Beam induced power in muon RCS RF systems

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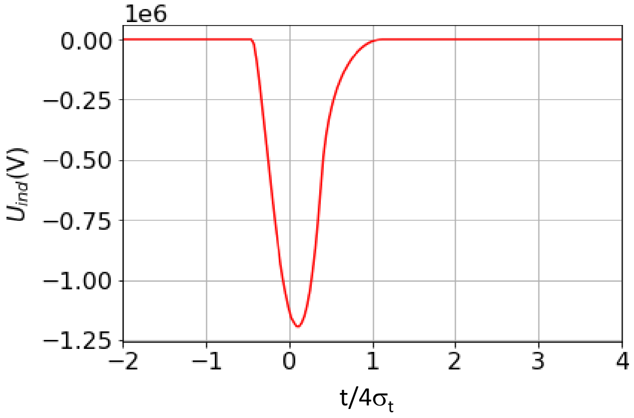
HEMAC meeting #14
19/1/2023

HOM power for the TESLA cavity:



- Bunch population $2.54\text{x}10^{12}$, T_{rev} = 20 μs → ***I* = 20.4 mA**
- Short-range induced voltage U_{ind} = 1.1 MV

→ Rough limit estimate per cavity: *P* = 20.4 mA x 1.1 MV = 22.4 kW

→ Calculate power loss through loss factor $k_{||}$ for each simulation step / RF station:

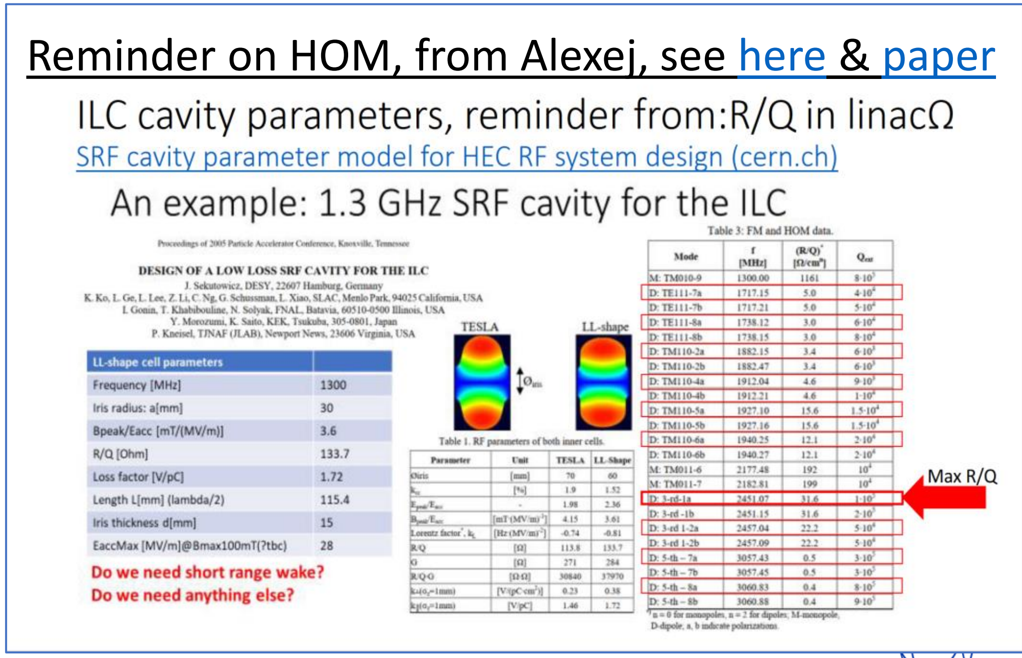
$$k_{||} = \int \lambda(t) W_{||}(t) dt$$

$$P = k_{||} * \frac{Q^2}{T_B}$$ with bunch charge *Q* and bunch spacing T_B = T_{rev}

The geometry of the cavity defines all HOM, i.e. for single-bunch cases, the short-range wakefield from K.Bane includes the HOM power losses

As a check, the approximation for short Gaussian bunches gives

$$k_{||} = |\frac{R}{Q}| \frac{\omega_r}{2} \quad (\frac{\omega_r}{4} \text{ for Linac norm})$$



Reminder on HOM, from Alexej, see here & paper

ILC cavity parameters, reminder from:R/Q in linacΩ
SRF cavity parameter model for HEC RF system design (cern.ch)

An example: 1.3 GHz SRF cavity for the ILC

Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee

DESIGN OF A LOW LOSS SRF CAVITY FOR THE ILC

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LL-shape cell parameters	
Frequency [MHz]	1300
Iris radius: a[mm]	30
Bpeak/Eacc [mT/(MV/m)]	3.6
R/Q [Ohm]	133.7
Loss factor [V/pC]	1.72
Length L[mm] (lambda/2)	115.4
Iris thickness d[mm]	15
EaccMax [MV/m]@Bmax100mT(?tbc)	28

Do we need short range wake?
Do we need anything else?

TESLA LL-shape $Ø_{iris}$

Table 1. RF parameters of both inner cells.

Parameter	Unit	TESLA	LL-Shape
Øiris	[mm]	70	60
k_{cc}	[%]	1.9	1.52
E_{peak}/E_{acc}	-	1.98	2.36
B_{peak}/E_{acc}	[mT/(MV/m)]	4.15	3.61
Lorentz factor*, k_L	[Hz/(MV/m)^2]	-0.74	-0.81
R/Q	[Ω]	113.8	133.7
G	[Ω]	271	284
R/Q·G	[Ω·Ω]	30840	37970
$k_\perp(\sigma_z=1mm)$	[V/(pC·cm^2)]	0.23	0.38
$k_{||}(\sigma_z=1mm)$	[V/pC]	1.46	1.72

Table 3: FM and HOM data.

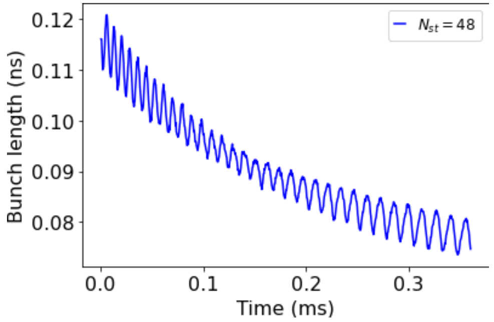
Mode	f [MHz]	(R/Q)* [Ω/cm^{2n}]	Q_{ext}
M: TM010-9	1300.00	1161	8·10^5
D: TE111-7a	1717.15	5.0	4·10^4
D: TE111-7b	1717.21	5.0	5·10^4
D: TE111-8a	1738.12	3.0	6·10^4
D: TE111-8b	1738.15	3.0	8·10^4
D: TM110-2a	1882.15	3.4	6·10^5
D: TM110-2b	1882.47	3.4	6·10^5
D: TM110-4a	1912.04	4.6	9·10^5
D: TM110-4b	1912.21	4.6	1·10^4
D: TM110-5a	1927.10	15.6	1.5·10^4
D: TM110-5b	1927.16	15.6	1.5·10^4
D: TM110-6a	1940.25	12.1	2·10^4
D: TM110-6b	1940.27	12.1	2·10^4
M: TM011-6	2177.48	192	10^4
M: TM011-7	2182.81	199	10^4
D: 3-rd-1a	2451.07	31.6	1·10^5
D: 3-rd -1b	2451.15	31.6	2·10^5
D: 3-rd 1-2a	2457.04	22.2	5·10^4
D: 3-rd 1-2b	2457.09	22.2	5·10^4
D: 5-th – 7a	3057.43	0.5	3·10^5
D: 5-th – 7b	3057.45	0.5	3·10^5
D: 5-th – 8a	3060.83	0.4	8·10^5
D: 5-th – 8b	3060.88	0.4	9·10^5

*n = 0 for monopoles, n = 2 for dipoles; M-monopole, D-dipole; a, b indicate polarizations.

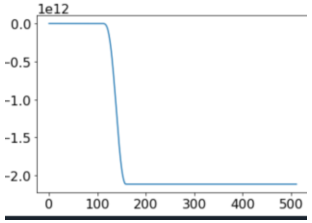
Max R/Q

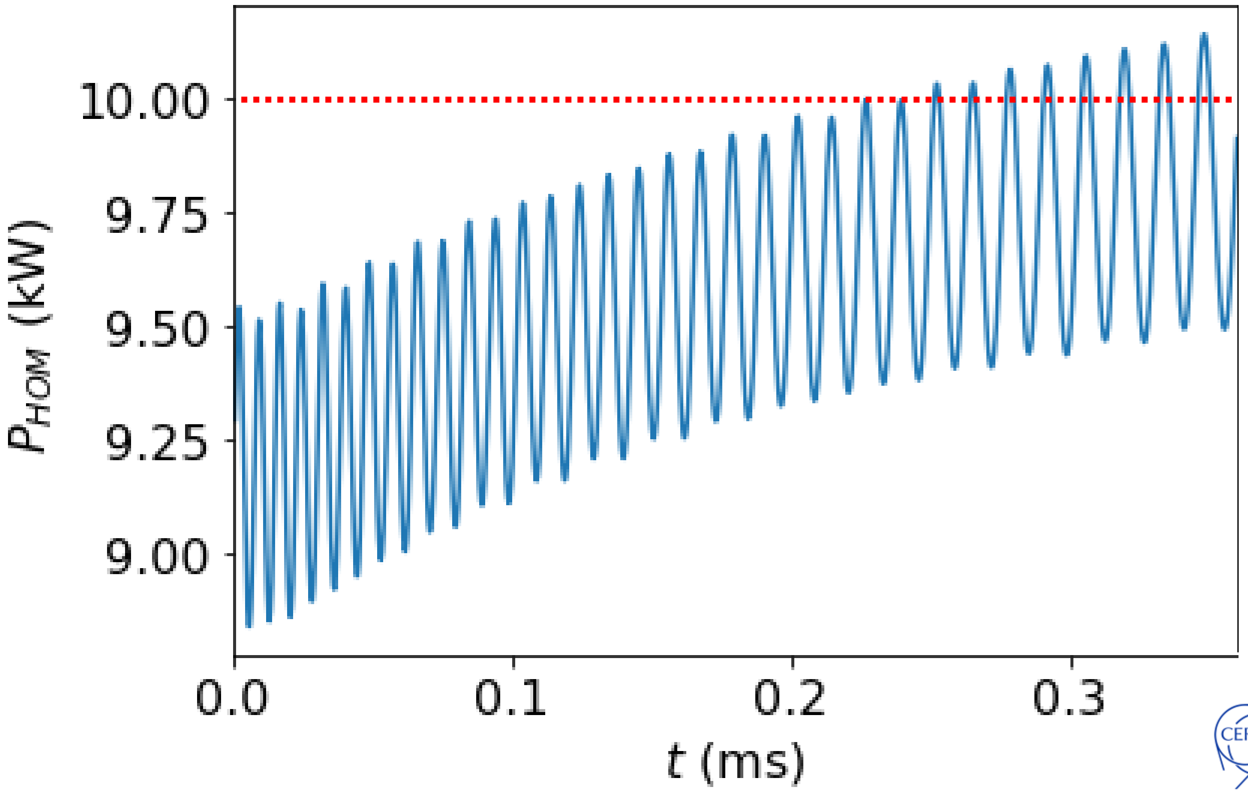
Beam-induced power in RCS1:

- Used parameters: RCS1, 48 RF stations, 696 cavities, 90% survival, bunch length 0.1 ns



- The loss factor reaches $k_{||} = \int \lambda(t) W_{||}(t) dt$ = - 2.11 V/pC





- The power loss per cavity reaches 10.4 kW!

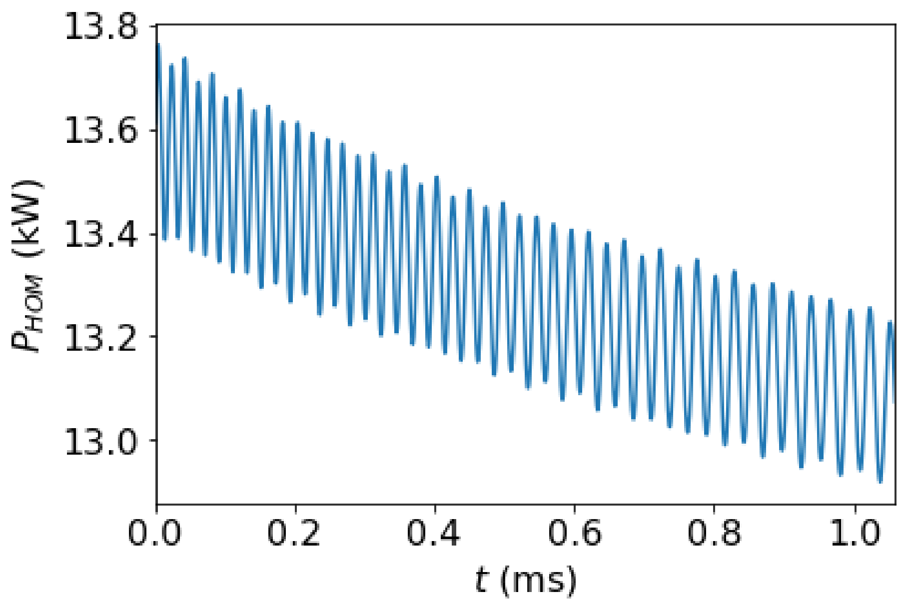
- Consistent with upper limit of 22.4 kW

- and the loss using $k_{||} = \left|\frac{R}{Q}\right| \frac{\omega_r}{2}$ → P = 10.0 kW

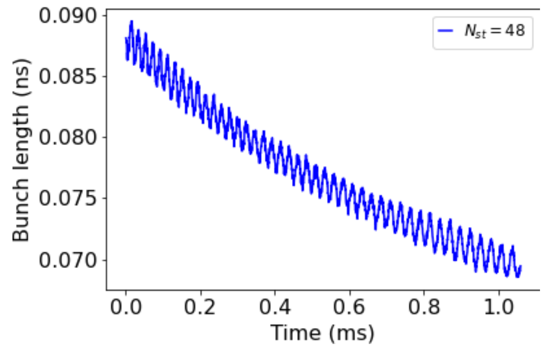
(comment: this used the fundamental mode, but since short-range and fund. mode induce the same voltage, this is ok for comparison)

Beam-induced power in the other RCSs:

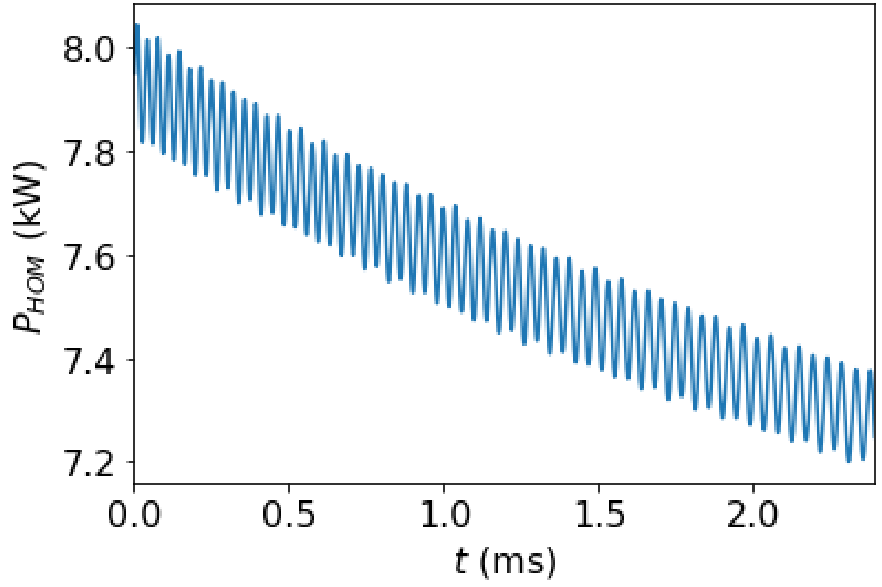
- **RCS2, 48 RF stations:**



Larger power loss due to shorter bunches:



RCS3, 48 RF stations:



Larger ring gives smaller average power

Comparison with ILC:

- **From Heiko's presentation:**

	ILC	RCS1
Number of bunches, n_b	1312	1 each μ^+ and μ^-
Bunch length σ_z	300 μm	0.1 ns to 0.02 ns (5 mm)
Bunch spacing, τ_{bs}	554 ns	T_{rev} = 20 μs
Bunch intensity, N_b	$2 \cdot 10^{10}$ p/b	$2.5 \cdot 10^{12}$ p/b
Average beam current, I_b	5.8 mA	2 $\times$ ~20 mA

- **A rough estimate of the short-range power loss per cavity gives:**

Field		Result
Accelerating mode	Depend on Q of HOM coupler	Eq. (2)
Short range longitudinal wake	From parameters in TESLA-TDR	~ 400 W/cavity
Long range longitudinal wake	Depend on parameters of modes	Eq. (7)
Dipole and higher mode	Depend on beam - cavity offset	Negligible

[K. Kubo , Link]

- **More under cavities under [link, p.78]** →

Type /No. of cavities			*P_{beam}/cavity [kW]*	*P_{HOM}/cavity [kW]*
KEK-B 0.5 GHz  x 8	*Single-cell with max I_{beam}*	*I_{beam} = 1.34 A 1389 bunches cw*	*350*	*16*
HERA 0.5 GHz x 16	*Multi-cell with max I_{beam}*	*I_{beam} ≤ 40 mA 180 bunches cw*	*60*	*0.13*
TTF-I , 1.3 GHz  x 1	*Multi-cell with max E_{acc}*	*E_{acc} = 35 MV/m 1.3ms/pulse 1Hz PRF*	*~100 Almost no beam loading*	*0*

Summary / Discussion:

- The induced power is very large, above 10 kW for RCS 1&2 per bunch -> bunch crossings?
- HOM power capability limit is 3-4 kW
- Without other adjustments, the wakefields scale with a^2, a the iris radius

→ A factor of 2.5 in power corresponds to √2.5 in iris radius or frequency

→ 1.3 GHz / √2.5 = 822 MHz ?

→ BUT: The JLAB cryomodule (750 MHz) HOM power capability is estimated to be 20kW per cavity [ref], with 5 HOM waveguide absorbers per cavity: [R.Rimmer]

→ Need definition of maximal acceptable power level to keep 1.3 GHz or switch to lower frequency

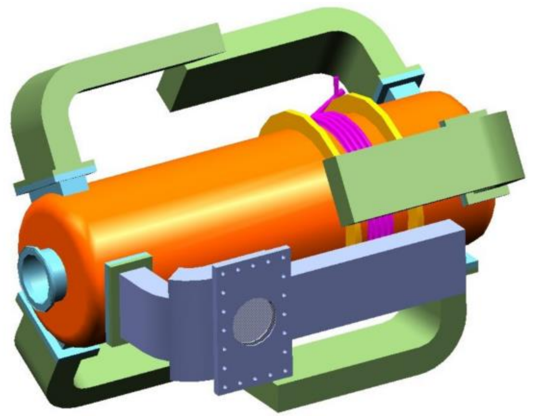


Figure 1: JLab Ampere class cavity with HOM loads and waveguide fundamental power coupler.

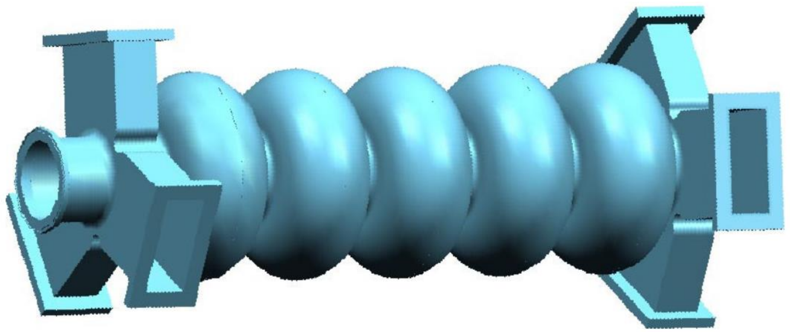
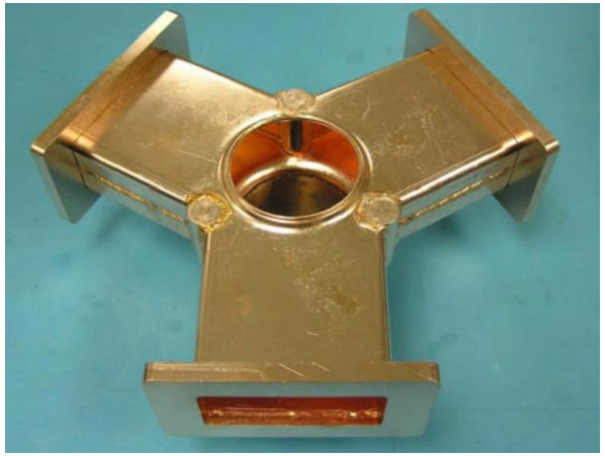


Figure 3: Five cell cavity with waveguide end groups.



all from [R.Rimmer]

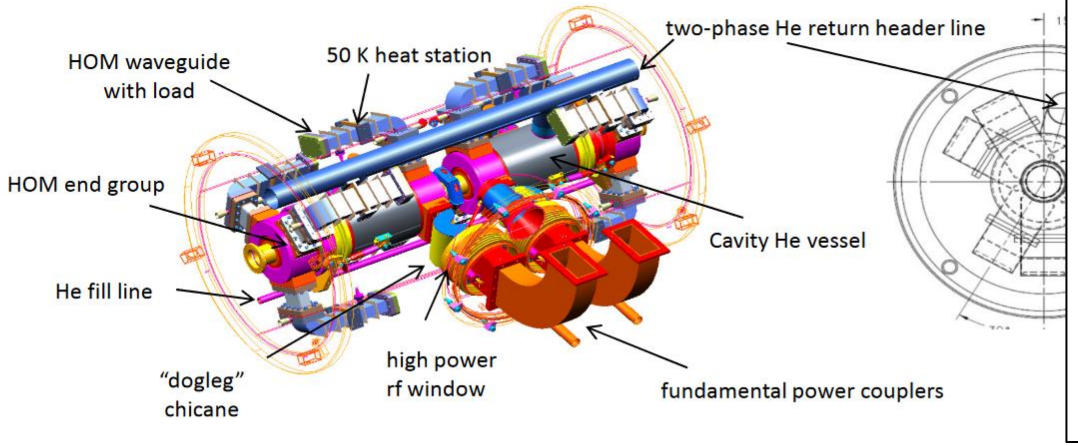
Summary / Discussion:

- **Concepts with up to 4 kW and 1.5 GHz presented: see [F.Marhauser2009, PERLE coll. Meeting 2022]**

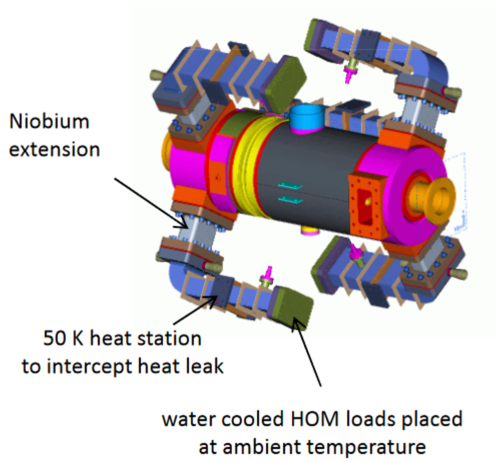
See also Shahnam's PhD thesis

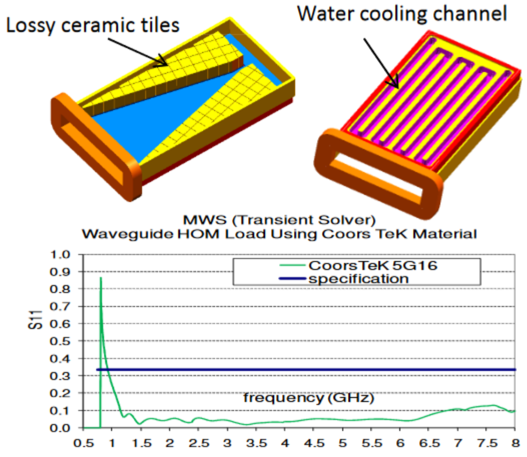
JLAB HC Cryomodule Development
Conceptual Design

- ❑ Conceptual design worked out for next generation of compact ERL-based high power FELs to transport very high beam currents
- ❑ Requirements:
  - Combination of high gradient, multi-cell cavities
  - Strong HOM damping to increase BBU threshold limits
- ❑ Concepts developed both for very high current or multi-pass ERL's requiring rather low frequency cavities (< 1 GHz) with large apertures and for higher frequencies (1.3-1.5 GHz) for low to moderate beam currents (up to 100 mA)



Conceptual design of a cavity-pair injector cryomodule (L=2.6m)





High power load design and simulation results

ERL Workshop, Cornell University , Ithaca, 8-12. June 2009
Jefferson Lab

What would look different with 802 MHz cavities?

- **Some parameter that change with the FCC-ee 5-cell cavity:**

	TESLA/ILC	FCC-
Frequency f_{RF} [MHz]	1300	801.58
Cells	9	5
Active length L_{active} [mm]	1038	935
Cavity length L_{cav} [mm]	1276	1291
Gradient [MV/m]	30 (conservative)	25
Number of cavities RCS1	696	835
Straight length RCS 1	2334	2334
Straight length with RF	38 %	46 %

CERN