# Energy Recovery Linacs

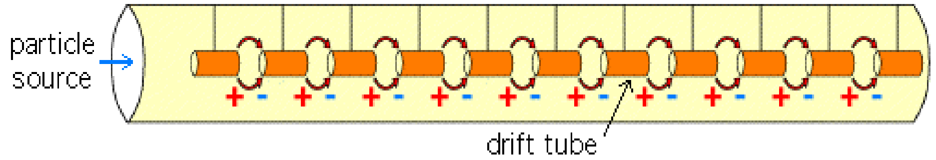
Erk Jensen/CERN

Rama Calaga, Ed Ciapala, J. Tückmantel/CERN

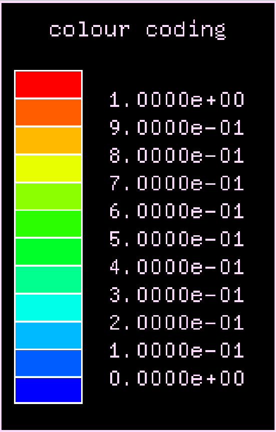
and many others

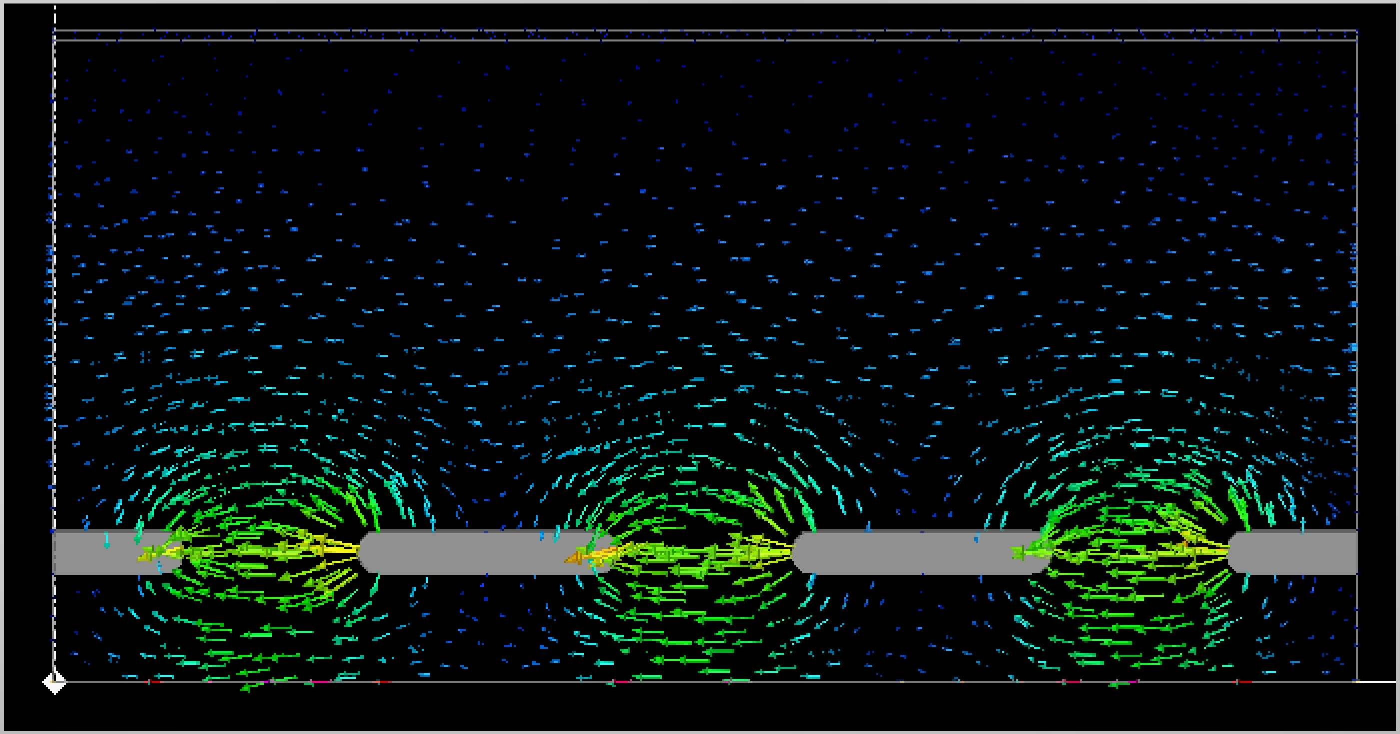
# Introduction:
# Linacs, efficiency, energy recovery

# Reminder: How a Linac works (here DTL)

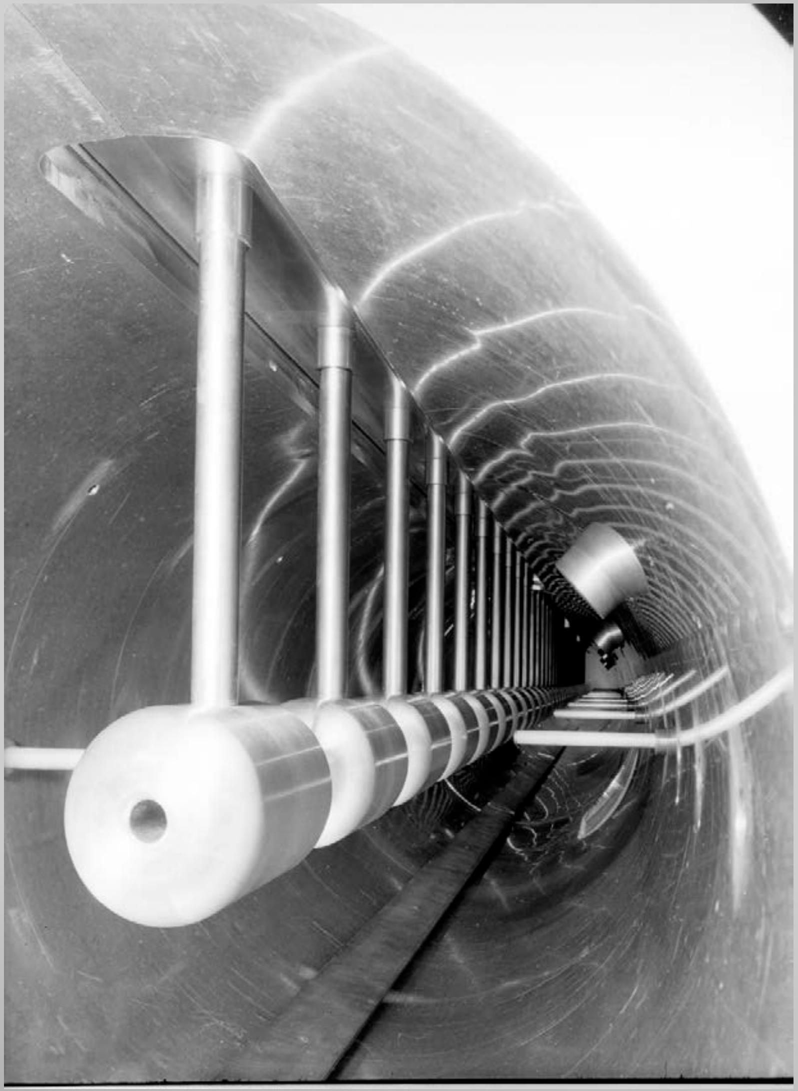


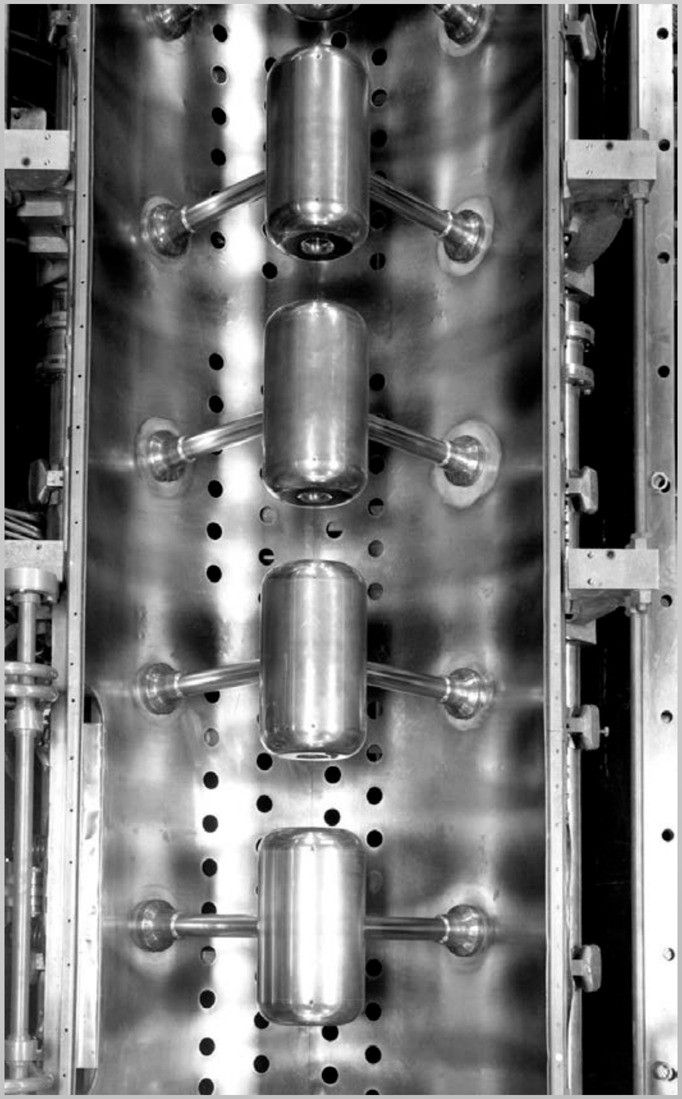
Electric field strength



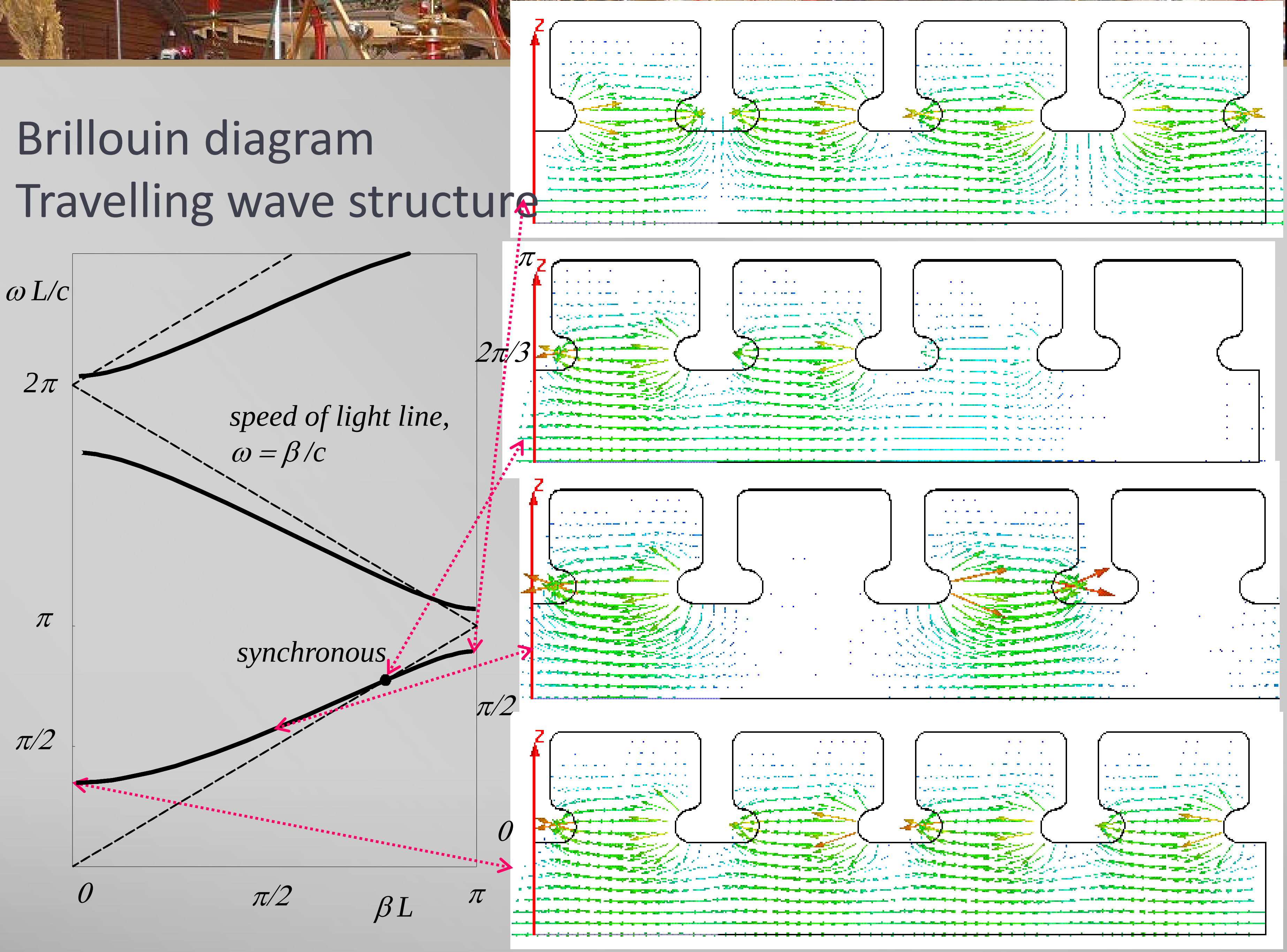


# Drift tube linac – practical implementations

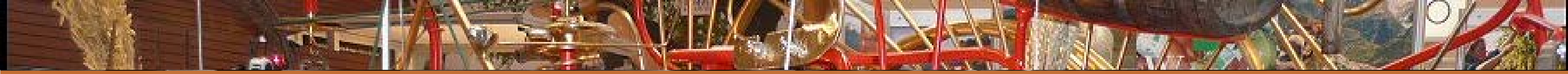




# Brillouin diagram
# Travelling wave structure



# View inside CERN’s SPS 200 MHz TW cavity



# Let’s talk about RF → beam efficiency!

- With zero beam current, RF power fed into the cavity excites a gap voltage, but it will be entirely lost in the cavity walls; this is characterized by the shunt impedance $R$:

$$|V_{acc}| = \frac{1}{2}\left(\sqrt{(4P)R}\right)$$

- A non-zero beam current induces a voltage reducing the gap voltage*); this is known as **beam loading** and normally considered a disadvantage.

$$|V_{acc}| = \frac{1}{2}\left(\sqrt{(4P + I_{beam}^2 R)R} - I_{beam}R\right)$$

- But: if we define the RF to beam efficiency as “increase of beam power” divided by “RF input power”, we find that large efficiency can be obtained only with large beam loading (at the expense of reduced accelerating voltage).
- Example: CLIC drive beam accelerated with 98% RF to beam efficiency.

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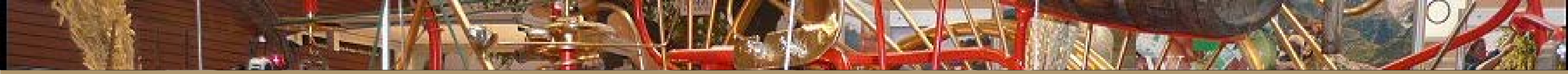
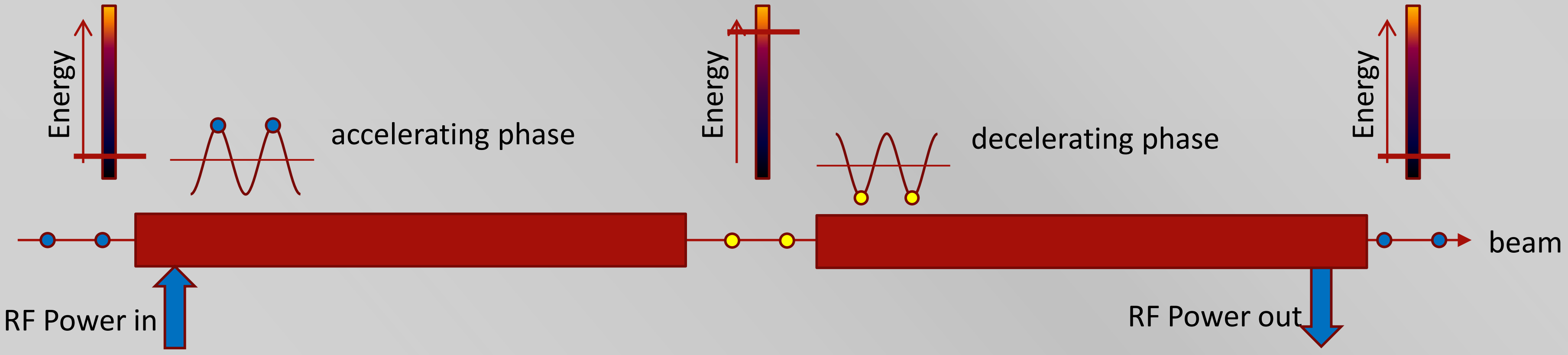
*) for an accelerated beam! For a decelerated beam the voltage is increased



# Recovering the energy from the beam – the concept



Energy

accelerating phase

Energy

decelerating phase

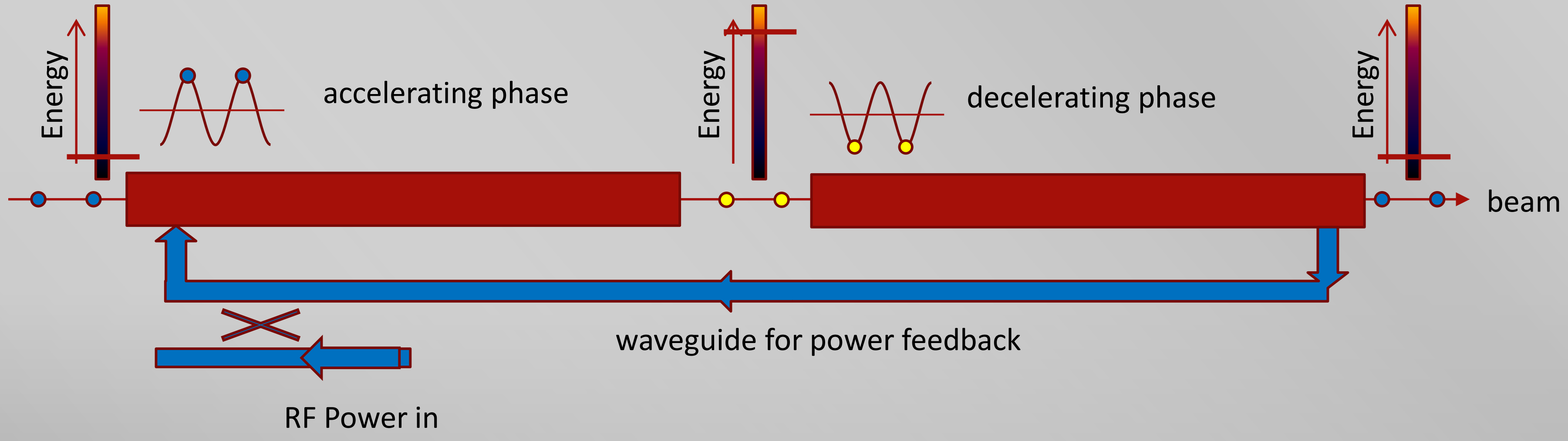
Energy

beam

RF Power in

RF Power out

One could use a waveguide and reuse the RF power!



Energy

accelerating phase

Energy

decelerating phase

Energy

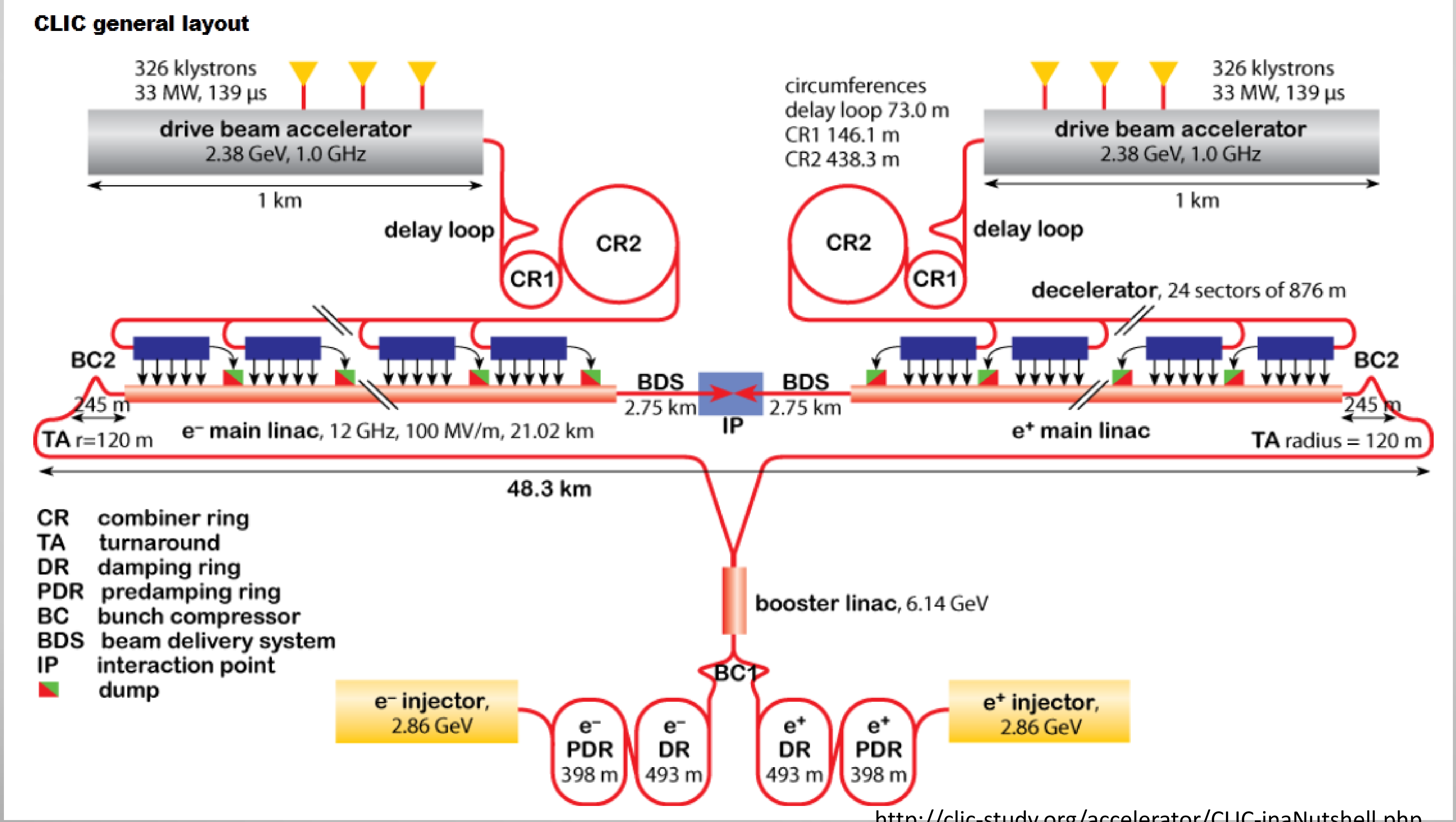
beam

waveguide for power feedback

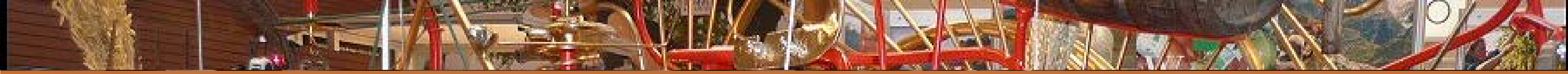
RF Power in

# A word about CLIC:

***In the CLIC scheme, 90% of the drive beam power is recovered (to produce the RF power for the main beam)***

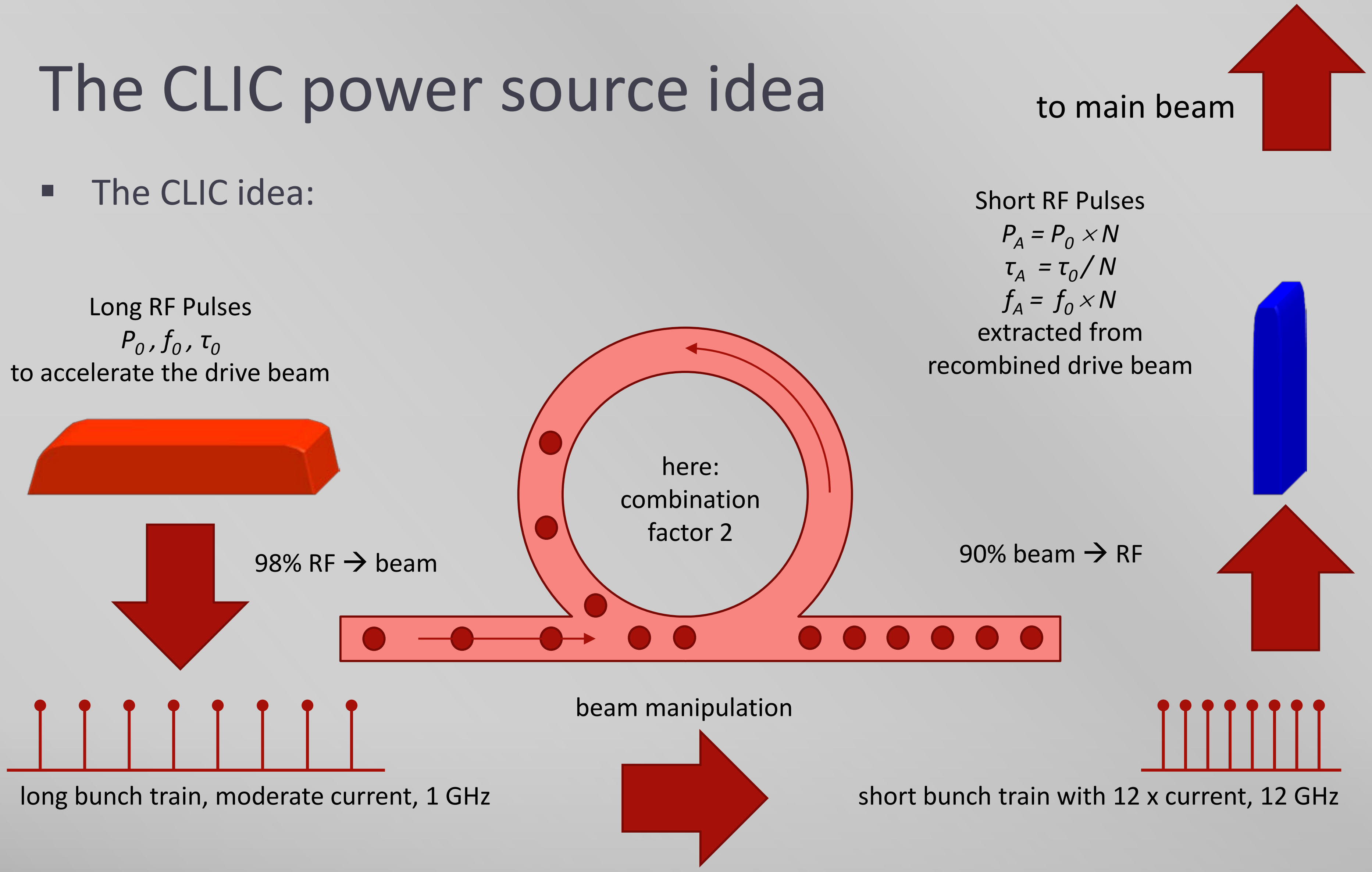


http://clic-study.org/accelerator/CLIC-inaNutshell.php



# The CLIC power source idea

- The CLIC idea:



to main beam

Short RF Pulses
$P_A = P_0 \times N$
$\tau_A = \tau_0 / N$
$f_A = f_0 \times N$
extracted from
recombined drive beam

Long RF Pulses
$P_0, f_0, \tau_0$
to accelerate the drive beam

here:
combination
factor 2

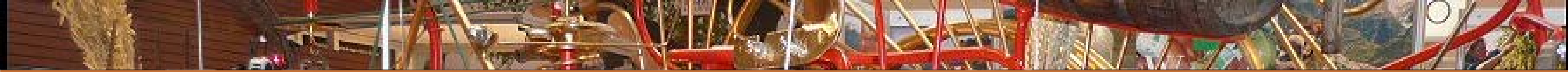
98% RF → beam

90% beam → RF

beam manipulation

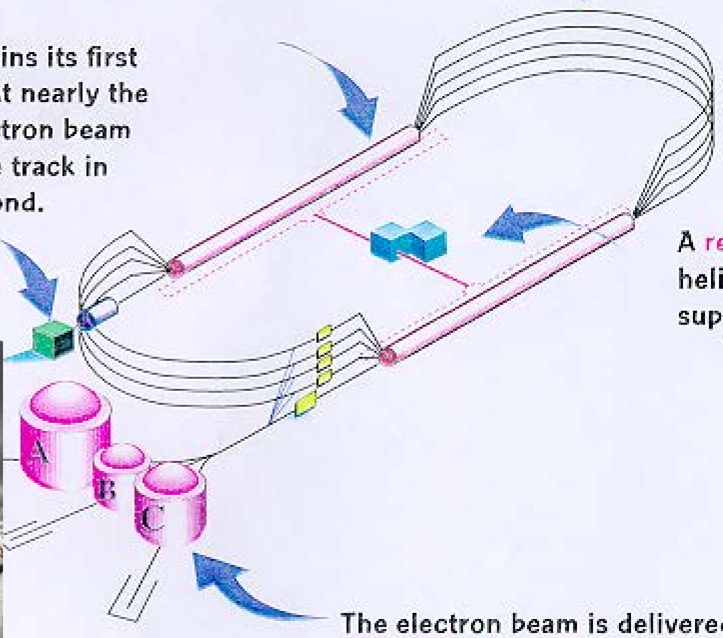
long bunch train, moderate current, 1 GHz

short bunch train with 12 x current, 12 GHz



# Recirculating Linac

- One could use the same accelerating structure more than once!
- CEBAF (Continuous Electron Beam Accelerator Facility) at JLAB, Newport News, VA, USA has been using this scheme successfully for many years.



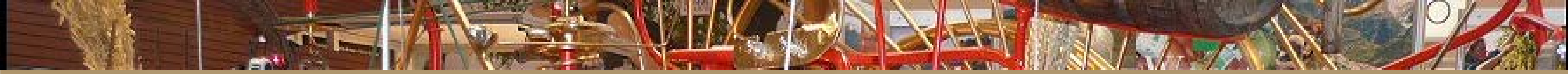
Each linear accelerator uses superconducting technology to drive electrons to higher and higher energies.

Magnets in the arcs steer the electron beam from one straight section of the tunnel to the next for up to five orbits.

The electron beam begins its first orbit at the injector. At nearly the speed of light, the electron beam circulates the 7/8 mile track in 30 millionths of a second.

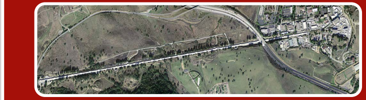
A refrigeration plant provides liquid helium for ultra-low-temperature, superconducting operation.

The electron beam is delivered to the experimental halls for simultaneous research by three teams of physicists.



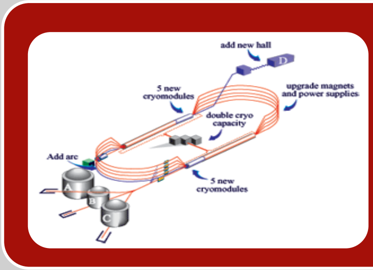
# Recirculating Linac compared to linac and synchrotron

## Linac



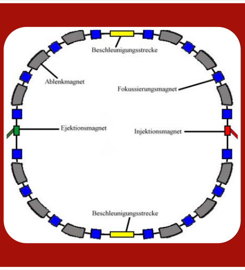
- Accelerating Structure used for 1 passage
- Less efficient
- Only single pass instabilities

## Recirculating Linac



- Accelerating Structure used for some (2-10) passages
- Return arcs different for different energies
- Concerning instabilities, a good compromise

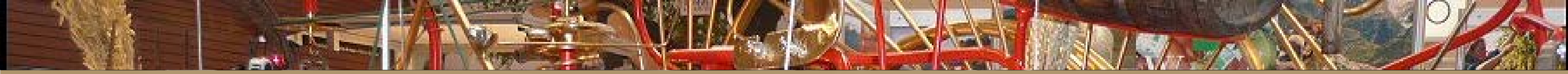
## Synchrotron



- Accelerator Structure used many times
- Periodic lattice
- Instabilities develop over many turns (coupled bunch, mode coupling

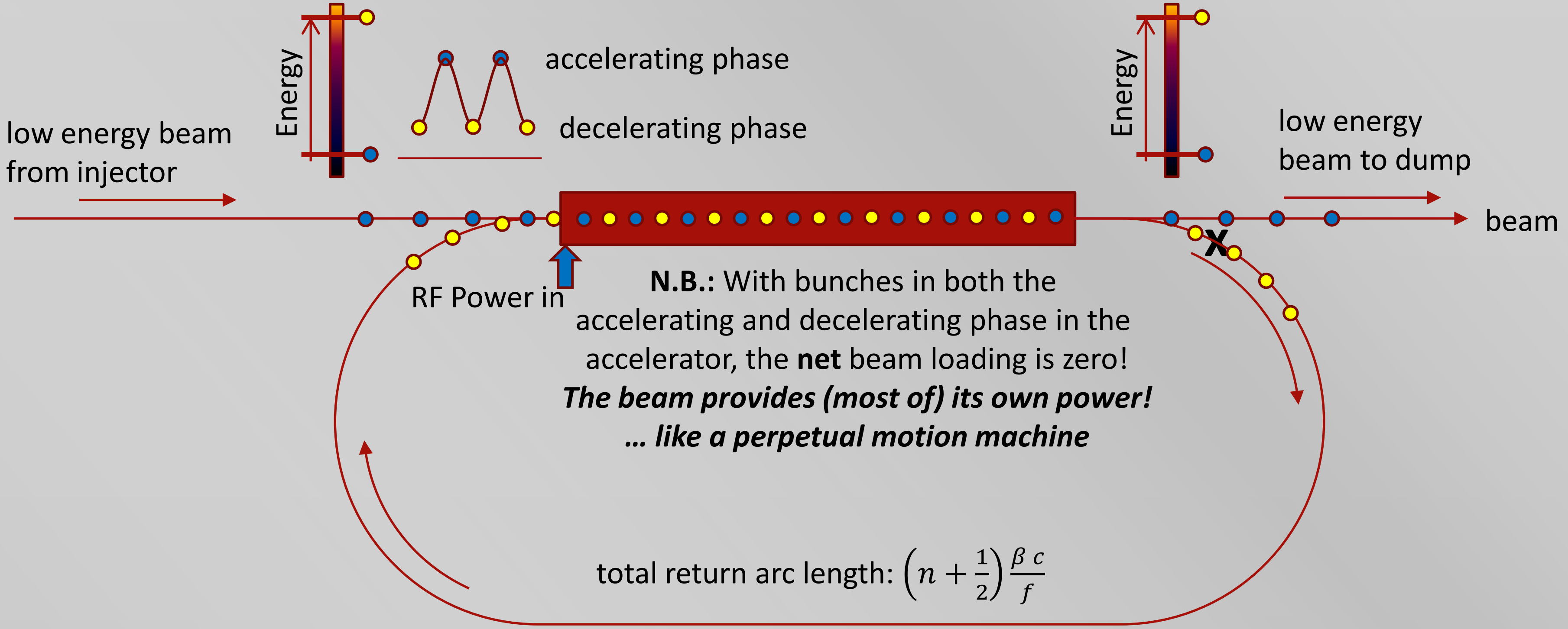
L. Merminga ‘07: *In a storage ring, electrons are stored for hours in an equilibrium state, whereas in an ERL it is the energy of the electrons that is stored. The electrons themselves spend little time in the accelerator (from ~1 to 10’s of µs) thus never reach equilibrium. As a result, in common with linacs, the 6-dimensional phase space in ERLs is largely determined by the electron source properties by design. On the other hand, in common with storage rings, ERLs have high current carrying capability enabled by the energy recovery process, thus promising high efficiencies.*

*http://accelconf.web.cern.ch/AccelConf/p07/PAPERS/MOYKI03.PDF*



# Energy Recovery Linac:

## Combine “Energy recovery” and “recirculating”



low energy beam from injector

low energy beam to dump

beam

RF Power in

**N.B.:** With bunches in both the accelerating and decelerating phase in the accelerator, the **net** beam loading is zero!

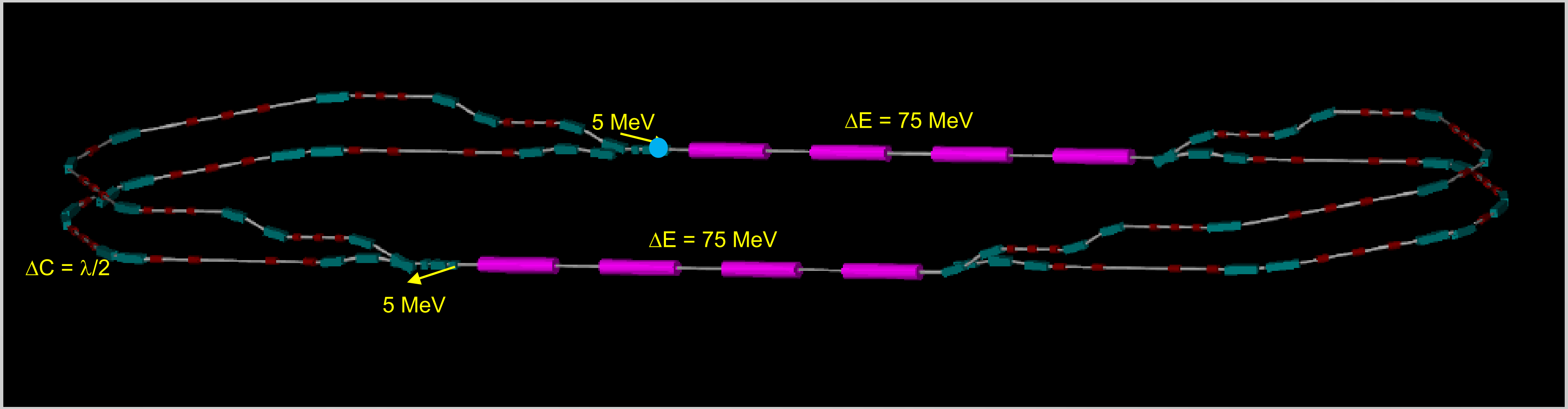
***The beam provides (most of) its own power!***

***… like a perpetual motion machine***

total return arc length: $\left(n+\frac{1}{2}\right)\frac{\beta\,c}{f}$

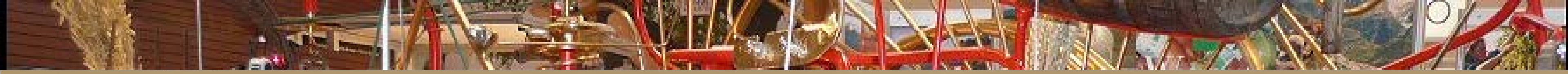
# LHeC ERL-TF (300 MeV) – Layout

This model and animation by Alex Bogacz, Jefferson Lab



Two passes ‘up’ + Two passes ‘down’

# Different ERLs around the world



# Low Energy ERLs / Test Facilities (1)

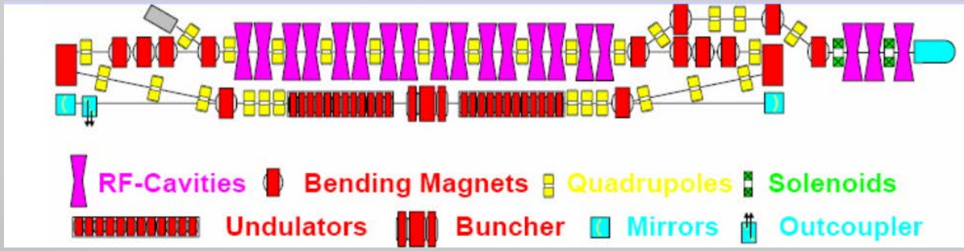
500 MHz + DC Gun

5 mA, 17 MeV, 12 ps

JAERI, Tokai

Normal Conducting 180 MHz + DC Gun

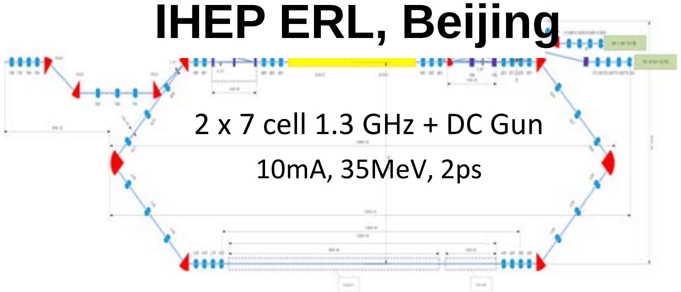
30 mA, 11 MeV, 70-100 ps



BINP, Novosibirsk

# Low Energy ERLs/Test Facilities

## IHEP ERL, Beijing



2 x 7 cell 1.3 GHz + DC Gun

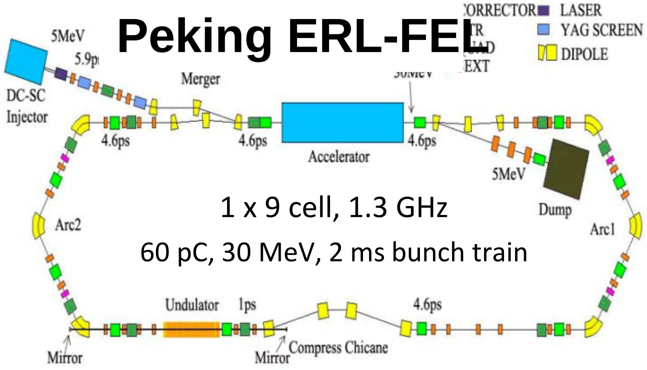
10mA, 35MeV, 2ps

## BERLinPro

3 x 7 cell cavities, 1.3 GHz

100mA, 50MeV, 1 mm mrad (norm), 2ps

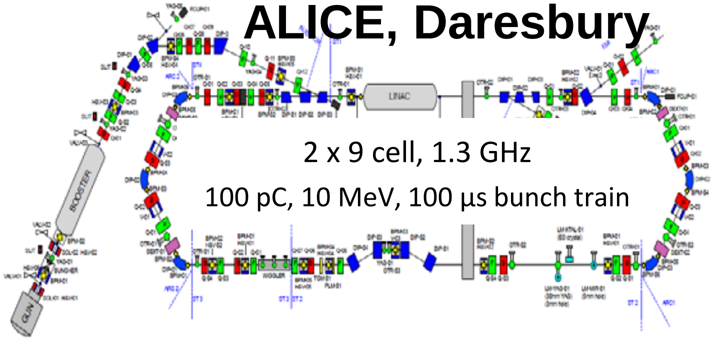
## Peking ERL-FEL



1 x 9 cell, 1.3 GHz

60 pC, 30 MeV, 2 ms bunch train

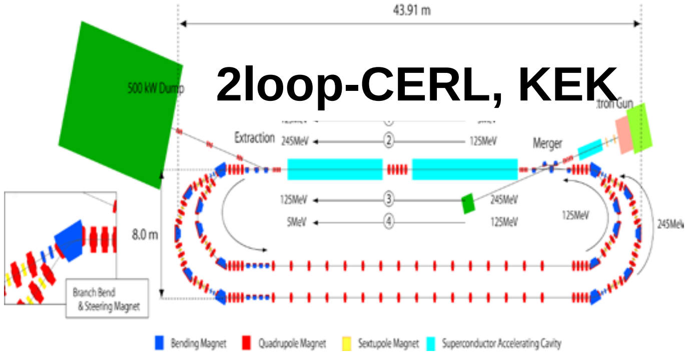
## ALICE, Daresbury



2 x 9 cell, 1.3 GHz

100 pC, 10 MeV, 100 μs bunch train

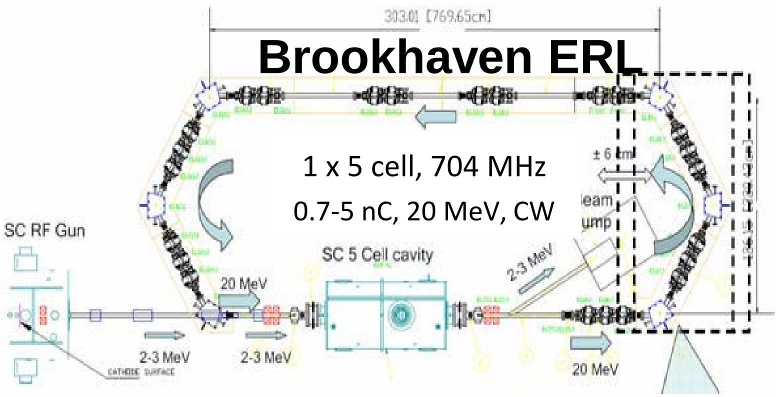
## 2loop-CERL, KEK



9 cell, 1.3 GHz cavities, 4 modules

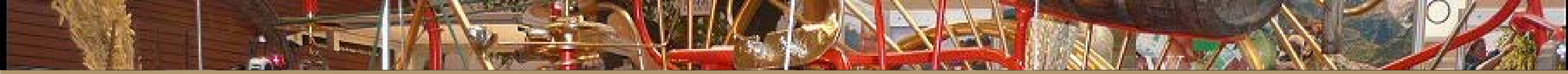
77 pC, 245 MeV, 1-3 ps

## Brookhaven ERL

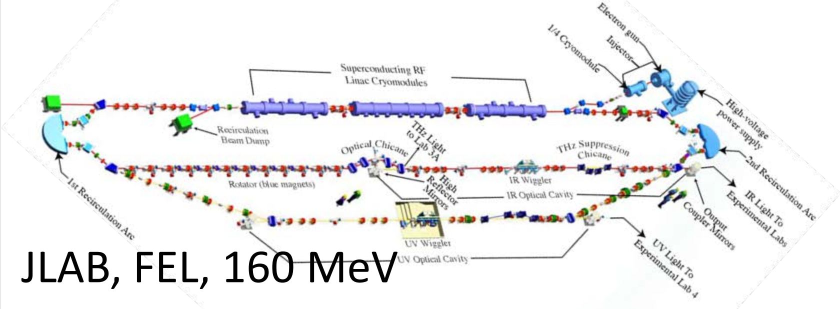


1 x 5 cell, 704 MHz

0.7-5 nC, 20 MeV, CW

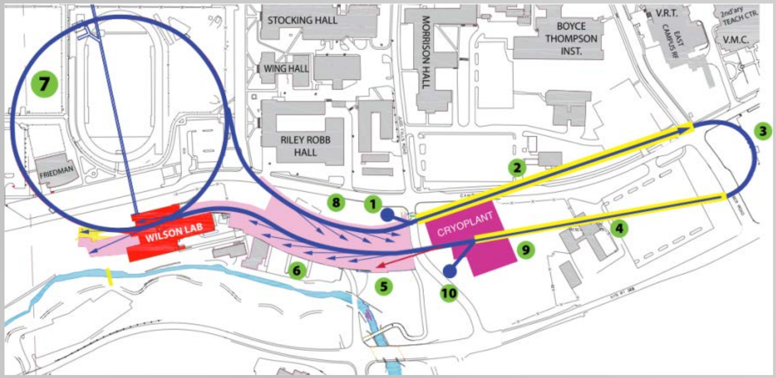


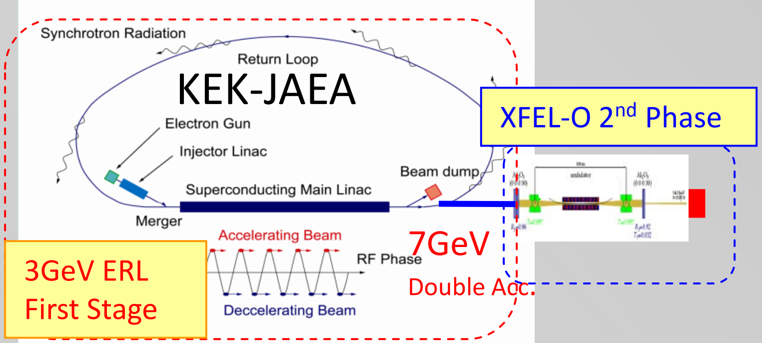
# High Energy ERLs, Light Sources, FELs



JLAB, FEL, 160 MeV

Cornell ERL Light Source, 5 GeV





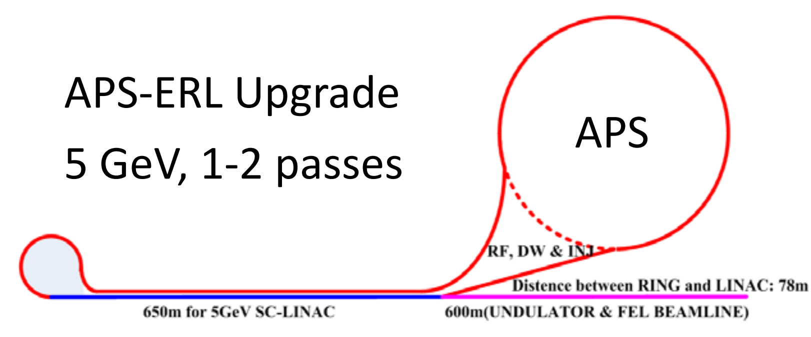
KEK-JAEA

XFEL-O 2nd Phase

7GeV

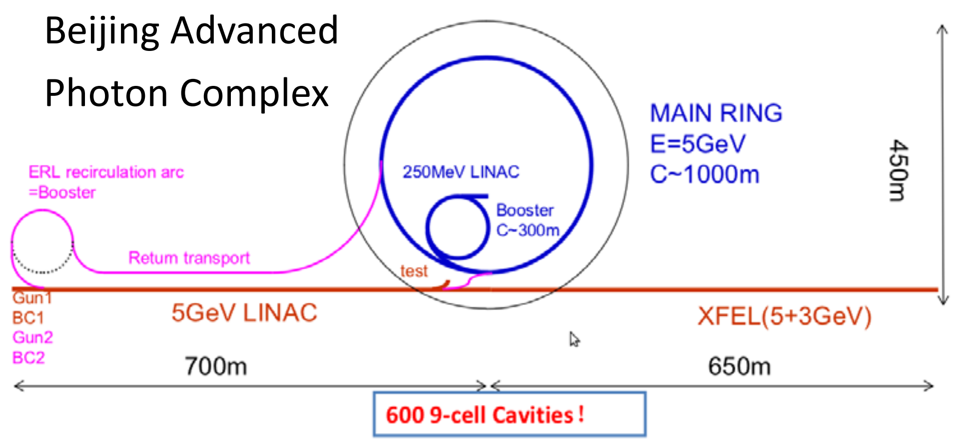
Double Acc.

3GeV ERL
First Stage



APS-ERL Upgrade

5 GeV, 1-2 passes



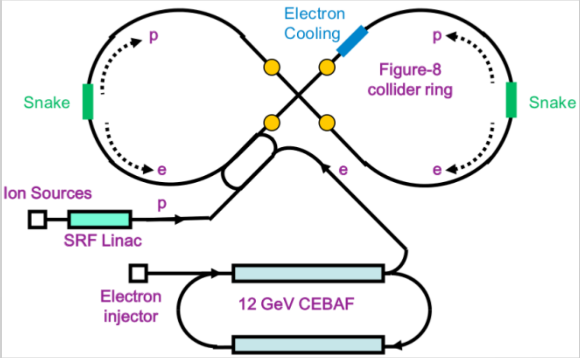
Beijing Advanced

Photon Complex

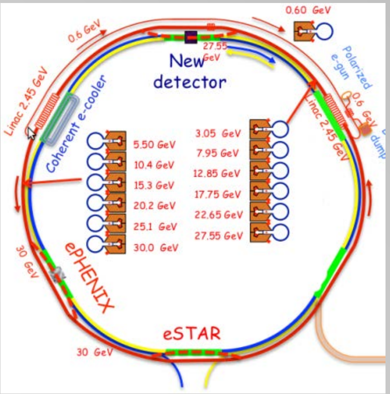
600 9-cell Cavities !

# High Energy ERLs, EICs (Electron Ion Colliders)

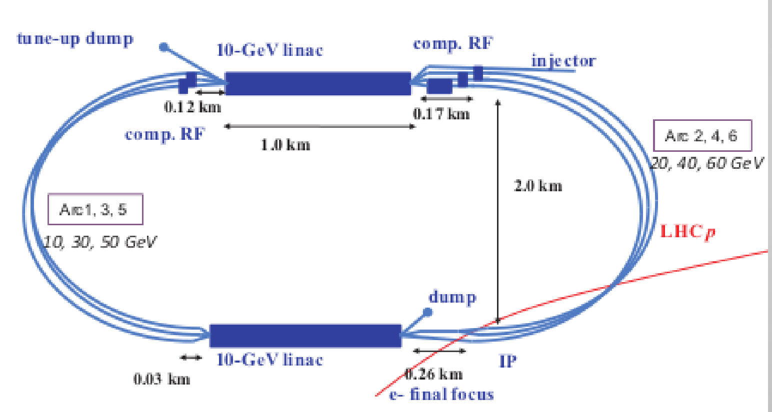
JLAB, MEIC



BNL, eRHIC



CERN, LHeC

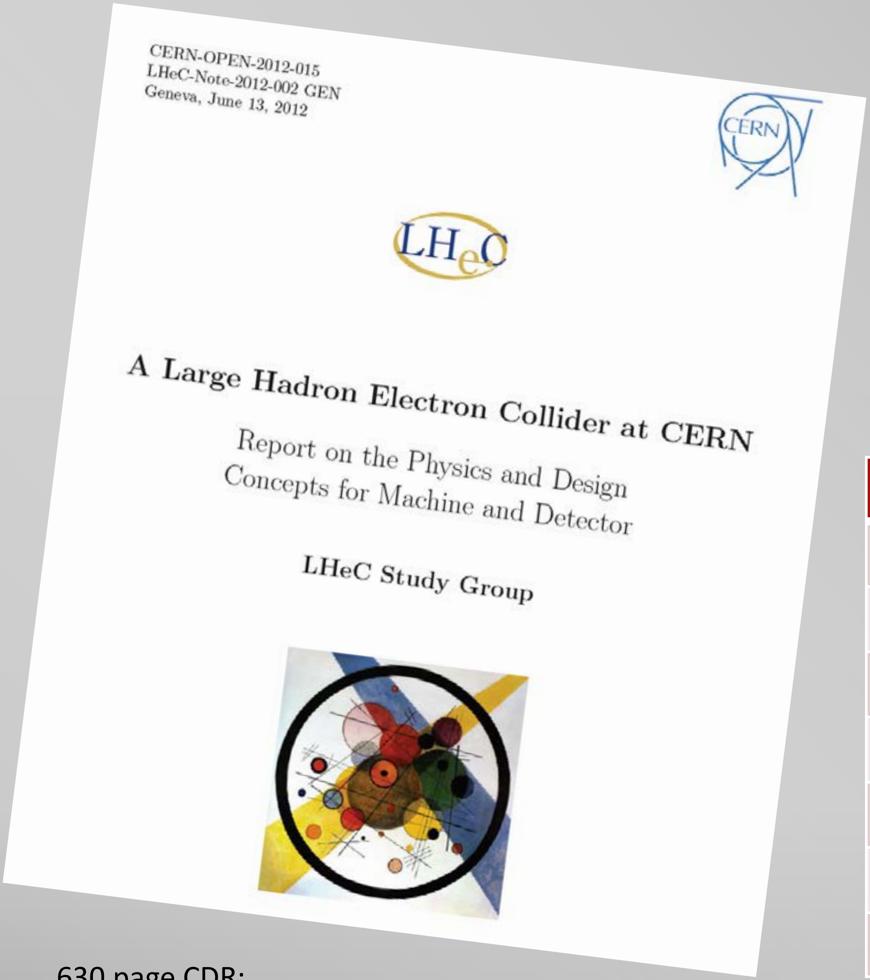


| JLab<br>MEIC | BNL<br>eRHIC | CERN<br>LHeC |
|---|---|---|
| 5-10 GeV | 20 GeV | 60 GeV |
| 750 MHz<br>? passes | 704 MHz<br>6 passes | 704 MHz<br>3-passes |
| 3 A | 50 mA | 6.4 mA |
| 4 nC | 3.5 nC | 0.3 nC |
| 7.5 mm | 2 mm | 0.3 mm |
| Planned | Planned | Planned |

# The LHeC – an extension of the LHC

… to make an electron proton collider.

Physics goals: Energy Frontier, Higgs,
High precision Deep Inelastic Scattering,
electron-deuteron & electron ion,
Factor 30 larger $Q^2$ & factor 100 larger luminosity than HERA



CERN-OPEN-2012-015
LHeC-Note-2012-002 GEN
Geneva, June 13, 2012

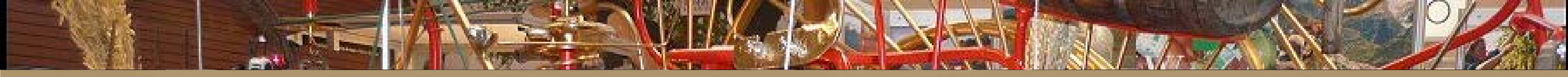
A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

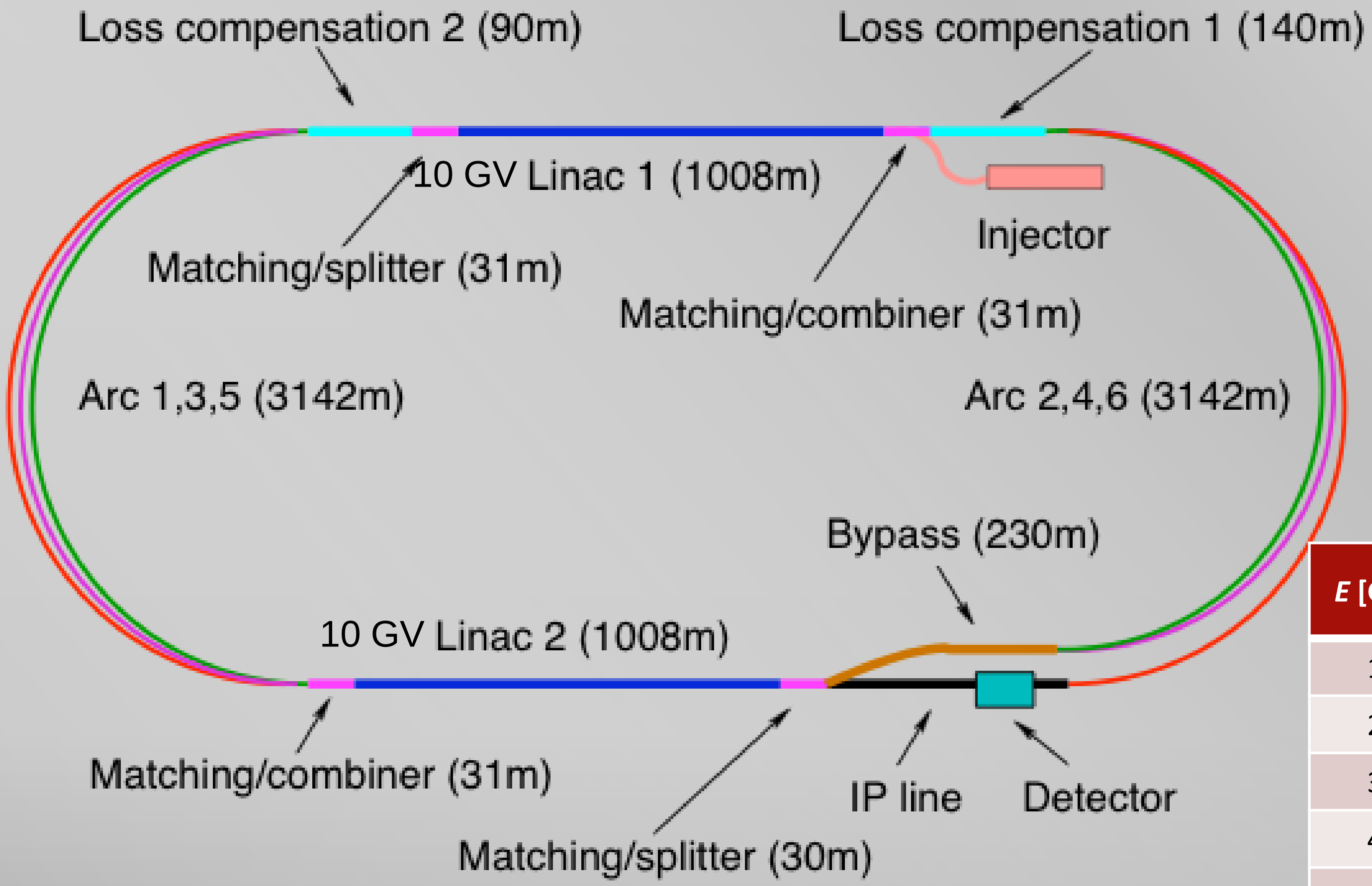
LHeC Study Group

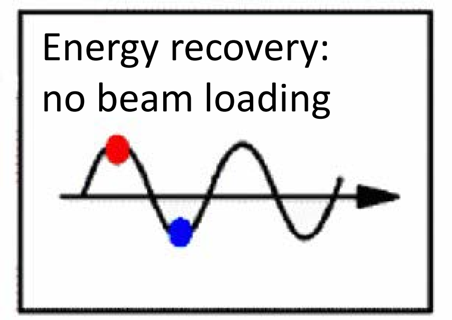
630 page CDR:
http://iopscience.iop.org/0954-3899/39/7/075001/

| *LHeC parameters* | Units | Protons | RR e- | LR e- |
|---|---|---|---|---|
| Energy | [GeV] | 7,000 | 60 | 60 |
| Frequency | [MHz] | 400.79 | 721.42 or 1,322.6 | |
| Norm. $\varepsilon$ | [µm] | 3.75 | 580, 290 | 50 |
| $I_{\mathrm{beam}}$ | [mA] | >500 | 130 | 6.6 |
| Bunch spacing | [ns] | 25, 50 | 50 | 50 |
| Bunch population | | $1.7 \cdot 10^{11}$ | $3.1 \cdot 10^{10}$ | $2.1 \cdot 10^{9}$ |
| Bunch length | [mm] | 75.5 | 0.3 | 0.3 |



# The LHeC ERL





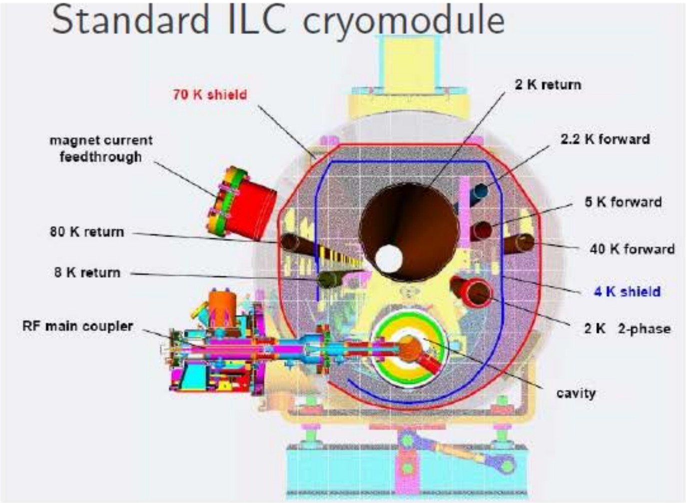
synchrotron radiation loss!

| *E* [GeV] | Energy lost (SR) [MeV] | RF power [MW] |
|---|---|---|
| 10 | 0.8 | 0 |
| 20 | 14 | 0.1 |
| 30 | 70 | 0.5 |
| 40 | 230 | 1.7 |
| 50 | 550 | 4.0 |
| 60 | 570 | 4.2 |

# Potential Options for the frequency:

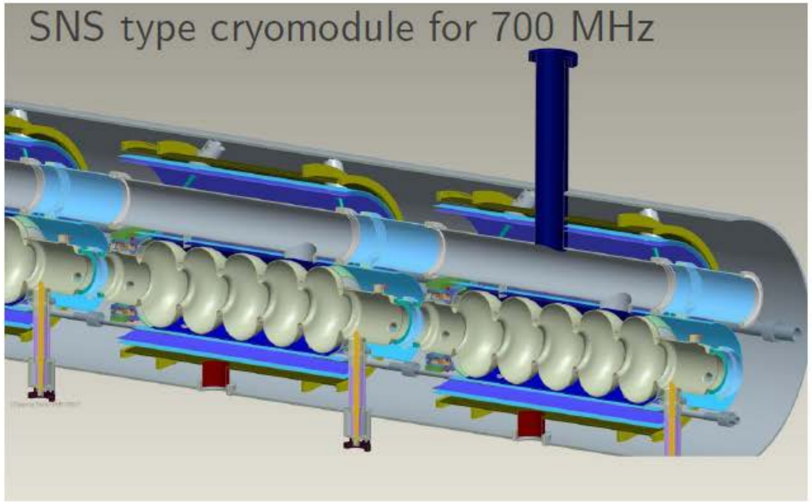
1,323 MHz

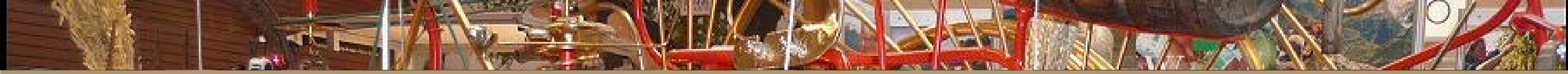
ILC Collaboration


Standard ILC cryomodule

721 MHz

ESS, eRHIC, SPL

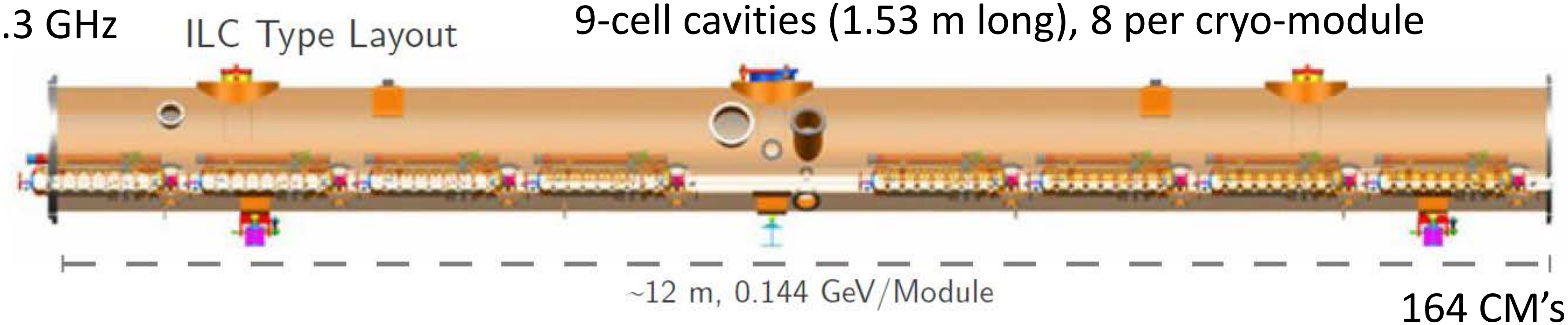

SNS type cryomodule for 700 MHz



# Cryomodule layout

1.3 GHz

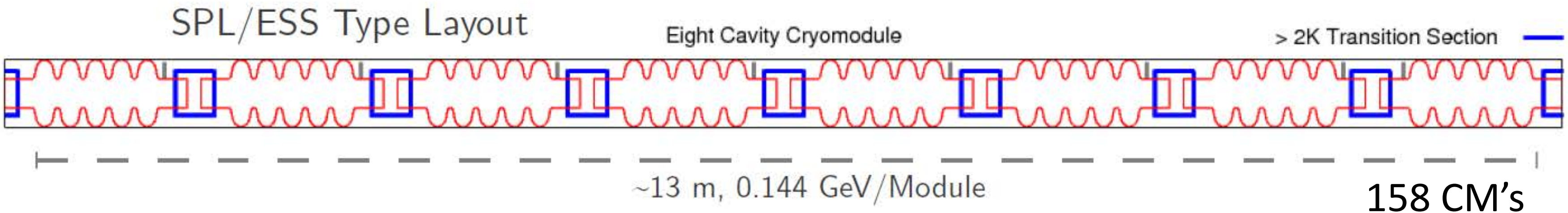
9-cell cavities (1.53 m long), 8 per cryo-module



164 CM's

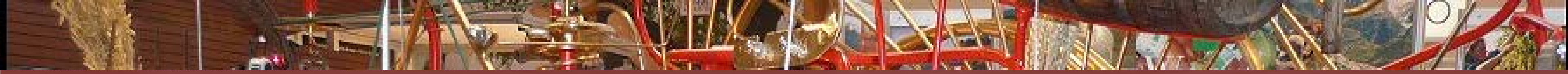
704 MHz

5-cell cavities (1.6 m long), 8 per cryo-module



158 CM's

Approximate cavity length is similar
The ILC type cryomodule could be used for either frequency.



# Which frequency? – 700 MHz vs. 1300 MHz

### ADVANTAGES 700 MHZ

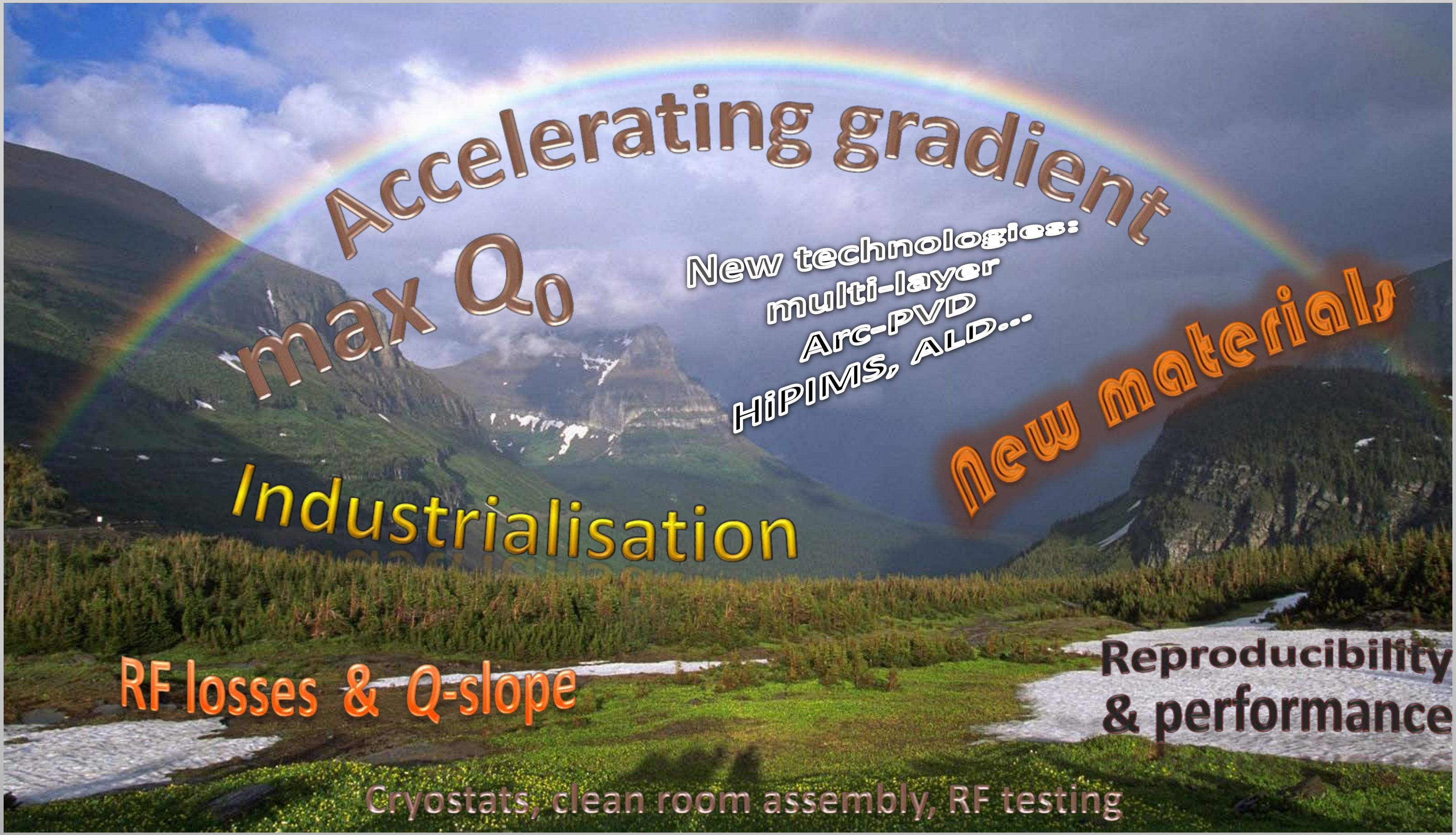
- Synergy SPL, ESS, JLAB, eRHIC
- Smaller BCS resistance
- Less trapped modes
- Smaller HOM power
- Beam stability
- Less cryogenic power
- Power couplers easier
- Power source easier

### ADVANTAGES 1300 MHZ

- Synergy ILC, X-FEL
- Cavity smaller
- Larger *R/Q*
- Smaller RF power (assuming same $Q_{ext}$)
- Less Nb material needed
  - ($\propto f^{-2} \ldots f^{-1}$)

# Technology & Innovation Challenges

# Superconducting RF R&D



Accelerating gradient

max $Q_0$

New technologies:
multi-layer
Arc-PVD
HiPIMS, ALD…

New materials

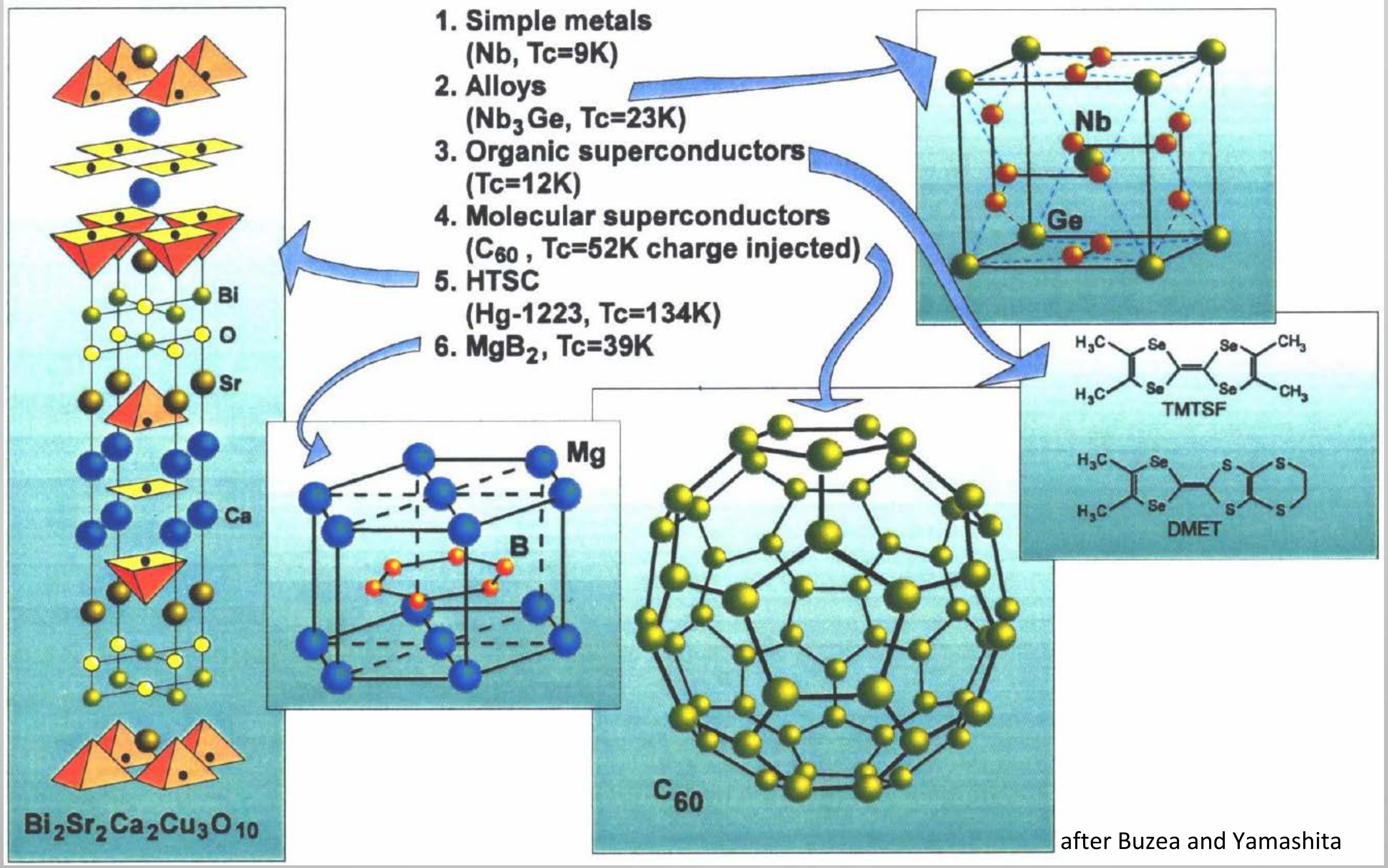
Industrialisation

RF losses & Q-slope

Reproducibility
& performance

Cryostats, clean room assembly, RF testing

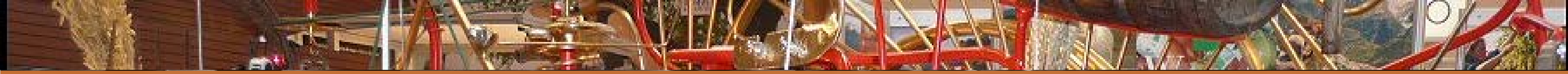
# New SC Materials



1. Simple metals
   (Nb, Tc=9K)
2. Alloys
   ($Nb_3Ge$, Tc=23K)
3. Organic superconductors
   (Tc=12K)
4. Molecular superconductors
   ($C_{60}$ , Tc=52K charge injected)
5. HTSC
   (Hg-1223, Tc=134K)
6. $MgB_2$, Tc=39K

after Buzea and Yamashita

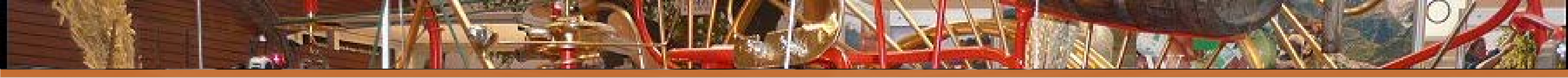
V. Palmieri: Applied Superconductivity, CERN Academic Training Lecture Regular Programme, 2007



# Nb coating techniques

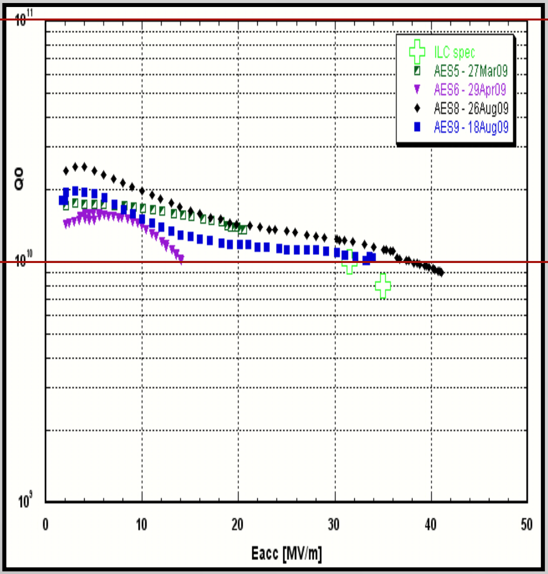
- Sputtering Nb on Cu (S. Calatroni: Niobium Coating Techniques, Journal of Physics: Conference Series **114** (2008)
  - Advantages:
    - Due to the high cost of Nb, this can reduce cost!
    - The Cu substrate increases the mechanical & thermal stability (quench resistance).
  - Technology initially developed at CERN (Benvenuti, LEP, 1980); experts today at JLAB, Legnaro, Saclay, Sheffield & CERN
  - Technique used today for ALPI (LNL), Soleil, LHC & HIE-Isolde
  - Today, the max. fields are still smaller than for bulk Nb – is this an intrinsic limitation? An interesting field of R&D!
    - Can this technique be extended to new materials? (NbTiN, $V_3Si$, $Nb_3Sn$, HTS?)
- “Energetic Condensation”- HiPIMS
  - Gas phase deposition of Nb with additional kinetic energy to slow ions.
- Cathodic Arc Deposition
- …

A rich and promising field of R&D

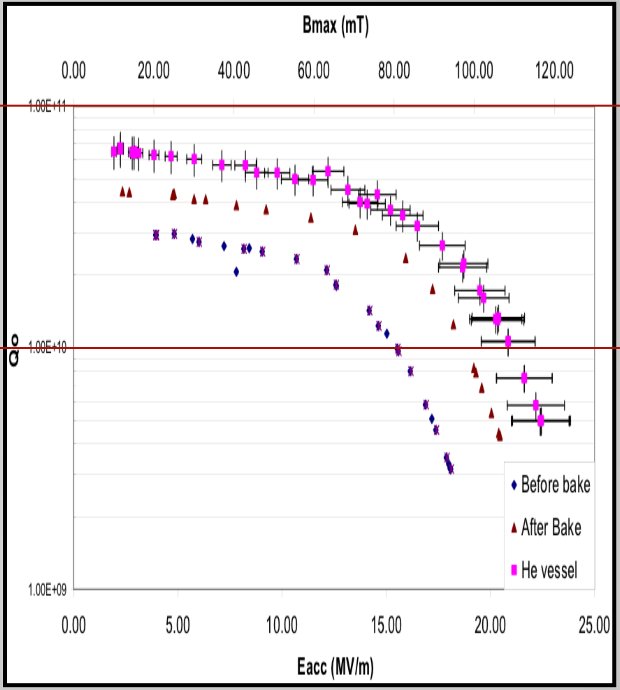


# Extremely high $Q_0$ superconducting cavities

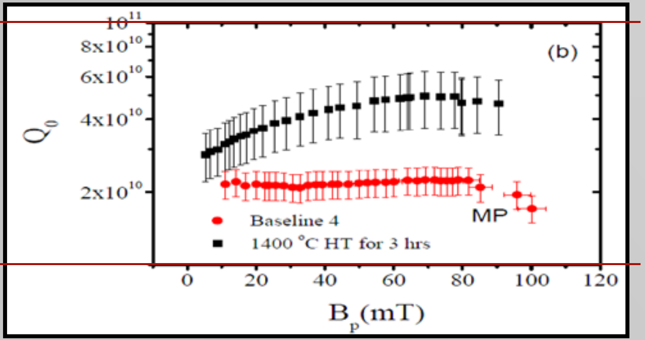
- With (almost) zero net beam loading, the challenge is to get extremely high $Q_0$! This would allow for large stored energy with modest RF power.
- Recent progress:



JLAB 1.3 GHz, 2009: $2.5 \times 10^{10}$
www.jacow.org/srf2009/papers/tuppo015.pdf

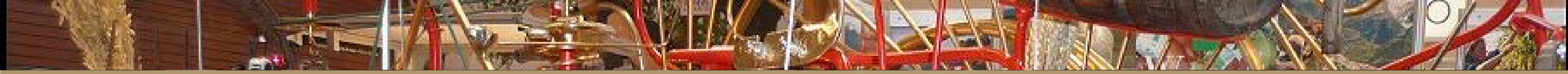


BNL, 704 MHz, 2010: $6 \times 10^{10}$

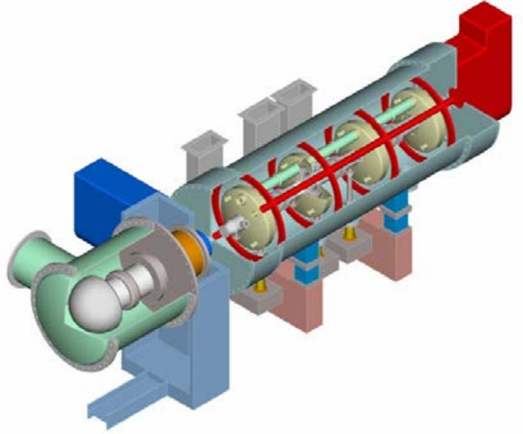


JLAB, 1.5 GHz, 2012: $5 \times 10^{10}$
(http://arxiv.org/abs/1205.6736)

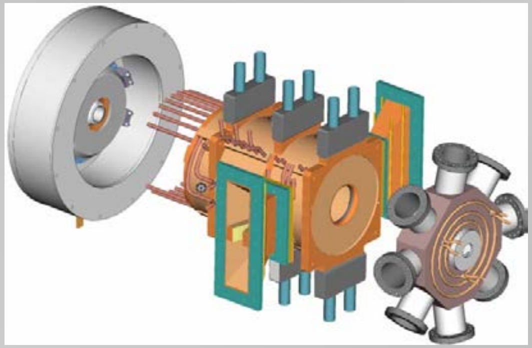
**Record:**
**4E10 @ (1.5 GHz, 90 mT, 2 K),**
**2E11@1.5K**



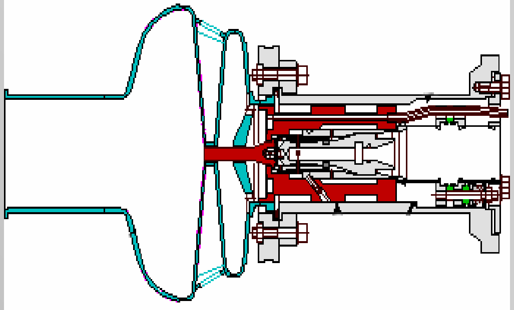
# Injector R&D (~700 MHz)



DC Gun + SRF CM (JLAB-AES)

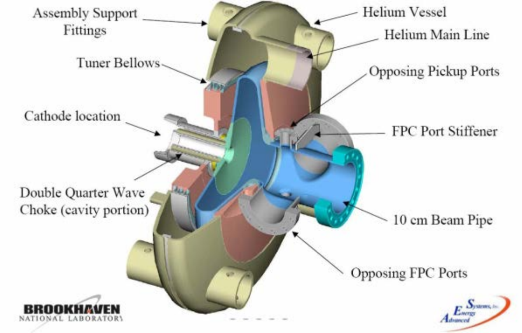


NC Gun (LANL-AES)



SRF Gun (FZR-AES-BNL)

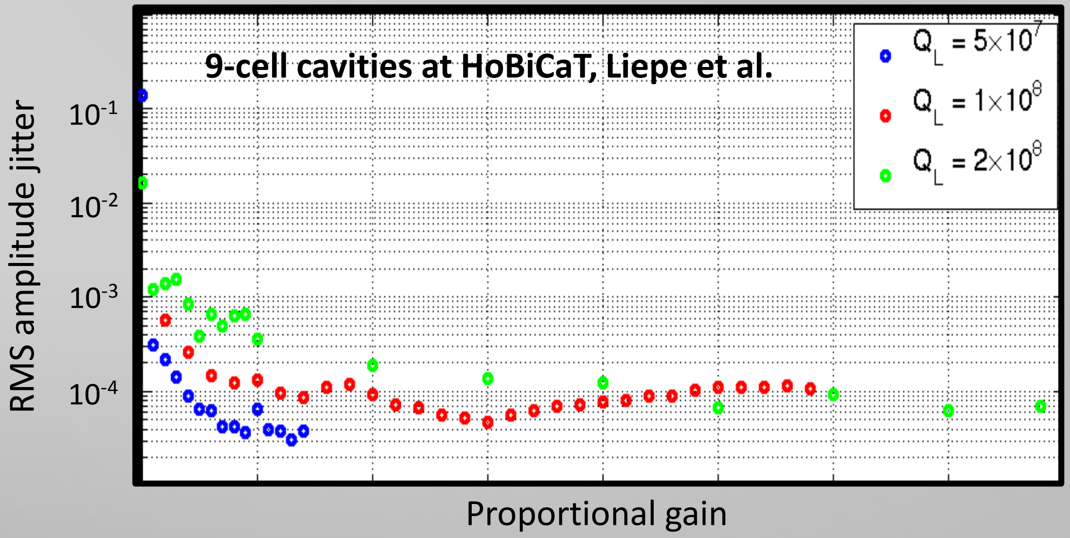
| | DC+SRF-CM | NC | SRF |
|---|---|---|---|
| Energy | 2-5 MeV | ? | 2 MeV |
| Current | 100 mA | 100 mA | 1000 mA |
| Long. Emit | 45 keV-ps | 200 keV-ps | - |
| Trans. Emit | 1.2 µm | 7 µm | < 1 µm |

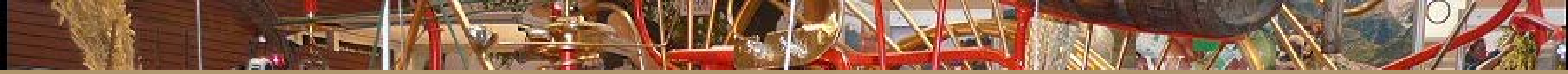


SRF Gun (BNL-AES)

# LLRF – controls – stabilisation

- Extremely high $Q_0$ allows low losses – but results in an extremely small bandwidth (700 MHz/1E11 = 7 mHz! – read: Milli-Hertz!)
- To really run with low power, the $Q_{ext}$ should follow!
- How high you can dare to go, will depend on the stability! (cavity, amplifier chain, beam, system)
- It is extremely challenging to stabilise a system with very high $Q_{ext}$!





# RF Power need

→ 5 MeV injector → $P_{beam} \sim 50$ kW (10 mA)

… will need higher powers if we go to 100 mA+

→ Main LINAC

(zero beam loading)

$$P_g = \frac{V^2}{R/Q} \cdot \frac{\Delta f}{f} \qquad \{Q_{opt} = \frac{1}{2} \cdot \frac{f}{\Delta f}\}$$

Peak detuning

| | **721 MHz** |
|---|---|
| Q=1 x $10^6$ | 250 kW |
| Q=5 x $10^6$ | 50 kW |
| Q=1 x $10^7$ | 25 kW |

Commercial television

IOT @700 MHz

←

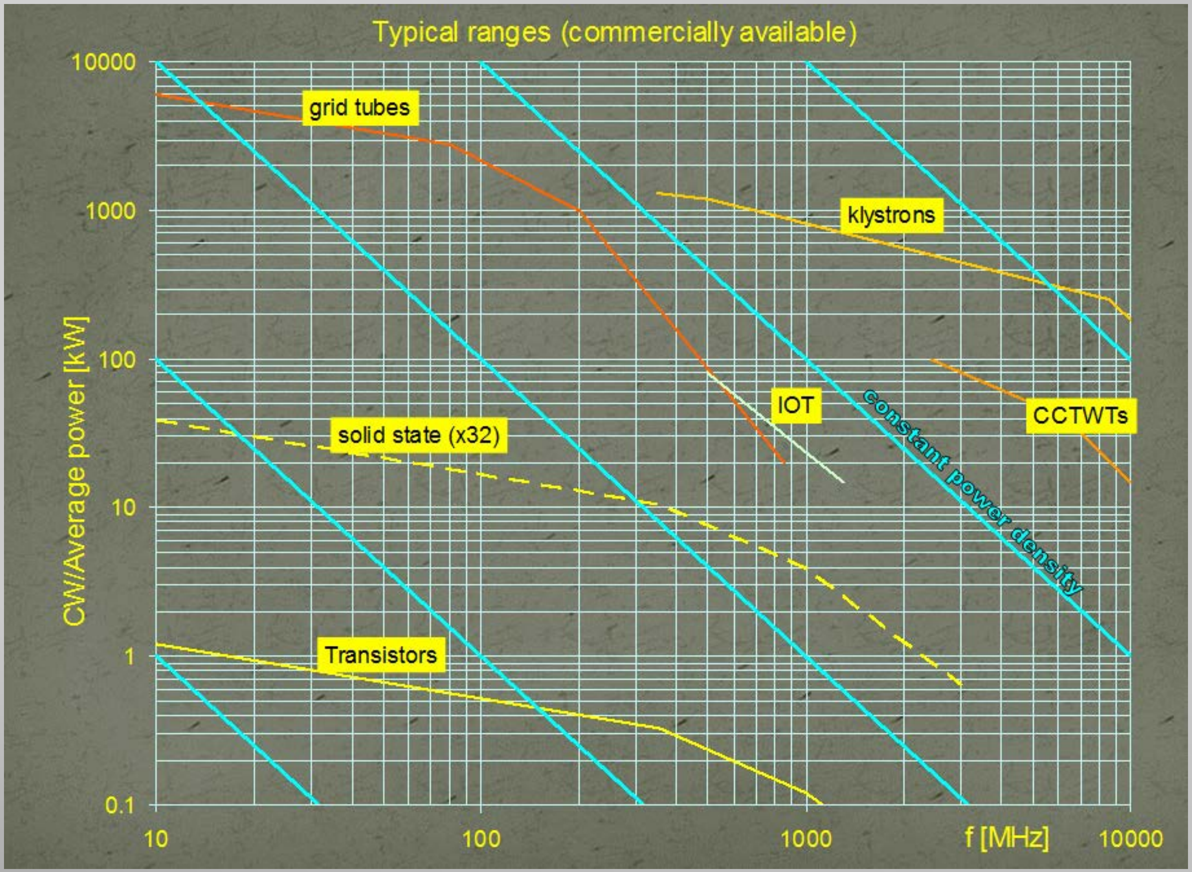
Possibly solid state?

(SSPA)

# RF Power

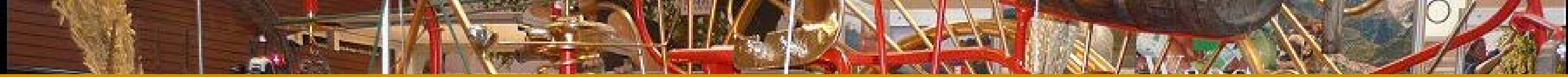
Use of IOTs ~ 50-100 kW at 700 MHz

- High efficiency, low cost
- Amplitude and phase stability



50 kW TV Amplifier, BNL

At 700 MHz



# Conclusions

- Energy Recovery Linacs recycle the otherwise lost beam power to produce (most of) the RF power needed for acceleration.
- They’re thus almost ***perpetual motion machines*** (see my background image)
- PMMs are of course impossible, but the mains → beam @ interaction can be 500% or so!
- This is possible only if the beam is still usable after “interaction”!
- Possible applications: Light sources and Colliders!
- Technology and Innovation:
  - Challenging R&D on Superconducting RF (max. $Q_0$, operation at max. $Q_{ext}$, coating techniques, new SC materials, stabilisation, …)

***Thank you very much!***