The Abdus Salam
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Energy Agency

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Accelerator Design for Spallation Neutron Sources

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Accelerator Design for Spallation Neutron Sources

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Course description

Level: Introductory; overview

Prerequisites: Physics 101

Duration: 2 x 1h 30 min

Topics:

- General concept of accelerator for Spallation Neutron Source
- Fundamentals of accelerators; vocabulary; concepts
- Example: design of the SNS

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Acknowledgments:

In preparation of this lecture I used materials generously provided by my colleagues from the SNS, in particular by N. Holtkamp, S. Henderson, R. Campisi, M. Plum, S. Assadi, J. Stovall, and J. Wei.

Units

SI units will be used with one exception:

Beam kinetic energy is expressed in electron volt (eV), instead of Joules.

1eV=energy acquired by a particle with electronic charge 1.602 X 10-19 C accelerated through 1 Volt.

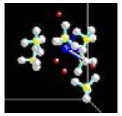
1MeV = 10^6 eV

1GeV = 10^9 eV

Mega Watt Class Accelerator Projects

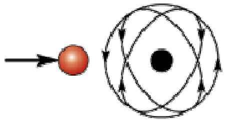
	Energy [GeV]	Current [mA]	Rep.-rate [Hz]	Ave. power [MW]	Type
SNS	1	2	60	2 **(23)**	LAR
ESS	1.33	1.9	50	2.5x2	LAR
JKJ	3	0.33	25	1	RCS
CERN PD	2	2	100	4	LAR
RAL PD	5	0.4	25	2	RCS
FNAL PD	16	0.25	15	2	RCS
EA	1	10 -- 20	CW	10 -- 20	cyclotron
APT	1.03	100	CW	103	linac
TRISPAL	0.6	40	CW	24	linac
ADTW	0.6 – 1.2	20 -- 50	CW	> 20	linac
μ-collider driver	30	0.25	15	7.0	RCS

Why Neutrons?



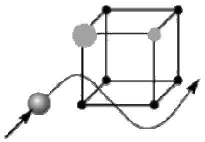
1. **Neutrons have the right wavelength**

   Neutrons probe a broad range of length scales



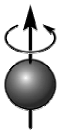
2. **Neutrons see the Nuclei**

   Can offer greater contrast than x-rays (e.g. H); isotopic contrasting



3. **Neutrons penetrate deep into Matter**

   Study material properties deep inside materials; characterizing deep welds and their associated stresses

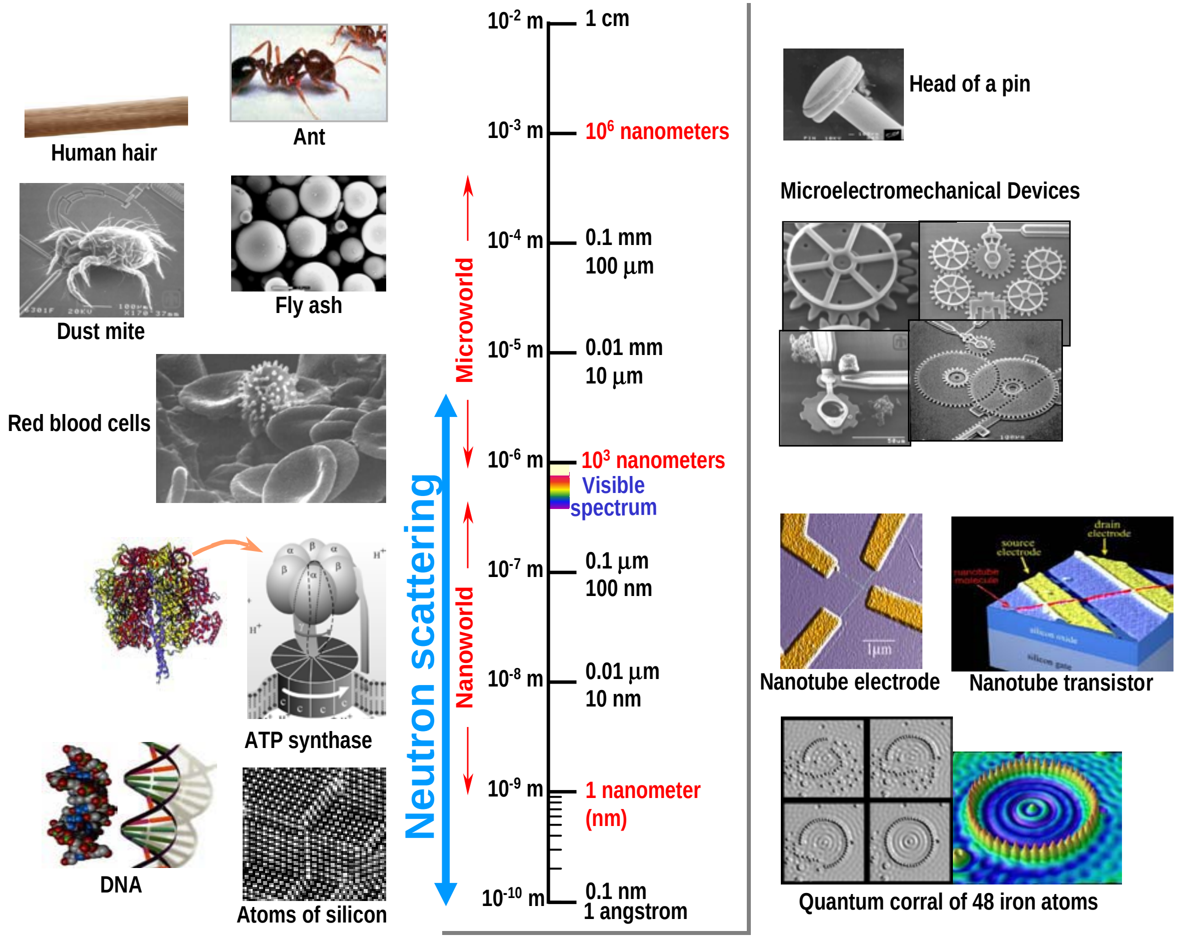


4. **Neutrons see Elementary Magnets**

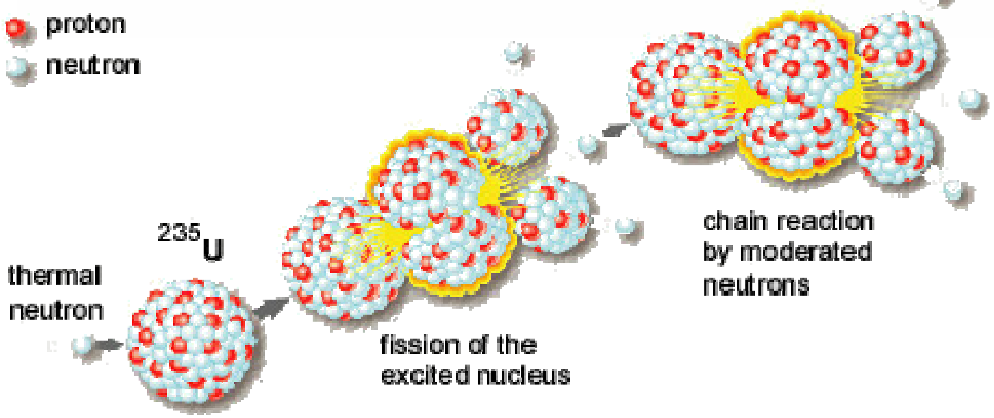
   Study magnetic structure of materials; advanced magnetic materials

Neutrons probe a broad range of length scales

Nanoscale science and technology presents extraordinary opportunities



Spallation-Evaporation Production of Neutrons and Why to use heavy metal target!

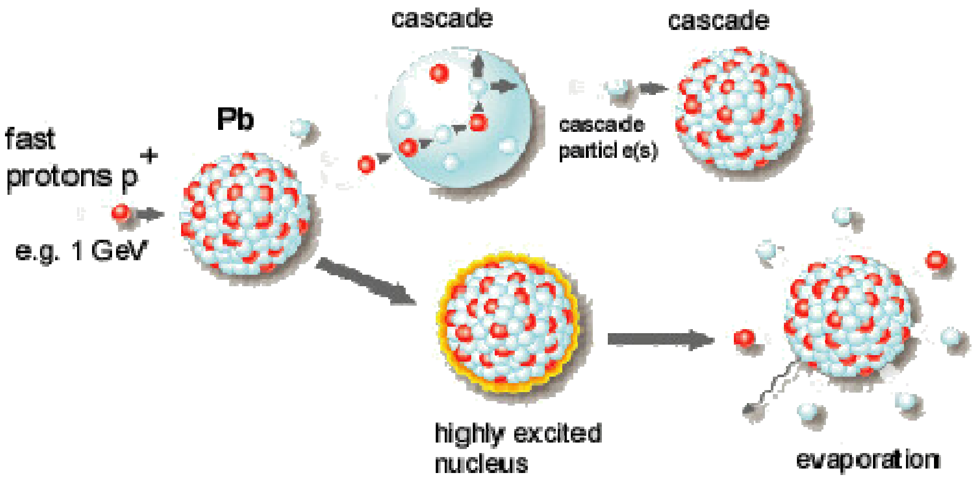


Fission

- chain reaction
- continuous flow
- 1 neutron/fission

$$\overline{P}_{beam} = E[eV] \cdot I[A] \cdot T_{pulse}[sec] \cdot f_{rep}[Hz]$$

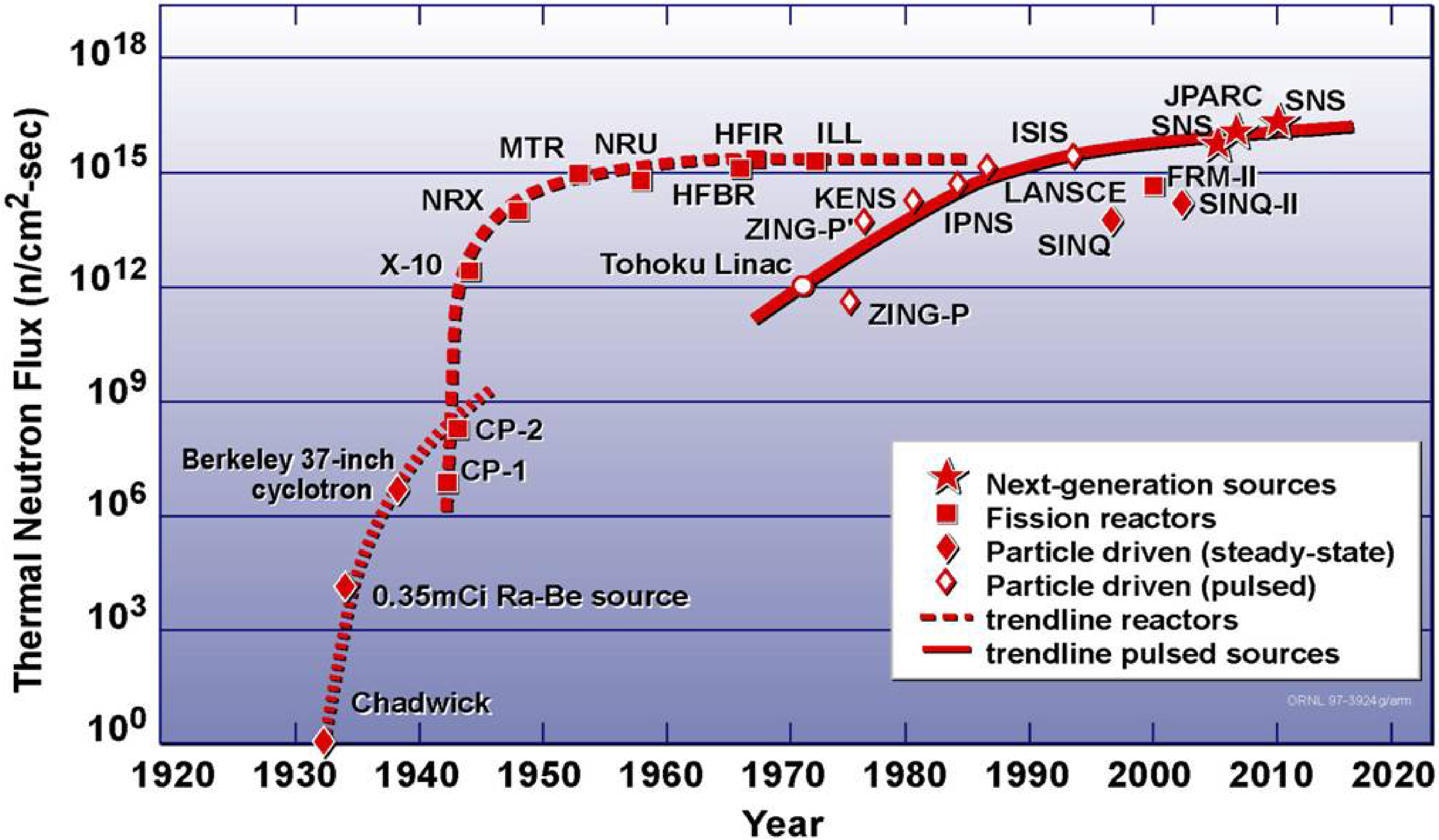
SNS : Goal is to achieve 1.4 -> 2 ++ MW average power



Spallation

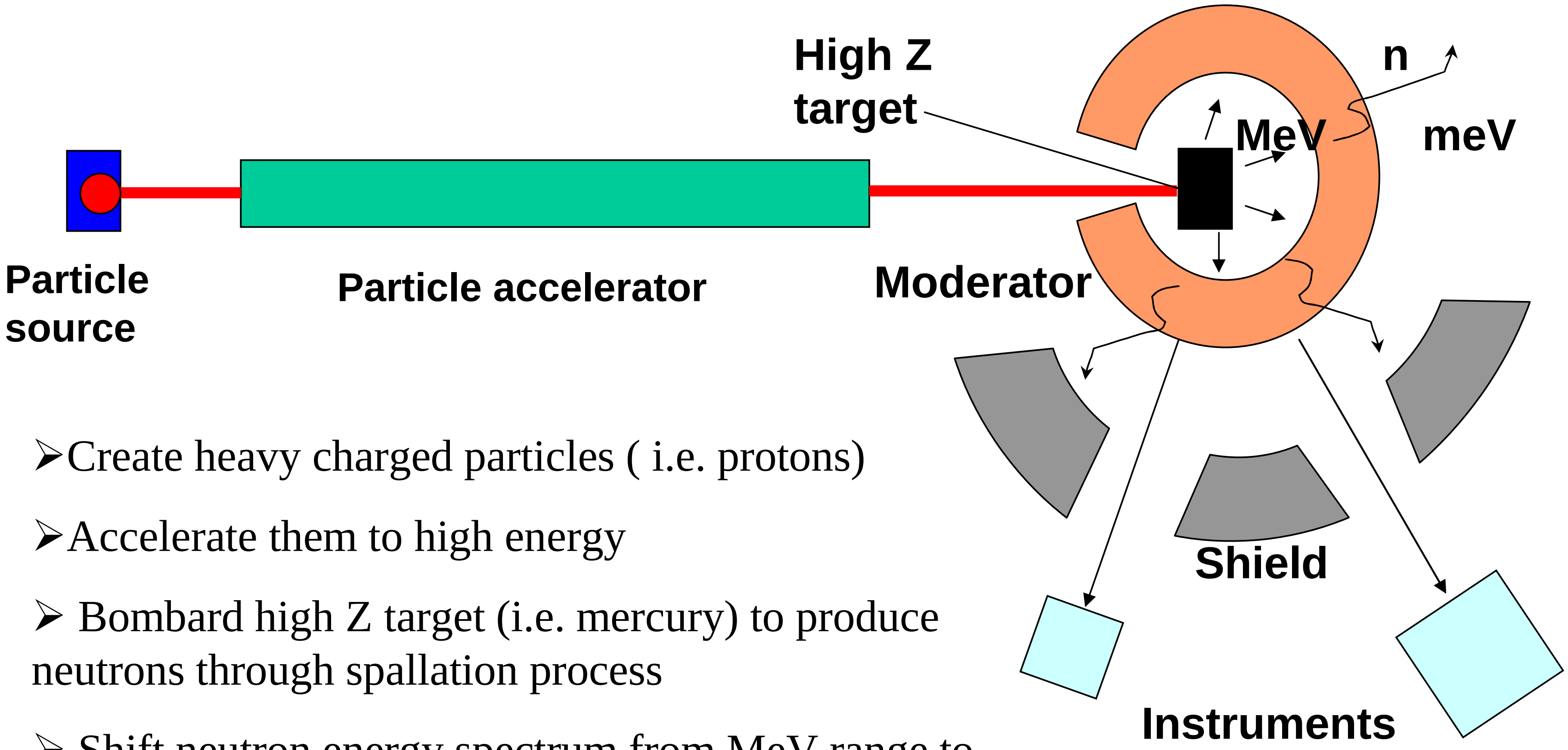
- no chain reaction
- pulsed operation
- 30 neutrons/proton
- Time resolved exp.

Development of neutron science facilities



(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

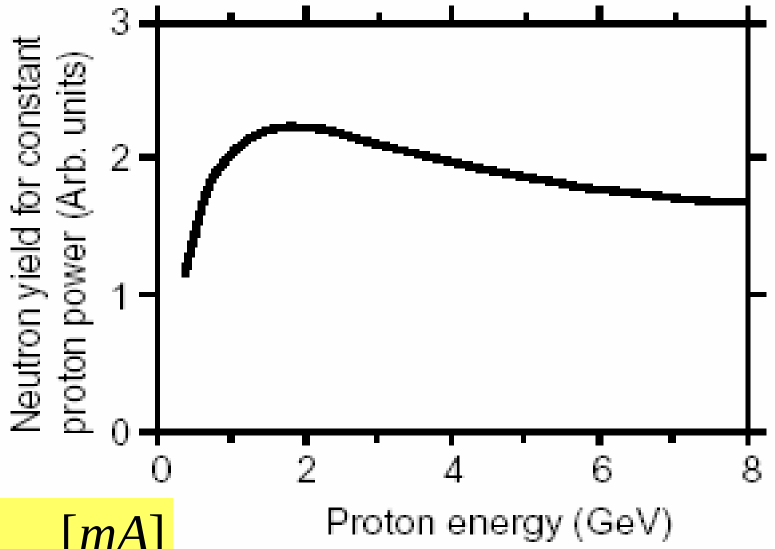
Simplest Spallation Neutron Source layout



- ➢Create heavy charged particles (i.e. protons)
- ➢Accelerate them to high energy
- ➢ Bombard high Z target (i.e. mercury) to produce neutrons through spallation process
- ➢ Shift neutron energy spectrum from MeV range to thermal in moderator (through multiple collisions)

Choosing design parameters : beam energy

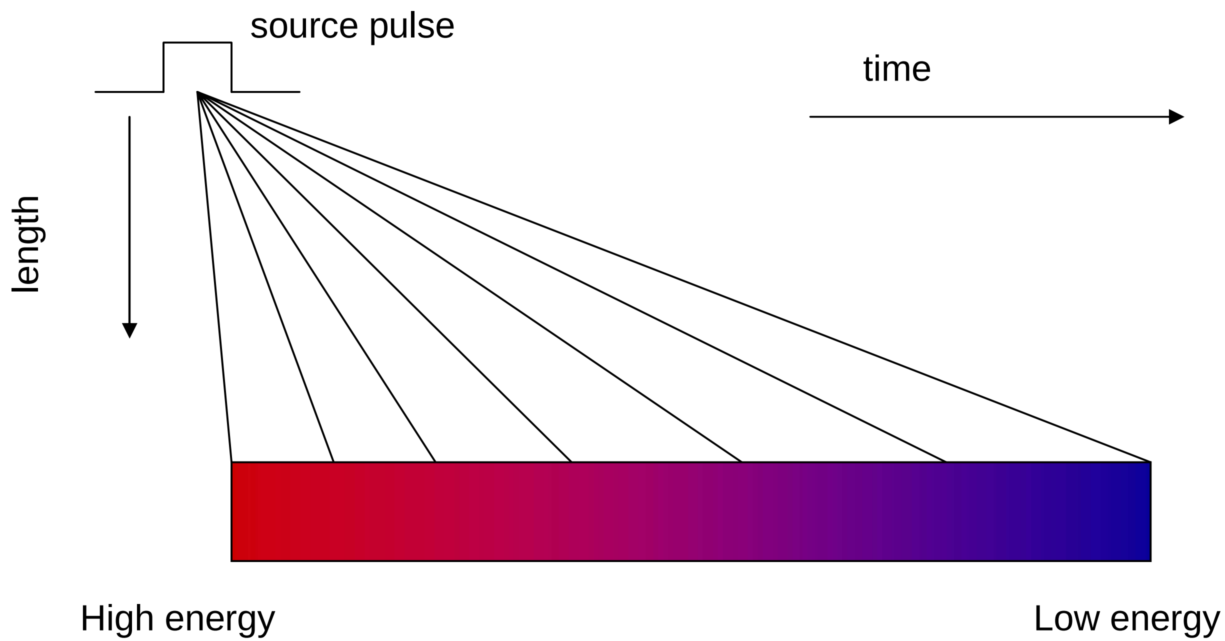
- Neutron yield per 1W of proton beam power is almost independent on beam energy above ~ 1GeV



$$N[\frac{n}{\sec}] = k \cdot P_{beam}[MW] = k \cdot W_{beam}[GeV] \cdot I_{beam}[mA]$$

- Efficient use of beam power requires W > 1GeV
- Approximately same neutron yield will be produced by 1 GeV * 2 mA beam and 2 GeV * 1 mA beam
- Trade off between beam current and energy provides flexibility in choosing type of accelerator (will be discuss later)

Pulsed Neutron Source and Time-of-Flight separation

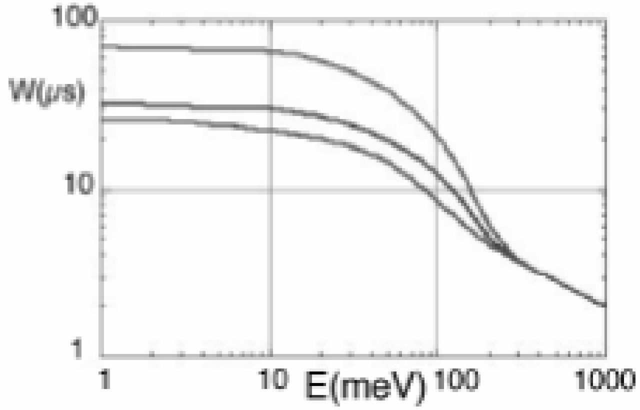


➢ Pulsed operation allows neutron energy separation by resolving time of arrival to the detector: faster neutrons arrive earlier slower neutrons arrive later

Choosing design parameters : beam pulse time structure

➢ Beam pulse length τ should be much shorter than neutron pulse widening in the moderator to preserve resolution of Time-of-Flight energy separation. Typically, τ < 1 μs.

➢ Time between pulses T should be large enough to prevent "frame-overlap" from consecutive pulses. Typically, T > 10 ms (or repetition rate < 100 Hz).



Time widths W (FWHM) of neutrons emerging from a room-temperature water moderator in different regimes.

➢ Accelerator stability improves if pulse rate is synchronized with AC power line: 60 Hz, 30 Hz, 20 Hz … in USA (50 Hz, 25 Hz, 10 Hz … in Europe).

! In pulsed systems distinguish peak values of parameters (e.g. current, power) vs. average values.

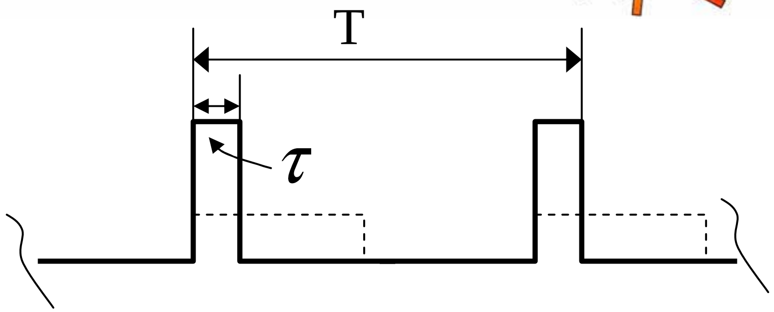
Choosing design parameters : example

Average beam power: P = 1.0 MW

Beam kinetic energy: W = 1.0 GeV

Beam pulse length: τ = 1.0 μs

Repetition rate: R = 50Hz



Average beam current: $$I_{av} = \frac{P}{W} = \frac{1 \cdot 10^{6}\, watt}{1 \cdot 10^{9}\, eV} = 1 \cdot 10^{-3} A = 1.0\, mA$$

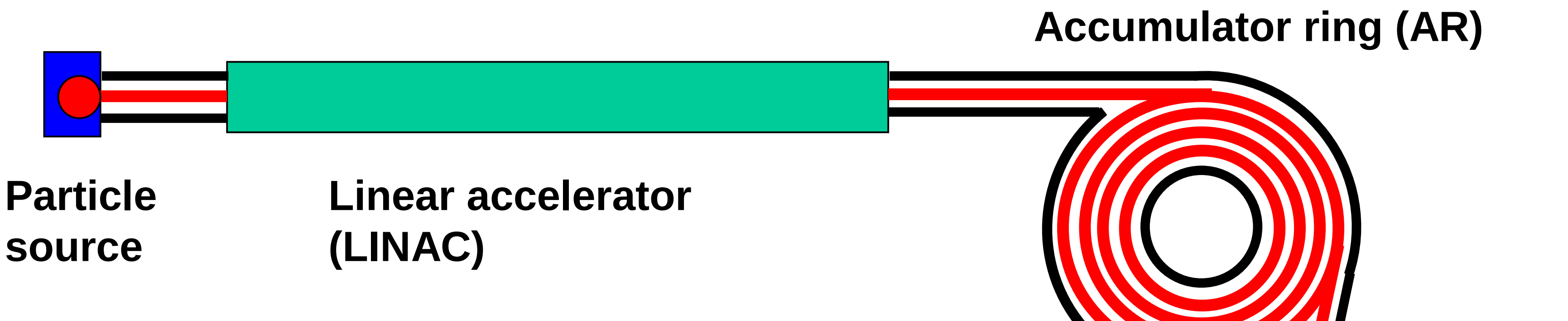
Peak beam current: $$I_{pk} = \frac{I_{av} \cdot T}{\tau} = \frac{I_{av}}{\tau \cdot R} = \frac{10^{-3} A}{10^{-6} s \cdot 50\, Hz} = \boxed{20\, A}$$

Maximum peak beam current in modern proton linear accelerator is ≈ 0.1 A

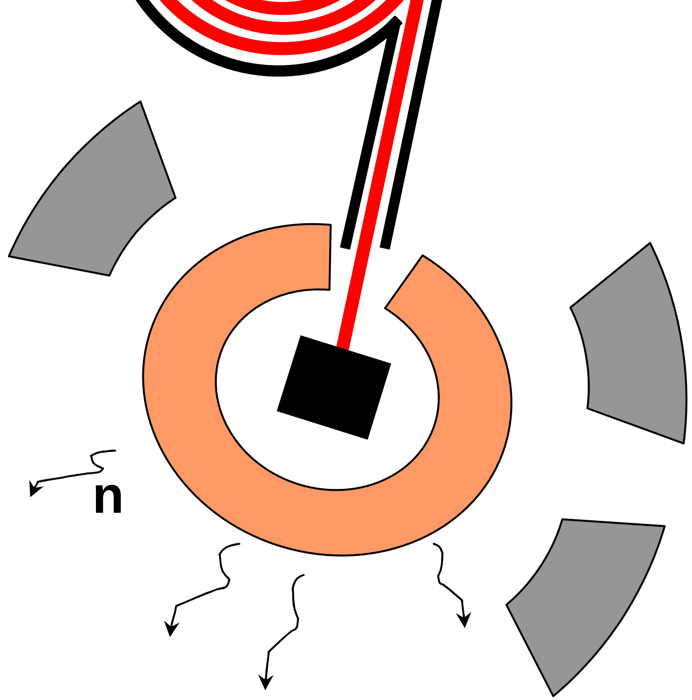
How to resolve discrepancy?

1. ~~Increase beam energy~~ to 200 GeV. Impractical and cost prohibitive.
2. Accelerate 200 μs long beam pulse then compress it to 1 μs.

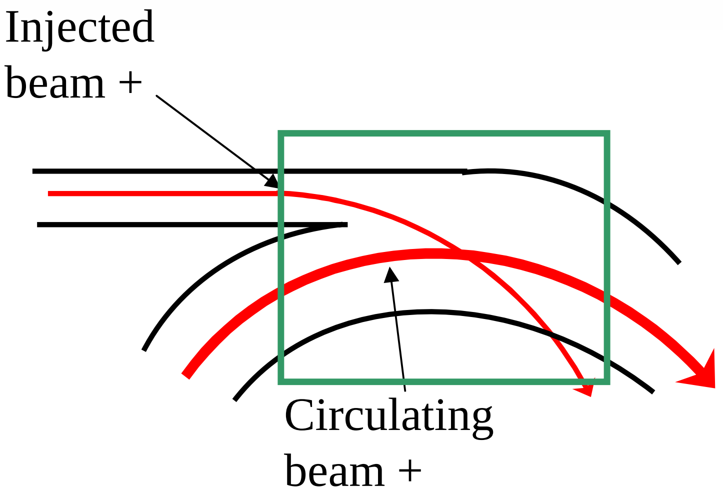
Layout of pulsed SNS with pulse compression



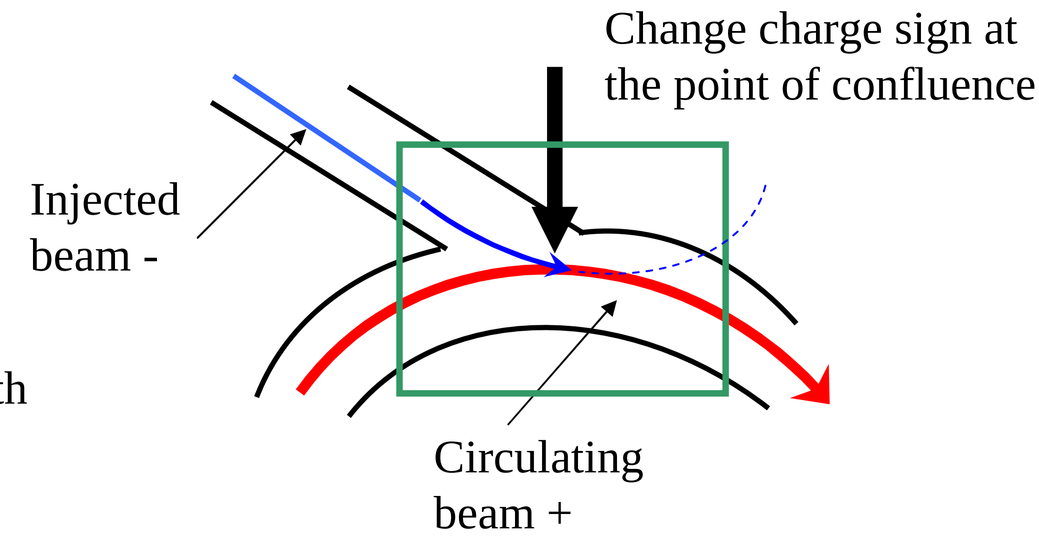
- Accelerate low peak current beam in linear accelerator
- Continuously inject into the ring wrapping beam around for N turns
- Extract from the ring during one turn
- Peak current increases N times, average current doesn't change
- Additional acceleration can be applied in the ring to increase beam energy. That type of ring is called Rapid Cycling Synchrotron (RCS)



Multi-turn injection into the ring



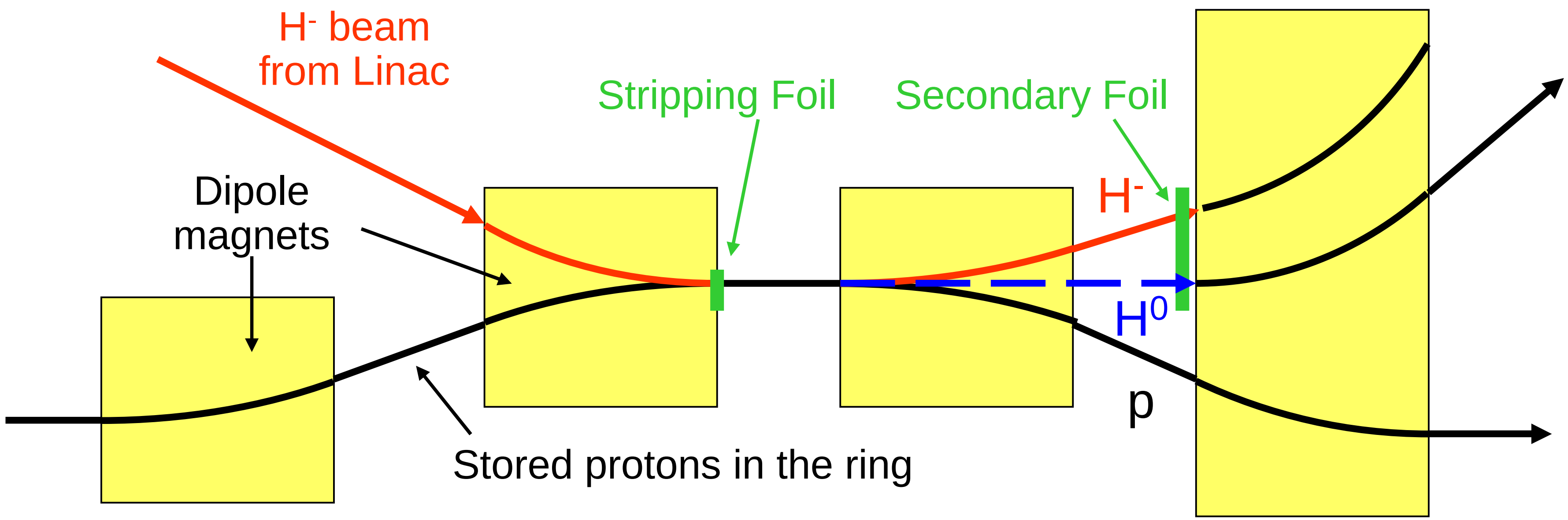
Injection without charge exchange doesn't allow confluence of two beams



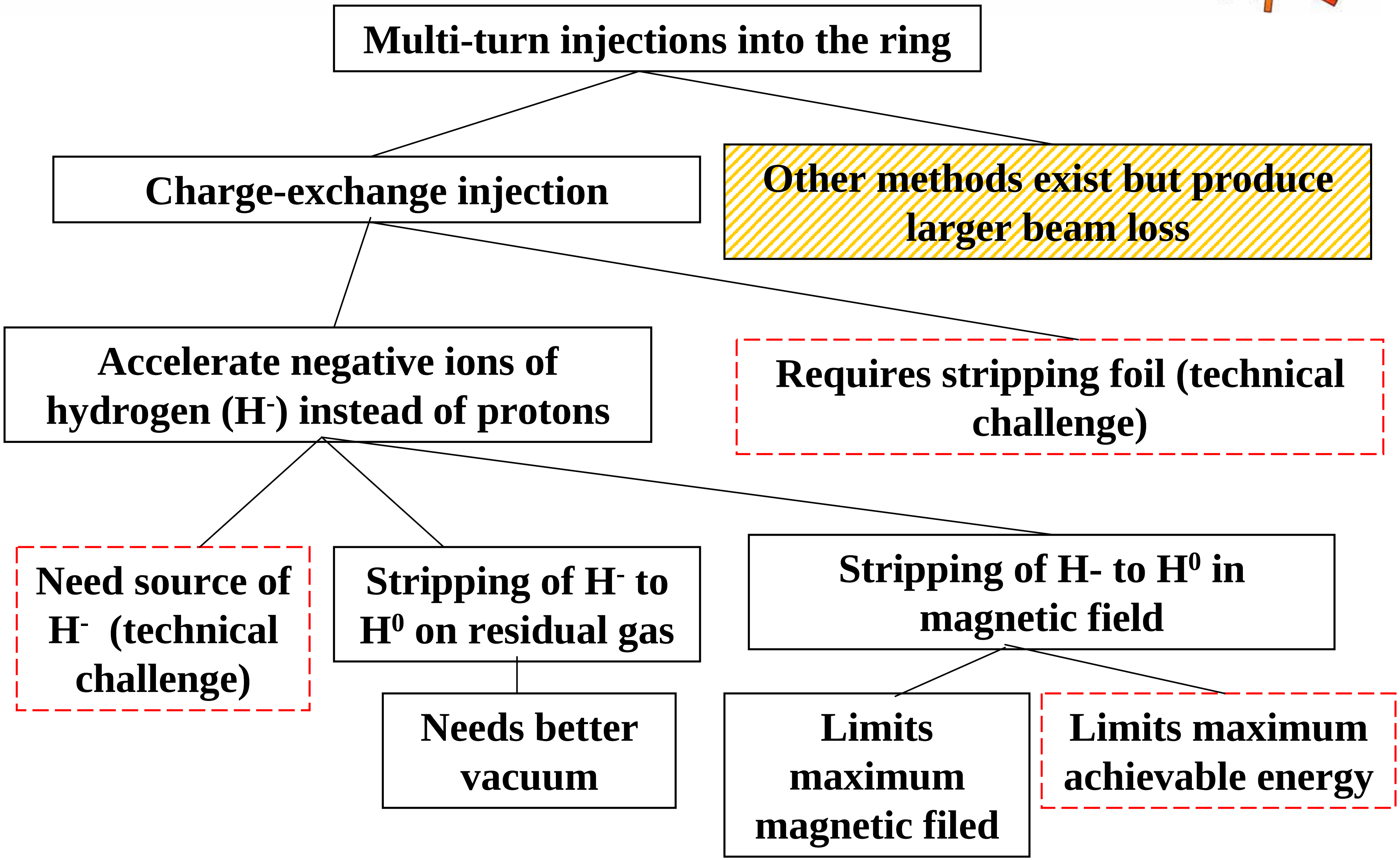
Injection in magnetic field with charge exchange does allow confluence of two beams

Multi-turn charge-exchange injection in practice

- Negative ions of hydrogen (bound state of proton + 2 electrons) are produced in the source and accelerated
- 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

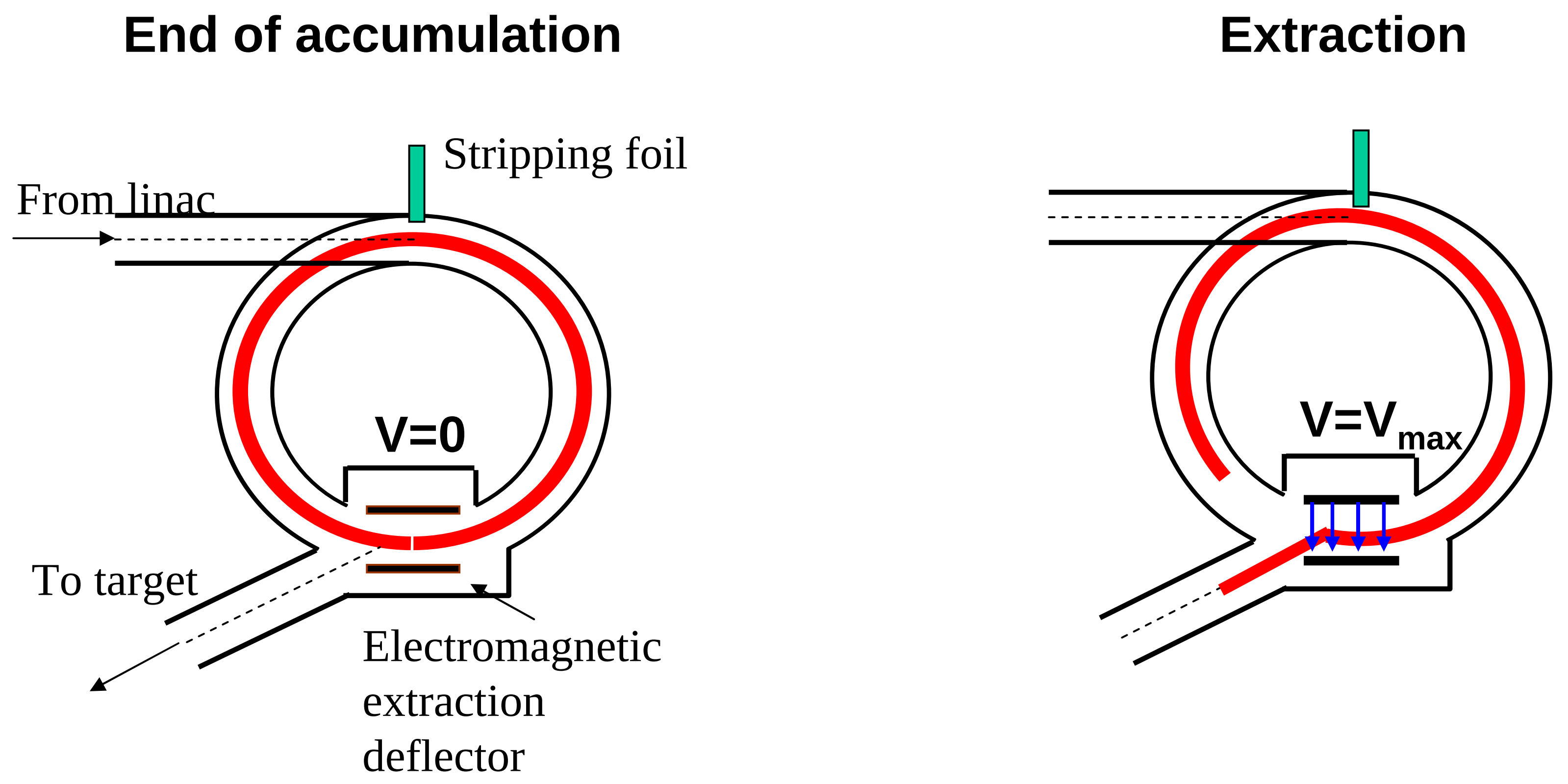


Multi-turn charge-exchange injection implications

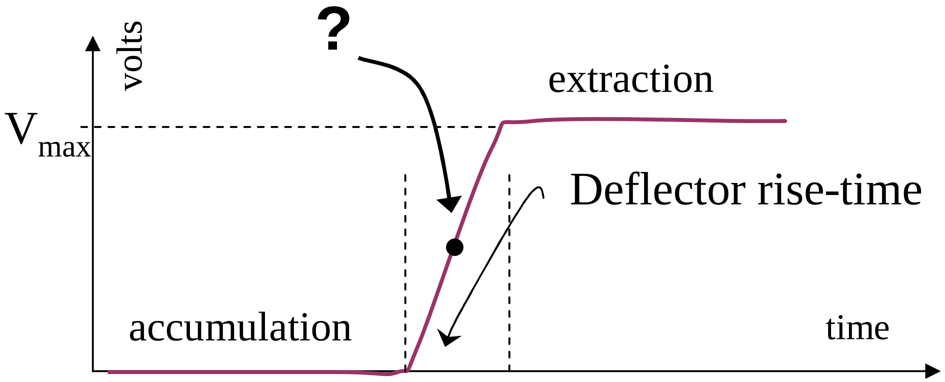


Single-turn extraction from the ring

- Install electro-magnetic deflector in the ring.
- Zero voltage on deflector. No deflection. Beam is circulating.
- Maximum voltage on deflector. Beam is deflected to extraction channel.



Extraction losses

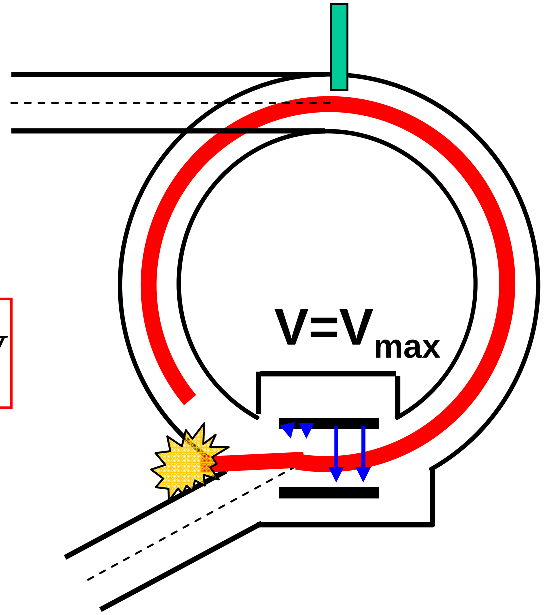


- Deflector can't switch on instantly
- Typical rise-time ~ 200ns
- What happens to partially deflected beam?

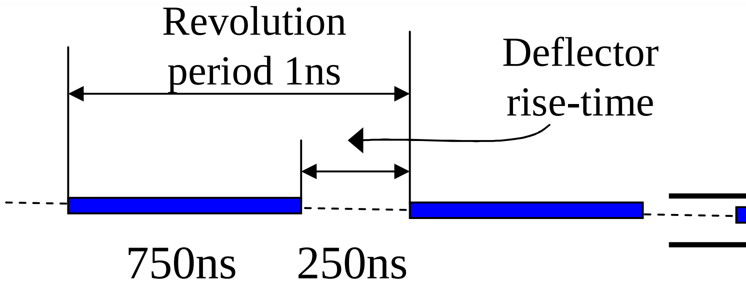
- Half-deflected beam misses extraction channel and hits the wall
- Power of lost beam

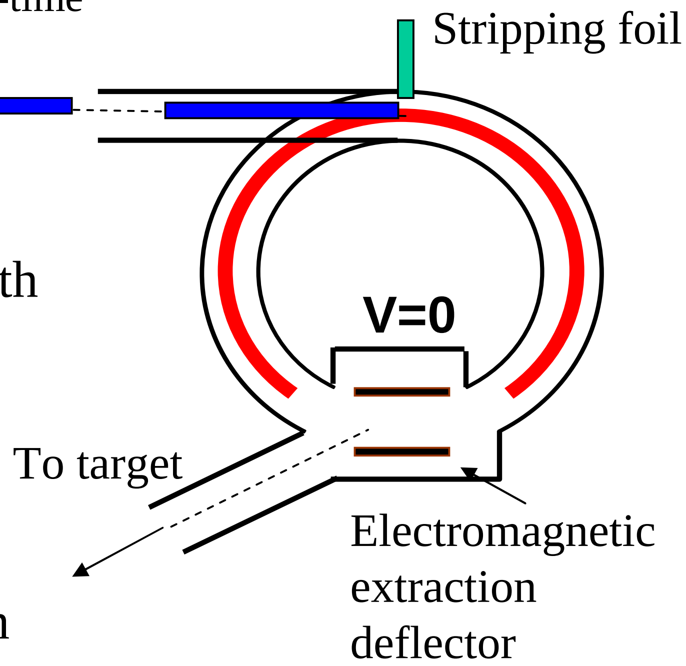
$$\approx \frac{deflector\ rise\ time}{revolution\ \ period} \cdot P \approx \frac{0.2\mu s}{1\mu s} \cdot 1MW = \boxed{200kW}$$

- Unacceptably high. *Higher than power on target for best existing machines!*



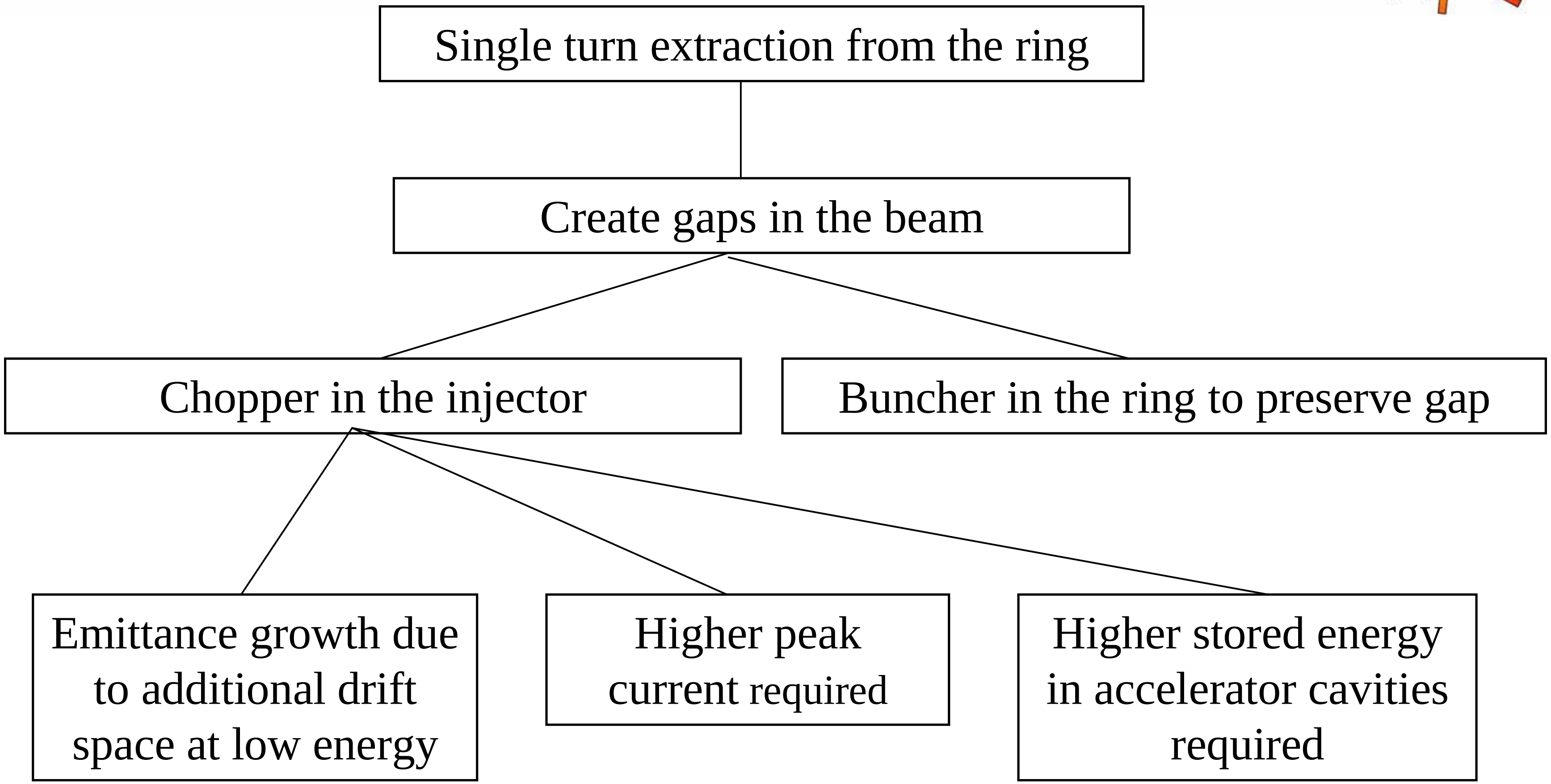
Extraction losses mitigation





- Divide beam on separate chunks synchronized with ring revolution period
- Gap between chunks > deflector rise-time
- Switch on deflector during the gap
- No beam during deflector rise-time. No extraction losses.
- Have to add “chopper” creating gaps in the beam
- Chopper should be placed at as low energy as possible to minimize power of beam removed from the gaps

Single-turn extraction implications



Acceleration

- Lorentz force: $\vec{F} = e(\vec{E} + \vec{v} \times \vec{B})$

- Total particle energy: $T = mc^2 + W$

- Energy change by external force: $\frac{dT}{dt} = \vec{v} \cdot \vec{F} = e\vec{v} \cdot (\vec{E} + \vec{v} \times \vec{B}) = e\vec{v} \cdot \vec{E}$

Only electrical field collinear with particle velocity can change its energy

- For velocities v≈c a moderate magnetic field of 1Tesla creates transverse force corresponding to a huge electric field of 3000 kV/cm.

- Use magnetic fields to deflect particles at high energy, v≈c

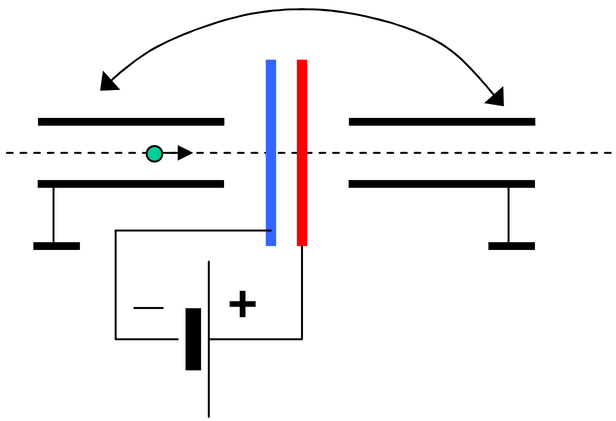
- Use electric field to deflect particles at low energy, v<<c

Radio Frequency Acceleration Principle

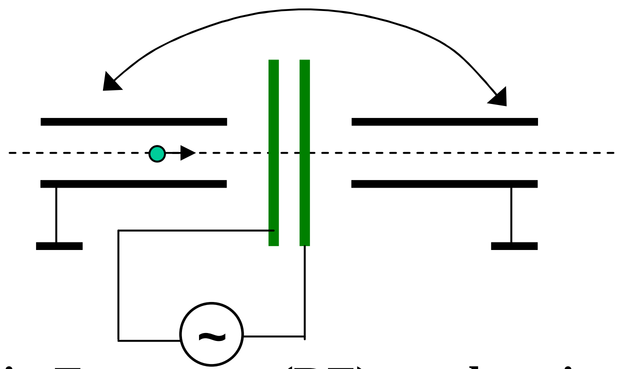
- Need electric field to accelerate particles
- From Maxwell equations: $\vec{E} = -\nabla\varphi - \frac{\partial}{\partial t}\vec{A}; \qquad \vec{B} = \nabla \times \vec{A}$
- Electrostatic field is associated with difference of potentials
- To gain 1GeV energy particle needs to traverse 1 Giga-Volt potential difference. Absolutely not feasible technically. Maximum energy of DC accelerator ~10MeV: Van de Graaff, Cockcroft-Walton, Tandem…

- Have to use time-varying field

Same potential ⇔ no acceleration

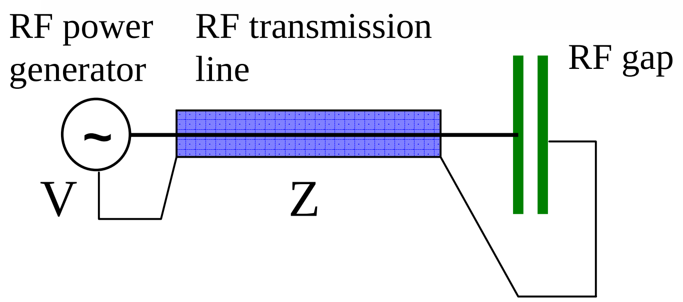


Same potential but can be an acceleration because time varying field is not conservative



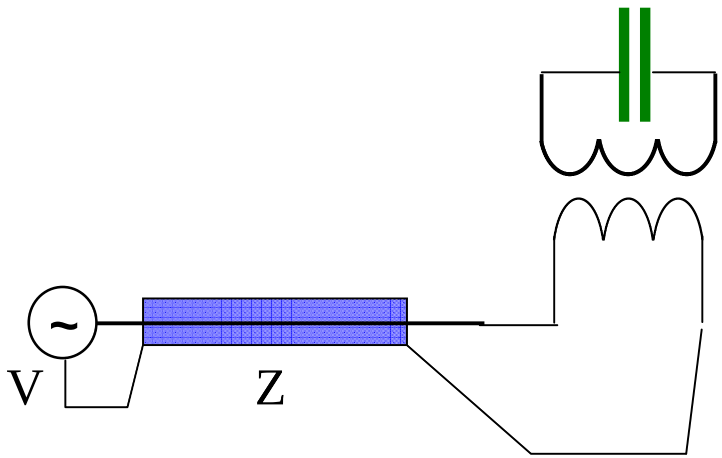
Radio-Frequency (RF) acceleration principle

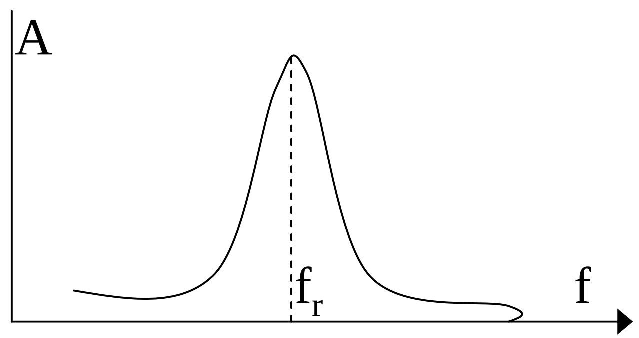
Inducing voltage in the gap



➢ Rf power required to create 100kV voltage in the gap:

$$P = \frac{V^2}{2Z} = \frac{(10^5 volt)^2}{2 \cdot 50\Omega} = \boxed{10^8 Watt}$$





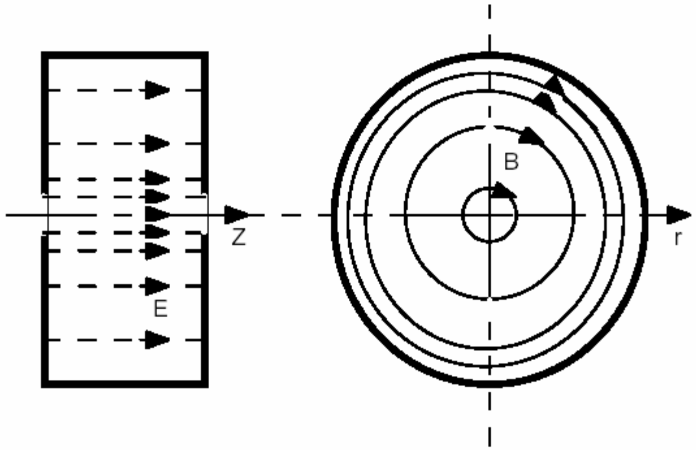
➢ Transformer allows higher voltage without power increase

➢ Gap capacitance and transformer inductance form resonant LC circuit

➢ If driven at resonant frequency allows significantly (10^2 - 10^4) higher voltage without power increase

➢ At high frequencies (10^7 - 10^{11} Hz) RF cavity is more efficient than ordinary LC circuit

RF cavity



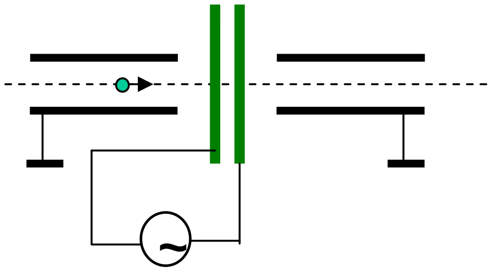
Electric E and magnetic B fields for the lowest mode in a cylindrical (pillbox) cavity resonator.

- Solution of Maxwell equations for e/m fields inside a conducting boundary can be represented as an infinite sum of specific field configurations (field eigenvectors or modes) oscillating at specific frequencies (eigenvalues or resonant frequencies)
- If driven at resonant frequency only the corresponding mode is excited

- Final conductivity of the cavity walls cause resistive energy losses $P_{loss} \sim E$
- Energy of the filed in the cavity is stored energy $U \sim E^2$
- Quality factor is figure of merit for cavity efficiency $Q = \frac{\omega U}{P_{loss}}$

- Balance of power $P_{generator} = P_{loss} + P_{beam}$

Energy gain in RF gap

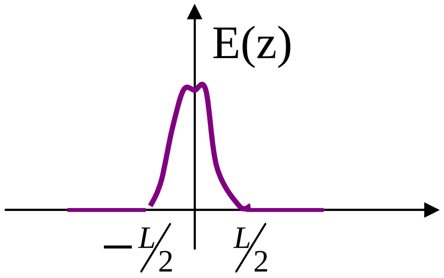


$$E(z,t) = E_0(z)\cdot\cos(\omega t+\phi)$$

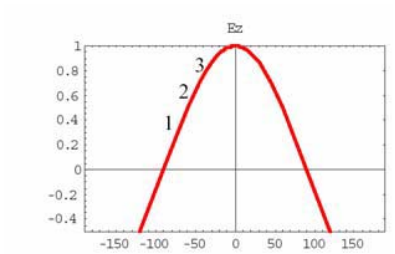
$$\Delta W = e\int_{-L/2}^{L/2} E(z,t)dz = e\int_{-L/2}^{L/2} E_0(z)\cdot\cos(\omega t+\phi)dz =$$

$$= e\int_{-L/2}^{L/2} E_0(z)\cdot[\cos\omega t\cdot\cos\phi - \sin\omega t\cdot\sin\phi]dz =$$

$$= e\cdot V_0\cdot T\cdot\cos\phi,$$



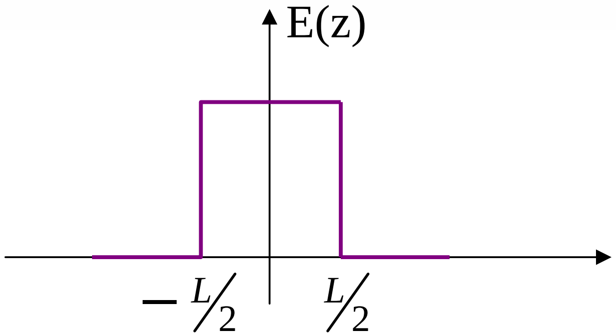
where $V_0 = \int_{-L/2}^{L/2} E_0(z)\cdot dz$, RF voltage.



1. Particle enters the gap
2. Particle in the middle
3. Particle exits the gap

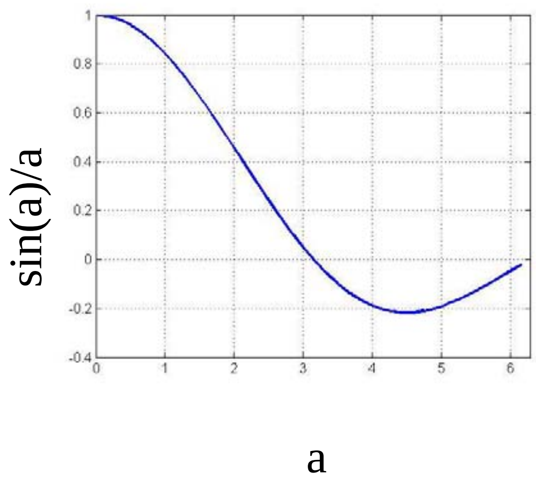
$$T = \frac{\int_{-L/2}^{L/2} E_0(z)\cdot\cos\omega t\cdot dz}{V_0} - \frac{\int_{-L/2}^{L/2} E_0(z)\cdot\sin\omega t\cdot dz}{V_0}$$

Transit-Time Factor



- Assume uniform electric field in the gap
- Assume particle velocity v change in the gap is small

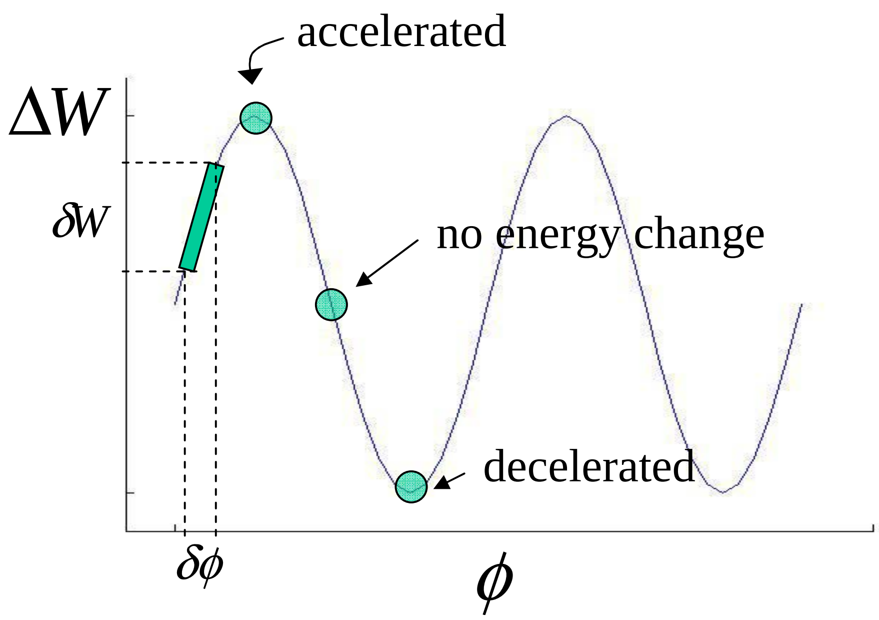
$$T = \frac{\sin \frac{\omega L}{2v}}{\frac{\omega L}{2v}}$$



- Transit-time factor decreases with gap width
- Transit-time factor increases with particle velocity
- Transit-time factor is "geometrical" factor – depends on gap geometry but doesn't depend on electrical field strength

Accelerating phase

$$\Delta W = e \cdot V \cdot T \cdot \cos\phi$$



➢ Energy gain for individual particle depends on arrival phase

➢ If particles in the beam occupy a finite range of phases $\delta\phi$,the output energy will occupy range of energies – energy spread δW

➢ To obtain accelerated beam with small energy spread requires grouping particles in the narrow range of phases (bunch) around the accelerating phase

Typical values :

$$\delta W \approx (10^{-3} \div 10^{-2}) \cdot W$$

$$\delta\phi \approx 1^\circ - 10^\circ$$

Gap voltage

$$V_0 = \int_{-L/2}^{L/2} E_0(z) \cdot dz$$

In uniform field: $V_0 = E_0 \cdot L$

- To increase energy gain:
  - ✓ increase gap length L
    - limited by transit-time factor decrease
  - ✓ increase electrical field strength E
    - limited by electrical breakdown; available RF power

Typical values :

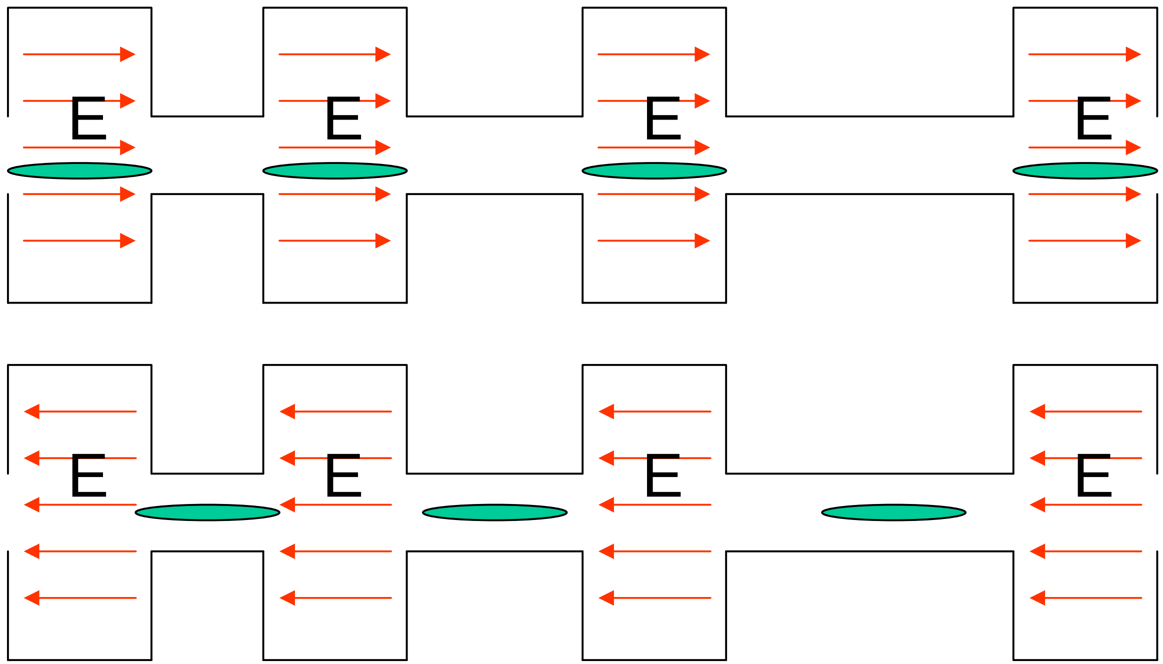
$$E = 3 \div 30 \, {}^{MV}\!/_{m} \qquad L \approx \frac{\beta\lambda}{4} = .01 \div .1m$$

$$V \approx .03 \div 3MV$$

- Can not reach large acceleration in single gap **-**➢ use multiple gaps

Multi – gap acceleration

- 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



Synchronous Particle and Synchronous Phase

➢ A synchronous particle is one whose velocity is such that particle appears in the center of successive accelerating gaps in step with the RF fields. That is, the particle arrives at each gap center at the synchronous phase ϕ_S

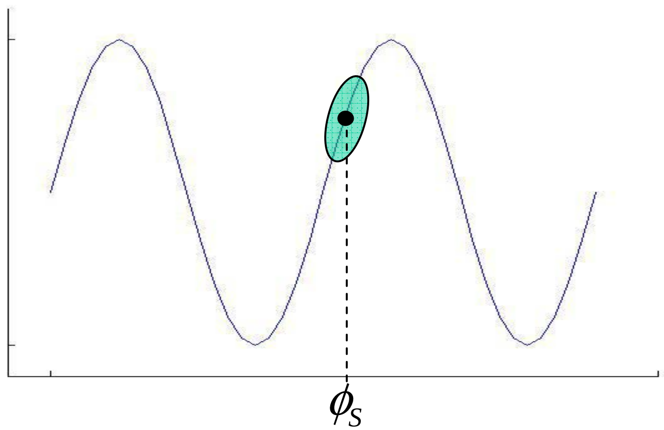
➢ For synchronous particle to exist the accelerator has to be properly designed:

- ➢Time of flight from one gap center to another is multiple of the RF period

➢ Synchronous particle has exact phase and energy.

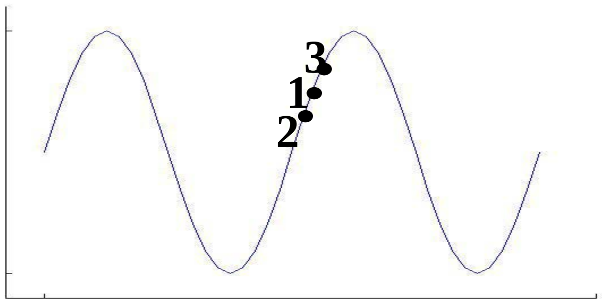
➢ Other particles in the bunch do not satisfy the synchronicity condition

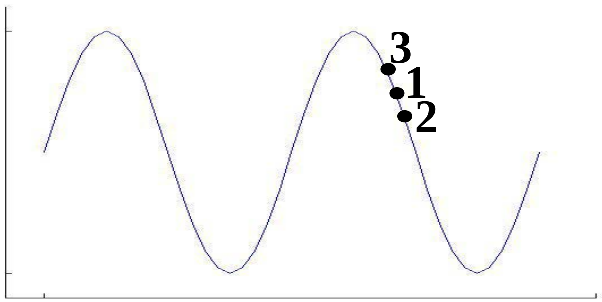
➢ How to keep particles in compact bunch around the synchronous phase?



! Autophasing mechanism can provide longitudinal focusing

Autophasing mechanism





#1 – synchronous particle arrives at synchronous phase; gets design energy increment

#2- fast particle arrives at smaller phase; gets smaller energy increment

#3 - slow particle arrives at larger phase; gets larger energy increment

fast particle decelerates until it becomes slow particle, then accelerates and so on – stable oscillations around the synchronous phase

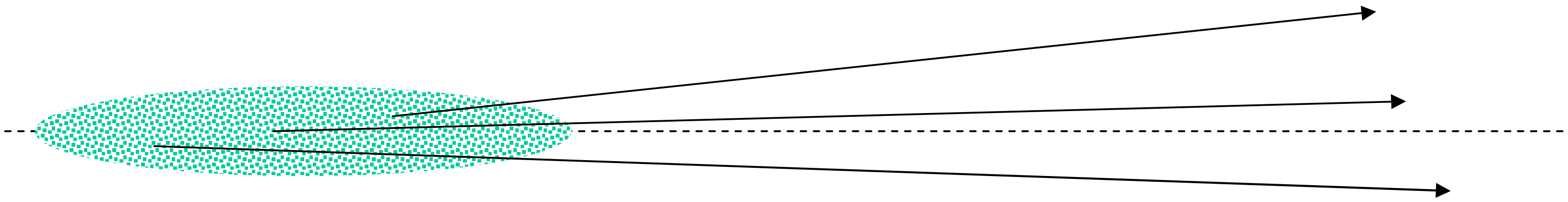
#1 – synchronous particle arrives at synchronous phase; gets design energy increment

#3- fast particle arrives at larger phase; gets larger energy increment

#2 - slow particle arrives at smaller phase; gets smaller energy increment

fast particle accelerates, slow particle decelerates – unstable longitudinal motion.

Transverse focusing

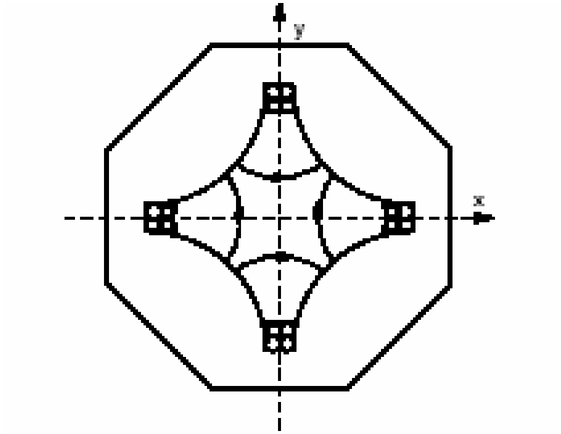


- Need many accelerating gaps to achieve high energy thus long particle path

- Particles tend to travel away from the axis because of
  - Spread of initial transverse angles
  - Coulomb repulsion of charged particles
  - Transverse component of RF field in the gaps
  - Stray magnetic field (Earth, cables….)

- Need mechanism to keep particles near the axis of the accelerator (Transverse focusing)
  - Electric fields (at low energy) – electrostatic lenses, RFQ
  - Magnetic fields (at high energy) – magnetic lenses

Quadrupole focusing



Quadrupole magnet cross section showing magnetic field pattern

➢ In an ideal quadrupole field the pole tips have hyperbolic profiles and produce a constant transverse quadrupole gradient:

$$G = \frac{\partial B_x}{\partial y} = \frac{\partial B_y}{\partial x}$$

➢ For a particle moving along the z direction with velocity v and transverse coordinates (x,y), the Lorentz force components are:

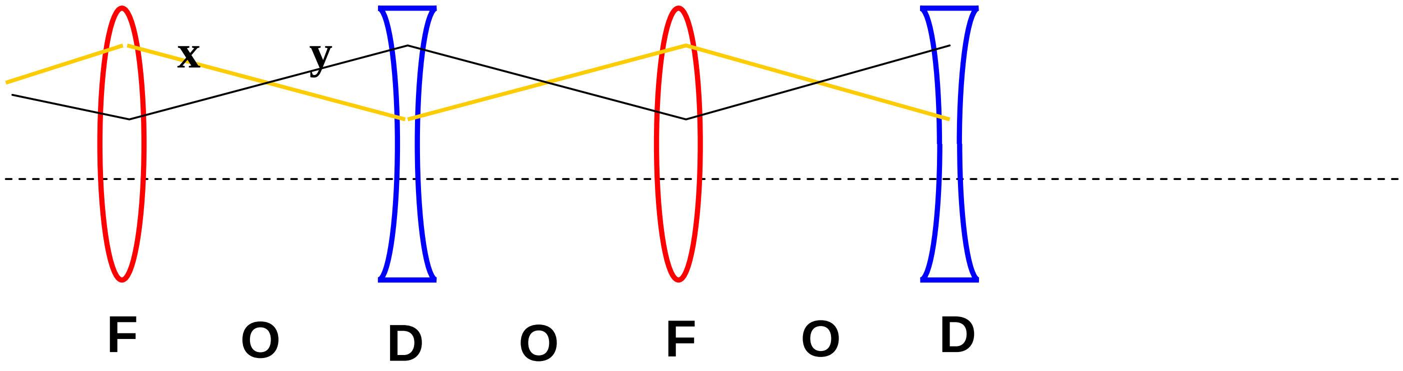
$$F_x = -e \cdot v \cdot G \cdot x, \quad F_y = e \cdot v \cdot G \cdot y$$

➢ For a pole tip with radius a and pole-tip field B, the gradient is G=B/a

➢ If e·G is positive, the lens focuses in x and defocuses in y

➢ Although individual quadrupole lenses focus in only one plane, they can be combined in systems to give overall strong focusing in both transverse plains.

FODO channel

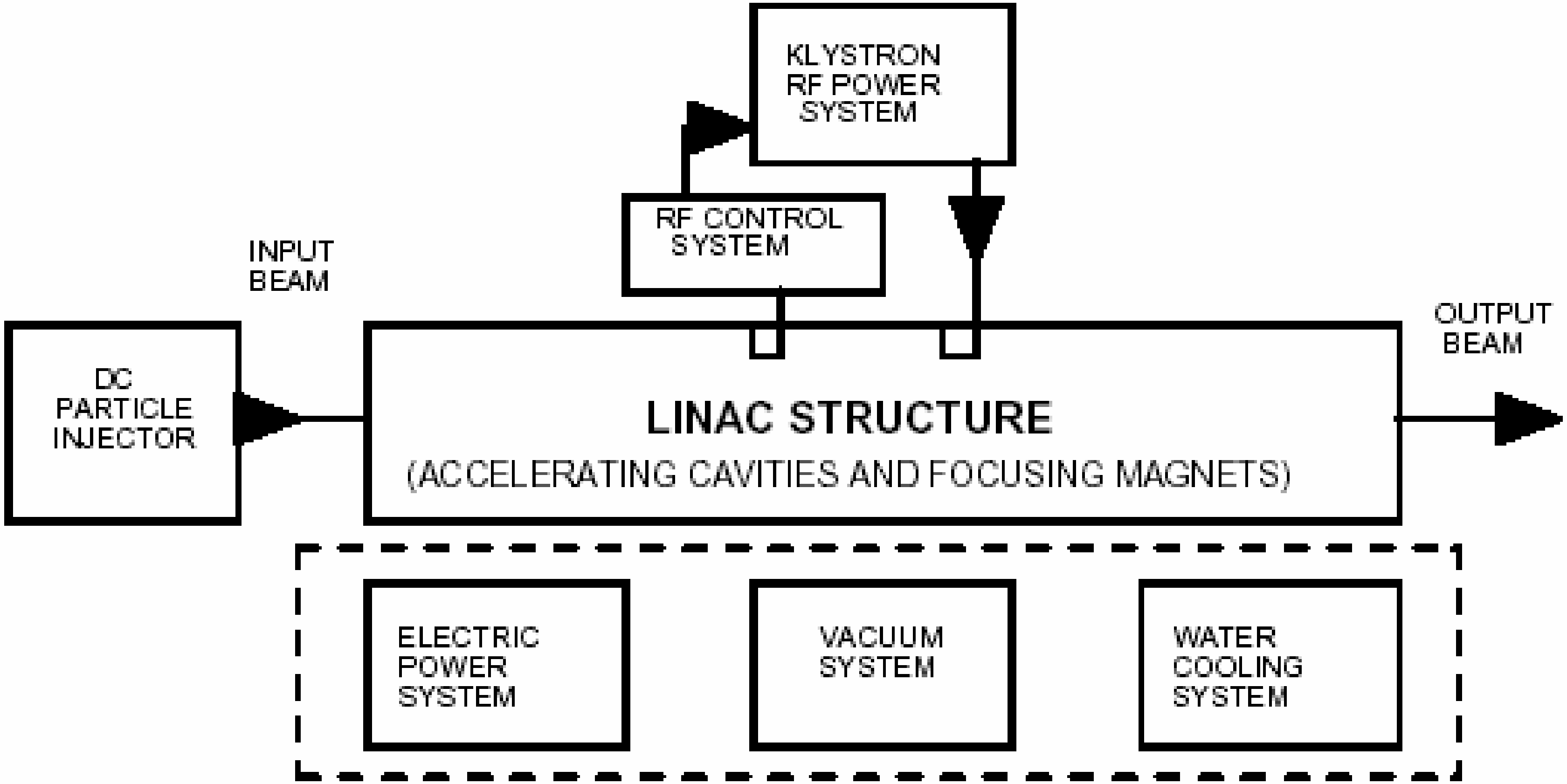


➢ The FODO lattice periodic structure is the most common focusing structure in accelerators.

➢ Provides focusing in both transverse plains

➢ Certain relations between focusing strength of the lenses and distance between them should be satisfied to ensure stability. Well developed mathematical methods exist. Matrix formalism.

Block diagram of an RF linac system



The Spallation Neutron Source (SNS)

SNS main parameters

Power on target	**1.4**	**MW**
Proton beam energy on target	**1.0**	**GeV**
Proton pulse width on target	695	ns
Linac pulse width	1.0	ms
Linac peak current	38	mA
Pulse repetition rate	60	Hz
Beam availability	>95	%
Linac length	335	m
Accumulator ring circumference	248	m
Peak power	**23**	**MW**

The SNS cost breakdown

WBS	Description	November 2003 Review Baseline ($M)	Net Forecast Changes ($M)	Management EAC ($M)	
1.2	Project Support	75.6	0.3	75.9	
1.3	Front End Systems	20.8	-	20.8	
1.4	Linac Systems	313.2	1.4	314.6	
1.5	Ring and Transfer Systems	141.2	0.9	142.1	
1.6	Target Systems	106.5	1.6	108.1	
1.7	Instrument Systems	63.3	0.0	63.3	
1.8	Conventional Facilities	367.5	9.4	376.9	
1.9	Integrated Controls	59.6	(0.0)	59.6	
BAC		1,147.9	13.5	1,161.4	
Total Contingency		44.8		31.3	21.8%*
	TEC	1,192.7		1,192.7	
	OPC	219.0		219.0	
	TPC	1,411.7		1,411.7	

Spring 1999

Spring 2000

Spring 2001

Spring 2002

Spring 2003

Spring 2004

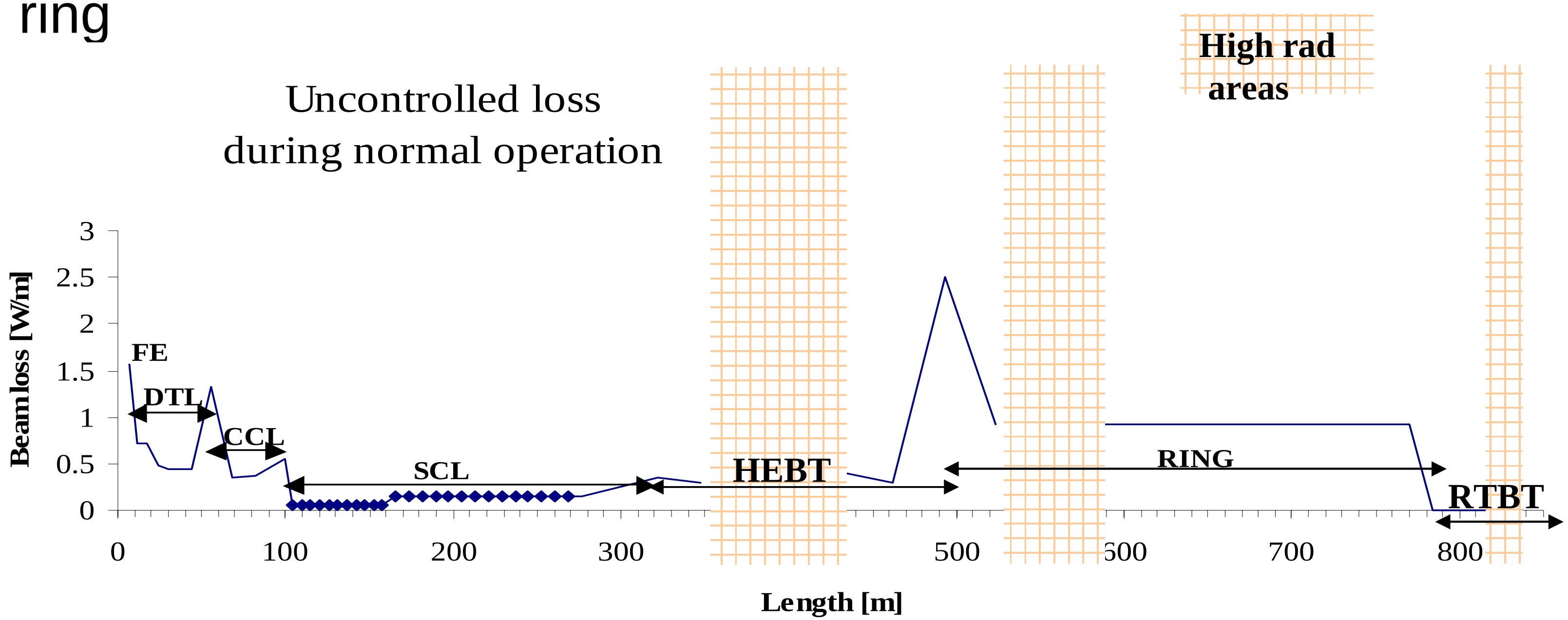
November 2004

Challenges of Accelerator for Spallation Source Design

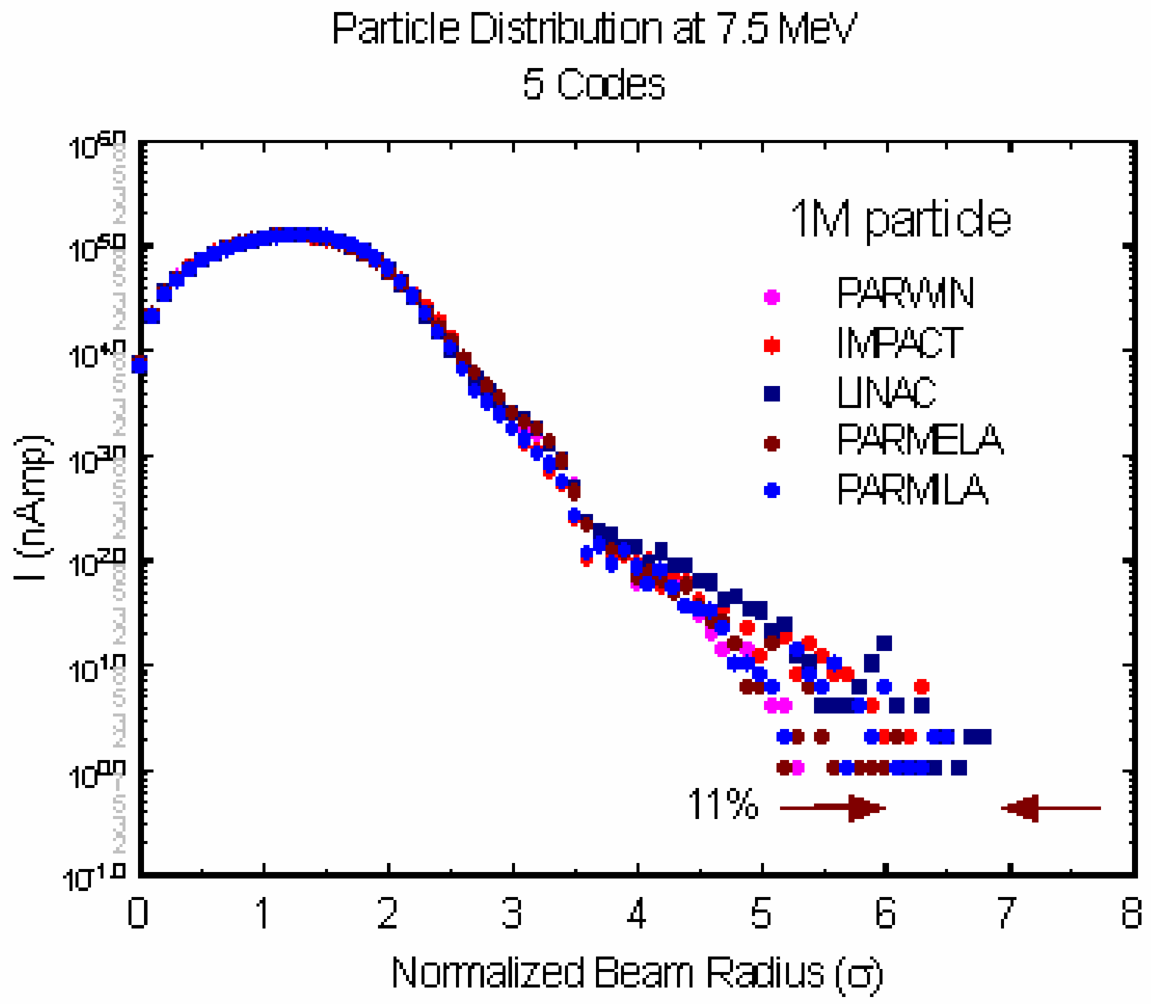
- Accelerator physics
  - To ensure small beam loss during acceleration and transport. Typical requirement is <1W/m (<1ppm at 1GeV)
  - To provide required current from the source
  - To provide reliable stripping foil
- Operation
  - To provide personnel protection and accelerator protection in case of an accident
  - To provide high reliability and availability of all systems. Typical requirement is >95%
- Economics
  - To optimize construction and operation cost
- Technical
  - Numerous

Primary Concern:
Uncontrolled Beam Loss

- Hands-on maintenance: no more than 1 mSv/hour residual activation (4 h cool down, 30 cm from surface)
- 1 Watt/m uncontrolled beam loss
- Less than 10^{-6} fractional beam loss per tunnel meter; 10^{-4} for ring

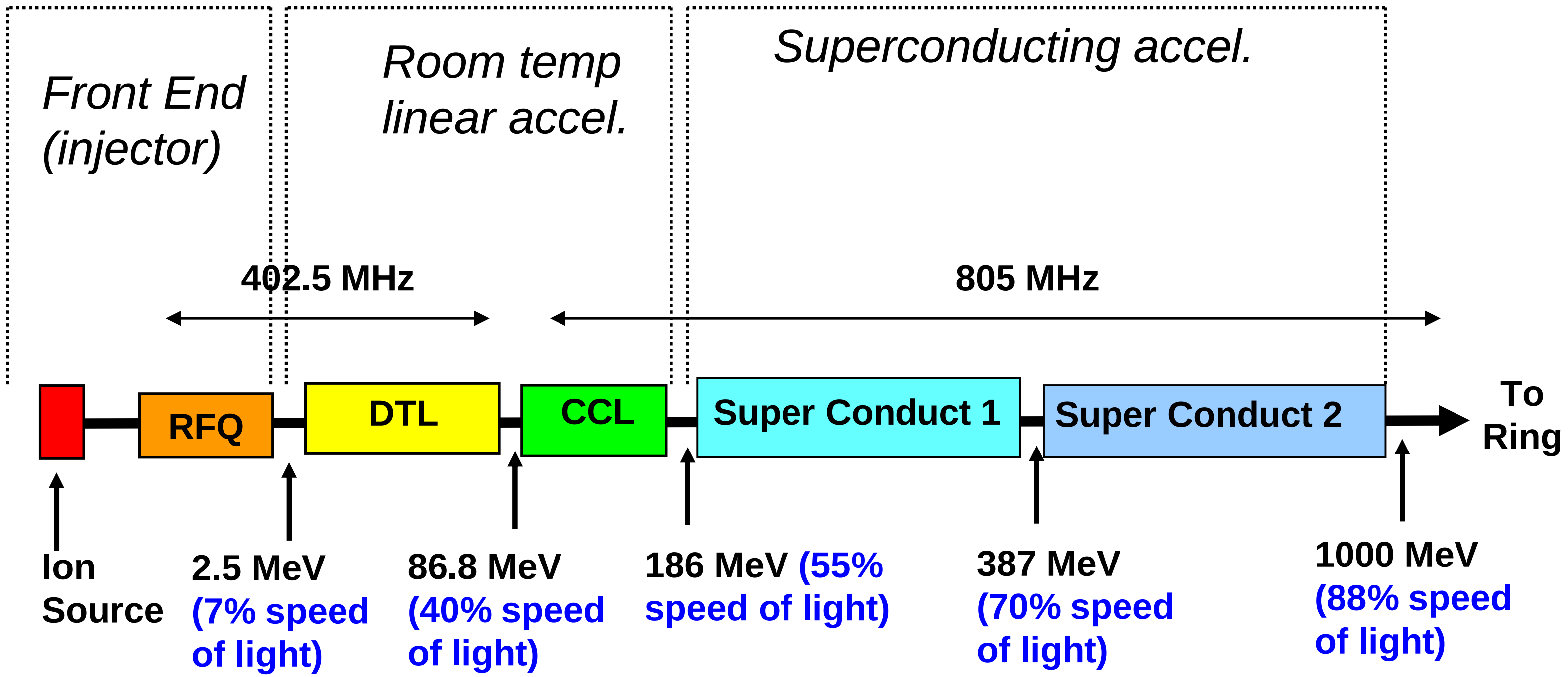


Beam dynamics simulation codes comparison

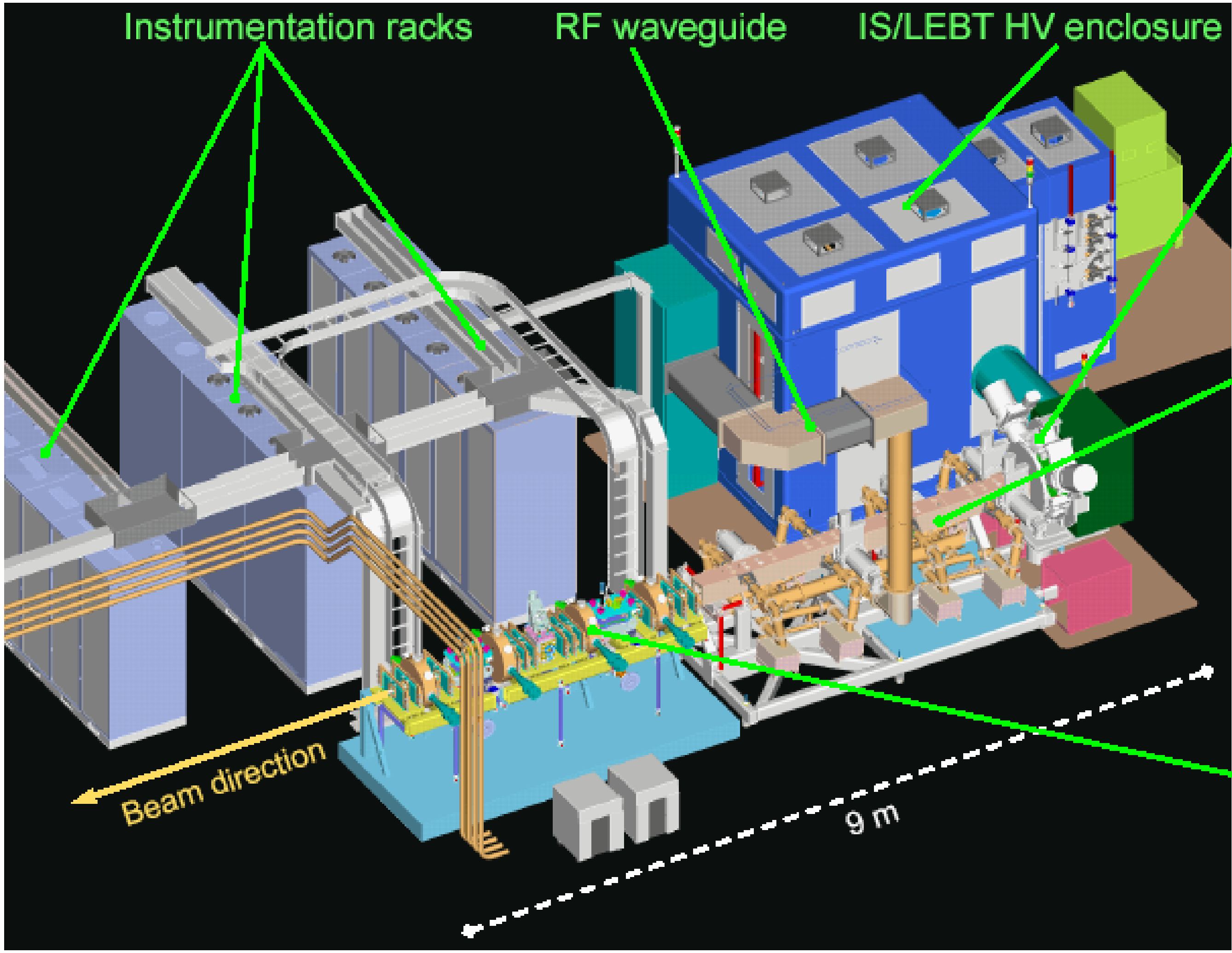


The SNS Linear Accelerator (LINAC)

➢ The SNS Linac is constructed of 5 different types of accelerating cavities.
➢ Each is optimized to a certain range of H- beam velocities



The SNS Front End layout



Ion Source (IS) and Low-Energy Beam Transport (LEBT)

Create ~50 mA pulsed H^- ion beam
1 ms - 60 Hz

Radio-Frequency Quadrupole (RFQ) accelerator

Accelerate beam to 2.5 MeV

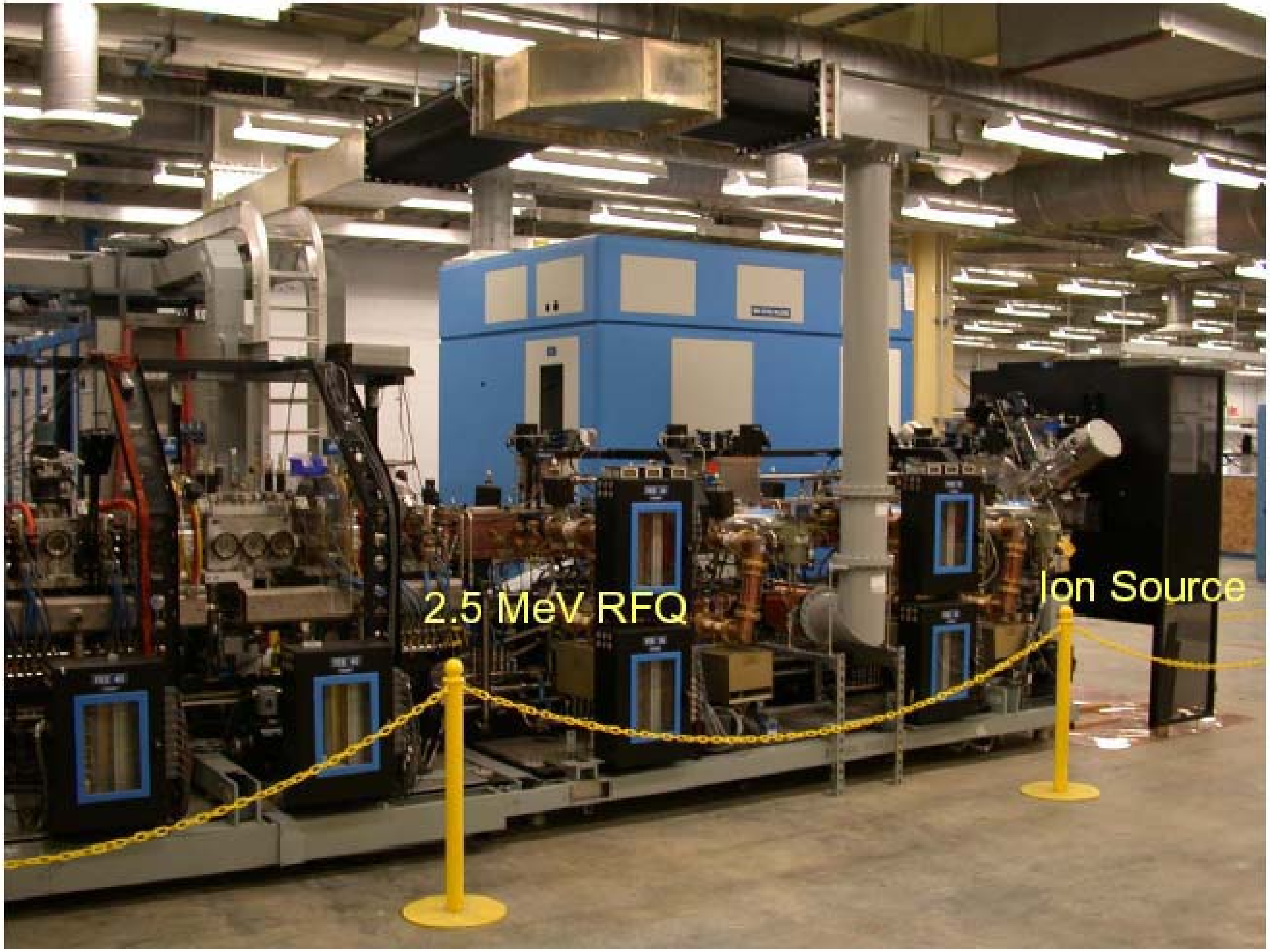
LEBT/ MEBT

Chop beam into 650 ns mini pulses

Medium-Energy Beam transport (MEBT)

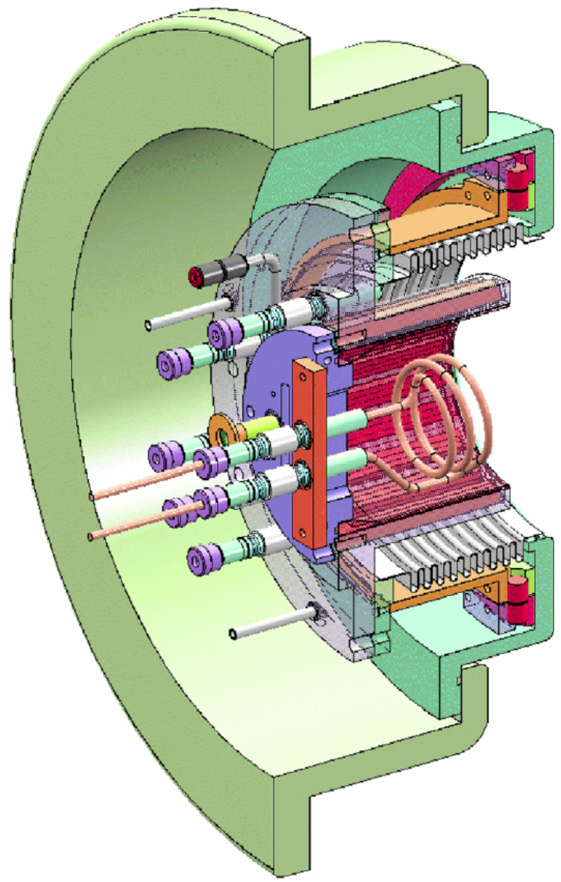
Match 38 mA beam into Linac

The SNS Front End

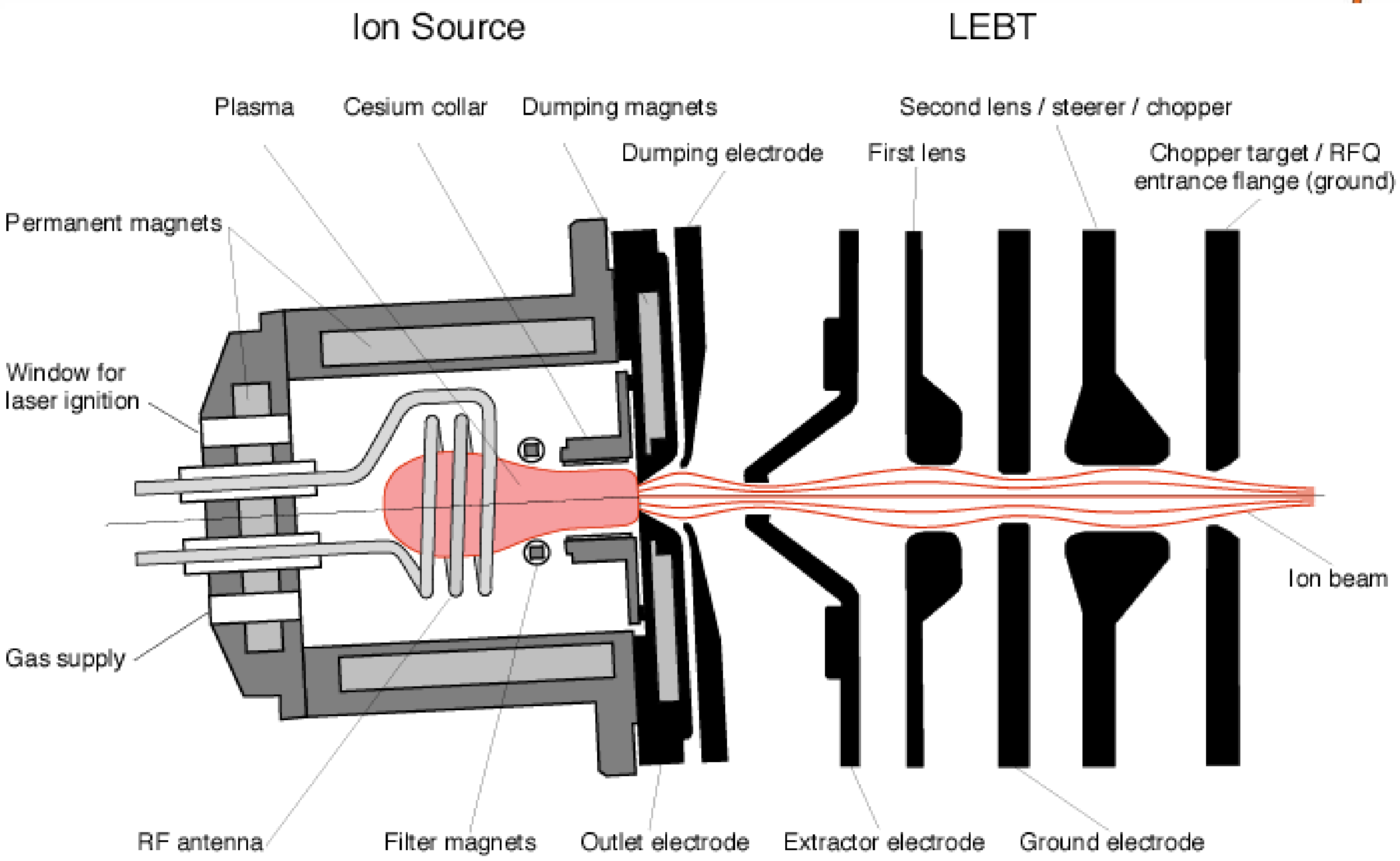


The SNS Ion Source

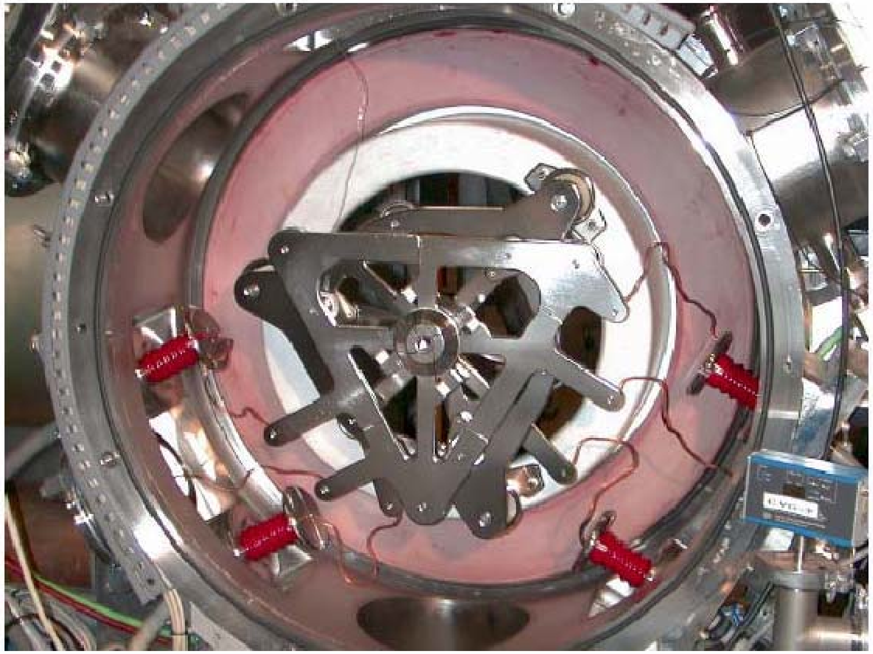
Ion species	**H^-**
Extraction Energy (keV)	**65**
H^- output current (mA)	**48**
Normalized rms emittance (π mm mrad)	**0.2**
Pulse length (ms)	**1.2**
Duty factor	**6%**
Repetition rate (Hz)	**60**

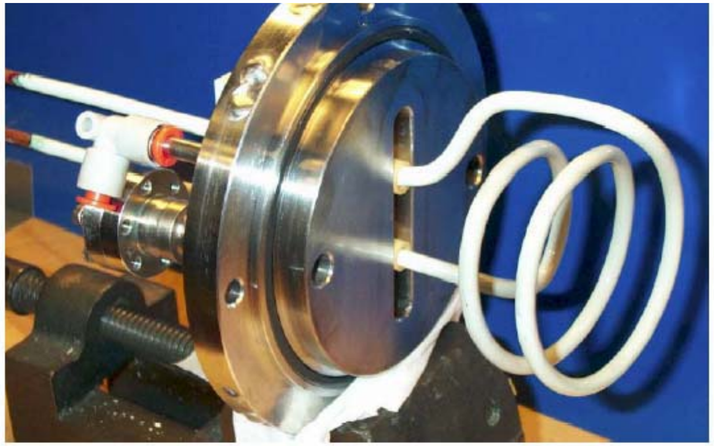


The SNS Ion Source and LEBT layout



Some magnet orientations are rotated into the viewing plane of this illustration



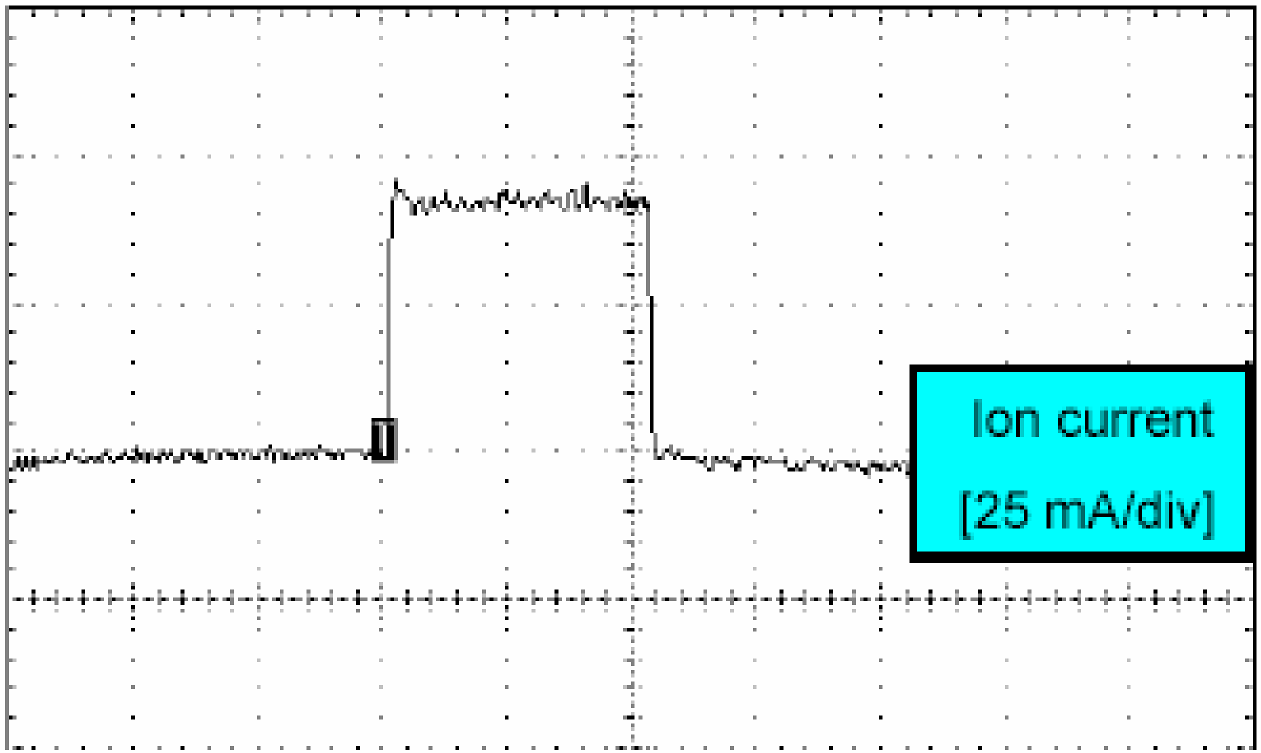


Plasma glow in the RF discharge chamber

Electrodes of the LEBT

2MHz RF antenna

Ion Source Beam Pulse



➢ Ion source produce pulse of continues current (DC), not divided on bunches.

The SNS Radio Frequency Quadrupole RFQ accelerator

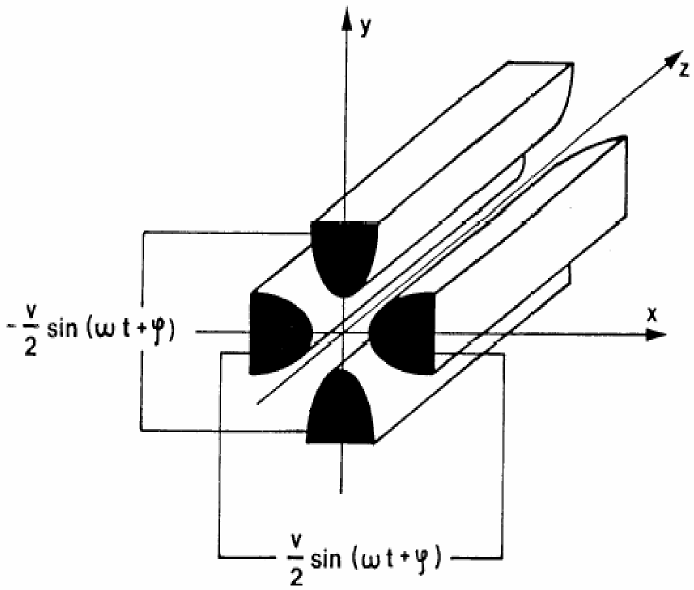
- The invention of the RFQ made major improvement in the current limit for ion RF linacs. ***I.M.Kapchinskiy and V.A.Tepliakov, Prib.Tekh.Eksp. 2,19-22(1970)***

- The RFQ RF structure provides rf electric field for bunching (dividing continuous beam on separate bunches), acceleration, and longitudinal and transverse rf focusing.

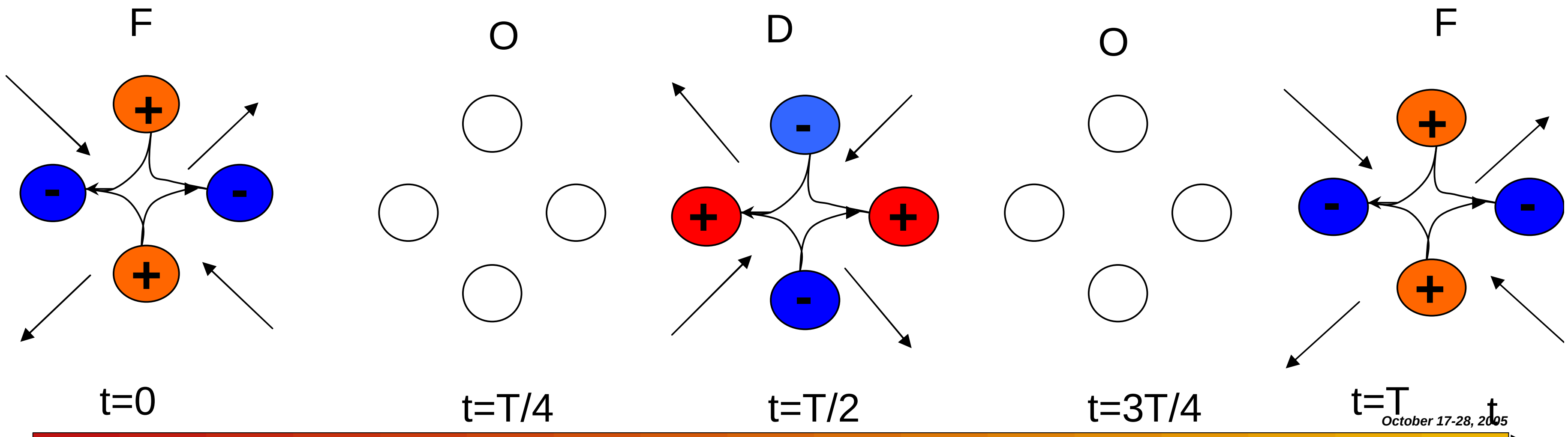
The SNS RFQ Parameters

Input energy	65 kV
Output energy	2.5MeV
Beam current	15-60mA
RF frequency	402.5MHz
Peak RF power	720kW with nominal beam
Average RF power	45kW with nominal beam

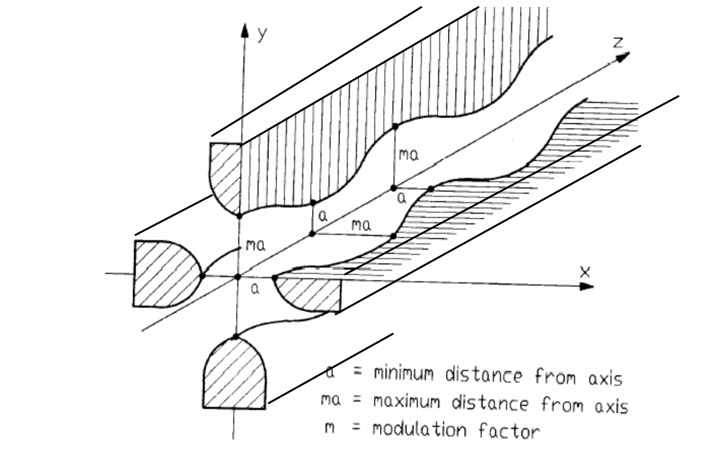
RFQ principle of operation



- Action of RF quadrupole focusing channel is similar to conventional FODO structure
- Quadrupole configuration of electrical field provides transverse focusing/de-focusing
- Focusing strength varies in time not in space (it is the same from particle point of view)
- No acceleration yet!



RFQ principle of operation



➢ Longitudinal electric field is created by modulating electrode shape along the longitudinal axis

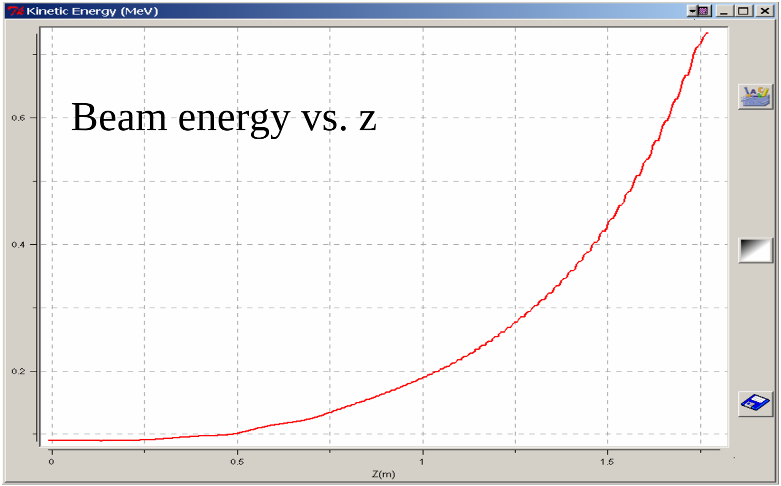
➢ When longitudinal RF field is introduced then synchronous phase can be defined. Bunching and acceleration becomes possible

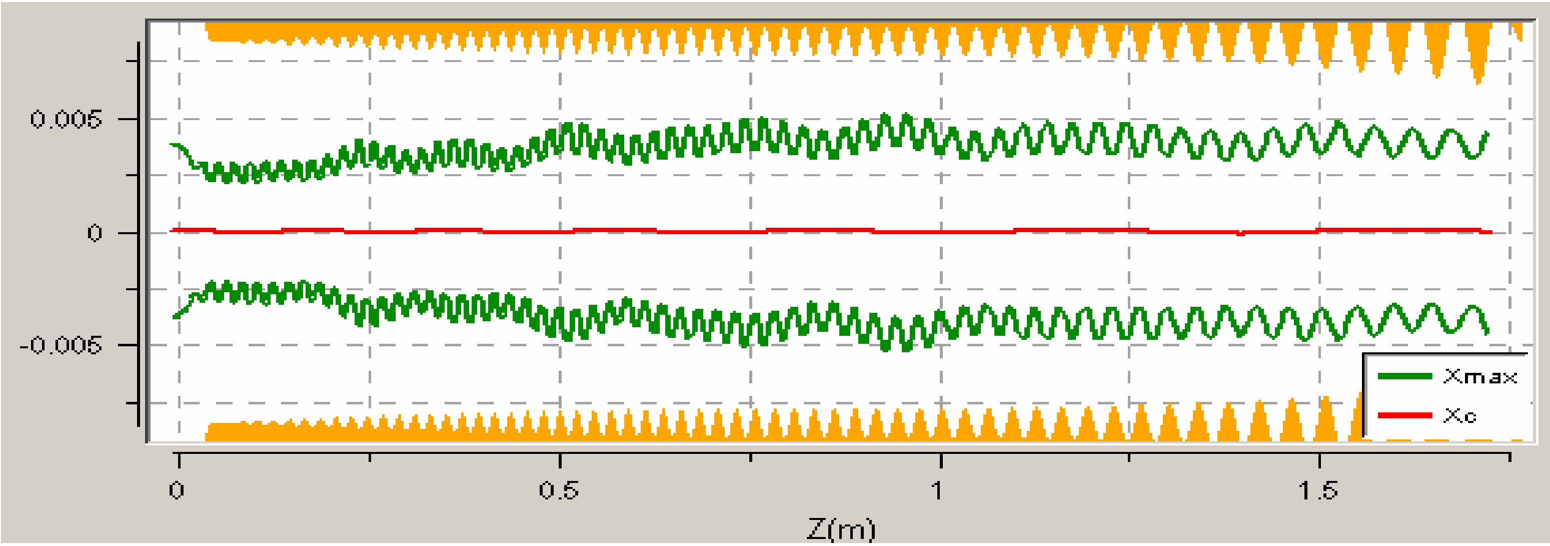
➢ Configuration and strength of the longitudinal field is defined by geometrical pattern of the modulation, which can be varied along RFQ smoothly and in wide range. That gives powerful control over longitudinal beam dynamics:

➢ Starting from zero at RFQ entrance and slowly increasing the longitudinal field strength (controlled by modulation depth) one can bunch incoming DC beam with high efficiency

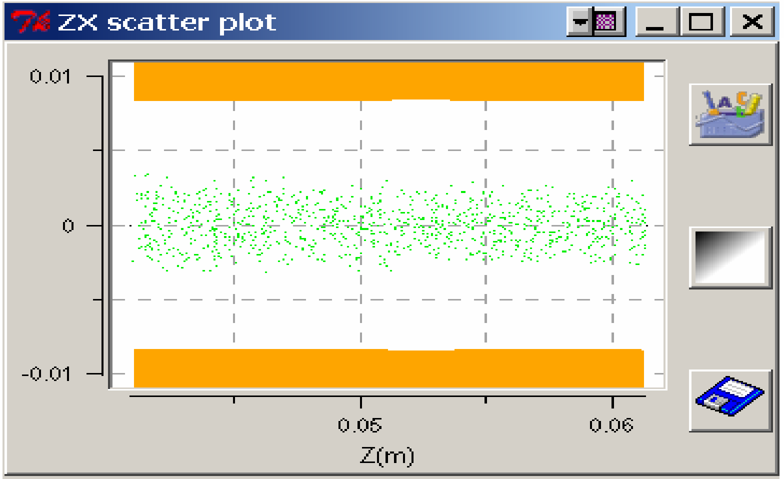
➢ Slowly change synchronous particle phase (controlled by modulation period) from bunching to acceleration

Beam in RFQ: simulation



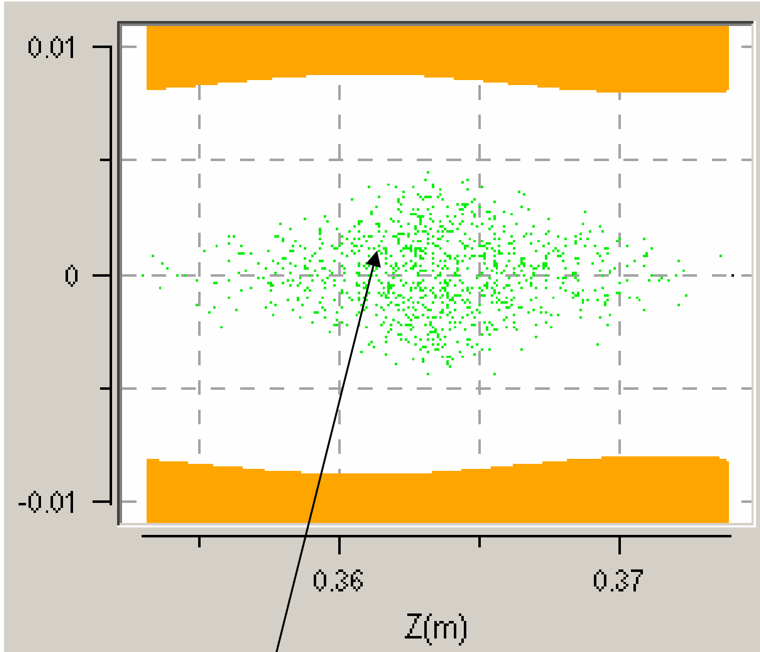


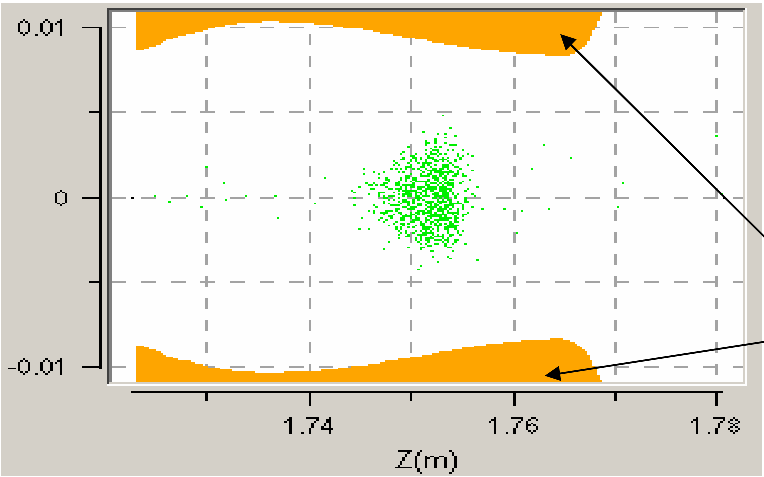
Beam in RFQ: simulation



RFQ entrance. Bunching starts.

Middle of RFQ. Bunching finished, acceleration starts.



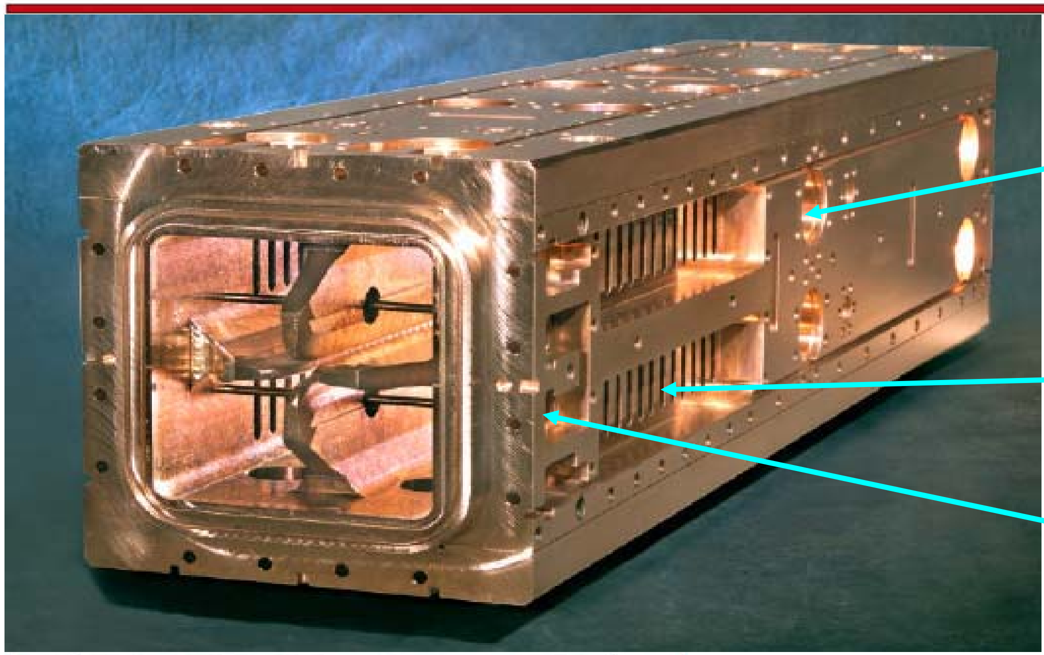


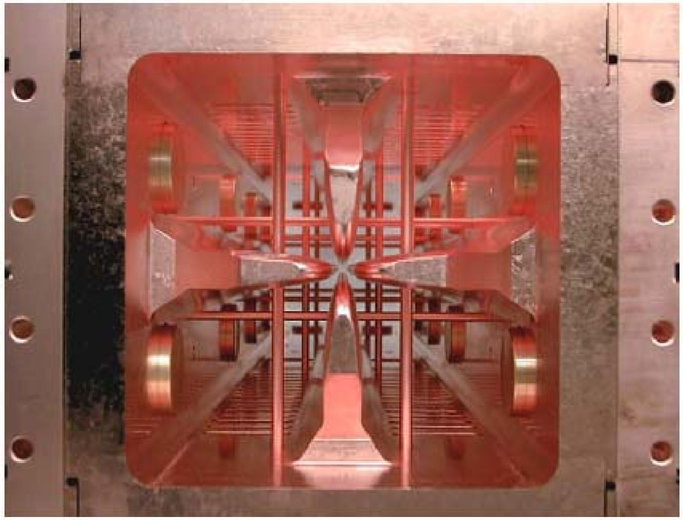
poles

particles

RFQ exit. Acceleration finished

The SNS RFQ cavity

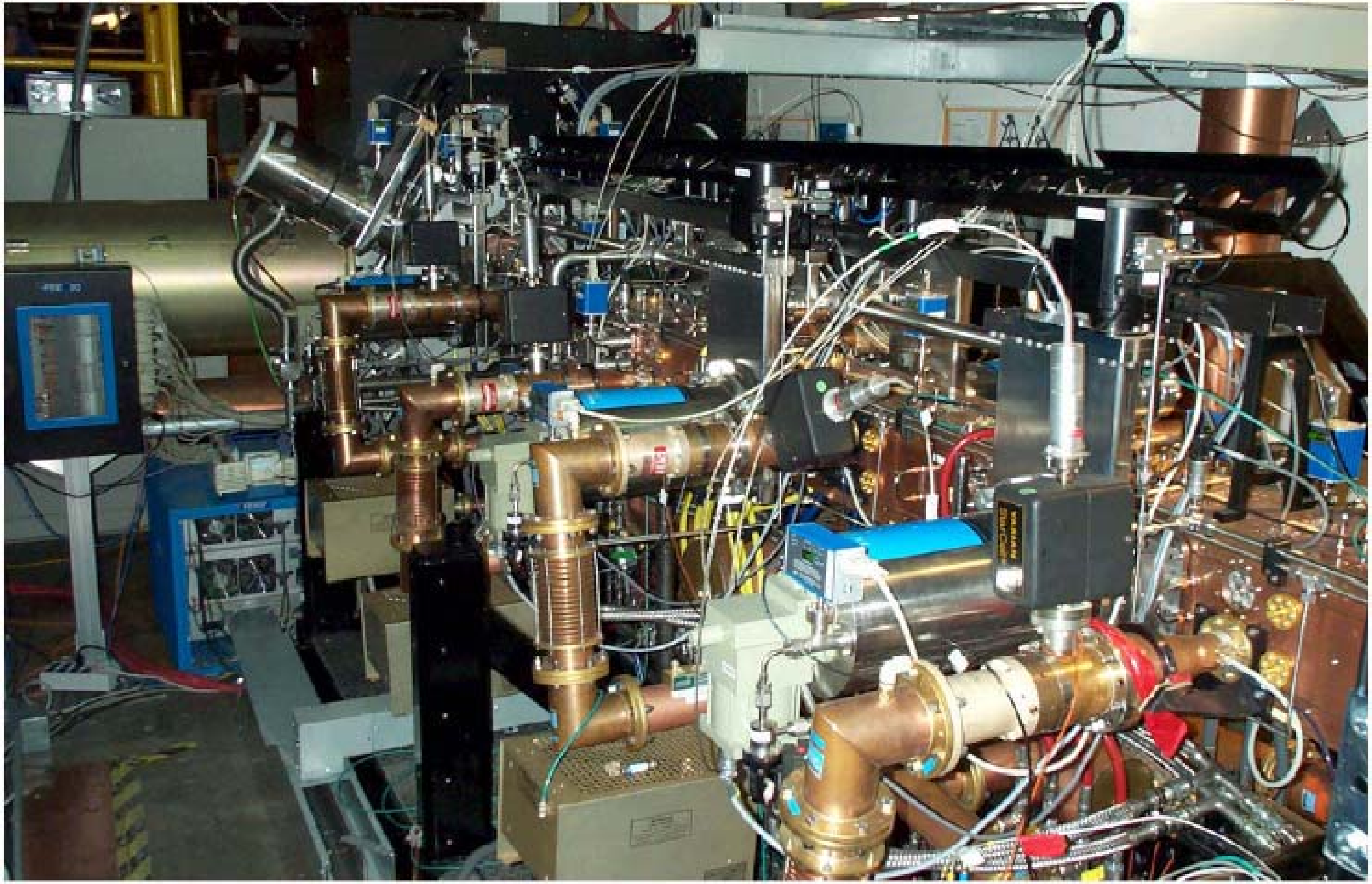




➢ To make it work we need to add:

- Vacuum system
- RF power system
- Cooling system to control temperature

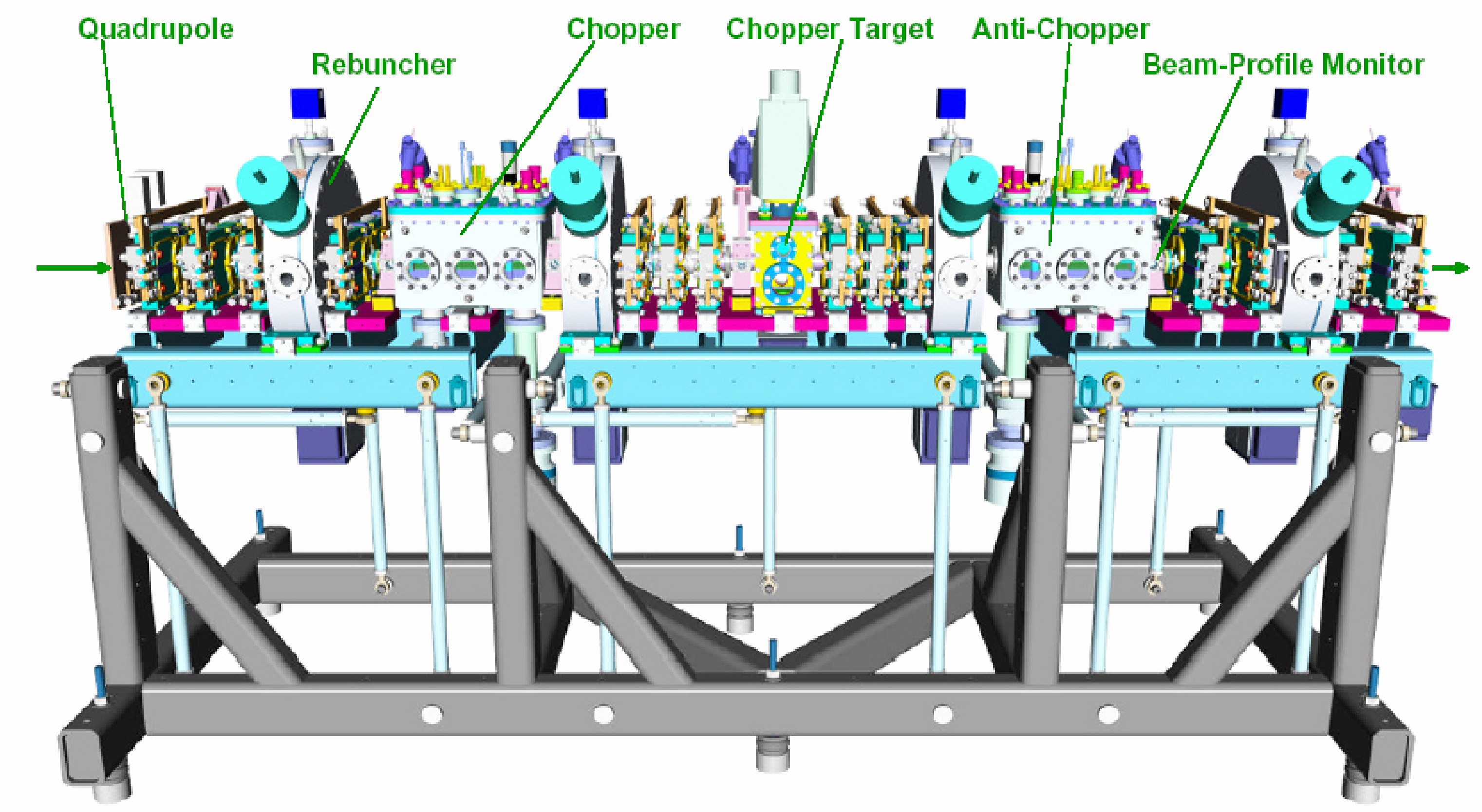
The SNS RFQ



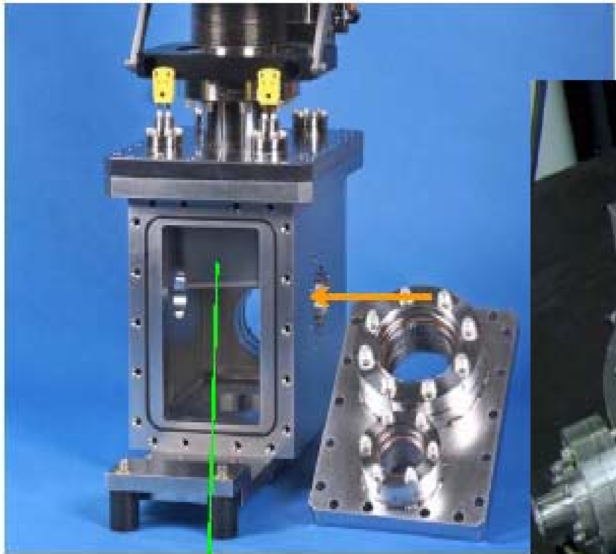
Medium Energy Beam Transport line (MEBT) layout

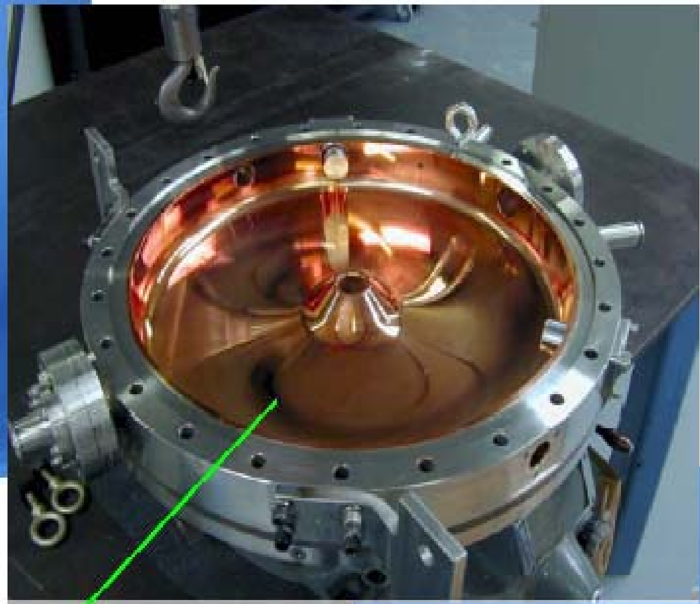
➢ After the RFQ beam is ready to be injected into the linear accelerator but still has to be chopped for lossless ring extraction

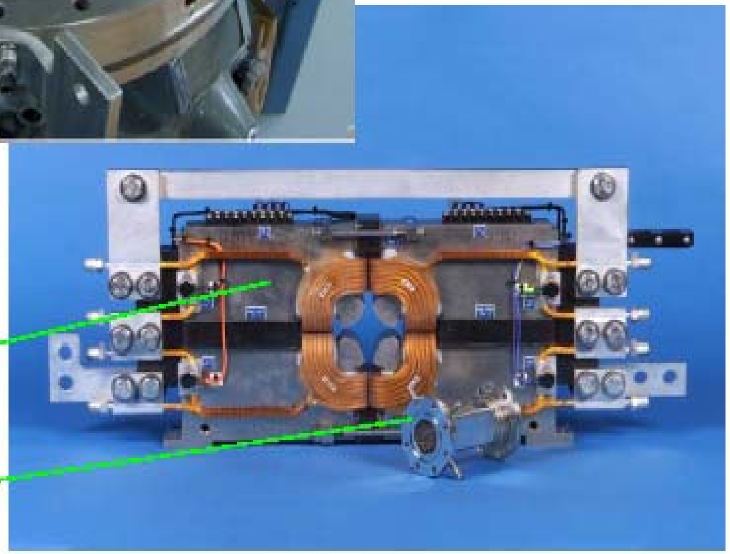
➢ MEBT provides place for the chopper and various beam diagnostics



MEBT Components







Chopper Target

Rebuncher Cavity

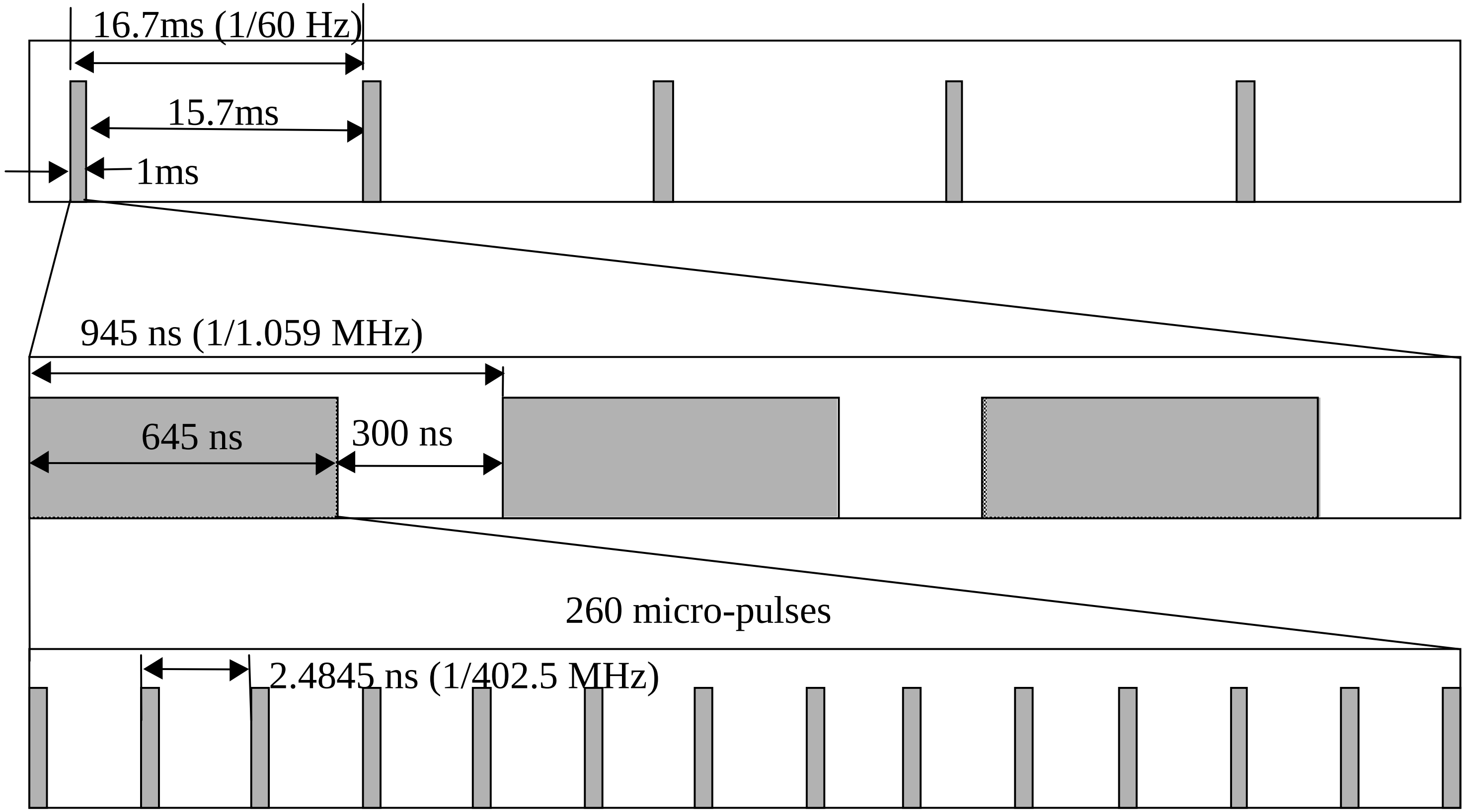
Quadrupole Magnet
with Beam-Position Monitor

Beam pulse structure after the Front End – very complex!

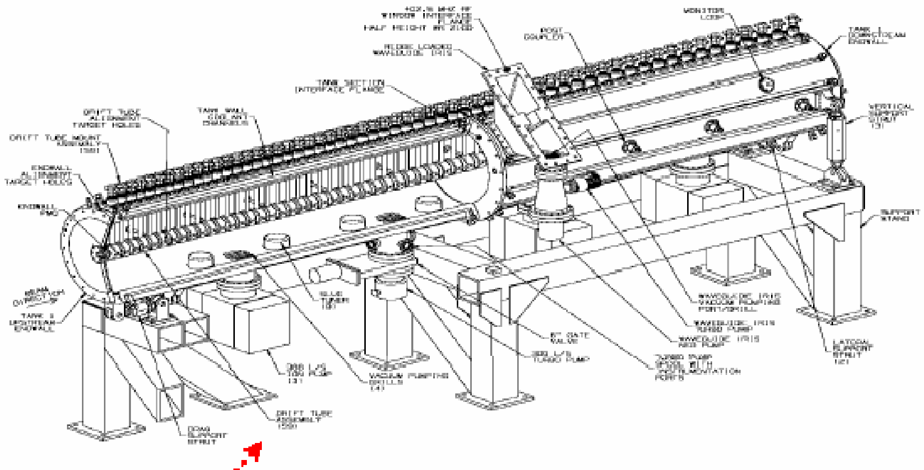
Macro-pulse
Structure (made by the Ion Source)

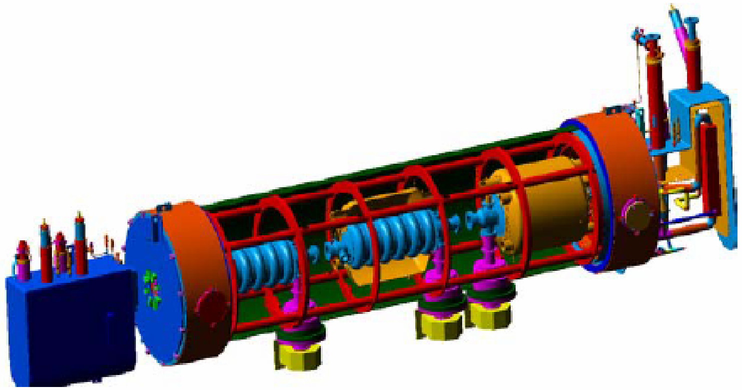
Mini-pulse
Structure (made by the choppers)

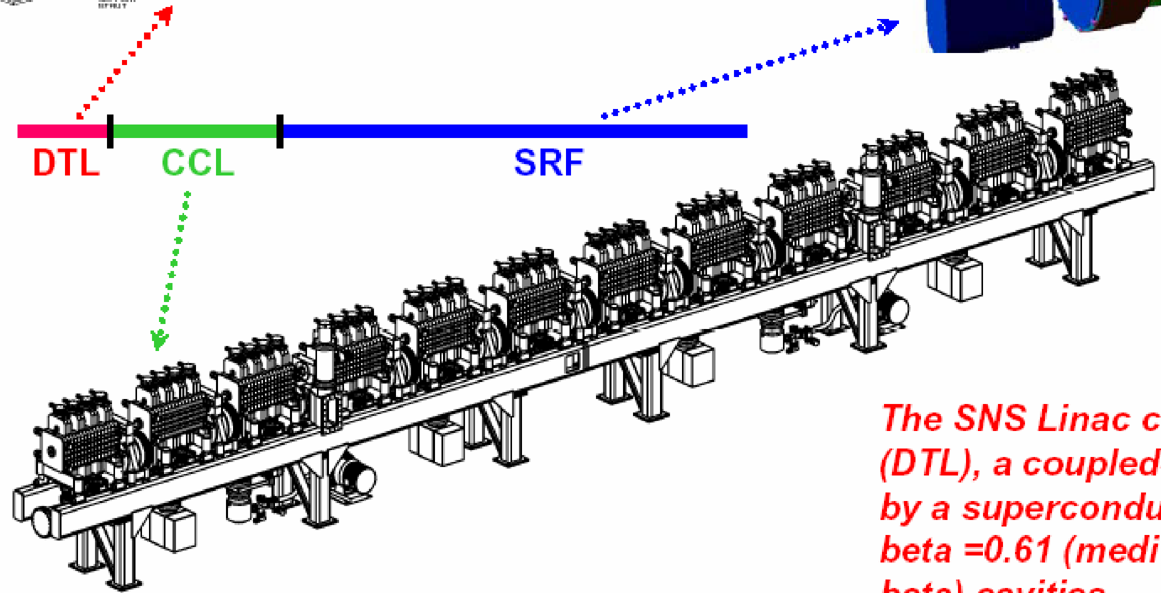
Micro-pulse
structure (made by the RFQ)



Accelerating structures of the SNS linac





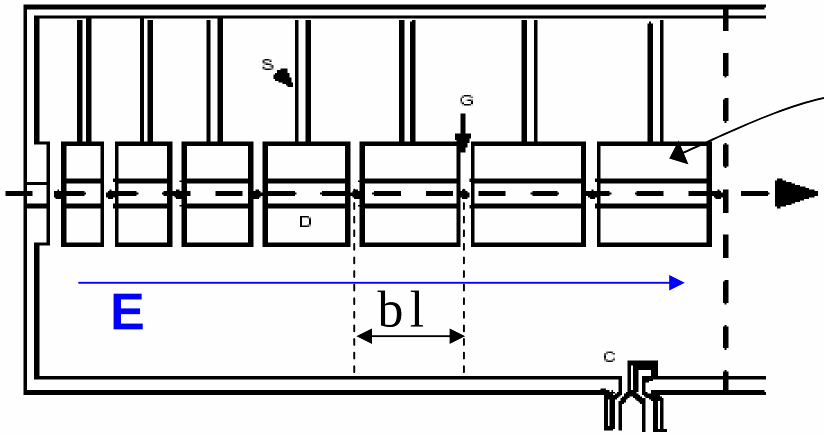


The SNS Linac consists of a drift-tube linac (DTL), a coupled-cavity linac (CCL), followed by a superconducting RF (SRF) linac with beta =0.61 (medium beta) and beta=0.81 (high beta) cavities.

The SNS DTL parameters

Input energy:	**2.5 MeV**
Output energy:	**86 MeV**
Peak current:	**38 mA**
Number of tanks:	**6**
Total number of cells:	**216**
Total length:	**36 m**
RF frequency:	**402.5 MHz**
Synchronous phase:	**-37° to -26°**

Drift Tube Linac (DTL) Principle of Operation



Focusing quadrupoles are inside drift-tubes.

b = v/c particle velocity
l - RF wavelength
bl - distance particle travels in one RF period

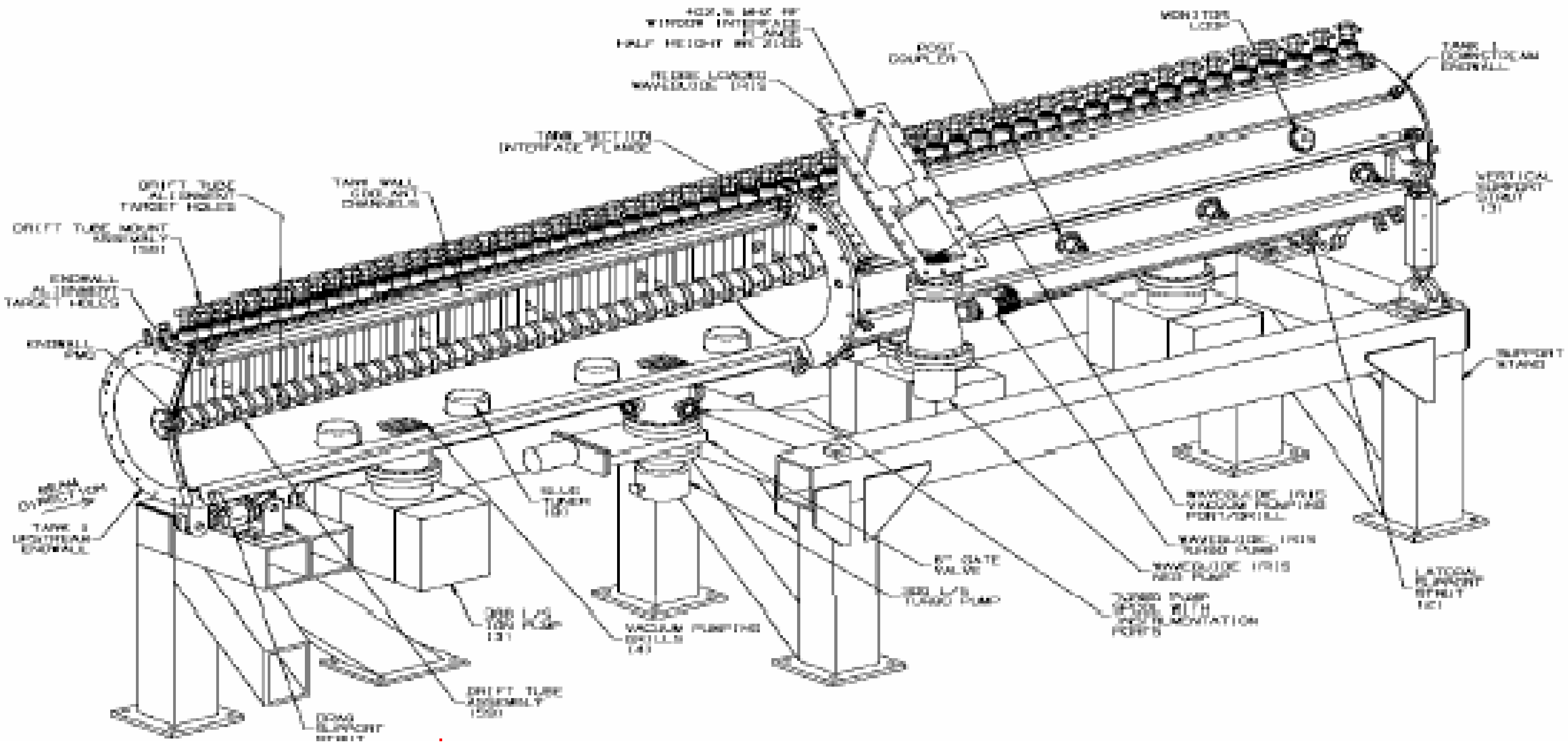
➢ DTL is a multi-cell cavity obtained by installing drift tubes in a long pillbox cavity operating in a TM010 mode.

➢ Motivation: When pillbox cavity length > βλ/2, acceleration becomes inefficient because Transit-Time factor becomes small.

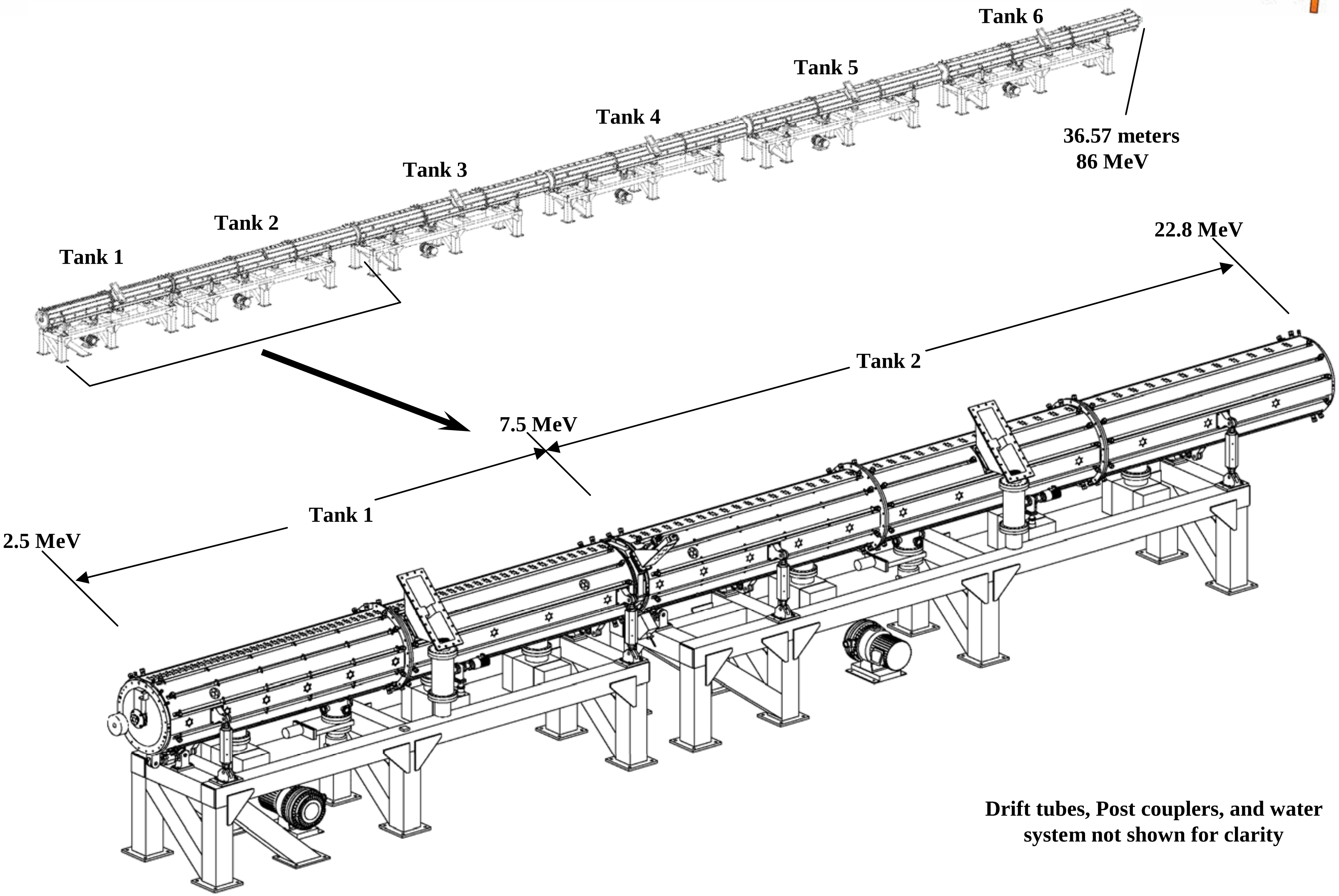
➢ The idea is to introduce hollow drift tubes to shield the beam from the decelerating fields, dividing cavity into cells of length βλ. As β increases, cell lengths increase.

➢ Designed for fixed velocity profile.

The SNS DTL layout



86.7 MeV DTL System



DTL design steps

➢ Physics design of representative cells

- aperture, peak surface fields, efficiency

➢ Engineering design studies

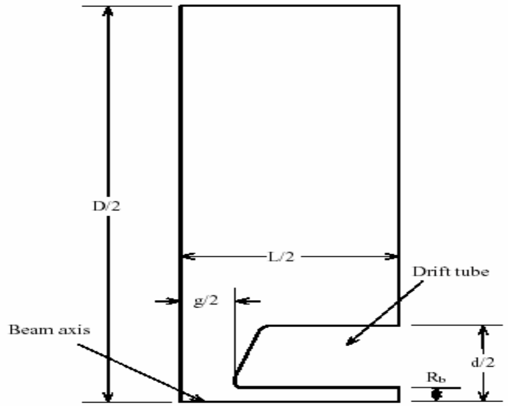
- thermal and structural analysis

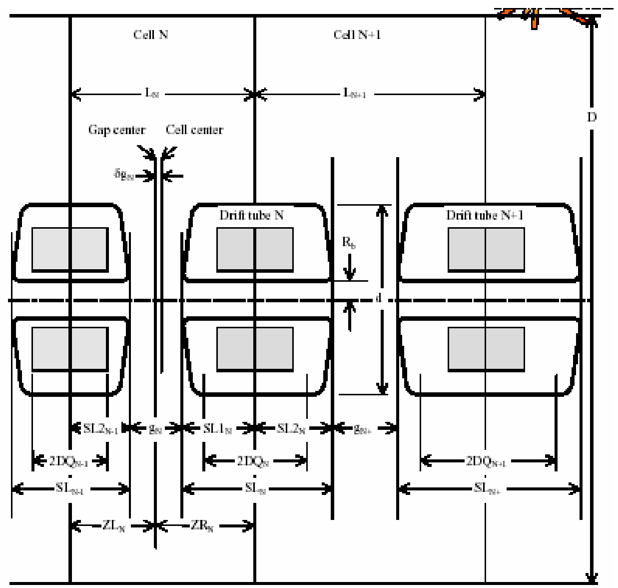
➢ Beam dynamics study

- particle tracking in design fields

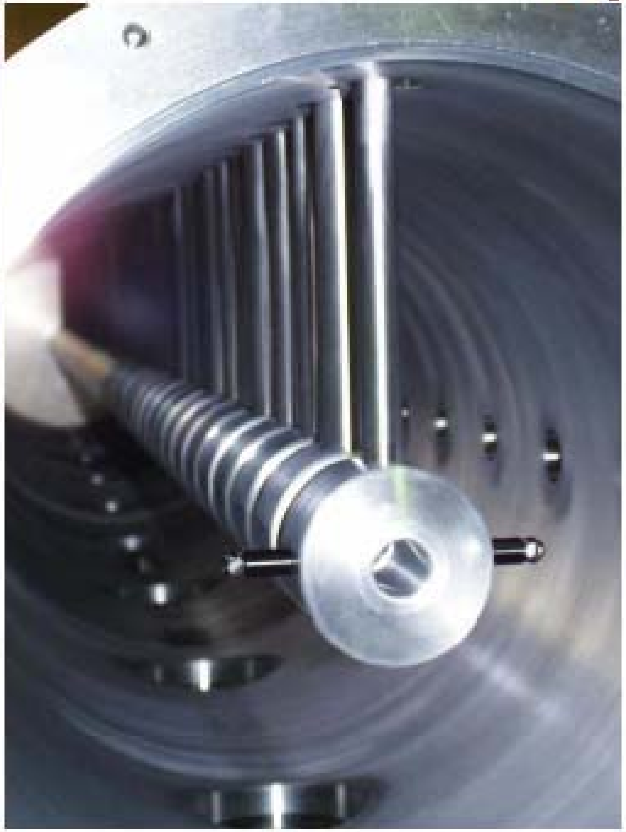
➢ Integrated tank design

- cooling, vacuum system, RF input, ….
- mechanical drawings





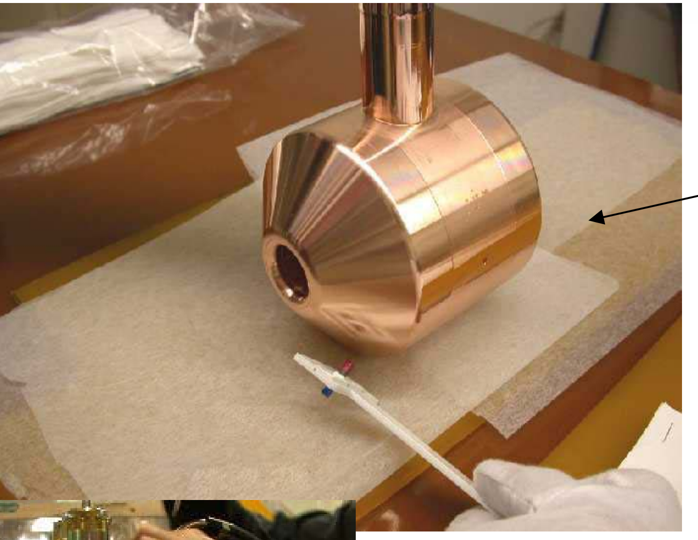
Cold model



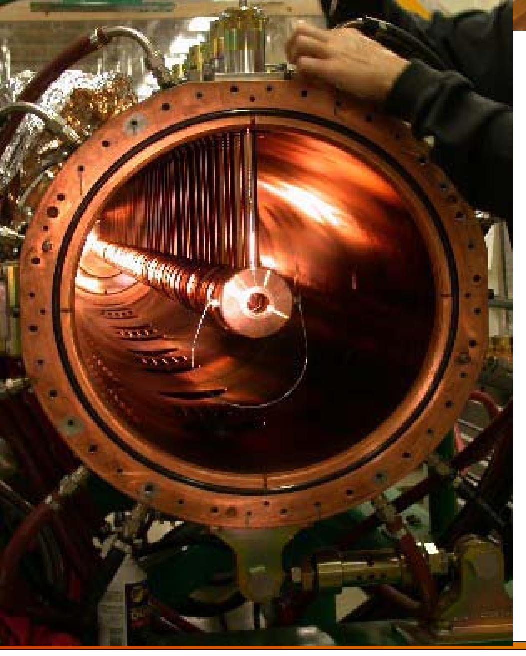
- Accuracy of calculations and computer simulations is still not sufficient to build tank from “paper” design
- “Cold model” is build to verify calculations and make final adjustments
  - resonant frequency
  - field distribution
  - tuning procedures

Building the DTL

Tank body



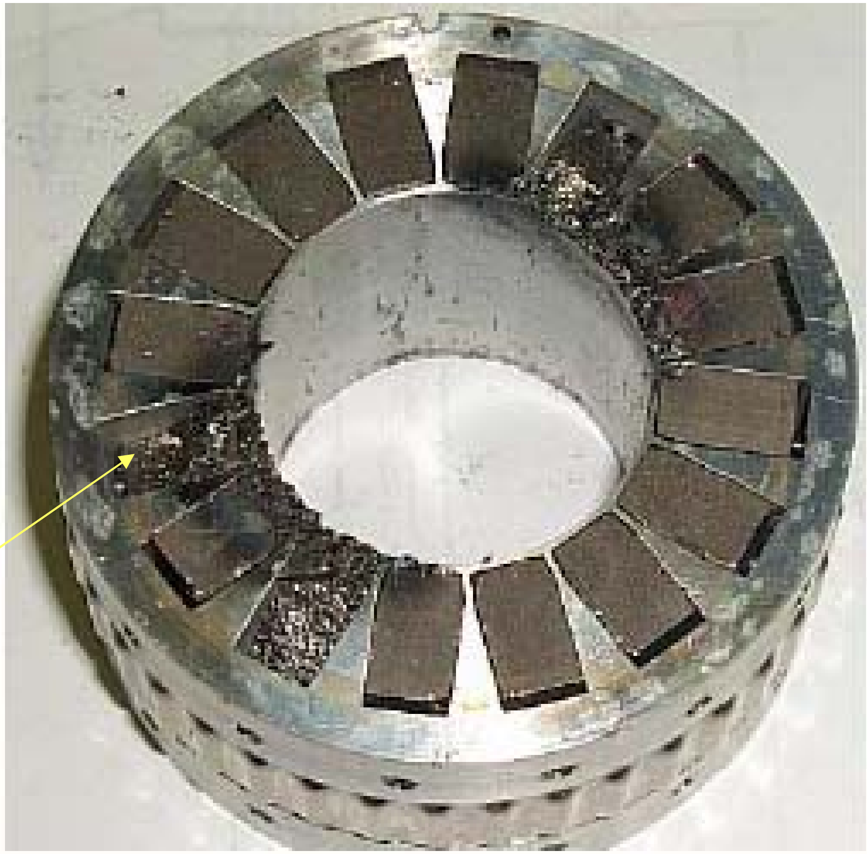
Drift tube



DTL tank with drift tubes installed

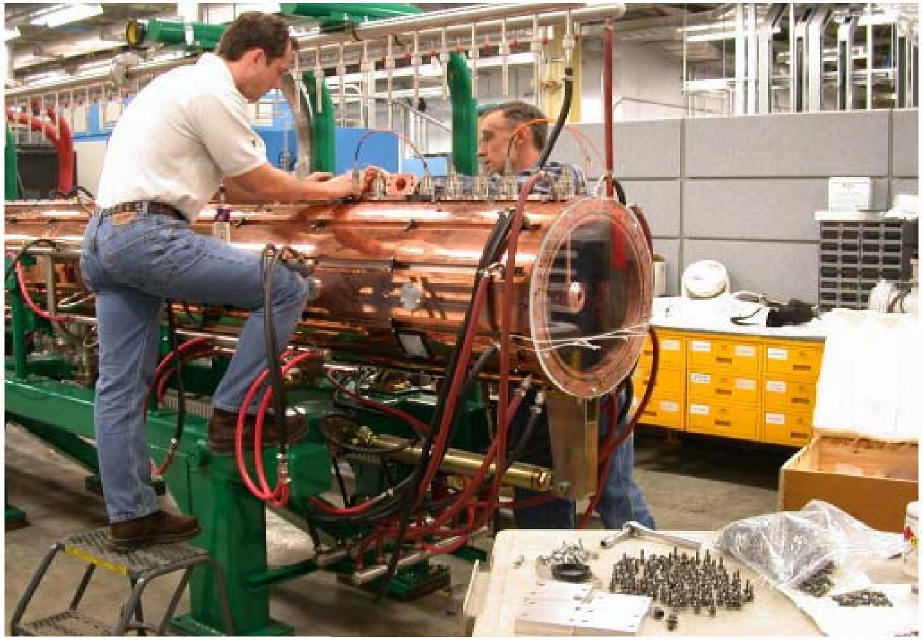
Cross-cut of the drift tube with permanent magnet inside

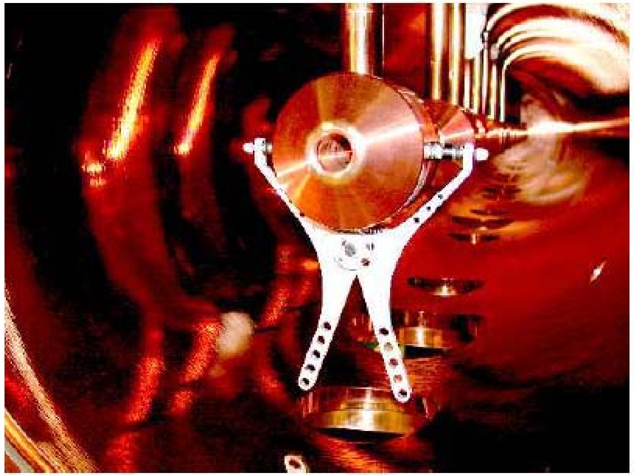
Mishaps happen !



- Standard electron beam welding didn't work in the presence of the magnetic strong magnetic field
- Plan ahead but be prepared for unplanned

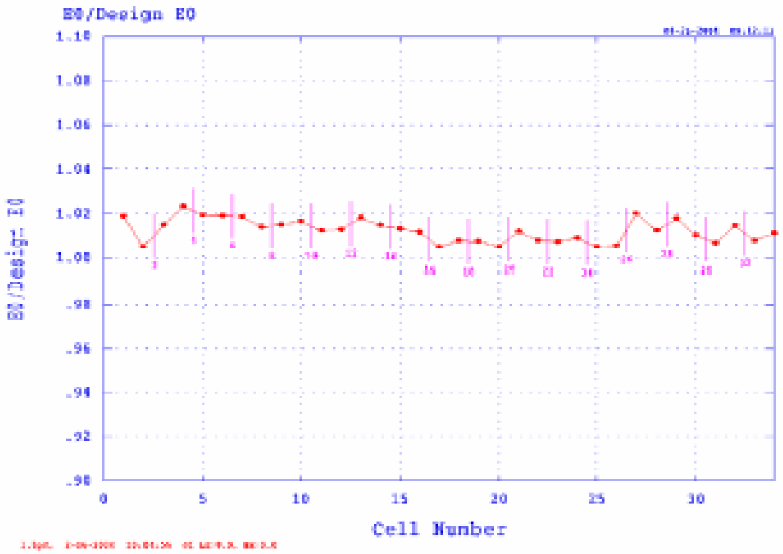
Assembly, alignment and tuning



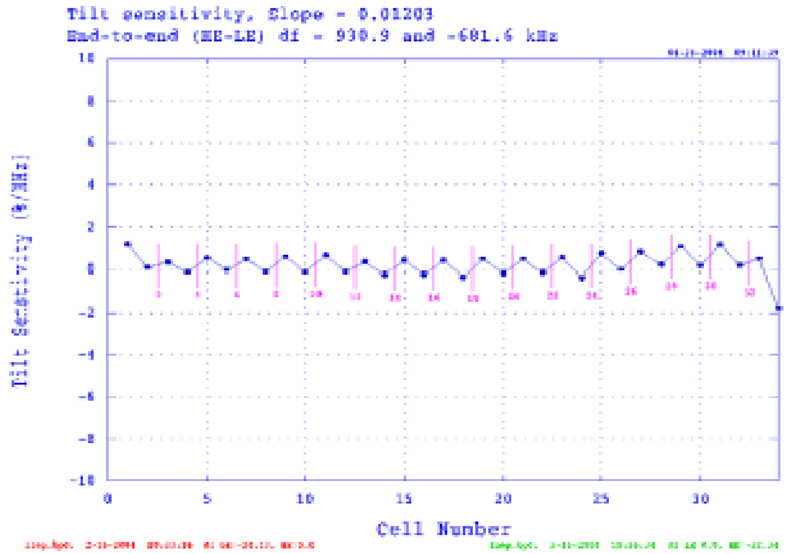


Final field profile measurements

E_o/E_{design}



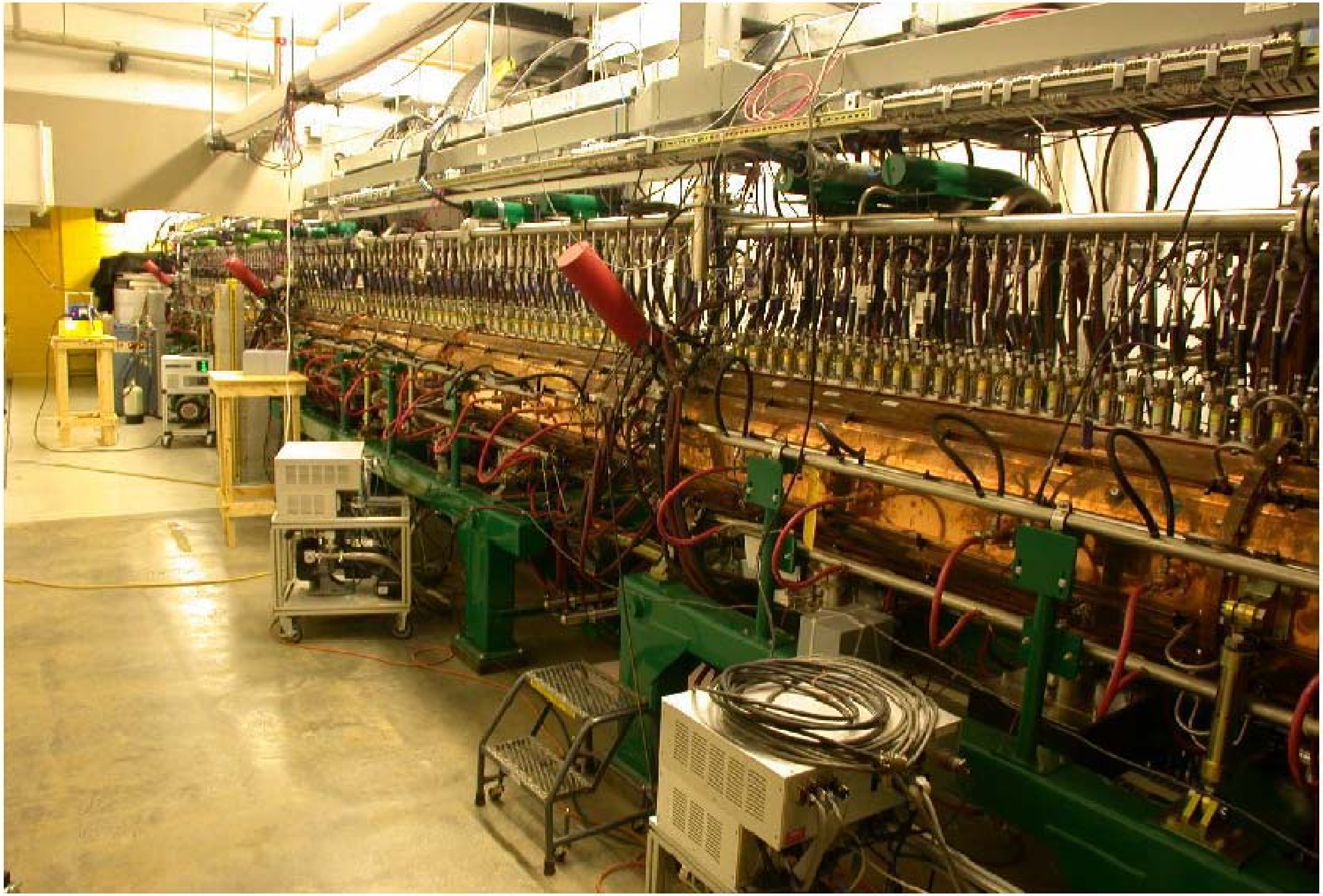
Tilt Sensitivity



Q_o=48,300 Q_L=17,700 f_o=402.5 MHz at 28.8 C

- DTL is designed to work with fixed electrical field particle velocity profile
  - Typical tolerance < 1%
- Sensitivity to perturbations is as important

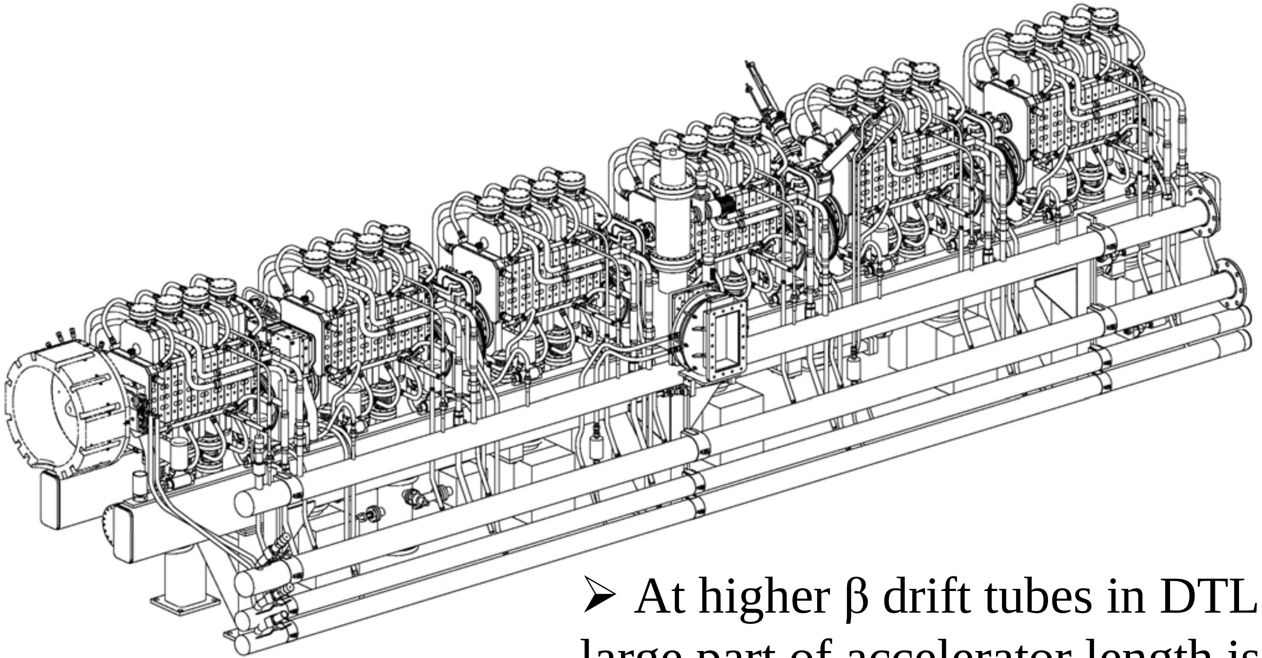
The SNS DTL in the tunnel



The SNS CCL parameters

Input energy:	**86 MeV**
Output energy:	**186 MeV**
Peak current:	**38 mA**
Number of tanks:	**4**
Total number of cells:	**386**
Total length:	**55 m**
RF frequency:	**805 MHz**
Synchronous phase:	**-30° to -28°**

Coupled-Cavity Linac (CCL)



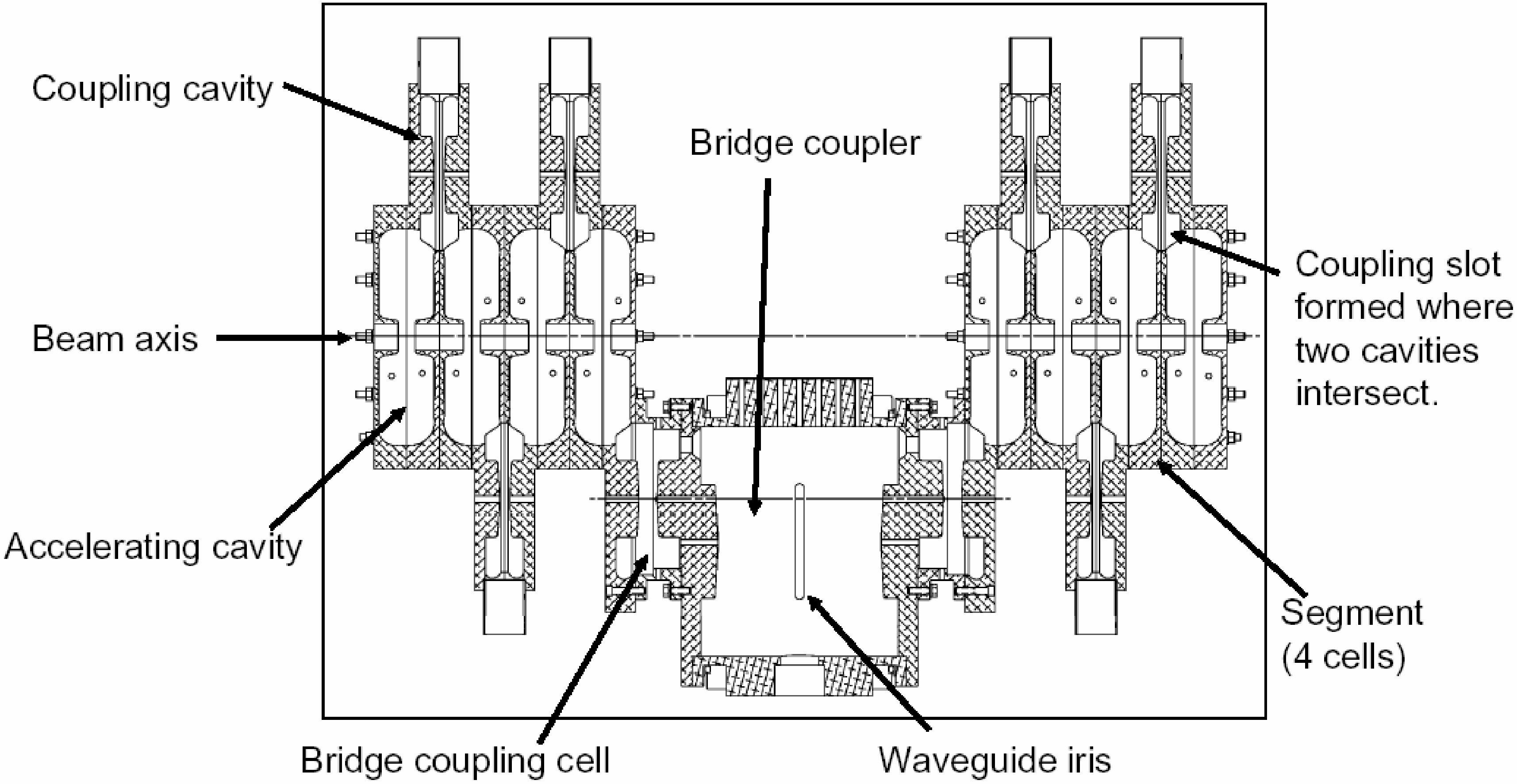
➢ At higher β drift tubes in DTL become too long and large part of accelerator length is “wasted” for drifting in the tube. Need more efficient structure

➢ If use separate cavities than field in adjacent cells does not need to be in phase

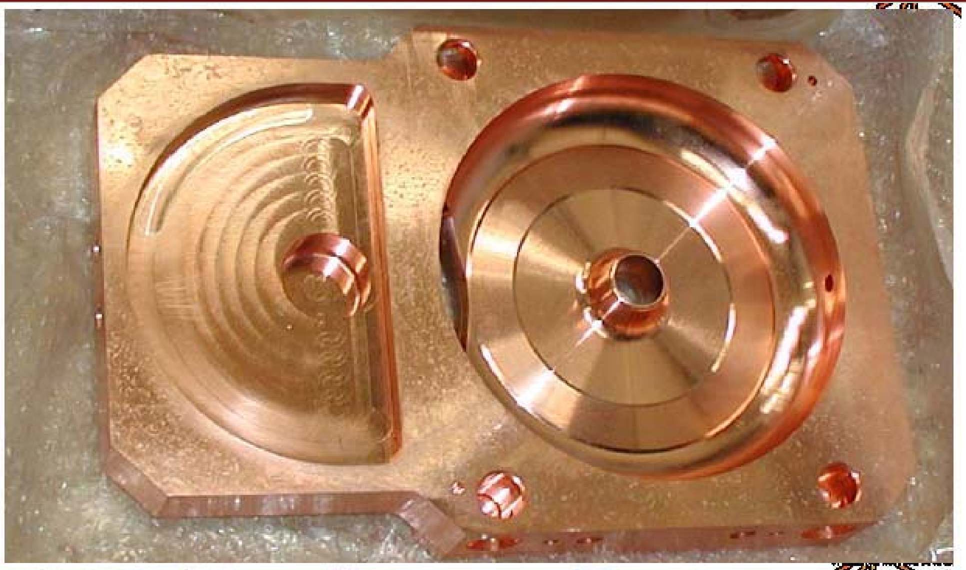
➢The coupled-cavity linac (CCL) consists of an array of single-gap cavities or cells, that are electromagnetically coupled together to form a multi-cell accelerating structure.

➢ Main motivation for coupling: we want long multi-cell accelerating structures that can be driven by a single high power generator.

CCL structure



Building the CCL



- 8 cells of the segment are identical
- 48 segments are all different
- Many measurement/tuning steps in the process of manufacturing: cell, segment, module

Tuning the CCL

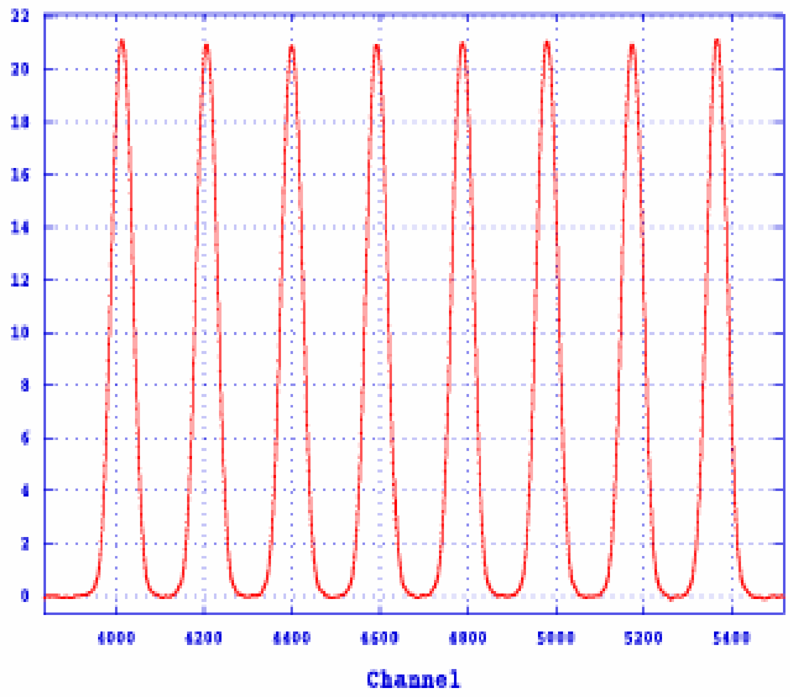
➢ Price to pay for having single RF source in a coupled cavity structure:

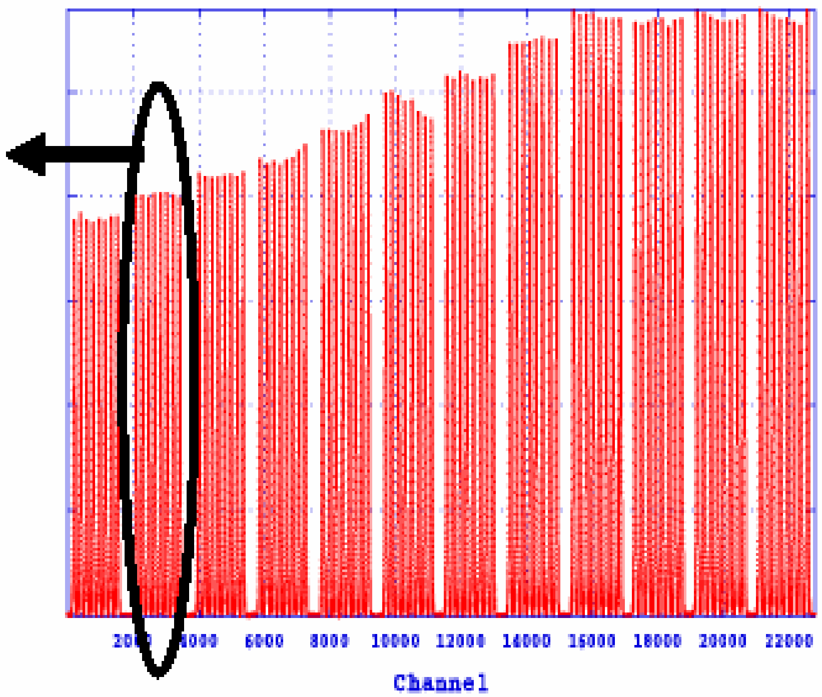
- Elaborate tuning of many individual cells by hand
- High price of error: can't have a spare cell or segment – they are unique

➢ Advantage:

- Field strength and mutual phase between cells is fixed after tuning. Only 2 settable parameters (RF phase and amplitude) instead of 96 in case of individually powered cavities

Tuning the CCL

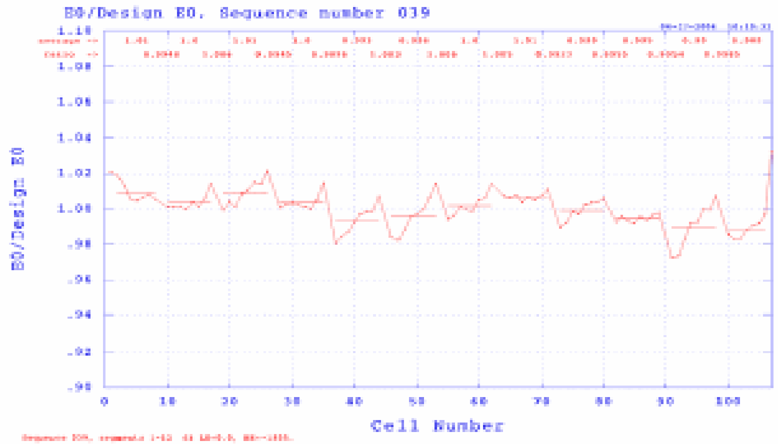




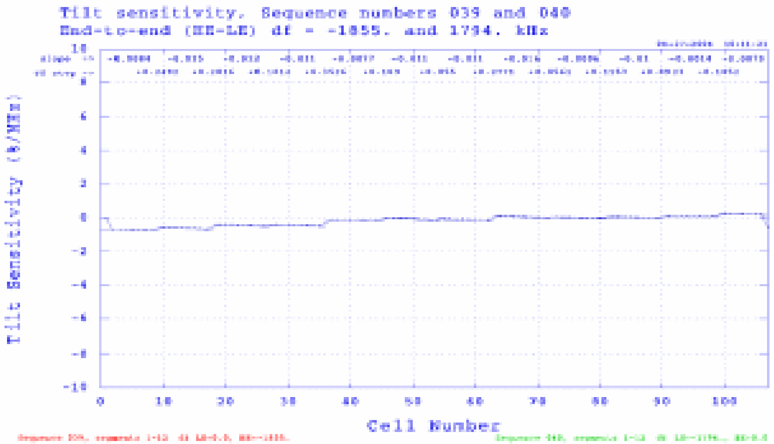
- Uniform electric field strength within segment
- Can ramped electric field from segment to segment
- All cells, segments resonate at the same frequency

Final field profile measurements

E_o/E_{design}



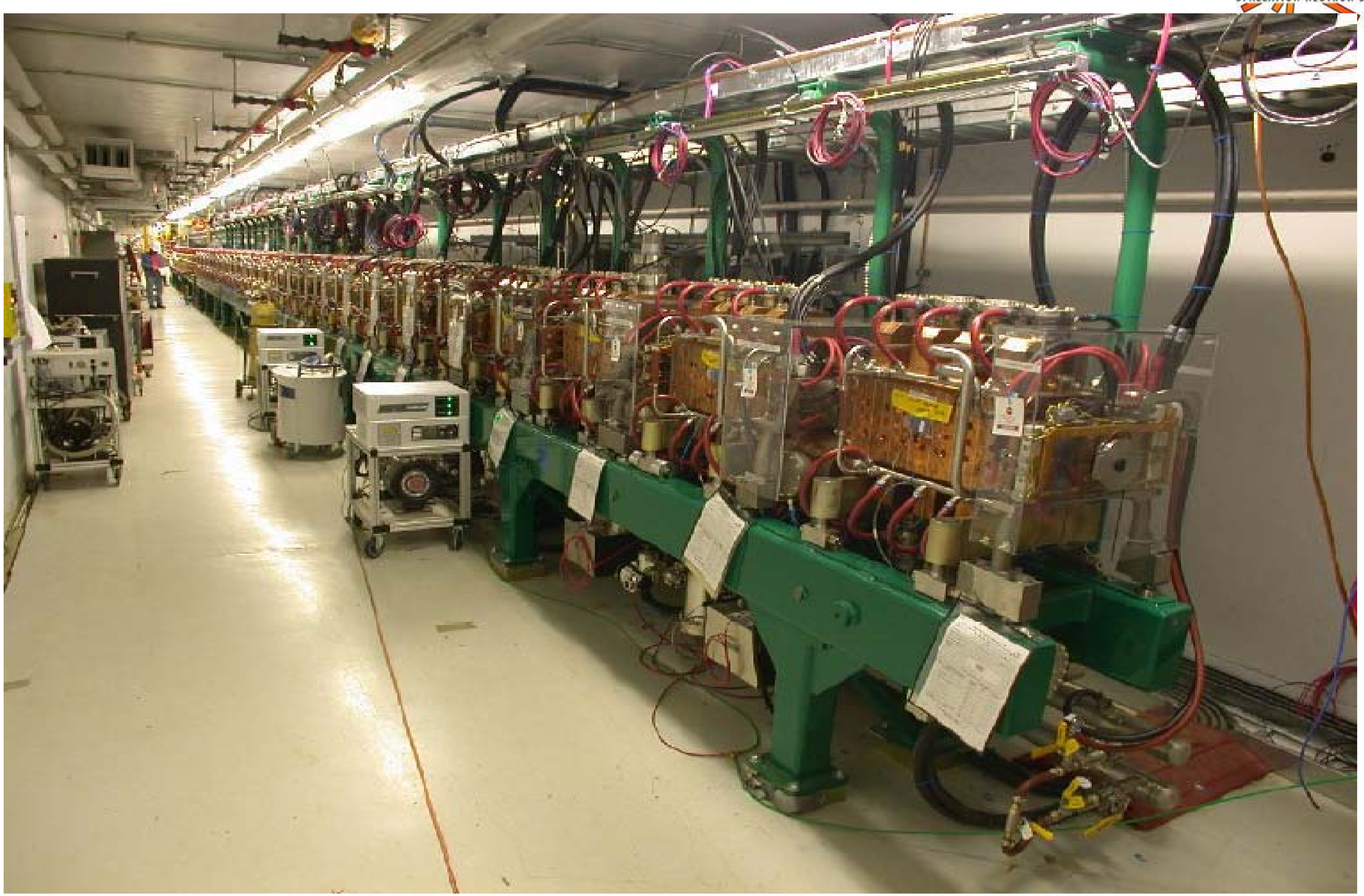
Stability



Coupling=0.618+0.612=1.220, f_o=805.100 at 20C, Q_o=16,000

- CCL is designed to work with fixed electrical field particle velocity profile
  - Typical tolerance < 1%
- Sensitivity to perturbations is as important

The SNS CCL in the tunnel



Super Conducting Linac (SCL)

- CCL accelerating structure is suitable for acceleration up to relativistic energies. Why need another one?
- Disadvantages of copper (normal temperature or warm) linacs:
  - Large rf power dissipation results in
    1) High cost of RF system
    2) High operating costs for AC power
    3) Cooling requirement can limit accelerating gradient
- Example: RF power budget for the SNS CCL module

$$P_{generator} = P_{wall} + P_{beam} = 2.2MW + .52MW$$

- Significant reduction of resistive losses due to use of superconducting material for cavity walls eliminates warm linac disadvantages.

- There is price to pay:

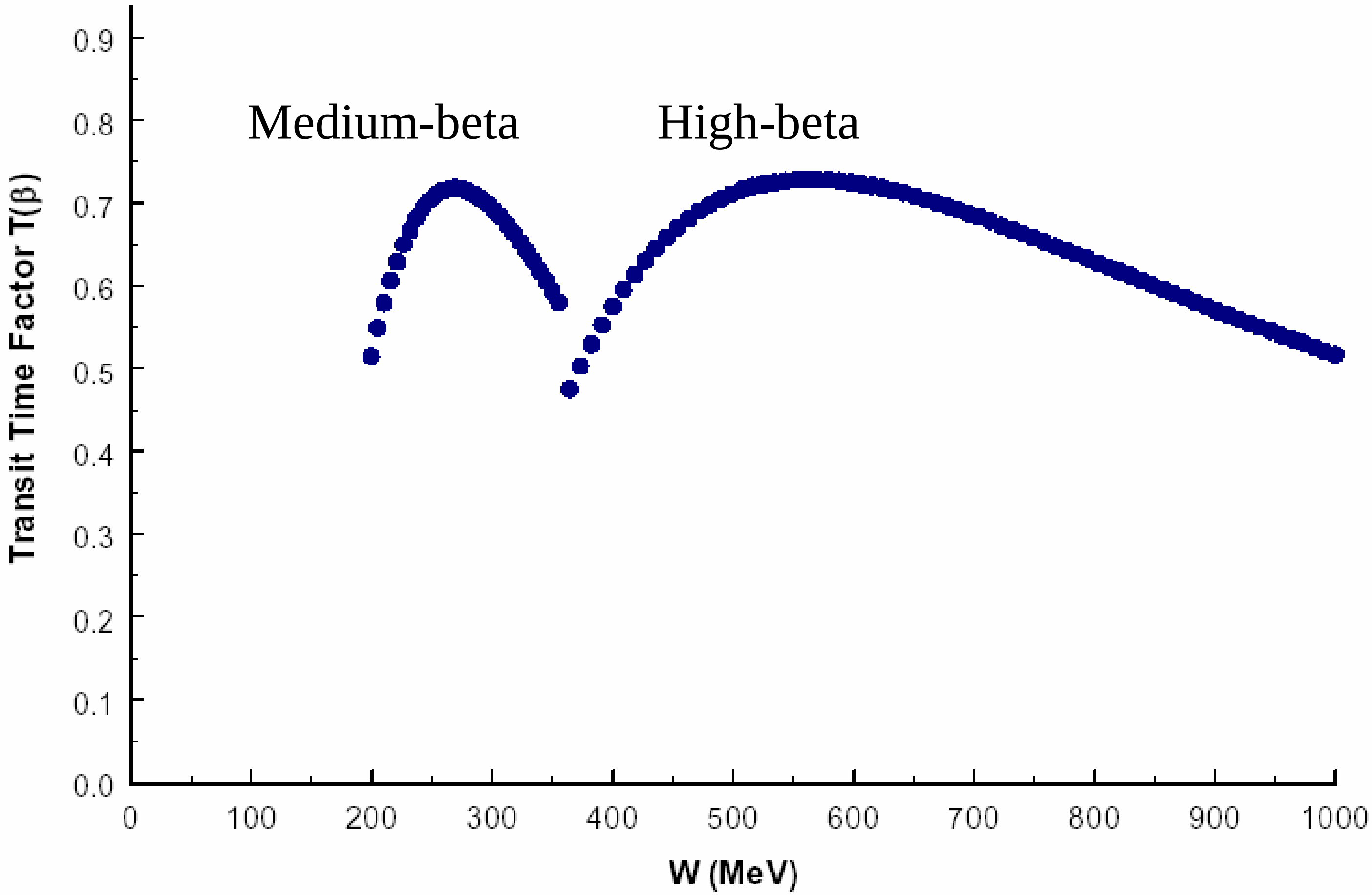
  - Must operate linac at cryogenic temperature (2-4 K)

  - Must maintain ultra clean environment during cavity manufacture, handling and operation

The SNS superconducting cavity

Material:	**niobium (NB)**
Operating frequency	**805MHz**
Number of cells per cavity	**6**
Operating temperature:	**2.1K**
Number of cavities	**33 (b=.61) + 48 (b=.81)**
Total length	**157 m**
Total energy gain	**814 MeV**

Two types of the SNS SRF cavities



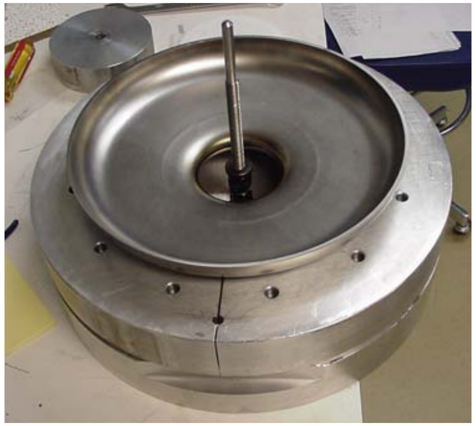
➢ Two cavity types cover energy range from 200MeV to 1000MeV

Cavity Fabrication

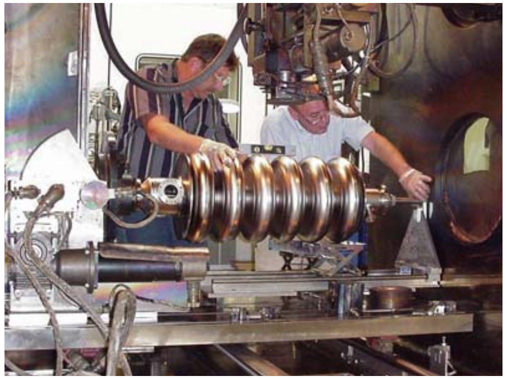
Deep drawing & machining

Dumb-bells

Frequency adjust.

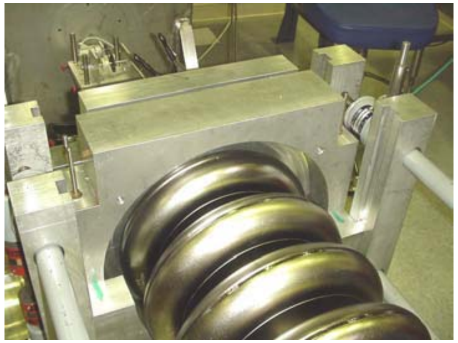


Welding



SNS β=0.61

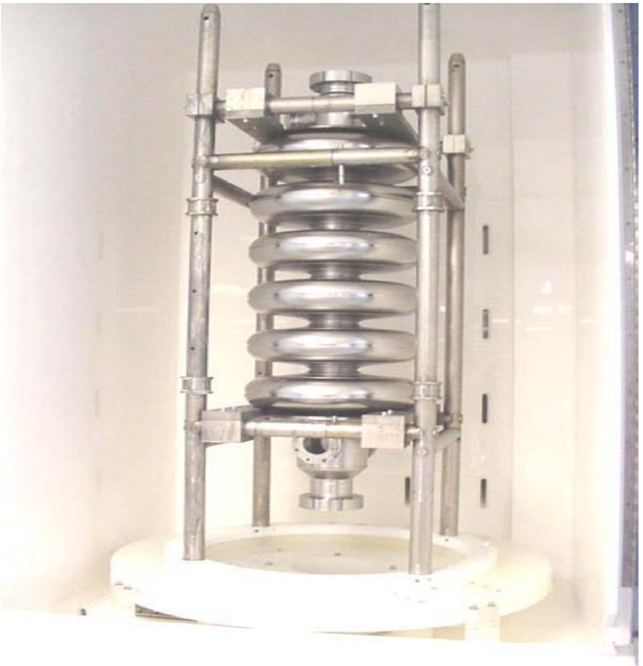
Tuning



Cavity Cleaning

- Surface cleanness is the major factor in final cavity performance

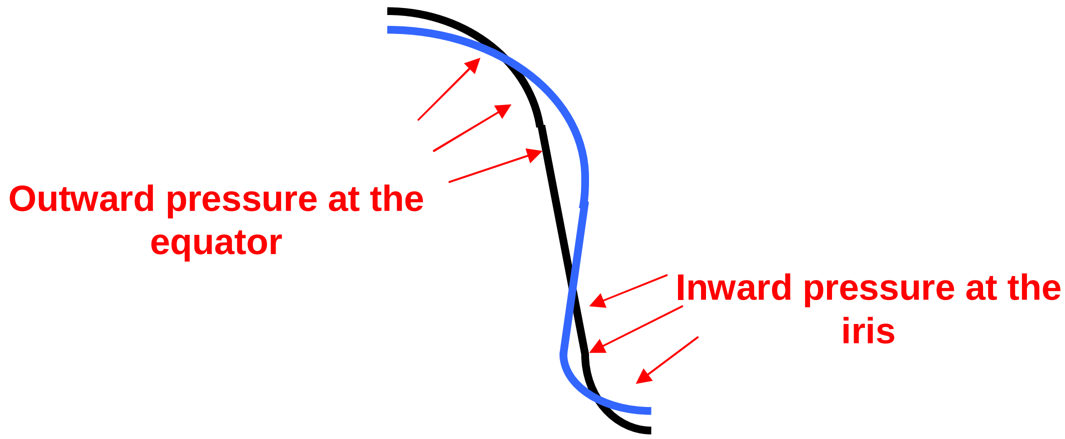
~1hr High Pressure Rinsing



Assembly in clean room (class 100)

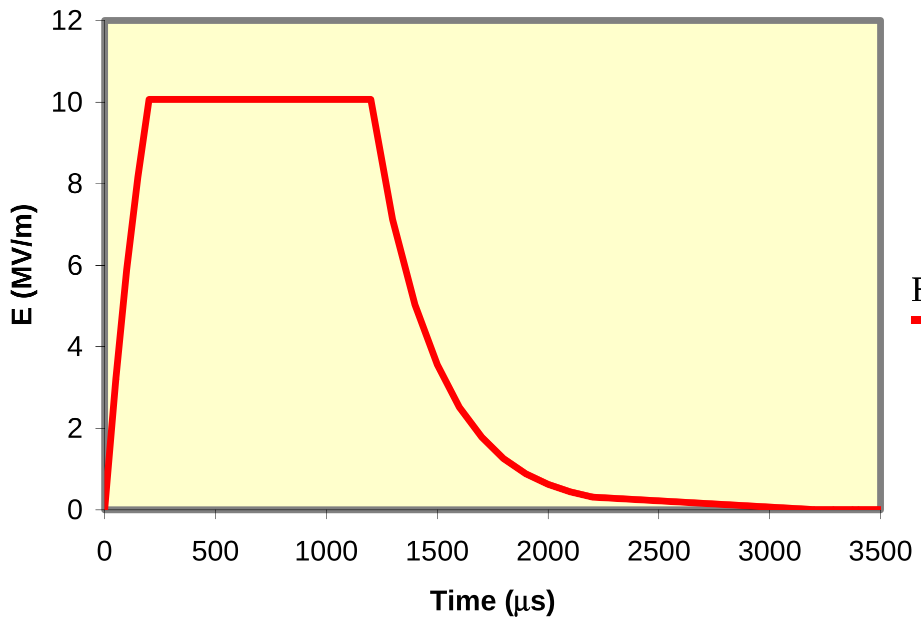
Lorentz Force Detuning

- RF power produces radiation pressures : $P = (\mu_0 H^2 - \varepsilon_0 E^2)/4$
- Pressures deform the cavity wall:

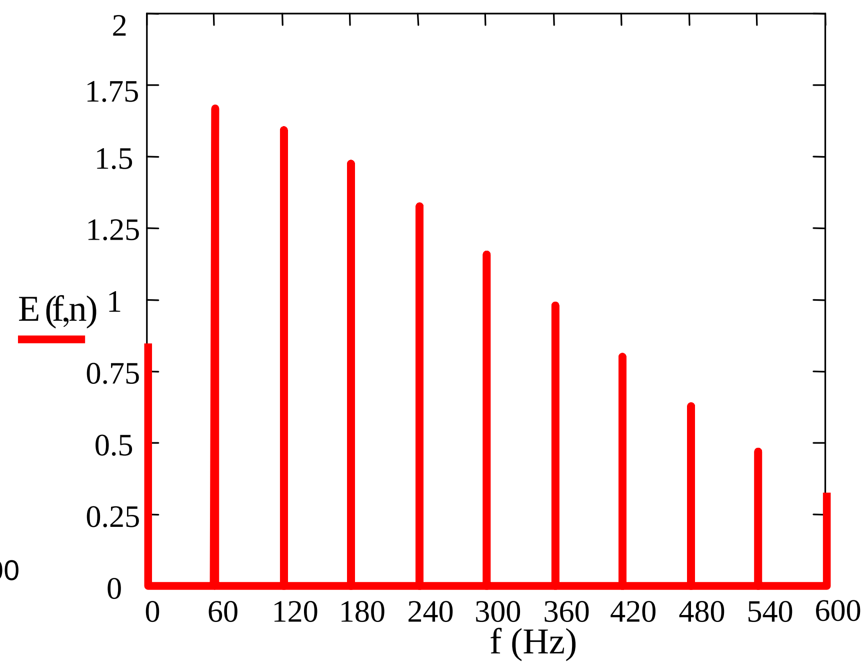


- Deformations produce a frequency shift : $\Delta f = KL^* E^2_{acc}$
- SNS Lorentz force coefficient (*KL*) specification, less than |-3|
- Pulsed RF causes time varying deformations that can be significantly different from a continuous RF system

SNS RF Pulse

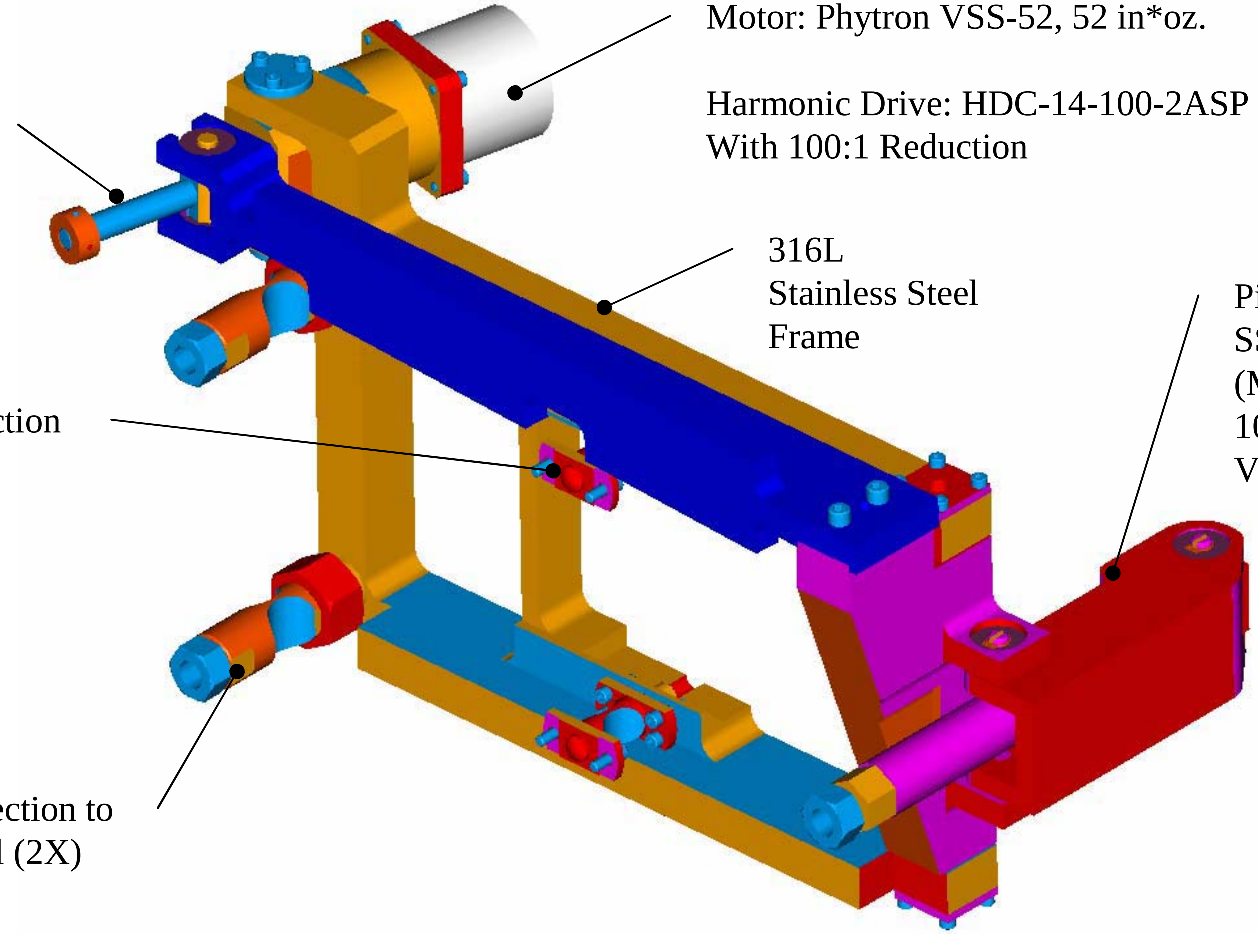


SNS RF Power Spectrum



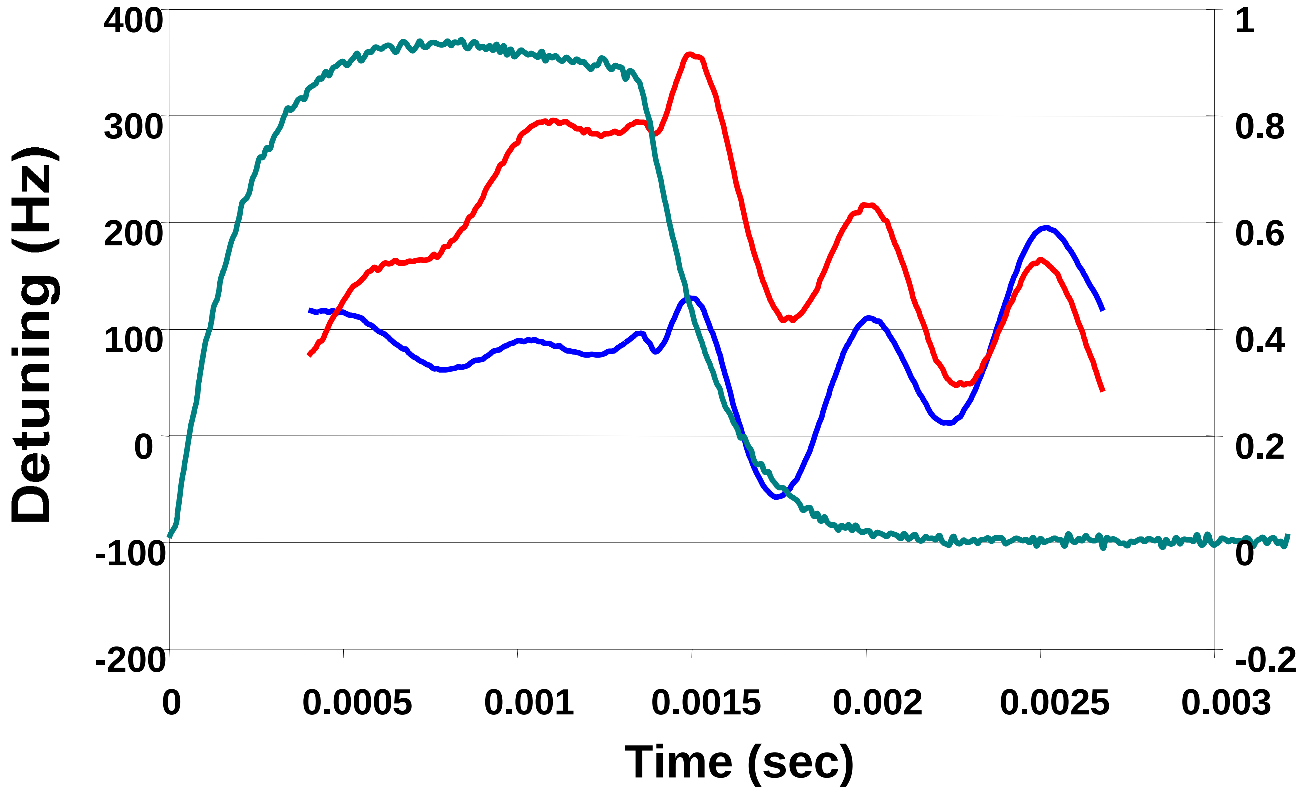
- SNS RF pulse has a 1ms flat-top and is cycled at 60 Hz.
- Capable of exciting relatively high mechanical modes.

Tuner Assembly w/ Piezo Actuator

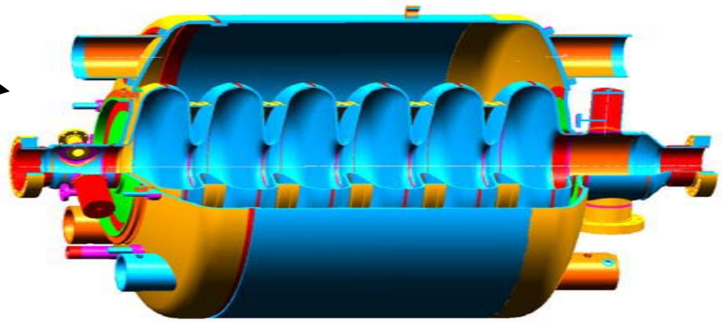


Dynamic Lorentz force detuning and compensation

2 kHz oscillation

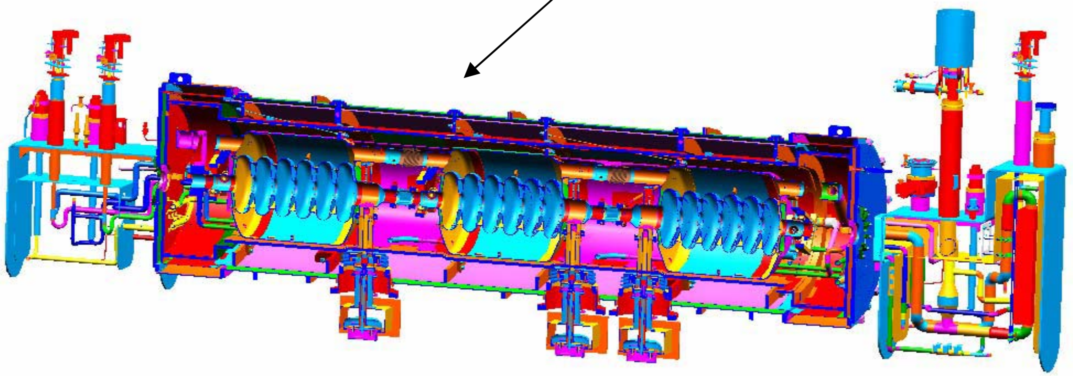


Cavities are contained in a Helium Vessel

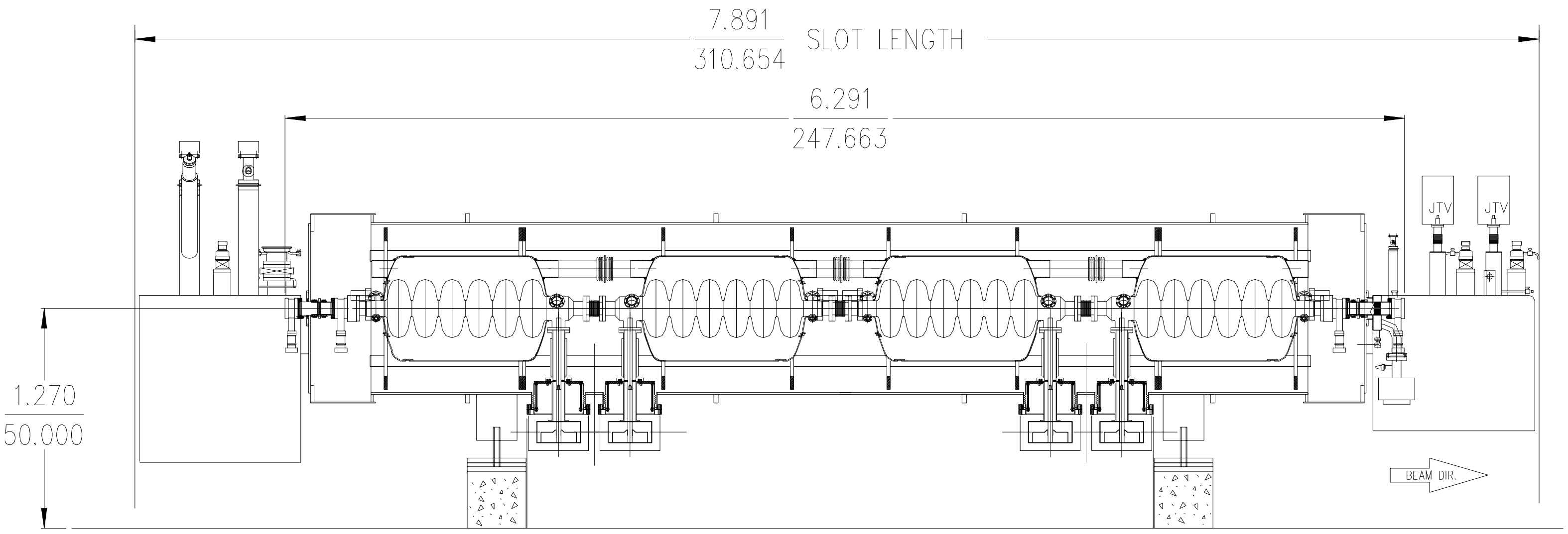


Vessels are assembled into a String

String is placed in a cryomodule (11 +12 cryomodules)



High beta cryomodule



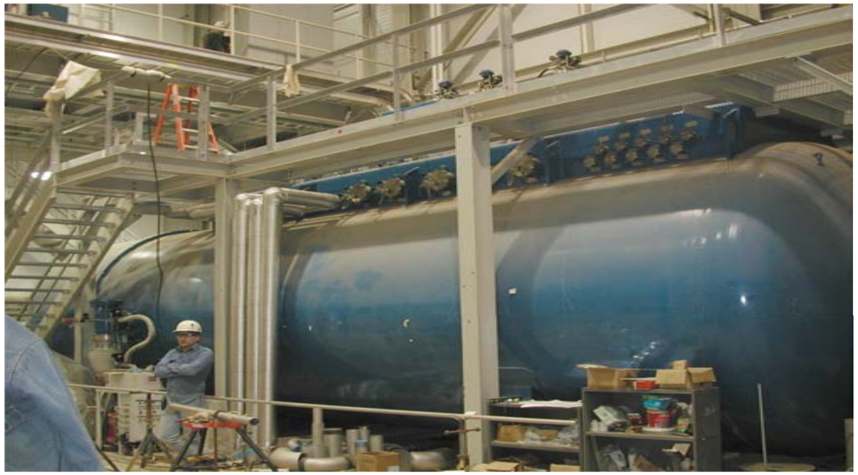
The SNS SCL in the tunnel

- Quadrupole magnets for transverse focusing are between the cryomodules (warm sections)
- Beam diagnostics are in the warm sections

Cryogenic plant and He transmission line

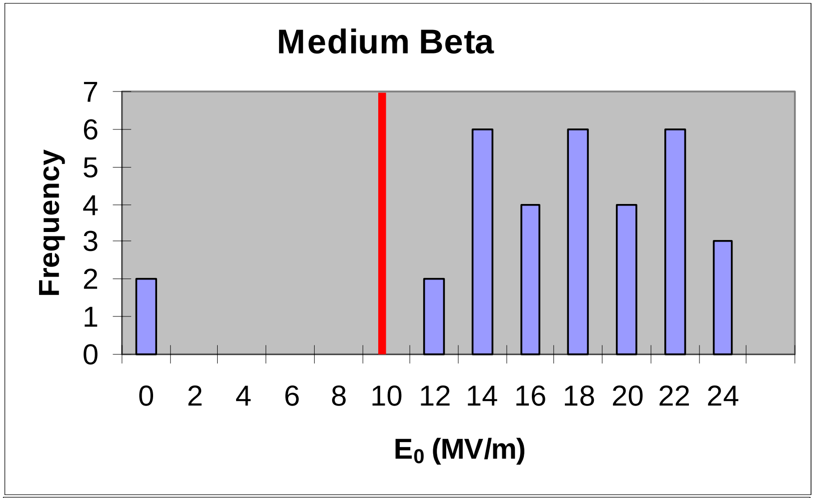
➢ All cryomodules are cooled by liquid He from the cryo-plant (huge helium liquefaction station; ~2.4kW at 2.1K)

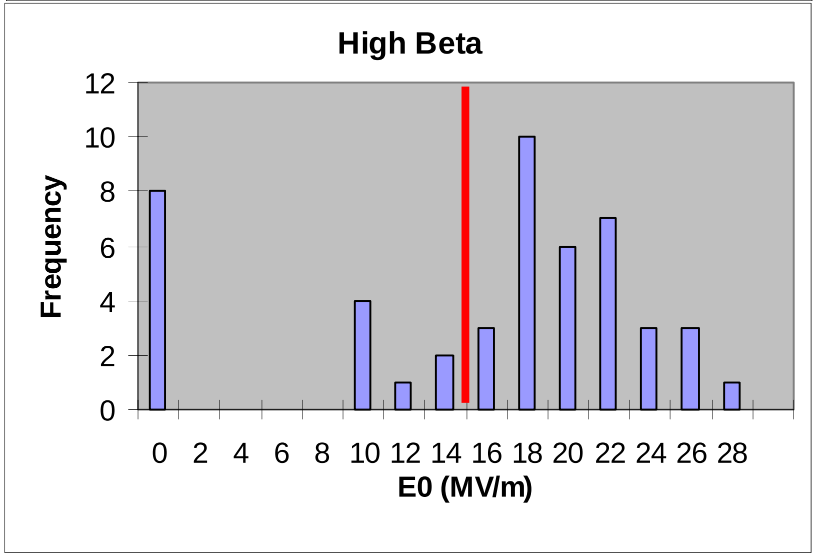
➢1W at 2.1K is approximately equivalent to 1kW at 300K



Final Performance of Super Conducting Cavities

- There is large scattering in maximum field strength of the individual cavities due to manufacturing process
- Use conservative beam dynamics design and set cavities in accordance to the design. Sacrifice some efficiency
- Set cavity field individually for each cavity. Maximizes efficiency but requires flexible beam dynamics design
- Immunity to failures of one or several cavities. Unlike DTL or CCL where accelerator is inoperable in case of failure of a single cell





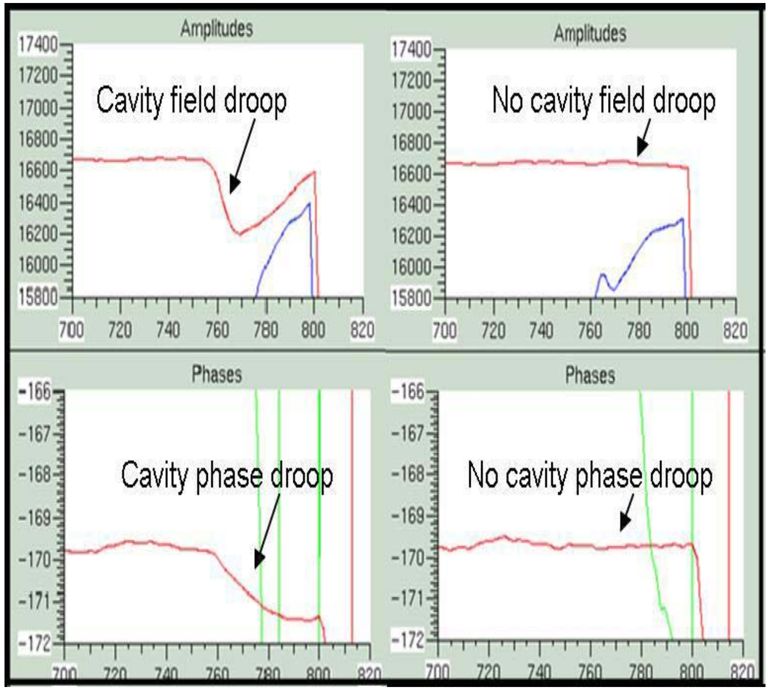
High Power RF Generators

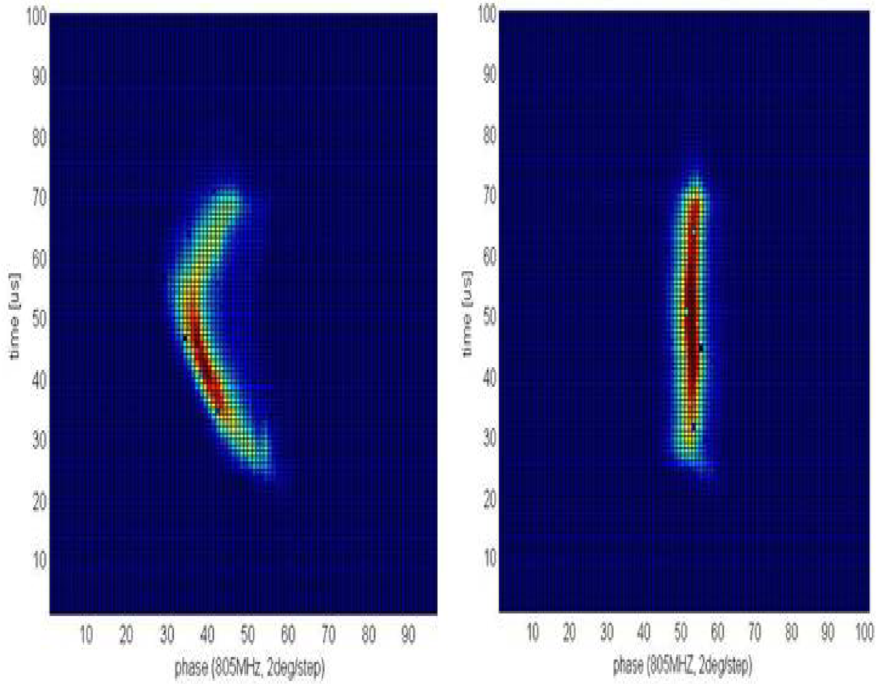
Warm linac: 7 – 2.5MW, 4 – 5MW klystrons

Super Conducting Linac: 81 - .5MW klystrons

Effect of beam loading in the Linac

- Low Level RF system keeps field in the cavity constant





Cavity field and phase droop with feedback alone (left) and feedback + feedforward (right) beam loading compensation.

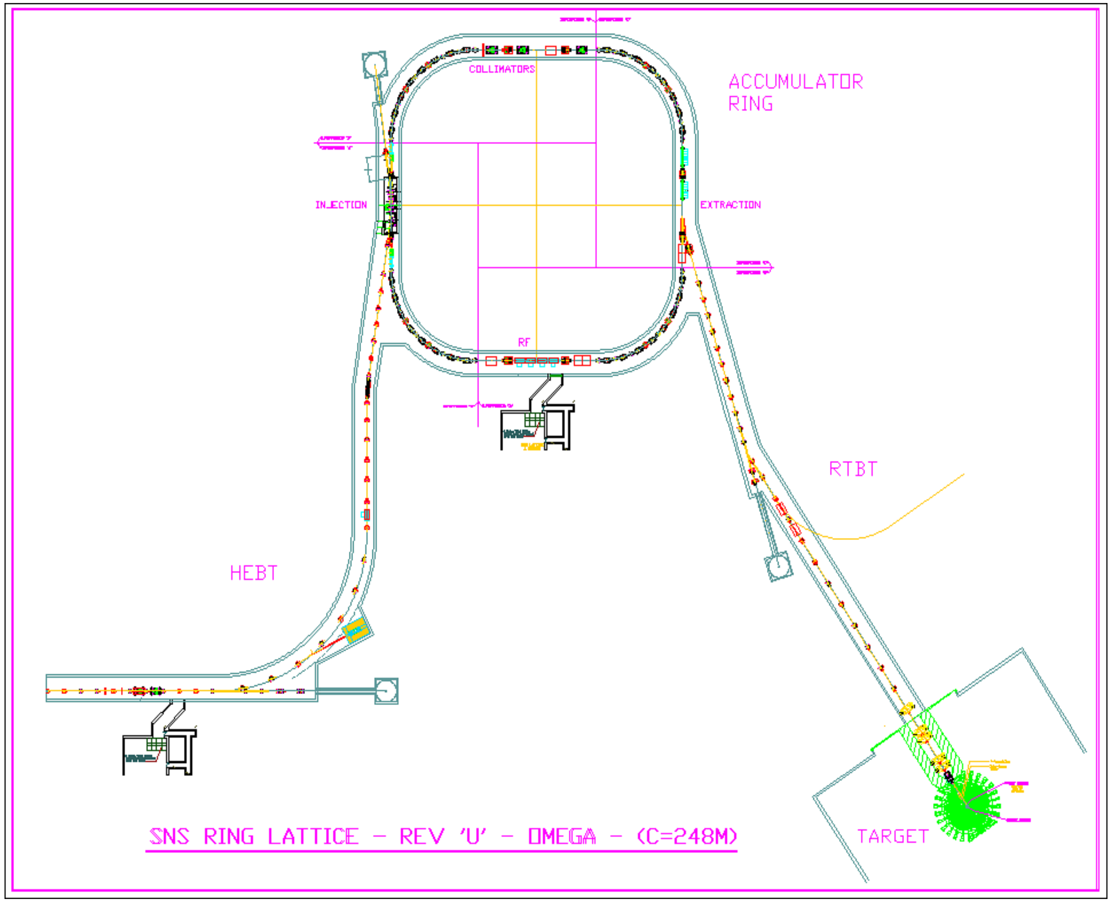
Phase width of the bunch along the pulse with feedback alone (left) and feedback + feedforward (right)

LLRF performance in SCL

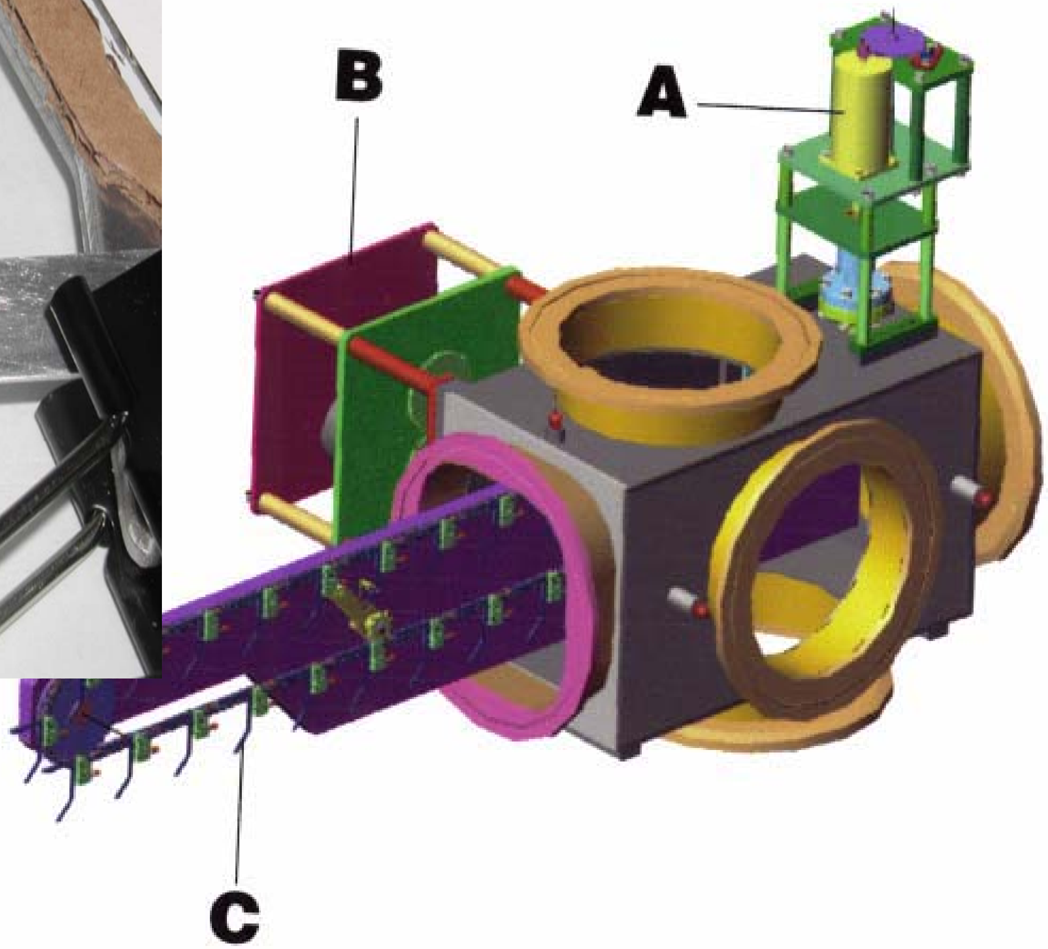
➢ Compensates for Lorentz force detuning, microphones, beam loading, klystron power supply droop

The SNS Accumulator Ring

Circumference	248 m
Energy	1 GeV
Revolution period	1 μs
Number of turns	1060
Final Intensity	1.5×10^{14}
Peak Current	52 A
Number of magnets (bend and focusing)	>300



Injection foil and exchange mechanism



The SNS Ring in the tunnel

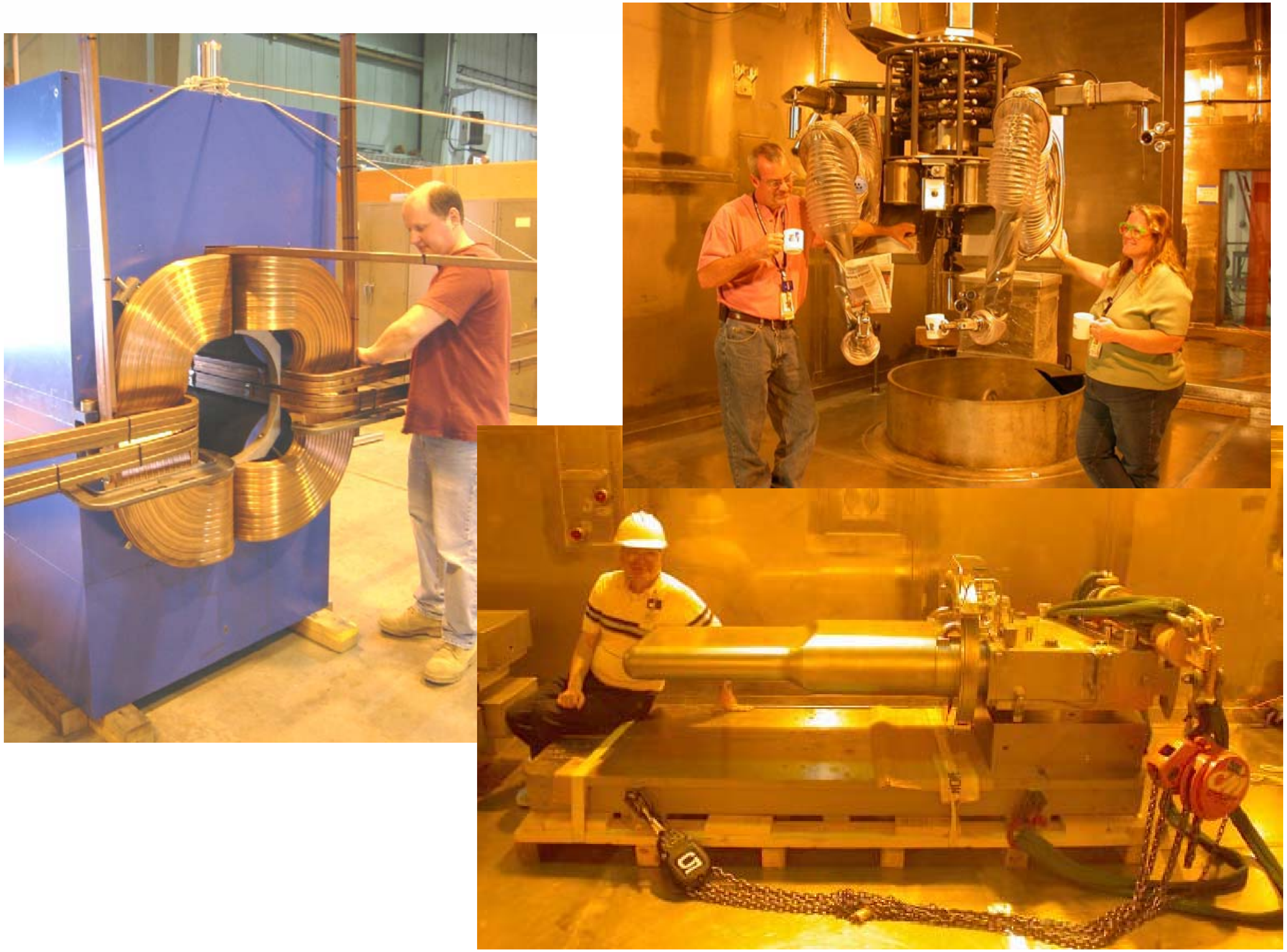
SNS
SPALLATION NEUTRON SOURCE

Quadrupole Magnet (focuses the beam)

Corrector magnet (steers the beam)

Dipole Magnet (bends the beam)

Mercury Spallation Target is Beam Final Destination

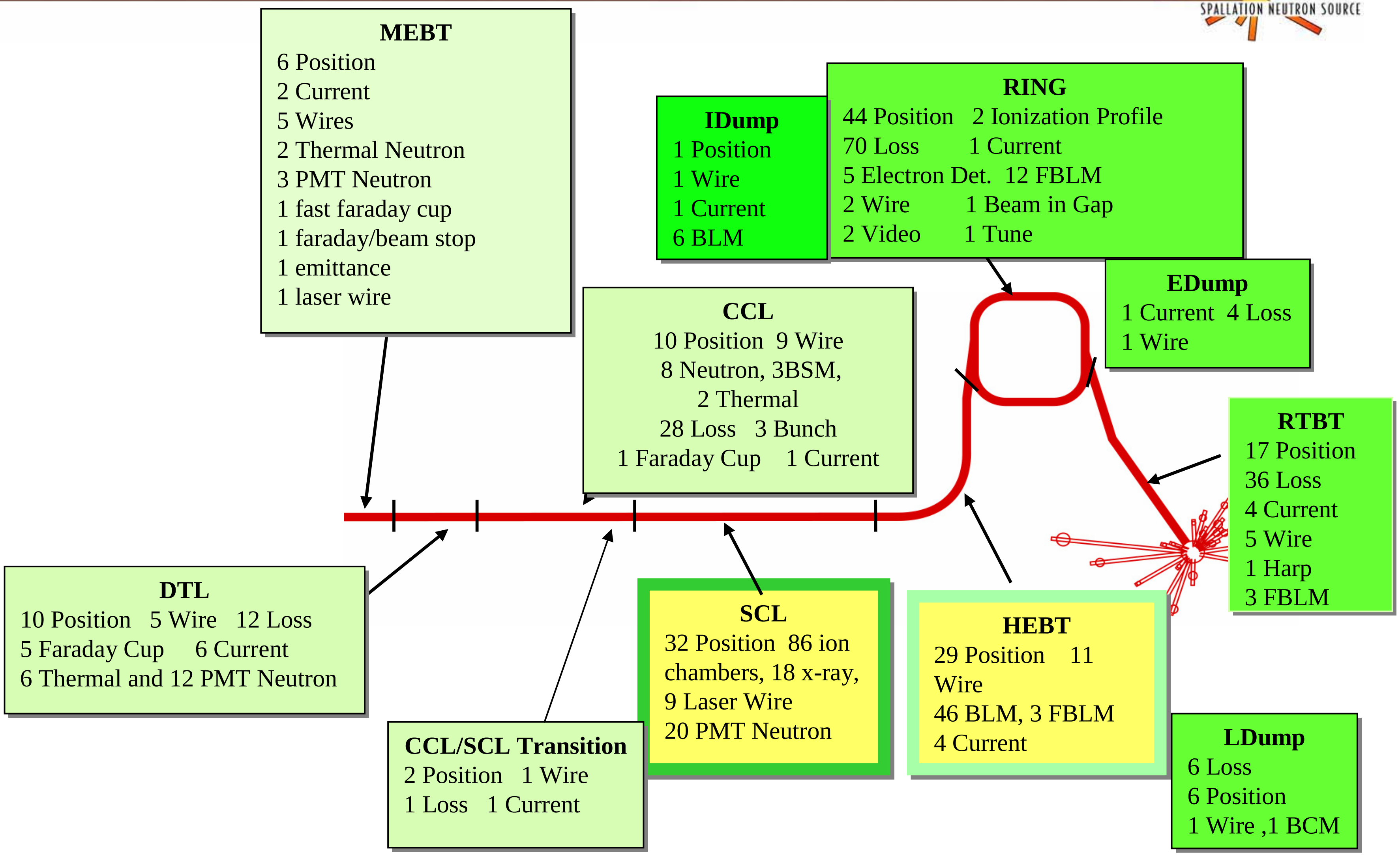


How to make it work

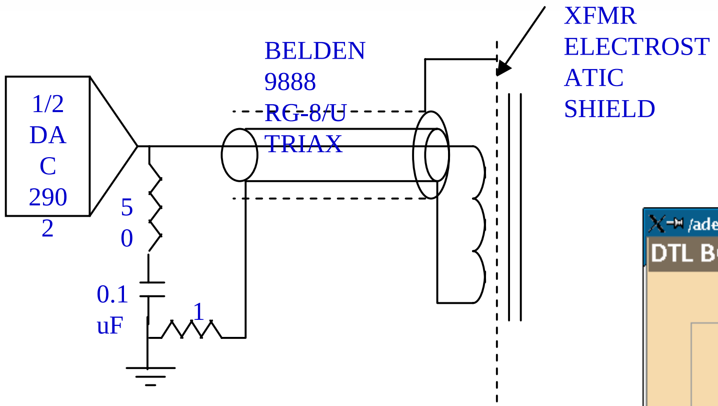
➢ Adequate beam diagnostics is of paramount importance for successful beam commissioning:

- beam current
- beam position; transverse (trajectory) and longitudinal (phase)
- beam size (profile); transverse and longitudinal
- beam energy
- beam emittance
- beam loss

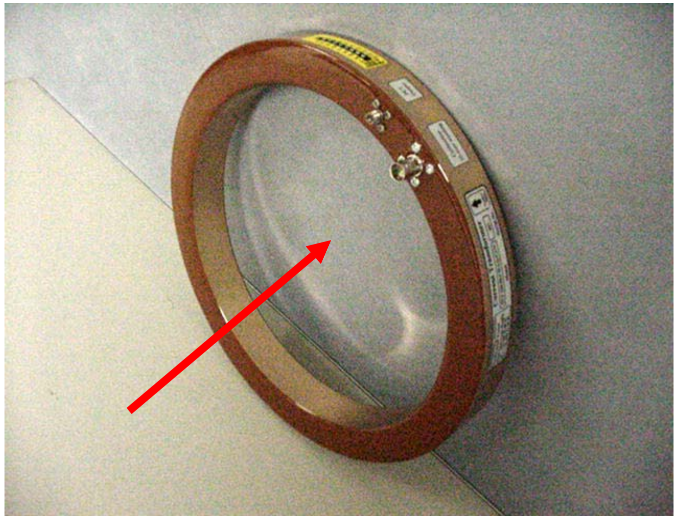
SNS Diagnostics Deployment



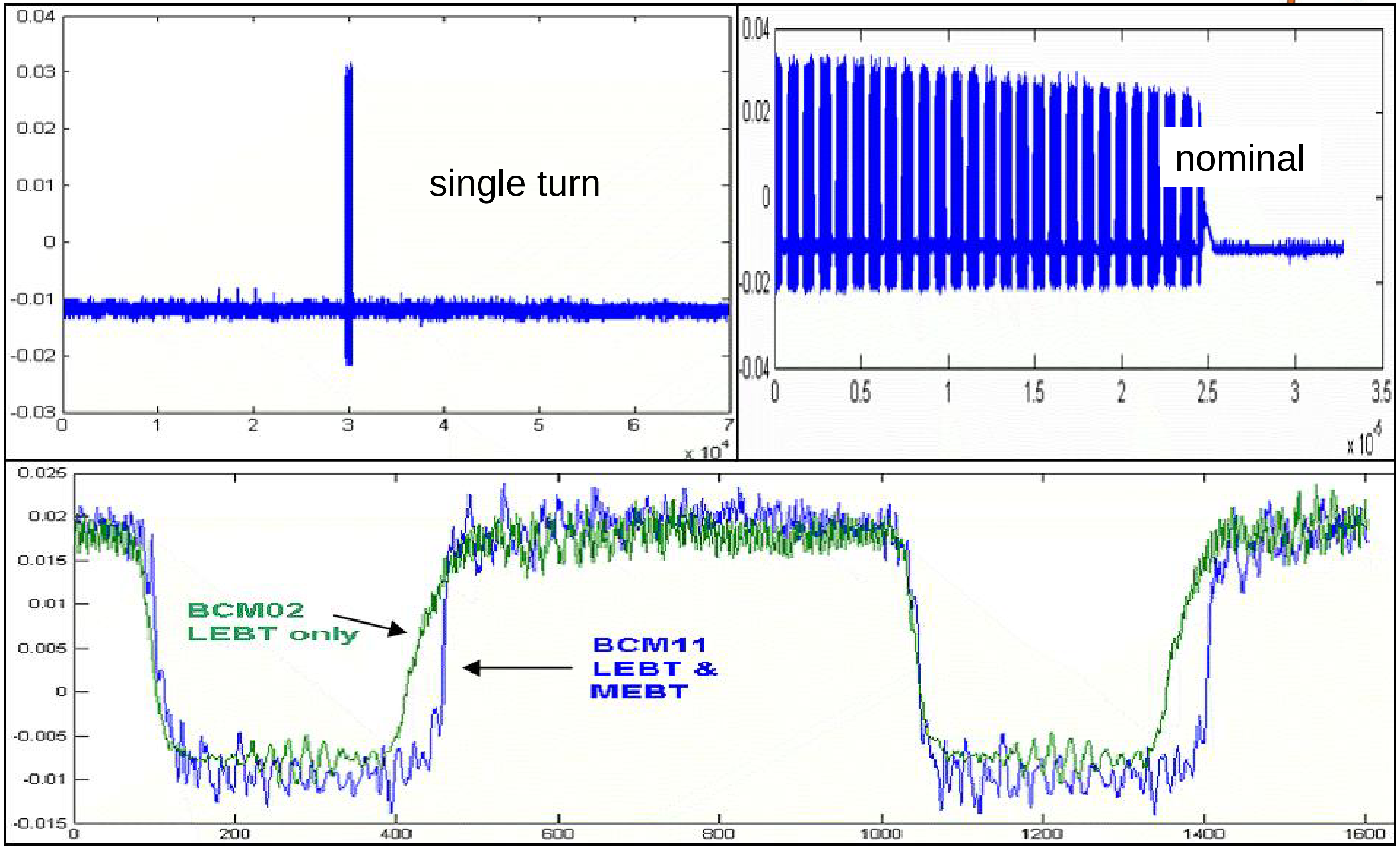
Beam Current Monitor (BCM)



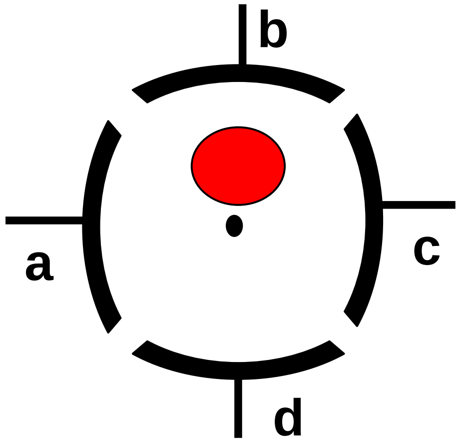
- Beam current transformer
- Non - interceptive



Fast measurements with BCMs

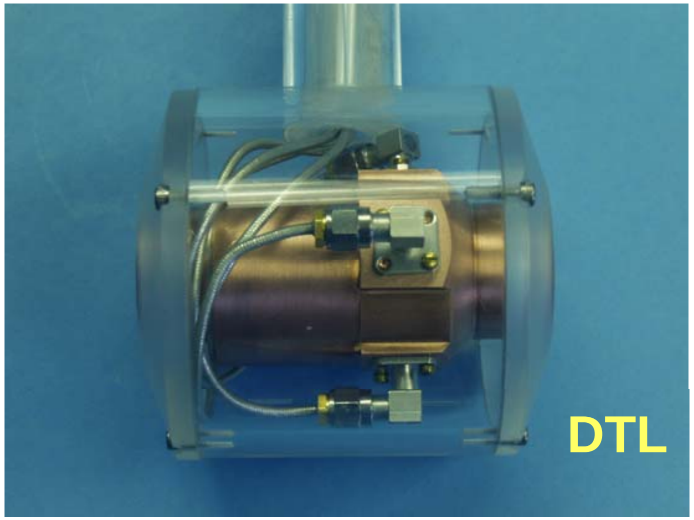


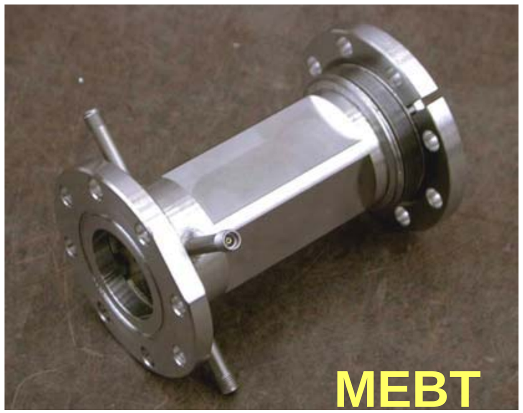
Beam Position Monitor (BPM)

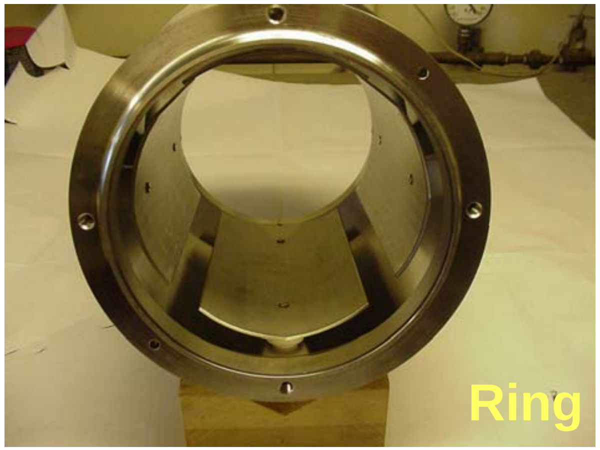


$$x = \frac{a - c}{a + c}, \qquad y = \frac{b - d}{b + d}$$

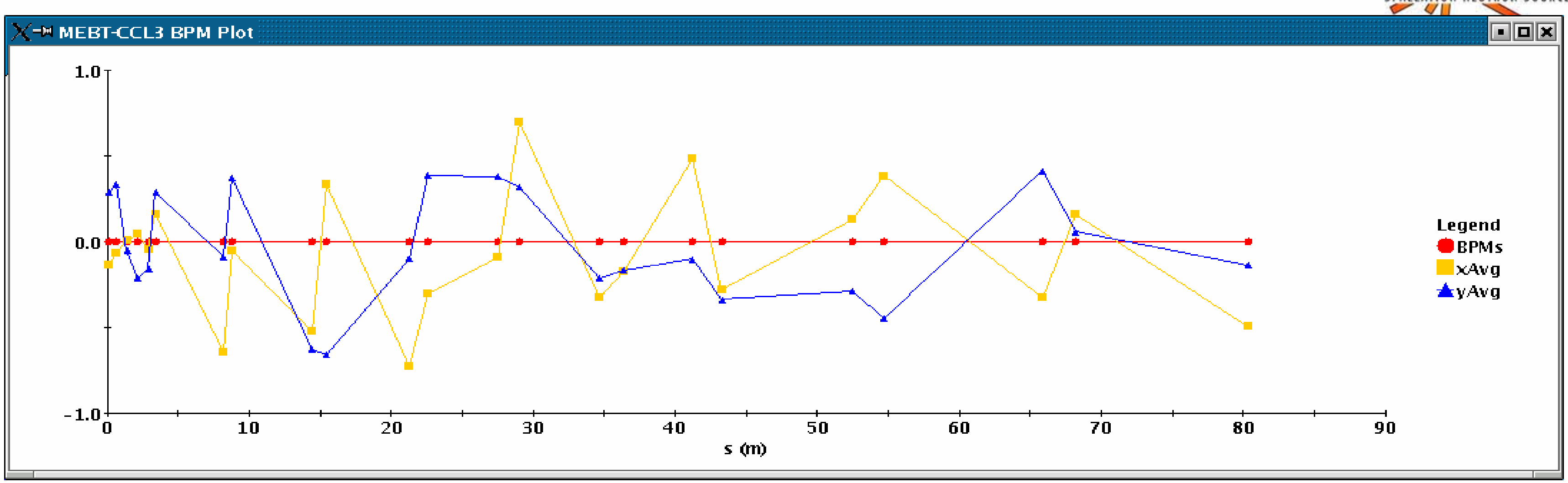
- Matched strip-line electrodes allow large bandwidth
- Phase measurements
- Non – interceptive



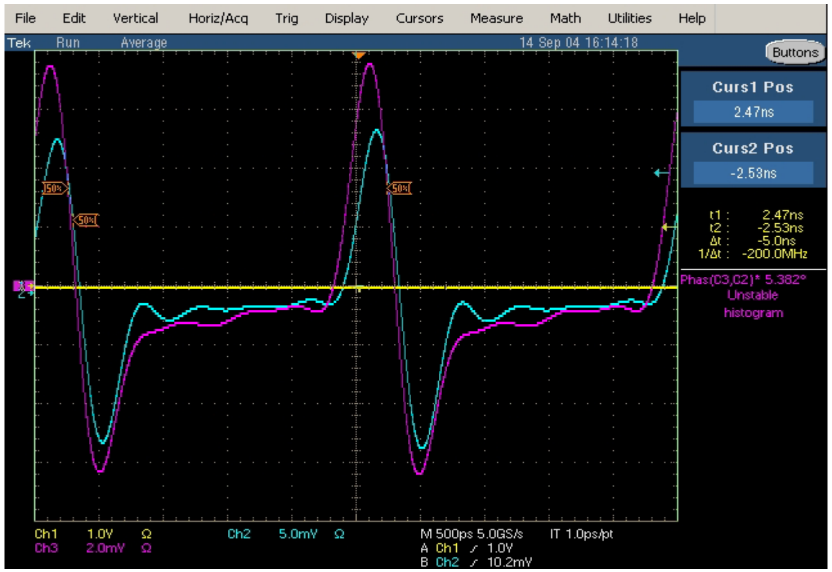




Use of Beam Position Monitors

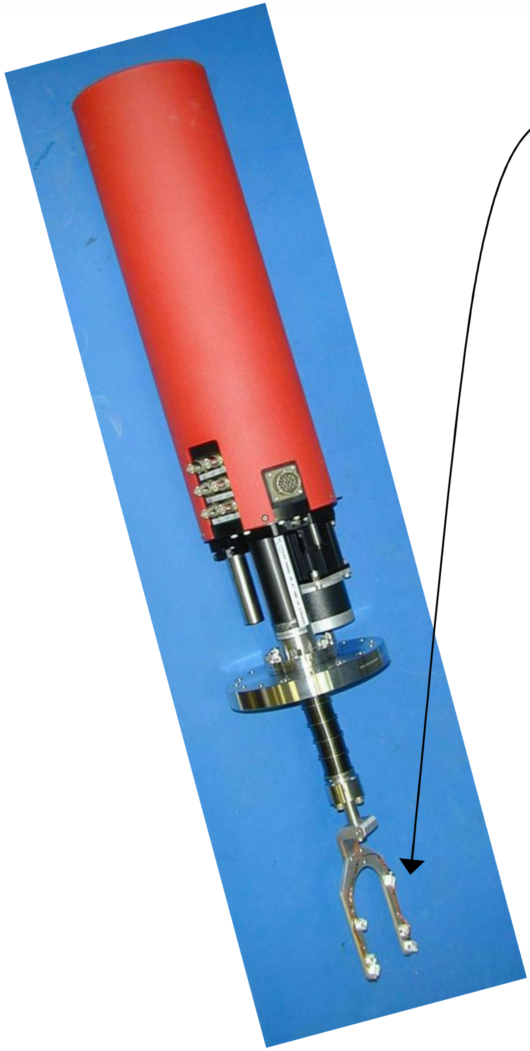


Beam trajectory in the warm linac



Time of flight energy measurement using a pair of BPMs

Wire scanner system

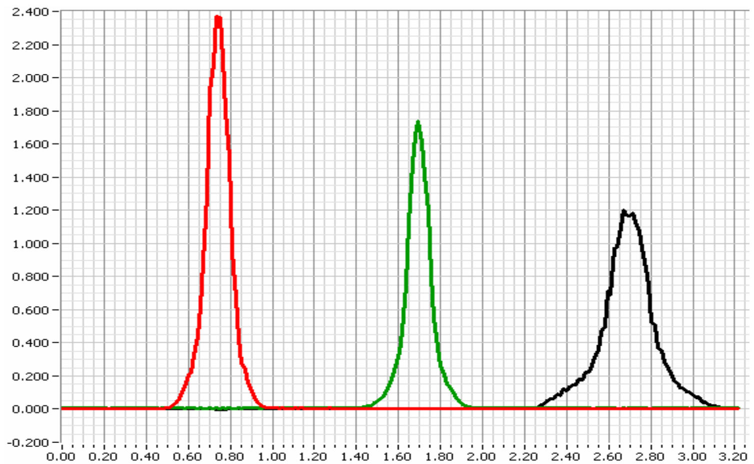


➢ 32 um carbon or tungsten wires mounted on movable fork intercept beam

➢ Measures horizontal, vertical and diagonal transverse beam profile in one pass

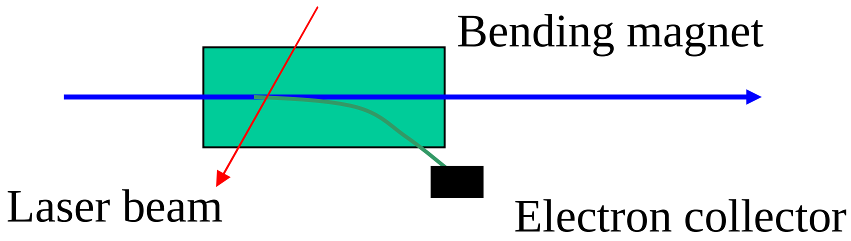
➢ Can take limited beam power : 50us,1Hz

➢ Not suitable for Super Conducting Linac because of risk of contamination if wire is broken

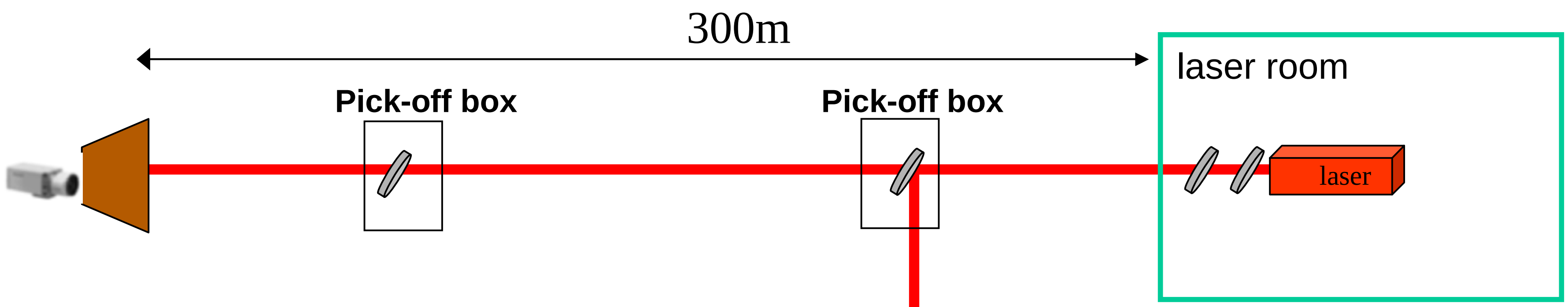


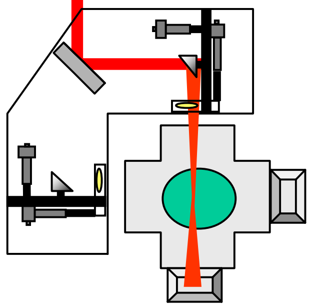
Laser wire in the SCL

$$H^- + h\nu \Rightarrow H^0 + e$$

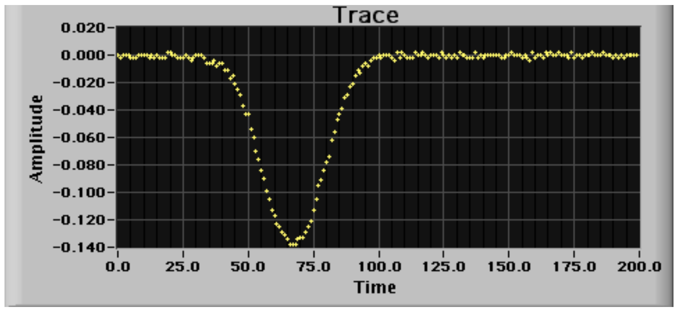


- Laser pulse knocks off one electron from each H-
- Electrons are separated in magnetic field and measured
- Non -interceptive



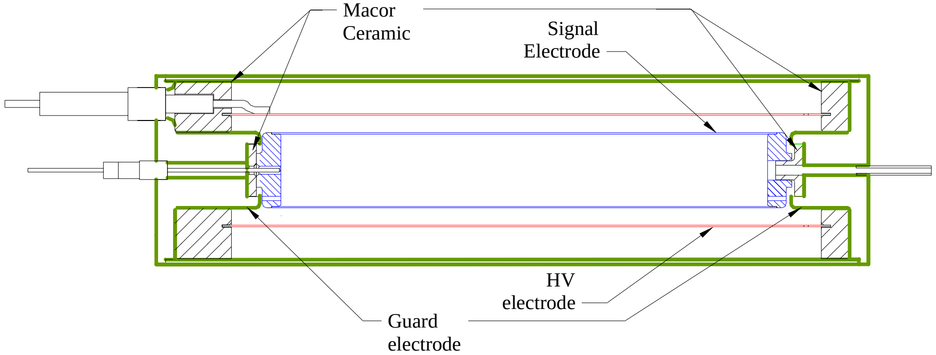


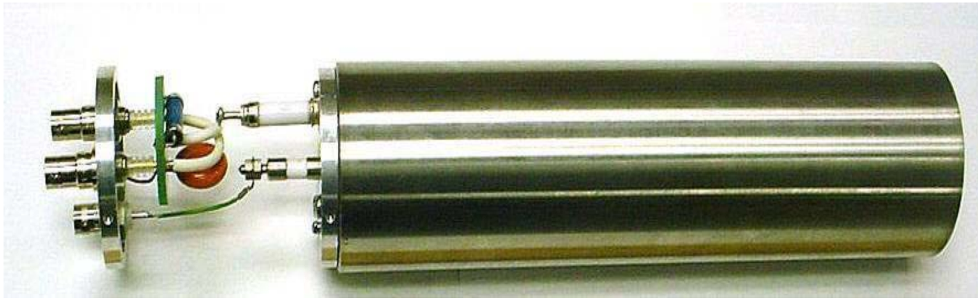
Warm section Optics box



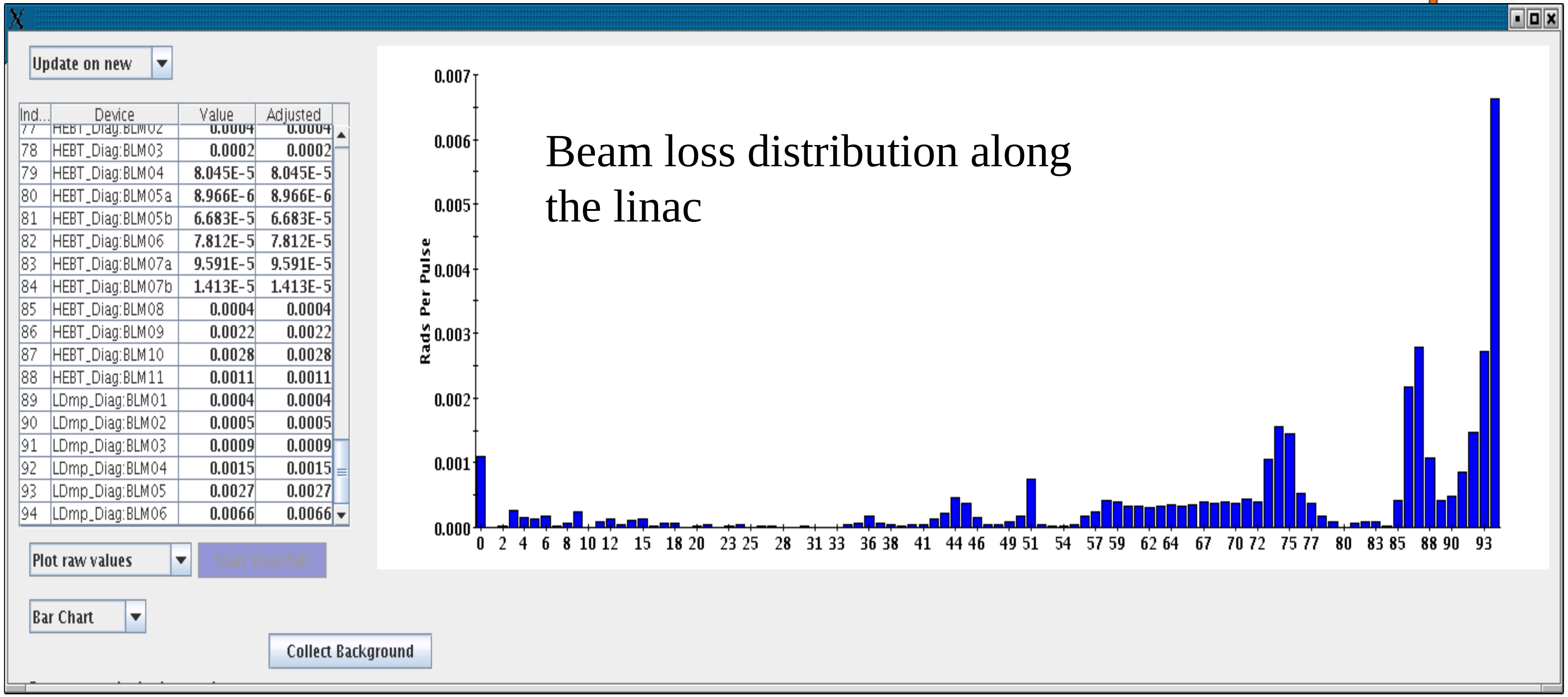
Beam Loss Monitors

- Detectors:
  - Argon ion chambers (primary system)
  - Neutron detectors
  - Fast photomultipliers





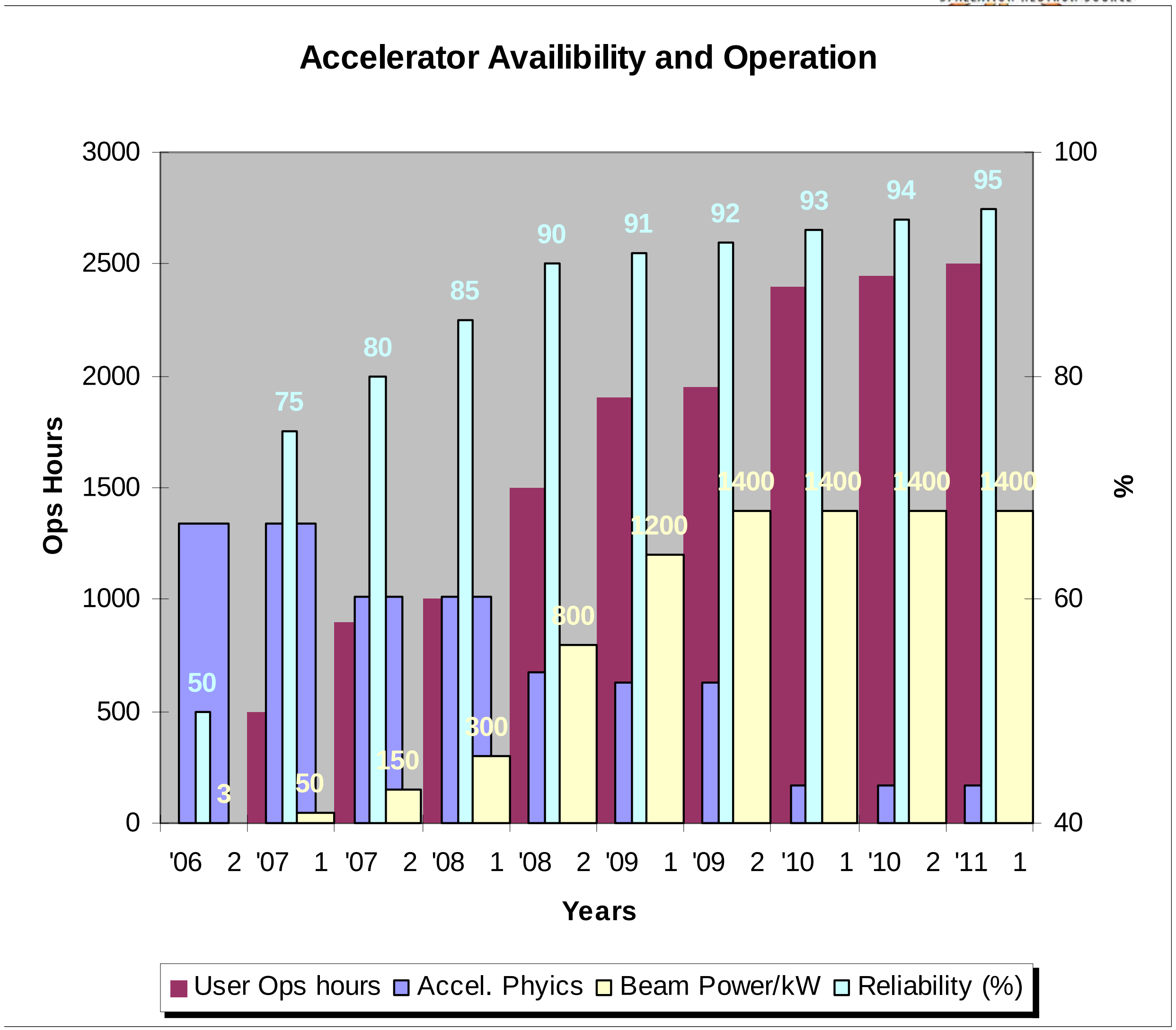
Use of Beam Loss Monitors



➢ Beam loss monitors provide input for Machine Protection System

- the fastest way to shut off the beam in case of an accident

- We will ramp up beam power, reliability and operational hours gradually



The SNS is the first pulsed spallation source of megawatt class and the first pulsed superconducting linac ever build - will provide many lessons to learn