Or: ERLs and FELs:

A Bright Future for Superconducting Cavities

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Challenges for Future Light Sources

- **Why FELs and ERLs?**
- **Electron beam requirements and SRF linacs**
- **FELs, FEL-ERLs and SLS-ERLs**
  - **SRF Challenge I:** Low emittance preservation
    - *Injector*
    - *Wakefields*
    - *Coupler kicks*
  - **SRF Challenge II:** Beam current issues
    - *BBU and HOM damping for high current beams*
    - *High Q_L operation with low current beams or energy recovery*
  - **SRF Challenge III:** High gradient and cryogenic losses
    - *CW cavity operation*
    - *The importance of a high Q_0*
- **Outlook: A bright future**

Today's Workhorse Light Sources: Storage Rings

- **1st generation**
  parasitic SR on high energy physics storage rings
- **2nd generation**
  dedicated bending magnet sources, designed for high flux SR
- **3rd generation**
  dedicated undulator sources optimized for brilliance, using high current, low emittance

Some rings use superconducting RF

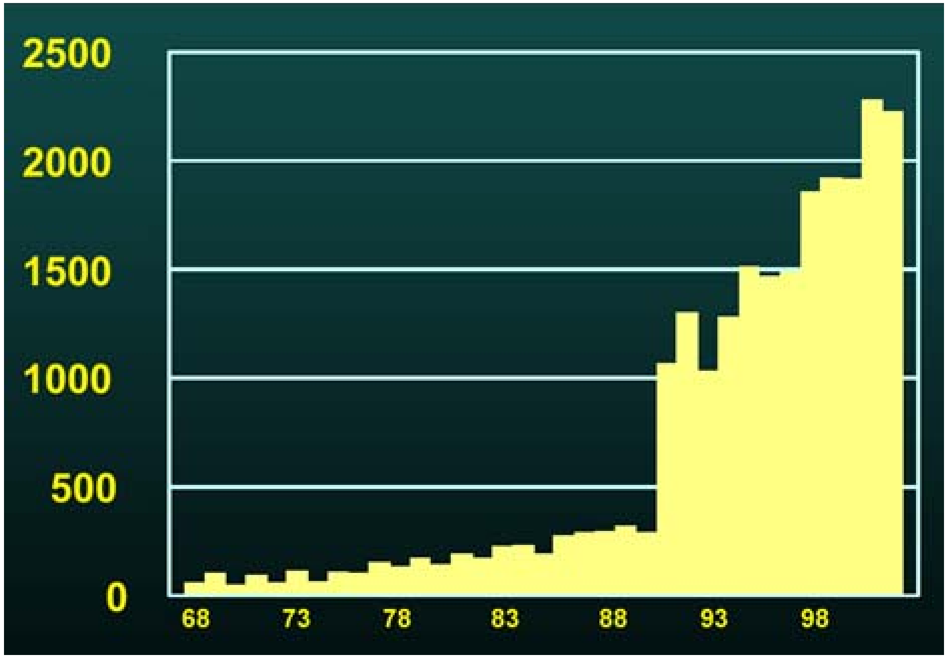
Storage ring light sourses give:

- Repetition rate
- Stability
- Tunability
- Polarisation
- High flux, brilliance – average/peak

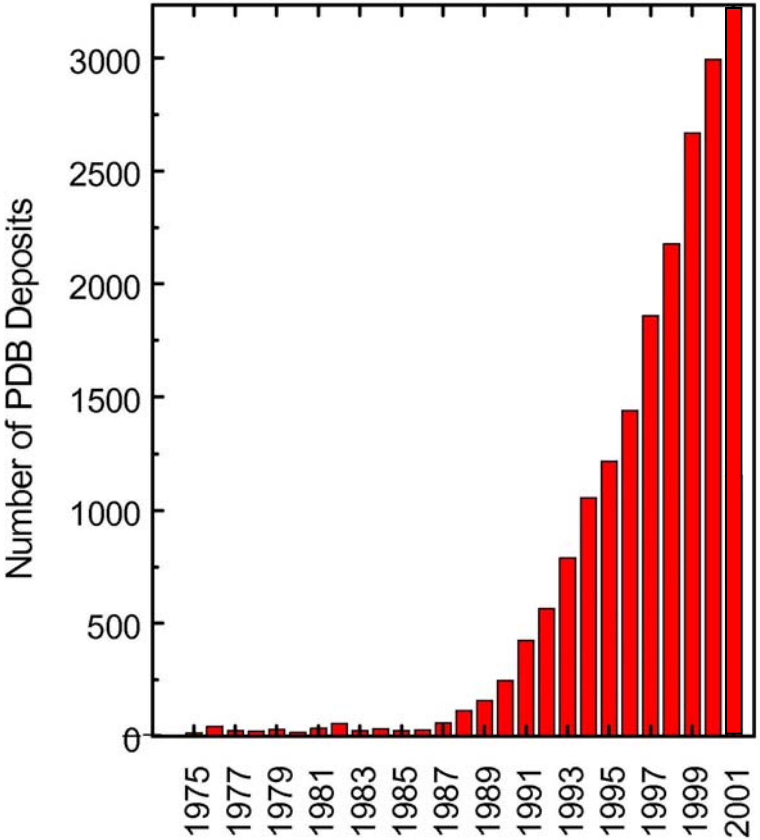
More Users…

Historical Growth of Synchrotron Publications Worldwide: ISI data 1968 to 2002, Keyword: "synchrotron"

(from G. Margaritondo)



Protein structures in Protein Data Bank (Mostly from SR)



… More Demands: What do we need in the future?

1. High average and high peak
- **Brilliance (photons/s/0.1% bw/mrad²/mm²)**
- **Flux (photons/s/0.1% bw)**

2. Coherence

3. Flexible pulse structure
- **Programmable pulse trains (interval, bunch size)**
- **Adjustable pulse lengths down to the femtosecond regime**

3. Small x-ray source size of desired shape, e.g. circular

4. Flexibility of source operation
- **No fill decay**
- **Stability & robustness**
- **Easily upgraded**

RF linacs!

→ **3.5th gen** | **FEL** | **ERL** | **?**

Important Beam Parameters: A Wish List

Low emittance (6D)

- Decreasing the electron beam emittance down to diffraction limit

$$\varepsilon_x < \frac{\lambda}{4\pi} \sim 10^{-11}\,mrad \left(\lambda \sim 1\,\mathring{A} \right)$$

- Short bunches

→ **Long undulator** ← **Low energy spread**

- High spectral brilliance SR sources

$$B \propto 1/\varepsilon_x \varepsilon_y \tau$$

- High coherence fraction:

$$p_c = \lambda^2/(4\pi)^2 \varepsilon_x \varepsilon_y$$

High beam current → **High flux** ← **High bunch charge**

$$F \propto I_{beam}$$

How do we get these Beam Parameters? Limits of Storage Rings

- Electron beam emittance, bunch profile and energy spread in a storage ring is determined by equilibrium between radiation damping and two main diffusion processes:

  - quantum fluctuation of the SR and

  - the intrabeam scattering.

$\Rightarrow$ There is no (affordable) way to decrease the horizontal emittance in storage ring $\varepsilon_x < 10^{-10}$ m·rad and energy spread $\sigma_E/E < 10^{-3}$.

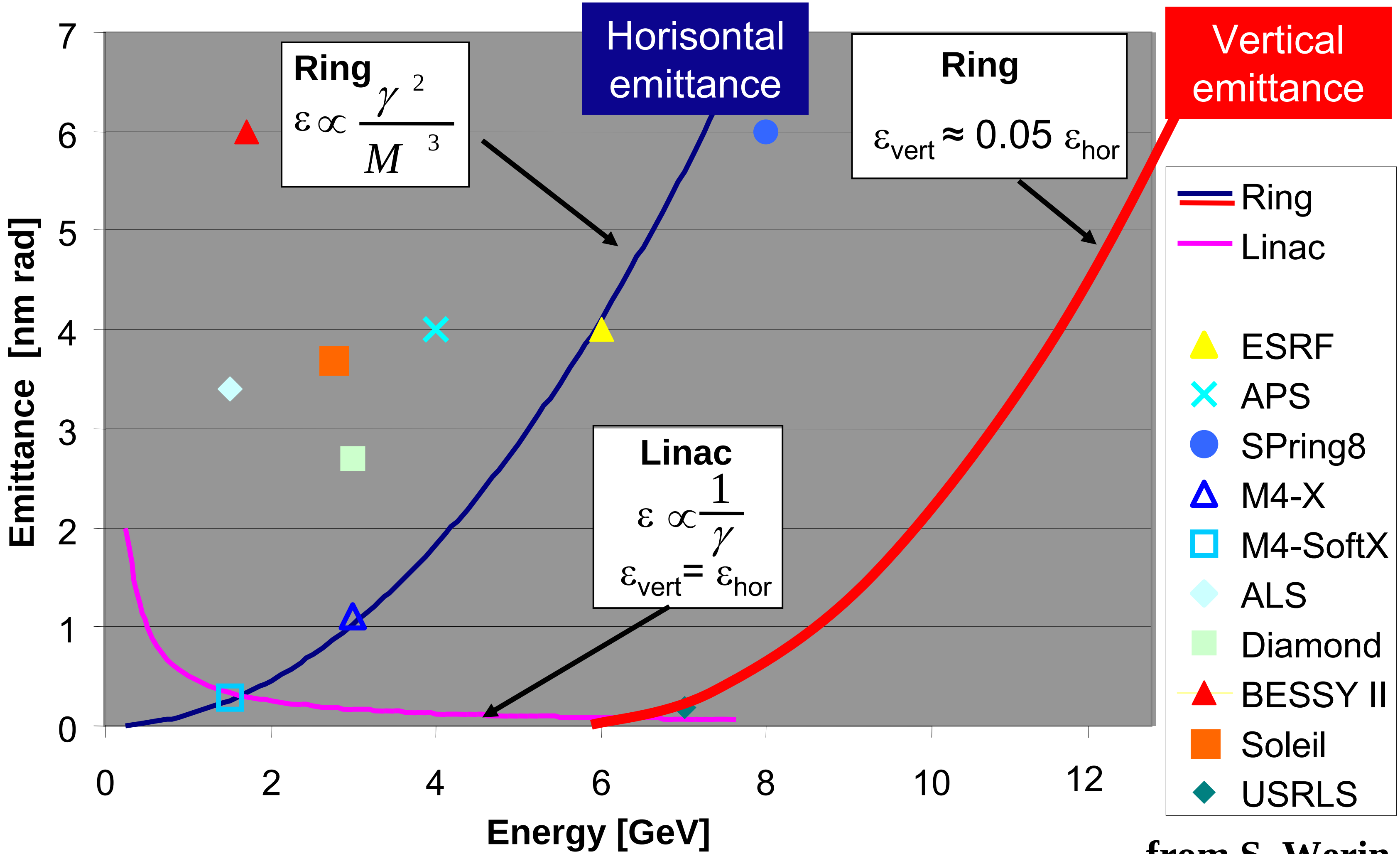
- Beam lifetime limits bunch length to about 10 ps. Too long for many dynamic processes.
- Technology well developed. Theoretical limits are being approached.
- Time structure cannot be tailored to user needs.
- Fills are necessary, intensity is not constant.

$\Rightarrow$ **Equilibrium dynamics determines almost all the parameters on our wish list!**

How do we get these Beam Parameters? The Alternative: Linacs

- Injectors can be built with very brilliant e- beams and linacs can accelerate with very low emittance growth (if we do it right).
  - Emittance & pulse length determined by injector.
  - Single pass non equilibrium device.
  - Easy upgrade path: Better e^- source gives higher brilliance.
  - Due to adiabatic damping an emittance $\varepsilon \sim 10^{-11}$ m·rad and energy spread $\sigma_E/E \sim 10^{-4}$ is possible for energies E > 5 GeV.
  - Potential for ultra high brilliance.
- Complete flexibility of bunch timing.
- No fill decay, constant intensity.
- Electron bunches dumped after single pass.
- Problem: get high average beam current, i.e. high flux; lower efficiency (compared to storage rings).

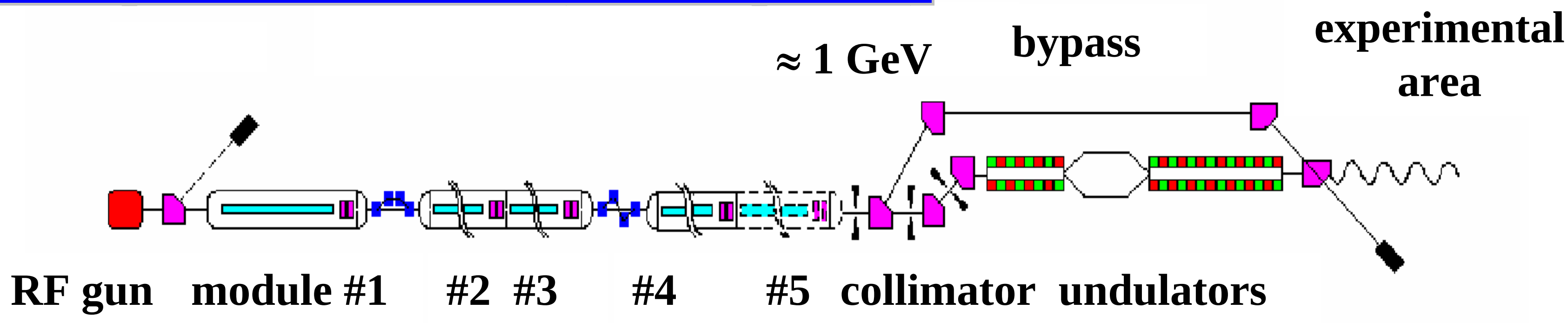
Emittance Comparison: Ring vs. Linac



from S. Werin

Linac Light Sources: Low (Average) Current Layout for X-FELs

Example: TTF II FEL (1 GeV, pulsed)

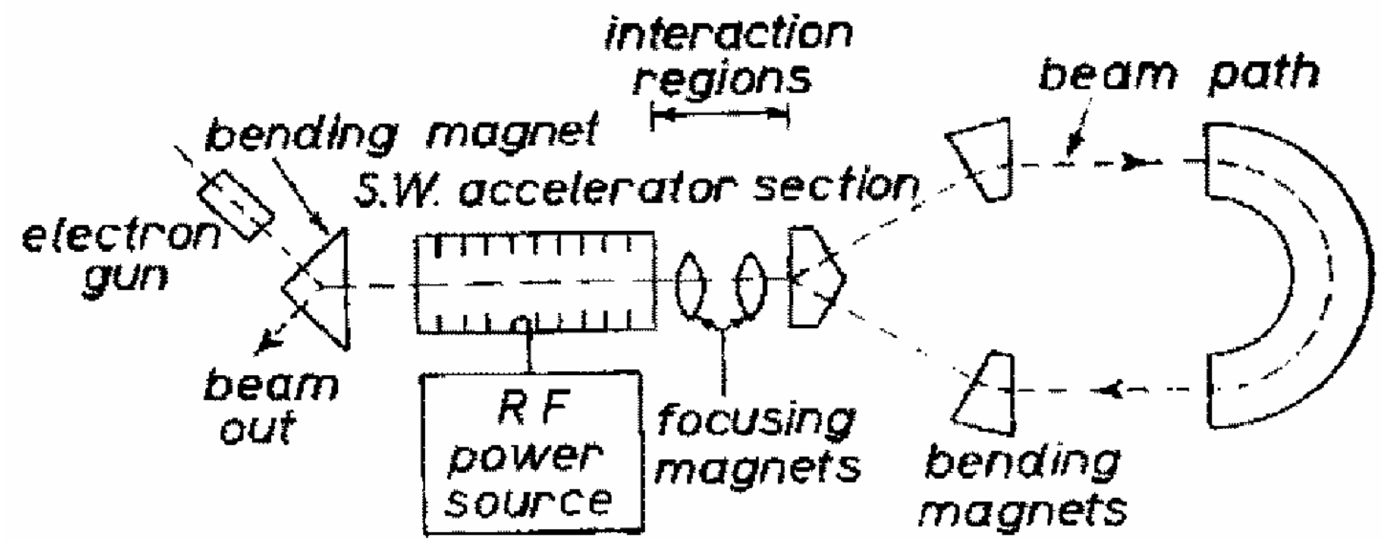


- Pulsed or cw operation.
- Low average beam current.
- In pulsed operation: higher (mA) beam currents possible:
  - High pulsed klystron power available.
  - Low average beam dump power.
- For X-FELs: nC bunch charges for high peak brilliance.

Linac Light Sources: How to get high currents? High Current Layout (SLS-ERL, FEL-ERL)

- **High photon flux ⇒ need high current**
- **But: With a simple linac you'd go broke!!**
- **Example: 5 GeV * 100 mA = 500 MW**

Solution: Use energy recovery. First proposed by M. Tigner in 1965.

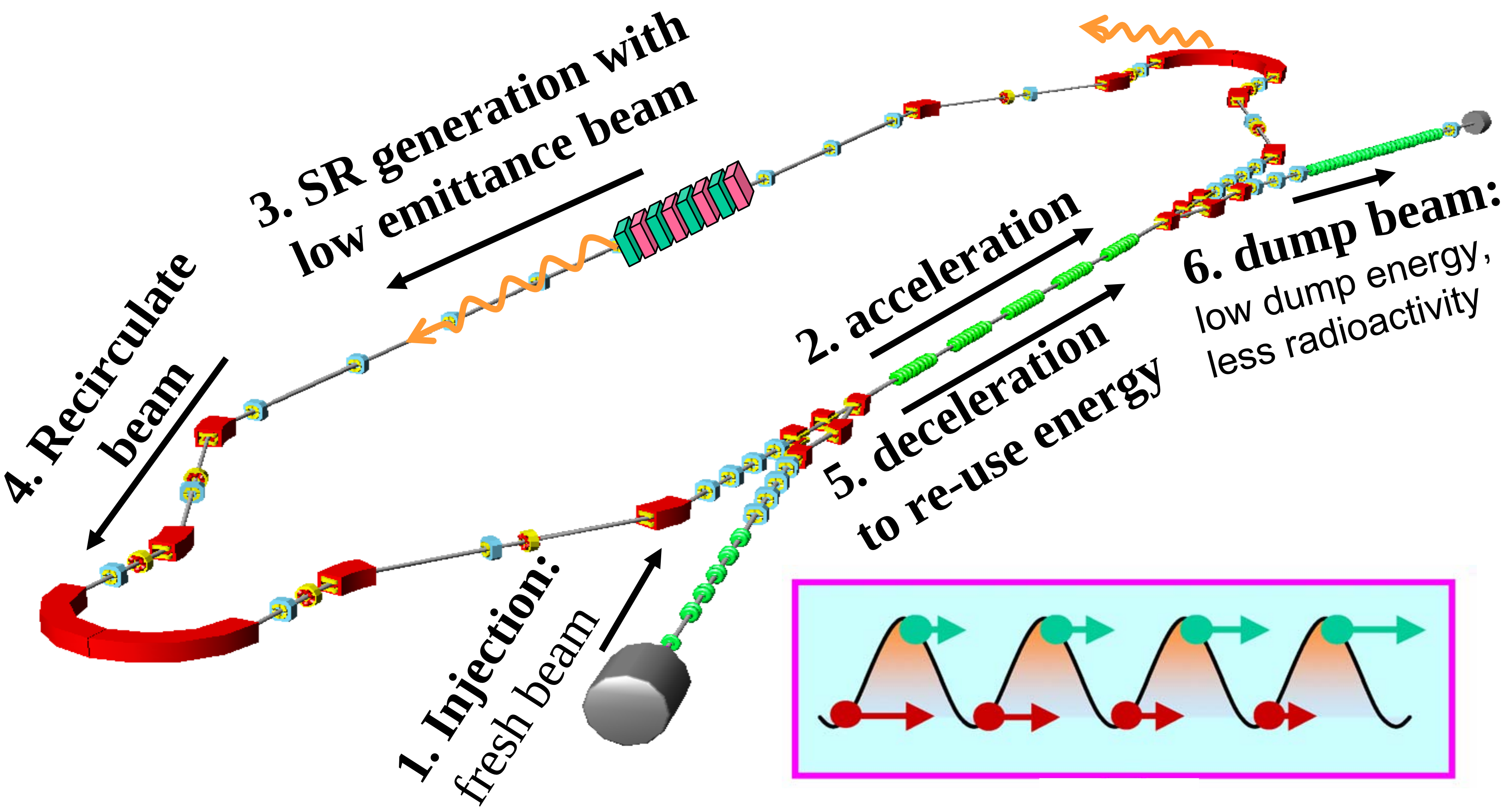


ERLs: What is the trick?

- *Re-use energy of beam after SR generation.*
- *Recirculate beam and pass it through the linac a second time, but 180 deg. out of phase to decelerate beam.*
- *⇒ "Energy Storage Ring" but not "Beam Storage Ring".*

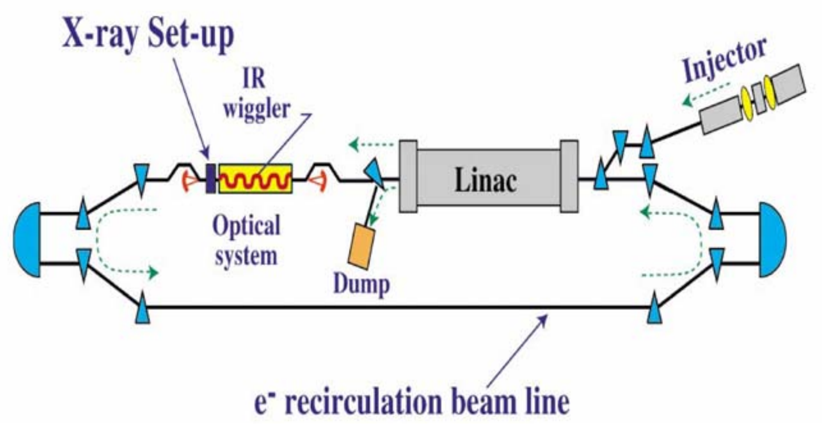
- **Emittance defined by source/gun (not ring equilibrium)** **$\varepsilon < 10^{-10}$ m·rad possible, close to diffraction limit**
- **Small pulse length < 100 fs possible (not ring equilibrium)**
- **Potential for brilliance >= storage rings**
- **High beam current possible ⇒ high flux SR, high power FELs**
- **SC linac; RF power: independent of current**

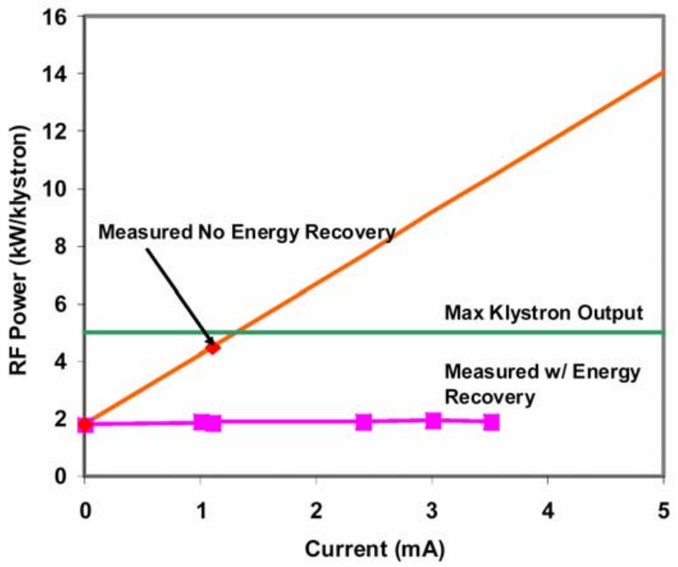
ERLs: What is the trick?



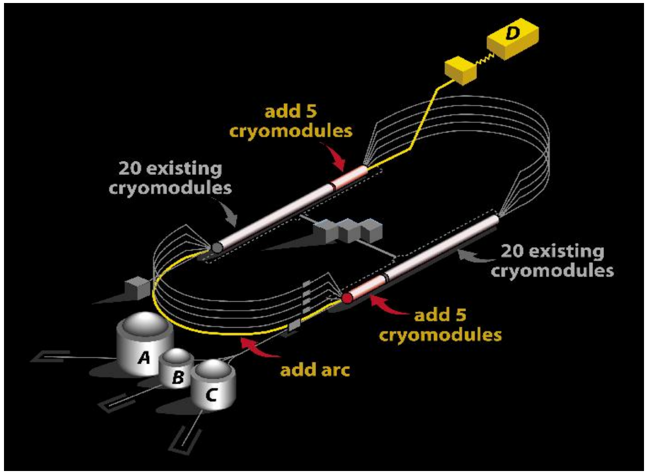
ERLs: It works!

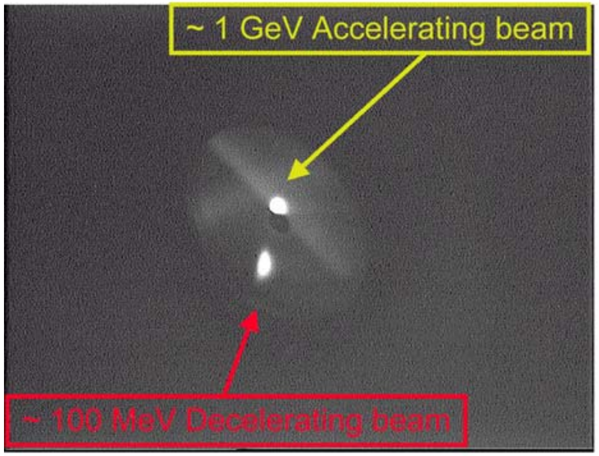
- ***JLAB FEL-ERL, 40 MeV, 5 mA:***





- ***CEBAF: First Energy Recovery Experiment at High Energy***

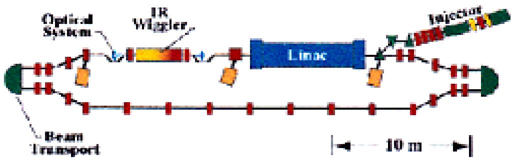




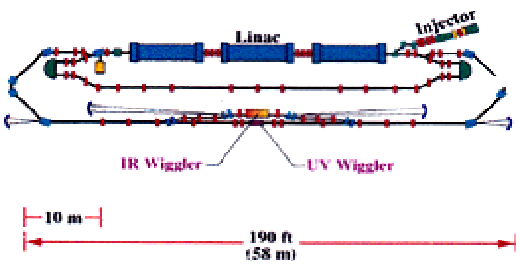
Energy Ratio of up to 1:50 tested (20 MeV $\rightleftarrows$ 1 GeV)

S. Chattopadhyay, G. Krafft et al.

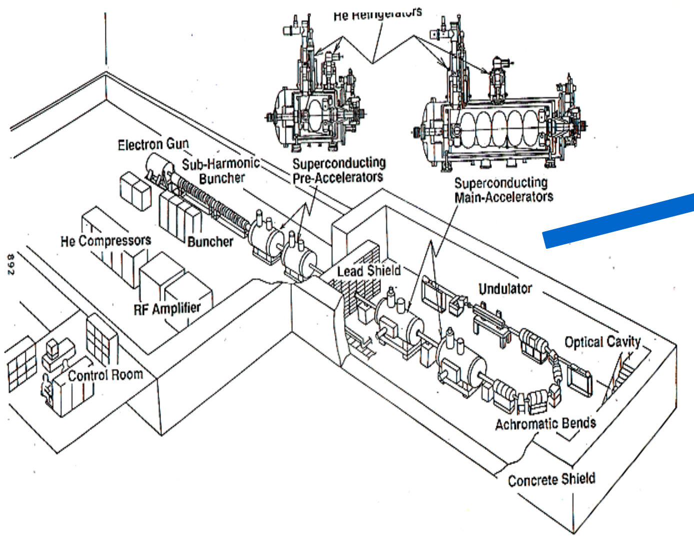
High Power CW FEL-ERLs

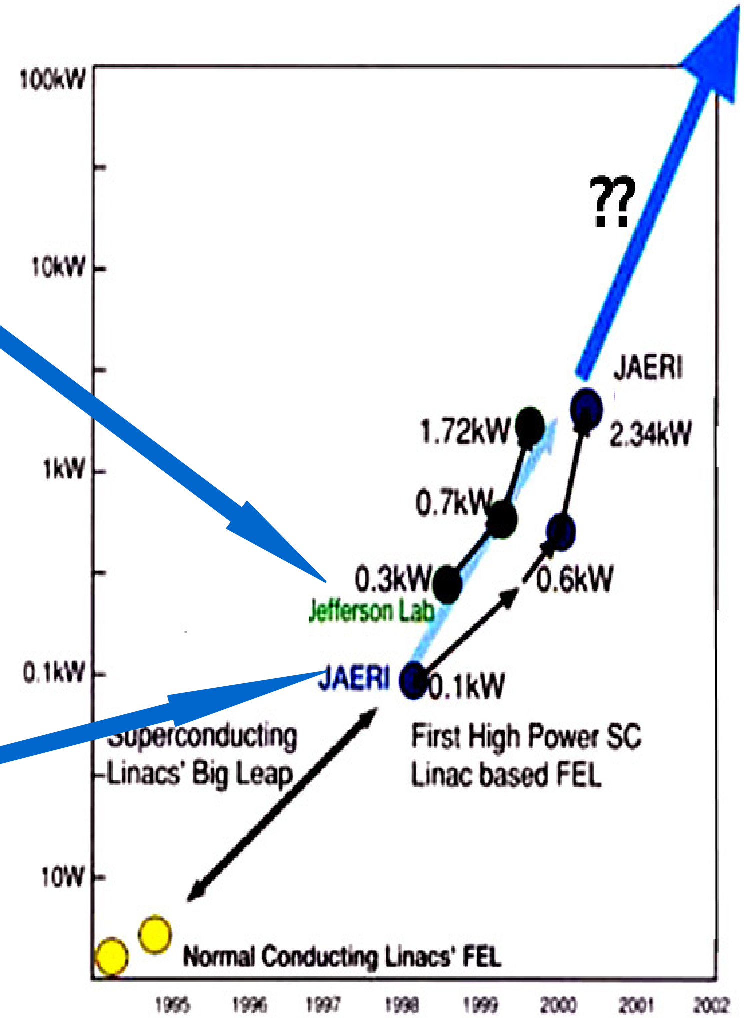


Infra-red



Ultra-violet





ERLs Worldwide (FEL-ERLs and SR-ERLs)

1960

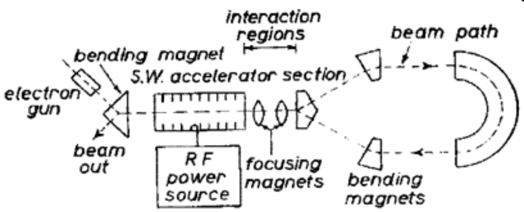
1970

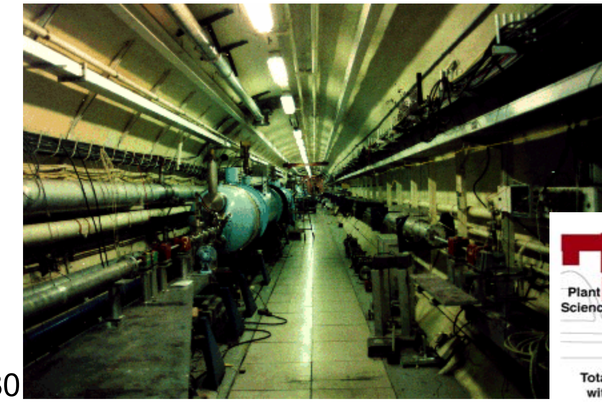
1980

1990

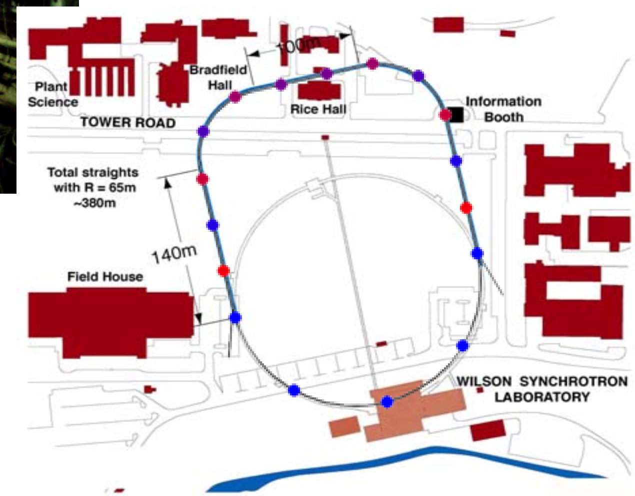
2000

M. Tigner, 1965





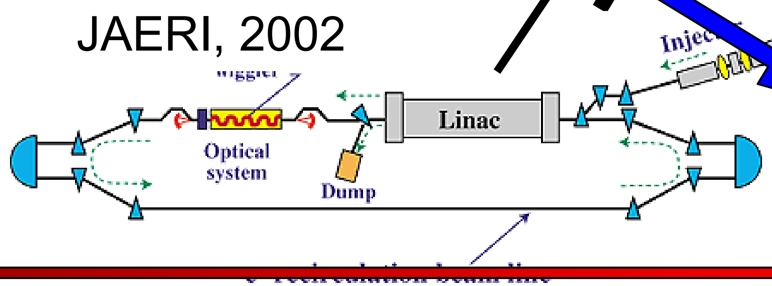
SCA, Stanford, 1986



S-DALINAC, 1990

IR FEL Jlab, 1999

JAERI, 2002



Cornell ERL

LUX (LBL)

PERL (NSLS)

4 GLS (Daresbury)

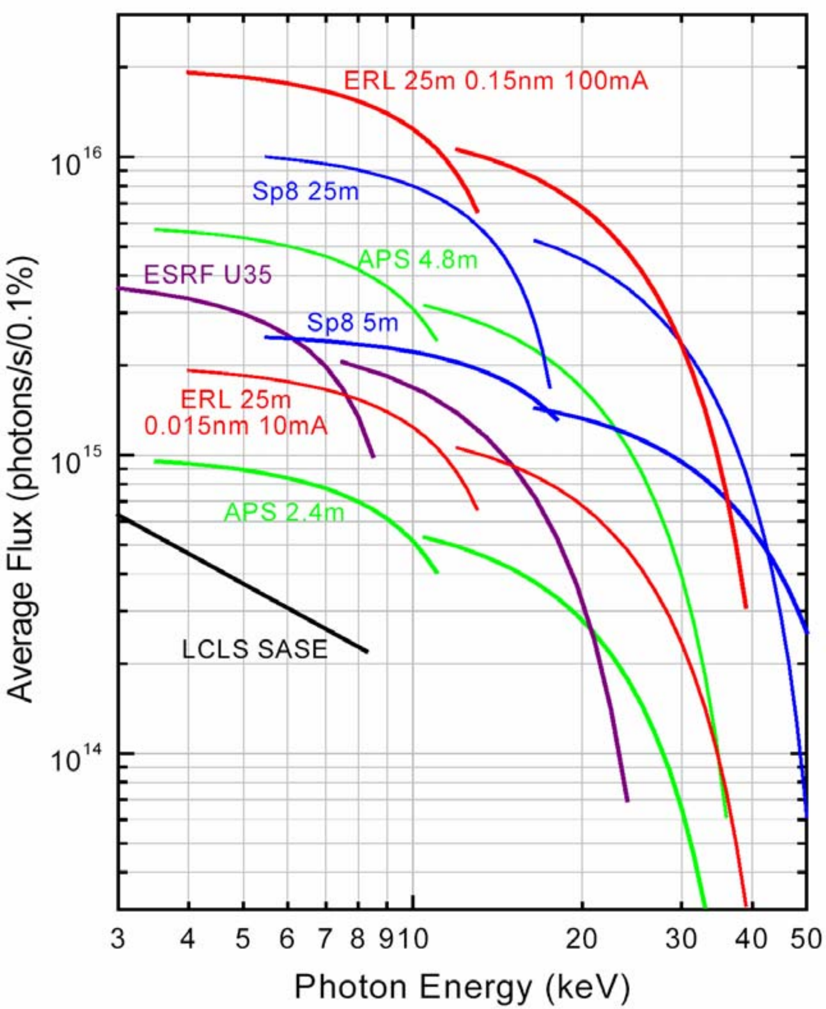
ERLSYN (Erlangen)

KEK

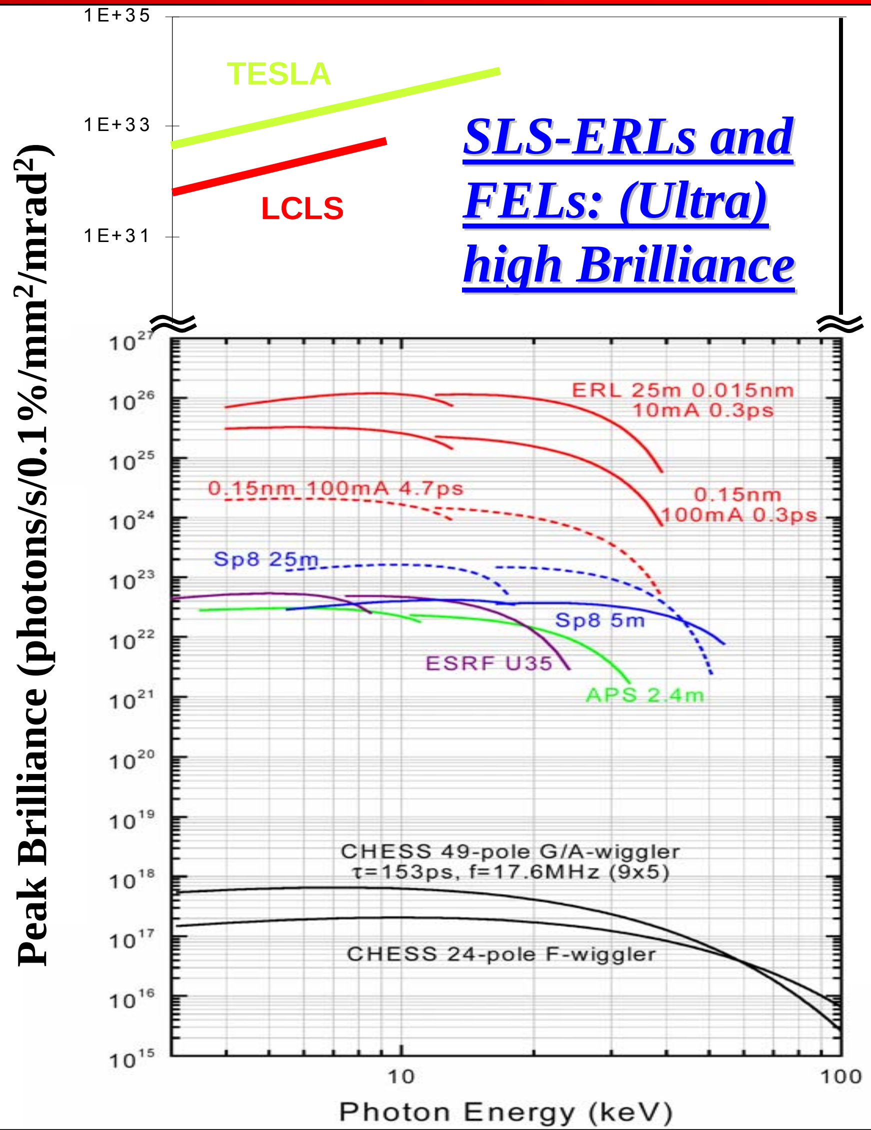
…

Flux and High Peak Brilliance

SLS-ERLs: Flux similar to rings

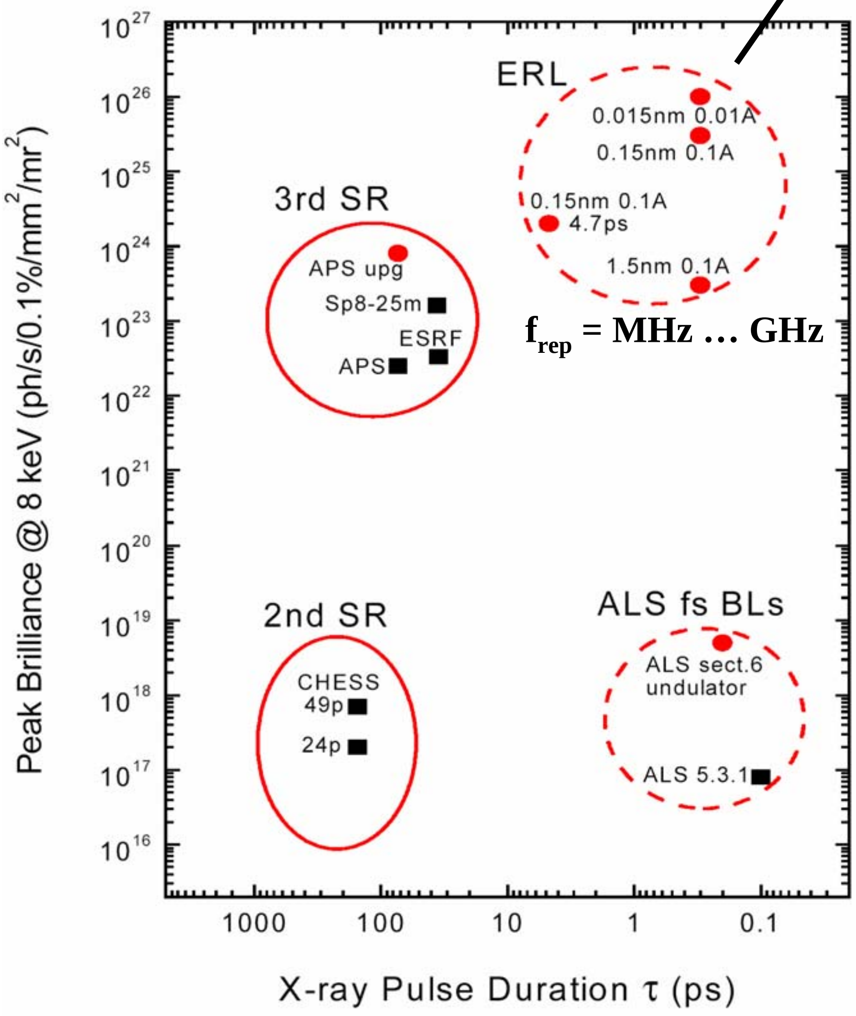


SLS-ERLs and FELs: (Ultra) high Brilliance



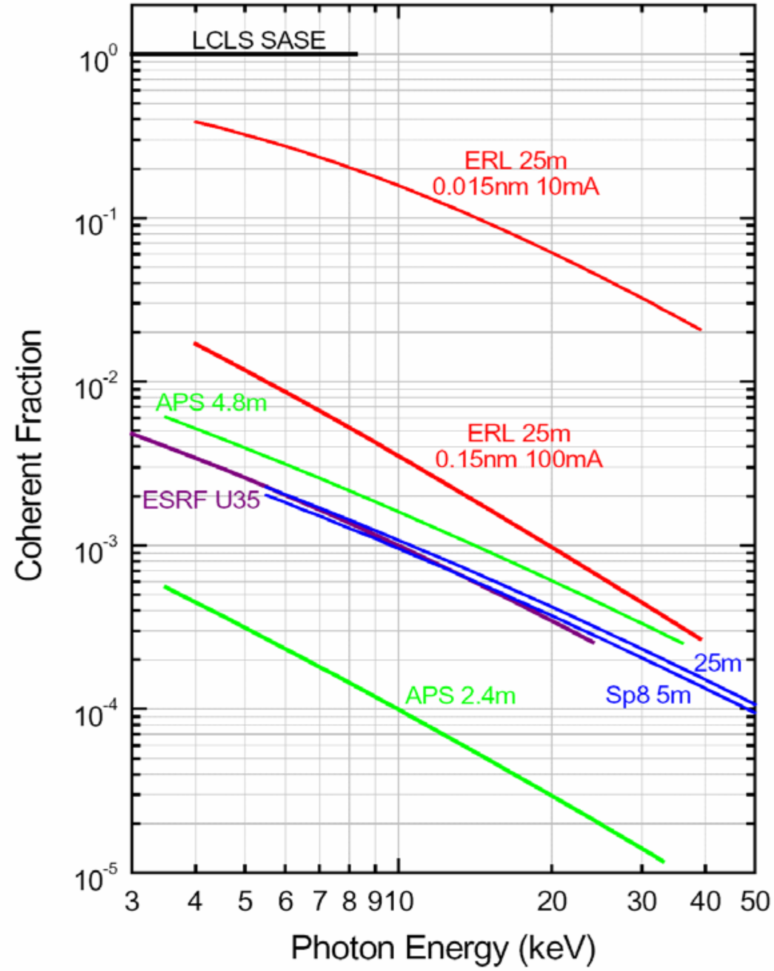
SR-ERLs and FELs: Parameters in New Regimes

Short pulses, high brilliance: → **FELs**



f_{rep} = MHz … GHz

High coherent fraction:



plots from Q. Shen

RF Linacs: Why SRF?

SRF linacs can deliver beams of superior quality:

- **Smaller emittance (lower impedance) ⇒ higher brilliance**
- **Better RF control and stability ⇒ lower energy spread**
- **CW operation at high gradient ⇒ flexibility in pulse train, lower impedance, cost saving**

In addition, SRF gives

- **Higher power conversion efficiency**
- **ERL option (very low wall losses) ⇒ high beam current, high flux**

Challenges

Challenges to Achieve the Required Beam Properties (1)

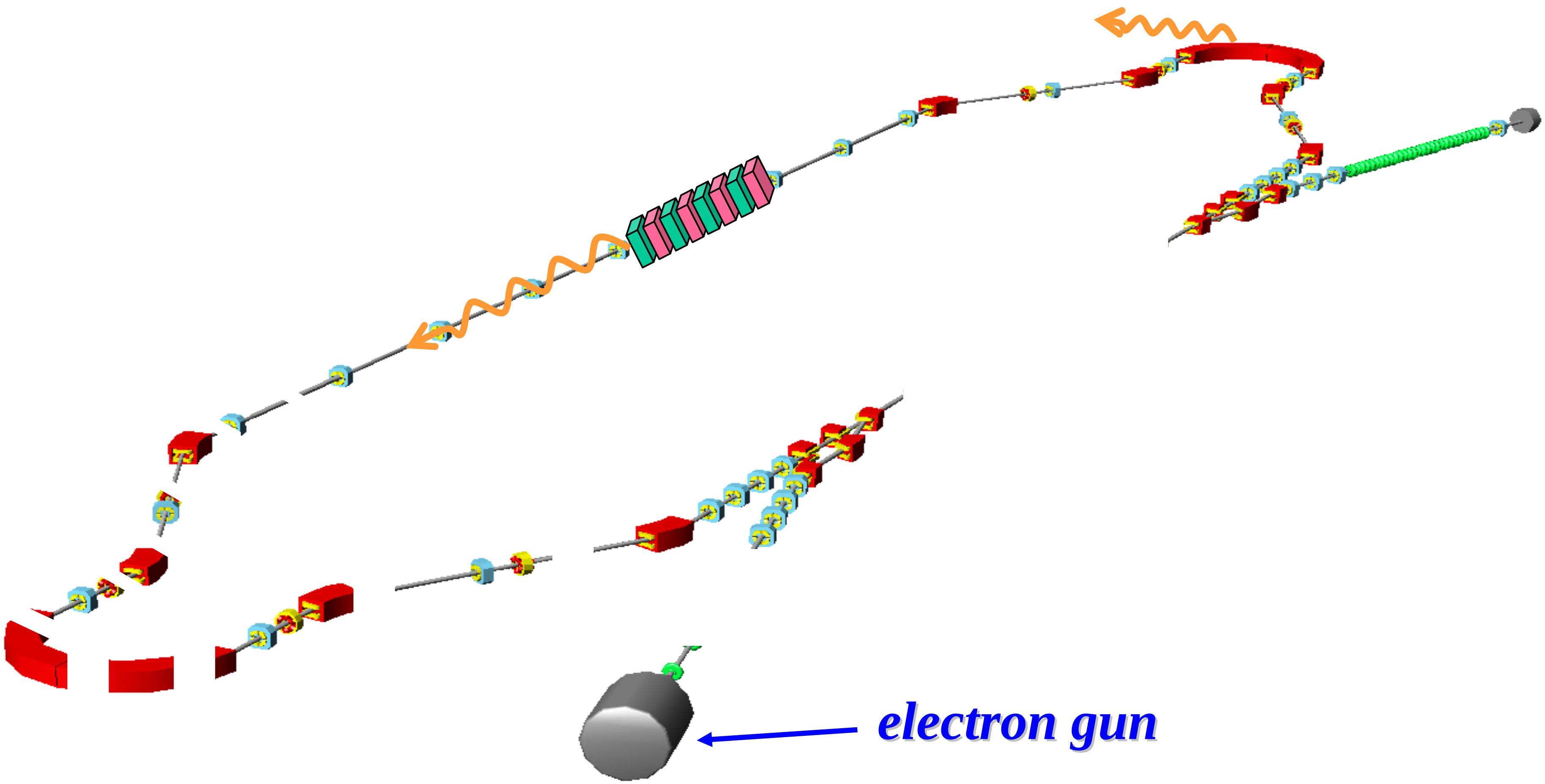
- Generation and preservation of low emittance beams:
  - (CW) gun ⇔ production of low emittance beam
  - Injector section, main linac, transport lines, bunch compressor ⇔ space charge dilution, CSR, wakefields, coupler kicks, …
- RF and beam control:
  - Flexibility and stability with small $\Delta E/E$
  - High loaded Q cavity operation (in presents of microphonics and Lorentz-force) ⇒ efficient cavity operation
  - ERLs: efficient energy recovery and RF control of random beam loading
- HOM damping and extraction:
  - Achieve sufficient beam stability ($I_{BBU} > I$)
  - Design cavity and mode damping for high current machines
  - Extraction of HOM power at temperature with good cryo-efficiency

Challenges to Achieve the Required Beam Properties (2)

- Cavity module operation:
  - High field gradients, cavity treatment
  - CW operation (high Q_0 essential), high heat loads, optimal temperature
  - Cavity design for minimized cryogenic losses
  - Optimization of mechanical design (cavity stiffness, mechanical resonances, …)
- Non intercepting beam diagnostic for short bunches with low emittance
- Beam halo and beam loss control
- …

In the following I will focus on the SRF related challenges!

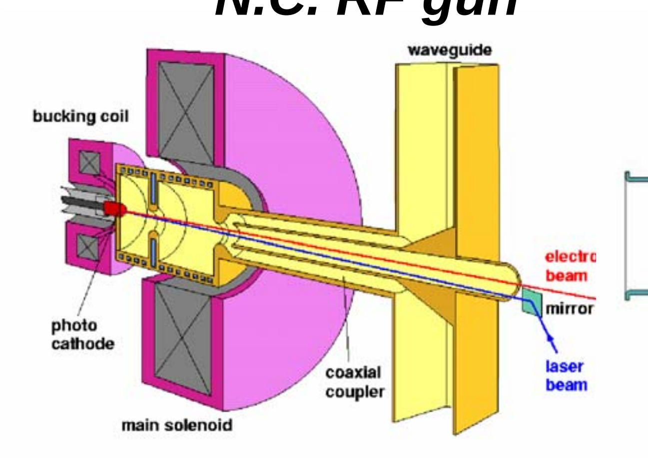
Challenges: Let's built a Light Source (1)



Guns: The Game of low Emittance

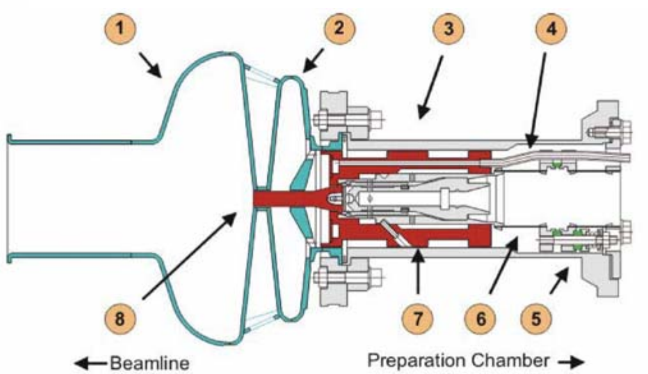
The best choice depends on your machine parameters: (and your history…)

N.C. RF gun



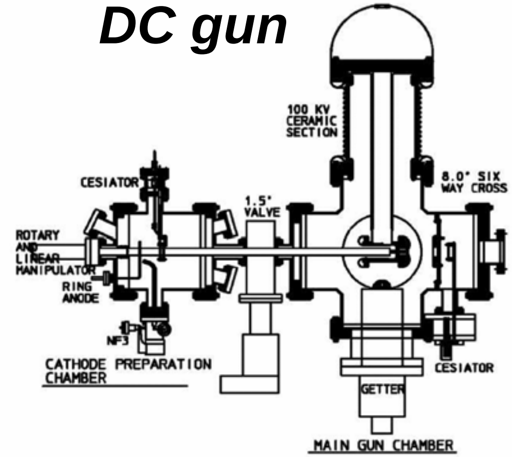
- high pulsed fields
- nC bunch charge
- high RF losses

S.C. RF gun



- high cw field
- still in R&D phase

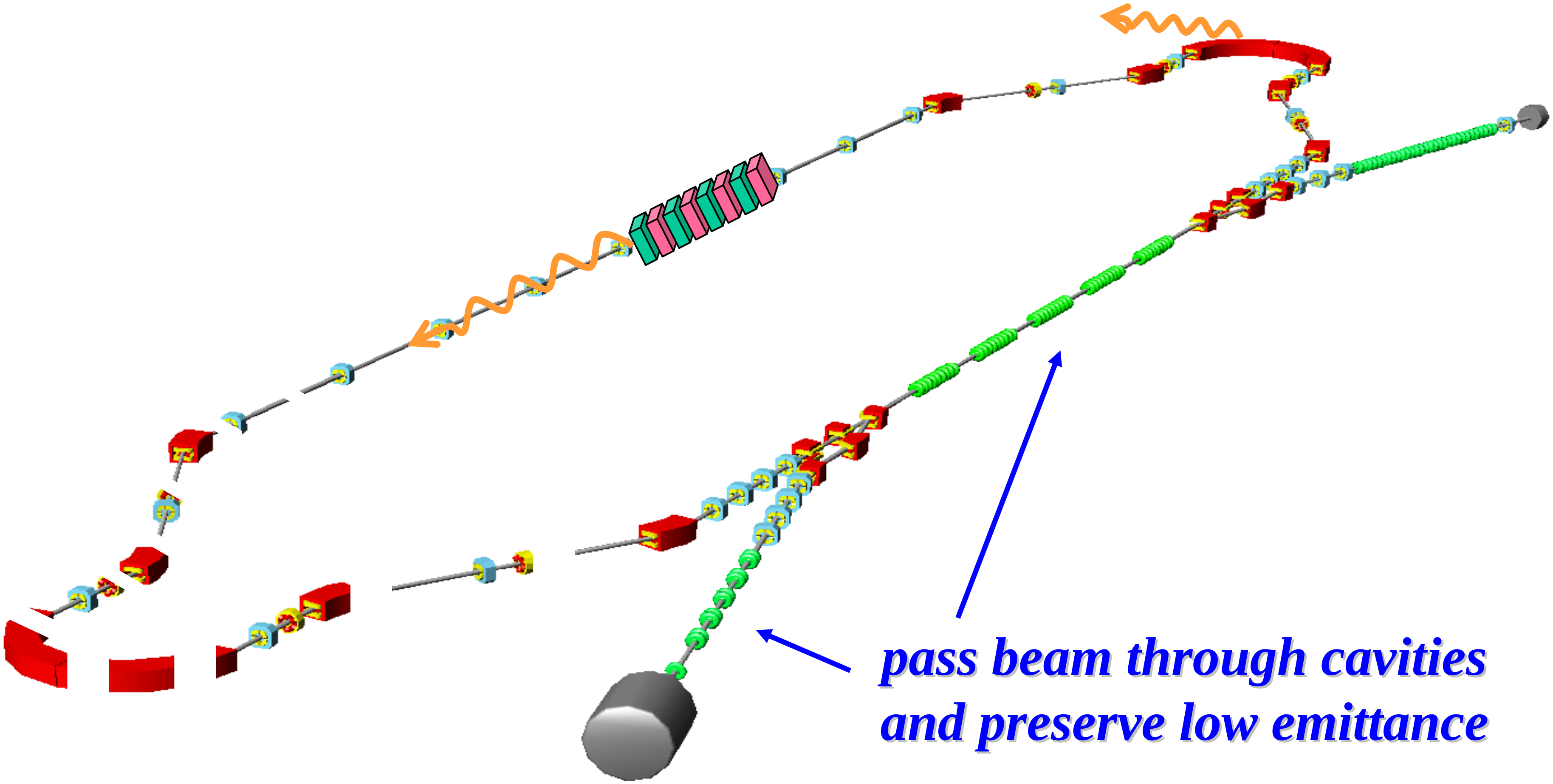
DC gun



- relative high cw field
- very low emittance beams with low bunch charge

R&D is ongoing for all gun types to minimize the emittance.

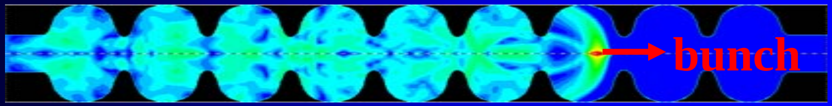
Challenges: Let's built a Light Source (2)



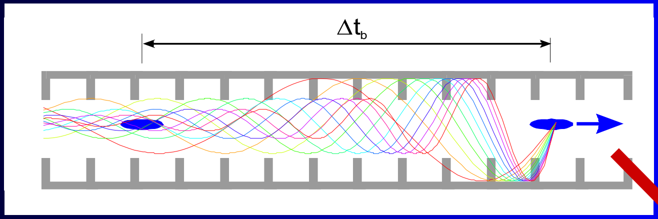
pass beam through cavities and preserve low emittance

Low Emittance Preservation in the Linac

Wakefields:

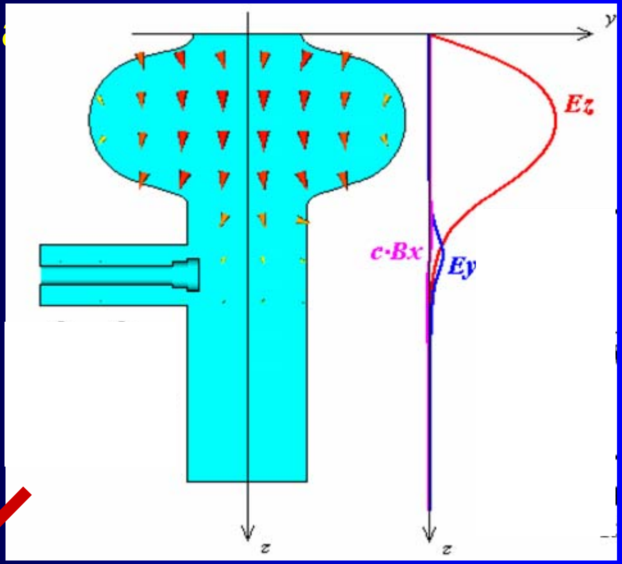


- longitudinal wakes generate energy spread
- transverse wakes generate time dependent kick fields ⇒ transverse emittance growth
- ⇒ multi- and single-bunch beam breakup



Coupler kicks:

- Rotation asymmetry of input coupler and HOM coupler gener-ates time dependent transverse kick fields on the c



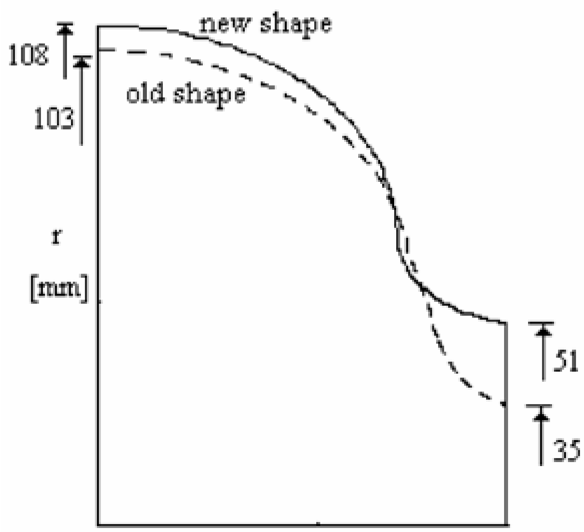
Emittance growth

Low Emittance Preservation: Potential Solutions (1)

- **Reduce wakefield emittance growth:**

  - **change cavity shape and frequency to lower loss factor:**

$$W_L \propto r^{-2} \qquad W_t \propto r^{-3}$$
$$W_L \propto f^{2} \qquad W_t \propto f^{3}$$



  - **Improve cavity alignment (offset and tilt)**

Example: TTF linac: Calculated emittance growth including 1 mm beam offset:

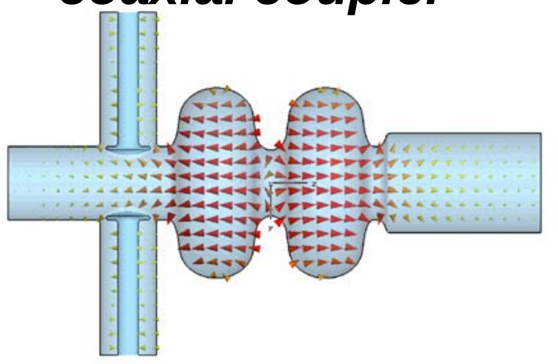
Rms cavity offset (mm)	Emittance growth
0.5	0.6%
0.8	0.9%
1	1.2%

Calculation done by Feng Zhou, DESY

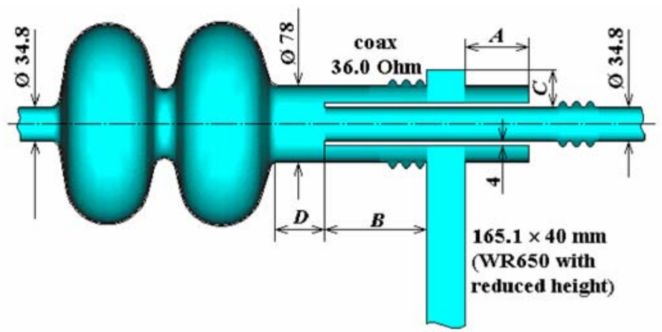
Low Emittance Preservation: Potential Solutions (2)

- **Reduce coupler kicks:**

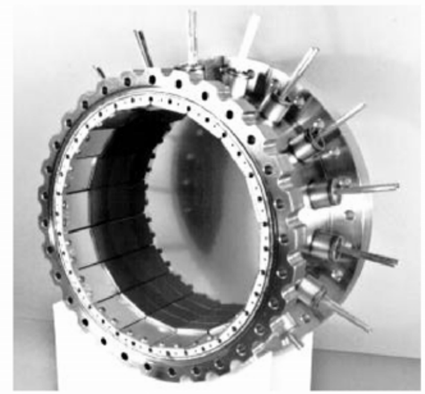
Symmetric twin-coaxial coupler



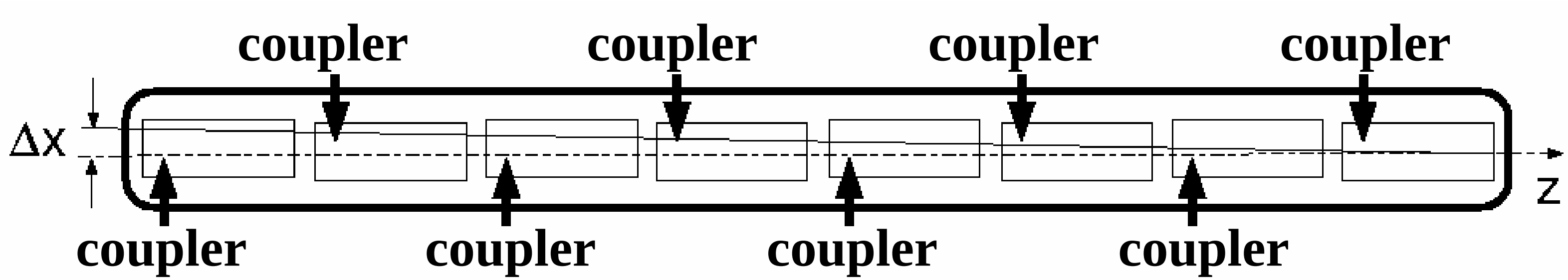
Waveguide-coaxial coupler



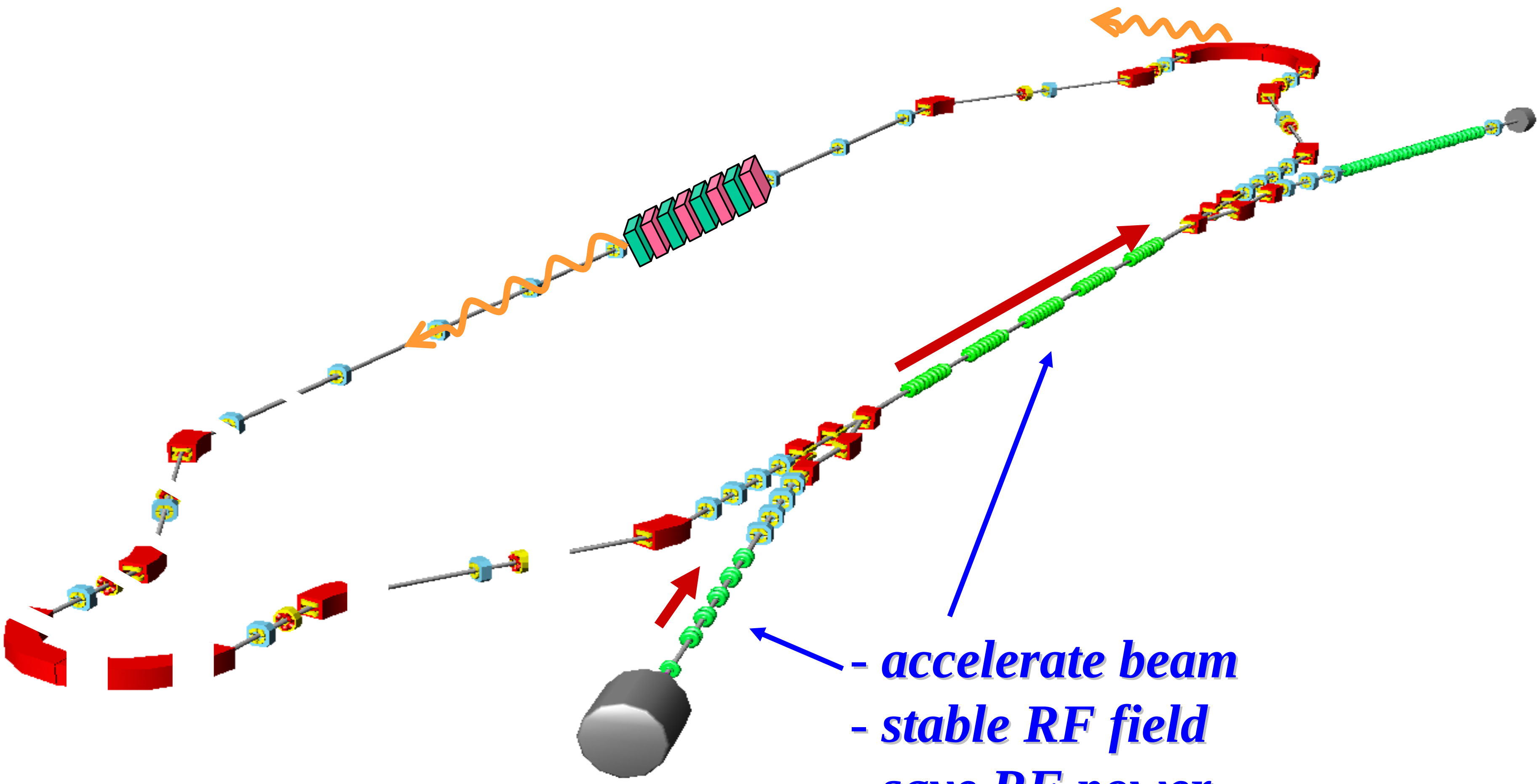
Symmetric HOM absorber



Alternating RF coupler placement



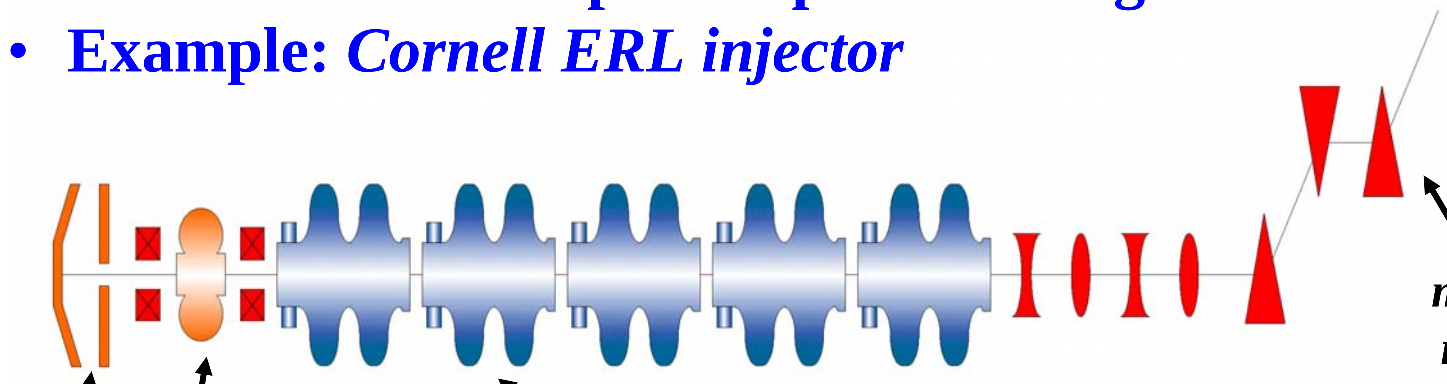
Challenges: Let's built a Light Source (3)

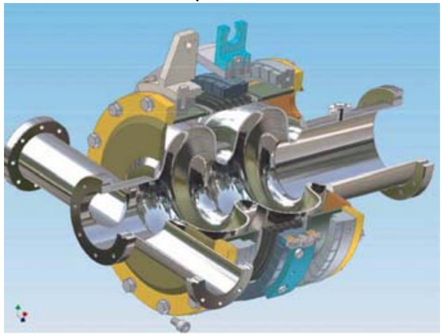


- accelerate beam
- stable RF field
- save RF power

Injector RF Challenges

- **Emittance preservation ⇒ fast beam acceleration (space charge), small transverse kick fields**
- **High RF power transfer to beam for acceleration of high current beam ⇒ input coupler challenge**
- **Example: *Cornell ERL injector***





- **2-cell cavities with propagating TM monopole and dipole modes ⇔ high current design**
- **50 kW RF power per input coupler ⇒ Coupler R&D needed (cooling)**

Main Linac Accelerating RF Field

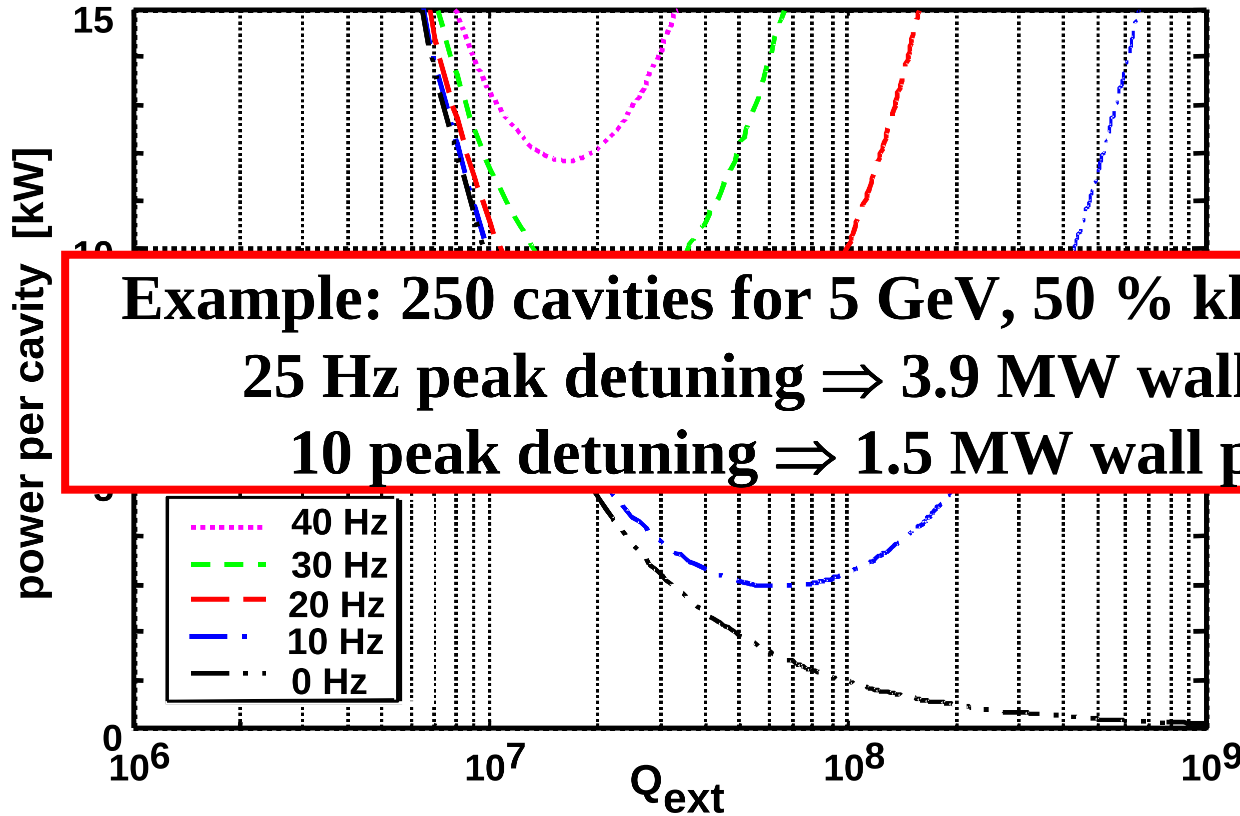
- High Q_L operation with low current beams or energy recovery:
  - RF control in presents of microphonics and Lorentz-force detuning, optimal loaded Q?
  - Minimum RF power required?
  - ERLs: efficient energy recovery and RF control of random beam loading

↓

- Advanced digital control systems
- Passive reduction of microphonics
- Active compensation of microphonics (piezo-tuner)

Example: Required RF Power without Beam Loading (ERL)

9-cell TESLA cavity at 20 MV/m:



$$V = \frac{\sqrt{4\frac{R}{Q}Q_L P_g}}{\sqrt{1+\left(\frac{f-f_0}{f_{1/2}}\right)^2}}$$

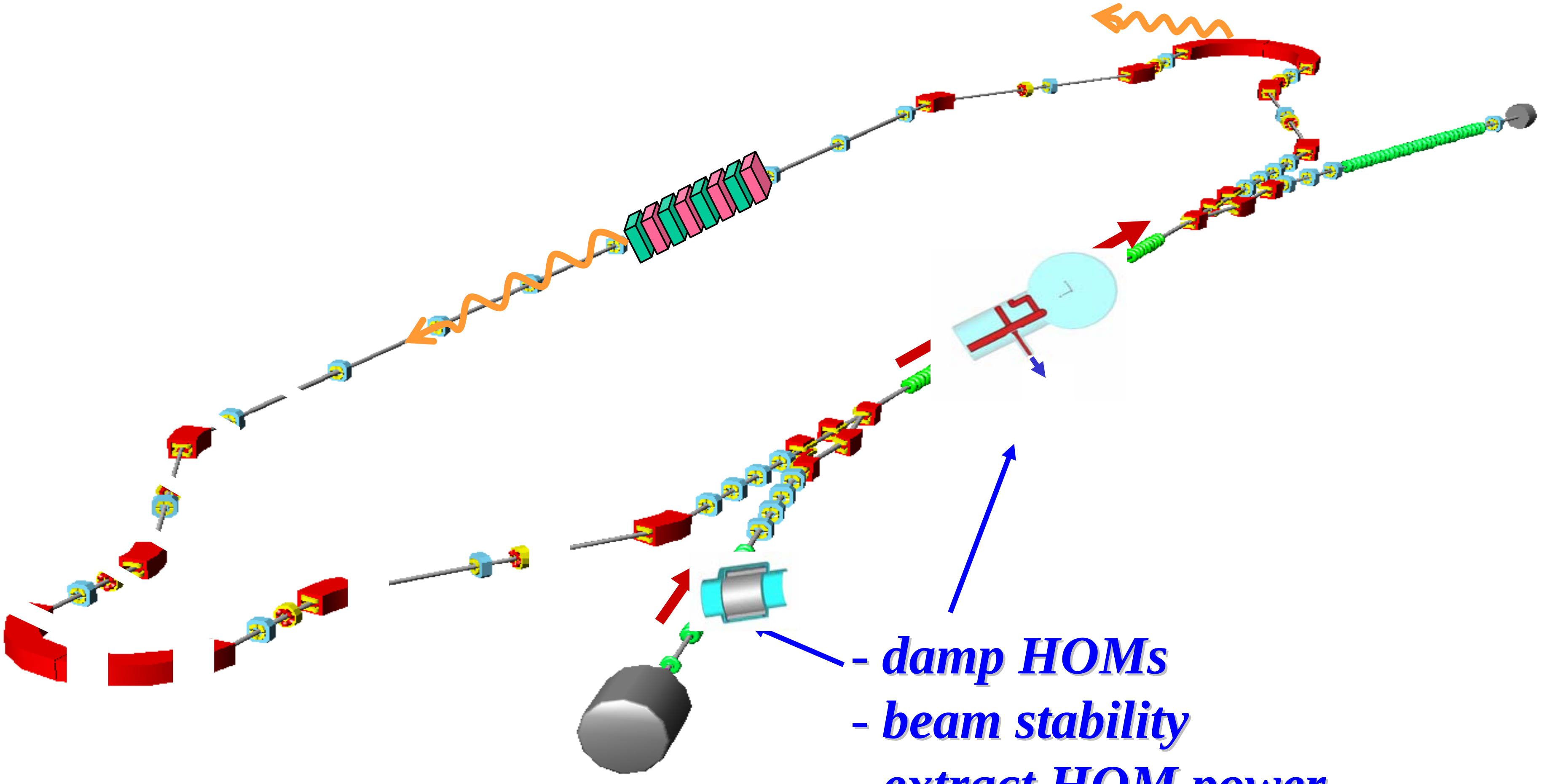
Example: 250 cavities for 5 GeV, 50 % klystron efficiency
25 Hz peak detuning ⇒ 3.9 MW wall plug power
10 peak detuning ⇒ 1.5 MW wall plug power

$$Q_{opt} = \frac{1}{2}\frac{f}{\Delta f}$$

$$P_{g,\min} = \frac{V_{acc}^2}{R/Q}\frac{\Delta f}{f}$$

Peak microphonics detuning important!

Challenges: Let's built a Light Source (4)



- *damp HOMs*
- *beam stability*
- *extract HOM power*

HOM Damping

- short bunches (X-FELs): radiate at high frequencies up to THz

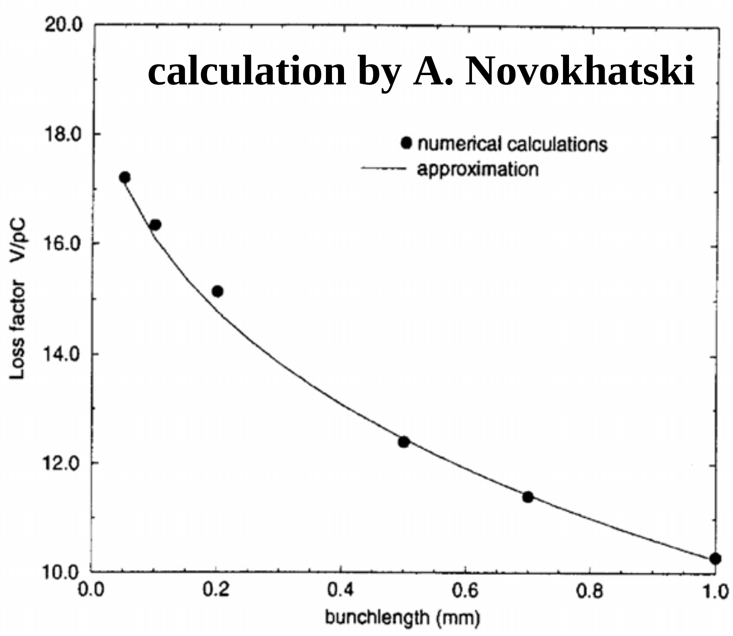
- High beam current:
  - HOM power extraction at temperature with good cryo-efficiency
  - beam stability limit

→ Strong HOM damping

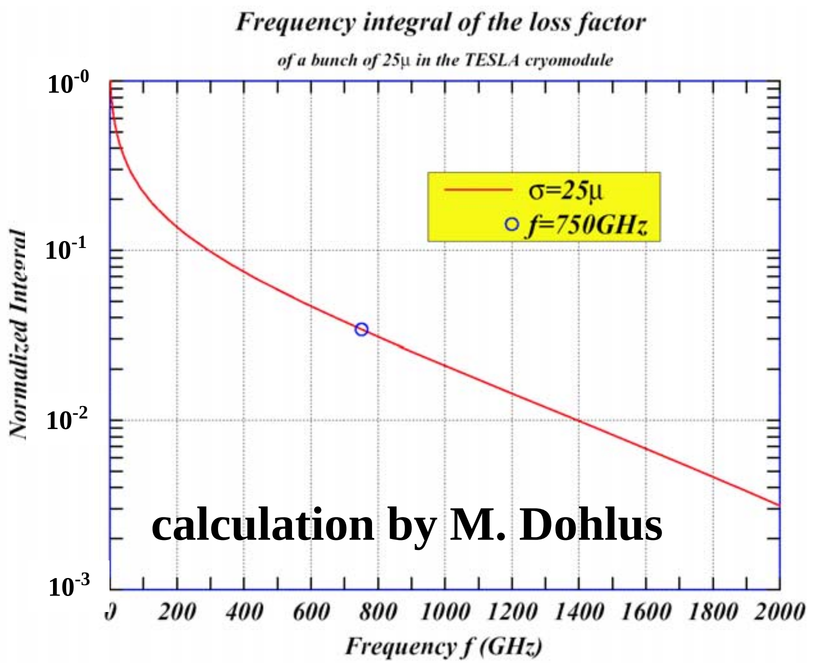
Short Bunches

- **Especially X-FELs require to accelerate very short bunches (down to some 10 µm):**

⇒ **Higher loss factor:**



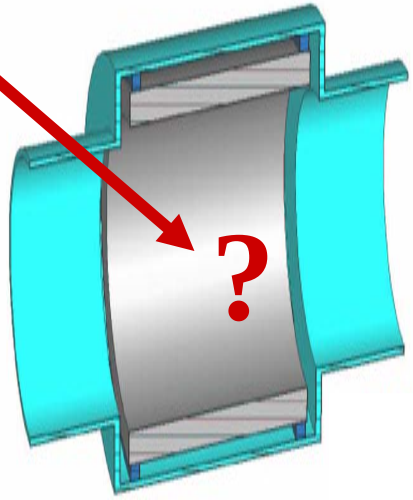
⇒ **Higher frequencies (up to THz):**



- **Where is the high frequency RF power absorbed? (s.c.walls for f > 750 MHz; n.c. walls, e.g. tubes bellows, input coupler ; RF absorber)**
- **Best broadband absorber material?**

Broadband Absorber: Materials

	requirements	Al_2O_3&Mo UNIPRESS	AlN & carbon CERADYNE	ferrite
comment		collaboration; reproducibility ? furnace for large probes ?	used @ 2K in CEBAF; what material? large probes ?	used @ 300K In CESR
rf propperties	$P^{(t)}/P^{(inc)} > 0.5$ $\alpha(10\text{GHz}) > 1/(1\text{cm})$	ok for some materials 80 K test @ X-band (early probes)	ok for some materials 80 K test @ X-band	absorption mechanism for f > 10 GHz unclear;
dc conductivity @ 80 K !!!	depends strongly on geometry & holder $>10^{-12}$ S/m cylinder type $>10^{-9}$ S/m rod type		$2 \cdot 10^{-9}$ S/m @ 300K	
thermal conductivity @ 80 K !!!	depends strongly on geometry & holder >100 W/(m·K) should be ok	≈ 150 W/(m·K) @ 86K		
radiation resistivity	no definition, so far			
vacuum		probes rejected	ZR10CB5 tested	
handling (mechanical prop., brazing, ...)		density & porisity measured; SEM photographs	ZR10CB5 used in module 1*	



High Beam Currents and HOM Monopole Power

In *average* the total HOM losses per cavity are given by the single bunch losses (Example:TESLA cavity, 77 pC bunch charge, 2.6 GHz bunch repetition rate, σ_b = 600 μm):

$$P_{||} = k_{||} Q_{bunch} I_{beam} = 10.4\,\mathrm{V/pC} \cdot 77\,\mathrm{pC} \cdot 0.2\,\mathrm{A} = 160\,\mathrm{W}$$

But: If a monopole mode is excited on resonance, the loss for this mode can be much higher:

$$P = \left(\frac{R}{Q}\right) Q I_{beam}^2$$

Strong HOM damping!

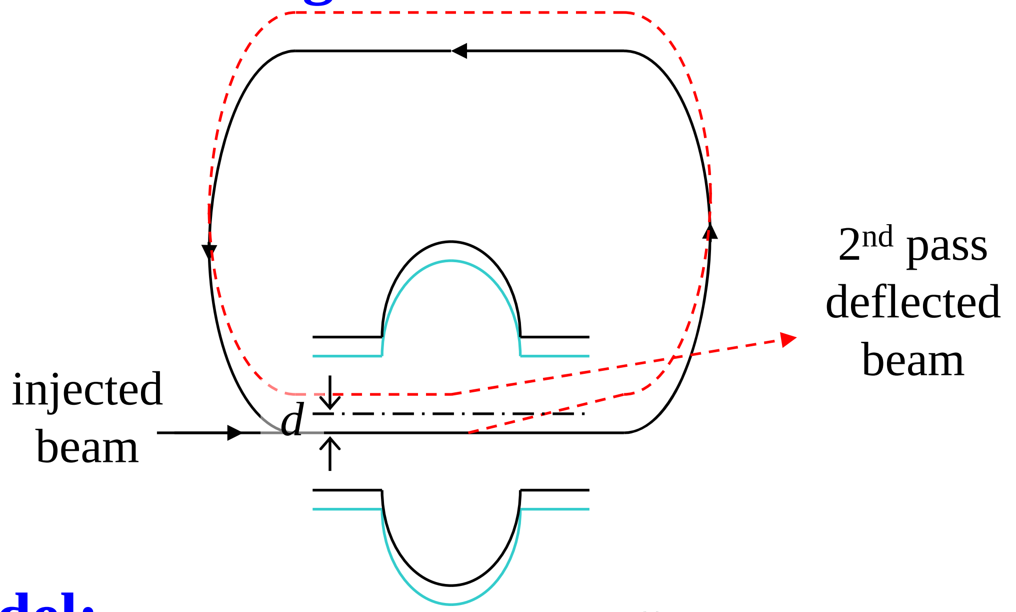
⇒ Example: R/Q = 10 Ohm, I = 100 mA

$Q = 10^3 \Rightarrow P = 100$ W

$Q = 10^4 \Rightarrow P = 1000$ W

Example: Beam Breakup (BBU) Limit for ERLs

- **In an ERL the feedback system formed between cavities and the beam is closed. ⇒ Instability can result at sufficient high currents.**

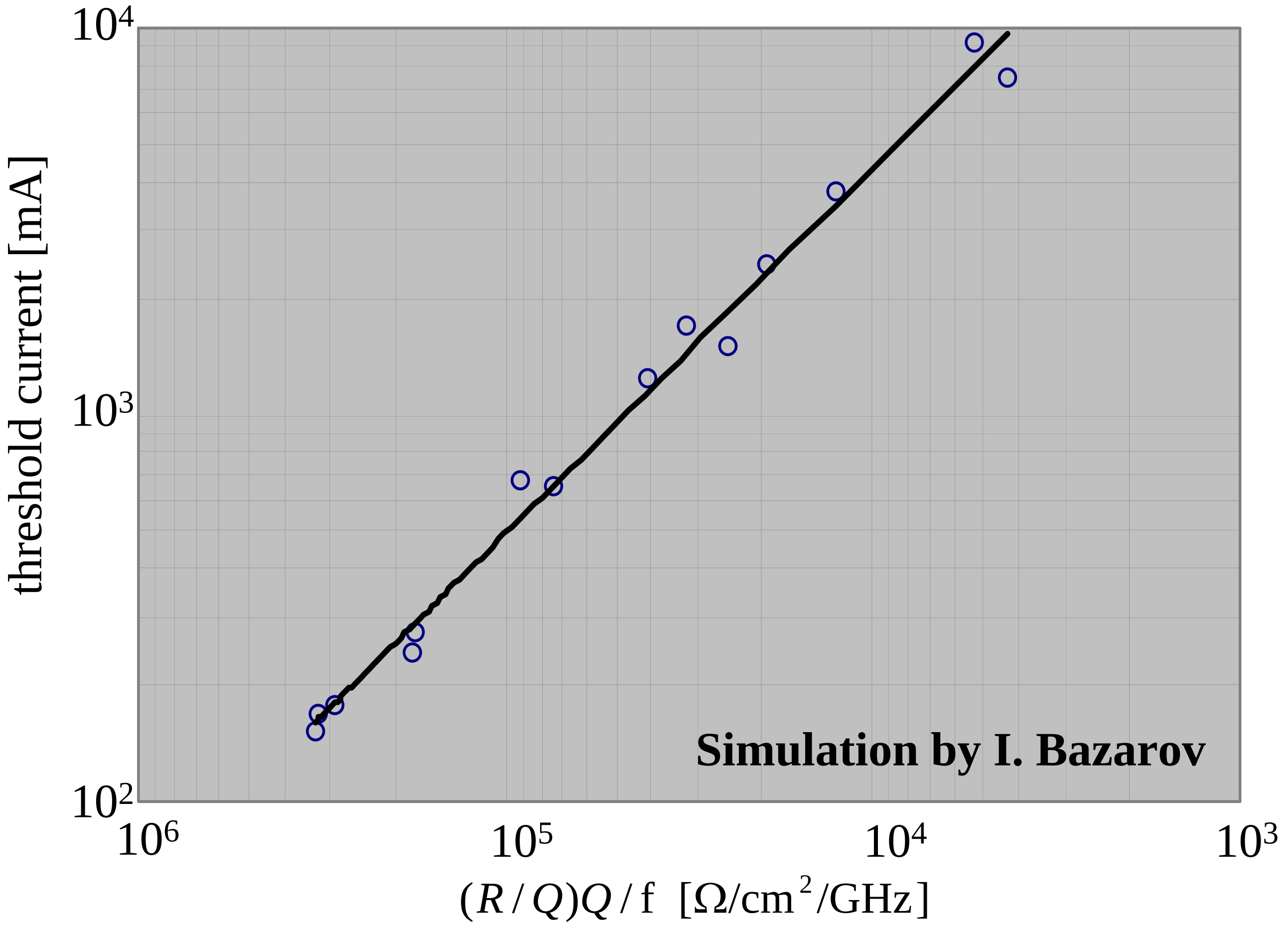


- **simple model:**

$$I_{BBU} \propto \frac{\omega}{(R/Q)\ Q}$$

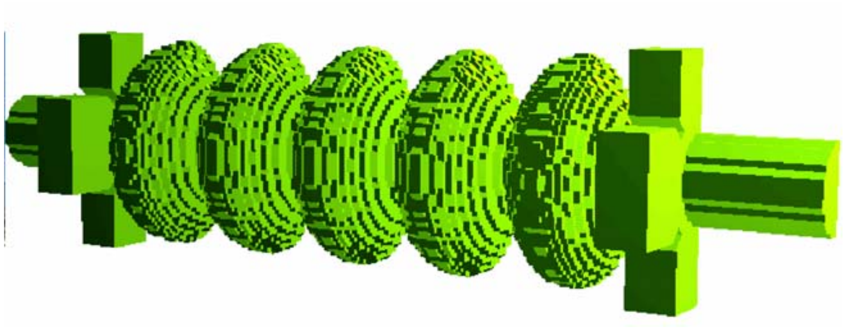
Strong HOM damping!

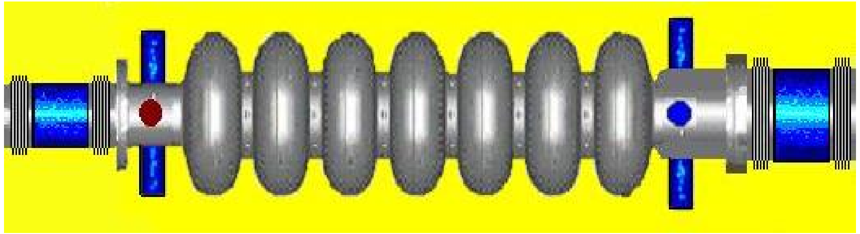
BBU Limit Example: Cornell 5 GeV, 100 mA ERL

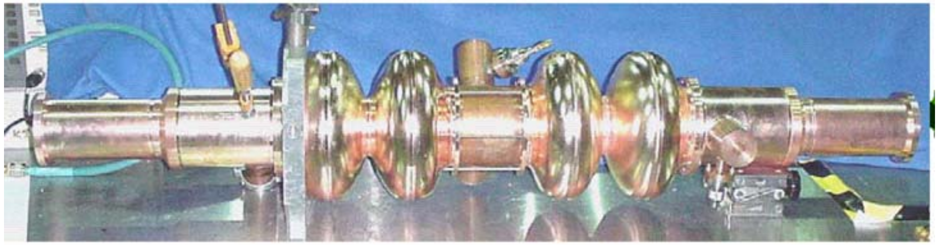


$\Rightarrow$ Q of 10^4 to 10^5 required for BBU instability limit > 100 mA

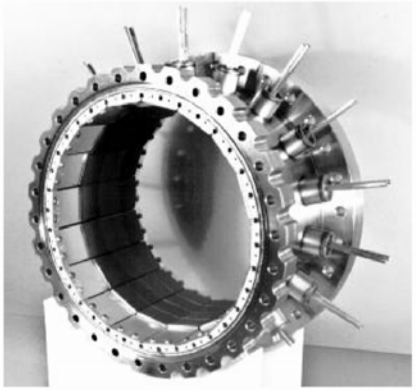
Achieving Strong HOM Damping



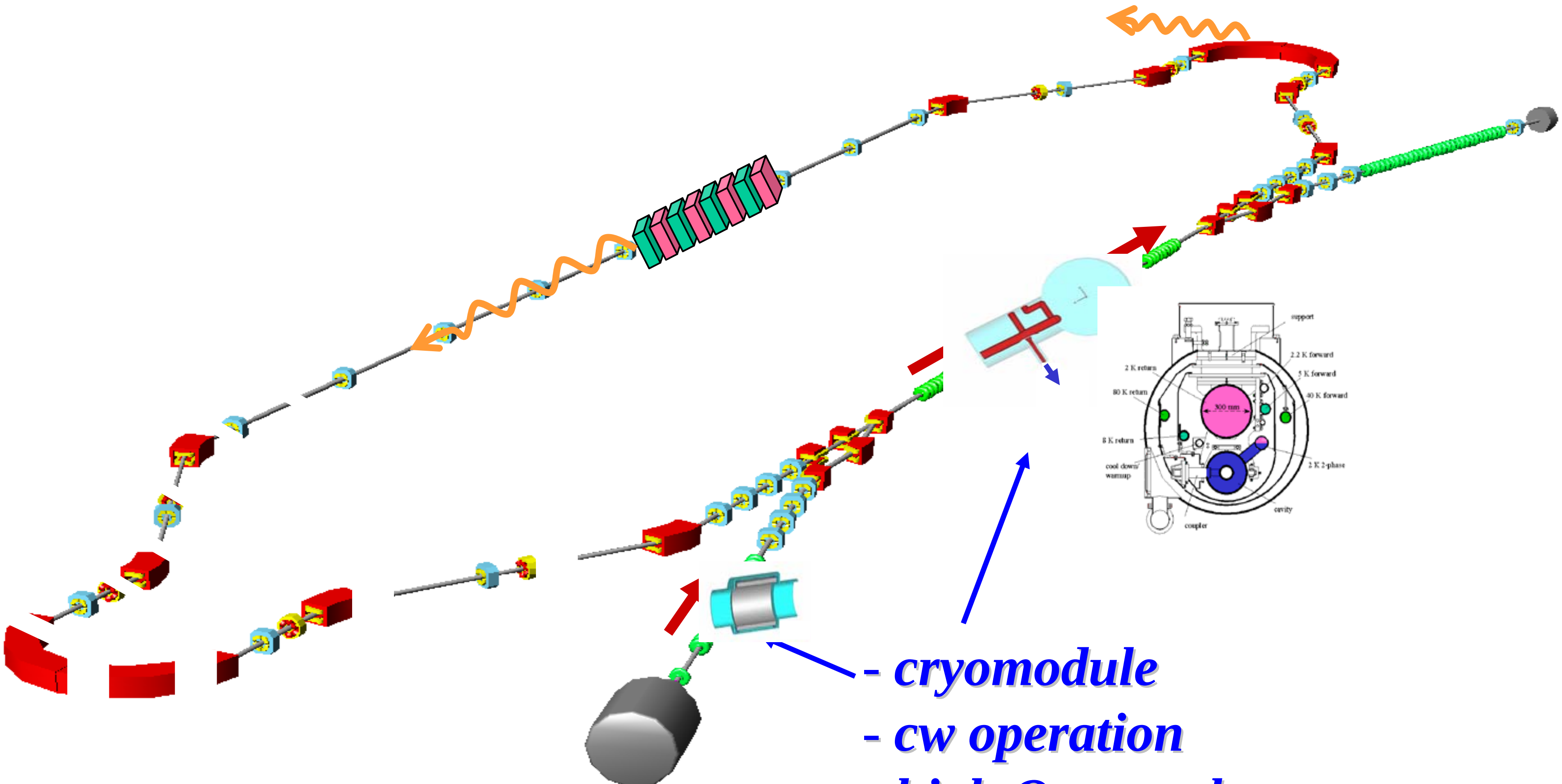




- Open beam pipes to propagate HOMs
- More loop couplers, waveguide couplers, broadband absorbers
- Smaller number of cells
- Superstructure concept
- …



Challenges: Let’s built a Light Source (5)



- ***cryomodule***
- ***cw operation***
- ***high Q_0, cryo losses***

Cryogenic losses

- High gradient cw operation: dynamic head load dominates: Example: 20 MV/m, $Q_0 = 10^{10} \Rightarrow$ 40 W/m
- Module design:
  - Heat transfer through LHe
  - Mass transport of helium gas
  - HOM losses
- Cavity:
  - Design: Maximize R/Q and G for the accelerating mode

$$P_{diss} = \frac{V_{acc}^2}{R/Q \cdot G} R_S$$

  - Cavity treatment for high Q_0
  - Optimal bath temperature?

Example: Cryogenic Loads per Module with 10 7-cell Cavities (20 MV/m, 100 mA, $Q_0=10^{10}$)

2 K static loads	
Supports	0.5 W
Instrum. cables	0.21 W
Input Couplers	0.2 W
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
Input couplers	1.6 W
HOM absorber	15 W
HOM Couplers	6 W
Total 2 K	363.1 W
2 K efficiency (TESLA TDR)	588 W/W
Total wall plug power	213.5 kW

5 K static loads	
Radiation	1.7 W
Supports	2 W
Instrum. cables	1.2 W
Input Couplers	1.3 W
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
Input couplers	12 W
HOM absorber	150 W
HOM Couplers	12 W
Total 5 K	201.1 W
5 to 8 K efficiency (TESLA TDR)	168 W/W
Total wall plug power	33.8 kW

77 K static loads	
Current leads	13 W
Radiation	38.4 W
Supports	5 W
Instrum. cables	4.5 W
Input Couplers	65 W
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
Input couplers	210 W
HOM absorber	1335 W
HOM Couplers	60 W
Total 77 K	1742.3 W
77 K efficiency (TESLA TDR)	17 W/W
Total wall plug power	29.6 kW

Example: 5 GeV, 20 % cryo overhead

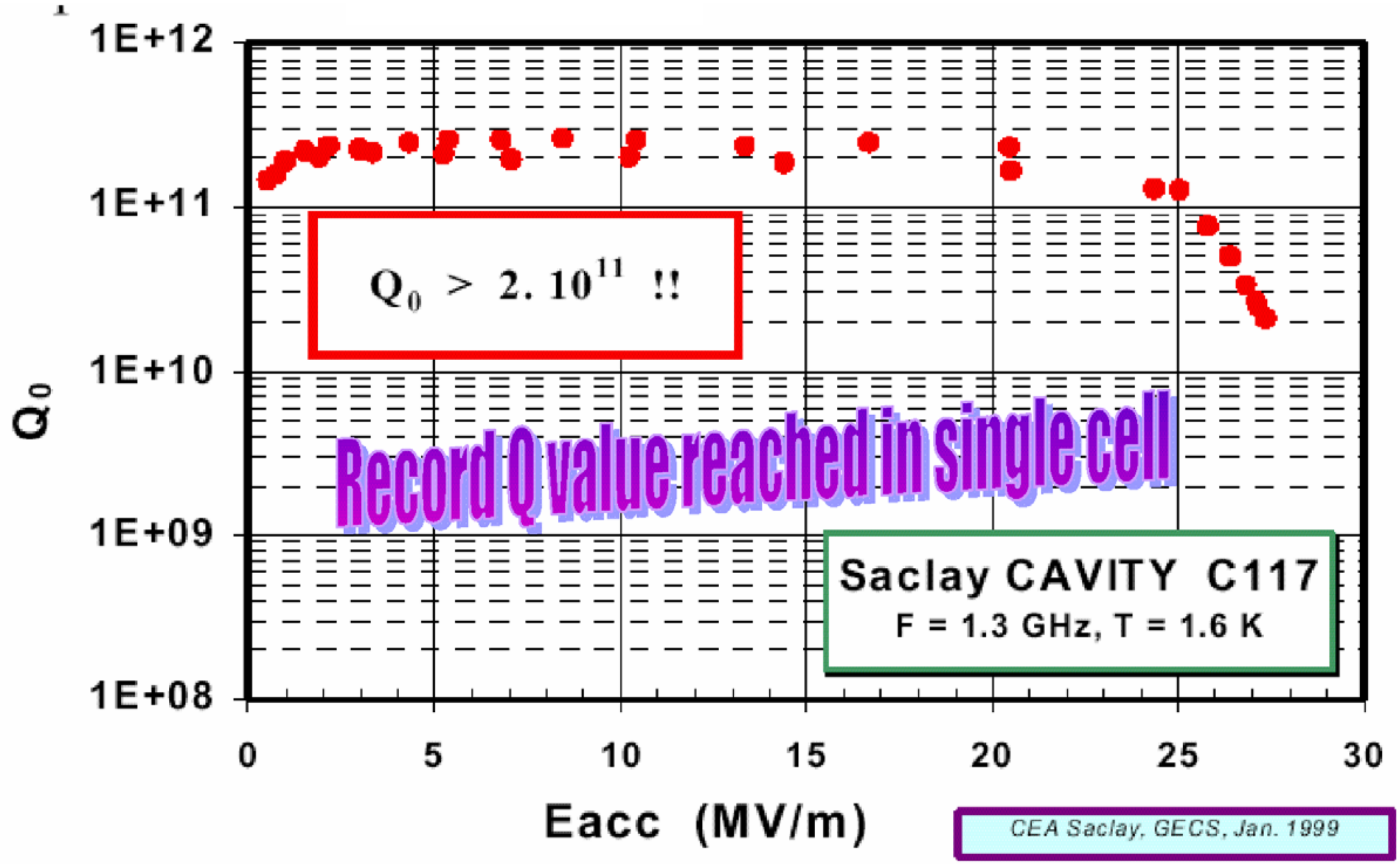
$Q_0 = 1\cdot10^{10} \Rightarrow$ 10.3 MW wall plug power

$Q_0 = 2\cdot10^{10} \Rightarrow$ 6.7 MW wall plug power

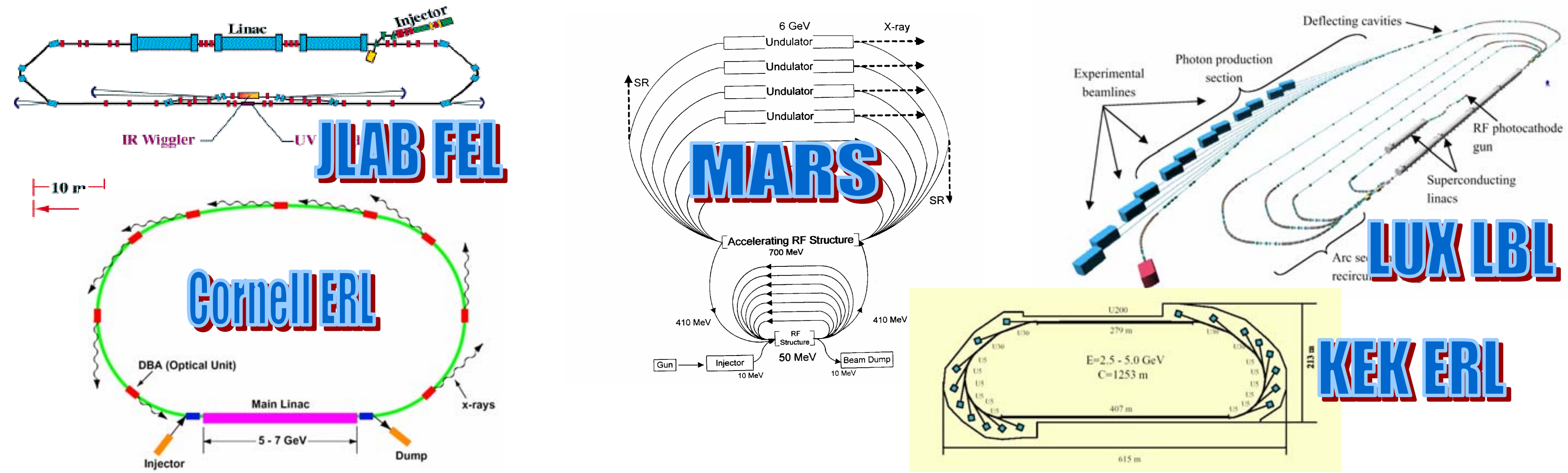
R_{BCS} and LHe Bath Temperature

- **R_{BCS} decreases significantly if T is lowered.**
- **Important: The residual resistance must be low to make use of this! ⇒ Very good shielding of Earth's magnetic field (< some mOe).**
- **Examples:**
  - **T = 2.0 K ⇒ Q = $2.6 \cdot 10^{10}$**
  - **T = 1.8 K ⇒ Q = $6.3 \cdot 10^{10}$**
  - **T = 1. 6K ⇒ Q = $1.9 \cdot 10^{11}$**
- **A dream?…**

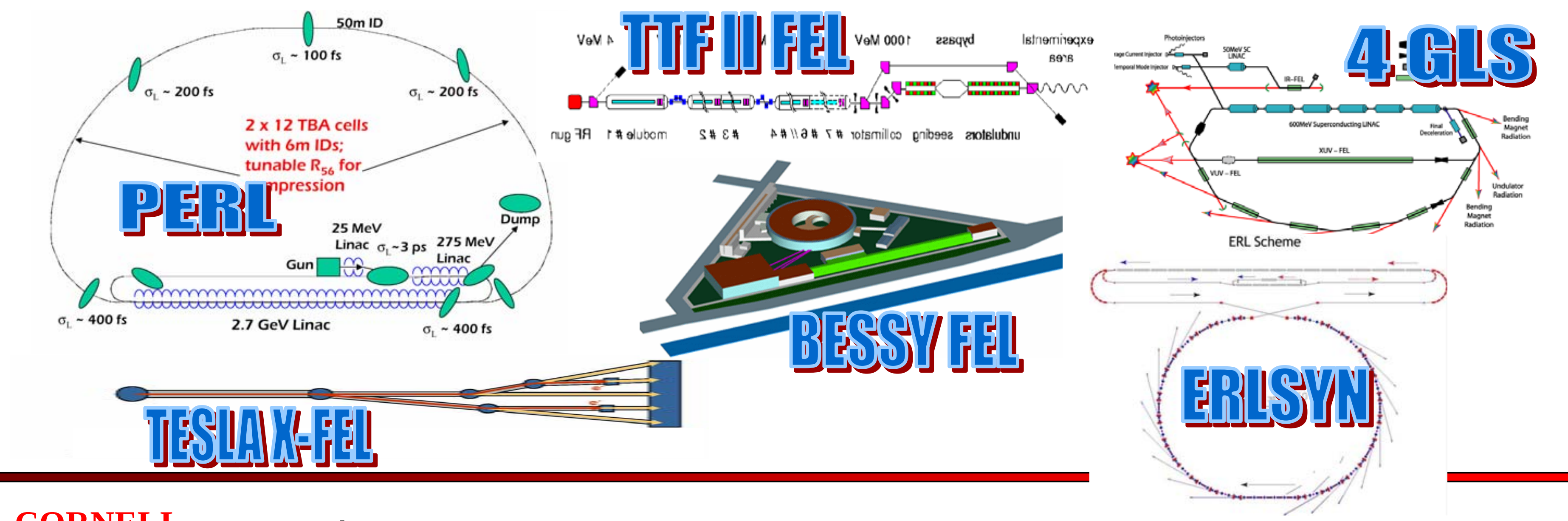
High Q_0 : Let's dream…



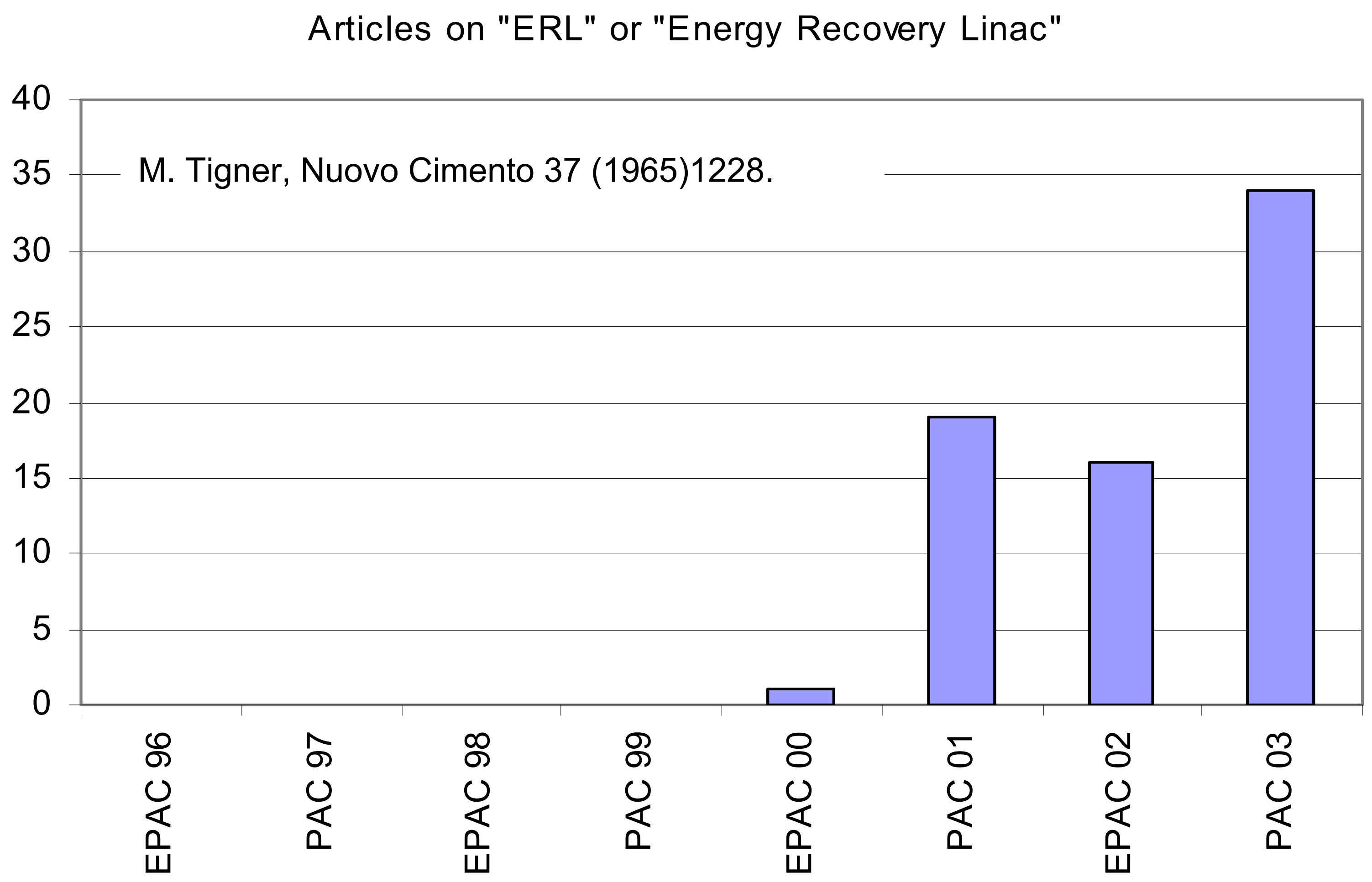
⇒ 2 W/m losses at 1.6 K instead of 20 to 40 W/m losses at 2 K?



New FEL and ERL Projects: A Bright Future for SRF



Workshop Papers: ERLs



Summary

- ERLs and FELs have the potential to produce ultra high brilliance photon beams.
- SRF is the key technology for these machines.
- The production and preservation of low emittance electron beams is essential.
- Many challenges need our attention:

wakefields
coupler kicks
HOM damping
BBU
RF control
microphonics
High Q_0
gun
Cw module operation

Are you ready?


The sunset of this talk.
The sunrise of a bright future for s.c. cavities.