Course Outline

1. INTRODUCTION TO RECIRCULATED LINEAR ACCELERATORS
    1. Properties of Storage Rings, Linear Accelerators, and Recirculated Linear Accelerators
    2. Beam Recirculation: Opportunities and Challenges
    3. Superconducting RF (SRF)
    4. Microtrons, Racetrack Microtrons, and Polytrons
    5. Independent Orbit Recirculators
    6. Energy Recovered Linacs (ERLs)
2. INTRODUCTION TO LINEAR OPTICS
    1. Particle Motion in the Linear Approximation
    2. Ellipses in Beam Optics and the Area Theorem
    3. Unimodular Matrices and their Twiss Parameters
    4. Hill's Equation and its Solution
    5. Dispersion Tracking and Longitudinal Stability
    6. Beam Matching and *Rms* Emittance
3. SINGLE PARTICLE DYNAMICS
    1. Longitudinal Dynamics
        1. Longitudinal gymnastics
        2. Longitudinal tune choices
        3. Correcting RF curvature (T566 or sextupoles)
        4. Energy spread estimates
    2. Transverse Dynamics
        1. Basic considerations
        2. Betatron Motion Damping and Antidamping

Course Outline

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1. Laser-driven photocathode guns
    1. DC guns
    2. RF guns
2. Polarized electron sources
3. Examples of high brightness electron sources

7. RADIATION AND BEAM TRANSPORT IN RECIRCULATING LINACS
    1. Radiation from relativistic electrons
    2. Quantum fluctuations and particle diffusion
    3. Aberations and higher-order transfer maps
    4. Practical beam optics designs
8. PERFORMANCE OF PRESENT RECIRCULATING LINACS
    1. Electron beam diagnostics devices
    2. Feedback systems
    3. Transverse beam stability
    4. Energy stability
    5. Longitudinal beam stability
    6. Beam polarization
9. FUTURE APPLICATIONS
    1. CEBAF physics upgrades
    2. FELs
    3. Synchrotron Light Sources (ERL,PERL,MARS)
    4. Electron-Ion Collider (EIC)

USPAS Course on
Recirculated and Energy Recovered Linear Accelerators

G. A. Krafft and L. Merminga
Jefferson Lab
I. Bazarov
Cornell

Lecture 1

Lecture Outline

- Schematic Representation of Accelerator Types

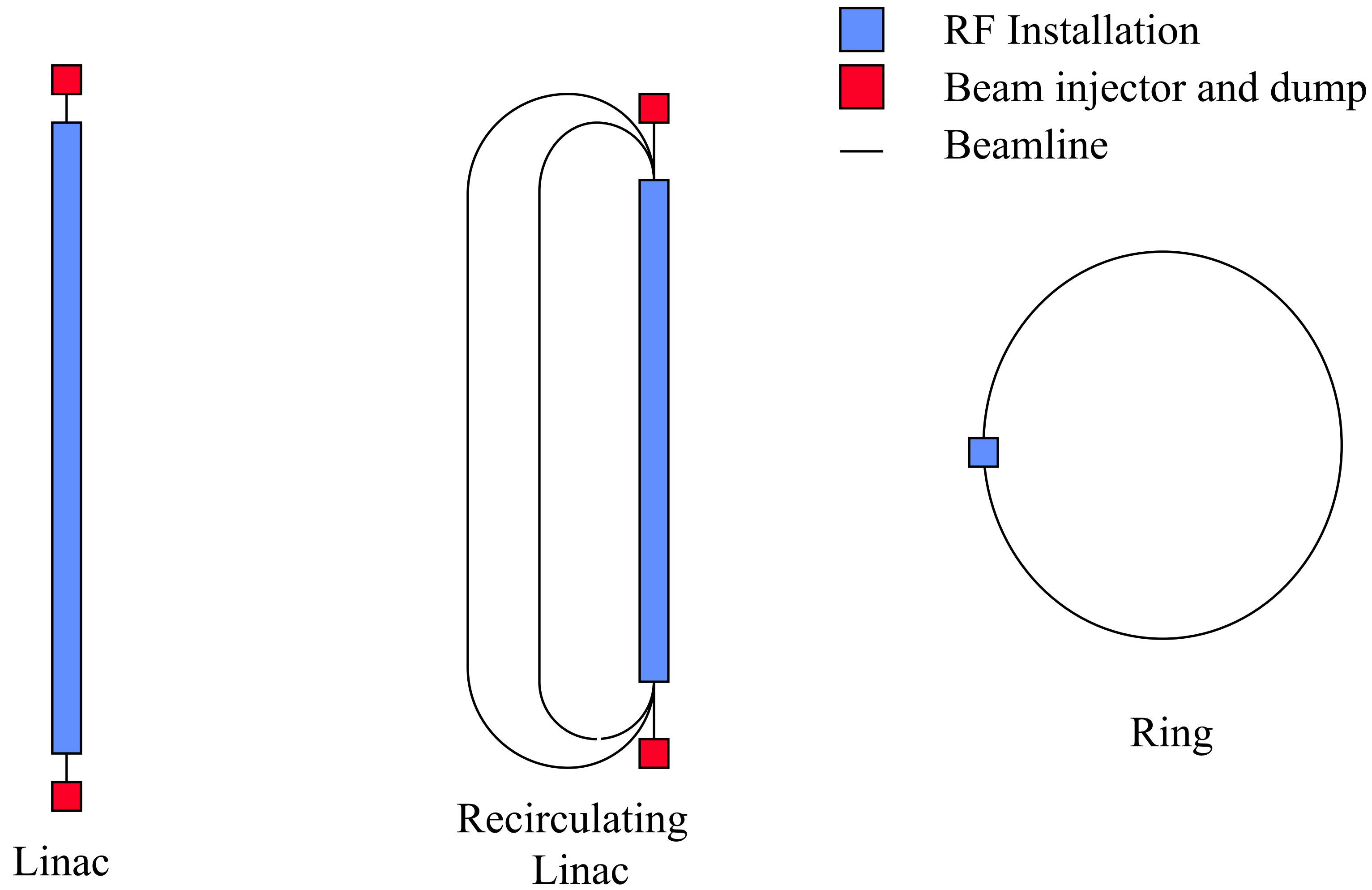
- Development of Linear Accelerators
  - WWII and Microwaves
  - MIT Rad Lab
  - Hansen, Alvarez, Panofsky, et al.

- Main Parameters Describing Linacs
  - MV/m, Beam Current, Beam Power, Transit Time,
  - RF Pulse Length/Duty Factor, Beam Quality
  - Normal or Superconducting

Lecture Outline (Contd)

- Why Recirculate?
  - Performance Upgrades after the Fact
    - Energy
  - Cheaper to Get a Given Performance
    - Energy
    - Current
  - Achieving Beam Parameters "Unachievable" without Recirculation
  - Compare/Contrast Linacs and Storage Rings
- Downsides to Beam Recirculation
  - Additional Linac Instability
  - Turn around Optics
  - High Current Source to Provide Beam

Schematic Representation of Accelerator Types



Development of Microwave Equipment

Brief History Lesson

- (1886) Hertz Observes that solid objects reflect radio waves
- (1922) Marconi Suggests "short waves" for radio position detection
- (1925) Breit and Tuve Determined height of ionosphere by pulsed RF
- (1935) Watson-Watt Serious proposal for a radar system, occurred to others in America, France, and Germany
- Early Aircraft Detection Radars
- (1939) British CH (Chain, Home) System:

  f=22-28 MHz, 12 m wavelength, 240 ft. towers, 12.5-25 pulses per second (pps), pulse width 2-25 microseconds up to 80 kW average power broadcast, 150 kW→1 MW peak

  upgraded to 200 MHz (1.5 m) systems in 1940

Development of Microwave Equipment

- (1939) U.S. Naval Research Lab, CXAM:

  f=195 MHz (1.5 m), ship based, common Xmit/receive antenna,

  1640 pps, pulse width 3 microseconds, 15 kW peak power,

  range of 70 miles for bombers and 50 miles for fighters
- (1940) U.S. Army, SCR-270:

  f=106 MHz (3.0 m), mobile, 621 pps, pulse width 10-25 microseconds,

  100 kW peak power, range of 100 miles for bomber detection
- Airborne Radar (really MIDAR!)

  First applications were for surface ship detection and aircraft intercept

  British tried pre-developed 1.5 m systems and found a sharper beam (power on airplane lower!) was needed. Focused on getting to shorter wavelengths.

MIT Rad Lab

- (1940) CAVITY MAGNETRON (a high power microwave source)
- (Sept. 1940) British Technical Mission: Americans to develop microwave aircraft equipment and microwave position finder
- (Nov. 1940) MIT Radiation Lab Established
- (Jan. 1941) First microwave echoes observed (buildings in Cambridge)
- (July 1941) First Navy contract for microwave equipment
- (June 1945) $2,700,000,000 worth of microwave equipment delivered, production rate $100,000,000/month. No one uses radio waves for “detection and ranging” any more!
- For the future of physics and technological development, perhaps the most significant result of this work is the vast amount of information that was distributed after the war in the RAD lab microwave series, 28 volumes, and in the participant’s heads!

Cavity Magnetron: Picture and Operating Principal

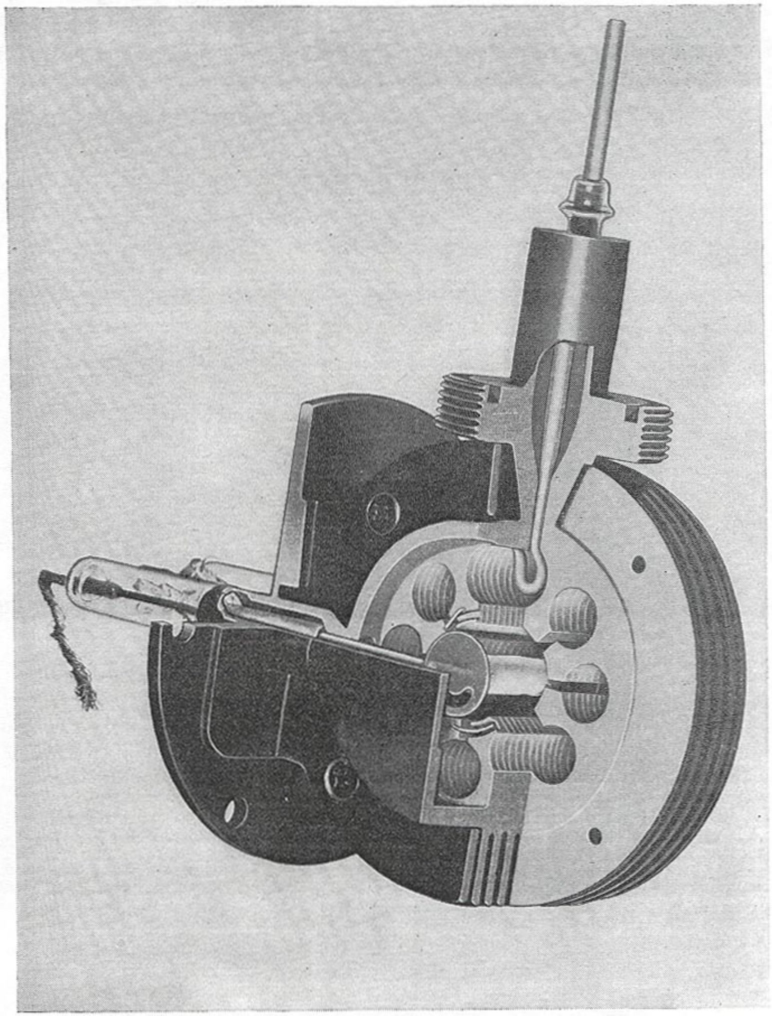


FIG. 10·2.—Cutaway view of type of magnetron shown in Fig. 10·1.

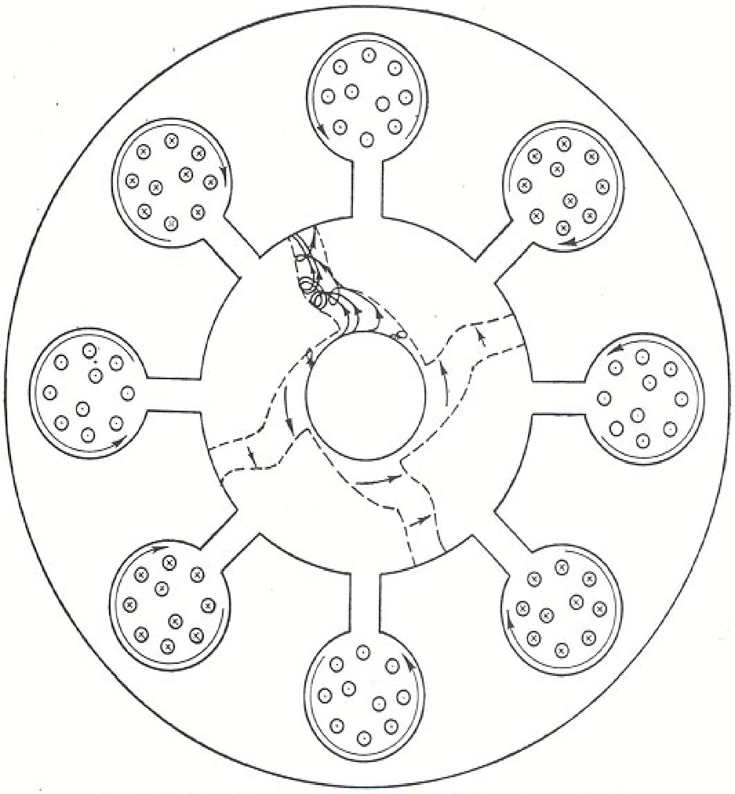


FIG. 10·15.—Space charge in oscillating magnetron.

Cavity Magnetron Performance

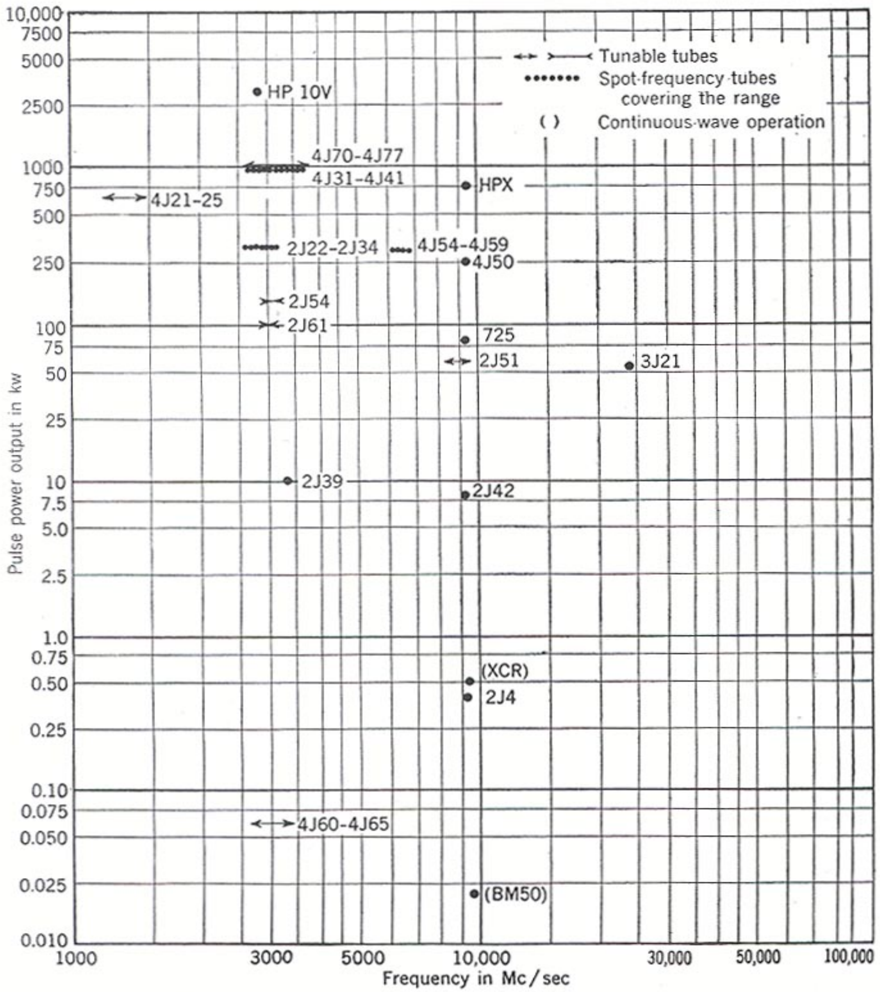


FIG. 10·18.—Diagram showing power and frequency distribution of representative microwave magnetrons developed up to 1945.

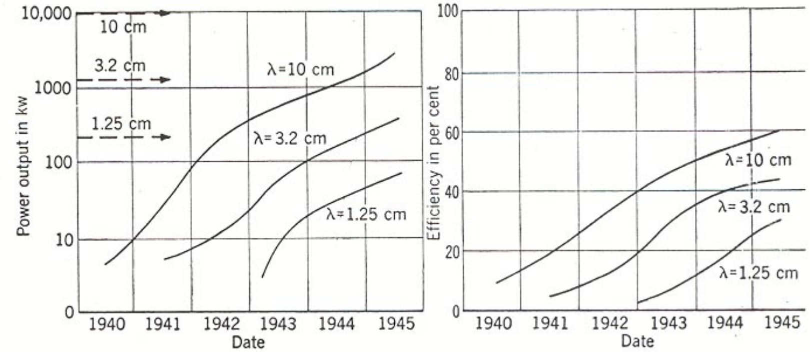


FIG. 1·5.—Historical development of microwave magnetrons.

TABLE 10·2.—INPUT CHARACTERISTICS OF MICROWAVE MAGNETRONS

Tube No.	Input pulse power, kw	Pulse voltage, kv	Input impedance, ohms
4J60	2	1.5	1125
2J38	25	5	1000
2J32	250	15	900
4J31	2500	30	360
HP10V	6000	50	415

TABLE 10·1.—AVERAGE AND PULSE POWER OUTPUTS OF MICROWAVE MAGNETRONS

RMA type No.	Frequency, Mc/sec	Maximum average power output, w	Pulse power output, kw	Maximum pulse length, μsec
4J21	1,180	800	800	6.0
4J73	3,100	600	1000	2.5
725	9,400	80	80	2.5
3J21	24,000	25	55	0.5

Brief History of Linear Accelerators (Linacs)

- (1925) Ising AC fields for acceleration
- (1928) Wideroe AC field can double effective voltage, (aside: E. O. Lawrence in his Nobel address credited this idea as the stimulus on his thinking on cyclotrons (why not triple, …, times n!))
- (1939) Hansen Publishes a study on determining frequency of a resonator

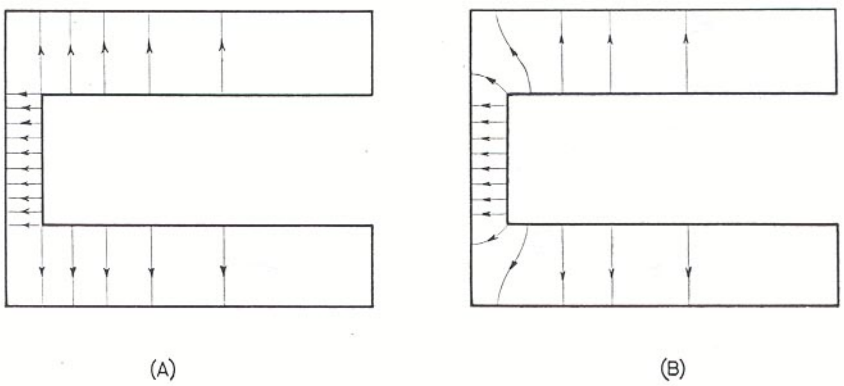


FIG. 2a. Qualitative drawing of an assumed field distribution. 2b. Another, and better, field distribution.

History of Linacs, contd.

- (1948) Ginzton, Hansen, and Kennedy, Rev. Sci. Instrum. **19,** 89 (1948)
  Acceleration of electrons by disc loaded waveguides

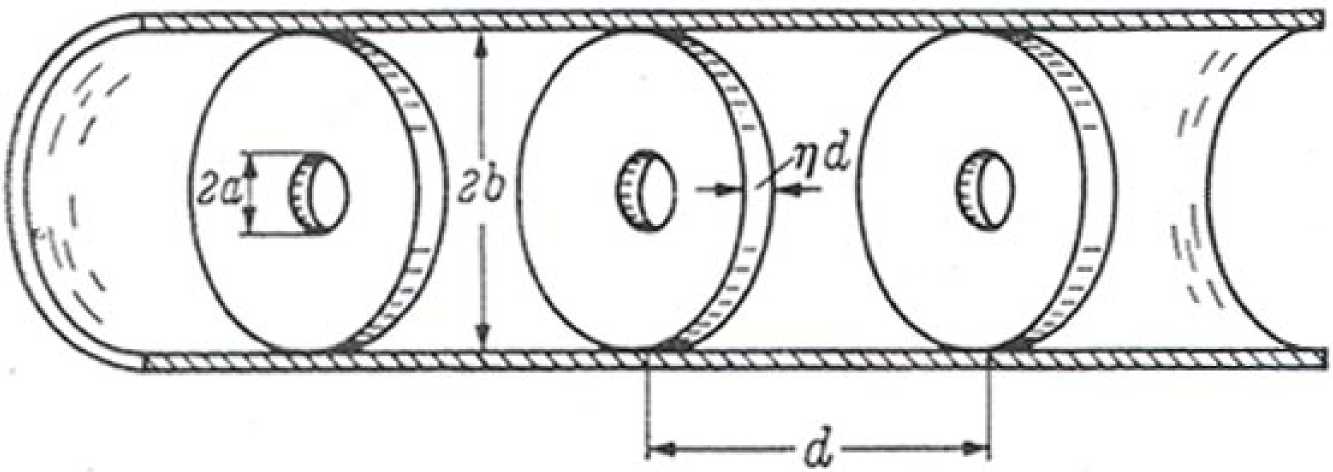


Fig. 2. Structure of disk-loaded accelerator showing important design dimensions [2].

Footnote in 1948 paper

[1] A few random historical notes may be of interest. One of the authors (W.W.H.), in his study of cavity resonators, was motivated by a desire to find a cheap method of obtaining high energy electrons. This cavity acceleration work was put aside, largely because of the change in standard of success caused by the advent of Kerst's betatron. The first suggestion of a linear accelerator known to us was made by Dr. J. R. Woodyard, who pointed out in 1939 the possibility of introducing "drift tubes" into a long resonator with unidirectional axial field, in the manner now being used in the University of California linear proton accelerator. Electron acceleration, using fields periodic in space, was suggested by D. Sloan, U. S. Patent No. 2,398,162. By the end of the war many people were interested, possible reasons being: (*a*) widespread knowledge of cavity properties and technique, (*b*) the enormous pulsed powers made available by radar developments. Little has been published, but reference may be made to J. R. Woodyard, Phys. Rev. **69**, 50 (1946), J. C. Slater, Phys. Rev. **70**, 799 (1946), and Allen and Symonds, Proc. Phys. Soc. **59**, 622 (1947). At present, at least eight groups are known to be working on the electron acceleration problem: G. E. (Lawton); M.I.T. (Slater); Purdue (Rieke); Radiophysics Laboratory (Allen and Symonds); T.R.E. (Fry); Virginia (Beams); Yale (Schultz, Beringer, Clarke, Lockwood, McCarthy, Montgomery, Rice, and Watson—see Phys. Rev. **72**, 346, 1947); and the group at Stanford. The projects at M.I.T., Yale, and T.R.E. are on a considerable scale and may, therefore, be expected to lead to important results soon. Published information is rather scanty, but it appears that there is a close parallelism between at least some of the work at T.R.E. and Stanford.

History of Linacs, Contd.

- (1945-1955) Alvarez Proton Linac

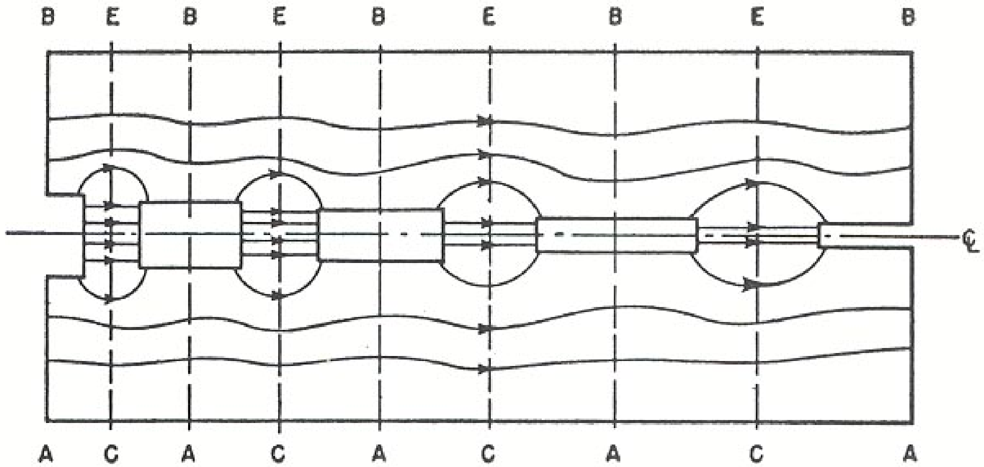


FIG. 2. Linear accelerator produced by introducing drift tubes into cavity excited as in Fig. 1. Division into unit cells.

Alvarez, Bradner, Frank, Gordon, Gow, Marshal, F. Oppenheimer, Panofsky, Richman, and Woodyard, Rev. Sci. Instrum., **26**, 111-133, (1955)

Interesting Quote from Paper

> The argument was essentially as follows: The cost of a relativistic magnetic accelerator varies roughly as the cube of the energy, so long as the basic design is merely scaled in its linear dimension, which is proportional to the energy. On the other hand, the cost of a linear accelerator varies directly as the first power of the energy. If these cost-*vs*-energy curves are plotted on double logarithmic paper, they are straight lines with slopes three and one. There will always be an intersection of the two lines, and for energies greater than the "crossover" energy, the cost of a linear machine will be less than that of the circular machine. Because the cost of either machine is high, it was felt that even though a linear accelerator might be more complex than a synchrocyclotron, the design decision might have to be made on economic grounds.

This argument drives one to linear accelerators for the highest electron energy presently (2005)

Alvarez Linac Parameters

f	200 MHz
RF Power	450 kW peak/tube
Repetition Rate	15 pps
RF Pulse Width	600 microseconds, 400 in flat
Number EIMAC 3W10000A3 “tubes”	9
Proton Beam Energy	32 MeV
Accelerator Length	40 feet
Accelerating Gradient	2.6 MV/m

Started with 36 war-surplus GL-434 triode tubes, with 4 tubes parallel connected to get the power. These tubes “had such a high casualty rate while in operation” had to upgrade. They were particularly proud of their discovery of “edge focusing”

Mark III

- (1955) Report on the Stanford Mark III accelerator

f	2856 MHz
RF Power	20 MW peak/tube
Repetition Rate	60 pps
RF pulse width	2 microseconds
Number RK-5586 Magnetrons	21
Electron Beam Energy	630 MeV
Accelerator Length	220 feet
Average Gradient	9.4 MV/m

Chodorow, Ginzton, Hansen, Kyhl, Neal, Panofsky, and the staff of W. W. Hansen Laboratories of Physics, Rev. Sci. Instrum., **26**, 134-209, (1955)

Parameters Describing Linacs

- Gradient (MV/m)

  Machine Average Accelerating Gradient G:

  Beam Energy Gain/Accelerator Length. This parameter is important because given the energy required, it gives the scale of the final accelerator

  Cavity Average Accelerating Gradient G_c:

  Maximum Energy Gain through Cavity/Cavity Length

  Roughly, the average longitudinal Electric Field the particle sees in the cavity

  The voltage gain per cavity is $V_c = G_c L_c$

  Clearly $G_c > G$, because an accelerator cannot be all cavities

RF Pulse Length, Duty Factor

- RF Pulse Length is defined to be the time that the RF pulse is actually on during a single RF burst, t_{burst}

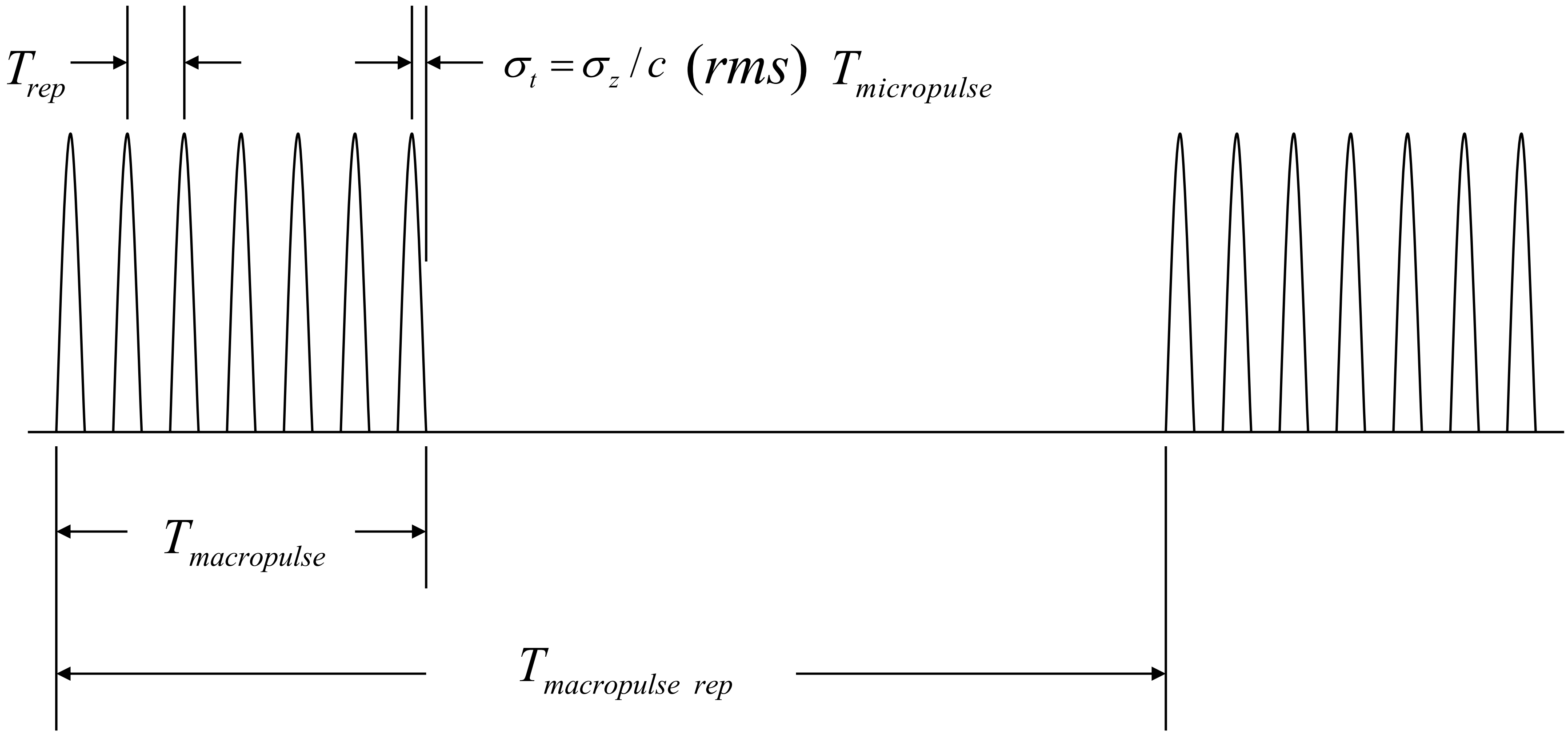
- The repetition rate f_{burst} , is defined to be the frequency of RF bursts

- The Duty Factor, DF, is the percentage of time that the RF is on.

$$\mathrm{DF} = f_{burst}\, t_{burst}$$

It is the quantity that relates the peak and average RF power requirements. For normal conducting linacs it’s around 0.5% and for most superconducting accelerators it is 1.

Beam Current Time Definitions



Beam Current

- General Formula for current is

$$I = e(dN/dt)$$

Macropulse current, I_{mp}

$$I_{mp} = eN_{bunch} f_{rep} = eN_{bunch} / t_{rep}$$

Micropulse current (peak current), I_{peak}

$$I_{peak} = ecN_{bunch} / \sigma_z$$

Average current, I_{ave}

$$I_{ave} = I_{mp} \mathrm{DF}$$

Beam Power

- The beam power is simply the beam energy multiplied by the beam current

Peak Beam Load Power

$$P_{b,peak}^{load} = E_b I_{mp} / e$$

Peak Beam Power

$$P_{b,peak} = E_b I_{peak} / e$$

Average Power

$$P_{b,ave} = E_b I_{ave} / e = P_{b,peak}^{load} \mathrm{DF}$$

Transit time

- The time it takes one particle to complete a full transit through the accelerator will be called the transit time t_{tot}. For an accelerator of linear length 1 km, this time is 3.3 microseconds for velocity of light particles.

Normal or Superconducting

- Linear accelerators may be distinguish by whether the accelerating structures are normal conducting or superconducting. As will be discussed in detail later, this choice USUALLY (but not always!) means

Normal Conducting

Temperature somewhat higher than room temperature. Pulsed RF, Duty Factor less than 1%, higher accelerating gradients order 50 MV/m or higher, higher peak current and bunch charges, fewer bunches accelerated

Superconducting

Temperatures within a few degrees of absolute zero. CW or other high Duty Factor RF, lower accelerating gradients around 10-20 MV/m, lower peak current and bunch charge, many more bunches accelerated

Beam Quality

- Quantified by Beam Emittances

  If $f(z; x, y, \varphi, x', y', \Delta E)$ denotes the single particle distribution function for particles within the beam at a given point z in the accelerator, and if this distribution function is used to define statistical averages

$$\langle \cdots \rangle = \int \cdots \; f dx dy d\varphi dx' dy' d\Delta E$$

  Then the transverse *rms* emittances are defined by

$$\varepsilon_x = \sqrt{\left\langle \left(x - \langle x \rangle\right)^2 \right\rangle \left\langle \left(x' - \langle x' \rangle\right)^2 \right\rangle - \left\langle \left(x - \langle x \rangle\right)\left(x' - \langle x' \rangle\right) \right\rangle^2}$$

  and likewise for the y direction.

Homework Exercise on Emittance

Normalize, and compute the emittance of the following distributions:

1. Gaussian $$f(x,x') = A \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{x'^2}{2\sigma_{x'}^2}\right)$$
2. Waterbag $$f(x,x') = A\,\Theta\left(1 - \frac{x^2}{\Delta x^2} - \frac{x'^2}{\Delta x'^2}\right)$$
3. K-V, or microcanonical $$f(x,x') = A\delta\left(1 - \frac{x^2}{\Delta x^2} - \frac{x'^2}{\Delta x'^2}\right)$$
4. Klimontovich $$f(x,x') = A\sum_{i=1}^{N}\delta(x - x_i)\delta(x' - x'_i)$$

Treat σ_x, $\sigma_{x'}$, Δx, $\Delta x'$, x_i, x'_i as parameters. Θ Unit step, δ Dirac's delta

For distributions (1)-(3), what do the projected distributions, e.g., $p(x) = \int f(x,x')dx'$ look like?

More on emittance

- Sometimes numbers are reported as "full" or 95% emittances, meaning that 95% of the particles are within this amount of phase space area. The Jefferson Lab convention is

$$\varepsilon_{full} = 4\varepsilon$$

- Relation to beam size (at a location of zero dispersion)

$$\sigma_x = \sqrt{\varepsilon_x \beta_x}$$

where the "beta" function describes the beam optics, and is typically computed by beam opticians with computer design codes.

- π's are archaic. Usually, but be careful, you can ignore them in reports that contain them.

Invariant Emittance

- The "invariant" or "normalized" emittance is defined to be

$$\varepsilon_n = \beta\gamma\varepsilon$$

where now $\beta = v_z / c \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{E_{beam}}{mc^2}$

- It does not change as beam is accelerated. Pf: Conservation of momentum

$$\frac{d(\gamma m v)}{dt} = -e\left[E + v \times B\right]$$

$$\frac{d(\gamma m v_x)}{dt} = 0$$

$$\gamma mc\,\beta_x(\text{after}) = \gamma mc\,\beta_x(\text{before})$$

$$\gamma\beta_z x'(\text{after}) = \gamma\beta_z x'(\text{before})$$

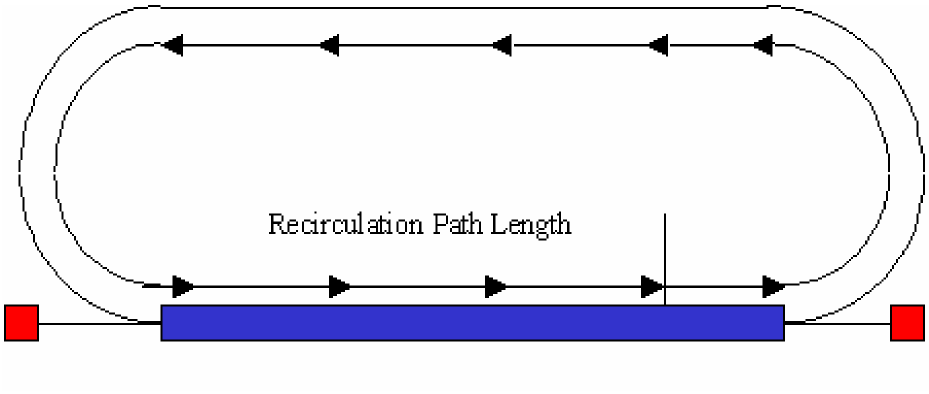
Why Recirculate?

- Performance upgrade of an installed linac
  - HEPL SCA and MIT Bates doubled their energy this way

- Cheaper design to get a given performance
  - Microtrons, by many passes, reuse expensive RF many times to get energy up. Penalty is that the average current has to be reduced proportional to 1/number passes, for the same installed RF.
  - CEBAF type machines: add passes until the "decremental" gain in RF system and operating costs pays for additional recirculating loop
  - Jefferson Lab FEL and other Energy Recovered Linacs (ERLs) save the cost of higher average power RF equipment (and much higher operating costs) at higher CW operating currents by "reusing" beam energy through beam recirculation.

Beam Energy Recovery

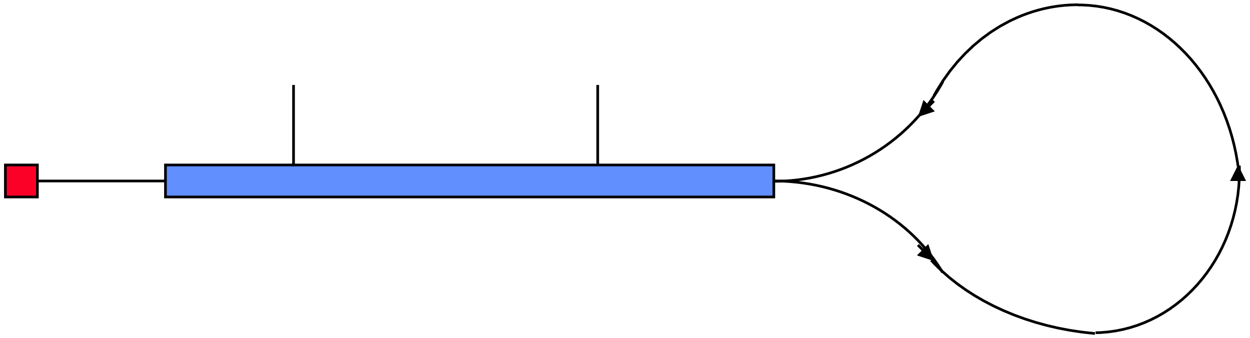
$$\frac{d\gamma}{dt} = \frac{e\vec{E}\cdot\vec{v}}{mc^2}$$



Recirculation path length in standard configuration recirculated linac. For energy recovery choose it to be $(n + 1/2)\lambda$. Then

$$\frac{d\gamma_{tot}}{dt} = 0$$

Beam Energy Recovery



Recirculation path length in herring-bone configuration recirculated linac. For energy recovery choose it to be $n\lambda$. Note additional complication: path length has to be an integer at each and every different accelerating cavity location in the linac.

Comparison between Linacs and Storage Rings

- Advantage Linacs

  Emittance dominated by source emittance and emittance growth down linac

  Beam polarization "easily" produced at the source, switched, and preserved

  Total transit time is quite short

  Beam is easily extracted. Utilizing source control, flexible bunch patterns possible

  Long undulators are a natural addition

  Bunch durations can be SMALL

Comparison Linacs and Storage Rings

- Advantage Storage Rings

  Up to now, the stored average current is much larger

  Very efficient use of accelerating voltage

  Technology well developed and mature

- Disadvantage of Storage Rings

  Technology well developed and mature

  There's nothing you can do about synchrotron radiation damping and the emittance it generates

Power Multiplication Factor

- An advantage of energy recovered recirculation is nicely quantified by the notion of a power multiplication factor:

$$k = P_{b,ave} / P_{rf}$$

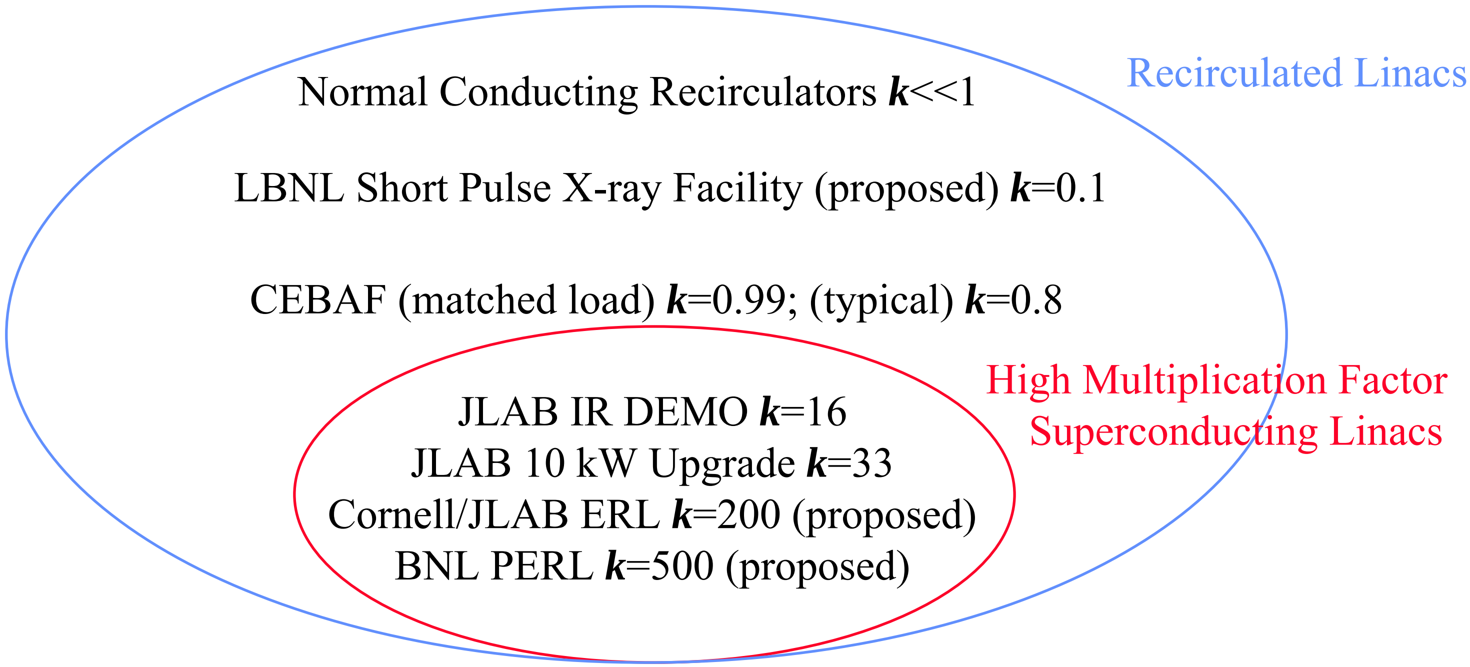
where P_{rf} is the RF power needed to accelerate the beam

- By the first law of thermodynamics (energy conservation!) $k < 1$ in any linac not recirculated. Beam recirculation with beam deceleration somewhere is necessary to achieve $k > 1$

- If energy IS very efficiently recycled from the accelerating to the decelerating beam

$$k >> 1$$

High Multiplication Factor Linacs



Will use the words "High Multiplication Factor Linac" for those designs that feature high ***k***.

Comparison Accelerator Types

Parameter	High Energy Electron Linac	High *k* Recirculated Superconducting Linac	Ring
Accelerating Gradient[MV/m]	>50	10-20	NA
Duty Factor	<1%	1	1
Average Current[mA]	<1	5 going to 100	1000
Average Beam Power[MW]	0.5	0.25 going to 700	3000
Multiplication Factor	<1	13 going to 200	1000
Normalized Emittance[mm mrad]	1	1	4
Bunch Length	100 fsec	100 fsec	20 psec

Best results by accelerator type

Another Reason to Recirculate!

- A renewed general interest in beam recirculation has arisen due to the success in Jefferson Lab's high average current FEL, and the broader realization that it may be possible to achieve beam parameters "Unachievable" in linacs without recirculation.

  ERL synchrotron source: Beam power is (100 mA)(5 GeV)=500 MW. Realistically, the federal govt. will not give you a third of a nuclear plant to run a synchrotron source. Use the high multiplication factor possible in energy recovered designs to reduce the power needed. Pulse lengths of order 100 fsec or smaller may in be possible in a ERL source: "impossible" at a storage ring. Better emittance too.

The limits, in particular the average current carrying capacity of possible designs, are not yet determined and may be far in excess of what the FEL can do!

Therefore

- WW II microwave work “enabled” pulsed operation of electron accelerators at a level of 10 MV/m.
- Development of superconducting cavities, to be discussed in later lectures, has enabled CW operation at energy gains of >10 MV/m, but initially accelerating relatively modest average beam currents of several hundred microAmp.
- Beam recirculation plus energy recovery, promises to enable high average gradient CW accelerators with high average currents, approaching 100 mA, to be designed and operated.

Challenges for Beam Recirculation

- Additional Linac Instability
  - Multipass Beam Breakup (BBU)
  - Observed first at Illinois Superconducting Microtron
  - Limits the average current at a given installation
  - Made better by damping HOMs in the cavities
  - Best we can tell at CEBAF, threshold current is around 20 mA, similar in the FEL
  - Changes based on beam recirculation optics
- Turn around optics tends to be a bit different than in storage rings or more conventional linacs. Longitudinal beam dynamics gets coupled strongly to the transverse dynamics.
- HOM cooling will perhaps limit the average current in such devices.

Challenges for Beam Recirculation

- High average current source to provide beam
  - Right now, looks like s good way to get there is with DC photocathode sources as we have in the Jefferson Lab FEL.
  - Need higher fields in the acceleration gap in the gun.
  - Need better vacuum performance in the beam creation region to reduce ion back-bombardment and increase the photocathode lifetimes.
  - Goal is to get the photocathode decay times above the present storage ring Toushek lifetimes

- Beam dumping of the recirculated beam can be a challenge.

CONCLUSIONS

• We've defined many parameters that you will run across, both in this course and elsewhere.

• We've provided a road map for this course, and a preliminary indication of where some of the problems are in this field. Much more to come!

• I hope that I've conveyed some enthusiasm about what we're doing. Not too many times in one's career does one get to explore the limits of a new machine type.

• Next lecture: Review of RF superconductivity