



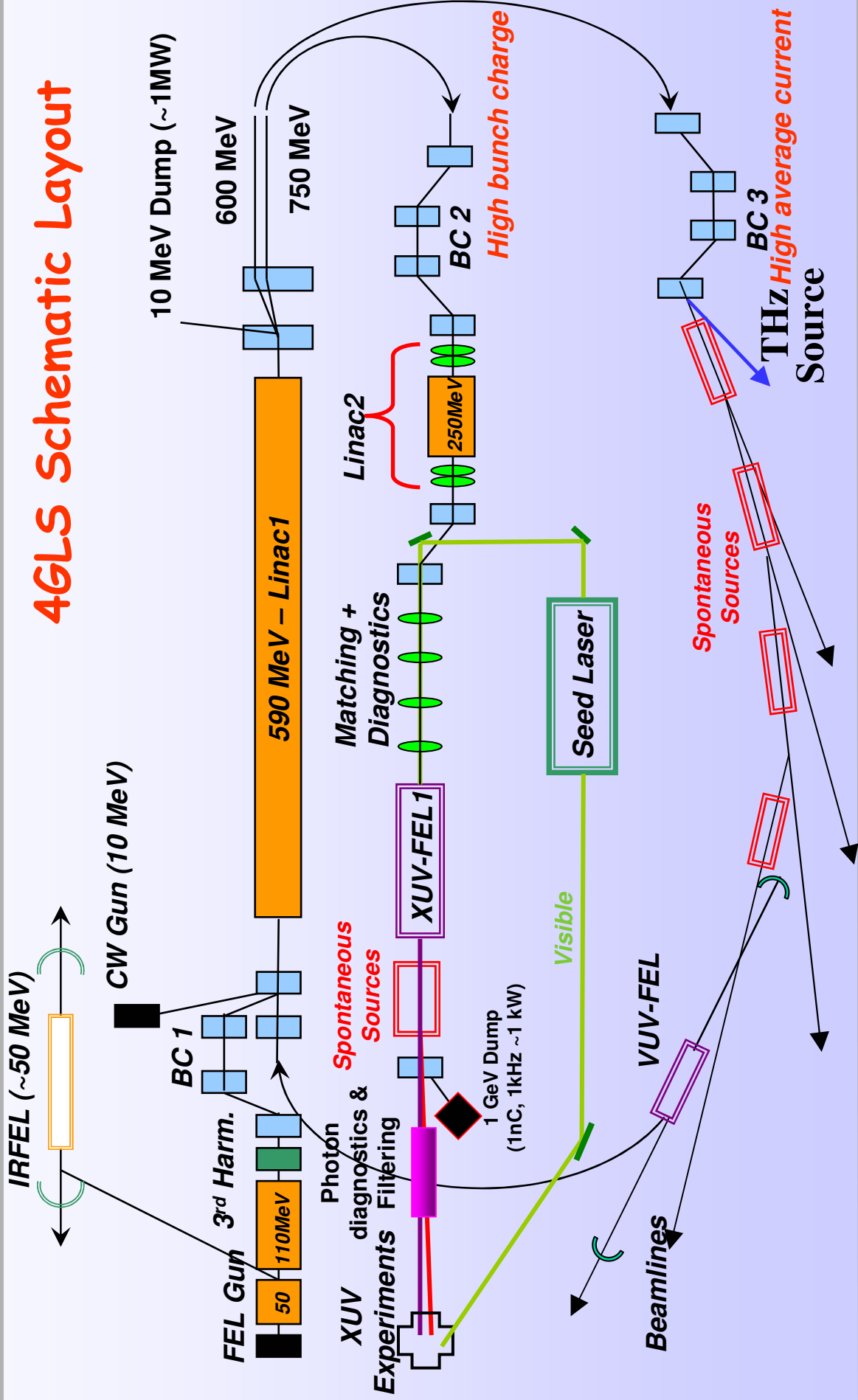
ERL Workshop Review

Mike Dykes
ASTeC, Daresbury Laboratory



What is an ERL?

4GLS Schematic Layout



ERL2005

32nd ICFA Advanced Beam Dynamics
Workshop on Energy Recovering Linacs
Jefferson Lab, Virginia, USA
March 19-23, 2005

Charting New Territories

Energy Recovering Linacs (ERLs) are emerging as a powerful new paradigm of electron accelerators as they hold the promise of delivering high average current beams with efficiency that approaches that of storage rings, while maintaining beam quality characteristics of linacs, as their 6-dimensional phase space is largely determined by electron source properties. Envisioned ERL applications include accelerators for the production of synchrotron radiation, free electron lasers, high-energy electron cooling devices, and electron-ion colliders. The ERL2004 workshop is the first of its kind, to address issues related to the generation of high brightness and simultaneously high average current electron beam, and its stability and quality preservation during acceleration and energy recovery.

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For more information please email erl@jlab.org
www.jlab.org/intralab/calendar/archive04/erl/



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Cornell 15th July 2005



1 Plenary

4 Working Groups

1. Electron Guns and Injector
Designs

2. Optics and Beam Transport

3. Superconducting RF and RF
Control

4. Synchronization and
Diagnostics/Instrumentation

<http://www.jlab.org/intralab/calendar/archive04/erl/program.html>



Contents



- Acknowledgements
- Charge
- Programme
- Highlights and Recommendations
- Conclusions



Acknowledgements



All 25 people who made presentations,
and whose work I am reporting; I also
thank them for the material used in
this presentation



Charge



- ...to identify critical SRF related items for the construction of ERLs, evaluate the readiness of the related science and technology, and to lay out an R&D path for solving remaining open issues.



Charge



- Review parameter space covered by ERLs, concentrate on the difficult ones
- What are the SRF-related ERL-specific challenges?
- What solutions have already been developed?
- Which components still need more R&D work?
- Organise R&D effort, develop a roadmap to coordinate studies and identify collaborative possibilities



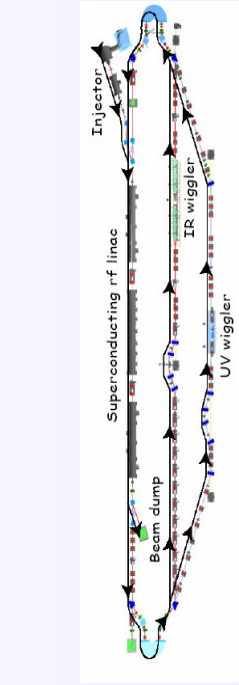
Program



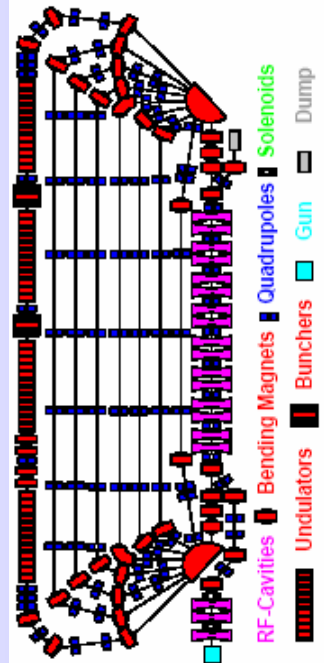
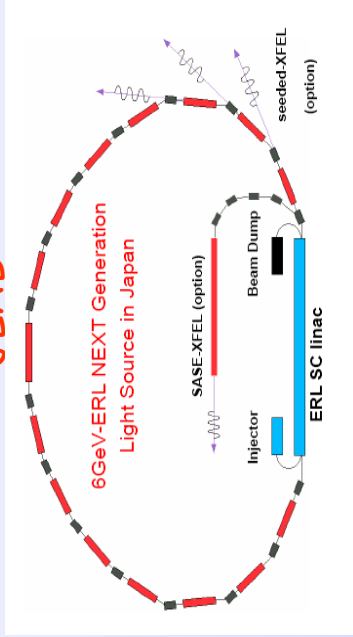
1. Introduction and Overview
2. Cavities/Modules
3. Cavity Cell Shape/Design
4. HOM Damping and Power Requirements
5. High Q Operation
6. Microphonics
7. Tuners
8. RF Control
9. Couplers
10. RF Power Sources and Transmission
11. Assembly - Transfer to Industry
12. Cryogenics
13. Injector Modules



Overview



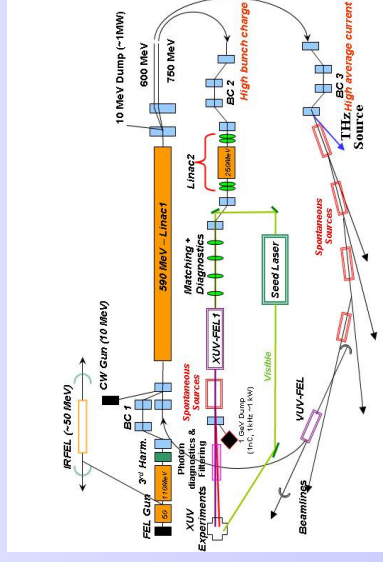
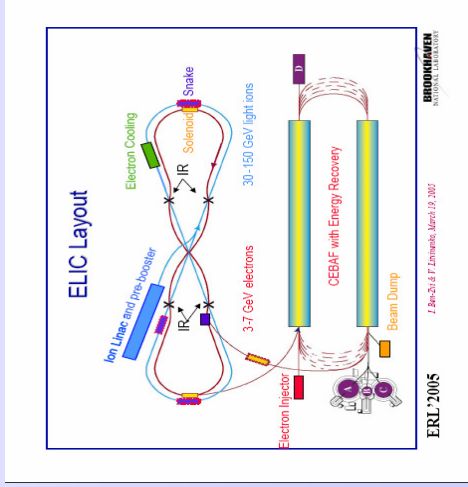
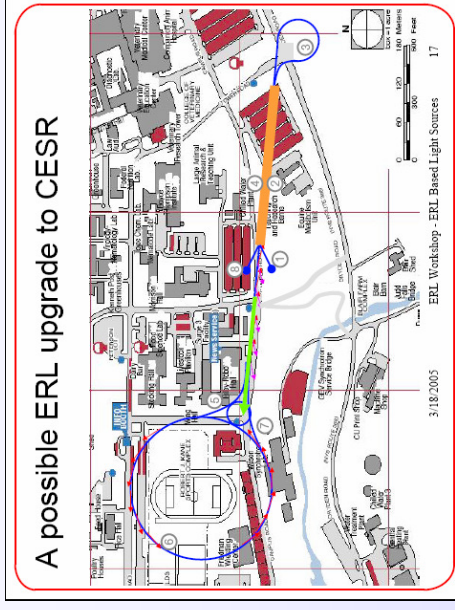
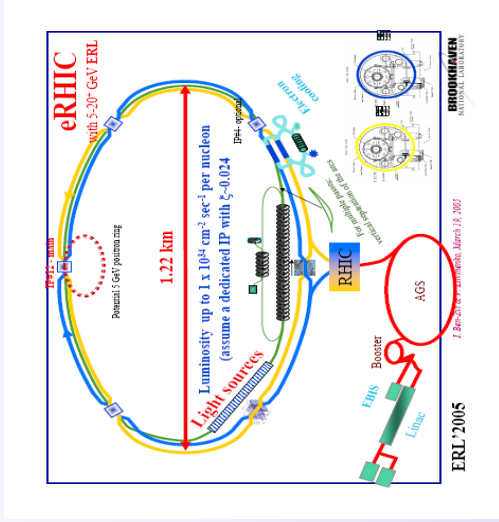
JLAB



BINP

- RF-Cavities
- Bending Magnets
- Quadrupoles
- Solenoids
- Undulators
- Bunchers
- Gun
- Dump

Mike Dykes



4GLS

SRF2005, Cornell 15th July 2005

ERL 2005
EBF S002

Highlights and Recommendations Cryomodules



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JLab Cryomodules for ERL Applications

The Future - Renaissance (II)

- String assembly complete, cryomodule assembly underway
- Ready for test ~ 7/1/05

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Cryomodule Components (A. Burger, D. Holmes et al.)

Labels in diagram: 4" RF shielded gate valve, HOM ferrite assembly, Tuner location, 2K main line, Space frame support structure, Cavity assembly, Vacuum vessel, 2K fill line, Outer magnetic shield, Thermal shield, Inner magnetic shield, Heater, He vessel, Fundamental Power Coupler assembly.

See ERL Optimization Talk for Cavity Details

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

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JLab Cryomodules for ERL Applications

The Future: 1 A Cryomodules

- CW: 750 MHz
- 2005: conceptual design & copper models
- 2006: working Nb version
- Two concepts being evaluated:

1.5 GHz model of 'superstructure' cavity with coaxial HOM couplers

5-cell cavity with enhanced waveguide coupling of HOMs

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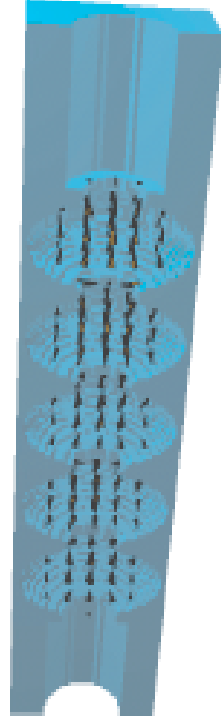


Highlights and Recommendations Cavity Shape

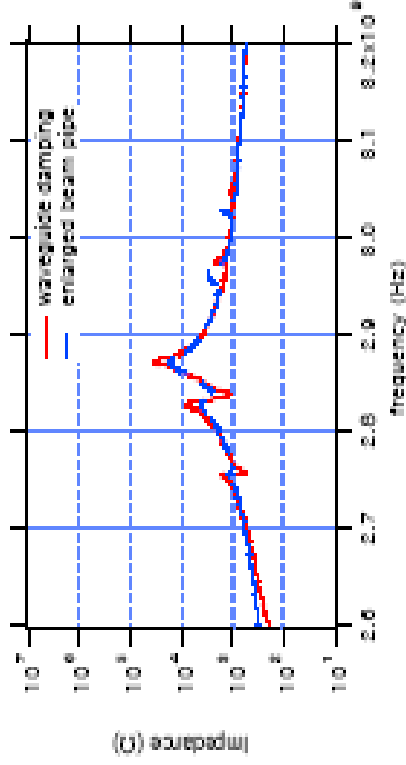


- Can optimize cavity shape for losses and HOM extraction simultaneously.
- 500 MHz cavities are not option at present.
- For up to 100 mA, present L-Band technology works. Residual losses (at low T_{bath}) push up frequency.

Compare waveguides with beam pipe loading:



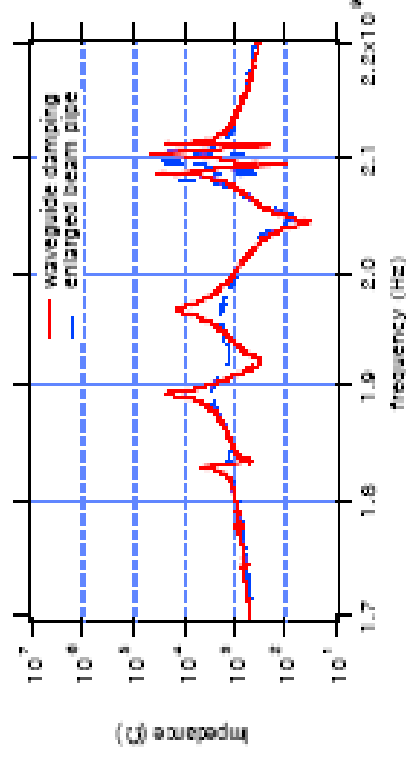
5-cell cavity with beam-pipe loads.



TM₀₁₁. 5-cells, wg and beam-pipe loads.



5-cell cavity with waveguide loads.



Dipole, 5-cells, wg and beam-pipe loads.

Impedance is good in either case, real estate gradient is better for waveguides.



Highlights and Recommendations HOM Damping

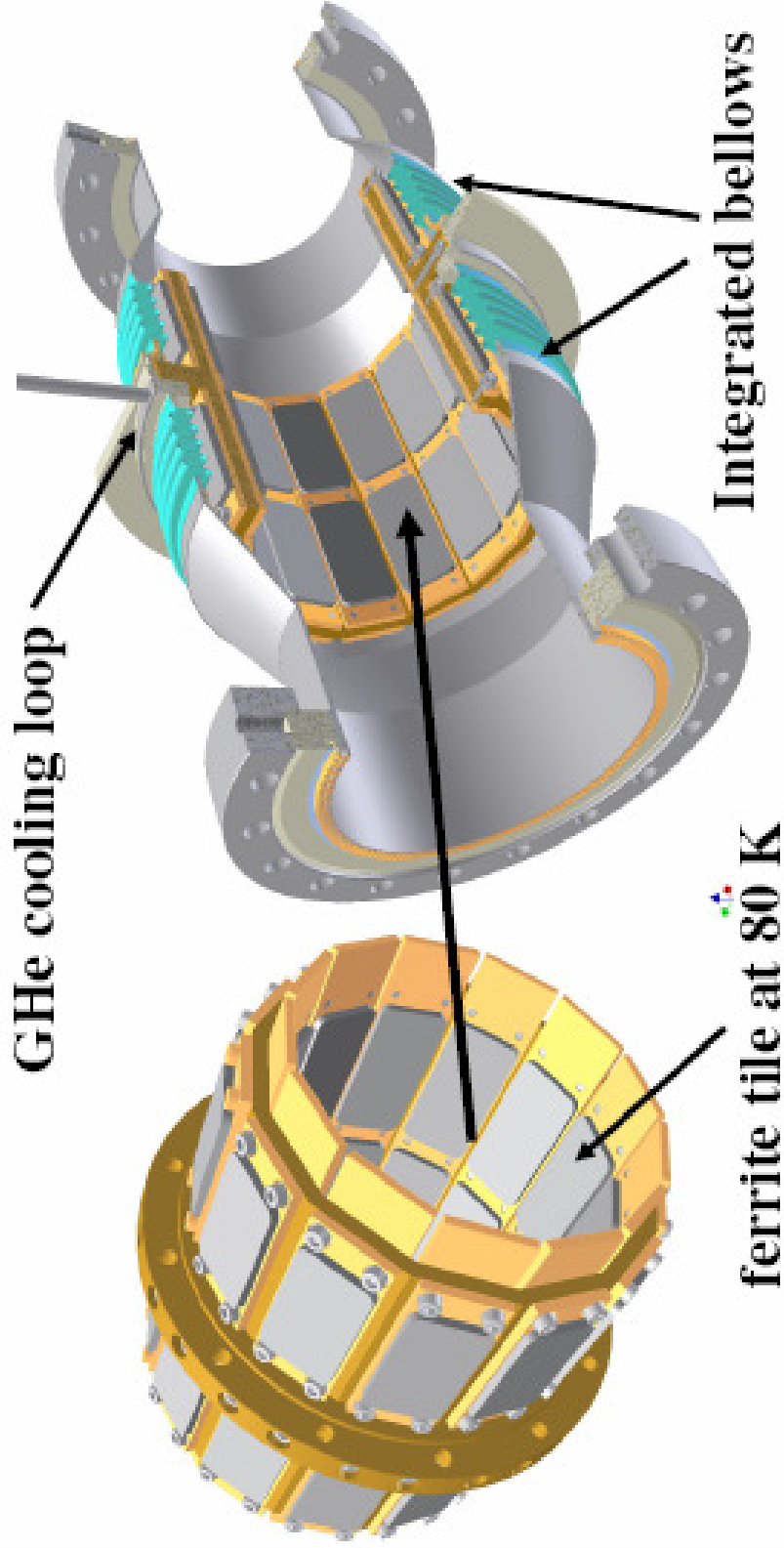


- Many schemes will work equally well, (except for loop couplers).
Based on simulation and initial experiments
- $Q = 10^3$ to 10^4 which is good enough for 1 A machines.
- HOM power is a concern



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Beam-pipe absorber
Example: Cornell ERL Prototype



GHe cooling loop

Integrated bellows

ferrite tile at 80 K



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Highlights and Recommendations Cavity Preparation



- Eddy Current Scanning, Squid Scanning
(successfully used at DESY on TTF cavities)
- Degreasing (ultrasound + soap+water, solvents)
- BCP (HF:HNO₃:H₃PO₄ as 1:1:1, 1:1:2, 1:1:4)
(room temperature or below to avoid excessive hydrogen pick-up)
- Electropolishing (HF/H₂SO₄ Siemens-KEK-Recipes)
- Barrel Polishing
- High pressure Ultrapure Water Rinsing
- High Temperature Heat Treatment (600C to 1400C for Hydrogen degassing, Post Purification)
- "In-situ" baking (typically 120C for > 24 hrs)
- Alternative Cleaning: CO₂ Snow, Megasonic, UV Ozon..

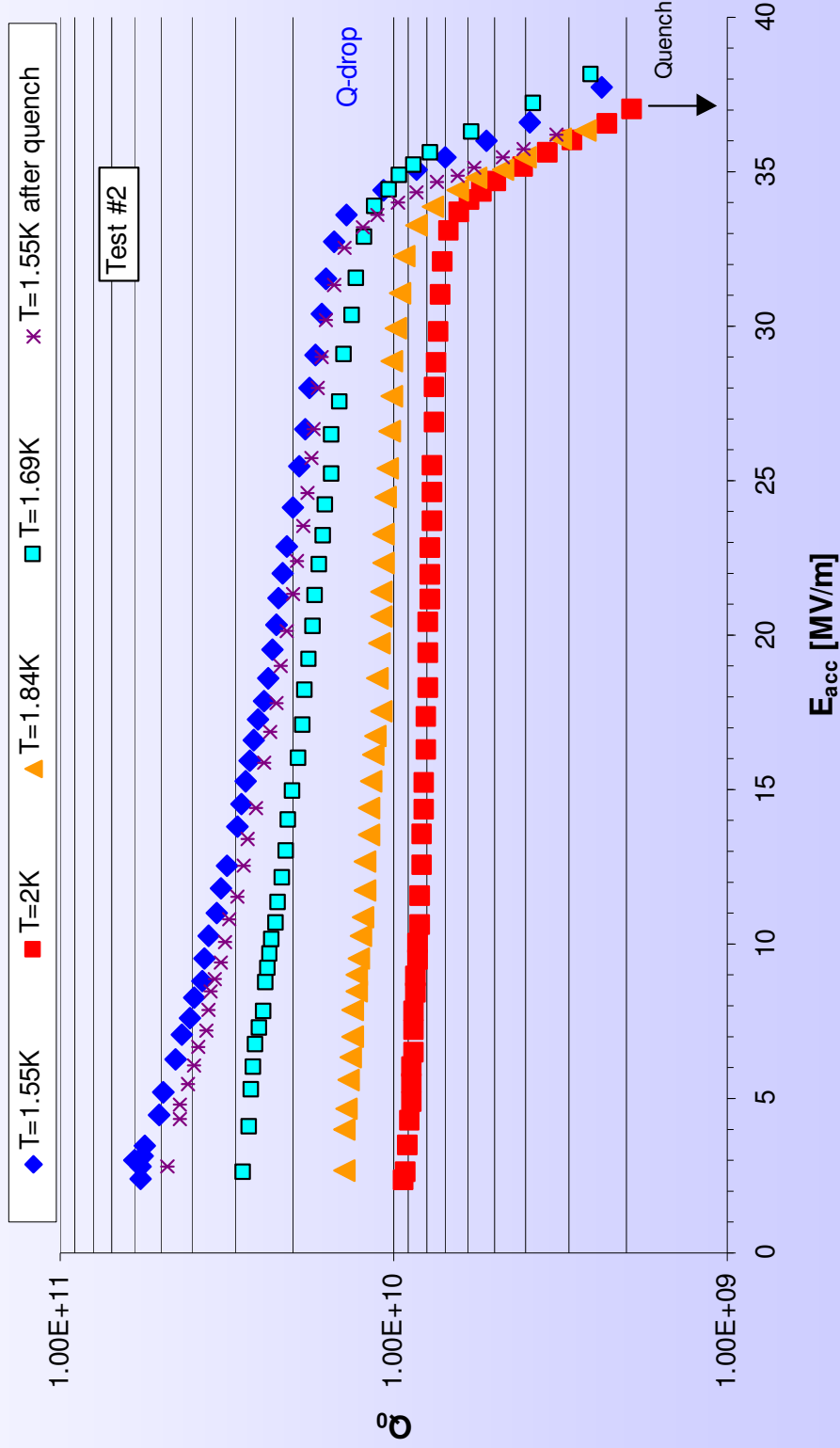


Highlights and Recommendations Single Crystal Cavity



2.2 GHz Single crystal single cell cavity after post-purification, 70 μ m BCP 1:1:1, 30min HPR

Q_0 vs. E_{acc}





Highlights and Recommendations Cavity Preparation

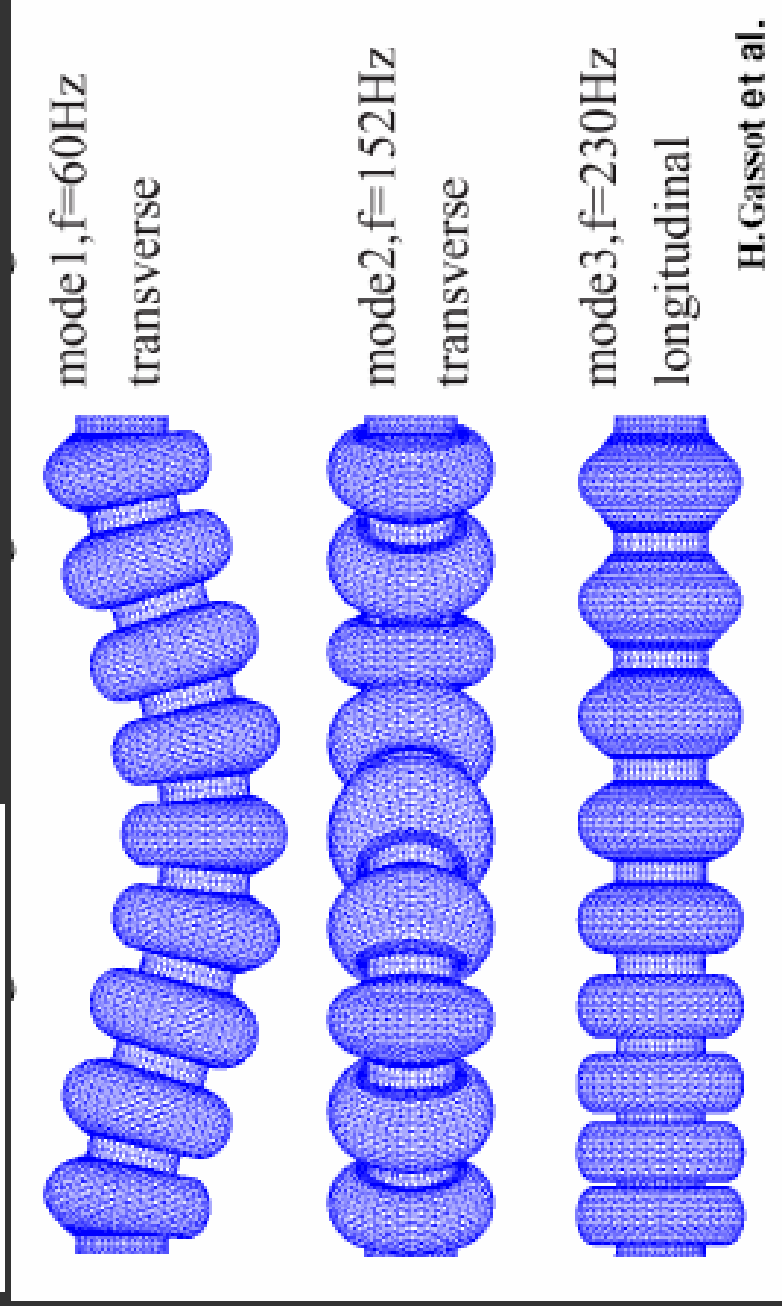


- Q research still needed,
- Q 10^{10} , 20 MV/m
- EP not necessary, but may help
- Single crystal cavities are proving very promising and may be cheaper.
Needs more research!
- Also magnetic shielding in modules needs to be investigated and possibly improved!!!



Cornell University *Microphonics*

Example: TTF 9-cell cavity



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5



Highlights and Recommendations Microphonics



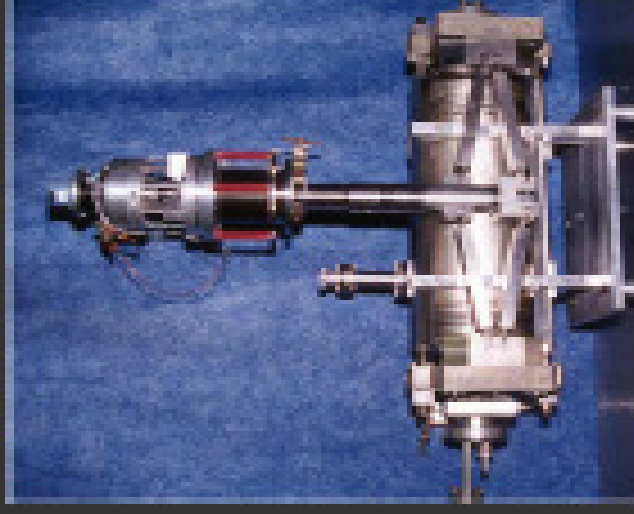
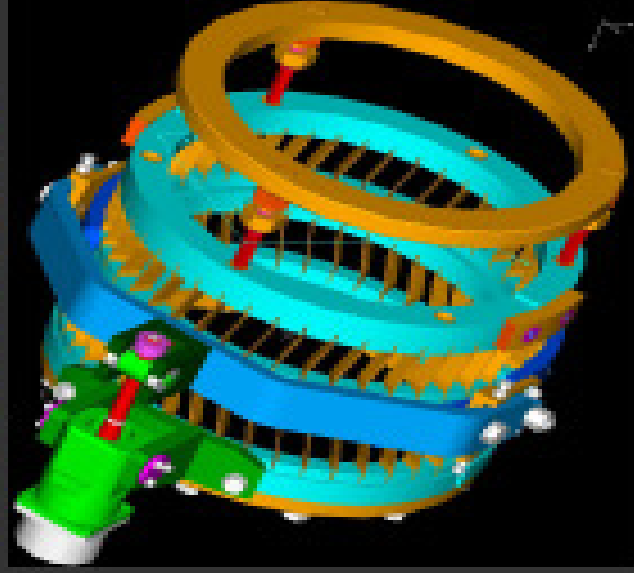
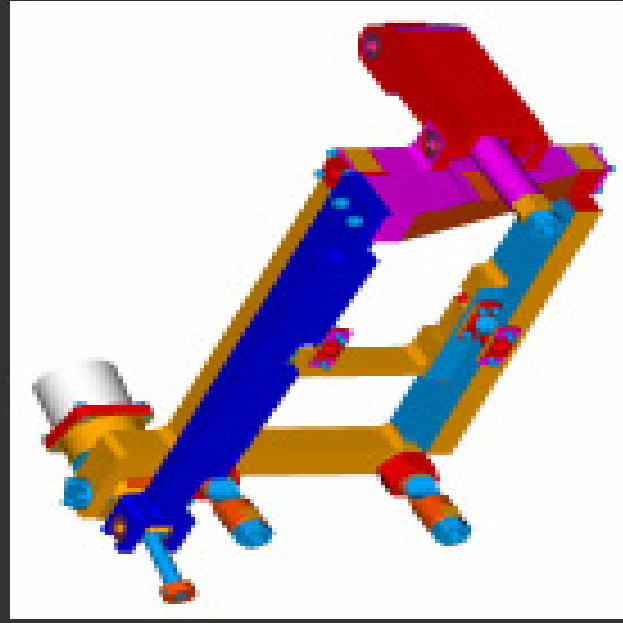
- Proof of principle that low (10Hz pk) microphonics modules exists.
- But even high-microphonics can be controlled so again this is a cost issue!
- Microphonics fluctuate from cavity to cavity and this must be investigated with big statistics at JLAB or SNS.
- Also correlations must be investigated.



Highlights and Recommendations Tuners



- Several designs with integrated piezos have been tested:
SNS tuner **TTF blade tuner** **JLAB tuner**





Highlights and Recommendations Tuners



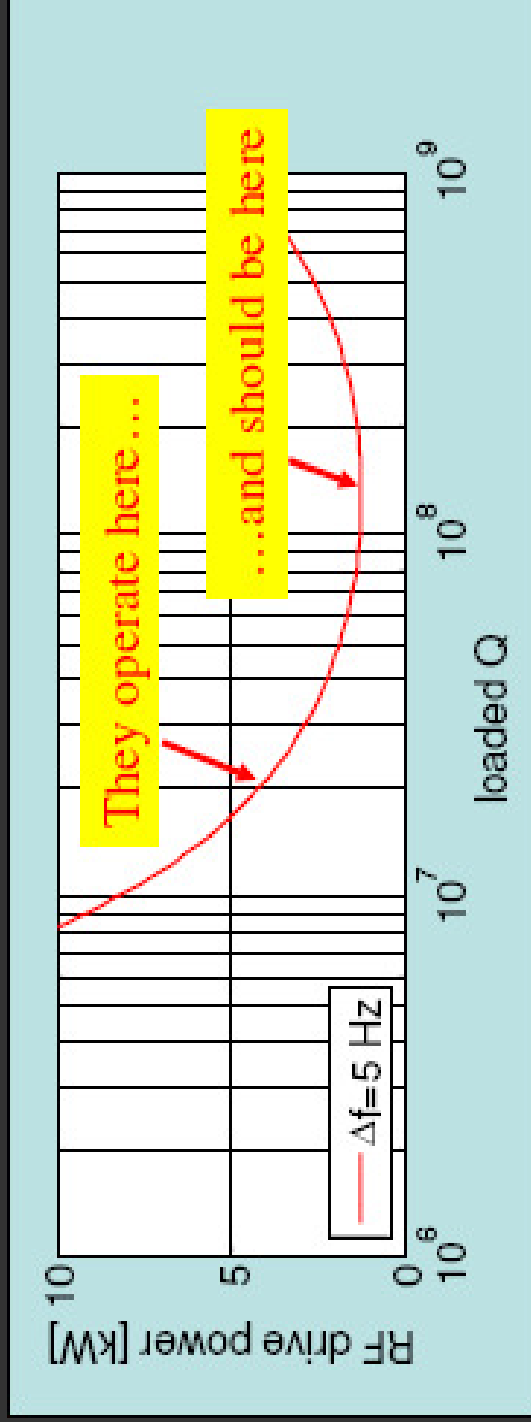
- Piezo element is required for fine tuner control
- Several designs have been tested (RIA has shown active control)
- Reliability is still a concern



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Where are we today?
State of the Art (II)

JLAB FEL:

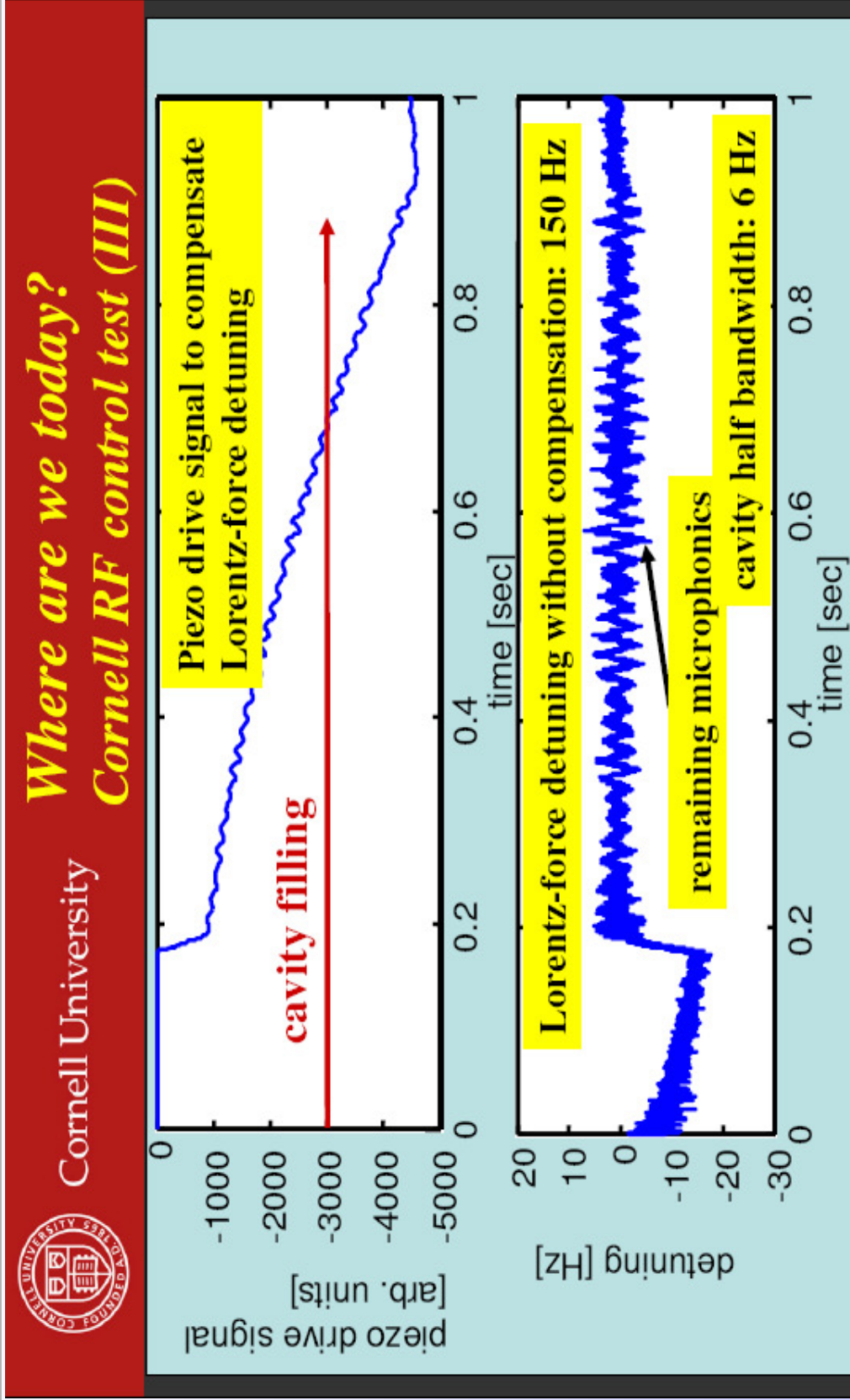


⇒ A good mechanical design results in very low microphonics levels, and would allow to run at a $Q_L \approx 10^8$!

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9



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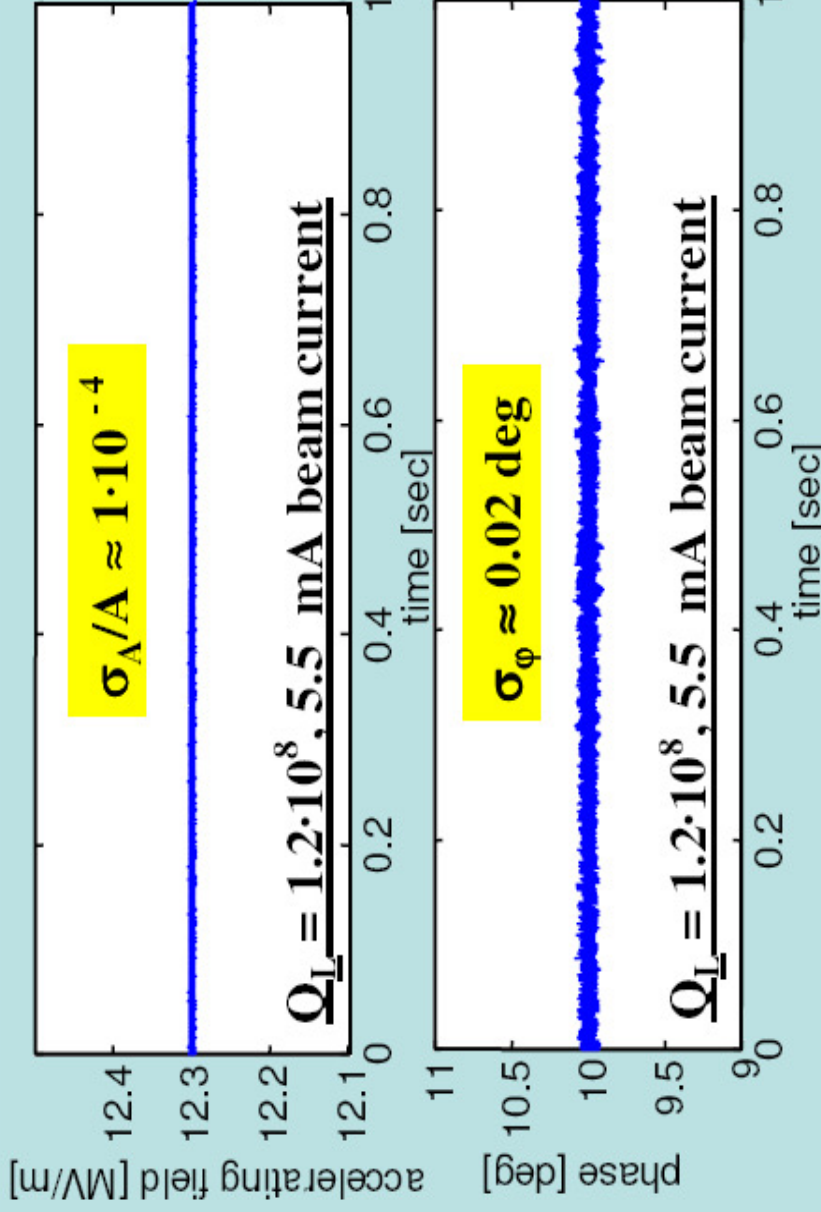


Highlights and Recommendations RF Control



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Where are we today? Cornell RF control test (IV)



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Highlights and Recommendations RF Control

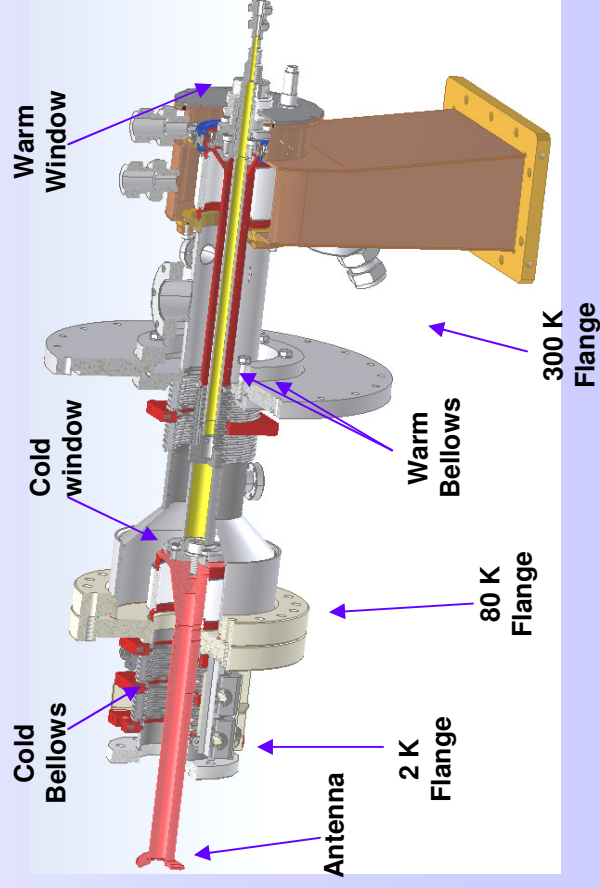


- No fundamental limit to operation
- $Q = 10^8$
- Proof of principle 10^{-4} is OK and 0.01 deg is OK.
- Distribution system must be able to handle this.
- The consensus was that a digital system was the way to go.

Highlights and Recommendations Power couplers

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



Highlights and Recommendations Power couplers



- Power couplers suitable for the main linac have been demonstrated
- Injector power coupler under development
- Adjustability is desirable, but may not be essential
- Coupler is a critical item and cost driver.

Q(T) is linked to the BCS surface resistance

R_s : BCS surface resistance
 A : material constant
 f : frequency
 Δ : BCS energy gap
 k : Boltzmann constant
 T : temperature

$$R_s = A f^2 \exp^{-\Delta/kT} (+ R_0)$$

R_0 : residual resistance

1.5 K is taken here as a reasonable lower limit of BCS $Q=Q(T)$ dependence

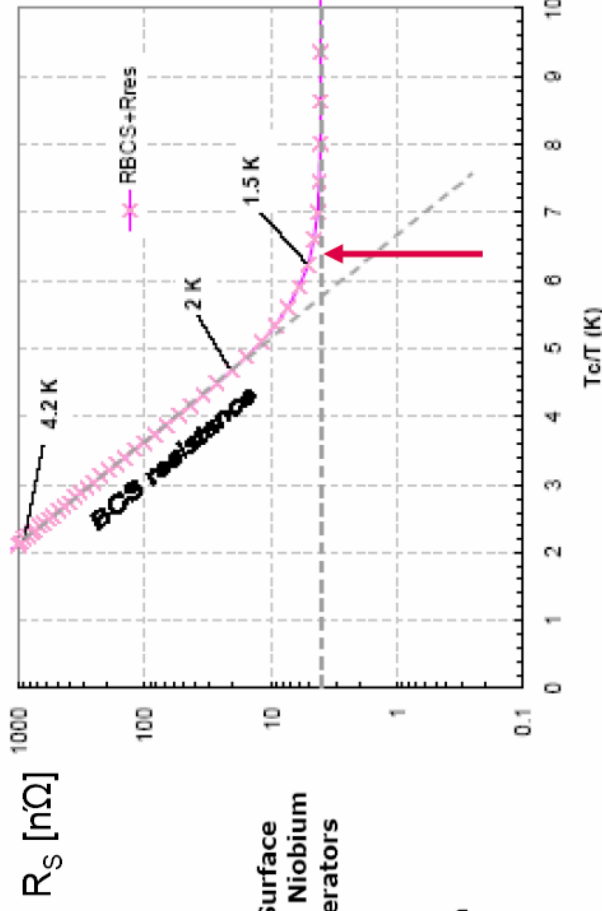


Diagram taken from:

Review of Models of RF Surface Resistance in High Gradient Niobium Cavities for Particle Accelerators

P. Bauer
Fermilab, Technical Division

TD-04-014, June 2004

ERL2005 Bernd Petersen DESY



Highlights and Recommendations Cryogenics 1



- **Fight residual resistance, then go lower in temperature (down to 1.8 K looks safe), retrofit system is possible.**
- **Module design for 2K should work at 1.8K provided BCS losses dominate.**
- **Capital cost does not increase as you lower the temperature (provided BCS losses dominate.) You trade off cold compressors versus warm screw compressors.**



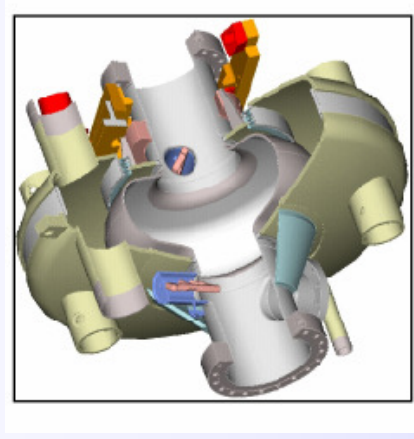
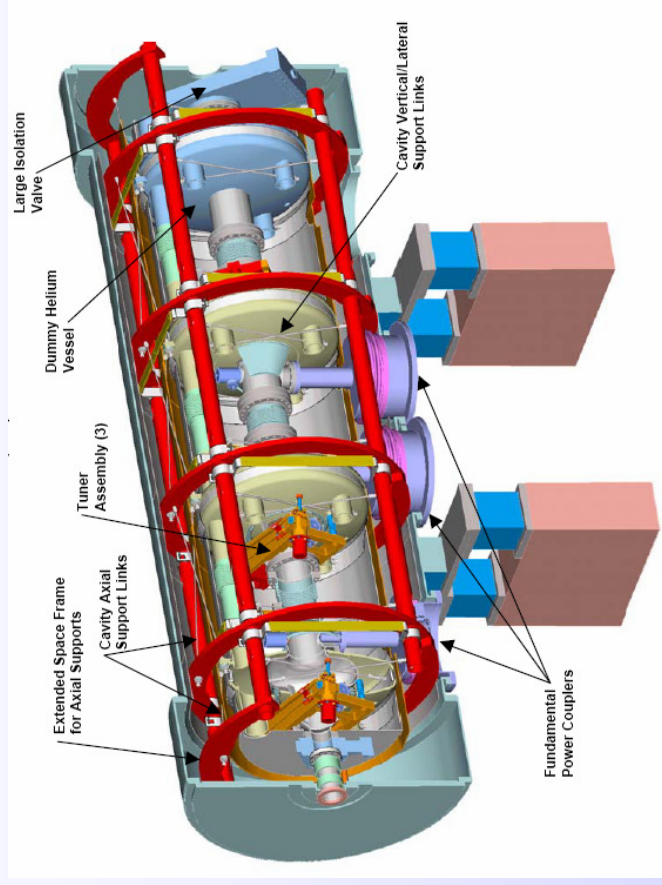
Highlights and Recommendations Cryogenics 2



- Design headroom used is 50% by several large institutions. (This is a minimum)
- 4 K shield comes for free (capital cost versus 10 year operating) and 4K heat intercept is useful for coupler etc. anyway. And each 2K watt takes you closer to the limit. (Based on the TESLA module)



Highlights and Recommendations Injectors - JLab 750MHz

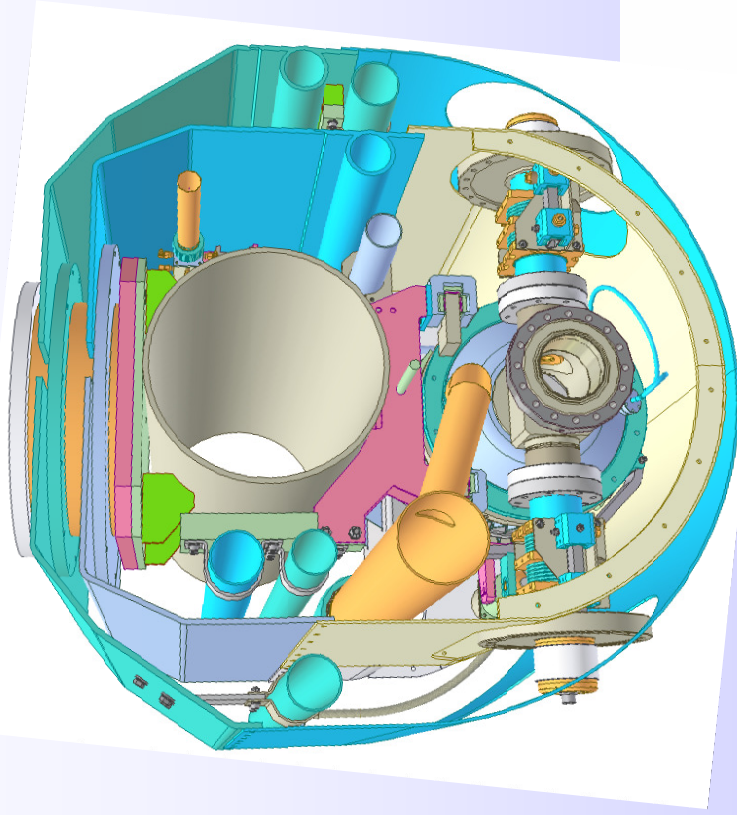


Three single-cell 750-MHz cavities will accelerate beam consisting of 133 pC, 6.3 ps long bunches to 7 MeV. The fourth upstream vessel is presently used for helium inventory and does not contain an accelerating cell. The cavity Q factor is $> 10^{10}$.

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.

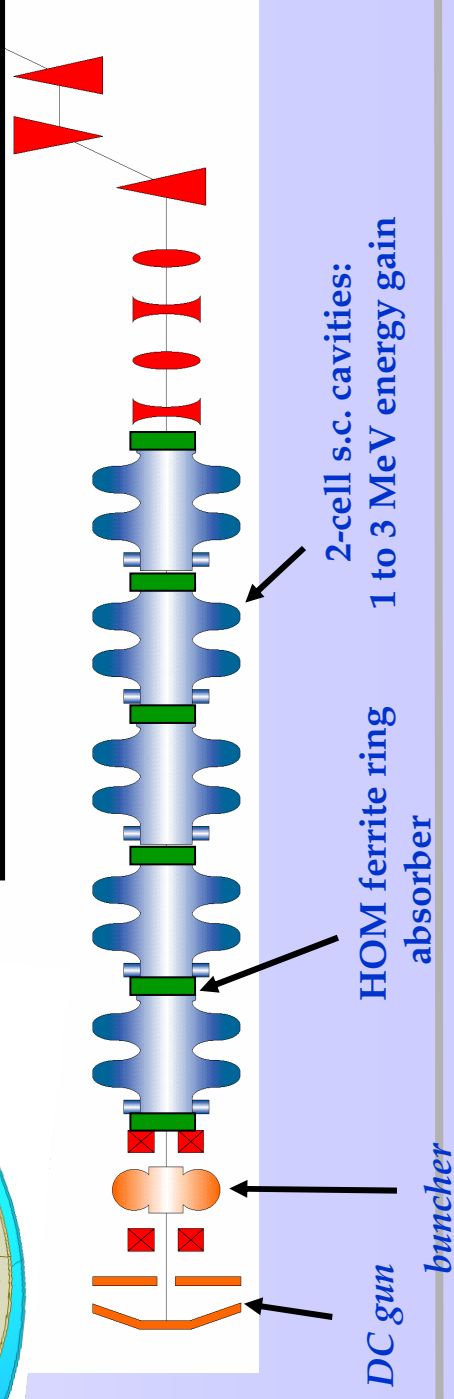
Four cavities have been delivered from AES and are being prepared for chemistry and an eventual vertical test.

Highlights and Recommendations Injectors - Cornell 1.3GHz



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	$< 0.5 \mu\text{m rad}$
max. emittance growth	$< 0.1 \mu\text{m rad}$
bunch length	0.6 mm
beam energy gain	5 MeV





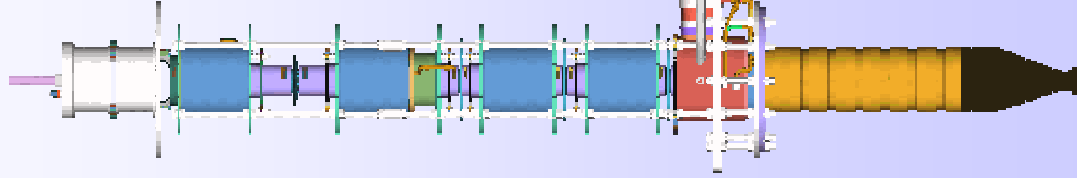
Highlights and Recommendations Injectors



- Active field, three projects (Cornell injector, JLab 100 mA injector)

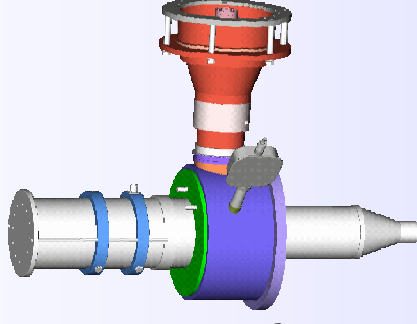


Highlights and Recommendations Power Sources



Klystron

- Electron Bunches formed by density modulation from the cavities.
- Several bunching cavities
 - High Gain
 - Long Device
 - Expensive
- Considerable velocity spread
- Maximum gap voltage determined by the slower electrons
- Rapid reduction in efficiency for reduced output power
- High Gain



IOT

- Velocity modulation direct from the cathode
- Little velocity spread
- Higher gap voltage
 - Increased output power
 - Higher efficiency
- Efficiency is approximately constant for reduced output power
- Low Gain
- Grid geometry will not permit IOTs to operate at high frequencies like Klystrons.



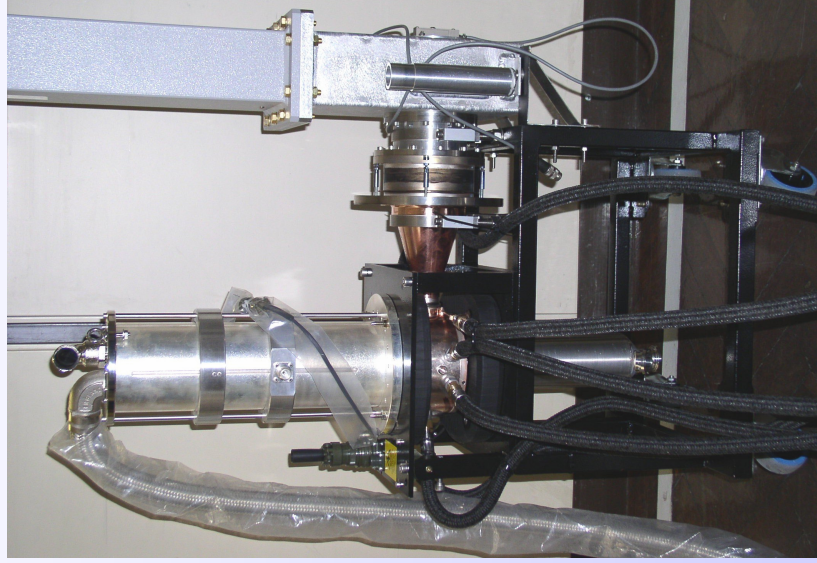
Highlights and Recommendations Power Sources



1.36GHz IOTs



CPI



e2v 116



Thales TH713



Highlights and Recommendations Power Sources



- IOTs look like the way to go for main linac, development nearly complete.
- Efficiency must still be demonstrated with the gain at the same time.
- Drive amplifier becomes a cost driver.



Highlights and Recommendations Technology Transfer to Industry



- Lab must demonstrate in more module than 1 that the desired guarantees can be achieved.
- Small labs cannot do this and must therefore do “research” together with the bigger Labs and industry.



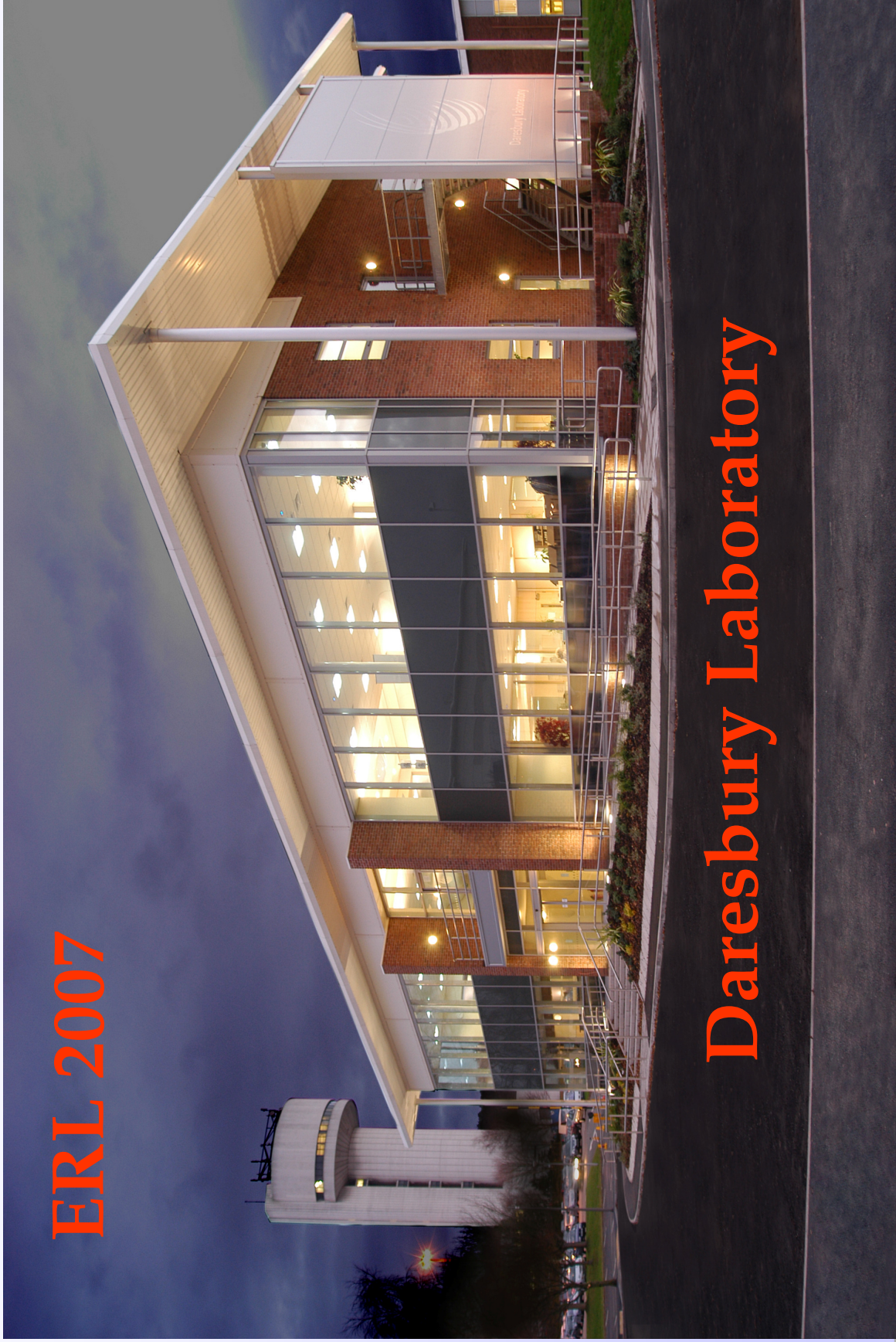
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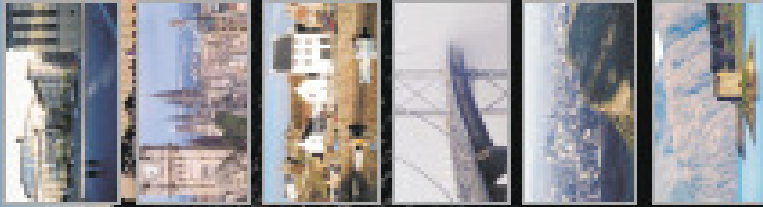
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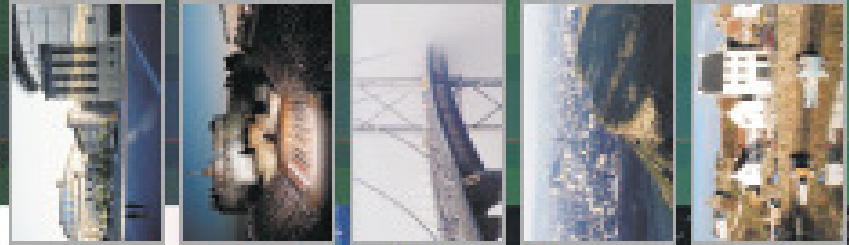
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