Bias Magnetic System Update

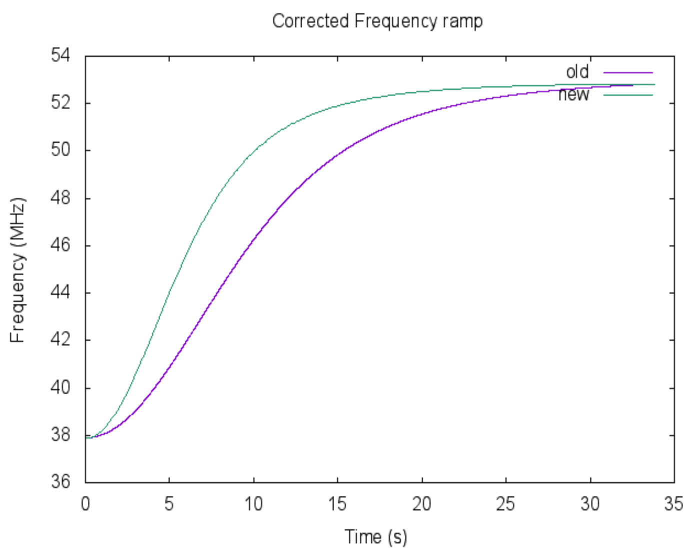
May 19 concerns:

Update is required because bias parameters changed significantly since the tetrode was introduced in the 3D model and details of the main cavity design evolved.

Concerns include:

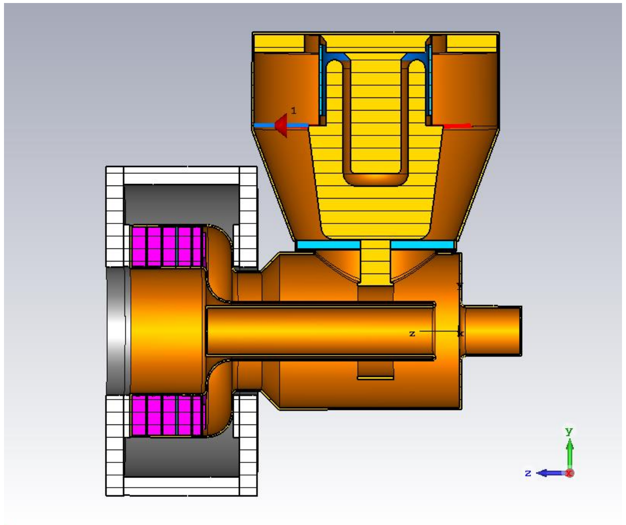
- Magnetic flux density increase (FR saturation).
- Cooling capability.

Added concerns (May 31 - thanks to Tan):
Wrong frequency ramp table was used while calculating the current ramp.

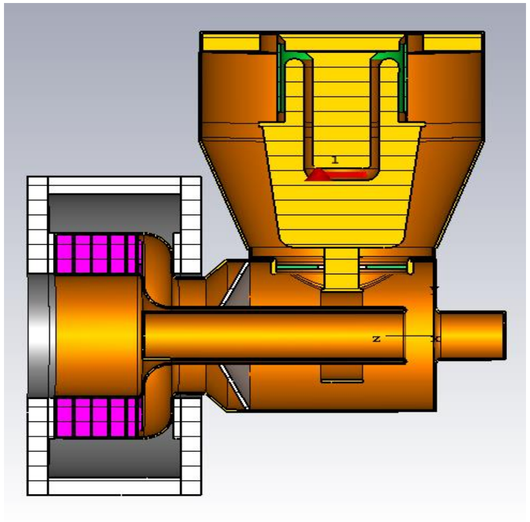


To avoid this kind of flaws, it looks like it is just the time to start using a reference design document where main input parameters are kept and updated in a centralized manner.

Cavity configuration – May 2016



In process



Results of 3D modeling (N = 30) → need further updates

I (A)	245.5	300	400	500	650	800	1000	1150	1300	1500	1700	2000
Iw (A)	7365	9000	12000	15000	19500	24000	30000	34500	39000	45000	51000	60000
f (MHz)	77.1	82.5	89.6	93.75	97.37	98.75	101.46	102.29	102.9	103.75	104.2	104.76

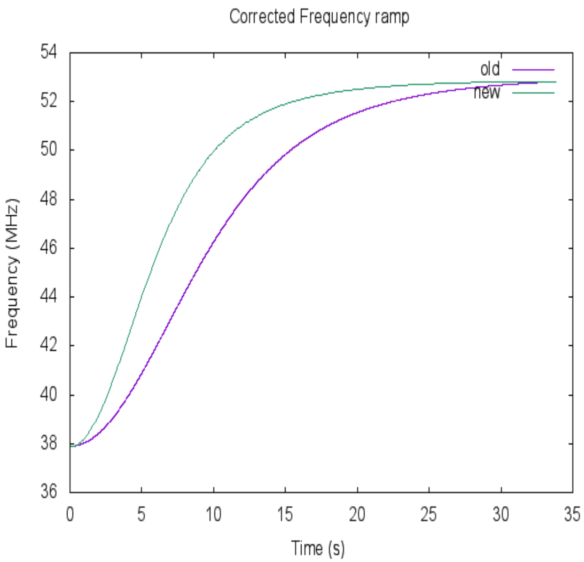
Current ramp based on the “old” frequency ramp

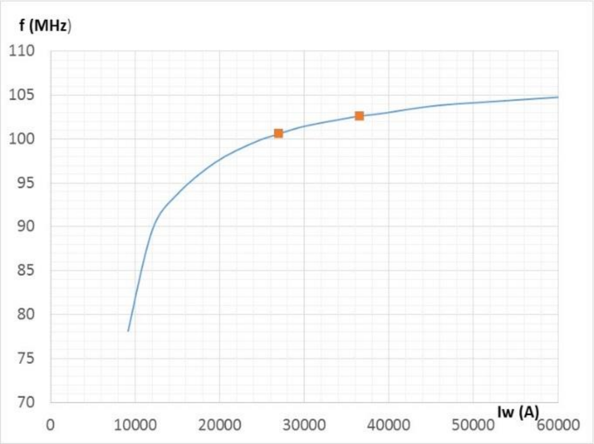
Iw (A)		9150	12000	15000	19500	24000	27000	30000	34500	36540	39000	45000	51000	60000
f (MHz)	75.794	78.128	89.6	93.75	97.37	99.6	100.6	101.46	102.29	102.62	102.9	103.75	104.2	104.76
t (ms)	0	3	8.56	10.67	13.0	14.1	16.0	17.1	18.4	19.0	19.55	21.65	23.13	25.62

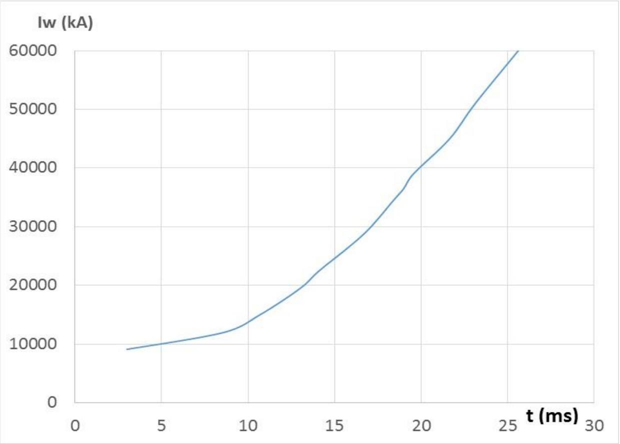
Current ramp based on the “new ≡ correct” frequency ramp

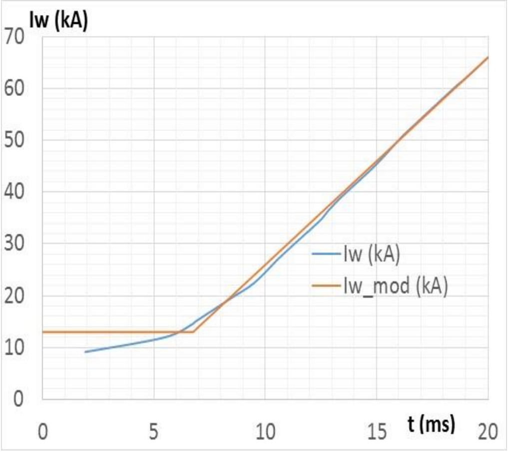
t (ms)	0	1.9	5.5	6.75	6.85	8.45	9.5	10.55	11.3	12.45	12.85	13.4	14.9	16	16.2	18.45	19	20
Iw (kA)		9.15	12	14.6	15	19.5	22.5	27	30	34.5	36.54	39	45	50.077	51	60	62	66
Iw_mod (kA	13	13	13	13	13.4	19.8	24	28.2	31.2	35.8	37.4	39.6	45.6	50	50.8	59.8	62	66

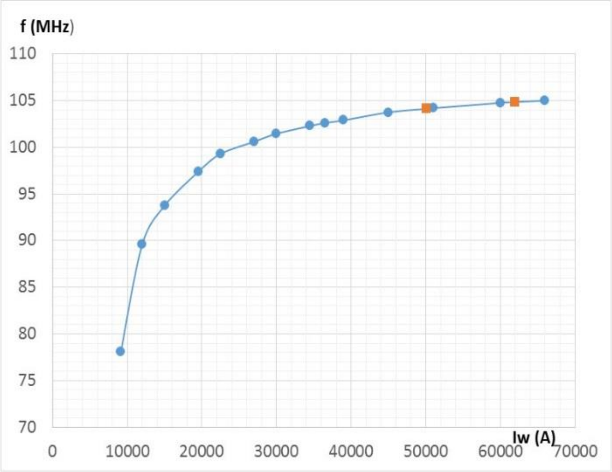
Tuning Curve

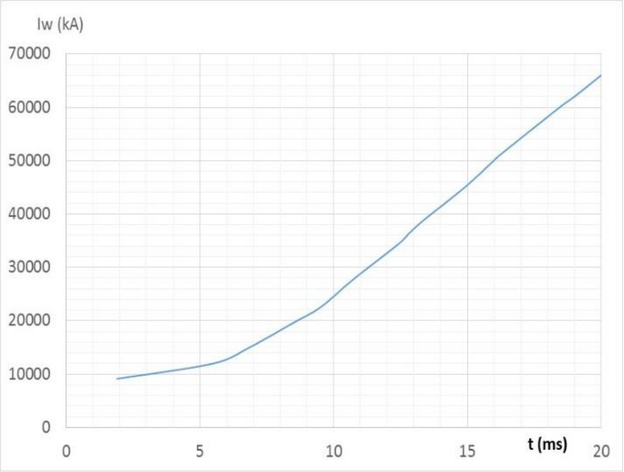












Iw = 13 kA at t < 6.75 ms

Iw (kA) = 13[kA] + 4[kA/ms]*(t[ms]-6.75) at 6.75 ms < t < 20 ms

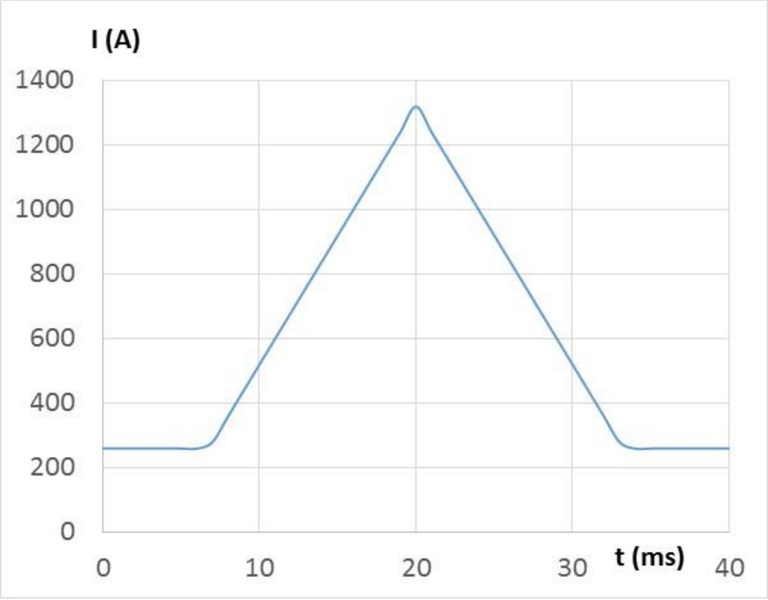
dIw/dt = 4 kA/ms or 80 A/s

Maximum current at 20 ms is 1320 A

Heat deposition in the coil

R = 0.02 Ohm

Simplified current shape (N = 50)



1. Energy per cycle at the low current:
$Q = 0.02\ \Omega * 260^2\ A^2 * (66 - 2*(20-6.75))E\text{-}3\ s = 53.4\ J$

2. Energy per cycle during the single ramp I = 260 + 80*t
Where t changes from 0 to (20-6.75) = 13.25 ms:
$Q = 0.02\ \Omega*10^{-3}*\int dt(260 + 80*t)^2 = 2E\text{-}5*\{260^2*13.25 + 2*260*80*13.25^2/2 + 80^2*13.25^3/3\} = 2E\text{-}5*\{895700 + 3651700 + 4962566.7\} = 2E\text{-}5*9.51E6 = 190\ J$
For two ramps per cycle, the energy in the coil is 380 J

3. Total energy per cycle is Q = 434 J

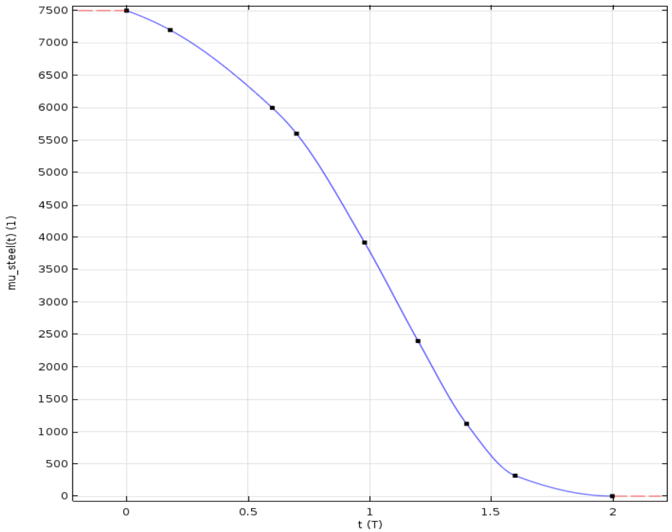
5. At 15 Hz, P = 6510 W

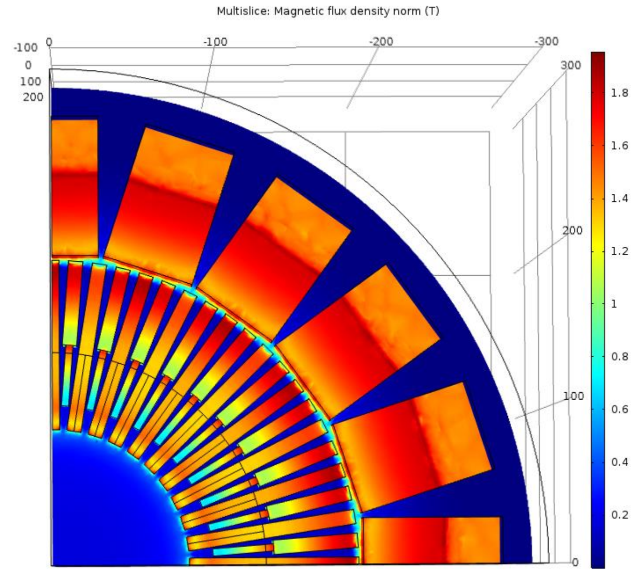
This power exceeds current capabilities of the coil →
the cooling circuit design needs to be modified

What happens if we have **four cooling circuits**?
Velocity of water with ΔT = 10°C – Q = 0.24*1750/10 = 0.042 l/s → 2.52 l/min
Water velocity v = 1.6 m/s
The lengths of the longest circuit is ~22 m
$\Delta p = 1.6^2 \cdot 22/20.7 = 2.7\ kG/cm^2$ or ~40 PSI.
This is realistic → the 6.5 kW power in the coil can be handled.

Flux return saturation at the 62.5 kA excitation current

Simplified magnetization curve for the electric Silicon Steel



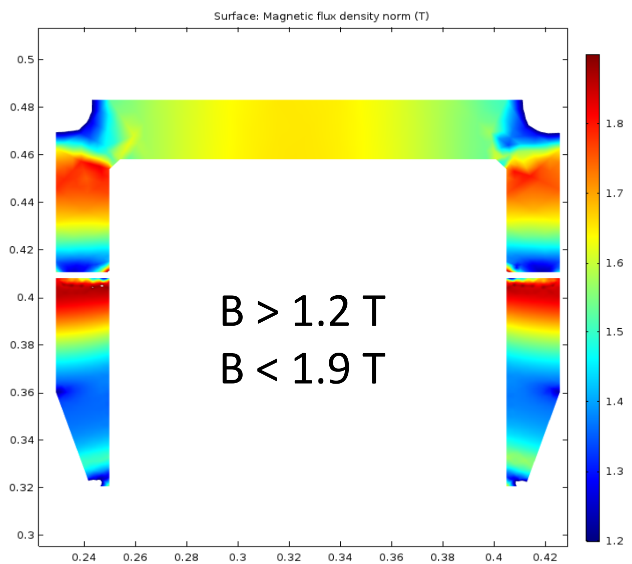


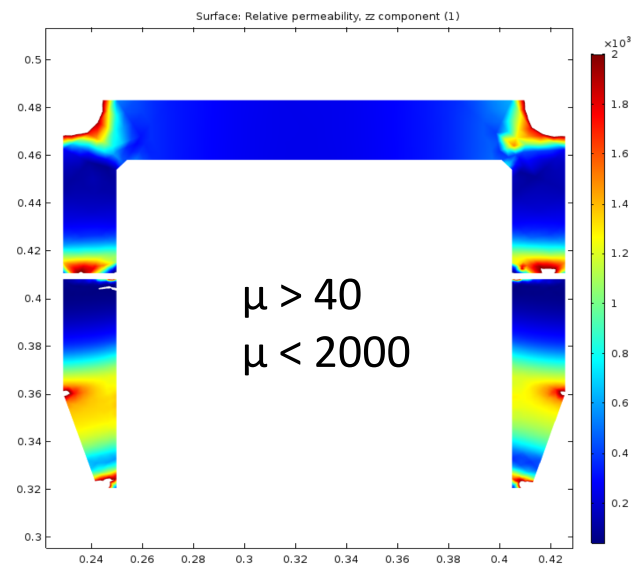
Material is in the highly saturated condition →

1. Better filling density: fill all gaps tighter.

2. Better material: use low silicon content grades of steel, e.g. M47.

3. Thicker pole parts





Power supply requirement update

With the simplified shape of the current rise, energy loss per cycle is Q ≈ 125 J
→ At 15 Hz, we have P ≈ 6500 W;
We need to update requirements for the power supply having in mind the new current shape.

Assumed parameters of the bias solenoid:
Inner radius – 185 mm
Outer radius – 235 mm
Coil length – 166 mm
Wire - 10.4 mm rectangular copper wire with 5mm diameter cooling channel (S_{Cu} = 80 mm^2).
Assumed number of turns – 50 (can be increased to 56)
Resistance – 0.019 Ohm (56 turns)
Inductance – 3.5 mH (56 turns)

Minimum current -- 150 A
Maximum current -- 1250 A
Maximum dI/dt = 80 A/ms → maximum inductive voltage V_{ind} ≈ ±280 V.
Maximum resistive voltage - V_R = 25 V
Maximum power at 1250 A - $P = I^2*R$ ≈ 31,250 W
Required Volt-Amperes – 280 V * 1250 A ≈ 350 kVA
Average power at 15 Hz is ~ 7 kW

Nearest plans

1. Clarify material choice (magnetization curve);
2. Modify Flux Return design concept for better filling factor;
3. Use the latest tuning curve from 3D modeling;
4. Iterate on the power loss calculation if needed;
5. Flux penetration modeling with the updated current ramp;
6. 3D model of flux penetration (slotted RF shell).

Bandwidth Requirement

Bandwidth requirement comes from the needed precision of following the prescribed frequency.

See J.D. Rogers, et al, An Updated Overview of the LEB RF System, SSSL-Preprint-67, March 1992.

Pulse Width Modulated (PWM) regulator. Frequency of operation 80 – 120 kHz.
Signal bandwidth ~10 kHz.
Waveform tracking accuracy within 200 ppm ($2*10^{-4}$ or 0.02%)
SSC power supply: Imax = 1500 A

SYSTEM DESCRIPTION

Each rf system for the LEB consists of the major subsystems depicted in Figure 1. The power amplifier consists of a high power tetrode and associated input and output matching sections. The 5 KW driver amplifier is a solid state unit with less than 50 ns group delay. The low-level rf subsystem includes feedback loops to maintain amplitude and phase stability of the accelerating voltage. The rf system is broadband over the 47.5 MHz to 59.8 MHz frequency range, except for the accelerating cavity, which is ferrite-tuned over the frequency range in 50 ms.

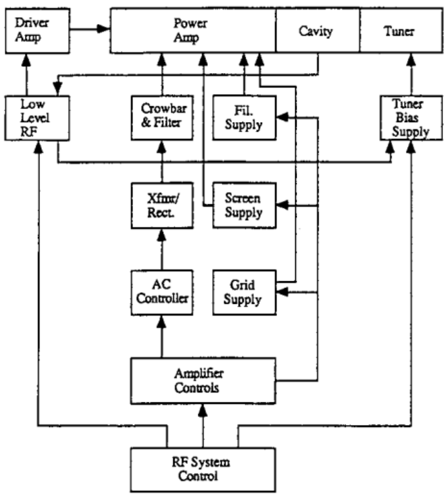


Figure 1. Rf System block diagram.

The LEB Cavity is a quarter-wave resonant structure with a ferrite-filled tuner comprising the high-current end. The rf amplifier, which provides the excitation energy to the cavity, uses a 4CW150,000E tetrode. The amplifier circuit employs tight capacitive coupling to the cavity such that the cavity becomes the tuned output circuit for the tetrode amplifier. The resonant frequency of the cavity is varied over the required frequency range by controlling the magnetic field bias applied to the ferrite. This bias determines the permeability of the ferrite and therefore controls the resonant frequency of the cavity. The tuner bias supply is controlled by a "feed-forward" signal derived from previous pulses to within 10% of the desired frequency. A feedback signal derived from the cavity is then used to closely track the desired resonance frequency.

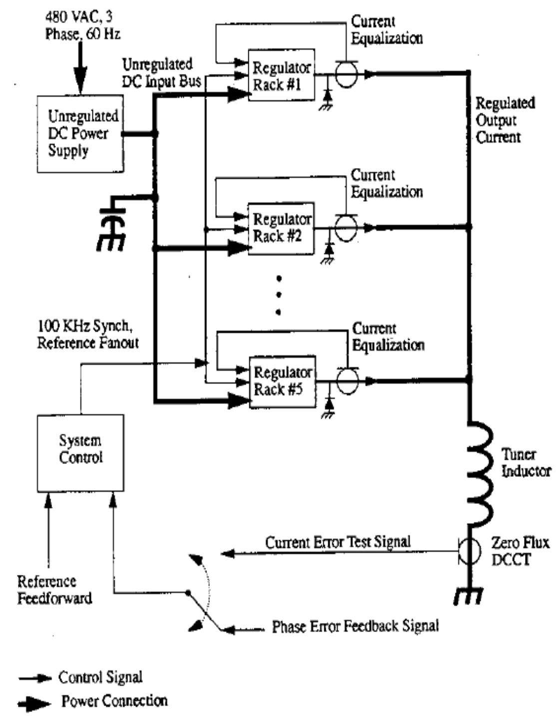


Figure 4. LEB Bias Current Regulator Block Diagram.

The power supply connected to the input of the bias regulator provides an unregulated voltage source. The DC output of the power supply is tap-selectable to yield voltages of 150 VDC, 200 VDC, 250 VDC, or 300 VDC. The power supply is capable of providing 1500 A of output current. The electrical characteristics of the power supply are listed below.