RF Systems for a Neutrino Factory

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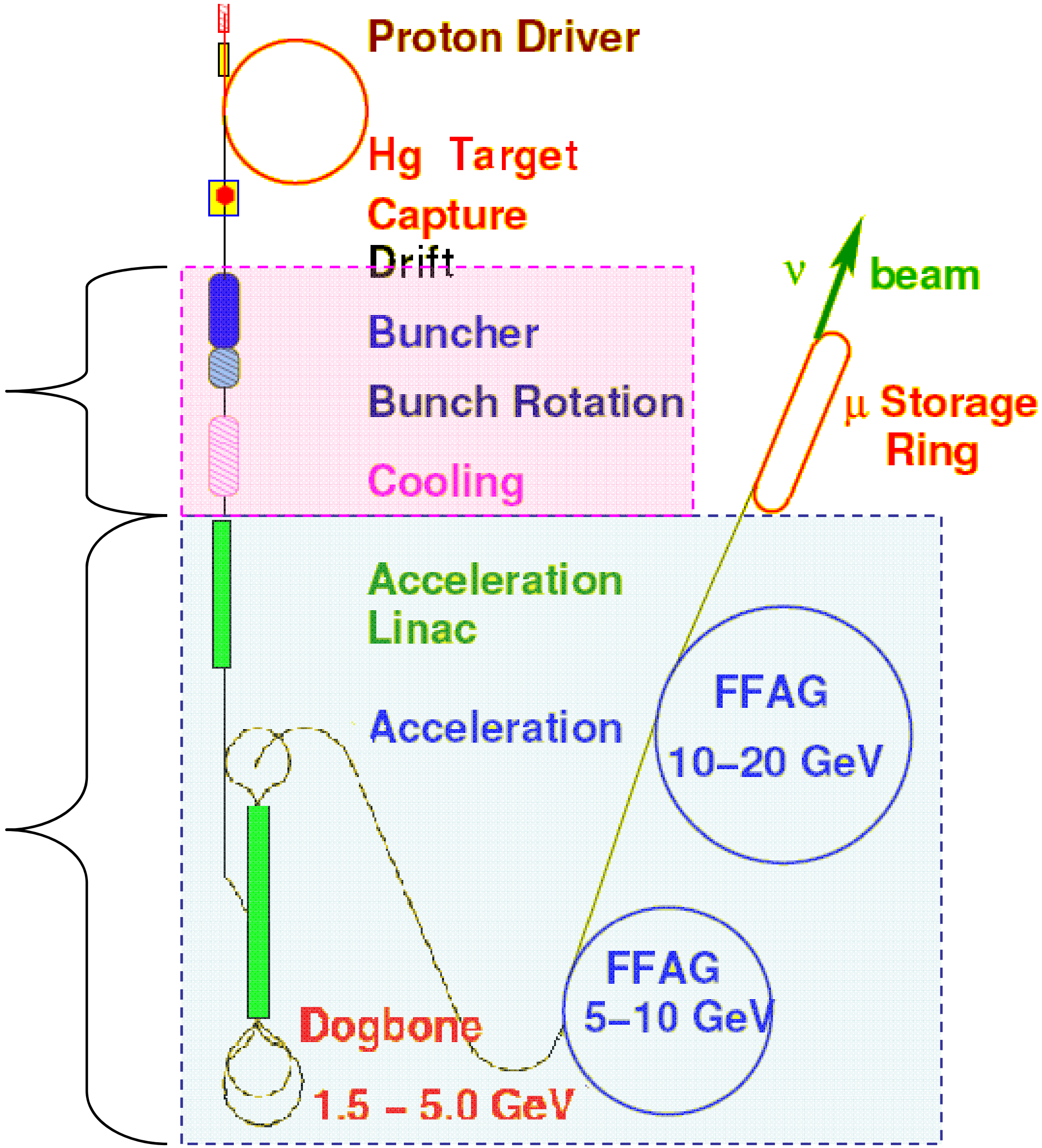
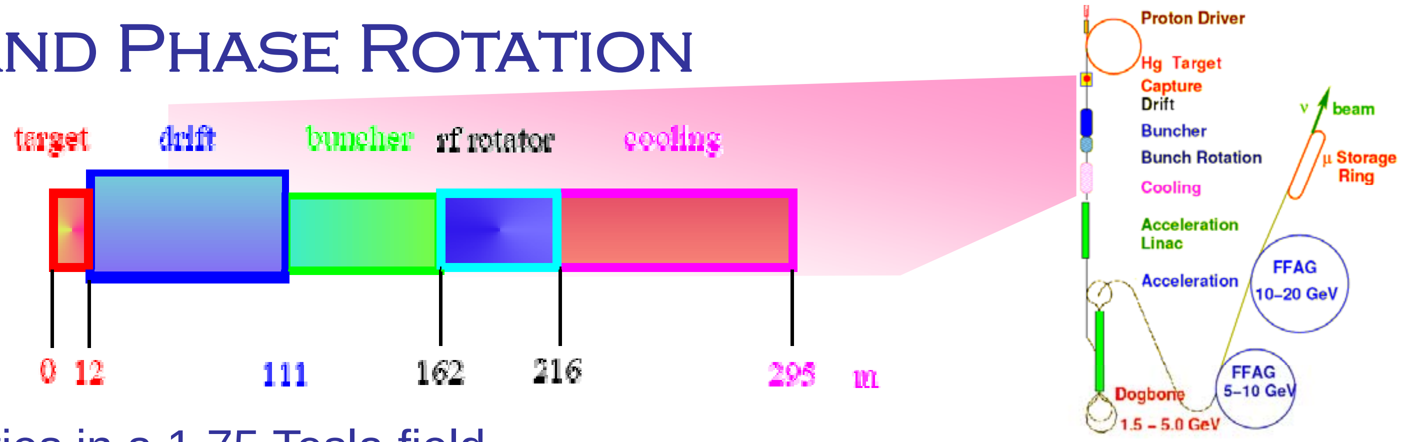
Lancaster University

Taken from US Study IIa


Proton Driver
Hg Target
Capture
Drift
Buncher
Bunch Rotation
Cooling
ν beam
μ Storage Ring
Acceleration Linac
Acceleration
FFAG 10–20 GeV
FFAG 5–10 GeV
Dogbone
1.5 – 5.0 GeV

Buncher and Phase Rotation



Buncher

- 27 RF Cavities in a 1.75 Tesla field
- 13 discrete frequencies, decreasing from 333 MHz to 234 MHz
- Accelerating gradients from 5 – 10 MV/m
- Be windows

Rotation

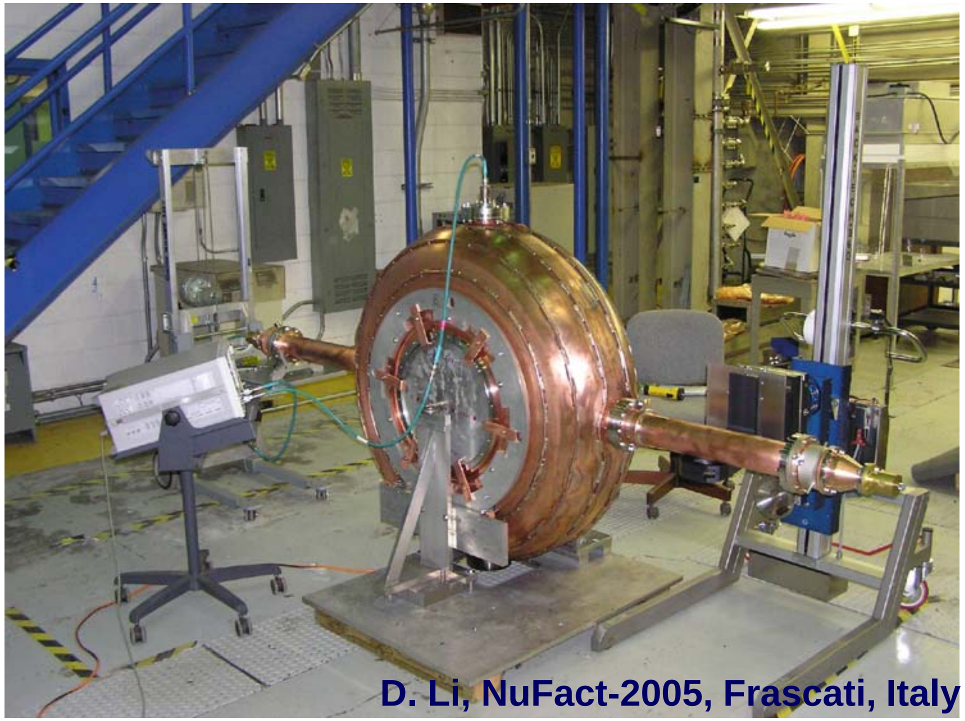
- 72 RF Cavities in a 1.75 Tesla field
- 15 discrete frequencies, decreasing from 232 MHz to 201 MHz
- Accelerating gradient of 12.5 MV/m
- Be windows

Cooling

- RF Cavities in alternating 2.8 Tesla field
- 201.25 MHz
- Accelerating gradient 15.25 MV/m
- Windows 1cm LiH coated with 25μm Be

Neutrino factory cooling channel parameters

- 201.25 MHz operating in an alternating 2.8 Tesla field
- 15.25 MV/m peak accelerating gradient
- Peak input RF power ~ 4.6 MW per cavity
- Average power dissipation per cavity ~ 8.4 kW
- Average power dissipation per Be window ~ 100 watts



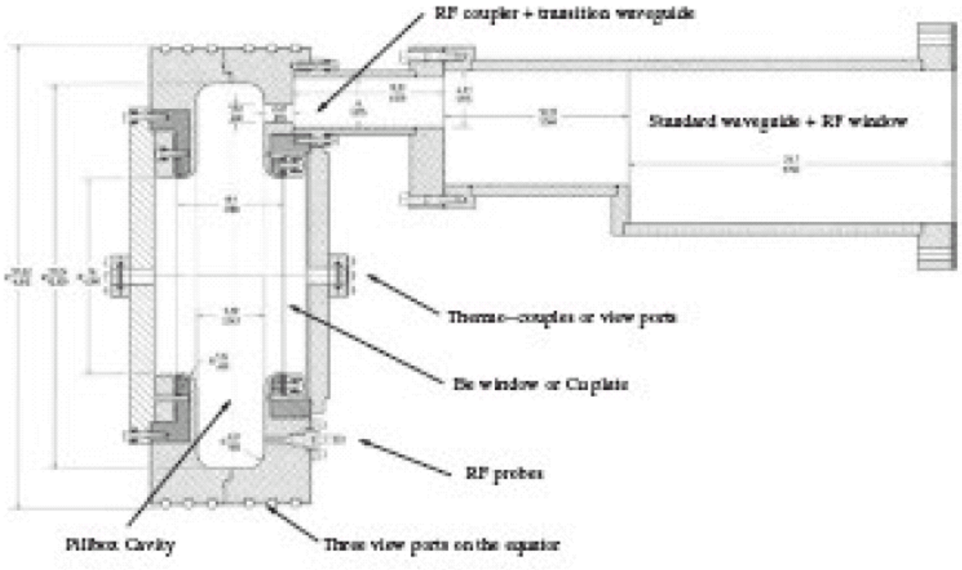
D. Li, NuFact-2005, Frascati, Italy

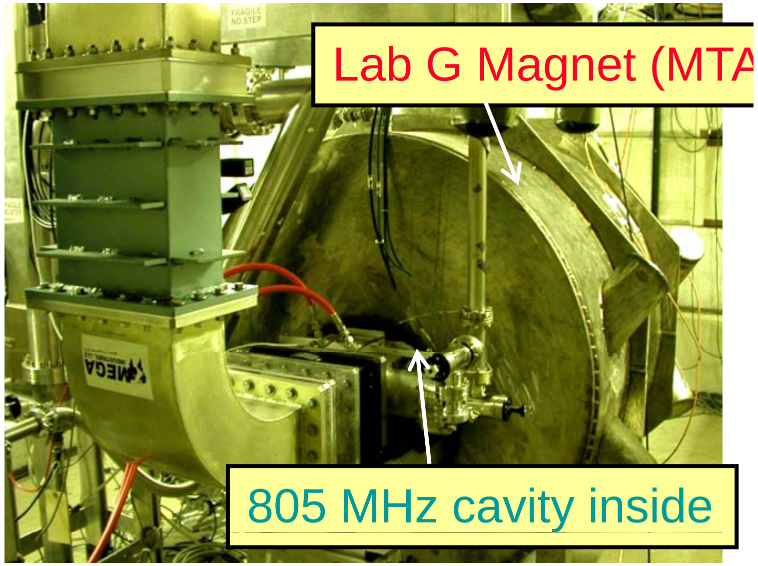
Window electricaly closes, great control over phase in each cavity

- Gas filled → Breakdown ?
- Open cavity → Phase control ?

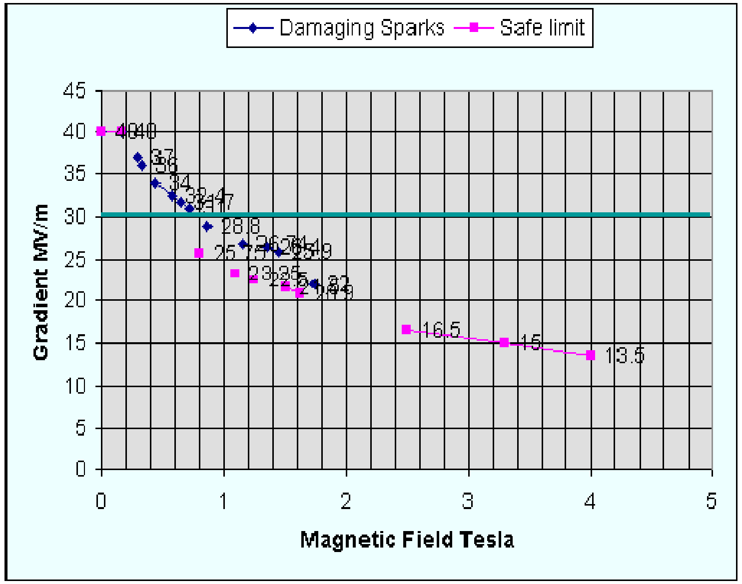
MTA: NCRF Experimental studies at 805 MHz

D. Li, NuFact-2005, Frascati, Italy

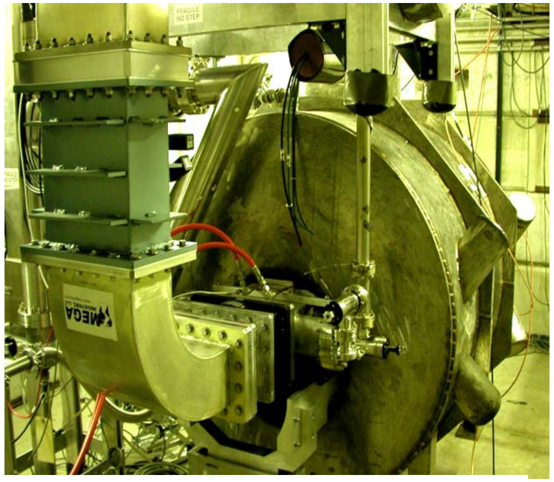




- MUCOOL experiment to examine the effects of field / material/ surface
- Accelerating gradient function of B field
- Be windows can withstand field

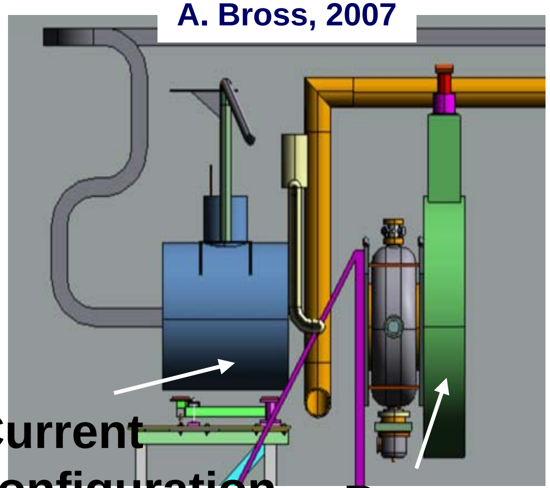


MTA: NCRF Experimental studies at 201 MHz



D. Li, NuFact-2005, Frascati, Italy

A. Bross, 2007

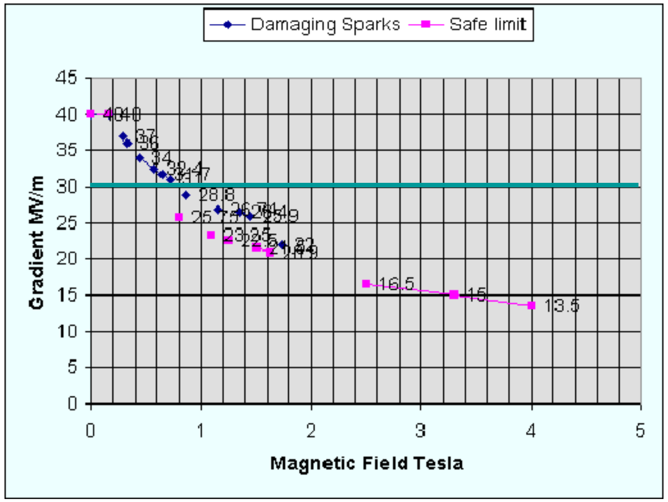


Current 201 MHz operation in B Field limited to few hundred Gauss

Initial results no field E_{acc} ~16MV/m

Require @ 2.8 T E_{acc} 15.25MV/m

How to interpolate the 805 MHz results to 201 MHz cavities?



40 MV/m no field

16 MV/m @ 2.8 T

Very limited data

This leaves a number of question about cavity manufacture

- Reproducibility
- Effects of manufacture
- Dominate phenomena

U.K. Consortium working in collaboration with MUCOOL

- Imperial College
- Cockcroft Institute (Lancaster)
- Brunel University
- Liverpool University
- Shakespeare Engineering

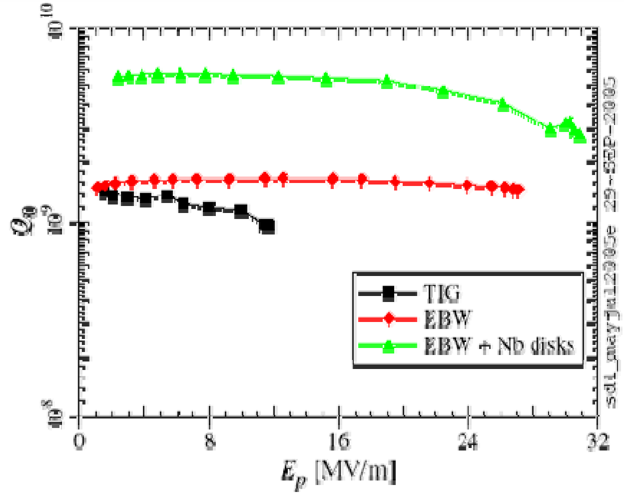
To understand the factors effecting:

- Accelerating gradient
- Reproducibility

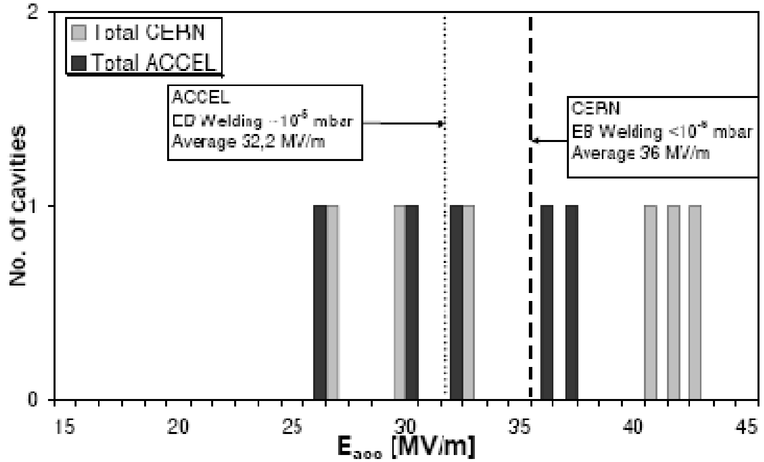
Fabrication Process

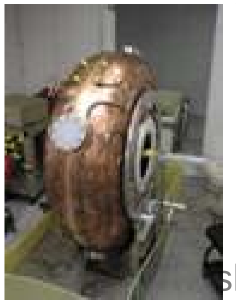
Spinning Cu into Half Shell

D. Li, NuFact-2005, Frascati, Italy



E Beam Welding





Electropolishing

(Blackart)

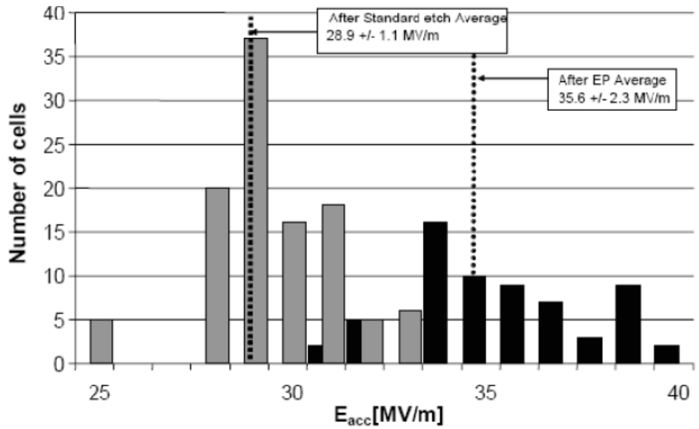


Figure 4: Accelerating gradient comparison between chemically etched and electropolished cavities

Improved Surface Treatment of the Superconducting TESLA Cavities[1]

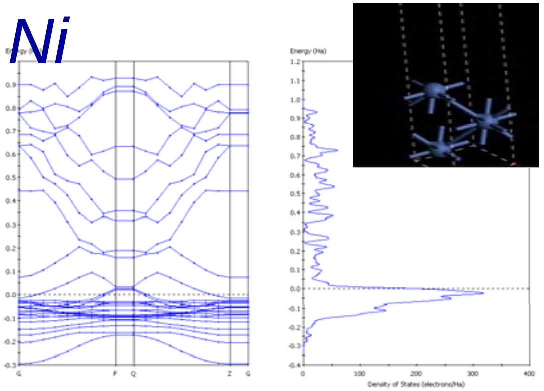
L. Lilje [2], A. Matheisen, D. Proch, D. Reschke, D. Trines,

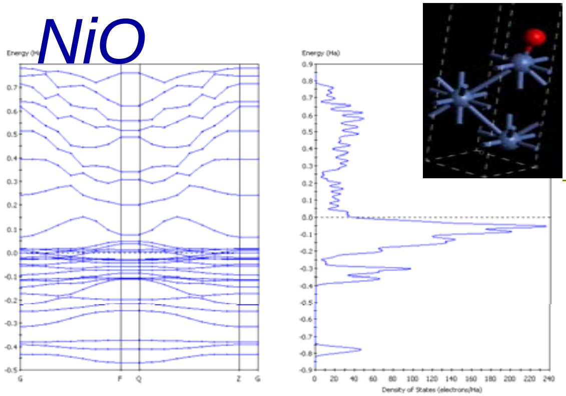
At each stage in the manufacturing process:

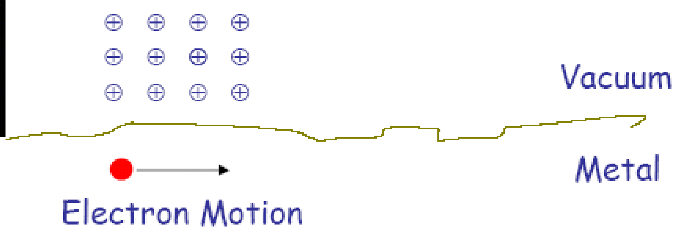
- Atomic Force Microscope / Scanning Electron Microscope
  - Surface topology, Average roughness, Stress, Planarisation

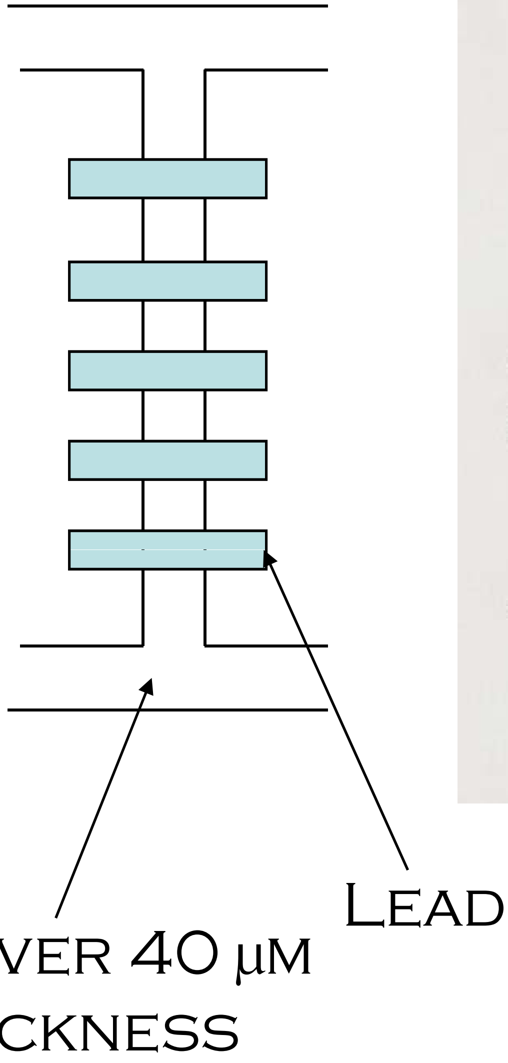
- X-ray photoelectron Spectrometer
  - Chemical make up of the surface layers of the RF surface, Identifying Orbitals involved in bonding impurities

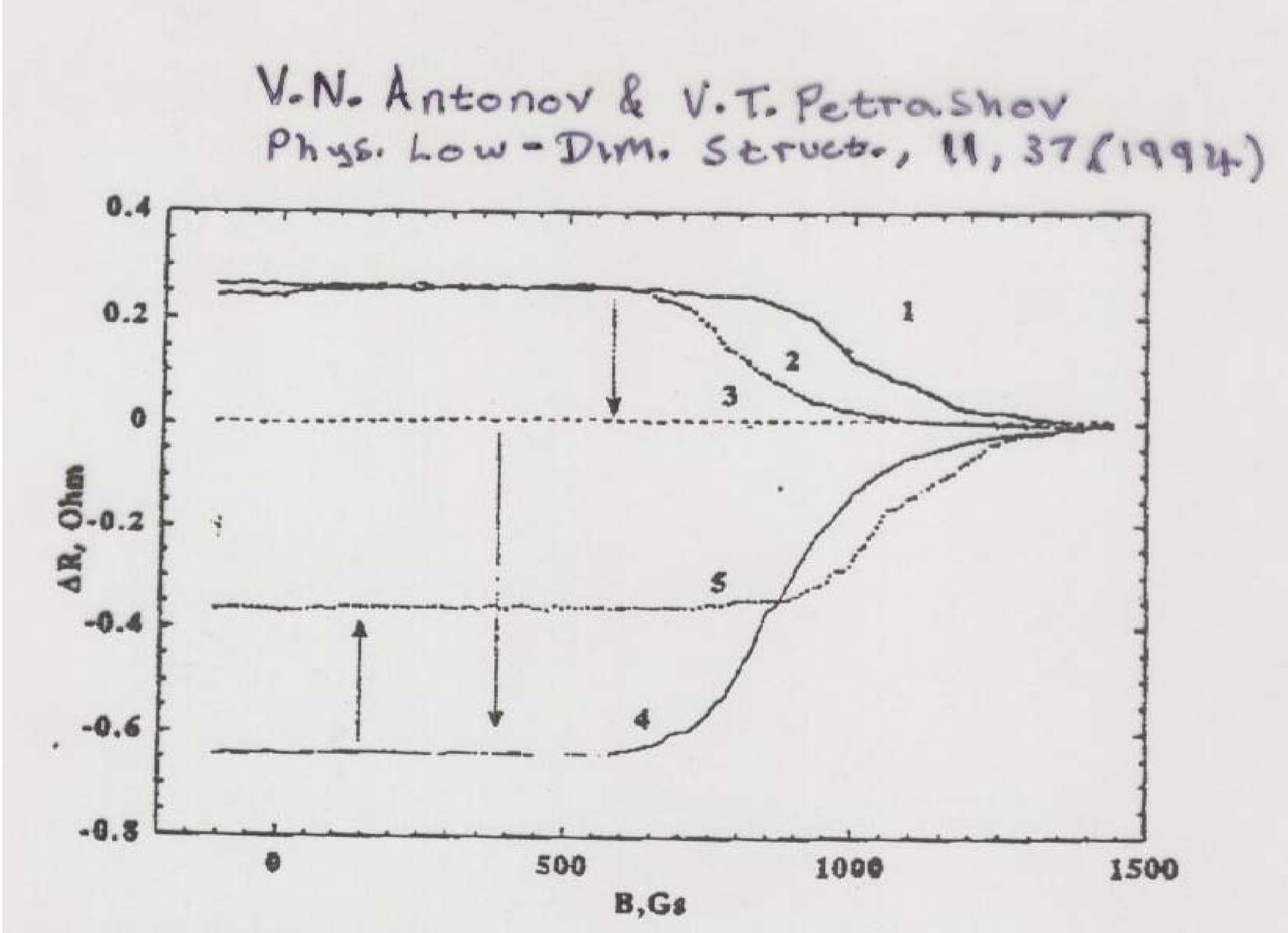
Skin Depth in Cu @ 201 MHz = 4.6 μm











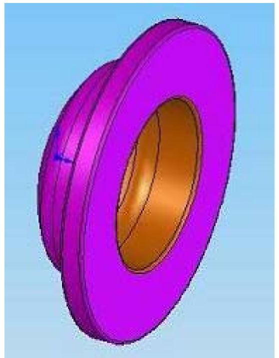
Skin Depth

Cu @ 200MHz → 4.6 micros

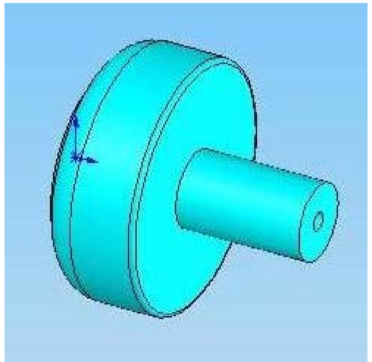
Nb @ 1.3 GHz ~ 0.08 Micros (80 nm)

Seeking funding for full insitu cavity study

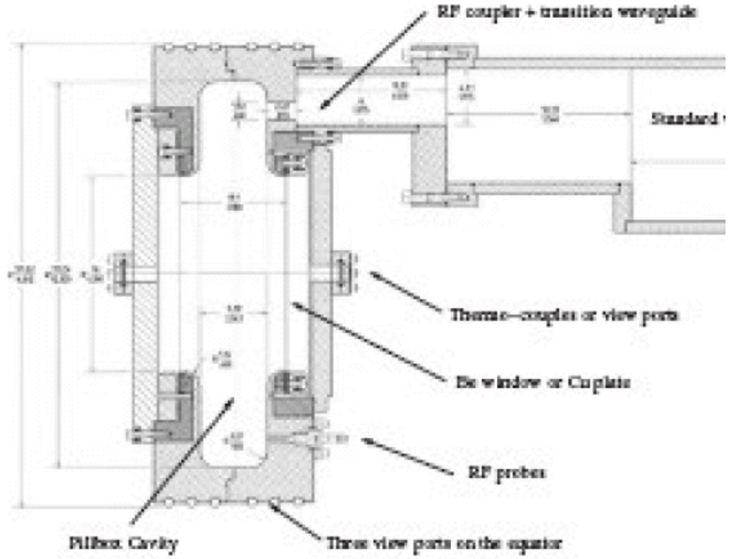
Current funding £10k,
MUCOOL test button sample evaluation



Cap



Holder



Allows evaluation of:

- different materials (T102, T103)
- different manufacturing
- different surface treatment process
- factors contributing to cavity performance

Be window :

- Toxic
- Difficult to work
- Hard to find companies willing to work with Be
- Expensive

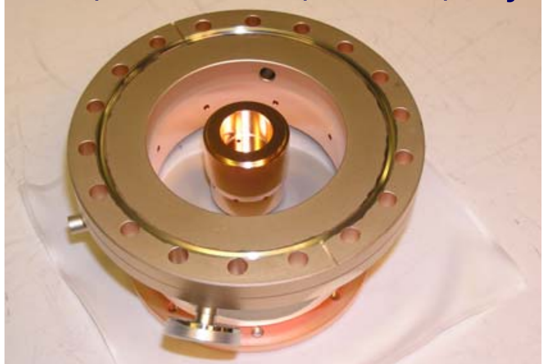
D. Li, NuFact-2005, Frascati, Italy

* Could consider alternatives

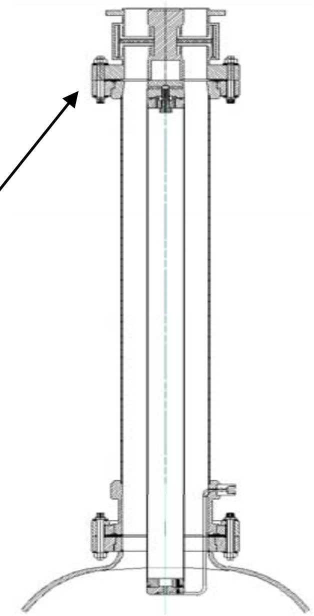
Peak input RF power ~ 4.6 MW per cavity
Toshiba SNS style RF window limited to 2.5 MW peak

* Development of a 5 MW RF Window

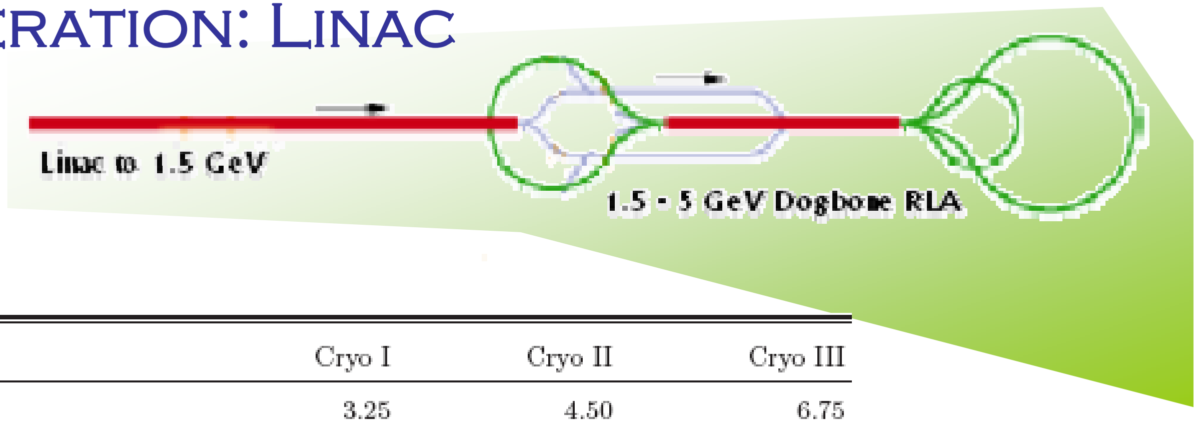
D. Li, NuFact-2005, Frascati, Italy

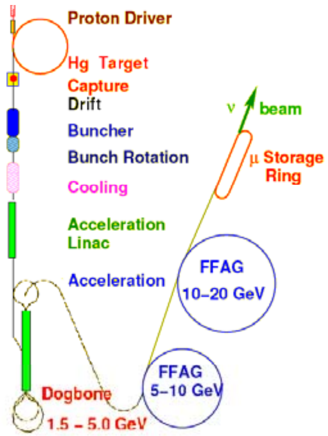


Ceramic RF window

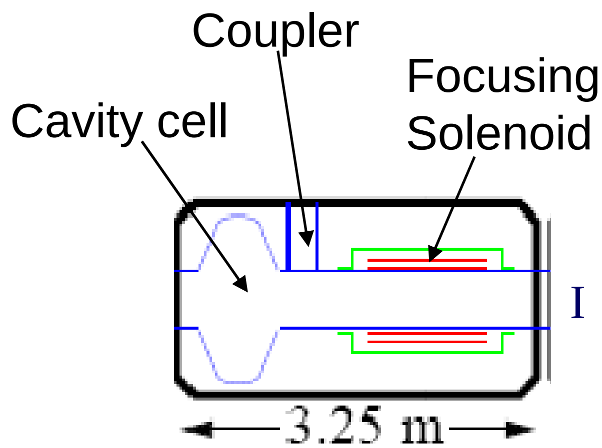


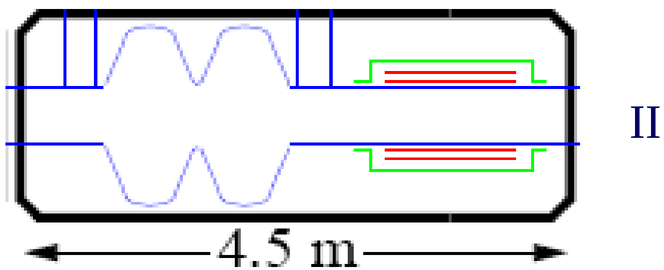
Acceleration: Linac

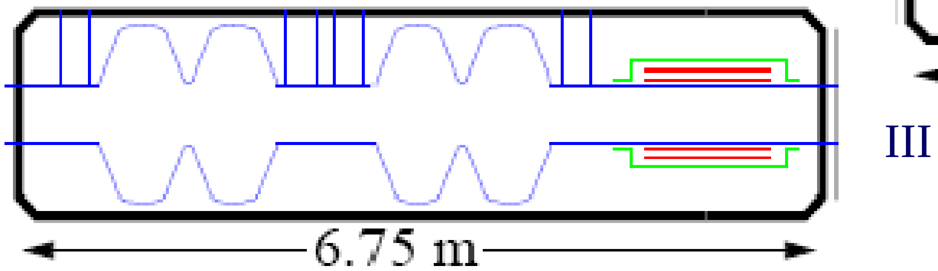




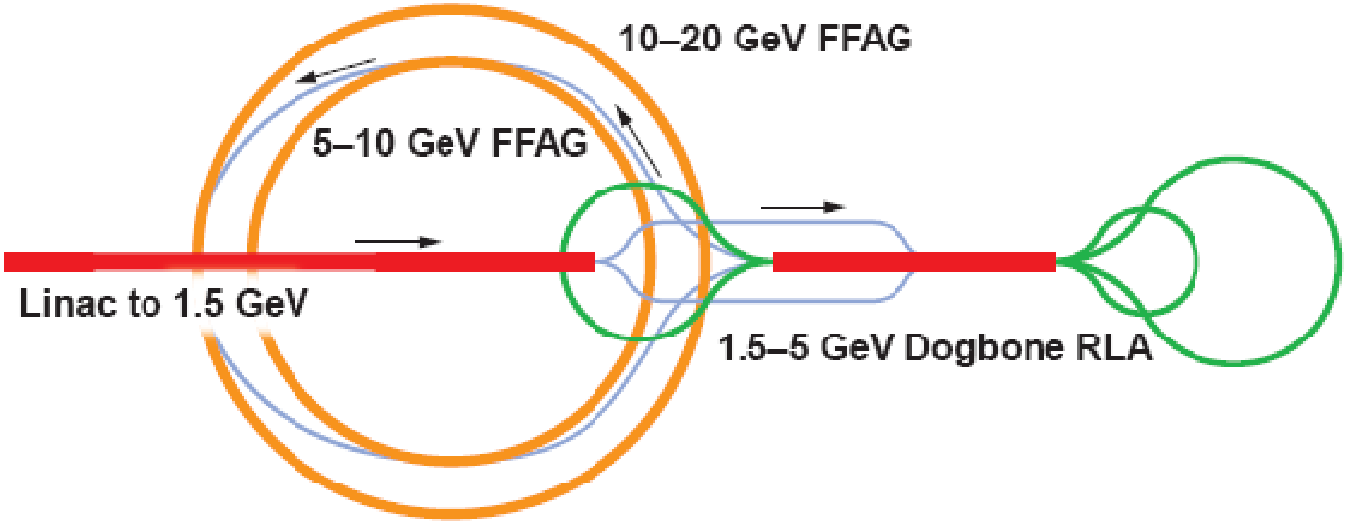
	Cryo I	Cryo II	Cryo III
Length (m)	3.25	4.50	6.75
Minimum allowed momentum (MeV/c)	273	378	567
Number of modules	18	12	23
Cells per cavity	1	2	2
Cavities per module	1	1	2
Maximum energy gain per cavity (MeV)	11.25	22.5	22.5
RF Frequency (MHz)	201.25	201.25	201.25
Solenoid length (m)	1	1	1
Solenoid field (T)	2.1	2.1	2.1







(RLA uses 4x 2-cell Cavities)



Maximum energy gain per cavity (MeV)		7.5	
Stored energy per cavity (J)		368	
Cells without cavities		8	
RF drift length (m)		2	
Drift length between quadrupoles (m)		0.5	
Initial total energy (GeV)	5		10
Final total energy (GeV)	10		20
Number of cells	90		105

~200x 201 MHZ Single cell cavities at 10 MV/m

SCRF

Fabricated at CERN with the standard Nb sputtering technique as used for LEP2 cavities.

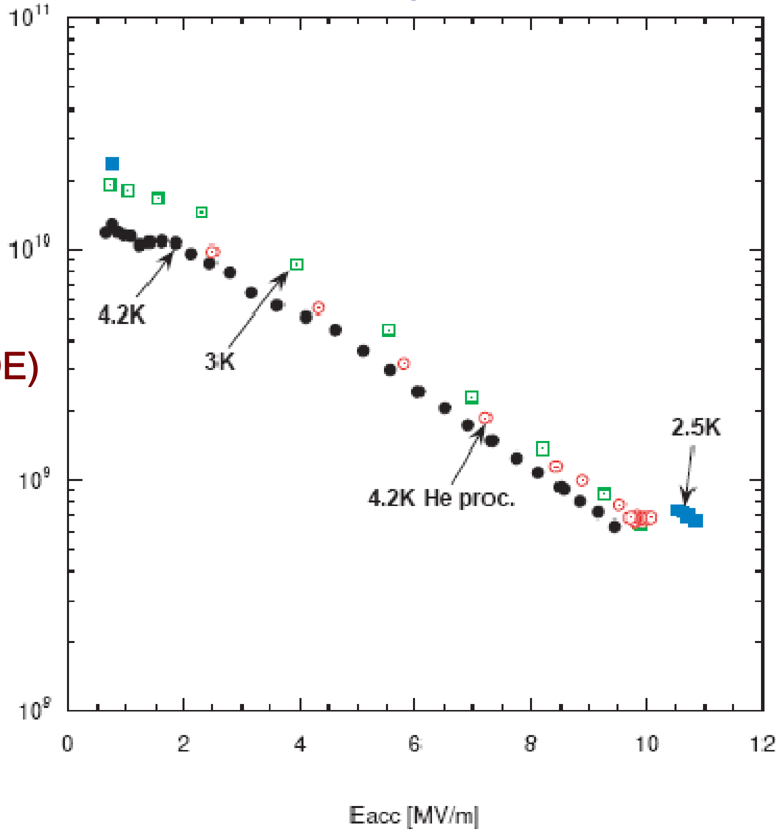
NF Requirements:

- 11.25 MV/m at a Q_0 of 6×10^9.

Need to :

- Understand Q slope
- Understand reproducibility
- Understand effect Muon Radiation
- Understand max E_{acc}
- Develop film techniques (LNL-INFN, REX ISOLDE)
- Develop 200MHz power sources

R.L.Geng, PAC 2003



Need to develop 200MHz power sources (about 10 MW peak)

- Development of Multibeam Klystron (China, Lancaster (Carter, Lingwood))
- or Inductive Output Tube (Lancaster (Carter, Crane))
- or Phase locked Magnetron (Lancaster (Carter, Dexter))

Increasing RF source conversion efficiency is an important research objective for the next generation of accelerators

	IOT		Klystron	Solid-State	
Transmitter peak sync. power (V + A)	40+4		40+4	40+4	kW
Transmitter power consumption	52		108	128	kW
Power cost per kilowatt (yr 1)	0.07	)7	0.07	0.07	$
Cost of replacement tube (yr 1)	37,175		33,000	N/A	$
Maintenance cost per annum	1,000		1,000	500	$
On-air time per day	20		20	20	hours
Average inflation per annum	4		4	4	%
Average life of tube 1 (** see below)	30,000		35,000	N/A	hours
Average life of tube 2 (sound)	N/A		45,000	N/A	hours
Replacement solid-state modules (year 1 per annum)	N/A		N/A	500	$
Tube/module cost over 20 years	287,167		310,965	15,403	$
Power cost over 20 years	818,551		1,700,069	2,014,894	$
Maintenance cost over 20 years	30,969		30,969	15,485	$
Transmitter cost	350,000		360,000	750,000	$
Total cost	1,486,687	1	2,402,003	2,795,782	$
Relative cost	100		162	188	%

Table 3. Typical cost of ownership calculations for IOT, ESC, Klystron and solid-state transmitters.

**Average life stated is life that is reasonably expected, not guaranteed for any particular sample.

	Diacrode	IOT	Magnetron
Anode voltage	**14 kV**	**95 kV**	**60 kV**
Anode current	**103 A**	**58 A**	**20 A**
Efficiency	**71%**	**65% (>75% with a multi-element depressed collector**	**90 %**
Gain	**13 dB**	**23 dB**	**> 30 dB**
Drive power	**50 kW**	**5 kW**	**< 1 kW**
Cooling	**Anode**	**Collector**	**Anode and (probably) cathode**
[illegible]	[illegible]	[illegible]	[illegible]
Availability	**Yes**	**Would require 2 - 3 years R&D**	**Would require 4 – 5 years R&D**
R&D issues	**None**	**Mechanical stability of control grid** **Multi-element depressed collector design** **Multi-beam and radial beam designs**	**Cathode choice for long life** **Development of switched mode power supply** **Demonstration of simultaneous control of amplitude and phase** **Stability**

Neutrino Factory

Need to;

- Develop an understanding of NC RF cavity operation in B Field

- Develop an understanding of the Q slope in SCRF sputtered cavit

- Develop High power RF sources

- Understand how fabrication process effects:
    - performance
    - reproducibility

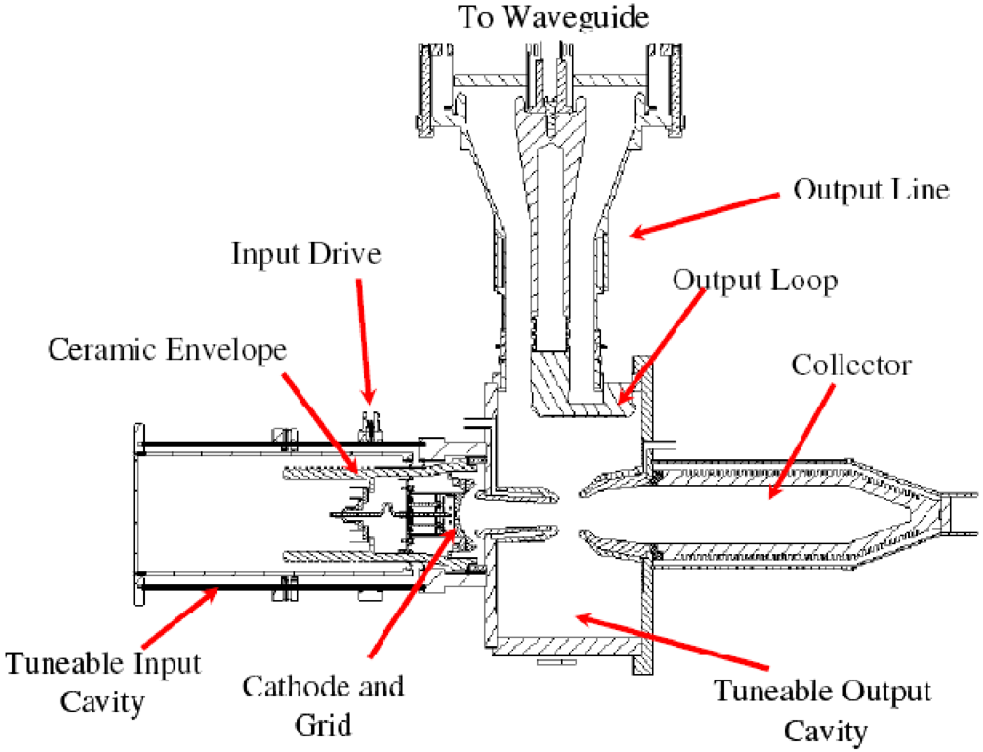
- Consider RF windows Capable of high power operation
- Consider alternatives to Be
- Consider alternative manufacturing techniques
- Consider the effect of muon radiation on cavity performance

“ Materials is the queen technology of any advanced technical system.

… the physicists will give way to the materials engineers as the leading lights…"

E. E. Kintner, 1975

Inductive Output Tube (IOT)



- Electron bunches formed by a gridded gun
- RF power extracted by a cavity resonator
- State of the Art

Frequency	267 MHz	500 MHz	1300 MHz
RF Power	250 kW	80 kW	30 kW
DC Voltage	66 kV	36 kV	34 kV
DC Current	5.5 A	3.4 A	1.39 A
Efficiency	73%	65%	64%
RF gain	21 dB	23 dB	21 dB