Making Neutrons at SNS

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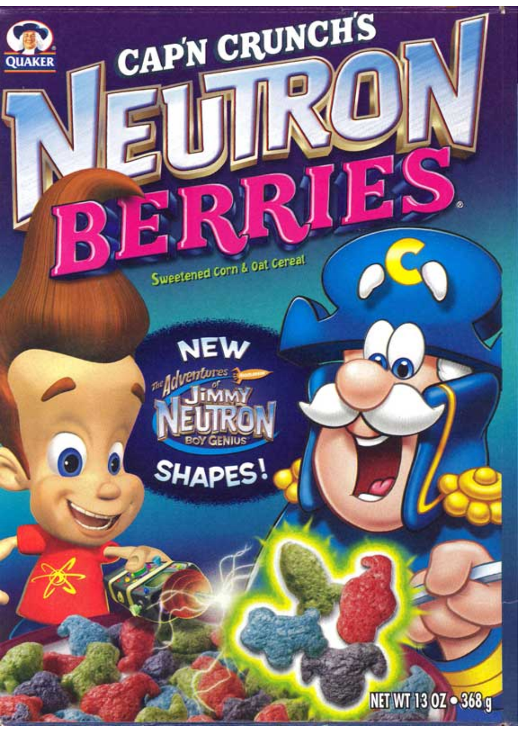
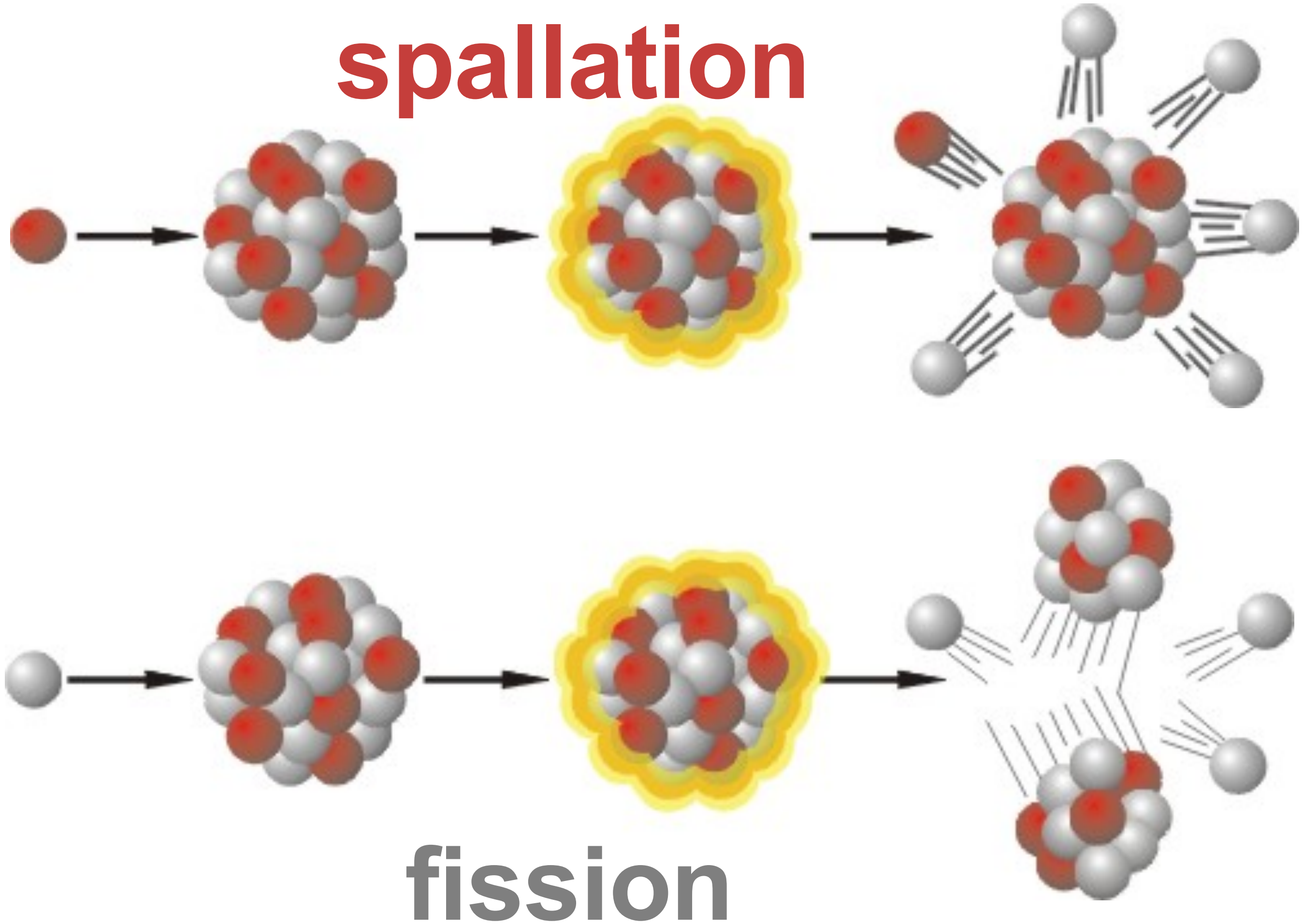
for the US Department of Energy

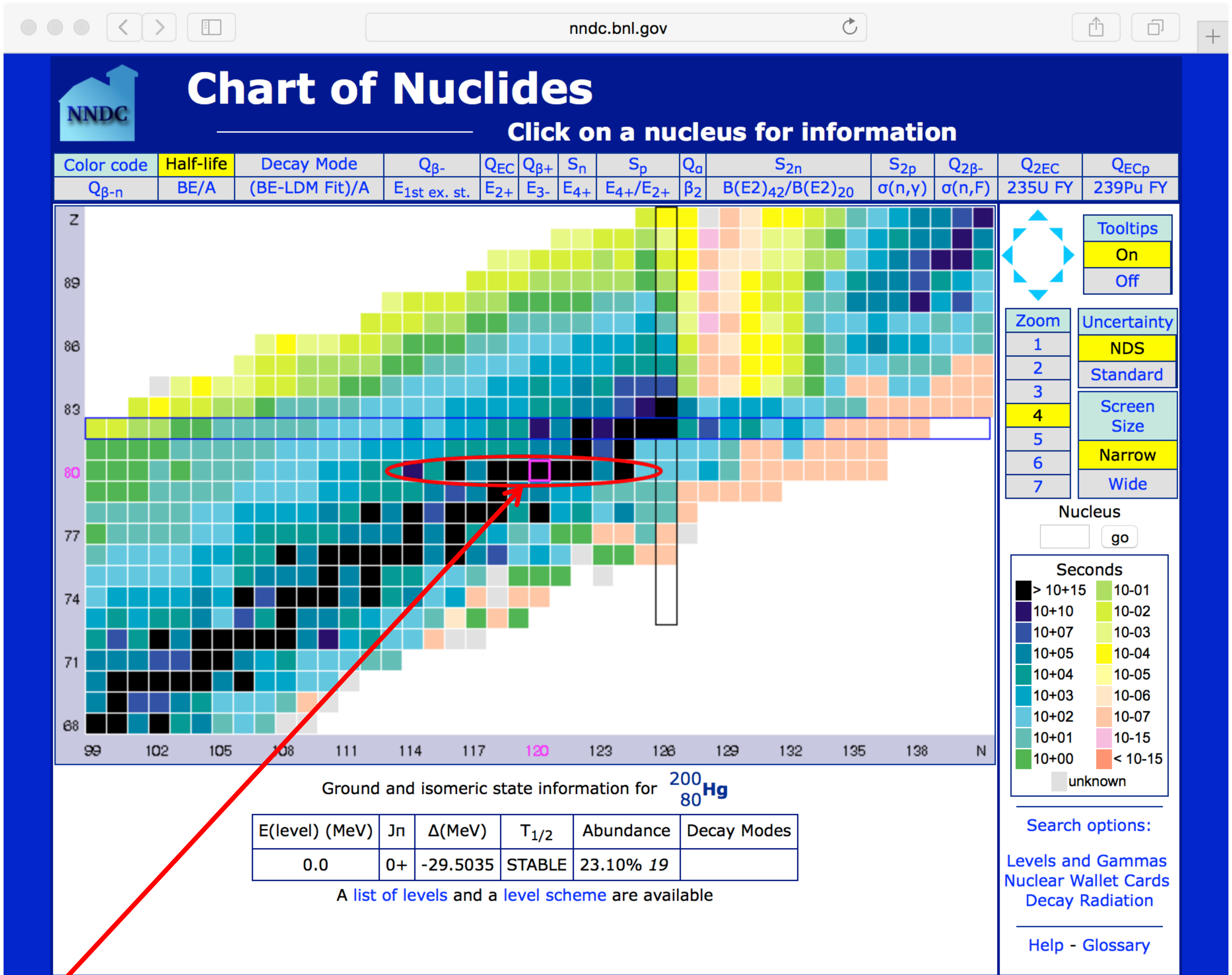
There are two efficient ways to produce neutrons in good quantity – in each case either a proton or a neutron is used to release neutrons from a heavy nucleus





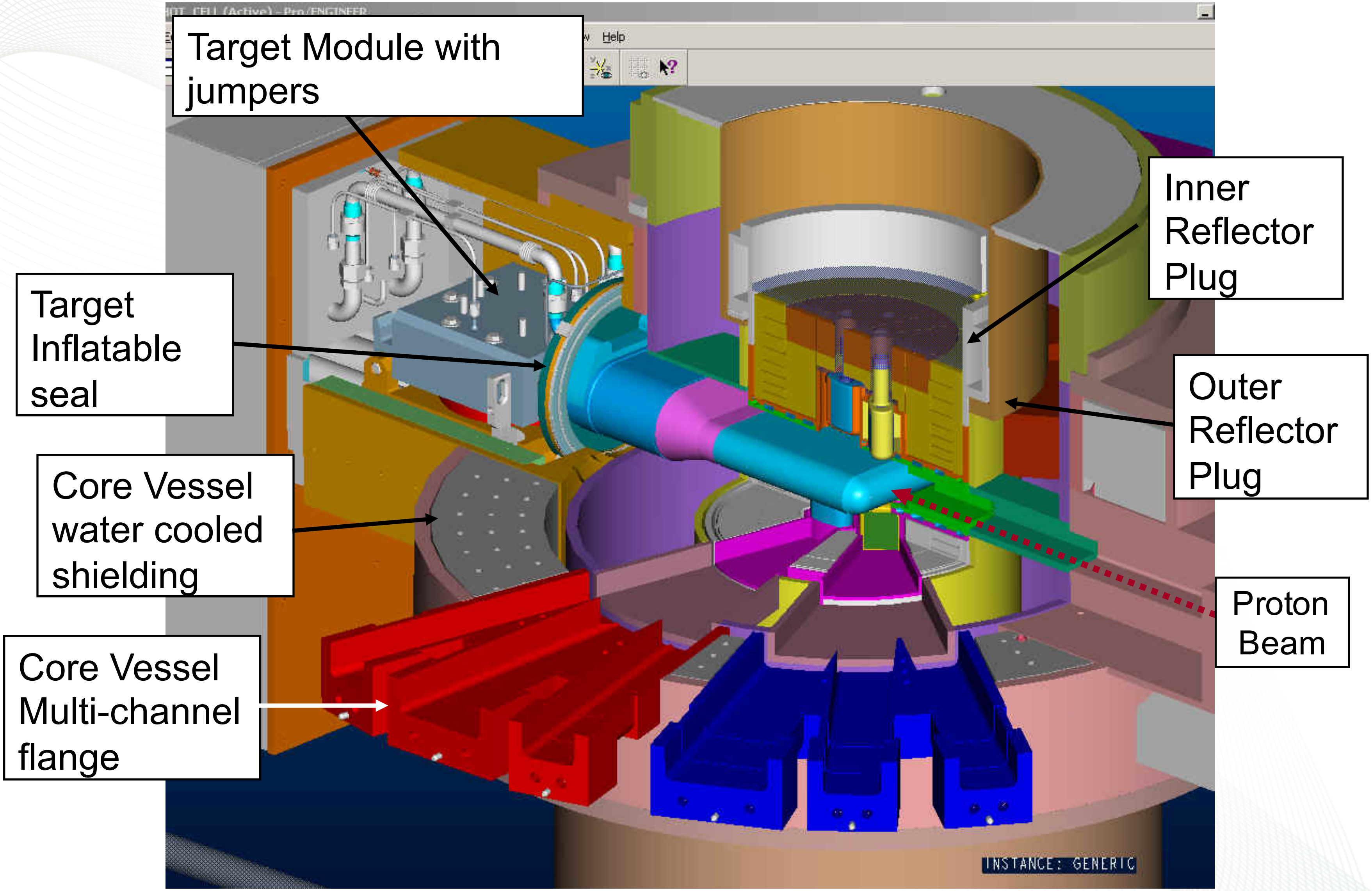
Where do we find suitable candidate materials for spallation?

- Pretty much any stable material from mass 170 to 238 will do
- Choice depends on engineering parameters
- Heat extraction
- Machinability
- Durability
- Resistance to water erosion
- Residual decay heat



SNS uses liquid mercury – we get ~25 neutrons per proton

A quick look at the hardware associated with making the neutrons – you'll hear details on moderation and neutron spectra from others



If we use high energy protons as the hammer to induce spallation, how do we make them into the hammer? – We need an accelerator

- Need a proton beam
- Need to accelerate it to ~1 Giga-electron-volt (GeV, about 88% speed of light)
- The beam needs to be pulsed
- Need to deliver the proton beam to the target in a short burst (<< time between beam pulses)
- Each beam pulse needs to be very intense

Proton beam energy on target	**1.0**	**GeV**
Proton beam current on target	**1.4**	**mA**
Power on target	**1.4**	**MW**
Pulse repetition rate	60	Hz
Beam macropulse duty factor	6.0	%
Ring fill time	1.0	ms
Protons per pulse on target	1.5×10^{14}	
Proton pulse width on target	695	ns
Linac length	335	m
Total Beamline Length	903	m

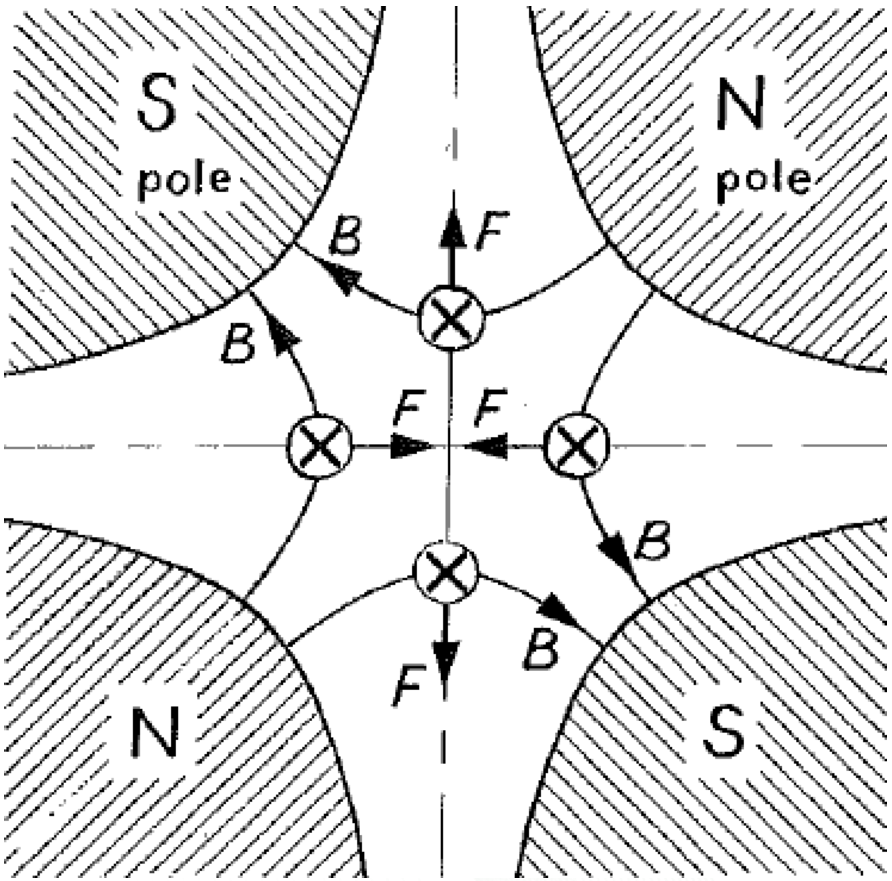
This is a lot of power! Highest power linear accelerator in the world

Before we go on, what do we mean by a "beam" of particles?

- Most modern accelerators are not "continuous"
- A "beam" consists of a series of bunches of charged particles
- These bunches (in our machine we call them micropulses) contain reasonably large number of particles – the average accelerated SNS micropulse for 1 MW contains about 2.6×10^{10} particles
- Each bunch has a distribution of energies and transverse displacements and angles which we call a 6 dimensional phase space – the 2D projections are called emittances
- Since like charges repel and all these charges are compacted into a small space, the tendency of any bunch is to grow (longitudinally and transversely)
- So, not only do we have to accelerate the bunch to achieve the desired energy, we also have to focus it transversely and longitudinally to transport it effectively without loss

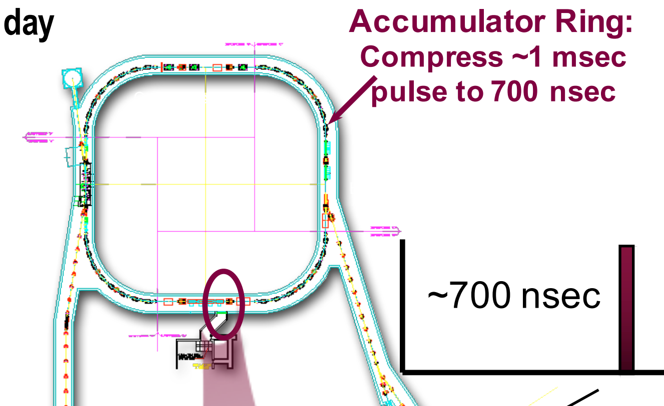
A quick word about directing and focusing charged particle beams

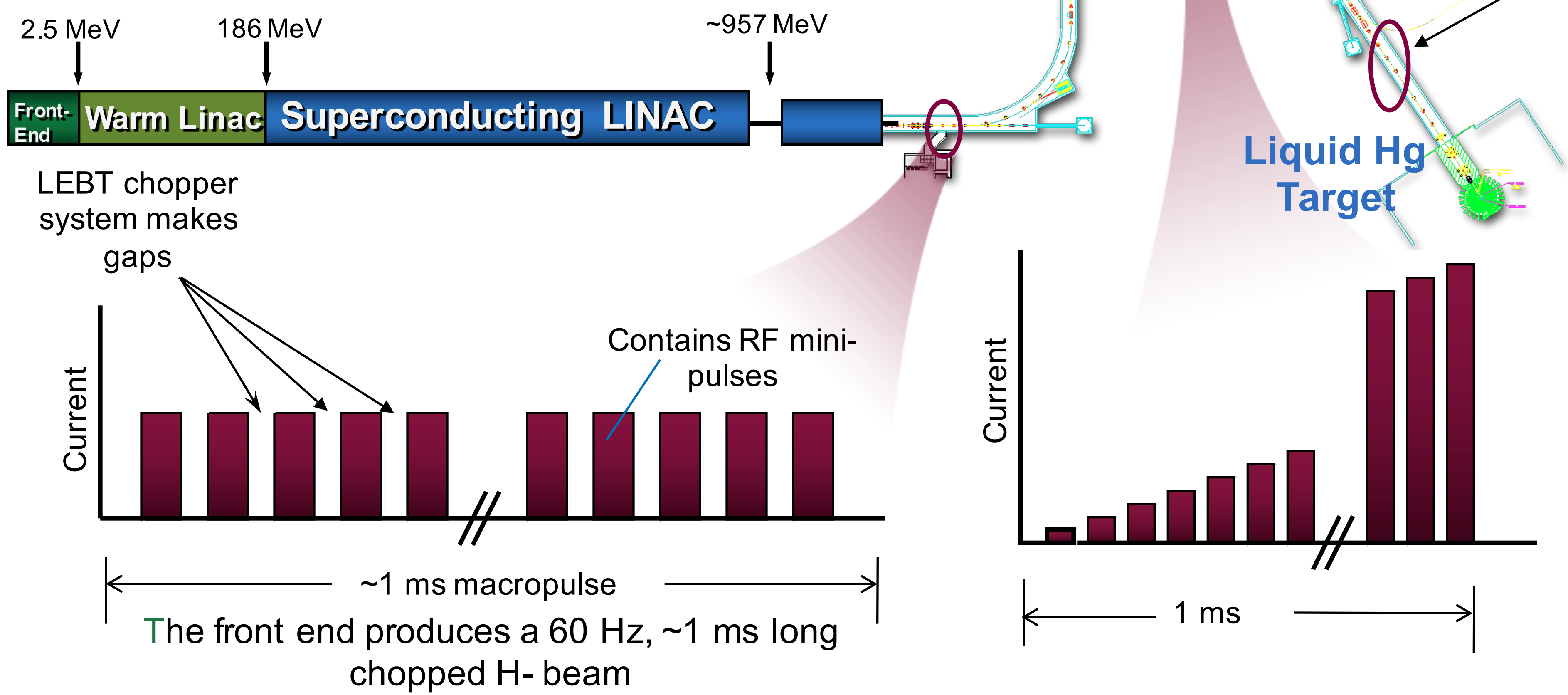
- Charged particles in motion in magnetic fields experience forces transverse to the direction of motion, and hence can be “bent”
- A dipole can be used to bend the beam in a given plane, or provide a small angular “kick” to correct an orbit
- Quadrupoles are used to focus a distribution in one transverse plane, and defocus in the orthogonal plane – reversing the polarity of the magnet switches the focusing and defocusing planes for a given beam charge state
- Combinations of quadrupoles can be used to make compound lenses
- Sextupoles and octupoles can be used to correct chromatic aberrations



What does it take to make the number of protons we need moving at the speed we need them to?

- The SNS machine has over 100,000 control points and cycles ~5.2 million times a day
- Power (and base neutron flux) is the product of:
  - Beam Energy
  - Peak Current
  - Chopping Fraction
  - Pulse Length
  - Repetition Rate



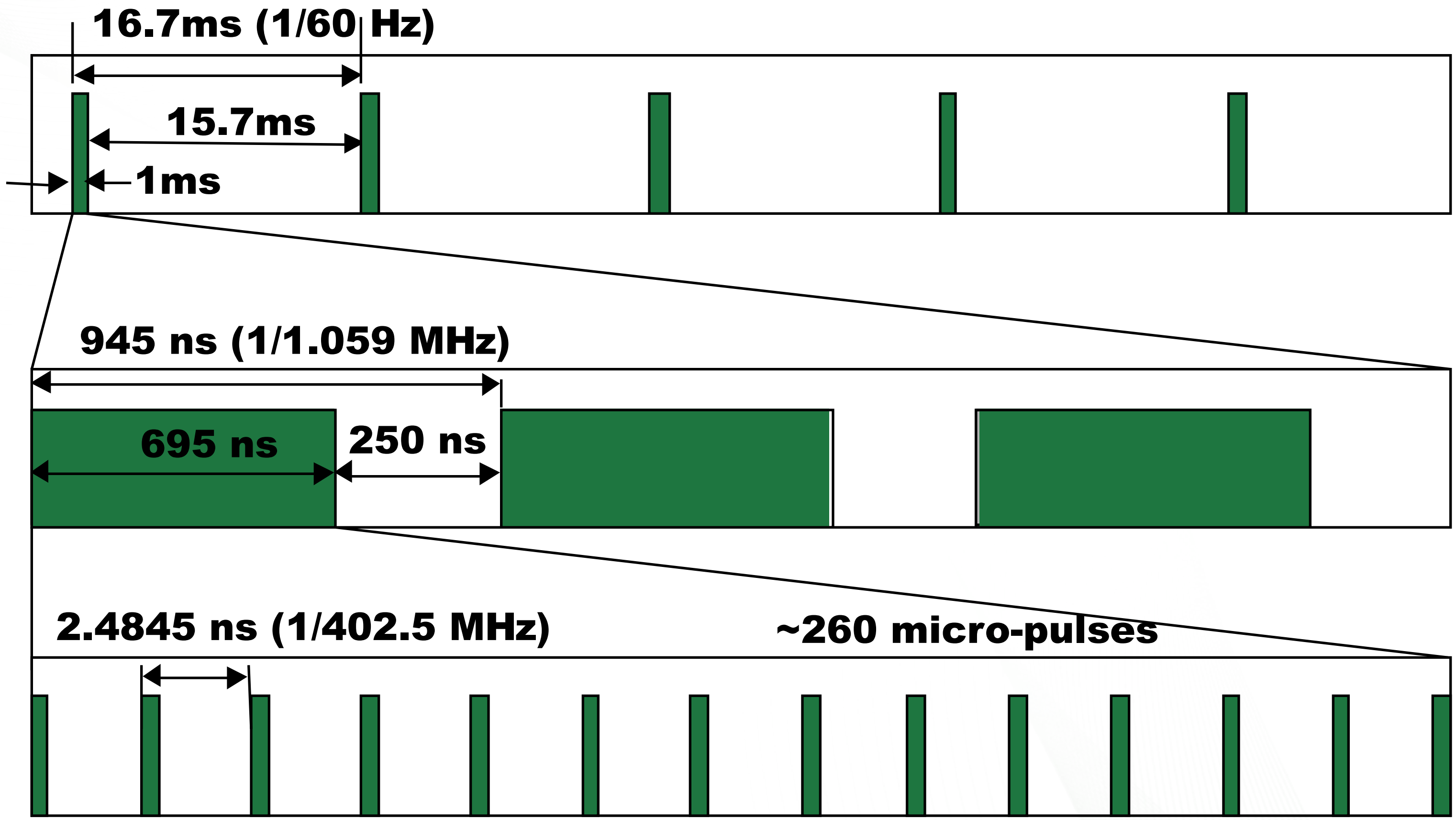


The accelerator beam pulse structure is quite complex – and things happen quite quickly

Macro-pulse
Structure
(made by the
High power
RF)

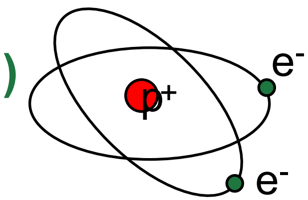
Mini-pulse
Structure
(made by the
choppers)

Micro-pulse
structure
(made by the
RFQ)



The beam starts at the Ion Source where we make H^- ions

(H^-: 1 proton + 2 electrons)



- Inside the ion source, an antenna couples radio-frequency power into a low pressure (~10^{-5} atm) hydrogen gas chamber to create a plasma (soup of dissociated particles) - the plasma glows like a fluorescence light.
- Low energy ions, electrons, atoms, and excited molecules drift through a magnetic field towards the exit aperture where some of them form negative Hydrogen ions with the aid of Cesium-coated surfaces
- An electrode clears away unwanted electrons, after which the H^- ions are extracted by a 65kV electric field

Almost no acceleration yet!
Beam Energy is 65 keV

Photograph of glowing plasma generated by ion source antenna.

or

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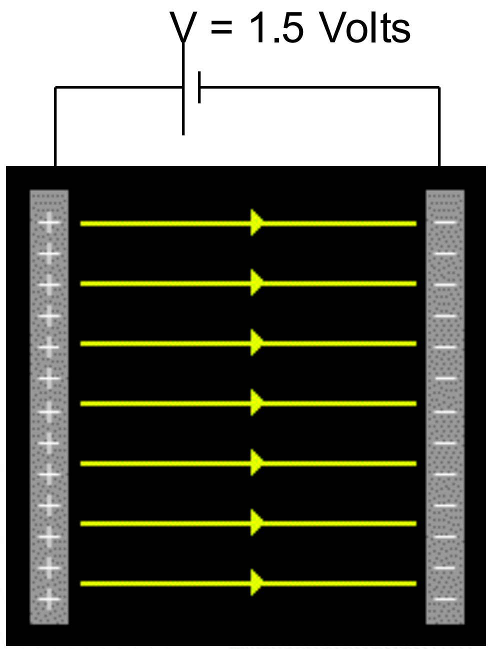
The SNS uses electric forces to rapidly and efficiently accelerate charged particles

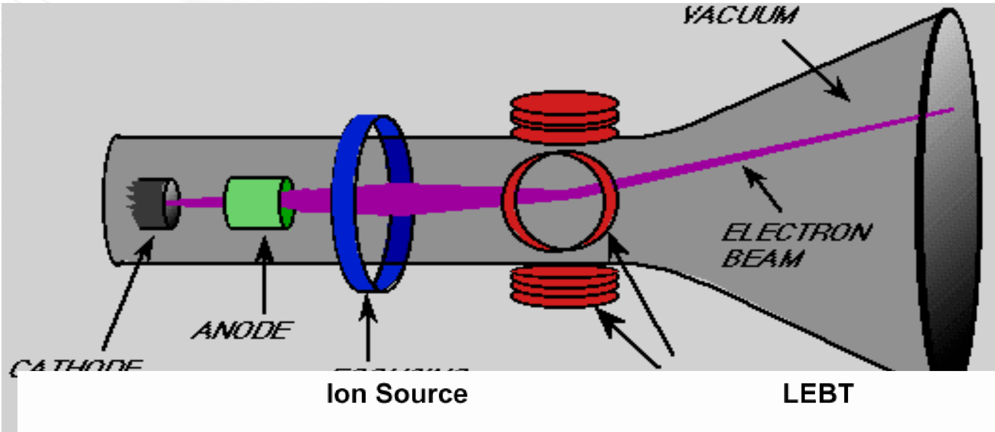
- The Electric Force:
  - Opposite charges attract, like charges repel
  - Force = Charge x Electric Field, directed along the electric field
  - We can accelerate a charged particle by placing it in an electric field

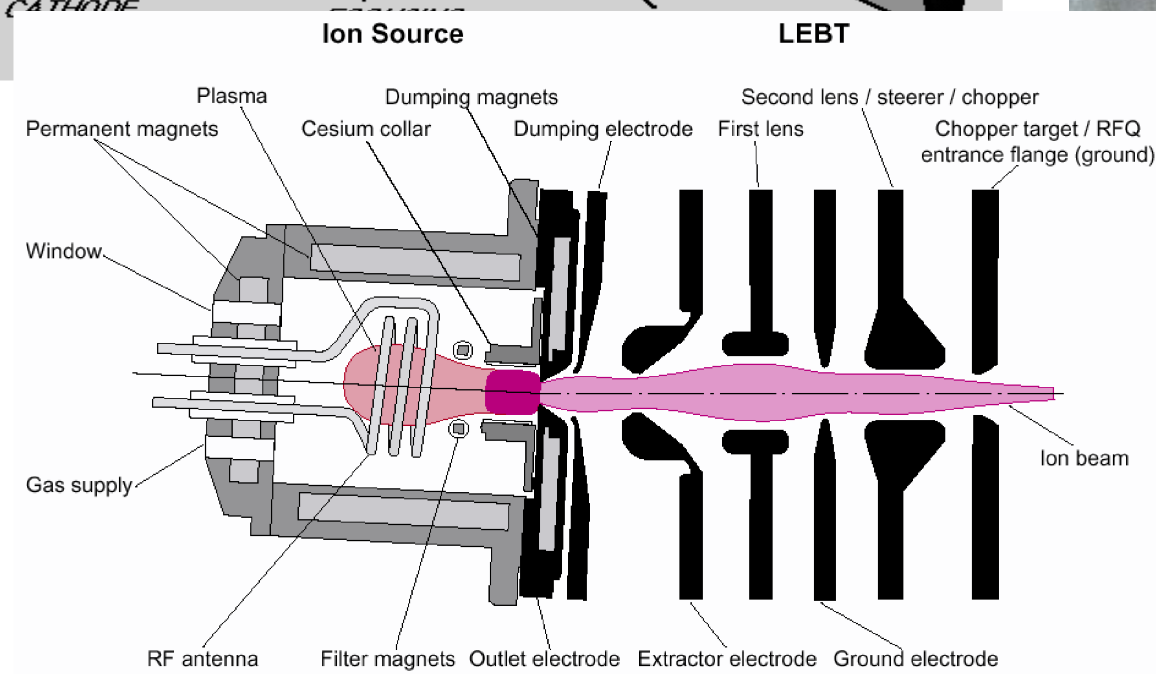
- The Electric Field:
  - E = voltage/separation
  - Suppose the plates are separated by 1 meter, E=1.5 Volts/m
  - A particle with the charge of an electron, (like an H- ion) released from the – plate would have an energy of 1.5 eV when it strikes the + plate



DC electrostatic accelerators have been used effectively for many years

- We have just described an "Electrostatic" Accelerator





Holifield Tandem Electrostatic Accelerator
25 MV on terminal –
ORNL main campus

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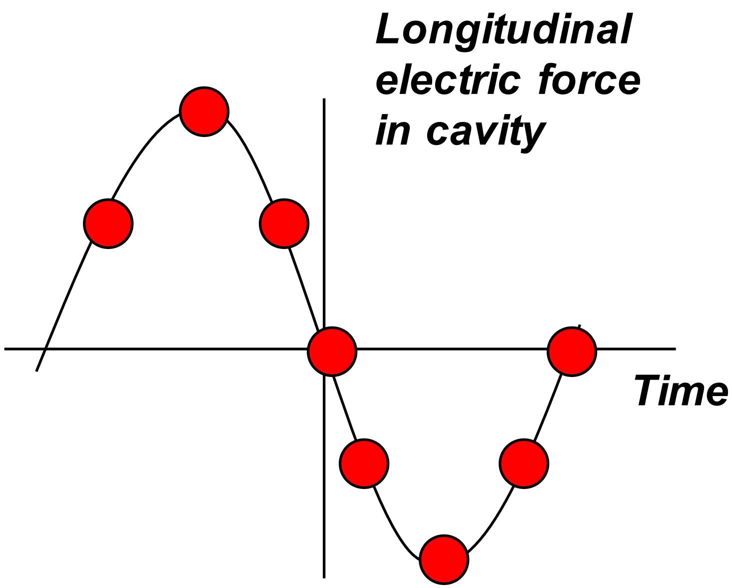
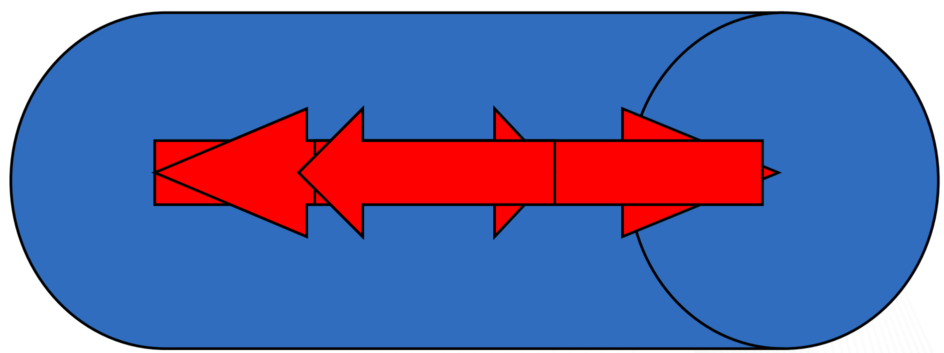
But we need 1 Billion Volts?

- A state of the art Electrostatic Accelerator might have a 25-30 MV terminal voltage in the large cylindrical concrete building you see on the main campus down the hill
- But we need 1000 MV? What can we do?
  - Use Radio Frequency (RF) waves to generate very strong sinusoidal oscillating electric fields with the right time structure
- Use resonant structures and standing electromagnetic waves
- Timing is everything…..
- Tune in to 402.5 and 805 on your FM dial!

Radio-Frequency Accelerating Cavities (a.k.a. “RF Cavities”)

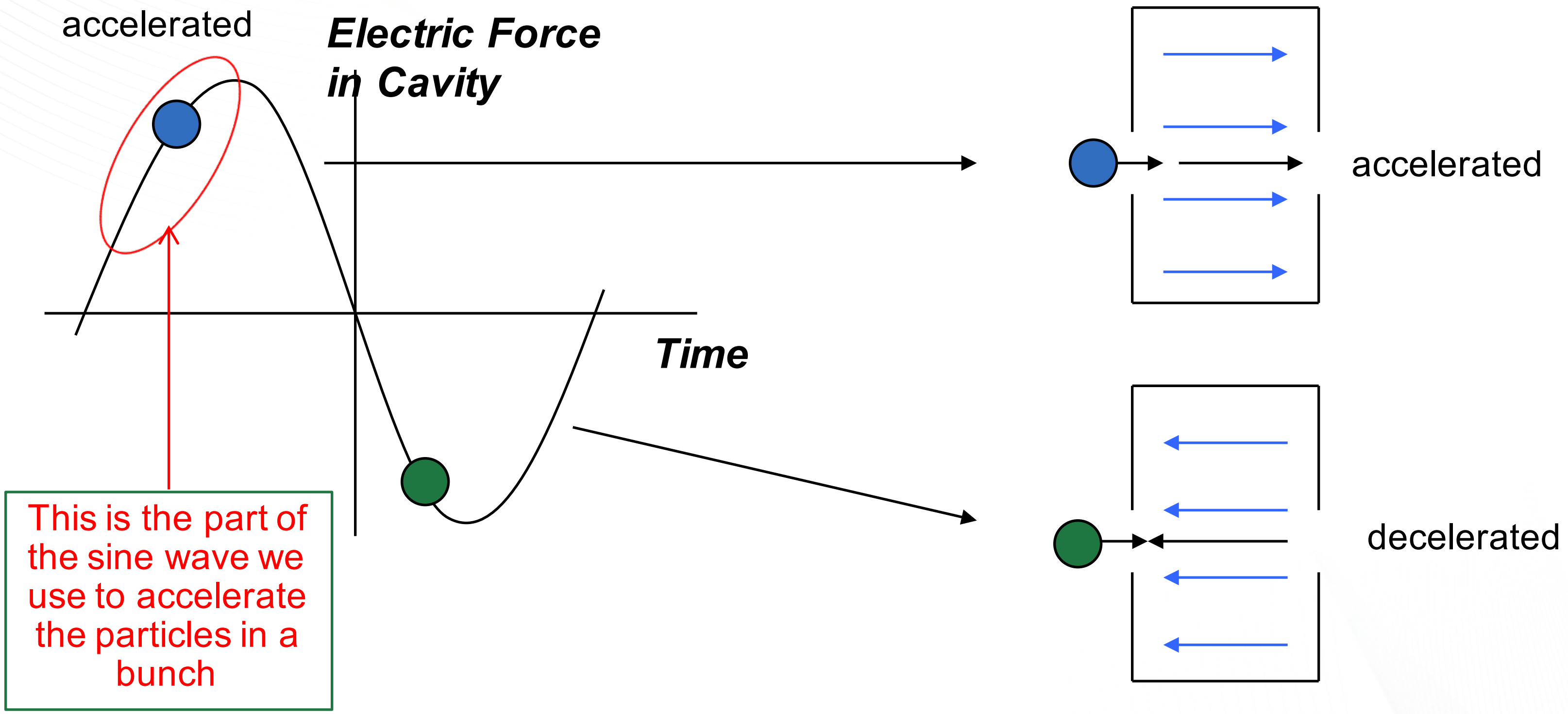
- An RF Cavity has a characteristic “resonant frequency, just like a bell or musical instrument (organ pipe) has a resonant frequency (a note that rings)
- Like a musical instrument, the smaller the cavity, the higher the resonant frequency
- When RF waves with frequency equal to the resonant frequency are introduced into the cavity, the cavity resonates (the bell rings)
- The electric field that accelerates particles oscillates in time





The RF fields SNS uses are sinusoidal

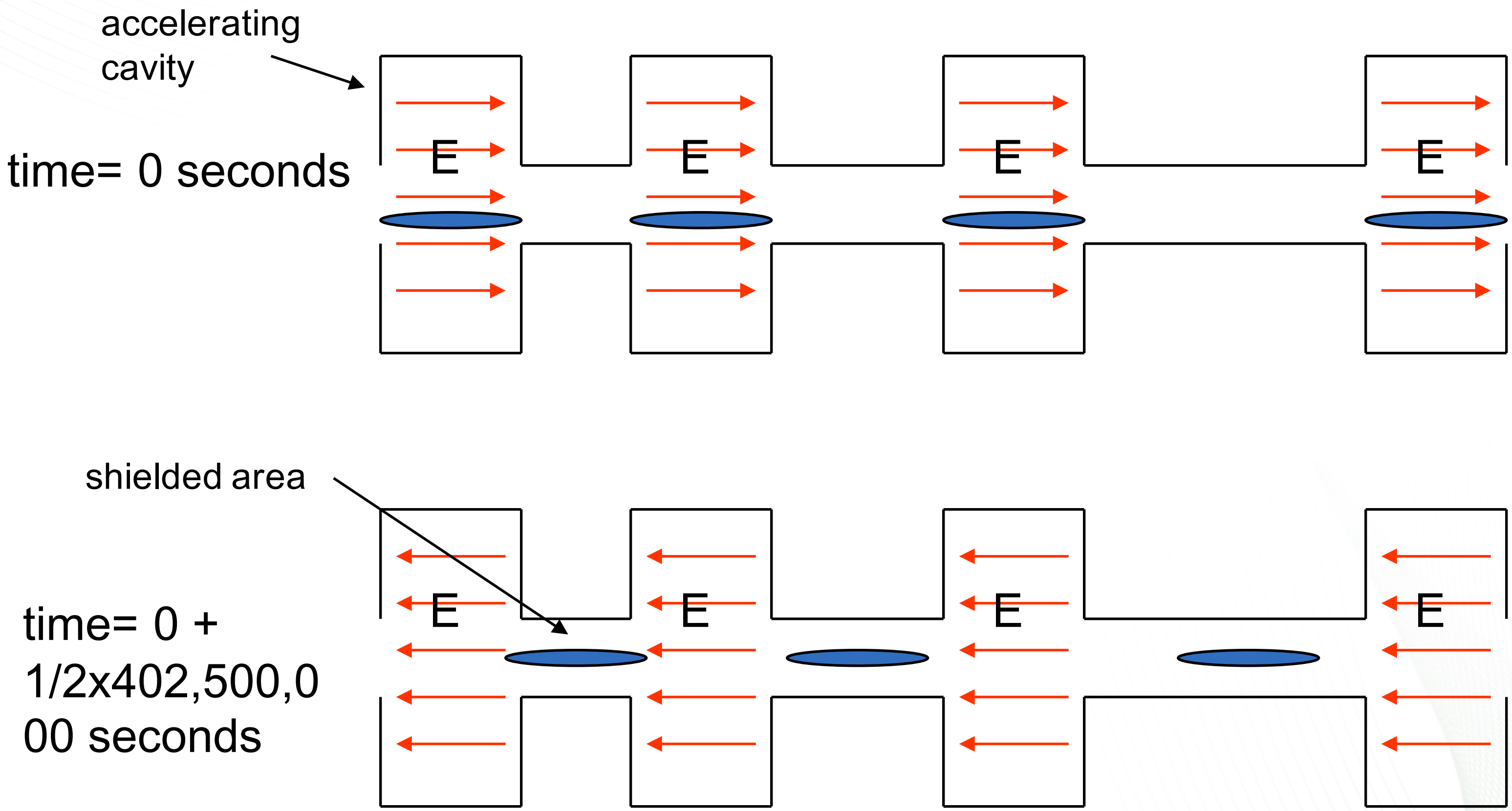
RF fields are sinusoidal and therefore change direction (sign) with time
The beam must be timed right to pass through the field only during acceleration, and be shielded from the field during deceleration.



The SNS beam is accelerated at a frequency of 402.5 MHz (over 4 hundred million sign changes of the field per second) to create the beam micropulse structure – but we use two different RF frequencies, 402.5 MHz and 805 MHz (2nd harmonic)

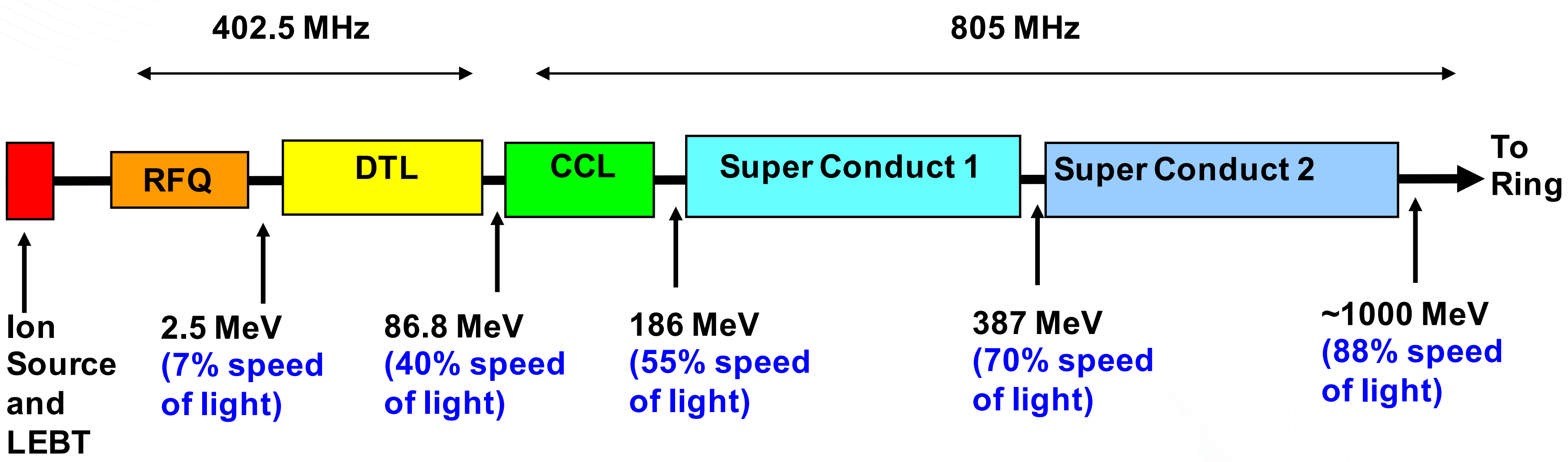
Now that we've discussed a single cavity, how do we make an RF accelerator?

- We can make an accelerator by "stringing" together many individual accelerating cells, one after the next
- Since the particle is accelerated in each cell, we have to space the cells farther apart as the velocity increases

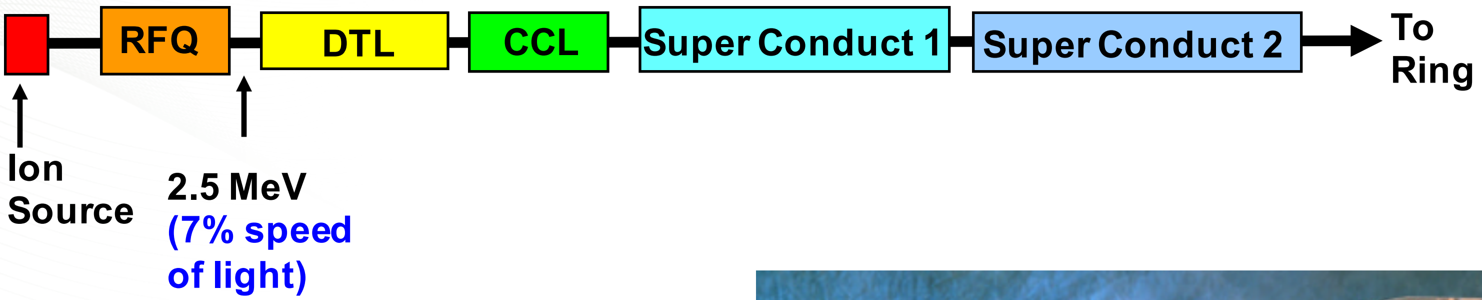


So what does the SNS Linear Accelerator (LINAC) really look like?

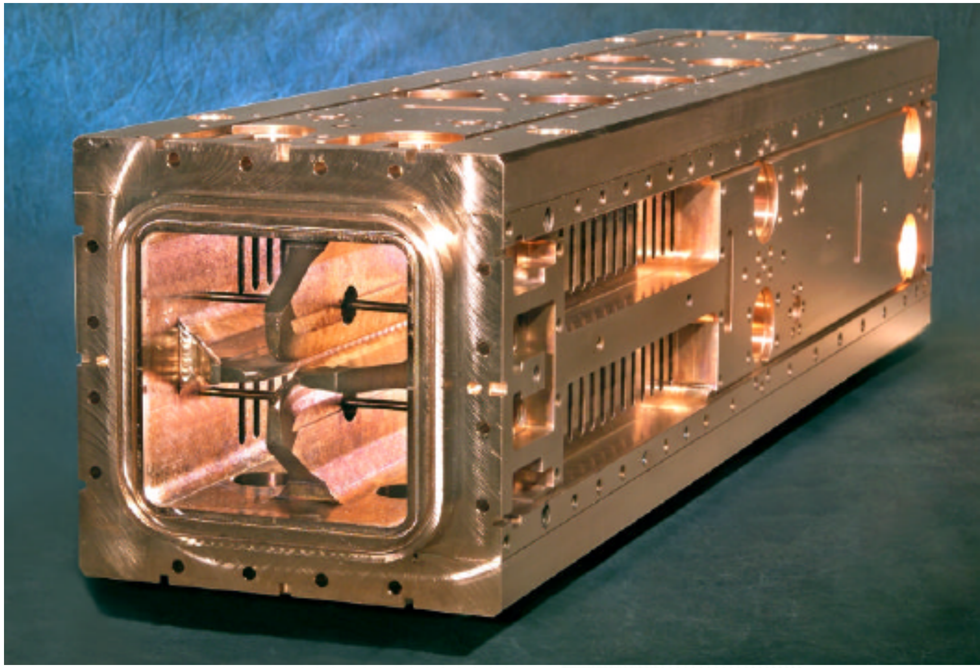
The SNS Linac is constructed of 5 different types of linear accelerator “building blocks”, each of which is optimized to a certain range of H- beam velocities



The RFQ does the initial work to get the beam to 2.5 MeV, establish periodic transverse focusing, and impose the RF time structure



- The first RF accelerator in the SNS is the “Radio Frequency Quadrupole” (RFQ)
- The beam enters at 65 keV, and is accelerated to 2.5 MeV
- The RFQ does three crucial things:
  - Accelerates the beam
  - Focuses the beam
  - Bunches the beam (makes small packets of charge



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The Drift Tube Linac (DTL) is the second low-beta structure

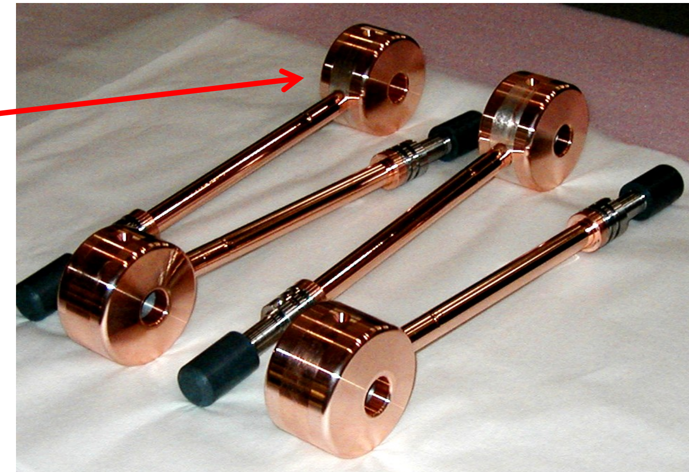
Ion Source → RFQ → DTL → CCL → Super Conduct 1 → Super Conduct 2 → To Ring

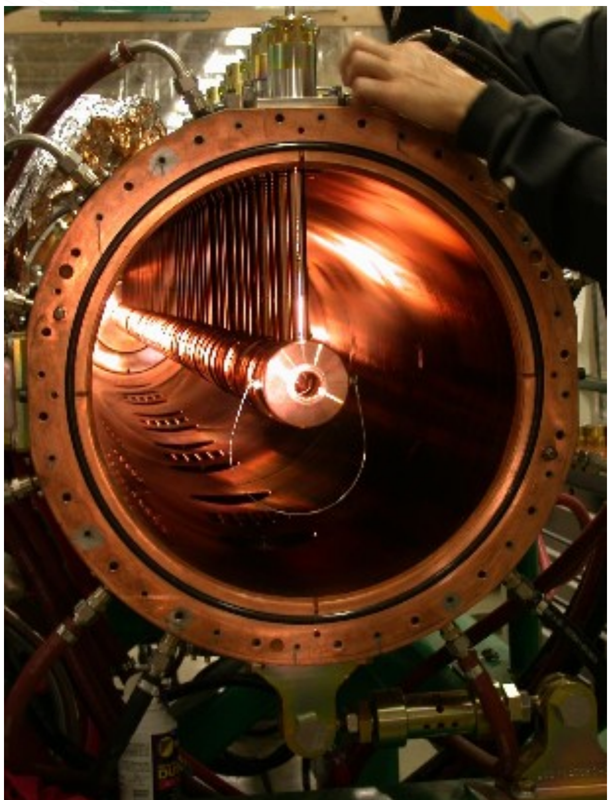
Ion Source

2.5 MeV (7% speed of light)

86.8 MeV (40% speed of light)

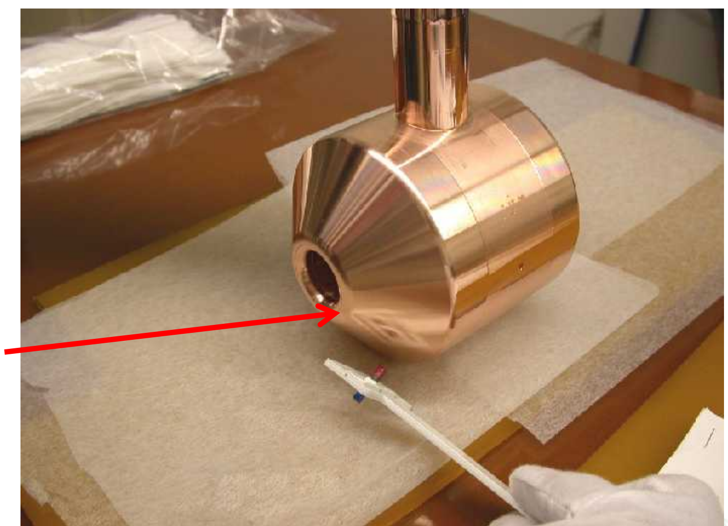
Tank 1 drift tubes are short



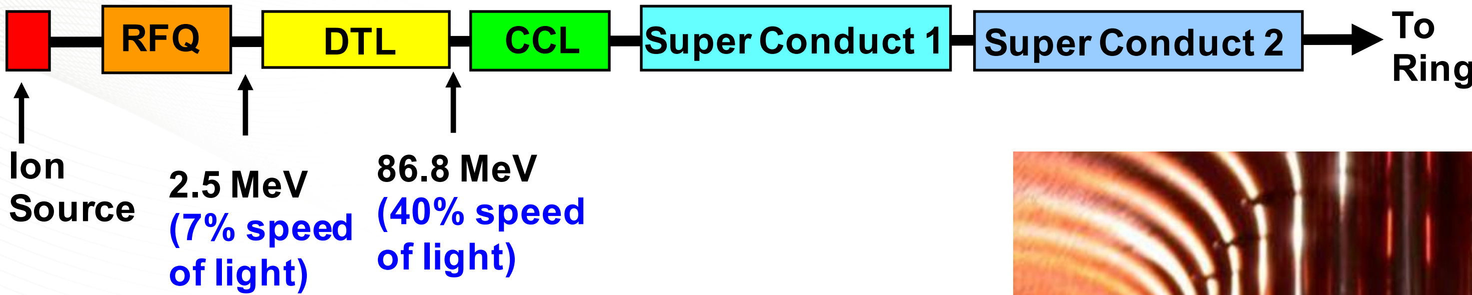


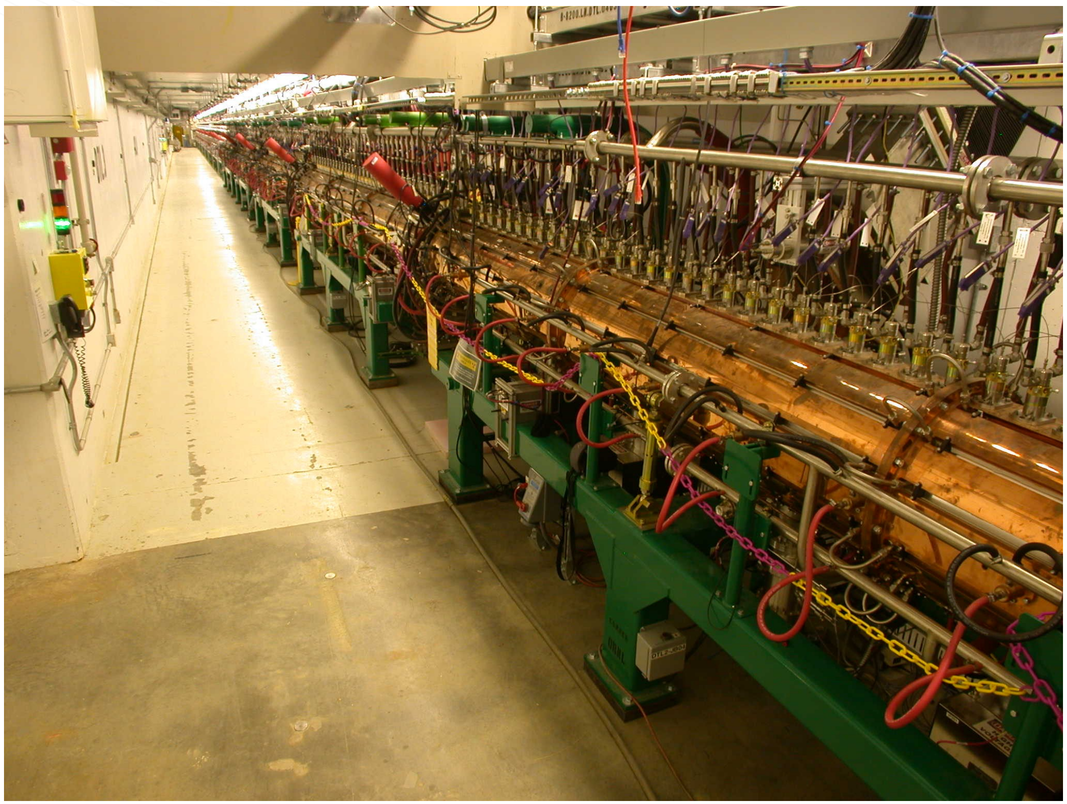
Drift tubes contain permanent magnet quadrupoles to focus the beam

Tank 3 drift tubes are longer and spacing greater

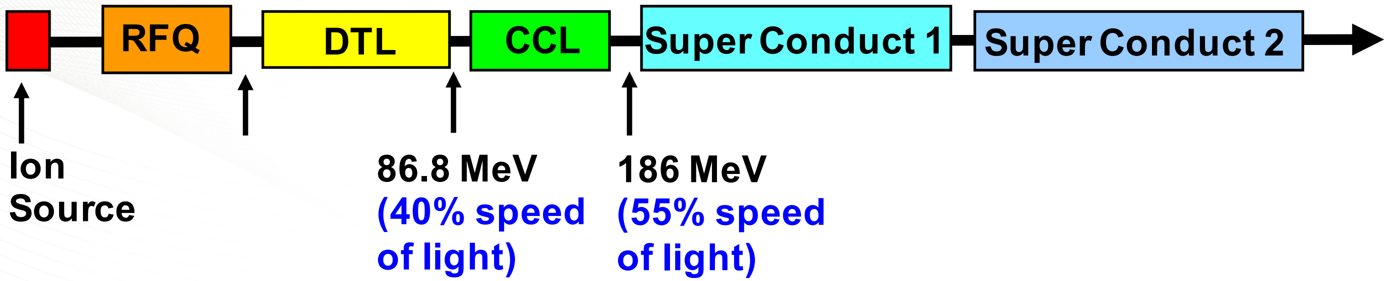


The Drift Tube Linac (DTL)

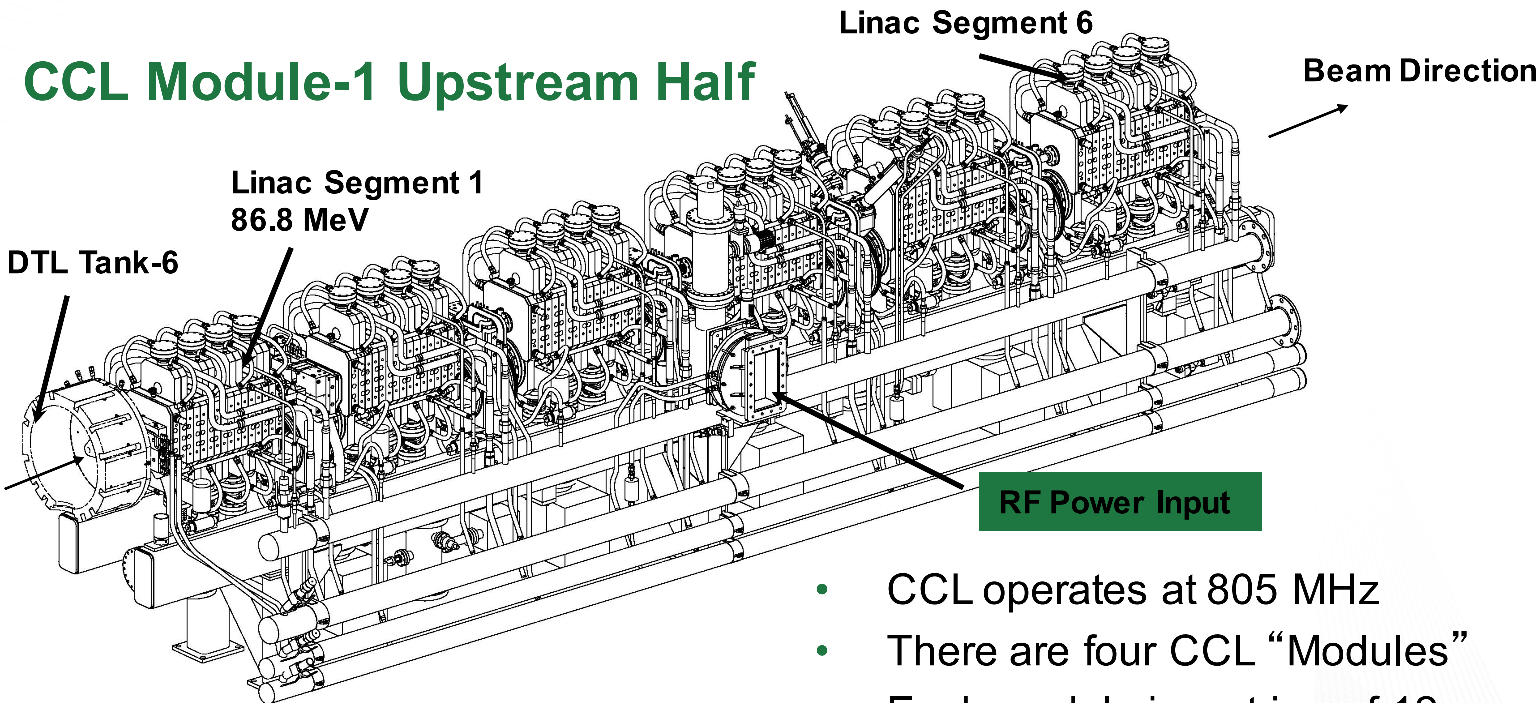




The Coupled-Cavity Linac (CCL) follows the Drift Tube Linac



CCL Module-1 Upstream Half



- CCL operates at 805 MHz
- There are four CCL “Modules”
- Each module is a string of 12 “segments”
- Each segment has 8 accelerating cells

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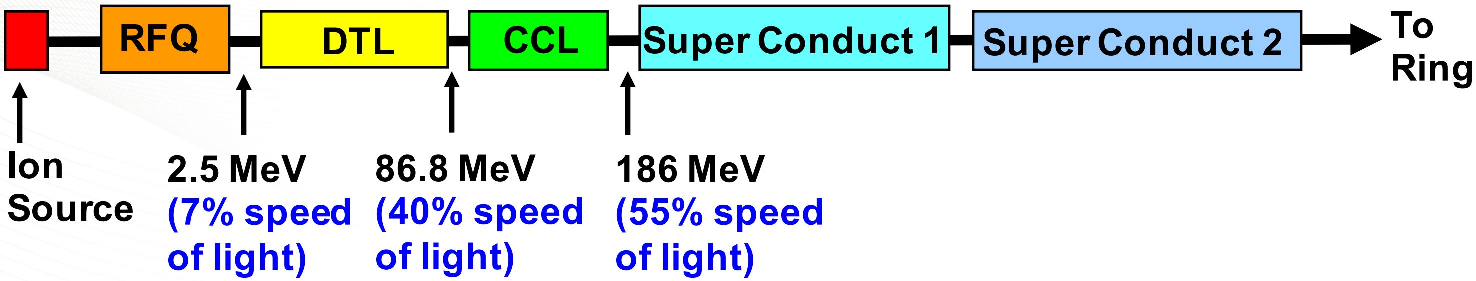
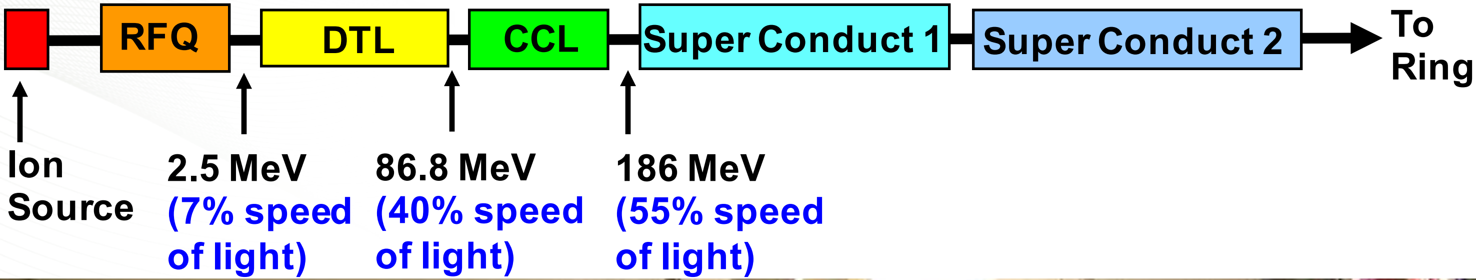
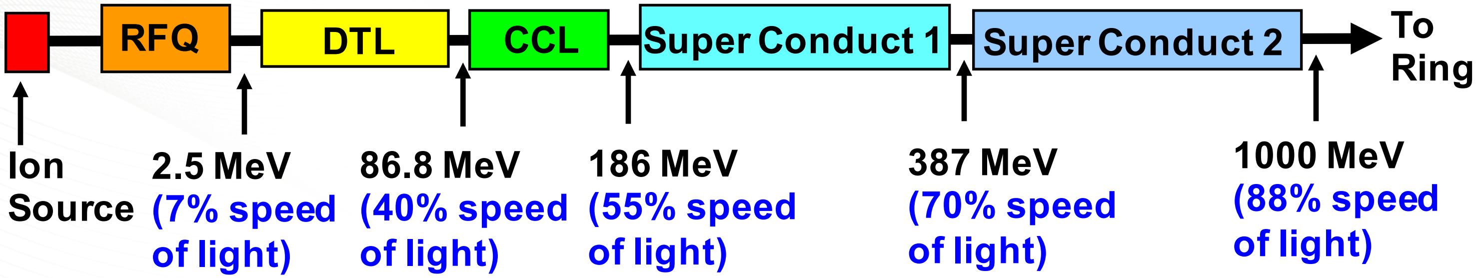
The Coupled Cavity Linac (CCL)



The Coupled Cavity Linac (CCL)



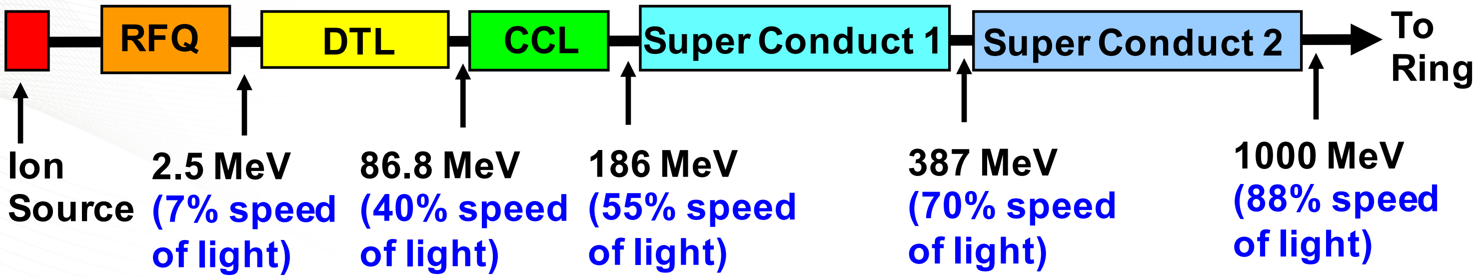
Why do we switch from a room-temperature copper structure to a superconducting niobium structure?



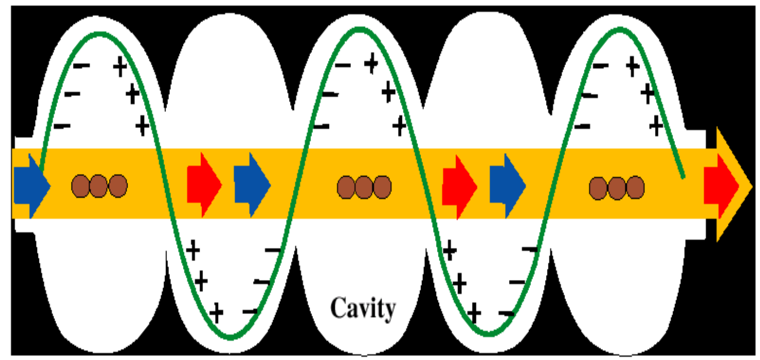
There are several advantages to using superconducting materials in a linear accelerator - two of the most important are:

1. Power dissipation (I^2R) in the copper linac structures (DTL and CCL) is substantial.
   - Example: DTL Tank 3: 1200 kW peak power dissipated in the cavity, whereas 440 kW is transferred to the beam
   - Lots of power used to heat up the cavity! And it’s expensive!
   - With a superconducting cavity, most of the power goes into the beam
2. Accelerating gradients are limited to few MV/m in Copper cavities
   - Gradients up to 45 MV/m have been achieved
   - Makes for a more “compact” accelerator

SNS uses two types of superconducting multicell cavities



Remember that as the particles go faster, the accelerating cells need to be spaced farther apart



Two types of superconducting cavities:

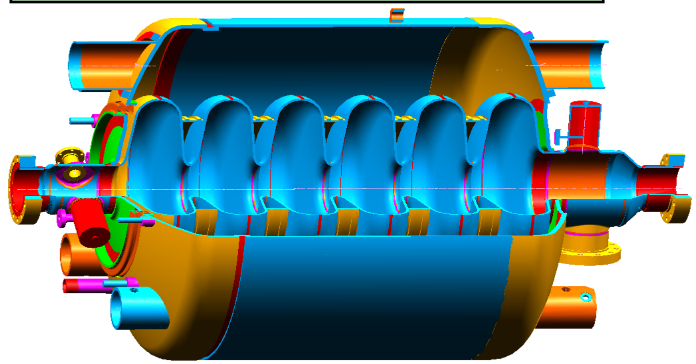
- Medium Beta: designed for v = 61% speed of light
  - Gives ~10 MV/m

- High Beta: designed for v = 81% speed of light
  - Gives ~15 MV/m

Cavity strings are grouped in packages of 3 or 4 in cryomodules that provide vacuum, superinsulation and liquid nitrogen surroundings for the 2K liquid Helium

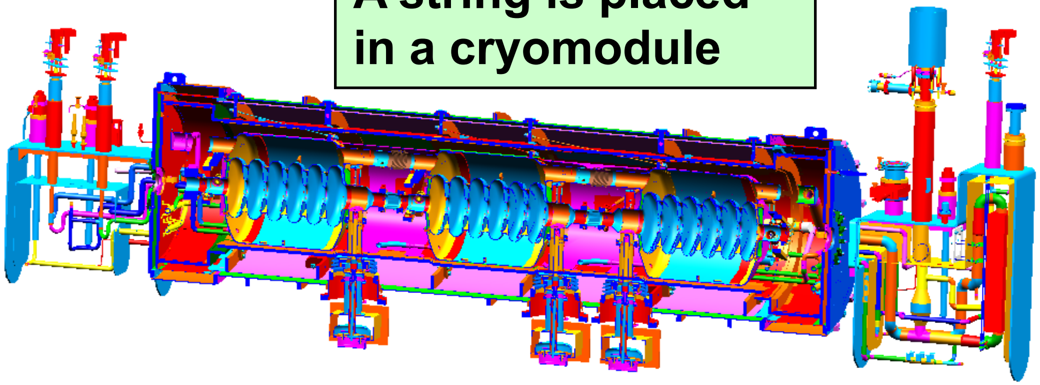
- All cavities operate at 805 MHz
- The cavities are made of Niobium
- They are cooled to 2 degrees K by liquid Helium (~6000 gallons)
- There are 33 medium beta cavities in 11 "cryomodules" (3 per CM)
- There are 48 high-beta cavities in 12 "cryomodules" (4 per CM)

Cavities are contained in a Helium Vessel

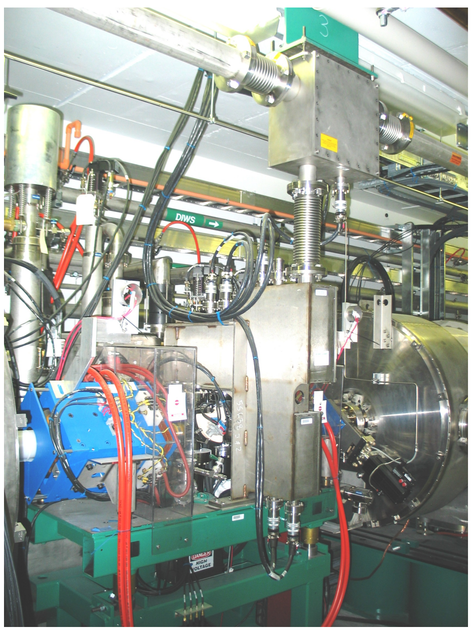


Cavities are assembled into a String

A string is placed in a cryomodule



Superconducting cryomodules inside the tunnel

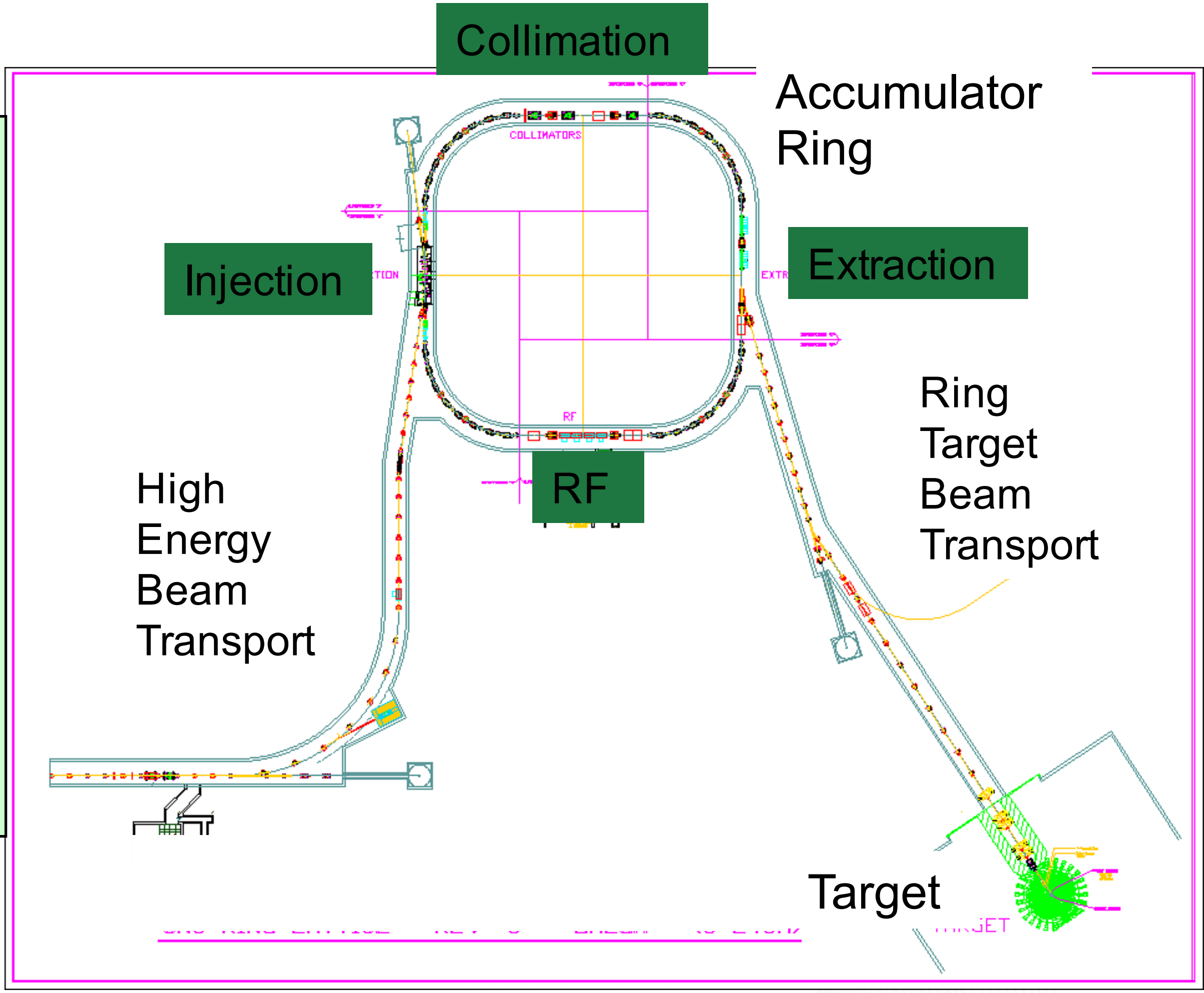


Now, how do we compress the sequence of minipulses we've accelerated into the short, intense pulses needed for the target? We need an accumulator ring!

- The Linac is "pulsed" at 60 Hz, with a pulse length of 1/1000th of a second (1 msec).
- The Linac "Duty Factor" is 60/sec x 0.001 sec = 0.06 = 6%
- The Linac pulse length (1 msec) is too long to use as is. Experimenters want a very short burst of neutrons.
- The Ring to the rescue!
  - It "accumulates" a very long linac pulse, and in the process, turns it into a very intense, short pulse
- The 1 msec linac pulse is about 250 km in length, whereas the ring is about 250 m around
- The long linac pulse is "wrapped around" the ring 1000 times, like a string is wrapped around a spool

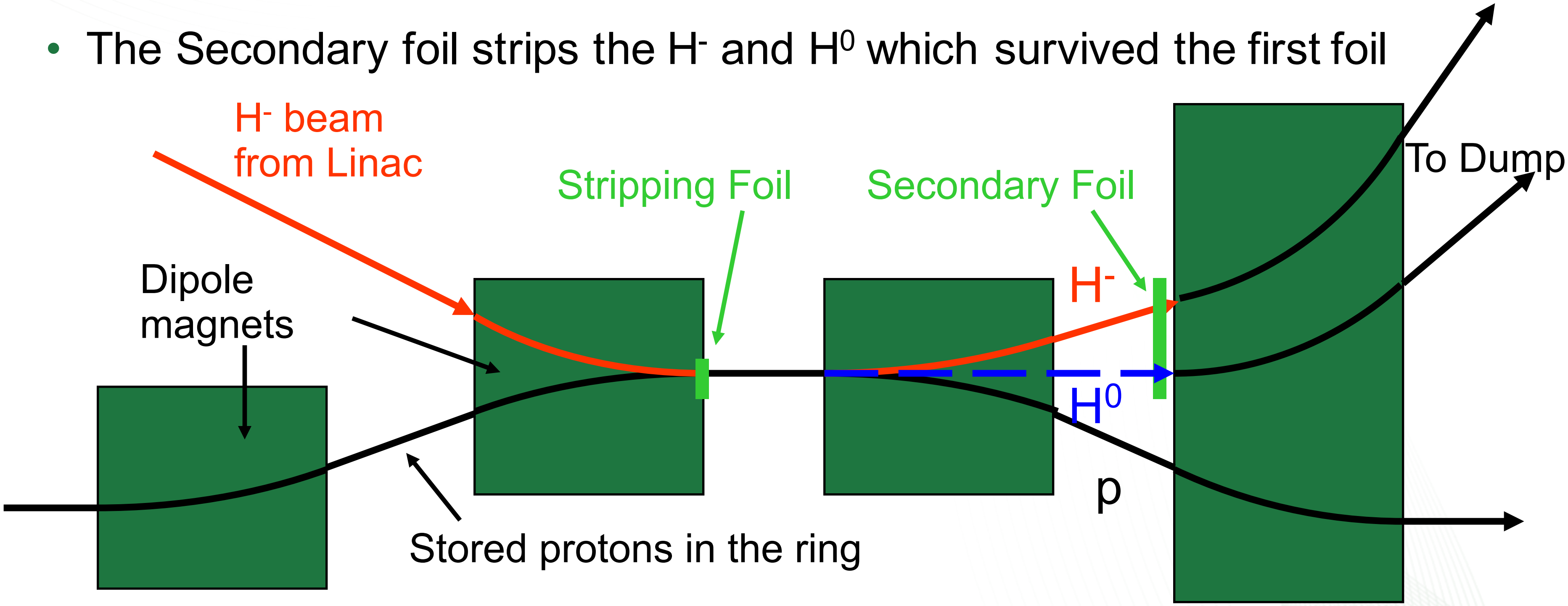
The Ring and Transport Lines are magnetic lattices (with a little RF in the ring to keep the bunch constrained)

Circum	248 m
Energy	1 GeV
f_{rev}	1 MHz
Accum turns	1060
Final Intensity	1.5×10^{14}
Peak Current	52 A
Number of magnets	>300



Beam injection is accomplished efficiently by removing the electrons from the H^- using a carbon stripper foil

- The SNS relies on Multi-Turn Charge-Exchange Injection to create a short pulse of protons in the Ring (250m) from a long beam pulse delivered by the Linac (250 km in length)
- Two electrons are removed by the stripping foil, injected protons are merged with previously accumulated beam
- The Secondary foil strips the H^- and H^0 which survived the first foil



And that's it! Voila – neutrons!

- Thanks for listening

- Questions?