# COMMISSIONING AND OPERATION OF SUPERCONDUCTING LINAC AT IUAC DELHI

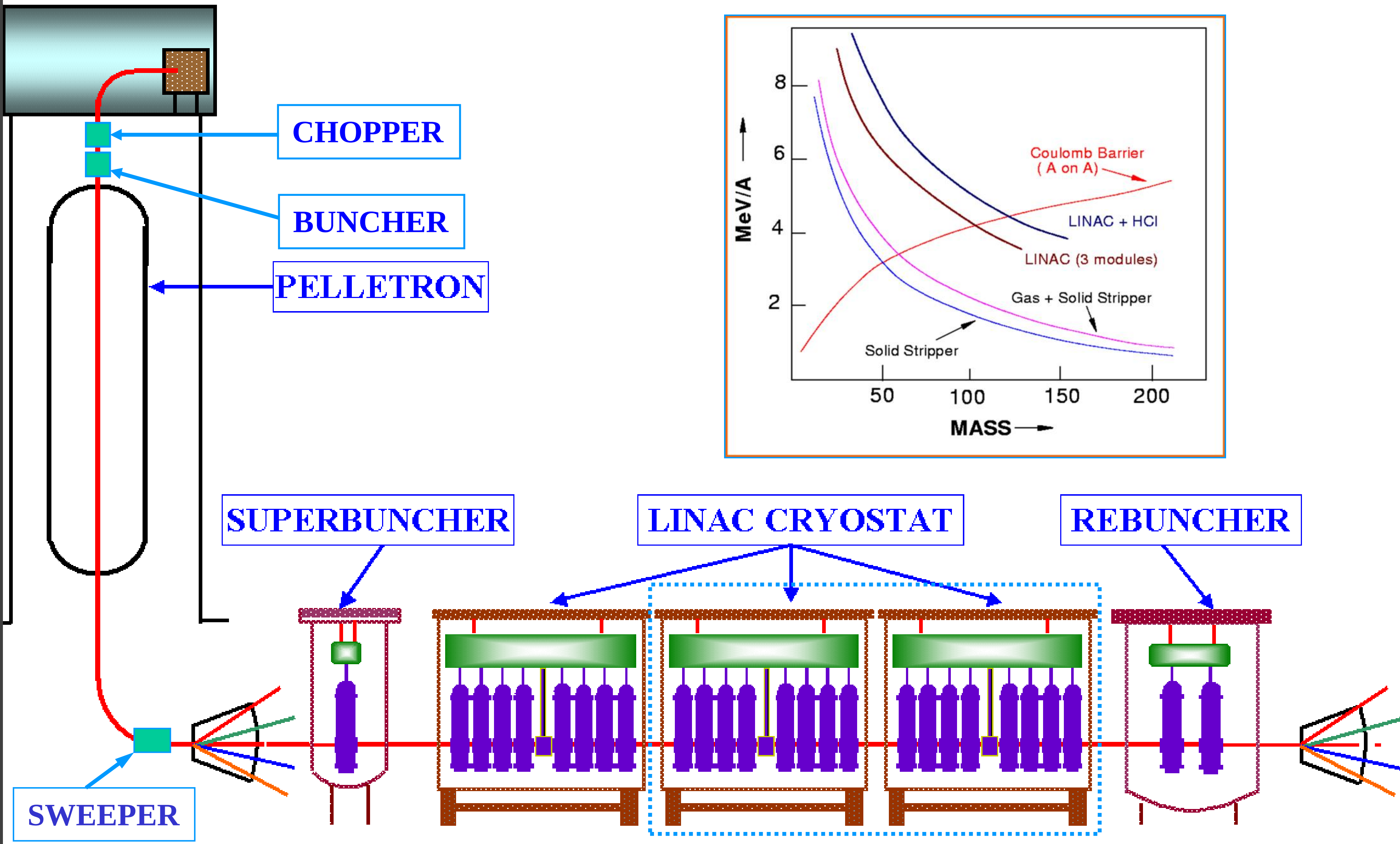
S. Ghosh
On behalf of Linac, IFR, Cryogenics, RF and beam transport group members

**Inter University Accelerator Centre**
**New Delhi – 110067**
**India**

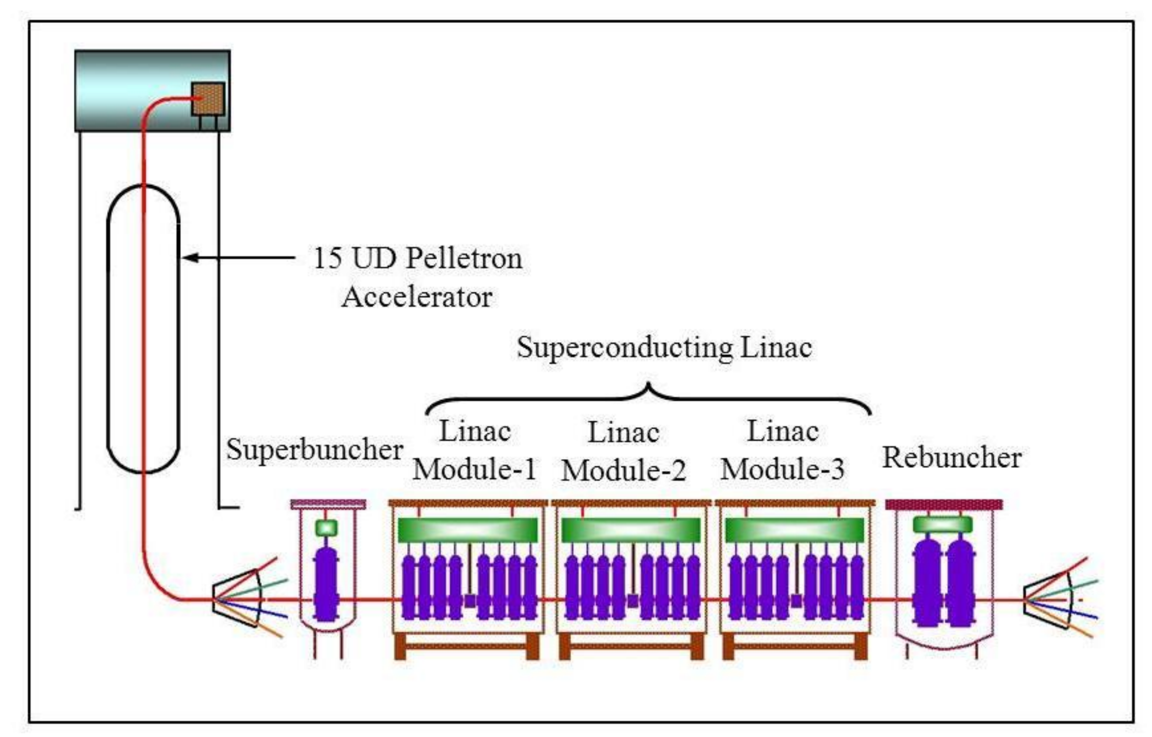
# Highlights of presentation

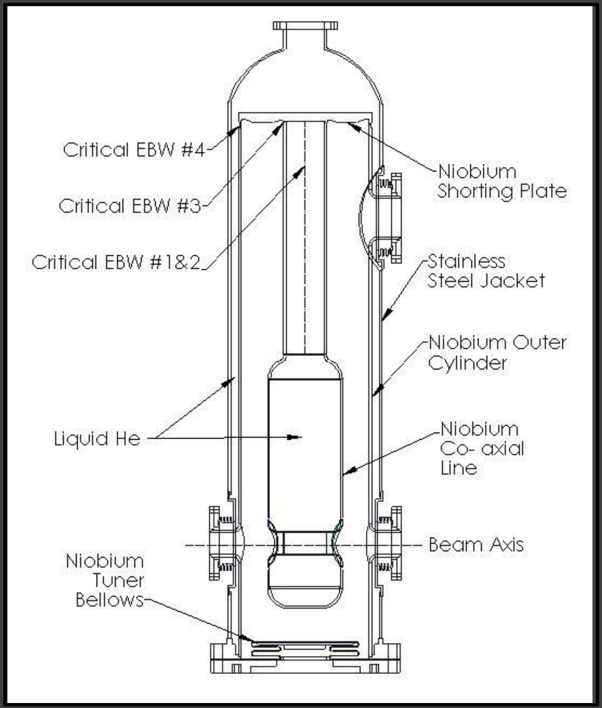
1. Introduction to Linear accelerator system of IUAC
2. Main Components of SC Linac
3. Delivery of linac beam by first two cryostats
4. Remaining Challenge
5. Random Phase focussing
6. Status of completion
7. Conclusions

# Layout of the Accelerator system of IUAC



# Superconducting Linac at IUAC



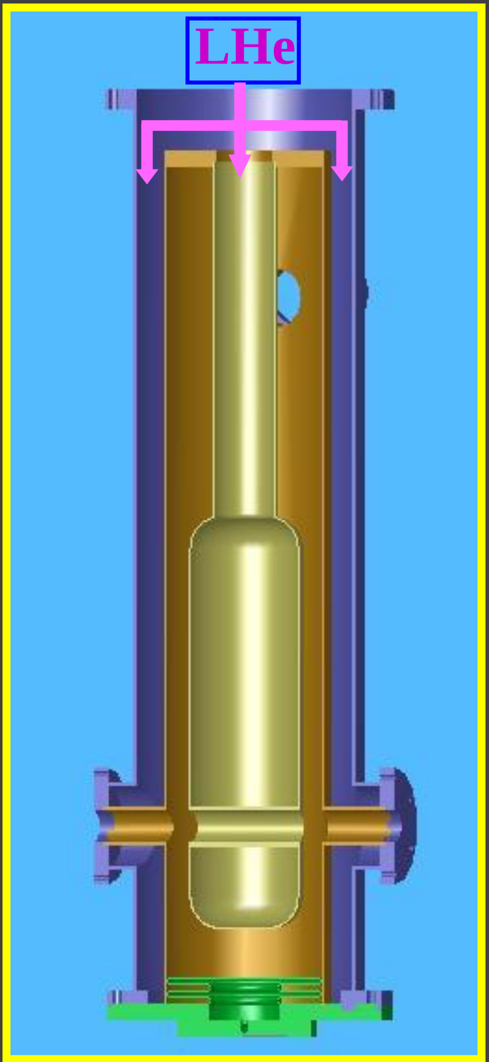




Nb Quarter Wave Resonator, Total no. of EBW joints ~ 35

$E_{Gain}$ = 15 MV (Pelletron) + 15 MV (SC Linac)

- All identical structures
- 27 resonators
- f = 97 MHz
- $\beta = 0.08$

# Quarter Wave Resonator (QWR) of IUAC



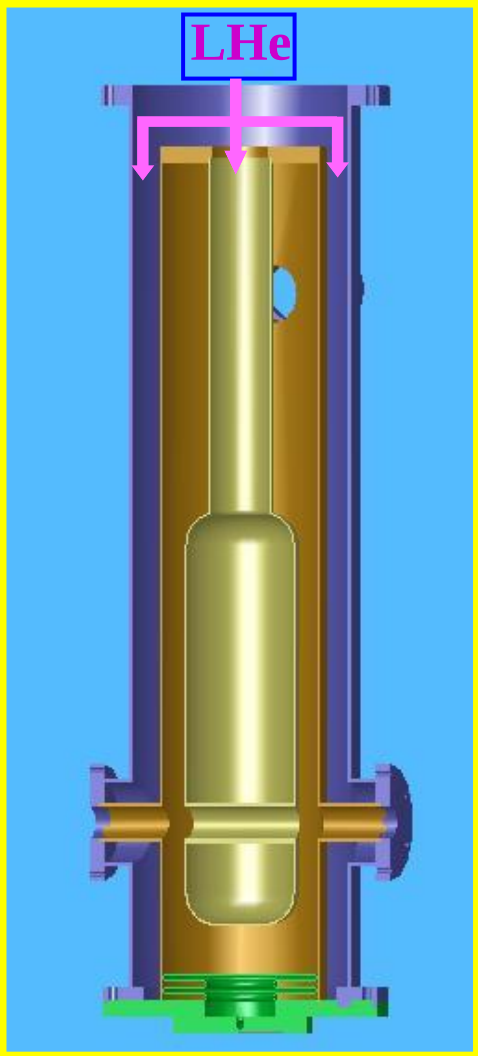

QWR sectional view

Mechanical tuner (Nb)

RF Power coupler

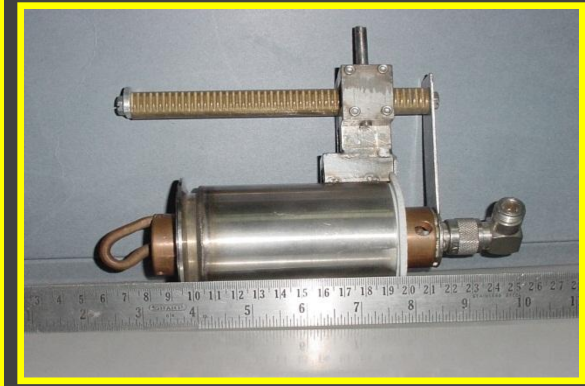
SS-jacketed Nb QWR

# Quarter Wave Resonator (QWR) of IUAC

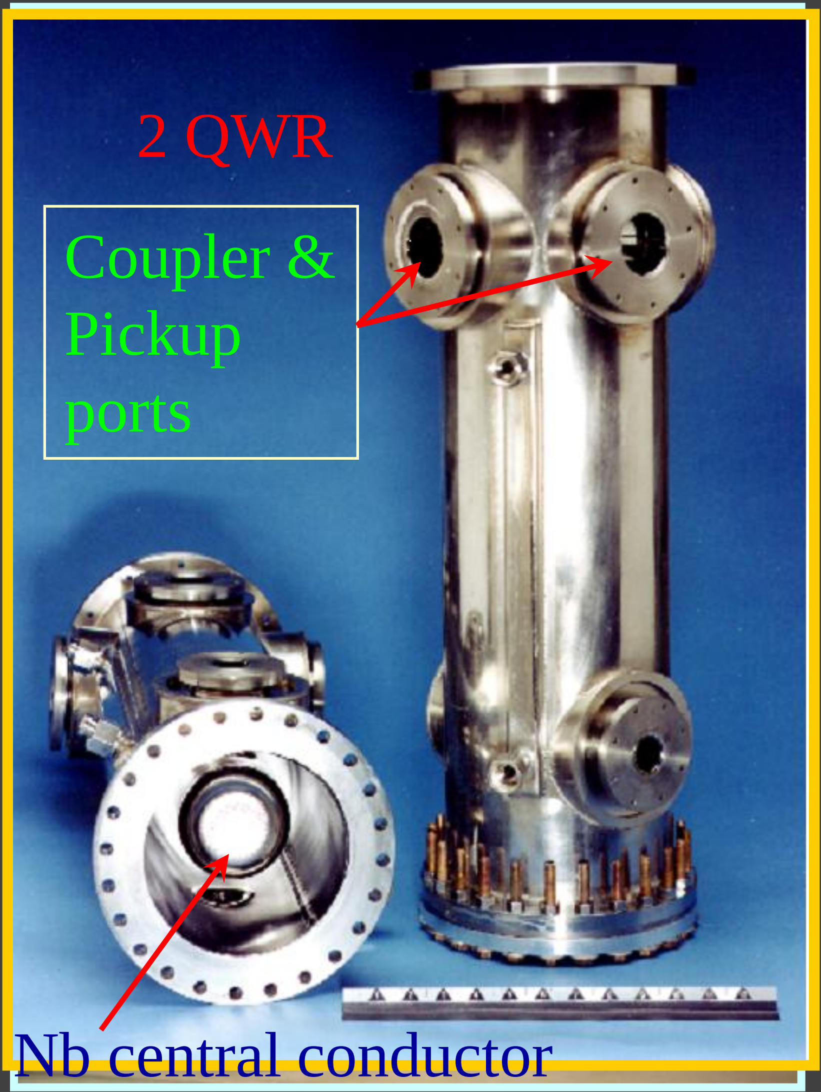



QWR sectional view

Mechanical tuner (Nb)



RF Power coupler




SS-jacketed Nb QWR

# SC Linac-Quarter Wave Resonator

- Prototype Quarter Wave Resonator (QWR) was designed and developed in collaboration with Argonne National Laboratory (ANL), USA.

- QWRs for the 1st Linac Module were built in collaboration with ANL, by using commercial vendors.
  Acknowledgement: Dr. K.W. Shepard, others at ANL

- The infrastructure at IUAC was ready by mid ‘2002. By using in-house developed facilities, remaining resonators
  are fabricated.

# A complete Linac cryostat with eight resonators and a solenoid magnet

Liquid He-vessel

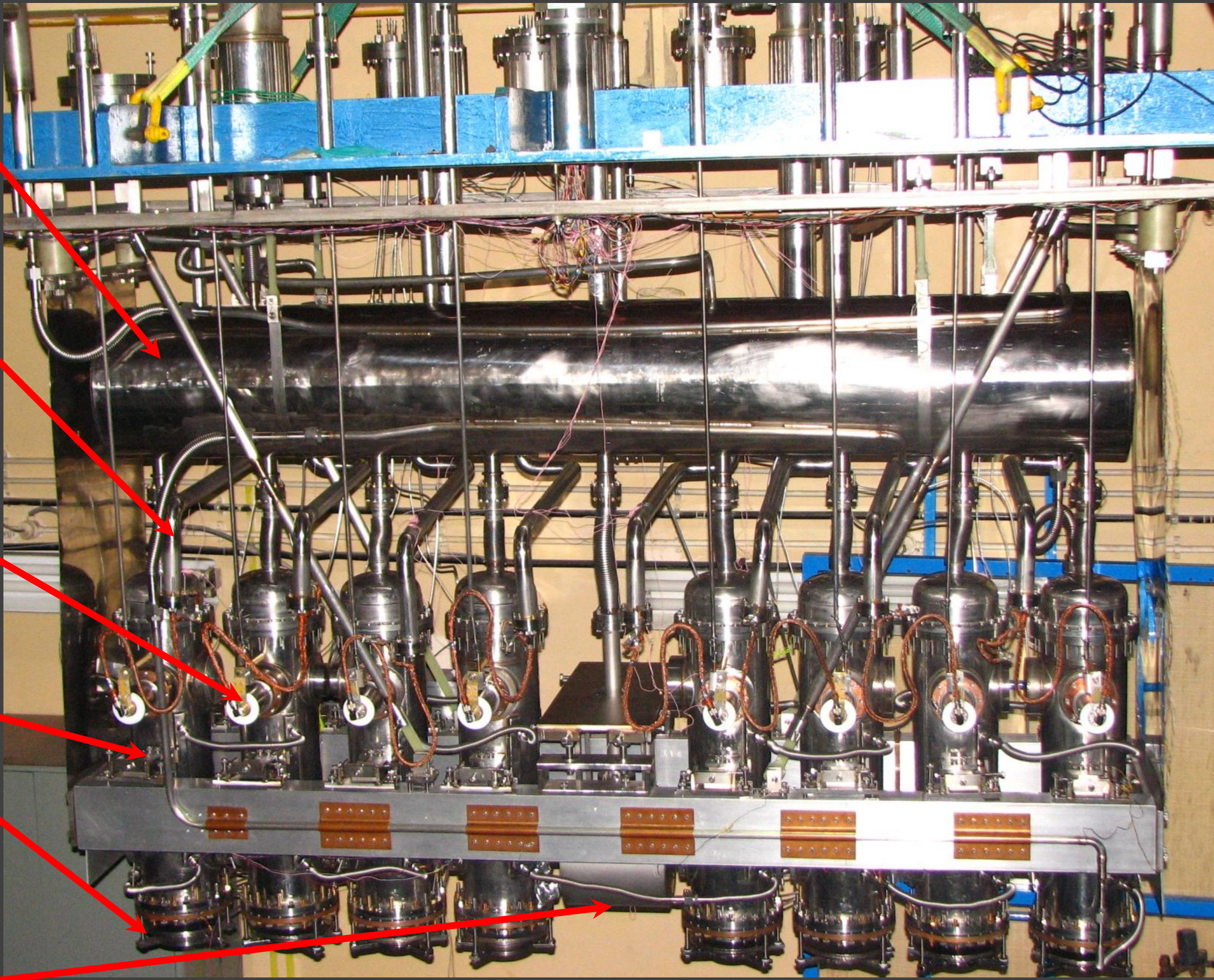
LN2 manifold to cool Power cable

Drive coupler

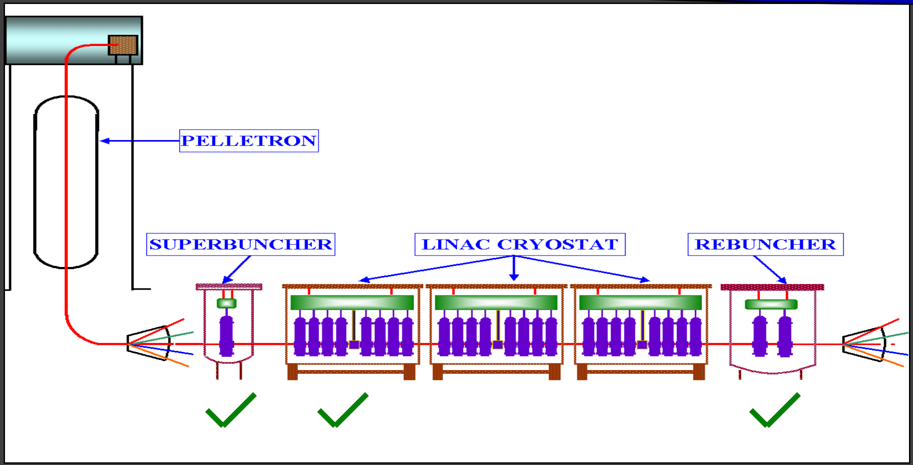
Resonators

Mechanical Tuner

Solenoid



# Beam acceleration by all eight resonators (Linac-1) in 2009 and 2010




❖ In 2009, (SB, linac-1 & RB)

Beam acceleration through Linac ~ 1.5 month

Beam delivered at NAND, HYRA, MatSc-2

❖ In 2010, (SB, linac-1 & RB)

Beam acceleration through Linac ~ 2.5 month

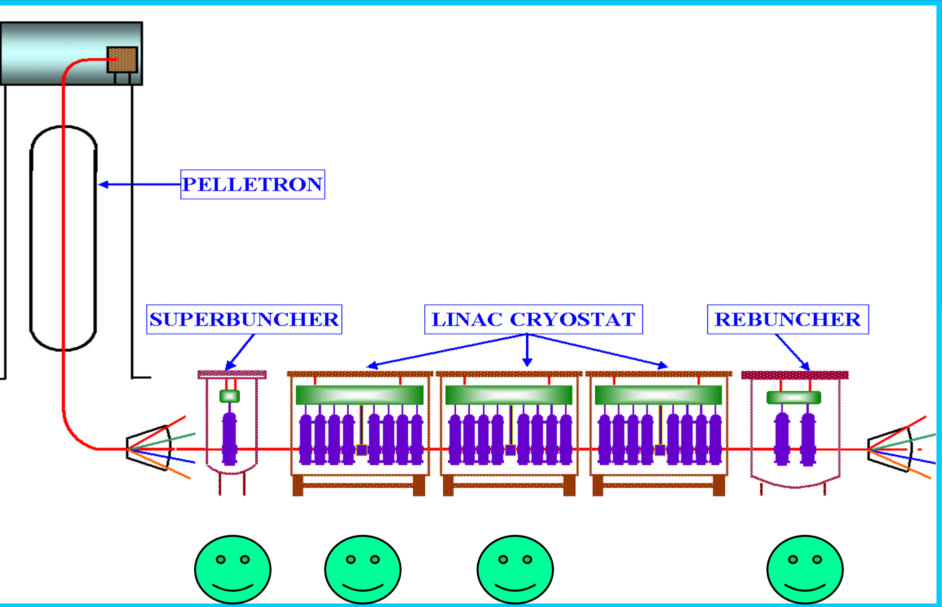
Beam delivered at NAND, HYRA

| Beam | Energy from Tandem (MeV) | Δt by MHB (ns) | Δt by SB (ps) | Energy gain LINAC (MeV) |
|---|---|---|---|---|
| $^{12}C^{+6}$ | 87 | 0.95 | 250 | 19.2 |
| $^{16}O^{+8}$ | 100 | 0.95 | 150 | 26 |
| $^{18}O^{+8}$ | 100 | 0.96 | 182 | 20 |
| $^{19}F^{+9}$ | 115 | 1.08 | 140 | 25.1 |
| $^{28}Si^{+11}$ | 130 | 1.2 | 182 | 37.5 |
| $^{30}Si^{+11}$ | 126 | 1.2 | 140 | 40 |
| $^{48}Ti^{+14}$ | 162 | 1.68 | 176 | 51.2 |
| $^{107}Ag^{+21}$ | 225 | 1.7 | 232 | 74.6 |

## ❖ Operational Highlights:

- All eight QWRs in Linac-1 operational
- Linac Energy gain ~ 3.25 MeV/q
- Locked fields were reduced than that obtained at 6 watts of power
- Rate of unlocking
  ~few hours (initially), 8-10 hrs (stable)
- No major problem was experienced
- Automation of different operation done
- Easy transition to the operational staff

# Beam acceleration by all eight resonators (Linac-1 and 2) in 2011




❖ In 2011, (SB, linac-1, linac-2 & RB)

Beam acceleration through Linac ~ 1.5 month

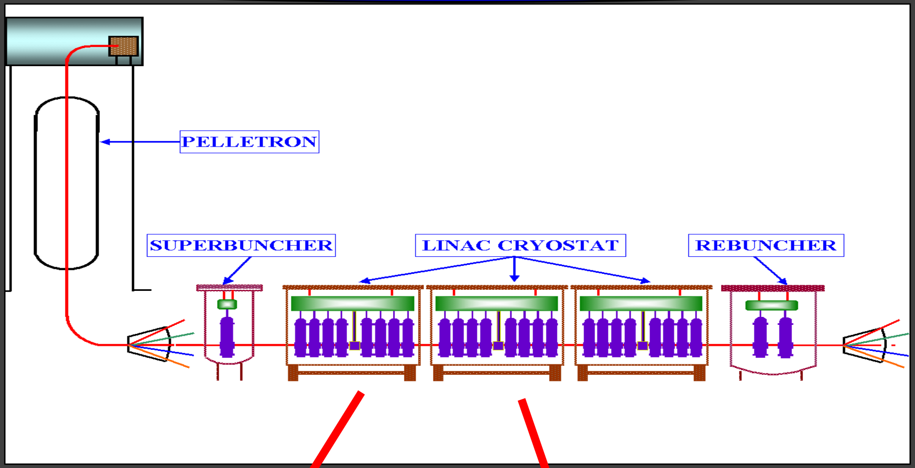
Beam delivered at NAND, HYRA

| Beam | Energy from Tandem (MeV) | Energy gain LINAC (MeV) | Total energy delivered |
|---|---|---|---|
| $^{19}F^{+7}$ | 100 | 37 | 137 |
| $^{28}Si^{+11}$ | 130 | 60 | 190 |
| $^{31}P^{+11}$ | 130 | 58 | 188 |

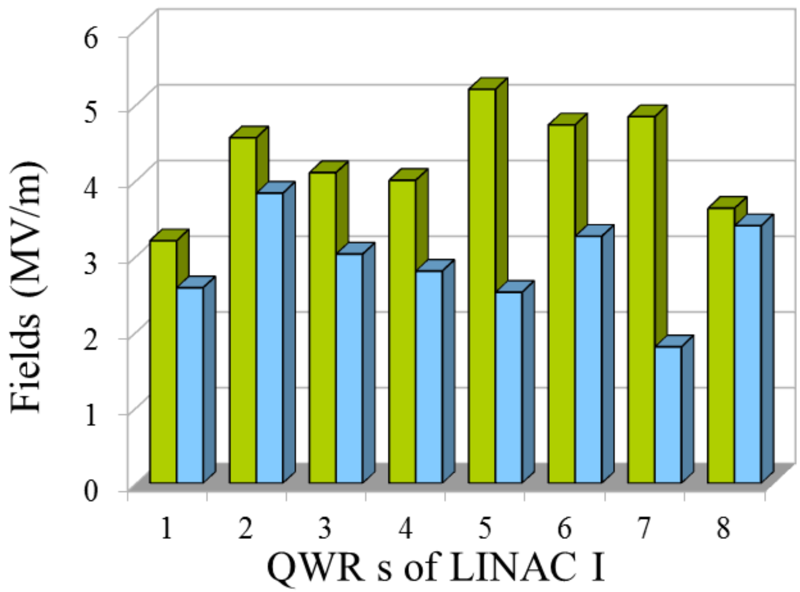
## ❖ Operational Highlights:

- All 16 QWRs in Linac-1&2 operational
- Three beams were accelerated
- Locked fields were reduced than that obtained at 6 watts of power
- Rate of unlocking
  ~few hours (initially), 8-1**0** hrs (stable)
- Being the first test of Linac-2, few problems were encountered
- Concept of Random phase focussing demonstrated successfully

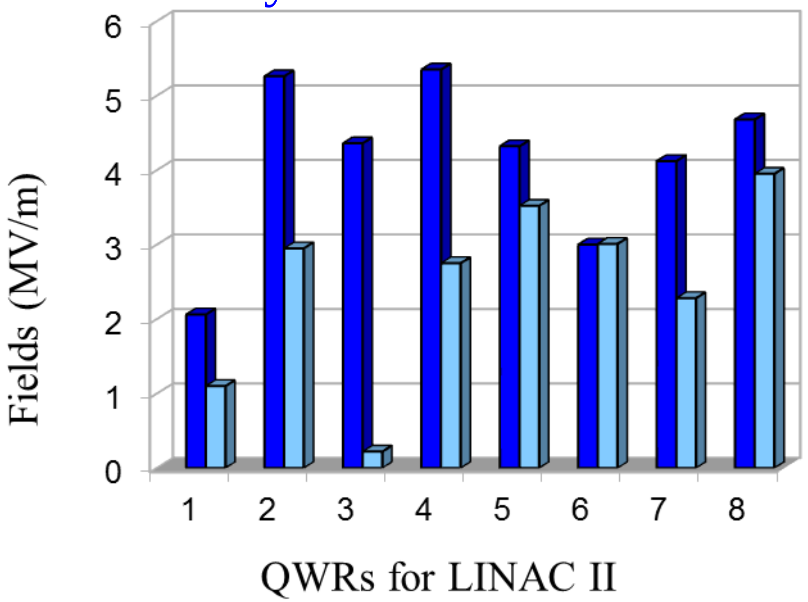
# Beam acceleration by all sixteen resonators (Linac-1 and 2)




Fields@ 6W and locked fields during July 2011 for LINAC-1




Fields@6W and locked fields during July 2011 for Linac-2



# Remaining challenge in linac project

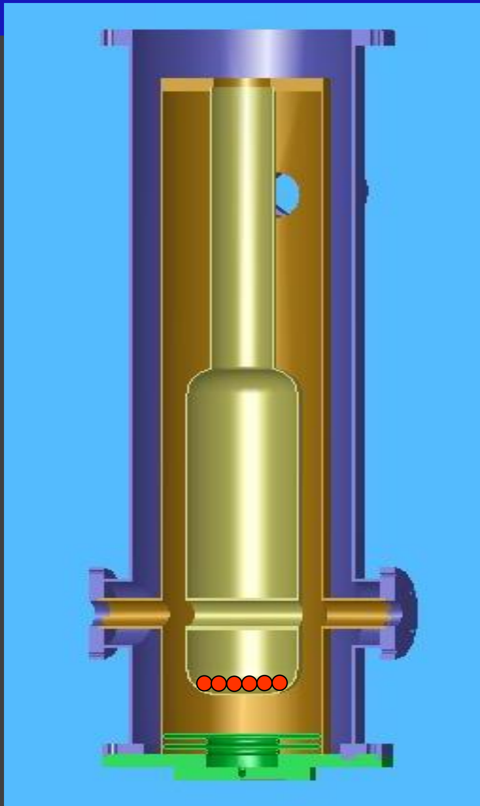
## Lock QWR @ higher fields obtained at 6 watts of helium power

- To lock resonators at fields @ 6 watts, due to presence of microphonics, huge power ≥ 300 watts are necessary.
- When ≥ 300 watts were supplied, cable melting, heating up of the drive coupler causing increased cryogenic loss, metal coating inside resonator and power coupler were observed.

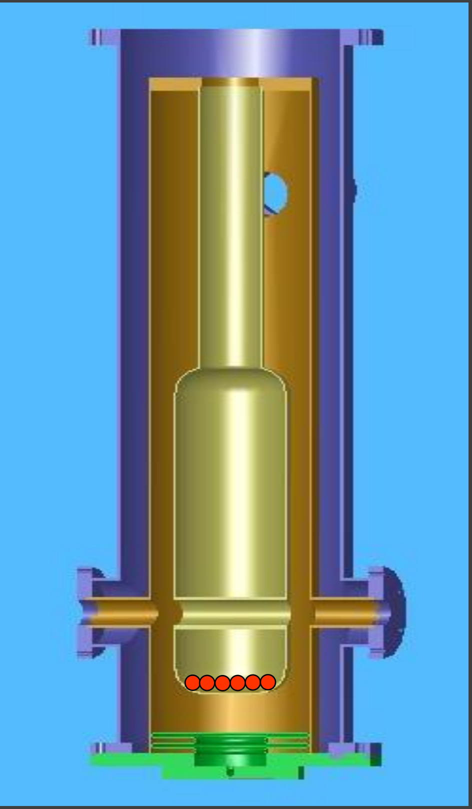
S. Ghosh et al., PRST –Accelerator and Beam, 12, 040101, (2009)

## Actions taken in the recent past

- SS-balls (4 mm dia) has been used as vibration damper to reduce the effect of microphonics
- The power was reduced to ≤ 150 watts to get the same field locked what was obtained at 6 W of helium power
- As it was found out 150 watts was also not safe for long term operation extending months so resonators are operated at ≤ 100 watts of power level



# Remaining challenge in linac project



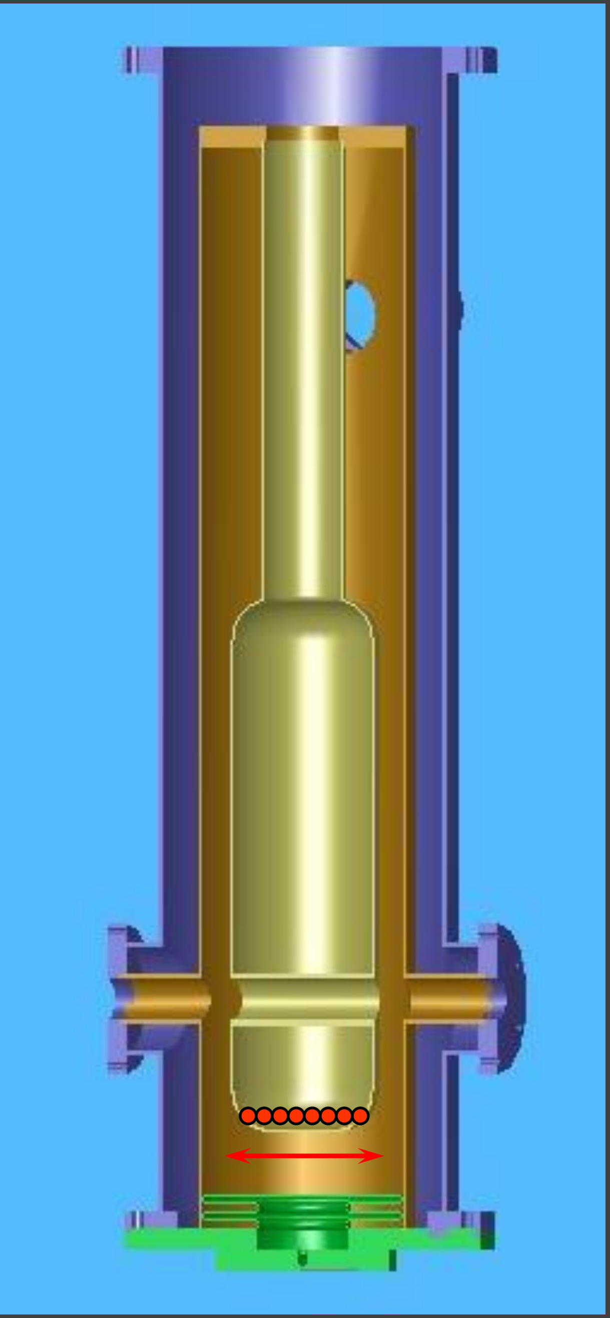
## New Actions

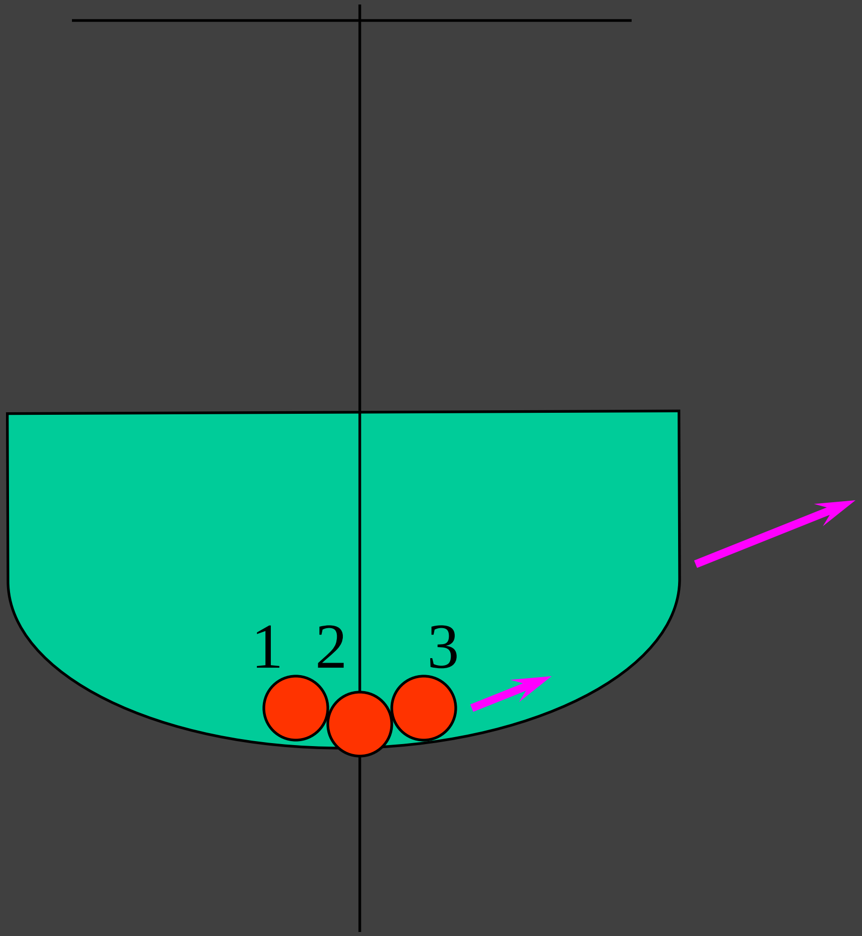
- Instead of using 4 mm balls alone, larger diameter of SS balls are being tried out to increase the efficiency of vibration damping
- An alternate tuning mechanism has been tried out successfully
- An additional cooling mechanism is successfully tested to cool down the power coupler and that will be implemented on Linac-3 resonators
- A commercial high temperature cable (HP226, 275 C) (100% shielded) is tested successfully with higher power and will be connected with the linac resonators.

## Modifications

- A few modifications are tried to improve cavity performance
  - Nitrogen gas bubbling through acid mixture while EP
  - Warm water (~60 C) rinsing with DI water & special detergents

# Physical explanation behind Damping





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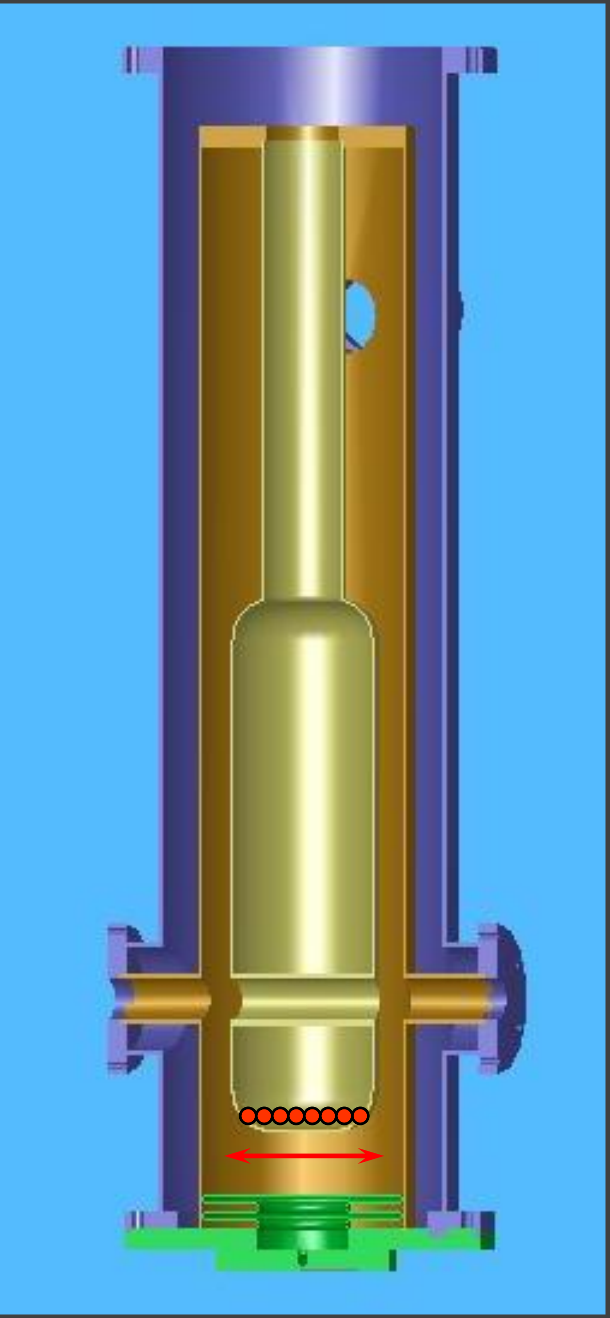
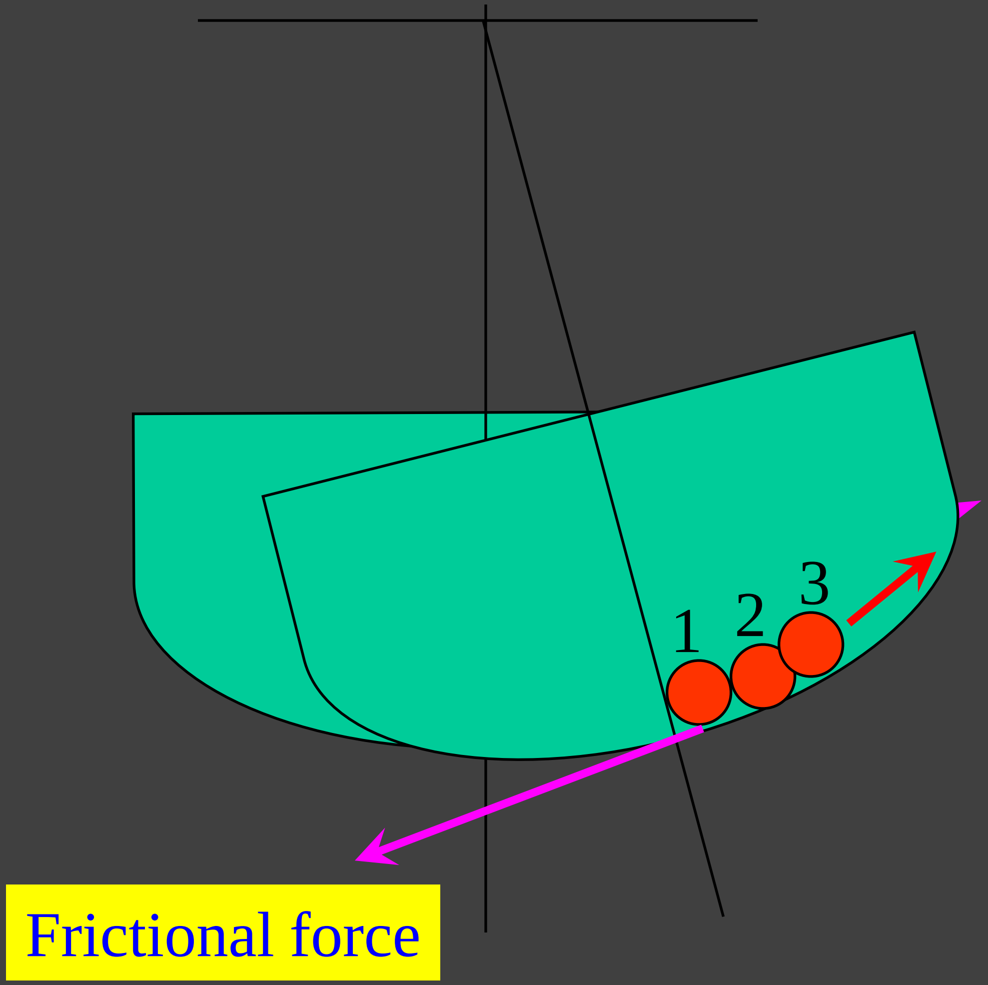
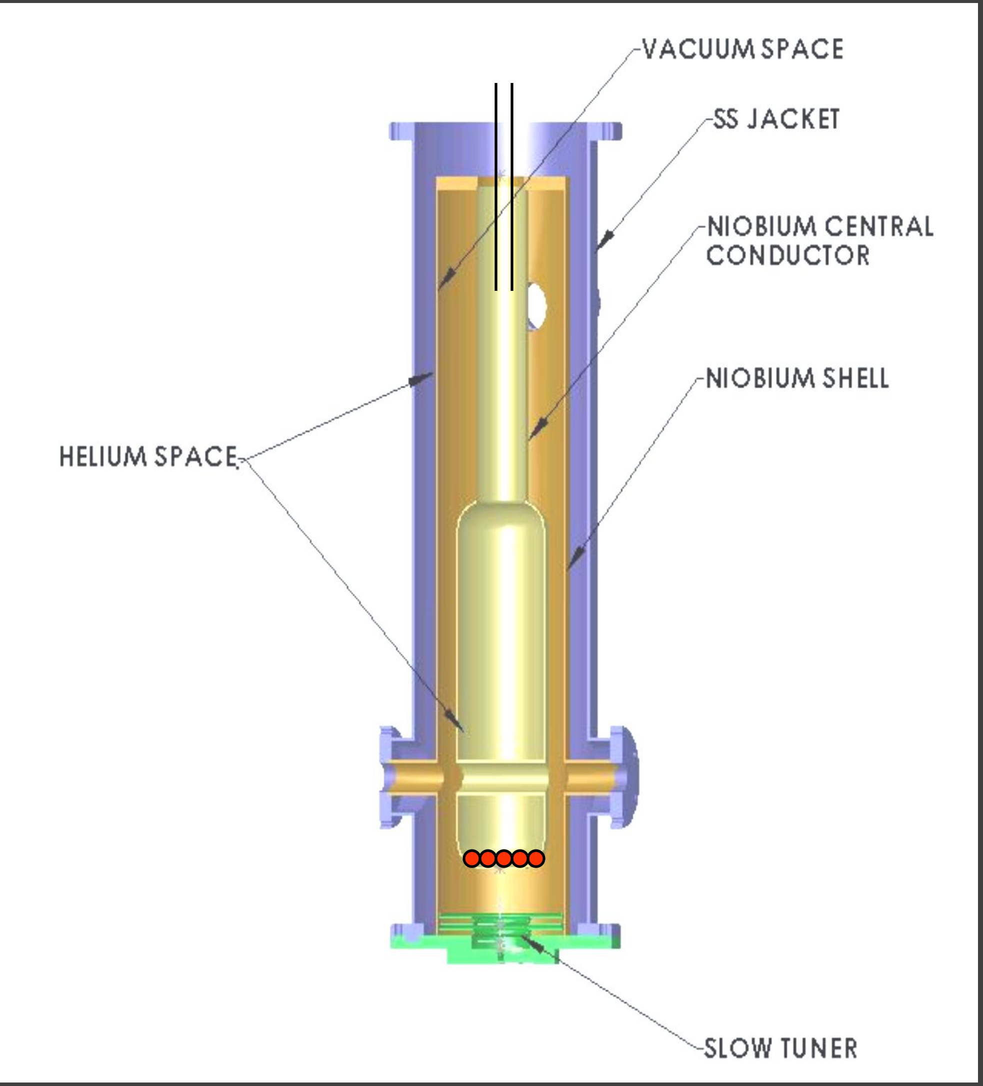


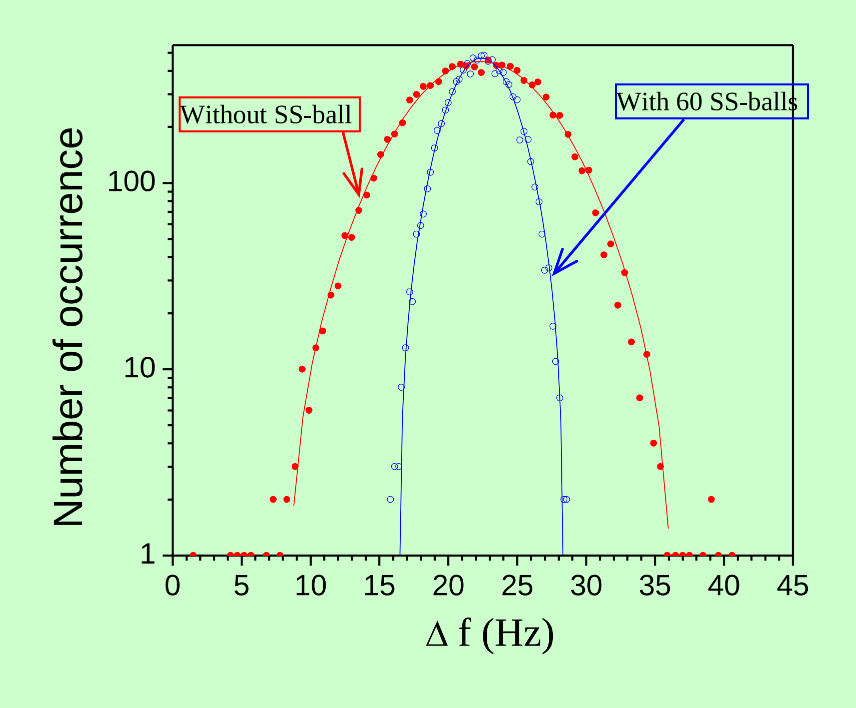


# Damping of resonator vibration

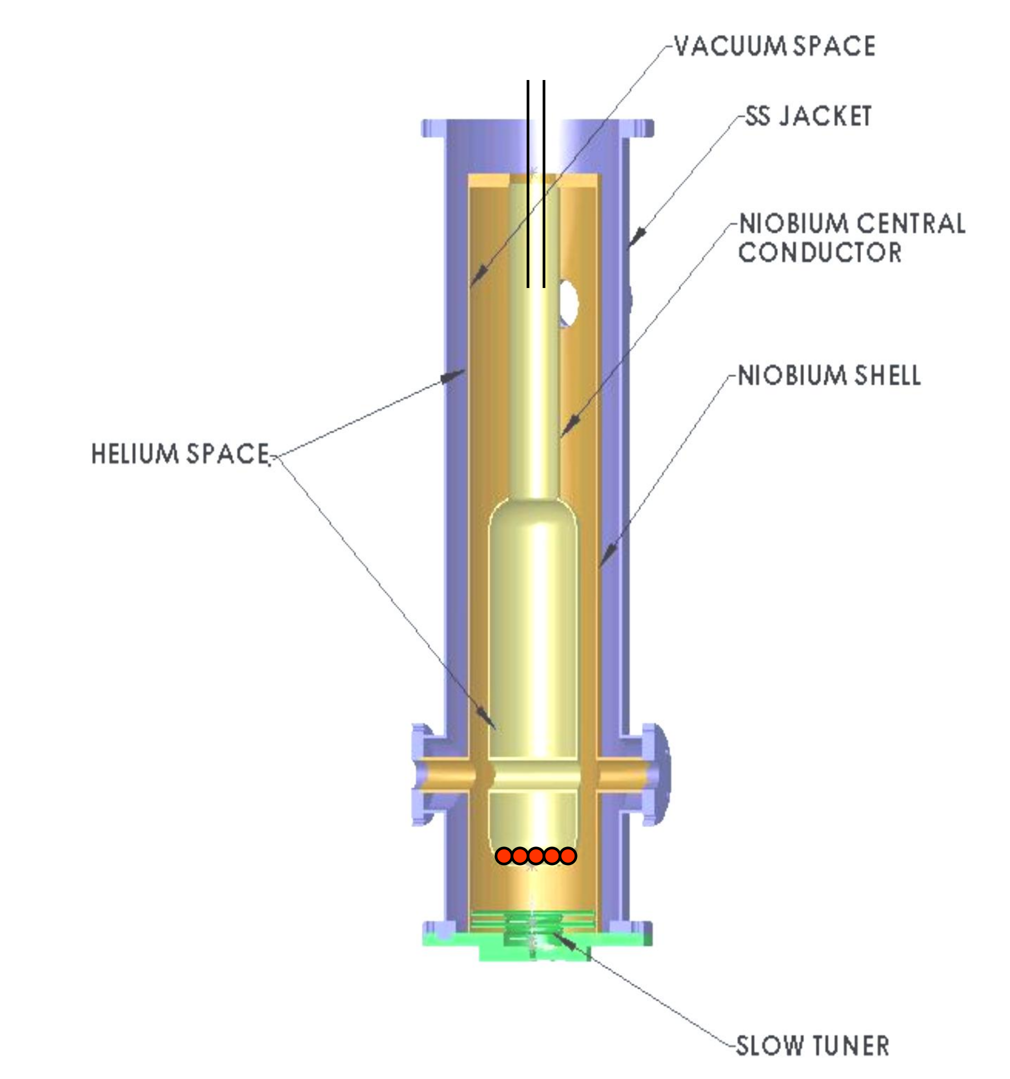



Frequency excursion (Δf) of a niobium resonator at room temperature without SS-ball and with 60 SS-balls (4 mm dia).

❖ At room temperature

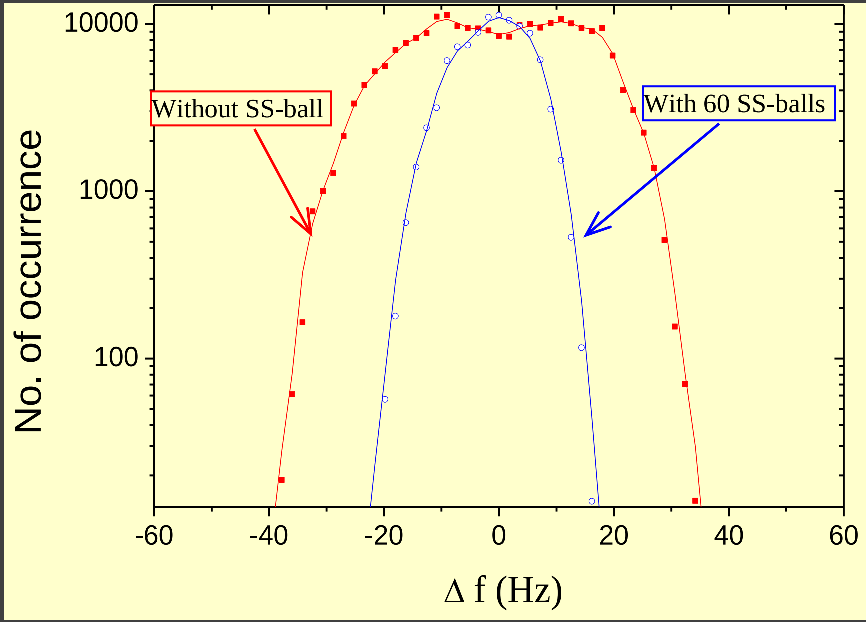


# Damping of resonator vibration




Frequency excursion (Δf) of a niobium resonator at LHe temperature without SS-ball and with 80 SS-balls (4 mm dia)

❖ At LHe temperature



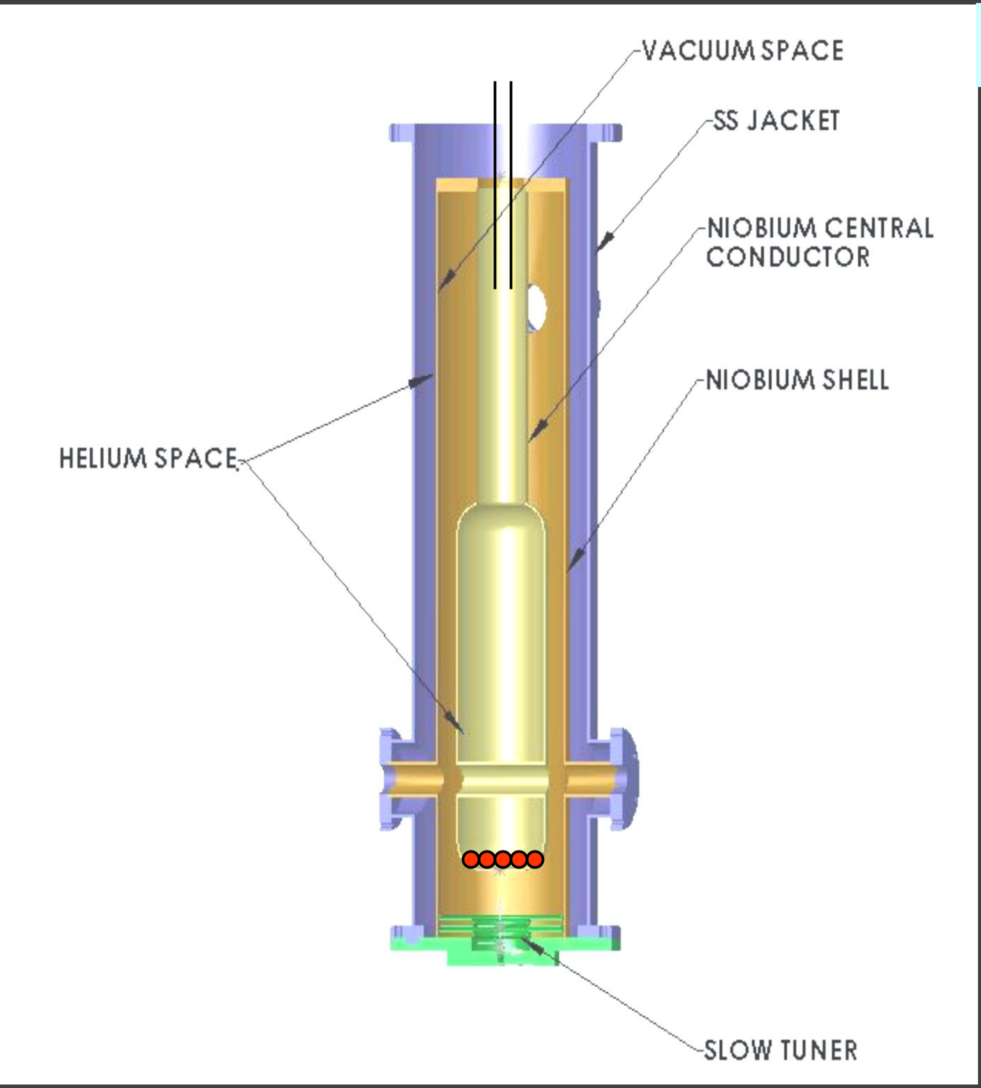
# Results at liquid He temperature

Resonator test with damping mechanism in test and Linac cryostat

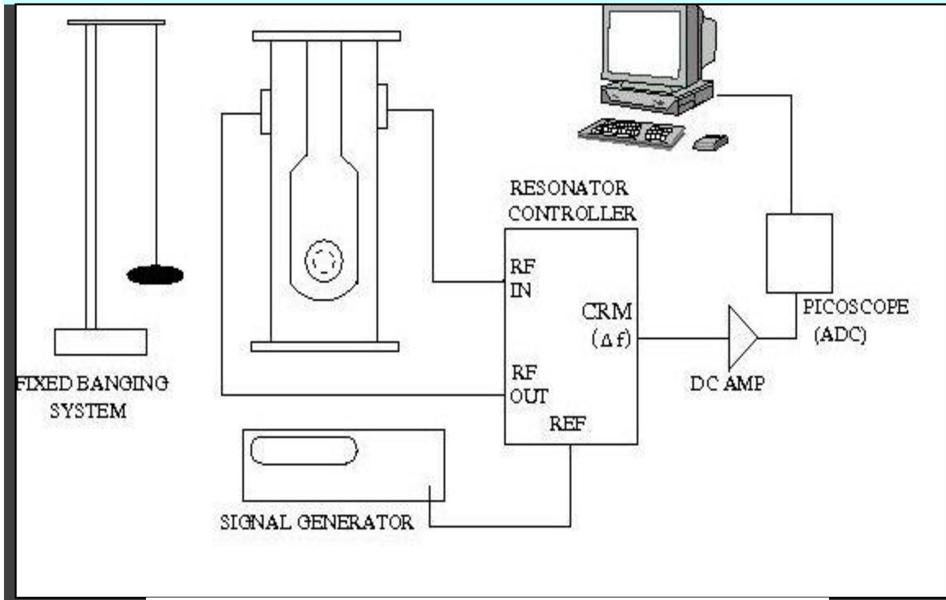
| Cryostat | QWR | $Q_0$@ 6 Watts | $E_{acc}$ (MV/m) @ 6 watt | $E_{acc}$ (MV/m) during phase lock | Required power (W) without damping | Required power (W) with damping |
|---|---|---|---|---|---|---|
| Test | 1 | $1.6 \times 10^8$ | 3.5 | 3.5 | 60 | 28 |
| | 2 | $4.7 \times 10^8$ | 6.0 | 5.0 | 80 | 35 |
| Linac | 3 | $2.1 \times 10^8$ | 4.0 | 3.1 | 218 | 90 |
| | 4 | $2.1 \times 10^8$ | 4.0 | 2.5 | 280 | 100 |

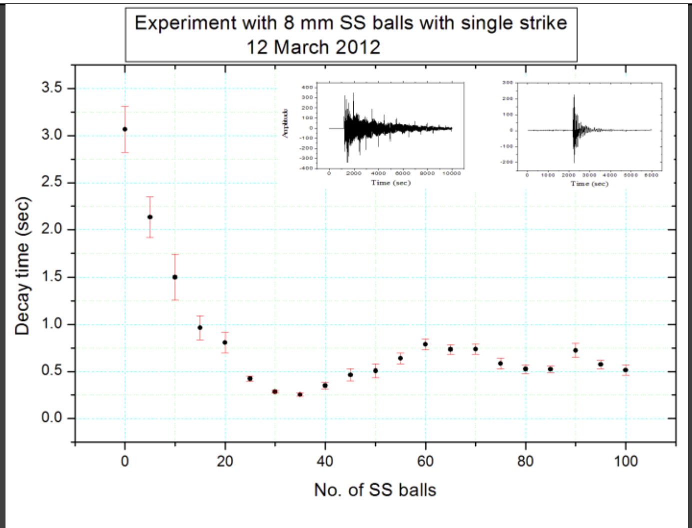
S. Ghosh et al., PRST –Accelerator and Beam, 10, 042002 (2007)

# More experiments to enhance the damping efficiency with bigger diameter SS-balls and their mixtures




## Decay of mechanical vibration is measured

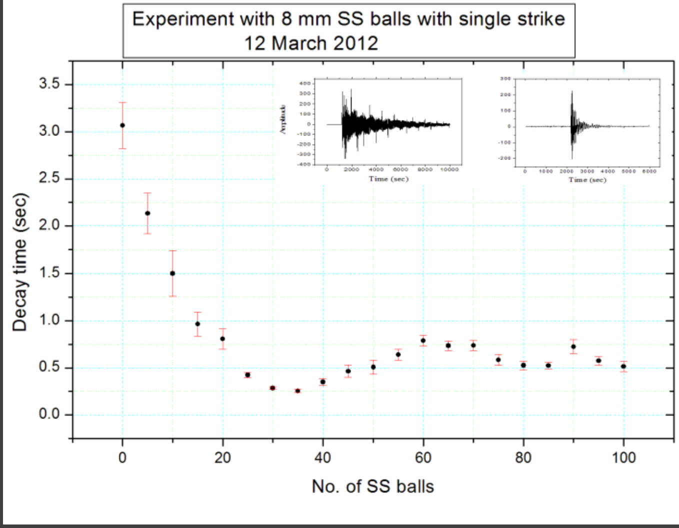


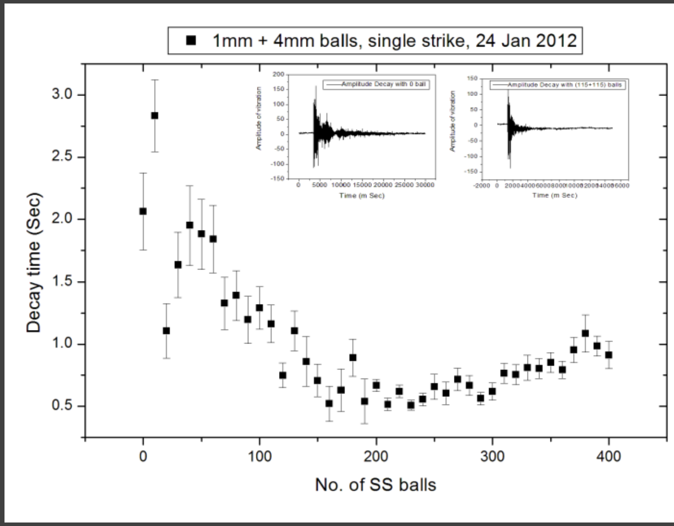



# More experiments to enhance the damping efficiency with bigger diameter SS-balls and their mixtures

## Amplitude Decay time comparision for all the diameters (QWR#I09) from single strike

| Ball Dia# | Decay time with 0 SS balls | Decay time with optimum no. of SS balls | No. of balls for minimum decay time | Reduction factor |
|---|---|---|---|---|
| 1 | To be done | | | |
| 2 | 3.72 | 0.58 | 300 | 6.4 |
| 3 | To be done | | | |
| 4 | 3.14 | 0.40 | 80 | 7.9 |
| 5 | 3.03 | 0.51 | 75 | 5.9 |
| 6 | 2.87 | 0.30 | 65 | 9.6 |
| 7 | 3.25 | 0.39 | 45 | 8.3 |
| 8 | 2.98 | 0.26 | 35 | 11.5 |
| 9 | 3.02 | 0.27 | 25 | 11.2 |
| 10 | 2.11 | 0.29 | 20 | 7.3 |
| 11 | 2.61 | 0.28 | 20 | 9.3 |
| 12 | 2.70 | 0.26 | 17 | 10.5 |
| 2+4 | 4.36 | 0.77 | 70+70 | 5.7 |
| 1+4 | 2.66 | 0.50 | 80+80 | 5.3 |




The cold test with optimum diameter is to be validated soon

# Alternative frequency tuning mechanism

Necessity of continuous frequency tuning

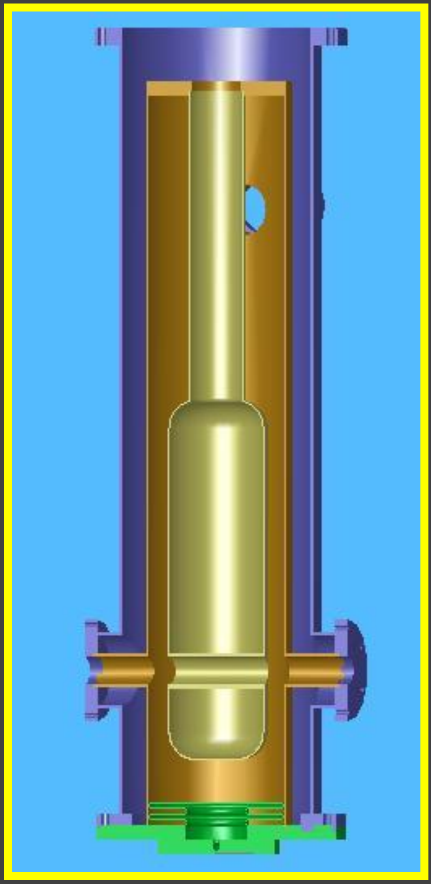
- Typical bandwidth of SC QWR ~ 0.1 Hz ( Q-value ~ $10^9$)
- Vibration induced fluctuation from ambience ~ few tens of Hz
- Frequency drift due pressure fluctuation etc. (hundreds of Hz)

Frequency fluctuation happens in two time scale –

- Fast – due to presence of microphonics
  - controlled by increasing the bandwidth of the resonator with the supply of additional RF power
- Slow – due to Helium pressure fluctuation etc.
  - arrested by flexing the tuner bellows with pure He - gas

Status of present frequency tuning

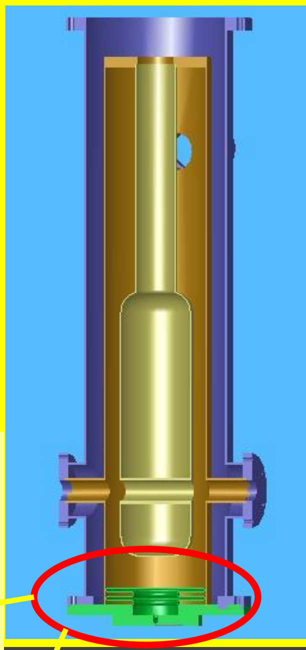
- Working satisfactorily and beam is being accelerated
- Operational in 19 resonators, SB, Linac-1 and 2 and RB cryostats



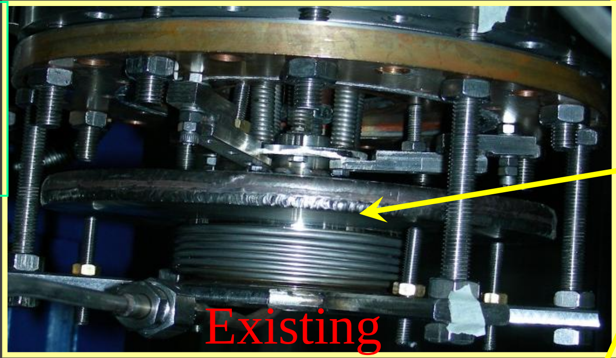
# Alternative frequency tuning mechanism

Why alternative frequency tuning mechanism

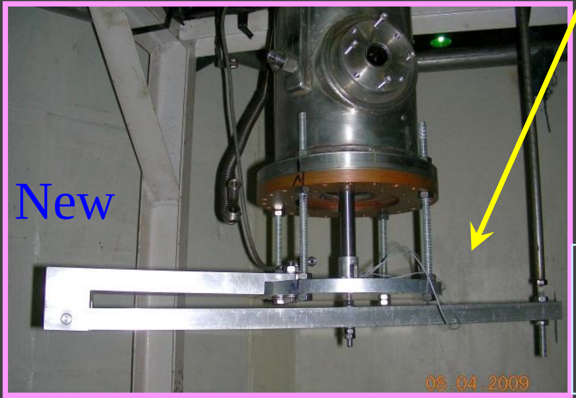
- Average RF power for phase locking will be reduced
- Improved dynamics for the phase and frequency control
- Flexing the tuner bellow by helium gas – Not so simple method
- Continuous usage of pure helium gas – expensive



Piezo-Crystal specifications:
Model – P-844.60, Voltage: -20 to 100 V, Open loop travel: 90 μm, length: 137 mm. Dia:19.8 mm

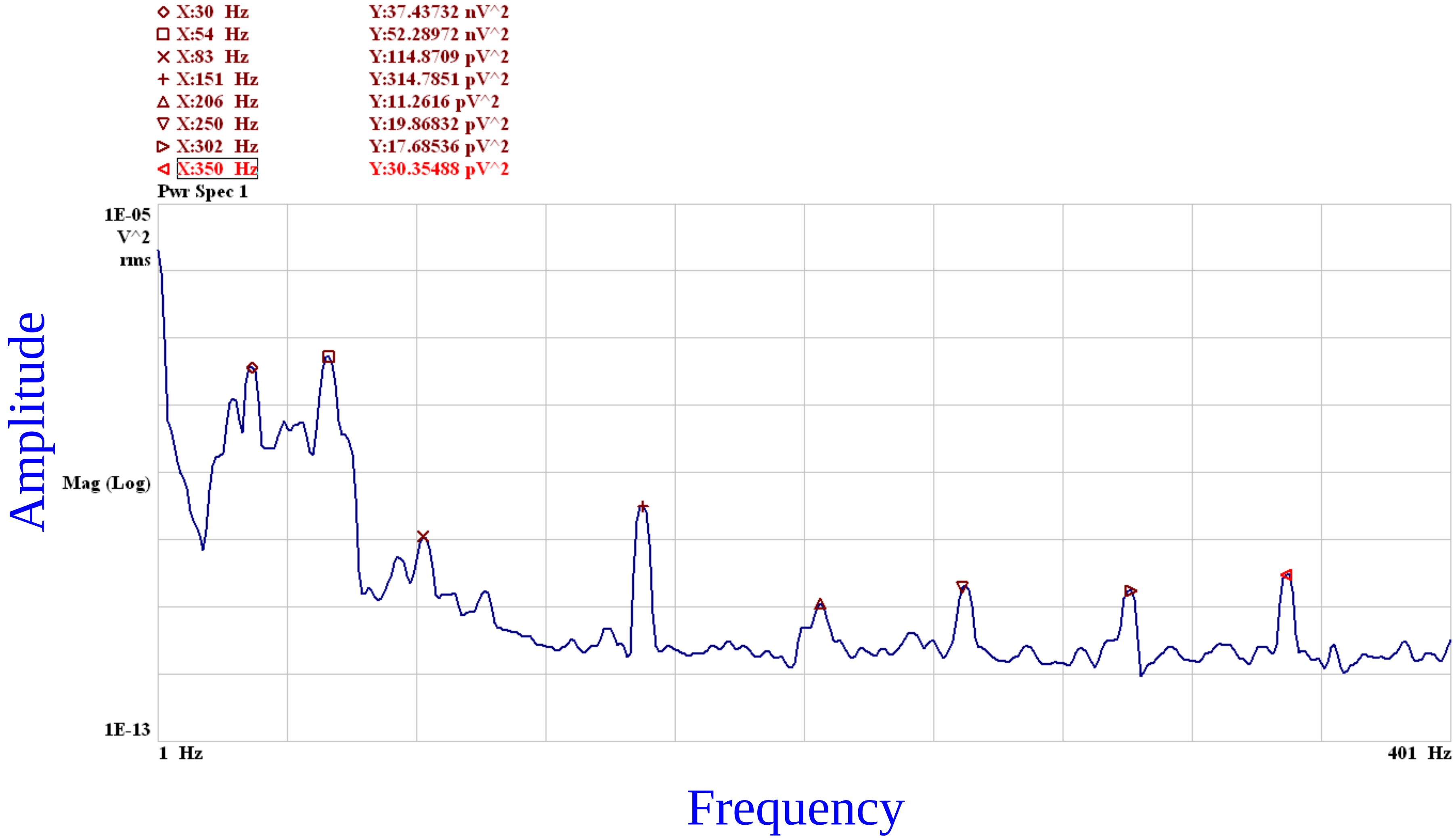



| Gas controlled tuner (Present) | | | Piezo-crystal tuner (new) | | |
|---|---|---|---|---|---|
| Resp. Time | Freq Varia-tions | Amp. Power | Resp. Time | Freq Varia-tions | Amp. Power |
| Seconds | 97,000,000 ± 50 Hz | 100 + 80 watts | ~ 50 msec | 97,000,000 ± 2.5 Hz | 100 + 4 watts |

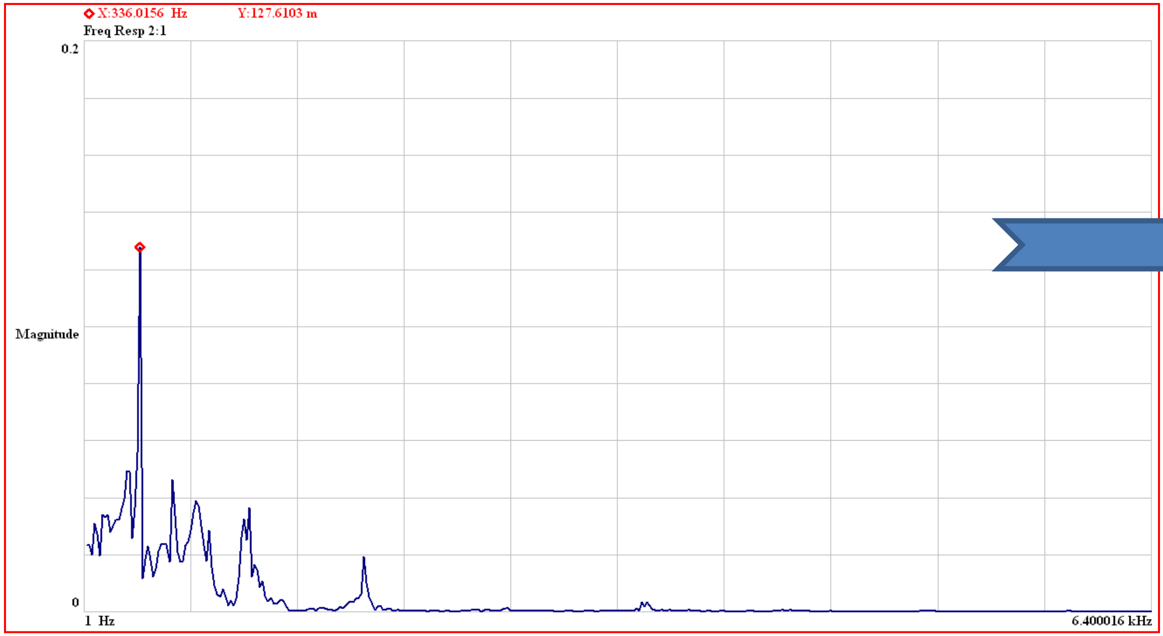



Successfully tested

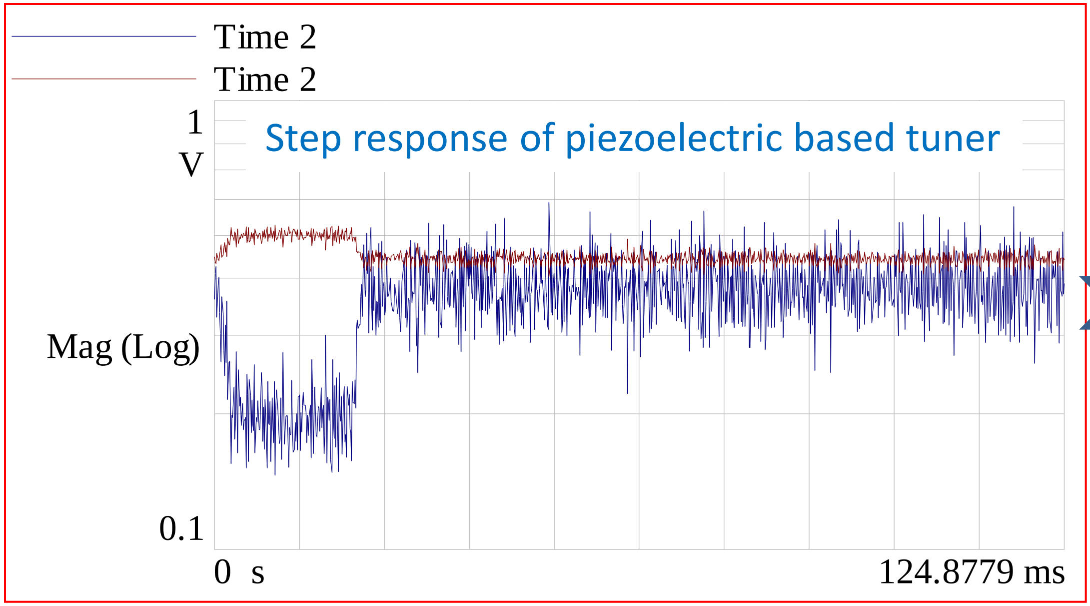
# Resonating modes of the mechanical vibration of a superconducting cavity



# Frequency response of piezoelectric actuator (open loop) based tuner




- 10 V increased on 40 V
- Changing rate (40 – 50V) varied from 1 Hz to 6 kHz (Dynamic Signal Analyser)
- Picks up at 334 Hz
- So correction/response time of the piezo to be kept at ≤ 300 Hz
- Presently it can't replace the fast tuner




- 10 V added on 40 V
- Piezo expanded, freq. decreased
- Rate of change of voltage and frequency seems to be same.

# Alternative frequency tuning mechanism

Tuning range by mechanical movement:

~ 150 kHz at RT

~ 100 kHz at 4.2K

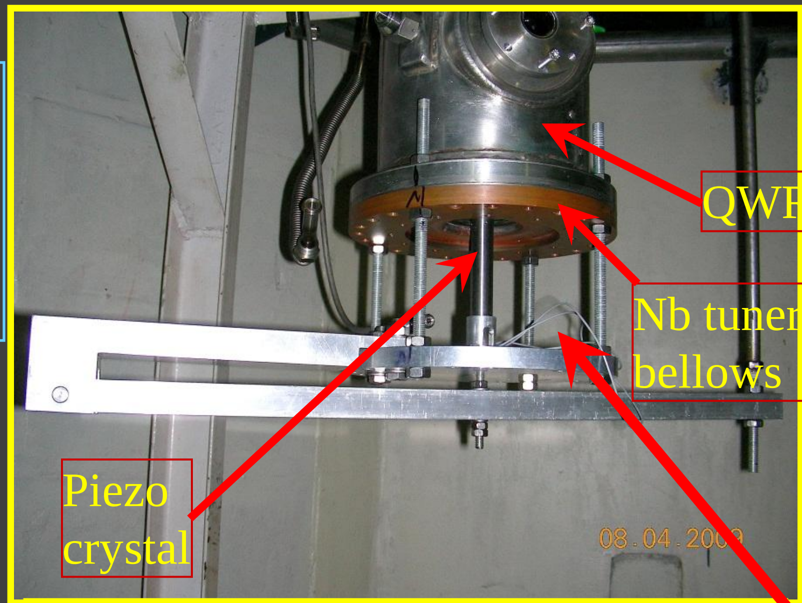
Tuning range by Piezo control:

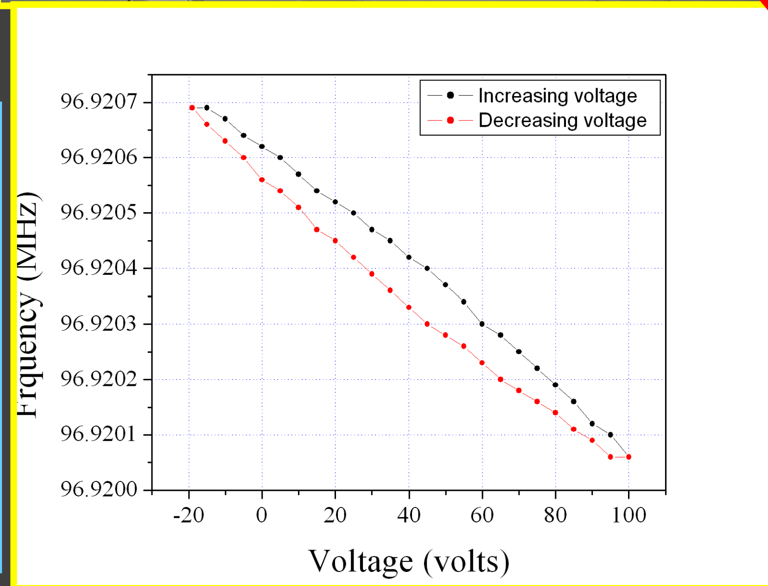
~ 2.5 kHz at RT

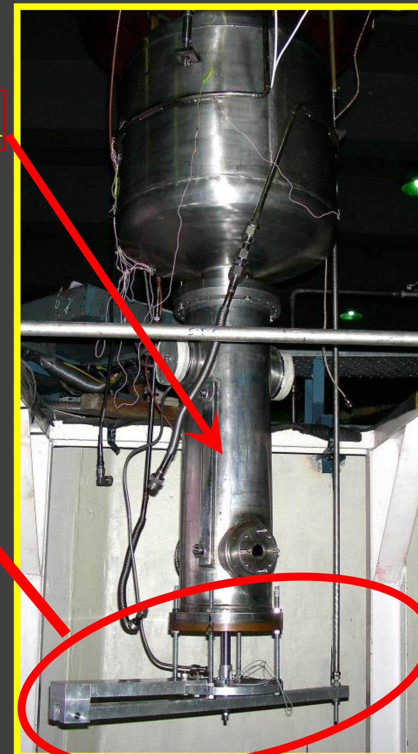
~ 900 Hz at 4.2K

During the last test

- Locking worked very well
- QWR locked @ 3.6 MV/m with less forward power
- Lock was very stable even with induced artificial vibration on the cryostat



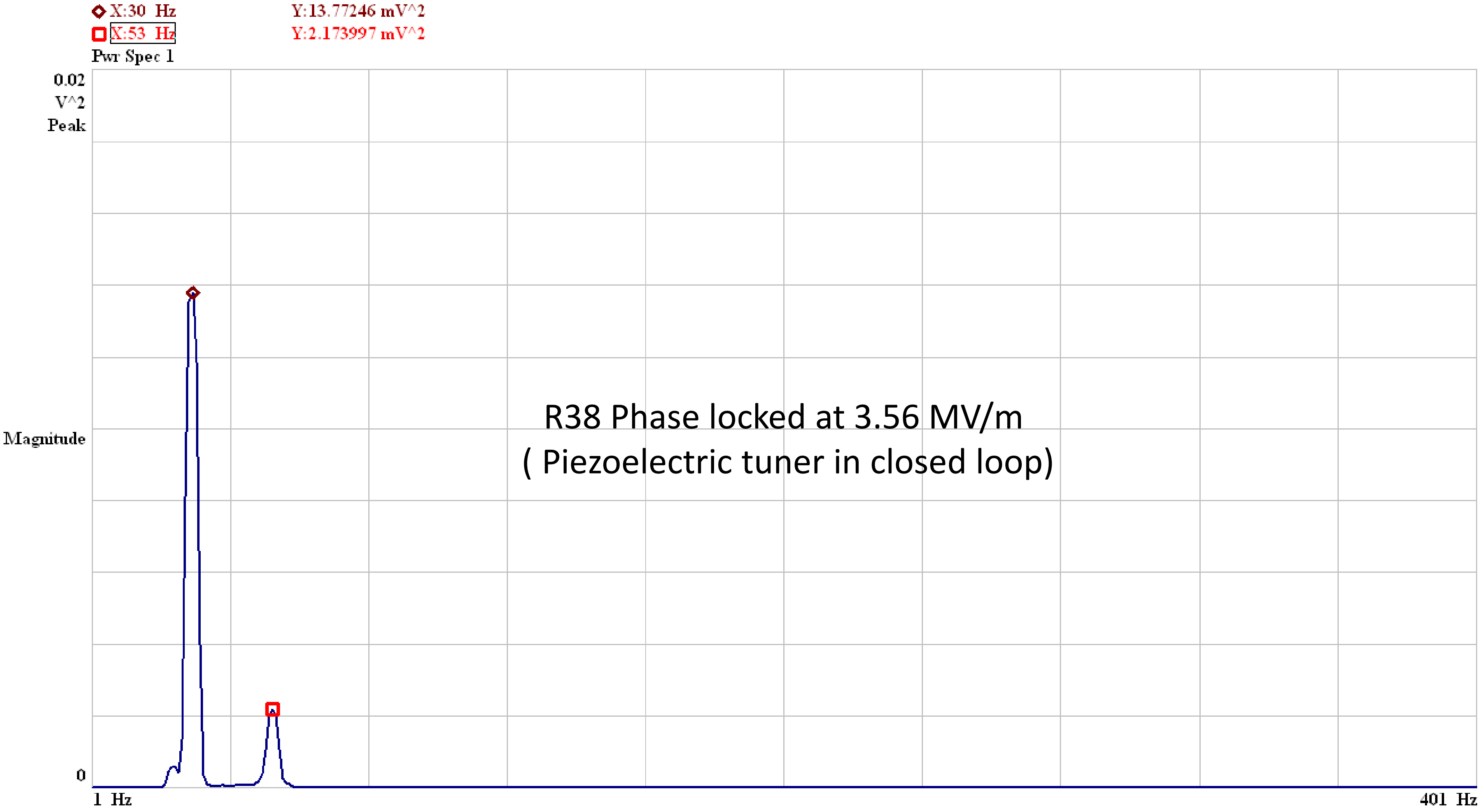



Piezo-Crystal – Bought from Physik Instrumente

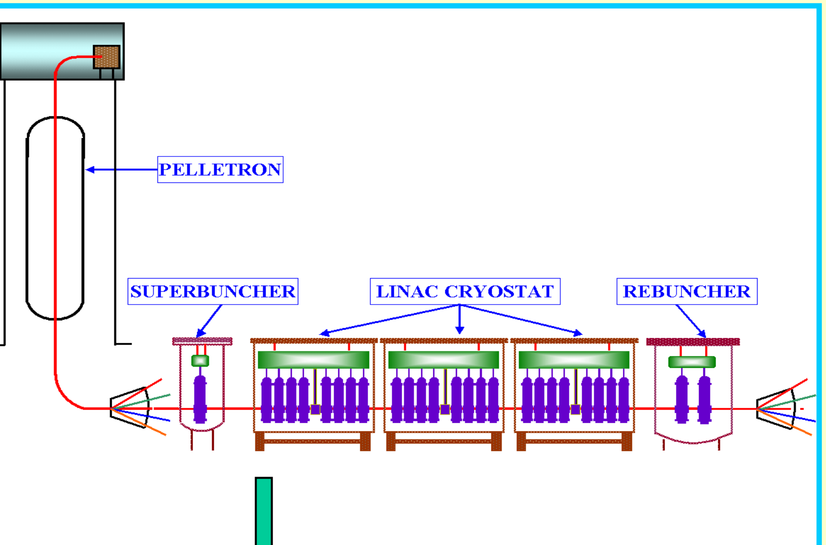
# Frequency response of piezoelectric actuator (close loop) based tuner

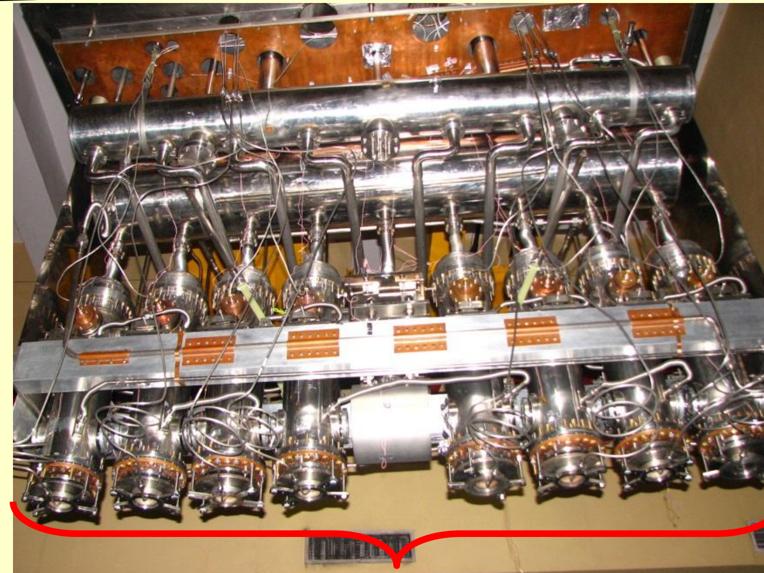
- Fastest correction/response time applied on the piezo was 10 msec
- So all the frequency variation of the resonator up to ≤100 Hz will be corrected

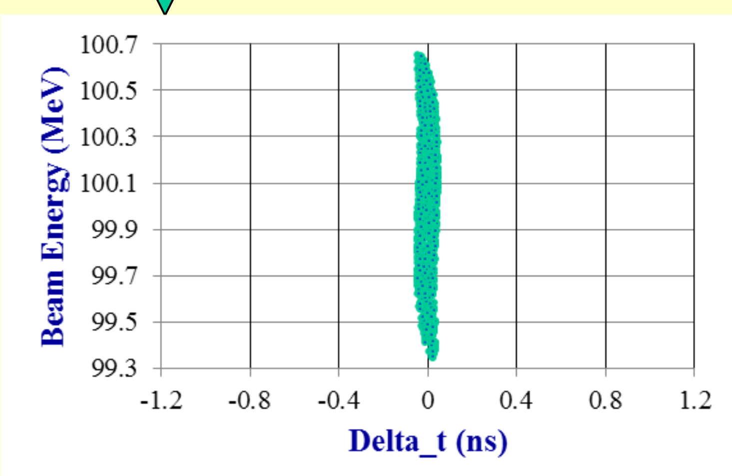


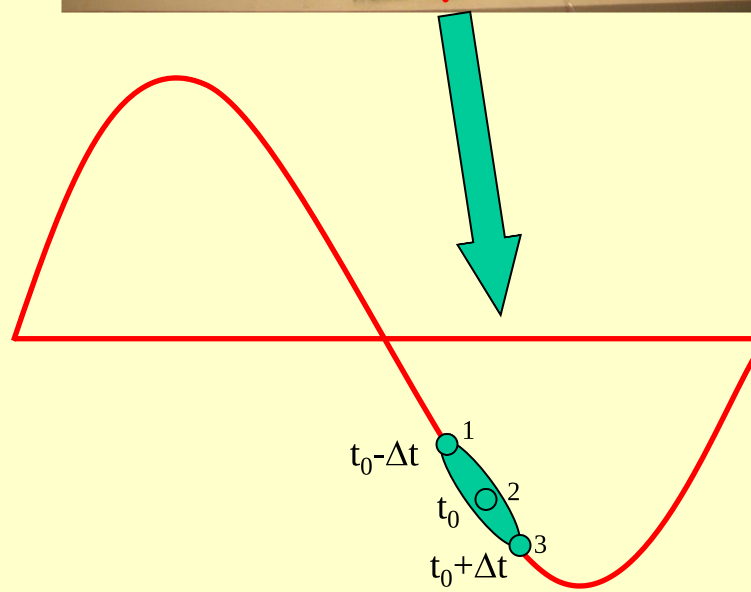
# Random Phase Focussing through linac

Acceleration by linac resonators



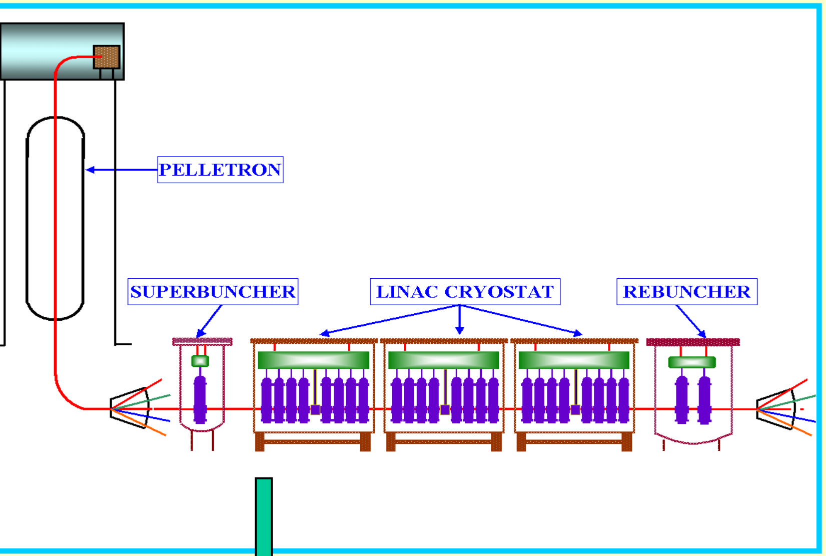


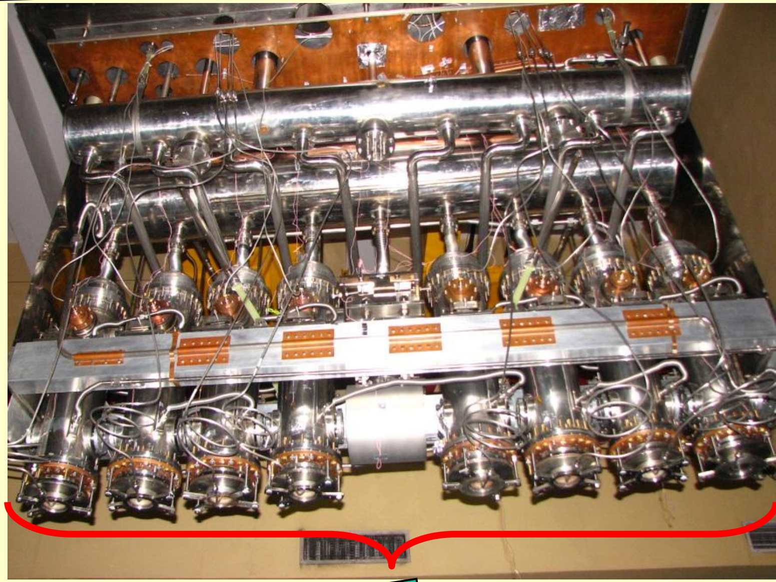



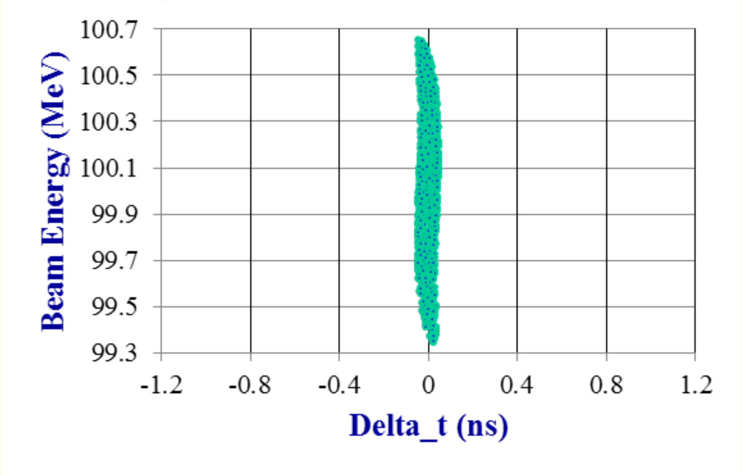

Acceleration at $70^0$ & $110^0$ phase angle

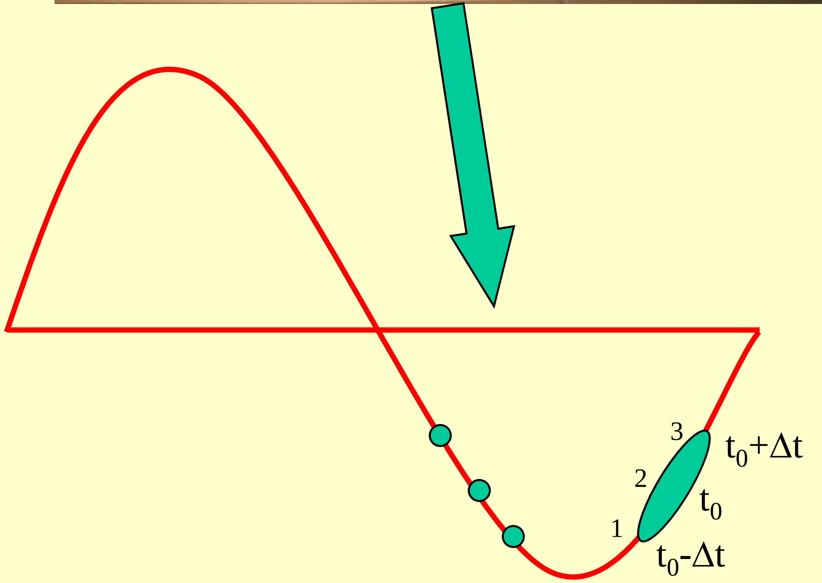
# Random Phase Focussing through linac

Acceleration by linac resonators






Acceleration at $70^0$ & $110^0$ phase angle

# Random Phase Focussing through linac

**A program was developed to understand random phase focussing of linac resonator**

| Beam | Energy (Pelletron) (MeV) | Total Energy (after linac) (MeV) | Acceleration Phases (8 QWRs of Linac-1) | Calculated Time width (GPSC) |
|---|---|---|---|---|
| $^{16}O^{+8}$ | 100 | 125 | All $70^0$ | 1.35 |
| | | | 110, 70 x 7 | 0.886 |
| $^{28}Si^{+11}$ | 130 | 168 | All $70^0$ | 2.12 |
| | | | 110, 70, 110, 70, 70, 70, 70, 70 | 0.95 |
| $^{48}Ti^{+14}$ | 162 | 212 | All $70^0$ | 3.4 |
| | | | 70, 110, 70, 70, 70, 110, 70, 70 | 0.97 |
| $^{107}Ag^{+21}$ | 225 | 297 | All $70^0$ | 4.72 |
| | | | 110, 110, 70, 70, 110, 70, 70, 70 | 1.24 |

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| | | | 7[illegible] | [illegible] |
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## Experimental observation

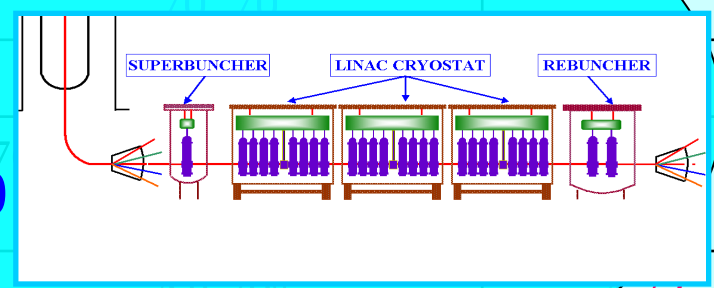
96 (Pell) + 21.5 (Linac) = 117.5 MeV

R12-R18 ON, Phases all @ $70^0$,

**$\Delta t$ = 971 ps**

R12-R18 ON, @ NA, 70, 70, 110, 70, 70, 70, 70

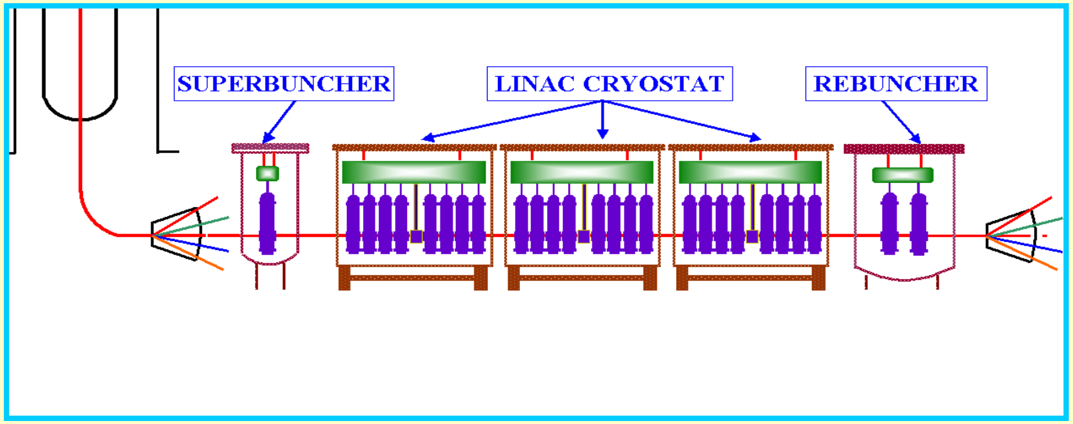
**$\Delta t$ = 800 ps**

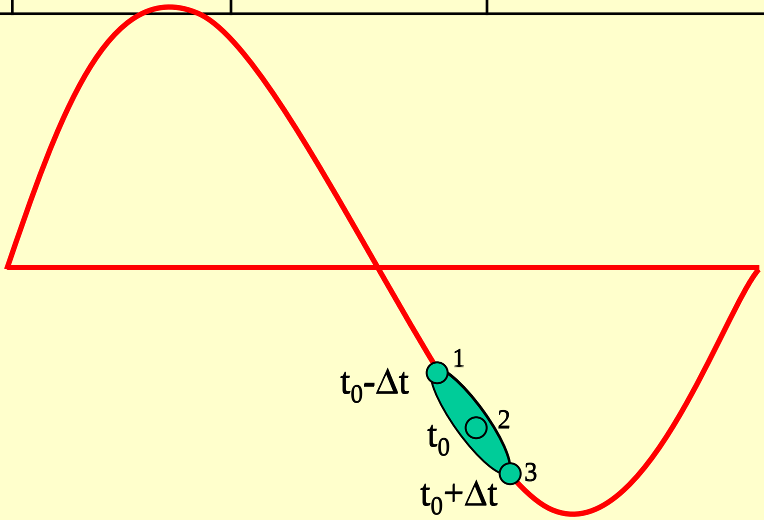


# Random Phase Focussing through linac

**Experimental results of random phase focussing of 16 QWRs**
**In linac 1 and 2**

| Beam | Energy (Pell.) (MeV) | Total Energy (after linac-1 and 2) (MeV) | Predicted acceleration Phases of resonators in linac-1 and 2 to obtain minimum time width | Predicted reduction in delta_t (%) | Measured Time width (GPSC - II) | Experimental reduction in delta_t (%) |
|---|---|---|---|---|---|---|
| $^{28}Si^{+11}$ | 130 | 186 | All $70^0$ | | 2.88 | |
| | | | 70, 70, 110, 110, 110, 70, 70, 70<br>70, 70, 70, 70, 70, 70, 70, 110 | 38.5 | 1.73 | 40 |

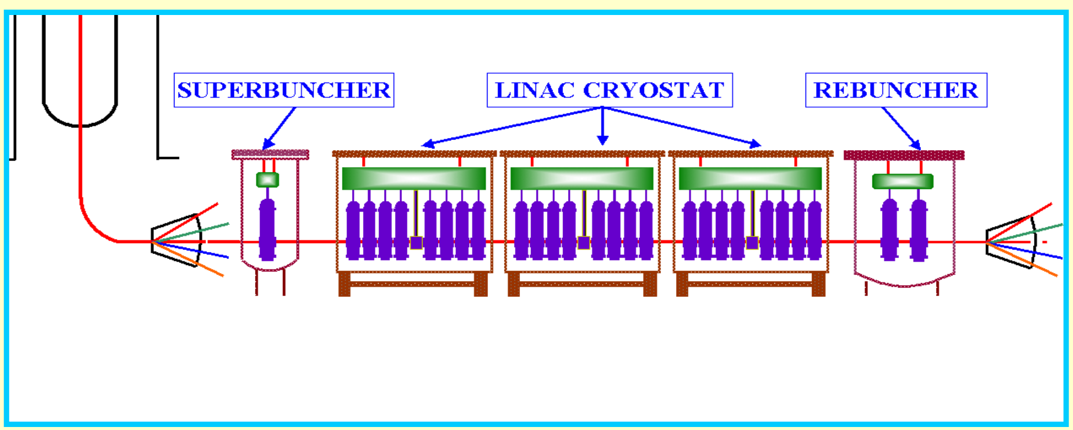


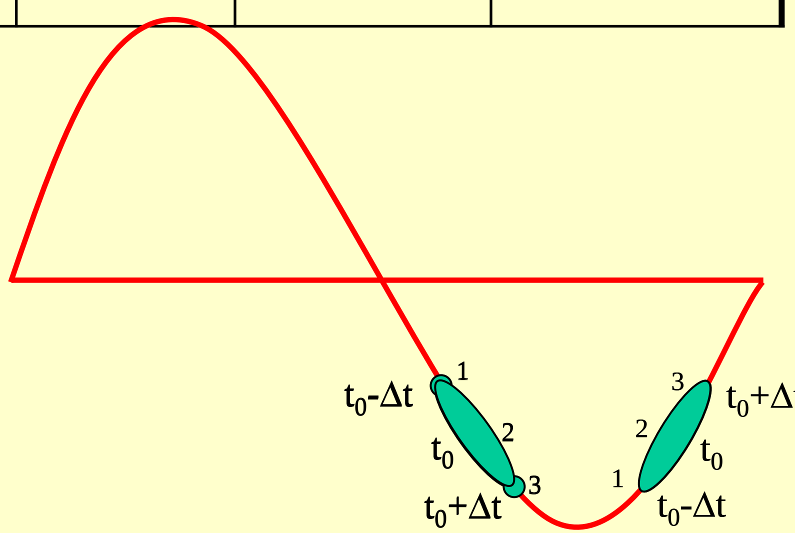



# Random Phase Focussing through linac

**Experimental results of random phase focussing of 16 QWRs In linac 1 and 2**

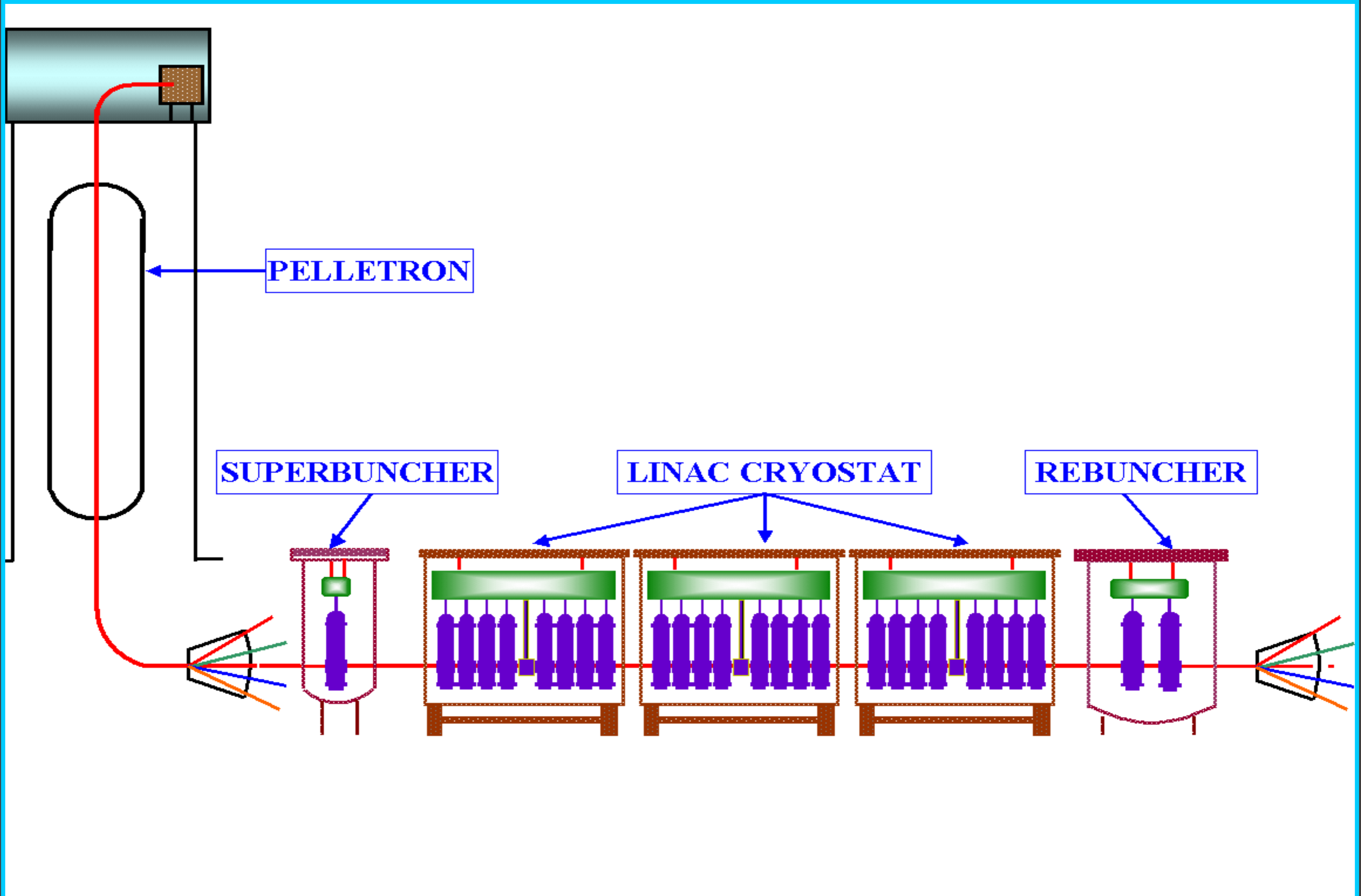
| Beam | Energy (Pell.) (MeV) | Total Energy (after linac-1 and 2) (MeV) | Predicted acceleration Phases of resonators in linac-1 and 2 to obtain minimum time width | Predicted reduction in delta_t (%) | Measured Time width (GPSC - II) | Experimental reduction in delta_t (%) |
|---|---|---|---|---|---|---|
| $^{28}Si^{+11}$ | 130 | 186 | All $70^0$ | | 2.88 | |
| | | | 70, 70, 110, 110, 110, 70, 70, 70 70, 70, 70, 70, 70, 70, 70, 110 | 38.5 | 1.73 | 40 |



# Use of the last resonator (8th one) from linac-1 as Rebuncher

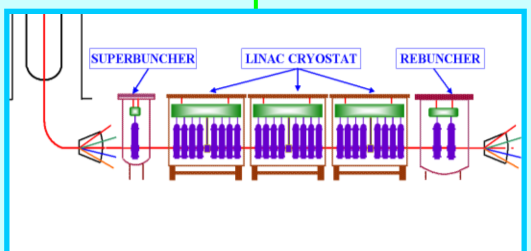
By using the same program developed for Random phase focussing



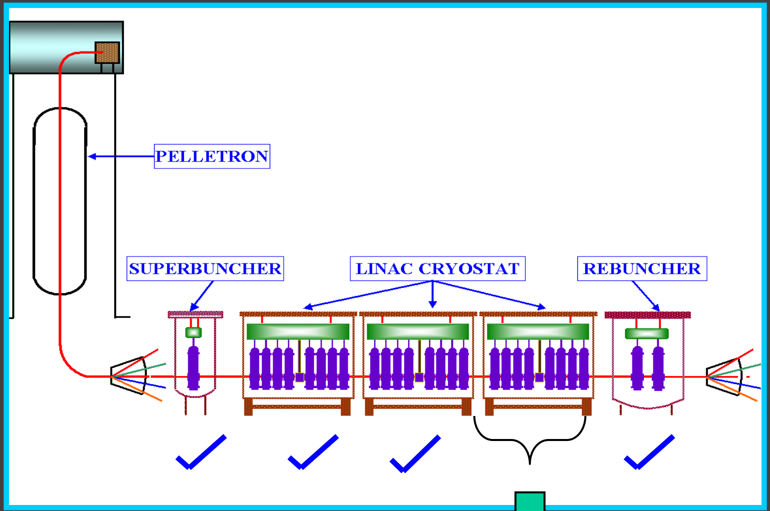
# Use of the last resonator (8th one) from linac-1 as Rebuncher

By using the same program developed for Random phase focussing

| Beam | Energy (Pelletron) (MeV) | Total Energy (after linac) (MeV) | The last linac-1 resonator kept at a field of (MV/m) (Calculated = Experiment) | Measured Time width (GPSC) (ns) |
|---|---|---|---|---|
| $^{16}O^{+8}$ | 96 | 113 *(R12-R17 ON)* | 0.0 | 0.84 |
| | | | 0.4 | 0.5 |
| | | 106.8 *(R12-R15 ON)* | 0.0 | 2.11 |
| | | | 1.7 | 0.8 |
| | | 104.5 *(R12-R14 ON)* | 0.0 | 2.68 |
| | | | 1.7 | 1.24 |
| $^{19}F^{+9}$ | 115 | 125 *(R11-R14 ON)* | 0.0 | 1.82 |
| | | | 2.08 | 0.82 |
| | 107 | 122.1 *(R12-R16 ON)* | 0.0 | 1.75 |
| | | | 0.51 | 1.09 |
| | | 118.8 *(R12-R15 ON)* | 0.0 | 2.2 |
| | | | 1.35 | 1.47 |



# Status of completion of the linac project at IUAC




- Presently, SB, Linac-1, 2 and RB are operational
- Accelerated beam is delivered to conduct Expts

- The 3rd. cryostats are fabricated, installed & leak tested in cold condition
- Resonators are fabricated in-house for cryostats 3 and performance tested in test cryostats
- 4 resonators in linac-3 were tested successfully
- Remaining resonators are being installed
- Beam acceleration through complete Linac is planned in August 2012

# Conclusion

- Superconducting Linac facility of IUAC are operational since last few years and accelerated beams are delivered for scheduled expts.
- The last accelerating linac module is being commissioned.
- Efforts are on to improve the phase locked fields of the resonator.
- Vibrational damping efficiency is improved, ready for testing at 4.2 K.
- Alternate Piezo tuning mechansim has been tested with a great success. Soon the new tuning mechanism will be implemented in linac resonators. Operation will be easier and power requirement will be reduced.

# Acknowledgement


- Dr. Amit Roy, Director, IUAC and Ex Project leader – SC Linac
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- M/S DonBosco Technical Institute, New Delhi, India


Thank you all