Superconducting RF in the Cornell University Energy Recovery Linac

- Challenges and Solutions -

Matthias Liepe

Cornell University

- **ERL Light Source: Why?**
- **The Cornell ERL: An Overview**
  - **Prototype**
  - **5 GeV SR Source**
- **SC RF in the Cornell ERL Injector**

  - Challenges and Solutions -
- **SC RF in the Cornell ERL Main Linac**

  - Challenges and Solutions -
- **Outlook and Summary**

Today's Workhorse Light Sources: Storage Rings

- **1st generation**
  parasitic SR on high energy physics storage rings
- **2nd generation**
  dedicated bending magnet sources, designed for high flux SR
- **3rd generation**
  dedicated undulator sources optimized for brilliance, using high current, low emittance

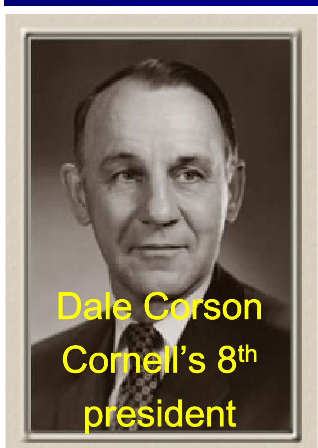
Some rings use superconducting RF

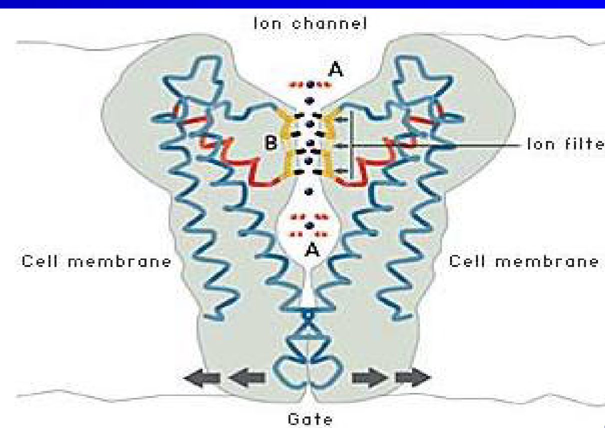
Storage ring light sourses give:

- **Repetition rate**
- **Stability**
- **High flux, brilliance – average/peak**

Synchrotron Radiation at Cornell

- 1952: 1st accurate measurement of synchrotron radiation power by Dale Corson with the Cornell 300MeV synchrotron.
- 1953: 1st measurement of the synchrotron radiation spectrum by Paul Hartman with the Cornell 300MeV synchrotron.
- Worlds 1st synchrotron radiation beam line (Cornell 230MeV synch.)
- 1961: 1st measurement of radiation polarization by Peter Joos with the Cornell 1.1GeV synchrotron.
- 1978: X-Ray facility CHESS is being build at CESR
- 2003: 1st Nobel prize with CESR data goes to R.MacKinnon



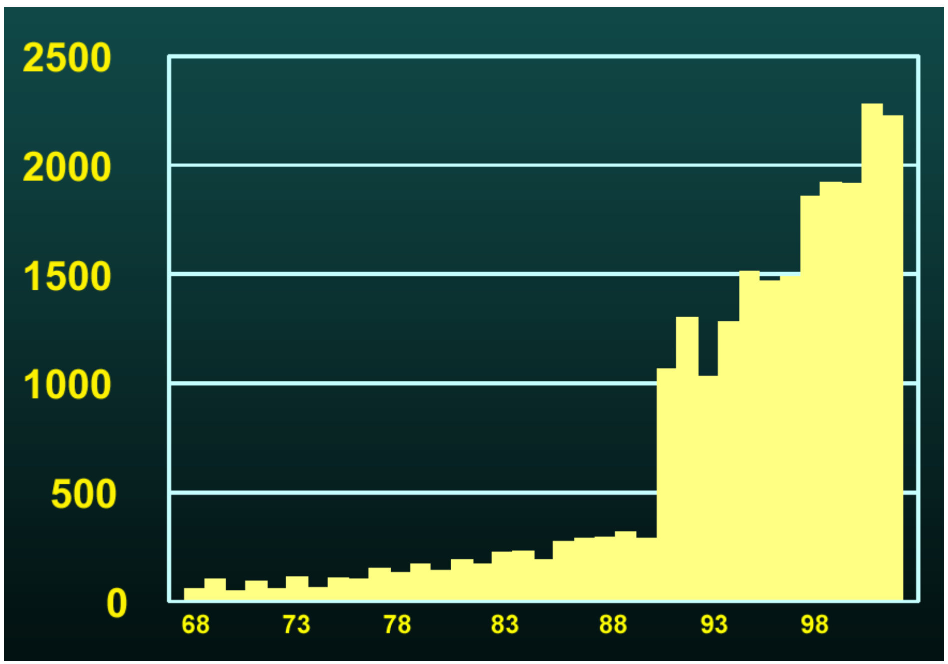


Roderick MacKinnon

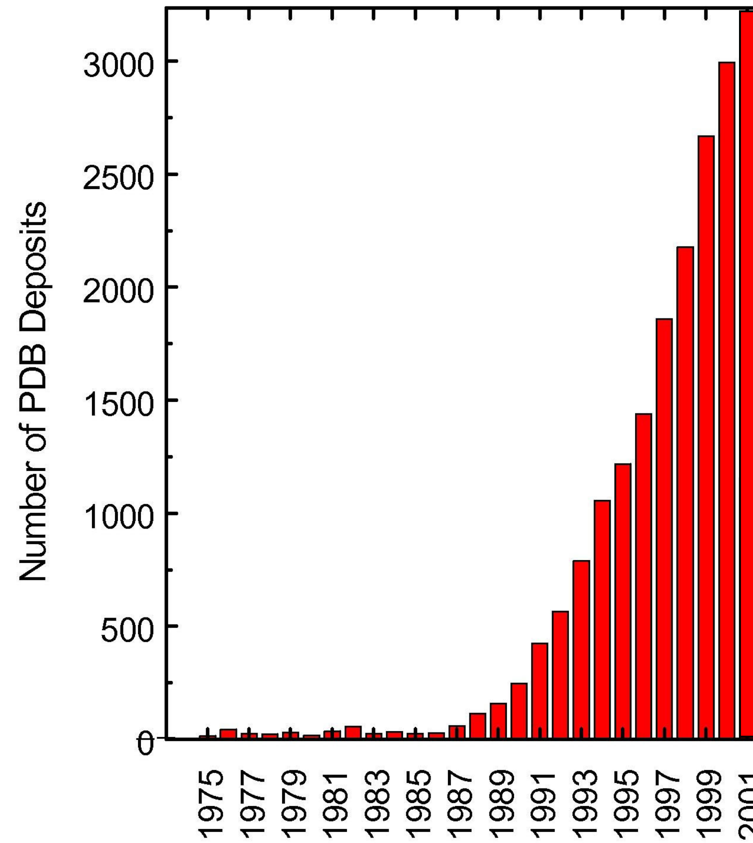
More Users…

Historical Growth of Synchrotron Publications Worldwide: ISI data 1968 to 2002, Keyword: "synchrotron"

(from G. Margaritondo)



Protein structures in Protein Data Bank (Mostly from SR)



… More Demands: What do we need in the future?

1. High average and high peak

- Brilliance (photons/s/0.1% bw/mrad^2/mm^2)
- Flux (photons/s/0.1% bw)

2. Coherence

3. Flexible pulse structure

- Programmable pulse trains (interval, bunch size)
- Adjustable pulse lengths down to the femtosecond regime

3. Small x-ray source size of desired shape, e.g. circular

4. Flexibility of source operation

- No fill decay
- Stability & robustness
- Easily upgraded

→ FEL   ERL

Important Beam Parameters: A Wish List

Low emittance

- Decreasing the electron beam emittance down to diffraction limit

$$\varepsilon_x < \frac{\lambda}{4\pi} \sim 10^{-11}\,mrad \left(\lambda \sim 1\,\mathring{A} \right)$$

Long undulator

Low energy spread

Short bunches

- High spectral brilliance SR sources

$$B \propto 1/\varepsilon_x \varepsilon_y \tau$$

- High coherence fraction:

$$p_c = \lambda^2/(4\pi)^2 \varepsilon_x \varepsilon_y$$

High beam current

High flux

$$F \propto I_{beam}$$

How do we get these Beam Parameters?
Limits of Storage Rings

- Electron beam emittance, bunch profile and energy spread in a storage ring is determined by equilibrium between radiation damping and two main diffusion processes:

  - quantum fluctuation of the SR and

  - the intrabeam scattering.

⇒ There is no (affordable) way to decrease the horizontal emittance in storage ring $\varepsilon_x < 10^{-10}$ m·rad and energy spread $\sigma_E/E < 10^{-3}$.

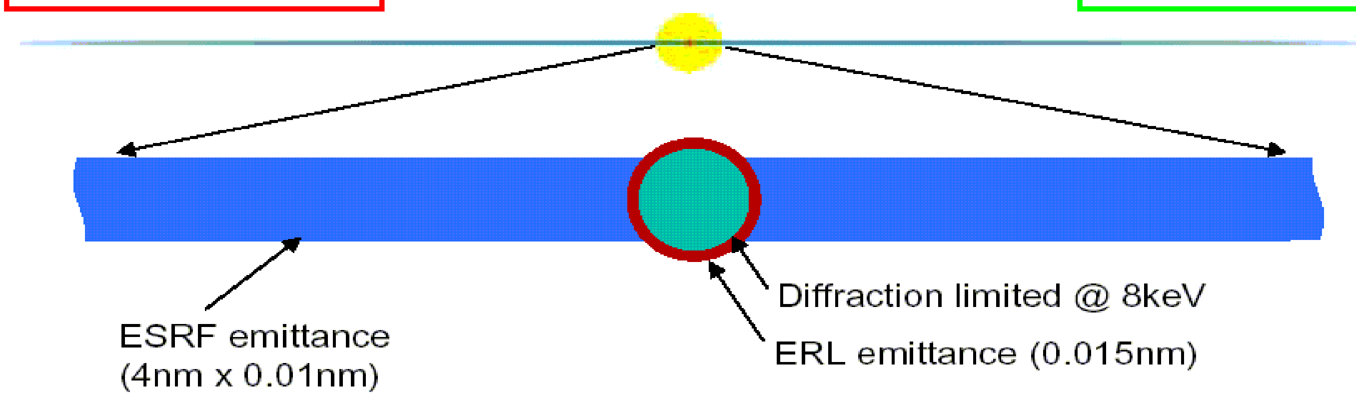
- Beam lifetime limits bunch length to about 10 ps. Too long for many dynamic processes.
- Technology well developed. Theoretical limits are being approached.
- Time structure cannot be tailored to user needs.
- Fills are necessary, intensity is not constant.

⇒ Equilibrium dynamics determines almost all the parameters on our wish list!

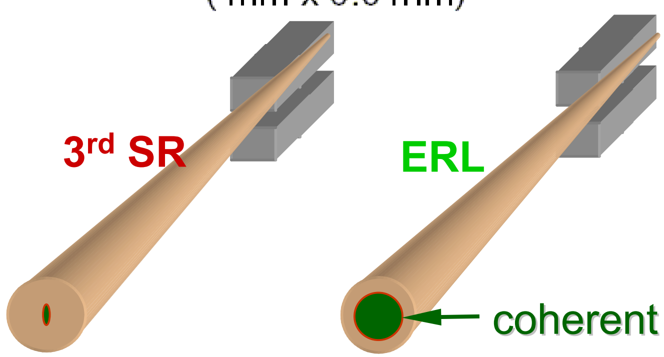
How do we get these Beam Parameters?
The Alternative: Linacs

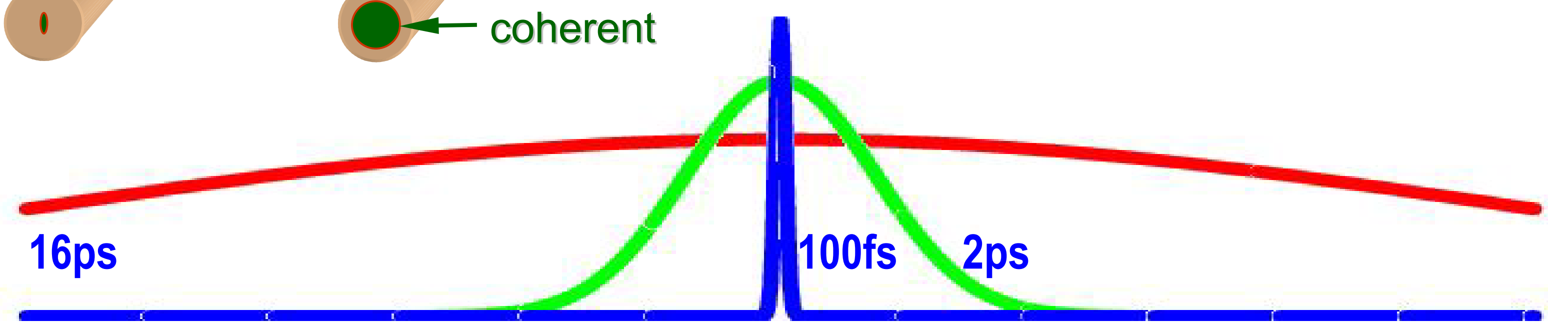
- **Injectors can be built with very brilliant e- beams and linacs can accelerate with very low emittance growth (if we do it right).**
  - **Emittance & pulse length determined by injector.**
  - **Single pass non equilibrium device.**
  - **Easy upgrade path: Better e^- source gives higher brilliance.**
  - **Due to adiabatic damping an emittance $\varepsilon \sim 10^{-11}$ m·rad and energy spread $\sigma_E/E \sim 10^{-4}$ is possible for energies $E > 5$ GeV.**
  - **Potential for ultra high brilliance.**
- **Complete flexibility of bunch timing.**
- **No fill decay, constant intensity.**
- **Electron bunches dumped after single pass.**

The Alternative: Linacs
Small Beam Size, Coherence, Short Bunches



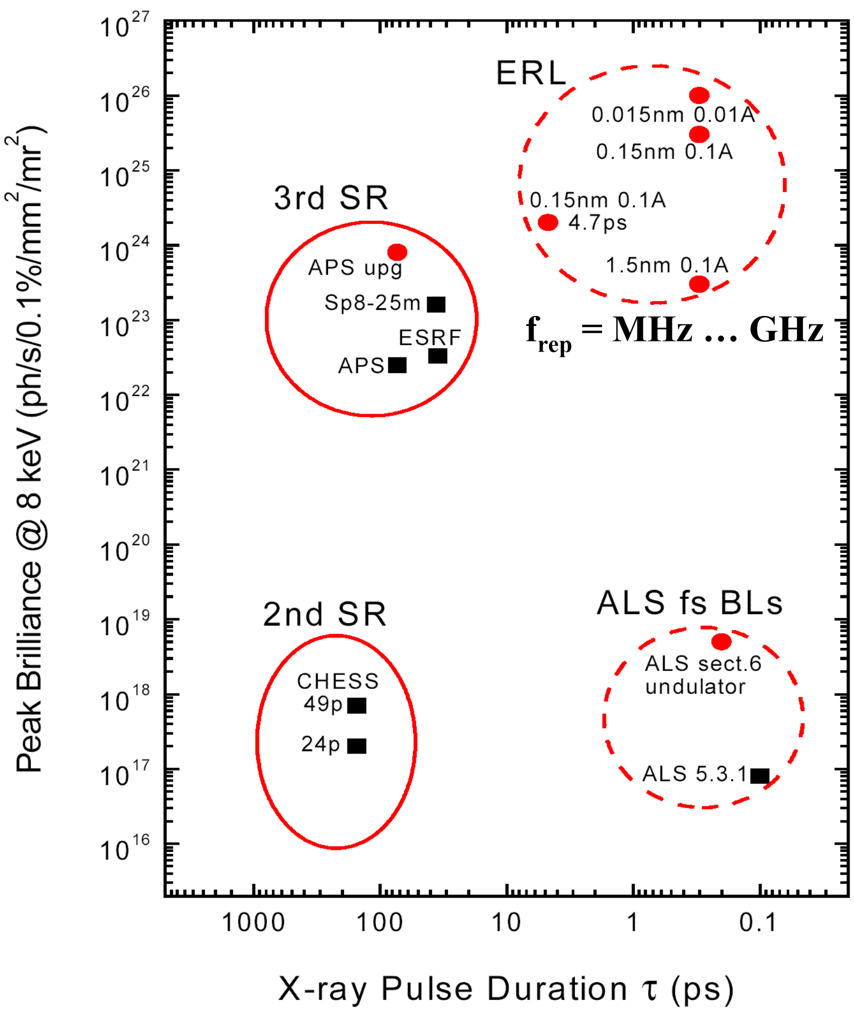
Factor 100 more coherent flux for ERL for same x-rays, or provide coherence for harder x-rays



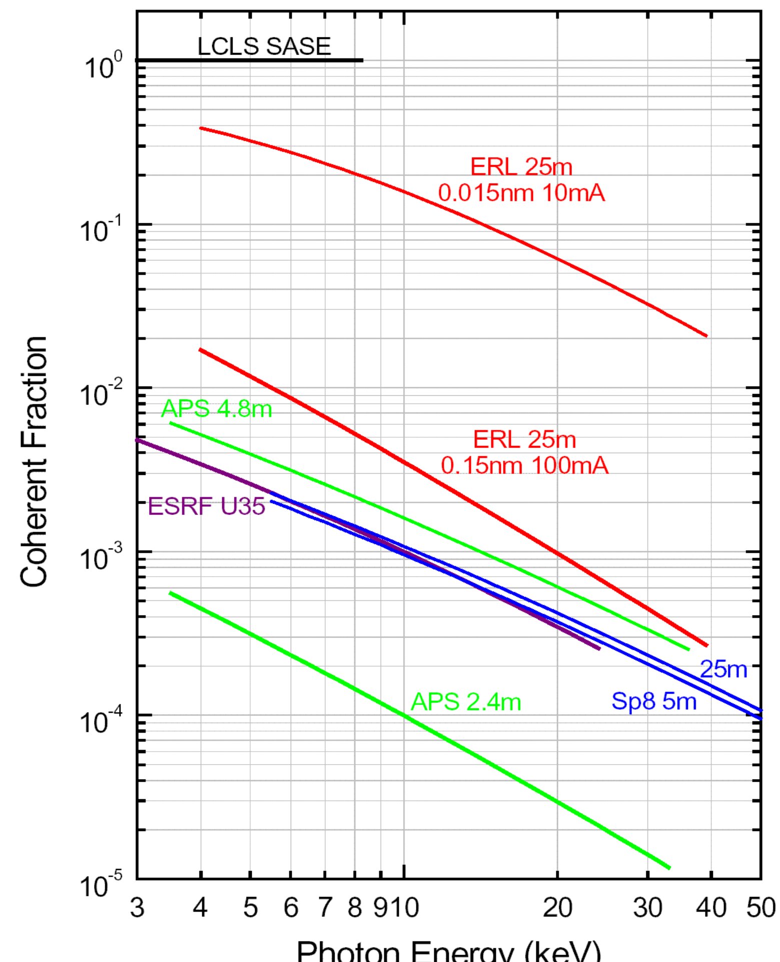


Linac Light Source: X-Rays Studies in New Regimes

Short pulses, high brilliance:



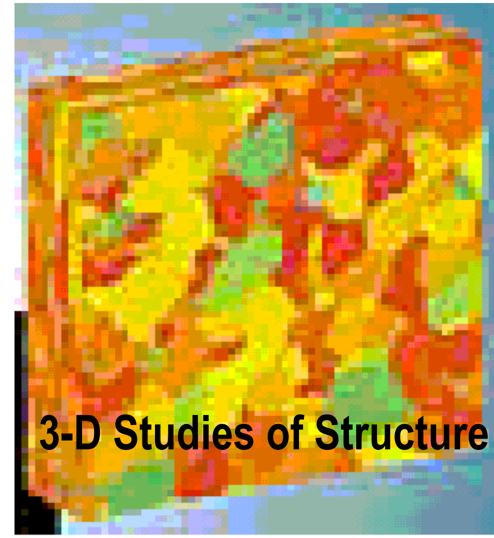
High coherent fraction:



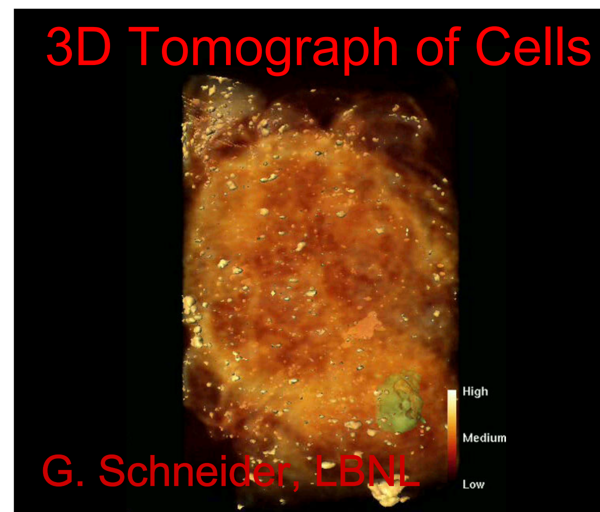
plots from Q. Shen

Linac Light Source: X-Rays Studies in New Regimes

- **Smaller beams lead to better spatial resolution (currently sub mm)**
  - ERL: 100 to 1000 times smaller area
- **Smaller emittance leads to high brilliance.**
  - ERL: 10 to 1000 more brilliance.
- **Shorter bunches allows much higher time resolution.**
  - ERL: 100 times shorter bunches



Field museum of Chicago & APS, Argonne National Lab.

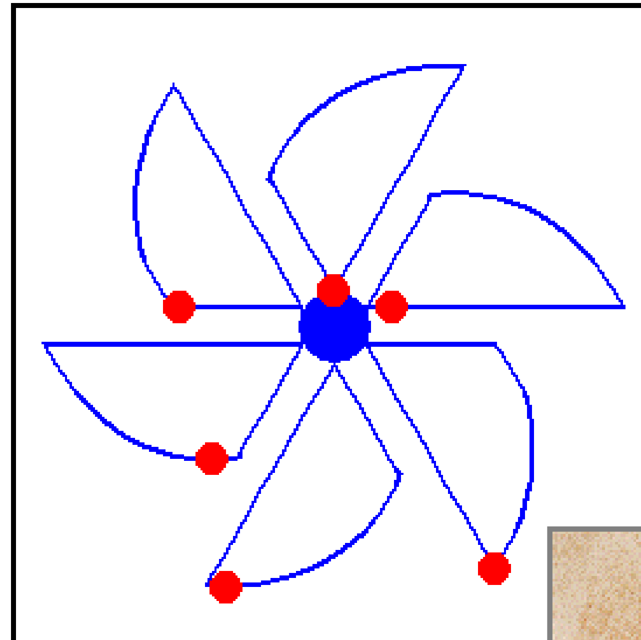


Linac Light Sources: How to get high currents?

- **High photon flux ⇒ need high current**
- **But: With a simple linac you'd go broke!!**
- **Example: 5 GeV * 100 mA = 500 MW**

⇒ The energy of the spent beam has to be recaptured for the new beam.

Previous Energy Recovery Machines

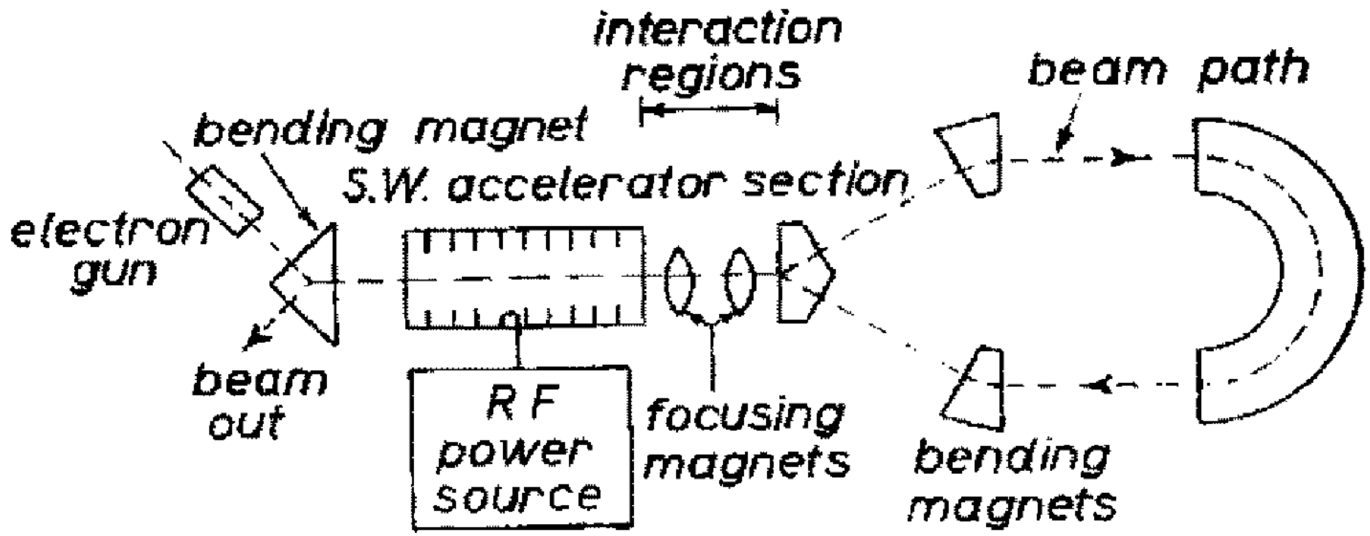


Leonardo da Vinci

(1452-1519)

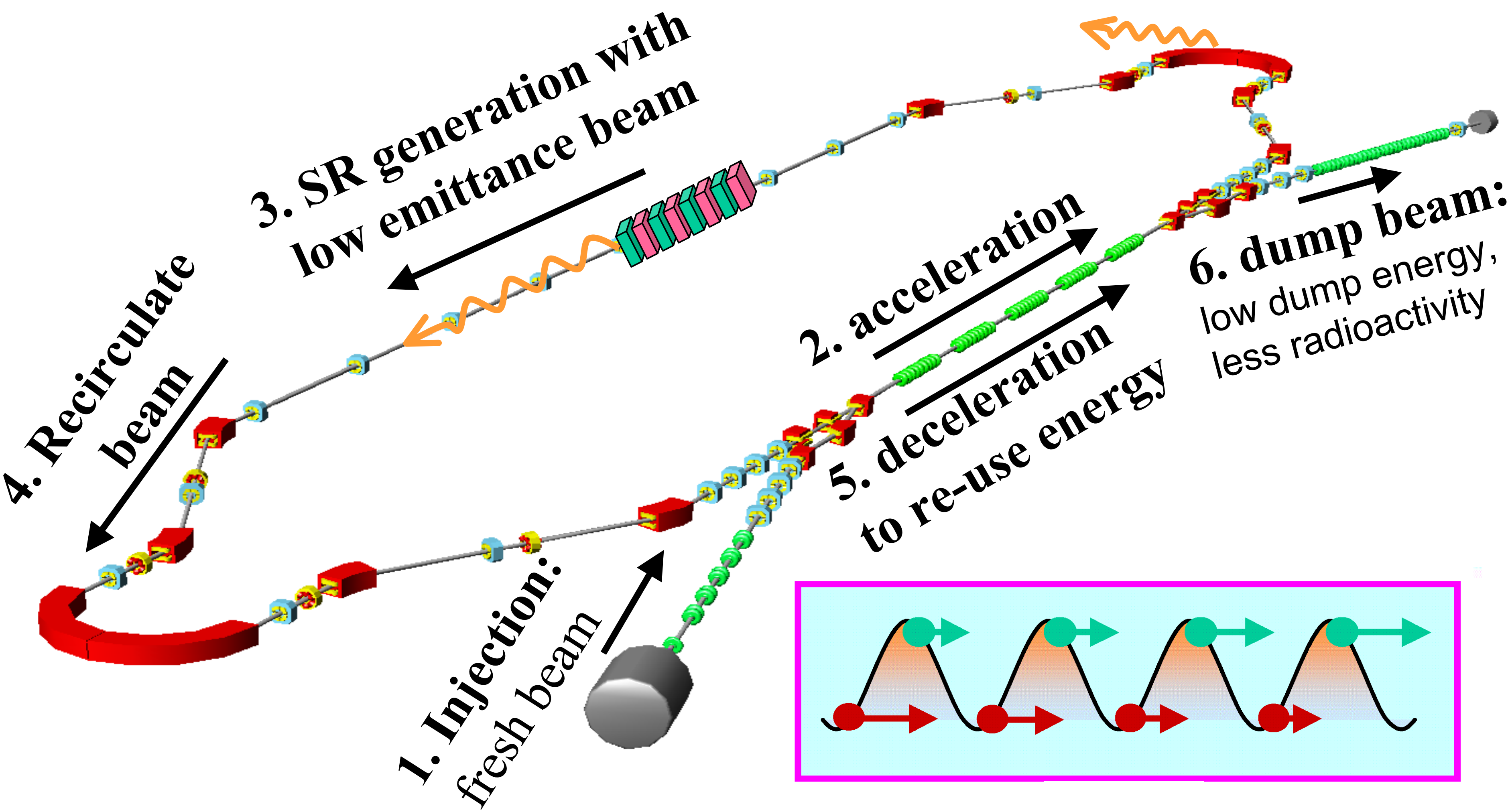
Linac Light Sources: How to get high currents? The Energy-Recovery-Linac

Solution: Use energy recovery. First proposed by M. Tigner in 1965.



- *Re-use energy of beam after SR generation.*
- *Recirculate beam and pass it through the linac a second time, but 180 deg. out of phase to decelerate beam.*
- *⇒ "Energy Storage Ring" but not "Beam Storage Ring".*

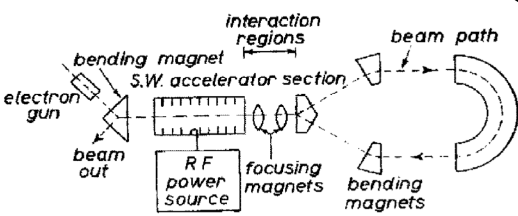
ERLs: What is the trick?

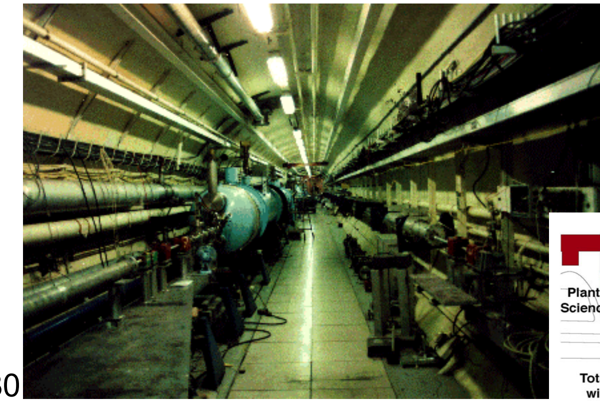


ERLs Worldwide (FEL-ERLs and SR-ERLs)

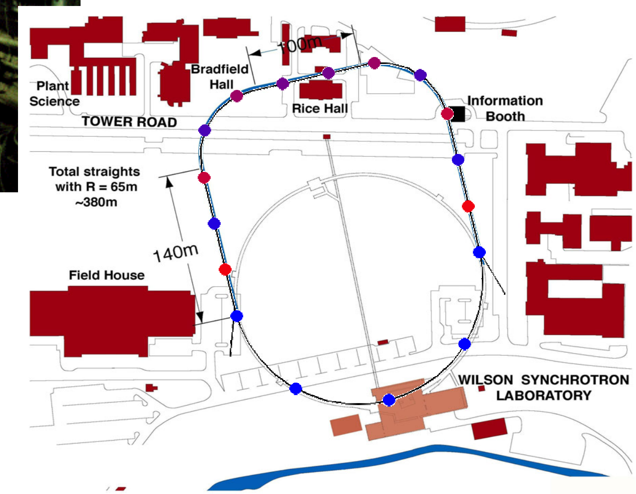
1960
1970
1980
1990
2000

M. Tigner, 1965

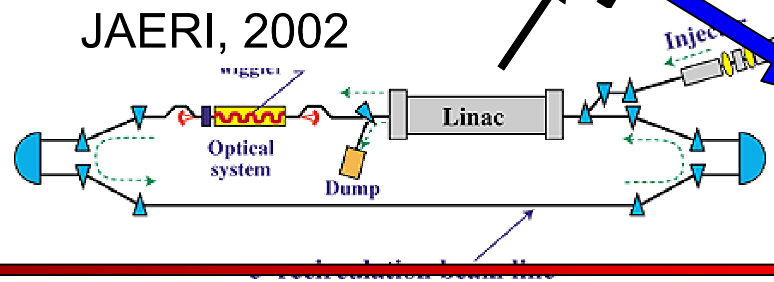




SCA, Stanford, 1986



S-DALINAC, 1990
IR FEL Jlab, 1999
JAERI, 2002



Cornell ERL
LUX (LBL)
PERL (NSLS)
4 GLS (Daresbury)
KEK
…

ERL Linacs: Why Superconducting Cavities?

SRF linacs can deliver beams of superior quality:

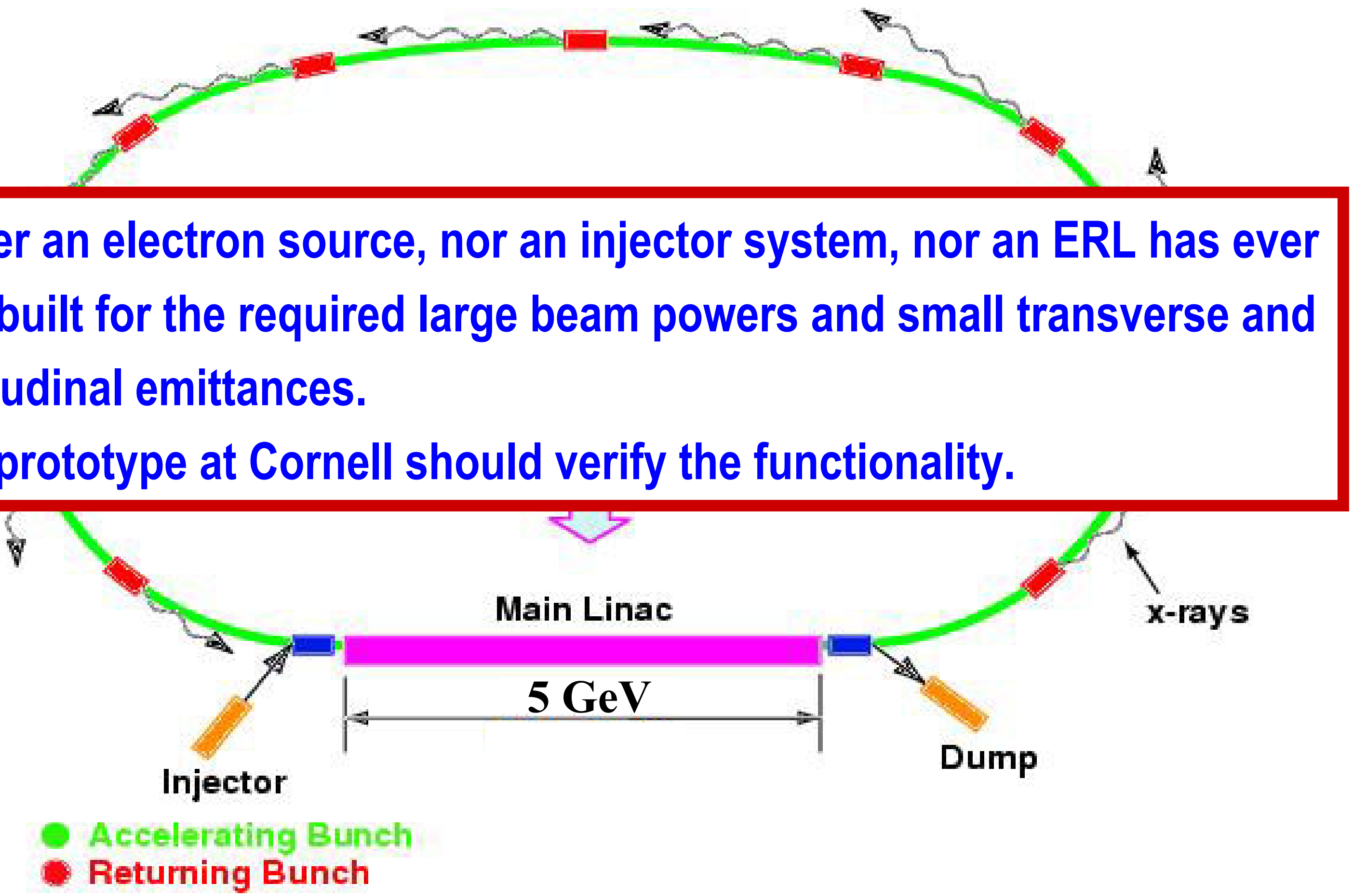
- **Smaller emittance (lower impedance) $\Rightarrow$ higher brilliance**
- **Better RF control and stability $\Rightarrow$ lower energy spread**
- **CW operation at high gradient $\Rightarrow$ flexibility in pulse train, lower impedance, cost saving**

In addition, SRF gives

- **Higher power conversion efficiency**
- **ERL option (very low wall losses) $\Rightarrow$ high beam current, high flux**

ERL @ Cornell

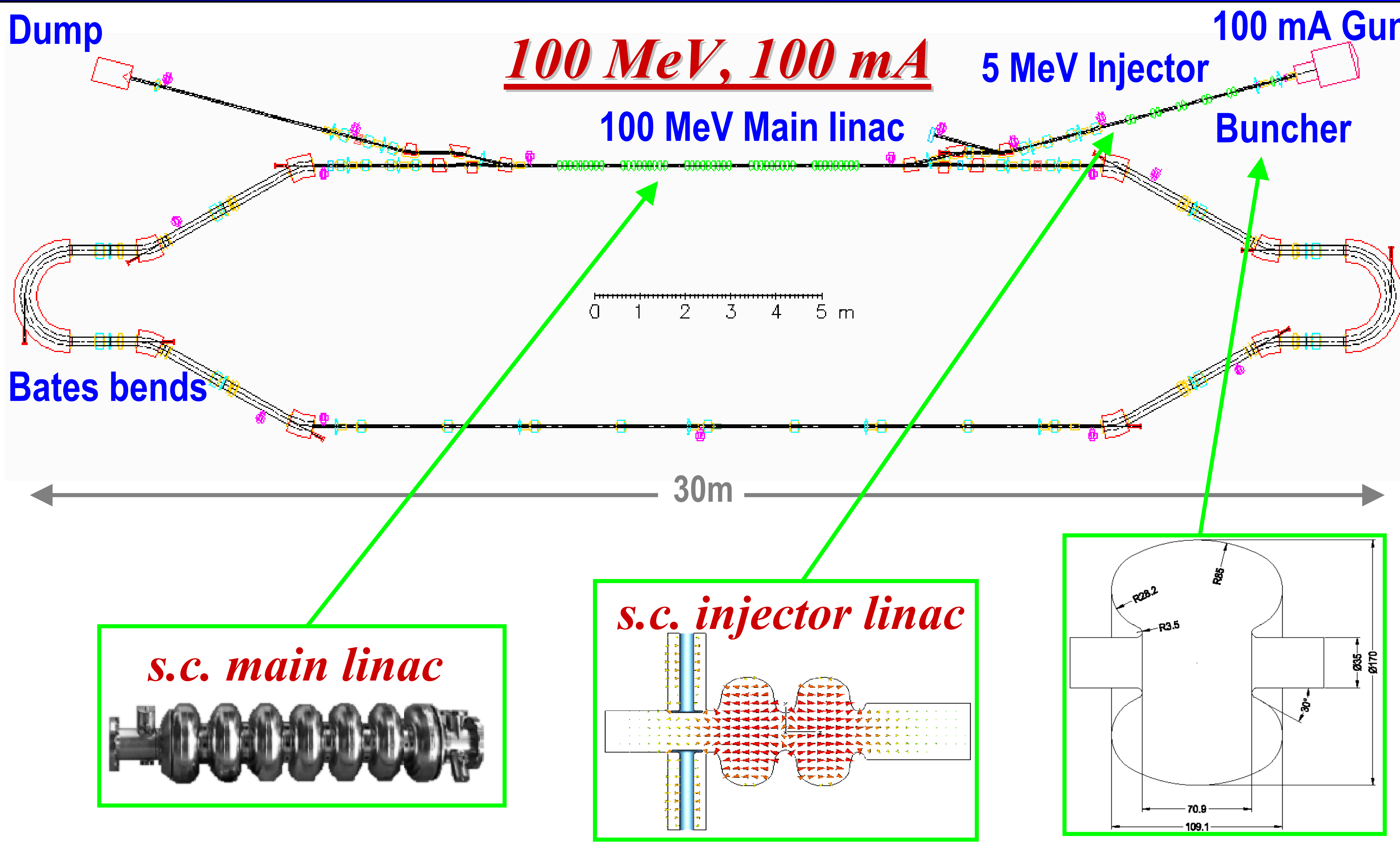
5 GeV, 100 mA



Neither an electron source, nor an injector system, nor an ERL has ever been built for the required large beam powers and small transverse and longitudinal emittances.

→ A prototype at Cornell should verify the functionality.

Cornell ERL: Phase 1, the Prototype



Cornell ERL Prototype: SRF Parameter

	ERL buncher cavity	ERL s.c. injector cavities	ERL s..c. main linac cavities
frequency [MHz]	1300	1300	1300
number of cavities	1	5	7
cells per cavity	1	2	7
R/Q [Ω] (circuit def.)	105	109	392
Q_0	20,000	$> 5 \cdot 10^9$	$> 10^{10}$
Q_{ext}	9,900	$4.6 \cdot 10^4$ ($4.1 \cdot 10^5$)	$2.6 \cdot 10^7$ for 25 Hz peak detuning
acc. voltage per cavity [MV]	0.12	1 (3)	≈ 16 (20 MV/m)
required klystron power per cavity [kW]	7	130	11
required relative amplitude stability (rms)	$8 \cdot 10^{-3}$	$1 \cdot 10^{-3}$	$3 \cdot 10^{-4}$
required phase stability (rms)	0.1°	0.1°	0.06°

Initial idea

Laboratory of Elementary Particle Physics, Cornell University

June, 2002 ERL 02-6

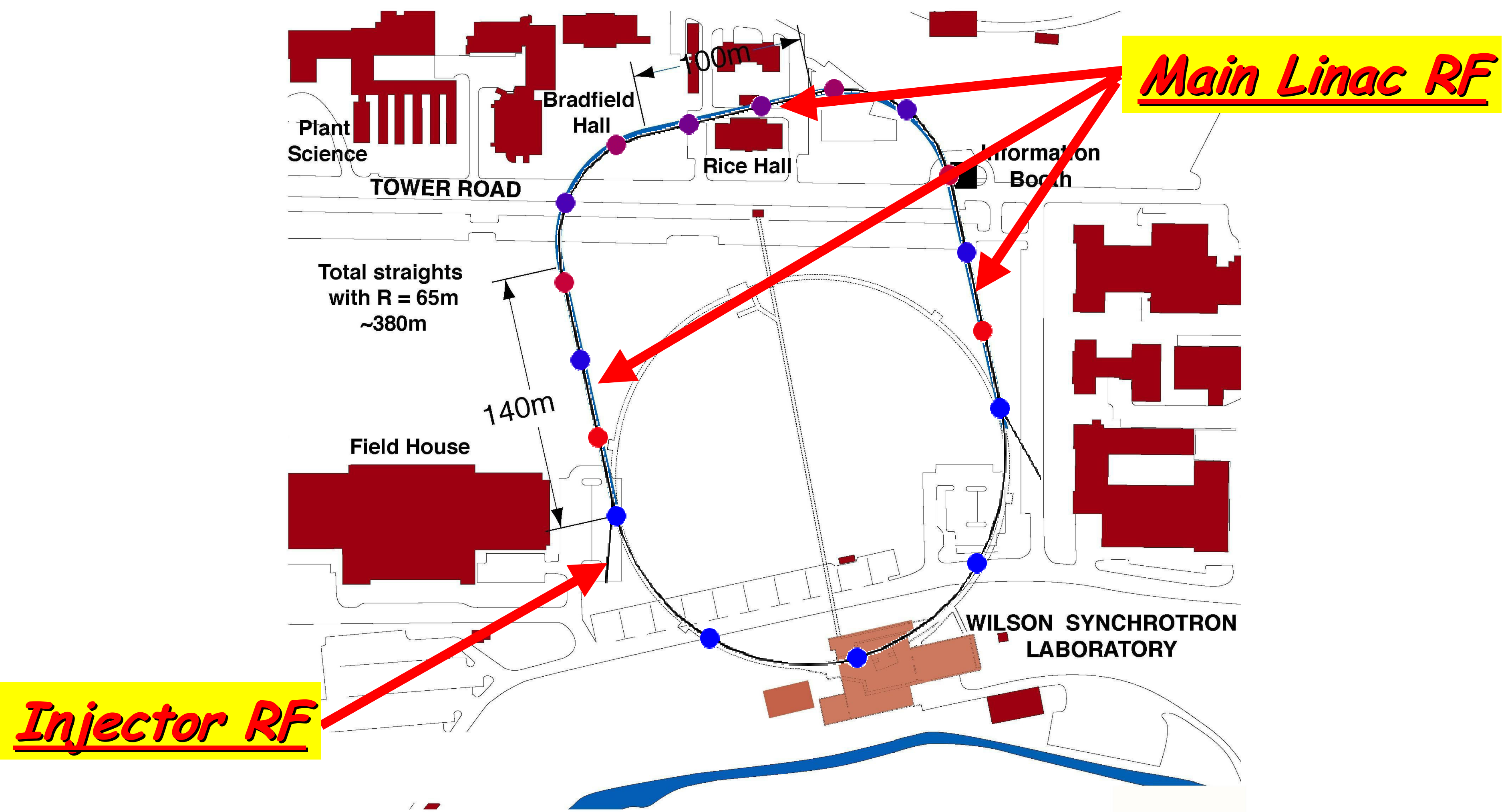
Energy Recovery Linac in the Wilson Tunnel

Richard Talman

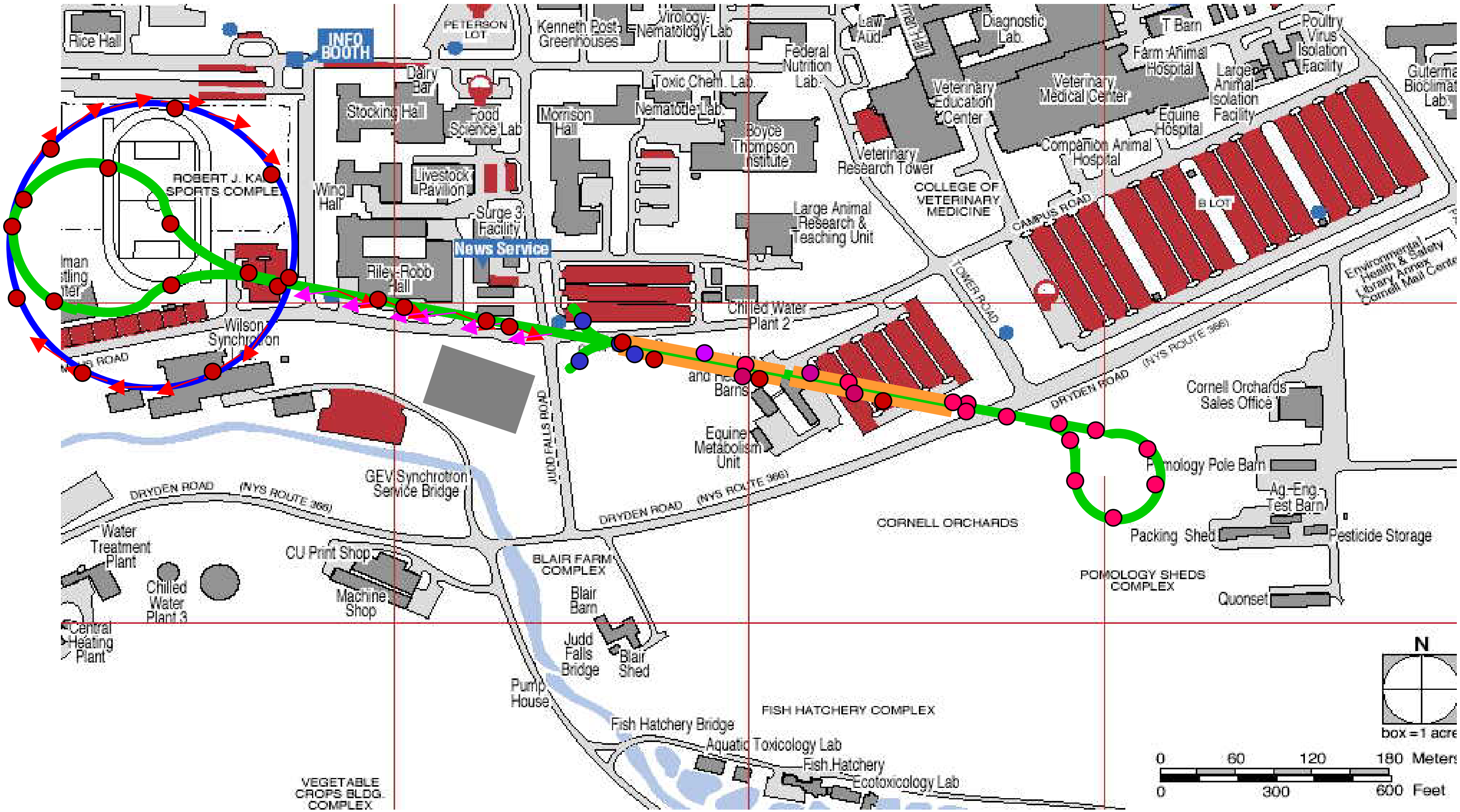
ABSTRACT

This is a brief discussion of two out of the many modifications that will be needed to retrofit the Wilson laboratory as an energy recovery linac (ERL). The two issues are: fitting the facility within the existing site boundaries; and designing the approximately isochronous yet adjustable arcs needed to transport ultrashort bunches.

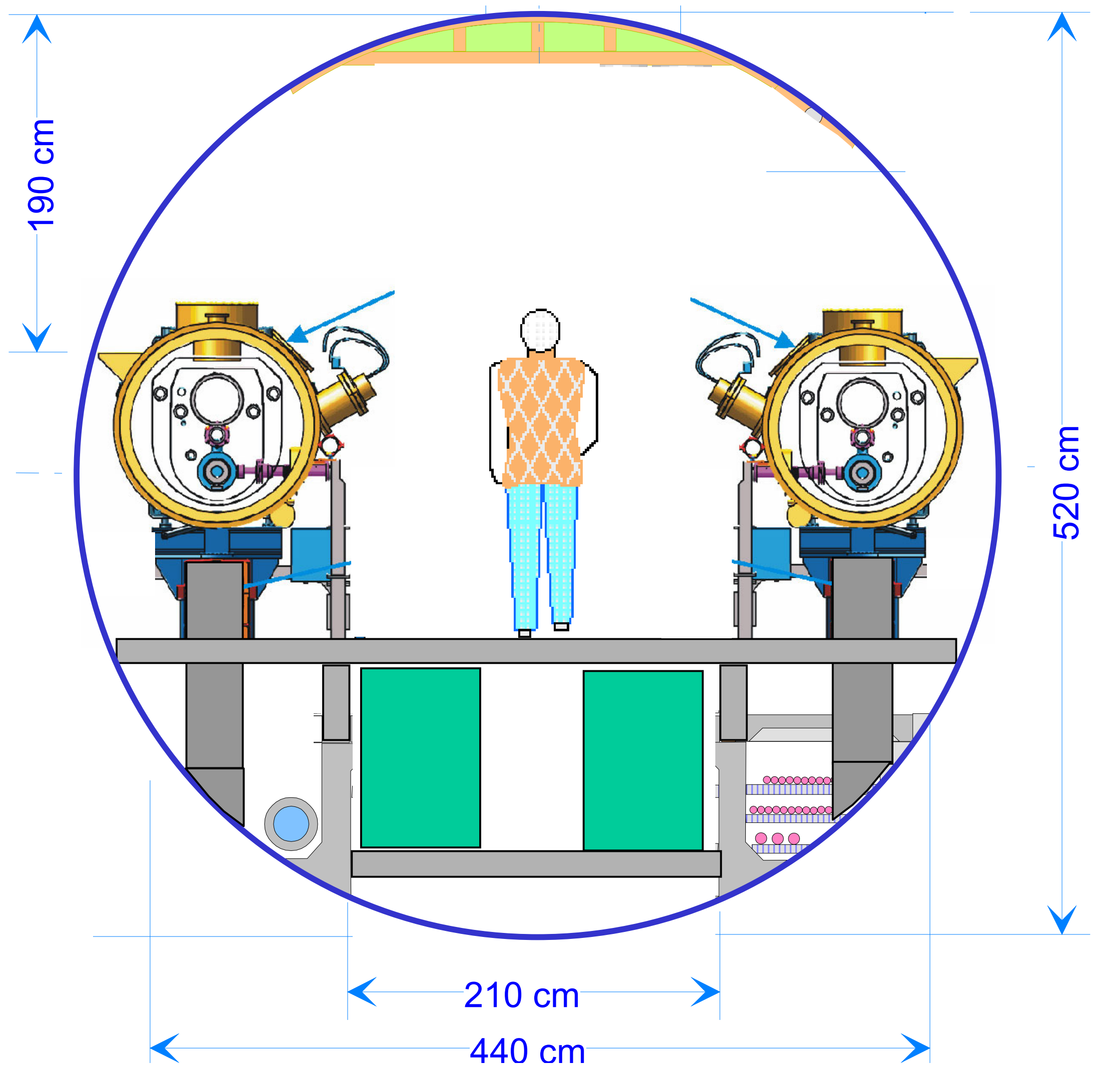
Phase 2: Cornell ERL @ CESR



Cornell ERL @ CESR: Work in Progress



Main Linac Tunnel with Two Linacs



Injector SRF

Cornell ERL Injector RF Challenges

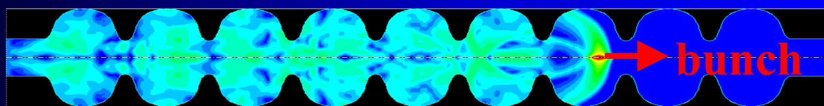
- **High RF power transfer to beam for acceleration of high current beam ⇒ input coupler challenge**

  1 MeV per cavity * 0.1 A = 100 kW!

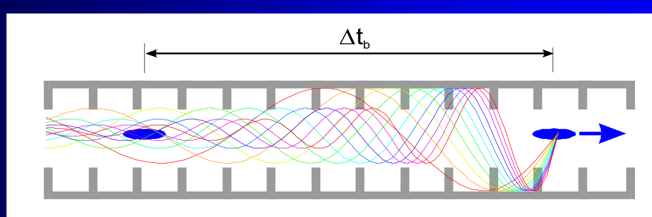
- **Strong damping of HOMs essential for beam stability and to reduce monopole power.**
- **Emittance preservation ⇔ space charge, small transverse kick fields**

Low Emittance Preservation in a Linac

Wakefields:

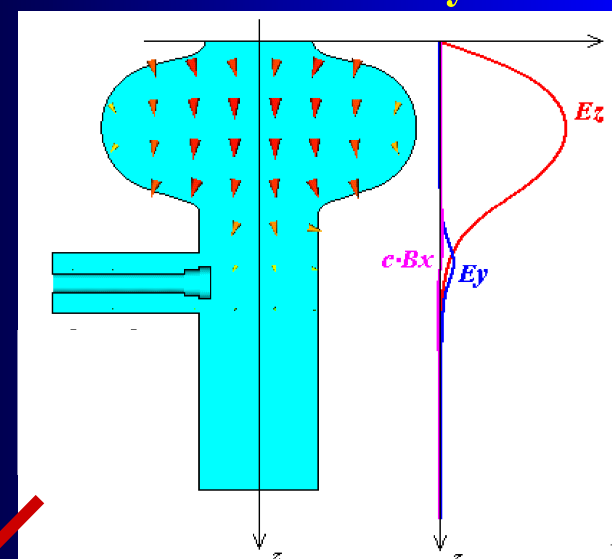


- longitudinal wakes generate energy spread
- transverse wakes generate time dependent kick fields $\Rightarrow$ transverse emittance growth



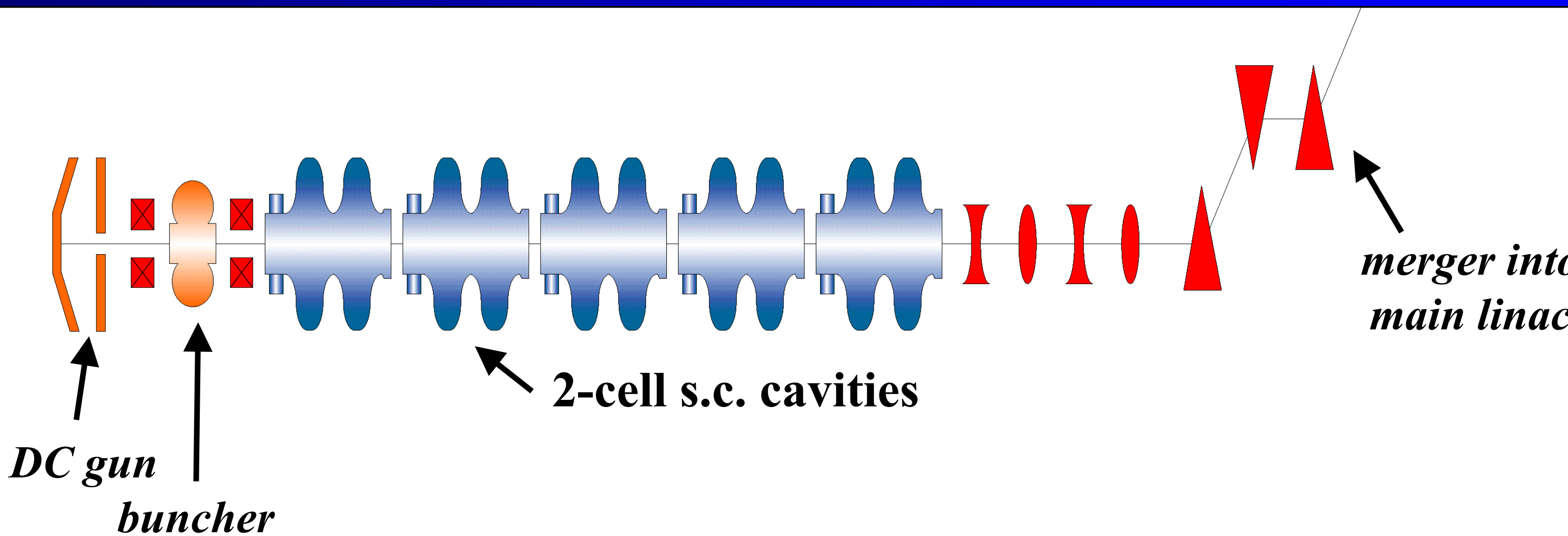
Coupler kicks:

- Rotation asymmetry of input coupler and HOM coupler generates time dependent transverse kick fields on the cavity axis



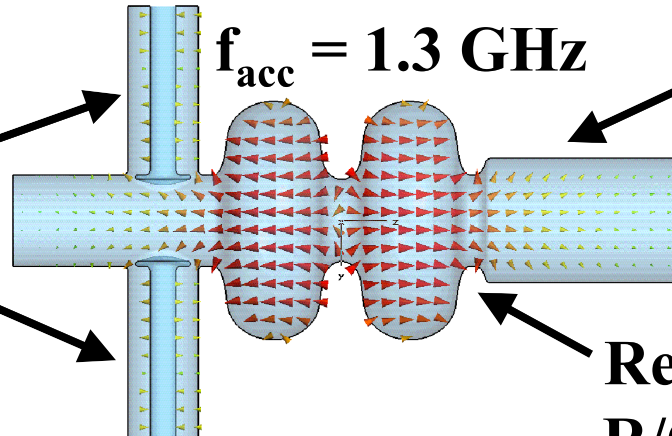
Space Charge → **Emittance growth**

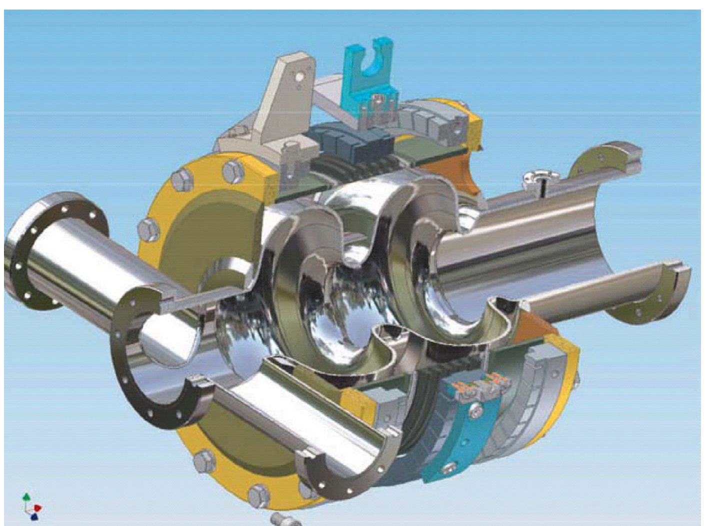
Cornell ERL Injector

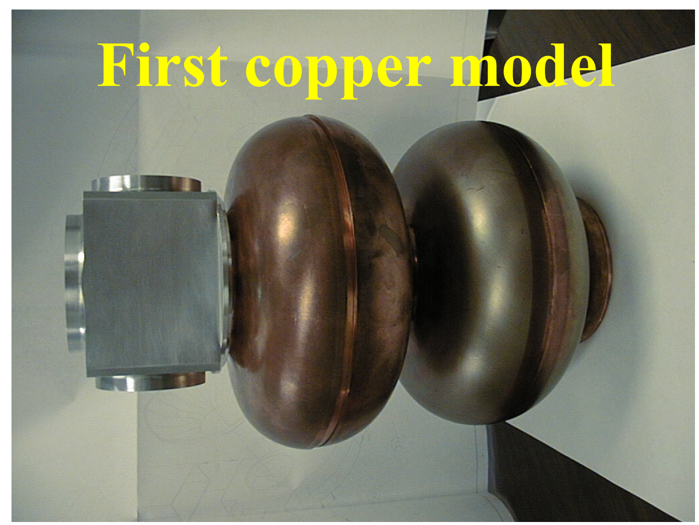


- DC gun produces low emittance beam (Q_b= 77 pC).
- Fast acceleration in first cavity to reduce space charge effects.
- Short 2-cell cavities to reduce RF power per input coupler and to achieve strong HOM damping.

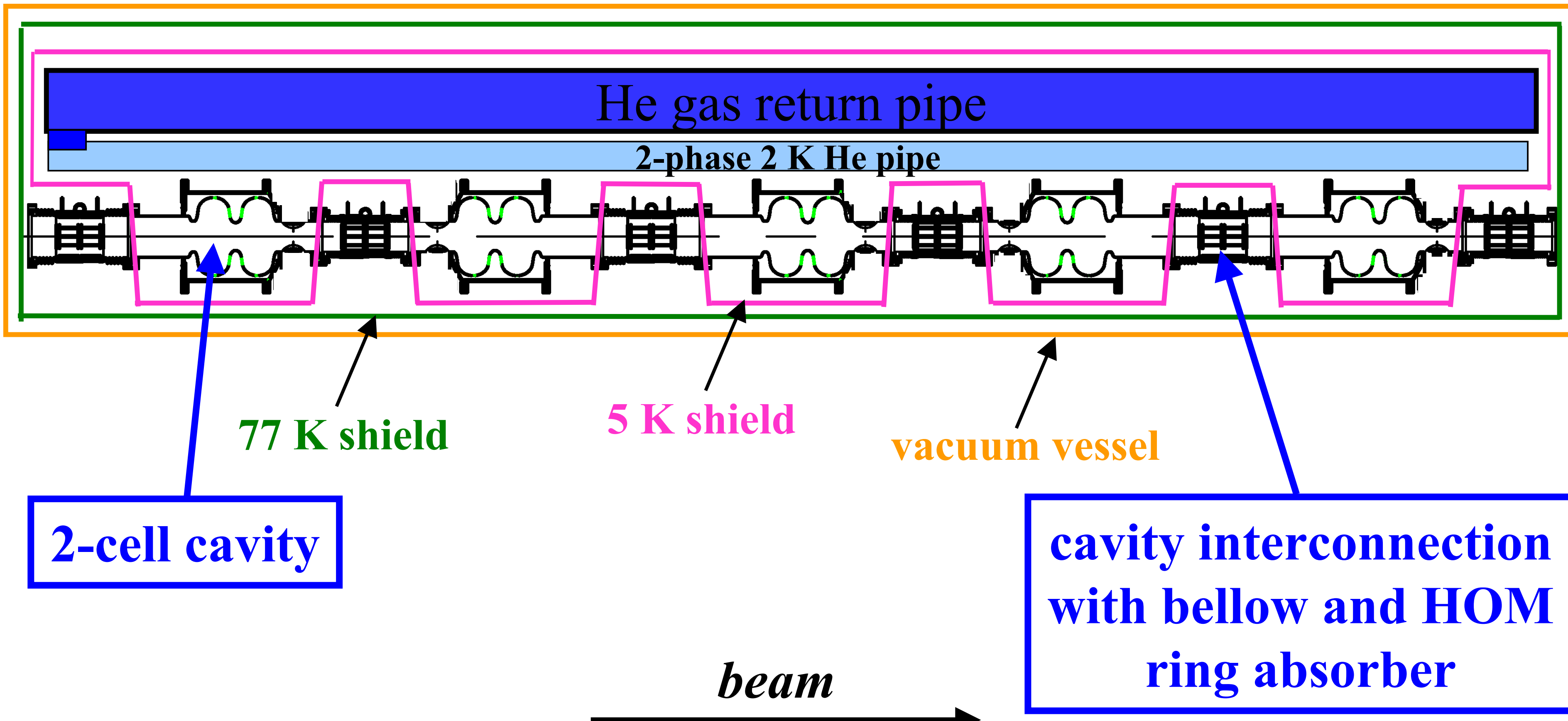
Cornell ERL Injector: 2-Cell Cavity



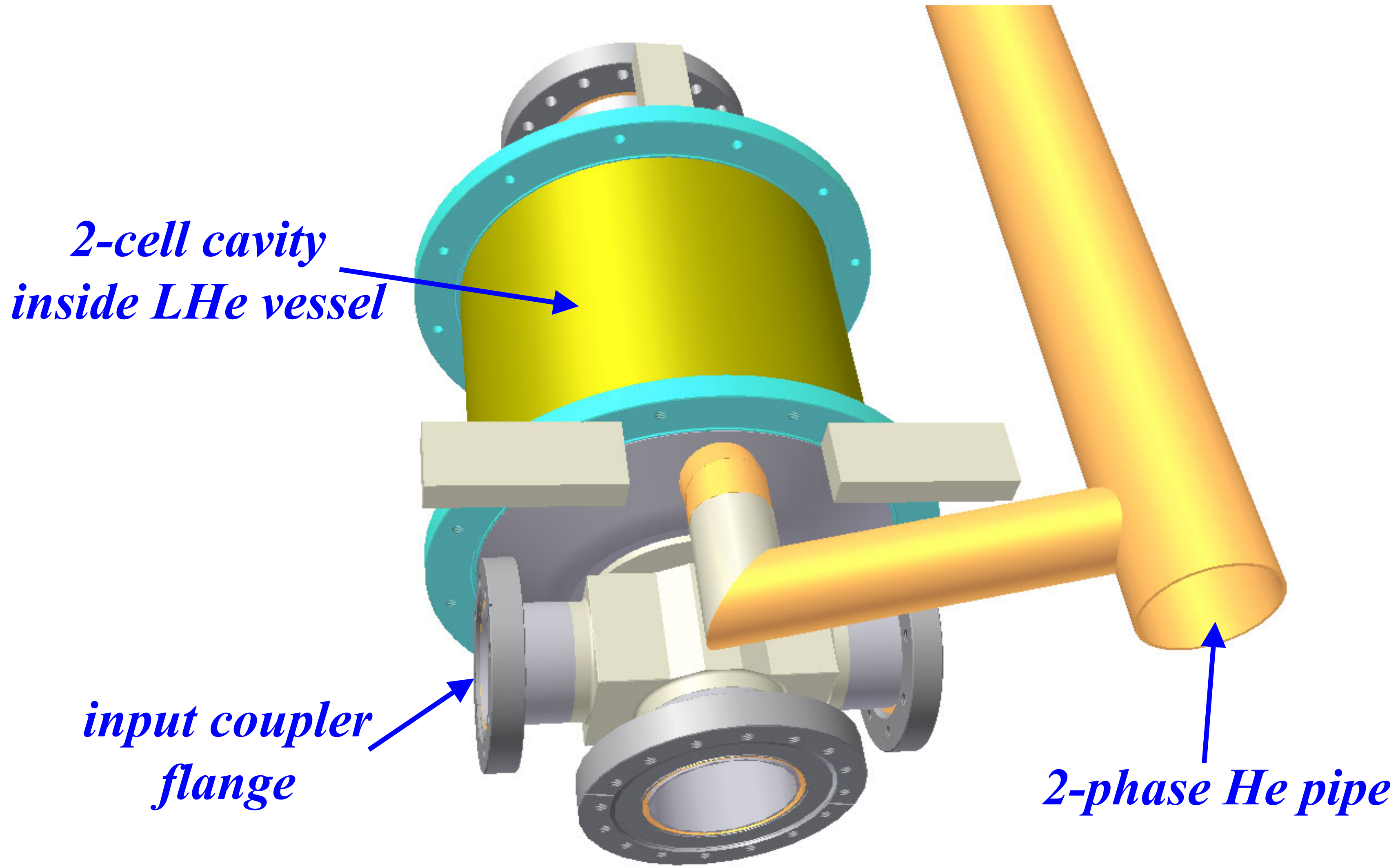




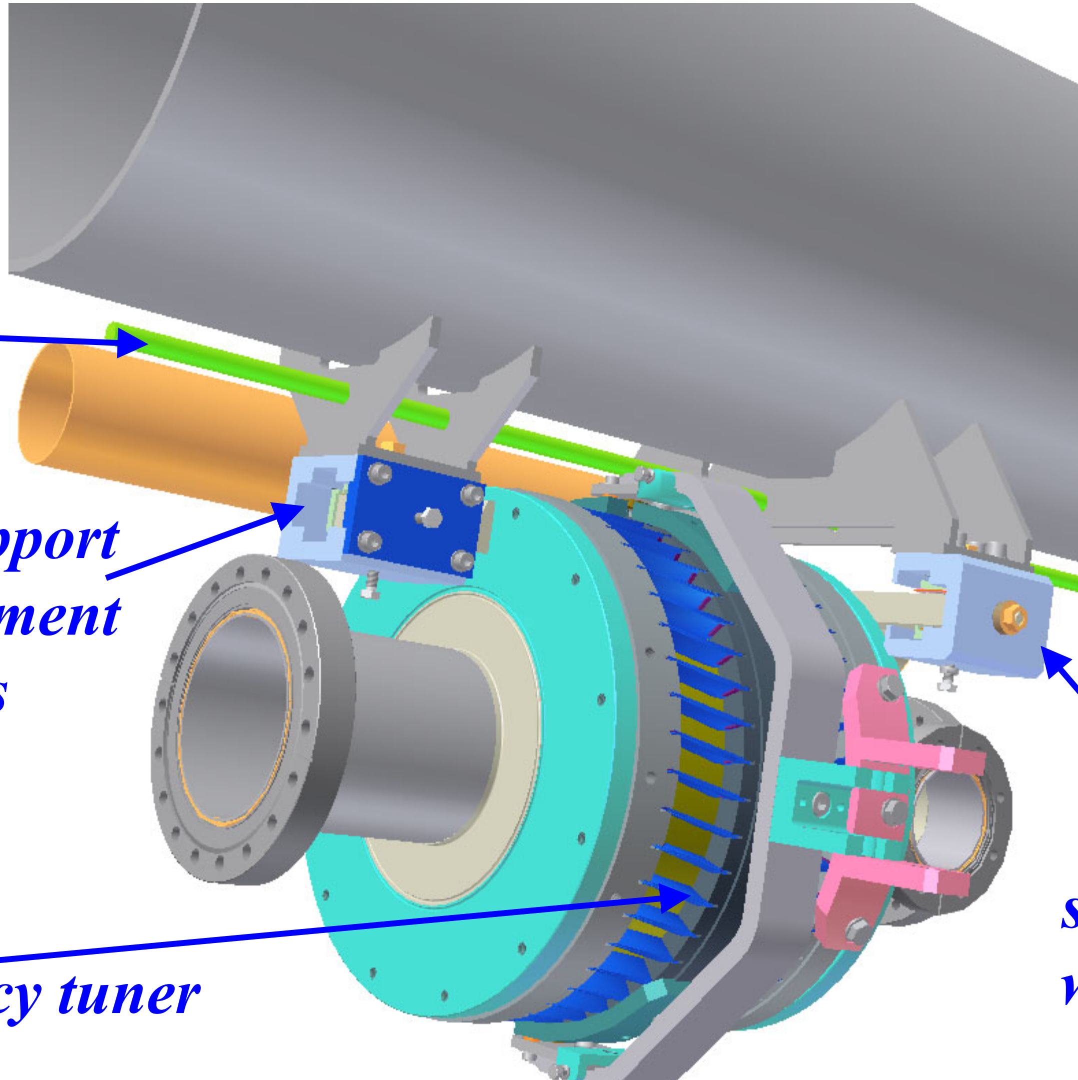
Cornell ERL Injector Cryomodule Concept



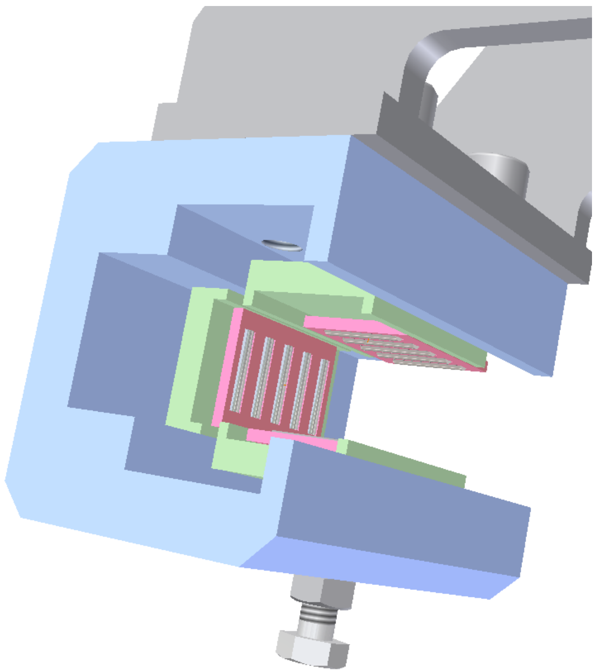
Cornell ERL Injector: 2-Cell Cavity with LHe Vessel

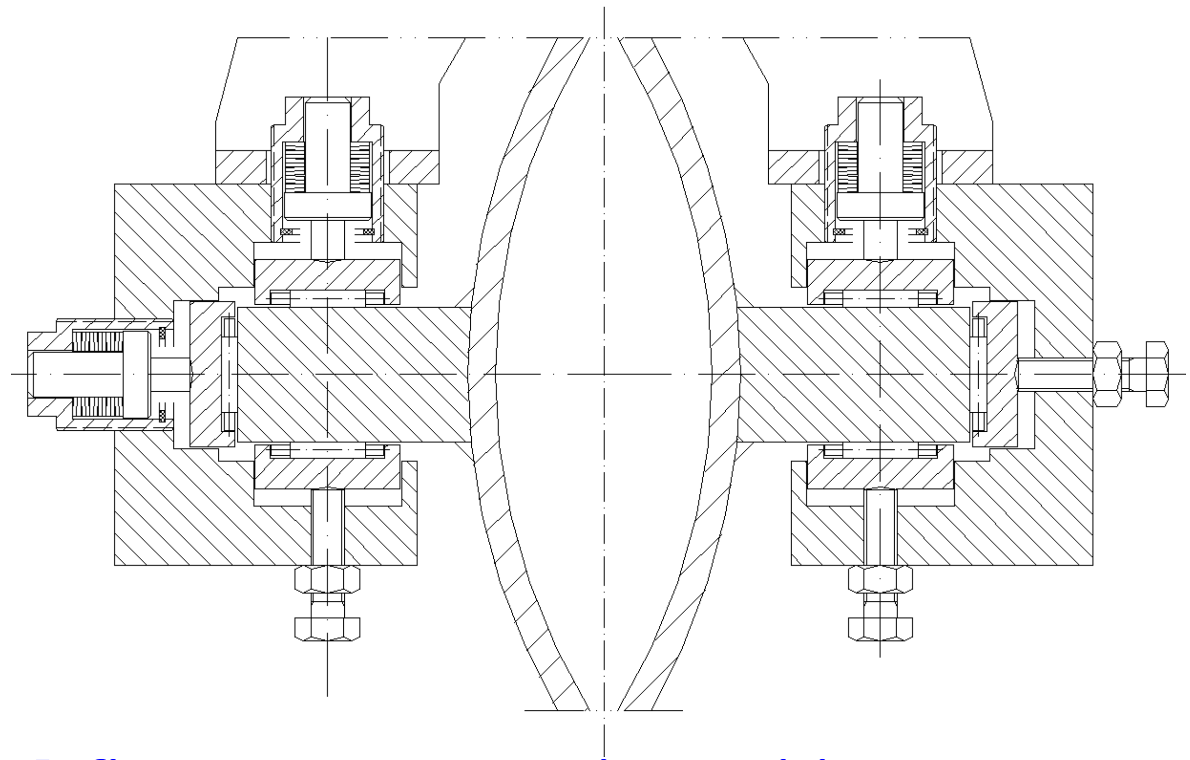


Cornell ERL Injector: Cavity with Support and Alignment Structure



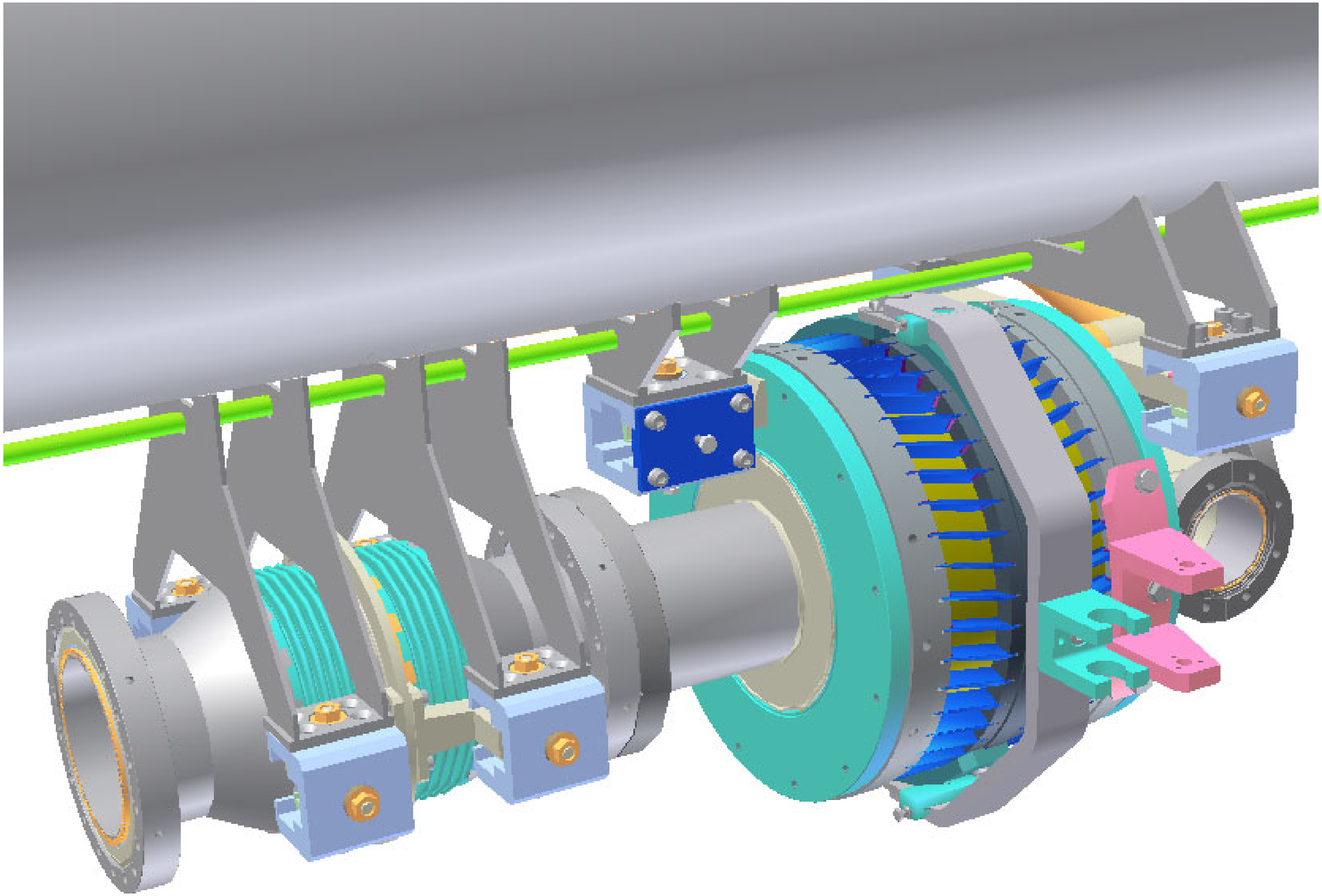
Sliding Cavity Support (TTF Module Style)



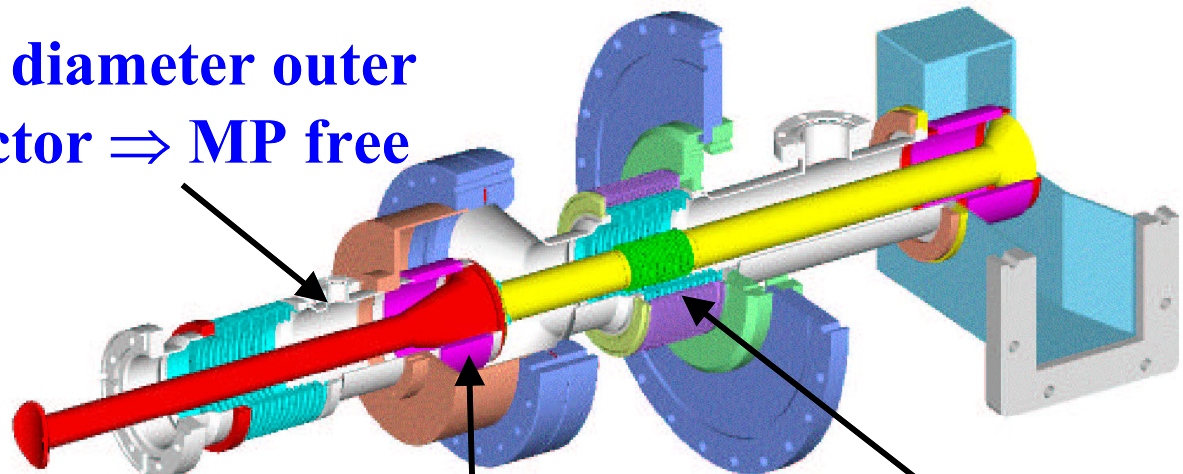


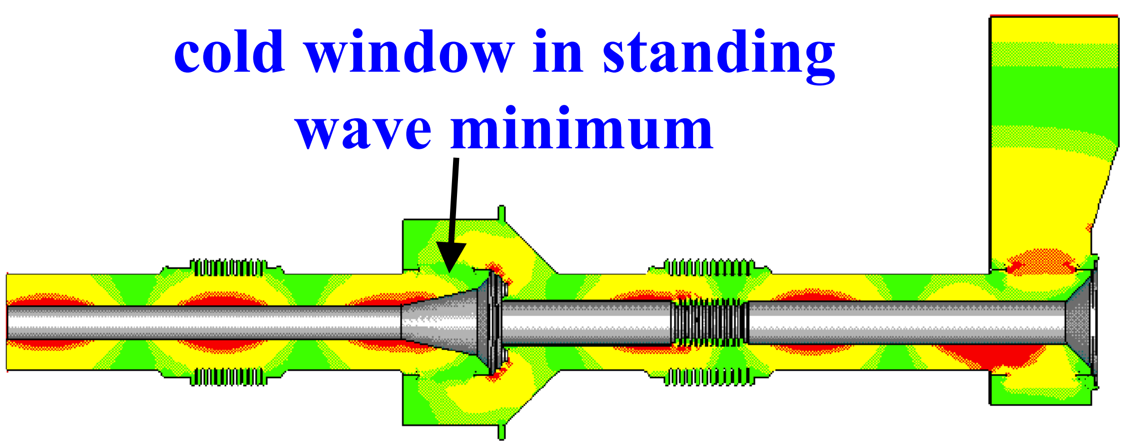
- Sliding supports define transverse cavity positions.
- Longitudinal position is defined by invar rod.
- Cavity stays in place during cool-down to 2 K.

Cornell ERL Injector Cryomodule: Cavity with HOM Absorber



Cornell ERL Injector: 50 kW CW Input Coupler

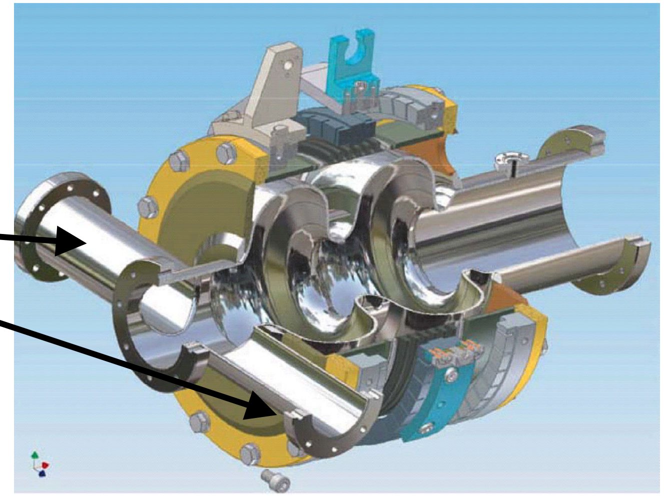




Design studies under progress, high power cw test planed.

Symmetric Twin Input Coupler

Symmetric twin input coupler

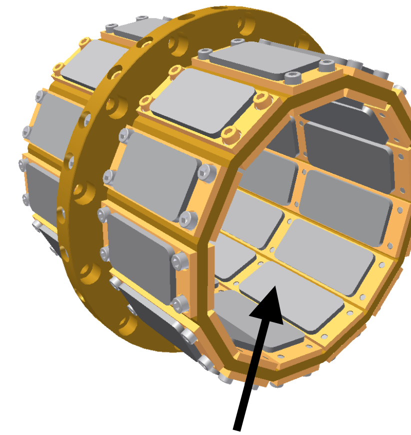


- 50 % less power per coupler.
- Reduced emittance growth in the injector.

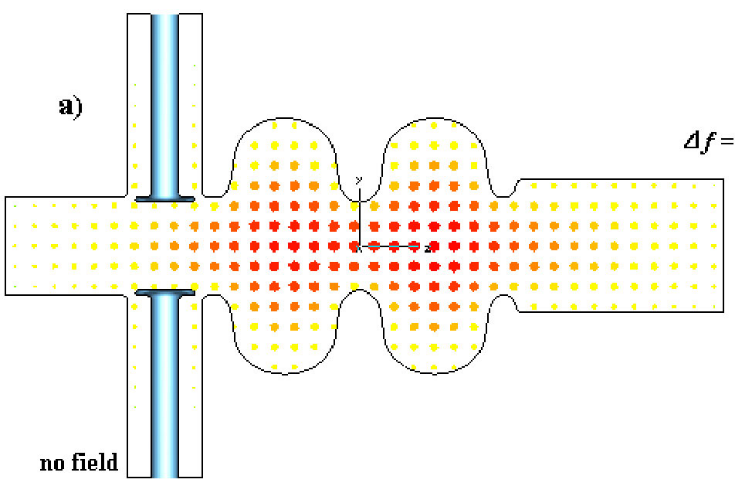
	q [pC]	V_{acc} [MV]	ε_0 [µm]	σ_z [mm]	σ_x [mm]	emittance growth
single input coupler	77	1	1.0	0.6	2.0	6 %
	77	3	1.0	0.6	0.9	3 %
	8	1	0.1	0.6	0.6	16 %
	8	3	0.1	0.6	0.3	28 %
twin input coupler	77	1	1.0	0.6	2.0	4 %
	77	3	1.0	0.6	0.9	1 %
	8	1	0.1	0.6	0.6	4 %
	8	3	0.1	0.6	0.3	1 %

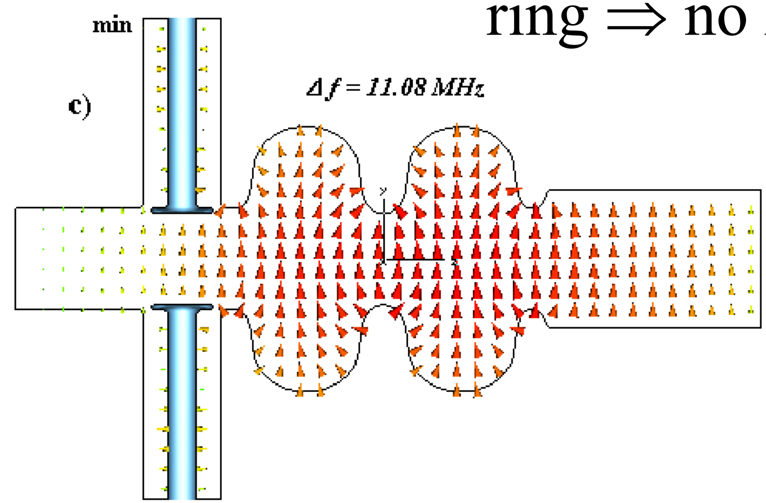
Cornell ERL Injector Cryomodule: HOM Damping

- **Accelerating mode does not propagate in tubes.**
- **All TM monopole HOMs and all dipole modes propagate in tubes and are damped by ferrite ring absorber between cavities.**
- **Example: Lowers frequency dipole mode:**

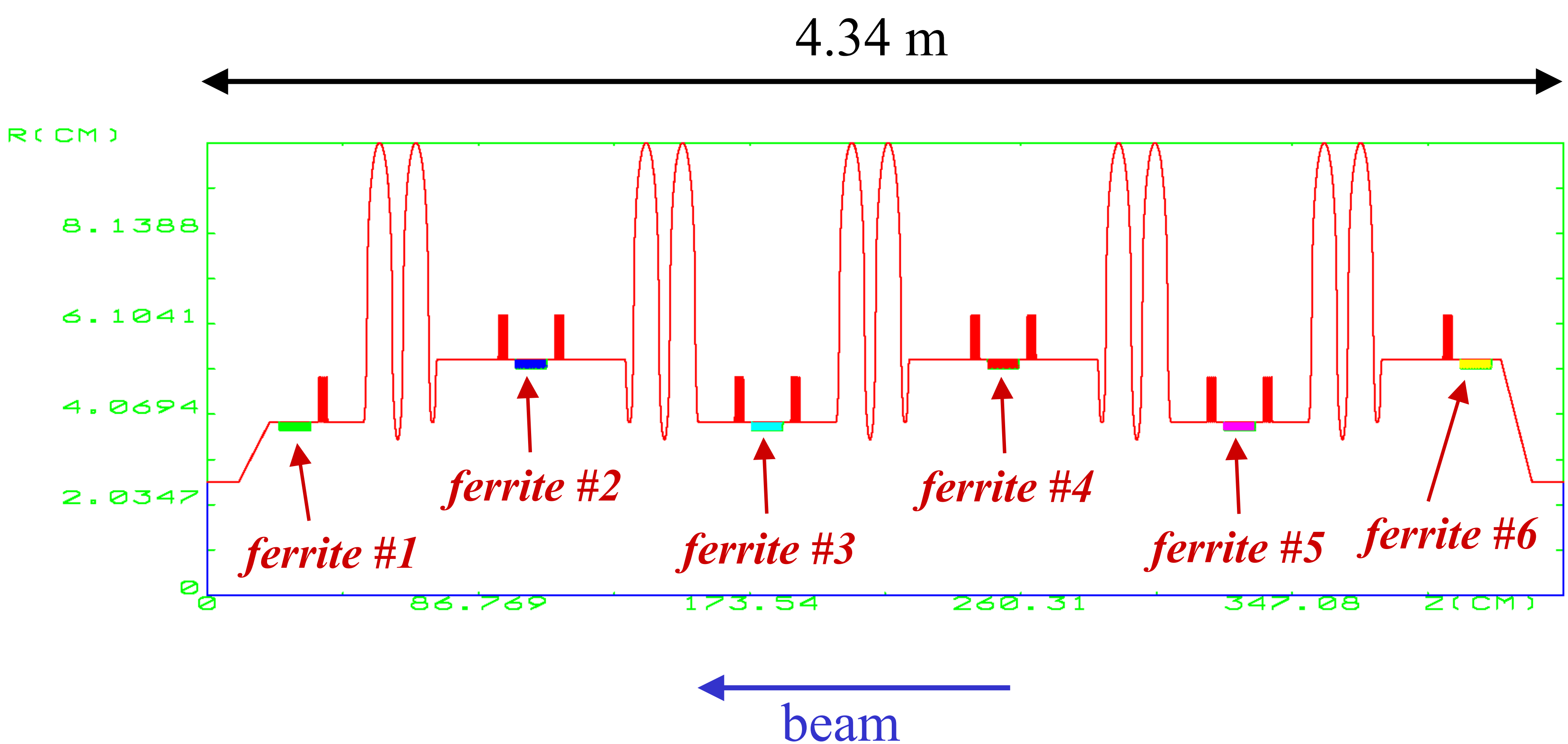


symmetric ferrite ring ⇒ no kick

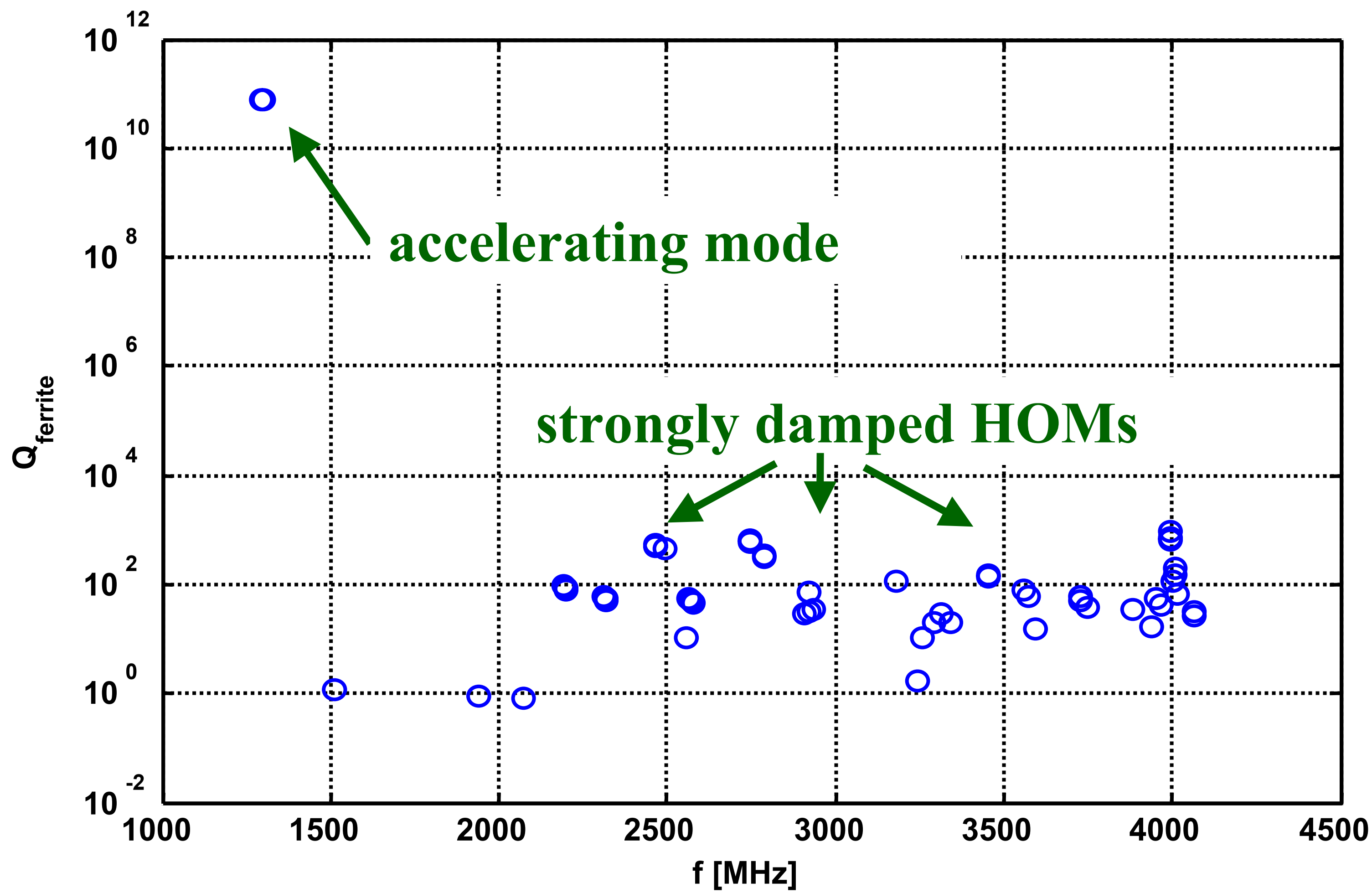




ERL Injector: HOM Monopoles (CLANS Model)



ERL Injector: Damping of HOM Monopoles (CLANS Simulation)



Main Linac SRF

Cornell ERL Main Linac RF Challenges

- Strong damping of HOMs essential for beam stability and to reduce monopole power.
- HOM power extraction at temperature with good cryo-efficiency.
- Emittance preservation ⇔ small transverse kick fields.
- RF field control and efficient cavity operation.
- Cavity module operation at high cw field gradient with large cryo-losses.

HOM Damping Challenge 1: High Beam Currents and HOM Monopole Power

In *average* the total HOM losses per cavity are given by the single bunch losses (7cell ERL cavity, 77 pC bunch charge, 2.6 GHz bunch repetition rate, $\sigma_b = 600\ \mu m$):

$$P_{\|} = k_{\|} Q_{bunch} I_{beam} = 9.1\,\text{V/pC} \cdot 77\,\text{pC} \cdot 0.2\,\text{A} = 140\,\text{W}$$

But: If a monopole mode is excited on resonance, the loss for this mode can be much higher:

$$P = 2\left(\frac{R}{Q}\right) Q I_{beam}^2$$

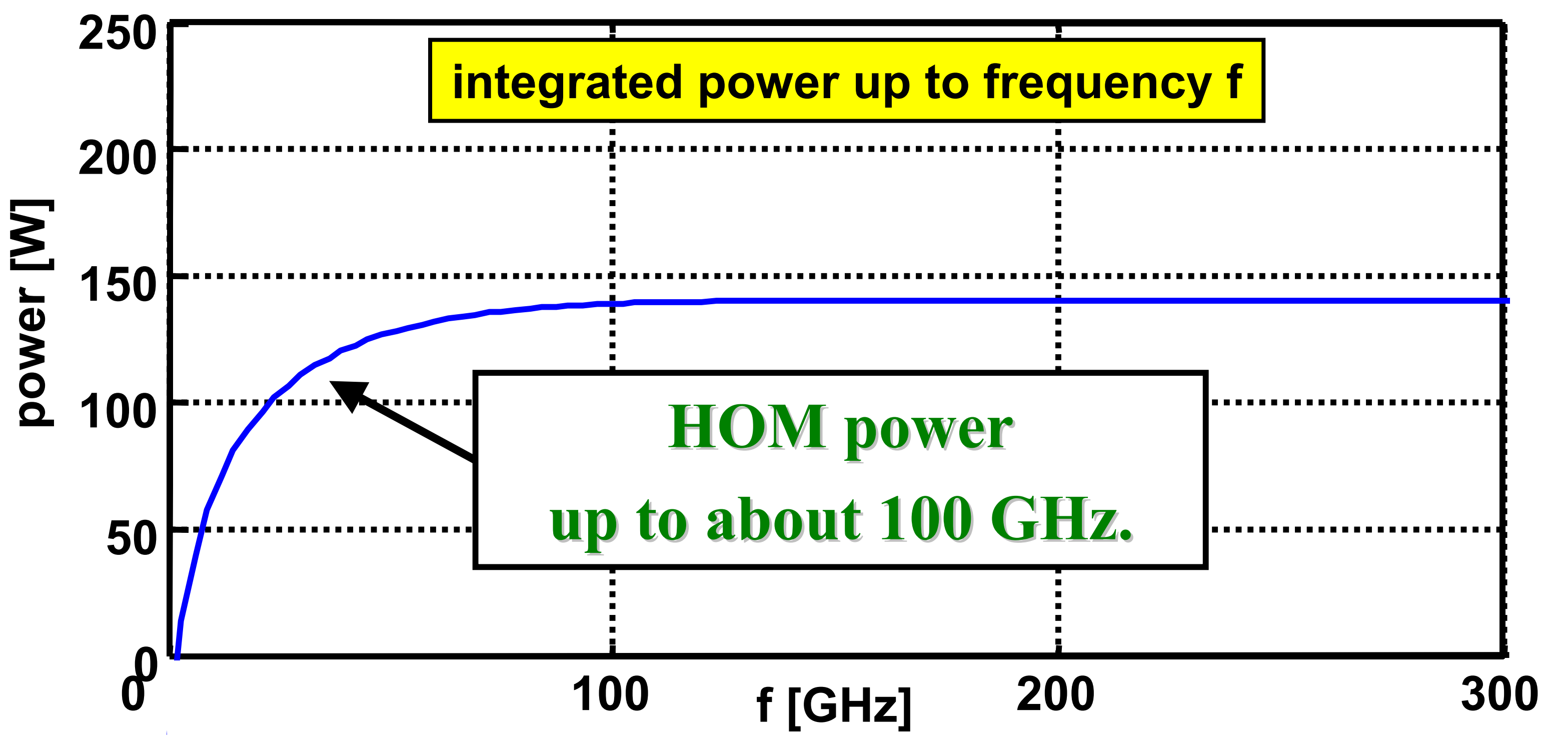
Need strong HOM damping!

⇒ Example: To stay below 200 W (I=2*100 mA):

- **achieve (R/Q)Q < 2500 Ω,**
- **or avoid resonant excitation of the mode.**

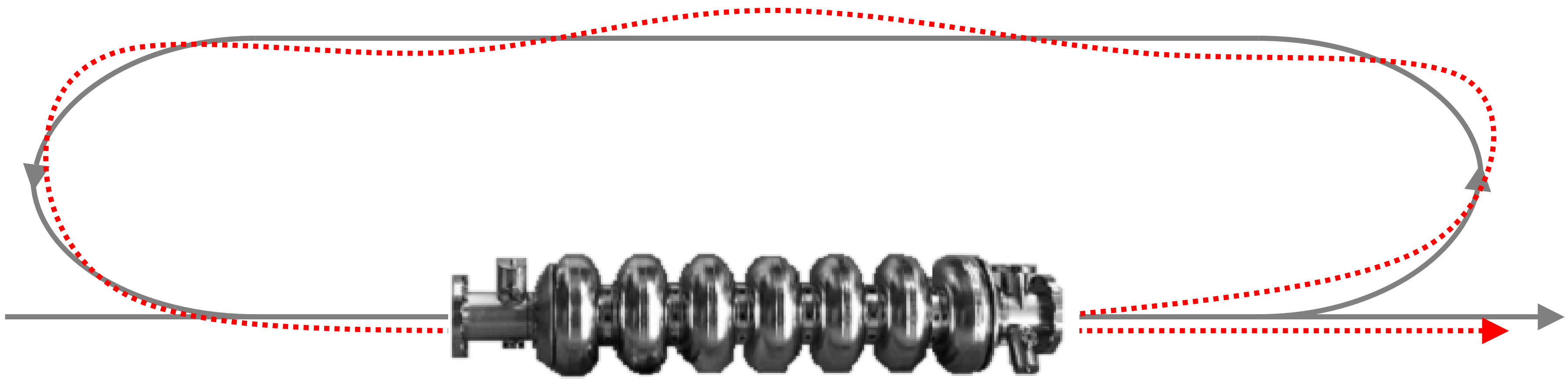
HOM Damping Challenge 2: HOM Monopole Power at High Frequencies

600 μm bunch length in the linac



HOM Damping Challenge 3: Avoid Beam Breakup (BBU)

- **In an ERL the feedback system formed between cavities and the beam is closed. ⇒ Instability can result at sufficient high currents.**



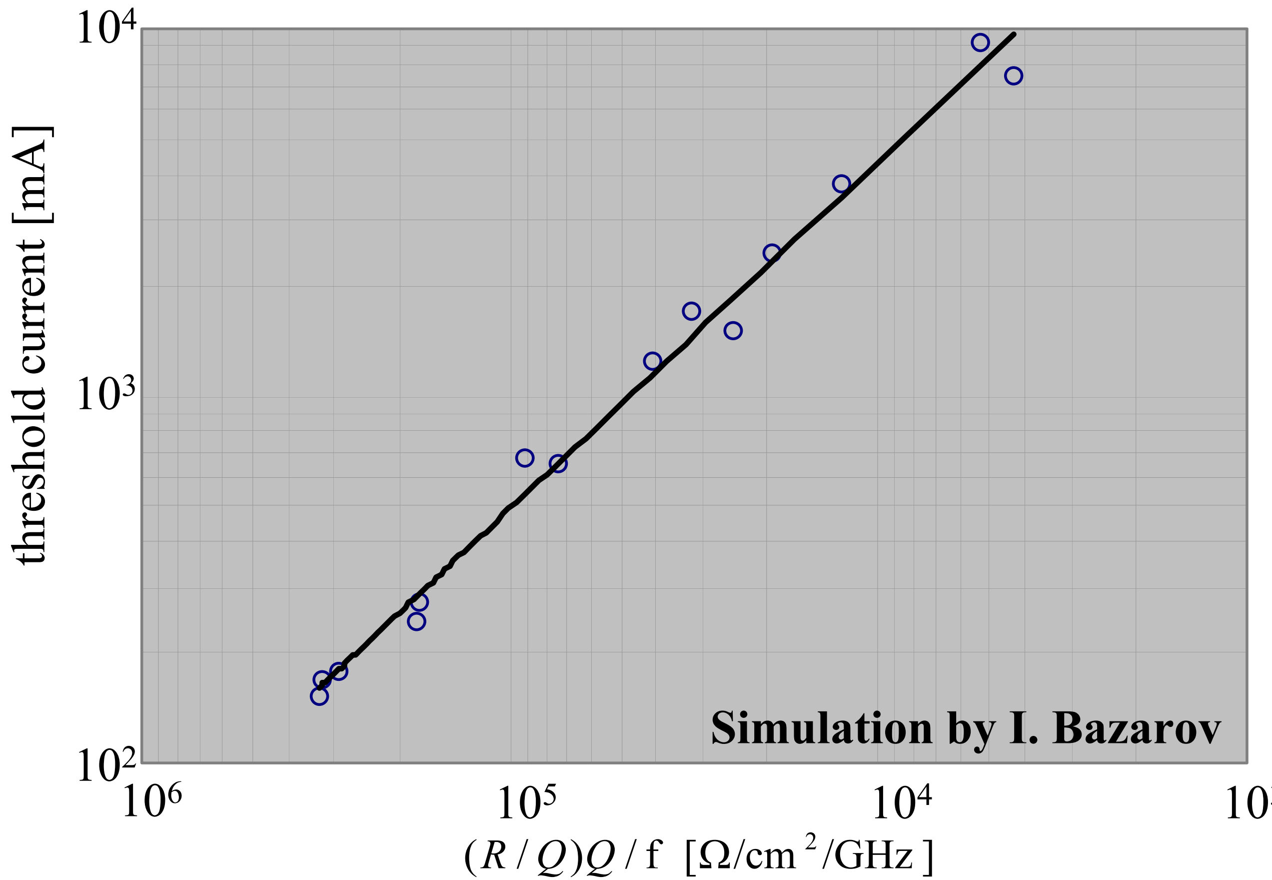
- **simple model for instability beam current:**

$$I_{BBU} \propto \frac{\omega}{(R/Q)\ Q}$$

Strong HOM damping!

Need I_{BBU} > 100 mA!

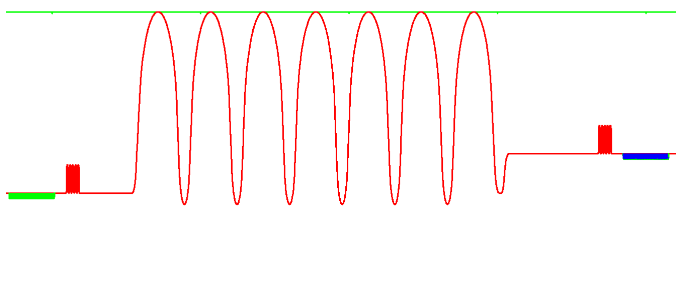
BBU Limit for the Cornell 5 GeV, 100 mA ERL



⇒ (R/Q)Q/f < $2 \cdot 10^5$ $\Omega/cm^2/GHz$ required for BBU instability current > 100 mA (with safety-factor).

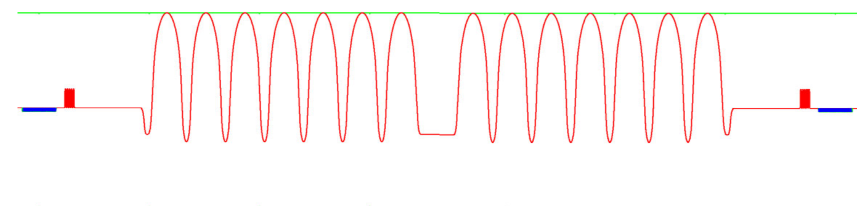
HOM Damping in the Cornell ERL Main Linac: RF Structure Candidates

7-cell cavities:



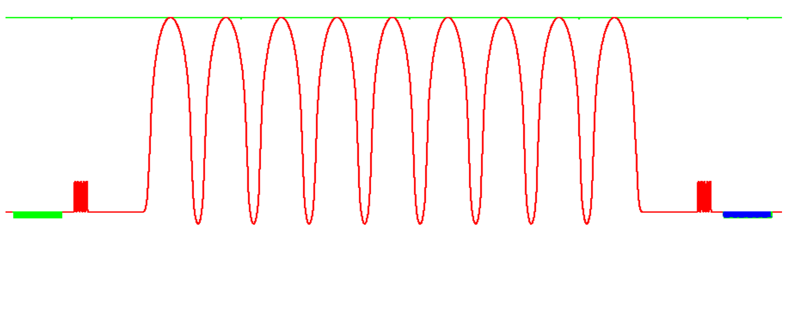
good for 100 mA

2x7-cell superstructure:



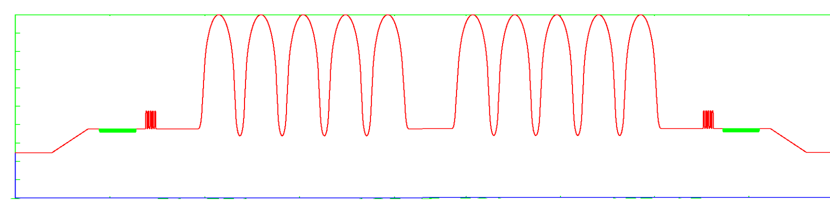
good for 10 mA

9-cell cavities:



good for 10 mA

2x5-cell superstructure:

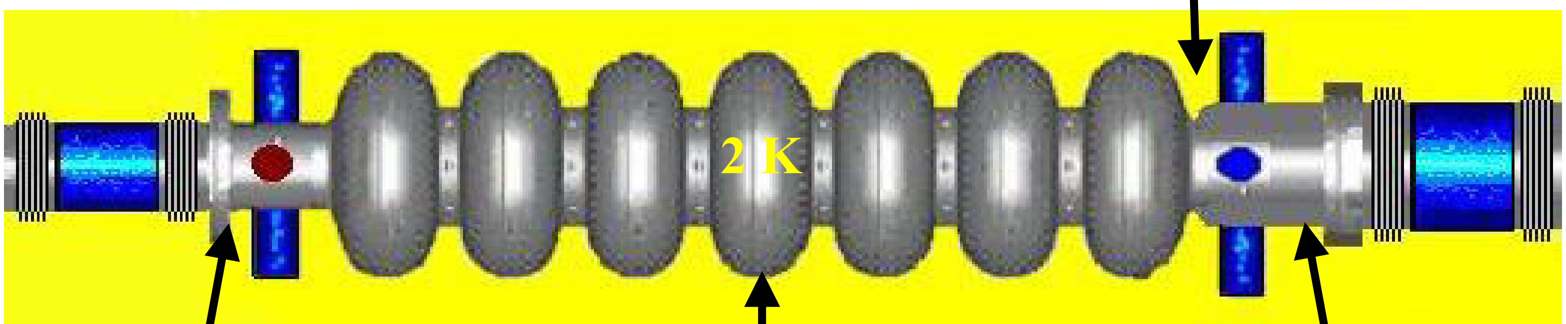


good for 100 mA ?

HOM Damping in the Cornell ERL Main Linac: 7-Cell Cavity

f_{acc} = 1.3 GHz

reduced iris to maximize R/Q of accelerating mode

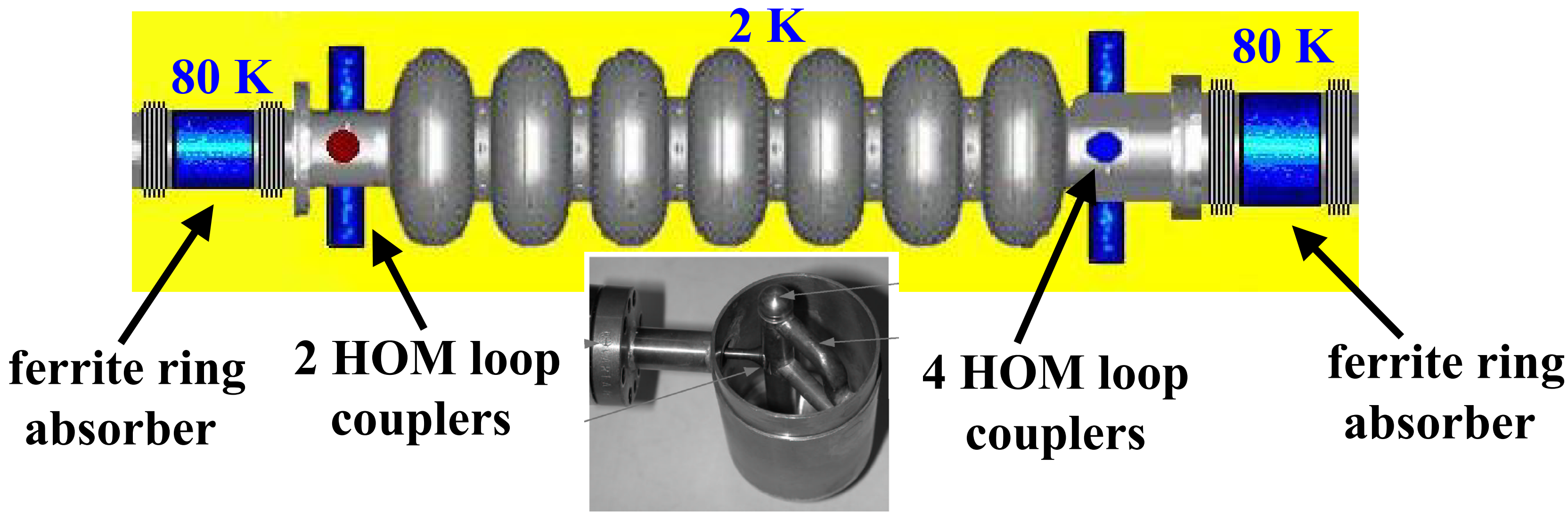


small 78 mm beam tube

7-cell s.c. cavity, TESLA shaped center cells

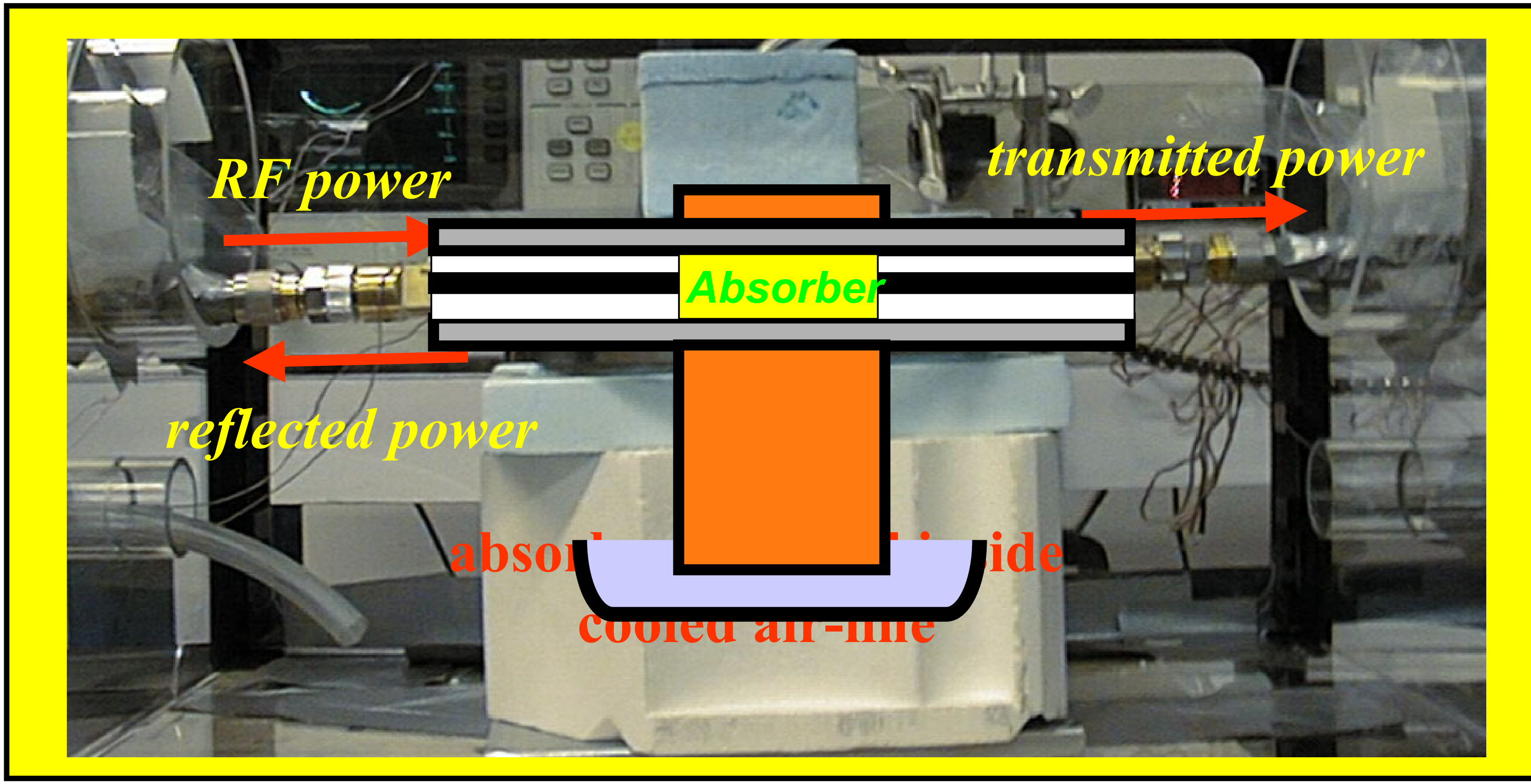
large 106 mm diameter tube to propagate all TM monopole HOMs and most dipole modes

HOM Damping in the Cornell ERL Main Linac: Damping Concept



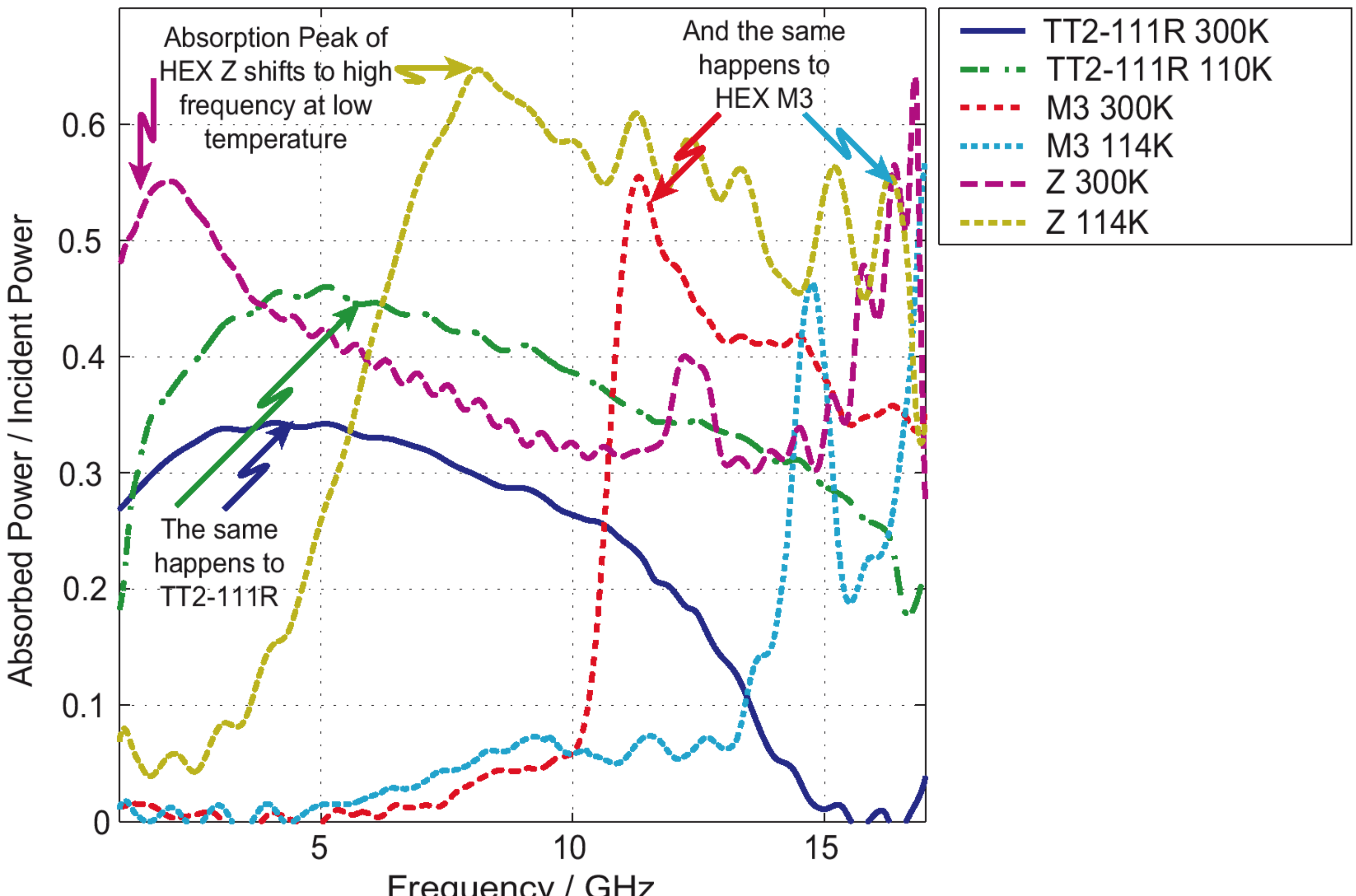
- **Enlarged beam tube on one side to propagate all TM monopole modes and most dipole modes.**
- **Ferrite broadband absorbers at 80 K between cavities to damp propagating modes at temperature with good cryo-efficiency.**
- **6 HOM loop coupler per cavity to reduce power per coupler and to damp quadrupole modes reliable.**
- **Opposite HOM couplers to reduce transverse kicks.**

Setup to measure Ferrite Absorber Losses at ≈ 100 K

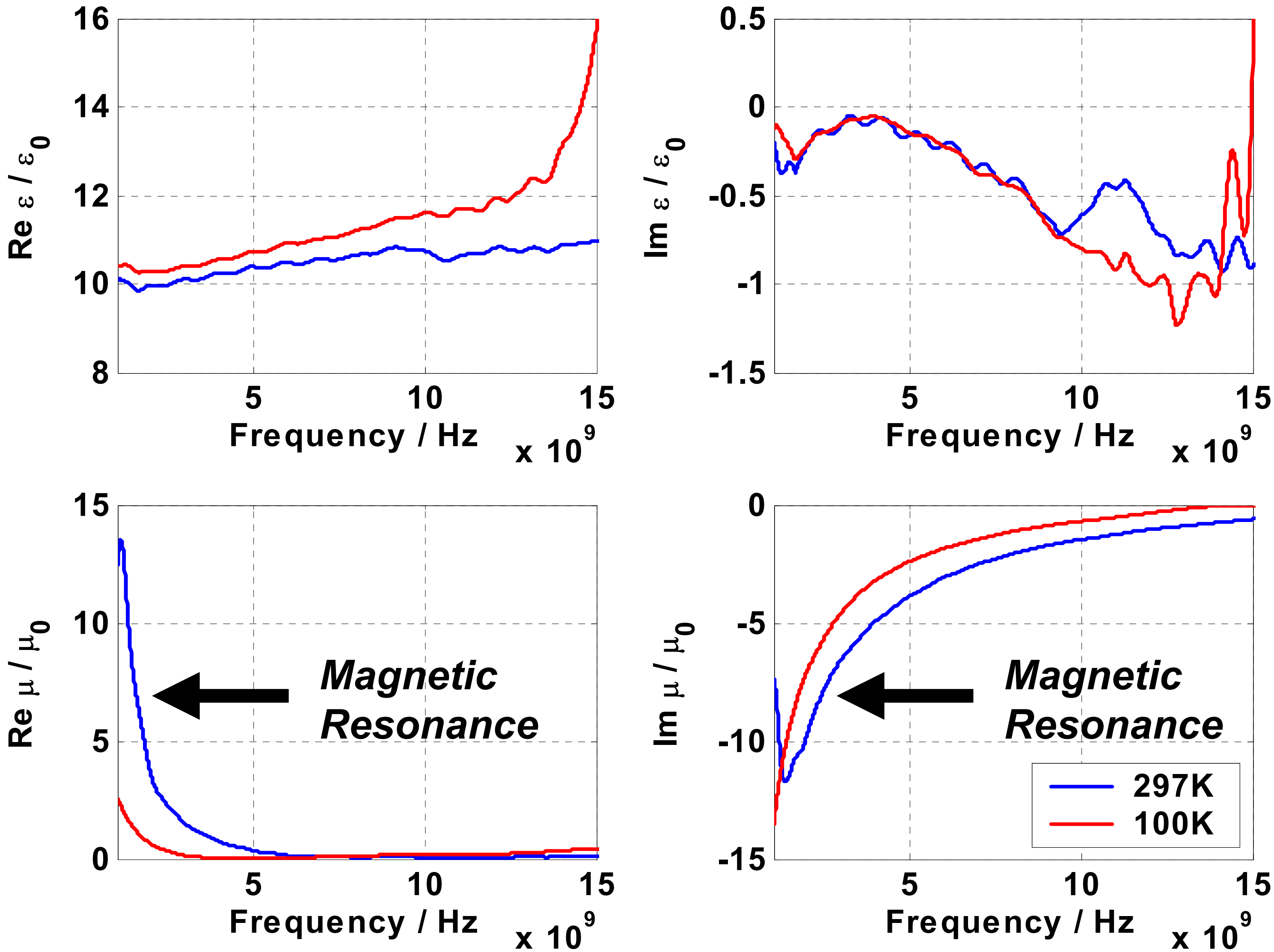


RF losses in the absorber material can be calculated from the reflected and transmitted power as function of the RF frequency.

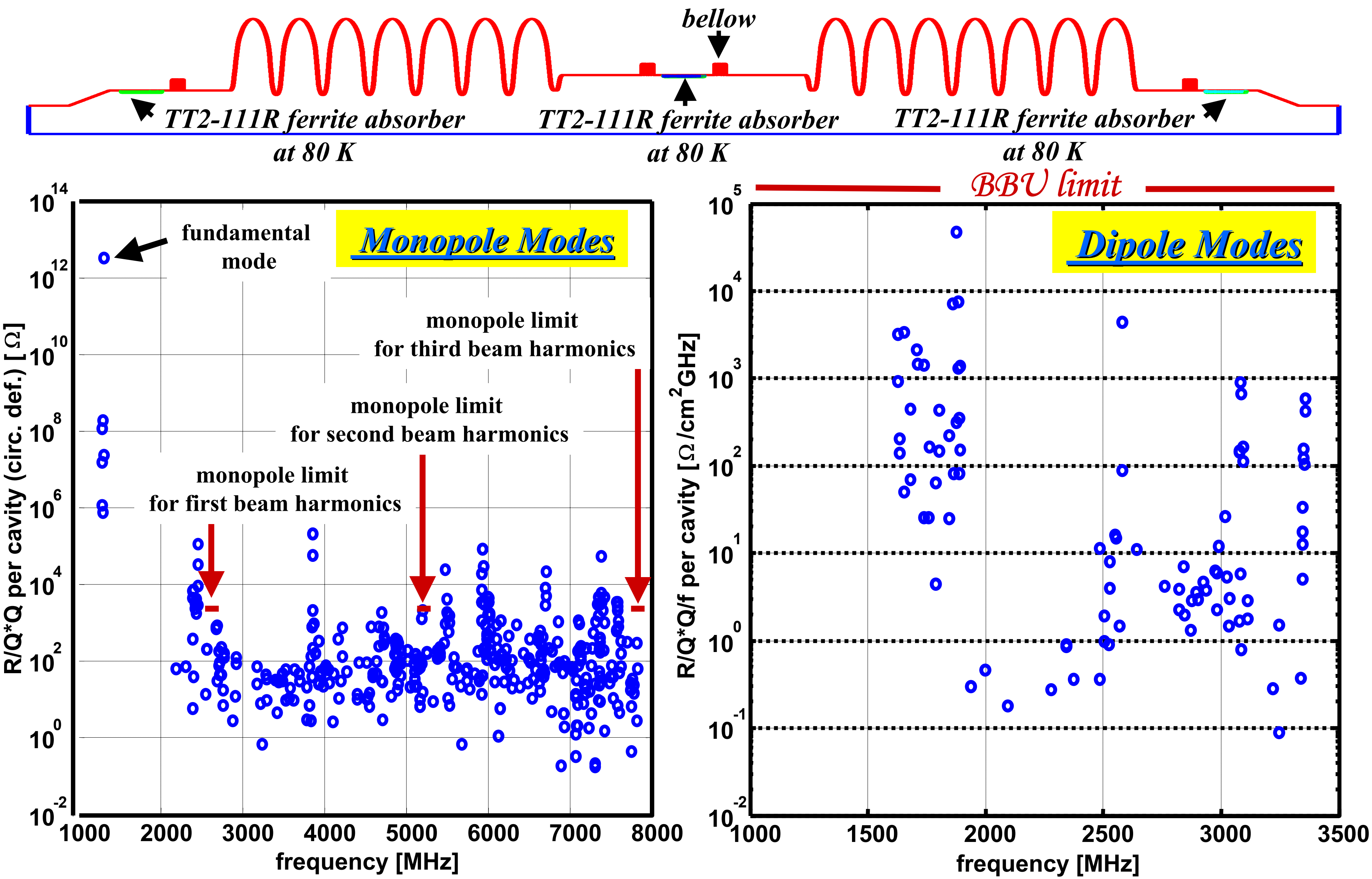
Measured Ferrite Absorber Losses

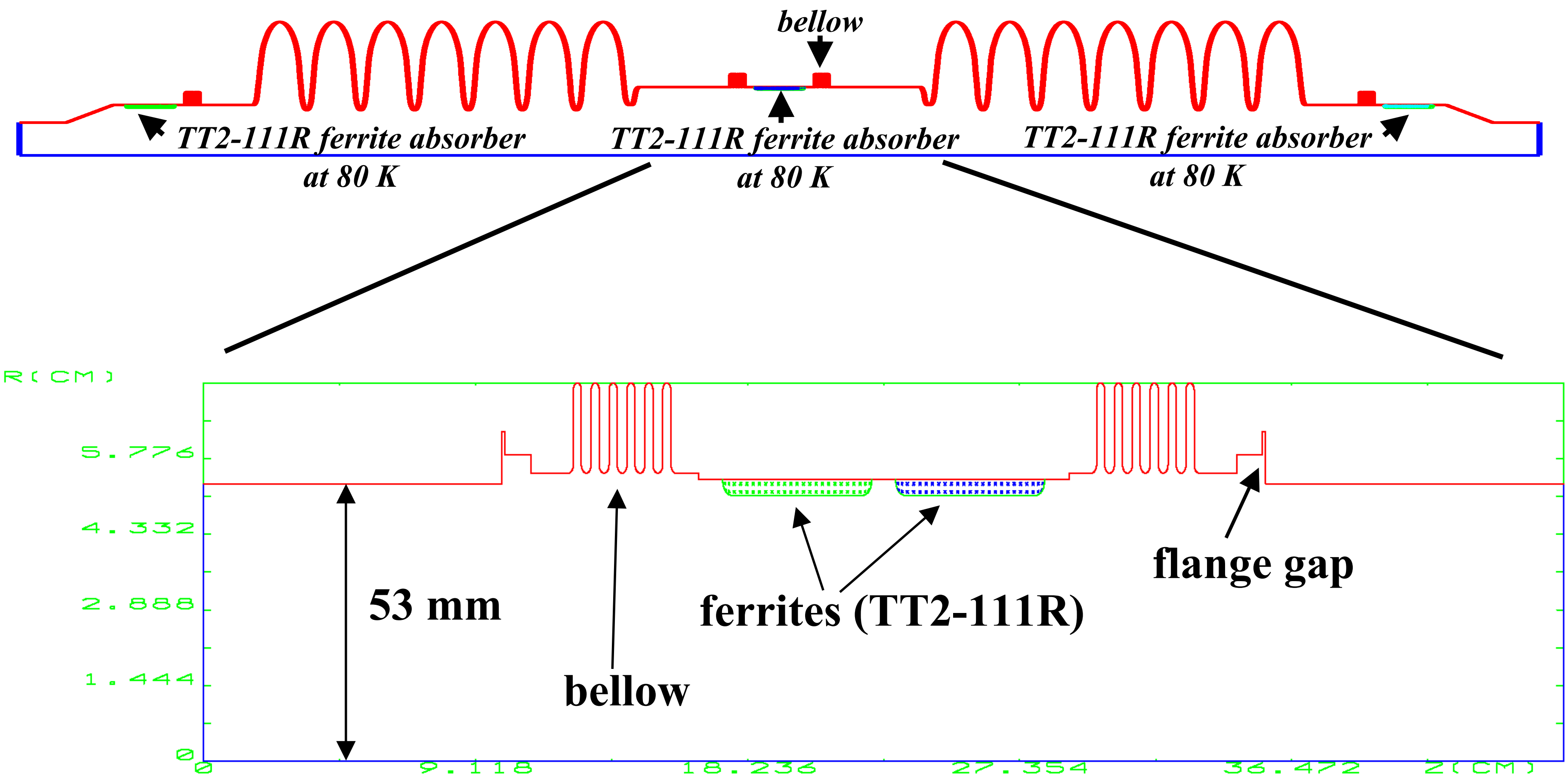


Example: Ferrite TT2-111R Absorber Properties at 300 K and 80 K



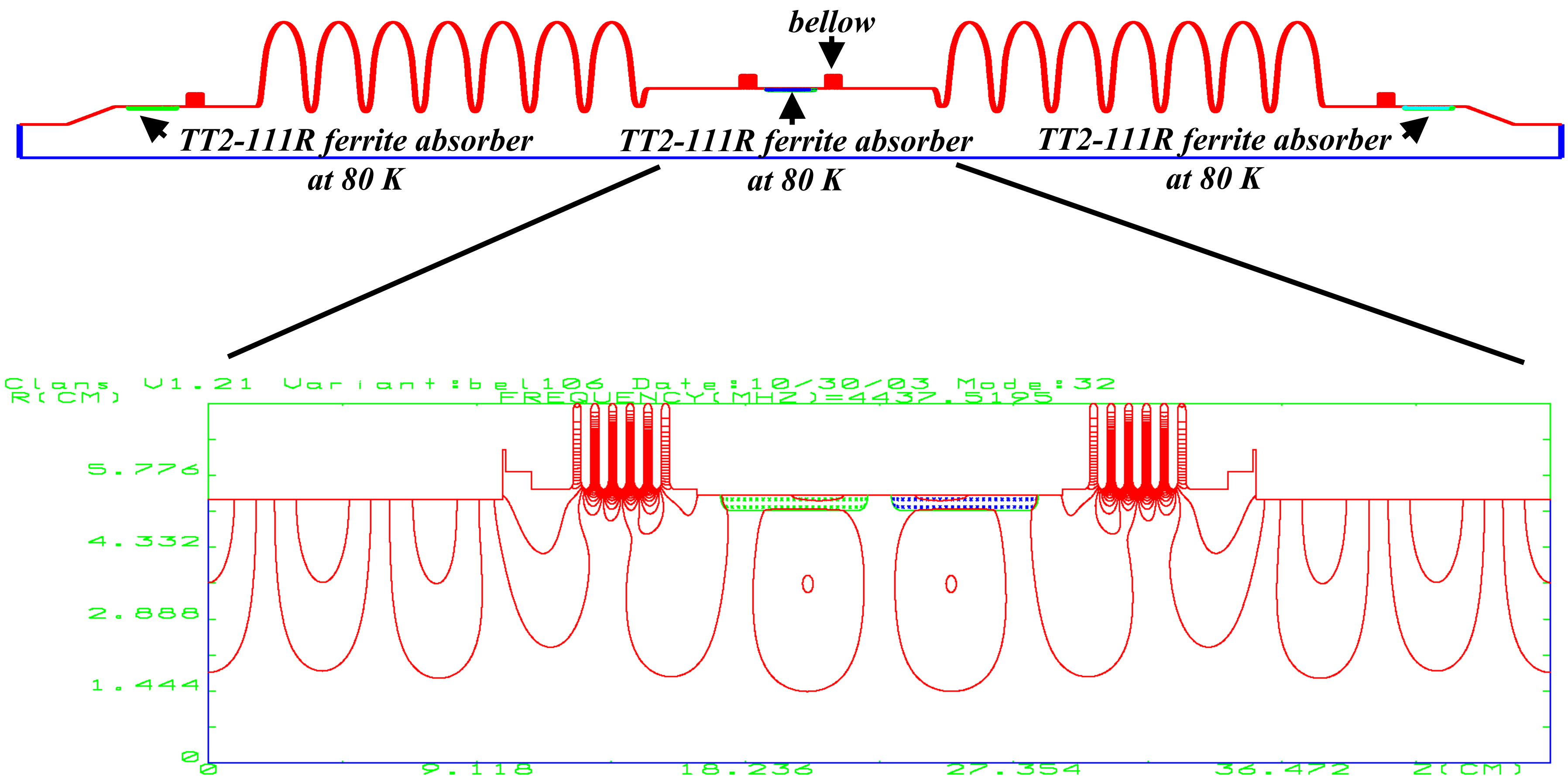
HOM Damping in the Cornell ERL Main Linac: CLANS Simulations





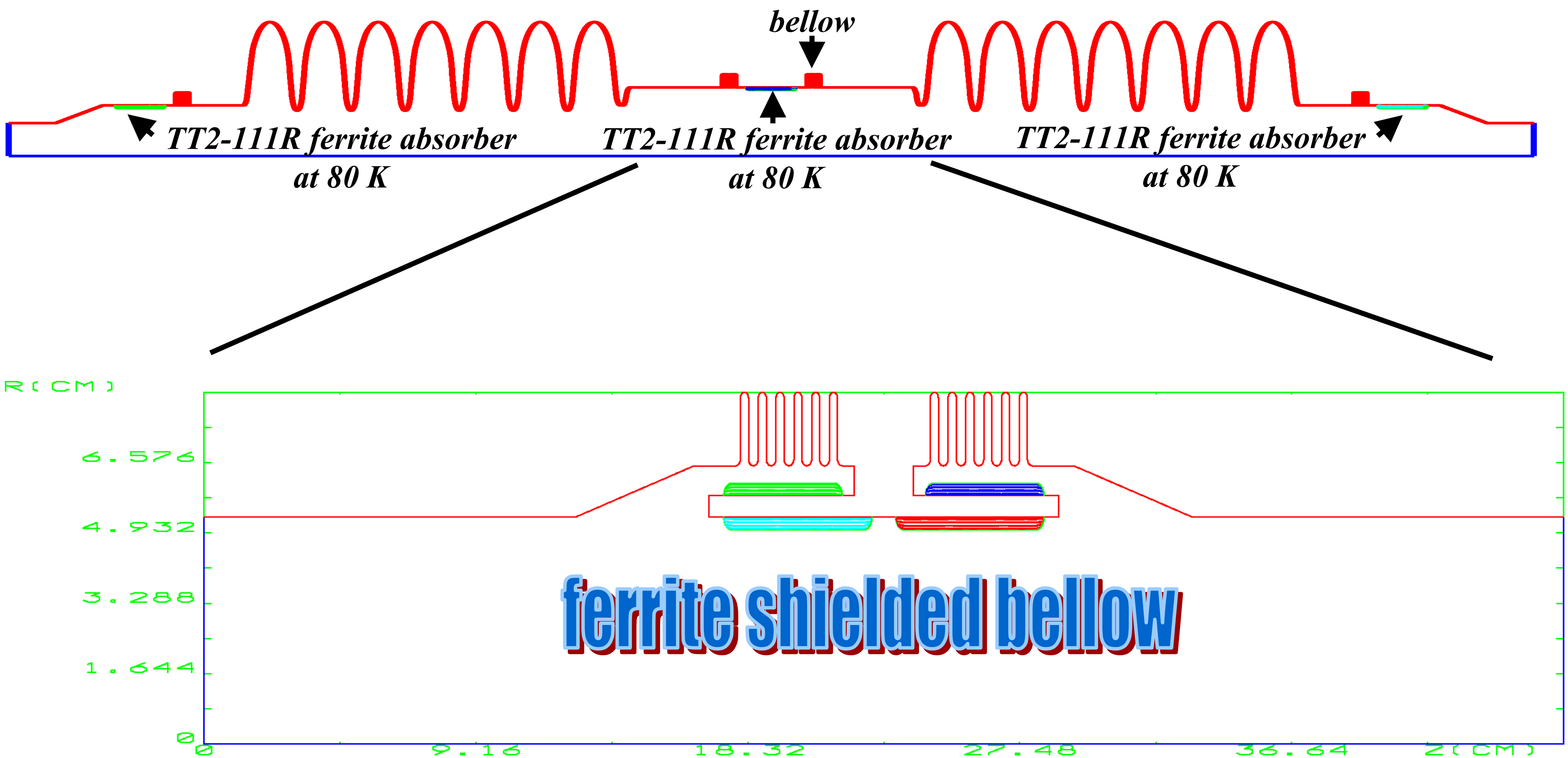
longitudinal loss factor $k_{||}$ = 1.4 V/pC

HOM Damping in the Cornell ERL Main Linac: Bellow-Ferrite-Bellow Section



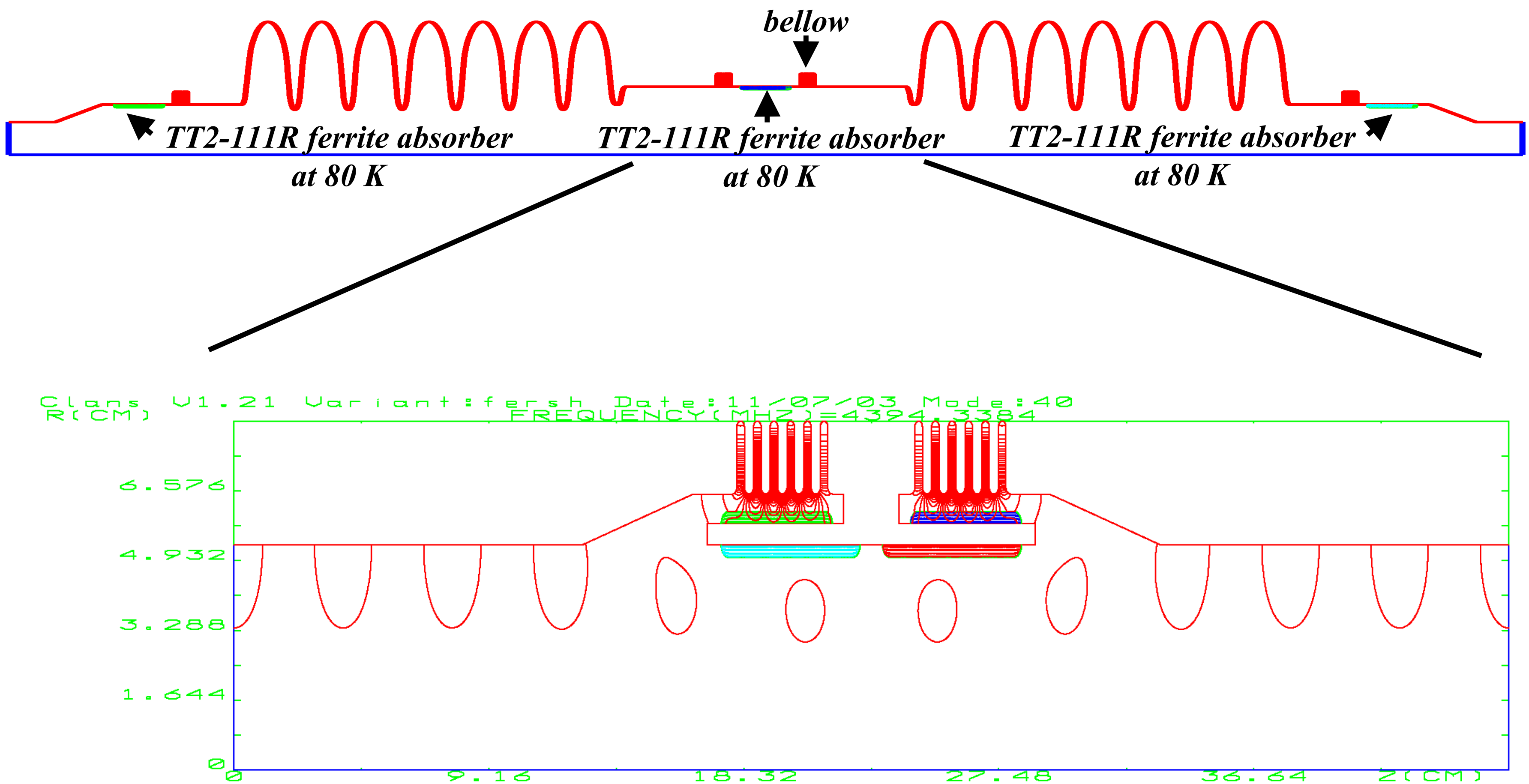
Trapped modes in bellows: HOM power goes into wall, not into cooled ferrite!

HOM Damping in the Cornell ERL Main Linac: Improved Bellow-Ferrite-Bellow Section



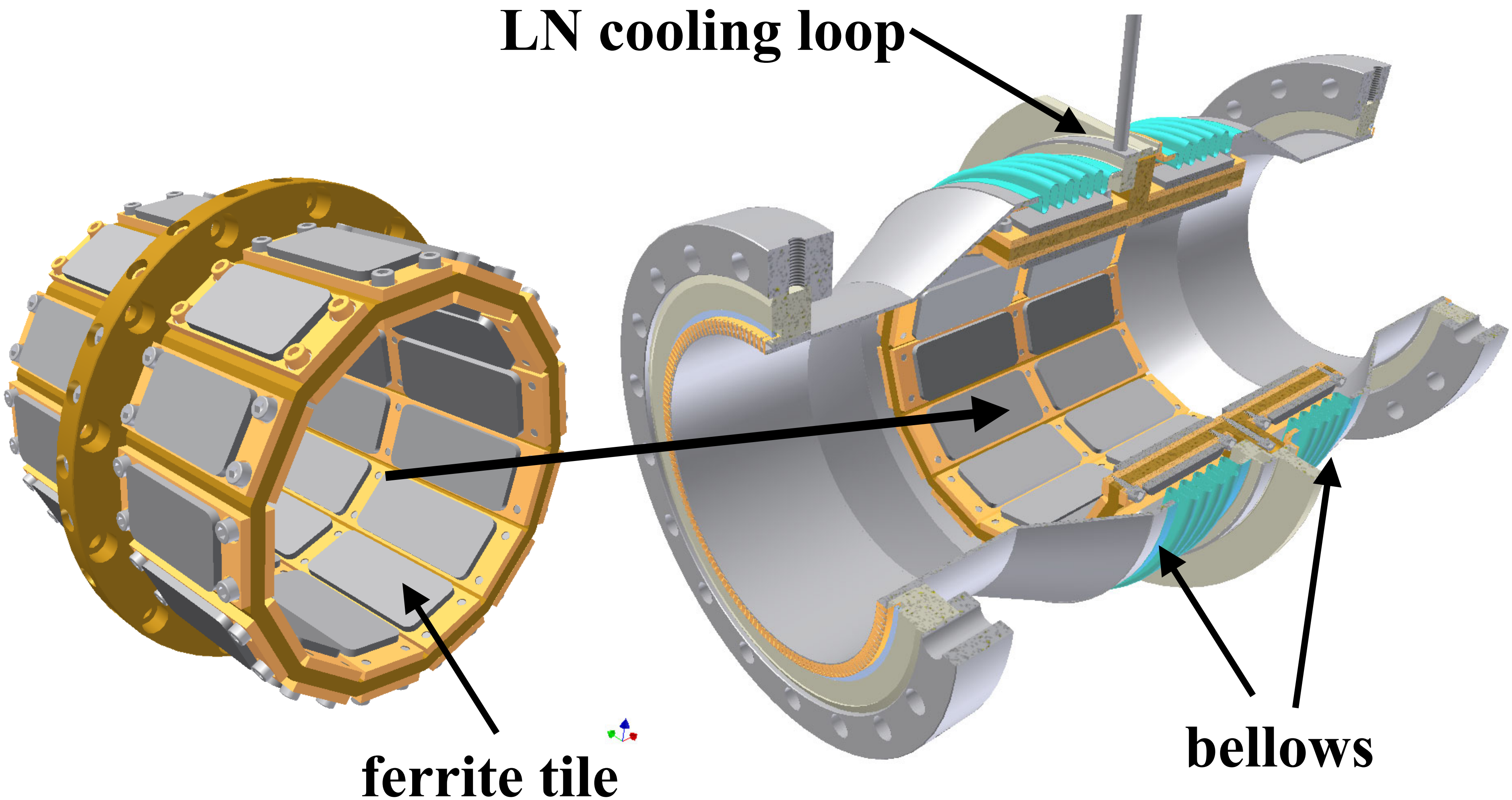
longitudinal loss factor $k_{||}$ = 1.2 V/pC

HOM Damping in the Cornell ERL Main Linac: Improved Bellow-Ferrite-Bellow Section



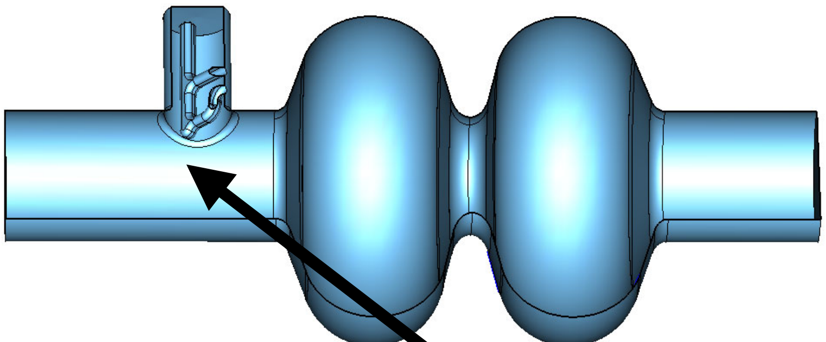
HOM power goes into cooled ferrite!

Ferrite Shielded Bellow

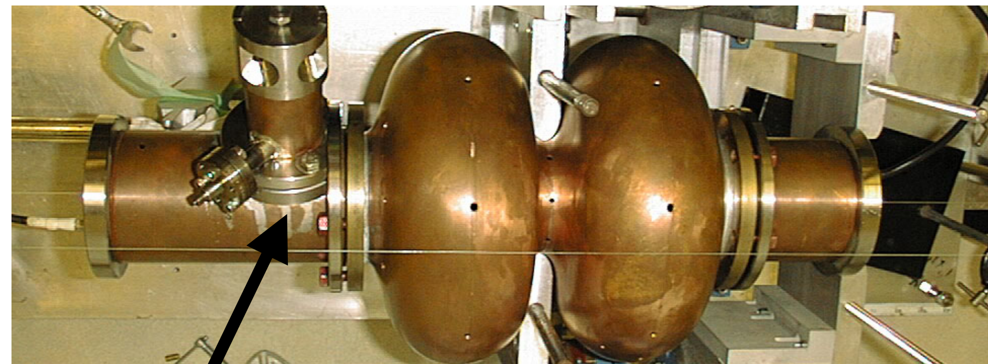


HOM Loop Coupler Studies:

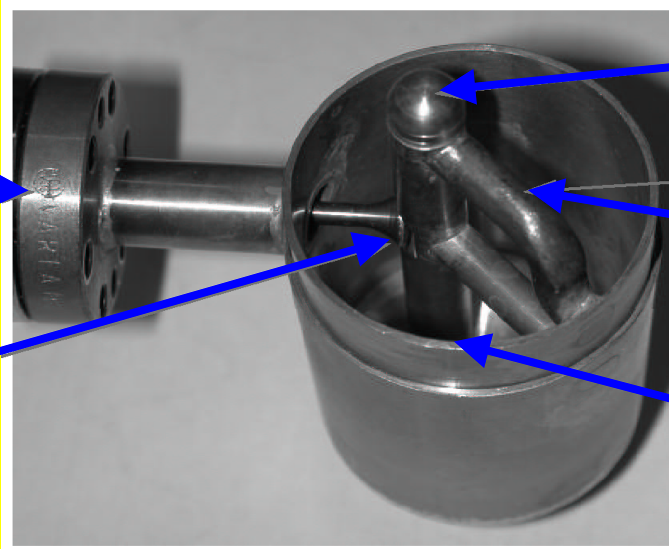
Microwave Studio model:



Copper model:



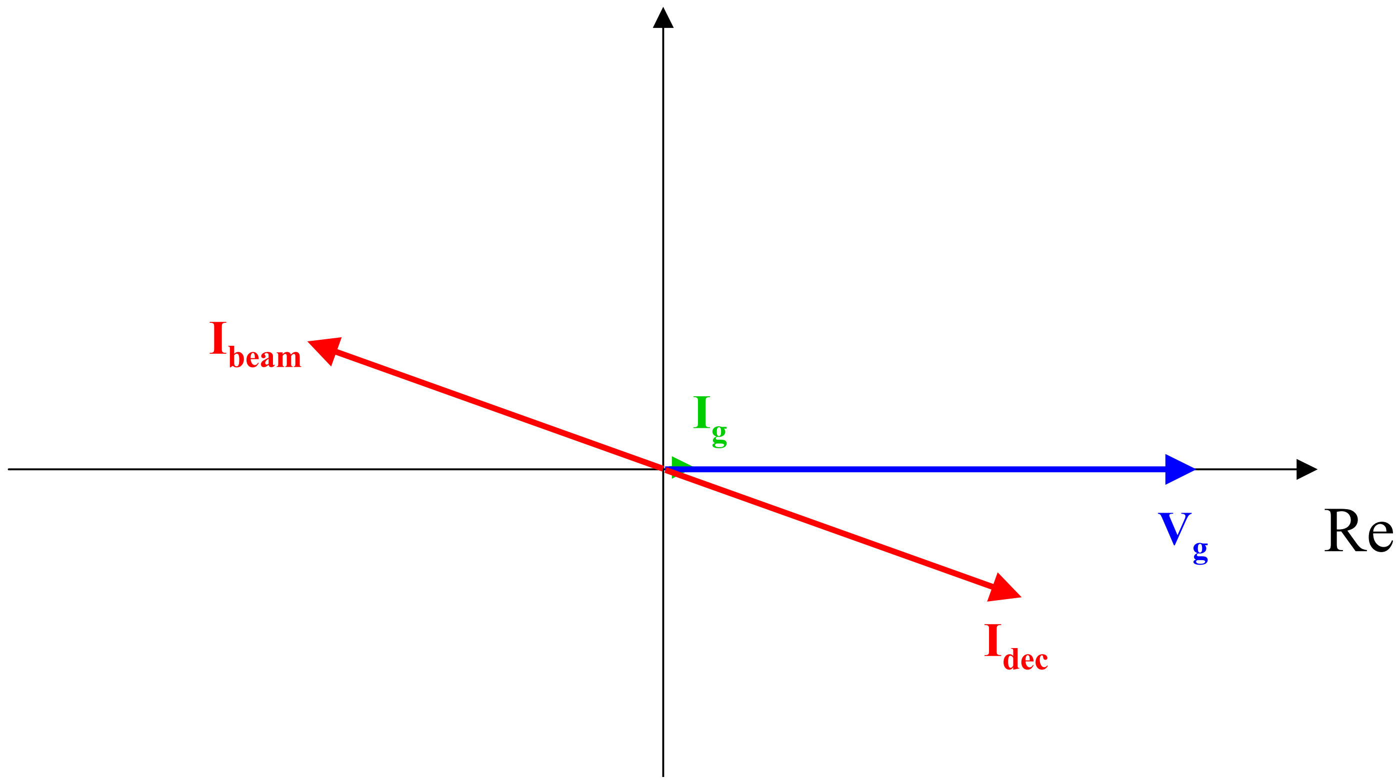
Coupler model:



Main Linac Accelerating RF Field

- *Flexibility and stability with small $\Delta E/E$*
- *Efficient high Q_L operation with energy recovery:*
  - *efficient energy recovery and RF control of random beam loading*
  - *RF control in presents of microphonics and Lorentz-force detuning $\Rightarrow$ optimal loaded Q?*
  - *Minimum RF power required?*

ERL: RF Control of Random Beam Loading

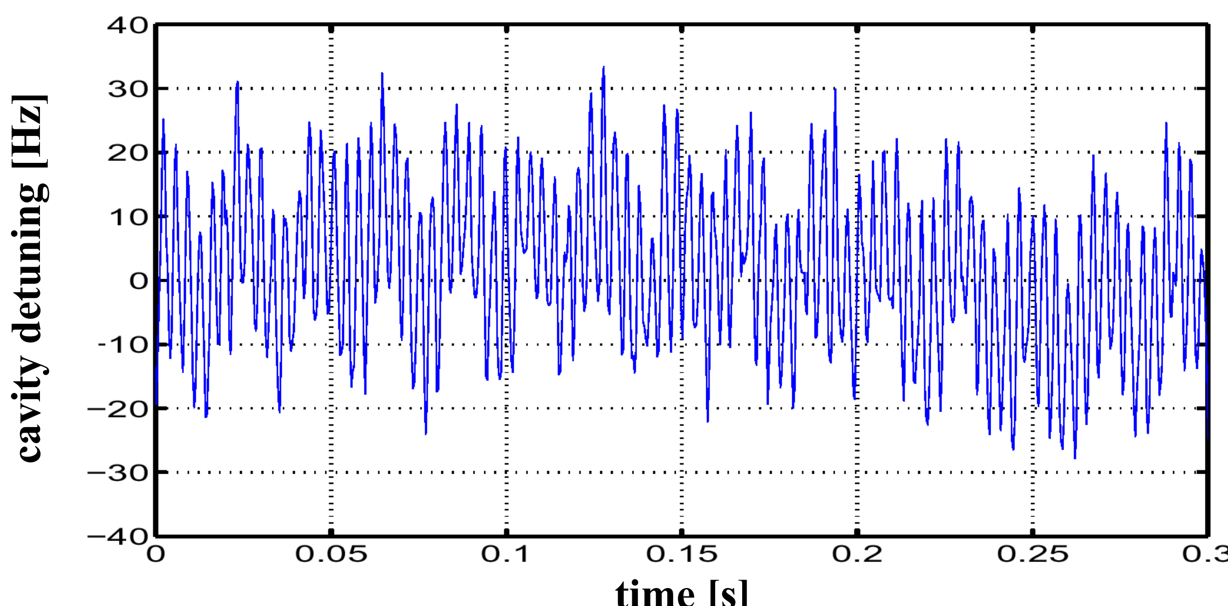


⇒ Path length errors (phase errors) and non-zero recirculation time will result in beam loading with fluctuation!

Microphonics

- ***Microphonics:*** **modulation of resonance frequency by external mechanical disturbances**
  - **thin wall thickness and small bandwidth of superconducting cavities**
    ⇒ sensitive to microphonics

Example: TTF 9-cell cavity in a horizontal test cryostat (cw operation)



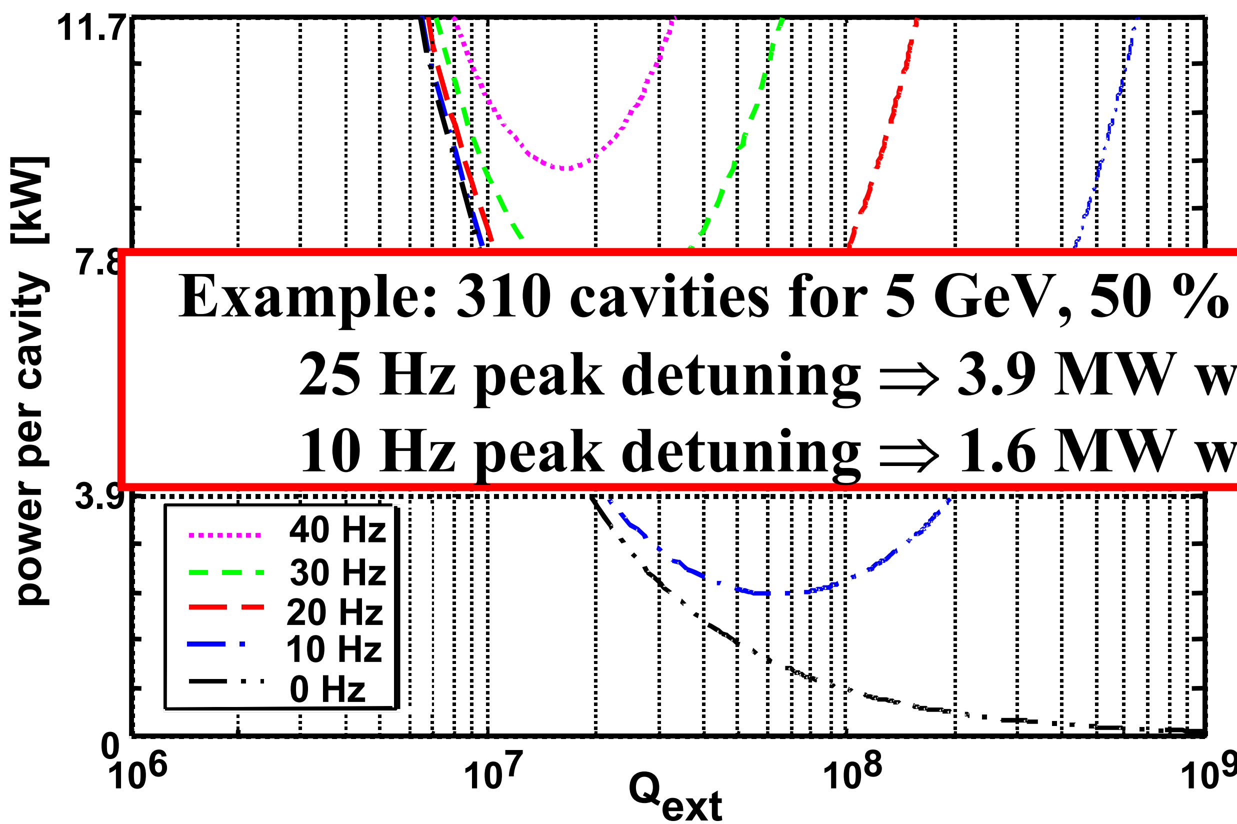
Cornell ERL:

Cavity bandwidth = 25 Hz !

⇒ Large field errors without field control!

Cornell ERL: Required RF Power without Beam Loading

7-cell main linac cavity at 20 MV/m:



$$V = \frac{\sqrt{4 \frac{R}{Q} Q_L P_g}}{\sqrt{1 + \left(\frac{f - f_0}{f_{1/2}} \right)^2}}$$

$$Q_{opt} = \frac{f}{2\,\Delta f}$$

$$P_{g,\min} = \frac{V_{acc}^2}{R/Q} \frac{\Delta f}{f}$$

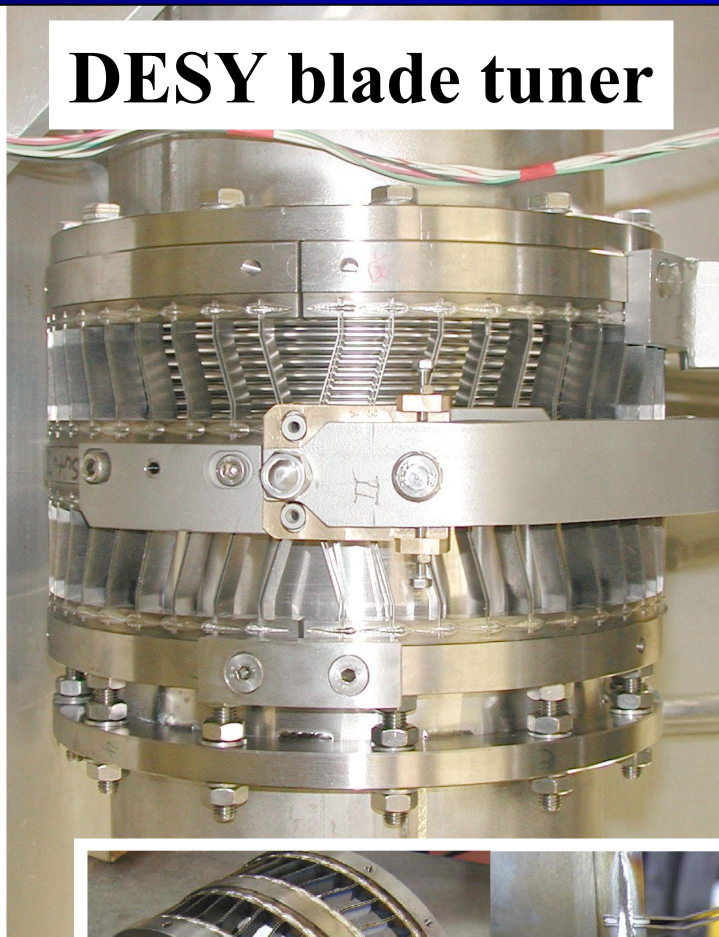
Example: 310 cavities for 5 GeV, 50 % klystron efficiency

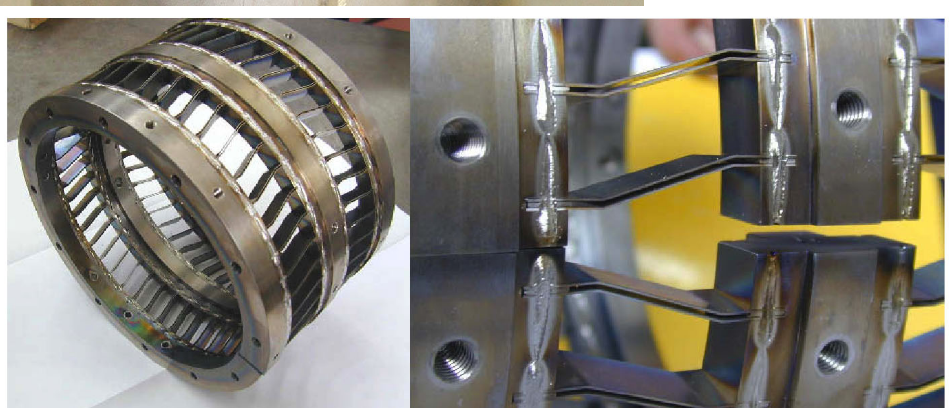
25 Hz peak detuning ⇒ 3.9 MW wall plug power

10 Hz peak detuning ⇒ 1.6 MW wall plug power

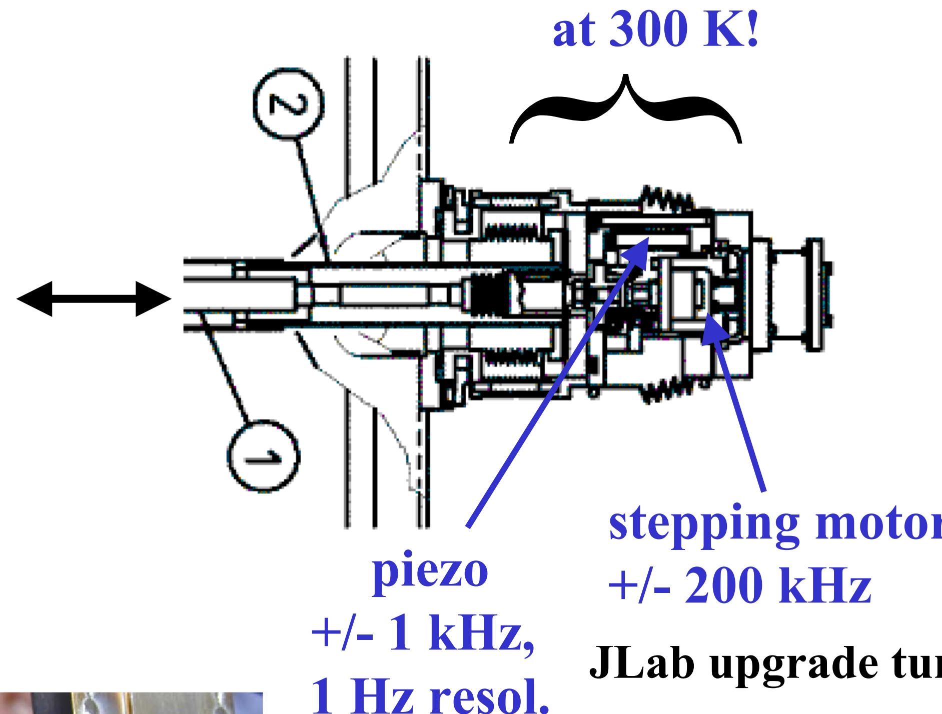
Peak microphonics detuning important!

Cornell ERL: Frequency Tuner



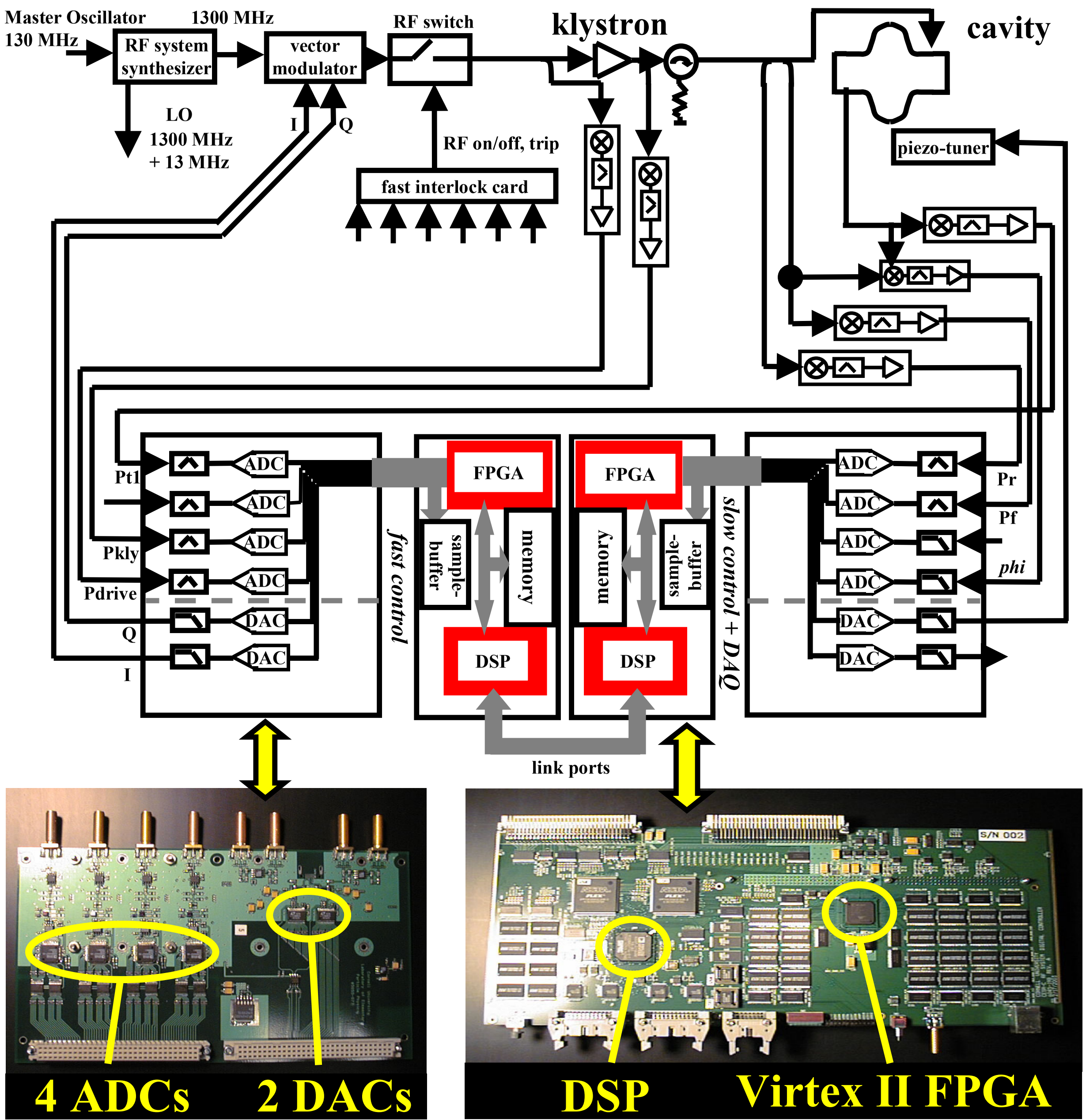


$\Rightarrow$ **Slow and fast frequency control!**



JLab upgrade tuner

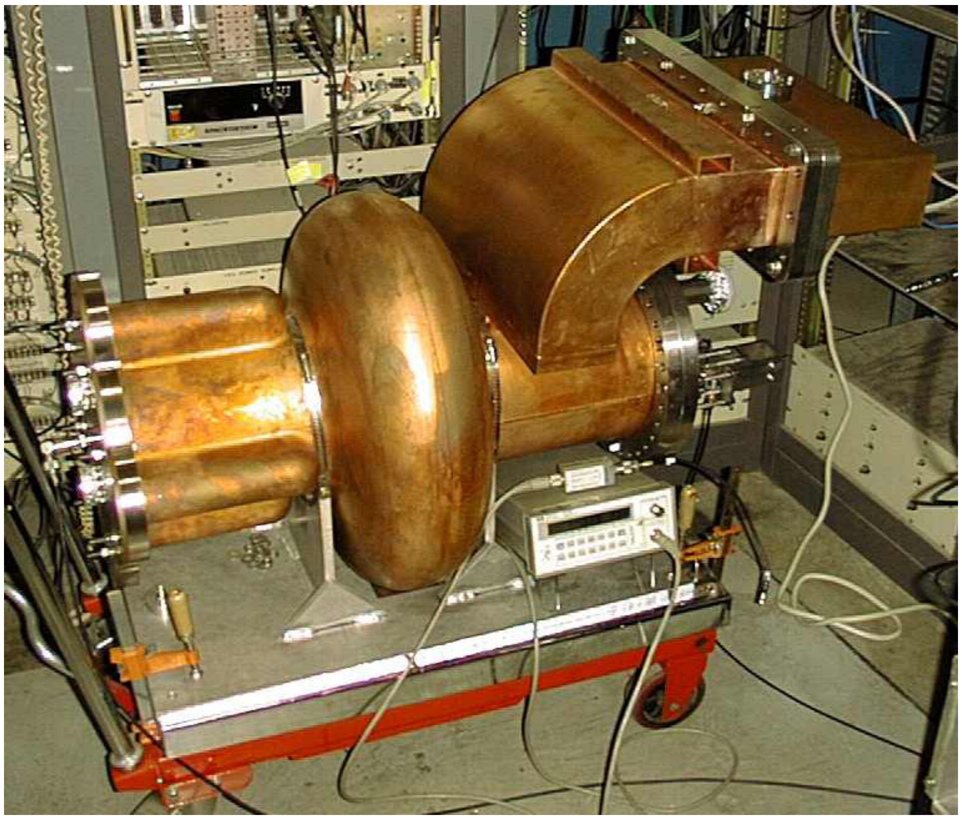
Ultra-Fast Digital RF Field Control System for the Cornell ERL



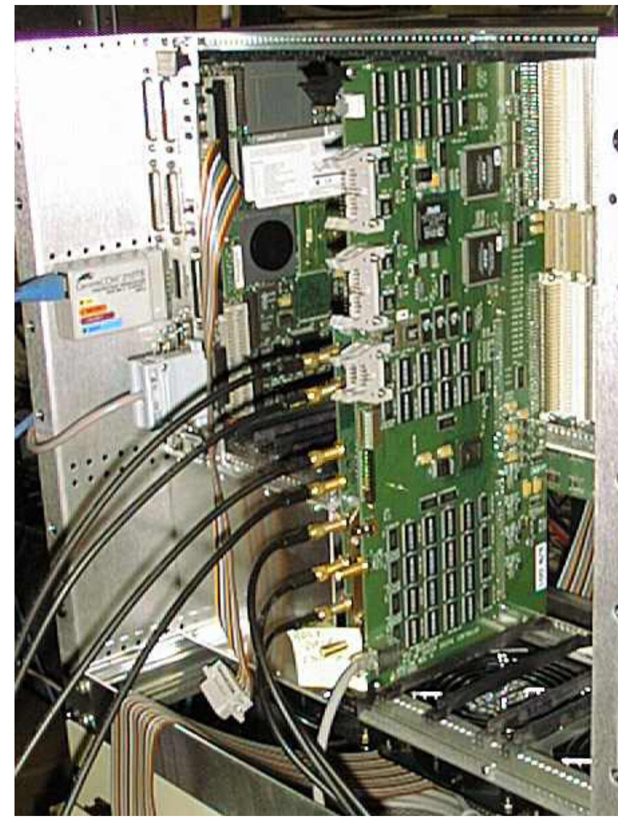
- *very low delay in the control loop (< 1 μs)*
- *Field Programmable Gate Array (FPGA) design combines the speed of an analog system and the flexibility of a digital system*
- *high computation power allows advanced control algorithms*
- *all boards have been designed in house*
- *generic design: digital boards can be used for a variety of control and data processing applications*

Test with Copper Cavity

500 MHz CESR copper cavity:



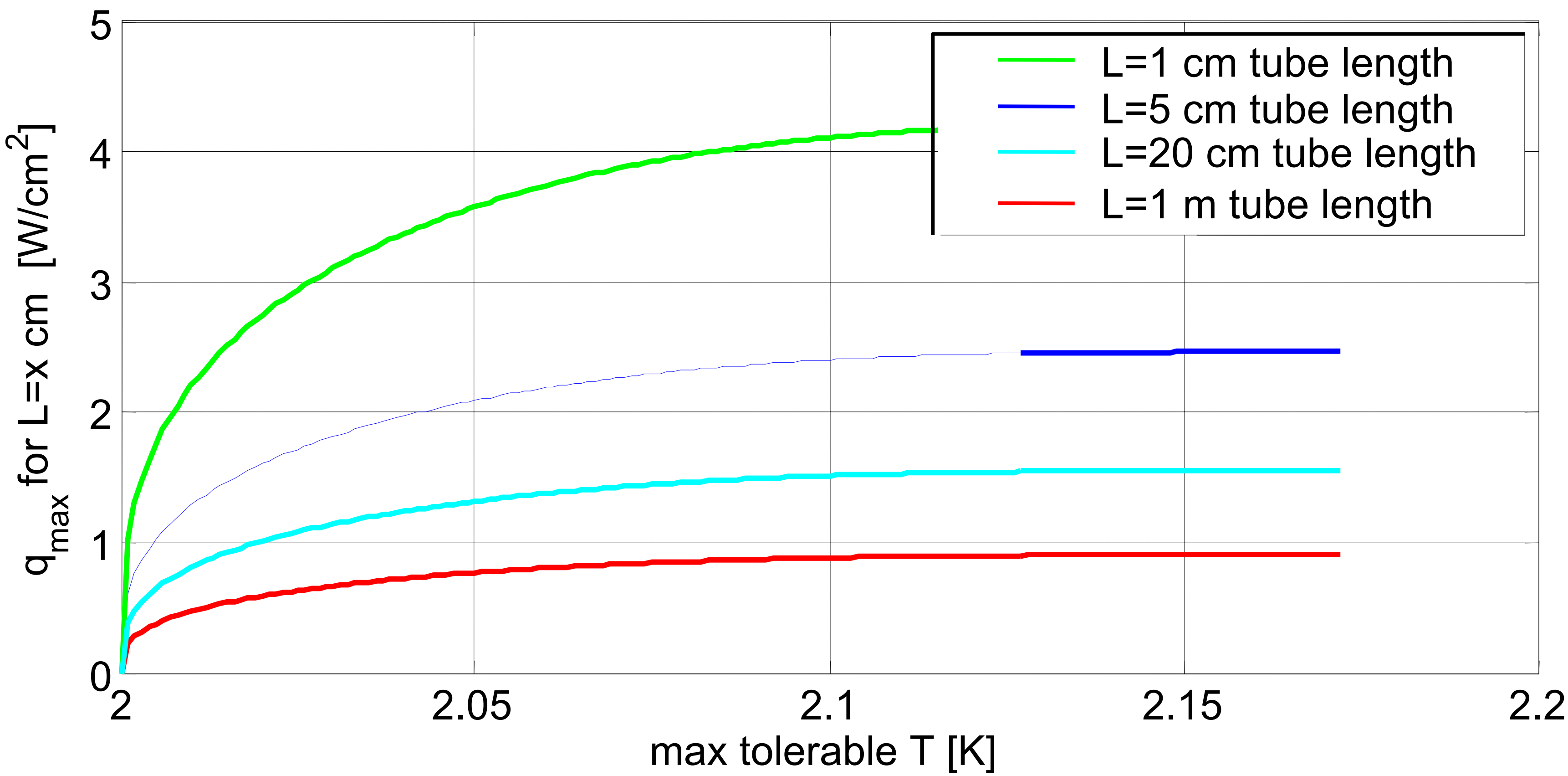
Digital Boards:



Cryogenic Challenges

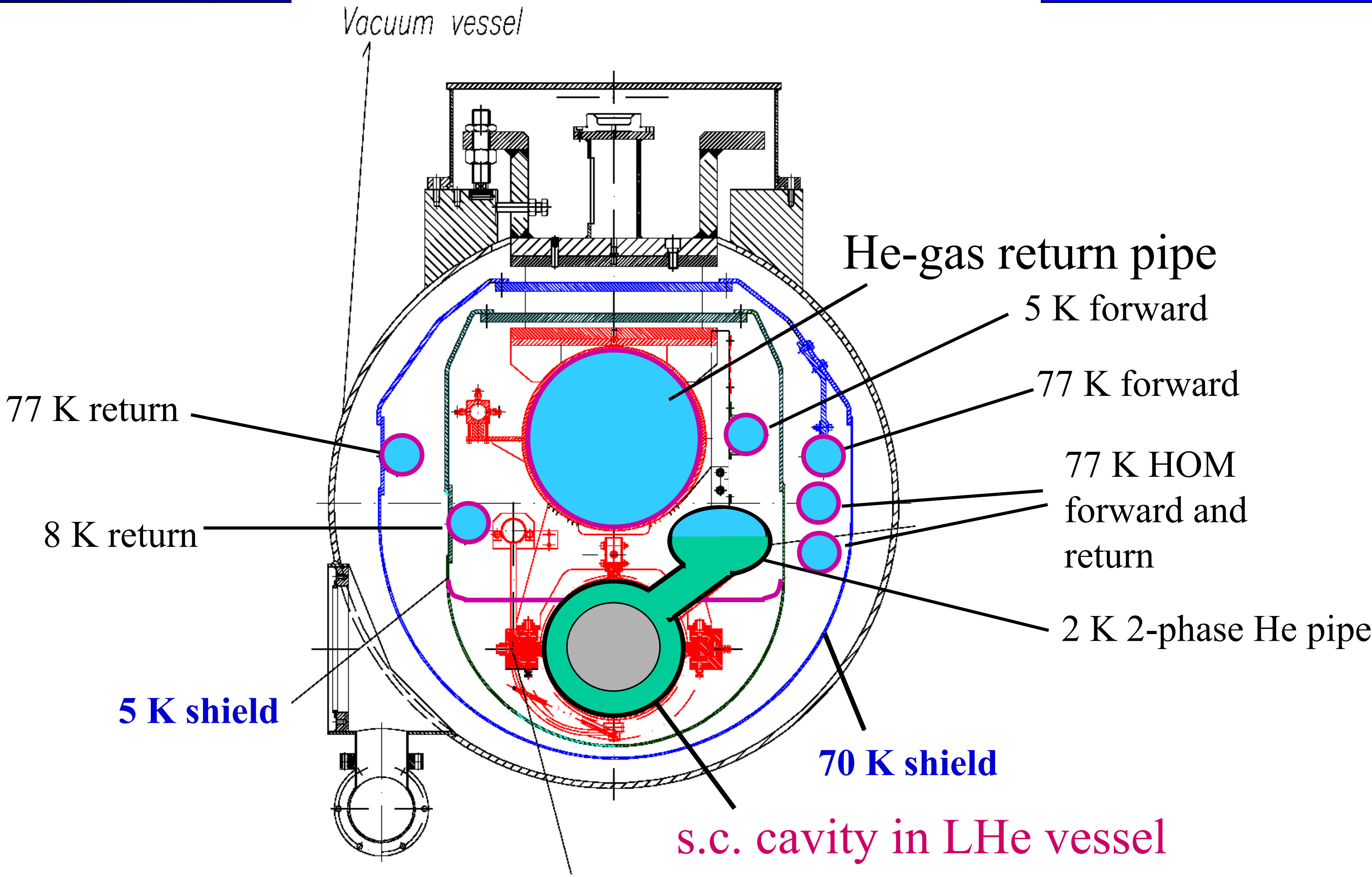
- **High gradient cw operation: dynamic head load dominates: Example: 20 MV/m, $Q_0 = 10^{10} \Rightarrow 40$ W/m**
- **Module design:**
  - **- Heat transfer through LHe $\Rightarrow$ need large enough pipes**
  - **- Mass transport of helium gas $\Rightarrow$ need large enough pipes**
  - **- HOM losses $\Rightarrow$ need cooling of absorbers**
- **Cavity:**
  - **- Cavity treatment for high Q_0**
  - **- Optimal bath temperature?`**

Maximum Heat Flux in a 2 K LHe II Bath



⇒ need large enough LHe pipes

Cornell ERL Cryomodule Concept: TTF Module modified for CW Operation



C-ERL: Cryogenic Loads per Module with 10 7-cell Cavities (20 MV/m, 100 mA, $Q_0=10^{10}$)

2 K static loads	
Supports	0.5 W
Instrum. cables	0.21 W
Input Couplers	0.2 W
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
Input couplers	1.6 W
HOM absorber	15 W
HOM Couplers	6 W
Total 2 K	**363.1 W**
2 K efficiency (TESLA TDR)	**588 W/W**
Total wall plug power	**213.5 kW**

5 K static loads	
Radiation	1.7 W
Supports	2 W
Instrum. cables	1.2 W
Input Couplers	1.3 W
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
Input couplers	12 W
HOM absorber	150 W
HOM Couplers	12 W
Total 5 K	**201.1 W**
5 to 8 K efficiency (TESLA TDR)	**168 W/W**
Total wall plug power	**33.8 kW**

77 K static loads	
Current leads	13 W
Radiation	38.4 W
Supports	5 W
Instrum. cables	4.5 W
Input Couplers	65 W
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
Input couplers	210 W
HOM absorber	1335 W
HOM Couplers	60 W
Total 77 K	**1742.3 W**
77 K efficiency (TESLA TDR)	**17 W/W**
Total wall plug power	**29.6 kW**

Example: 5 GeV, 20 % cryo overhead

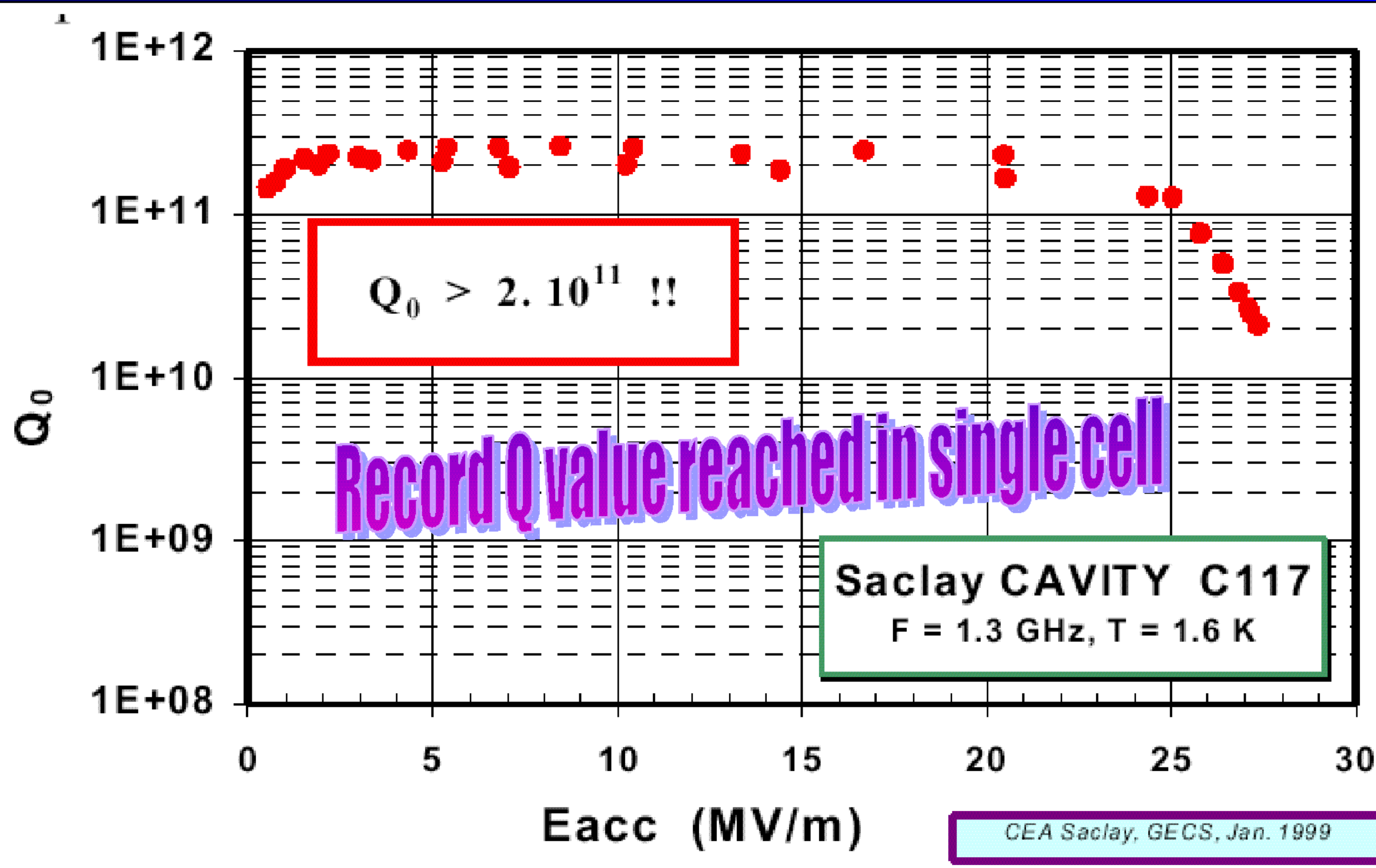
$Q_0 = 1\cdot10^{10} \Rightarrow$ 10.3 MW wall plug power

$Q_0 = 2\cdot10^{10} \Rightarrow$ 6.7 MW wall plug power

R_{BCS} and LHe Bath Temperature

- R_{BCS} decreases significantly if T is lowered.
- Important: The residual resistance must be low to make use of this! ⇒ Very good shielding of Earth's magnetic field (< some mOe).
- Examples:
  - $T = 2.0\ K \Rightarrow Q = 2.6 \cdot 10^{10}$
  - $T = 1.8\ K \Rightarrow Q = 6.3 \cdot 10^{10}$
  - $T = 1.\ 6K \Rightarrow Q = 1.9 \cdot 10^{11}$
- A dream?…

High Q_0: Let's dream…

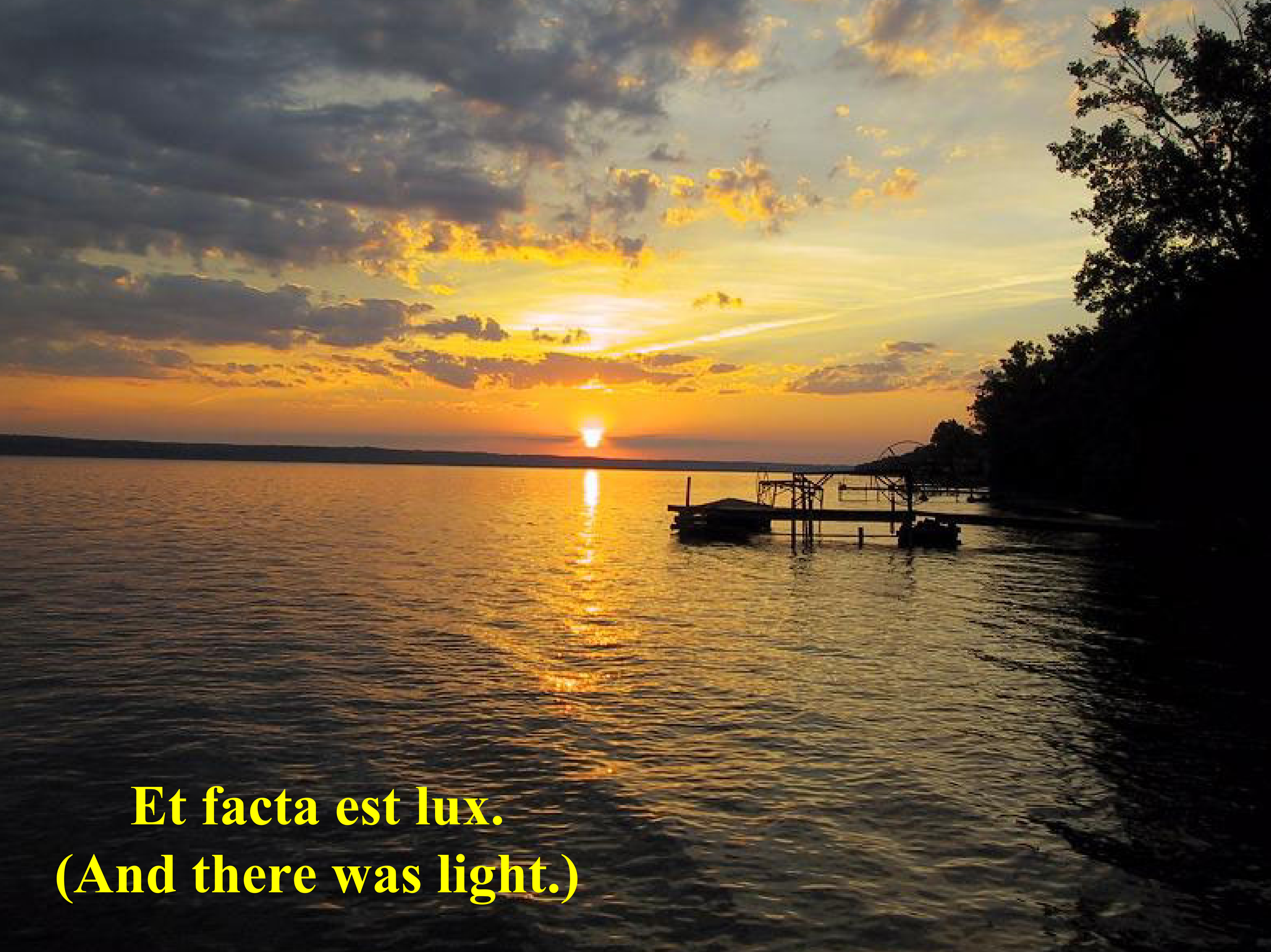


⇒ **2 W/m losses at 1.6 K instead of 20 to 40 W/m losses at 2 K?**

Outlook and Summary: SRF @ Cornell ERL

- **ERLs have the potential to produce photon beams with ultra high brilliance, coherence and ultra short pulses.**
- **Cornell is proposing to built an 100 MeV, 100 mA ERL prototype and we study a 5 GeV SR ERL light source.**
- **SRF is a key technology for these machines.**
- **Many challenges need our attention:**

  HOM damping, emittance preservation, RF field control, cw cavity operation at high fields, high power input couplers, ...
- **We have started to work in these areas and hope to start with the construction of the injector soon.**
- **Next year: first 2-cell cavity, first 50 kW input coupler, first HOM ferrite ring-absorber, injector module design.**


Et facta est lux.
(And there was light.)