Photo-neutralization: technologies and developments

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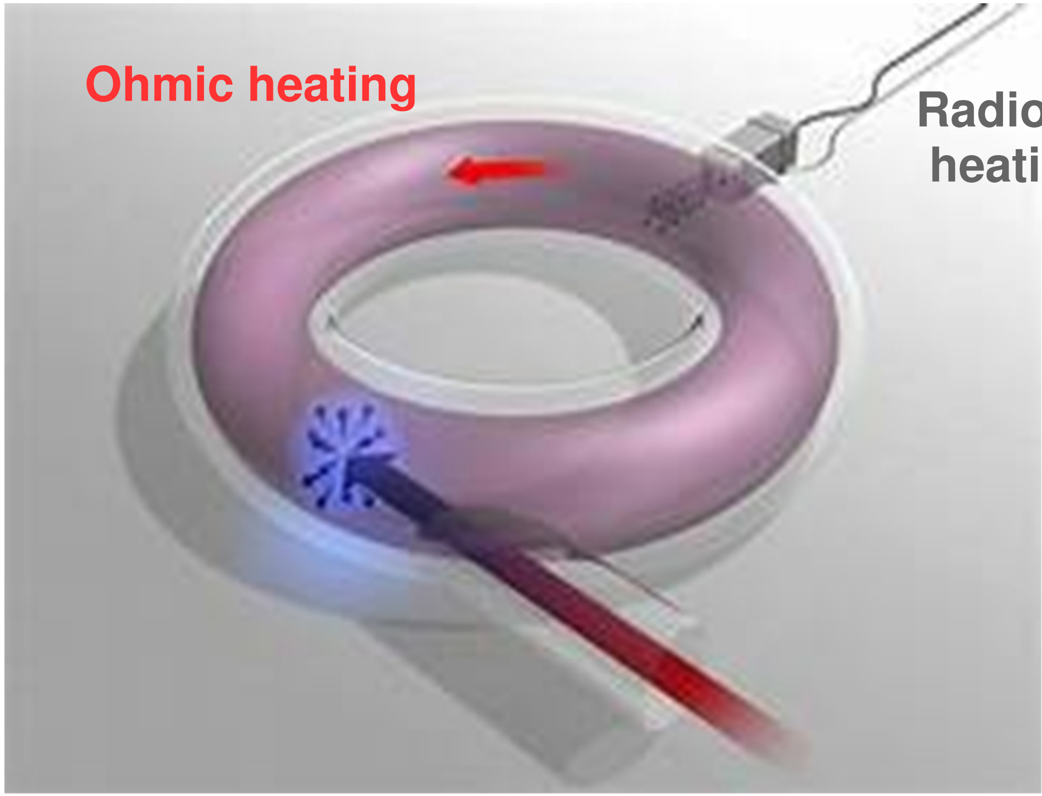
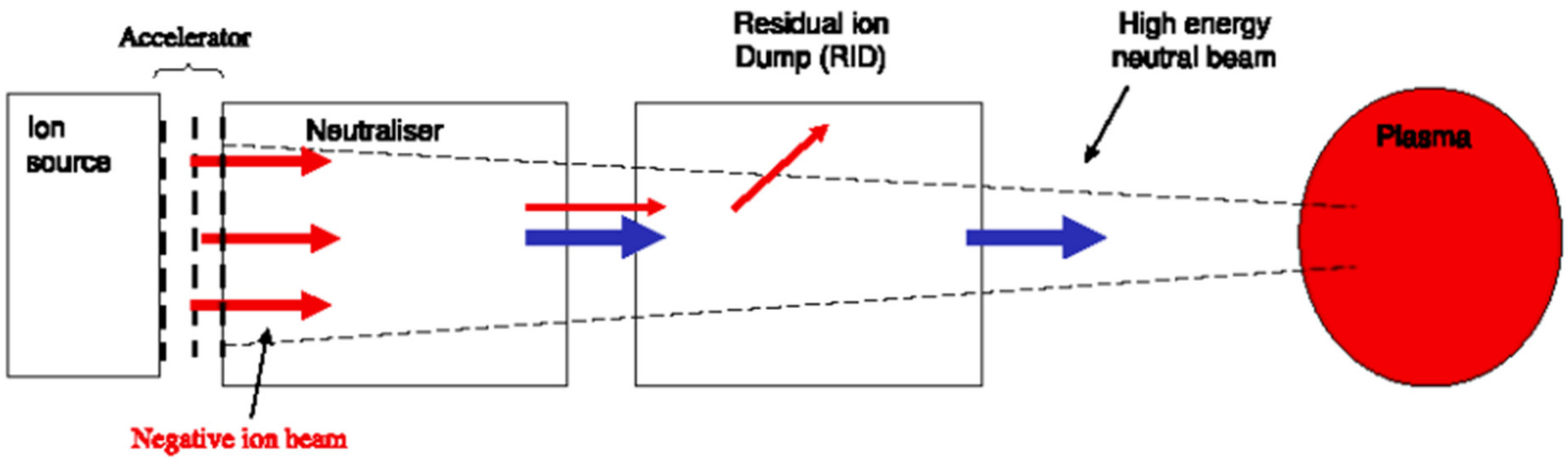
Why photo-neutralization?



Why photo-neutralization?



NBI system scheme (Chaibi et al., 2009)

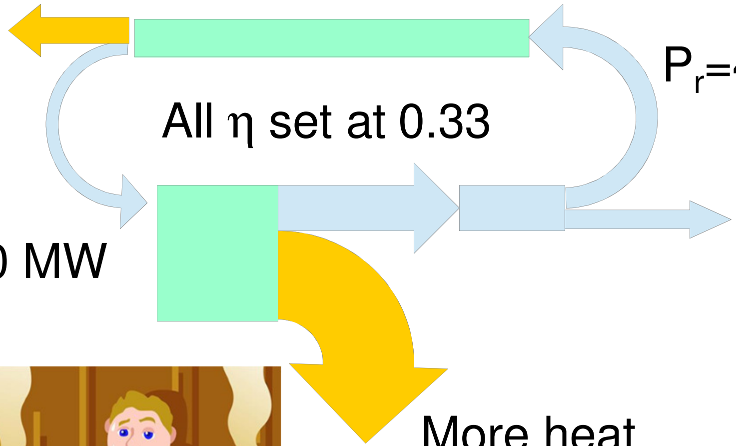
Efficiency of Neutral Beam Injector (NBI) based on gas neutralization of negative ion beams is <30%.

Neutral Beam Injector based on plasma neutralization of negative ion beams has similar losses and more complicated neutralizer.

Photo-neutralization would allow for Nuclear fusion reactor efficiency improvement by increasing the NBI system efficiency (about 90%).

Why photo-neutralization?

The importance of increasing the plasma heating systems efficiency

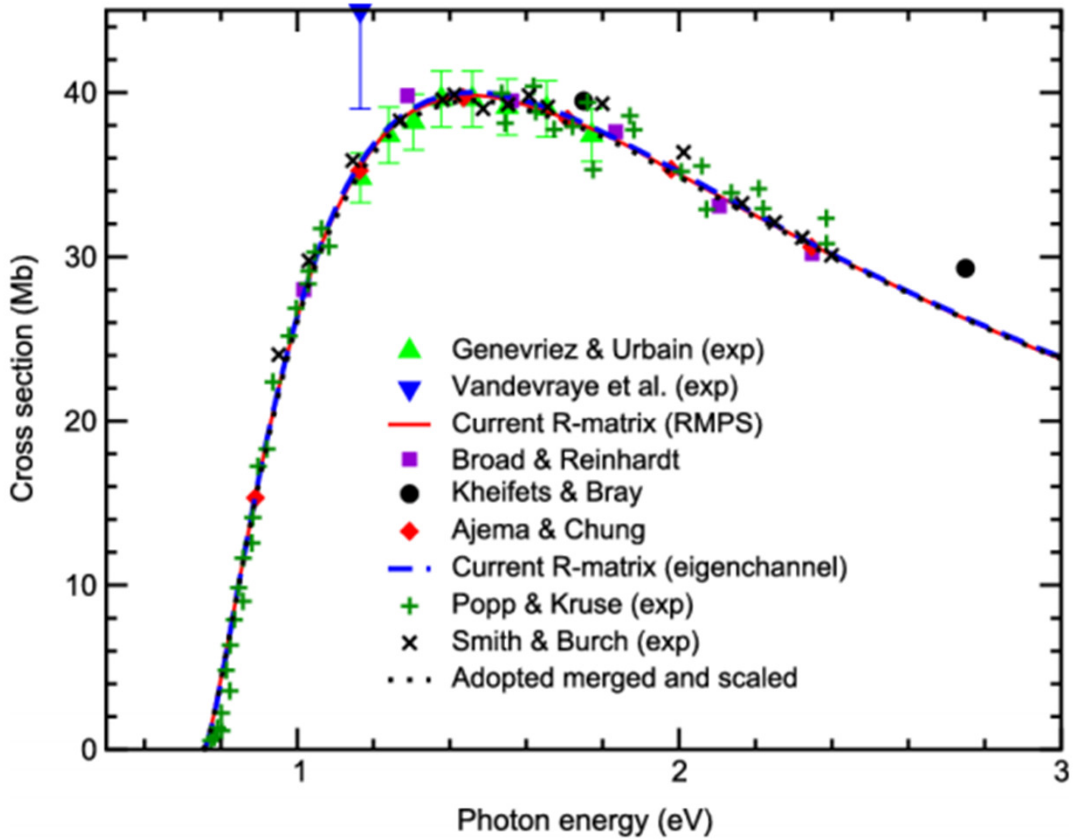


$Q=20=P_{th}/P_{in}$

$$R_{eh} = \frac{P_e}{P_{th}} = \frac{\eta_{th} P_{th} - P_r}{P_{th}} = \frac{\eta_{th} Q P_{in} - P_{in}/\eta_{au}}{Q P_{in}} = \frac{\eta_{th} Q - (\eta_{au})^{-1}}{Q}$$

Photo-neutralization, how?

The main technological challenge is the level of optical power required (several MW), due to the small cross section of the process



(Mclaughlin et al. 2017)

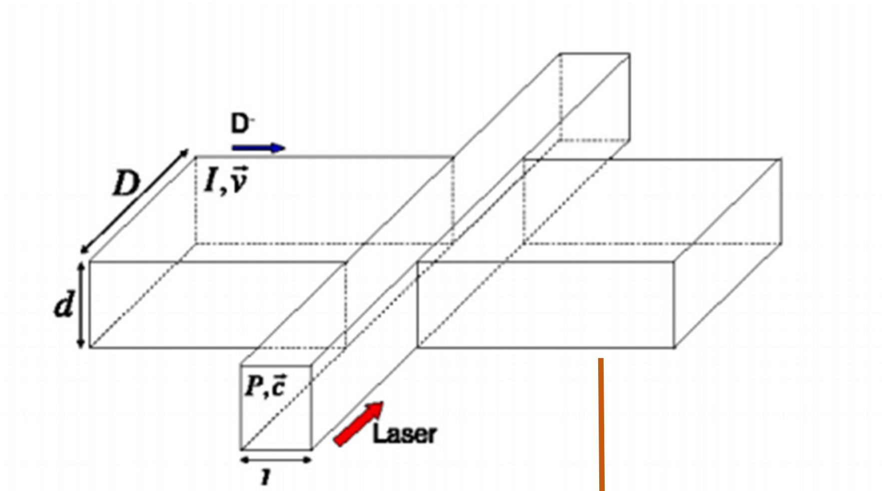
Photo-neutralization, how?

$$\frac{dn}{dt} = -\frac{\sigma}{S}\frac{P}{h\nu} \times n$$

Exponential decrease of ion population

$$P_s = \frac{hc||\vec{v}||d}{\lambda\sigma(\lambda)}$$

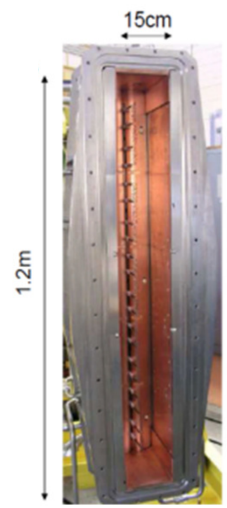
Neutralization rate of 1-1/e=63%



The source should produce laminar ion beams

- Deuterium @1 MeV acceleration energy $\rightarrow ||\vec{v}|| \cong 10^7$ m/s
- $d \cong$ a few cm
- $\lambda \cong 1.064\mu m \cong 1.2$ eV
- $\sigma \cong 10^{-21}$ m^2

$\boxed{P_s \rightarrow \textbf{a few MW}}$



(Simonin et al. 2015)

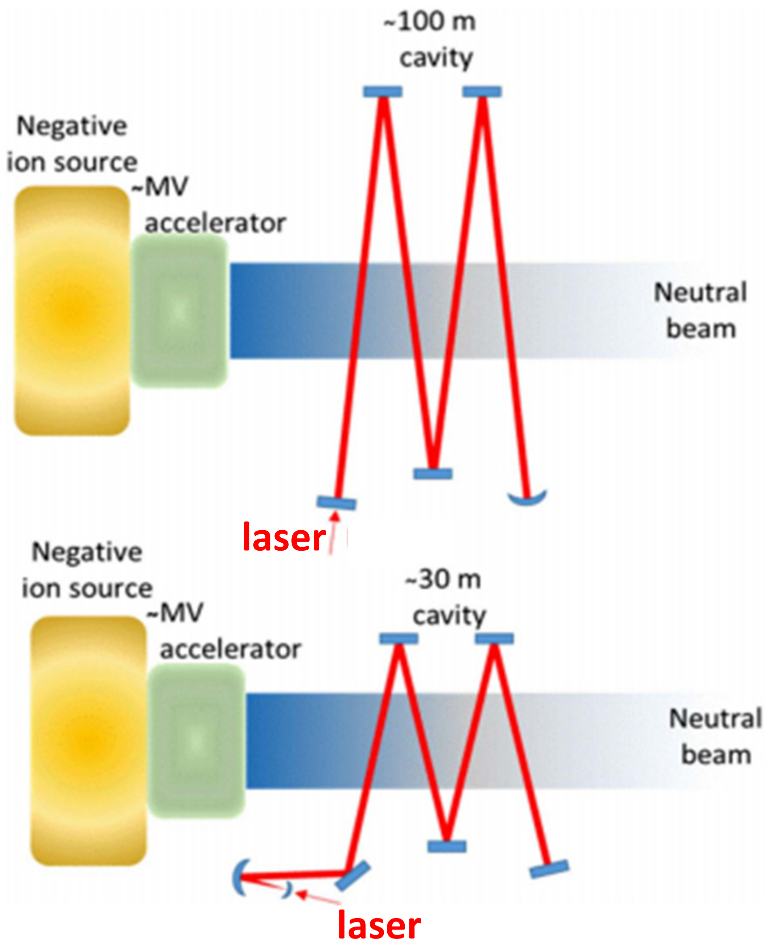
Photo-neutralization, how?

Optical power in the range of MW → direct illumination of ion beam is forbidden, some form of light trapping is required:

- Resonant optical cavity;
- Non resonant optical cavity with second harmonic trapping;
- Other concepts to be explored (e.g. FEL).

Photo-neutralization, how?

Resonant optical cavities



(Fiorucci et al. 2018)

Issues:

- Design of the cavity to fit the ion beam geometry and the space availability;
- Cavity stability (reduced sensitivity to misalignments);
- Thermal effects due to the high level of *intracavity* optical power.

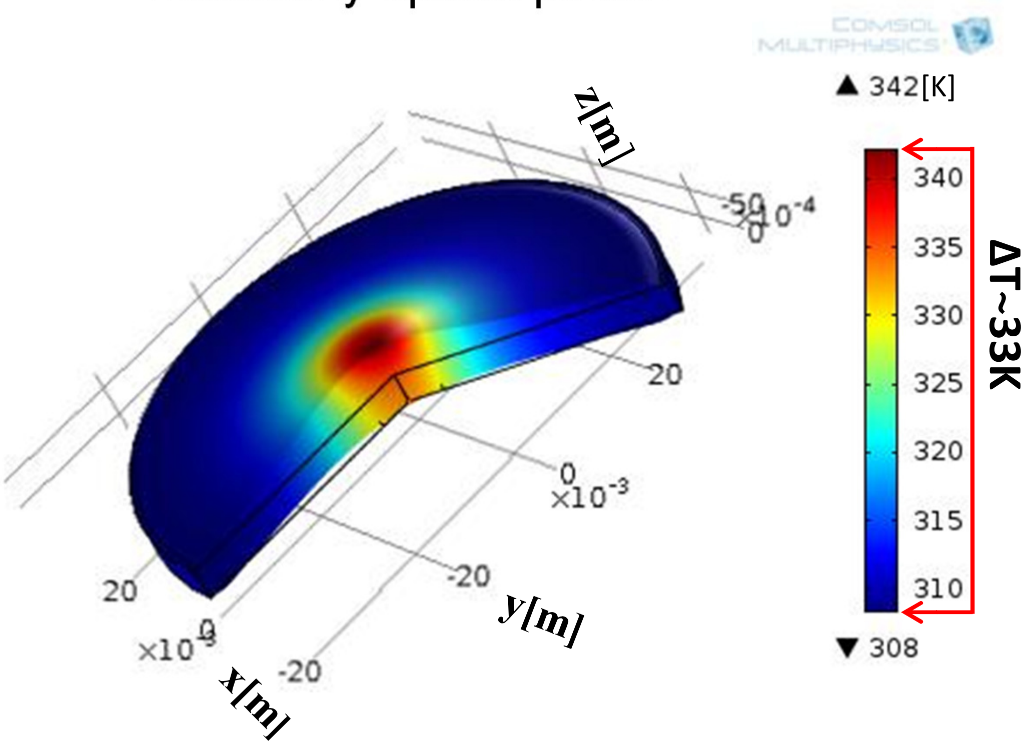
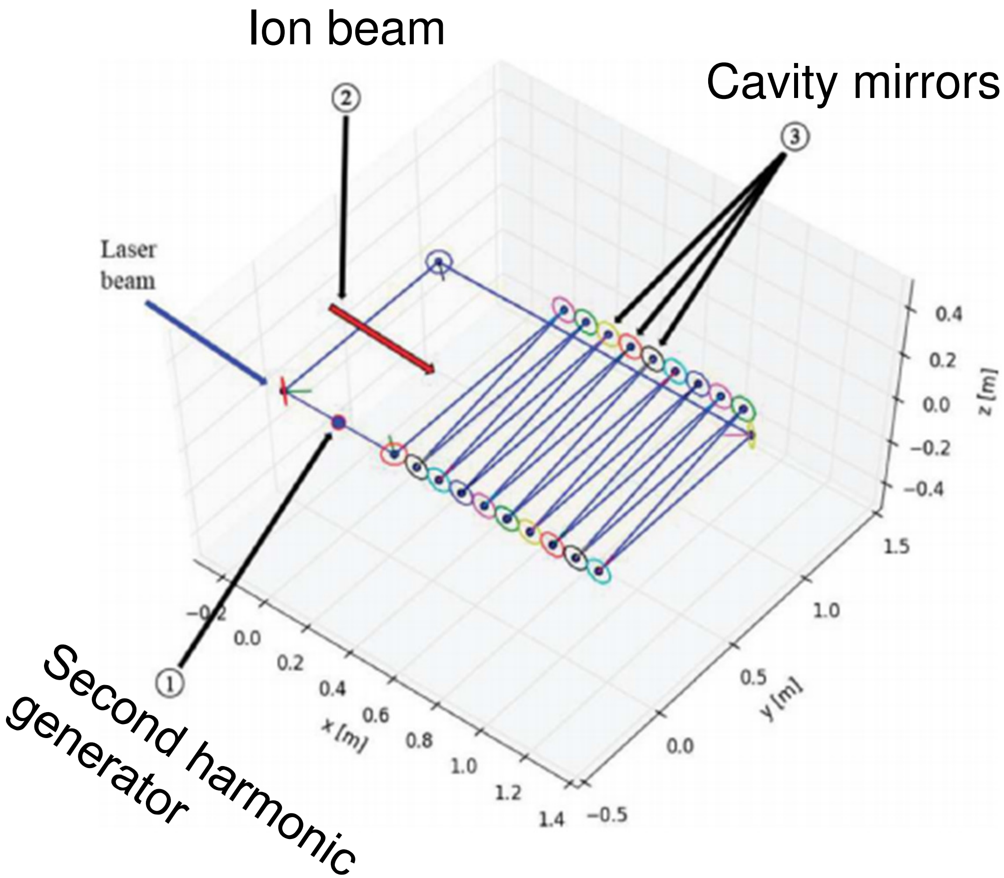


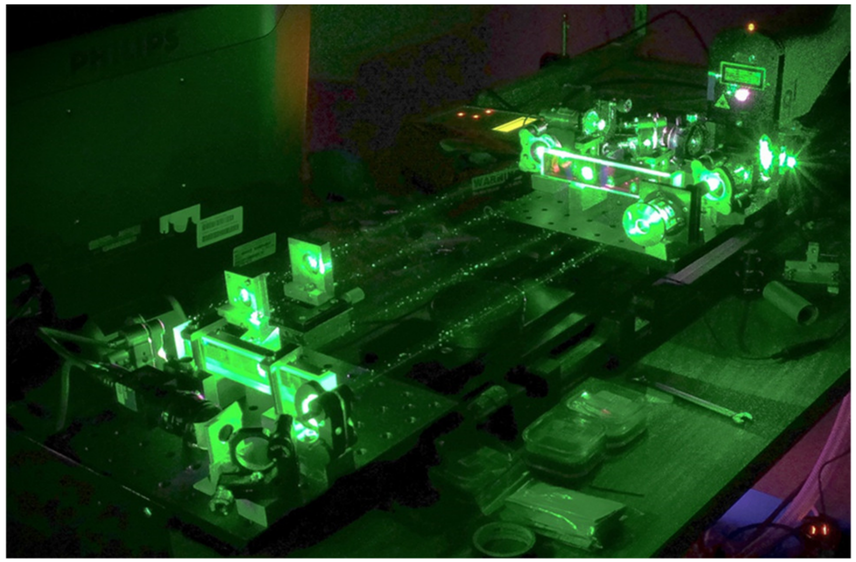
Photo-neutralization, how?

Non resonant optical cavities with second harmonic trapping



Issue:

- **Pulsed laser,** required repetition rate ≅ MHz, pulse length 100 ps, a few mJ.



(Fassina et al. 2016)

Photo-neutralization, how?

Resonant vs non resonant optical cavities with second harmonic trapping

Resonant optical cavities allows for a higher enhancement of the input optical power e.g. 1kW of input laser power can be used to obtain 10 MW of intracavity laser power, Input power amplification factor: about 10^4.

Resonant optical cavities are more affected by thermal effects, since the power gain can be strongly reduced by mirrors thermoelastic deformations.

Non resonant optical cavities have lower amplification factor (100-300) of the input laser power e.g. a few tens of kW of input laser power are required to obtain MW of intracavity laser power

Non resonant optical cavities are less affected by thermal effects, since the power gain is less sensitive to mirrors thermoelastic deformations, the most sensitive element is the non-linear crystal

Photo-neutralization, how?

Optical power in the range of MW → direct illumination of ion beam is forbidden, some form of light trapping is required:

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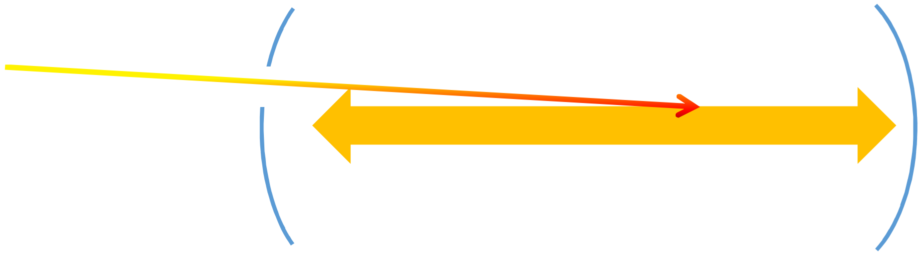
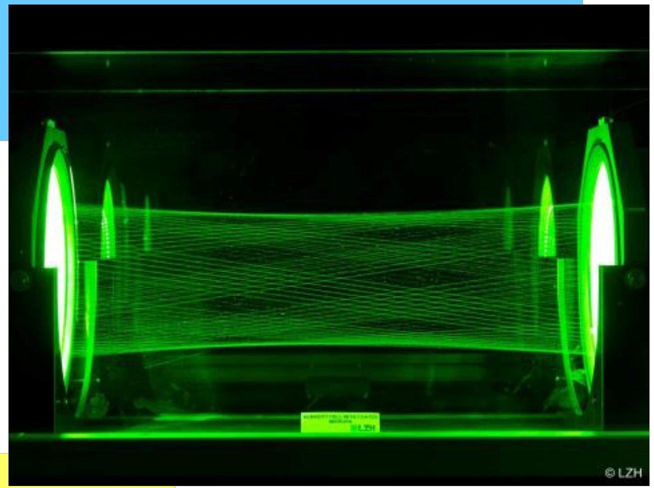
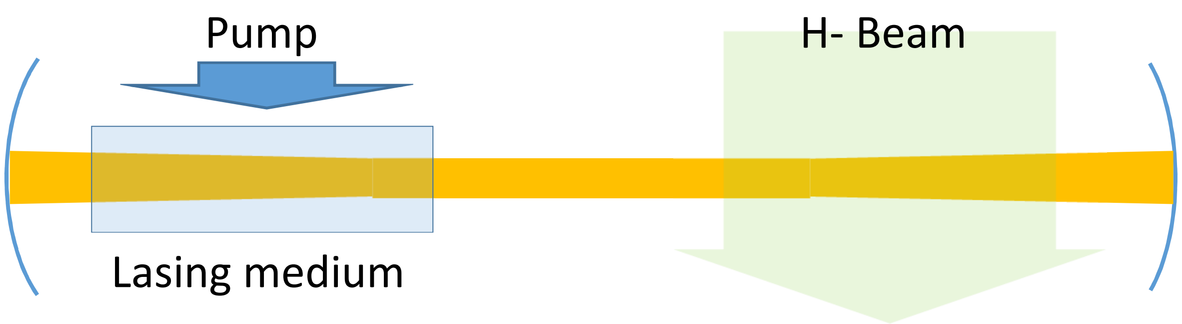
Other concepts

Multipass cavity: the beam enters from a hole in one of the cavity mirror and diffuse.
-Generalization of Herriott cells





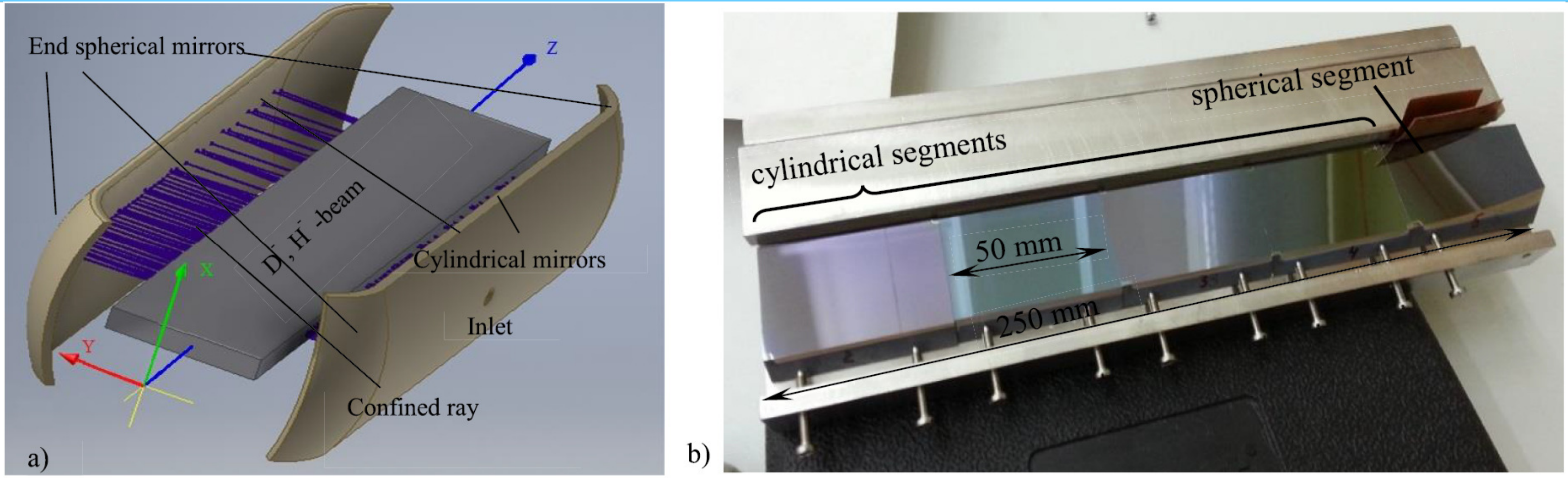
Internal lasing: old concept but difficult to implement
(full power recirculating on laser medium)



Multipass cavity

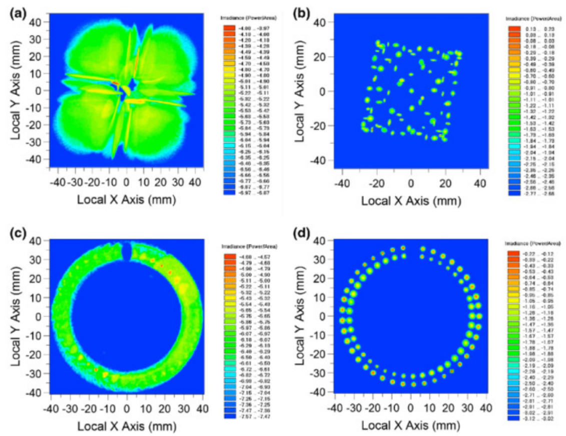
Adiabatic photon trap concept.

Easy to implement:
In the hypotesis of beam diffusion and high reflectivity (R ~ 1),
losses per roundtrip are of the order of A_{hole}/A_{mirror}, probably up to a few hundreds.

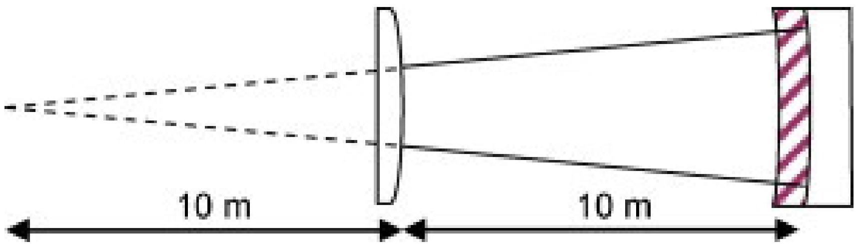


Demonstrated on small beams (Popov et al. Nucl. Fusion 2018)

To be assessed:
-Beam patterning (in Herriott cell the beam defines periodic structures)
-Control of hot spots on mirrors



Internal lasing: standard

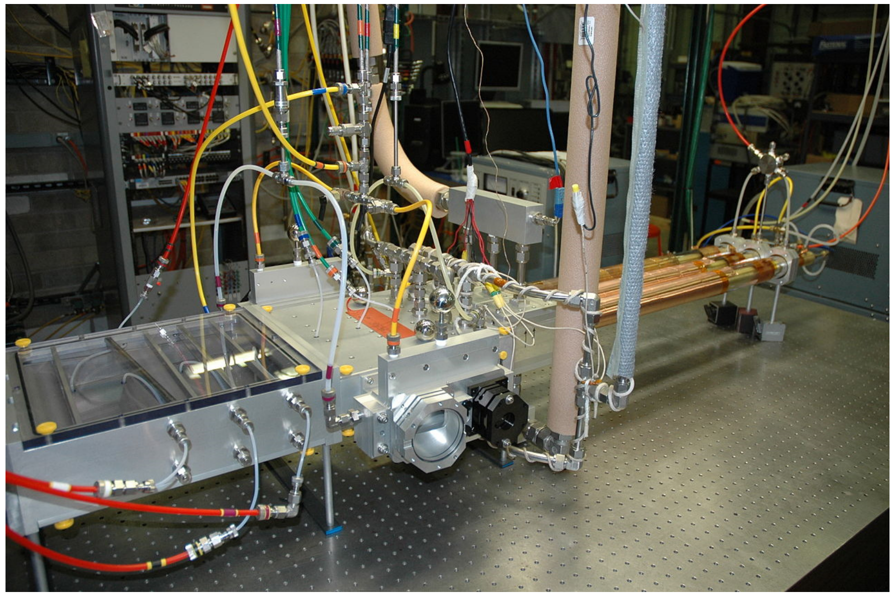


Kovari, Crowley (2010) concept:
-thin disk architecture,
-marginally stable cavity (concentrical)

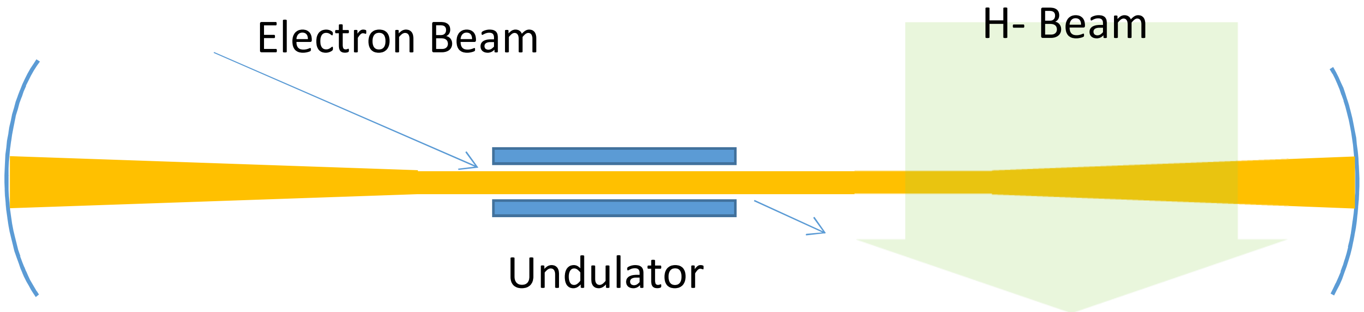
Up to date no practical implementation:
- “Naïve” optical analysis
-Alignment problems (needed both a large footprint on medium and a small one on the beam)
-Absorption losses and thermal management of lasing medium.

A high power gas laser would solve most problems:
Low beam distortion, no medium damage.
low residual absorption, only thin windows (Brewster) needed.

Unfortunately, no high power laser is available at ~ 1 um, except for EOIL (Electrical Oxigen Iodyne Laser).
-Closed cycle version of COIL (multi MW), lasing by Iodine collisionaly pumped by Oxygen in singlet state.
-Unfortunately up to date only 500 W obtained



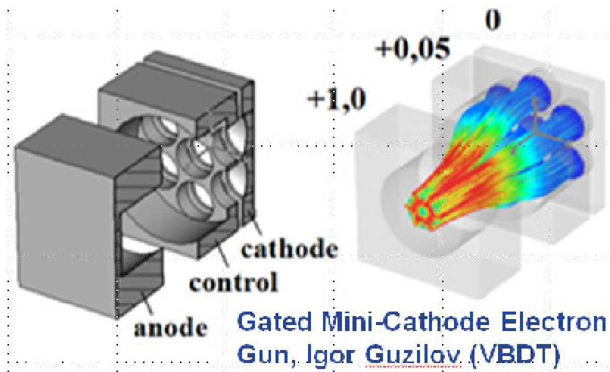
Internal lasing: FEL



No evident absorption mechanism, efficiency not high (some %) but maybe acceptable.
e beam energy 70-80 MeV, for lasing @ 1 um -> RF accelerators.
Optical problems :
  Thin waist in the undulator, low divergence (RL ≈ undulator L). Loads on mirrors?
Cost problem:
  use room temperature linacs (compact, cheap), but must be fed in burst mode
  use superconducting linacs (bulky, costly) in CW

Operation in burst mode: Klystron repetition rate currently is only few tens of Hz; in order to keep the optical power stable must be:
t_{rep} << photon lifetime ≈ 10-100 us.

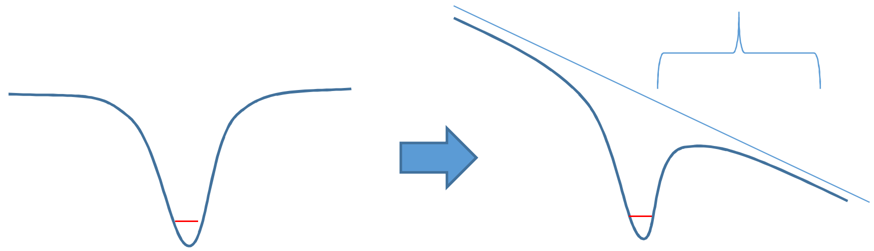
Is there a way out ? Gated klystrons (triode gun)?
Ongoing development



Gated Mini-Cathode Electron Gun, Igor Guzilov (VBDT)

Exotic concepts

Field effect enhancement:



$E \approx V_{ph}/R_{ion} = 0.8 \;/\; 200\text{pm} = 3 \cdot 10^9 \text{V/m}$

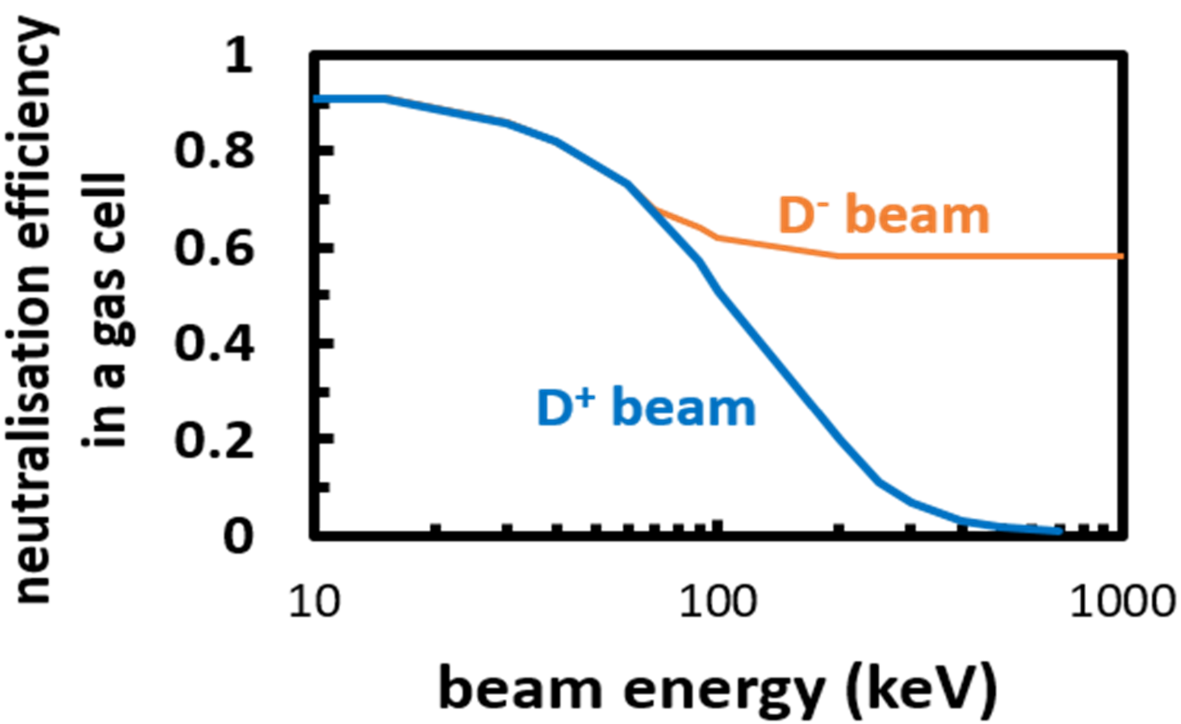
$I = cn\varepsilon_0 |E|^2/2 \approx 2 \cdot 10^{12}$ W/cm^2 or lower (tunneling)

Cross section modulation:

-Resonant modulation in cross section near lower threshold due to combined effect of electric and magnetic field (emersion of Landau-like levels), pumping times / intervals

-Unlikely to be useful due to strict requirement on photon energy and magnetic field uniformity

THANK YOU!



neutralisation efficiency
in a gas cell
1
0.8
0.6
0.4
0.2
0
10
100
1000
beam energy (keV)
D- beam
D+ beam