Accelerators-recuperators as 4th generation X-ray light sources

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Lecture 3

Technical solutions for realization of the 4th generation SR sources based on accelerators-recuperators

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Technical solutions for realization of the 4^{th} generation SR sources on the base of accelerators-recuperators

Development of accelerators-recuperators for various purposes (FEL, SR sources, electron cooling) have been discussed in detail at the Conferences ERL-2005 and ERL-2007. Independently of the posed tasks, many accelerator-recuperator systems can technically be realized.

Therefore, at present, it is more right to discuss parameters of different systems, required for creation only of the 4th generation SR sources on the base of a single-pass or multi-pass accelerator-recuperator.

Electron gun

- In recirculating accelerators – recuperators (single or multi-pass) low emittance of electron beam ε_n must be produced at electron gun. Then owing to adiabatic damping during acceleration up to high energies (E > 5 GeV, $\gamma > 10^4$) it is possible to obtain emittance

$$\varepsilon_{x,z} = \frac{\varepsilon_n}{\gamma}$$

- For diffraction limited X-ray source emittance of electron beam at final energy must be $\varepsilon_{x,z} < \frac{\lambda}{4\pi}$ for $\lambda = 0.1$ nm, $\varepsilon_{x,z} < 10^{-11}$ m·rad.

- Main requirements for electron gun

$$\varepsilon_n < \varepsilon_{x,z} \cdot \gamma \qquad \varepsilon_n < 10^{-7}\, m \cdot rad \,!!$$

- Different types of electron guns such as DC-thermoionic emission, DC-photocathode, normal conducting photocathode RF guns, superconducting photocathode guns has been constructed and tested, some electron guns are under construction or under analysis.

Photoemission offers several advantages over thermal emission:

- higher current density;
- bunched beams are generated through a laser with appropriate time structure bunches ~ 10 ps long – readily available from photocathodes: no need for chopping as in the case of thermal emission;
- Colder beam (lower thermal emittance) is possible.

Main requirements for photocathode of the photoinjector for accelerator – recuperator:

- CW operation (up to 1.3 GHz);
- operable in high field (> 5 MV/m);
- high average current – (up to 10 mA);
- high quantum efficiency (5 – 10) %;
- long operational lifetime ($10^3 \div 10^4$ hours);
- small thermal emittance ($\varepsilon_n < 10^{-7}$ m·rad);
- small cathode dark current (I < 10 pA at gradient more than 5 MV/m);
- prompt response time (~ 100 fs);
- short recovery time.

- minimum possible normalized emittance, determined initial thermal energy spread, is fundamental and uncorrectable

$$\varepsilon_n = \frac{r_c}{2}\left(\sqrt{\frac{E_{thermal}}{mc^2}}\right)^{1/2}$$

$$\varepsilon_n = (1.5 \div 4.5)10^{-4} r \qquad E_{thermal} = (35 \div 300)\, MeV$$

- distortion of phase space and emittance growth due to RF time dependent effects and space charge induced effects, could be corrected (long RF wave length, using photocathodes, small peak current, high accelerating gradient …)

$$\varepsilon_n\left[mm\cdot mrad\right]\geq 4\left(\frac{Q\left[nC\right]E_{thermal}}{E_{cath}\left[MV/m\right]}\right)^{1/2}$$

- the normalized emittance of $\varepsilon_n < 10^{-7}$ m·rad been obtain for bunches of electrons with a charge of $Q = 7.7 \cdot 10^{-12}$ Coul and duration $\tau_{pulse} = 14$ ps (ERL-2005).

example: I_{peak} = 100 A

$J \sim 400$ A/cm^2

t = 10 ps

r = 3 mm

Q = 1 nC

ε_n = 10^{-6} m·rad

I_{peak} = 0.4 A

$J \sim 400$ A/cm^2

t = 10 ps

r = 0.2 mm

Q = 4 pC

ε_n = $6 \cdot 10^{-8}$ m·rad

- in light source based on recirculators accelerators – recuperators brightness of light beam is paramount

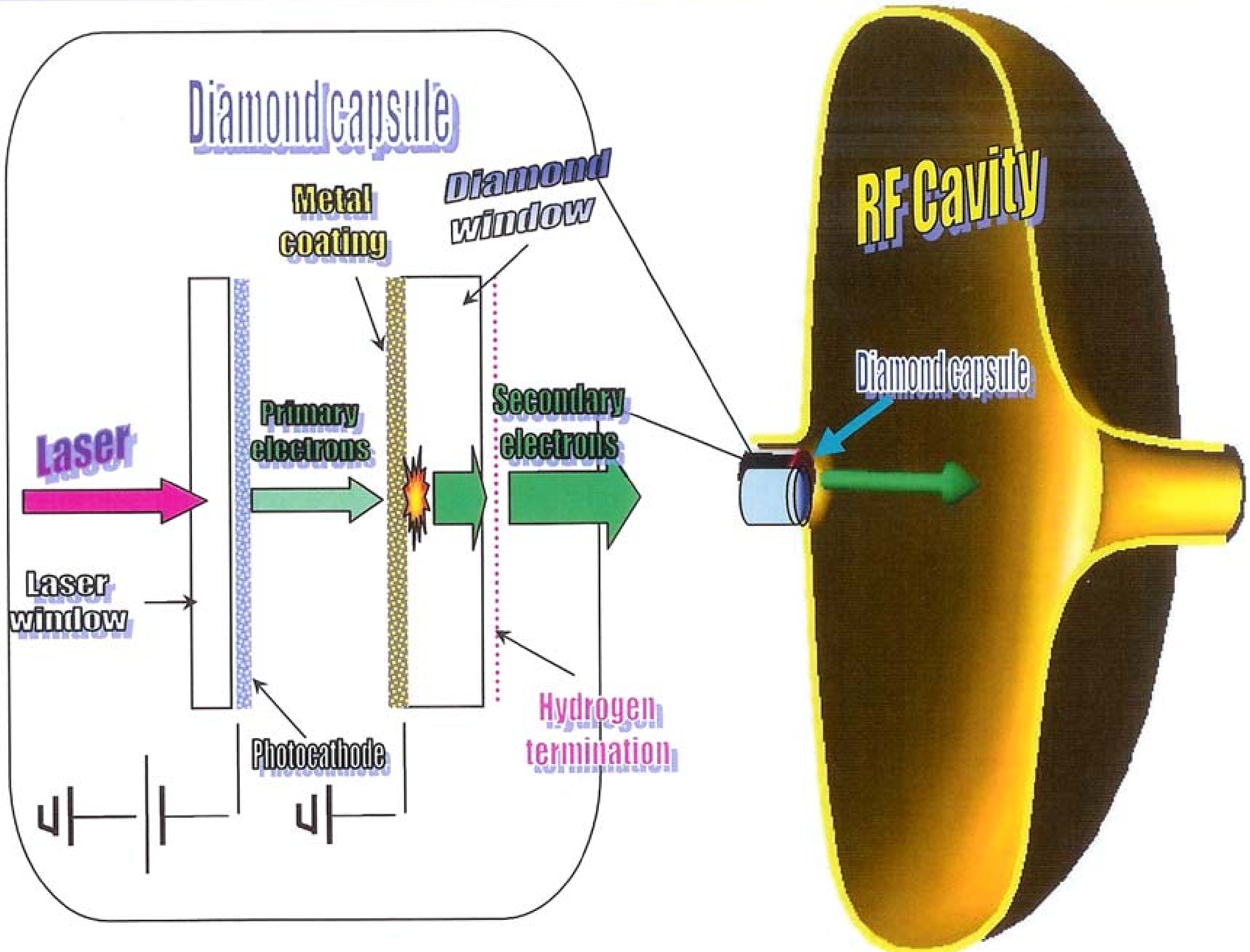
$$B \rightarrow \frac{I}{\varepsilon_x \varepsilon_y};$$

- Electron beam thermal emittance is proportional to the square root of the bunch charge; due to spectral brightness of SR source independent from bunch charge, down to diffraction limit (of course flux is increased; after diffraction limit flux is increase, but spectral brightness is decreasse;

Four families of high quantum efficiency photocathodes:

- the alkali antimonides (K_2GsSb);
- the alkali tellurides (KCsTe);
- the negative electron affinity (NEA) semiconductors (CsGaAs), NEA semiconductor cathodes have additional advantage – very small thermal emittance and better quantum efficiency;
- diamond amplified photocathodes.

Diamond amplified photocathode



Courtesy Xiangyun Chang. See talk by Triveni Rao.

Optical source for photoinjector:

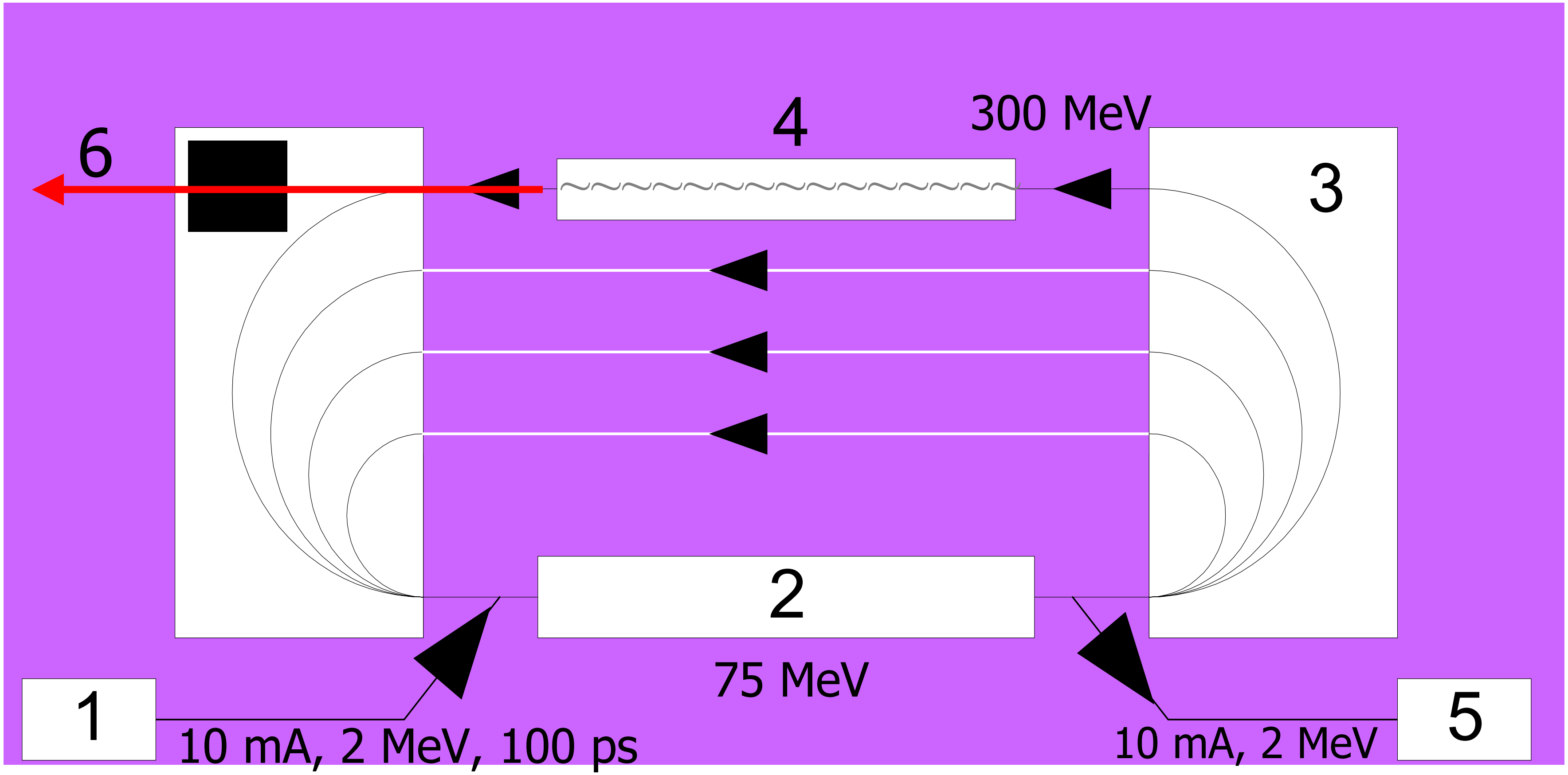
Quantum efficiency depend of wavelength and increase for wavelength shorter 200 nm.

Lasers, providing the necessary high frequency optical pulse train at the proper wavelength with laser beam shaping for using with all families of photocathodes have been demonstrated (ERL-2005, ERL-2007).

It is possible to discuss creation of undulator source, based on 300 MeV accelerator – recuperator, providing the necessary high frequency short light pulses, synchronized with RF for use with high efficiency photocathodes.

Layout of the undulator source for photoinjector

P ~ 1 W, τ ~ 10 ps
λ ~ (150 – 300) nm



1 - injector, 2 - RF accelerating structure, 3- 180-degree bends, 4 – undulator ($\lambda_{\mathbf{u}}$ = 4.5 cm, $N_{\mathbf{u}}$ = 200), 5- beam dump, 6 – output light beam.

Principle of an X-ray ERL

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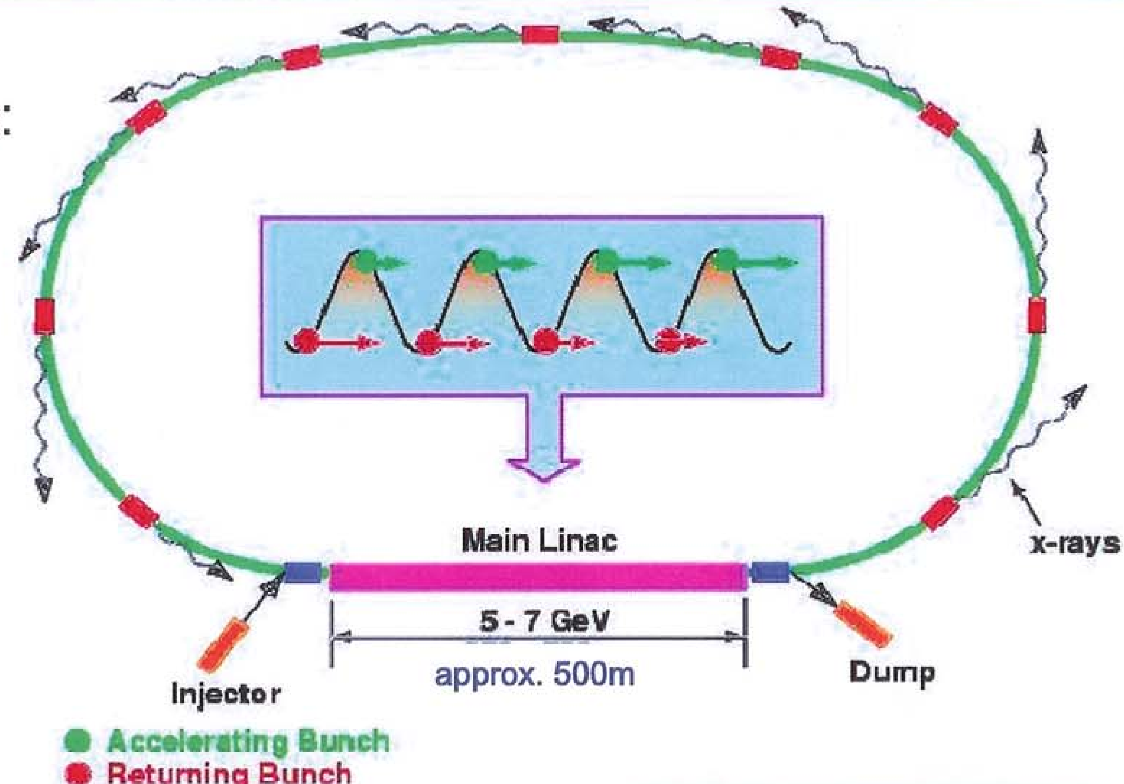
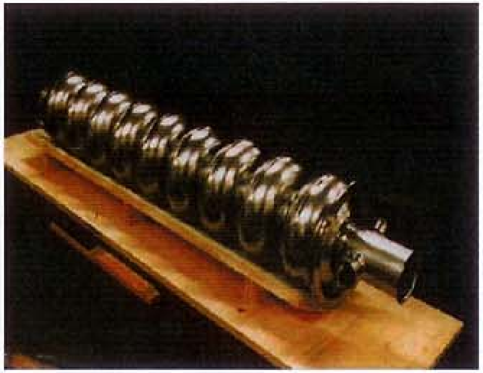
X-ray analysis with highest resolution in space and time:



Challenges:

- Low emittance, high current creation
- Emittance preservation
- Beam stability at insertion devices
- Accelerator design
- Component properties, e.g. SRF



Assembly of the injector accelerator

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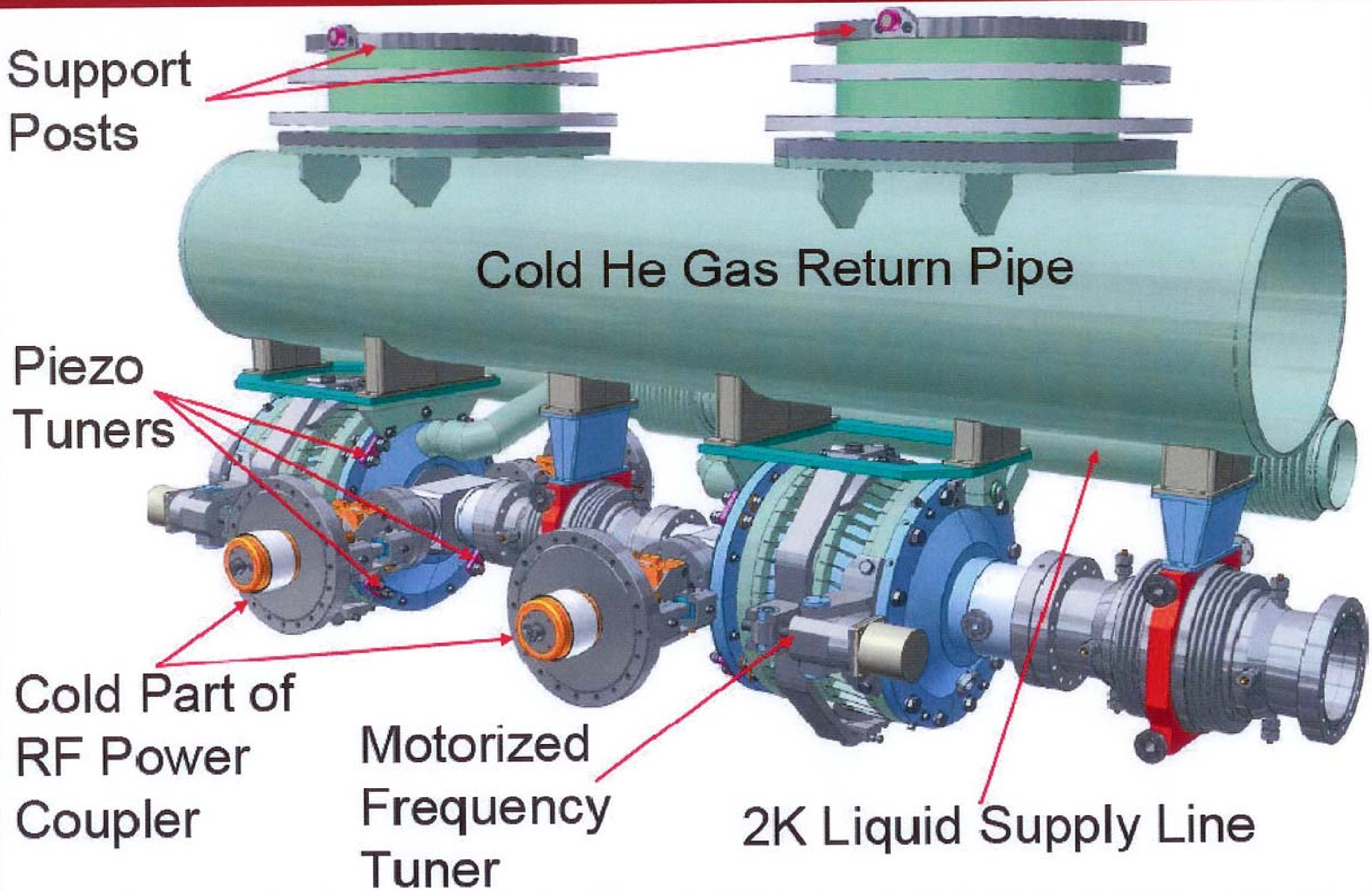
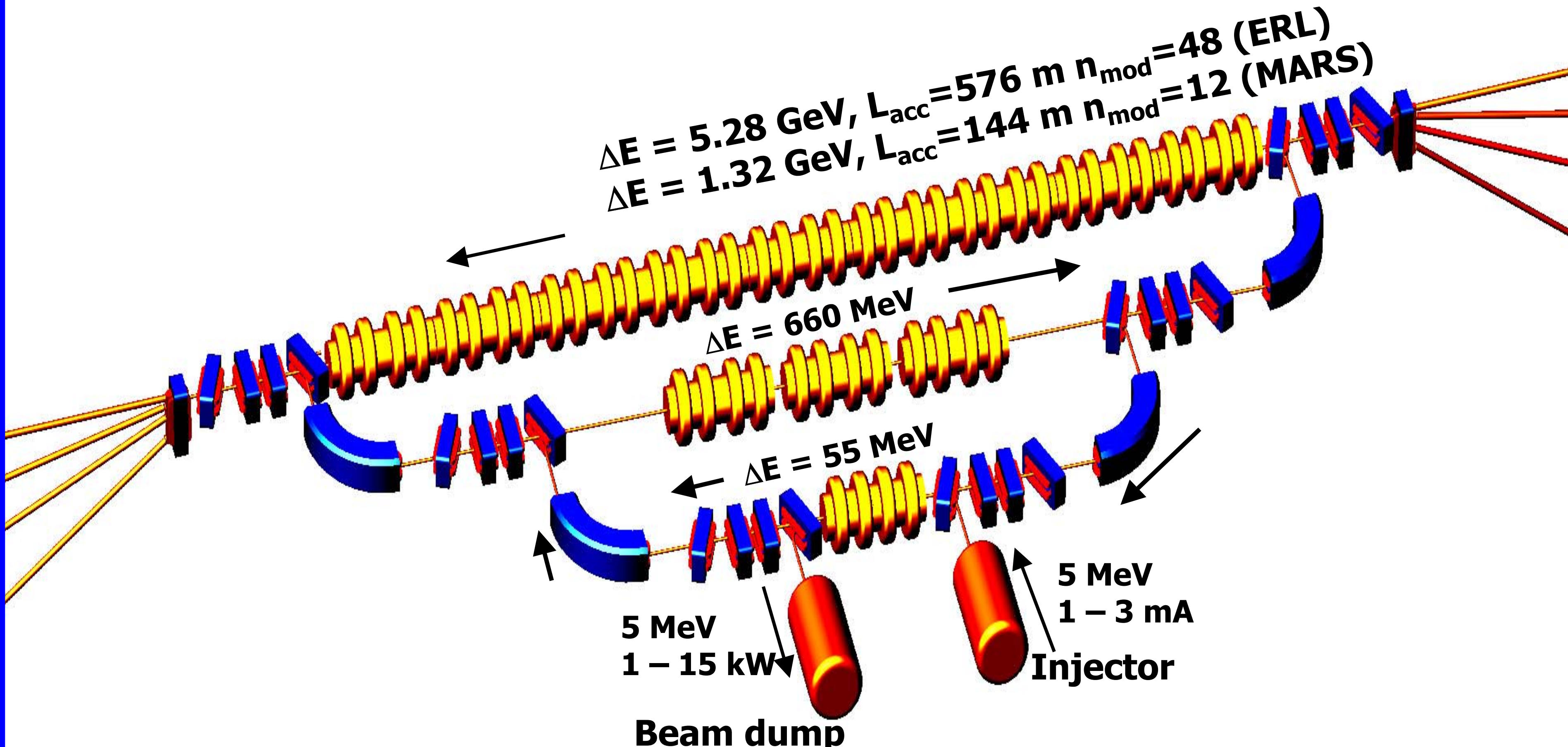


Cascade scheme of injection

First linac has 5-10 MeV energy and does not use energy recovery.

To booster linacs (55 MeV and 660 MeV energy gain) energy recovery used.



Cascade scheme of injection is provided effective and economical solution of the next problems:

- Decreasing of radiation hazard and limitation of induced radioactivity;
- Reduction of the cost of building and the cost of the RF power system for injector;
- Simplifying the problem of focusing particles of different energies, which are traveling simultaneously in the accelerating structure, because cascade scheme enables injection of electrons into all the accelerating structures with energies of no less than $E_{max}/10$ (E_{max} is the maximum energy of electrons traveling in the accelerating structure).

Superconducting linac

Superconducting electron linac would provide:

- continuous (CW) operation using different cavity on RF frequency (0.5-1.5 GHz).
- high accelerating gradient
- exceptional stability
- energy spread in electron beam better than 10^{-4}

Currently existing SC modules or modules that are presently under construction include:

- CEBAF type module developed by TJNAF
- TTF module, developed by TESLA collaboration
- Injector cryomodule presently under construction for the Cornell ERL.
- KEK type module developed in Japan.

Reliability study for 7cell cavities

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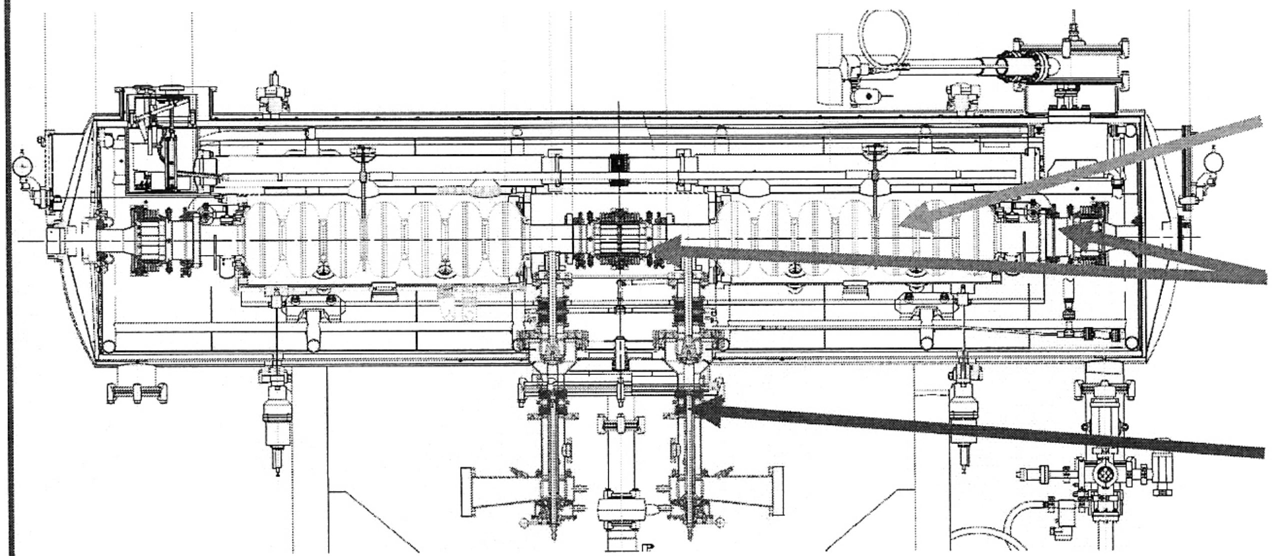

- Two 1.3 GHz 7 cell cavities
- Cornell-style cold HOM load
- Cornell-style input coupler

- Collaborative development (Daresbury, Cornell, LBNL) for an advanced high-Q_0 cavity and cryomodule system for ERLs (I=100 mA)
- Housed in a modified Stanford/Rossendorf cryomodule
- Beam test on ERL-P in 2008 / possibly at Cornell with 100mA ?

Cavities

Parameters:

1) Challenge of low dynamic loss leads to
   a) Optimized cavity shape
   b) large $Q_0 = 2x10^{10}$ / operating temperature = 1.8K

2) Challenge of low total cost and high operational stability leads to
   a) Operating voltage = 16MV/m

3) Challenge of high current leads to
   a) Number of cells = 7
   b) Beam pipe diameter to HOM absorber = 53 / 39mm

4) Challenge of low emittance growth leads to
   a) Summarizing input coupler region by a stub to limit coupler kick
   b) Cavity alignment tolerance = 1mm (needs more detailed study)

ERL cavity performance

Operation spec: 16 MV/m

But to have sufficient safety margin we design the Cryomodule for:

- max. supported gradient by cryo module: 20 MV/m at $Q = 1\cdot10^{10}$
- RF power installed for 20 MV/m, 20 Hz peak detuning = 5kW / cavity
- Min. (guaranteed) cavity performance in linac: 16 MV/m at $Q = 2\cdot10^{10}$
- Average cavity performance in linac: 18 MV/m at $Q = 2\cdot10^{10}$ with $\pm$2 MV/m spread to allow loosing 4 cryomodules.
- 5GeV requires 390 seven-cell cavities !
- $\Rightarrow$ Can use BCP cavities (Q-lope starts at $\approx$ 20 MV/m)

- This provides more than 10% safety margin

Low microphonic cavity and cryomodule design is very important task (especially for low current operation I<10 mA):

- minimize cavity vibration and coupling of external sources to cavities
- low sensitivity to He pressure changes (of 0.1 – 1 mbar)
- high mechanical vibration frequencies
- active frequency control and fast frequency tuning (piezo tuner) essential for realistic microphonics (20-30 Hz peak detuning) and $Q_L > 3x10^7$.

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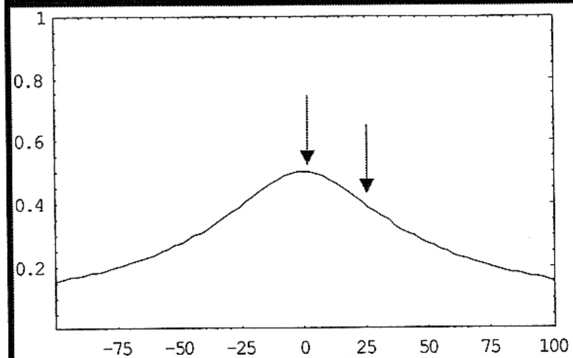
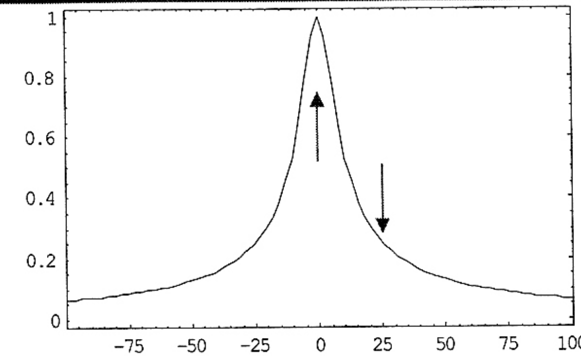
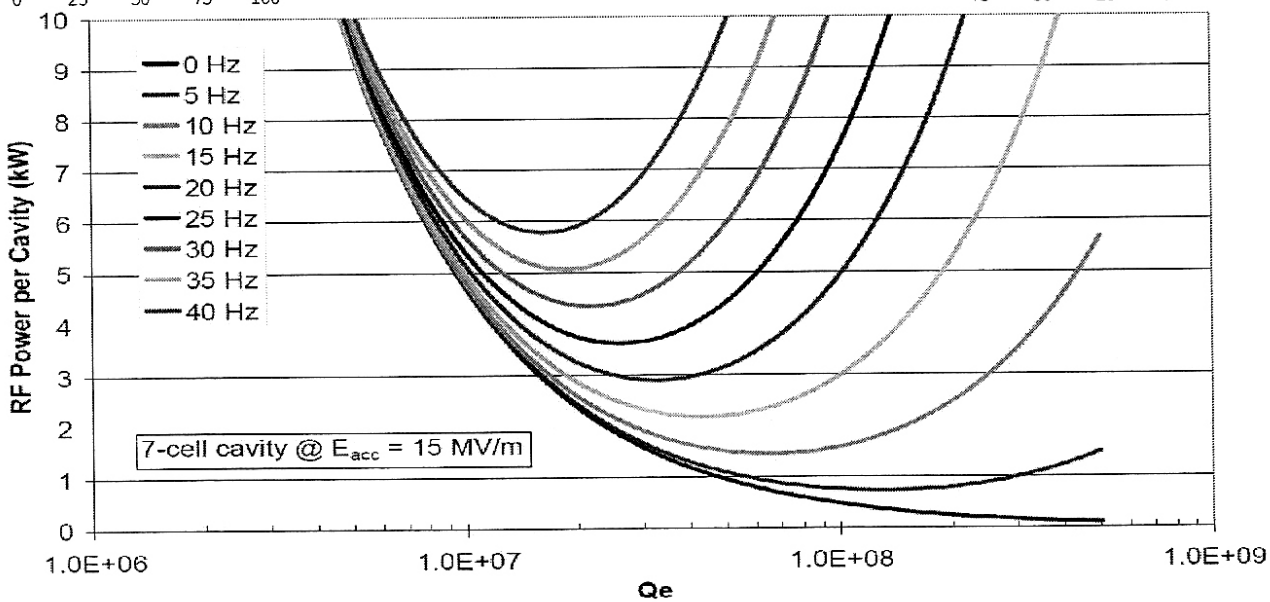
Microphonics and the optimal Q



Higher Q → less power needed

Detuning → more power needed
especially for larger Q





- **Cavity and cryostat design for low microphonics**
- **Active frequency control (fast frequency tuner)**
- **Lacking detailed knowledge, we work with 20Hz peak detuning.**

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Measured microphonics levels

Machine	σ [Hz]	6σ [Hz]	Comments
CEBAF	2.5 (average)	15 (average)	significant fluctuation between cavities
ELBE	1 (average)	6 (average)	
SNS	1 to 6	6 to 36	significant fluctuation between cavities
TJNAF FEL	0.6 to 1.3	3.6 to 7.8	center cavities more quiet
TTF	2 to 7 (pulsed)	12 to 42 (pulsed)	significant fluctuation between cavities

$$Q_{L,\mathrm{optimal}} = \frac{1}{2}\frac{f_0}{\Delta f} \qquad P_{g,\mathrm{minimal}} = \frac{V_{acc}^2}{2R/Q}\frac{\Delta f}{f_0}$$

- **Assume optimistic 10 Hz as typical detuning (< 20 Hz peak).**
- **⇨ QL=6.5·107**
- **This minimizes the typical (average) power need, not the maximum power that has to be available.**

RF Generator

Superconducting RF ("ERL 2005" Conference)

Superconducting RF technology was developed by Cornell University, KEK, CERN, Jefferson Lab, DESY.

Parameters of TESLA cryomodule:

- Length of cryostat — L= 12 m
- Gradient — 15 MV/m
- Energy gain — ΔE = 110 MeV

Cost of cryomodule:

- Accelerator structure, Cryostat, RF generator, Cryogenic equipment 5-9 M$
- AC power 0.6-0.9 MW per cryomodule

We will use for estimation the superconducting TESLA module (L = 12 m, f_{RF} = 1.3 GHz, ΔE = 110 MeV as the accelerating gradient in cells of 15 MeV/m), the total length of a structure L_{acc} is about ~ 150 m for n_t = 4 and about 500 m for n_t = 1 (n_t is the number of turns).

Therefore, let us choose the section lengths to be L_{sect} = 200 m for n_t = 4 and L_{sect} = 550 m for n_t = 1. The arcs radii should be of R>100 m to prevent the beam emittance degradation by the quantum fluctuations of synchrotron radiation.

Project "MARS" as example

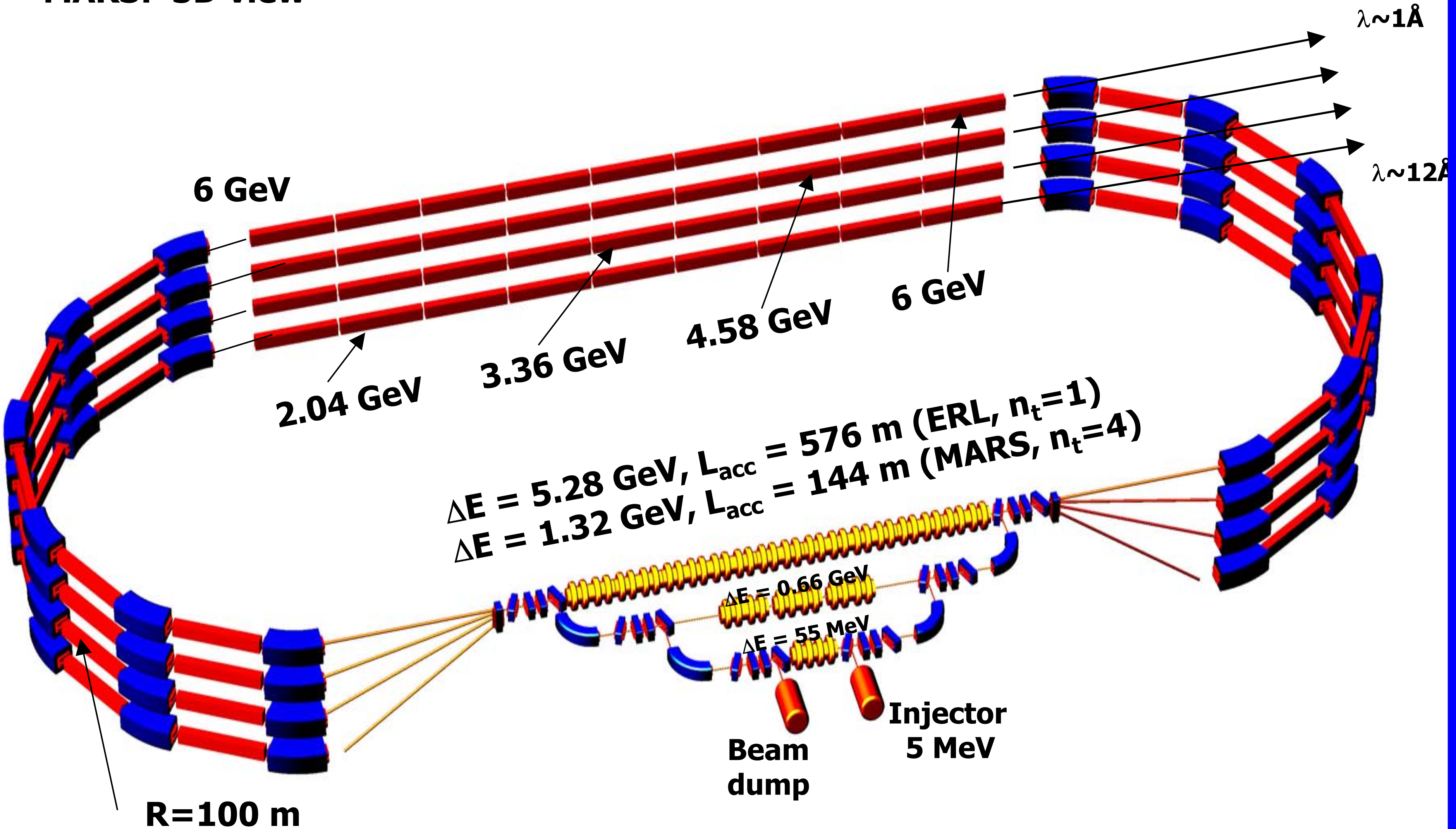
We will use for estimation the superconducting TESLA module ($L = 12$ m, $f_{RF} = 1.3$ GHz, $\Delta E = 110$ MeV as the accelerating gradient in cells of 15 MeV/m), the total length of a structure L_{acc} is 144 m for $n_t = 4$ and 576 m for $n_t = 1$ (n_t is the number of turns).

The next figure presents the layout of the four-turn recirculating accelerator-recuperator MARS (Multi-turn Accelerator-Recuperator Source), which is at present being developed by our team. In MARS, the electrons obtained in the injector with an energy of ~ 5 MeV are then accelerated in an additional two-cascade injector, after which they pass through the main accelerating high-frequency structure four times, thus increasing their energy up to 6 GeV.

After acceleration, the electrons again travel in the same direction through the same high-frequency structures, but in a deceleration phase, decrease their energy to 5 MeV, and then land in the dump. In the MARS, electrons undergoing acceleration and deceleration travel simultaneously along four tracks.

Basic overall dimensions of ERL and MARS (E_{max} = 6 GeV)

MARS: 3D view



- The users of synchrotron radiation will perceive the radiation from the MARS undulators like radiation from a storage ring, with the only difference that each time new ('fresh') electrons are used with a small emittance ε_{min} ~ 10^{-2} nm rad and energy spread σ_E/E ~ 10^{-4}.

- For MARS project, four undulators 150 – 200 m long (N ~ 10^4) are placed in the four tracks, as well as several dozen undulators 5 – 20 m long (N = 10^2 – 10^3) into the arcs.

The undulator

- Undulator gap will be limited mainly by radiation losses in the walls of vacuum chamber; *g* = 0.5 cm seems reasonable.
- Choosing the undulator parameter K ~ 1 for *g* = 0.5 m on can obtain from Hallbach equation λ_u – 1.5 cm.

Maximum length of undulator is determined by the increase of energy spread in undulator due to quantum fluctuation of undulator radiation.

- Increasing of energy spread in electron beam due to radiation from undulator:

$$\left(\frac{\sigma_E}{E}\right)^2 = N_{ph.und}\frac{\varepsilon_{und}}{E^2}, \qquad N_{ph.und} = \frac{\Delta E_{und}}{\varepsilon_{und}}$$

Radiation energy loss in undulator: $\Delta E_{und} \sim \dfrac{E^2 K^2 L_u}{\lambda_u^2}$

Energy of photons from undulator: $\varepsilon_{und} \sim \dfrac{E^2}{\lambda_u \left(1+\dfrac{K^2}{2}\right)}$

Number of emitting photons from undulator:

$$N_{ph.und} \sim \frac{\Delta E_{und}}{\varepsilon_{und}} \sim \frac{K^2\left(1+\dfrac{K^2}{2}\right)L_u}{\lambda_u}$$

Energy spread: $\left(\dfrac{\sigma_E}{E}\right)^2 \sim \dfrac{E^2 \cdot L_u}{\lambda_u^3} \dfrac{K^2}{1+\dfrac{K^2}{2}}$

$$\frac{\sigma_E^2}{E^2} \approx 7\cdot 10^{-13} \frac{E^2[GeV]\ K^2\ L_u\ [m]}{\lambda_u^3[cm]\ \ \left(1+\dfrac{K^2}{2}\right)}$$

- This energy spread must be less, than acceptable energy spread $\left(\frac{\sigma_E}{E}\right)_{\max}$, therefore length of undulator must be smaller

$$L_u[m] < \frac{\left(\frac{\sigma_E}{E}\right)^2_{\max} \lambda_u^3[cm]}{E^2[GeV]} \qquad \frac{1+\frac{K^2}{2}}{K^2}$$

$$For \quad E = 6\,GeV; \left(\frac{\sigma_E}{E}\right)_{\max} = 3\cdot 10^{-5} \qquad \lambda_u = 1.5\,cm; K = 1 \quad L_u < 180m$$

- Undulator must be segmented in sections of L ~ 5 m with 1 m straight section in between. Each straight section contains 3-pole phase adjuster, focusing quadrupoles, steering magnets and beam position monitor.

- Quadrupoles between the undulator sections are necessary for providing the equal and almost constant (inside undulators) beta functions $\beta_x \sim \beta_z$

- For tuning of the photon energy superconducting technology or combination of electromagnet and permanent magnet technology (equipotential-bus electromagnetic undulator) may be more appropriate for very long undulator.

- Photon beam monitors and monochromator for spectral measurements have to be install on beamline for feedback to the steering coils and phase adjusters.

Radiation production

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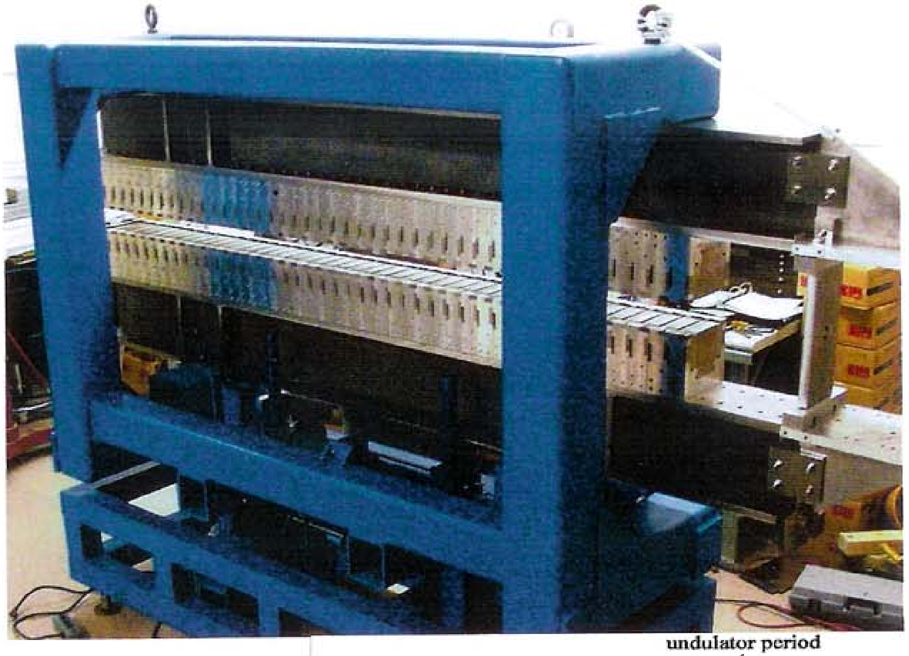
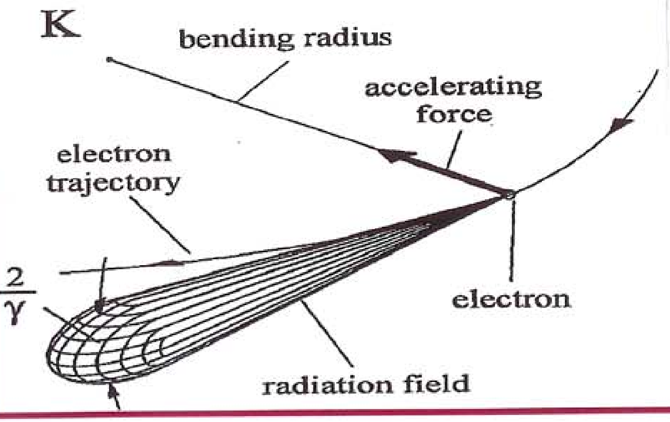
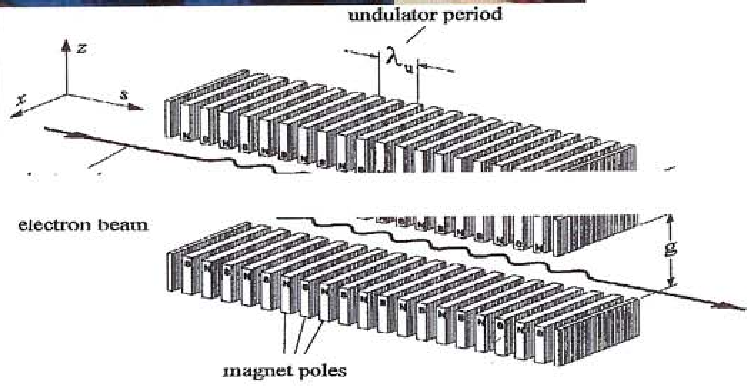




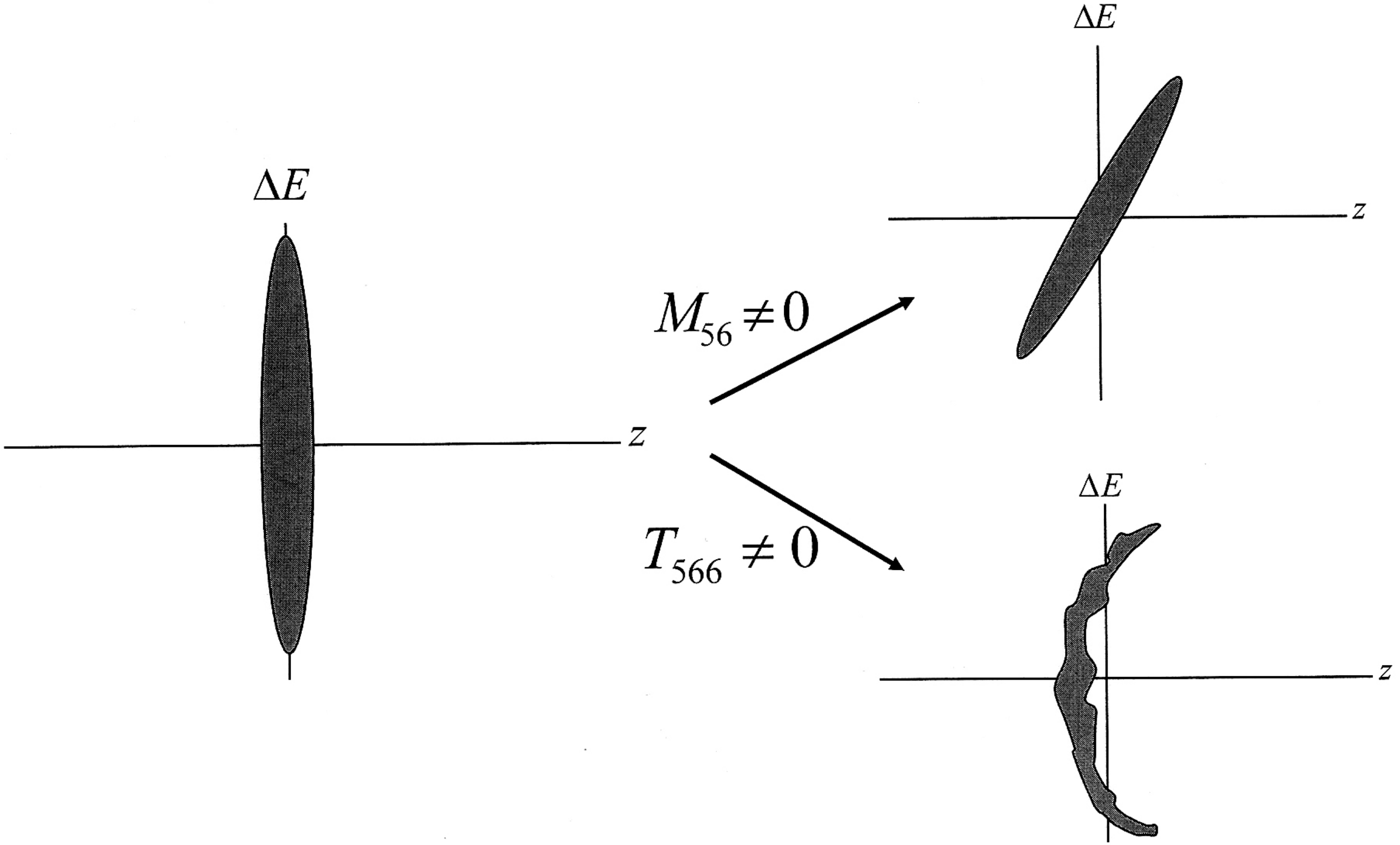


Magnetic lattice

Minimization of growing transverse and longitudinal emittance in injector during capture compression from 10 ps up to 2 ps. (bunch length 2 ps is need for limiting increasing the energy spread of electron in process of acceleration of electron bunch from zero energy to 5-10 MeV at f_{RF}=1.3 GHz).

Injector-to-linac system and linac-to-linac system must be achromatic and isochronous for minimization of pass-to-pass tolerance for RF phase or path length <100 μm; using sextupoles to get T_{566} in bending arc to compensate any curvature induced term.

Effects of Nonlinearities



Due to using small bunch charge (Q=8 pC) and relatively long bunch length (2 ps) we hope do not observe effects of growth of transverse and longitudinal emittance and beam loss due to:

- coherent synchrotron radiation.
- intrabeam scattering (Touschek)
- disturbance from ions.

Magnetic lattice

- The quantum fluctuation induced growth of energy spread of electron beam in 180^0 arcs

$$\left(\delta E/E\right)^2_{arc} \sim N_{ph.arc} \cdot \frac{\varepsilon_c^2}{E^2}; \quad N_{ph.arc} \sim \frac{1}{137}\frac{E}{m_0 c^2}; \ \varepsilon_c \sim \frac{E^3}{R}$$

$$\left(\delta E/E\right)^2_{arc} \sim \frac{E^5}{R^2}\left(\frac{\sigma_E^2}{E^2}\right)_{arc} = 2.6\cdot 10^{-10}\,\frac{E^5\left[GeV\right]}{\rho\left[M\right]}\frac{\Theta}{2\pi}$$

- This energy spread must be less, than acceptable energy spread $\left(\frac{\sigma_E}{E}\right)_{\max}$, therefore bending radius ρ in magnets must be large

$$\rho\left[m\right] > \left(\frac{2.6 \cdot 10^{-10} \quad E^5\left[GeV\right]}{\left(\frac{\sigma_E}{E}\right)^2_{\max}} \frac{\Theta}{2\pi}\right)^{1/2}$$

- For E = 6 GeV: $\left(\frac{\sigma_E}{E}\right) \sim 3 \cdot 10^{-5} \quad \rho\left[m\right] > 33m$

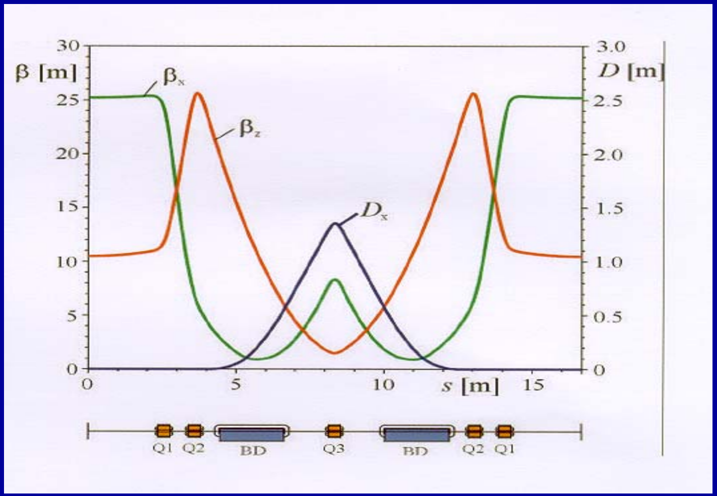
- The magnetic system of arcs consist from small emittance achromat cell, typical for structure of low emittance light sources (DBA, TBA…). Examples of such structures are shown in the next slide.

- Quadrupole magnets arrangement in the accelerating sections provides focusing for beams of all energies from the injection energy to the maximum energy.

- The behavior of the lattice functions has bilateral symmetry to get similar focusing for both accelerating and decelerating beams.

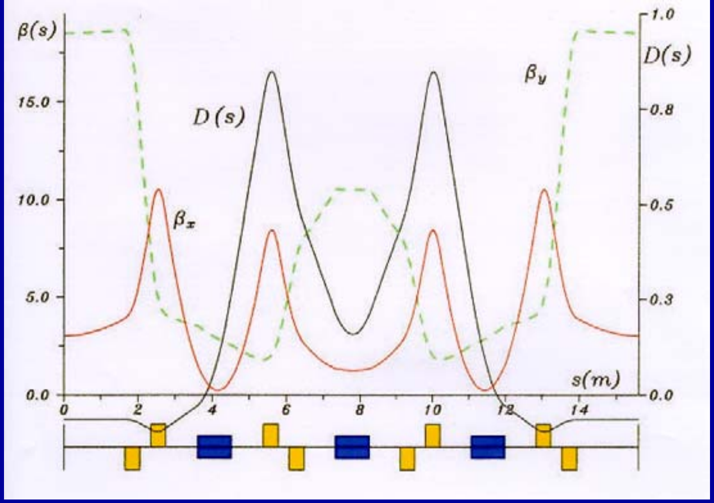
SMALL EMITTANCE LATTICES: ACHROMAT STRUCTURES

$$\varepsilon_x = \frac{c_q \gamma^2}{J_x} \cdot K \cdot \theta_B^3$$



DBA / Double Bend Achromat

$$K = \frac{1}{4\sqrt{15}} \approx 6{,}5 . 10^{-2}$$



TBA / Triple Bend Achromat

$$K = \frac{7}{36\sqrt{15}} \approx 5 . 10^{-2}$$

- An arrangement of the matching quadrupoles both adjust the lattice functions between the RF sections and arc and provides optimal lattice functions in rather strong separating magnet (that separate the beams with different energies). The emittance growth in this magnet is very sensitive to the lattice functions behavior.

Taking into account that the accelerators-recuperators are single-flight system, the gap for bending magnets can be taken to be g=1cm; the incicle diameter in quadrupoles is Φ_q=1.5 cm, in sextupoles - Φ_s=2 cm thereby reducing substantially the overall dimensions, weight, power supply and the cost of the magnetic system.

With an account for the fact that in the single-flight system it is enough to have a vacuum of P ~ $10^{-7} \div 10^{-8}$ tor, the vacuum system seems to be rather simple.

Summary

Accelerator scheme and the most of the key systems, discussed here, were already tested at different facilities (Budker INP, CEBAF, MAMI, Cornell Univ., KEK).

Thank you for your attention

BrightLight: Palletizable 100 kW FEL Driver

- ERL driven 1-1.6 mm 100 kW FEL
- Considerable operational flexibility, but relatively compact
- Based on JLab 750 MHz "1 Amp Cryomodule" (in prototype)
- Supports either cavity oscillator (illustrated) or amplifier FEL

I	100 mA (75 MHz X 1.4 nC or 750 MHz X 135 pC)
$E_{inj/full/dump}$	5, 100, 4 MeV
f_{RF}	748.5 MHz
h_{FEL}	1%
$P_{e^-\ beam/FEL}$	10 MW/100 kW

Courtesy: D. Douglas