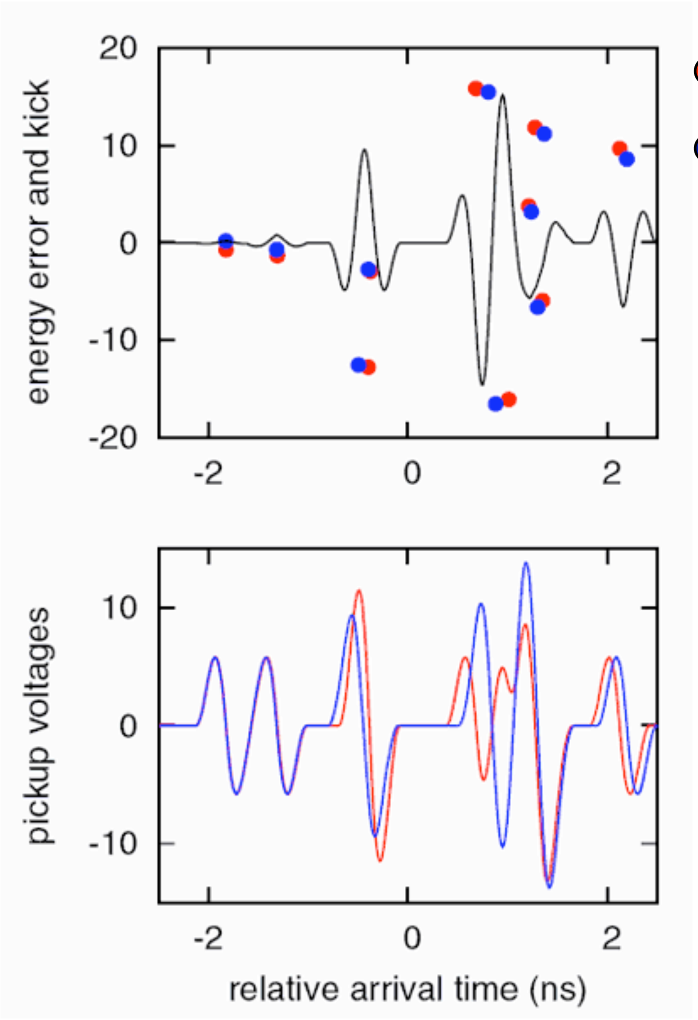


RHIC II Luminosities with Electron Cooling

Gold collisions (100 GeV/n x 100 GeV/n):	w/o e-cooling	with e-cooling
Emittance (95%) $\pi\mu m$	15 → 40	15 → 3
Beta function at IR [m]	1.0	1.0 → 0.5
Number of bunches	112	112
Bunch population [10^9]	1	1 → 0.3
Beam-beam parameter per IR	0.0016	0.004
Ave. store luminosity [10^{26} cm^{-2} s^{-1}]	8	70

Pol. Proton Collision (250 GeV x 250 GeV):		
Emittance (95%) $\pi\mu m$	20	12
Beta function at IR [m]	1.0	0.5
Number of bunches	112	112
Bunch population [10^{11}]	2	2
Beam-beam parameter per IR	0.007	0.012
Ave. store luminosity [10^{32} cm^{-2} s^{-1}]	1.5 5.0	

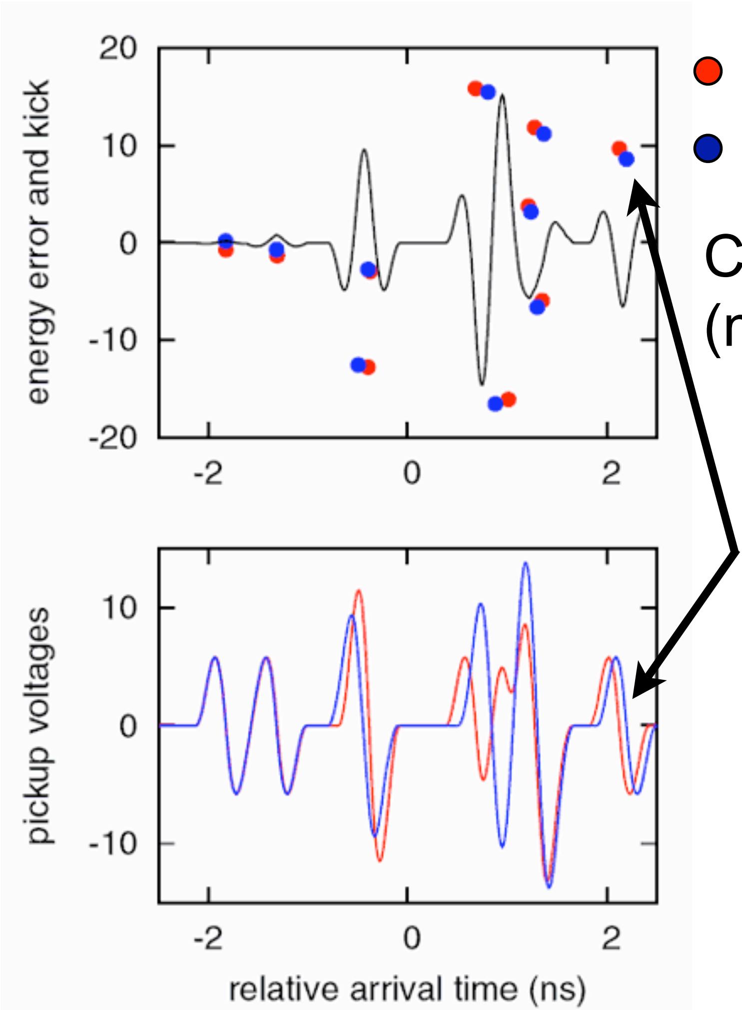
Alternative for RHIC-II: Stochastic Cooling



- Energy error: turn N
- Energy error: turn N+1

Change in arrival time ~ energy error (more energy take longer around ☺)

Alternative for RHIC-II: Stochastic Cooling

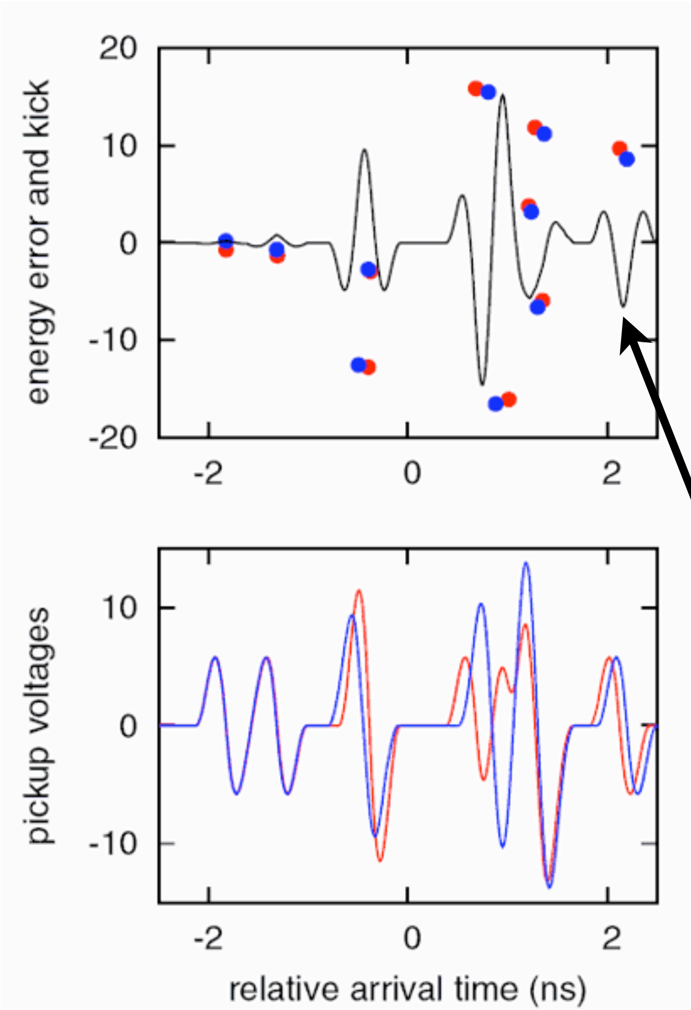


- Energy error: turn N
- Energy error: turn N+1

Change in arrival time ~ energy error
(more energy take longer around ☺)

Stochastic Cooling:
measure relative arrival time for 2 turns

Alternative for RHIC-II: Stochastic Cooling

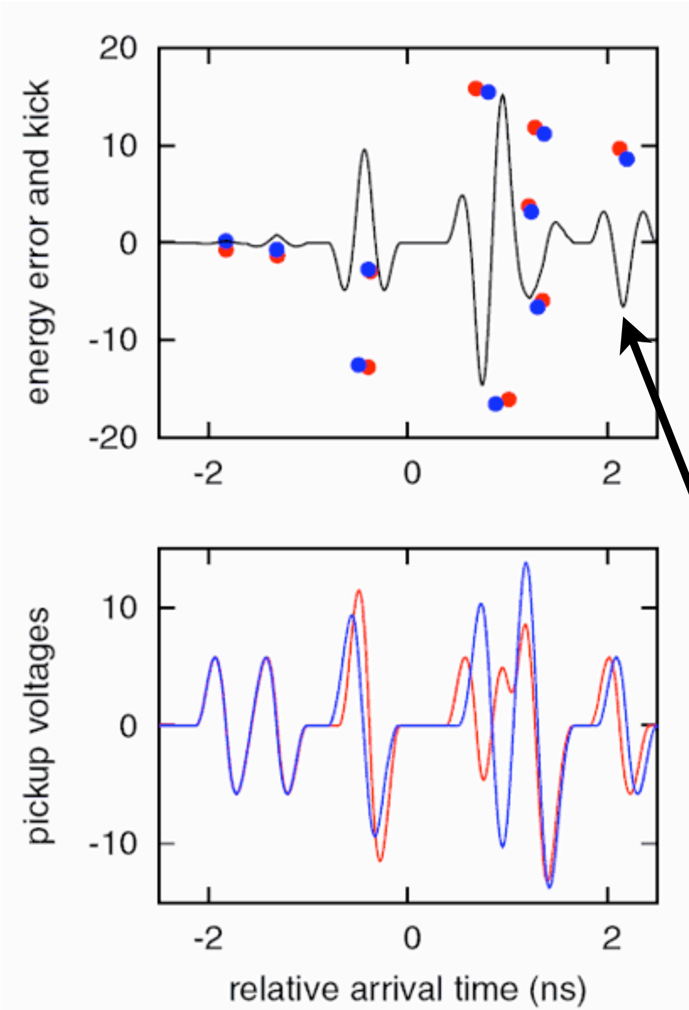


- Energy error: turn N
- Energy error: turn N+1

Change in arrival time ~ energy error
(more energy take longer around ☺)

Stochastic Cooling:
measure relative arrival time for 2 turns
required kick: red-blue
⇒ Reduction of energy spread

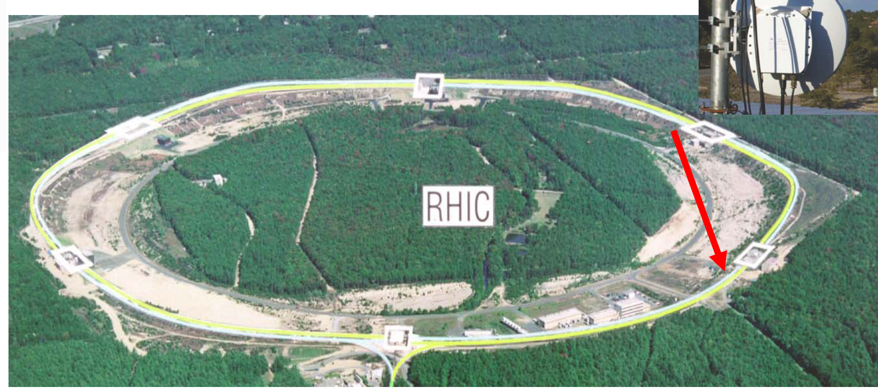
Alternative for RHIC-II: Stochastic Cooling



- Energy error: turn N
- Energy error: turn N+1

Change in arrival time ~ energy error
(more energy take longer around ☺)

Stochastic Cooling:
measure relative arrival time for 2 turns
required kick: red-blue
⇒ Reduction of energy spread



RHIC-II: Stochastic Cooling

Run 7 (2007):

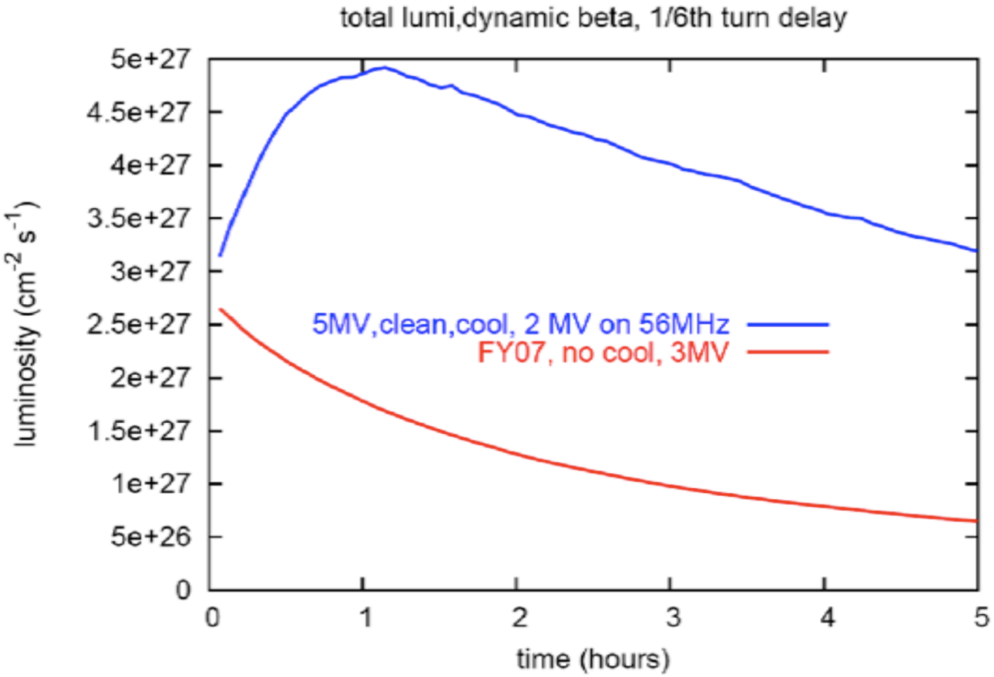
- Longitudinal bunched beam stochastic cooling
- Longitudinal stochastic cooling in blue ring under construction.
- Transverse stochastic cooling in RHIC at 100 GeV/n might be possible using the same approach.

Electron Cooling

- TPC: $95M (FY07$)
- Funding ... 2012-2015

Stochastic Cooling

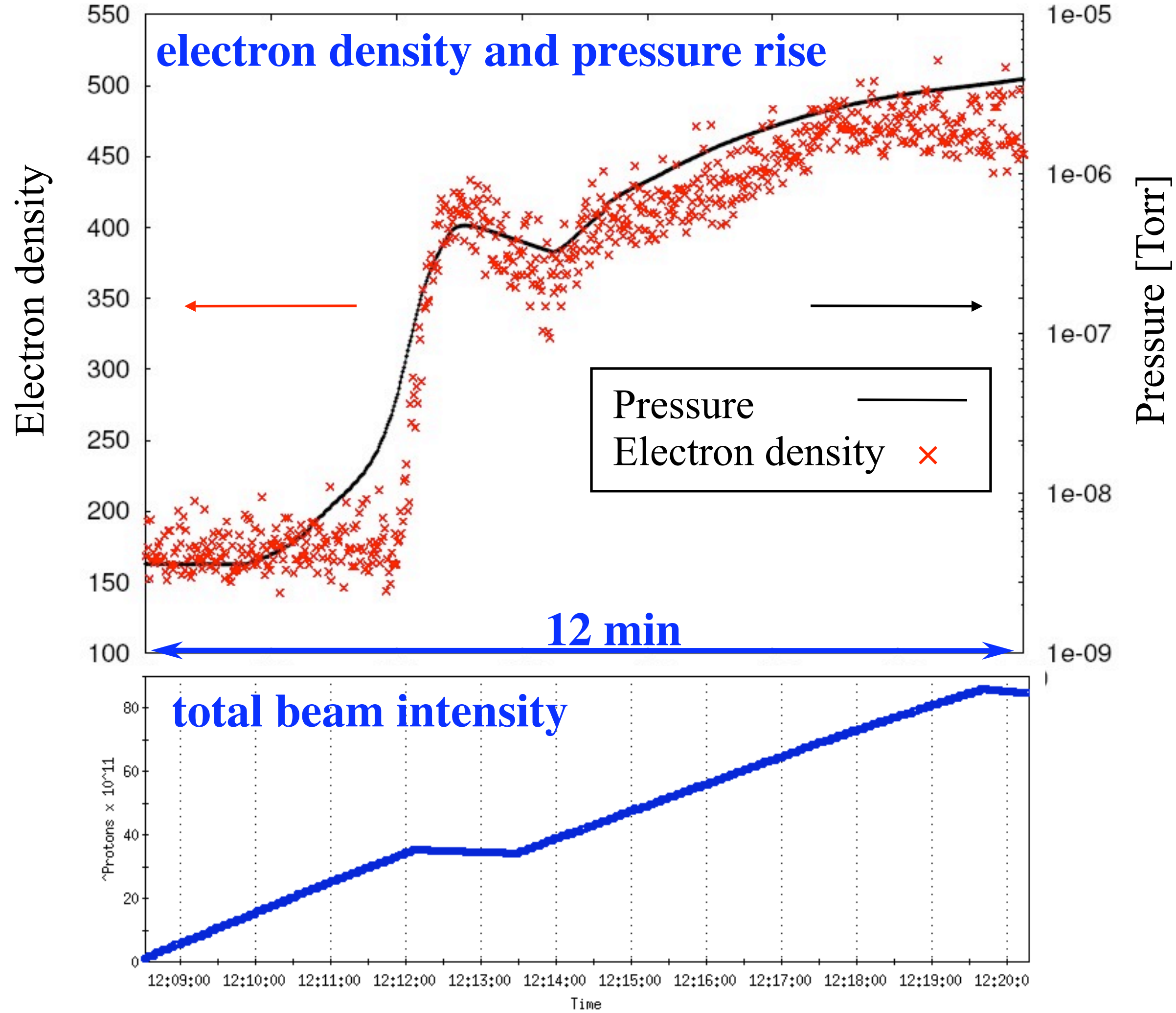
- ~ $7M
- much earlier than above ...



L(e-cooling) ≈ 2-3 × L(stochastic-cooling)

Luminosity Limit – Dynamic Pressure Rises

$86 \cdot 10^{11}$ p^+ total, $0.78 \cdot 10^{11}$ p^+/bunch, 110 bunches, 108 ns spacing



All operational relevant pressure rises can be explained by electron clouds

→ NEG (non-evaporative getter) coated beam pipes installed in warm areas

RHIC: Brief Summary

RHIC:

- Flexible dedicated HI machine
- Complex chain of machines: Van de Graaff, Booster, AGS, RHIC
- Any A on any A
- $\sqrt{s}_{max}$ = Z/A × 500 GeV
- Exceeds design luminosity by factor 4-6
- Luminosity limited by intra-beam scattering

RHIC-II:

- Stochastic Cooling
- May be electron cooling
- New ion source (U+U) EBIS