Fermilab
Vertical Cavity Test Facility

Accelerating RF cavities for the ILC Main Linac

Superconducting RF Technical Challenges

Vertical Cavity Test Facility

Part 1

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The What and the Why

The ILC design today

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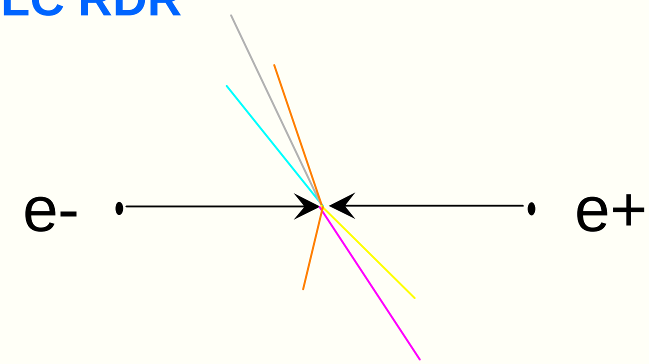
ILC RDR



ILC Specifications

- Initial center-of-mass energy up to 500 GeV, upgradeable to 1 TeV
- Ability to scan in energy between 250 and 500 GeV
- Integrated luminosity in the first four years 500 fb-1 at 500 GeV
  - Peak luminosity 2 x 10^{34} cm^{-2} s^{-1}, 75% duty factor

Main Linac

- Two 11-km linacs, one for electrons and one for positrons
- Accelerate from injected energy of 15 GeV to the final beam energy of 250 GeV

  ~**16000** 1.3 GHz superconducting RF cavities, operating at average gradient **31.5 MV/m**

The SRF cavities

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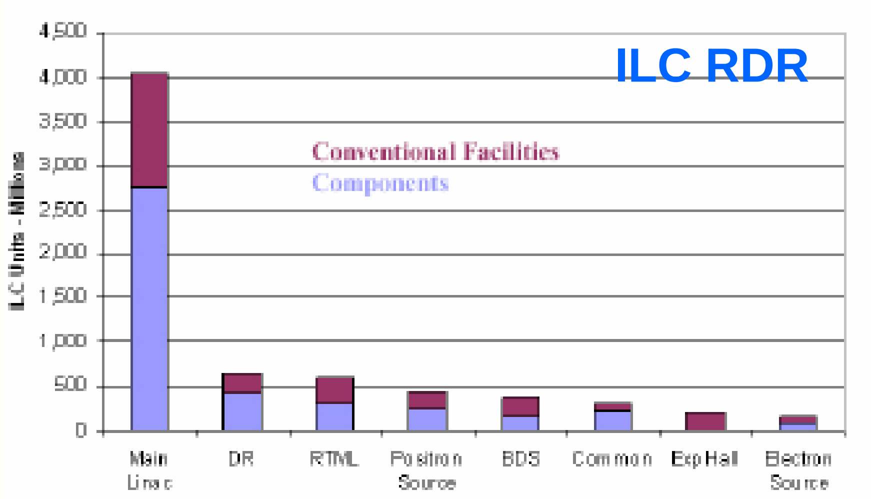
A TESLA 9-cell 1.3 GHz superconducting niobium RF cavity

this cavity today costs 75 k$

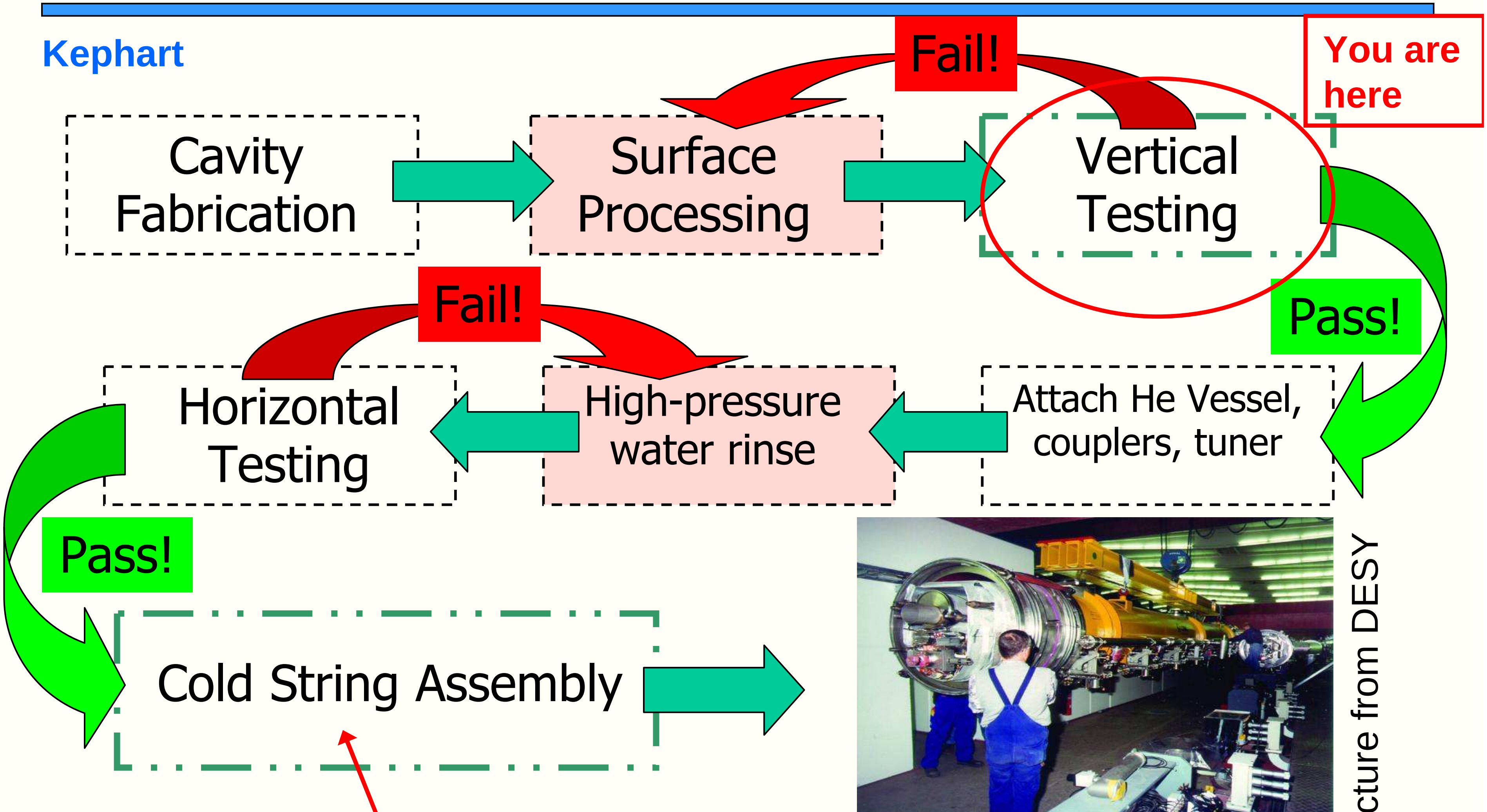
1 ILC unit = 1 US 2007$



- SRF cavities constitute a huge portion of the total ILC cost
- Also, a big technical challenge

From Cavity to Accelerator

Kephart

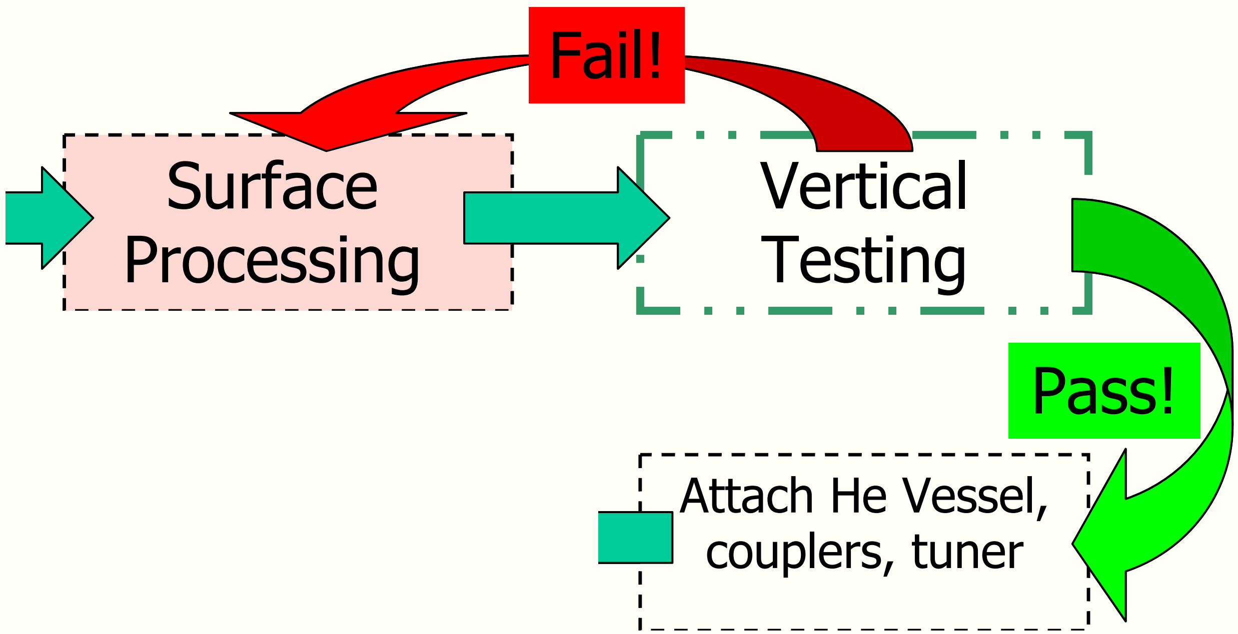


Picture from DESY

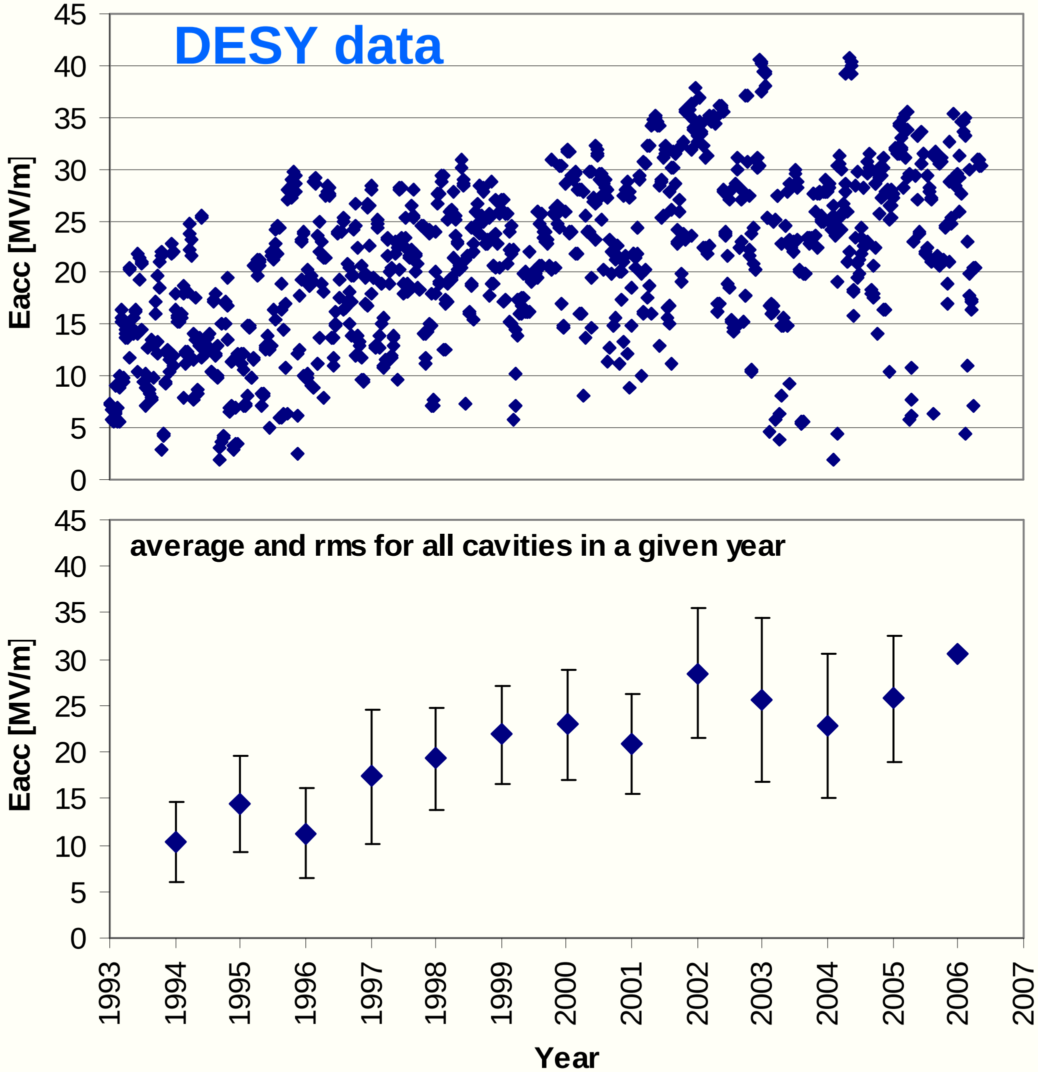
aka cryomodule – an accelerator piece

Reasons for Vertical Cavity Testing

- Acceptance test before further assembly
  - Currently difficult to get <E_{acc}> of >31.5 MV/m…
  - Vertical testing goes hand-in-hand with surface processing
    - Use to confirm technique effectiveness



difficult to reach ⟨ E_{acc} ⟩ >31.5 MV/m



- DESY/TTF data
- Vertical cavity tests all tests, all cavities Mar 1993 - Jan 2006
- $<E_{acc}>$ increasing with time
- Significant spread all years
- Technical challenge!

Improve Gradient Reproducibility

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- The need of making gradients more reproducible is a top priority
  - "S0" Goal: Achieve 35 MV/m at $Q_0=10^{10}$ in 9-cell cavity in vertical dewar tests (low-power) with a sufficient yield (> 90% for more than 100 preparation and test cycles). Two parts:
    - S0.1: Tight loop to improve "final preparation" yield
    - S0.2: Production-like activities to determine overall yield for cavity materials, fabrication and full cavity processing
- S0/S1 Task Force
  - E. Elsen (DESY), Lutz Lilje (DESY, chair), H. Hayano (KEK), T. Higo (KEK), J. Mammosser (JLab), A. Yamamoto (KEK), H. Padamsee (Cornell), M. Ross (FNAL), Kenji Saito (KEK), Bill Willis (Columbia),
  - New: P. Pfund (FNAL) Task Coordinator

    and CMG (FNAL) Principle Investigator
- Goal: Multiple facilities get the same results for equivalent surface treatments

What a Vertical Cavity Test is

- Make the cavity superconducting (2K)
  - Put the cavity, in a vertical orientation, in a dewar
  - Fill the dewar with liquid helium (4K)
  - Pump on the helium bath to cool the cavity to 2K
- Put RF power with an antenna into the cavity, with appropriate resonant frequency (1.3 GHz), turning on and off judiciously
- Measure (minimally) as a function of time
  - P_t transmitted power (another antenna at the other end)
  - P_r reflected power
  - P_f input or forward power
  - Frequency (frequency generator not that accurate)
  - Helium bath temperature
- Calculate Q, Eacc, etc.

Vertical Test (1): Q vs. Eacc

Quality coefficient: a measure of the surface material/quality

$$Q_0 = \frac{2\pi f\ U}{P_d} = \frac{G}{R_s}$$

[dimensionless]

f = RF frequency [Hz]
U = stored energy [J]
P_d = dissipated power [W]
R_s = surface resistance [Ω]
G = geometric factor [Ω]

Accelerating Gradient: depends mainly on the cavity geometry

$$E_{acc} = (1/L) \int_{z=0}^{z=L} E\, dz$$

[V/m]

L = cell length [m]
z = acceleration axis [m]
E = electric field [V/m]

Vertical Cavity Tests (1)

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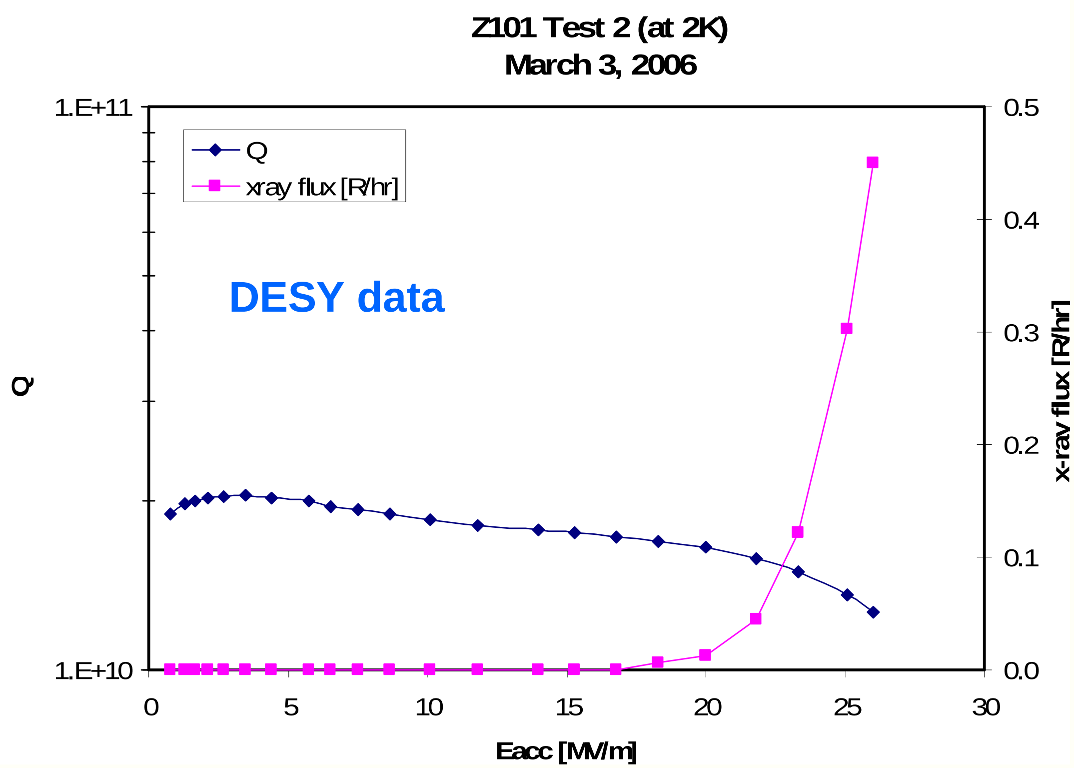
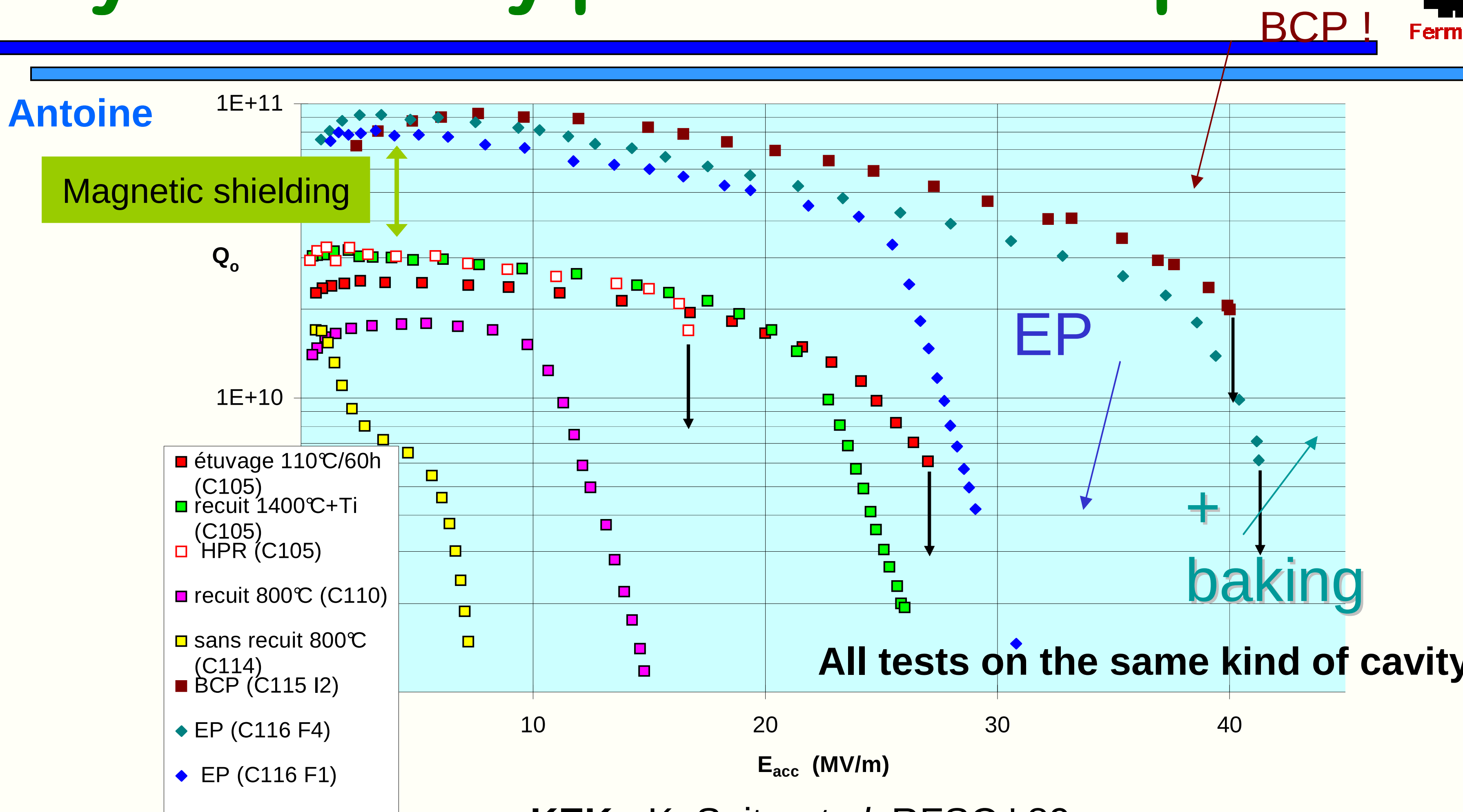
Test cavity quality (Q vs. E_{acc})

- Study cavity production quality and processing effectiveness
- Cavity acceptance test prior to cryomodule assembly



- "typical" Q vs. E_{acc}
- Z101 is a 9-cell Tesla-style cavity
- onset of field emission Eacc~18 MV/m
- X-ray flux measured with ionization chamber at top plate

15 yrs of cavity process development



KEK - K. Saito *et al.* RFSC ' 89

DESY-CERN-Saclay - L.Lilje *et al, TTF report, 1999*

Just to give you a flavor for the effects we are looking for!

DESY vertical test data

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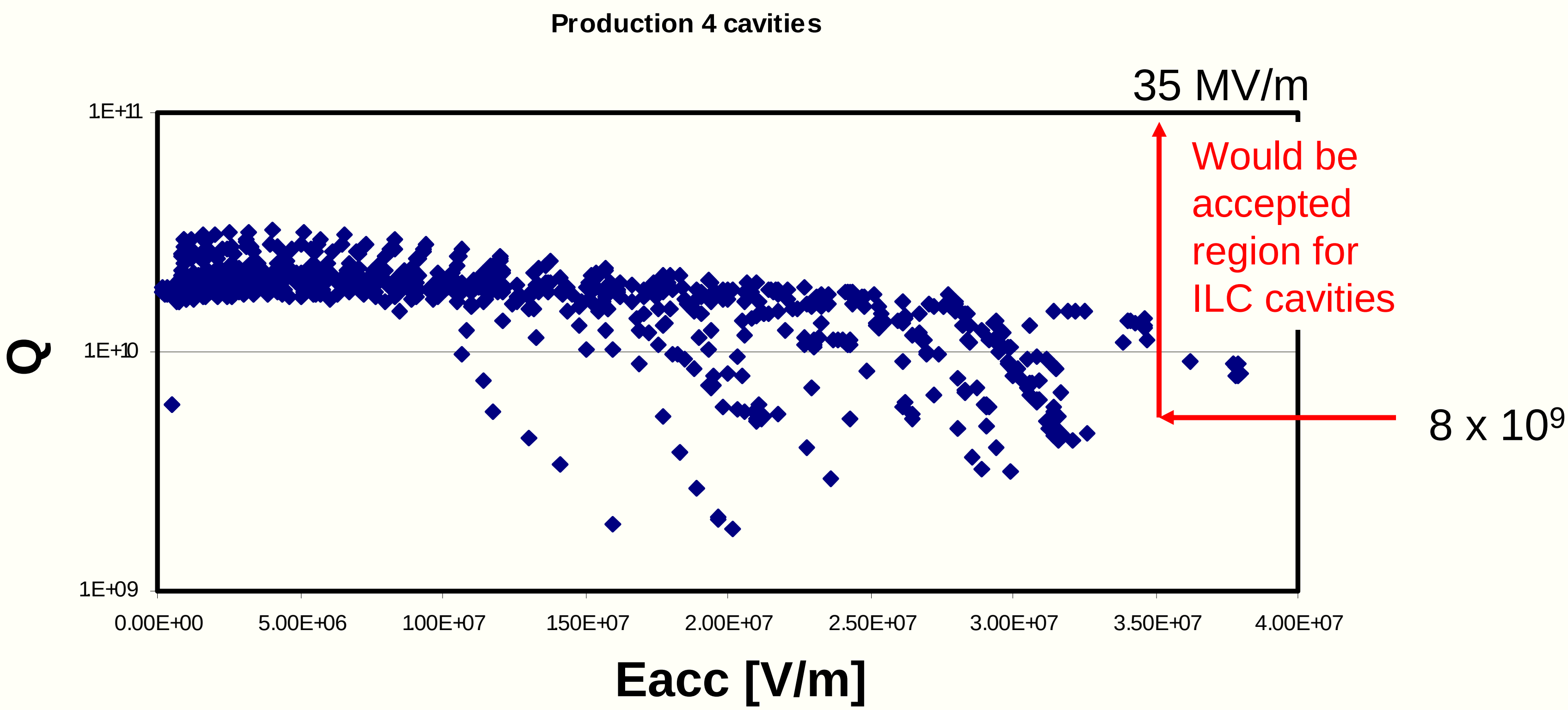
- Latest greatest Production 4 TESLA-style cavities tested 2005-2006
- All have (almost) the same surface treatment
- Nevertheless have significant variation in performance
  - Needs study – diagnostic instrumentation important!
  - Concentrate on quench detection, and field emission

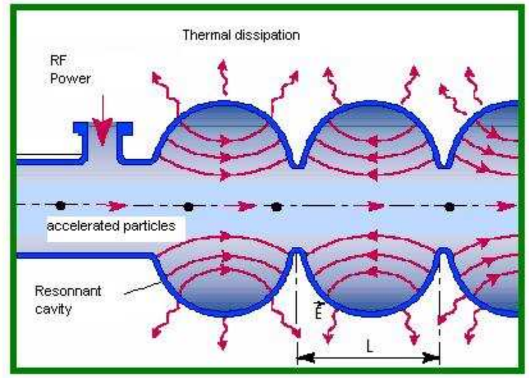


Vertical test (2): Surface Resistance

- To support RF fields in the cavity, currents flow within a thin inner surface layer
- Superconductivity:
  - Above Tc, all electrons unpaired
  - At T=0, all electrons paired (Cooper pairs)
  - As T drops from T=Tc to T=0, number of unpaired electrons drops as $\exp(-\Delta/kT)$
- DC case: energetically favorable for pairs to carry entire current while unpaired electrons remain inert

  Zero resistance
- RF case: pairs have inertia – forces must be applied to accelerate/decelerate

  Finite but small resistance, which depends on RF frequency



Superconducting: R_S(Nb) ~ 10's of nΩ (@ 2K)

Normal conducting: R_S(Cu) ~ few 100 μΩ

Vertical Cavity Tests (2)

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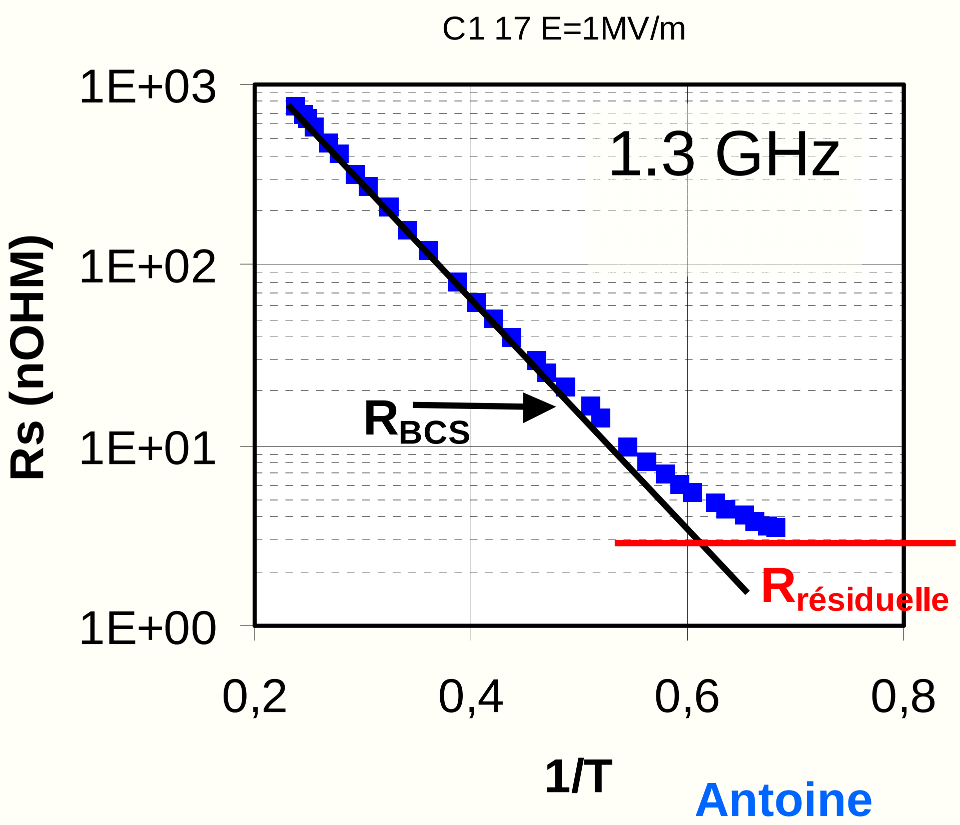
Test cavity surface resistance (Q vs. T)

- **Measure residual resistance**

$$R_S = R_{BCS} + R_{\mathrm{Res}}$$

$$R_{BCS} = A(Nb)\frac{(2\pi f)^2}{T}e^{-\Delta/kT}$$



SC: R_S(Nb) ~ 10's of nΩ (@ 2K)

NC: R_S(Cu) ~ few 100 μΩ

Part 2

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Vertical Cavity Test Facility Design

VCTF Initial Project Scope

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- One Vertical Test Stand (VTS) in Industrial Building 1
- Single, bare 1.3 GHz 9-cell Tesla-style cavities
  - Measure Q vs. T (T_{min}~1.5 K)
  - Measure Q vs. E_{acc} at 2 K
- RF design parameter: 250 W (CW) max power at cavity
  - $Q>5x10^9$ and Eacc<35 MV/m

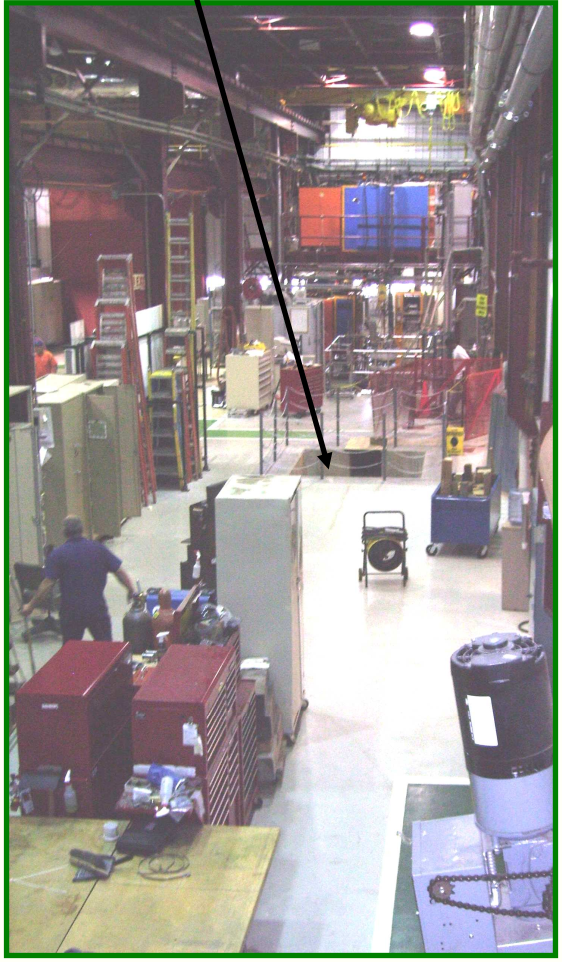
    or generally: $P_d = (1.04 \times 10^{-3}) * E_{acc}^2/Q < 250$ W
- Use existing IB1 cryogenic capacity ~125 W at 2 K
  - 250 W for short periods without excessive helium bath temperature increase
- Maintain "Controlled Area" radiation status in IB1
  - < 5 mrem in an hour immediately outside the shielding
  - <0.25 mrem/hr in normal working areas

VCTF in Industrial Building 1

Existing IB1 cryoplant/infrastructure
for Magnet Test Facility (MTF)

- **Significant cost savings & faster implementation**
  - **Current replacement value ~$10M**
- **Knowledgeable technical staff**
  - **4 cryogenic magnet test stands**
    FY06: tested 29 superconducting magnets
  - **3 conventional magnet test stands**
    FY06: tested 21 conventional magnets
  - **Cryogenic engineering, data acquisition systems, diagnostic instrumentation, software and data management, etc.**
- **Continue to share cryogenic system and IB1 infrastructure with magnet test program**
  - **Cryogenically demanding LHC magnet production tests are finished**

VTS pit



VTS Cryostat/Insert Design

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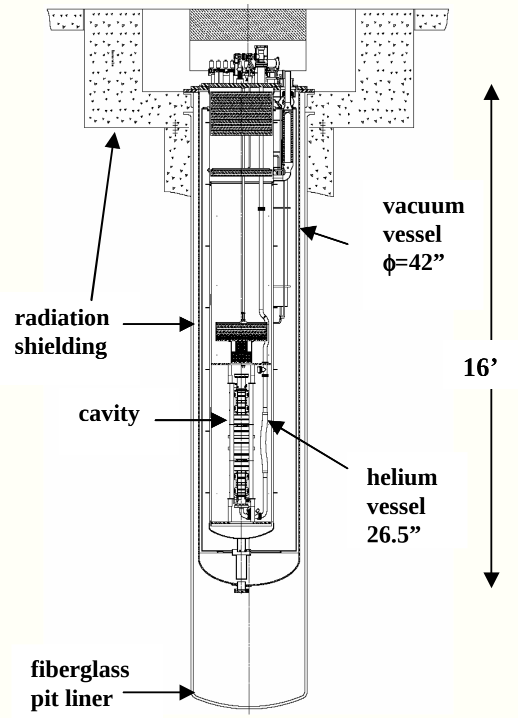
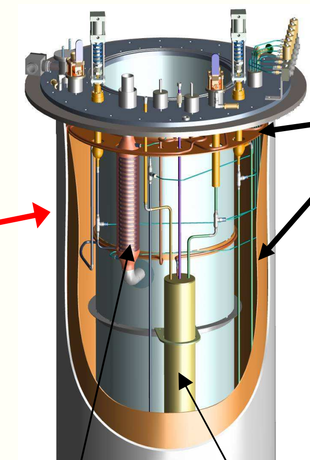
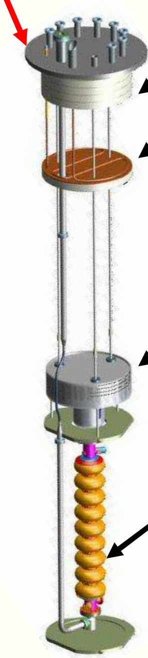
Based on Fermilab design of DESY/TTF/VTS
Added phase separator for better quality He



Cryostat



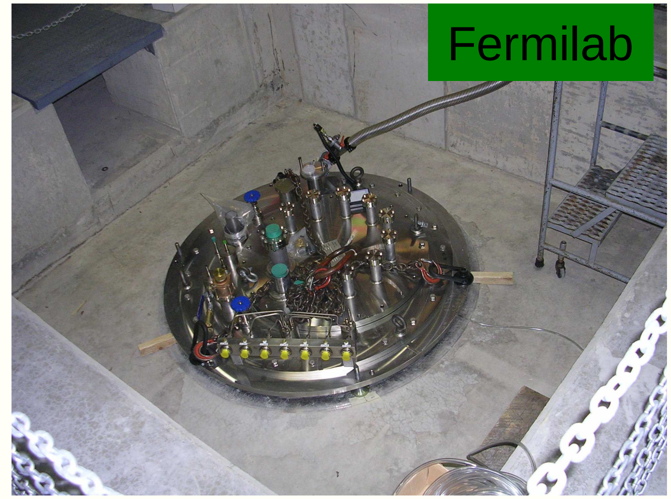
Top plate insert

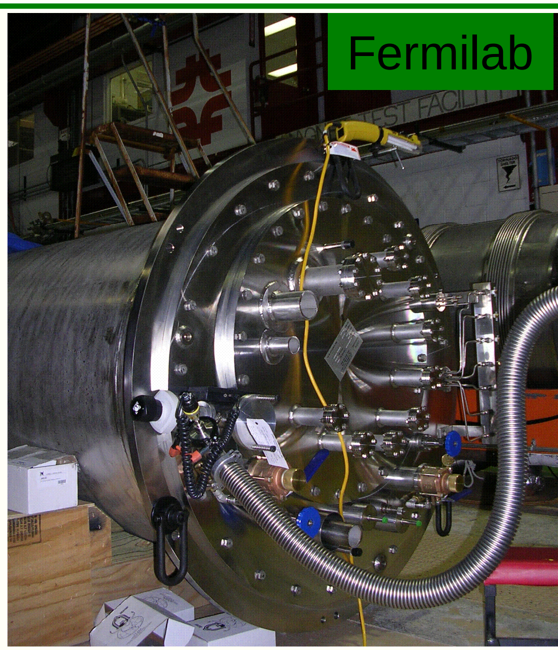


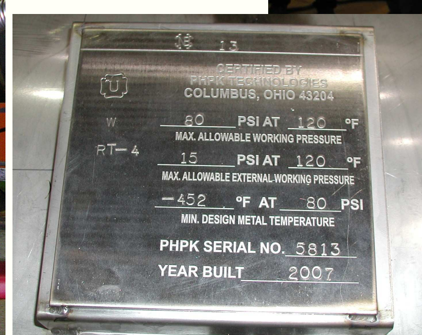
Cryostat manufactured by PHPK Technologies, Columbus OH

Cryostat photos

September 2006: Cryostat ordered
January 2007: He vessel ASME code stamped
February 2007: Received at Fermilab
March 2007: Temporarily installed
April 2007: Permanently installed
May 2007: Cryogenic Safety Review
Thanks to review panel: W. Soyars (chair), H. Cease, J. Makara
May 2007: First cold test and commissioning







Magnetic Shielding

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- Surface resistance increases due to trapped magnetic flux in localized normal-conducting surface impurities -> reduces cavity Q
  - Existing magnetic field at IB1 floor in pit region measured to be consistent with Earth's magnetic field (~0.5 G)
  - Shield to <0.01 G at cavity
- Two-layer design to shield magnetic field
  - Outer room-temp cylindrical shield, attached to vacuum vessel OD
    - Amumetal® (80% Ni alloy) 0.040" thick
  - Inner 2K cylindrical shield, attached to helium vessel ID, with perforated (for LHe flow) endcap
    - Cryoperm 10® 0.040" thick
  - Both "permanently" installed in/on cryostat to avoid damage
- Constructed by Amuneal Manufacturing Corp., Phila., PA
  - Outer shield – complete March 2007, installed April 2007
  - Inner shield – some issues – complete September 2007

Cavity degradation in B field

$B_0 \rightarrow$ higher surface resistance $\rightarrow$ lower cavity Q

$$Q = G/R_s$$

G = geometric factor

R_s = cavity surface resistance

$$R_s = R_{\mathrm{BCS}} + R_{\mathrm{res}} + R_{\mathrm{mag}}\ .$$

R_{BCS} = BCS resistance

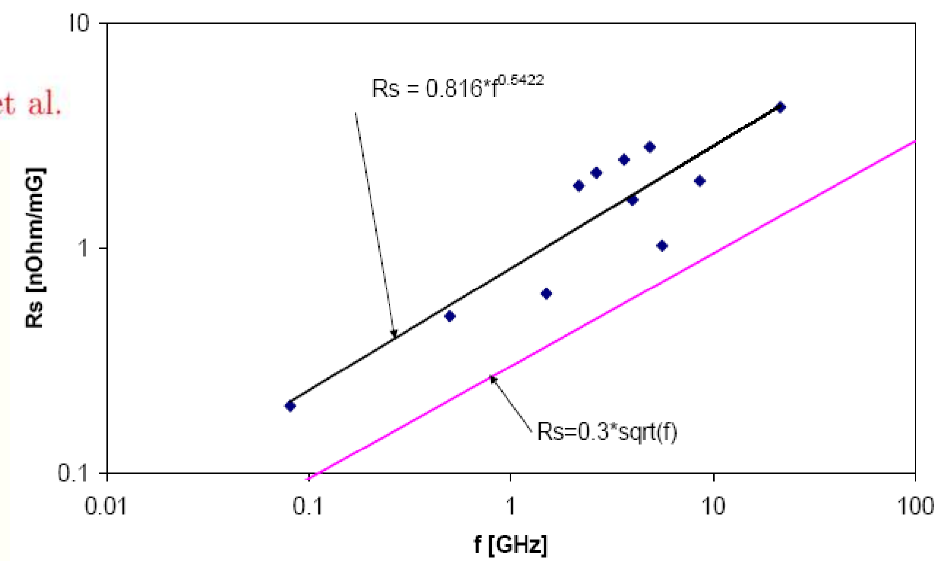
R_{res} = residual surface resistance due to cavity surface condition

R_{mag} = resistance due to trapped magnetic flux $\leftarrow$

For a niobium SCRF cavity

$$R_{\mathrm{mag}} = 0.3\, B_0[\mathrm{mOe}]\, \sqrt{f[\mathrm{GHz}]}\, n\Omega \quad \text{Padamsee et al.}$$

compilation by Vallet et al.



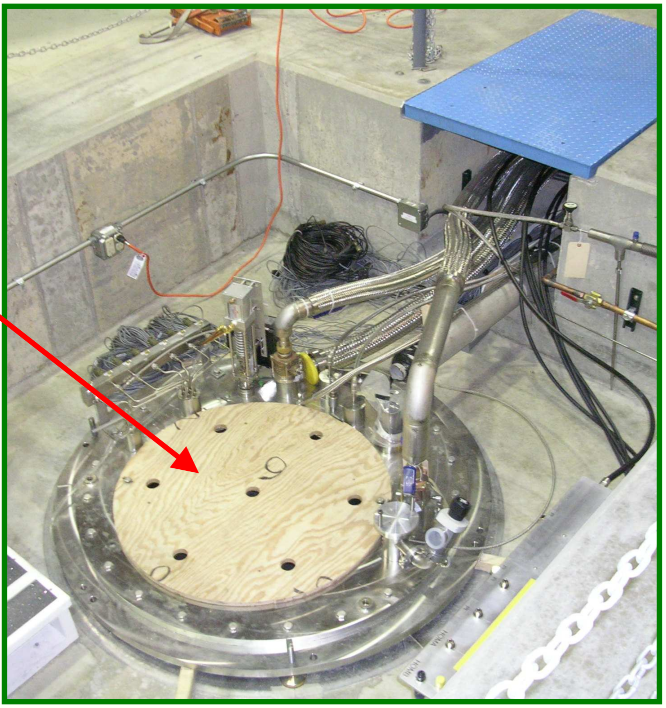
Outer Magnetic Shield

- Installation April 2007 on outside of vacuum vessel
- cylindrical shape
- 0.040" thick Amumetal® (80% Ni alloy)
- length 166", ID 42.125"
- half-cylinder pieces, tightened against vacuum vessel OD using Amumetal® joiner bands, PEM fasteners, 304 SS screws
- More support provided by turn buckles between the top of the shielding and vacuum vessel top flange

Magnetic Shielding Measurements

Sergatskov

- magnetic field measured inside cryostat
  - Few fixed depths as probe lowered/raised along plastic guide tube
  - Tube could be positioned in one of 7 locations inside cryostat
  - Multiple successive measurements to determine reproducibility < 0.1 mG (rms)
  - Repositioning error ~0.1 mG
- three-axis fluxgate sensor, Mag-03MC1000 (GMW)
  - B < 10 G
  - Sensitive: 0.5 mG offset accuracy, noise level ~0.01 mG
  - probe was attached to a power supply/controller unit Mag-03PSU, also from GMW, via a 5m cable
  - controller connected to a digital multimeter, read out via GPIB to a LabView® program.



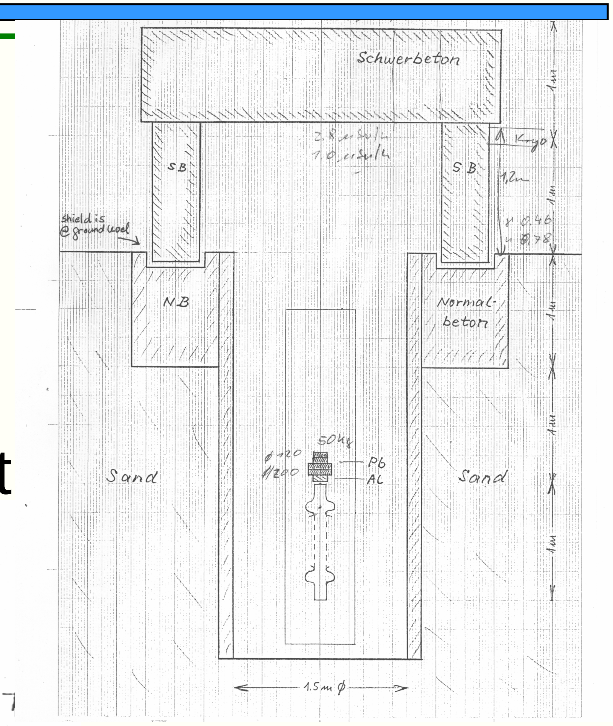
- **Measurement results so far**
  - Pit with or without cryostat
    - consistent with Earth B~0.5 G, few local enhancements
  - Pit with cryostat and outer magnetic shielding (only)
    - B < 0.05 G
    - Permeability of outer shield ~40000 (close to expected)
  - Pit with cryostat, both inner & outer shielding to be after VTS commissioning

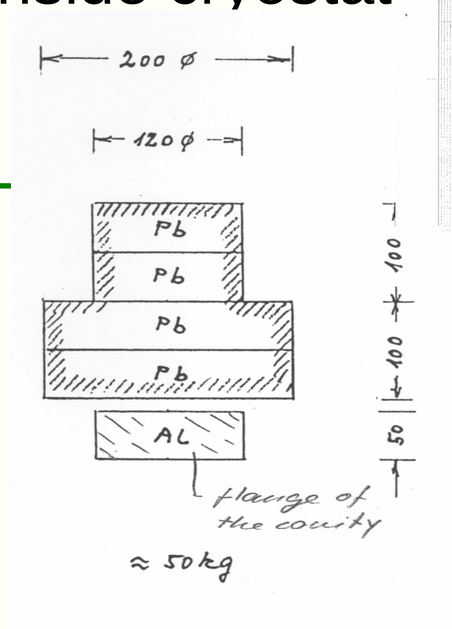
Radiation Shielding Analysis

DESY data measured over ~12 years,
~85 cavities

X-ray flux measured

- ~5 cm off axis
- above 1” SS top plate
- above 50 kg shielding inside cryostat
  - 20 cm Pb + 5 cm Al





Moeller

Radiation Shielding Analysis

DESY Vertical cryostat 2

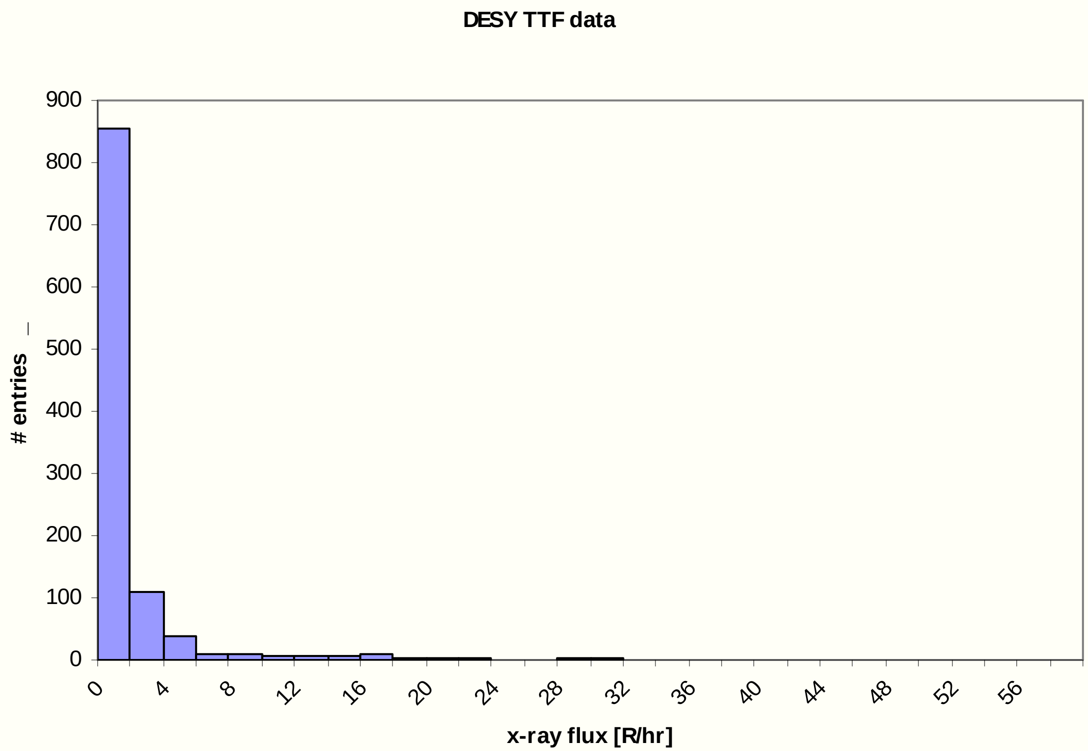
1m (heavy concrete)

Movable radiation shield shell

0.5m heavy concrete

Cryostat top plate

DESY radiation data



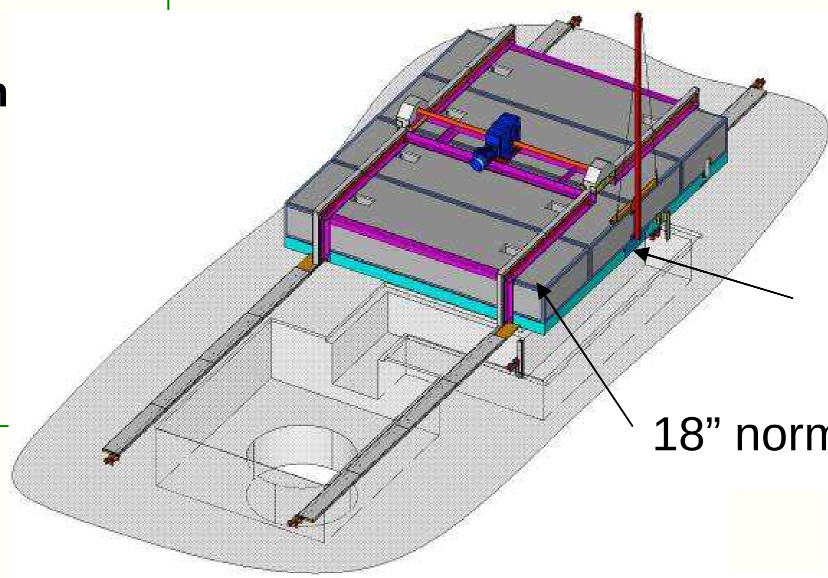
Measured x-ray flux above top plate
< 6 R/hr 90% of the time
< 30 R/hr 99% of the time
Always <58 R/hr

} Use as input to VTS shielding design

Unfortunately, we don't know the radiation geometric distribution

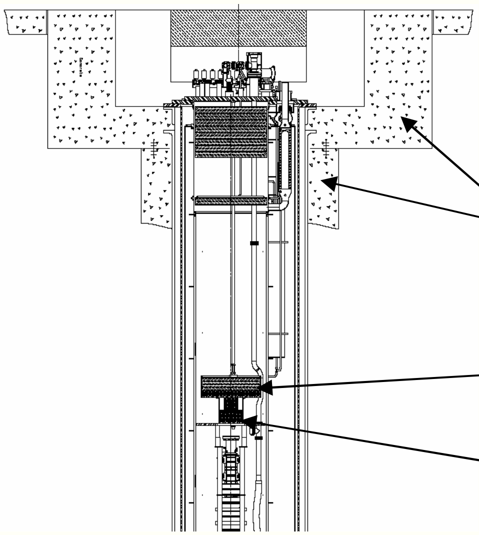
Radiation Shielding

- **X-rays estimated from DESY data**
  Thanks DESY staff!
- **Design from MARS15 simulation approved by ES&H**
  (Fermilab-TM-2350-AD)
- **Tritium production negligible**
- **"Controlled area" satisfied**
- **Assembly complete next week**



6" steel

18" normal concrete



normal concrete

Additional borated poly at instrumentation trench opening (not shown)

borated polyethylene, steel

lead

Rakhno: radiation shielding design
Poloubotko: lid mechanical design

RF/DAQ System

J. Ozelis, R. Nehring

- **Based on proven Jefferson Lab VTS RF/DAQ system**
  - **RF system with technology advances**
  - **LabView-based data acquisition system**
    - **Very user friendly, useful when we have visitors at test stand**
- **Collaboration with Jefferson Lab established** **Thanks JLab!** **(T. Powers, C. Grenoble)**
  - **added to Jefferson Lab MOU**
- **System status**
  - **Internal Fermilab design review 24 August 2006**
    - **Thanks to review committee: R. Pasquinelli (Chair), J. Steimel, B. Chase, C. Worel, J. Reid, W-D. Moeller**

    - all reviewers' recommendations incorporated
  - **RF personnel safety interlocks design (C. Worel)**
    - **approved by ES&H**
  - **RF amplifier (500 W CW) fully characterized**

    (R. Pasquinelli et al.)
  - **Low-level RF commissioning ongoing**

VCTF research goals

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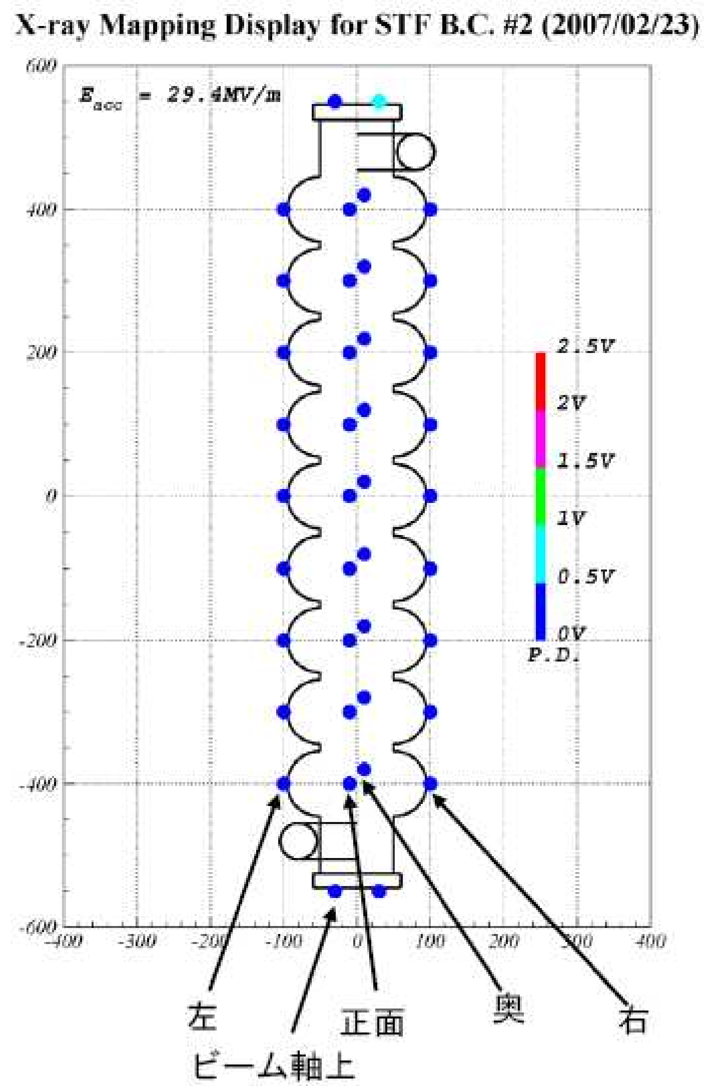
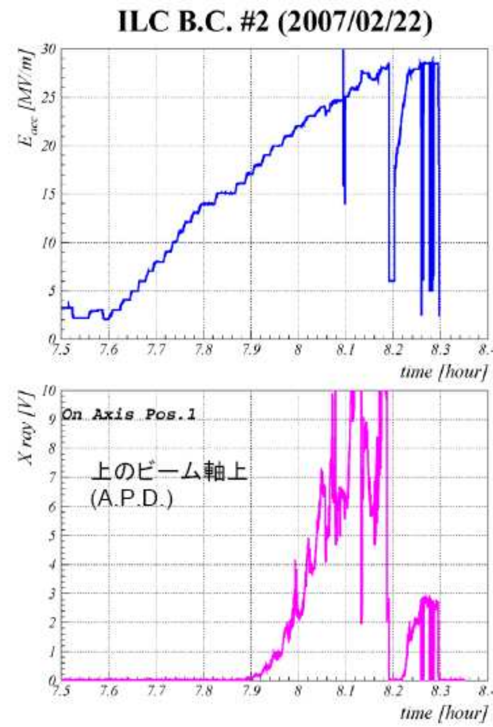
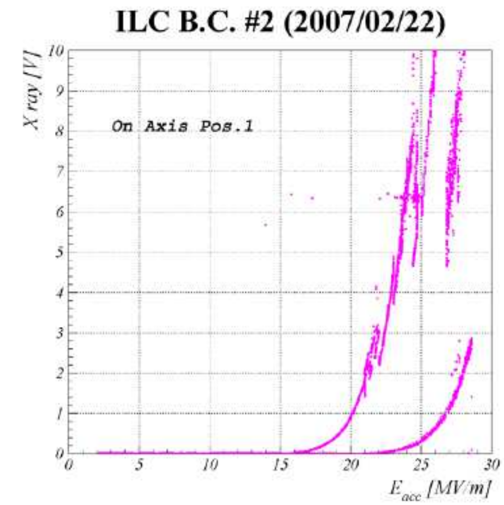
- "Diagnostic" top plate insert, ready to go when high-throughput cavity tests are paused
  - More instrumentation feedthroughs
  - Variable input coupler
- Program will evolve depending on outcome of ongoing R&D. Current proposals:
  - Thermometry for quench location in 9-cells (Mukherjee, Dhanaraj)
  - Field emission studies with x-ray detectors
  - Systematic study of magnetic field on cavity performance
  - Single-cell studies (processing techniques, large grain Nb, other materials, other cavity shapes)
  - "Collaboration" established and developing with Fermilab PPD scientists with instrumentation experience. Anticipate involving others from Fermilab, universities, other laboratories
- Operating VCTF very close to capacity would negatively affect research goals

KEK field emission data

Kirk Yamamoto







- **Example of something interesting to do**
- **Photodiodes placed around cavity**
- **Hamamatsu S1223-01 3.6 mm x 3.6 mm**
- **No thermal contact required – simple ass'y**
- **Excellent correlation between gradient and x-ray flux; also one FE burn off observed**

Part 3

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Vertical Cavity Test Facility Operations

Single VTS Test Cycle Duration

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Task	Duration (hours)
Receive cavity and cage	**0**
Mount cage to insert	**1**
Connect cables and TDR test	**1**
Install insert in dewar	**1**
Perform Dewar seal check	**0.5**
Perform Dewar leak check	**1**
Backfill Dewar, helium contamination check	**0.5**
Cool down to 100K, 8 g/sec	**0.5**
Wait at 100K for 8 hours (for Q-disease study)	**8**
Cool down to 4K	**1**
Fill @ 4K	**2**
Pump to 2K	**3**
RF Test at 2K	**4**
Boil off LHe	**4**
Warm up Dewar	**17**
Remove insert	**1**
Remove cavity cage from insert	**1**
Total single-cavity test cycle duration	46.5

RF test is ~10% of total test time

46.5 hours becomes 5 days with current infrastructure, primarily due to sharing of people and equipment with magnet test program, and shift schedules

Annual VTS Test Cycle Throughput

Downtime cause	# days/year	Comments
Cryogenic system down	60	Largest contribution is system contamination due to air-leaks
Pumps unavailable	24	Resource sharing with magnet test program
LHe supply unavailable	12	
VTS unavailable	15	Cavity-test-stand-specific problems
Total equipment unavailability	111	
Holidays	10	
Total down days	121	Out of 365 days/year

VTS test cycle (days)	5	Includes shift operations

# tests/year	48

address these with cryogenic system upgrades

Projected US Total # Cavity Processes

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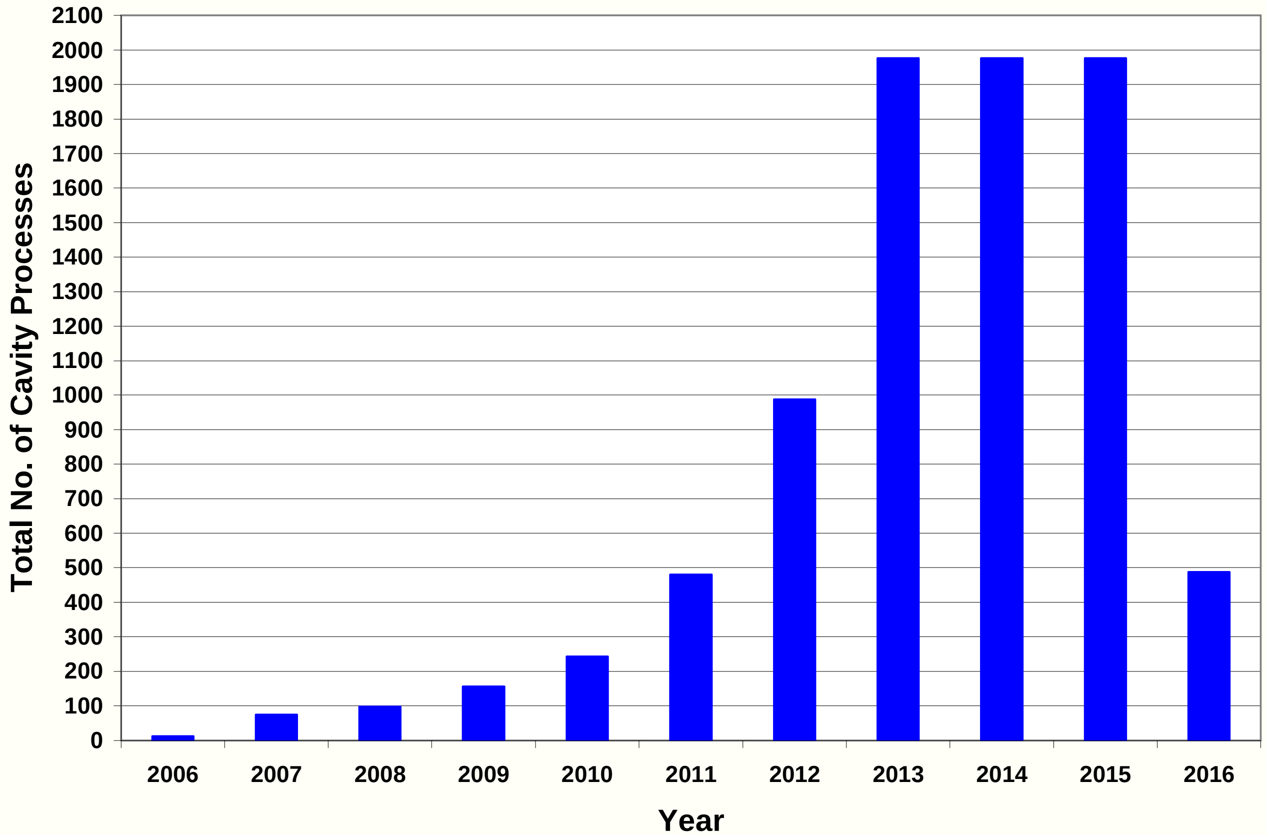
Mishra

Each process requires a Cavity Vertical Test



Expected VTS throughput 48 tests/year

US Laboratories' GDE request

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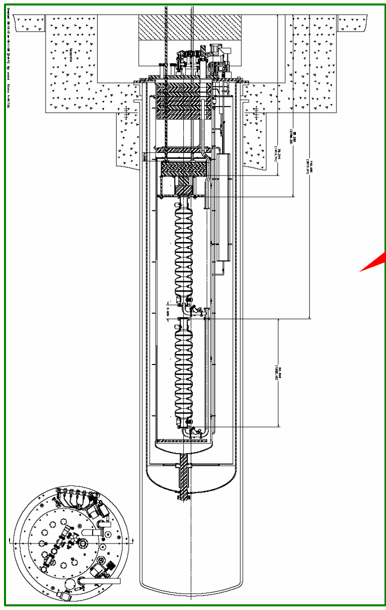
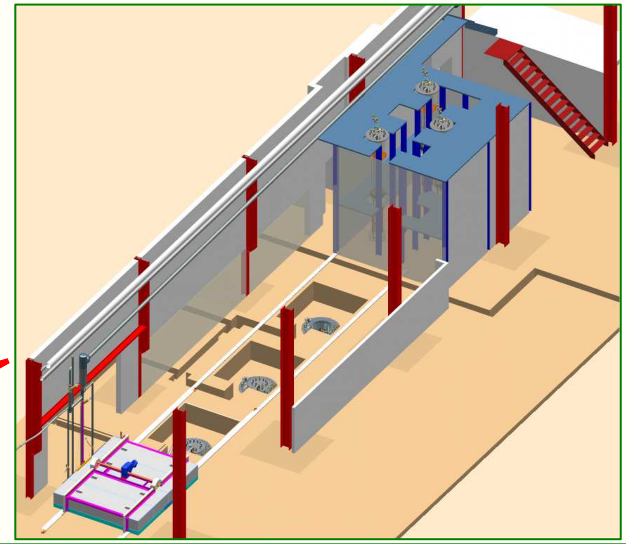
Program	FY07	FY08	FY09	FY10	Capacity Needed/yr by FY10
Cavity Processing (EP, HPR, Bake)	Jlab-30 Cornell-10	Jlab-40 Cornell-10 ANL-40	Jlab-40 Cornell-10 ANL-40 Fermilab-20	Jlab-40 Cornell-10 ANL-40 Fermilab-100	200
Vertical Testing	Jlab-30 Cornell-10 Fermilab-20	Jlab-40 Cornell-10 Fermilab-75	Jlab-40 Cornell-10 Fermilab-75	Jlab-40 Cornell-10 Fermilab-200	200
Horizontal Testing	Fermilab-6	Fermilab-24	Fermilab-24	Fermilab-72	72
Cryomodule Assembly	Fermilab-1	Fermilab-4	Fermilab-12	Fermilab-12	12
Cryomodule Test	Fermilab: ILCTA_NML	Fermilab: ILCTA_NML	Fermilab: ILCTA_NML	Fermilab: ILCTA_NML CMTS	12

Add vertical test throughput

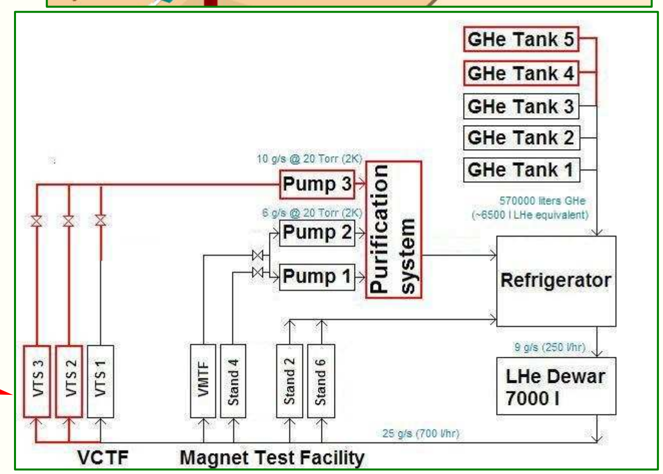
increase cavity throughput by > factor of two by FY10



Upgrade VTS for two-cavity operation



Add two more vertical test stands to VCTF



Upgrade cryogenic infrastructure

Part 3

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Wrap it up

Project Status

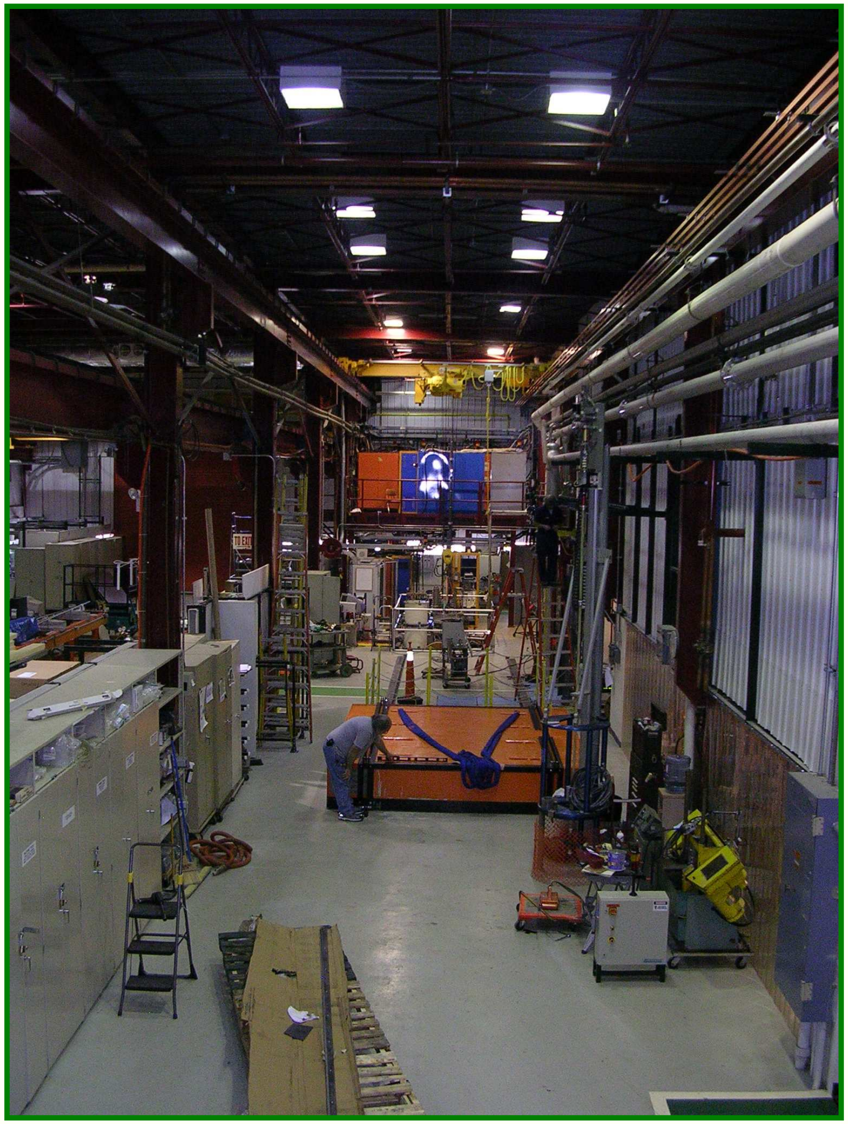
- **Cryogenic system commissioning May 2007**
  - **System performed very well**

Thanks to review panel: W. Soyars (chair), H. Cease, J. Makara

- **LLRF commissioning ongoing**
  - **Low power, i.e., < 1 W**
  - **Single-cell cavity**
- **Integrated commissioning next week**
  - **9-cell cavity from JLab (or use 1-cell)**
  - **Radiation shielding movable lid complete**
  - **RF interlocks (personnel safety) complete**
  - **Operational Readiness Clearance/Safety Assessment Document complete**

View from today

- **Radiation shielding lid is now there**
- **Making it movable on rails with a motor**
  - **In progress**



Conclusions

Fermilab

- Vertical Cavity Test Facility with one Vertical Test Stand well underway, to be operational in FY07
  - Will establish Fermilab as an ILC cavity testing facility
- Develop Fermilab SRF expertise
  - Study cavity characteristics
  - Develop cavity diagnostic instrumentation
  - Apply advances to new projects
  - Collaborate with university groups & other labs
    - Accommodate visitors with user-friendly facility
- Success: Even before the project is complete, made upgrade proposal
- Upgrade proposal based on analysis of existing system capability
  - Inputs: Considerable experience from Fermilab Magnet Test Facility, and cavity test operations information from other labs
  - Cryo upgrade planned for FY08
  - Additional VTS's planned for FY09
- Advance Fermilab's role in advancement of SRF technology

Acknowledgements/for more information

C. Antoine, AD/TD Seminar February 22, 2007
http://beamdocs.fnal.gov/DocDB/0026/002667/001/T_Fermi_Seminaire-2006.ppt

R. Kephart, DOE SRF Review, Feb.13-14, 2007
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http://media.linearcollider.org/rdr_draft_v1.pdf
http://www.linearcollider.org/pdf/RDR_Machine%20Overview_v5-1.pdf

Thanks Cornell, DESY, JLab, KEK, Saclay!

Thanks for strong support of IB1 Technical Staff!

VTS Group: CMG (Project Physicist), Cosmore Sylvester (Project Engineer)
R. Carcagno (IB1 Infrastructure Project Leader), Y. Huang, R. Nehring, B. Norris, J. Ozelis, V. Poloubotko, R. Rabehl, I. Rakhno, C. Reid, T. Peterson, M. Wong, C. Worel, A. Yuan

Important VTS contributions: C. Brown, A. Lunin, A. Mukherjee, O. Prokofiev, D. Sergatskov, TD Support Department