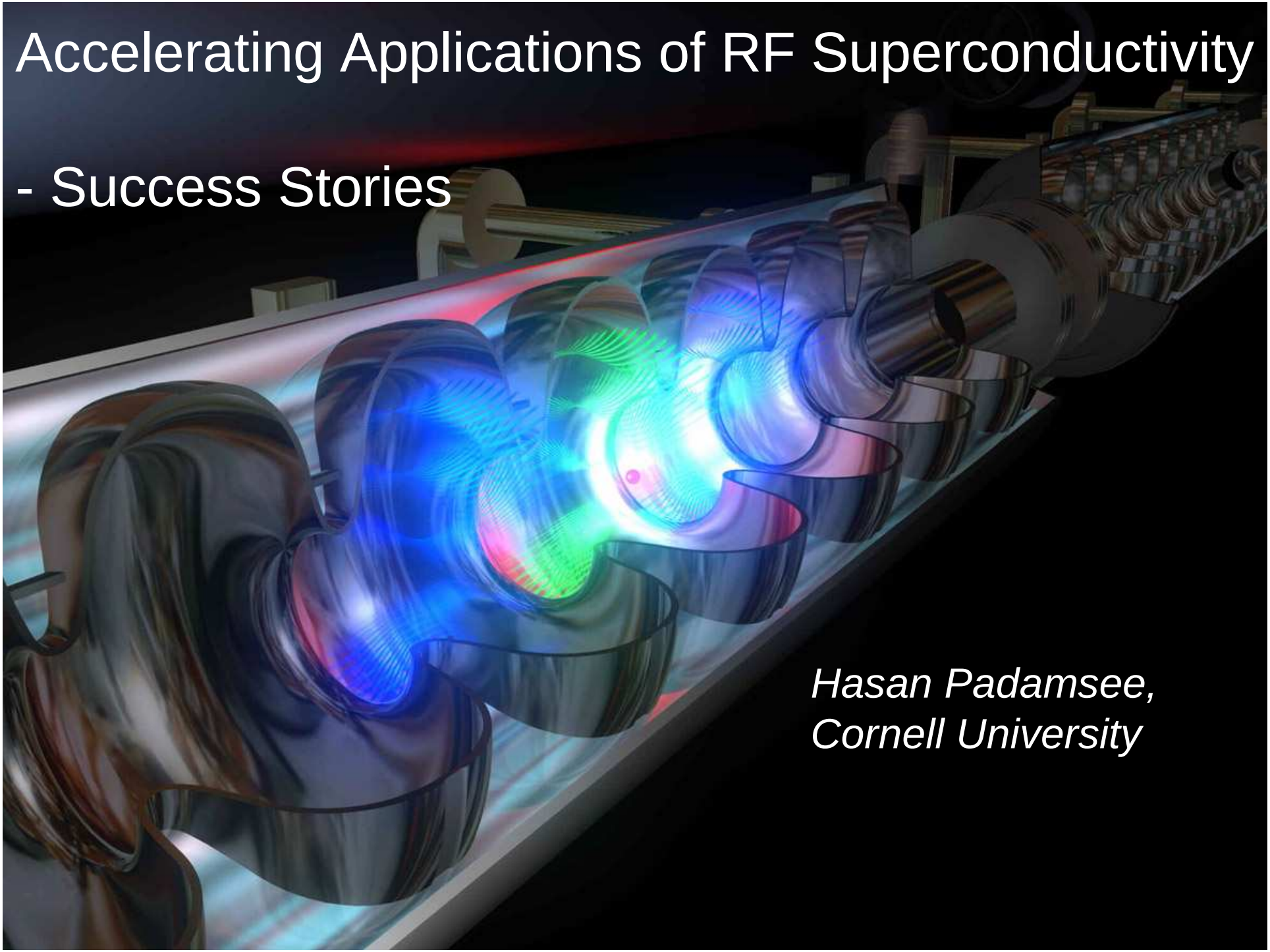
Accelerating Applications of RF Superconductivity

- Success Stories



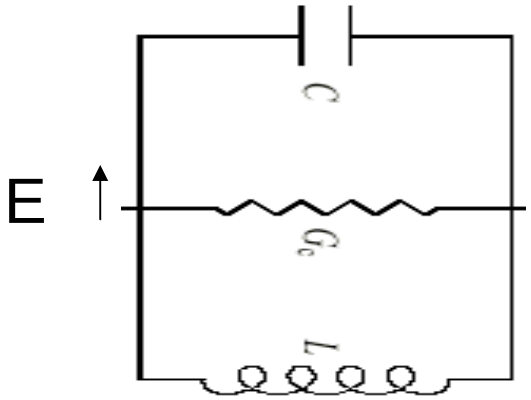
Hasan Padamsee,
Cornell University

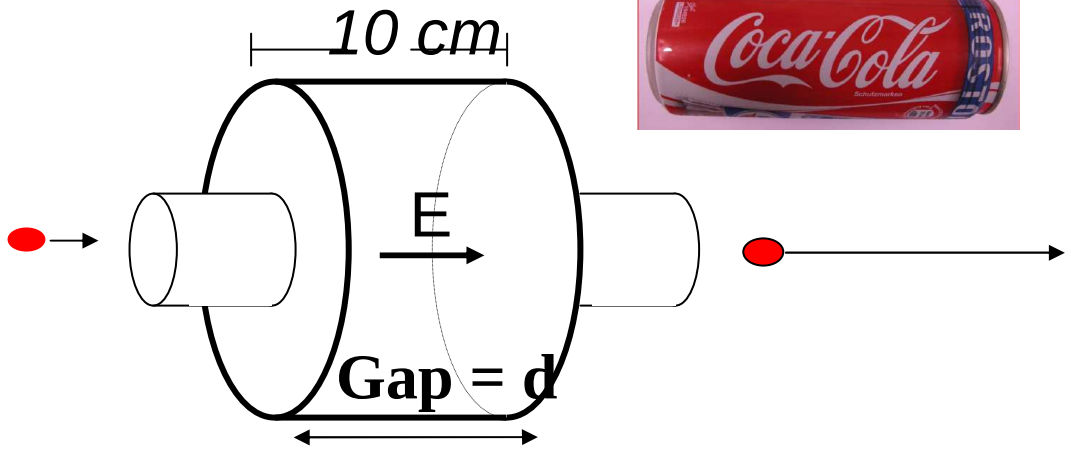
Accelerating Applications of RF Superconductivity - Success Stories

Hasan Padamsee, Cornell University

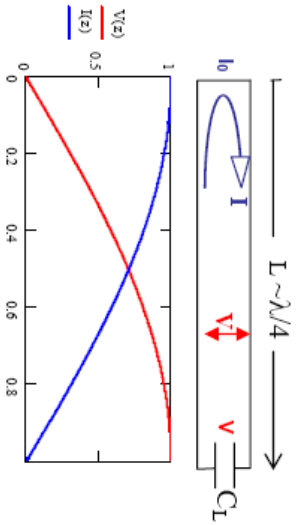
- Introduction: Basics of RF superconductivity for Acceleration
  - Superconducting Structures
- Completed Applications…. Success Story #1
  - Particle Physics, Light Sources, Nuclear Physics
- Dramatic Progress in Performance: Success Story #2
  - Short version (Matthais – Long Version)
- New applications Take Off- Success Story #3
  - Spallation Neutron Source
  - New Light Sources: XFEL, ERL…
  - Electron cooling for RHIC, electron-ion collisions
  - Rare Isotope Accelerator
  - Proton Drivers
  - International Linear Collider
- Far Future Possibilities
  - Neutrino Factory… Muon Collider

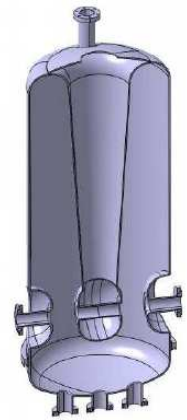
RF Acceleration With Superconducting Cavities

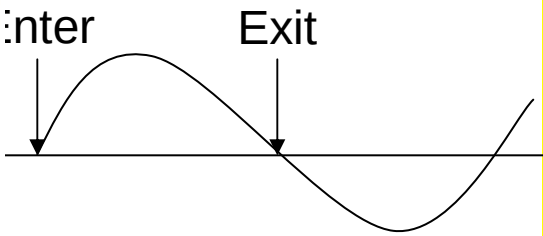




V_C = One Million Volts







time

Freq = 1.5 GHz

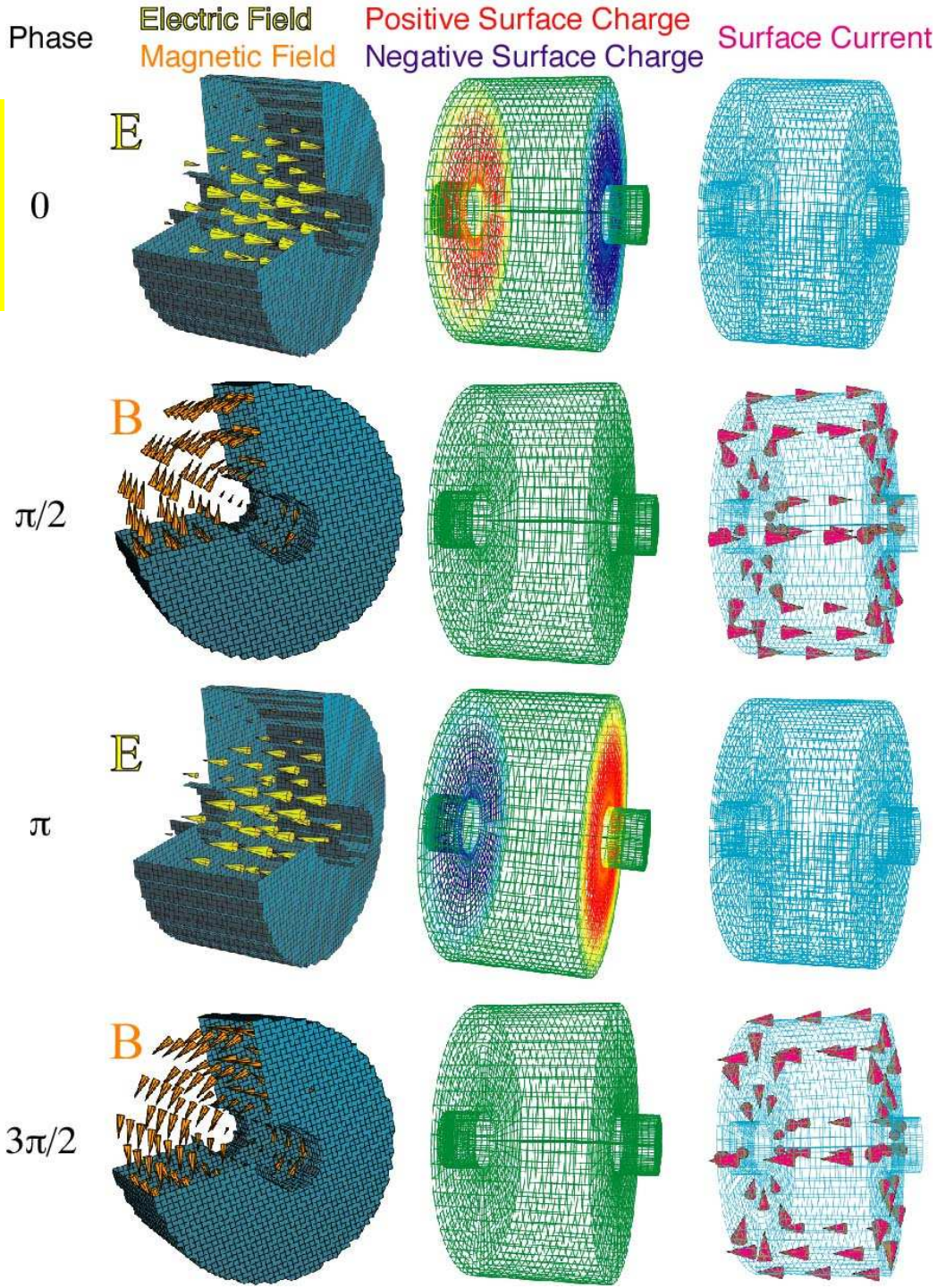
Copper
$Q \approx 10^4$
One million watts CW

Superconductor
E.g. Niobium 2K
$Q \approx 10^{10}$

One watt !
Into Liquid Helium

≈ 1kW AC power
CW

RF accelerator cavity fields



Important Figures of Merit of Superconducting Accelerating Cavities

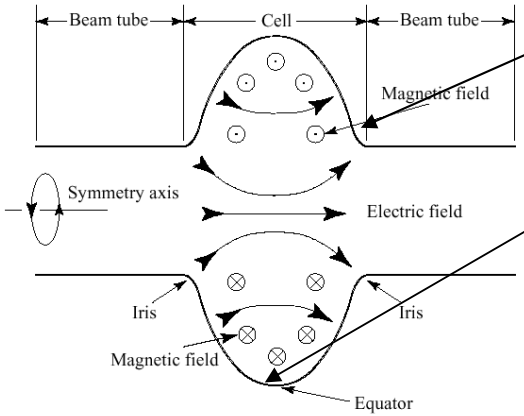
- Accelerating voltage V_c
- Accelerating field $E_{acc} = V_c/d$
- Dissipated power in cavity wall
- Stored energy

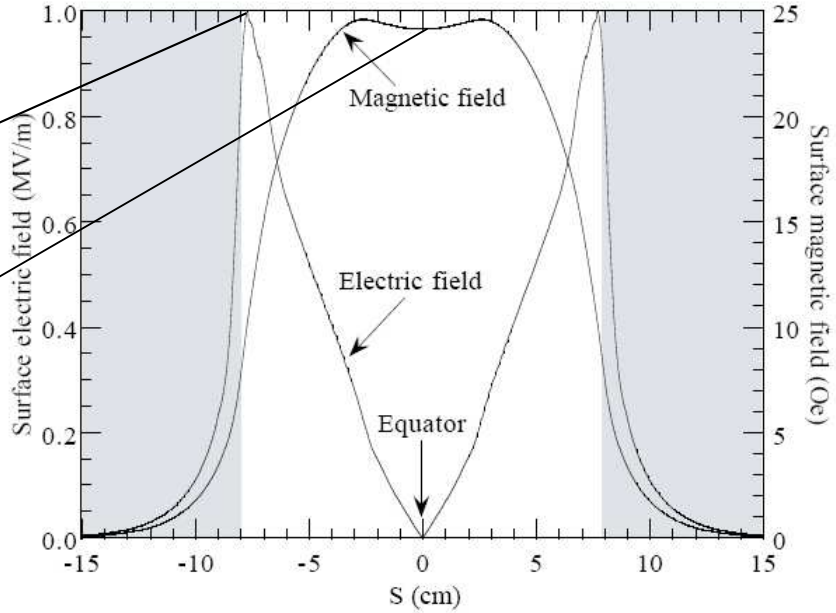
$$P_c = \frac{1}{2} R_s \int_S |\mathbf{H}|^2 \, ds$$

$$U = \frac{1}{2} \mu_0 \int_V |\mathbf{H}|^2 \, dv$$

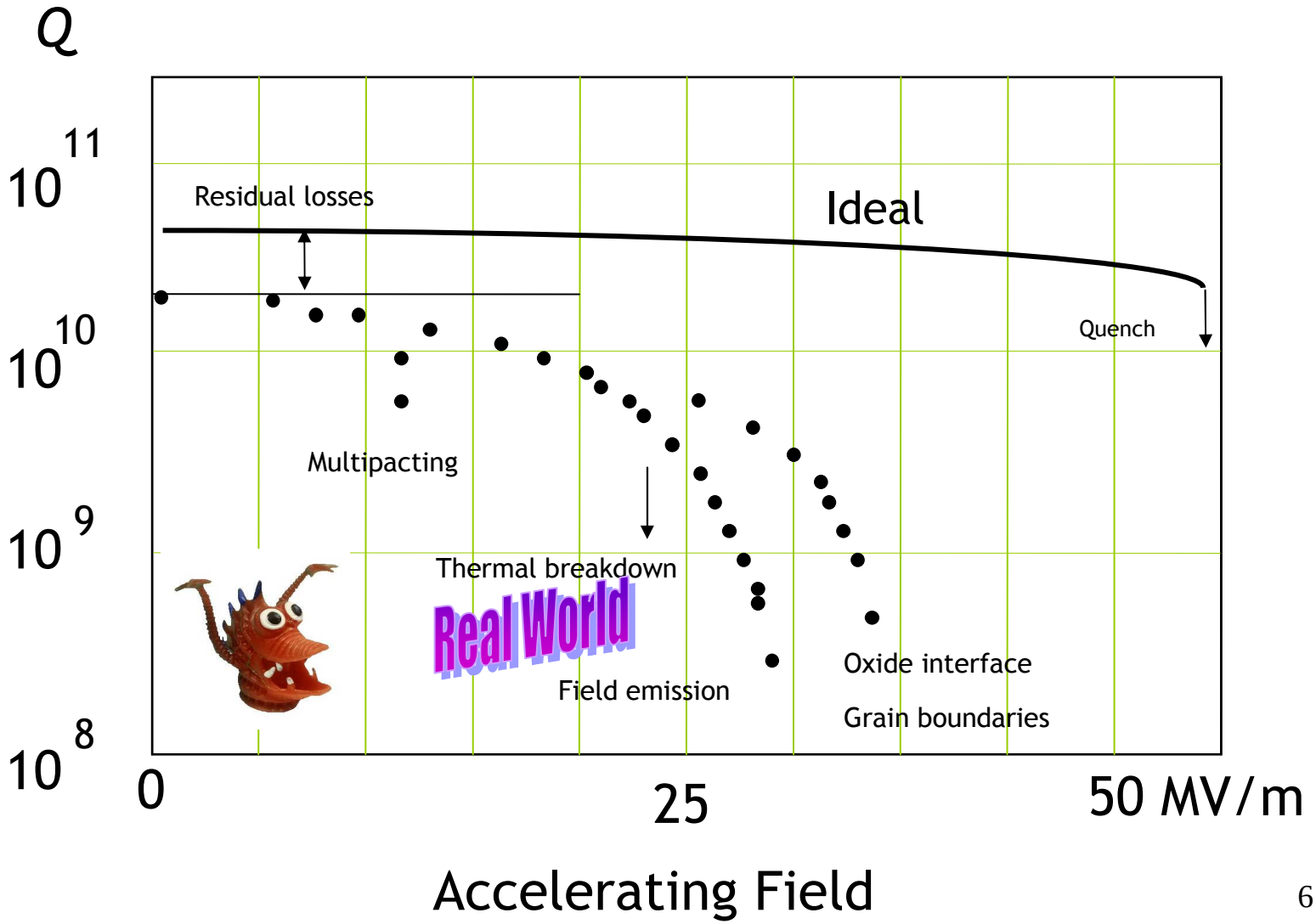
- Surface fields
  - E_{pk}/E_{acc} typically 2 – 2.6
  - H_{pk}/E_{acc} typically 40 - 50 Oe/MV/m

- Q value $$Q_0 = \frac{\omega_0 U}{P_c}$$

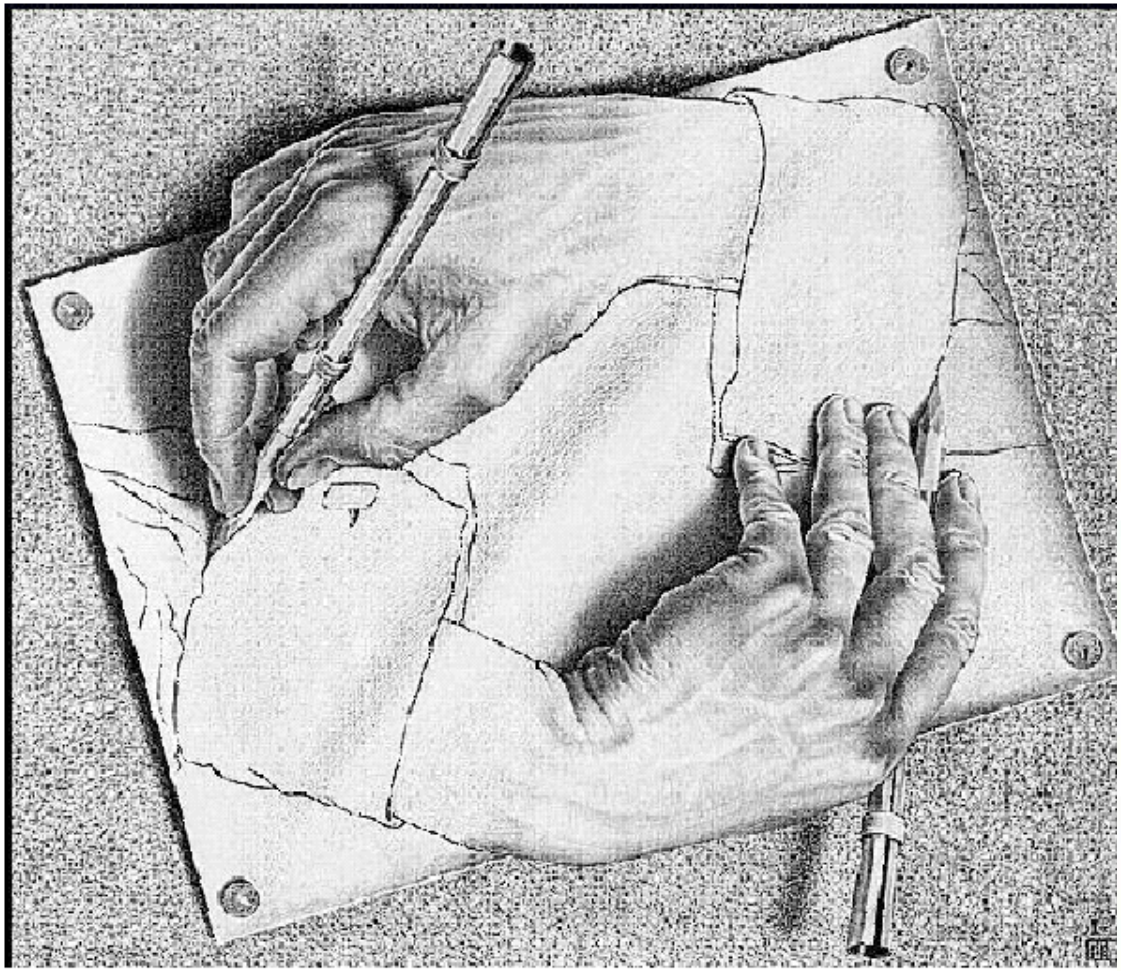




Most Important Cavity Performance Characterization
Q vs E curve



Cavity Design is a Work of Art and Science Calling for Imagination, Calculation, Symmetry…..

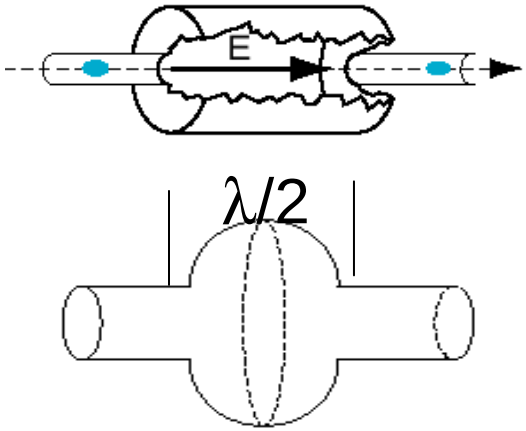


M. Duchamps,
Nude Descending a Staircase

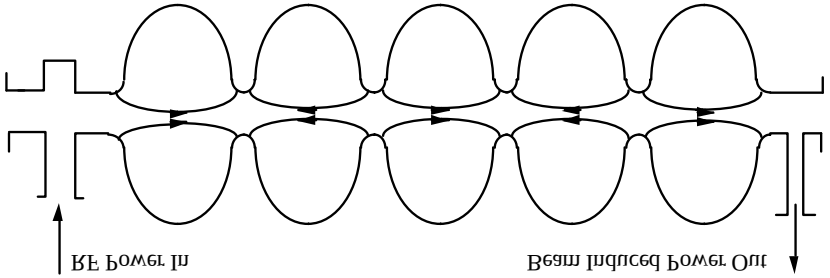
There are a variety of designs for accelerating charged particles moving at velocities from c to 0.01 c

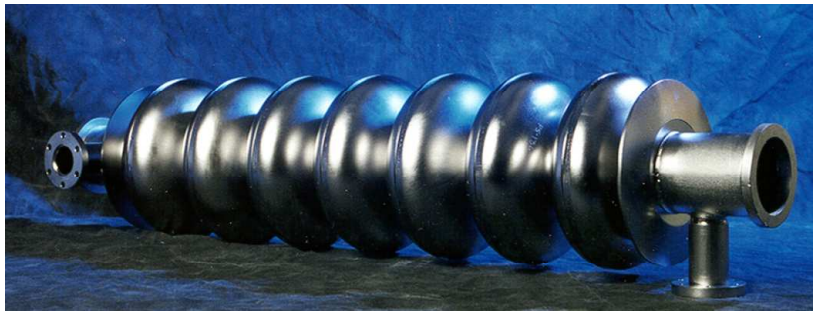
We move from high velocity to low velocity acceleration

High and Medium Velocity Structure Examples
$\beta = v/c$ = 1 -> 0.5

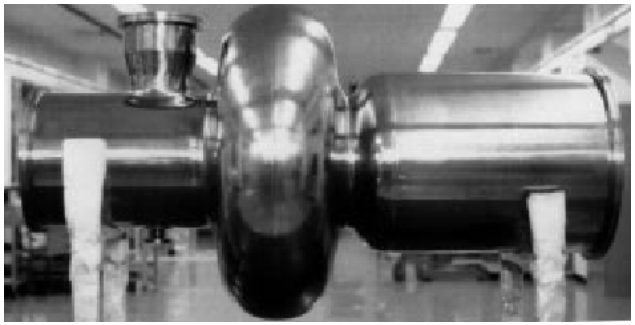


Basic Principle, *v/c* = 1

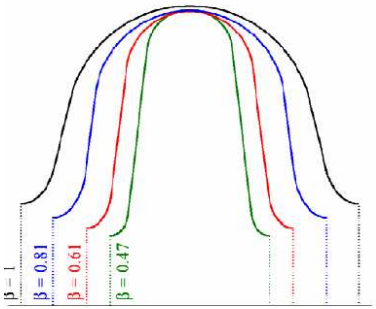


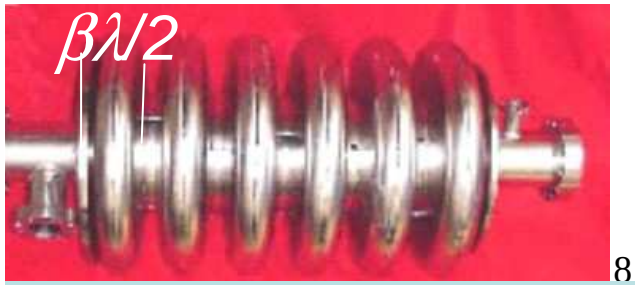


Multi-Cell Cavity



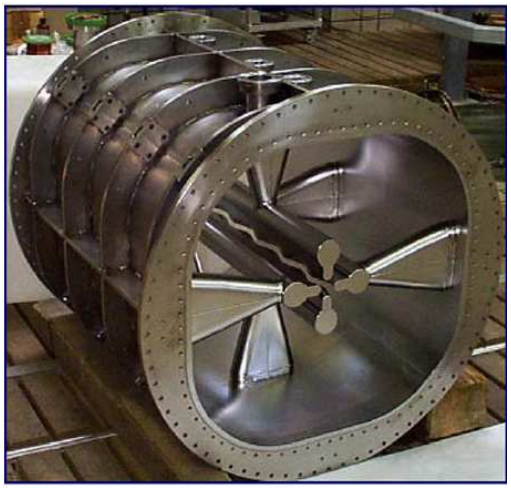
Single Cell

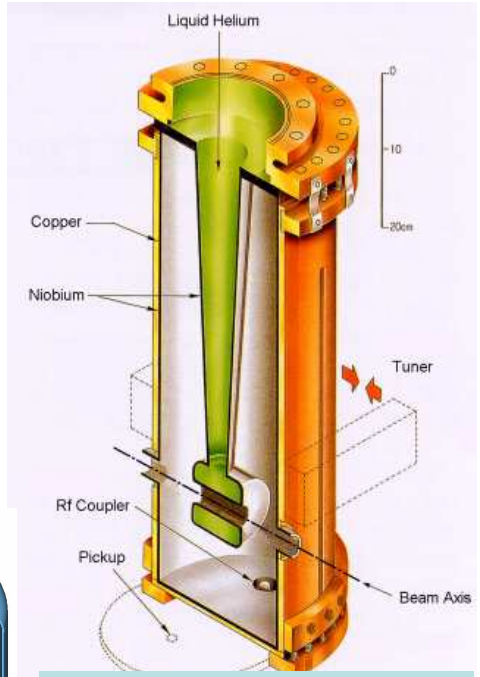




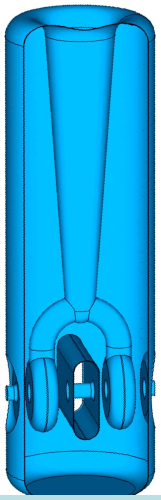
Squeezed Cells for v/c = 0.5

Low Velocity Structures, $\beta = v/c$ = 0.001 to 0.2



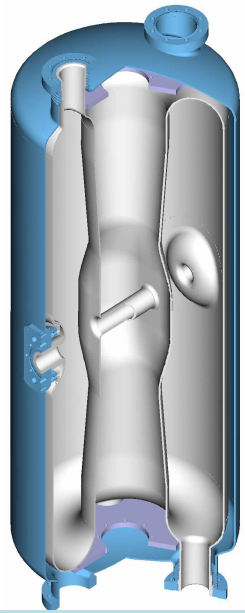


Quarter Wave



Inter-Digital

Split -Ring



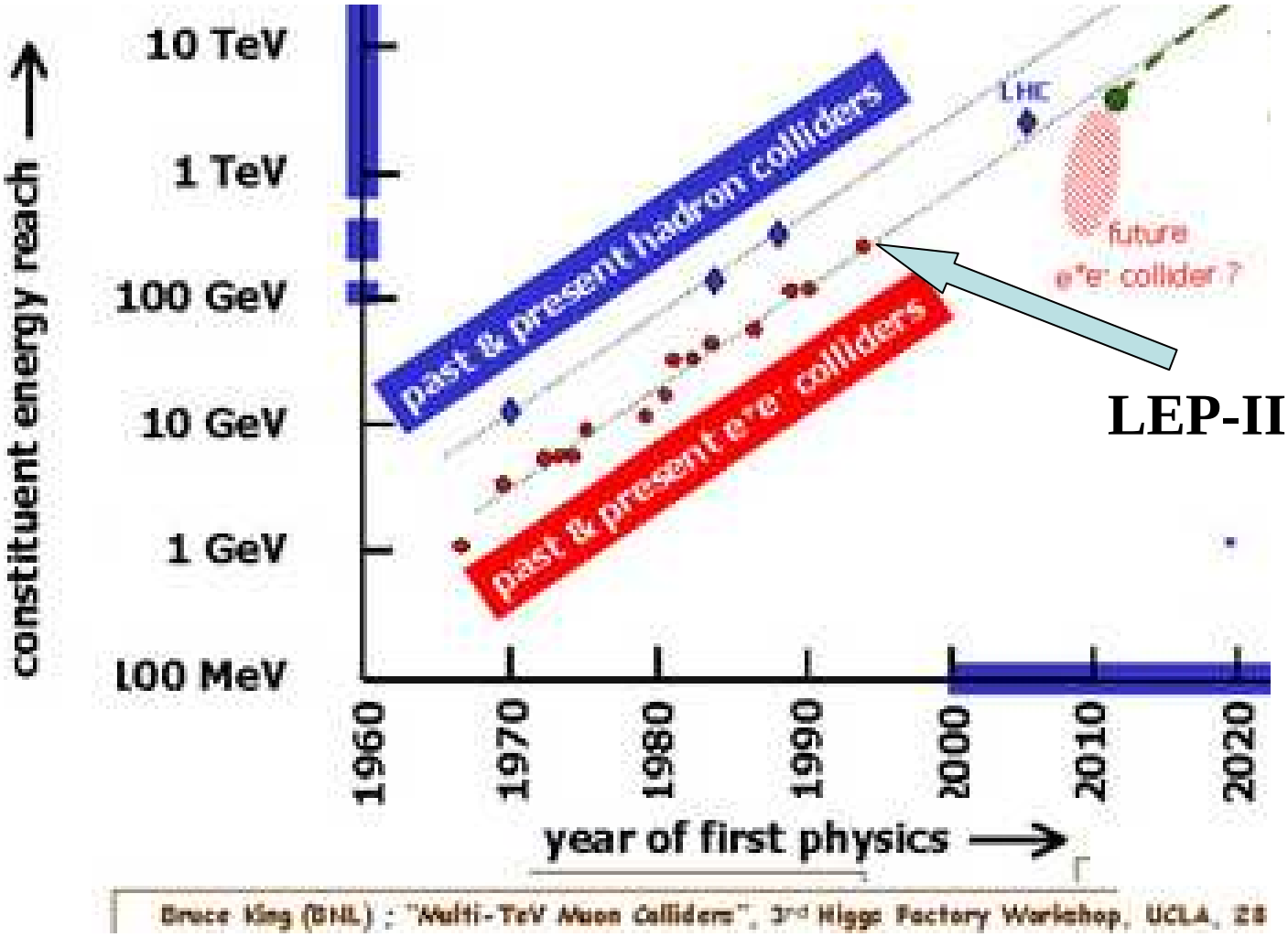
Half-Wave

Spoke

Completed Applications Success Story #1

- High Energy
  - Energy Frontier
  - Flavor Physics (e.g. B-factory, CESR-C)
- Medium Energy
  - Quark-Gluon Nuclear Structure
  - Light Sources : IR-UV-Xray
- Low Energy
  - Nuclear Physics
  - RadioIsotope Beams for Nuclear Astrophysics

High Energy Physics



SC Cavites in

TRISTAN

HERA

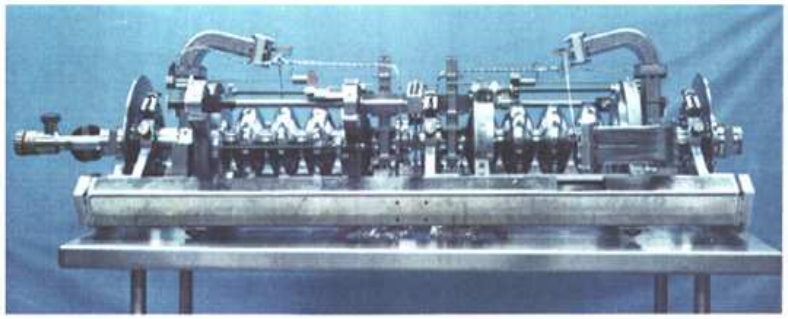
LEP-II

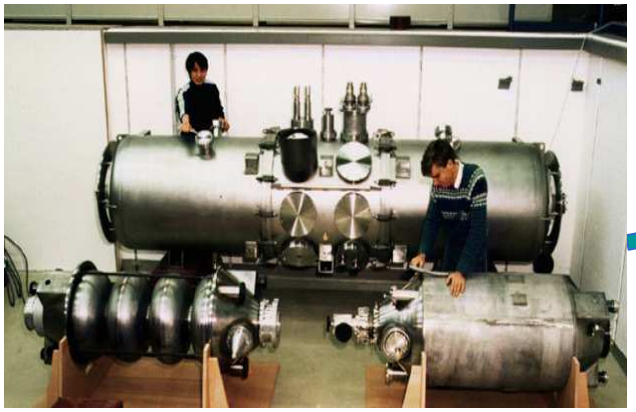
CESR

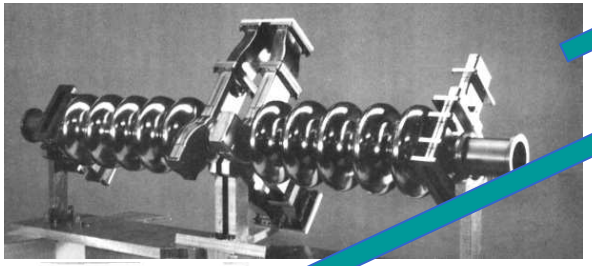
KEK-B

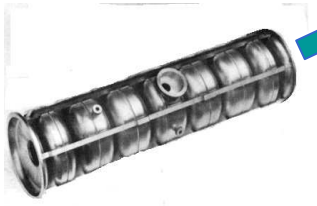
LHC

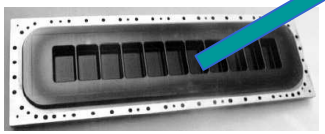
Total Installation > 1000 m
Provided > 5 GV

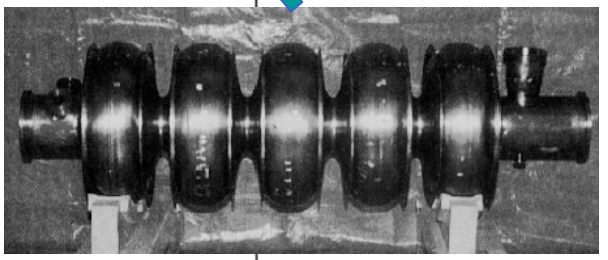


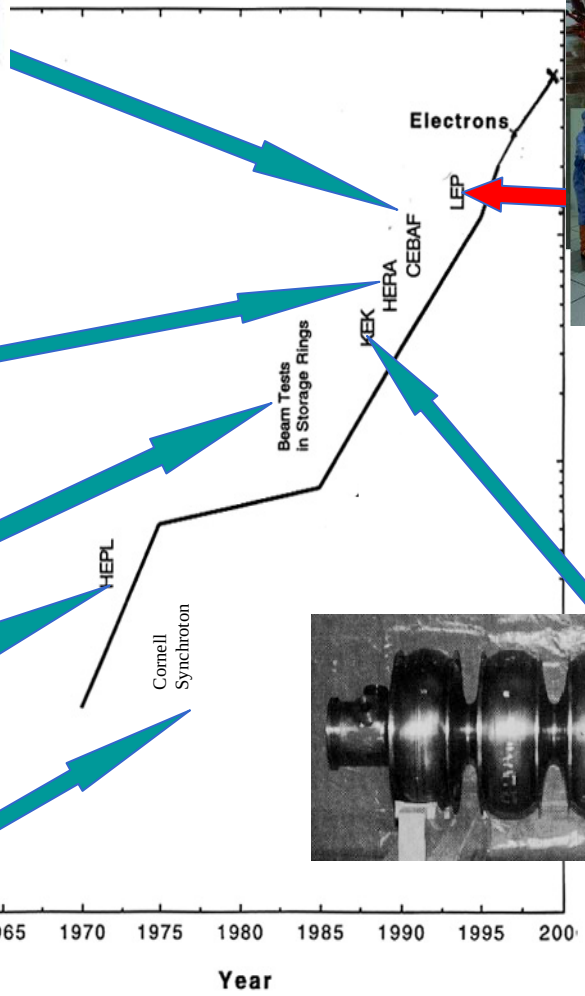


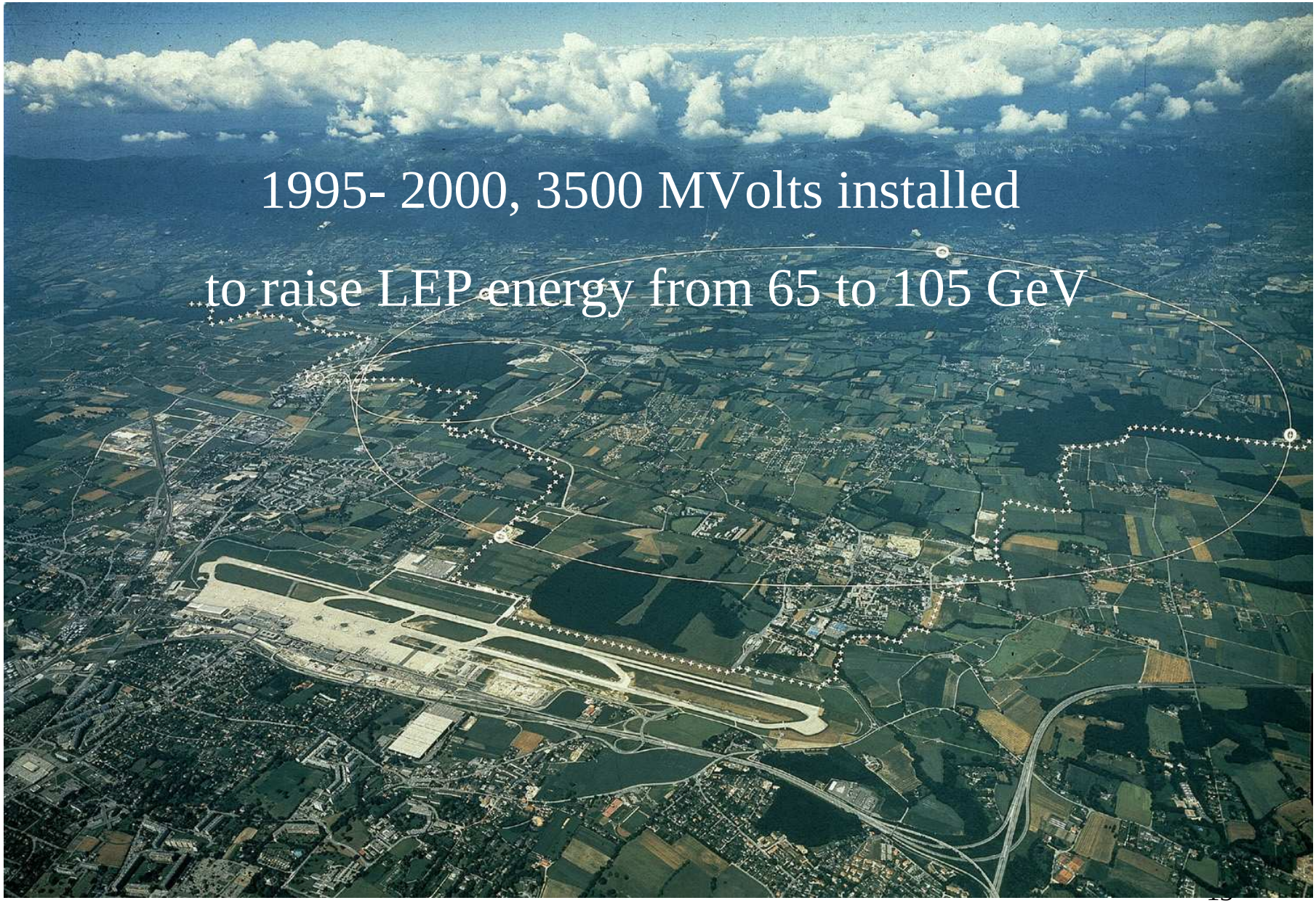




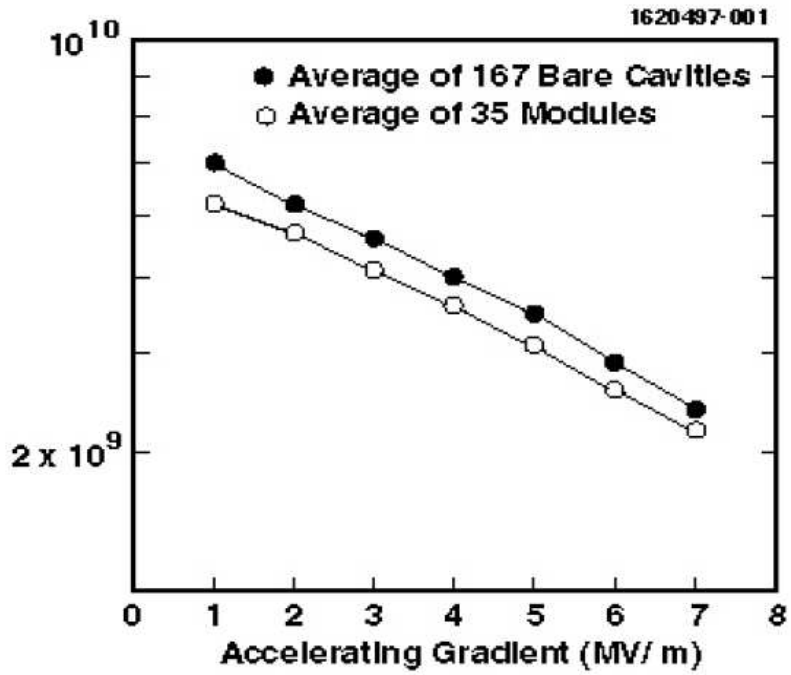


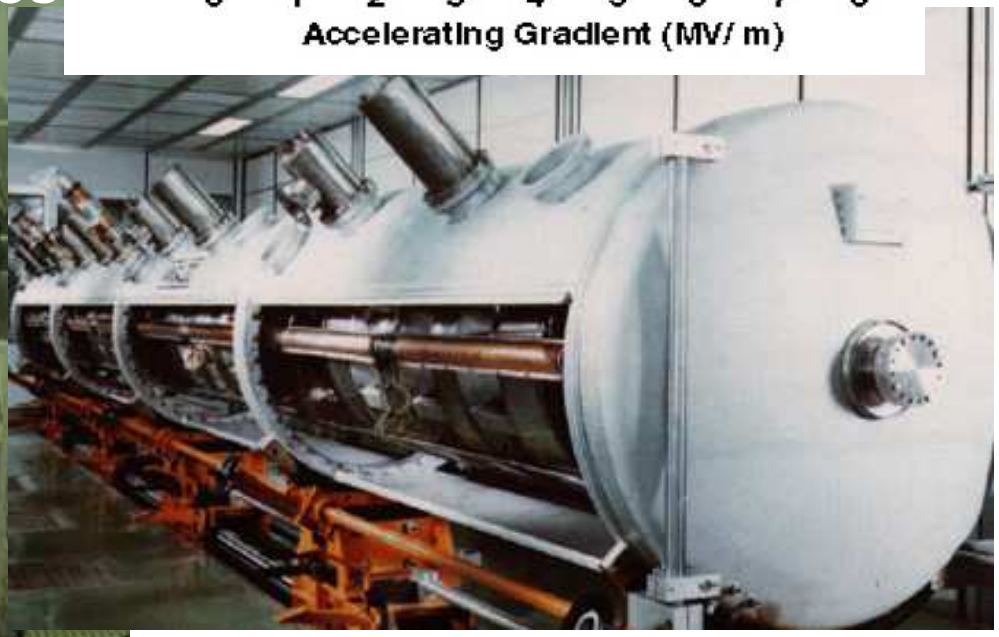


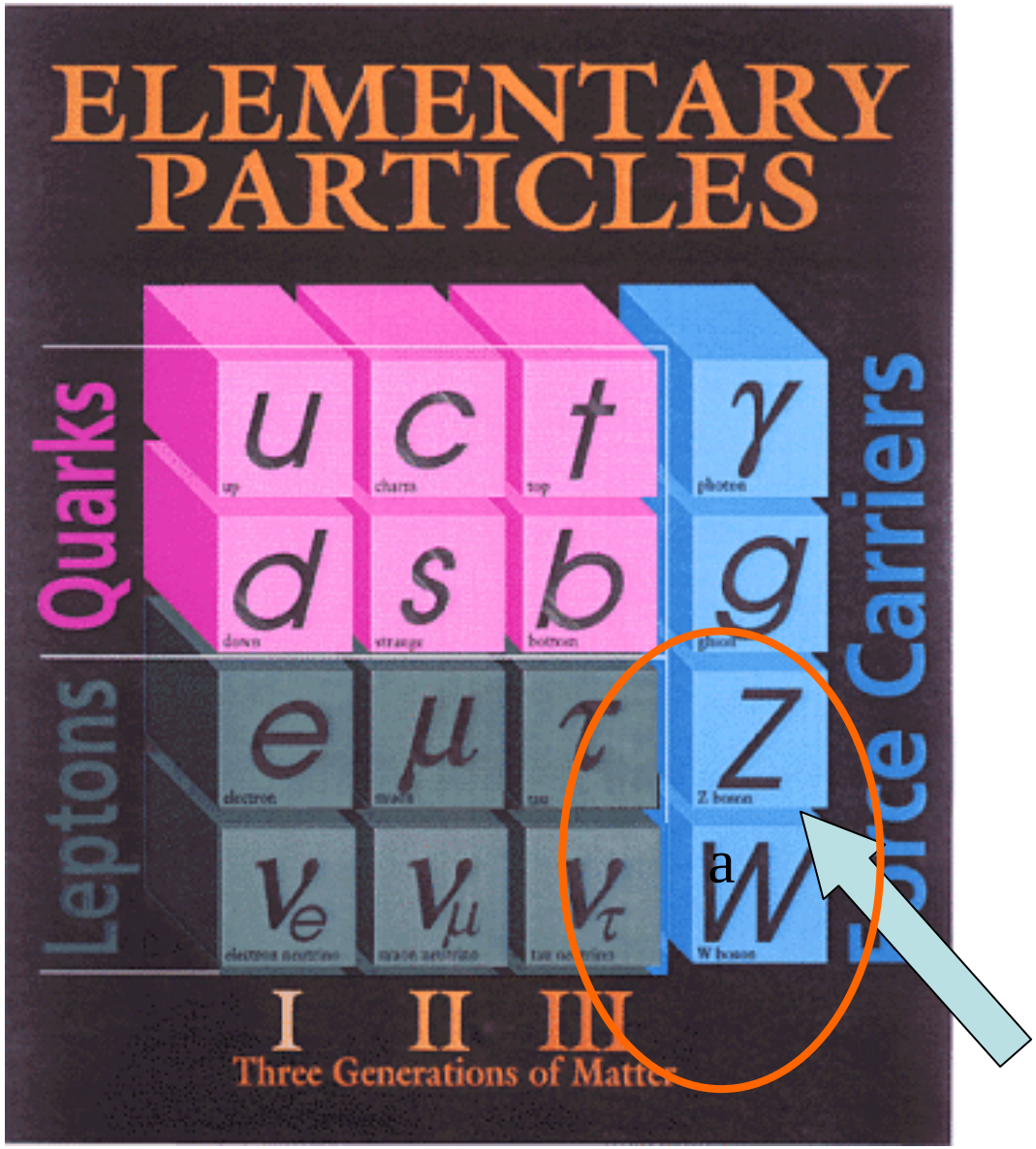



1995- 2000, 3500 MVolts installed
to raise LEP energy from 65 to 105 GeV

350 MHz Nb-Cu Cavities for LEP-II







Major LEP-II studies & discoveries

Predicted from Unification of Weak and em forces

SRF in Storage Rings

Electron - Positron

- TRISTAN - Japan
- HERA - Germany
- LEP-II - CERN (Europe)
- CESR-III - USA
- KEK-B Japan
- 5 - 8 MV/m

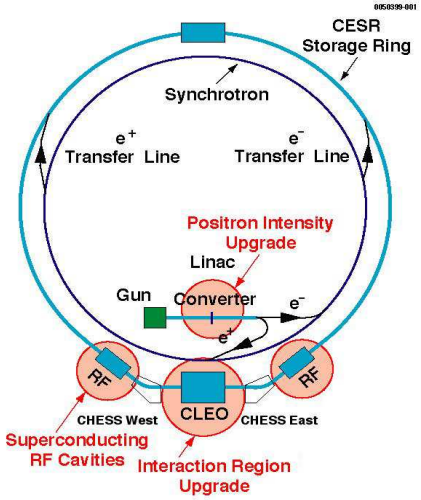
Proton-Proton

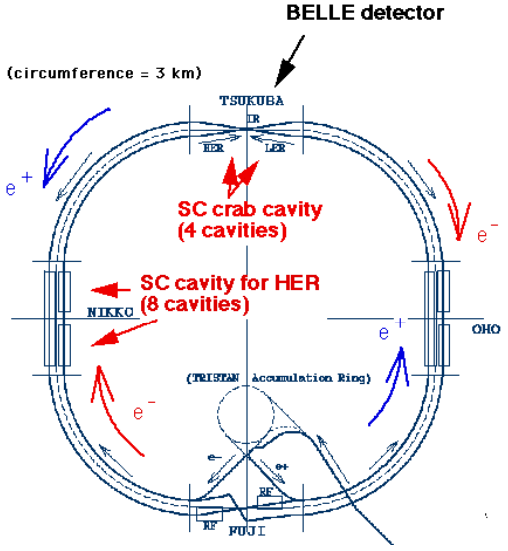
- LHC- CERN

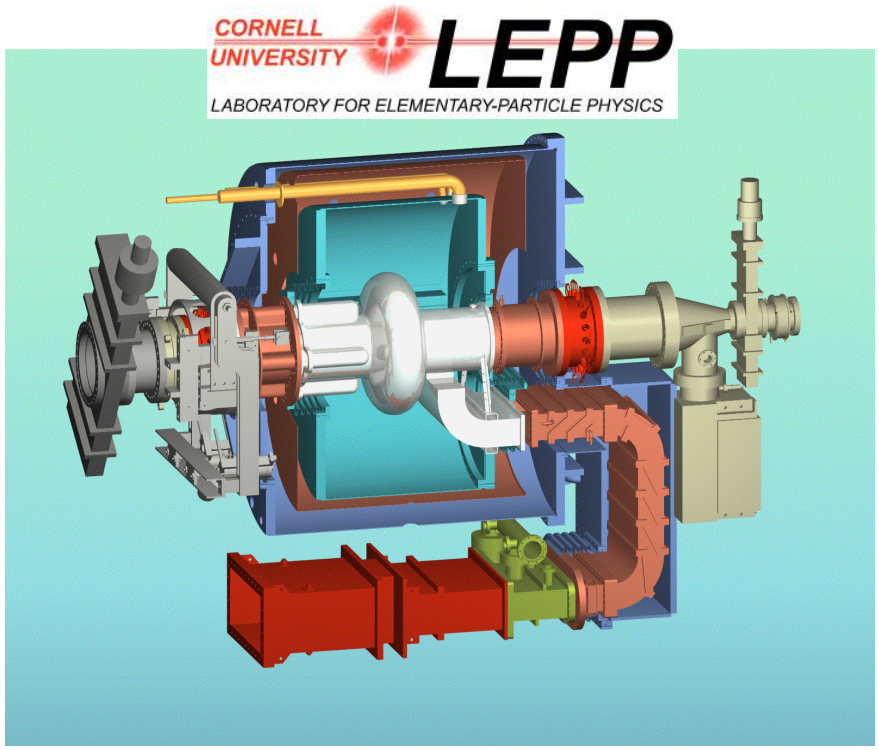
Cornell-KEK-B Collaboration

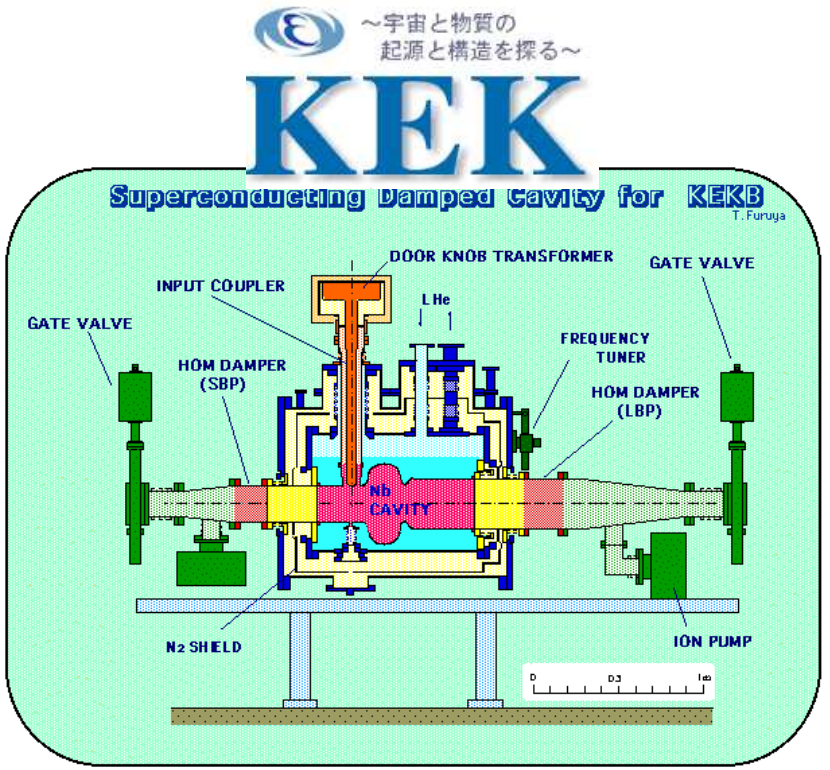
CORNELL UNIVERSITY LEPP
LABORATORY FOR ELEMENTARY-PARTICLE PHYSICS

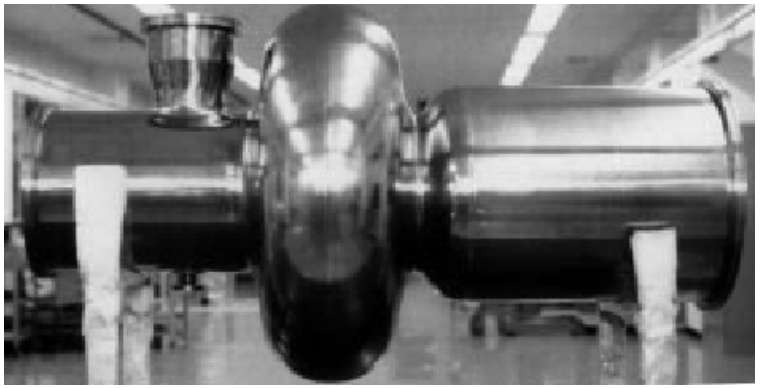
~宇宙と物質の起源と構造を探る~ KEK






CORNELL
UNIVERSITY
LEPP
LABORATORY FOR ELEMENTARY-PARTICLE PHYSICS


～宇宙と物質の
起源と構造を探る～
KEK
Superconducting Damped Cavity for KEKB
T. Furuya
DOOR KNOB TRANSFORMER
GATE VALVE
INPUT COUPLER
LHe
GATE VALVE
FREQUENCY
TUNER
HOM DAMPER
(SBP)
HOM DAMPER
(LBP)
Nb
CAVITY
N2 SHIELD
ION PUMP

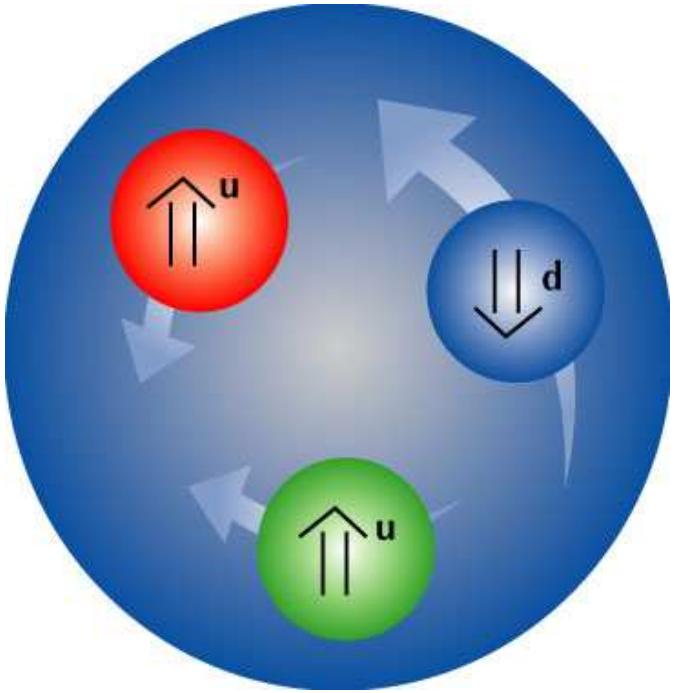


SRF Modules Installed in LHC

- 16 Nb-Cu Cavities
- 4 Cryomodules
- 16 MV per beam
- 10 MV/m

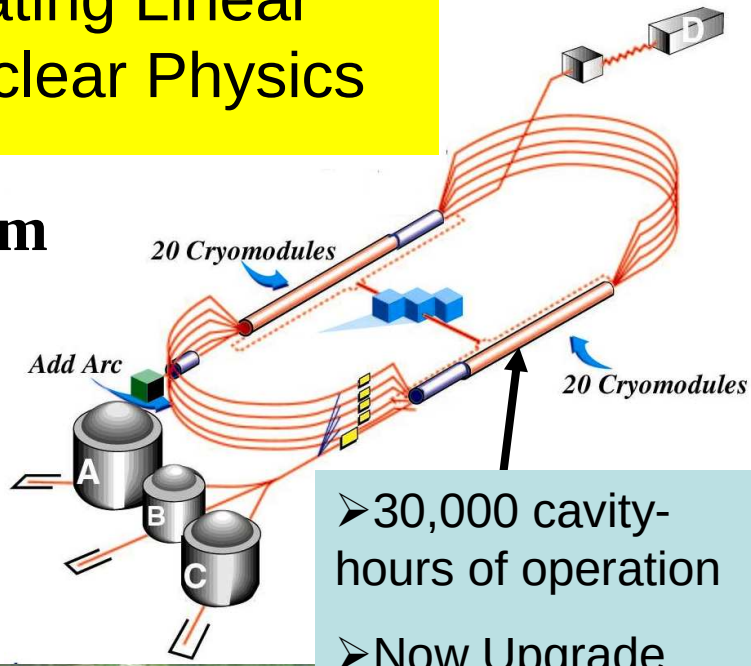
Medium Energy Nuclear Physics

- Understanding the quark-gluon structure of nucleus
- Distribution of nuclear spin

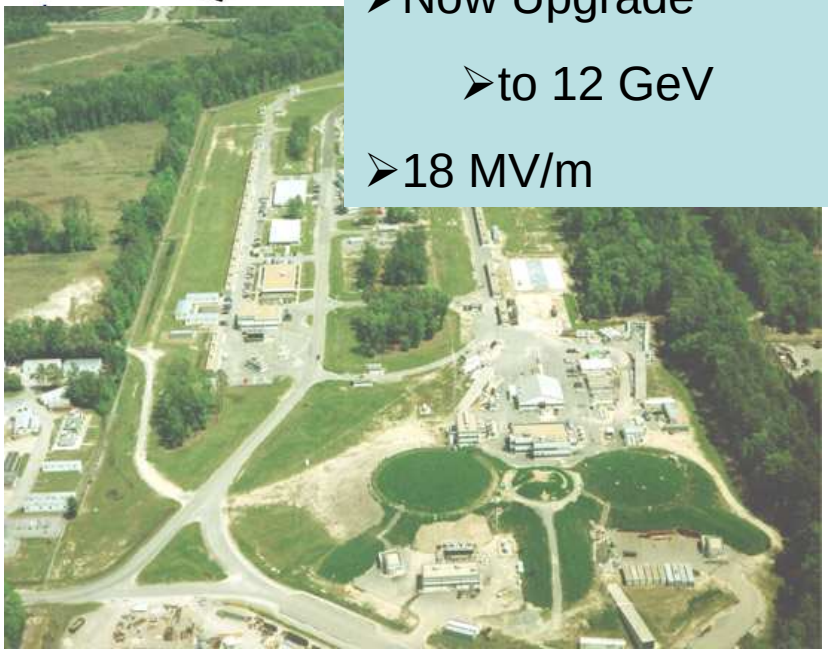


6 GeV Re-circulating Linear Accelerator for Nuclear Physics

7 MV/m



- 30,000 cavity-hours of operation
- Now Upgrade
  - to 12 GeV
- 18 MV/m



Light Sources

From IR-UV-Xrays

X-ACTLY SO !

The Roentgen Rays, the Roentgen Rays

What is this craze?

The town's ablaze

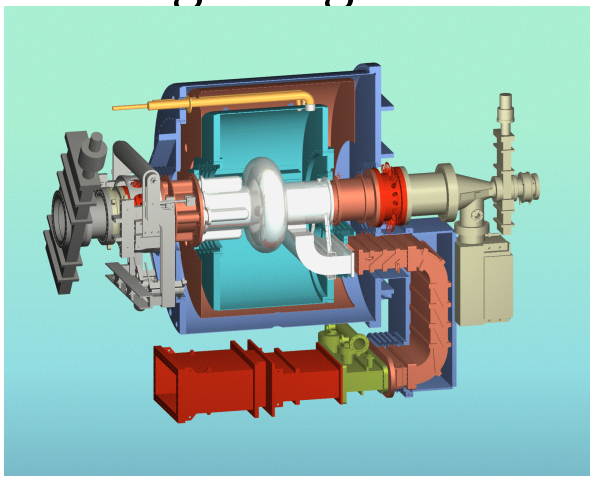
With the new phase

Of X-ray's ways

A Christmas present to civilization at the turn of the 20th century

SRF in Electron Storage Rings (X-Rays)
Installed

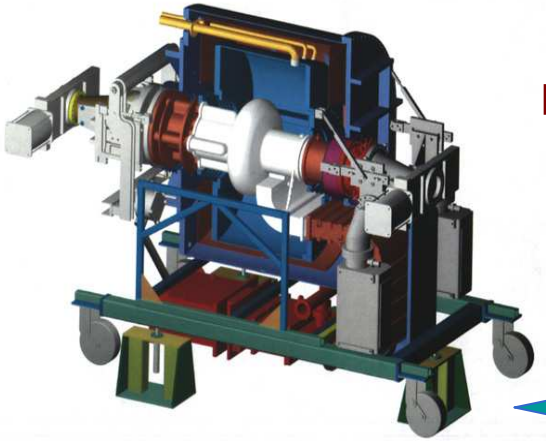
- CESR/CHESS - USA
- Canadian Light Source
- Taiwan Light Source
- DIAMOND Light Source (UK)
- Shangai Light Source



- SOLEIL (France)
- Beijing Tau-Charm Factory
- Swiss Light Source
  - For life time increase
- ELETTRA (Italy)
  - For life time increase

CESR SRF => Taiwan, Canada, U.K, Shangai (via ACCEL co.)

CESR Technology Transfer to Industry



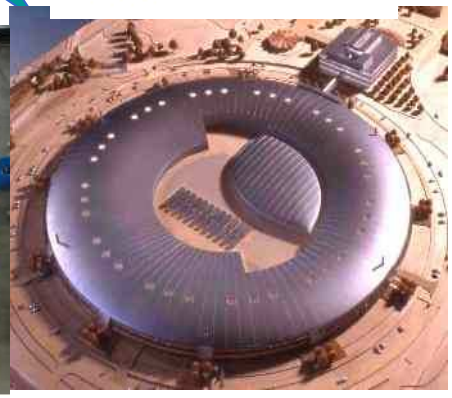
ACCEL

Turn-Key Systems

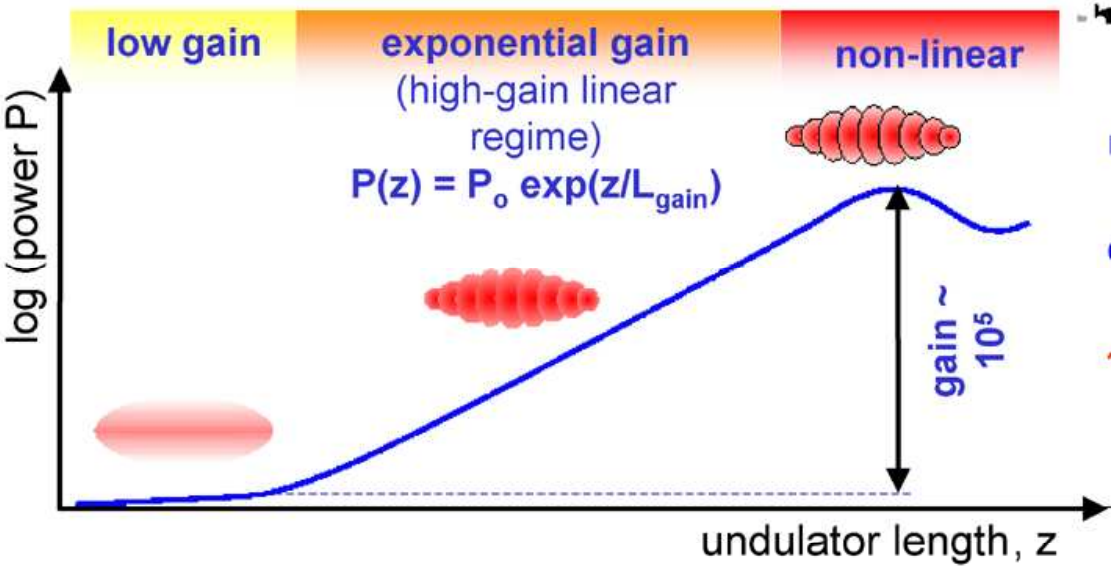
National Synchrotron Radiation Research Center

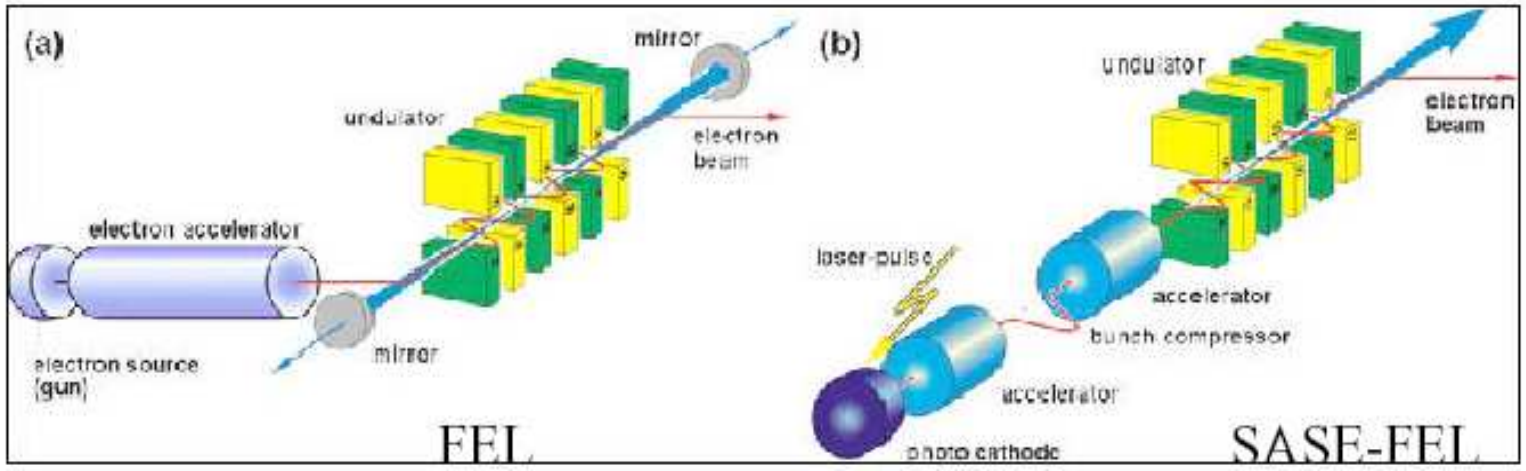
Canadian Light Source Inc.

diamond



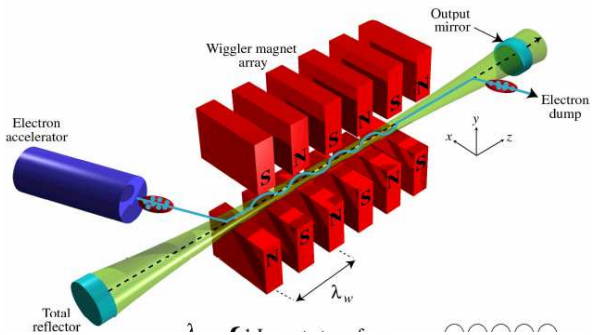
Lasers : Infra red, UV, X-ray

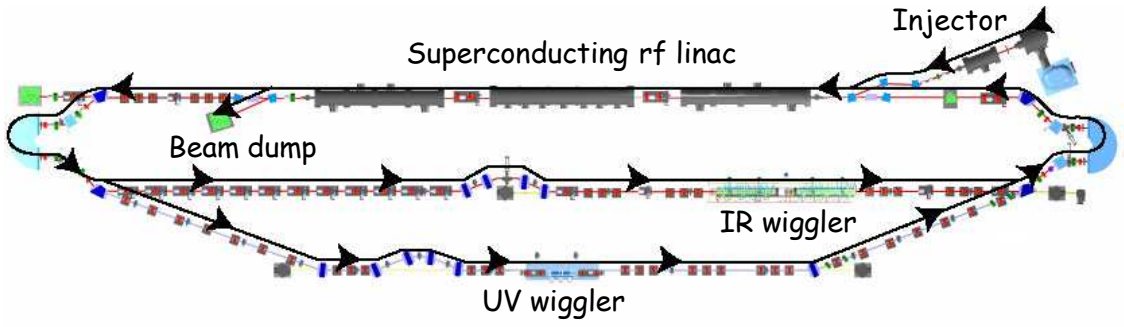


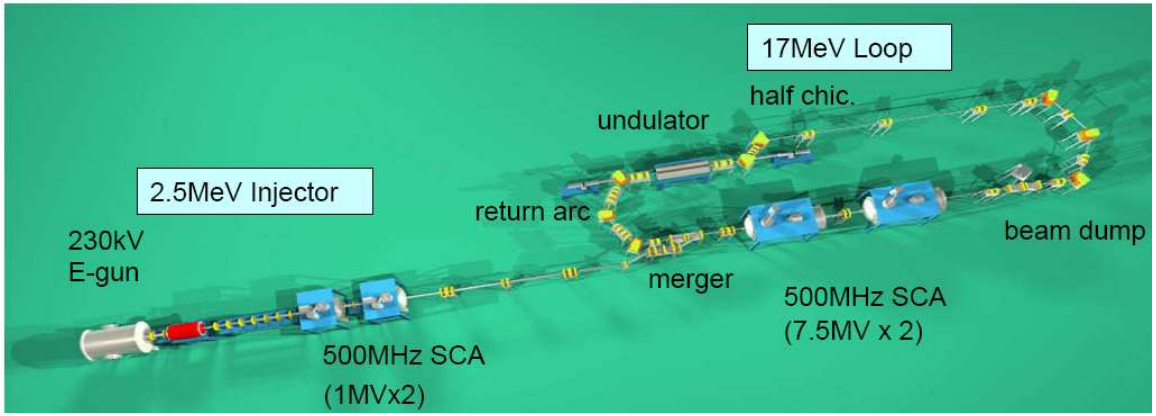


Optical Cavity FELs

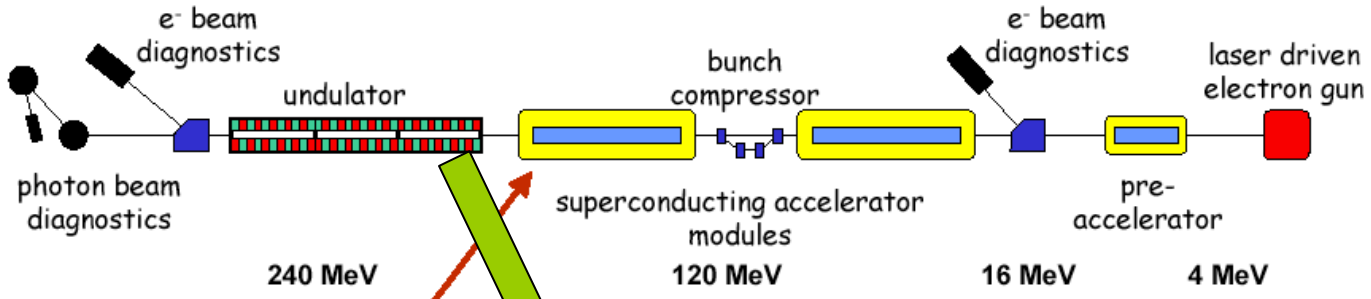
- Jlab FEL/ERL
  - IR, UV upgrade
  - 14kW beam power
- JAERI FEL
  - IR

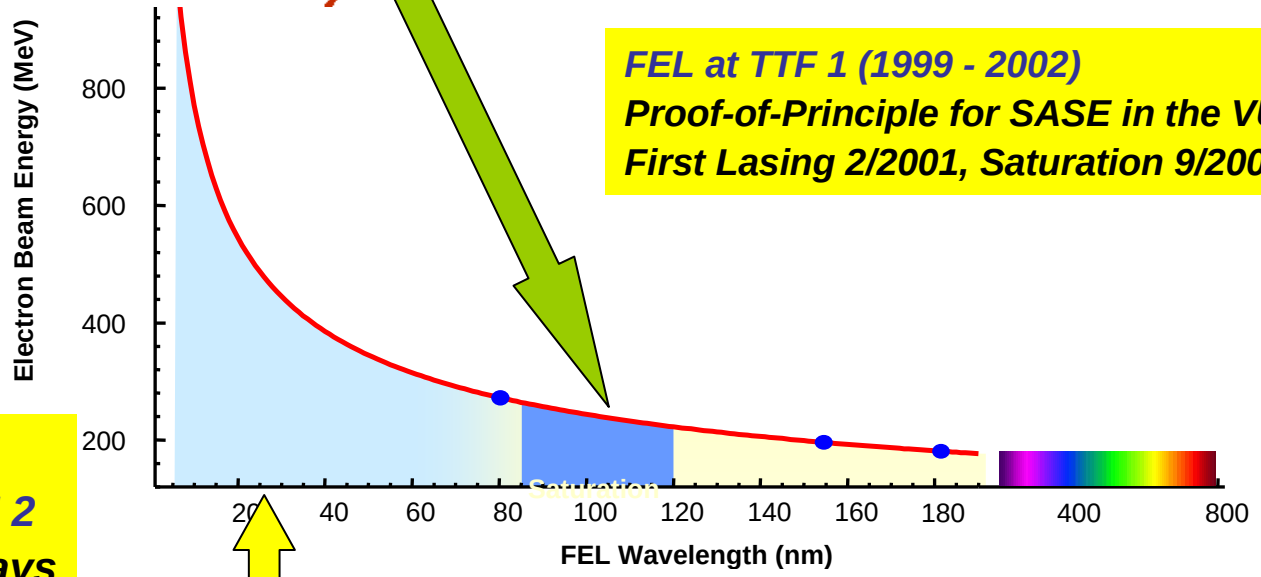






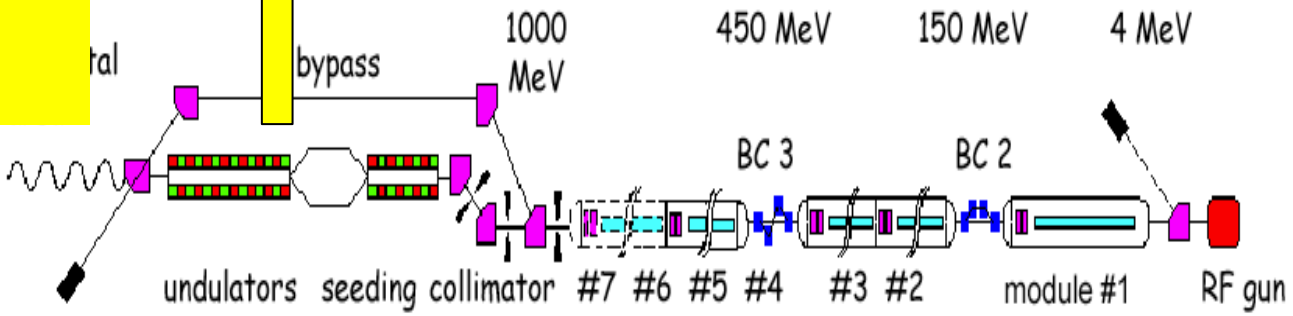
SASE-FELs VUV => X-Rays





FEL at TTF 1 (1999 - 2002)
Proof-of-Principle for SASE in the VUV
First Lasing 2/2001, Saturation 9/2002

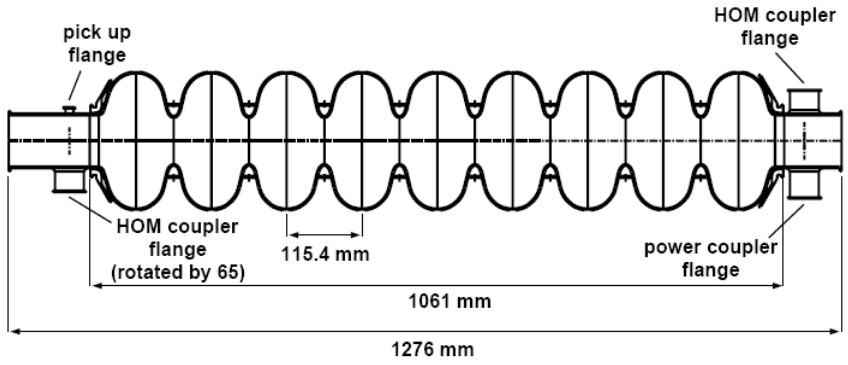
2004:
VUV FEL at TTF 2
VUV to Soft X-rays
: 100 - 6 nm
User facility



TTF-II

Based on TESLA Technology Developed by TESLA Collaboration

- 9-cell Nb, 1.3 GHz cavities

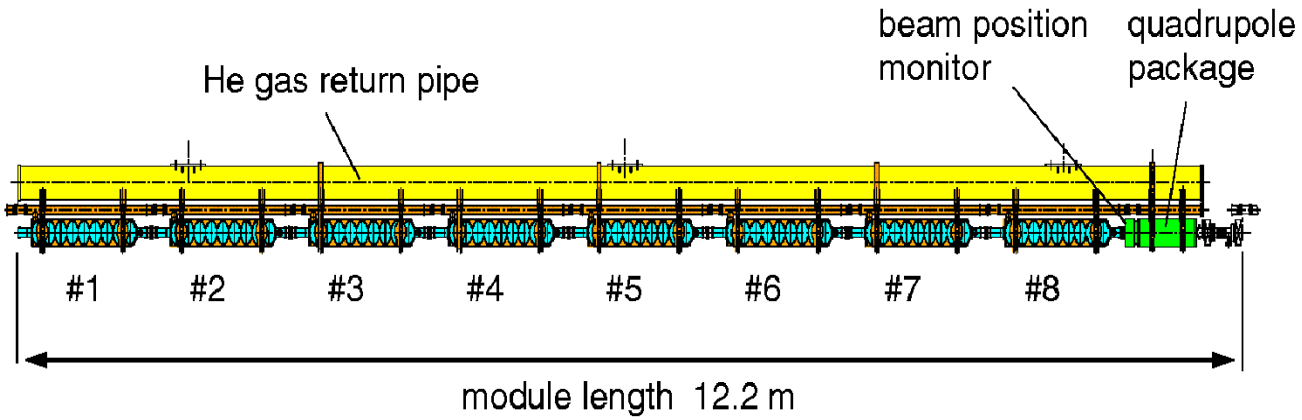


TTF- TESLA Test Facility Collaboration

Preparation of TESLA Cavities

Large experience base, > 12 cryomodules assembled (100 meters active)……..Integrated cold time: 10 module-years

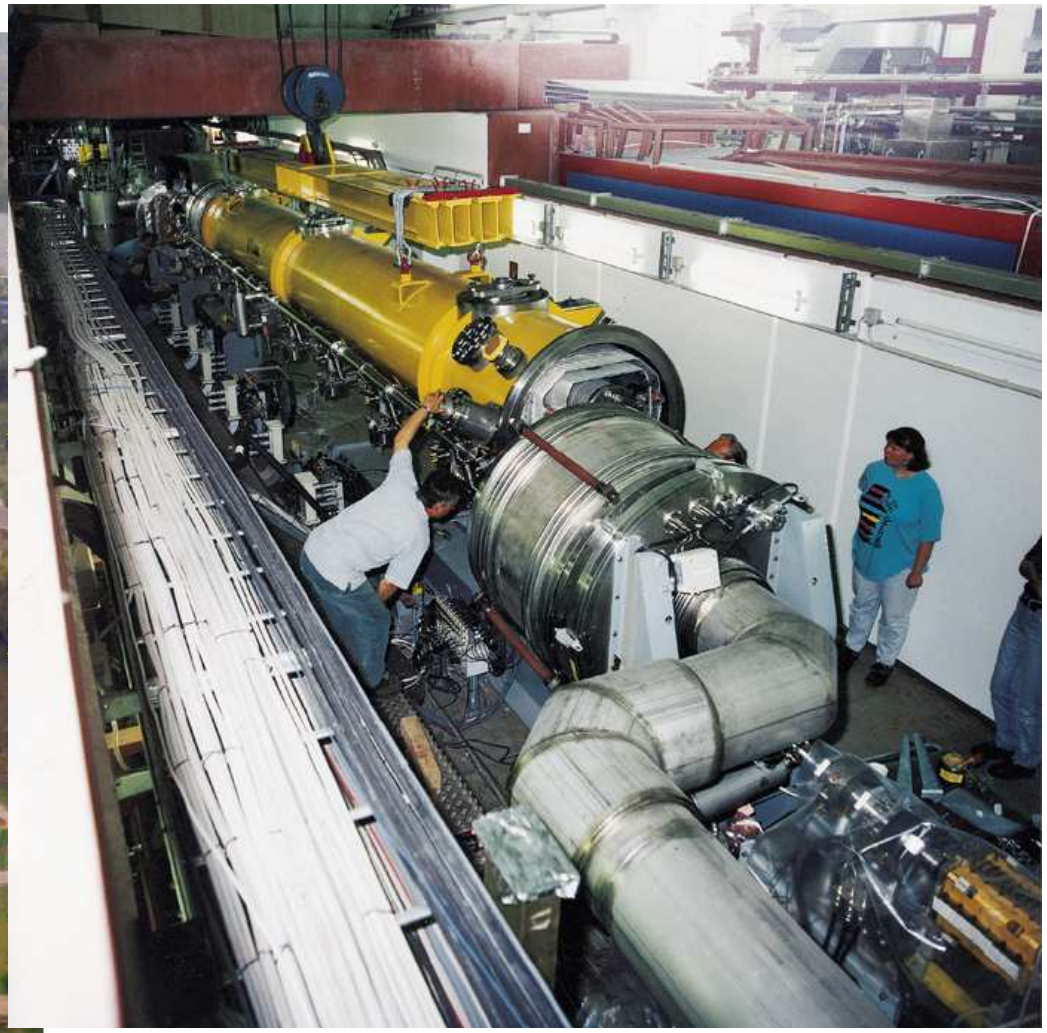
8-Cavity Module



TTF-I

&

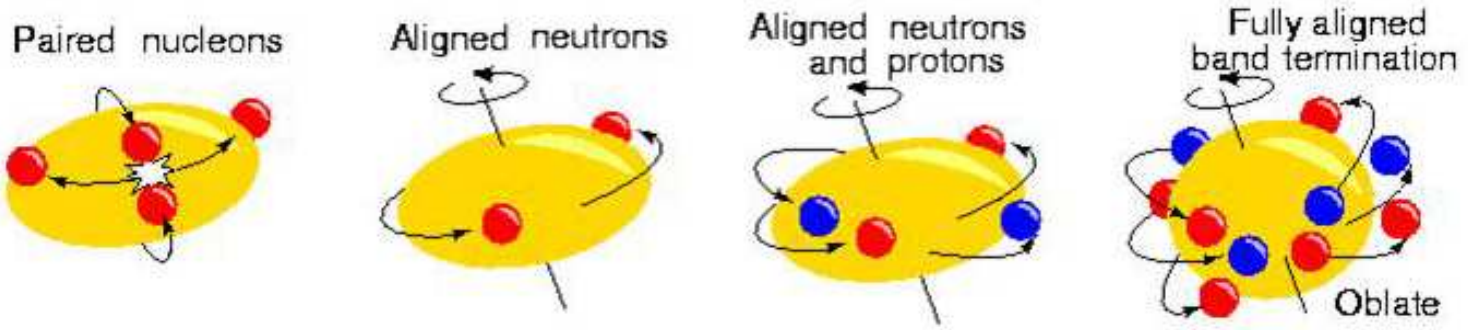
TTF-II

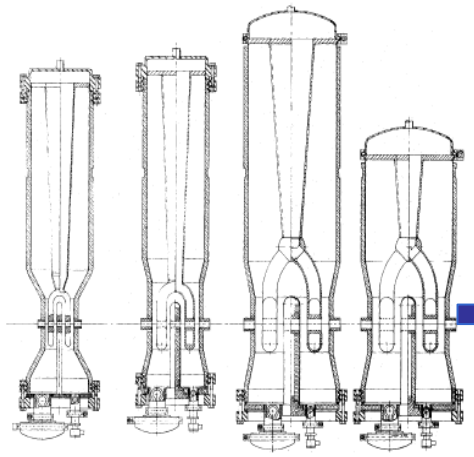


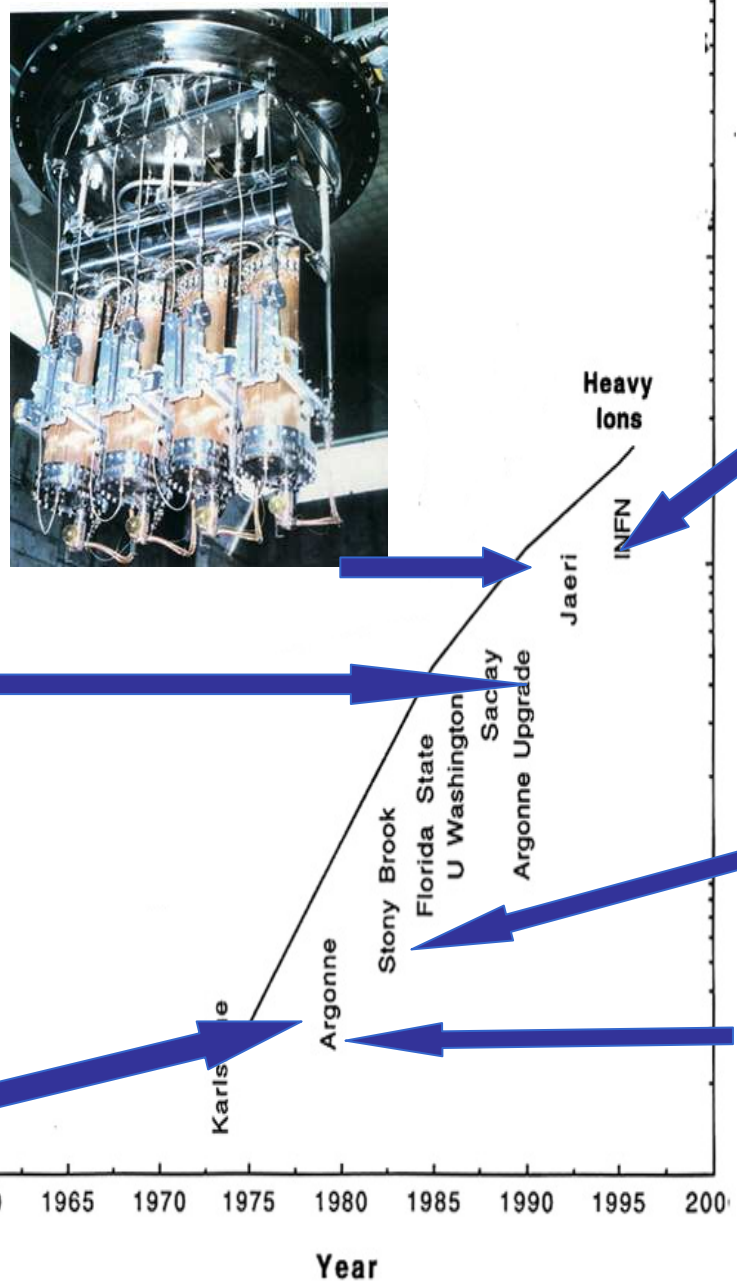
Low Energy Nuclear Physics,

What's it good for?

Understanding nuclear structure, nuclear shape, spin, vibration, rotation



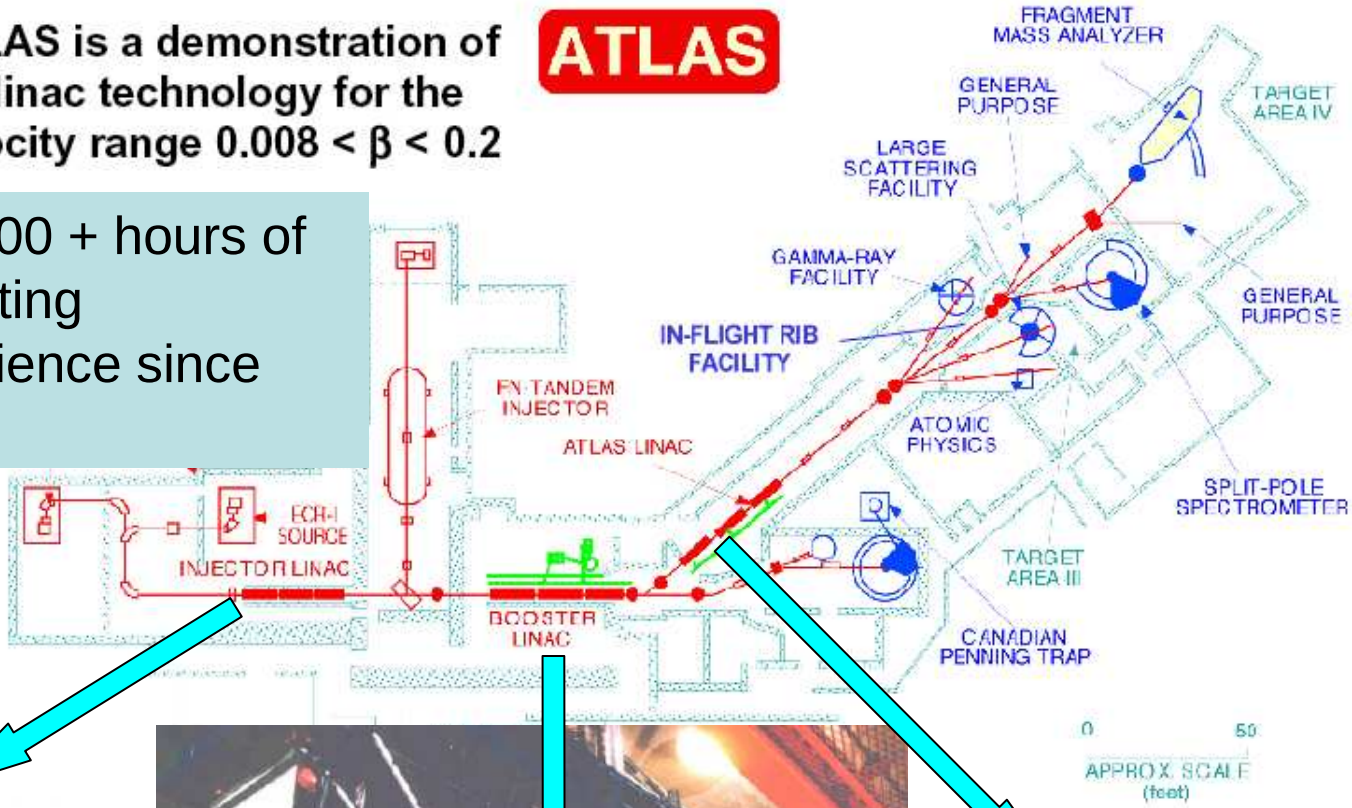


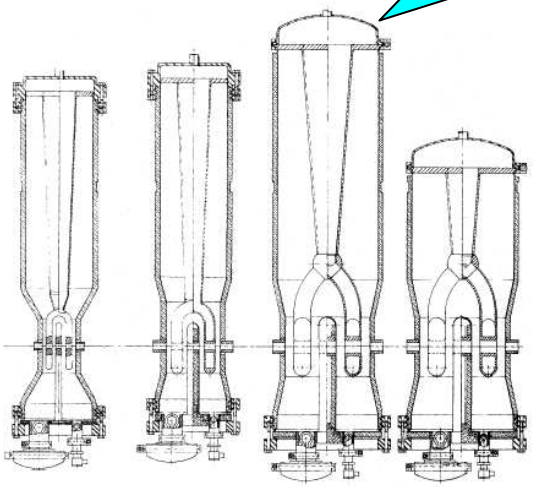

10000
1000
100
10
1
Total Voltage (MV)
1960
1965
1970
1975
1980
1985
1990
1995
200
Year
Heavy Ions
INFN
Jaeri
Argonne Upgrade
Sac ay
U Washington
Florida State
Stony Brook
Argonne
Karls e

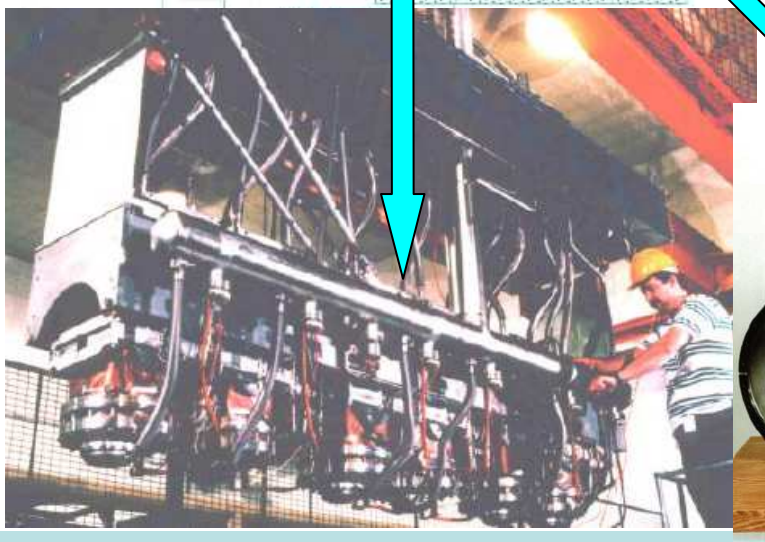
ATLAS is a demonstration of SC linac technology for the velocity range $0.008 < \beta < 0.2$

ATLAS

100,000 + hours of operating experience since 1978







Superconducting Accelerating Structures

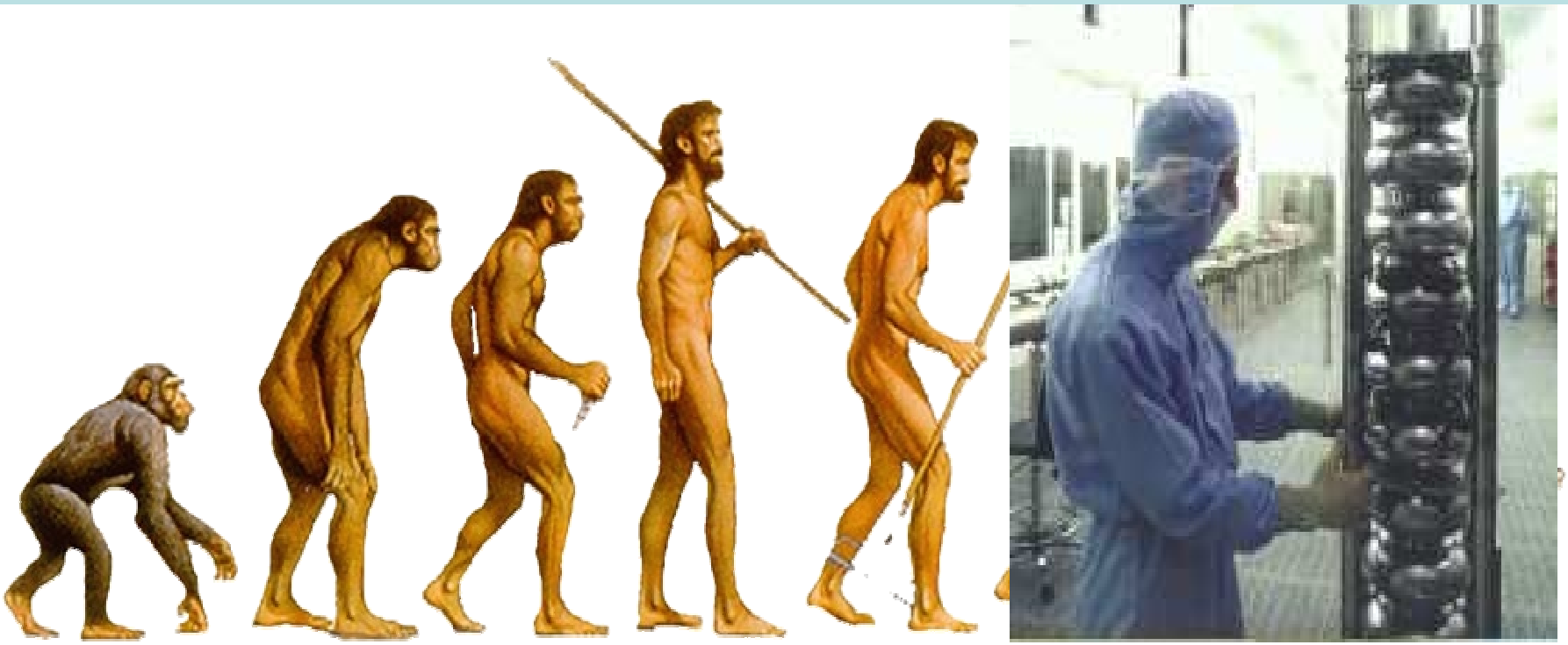
10 Heavy Ion Linacs Completed

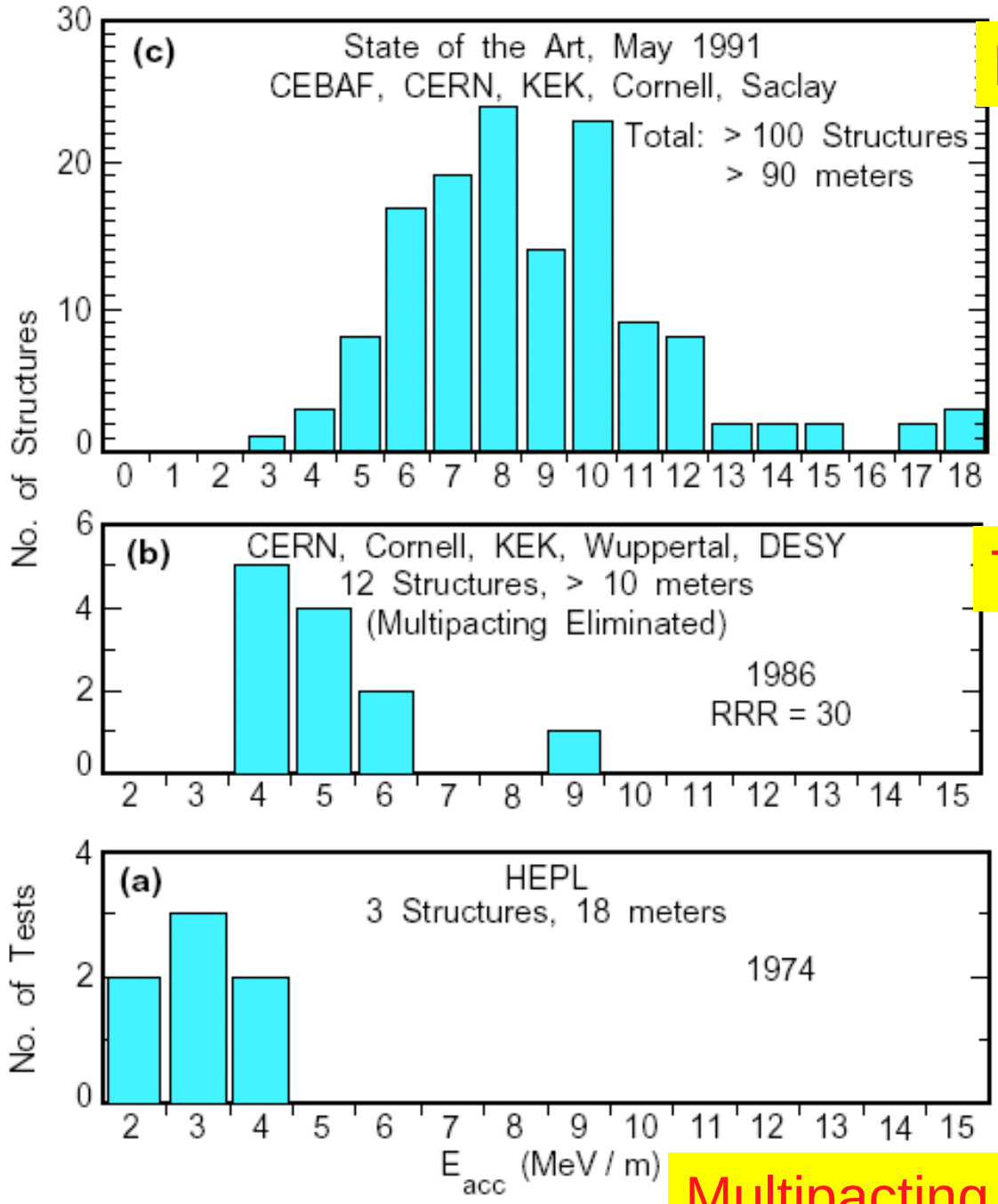
- **ATLAS (Argonne) US**
- **Stony Brook**
- **U. of Washington**
- **Florida State U**
- **Kansas State U**
- **Delhi U**
- **JAERI (Japan)**
- **ALPI (Italy)**
- **ANU (Australia)**
- **ISAC-II (TRIUMF-Canada)**

- > 270 SC structures
- 3-5 MV/m

Success Story #2
(short version)

How SRF Technology Evolved Over Last Few Years





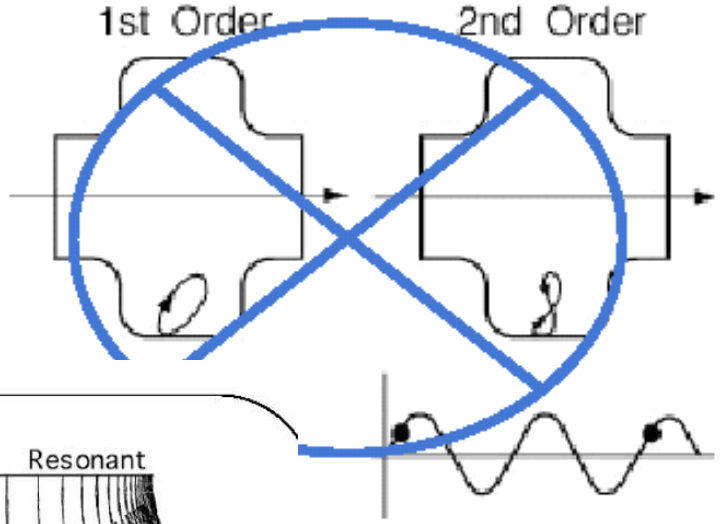
Field Emission

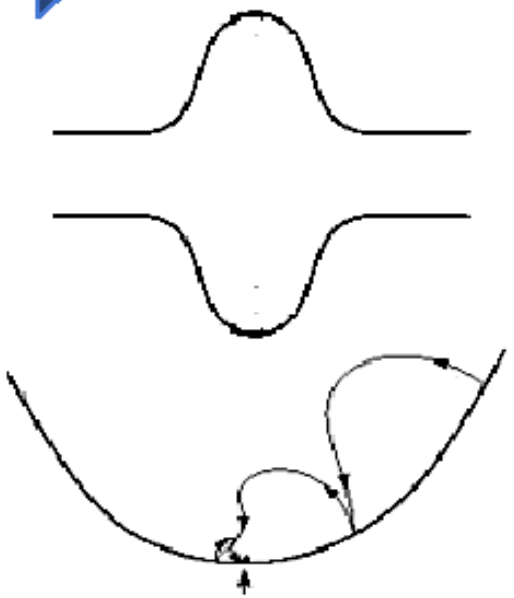
Thermal breakdown

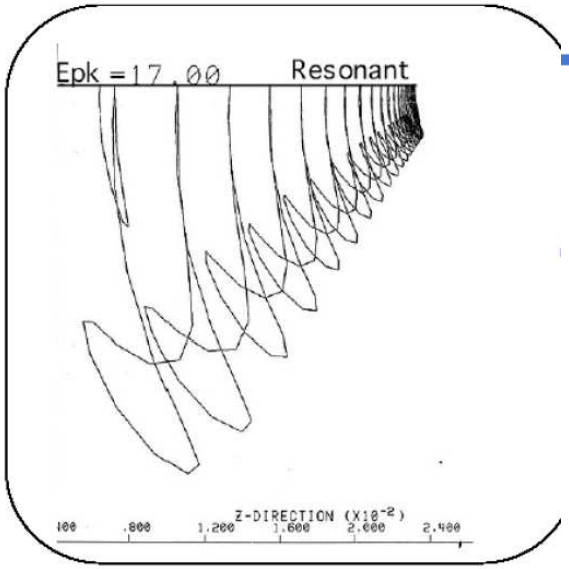
Multipacting

Gradients have been improving steadily due to understanding of limiting phenomena and invention of effective cures

Solution to Multipacting

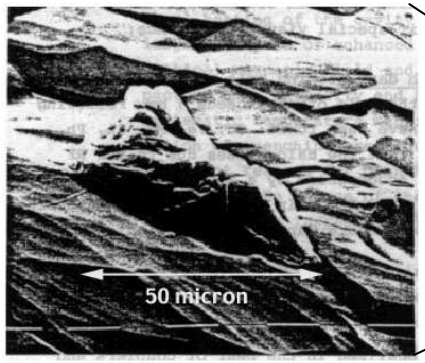


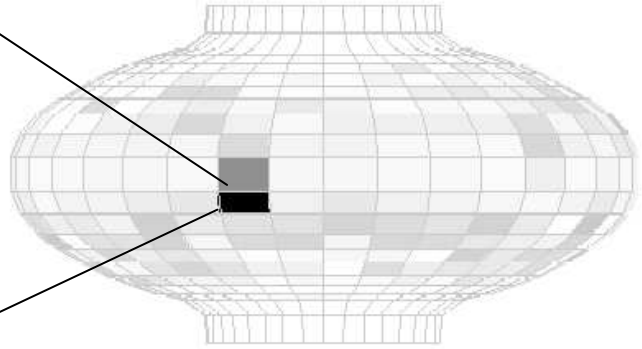


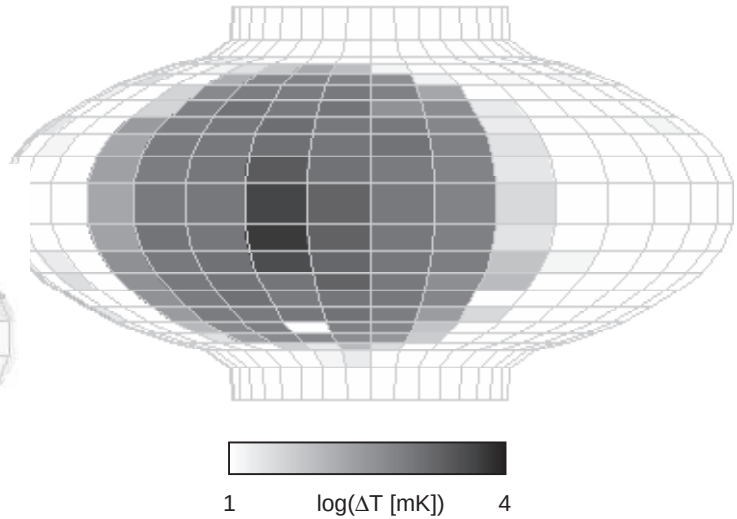


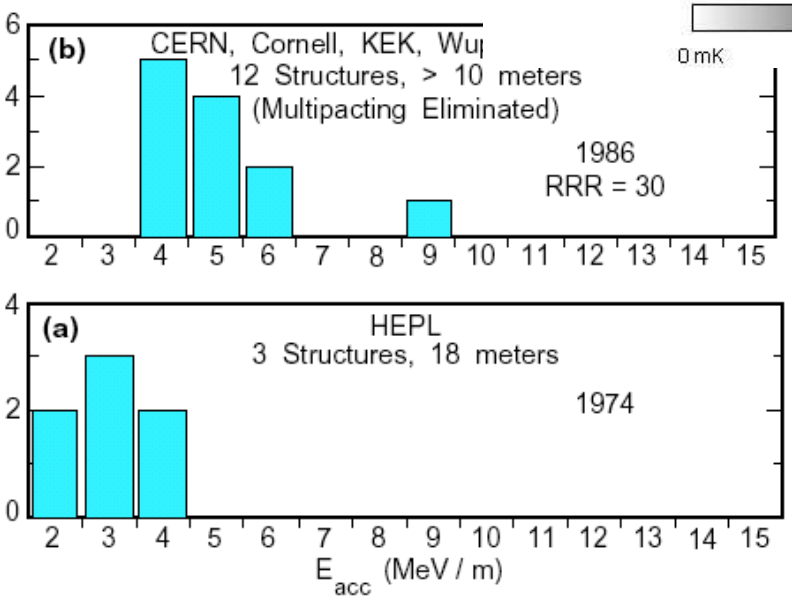
Electrons drift to equator
Electric field at equator is ≈ 0
→MP electrons don't gain energy
→MP stops

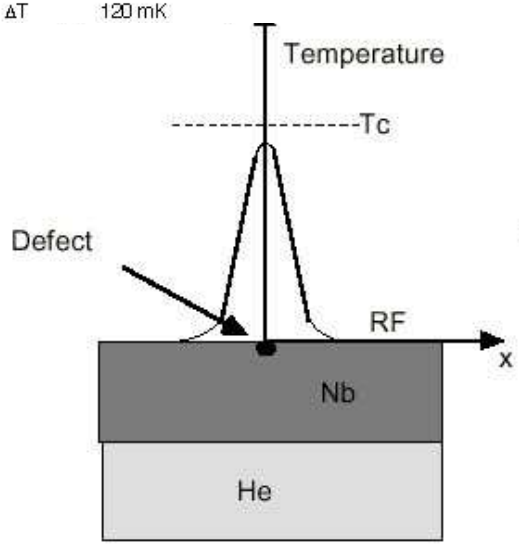
Sub-mm Size Defects Lead to Quench of Superconductivity

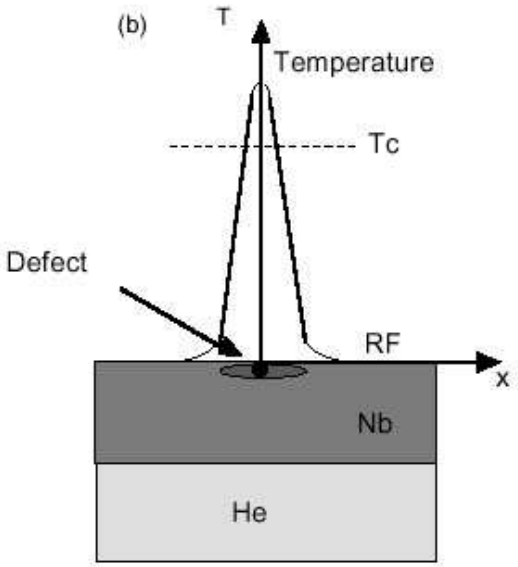




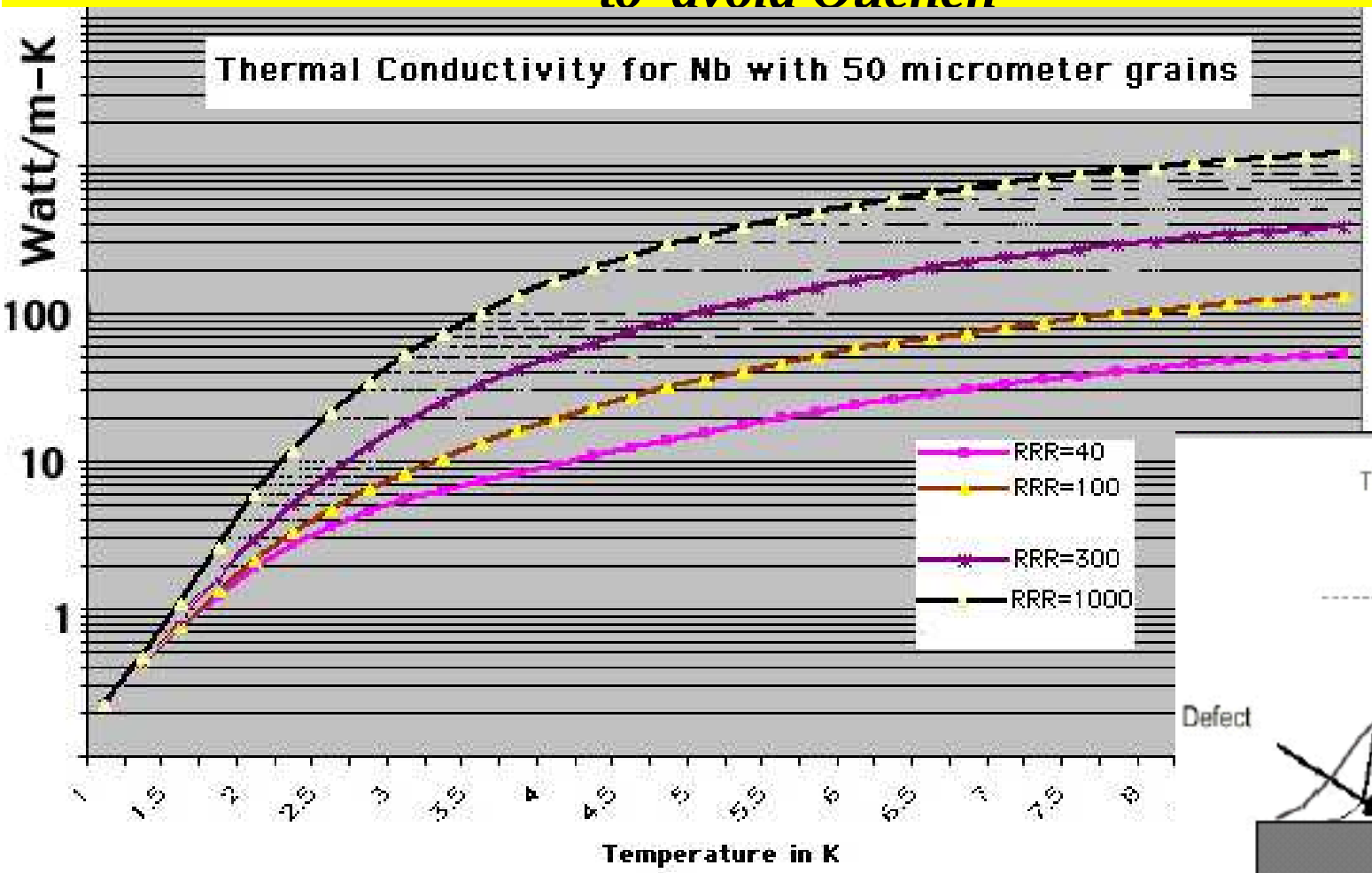


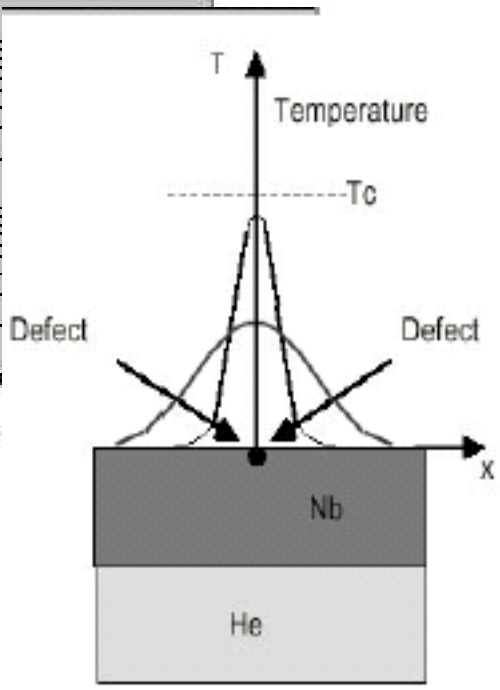




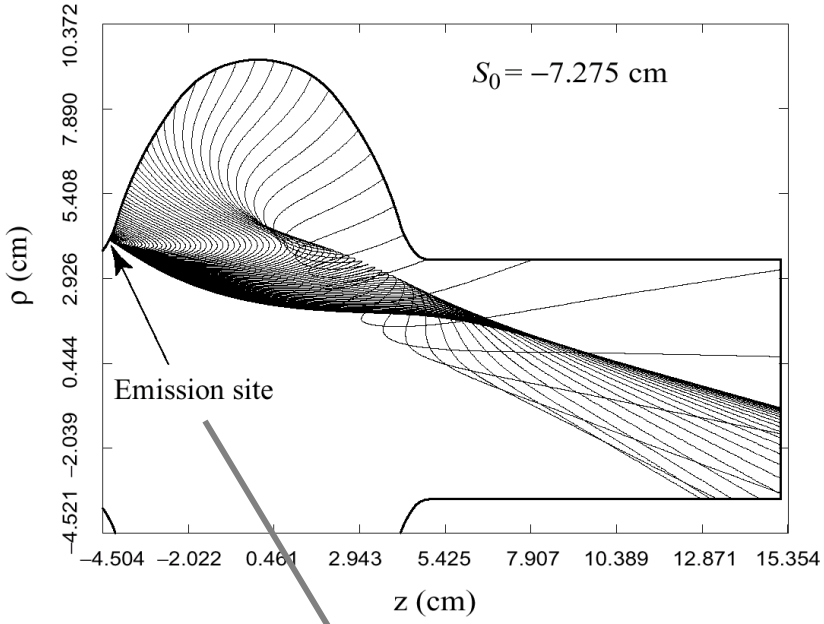


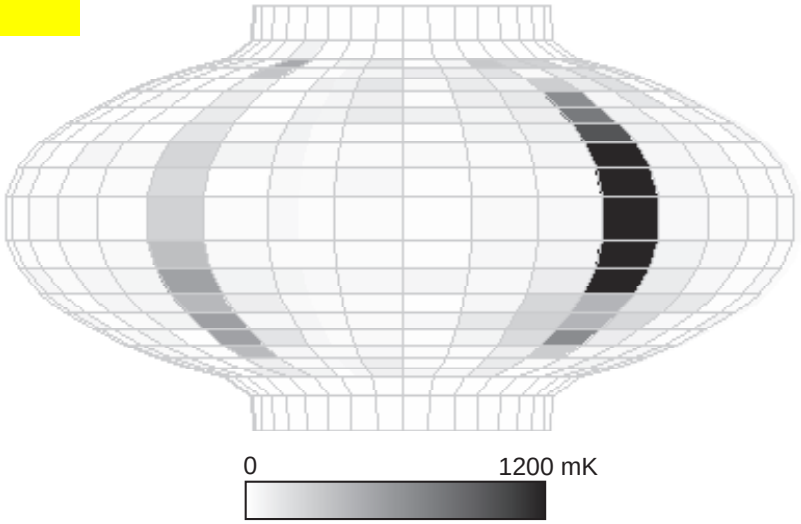
Improve Bulk Thermal Conductivity (and RRR) by raising purity to avoid Quench





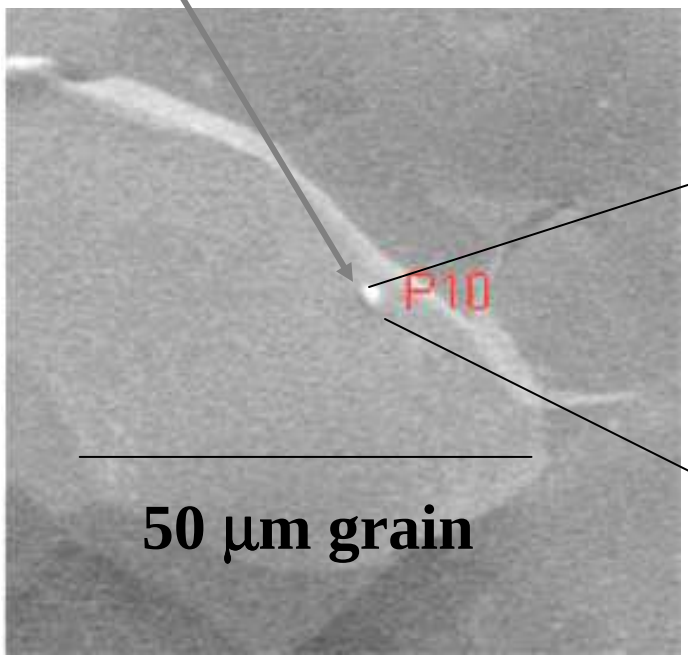
Electron field emission

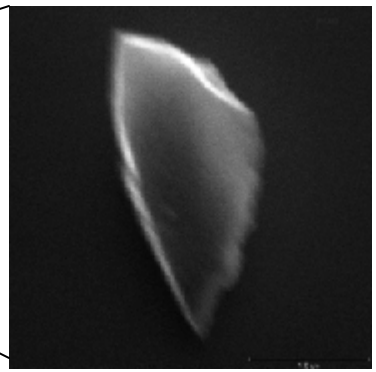




Increased Losses

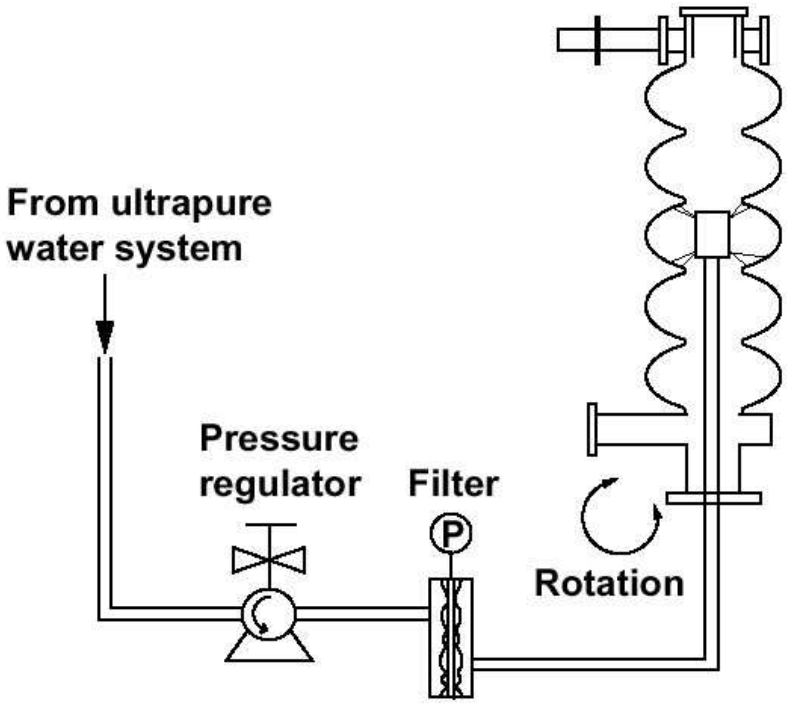
Lower Q

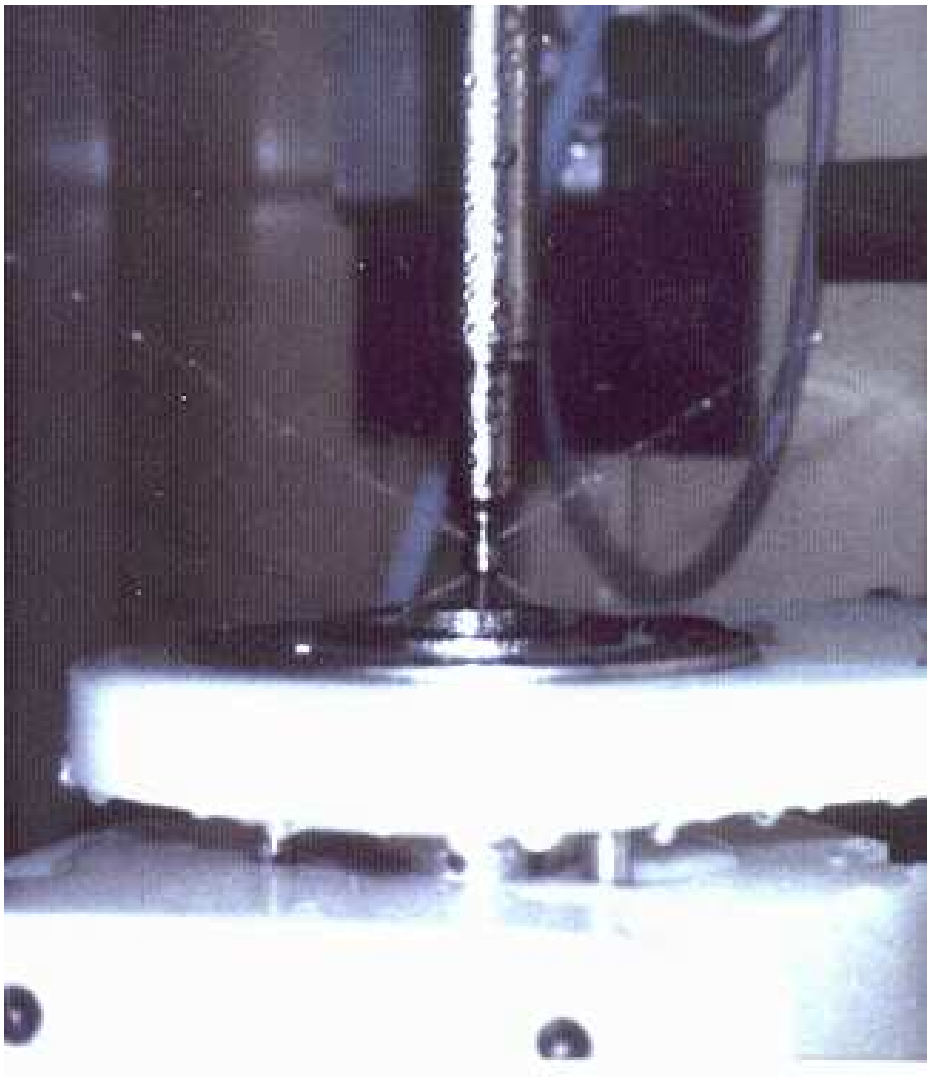




1 - 2 μm, C

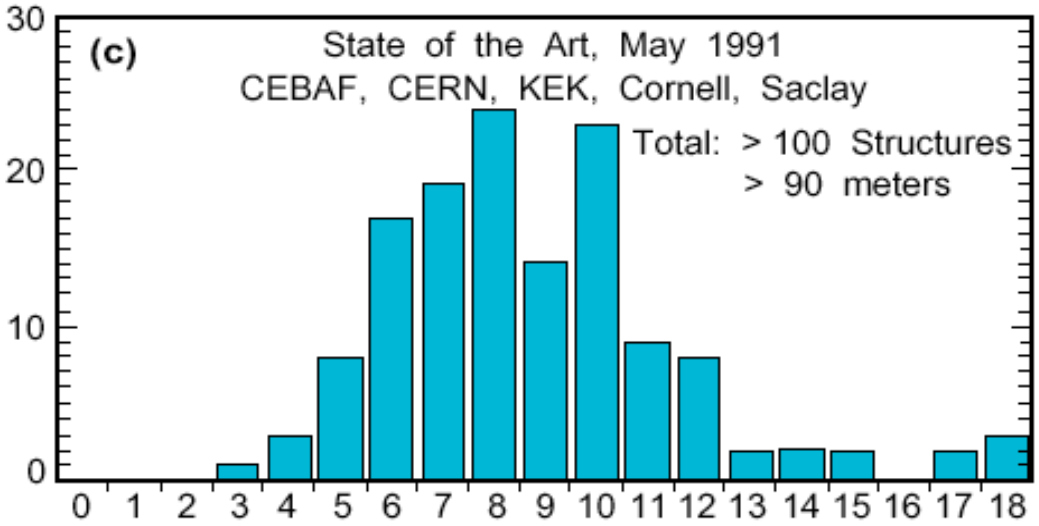
100 Bar High Pressure Rinsing





100 atm jet water rinsing

Class 10 – 100, Clean Room



1991≈ 10 MV/m

Limited by Field Emission

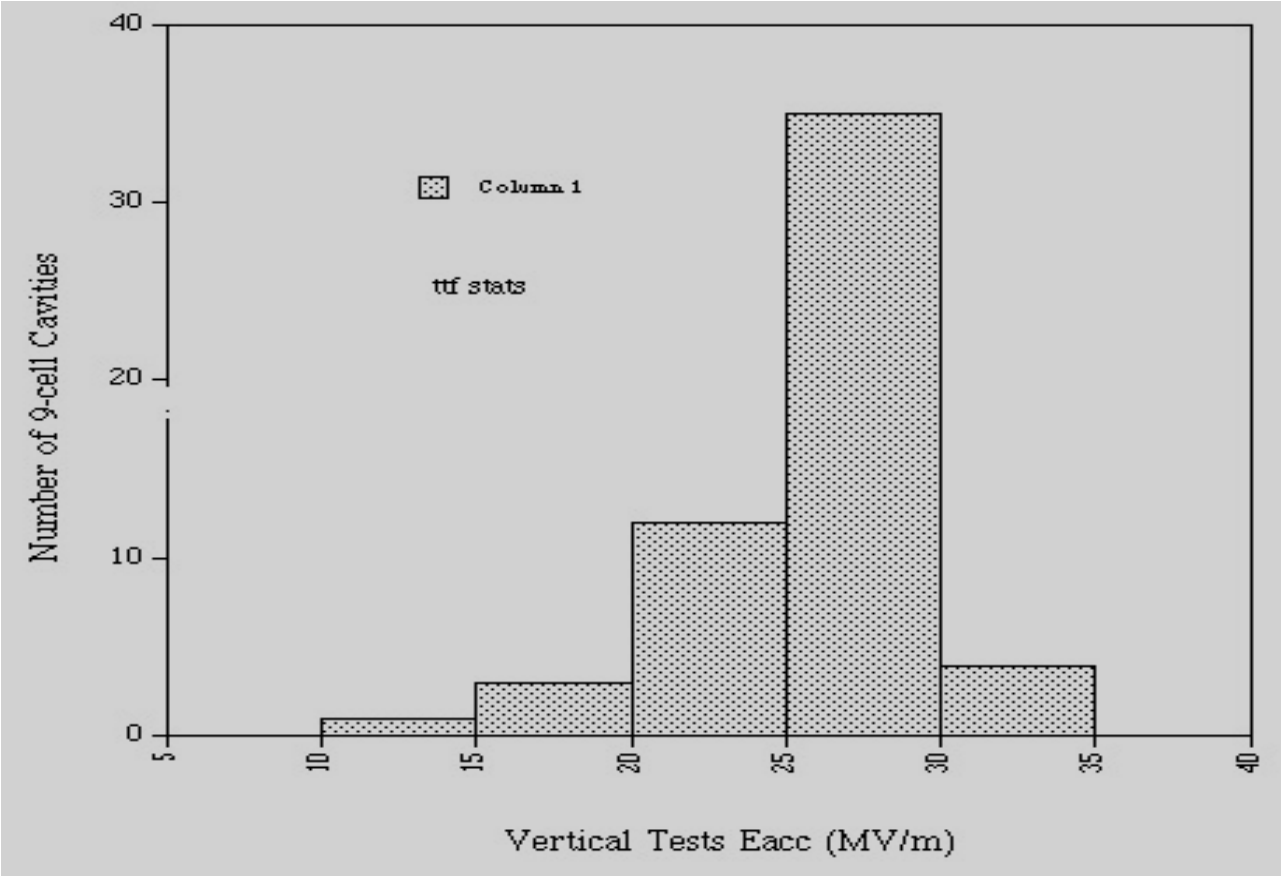
X 3 !

2000 -

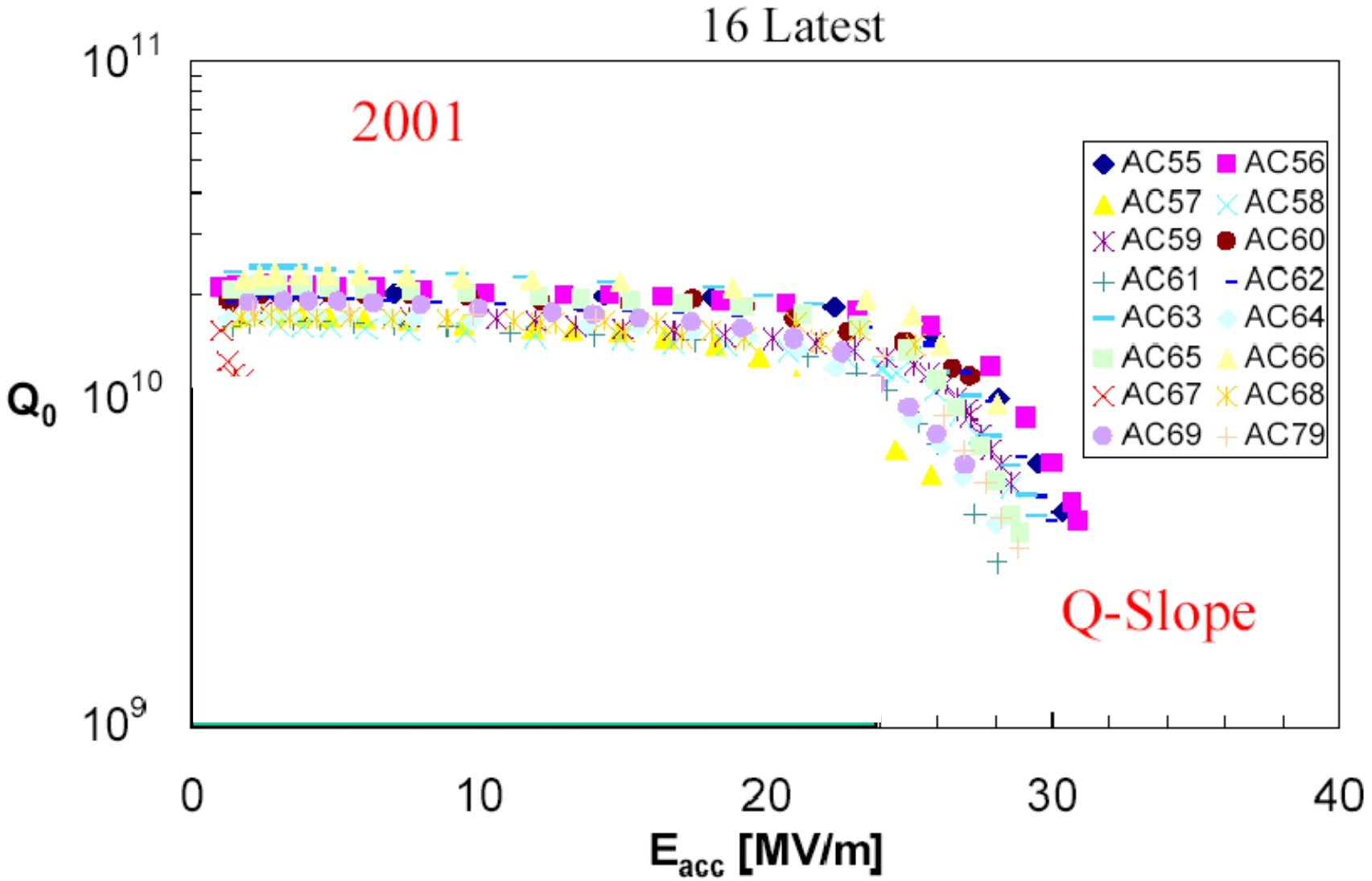
25 MV/m

9-cell Cavities

DESY



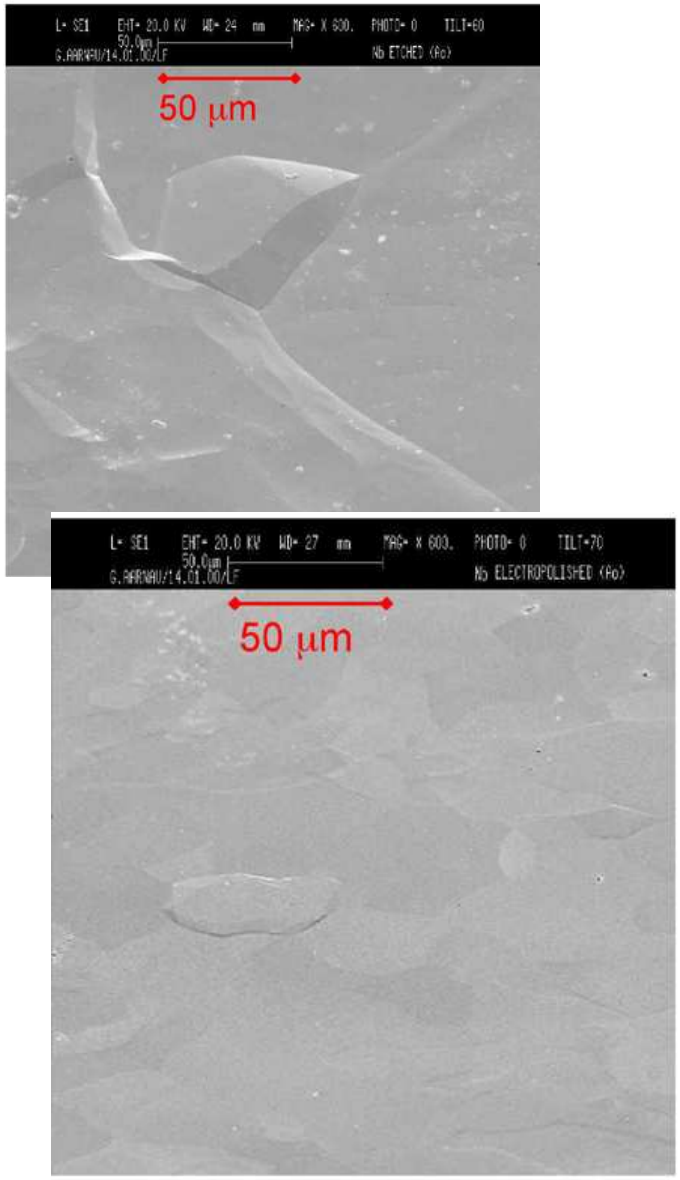
3rd Cavity Production - BCP



There is more good news !

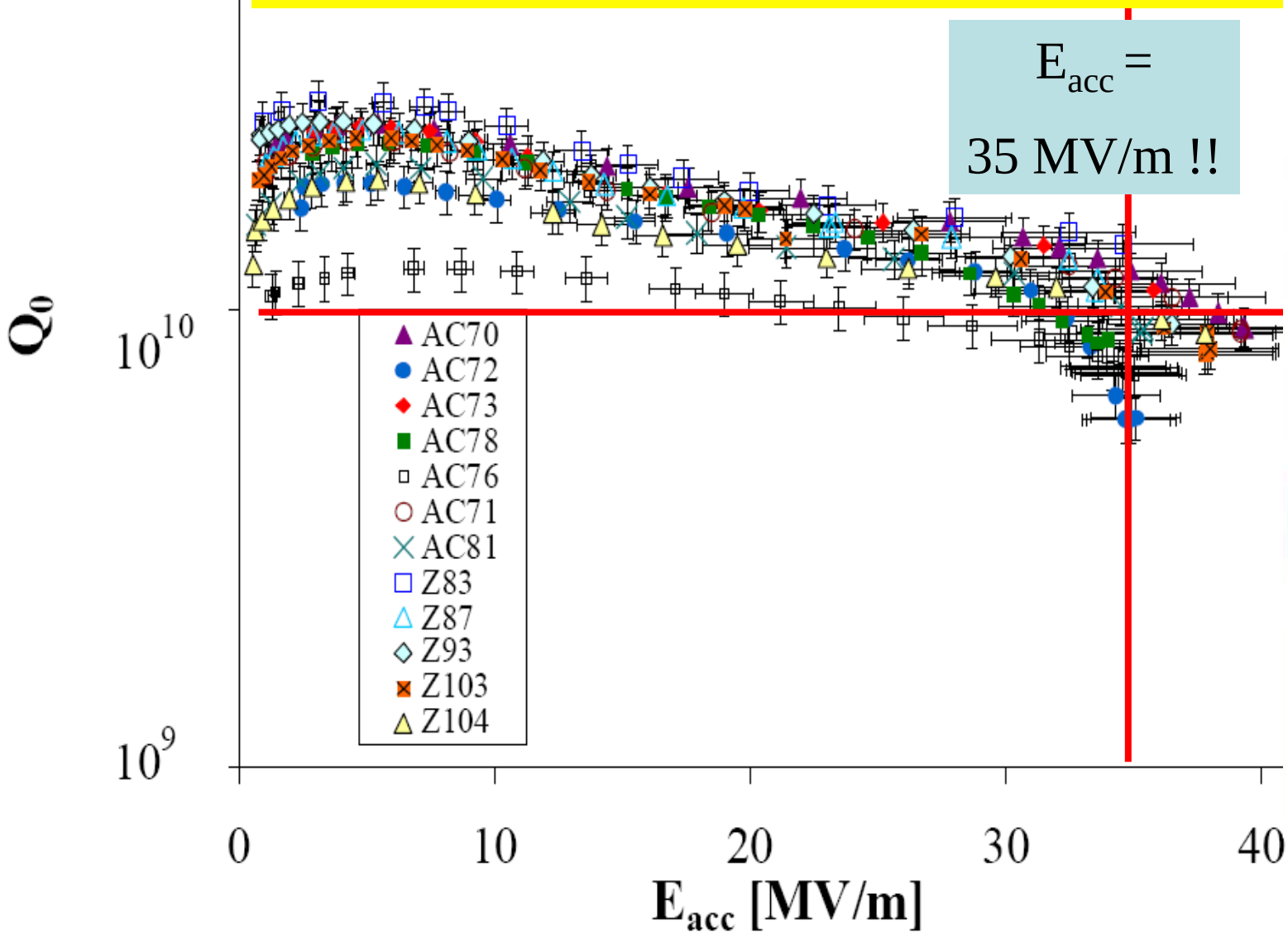
There is more good news !

- Electropolishing and Baking 120 C
  - Smooth Surfaces
- Baking
  - Heals the rf surface of ??
  - (Romanenko Talk)



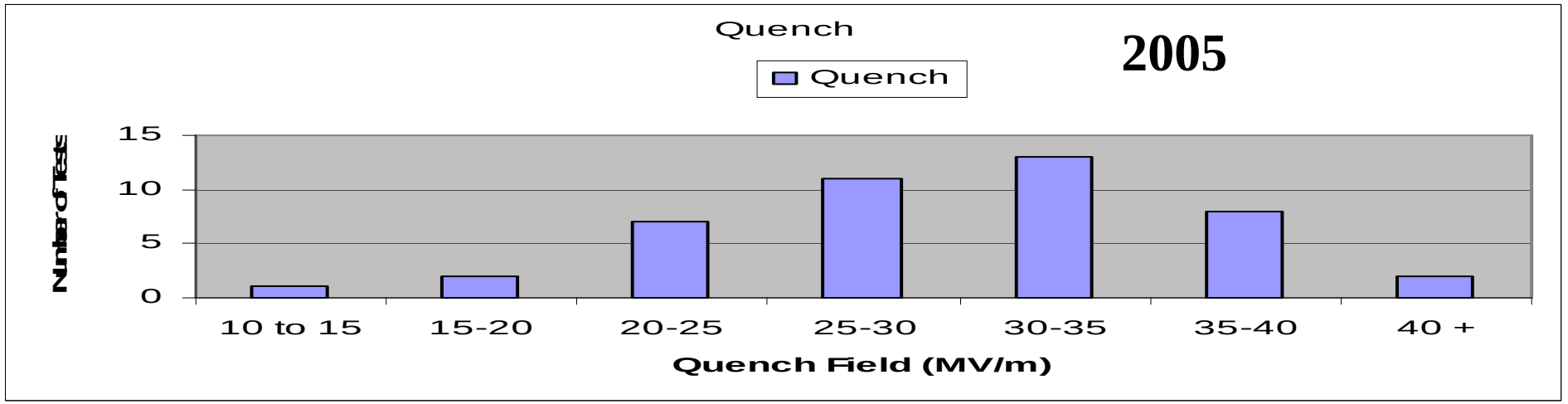
EP + Bake > 35 MV/m Proof-of-Principle

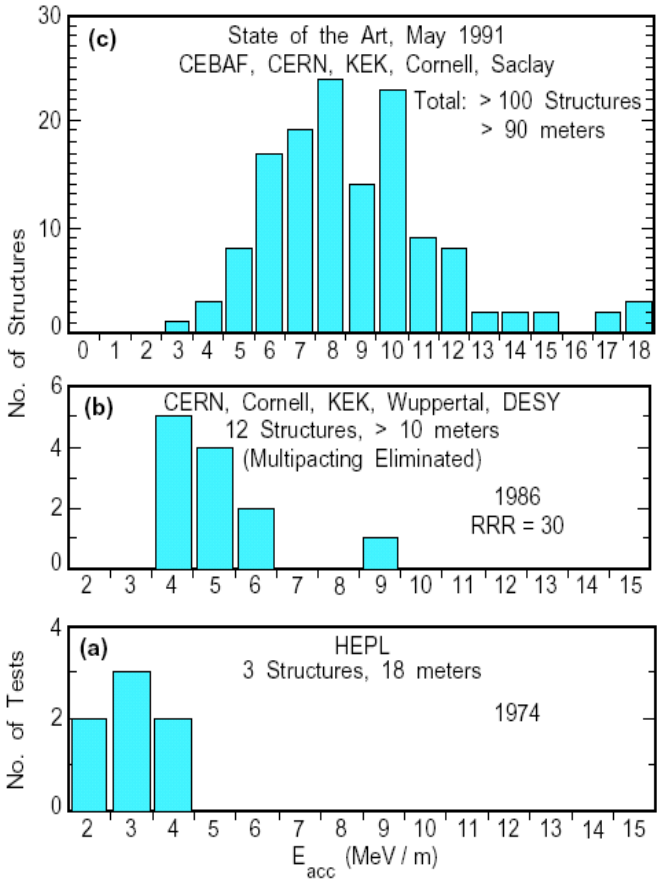
DESY-KEK 12 best cavities, 9-cell TTF cavities
Vertical Tests



But Low Yield of Cavities > 25 MV/m

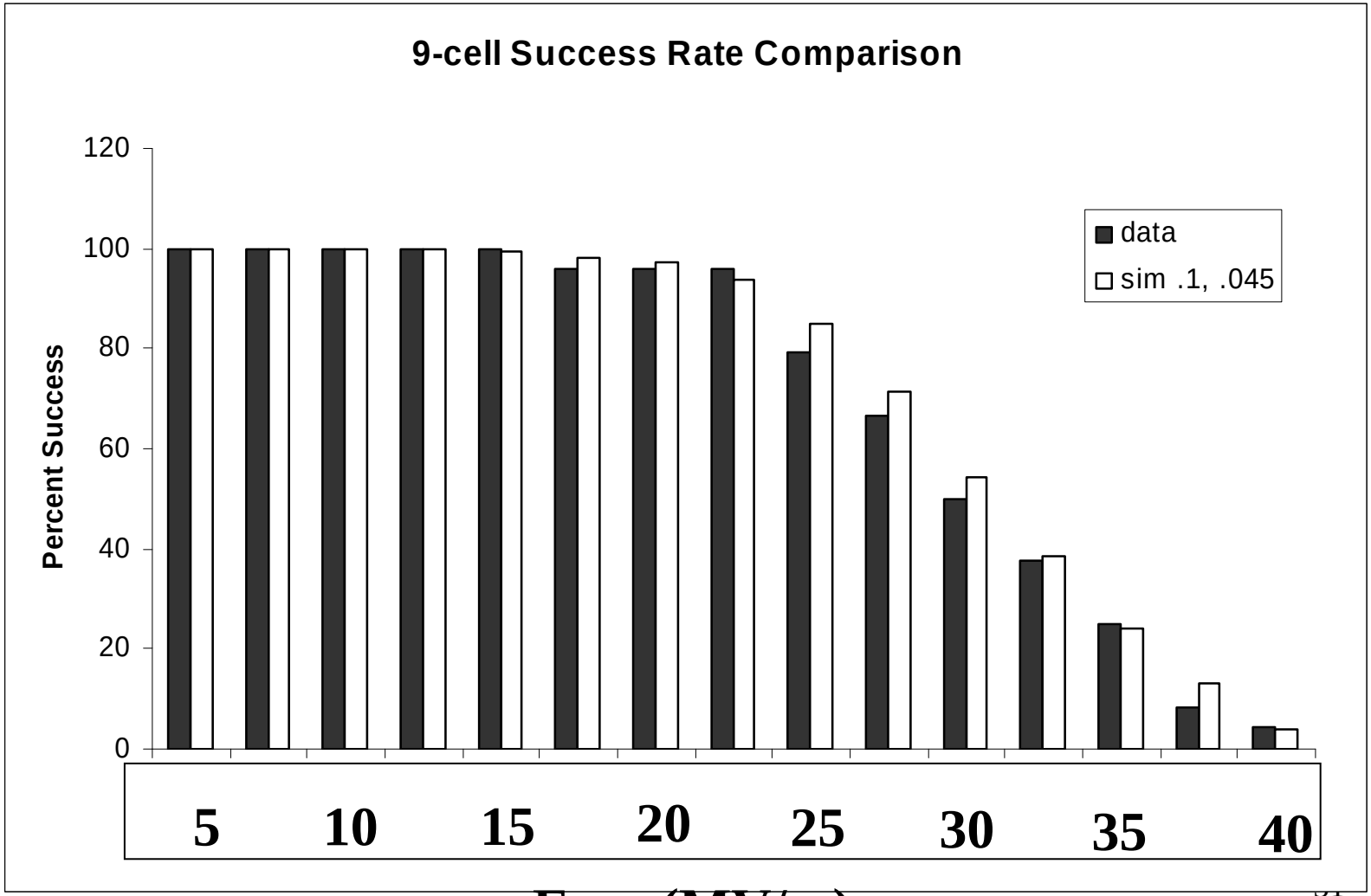
- Quench limitations
- Field emission limitations



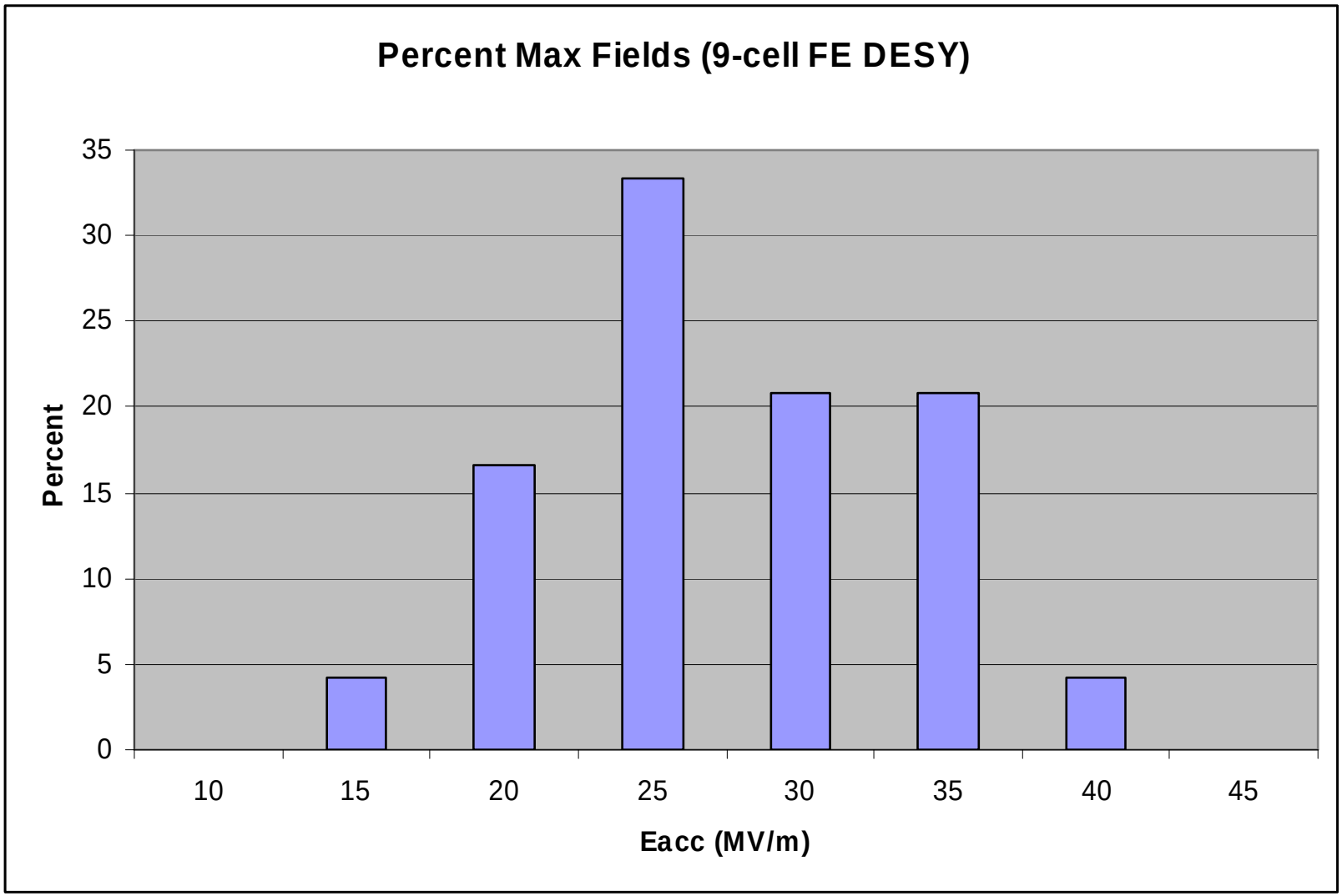


- **Improvements**
  - **Niobium Sheet Scanning**
  - **High Pressure Water Rinsing**
  - **Clean Room Assembly**
  - **Electropolishing**
  - **Mild Bake**

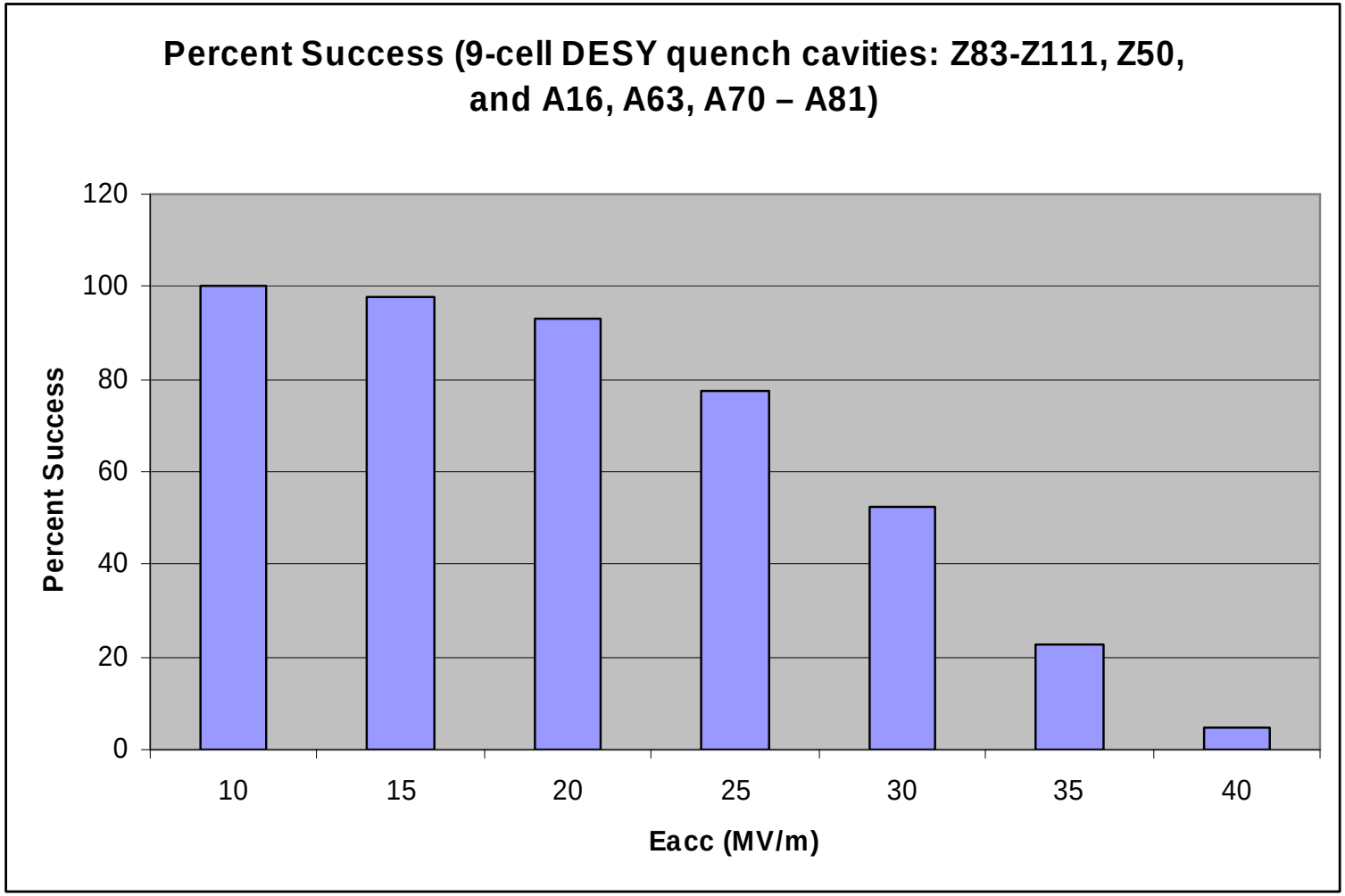
Yield Due to Field Emission Limitations



Gradient Distribution of Field Emission Limited Cavities



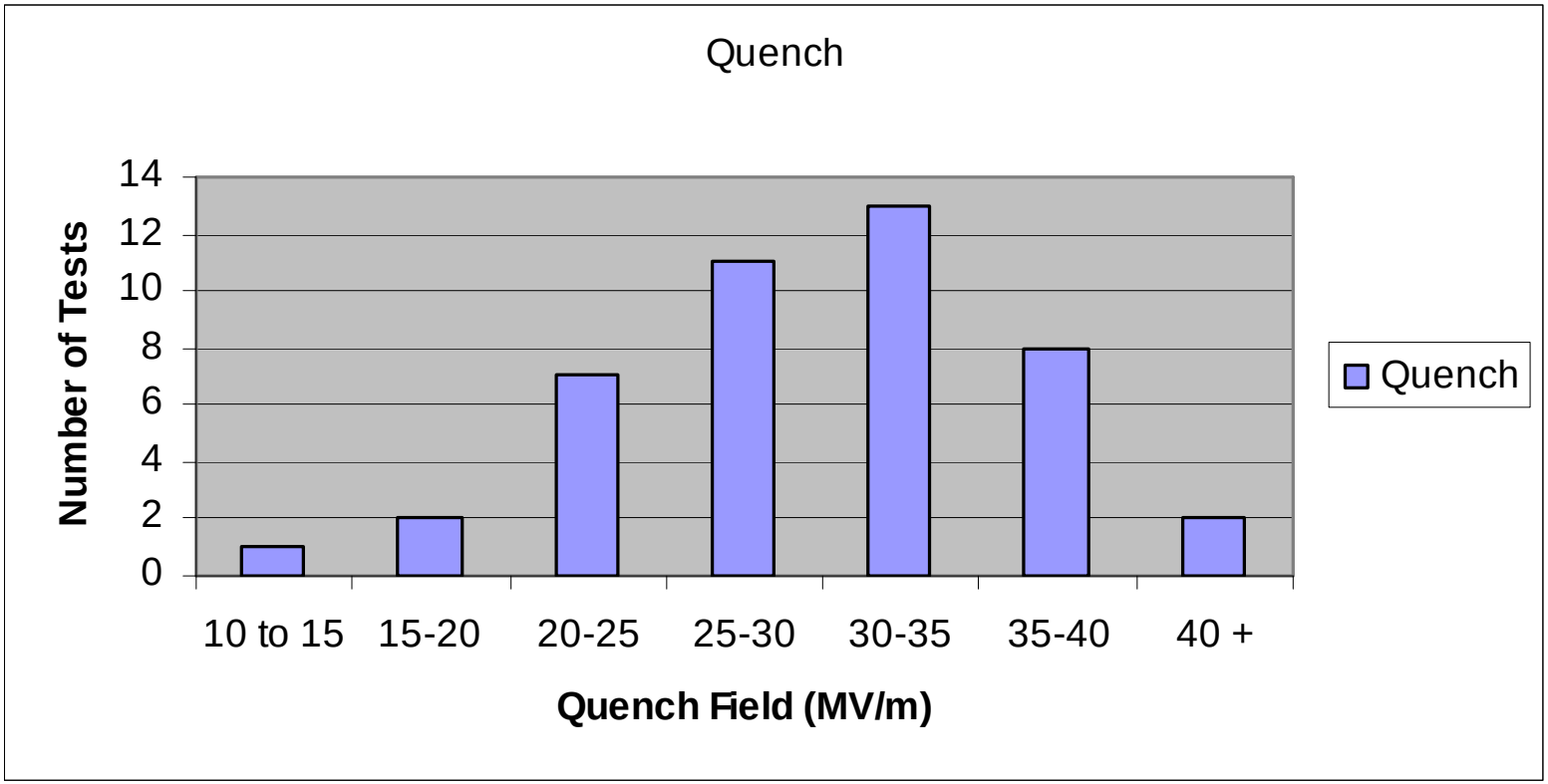
Yield Due to Quench



Distribution of “Quench Only”Gradients

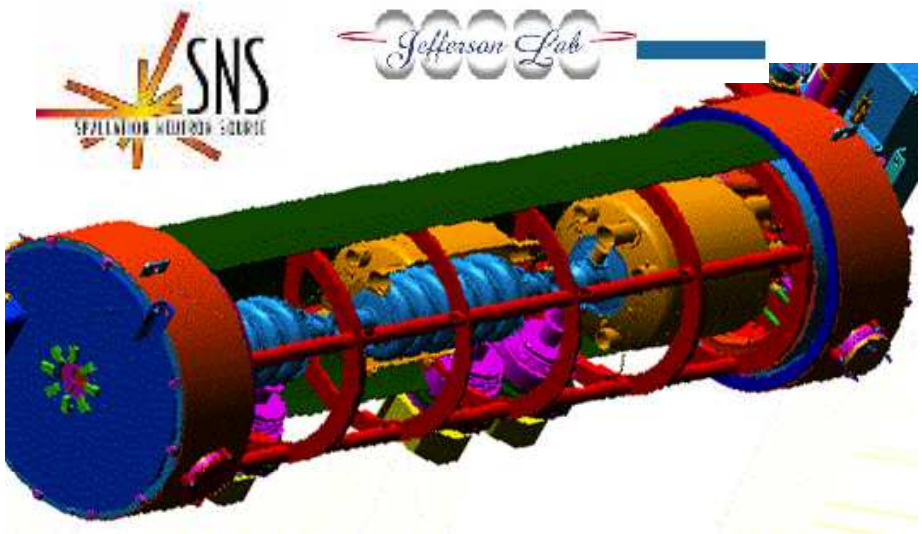
DESY 9-cell Cavities

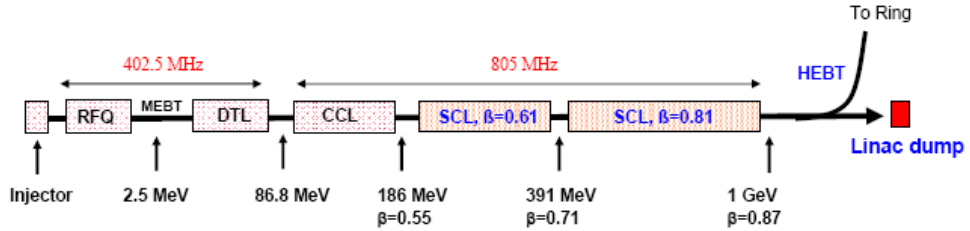
Z83-Z111, Z50, and A16, A63, A70 – A81



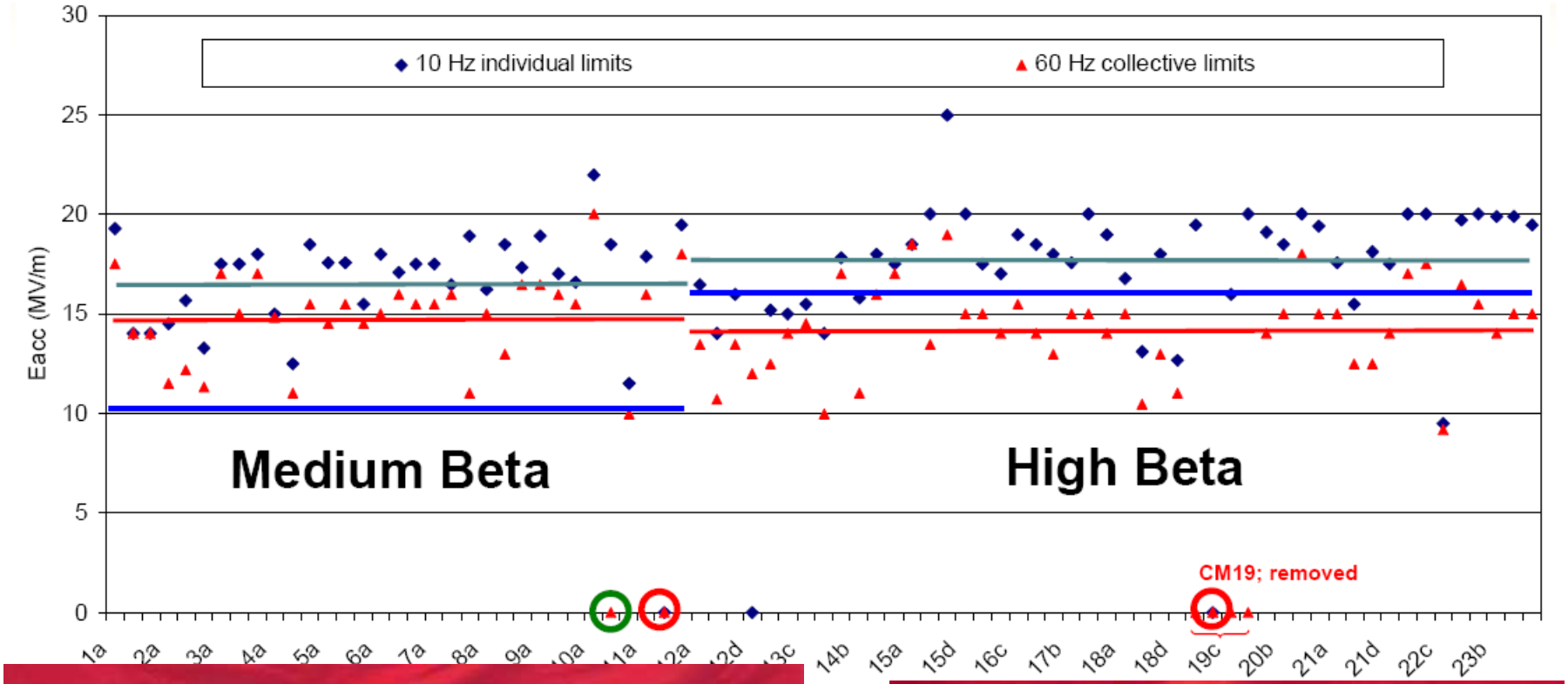

• Improved Performance of Cavities
• Explosion in Applications
Success Story #3

Spallation Neutron Source at Oak Ridge





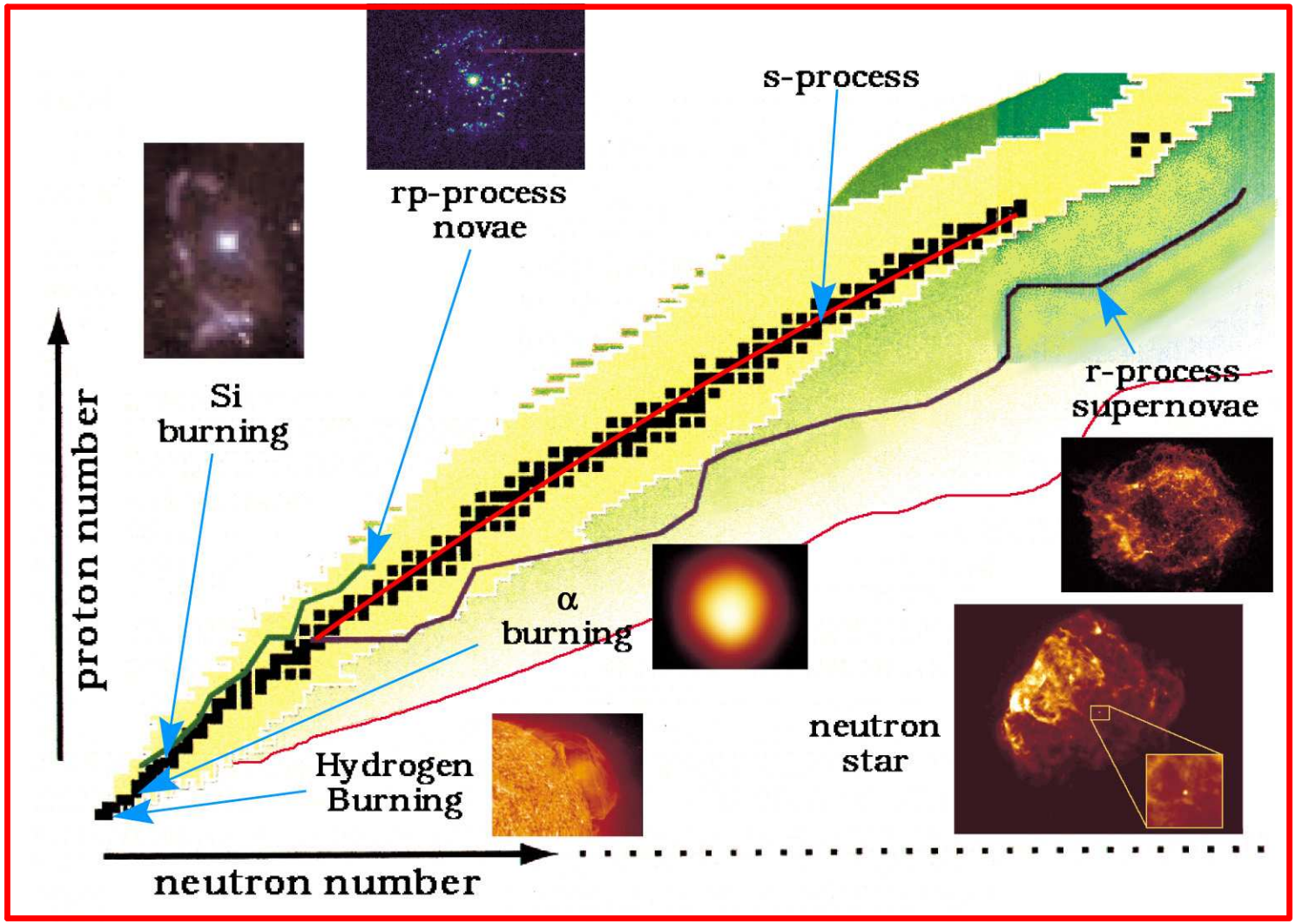
In-Line Performance - SNS



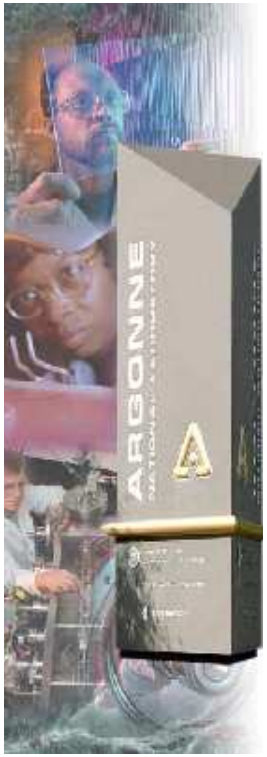
Nuclear Astrophysics - Rare Isotope Accelerator - RIA

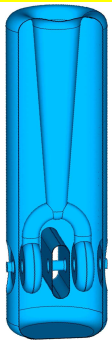
Exploration of structure and reactions involving radioactive nuclei far from the valley of stability.

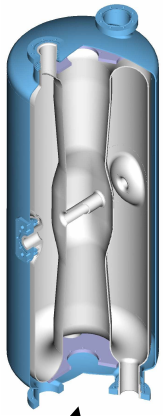
These nuclei participate in explosive nucleo-synthesis in novae, x-ray bursts, and supernovae via rapid proton and neutron capture



Superconducting Structures for RIB







Rare Isotope Beams

ECR

RFQ Low β SRF St. 1

q=28,29

12 keV/u 160 keV/u

9.3 MeV/u

Medium β SRF St. 2

q=69,70,71,72,73

80.3 MeV/u

400 MeV/u Beam

q=87,88,89,90

High β SRF

NSCL

TRIUMF

ISAC-II

MSU

Prototype

Re-Accelerator

Argonne

Prototype:
Advanced Exotic Beam Laboratory

EURISOL

beta = 0.81 beta = 0.61 beta = 0.5

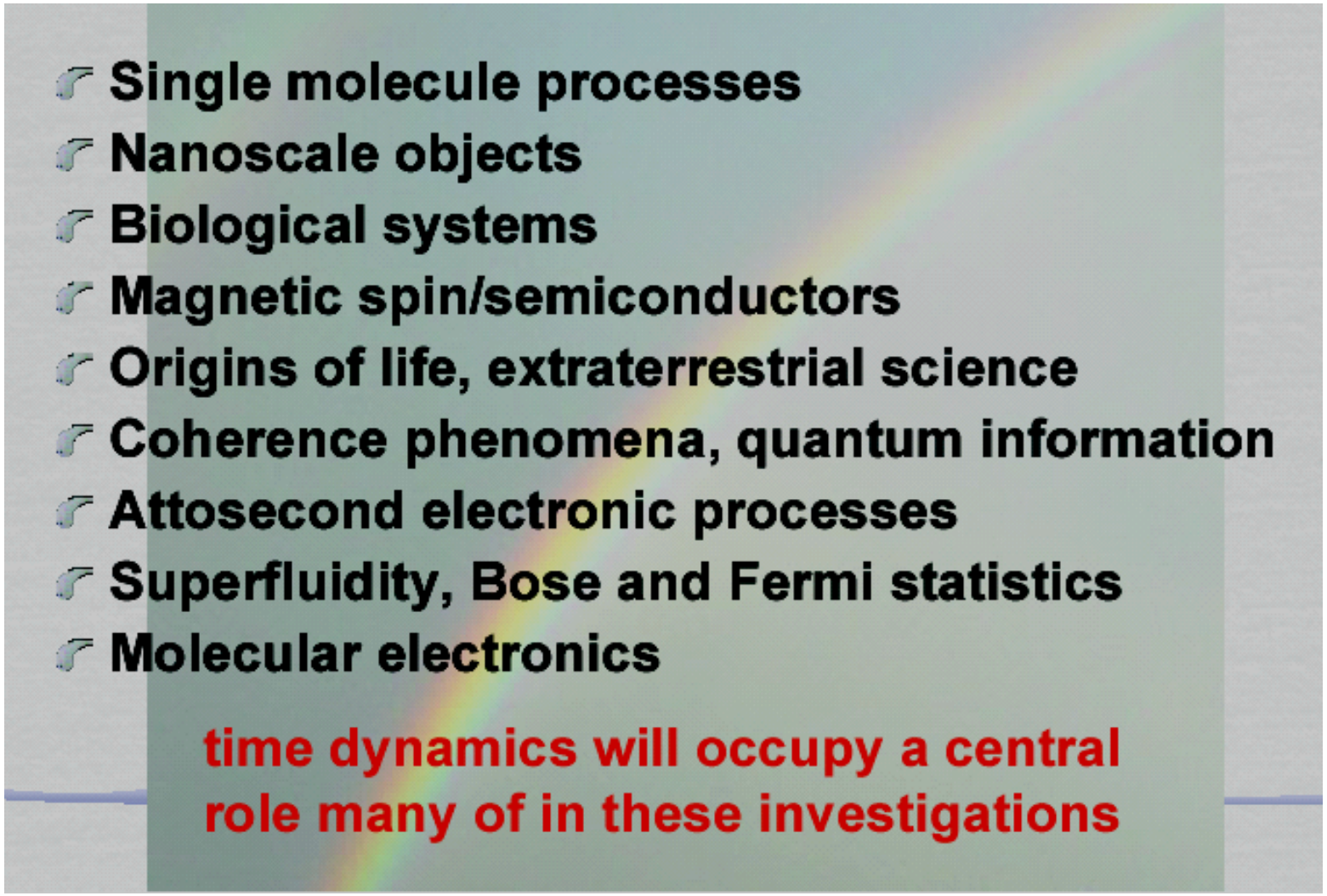
High Intensity Proton Linacs
Beam Power 1 – 5 MW

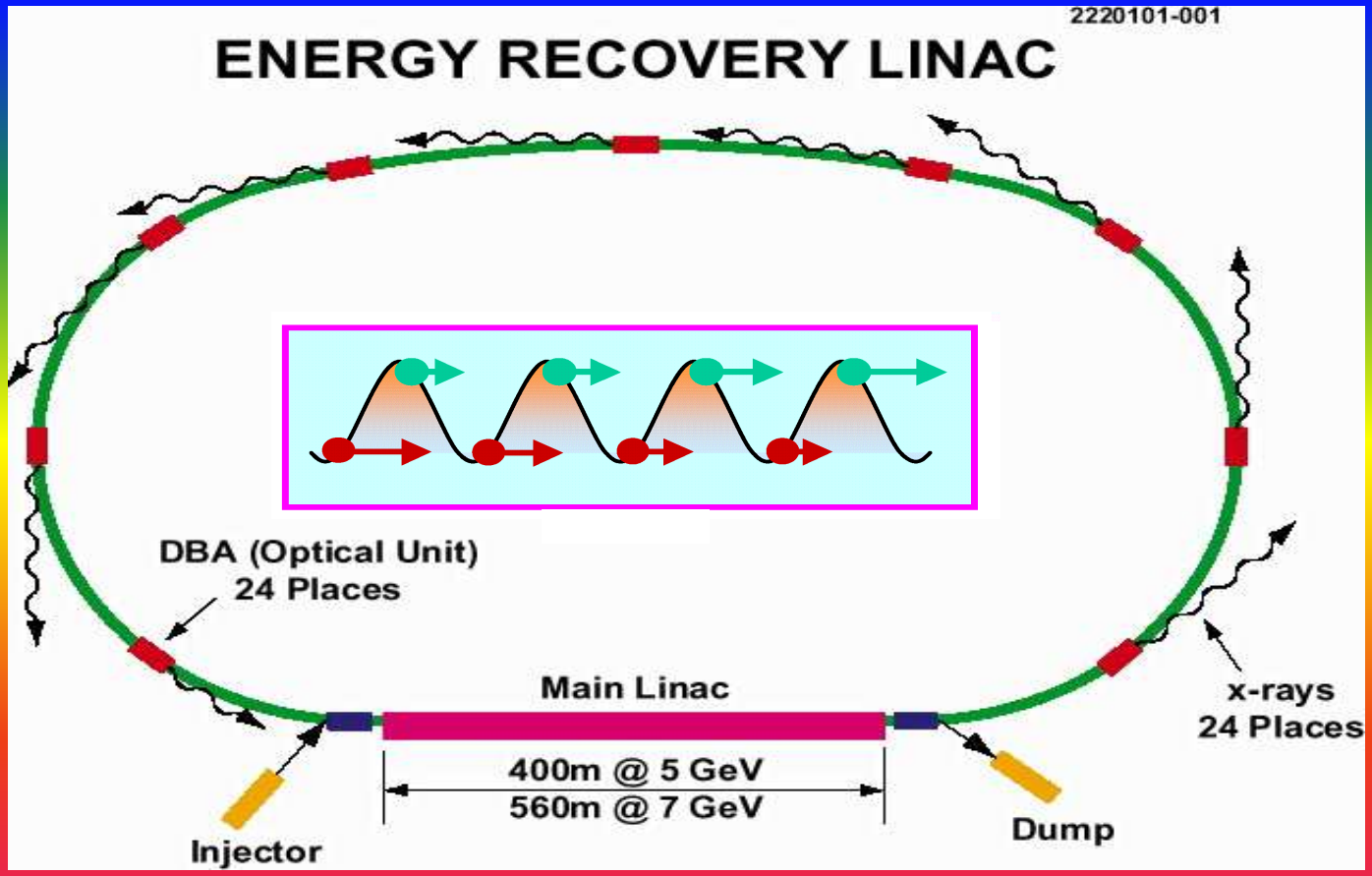
- Installed
- SNS - Oak Ridge (US)
- 15 MV/m

- Anticipated
- ESS
- European Spallation Source
- Proton Driver – Project X (Fermilab)
- SPL (CERN)
- XADS (Europe)
- Joint Project Upgrade (Japan- JPARC)

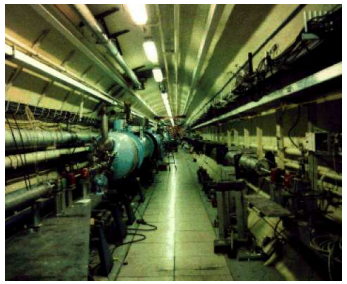
New Generation of Light Sources

- X-Ray FELs and ERLs




2220101-001
ENERGY RECOVERY LINAC
DBA (Optical Unit)
24 Places
Main Linac
400m @ 5 GeV
560m @ 7 GeV
Injector
Dump
x-rays
24 Places

ERL:
A New Class of Light Source



1986: Stanford SCA

1965: M. Tigner
Nuovo Cimento
37 (1965) 1228

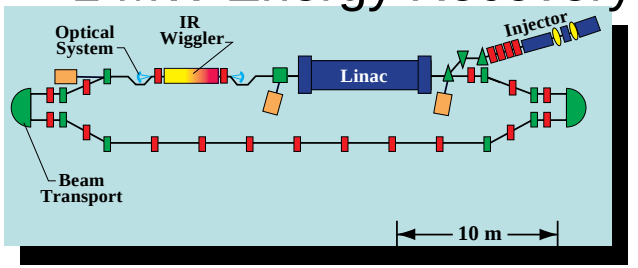
1960
1970
1980
1990
2000
2010

1999: JLAB DEMO-FEL
2002: JAERI FEL

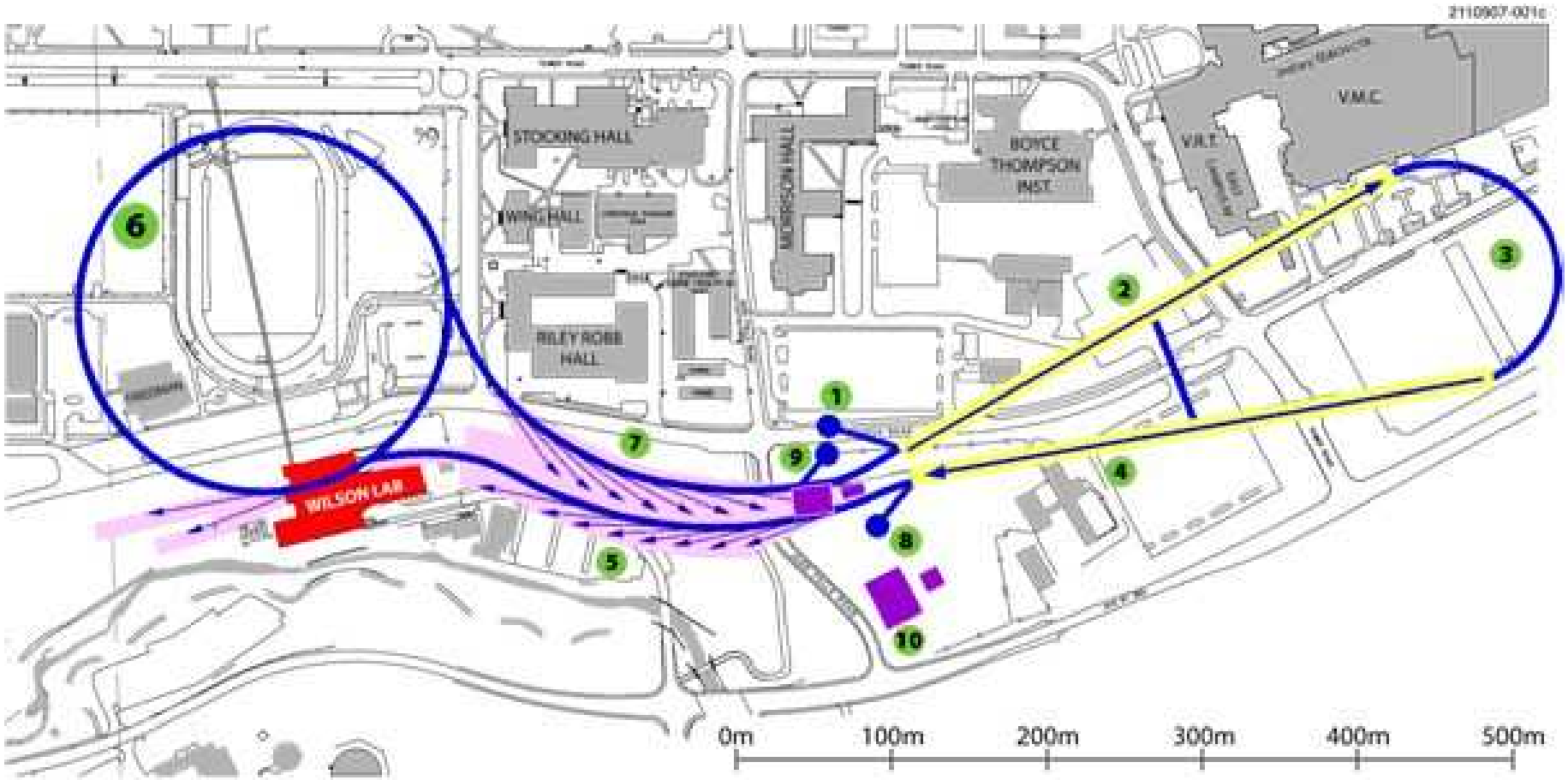
1990: S-DALINAC
(Darmstadt)

2004: JLAB FEL Upgrade

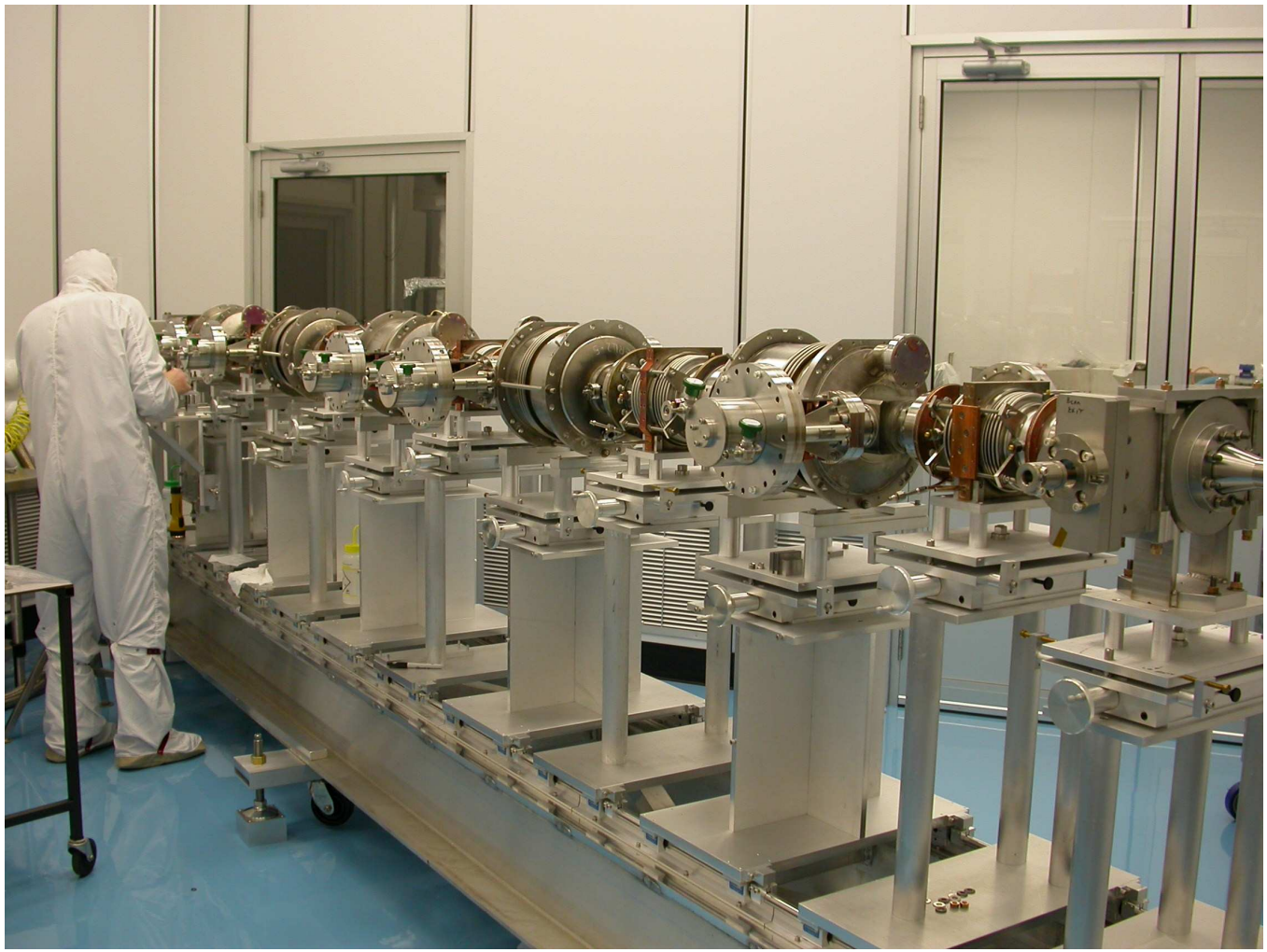
1 MW Energy Recovery



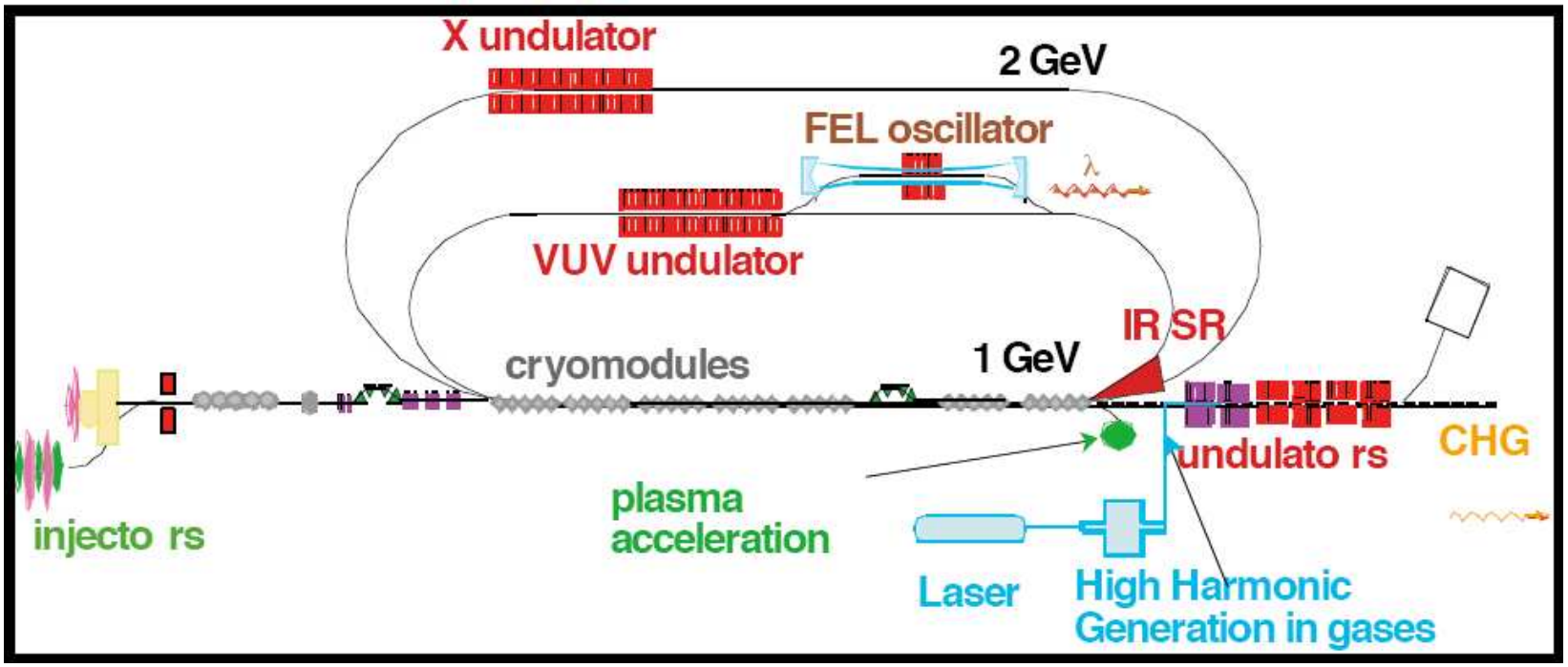
Cornell ERL Layout



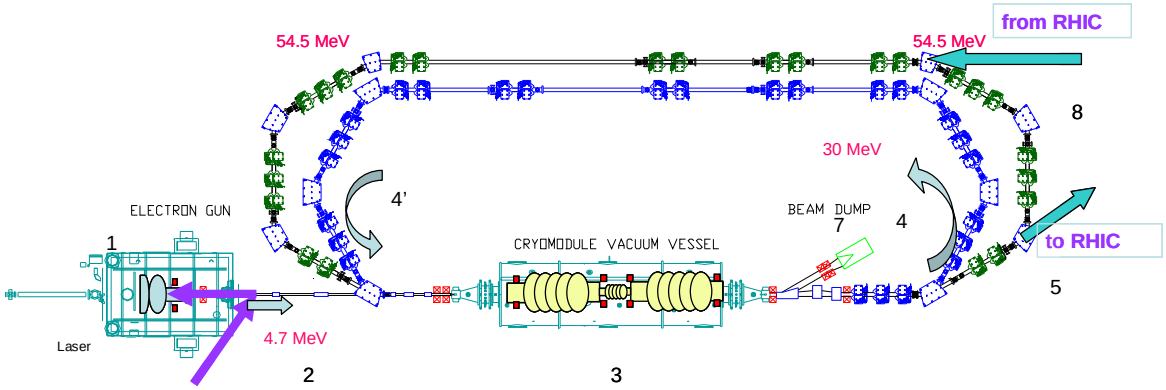
Started the Injector SC Cavity String

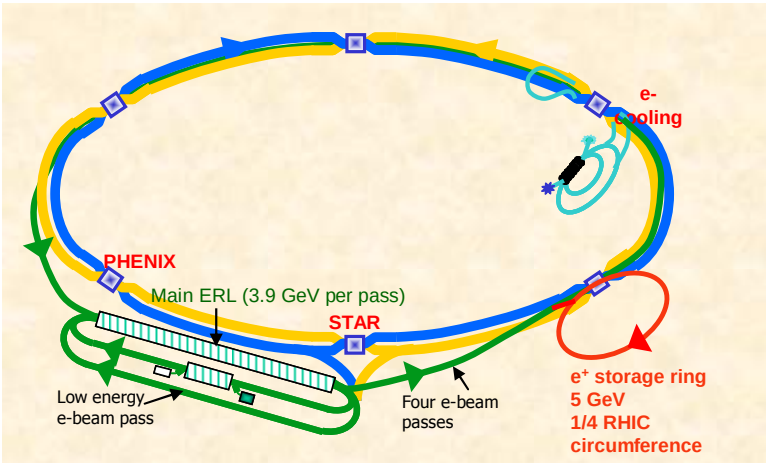


Other ERL Projects Forseen
ERL in France



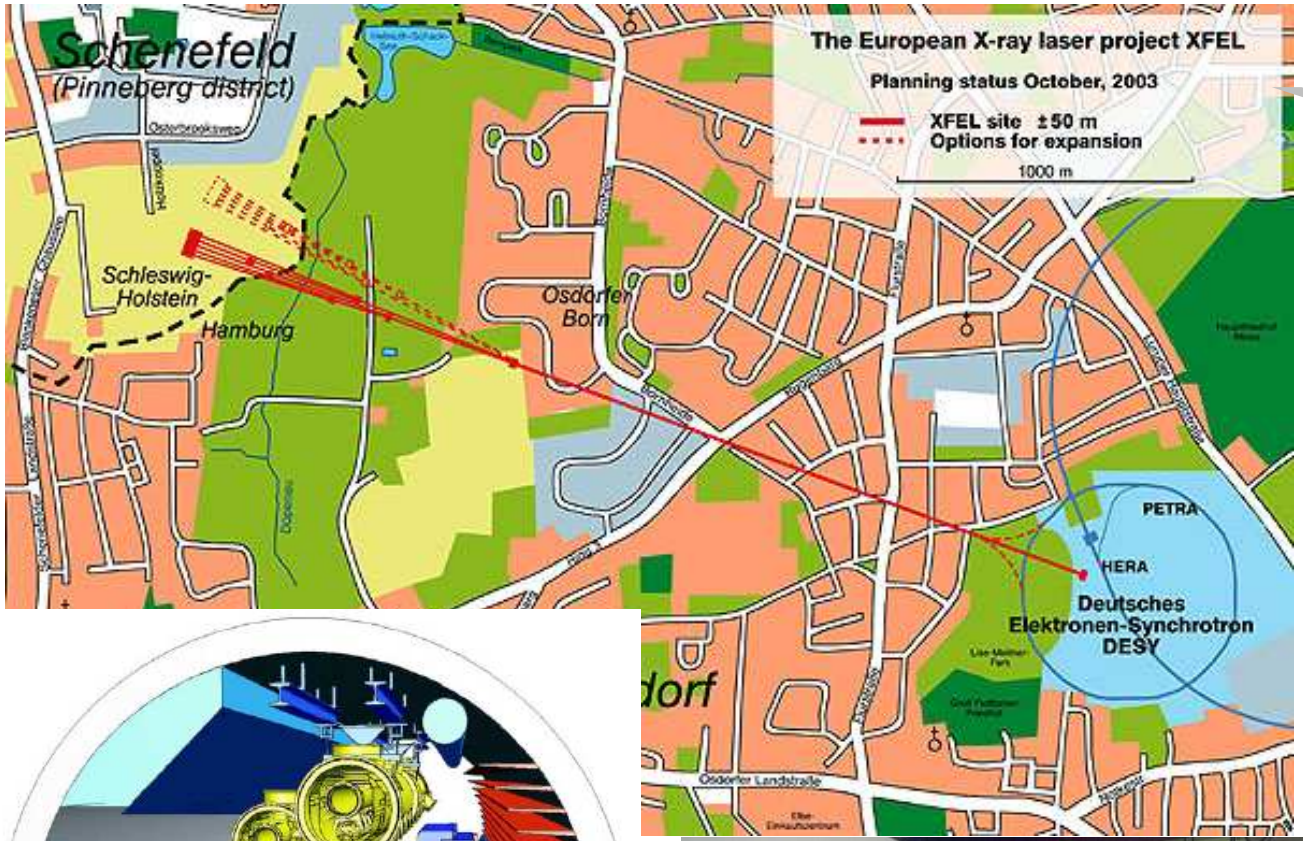
ERLs at BNL





- ERL for electron cooling the RHIC beam
- ERL for e-ion collider.

Revolutionary X-Ray Source @ DESY



X-FEL

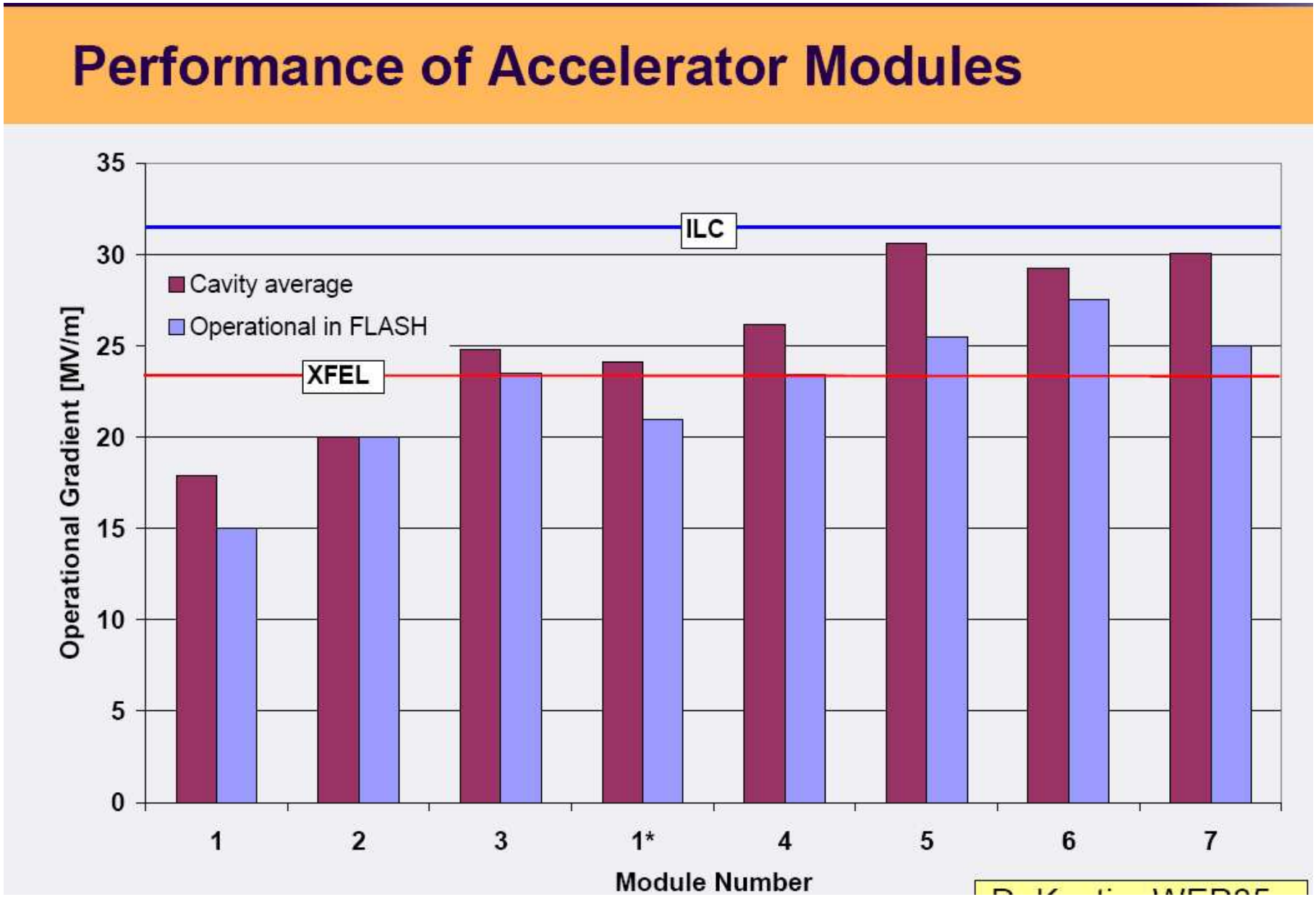
20 GeV

Peak Brilliance
8 Orders of
Magnitude
Higher than
ESRF !

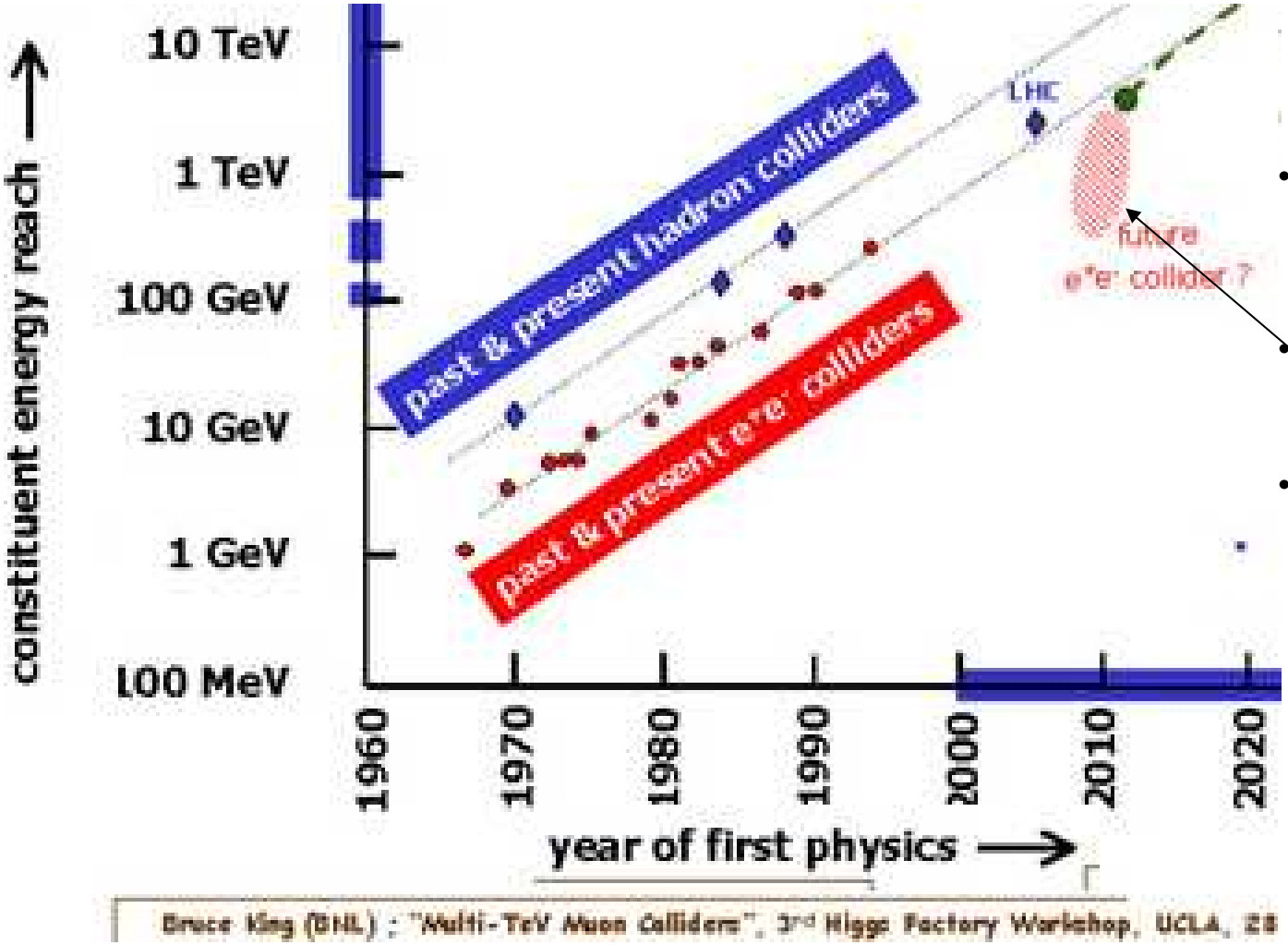
1000

100 Cryomodules

TTF Cavity-Module Performance (Pulsed Operation)



Particle Physics Is Entering An Exciting New Era



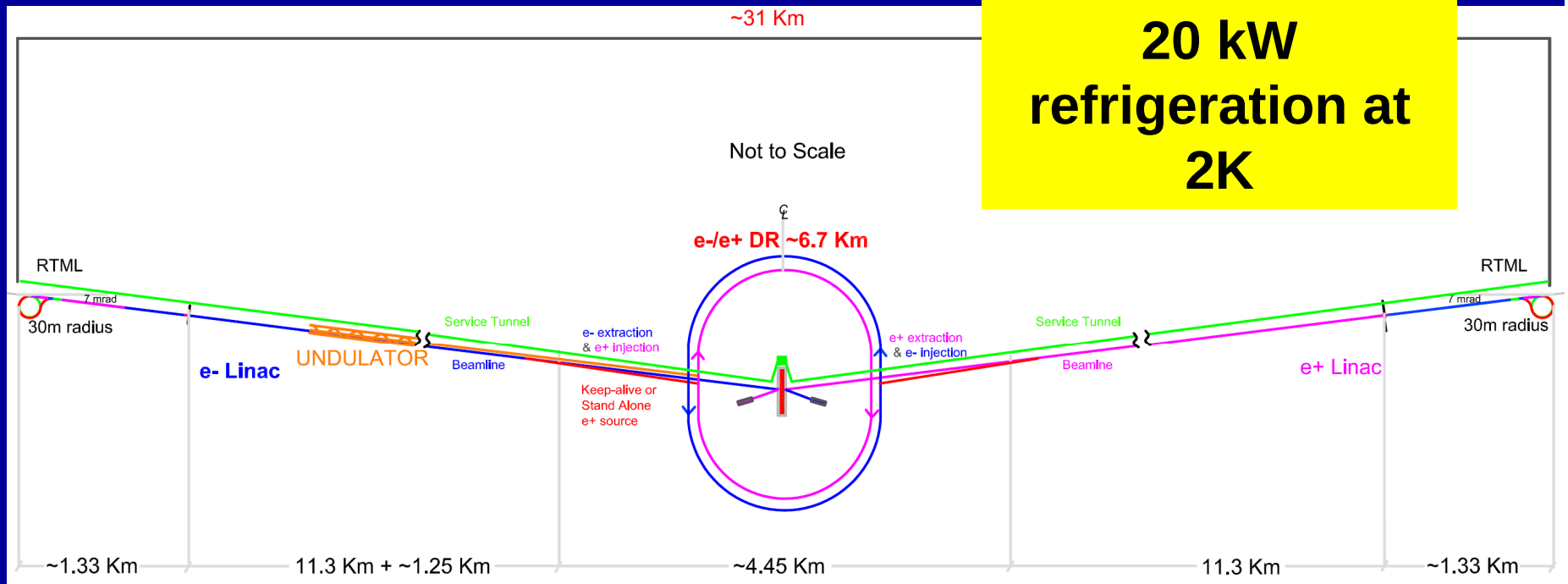
- Cosmology and particle physics point to new physics at the TeV
- Astrophysics cosmology and theory provide clues, but we will need accelerators
- LHC and linear collider – to sort it all out
- And reveal the physics that is yet to come …

Excitement About Linear Collider

20,000 Cavities

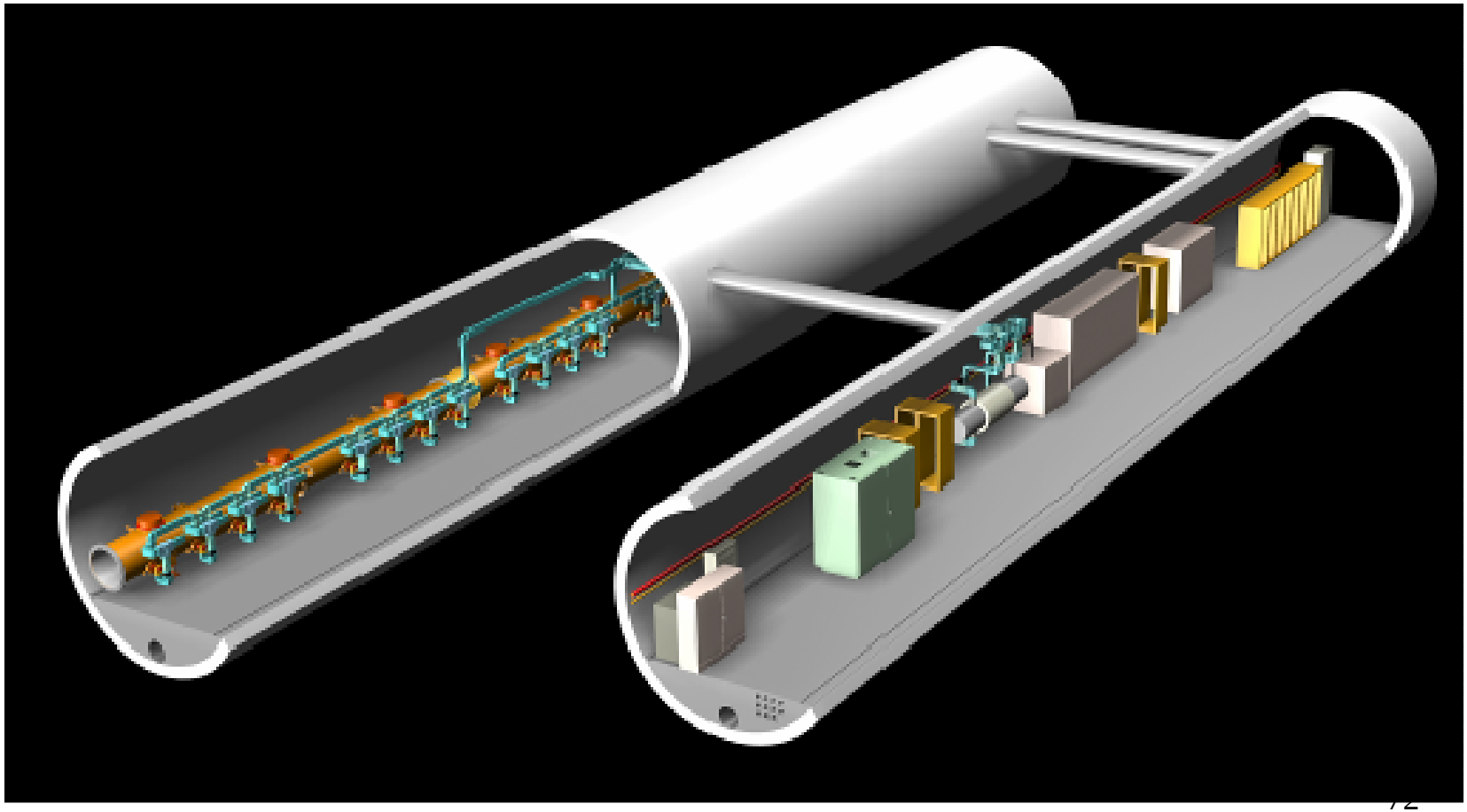
500 tons of high purity niobium

20 kW refrigeration at 2K



Schematic Layout of the 500 GeV Machine

ILC Tunnel Layout



Main Advantages of SC - LC

- SC Cavity => Fill energy slowly
  Strong Reduction of Peak RF Power
- SC => Low Frequency, Large beam hole =>
  Lower Wake fields
- Higher conversion efficiency
  AC power to beam power
- Long RF pulse length
  Large spacing between bunches
  Wakefields die out
  Feedback between bunches

You've got 60 seconds to explain What's it good for?

"6 billion bucks! What's this *thing* for?"

Does it make oil?

No! But it might make Dark Matter !

Neil Calder

Far Future Projects

- Neutrino Factory
- (20 GeV Muon accelerator)
- Muon Collider
  - 3 – 5 TeV

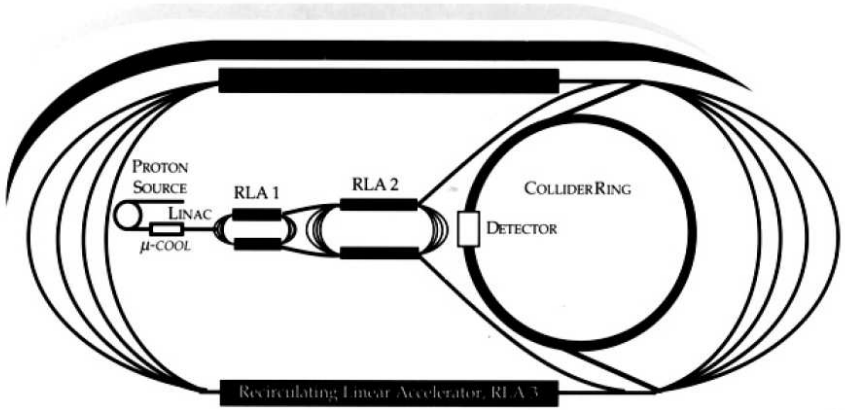
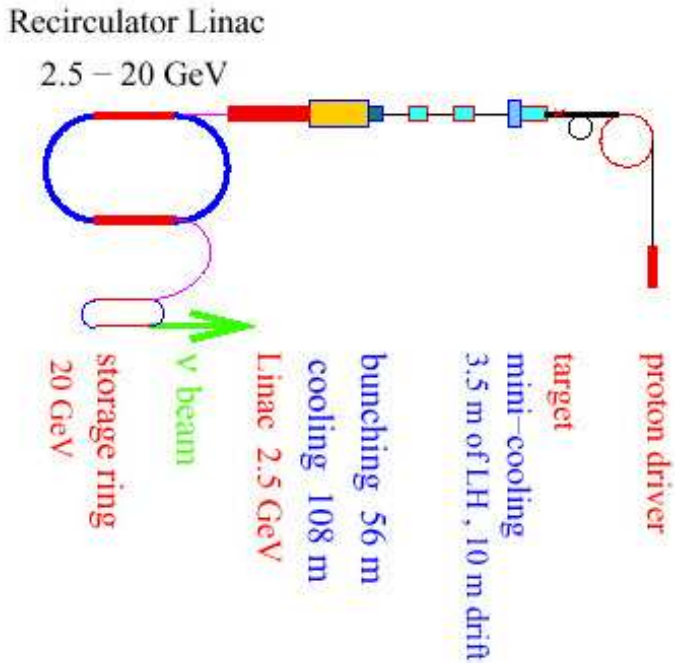


Fig. 1: Generic Layout for a 3 TeV collider [2].



The Road to 50 MV/m is Now Open !

- See talks by Liepe, Eremeev and Romanenko