HZB Helmholtz Zentrum Berlin

Radiation loss & CSR at BERLinPro

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Design parameters and operation modes of BERLinPro

MAIN PARAMETRS

Average current up to	100 mA
Max. beam energy	50 MeV
Nominal bunch charge	77 pC
Max. repetition rate	1.3 GHz

SRF GUN

Beam energy up to	2 MeV
Thermal emittance	0.3 mm mrad
Energy spread, rms	10^{-2}
Bunch length, rms	5 ps
Peak current	7 A

INJECTOR

Beam energy	7 MeV
Energy spread, rms	10^{-2}
R_{56}	0.11 m
Bunch length, rms	2 ps
Peak current	20 A

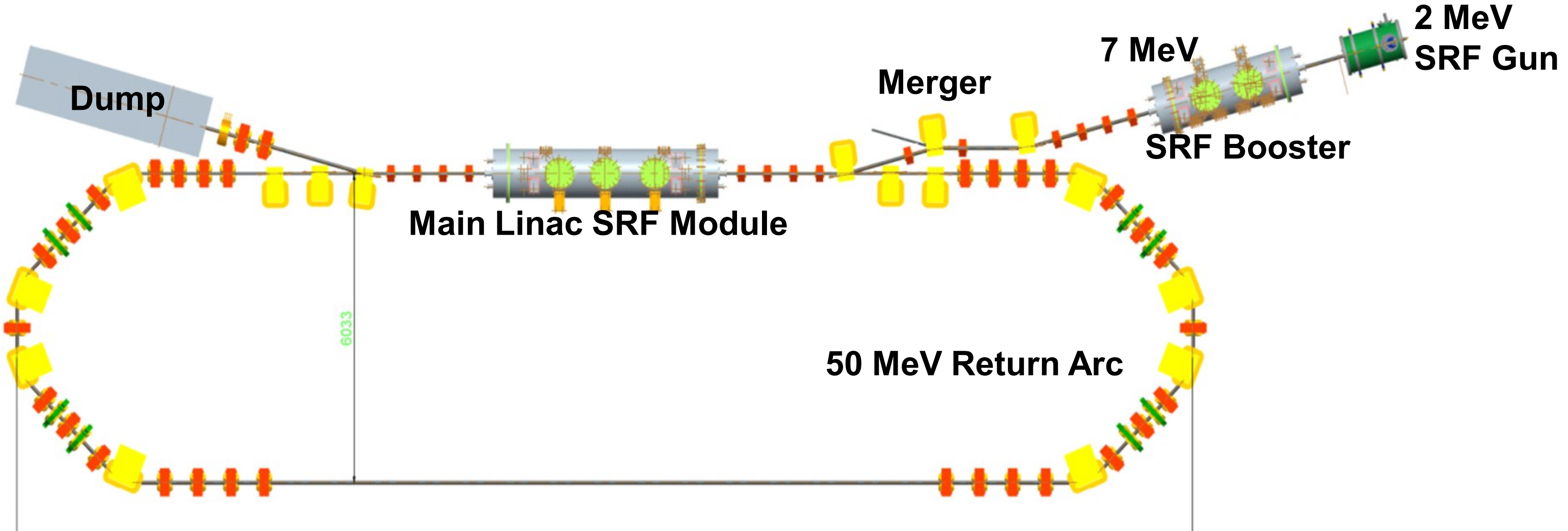
RECIRCULATOR

Low Emittance Mode

Bunch length, rms:	2 ps
Normalized emittance	1 mm mrad

Short Bunch Mode

Bunch length, rms:	140 fs



Motivation

The main effects of SCR:

- Beam longitudinal and transversal emittance degradation
- High power
- Absorbtion in cryomodule

The incoherent synchrotron radiation in BERLinPro is low due to the low beam energy.

$$P_{ISR}[W] = 10^{9} \cdot 8.846 \cdot 10^{-5}[m \cdot GeV^{-3}] \cdot \frac{E[GeV]^{3}}{R[m]} I[A] \approx 1.5W$$

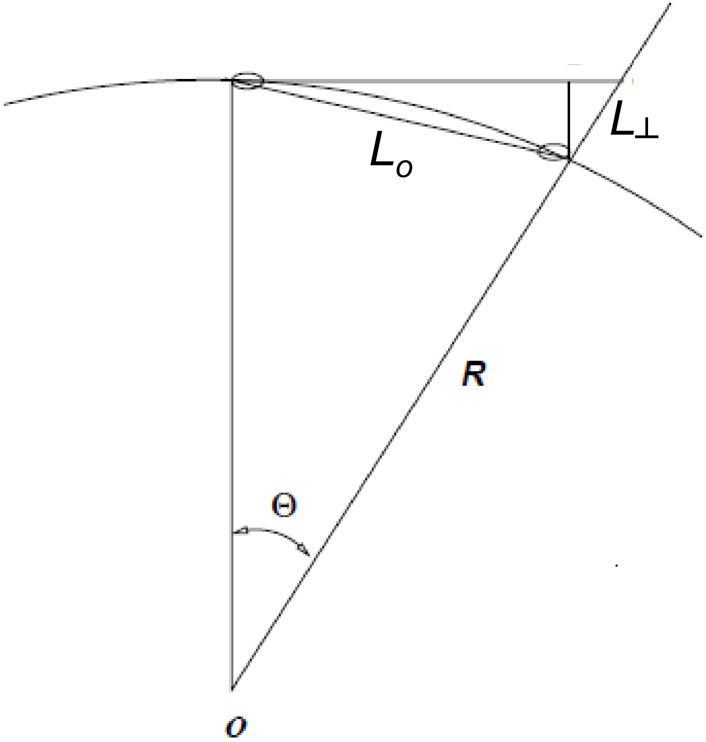
$$\varepsilon_{ISR}[eV] \approx 2.218 \cdot 10^{3} \cdot \frac{E[GeV]^{3}}{R[m]} \approx 0.36eV$$

Geometrical parameters of CSR, shielding & 1D approximation

Consider a bunch with a length σ_z, transversal size $\sigma_\perp$ moving on bending radius *R* inside a vacuum chamber with a size D.

Geometrical parameters of CSR defined by Ya.S. Derbenev et al., 1996

Overtaking distance is the distance which the beam passes, until radiation from the tail overtakes the head: $L_o = 2\sqrt[3]{3\sigma_z R^2}$



Overtaking angle: $\theta = \frac{L_o}{R} = 2\sqrt[3]{3\sigma_z / R}$

Characteristic transverse distance is the deviation of tangent from the path of the beam at the overtaking distance :

$$L_\perp = \frac{\theta L_o}{2} = 2\sqrt[3]{9\sigma_z^2 R}$$

Geometrical parameters of CSR, shielding & 1D approximation

Shielding important if $D < L_\perp$

1D model valid if $\sigma_\perp < L_\perp$

In accelerator allways $\sigma_\perp \ll D$

So there are 3 regime of CSR in accelerator:

1) $L_\perp < \sigma_\perp \ll D$ 3D CSR without shielding
2) $\sigma_\perp < L_\perp < D$ 1D CSR without shielding
3) $\sigma_\perp \ll D < L_\perp$ 1D CSR with shielding

In BERLinPro R=0.76 m, D=40 mm, $\sigma_\perp \leq 1$ mm

For LEM σ_z=0.6 mm $L_\perp = 2\sqrt[3]{9 \cdot 0.76m \cdot (0.6mm)^2} \approx 25mm$

For SBM σ_z=0.045 mm $L_\perp = 2\sqrt[3]{9 \cdot 0.76m \cdot (0.03mm)^2} \approx 5mm$

For BERLinPro in both mode (LEM & SBM) we are in 2nd SCR regime:
1D CSR without shielding.

CSR power

Let's calculate SCR power for LEM. Longitudinal beam distribution does not change in accelerator, and we can use the analytical formula. For rectangle bunch and isomagnetics ring from N magnets we have (E.L.Saldin, et al. 1997).

$$P_{CSR} = \frac{f_0 Q^2 R^{1/3}}{4\sqrt[3]{2}\varepsilon_0 \sigma_z^{4/3}} \left\{1 + N \frac{2\sqrt[3]{2}}{3\pi\sqrt{3}} \frac{\sigma_z^{1/3}}{R^{1/3}} \left[\ln\left(\frac{\sqrt{12}\sigma_z \gamma^3}{R}\right) - 4\right]\right\}, \quad \frac{1}{\gamma} \ll \left(\frac{48\sqrt{3}\sigma_z}{R}\right)^{1/3} \le \frac{2\pi}{N}.$$

Q is bunch charge, f_0 is repetition frequency, ε_0 is electrical permeability of vacuum.

$$P_{CSR} = \frac{1.3GHz(77pC)^2(0.6m)^{1/3}}{4\sqrt[3]{2}\cdot 8.8510^{-12}Fm^{-1}(0.6mm)^{4/3}} \left\{1 + 8\frac{2\sqrt[3]{2}}{3\pi\sqrt{3}} \frac{(0.6mm)^{1/3}}{(0.6m)^{1/3}} \left[\ln\left(\frac{\sqrt{12}\cdot 0.6mm \cdot 100^3}{0.6m}\right) - 4\right]\right\} \approx 4.4kW$$

CSRtrack simulation gives us about 5 kW for LEM. It seams that difference came from differences in longitudinal profile.

For SBM longitudinal beam distribution change in accelerator, and calculation has made only by CSRtrack. Result is 25 kW.

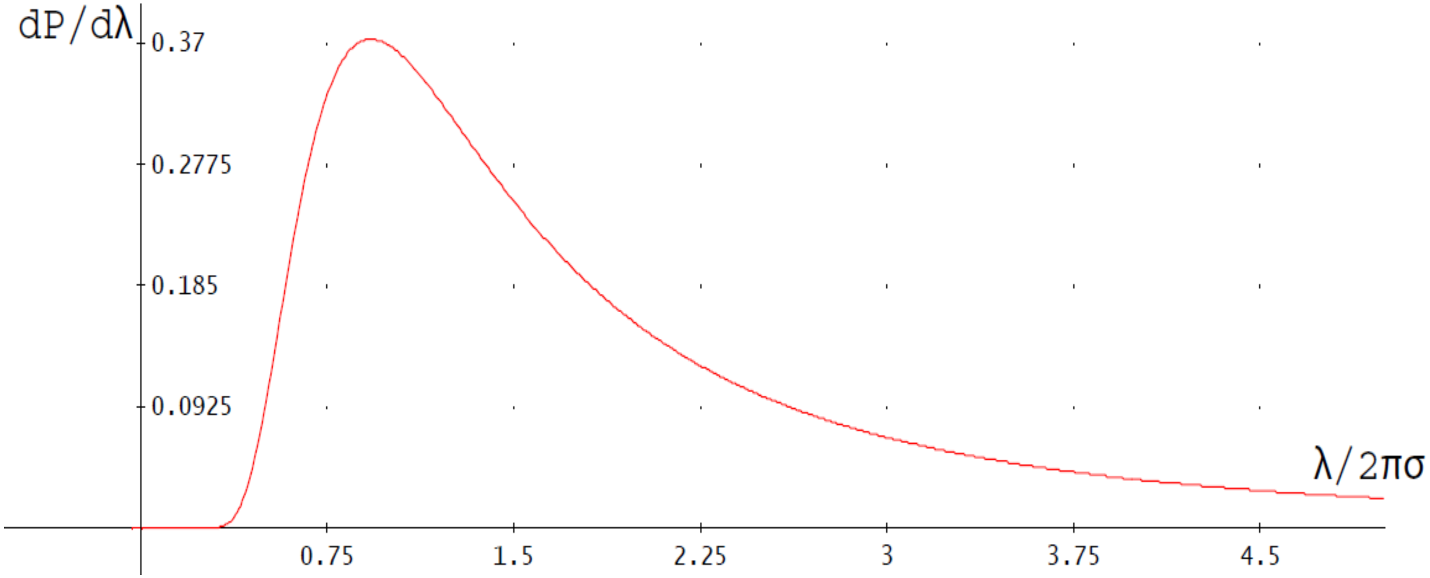
CSR spectrum distribution

For longitudinal gaussian distribution

$$\frac{dP_{CSR}(\lambda)}{d\lambda} = \frac{dP_{ISR}(\lambda)}{d\lambda} N_e \exp(-\frac{4\pi^2 {\sigma_z}^2}{\lambda^2})$$

in H. Wiedemann

$$\frac{dP_{CSR}(\lambda)}{d\lambda} \approx 1.5 \frac{P_{CSR}}{2\pi\sigma} \cdot \left(\frac{2\pi\sigma_z}{\lambda}\right)^{7/3} \exp(-\frac{4\pi^2 {\sigma_z}^2}{\lambda^2}).$$



So the average wave length of CSR $\lambda_{csr} \approx 2\pi\sigma_z$.

In LEM $\lambda_{csr} \approx 3.75$ mm, and average frequency of CSR $f_{csr} \approx c/\lambda_{csr} \approx c/(2\pi\sigma) \approx 80 \cdot$GHz

In SBM $\lambda_{csr} \approx 0.2$ mm, and average frequency of CSR $f_{csr} \approx c/\lambda_{csr} \approx c/(2\pi\sigma) \approx 1.6 \cdot$THz

CSR absorption in cryomodule & vacuum chamber

Consider BERLinPro vacuum chamber and cryomodule like one cavity, because CSR is experiencing multiple reflections.

Power absorption in the wall of this cavity is

$$P = \frac{1}{2}\int R\left|H\right|^{2} ds$$

where *R* is real part of surface impedance.

In LEM f_{csr}=80·GHz the surface resistance of superconductor R_s=0.5·mΩ.

The surface resistance of normal conductor (Al)

$$R_n = \sqrt{\frac{\omega\mu_0}{2\sigma}} \approx \sqrt{\frac{2\pi 80GHz\cdot 4\pi 10^{-7}\,Hm^{-1}}{2\cdot 3.8\cdot 10^{7}\,\Omega^{-1}m^{-1}}} \approx 91m\Omega$$

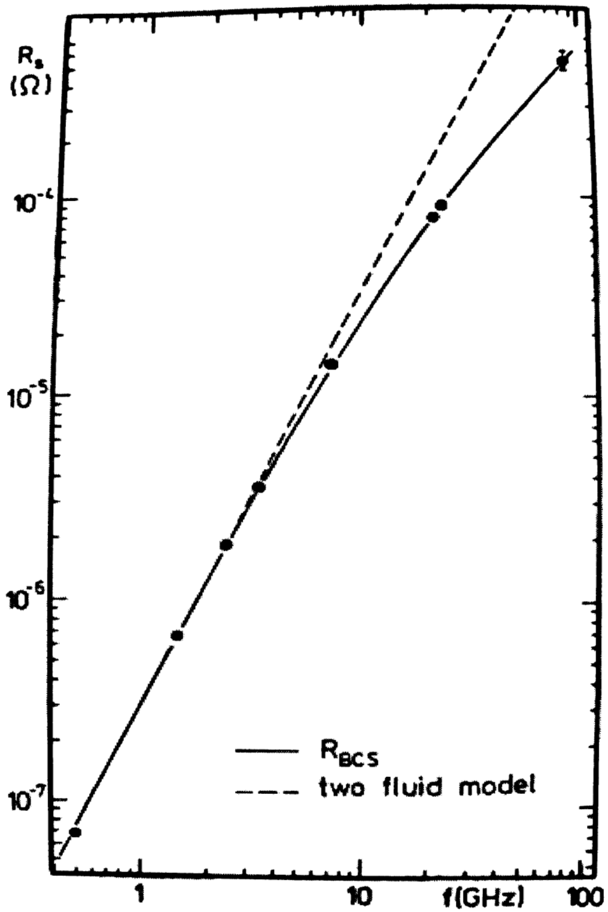
Let’s estimate the power which is absorbed in cryomodule in LEM

$$P_{crio} \approx P_{csr}\frac{R_s\frac{1}{2}\int\left|H\right|^{2}ds}{R_n\frac{1}{2}\int\left|H\right|^{2}ds + R_s\frac{1}{2}\int\left|H\right|^{2}ds} \approx P_{csr}\frac{R_s}{R_n}\frac{S_{crio}}{S_{acc}} \approx P_{csr}\frac{R_s}{R_n}\frac{L_{crio}}{L_{acc}} \approx 5kW\frac{0.5m\Omega}{91m\Omega}\frac{6m}{30m} \approx 5W$$

CSR absorption in cryomodule & vacuum chamber for Short Bunch Mode

There is no measurements of the surface impedance at 1.6 THz, so the results were extrapolated to THz range using the known data*

$$R_s \propto f^{1.25}$$



The surface resistance of a normal conductor

$$R_n \propto \sqrt{f}$$

Crude estimation:

$$P_{crio}(f) \approx P_{csr}\frac{R_s}{R_n}\frac{L_{crio}}{L_{acc}} \approx P_{crio}(80GHz)\cdot\frac{P_{csr}(f)}{P_{csr}(80GHz)}\left(\frac{f}{80GHz}\right)^{0.75}$$

In SBM $P_{crio}(1.6THz) \approx 5W\cdot\frac{25kW}{5kW}(20)^{0.75} \approx 240W$

For SBM precise calculation of surface resistivity at THz frequencies with BCS model is necessary

CSR absorption in a cryomodule is one of the limitations for short bunches in ERL.

*H. Padamsee, J. Knobloch, T. Hays,
RF Superconductivity for Accelerators

CONCLUSION

CSR power in LEM in BERLinPro ≈5 kW

CSR power in SBM in BERLinPro ≈25 kW

Average frequency of CSR in LEM ≈80·GHz, in SBM ≈1.6·THz

CSR power absorption in LEM in BERLinPro cryomodule ≈5 W

High CSR power and absorption in the linac cryomodule are the limitations for high current operation of BERLinPro, especially for short bunch mode