Director's Review of the Project X Cost Range Estimate: Low Energy Linac

Giorgio Apollinari
Project X Director's Review
March 16, 2009

LE Cavities and Cryomodules

Outline

- Scope of Estimated Work
- Boundary Conditions /Assumptions
  - Covered in this and Tom's talks
- Basis of Estimate
  - Technical/Performance Experience (this talk)
  - Cost Experience (Tom's talk)
- Technical Risks/Associated Cost Exposure
  - Physics/Beam Dynamics Risks in this talk
  - Engineering/Cost Risks in Tom's talk
- Potential Technical Revisions
  - Mostly this talk
- Role of Outside Collaborators
- Summary

LE Cavities and Cryomodules

Requirements

- Serve as the low-energy front-end to the 1.3 GHz Linac section
- Deliver 1.25 msec pulses of 1.6E14 H- ions at 420 MeV at pulse rates up to 5 Hz
- Provide transverse and longitudinal beam emittance and bunch parameters required to:
  - Match into the 1.3 GHz Linac
  - Avoid unacceptable beam losses at high energies
- Incorporate, into the 1.25 msec beam pulse, a 53 MHz structure to facilitate pseudo bunch-to-bucket transfer into the Recycler Ring and an 89 kHz structure to facilitate a 700 μsec abort/extraction gap in the Recycler ring

LE Cavities and Cryomodules

Scope of Estimated Work

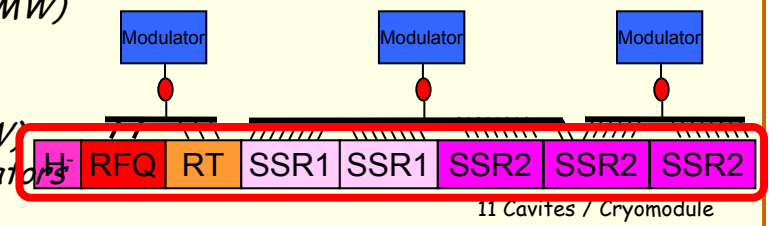
Project X
1000 kW 8GeV Linac

31 Klystrons (2 types)
453 SC Cavities
57 Cryomodules

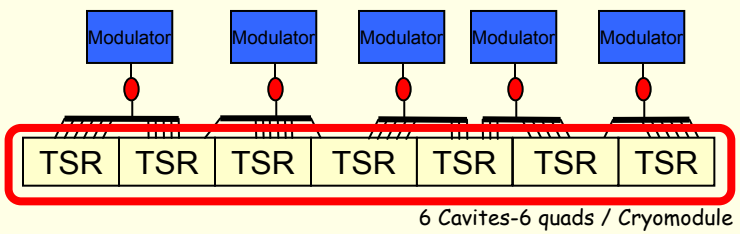
Front End Linac

325 MHz 0-10 MeV
1 Klystron (JPARC 2.5 MW)
RFQ + 18 RT Cavities

325 MHz 10-120 MeV
2 Klystrons (JP 2.5 MW)
51 Single Spoke Resonators
5 Cryomodules



325 MHz 0.12-0.42 GeV
5 Klystrons (JPARC 2.5 MW)
42 Triple Spoke Resonators
7 Cryomodules



2.5 MW JPARC Klystron

Multi-Cavity Fanout
Phase and Amplitude Control

- RFQ operate at ~0.5 MW, RT cavities at ~10 kW
- Solenoids operated at ~ 3-10 T
- SC Spoke Resonator average gradient ~10 MV/m and from ~30 to 100 kW

LE Cavities and Cryomodules

Scope of Estimated Work

- Configuration is based on Proton Driver/HINS design and technologies
- 50 keV H- ion source
- 2.5 MeV RFQ
- 2.5 MeV Medium Energy Beam Transport (MEBT) including two re-buncher RF cavities and a 325 MHz beam chopper
- Sixteen copper crossbar-H cavities in room temperature section to 10 MeV
- Eighteen β=0.22 SC single-spoke resonator (SSR1) cavities to 30 MeV
- Thirty-three β =0.4 SC single-spoke resonator (SSR2) cavities to 120 MeV
- Forty-two β =0.6 SC triple-spoke resonator (TSR) cavities to 420 MeV
- SC solenoids provide transverse focusing from the RFQ through the SSR2 section (total of 55 SC Solenoids)
- SC quadrupoles provide transverse focusing starting in the TSR section.
- *Eight Toshiba E3740A(Fermi) 2.5 MW klystrons driven by Fermilab bouncer-type pulse modulators provide the necessary RF power*
- *RF distribution system with fast ferrite vector modulators for amplitude and phase control of each individual*

Red = included for completeness, not part of scope costed in this breakout session

Boundary Conditions & Assumptions

- Estimated Work for "LE Cavities and cryomodules "relies heavily on two R&D programs actively pursued at Fermilab: **HINS** and **SRF** Development.
  - The High Intensity Neutrino Source (**HINS**) R&D Program is an effort that began in late 2005 to demonstrate the application of technologies that are innovative for a low-energy, high-intensity hadron beam linear accelerator
    - HINS technology is the front-end in the Project X Linac ICD
  - The **SRF** program is an effort to develop infrastructure at FNAL and other laboratories (most notably ANL) for the Supercondting RF technology:
    - Surface Processing facilities
      - Chemical Processing (EP, BCP, thumbling ..)
      - Ancillary Processing/Cleaning (Vacuum Ovens, HPR, ..)
    - Testing Facilities
      - VTS, HTS
    - (Clean Room) Assembly Facilities

HINS vis a vis Project X …

- Management and funding of HINS currently remains independent of, but not oblivious to, Project X
  - HINS managers participate intimately in Project X developments
- HINS efforts are expected to continue in support of Project X technology choices and upgrade options
- Integration of HINS management and funding with Project X will be considered subsequent to Project X CD-0
- Whether/when the integration actually occurs will be strongly coupled to whether or not HINS is expected to serve as the Project X front end
  - If yes, the answer is obviously quick and complete integration
  - If no, the intent would be to keep HINS as a separate program aimed at a Project X upgrade developments
- HINS is the path to achieve technology demonstrations that are important to Project X in the 2009-2012 time frame
- HINS future scope
  - Originally, HINS aimed at achieving ~90 MeV with 2 SSR1 and 1 SSR2 CMs
  - Fiscal reality pushes to consider only two SSR1 CM taking beam to 30 MeV
  - the original HINS goals could be substantially achieved with 20 MeV beam provided by just one SSR1 CM

HINS vis a vis Project X … …vis a vis SRF

- HINS/Project X Front End has benefited greatly from SRF some of the Infrastructure developed mainly for 1.3 GHz/ILC
  - Vertical Testing Facilities for CW test of naked cavities
  - Manpower expertise in cavities HPR cleaning and assembly
- Chemical Processing development in SRF Infrastructure mainly geared toward 1.3 GHz Technology
  - BCP processing (as opposed to EP) appears to be sufficient for LE goals
  - Reasonable plans to process ~9-18 SSR1 cavities needed in HINS
  - No plan yet developed to process ~100 Spoke Resonators needed in the ICD LE front end
    - Issue made more interesting by the possibility of various collaborators (ANL, JLAB, India) participating/contributing to the spoke resonator construction.
- Although space/manpower bandwidth appears to be available, one of the future challenges is the development of infrastructure development for Spoke Resonator cryomodule assembly

LE Cavities and Cryomodules

Assumptions

- Project X "LE Cavities and Cryomodules" ICD assumes that:
  - **HINS** Program will deliver a fully operational 30 MeV Linac addressing the following technical elements:
    - RT injector based on IS, RFQ and RT cavities
    - beam acceleration using pulsed superconducting spoke-type cavity structures starting at a beam energy of 10 MeV
    - multiple high power RF vector modulators controlling RF cavities driven by a single high power klystron for acceleration of a non-relativistic beam
    - beam halo and emittance growth control by the use of solenoid focusing optics
    - a fast, 325 MHz bunch-by-bunch, beam chopper
      - Byproducts: design and "single" production line for:
        - » 325 MHz Horizontal Testing Facility
        - » Power Coupler processing facility
  - **SRF** Program will contribute to the preparation of facilities for processing, testing and assembly into cold –strings and cryomodules of spoke cavities and focusing elements

LE Cavities and Cryomodules

Interfaces

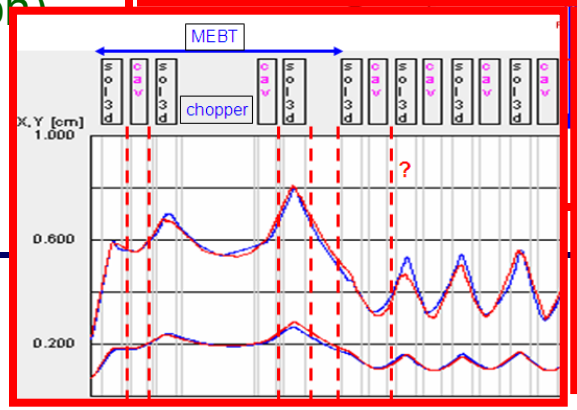
- Main interfaces with:
  - RF powering system
    - High Power RF
      - Ex: 1% amplitude, 1^0 phase control
    - LLRF
  - Cryogenic System (4 K operation)
  - Beam Diagnostic
  - General Services
    - Magnet PS
    - Cooling Water (RT Section)
    - Interlocks

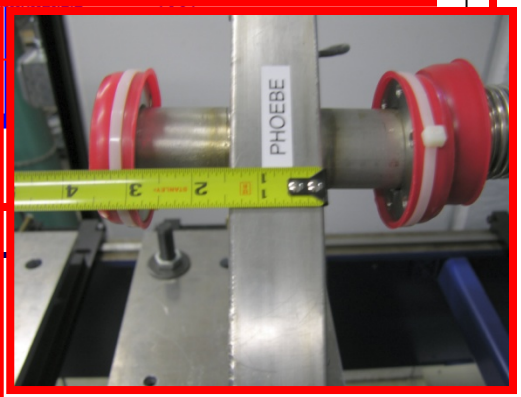
Meeting on HINS
Beam Dynamics & Diagnostics

Location:	Fermilab, Batavia, IL
Time:	Friday, March 13, 2009; 9:00 AM – 4:30 PM
Room:	Wilson Hall, 1st floor, 1 North

Schedule

Time	Presentation, Activity	Speaker
09:00 – 09:15	Welcome	M. Wendt, G. Apollinari
09:15 – 09:35	Introduction to Project X	S. Nagaitsev
09:35 – 10:00	Overview and Status of HINS, discussion	G. Apollinari
10:00 – 10:25	HINS/PD/PrX Beam Dynamics Simulations & Issues, discussion	J.-P. Carneiro
10:25 – 10:45	HINS Simulations on Beam Jitter and Tolerances, discussion	B. Mustapha
10:45 – 11:15	Break	
11:15 – 11:45	HINS p-Source & LEBT Beam Studies, discussion	W.-M. Tam
11:45 – 12:30	HINS MEBT Beam Diagnostics: Plans & Issues, discussion	V. Scarpine
12:30 – 13:30	Lunch	
13:30 – 14:15	CERN LINAC4 & 3 MeV Test Stand: Overview, Beam Dynamics & Diagnostics Issues, discussion	A. Lombardi
14:15 – 15:00	SNS Linac MEBT Beam Dynamics: Simulations vs. Measurements, Commissioning & Operation Experience, Lessons Learned, discussion	S. Aleksandrov
15:00 – 15:30	Break	
15:30 – 16:30	Discussion	
16:30	Adjourn	



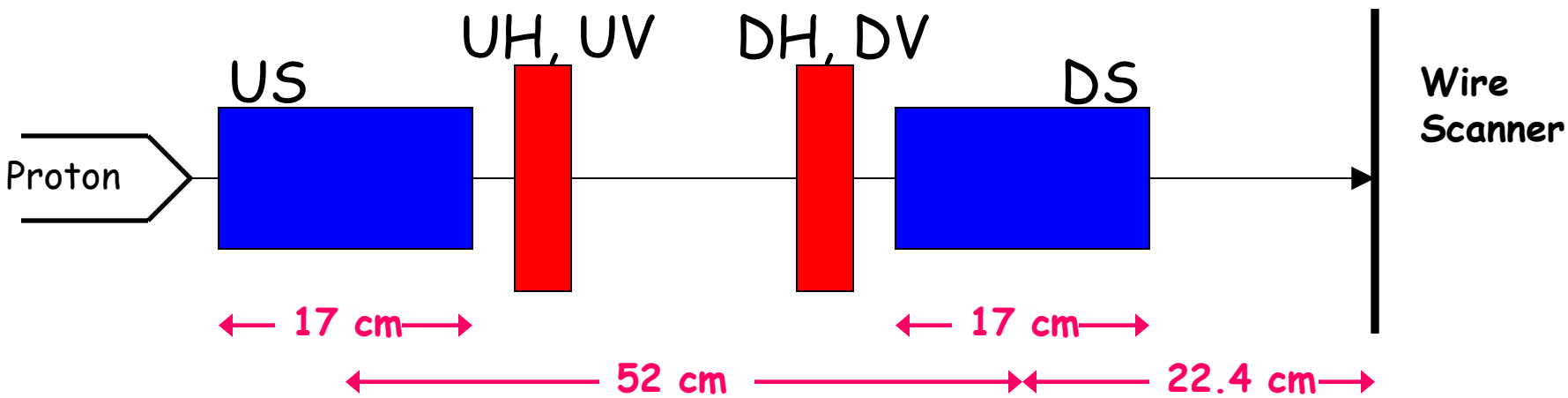


Basis of Estimate

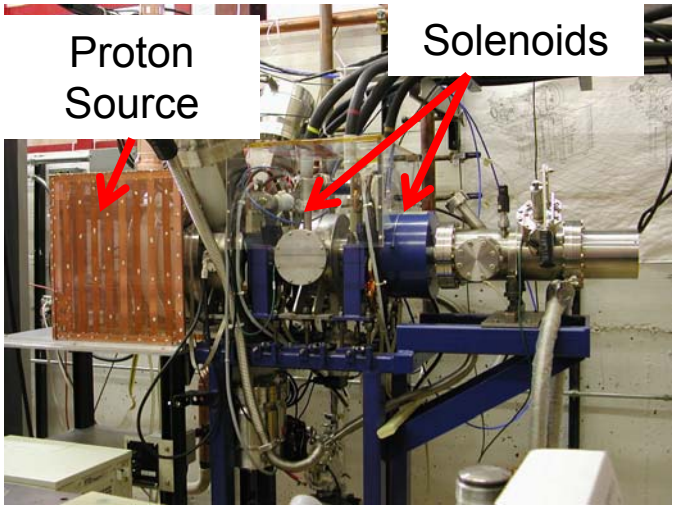
- The cost figures are contained in Tom's presentation
- Most of the remainder of this presentation will cover technical features of the "LE Cavities and Cryomodules" to:
  - indicate their present status of development
  - show that the cost estimate are based on real hardware mostly meeting the PrX requirements
  - support the PrX estimate on RD&D activities not covered by HINS or SRF Infrastructure
- Based on HINS Program
  - Ion Source
  - RFQ
  - MEBT Region
  - RT Section
  - SSR1 Cavities Development, Construction & Testing

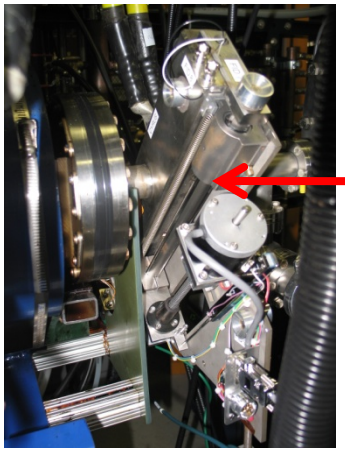
Ion Source

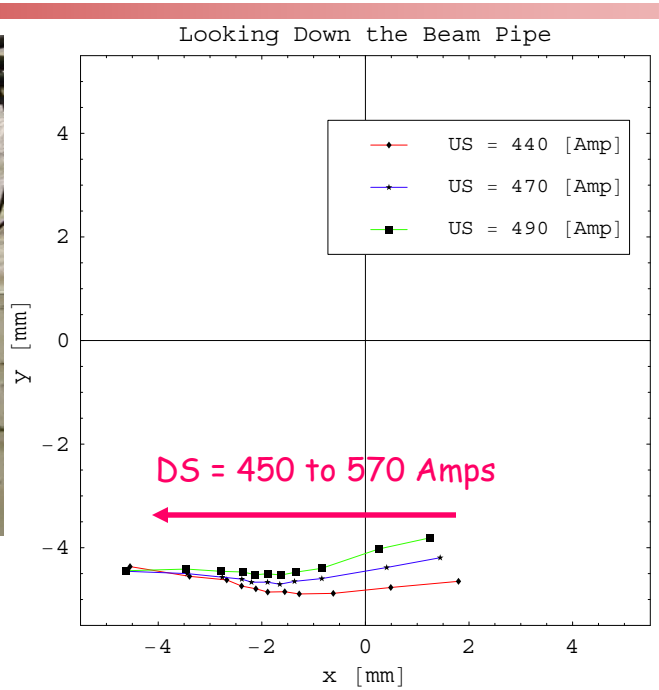
- HINS presently using p source and LEBT developed in late '80s for the LOMA Linda machine.
  - Goal: show performance and ability to measure, handle and aim 50 keV beam (operation experience).
  - No input on cost estimate.

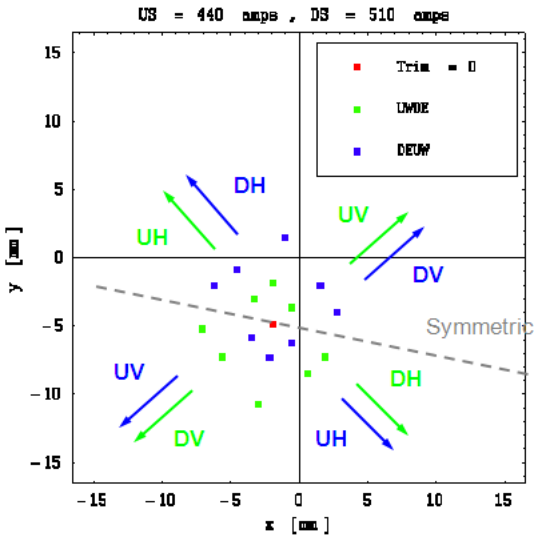


LEBT Beam Steering



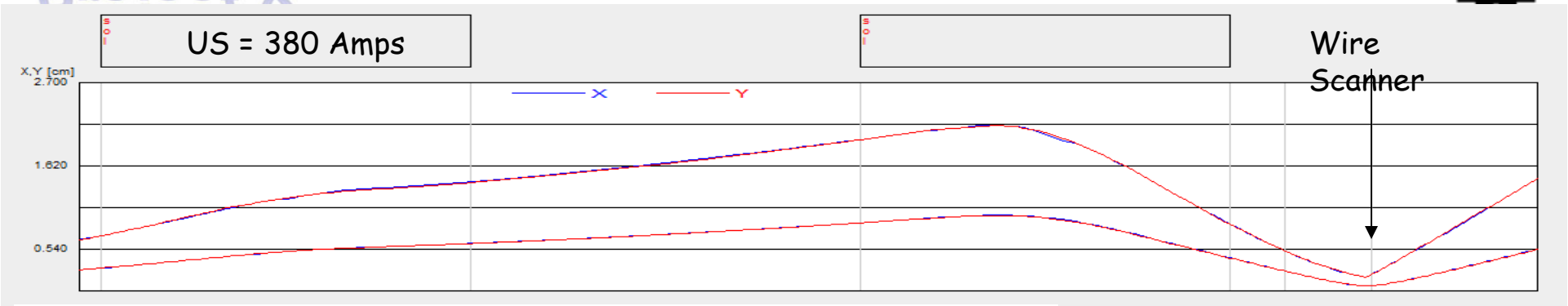


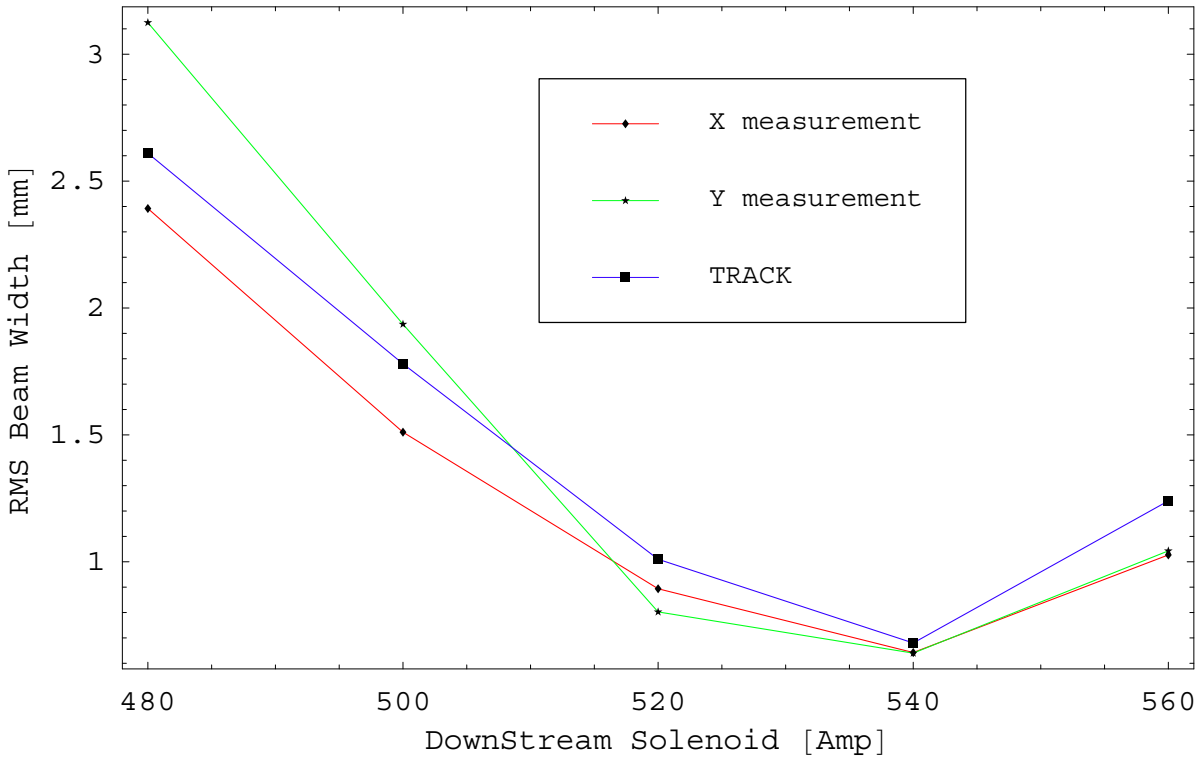




- Can handle and aim LEBT beam (see SNS)
- Acquire invaluable operating experience in solenoidal beam handling

LEBT Beam Steering





Current = 8 mA
Energy = 50 keV

Input Beam for TRACK:

ε(n,rms) = 0.233 πmm-mrad

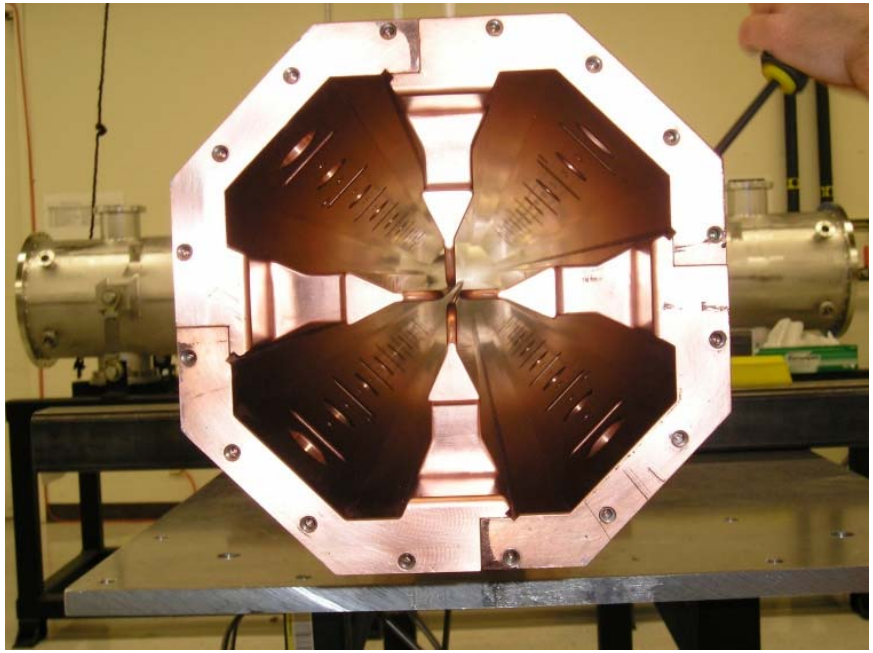
α = -1.82

β = 0.331 mm/mrad

Giorgio Apollinari

LE Cavities and Cryomodules

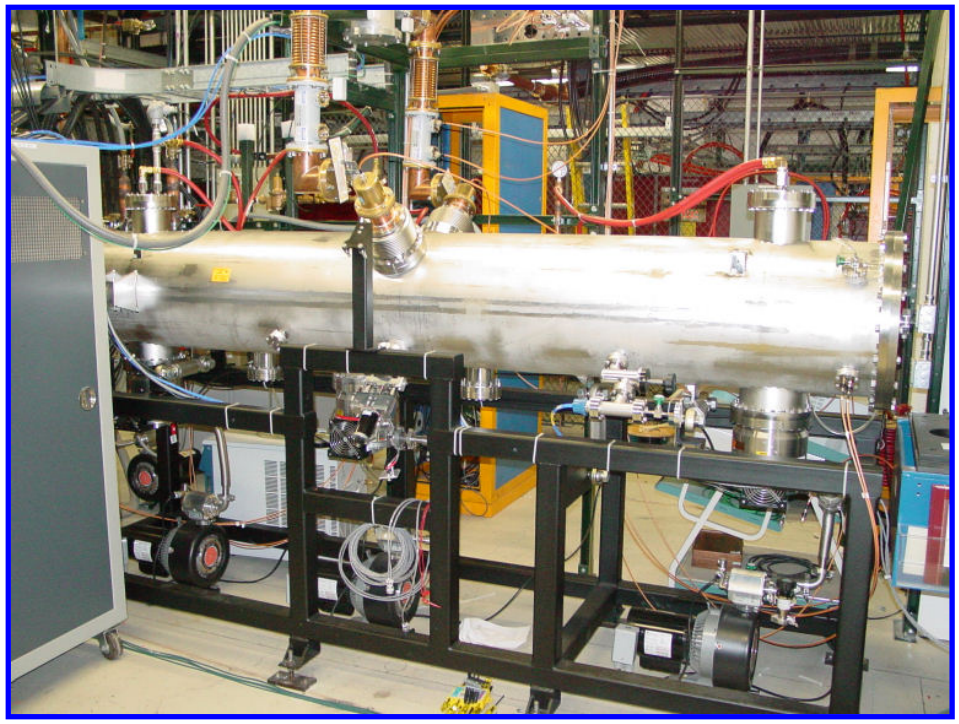
RFQ



- Construction completed in late summer ’08.
  - Mechanical construction delays on machining of vanes
  - Cooling manifold mistakes required return to company for fix

LE Cavities and Cryomodules

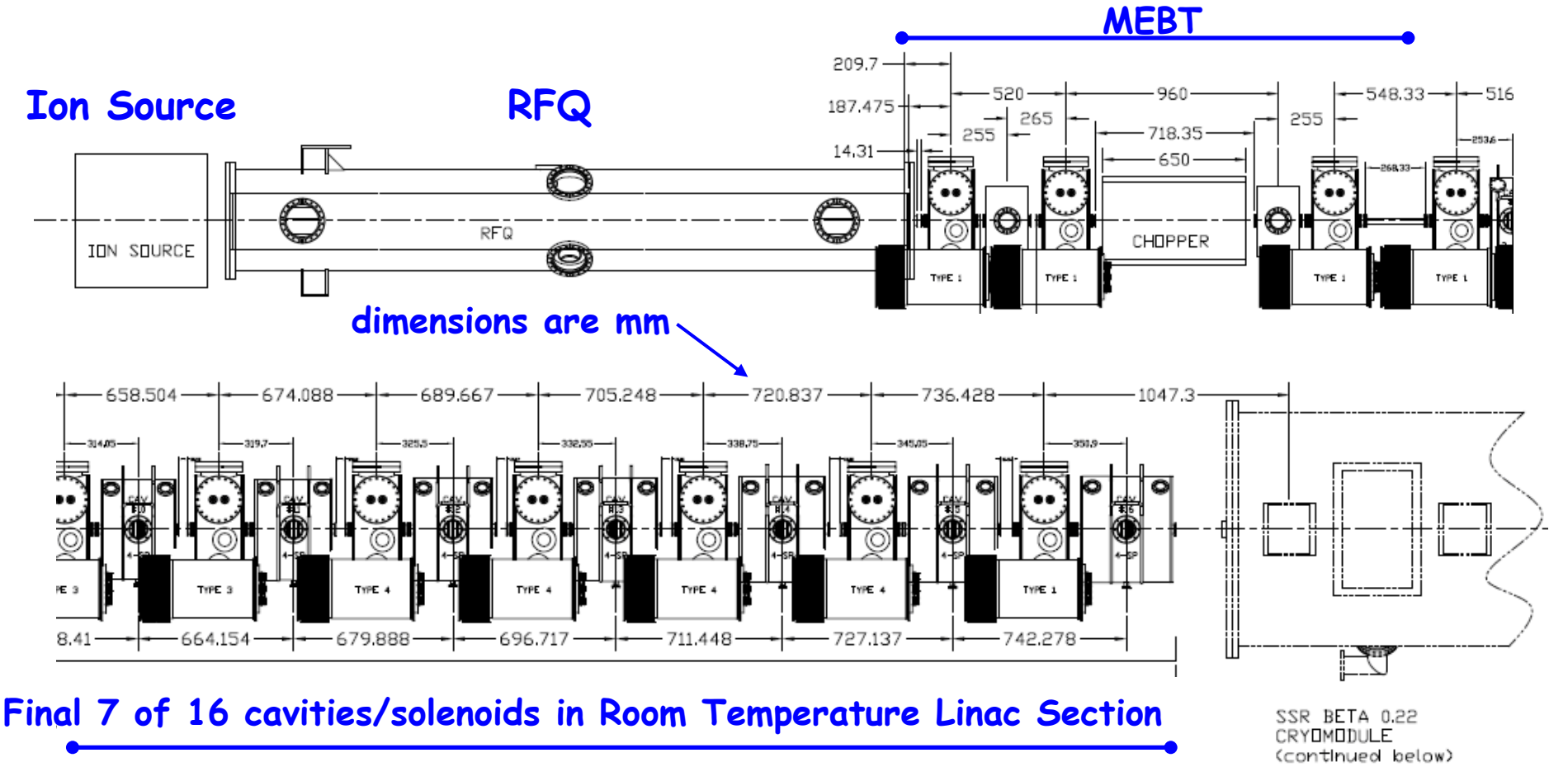
RFQ



- Commissioning taking place in HINS Meson Building area with power fed from 325 GHz JPARC klystron
- Issues:
  - Sparks/leaks at Power Coupler
    - Cleanness problems, fixed
  - Observe f runaway (~kHz level) when average power is increased
    - OK at 200 W average for ~hours
    - Runaway at 800 W after ~20 min, returning to normal values after "cool-down" period
    - Suspect cooling system problem. To be investigated and solved within the HINS program

LE Cavities and Cryomodules

RT Section

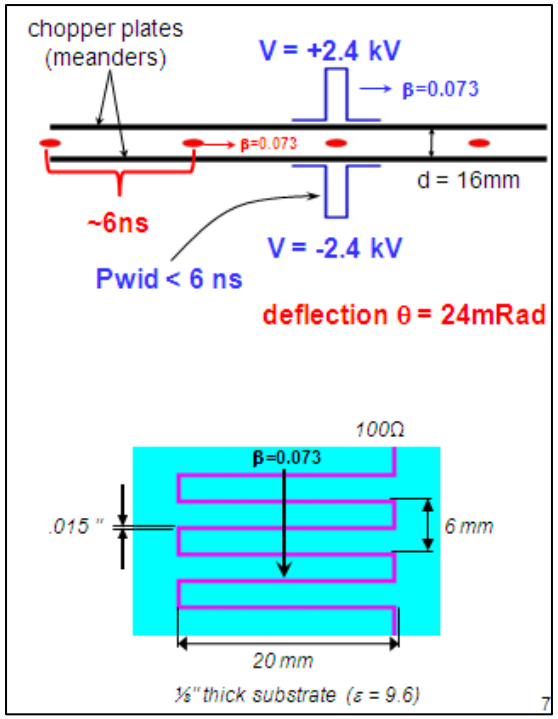


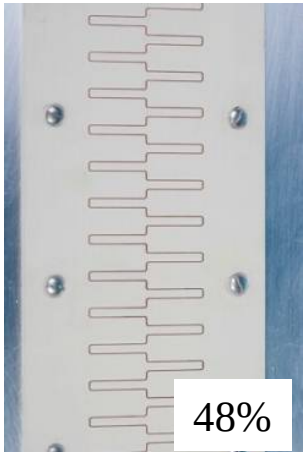
Final 7 of 16 cavities/solenoids in Room Temperature Linac Section

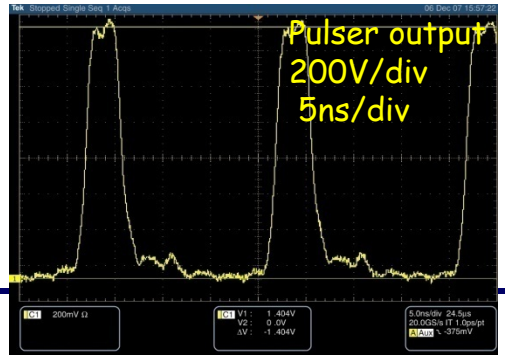
Start of first SSR1 Cryostat

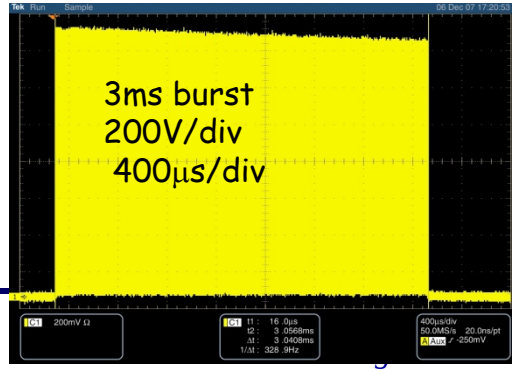
MEBT Chopper

- Chopper based on travelling wave structure
- Studied different structure for best “coverage factor”
- Successfully developed 1.2 kV power supply with Kentech

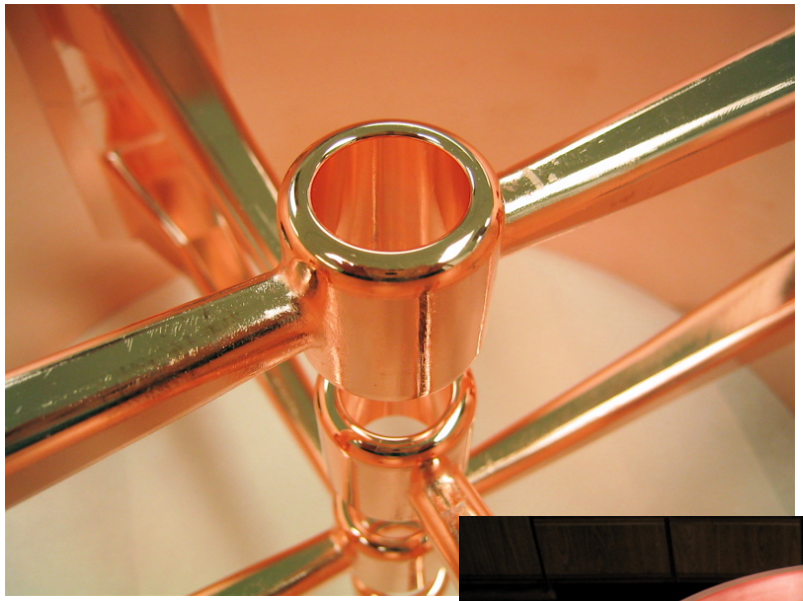


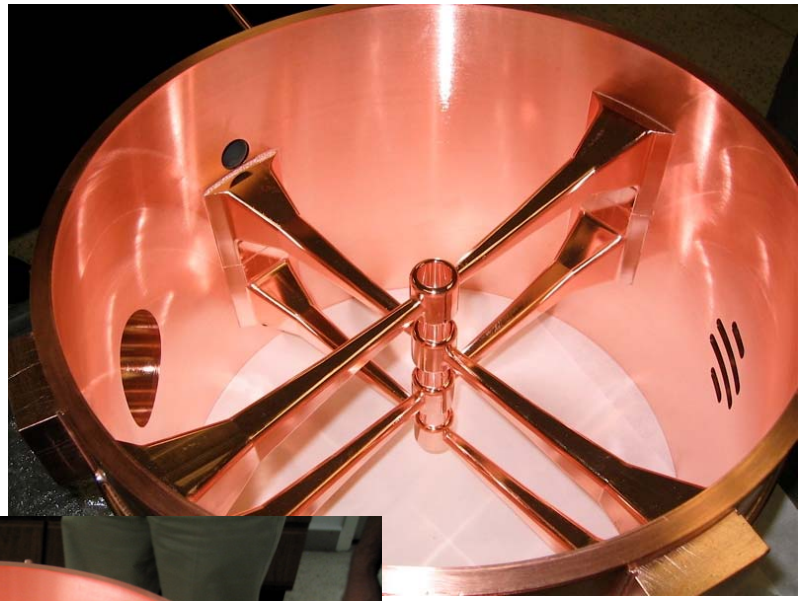




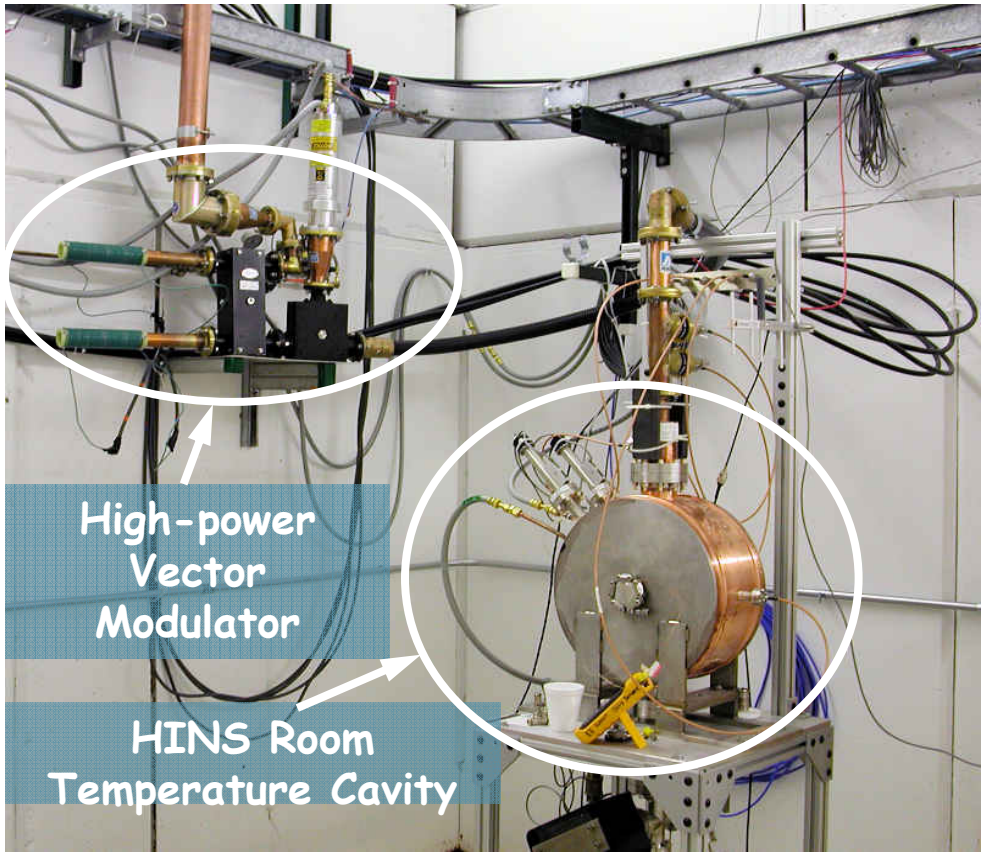


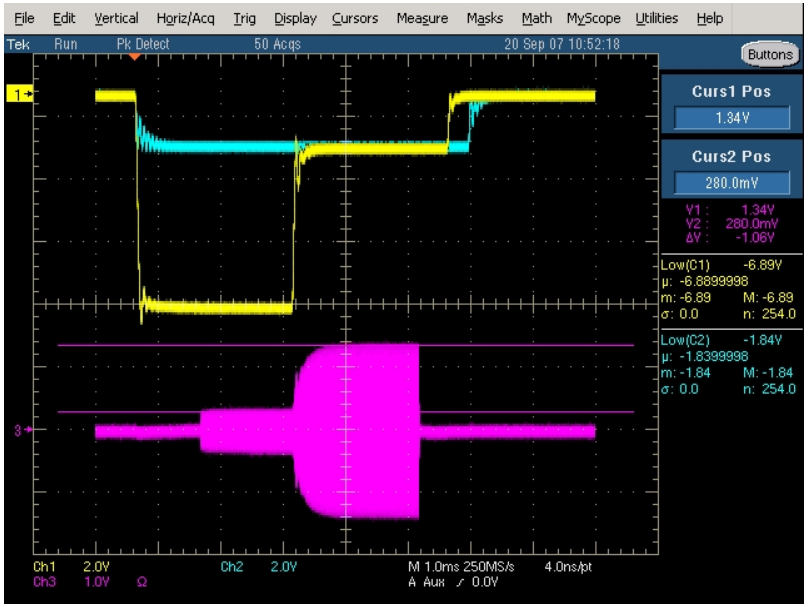
RT Cavities





RT Cavity and Vector Modulator



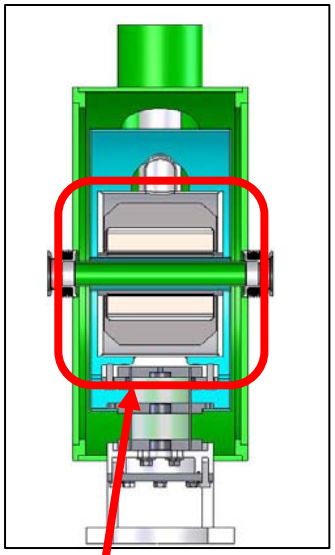


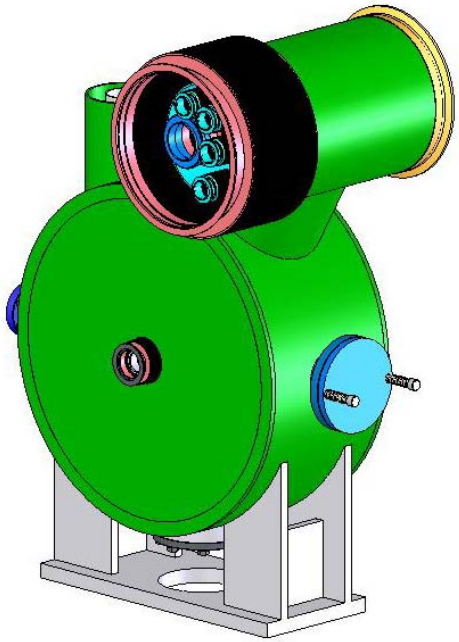
13 dB Amplitude Control with Vector Modulator for 6 kW 3.5 msec RF Pulse

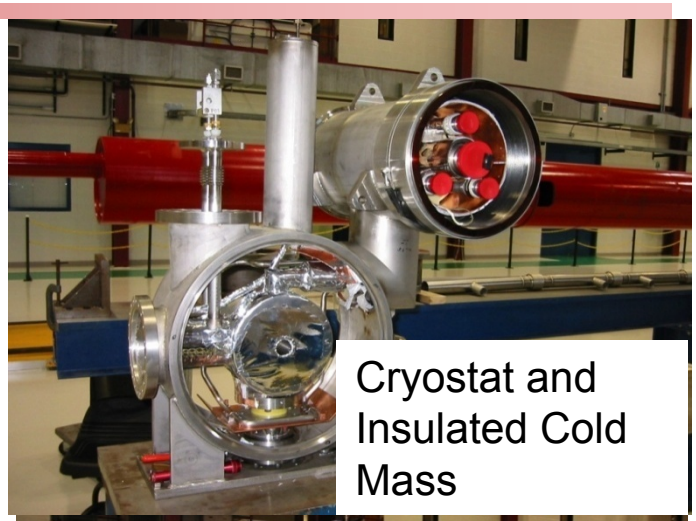
Red trace is cavity RF amplitude; blue and yellow are vector modulator bias currents

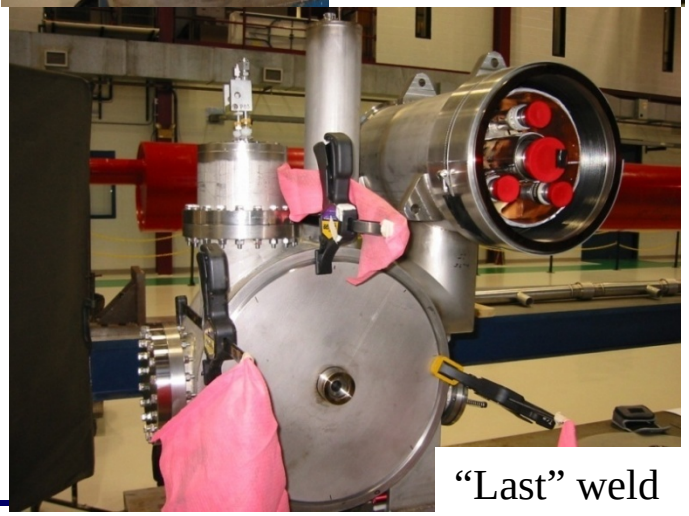
RT Focusing Solenoids

- Prototype RT superconducting solenoid and cryostat are complete
- Testing is underway
- Production solenoids and cryostats are in process

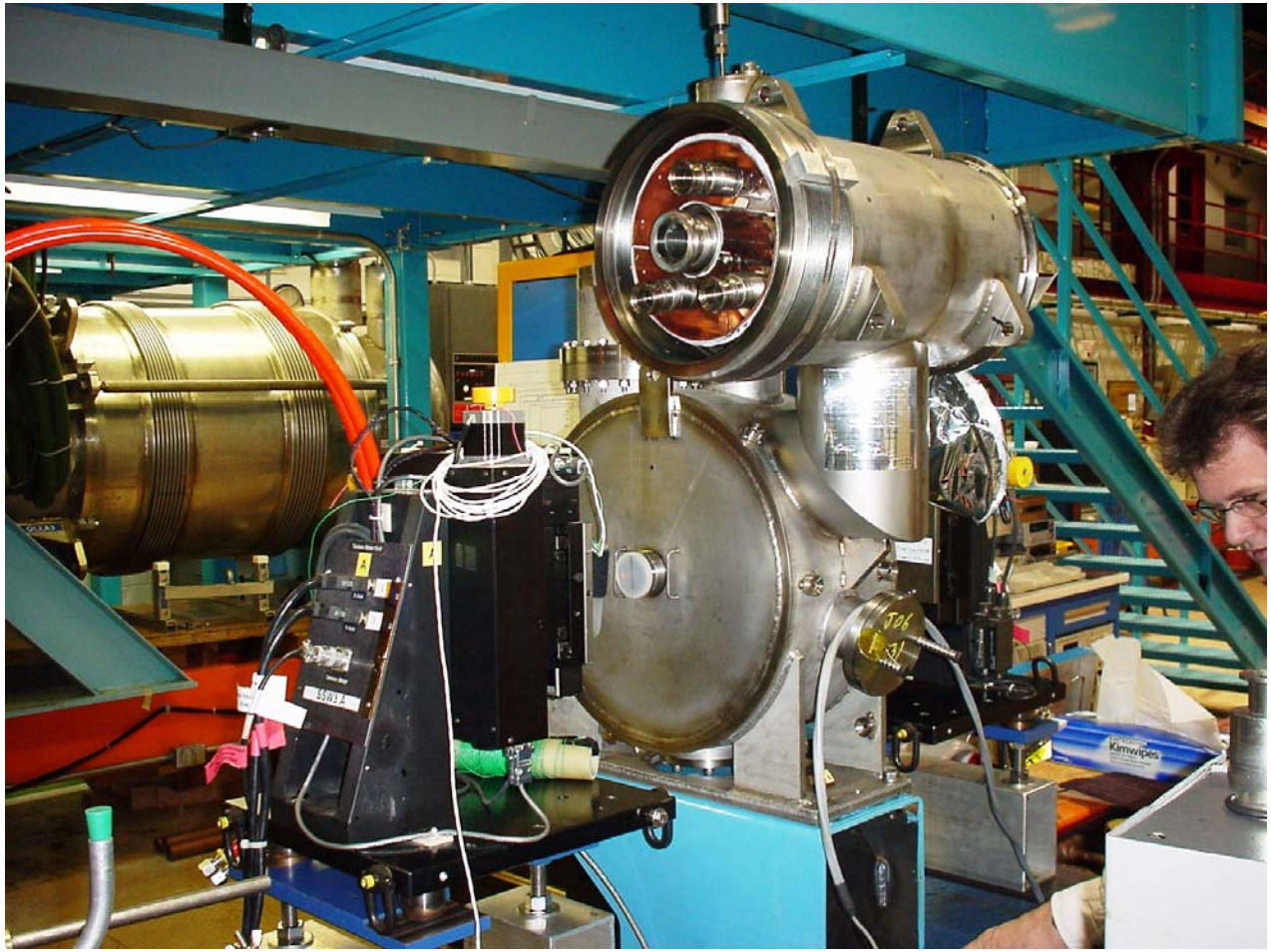






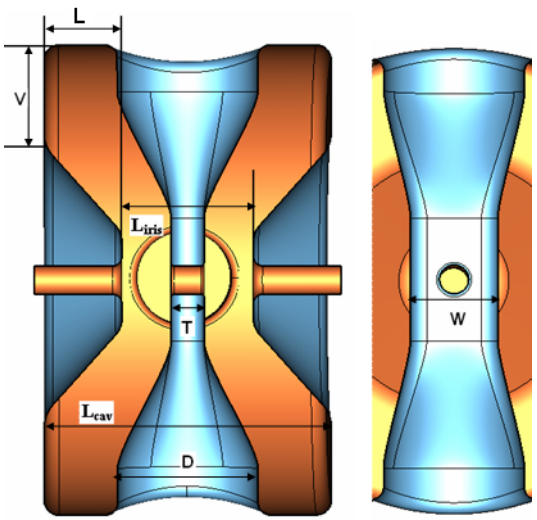


RT Focusing Solenoids

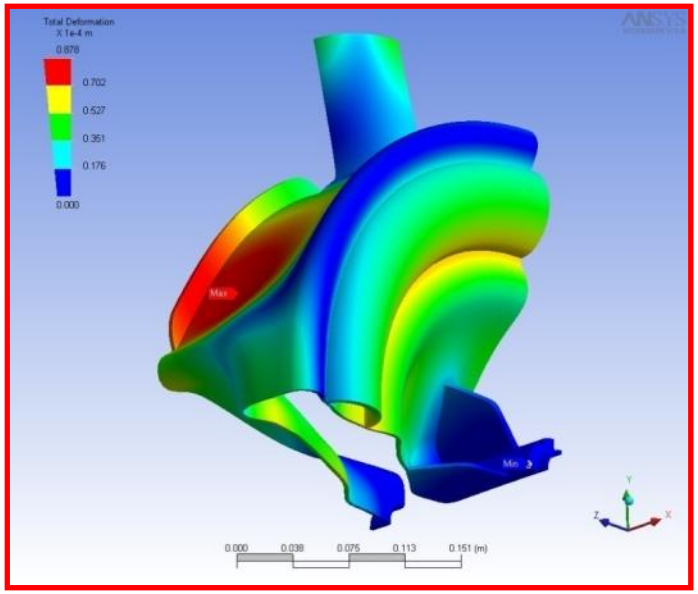


SSR1 Cavities

- Four-years R&D effort with very promising results
  - From RF design (2005) to engineering design (2006) to mechanical construction (2007) to chemical processing/testing (2008) to HP testing (2009)



	R/Q			
V\L	50	60	70	80
30	234.19	236.89	238.16	239.8
55	240.67	243.76	246.19	249.14
80	248.41	251.77	256.2	259.61
105	257.27	262.66	267.63	272.24
	Epeak/Eacc			
	50	60	70	80
30	2.86	2.83	2.73	2.69
55	2.83	2.74	2.72	2.66
80	2.84	2.69	2.64	2.62
105	2.69	2.64	2.61	2.55
	Q			
	50	60	70	80
30	1.41E+09	1.44E+09	1.39E+09	1.45E+09
55	1.44E+09	1.50E+09	1.55E+09	1.51E+09
80	1.49E+09	1.53E+09	1.60E+09	1.65E+09
105	1.52E+09	1.58E+09	1.65E+09	1.71E+09
	Bpeak/Eacc			
	50	60	70	80
30	7.06	6.30	5.83	5.35
55	6.86	6.22	5.71	5.23
80	6.65	6.02	5.52	5.08
105	6.50	5.88	5.36	4.87

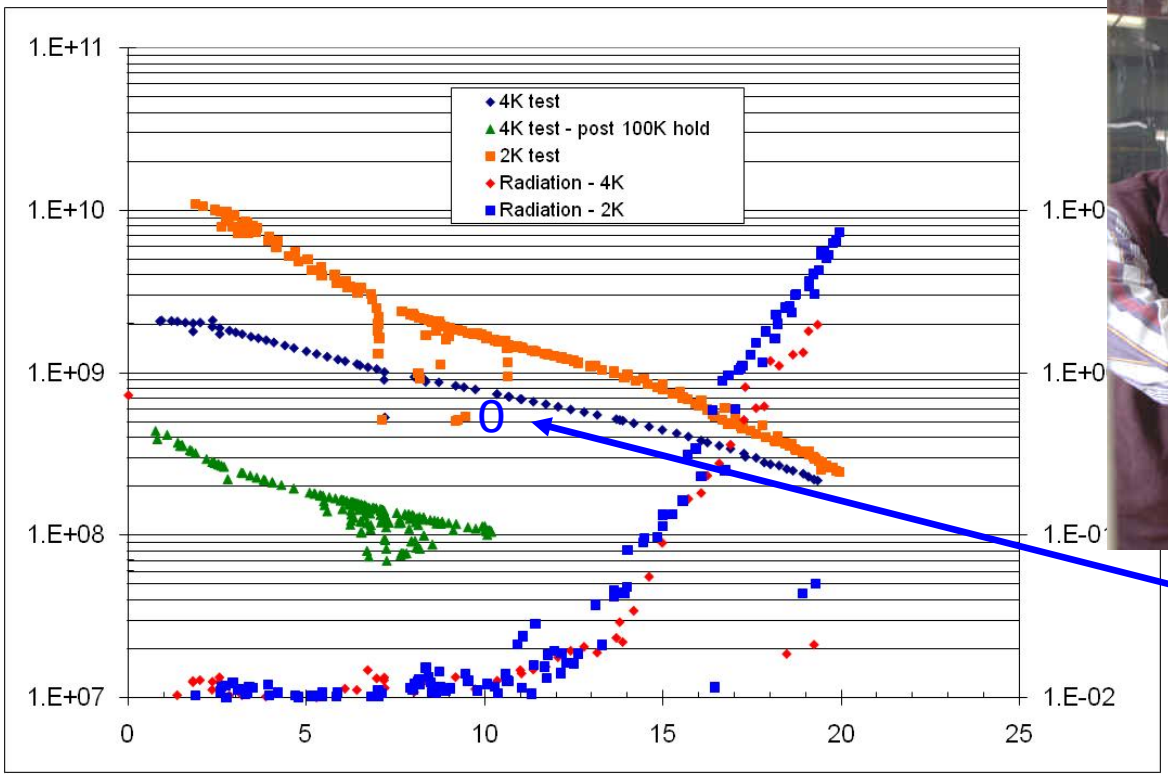


Total Deformation [m]

Max: 88 mm

SSR1-01 Cavity

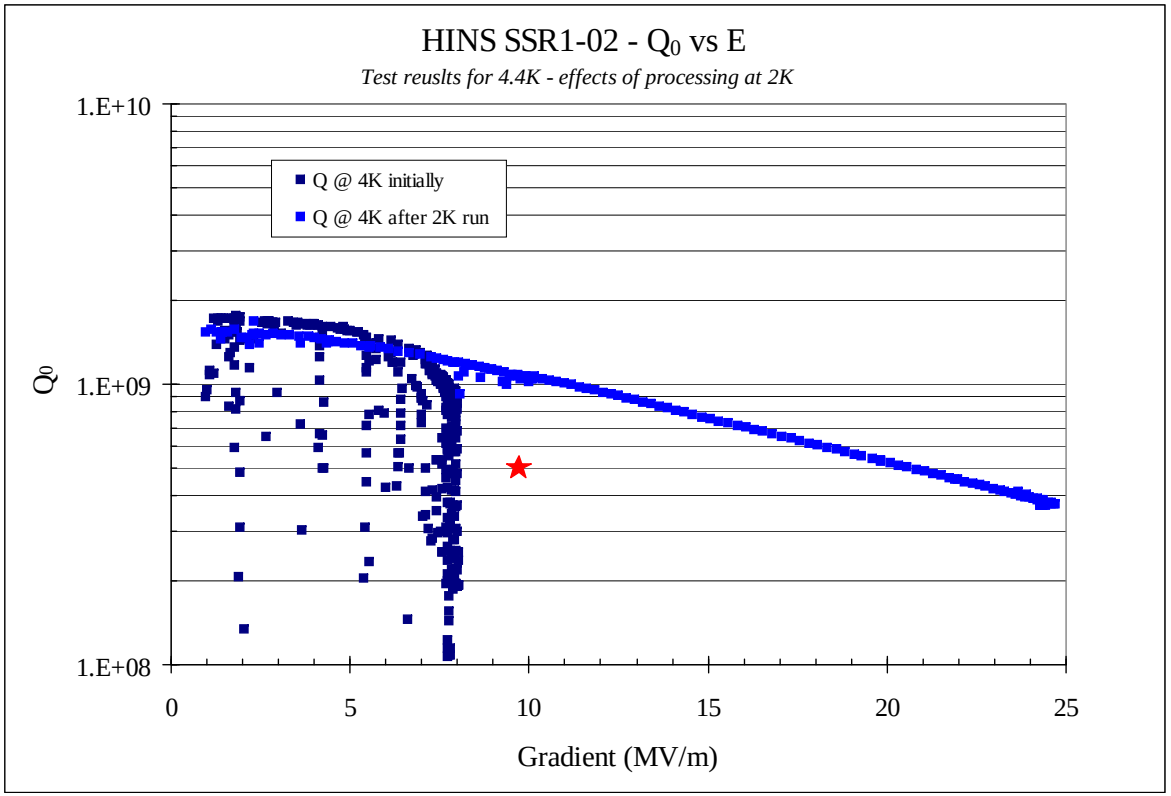
SSR1-01 Vertical Test
Q vs. E



Dressed Cavity
Operating Goal @ 4K

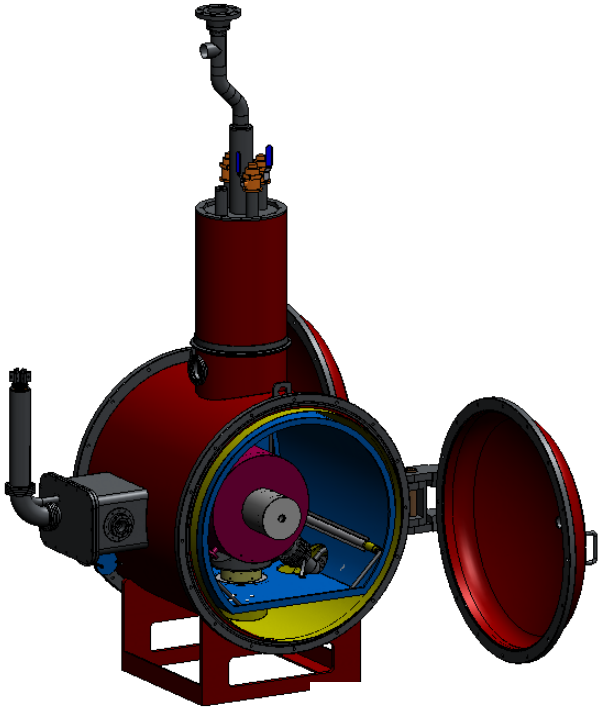
Accelerating Gradient MV/m

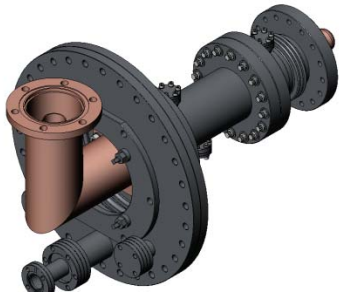
SSR1 -02 Cavity



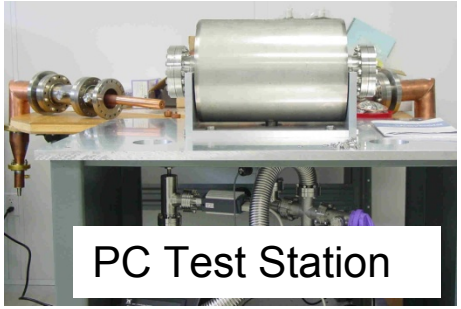
- At low-power levels, first 2 SSR1 prototypes exceed expectations !
- Two more prototypes being built in India (IUAC) expect by end of FY09

SSR Test Cryomodule and PC

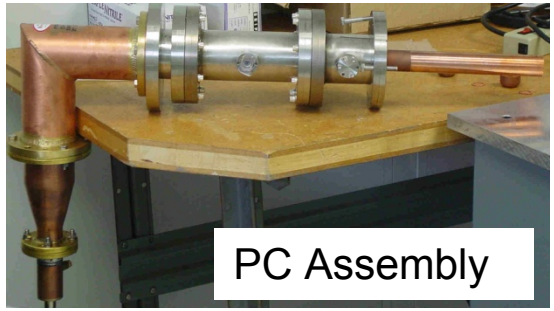




Horizontal test Cryostat



PC Test Station

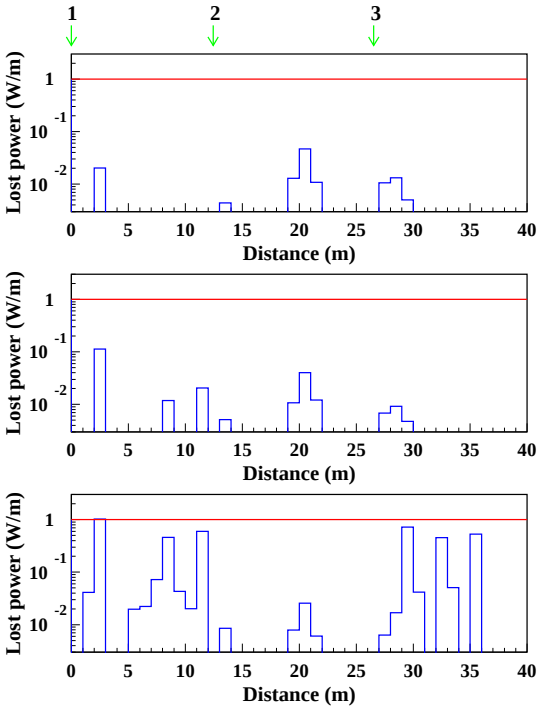


PC Assembly

Technical Risks

- Engineering Risks on Alignment
  - Demanding mechanical tolerances for High Intensity Beam delivery to HE Linac
  - Exposure is x2-4 cost increase in magnet design and/or alignment survey (WAG)

	Description	Value	Distribution
1	RFQ end displacement	0.1 mm (max.)	Uniform
2	Cavity end displacement RT SC, spokes SC, elliptical	 0.5 mm (max.) 0.5 mm (max.) 1.0 mm (max.)	Uniform
3	Solenoid end displacement Type 1 (RT and SSR-1 section) – 18 cm Type 2 (SSR-2 and TSR) – 32 cm	 0.15 mm (max.) 0.2 mm (max.)	Uniform
4	Cavity field error (dynamic)	1.0% (rms)	Gaussian
5	Cavity phase error (dynamic)	1.0° (rms)	Gaussian



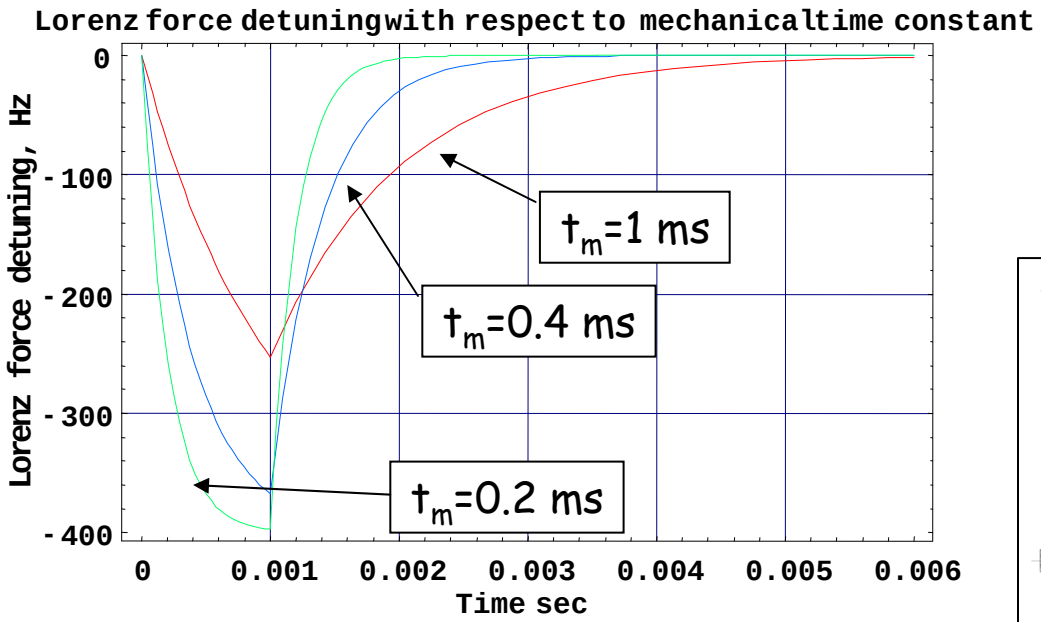
Nominal errors

Intermediate errors

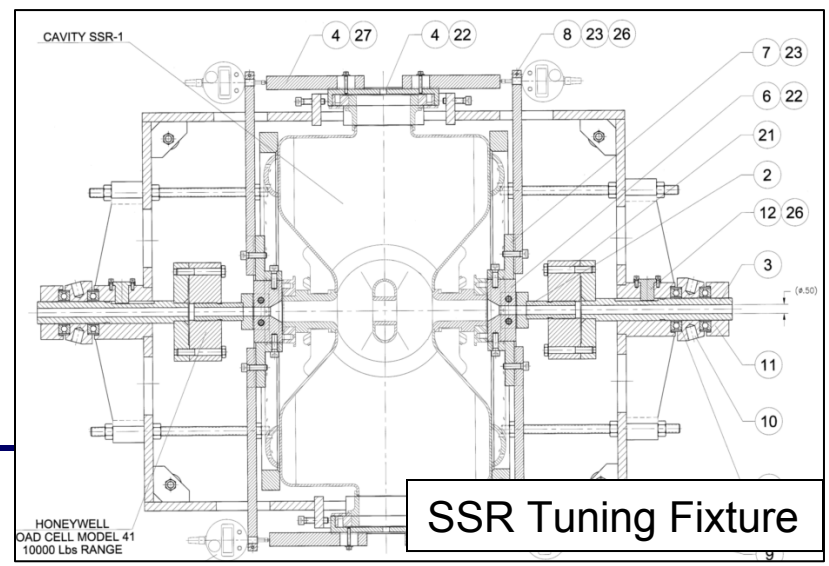
Double errors

Technical Risks

- Operational Risk on SSR Lorentz Detuning
  - Spoke Resonator Superconducting Cavities never operated in pulsed mode
  - One of major goals of HINS effort for FY09, actively being pursued



Along with other parameters, the mechanical time constant t_m determines maximum of Lorenz force detuning and weather the detuning decays completely or not at the instance of a new RF pulse.



SSR Tuning Fixture

Potential Technical Revisions

- HINS and SRF programs are just beginning to give results and are not fully exploited for Project X. Nevertheless, initial indication(s) may pave the way to some potential technical revisions
  - Known Unknowns
    - RFQ improperly designed for high power operations
      - Exposure at ~ 1 M$ level if "more expensive" (either in R&D or construction effort) RFQ is needed
    - SSR prototype average field higher than expectations.
      - Possible reduction of the number of 325 MHz cryomodules by 1 or 2 units. Potential savings of ~4-8 M$.
  - Unknown Unknowns
    - Alignment Control
      - Possibly protracted engineering effort with ~limited bottom line effect
    - SSR pulsed power operations
      - Redesign of SSR cavities with stiffer element or refined tuning control

LE Cavities and Cryomodules

Risk Limitation through RD&D

- HINS and SRF programs will not perform all the R&D needed o initiate the construction of PrX with a limited and controlled risk
- PrX “LE Cavities and Cryomodules“ RD&D Program will cover the following elements:
  - Development of SSR2 and triple-spoke (TSR) superconducting 325 MHz cavities design. Two prototypes cavities of each with helium vessel, power couplers and slow & fast tuners will be constructed. Mechanical vacuum, cryogenic, low level and high power RF testing will be performed using HINS infrastructure.
  - Design of SSR2 and TSR cryomodules, possibly following SSR1 design.

Collaborators

- Several laboratories are participating, collaborating or exchanging informations with the HINS and SRF programs efforts and have the potential to continue to collaborate with Project X in the future (Nov. '08 PrX Collaboration Meeting
  - ➢ ANL
    - – Physics design and tracking simulations
    - – Spoke cavity and cryomodule development, esp. triple spokes
  - ➢ CERN
    - – Chopper development
    - – High power RF vector modulator development
  - – Indian institutions
    - ➢ All aspects of superconducting cavity, power coupler and cryomodule design, fabrication, and testing

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Collaborators (cont)

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- JLAB
  - SC cavity processing and dressing
  - Cryogenics systems design
- LBNL
  - Low level RF
  - Low energy (RFQ/MEBT) section design and components
  - Beam Instrumentation
- SNS
  - Ion Source

Summary

- The Project X ICD describes the 325 MHz low-energy section of the Project X Linac extending to 420 MeV and based on HINS technologies
- The HINS programs actively pursues and is accomplishing technological developments important to Project X and its upgrade paths
- The cost range presented in this review for the "LE Cavities and Cryomodules" is based in several cases on *actuals* rather than *estimates* for beam elements meeting the PrX requirements
- The January 2008 RD&D document identifies the issues important to the 325 MHz Linac and lays out a timeline for addressing those
- Potential collaborators for major 325 MHz Linac systems and components have made their interests known