The SNS Accelerator System - 101

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SNS Lecture Series

5/23/01

Thanks to the ASD staff, LBNL, LANL, Jlab, and BNL collaborators

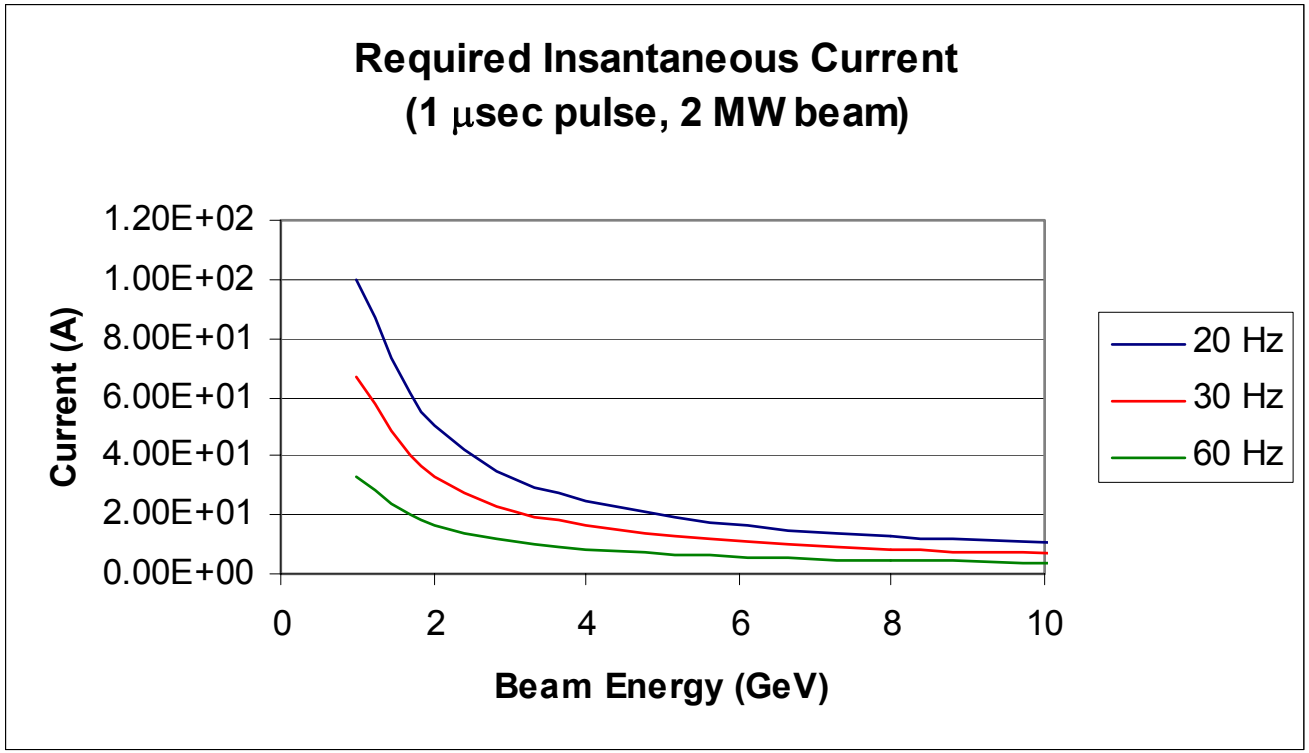
Outline

- Rational for the SNS accelerator design
- Description of the accelerator components
- Give a status update

System Requirements

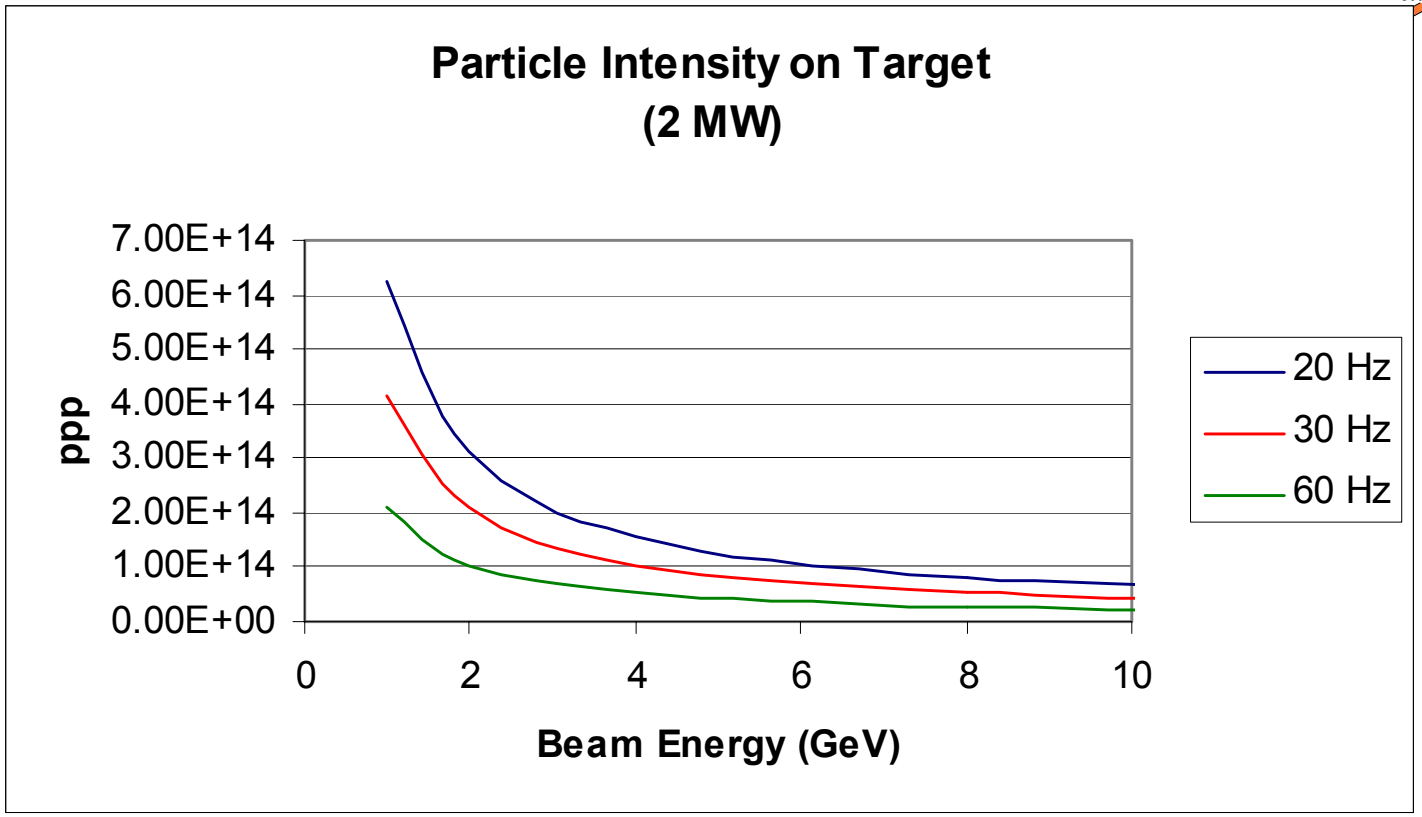
- Pulse should be short (< 1 μsec)
- Energy in 1-10 GeV range (maximize neutrons/MW)
- Repetition rate ~ < 60 Hz
- Deliver a high power proton beam to the neutron target (2 MW)
  - Peak to average power deposition < ~2
  - Beam size = 20 x 7 cm
  - < 4% misses the target
- High availability
  - Hands on maintenance
- Cost of facility < ~$1.4 B

Would a linac alone work?



- Present day ion sources 100s of mA
- Peak power GW!
- Space charge too excessive

Required Particles per Pulse



- Accumulating the required intensity in a ring is more practical

Ring comparison

	PSR	AGS/ Bst	KEK PS Bst	CERN PS	ISIS (inj.)	ISIS (ext.)	ESS	SNS
C [m]	90.2	201.7	37.7	628.3	163.4	163.4	248	248
E_k [GeV]	0.799	0.2	0.04	1.0	0.07	0.8	1.334	1.0
Acc. [μm]	140	100	241/ 49	60/20	500	500	480	480
$\varepsilon_{un,rms}$ [mm]	7/13	8	3 - 8	7/3	50	17	30	48
N (10^{14})	0.38	0.4	0.035	0.03	0.4	0.25	2.34	2.08
B	0.37	1	1	0.048	1	1	0.5	0.5
Dnsty (1D)	11.4	2	0.93	1.0	2.5	1.6	18.9	16.8
Dnsty (3D)	0.21	0.04	0.13	0.02	0.009	0.016	0.085	0.055

Ring Options

- Accumulator Ring
  - Linac provides all the acceleration (~ 1 – 1.5 GeV)
  - Accumulation time ~ 1 msec
  - High repetition rate (60 Hz)
  - Ring is simple (good for low loss)
- Synchrotron
  - Ring provides substantial acceleration
    - Injection energy few hundred MeV, extraction energy 2-10 GeV
  - Lower repetition rate (20-30 Hz)
  - Acceleration time 10-20 msec
  - Ring is more complex

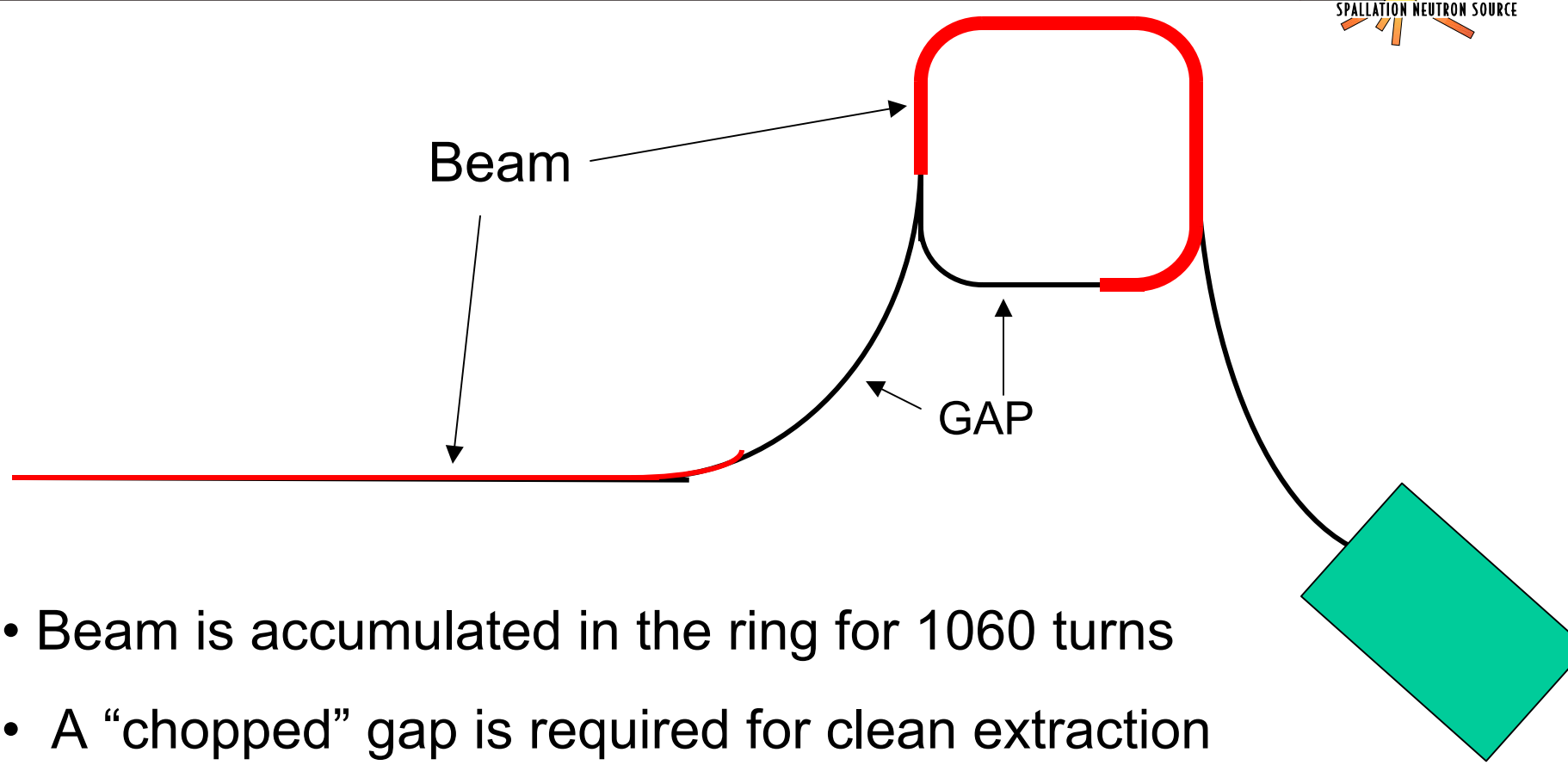
Mega Watt accelerator applications

- Spallation Neutron Sources (SNS; ESS; JJP; …)
- Accelerator Production of Tritium (APT; TRISPAL; …)
- Nuclear Transmutation (ADTW; ATW; …)
- Radioactive ion beam (Japan; GSI; US; …)
- Energy Amplifier (CERN EA; …)
- Muon-collider proton driver (BNL; FNAL; CERN; …)
- Neutrino factory proton driver (CERN / RAL; US; Japan …)

Mega Watt facility comparison

	Energy [GeV]	Current [mA]	Rep.-rate [Hz]	Ave. power [MW]	Type
SNS	1	2	60	2	LAR
ESS	1.33	1.9	50	2.5	LAR x 2
JJP	3	0.33	25	1	RCS
CERN PD	2.2	1.8	75	4	LAR
RAL PD	5	0.4	25	2	RCS x 2
FNAL PD	16	0.125	15	2	RCS x 2
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 - PD	30	0.25	15	7.5	RCS

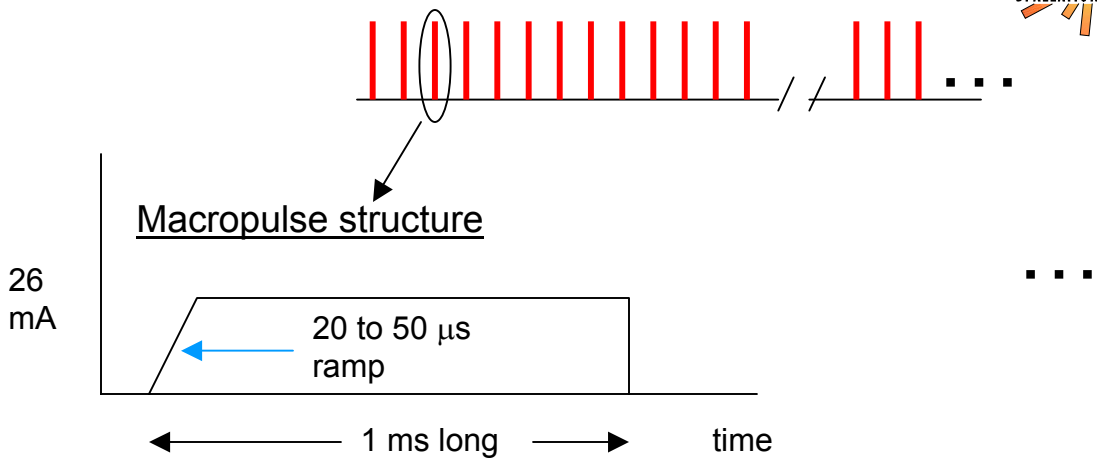
SNS Beam Accumulation

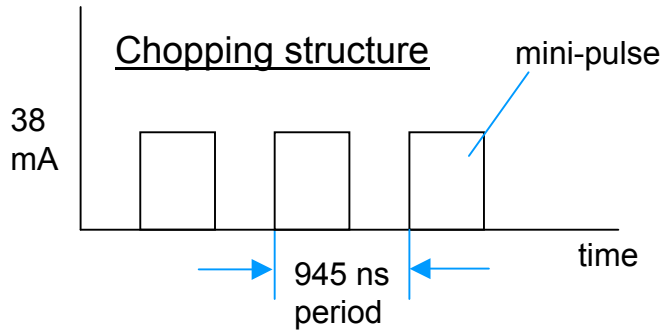


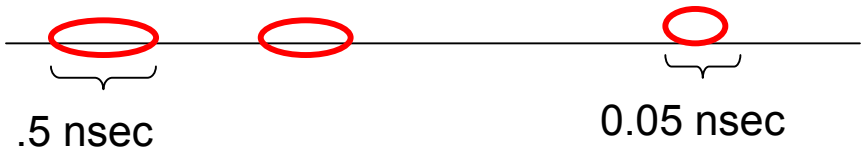
- Beam is accumulated in the ring for 1060 turns
- A “chopped” gap is required for clean extraction from the ring

SNS Beam Time Structures

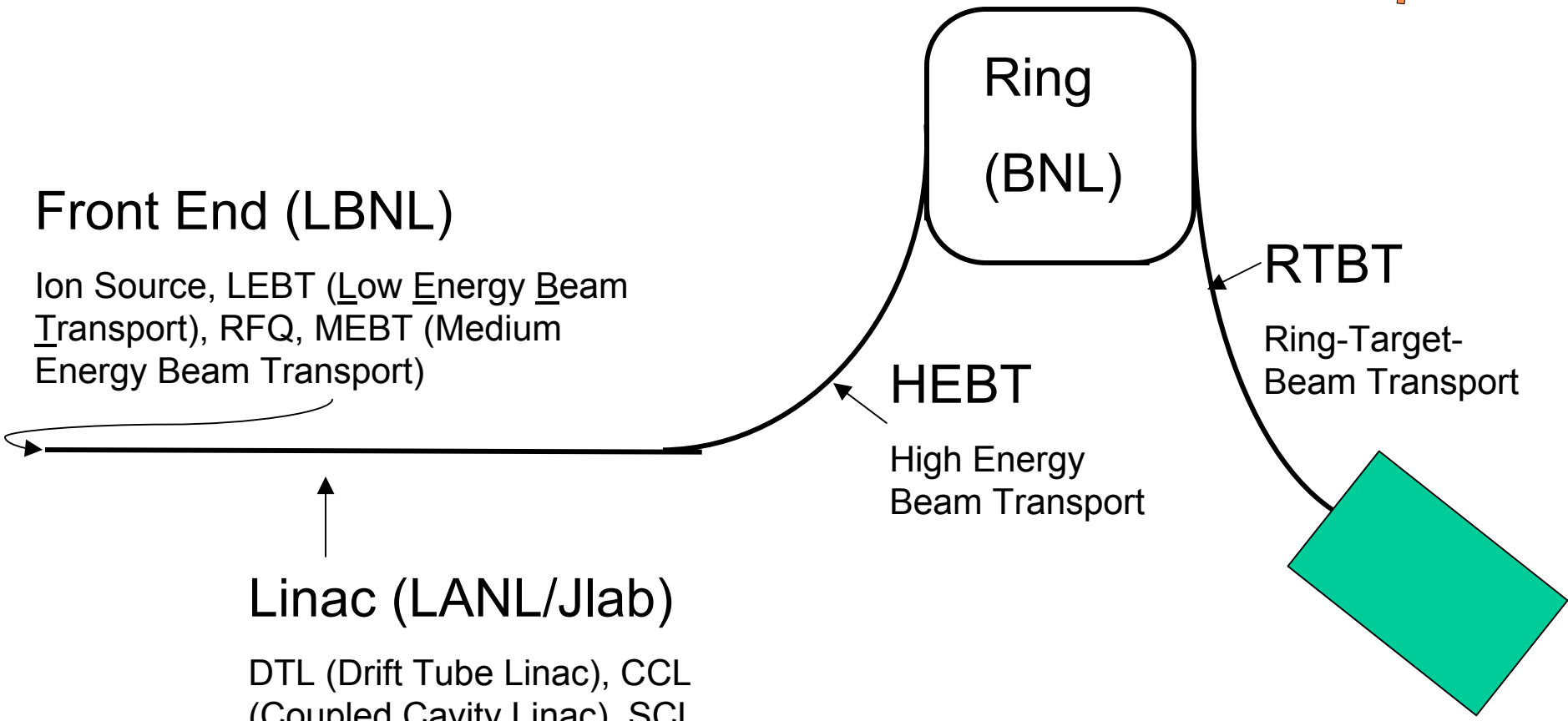
- 60 Hz macro-pulses
- Macro-pulse:
  - 1 msec
- Mini-pulse
  - 945 n sec
  - 1 turn in ring
- Micro-pulse
  - Single RF bunch
  - 402.5 MHz







SNS Accelerator Components



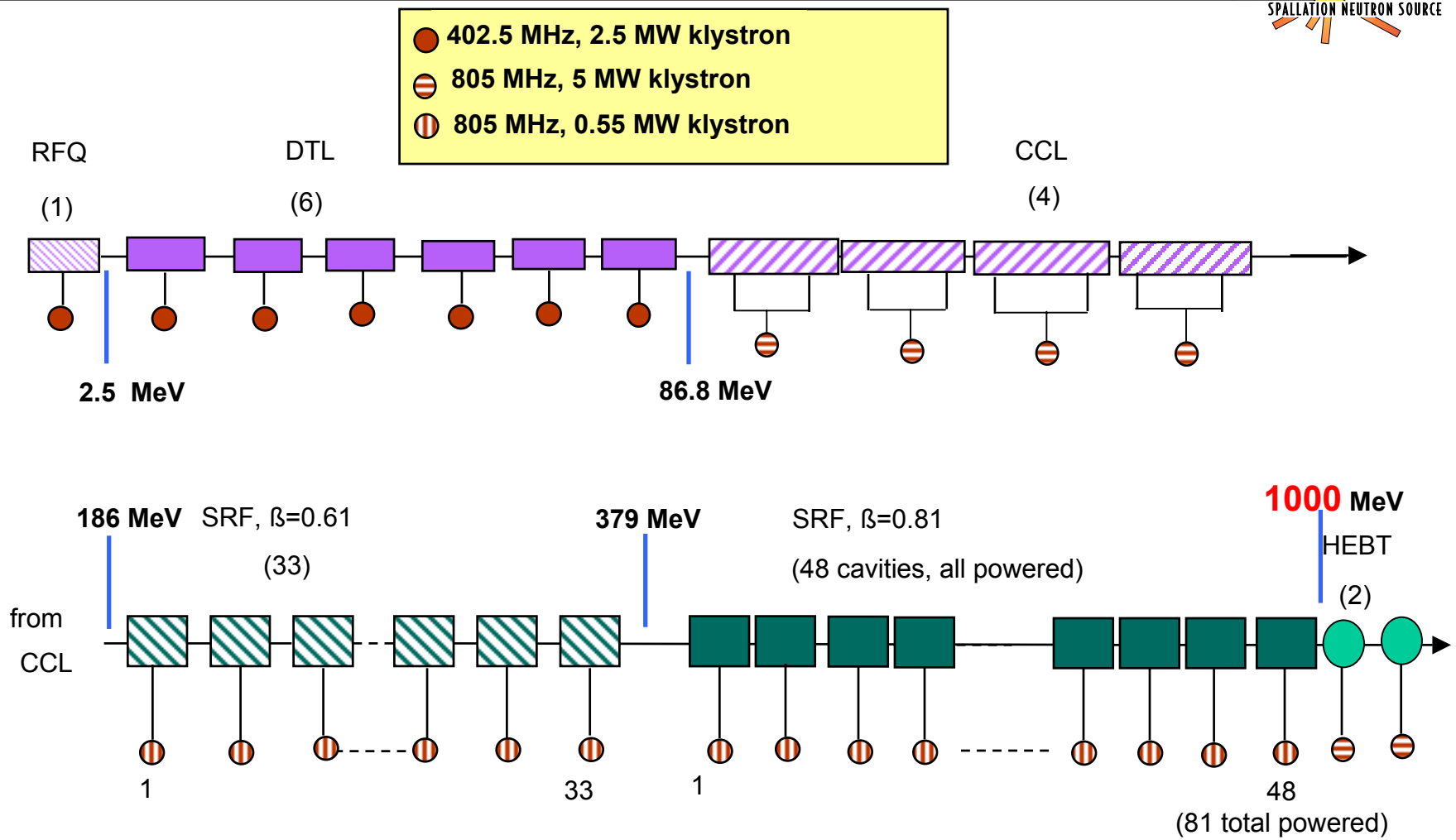
Summary Parameters for the SNS

• Proton beam power on target	1.4 MW
• Average proton beam current on target	1.4 mA
• Pulse repetition rate	60 Hz
• Peak linac H- current	38 mA
• Chopper beam-on duty factor	68 %
• Front-end and linac length	337 m
• RFQ output energy	2.5 MeV
• DTL output energy	87 MeV
• CCL output energy	185 MeV
• Transition Energy between β = 0.61 and 0.81 cavities	382 MeV
• SRF linac output beam energy	~1.0 GeV
• Number of powered SRF cavities	81
• Number of β = 0.61 cavities	33
• Number of β = 0.81 cavities	48
• Linac beam duty factor	6.0 %

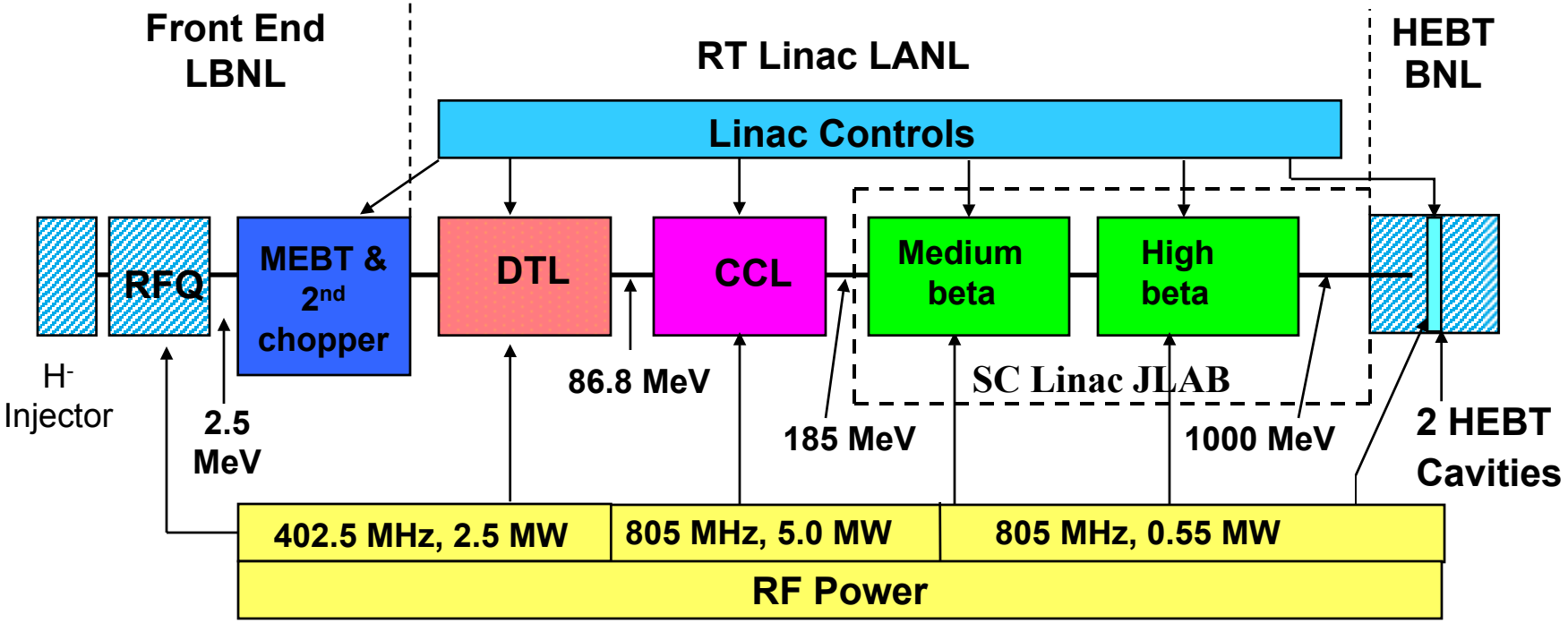
Summary Parameters for the SNS (cont'd)

• HEBT length	172 m
• Accumulator ring circumference	248.0 m
• Ring orbit rotation time	945 ns
• Number of injected turns	1060
• Ring fill time	1.0 ms
• Ring beam extraction gap	250 ns
• RTBT length	151 m
• Protons per pulse on target	1.5E+14
• Proton pulse width on target	695 ns

Layout of Linac RF with NC and SRF Modules



Linac Configuration

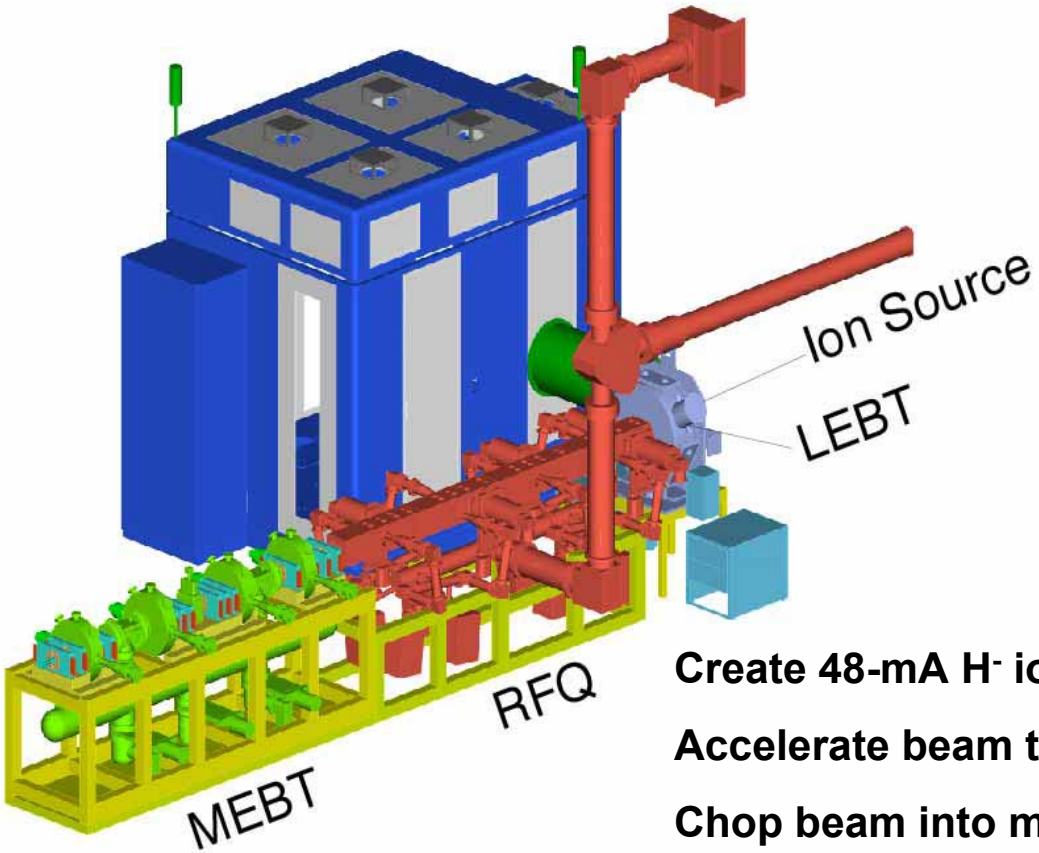


Linac Architecture Summary

Structure	W_{final}	Total Length	Cells per Cavity	Cavities per Module	Modules	No of Klystrons	Structure Length
	MeV	m					m
DTL	86.8	36.6	60 to 21		6	6	36.6
CCL	185.6	91.9	8	12	4	4	55.4
SRF I	379.2	157.7	6	3	11	33	64.2
SRF II	1000	276.0	6	4	12	48	94.7
SRF upgrade	~1300	323.4	6	4	9	36	71

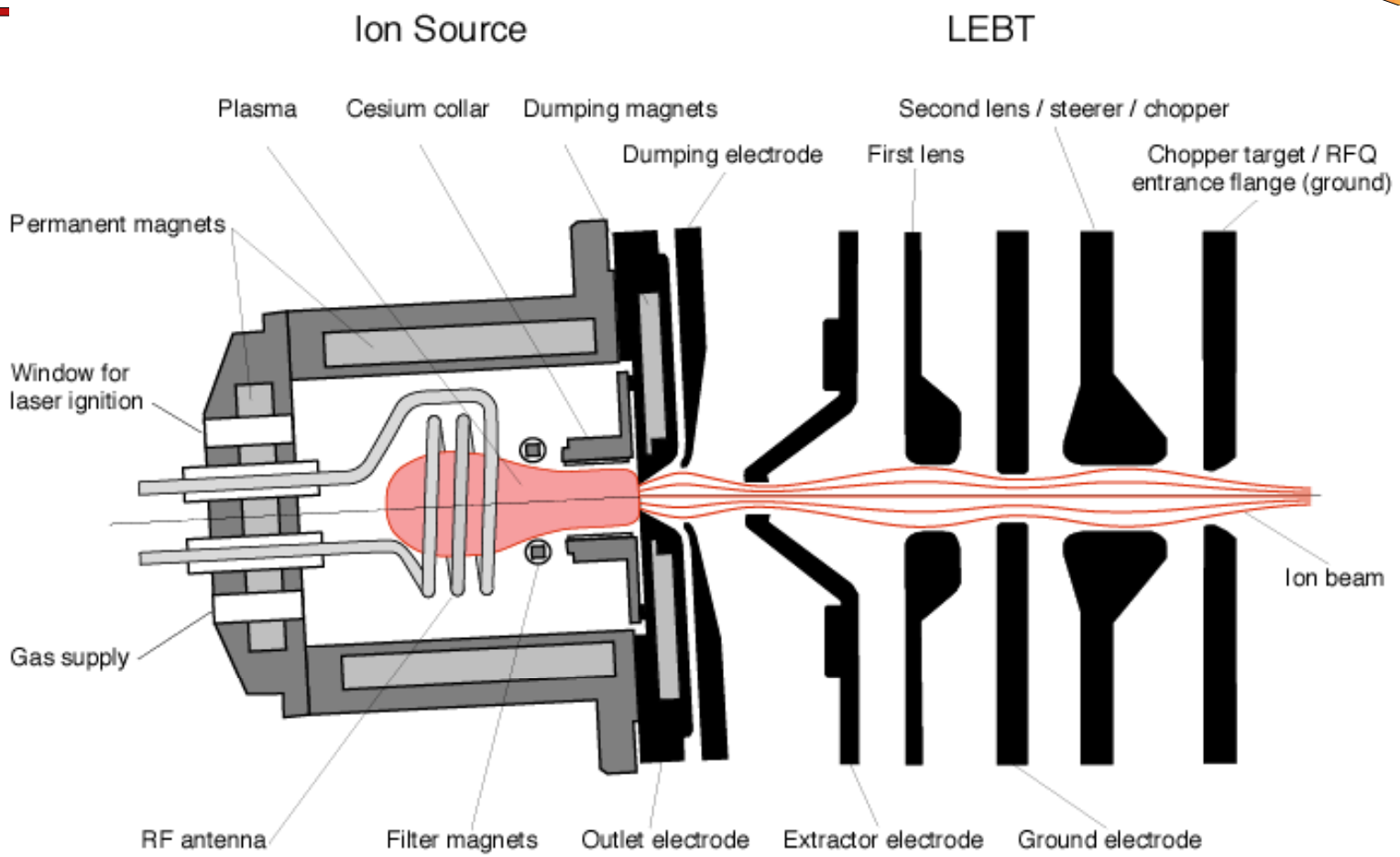
Structure	HVPS	HVPS Power	Transmitters	Klystrons	Klystron Power
		MW			MW
RFQ & DTL	3	10	7	7	2.5
CCL & HEBT	5	10	6	6	5.0
SRF I & II	8	10	13	81	0.55
SRF upgrade	3	10	7	36	0.60

Front End System Function



Create 48-mA H^- ion beam	Ion Source/LEBT
Accelerate beam to 2.5 MeV	RFQ
Chop beam into mini-pulses	LEBT/MEBT
Match 38-mA beam into DTL	MEBT

Ion Source and LEBT Schematic

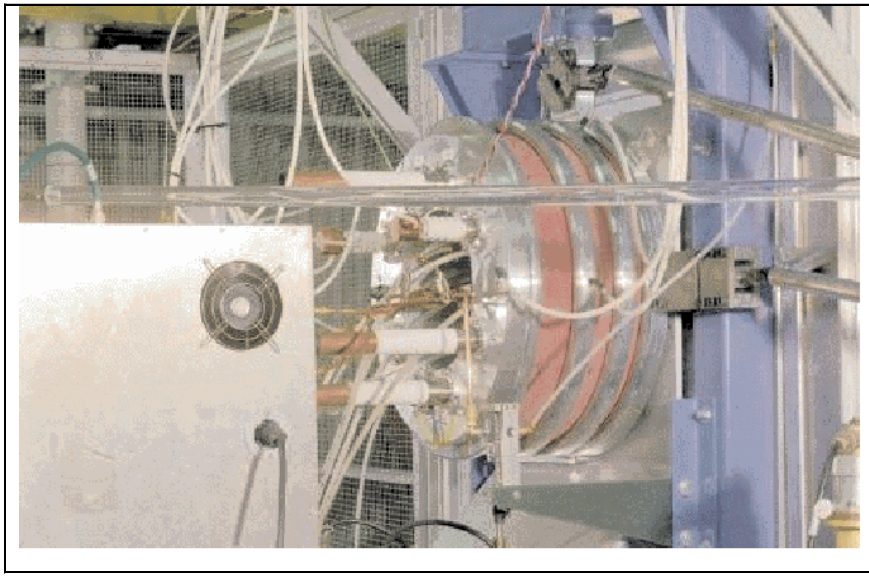


Some magnet orientations are rotated into the viewing plane of this illustration

Front-End Requirements

Ion species	H^-
Energy (MeV)	**2.5**
Front End peak H^- output current (mA)	**38**
Ion source output current (mA, estimated)	48
Normalized rms output phase space	
LEBT ε transverse (π mm mrad)	0.20
MEBT ε transverse (π mm mrad)	**0.27**
Duty factor	**6%**
Repetition rate (Hz)	**60**
Chopper system rise time (ns)	**10**
Chopped beam off/on current ratio	**10^{-4}**

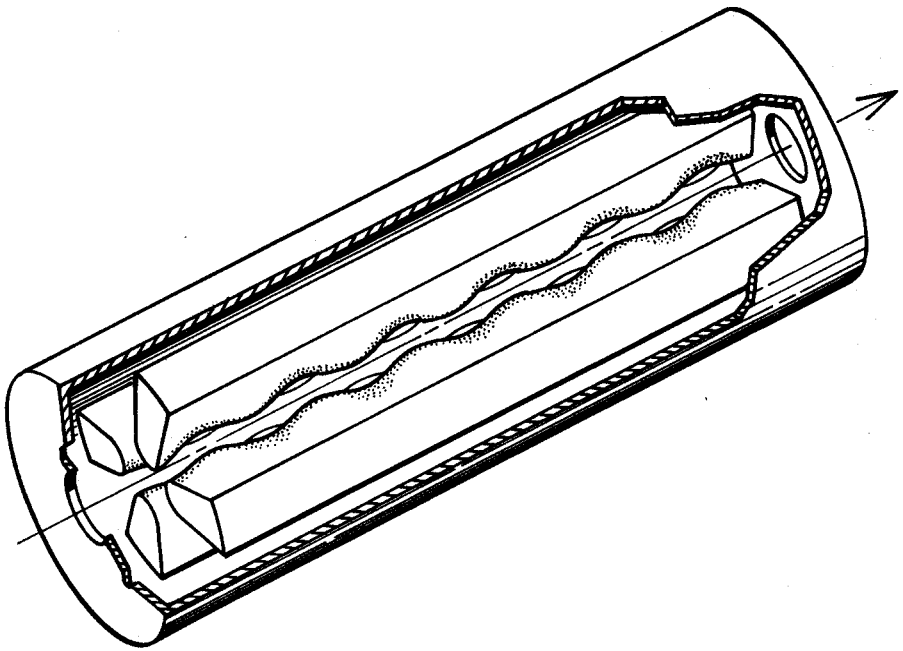
Ion Source Test Stand and LEBT



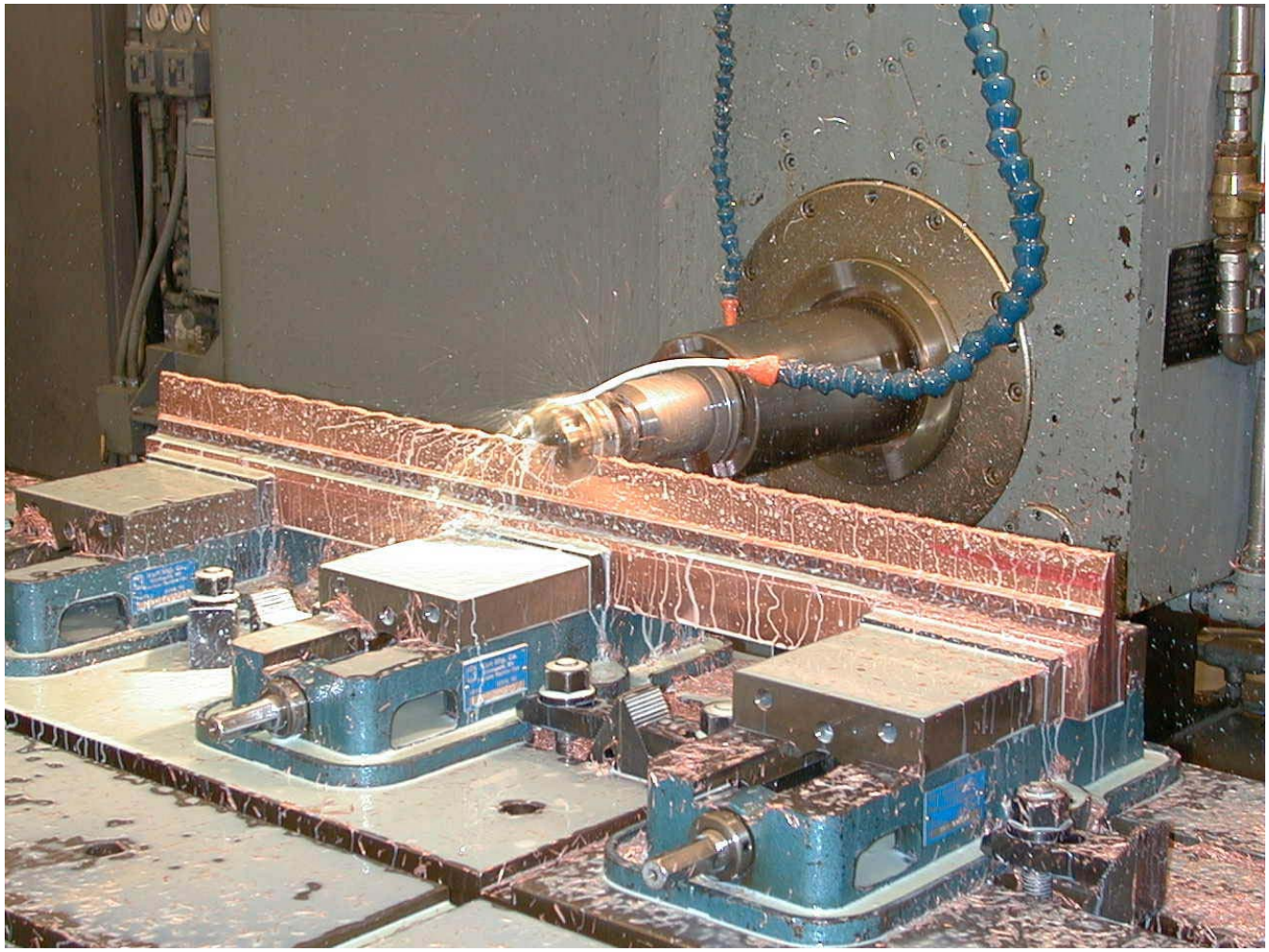
Radio Frequency Quadrupole

- RFQ structure has 4 vanes with undulations within a tank

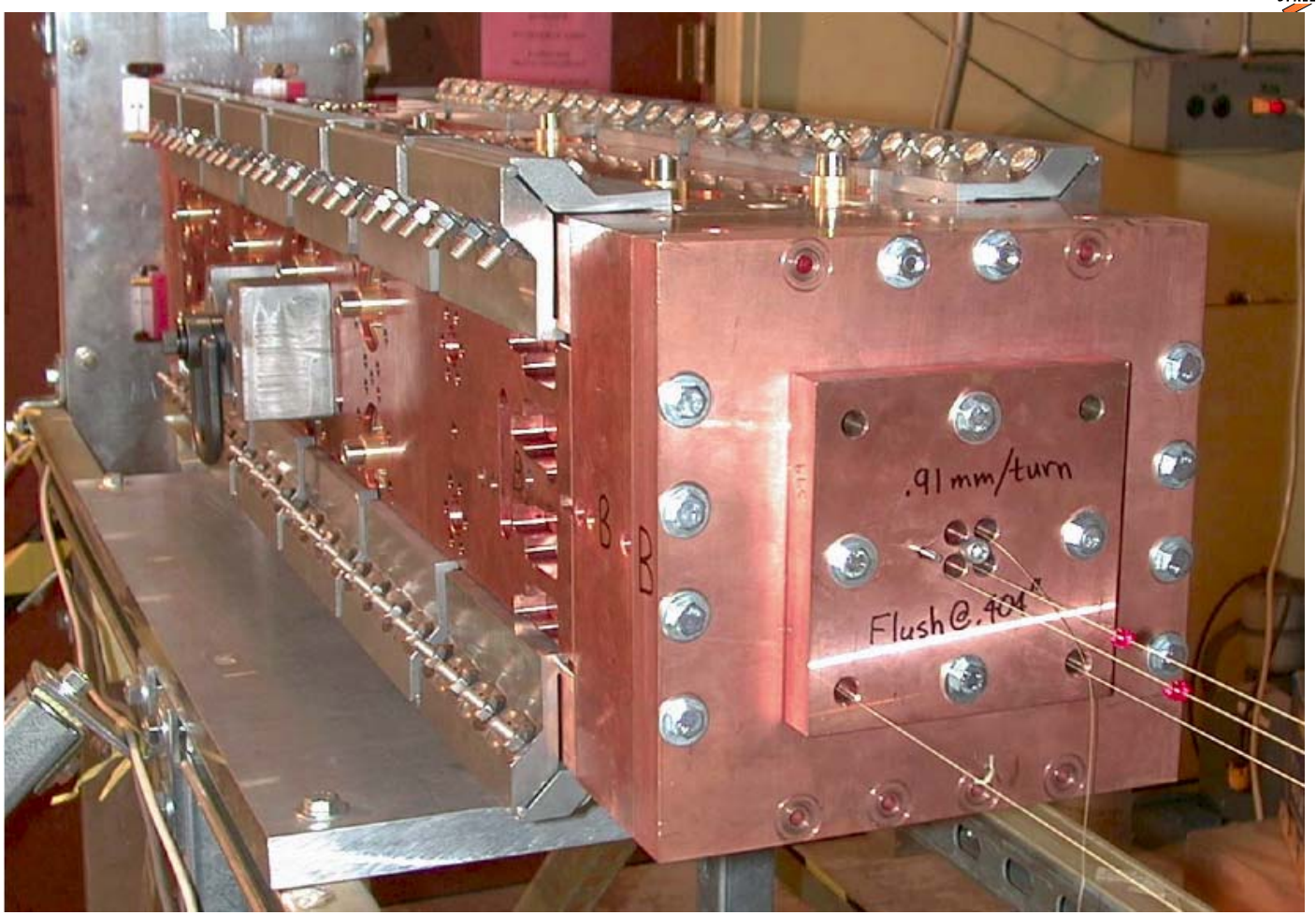
- RFQ field provides
  - Acceleration (to 2.5 MeV)
  - Initial bunching of the beam
  - Transverse focusing



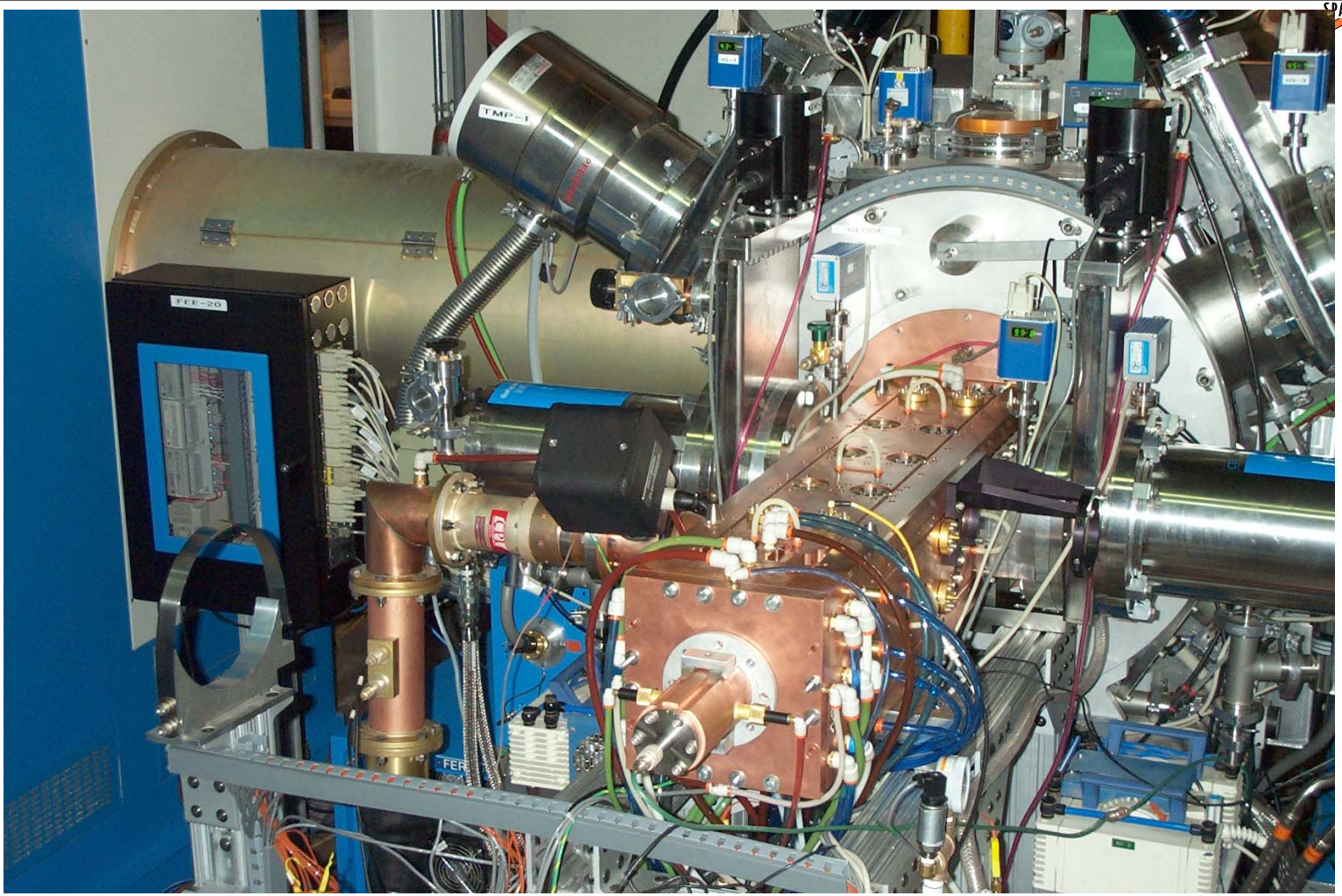
RFQ Module #4
Vane Test-Machining at LBNL



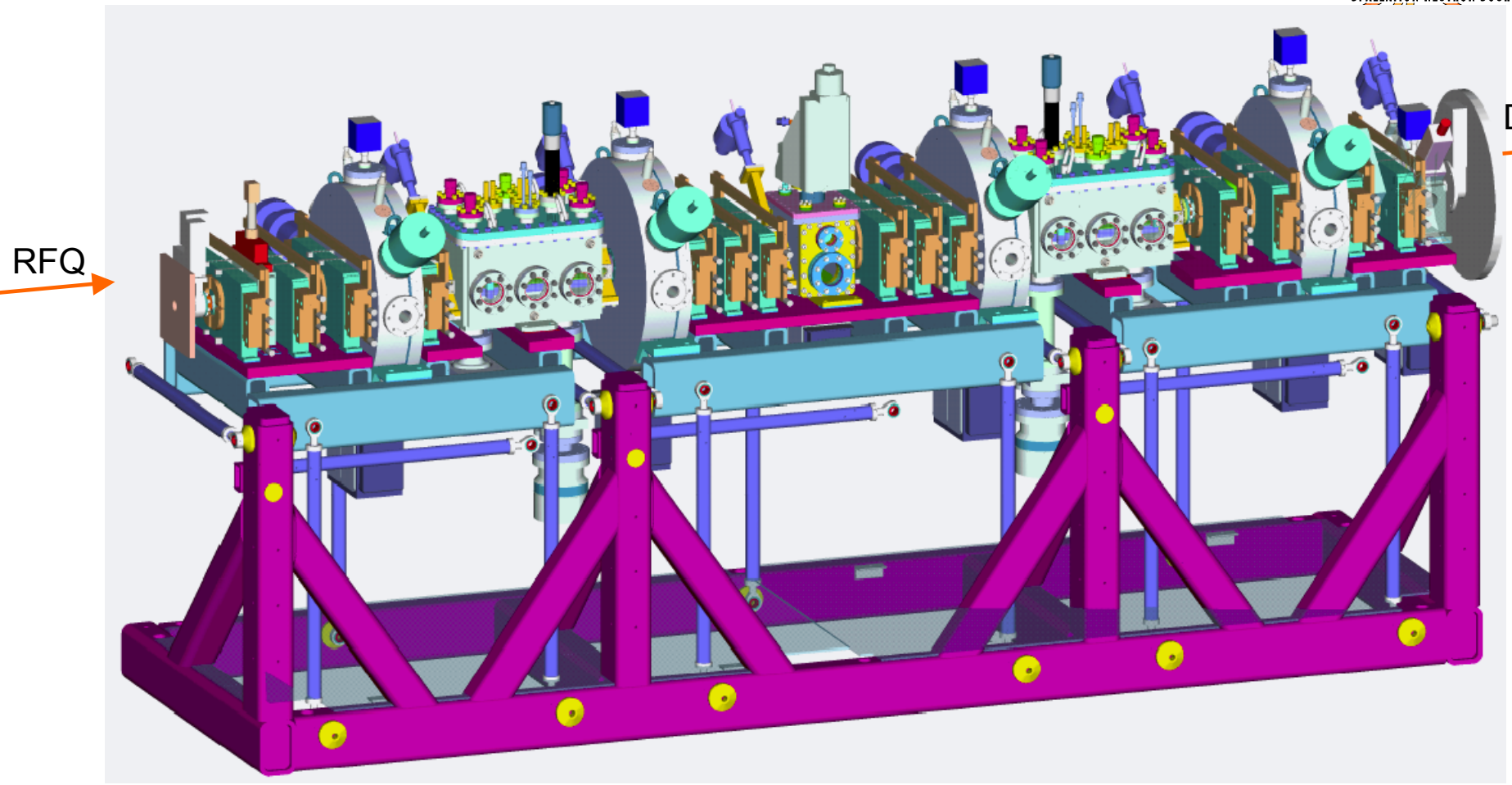
RFQ Module #2
Bead-Pull Frequency Measurement



RFQ connected to LEBT on 4/19/01

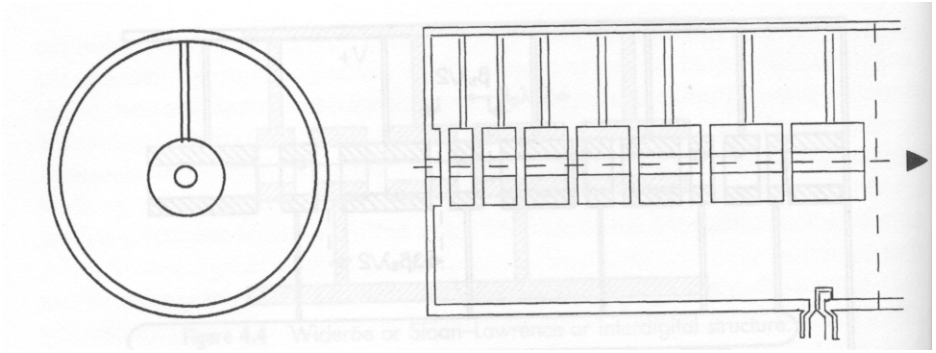


MEBT Layout



Drift Tube Linac

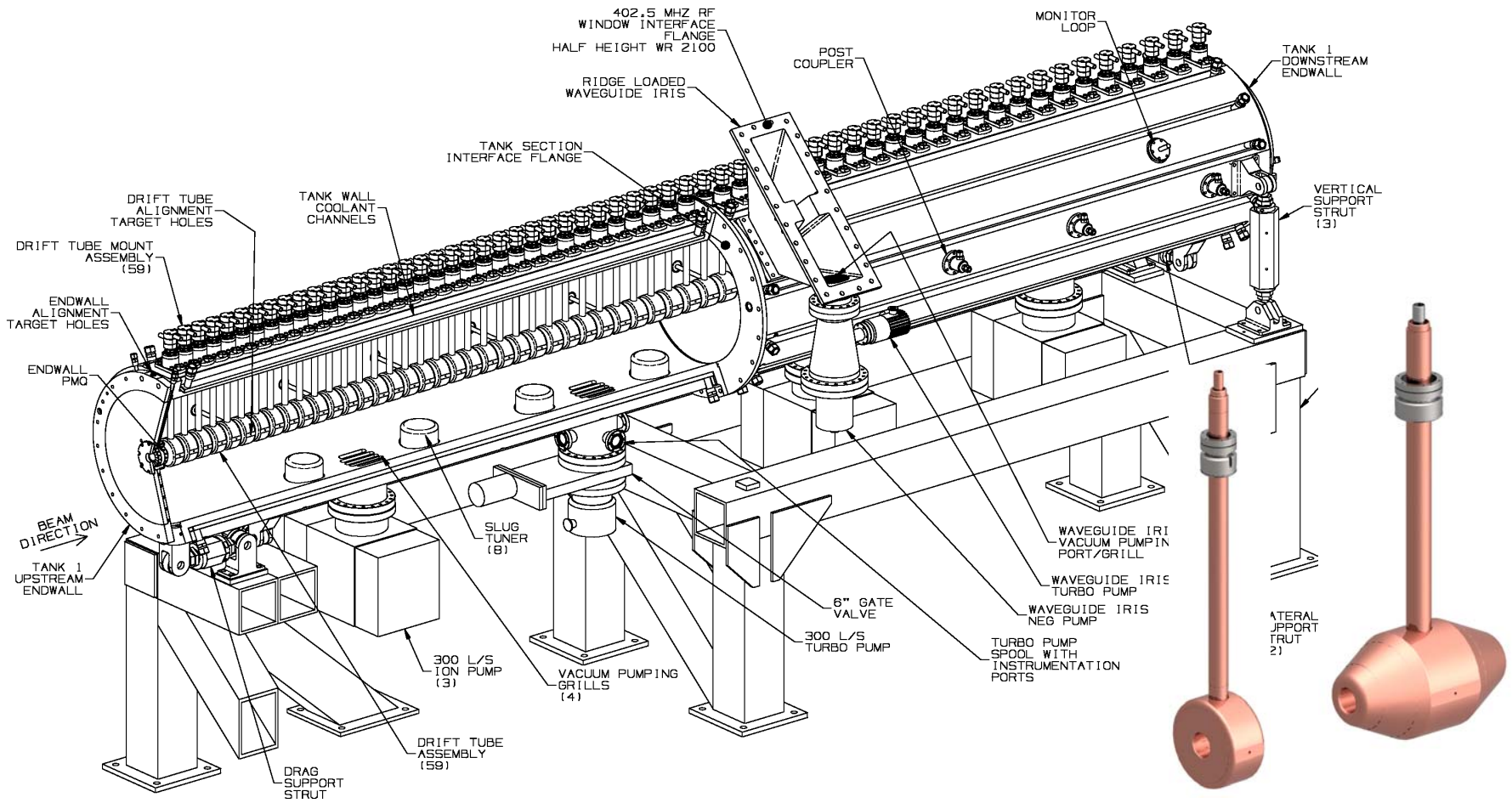
- Drift tubes shield beam from de-accelerating RF field
- Drift tubes hold quadrupoles which provide transverse focusing
- Efficient structure for $0.05 < \beta < 0.4$
  - ~ 40 MΩ/m shunt impedance
  - ~3MV/m accelerating gradient
- Each drift tube is unique (210 drift tubes)
- Bore radius 1.25 cm



End View

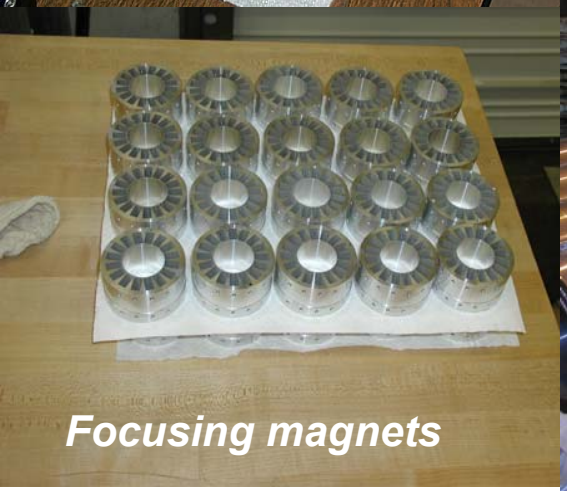
Side View

DTL Tank 1 Assembly Cutaway View

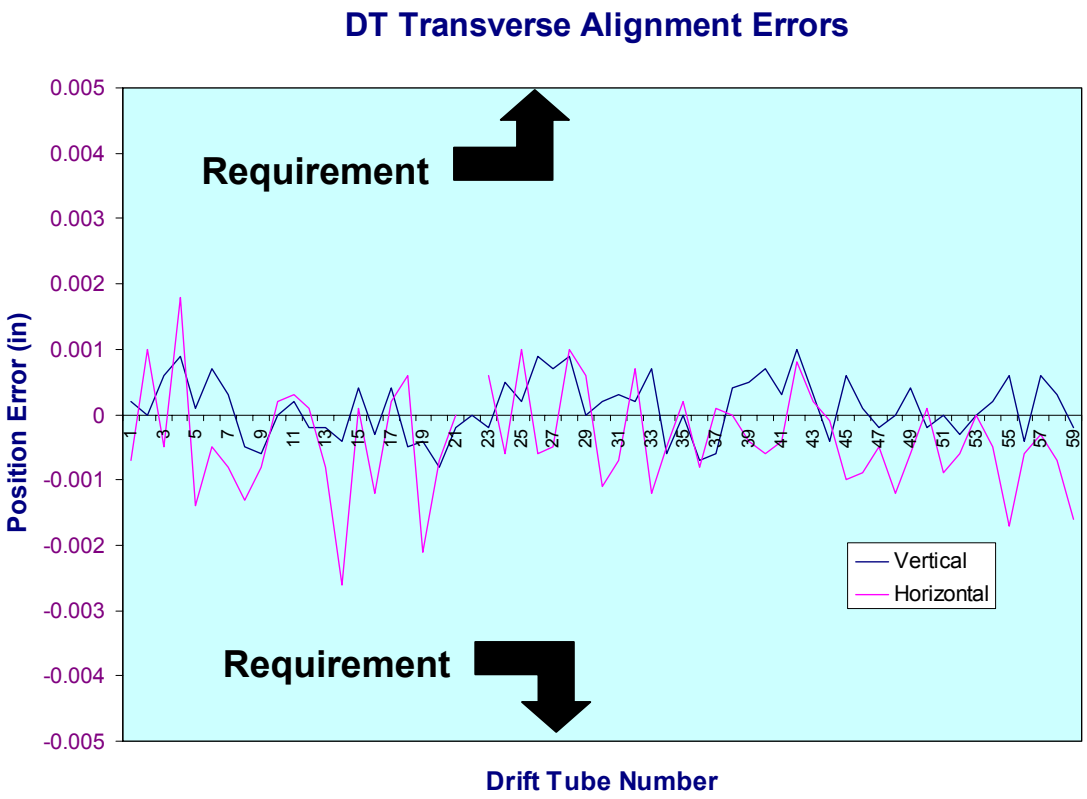


"Finish the DTL design ... and undertake procurement to lock-in pricing."

Drift Tube Linac design is complete and fabrication is underway



Cold Model Alignment Procedure Test Results Prove Positive



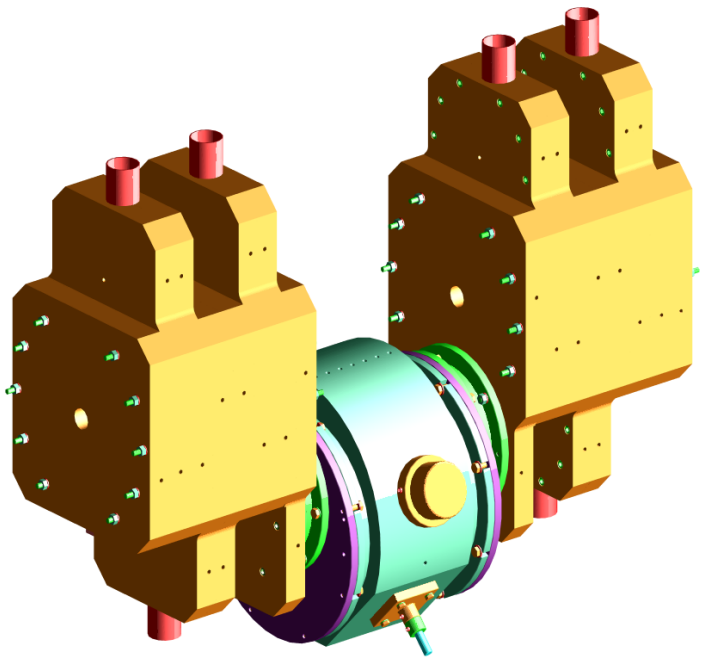
Cold Model drift tubes aligned with the Leica Laser Tracker verify the general alignment procedure as able to meet the +/- 0.005 inch (5 mil) maximum transverse error criteria. The less critical longitudinal errors also ok.

Coupled cavity linac

- From 86 to 185 MeV
- 384 cavities
- Bridge couplers provide room for EM quads (49)

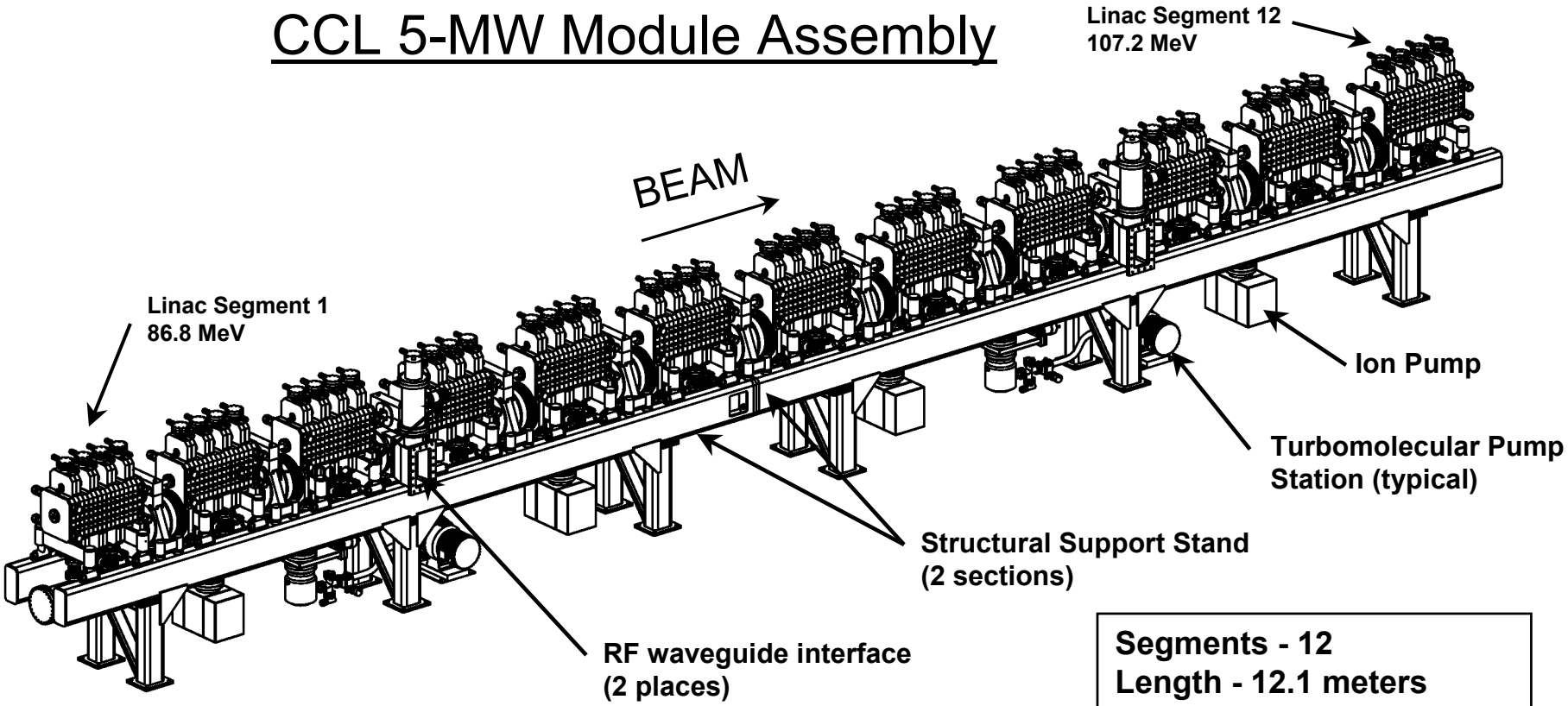
- Efficient structure for $0.4 < \beta < 1$
  - 20-30 MΩ/m shunt impedance
  - ~ 2 MV/m accelerating gradients

- Bore radius 1.5 cm



Module 1 Assembly Layout

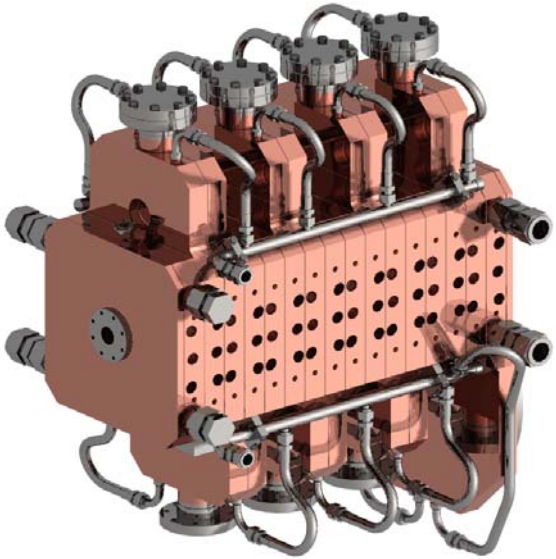
CCL 5-MW Module Assembly

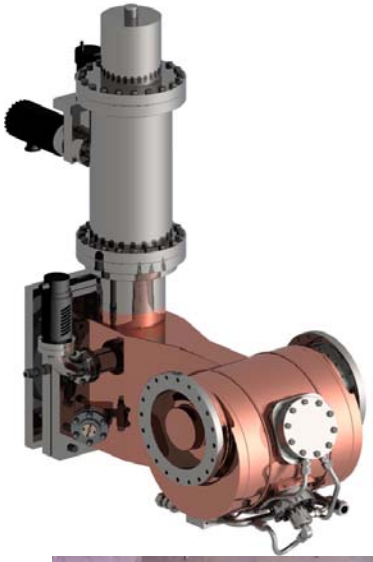


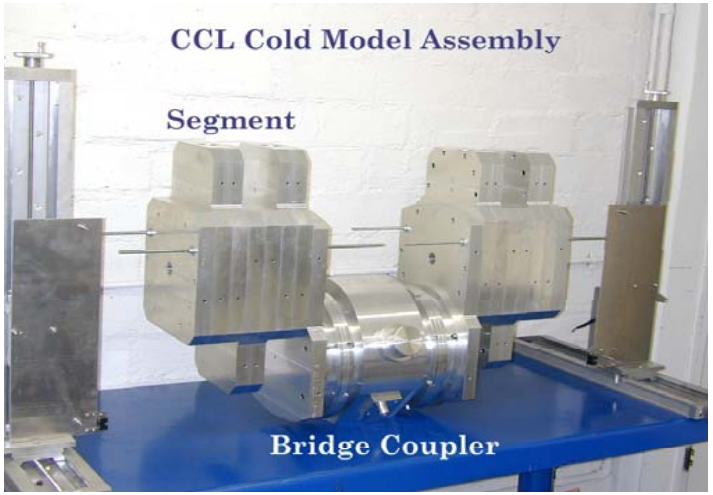
Segments - 12
Length - 12.1 meters
Number of cells - 96
Intersegment gaps - 2.5Bλ

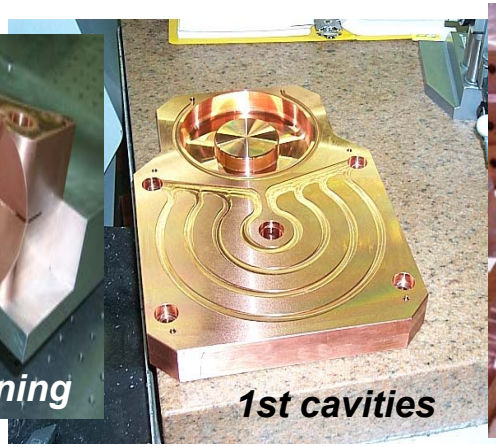
"Perform the hot model test of the CCL, finish CCL design, and undertake procurement to lock-in pricing."

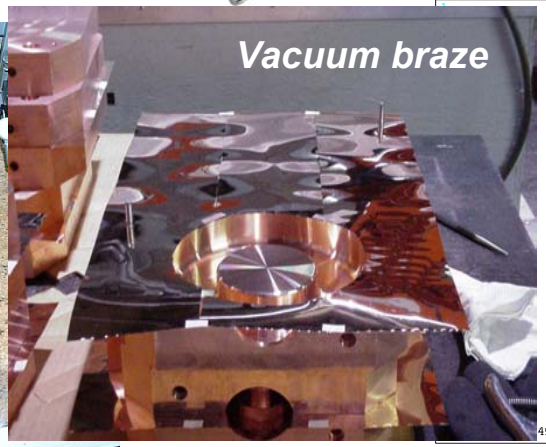
Coupled-Cavity Linac preliminary design is complete with prototyping well underway

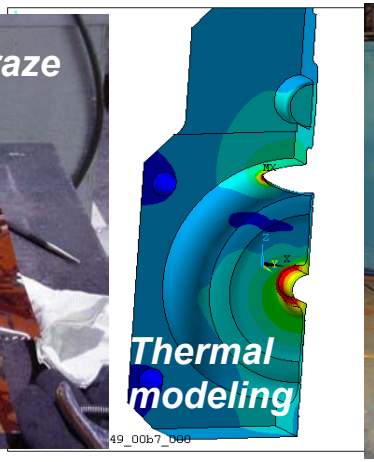


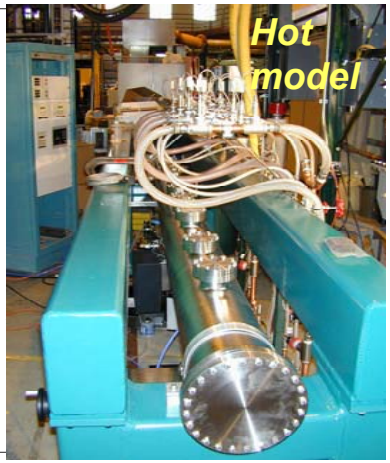












Superconducting Linac

- Superconducting cavities are Nb cells at 2K
  - High gradients (10-15 MV/m)
  - No RF losses in cavity walls
- SNS uses two cavity types
  - Cost/schedule constraints
  - 33 β = 0.61 cavities (Medium beta)
  - 48 β = 0.81 cavities (High beta)
- Each cavity
  - Has 6 cells
  - Has its own RF power source
  - Bore radius = 4.3 cm
- SRF accelerates from 186 MeV to 1000 MeV

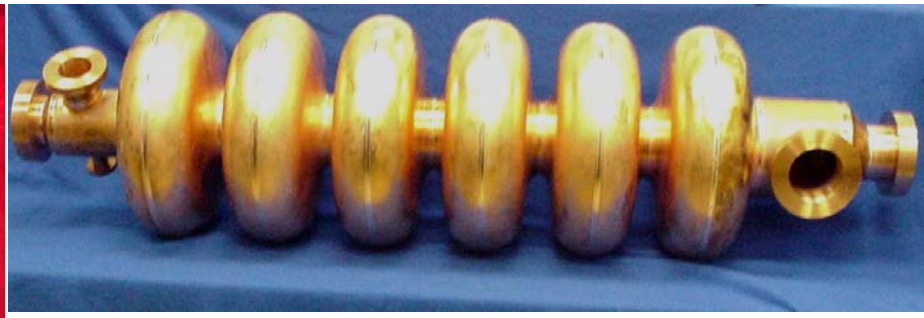
0.682 m

First Nb High Beta Cavity With Stiffening Rings

Cavities

Beta = 0.61

Beta = 0.81

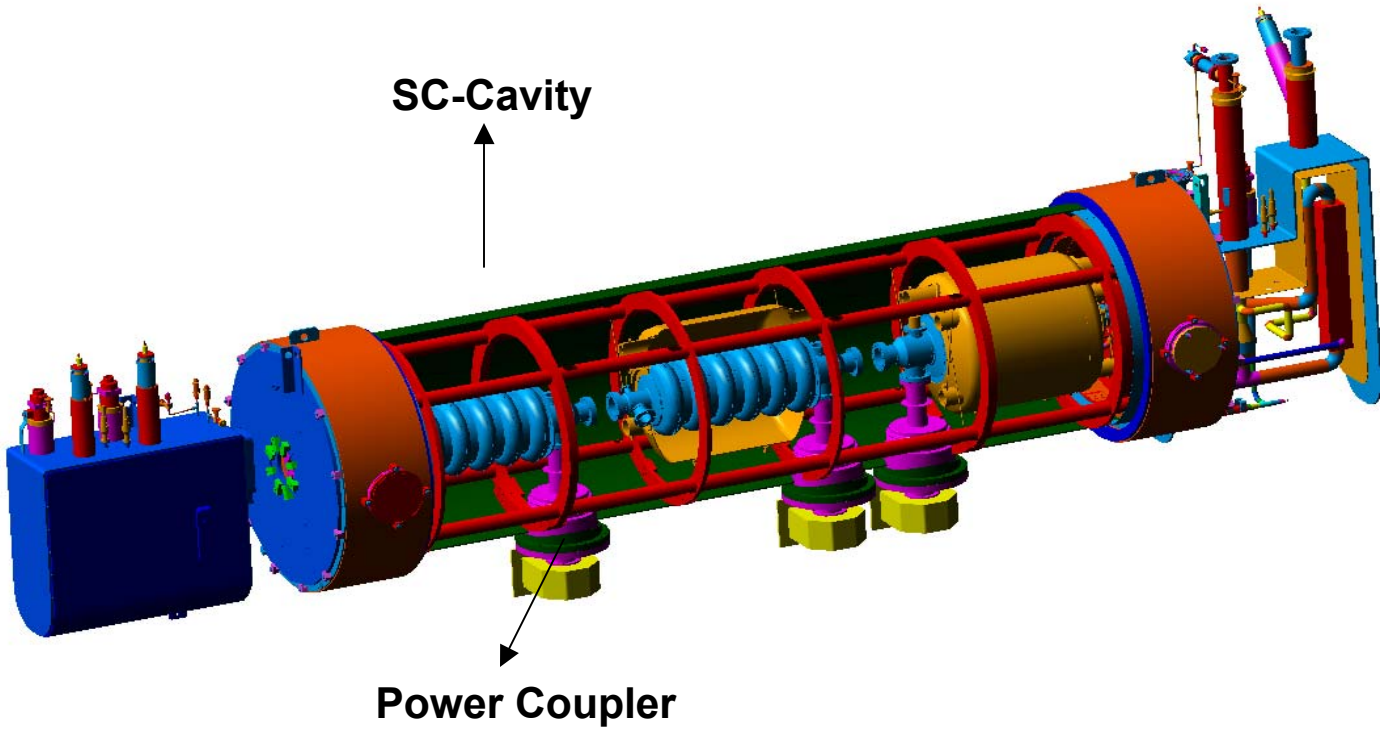


Superconducting Linac Design

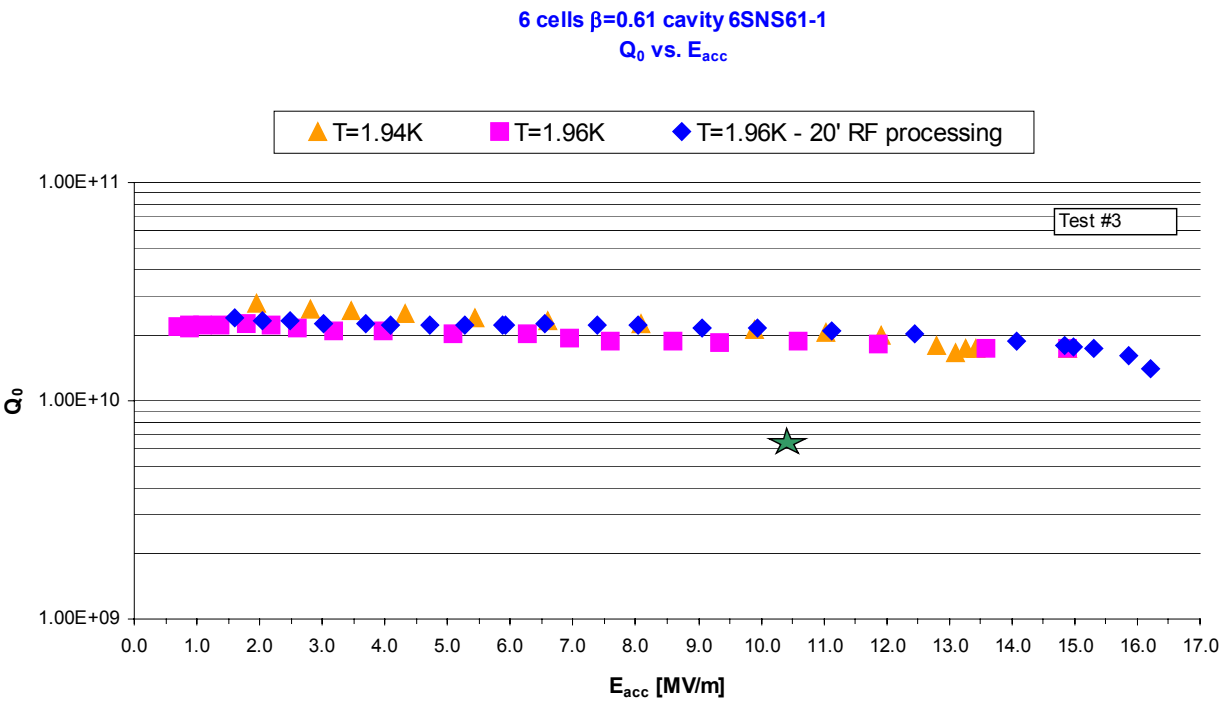
- Cavities are housed in a cryomodule
  - 3 cavities/cryomodule (β = 0.61), 4.239 m long
  - 4 cavities/cryomodule (β = 0.81), 6.291 m long

- A warm section is between each cryomodule
  - 1.6 m long
  - 2 quadrupoles for transverse focusing
  - Diagnostics (beam position monitor, wire scanner)
  - Bore radius 3.65 cm

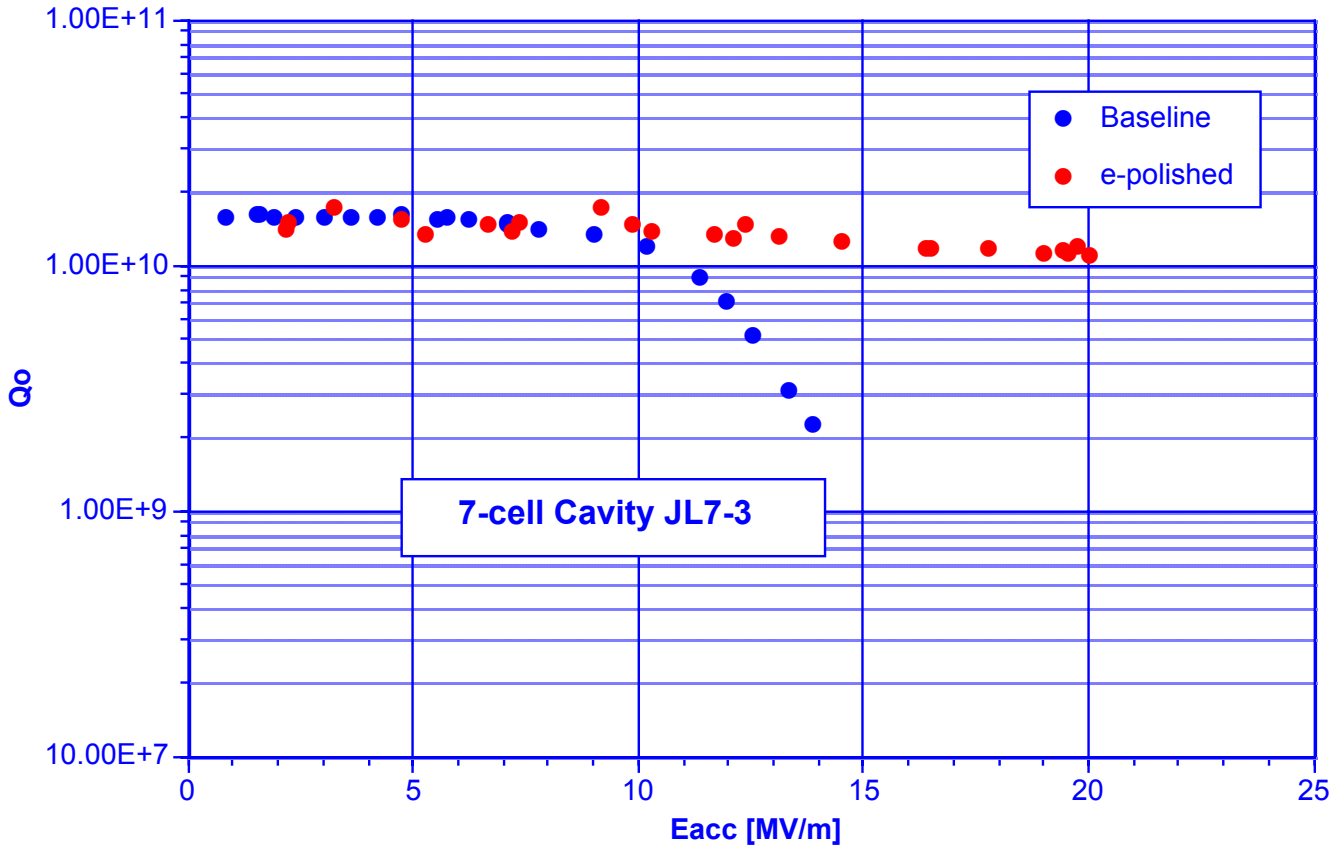
SNS Medium Beta Cryomodule Cutaway



Experimental Results, $\beta = 0.61$

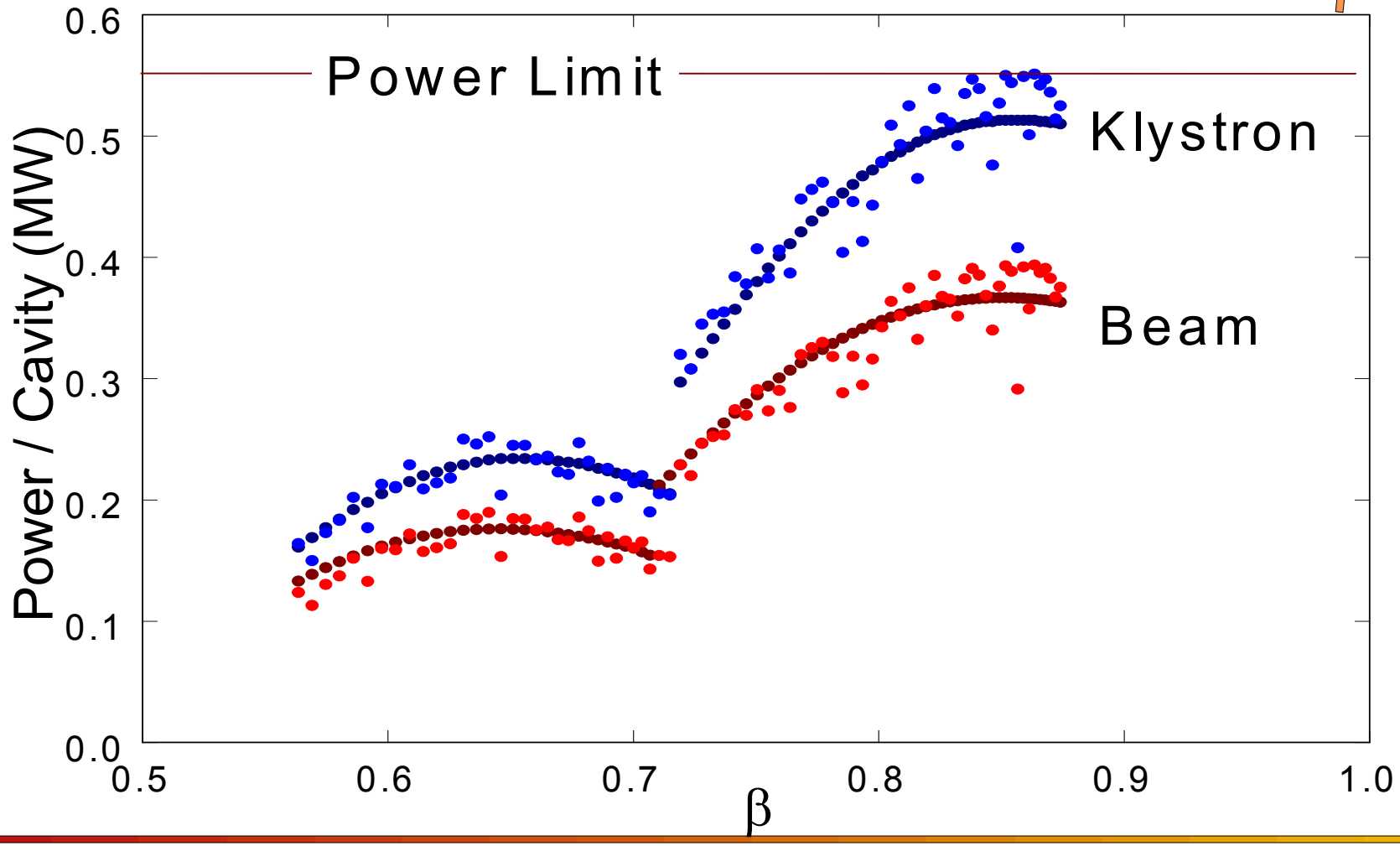


Electropolishing of 7 - Cell Cavity



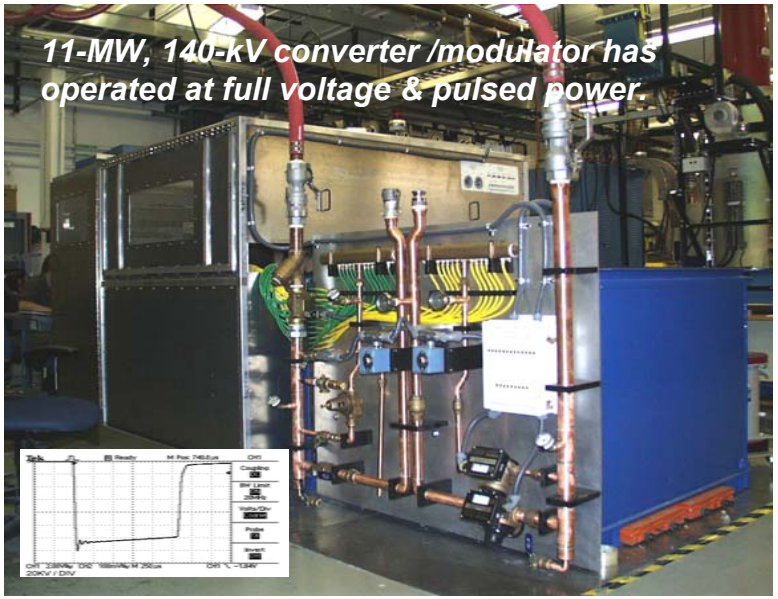
- High beta cavities will be electropolished
- Higher gradients => fewer cavities

Acceleration is Limited by Cavity Quality, Beam Current is Limited by Klystron Power



Linac RF System is defined with purchases, designs, & tests proceeding well

First 402.5-MHz klystron for the SNS DTL.
All SNS klystrons are now under contract.



11-MW, 140-kV converter /modulator has operated at full voltage & pulsed power.

600 kW Water Load for SRF Circulator

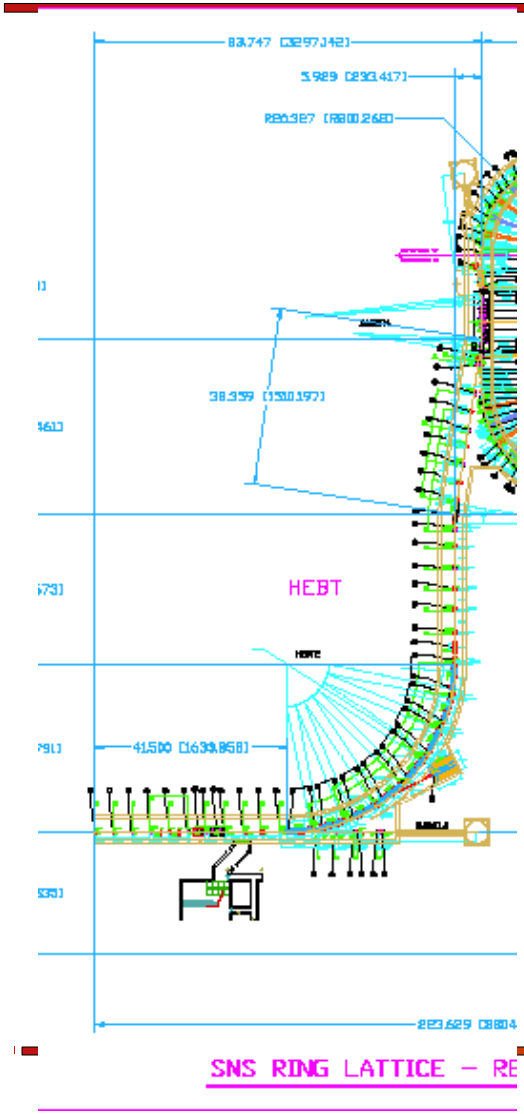
Ring Performance Specifications

	Requirements
• Injection energy	~1 GeV (H^-)
• Beam average power	1.4 MW
• Repetition rate	60 Hz
• Pulse length	~ 700 nsec
• Intensity	1.5×10^{14} pp
• Uncontrolled loss	~ 10^{-4}
– existing record PSR	~ 3x 10^{-3}
• Availability	$\geq$ 98%

Scope of Ring System

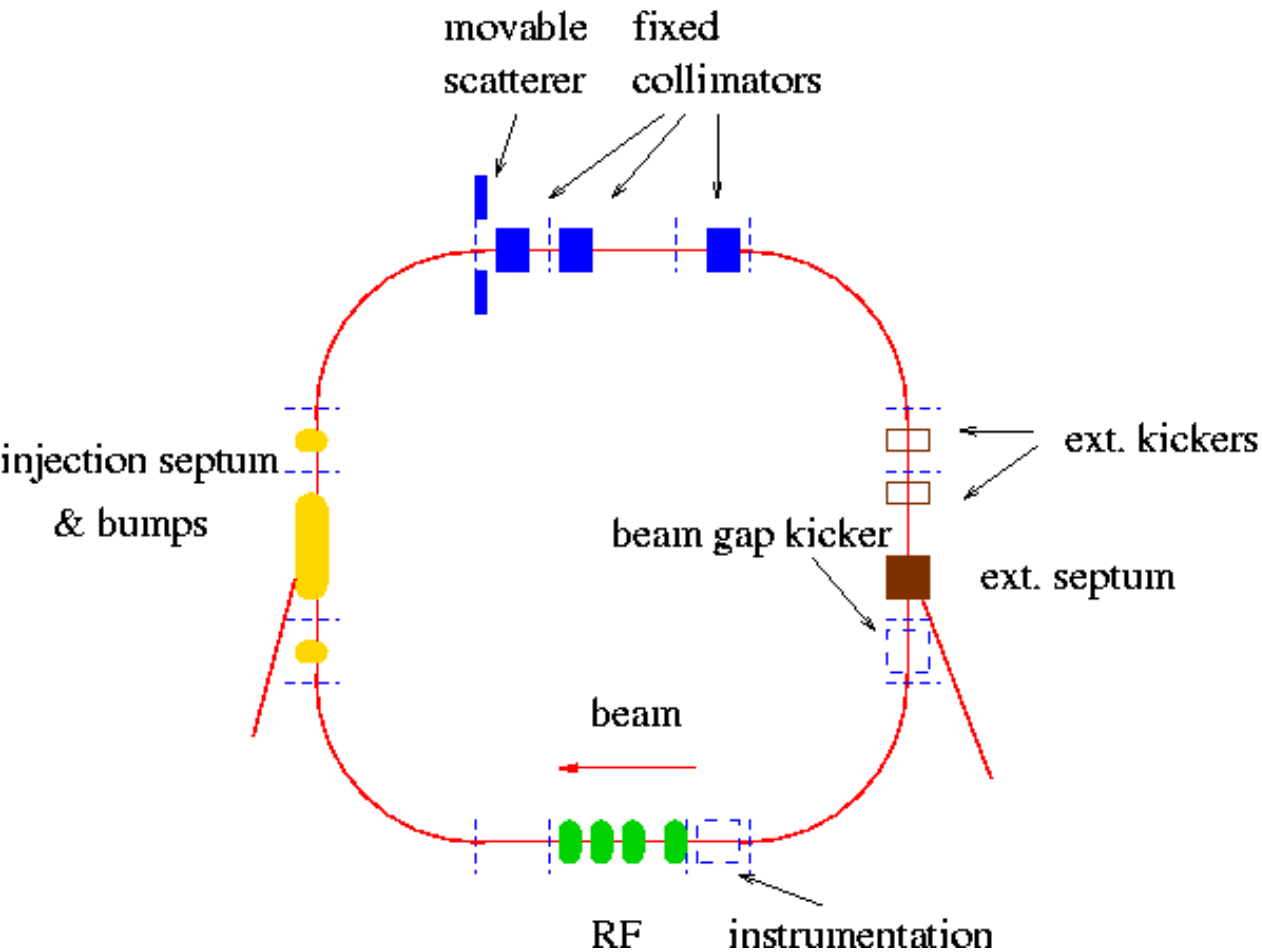
System	HEBT	AR	RTBT
• Length (m + beam dump)	170(41)	248(29)	153 (36)
• Vacuum Ion Pumps	18	44	12
• Dipole/Quad	9/40	39/53	2/32
• Correctors	18	70	17
• Power Supplies	56	158	43
• Kickers (extraction/injection)		(14/8)	
• Position Monitors	18	40	16
• Profile Monitors	14	3	10
• Collimators (scrapers/absorbers)	5/3	4/3	0/2
• RF Stations	2	4	

HEBT TRANSFER LINE



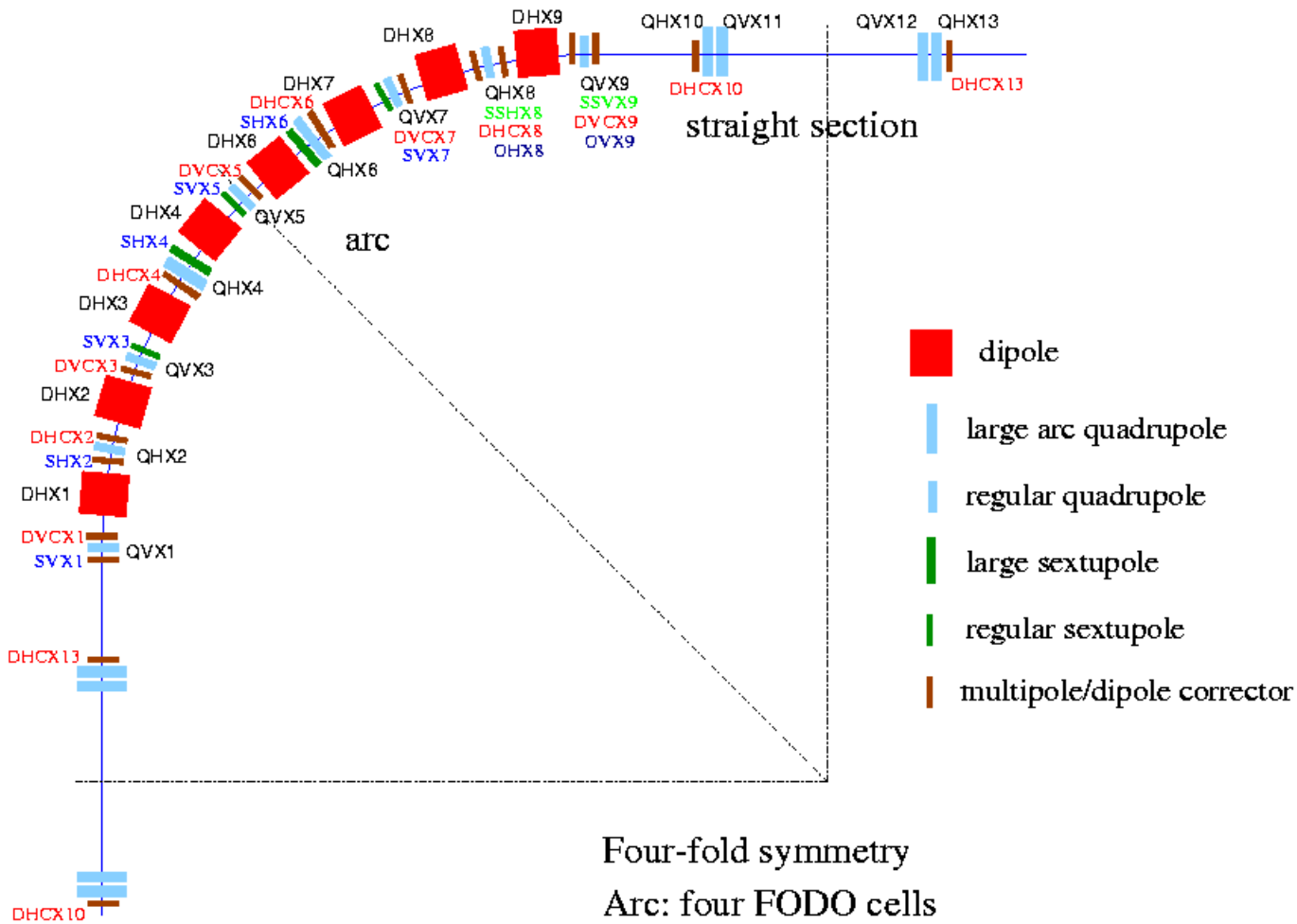
- Collimation in transverse and longitudinal directions
- Energy correction and spreading RF cavities

SNS ring layout



- Separate functions in each straight
- Four straights: 12.5 m; 2 x 6.85 m
- Injection modules
- Two-stage collimation
- 3 (h=1)+1 (h=2) interchangeable RF cavities
- Beam-in-gap kicker
- Empty section for future use

SNS ring magnet layout

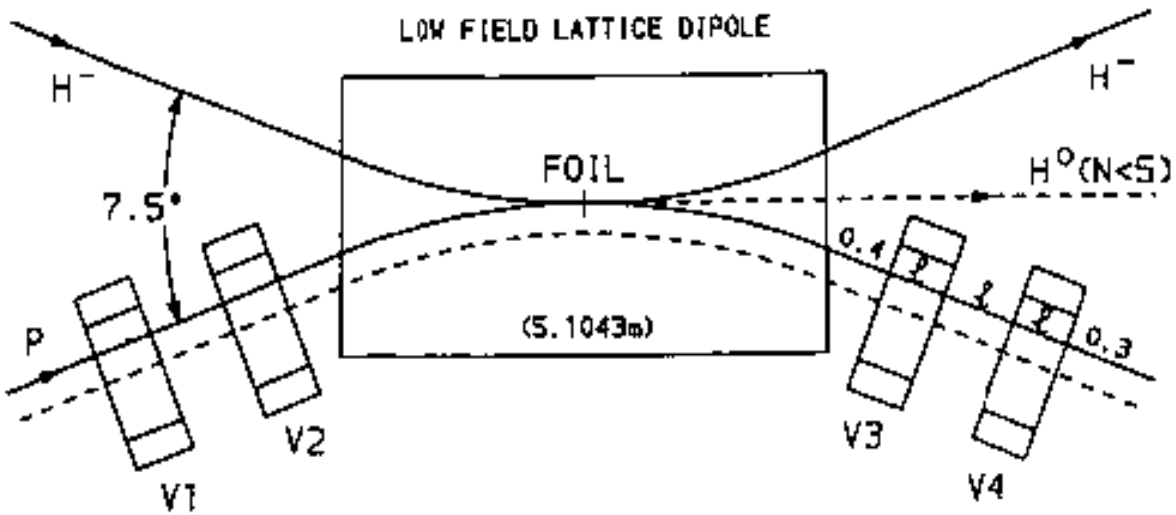


Four-fold symmetry

Arc: four FODO cells

S.S.: doublets

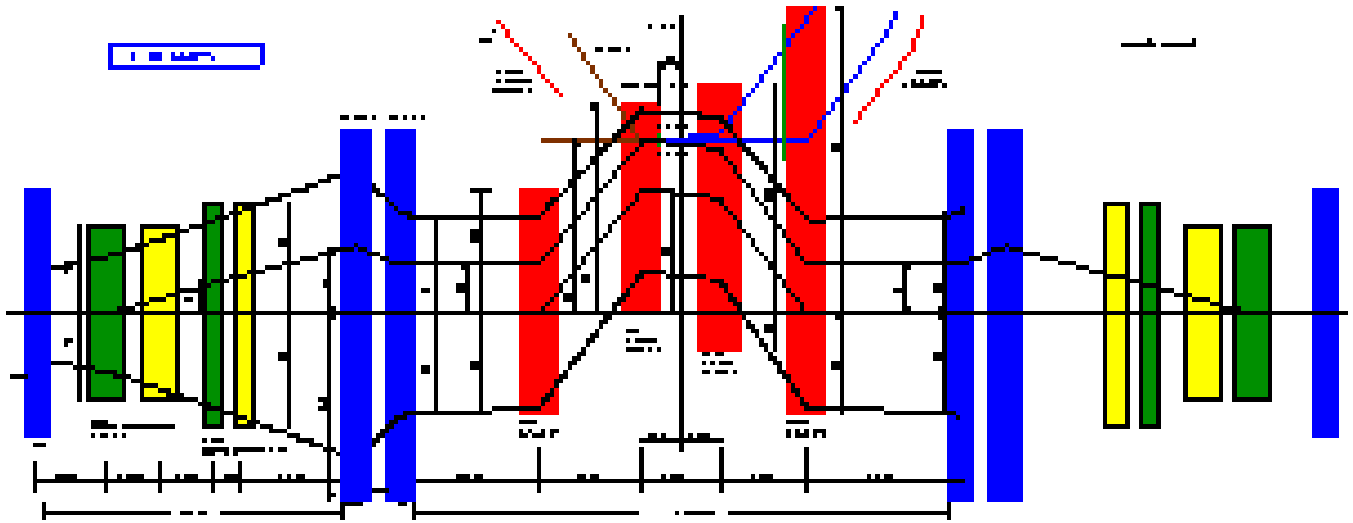
H- injection schematic



- Foil strips the electrons from H- to form H+
- Allows multi-turn injection with minimal beam size blowup

courtesy G. Rees, C. Prior

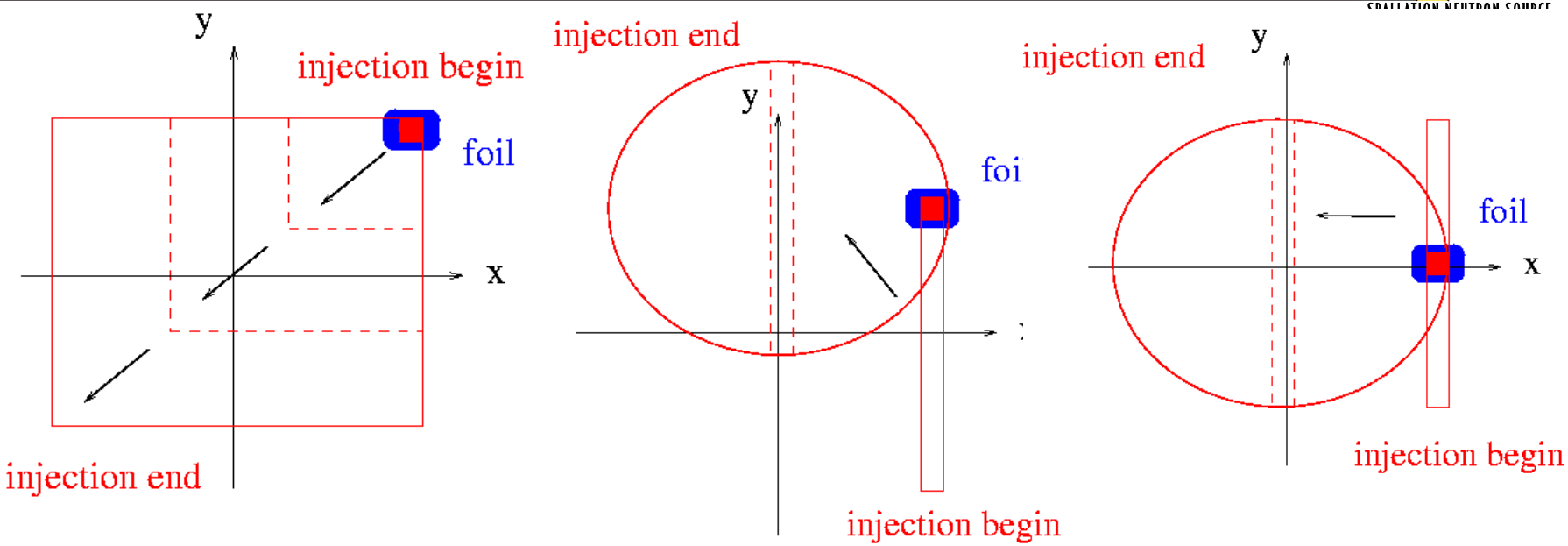
SNS injection (zero-dispersion)



- Circular & square profile both attainable
- Energy corrector & spreader in HEBT
- Tolerable to momentum errors

- Programmable bump magnets provide independent H, V, control

Injection painting schematic



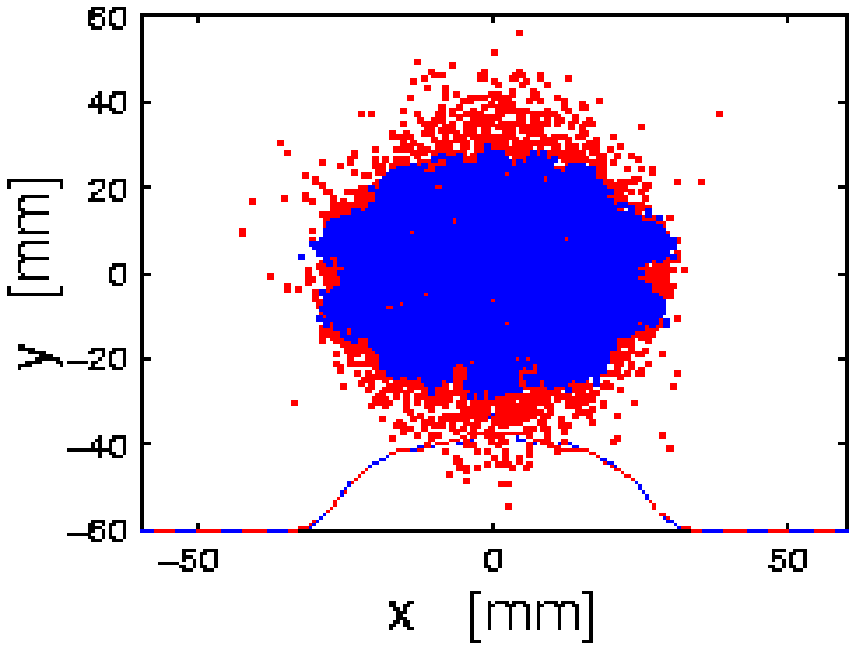
Correlated bumps

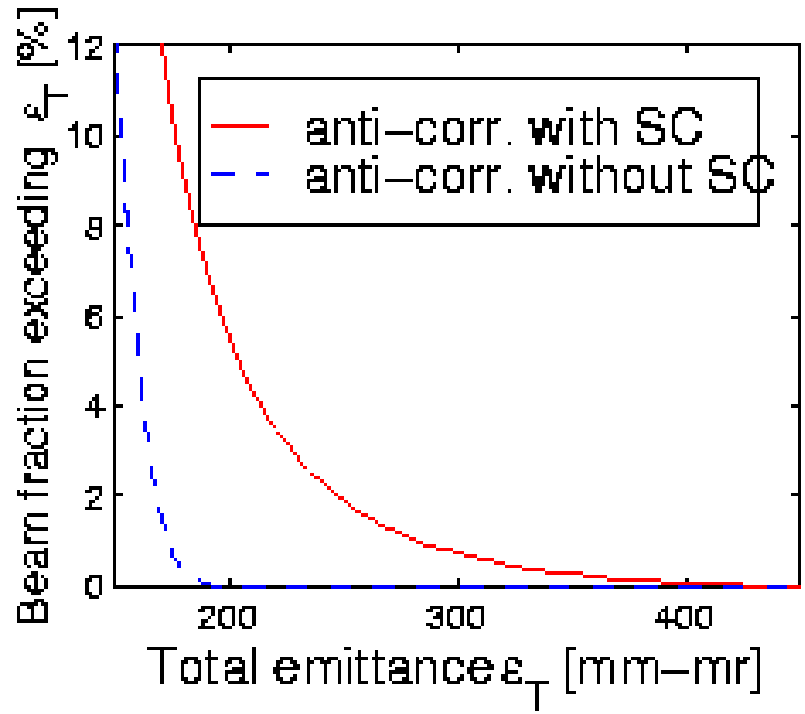
Anti-Correlated bumps

Paint (H)/ steer (V)

- Final distribution is “adjustable”

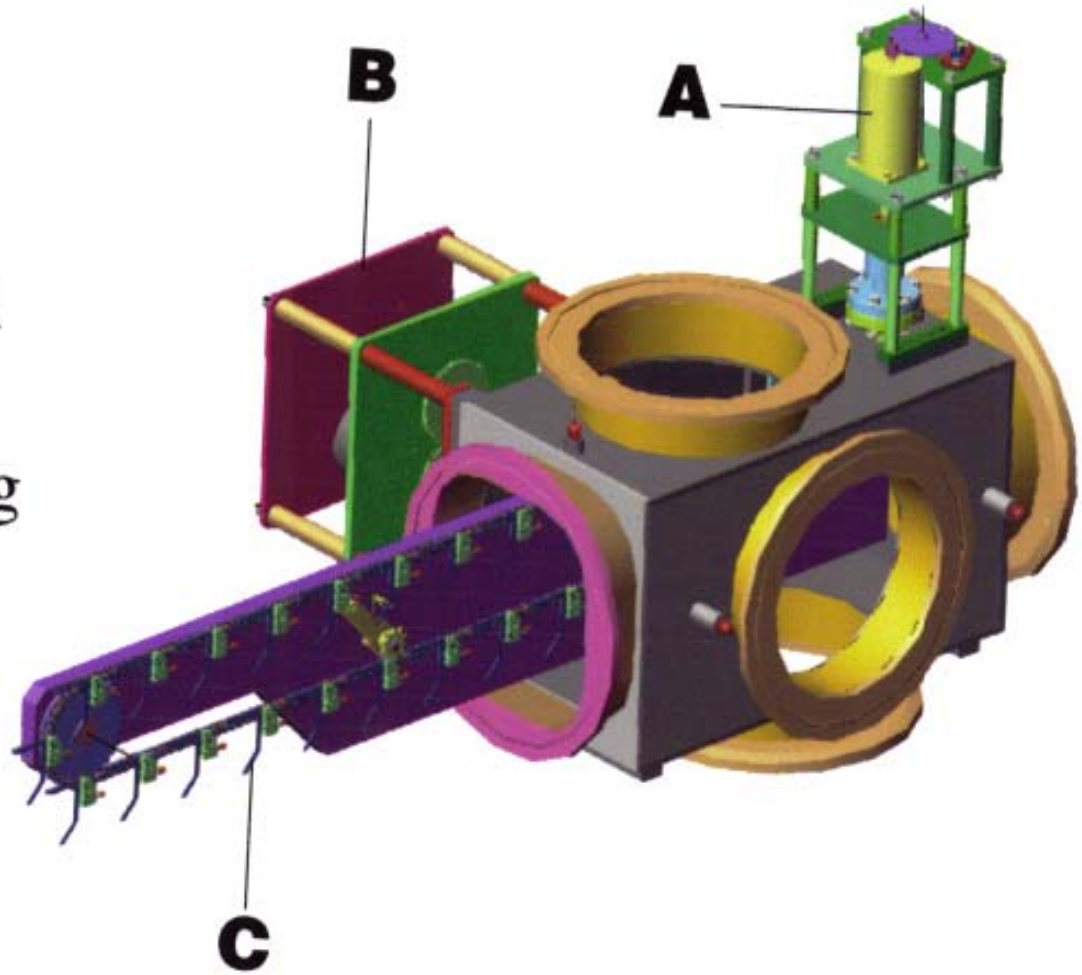
Space charge & halo formation





- Space charge has a strong effect on the final distribution

SNS injection foil device



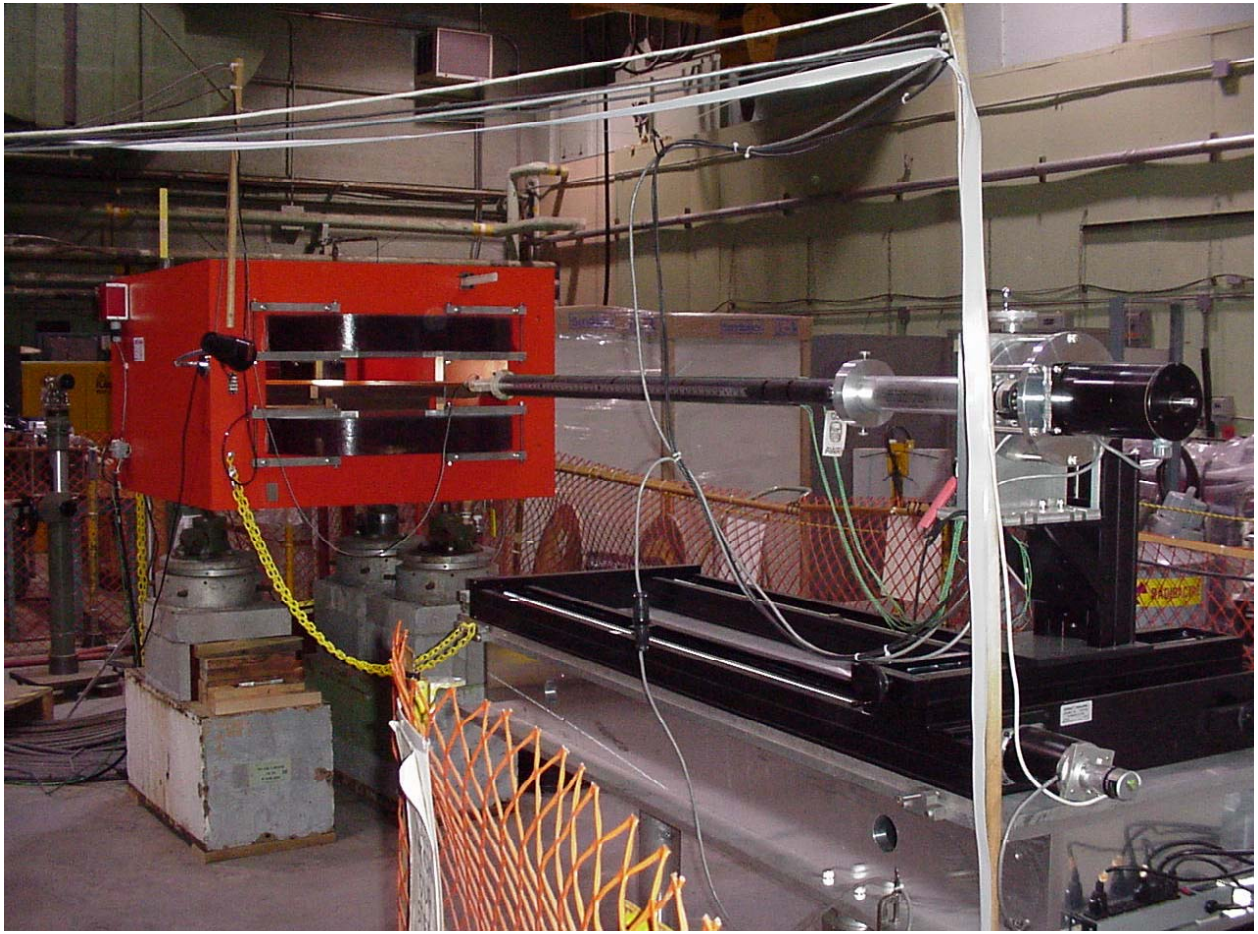
A. Foil Insertion Control

B. Foil Changing Control

C. Foil Holders

Magnet Assembly Area – Bldg. 902

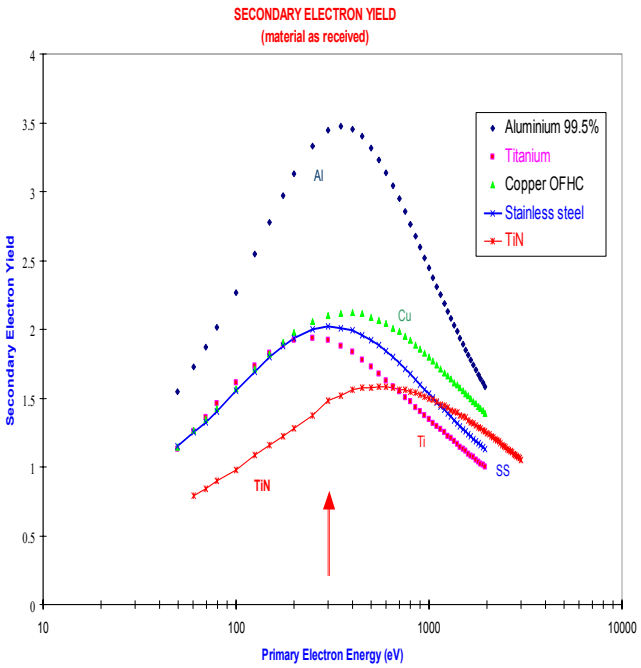
Ring Dipole under Measurement



Quad and Corrector Interference Measurement

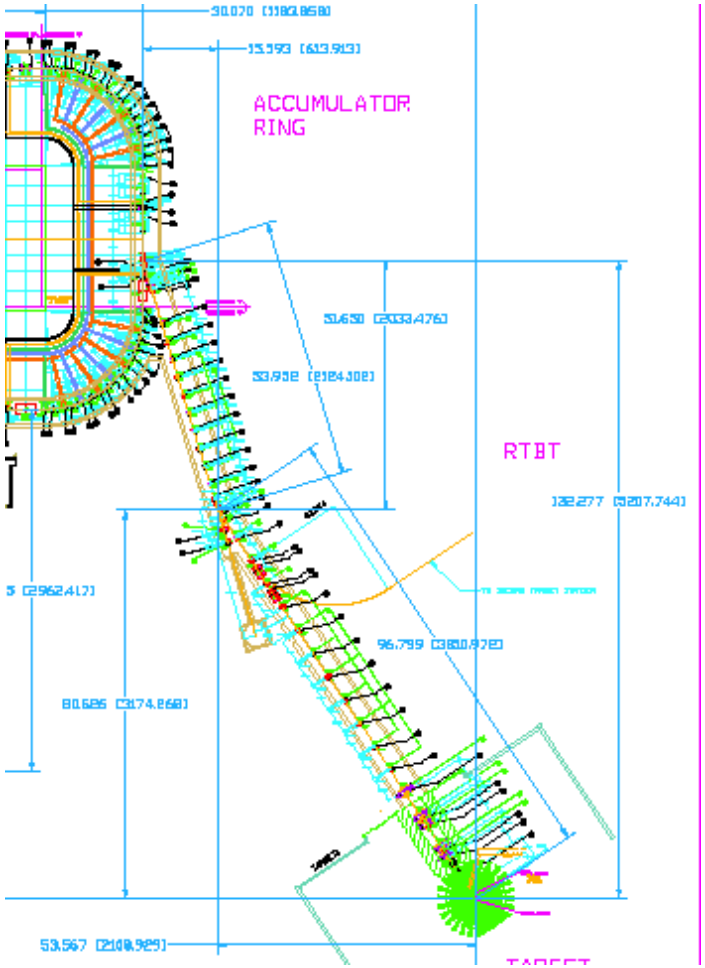
Assembly of 1st RF Cavity

TiN Coating Development



RTBT Transfer Line

- Transport the beam from the ring to the target
- Collimation to remove any halo
- Extraction dump



Summary

- SNS accelerator is a major advance in high intensity proton drivers
- Reliability and low loss are major considerations
  - Use of an accumulator ring
  - Large aperture
- SNS will provide the first pulsed proton superconducting linac
  - Large accelerating gradients provide flexibility