Current-Dependent Effects in Muon Acceleration

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Basic Parameters

- Accelerate from 90 GeV to 4 TeV in 2 stages
  - 90 GeV to 600 GeV
  - 600 GeV to 4 TeV
- One bunch each sign
- 2×10^{12} per bunch
  - Will discuss lower charge
- $\sigma_z = 3$ mm throughout

ILC Accelerating Structures

- Assume ILC accelerating structures
- No bunch trains, can pick frequency
- SCRF: don't win at higher frequency

ILC Accelerating Structure

Frequency	1.3 GHz
Cells	9
Active Length	1038 mm
Structure Length	1384 mm
R/Q	1036 Ω
Loss factor ($\sigma_z = 1$ mm)	9.24 V/pC
Iris diameter	70 mm
Nominal Gradient	31.5 MV/m
Max Energy Gain ($v = c$)	32.7 MeV
Stored Energy	126 J

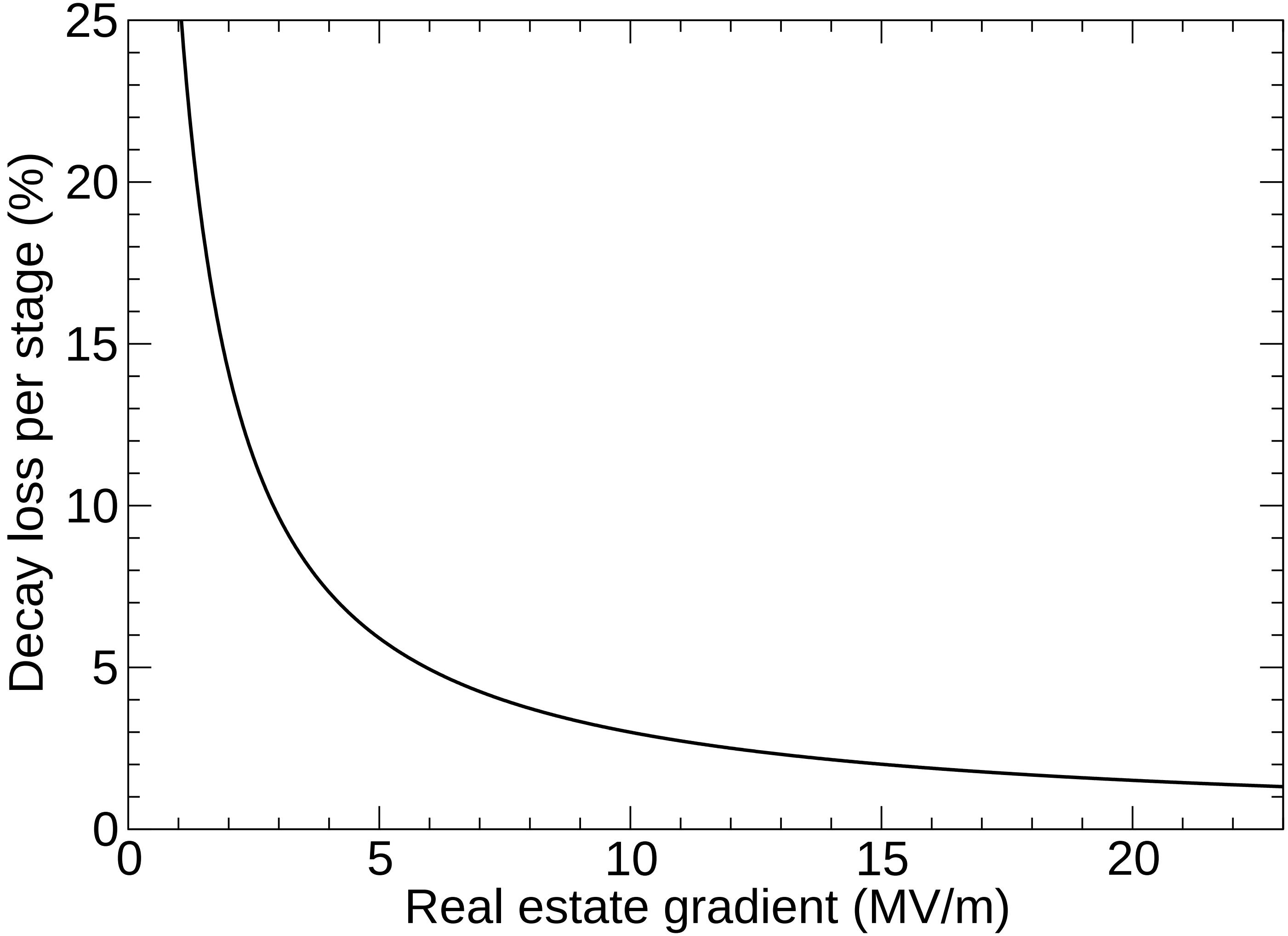
Decay

- Assume constant accelerating gradient V

$$\frac{N}{N_0} = \left(\frac{E + \sqrt{E^2 - (mc^2)^2}}{E_0 + \sqrt{E_0^2 - (mc^2)^2}}\right)^{-\frac{mc^2}{qVc\tau}}$$

- Factor in energy gain determines decay
- Decays are relatively modest
  - With decent real estate gradient ($>$ 4 MV/m)
  - Above 10 MV/m little is gained

Decays vs. Gradient



Passes through RF

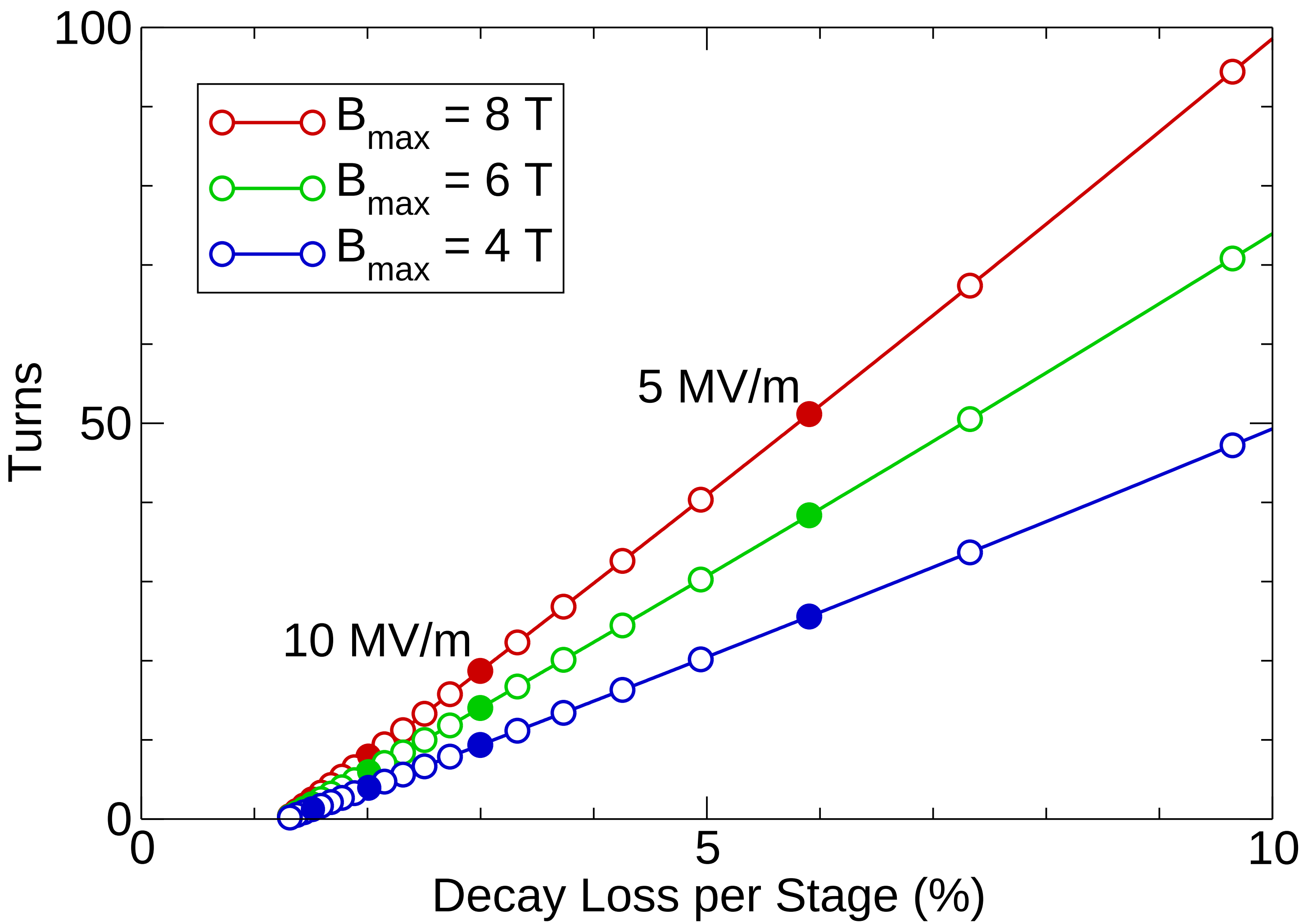
- More passes through RF cavities is better
- Fewer structures
  - Less hardware cost
  - Lower static cryogenic load
- More efficient with RF power
  - Energy cavity initially filled with
  - Lower dynamic cryogenic load

Passes through RF

$$n = \frac{1}{2\pi}\frac{\Delta E}{p_{\mathrm{max}}c}\frac{B_{\mathrm{avg}}c}{V_{\mathrm{avg}}}$$

- Tradeoff in fractional space usage
- Higher average gradient
  - Larger fraction of ring occupied by cavities
  - Lower average magnetic field (longer ring)
  - Fewer decays
  - Fewer turns

Turns vs. Decay Loss



Beam Loading

- Definition: reduction in amplitude of accelerating voltage by beam
  - Cavity stored energy transferred to beam
- Beam loading is *good*
  - Otherwise stored energy is wasted
- Many turns: must replace lost energy
  - Requires RF power

Beam Loading: Straight Linac

- At 3 Hz, 7.7 MW in the beams
  - Independent of charge for fixed luminosity
- Two linacs: 90 MW of RF stored energy
  - Increases with repetition rate
  - Fixed luminosity, increase rep rate if charge goes down
  - Wall plug some factor higher. . .
- Not to mention 240,000 ILC structures. . .

Replacement RF Power

- Each bunch extracts 10.5 J (out of 126 J)
- Many passes, must replace lost energy
- Peak power challenging
  - Directly impacts klystron cost
  - Limitation of input coupler?
- Longer circumference, less power required
- Less charge, less power required

Replacement RF Power Example Numbers

- Low energy ring

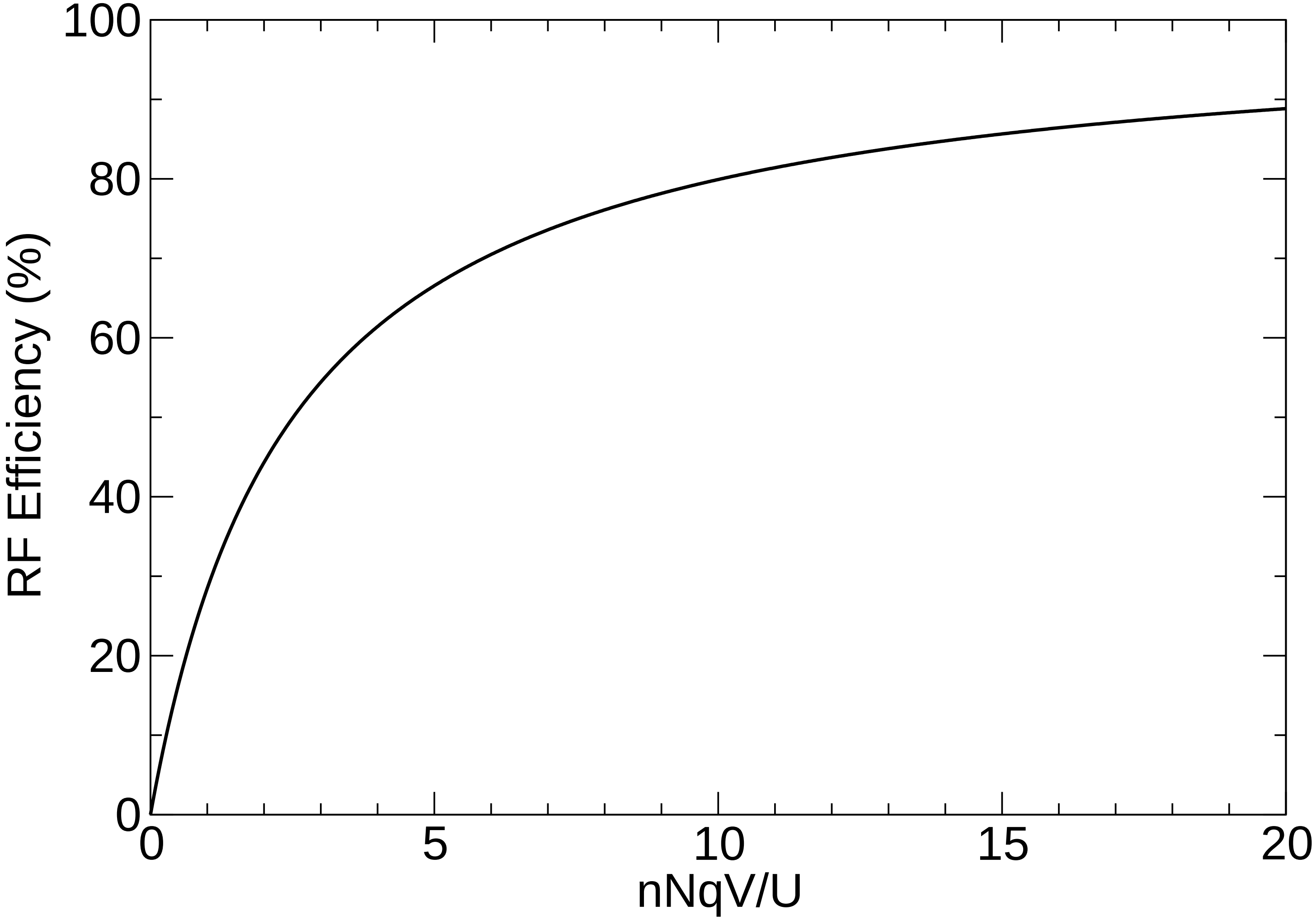
V_{avg} (MV/m)	B_{max} (T)	Power (MW)
5	4	1.58
10	4	1.15
5	8	3.15
10	8	2.30

- These powers are high for input coupler
  - Cavities with fewer cells
- 6.67 times lower for high energy: reasonable

RF Power Efficiency

- RF power efficiency depends product of
  - Number of turns
  - Fractional energy extraction
    - 16.6% my numbers
- Product ideally around 4 (24 turns)
- Lower charge
  - Efficiency more important (higher rep rate)
  - More turns to get good efficiency

RF Power Efficiency



“Higher Order Mode” Losses

- Characterized by loss factor
- Short bunches: proportionally to inverse square root of bunch length
- Single pass
  - 1.07 MV average energy loss
  - Also half energy spread
  - Out of 32.7 MeV energy gain
- Additional nonlinear effects
- Can lead to instabilities

“Higher Order Mode” Losses Compensation

- Run off-crest to compensate
  - 12° is sufficient
- Allow to generate RF slope
  - Synchrotron oscillations desirable
  - Naturally in right direction
- Nonlinearities will mess this up
  - Emittance growth
- Need inductive impedance also

“Higher Order Mode” Losses Instabilities

- Haven’t studied very much
- Synchrotron tune in principle very high
  - Stabilizes short-range instabilities
- Talking about small number of turns
  - 25 or so
  - Typical instability growth times: 10^4 turns or more
  - But normally not so much impedance

RF Frequency Adjustment

- Time of flight depends on energy
  - Except for RLAs
- Adjust RF frequency to match
  - Synchrotron, low energy, $Q_L \approx 1.5 \times 10^6$: OK
  - Don's hybrid, $Q_L \approx 4 \times 10^4$: No
  - Scaling FFAG, low E, $Q_L \approx 1.4 \times 10^3$: No
  - Scaling FFAG, high E, $Q_L \approx 6.5 \times 10^5$: Maybe

RF Frequency Adjustment Ideas

- Refine hybrid designs to reduce time variation
- R&D on frequency shifting
- Use RLAs
  - Polygon shape: more synchrotron oscillation
  - Poor efficiency
- FFAG/RLA hybrid?
- Low current: linac-like accelerating mode
  - Semi-isochronous FFAGs

Conclusions

- Decays small if average gradients above 10 MV/m
- RF power efficiency comes from more turns
  - Bigger problem with smaller currents
  - Higher fields always help
- "Higher order mode" losses significant
  - Biggest problem: longitudinal emittance growth from potential well distortion
  - Instabilities likely OK, but check

Conclusions

- Biggest problem is time of flight variation
- Polygon-shaped RLA is ideal solution
- Low currents avoid short range wakes
  - Can consider linac-like accelerating modes