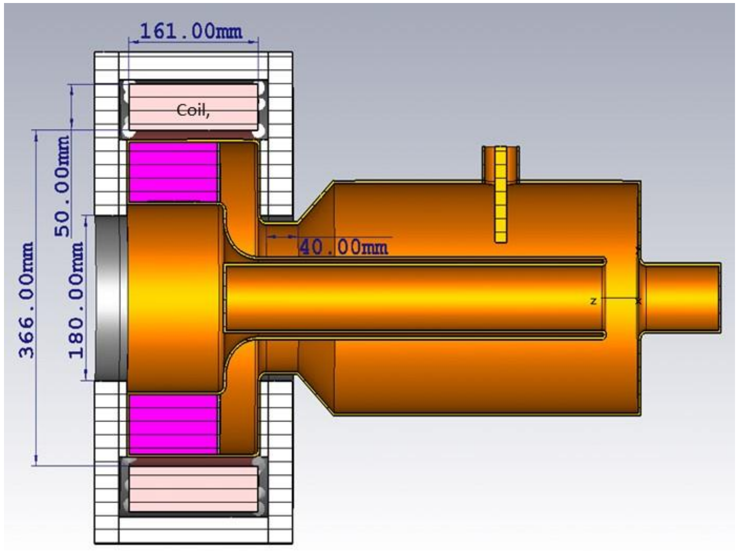
Bias Magnetic System Update

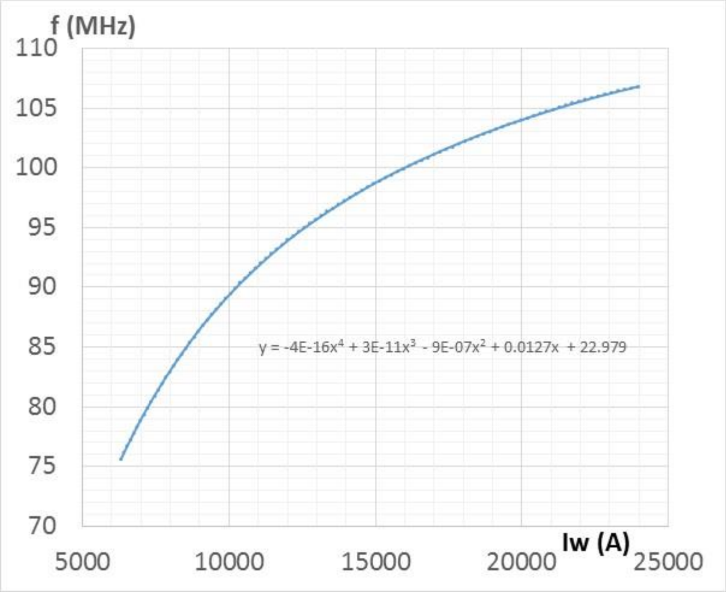
Update is required because bias parameters changed significantly since the tetrode was introduced in the 3D model and details of the main cavity design evolved.

Concerns include:

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

Cavity configuration – Sept 2015





Required frequency profile

t (ms)	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5
f (MHz)	75.73	75.90	76.41	77.24	78.34	79.68	81.20	82.85

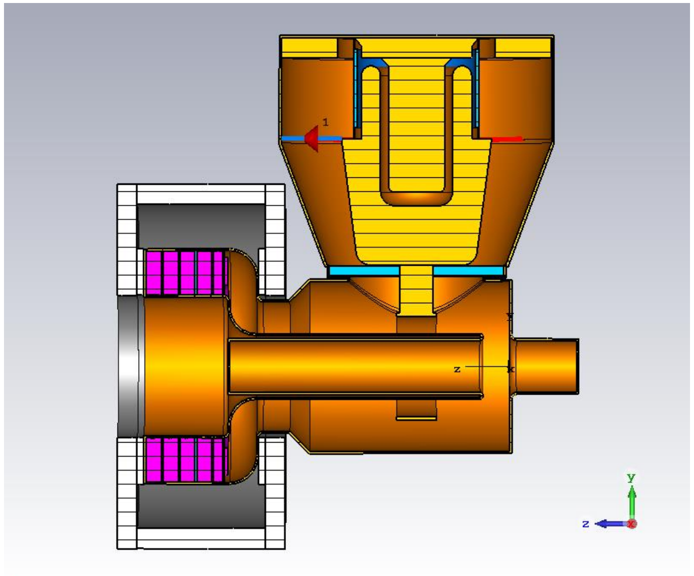
t (ms)	15.5	16.0	16.5	17.0	17.5	18.0	18.5	19.0	19.5
f (MHz)	103.99	104.16	104.31	104.44	104.57	104.67	104.77	104.86	104.94

Bias current profile (I·w)

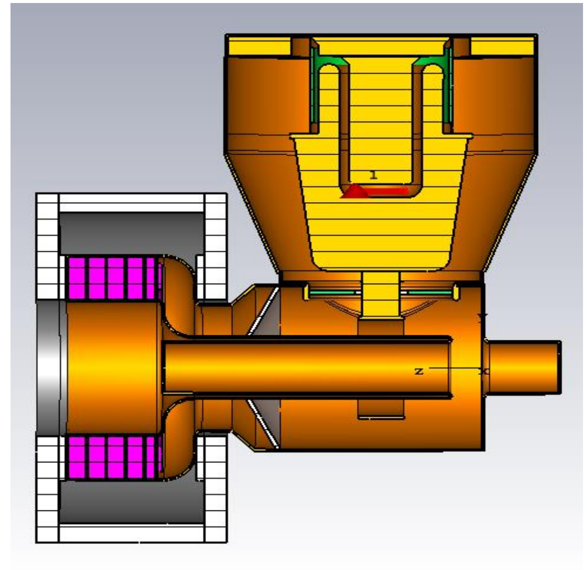
t (ms)	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5
Iw (kA)	6.6625	6.69	6.765	6.90	7.08	7.32	7.60	7.94
f (MHz)	75.73	75.914	76.402	77.256	78.341	79.7	81.175	82.827

t (ms)	16.0	17.0	17.5	19.0
Iw (kA)	16.7	17.0	17.1	17.4
f (MHz)	104.05	104.42	104.53	104.88

Cavity configuration – May 2016



In process



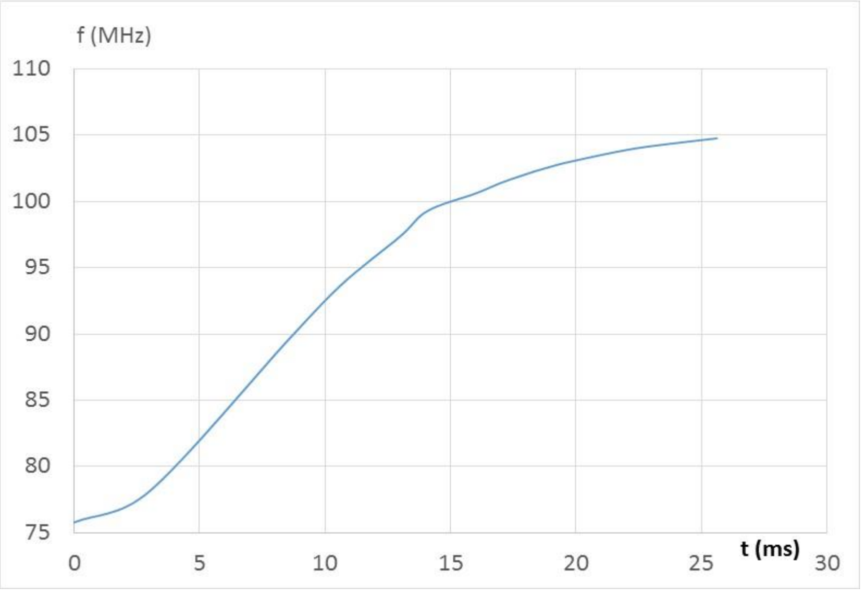
Results of 3D modeling

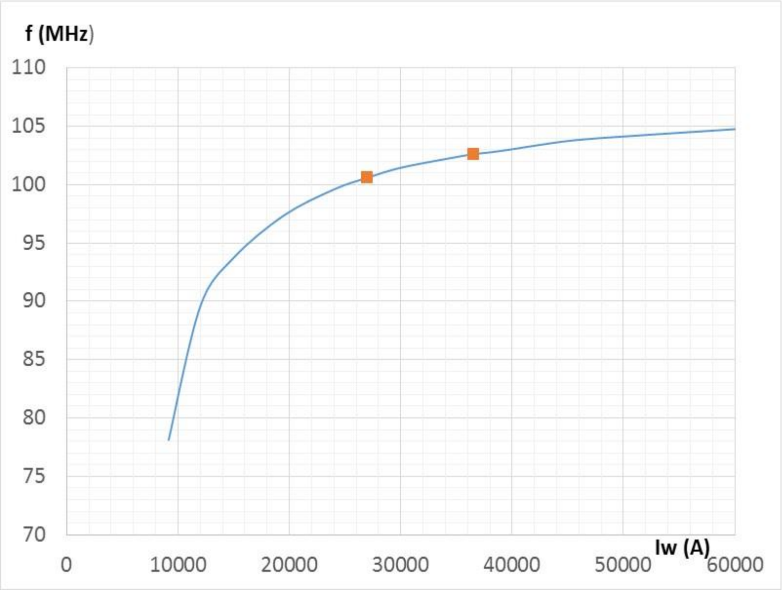
I (A)	245.5	300	400	500	650	800	1000	1150	1300	1500	1700	2000
Iw (kA)	7365	9000	12000	15000	19500	24000	30000	34500	39000	45000	51000	60000
f (MHz)	77.1	82.5	89.6	93.75	97.37	98.75	101.46	102.29	102.9	103.75	104.2	104.76

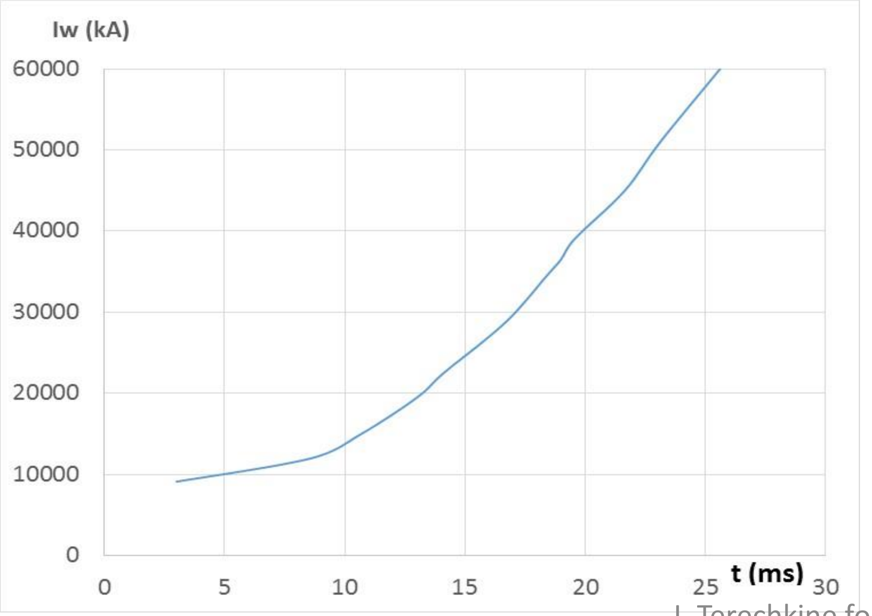
Requirements in accordance with the timing table

Iw (kA)		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

Tuning Curve





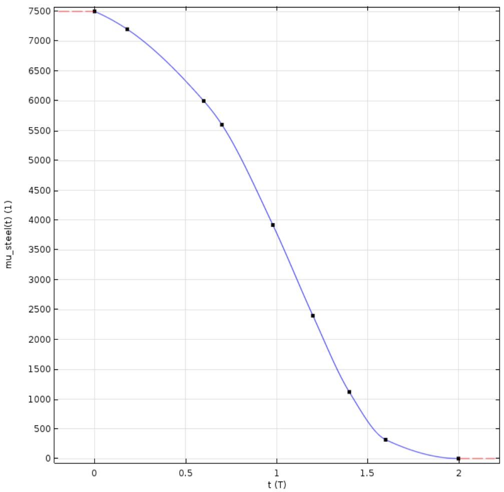


As the maximum current is two times higher (40 kA vs 20 kA), expected power consumption is more than four times higher (because of the specific non-linearity of the tuning curve).

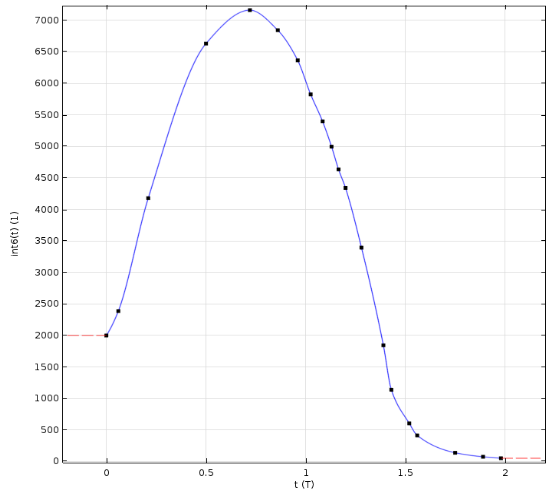
As only the second active 3-ms interval is of importance, it is possible to adjust the assumed current shape.

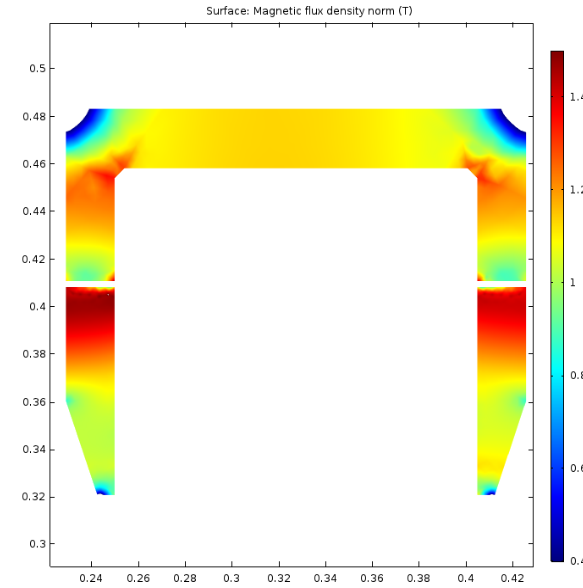
Flux return saturation at the 40 kA excitation current

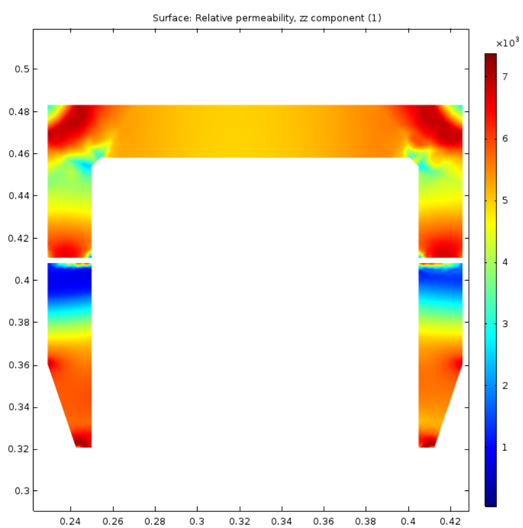
Simplified magnetization curve for the electric Silicon Steel

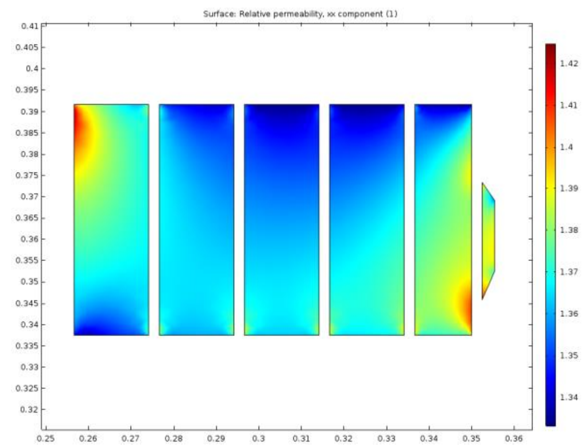


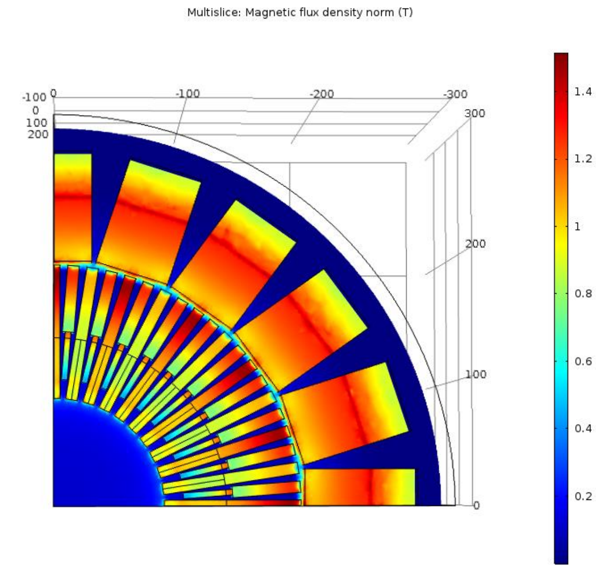
Magnetization curve for the 135-50A Steel









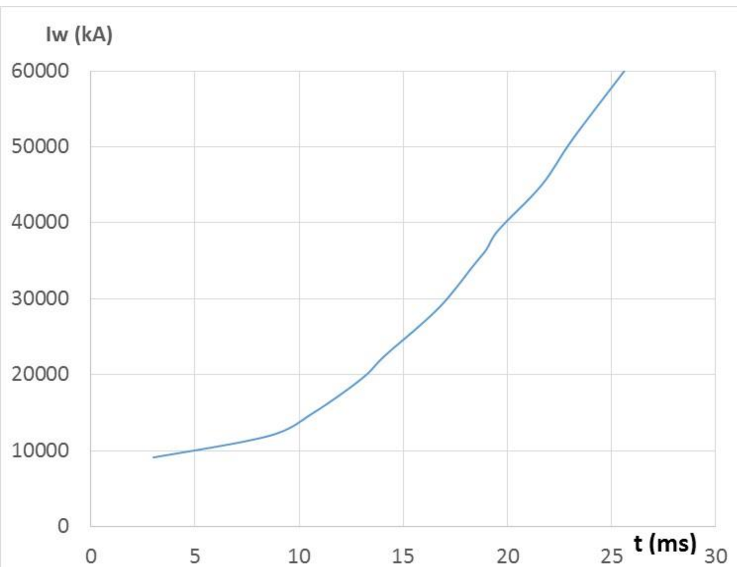


Heat deposition in the coil

N = 50
R = 0.02 Ohm

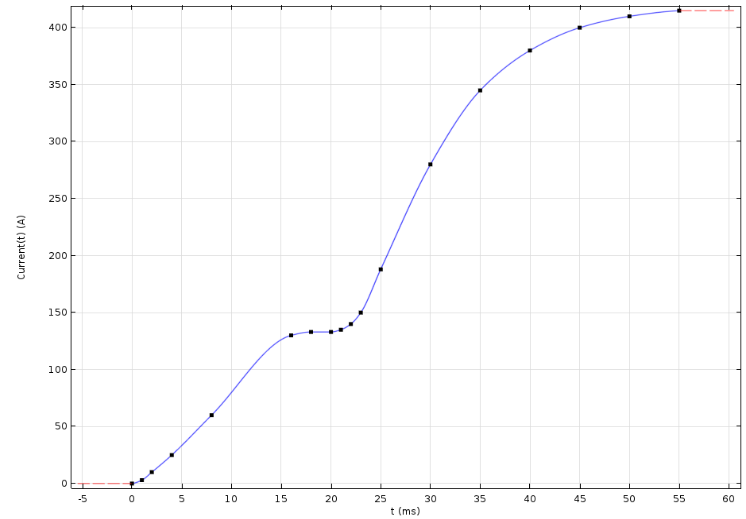
Ideal current shape

- For the initial 3 ms:
Iw = 10000 A → Q = 0.25E6*R J → 2 J → 30 W at 15 Hz
- For the second 3-ms interval
Iw = (27000 ÷ 36540) A → Q = 3E6*R J → 24 J → 360 W at 15 Hz
- For the maximum current during the second interval
Iw = 36540 A → Q = 4E6*R J → 32 J → 480 W at 15 Hz.

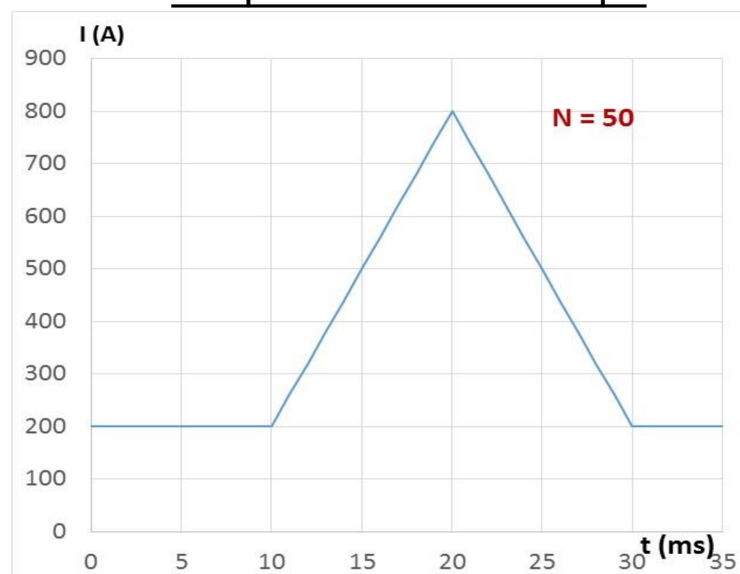


$d(Iw)/dt|_{max} \approx 3.5$ kA/ms
→ $dI/dt|_{max} \approx 70$ A/s

"Old" current shape



Simplified current shape



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 ≈ 1900 W;
Cooling capacity of the current design is ~2000 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 -- 800 A (was 400)
Maximum dI/dt = 75 A/ms (was 20) → maximum inductive voltage V_{ind} ≈ ±260 V. (was 70)
Maximum resistive voltage - V_R = 16 V (was 7.6)
Maximum power at 800 A - $P = I^2 * R$ ≈ 13,000 W (was 3000)
Required Volt-Amperes – 260 V * 800 A ≈ 200 kVA (was 32 kVA)
Power consumption at 15 Hz is ~ 1900 W (was ~1500 W)

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.

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.

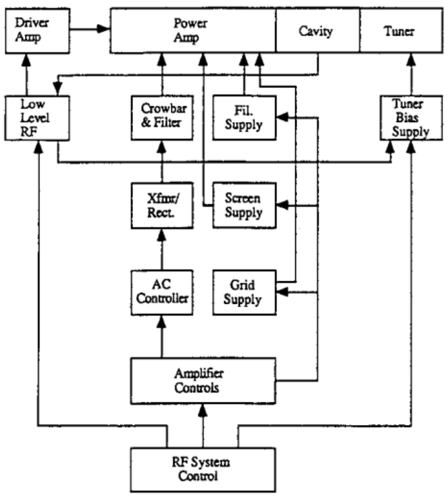


Figure 1. Rf System block diagram.

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.

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

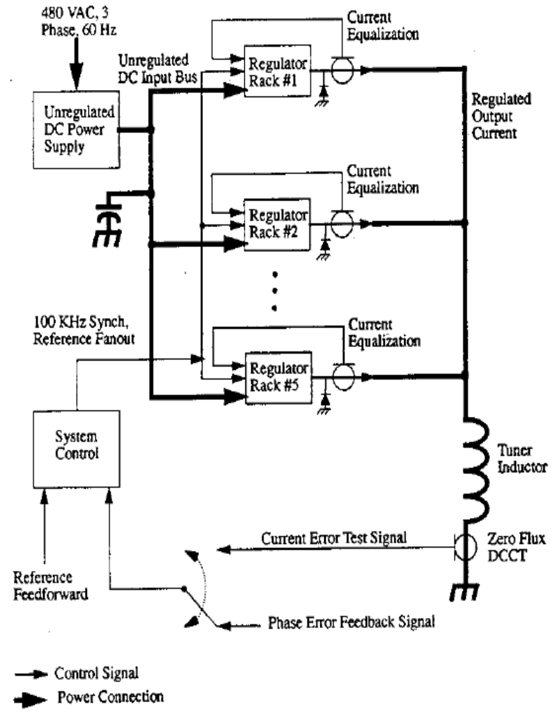


Figure 4. LEB Bias Current Regulator Block Diagram.

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.