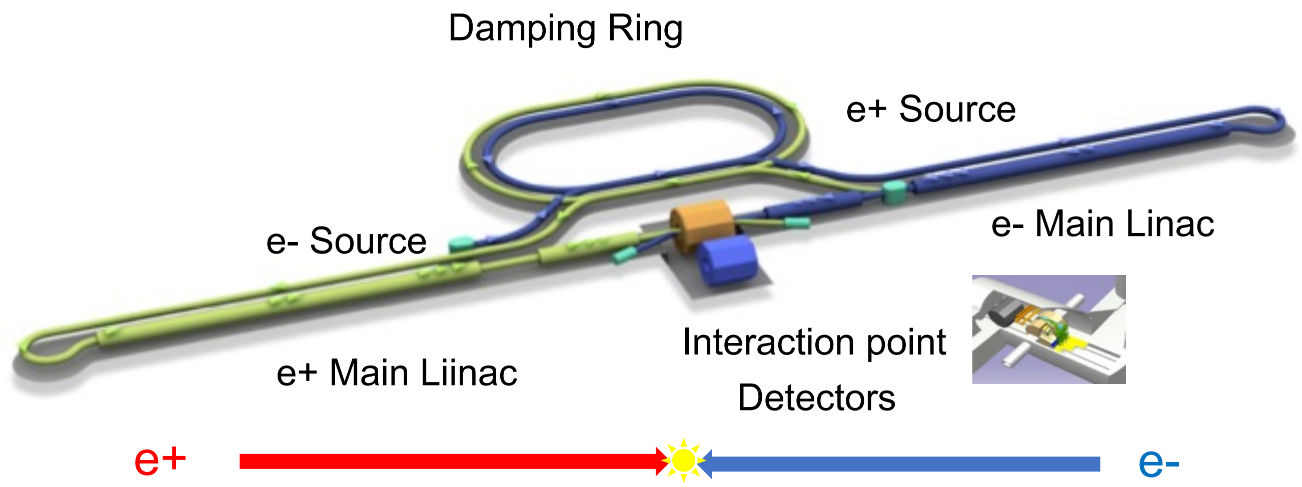
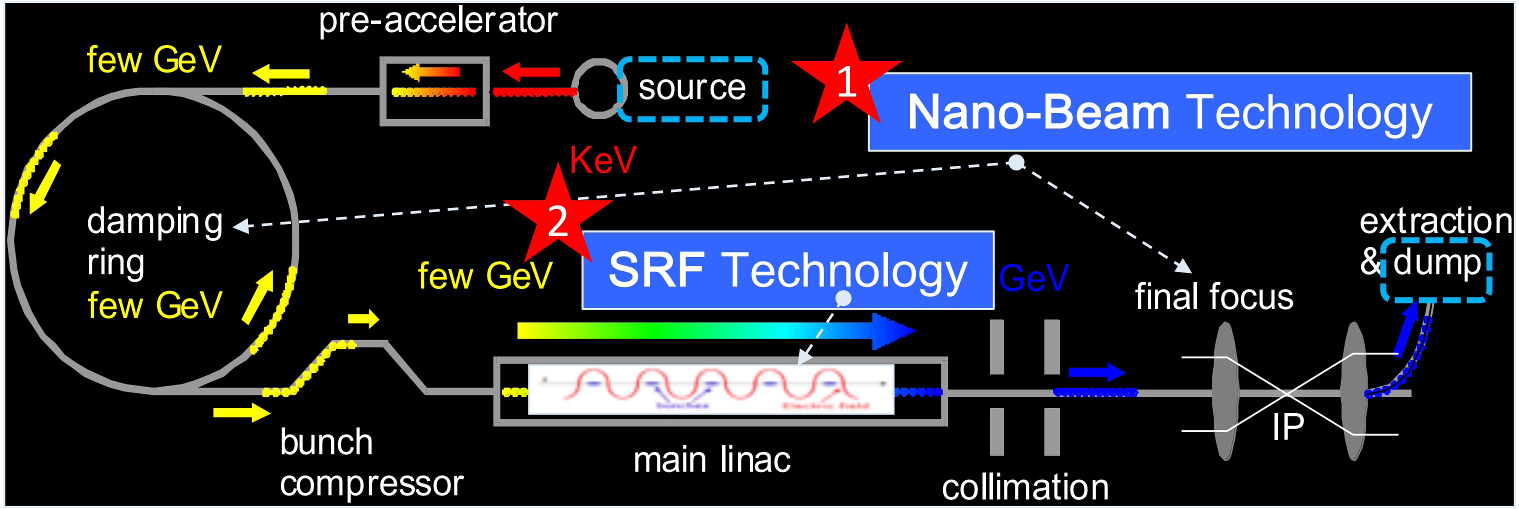
ILC accelerator technology and its physics background

Akira Miyazaki
CNRS/IN2P3/IJCLab Université Paris-Saclay

LCWS2024 pre-school

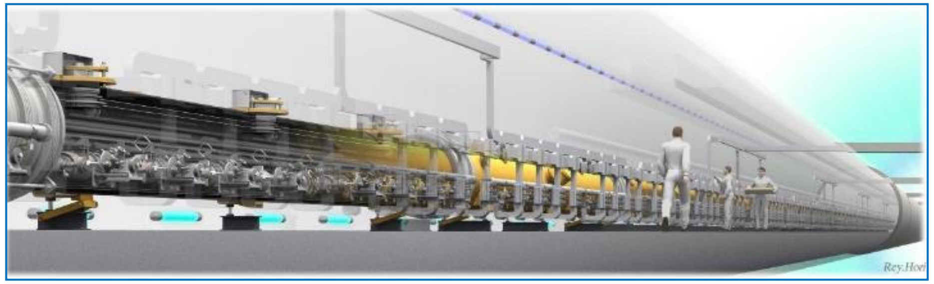
ILC and the Accelerator Technology





TDR was published in 2013.

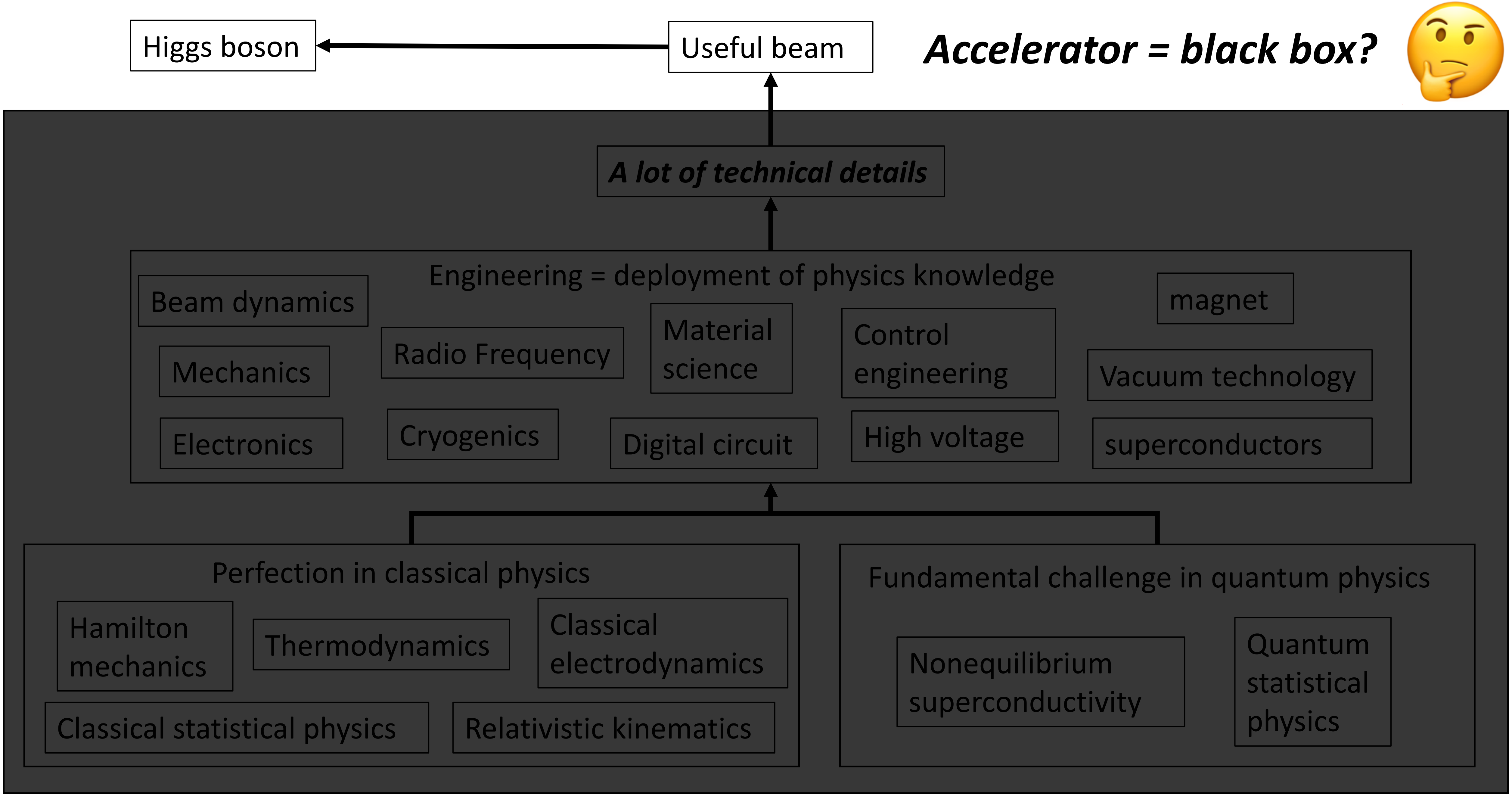
Courtesy: Shin Michizono SRF2023



Baseline / upgrade

Parameters	Value
Beam Energy	125 + 125 GeV
Luminosity	1.35 / 2.7 x 10^{34} cm^{-2}/s
Beam rep. rate	5 Hz
Pulse duration	0.73 / 0.961 ms
# bunch / pulse	1312 / 2625
Beam Current	5.8 / 8.8 mA
Beam size (y) at FF ★1	**7.7** nm
SRF Field gradient ★2	< 31.5 > MV/m (+/-20%) Q_0 = 1x10^{10}
#SRF 9-cell cavities (CM)	~ 8,000 (~ 900)
AC-plug Power	111 / 138 MW

Accelerator = black box? 🤔



Higgs boson

Useful beam

A lot of technical details

Engineering = deployment of physics knowledge

- Beam dynamics
- Mechanics
- Electronics
- Radio Frequency
- Cryogenics
- Material science
- Digital circuit
- Control engineering
- High voltage
- magnet
- Vacuum technology
- superconductors

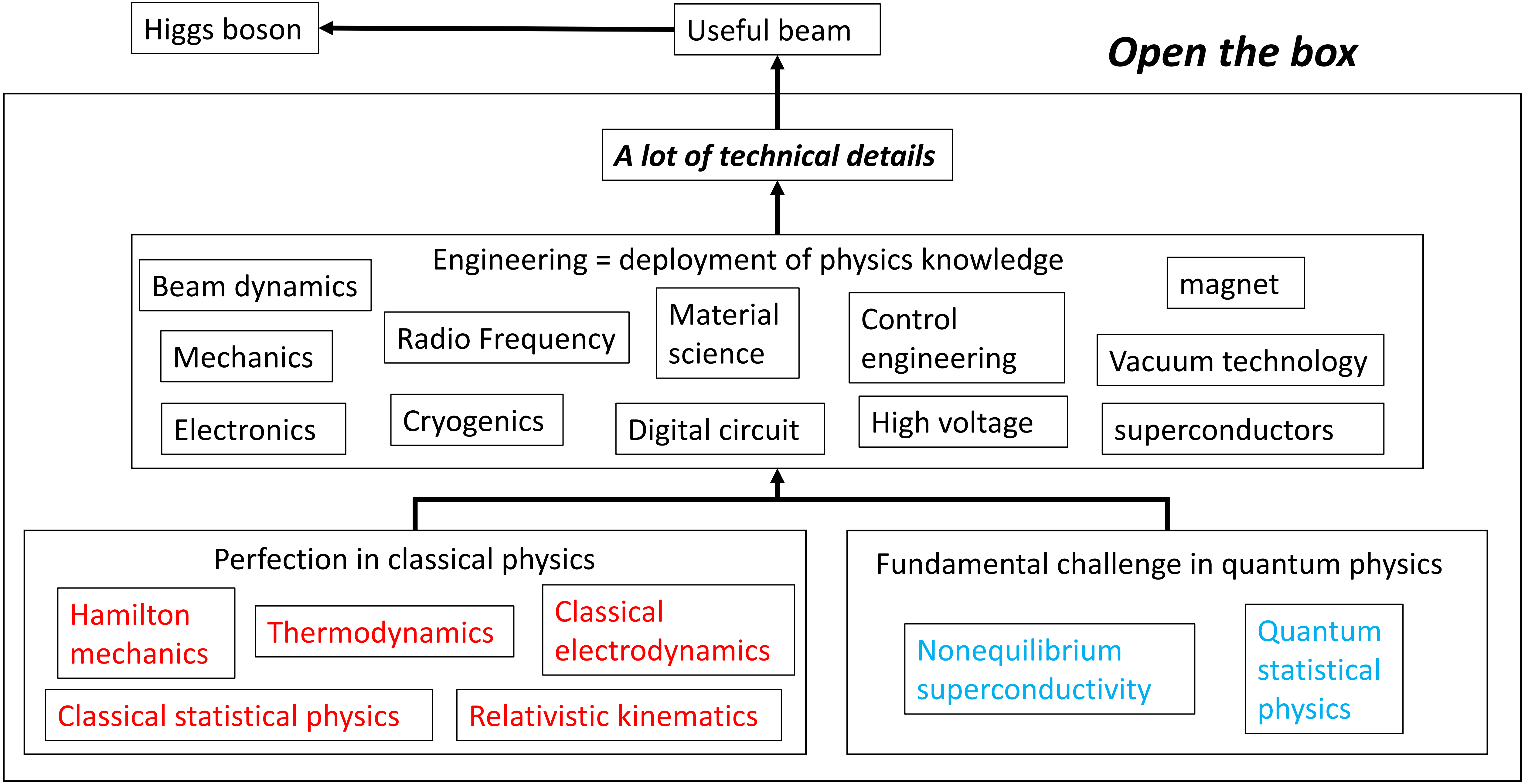
Perfection in classical physics

- Hamilton mechanics
- Thermodynamics
- Classical electrodynamics
- Classical statistical physics
- Relativistic kinematics

Fundamental challenge in quantum physics

- Nonequilibrium superconductivity
- Quantum statistical physics

Open the box



Higgs boson

Useful beam

A lot of technical details

Engineering = deployment of physics knowledge

Beam dynamics

Mechanics

Electronics

Radio Frequency

Cryogenics

Material science

Digital circuit

Control engineering

High voltage

magnet

Vacuum technology

superconductors

Perfection in classical physics

Hamilton mechanics

Thermodynamics

Classical electrodynamics

Classical statistical physics

Relativistic kinematics

Fundamental challenge in quantum physics

Nonequilibrium superconductivity

Quantum statistical physics

Outline

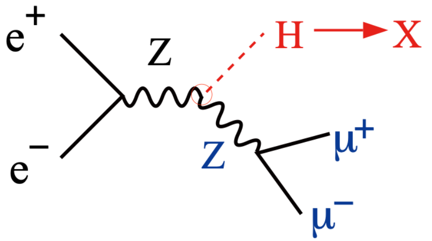
- How to measure Higgs boson precisely? (10 min)
  - High luminosity with high energy
  - Solutions: circular vs linear
- High luminosity (10 min)
  - Nano beam technology
- High energy (10 min)
  - Superconducting Radio Frequency technology
- Conclusion

Outline

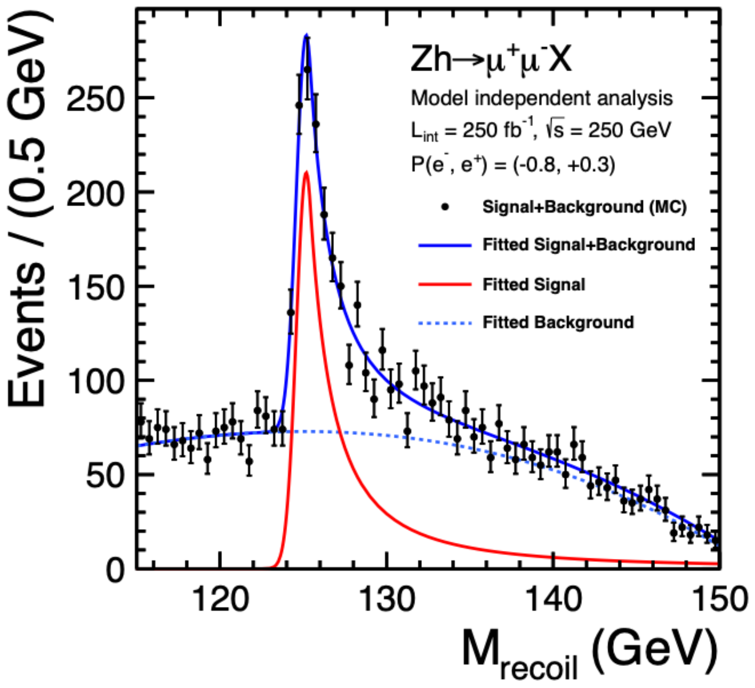
- How to measure Higgs boson precisely? (10 min)
  - High luminosity with high energy
  - Solutions: circular vs linear
- High luminosity (10 min)
  - Nano beam technology
- High energy (10 min)
  - Superconducting Radio Frequency technology
- Conclusion

Start from a purpose of ILC: Higgs boson

arXiv:1407.2133



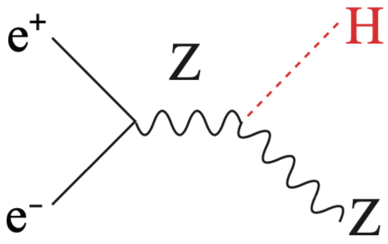
$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

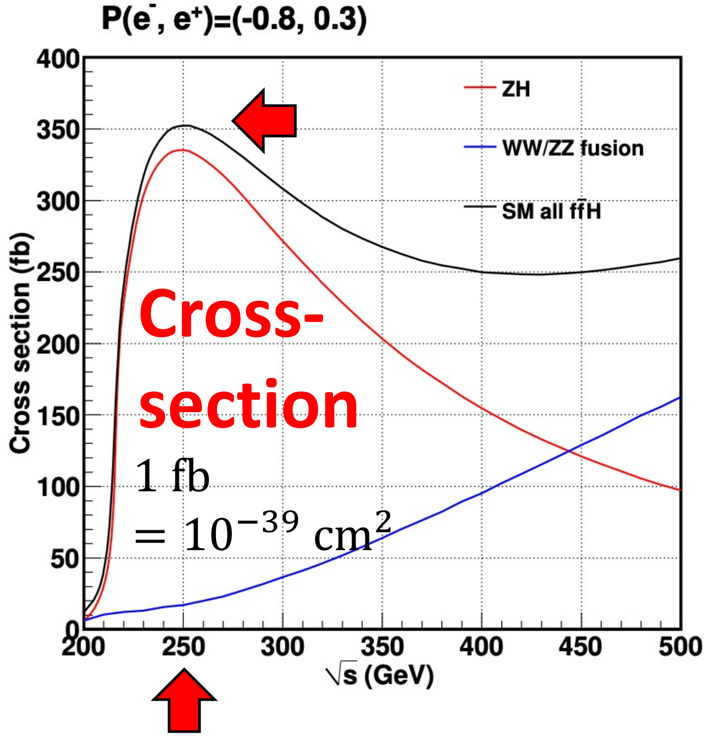


$\sim 3.5\%$

$= BR \times$

$$\text{error} \sim 1/\sqrt{\text{statistics}}$$





Cross-section

1 fb $= 10^{-39}\ \mathrm{cm}^2$

Energy

$\sqrt{s} \sim 250\ \mathrm{GeV}$

$(\sqrt{s}, \mathcal{L}, t)$

$\sim 250\ fb^{-1}$

$\times\ L_{int}$

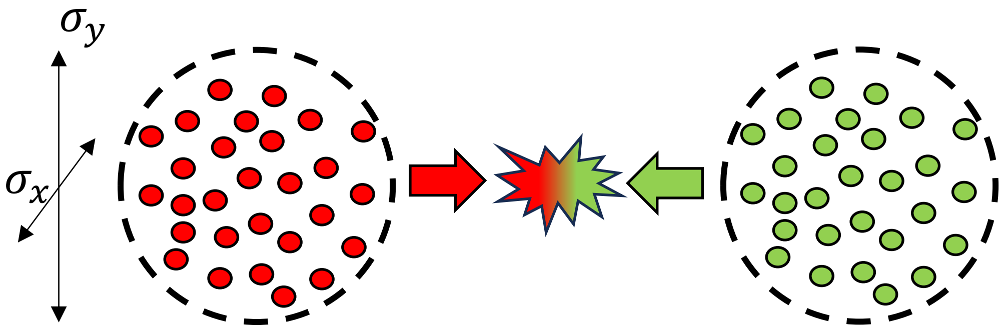
$$L_{int} = \boxed{\mathcal{L}} \times t$$

Peak luminosity

$\mathcal{L} = 1.35 \times 10^{-5}\,\mathrm{fb}^{-1}\mathrm{s}^{-1}$

$t \sim 0.6\ \mathrm{yr} = 1.8 \times 10^7\,\mathrm{s}$

How to achieve higher $\mathcal{L}$: circular collider



e^+ bunch
N_{e^+} particles

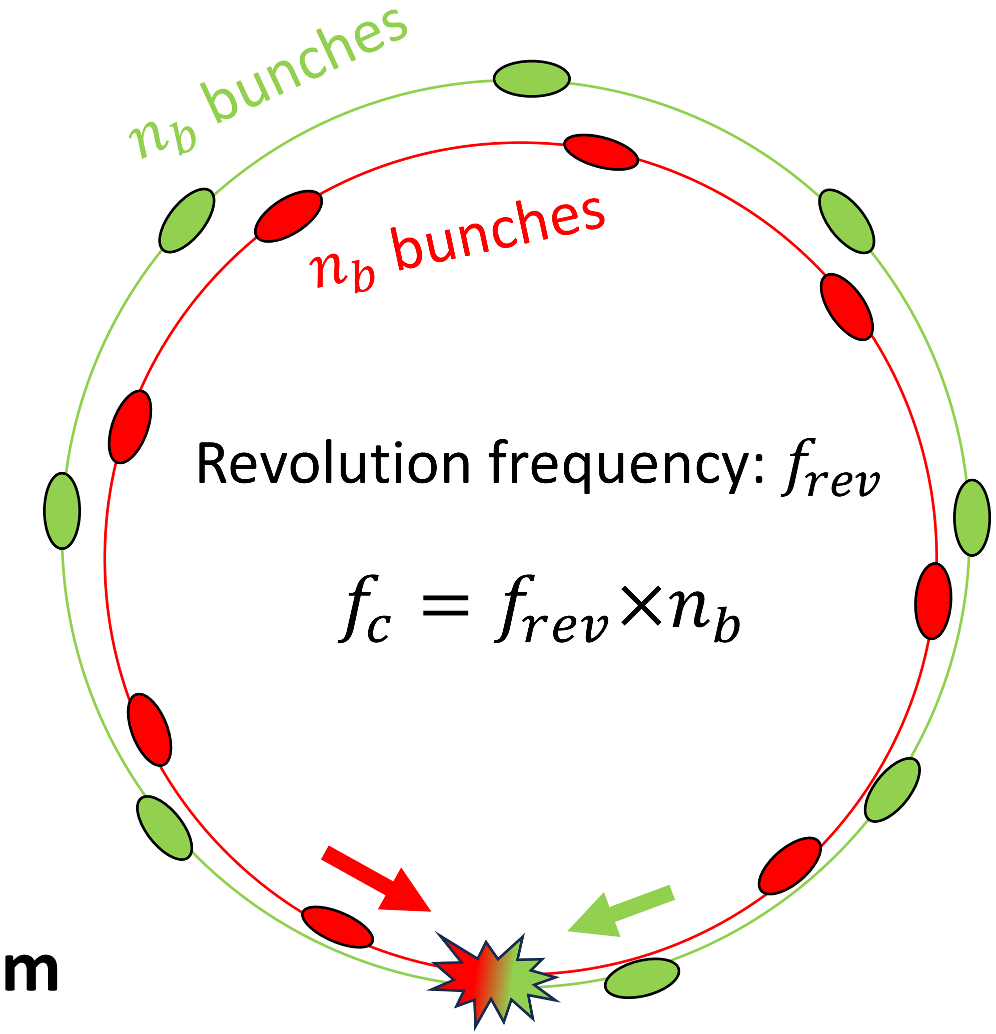
e^- bunch
N_{e^-} particles

$$\mathcal{L} \sim \frac{N_{e^+} N_{e^-}}{4\pi\sigma_x\sigma_y} \times f_c$$

Beam current

$$N = eNf_c$$

$$\rightarrow \mathcal{L} \sim \frac{\boxed{I_{e^+} I_{e^-}}}{4\pi\sigma_x\sigma_y} \times \frac{1}{f_c e^2}$$



Revolution frequency: f_{rev}

$$f_c = f_{rev} \times n_b$$

Typical solution:
high current beam

Synchrotron radiation: a limitation of rings

$$\Delta E \propto \frac{\gamma^4}{R} = \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

For electrons

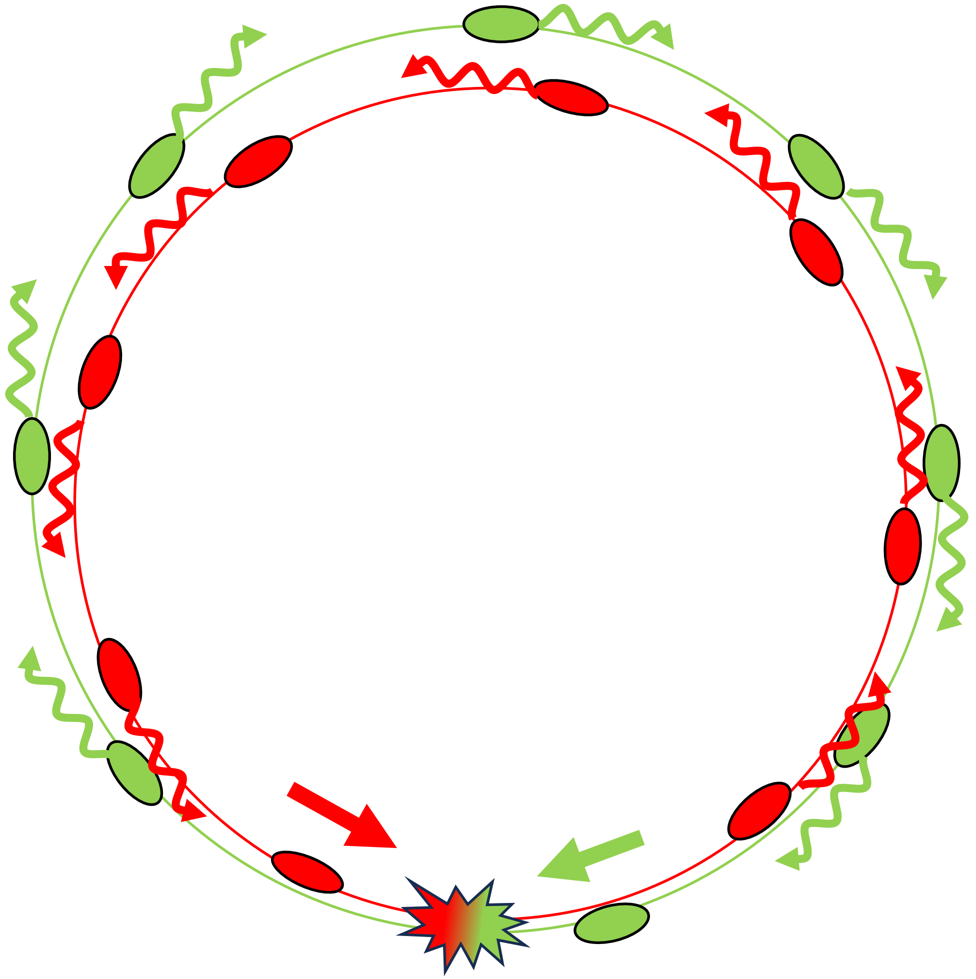
$$\Delta E[\mathrm{keV}] = 88.5 \times \frac{(E\ [\mathrm{GeV}])^4}{R\ [\mathrm{m}]}$$

For FCCee ZH operation (125 GeV, 26.7 mA)

$$\Delta E[\mathrm{keV}] \sim 1.89\ \mathrm{GeV}$$

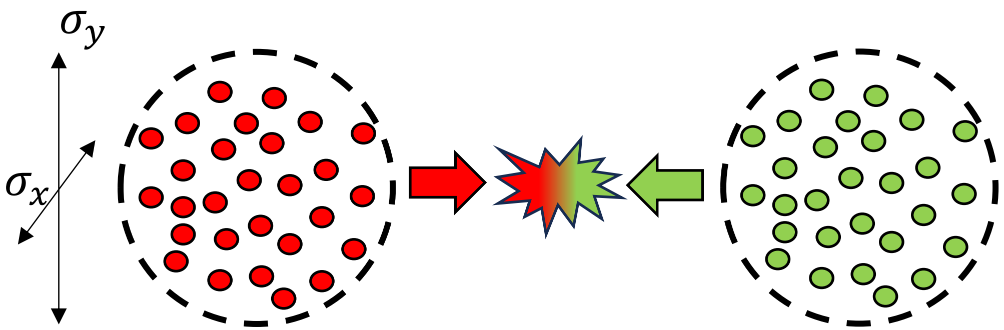
Power loss

$$P = 2 \times \Delta E \times I_e = \boxed{100\ \mathrm{MW}}$$



One nuclear power plant: 1 GW→ 10% …

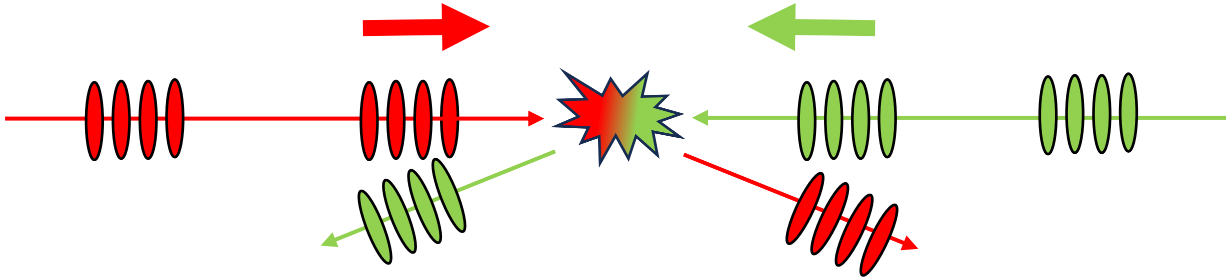
How to achieve higher $\mathcal{L}$: linear collider



e^+ bunch
N_{e^+} particles

e^- bunch
N_{e^-} particles

Repetition frequency of pulses: f_{rep}
Pulse length: L_{pulse}
# of bunches inside one pulse: n_b



$$\mathcal{L} \sim \frac{N_{e^+} N_{e^-}}{4\pi \boxed{\sigma_x \sigma_y}} \times f_c$$

Solution:
nano-beam

$$f_c = f_{rep} \times n_b$$

For ILC250 operation (125 GeV, 5.8 mA, 5 Hz, 0.73 ms)

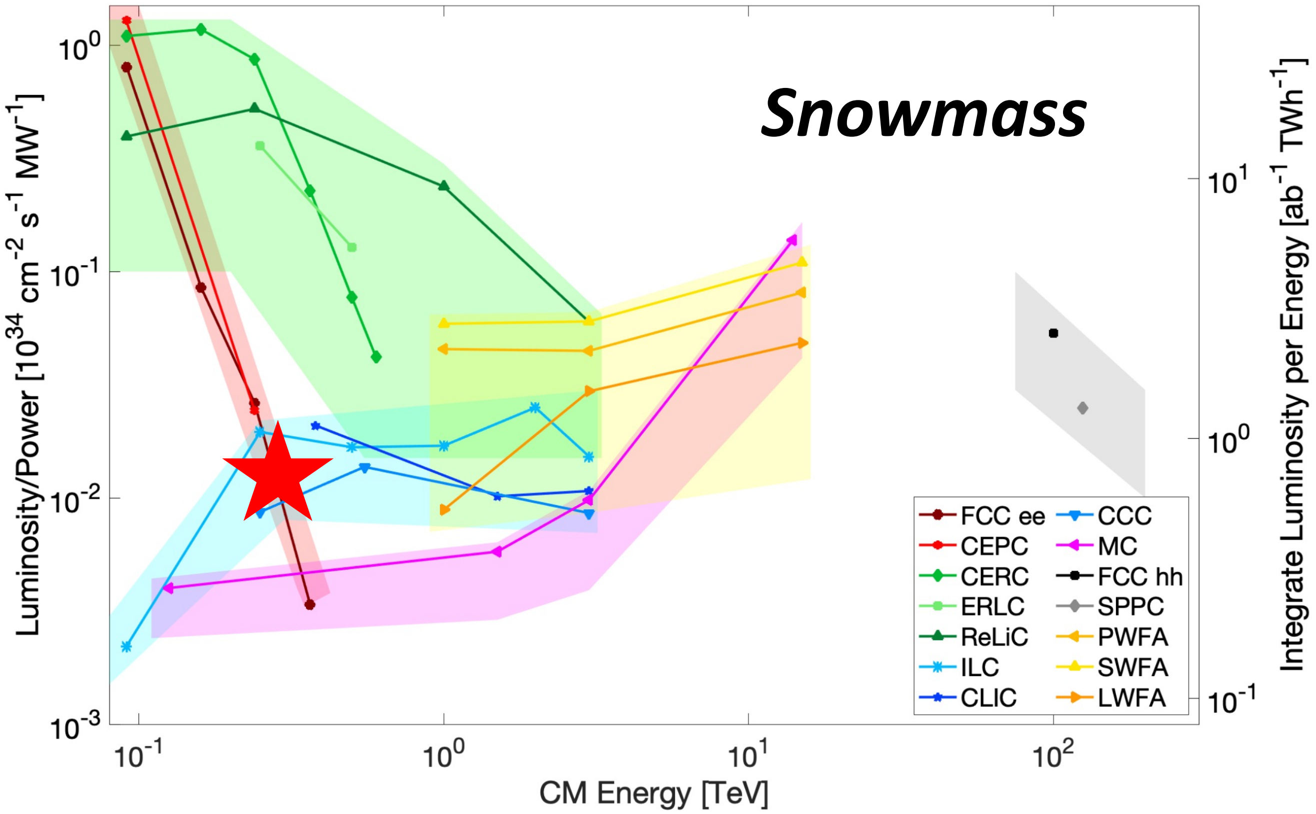
Duty cycle $5 \times 0.73 = 0.36\%$

Power loss (beam dump)

$$P = 2 \times E \times I_e \times f_{rep} \times L_{pulse} = \boxed{5.3\ \mathrm{MW}}$$ (Still quite waste…)

Compare ILC and FCCee (and others…) $\mathcal{L} \sim \frac{N_{e^+} N_{e^-}}{4\pi\sigma_x\sigma_y} \times f \times n_b$

	ILC	FCCee ZH
$\mathcal{L}\ [\mathrm{cm^{-2}s^{-1}}]$	1.35×10^{34}	6.9×10^{34}
N_e	2.0×10^{10}	2.0×10^{17}
$f\ [\mathrm{Hz}]$	5	3000
n_b	1312	260
$\sigma_x[\mathrm{nm}]$	516	6300
$\sigma_y[\mathrm{nm}]$	7.7	28



- Both are almost comparable for Higgs measurement
- Circular colliders are better for lower energy (Z-pole)
- Linear colliders are more advantageous for higher energy (ttbar, HHH)
- For even higher energy: FCChh, MuCol, Plasma (energy scale of new physics?)

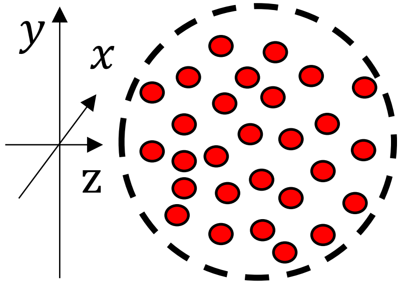
Outline

- How to measure Higgs boson precisely? (10 min)
  - High luminosity with high energy
  - Solutions: circular vs linear
- High luminosity (10 min)
  - Nano beam technology
- High energy (10 min)
  - Superconducting Radio Frequency technology
- Conclusion

Particle bunch in the phase space

$\boldsymbol{x} = \{x_1, x_2, \dots x_N\}$

$N = 2\times 10^{10}$



Distribution function

$$f(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z},\boldsymbol{v}_x,\boldsymbol{v}_y,\boldsymbol{v}_z)\,d\boldsymbol{x}\,d\boldsymbol{y}\,d\boldsymbol{z}\,d\boldsymbol{v_x}\,d\boldsymbol{v}_y\,d\boldsymbol{v_z}$$

$$\sim \boxed{f_{x,v_x}(\boldsymbol{x},\boldsymbol{v}_x)\,d\boldsymbol{x}\,d\boldsymbol{v_x}}\times f_{y,v_y}(\boldsymbol{y},\boldsymbol{v}_y)\,d\boldsymbol{y}\,d\boldsymbol{v_y}\times f_{z,v_z}(\boldsymbol{z},\boldsymbol{v}_z)\,d\boldsymbol{z}\,d\boldsymbol{v_z}$$

$f_{v_x}(\boldsymbol{v}_x) \sim \exp\left(-\frac{m v_x^2}{2k_B T}\right)$: Maxwell Boltzmann

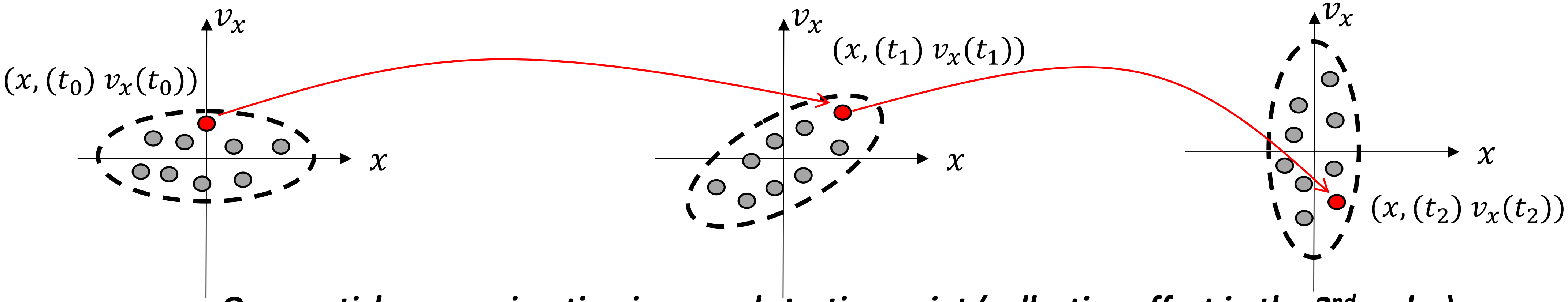
$f_x(\boldsymbol{x}) \sim \exp\left(-\frac{x^2}{2\sigma_x^2}\right)$: confined by Magnetic fields

Mixed with

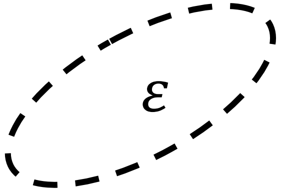
$$\frac{dp_x}{dt} = -\frac{\partial H}{\partial x}$$

$$\frac{dx}{dt} = \frac{\partial H}{\partial p_x}$$

Hamilton equations with focusing magnetic fields (conservative force)



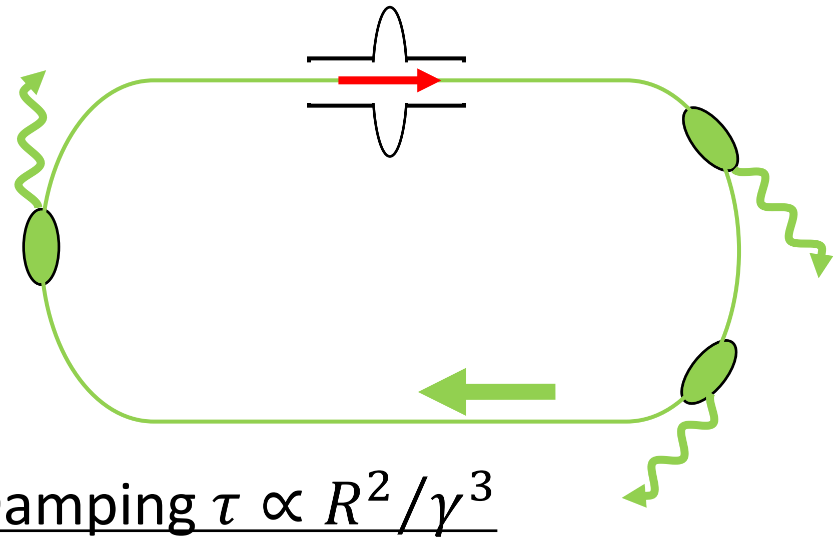
One particle approximation is a good starting point (collective effect in the 2nd order)



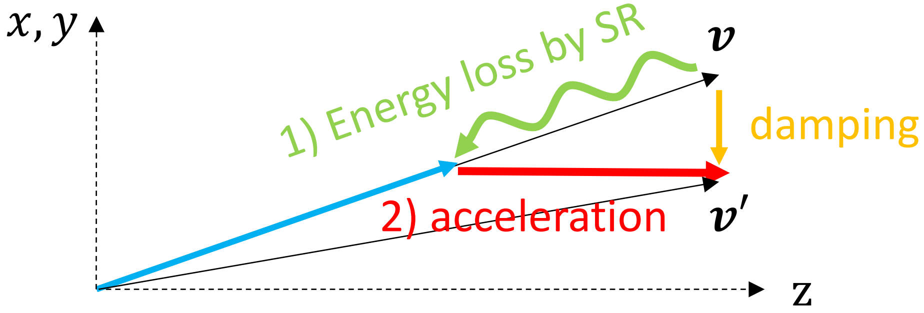
Area in phase space is constant: emittance $\varepsilon \sim \int dr\,dp$ → entropy $S \sim \log(\varepsilon)$

Cooling (reduce emittance)

- Electron cooling (→ ion)
- Stochastic cooling (→ p/pbar)
- Ionization cooling (→ μ^-/μ^+)
- Radiation damping (→ e^-/e^+)



Damping $\tau \propto R^2/\gamma^3$



$$\frac{d\varepsilon}{dt} = -\frac{\varepsilon}{\tau} + r$$

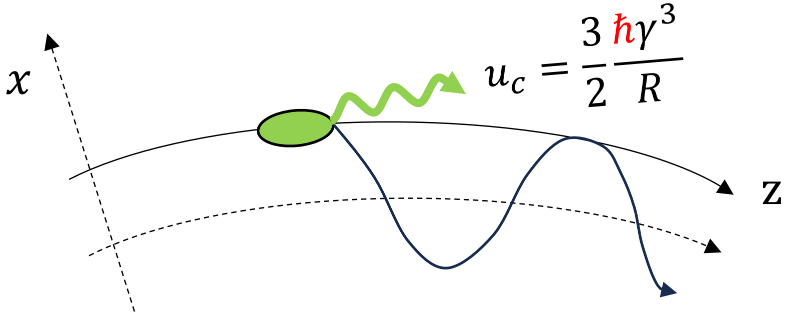
Equilibrium
emittance

$$\varepsilon\,(t) = \varepsilon_0 e^{-t/\tau} + r\tau\left(1 - e^{-t/\tau}\right) \xrightarrow{t\to\infty} r\tau \propto \frac{\gamma^2}{R}$$

ILC:
E = 5 GeV
$2\pi R$ = 6.7 km

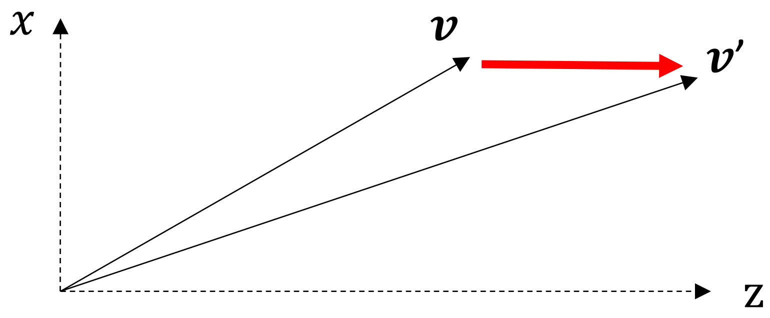
		Injection	ejection
e^-	$\varepsilon_{n,x}$ [rad · m]	7×10^{-5}	4×10^{-6}
	$\varepsilon_{n,y}$ [rad · m]		2×10^{-8}
e^+	$\varepsilon_{n,x}$ [rad · m]	1×10^{-3}	4×10^{-6}
	$\varepsilon_{n,y}$ [rad · m]		2×10^{-8}

Quantum excitation $r \propto \gamma^5/R^3$



$$u_c = \frac{3}{2}\frac{\hbar\gamma^3}{R}$$

Lorentz boost and emittance(s)



$$v_x = \frac{dx}{dt}$$

$$z = v_z t \sim ct \rightarrow \frac{1}{c}\frac{d}{dt} = \frac{d}{dz} \quad \rightarrow v_x = \frac{dx}{dz} \qquad (c = 1)$$

Normalized emittance

$$\varepsilon_{nx} = \frac{1}{m}\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle x p_x\rangle^2} \quad \longrightarrow$$

Lorentz invariance (→ entropy)

Geometrical emittance

$$\varepsilon_x = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle x x'\rangle^2}$$

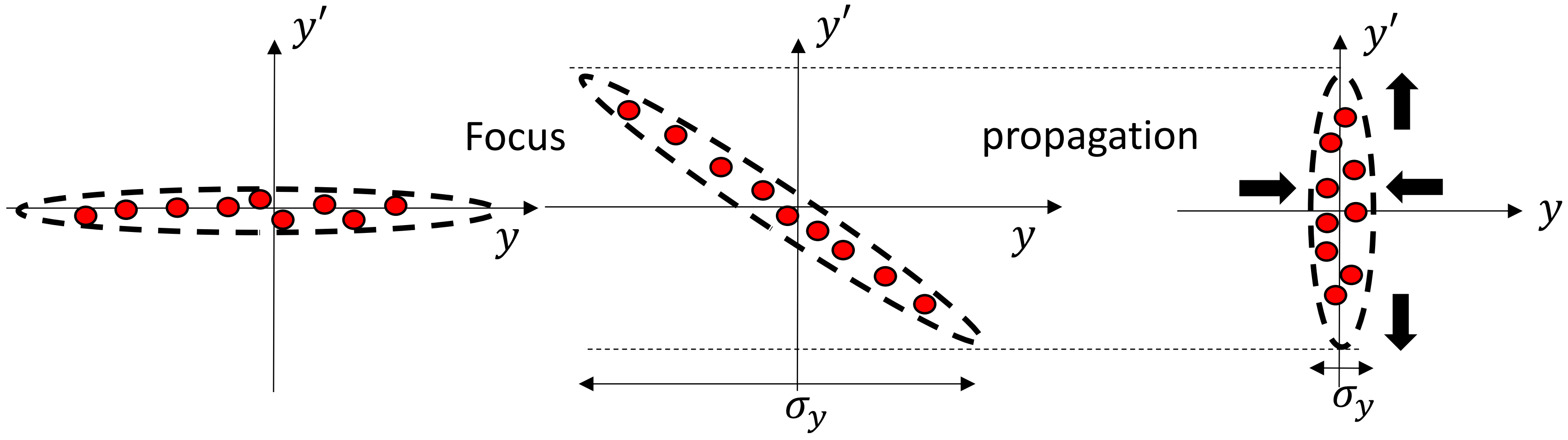
Adiabatic damping

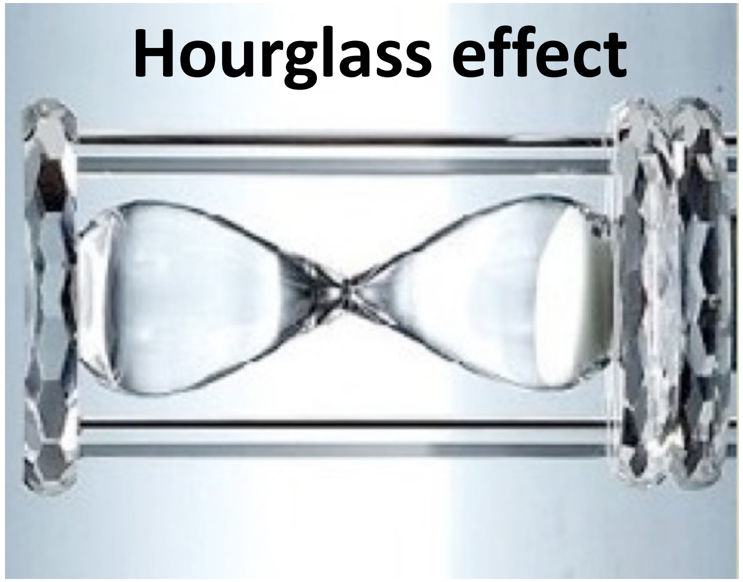
$$\varepsilon_x \sim \frac{\varepsilon_{nx}}{\gamma} \quad \rightarrow \sigma_x = \sqrt{\langle x^2\rangle} \propto \sqrt{\varepsilon_x} \sim \sqrt{\varepsilon_{nx}/\gamma}$$

Nanobeam prototype @ KEK

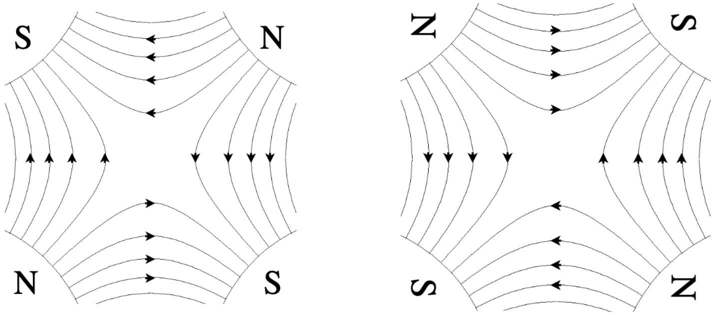
	ILC	**ATF2**
E [GeV]	125	1.28
ε_x [nm]/ε_y [pm]	0.02 / 0.07	2 /12
$\gamma\varepsilon_x$ [nm]/$\gamma\varepsilon_y$ [nm]	5000 / 35	5000 / 30
σ_x [nm]/σ_y [nm]	516 / 7.7	8900 / 37

Focusing towards Nano-beam

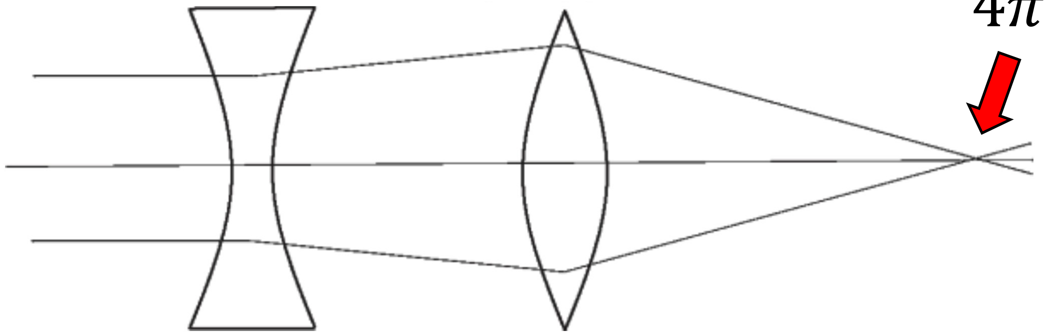


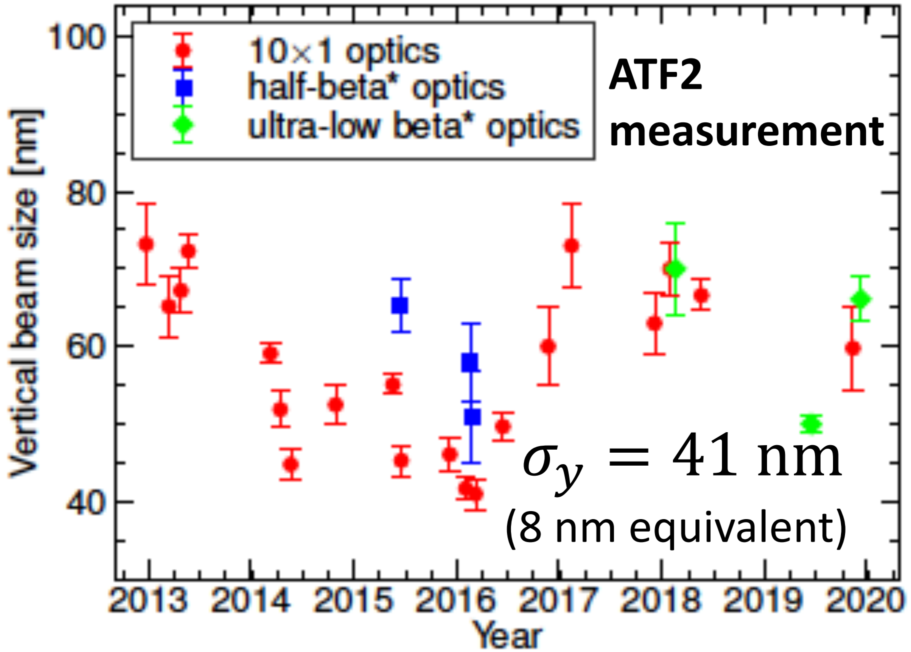

Hourglass effect

Quadrupole magnets x 2



$$\mathcal{L} \sim \frac{N_{e^+} N_{e^-}}{4\pi \sigma_x \sigma_y} \times f_c$$



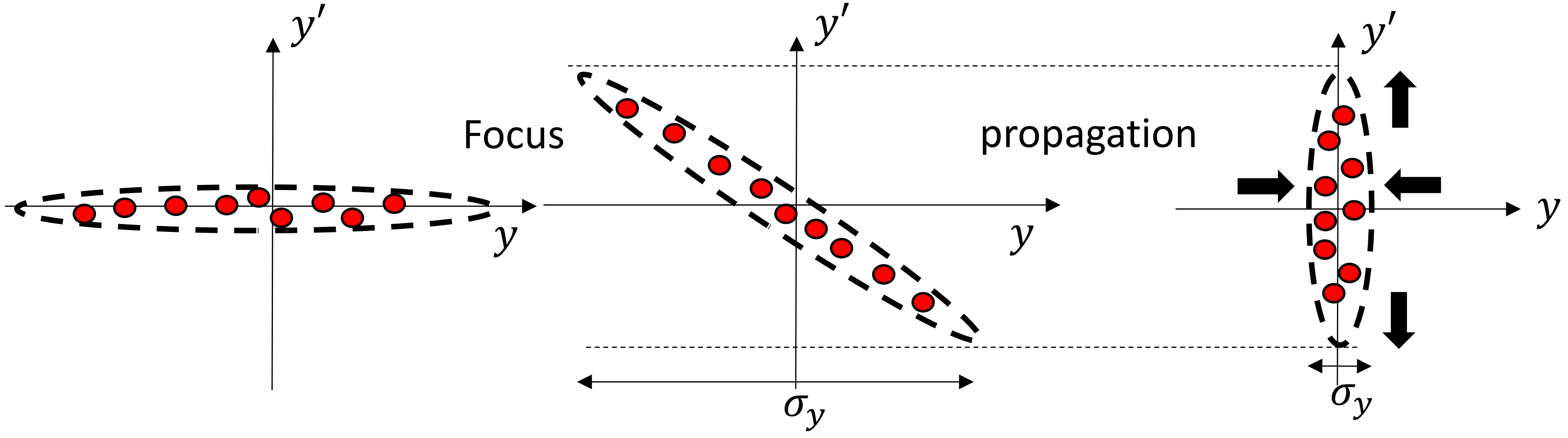


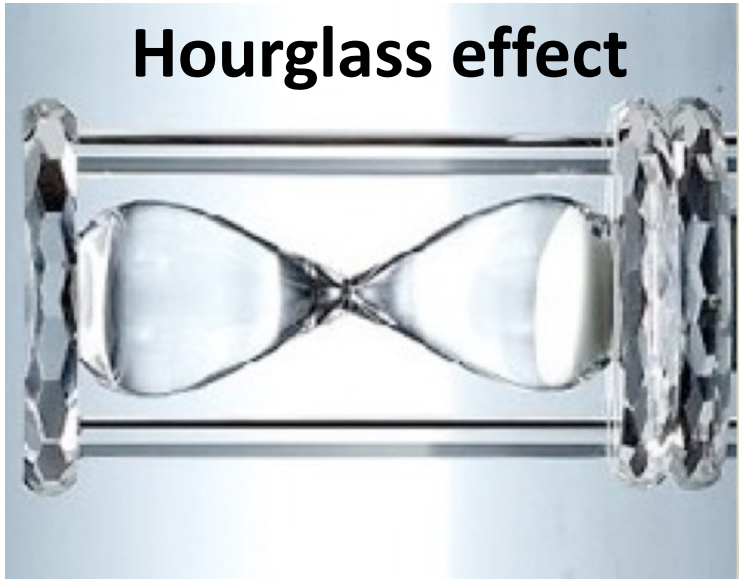
ATF2 measurement

$\sigma_y = 41$ nm

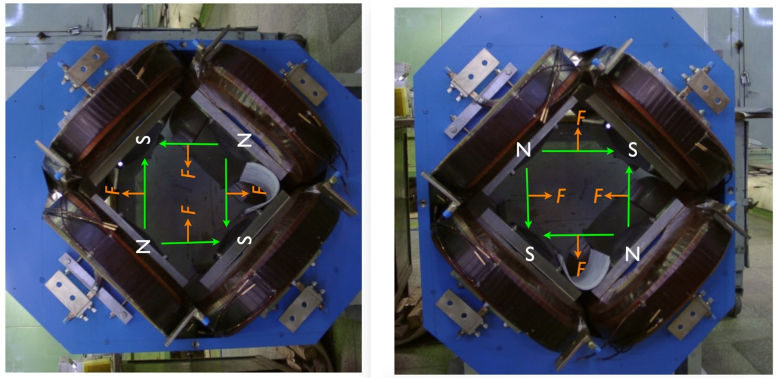
(8 nm equivalent)

Focusing towards Nano-beam

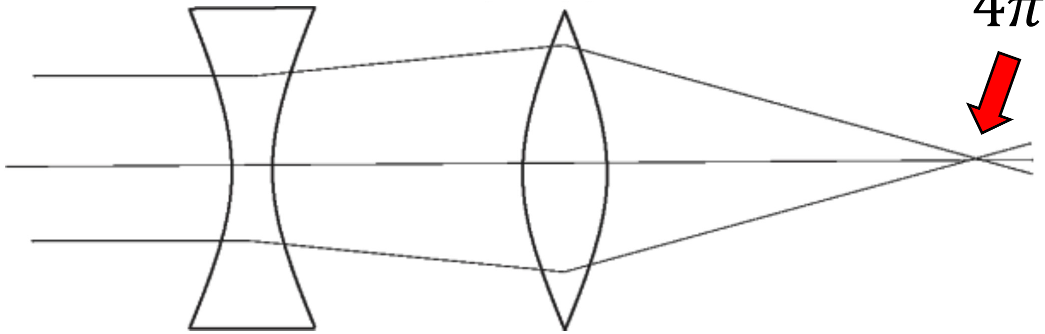


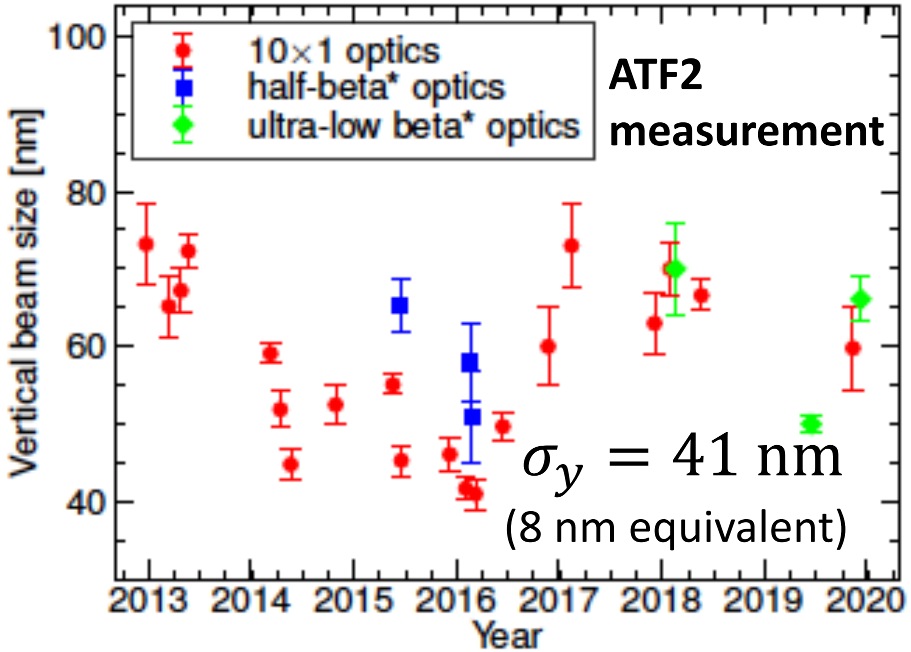

Hourglass effect

Quadrupole magnets x 2



$$\mathcal{L} \sim \frac{N_{e^+}N_{e^-}}{4\pi\sigma_x\sigma_y}\times f_c$$





ATF2 measurement

$\sigma_y = 41$ nm

(8 nm equivalent)

Relativistic thermodynamics (?)

Relativistic Thermodynamics of Moving Systems

N. G. van Kampen
Physics Department, Howard University, Washington, D.C.
(Received 10 May 1968)

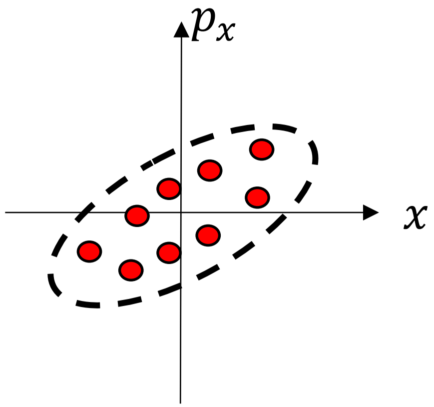
Progress of Theoretical Physics, Vol. 128, No. 3, September 2012

Three Views of a Secret in Relativistic Thermodynamics

Tadas K. Nakamura

Fukui Prefectural University, Fukui 910-1195, Japan

Entropy = normalized emittance: Lorentz invariance



$$S \sim \log(\varepsilon_n)$$

How about temperature?

$$f_{v_x}(\boldsymbol{v}_x) \sim \exp\left(-\frac{mv_x^2}{2k_B T}\right)$$

$$\begin{cases} \text{I)} & T' = T\gamma^{-1}\,, \\ \text{II)} & T' = T\gamma\,, \\ \text{III)} & T' = T\,, \end{cases}$$

More fundamentally, what is the temperature in an accelerated frame?

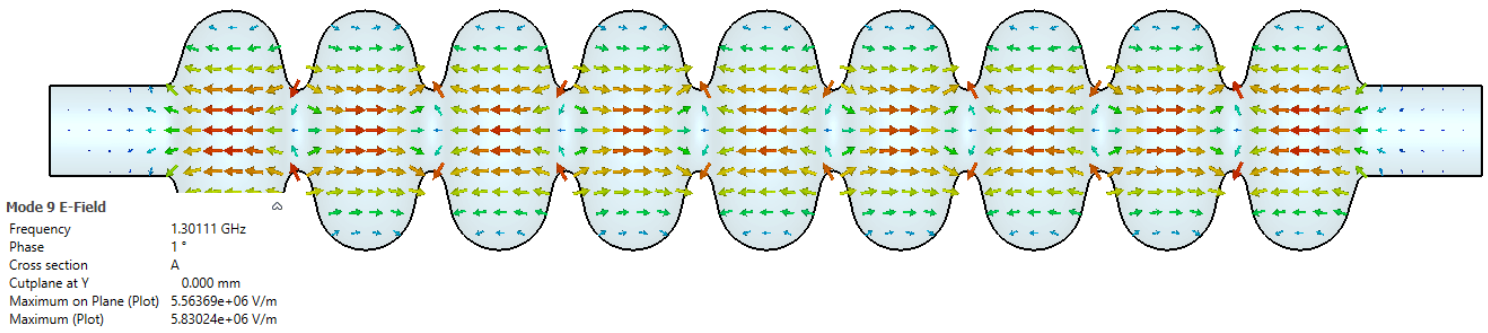
(→ temperature under gravity)

Outline

- How to measure Higgs boson precisely? (10 min)
  - High luminosity with high energy
  - Solutions: circular vs linear
- High luminosity (10 min)
  - Nano beam technology
- High energy (10 min)
  - Superconducting Radio Frequency technology
- Conclusion

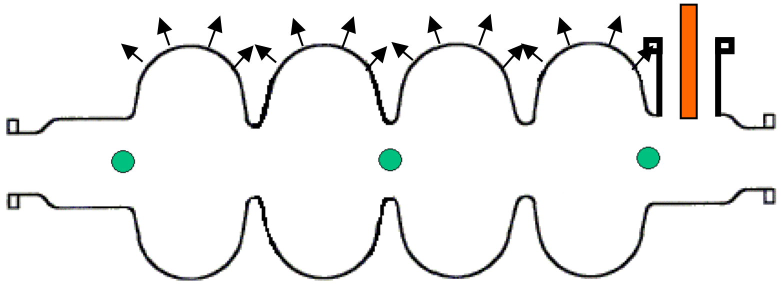
RF electric fields accelerate synchronized particles

E-field vector

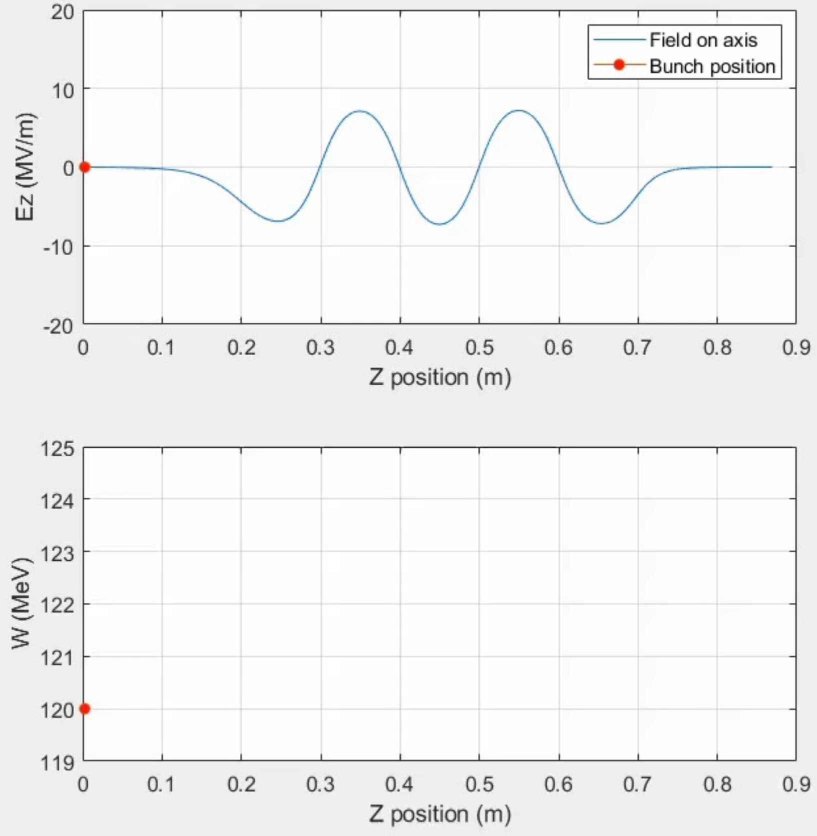


Mode 9 E-Field

Frequency	1.30111 GHz
Phase	1 °
Cross section	A
Cutplane at Y	0.000 mm
Maximum on Plane (Plot)	5.56369e+06 V/m
Maximum (Plot)	5.83024e+06 V/m



Courtesy: F. Bouly



$$\begin{cases} \nabla \cdot \boldsymbol{E} = 0 \\ \nabla \times \boldsymbol{E} = -\dfrac{\partial \boldsymbol{B}}{\partial t} \\ \nabla \cdot \boldsymbol{B} = 0 \\ \nabla \times \boldsymbol{B} = \dfrac{1}{c^2}\dfrac{\partial \boldsymbol{E}}{\partial t} \end{cases}$$

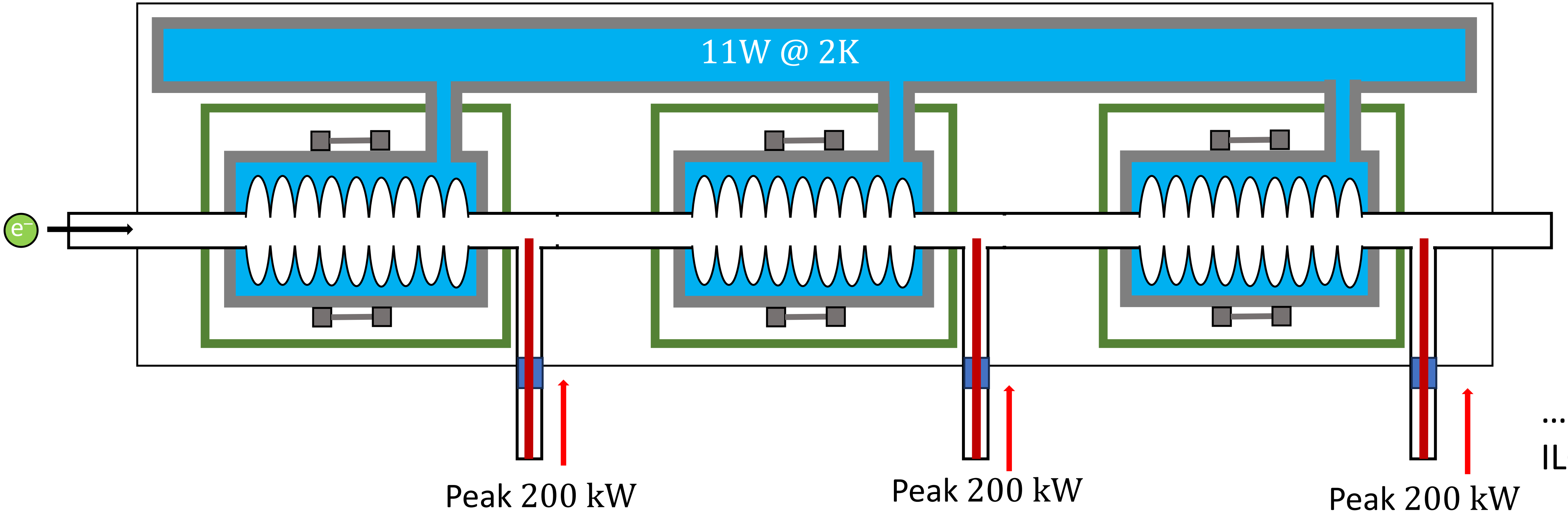
- Maxwell equations under boundary conditions
- Eigenmode solution:

TM_{010} π mode 1.3 GHz

$$\frac{d\boldsymbol{p}}{dt} = q[\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B}]$$

Acceleration of particles

Cryomodule: SRF cavity cryostat in accelerators



…8 or 9 cavities in ILC cryomoudles

- Beam takes (per cavity)
  $31.5\ \mathrm{MV/m} \times 1\mathrm{m} \times 5.8\ \mathrm{mA} \sim 183\ \mathrm{kW}$
- Cryogenic loss
  static loss 1 W, cavity RF loss 10 W
- Beam power >> cryogenic power

Question

Why do superconducting cavities have finite RF loss?

Superconducting cavity for $R_s \to 0$?

Ohm's law

Applied DC electric field E

DC Current J

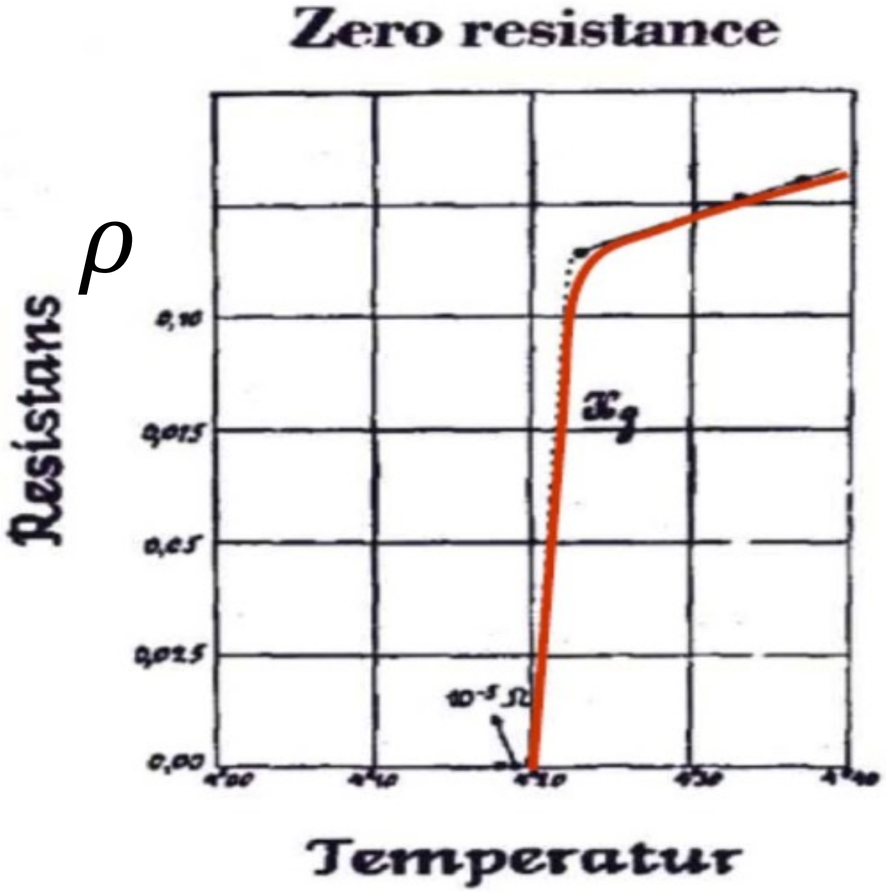
DC resistivity ρ

$$\rho \equiv \frac{E}{J}$$

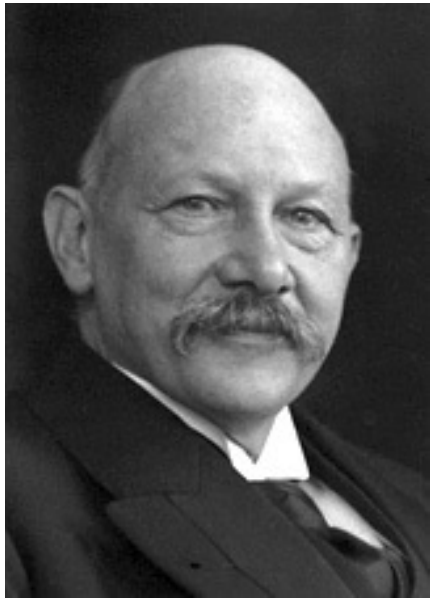
DC conductivity σ

$$\sigma = \frac{1}{\rho} \equiv \frac{J}{E}$$

Cool down the resistor…



$\boldsymbol{\rho = 0}$ below transition temperature T_c



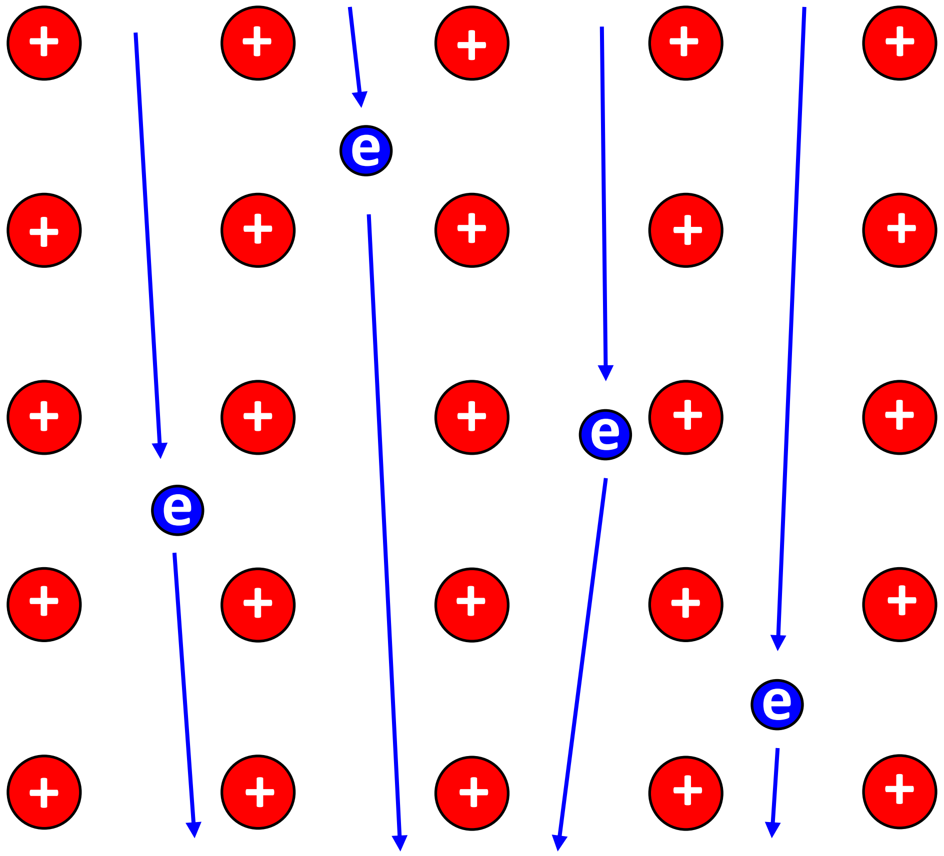
Heike Kamerlingh Onnes

Nobel prize in 1913

Electrons in a *perfect* metal are free (or independent)

Electron-electron scattering?
→Pauli's exclusion principle
Cf. Fermi-liquid theory by Landau

Perfectly periodic potential by ions does ***NOT*** scatter electrons (Bloch's theorem)



These electrons are ***NOT*** our favorite elementary particle of

$$m = 511\ \mathrm{keV}$$

These electrons are ***dressed*** by complicated electromagnetic property of metals to have an effective mass m^*given by a band structure

→ ***Quasi-particles***

In reality, imperfection causes quasi-particle scattering

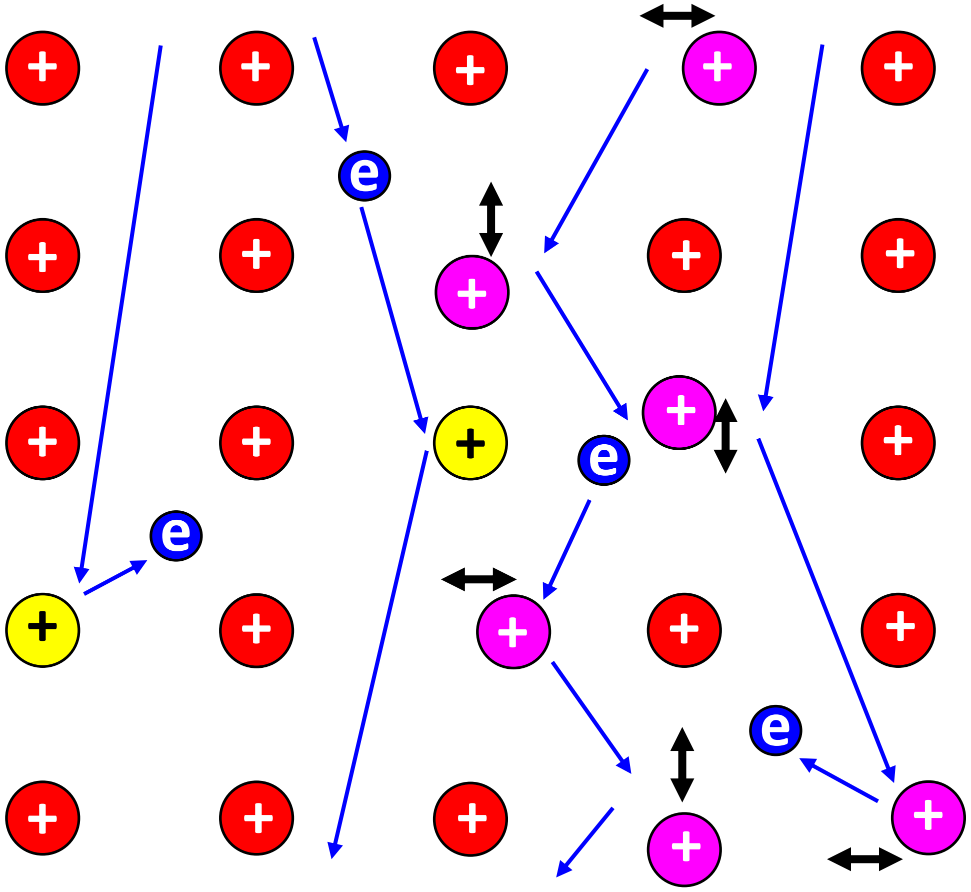
Electrons in real metals show Ohmic loss

Imperfections causes ***local*** scattering

1. Impurity, defects (scattering time τ_{def})
2. Lattice vibration, phonon (τ_{ph})

Total scattering time

$$\frac{1}{\tau} = \frac{1}{\tau_{\text{def}}} + \frac{1}{\tau_{ph}}$$



Macroscopic phenomenology (Drude model)

An electron accelerated by an electric field

$$m^* \frac{dv}{dt} = -eE$$

is scattered by imperfections per τ, and its velocity relaxes to a mean velocity

$$\langle v \rangle = -\frac{e}{m^*} E\tau$$

Electric current is a collective flow of n electrons

$$j = -en\langle v \rangle = \boxed{\frac{e^2 n\tau}{m^*}} E$$

Electrical conductivity σ

Ohm's law

$$\boxed{\boldsymbol{j} = \sigma \boldsymbol{E}}$$

Paired electrons can avoid Ohmic loss

If electrons ***in a distance*** (>39 nm) are bounded, ***local*** (< 0.5 nm) scattering can be avoided

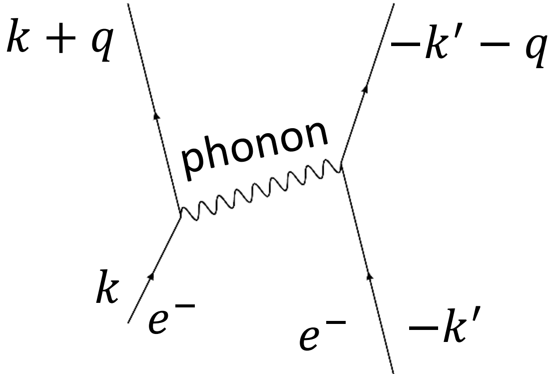
Any small attractive interaction V between electrons can lead to a ***Cooper pair*** coupled with an energy 2Δ, below critical temperature T_c

BCS gap equation (1957)

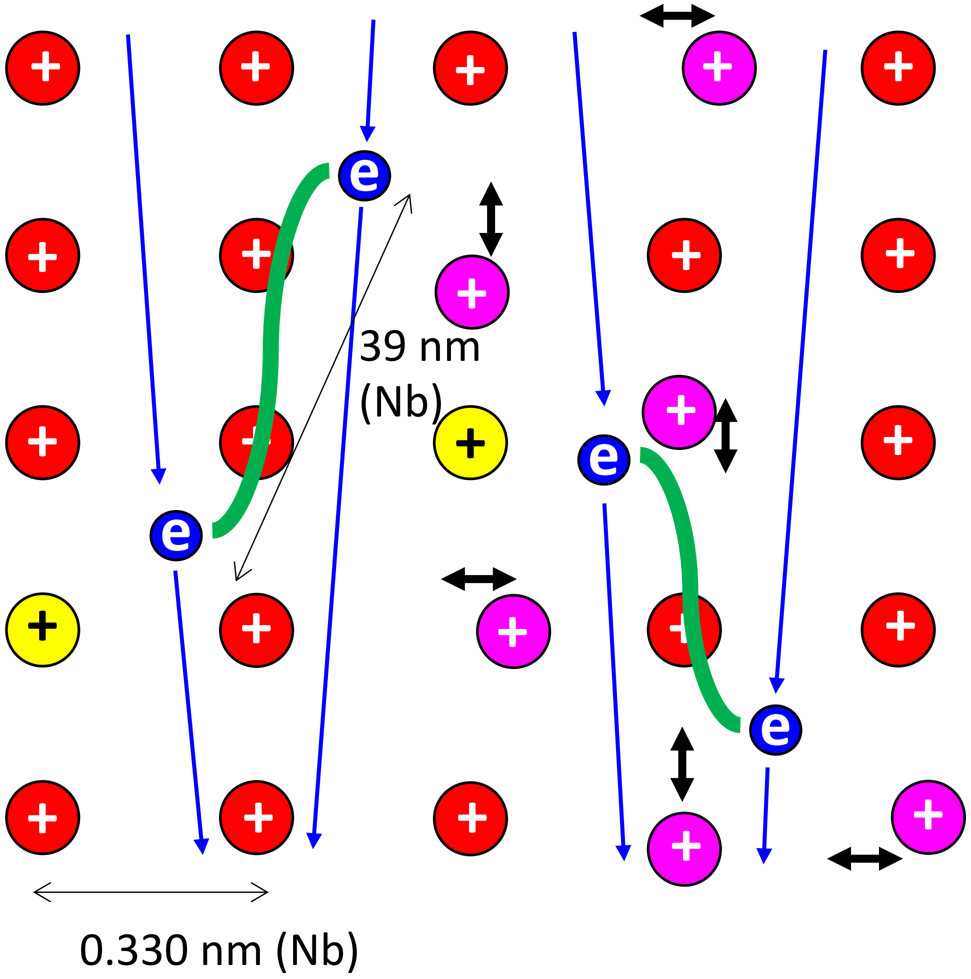
Non-perturbative!

$$\Delta = n(E_F)V \int_{\Delta}^{\hbar\omega_D} \frac{\Delta}{\sqrt{\xi^2+\Delta^2}} \tanh\left(\frac{1}{2}\frac{\sqrt{\xi^2+\Delta^2}}{k_B T}\right) d\xi$$

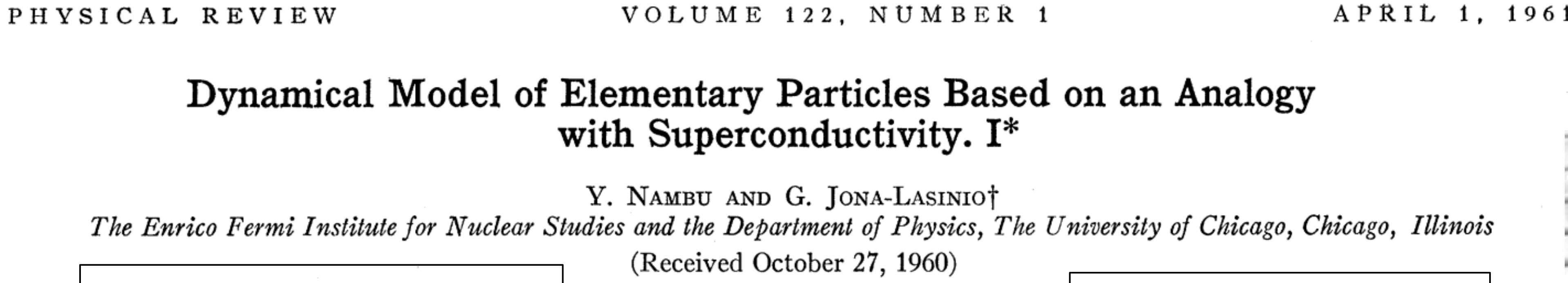
Classical superconductors' attractive potential is from ***longitudinal mode of lattice vibration***



If energy transfer $|\epsilon_{k+q} - \epsilon_k|$ is smaller than phonon energy the interaction is attractive (Flöhlich)
→ Eliashberg's strong coupling superconductor (1960)



Cross-over of particle physics and condensed matter physics



PHYSICAL REVIEW VOLUME 122, NUMBER 1 APRIL 1, 1961

Dynamical Model of Elementary Particles Based on an Analogy with Superconductivity. I*

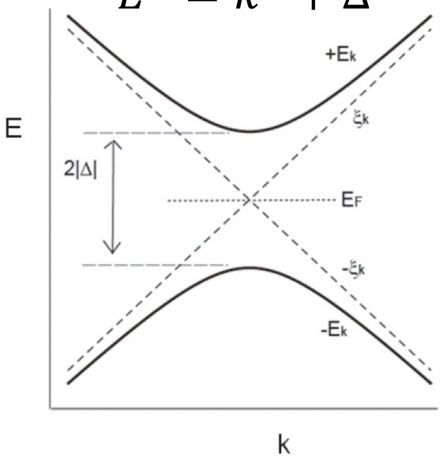
Y. Nambu and G. Jona-Lasinio†

The Enrico Fermi Institute for Nuclear Studies and the Department of Physics, The University of Chicago, Chicago, Illinois

(Received October 27, 1960)

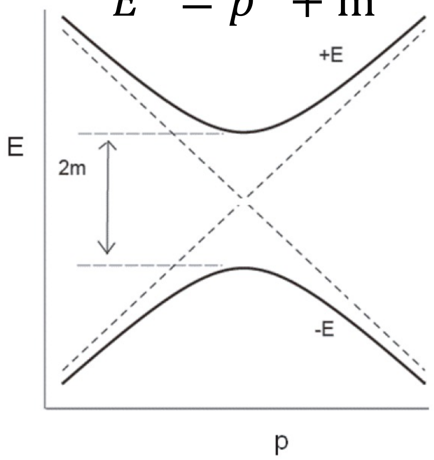
Superconductivity

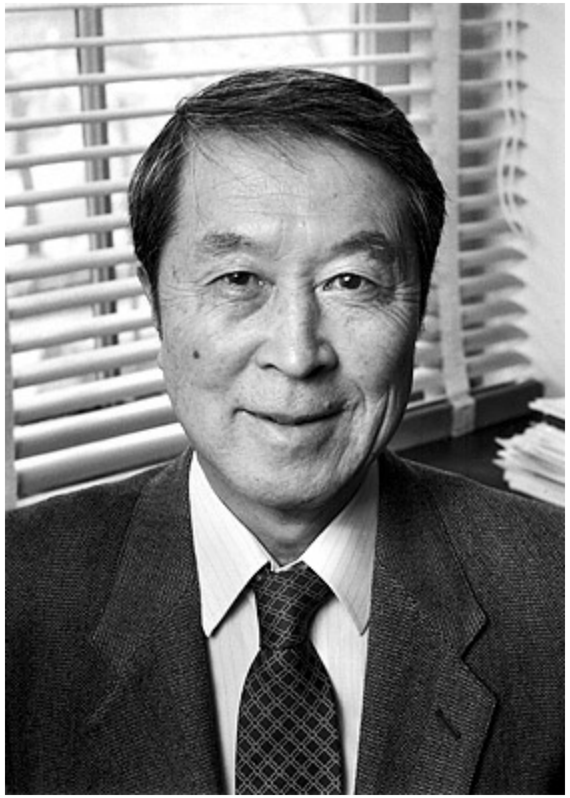
$E^2 = k^2 + \Delta^2$



Particle physics

$E^2 = p^2 + \mathrm{m}^2$





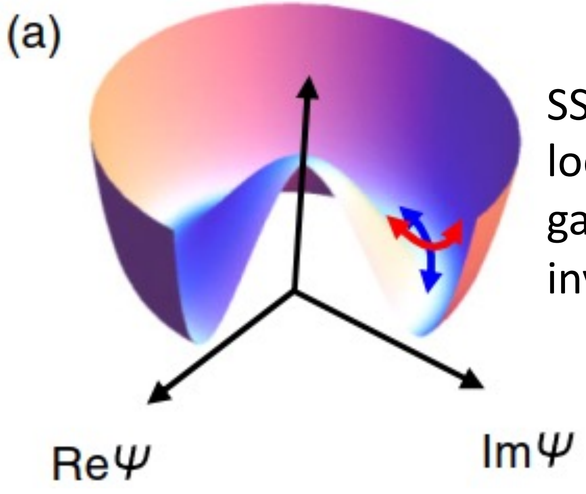
Yoichiro Nambu

The vacuum is similar to the superconducting state

Particle mass = superconducting gap (gauge symmetry is spontaneously broken in the ground state)

→ Chiral symmetry breaking, Higgs mechanism, Electroweak theory, (and new physics?)

Nonrelativistic composite $\mathrm{U(1)_{EM}}$ Higgs



SSB of local gauge invariance

R. Matsunaga et al PRL 111 057002 (2013)

Ginzburg-Landau theory ($T\rightarrow T_c$ of BCS theory, $\Psi=\Delta$)

$$F=(\nabla\times A)^2+\frac{\hbar^2}{4m_e}|(\nabla+ieA)\Psi|^2+\frac{g}{4}(|\Psi|^2-v^2)^2 \qquad \sim\phi^4 \text{ theory}$$

EM energy　Scaler Kinetic energy　Scaler potential

Excitation around potential minimum v at fixed gauge (Unitary gauge)

$$\Psi(\mathrm{x})\rightarrow v+\phi(x)$$

Kinetic term

$$|(\nabla+ieA)\Psi|^2=|\nabla\phi|^2+e^2v^2|A|^2+\cdots$$

Gauge field gains mass: Nambu-Goldston mode is absorbed by photon

$$e^2v^2|A|^2\equiv m_v|A|^2$$
$$(\nabla^2-m_v^2)A=0$$

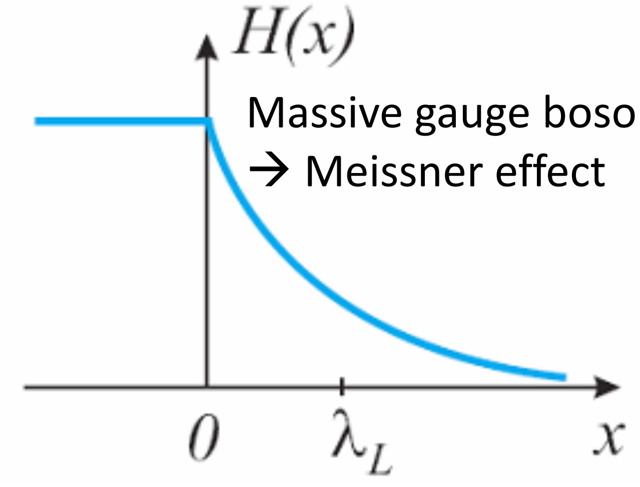
Massive vector boson eq.
↔London eq.

→ Massive photon → finite interaction length: penetration depth

$$\lambda_L=\frac{1}{m_v}\sim 36\ \mathrm{nm} \qquad \text{(Nb)}$$

Higgs mode ϕ has a mass $m_S=v\sqrt{g}$: coherence length

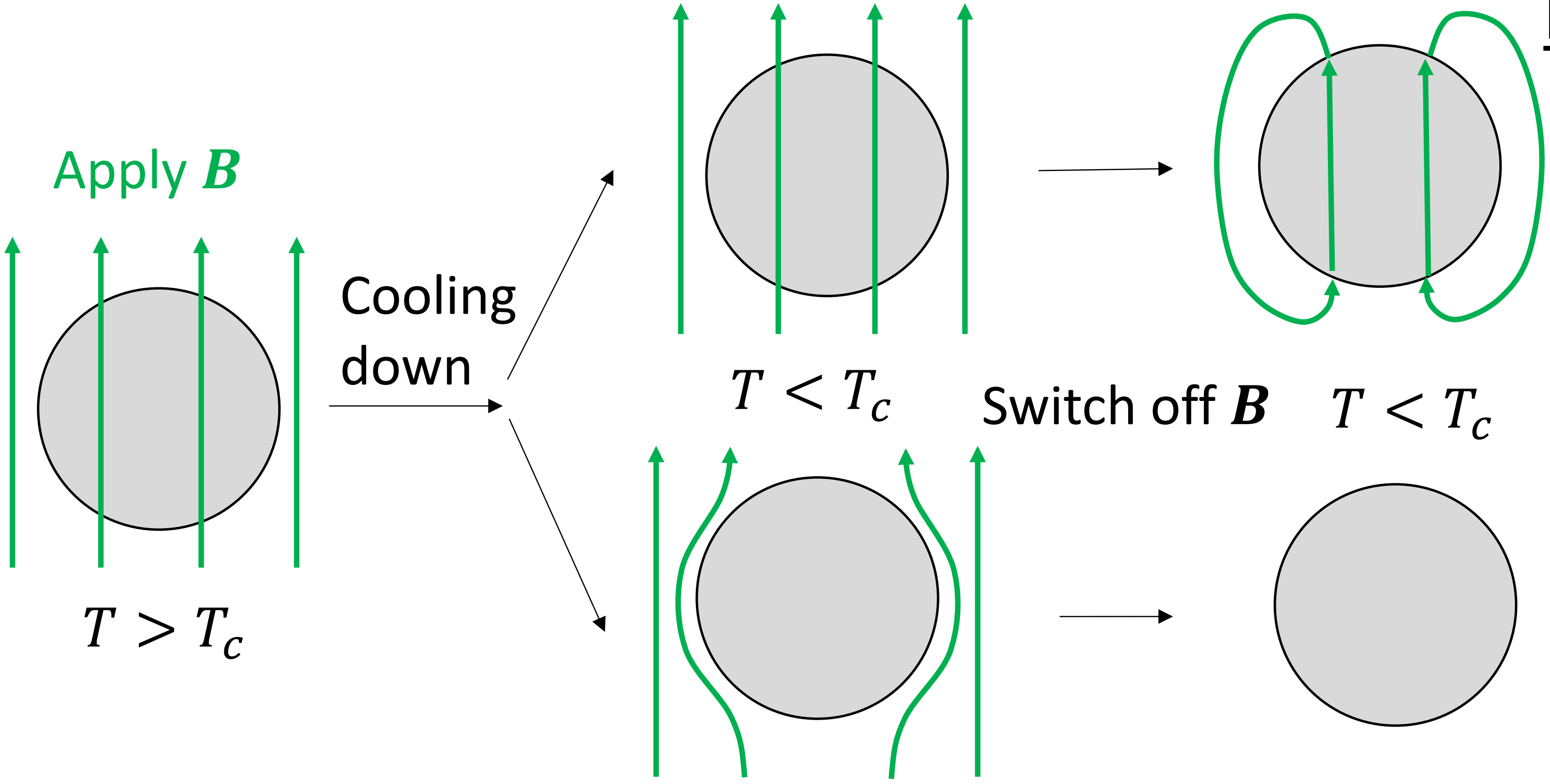
$$\xi_0=\frac{1}{m_S}\sim 39\ \mathrm{nm} \qquad \text{(Nb)}$$



Massive gauge boson
→ Meissner effect

Superconductor ≠ Perfect electric conductor

Meissner effect **differentiates them**



Perfect Electric Conductor

$$\nabla^2\left(\frac{\partial \boldsymbol{B}}{\partial t}\right) - \frac{1}{\lambda_L^2}\left(\frac{\partial \boldsymbol{B}}{\partial t}\right) = 0$$

Preserve initial condition!

Superconductor

Zero field!

$$\nabla^2 \boldsymbol{B} - \frac{1}{\lambda_L^2}\boldsymbol{B} = 0$$

London equation

Additional constraint (broken Gauge symmetry)

Superconductivity is a thermodynamical state which expels magnetic fields and cannot be explained by classical electrodynamics (input from quantum physics!)

Response to RF – two fluid model –

Supercurrent

$$\left.\begin{aligned} &\frac{\partial j_s}{\partial t} - \frac{n_S e^2}{m^*} E = 0 \\ &j_s = j_0 \exp(i\omega t) \end{aligned}\right\} \qquad j_s = -i \boxed{\frac{n_S e^2}{m^* \omega}} E$$

$$\equiv \sigma_S$$

Normal current

Ohm's law →

$$j_N = \boxed{\frac{n_N e^2 \tau}{m^*}} E$$

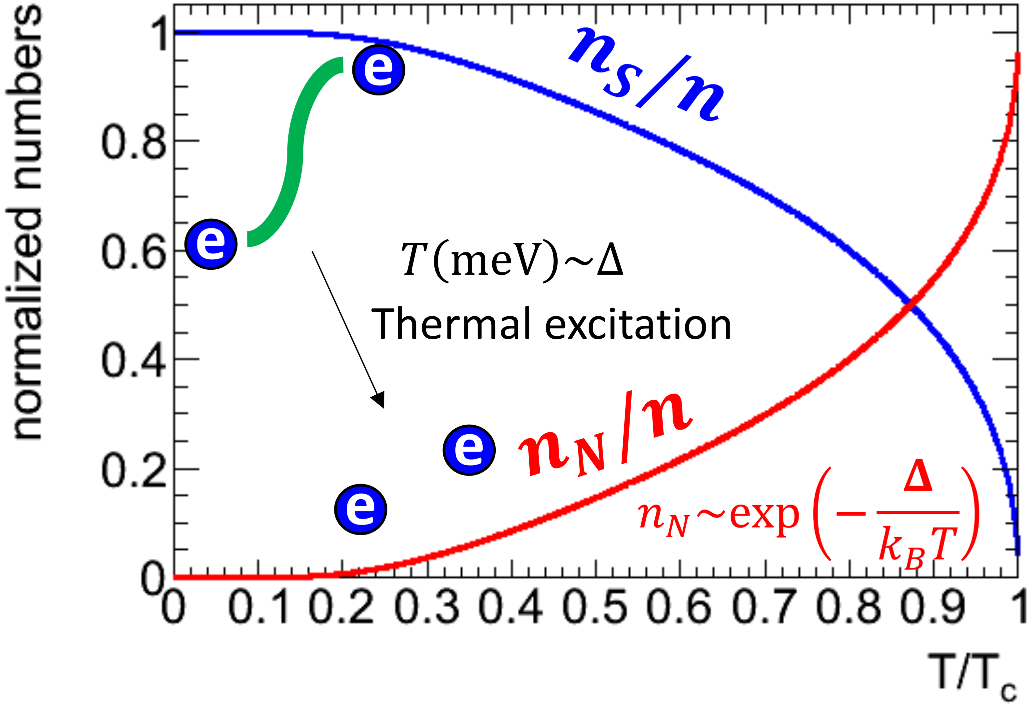
$$\equiv \sigma_N$$

Total current induced by RF

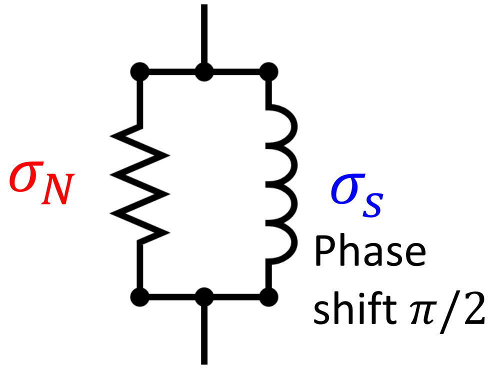
$$j = j_S + j_N \quad \rightarrow \quad j = (\sigma_N - i\sigma_S)E$$

Dissipation by quasi-particles →resistive

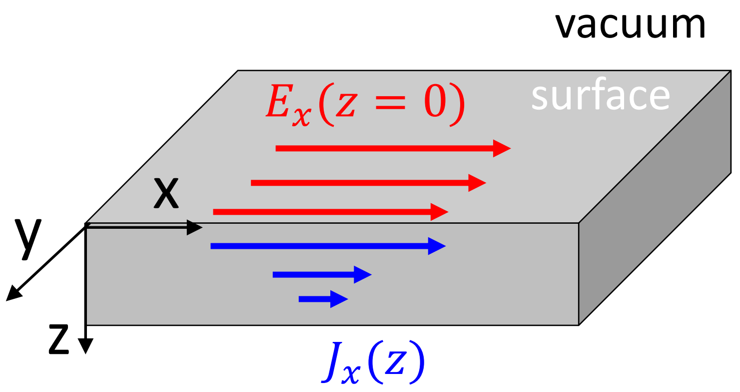
Inertia of Cooper pairs → inductive



Equivalent circuit



Surface resistance of superconductor



$$\begin{cases} j_x = (\sigma_N - i\sigma_S)E_x \\ E_x(z) = E_0 \exp(-z/\lambda_L) \end{cases}$$

$$\rightarrow R_s \equiv \mathrm{Re}\left(\frac{E_x(z=0)}{\int_0^\infty J_x(z)dz}\right) \sim \frac{1}{2}\frac{\sigma_N}{\sigma_S}\sqrt{\frac{\omega\mu_0}{\sigma_S}} = \frac{\mu_0^2}{2}\lambda_L^3\sigma_N\omega^2 > 0$$

$$\sigma_N = \frac{e^2 n_N \tau}{m^*} \propto n_N \propto \exp\left(-\frac{\Delta}{k_B \boldsymbol{T}}\right)$$

Typically
$R_s \sim 10\ n\Omega$

Lessons

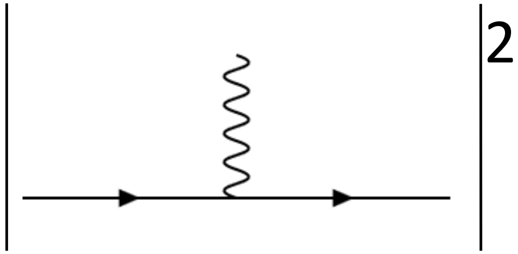
- One origin of the finite R_s of superconductors is quasi-particles
- Quasi-particles are thermally activated from Cooper pairs at $0 < T < T_c$
- R_s exponentially decreases by lower T because quasi-particles are frozen out
- Higher RF frequency increases $R_s \sim \omega^2$

A bit more fundamental: linear response theory

Ryogo Kubo

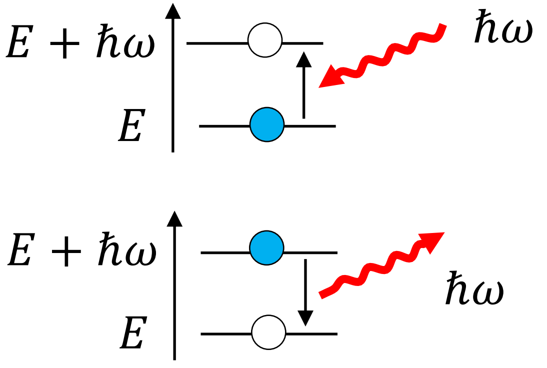
Fermi’s Golden rule [Z. Physik 266 p.209 (1974)]

$R_s \propto P \cong \Sigma_{p,p',\hbar\vec{k}}$



$\propto$ (photon energy) x (net # of absorbed photons)

$$= \hbar\omega(n_+ - n_-) = \hbar\omega \int_{\Delta}^{\infty} dE\,[f(E) - f(E+\hbar\omega)]\times N(E)N(E+\hbar\omega)$$



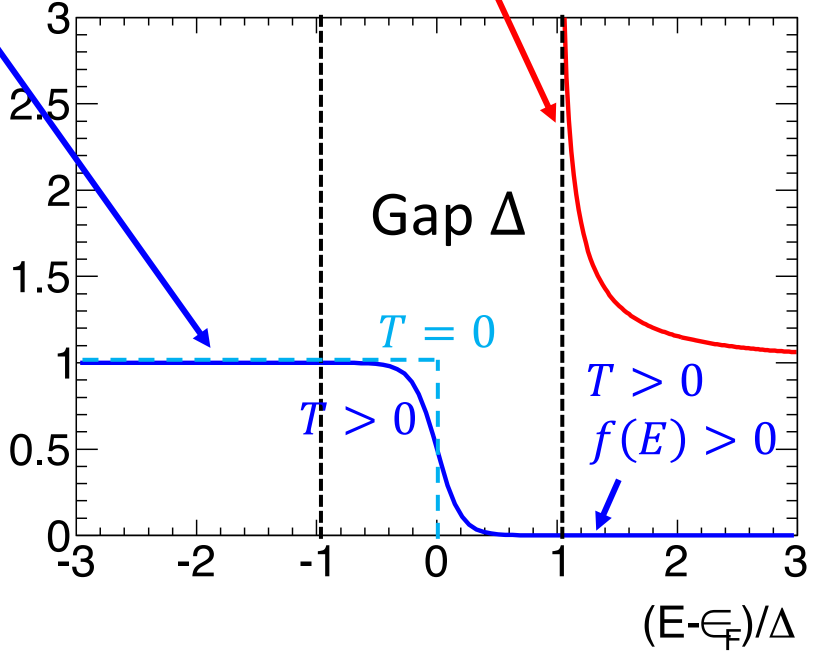
All quasiparticles
$\Delta < E < \infty$

$N(E)$: density of states (how many quantum states at energy E: a kind of degeneracy)

$f(E)$: distribution function (how many electrons are in one state at energy E)

Fermi-Dirac function in equilibrium state

$$f(E) = \frac{1}{\exp(-E/k_B T) + 1}$$

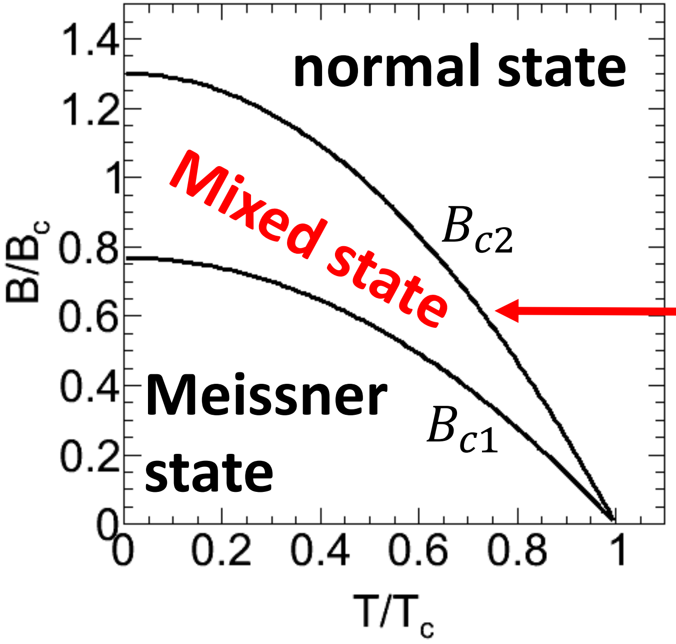


$$R_s \propto \frac{\omega^{1.5}}{T}\exp\left(-\frac{\Delta}{k_B T}\right)$$

$R_s(T=0) = 0$

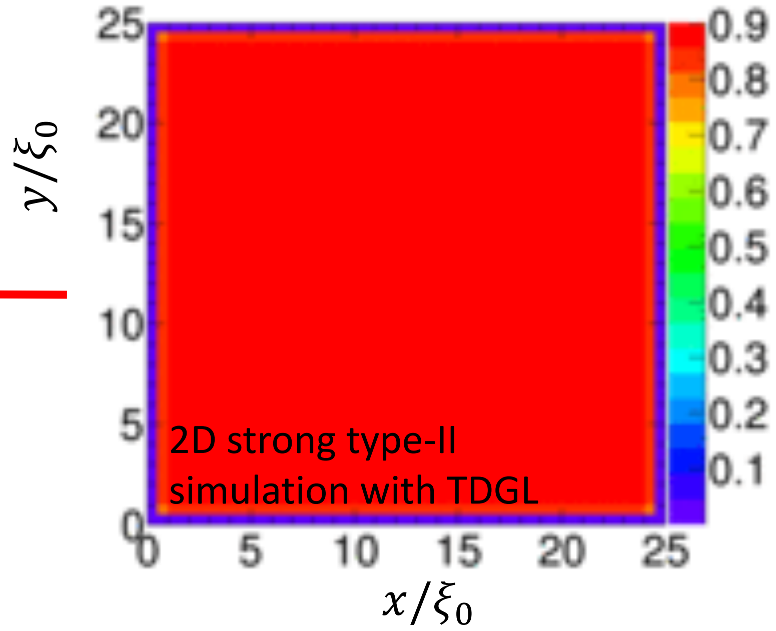
Strong and static magnetic field → topological defects

$$\kappa = \frac{\lambda}{\xi} > \frac{1}{\sqrt{2}} = 0.71$$



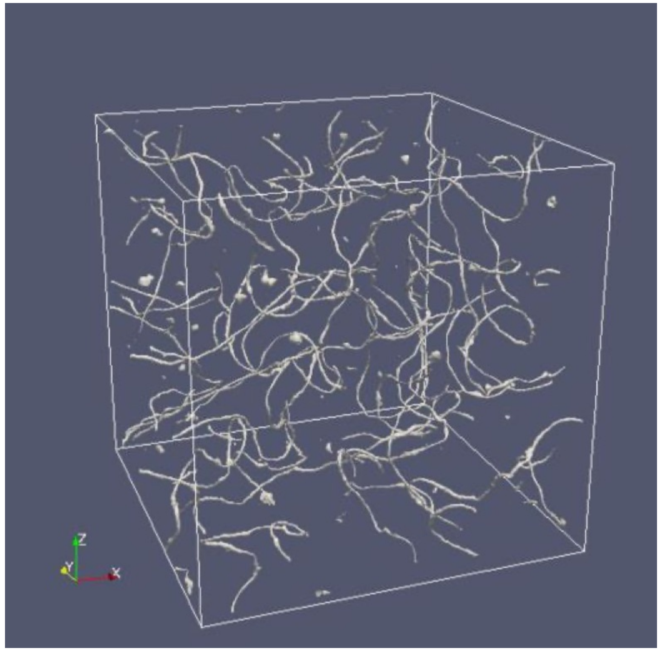
$$\kappa_{Nb} \sim \frac{36\ \text{nm}}{39\ \text{nm}} \sim 0.92$$

SC vortex U(1)$_{EM}$



Courtesy of Nagai-san

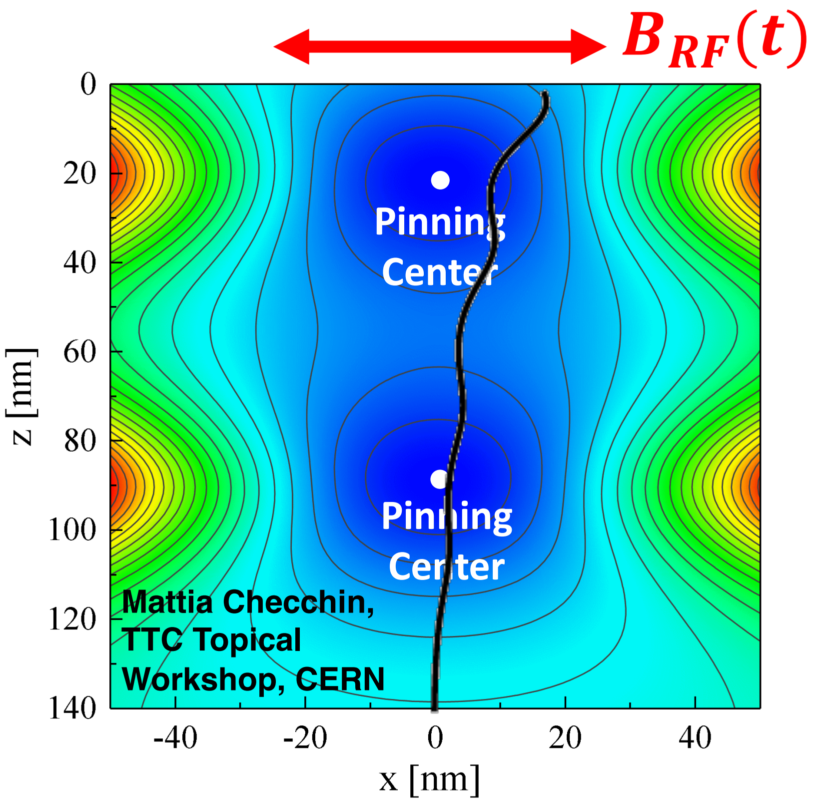
Axion string U(1)$_{PQ}$



Courtesy of Hiramatsu-san

→ Trapped magnetic vortices are harmful to SRF cavities

Additional loss from magnetic flux oscillation



Mattia Checchin, TTC Topical Workshop, CERN

Phenomenological equation of motion (Bardeen Stephen)

$$M\frac{\partial^2 \boldsymbol{u}}{\partial t^2}+\eta\frac{\partial \boldsymbol{u}}{\partial t}-\epsilon\frac{\partial^2 \boldsymbol{u}}{\partial z^2}+\nabla U(z,u)=\boldsymbol{J}_{RF}(z,u)\times\boldsymbol{B}_{\mathrm{ext}}$$

Effective inertia

Effective viscosity

Effective tension

Pinning potential

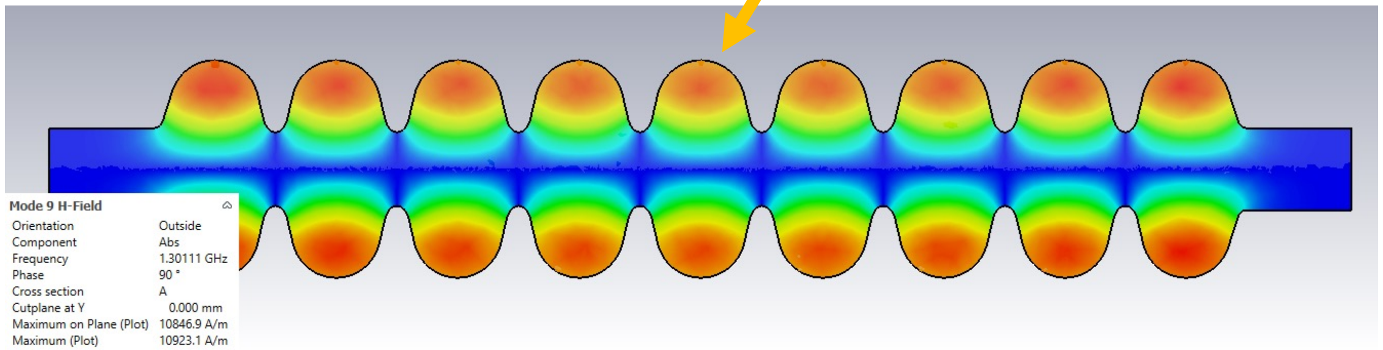
Lorentz force drives flux oscillation

Earth field B_{ext}=50uT
B_{c2}~400 mT (Nb)
R_n~1.3 mΩ at 1.3 GHz (Nb)

$$R_{\mathrm{mag}}\sim N\times\pi\xi_0^2\times R_{\mathrm{n}}\sim\frac{B_{\mathrm{ext}}}{2B_{c2}}R_{\mathrm{n}}\sim 100\ \mathrm{n}\Omega$$

→ Magnetic shield is MUST

$B_{RF}\sim 120\ \mathrm{mT}\ @\ 30\ \ \mathrm{MV/m}$



Mode 9 H-Field

Orientation	Outside
Component	Abs
Frequency	1.30111 GHz
Phase	90 °
Cross section	A
Cutplane at Y	0.000 mm
Maximum on Plane (Plot)	10846.9 A/m
Maximum (Plot)	10923.1 A/m

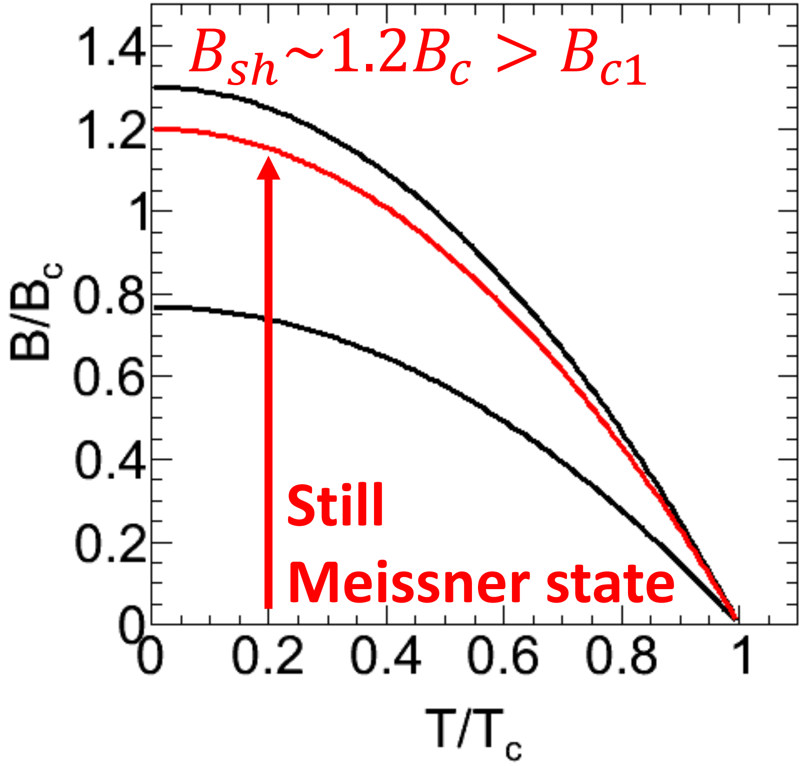
How about RF B-field itself?
If field penetrates, it is catastrophic!

Relevant critical field for SFR: superheating field

1^{st} order phase transition can be ***metastable***

https://tenor.com/view/diy-science-hack-ice-water-gif-3448836

Nb (type-II)

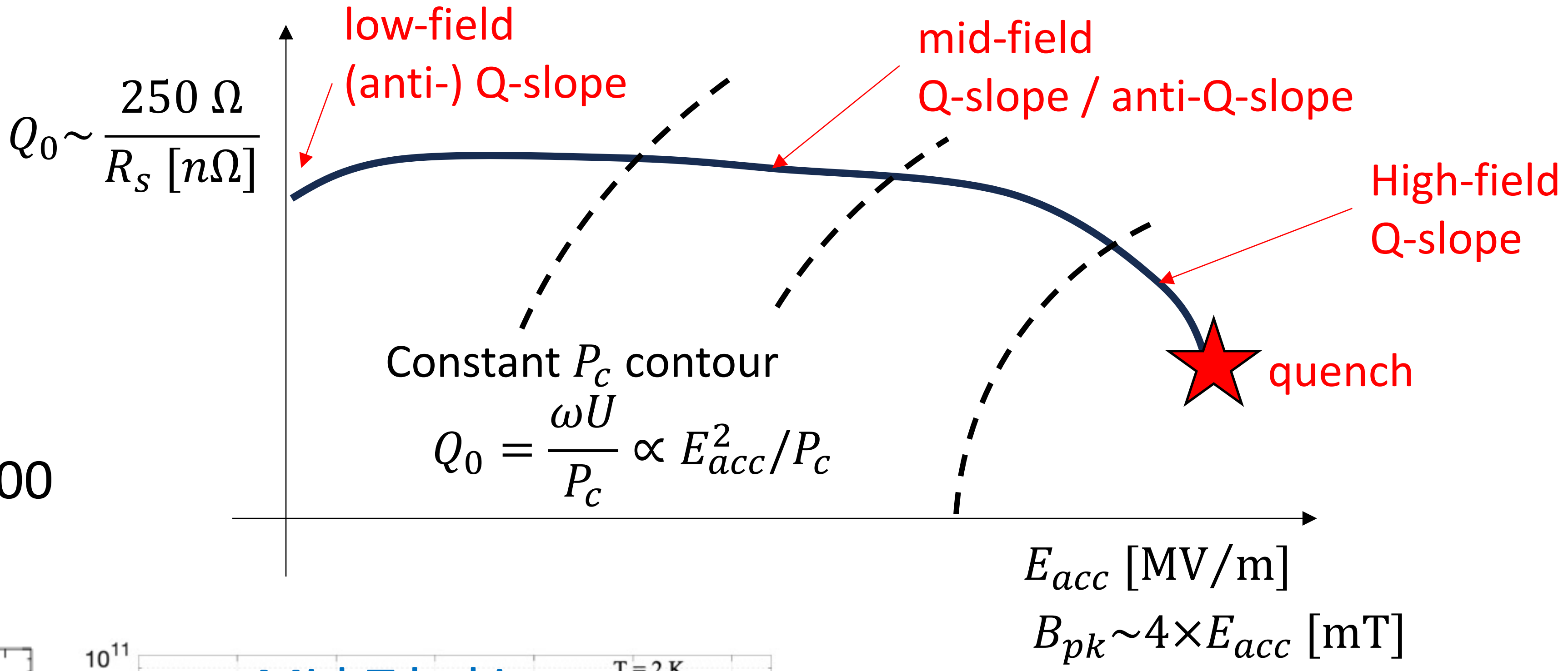


NC→SC phase transition from by very strong **RF** field is an open field of research: RF frequency vs relaxation time

→ Crucial for ultimate gradient of ILC cavities

Q vs E

- Upper right is better
- Unknown causes of nonlinear behavior
- Quench limits
- Dramatic change by 100 nm surface treatment



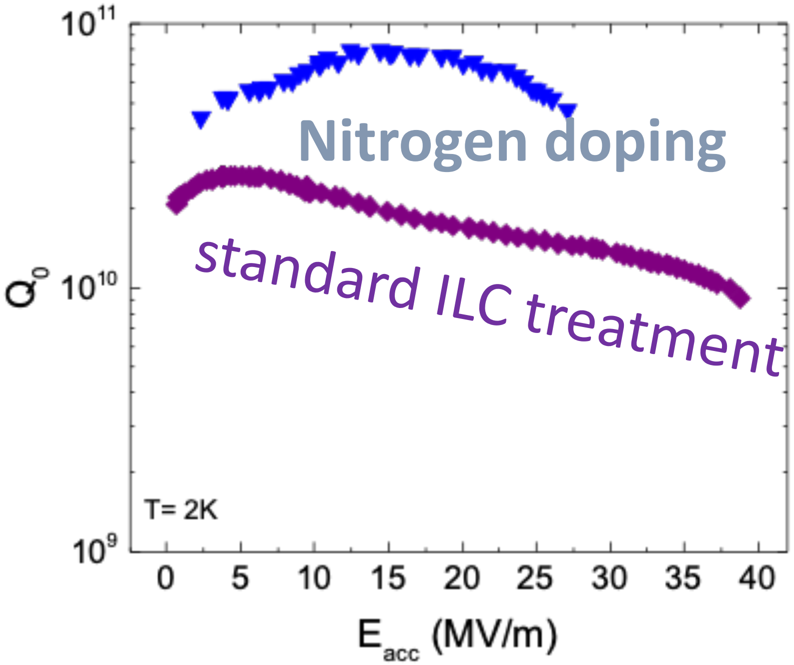
$$Q_0 \sim \frac{250\ \Omega}{R_s\ [n\Omega]}$$

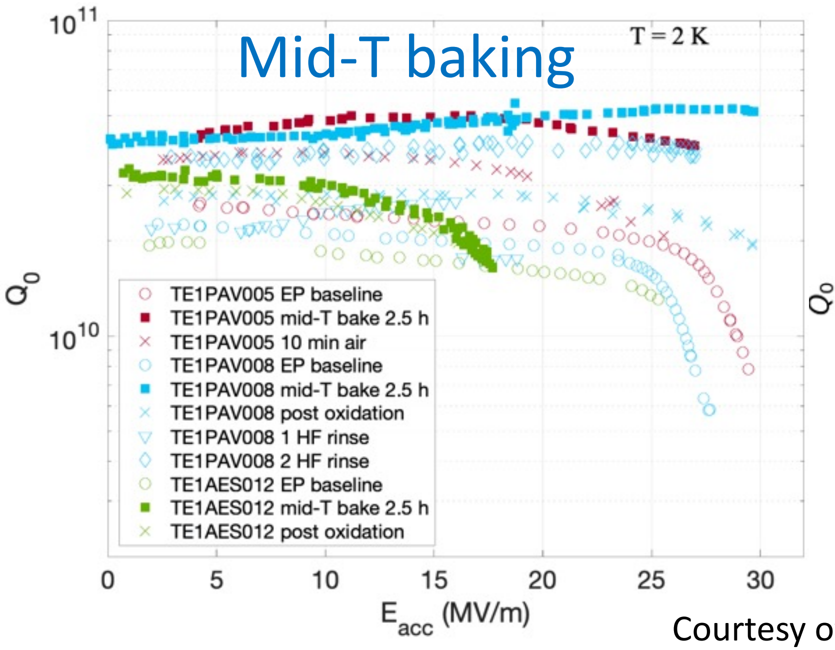
Constant P_c contour

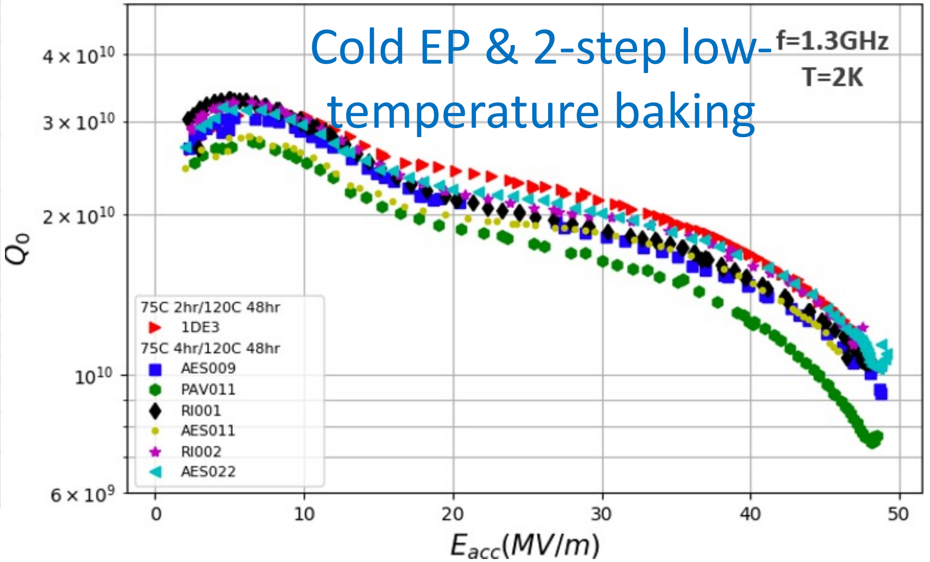
$$Q_0 = \frac{\omega U}{P_c} \propto E_{acc}^2/P_c$$

E_{acc} [MV/m]

$B_{pk} \sim 4 \times E_{acc}$ [mT]







Courtesy of Sergey Belomestnykh

Outline

- How to measure Higgs boson precisely? (10 min)
  - High luminosity with high energy
  - Solutions: circular vs linear
- High luminosity (10 min)
  - Nano beam technology
- High energy (10 min)
  - Superconducting Radio Frequency technology
- Conclusion

Conclusion

- It is not easy to learn accelerator physics
  - A lot of technical details are all crucially important to realize the machines
  - Basic concepts over broad area of physics
- The goals of ILC require high luminosity and high energy
  - Linear accelerator can avoid synchrotron radiation
- Nano-beam is the key concept for high luminosity
  - Reduce emittance (entropy) via radiation damping
  - Lorentz boost & focusing magnets
- Superconducting cavities offer open research field
  - Nonrelativistic $U(1)_{EM}$ composite Higgs boson and its thermal excitation
  - The thermal excitation causes finite loss against RF
  - RF magnetic fields do not penetrate superconducting surfaces easily
  - Phase transition and its improvement is still an open question and of crucial importance for ILC

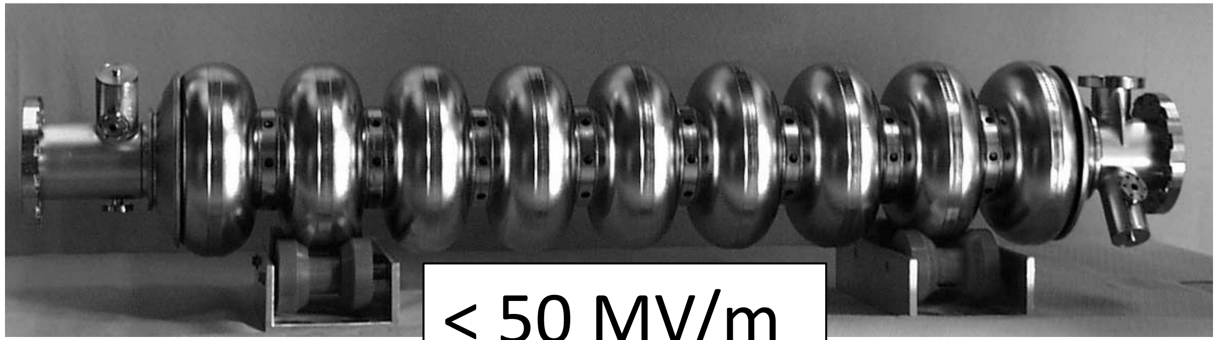
Job opportunities in Europe

- CALO5D (French-German collaboration of imaging calorimeters)
  - Two year post-doc at IJCLab (Orsay, South of Paris)
  - Three year post-doc and two year post- doc at LLR (Palaiseau, South of Paris)
  - Contacting:
    - Roman Pöschl (roman.poeschl@ijclab.in2p3.fr)
    - Vincent Boudry (boudry@llr.in2p3.fr)
- Superconducting accelerator technology (magnets and cavities) in Sweden
  - Two year post-doc at Uppsala University (North of Stockholm)
  - Application: https://www.jobb.uu.se/details/?positionId=737113
- Superconducting cavity engineering (cavities) in Sweden
  - Permanent research engineer at Uppsala University
  - Application: https://uu.varbi.com/en/what:job/jobID:738369/

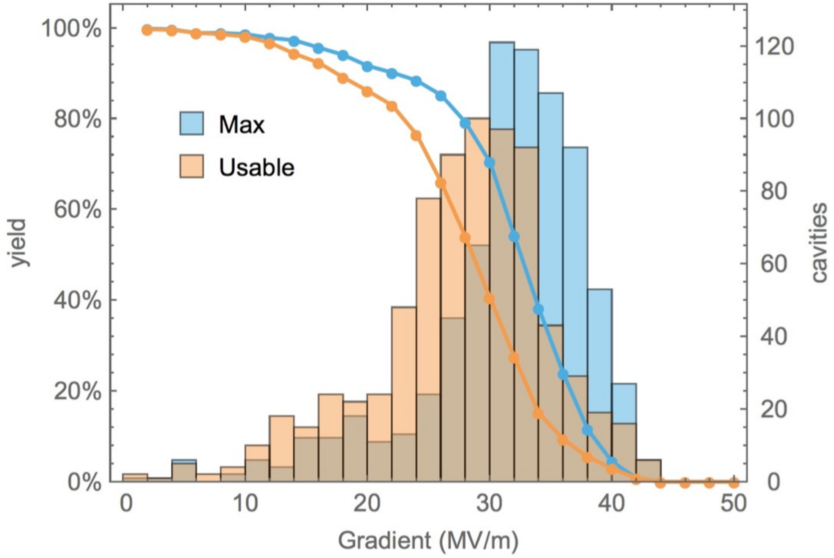
backup

Accelerating cavities

Superconducting niobium cavities (TESLA)



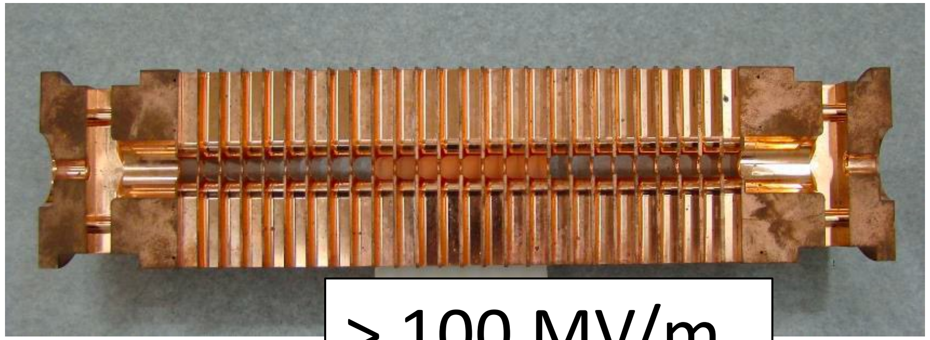
< 50 MV/m



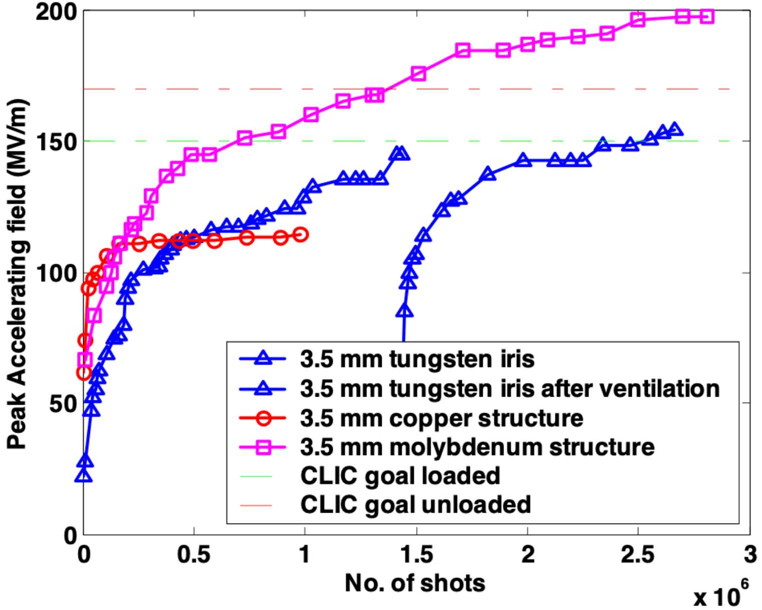
PHY REV ST - ACCEL BEAMS, **3**, 092001 (2000)
PHY REV ACCEL BEAMS 20, 042004 (2017)

>×2

Normal conducting copper cavities



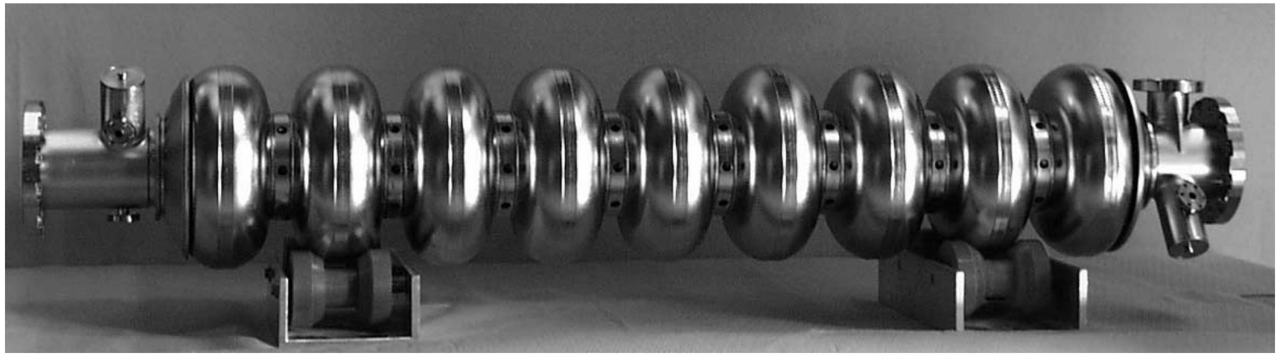
> 100 MV/m

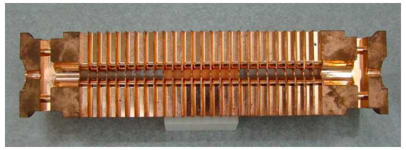


Courtesy: Walter Wuensch

Superconducting vs normal conducting

Aperture

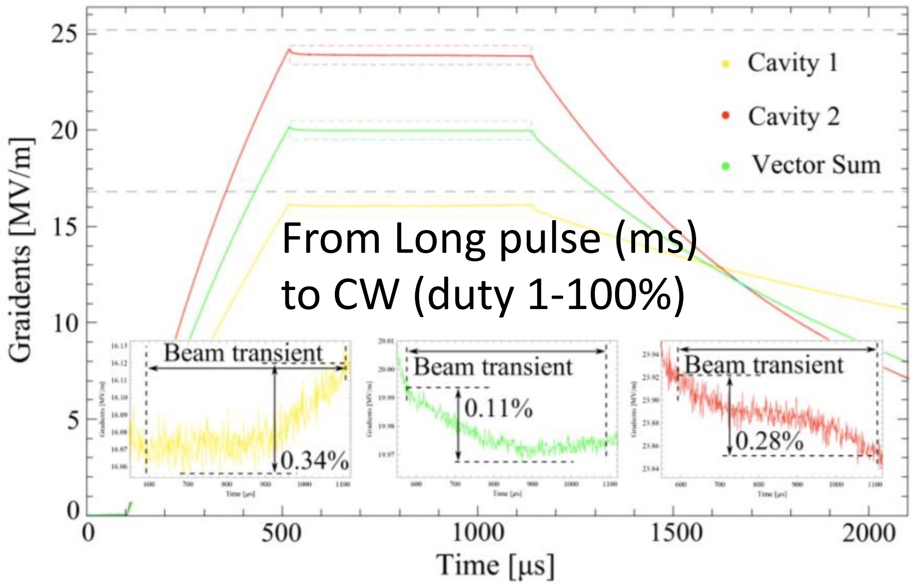




Superconducting cavities can keep high gradient at low frequency
→ large aperture (ILC: ϕ70 mm)

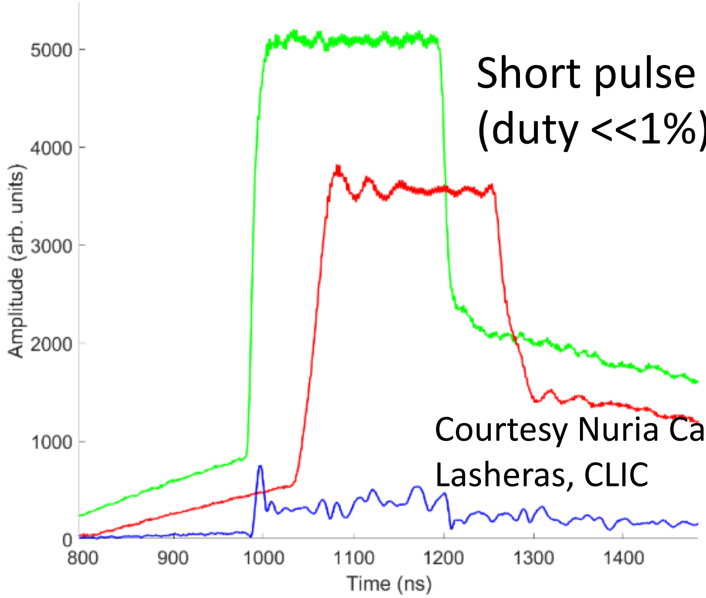
Normal conducting cavities are efficient at high frequency
→ small aperture (CLIC X-band: around ϕ3 mm)

Pulse length and duty cycle



From Long pulse (ms)
to CW (duty 1-100%)

M. Omet
SRF2021
lecture

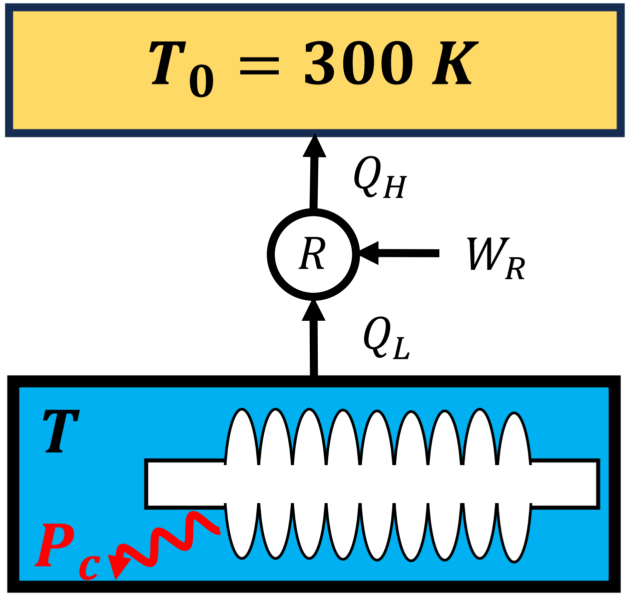


Short pulse (μs)
(duty <<1%)

Courtesy Nuria Catalan Lasheras, CLIC

SC cavities' quality factor
×10^6
than copper cavities
→ power dissipation
×10^{-6}
but in ***cryogenics***!

Cooling efficiency < Carnot cycle

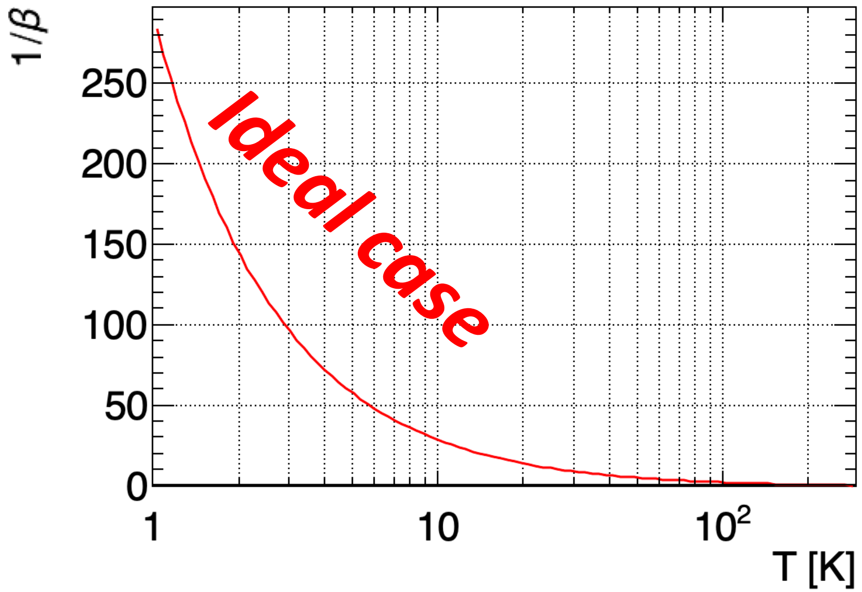


$$\beta = \frac{Q_L}{W_R} = \frac{Q_L}{Q_H - Q_L} \overset{\text{Carnot's theorem}}{\overset{\downarrow}{=}} \frac{T}{T_0 - T}$$

Required power

$$P_{cryo} > W_R = \frac{P_c}{\beta}$$

(typically 5 kW/W @ 2 K for AC plug)



SC cavities

$P_c = 100$ W (CW)
Duty cycle 10^{-2}
$T = 2$ K

$$P_{NET} \sim 100\ \mathrm{W} \times 1\% \times 150 = 150\ \mathrm{W}$$

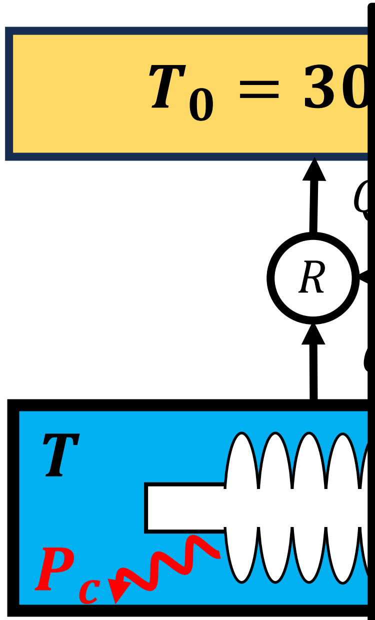
NC cavities

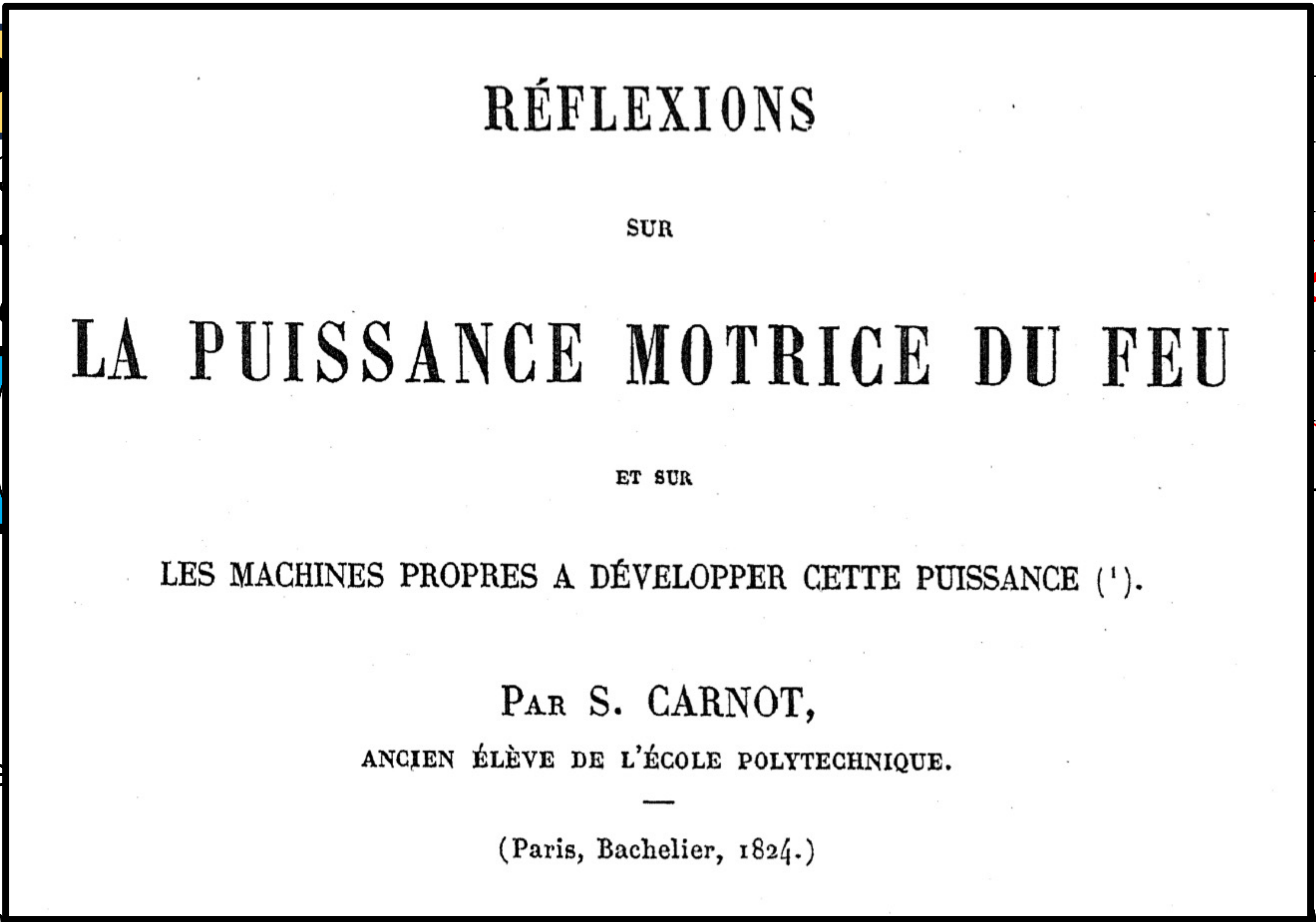
$P_c = 10$ MW (CW)
Duty cycle 10^{-5}
Water cooling

$$P_{NET} \sim 10\ \mathrm{MW} \times 10^{-5} \times 1 = 100\ \mathrm{W}$$

→ Short pulsed NC cavities and long pulsed SC cavities are similar in power consumption

Cooling efficiency < Carnot cycle





RÉFLEXIONS

SUR

LA PUISSANCE MOTRICE DU FEU

ET SUR

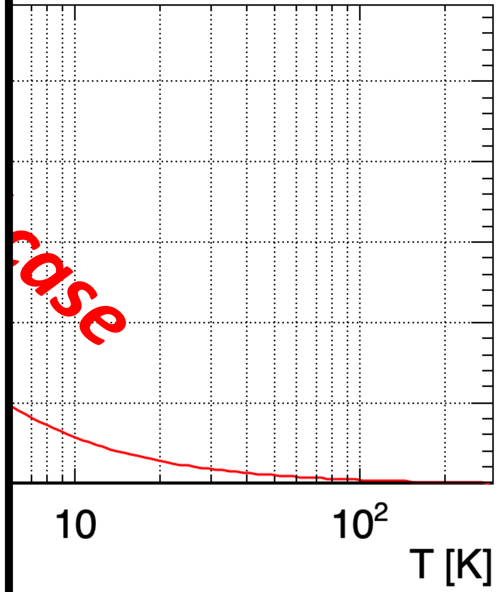
LES MACHINES PROPRES A DÉVELOPPER CETTE PUISSANCE (¹).

PAR S. CARNOT,

ANCIEN ÉLÈVE DE L'ÉCOLE POLYTECHNIQUE.

—

(Paris, Bachelier, 1824.)



SC cavities

$P_c = 100$

Duty cycle

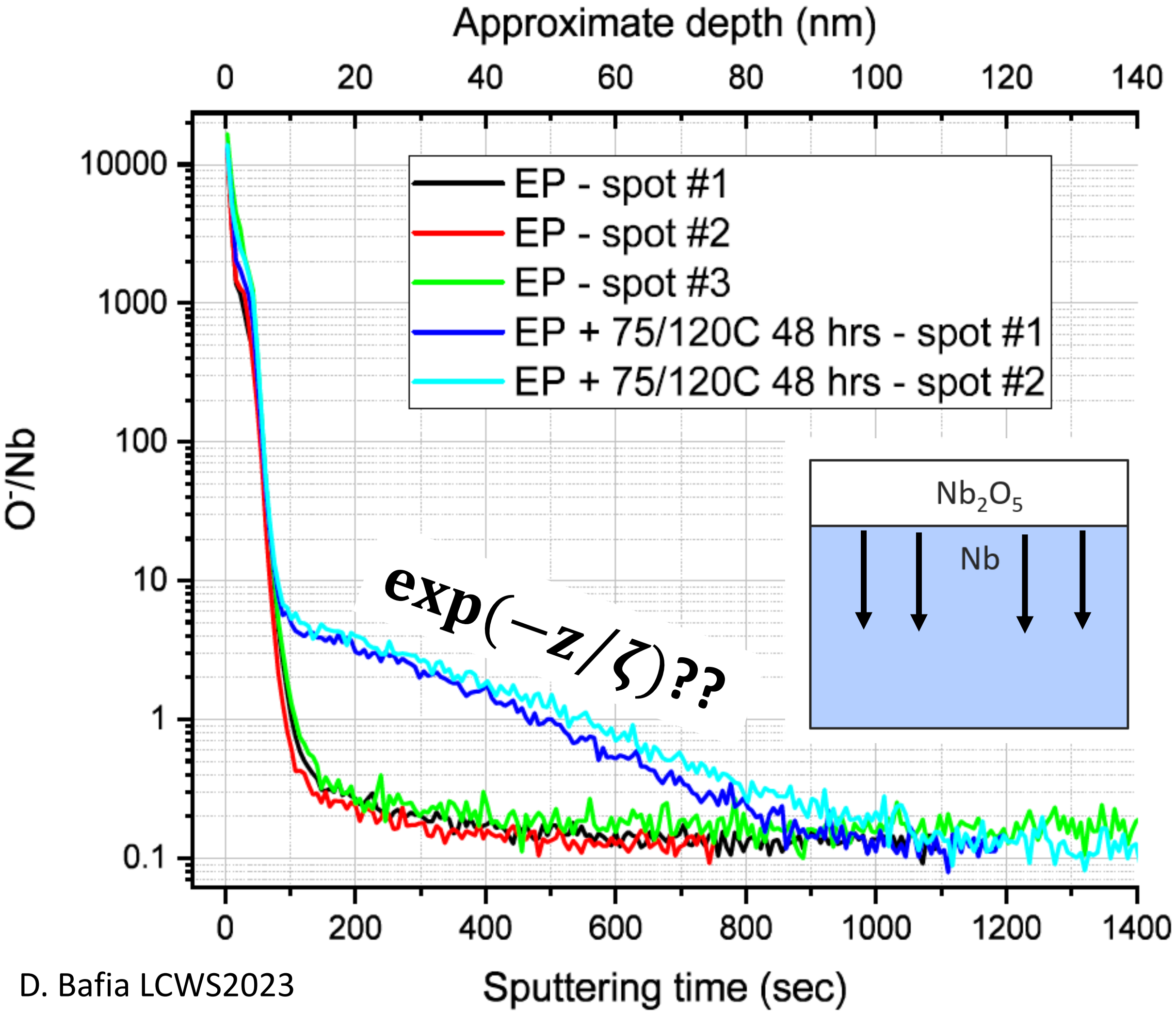
$T = 2$ K

P_{NET}~100 W×1% ×150 = 150 W

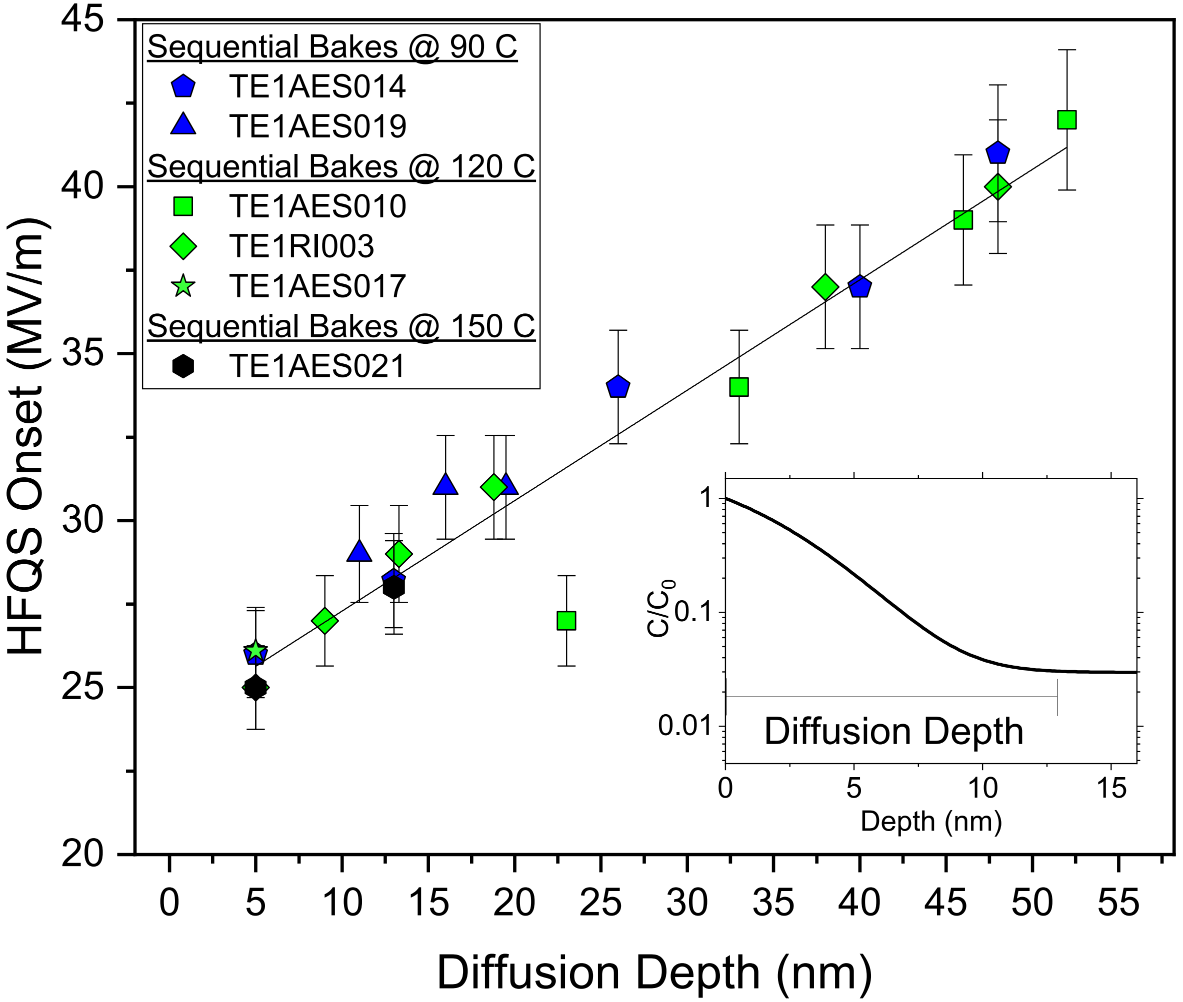
P_{NET} 10 MW×10 ×1 = 100 W

→ Short pulsed NC cavities and long pulsed SC cavities are similar in power consumption

Higher/lower gradient by low-T / 2-step baking



D. Bafia LCWS2023



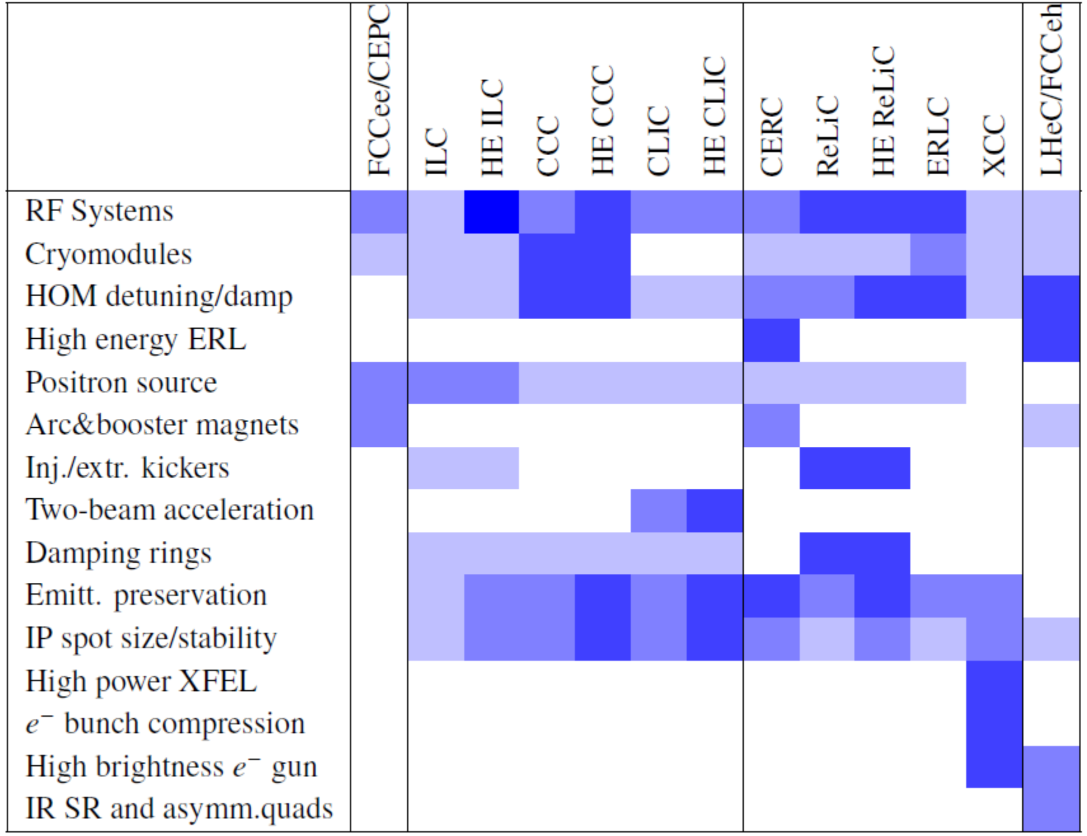
Inhomogeneity of disorder anisotropy of Fermi surface seem like key

→ New data and models (classical and quantum phenomenology)

Table 1. TRL scoring chart and color codes (used below in the summary table 9).

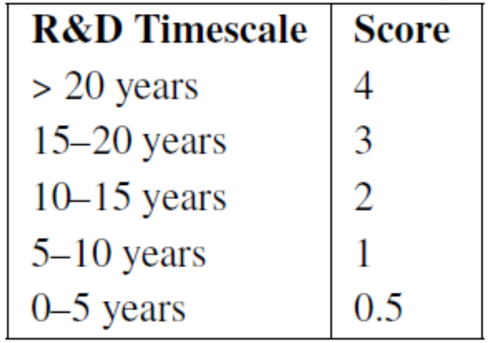
Technical Risk Factor	**Score**	**Color Code**
TRL = 1, 2	4	█
TRL = 3, 4	3	▓
TRL = 5, 6	2	▒
TRL = 7, 8	1	░

Table 2. Technical risk registry of accelerator components and systems for future e^+e^- and ep colliders: lighter colors indicate progressively higher TRLs (less risk), white is for either not significant or not applicable.



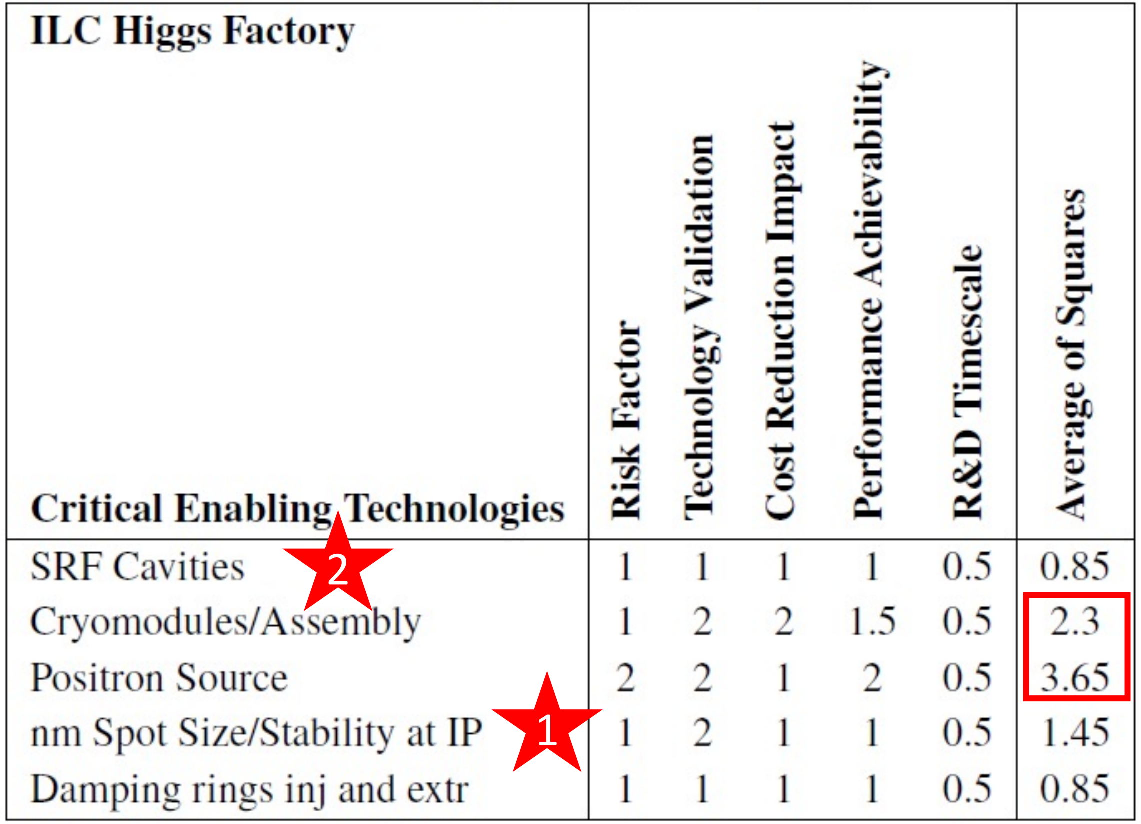
	FCCee/CEPC	ILC	HE ILC	CCC	HE CCC	CLIC	HE CLIC	CERC	ReLiC	HE ReLiC	ERLC	XCC	LHeC/FCCeh
RF Systems	▒	░	█	▒	▓	▒	▒	▒	▓	▓	▓	░	░
Cryomodules	░	░	░	▓	▓			░	░	░	▒	░	░
HOM detuning/damp		░	░	▓	▓	░	░	▒	▒	▓	▓	░	▓
High energy ERL								▓					▓
Positron source	▒	▒	▒	░	░	░	░	░	░	░	░		
Arc&booster magnets	▒							▒					░
Inj./extr. kickers		░	░						▓	▓			
Two-beam acceleration						▒	▓						
Damping rings		░	░	░	░	░	░		▓	▓			
Emitt. preservation		░	▒	▒	▓	▒	▓	▓	▒	▓	▒	▒	
IP spot size/stability		░	▒	▒	▓	▒	▓	▒	░	▒	░	▒	░
High power XFEL												▓	
e^- bunch compression												▓	
High brightness e^- gun												▓	▒
IR SR and asymm.quads													▒

Table 7. R&D time frame scoring chart.



R&D Timescale	**Score**
> 20 years	4
15–20 years	3
10–15 years	2
5–10 years	1
0–5 years	0.5

Table 8. ILC Higgs Factory scoring example.



ILC Higgs Factory **Critical Enabling Technologies**	**Risk Factor**	**Technology Validation**	**Cost Reduction Impact**	**Performance Achievability**	**R&D Timescale**	**Average of Squares**
SRF Cavities ★2	1	1	1	1	0.5	0.85
Cryomodules/Assembly	1	2	2	1.5	0.5	2.3
Positron Source	2	2	1	2	0.5	3.65
nm Spot Size/Stability at IP ★1	1	2	1	1	0.5	1.45
Damping rings inj and extr	1	1	1	1	0.5	0.85

https://arxiv.org/abs/2208.06030

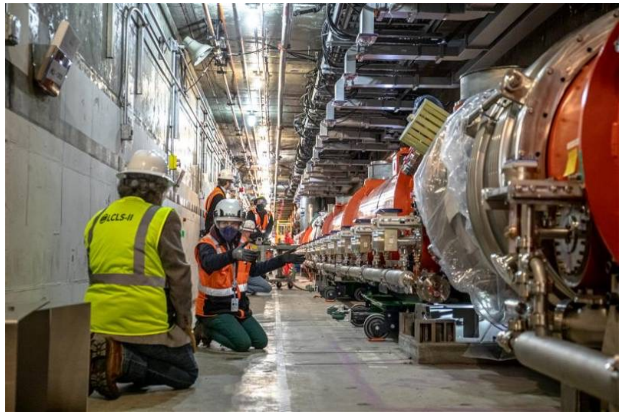
State-of-the-art

Superconducting cavities: matured

EuXFEL in operation
@ DESY

© Heiner Müller-Elsner / European XFEL 2016

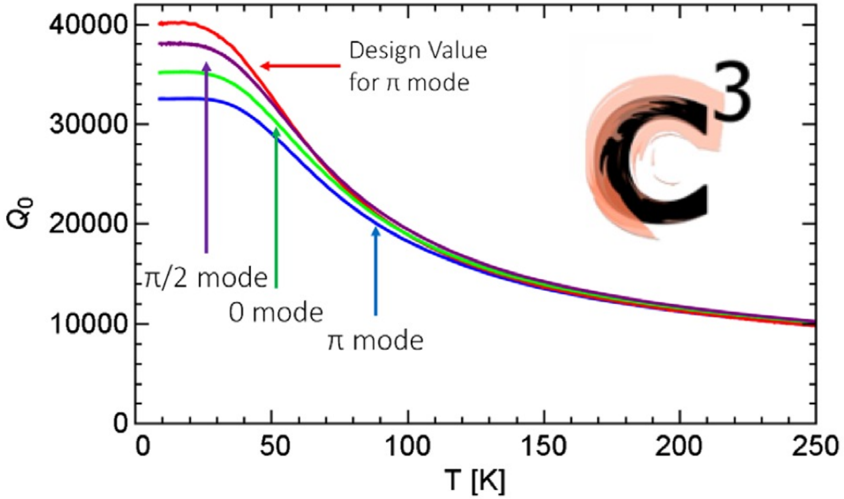
LCLS-II in construction
@ LCLS-II

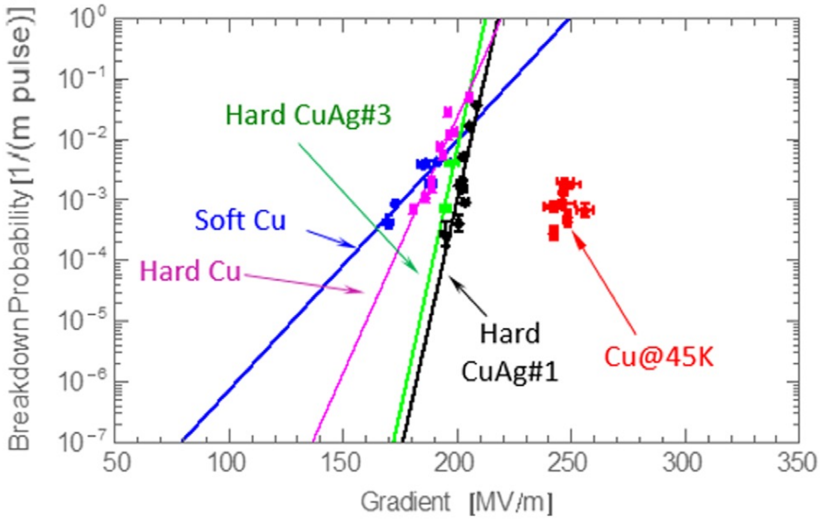


Other SRF linear accelerators (not collider) have been operated and/or constructed (SNS, ESS, MYRRAH, PIP-II, SHINE, CiADS, …)

https://fr.futuroprossimo.it/2023/09/lcls-ii-acceso-il-laser-a-raggi-x-piu-potente-del-mondo/

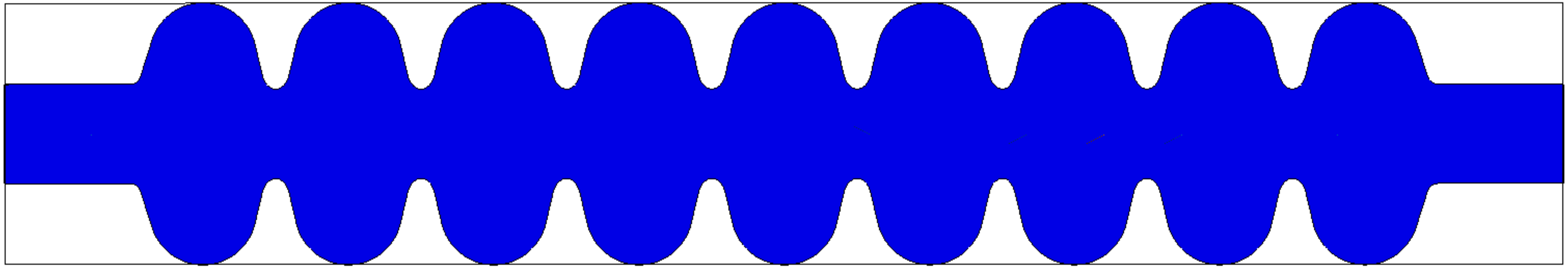
Nitrogen cooled copper cavities





A. D. Cahill et al Phys. Rev. Accel. Beams **21**, 102002

Electrodynamics is not simply cause and effect



e-field (t=0..end(0.02)) [pb]

Component	Abs
Sample	1/223
Time	0 ns
Cross section	A
Cutplane at Y	0.000 mm
Maximum on Plane (Sample)	0 V/m
Maximum (Sample)	0 V/m
Maximum (Global)	722411 V/m

$$\begin{cases} \nabla\cdot\boldsymbol{E} = \boxed{\rho(t,\boldsymbol{r})} \\ \nabla\times\boldsymbol{E} = -\dfrac{\partial\boldsymbol{B}}{\partial t} \\ \nabla\cdot\boldsymbol{B} = 0 \\ \nabla\times\boldsymbol{B} = \boxed{\mu_0\boldsymbol{J}(t,\boldsymbol{r})} + \dfrac{1}{c^2}\dfrac{\partial\boldsymbol{E}}{\partial t} \end{cases}$$

Trajectory of charged particles

→Induce RF fields of ***multiple*** modes

- Influence to accelerating mode (beam loading)
  - → Compensation with amplifier
- Influence to other modes
  - → kick following bunches
  - → Needs to be damped (Higher Order Mode damper)

→ SRF cavities' Large aperture helps