Accelerator Physics*

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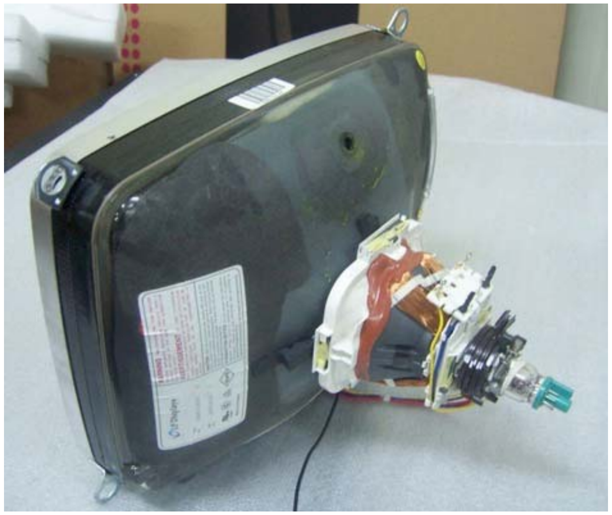
(*These slides are based on the lecture slides prepared by Prof. Litvinenko and you can find more materials from CASE website: http://case.physics.stonybrook.edu/index.php/Main_Page)



Billions of these tubes were made in 20th century – now most of them are in the landfills…

Outline

- How accelerators work
  - Overview of an accelerator facility
  - Charged particle sources
  - Way to accelerate charged paricles
  - Circular accelerator
    - ➢Phase stability/auto-phasing (how to keep particles together in the longitudinal direction)
    - ➢Orbit stability (how to keep particle together in the transverse direction)

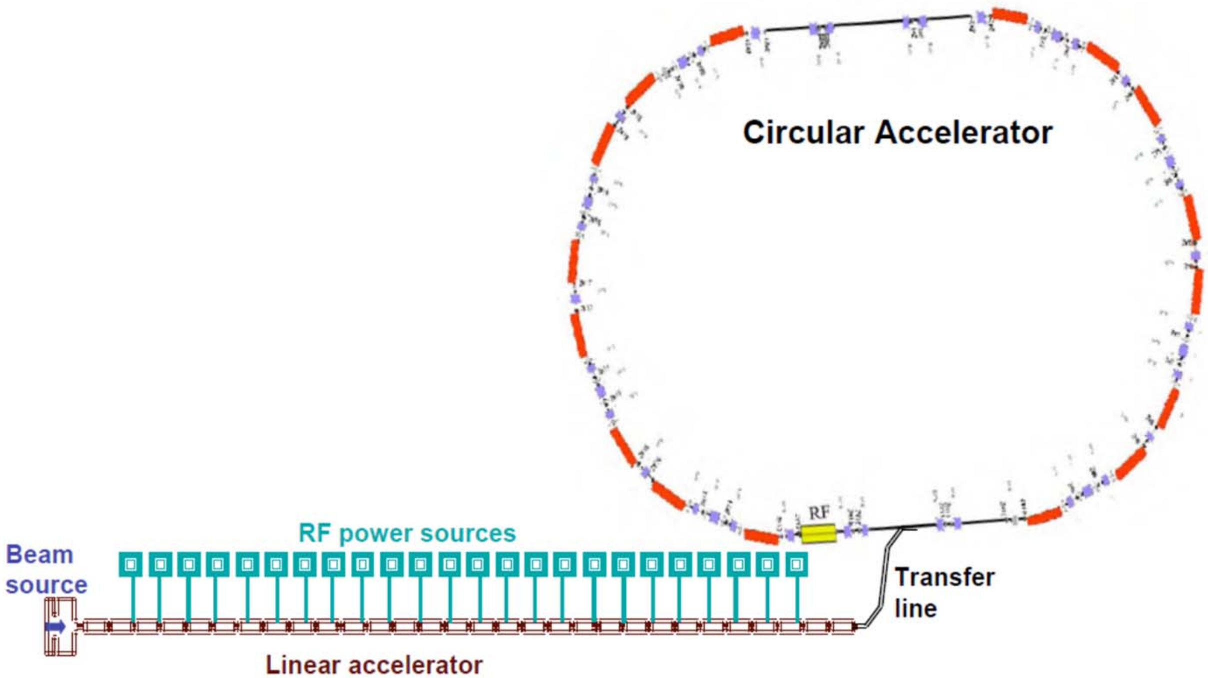
Outline continued

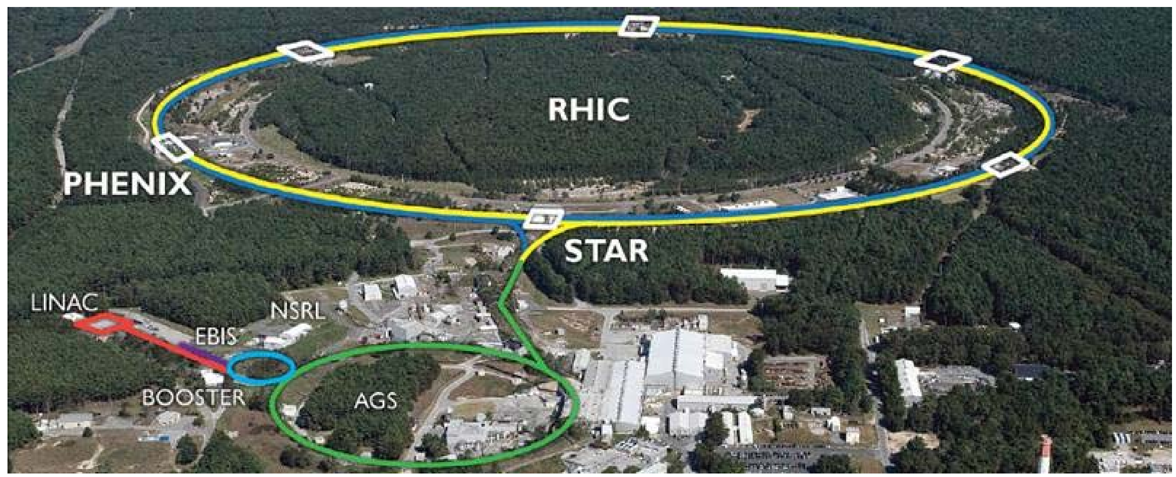
- Application of accelerators
  - Scientific applications
    - Fundamental particle physics: colliders
    - Fundamental sciences using of synchrotron radiation, and FEL radiation
  - Medical
    - Medical diagnostics, cancer therapy, pharmaceutical research
  - Material science
    - Ion implant (essential for semiconductor industry), crosslinking of rubber, electron beam welding
  - Sterilization

What Accelerators Are Good For

- High Energy Physics
  - Explore the electro-weak bosons Z, W (LEP)
  - Find and exploit “new“ and heavy quarks (Tevatron)
  - Find the HIGGS (LHC)
  - Well, this list will never be complete .....
- Nuclear Physics (RHIC, SPS)
  - First evidence of a new state of matter, quark gluon plasma? (SPS)
  - Create the QGP and determine its properties (RHIC)
  - Could it be something else? (EIC)
- Chemistry, Biology, Medicine, Material Sciences
  - Find the structure of molecules, proteins, cells…
  - Could people survive interstellar travel? (NASA Space Radiation Laboratory (NSRL))
  - Time-resolved structural changes in a natural (fsec) time scale
- Civil, Industrial and Military Applications
  - Treat cancers, produce isotopes for medical imaging, sterilize products…
  - Scan containers in ports for undesirable content (n’s?)
  - High power free electron lasers as weapons for a ship defence

Overview: Generic accelerator facility





What do we accelerate?

- Usually we accelerate stable **charged** particles (particle has to be charged since we use electric field to accelerate them)

Particle	Charge	Charge, C	Rest mass, kg	Rest mass, eV/c^2
Electron, e^-	-e	$-1.60 \cdot 10^{-19}$	$9.11 \cdot 10^{-31}$	$0.511 \cdot 10^6$
Positron, e^+	+e	$+1.60 \cdot 10^{-19}$	$9.11 \cdot 10^{-31}$	$0.511 \cdot 10^6$
Proton, p	+e	$+1.60 \cdot 10^{-19}$	$1.6726 \cdot 10^{-27}$	$938.27 \cdot 10^6$
Antiproton	-e	$-1.60 \cdot 10^{-19}$	$1.6726 \cdot 10^{-27}$	$938.27 \cdot 10^6$
Ion, $^Z{}_A$	Ze		$\sim A \cdot u$	$\sim A \cdot u$
Atomic mass unit, u			$1.6605 \cdot 10^{-27}$	$931.49 \cdot 10^6$

Speed of the light, c **$2.99792\ 10^8$ m/sec**

$$1eV = 1.602 \cdot 10^{-19} J$$

1 eV – energy gained by an electron passing through a 1V potential differential

- Dedicated radioactive ion facility to accelerator unstable ion: FRIB at MSU
- There are discussions and developments towards a collider using unstable muon beam which has 2 microsecond lifetime in the rest frame.

How to tell the performance of an accelerator?

(Key parameters)

- **Energy** of the particle : keV, MeV, GeV, TeV…

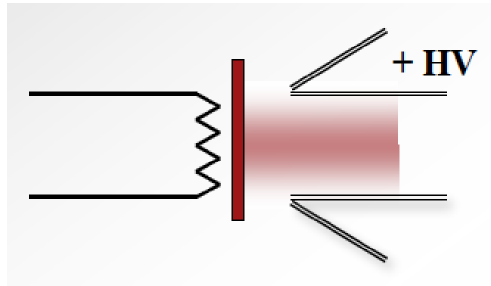
  Au… 28 TeV at RHIC, 7 TeV protons at LHC, 10 keV electrons in X-ray tube, few MeV protons in Van-De-Graph (SBU basement),
- **Luminosity** or event rate, instantaneous and integrated luminosity
- **Beam intensity -** Number of particles per second, i.e. beam current (=> instantaneous luminosity)
- **Beam quality -** transverse and longitudinal emittance, which is simply phase-space (remember Louisville theorem) occupied by the particles and its projections (=> instantaneous luminosity)
- **Beam lifetime** – number of particles lost per second, i.e. Loss rate, lifetime limiting processes (=> integrated luminosity)

1keV = 10^3 eV, 1 MeV = 10^6 eV, 1 GeV = 10^9 eV , 1TeV= 10^{12}eV, …1eV = 1.6 10^{-19} J

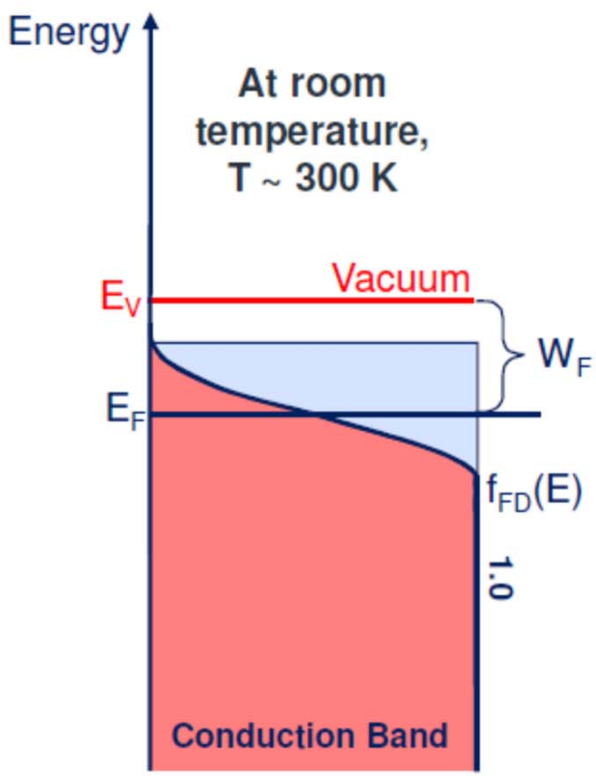
1 nsec = 10^{-9} sec, 1 psec = 10^{-12} sec, 1 fsec = 10^{-15} sec, 1 asec = 10^{-18} sec….

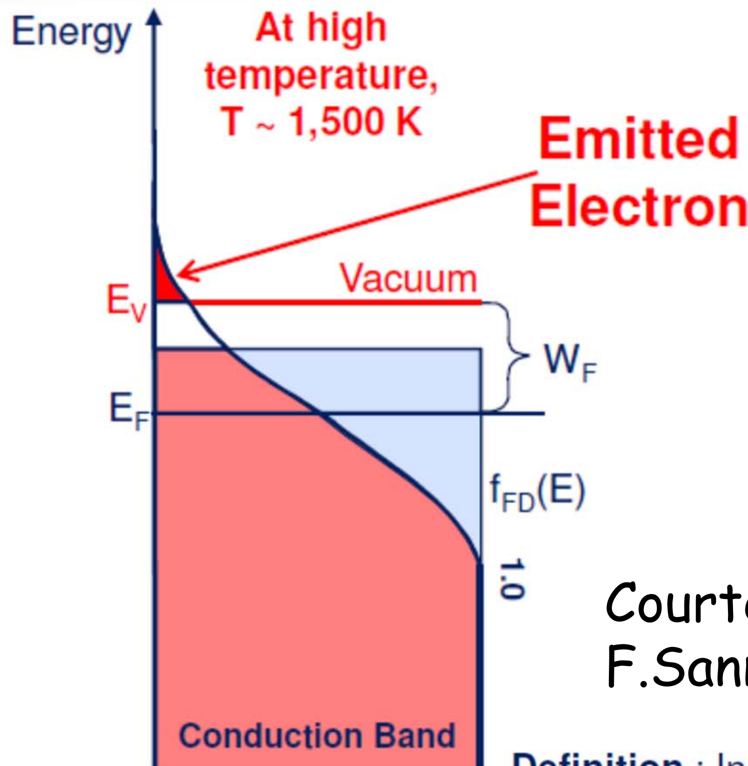
Thermionic electron source

- Heated metals



Definition: the **work function** W_F is the energy needed to bring an electron from the Fermi level to the vacuum level





Courtesy to F.Sannibale

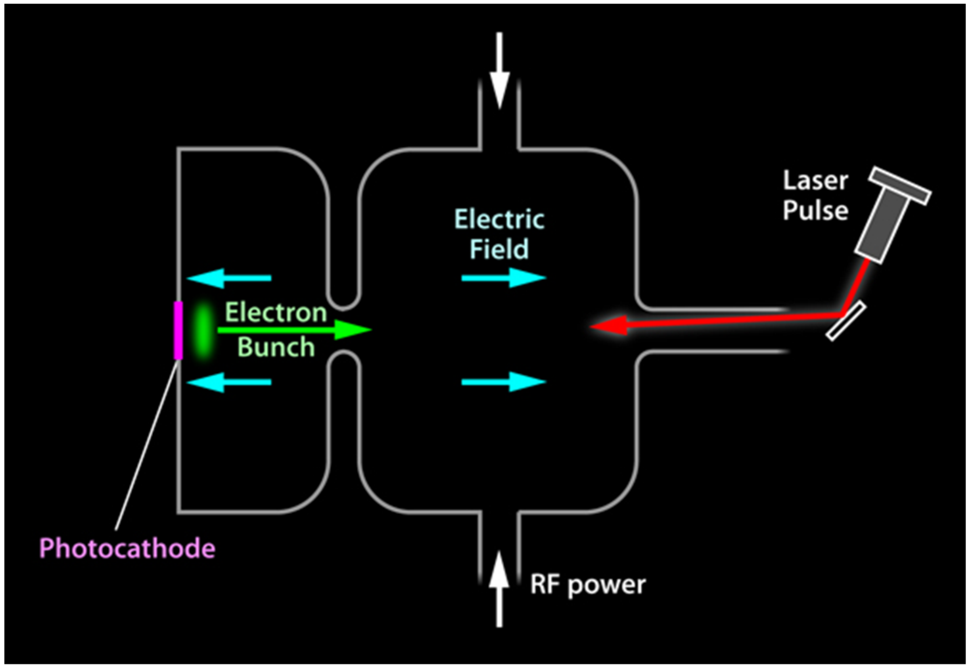
$$J = AT^2 e^{-w/kT}$$

$$A = \frac{4\pi mk^2 e}{h^3} = 1.20173\times10^6 \ \ A m^{-2} K^{-2}$$

$w \equiv work \ \ function$

Definition : In a system of fermions the **Fermi energy E_F** is the energy of the highest occupied state at zero temperature.

Photo-emission electron source



A **photocathode** is a surface engineered to convert light (photons) into electrons using the photoelectric effect. Photocathodes are important in accelerator physics where they are used inside of a photoinjector to generate high brightness electron beams.

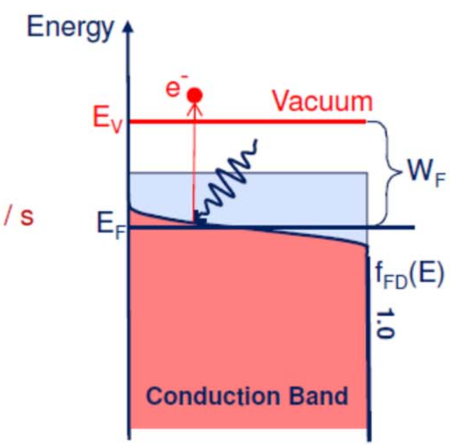
$$Photon\ Energy = E_{ph} = h\nu$$

photon frequency

Planck Constant= 6.626068 × 10^{-34} m² kg / s

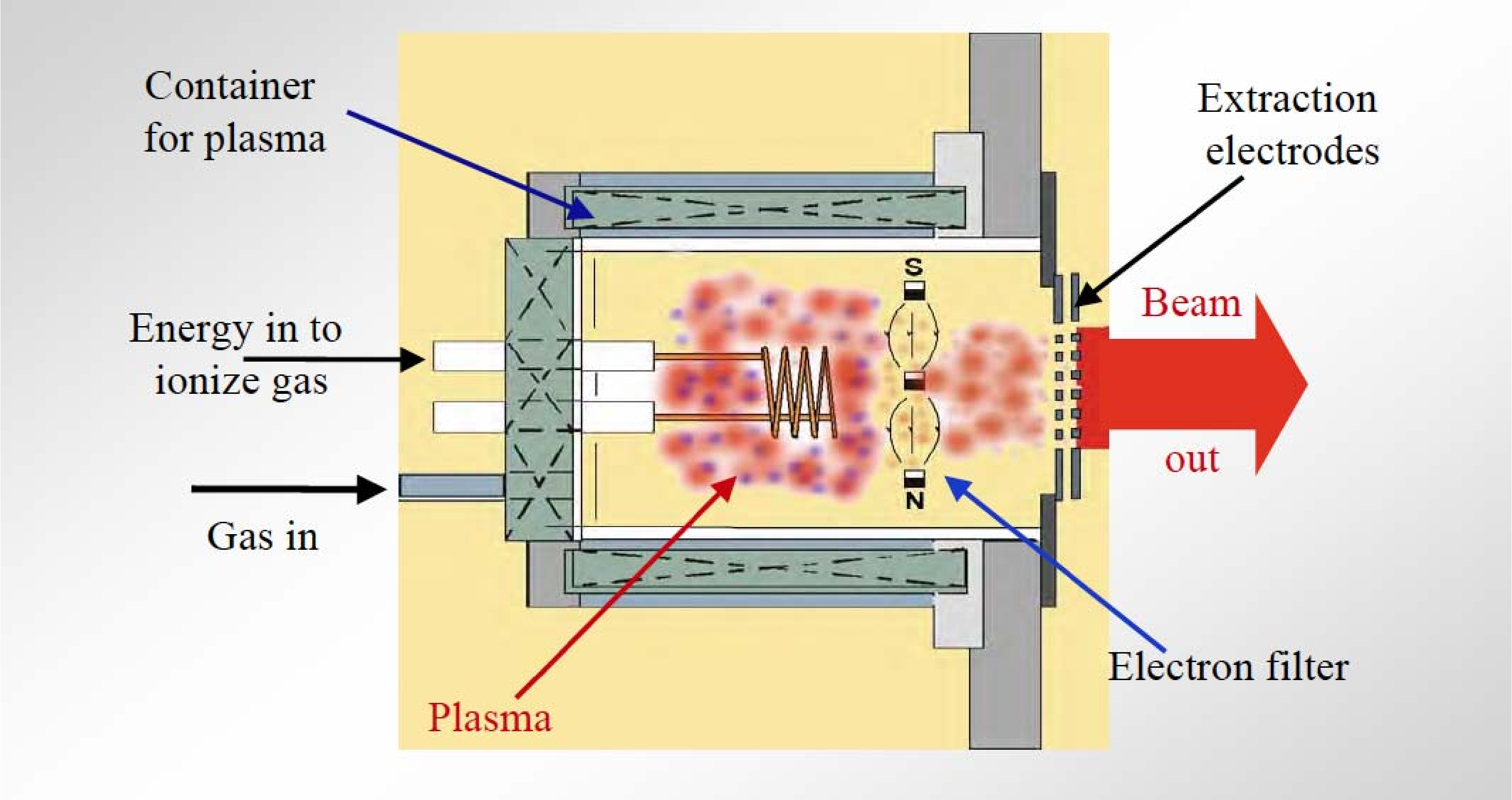
$$If\ \ E_{ph} \geq W_F$$

$$T_{e-} = E_{ph} - W_F$$



Courtesy to F.Sannibale

Typical ion source



Electron beams can also be used to ionize the gas or sputter ions from a solid

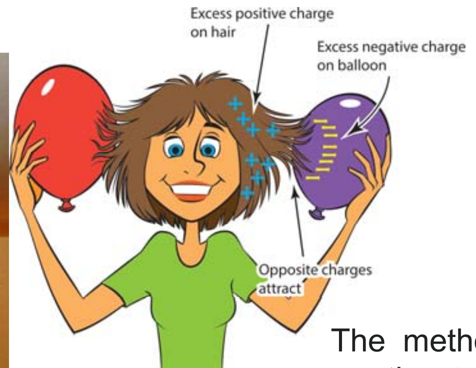
Courtesy of W. Barletta

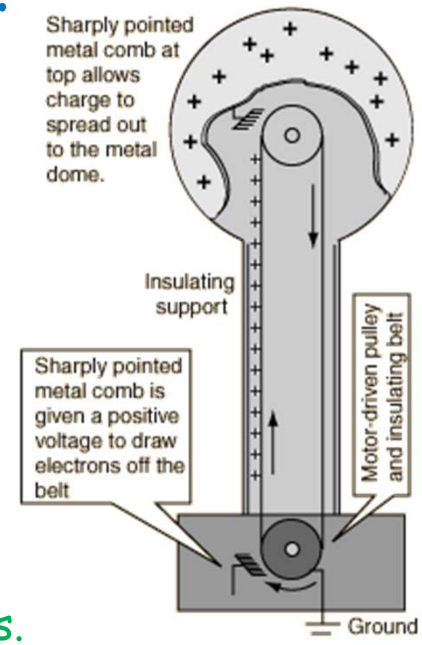
How to Accelerate charged particle?

- Methods of acceleration:
  - Electrostatic acceleration
  - Induction acceleration
  - Radio-Frequency (RF) fields
  - Advanced acceleration methods
    - Plasma wakefield accelerations
    - Dielectric wakefield accelerators
    - Photonic gap acceleration

How to Accelerate charged particle?

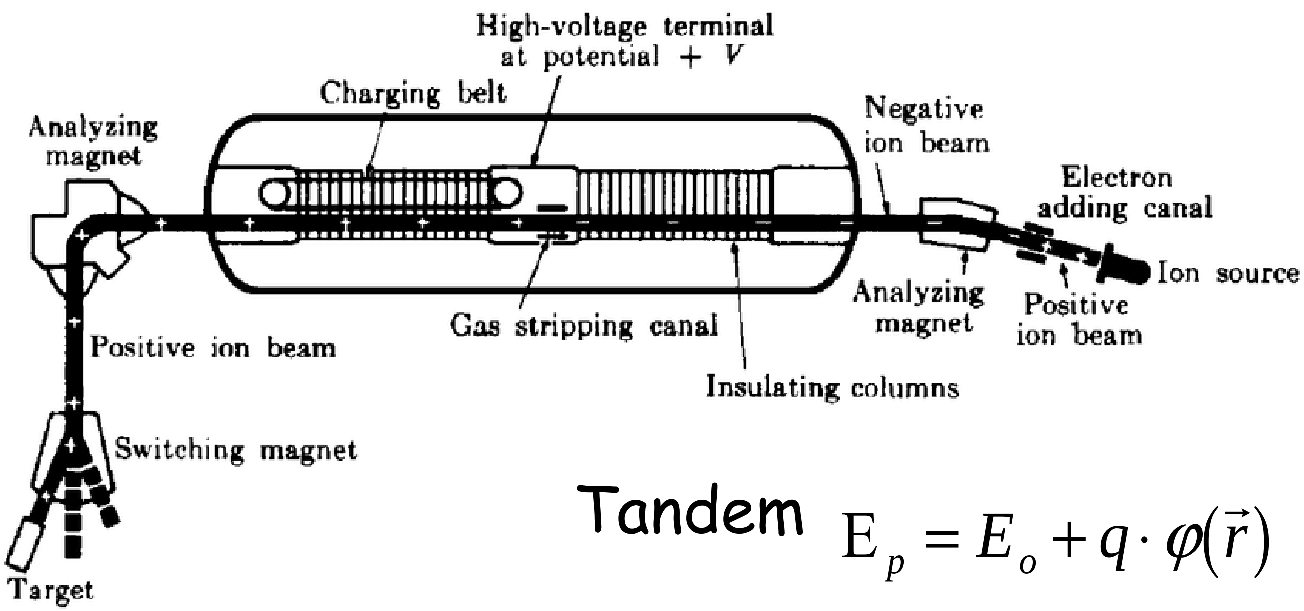
Electrostatic: Van De Graff Generator



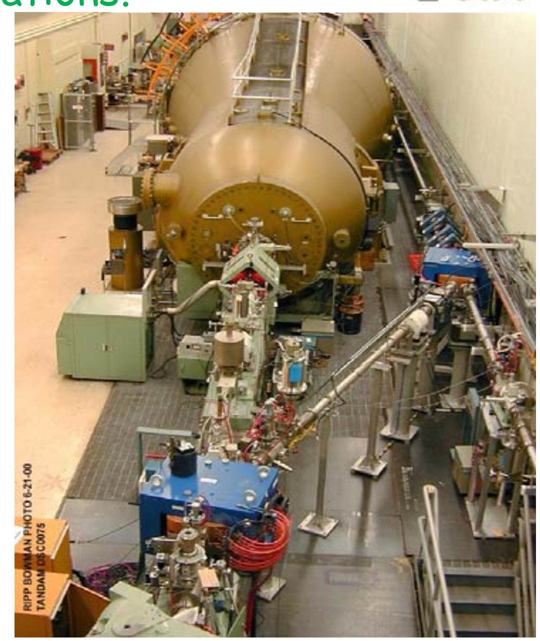


The method of charging is based on the triboelectric effect, such that simple contact of dissimilar materials causes the transfer of some electrons from one material to the other.

Tandem accelerator is an updated configuration with two accelerations.



Tandem $E_p = E_o + q \cdot \varphi(\vec{r})$

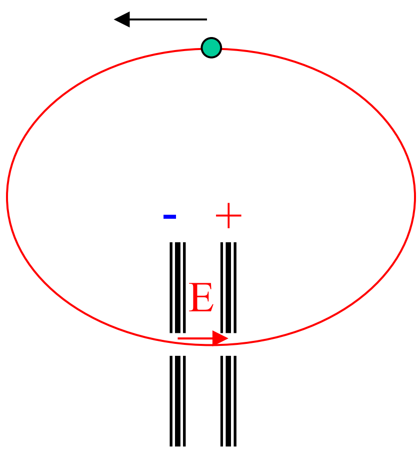


What LIMITS electrostatic acceleration?

Is it possible to accelerate particle many times in the same DC accelerator?

NO!

EM II: 1st pair of Maxwell's Equations



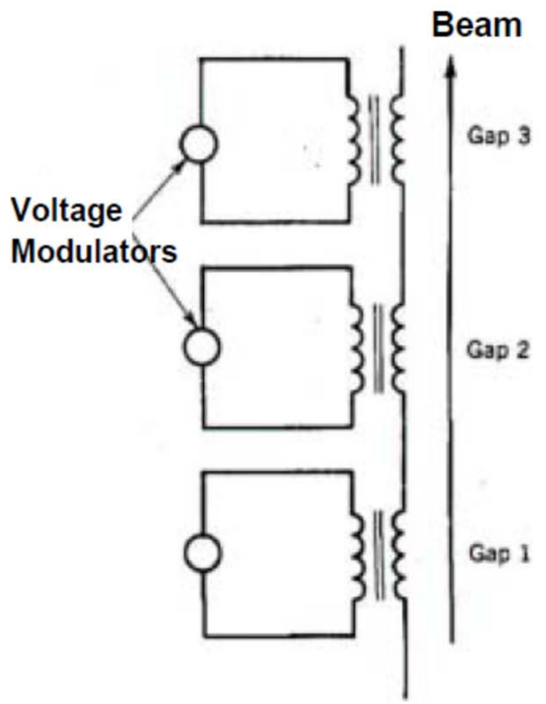
$$\vec{E} = -grad\varphi - \frac{1}{c}\frac{\partial \vec{A}}{\partial t};$$
$$\vec{H} = curl\vec{A};$$

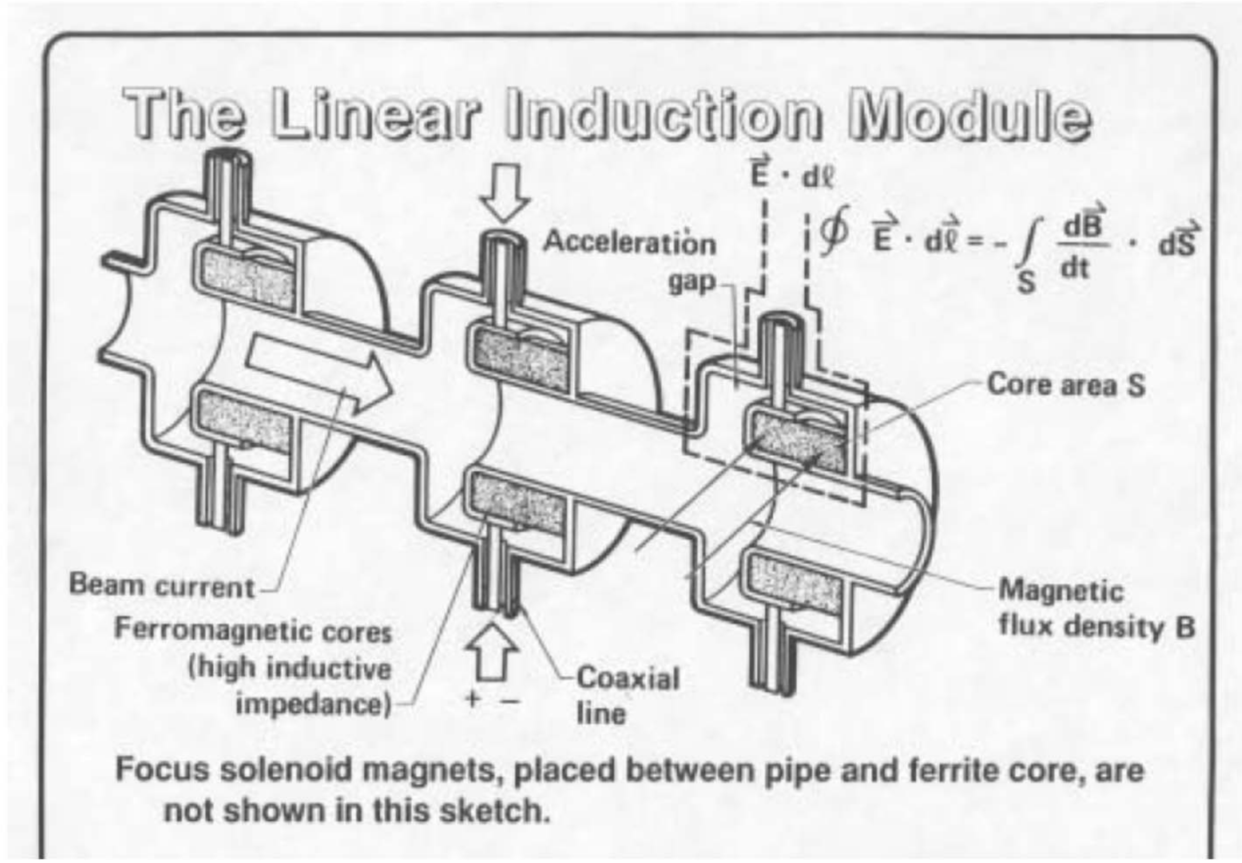
$$dE = q\left(\vec{E}\cdot d\vec{r}\right) \Rightarrow \Delta E_{turn} = q\oint \vec{E}\cdot d\vec{r} = -q\left(\varphi\left(\vec{r}_o, t+\tau\right) - \varphi\left(\vec{r}_o, t\right) + \frac{1}{c}\oint \frac{\partial \vec{A}}{\partial t}\cdot d\vec{r}\right);$$

Hence static field has limitation: $\frac{\partial \vec{A}}{\partial t} = 0,\ \frac{\partial \varphi}{\partial t} = 0 \Rightarrow \Delta E_{turn} = 0;$

Induction Accelerator

Cells and beam act like
1:1 transformers



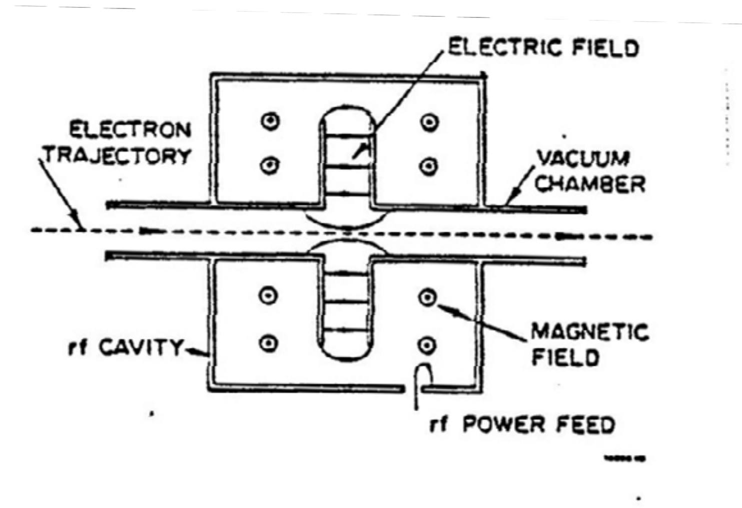


Changing magnetic fields generate accelerating electric field.

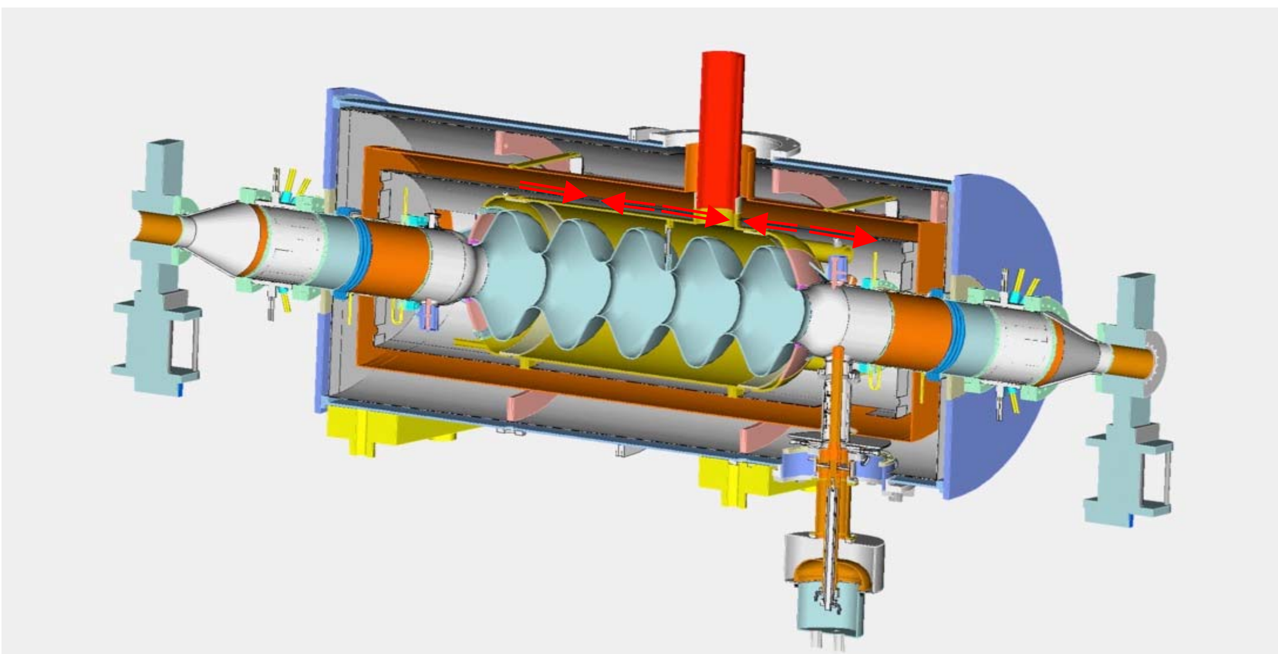
Pro/Cons: Low energy, high current applications:

- Induction accelerators can handle very large currents (up to 10KA)
- Generate much **lower voltage** than typical RF accelerators.

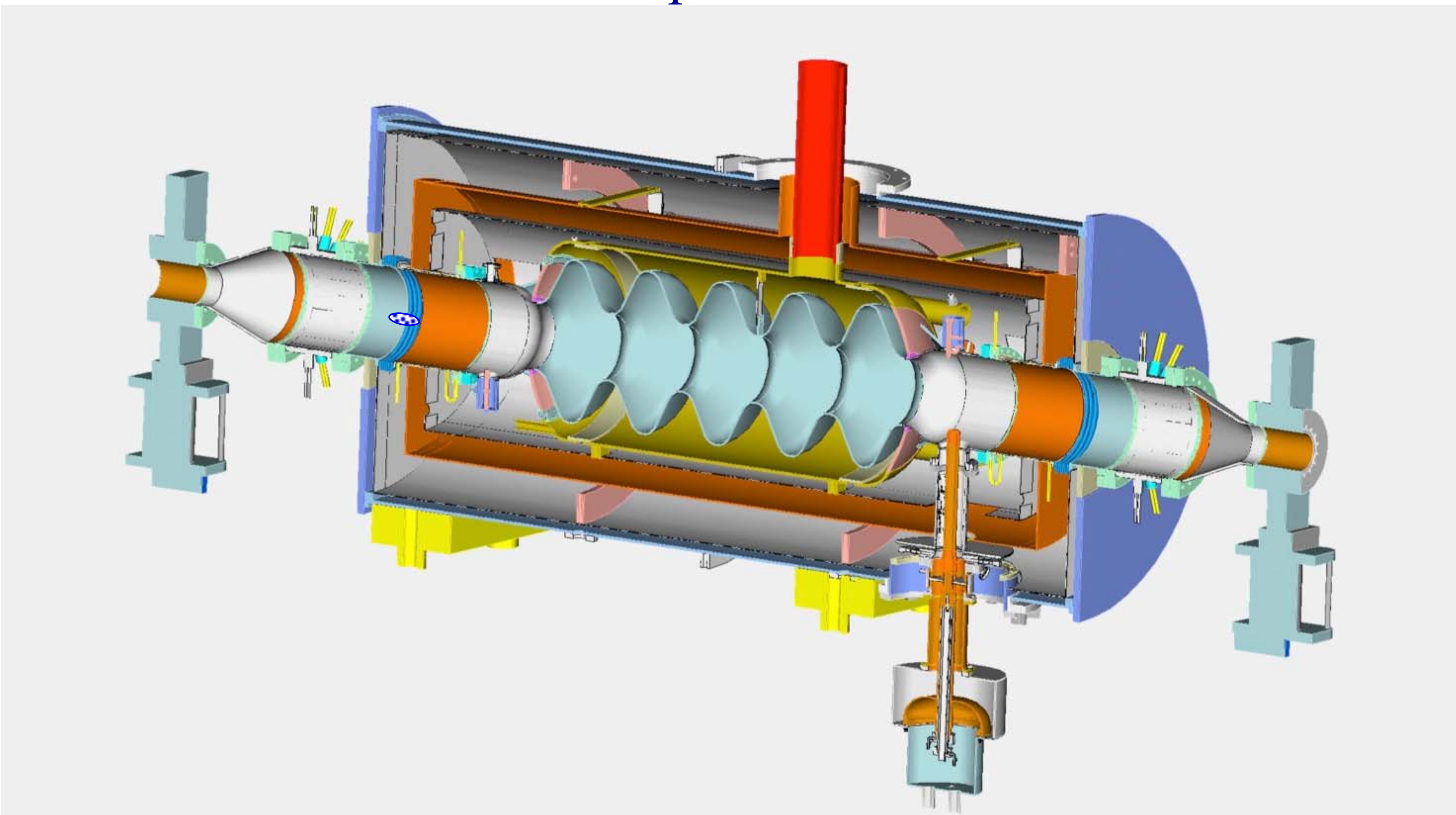
RF accelerators



-Schematic diagram of an rf accelerating cavity.



How β=1 RF accelerator works?
In pictures



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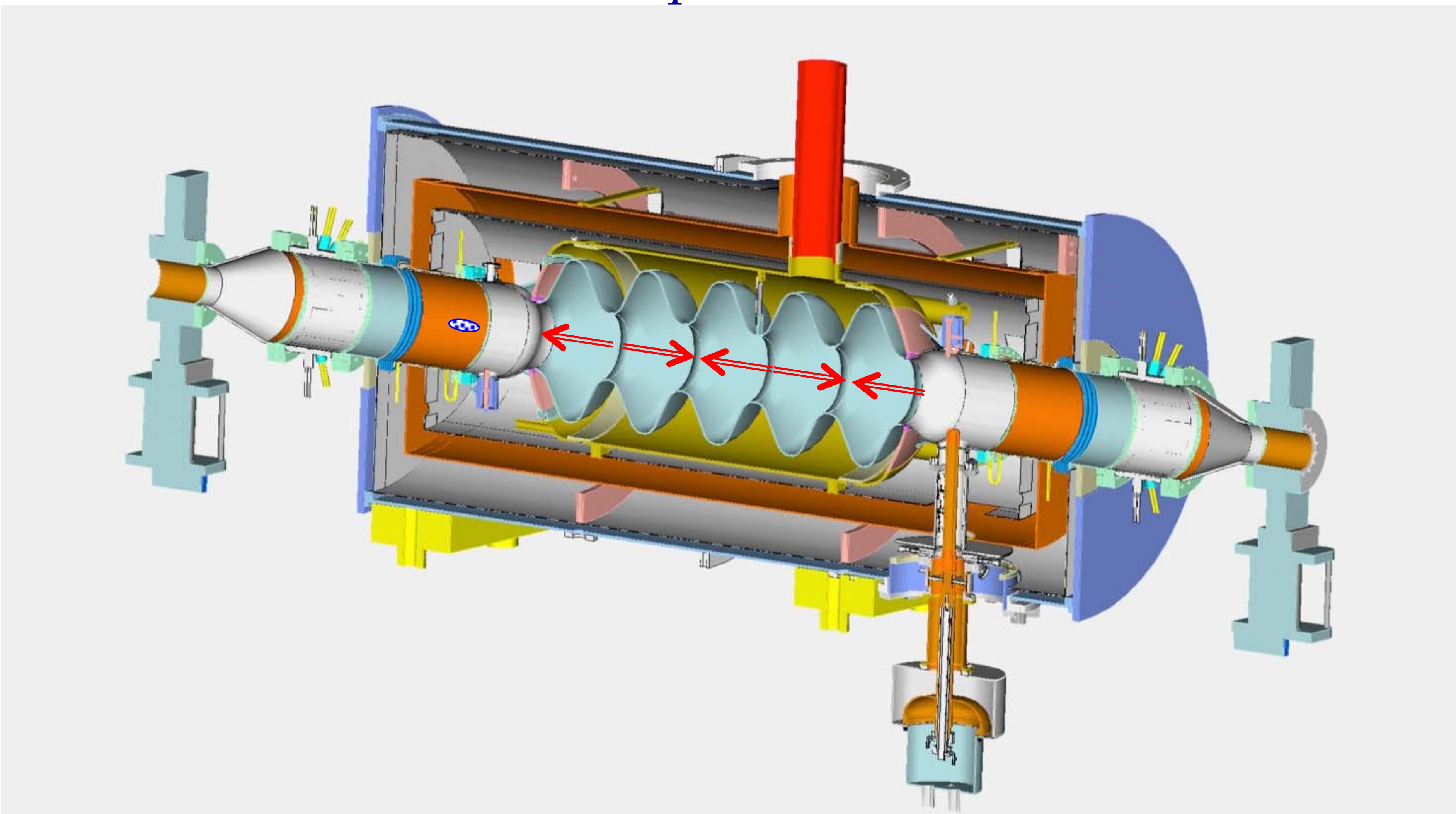

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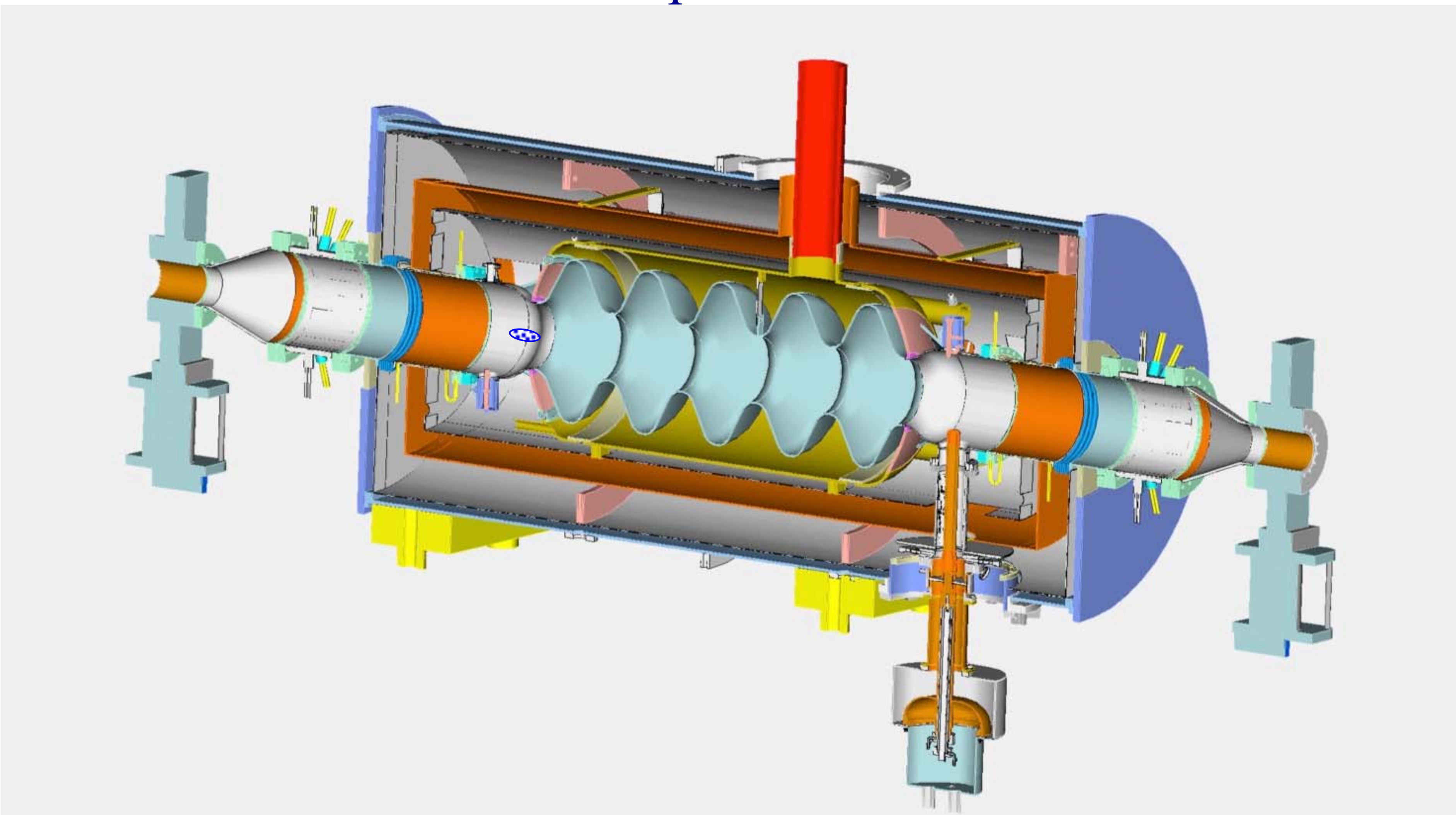

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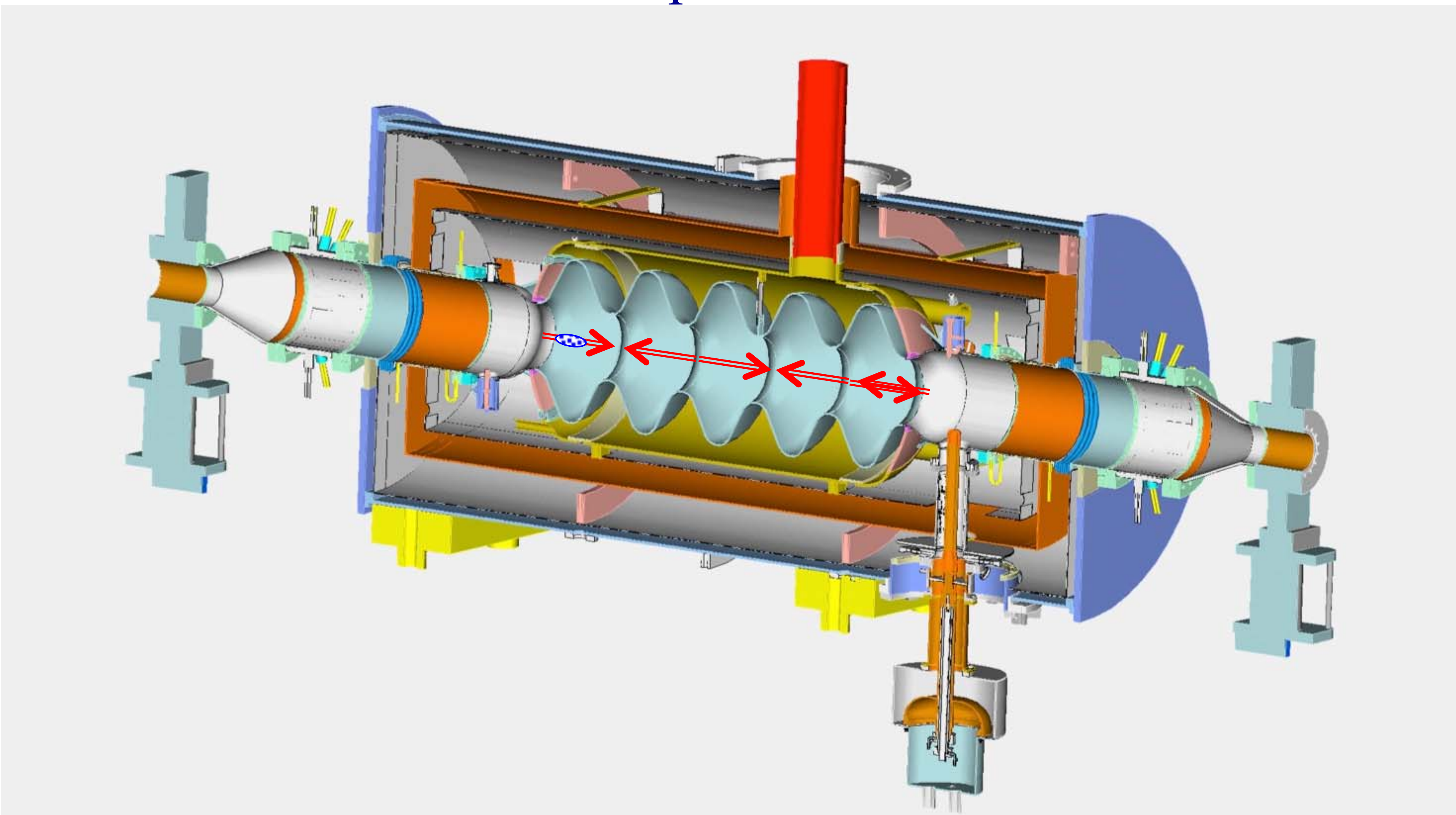

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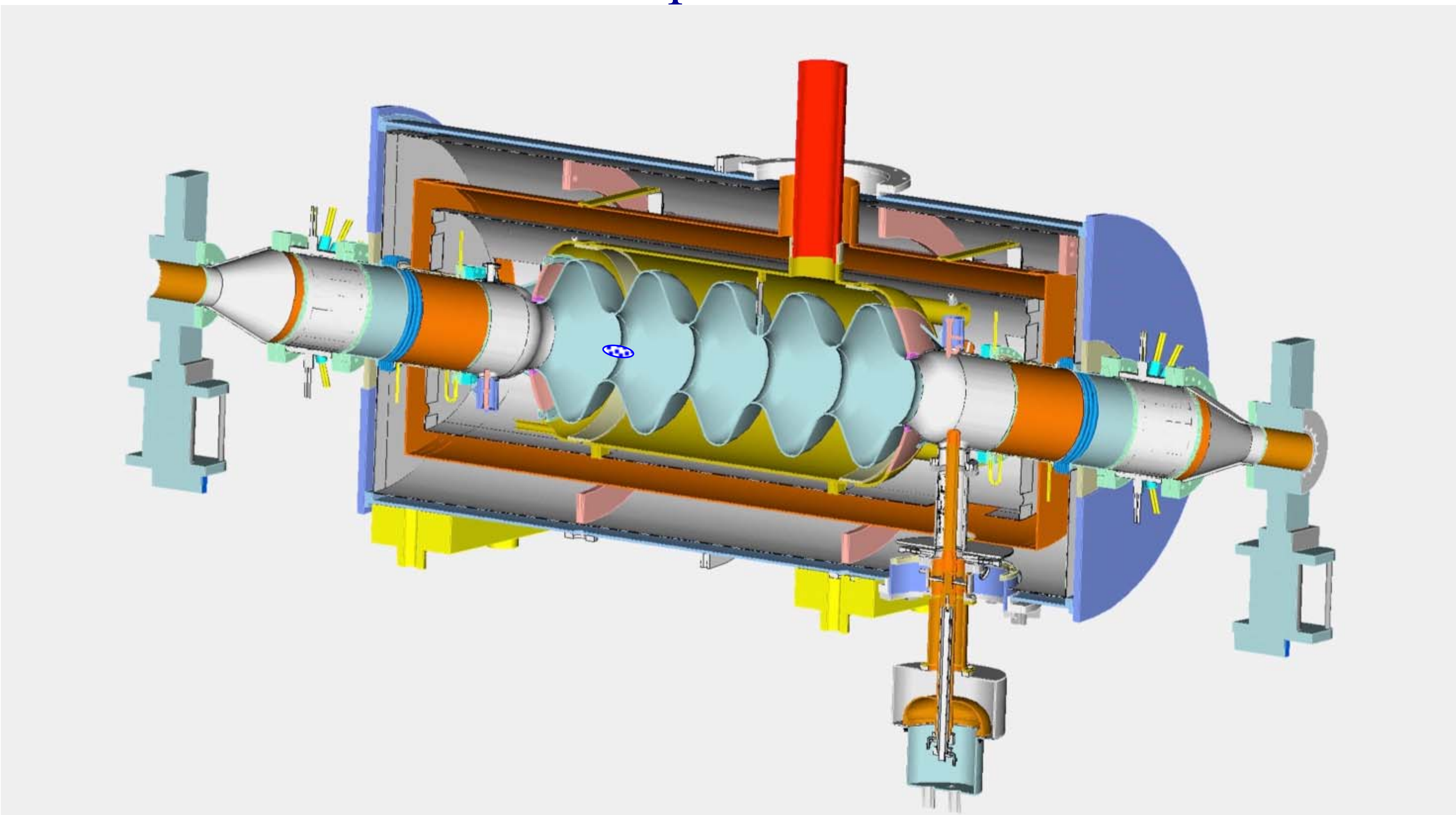

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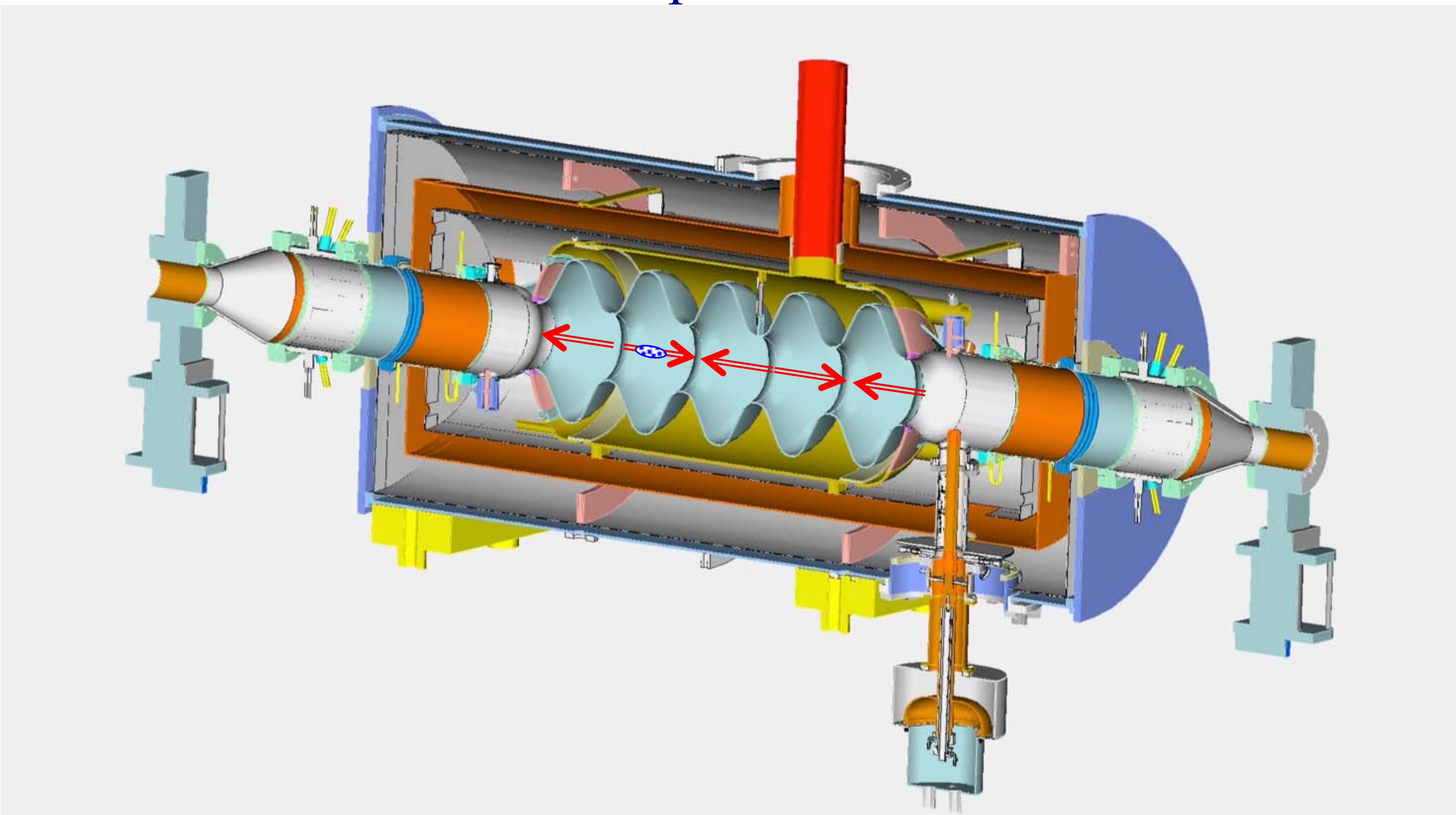

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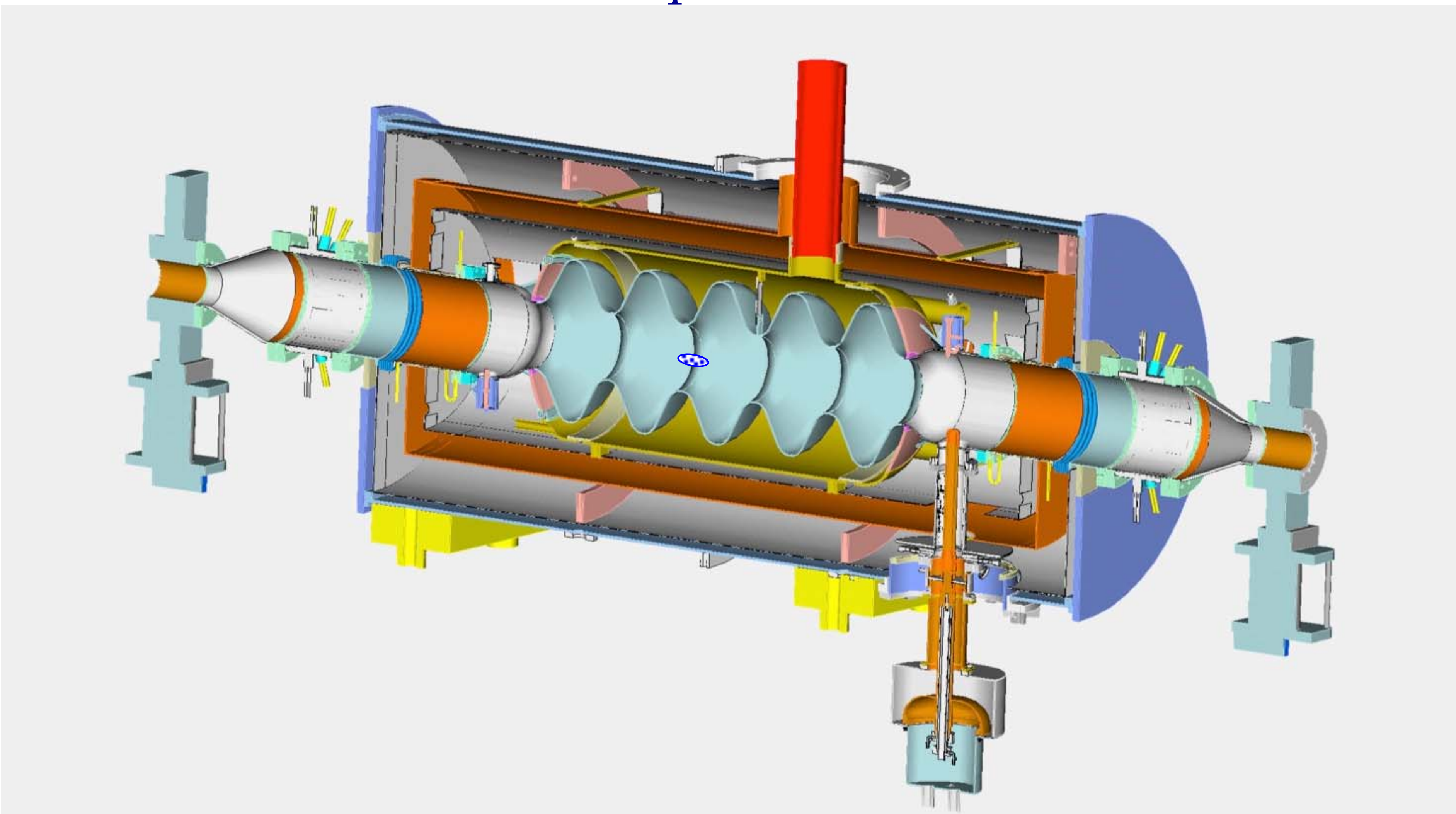

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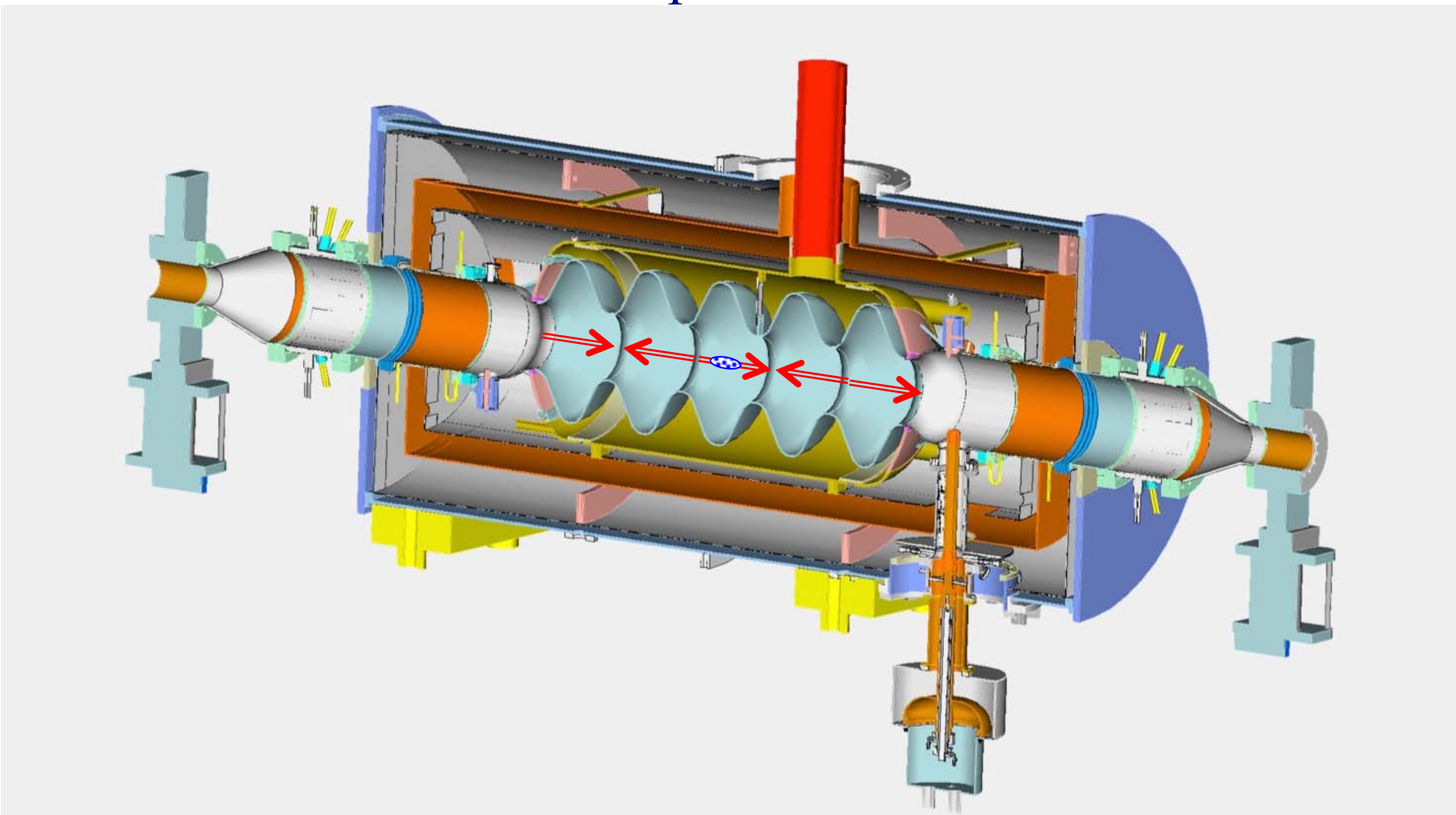

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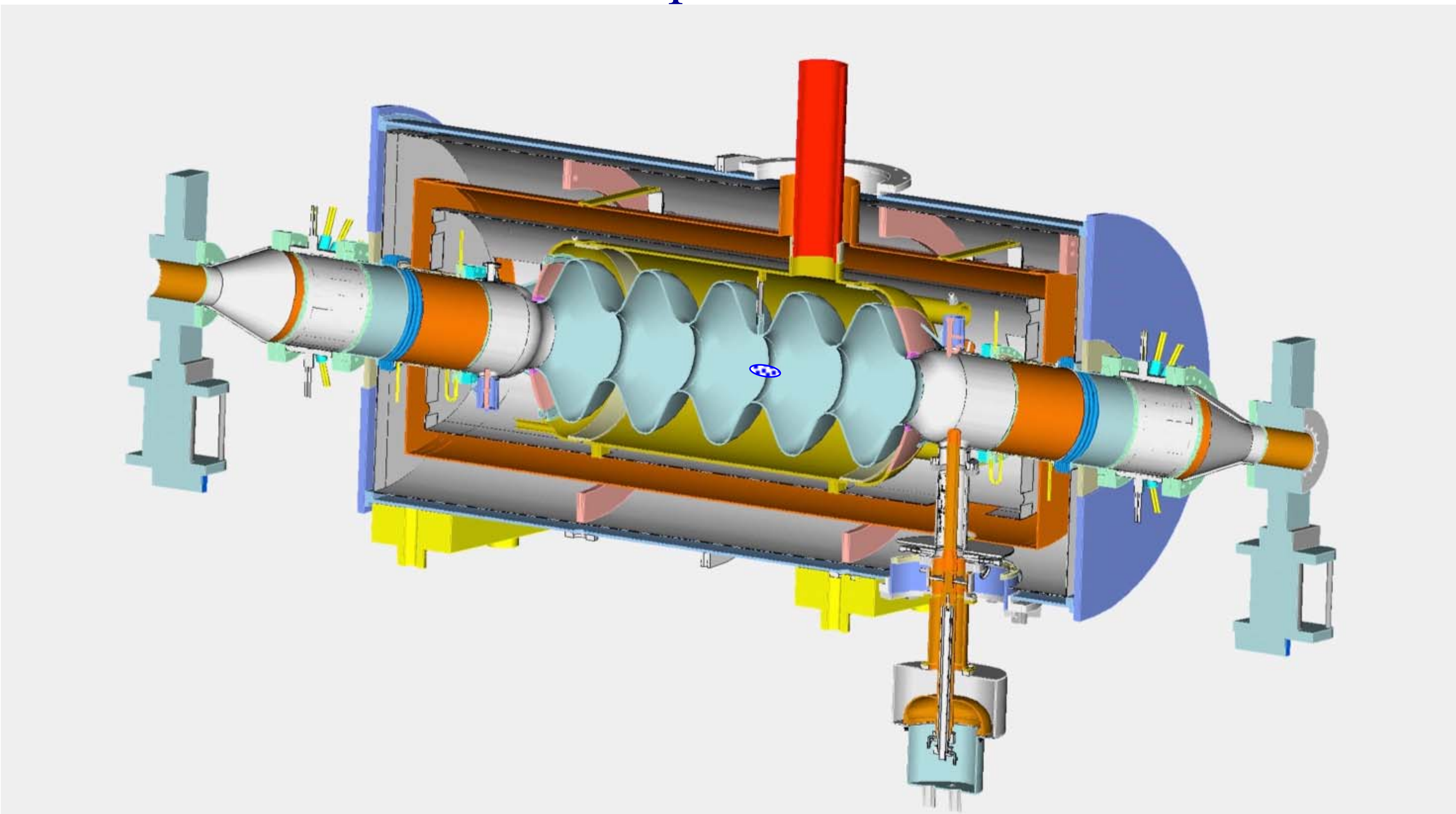

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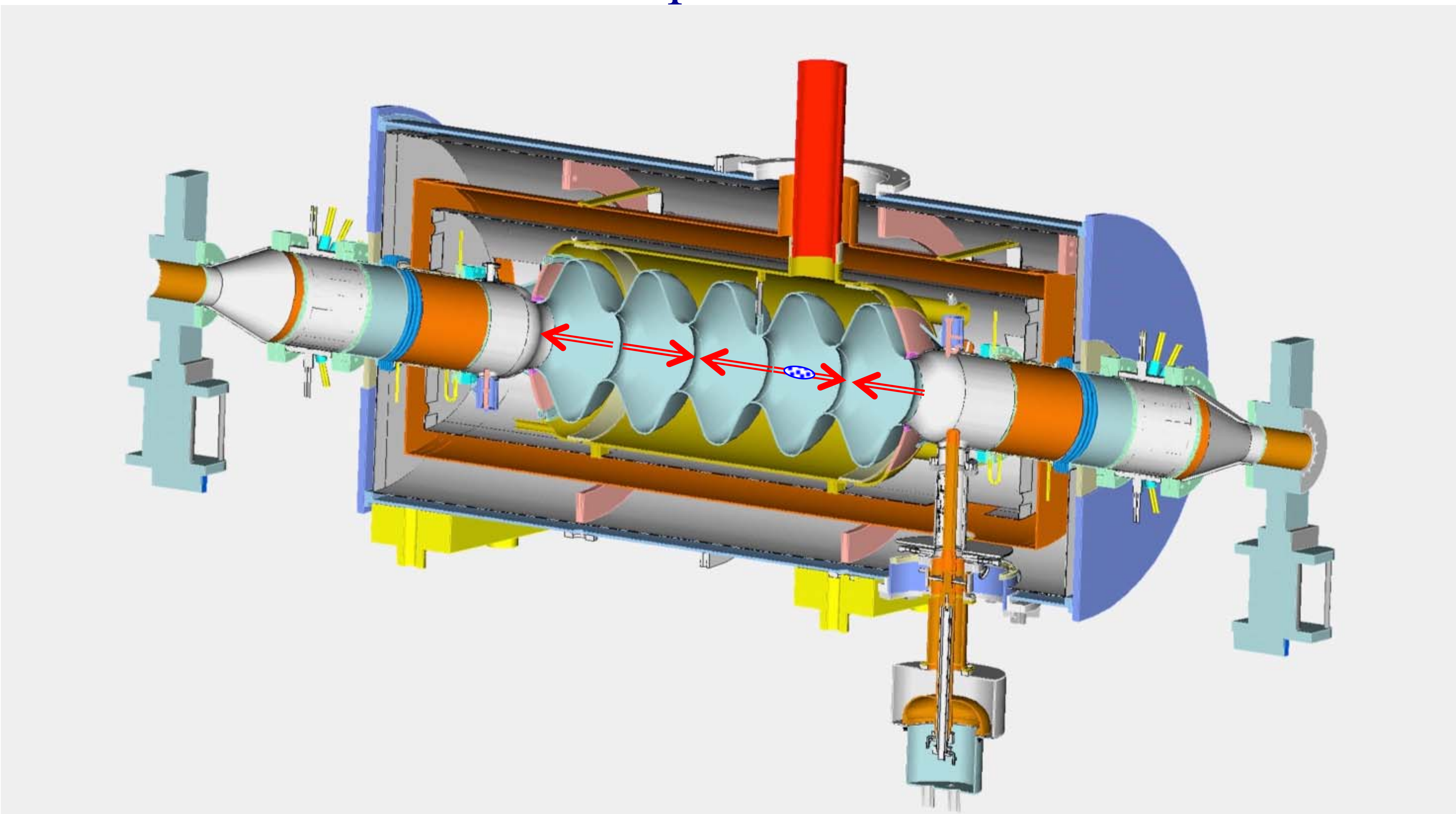

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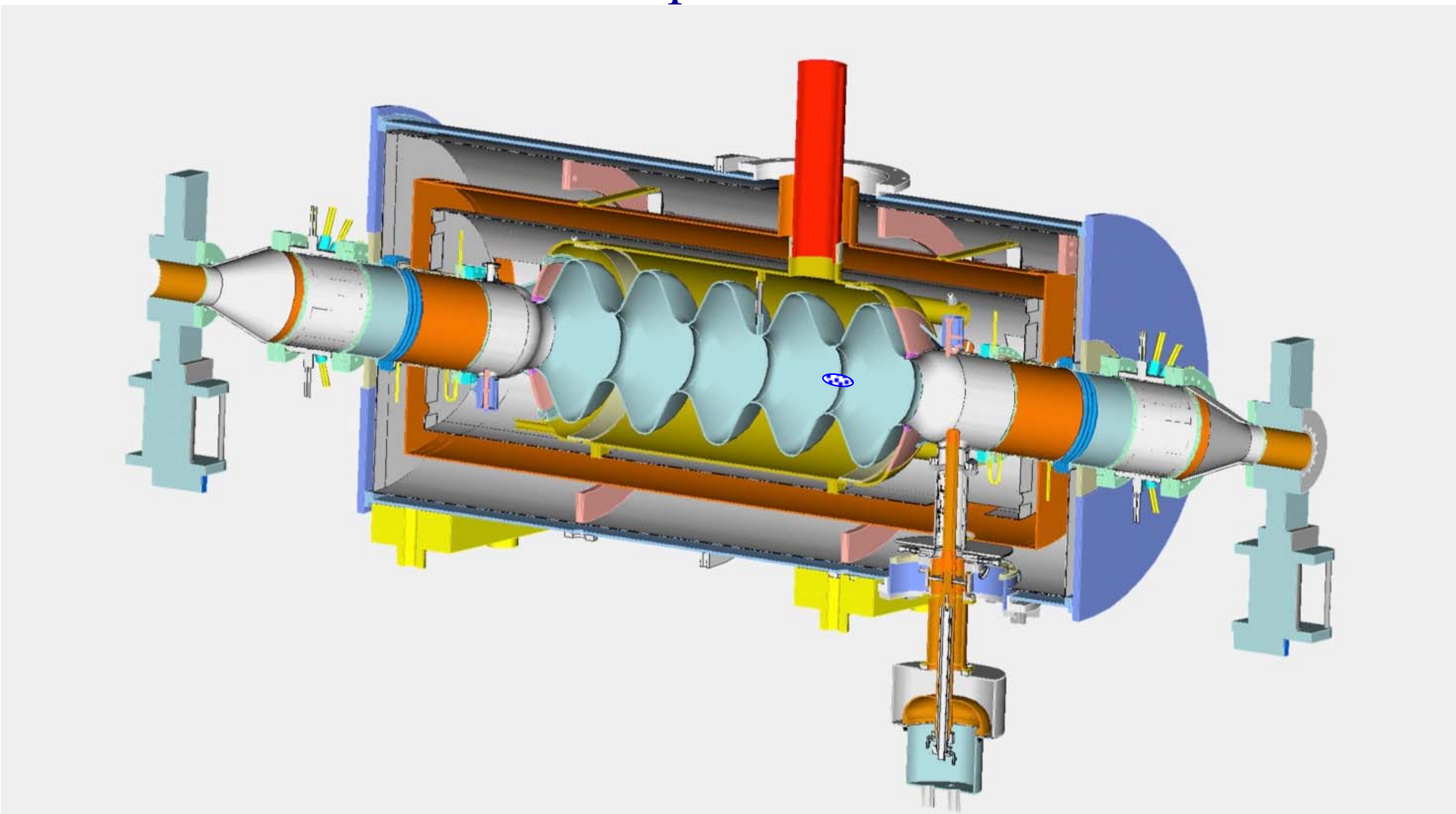

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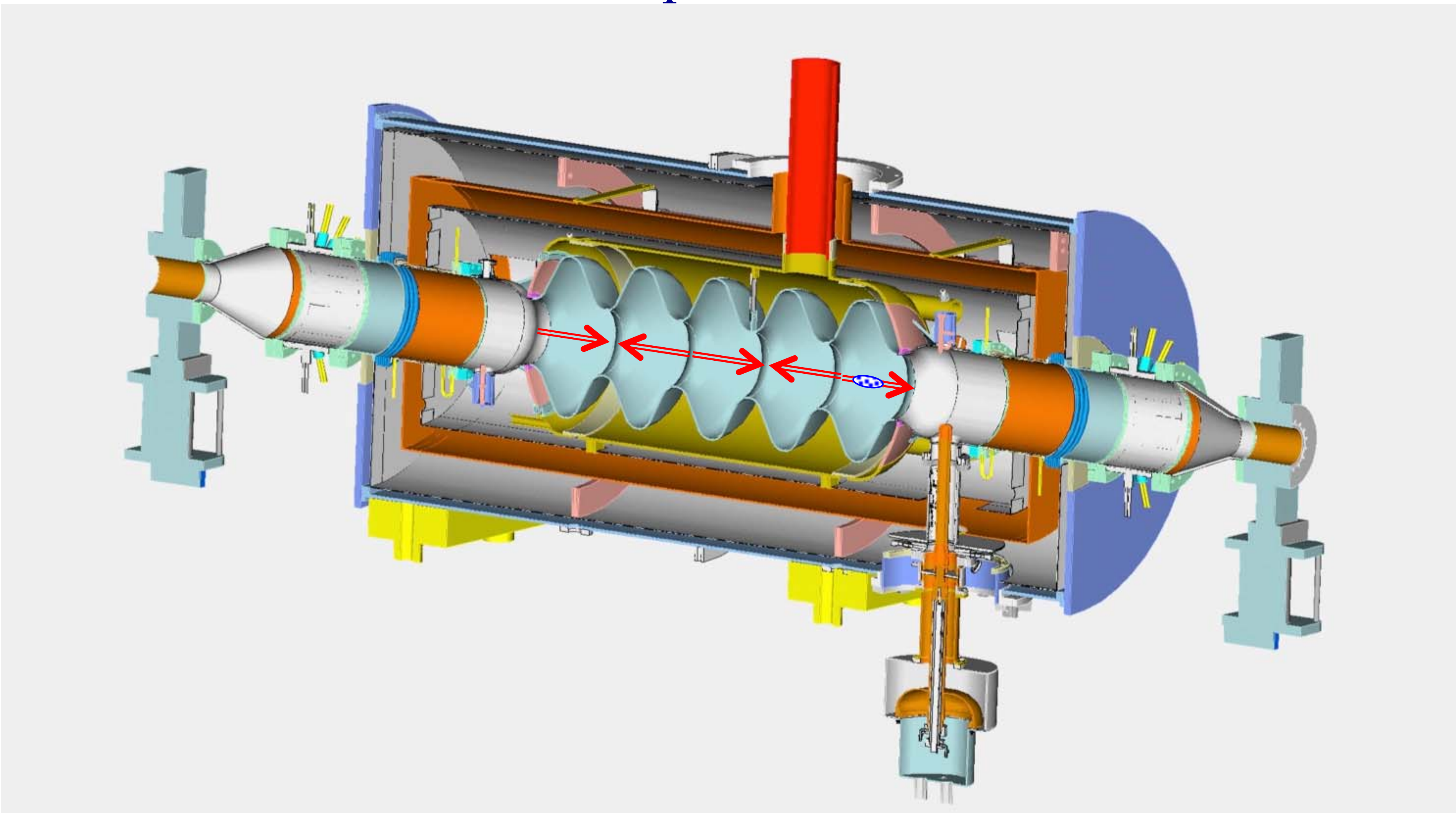

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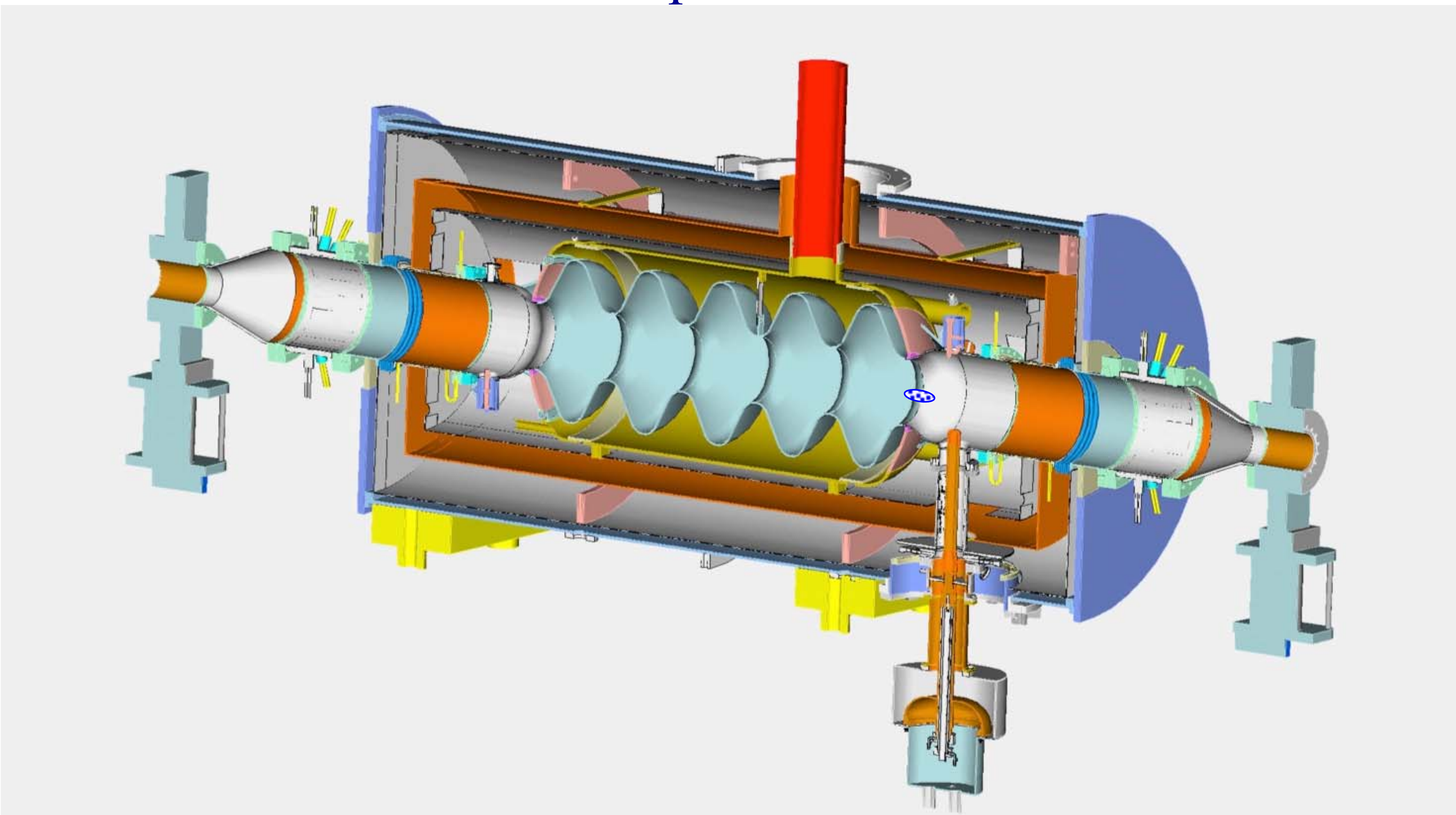

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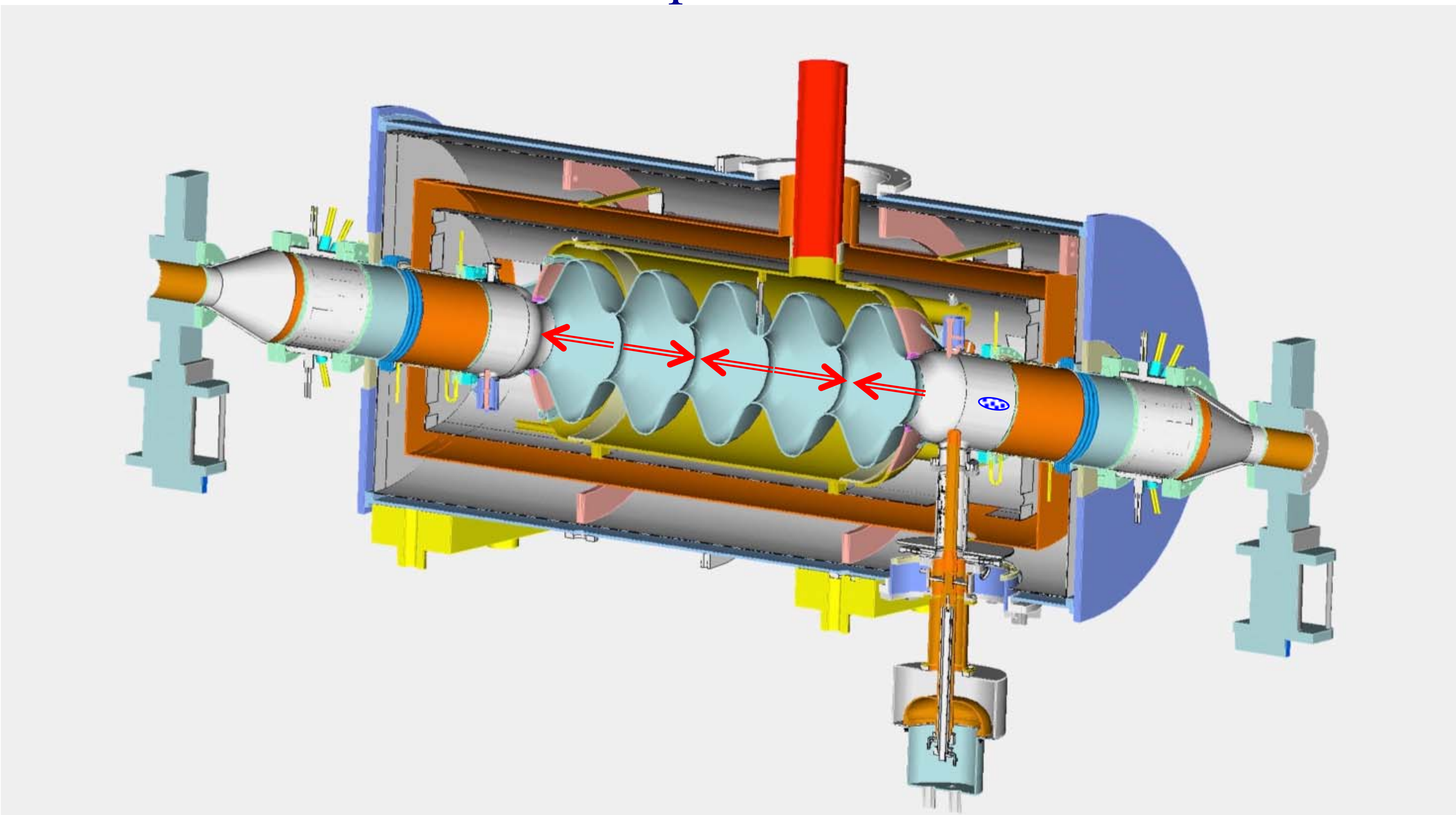

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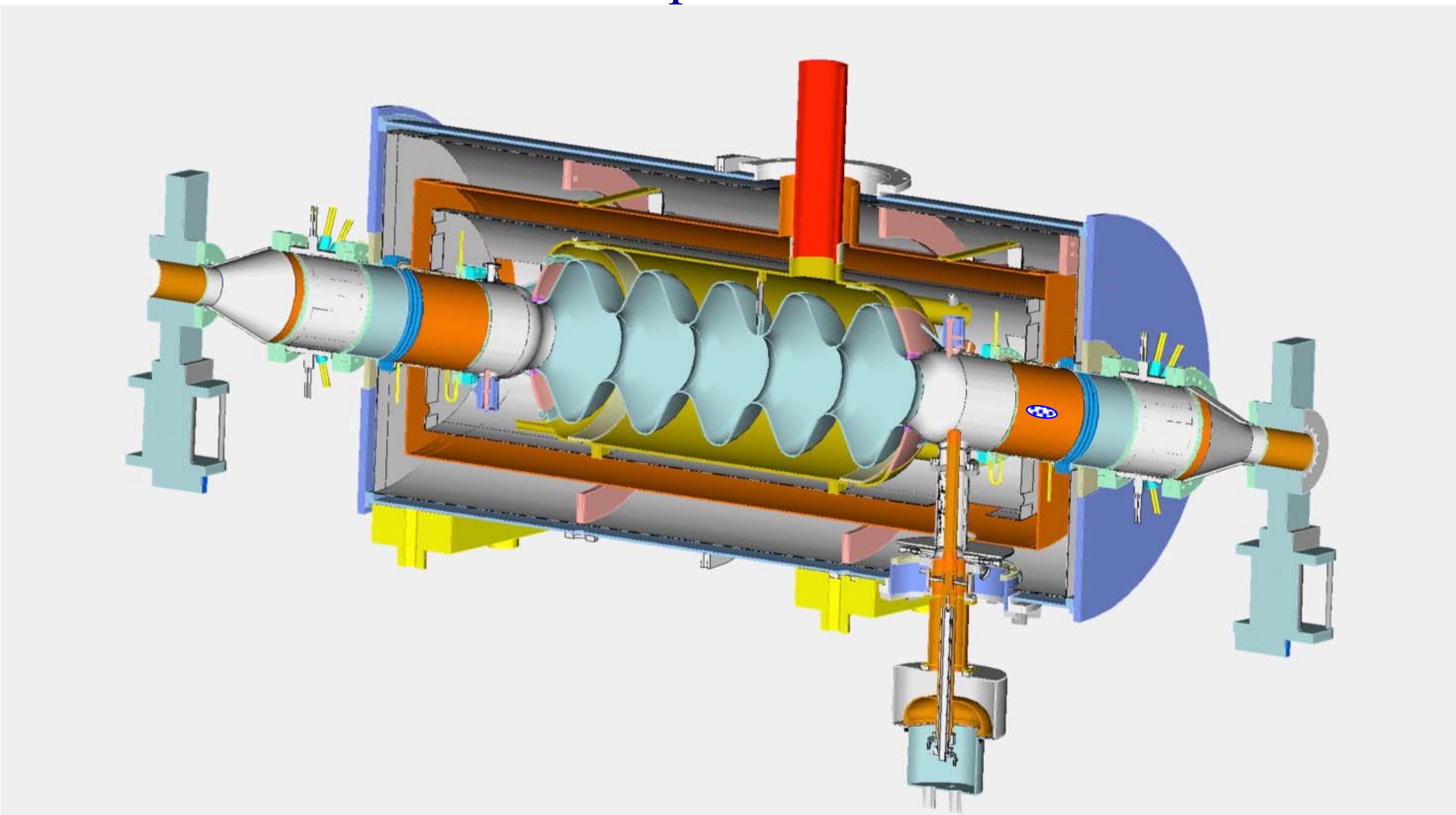
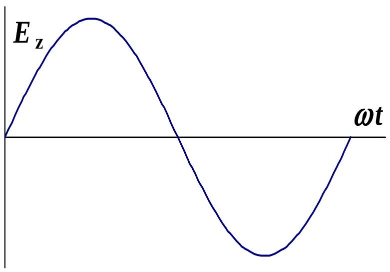
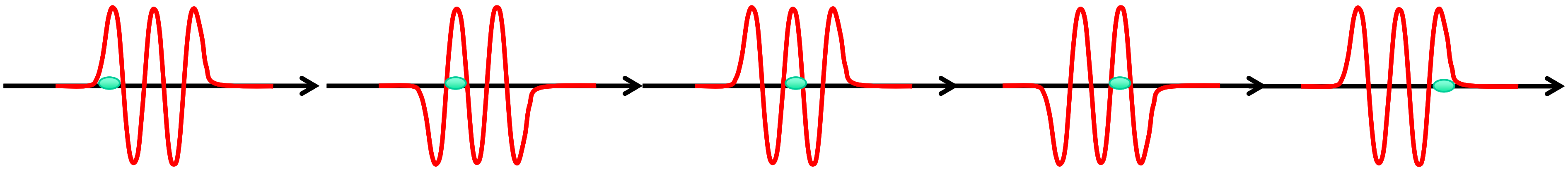


RF accelerator

$$\frac{dE}{dt} \equiv mc^2 \frac{d\gamma}{dt} = e\vec{\mathbf{E}}(\vec{r},t)\cdot\vec{\mathrm{v}};$$





$$\left\langle e\vec{\mathbf{E}}(\vec{r},t)\cdot\vec{\mathrm{v}}\right\rangle \neq 0$$

The field limits of RF accelerator

Some limiting factor

- Heating

  RF field deposits power as heat, which, if not being removed efficiently, can lead to damage of the cavity.
- RF breakdown

  Breakdown occurs when a plasma discharge is generated in the cavity. When it occurs, all the incoming RF is reflected back up the coupler.
- Field emission/dark current trapping
- Multipacting
- Quench

RF accelerators limits:

Room t°: pulsed ~150 MV/m

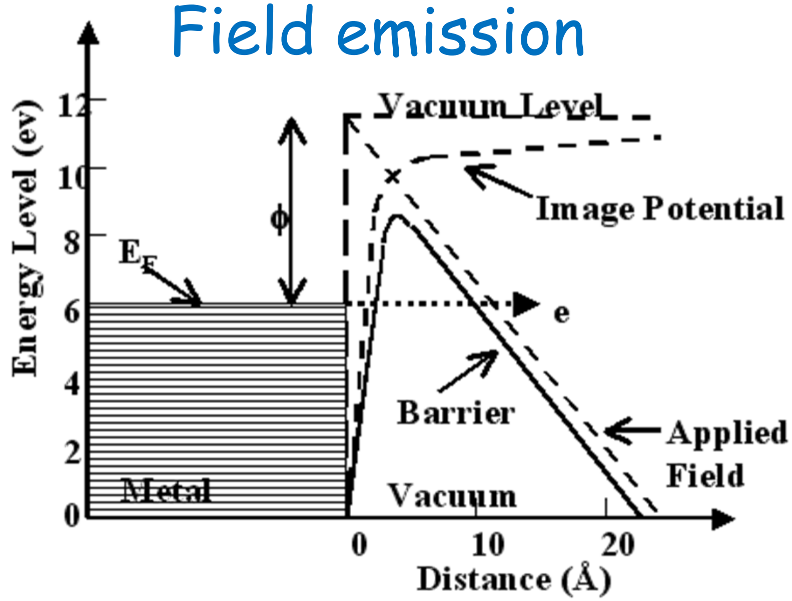
CW ~2 MV/m

Superconducting (2K°)

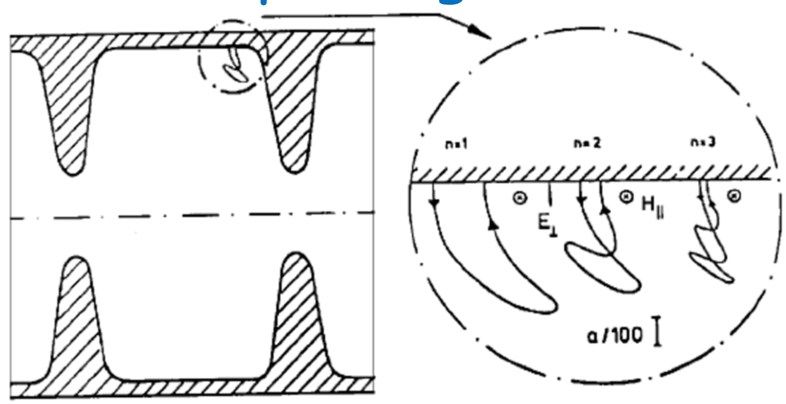
pulsed ~50 MV/m

CW ~20 MV/m

Field emission

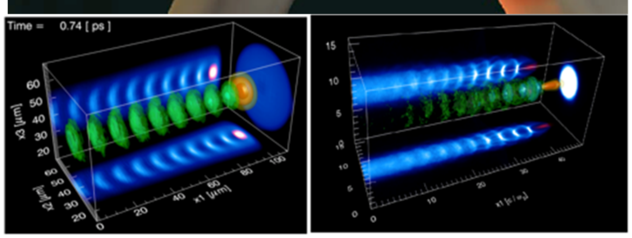


Multipacting



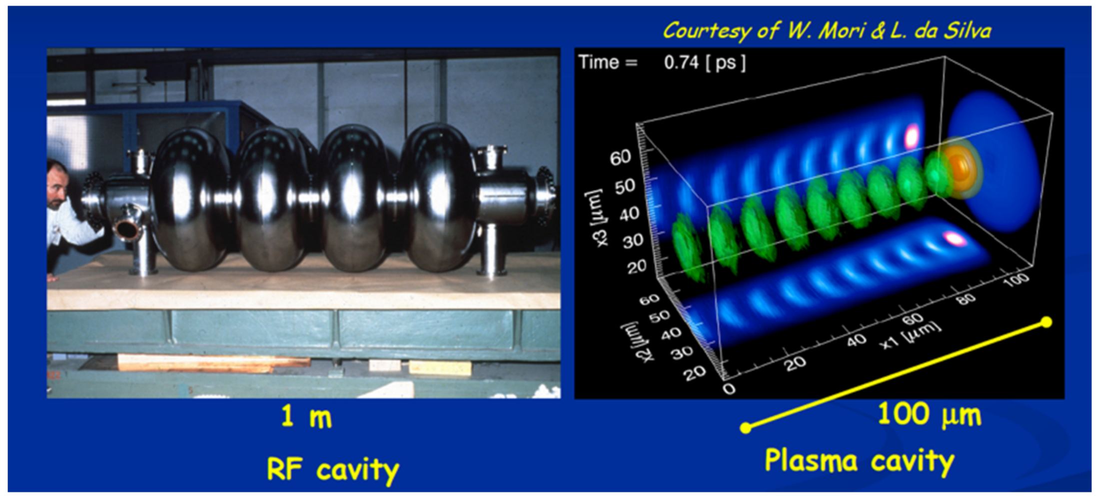
Courtesy to Dr. G. Burt

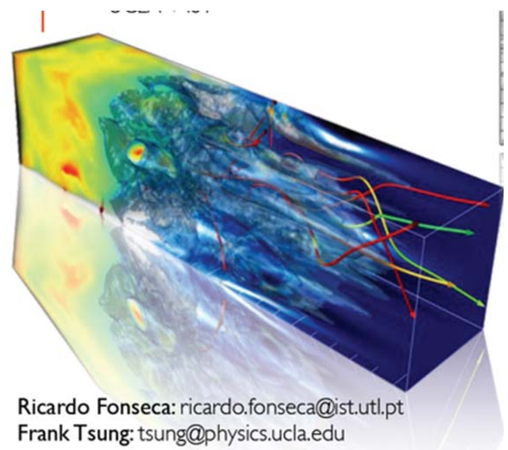
Plasma accelerators



Laser Wake

Electron beam Wake



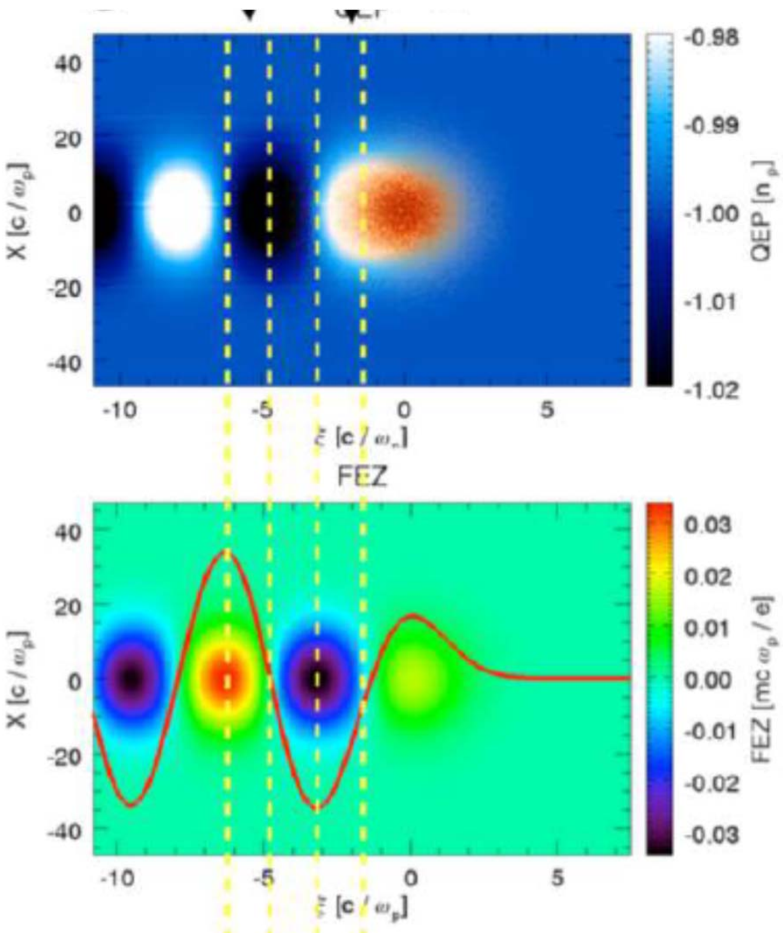


Plasma accelerators

When the driver is weak, i.e

$$a_0 = \frac{eE_o\lambda_o}{2\pi mc^2} << 1$$

the system works on linear regime.

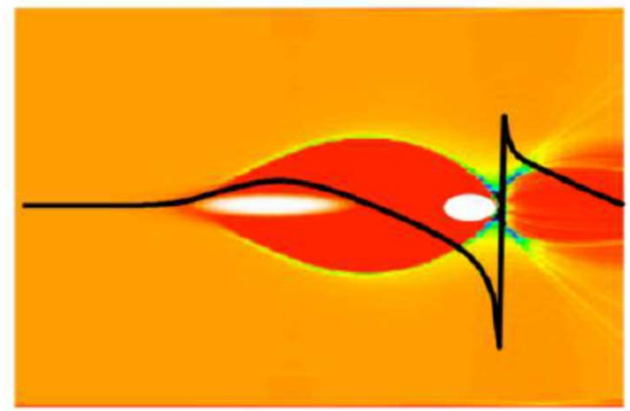


When the driver is strong, i.e.

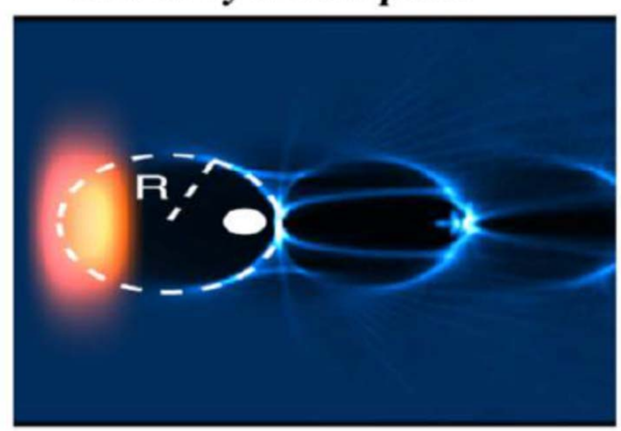
$$a_0 = \frac{eE_o\lambda_o}{2\pi mc^2} >> 1$$

The system works on nonlinear regime and ‘bubble’ is created.

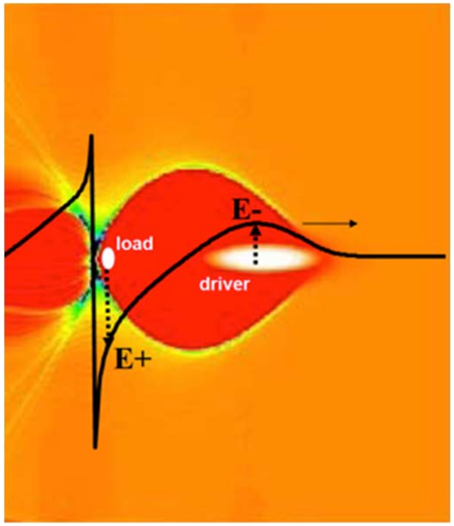
Driven by an electron beam



Driven by a laser pulse



Plasma accelerators



Electrons motion is nonrelativistic, linear plasma

$$a_0 = \frac{eE_o \lambda_o}{2\pi mc^2} >> 1$$

Relativistic motion of electrons, nonlinear plasma, blow-out regime (e.g.

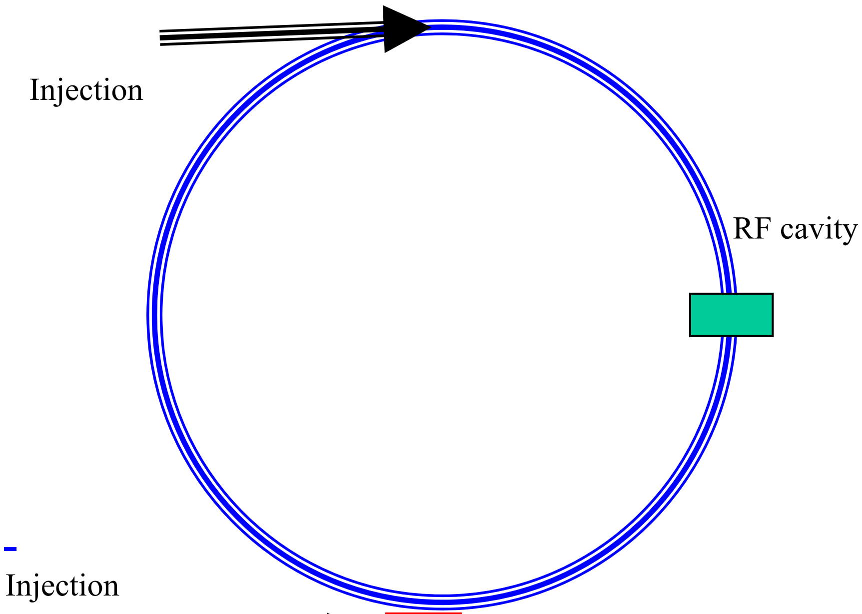
$$l_{buble} \sim \frac{c}{\omega_p}; \quad r_{buble} \sim l_{buble}/2; \quad E \sim \frac{q}{\pi\varepsilon_0 r^2_{buble}} \cong en_o \frac{l_{buble}\pi r^2_{buble}}{\varepsilon_0 \pi r^2_{buble}} \cong \frac{ecn_o}{\varepsilon_0 \omega_p} = c\sqrt{\frac{mn_0}{\varepsilon_0}}$$

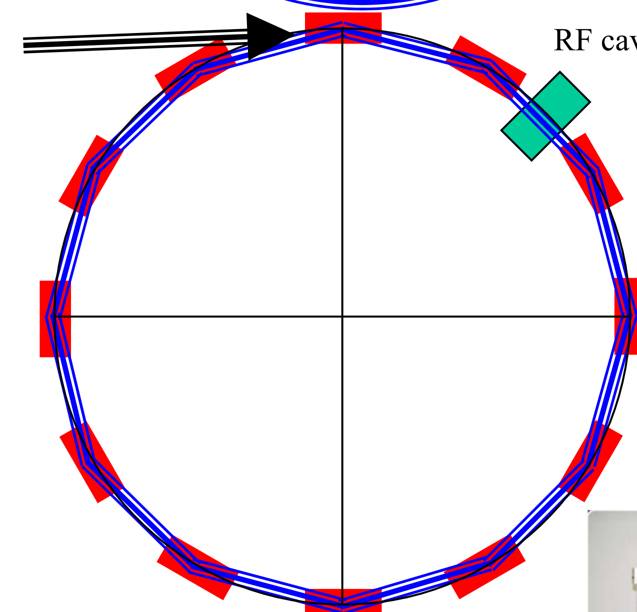
$$n_o = 10^{19} cm^{-3}; E \approx 300 GV/m$$

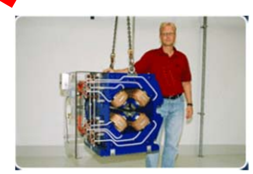
Compare this 300 GeV/m with 150 MeV/m in RF linacs

Circular accelerators

- Allow to accelerate or store particles to millions and billions of turns
- Largest energies of colliding beams today – **hadrons:** 14 TeV p-p, in LHC, 1 TeV for proton-antiproton (10^{12} eV) at Tevatron (closed) , 24 TeV in Au-Au at RHIC, 1,150 TeV in Pb-Pb collisions in LHC, **electron-positron:** 208 GeV at LEP (closed)
- Many medium energy electron accelerators (1-8 GeV) as synchrotron radiation sources
- Electrons and positrons radiate too much at high energy (~ E^4 - you should learn it soon) - hence this is the main limit to their energy







Why to use magnetic field to guide particles?

Why not electric field?

It is practical matter of what you can do easier or what you can do at all?

1 Gs = 29979 V/m -> warm magnet 20 kGs (2T) .eq. to 600 MV/m
-> superconducting magnets 15T .eq. to 4.5 GV/m

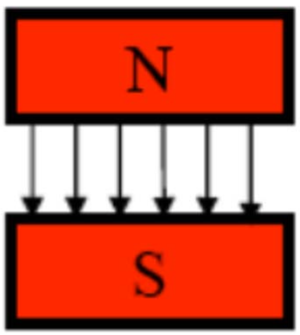
Almost everything arcs at few MV/m

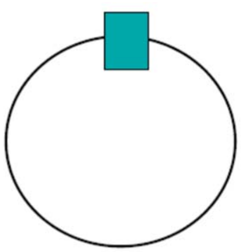
There is no chance to create DC electric field at Earth with the same intensity as DC magnetic filed - it has something to do with absence of magnetic charges and, hence, no arcing………

1997 - BERKELEY, CA -- The world record for field strength in a dipole magnet has been shattered by researchers at the Ernest Orlando Lawrence Berkeley National Laboratory (Berkeley Lab). A one-meter long superconducting electromagnet, featuring coils wound out of 14 miles of niobium-tin wire, reached a field strength as high as 13.5 Tesla, far-surpassing the previous high of 11.03 Tesla set by a Dutch group in 1995.

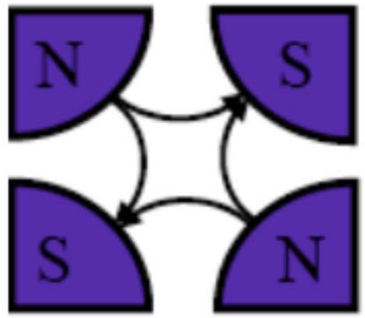
Magnets for stable transverse motion in circular accelerators

Dipoles:
Used for steering
$B_x = 0$
$B_y = B_o$





Quadrupoles:
Used for focusing
$B_x = Ky$
$B_y = Kx$



Sextupoles:
Used for chromatic correction
$B_x = 2Sxy$
$B_y = S(x^2 - y^2)$