USPAS Course on
Recirculated and Energy Recovered Linear Accelerators

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Lecture 2

Outline

- Homework
- Some More Definitions
- Need for of High Duty Factor Linacs
- Superconducting RF (SRF)
  - Historical Foundations of SRF
  - State of the Art in SRF in the 70’s, 80’s and 90’s
  - SRF Performance Limitations
    - Multipacting
    - Thermal Breakdown
    - Field Emission
  - State of the Art in SRF in 2000
  - More Examples of Superconducting Recirculated and Energy Recovered Linacs
- Conclusions

Homework

Starting with the Lagrangian of a point particle with charge q and rest mass m in an electromagnetic field specified by the scaler potential Φ and the vector potential **A**

$$L = -mc^2\sqrt{1-\vec{v}\cdot\vec{v}/c^2} - q\phi + q\vec{v}\cdot\vec{A},$$

show the Euler-Langrange equations reduce to the well-known relativistic Lorentz Force Equation

$$\frac{d\left(\gamma m\vec{v}\right)}{dt} = q\left(\vec{E} + \vec{v}\times\vec{B}\right),$$

where **E** and **B** are the electric field and magnetic field given by the usual relation between the fields and potentials

$$\vec{E} = -\vec{\nabla}\phi - \frac{\partial\vec{A}}{\partial t}$$

and

$$\vec{B} = \vec{\nabla}\times\vec{A}.$$

Homework

From the relativistic Lorentz Force Equation in the previous problem, derive

$$\vec{\mathrm{v}} \cdot \frac{d\left(\gamma m \vec{\mathrm{v}}\right)}{dt} = q\vec{\mathrm{v}} \cdot \vec{E}.$$

From the usual expression

$$\gamma = \frac{1}{\sqrt{1 - \vec{\mathrm{v}} \cdot \vec{\mathrm{v}} / c^2}},$$

show

$$\frac{d\left(\gamma m c^2\right)}{dt} = q\vec{E} \cdot \vec{\mathrm{v}}.$$

Therefore, even at relativistic energies, magnetic fields cannot change the particle energy when radiation reaction is neglected.

Energy Gain and Cavity Voltage

For standing wave

$$\vec{E}(x,y,z,t)=\vec{E}(x,y,z)\,\mathrm{Re}\,e^{i\omega_c t+\delta}$$

$$\Delta\gamma mc^2 = eV_c = \int \mathrm{Re}\,\beta_z ceE_z(0,0,\beta_z ct)e^{i\omega_c t+\delta}dt$$

Maximum Energy Gain

$$\Delta E_{max} = |eV_c| = \left|e\tilde{E}_z(\omega_c/\beta_z ct)\right|$$

$$\tilde{E}_z(k)=\int E_z(0,0,z)e^{-ikz}dz$$

Definition: Quality Factor

- Quality Factor Q_0

$$Q_0 = \frac{\omega_0 U}{P_c} = \frac{\text{Energy stored in cavity}}{\text{Energy lost to walls in one rf period}}$$

- Q_0 gives the number of oscillations a resonator will go through before dissipating its stored energy.
- Q_0 is frequently written as: $Q_0 = \frac{G}{R_s}$
- G is the *geometry constant* and R_s is the surface resistance:

$$R_s = R_{BCS}(T) + R_0$$

- A convenient expression and a good fit for the BCS term is,

$$R_{BCS}(\text{ohm}) = 2\times10^{-4}\frac{1}{T}\left(\frac{f}{1.5}\right)^2 \exp\left(-\frac{17.67}{T}\right)$$

- A well-prepared niobium surface can reach a residual resistance R_0 of 10-20 nΩ. Record values are near 1 nΩ.

Definition: Cavity Shunt Impedance

- An important quantity used to characterize losses in a cavity, is the shunt impedance R_a (ohms per cavity) defined as

$$R_a = \frac{V_c^{\,2}}{P_c}$$

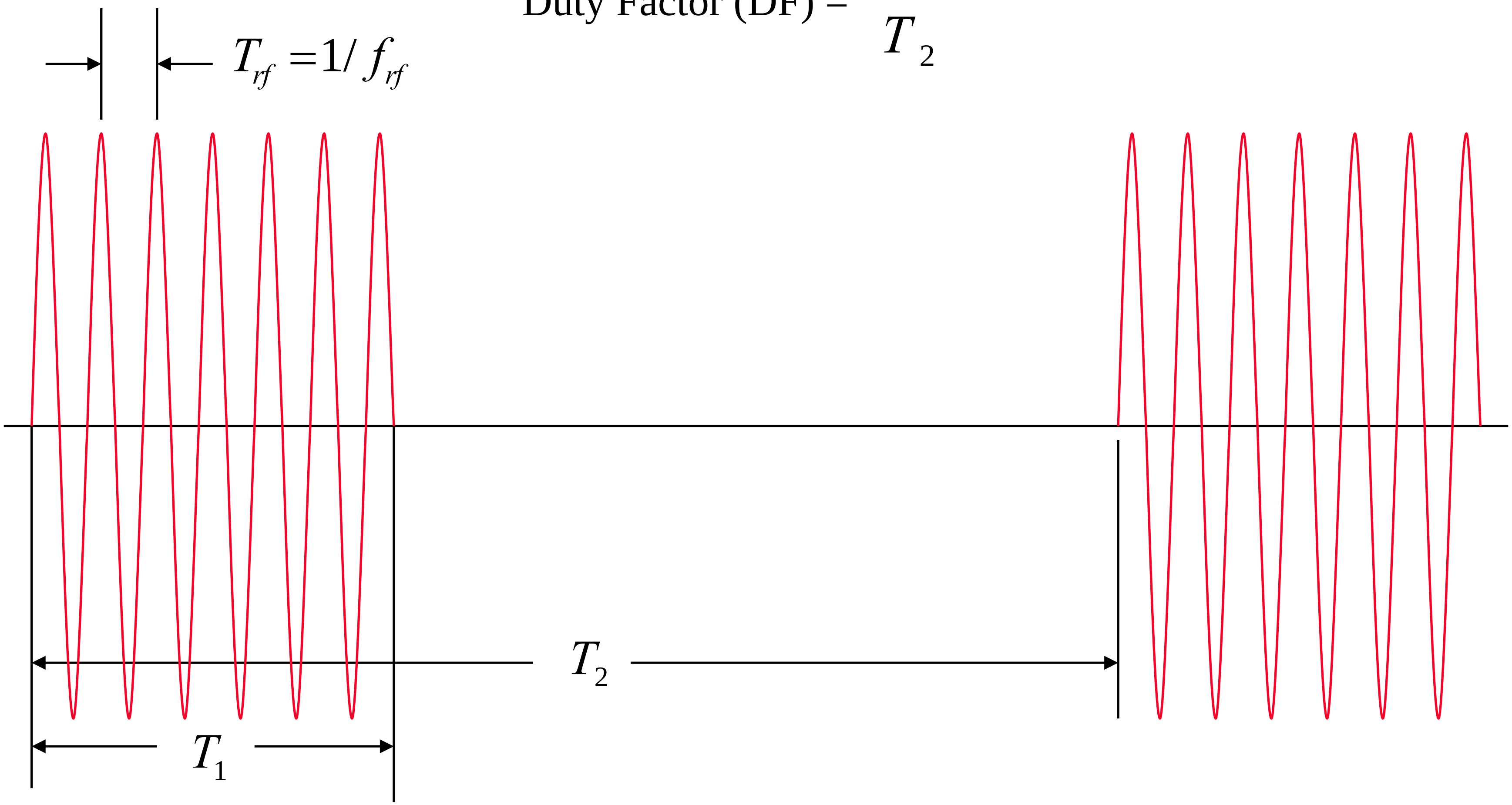
- Ideally one wants R_a to be large for the accelerating mode so that dissipated power is minimized. Optimizing up particularly important for NC Cu cavities!
- Note that R_a/Q_0 is:
  - independent of the surface resistance
  - independent of cavity size, $R_a/Q_0 \sim 100\ \Omega$/cell
- Will see later that the same R_a/Q_0 is used to determine the level of mode excitation by charges passing through the cavity.
- In NC cavities R_a/Q_0 is maximized by using small beam aperture
  - But R_a/Q_0 of HOMs tend to increase also

    $\Rightarrow$ beam interacts more strongly with the HOMs

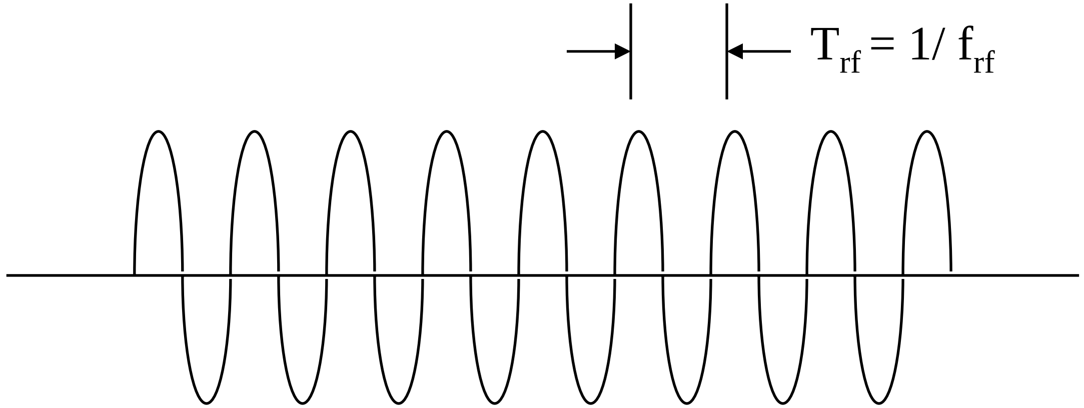
    $\Rightarrow$ beam quality degrades $\Rightarrow$ bunch charge is limited.

Duty Factor – CW Operation: Definitions

$$\text{Duty Factor (DF)} = \frac{T_1}{T_2}$$



Duty Factor – CW Operation: Definitions (cont'd)



- CW RF: rf is continuously on
- CW Beam: Beam pulse is continuously on at the RF repetition rate or a subharmonic of it
  - Example 1. JLAB FEL: cw rf at 1497 MHz
    cw beam at 74.85 MHz, the 20th subharmonic of the rf wave
  - Example 2. CEBAF: cw rf at 1497 MHz
    cw beam at 499 MHz, the 3rd subharmonic of the rf wave
- High Duty Factor: Duty Factor > 10% with beam pulse lengths of several msecs or more.

The Need for High Duty Factor

- High energy electrons have been used as nuclear probes: the electromagnetic interaction provides an ideal tool to measure the structure of nuclei.
- In 1977, Livingston Panel to examine: “The Role of Electron Accelerators in U.S. Medium Energy Nuclear Science.”
- Livingston report:
  - Points out that almost all significant investigations to that date were “single-arm” experiments: only the scattered electron was detected. One reason: the event rate for coincidence experiments was limited by the best duty factor available from medium energy electron accelerators to only ~1%.
  - Recommends the next generation of electron accelerators to be capable of carrying out coincidence experiments: both the scattered electron and the associated ejected particle are detected.
- Conclusions of Livingston Panel are reinforced by sub-committee of the U.S. Nuclear Science Advisory Committee (Barnes et al. 1982).
- This committee recommends the construction of at least one cw electron accelerator with maximum energy of 4 GeV.

The Need for High Duty Factor (cont'd)

- Coincidence experiments proceed faster using incident beams of high duty factor.
- The reason:
  - In a typical experiment, particles detected in one channel may be totally unrelated to particles detected in the opposite channel.

    $\Rightarrow$ need probability of observing "accidental coincidence" involving two unrelated particles to be small.
  - Probability of "accidental coincidence" $\propto I^2_{peak}$
  - "True coincidence" rate $\propto I_{peak}$
  - For a given I_{ave} or a given true event rate, $I_{peak} \propto 1/DF$

    $\Rightarrow$ the higher the DF, the lower the "accidental coincidence" rate compared to the true rate.

SRF Recirculated Linacs for Nuclear Physics

- The original motivation (Schwettman et al., 1967) for building a superconducting electron linac at Stanford-HEPL for Nuclear Physics research was to provide:
  - continuous operation
  - high accelerating gradients
  - exceptional stability
  - energy resolution of order 10^{-4}
  - beam currents up to 400 μA

- These characteristics continue to be desirable in modern electron accelerators for Nuclear Physics.

It took longer than anticipated, but eventually all these objectives have all been met!

SRF Recirculated Linacs for Nuclear Physics (cont’d)

- For cw operation, power dissipated in the walls of a Cu structure is substantial. Not so for superconductors:
  - Power dissipated in cavity walls is: $P_{diss} = \frac{V_c^2}{(R/Q)Q_0}$
    - Microwave surface resistance of a superconductor is ~ 10^{-5} lower than Cu

$$\Rightarrow Q_0^{SC} \sim 10^5 Q_0^{Cu}$$

Option	Superconducting	Normal Conducting
Q_0	2×10^9	2×10^4
R/Q (ohm/m) @ 500 MHz	330	900
P_{diss}/L (Watt/m) @ E_{acc}=1MV/m	1.5	56000 !!!
AC Power (kW/m)	0.54	112

- Furthermore, the RF power to beam power efficiency is much higher in SC accelerators.

SRF Recirculated Linacs for Nuclear Physics (cont'd)

- For applications demanding high cw voltage, SC cavities have a clear advantage:
  - Recall: $P_{diss} \sim E_{acc}^2$
  - High fields (>50 MV/m) can be produced in Cu cavities, but only for μsecs, because the rf power required becomes prohibitive and cooling becomes impossible!
  - Operating gradient in NC cavities, in cw mode, is limited to <1.75 MV/m!

SRF Recirculated Linacs for Nuclear Physics (cont'd)

- Because $P_{diss} \sim 1/(R/Q)$, in NC cavities R/Q must be maximized by using a small beam aperture.

- In SC cavities, one can afford to make the beam aperture much larger than NC cavities:
  - The resulting drop in R/Q for the accelerating mode is not a concern, because of the immensely larger Q_0 .
  - And, advantages of bigger beam aperture are:

    a) It reduces short-range wakes $\Rightarrow$ reduces emittance growth along the linac

    b) It reduces the impedance of dangerous Higher Order Modes (HOMs)

    c) It reduces beam loss and beam-loss-induced radioactivity

SRF Recirculated Linacs for Nuclear Physics (cont'd)

- cw srf linacs make highly stable operation possible

  ⇒ rf phase and amplitude can be controlled very precisely

  ⇒ very low energy spread (~ 10^{-5} at CEBAF)

- In cw operation (made possible by srf cavities) high average current can be achieved with low peak current.

  ⇒ interaction of beam with cavity and vacuum chamber is weak and small beam emittance can be preserved through the linac!

SRF Recirculated Linacs as FEL Driver Accelerators

- There are many candidate drivers for an FEL: dc electrostatic accelerators, storage rings, induction linacs, rf linacs

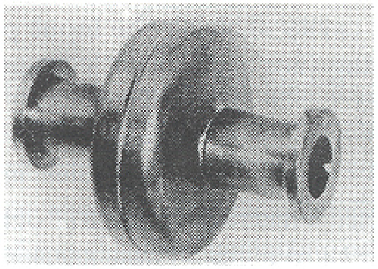
- RF linacs are suitable for a variety of FELs because they
  - Offer high extraction efficiency ⇒ higher P_{FEL}
  - Offer good beam quality: low energy spread and low emittance, necessary for adequate overlap between laser and electron beam

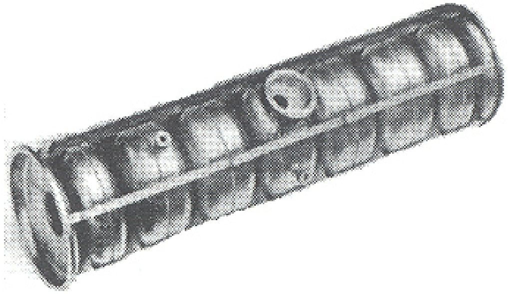
- SRF linacs are ideal as FEL drivers because:
  - excellent beam quality (as outlined earlier)
  - allow both high average power (in cw mode) and high efficiency!

- In most high-power lasers, most of input energy is rejected as waste heat ⇒ ability to remove heat sets power limitation (e.g. CO_2 lasers)
- In an FEL, the waste heat is in the form of electron beam power ⇒ electron beam not converted to laser power is largely recoverable!

Historical Foundations of SRF

- HEPL at Stanford University was the pioneer laboratory in exploration of srf for accelerator applications. In 1965 they accelerated electrons in a lead-plated resonator
- In 1977 HEPL completed first Superconducting Accelerator (SCA) providing 50 MV in 27m linac at 1.3 GHz.


(a)

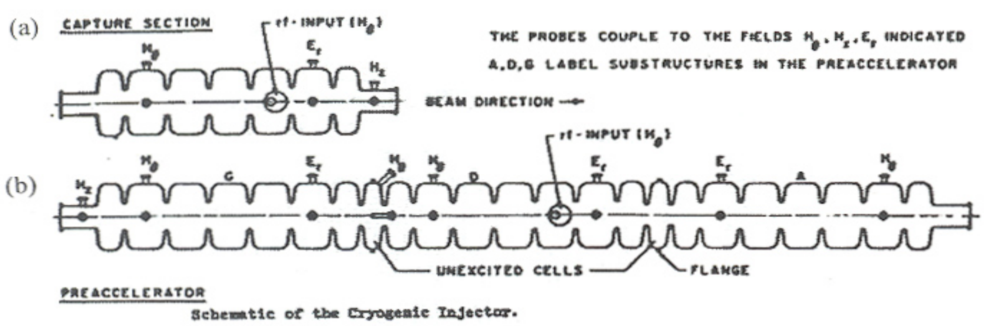

(b)

(a) Single-cell HEPL Nb cavity, resonant frequency 1.3 GHz

(b) HEPL 7-cell subsection

Historical Foundations of SRF

- In 1977 the U. of Illinois completes construction of a microtron MUSL-2 with SCA sections that provided 13 MV.
- Both SCA and MUSL-2 aimed to provide cw high current (~ several 10 μA) for precision Nuclear Physics research.
- Both operated at accelerating gradient of ~ 2MV/m
- Multipacting limited the achievable gradient.



(a) 7-cell subsection of the HEPL structure, with 5 cells and 2 half end-cells

(b) Multicell subsection of the HEPL SCA. Several subsections are joined together at the unexcited cells

Historical Foundations of SRF

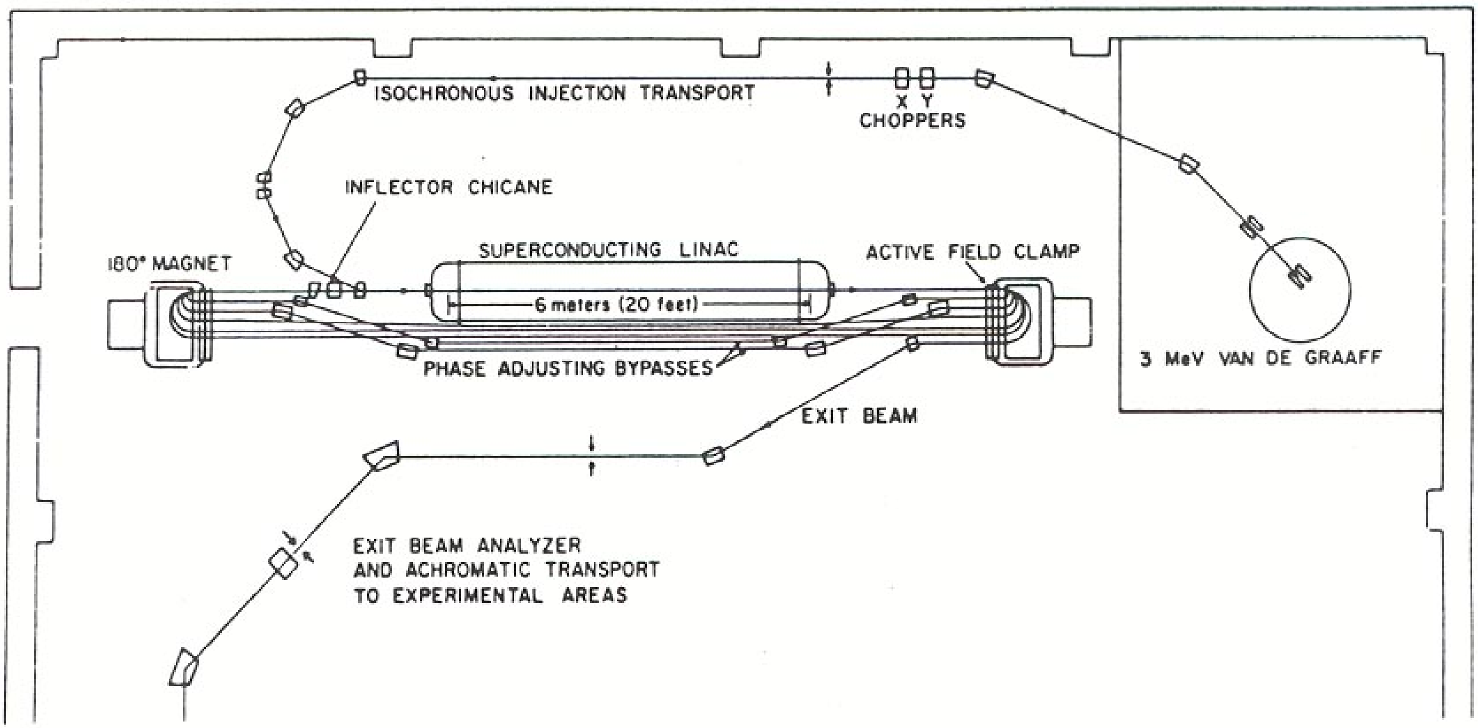
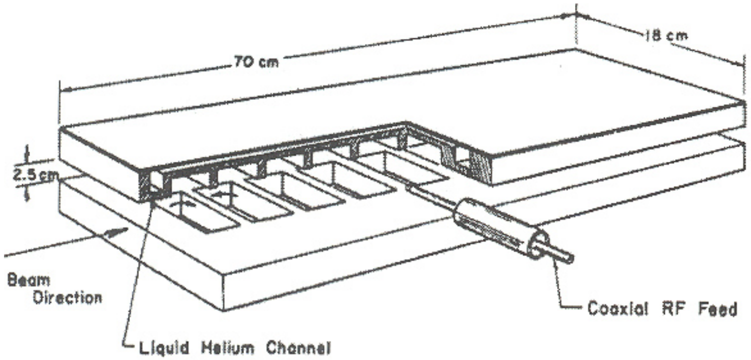


Figure 5.3 The second Illinois superconducting race-trace microtron, MUSL-2 (Axel *et al.*, 1977; © 1977 IEEE)

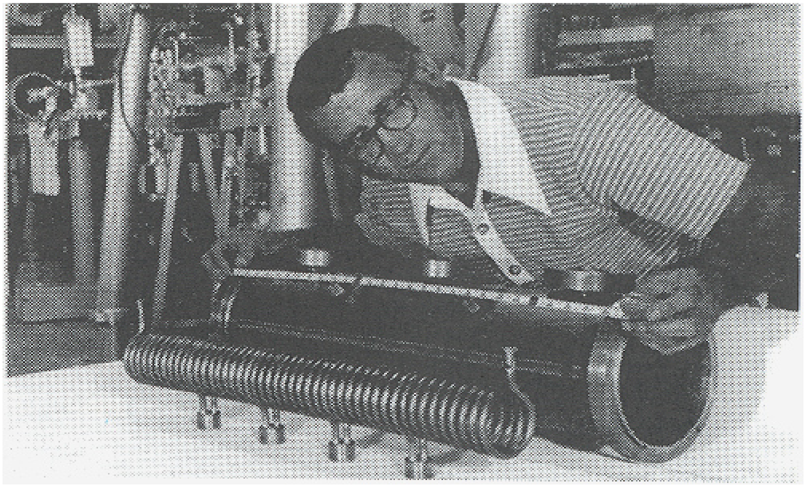
Historical Foundations of SRF

- At the same time Cornell wants to increase the energy of the 12 GeV CESR storage ring using high gradient srf structures.
- In aiming for high gradient, an important idea was to use higher rf frequency (2.86 GHz).
- It would push the fields at which multipacting would occur to higher values!
- In 1975 the muffin-tin structure was developed. It accelerated electron beam of 100 μA to 4 GeV.
- It operated at 4 MV/m, at Q_0~10^9.
- It was limited by thermal breakdown.



Historical Foundations of SRF (cont'd)

- In parallel srf activities are going on at the protons and heavy-ions front:
- In late 1960's, KFK began exploring an srf linac for protons using helically loaded Nb cavities.
- Similar exploration started at ANL.

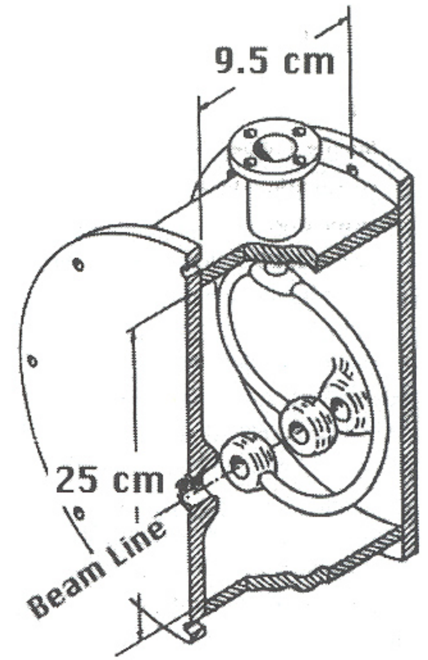


Helical Nb resonator developed at ANL for a heavy-ion linac.

- The structure exhibits poor mechanical stability: vibrations make control of rf phase difficult.

Historical Foundations of SRF (cont'd)

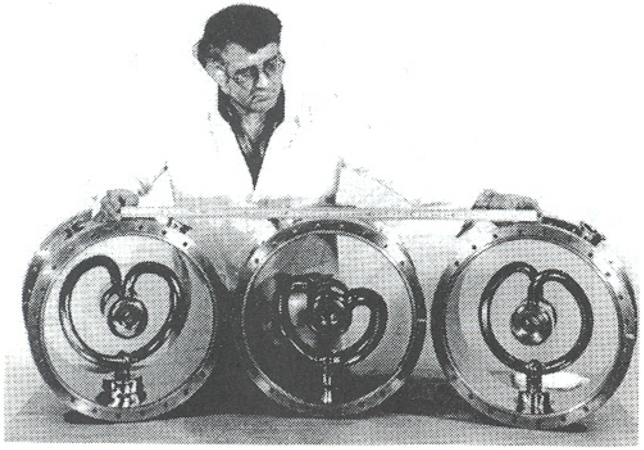
- In 1974 Caltech develops a split-ring cavity geometry and successfully tackles the stability problem.
- It was fabricated from a thin film of lead electroplated on a Cu structure.
- It became the basis of the booster accelerator at SUNY.
- Typical operating gradient ~ 2.5 MV/m.



The three-gap split-loop, lead-on-copper resonator originated at Caltech. It accelerated charged particles with β=0.1, rf frequency is 150 MHz.

Historical Foundations of SRF (cont'd)

- In 1975 ANL starts development of Nb split-ring structure. It became the basis of ATLAS.



Nb split-ring resonators used in ATLAS. The Nb components are hollow and filled with liquid He at 4.2 K. Outer housing is made from Nb-Cu composite.

- ATLAS was commissioned in 1978.
- Holds world record for longest running srf accelerator.
- Operating gradient for the split-ring Nb structures is ~ 2.5-3.5 MV/m.

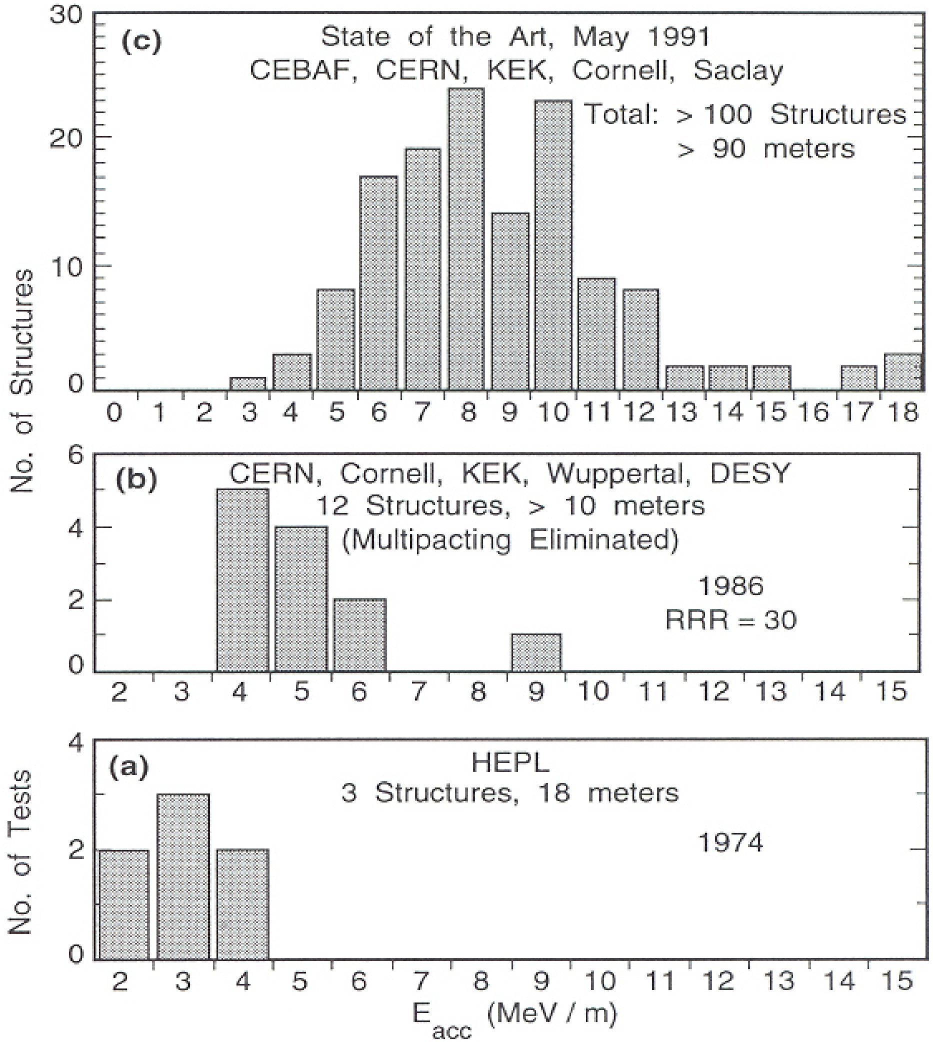
State of the Art in SRF in the 70's, 80's and 90's

(a) Gradients limited by multipacting

(b) Multipacting is solved but gradients are limited by thermal breakdown.

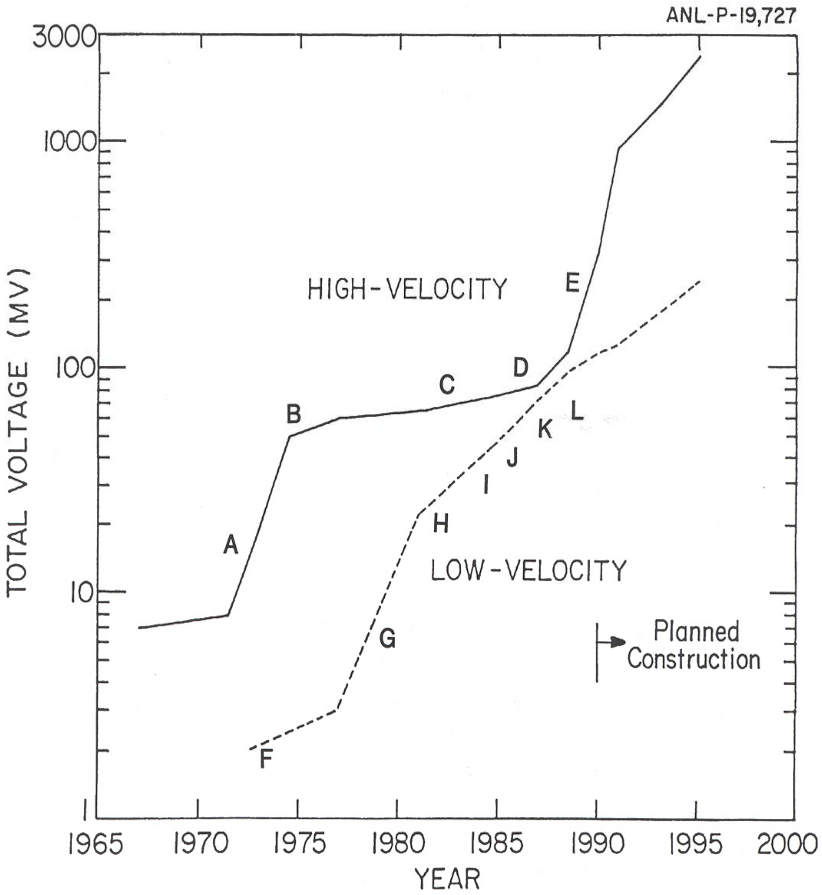
(c) Thermal breakdown is alleviated by using high-purity, high-thermal-conductivity Nb. Now gradients are predominantly limited by field emission, although thermal breakdown is also encountered.

(Courtesy of H. Padamsee.)



State of the Art in SRF in the 70's, 80's and 90's

Total installed voltage capability with srf cavities for electron and heavy-ion accelerators. The growth for electron accelerators levels out between 1974 and 1984 because of problems with multipacting and thermal breakdown.



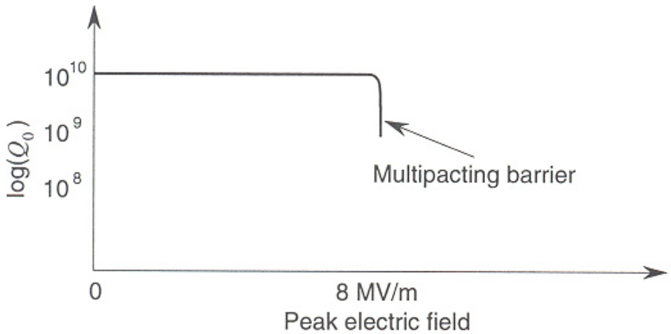
(Courtesy of Jean Delayen)

SRF Performance Limitations - Multipacting

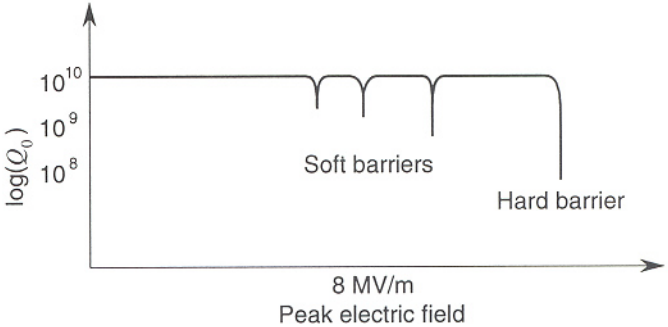
- Multipacting was a major performance limitation of srf cavities in the past.
- Multipacting in rf structures is a resonant process.
- A large number of electrons build up and multipacting, absorbing rf power so cavity fields can not increase by raising incident power.
- Electrons collide with structure walls, leading to large temperature rise and, in srf cavities, thermal breakdown.
- Multipacting can be avoided in β=1 cavities by selecting proper cavity shape.

Multipacting (cont'd)

- Onset of multipacting (MP) is usually recognized when the field level in the cavity remains fixed, as more rf power is supplied. In effect, Q_0 abruptly reduces at the MP threshold.
- Often a MP barrier can be overcome by processing.
- Barriers that can be processed are *soft* barriers, ones that persist are *hard* barriers.
- A processed soft barrier may reappear after the cavity is exposed to air: MP is strongly dependent on the condition of the first few monolayers of rf surface.



(a)



(b)

Q_0 vs. E_{pk} curves for srf cavity when one (a) or several (b) MP barriers are encountered.

Multipacting (cont'd)

Multipacting Mechanism

- An electron is emitted from one of the structure's surfaces. The emitted electron is accelerated by the rf fields and eventually impacts a wall again.
- Secondary electrons (SE's) are produced.
- The number of SE's depends on the surface characteristics and impact energy of the primary.
- The SE's are accelerated, impact and produce another generation of electrons, etc…
- If the number of emitted electrons exceeds the number of impacting, then the electron current will increase exponentially.

$$N_e = N_0 \prod_{m=1}^{k} \delta(K_m)$$

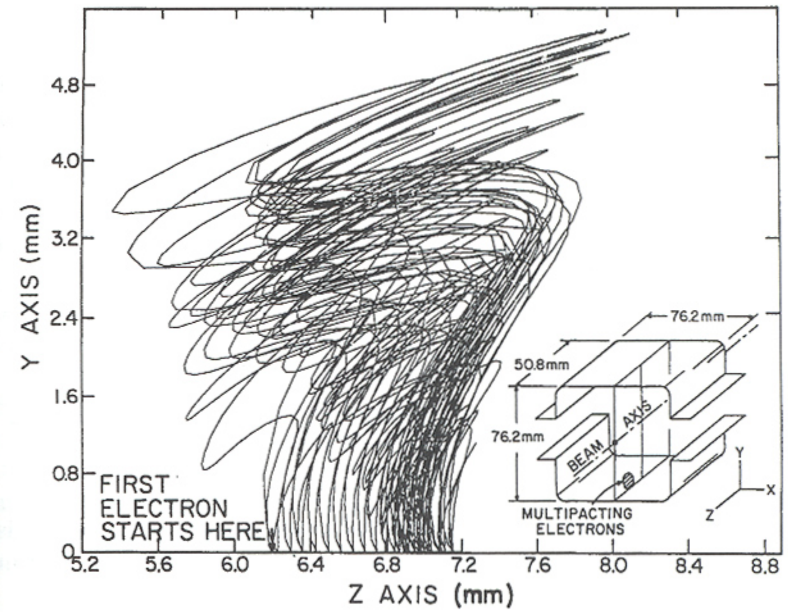
$\delta(K_m)$: the secondary emission coefficient (SEC), material-dependent, function of impact energy. If $\delta(K_m)>1$ for all impact sites, MP will occur.

- Electron current will only be limited by available power or space charge effects.

Multipacting (cont'd)

A Common Multipacting Scenario

- Most frequent type of MP in β=1 cavities: charges impact the cavity wall at, or near, the emission site itself.
- Emitted electrons are accelerated by $E_{\perp}$ to the surface while the surface magnetic field force electrons in quasi-circular orbits, so they return to their point of origin.



Multipacting (cont'd)

Several solutions were explored:

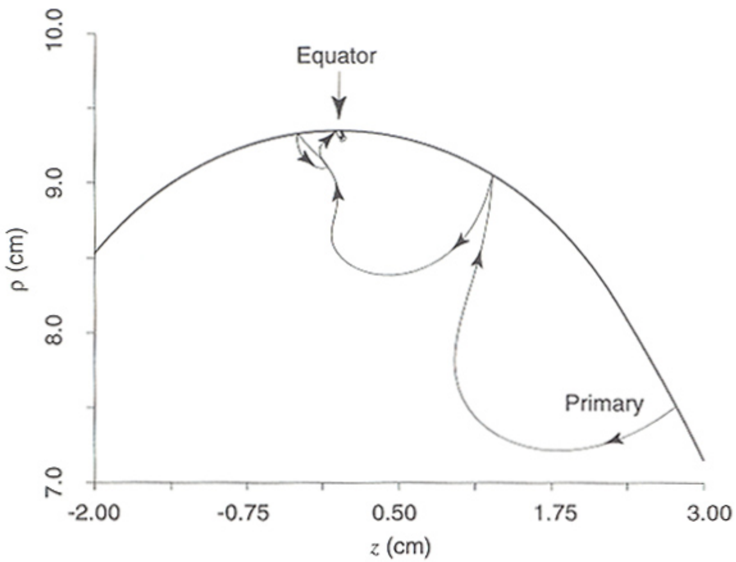
- Reducing the E field by making subtle alterations to the shape of the cavity.
  Was done on the HEPL cavities. Method was successful for the muffin-tin cavity.

- Placing grooves in the surface where MP occurs. $E_{\perp}$ is strongly attenuated at the bottom of the grooves, and secondaries remain trapped.

- The most successful solution to MP problem was to make a spherical cavity. The magnetic field varies along the entire cavity wall , so there are no stable trajectories, as the electrons drift to the equator. At the equator, $E_{\perp}$ vanishes, so secondaries do not gain any energy.

- Elliptical is better than spherical from mechanical stability point of view. Elliptical cavity shapes are now universally adopted for β=1 SRF cavities and MP is no longer a serious problem.

Multipacting (cont'd)



Electron trajectories in an elliptical cavity. The charges drift to the equator where MP is not possible.

Multipacting (cont'd)

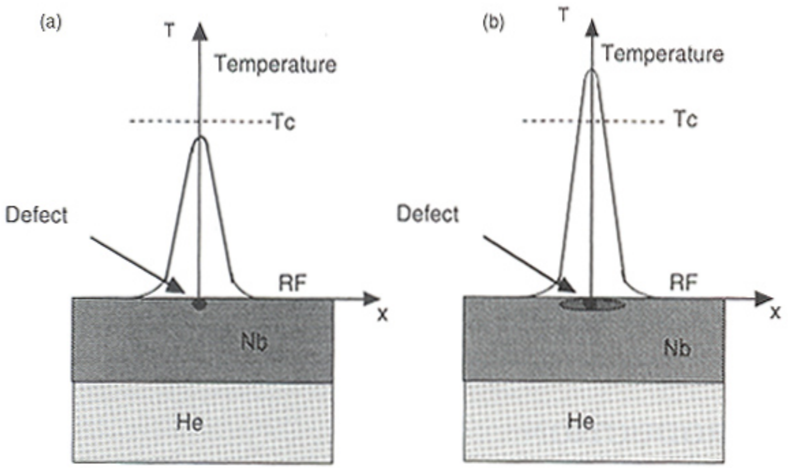
Avoiding Multipacting

- Localize MP orbits by diagnostic tools. Track electrons and implement geometric modifications to shift barriers or to change resonant conditions.
- Use materials with low SEC.
- Cleanliness is imperative.
- Destabilize MP trajectories at the operating fields by applying a dc electric or magnetic field, such that it alters the MP trajectories.

SRF Performance Limitations –Thermal Breakdown

- Phenomena that limit the achievable magnetic field: thermal breakdown of superconductivity and field emission.

- Thermal breakdown (or "quench") originates at sub-mm-size regions, "defects," that have rf losses substantially higher than the surface resistance of an ideal superconductor.
- In dc case, supercurrents flow around the defects.
- At rf frequencies, the reactive part of the impedance causes the rf current to flow through the defect, producing ohmic heating.
- When T at the outside edge of the defect exceeds T_C, the superconducting region surrounding the defect becomes normal -> power dissipation is increased.
- As NC region grows, power dissipation increases and results in thermal instability.



Thermal Breakdown (cont'd)

- Examples of defects:
  - 50 μm Cu particle attached to Nb surface
  - Chemical or drying stain 440 μm
  - 50 μm crystal containing S, Ca, Cl, K
- There are many opportunities for such defects to enter an srf cavity during the various stages of production and preparation.
- Statistically, number of defects increases with cavity area $\Rightarrow$ larger cavities break down at lower fields.

Thermal Breakdown (cont'd)

- Solutions to thermal breakdown

a) Guided Repair

One or two gross defects can be located by thermometry and removed by mechanical grinding. Example: 350 MHz single-cell Nb cavity E_{acc} was increased from 5 MV/m ->10 MV/m.

Not easy for smaller defects.

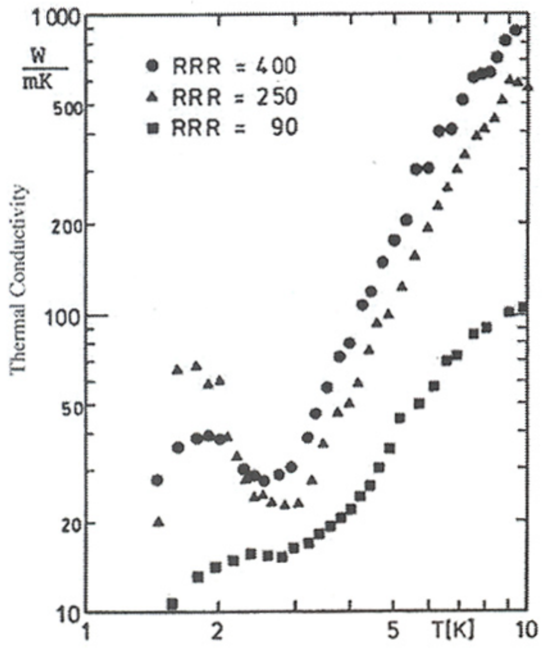
b) Raising Thermal Conductivity of Niobium

$H_{max} \propto \sqrt{\kappa} \Rightarrow$

If raise κ, H_{max} will increase.

Defects will be able to tolerate more power before driving neighboring superconductor into normal state.

Approximately, κ = 0.25 (W/m-K) x RRR

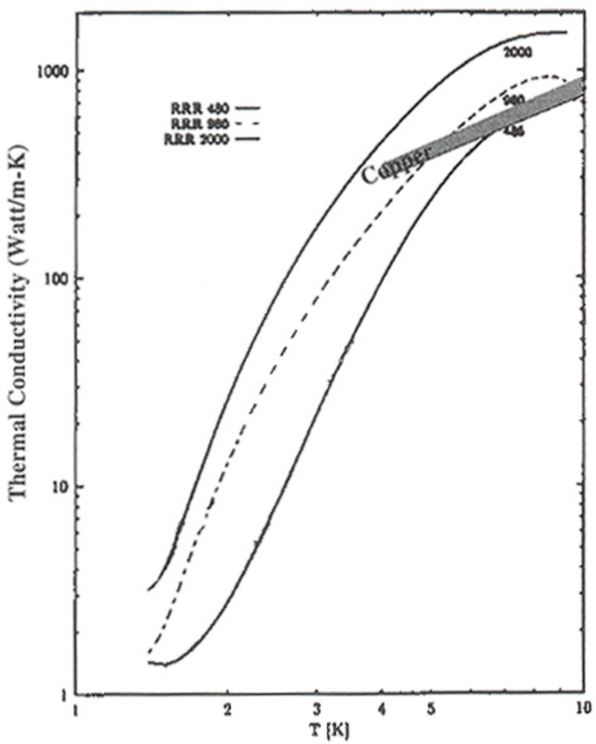


Thermal conductivity of Nb with different RRR values.

Thermal Breakdown (cont'd)

c) Thin Films of Niobium on Copper

- Use µm-thick film of Nb on a thermally stabilizing copper substrate.
- Thermal conductivity of Cu is much greater than of Nb.



Thermal conductivity of high-purity Cu samples compared to low-temperature thermal conductivity of Nb samples of various RRR. Note that at RRR~1000, the thermal conductivity of Nb begins to approach that of Cu.

State of the Art in SRF in 2000

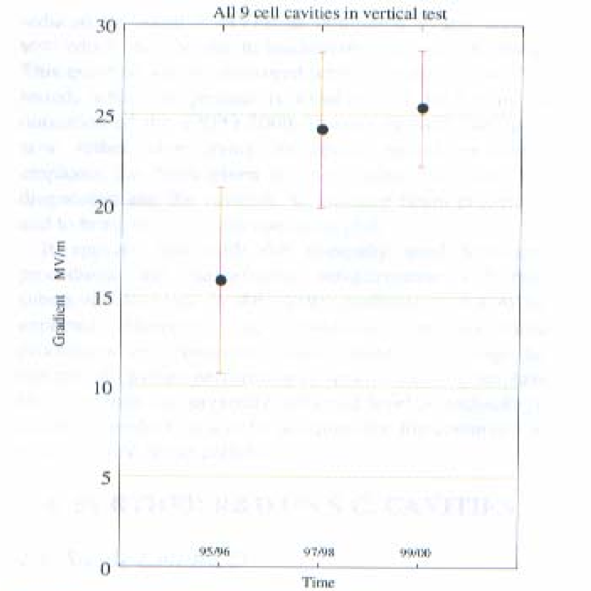


Figure 3: Average gradient of all 9-cell cavities measured in vertical tests during the past 5 years.

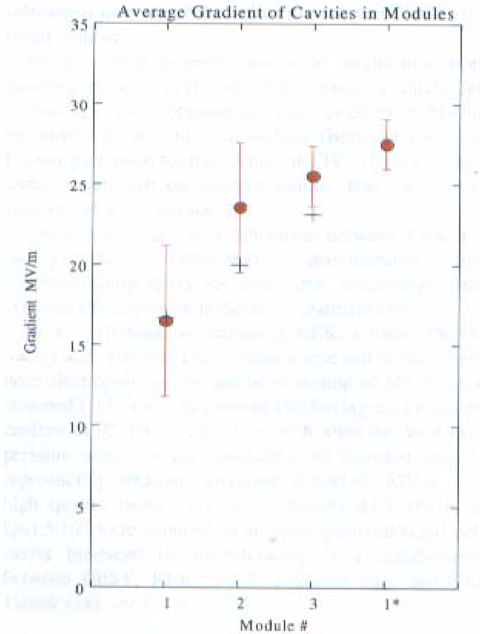


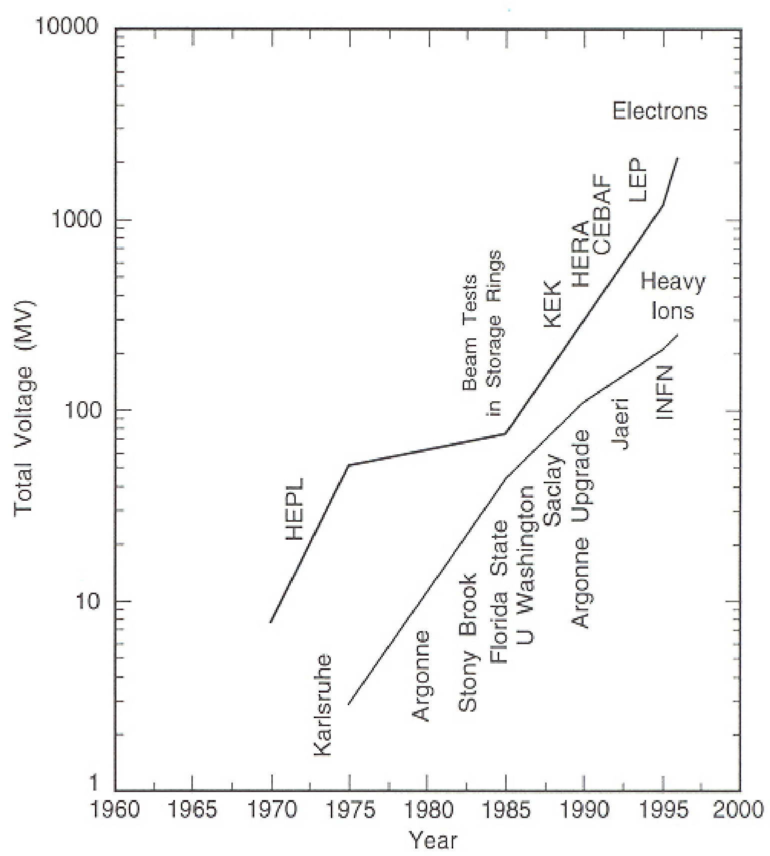
Figure 4: Average gradient, as measured in vertical tests, of the 9-cell cavities assembled into accelerator modules.

(a) (b)

(a) Average gradient in all 9-cell TESLA cavities measured in vertical tests during the past 5 years.

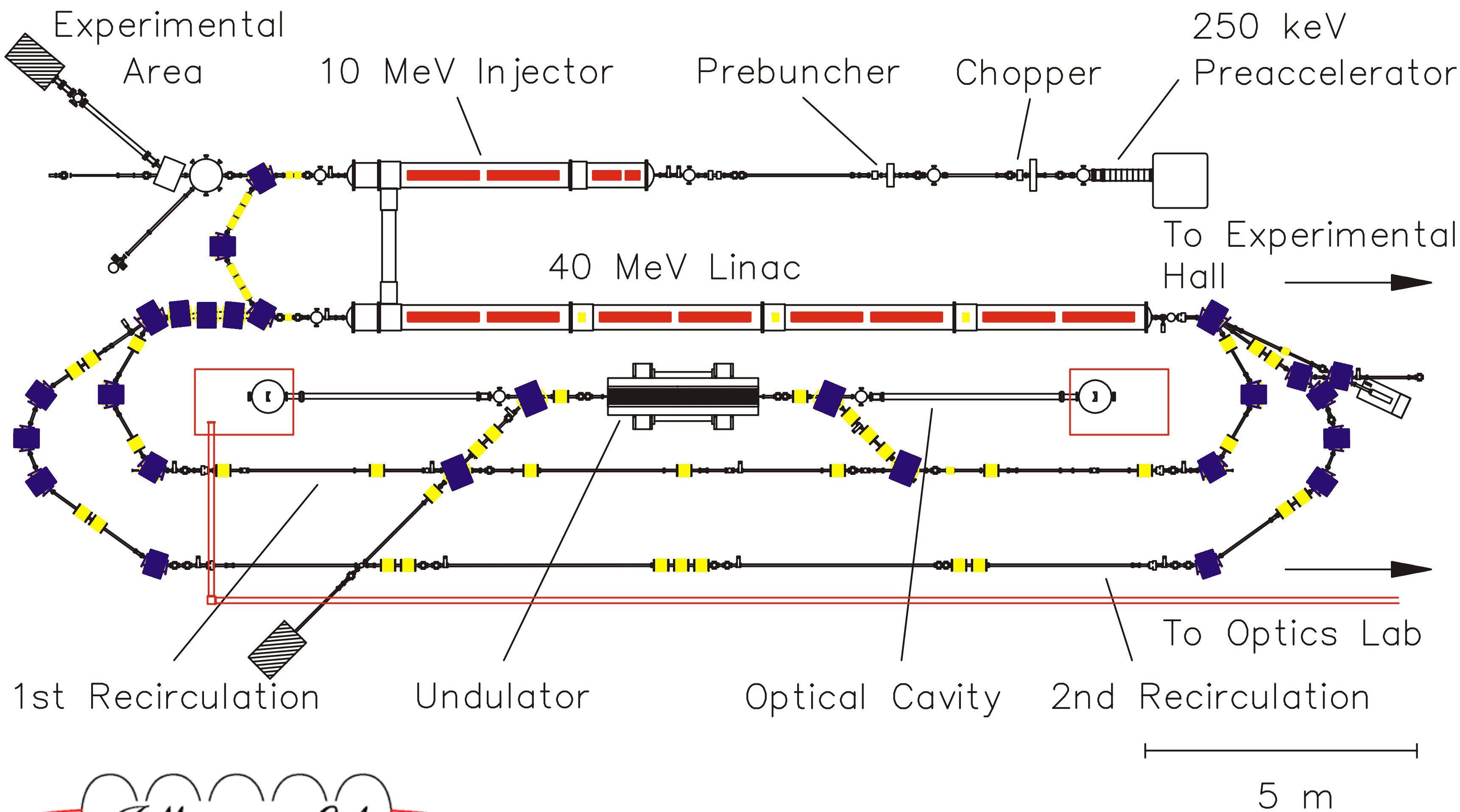
(b) Average gradient as measured in vertical tests, of the TESLA 9-cell cavities assembled into accelerator modules.

State of the Art in SRF in 2000

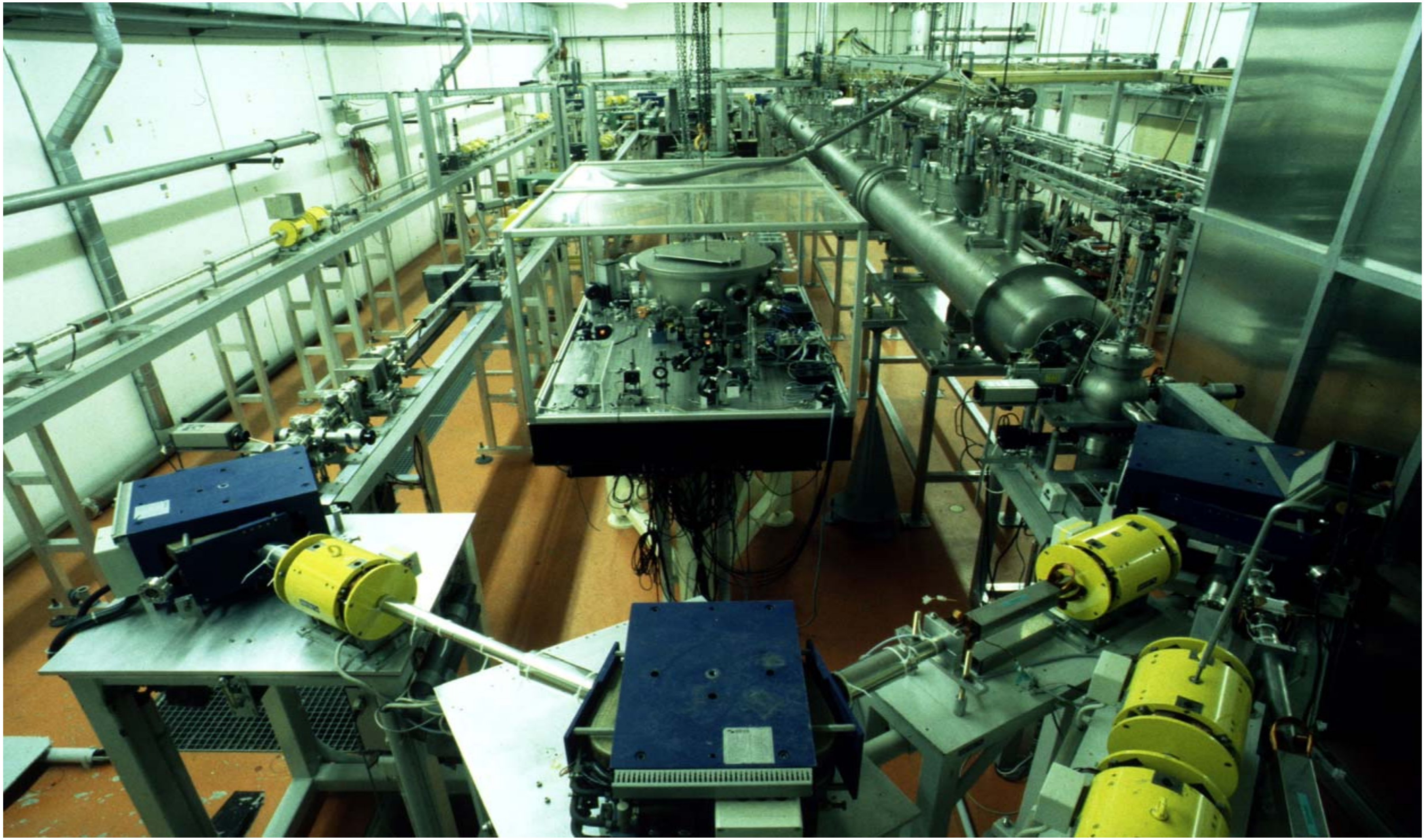


Total installed voltage capability with srf cavities for electron and heavy-ion accelerators.

Layout of S-DALINAC (Darmstadt)



S-DALINAC



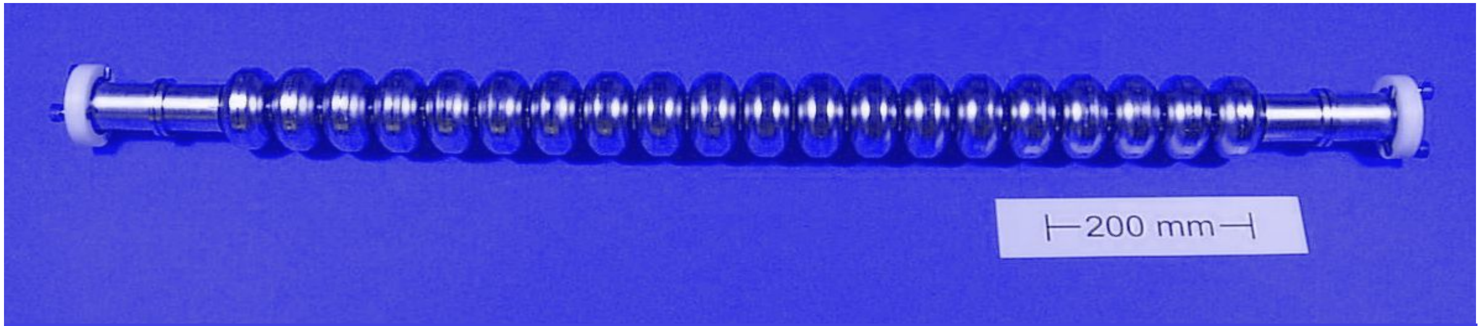
S-DALINAC Beam Parameters

Experiments	Energy (MeV)	Current (μA)	Mode	Time (h)
(γ,γ')	2.5 – 10	50	3 GHz, cw	6400
LEC, PXR	3 – 10	0.001 - 10	3 GHz, cw	2100
HEC, PXR	35 – 87	0.1	3 GHz, cw	800
(e,e'), (e,e'x)	22 – 120[1)]	5	3 GHz, cw	7800
FEL	30 – 38	2.7 A_{peak}	10 MHz, cw	2900
				Σ 20000

1) Dutycycle 33%

Resolution: ΔE_{FWHM} = 50 keV @ 85 MeV, $\Delta E/E = \pm 3\cdot 10^{-4}$

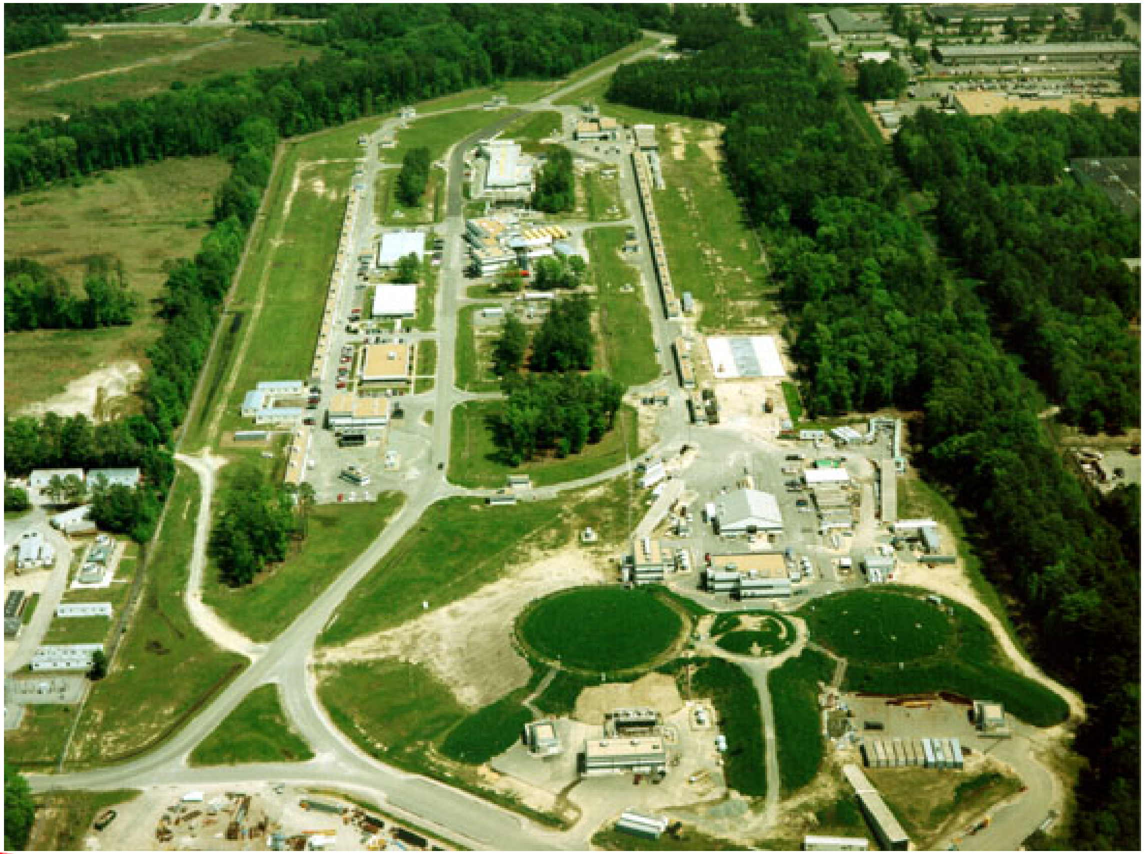
Superconducting 20-Cell Cavity



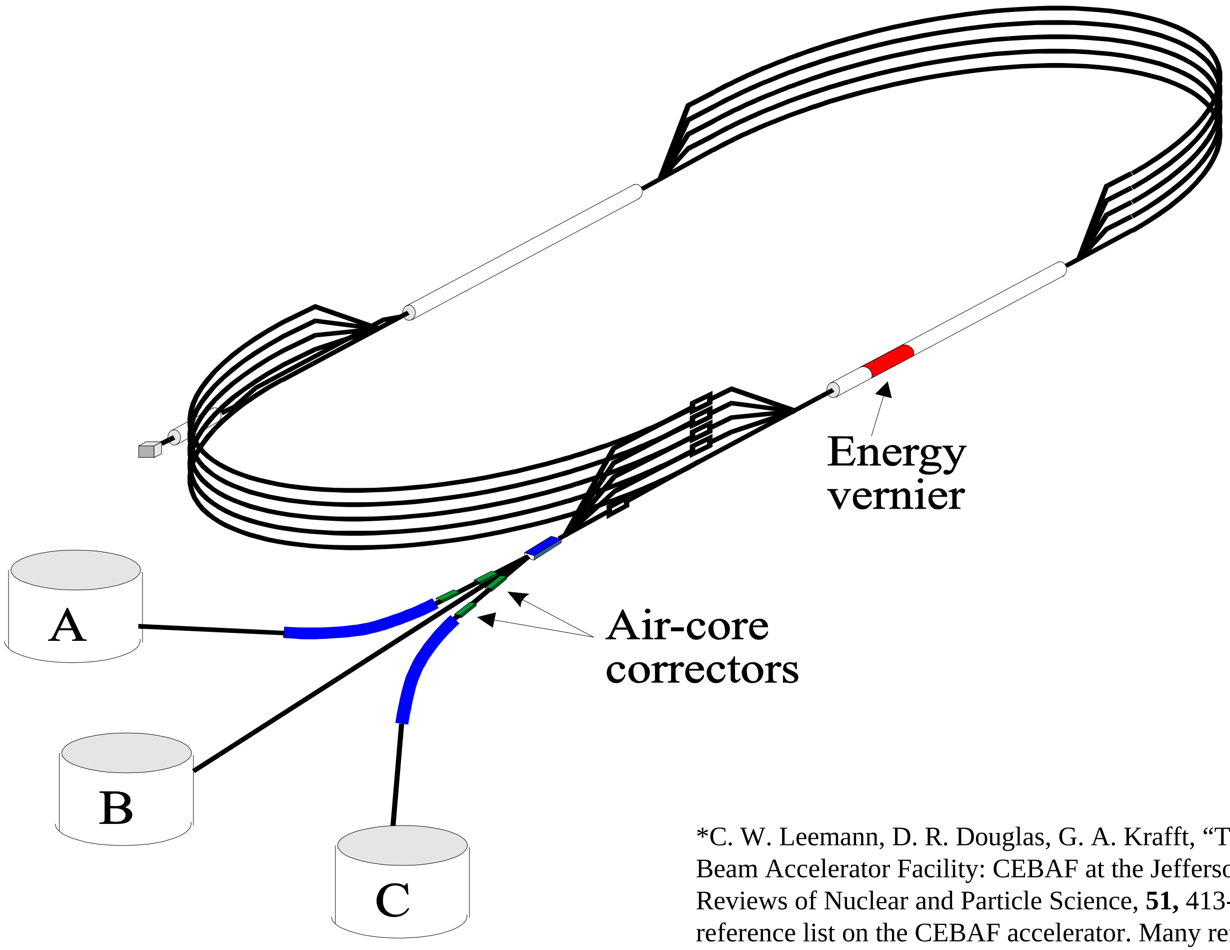
Material:	Niobium (RRR=280)
Frequency:	3 GHz
Temperature:	2 K
Accelerating Field:	5 MV/m
Q_0/Q_L:	$3 \cdot 10^9 / 3 \cdot 10^7$
$\Delta f/\Delta l$:	500 Hz/µm

The CEBAF at Jefferson Lab

- Most radical innovations (had not been done before on the scale of CEBAF):
  - choice of Superconducting Radio Frequency (SRF) technology
  - use of multipass beam recirculation
- Until LEP II came into operation, CEBAF was the world's largest implementation of SRF technology.



CEBAF Accelerator Layout*



*C. W. Leemann, D. R. Douglas, G. A. Krafft, "The Continuous Electron Beam Accelerator Facility: CEBAF at the Jefferson Laboratory", Annual Reviews of Nuclear and Particle Science, **51,** 413-50 (2001) has a long reference list on the CEBAF accelerator. Many references on Energy Recovered Linacs may be found in a recent ICFA Beam Dynamics Newsletter, #26, Dec. 2001: http://icfa-usa/archive/newsletter/icfa_bd_nl_26.pdf

CEBAF Beam Parameters

Beam energy	6 GeV
Beam current	A 100 μA, B 10-200 nA, C 100 μA
Normalized rms emittance	1 mm mrad
Repetition rate	500 MHz/Hall
Charge per bunch	< 0.2 pC
Extracted energy spread	$< 10^{-4}$
Beam sizes (transverse)	< 100 microns
Beam size (longitudinal)	<100 microns (330 fsec)
Beam angle spread	$< 0.1/\gamma$

Energy Recovered Linacs

- The concept of energy recovery first appears in literature by Maury Tigner, as a suggestion for alternate HEP colliders*
- There have been several energy recovery experiments to date, the first one in a superconducting linac at the Stanford SCA/FEL**
- Same-cell energy recovery with cw beam current up to 10 mA and energy up to 150 MeV has been demonstrated at the Jefferson Lab 10 kW FEL. Energy recovery is used routinely for the operation of the FEL as a user facility

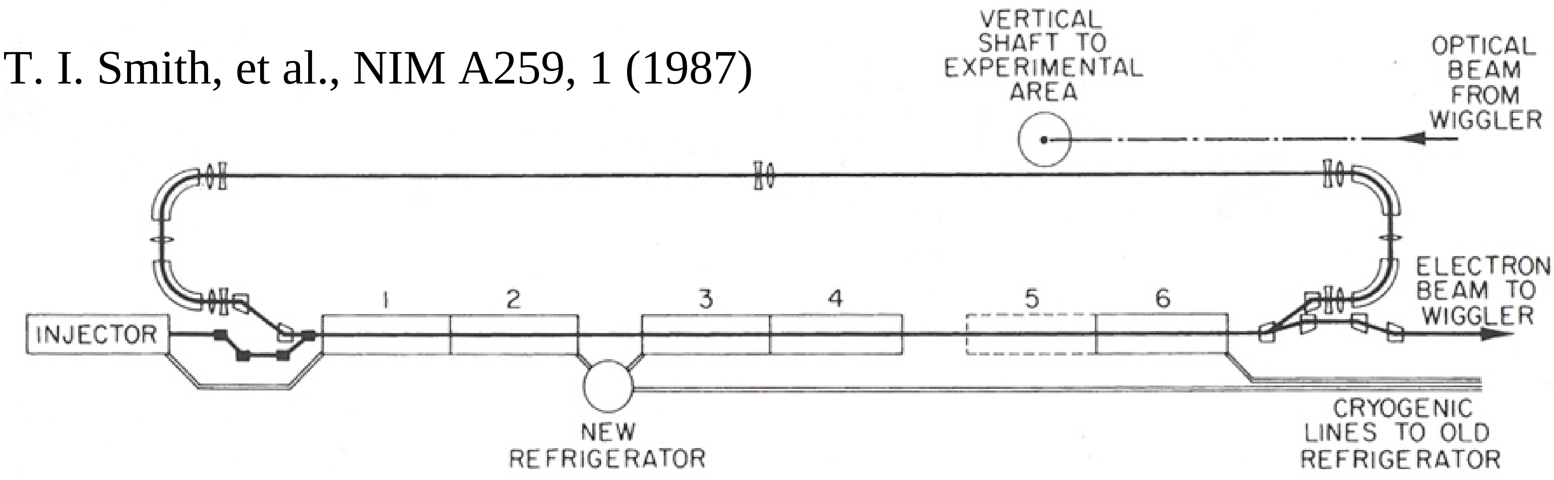
* Maury Tigner, Nuovo Cimento 37 (1965)

** T.I. Smith, et al., "Development of the SCA/FEL for use in Biomedical and Materials Science Experiments," NIMA 259 (1987)

The SCA/FEL Energy Recovery Experiment

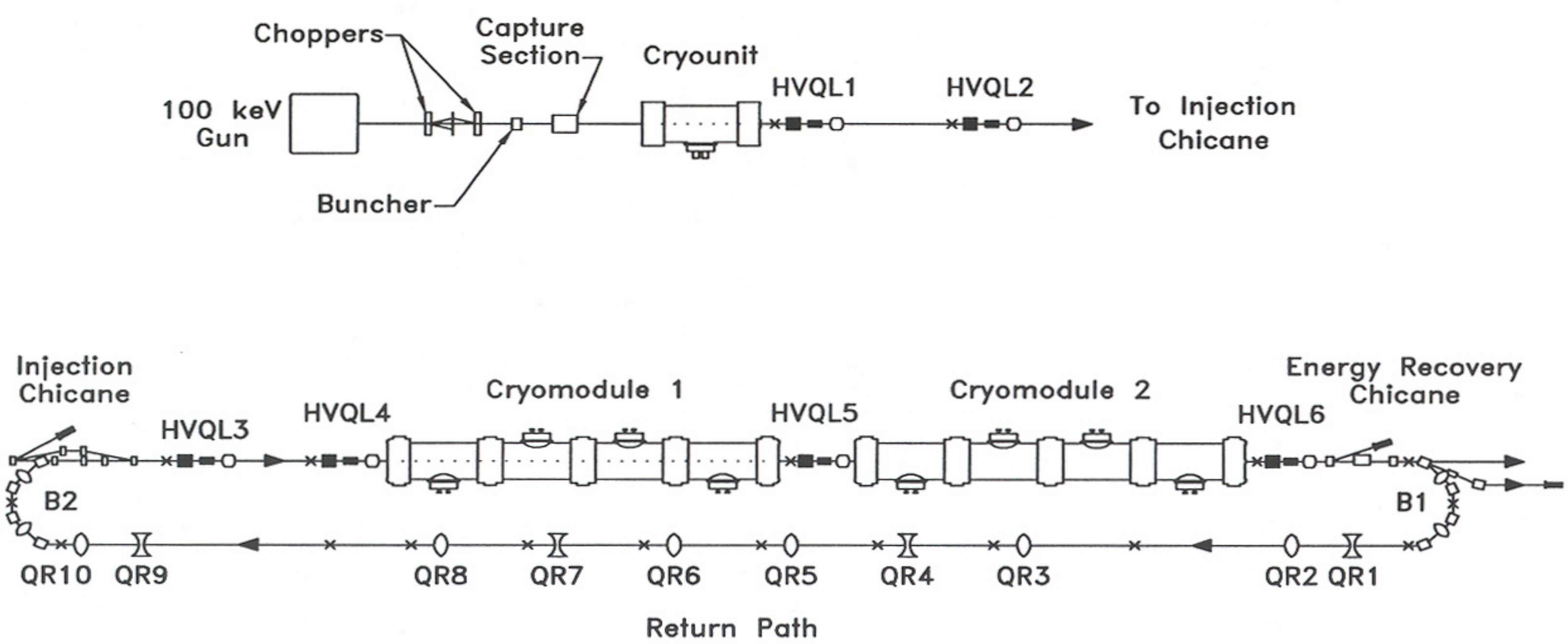
- Same-cell energy recovery was first demonstrated in an SRF linac at the SCA/FEL in July 1986
- Beam was injected at 5 MeV into a ~50 MeV linac
- The first recirculation system (SCR, 1982) was unsuccessful in obtaining the peak current required for lasing and was replaced by a doubly achromatic single-turn recirculation line.
- All energy was recovered. FEL was not in place.

T. I. Smith, et al., NIM A259, 1 (1987)

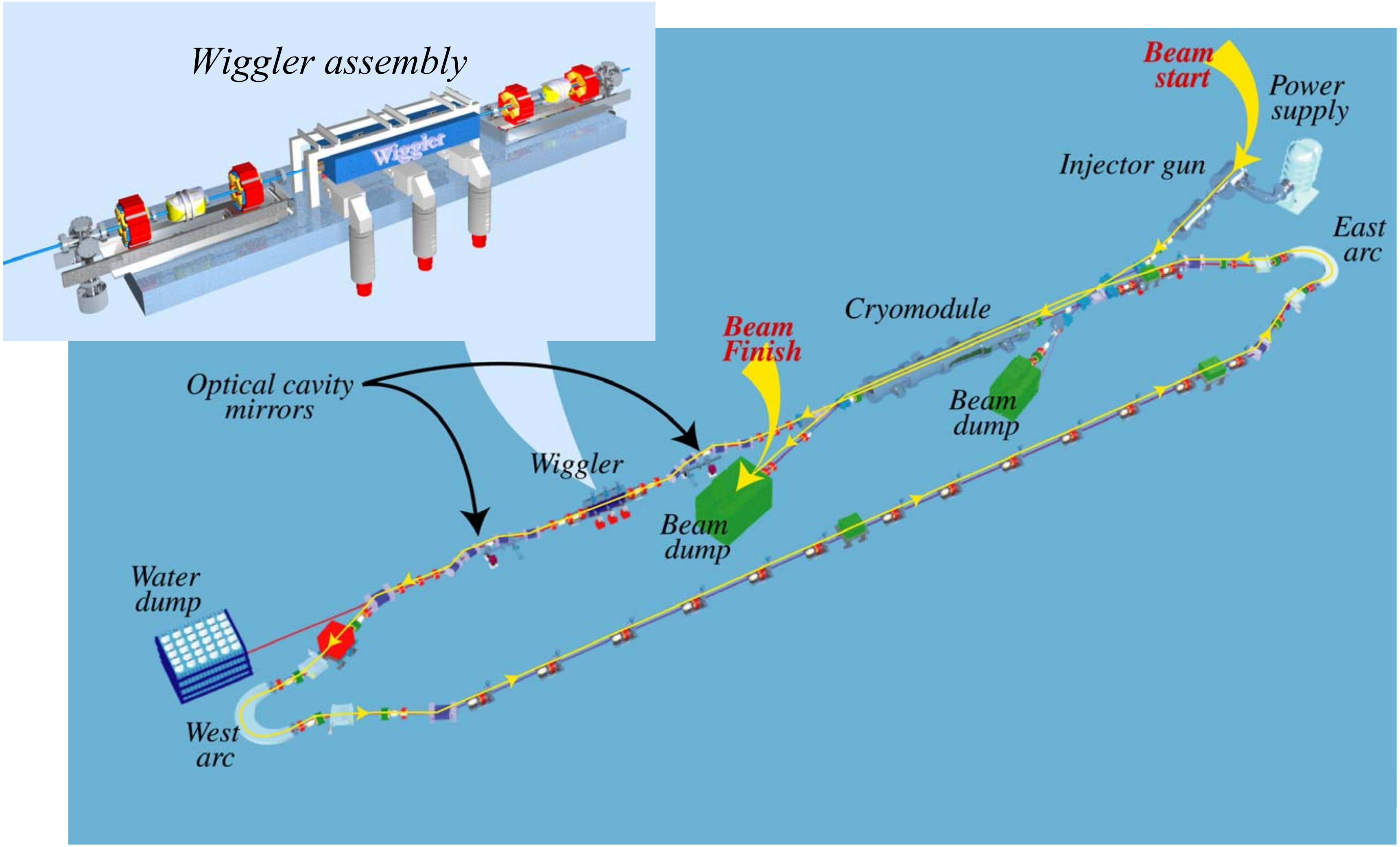


The CEBAF Injector Energy Recovery Experiment

N. R. Sereno, "Experimental Studies of Multipass Beam Breakup and Energy Recovery using the CEBAF Injector Linac," Ph.D. Thesis, University of Illinois (1994)



The Jefferson Lab IR FEL

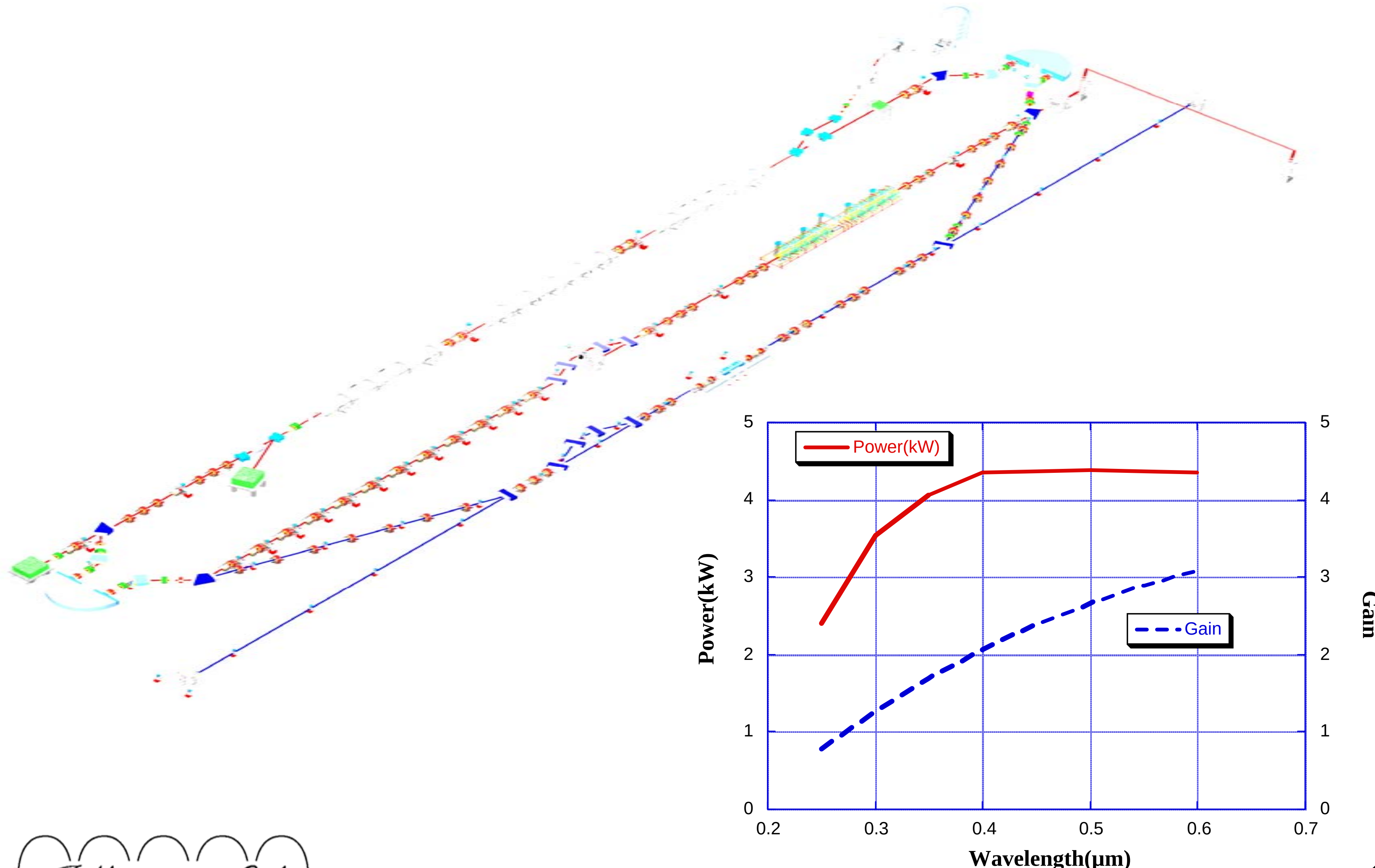


Neil, G. R., *et. al, Physical Review Letters,* **84,** 622 (2000)

FEL Accelerator Parameters

Parameter	Designed	Measured
Kinetic Energy	48 MeV	48.0 MeV
Average current	5 mA	4.8 mA
Bunch charge	60 pC	Up to 135 pC
Bunch length (rms)	<1 ps	0.4±0.1 ps
Peak current	22 A	Up to 60 A
Trans. Emittance (rms)	<8.7 mm-mr	7.5±1.5 mm-mr
Long. Emittance (rms)	33 keV-deg	26±7 keV-deg
Pulse repetition frequency (PRF)	18.7 MHz, x2	18.7 MHz, x0.25, x0.5, x2, and x4

IR FEL Upgrade



IR FEL 10 kW Upgrade Parameters

Parameter	Design Value
Kinetic Energy	160 MeV
Average Current	10 mA
Bunch Charge	135 pC
Bunch Length	<300 fsec
Transverse Emittance	10 mm mrad
Longitudinal Emittance	30 keV deg
Repetition Rate	75 MHz

Conclusions

- Recirculated linacs used for Nuclear Physics research or as driver accelerators for FELs and synchrotron radiation sources benefit from cw or high duty factor operation.
- CW or high duty factor operation at higher gradients/high currents practically necessitates the use of superconducting cavities.
- RF superconductivity applied to particle accelerators has made tremendous progress in the last ~ 30 years.
- Major srf limitations due to multipacting, thermal breakdown, and field emission have been understood and successfully combated to a large extent.
- CW operation at higher gradients (> 20MV/m) and higher average currents yet (~100 mA), is the new challenge rf superconductivity is facing!