

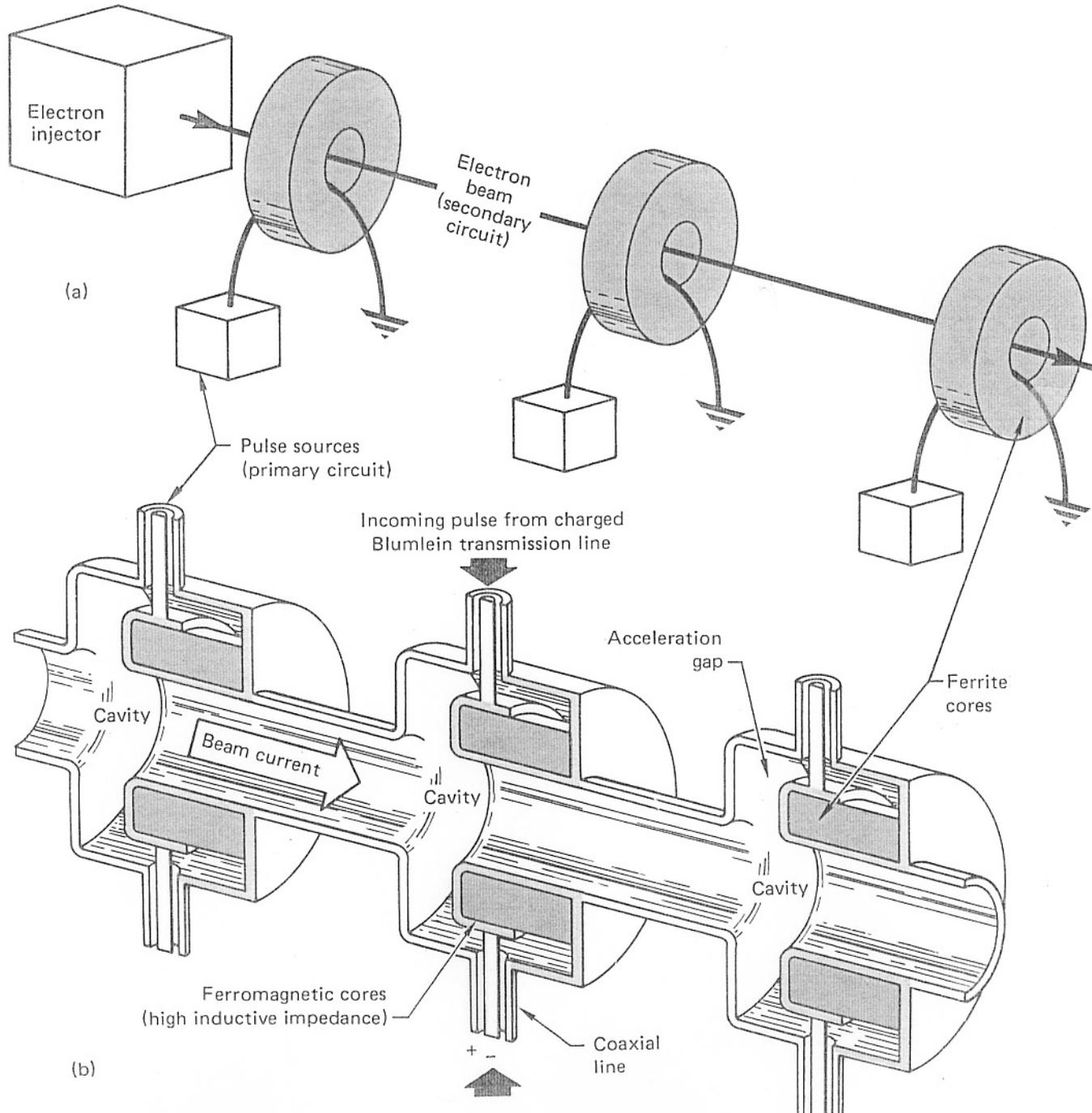
**Overview on a Role of
Induction Accelerators in High Energy Physics and Energy Science:
Historical Perspectives and Future Prospects**

Dick Briggs, SAIC

**International Workshop on Recent Progress in Induction
Accelerators, KEK, Tsukuba, Japan
October 29-31, 2002**

Outline of my talk

- 1. Basic features of induction accelerator technology**
- 2. Historical perspectives; Astron, ERA, ATA, etc.**
- 3. Possible future applications of induction accelerator technology in High Energy Physics and Energy Science**



Induction Accelerator Science and Technology Elements

Beam transport physics

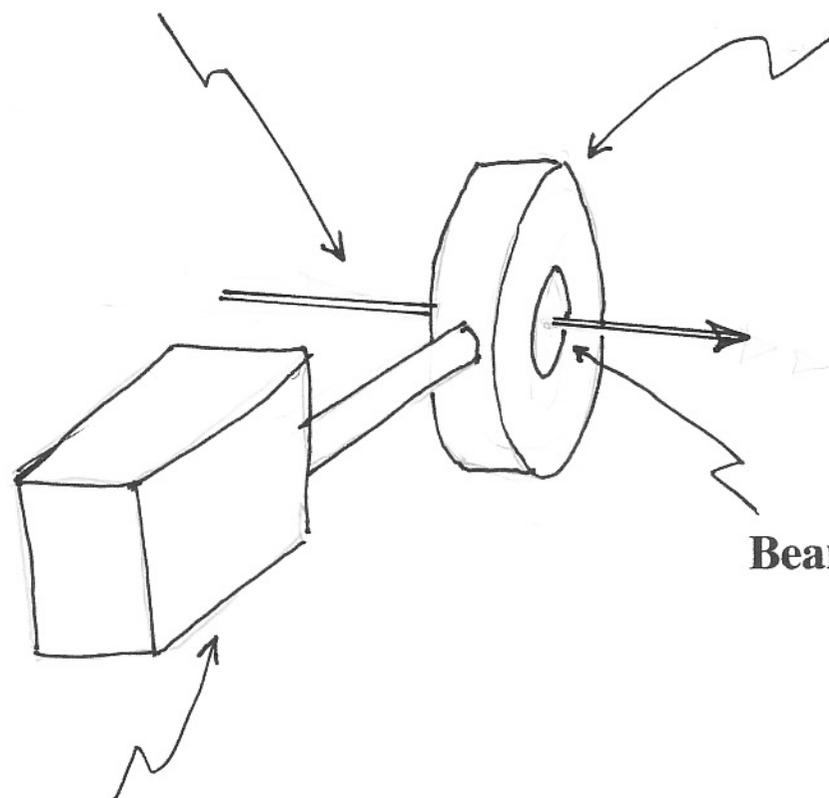
Accelerator cell

- core material, cooling
- insulator

Beam-cell interaction

- energy coupling, efficiency
- transverse and longitudinal interaction impedance

Pulse power systems

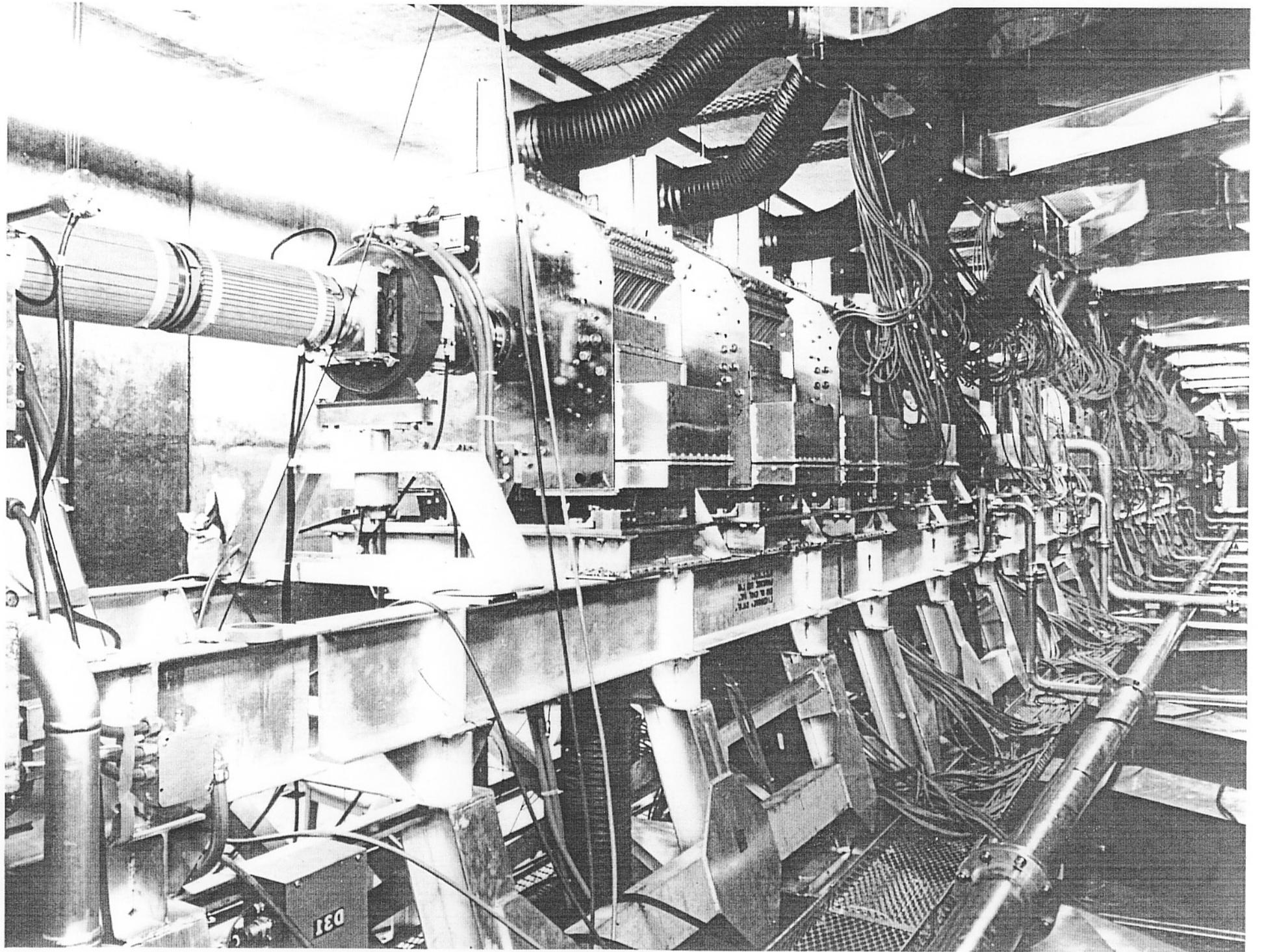


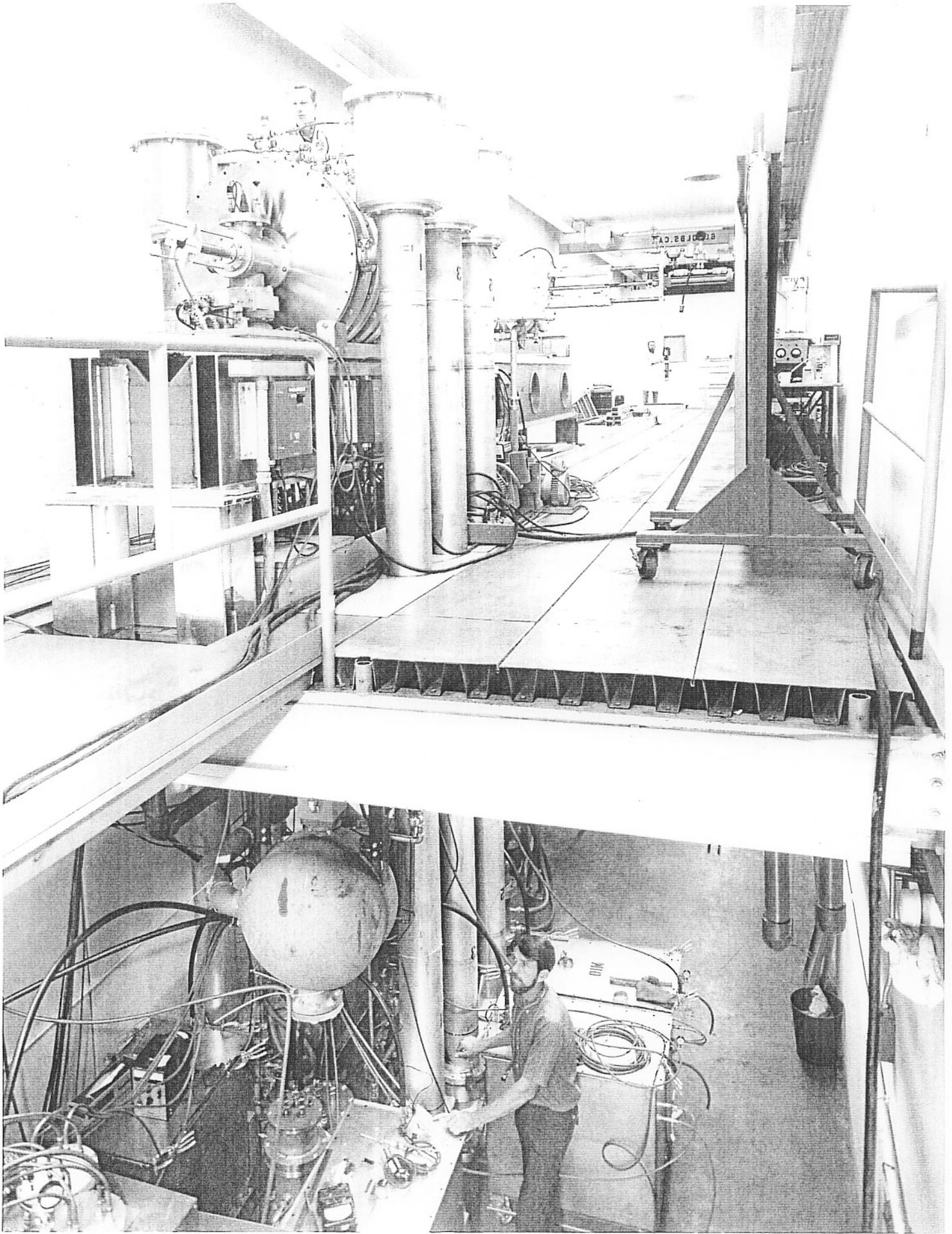
Early History of Induction Accelerators (in the USA)

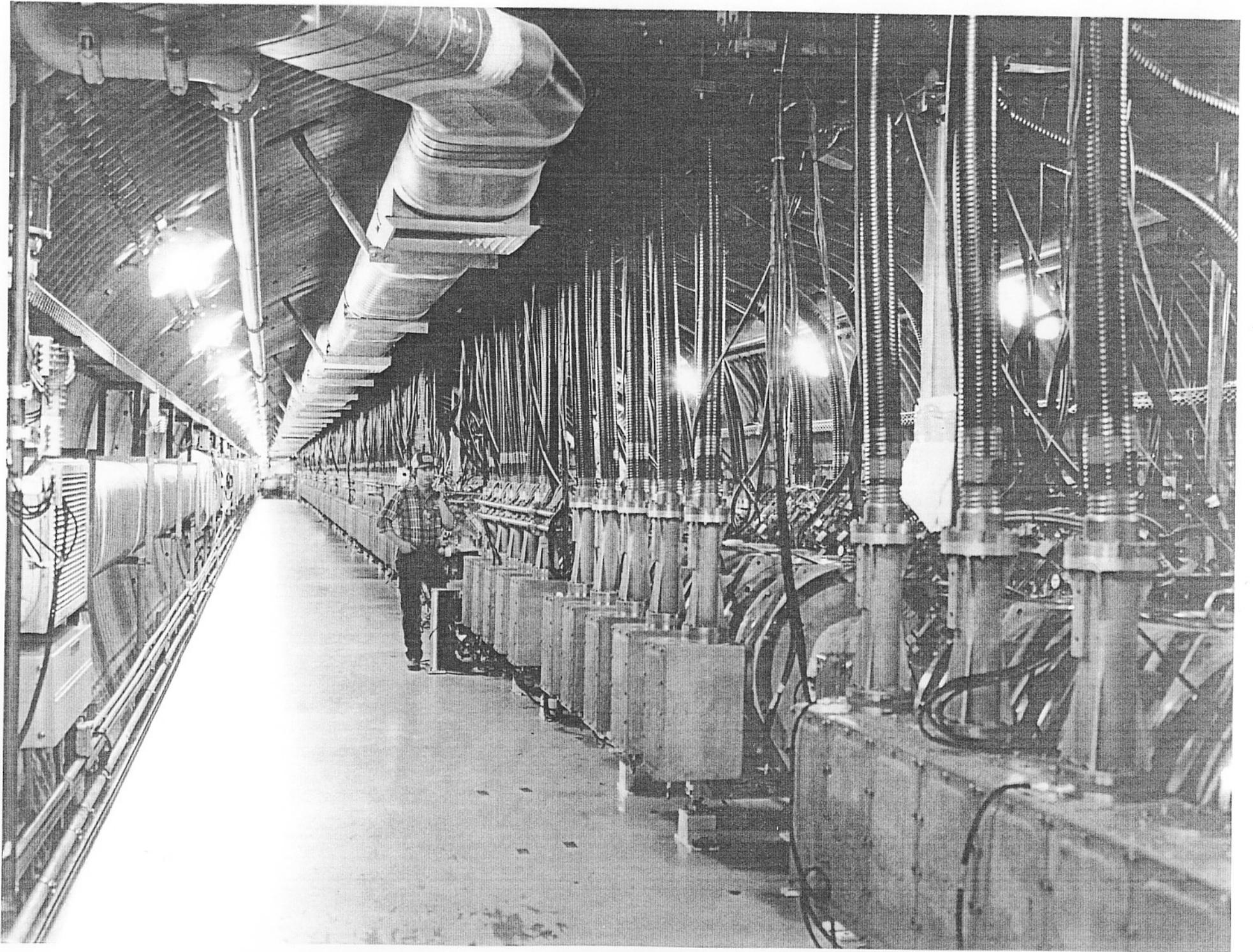
	Kinetic energy	Beam current	Pulse length	Average rep rate (max)	Burst rep rate (# of pulses)
Astron Inj, LLNL(1963)	3.7 MeV	350 A	300 ns	60 Hz	1440 Hz (100)
Upgrade (1968)	6.0 MeV	800 A	300 ns	60 Hz	800 Hz (100)
NBS Prototype (1971)	0.8 MeV	1,000 A	2,000 ns	< 1Hz	--
ERA Inj., LBL (1971)	4 MeV	1,000 A	45 ns	5 Hz	--
ETA, LLNL (1979)	4.5 MeV	10,000 A	30 ns	2 Hz	900 Hz (5)
FXR, LLNL (1982)	18 MeV	3,000 A	70 ns	0.3 Hz	--
ATA , LLNL (1983)	45 MeV	10,000 A	60 ns	5 Hz	1,000 Hz (10)

Early History of Induction Accelerators (in the USA) - II

	Core type	Switch (HV)	# of switch modules	Module (core) voltage	Accelerator length
Astron Inj, LLNL(1963) Upgrade (1968)	Ni-Fe tape "	Thyratron "	300 550	250 kV (12.5 kV)	~ 10 meters 30 meters
NBS Prototype (1971)	Steel tape	Spark gap	2	200 kV (40 kV)	1.3 meters
ERA Inj., LBL (1971)	Ferrite	Spark gap	17	250 kV	14 meters
ETA, LLNL (1979)	Ferrite	Spark gap	10	250 kV	10 meters
FXR, LLNL (1982)	Ferrite	Spark gap	62	250 kV	40 meters
ATA , LLNL (1983)	Ferrite	Spark gap	200	250 kV	53 meters





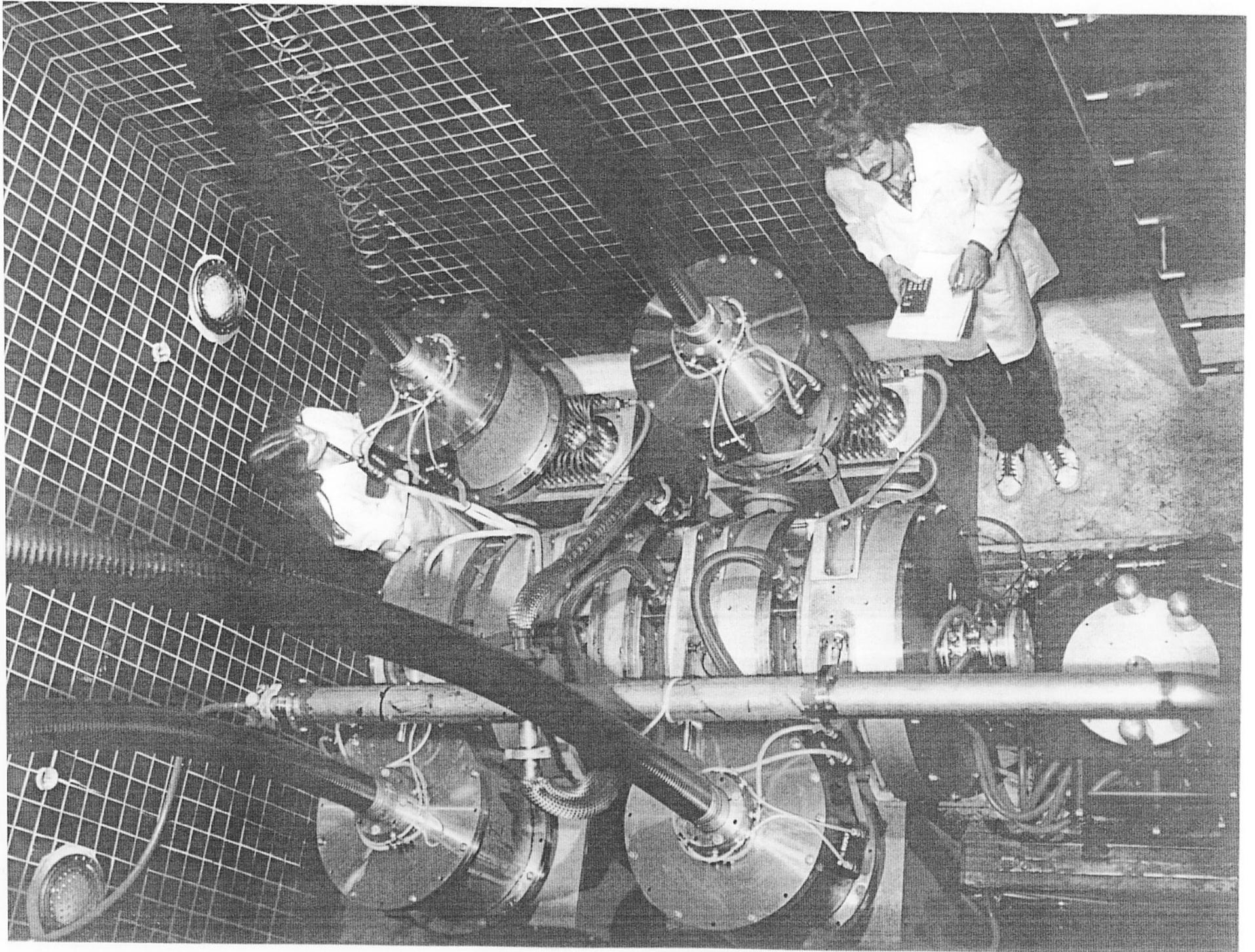


Development of Magnetic Modulators in the early 1980's was a major advance in Induction Linac Pulse Power Systems

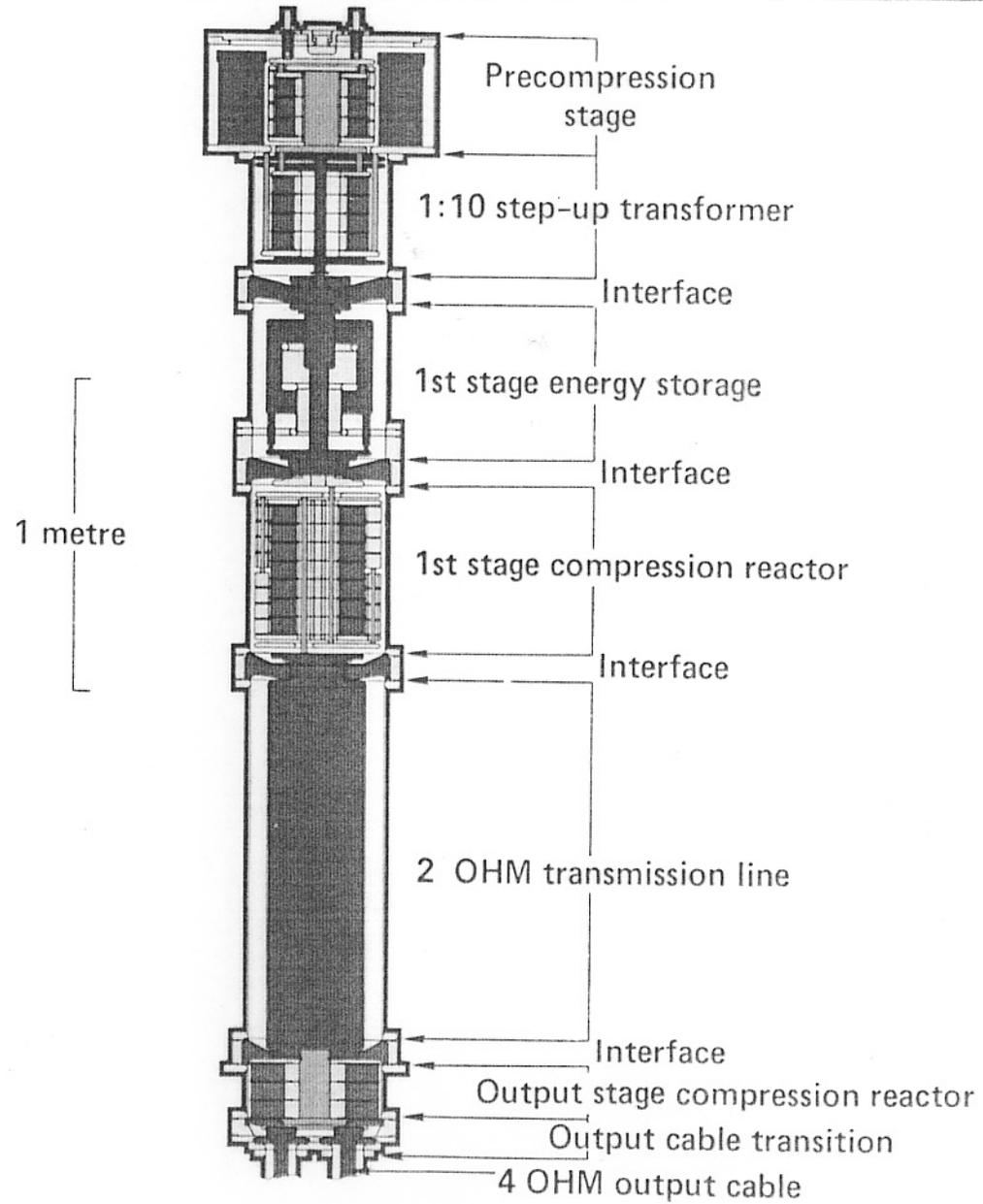
The MAG-I-D modulator (Dan Birx, LLNL) produced 125 kV, 70 ns pulses at a 5 kHz rep rate (quasi-CW); peak power ~ 8 GW, average power ~ 3 MW. (Thyratrons were the primary switch)

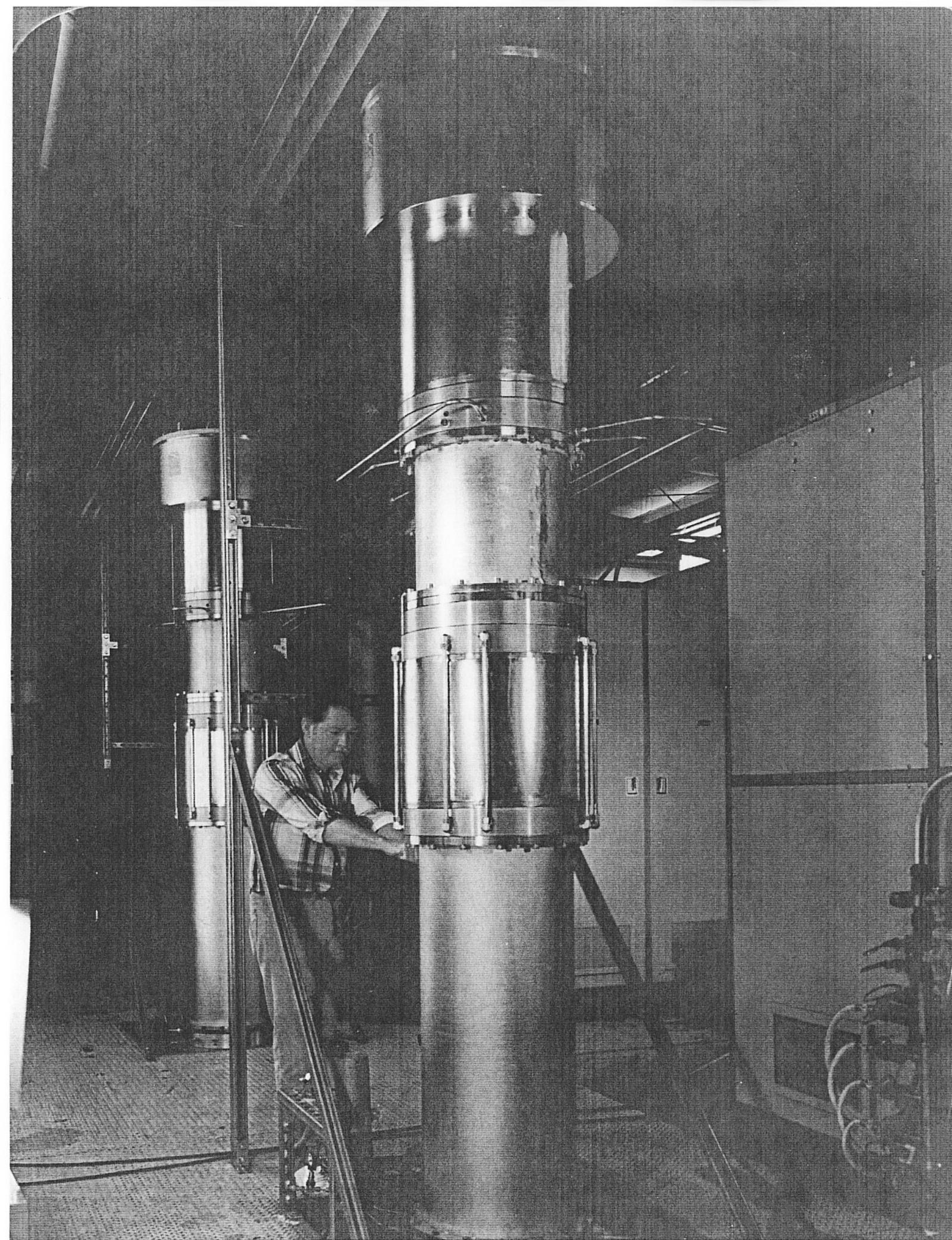
Three MAG-I-D's are used to drive 60 cells on the ETAII accelerator at LLNL built in the late 1980's:

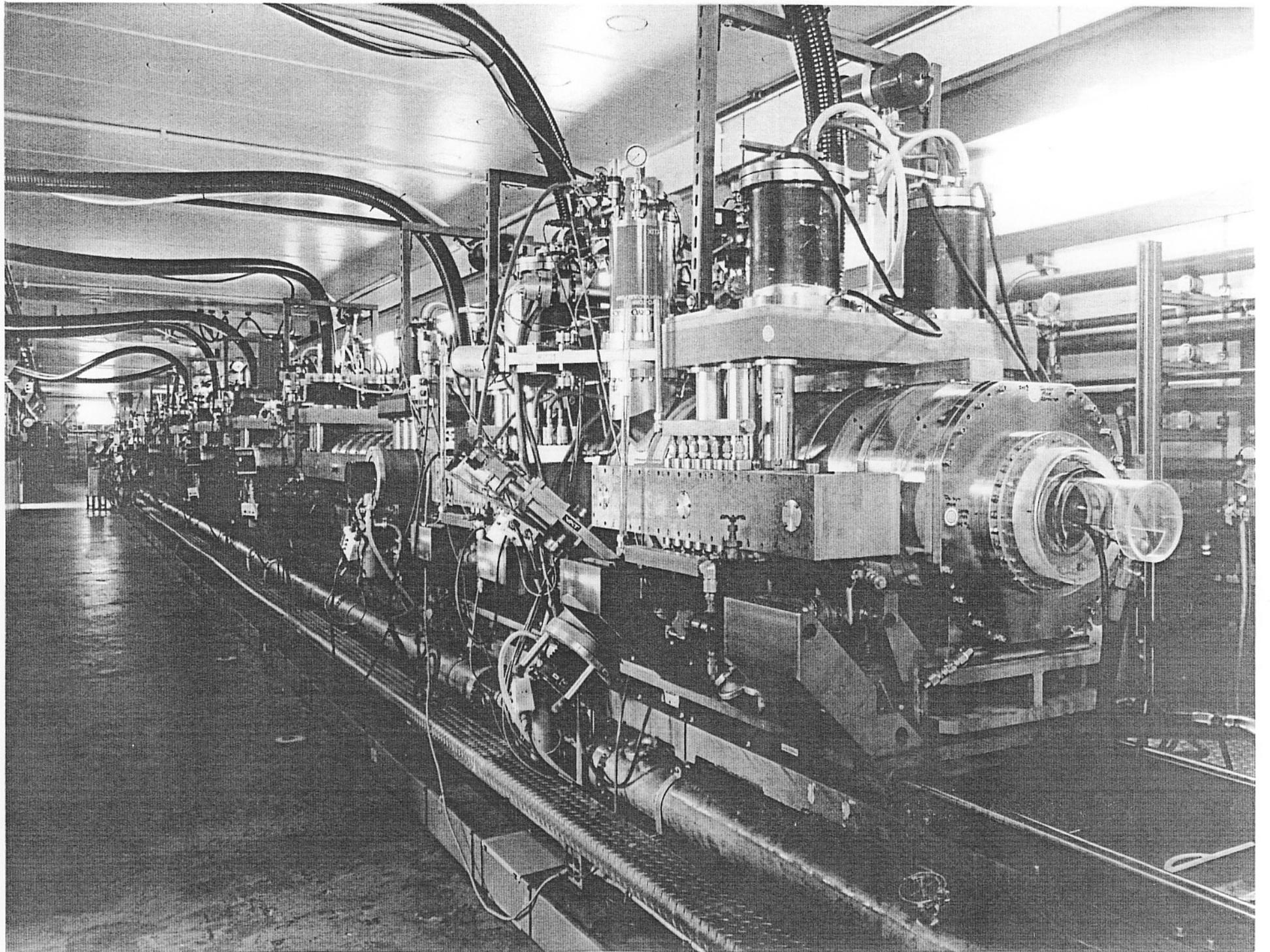
6 MeV, 2 kA, 40 ns flat-top very high brightness electron beam



MAG-I-D







Possible Future Applications of Induction Accelerator Technology in High Energy Physics and Energy Science

- 1. Induction Synchrotron KEK, LHC upgrade, 60 TeV hadron collider**
- 2. Linear Colliders TBA's, modulators for klystrons**
- 3. Muon Collider and Neutrino Factory**
- 4. Inertial Fusion Energy - Heavy Ion Fusion**
- 5. Spallation Neutron Source (next generation)**

For Each Application I Will Outline Briefly:

The basic idea and why induction accelerator technology might be a good way to go (what's the competition?)

A "sample" set of requirements to illustrate the general parameter regimes

The most critical physics and technology issues that need to be solved to meet the requirements

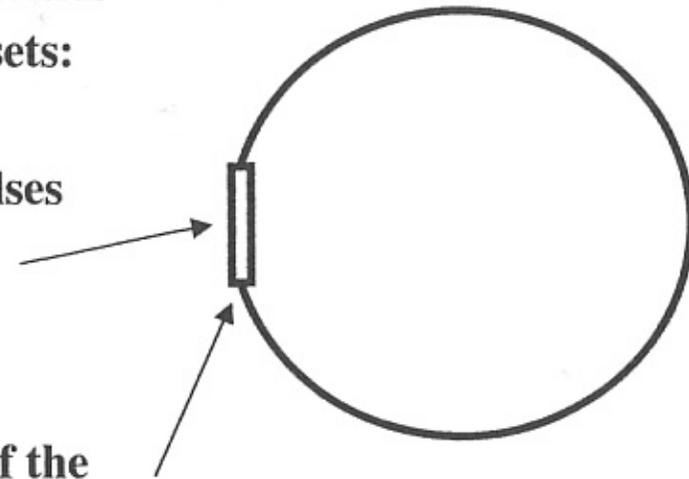


The main goal of this discussion is to highlight areas of common R&D needs, and synergism between the applications, that might be discussed at the workshop

Induction Synchrotron

Basic idea - replace the RF accelerator cavities in a synchrotron with two induction cell sets:

- 1. A set to provide flat-topped voltage pulses to accelerate long (microsecond scale), uniform density "superbunches"**
- 2. A set to provide axial "containment" of the bunches with short voltage pulses applied at the head and tail of the "superbunch"**



Potential advantage is a much higher "beam occupancy ratio" of the synchrotron's circumference, still keeping below limits to the local line density set by transverse beam dynamics.

Example - Very Large Hadron Collider (VLHC) With Superbunches

Example of the design parameters for a VLHC with 31 TeV on 31 TeV at a luminosity of 5×10^{34} cm²/sec (5x larger than the LHC design):

87 km rings with 26 superbunches per ring, 8×10^{13} protons per superbunch

The superbunches are 0.5 microseconds long, with a peak current of 25 amps, spaced by 11 microseconds

To accelerate the protons from an injection energy of 7 TeV to 31 TeV in an hour, induction accelerator cells producing the 0.5 microsecond pulses at a rep rate of 90 KHz are required with a total voltage of ~ 3 MeV.

Individual cells might produce 2.5kV (~ 25kV/M gradient), core loss ~ 1/2 kW/cell

Barrier bucket cells producing short voltage pulses of order 100 KeV (total) contain the bunches

The most critical induction accelerator physics and technology issues for induction synchrotrons:

Very high rep rate CW pulsers

Low loss magnetic core material

Cooling the induction cells and the pulsers

Minimizing the beam-cell RF interaction impedance (longitudinal and transverse?) - and especially the mitigation of high frequency resonances (above a few MHz)

An observation about cost and efficiency:

The acceleration system (using RF or Induction) in a large-scale synchrotron application will typically be a minor part of the overall facility construction cost, and a minor contributor to the electrical power consumption.

As a consequence, if the bunch parameters achievable with an induction system represent a significant performance enhancement (e.g., like 15x higher luminosity), a relatively high cost per watt (or per volt), and relatively low efficiencies, would be acceptable.

This is very different from the situation in most of the induction linac applications (like the TBA, HIF, etc.)

Linear Colliders - Two Beam Accelerators

**Basic idea of induction linac (LIA) driven relativistic klystron (RK):
Extend operating voltage of klystrons to multi-MeV region with LIA
(where debunching is retarded and many output cavities can be
driven)**

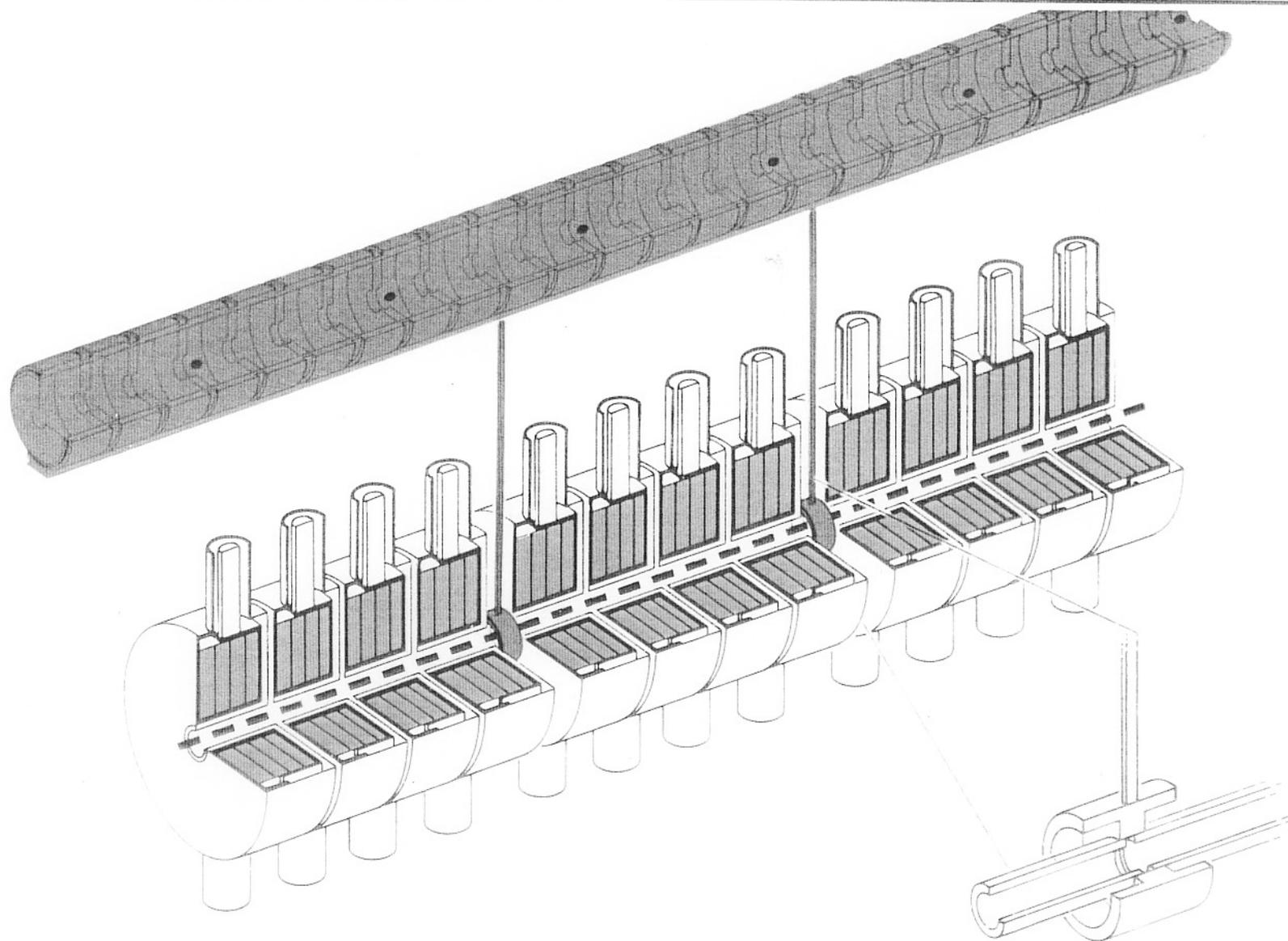
**The RK Two-Beam Accelerator (TBA) idea is to re-accelerate the
bunched beam many times.**

The competition includes

- 1. Extension of conventional klystron technology (magnetic pulse compression and SS modulators now playing a role)**
- 2. TBA with GeV beams from RF accelerators (CLIC)**

RK-TBA is a concept for klystron efficiency upgrade by electron beam recycling.

RK-TBA
LBNL - LLNL



Induction Accelerator Requirements for the RK-TBA

An induction accelerator driver for a 1 - 5 TeV linear collider with a high gradient accelerator structure (50 - 200 MeV/m) operating at 11.4 to 30 GHz:

Beam currents ~ 1kA, 0.3 MeV/m acceleration gradient maintaining a beam voltage of 10 MeV, pulse lengths ~ 50 -200ns

---- all very conventional --

but a very small bore is required to drive the microwave output coupling cavities.

Rep rates ~ 180 Hz are also somewhat higher than the current experience base.

The most critical induction accelerator physics and technology issues for the RK-TBA:

Beam dynamics -

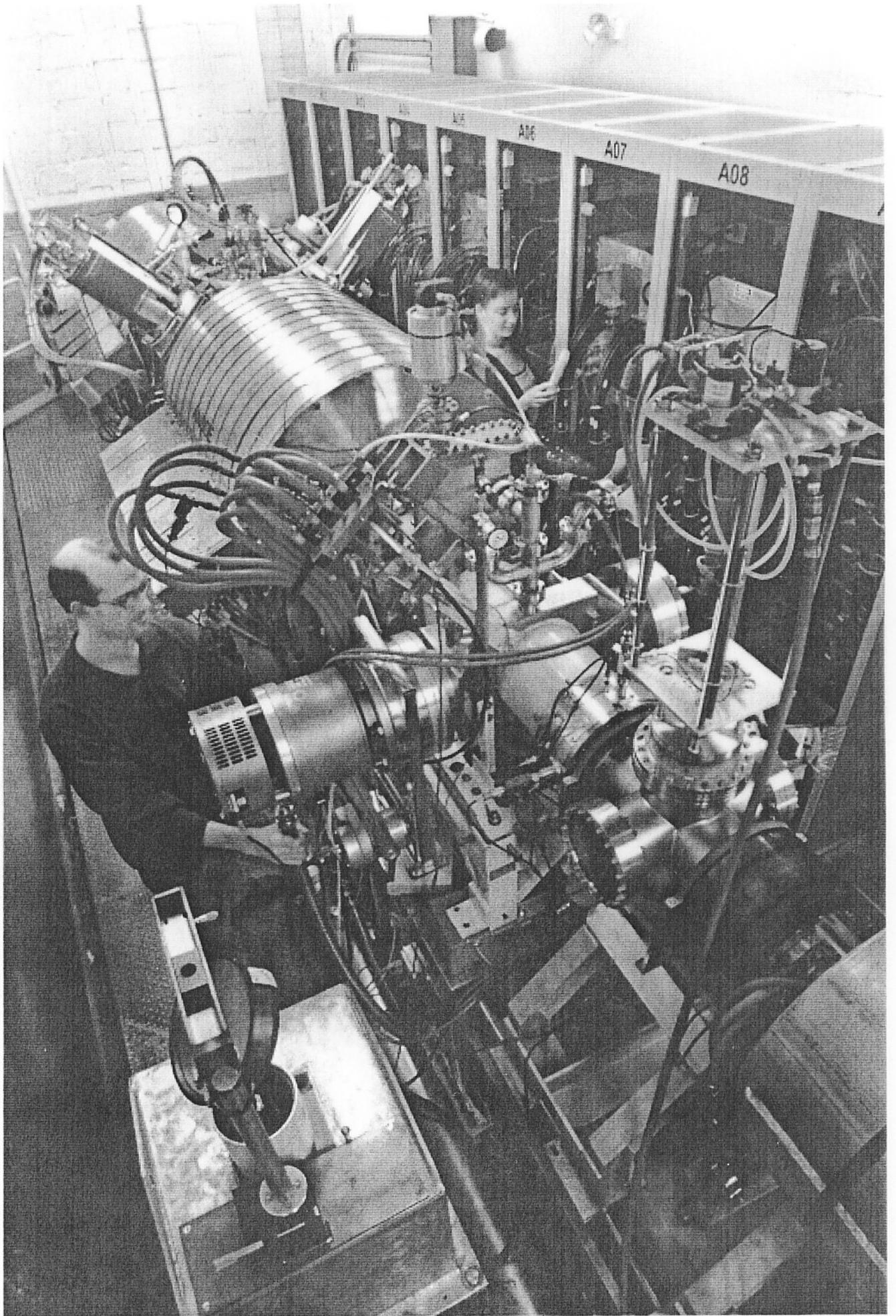
Longitudinal - maintaining tightly bunched beams through output cavities and accelerator cavities

Transverse - beam breakup instability (BBU) with the very small bore

+++ Demo of "betatron node" suppression of BBU in LBNL/LLNL exps

Efficiency - throughout the pulse power, LIA, RF conversion chain

Cost - the main discriminator vs. the competition



Neutrino Factory/ Muon Collider

Basic idea - use a linear induction accelerator to reduce the energy spread (do "phase rotation") of the pion/muon bunch produced by a nanosecond proton pulse impinging on a target.

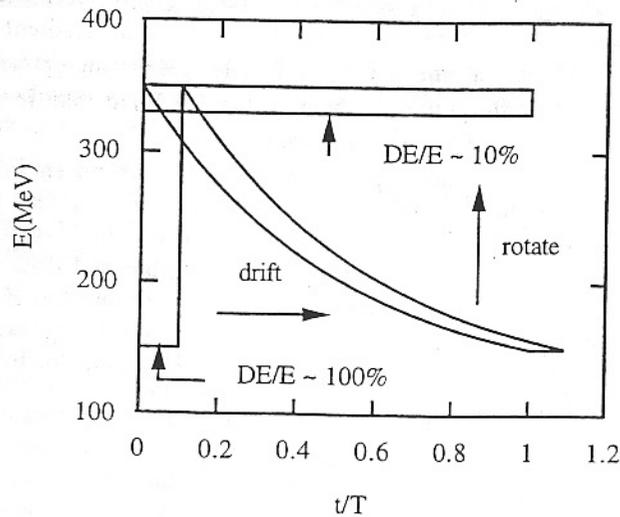


Fig. 1: Muon energy versus arrival time.

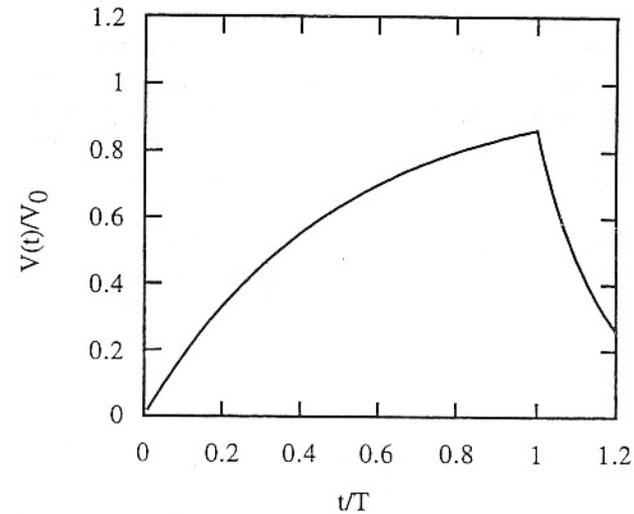


Fig. 2: Normalized cavity voltage versus arrival time.



Present Induction Linac Design Parameters



- 200 MV (head to tail) in 100 meters
 - 100 each 2 MV induction cells
- 15 Hz
- 4 pulses / burst
 - 100 ns pulse length (hyperbolic ramp)
 - 300 ns spacing (beam off time)
- 3×10^8 pulses / year
- 3.0 T (90% packing) at 20 cm bore radius (or equivalent BR^2)

The most critical induction accelerator physics and technology issues for the Neutrino Factory/Muon Collider phase rotation application:

High gradient accelerator structures (2 MV/M)

High burst rate

Power consumption

Capital cost

Reliability

Inertial Fusion Energy - Heavy Ion Fusion

Basic idea - use a linear induction accelerator to produce heavy ion beam pulses that can ignite a steady stream of fusion capsules in a reactor chamber.

Heavy ions are used to deposit very high energy densities in the capsule ($\sim 3\text{-}6$ GeV and $A \sim 130\text{-}200$)

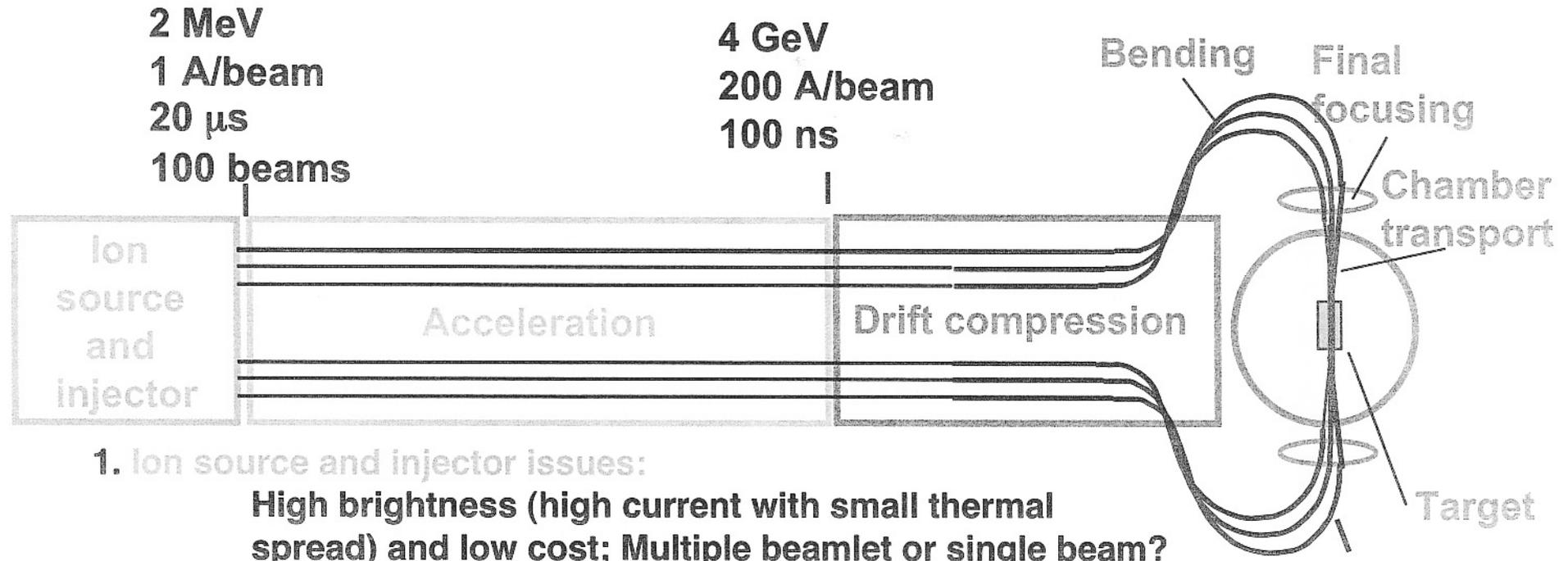
Heavy ion beam must deliver $\sim 3\text{-}6$ megajoules in ~ 10 ns on the capsule for ignition (\sim one millicoulomb)

Rep rate requirements are modest - few Hz - limited by chamber clearing timescales

Compression of the beam pulse as it is transported through the accelerator at the limits of space charge tune depression is essential for a feasible architecture, and acceleration of multiple beams in parallel will likely be required as well.

Induction acceleration for HIF can be broken into three broad accelerator areas

Typical Driver Parameters:



1. Ion source and injector issues:

High brightness (high current with small thermal spread) and low cost; Multiple beamlet or single beam?

2. Accelerator issues:

Maintenance of high brightness beams with low beam loss;
Control of electrons

3. Drift compression/final focus/chamber transport issues:

Neutralization of beam in chamber (reduction of space charge);
Minimizing focal spot size (by correcting aberrations)

Longitudinal physics: (control of beam length, velocity spread and "tilt")

Induction accelerator physics and technology issues for HIF

Physics issues like space charge dominated transport and acceleration of high brightness beams, and longitudinal dynamics and control, are the main focus of the current program.

Cost effective designs of multi-microsecond accelerator cells are essential for the next generation research facilities.

Longitudinal beam control systems could benefit significantly from further advances in the solid-state modulator technology capability, and reductions in cost.

Spallation Neutron Source

Basic idea - use a linear induction accelerator to produce the proton pulses required for the next generation spallation neutron sources (like ESS)

Requirement for ~ 1 GeV protons in pulses $<$ one microsecond long at a rep rate around ~ 50 Hz, with peak currents ~ 100 amps or more, is a very good match to induction linac technology.

Idea of using induction linacs in this application was proposed by Denis Keefe in an invited paper over 20 years ago!

(Vth International Collaboration on Advanced Neutron Sources, Julich/Karlsruhe, June 1981)

Reference Example - 5 MW Spallation Source

With 1 GeV protons (for efficient neutron production), 100 microcoulomb pulses at 50 Hz are required.

A beam line charge density of 2.6 microcoulombs/meter can be transported in a 3 T solenoid at a radius of 1.5 cm (space charge limited).

A 3 MeV injector producing 60 amp proton beam with a pulse length of 1.6 microseconds matches this line density. (Note: MFE sources have produced 90 amp proton beams in neutral beam sources, but with longer pulse lengths)

Using acceleration at constant line density in a uniform solenoidal field of 3 T, the pulselength decreases down the accelerator ($\sim 1/v$) and the current increases - at the output to a pulselength of ~ 150 ns and $I \sim 670$ amps.

The most critical induction accelerator physics and technology issues for the Pulsed Spallation Neutron Source application

High current, pulsed proton beam sources producing 10's of amps from multi-megavolt injectors that can be radially compressed and transported in a solenoid focusing system need to be developed.

The beam transport has to have very low losses.

Spallation sources need to have very high reliability and availability to be accepted by the neutron scattering community - induction technology will likely need to be applied on a relatively large scale in some other science user facility to gain that acceptance.

An Observation:

There is a high degree of synergism between many of the induction linac physics and technology developments needed for this application and those for HIF - like the transport and acceleration of high line charge density beams

-- but the neutron source requirements are generally less stressful (protons easier to generate and transport at high current, no high brightness requirement, lower voltage, etc.)

The exception is the 50 Hz rep rate.

Summary of Sample Induction Accelerator Requirements

	Voltage	Beam Current	Pulse length	Rep rate
Induction Synchrotron	3 MeV	25 A	500 ns	100 kHz CW
Linear Collider, RK/TBA	10 MeV, 0.3 MeV/m	1kA	50-200 ns	180 Hz
Neutrino Factory/ Muon Collider	200 MeV (2 MeV/m)	---	100 ns	4 pulses @ 3 Mhz, 15 Hz ave
Heavy Ion Fusion	4 GeV	0.2 → 10 kA	20 μs → 100ns	Few Hz
Spallation Neutron Source	1 GeV	60 → 600 A	1,600 → 160ns	50 Hz

Conclusions

- Over the next decade or two, it appears there are many exciting possibilities for Induction Accelerators to play an important role in High Energy Physics and Energy Science.**
- In the first two decades of induction accelerator development (1963-83), the technology was chosen mainly because it could produce very high peak currents (of electrons); duty factors were relatively low.**
- In future applications, the flexibility in the voltage waveform may as important as peak power, and the enabling technology of high rep rate solid state drivers could make the technology competitive with RF for higher duty factor applications.**