A Plasma based, Charge State Stripper for Heavy Ion Accelerators

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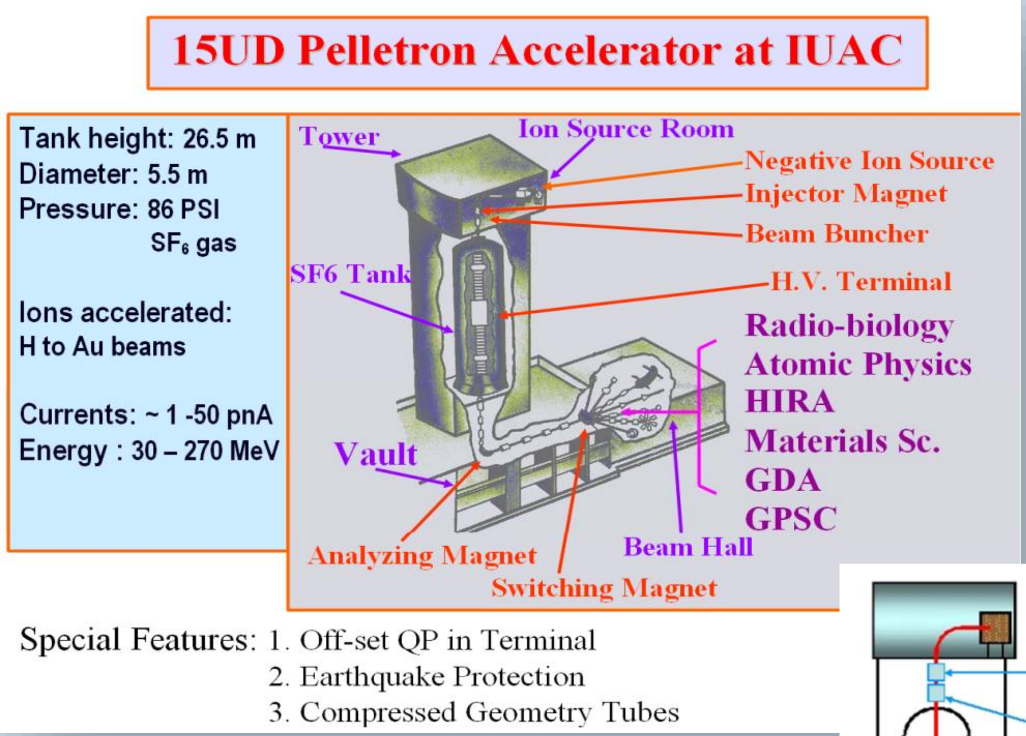
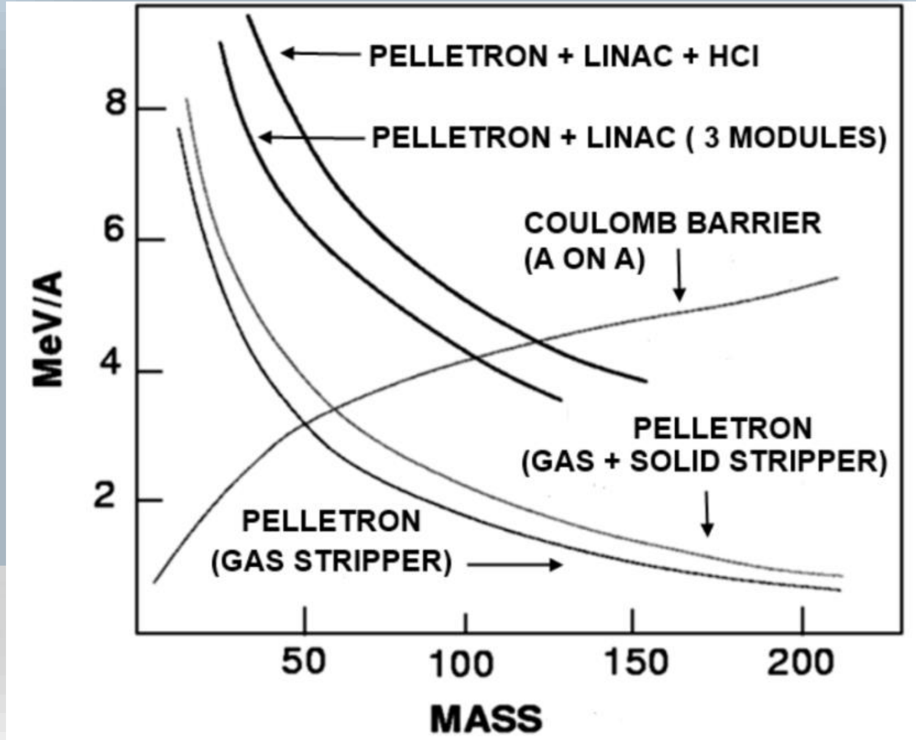
OUTLINE

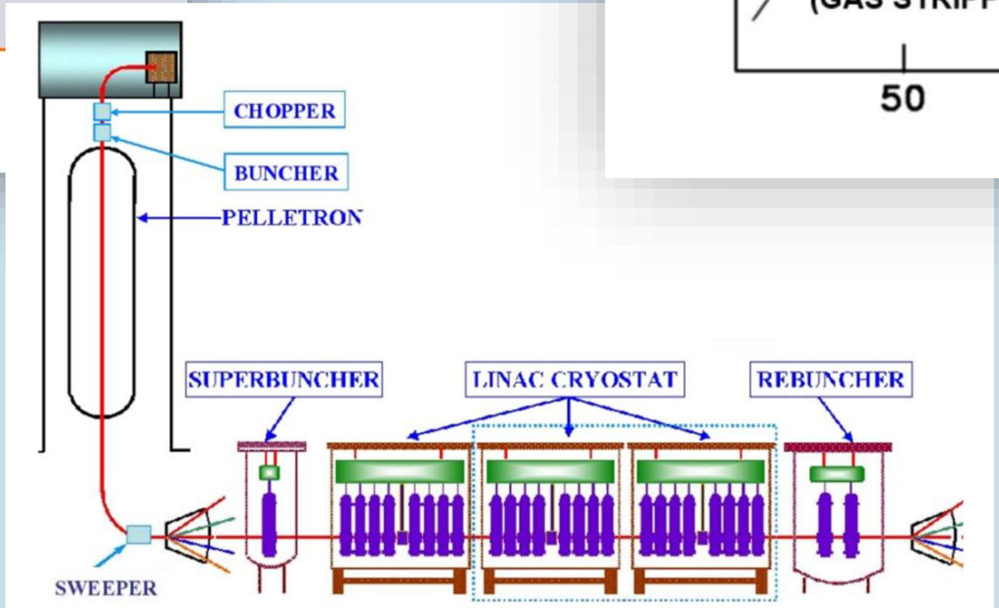
1. Introduction …some background
2. Collaboration …
3. ionization, recombination, charge exchange mechanisms
4. Use of Foils, Gaseous media (problems encountered, challenges, downtime etc)
5. How to improve/solve this problem using a plasma with free electrons (using low Z, highly ionized species)
6. Bethe formalism (Stopping power of plasmas as compared to foil/gas media)
7. Going back to the roots of fusion developments (tricks with the ECR, now with …)
8. Pinch plasmas (Z and theta devices), instabilities
9. Improvement of instabilities using a Dense Plasma Focus Device
10. Indigenous Development of Dense Plasma Focus Device
11. Possible device for heavy ion stripping
12. Test bench at the beamline of High Current Injector

Inter University Accelerator Centre, New Delhi

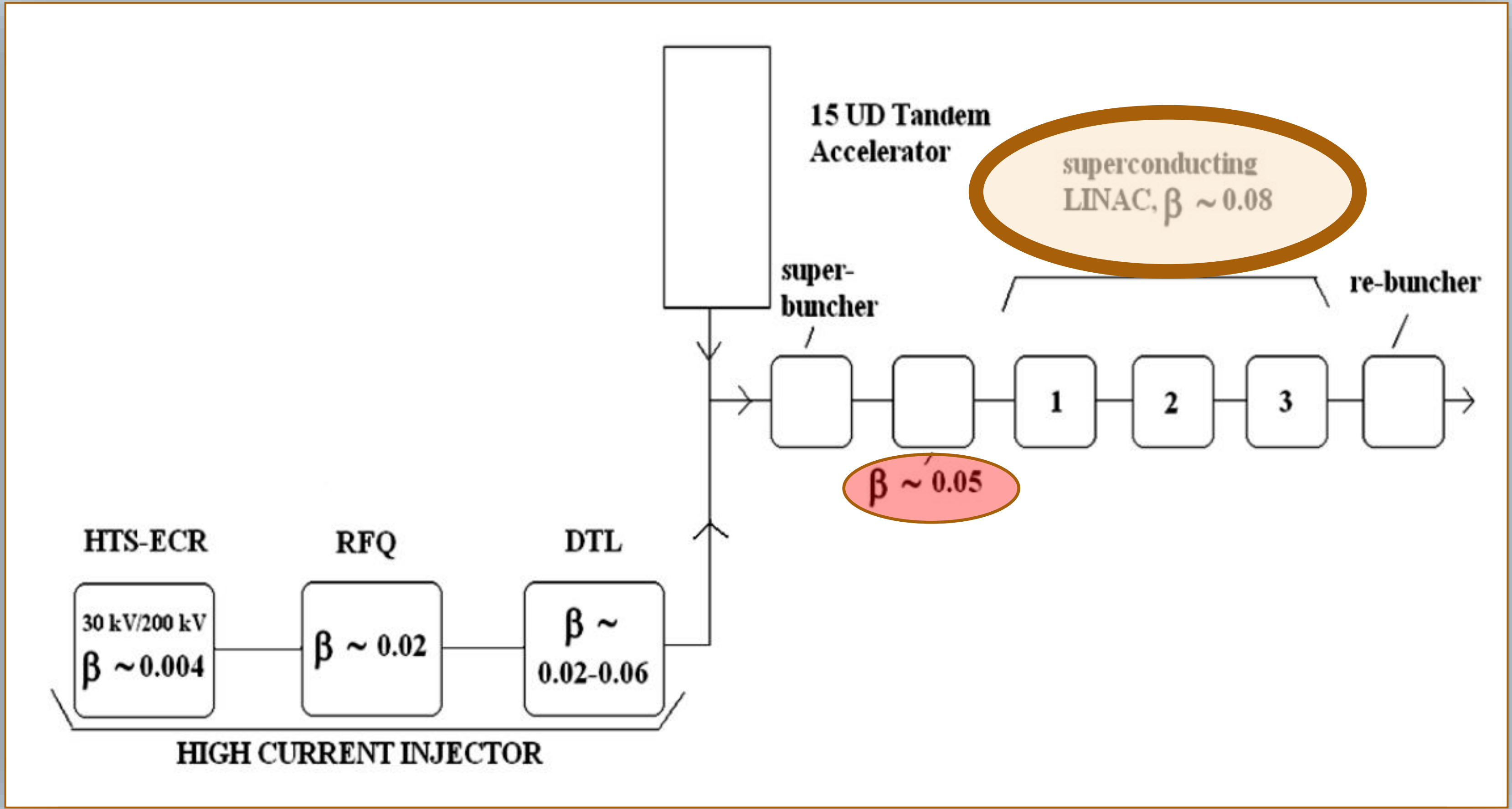
Accelerators at the Inter University Accelerator Centre



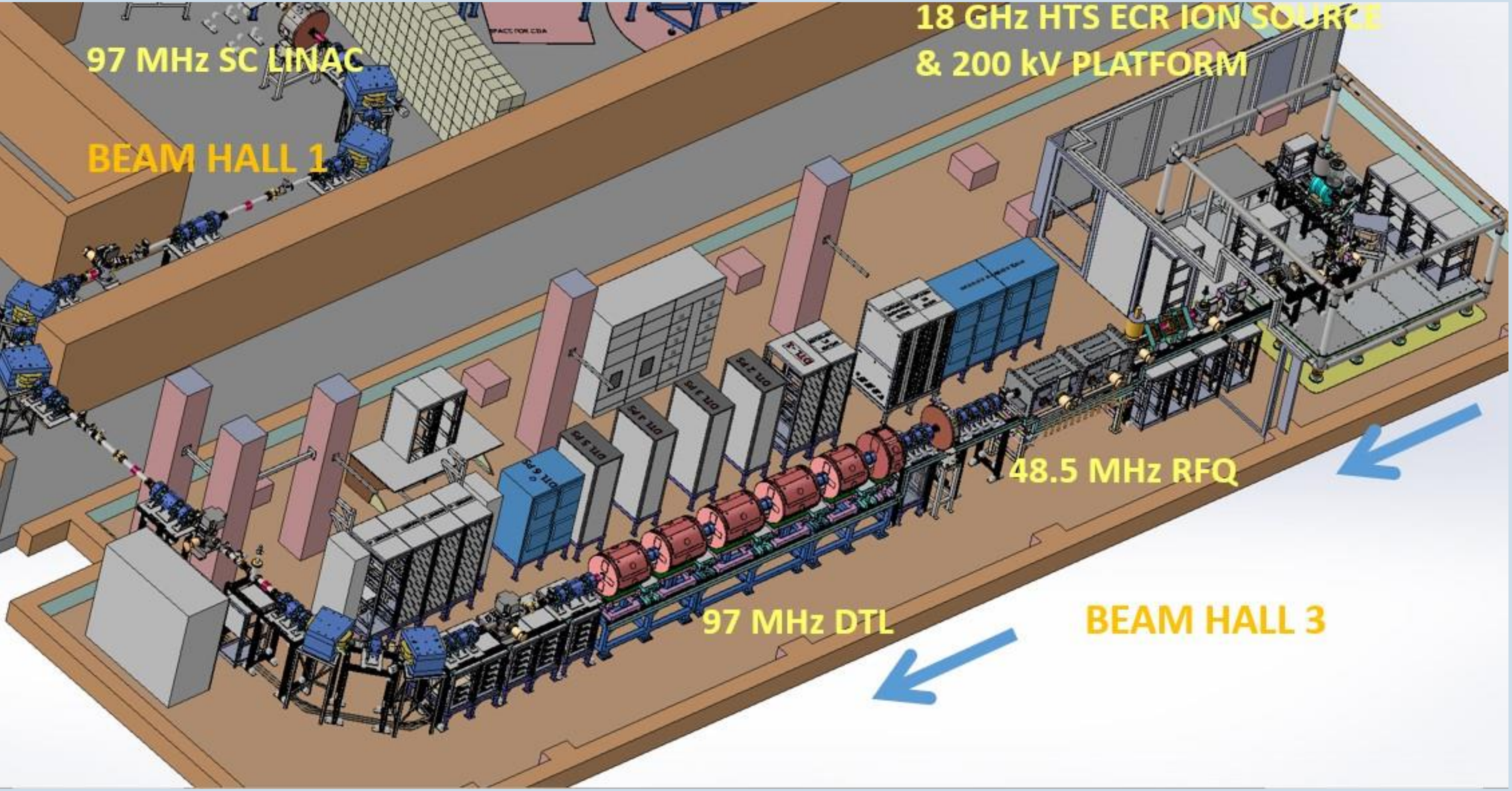




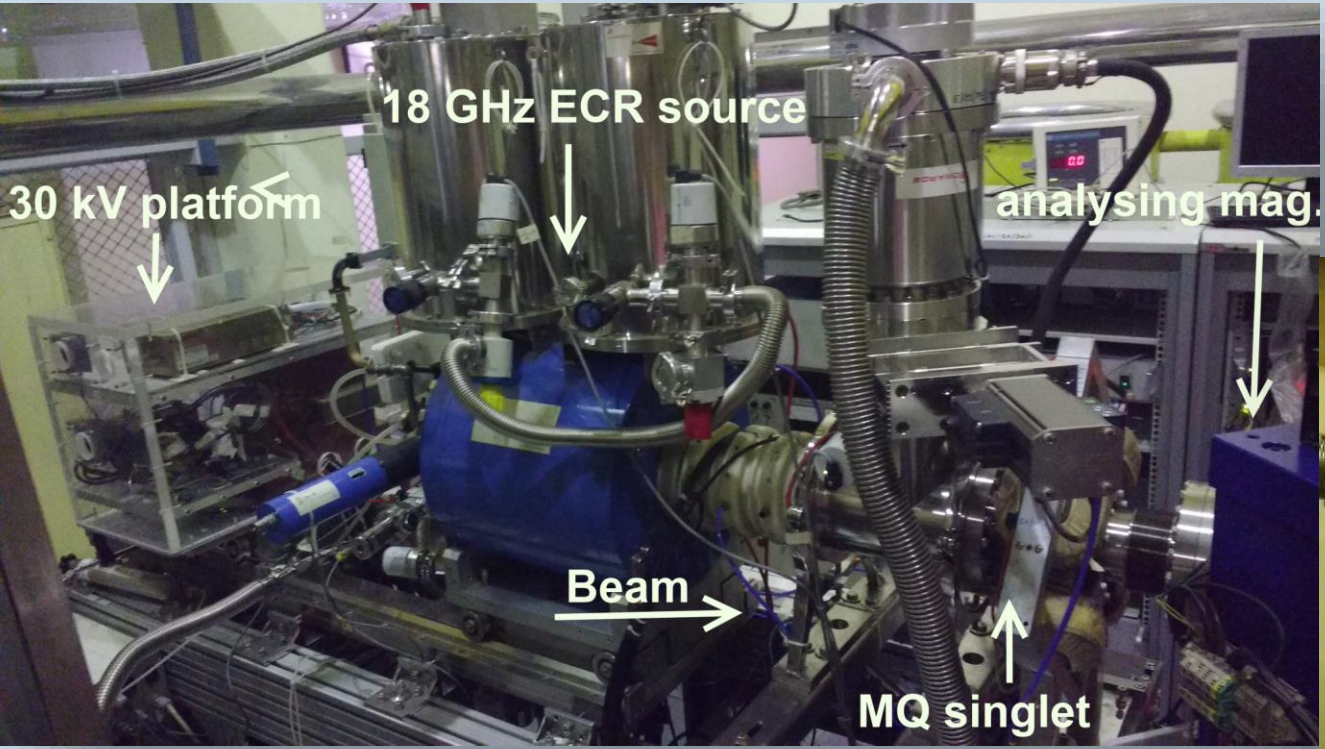
Schematic of the High Current Injector

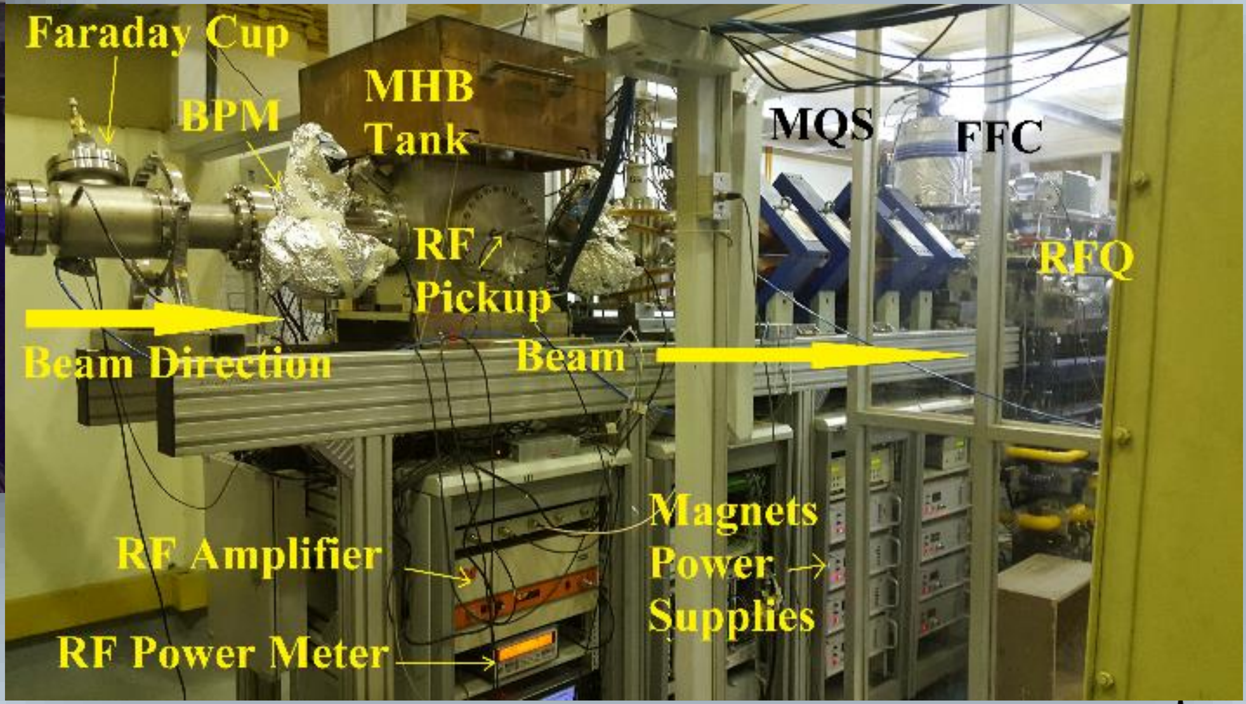


Layout of High Current Injector (HCI) Beamline

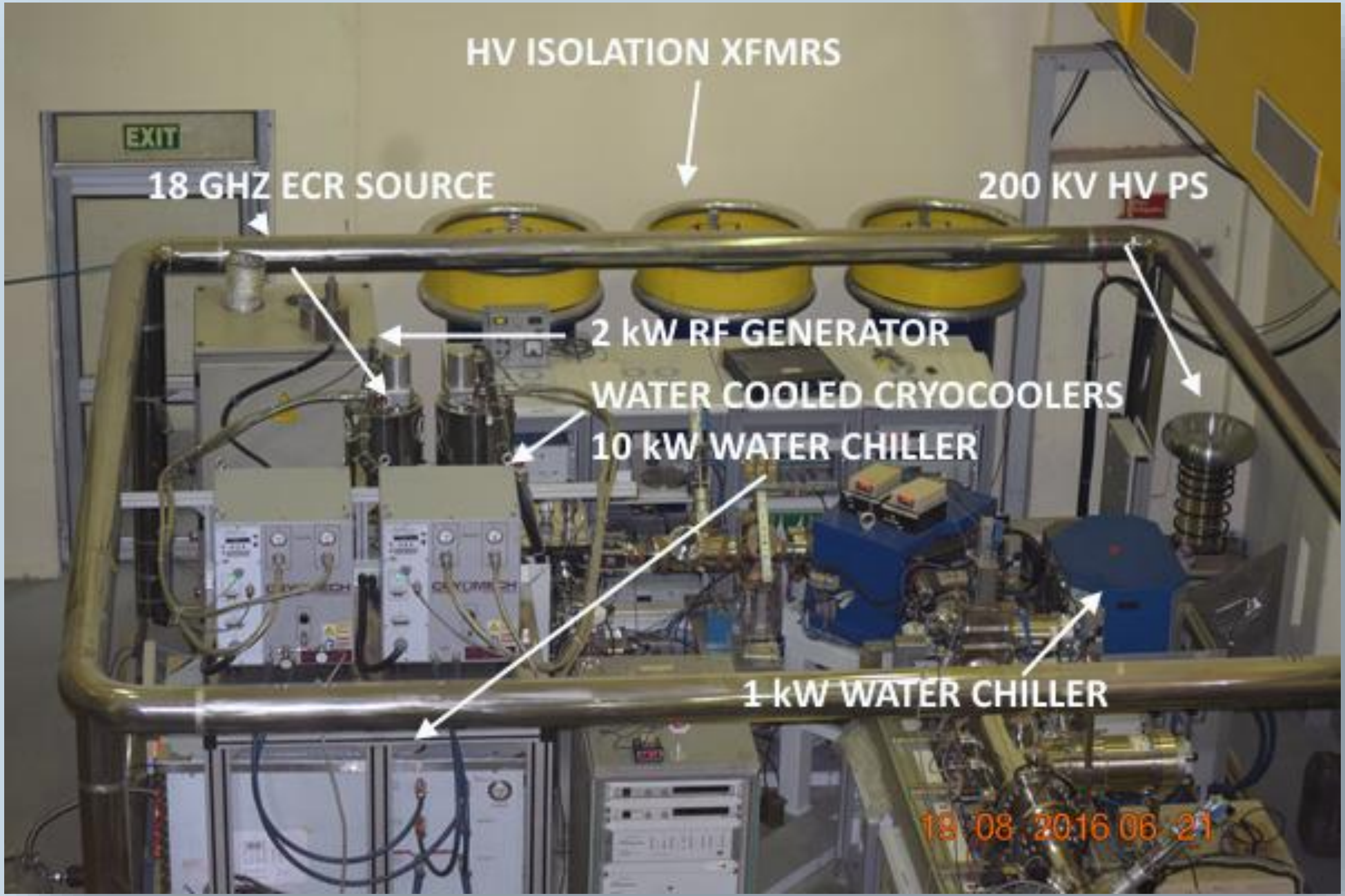


High Current Injector: View of the 18 GHz HTS ECR ion Source coupled to LEBT

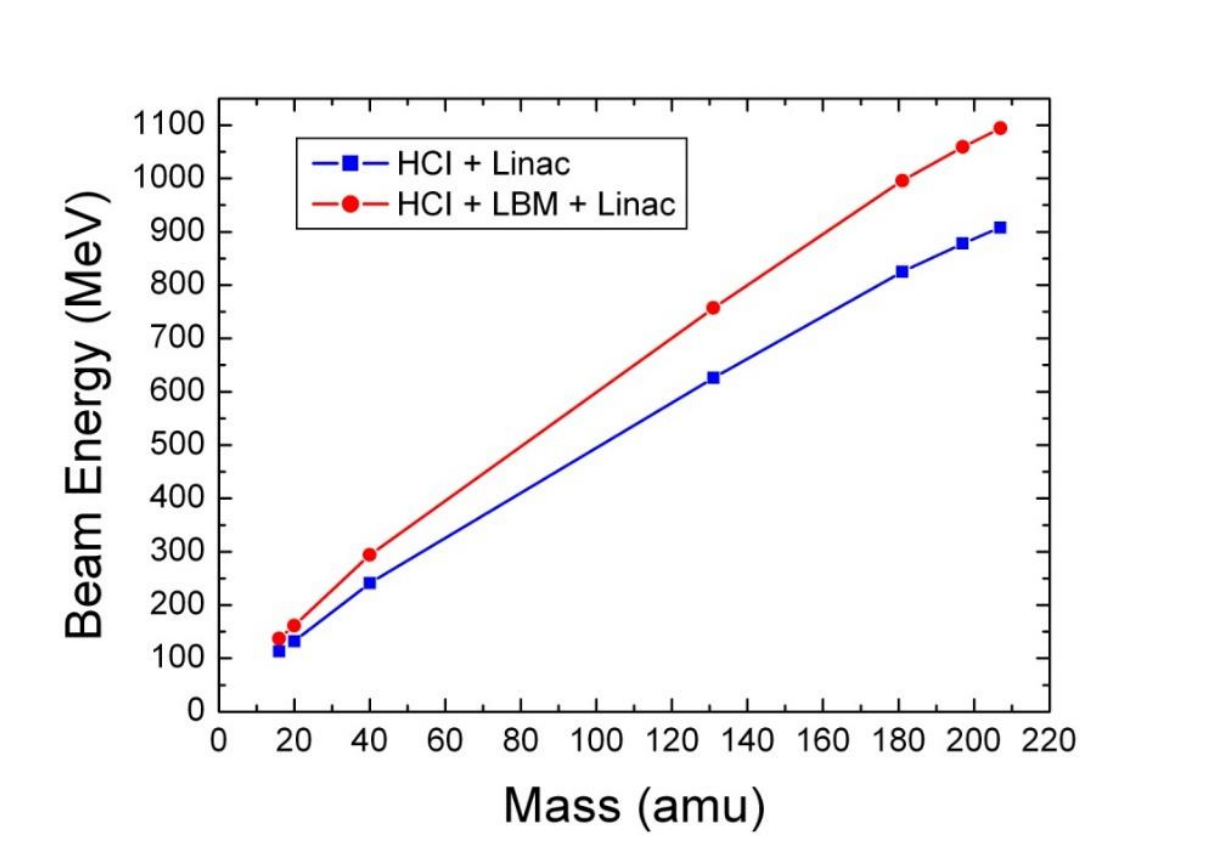


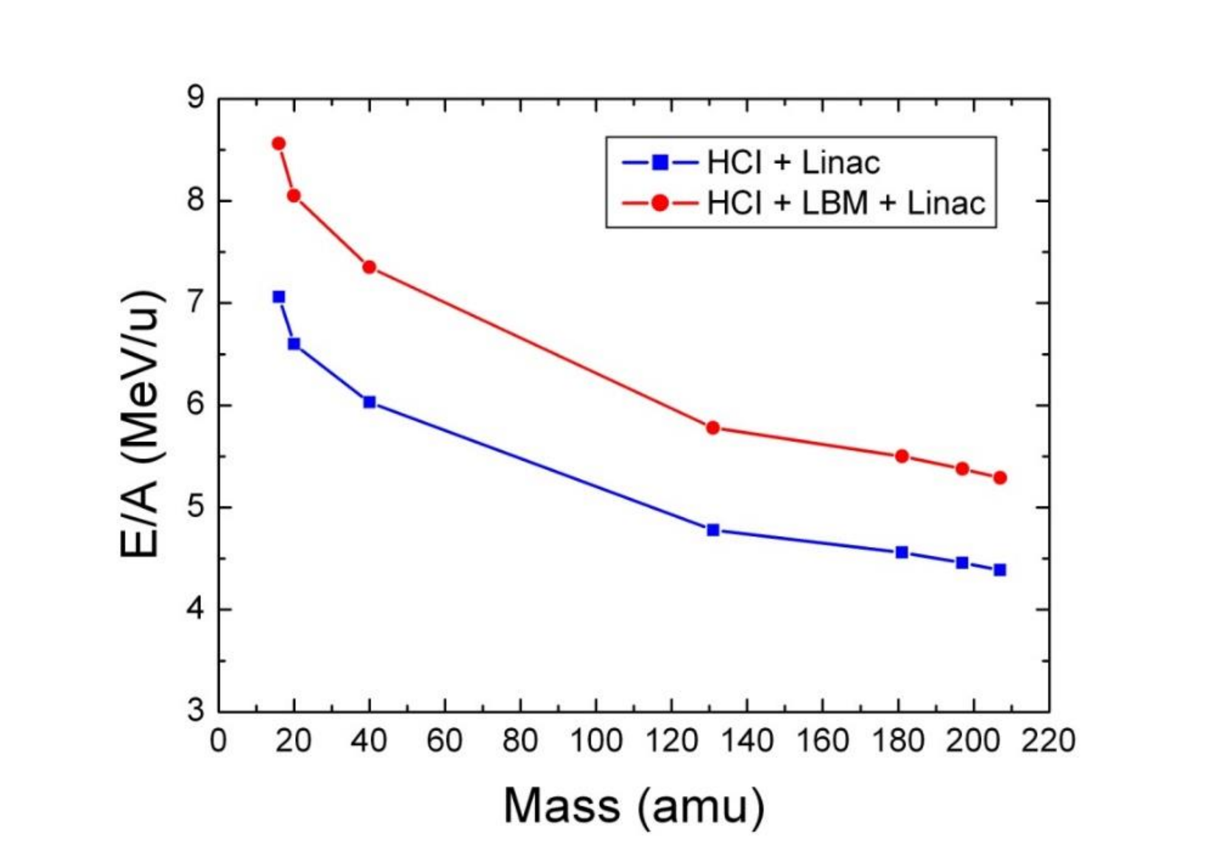


High Current Injector: View of the sub-systems on 200 kV HV Platform

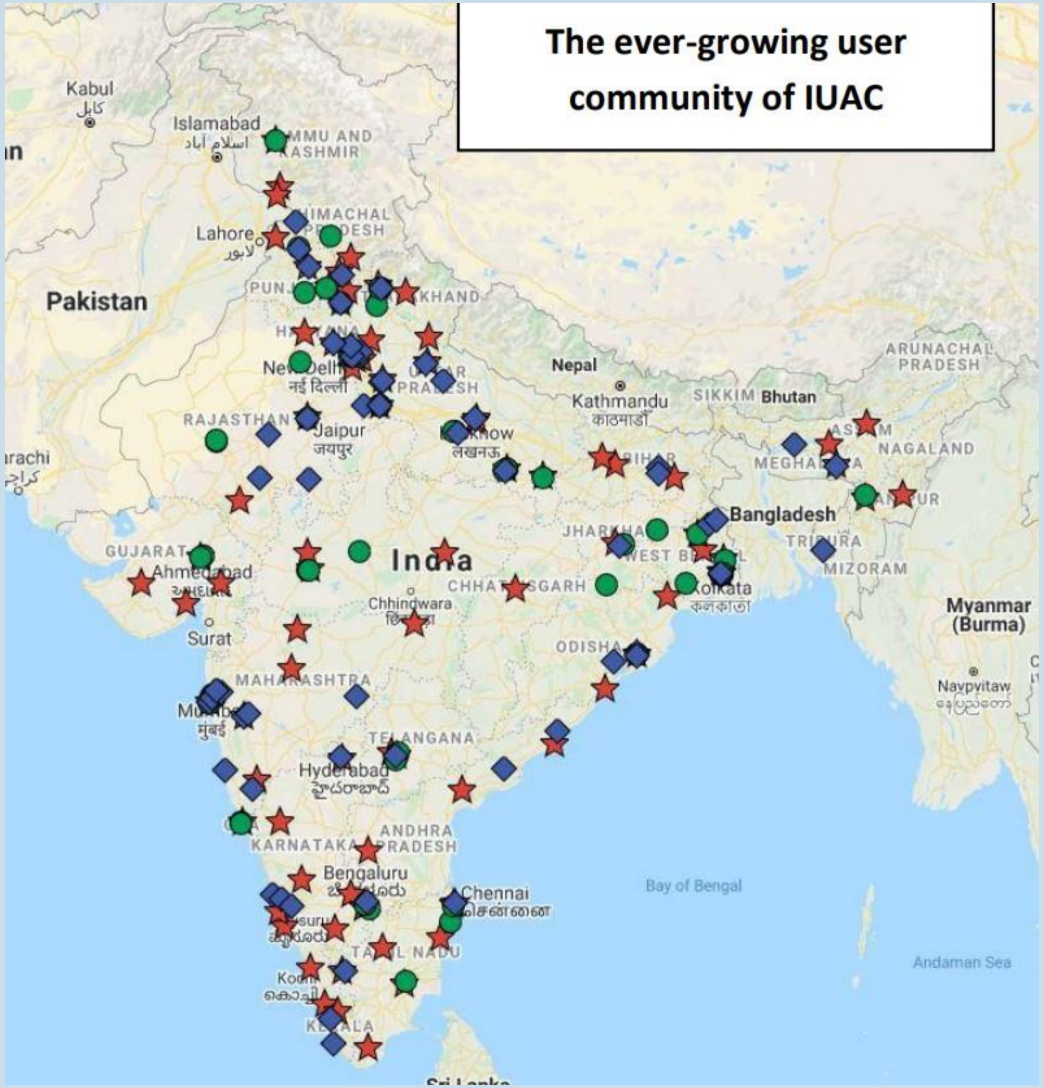


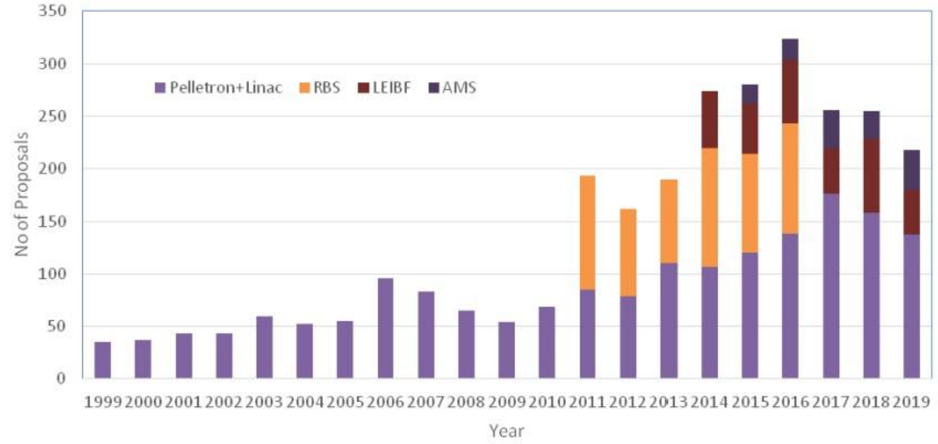
Energy gain, Energy per nucleon : High Current Injector + SC LINAC



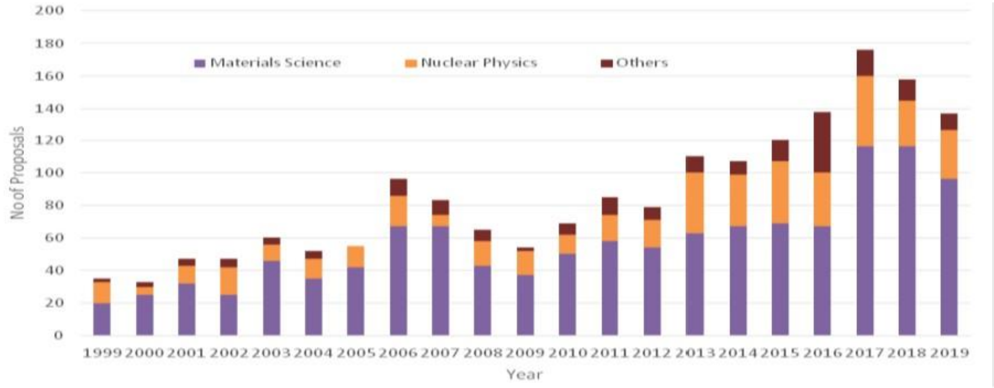


User Community of IUAC, New Delhi





Growth over the years; sanctioned proposals for different accelerator facilities



Growth over the years; sanctioned proposals for different research areas

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

iAP Institut für Angewandte Physik

Government of India
Department of Atomic Energy
Bhabha Atomic Research Centre

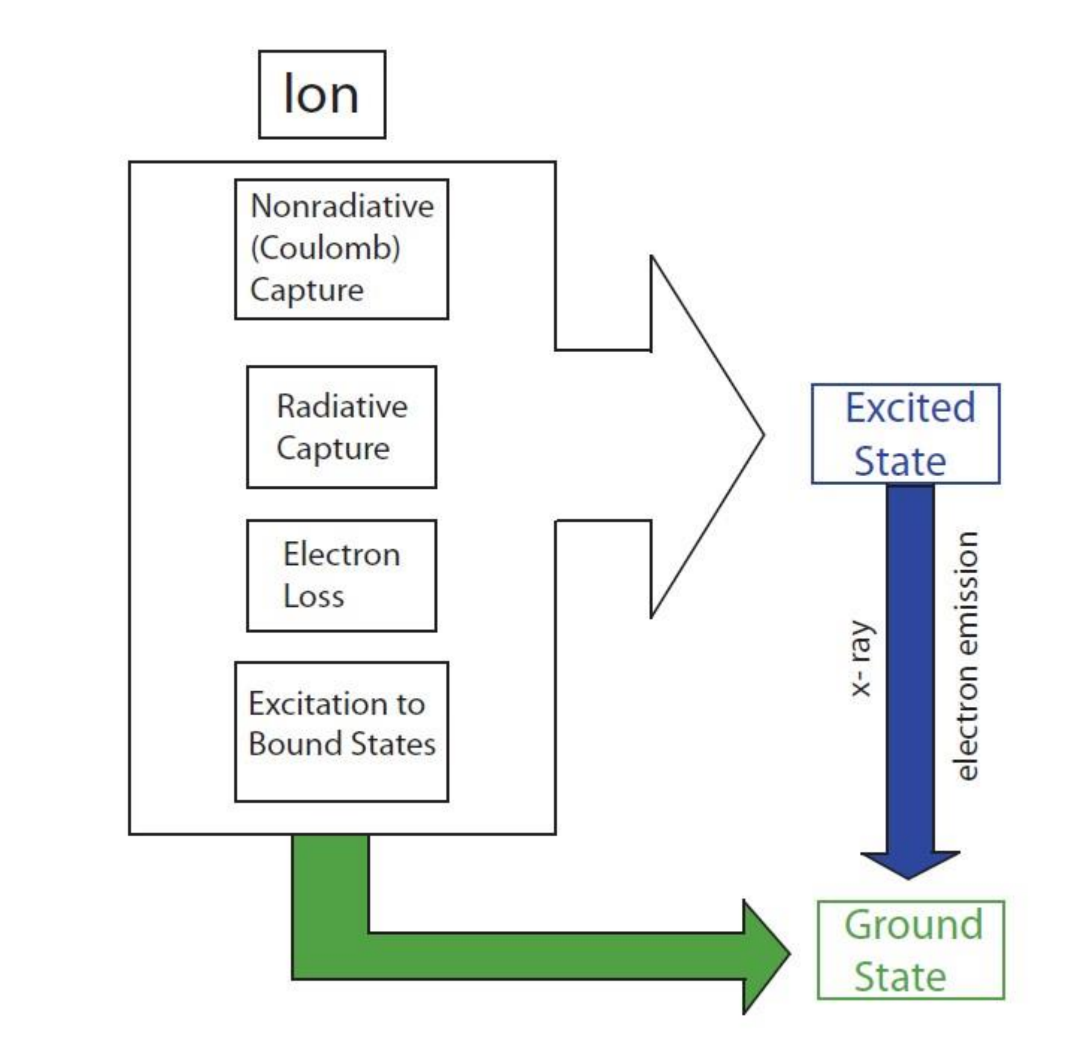
GSI
GSI Helmholtzzentrum für Schwerionenforschung GmbH

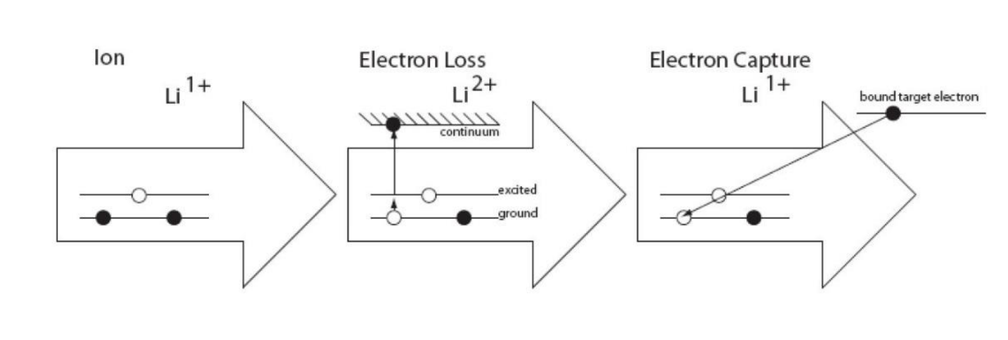
अंतर विश्वविद्यालय त्वरक केंद्र
Inter-University Accelerator Centre - (IUAC)

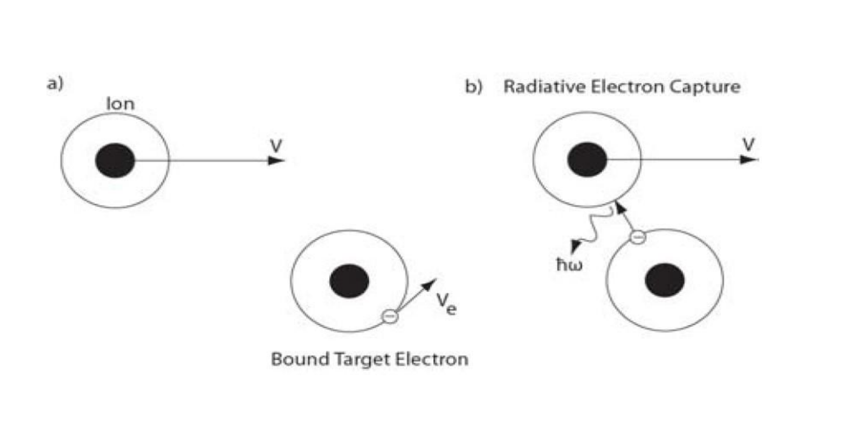
Indian Institute of Technology Delhi

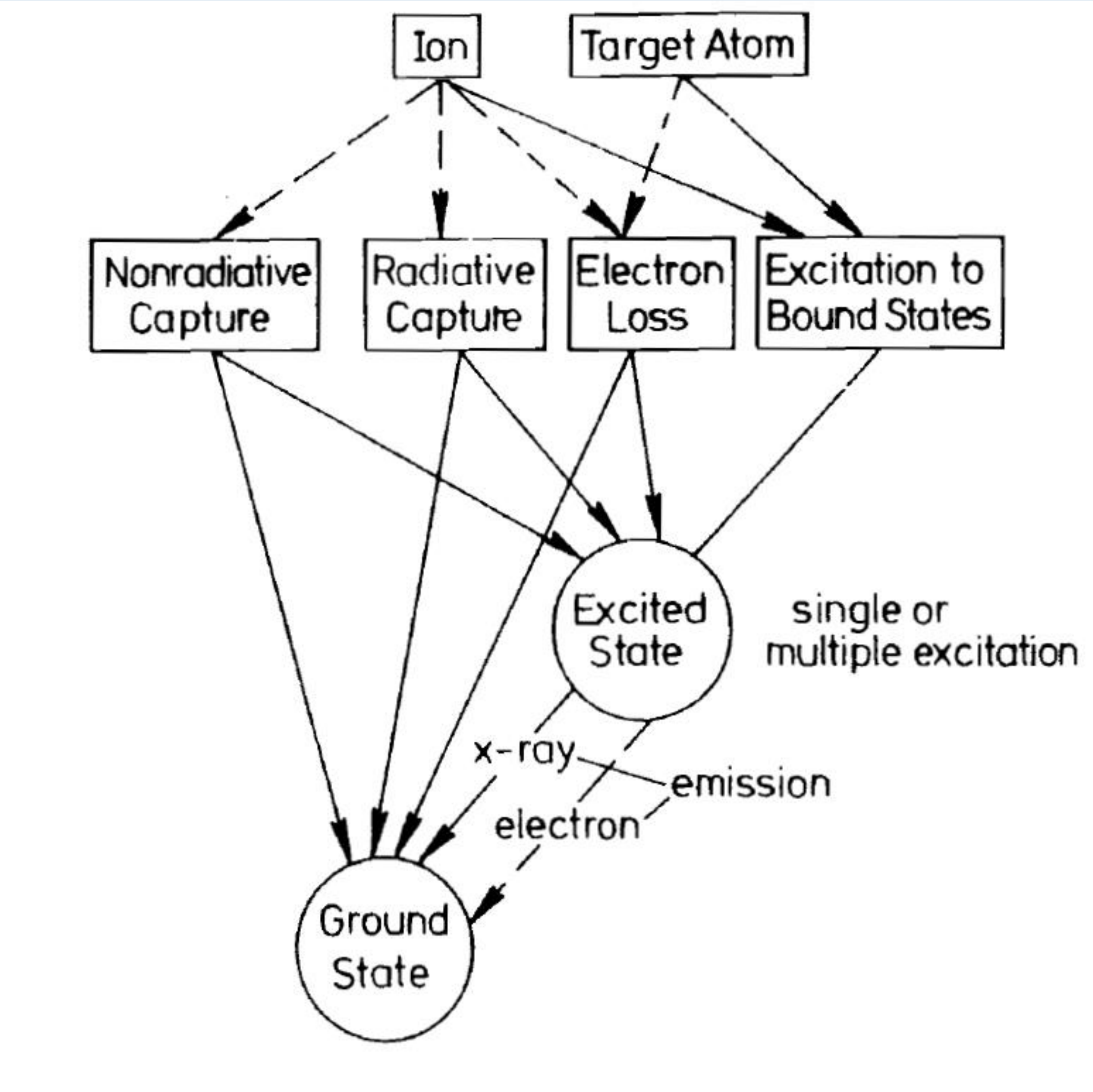
ECRIS 24

SOME GENERALITIES

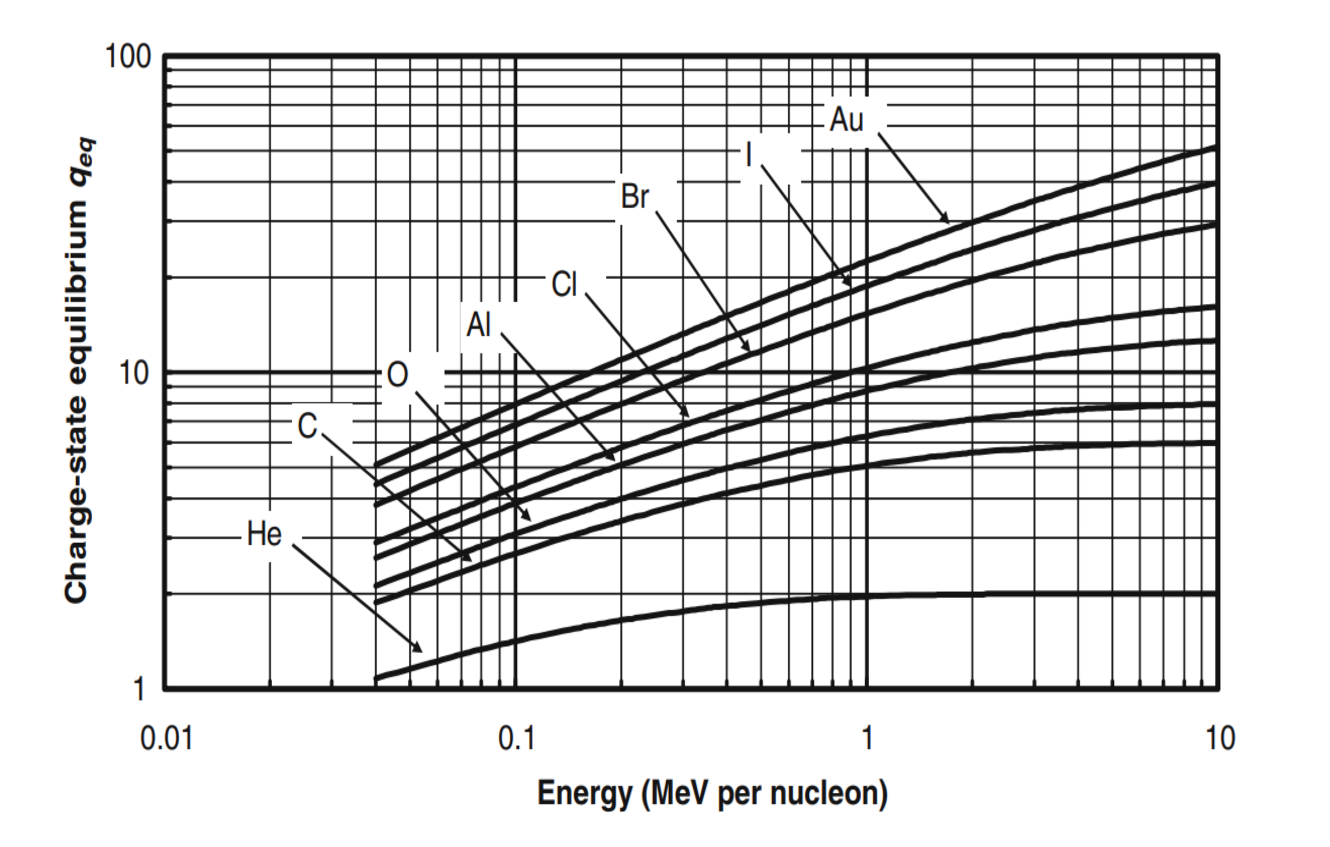








Scheme for basic collision-induced ion-atom processes, which lead to a change of the projectile charge state, either directly or via multiply excited states; the broken lines indicate charge-changing processes.



Charge state equilibrium (q_{eq}) as a function of input energy for various ions using the Thomas-Fermi effective charge model

- The charge state of heavy ions in cold matter (solid and gas targets) has been studied over a long period of time theoretically as well as experimentally
- Due to the high densities of the solid targets, an equilibrium charge state is usually reached after a short distance.
- Many experimental data have been collected and several empirical and semi-empirical formulas have been developed to estimate the charge state of the projectile as a function of its velocity and its atomic number with a very good agreement with the data at high velocities.
- A few codes are also available to calculate the charge state distribution and/or ionization & recombination cross sections, determining charge state

- **How to achieve stripping of ions using a plasma ?**
- **ECR sources generally do not make high density plasma because of the microwave cutoff at the plasma frequency. The plasma density does not increase much beyond cutoff. (The power efficiency of these plasma sources are never 100%, because of the line radiation associated with the gas used to make the plasma)**
- **Need to go for high power pulsed devices which can achieve very high densities**
- **Inductive plasmas are the only option**

- **In** plasmas and cold matter, charge states of a projectile ions are determined are determined by ionisation and recombination processes in the target
- Cross sections for electron capture in plasmas are much smaller than those in cold matter because there are fewer bound electrons in the plasma.
- Therefore, ions in a highly ionised plasma can reach much higher states than in cold matter(Here, a hydrogen plasma is most suitable)

(For projectile energies > 0.1 MeV/u, cross sections for bound electron capture and radiative electron capture increase as the projectile energy decreases)

- In “ionized matter”, energy loss processes are dominated by collisions between the heavy ions and free electrons in the plasma
- Direct capture of a free electron into a moving projectile violates the simultaneous fulfillment of energy and momentum conservation
- Therefore the above process is greatly reduced compared to the capture of bound electrons
- Need low Z, highly ionised species, H plasma !

Bethe-Bohr-Bloc Stopping Theory

$$-\frac{\mathrm{d}E}{\mathrm{d}z} = \frac{16\pi a_0{}^2 I_H{}^2 Z_p^2}{m_e v_p^2}\left[\sum_{Z=0}^{Z_K}(Z_K - Z)n_z \ln\left(\frac{2m_e v_p{}^2}{I_Z}\right) + n_e \ln\left(\frac{2m_e v_p{}^2}{\hbar\omega_p}\right)\right]$$

effective projectle charge

bound electron contribution

free electron contribution

Stopping Power for cold gas and plasma

$$-\left(\frac{dE}{dx}\right)_{\text{gas}} = \left(\frac{Z_{\text{eff}}\, e\, \omega_p}{v_p}\right)^2 \ln\left(\frac{2mv_p^2}{\bar{I}}\right)$$

H. Bethe, Ann. Phys. (N.Y.) 5, 325 (1930

For high projectile velocities >> thermal velocity of electrons ;

$$-\left(\frac{dE}{dx}\right)_{\text{plasma}} = \left(\frac{Z_{\text{eff}}\, e\, \omega_p}{v_p}\right)^2 \ln\left(\frac{mv_p^3}{Z_{\text{eff}}\, e^2 \omega_p}\right)$$

$$\omega_p^2 = 4\pi n_0 e^2 / m$$

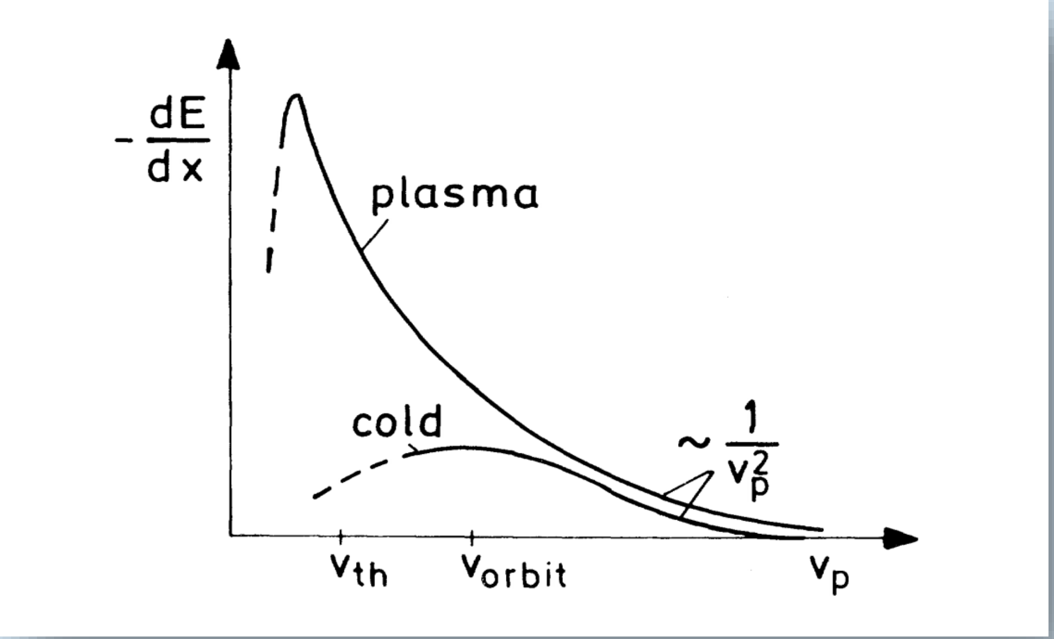
N. Bohr, Philos. Mag. 30, 581 {1915

FOIL/GAS STRIPPING Vs PLASMA STRIPPING

- Gas stripping does not reach sufficiently high charge states
- Foil strippers have difficulties in long lifetime

(radiation damage, sputtering, thermal and mechanical stresses due to irradiation, quality of ion beams is degraded more than from gaseous media)

- Plasma stripping (can solve) solves both the problems very well



$$\frac{dE}{dx} = -4\pi ne \frac{e^4 Z^2 eff}{mv^2} \ln \frac{4\pi mv^2}{h\omega p}$$

Thomas Peter & Jurge Meyer-ter-Vahn, Phy.Rev.A, Vol.43, No.4, 1998

DIELECTRIC THEORY OF STOPPING POWER

The stopping power of an ion is the force **F** that the ion experiences from its own induced field:

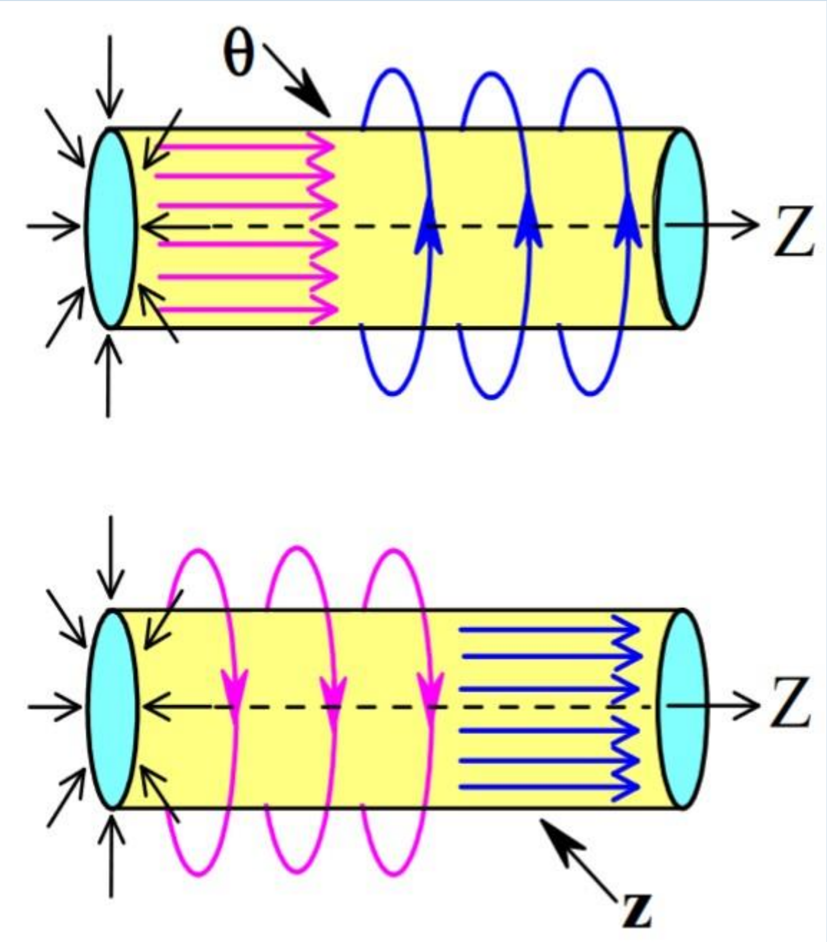
$$-\left(\frac{dE}{dx}\right) = -\mathbf{F}\cdot\mathbf{e}_x \bigg|_{\mathbf{r}=\mathbf{v}_p t} = Z_{\text{eff}}\, e \frac{\partial \Phi_1}{\partial x}\bigg|_{\mathbf{r}=\mathbf{v}_p t} . \qquad (17)$$

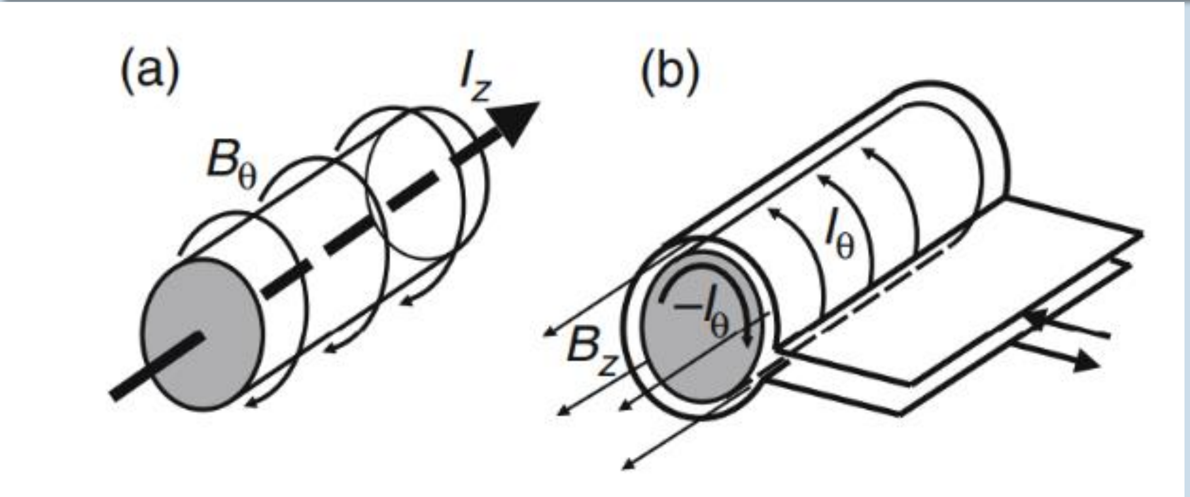
- **In the last three decades, a few experiments to measure the energy loss and the charge state of heavy ions traveling through ionized matter have been carried out**
- **In these experiments, two main effects of the ionized matter have been confirmed:**
- **the Enhanced Plasma Energy Transfer (EPET), which means a larger energy loss of ions in plasmas than in cold matter due to a more efficient energy transfer to the free electrons, and the Enhanced Projectile Ionization in Plasma (EPIP), which means a higher projectile charge state in plasmas than in cold matter mainly due to the reduction of capture cross sections with target free electrons.**

SOME BACKGROUND INFO ON FUSION STUDIES

- Many of the experiments in controlled thermonuclear fusion were z pinches
- They were highly unstable to the m=0, m=1 and the Rayleigh –Taylor instability
- Addition of axial magnetic field and removal of end losses to a toroidal geometry led to TOKOMAKS and reversed field pinch
- At fusion temperatures and practical values of magnetic fields, this restricts the plasma density to 10^{20} to $10^{21}/m^3$ and containment time of several seconds with plasma radius of 1 m
- Studies on plasma focus (similar to Z pinch) has shown achievable plasma densities of $10^{25}/m^3$ and temperature of 1 keV in a narrow filament of radius 1 mm
- It has enhanced stability properties and very suitable for ion stripping
- Development of high voltage, high current pulse technology to attain dense fusion plasmas

Z/θ PINCH PLASMAS



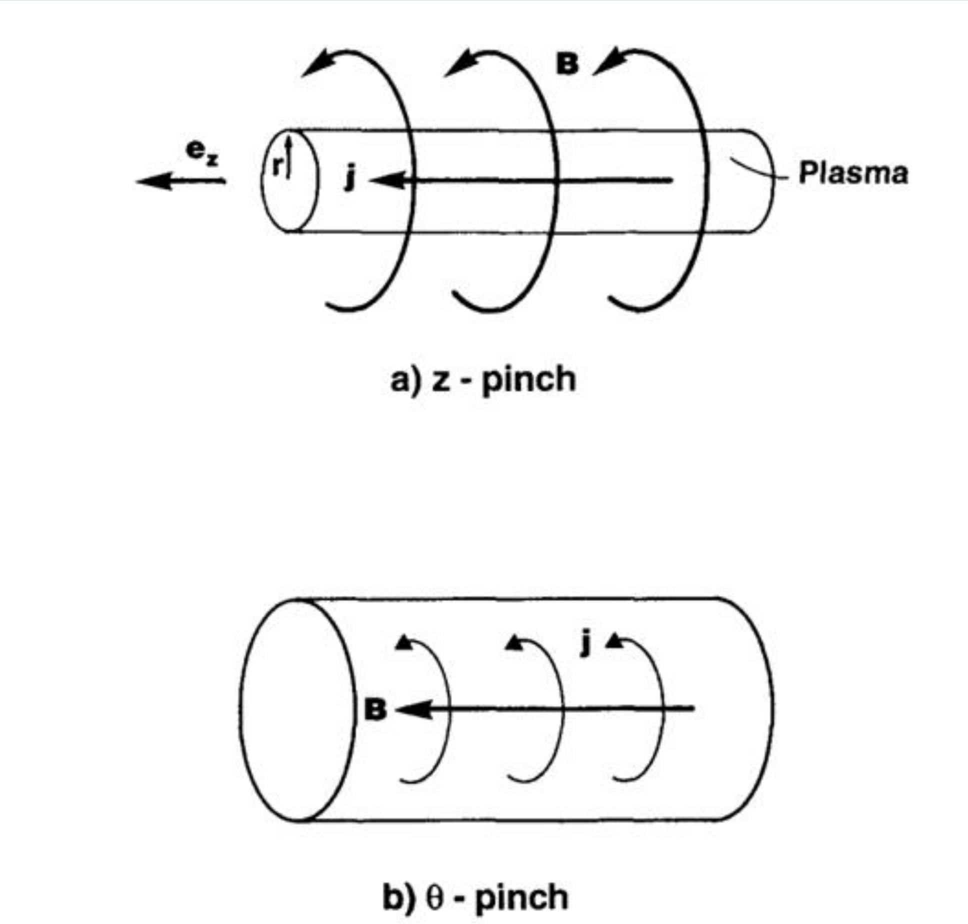


$$nk_B(T_e + T_i) = \frac{B^2(a)}{2\mu_0} \qquad B(a) = \frac{\mu_0 I}{2\pi a}$$

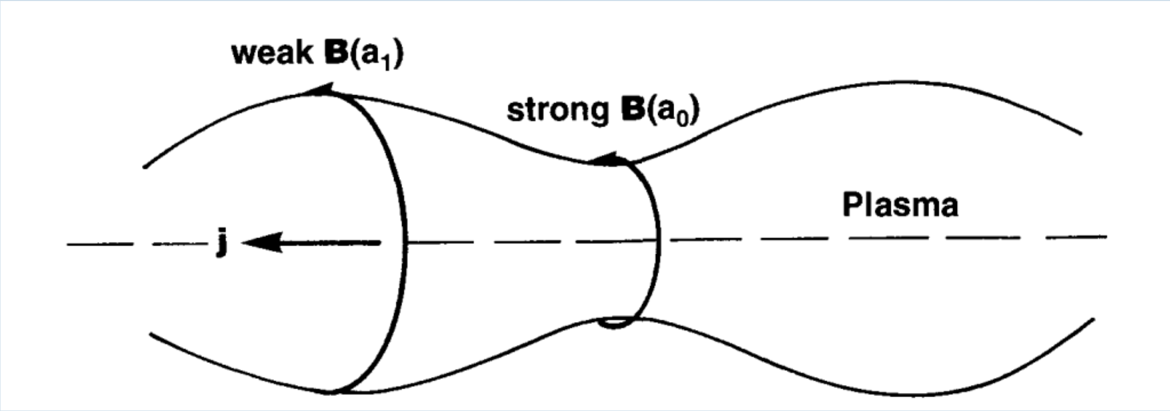
$$(T_e + T_i) \alpha \frac{I^2}{a^2}$$

$$I_c(mA) = 1.4x10^{-9} r_p(cm)\sqrt{n_e(cm^{-3})T(keV)}$$

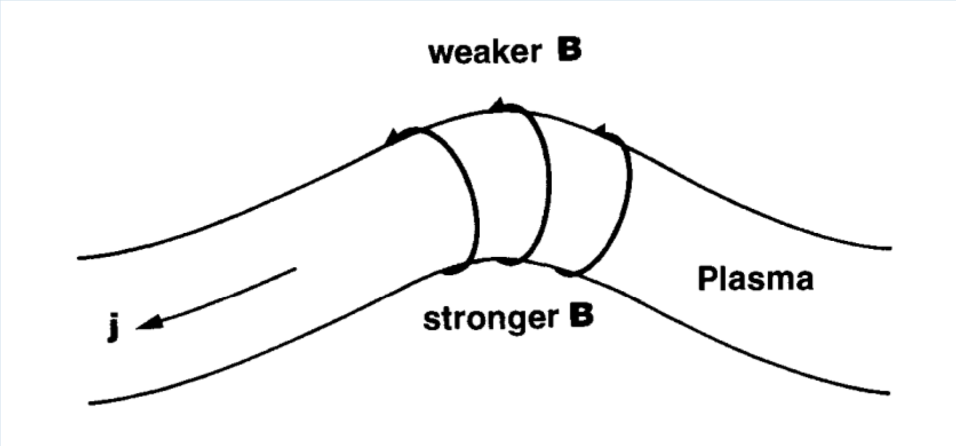
n_e~ 10^{19} cm^{-3}, T_e~ 5 keV, r_p~ 1 mm, I_c~1 mA



Sausage or pinch instability



Helical kink instability



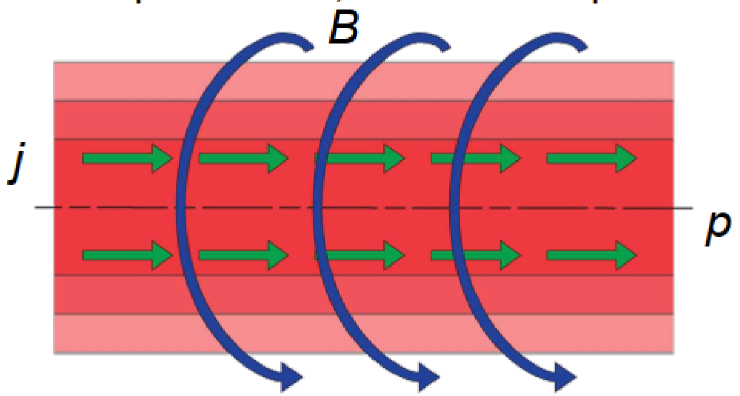
Z Pinch Device

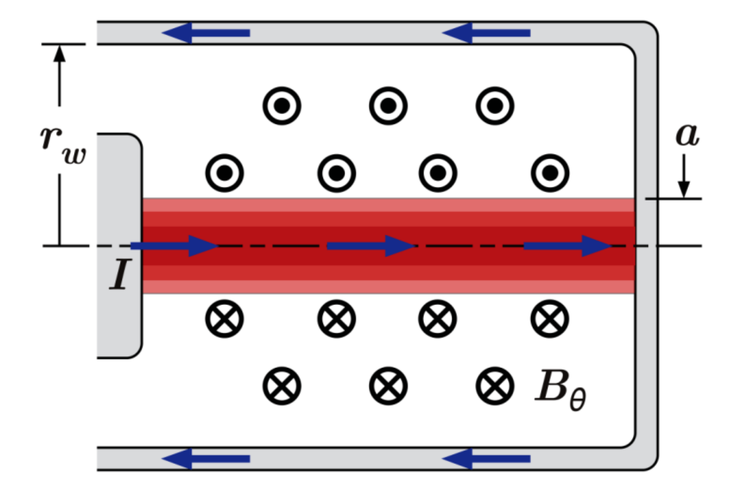
Z-pinch configuration has many appealing features

The Z-pinch has the simplest geometry of any magnetic confinement configuration:

$$\frac{dp}{dr} = -\frac{B}{\mu_o r}\frac{d(rB)}{dr}$$

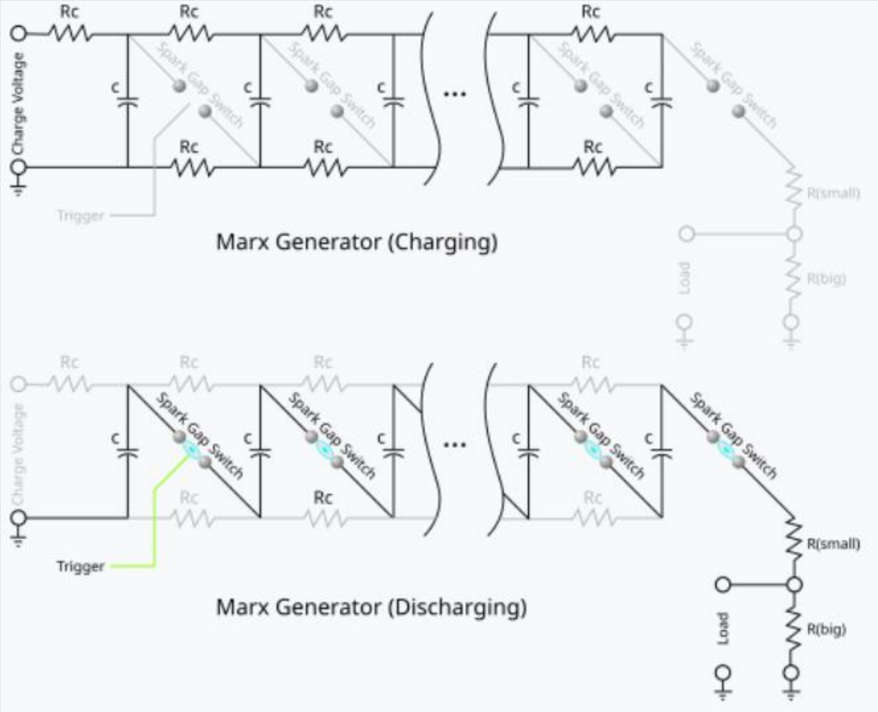
- cylindrical plasma column
- directly driven axial current
- self-generated magnetic field compresses the plasma
- ➢ perfect utilization of the magnetic field for compression, β=100%
- ➢ no magnetic field coils: greatly reducing cost, size, and complexity
- ➢ increasing the current generates higher plasma parameters, increased fusion production, and smaller plasma radius



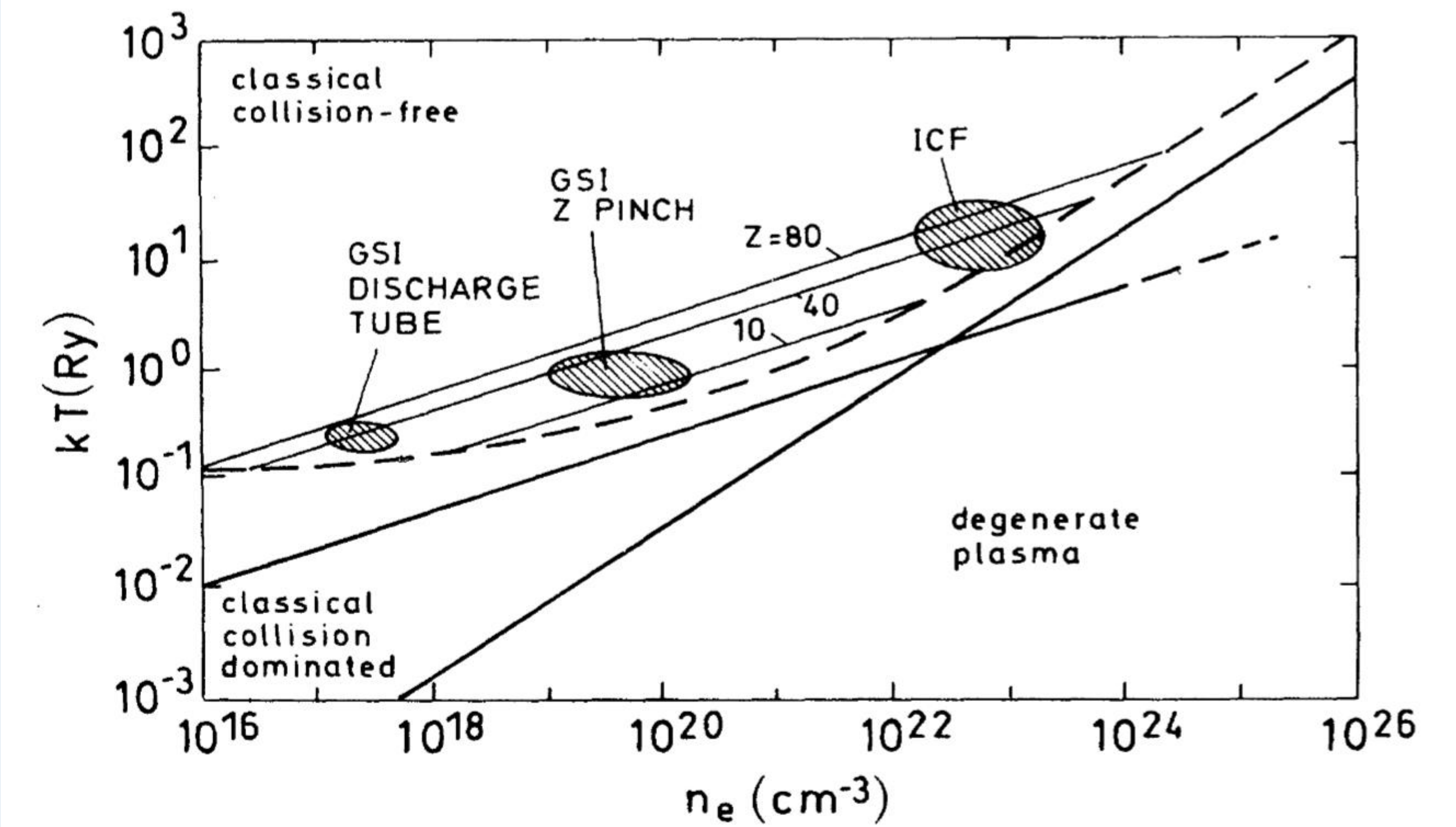


U.Shumlak, J. Appl. Phys. **127**, 200901 (2020); https://doi.org/10.1063/5.0004228

- **Generally, in pinch devices, the current is generally provided from a large bank of capacitors and triggered by a spark gap, known as a Marx Bank or Marx Generator.**
- **Its purpose is to generate a high-voltage pulse from a low-voltage DC supply.**
- **The circuit generates a high-voltage pulse by charging a number of capacitors in parallel, then suddenly connecting them in series.**



PHASE SPACE DIAGRAM



Thomas Peter & Jurge Meyer-ter-Vahn, Phy.Rev.A, Vol.43, No.4, 1998

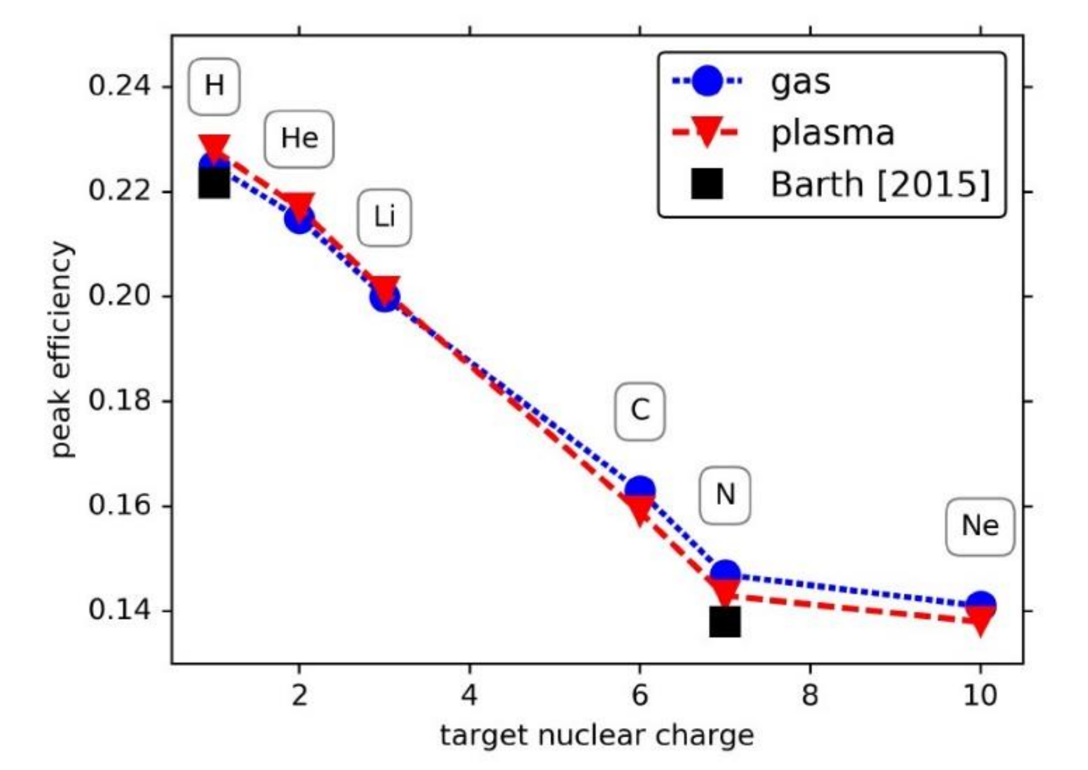
- Z pinch is one of the first concepts to be investigated as a potential fusion device, and the various embodiments were found to be susceptible to instabilities that severely limited the plasma lifetime.
- A dense plasma focus facilitates fusion reactions through a Z-pinch effect, but the reactions primarily rely on instabilities to produce large axial electric fields that accelerate ions and produce short-lived beam-target fusion

CURRENT STATE OF THE ART

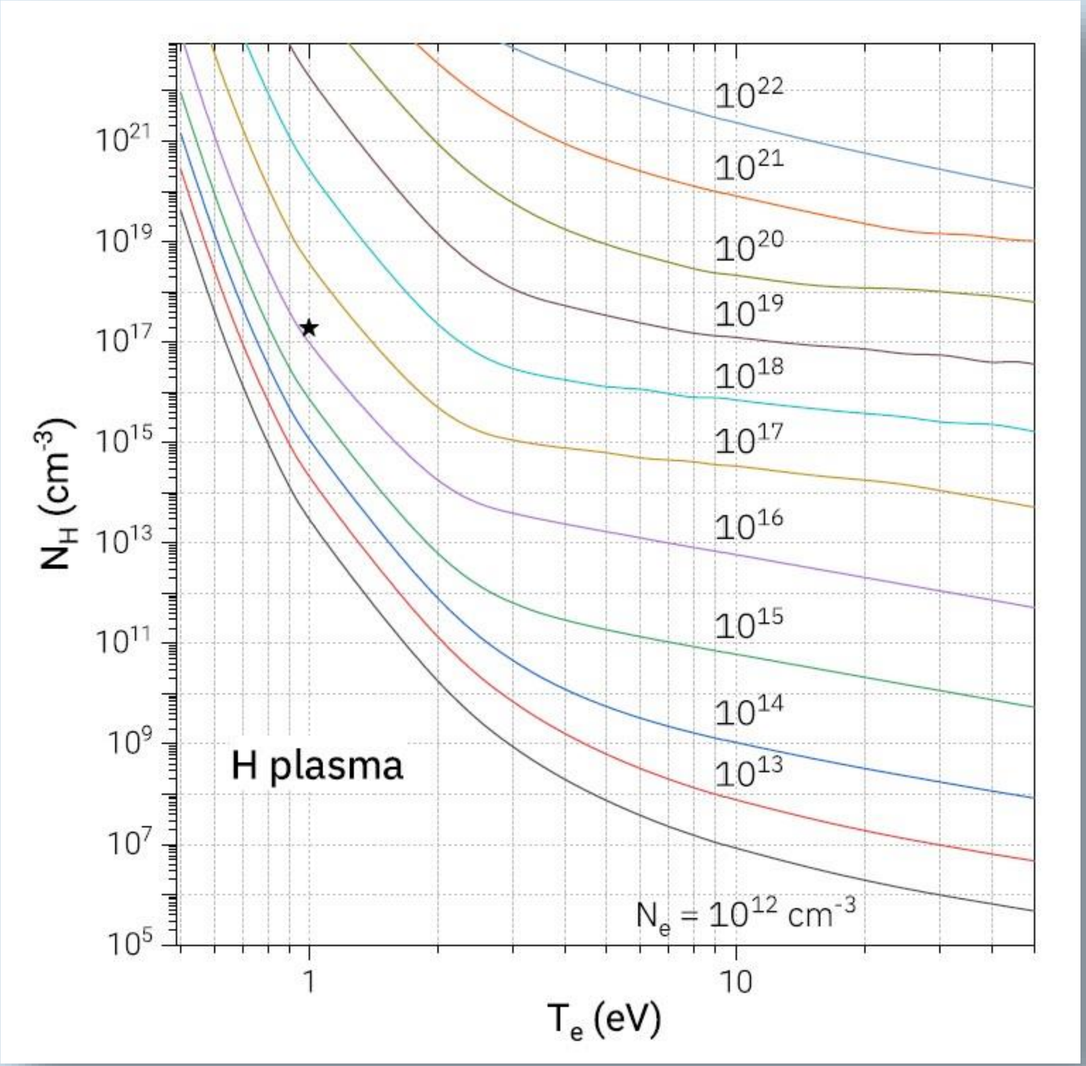
Z pinch plasma ---disadvantage is the electrode erosion effect and lifetime is reduced

Induction ignition of plasma ----an axial magnetic field extends

IAP at University of Frankfurt –researching on various alternatives to Z pinch (spherical theta pinch and spherical screw pinch experiments were performed)

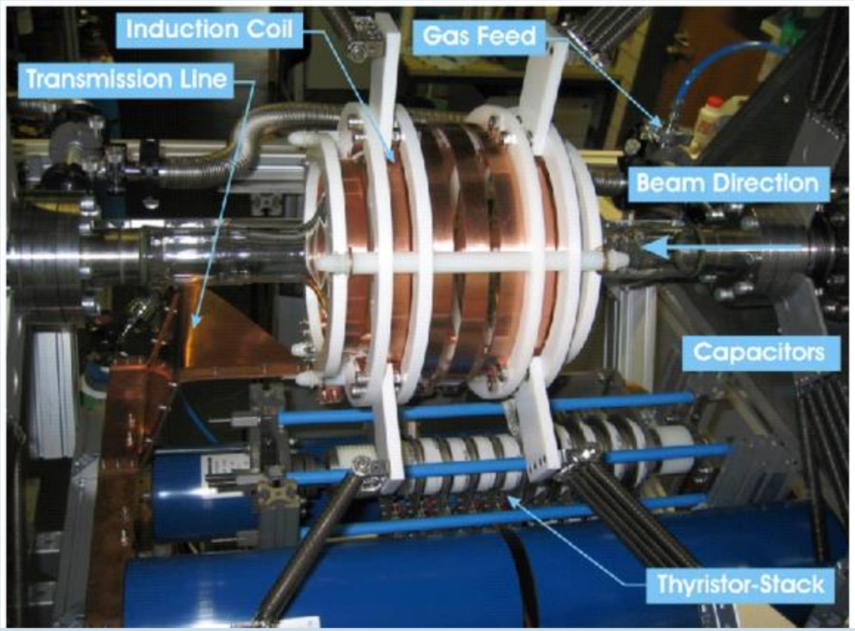


ESTIMATES OF THE FLYCHK CODE



N_H= (1.9 ± 0.7) · 1017 cm−3 at T_e= 1 eV and N_e= 1.9 · 1016 cm−3.

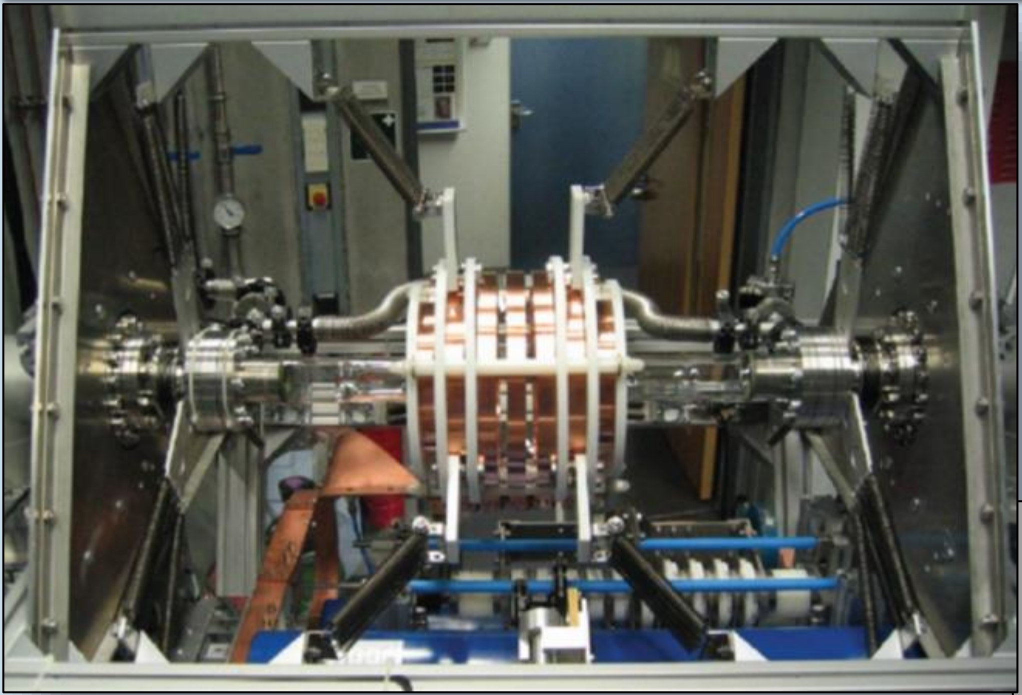
THETA PINCH DEVICE (IAP, FRANKFURT)



- Minimum breakdown condition is dB/dT ~ 10^8 G/s
- => dB/dT ~ 10 mT/μs
- Most “theta” pinch devices operate from 1 T/μs to 100 T/μs

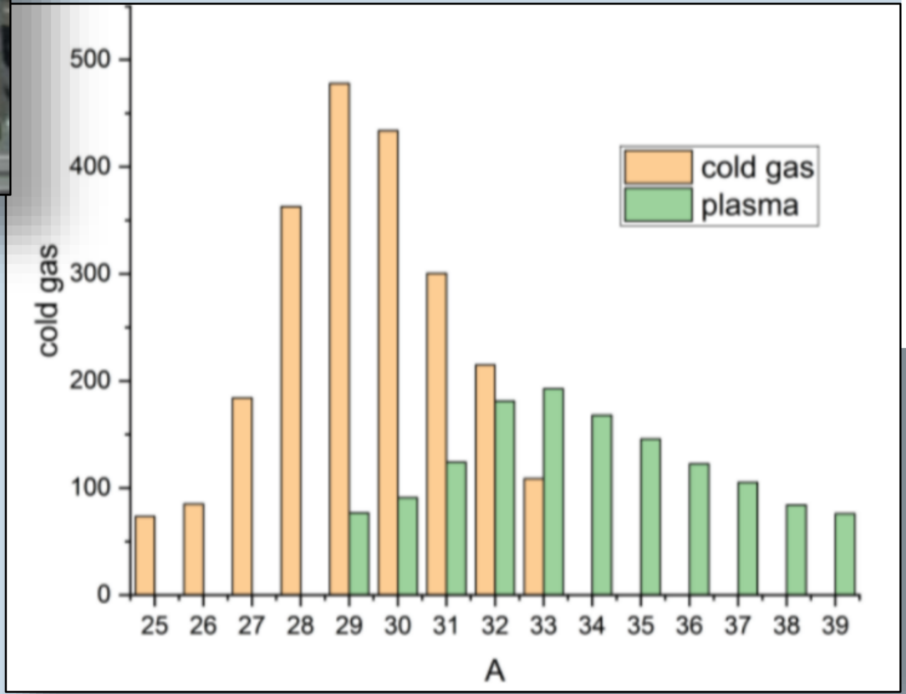
Courtesy: J.Jacoby (IAP, Frankfurt)

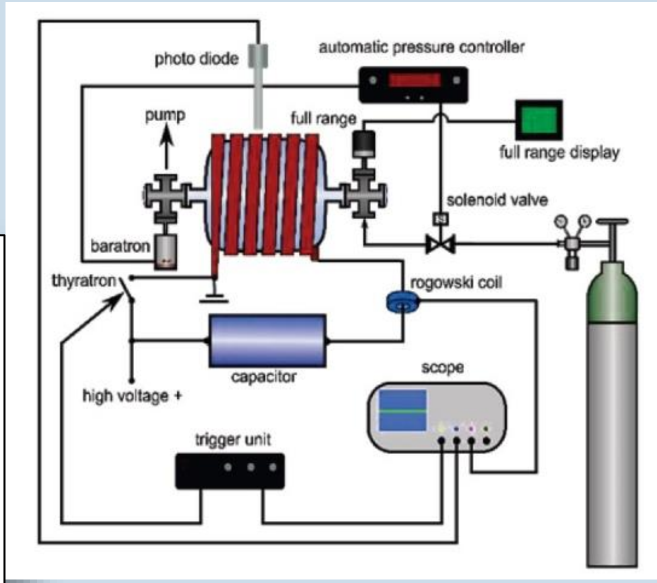
TEST SET-UP FOR "FAIR" PROJECT



View of the Spherical Theta Pinch device : beam tests at GSI, Darmstadt, Germany

Charge state distribution of a 3.6 MeV/u Au^{26+} beam after passing through a hydrogen plasma in comparison to a cold gas



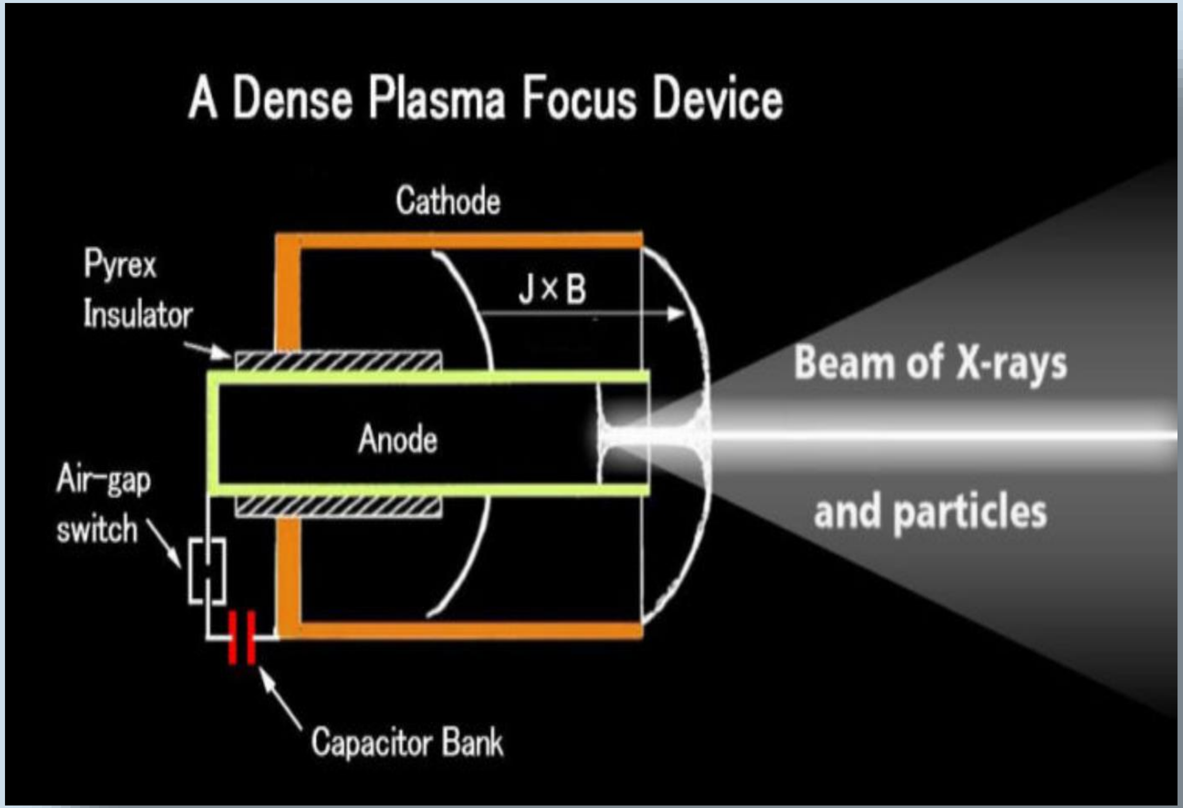


Courtesy: J.Jacoby (IAP, Frankfurt)

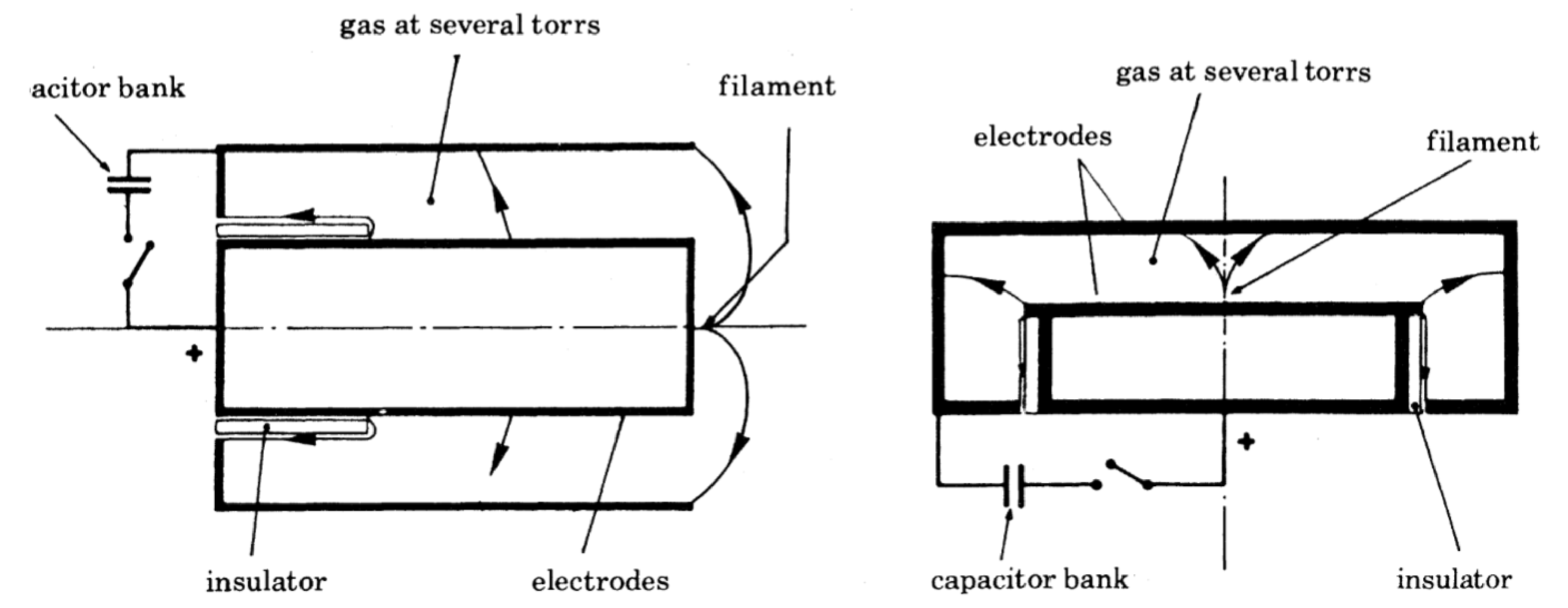
DENSE PLASMA FOCUS

A **Dense Plasma Focus** (DPF) is a device that produces, by EM acceleration and compression, short-lived plasma that is so hot and dense that it becomes a copious multi-radiation source. The EM compression of the plasma is called a "**pinch**"

Pulsed high voltage applied to a low pressure gas between co-axial cylindrical electrodes generating short duration, (~ 10 – 50 ns) high density plasma (10^{19} cm^{-3})

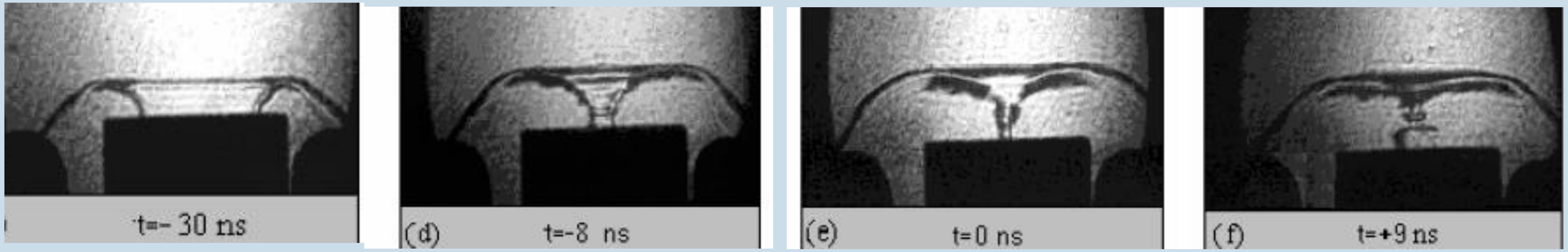


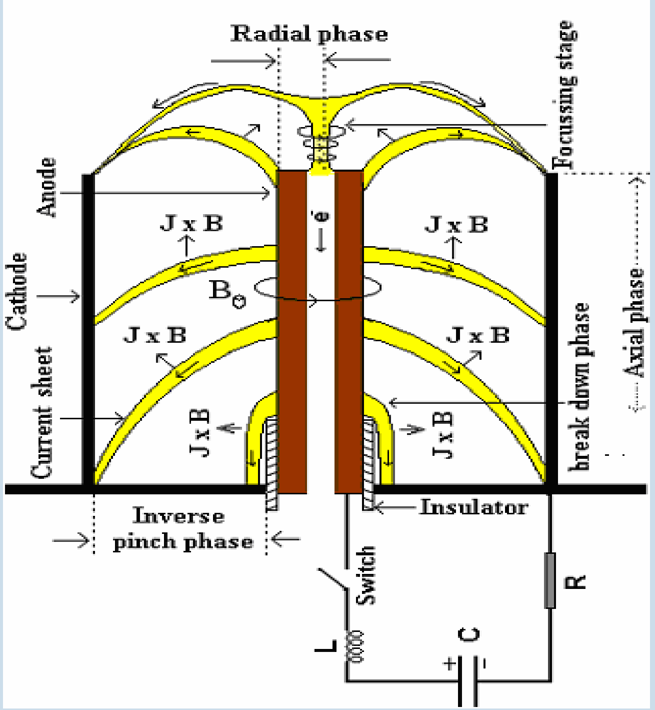
DENSE PLASMA FOCUS



Courtesy: R. Verma, S.K.Sharma, A.Sharma (BARC)

Radial Compression Phase and Plasma Characteristics





Plasma Characteristics at Compression:

- density: 10^{19} ions/cm^3
- electron temperature: 0.5-1 keV
- time of compressed phase: 20-500 ns

Plasma Characteristics at Fusion:

- density: 10^{22-24} ions/cm^3
- electron temperature: 3-10 keV
- time of ion acceleration: 1-5 ns
- abundant production of MeV ions, and hard X rays

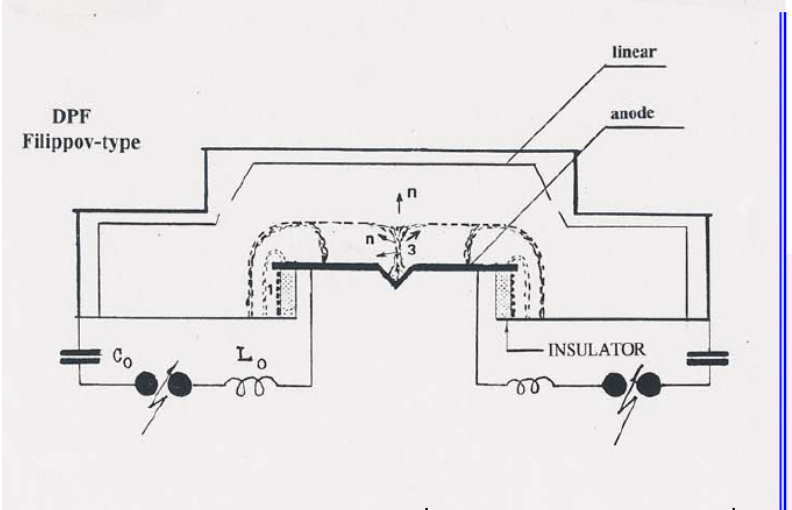
$$r_{min} = 0.12a \qquad t_{comp} = 4.5a$$

$$z_{max} = 0.8a \qquad t_{pinch} = 2a$$

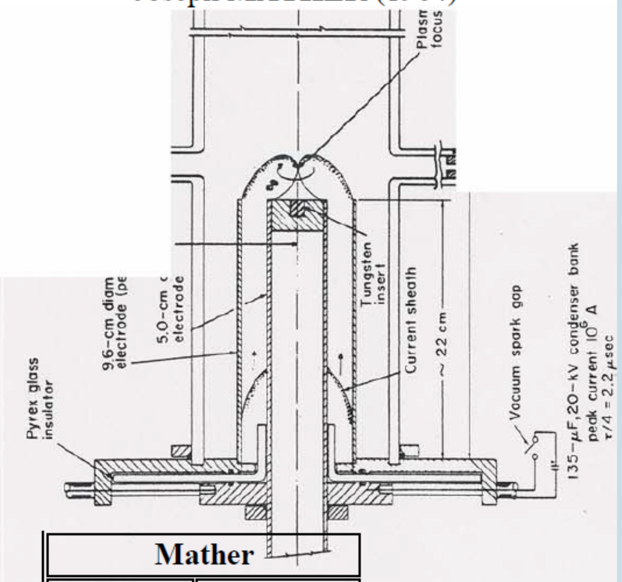
Courtesy: R. Verma, S.K.Sharma, A. Sharma (BARC)

GENERIC TOPOLOGIES OF PLASMA FOCUS

Nicolai and Tatiana **FILIOPPOV** (1961/62)



Joseph **MATHER** (1964)



AR < 1

AR > 1

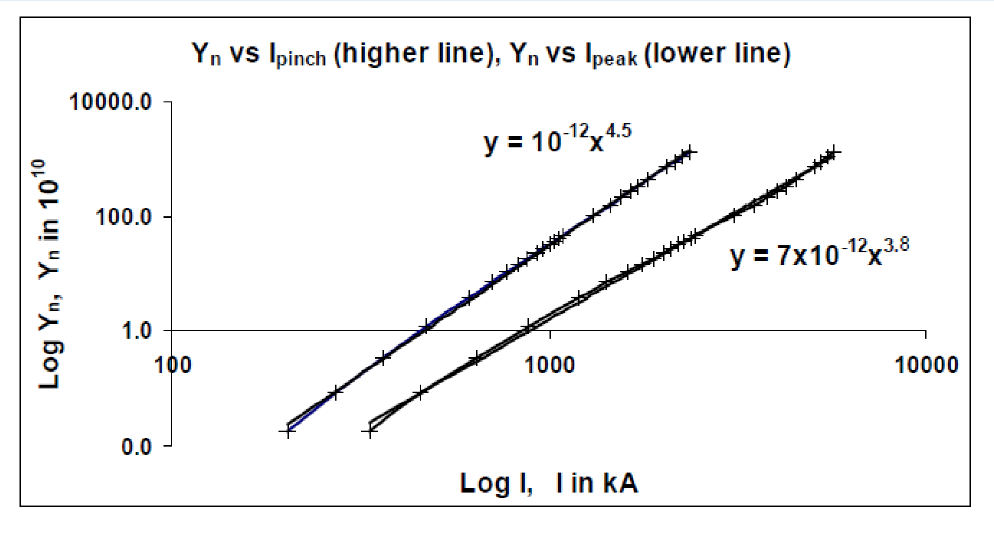
	Fillipov		Mather	
	50 kJ	**1 MJ**	**50 kJ**	**1 MJ**
Central electrode dia. [m]	0.5-0.7	0.9	0.04-0.08	0.16-0.25
Central electrode length [m]	0.12	0.26	0.2-0.3	0.5-0.6
D_2 gas Pressure [Torr]	0.5-2	1-3	3-8	5-10
Voltage [kV]	15-20	15	25-40	40-50
Neutron yield [per pulse]	$(1\text{-}3)\times10^{10}$	10^{12}	$10^{10}\text{-}10^{11}$	$(2\text{-}5)\times10^{12}$
PP Inductance [nH]	20	24	50	80
Pinch current [MA]	0.7-0.9	2-3	0.7-0.9	2-3

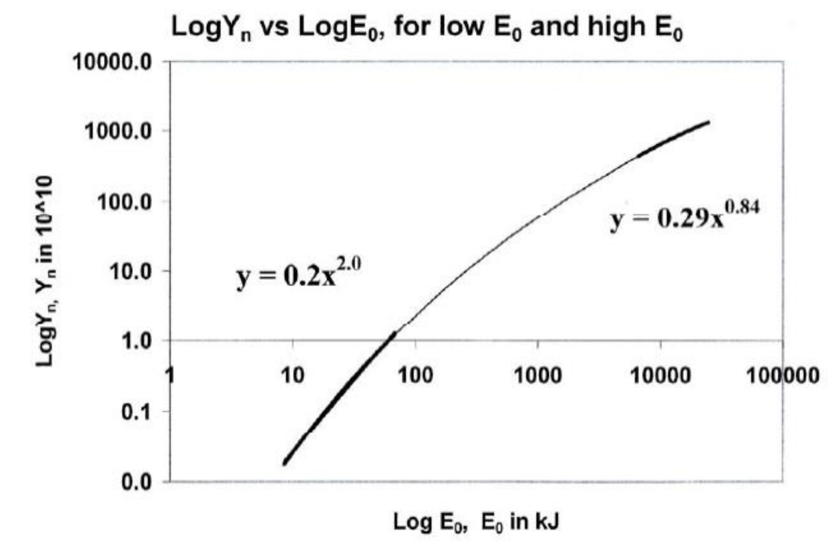
"Aspect Ratio (AR) is defined as the ratio of the height to the diameter of the anode"

Courtesy: R. Verma, S.K.Sharma, A. Sharma (BARC)

INSIGHT FROM THE STUDY OF NEUTRON YIELD SCALING LAWS

An in-depth systematic study has been carried out over wide ranges of energy; optimizing pressure, anode length and radius, to obtain scaling laws:





$Y_n = 3.2\times10^{11} I_{pinch}^{4.5}$

(I_{pinch} is in MA in the range of 0.2 to 2.4 MA)

$Y_n = 1.8\times10^{10} I_{peak}^{3.8}$

(I_{peak} is in MA in the range of 0.3 to 5.7 MA)

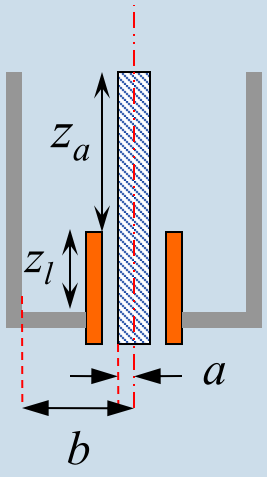
$Y_n \sim E_0^2$ from tens of kJ to $Y_n \sim E_0^{0.84}$ to MJ level

Courtesy: R. Verma, S.K.Sharma, A. Sharma (BARC)

PLASMA FOCUS ELECTRODE PARAMETERS

Courtesy: R. Verma, S.K.Sharma, A. Sharma (BARC)

- I_o - **Peak discharge Current**
- $t_{1/4}$ - **Quarter time period of the discharge current signal**
- L_o – **System Inductance**



Focus tube assembly

- a – **Anode radius**
- z_a – **Anode length**
- b – **Cathode radius**
- Z_l – **Insulator length**
- L_p – **Inductance of focus tube**

1. Anode radius (a)

Speed factor

(90 kA/cm/torr$^{1/2}$)

$I_o / ap^{1/2}$

2. Anode length (z_a)

Typical velocities in axial and radial phases

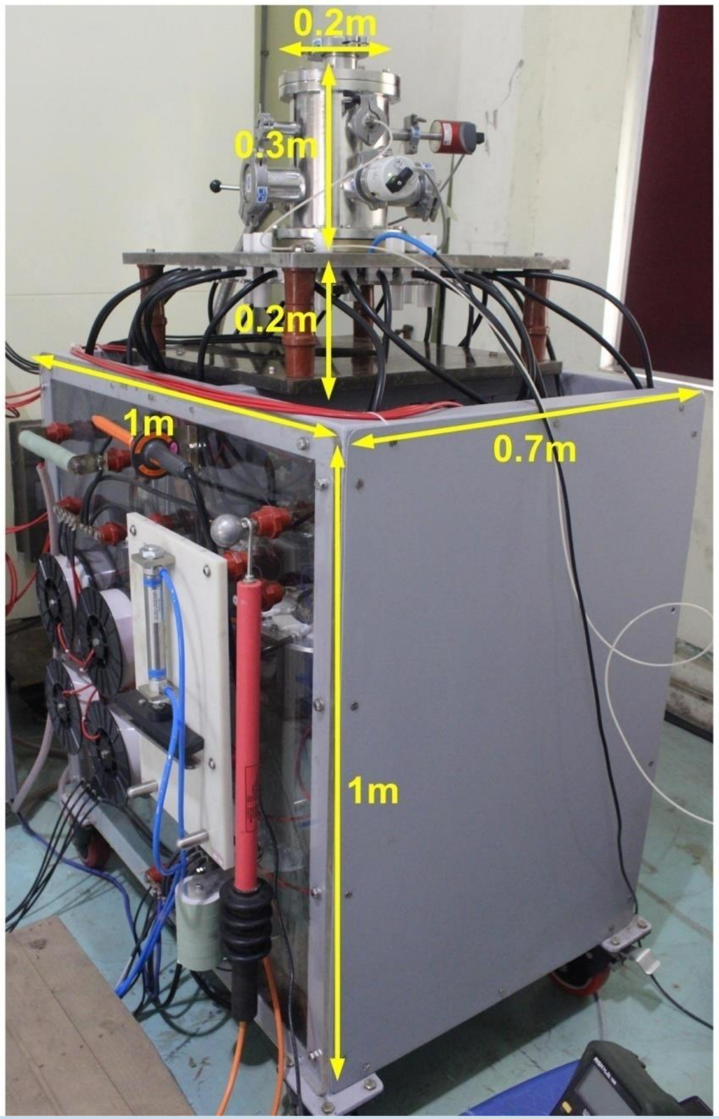
v_a : 10 cm/μs, v_r : 25 cm/μs

$z_o = v_a\{t_{1/4} - (a/v_r)\}$

3. Cathode radius (b) $L_o \geq L_p$ $\quad L_p = \mu_o/2\pi \ln(b/a) \times z_a$

4. Insulator length (z_l) $z_l < (b-a)$

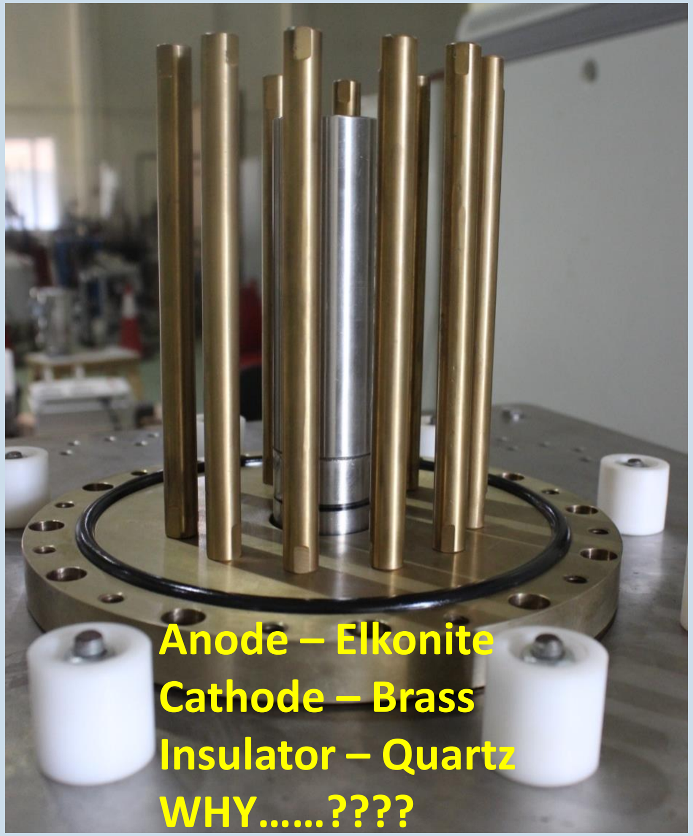
DD neutron yield per pulse	:	≥ 1×10^9 neutrons/pulse (average)
Neutron energy (DD)	:	~2.45 MeV (typical)
Neutron pulse duration	:	~50 ns (typical)
Plasma focus head	:	Replenish-able & Demountable
Total energy stored	:	10 kJ (maximum)
Total capacitance	:	50 µF (12.5 µF × 4 Nos.)
Charging voltage	:	20 kV (maximum)
Energy transfer switch	:	Pseudospark Switch (× 4 Nos.)
Peak discharge current	:	600 kA (maximum)
Eq. circuit inductance	:	~140 nH
Eq. circuit resistance	:	~33 mΩ
Anode length	:	120 mm
Anode radius	:	20 mm
Cathode radius	:	50 mm
Insulator length	:	30 mm
Insulator material	:	Quartz Glass
Size of plasma focus head	:	0.2 m (ϕ) × 0.3 m (h)
Overall weight of system	:	300 kgs (approx.)
Overall size of the system	:	1.5 m × 1 m × 0.7 m



Courtesy: R. Verma, S.K.Sharma, A. Sharma (BARC)

THE PLASMA FOCUS ELECTRODE ASSEMBLY

A figure of merit that is used to express material erosion resistance is called 'IMPULSIVITY (M)'



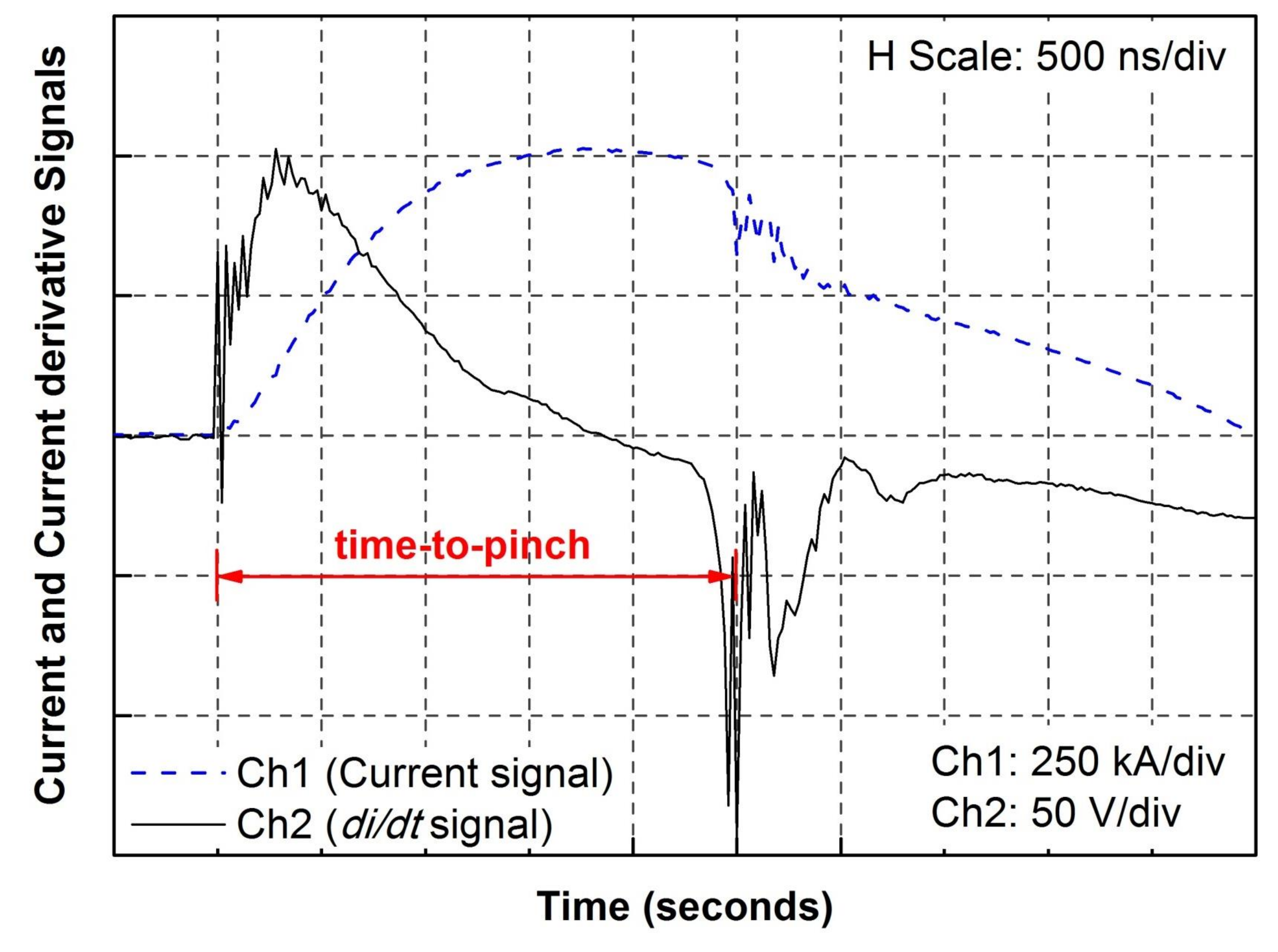
$$M = T_{melting} (\kappa \rho c)^{1/2}$$

Thermal conductivity (κ), density (ρ), Specific heat (c)

Materials	M ($J/cm^2 sec^{-1/2}$)
Tungsten	7000
Graphite	5700
Molybdenum	4800
Copper	4000
Stainless steel	1530
Aluminum	500

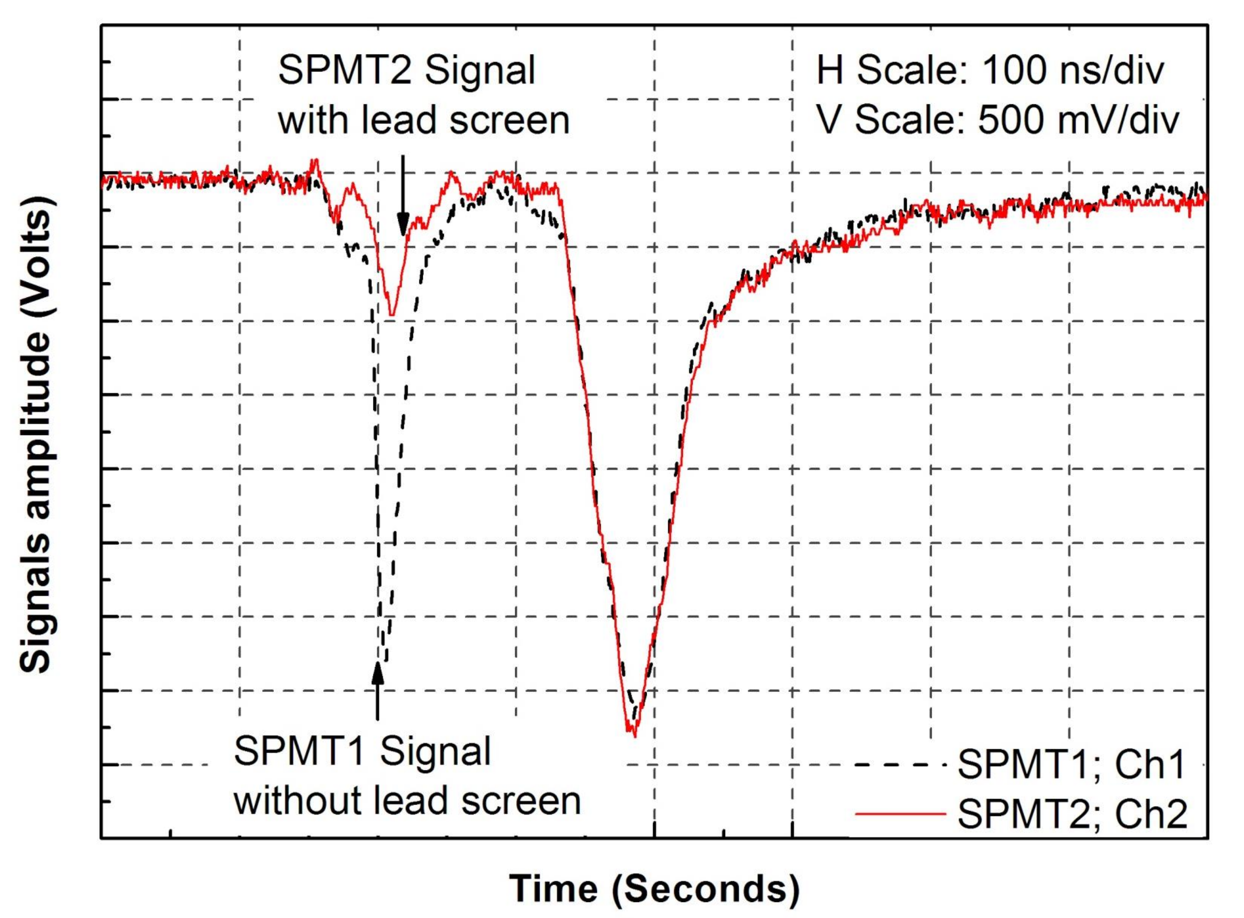
Courtesy: R. Verma, S.K.Sharma, A. Sharma (BARC)

Oscilloscope trace of typical *I* and *di/dt* signal



Courtesy: R. Verma. S.K.Sharma, A. Sharma (BARC)

Time resolved radiation measurements

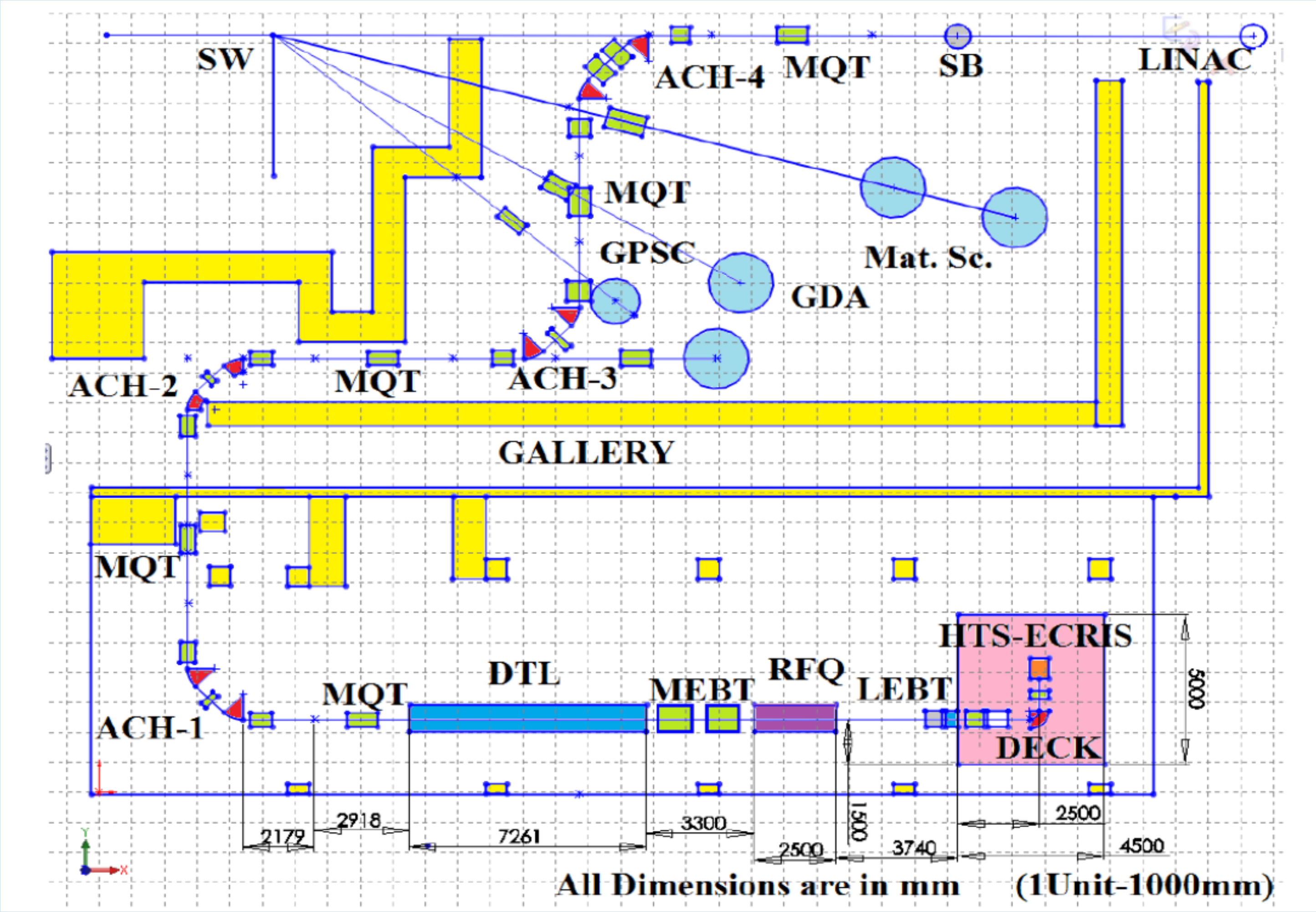


"Time resolved oscilloscope traces of two identical scintillator photomultiplier detectors kept at distance of ~4m (side-on) from PF device (TOF ~185ns)"

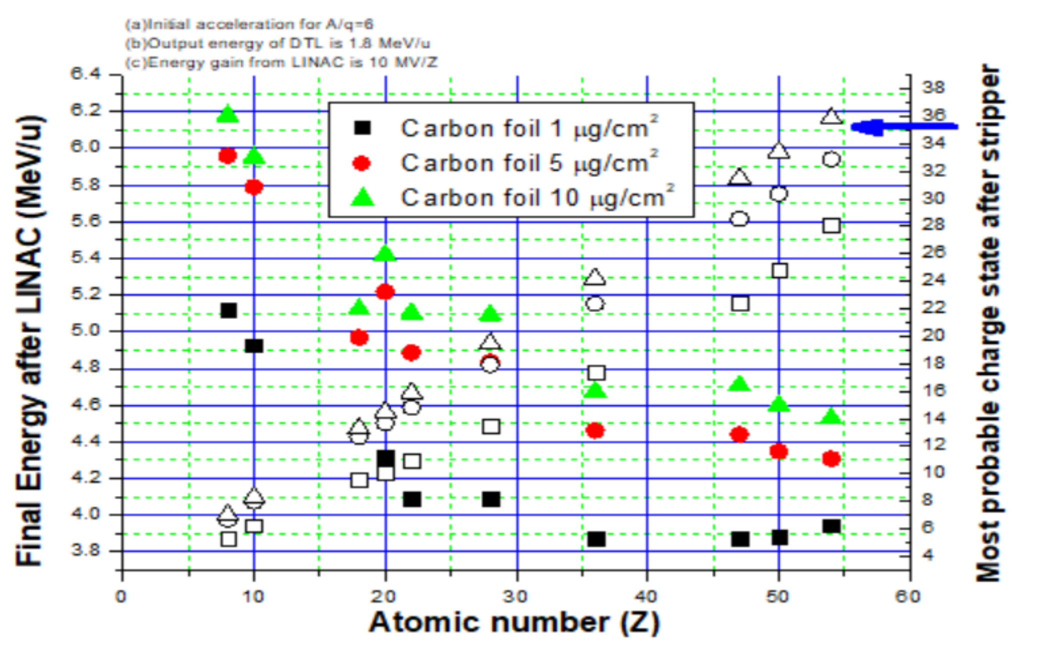
Courtesy: R. Verma, S.K.Sharma, A. Sharma (BARC)

- **15 UD/16 MV Tandem Pelletron Accelerator energy is boosted by the existing Super-Conducting Linear Accelerator operating at 97 MHz (energy input is 1.8 MeV/amu)**
- **High Current Injector will accelerate highly charged ions into the Super-Conducting Linear Accelerator operating at 97 MHz**
- **The output beam of final energy of 1.8 MeV/amu of HCI is similar to the output of the Pelletron Accelerator.**
- **In long term, HCI will operate as a parallel injector to Super-Conducting Linear Accelerator**

- **For the HCI, since the Multi-Harmonic Buncher is operational frequency at 12.125 MHz, the pulse to pulse separation is ~ 82.47 ns**
- **Bunchers are positioned all along the HCI beamline to preserve the bunch width, typically better than 1 ns to match with the super-buncher requirements (positioned just before entrance of SC-LINAC) for further acceleration into the SC-LINAC**

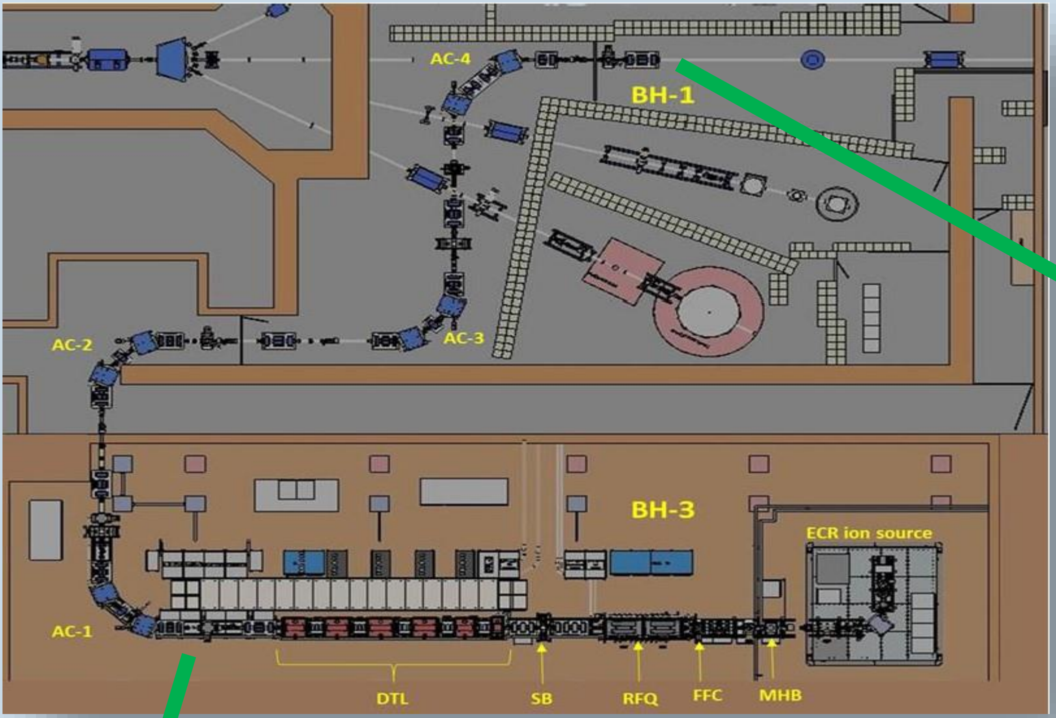


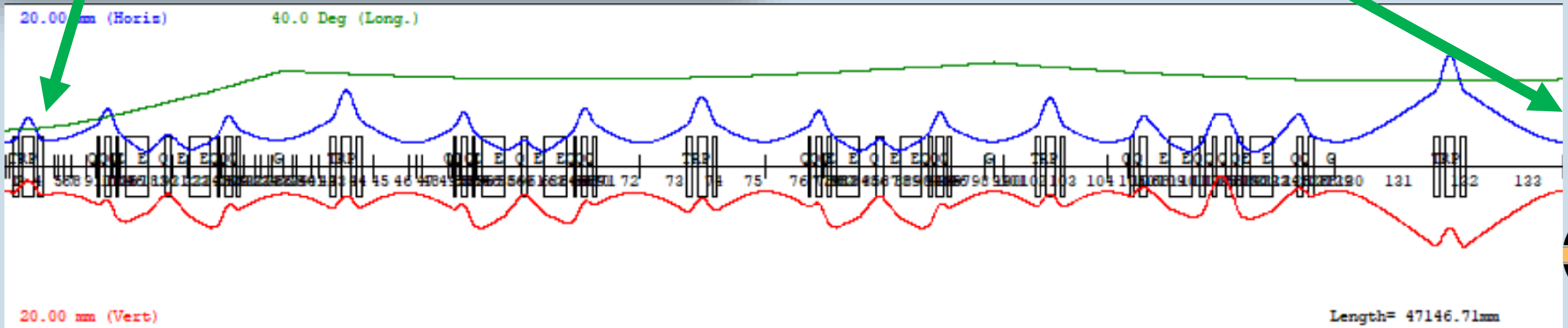
SW
ACH-4
MQT
SB
LINAC
MQT
GPSC
Mat. Sc.
GDA
ACH-2
MQT
ACH-3
GALLERY
MQT
HTS-ECRIS
DTL
RFQ
MQT
MEBT
LEBT
ACH-1
DECK
5000
2179
2918
7261
3300
2500
1500
3740
2500
4500
All Dimensions are in mm
(1Unit-1000mm)



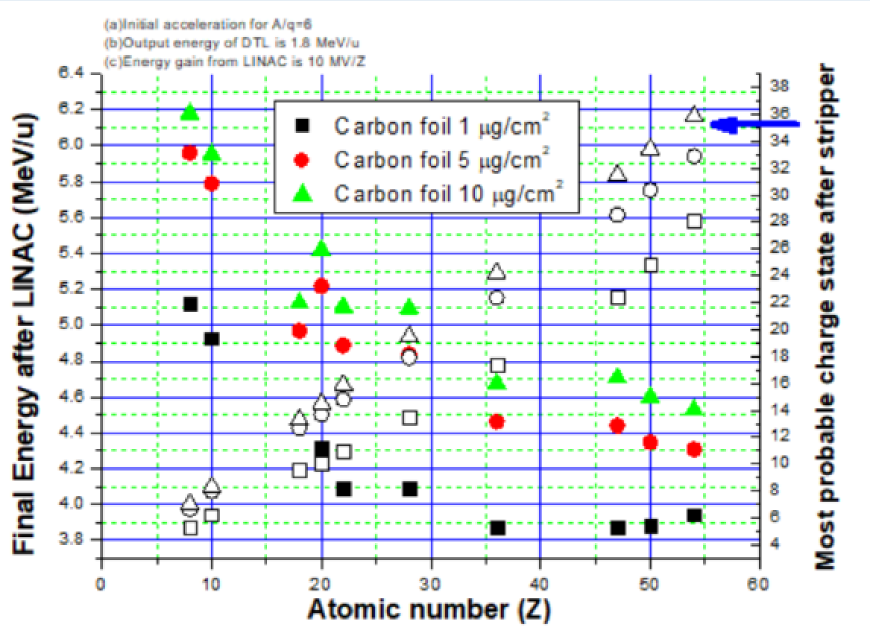
(a)Initial acceleration for A/q=6
(b)Output energy of DTL is 1.8 MeV/u
(c)Energy gain from LINAC is 10 MV/Z
Carbon foil 1 μg/cm²
Carbon foil 5 μg/cm²
Carbon foil 10 μg/cm²
Final Energy after LINAC (MeV/u)
Atomic number (Z)
Most probable charge state after stripper

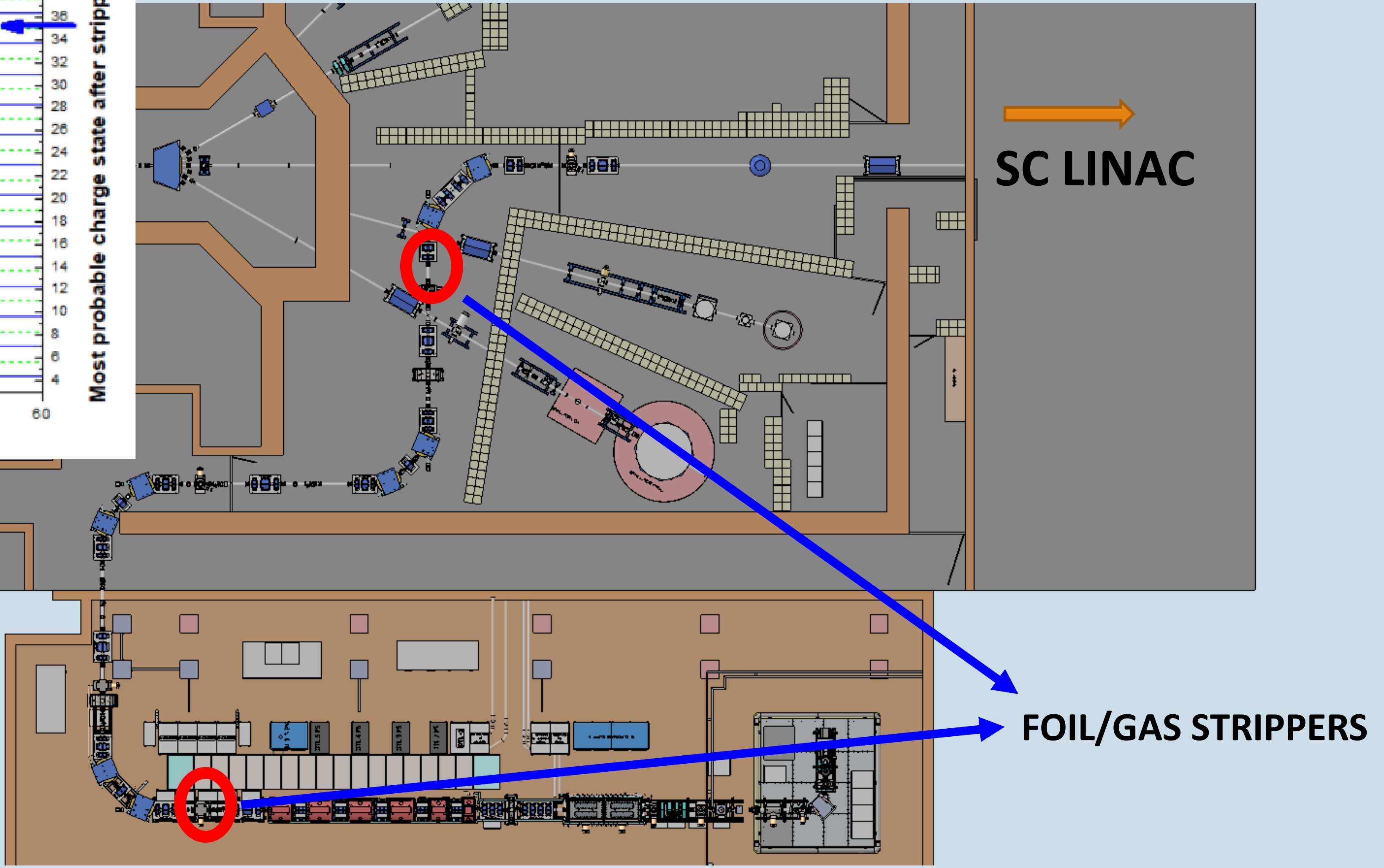
Layout of High Current Injector (HCI) Beamline





Foil/Gas Strippers





* Possibility of a plasma based stripper or hydrogen gas stripper

Conclusions

- A more stable pinch device is proposed and developed without magnetic field with densities ~ 10^{19} cm^{-3} characterized in the time scale of 10 to 50 ns.
- A 100 % fully ionized plasma is extremely important.
- Electrical optimizations (if required) may need to be planned to increase the discharge energy as well as the efficiency of the stripper cell.
- Initial Beam tests of the Dense Plasma Focus cell using heavy ions are planned this year end at IUAC, New Delhi
- Development of optical diagnostics for spatially and temporally resolved measurement of electron density
- Development of real-time monitoring of discharge parameters by interferometry
- Increasing the repetition rate (if required), and final beam tests with optical diagnostics

Thank You for your Kind Attention