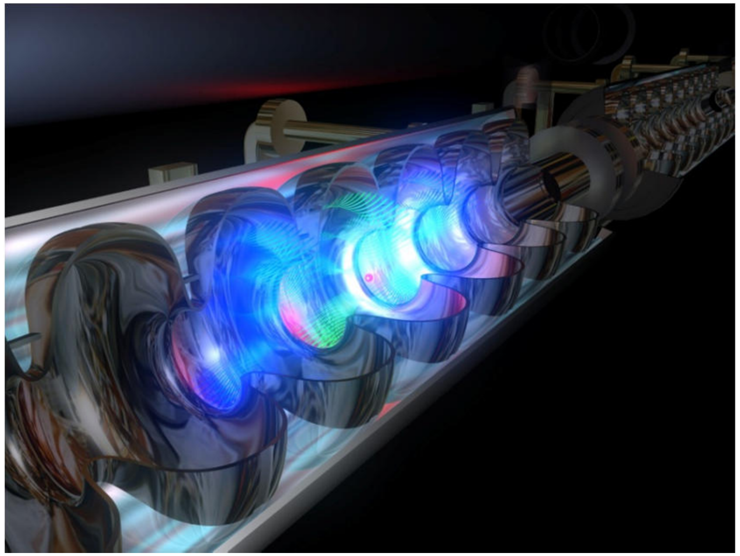
High gradient superconducting cavities

A worthy challenge

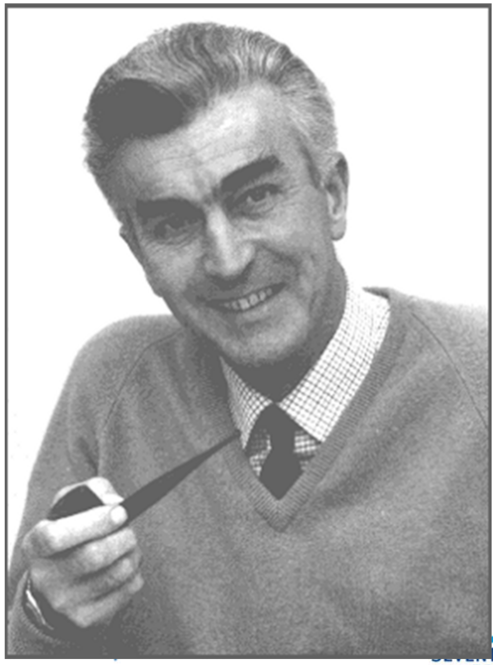
- ✓ Physical motivation
- ✓ Superconductivity revisited
- ✓ Needed quantities
- ✓ Surface treatment
- ✓ Diagnostic methods or
  “How do we learn?”
- ✓ Goals achieved so far…
- ✓ Ongoing R&D topics
- ✓ Summary



Marc Wenskat - DESY
@ John Adams Insitute
Oxford, 19. October 2011

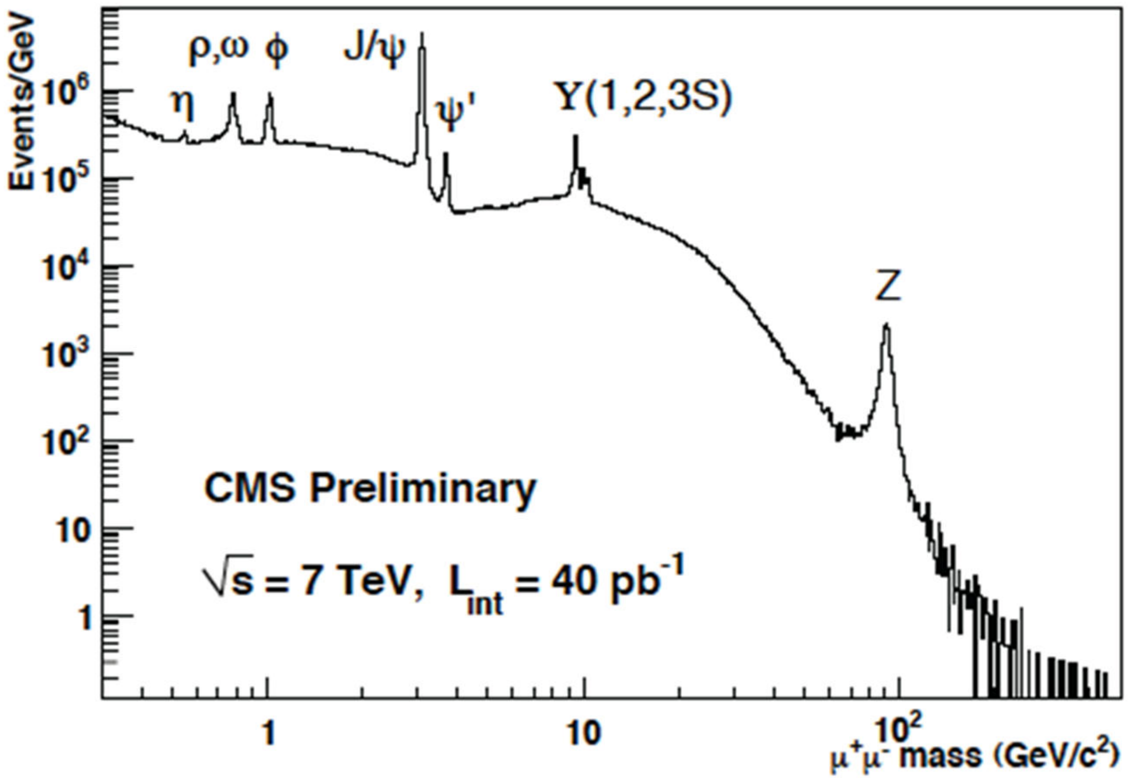
JAI & DESY or John Adams and Willibald Jentschke

- While John Adams was head of CERN Lab II (Prevessin), Willibald Jentschke was head of CERN Lab I (Meyrin) (1970-1976)
- Both strongly influenced CERN by designing / funding machines like the SPS, the ISR and LEP
- Jentschke was Head of DESY from 1959 till 1970



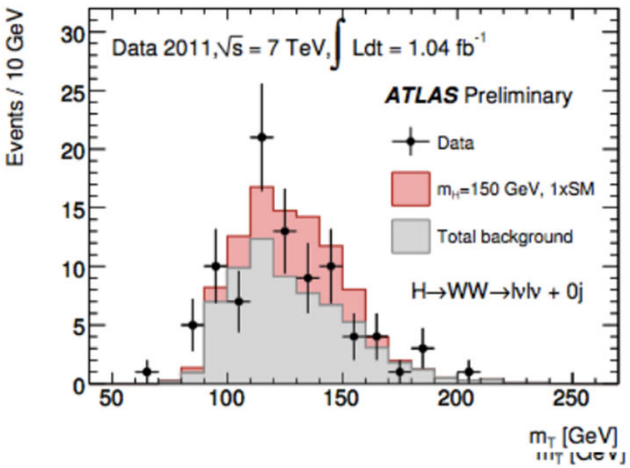
Physical motivation – LHC so far…

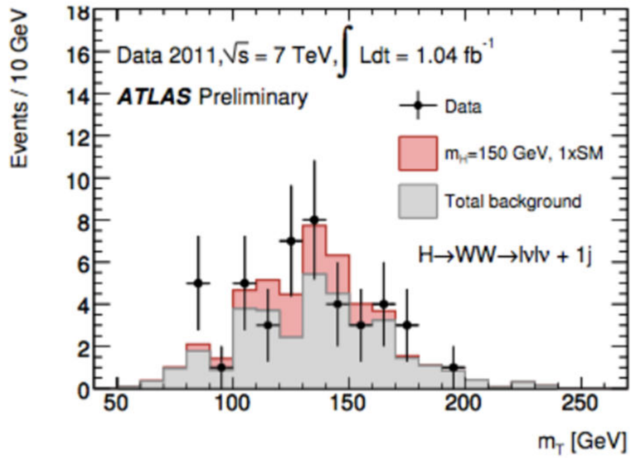
- Impressive rediscovery of the known ingredients of the Standard Model

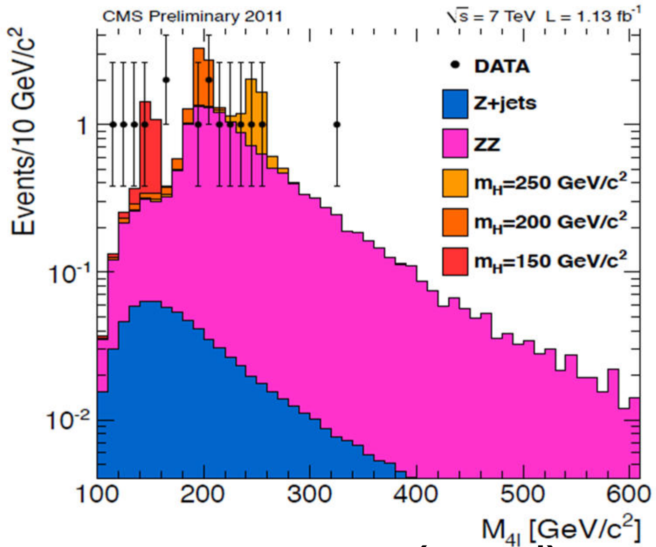


Physical motivation – LHC so far…

- No "smoking gun" for new physics (yet!?)







- But we expect (need) new physics
  - Higgs (reason for EW symmetry breaking?)
  - SUSY (DM? Hierarchy problem?)
  - something we have not thought of yet?

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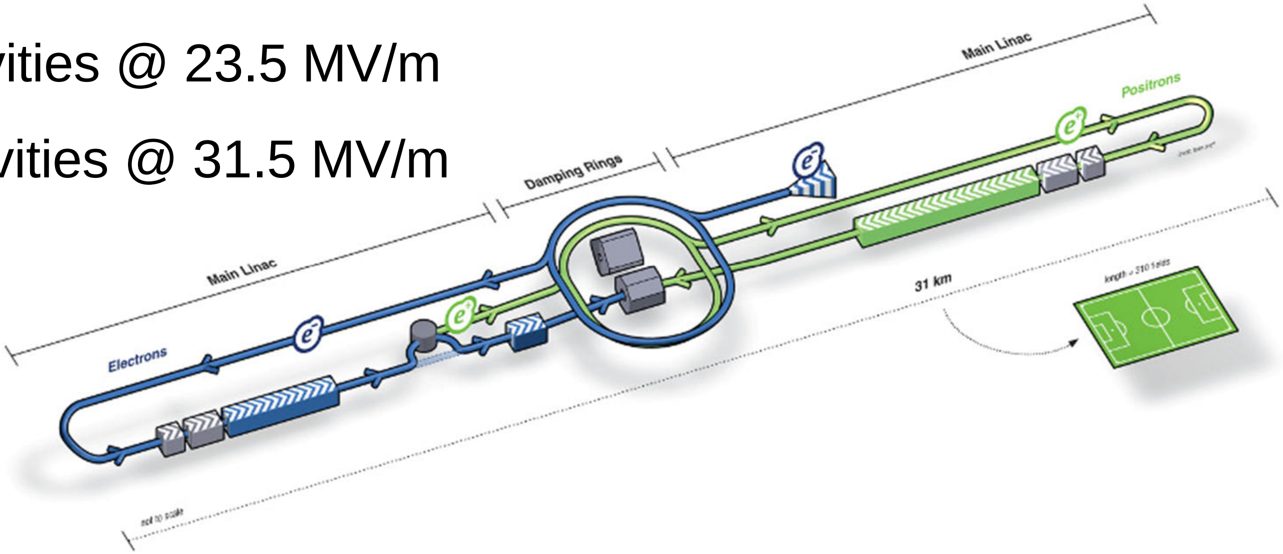
The pysics case for the linear collider

- If we see a Higgs like signal at the LHC… what is it?
  - SM-Higgs?
  - SUSY-Higgs?
- Further investigation of the coupling constants via „golden channel“ e+e- -> ZH (Higgs factory)
- If we see no Higgs like signal at the LHC… this is a major discovery!!
  - Ruled out SM-Higgs
  - Need to investigate regions where Higgs has been excluded more precisely
  - Nevertheless, clues for other mechanisms of EW breaking from precision measurements at the WW and t-tbar thresholds and at the Z pole

International linear collider

- Precision measurements
  - E can be scanned precisely
  - Initial state well known (energy, angular momentum….)
- Needs to be linear due to synchrotron radiation
- Acceleration technology based on known technique
  - FLASH: 56 Cavities
  - XFEL: 800 Cavities @ 23.5 MV/m
  - ILC: 14560 Cavities @ 31.5 MV/m



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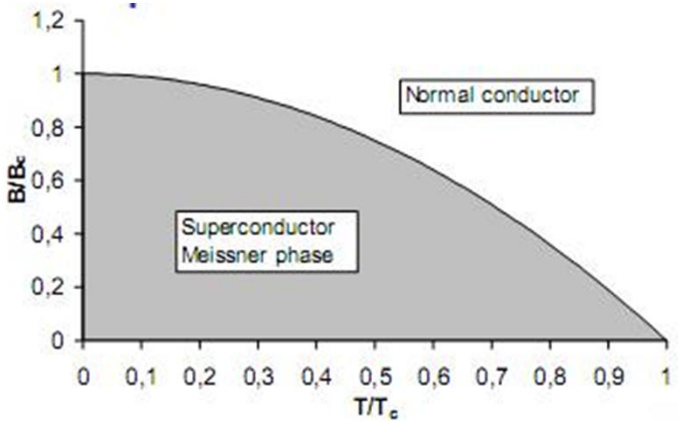
ILC – superconducting accelerator technology

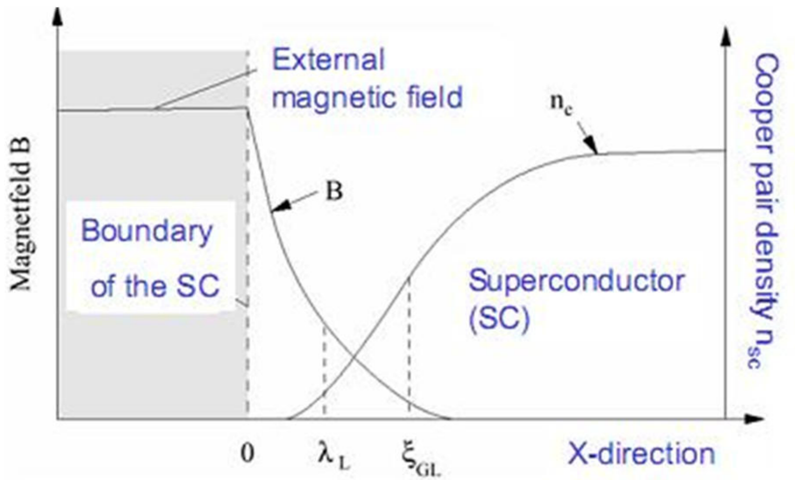
- Superconducting Cavities (SC) provide different advantages against normal conduction, e.g.
  - Continuous Wave (cw) or long-pulse acceleration doesn't lead to high dissipation
  - SC design allows to have larger beam holes which also provides higher beam qualities

The cavity of choice for FEL's or for colliders where high luminosity and beam quality is needed

Option	Superconducting	Normal Conducting
Q_0	2×10^9	2×10^4
AC Power (kW/m) for E_{acc} = 1MV/m	0,54	112
AC Power (kW/m) for E_{acc} = 5MV/m	13,5	2800

Superconduction



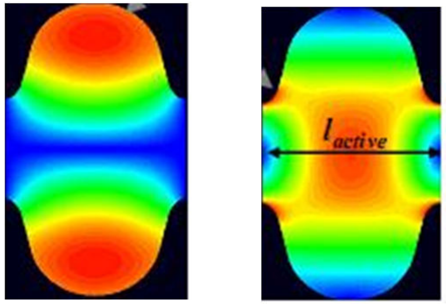


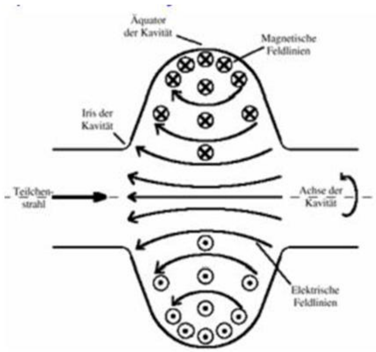
- Typ I superconductor
- Meissner phase repeals external magnetic field
- Penetration depth depends on T and material properties, so does Surface Resistance

$$R_{\mathrm{BCS}} = \frac{C}{T} f^2 \sigma_n \Lambda^3 \exp(-1.76\, T_c/T)$$

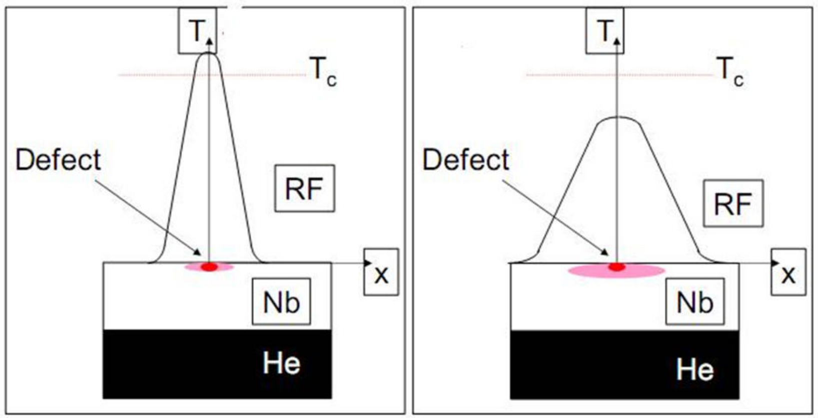
Important Limitations

- Ultimate Limit: peak magnetic Field (for Nb 0,23 T = 2300 Oe)
- Due to high RF Fields (nanosecond time scale) superheating field possible
- Maximum accelerating Field (thermodynamic):
  - **55 MV/m**

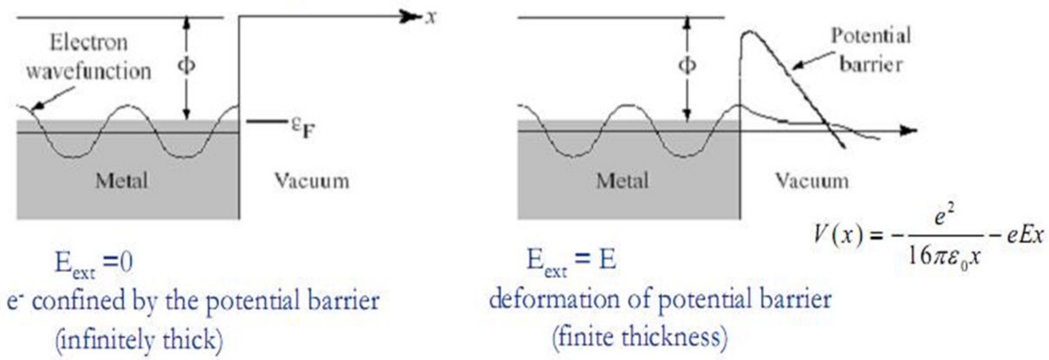




- Problems through FE
  - Dark current
  - Multiple Impacting (multipacting)
  - X-Ray's
  - Leads to Quench / Field Breakdown
- New geometry mainly solved problem (e.g. multipacting)



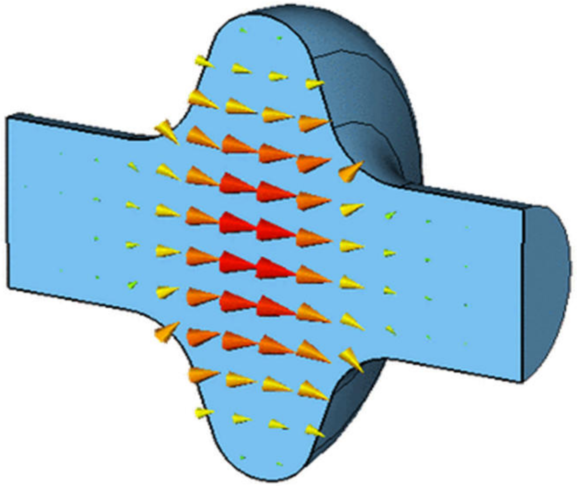
Electrostatic potential of metal – vacuum interface



Describing a Cavity

$$Q = \omega \frac{\text{Energy stored}}{\text{Power dissipated per Oscilation}} = \frac{\omega U}{P_c}$$

- Half width of resonance, decay & filling time
- A measure for the heat load
- A measure for the surface resistance



$$V_{acc} = \left| \int_{z=0}^{z=l} E_{el}\, dz \right| = \left| \int_{z=0}^{z=l} E_z(\rho = 0, z) e^{i\omega z/c} dz \right| = \left(\frac{2}{\pi} \right) l \cdot E_0$$

$$E_{acc} = \frac{V_{acc}}{l} = \frac{2E_0}{\pi}$$

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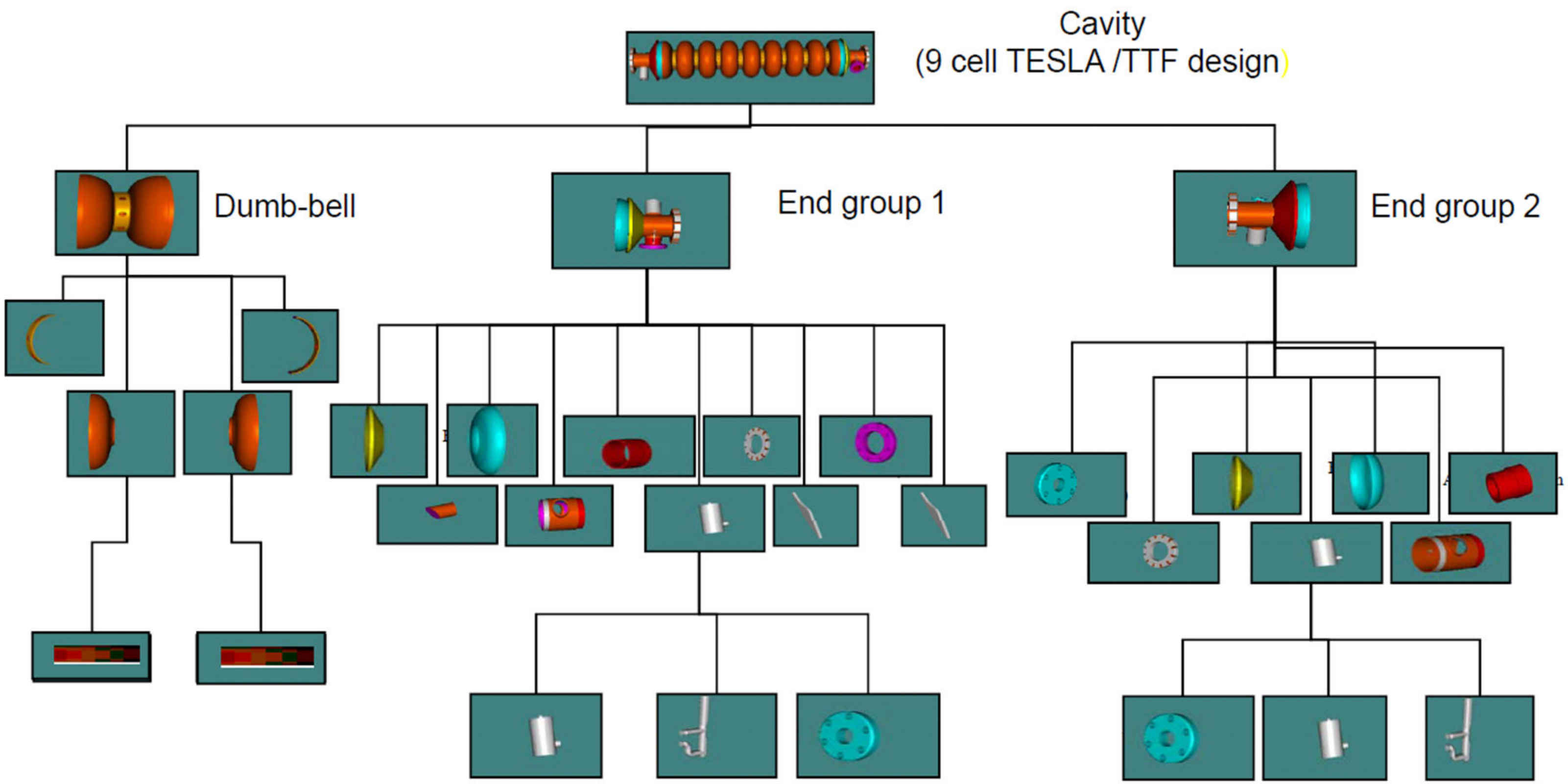
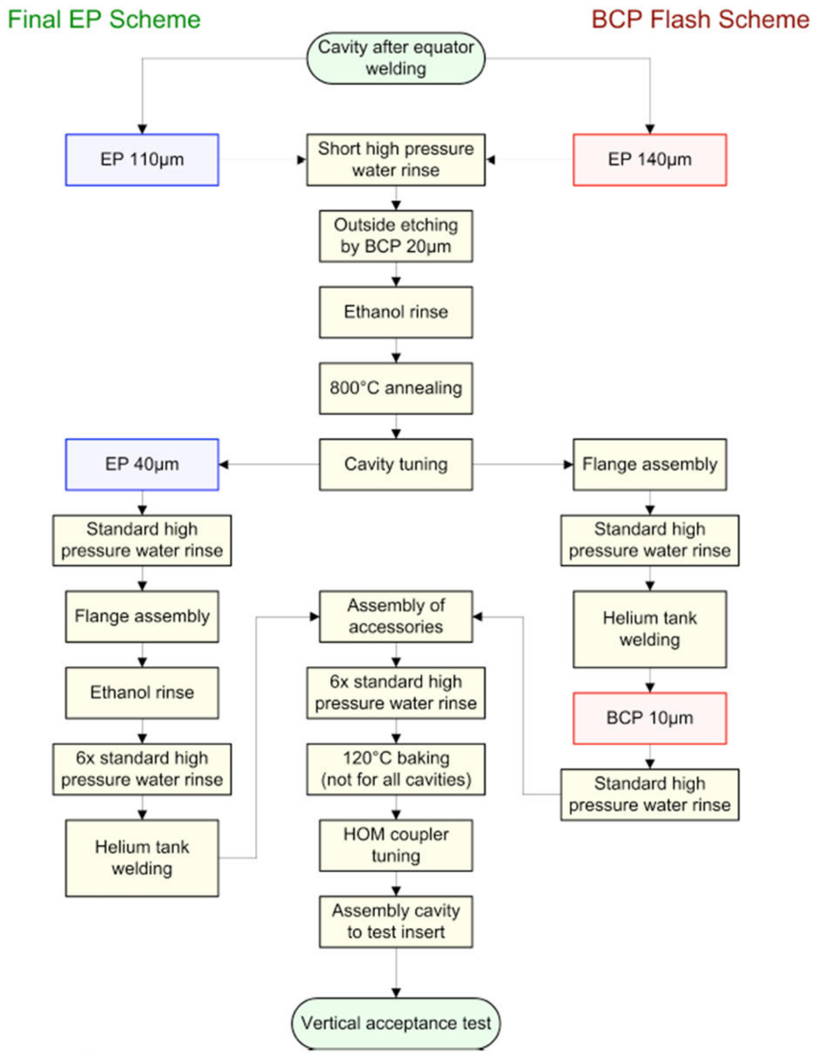
Cavity manufacturing



Surface Treatment – standard recipe

- Two different surface chemistries:
  - **Electropolishing**
  - **Buffered chemical polishing**
- EP shows a slightly better performance at higher gradients but both satisfy the XFEL specifications



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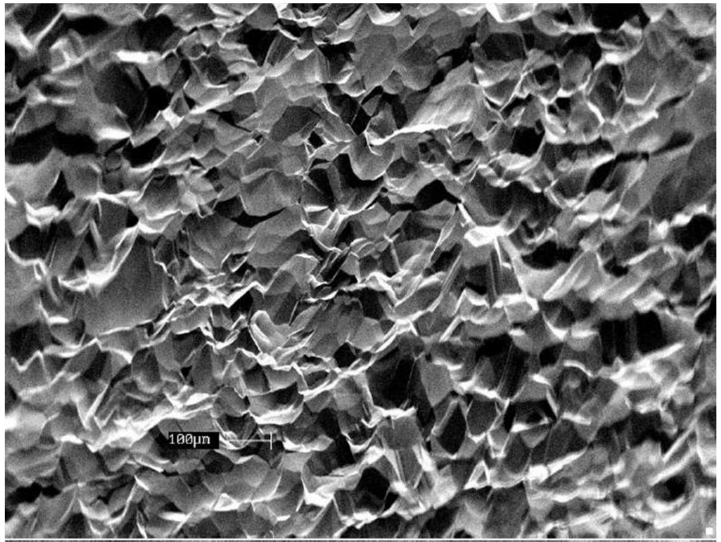
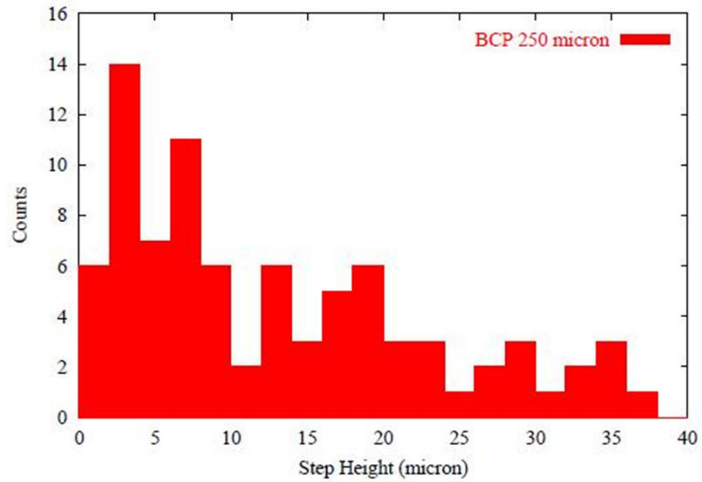
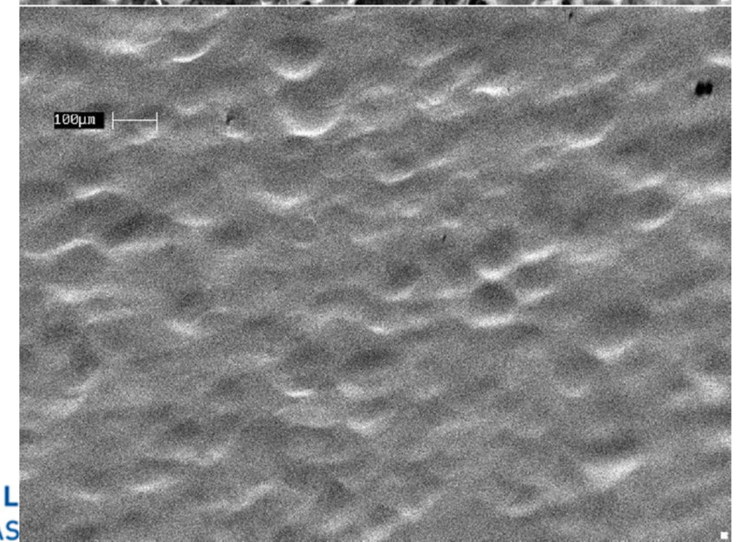
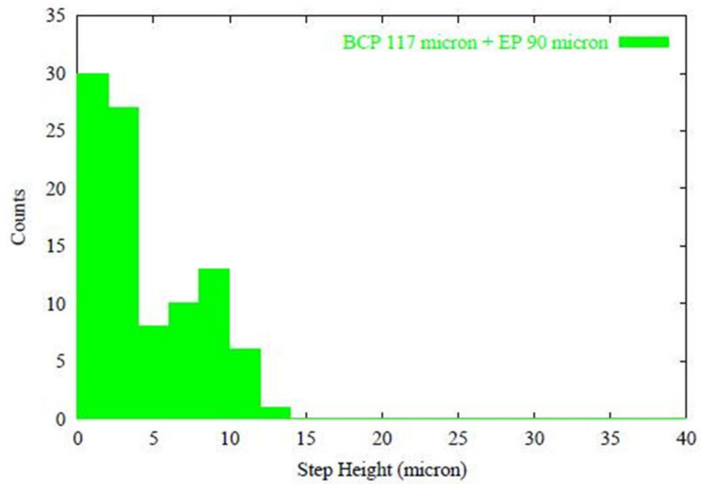
Surface Treatment – EP vs. BCP

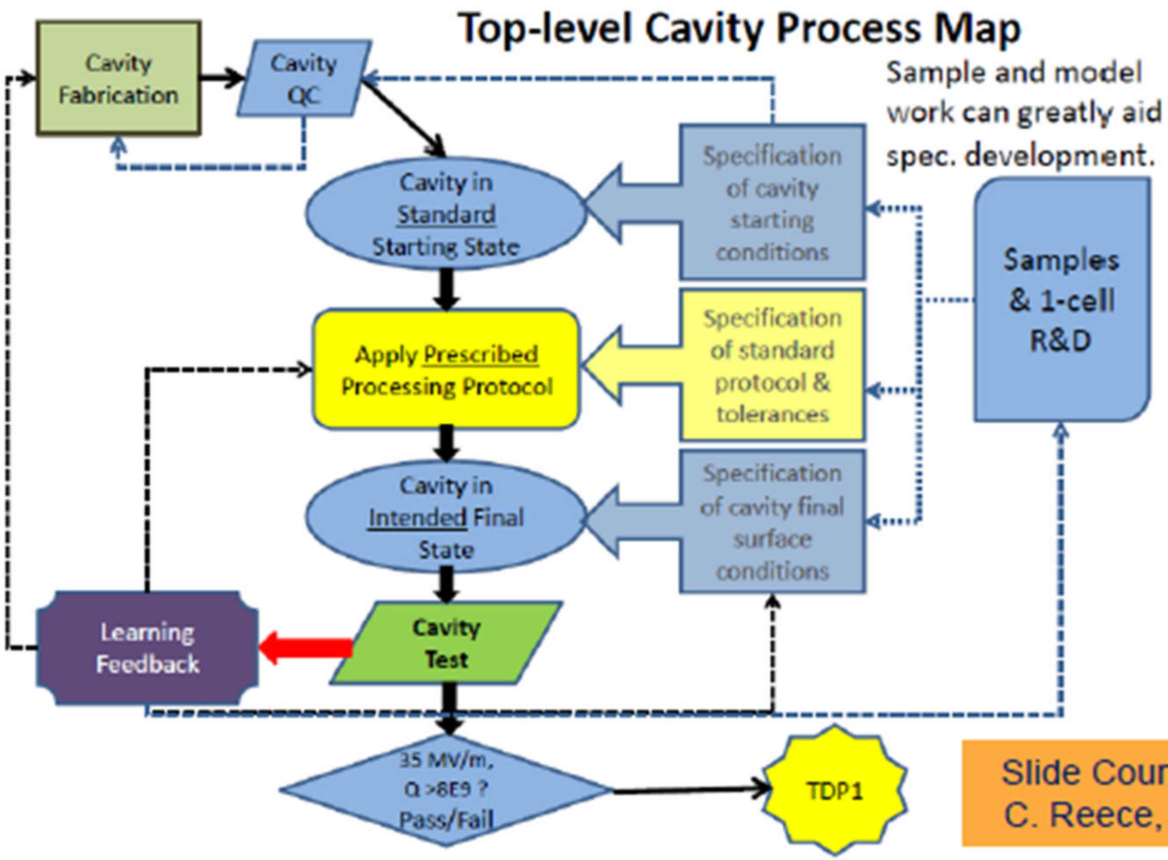






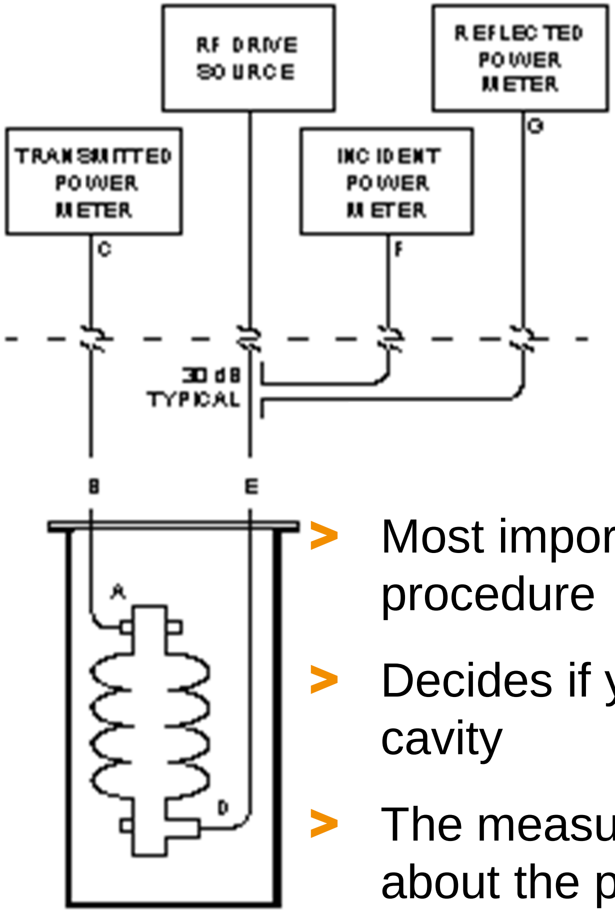


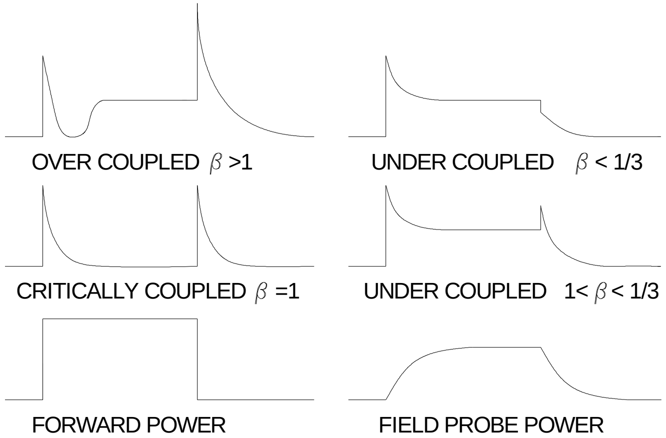
Surface Treatment – process flow



Slide Courtesy of C. Reece, J-Lab

Diagnostics – Cold RF Test





$$Q_L = 2\pi * f_0 * \tau$$

$$\beta = \frac{1}{2\sqrt{\frac{P_i}{P_e}} - 1}$$

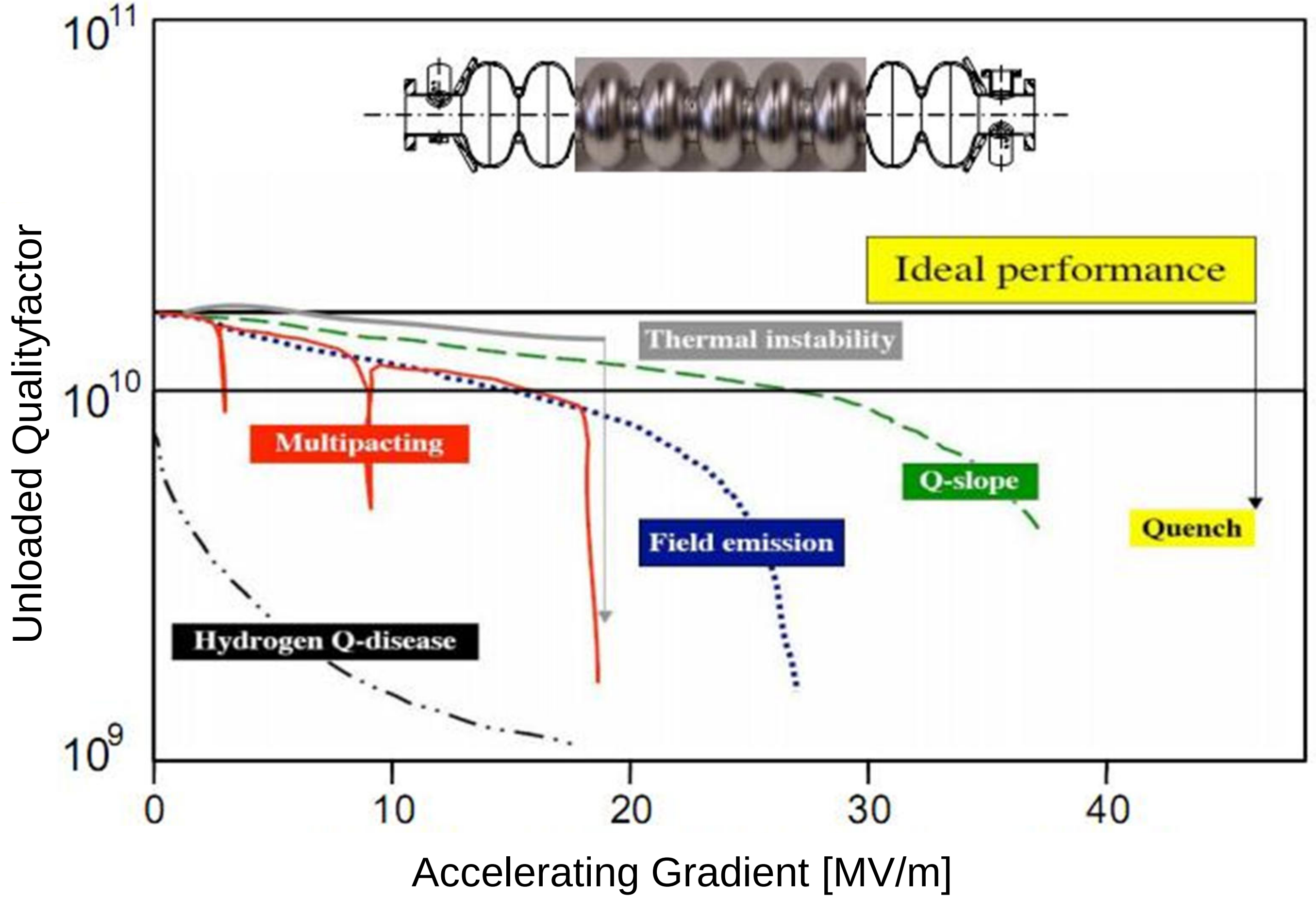
$$\boxed{Q_0 = \beta * Q_L}$$

$$P_{Diss} = P_f - P_r - P_t$$

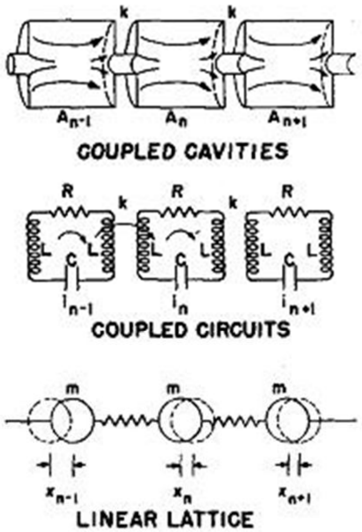
$$\boxed{E_{acc} = \sqrt{\frac{R/Q * Q_0 * P_{Diss}}{n * l}}}$$

- Most important test in assembling procedure
- Decides if you have a “good” or “bad” cavity
- The measured quantities tells a lot about the physics happening inside

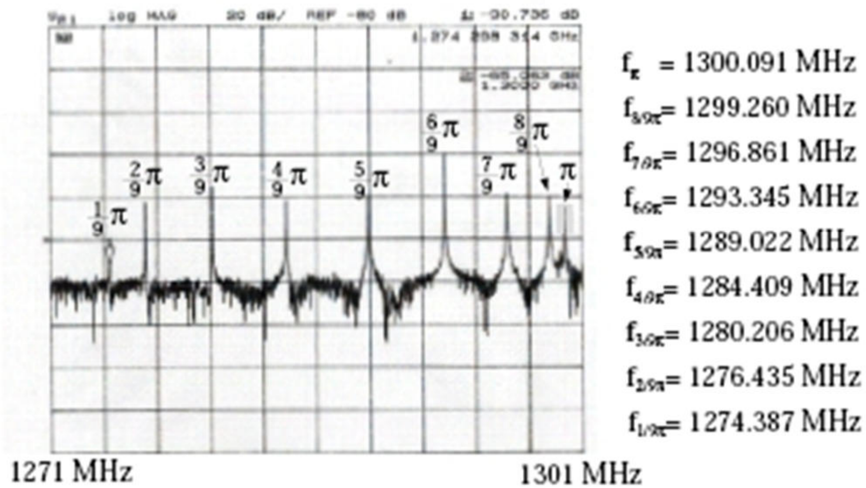
Diagnostics – Cold RF Tests: Q-E-Plots

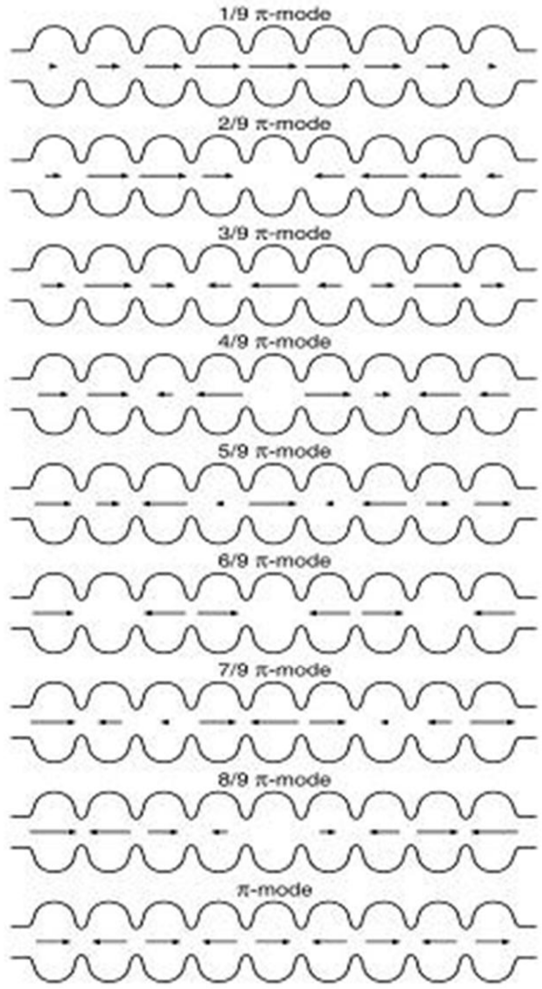


Diagnostics – Cold RF Test: Multi mode measurements



- Since you have a system of 9 coupled resonators, you have 9 modes per band
- Each mode has a different field strength distribution, allowing to probe specific cells





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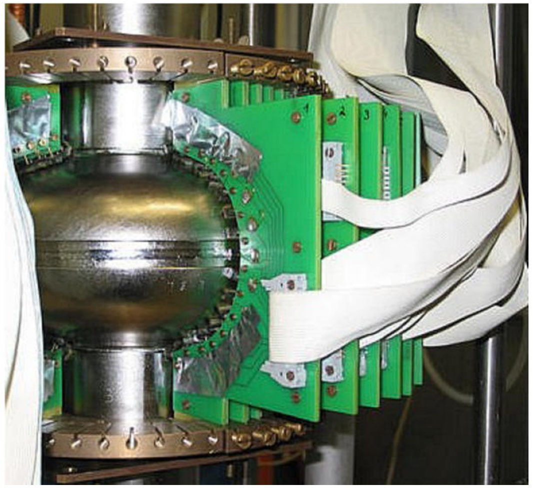
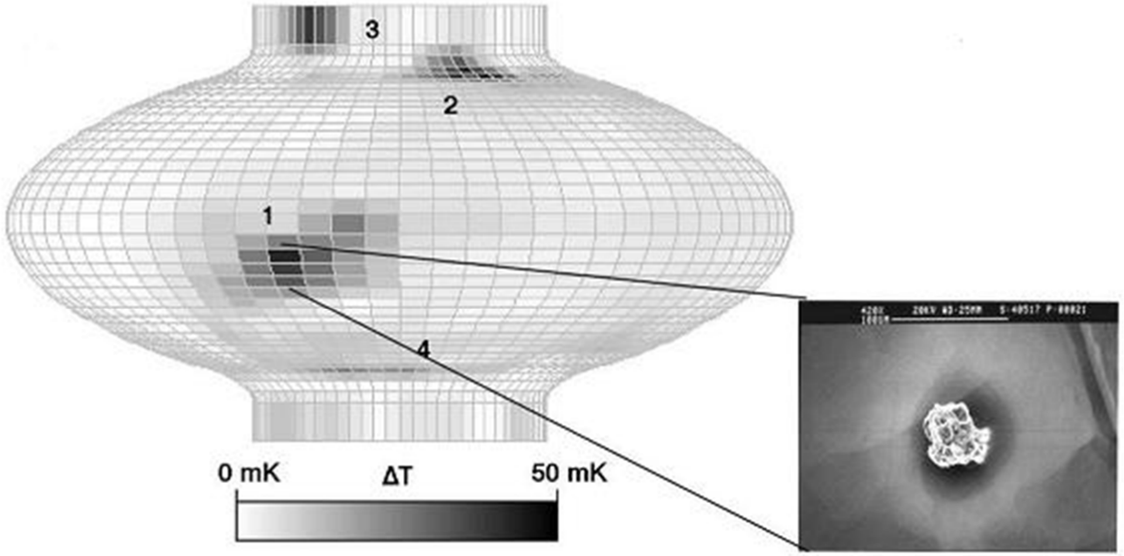
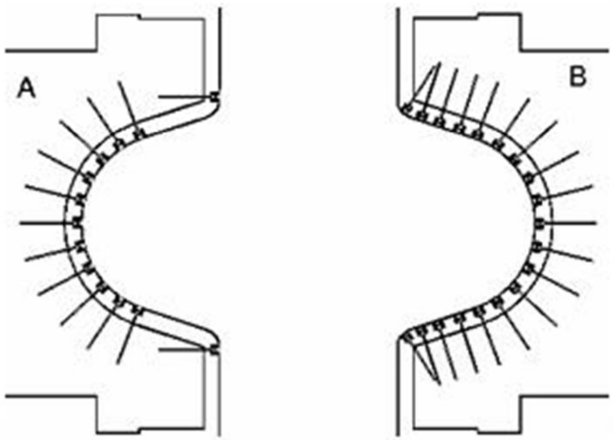
Diagnostics – Temperature Mapping







- Fixed, high sensitivity T-mapping system for single cell cavities (768 Sensors on 48 Boards)
- Rotating 9 cell T-mapping system with 128 sensors for quench detection

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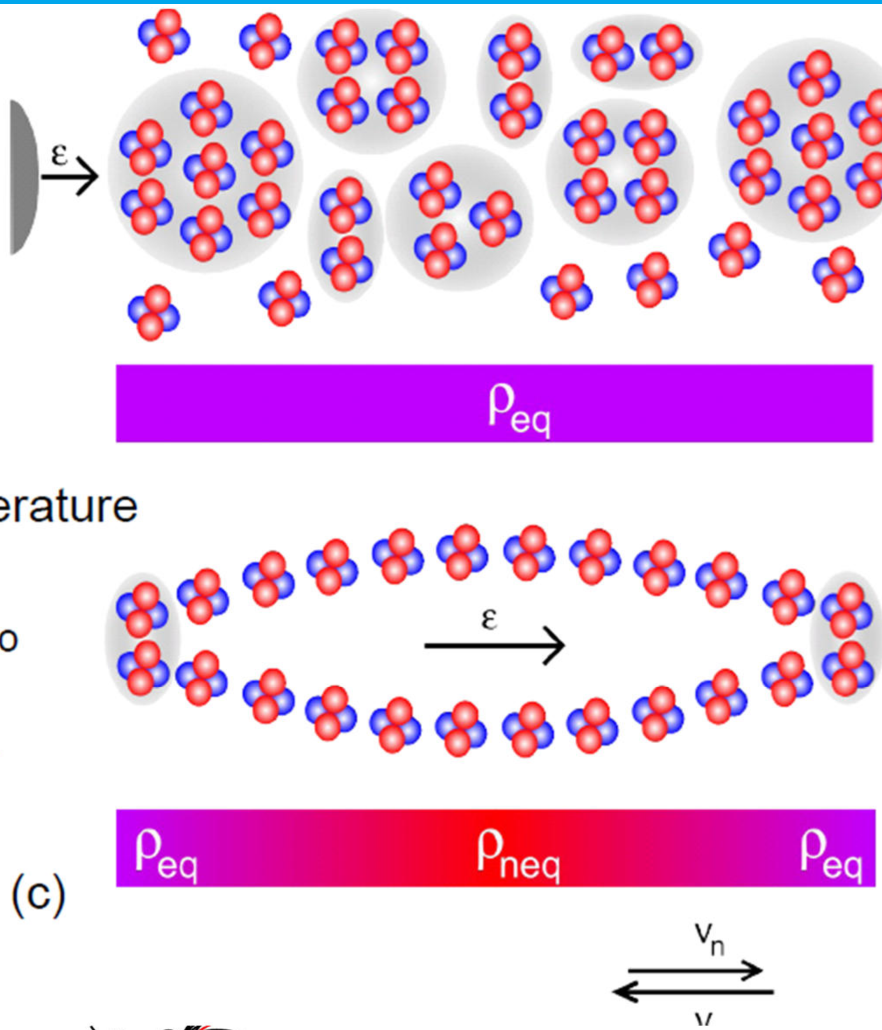
Diagnostics – Second Sound: Theory

- Two fluid model
  - 'normal' liquid helium: density ϱ_n
  - 'superfluid' helium: density ϱ_s (Bose-Einstein condensate)
- Density $\varrho_{eq}=\varrho_n+\varrho_s$ (a)
- Total flux $\vec{j}=\varrho_n\vec{v}_n+\varrho_s\vec{v}_s=0$
- Instantaneous heating: temperature wave (b)
  - Absorption: condensate breaks to normal liquid helium
- ϱ_n increases & ϱ_s decreases > ϱ_{eq} changes locally to ϱ_{neq}
- reaching equilibrium requires (c)

  $\vec{v}_n=-c\,\vec{v}_s$



(a)

(b)

(c)

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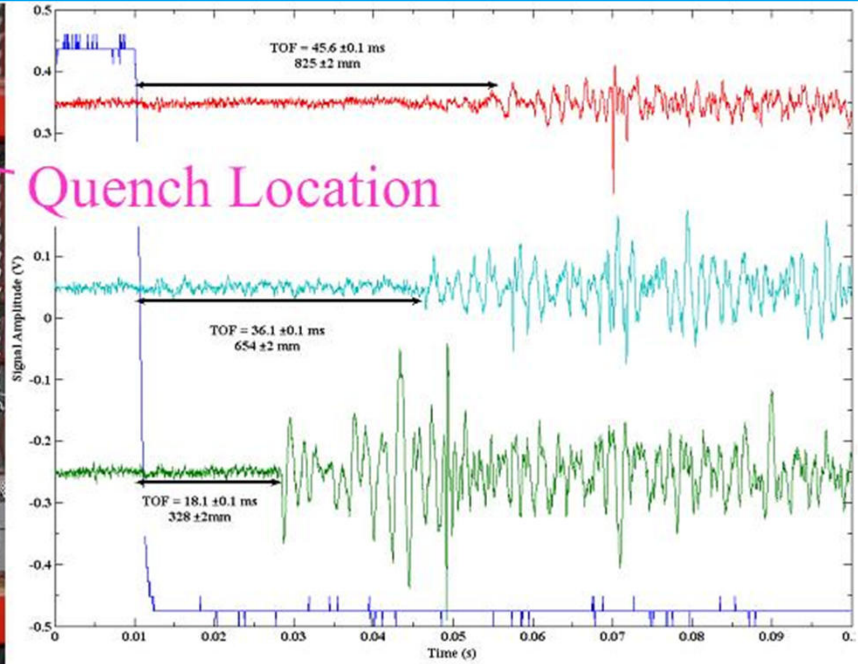
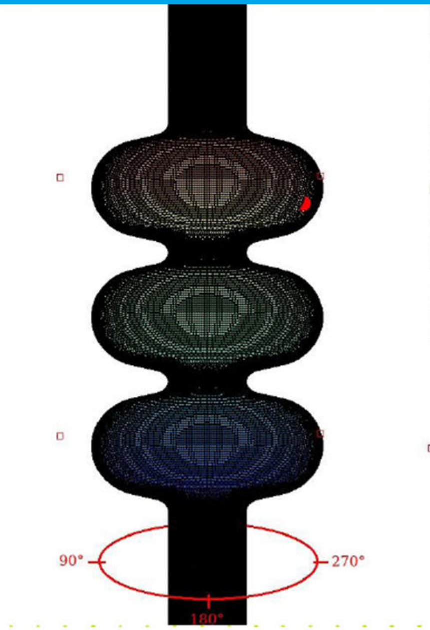
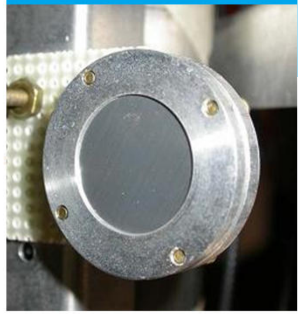
Diagnostics – Second Sound: Set up

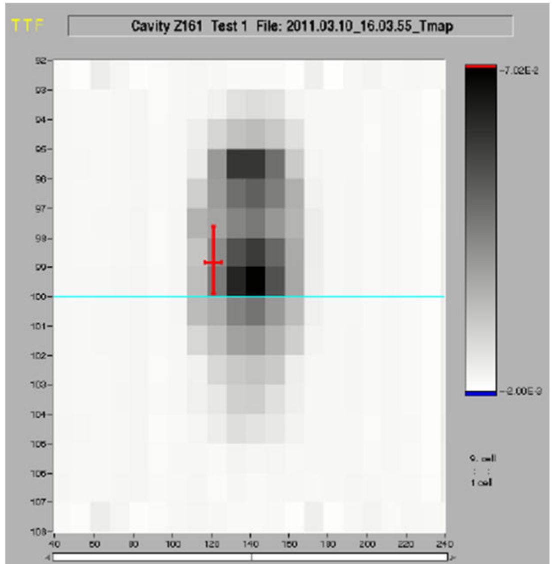


@ 2K (v_s = 16.68 m/s), horizontal scale = 5 ms/Div





- OST's are continuously installed at the testing frame
- No exchange necessary
- Automated read out and triangulation



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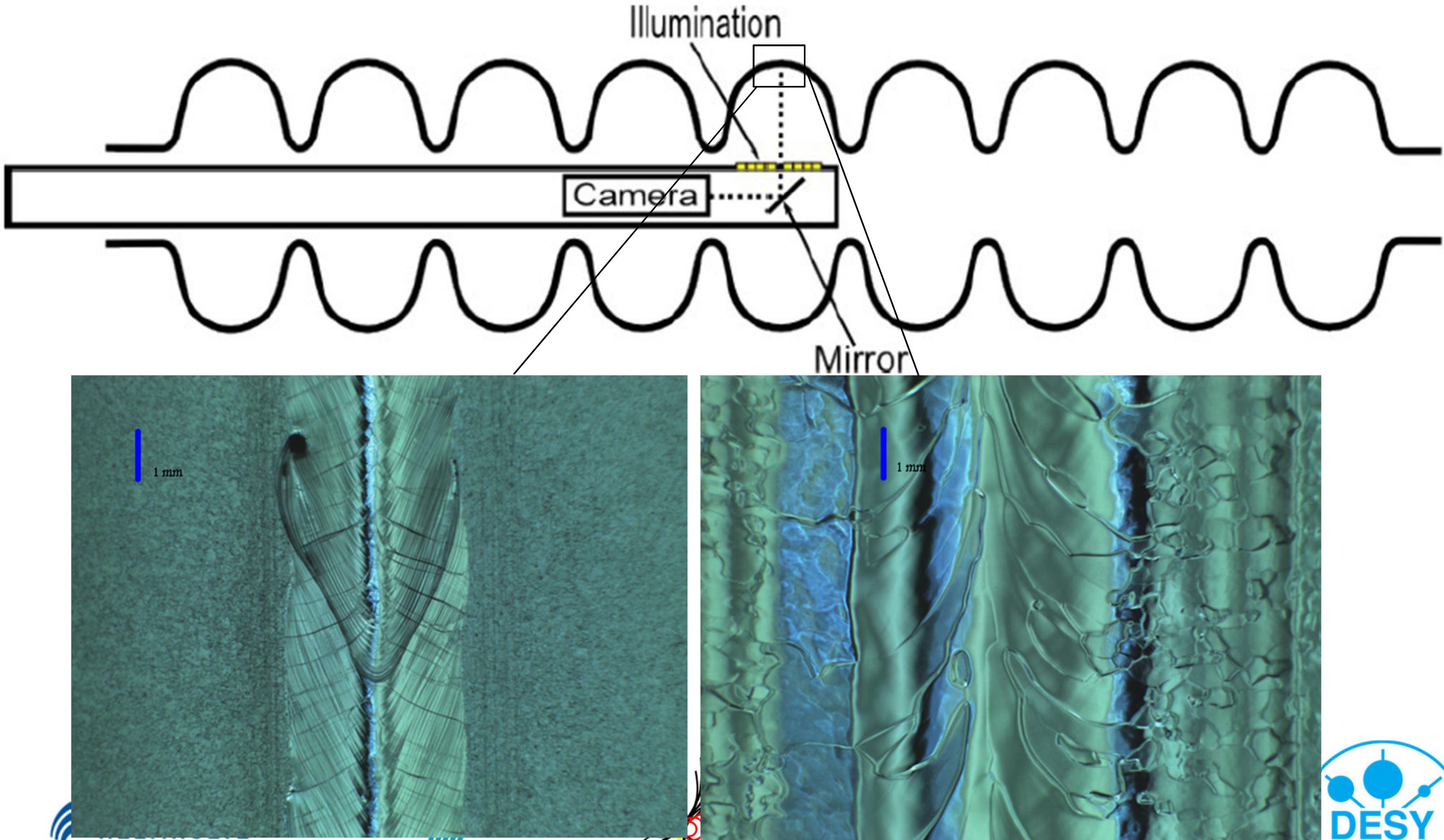
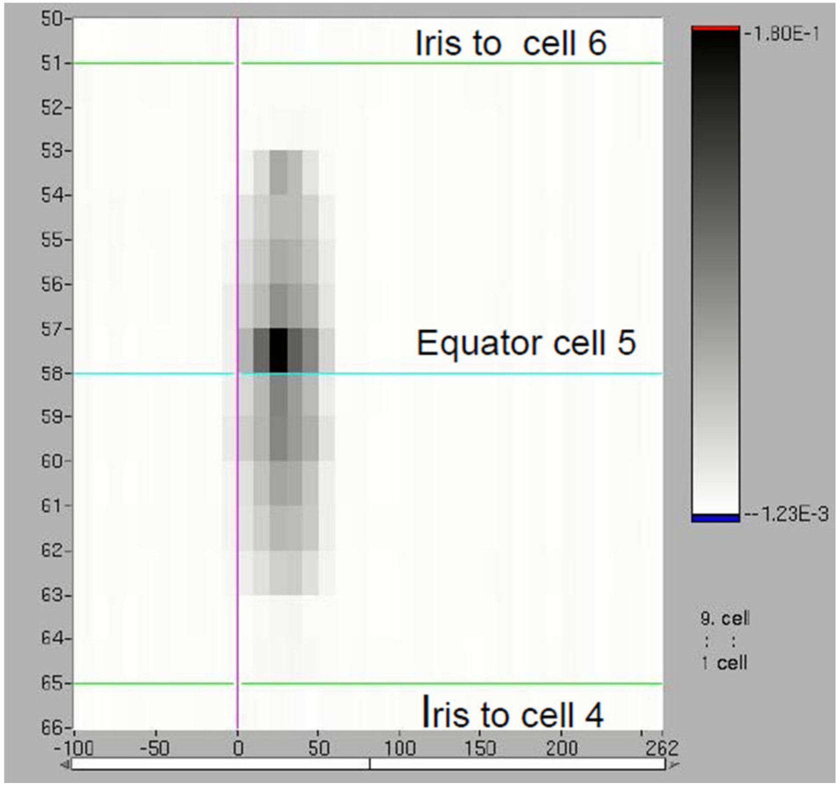
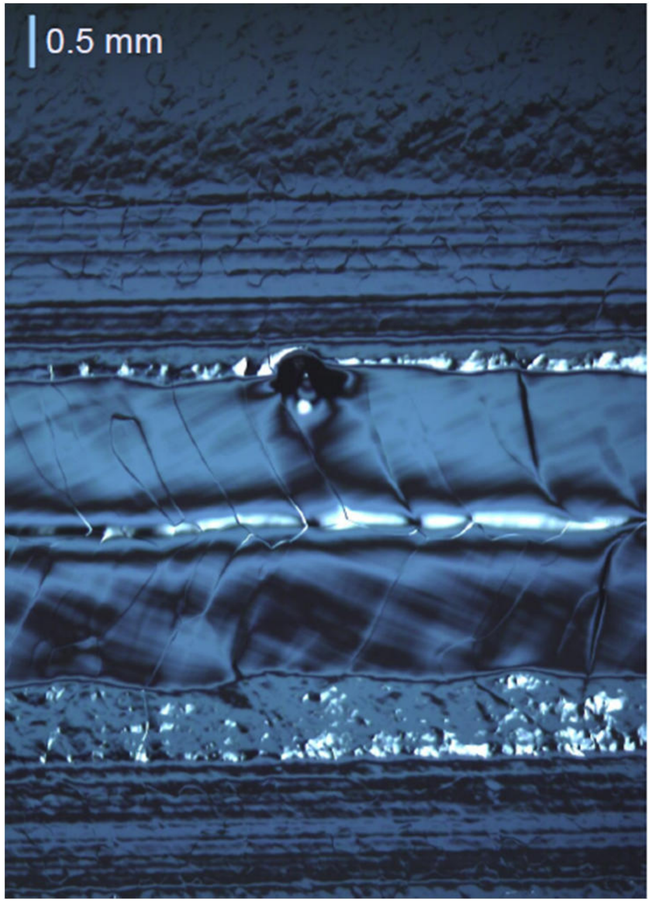
Diagnostics – Optical Inspection: Setup



Diagnostics – Optical Inspection: results





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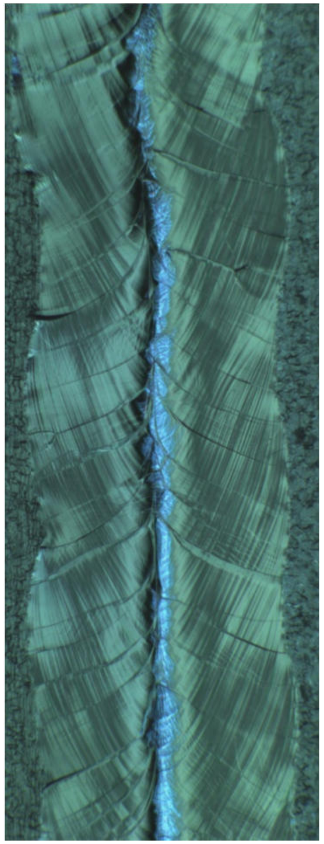
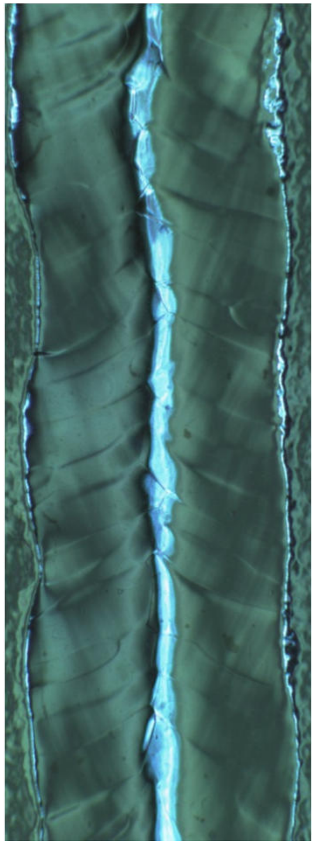
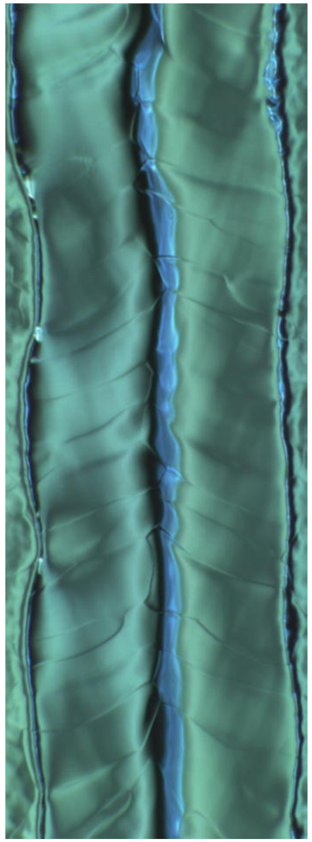
Diagnostics – Optical Inspection: automated results

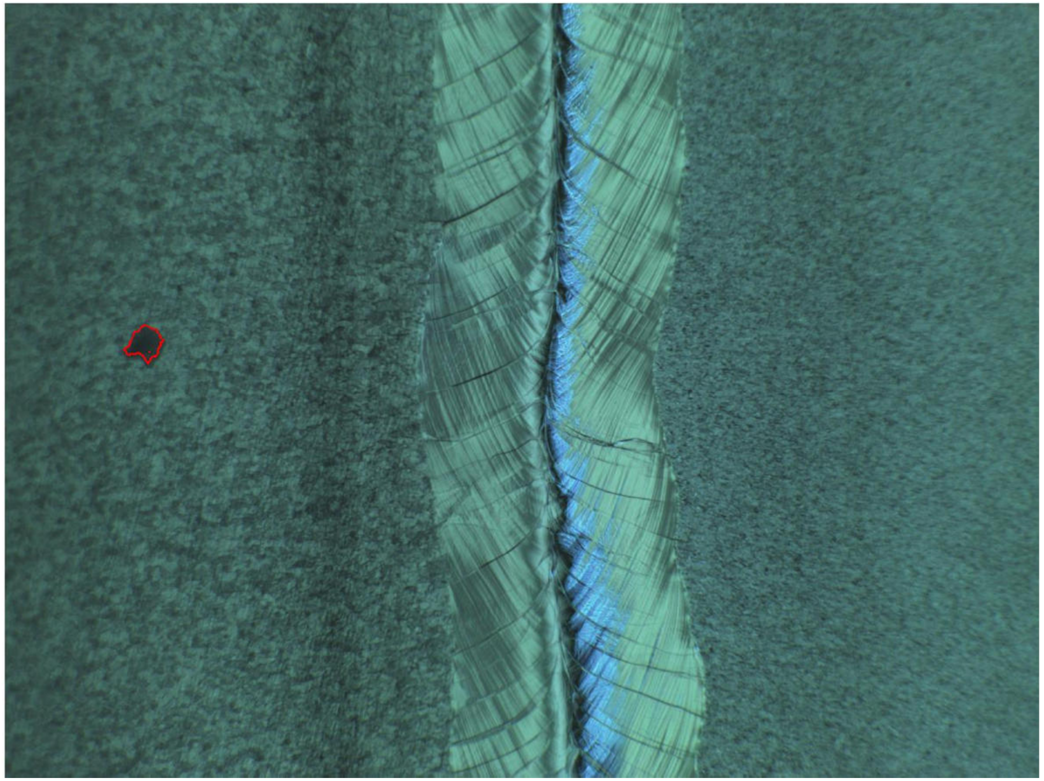
Before EP	After 1st EP	After 2nd EP
		

Most likely values

	Before EP	After 1st EP	After 2nd EP
	$R_{dq} = 0.312$	$R_{dq} = 0.112$	$R_{dq} = 0.117$
	$\sigma = 0.242$	$\sigma = 0.061$	$\sigma = 0.059$

Diagnostics – Optical Inspection: automated results

- One object was identified from an image processing algorithm as an irregularity
- The boundary of this object is shown in this image
- Fits well with the impurity on the surface



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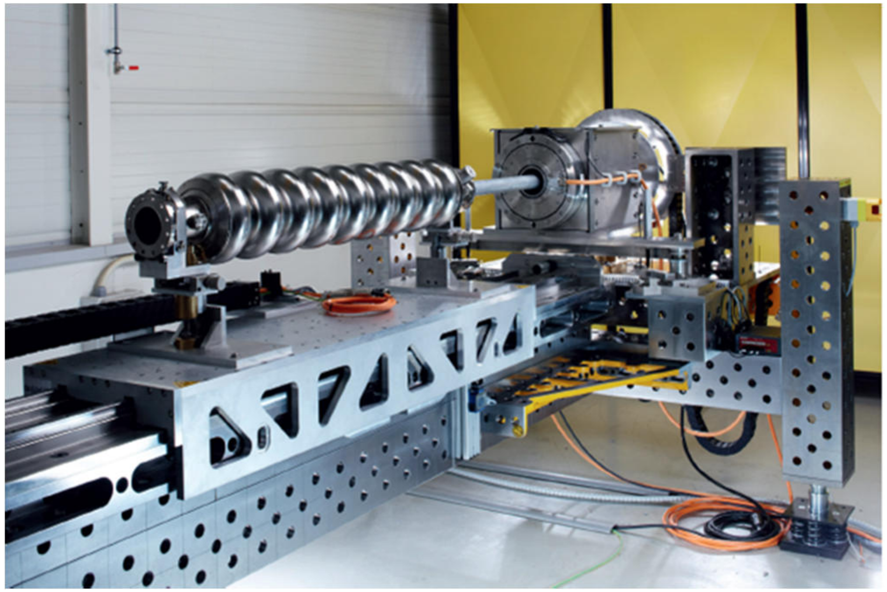
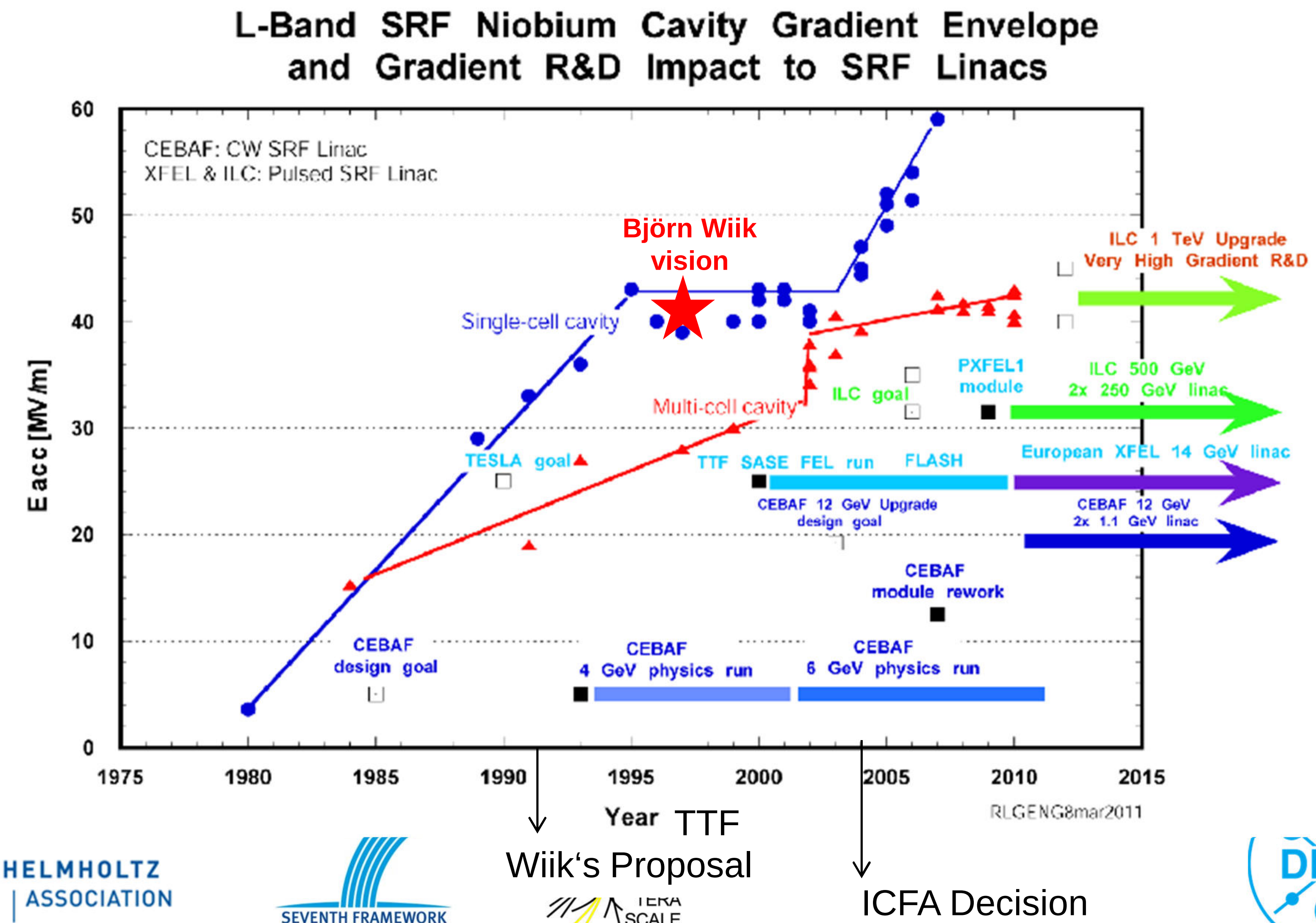
Diagnostics – Optical Inspection: OBACHT

- **O**ptical **b**ench for **a**utomated **c**avity inspection with **h**igh resolution and short **t**imescales



- Fully automated optical inspection: camera position, illumination, auto focus, image taking and image storing
- The timescale for a single inspection decreases from the order of days to half a day
- Image processing will run in parallel using the stored images
- Camera system based on Kyoto Camera Phys. Rev. ST. Accel. Beams 11, 093501 (2008)

Historical „Evolution“



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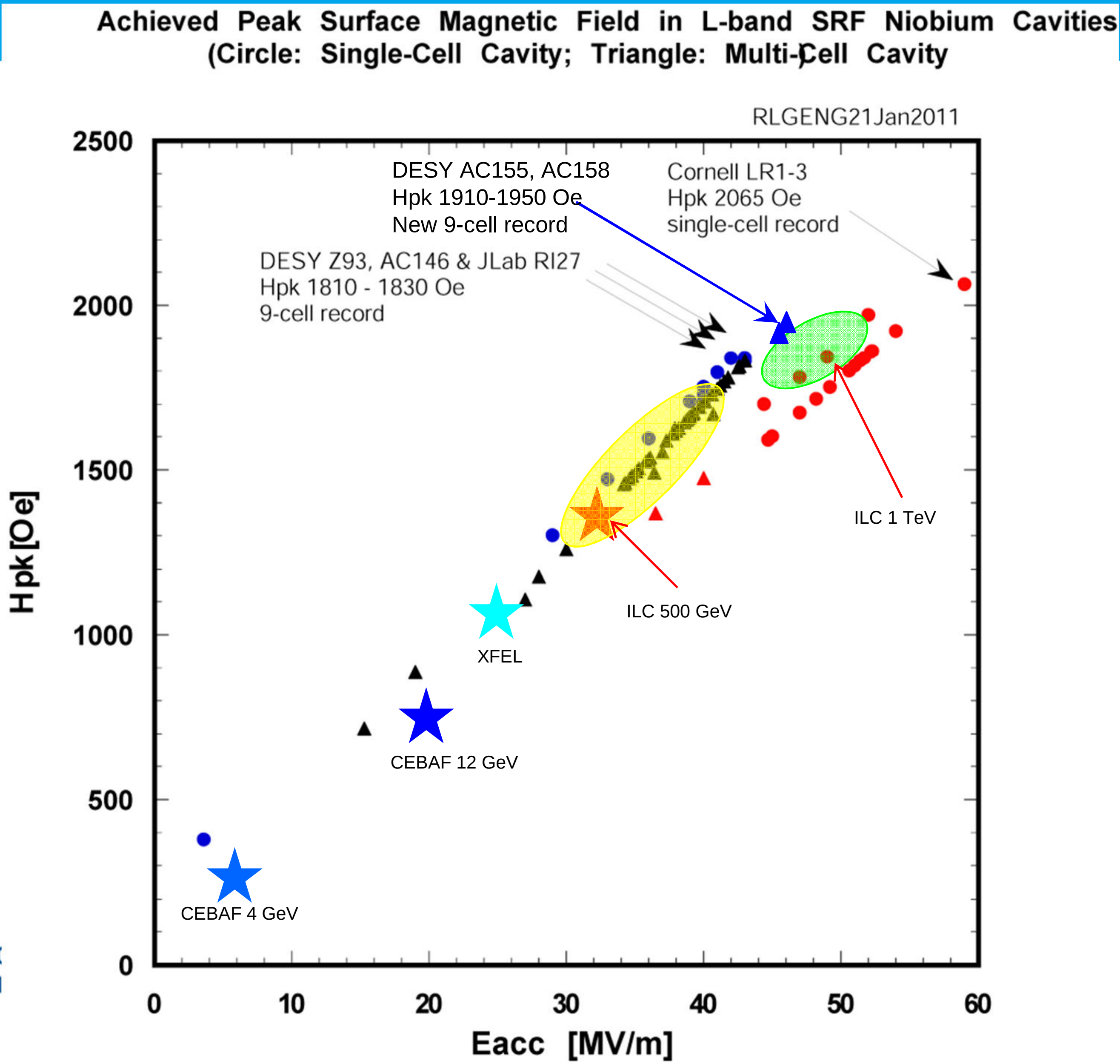
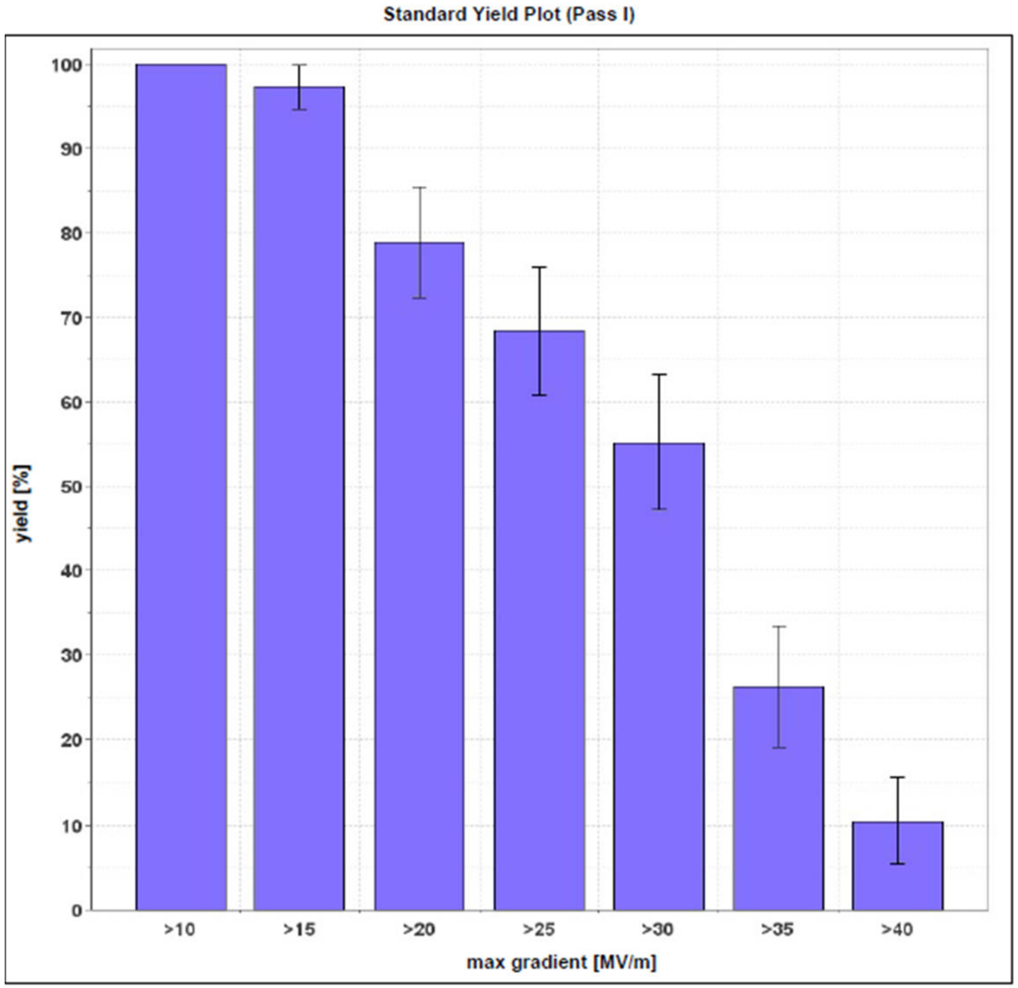
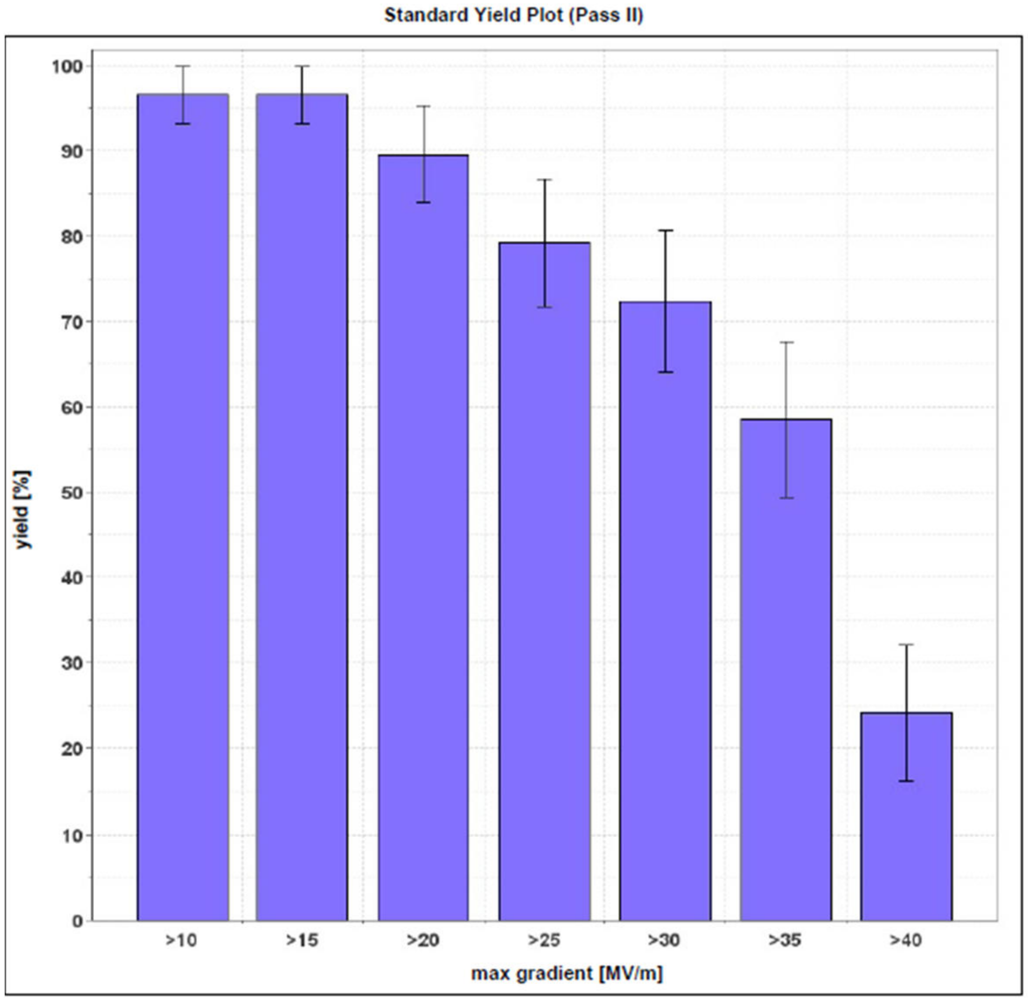
Historical „Evolution“ – another view



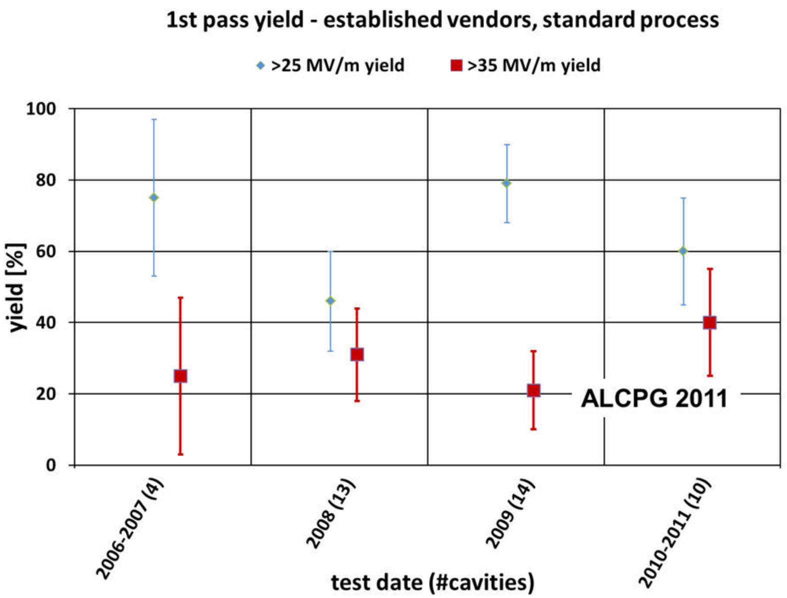
Results – Yield Plots (1st Pass)

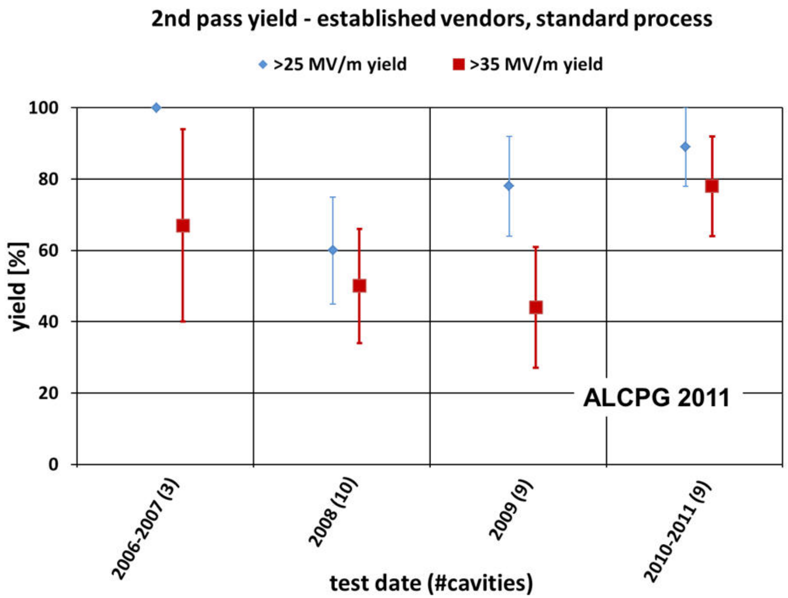


Results – Yield Plots (2nd Pass)



„Discrete time“ Yield Plots





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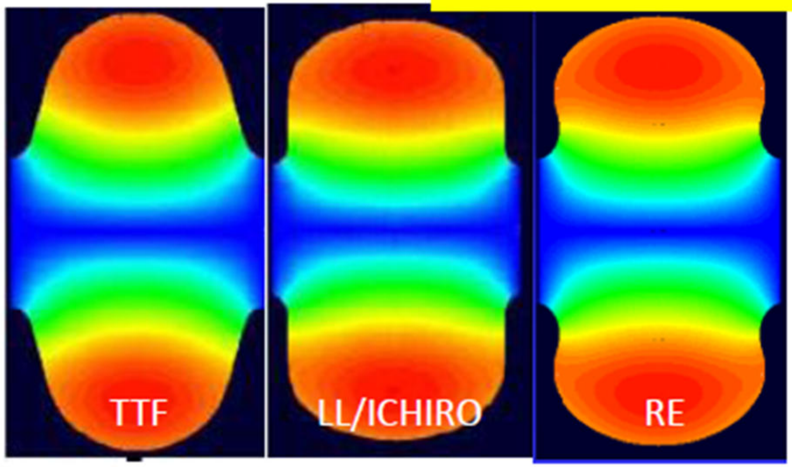
R&D – Other shapes

from J.Sekutowicz lecture Note

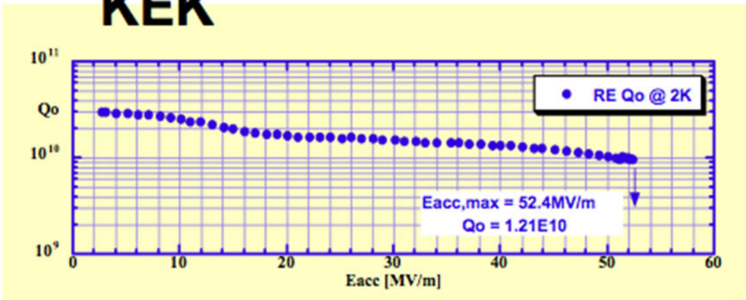


TTF: TESLA shape
Reentrant (RE): Cornell Univ.
Low Loss(LL): JLAB/DESY
LL/ICHIRO: KEK

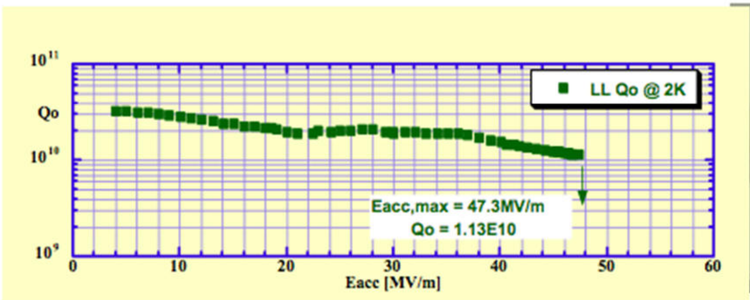
shape	TTF	LL/ICHIRO	RE
Iris Diameter [mm]	70	60	60
Ep/Eacc	1.98	2.36	2.28
Hp/Eacc [Oe/MV/m]	41.5	36.1	35.4

R&D – Other shapes

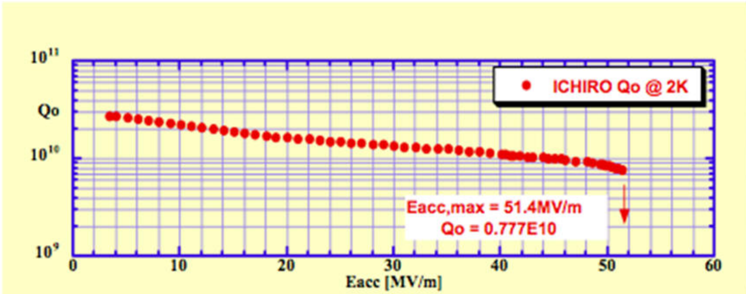
Successful Principle Proof of the 50MV/m at KEK



Diameter [mm]	60
Ep/Eacc	2.36
Hp/Eacc [Oe/MV/m]	36.1
R/Q [W]	133.7
G[W]	284
Eacc max	48.5



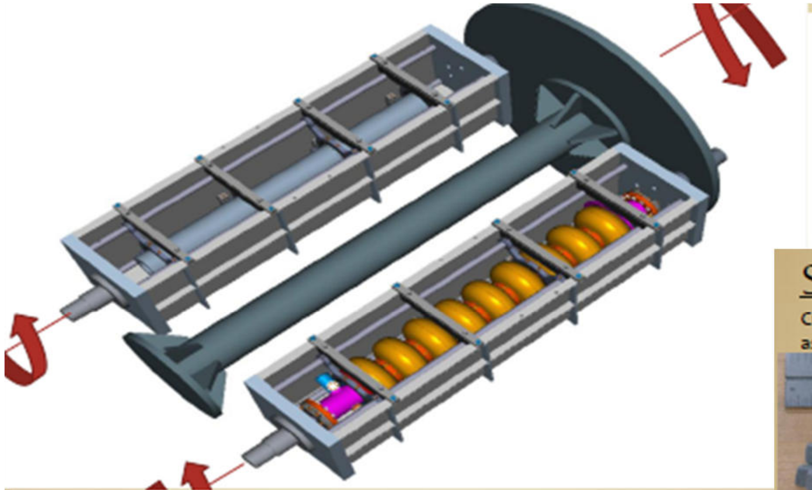
Diameter [mm]	66
Ep/Eacc	2.21
Hp/Eacc [Oe/MV/m]	37.6
R/Q [W]	126.8
G[W]	277
Eacc max	46.5



Diameter [mm]	61
Ep/Eacc	2.02
Hp/Eacc [Oe/MV/m]	35.6
R/Q [W]	138
G[W]	285
Eacc max	49.2

K. Saito, SRF2007, TU202, P.82-93 (2007).
F. Furuta, K. Saito, SRF2009, THPPO084, p. 821-823 (2009).

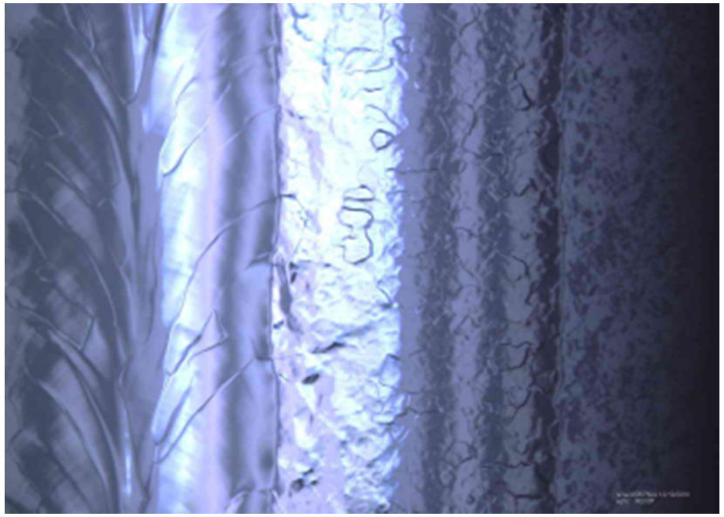
R&D – Central barrel polishing

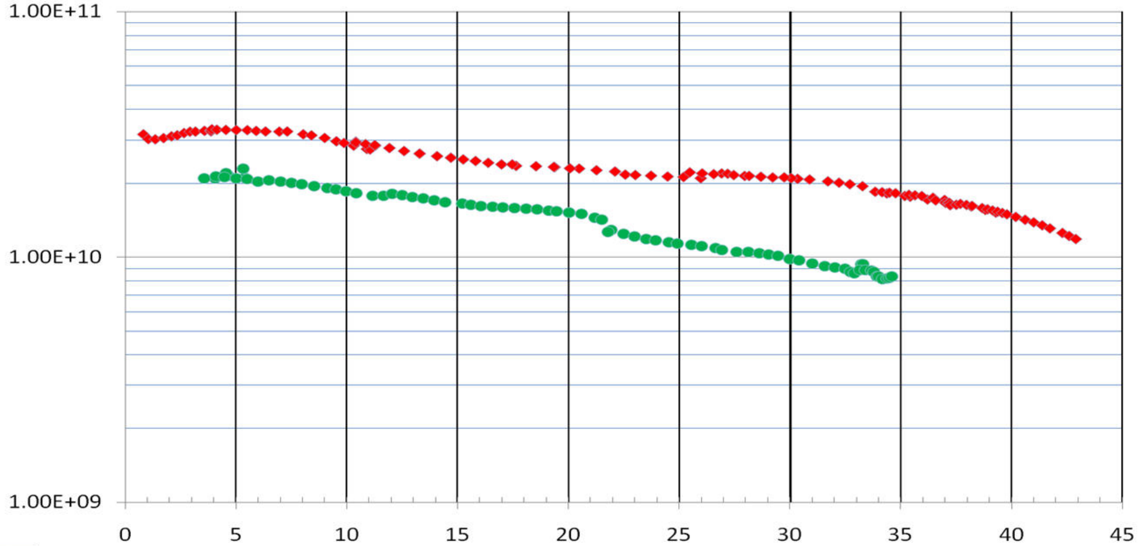


- Main shaft and individual barrels rotate with abrasive materials inside

- Uniform,smooth surface finish (Ra ~ 10s nm)
- Small amount of chemistry
- Simple technology
- Repair of defects that chemistry cant remove

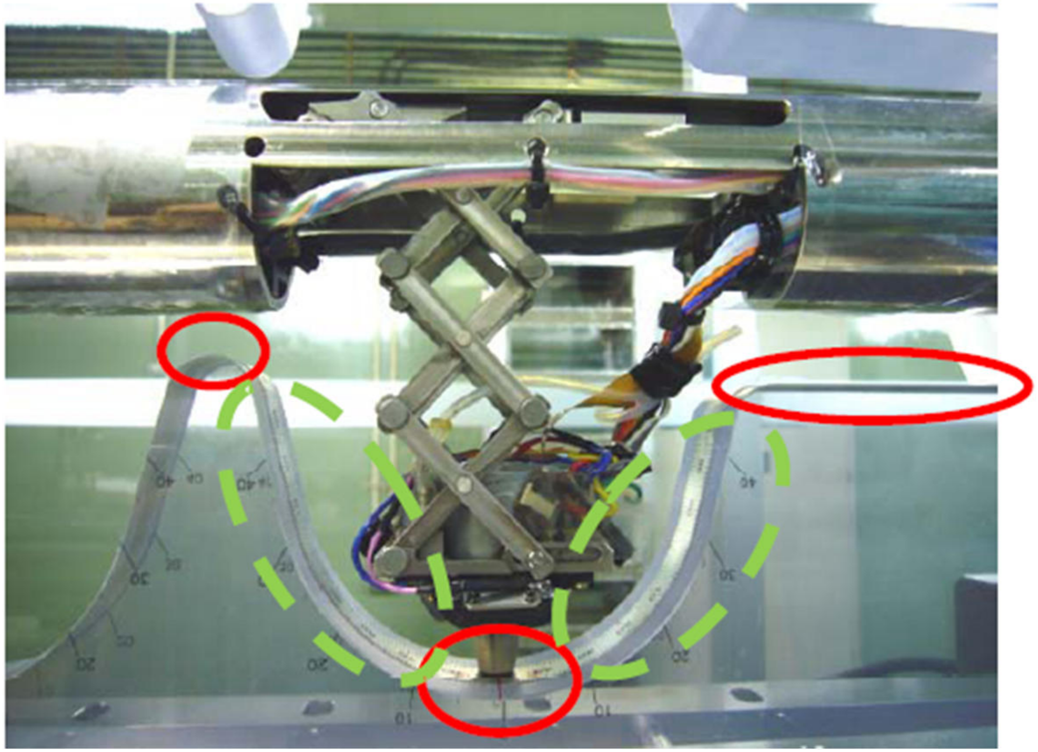
R&D – Central barrel polishing



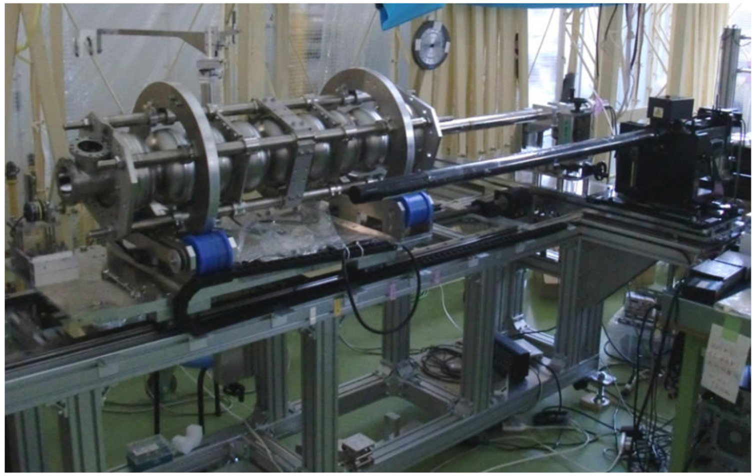


- Green line: baseline EP, red with additional CBP
- Higher yield expected
- Higher quality factor measured
  - From less hydrogen?
  - Smoother surface
  - Surface or subsurface effect?

R&D – Local Grinding



H. Hayano, K. Watanabe @ KEK



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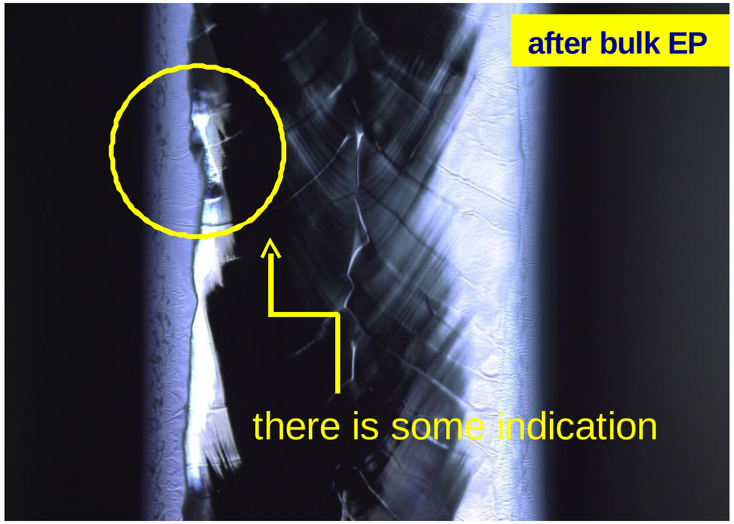
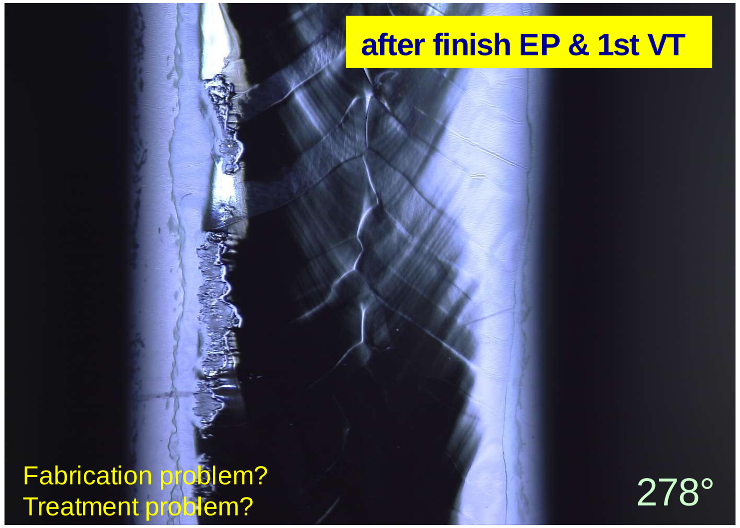
R&D – Local Grinding

MHI-014

Bump at Iris between Cell#8-#9 after 1st VT



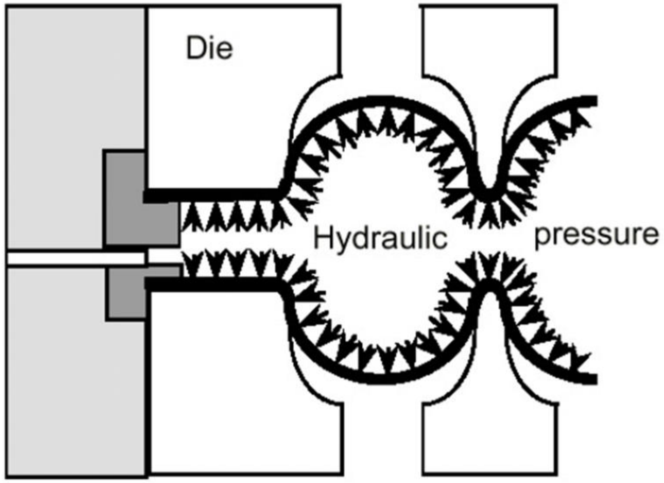


MHI-014
1st VT 26MV/m -> 14.0MV/m F.E. turned on Jan. 20,2011
2nd VT 26MV/m -> 13.0MV/m F.E. turned on Feb. 17,2011

Local grinding was applied on #8-#9iris bump, then EP

3rd VT 36.6MV/m @ Q0=6.1E09 June 16,2011
no X-ray emission was observed.
reached gradient was by power limit.

R&D – Hydroforming



- No weld contamination, no pits & bumps
- Less scattering in performance expected

- Machine developed at DESY (patent by W. Singer)
- Three 9 cell cavities were fabricated

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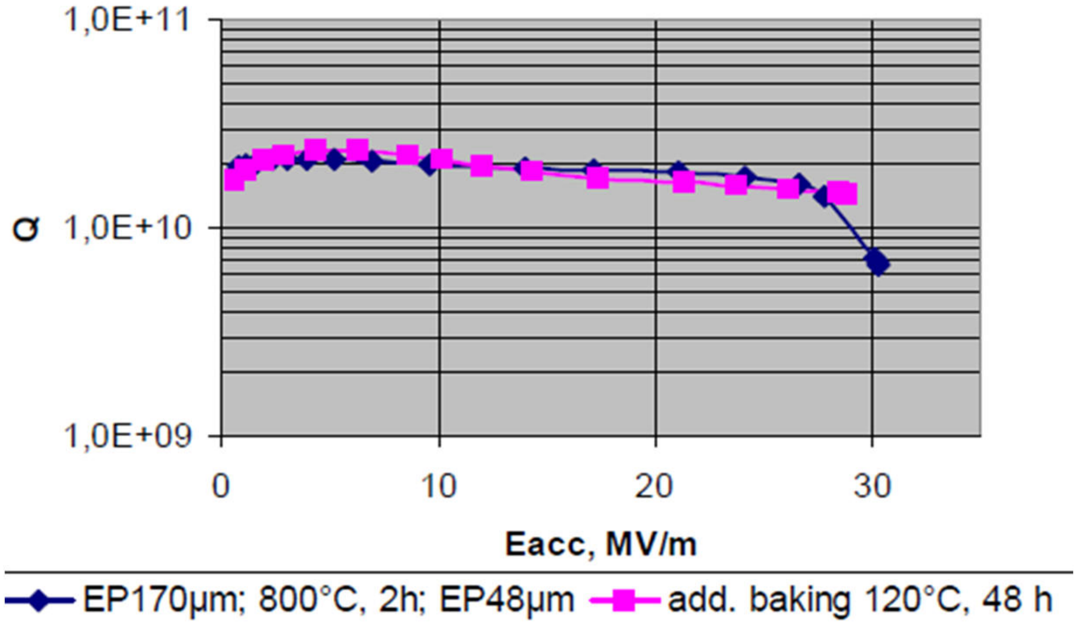
DESY

R&D – Hydroforming



- Z145 achieved 30 MV/m
  - **Individual cell achieved up to 39 MV/m**
- 2 more are getting tested

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DESY

Summary

- The global collaboration towards the ILC achieved several milestones
  - TDP1 goal achieved (50% @ 35 MV/m)
  - Many improvement made towards TDP2….more statistics needed
- XFEL will help to improve our knowledge in several fields
  - Industrialization & Handling
  - Surface treatment
- Further R&D is done for other / better fabrication & treatment steps to improve gradient AND quality factor
- It's a tricky but worthy challenge, since many accelerator projects will benefit

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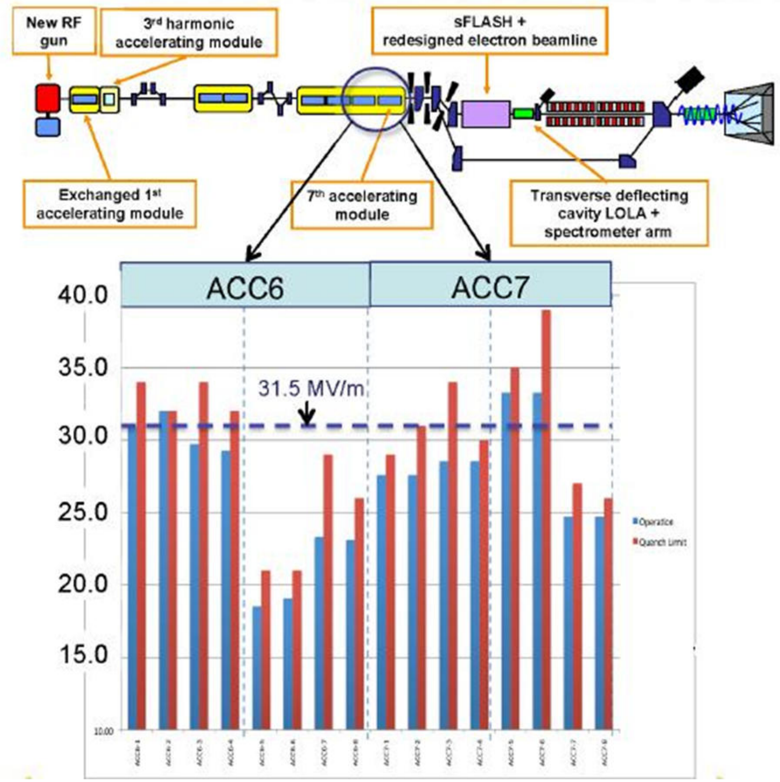
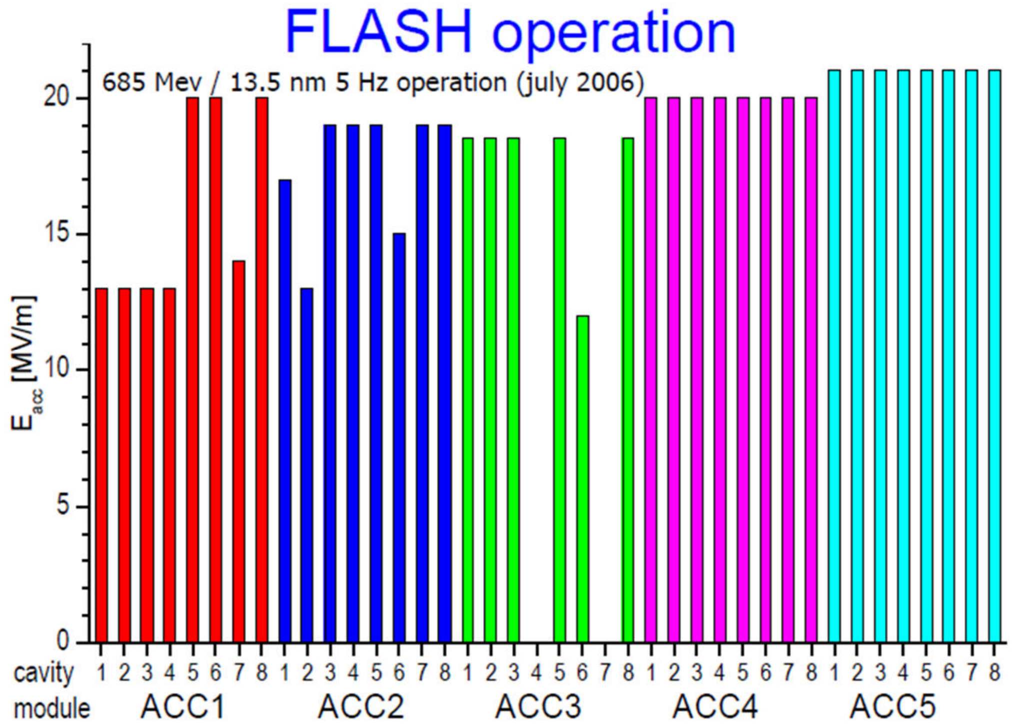
Back Up

LHC RF

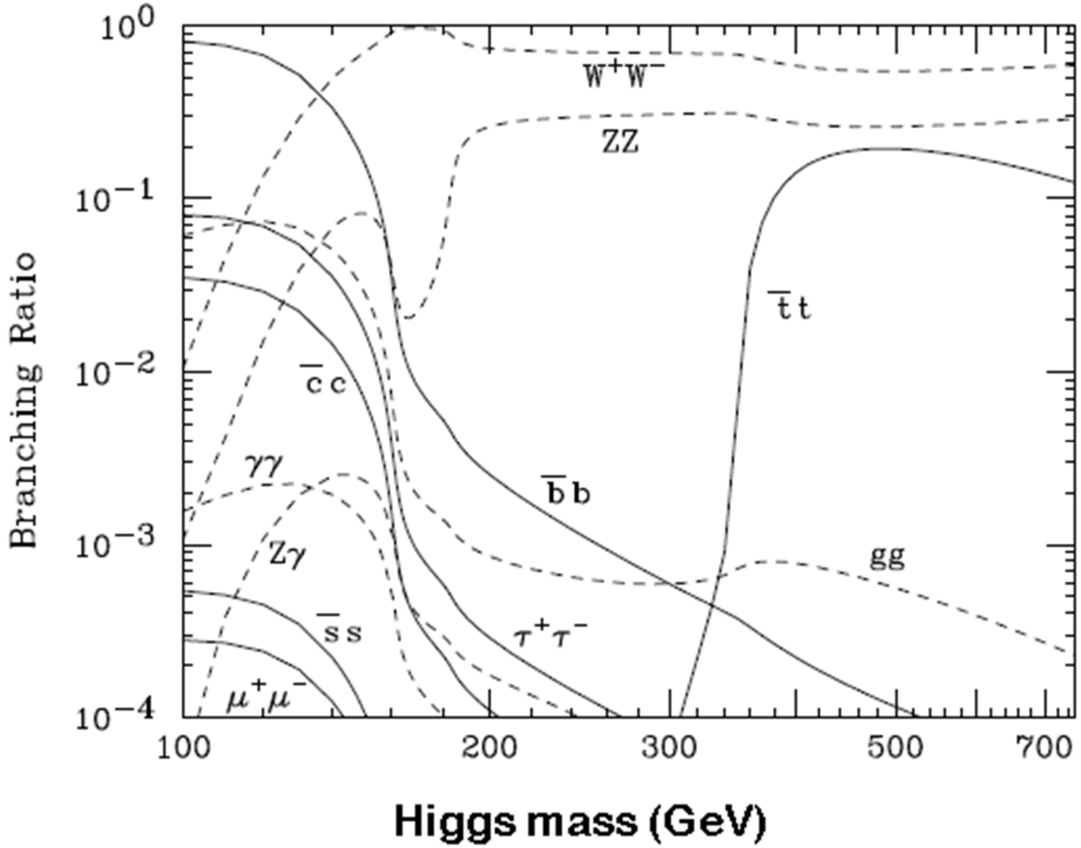
- Two independent rings
- 8 RF cavities per ring at 400.790 MHz [2]:
  - Super Conducting Standing Wave Cavities R/Q = 45 ohms, 6 MV/m nominal
  - Movable Main Coupler (20000 < Q_L < 180000)
    - 1 MV /cavity at injection with Q_L = 20000
    - 2 MV/cavity during physics with Q_L = 60000
  - 1 klystron per cavity
    - 300 kW max
    - 130 ns group delay (~ 10 MHz BW)
  - Mechanical Tuner range = 100 kHz

FLASH

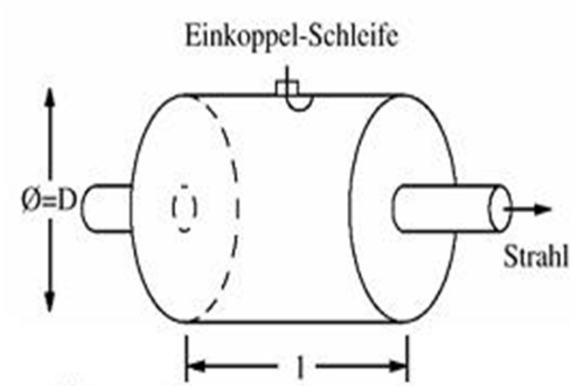

New RF gun
3rd harmonic accelerating module
sFLASH + redesigned electron beamline
Exchanged 1st accelerating module
7th accelerating module
Transverse deflecting cavity LOLA + spectrometer arm
ACC6
ACC7
40.0
35.0
30.0
25.0
20.0
15.0
31.5 MV/m


FLASH operation
685 Mev / 13.5 nm 5 Hz operation (july 2006)
E_{acc} [MV/m]
20
15
10
5
0
cavity 1 2 3 4 5 6 7 8 1 2 3 4 5 6 7 8 1 2 3 4 5 6 7 8 1 2 3 4 5 6 7 8 1 2 3 4 5 6 7 8
module ACC1 ACC2 ACC3 ACC4 ACC5

Higgs cross section



Cavity Toy Model: The Pillbox



$$V_{acc} = \left| \int_{z=0}^{z=l} E_{el}\, dz \right| = \left| \int_{z=0}^{z=l} E_z(\rho = 0, z) e^{i\omega z/c} dz \right| = \left(\frac{2}{\pi}\right) l \cdot E_0$$

$$E_{acc} = \frac{V_{acc}}{l} = \frac{2E_0}{\pi}$$

$$\frac{E_{peak}}{E_{acc}} = \frac{\pi}{2}, \frac{H_{peak}}{E_{acc}} = 30.5 \frac{Oe}{MV \cdot m^{-1}}$$

$$\frac{E_{peak}}{E_{acc}} = 2, \frac{H_{peak}}{E_{acc}} = 42 \frac{Oe}{MV \cdot m^{-1}} \text{(Tesla Cavity)}$$

$$Q = \omega \frac{\text{Energy stored}}{\text{Power dissipated per Oscilation}} = \frac{\omega U}{P_c}$$

Cavity Theory

> ordinary differential Equation (ODE) describes single Cavity

$$\frac{dV_c}{dt} + (\omega_{1/2} - j\Delta\omega)V_c = C\sqrt{\omega_{1/2}}V_{for} + 2\omega_{1/2}R_L I_b$$

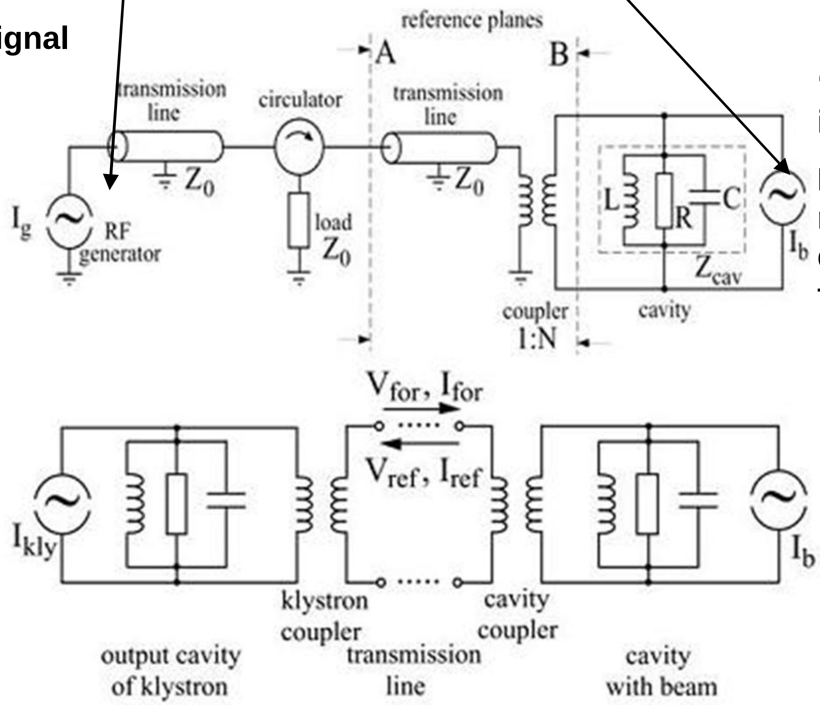
$$C = \sqrt{\left(\frac{r}{Q}\right)\frac{\omega_0}{Z_0}}$$

Driving signal

Oscillating electric Field inside the cavity

"Load" = Beam in cavity

Need to be matched with driving current from generator



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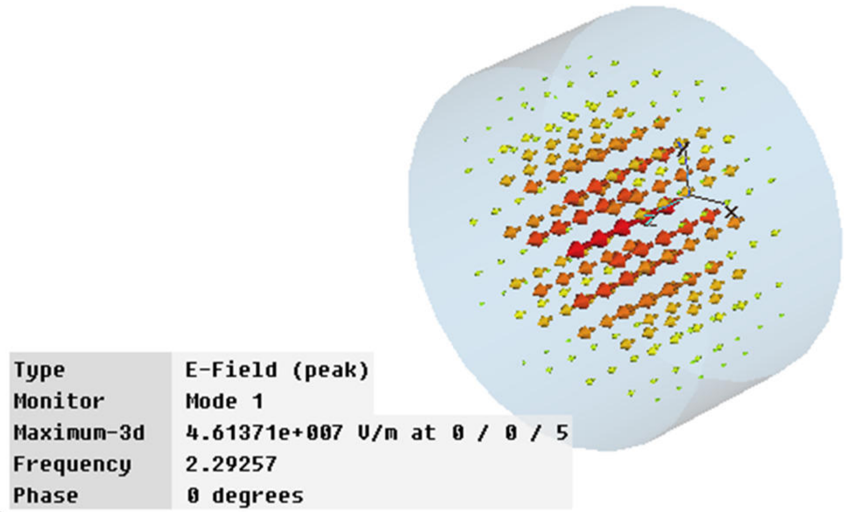
TM_{010} Accelerating mode

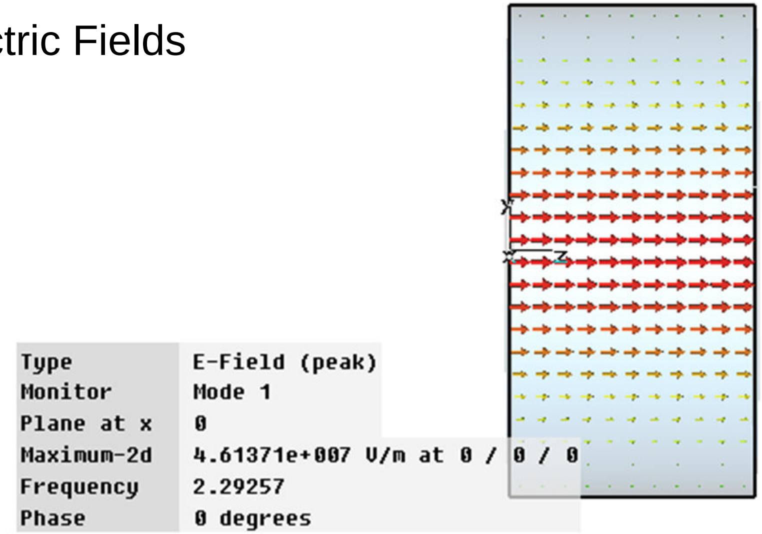


Almost every RF cavity operates using the TM_{010} accelerating mode.

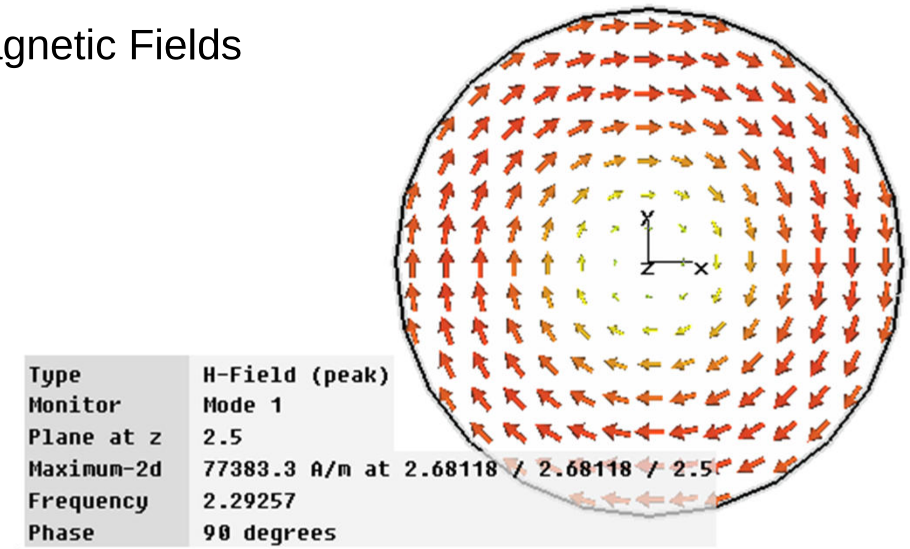
This mode has a longitudinal electric field in the centre of the cavity which accelerates the electrons.

The magnetic field loops around this and caused ohmic heating.

Electric Fields



Magnetic Fields



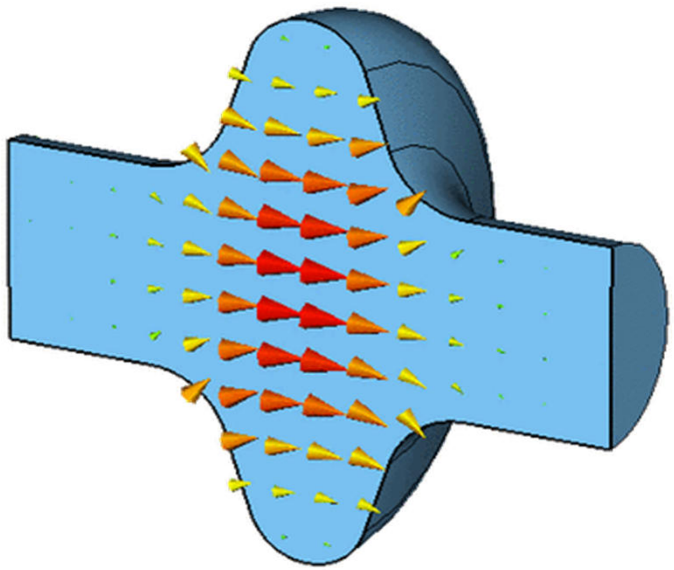
Accelerating voltage

- An electron travelling close to the speed of light traverses through a cavity. During its transit it sees a time varying electric field. If we use the voltage as complex, the maximum possible energy gain is given by the magnitude,

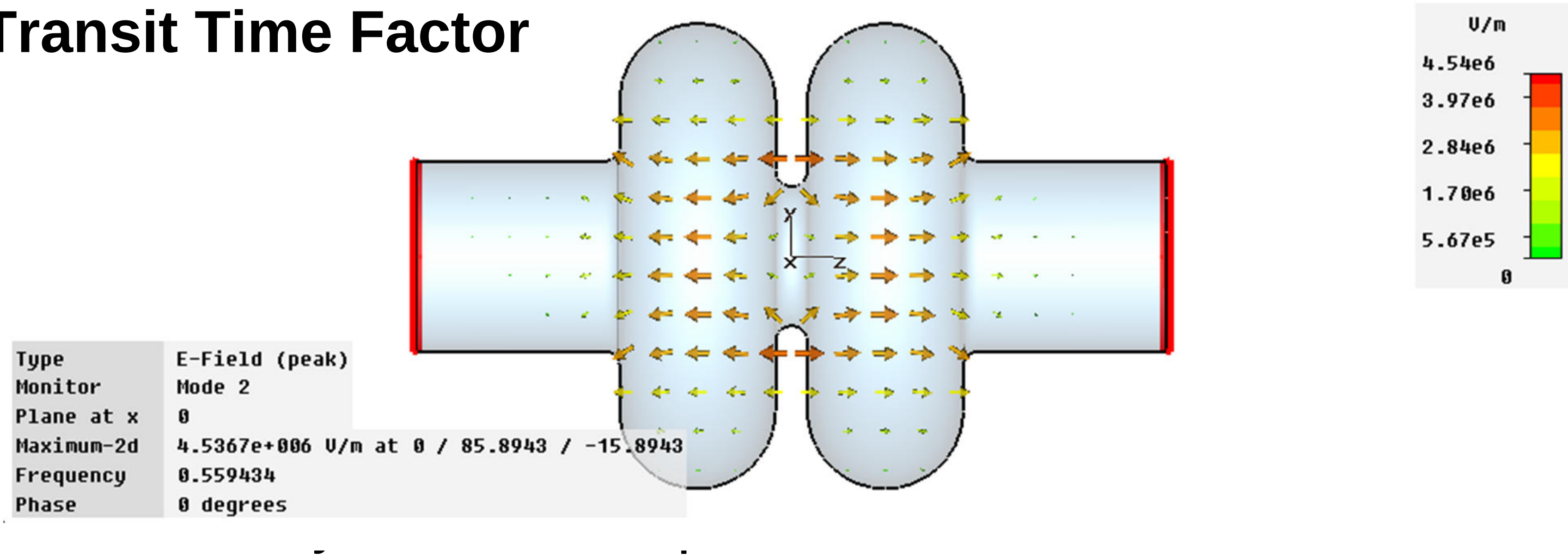
$$\Delta E = eV = e\left|\int_{-L/2}^{+L/2} E_z\left(z,t\right) e^{i\omega z/c}\, dz\right|$$

- To receive the maximum kick the particle should traverse the cavity in a half RF period.

$$L = \frac{c}{2f}$$



Transit Time Factor



- We can define an accelerating voltage for the cavity by

$$V = \Re\left\{ \int_{-L/2}^{+L/2} E_z\left(z,t\right) e^{i\omega z/c}\, dz \right\} = E_{z0} L T \cos\left(\omega t\right)$$

- This is given by the line integral of Ez as seen by the electron. Where T is known as the transit time factor and E_{z0} is the peak axial electric field.

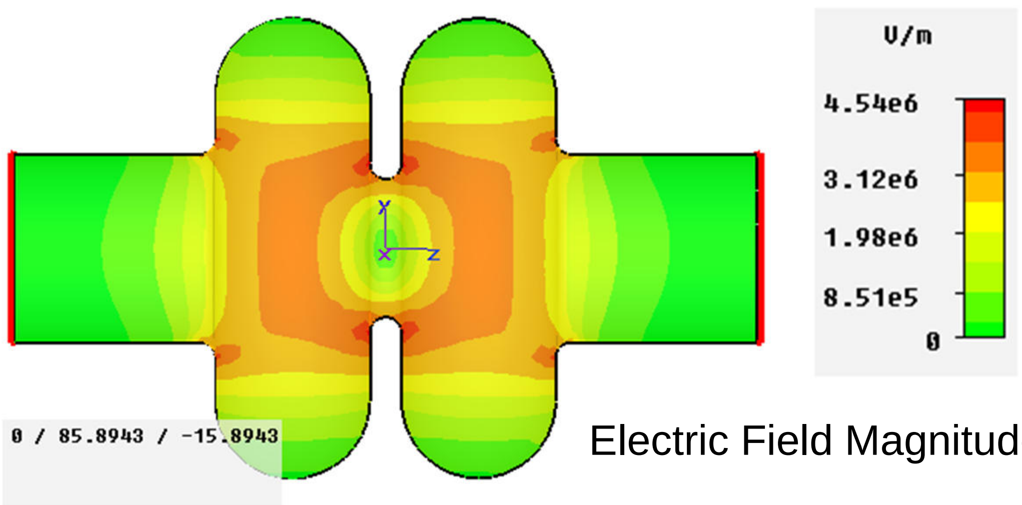
Peak Surface Fields

- The accelerating gradient is the average gradient seen by an electron bunch,

$$E_{acc} = \frac{|V|}{d}$$

- The limit to the energy in the cavity is often given by the peak surface electric and magnetic fields. Thus, it is useful to introduce the ratio between the peak surface electric field and the accelerating gradient, and the ratio between the peak surface magnetic field and the accelerating gradient.

$$\frac{E_{acc}}{E_{\max}} \qquad \frac{E_{acc}}{B_{\max}}$$



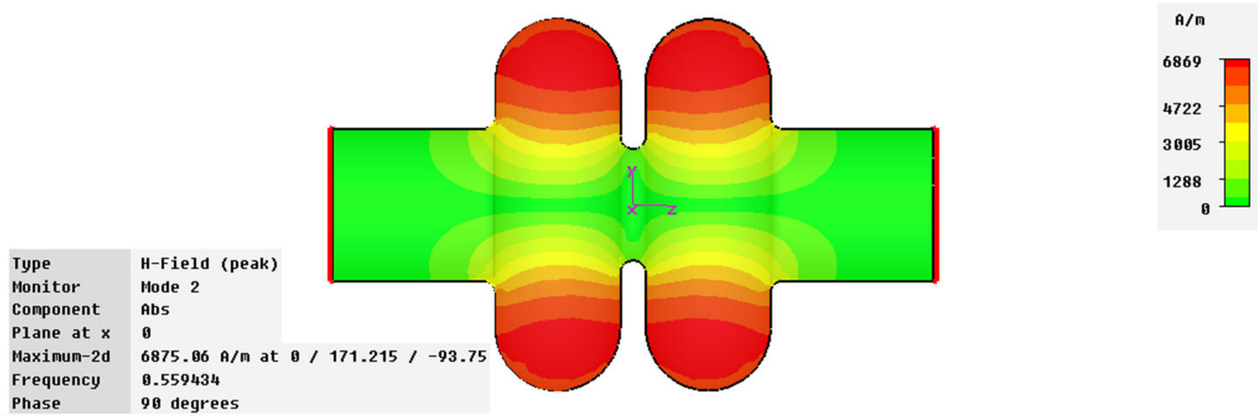
Electric Field Magnitude

Power Dissipation

> The power lost in the cavity walls due to ohmic heating is given by,

$$P_c = \frac{1}{2} R_{surface} \int |H|^2 dS$$

$R_{surface}$ is



> This is important as all power lost in the cavity must be replaced by an rf source.

> A significant amount of power is dissipated in cavity walls and hence the cavities are heated, this must be water cooled in warm cavities and cooled by liquid helium in superconducting cavities.

Cavity Quality Factor

- An important definition is the cavity Q factor, given by

$$Q_0 = \frac{\omega U}{P_c}$$

Where U is the stored energy given by,

$$U = \frac{1}{2}\mu_0 \int |H|^2 dV$$

The Q factor is 2π times the number of rf cycles it takes to dissipate the energy stored in the cavity.

$$U = U_0 \exp\left(-\frac{\omega t}{Q_0}\right)$$

- The Q factor determines the maximum energy the cavity can fill to with a given input power.

Geometry Constant

- It is also useful to use the geometry constant

$$G = R_{surface} Q_0$$

- This allows different cavities to be compared independent of size (frequency) or material, as it depends only on the cavity shape.
- The Q factor is frequency dependant as R_s is frequency dependant.

Shunt Impedance

- Another useful definition is the shunt impedance,

$$R = \frac{1}{2}\frac{|V|^2}{P_c}$$

- This quantity is useful for equivalent circuits as it relates the voltage in the circuit (cavity) to the power dissipated in the resistor (cavity walls).
- Shunt Impedance is also important as it is related to the power induced in the mode by the beam (important for unwanted cavity modes)

Geometric shunt impedance, R/Q

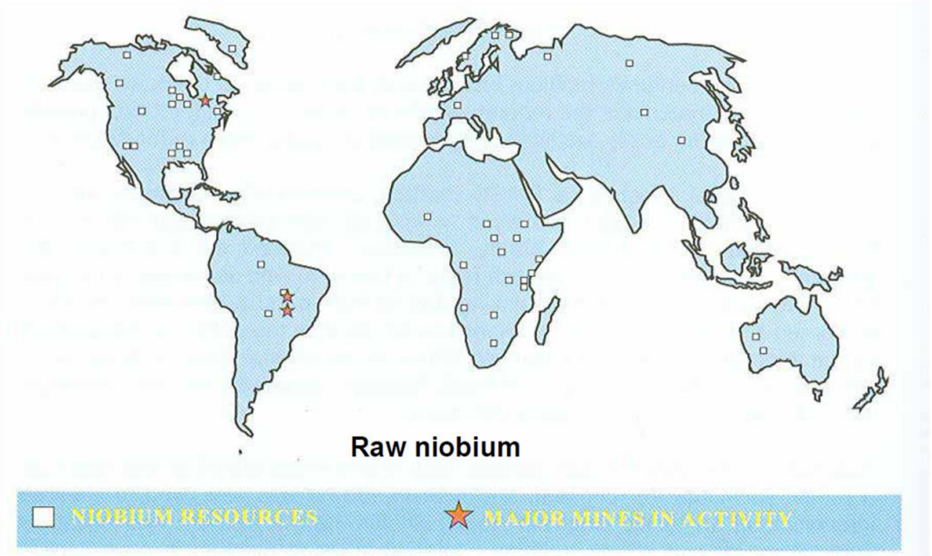
- If we divide the shunt impedance by the Q factor we obtain,

$$\frac{R}{Q} = \frac{|V|^2}{2\omega U}$$

- This is very useful as it relates the accelerating voltage to the stored energy.
- Also like the geometry constant this parameter is independent of frequency and cavity material.

Cavity manufacturing

- Niobium is produced from different companies
  - Wah Chang (USA)
  - Heraeus (Germany)
  - Tokyo Denkai (Japan)
  - Ningxia (China)
  - Niowave Roak (USA – to be qualified)
  - Pavac (USA – to be qualified)

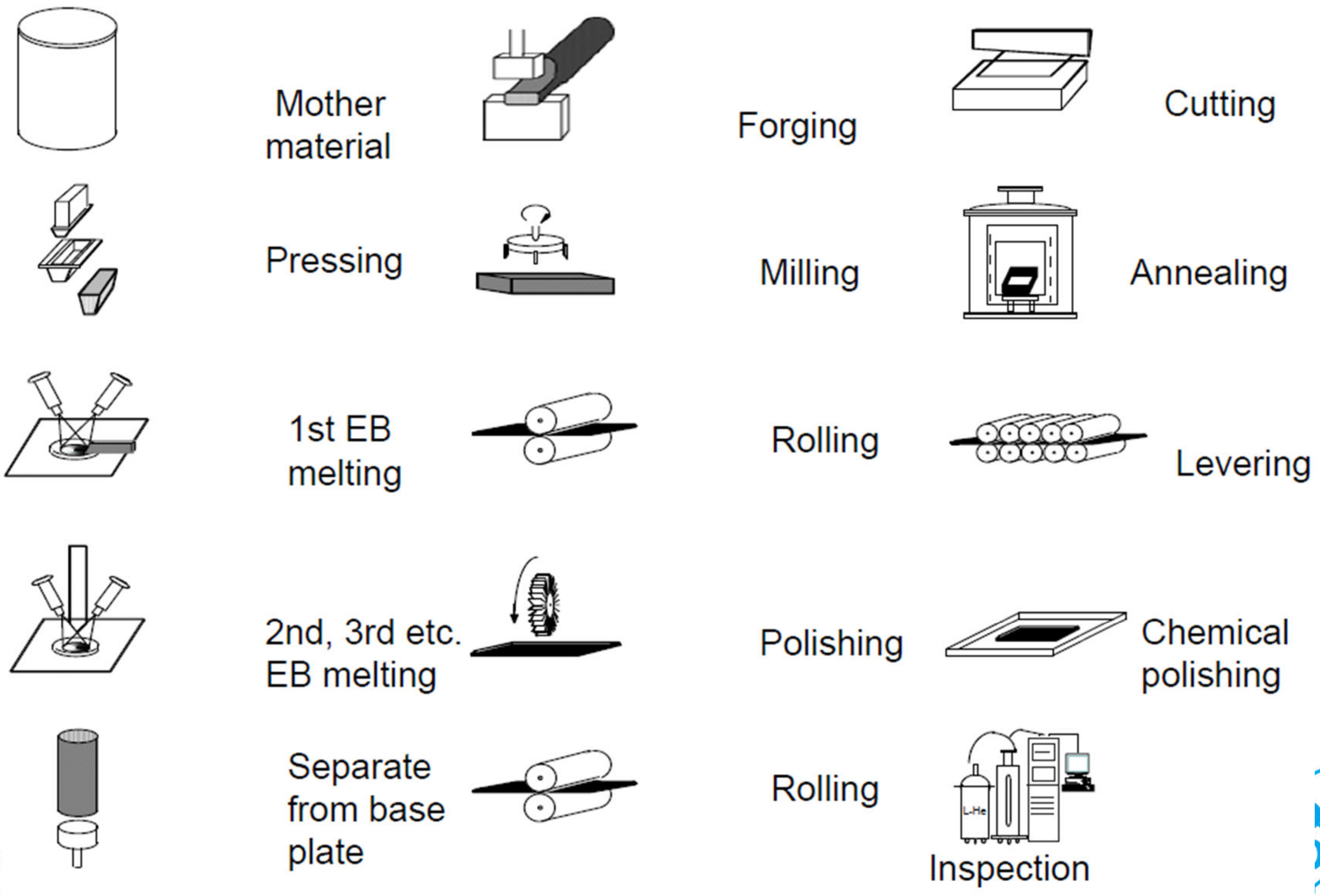


- After mining, purification of Niobium ore is purified with chemical methods and electron beam melting

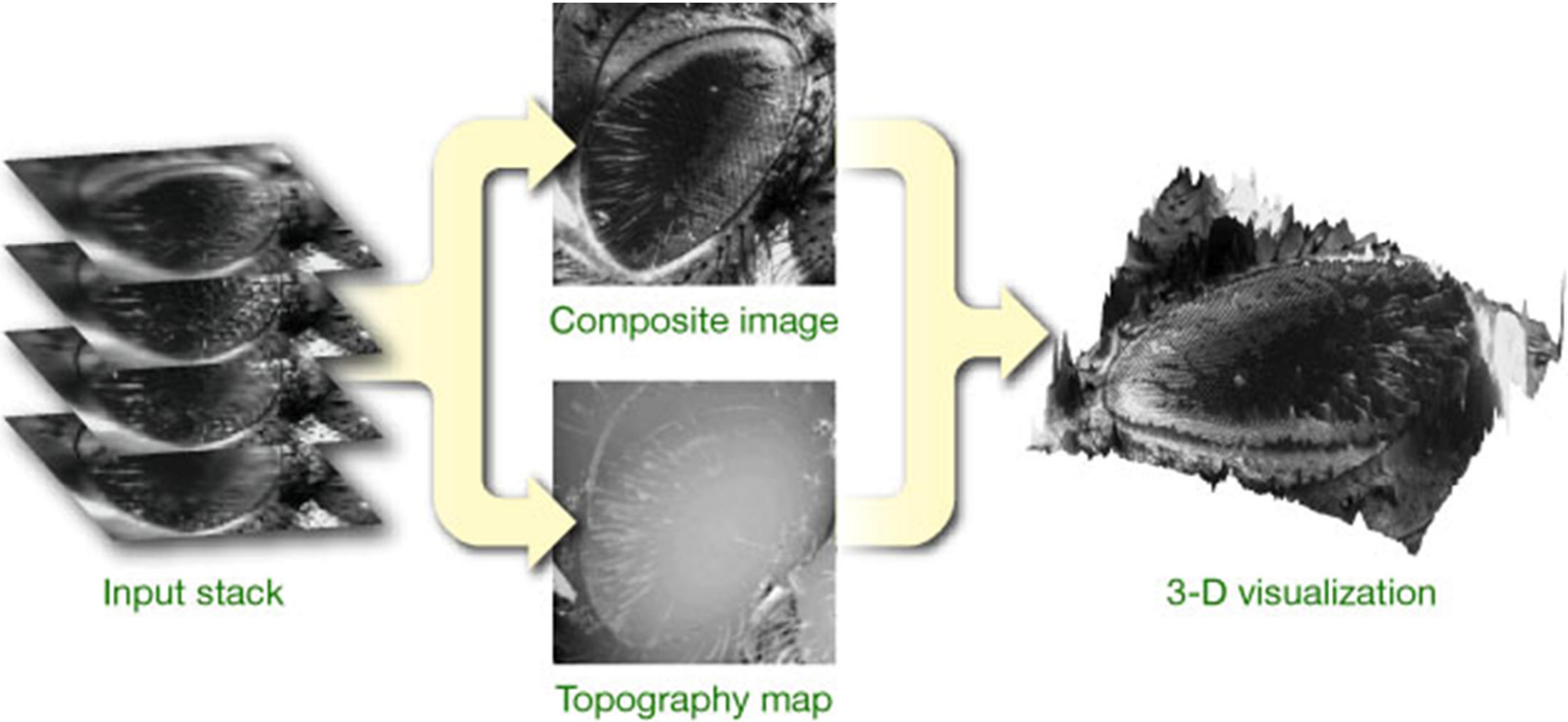
- After this, several mechanical steps are applied to have the sheets for deepdrawing

Cavity manufacturing

Fabrication of Nb sheets at Tokyo Denkai



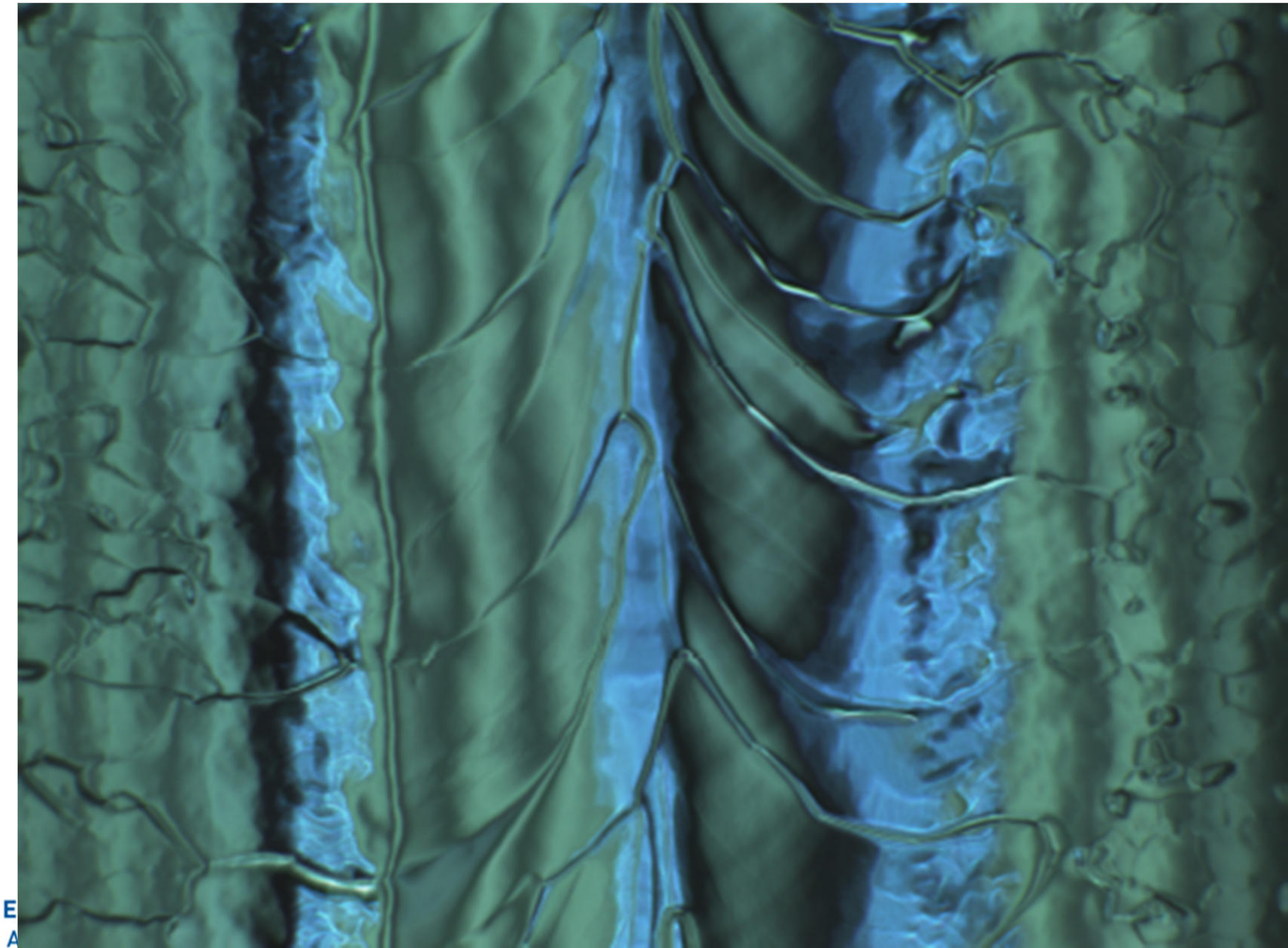
2D – 3D



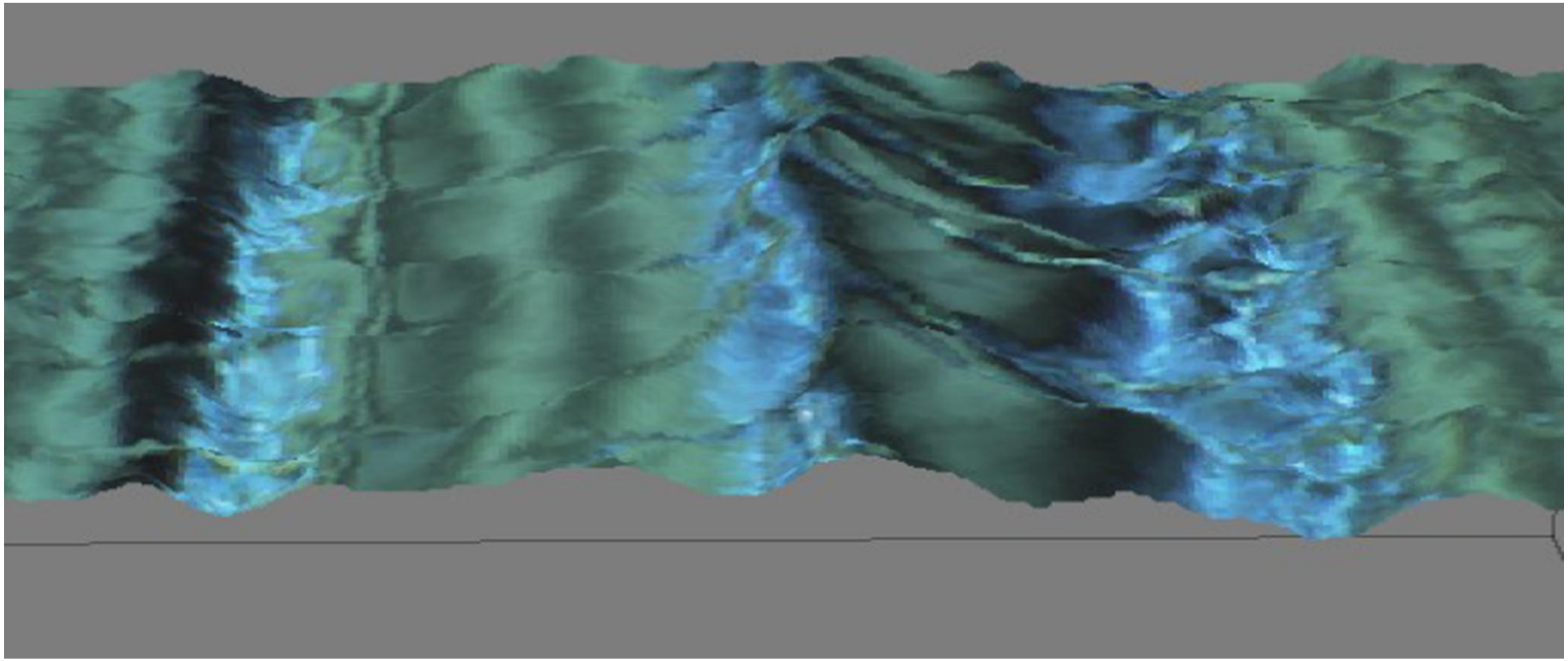
Externes Programm – ‚Complex wavelet-based method' (Focus Stacking)

B. Forster, D. Van De Ville, J. Berent, D. Sage, M. Unser,
"Complex Wavelets for Extended Depth-of-Field: A New Method for the Fusion of Multichannel Microscopy Images ," Microsc. Res. Tech., 65(1-2), pp. 33-42, September 2004.

2D – 3D



2D – 3D



Histogram – Eacc @ Jlab