Review of proposals of ERL injector cryomodules

S. Belomestnykh
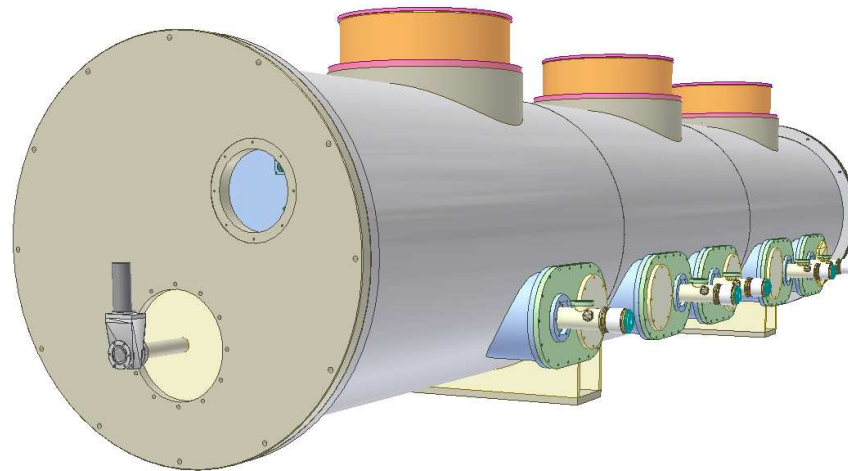
Introduction

In this presentation we will review injector cryomodule designs either already existing or under development for "high-average-current", "high-brightness" ERL proposals.

Overview of an injector cryomodule requirements & challenges

An injector cryomodule serves to accelerate "soft" beam obtained from an electron gun while preserving its emittance. The energy gain should be high enough to make it suitable for injection into a main linac of an ERL, but low enough to avoid unnecessary waste of power. Typically beam energy after a DC gun is ~ 0.5 MeV and to be "rigid" enough for the main linac, the beam energy should be in the range 5 to 10 MeV.
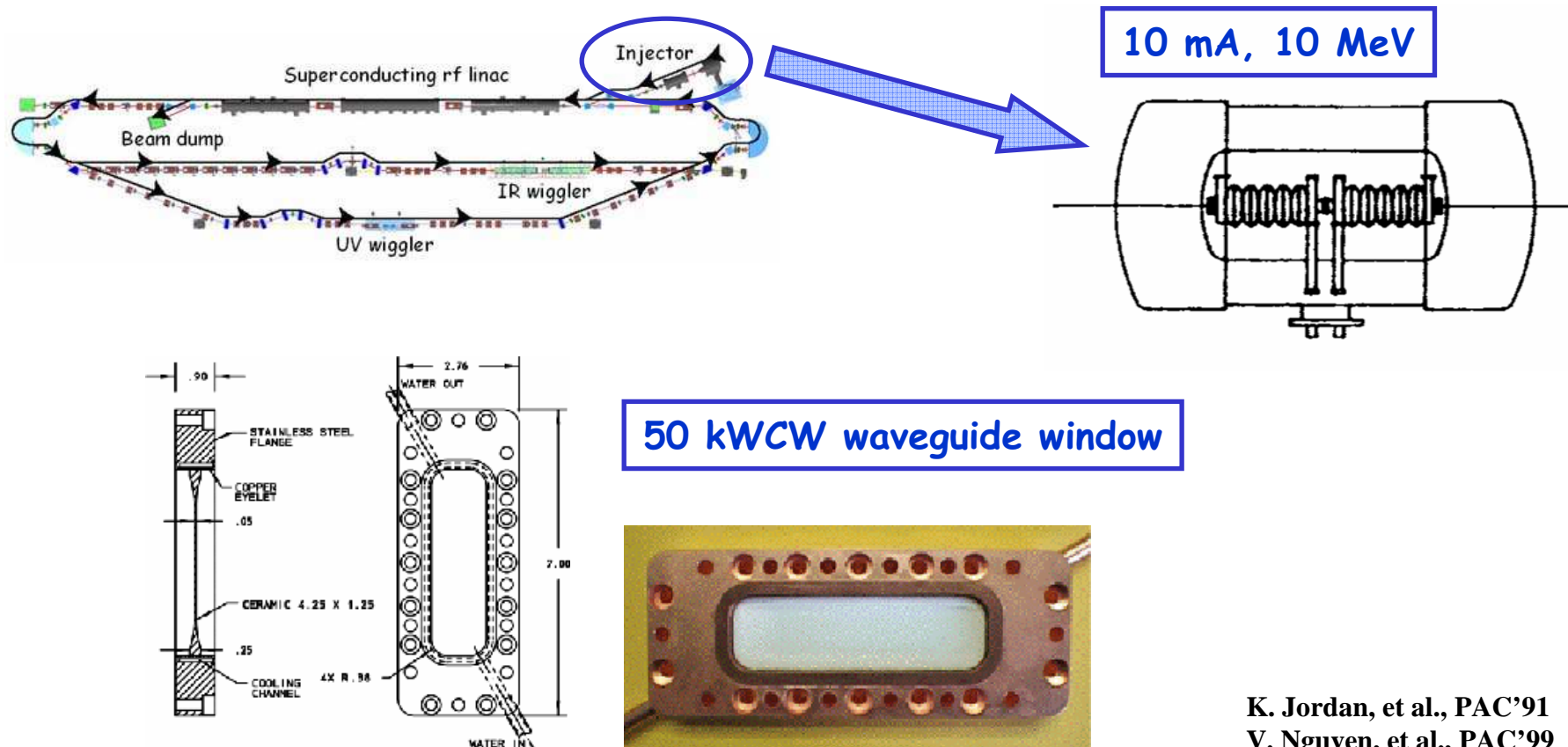
One may ask a question: Why the main linac cryomodule cannot be used in the injector? There are few reasons for that:
i)   Its energy gain is too high (for a cryomodule with eight 9-cell TESLA cavities operating at 20 MV/m, the energy gain is 160 MeV);
ii) Unlike the main linac cryomodule, operating at essentially zero beam loading, the injector cryomodule has to deliver significant amount of RF power to beam;
iii) Optimization of the emittance preservation may require more flexibility in arranging RF than is available with the main linac cavities.

In other respects the requirements to the injector cryomodule are similar or relaxed in comparison to the main linac cryomodule. Hence for a not very demanding machine (average beam current up to ~ 10 mA and transverse emittance of ~ 10 mm×mrad) one can shorten the main linac cryomodule to the desirable acceleration and boost an input coupler design to provide required RF power.
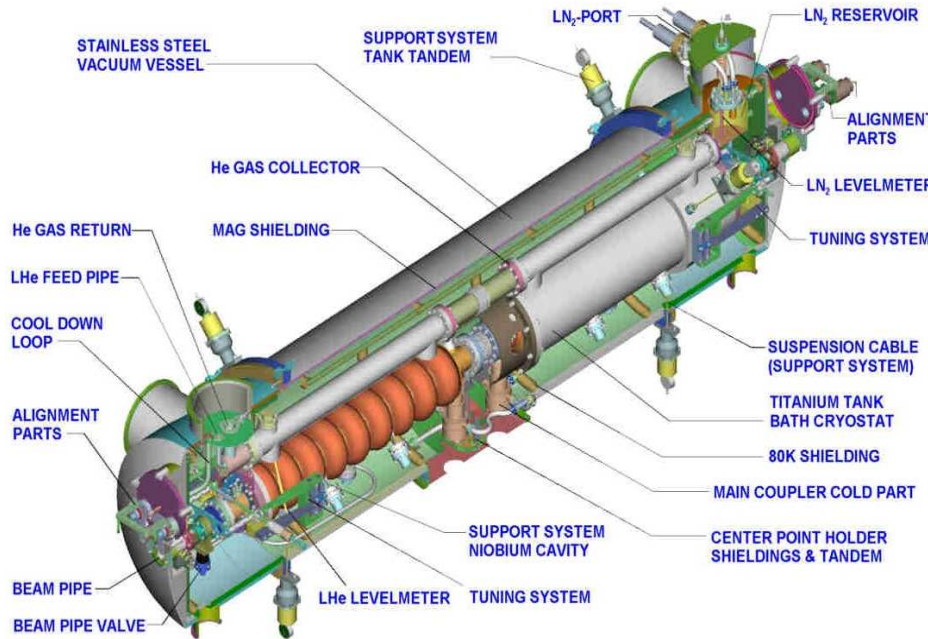
Example 1: JLAB FEL ¼ cryomodule

An example of this approach is JLAB FEL, where a ¼ - cryomodule (similar to ones used in CEBAF injector) was equipped with 50 kW waveguide windows. The result is an injector capable to deliver 10 mA, 10 MeV beam.

10 mA, 10 MeV

50 kWCW waveguide window

K. Jordan, et al., PAC'91
V. Nguyen, et al., PAC'99

Rossendorf's ELBE 2-cavity cryomodule

STAINLESS STEEL VACUUM VESSEL
SUPPORT SYSTEM TANK TANDEM
LN₂-PORT
LN₂ RESERVOIR
He GAS COLLECTOR
ALIGNMENT PARTS
LN₂ LEVELMETER
He GAS RETURN
MAG SHIELDING
TUNING SYSTEM
LHe FEED PIPE
COOL DOWN LOOP
SUSPENSION CABLE (SUPPORT SYSTEM)
ALIGNMENT PARTS
TITANIUM TANK BATH CRYOSTAT
80K SHIELDING
MAIN COUPLER COLD PART
SUPPORT SYSTEM NIOBIUM CAVITY
CENTER POINT HOLDER SHIELDINGS & TANDEM
BEAM PIPE
LHe LEVELMETER TUNING SYSTEM
BEAM PIPE VALVE

J. Tiechert, this workshop
M. Pekeler, et al., FEL'2004

Alternatively, one can adapt a design developed for a CW superconducting linac. An example is the cryomodule developed at Rossendorf for ELBE accelerator. It is based on two 9-cell TESLA cavities, but designed for CW operation at 10 MV/m and 1 mA beam current. The beam current is limited by 10 kW input couplers. Transverse emittance is ≤ 10 mm×mrad.

This cryomodule has recently become available from industry (ACCEL). The guaranteed performance values are:

RF frequency	1300 MHz
Operating temperature	2 K
Accelerating gradient	15 MV/m guaranteed 20 MV/m goal
Q_0 @ 15 MV/m	5×10^9
Rf power per coupler	8 kW cw
Stand by losses	<15 W
Length (flange to flange)	3.26 m

Example 2: ELBE cryomodules in 4GLS ERLP

At Daresbury ELBE cryomodules were chosen for 4GLS ERLP project and are used both in the injector and in the main linac. The booster cavities will operate at a reduced gradient of 4 MV/m.
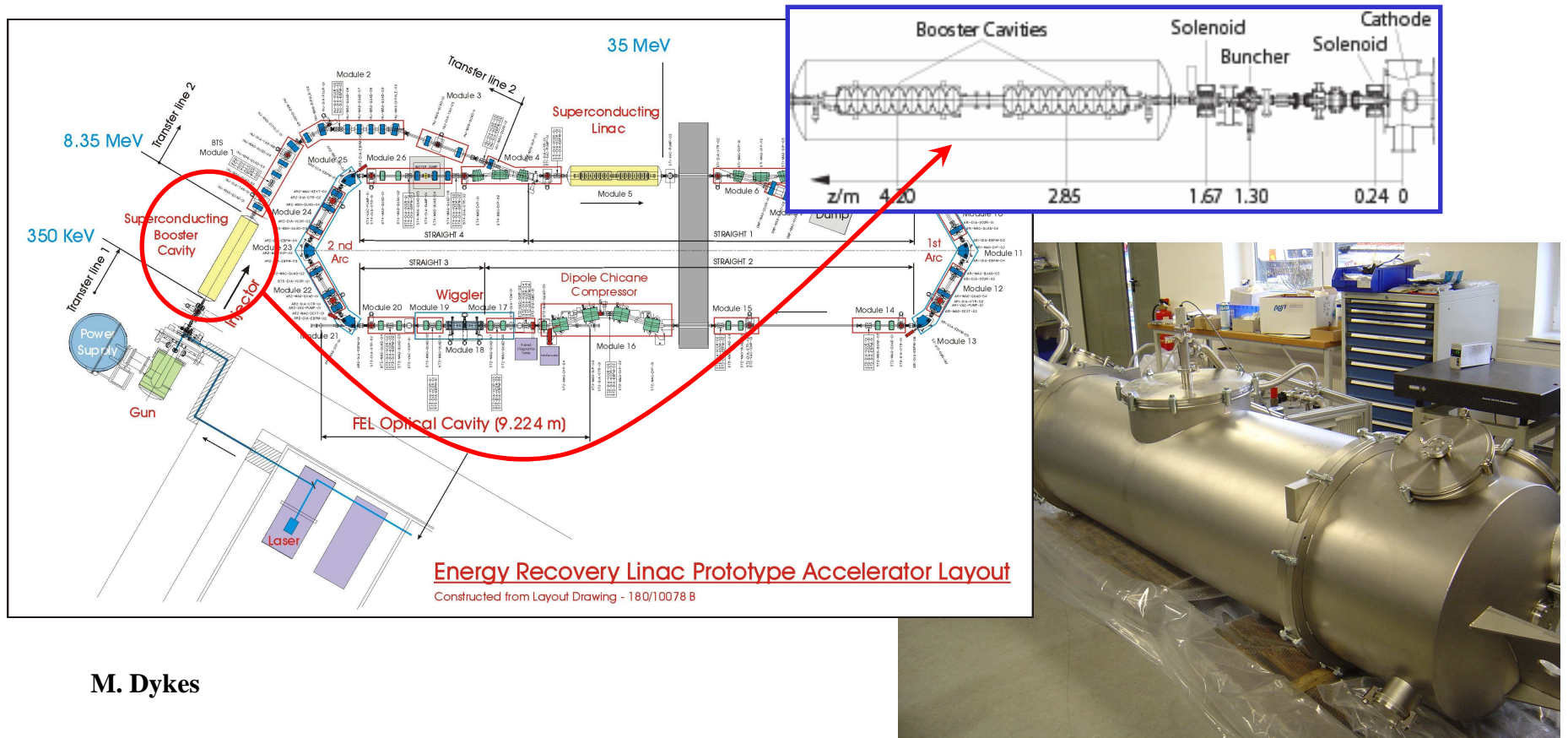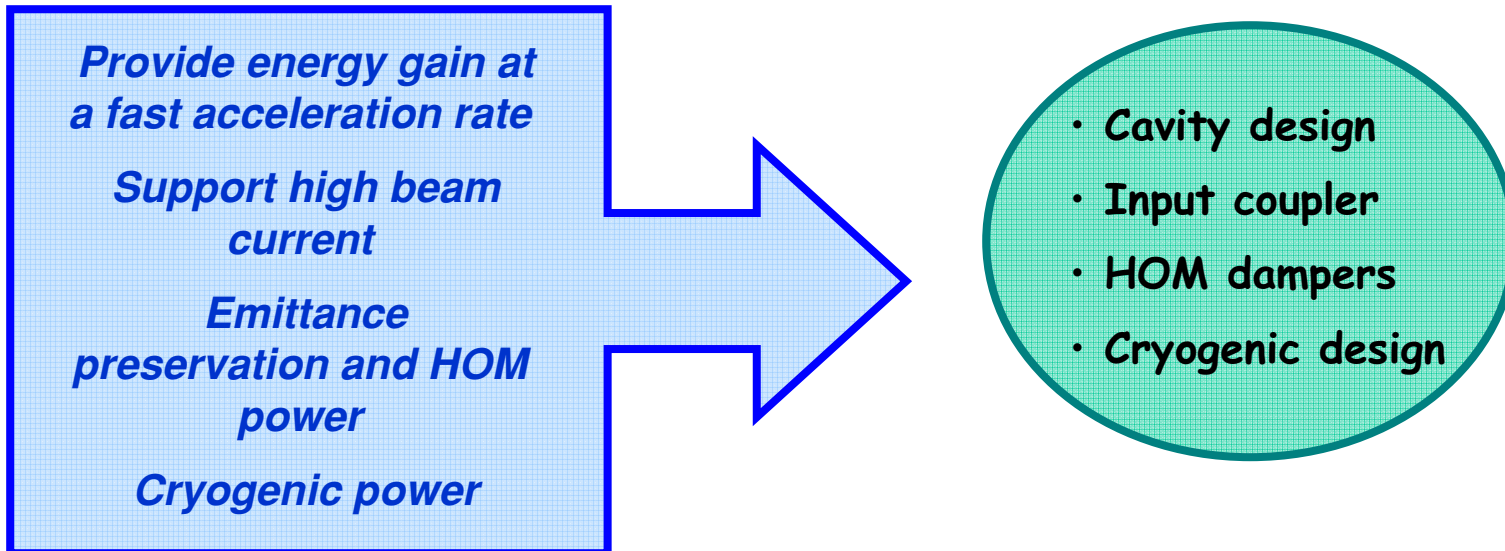

M. Dykes

100 mA average current cryomodules

As we had already mentioned, the major challenges here are: supporting high average beam current and preservation of the low transverse emittance obtained in the electron gun. Because of high beam power, the limiting factor is usually not the cavity's accelerating gradient, but the capability of an input coupler. The limit on the RF power determines the acceleration per cavity and the number of cavities in the injector. The need to reduce space charge effect dictates reasonably fast acceleration and hence drop in number of cells per cavity. This, in turn, eases HOM damping. Such effects as the input coupler kick and vacuum chamber wakefileds also should be taken care of to limit the emittance growth. A side benefit of larger number of cavities is more operational flexibility as one can chose different field amplitude and/or off-crest phase for different cavities. So "typical" high-average-current-capable injector cavities has several (three to five) one- or two-cell cavities equipped with 100-kWCW class input couplers and enhanced HOM damping ($R/Q \times Q_{HOM} \sim 10^4$).

Two injector cryomodules are under development for 100 mA average beam current operation. One is for a 100 kW FEL at JLAB, the other is for Cornell ERL. We will review the first one and then use the second one to highlight some possible design approaches.

Major issues and challenges

Provide energy gain at a fast acceleration rate

Support high beam current

Emittance preservation and HOM power

Cryogenic power

⟹

- Cavity design
- Input coupler
- HOM dampers
- Cryogenic design

- **High RF power transfer to beam for acceleration of high current beam $\Rightarrow$ input coupler challenge: 1 MeV per cavity * 0.1 A = 100 kW!**

- **High beam loading needs to be compensated very accurately $\Rightarrow$ RF control challenge.**

- **Emittance preservation $\Leftrightarrow$ reduce space charge effects, small transverse kick fields.**

- **Strong damping of HOMs essential for emittance preservation and to reduce monopole power.**

- **CW cavity operation at higher fields $\Rightarrow$ cryogenic power $\Rightarrow$ cryostat design challenge.**

Low emittance preservation in a Linac
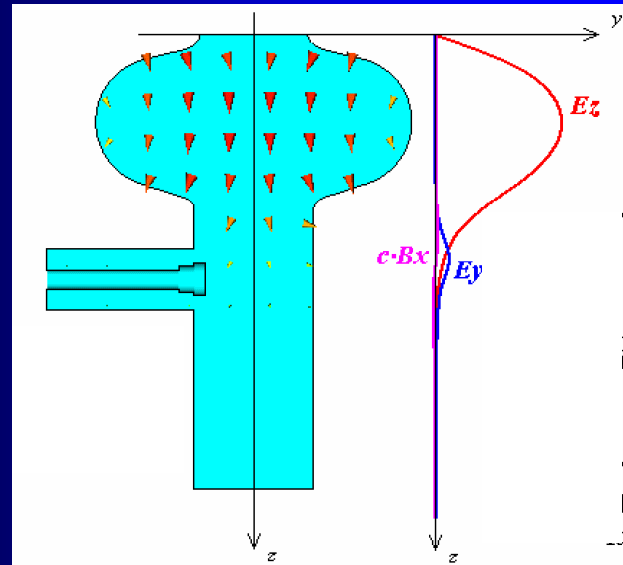
Wakefields:
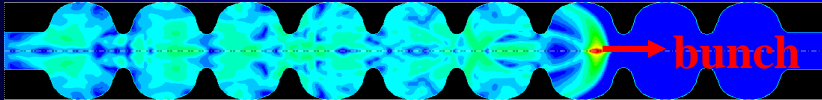
- longitudinal wakes generate energy spread

- transverse wakes generate time dependent kick fields $\Rightarrow$ transverse emittance growth
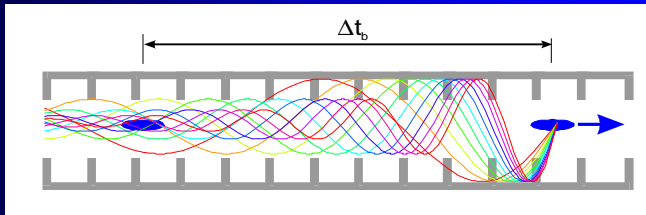
Coupler kicks:

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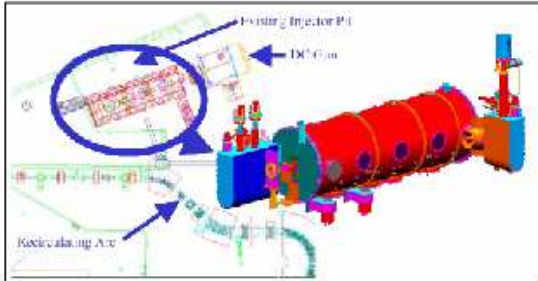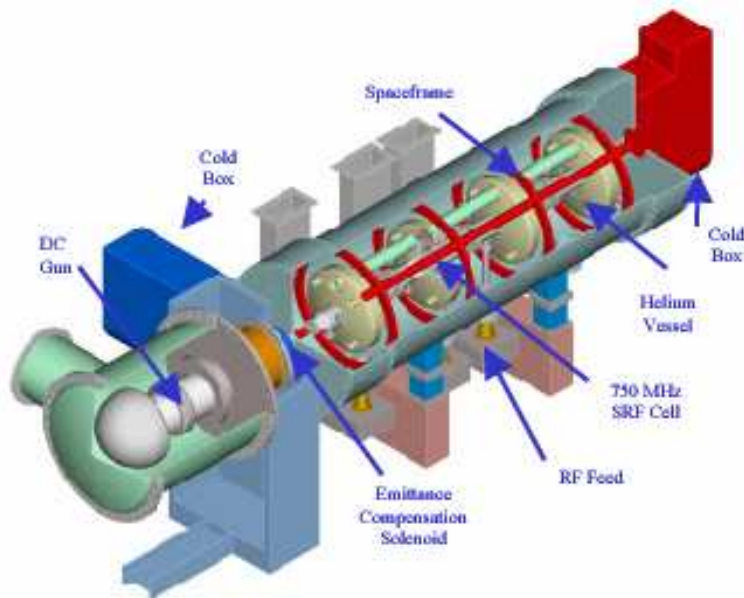

Space Charge → **Emittance growth** ← **Cavity offset/tilt**

Example 3: JLAB 100 kW FEL injector

The cryomodule is designed to replace the existing ¼ cryomodule injector. This will boost injector average beam current from 10 mA to 100 mA. It is developed by AES in collaboration with JLab.

Parameter	100 kW FEL requirements	Simulations
Beam current	> 100 mA	100 mA
Beam energy	7 MeV	7 MeV
Energy spread	< 1 %	0.5 %
Transverse emittance	< 10 microns	1.2 microns
Longitudinal emittance	< 100-200 keV×psec	44 keV×psec

A. Todd, et al., PAC'2003
H. Bluem, et al., EPAC'2004

# JLAB 100 kW FEL injector cryomodule
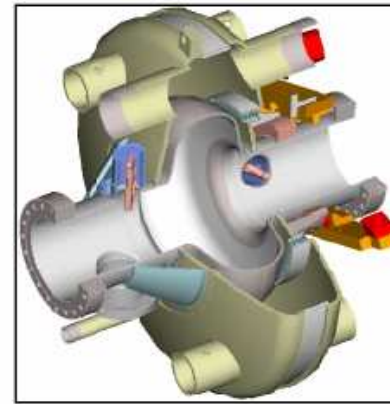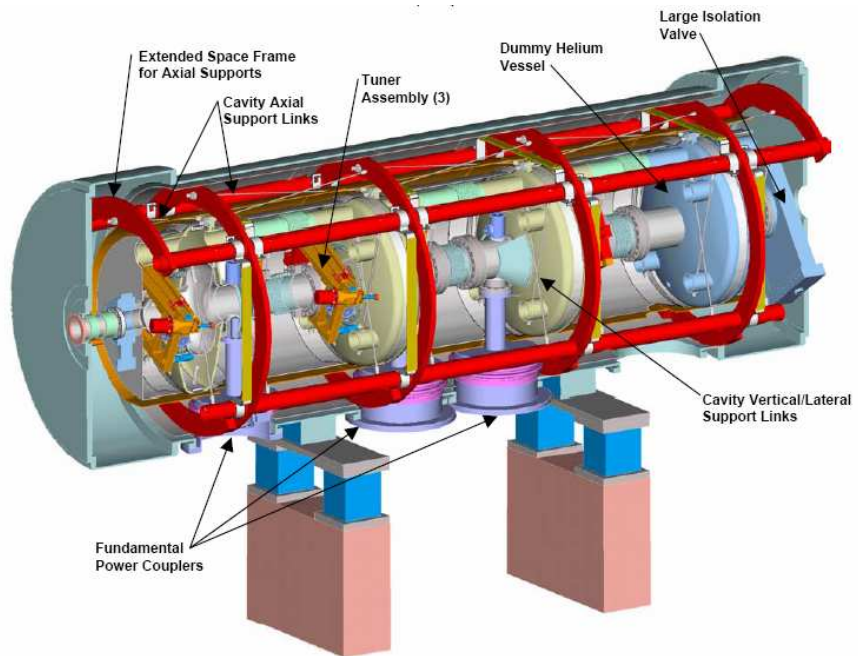
   Three single-cell 750-MHz cavities will accelerate beam consisting of 133 pC, 6.3 ps long bunches to 7 MeV. The fourth upstream vessel is presently used for helium inventory and does not contain an accelerating cell. The cavity Q factor is $> 10^{10}$.

   The cryomodule is "100-mA-compatible" with the exception of the three SNS-style couplers. 500 kW replacement couplers are under development. *a la* TTF HOM couplers are used in this design.
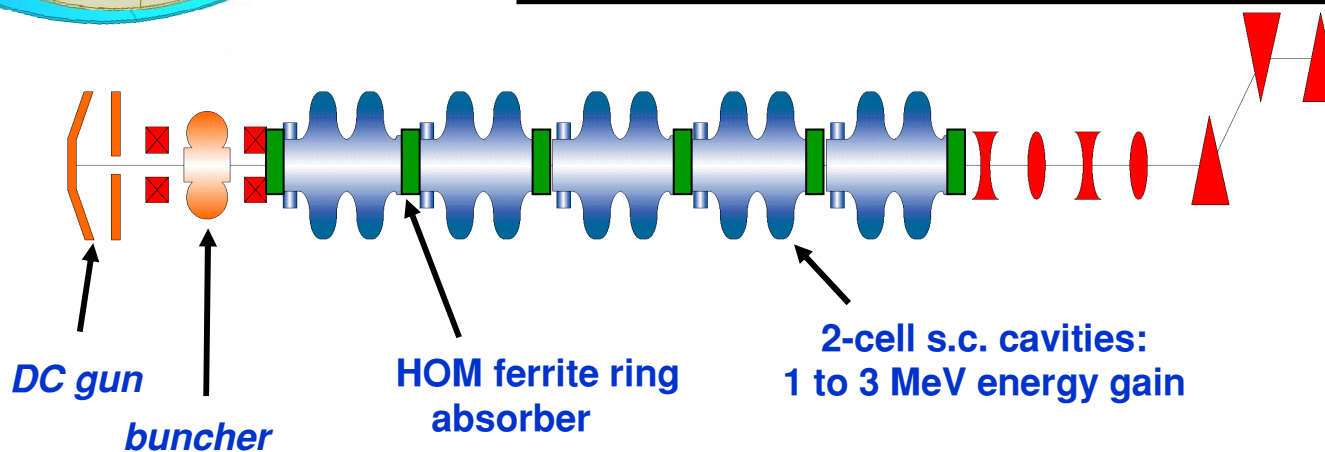
   Four cavities have been delivered from AES and are being prepared for chemistry and an eventual vertical test.
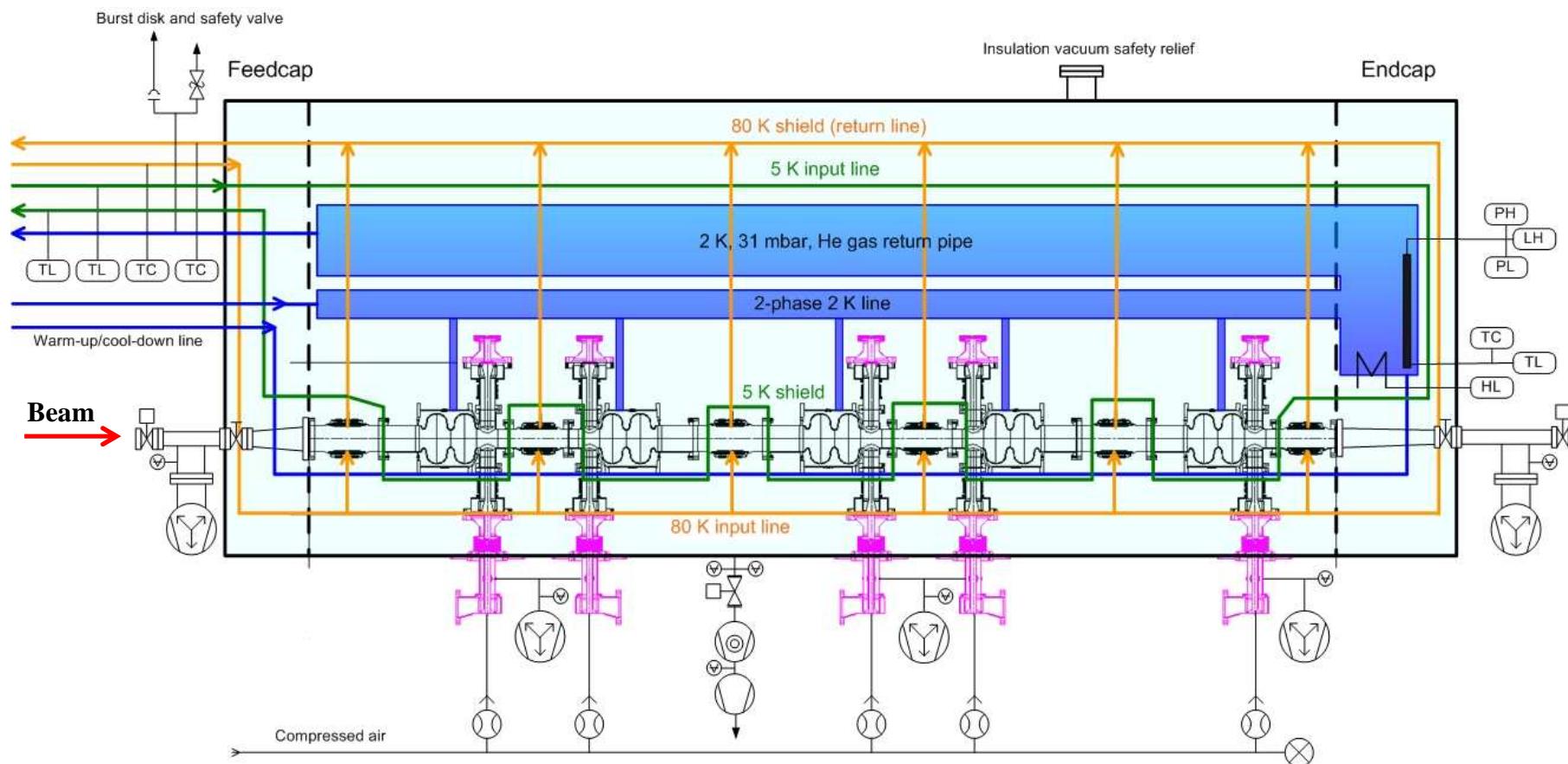
Exampe 4: Cornell ERL injector
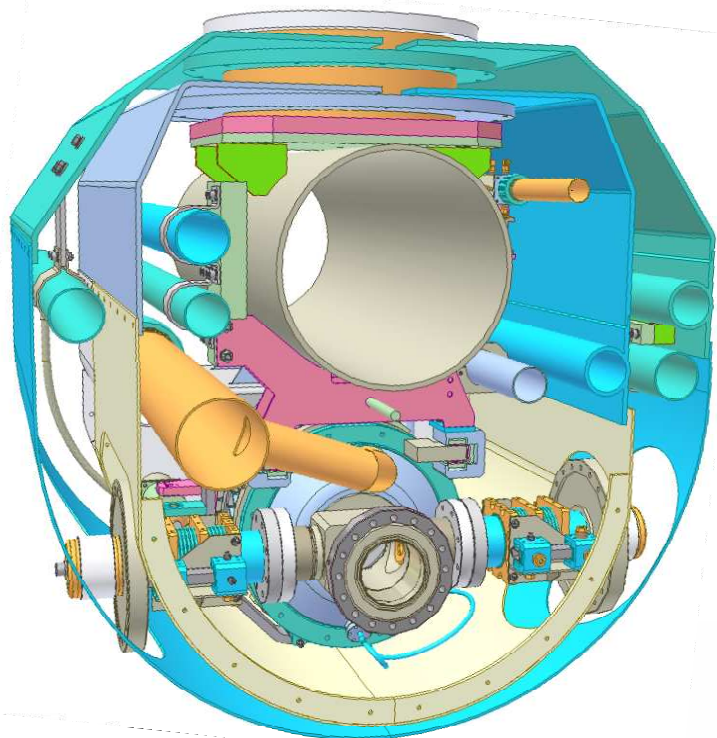
Beam Parameters:

max beam current at q = 77 pC	100 mA
max beam current at q= 1 nC	1 mA
bunch repetition rate	1.3 GHz
transverse emittance	< 0.5 μm rad
max. emittance growth	< 0.1 μm rad
bunch length	0.6 mm
beam energy gain	5 MeV

DC gun

buncher

HOM ferrite ring absorber

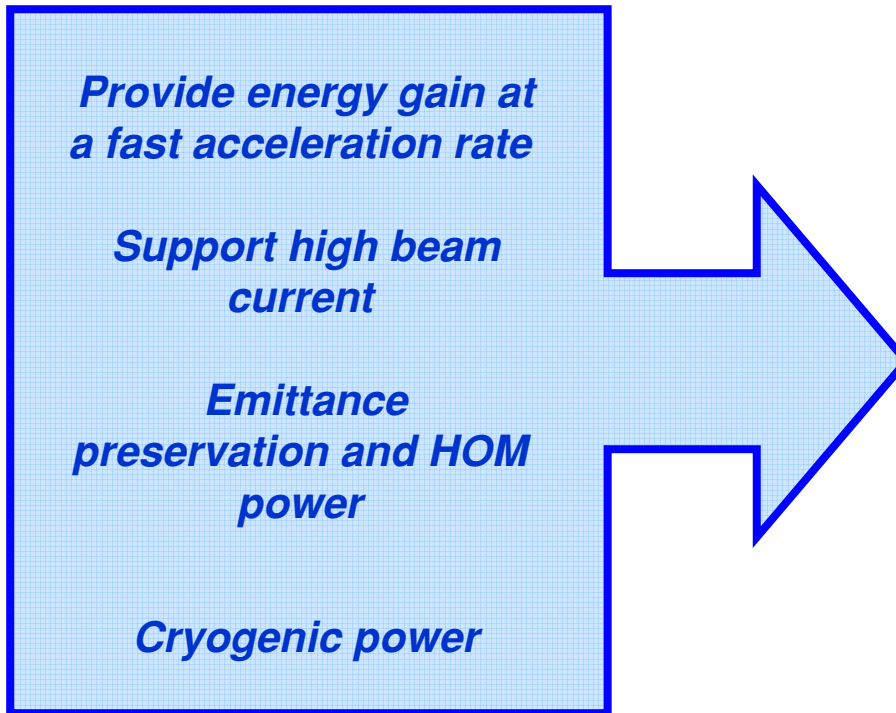**2-cell s.c. cavities: 1 to 3 MeV energy gain**
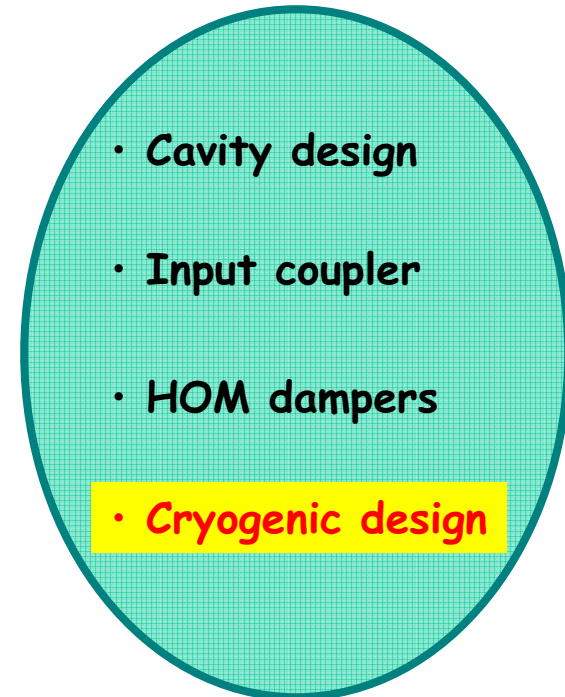
Overview

5 cavities, 6 ferrite HOM loads, 10 input couples, 2 gate valves.

Major issues and challenges: cryostat design

Major issues

Design challenges

Provide energy gain at a fast acceleration rate

Support high beam current

Emittance preservation and HOM power

Cryogenic power

- Cavity design

- Input coupler

- HOM dampers

- Cryogenic design

Cryogenic challenges

- **High gradient cw operation: dynamic cavity heat load dominates at 2 K**
- **Module design:**
  - **Heat transfer through LHe $\Rightarrow$ need large enough pipes**
  - **Mass transport of helium gas $\Rightarrow$ need large enough pump pipes**
  - **HOM losses $\Rightarrow$ need cooling of absorbers**
  - **High RF power $\Rightarrow$ more cooling for input couplers**
- **Cavity:**
  - **Cavity treatment for high Q_0**
  - **Optimal bath temperature?**

<u>Cryogenic load of the injector module:</u>

< 25 W at 2 K (dominated by dynamic cavity load),

< 68 W at 5 K (dominated by input coupler and HOM absorber load),

< 696 W at 80 K (dominated by input coupler load).

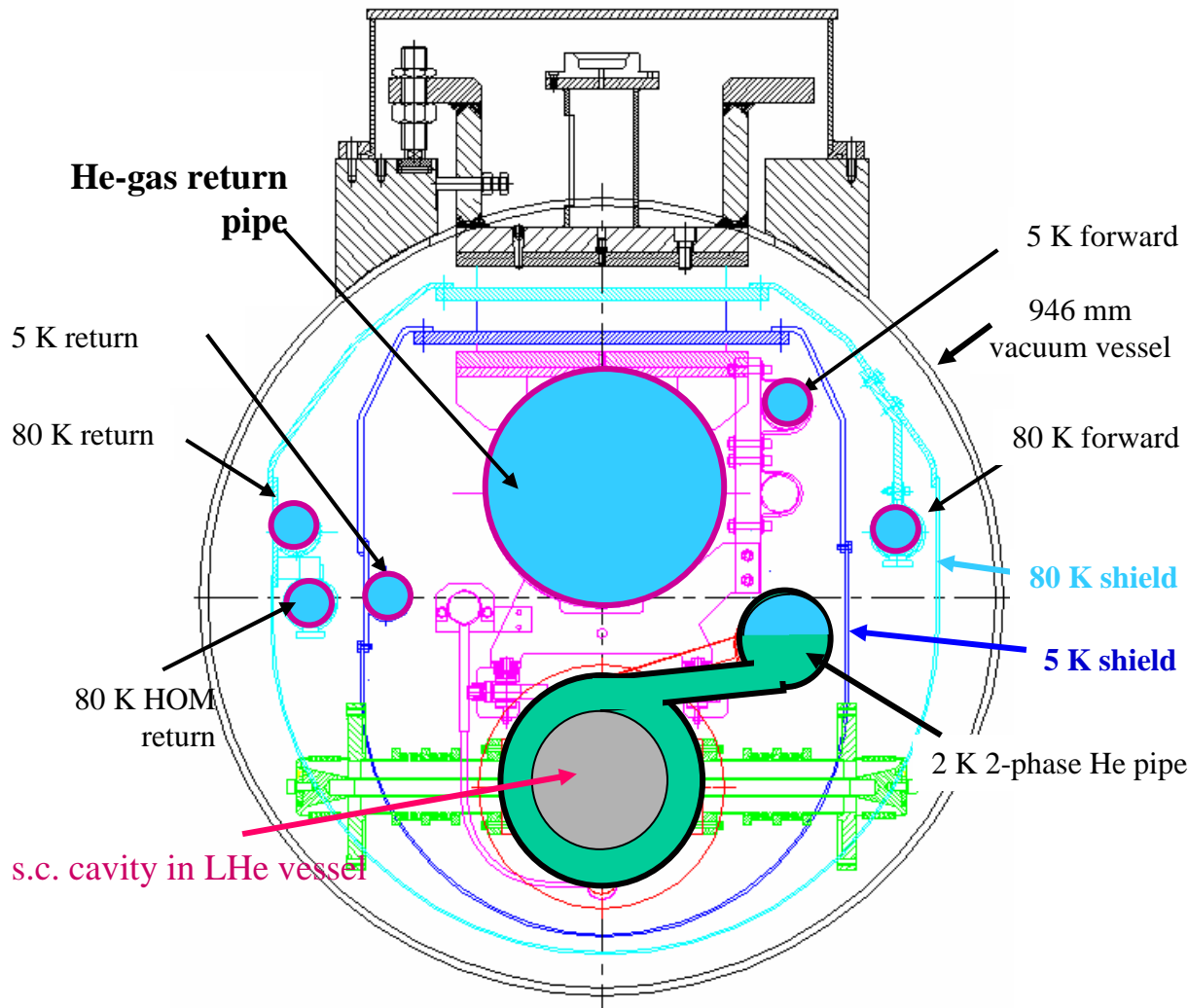# *ERL Injector cryomodule design: Philosophy*

- **Use the same cryomodule concept in injector and main linac.**

    - **Less work, smaller risk for phase 2.**

    - **Injector module serves also as a prototype cryomodule for the main linac.**

The cryogenic pipes in the injector module are sized for the heat loads in the main linac, which are significant higher.

- *Rely on well established and tested performance of the TESLA technology to reduce risk and minimize development time.*

    - **Don't have to reinvent, prototype and test most parts of the cryomodule.**

    - **ERL cavity string, tuner and input coupler are based on TESLA technology.**

    - **TESLA module: have already done several iterations to reduce cost.**

    - **TTF module concept is optimized for module strings. No separate transfer lines. No long warm-cold transitions between modules.**

    - **Demonstrated good cavity alignment and low microphonics.**

ERL Injector cryomodule concept

He-gas return pipe

5 K return

80 K return

80 K HOM return

s.c. cavity in LHe vessel

5 K forward

946 mm vacuum vessel

80 K forward

80 K shield

5 K shield

2 K 2-phase He pipe

Changes compared to TESLA module:

- **Reduced module length for ERL injector.**
- **2-cell cavities instead of 9-cell cavities. Larger tube diameter.**
- **CW operation with high beam currents**
- **Stainless steel cavity flanges.**
- **HOM absorbers between cavities. Pipes for HOM cooling.**
- **Modified 5 K shield to integrate HOM absorbers at 80 K.**
- **Increase diameter of 2-phase 2 K He pipe to about 10 cm.**
- **Improve magnetic shielding for very high Q_0.**
- **Injector: Two 62 mm ID input couplers instead of one 40 mm. Increased cooling for high average power.**
- **New end-cap and feed-cap concept with reduced length.**

Major issues and challenges: cavity design

Major issues

Design challenges

Provide energy gain at a fast acceleration rate

Support high beam current
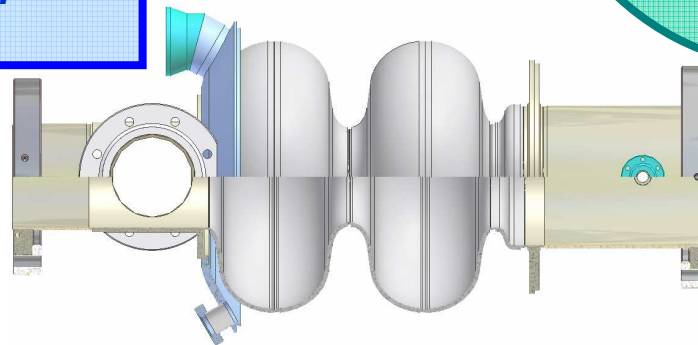
Emittance preservation and HOM power

Cryogenic power

- Cavity design
- Input coupler
- HOM dampers
- Cryogenic design

S. Belomestnykh, ERL 2005 workshop

Cavity design:
Two-cell kick-free, dipole-mode-free superconducting cavity

Why two cells?

1. Fewer number of cells is better: fewer number of HOMs, easier to damp them
2. 2 cells is optimal from the point of view of accelerating field strength (4.3 to 13 MV/m): we do not want to push gradient too high as we already pushing average RF power (100 kW per cavity)

Other requirements

1. Minimize coupler kick $\Rightarrow$ twin coupler scheme $\Rightarrow$ "kick-free" cavity
2. HOMs: extract all monopole and dipole modes $\Rightarrow$ "dipole-mode-free" cavity geometry $\Rightarrow$ use only broadband absorbers between the cavities
3. Optimize cavity shape to minimize peak surface fields and maximize R/Q of fundamental mode

Cavity design:
Two-cell kick-free, dipole-mode-free superconducting cavity

2 cells:
Upper limit set by 100 kW coupler power (max. energy gain per cavity)
Lower limit: Maximum field gradient < 20 MV/m
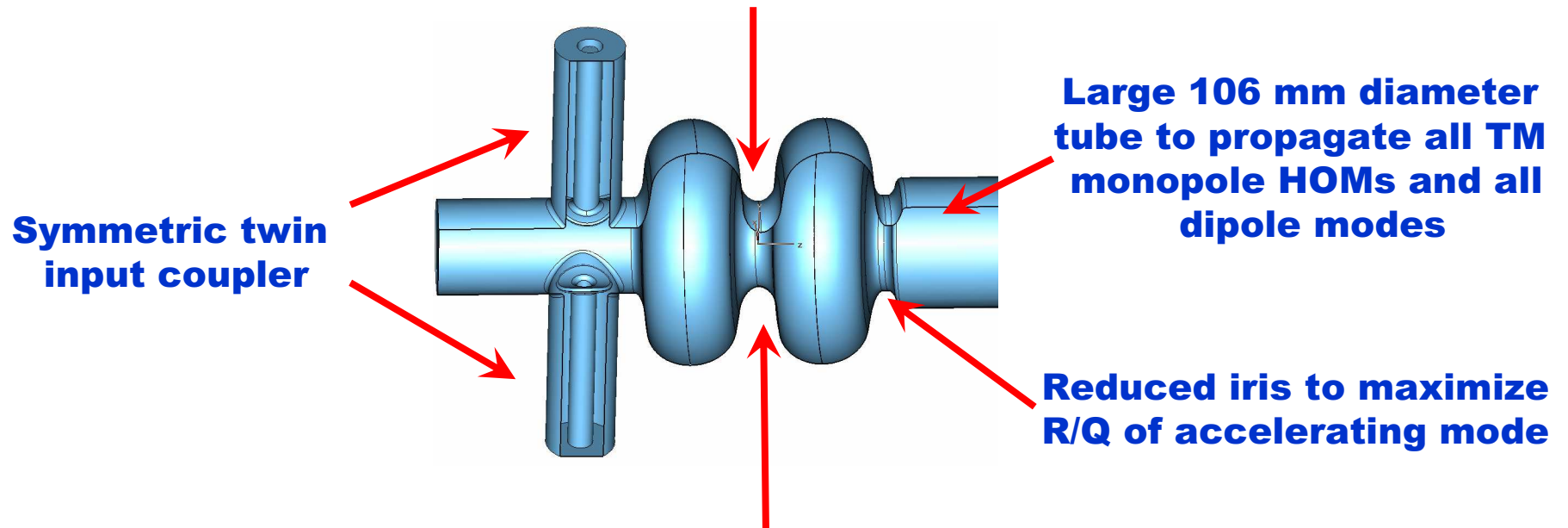
Large 106 mm diameter tube to propagate all TM monopole HOMs and all dipole modes

Symmetric twin input coupler

Reduced iris to maximize R/Q of accelerating mode

f_{acc} = 1.3 GHz (TESLA)
Optimum: 1 GHz – 1.5 GHz
Lower f: Larger cavity surface, higher material cost,...
Higher f: Higher BCS surface resistance, stronger wakes, ...

Cavity parameters
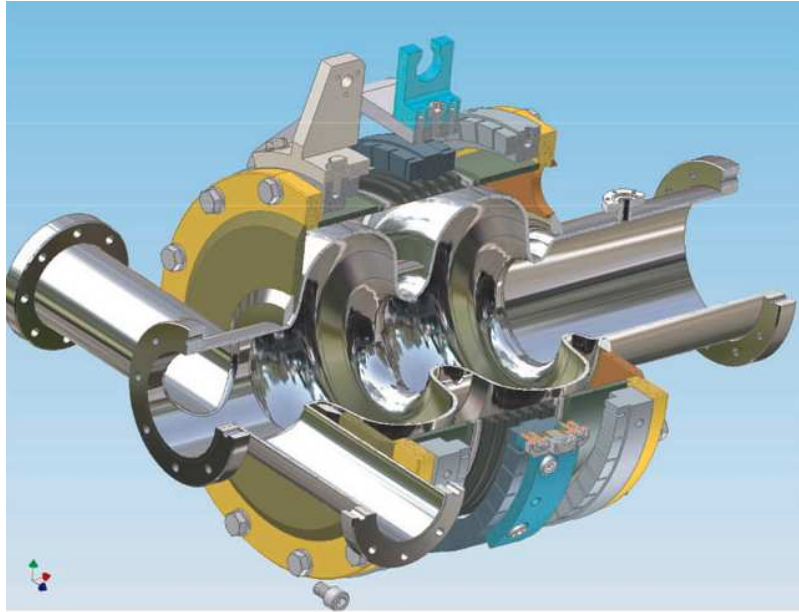
cavity frequency	1300 MHz
cells per cavity	2
R/Q per cavity	222 Ω
acc. voltage per cavity	1 to 3 MV
acc. gradient	5 to 14 MV/m
Q_0	$> 1 \cdot 10^{10}$
Q_{ext}	$> 4.6 \cdot 10^4$ to $4.1 \cdot 10^5$
active cavity length	0.218 m
total cavity length	0.536 m

Major issues and challenges: input coupler

Major issues

Design challenges

Provide energy gain at a fast acceleration rate

Support high beam current

Emittance preservation and HOM power

Cryogenic power

- Cavity design
- Input coupler
- HOM dampers
- Cryogenic design

80 K flange

300 K intercept

to cavity flange

2 K flange

5 K intercept

80 K intercept

transition to waveguide

cold ceramic window

warm ceramic window

Input coupler: major changes from TTF-III and parameters

1. The cold part was completely redesigned using a 62 mm, 60 Ohm coaxial line for stronger coupling, better power handling and avoiding multipacting.
2. Antenna tip was enlarged and shaped for stronger coupling.

3. "Cold" window was enlarged to the size of "warm" window.
4. Outer conductor bellows design was improved for better cooling.
5. Air cooling of the warm inner conductor bellows was added.
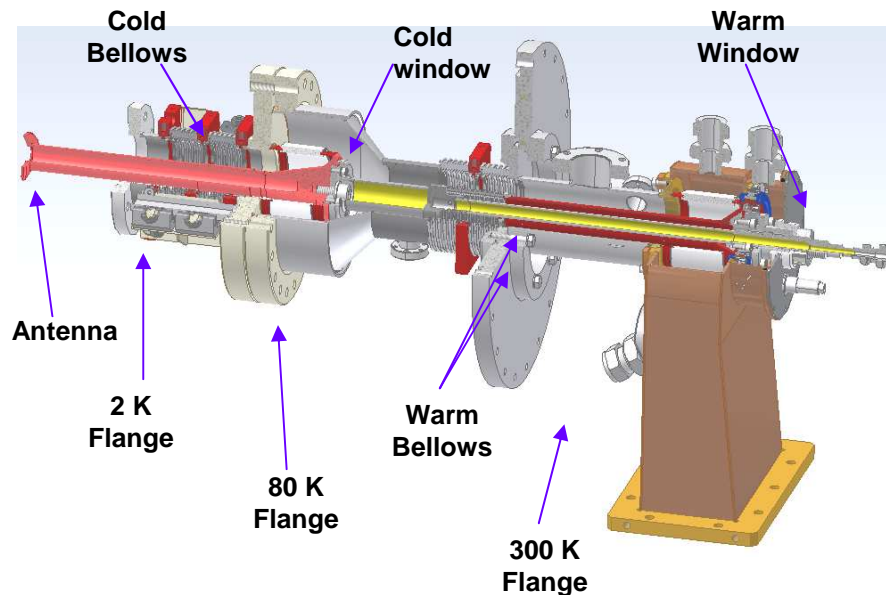
Frequency	1300 MHz
Bandwidth	+/- 10 MHz
Max. power to matched load	75 kW
Number of ceramic windows	2
Cold coax. line impedance	60 Ω
Warm coax. line impedance	46 Ω
Coaxial line OD	62 mm
Q_{ext} range	9.2 $\cdot 10^4$ to 8.2 $\cdot 10^5$
Antenna position change	16 mm

Cold Bellows
Cold window
Warm Window
Antenna
2 K Flange
80 K Flange
Warm Bellows
300 K Flange

Major issues and challenges: HOM dampers

Major issues

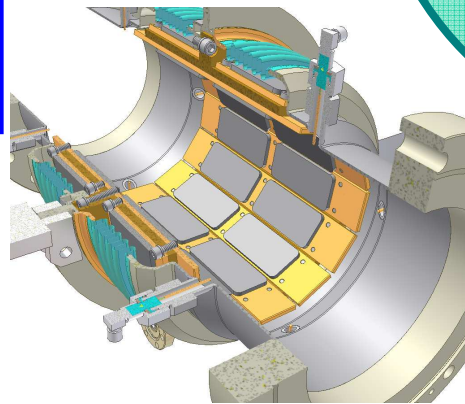Provide energy gain at a fast acceleration rate

Support high beam current

Emittance preservation and HOM power

Cryogenic power

Design challenges

- Cavity design
- Input coupler
- HOM dampers
- Cryogenic design

HOM damping challenge:
High beam current and HOM monopole power at high frequencies

On _average_ the total HOM losses per cavity are given by the single bunch losses (2cell ERL cavity, 77 pC bunch charge, 1.3 GHz bunch repetition rate, $\sigma_b = 600\ \mu m$):

$$P_{\parallel} = k_{\parallel} Q_{bunch} I_{beam} = 3.3\,\text{V/pC} \cdot 77\,\text{pC} \cdot 0.1\,\text{A} = 26\,\text{W}$$

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!

$\Rightarrow$ Example: To stay below _200 W_ (I=100 mA):
- achieve $(R/Q)Q < 10^4\ \Omega$,
- or avoid resonant excitation of the mode.

600 μm bunch length in the linac $\Rightarrow$ high frequencies

integrated power up to frequency f

HOM power up to about 100 GHz.

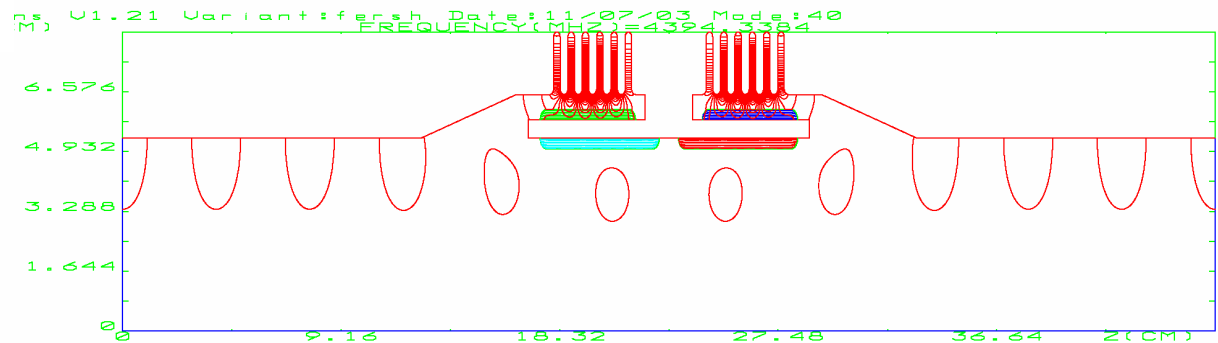Need to absorb power at temperature with good cryo-efficiency (not 2 K!)
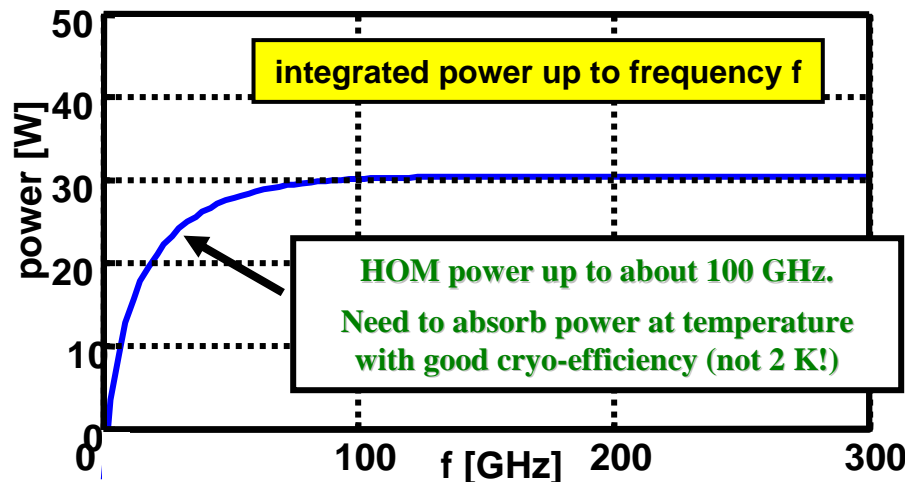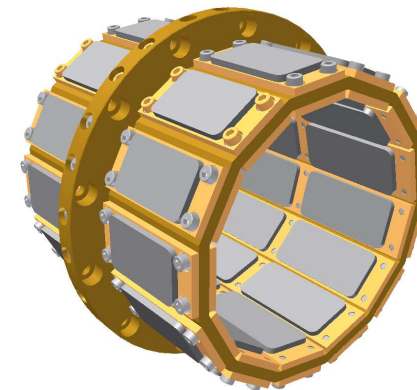
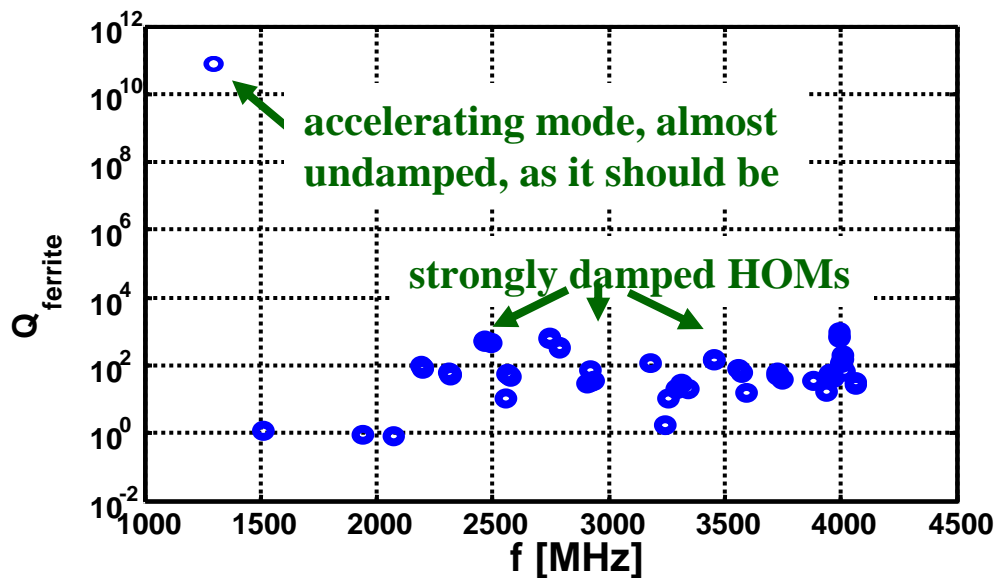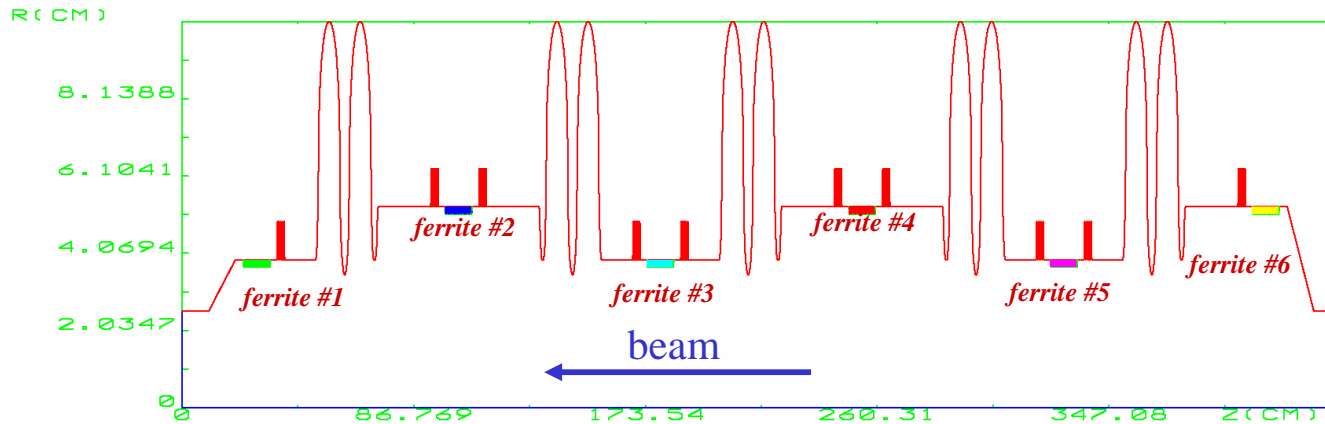# *Strong HOM damping: Solution*

- **Accelerating mode does not propagate in beam tubes.**

- **All TM monopole HOMs and all dipole modes propagate in tubes and are damped by ferrite ring absorber at 80 K between cavities.**
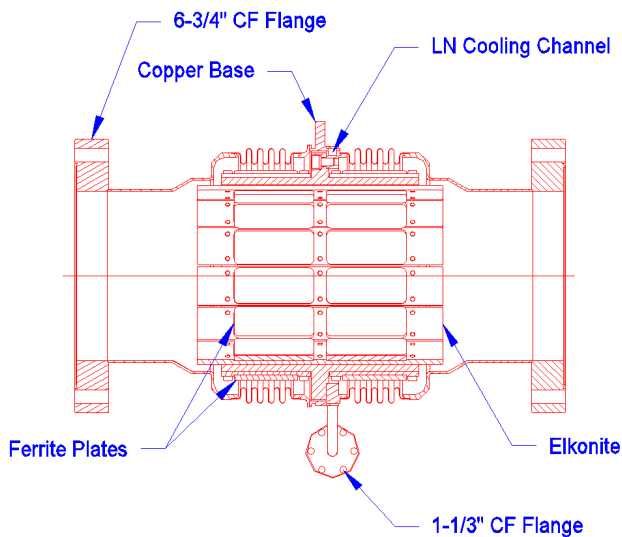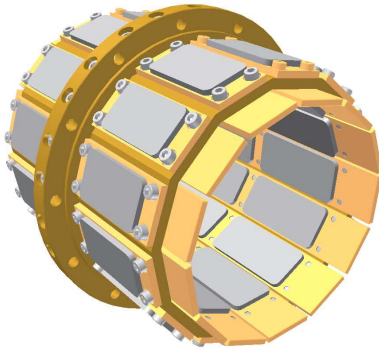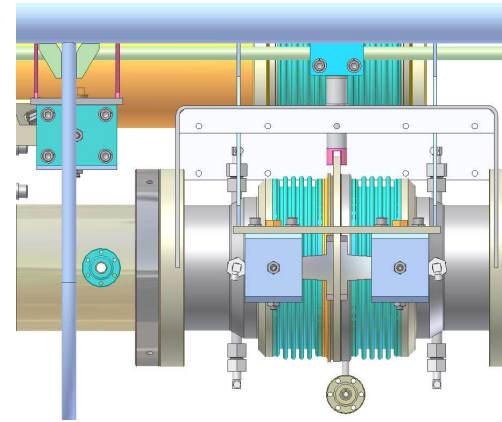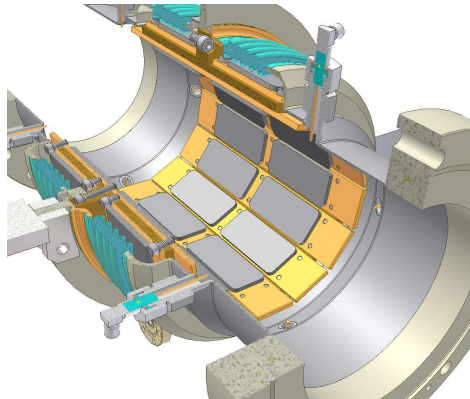

symmetric ferrite ring
⇒ no transverse kick

Ferrite HOM load parameters

Total number of absorbers	**3 + 3**
Average dynamic power per absorber	**26 W**
Max. power/absorber	**200 W**
HOM frequency range	**1.4 to 100 GHz**
Operating temperature	**80 K**
Coolant	**Cold He gas**
Absorber types (very prelim.)	**TT2, hex Z, C10**

Example 5:
Rossendorf's 3½ -cell superconducting RF gun cryomodule

D. Janssen, et al., FEL'2004
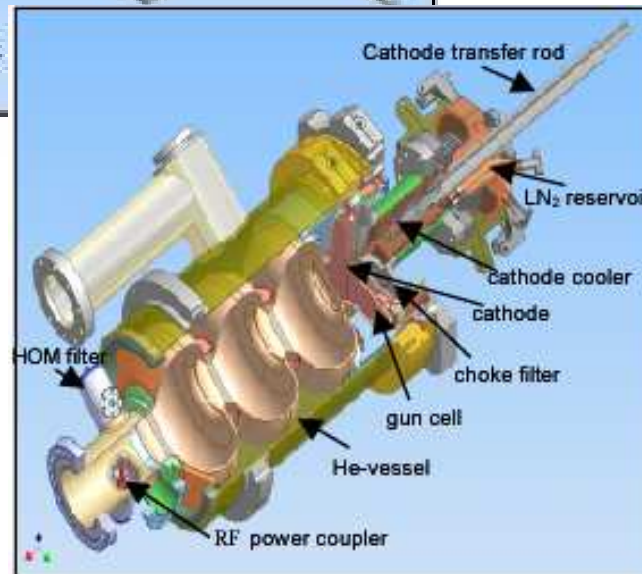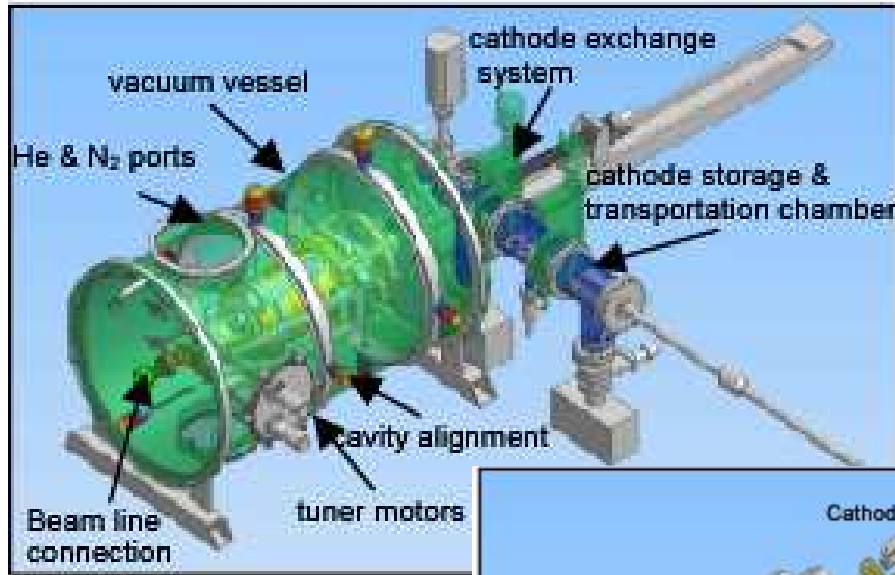
Energy	9.5 MeV
Beam current	1 mA
Frequency	1.3 GHz
RF power	10 kW
Ez max (½ cell)	33 MV/m
Ez max (TESLA cells)	50 MV/m
ε (q = 77 pC)	0.5 mm mrad
ε (q = 1 nC)	2.5 mm mrad

Summary

> The existing injector cryomodules can deliver 10 MeV beam with average current up to 10 mA and transverse emittance of the order of 10 mm×mrad.

> The future ERL projects require higher beam current ($\geq$ 100 mA) and lower transverse emittance ($\leq$ 1 mm×mrad), which necessitates developing new injector cryomodules.

> Two designs under development (at JLab and Cornell) will deliver 100 mA beams with low transverse emittances.

Acknowledgements

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