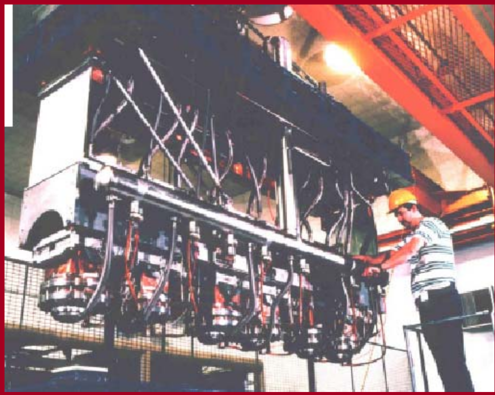
TRIUMF

The Impact of ATLAS on SRF Development and Applications

Bob Laxdal, Oct. 22, *ATLAS 25th Anniversary Celebration*



Outline

- Forward
- Chapter 1: The Pioneer
- Chapter 2: The Innovator
- Chapter 3: The Mentor
- Chapter 4: The Supplier
- Chapter 5: The Communicator
- Chapter 6: The world community
- Chapter 7: The Future
- Prologue

Forward

- I've treated this talk as a historical exercise: the present is known but how did we get here and what was the role of ATLAS in the story
- Like all historians I'm bound to get something wrong or distorted; let me apologize in advance
- The research for this talk was a real treat and left me very impressed as I educated myself on the ATLAS (r)evolution

TRIUMF

Why superconducting?

- Superconducting allows
  - Power efficient - cw and high duty cycle operation
  - Larger apertures, lower frequencies for increased acceptance
  - Short independently phase cavities – flexible beam delivery
- Applications
  - Post-accelerators
    - Shorter machines typically – broad velocity acceptance
    - Utilize maximum gradient to improve performance and/or reduce cost – operate each cavity at fixed power
    - Beam loading not an issue typically
  - Drivers – conservative gradient required
    - longer machines typically – large velocity swing – several cavity regimes
    - Beam loss (halo) an issue; careful beam dynamics required
    - Beam loading dominates rf power

Where are we?

- Initial applications used low beta SC resonators (split rings or quarter waves (QWR)) as post-accelerators for heavy ion tandems serving the nuclear physics community (Atlas, INFN-LNL, JAERI)
- Increased interest in Radioactive Ion Beams (RIBs) has created a renaissance in low and medium beta SC cavity development in the last ten years for both post-accelerators and drivers (ISAC-II, SPIRAL2, FRIB)
- High duty cycle driver linacs of protons and light ions are now proposed with SC sections beginning at lower beta values (SARAF, IFMIF, Project X)
  - Rise in performance (and relevance) of multi-gap spoke cavities and half-wave resonators (HWR) in the mid-beta regime

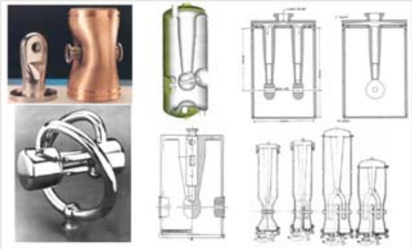
Electron vs Heavy Ion Acceleration

- It takes ~0.5MV to make an electron reasonably relativistic therefore all electron cavities are variants of the common TM elliptical cavities accelerating at v=c

TM 1.3GHz β=1

- It takes A*1000MV to get a heavy ion to the same speed
- Heavy ion linacs must accelerate through a large velocity range with cavities optimized for each range

TEM λ/4 – β ~ 0.04-0.15 ~(100 MHz)

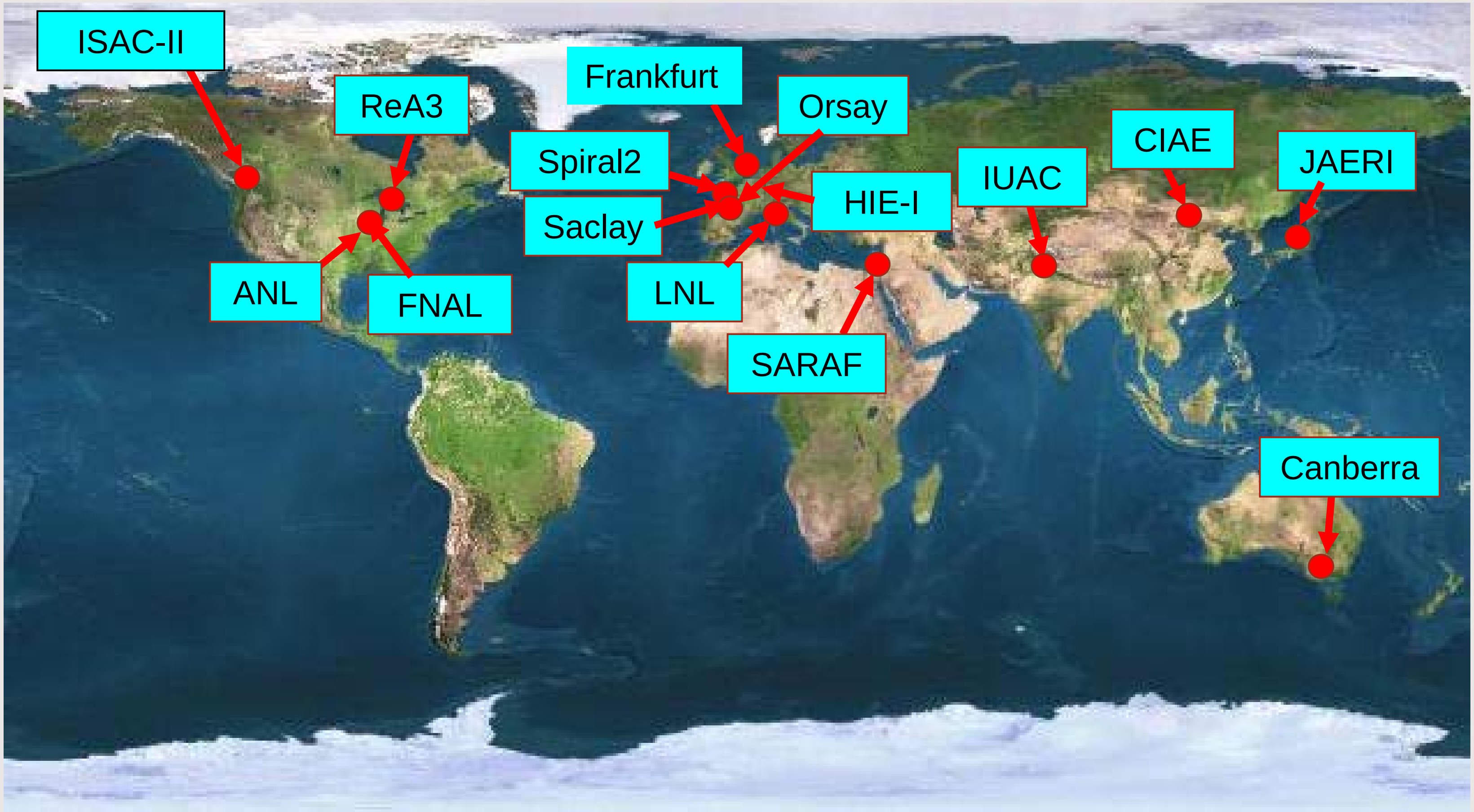


TEM λ/2 - β ~ 0.12-0.2 (~200MHz)

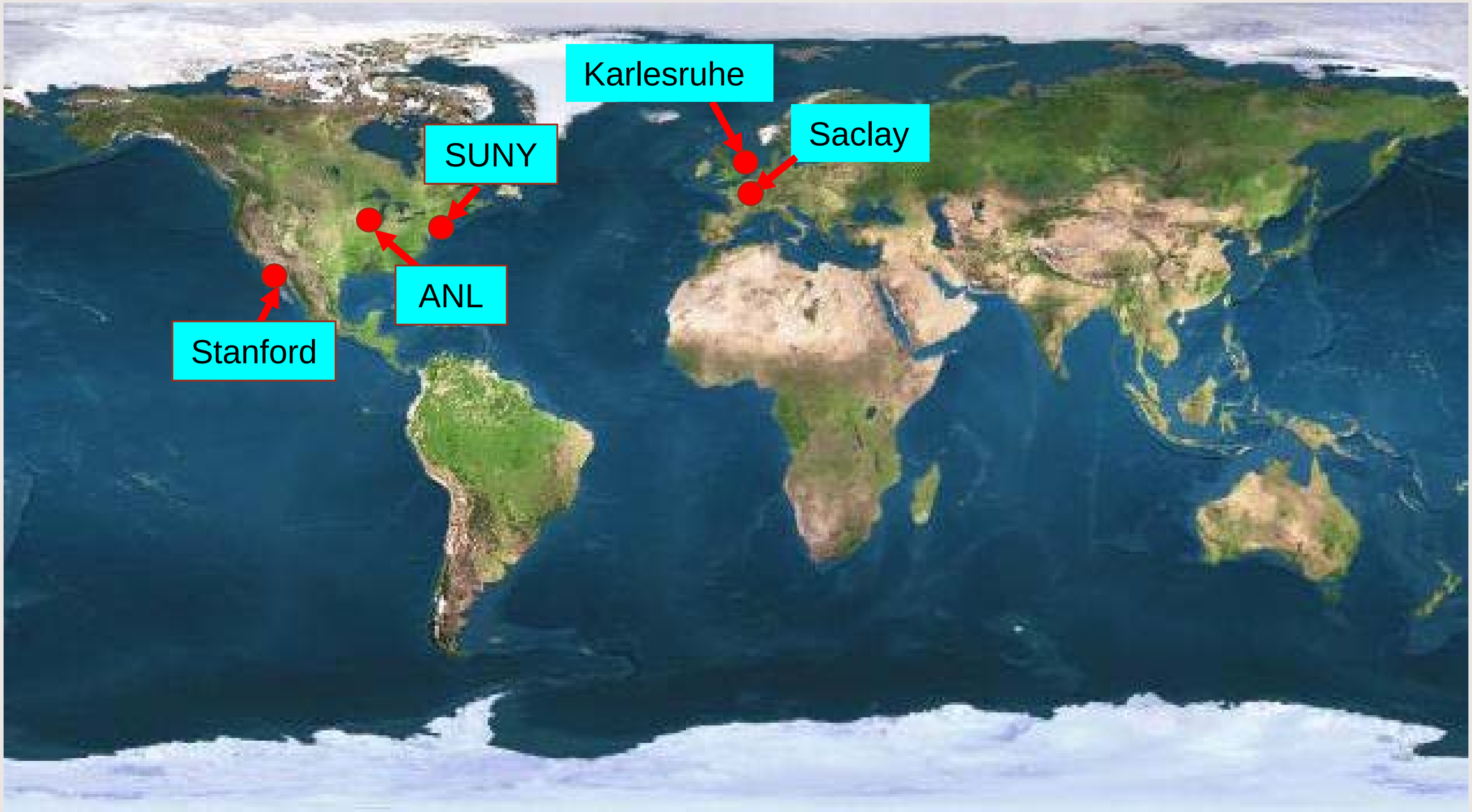
TEM λ/2 Single-spoke β~0.2-0.5

TEM λ/2 Multi-spoke β~0.2-0.5

Hadron SC-Linac Facilities and R+D



Hadron SC-Linac R+D 1975



Hadron SC-Linac Operating Facilities 1975

Chapter 1

ATLAS the Pioneer

Early SRF Studies 1973

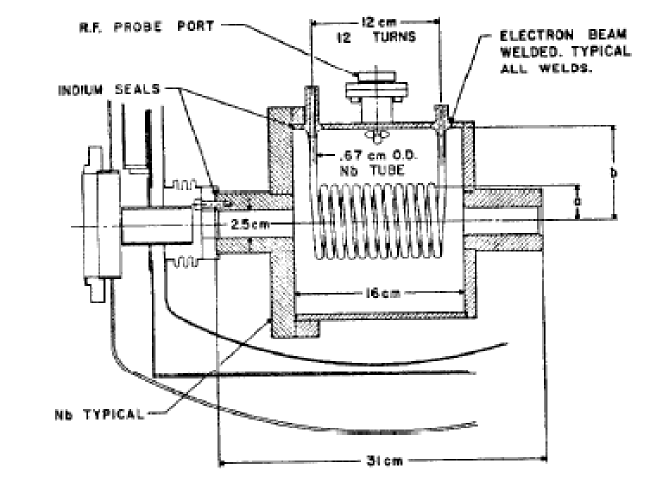
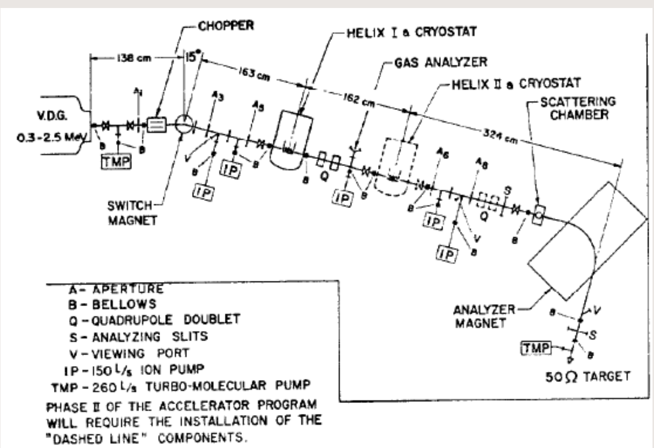


Fig. 3 Cross-section of the helix resonator

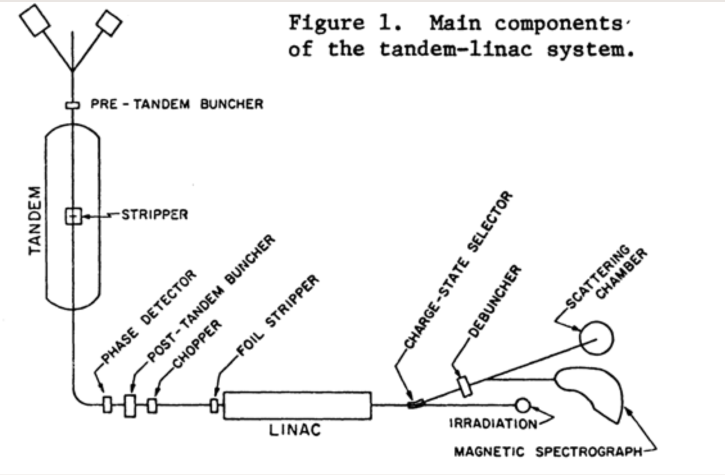


- Early ANL SRF activities chiefly centered around SC helix resonator
- Goals were to:
  - Test stability of the RF properties of the accelerating structure
  - Determine radiation damage of the anodized Nb surface.
  - Test contamination of the superconductor by the beam line
  - measure and control vibration levels in an accelerator environment
  - Document and solve engineering difficulties,

Prototype Booster Linac - 1975

A bold idea was proposed in the mid-70s for a prototype linac of bulk niobium rf resonators to be used as a post-accelerator to the Tandem.

- Split ring (three gap) cavities of 97MHz and β=0.105
- Niobium loading elements with explosively bonded Nb on Cu outer conductors
- Initial goal was 13.5MV booster with superconducting solenoid focussing



- Goal was to dev't technology while allowing a modular linac upgrade to expand the energy reach
- Short independently phased cavities perfectly suited a staged installation as $ and technology allowed

Booster Linac - 1976

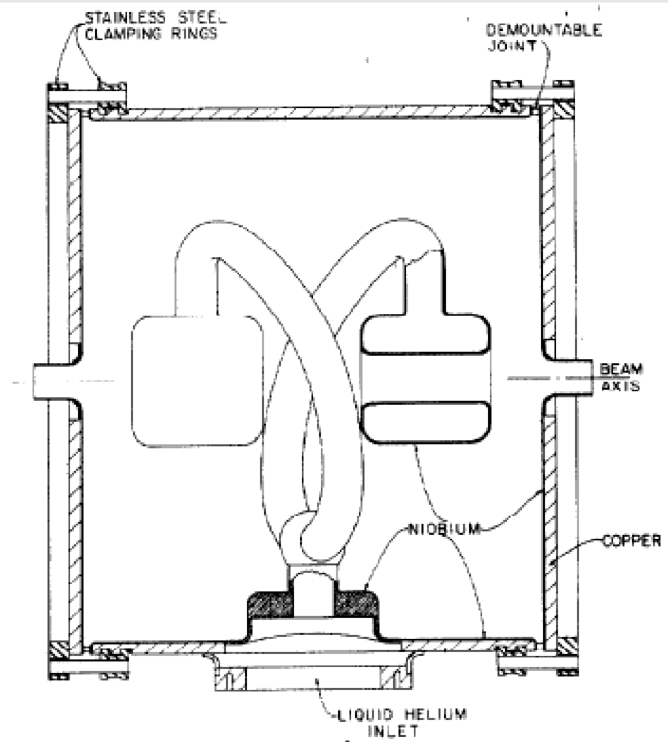
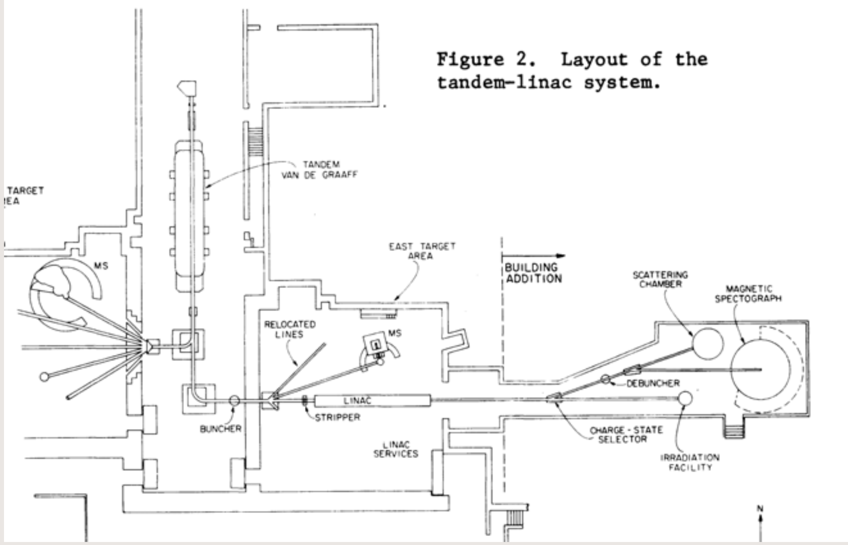
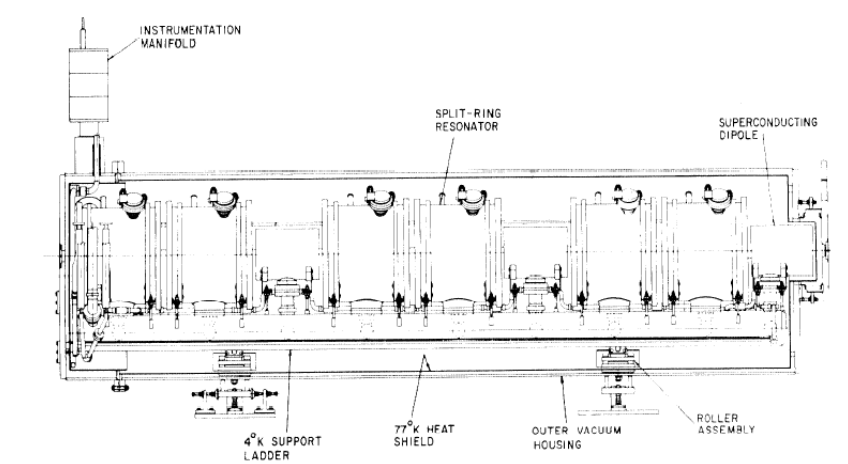


Figure 1. Section of the niobium split-ring resonator. The outer housing is made with an explosively bonded niobium-copper composite.

- Objectives
  - Provide ions above the Coulomb barrier for A<~80
  - Maintain tandem like beam quality
  - Provide easy energy variability
  - Modular solution to permit upgrades
- Started resonator fabrication Oct. 1976

First Heavy Ion SC Acceleration - 1978





- Split ring cryomodule
  - End loading
  - SC solenoids
- Installation of one module and two cavities by 1978
  - First Acceleration!
- Installation of two modules and eight cavities by 1979
- By June 1979 9.3MV was demonstrated

Success – 1981-1983

- •By1981 16 resonators on-line with 6000 hours of acceleration with a maximum voltage of 15MV
  - •resonator at β=0.06 added
- •By 1983 had 24 cavities and 4 modules installed to complete the booster

- •A revolutionary accomplishment; the bold initial goal was achieved
  - •Unequivocal Proof of principle that SC technology can successfully accelerate heavy ions
  - •Demonstrated stable operation useful for physics, characterized by ease of energy change and good beam quality
  - •Short independently phased cavities provide excellent redundancy and flexibility of beam delivery

ATLAS the proposal 1983

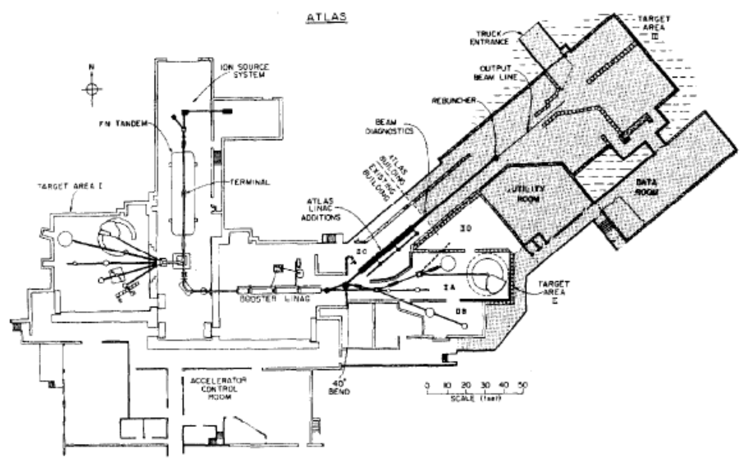
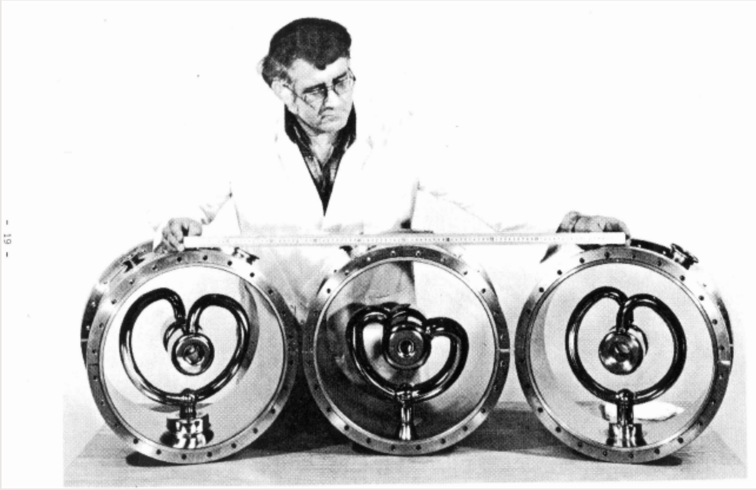


Fig. 3. Layout of the ATLAS facility.



- Success brings a new idea – ATLAS – pioneering phase over
  - Add three more CM's with 6 cavities per module
  - Develop a new β=0.16 145MHz split ring resonator
  - New experimental areas; medium energy supplied by booster and high energy supplied by ATLAS
- Success encourages others – SUNY, FSU, KSU, UW, Saclay, JAERI, INFN-LNL, …

Chapter 2

ATLAS the Innovator

Early SRF Developments-1979

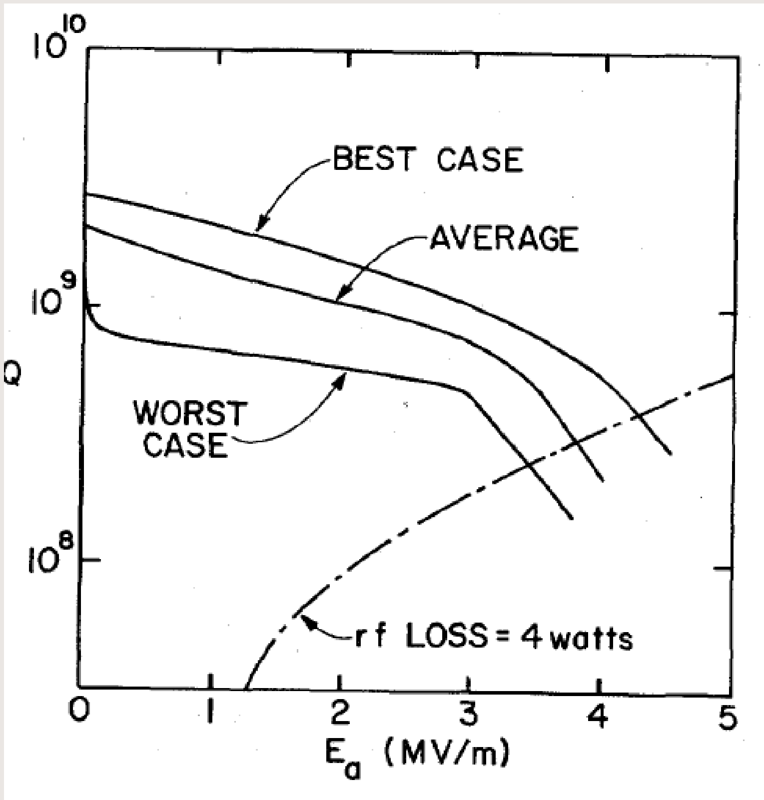
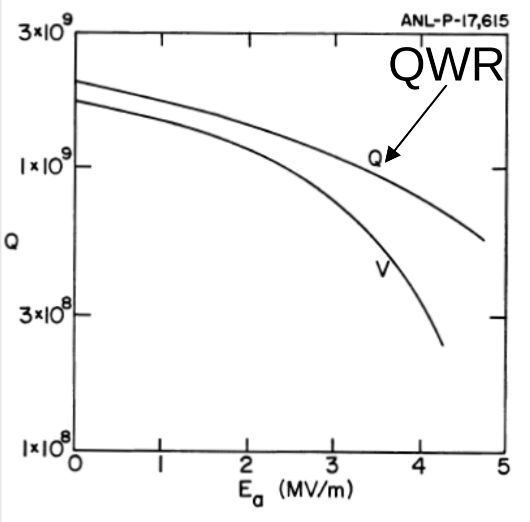


Fig. 4. Performance of the first six linac resonators at 4.2K. The accelerating field E_a is defined as the energy gain per unit charge for a synchronous particle divided by the interior length of the resonator (14 inches).

- Cavity and SRF dev't – new techniques
  - Second sound measurements as a diagnostic to locate defects in He-II
  - Diagnose weld quality – weld spatter, fissures/cracks in weld region, inclusions
  - Electro-polish as a surface preparation
  - Helium conditioning effective at reducing field emission

First Nb QWR- Shepard



- Photo shows a first Nb QWR 1984 (β=0.14 - 140MHz) as a precursor of the interdigital development for Positive Ion Injector Project
  - QWR first developed at SUNY in Pb on Cu
- Nb QWR form the basis of many low beta heavy ion linacs
  - JAERI, ISAC-II, INFN-LNL, SPIRAL-II

Positive Ion Injector – 1987-92

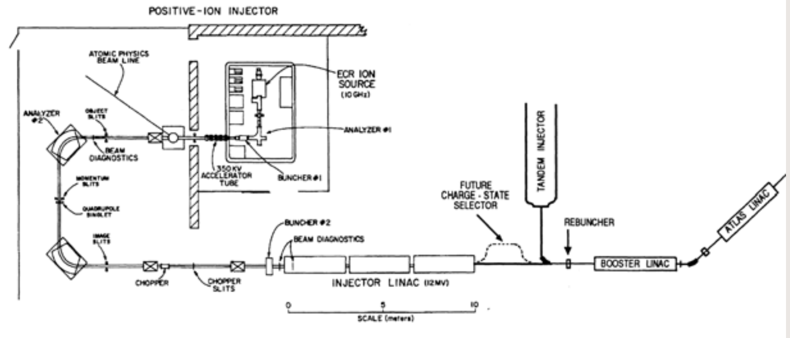
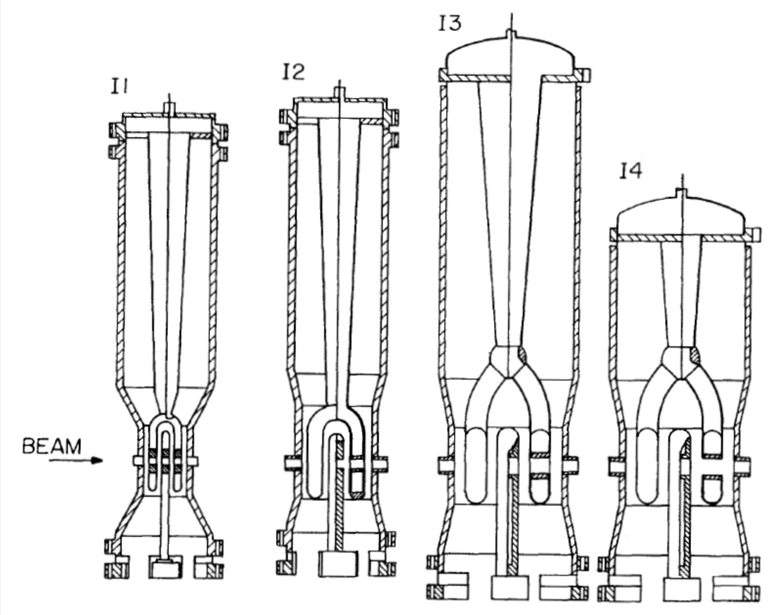
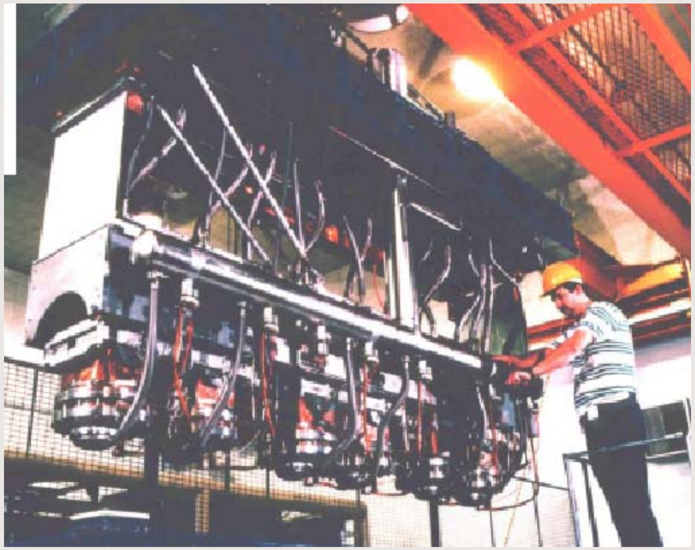


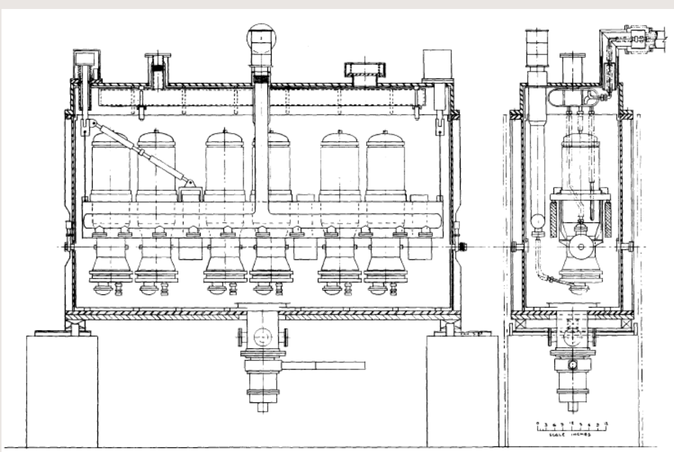
Fig. 1. Schematic floor plan of the ATLAS facility. The new PII is shown to scale with the remainder of the facility compressed and not to scale.



- Four cavity variants using quarter wave interdigital loading structure are used for the Positive Ion Injector (PII).
- Lowest frequency 48.5MHz QWR and lowest β=0.008 ever built (by a factor of five)
- demonstrated that SC technology could be used right from source potential
- PII addition forms the first all SC-linac

Top Loading Box Cryomodule

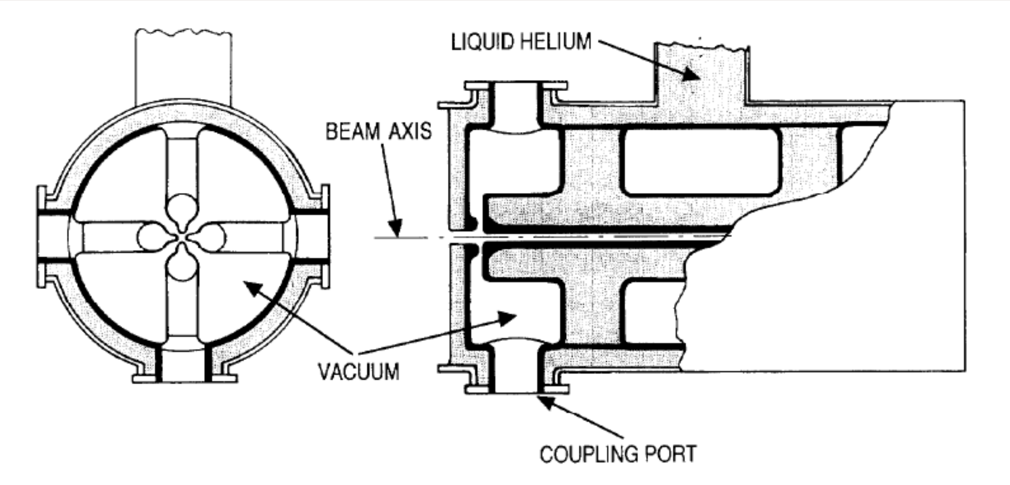




- Photo shows the top loading box cryomodule used for the Positive Ion Injector.
- Variants of the design used extensively in the SC heavy ion linac community
  - ISAC-II, SARAF, FRIB

Superconducting RFQ

- 6.5cm RFQ constructed, tested (Delayen, Shepard)
- 194MHz SC-RFQ designed
- Later on-line SC-RFQ finally realized at INFN-LNL



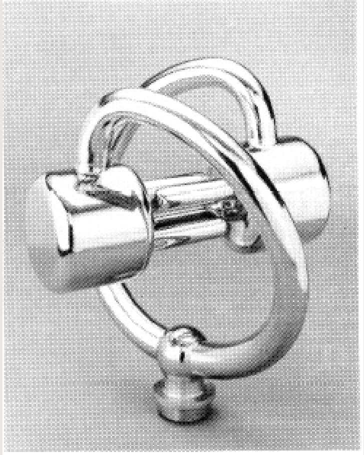
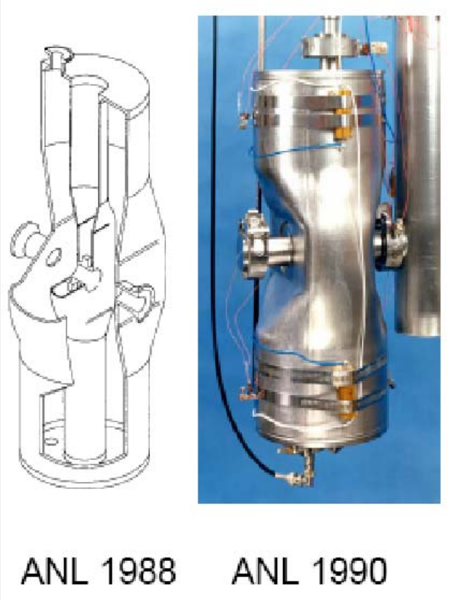


Fig. 1. Niobium split-ring assembly with RFQ vanes prior to being welding into the outer housing.

Half-Wave Cavity-Delayen

- Concept of a half wave cavity developed at ANL in 1988
- Cavity is a choice for higher velocities (beta~0.15-0.25) and light ions where asymmetric fields from QWR inner conductor leads to strong vertical kicks
- First demonstrated in 1990
- Cavity of choice for FRIB, SARAF, IFMIF



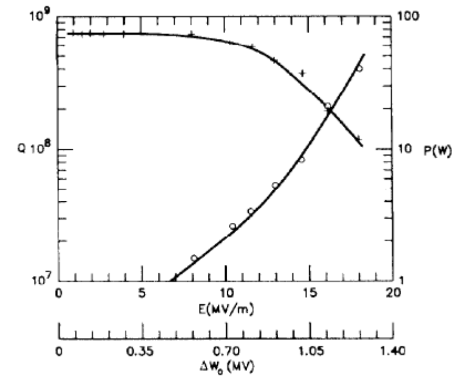


Figure 2. Q-curve (+) and power dissipation (o) for the 355 MHz coaxial-half-wave resonator.

Spoke Cavities-Delayen

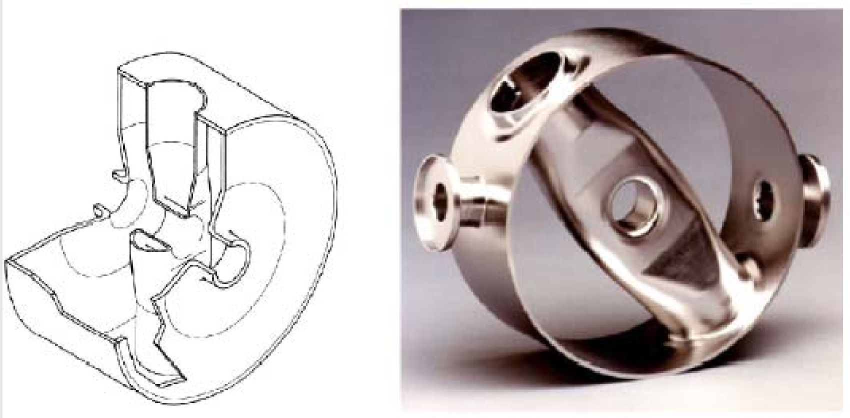


Figure 1: Single-spoke cavity [1, 3].

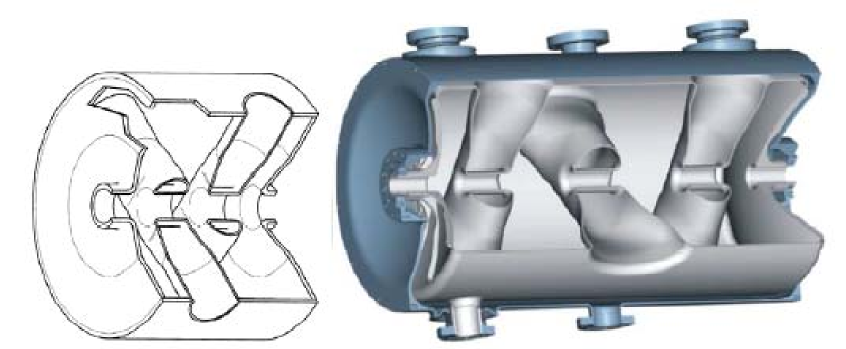
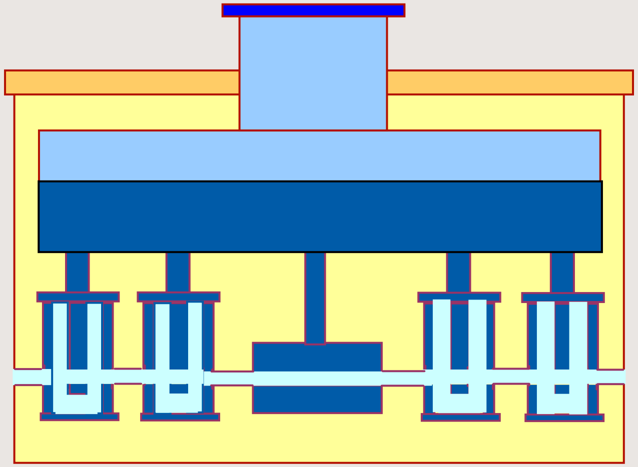


Figure 2: Double-spoke [1] and triple-spoke cavities [4].

- •Concept developed at ANL in 1988 and first realized in 1991
- •Spoke concept allows to stack multiple spokes in a single resonator for efficient high velocity acceleration of ions at medium beta (0.2-0.5)
- •Spoke resonators are in dev't for Project X, Eurisol

Separated Vacuum Cryomodule



- Traditionally, cavity vacuum and thermal isolation vacuum shared the same space in heavy ion linacs
    - ATLAS, INFN-LNL, JAERI, ISAC-II
- The ANL energy upgrade cryomodule is the first module to separate the vacuum to help restrict particulate from rf surface
- New projects are adopting this technique
    - SARAF, Spiral-II, FRIB, IFMIF

High Intensity Hadron Linac

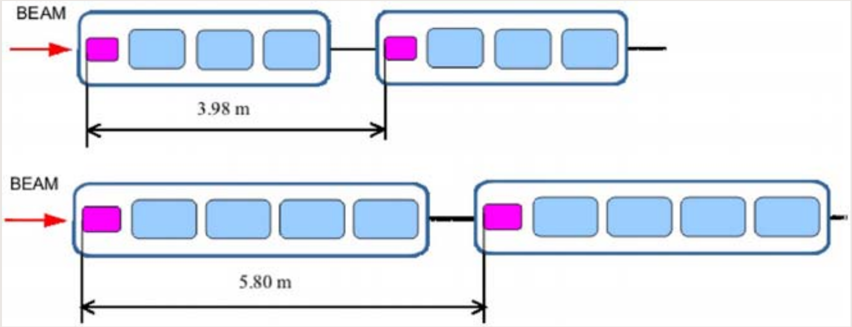


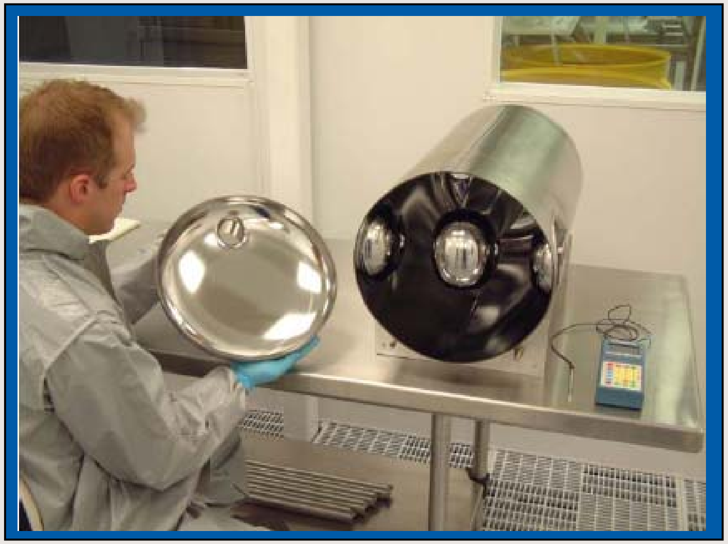
FIG. 4. (Color) Layout of the cryostats containing two types of triple-spoke-loaded superconducting cavity: *G* 0:5 (top) and *G* 0:62 (bottom).

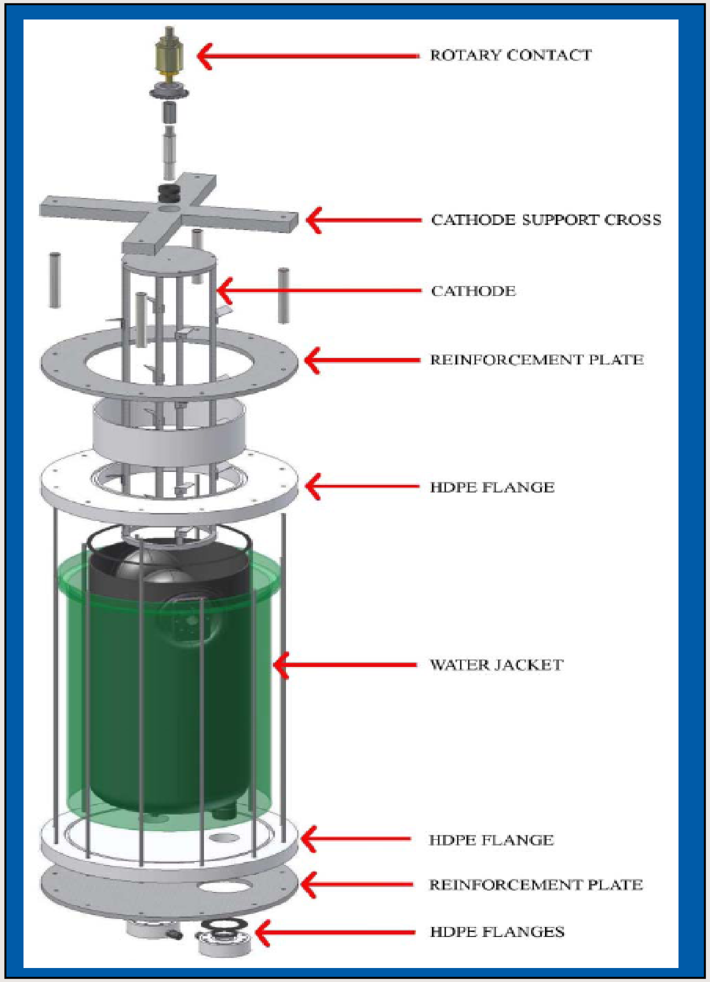
- Now generally accepted that high intensity proton linacs can start SC portion at lower energies – cavities and concept developed and promoted by ANL
  - Example - Project X

- ANL developed schemes for high intensity hadron linacs starting from low velocity to high using alternate structures including QWR and single and multiple spokes
- Showed that spokes are competitive with elliptical cavity to beta~0.7
- Low freq, large aperture, permit operation at 4K

Unique EP System for QWR

- ANL SRF team has used an electro-polish surface finish for low beta cavities from the beginning
- Each quarter wave processed as two major sub-assemblies then welded together
- Process continues to be refined



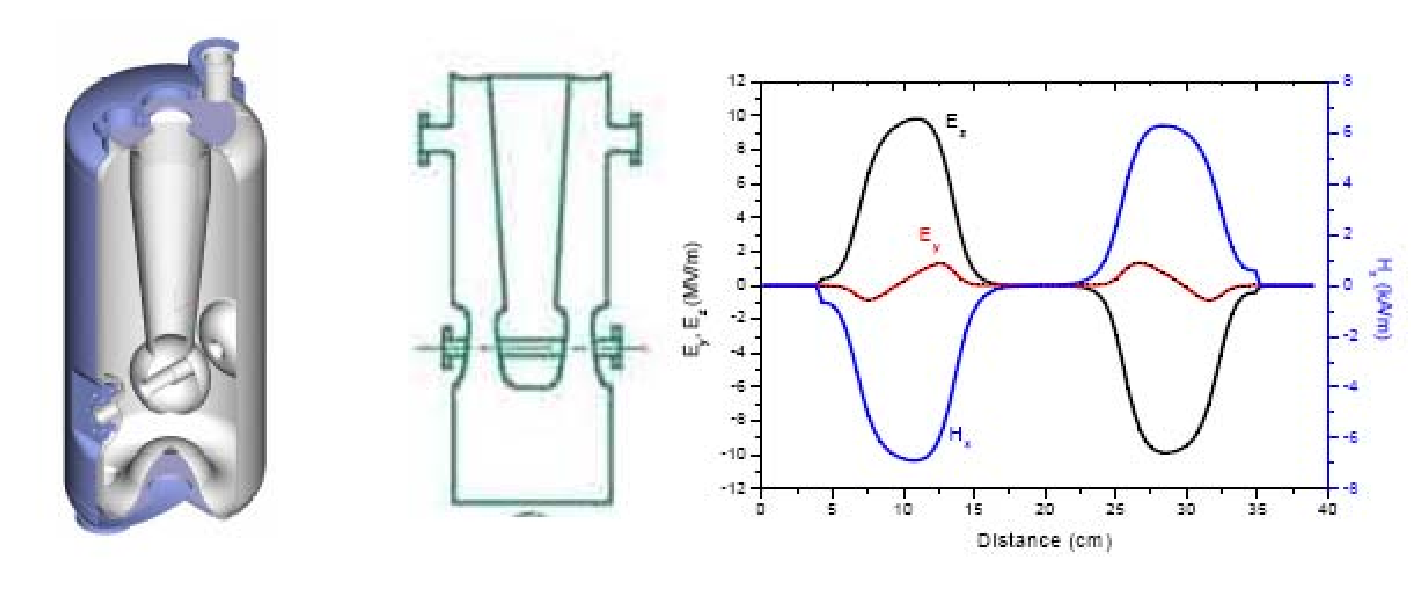


QWR Steering compensation

•A limitation to acceleration of light ions by quarter waves was the velocity and phase dependent beam steering due to asymmetry in the electric field and finite rf magnetic field

•ANL (Ostroumov, Shepard) developed a solution by tilting the drift tube face to cancel kicks

• allows use of QWR's for light ions at higher velocities



Multi-Charge State Acceleration 1999

•ANL (Ostroumov, Shepard) incorporated the concept of multi-charge acceleration in a high intensity heavy ion driver linac to improve the acceleration efficiency

• now incorporated in FRIB driver concept

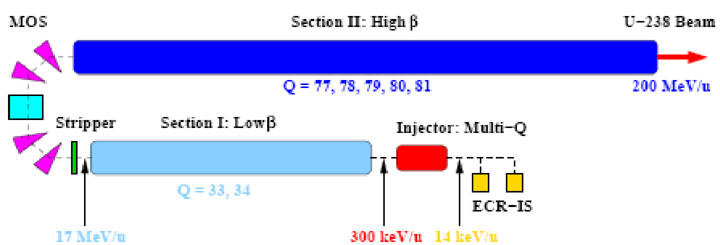


Figure 1: Schematic layout of the AEBL driver linac. For a uranium beam, two charge states (33^+,34^+) are accelerated from the ion source to a stripping station at 17 MeV/u after which five charge states (77^+,78^+,79^+,80^+,81^+) are accelerated in the high-β section up to 200 MeV/u.

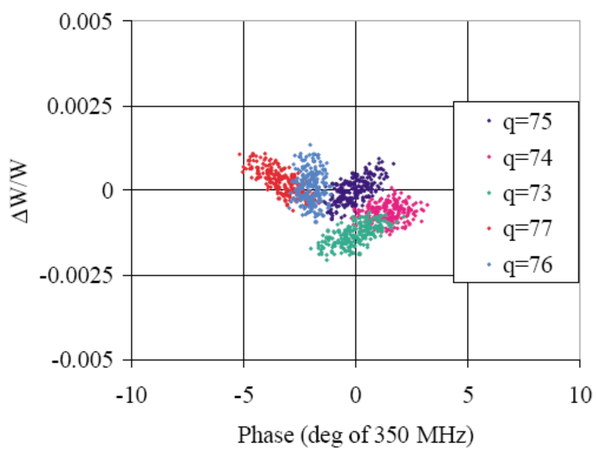


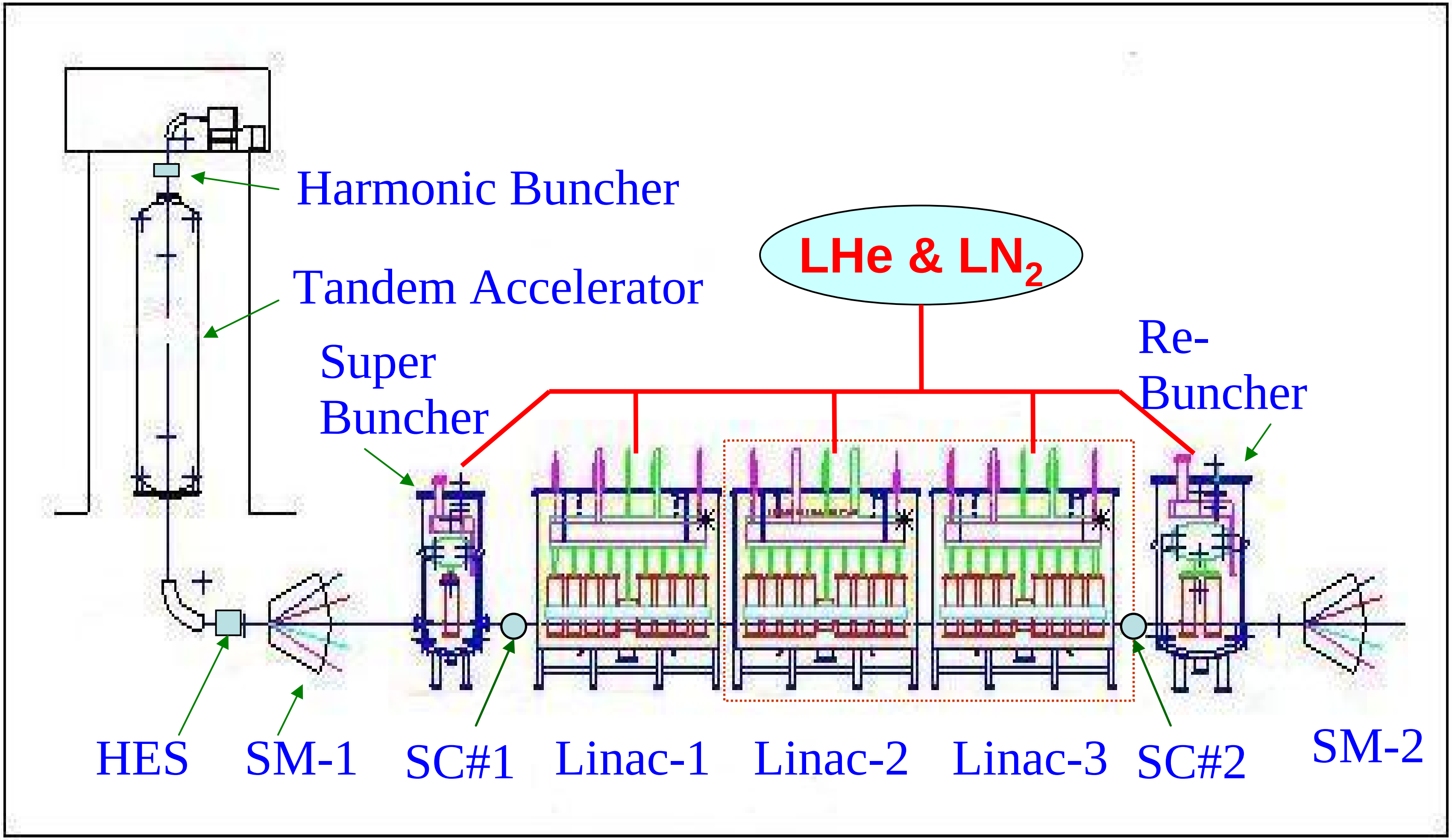
FIG. 7. (Color) Phase space plots of five charge state beam at 85 MeV/u before passing through the second stripper.

Chapter 3

ATLAS the Mentor

ATLAS the mentor

- IUCF
  - Design and build QWR's for post-accelerator
- JAERI
  - QWR design and prototype
- ISAC-II/TRIUMF
  - Cryomodule design
  - Indium seal flanges



Harmonic Buncher
Tandem Accelerator
LHe & LN$_2$
Super Buncher
Re-Buncher
HES
SM-1
SC#1
Linac-1
Linac-2
Linac-3
SC#2
SM-2

IUCF superconducting linac

- Linac requires 27 QWR
- 13 QWRs were built in collaboration with Argonne National Lab.
- Remaining resonators are being fabricated in-house in Delhi – in progress

JAERI Cavity Dev't

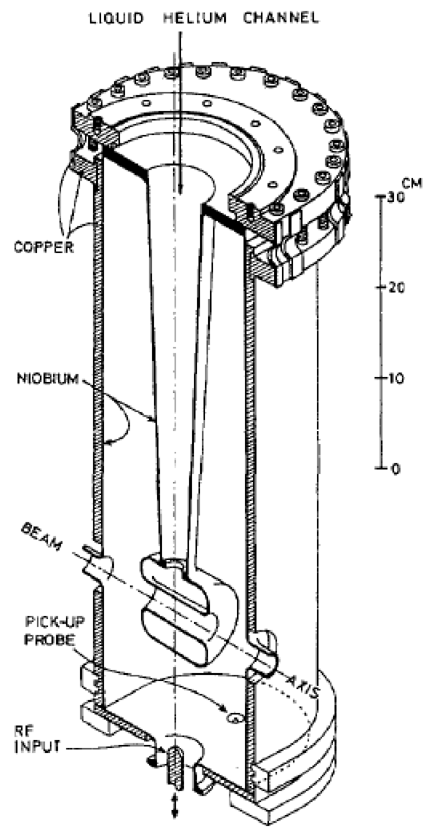


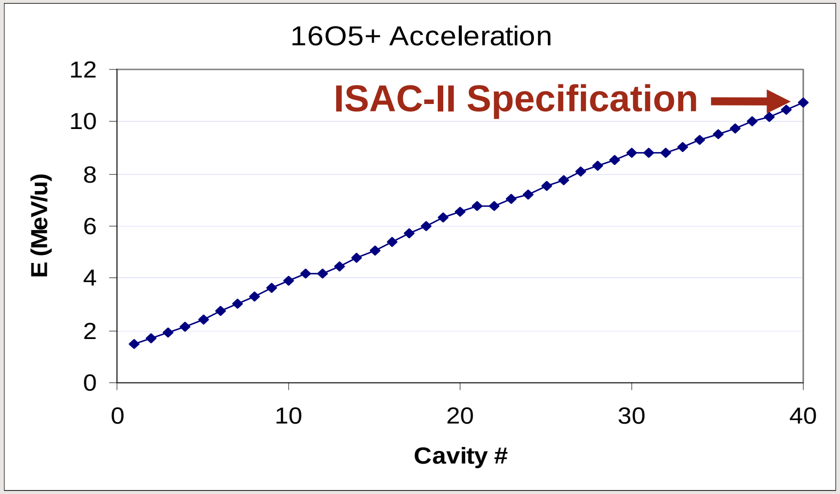
Fig. 1. Cut-away view of a prototype quarter wave resonator.

- Takeuchi visited ANL in 1985 and collaborated with Shepard and Zinkann on the QWR
- Central loading element of Nb and body from Nb on Cu
- JAERI went on to build resonators in Japanese Industry to produce a very successful SC linac

ISAC-II Cryomodules

- 2002 - Laxdal and collegues visit ANL for mini-workshop on cryomodule design
- ISAC-II top-loading box module aided by ANL collaboration
- Shepard gave valuable advice throughout the project

ISAC-II Phase II Acceleration



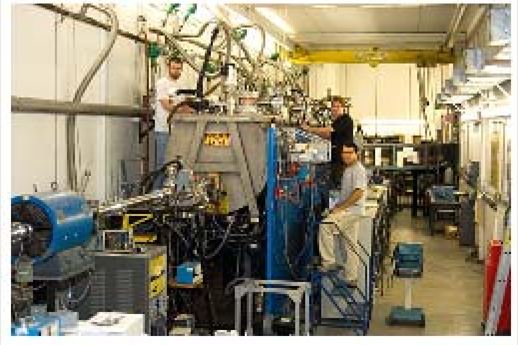
- Final cryomodule installed March 24
- First beam was accelerated April 24
- 16O5+ accelerated to 10.8MeV/u equivalent to 6.5MeV/u for A/q=6 (meets ISAC-II original specification on first acceleration)
- First stable beam delivered to experiment April 25
- First RIB's accelerated May 3

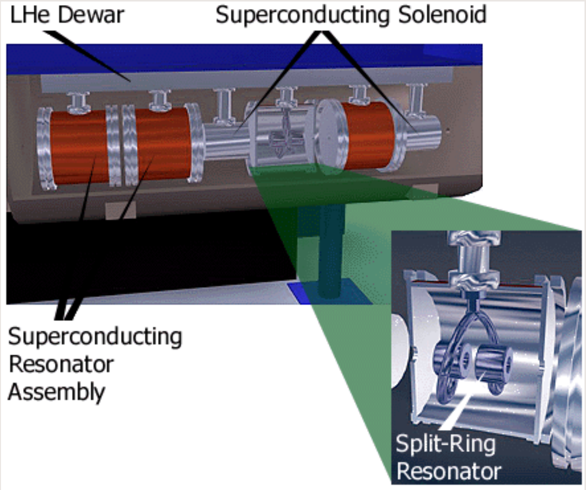
Chapter 4

ATLAS the Supplier

ATLAS the provider

- Florida State University added a SC post accelerator to their tandem with cavities produced at ANL
    - 12 Nb split ring resonators 1987
- Kansas State University added a post accelerator to their tandem with cavities produced at ANL
    - 12 Nb split ring resonators





Chapter 5

ATLAS the Communicator

Papers and Invited Speakers

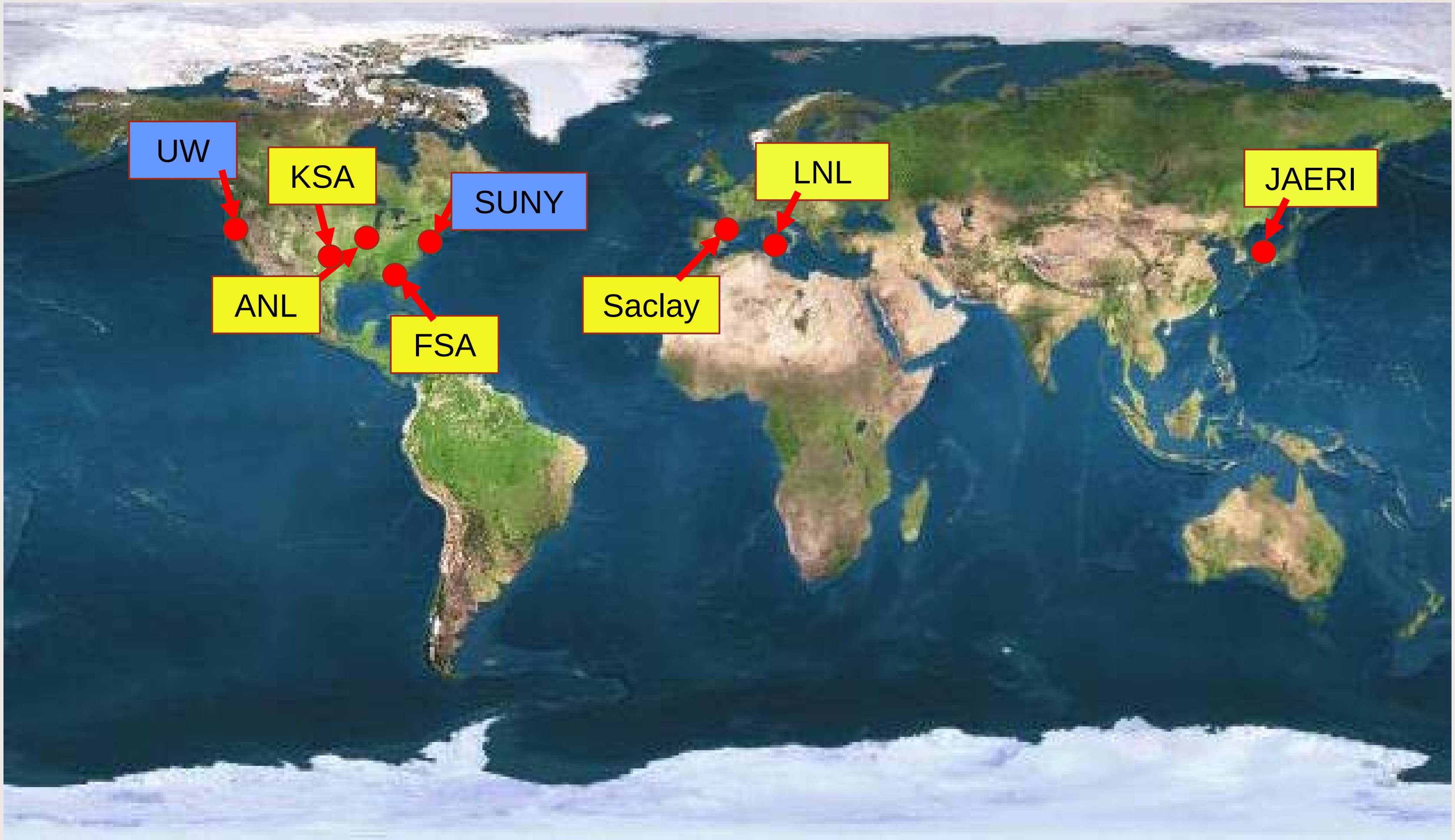
- ATLAS physicists and engineers have produced many excellent papers to refereed journals and to conferences
- Argonne has produced many world class accelerator physicists and engineers in SRF technology and operation and received an impressive number of invited presentations
  - Bollinger, Shepard, Delayen, Kelly, Pardo, Zinkann, Conway, Ostroumov, Nolan, Fuerst, Kedzie,…

Chapter 6

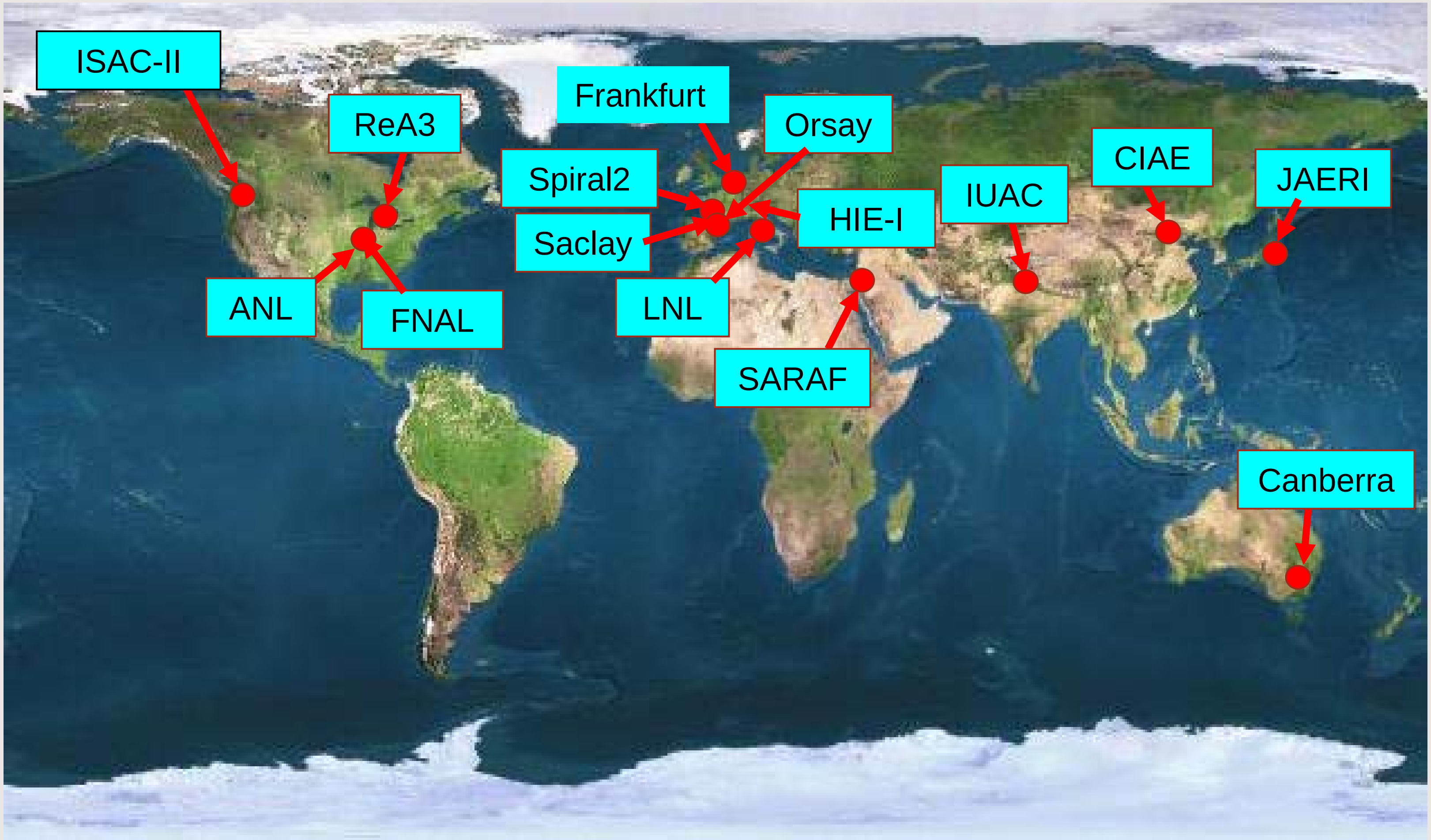
ATLAS and the World

Hadron Niobium SC-Linac - 1978

Hadron SC-Linac - 1990



Hadron SC-Linac Facilities and R+D-present



Upgrades, Projects and Proposals for Ions

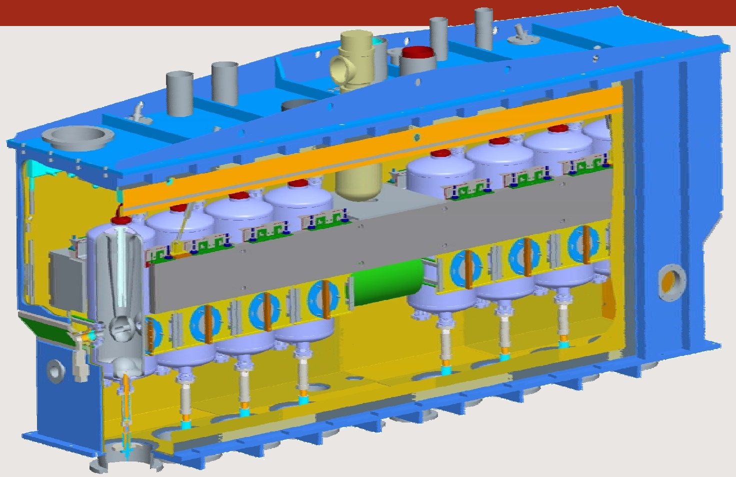
Project	Lab	Driver	Post-accelerator	Particle	Structure
ISAC-II	TRIUMF		√	HI	QWR
Upgrade	ANL		√	HI	QWR
Upgrade, SPES	LNL		√	HI	QWR
SPIRAL-II	GANIL	√		P, d, HI	QWR
SARAF	SOREQ	√		P, d	HWR
IUAC			√	HI	QWR
ReA3	MSU		√	HI	QWR
FRIB	MSU	√	√	HI/HI	QWR, HWR
HIE-REX	CERN		√	HI	QWR (sputter)
IFMIF		√		d	HWR
Project-X	FNAL	√		p	Spoke, elliptical
EURISOL		√	√	P, d / HI	QWR, HWR, Spoke

Chapter 7

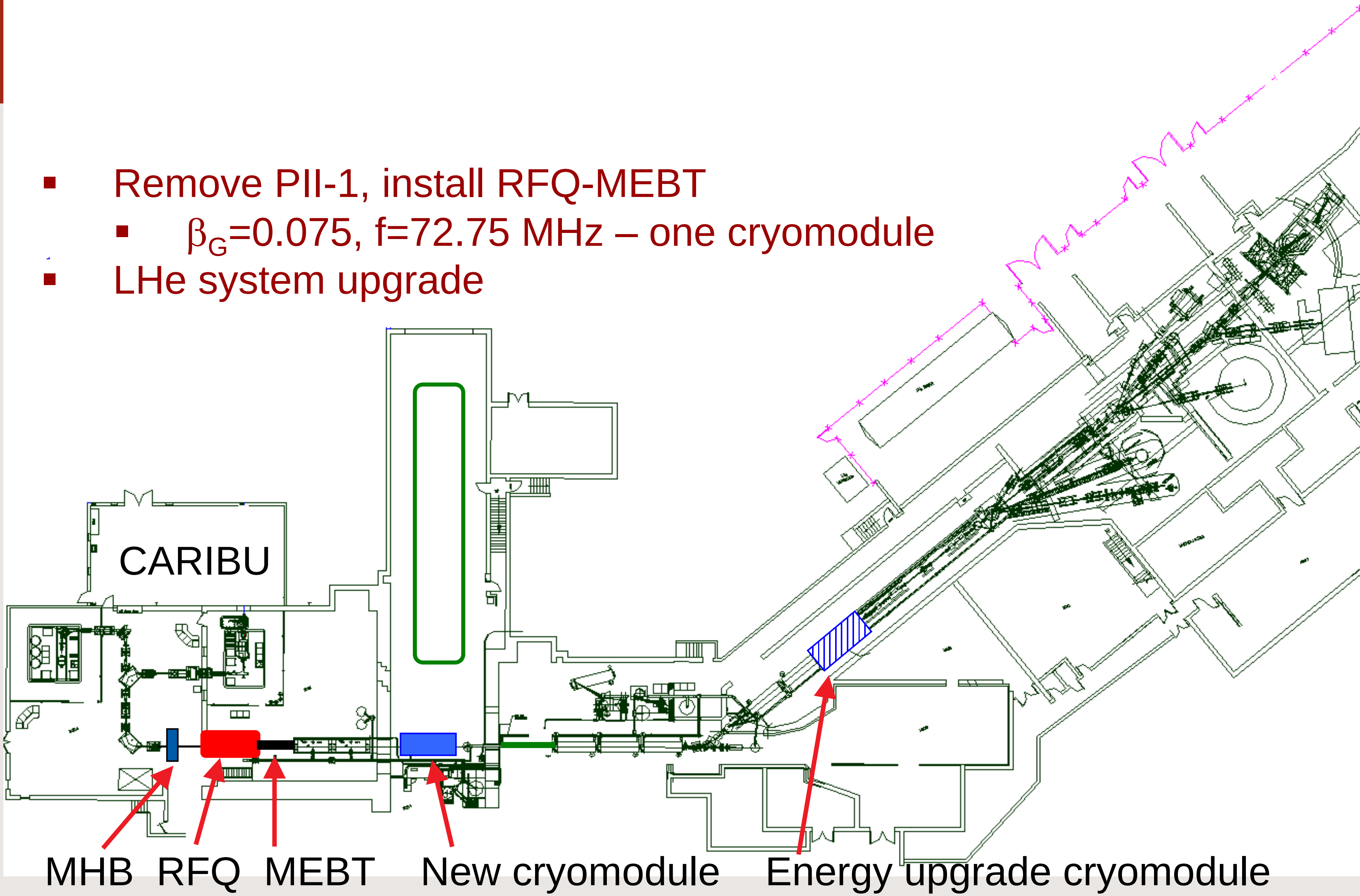
The Future

Dev’t of High Performance Cryomodules

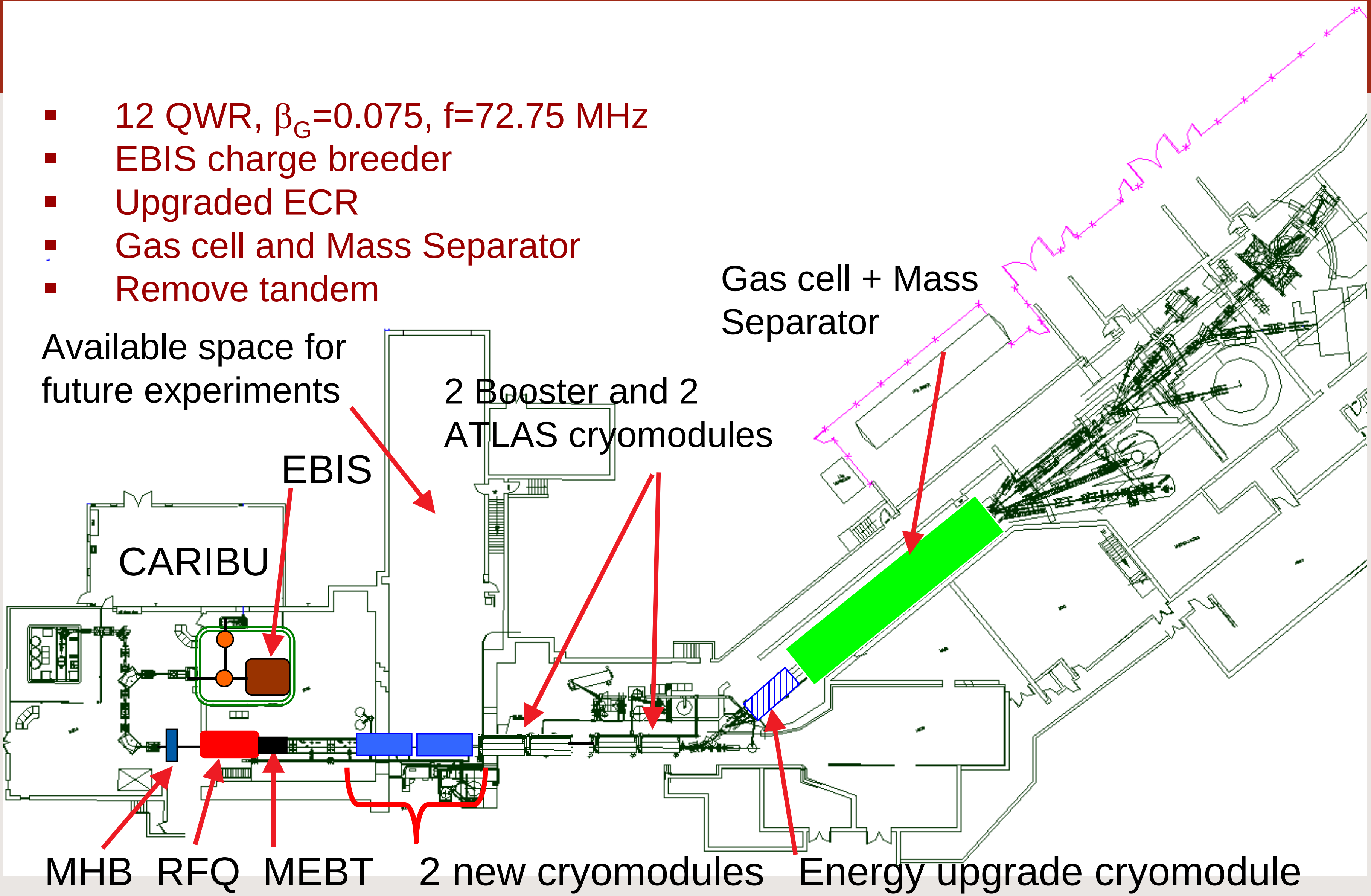
- Atlas SRF group now developing high performance cryomodules for in house upgrade
- Technology should find use in other future projects and collaborations



- Remove PII-1, install RFQ-MEBT
  - β_G=0.075, f=72.75 MHz – one cryomodule
- LHe system upgrade



- 12 QWR, β_G=0.075, f=72.75 MHz
- EBIS charge breeder
- Upgraded ECR
- Gas cell and Mass Separator
- Remove tandem



Prologue

ATLAS in the World

- It is hard to be quantize the impact of ATLAS in the heavy ion SC-linac world – the influence is everywhere
- As pioneer they proved to other labs that a linac based on SC technology was feasible - beyond that they showed it offered many advantages over existing technology
- Atlas paved the way for projects to be proposed and accepted – JAERI, INFN-LNL, ISAC-II, …

ATLAS in the World

- ATLAS was a leader in innovation - developing techniques for fabrication, processing, trouble-shooting - they engaged in the global effort to make the technology mainstream
- Structures developed in Argonne found use in other proposals and facilities to be further developed and optimized – the building blocks of low to medium beta SC accelerating structures are all strongly influenced by Argonne

ATLAS in the World

- ATLAS promotion of SC applications
  - SC booster for existing heavy ion machines particularly tandems
    - Short independently phased cavities perfectly suited to delivering a wide variety of heavy ions over a broad energy range
    - Post-accelerators for RIB facilities (ISAC-II, ReA3, HIE-Isolde)
  - SC linac as a high intensity cw hadron driver
    - Proved feasibility of acceleration from much lower energy than previously considered making cw application possible – neutrino source - Project X – ADS driver
    - Concept of multi-charge acceleration permits efficient acceleration of heavy ion beams – RIB drivers (FRIB)
    - Efficient acceleration of High intensity beams – material testing (IFMIF) – medical isotope production

SRF at ATLAS

- An amazing 35 years
  - Pioneering installation and POP
  - Innovative and influential R+D
  - Efficient production
  - Reliable operation

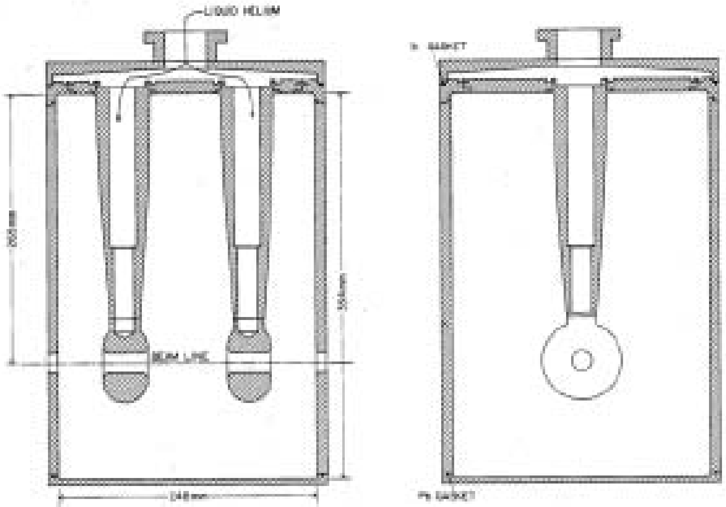
ATLAS SRF - ?

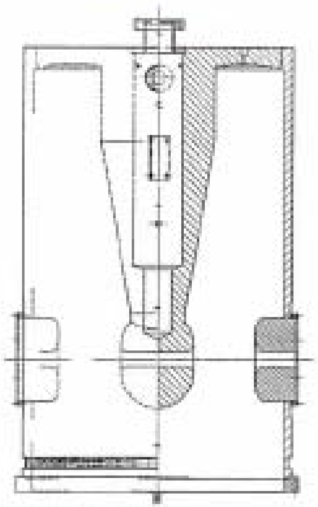
Thirty Five Years Old

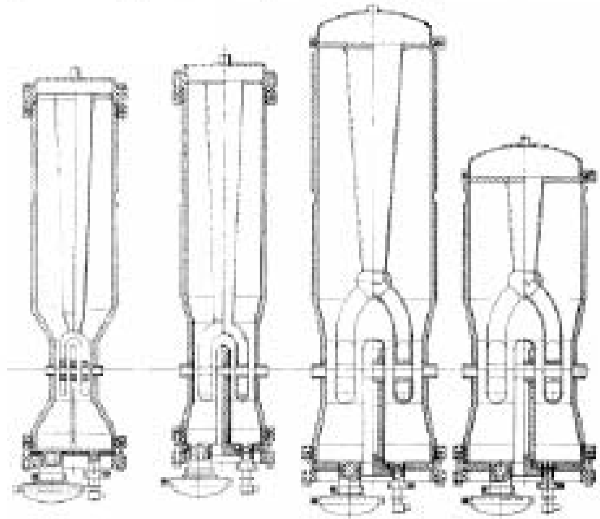
ATLAS SRF is strong

Thirty Five Years Young

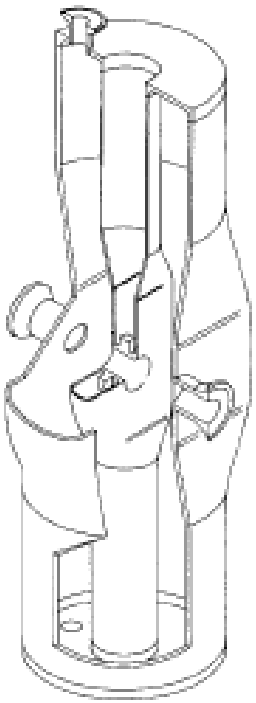
TEM Class $\lambda/4$ – $\beta \sim$ 0.04-0.15 (~100 MHz)



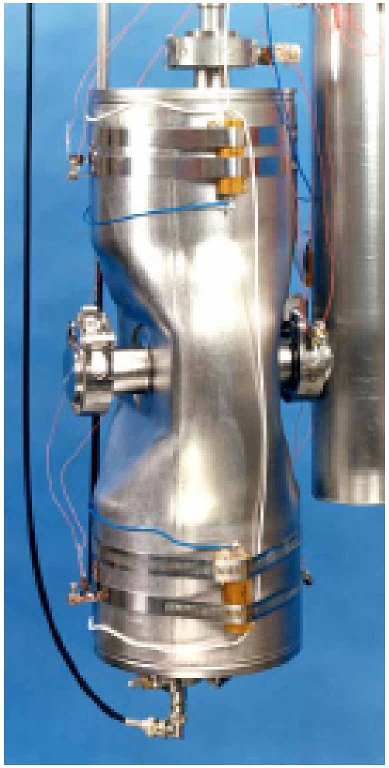




TEM Class $\lambda/2$ - $\beta \sim 0.12$-0.2 (~200MHz)

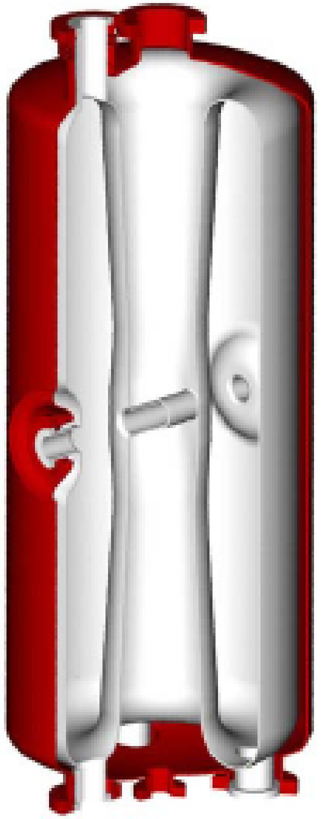


ANL 1988



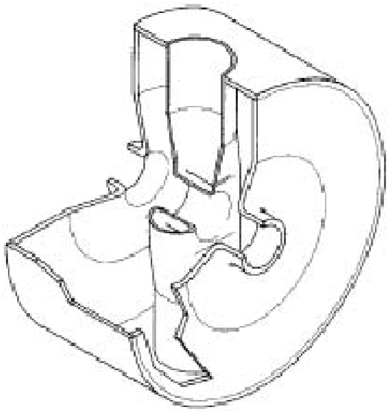
ANL 1990

MSU 2003



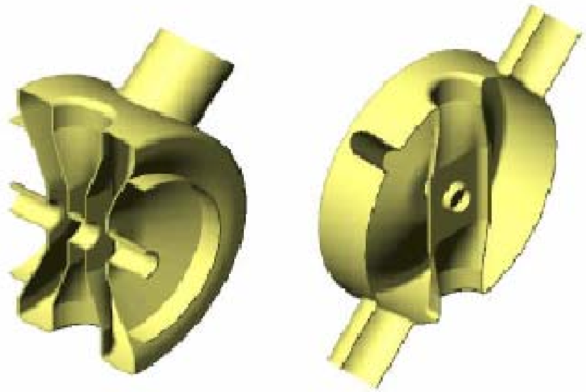
ANL 2003

TEM Class λ/2 Single spoke β~0.2-0.5



ANL 1988

ANL 1991

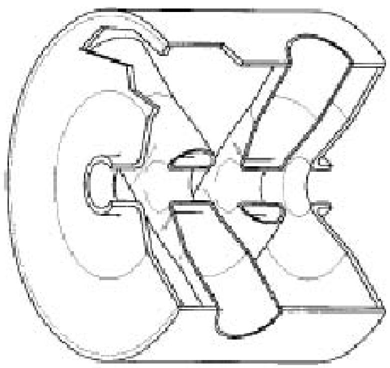


LANL 2001

ANL 1998

Orsay 2002

TEM Class $\lambda/2$ Multi-spoke $\beta\sim0.2\text{-}0.5$



ANL 1988

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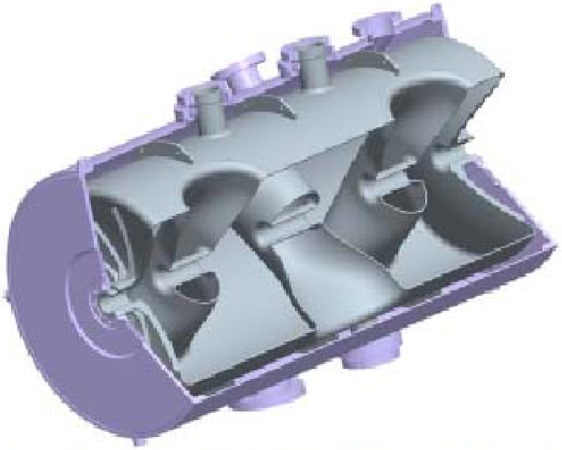

Juelich 2001

Juelich 2003

ANL 2004