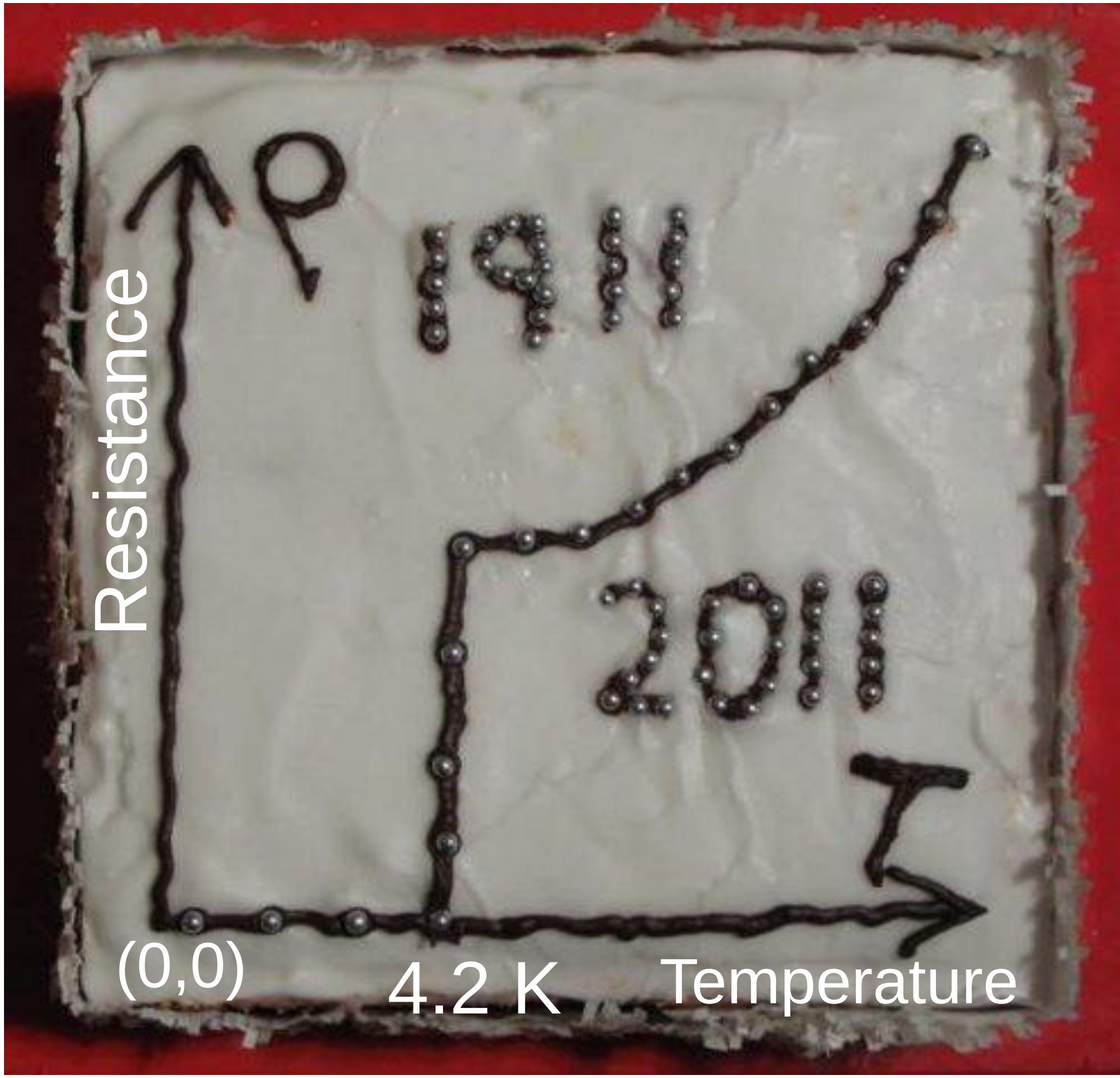
CERN Centennial Superconductivity Symposium

50 Years of RF Superconductivity

A Perspective



Hasan Padamsee

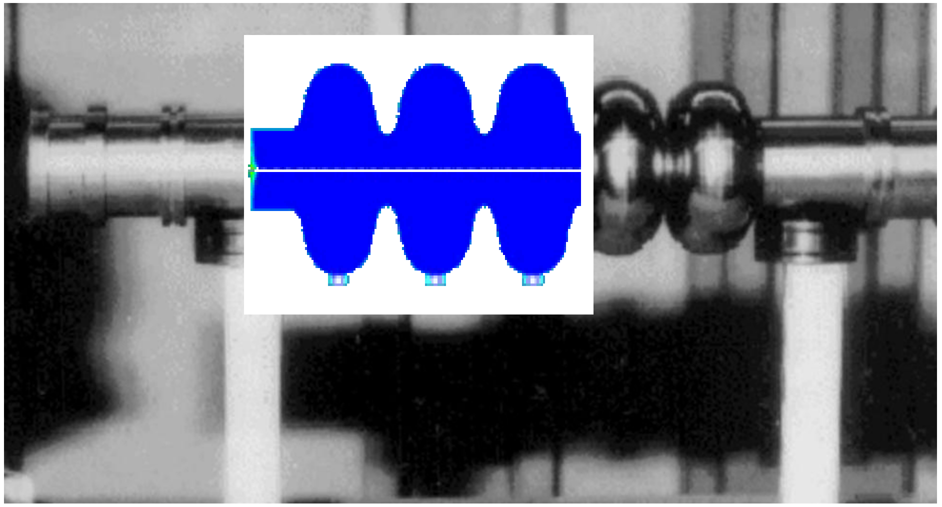
Cornell University

Outline

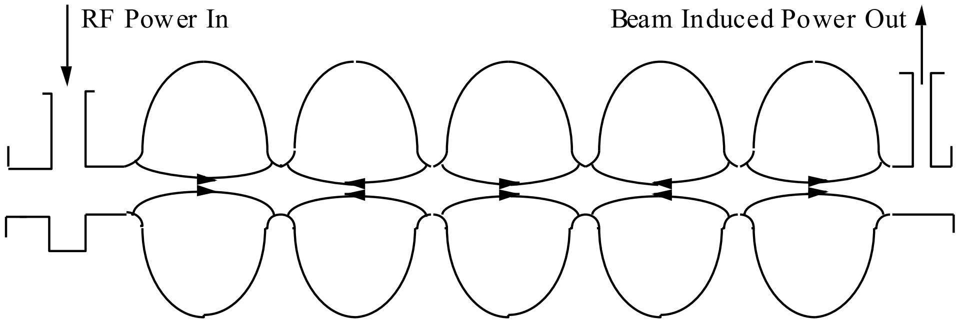
- HAPPY BIRTHDAY!!
- Quick Intro - RF Cavities
- Why Superconductivity?
- Present world-wide status of SRF
- Historical beginnings and growth
  - 50 Year Perspective
- The near future
- The far future
  - 50 Year Perspective

RF Cavities for Accelerators

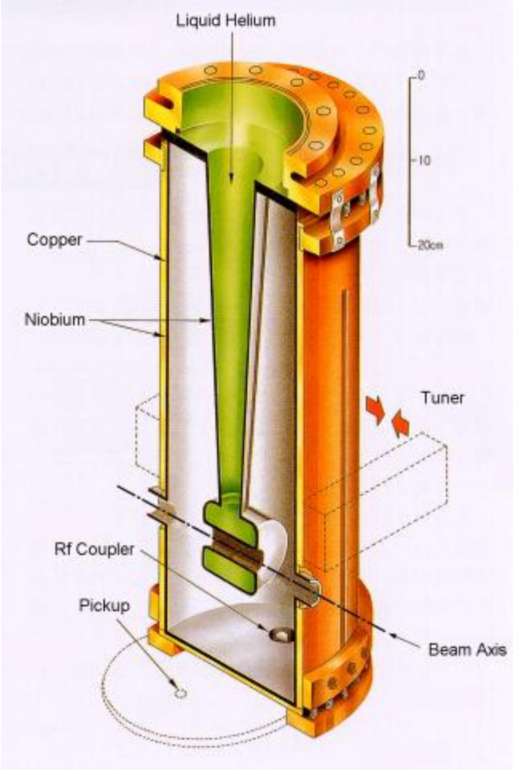
- Key component for acceleration
- Microwave cavity
  - RF frequency :100 MHz and 3000 MHz
- Imparts energy to charged particles.

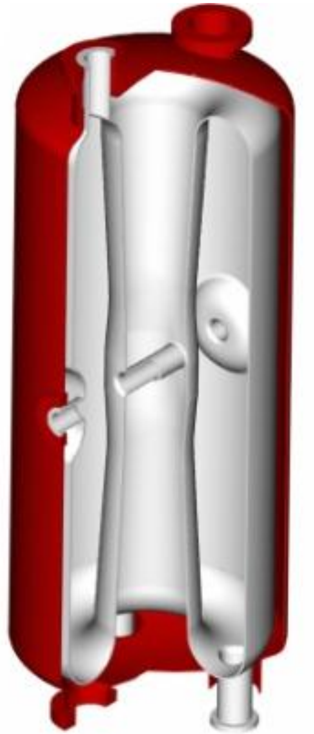


Accelerating Cavity for High Velocity Particles

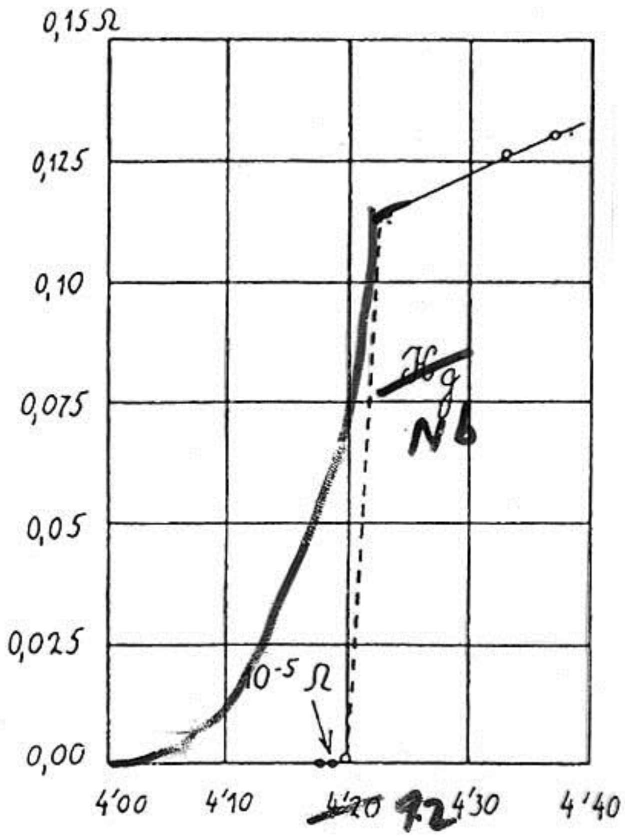


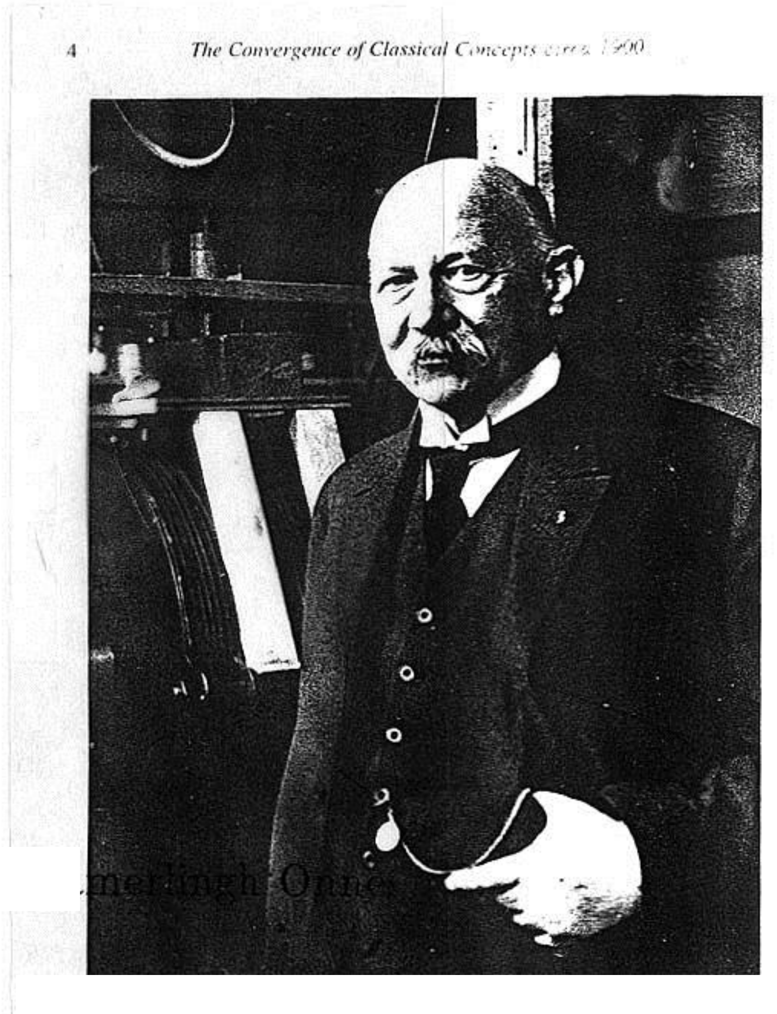
Typical Accelerating Cavity for Low Velocity Particles





The Miracle of Superconductivity

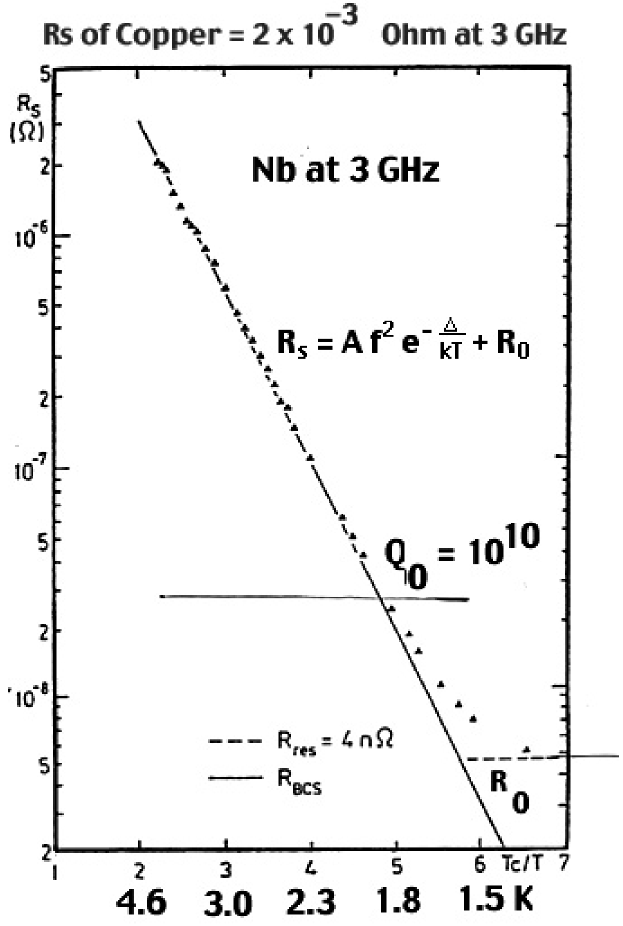




H. Padamsee

Main Advantage of Superconducting Cavities

- A superconducting cavity reduces the wall dissipation by many orders of magnitude over a copper cavity
- => Affordable higher CW/long pulse gradients
- Larger aperture cavity geometry for better beam quality



50 Years Ago !

A. P. Banford and G. H. Stafford

Plasma Physics, J.Nucl. Energy, Part C, 3, 287(1961)

THE FEASIBILITY OF A SUPERCONDUCTING PROTON LINEAR ACCELERATOR

A. P. BANFORD and G. H. STAFFORD
Rutherford High Energy Laboratory, National Institute for Research in Nuclear Science, Harwell, Berks.

(*Received* 9 *June* 1961)

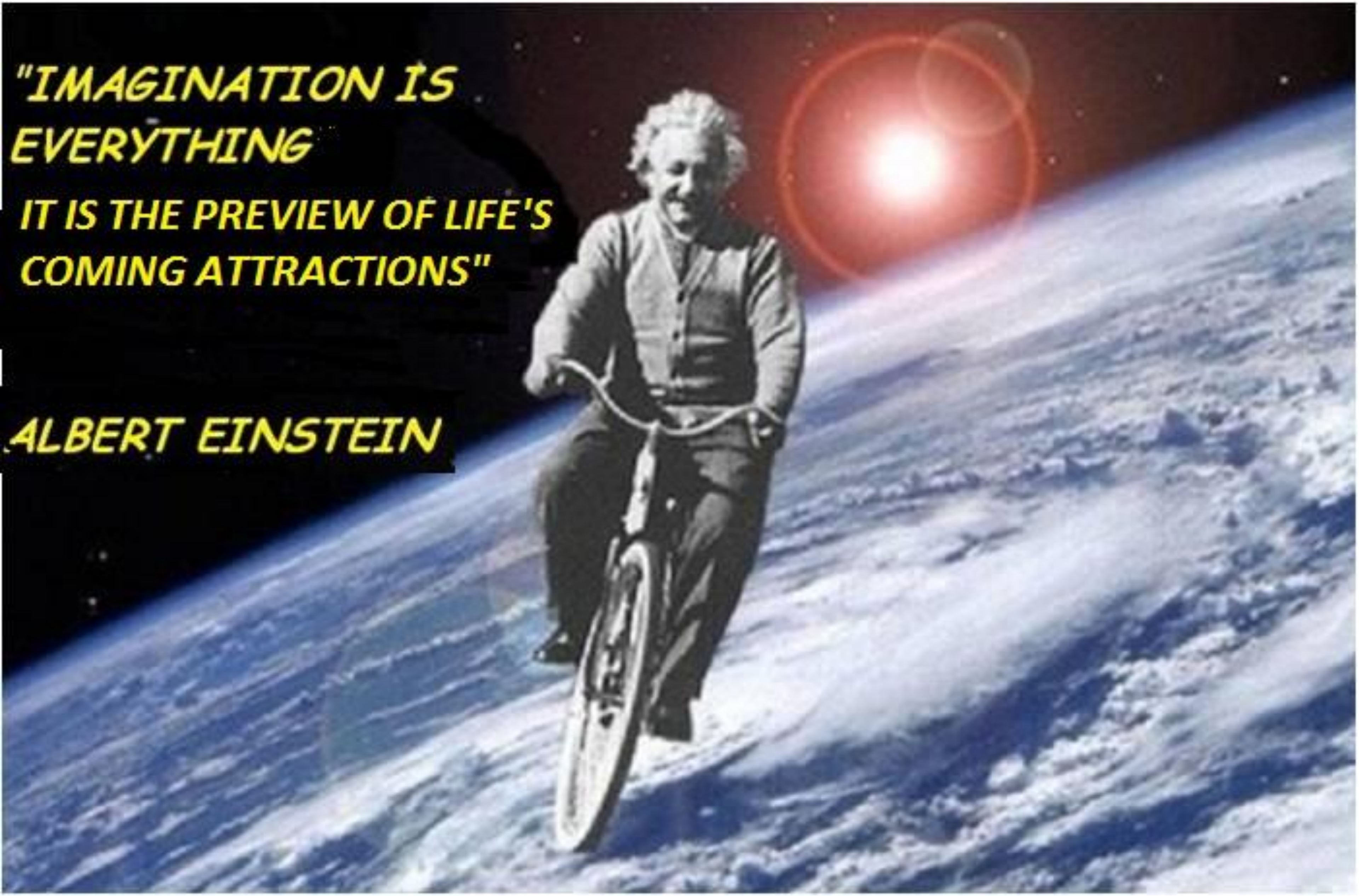
Quote from 1961 Paper

(P.L.A.) at the Rutherford Laboratory operates only at a duty cycle of 1 per cent although, in principle, it could operate at a 100 per cent duty cycle. We have, therefore, been looking into the possibility of applying superconducting principles to proton linear accelerator design. A linear accelerator is very suitable for this ···

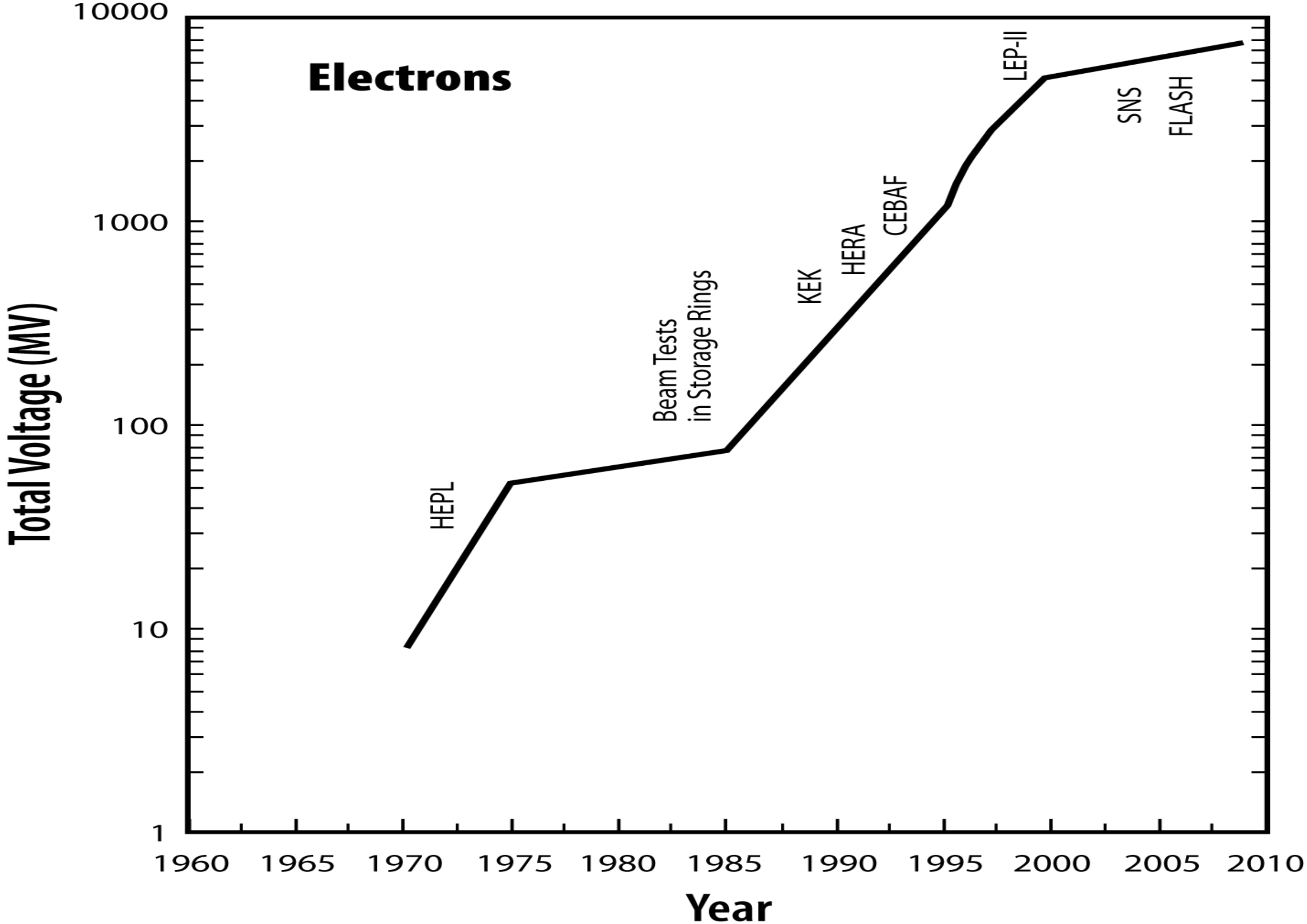
2005 The Dream of 1961 Comes Alive !!
Oak Ridge Laboratory - Tennessee

Even Though It Took 45 Years to Realize

We learnt something important!

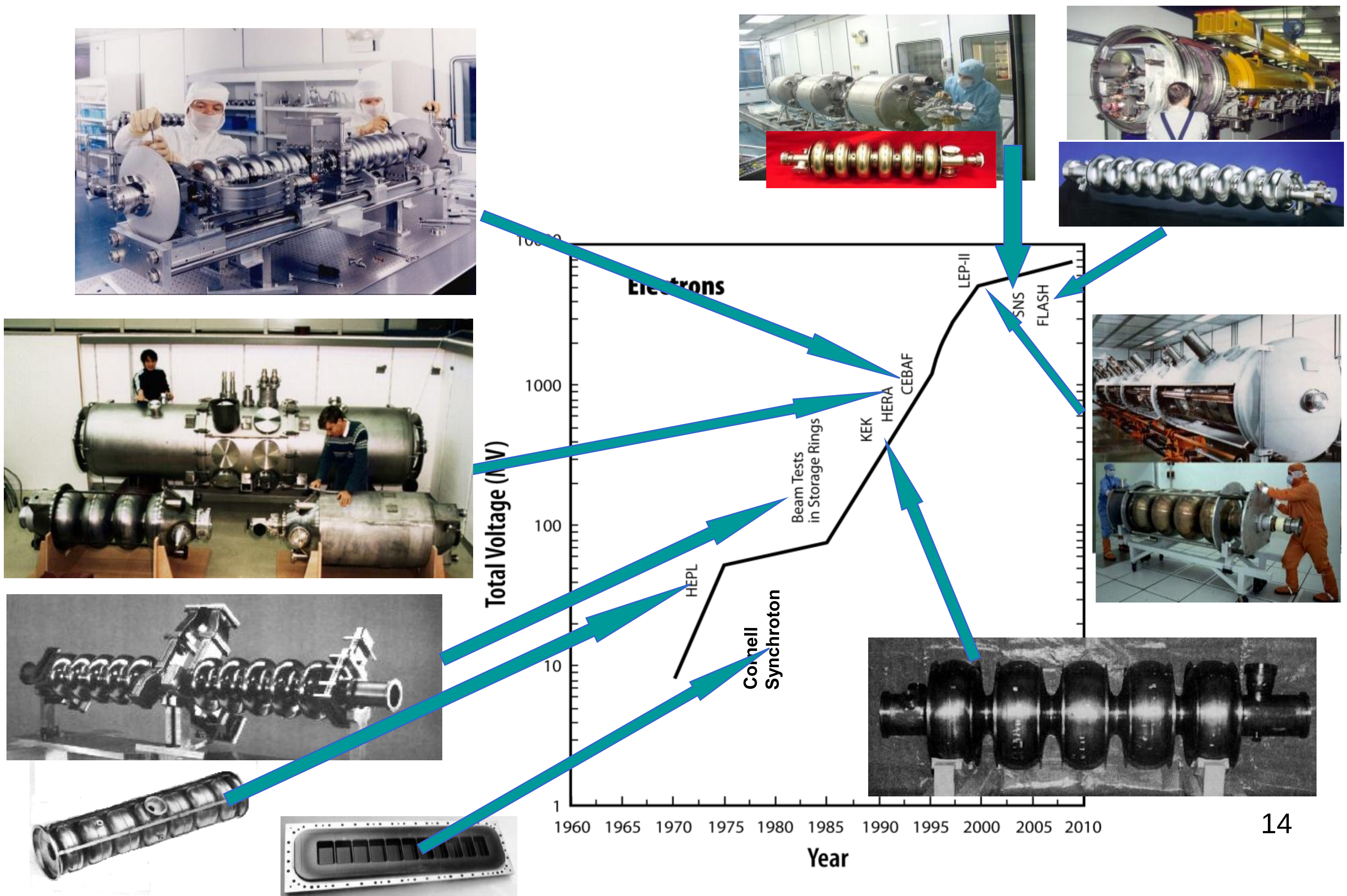

"IMAGINATION IS
EVERYTHING
IT IS THE PREVIEW OF LIFE'S
COMING ATTRACTIONS"
ALBERT EINSTEIN

50 Yr-Growth of Installed Voltage for *v/c = 1* Accelerators

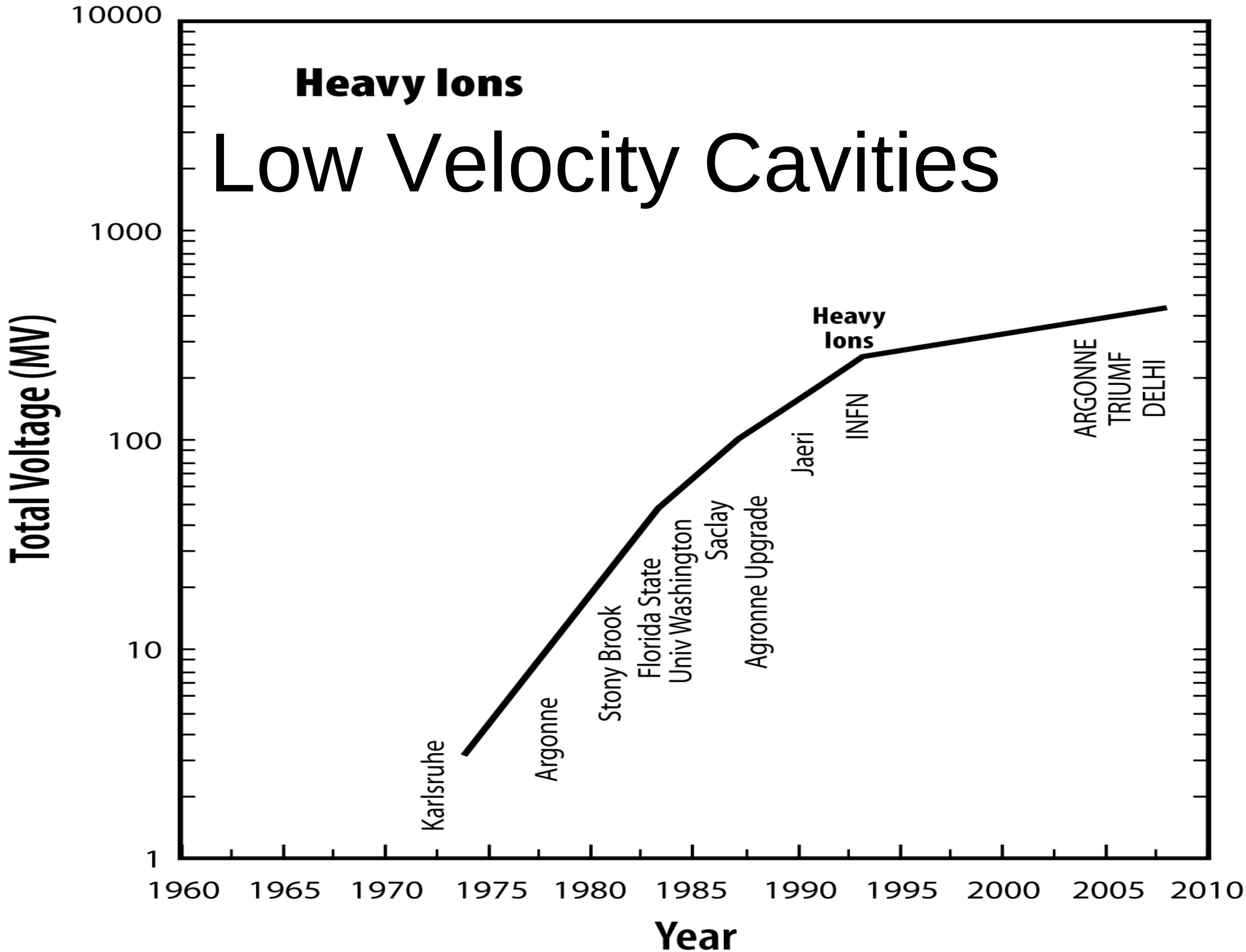


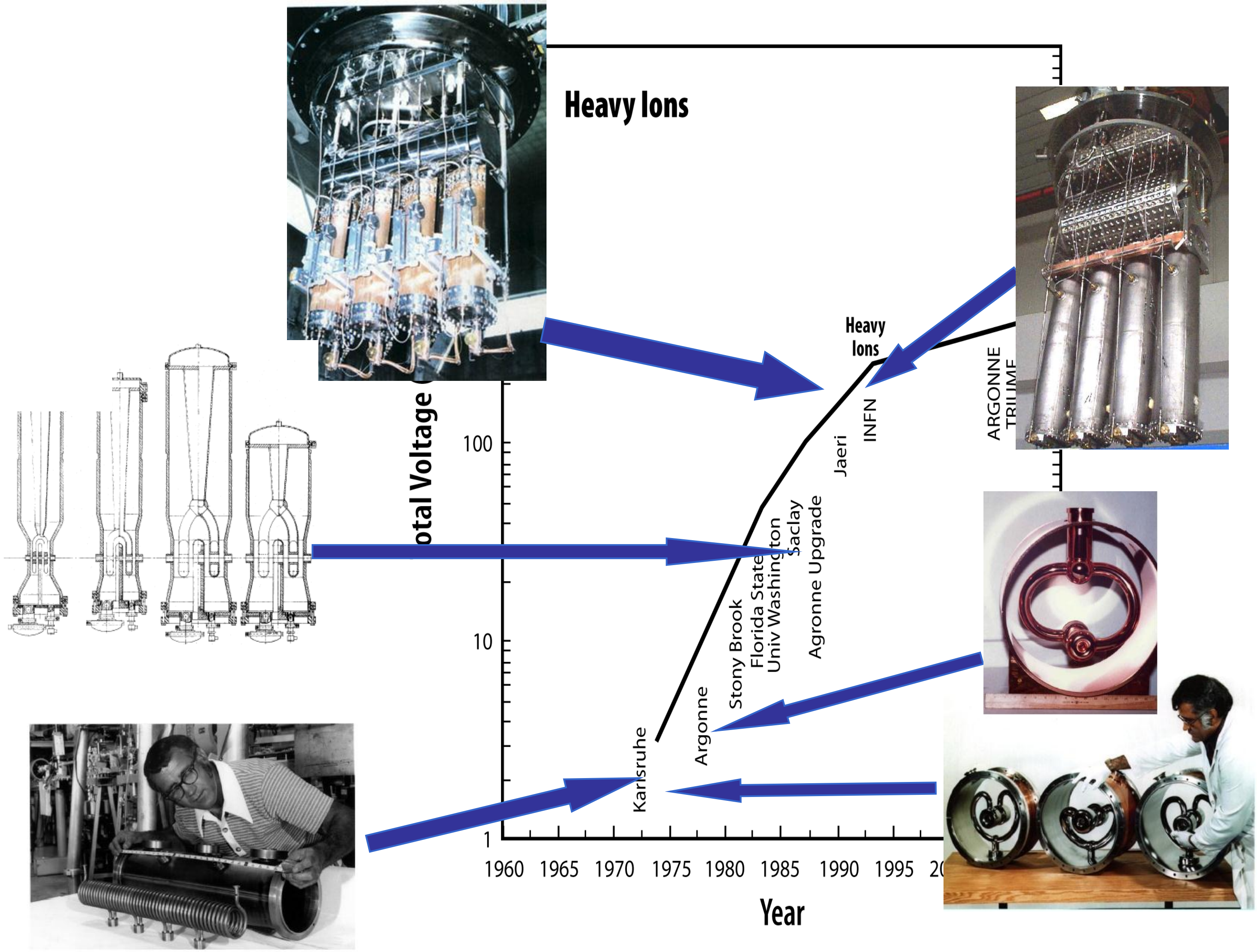
A "Livingston Plot" for RF Superconductivity

Total Installation > 1000 m, > 7 GV



Low Velocity Cavities




Heavy Ions
Heavy Ions
otal Voltage
100
10
1
1960 1965 1970 1975 1980 1985 1990 1995
Year
Karlsruhe
Argonne
Stony Brook
Florida State
Univ Washington
Saclay
Agronne Upgrade
Jaeri
INFN
ARGONNE

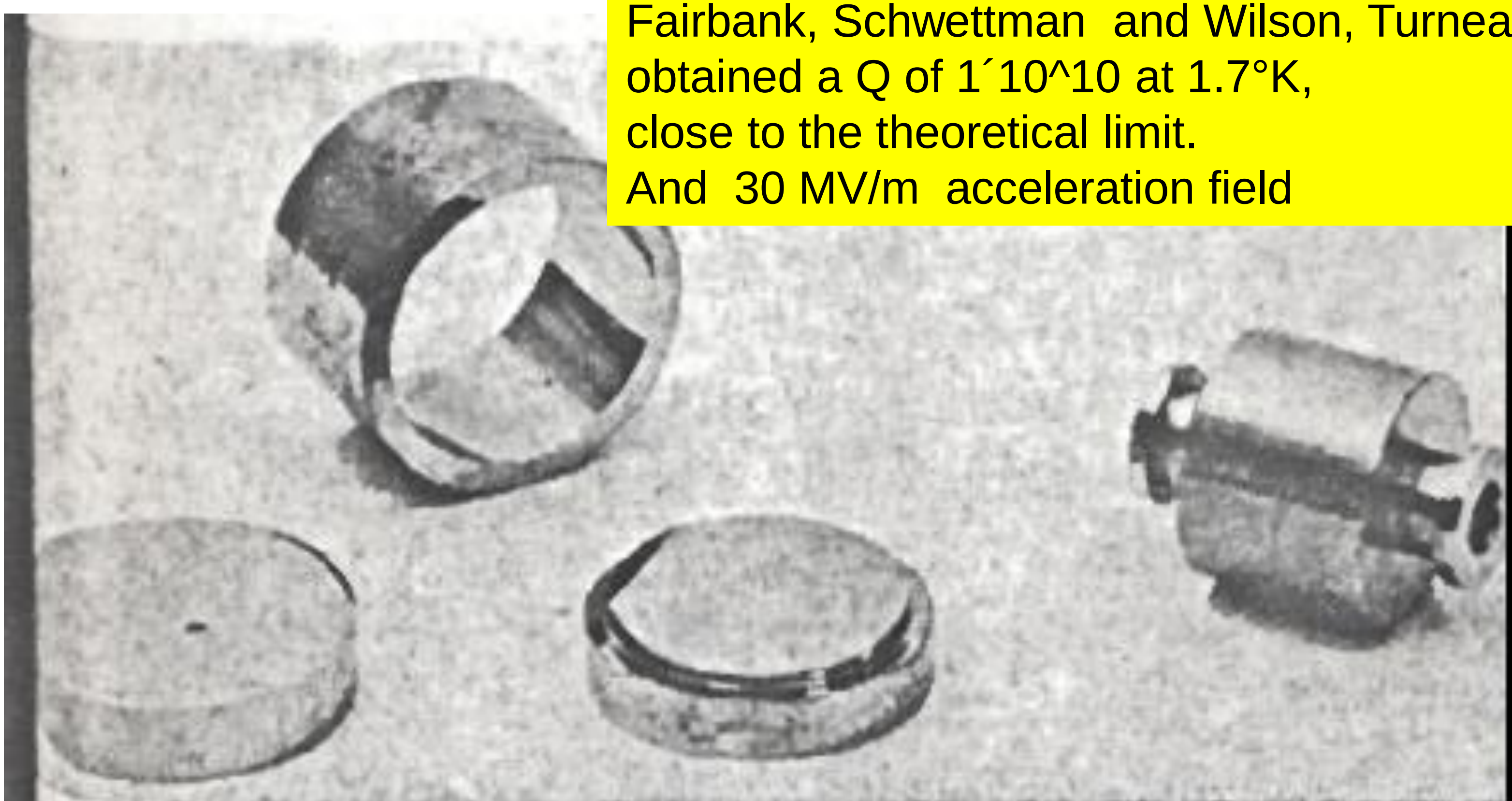
A Variety of Missions for SRF Accelerators

- Low energy nuclear physics, nuclear structure
  - Heavy Ion Linacs
- Medium energy nuclear physics, quark structure of nucleus
  - Recirculating linac
- Nuclear astrophysics
  - Facility for rare isotope beams (FRIB)
- X-Ray Light Sources for life science, materials science & engineering
  - Storage rings, free electron lasers, energy recovery linacs
- Spallation neutron source for materials science and engineering, life science, biotechnology, condensed matter physics, chemistry
  - High intensity proton linac
- High energy physics for fundamental nature of matter, space-time
  - Electron-positron storage ring colliders, linear collider, proton linacs for neutrinos
- Future High Intensity Proton Sources for
  - Nuclear waste transmutation. energy amplifier, power generation from Thorium

1962: Stanford Pioneers:

Small Scale TE011 and TM010 Cavities

Fairbank, Schwettman and Wilson, Turneaure
obtained a Q of 1´10^10 at 1.7°K,
close to the theoretical limit.
And 30 MV/m acceleration field



o. 2. Solid Nb X-band cavities. Left: TE_{011} mode; Righ
TM_{010} mode.

Stanford Charges Ahead

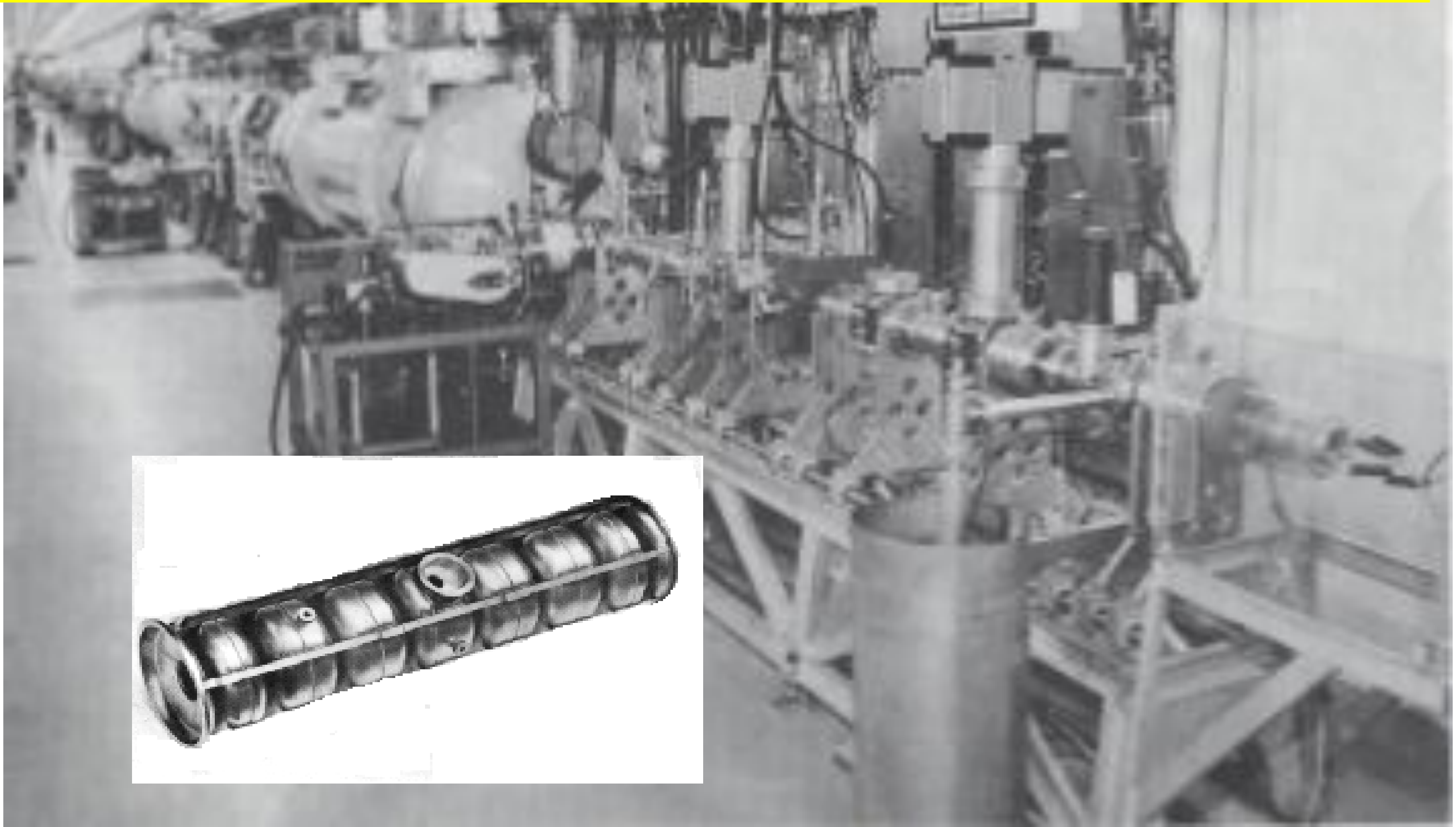
Stanford Charges Ahead !

- At the 1963 International Conference on High Energy Accelerators in Dubna the Stanford group published a very preliminary design of a
- 20 GeV !!!!! - 10% duty cycle superconducting accelerator
- This at a time when no real cavity had ever been built

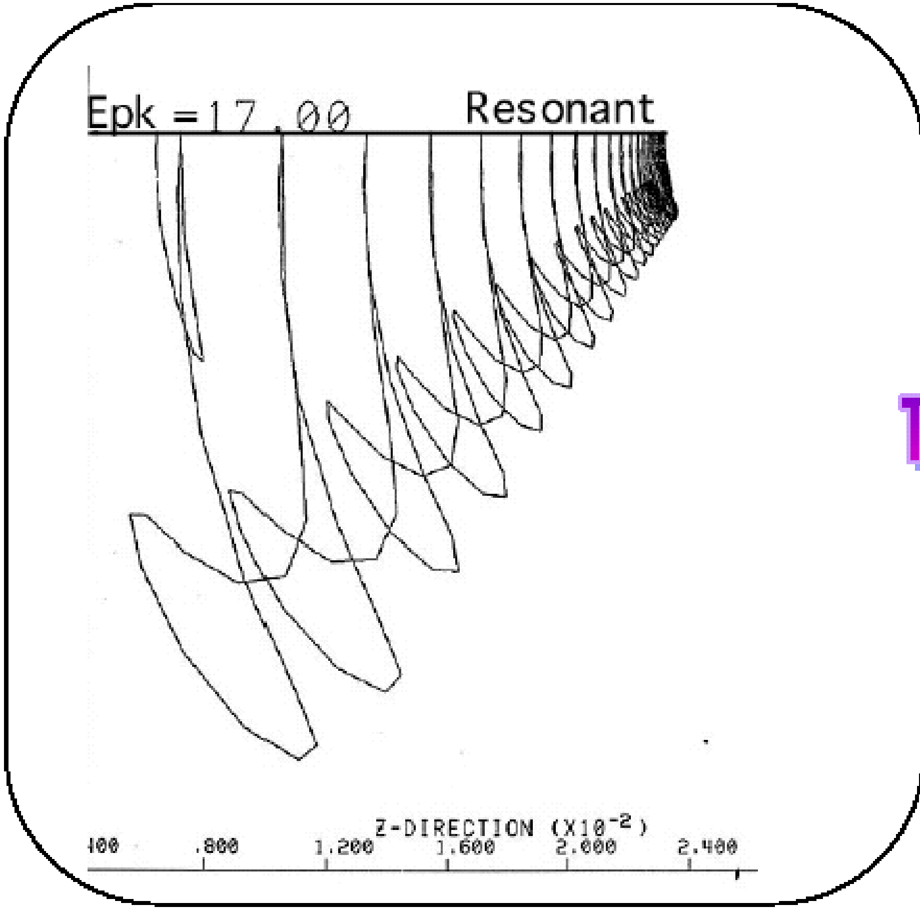
- Prof. Robert Hofstadter made plans to build a 2 GeV superconducting accelerator in a tunnel on the HEPL site. At gradient of about 13 MeV/m.
- Despite heroic efforts, they obtained a gradient of only 2-3 MeV/m in full scale accelerator structures at 1.3 GHz
- Electron multipactor was the culprit.

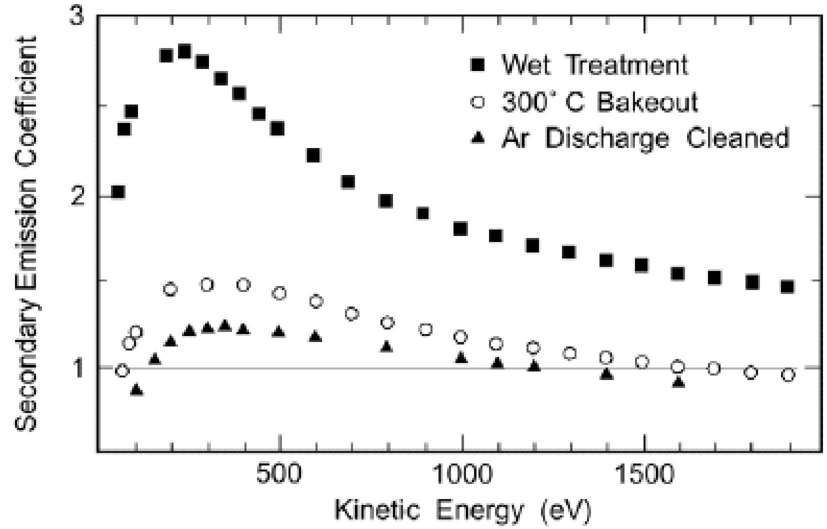
1970’s Snatching Victory from the Jaws of Defeat

- The superconducting accelerator structure is 48 m in length operating at a gradient of about 3MeV/m, giving a final energy of 600 MeV.
- Demonsrated first FEL
- Demonstrated 98% energy recovery

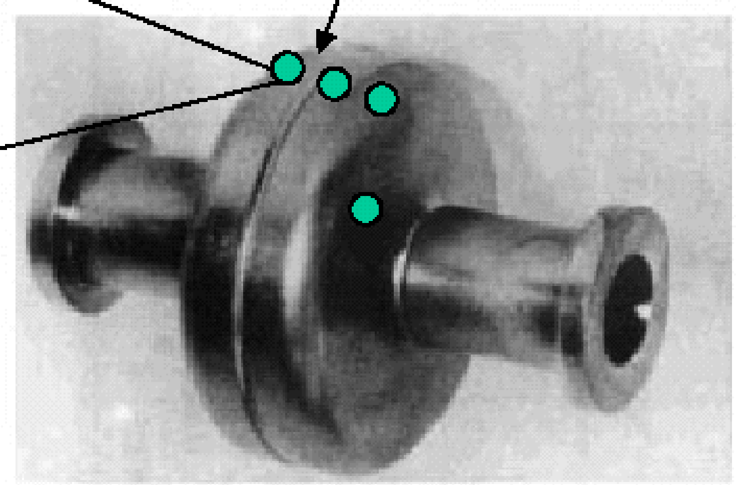


Simulated Electron Trajectories

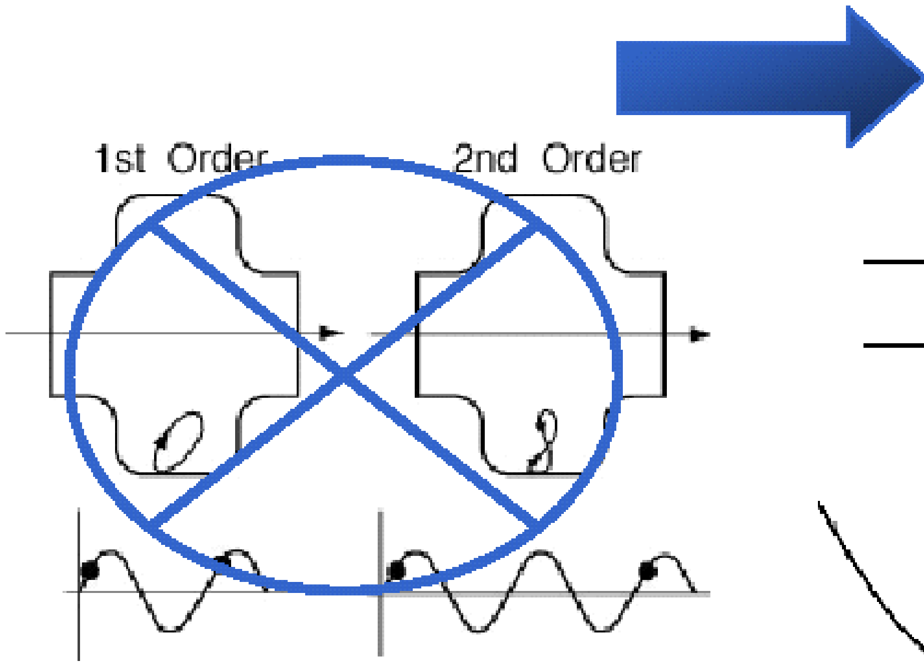


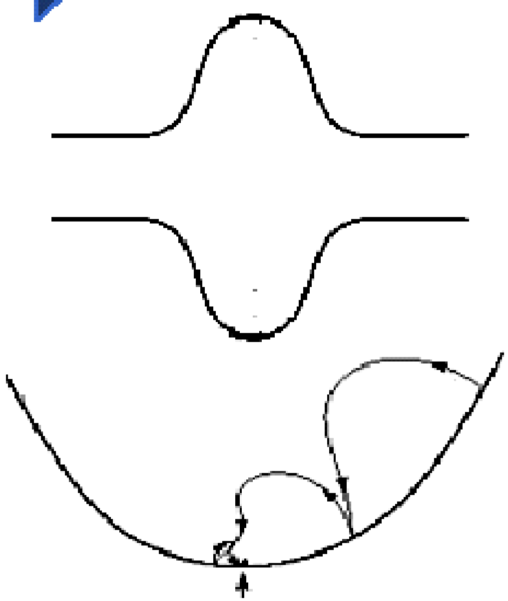


These thermometers show heating



Solution to Multipacting



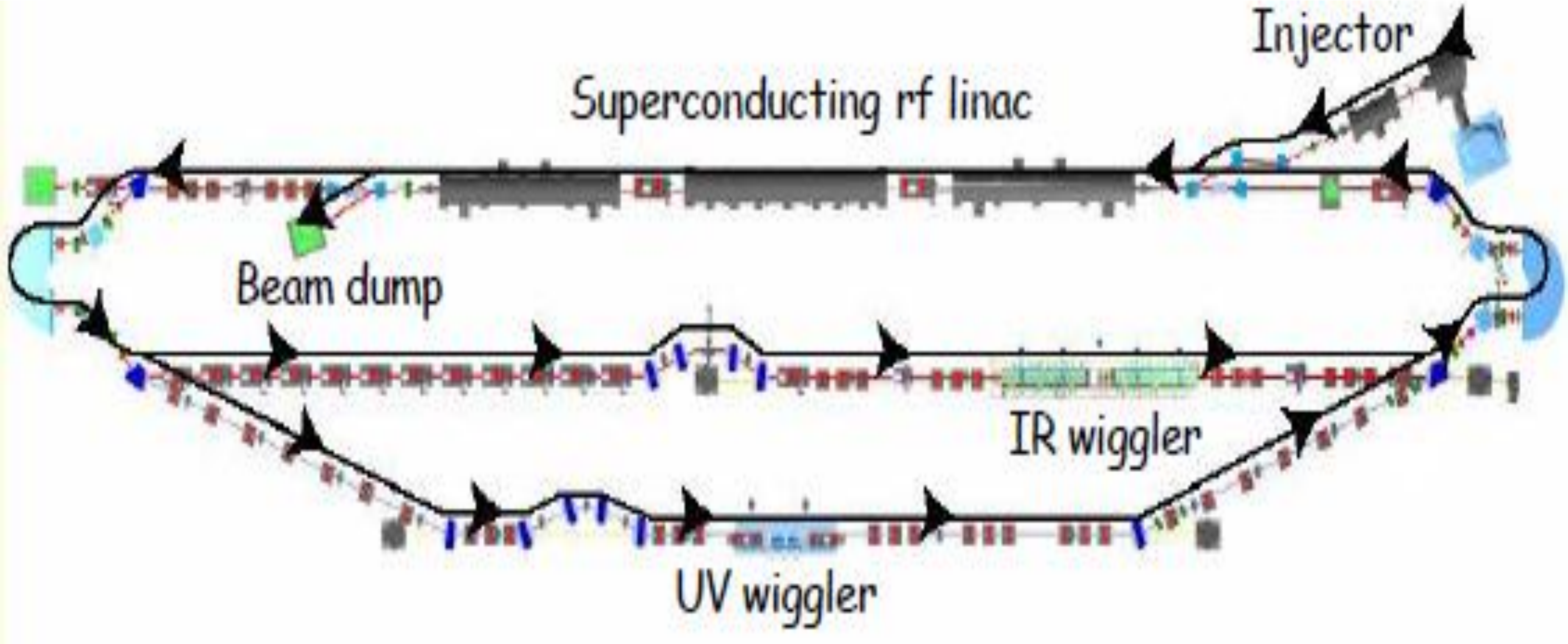


Electrons drift to equator
Electric field at equator is ≈ 0
→MP electrons don't gain energy
→MP stops

1990's :JLAB Completes 5 GeV Electron Recirculator

SOUTH LINAC CRYOMODULES

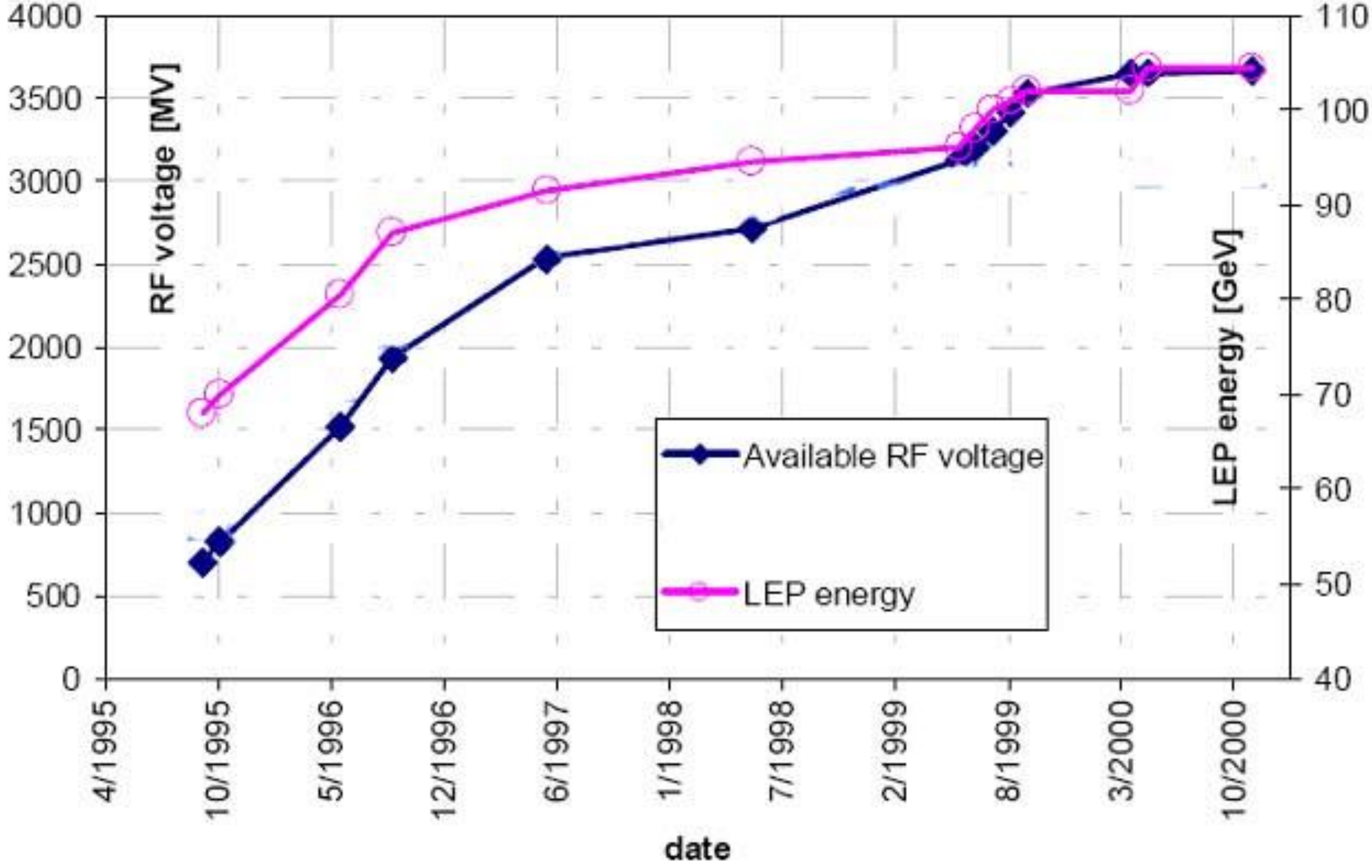
1990: JLAB : > 1 kW IR FEL
With > 99.9 % Energy Recovery



CERN Takes Lead in SRF Installations

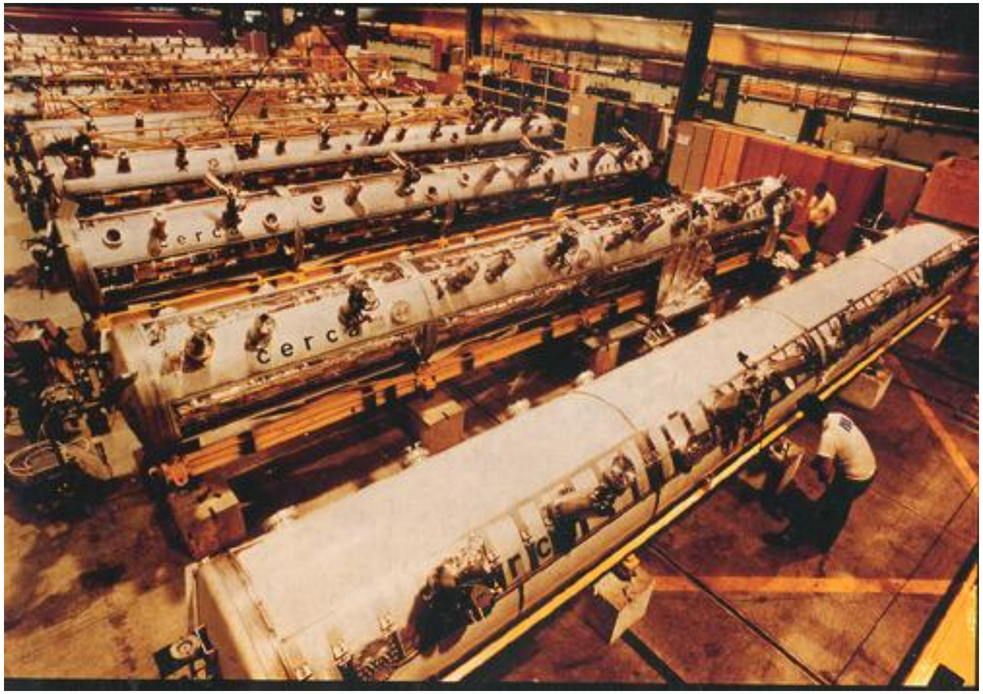
To Double LEP Energy

With 500 m = 3.6 GV of SRF Installation

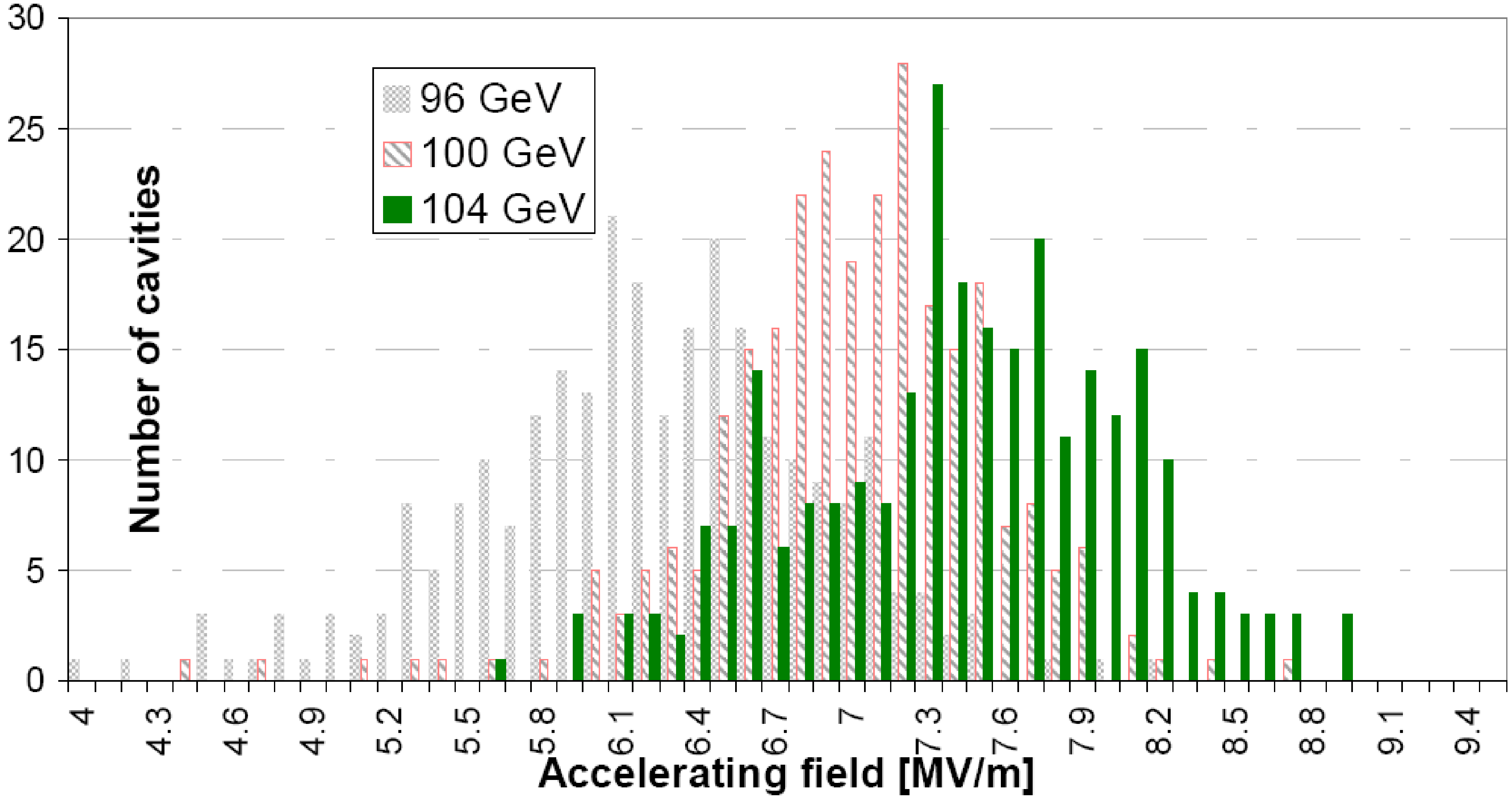


LEP Cavities and Cryomodules

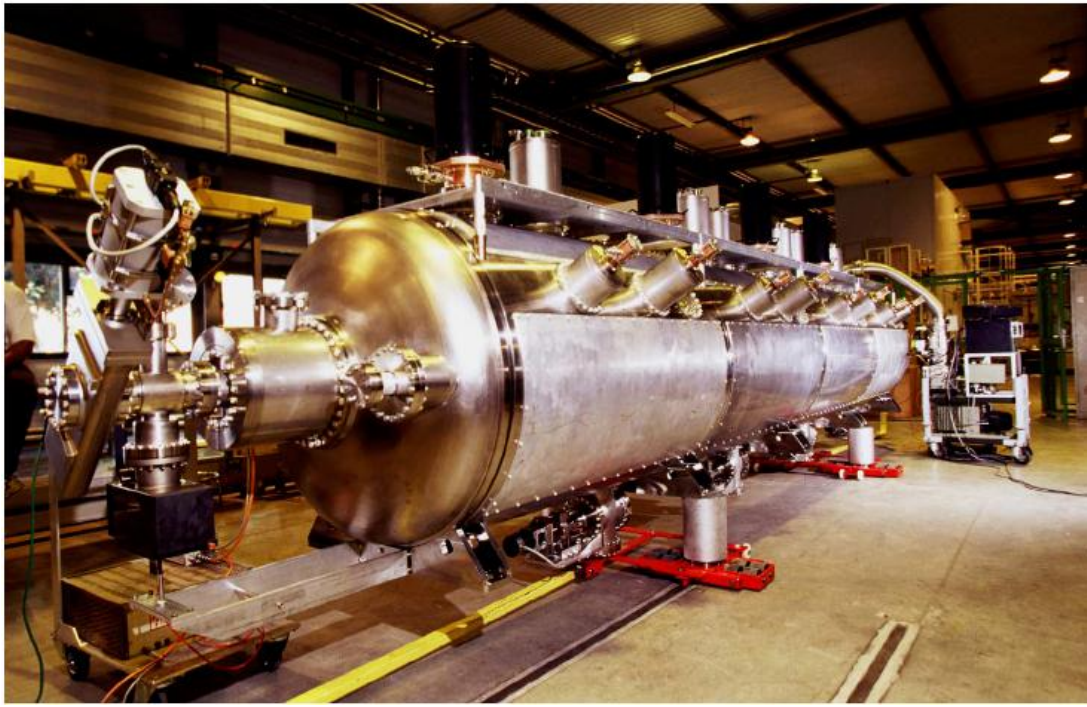
Sputtered Nb Film on Cu Substrate



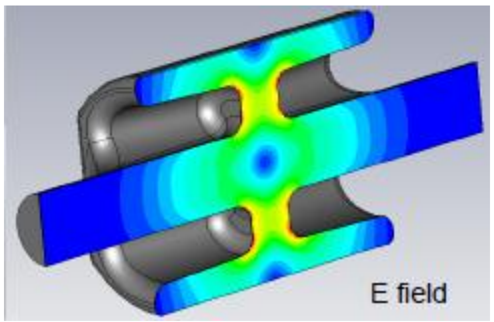
Pushing LEP Cavities Performance: 6 => 7.5 MV/m



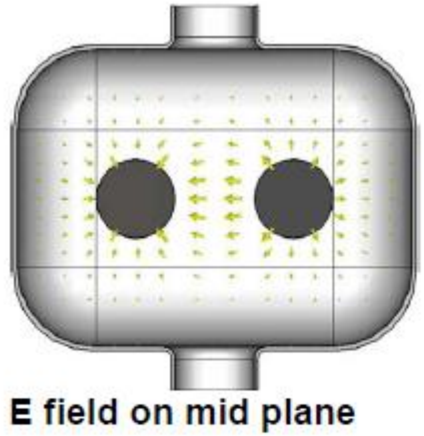
Continue for
LHC Cavity and Cryomodule



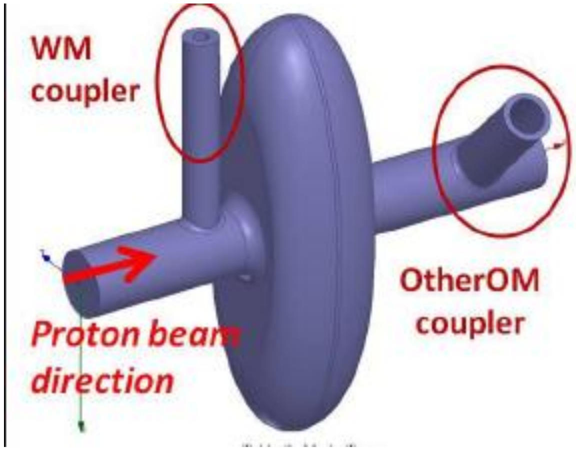
New LHC Challenge for SRF: Luminosity Upgrade Crab Cavity Designs



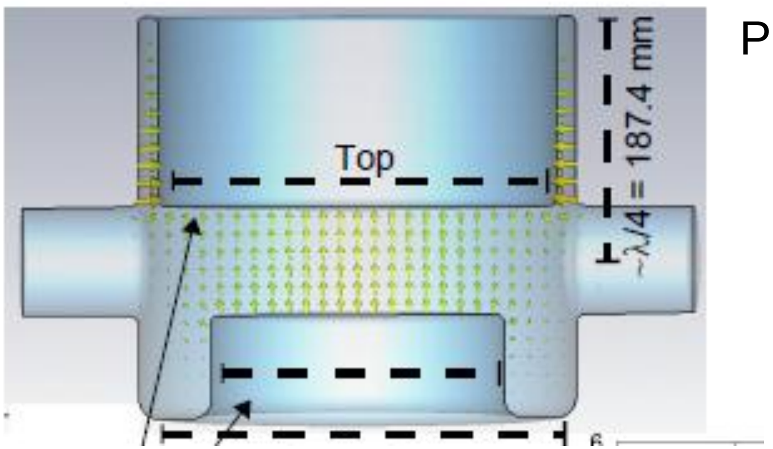
4-rod design



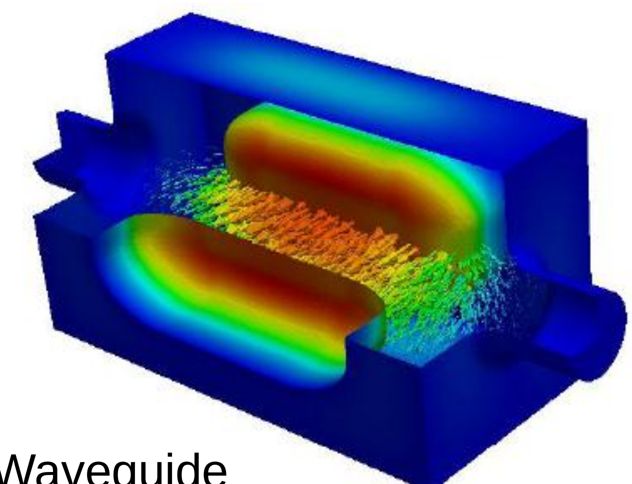
Parallel Bars



Slim Caivty

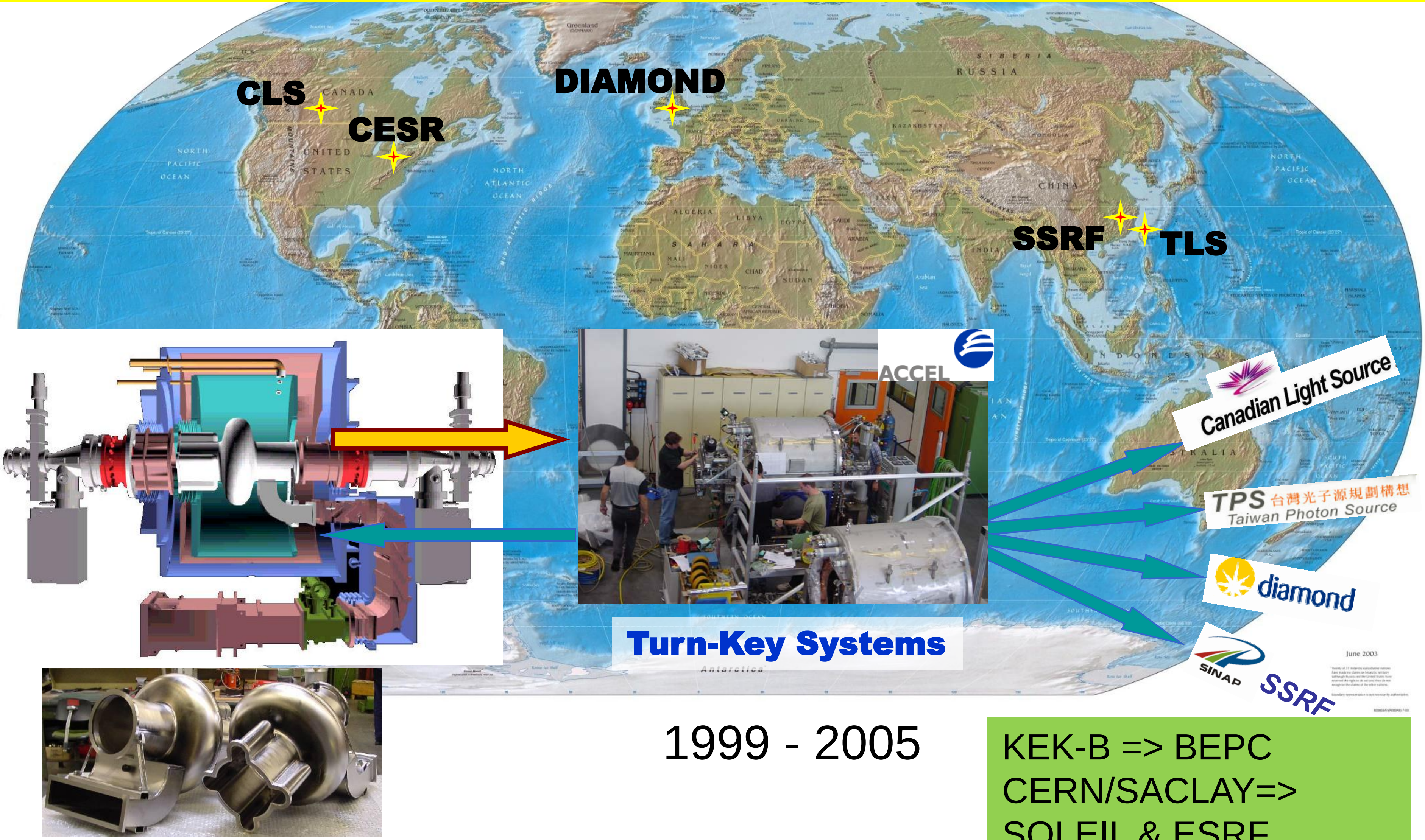


Quarter Wave Resionator



Ridged Waveguide

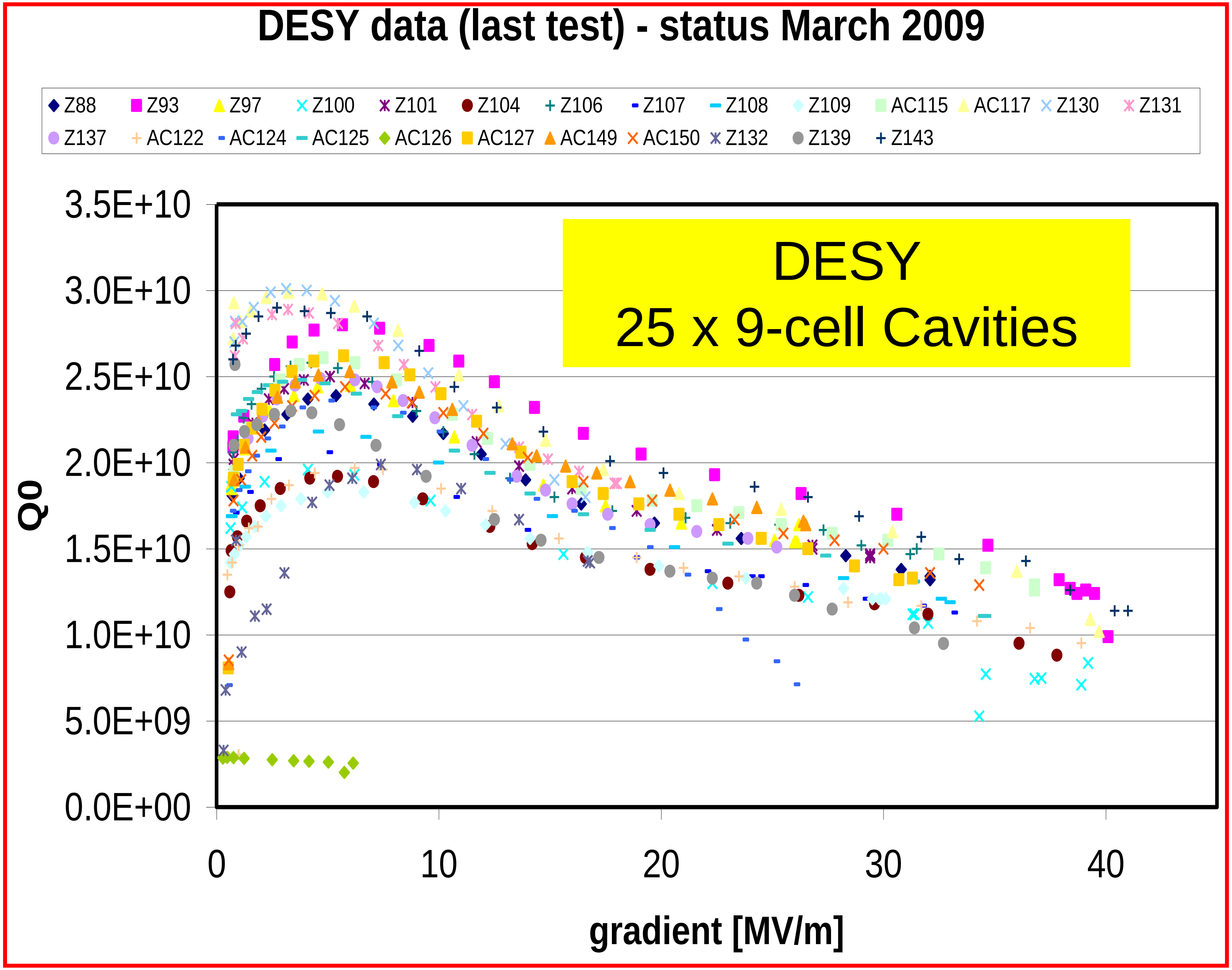
Beyond HEP =>
SRF for Storage Ring Light Sources

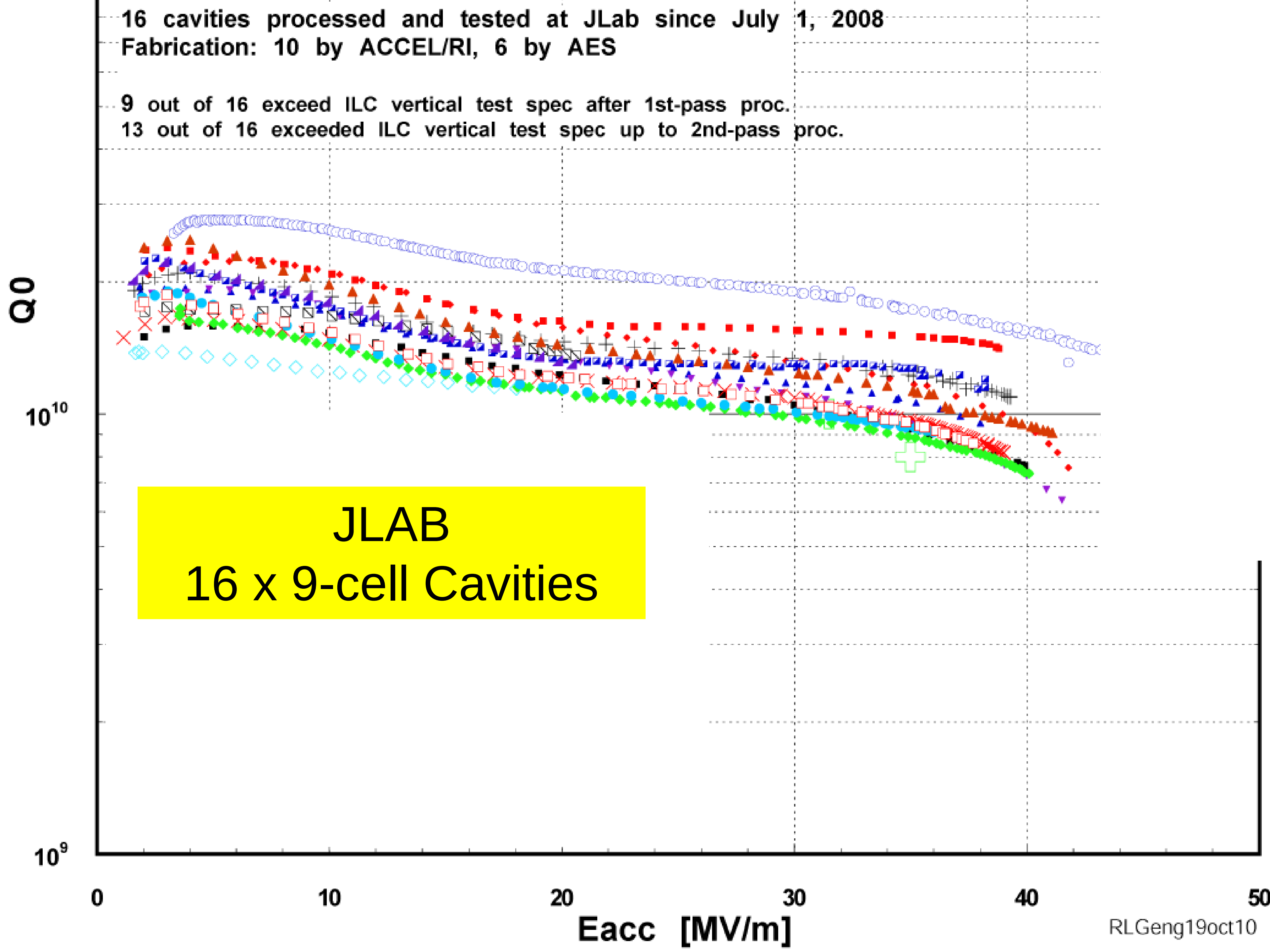


1999 - 2005

KEK-B => BEPC
CERN/SACLAY=>
SOLEIL & ESRF

Fast Forward: SRF Technology Advances
SRF Gradients Have Come A Long Way!


DESY data (last test) - status March 2009
Z88
Z93
Z97
Z100
Z101
Z104
Z106
Z107
Z108
Z109
AC115
AC117
Z130
Z131
Z137
AC122
AC124
AC125
AC126
AC127
AC149
AC150
Z132
Z139
Z143
DESY
25 x 9-cell Cavities
Q0
3.5E+10
3.0E+10
2.5E+10
2.0E+10
1.5E+10
1.0E+10
5.0E+09
0.0E+00
0
10
20
30
40
gradient [MV/m]



16 cavities processed and tested at JLab since July 1, 2008
Fabrication: 10 by ACCEL/RI, 6 by AES
9 out of 16 exceed ILC vertical test spec after 1st-pass proc.
13 out of 16 exceeded ILC vertical test spec up to 2nd-pass proc.
JLAB
16 x 9-cell Cavities
Q0
10^10
10^9
0
10
20
30
40
50
Eacc [MV/m]
RLGeng19oct10

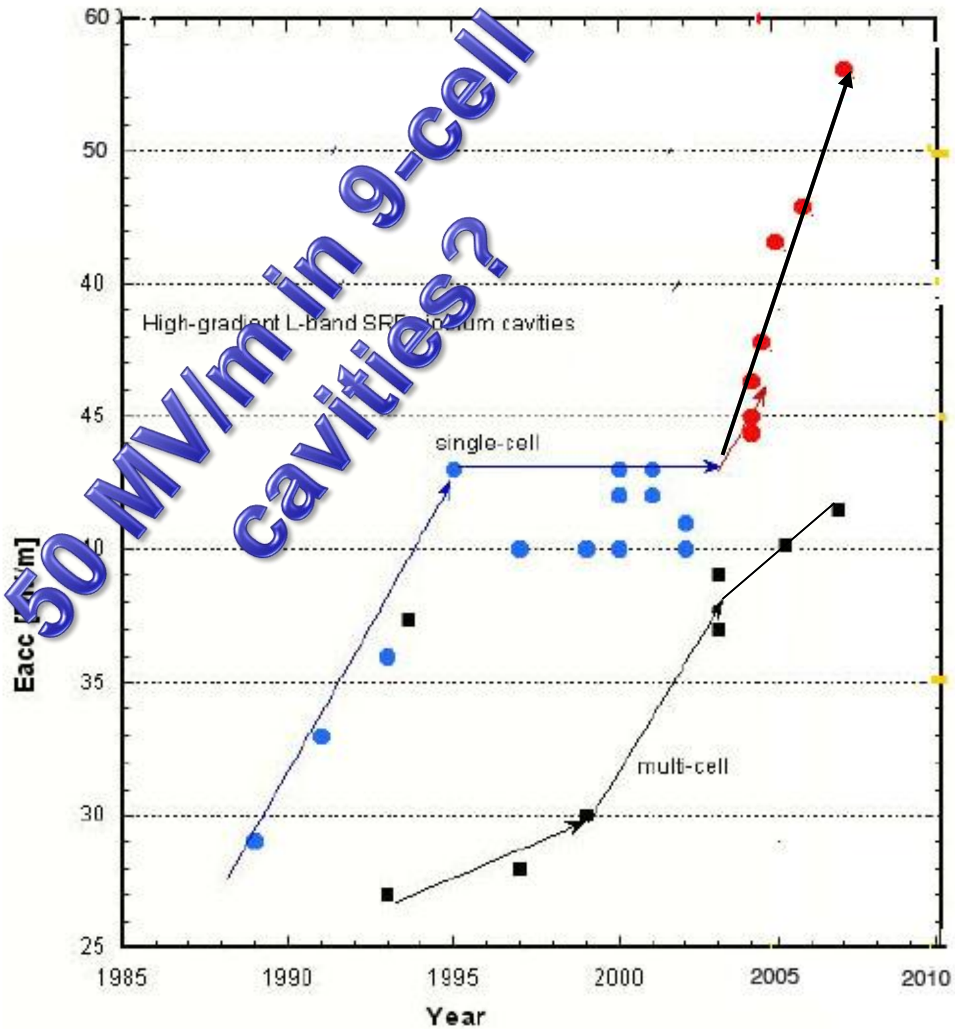
Outstanding Issue for Now

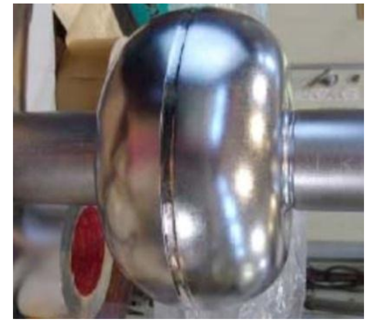
- We need a high Yield at 35 MV/m
  - Can we dream of 90% Yield
- We need a low gradient Spread
- Dominant causes, still
  - Quench
  - Field emission

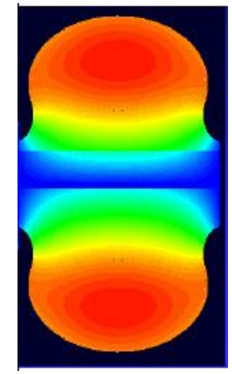
Looking to the Future SRF
The next 50 years?
Preview of Coming Attractions

- What can we expect from SRF Technology? Gradients, Q values
- What can we expect in Accelerator Applications?
  - Near Future – funded projects
  - Far Future projects

Gradients Beyond 40 MV/m ??
Better Shapes Reach 57 - 58 MV/m in Single Cells !
Lower Surface Magnetic Field & RF Lower Losses

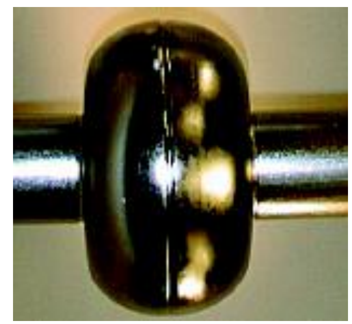


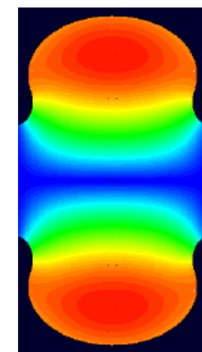




60 mm Re-entrant

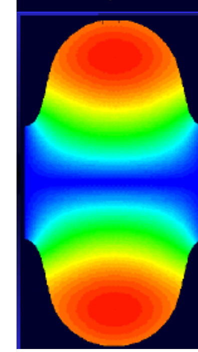
Cornell KEK





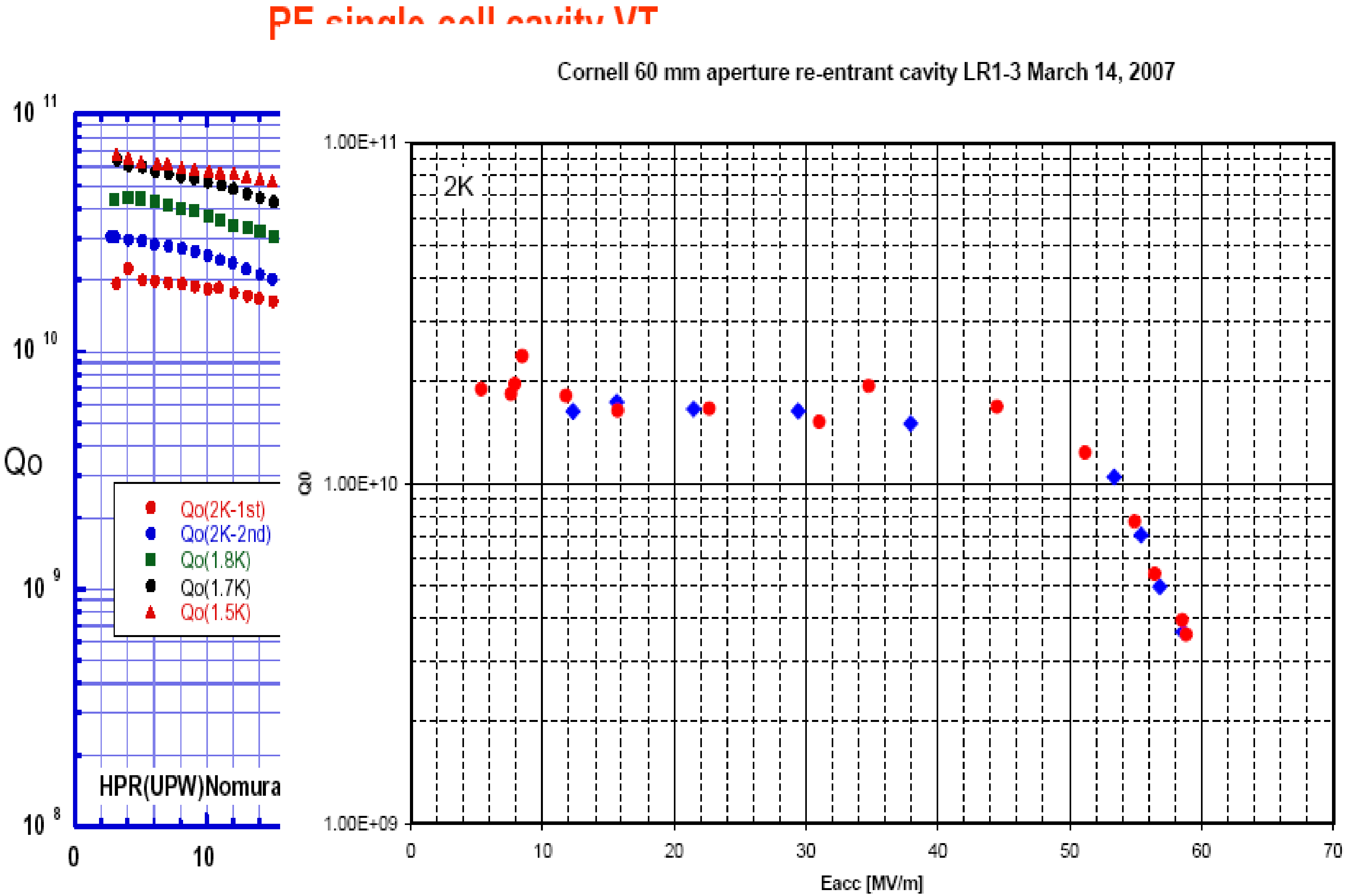
70 mm Re-entrant

Cornell KEK



70 mm Tesla Shape

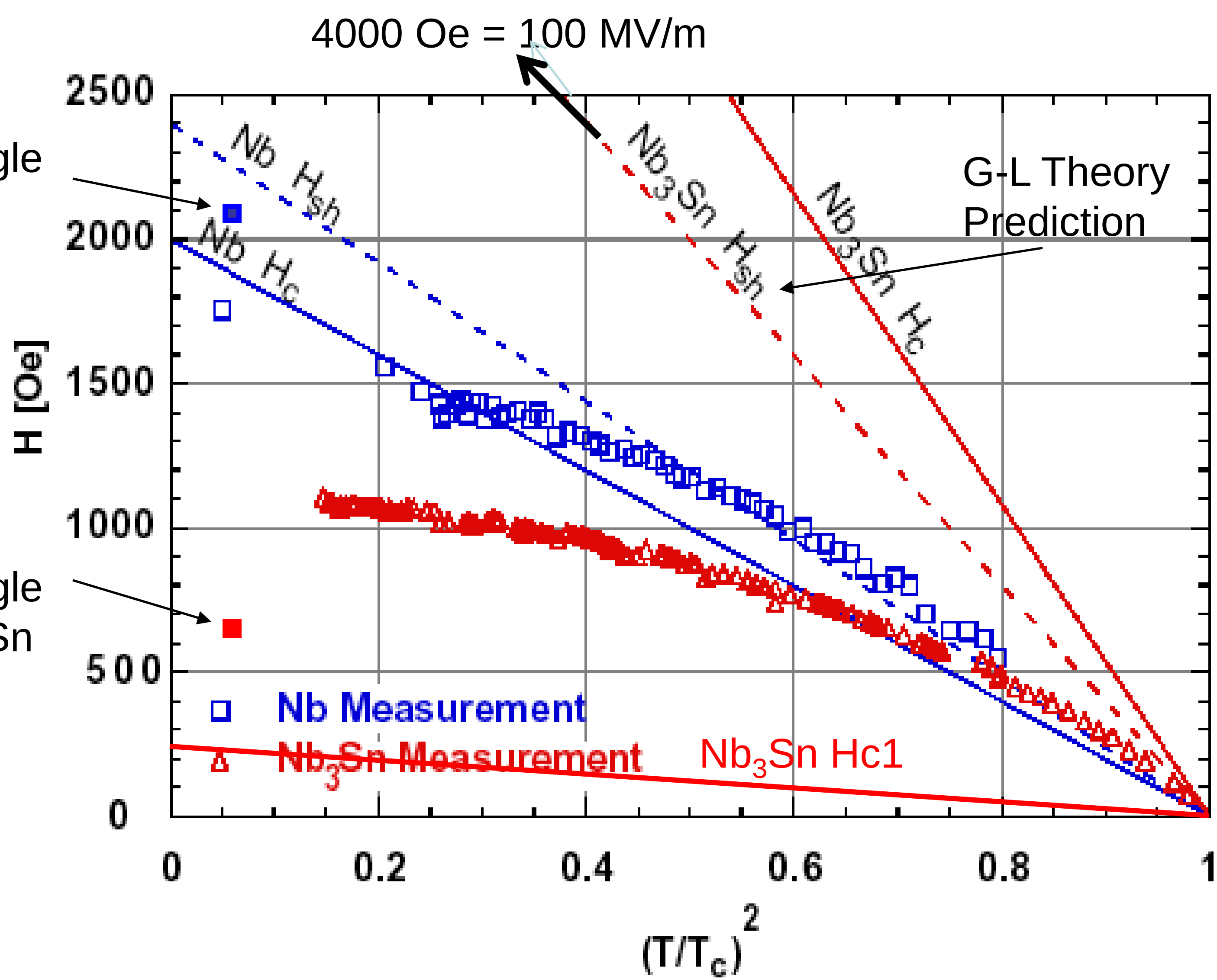
Best Nb Cavities



Beyond Nb? Nb3Sn
50 – 100 MV/m?

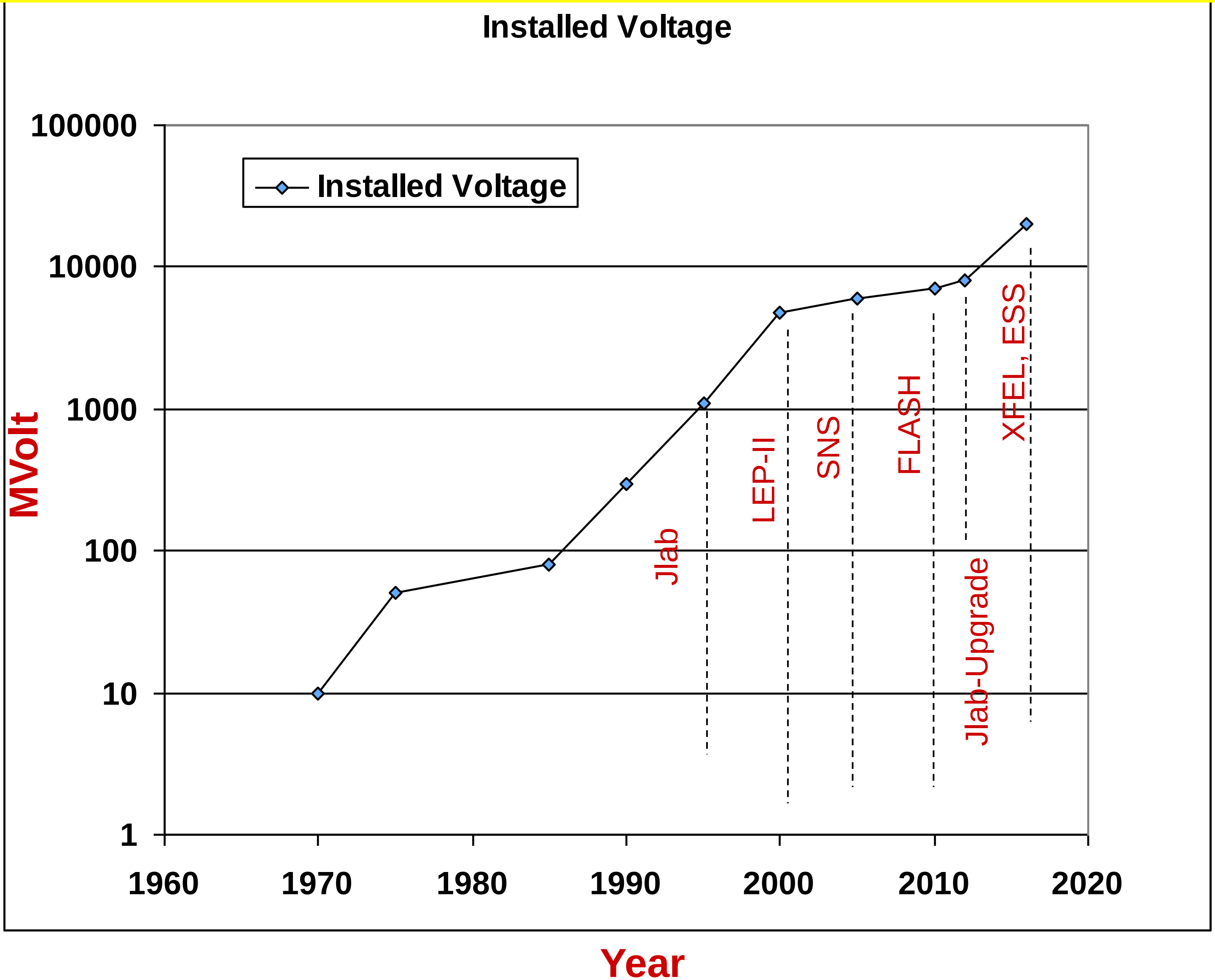
Best single cell Nb cavity result

Best single cell Nb_3Sn cavity result



Near Future Ambitions - Funded

(Total Installed Voltage)

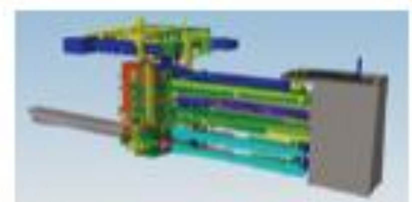


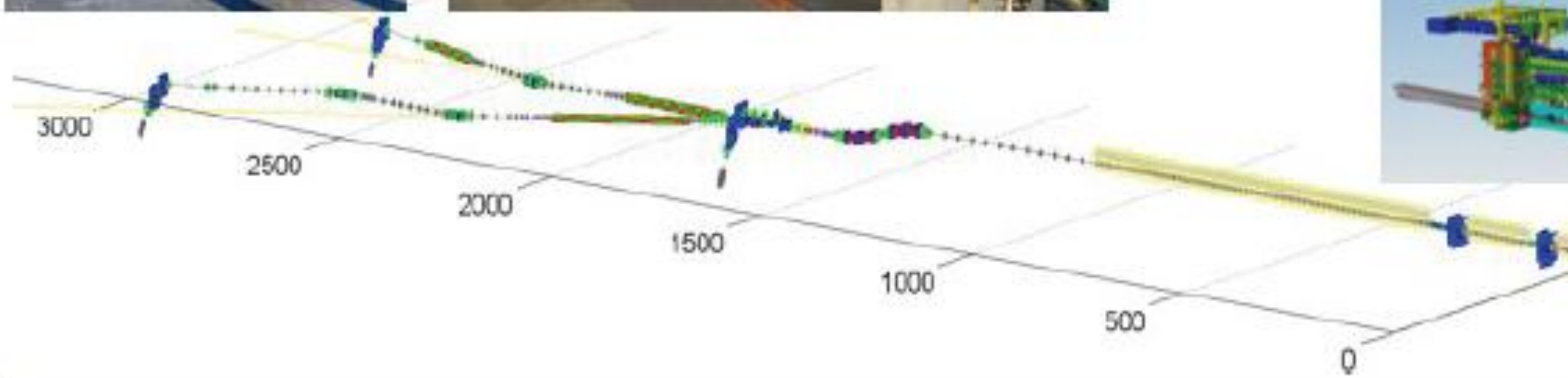
Accelerator Complex with New Parameters

80 accelerator modules

640 accelerating cavities
1.3 GHz / 24.3 MV/m

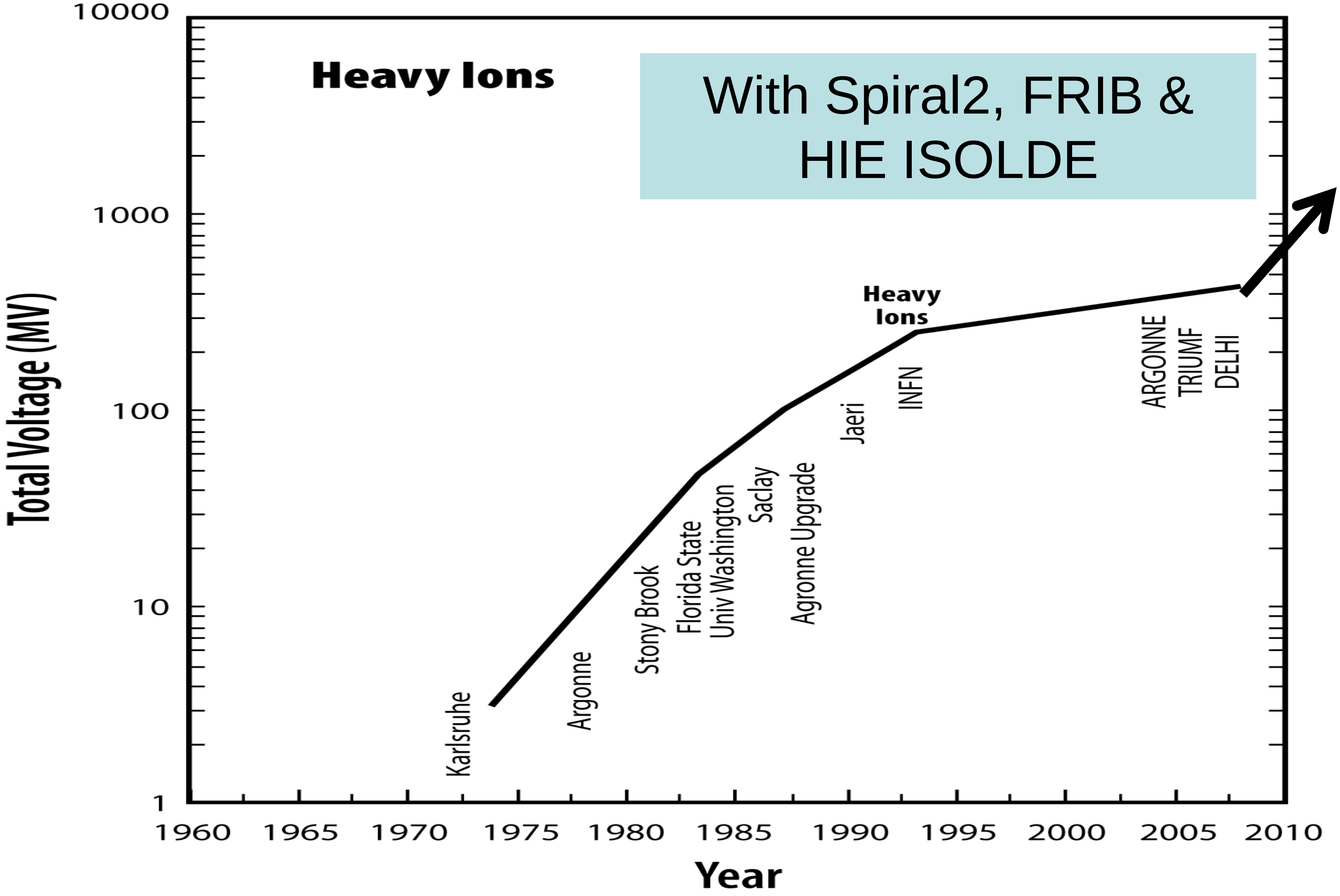
20 RF stations
5.2 MW each



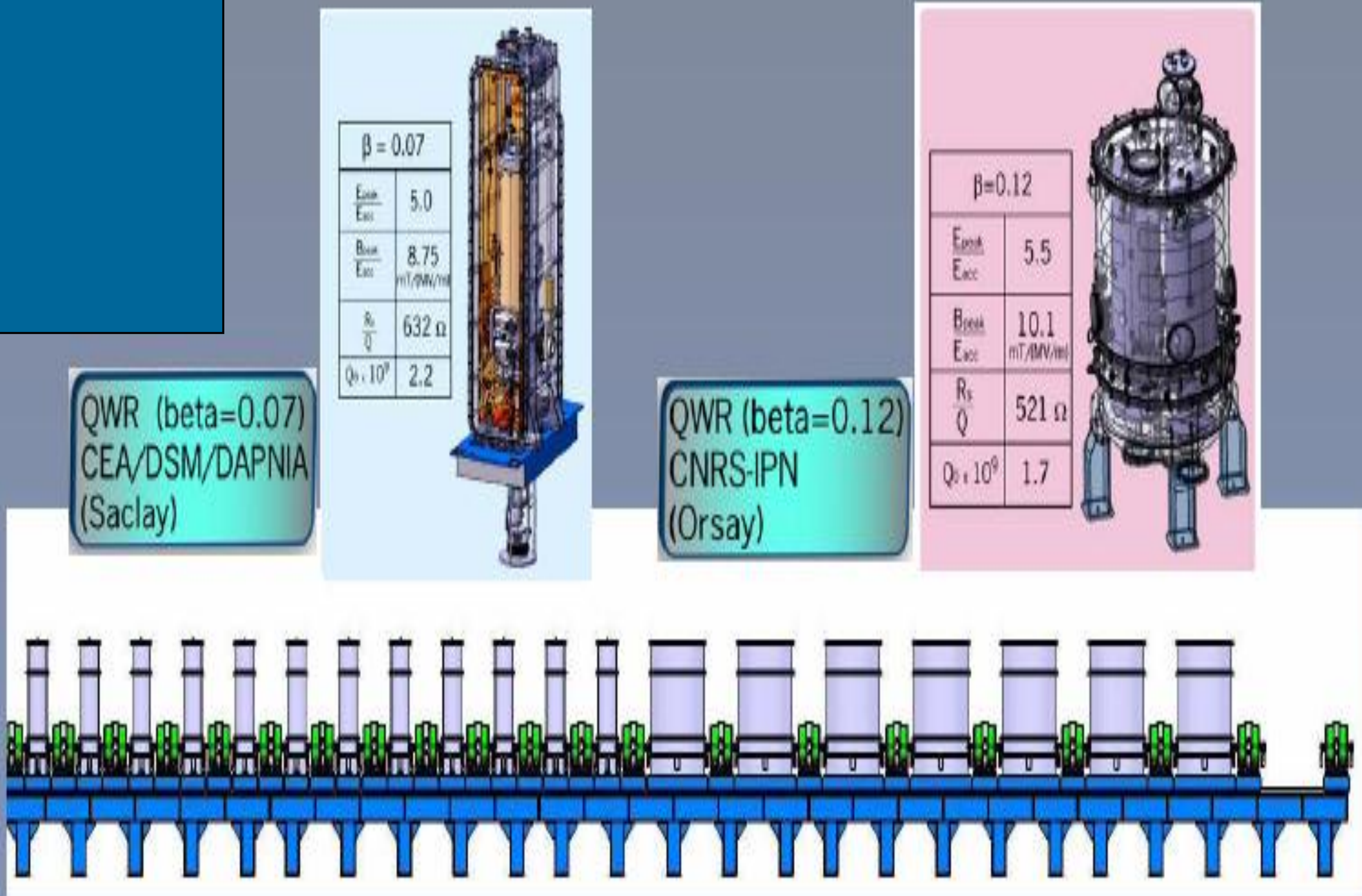


The First Tunnel Section

Total Low Velocity Apps > 1 GeV

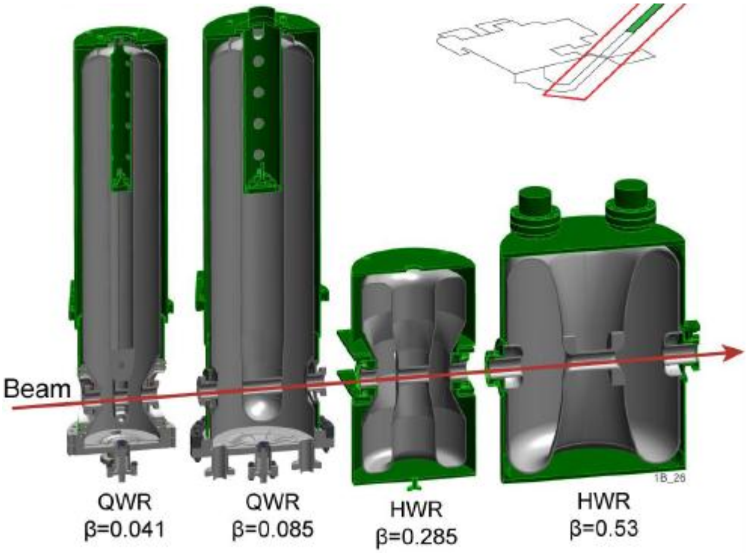


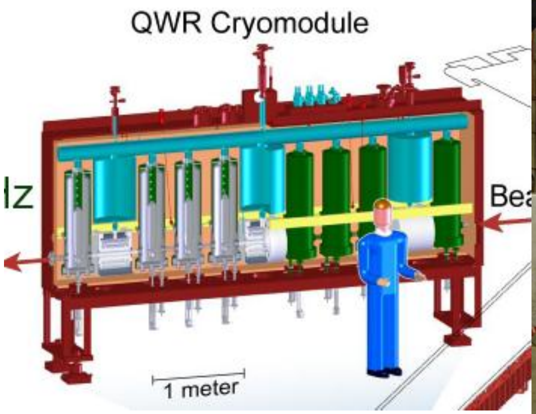
SPIRAL 2

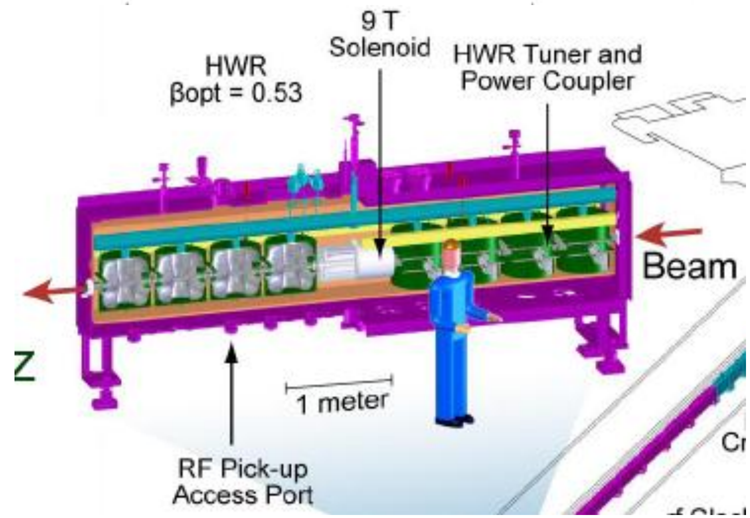

β = 0.07
Epeak/Eacc 5.0
Bpeak/Eacc 8.75 mT/(MV/m)
Rs/Q 632 Ω
Q0 x 10^9 2.2
QWR (beta=0.07)
CEA/DSM/DAPNIA
(Saclay)
QWR (beta=0.12)
CNRS-IPN
(Orsay)
β=0.12
Epeak/Eacc 5.5
Bpeak/Eacc 10.1 mT/(MV/m)
Rs/Q 521 Ω
Q0 x 10^9 1.7

FRIB, Facility for Rare Isotope Beams at MSU

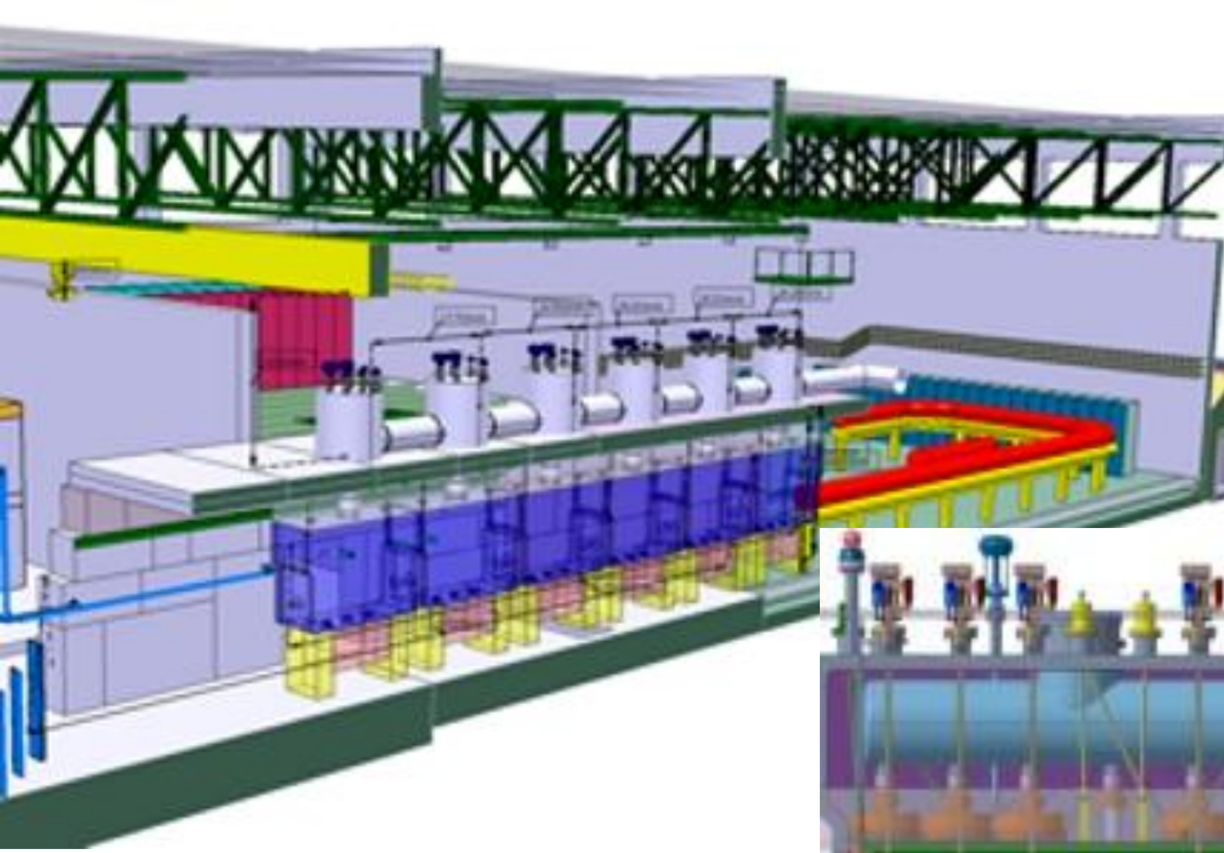
- FRIB will allow major advances in nuclear science and nuclear astro-physics
- 336 Resonators QWR and HWR

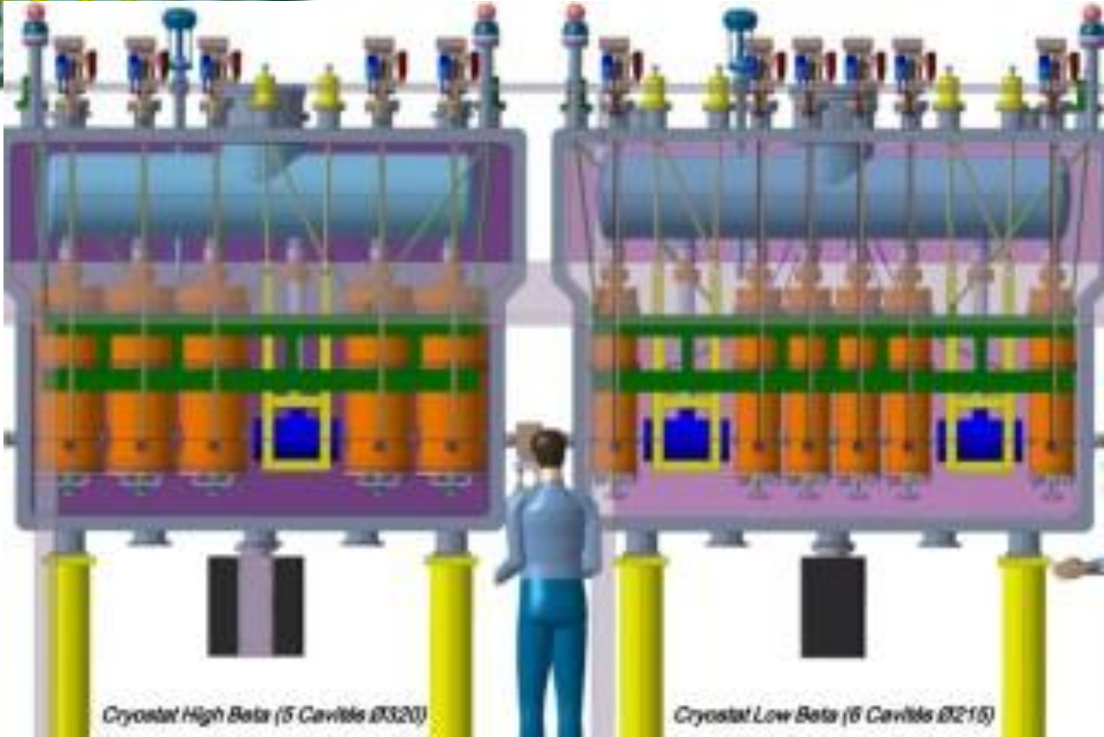






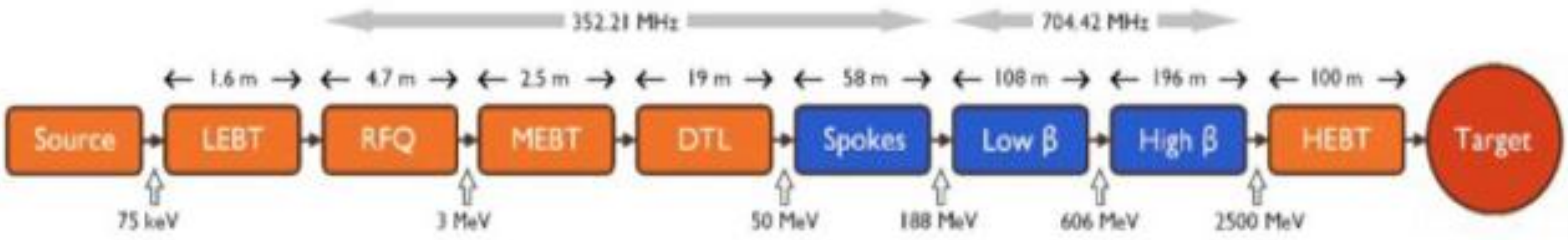
CERN HIE-ISOLDE





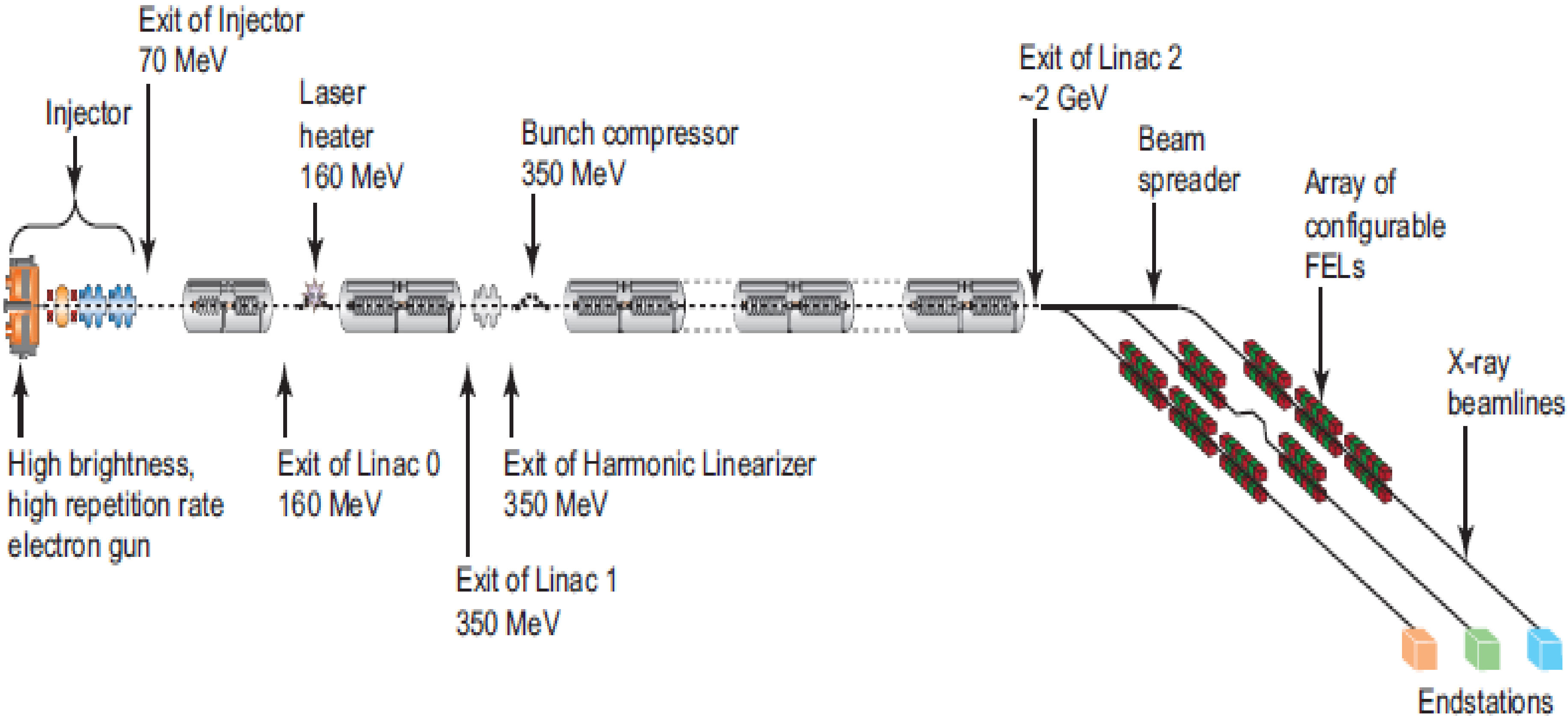
European Spallation Source - Lund

Combination of Low and High Velocities
Another 2.5 GeV

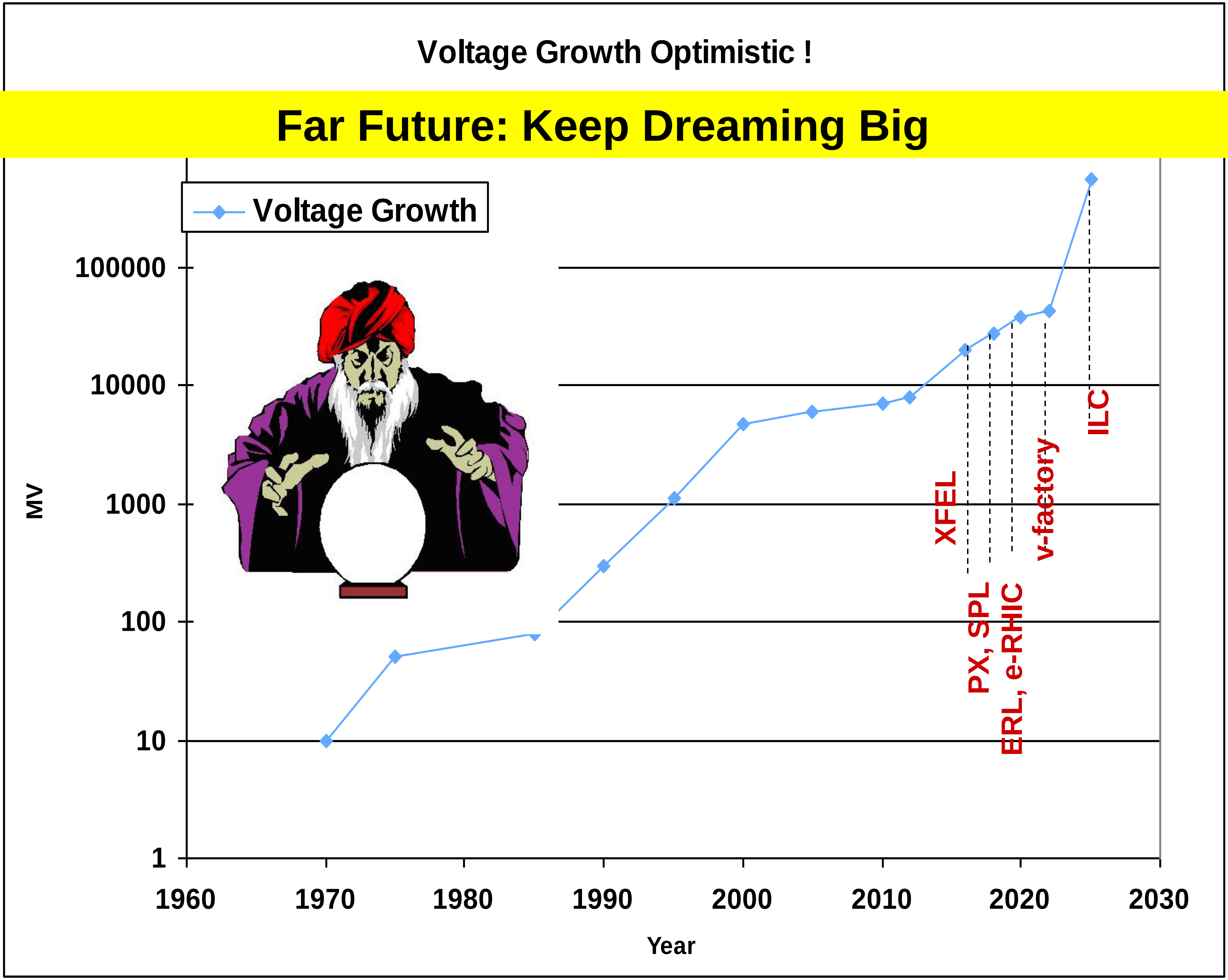


	Length (m)	Input Energy (MeV)	Frequency (MHz)	Geometric β	# of Sections	Temp (K)
RFQ	4.7	75×10^{-3}	352.2	--	1	≈ 300
DTL	19	3	352.2	--	3	≈ 300
Spoke	58	50	352.2	0.57	14 (2c)	≈ 2
Low Beta	108	188	704.4	0.70	16 (4c)	≈ 2
High Beta	196	606	704.4	0.90	15 (8c)	≈ 2
HEBT	100	2500	--	--	--	--

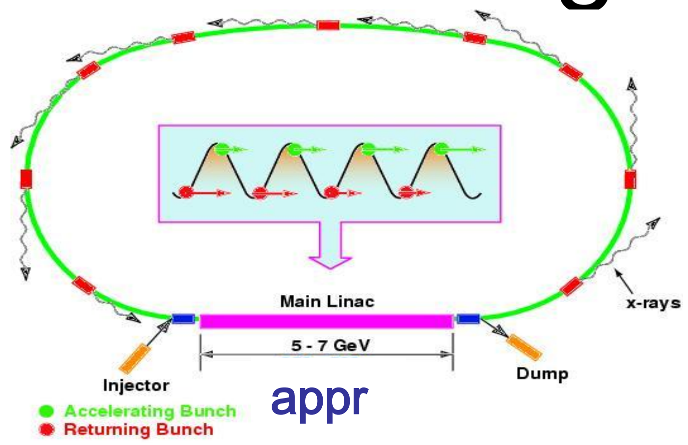
Soft X-ray FEL
2 GeV NGLS at LBNL – Berkeley



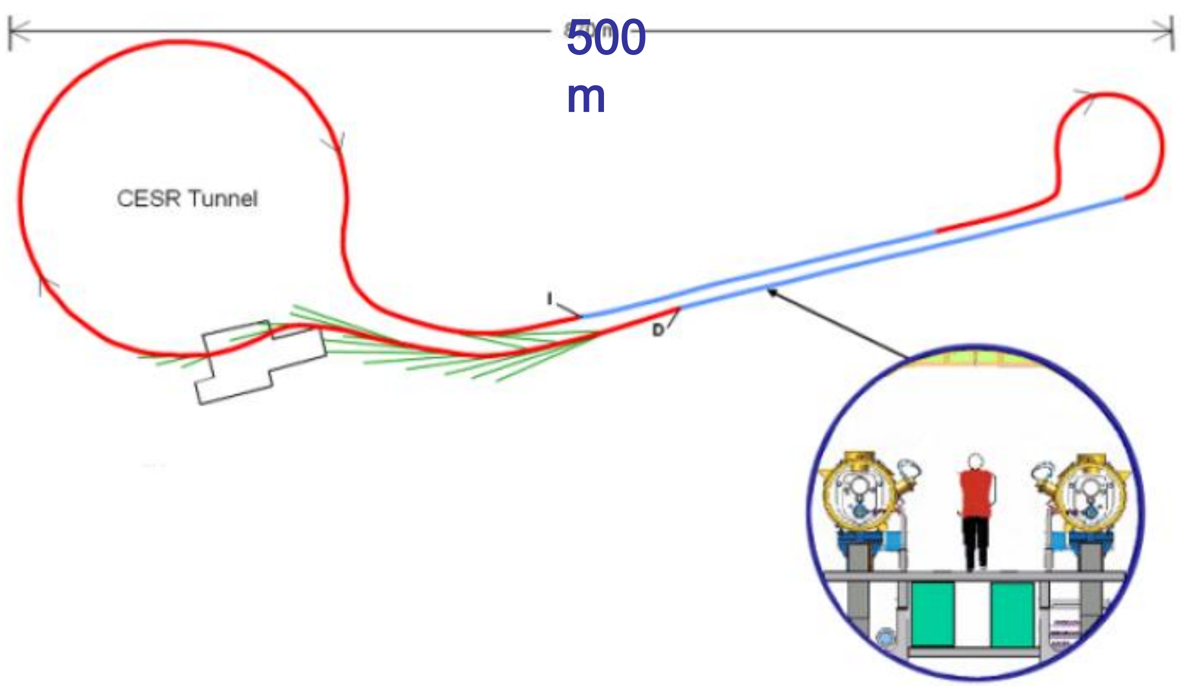
Far Future: Keep Dreaming Big



Energy Recovery Linac
Next Generation Light Source



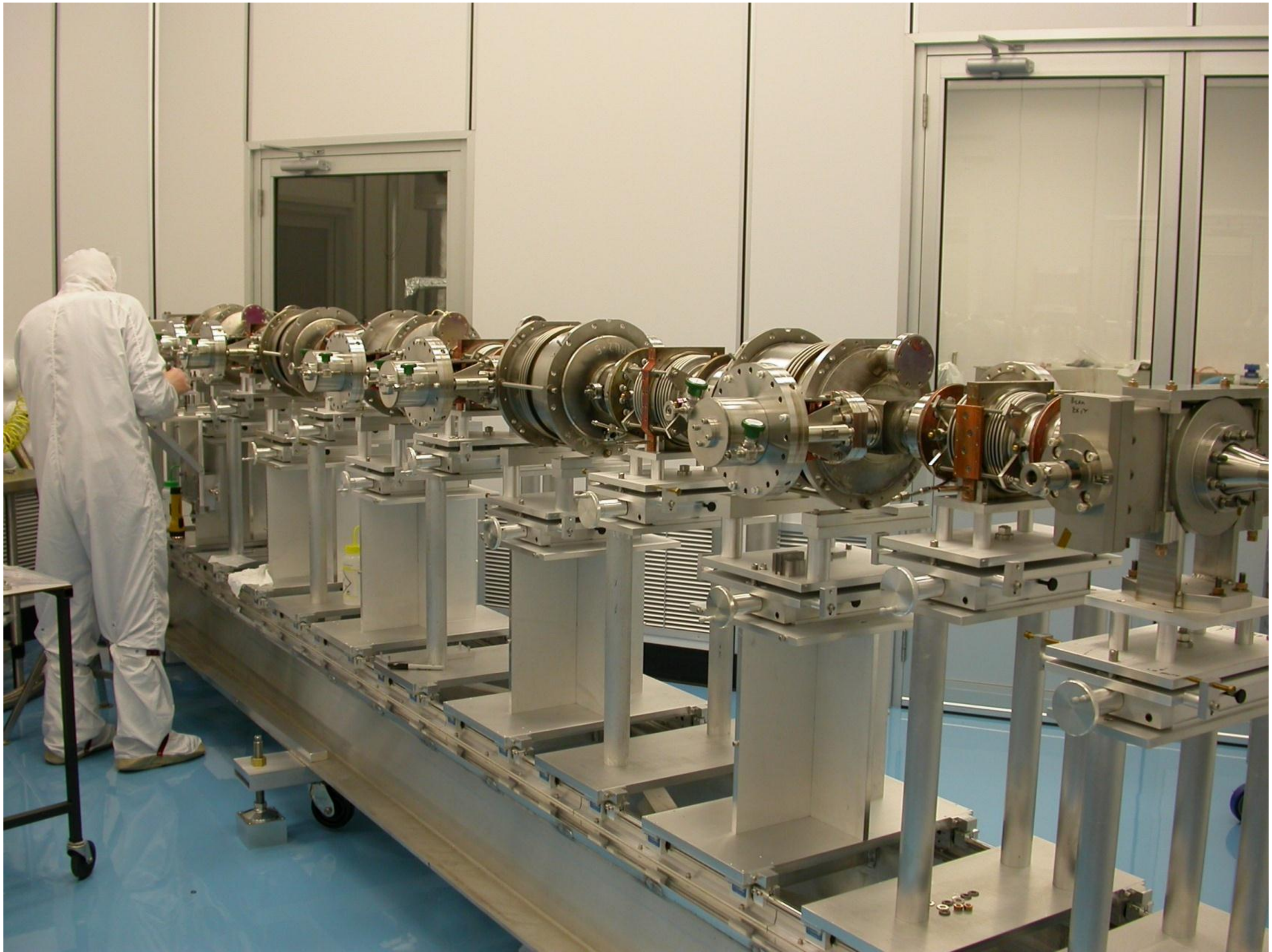
approx. 500 m



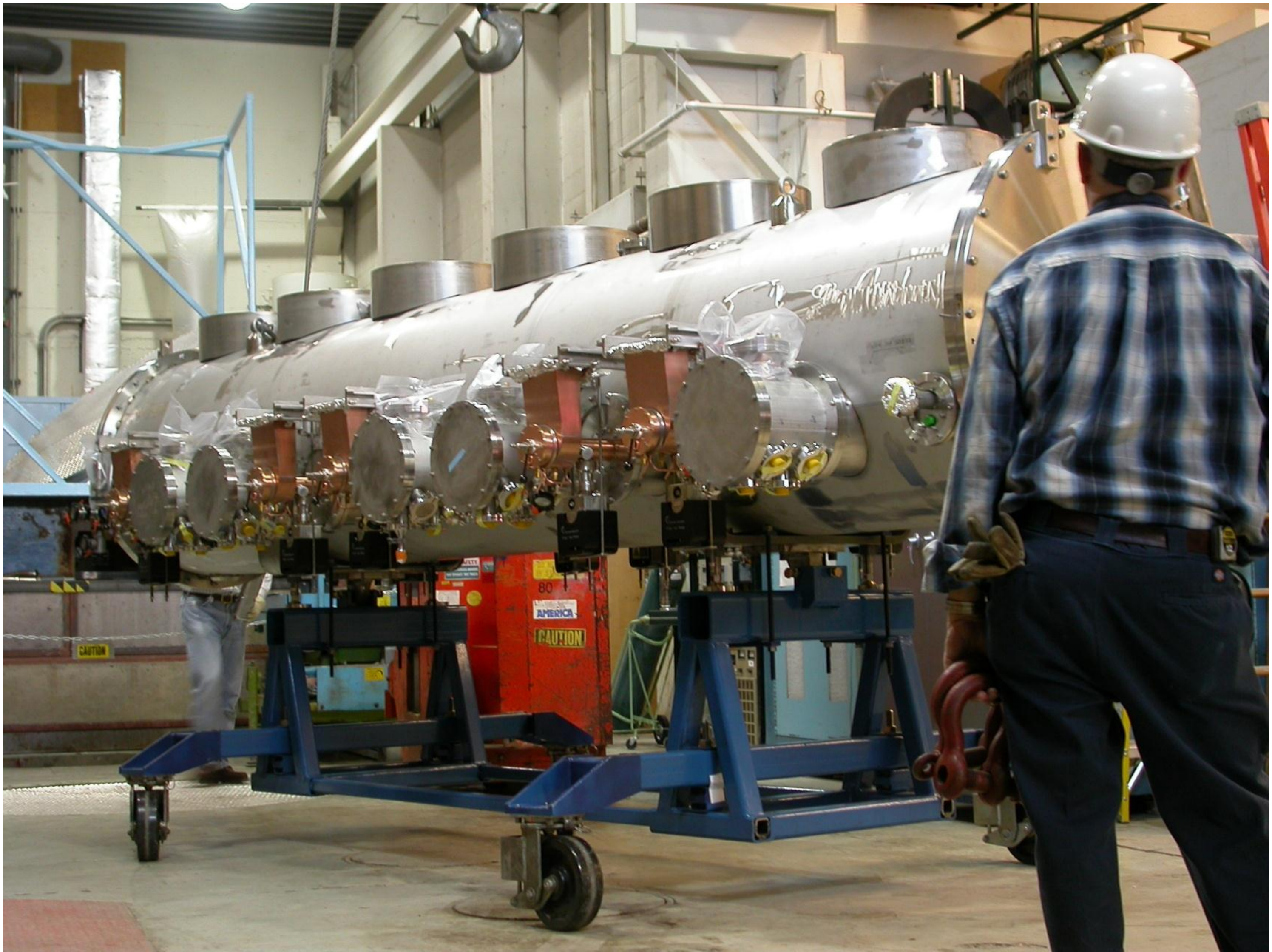
Many ERL Light Source Projects Under Study

- Will need higher Q's for CW applications at moderate gradients 20 MV/m
- Determine methods to get Q >$3x10^{10}$ at 1.8 K?
- Projects to benefit from high Q ERLs
  - Cornell
  - Daresbury ALICE
  - Berlin Prototype
  - KEK-ERL
  - BNL for cooling RHIC beams

Cornell Injector Cavity String
6 x 2-cell cavities



Cornell – Injector Cryomodule
15 MV/m, 25 mA CW beam injected



Best Q Value

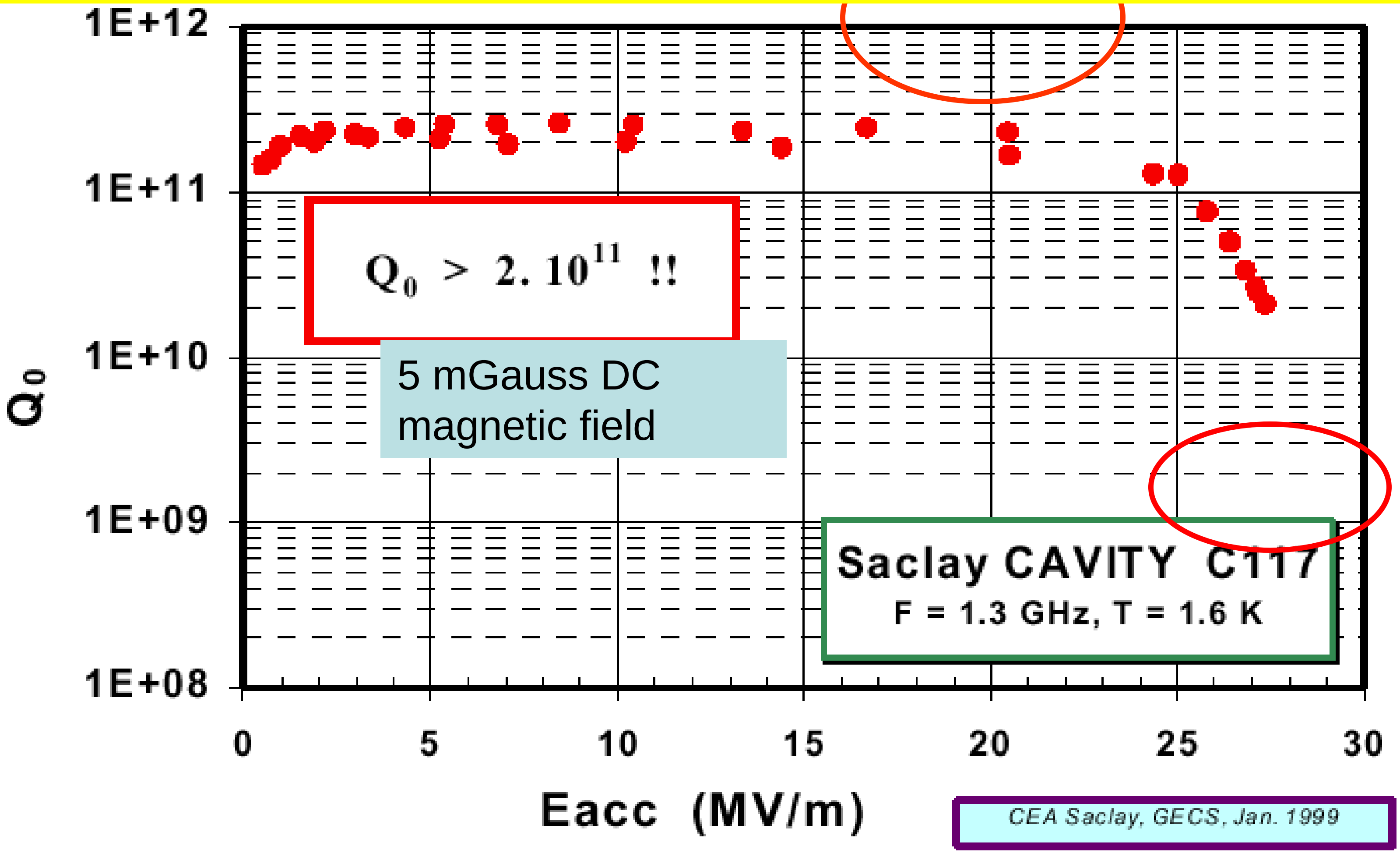
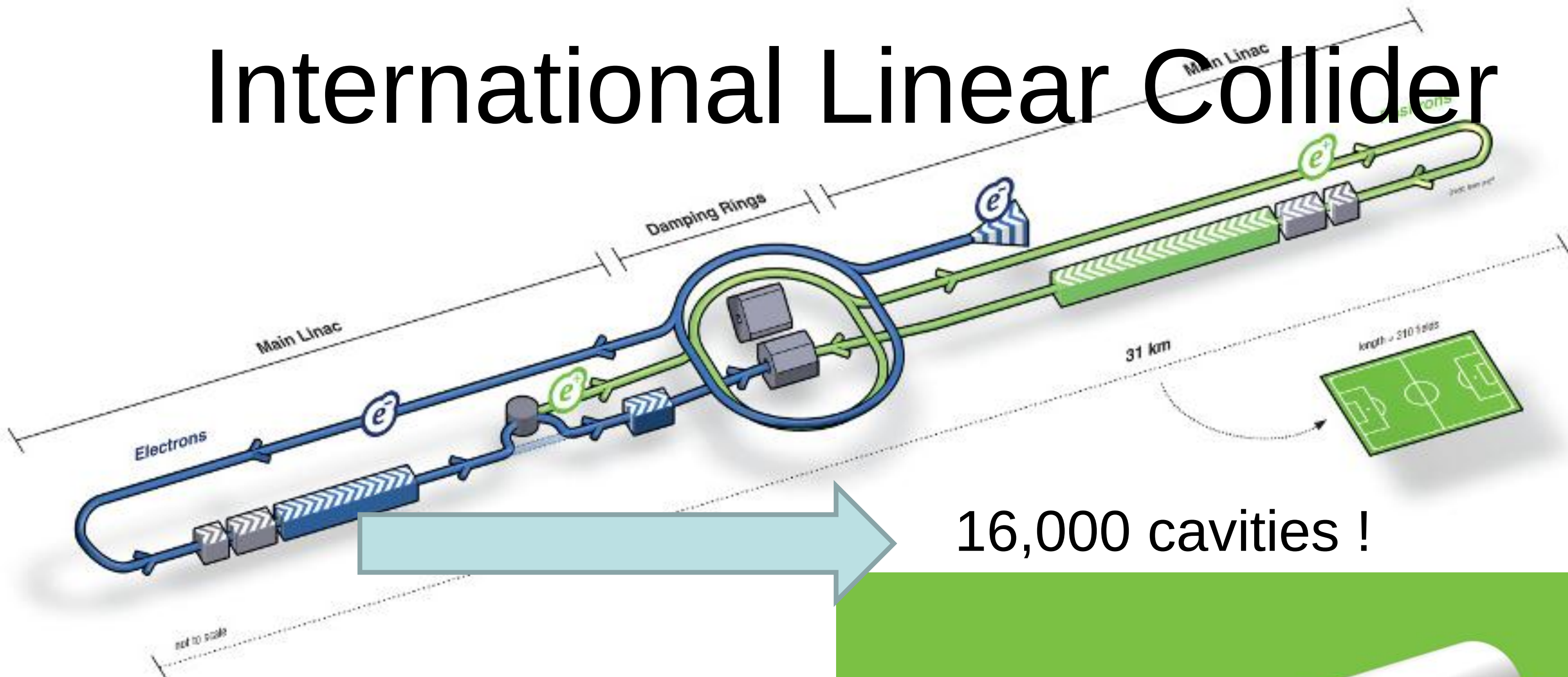


Figure 2 – Residual resistance as low as 0.5 nΩ is actually measured on large area cavities, giving an intrinsic quality factor Q_0 exceeding 2.10^{11}

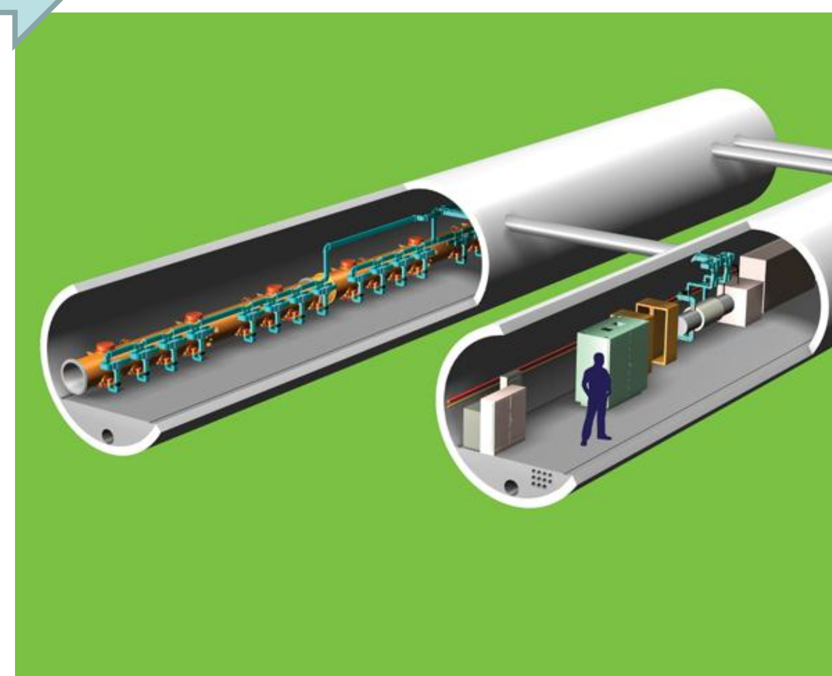
Prepare for the 800 Pound Gorilla

- The International Linear Collider (ILC)

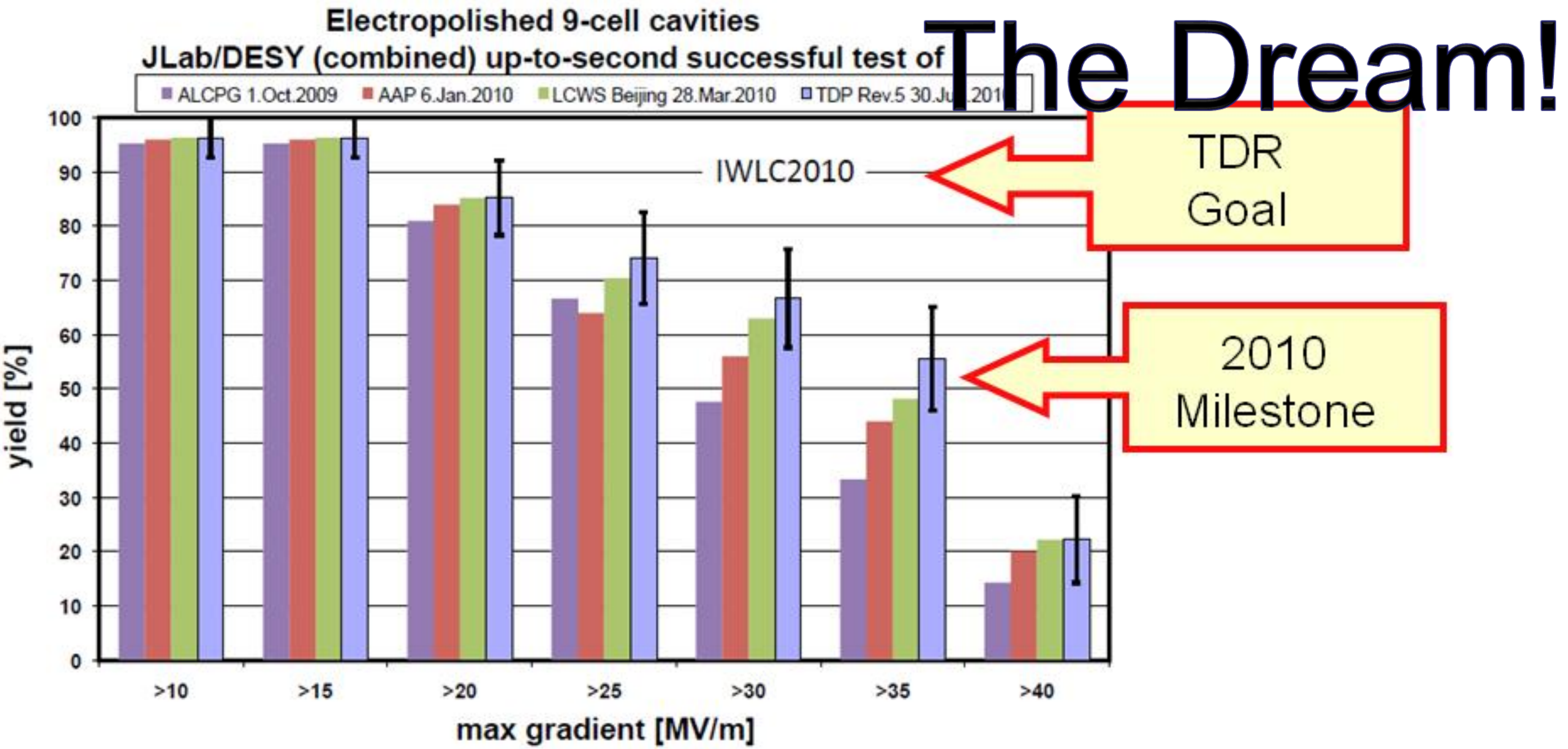
International Linear Collider



16,000 cavities !

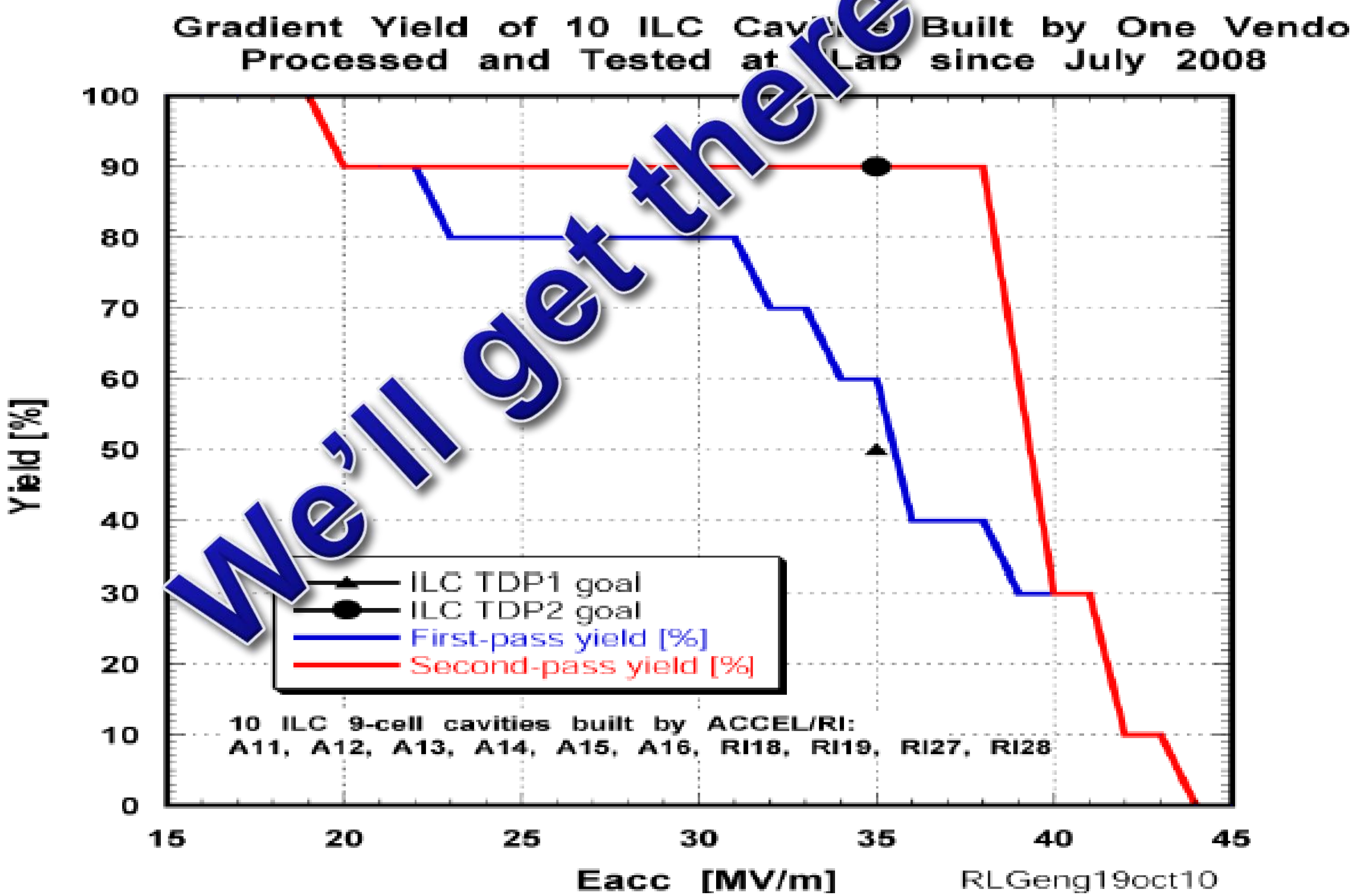


Cavity Gradient Milestone Achieved

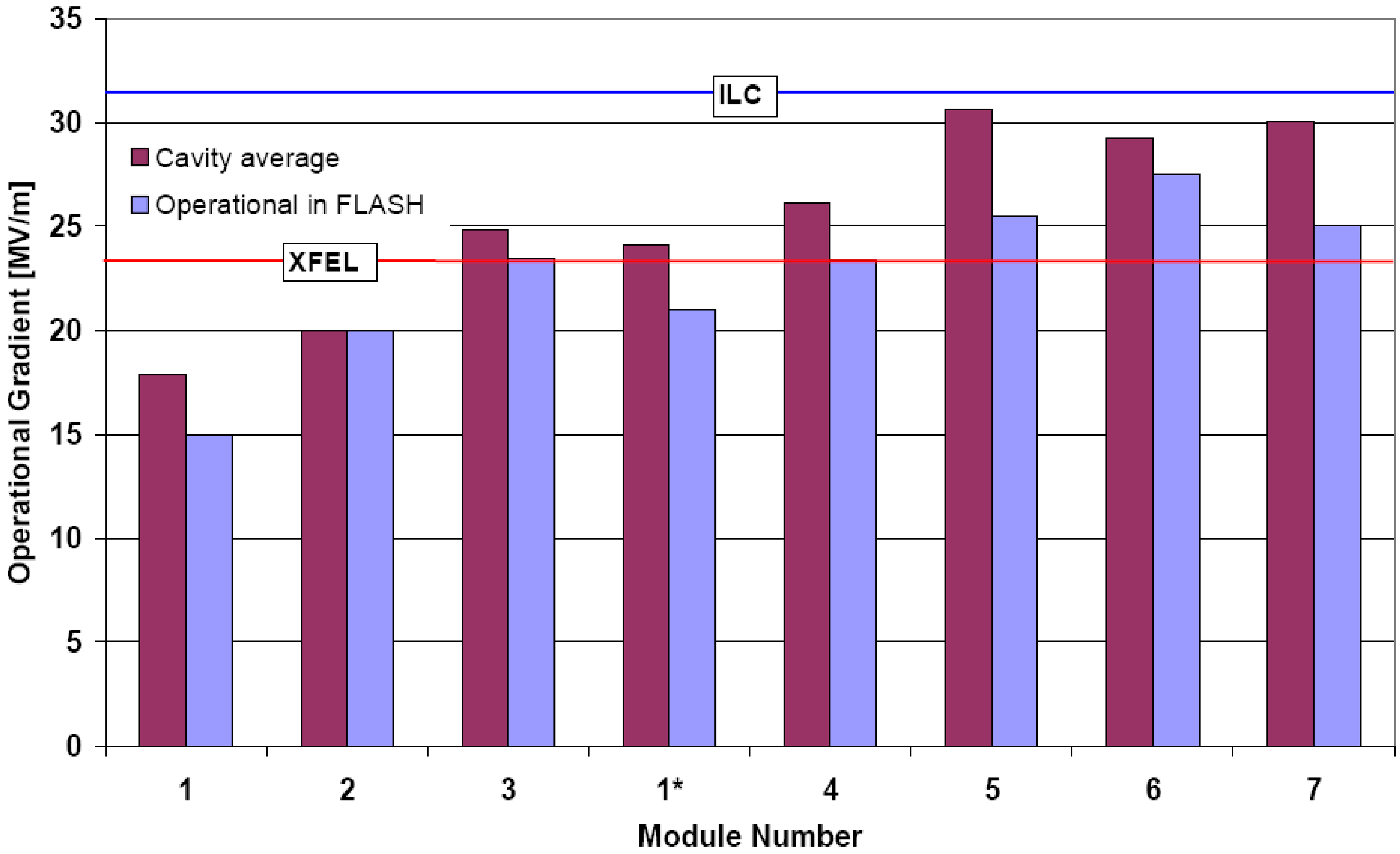


One (Best) Vendor Yield – 90%

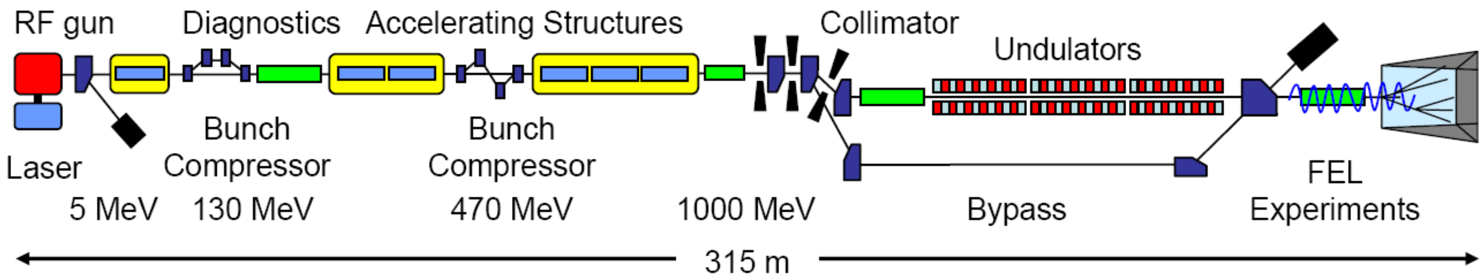
An example of 90% yield at 35 MV/m w/ Q0 >= 8E9
ACCEL/RI cavities without bias



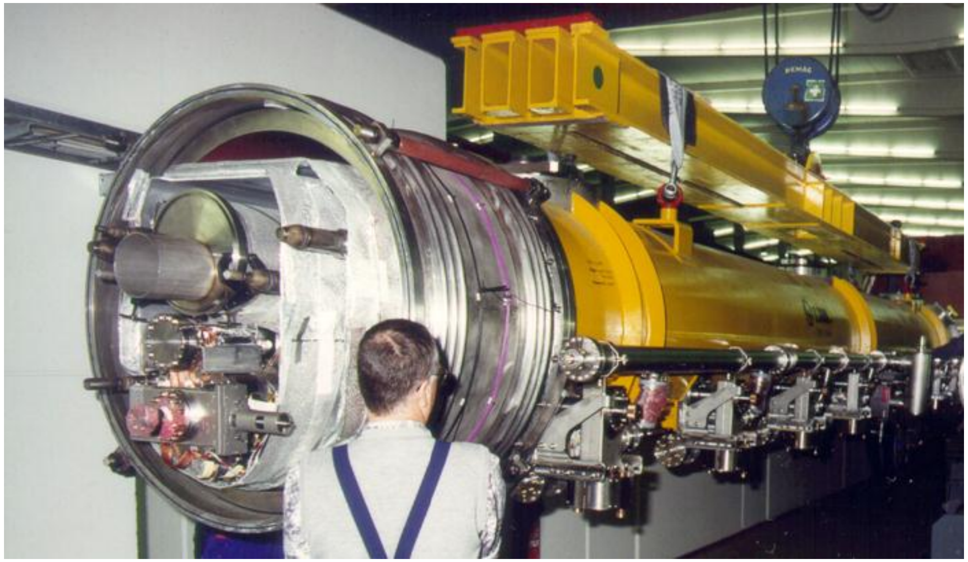
CryoModule Performance
ILC – Goal = 31.5 MV/m



Six modules installed in FLASH at DESY provide 1 GeV beam, ILC-Like Beam Accelerated:



With 48, 9-cell cavities operating between 20 – 25 MV/m.
Strong basis for XFEL which will also be a prototype for ILC



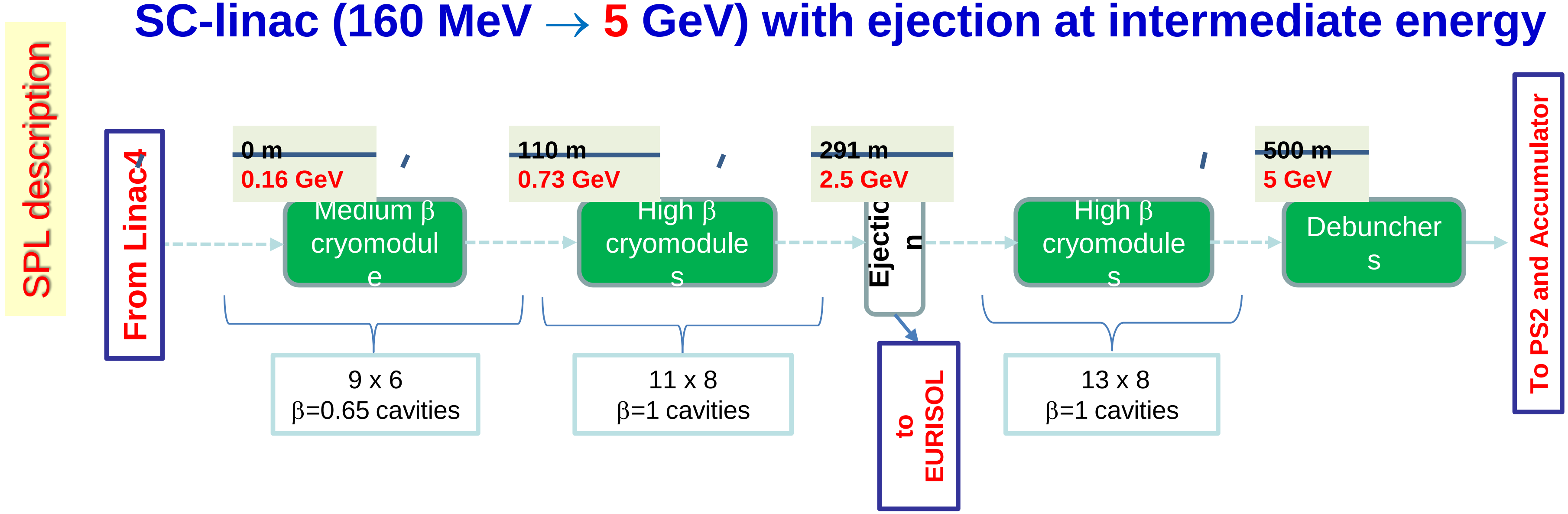
High Intensity Proton Frontier

- Upgrade proton injector complex
- High intensity neutrino beams
- Neutrino factory
- Muon collider
- Accelerator Transmutation Nuclear Waste
- Energy Amplifier with Thorium
  - Fermilab PX – 3 GeV
  - CERN SPL – 4 – 5 GeV (2 – 4 MW)
  - India high intensity accelerator >10 MW (eventually)

CERN - SPL

- Start with Low Power SPL, 4 GeV, 20 mA
- Upgraded infrastructure (RF, cooling & electricity, etc.)
- Add 5 high β cryomodules to accelerate up to 5 GeV (π production for ν Factory)
- Beam power 2 – 4 MW

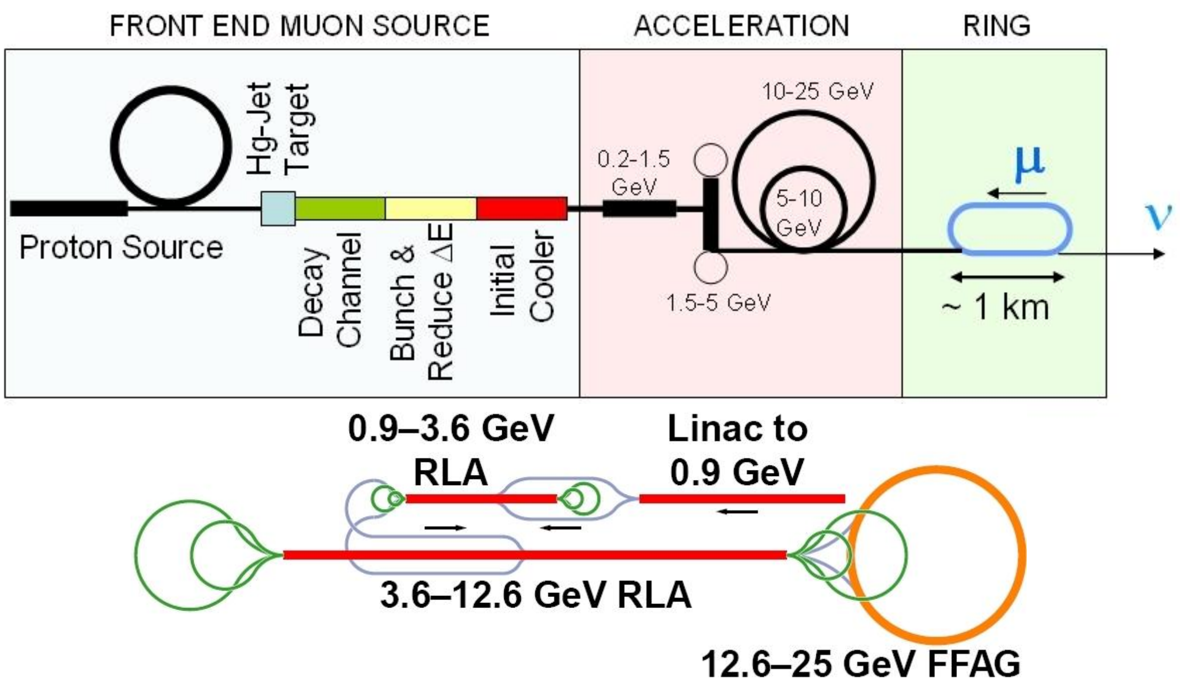
SC-linac (160 MeV → 5 GeV) with ejection at intermediate energy



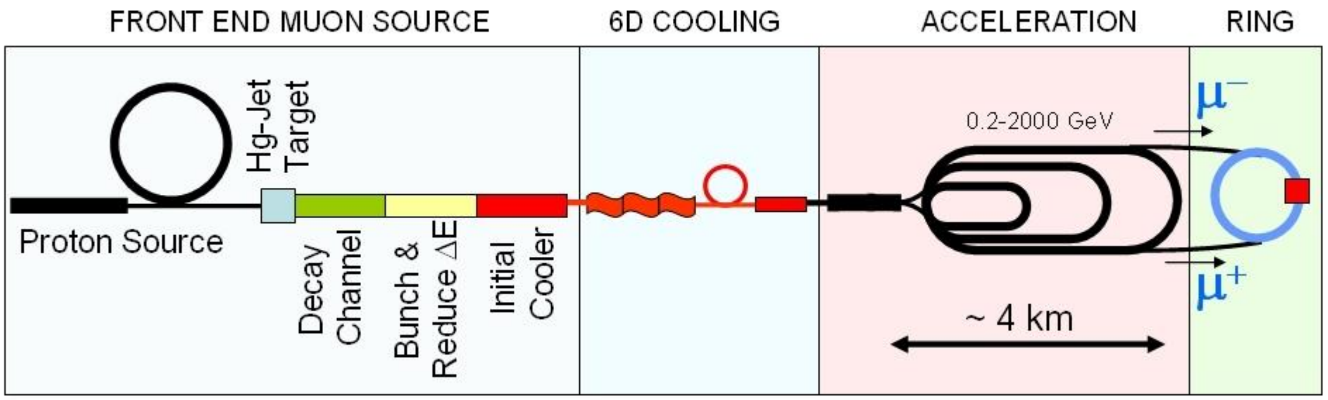
Length: ~500 m

High Power Protons:
Basis for a Future Neutrino Factory & Muon Collider

- Proton Driver needs 4 MW
- Neutrino Factory needs about 4 GV acceleration, multiple pas



- Muon Collider needs 200 GeV acceleration
  - Depending on number of passes in RLA
  - Five passes?



Concluding Wish!

May all these “coming attractions” face ZERO RESISTANCE !!