Injection to and Extraction from a Synchrotron

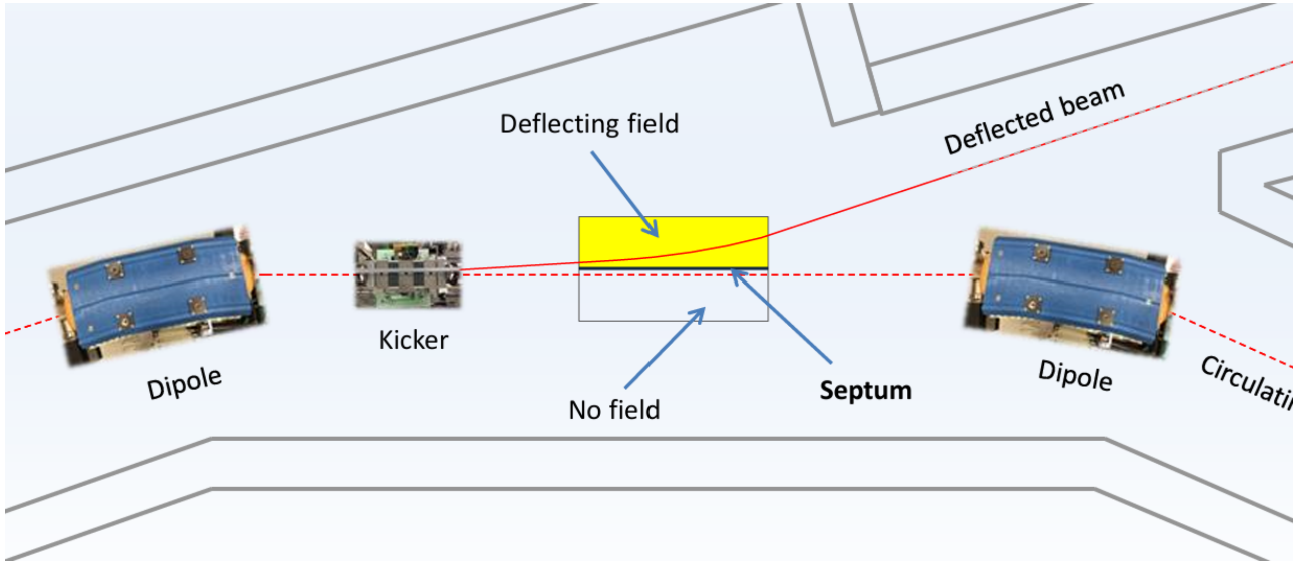
Lianhua Ouyang

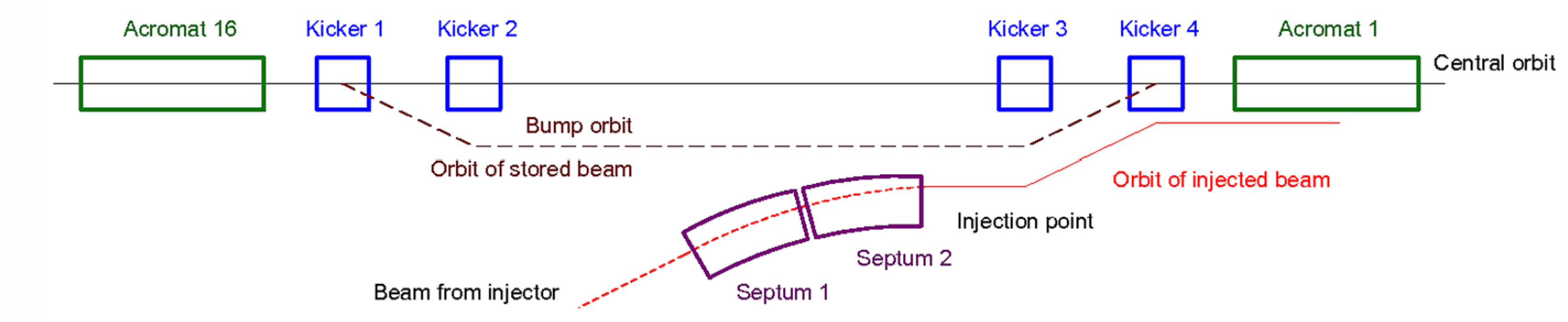
Contents

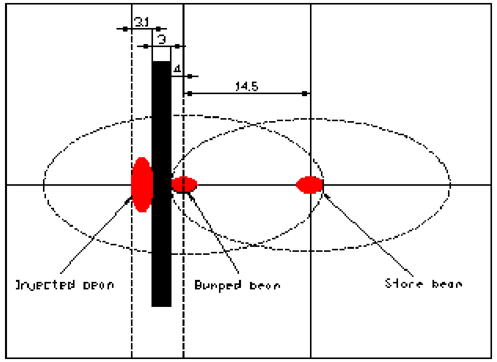
Why we need injection and extraction?

- An accelerator has limited dynamic range: a chain of accelerators is required to reach high energy. For examples, Light Source consists of: LINAC + Booster + Storage Ring; Medical Accelerator for Tumor Treatment: Injector+ Synchrotron +Treatment Rooms;
- Injection: inject a particle beam into a circular accelerator or accumulator ring, at the appropriate time;
- Extraction: extract the particles from an accelerator to a transfer line or a beam dump, at the appropriate time;
- The goals:
  - minimize beam loss;
  - place the particles onto the correct trajectory, with the correct phase-space parameters.

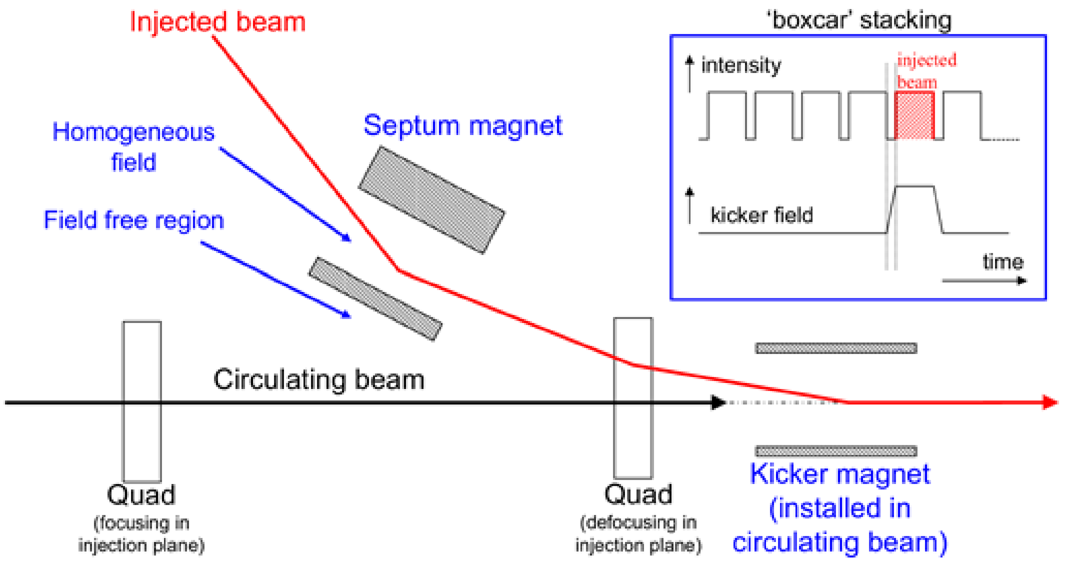
Why we need injection and extraction?

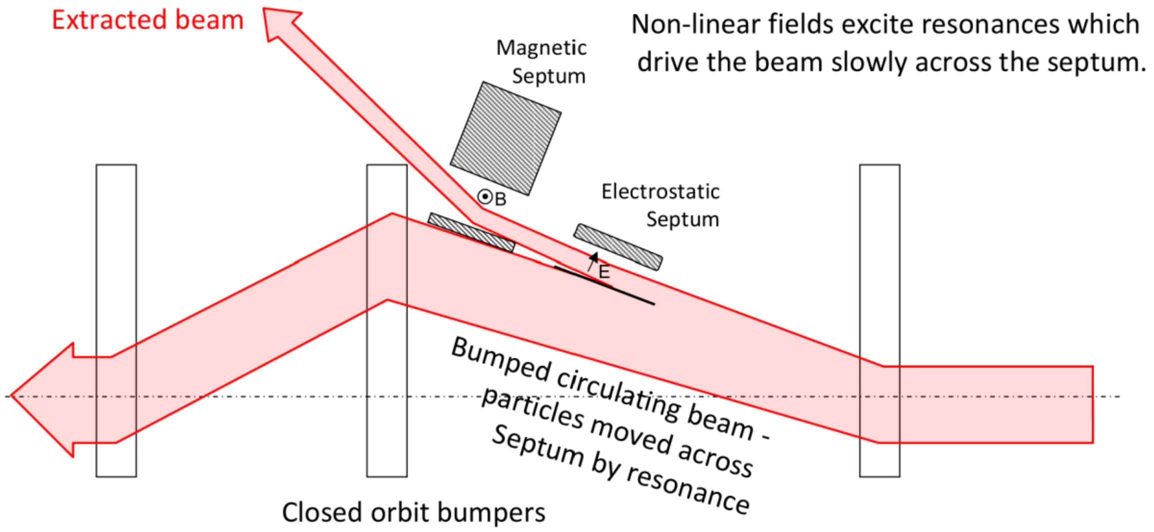






Why we need injection and extraction?

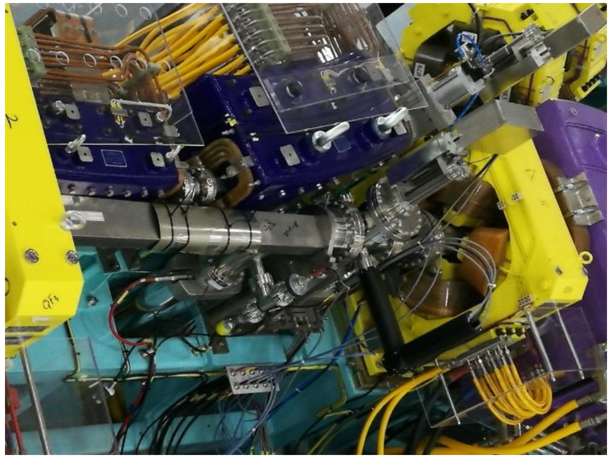




Fast single turn injection/extraction

Resonant multi-turn extraction

Why we need injection and extraction?



Background knowledge

- The force used to direct a charged particle beam is known as the Lorentz force. The Lorentz force is given by:

$$F = q\left[E + \left(v \times B\right)\right] \ ,$$

where

- F is the force (N),
- E is the electric field (V/m),
- B is the magnetic field (T),
- q is the electric charge of the particle (C),
- v is the instantaneous velocity of the particle (m/s),

Background knowledge

- The deflection of a charged particle beam in an electric field is given by

$$\theta_{E,x} = \tan^{-1}\left[\frac{1}{(p\cdot 10^9)\cdot\beta}\cdot\int_{z_0}^{z_1}|E_x|\,dz\right] = \tan^{-1}\left[\frac{|E_x|\cdot l_{eff}}{(p\cdot 10^9)\cdot\beta}\right] = \tan^{-1}\left[\frac{|V|\cdot l_{eff}}{d\cdot(p\cdot 10^9)\cdot\beta}\right],$$

- V is the potential difference between plates (V),
- d is the separation of the plates (m),
- p is the normalized beam momentum (GeV/c), you can replace it with βE
- Ex is the electric field in the x-direction (V/m),
- β is a unit-less quantity that specifies the fraction of the speed of light at which the particles travel (v/c), and
- $\theta_{E,x}$ is the deflection angle, in the x-direction, due to electric field Ex (radians).

Background knowledge

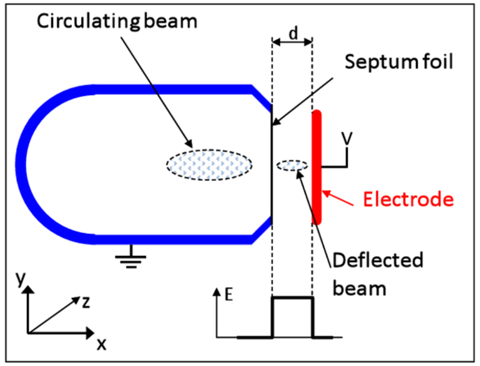
- The deflection of a charged particle beam in a magnetic field is given by :

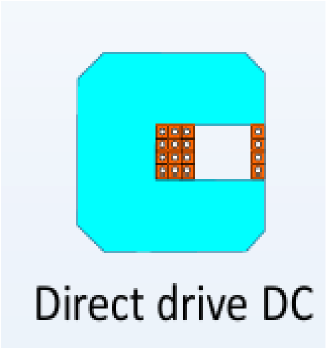
$$\theta_{B,x} = \left[\frac{0.2998}{p}\right] \cdot \int_{z_0}^{z_1} \left|B_y\right| dz = \left[\frac{0.2998 \cdot l_{eff}}{p}\right] \cdot \left|B_y\right| ,$$

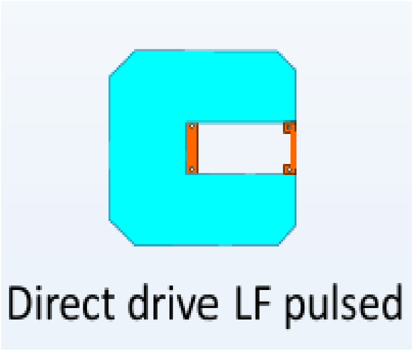
- B_y is the magnetic flux density in the y-direction (T),
- p is the normalized beam momentum (GeV/c), you can replace it with βE
- l_{eff} is the effective length of the magnet, and
- $\theta_{B,x}$ is the deflection angle, in the x-direction, due to magnetic field By (radians).

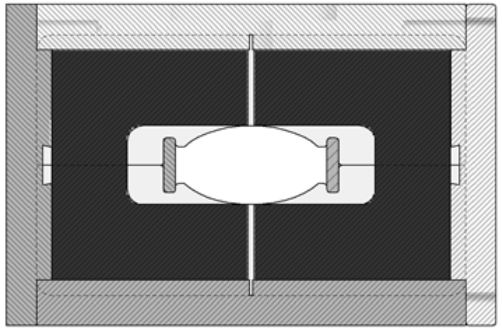
Types of injection & extraction elements

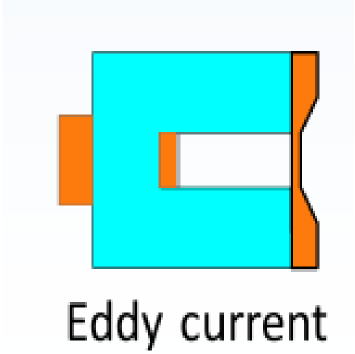
- Septum
  - Electrostatic septum
  - Megnetic septum
    - DC drive septum
    - Lambertson magnet
    - Eddy current septum
- Kicker and bumper
- Others: Non-linear Kicker, …







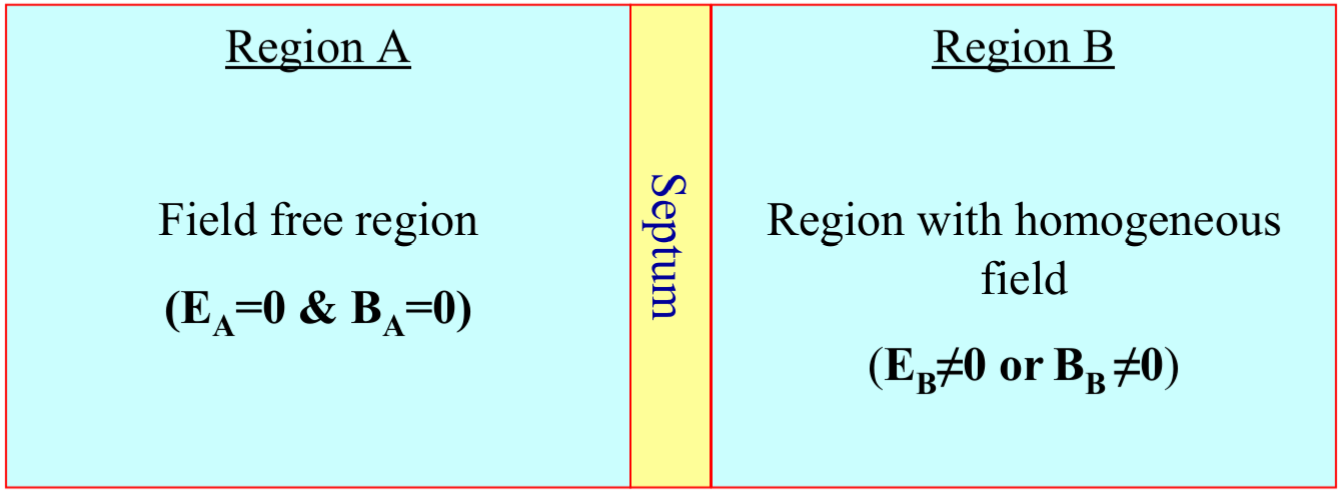




Background knowledge

What is a septum?

In a particle-accelerator, a septum (plural Septa) is a device which separates two field regions:



Background knowledge

Electrostatic vs Magnetic deflection ?

- It is more practical to use magnetic field!
- Too high electric field in vacuum could provoke electric breakdown. It is widely accepted that 10 MV/m is a practical limit.
- Electric deflection could be applied for situations where very thin septa and small deflection angle are needed and,
- Could be beneficial for non-relativistic particles (e.g. low energy beams(for instance, electron microscope), heavy ions etc.)

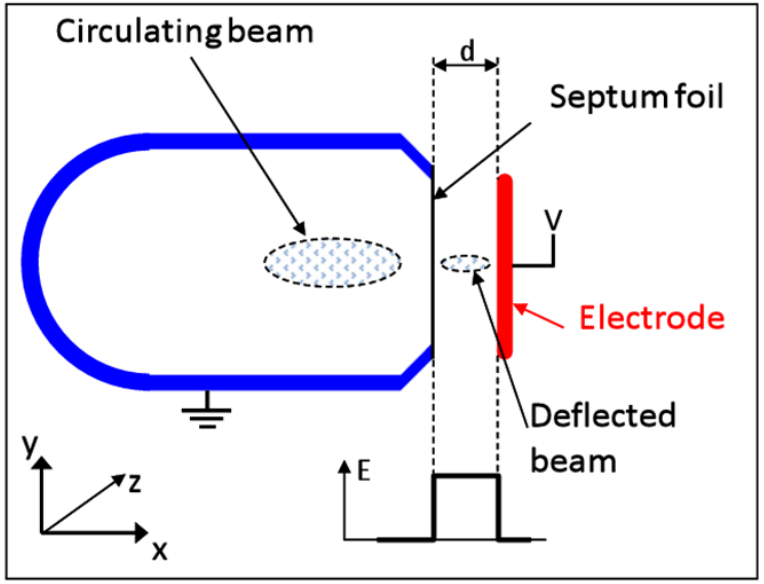
Background knowledge

Advantage vs. disadvantage

Electric septum	Magnetic septum
Near perfect no-field region	Field leakage relatively large
Thin septum	Thick septum
Less effective for relativistic beams(small deflection angle)	More effective for relativistic beams (strong deflection)
Strictly in-vacuum design	In-vacuum and in-air design is possible
Difficult to have high fields (breakdown)	Magnetic field up to 1.5 T

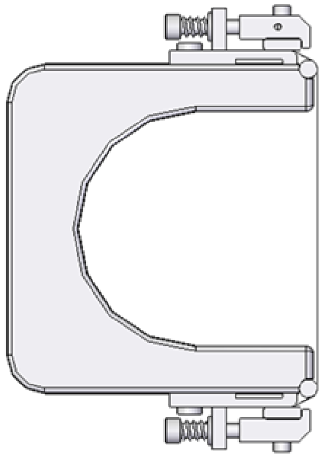
Electrostatic septum

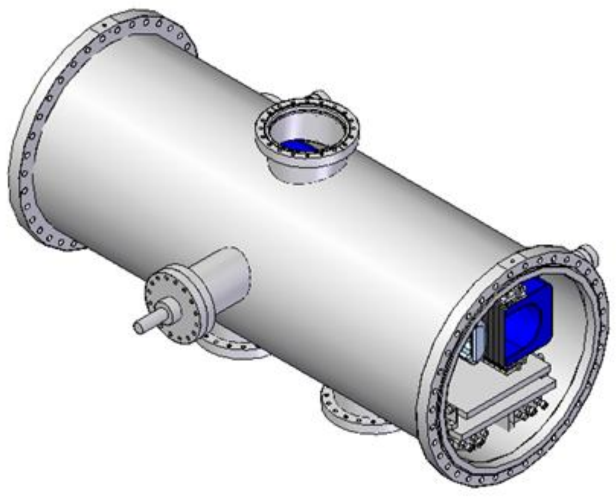
- A thin septum thickness results in small interaction with beam. The orbiting beam passes through the hollow strip support, which is a field-free region.
- To achieve a slow-extraction efficiency of greater than 98%, the effective thickness of the septum unit must be ≤ 100 μm. This may be realised by a very carefully aligned the septum,
- The extracted beam passes just on the other side of the septum (high, homogeneous, field region).



Electrostatic septum

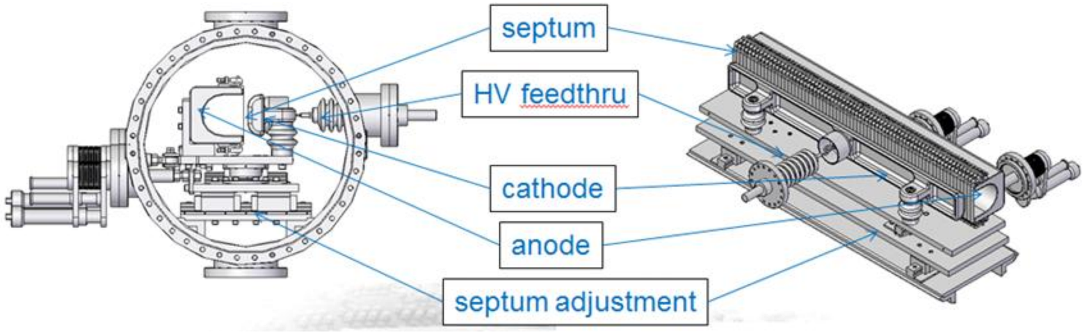
- Electrostatic septa use vacuum as an insulator, for there is a very high electric potential between septum(anode) and cathode, and it is prone to sparking and arcing.
- To allow precise matching of the septum position with the circulation beam trajectory, there is often a displacement system which allows parallel and angular movement with respect to the circulating beam.
- The septum strips are tensioned: this helps to prevent any sagging under the heat load resulting from collisions of intercepted beam particles.

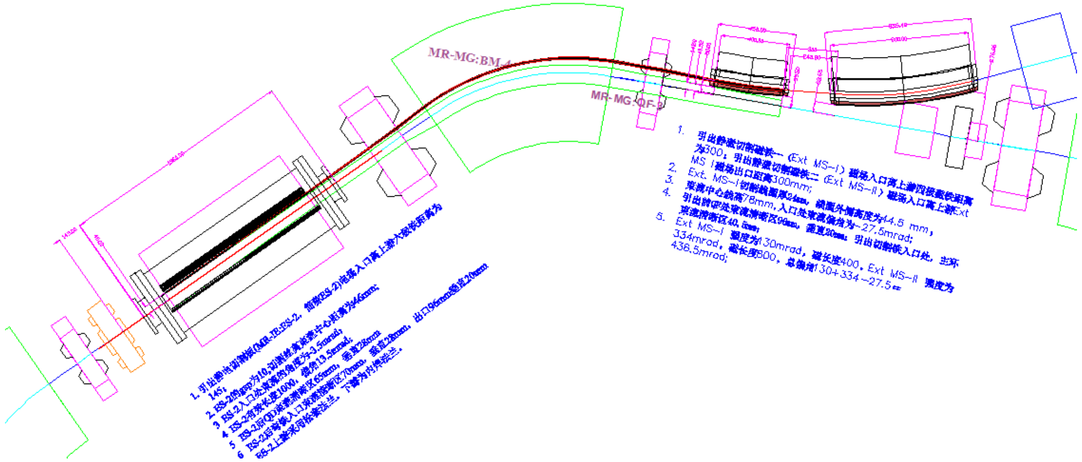




Electrostatic septum

	RF-Kicker	ES	MS-I	MS-II
Effective length (m)	0.25	1.0	0.4	0.8
Deflection angle (mrad)	0.001	13.5	130	334
Gap(mm)		10	40	40
Field strength	100V	60.4 kV	7904 Gs	10154 Gs
Scan frequency (MHz)	2-6	DC	DC	DC
Beam stay clear H×V (mm×mm)	125×50	10×30	30×30	30×30
Field stability		0.02%	0.02%	0.02%
Septum thickness (mm)	——	<0.1mm	26mm	45mm
Total length(mm)	500	1360	456	856





Note:
ES stands for Electrostatic septum;
MS stands for magnetostatic septum;

Electrostatic septum

The particles are protons(rest energy is 938.272 MeV), the kinetic energy is 250MeV， the deflection angle is 13.5 mrad, and the gap is 10 mm, the effective length is 1 m,

$$\beta = \sqrt{1-\gamma^{-2}} = 0.61361$$

The electric strength is

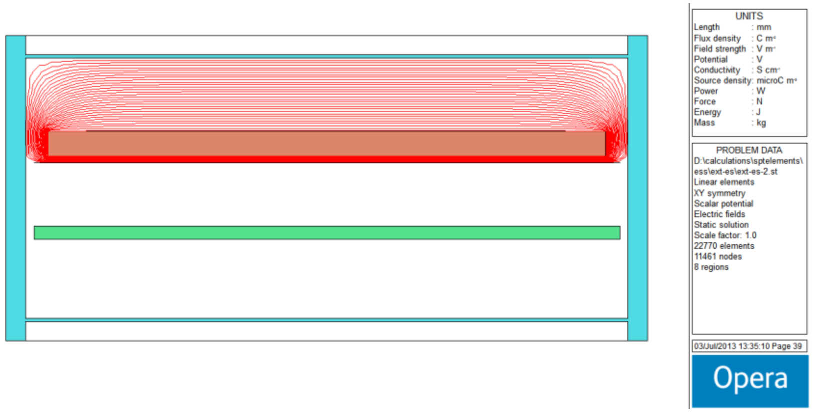
$$\mathbf{E} = 10^9 \times \tan\varphi \cdot E\beta^2 / L = 10^9 \times \tan(13.5/1000) \times 1.1883 \times 0.61361^2 / 1.0$$
$$= 6.04 \times 10^6 \; V/m$$

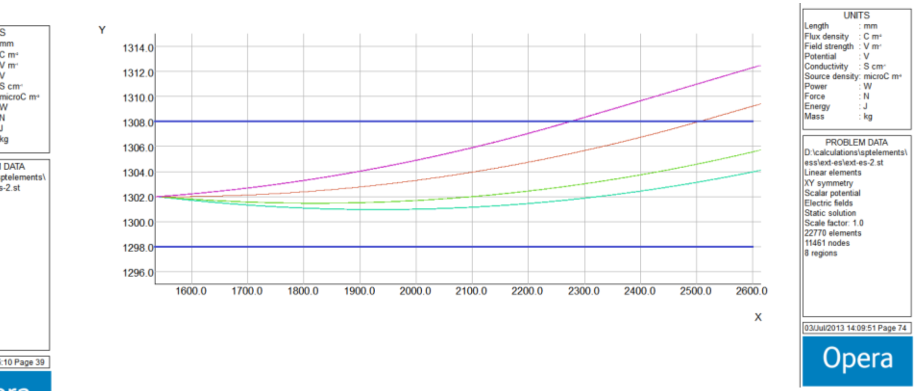
And the voltage is

$$V = \mathbf{E} * g = 60.4 \; kV$$

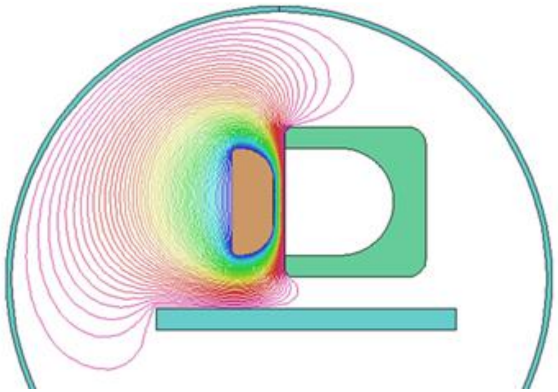
Electrostatic septum

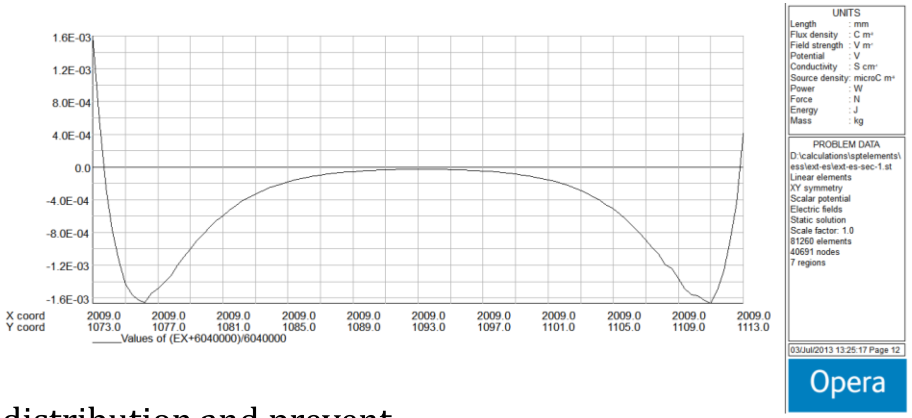
Electric field and particle trajectory





Proton trajectory: in between blue lines is gap. -0.5mrad(c), -0.35mrad(g), 0mrad(b), 0.35mrad(p)

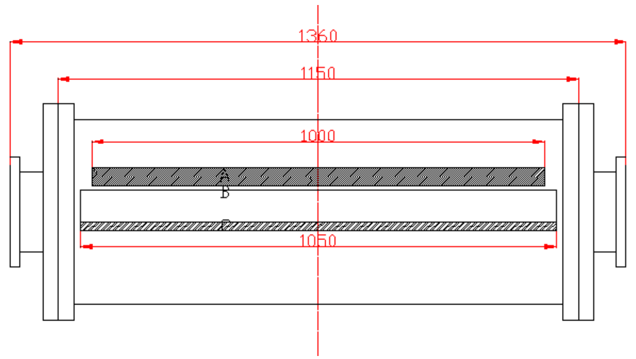


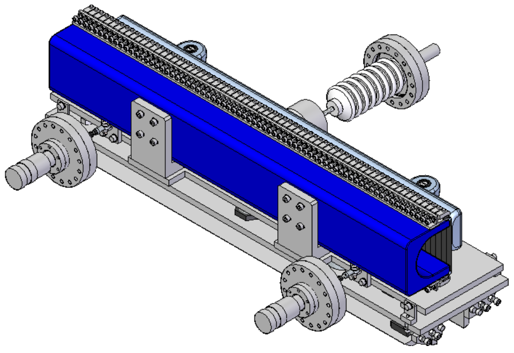


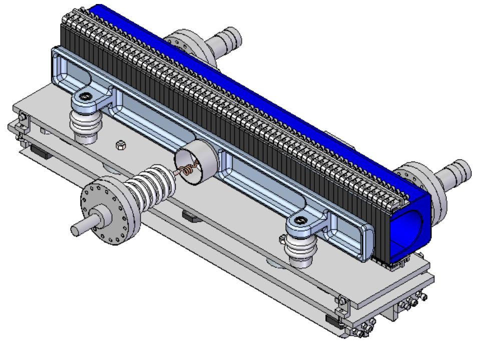
The goal of the simulation is to optimize electric distribution and prevent electric field concentration, avoiding electric breakdown.

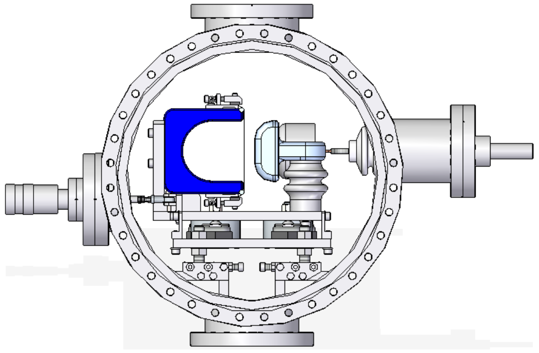
Electrostatic septum

■**Vacuum chamber:** cylinder, 1×10-8Torr;
■**Septum:** 0.1mm, molybdenum strip (foil) ;
■**Anode:** C-core, aluminum alloy;
■**Cathode (High voltage):** stainless steel 316L, cross section and end shapes optimization, electro-chemical polishing;
■**HV feedthrough:**100KV, self design or commercial;
■**Septum position adjustment system:** manually, both in the parallel and angular directions.









Electrostatic septum

Measures to prevent discharges and sparks:

- ■Surge-limiting resistor near HV feedthrough;
- ■Cathode: stainless steel 316L, cross section and end shapes optimization;
- ■Surface treatment: mechanical polishing, electro-chemical polishing(ECP), impurity removal, clean
- ■Anode is longer than cathode longitudinally, to reduce the possible end discharges;
- ■Reliable connections, insulations; corona ring;
- ■Conditioning carefully.

Electrostatic septum

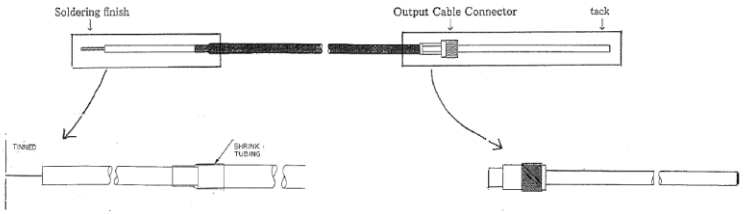
Typical technical data for an electrostatic septum include

- electrode length in the range 500 mm to 3000 mm;
- gap width variable in the range 10 mm to 35 mm;
- septum thickness of $\leq$ 100 μm;
- vacuum in the range 10^{-9} mbar to 10^{-12} mbar;
- voltage up to 300 kV;
- electric field strength up to 10 MV/m;
- septum foil of molybdenum (or tungsten-rhenium wires);
- electrode made of anodized aluminum, stainless steel or, for extremely low vacuum applications, titanium;
- some electrostatic septa are bake-able up to 300°C to achieve vacuum in the 10^{-12} mbar range (not applicable to an aluminum electrode).

Electrostatic septum

HV power supply parameters:

- Spellman SL100*300
- Output voltage 0-100kV, Continuous, stable adjustment
- Voltage Regulation: <0.005%
- Output current 0-3 mA;
- Output cable PMI;
- Ripple 0.1% RMS;
- Stability 0.01% per hour;
- Temperature coefficient 0.01% per degree C;
- Protection: Automatic current regulation protects against all overloads, including arcs and shorts, fuses, surge-limiting resistors, and low-energy components provide ultimate protection.



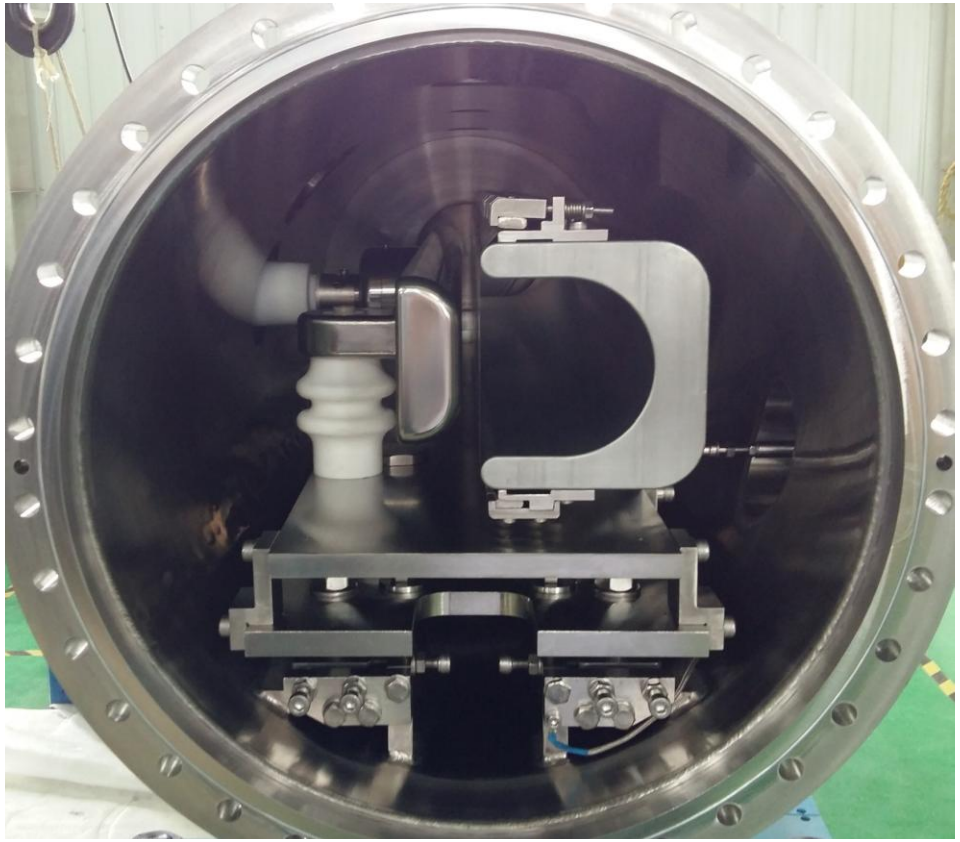
Characteristic impedance and spark current

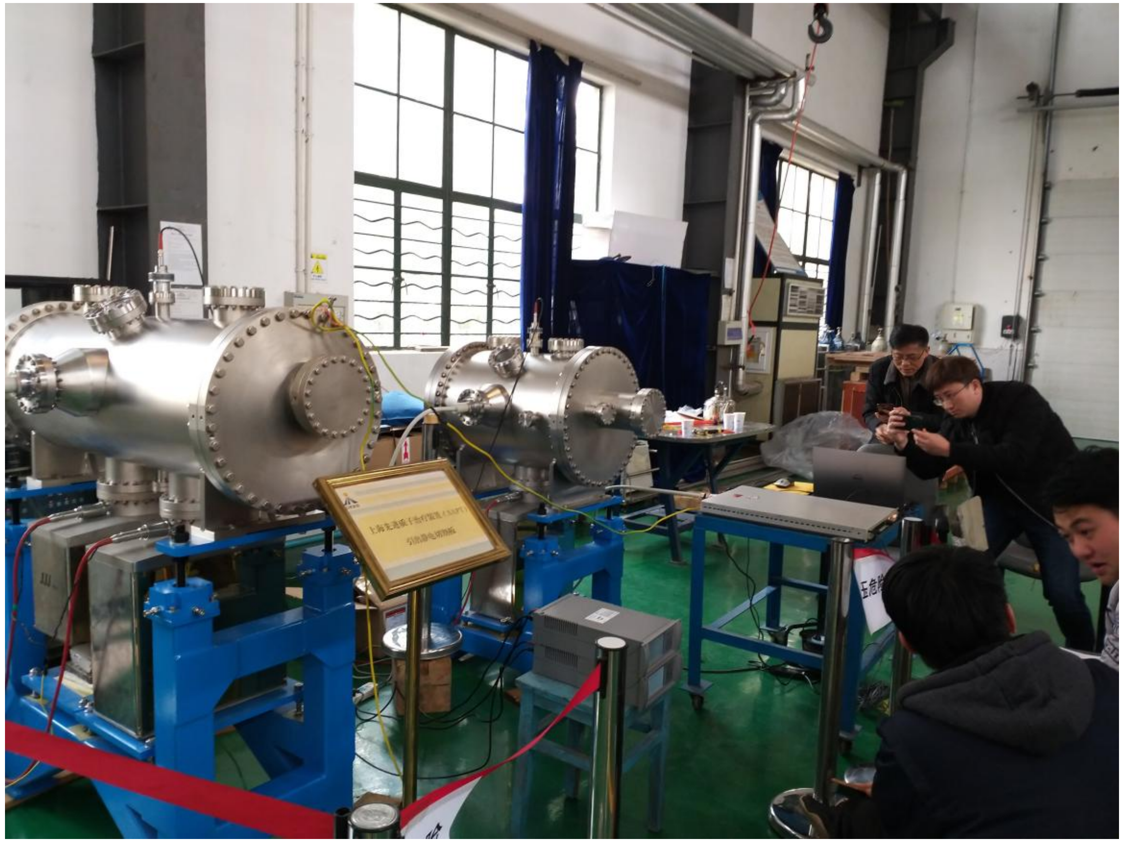
$$I = 4571(A) \quad Z_0 = 35.0(Ohms)$$

$$C = \varepsilon A/d = 8.854\times10^{-12}\times0.08/0.01 = 70.8(pF)$$

$$E = \frac{1}{2}CV^2 = 0.5\times70.8\times10^{-12}\times80000^2 = 0.223(J)$$

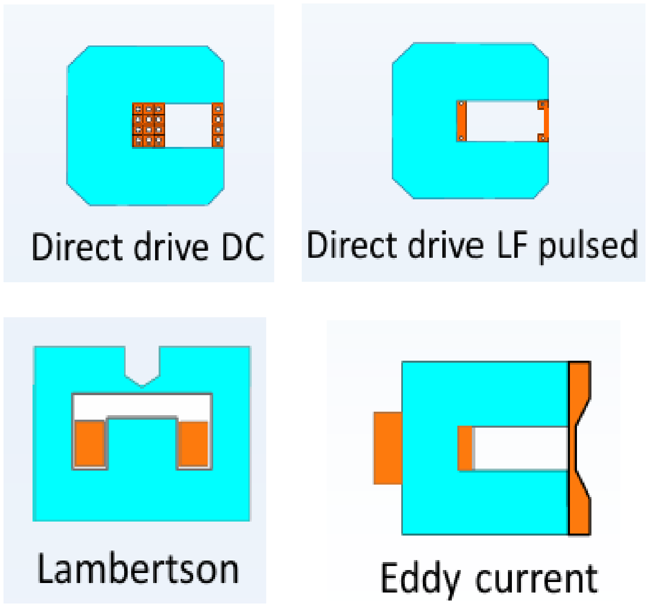
Electrostatic septum

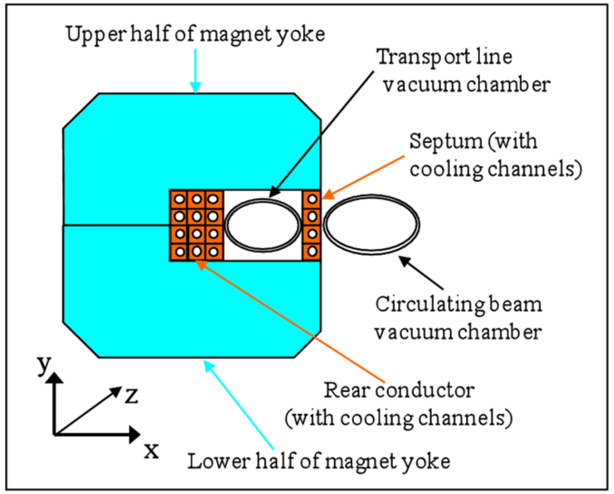




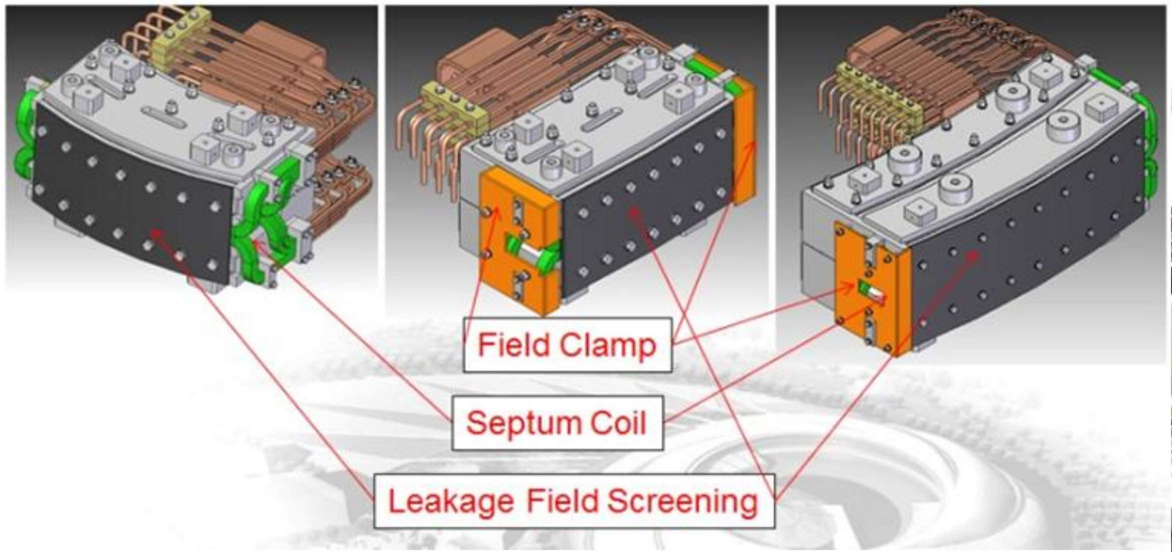
Magnetic septum

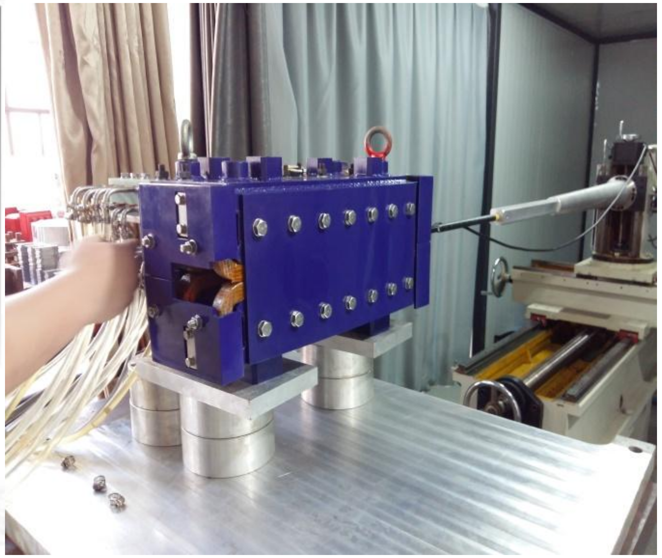
- There are several varieties of magnetic septa:
  - direct-drive DC septum magnet,
  - direct-drive pulsed septum magnet,
  - eddy-current septum,
  - Lambertson magnet
- The main difference between a dipole magnet and a magnetic septum is that the magnetic septum has a field-free region and a homogeneous dipole field region, separated by a relatively thin septum;
- As a consequence of the relatively thin septum there is often a high current density in the septum conductor.





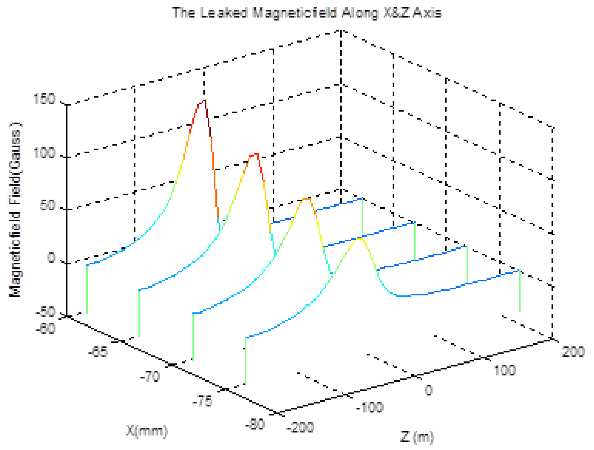
Magnetic septum



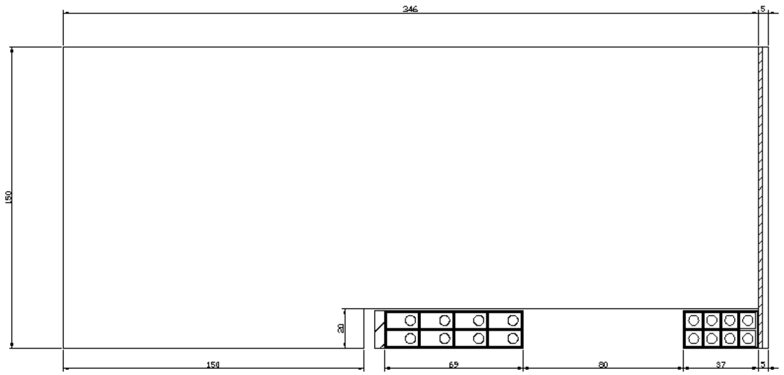


Technology considerations:

- Leakage field
  - Pure iron plate for leakage field screening;
  - field clamp at ends;
- Coils insulation and deformation
  - Polymide tape and fiberglass tape;
  - Coil deformation control;
- Heat loads
  - Water cooling;
  - Temperature detect switch;
  - Coil voltage variation monitoring (if necessary).



Magnetic septum

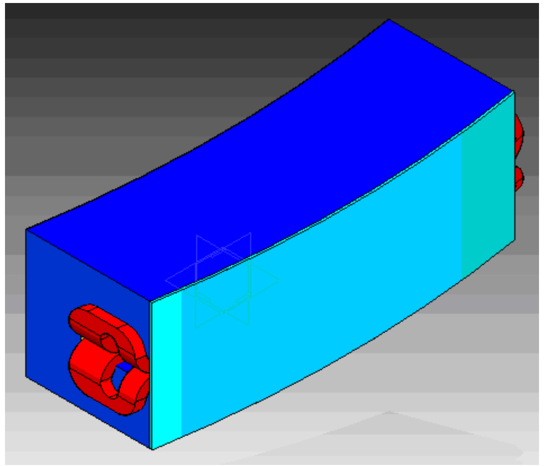


■Two half yokes of steel laminations;

■8 mm square section conductor with a ø 5 mm water cooling hole;

■Coil assemly vacuum moulded (impregnated) ;

■Pure iron plate for leakage field screening;



Length（mm）	800
Deflection angle（rad）	334
Field（T）	10154.1
Gap（mm）	40
Ampere turns	32981.3
Turns	16
Septum thickness（mm）	42（nominal45）
Current（A）	2061.33
Septum conductor dimension（mm）	8×8，water channelf5
Return conductor dimension （mm）	16×8，water channelf5
Current density（A/mm2）	46.463
Coil resistance（mΩ）	15.8
Voltage（V）	32.57
Power（kW）	67.14
Inductance（uH）	739.7
Coil time constant (ms)	61
Water pressure drop（kg/cm2）	1.3
Water velocity（m/s）	4.0
Water channel	16
Water flux（l/s）	1.257
Temperature rise（℃）	12.7
Magnet length（mm）	896
Core weight（kg）	758
Coil copper weight（kg）	224.5

Magnetic septum

Megnetic field calculation: the deflection angle is 130 mrad,, the effective length is 0.4 m,

$$\gamma = E/E_0 = 0.25/0.938272013 + 1 = 1.266447252$$

$$\beta = \sqrt{1-\gamma^{-2}} = 0.61360844$$

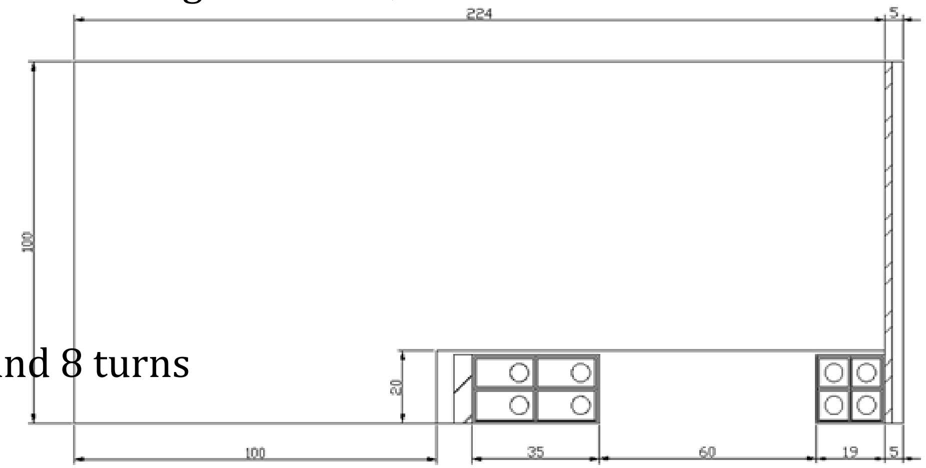
$$B = 1.1883 \times 0.13 \times 0.61361/0.2998/0.4 = 0.79044(T)$$

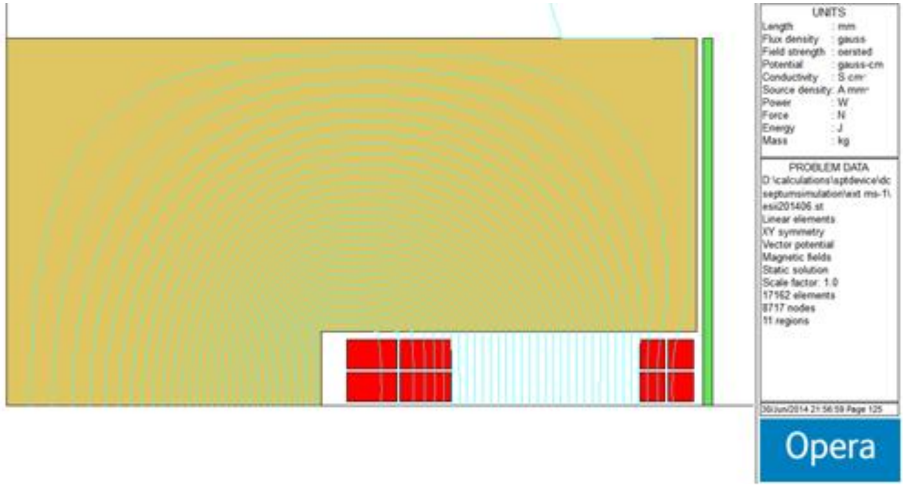
The Ampere turns calculation: Suppose the gap heigtht is 40mm, and 8 turns coils

$$NI = \frac{0.79044 \times 0.04}{4 \times \pi \times 10^{-7} \times 0.98} = 25674(AT)$$

Here we have a magnetic efficiency of 0.98, so the current is

$$I = \frac{NI}{N} = \frac{25674}{8} = 3209(A)$$





Magnetic septum

Septum current density

$$j = \frac{I}{S} = \frac{3209}{44.365} = 72.34\,(A/mm^2)$$

Copper electrical resistivity 0.01826Ω•mm^2/m，and the resistance is

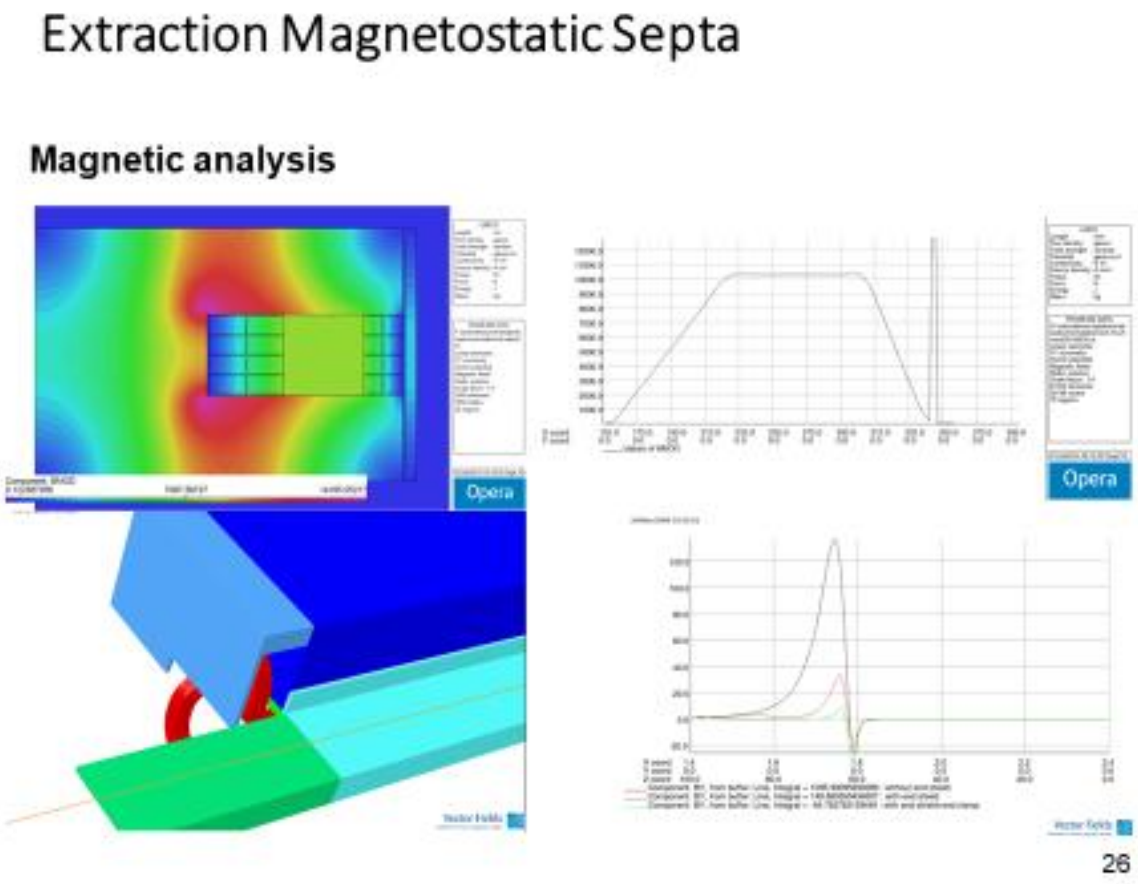
$$R_{8turns} = 5.38 \quad (m\Omega)$$

The voltage of coils

$$V = 3209 \times 5.38/1000 = 17.25\,(V)$$

The coil power

$$P = 3209^2 \times 5.38/1000 = 55.36\,(kW)$$



Magnetic septum

Water cooling the coil, the pressure drop is 0.85 kg/cm2, and the flow velocity

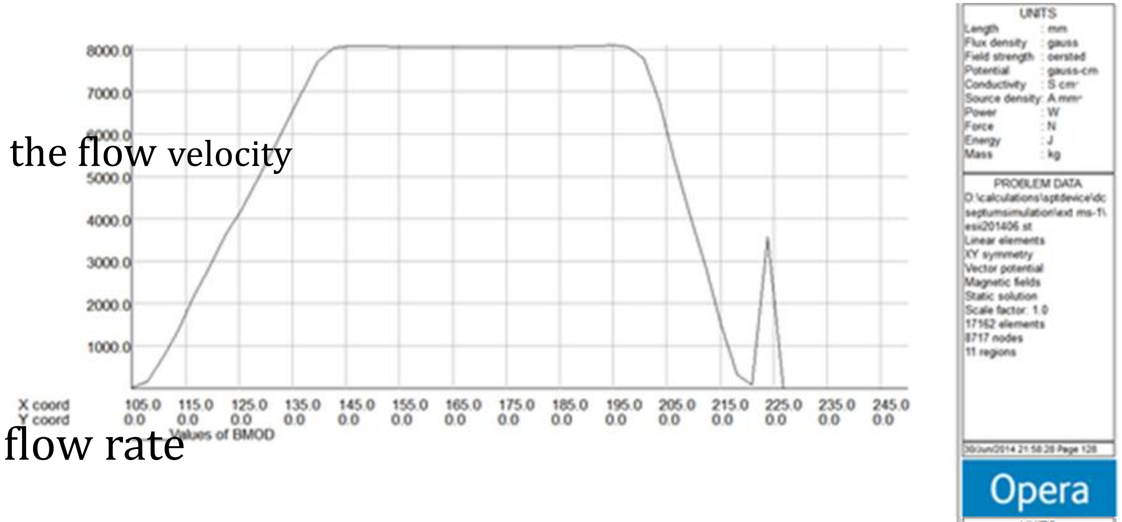
$$v=\left(\frac{\Delta P d^{1.25}}{0.28L}\right)^{\frac{1}{1.75}}=\left(\frac{0.85\times 5^{1.25}}{0.28\times 1.97}\right)^{\frac{1}{1.75}}=4.0(m/s)$$

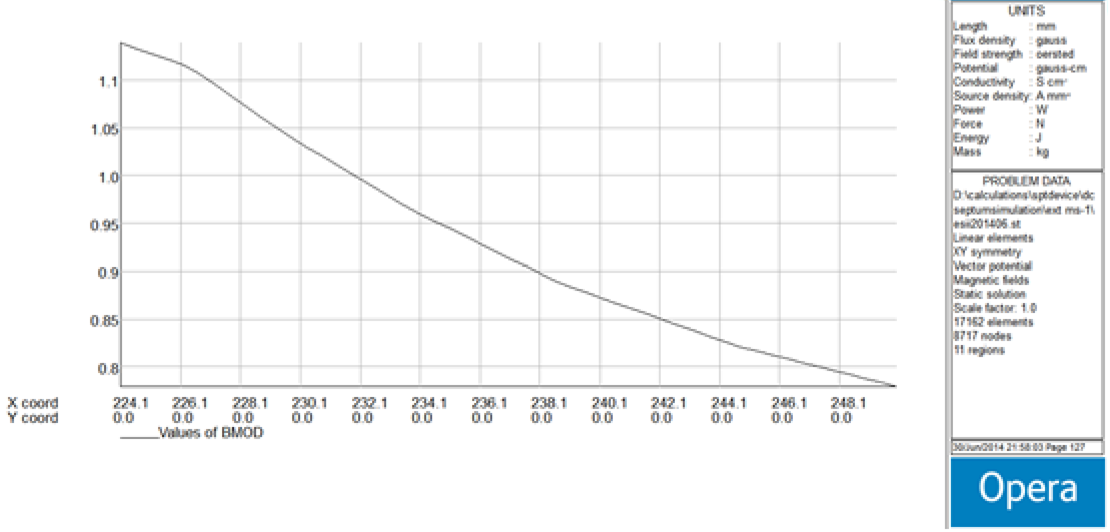
here L is cooling circuit length, and d is the diameter, q is the flow rate

$$q=8\times\frac{\pi}{4}d^{2}v\times 10^{-3}=0.6283(kg/s)$$

coil power is 55.36 KW，temperature increase is

$$\Delta T=\frac{P}{4.2q}=\frac{55.36}{4.2\times 0.6283}=21.0(^{\circ}C)$$





Magnetic septum

Typical technical data for a direct-drive DC septum magnet are

- magnetic length per magnet yoke in the range 400 mm to 1200 mm;
- gap height of 25 mm to 60 mm;
- septum thickness of 6 mm to 20 mm;
- outside vacuum;
- laminated steel yoke;
- multi-turn coil, with water cooling circuits (flow rate: 12 l/min. to 60 l/min.);
- current in the range 0.5 kA to 4 kA;
- power supplied by controllable rectifier;
- power consumption: up to 100 kW!
- Thus cooling of a DC septum is a significant issue.

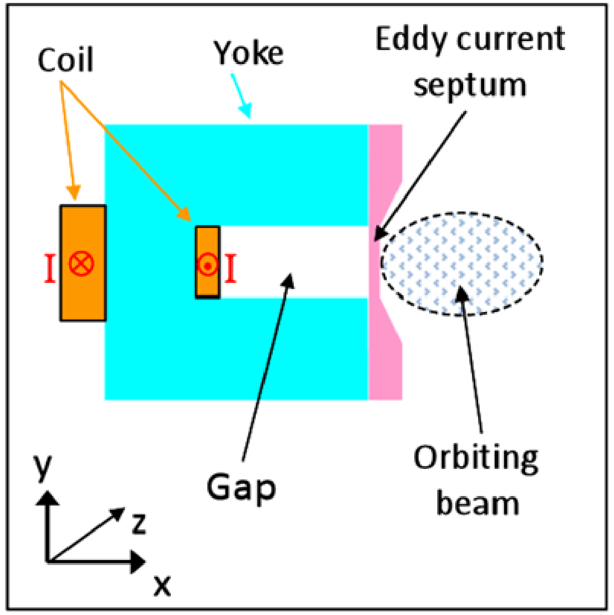
Magnetic septum

Typical technical data for a direct-drive DC septum magnet are

- The septum conductor is typically 6 mm to 20 mm thick: the current density in the septum conductor can be as high as 85 A/mm2.
- A magnetic screen may be used to further reduce the leakage field into the circulating beam region.
- A DC septum magnet is often used outside vacuum: in this case the coil and the magnet yoke can be split in two, an upper and a lower part, to allow the magnet to be ‘clamped’ over the vacuum chamber.

Eddy-current septum

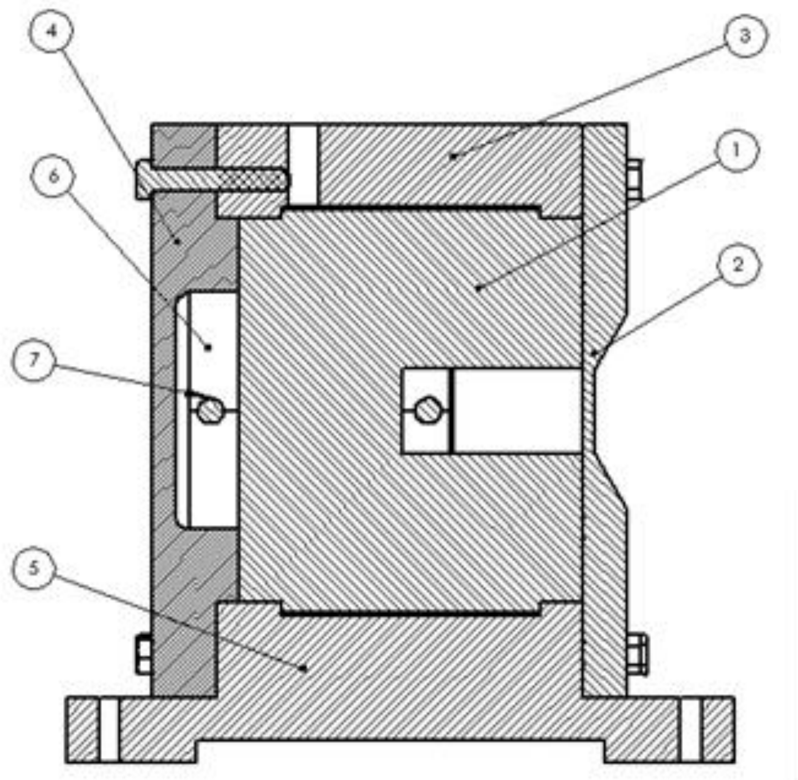
- An eddy-current septum is powered with a half or full sine wave current with a period of typically 50 μs.
- The coil is generally constructed as a single-turn, so as to minimize magnet self inductance.
- The coil is situated around the back leg of the C-shaped yoke, and therefore coil dimensions are generally not critical.
- When the magnet is pulsed, the magnetic field induces eddy currents in the septum, counteracting the fringe field created.
- The septum conductor can be made thinner than for the direct drive septum, but cooling circuits may be needed at the edges to cool the septum.

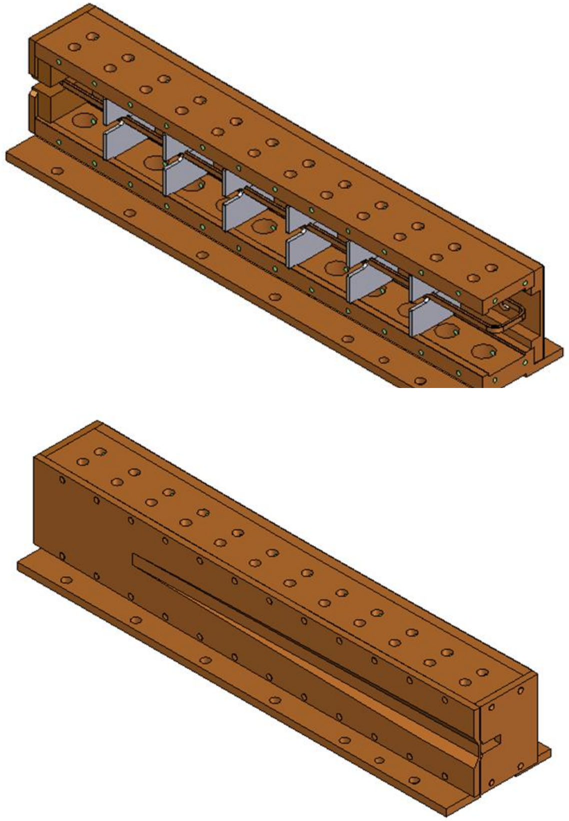


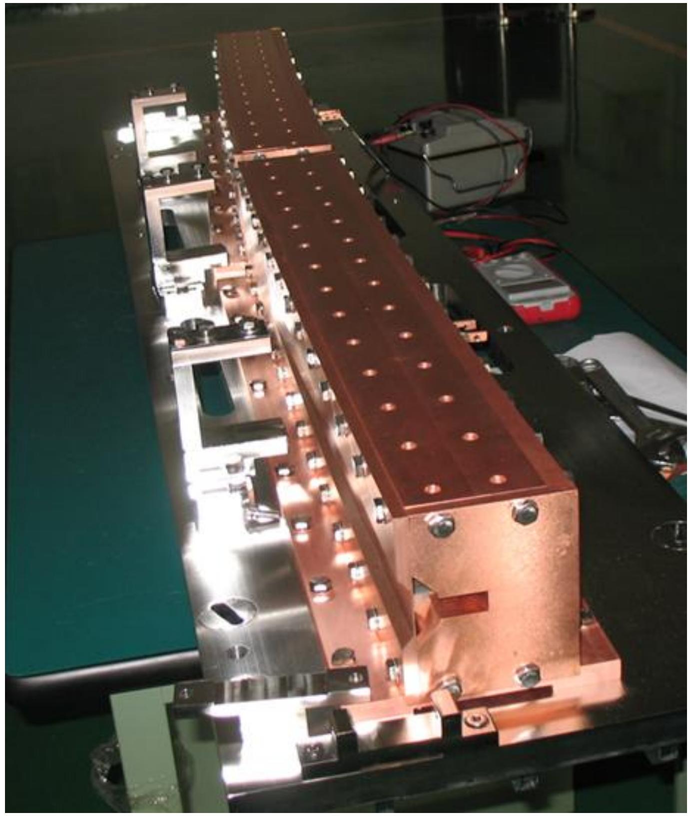
Eddy-current septum

- The field in the septum gap as function of time follows the coil current.
- The electrical resistance of the septum is kept low: once the septum current is flowing, it takes quite some time to decay away.
- magnetic screen: a typical maximum leakage field would be 10% of the gap field
- In addition a magnetic screen can be added next to the septum conductor. These modifications permit the fringe field, seen by the circulating beam, to be reduced to below 0.01% of the gap field at all times and places.

Eddy-current septum







Eddy-current septum

Excitation current wave form: half sine:

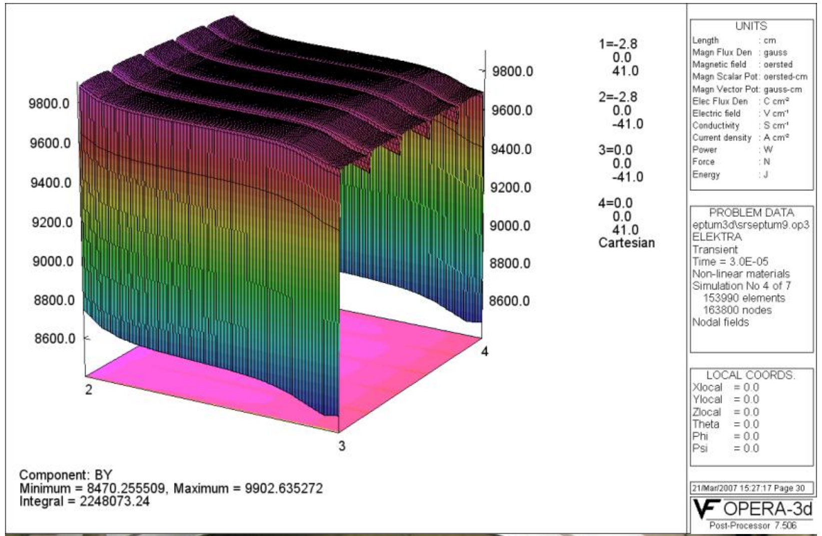
$$I = 8691.6 \sin(2 \times \pi \times 8333.3 \times t)\ (0 \le t \le 60\mu s)$$

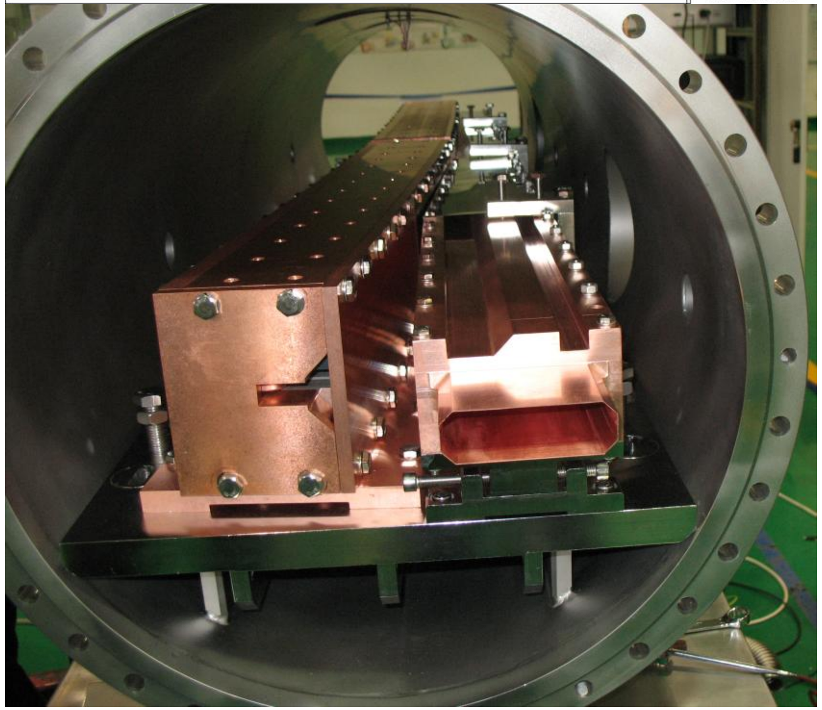
Stored energy

$$E = 2 \times 0.6845 \times 80 = 109.52(J)$$

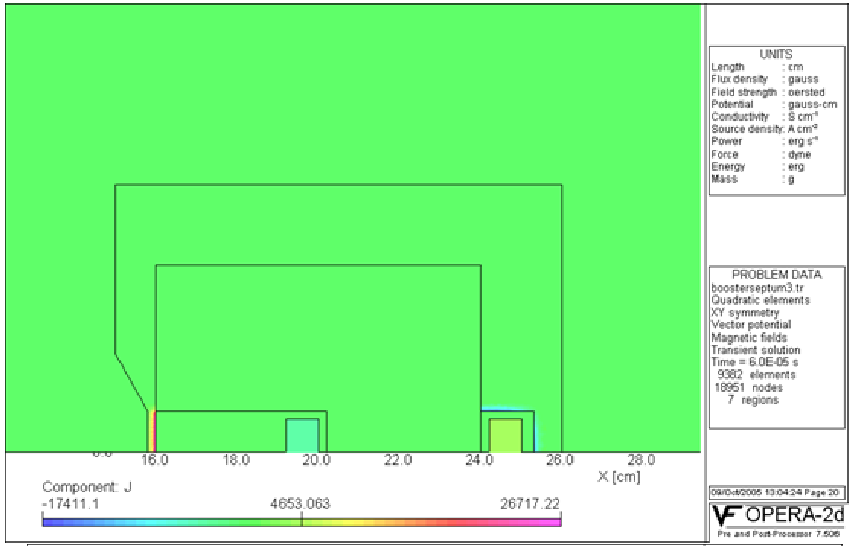
Magnetic inductance

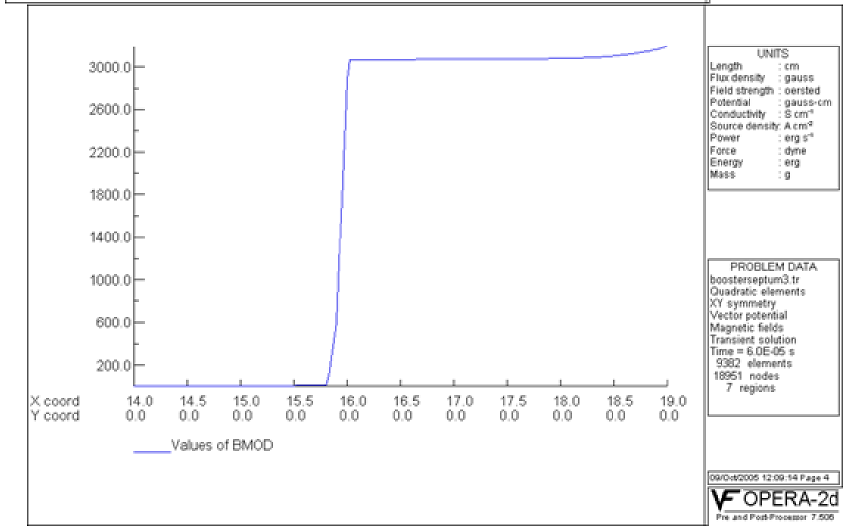
$$L = \frac{2 \times E}{I^2} = \frac{2 \times 109.52}{8691.6^2} = 2.9\ (\mu H)$$

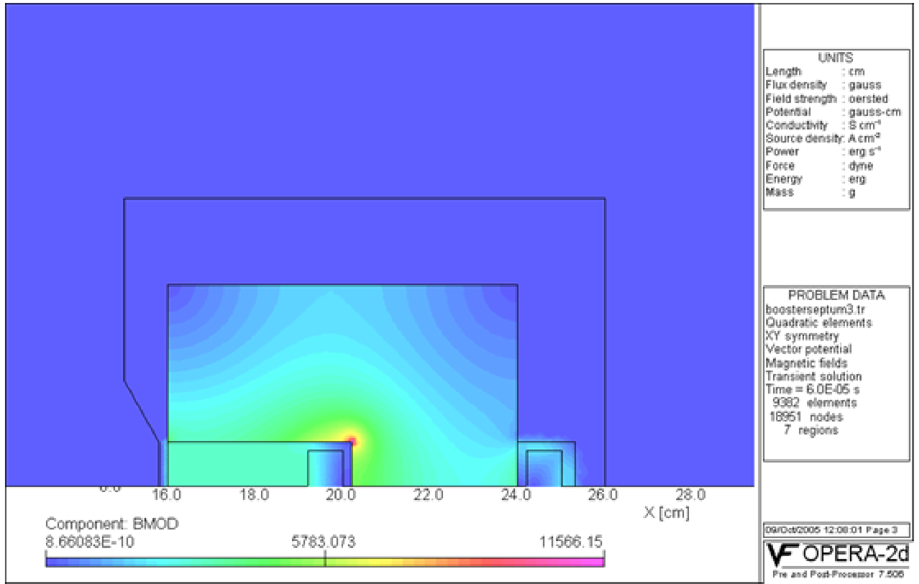


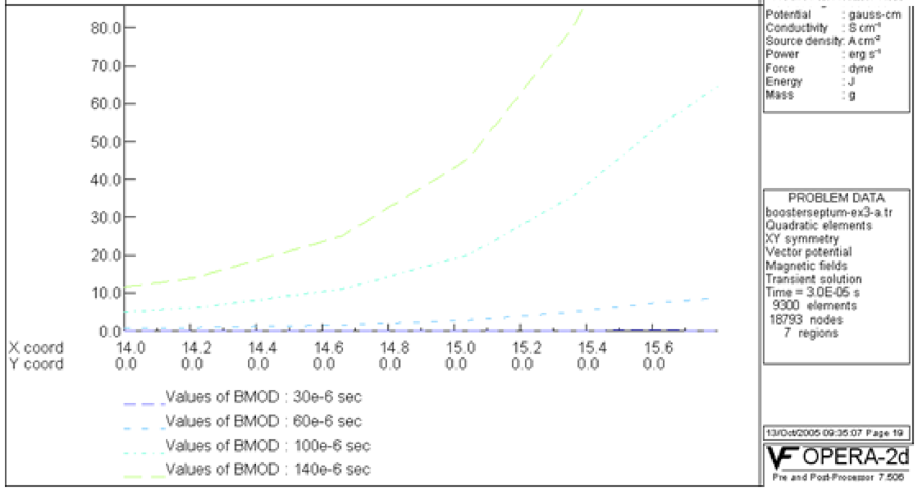


Eddy-current septum



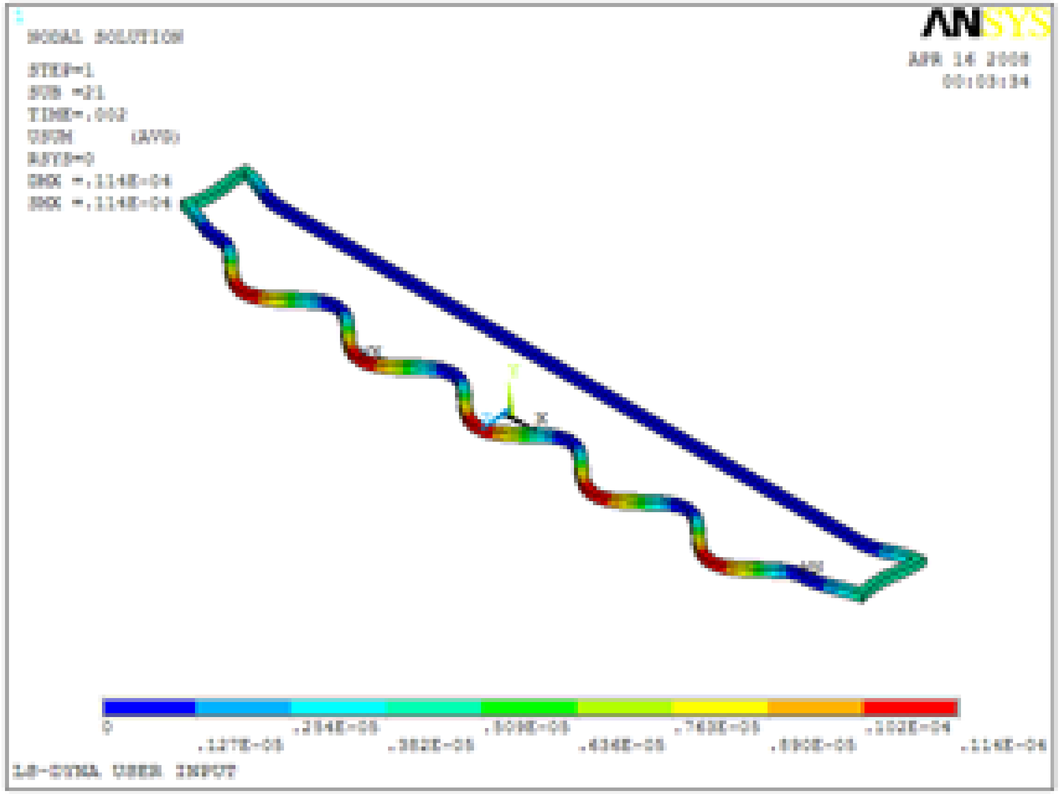


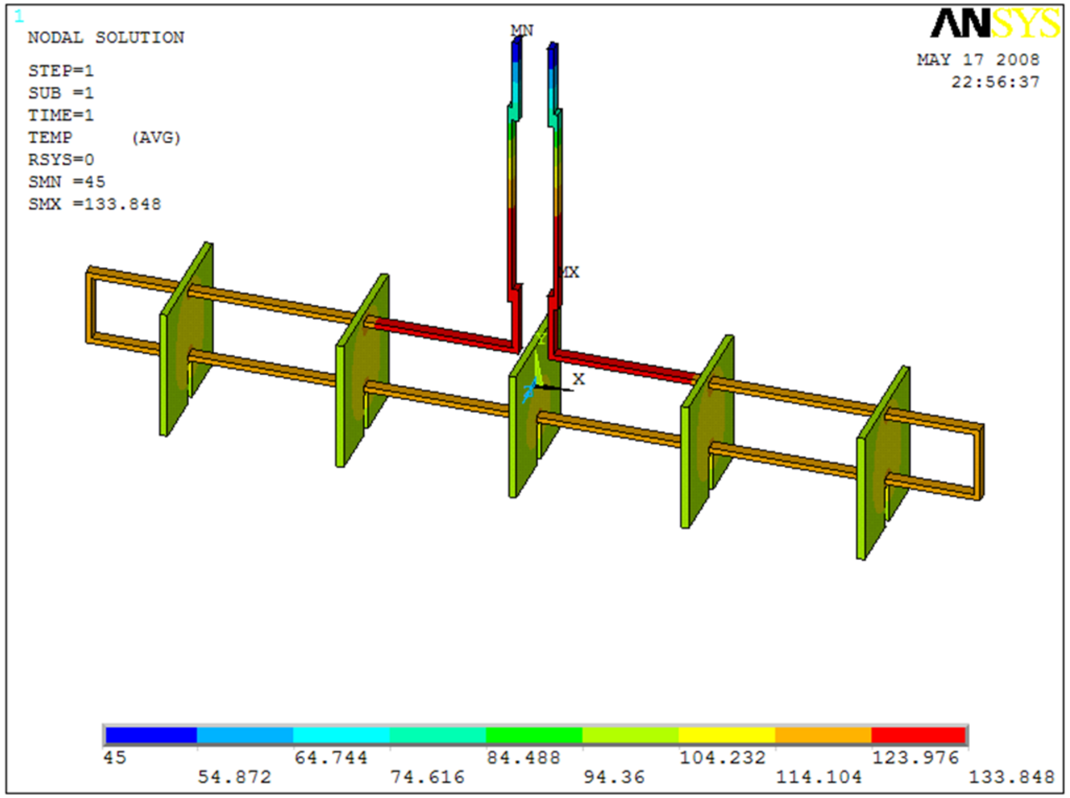




Eddy-current septum

COIL DEFORMATION, THERMAL ANALYSIS





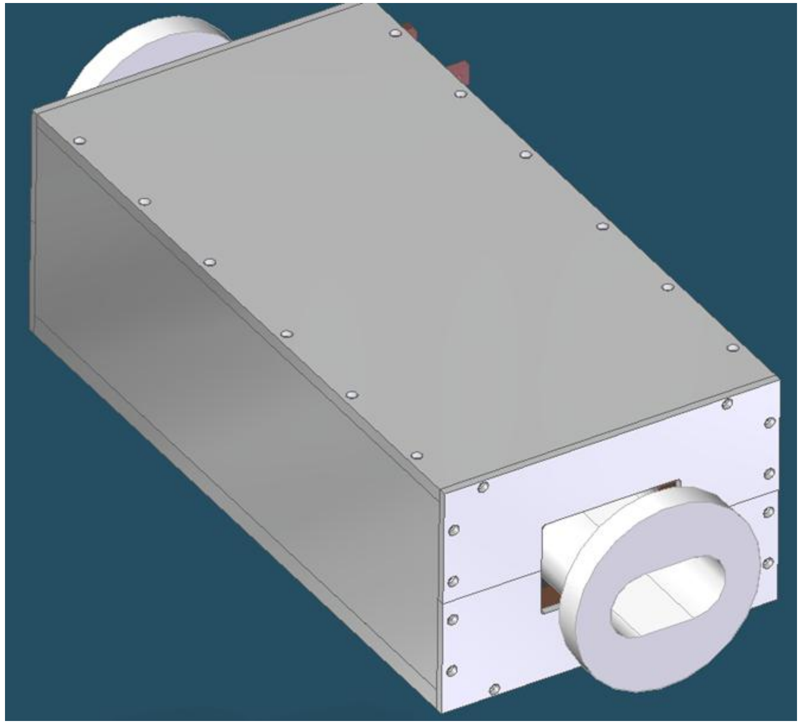
Eddy-current septum

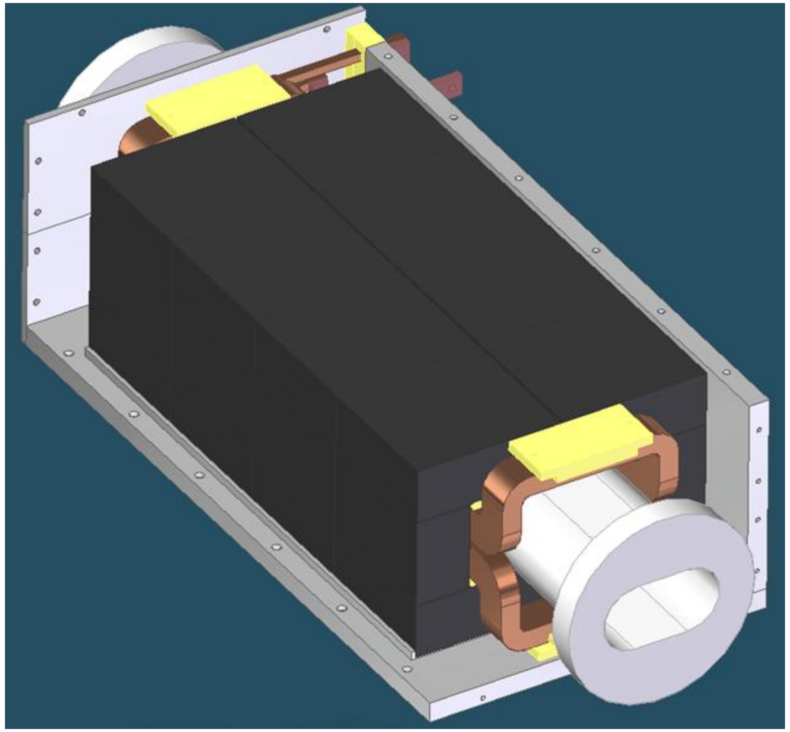
Typical technical data for an eddy-current septum are

- magnetic length per magnet yoke in the range 400 mm to 800 mm;
- gap height of 10 mm to 30 mm;
- septum thickness of 1 mm to 3 mm;
- vacuum of ~10^{-9} mbar, or out of vacuum;
- steel yoke with 0.1 mm to 0.35 mm thick laminations;
- single-turn coil, with water cooling circuits (flow rate: 1 l/min. to 10 l/min.); – current of ~10 kA peak;
- fast pulsed with 50 μs period;
- powered with a capacitor discharge: half-sine or full-sine wave.

Kicker/bumper magnets

- Window frame, ferrite core ;
- Ceramic vacuum chamber;
- Coating/no coating in the inner surface of vacuum chamber;
- Single turn coil of copper plate;





Kicker/bumper magnets

Beam energy 7 MeV，kick angle 30 mrad，magnetic length 0.20m, gap height 0.08m, magnetic efficiency 0.98，then the magnetic flux density

$$B = 0.945272 \times 0.03 \times 0.121473 / 0.2998 / 0.2 = 574.5\,(Gauss)$$

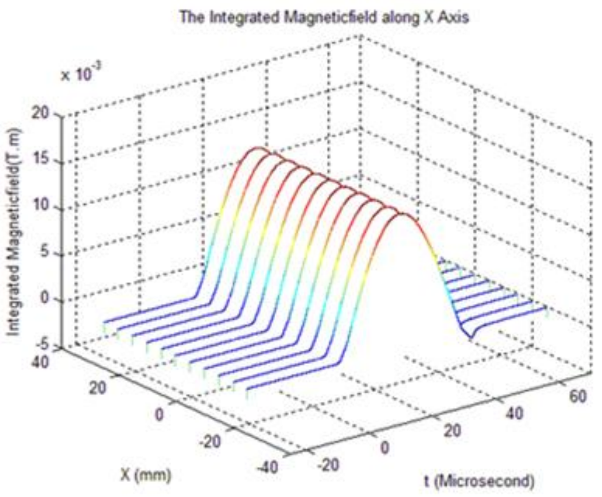
The peak current

$$I_m = 0.05745 * 0.08 / \mu_0 / 0.98 = 3732(A)$$

Current waveform

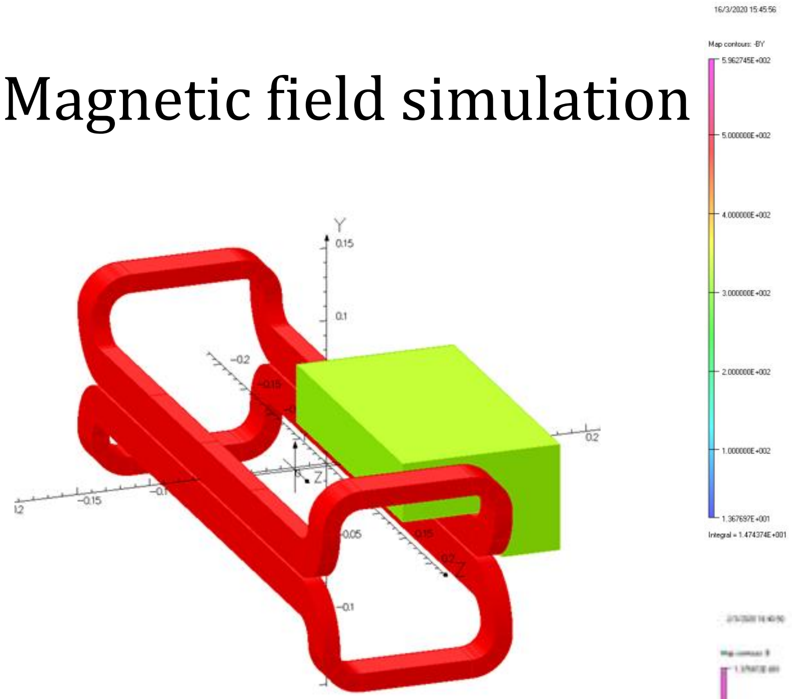
$$I = 3732\sin(2\pi * 12500 * t), \quad 0 \le t \le 40us$$

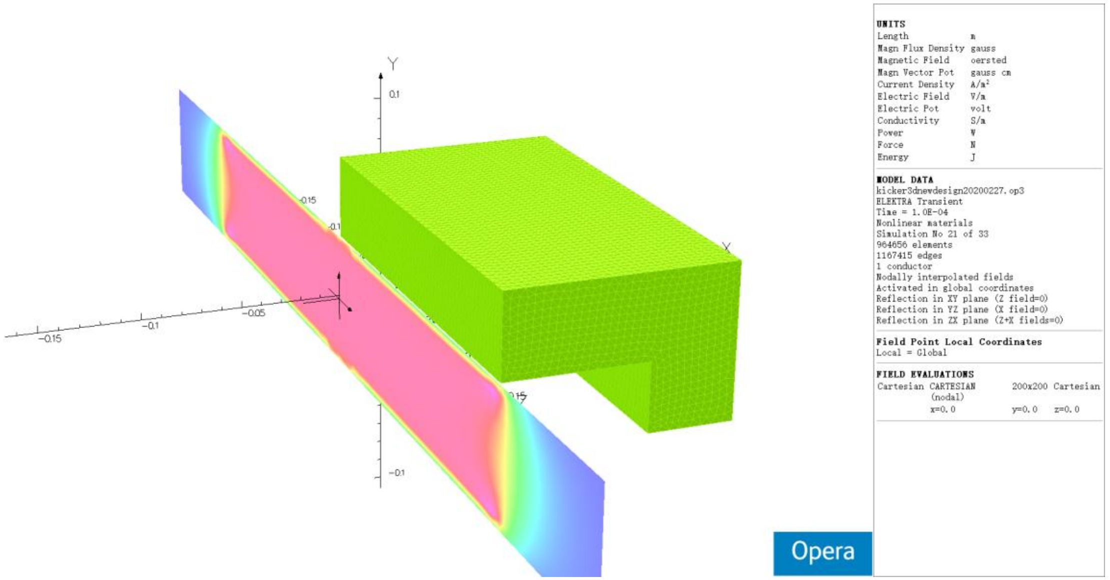
Deflection angle（mrad）	30
Effective length (mm)	200
Magnetic field(Gauss)	574.5
Beam stay clear H*V (mm*mm)	100 × 60
gap（mm）	80
turn	1
efficiency	0.98
inductance(uH)	0.38
Peak current(A)	3732
Waveform/width(us)	half sine/40
repetition(Hz)	0.1～0.2
Charge voltage (V)	258

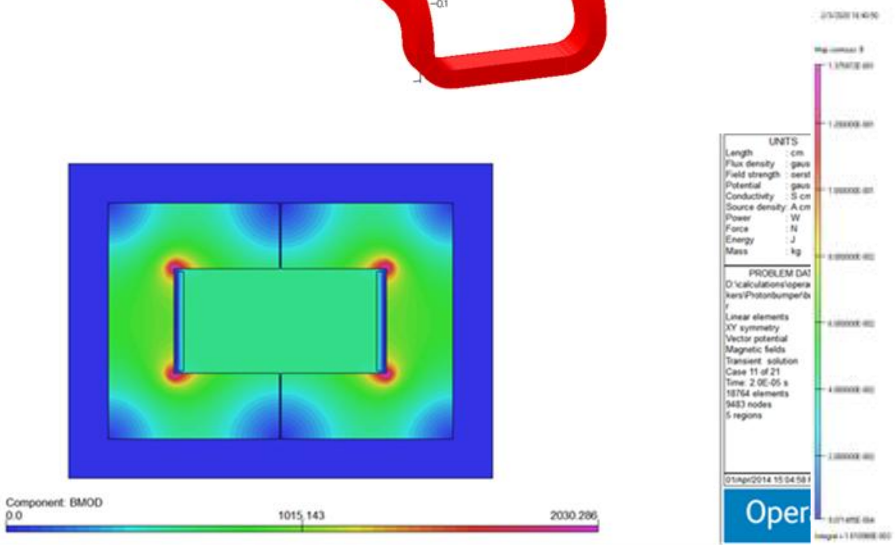


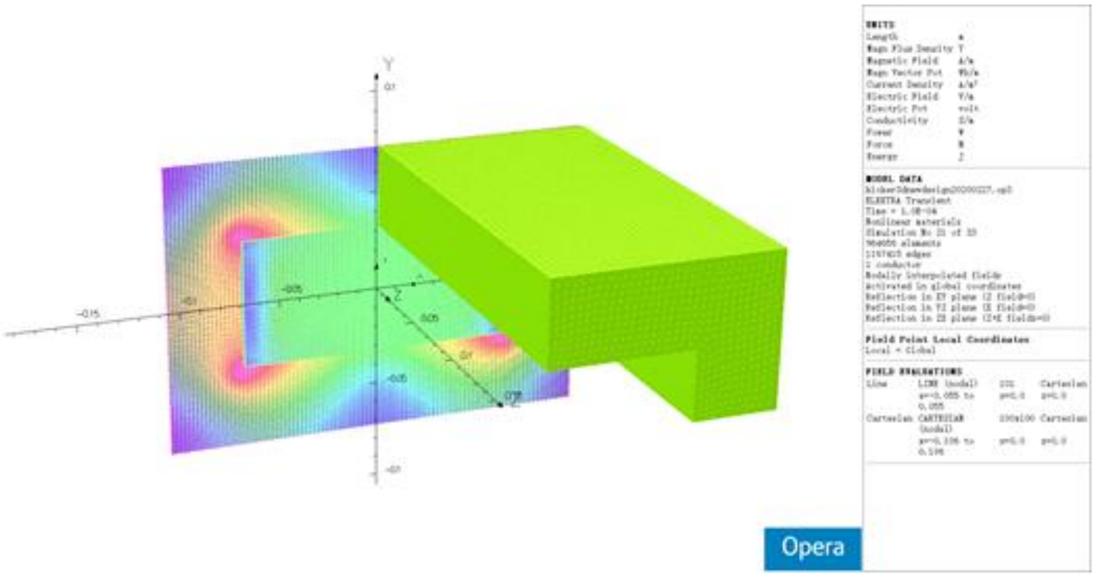
中国科学院上海高等研究院
SHANGHAI ADVANCED RESEARCH INSTITUTE, CHINESE ACADEMY OF SCIENCES

Magnetic field simulation









Kicker/bumper magnets

Magnetic inductance is

$$L_m = \mu_0 A/(g + l/\mu) = 0.459\,(\mu H)$$

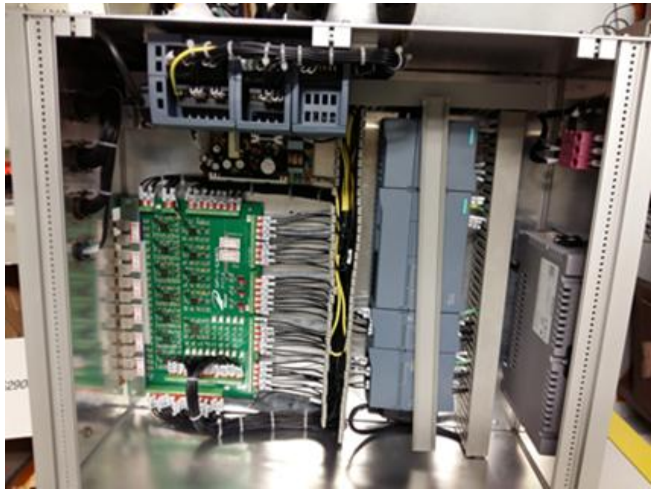
$$L_m = \frac{2\times E}{I^2} = \frac{2\times 20\times 0.163}{3732^2} = 0.468\,(\mu H)$$

The total inductance after considering some stray inductance

$$L = L_m + L_s = 0.47 + 0.5 \approx 0.97\,(\mu H)$$

Peak voltage

$$U_m = L * 2\pi f * I_m = 0.97 * 2\pi * 12500 * 3732/1000000$$
$$= 284.3\,(V)$$



Kicker/bumper magnets

SUMMARY OF TYPICAL FERRITE PROPERTIES

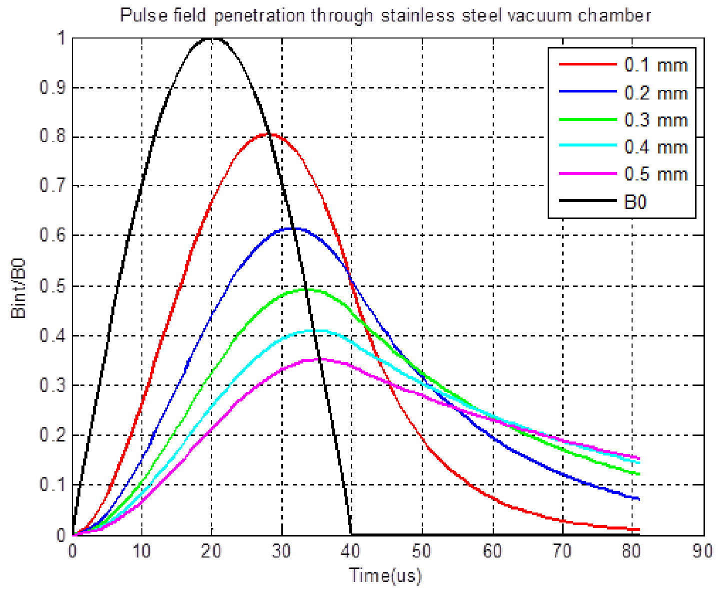
Mn-Zn FERRITES

Property	Symbol	Unit	MN95	MN98	MN67**	MN92	MN8TC	MN80C	MN90	MN8CX	MN30	BT100*	TC6000*	XTC5*	MN60	MN100**	MC25*	MC15K*
Initial Permeability	μ_i	-	1000	1100	1100	1200	1900	2050	2500	3100	4300	4700	7500	6000	6500	9,000	9500	15,000
Maximum Permeability	μm	-	6800	4500	7500	8000	6000	5000	6200	3700	7500	6400	13000	9300	8500	11,500	12,000	20,000
Saturation Flux Density	Bs	Gauss	5000	4800	5250	4800	4600	4900	4200	4500	4400	4500	3600	4500	4500	4700	3800	3900
Remanent Flux Density	Br	Gauss	2000	3600	2100	2100	1750	1600	600	850	750	1000			800	600		
Coercive Force	Hc	Oersted	0.14	0.29	0.15	0.12	0.15	0.18	0.085	0.20	0.07	0.12			0.08	0.03		
Curie Temperature	Tc	ºC	275	265	285	275	185	230	215	195	170	175	104	165	170	170	120	120
dc Volume Resistivity	Þ	ohm-cm	2500	5000	250	325	10^3	1600	4000	1200	150	200	5	60	500	200	149	10
Bulk Density	ρ	g/cc	4.7	4.7	4.7	4.7	4.5	4.75	4.42	4.7	4.75	4.85	4.85	4.83	4.8	4.8	4.9	4.85

* available only in pressed & fired parts
** available only in machined parts

Ni-Zn FERRITES

Property	Symbol	Unit	N40	C2075	XTH2	C2050	XCK	C2025	CM48	CM5	C2010	CM400	CMD10	CN20	CN20B	CMD5005
Initial Permeability	μ_i	-	15	50	80	100	125	175	190	290	340	400	625	925	1375	2100
Maximum Permeability	μm	-	50	270	440	600	350	850	1300	1200	1500	1600	3000	5000	4100	5500
Maximum Flux Density	B_M	Gauss	2500	3000	3600	3700	2500	3900	4400	3100	3900	4600	4300	4000	3500	3300
Remanent Flux Density	Br	Gauss	950	950	1200	2300	650	2500	3000	1700	2800	2400	2900	2600	2100	1300
Coercive Force	Hc	Oersted	8.00	2.60	2.00	2.00	0.95	1.40	1.00	0.65	0.70	0.65	0.36	0.20	0.20	0.12
Curie Temperature	Tc	ºC	600	420	300	340	400	270	410	280	245	300	250	185	160	130
dc Volume Resistivity	Þ	ohm-cm	10^{10}	10^9	10^8	10^9	10^9	10^{10}	10^{10}	10^8	10^7	10^{10}	10^{10}	10^{10}	10^8	10^{10}
Bulk Density	ρ	g/cc	4.8	4.6	4.6	4.6	4.25	4.7	5.2	4.4	5	5.15	5.2	5.24	5	5.27



Summary

- Because of the time limit, a lot of topics aren't covered；
- Injection and extraction device design, especially kicker and bumper, must be well integrated with its matching power supplies; and some accelerator physics knowledge is necessary.
- Septa design is a very complicated engineering thing, it involves many subjects such as accelerator physics, electrical engineering, material science, mechanics, and vacuum knowledge;
- Last but not least, engineering know-hows are very important, you can get them from practicing or/and from others.

Thank you for your attentions!

Any questions?